Fermi National Accelerator Laboratory

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Contributions to the Second Workshop on Medium Energy Eletron Cooling - MEEC96

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Contributions to the Second Workshop on Medium Energy Electron Cooling

Fermilab, 12 – 14 February 1996

(MEEC96)

J. MacLachlan, Editor

12 January 97

Preface: The Second Workshop on Medium Energy Electron Cooling MEEC96

J. MacLachlan, organizer

12 – 14 February 96

This second workshop on medium energy electron cooling (MEEC96) differed from its 1995 predecessor in soliciting attendance from a more general cohort of beam physicists. The 1995 workshop had as its principal goal a friendly review of the plausibility of cooling 8 GeV $\bar{p}$'s in a ring with the same circumference as the Main Injector, so generally invitations were directed to a few people selected to give expert guidance, and no attempt was made to generate formal proceedings. The premise for the 1996 gathering was to set a critique of Fermilab's R & D effort in the context of interests elsewhere. The organizer had the benefit of an advisory committee via e-mail. The members were

Nikolai Dikanski	BINP	Novosibirsk
Peter Schwandt	IUCF	Bloomington IN
Dag Reistad	the Svedberg Laboratory	Uppsala

Perhaps because the active constituency for medium energy cooling development is rather limited, about half of our thirty participants came from the twenty who attended the first workshop. Nonetheless, seven institutions from five countries were represented here. It appears that there is some interest in medium energy electron cooling at other labs but no imminent projects. Because there were no advance submissions, the initial agenda was set primarily to address Fermilab's specific plans.

MEEC96 was a workshop devoted primarily to discussion within four working groups, not a mini-conference of prepared reports. Therefore, although there are contributions bearing the name of a single author, much of what we learned came in extemporaneous discussion of the issues posed to the participants. The original plan to produce formal proceedings has been dropped because of the limited number of participants willing to write up their own contributions and because of the difficulty of converting free-wheeling discussion to the written word. However, the participants were very responsive and energetic in addressing the questions raised by the organizers; nearly every concern was considered at some level and several points were largely resolved. Perhaps more importantly, a few matters that had not been anticipated were raised and explored in the discussion.

As indicated, the following papers are not the proceedings for MEEC96. They would have been included in a full proceedings and contain an important fraction of what was considered. Perhaps an appropriate title for the collection would be something like "Selections from MEEC96", where the selection criterion has been what the originators were willing to put in writing. Perhaps the organizers of MEEC97 will discover a better technique for capturing a full representation of the workshop accomplishments.

Although the emphasis was certainly on the working groups, the workshop began with some talks in plenary session and the participants were gathered for other talks again during the workshop. The following plenary talks were presented:

1. The Fermilab Setting — Recycler, Stacking, Recycling, TeV33 (Gerry Jackson)
2. Present Concept and Provisional Parameters (Sergei Nagaitsev)
3. Status of R & D Activities and Plans (James MacLachlan)
4. Physical Installation of Pelletron and Electron Cooling System (Patrick Hurh)
5. Magnetization in Relativistic Electron Cooling (Vasilii Parkhomchuk)

Although the effort to distribute proper proceedings has foundered, it should be understood that the workshop itself was a resounding success. The results of the working group deliberations have contributed substantially to understanding the problems of medium energy cooling. Many participants added bits big and little here and there, but the discussion would not have been nearly as productive without the efforts of the working group leaders and their Fermilab associates. The organizer gratefully acknowledges their essential contributions. The working groups were

Working Group	Group Leader	Associate
Beam dynamics, stability, *etc.*	Nikolai Dikanski, BINP	Pat Colestock
Transport and cooling region	Sergei Nagaitsev, FNAL	Kirk Bertsche
Guns and collectors	William Herrmannsfeldt, SLAC	Thomas Kroc
Instrumentation and diagnostics	Gerry Jackson, FNAL	David Anderson

The topics for the working groups were chosen by the organizer. Participants started to amalgamate by joint group meetings almost from the beginning. As they expressed their interests and exercised their initiative, several found it more effective to work with the group for the cooling region, *i.e*, to relate their work more closely to the details of the current conceptual development. By the end of the workshop, those who started with theory or gun and collector issues were spread between the transport and cooling region group and the instrumentation group.

It was the goal of the workshop to advance understanding of the general character of the challenges to be met and to make incremental progress on design issues. In this it was rather successful. Therefore, there are tentative plans to continue the series with a next meeting in Novosibirsk. There will almost surely be changes in style, organization, the number of working groups, and the principal topics, but the emphasis will probably remain on working group sessions.

Organizer's Greeting

James A. MacLachlan

12 February 96

Fermilab's Tevatron collider will remain the principal facility for the experimental study fundamental particles at the highest energy until early in the twenty-first century. It is expected that the program during these years will include detailed study of top states as well as more speculative hunts for evidence of supersymmetry and the Higgs particle(s). The estimates of the luminosity required to fulfil program goals in this time frame are $\mathcal{L} \geq 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Because the $\bar{\mathrm{p}}$ tune shift is practically at its limit in the present operating regime, the possibility of significant luminosity gains rests on providing many more cooled $\bar{\mathrm{p}}$'s. It appears that microwave stochastic cooling of stacks ten times the present $1 - 2 \cdot 10^{12}$ is at the very least prohibitively expensive and quite possibly impracticable technically.

Fermilab has chosen to develop electron cooling of the 8 GeV antiprotons as the enabling technology. The idea is not entirely novel. It was suggested by the original designers of the Antiproton Source as an addition to the Accumulator cooling system. However, availability of the Recycler as a second stage accumulator adds new appeal to this old idea.

You could be here for any of several reasons having to do with experience in electron cooling, high brightness beams, storage rings, etc. Probably most of us at Fermilab are stimulated by the chase, be it for the holy Higgs or maybe an iconoclastic preon. Because we need medium energy electron cooling, we are setting about to learn how it can be done. We are asking for the help and encouragement of our visitors at this workshop and others in the beam physics community. It is our hope that a community of interest exists which will benefit directly from the things we discuss here. Because we expect to have a real project, we are likely to advance the technology to the benefit of other labs and bring some venerable ideas to fruition. We intend that there shall be later workshops where we share results of our efforts and help to serve a growing community of medium energy coolers. To each and all warmest greetings!

We are going to start out with some plenary talks and then divide into four working groups:

1. Beam dynamics, stability, *etc.* – a.k.a. "Theory"
2. Transport and cooling region design
3. Guns and collectors
4. Instrumentation and diagnostics

The choice of subjects for the working groups reflects some of our major concerns at the moment. However, it doesn't seem as though they are too narrow to accommodate the general interests of our visitors as well as the Fermilab development team. I hope that we will be able to look at a fairly broad range of subjects in enough detail to be useful and interesting. I list some possibilities below recognizing that not all can considered in meaningful depth in three days:

1. For medium energy cooling in general
   (a) look at physics fundamentals - stability, etc.
   (b) consider possibility of magnetized cooling
   (c) survey potential projects elsewhere wrt. to commonality & special needs
   (d) status and potential of hardware, instrumentation, and diagnostics
2. For the Fermilab Recycler system
   (a) examine appropriateness of parameters
   (b) review optics including acceleration and deceleration
   (c) examine gun and collector needs
   (d) develop instrumentation and diagnostics requirements
   (e) understand high voltage issues
   (f) comment on magnetic shielding, facility layout, *etc.*

I suspect that my preconceived categories and priorities will be developed by you in response to the experience and interests brought to the workshop. We have tried to make arrangements that will be sufficiently flexible to accommodate some improvisation.

Status of R & D Activities and Plans

J. MacLachlan

12 February 96

Program Goals

Electron cooling has been identified as the most promising means to enable the proposed 8 GeV Recycler storage ring to accumulate the low-emittance antiproton stack of 10^{13} or more needed to reach luminosity of 10^{33} cm^{-2}s^{-1} in the Tevatron, a goal which has been given the label TeV33. When the R & D effort was initiated in April 1995, the scope was restricted to the development of a system which would enable the Recycler to triple the official luminosity target then associated with the Main Injector (MI) project, *viz.*, from $8 \cdot 10^{31}$ to $2 \cdot 10^{32}$. Another guideline for the newly established group was to drop any consideration of cooling and bunch preparation for the protons, making a considerable simplification of the electron beam transport without important cost to Tevatron performance with Run II[1] parameters. In the mean time it has been concluded that the Recycler will be able to make its design stack using stochastic cooling; therefore the justification for proceeding with the Recycler does not depend on anticipating the success of electron cooling research. Right from the start, the $2 \cdot 10^{32}$ goal was considered by the developers as a step on the way to TeV33. The first steps in the electron cooling development program have not changed very much as a consequence, but *the de facto goal has changed slightly.* The programmatic goal is to produce during the collider Run II time frame (1999 – ~ 2002) an electron cooling system, robust enough for routine operation, having significantly higher performance than the stochastic cooling system in the Recycler. Furthermore, the design should be suitable for incremental improvements to the TeV33 level over an additional three years or so. Whereas initially the charge to the group was to realize a system with the electron beam current of 200 mA thought to be adequate for initial Recycler operation, that beam current value now serves to characterize the scale of one of the technical challenges but has little meaning as an end in itself. This change in emphasis has important consequences for how we proceed in the rather near future. If we conclude that a system which we could develop to run well with a 200 mA electron beam would be fundamentally inappropriate with a beam current of

2 A, in the present context we are obliged to reject the low current design. When the initial operation of the Recycler was to employ electron cooling, we could rationally consider getting a minimal system working as quickly as possible and scrapping it totally at some later time.

We have a document, a living document as one might say, called "Fermilab Electron Cooling R & D Work Plan" with a last version date of 7 February, just a week before this workshop. I quote the first paragraph below; it was probably outdated in some respects on its release date. The words "...disassembled and installed ..." refer to a plan to prototype the system in totality in the Neutrino Area experimental enclosures with precisely the geometry required by the MI layout and then to make a drop-in installation in the MI tunnel when everything appears to be functioning smoothly. After you hear Pat Hurh's description of what the Pelletron installation entails you may guess that doing it twice could be expensive, even if an existing shaft and tunnel in the bubble chamber area are used for the development site. Indeed, we are at a stage where it is still timely to examine whether a Pelletron-based system is the most promising.

> The goal of the Fermilab electron cooling R & D project is to prove medium energy electron cooling in support of the Recycler ring. In order to achieve this goal, it is necessary to conduct a number of parallel research efforts. For instance, the propagation of space charge dominated beams over very long distances and through small radius dipole magnets must be understood in order to design the optics for the electron beam recovery in the 5 MeV Pelletron. Because of financial limitations and long lead time components, a phased hardware approach to the facility has been proposed which ensures that as much knowledge about medium energy electron cooling issues is learned as soon as possible. The final phase of this R & D will be an exact working model of the Recycler ring electron cooling system. The intention is that once the system is fully commissioned and understood, it would be disassembled and installed into the Recycler. In addition, electron recirculation tests at the NEC corporation in Wisconsin will take place in parallel. The goal of these tests to demonstrate high efficiency electron collection with a Pelletron.

In the year since the first workshop we have held a five-week internal spring study and established a dedicated R & D group. The organizational changes are significant and promising. There are now four people full-time in the R & D group with a part-time project leader; the effort draws on several more at about the 50 % level — giving in round numbers 10 full-time equivalents. In response to time pressure we are trying to exploit existing facilities and make novel adaptations of standard hardware. Three generally complementary experimental activities are proceeding in parallel, *viz.*, electron beam collection efficiency experiment, optics development using a proton beam analog, and higher peak current optics tests using a modified medical electron accelerator. Each of these activities will be described separately. Serious work has started on system design, beam optics experiments, a high efficiency charge recovery experiment, and beam dynamics calculation and simulation. "Started" is the right word; we can tell you what we want to do and how we are currently attempting it, but we can not fuel this workshop with lots of firm results. We are still working with the IUCF proposal for the SSC MEB as a baseline concept.[2] This is a time when a perceptive comment or qualitative conclusion can have a very big leverage on future detailed efforts.

Development Lab

A Pelletron is big and expensive and requires significant time for procurement and installation. We need to try out our schemes for transport and cooling region optics very soon. However, to a very good approximation, the electron beam we need behaves the same as a proton beam of much lower current and energy.[3] The 200 mA electron beam of 4.3 MeV with rms emittance 10^{-6} m has the same beam perveance and momentum as a 12.5 keV proton beam of 60 nA and the same physical emittance. Duoplasmatron proton sources were used at Fermilab before the change to H^- charge exchange injection more than twenty years ago. We are developing what we call the proton analog using one of the original sources. To run continuously we want to reduce the source pressure to keep gas load tolerable. To avoid cooling problems we want to keep the arc current low. We quickly discovered that these are ideal conditions for surface charge exchange; our duoplasmatron produces much more H_2^+ and H_3^+ than protons. Therefore, it has been necessary to put in a bend for mass selection as indicated in the schematic layout in Fig. 1. Downstream of the bend is a pinhole iris to produce the desired emittance. Beam current will be controlled by source current and by the focus of the beam on the iris. Despite some reservations about detailed differences in the beam phase space and interaction with background gas, the proton beam is expected to provide an excellent model. We will know more about the momentum distribution as we begin to work on the bends in the transport system. It has a practical advantage in not producing ionizing radiation; therefore hands-on work can proceed without radiation safety concerns.

For some experiments the difference between electrons and protons might be crucial. One of our earliest ideas for getting a quick start on beam experiments was to use an inexpensive 4.3 Mev rf accelerator. Because the standard 5 MeV medical accelerator is now available as a surplus item, this is an inexpensive approach so long as the poor beam quality is not an issue. We are setting up a shielded enclosure in a external beamline tunnel to work with a modified medical accelerator being acquired from Idaho State University.[4] The pulse can be set long enough to study dc beam conditions, and there is plenty of beam current available for the study of intensity dependant effects to well above our initial target. The program for this facility is not quite so well defined as that for the proton analog, but it is certain that it will be convenient for tests of instrumentation and diagnostics.

Tests of charge recovery efficiency

From the first speculation about the possibility of electron cooling of 8 GeV antiprotons at Fermilab,[5] it has been understood that the level of efficiency of energy recovery from the electron beam would need to be quite good from the standpoint of economy in power supply capital cost and operational power. Indeed, thinking about medium energy electron cooling was stimulated by the efforts of a group at UCSB to develop cw free electron lasers based on a Pelletron electrostatic generator as an accelerator/decelerator.[6] This device was already in the 1980's a mature technology with good reliability and excellent energy regulation. The limitation on charging current to a few hundreds of μA raised the issue of efficient charge recovery to the highest priority. The UCSB group succeeded in circulating 1.2 A at 2.5 MeV with 99.4 % charge recapture. This is not sufficient to sustain dc operation but was adequate for good pulsed service. An effort using the same Pelletron at National Electrostatics Corporation by U. Wisconsin, Fermilab, and NEC personnel attained 100 mA continuous beam with about 99.99 % recovery efficiency at 2 MV.[7] However, the attempts to increase the current above this level failed. The source of their difficulty is not known for certain; however, plausible explanations have been suggested. Because IUCF wished to exploit the same approach for cooling at the SSC, they recognized the need to understand these problems and achieve substantially better results for a recirculation demonstration. At the time their project was terminated they had built many components for an improved beam line shown in Fig. 2 and were working on the design of a new gun and collector. The Fermilab group is pursuing the same test using as much of the IUCF apparatus as possible. However, to get going promptly we have elected to use the gun and collector from the original U. WI/Fermilab/NEC experiment. The gun is very similar to the one used in the UCSB tests. If the current should remain limited to $\sim$ 100 mA, a new gun and collector design would be a top priority. However, our preliminary EGUN and envelope equation calculations give reason to hope for considerably better result. In fact at about 500 mA or so the electrostatic focusing of the column and the space charge forces seem to be in nice balance for a nearly constant beam envelope of somewhat less than one centimeter radius. Thus, unless there is unexpectedly bad halo, the beam should fit easily through the one-inch diameter minimum aperture of the NEC columns. Our top priority for this test is to achieve 200 mA or more stably. For this stage of development one half hour of continuous operation has been defined as the criterion for stability. However, we should also learn a lot about how to make beam observations and how to control a Pelletron with standard Fermilab control system hardware and software.

Plans, schedule, *etc.*

We have an R & D plan which still is pointed toward early Recycler operation, *i.e.*, toward about 1999. However, the relative importance of when we have some system and what that system's ultimate capabilities will be has evolved with changes in the plans for the Recycler. Although we believe that there are good prospects that the present baseline design can evolve into a robust cooling system with useful performance, we do not wish to establish firm constraints on this workshop to ignore possibly superior approaches. Certainly if there are difficulties in the current approach, we want to hear about them and what the fixes might be whether or not they require fundamental changes to our present concept. Our time scale is a bit more flexible than it seemed a year ago; however, our standards for what we should accomplish have, if anything, grown more demanding. Although the R & D program charter is explicit about the short-term goal of a system with about 200 mA electron current, the subsequent evolution of the Recycler plans demands potential for upgrade. This workshop should be critical both with respect to concepts and proposed implementation. We will value your insight regardless of whether it reassures us on our course or challenges our current wisdom.

Outstanding Issues

At this stage we have many more questions than answers, and it is not even certain that we have correctly identified the most salient ones. Nonetheless, to indicate the state of our understanding and to provide something reasonably specific for launching discussions at this workshop, I list here a number of issues we have been thinking about or think we need to think about.

- Is 200 mA of electrons enough to surpass the stochastic cooling in the Recycler?
- Will it be satisfactory to have some $\bar{p}$ outside of e-beam radius? What is optimum radius?
- What simulations should we do? Available code?
- What types of instability should we be watching for?
- What will be effect of electron current on p-bar dynamics?

- What vacuum is required in the cooling straight?
- What clearing fields are required?
- What neutralization is tolerable (or perhaps desirable)?
- How well does the proton analog mimic the electron beam?
- What are the most promising concepts for a high efficiency collector? Primary energy selection by bend? Magnetic trap for neutralizing ions?
- Which kind of focusing element for electrons in the cooling straight? Electrostatic quads? Solenoids?
- How much emittance growth from achromatic bend at high current? Acceptable bend radius as a function of electron beam current?
- What instrumentation will be needed to obtain alignment of $\bar{p}$ and electron beams to within $\sim \pm 40\mu$rad over a 66 m cooling section?
- What diagnostic devices are needed? How do we cover the dynamic range 10μA – 200 mA (2 A)? What frequency to modulate beam for BPM's?
- Practically speaking, how does one shield the 66 m cooling straight to mG levels in presence of time dependent stray field of Main Injector?
- How will we tune up beam? For example, raise dc current in small steps or pulse a higher current beam in progressively longer pulses? Would a variable perveance electron gun be practical?

References

[1] Collider Run II Design Handbook, Stephen D. Holmes, ed., accessible from http://www-fermi3.fnal.gov (1995)

[2] MEB E-Cool Design Report 1992, Indiana U. Cyclotron Fac. (October 1992)

[3] James D. Simpson, private communication. The idea for using protons was suggested to us in conversation.

[4] Idaho Center for Small Accelerators, Idaho State U., Frank Harmon, Director

[5] Frederick E. Mills, The Use of the FEL Gun for Electron Cooling, Fermilab internal note, p-bar Note 144 (22 July 81)

[6] L. R. Elias and G. Ramian, Recirculating Electrostatic Accelerators, IEEE Trans. Nucl. Sci. **NS-32**, No. 5, 1732 (1985)

[7] D. B. Cline *et al.*, Intermediate Energy Electron Cooling for Antiproton Sources Using a Pelletron Accelerator, IEEE Trans. Nucl. Sci. **NS-30**, No. 4, 2370 (August 83)

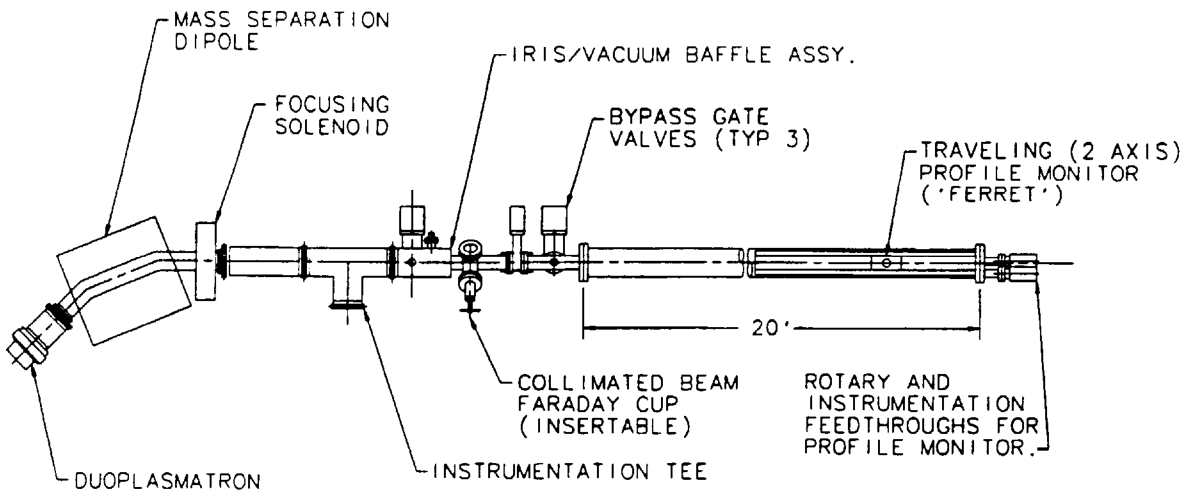

Figure 1: Proton source for a 12.5 keV analog of the 4.3 MeV electron beam

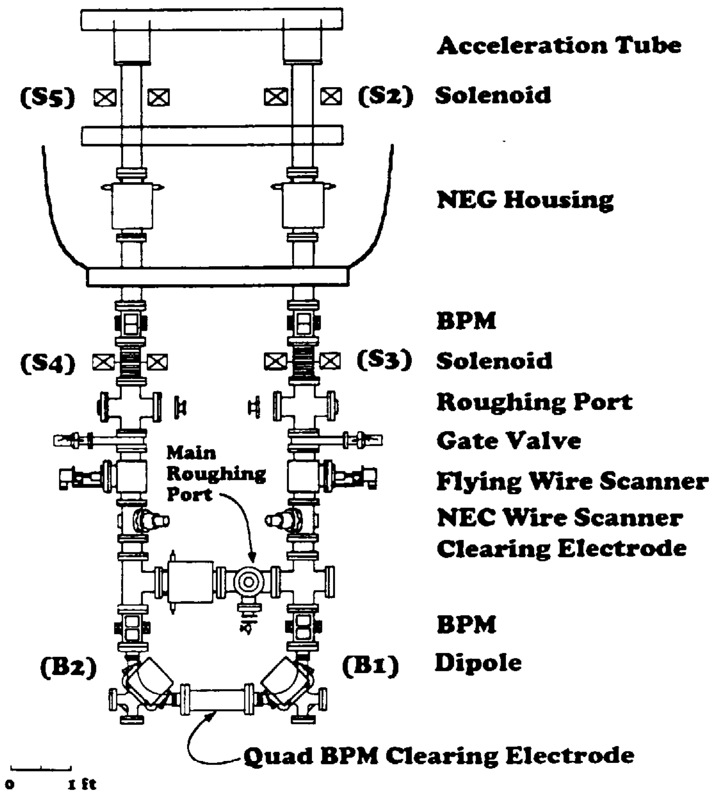

Figure 2: 2 MeV beam recirculation test transport line for 3 MeV NEC Pelletron

Electron Cooling for the Fermilab Recycler: Present Concept and Provisional Parameters

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February 12, 1996

Abstract

In all scenarios of the possible Tevatron upgrades, luminosity is essentially proportional to the number of antiprotons. Thus, a tenfold increase in luminosity could be achieved by putting five times more protons on the antiproton production target and gaining an additional factor of two from recycling antiprotons left over from the previous store. Stacking and storing ten times more antiprotons puts an unbearable burden on the stochastic cooling system of the existing Accumulator Ring. Thus, one is led to consider an additional stage of antiproton storage – the so called Recycler Ring. Electron cooling of the 8 GeV antiprotons in the Recycler could provide an attractive way around the problems of large stacks. Such a system would look much like the IUCF proposal to cool 12 GeV protons in the SSC Medium Energy Booster [1]. Although electron cooling has now become a routine tool in many laboratories, its use has been restricted to lower energy accelerators (< 500 MeV/nucleon). An R&D program is currently underway at Fermilab to extend electron cooling technology to the GeV range. This paper describes the electron cooling system design as well as the Recycler ring parameters required to accommodate this system.

1 Introduction

The Recycler is a fixed 8 GeV kinetic energy storage ring. It is located in the Main Injector tunnel directly above the Main Injector beamline. The Recycler beamline schematic is shown in Figure 1. The role of the Recycler ring is to provide

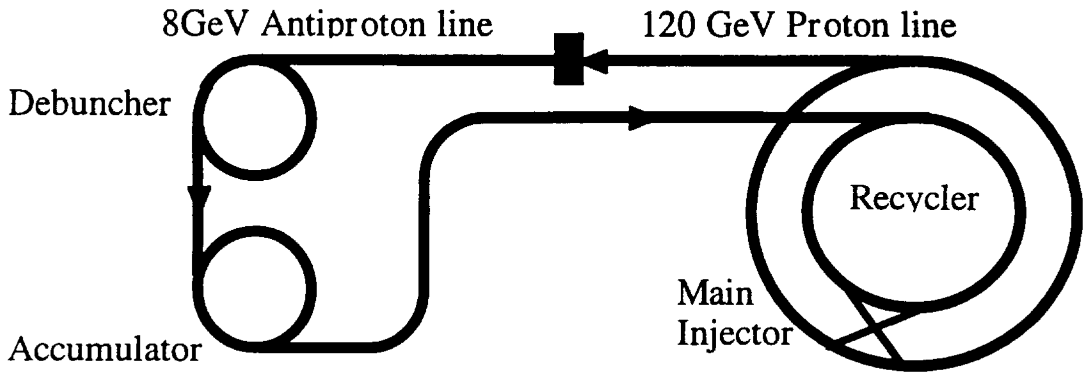

Figure 1: Recycler ring schematic.

more antiprotons for the Tevatron, which proportionally increases luminosity. This is accomplished by acting as a high-reliability post-Accumulator and receptacle for recycled antiprotons from the previous store. Even with the Recycler the problem of stochastic cooling of large stacks of antiprotons remains severe. Electron cooling [2] of the 8 GeV antiprotons provides a potentially attractive way around problems of large stacks. By itself electron cooling could not provide a complete solution to the antiproton cooling pipeline since the initial emittances of the antiproton beams are too large to be effectively cooled with electrons. This was apparently one of the major reasons that it was dropped as a technology under investigation at FNAL in the early 1980's. However, a hybrid system with initial stochastic cooling (in the Recycler itself or in the Accumulator) followed by electron cooling for the final stack has many attractive features.

Primarily, the proposed electron cooling system will have to compensate for a momentum spread increase, resulting from barrier-bucket stacking (see Figure 2). In addition, electron cooling can decrease beam emittance and, thus, relax the dynamic aperture and closed orbit error requirements. Since the electron energy in such a system has to be approximately 4 MeV, the use of traditional electron cooling technology with a Cockcroft-Walton (C-W) power supply and a magnetically-confined electron beam becomes impractical. In fact, compact commercial C-W voltage generators are limited to about 1 MV, about a factor of 3 times higher than the IUCF, CELSIUS, and GSI electron cooling systems. In the medium energy regime Pelletron (Van de Graaff generator type) electrostatic accelerators, having an operating range of about 2-20 MV, would replace the C-W generators. In this regime the continuous longitudinal magnetic field is no longer necessary for focusing, though such a scheme cannot

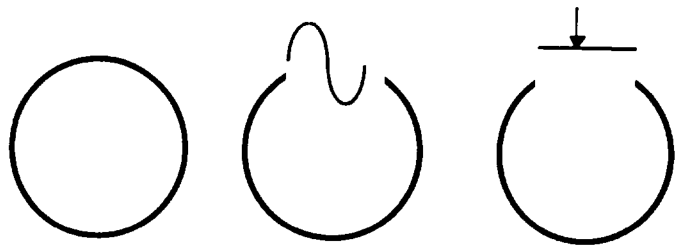

Figure 2: Barrier-bucket stacking: A - circulating antiproton stack, B - barrier-bucket gap ($h = 7$), C - fill gap with batch from the Accumulator ring.

be entirely ruled out. The beam focusing requirements are discussed in more detail below. Table 1 summarizes the parameters for the proposed electron cooling system.

2 Electron Beam Optics

Figure 3 is an overall view of the proposed electron cooling system in the Recycler. The electron beam is generated in the 4.3 MV terminal of a Pelletron accelerator. Two solenoids at the beginning of the cooling straight produce the required beam size and convergence. Following the cooling straight section, the beam is then transported back to the 4.3 MV terminal and collected. The simplest electron focusing channel in the cooling region is a series of very weak solenoids with focal length f_{sol} spaced by the distance L_{sol} . Figure 4 shows a typical 2-m long module incorporating the electron beam optics, alignment, vacuum, and diagnostics system in the cooling region. Each solenoid in this module provides just enough focusing to locally correct the electron beam expansion due to its space charge. Consequently, this section is optically equivalent to a drift: to first order, a particle entering off axis, but with no transverse momentum, will leave the section with the same transverse position and with no transverse momentum. Assuming that the electron beam current density is uniform one can obtain a simple relation, connecting the solenoid focal length, f_{sol} , with other parameters:

$$f_{sol} = \frac{r_b^2}{2KL_{sol}}; \quad K = \frac{I_e}{\beta^3\gamma^3 I_0}, \tag{1}$$

where $I_0 \approx 17$ kA, β and γ are the usual relativistic parameters; all other symbols are defined in Table 1. Thus, by choosing the 2 m long module, this expression gives the solenoid focal length $f_{sol} \approx 184$ m and the maximum beam divergence in this case is

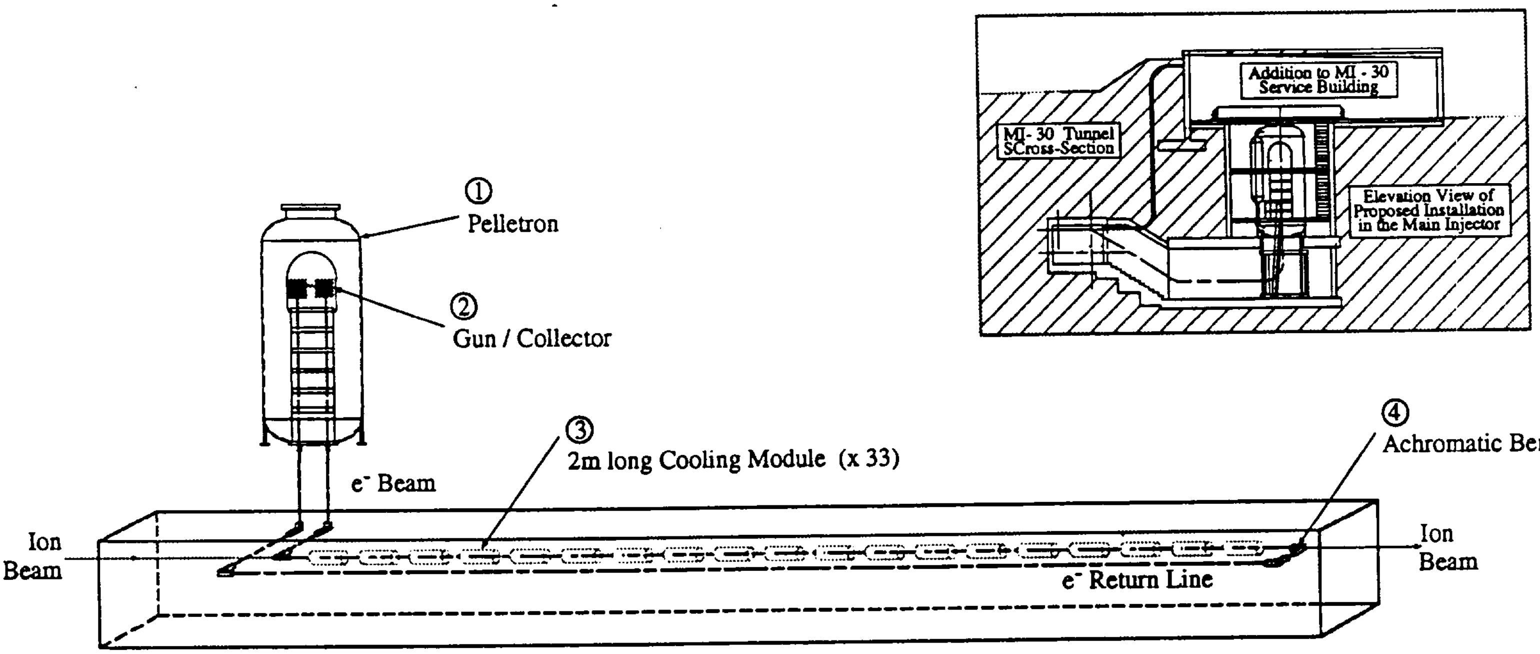

Figure 3: Electron cooling system layout in the Recycler.

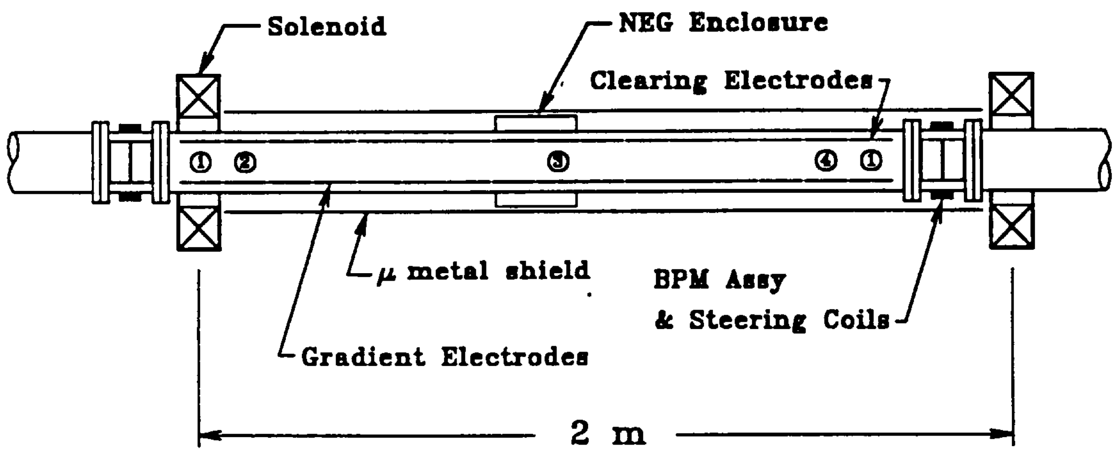

Figure 4: Electron confinement, alignment, vacuum, and clearing system. Every 2 m there ia a solenoid, beam position monitor (BPM) and steerer pair, nonevaporable getters (NEG's), and gradient and clearing electrodes.

$r_b/(2f_{sol}) \approx 27$ μrad.

Such a seemingly simple focusing system is not without drawbacks, however. For example, if the space charge of the electron beam is compensated by a factor of γ^{-2} (≈ 0.01) due to residual gas ions, the electron beam will converge in uncontrollable way (the solenoids can only focus the beam). In addition, suggested focusing scheme is susceptible to various electron beam instabilities, which might turn out to be detrimental for the high current electron beam transport through the cooling section.

3 Charge to the Workshop

The charge to this Workshop is (1) to determine the applicability of the cooling system to the Recycler Ring, and the impact of the cooling system upon the Recycler, (2) to consider the feasibility of the cooling system proposed, and (3) to make recommendations about future activities of the program. In what follows I would like to summirize the issues to be studied at this workshop:

• Possibility of the magnetic confinement for the electron beam transport. This subject includes both technical and physics issues: what value of the magnetic field is needed, how to combine high voltage acceleration tubes and solenoids, how to bend electron beam, *etc.* ?

• Weak periodic focusing: what level of magnetic shielding is required, what kind of focusing elements should be used (quads, Einzel lenses, or solenoids), how to achieve the desired level of ion clearing?

• What are the problems (if any) related to the high voltage tank vibrations? Is there a need for an active orbit correction system?

These are but few issues I felt needed to be addressed at this workshop. You can find a more complete list in the Jim MacLachlan's paper about the status the R&D program in this proceedings.

References

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Table I. Summary of the parameters for the proposed electron cooling system for the Recycler

Parameter	Symbol	Value	Units
Ring Properties			
Circumference	C	3319.4	m
Cooling region length	L_C	66	m
Fraction (L_C/C)	η	0.02	
Cooling region beta-function	β_l	200	m
Antiproton Beam Properties			
Momentum	p	8.9	GeV/c
Norm. rms emittance	ε_n		
stacking		1.6	π mm mrad
recycling		3.3	π mm mrad
Rms momentum spread	$\Delta p/p$		
stacking		2×10^{-4}	
recycling		9×10^{-4}	
Max. antiproton current	I_p	200	mA
Laslett tune shift	ΔQ_{SQ}	0.01	
Electron Cooling System Parameters			
Electron current	I_e	2	A
Electron kinetic energy	U	4.3	MeV
Electron beam radius	r_b	1	cm
Electron beam temperature	kT_e	0.2	eV
Transverse cooling time (stacking)	$\tau_\perp$	90	s
Longitudinal cooling time (stacking)	$\tau_\parallel$	20	s

Physical Installation of Pelletron and Electron Cooling System

Patrick Hurh

12 February 96

Present plans for electron cooling in the Recycler Ring incorporate the use of a 5 MeV electrostatic accelerator run in a recirculated beam mode. Accelerators of this type utilize the basic Van de Graaff generator principle to elevate a terminal to the high voltages required. A Pelletron is a commercially available, but custom built, machine from National Electrostatics Corporation (NEC) that uses a chain of charge carrying pellets rather than a typical Van de Graaff belt. The chain of pellets exhibits wear characteristics more favorable than those of conventional belts and ensures cleaner and more stable operation over the long term. Choosing and sizing a Pelletron for our needs is relatively easy; finding suitable installation sites is more difficult. The physical size of the Pelletron, the radiation created by the generated electron beam, and the hazards associated with a large volume of insulating gas combine to make site preparation for installation complicated and expensive.

A 5 MeV, dual column, vertically oriented Pelletron is roughly 3 meters diameter by 7.3 meters tall as seen in Figure 1. These dimensions are in part determined by the amount of sulfur-hexaflouride gas needed to insulate the high voltage terminal adequately. The insulating properties of the gas are enhanced by pressurizing the gas to around 7 atm, thereby necessitating an ASME rated pressure vessel for the containment vessel. An artist's conception of a 5 MeV Pelletron is shown in Figure 2.

The volume of insulating gas necessary to fill the vessel is estimated at 340 cubic meters (at 1 atm). The possibility of sudden escape of this gas requires adequate ventilation and/or containment measures plus continuous oxygen level monitoring for personnel safety.

Bremsstrahlung of 5 MeV electrons at a loss current of 50 microamp in the acceleration region is estimated to produce X-ray intensities of 7 Rad/sec. Radiation losses due to a mis-steer or sudden obstruction will of course be much higher still (estimated at 87,500 Rad/hr for a 0.5 mA beam current). It is estimated that 1.8 meters of concrete will be necessary to adequately shield the surrounding building areas at any possible Pelletron installation site.

To satisfy our present electron cooling development plan, two Pelletron installations are required, the first at our development lab in the Lab B/NEF Enclosure area and the second at the operational Main Injector service building, MI-30, in the Main Injector ring. The same actual Pelletron and electron beam-line components will be used at both locations. The Lab B installation will allow experimentation with actual high energy electron beam to develop the optics necessary for the cooling straight while Main Injector/Recycler commissioning is taking place. The MI-30 installation is obviously the permanent home for the Pelletron when electron cooling becomes operational. Construction plans for both installations will be discussed here.

Lab B/NEF Enclosure Installation

The research and development effort underway at the NEF Enclosure is planned to continue through three phases. Phase A utilizes the existing NEF Enclosure to house the proton analog source and a small portion of straight beam-line. Phase B involves constructing a major cross enclosure to mimic the Main Injector tunnel cooling straight region. Phase C is the installation of a 5 MeV Pelletron machine at Lab B to tie into the Phase B cross enclosure. This final phase will be constructed as close to the permanent installation beam-line dimensions at MI-30 in order to create an exact working model of the Recycler Ring electron cooling system.

Figure 3 shows a plan view of the NEF Enclosure with the proton analog source on the right and the electron LINAC which will be set up for tests of instrumentation and diagnostics on the left. Note that 1.8 meters of concrete shielding blocks has been added surrounding the LINAC. The NEF Enclosure itself exists above ground in a courtyard directly north of Lab G on the northernmost end of Fermilab's site. It is constructed of a poured concrete slab floor and concrete shielding block walls. The roof is likewise constructed of shielding blocks that have been sealed to protect against adverse weather conditions.

Figure 4 shows a plan view of the NEF Enclosure with the Phase B cross enclosure. The added east-west enclosure passes through the original north-south enclosure and is approximately 73 meters long. It effectively dissects the courtyard between the NEF Enclosure and Lab B as shown in Figure 5. The new cross enclosure will be constructed from pre-cast concrete hoops with the same inside dimensions as the MI tunnel as shown in Figure 6. An earthen berm will cover the hoops to provide the shielding necessary for running high energy electron beam later during Phase C.

Figure 5 also shows the proposed site for the Pelletron installation at Lab B. Lab B is the old fifteen foot bubble chamber building. The Pelletron will be installed in a hydraulic elevator pit just west of the large bubble chamber apparatus as shown in Figure 7. Figure 8 shows an elevation view of the Pelletron in the elevator pit. The electron beam enters and exits the containment vessel at the bottom of the tank. The beam-lines exit Lab B through a below ground stairwell that was originally used as an emergency exit for the bubble chamber experiment. The beam-lines then head upwards at about a 30 degree angle to the Recycler beam-line height above the floor in the cross enclosure. This vertical dogleg in the beam-lines simulates the same vertical dogleg that is necessary in the permanent installation at MI-30 (in order to keep the Pelletron underground).

Figure 9 shows another elevation view of the Pelletron installation at Lab B. This shows the various platforms that will be constructed to provide access to the three entrances to the tank, two side man-way entrances and one large flanged entrance on the top of the tank. The top entrance is used to install the accelerator equipment, the largest piece being the terminal shell or spinning which is shown in Figure 9 being extracted from the top of the tank. Underneath the tank is an, as of yet undesigned, hydraulic lift mechanism that can be used to lift the internal Pelletron service platform. This platform is necessary to easily access all parts of the accelerator inside of the tank.

The area around the Pelletron accelerator must be shielded from the X-rays it creates. The present plan calls for a large shield wall to be built out of concrete blocks inside the

Lab B building and several blocks to be strategically placed outside the building walls. However these plans have not been finalized.

Since sulfur-hexaflouride gas is much more dense than air, the area under the tank will need to be instrumented with oxygen monitoring alarms. Several ventilation ducts were installed in the pit area by the bubble chamber experiment to vent hydrogen out of the pit area. These ducts can be utilized with blower units to provide ventilation for any substantial leaks of sulfur-hexaflouride from our tank. Investigations are underway to determine the flowrates required and the level of oxygen deficiency hazard (ODH) the installation creates.

The roof area over the Pelletron must be removed for installation of the pressure vessel. When it is replaced, present plans call for it to be rebuilt at a higher elevation to allow installation of a crane. This small 5 ton crane will be used to lower equipment into and out of the containment vessel.

The cost estimate for all three phases of construction work at the Lab B/NEF Enclosure is not complete. However, preliminary estimates show a minimum cost of 1.5 million US dollars (not including the 2.0 million US dollars purchase price of the Pelletron itself). This cost may prove to be prohibitive to our research and development program so alternate plans should be explored.

Recycler Ring/MI-30 Installation

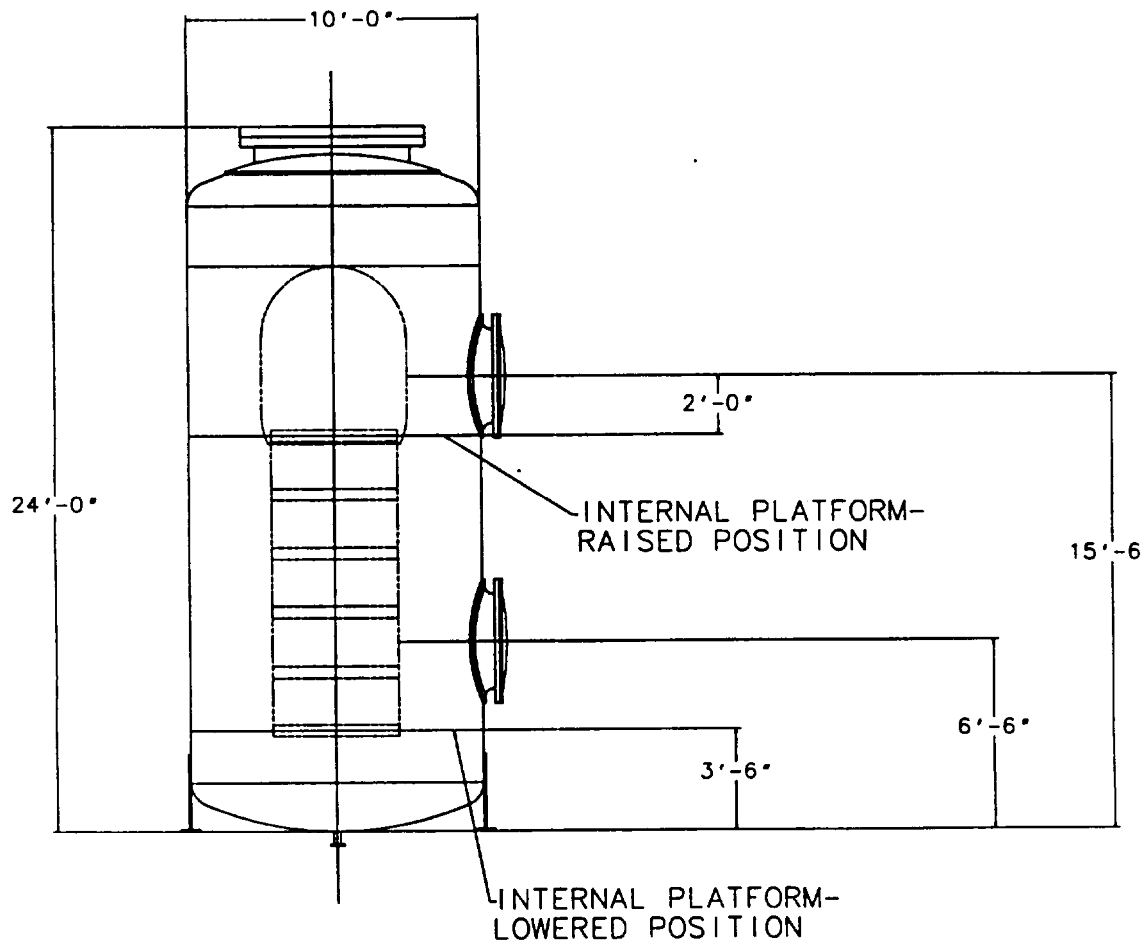
The installation of the Pelletron and the electron cooling beam-line into the MI tunnel at MI-30 service building looks (by design) similar to the installation at Lab B/NEF. The major difference is that at MI-30 the entire system is at a much lower elevation so that the Pelletron tank can be completely covered by earth. Figure 10 shows an elevation of the Pelletron installation at MI-30. The Pelletron will be supported within a large concrete and steel reinforced pit. The pit will have four levels, two for access to the side manways, one for access to the top flange, and the lower level for access to beam-line components and other mechanical equipment (sump pumps). The same hydraulic lifting mechanism built for the Lab B installation will be re-used here to raise and lower the interior service platform when maintenance is necessary.

Figure 11 is a plan view of the Pelletron installation showing the L-shaped pit area. A thick concrete shielding wall juts into the pit area to provide shielding of the elevator shaft area. The elevator and stairwell allow travel from the pit levels to the above grade service building. The service building will be extended to provide a control room and a pump room for insulating gas. A reservoir tank for the gas will be placed between the service building and the MI berm.

Another elevation view is shown in Figure 12. After the Pelletron tank is installed, a pre-cast concrete roof slab will be lowered over the pit opening and sealed in place. Earth fill will form a berm over the concrete roof slab to provide the necessary shielding. If the tank ever needs to be removed from the pit, the berm must be removed and the concrete roof slab excavated.

Since the Main Injector tunnel is not an ODH area, any sulfur-hexaflouride leaks must not be able to reach the MI tunnel elevation. Adequate ventilation must be provided in the pit (not shown) to force insulating gas to the outside atmosphere. Investigations into an adequate ventilation system have not yet been started.

Preliminary estimates for the construction work described here are around 2.0 million US dollars. Actual construction of the Pelletron pit area at MI-30 will have to begin in the summer of 1997 in order to keep impact on the Main Injector/Recycler startup minimal. It is not clear whether this is possible at this time. Construction techniques could be employed to add the Pelletron pit at a later date, similar to the techniques utilized at F-0/MI-60 three years ago. However, this would be more costly and could compromise the effectiveness of the design.



PELLETRON DIMENSIONS

Figure 1.

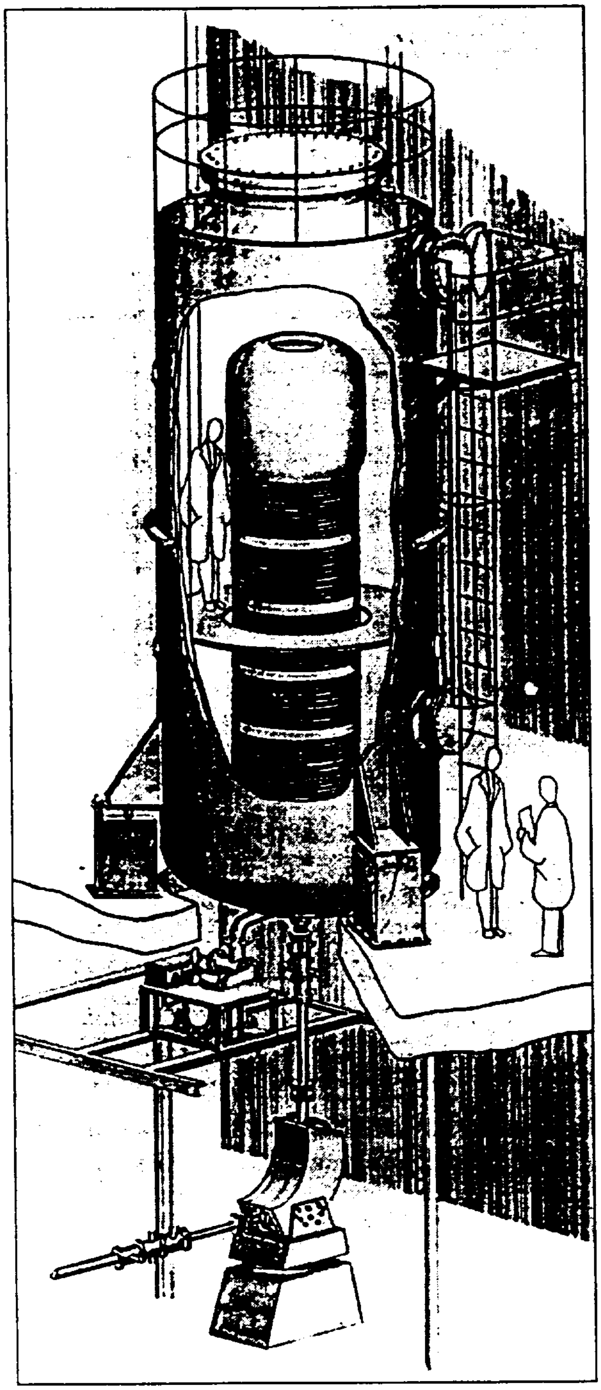


Figure 2.

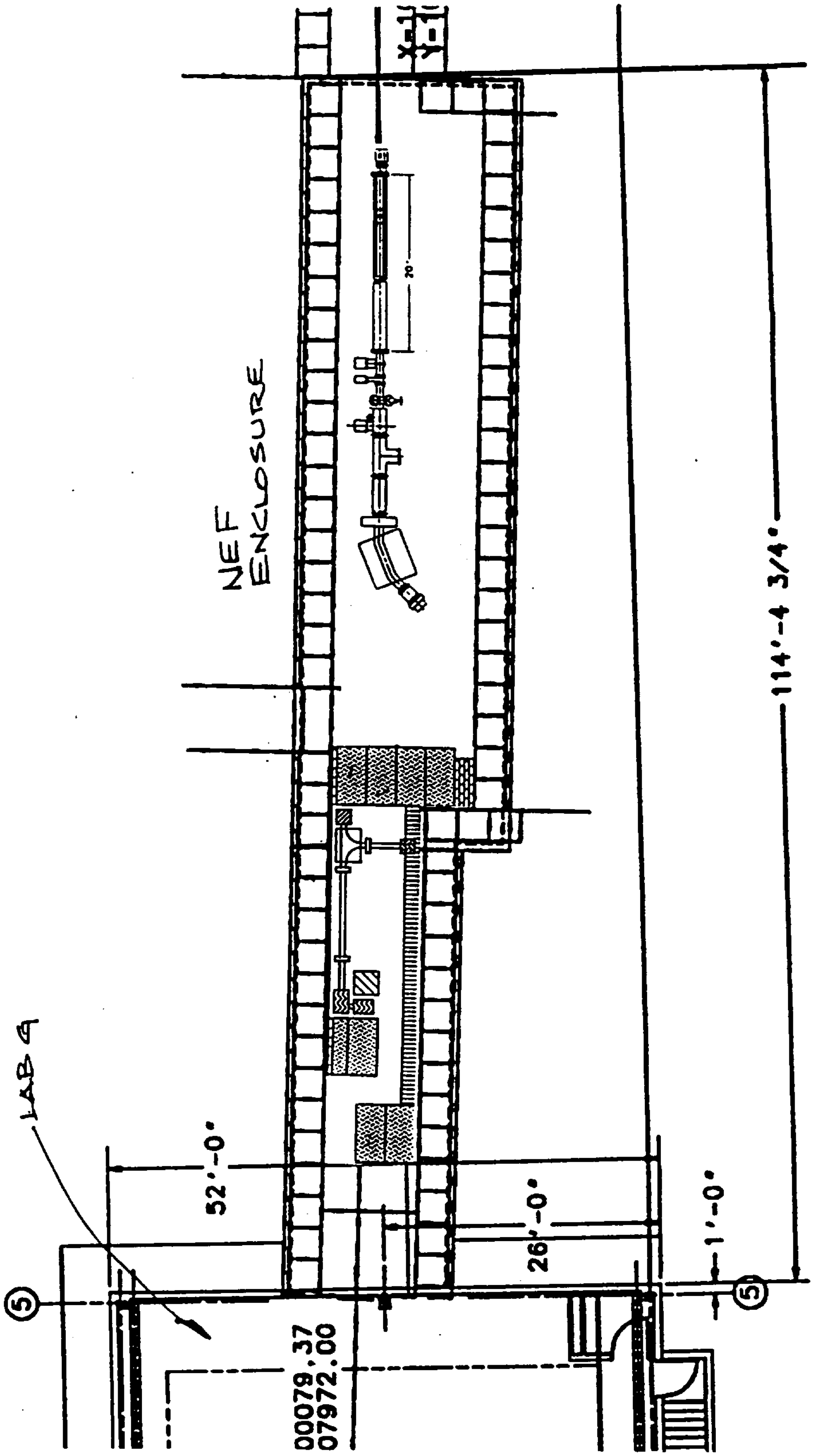
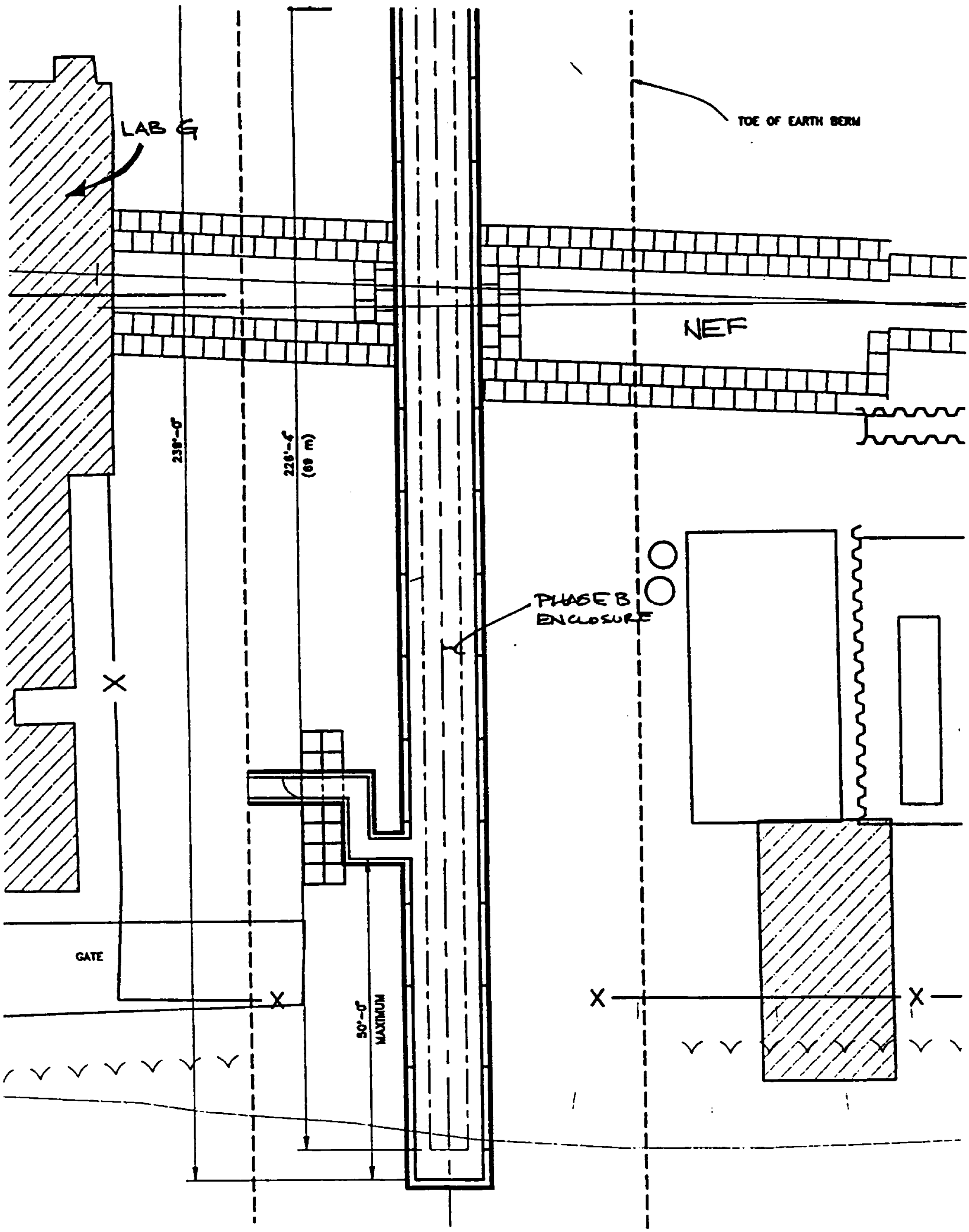
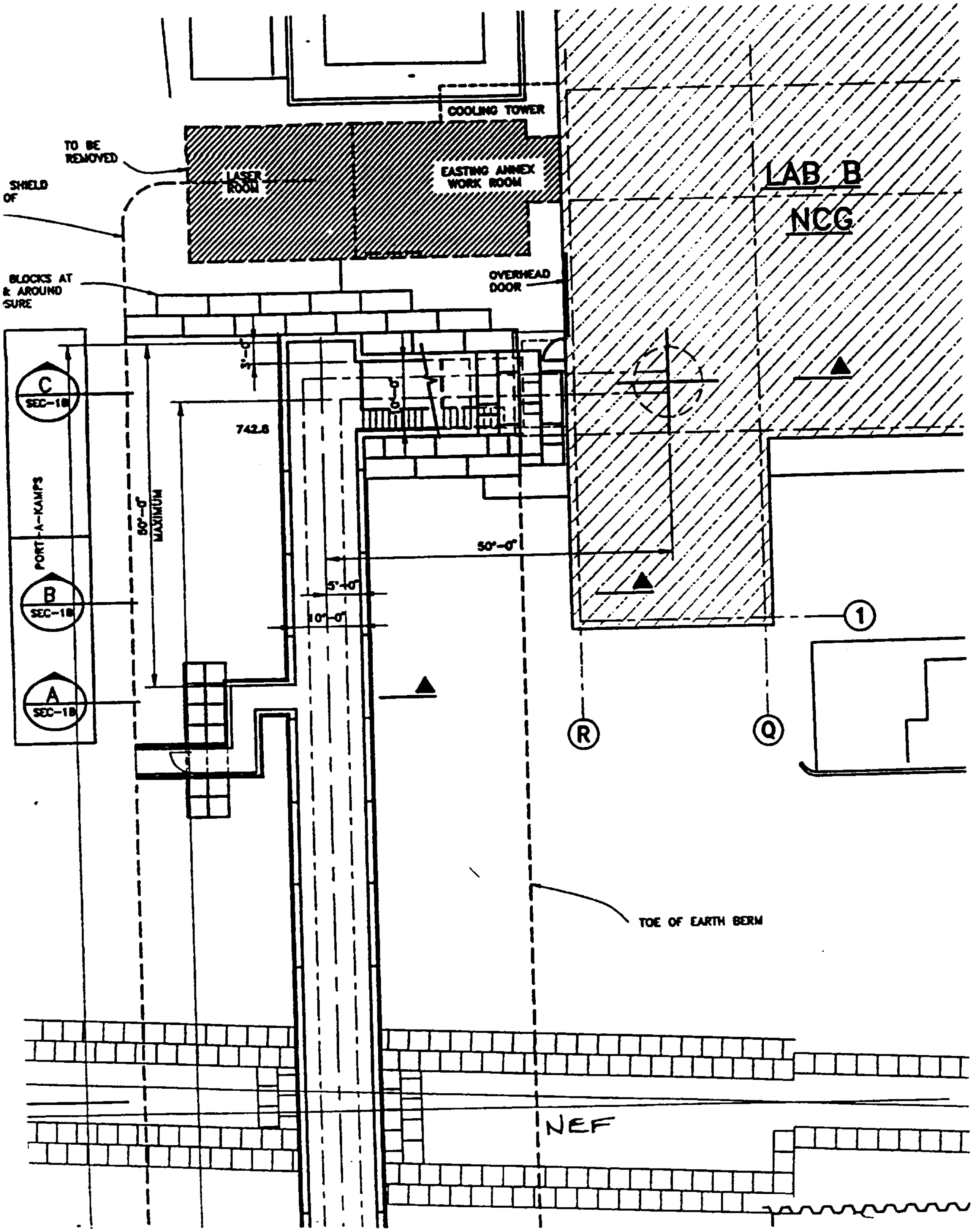


Figure 3.



LAB G
TOE OF EARTH BERM
NEF
238'-0"
226'-6"
(69 m)
PHASE B
ENCLOSURE
GATE
90'-0"
MAXIMUM

Figure 4.



COOLING TOWER
TO BE REMOVED
SHIELD OF
LASER ROOM
EASTING ANNEX WORK ROOM
LAB B
NCG
BLOCKS AT & AROUND SURE
OVERHEAD DOOR
C SEC-1B
B SEC-1B
A SEC-1B
PORT-A-KAMPS
742.8
50'-0" MAXIMUM
50'-0"
5'-0"
10'-0"
R
Q
1
TOE OF EARTH BERM
NEF

Figure 5.

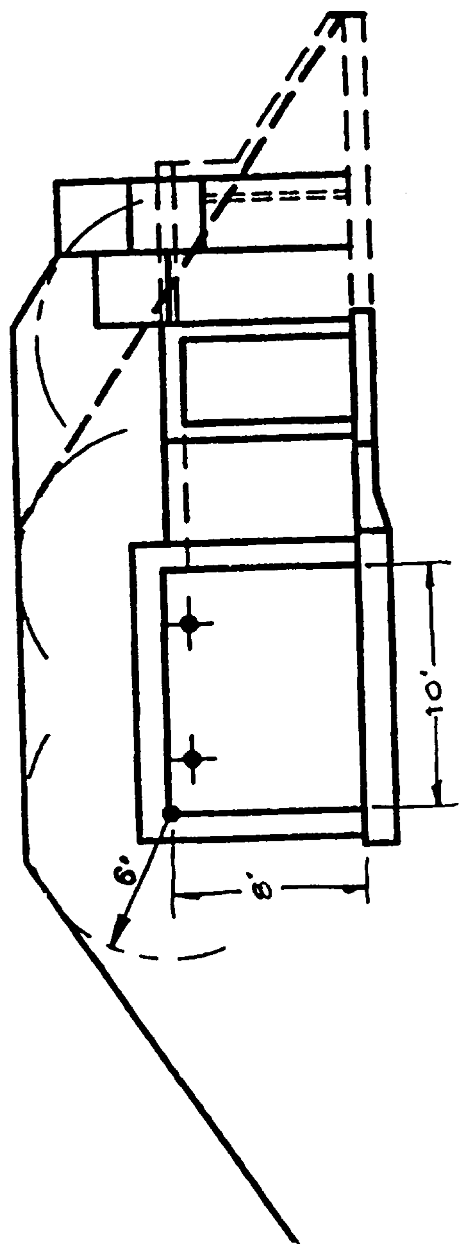


Figure 6.

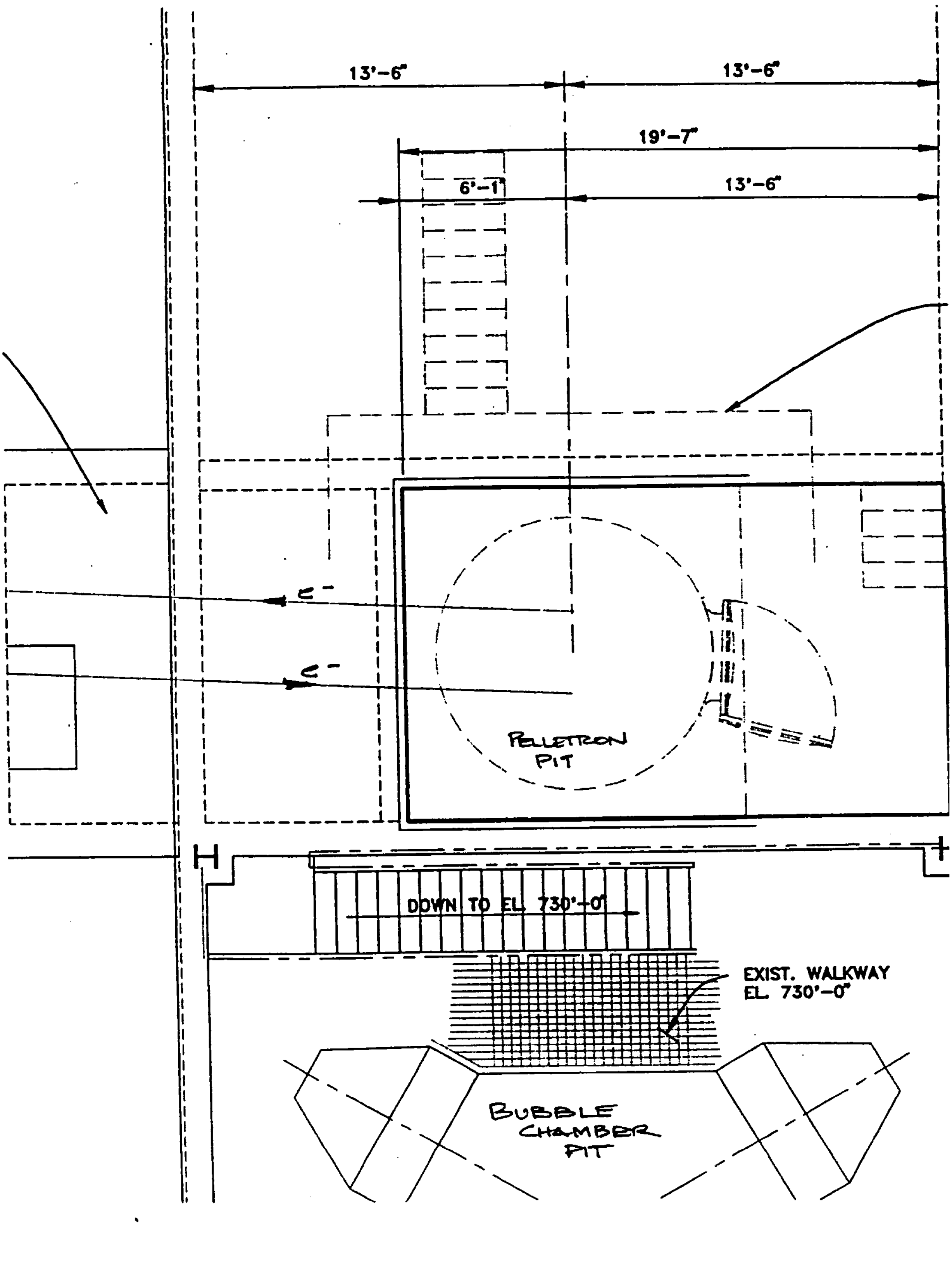

13'-6"
13'-6"
19'-7"
6'-1"
13'-6"
e⁻
e⁻
PELLETRON
PIT
DOWN TO EL. 730'-0"
EXIST. WALKWAY
EL. 730'-0"
BUBBLE
CHAMBER
PIT

Figure 7.

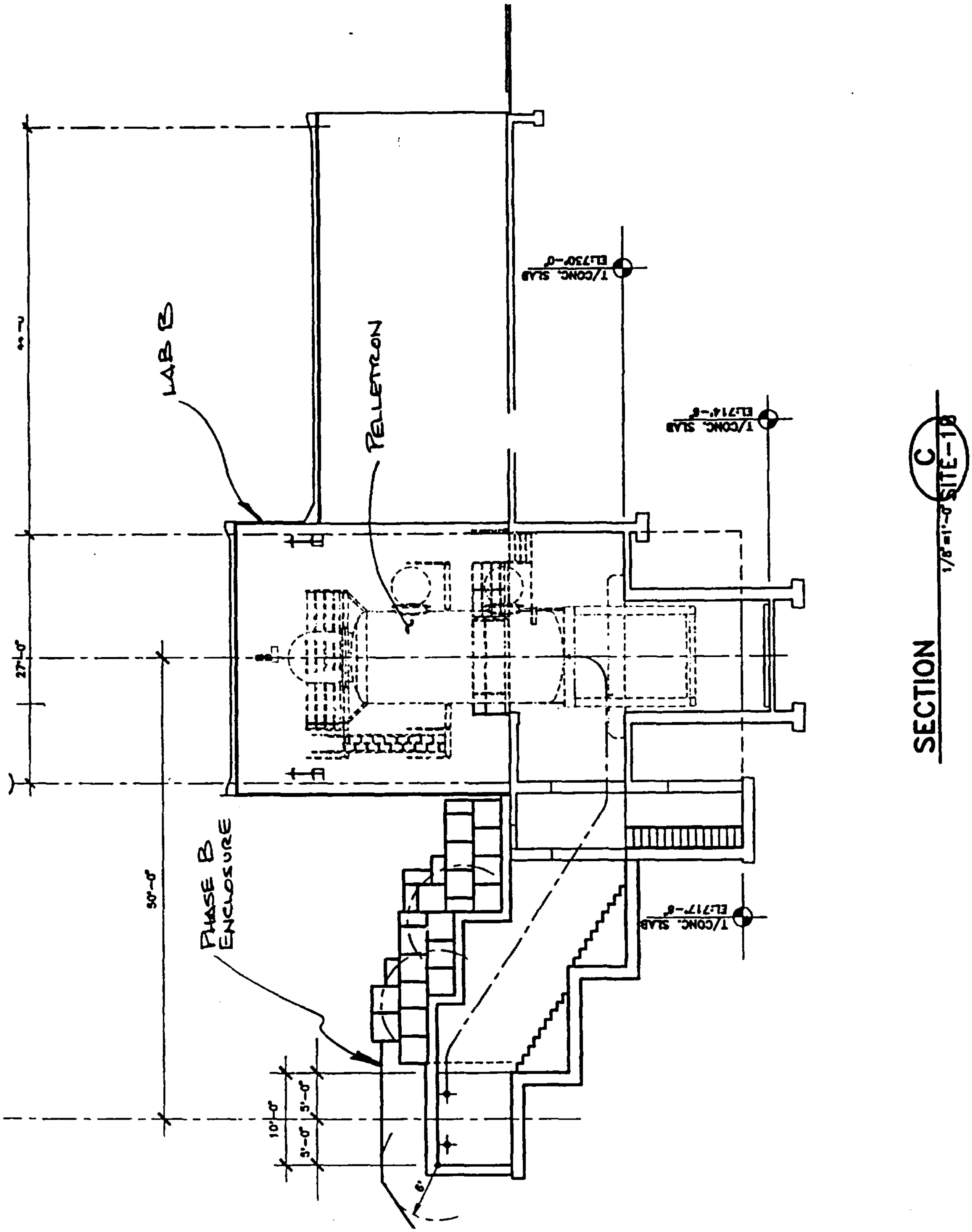

LAB B
PELLETRON
PHASE B ENCLOSURE
T/CONC. SLAB EL.730'-0"
T/CONC. SLAB EL.714'-6"
T/CONC. SLAB EL.717'-6"
27'-0"
50'-0"
10'-0"
5'-0"
5'-0"
SECTION
C
SITE-1B
1/8"=1'-0"

Figure 8.

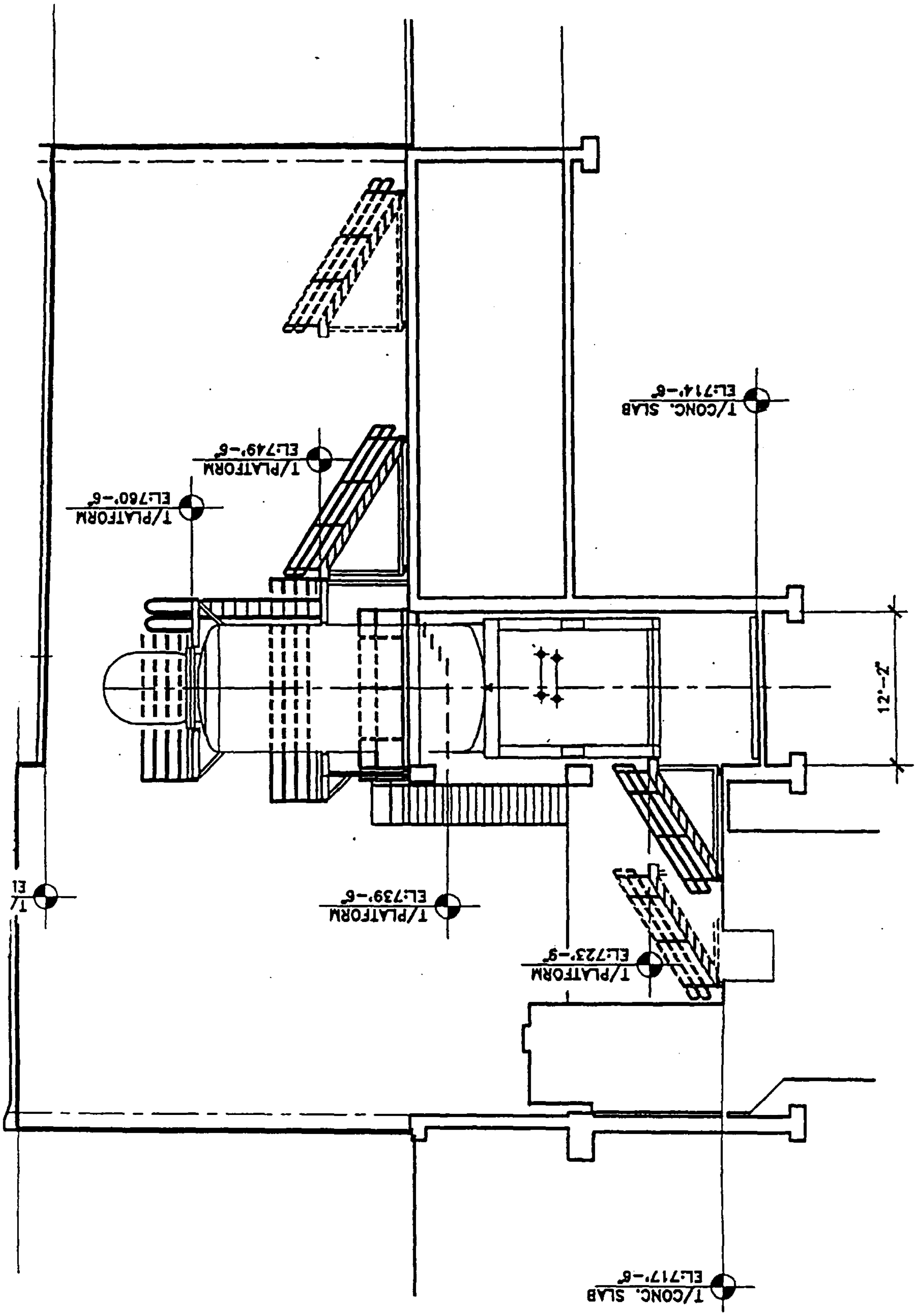

T/CONC. SLAB
EL:714'-6"
T/PLATFORM
EL:749'-6"
T/PLATFORM
EL:760'-6"
12'-2"
T/PLATFORM
EL:739'-6"
T/PLATFORM
EL:723'-9"
T/CONC. SLAB
EL:717'-6"

Figure 9.

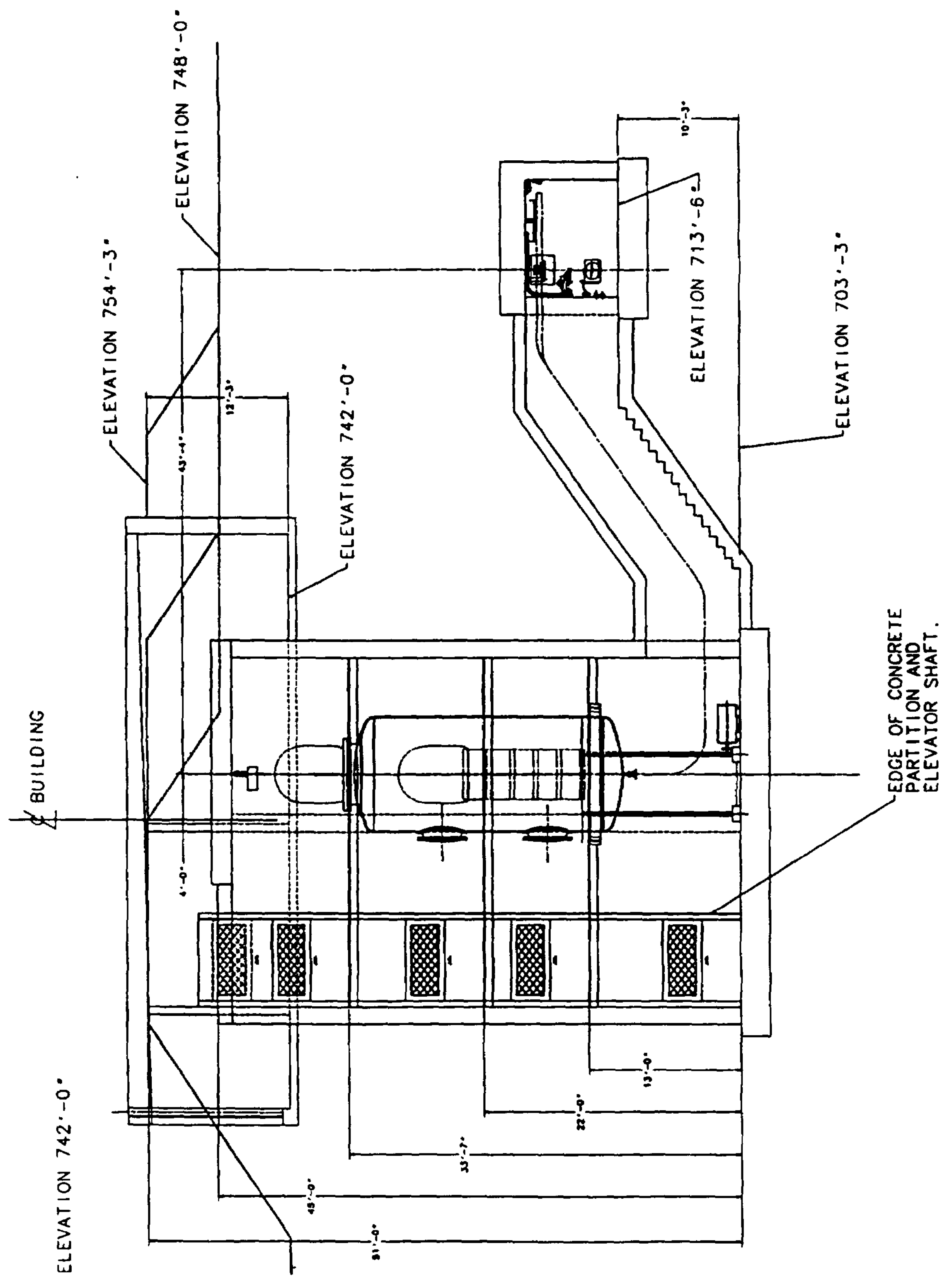

ELEVATION 748'-0"
ELEVATION 754'-3"
ELEVATION 742'-0"
ELEVATION 713'-6"
ELEVATION 703'-3"
BUILDING
EDGE OF CONCRETE PARTITION AND ELEVATOR SHAFT.
ELEVATION 742'-0"
10'-3"
12'-3"
4'-0"
13'-0"
22'-0"
45'-0"
51'-0"

Figure 10.

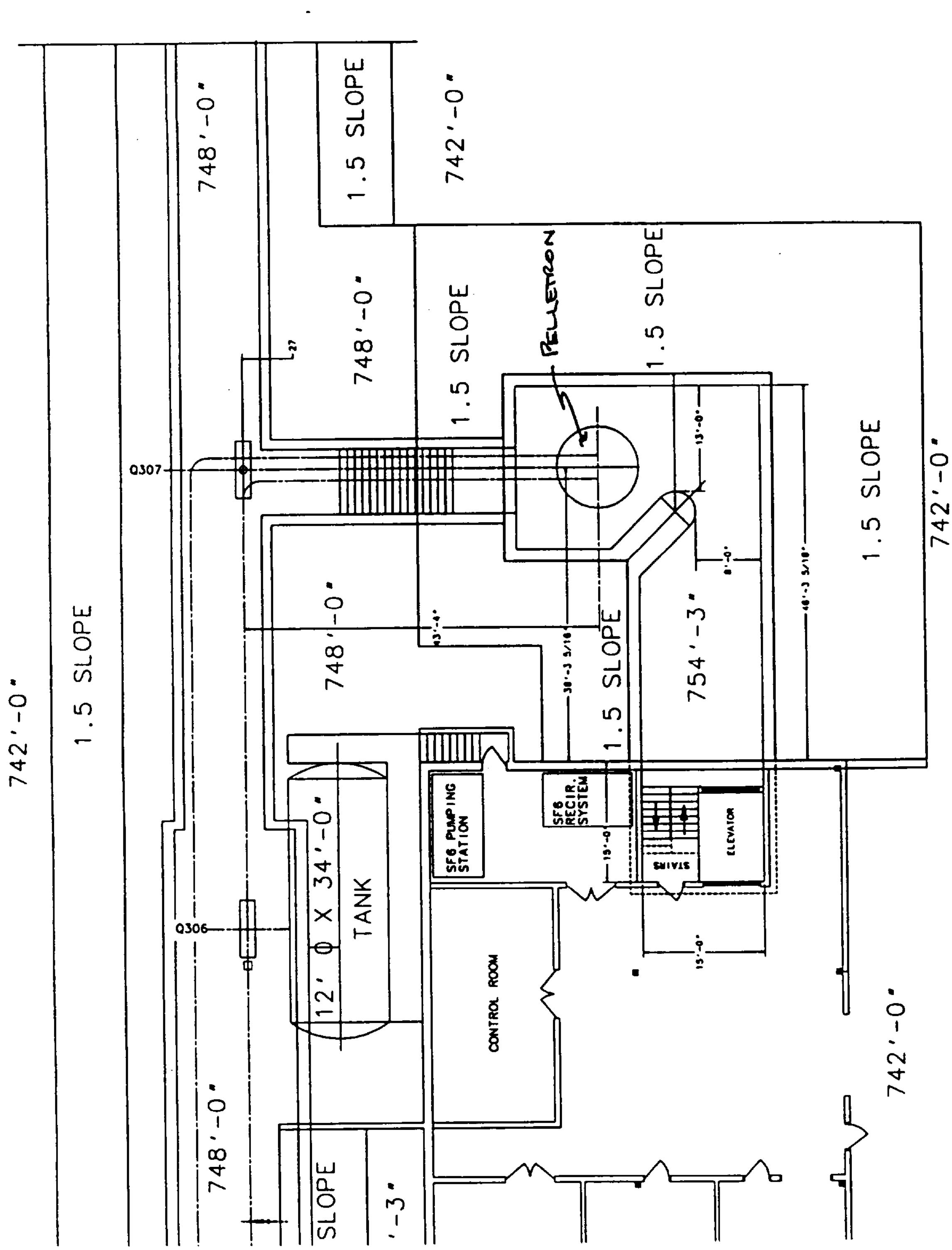

742'-0"
1.5 SLOPE
748'-0"
754'-3"
PELLETRON
Q307
Q306
12' Φ X 34'-0"
TANK
SF6 PUMPING STATION
SF6 RECIR. SYSTEM
STAIRS
ELEVATOR
CONTROL ROOM

Figure 11.

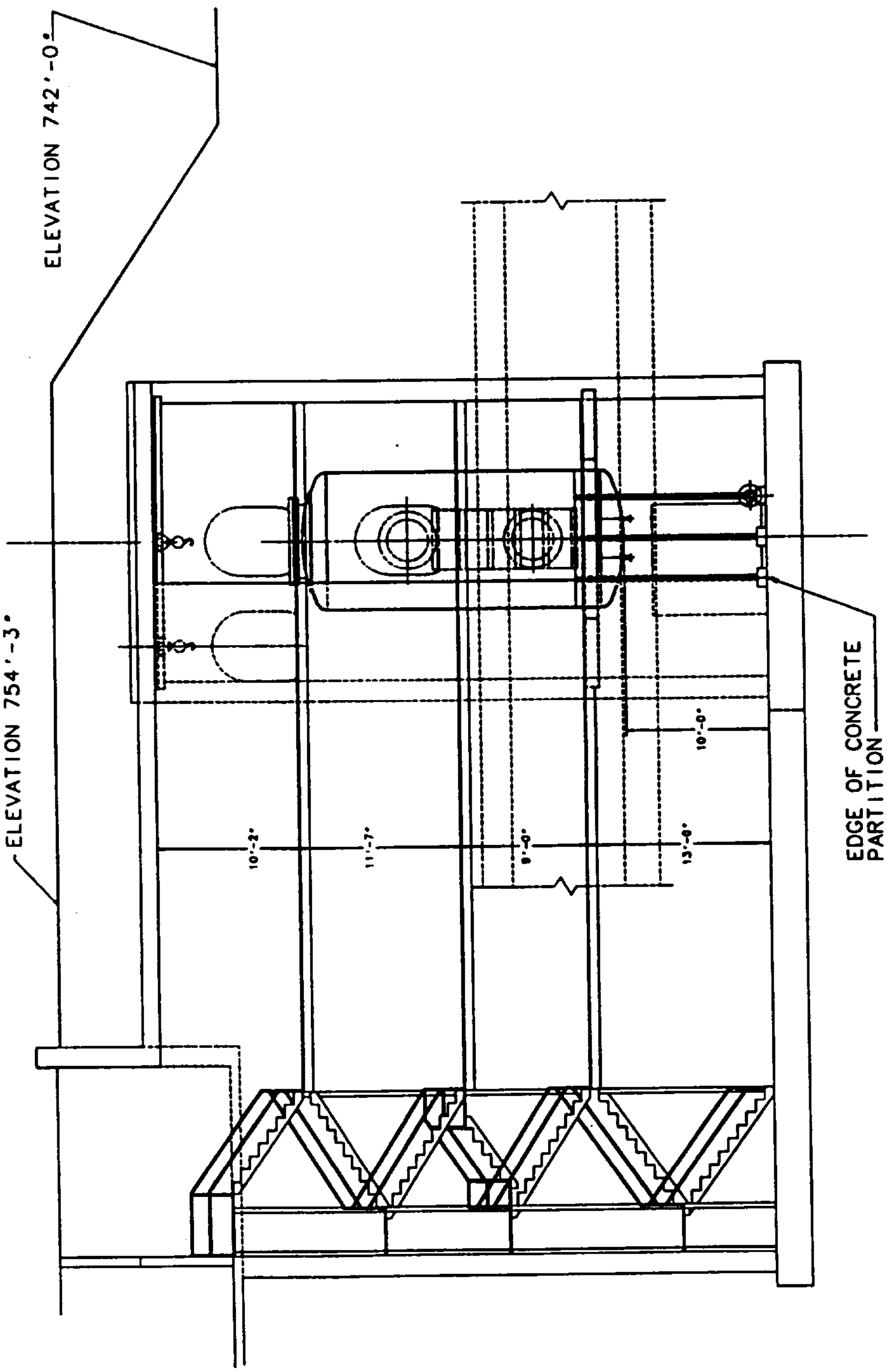


Figure 12.

High Energy Electron Cooling

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Abstract

High energy electron cooling requires a very cold electron beam. The questions of using electron cooling with and without a magnetic field are presented for discussion at this workshop.

1 Introduction

The electron cooling method was suggested by G. Budker in the middle sixties. The original idea of the electron cooling was published in 1966 [1]. The design activities for the NAP-M project was started in November 1971 and the first run using a proton beam occurred in September 1973. The first experiment with both electron and proton beams was started in May 1974. In this experiment good result [2] was achieved very close to theoretical prediction for a usual two component plasma heat exchange.

But the basically new results about electron cooling were obtained a few years later following experimental and theoretical investigation. In the course of the experiments carried out at the NAP-M facility it was discovered that the time required for the cooling, expected to be several seconds, in fact turned out to be 0.1 sec. Such an abrupt increase in the cooling efficiency was the result of a combined effect of two factors, first of all, the presence of the longitudinal magnetic field in cooling section and, secondly, the electrostatic acceleration of the electron beam, which is accompanied by a considerable decrease in the longitudinal velocity spread of electrons. The magnetic field "magnetizes" the transverse electron motion, and as result the cooling particles interact with a cool Larmor circle, but not with a hot free electron [3]. The effective temperature of a Larmor circle is only 1° K but free electrons have temperature of over 2000° K! A temperature 1°K for the particles' longitudinal motion was obtained for a proton beam with an energy of 65 MeV. The class of phenomena discovered aroused so much interest that the authors specifically called the process "fast electron cooling".

For a detailed study of the cooling under the condition of strong magnetization, an installation with a field of 4 kG and a very good field homogeneity, was built. The experiments performed at this facility in the regime of single transmission of an ion through an electron beam showed an essential difference in the friction force for positively and negatively charge particles. I will try to report in more detail on this investigation concentrating mainly on questions useful for the high energy electron cooling.

2 Fast electron cooling

After first successful experiments on the NAP-M cooler, the magnetic field homogeneity and the electron gun design were improved. For the study of the influence of the deviation of the electron velocity at the output of the electron gun two plates were installed to produce transverse electric field. This field excited the traverse Larmor rotation of electrons coming out from the electron gun. The results of measuring the cooling time are shown in Fig. 1a.

It was a big surprise to us that best cooling was obtained at a non-zero voltage on these plates. It means we had some misalignment at the electron gun and action of the plates compensates this motion of the electron beam. For testing this hypothesis we measured the voltage on these plates for optimum cooling versus the voltage on the gun anode, Fig. 1b. An increase in the anode voltage decreased the cathode-anode potential difference and decreased the amplitude of the transverse motion as shown in Fig. 1b. The maximum transverse decrement was very sensitive to the electron gun voltage ripples. To have a stable result we improved the high voltage power supply so that the cathode voltage ripple was no more than 10^{-5}. After improving all power supplies we had a maximum decrement over 20 s^{-1} or cooling time less 0.05 s. The results of these experiments indicated a partial magnetization.

3 Friction force

For a case of absence of the magnetic field at a cooling section the cooling force can be written as

$$F = -\frac{4\pi e^4 L_C n}{m} \int \frac{\vec{V} - \vec{V_e}}{\mid V - V_e \mid^3} f(V_e) d^3 V_e \ , \qquad (1)$$

where $L_C = \log(\rho_m ax/\rho_{min})$ is the Coulomb logarithm of interactions, $\rho_{max} = min(V/\omega_p, \tau V, a)$, $\rho_{min} = e^2/mV^2$, τ is the time of a particle's single path through the electron beam, V is the particle velocity, V_e is the electron velocity, and ω_p is the electron plasma

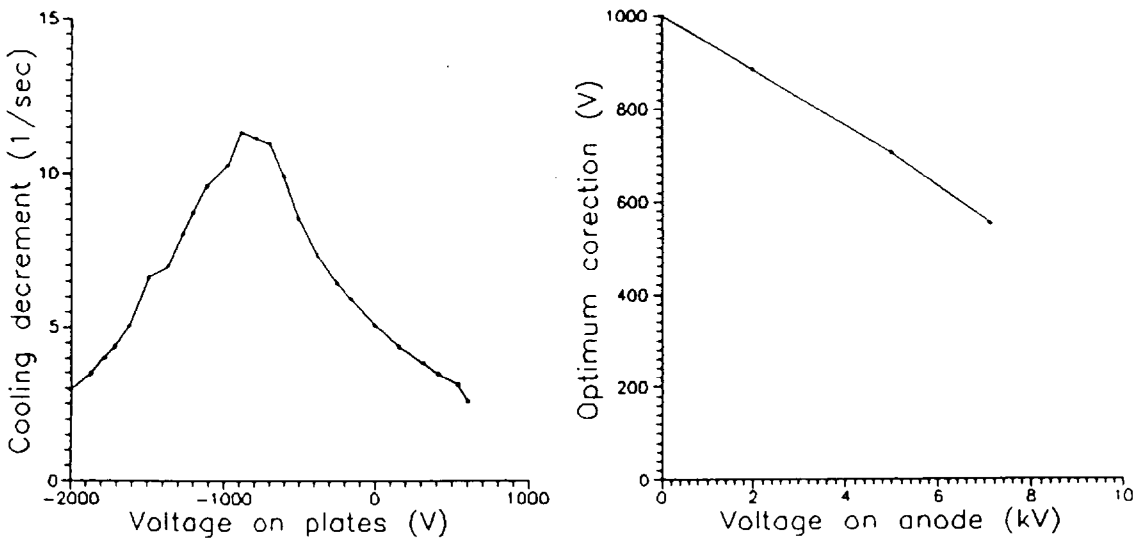

Figure 1: a – The inverse cooling time vs. voltage on the plates for exiting Larmor rotation of electron beam, energy 65 MeV, electron current 0.3 A b – The optimum Larmor rotation correction vs. voltage on the electron gun anode

frequency. The presence of the magnetic field generally results in the appearance of three different regions of impact parameters:

1. Small impact parameters, where the presence of the magnetic field is not essential
$$\frac{V_A}{\omega_L} > \rho > \rho_{min} = \frac{e^2}{mv_e^2} \ ,$$
where $\vec{V_A} = \vec{V} - \vec{V}_{\|e}$.

2. Intermediate impact parameters, where a multiple repeated passing of the electron by the particle is essential
$$\frac{V_e}{\omega_L} = \rho_L > \rho > \frac{V_A}{\omega_L}$$

3. Large impact parameters, where the particle interacts practically with the Larmor circle moving along the magnetic field

$$\rho_{max} > \rho > \rho_L$$

The contribution of these three regions to the friction force, for a longitudinally "flat" electron distribution $V_{\perp e} >> V_{\|e} = \sqrt{2e^2 n^{1/3}/m}$ can be written as follows:

1. The contribution of the fast cooling is

$$\vec{F} = -\frac{4\pi e^4 n}{m} \log(\frac{V_a/\omega_L}{e^2/(mV^2)}) \frac{\vec{V}_\perp}{V_{\perp e}^3} for V << V_e$$

2. In a multiply repeated collision region we estimate the friction force

$$\vec{F} = -\frac{4e^4 n}{m} \log(V_e/V) \frac{\vec{V}}{V^2 V_{\perp e}}$$

3. For large impact parameters, *i.e.*, the case of strong magnetization, the friction force is equal to

$$F_\perp = -\frac{2\pi e^4 n}{m} \log(\rho_{max}/\rho_L) \frac{V_\perp^2}{V^4}$$

for $V > V_{\|e}$

4. For a small V the friction force has its maximum near $V = V_{\|e}$, and maximum force is

$$F_{max} = 2e^2 n^{2/3}$$

At the NAP-M facility, in the case of a magnetic field in the cooling section of 1 kG, the behavior of the friction force corresponded well to the expression for the partially magnetized case, the friction force grew as 1/V.

For testing the ideas of fast cooling a single pass apparatus was constructed.[9] This equipment included an electrostatic accelerator for H^- ions (energy 830 keV), a solenoid with a very homogenous magnetic field ($\Delta B/B = 10^{-5}$) from 1 to 4 kG, and an electrostatic ion energy spectrometer. The change in the sign of the ion charge is achieved with a special magnesium target at the solenoid entrance where the double ionization of the hydrogen negative ions occurs. The electron beam is formed in the electron gun placed in the magnetic field of the solenoid and it is transported along the solenoid magnetic field to an electron collector. The interaction of ions with the electron beam results in a variation of their energy and transverse velocities and these changes are detected by the electrostatic spectrometer. As an example of the changing the ion energy Fig. 2a shows the measurement data for H^- and H^+ (electron current 3 mA, magnetic field 5 kG). The friction force for H^- is a few times more. With an increase in the electron current the friction force grows and attains its maximum value at a current 8 mA (for B=4kG). This limitation is connected with the growth of the longitudinal electron beam temperature.

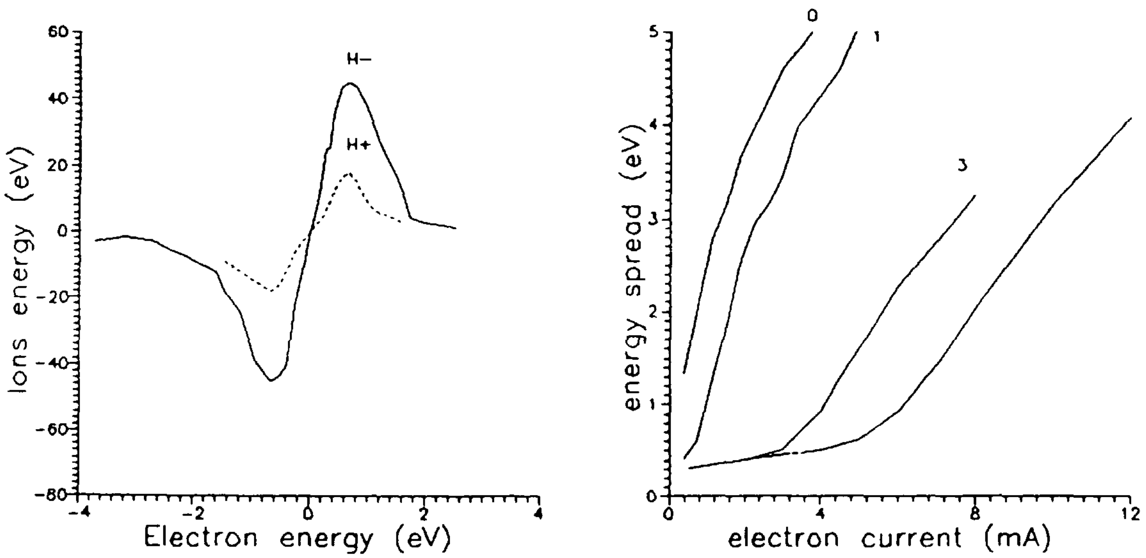

Figure 2: a – The friction force versus the electron energy (losses at a cooling length of 2.4m) for H^+ and H^- (B=4kG,I_e=3mA) b – The energy spread of electron beam after passing the cooling section versus the electron current

Fig. 2b shows the energy spread of the electron beam versus the electron current for the different magnetic fields 0, 1, 3, and 4 kG. For B=0 the data are calculated from the following expression:

$$\frac{dT_s}{ds} = \frac{\pi e^3 j L_c}{W}\sqrt{\frac{m}{T_\perp}} \ , \tag{2}$$

where s is the longitudinal coordinate, L_c is the Coulomb logarithm, and the electron energy spread is $\Delta E = \sqrt{2WT_s}$. The suppression of intrabeam scattering by the magnetic field can be described with the help of an empirical formula:

$$\frac{dT_s}{ds} = \frac{\pi e^3 j L_c}{W}\sqrt{\frac{m}{T_\perp}} \exp(-\frac{2.8e^2}{\rho_\perp(e^2 n_e^{1/3} + T_s)}) \ , \tag{3}$$

where $\rho_\perp = \sqrt{2T_\perp mc^2}/(eB)$ is the electron Larmor radius and $T_s = T_c^2/(2W) + 2e^2 n^{1/3}$ is the initial temperature of the electron beam. The maximum friction force is achieved for the ion velocity value equal to $V_m = \sqrt{2T_s/m}$.

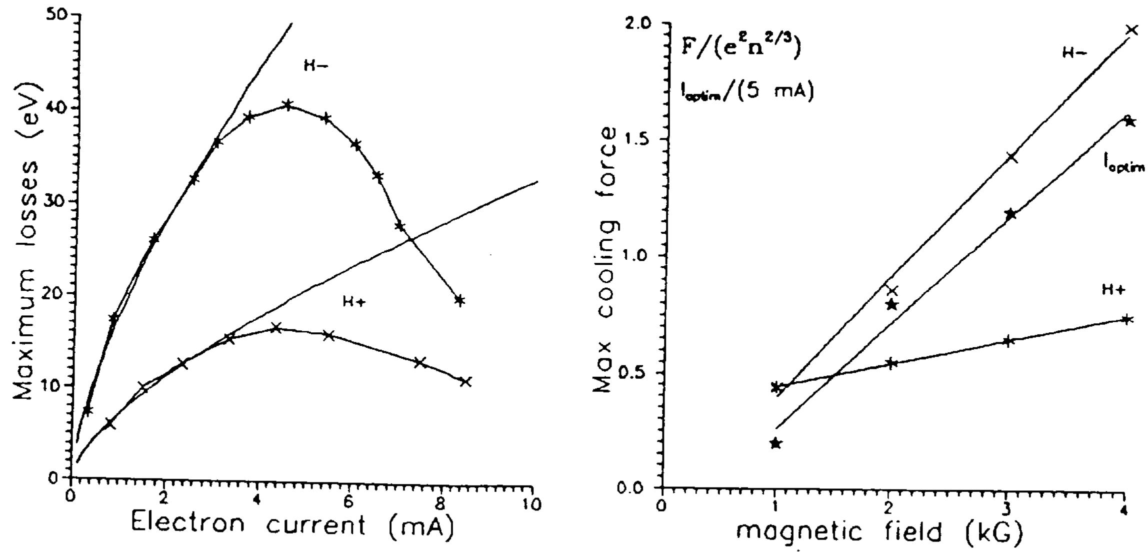

Figure 3: a - The maximum friction force losses versus of electron current (losses at cooling length 2.4m) for H^+ and H^- (B=3kG). Solid line is obtained with the expression $F_{max} = ke^2n_e^{2/3}$; k=1.82 for H^- and k=0.72 for H^+. b - the maximum force and the optimum electron beam currents versus the solenoid magnetic field

The maximum friction force measurements shown in Fig. 3a. The optimum the electron beam current is clearly shown. Fig. 3b shows the maximum force (in units $e^2n^{1/3}$) and an optimum electron beam current versus the magnetic field.

4 The beam-beam interaction

The limitation of cooling can be connected with beam-beam interaction. Coherent interaction of particles in the transverse direction results in reduction of focusing and shifts of betatron oscillation frequencies to resonances, which in principle may limit cooling of beam. To estimate the limiting emittance and intensity of cooling beam in this case one can use the tune shift of betatron oscillation frequencies:

$$\Delta\nu_{pp} = \frac{n_p C r_p < \beta_r >}{2\beta^2\gamma^3} , \qquad (4)$$

where n is the density of particles, C is length of orbit the storage ring, $r_p = e^2/Mc^2$ is the classical radius of particle, and β_r is the beta function of the ring.

The action of electron beam on the particle betatron motion we can write in form

$$\Delta\nu_{pe} = \frac{n_e r_p l \beta_c}{2\beta^2\gamma^3} , \qquad (5)$$

where l is the length of cooling section and β_c is the beta function at cooling section.

The tune shift of the transverse betatron motion of the electron by the particle space charge of the cooled beam can be written in form

$$\Delta\nu_{ep} = \frac{n_p r_e l \lambda}{2\beta^2\gamma^3} \quad , \tag{6}$$

where λ is the beta function of electron motion. For focusing by longitudinal magnetic field $\lambda = c\beta/\omega_L$.

The tune shift of the transverse betatron motion of the electron by the background ions at the electron beam can be written in form

$$\Delta\nu_{ei} = \frac{n_e \alpha r_p l \lambda}{2\beta^2\gamma^3} \quad , \tag{7}$$

where the neutralization factor α is the ion fraction ions at the electron beam.

The electron beam tune shift is essential for adjusting the electron beam capture into a collector. The large value of the tune shift means problems for operation of a high-voltage electron cooling device.

5 Numerical estimation of the cooling

charge of particle Z=1
mass of particle $A = 1$
circumference $C = 3319$ [m]
length cooling section $l = 66$ [m]
kinetic electron energy $E = 4360$ [keV]
electron current density $j = 0.016$ $[A/cm^2]$
electron beam density $n = 0.33 \cdot 10^7 [\mathrm{cm}^{-3}]$
antiproton beam density $n_p = 0.2 \cdot 10^6 [\mathrm{cm}^{-3}]$
travsv. dp/p = 10^{-4}
longit. dp/p = $5 \cdot 10^{-4}$
transverse temp. = 2304 deg K
longitudinal temp. = 8 deg K
cooling time trasv. = $1.20 \cdot 10^4$ s
cooling time longit. = 716 s
magnetic field in cooling section B = 1 [kG]
$\lambda = 17$ cm for B=1 kG
$\lambda = 200$ m for B=1 kG
$\Delta\nu_{pe} = 0.00004$
$\Delta\nu_{ep} = 0.004$ for B=0

$\Delta\nu_{ei} = 6.0 \cdot \alpha$ for B=0

$\Delta\nu_{ei} = 0.005 \cdot \alpha$ for B=1 kG

It is easy to see the main problem is stability of electron beam without magnetic field.

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Electron Beam Focusing System

N. Dikansky, S. Nagaitsev, and V. Parkhomchuk

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Abstract

The high energy electron cooling requires a very cold electron beam. Thus, the electron beam focusing system is very important for the performance of electron cooling. A system with and without longitudinal magnetic field is presented for discussion. Interaction of electron beam with the vacuum chamber as well as with the background ions and stored antiprotons can cause the coherent electron beam instabilities. Focusing system requirements needed to suppress these instabilities are presented.

1 Introduction

In order to achieve the highest possible cooling rate it is necessary to preserve the electron beam transverse emittance during the electrostatic acceleration and transport through the cooling channel. Electron beam temperature T, for a cathode temperature of 1200K, is ≈ 0.1 eV. Effective normalized emittance of electron beam with uniform current density is

$$\epsilon_n = 2a_c\sqrt{\frac{T}{mc^2}}, \tag{1}$$

where a_c is the cathode radius, m is electron mass and c is the speed of light. This expression yields emittance of $\approx 4\pi$ mm·mrad for a cathode radius of 4 mm. After electrostatic acceleration to $W \approx 4.3$ MeV (kinetic energy) and adiabatic expansion to a radius of 20 mm, the emittance ϵ will be decreased by a factor of $\beta\gamma$: $\epsilon = \epsilon_n/(\beta\gamma)$ and the rms (2-D) electron beam divergence will be about 10 μrad. However, if there exists a misalignment between the electron and ion beam trajectories of this order or greater, or if the electron beam optics is not adjusted so as to make the beam parallel to this tolerance, there will be effective temperatures in excess of the cathode temperature. The present design goal is an rms angular misalignment of 40 μrad, corresponding to effective-temperature of ≈ 0.1 eV. In this paper we discuss various electron beam confinement scenarios capable of meeting such requirements.

In a smooth approximation an envelope equation describing evolution of the electron beam radius can be written as:

$$\frac{d^2a}{ds^2} = \frac{\epsilon^2}{a^3} + \frac{2K}{a} - \frac{a}{\lambda_0^2}, \tag{2}$$

where a is the electron beam radius, s is the laboratory frame distance along the beam axis and K is the generalized electron beam perveance defined as:

$$K = \frac{eI_e}{\beta^3\gamma^3 mc^3}, \tag{3}$$

with e being the electron charge, m electron mass, c the speed of light, I_e an electron beam current, and λ_0 a betatron wave length (β function) for the smooth focusing system.

For the matched condition $a'' \approx 0$ (small beam envelope ripple along the cooling section) we have the following solution:

$$a = \lambda_0 \sqrt{\sqrt{\frac{\epsilon^2}{\lambda_0^2} + K^2} + K}. \tag{4}$$

In the limiting case of a space charge dominated beam ($K \gg \epsilon/\lambda_0$) we have for the beam radius

$$a \approx \lambda_0 \sqrt{2K}. \tag{5}$$

In the opposite case of emittance dominated beam ($K \ll \epsilon/\lambda_0$) the electron beam radius has a form of

$$a \approx \sqrt{\lambda_0 \epsilon}. \tag{6}$$

For a FERMILAB cooler we have a =2 cm, $\epsilon \approx 0.4\pi$ mm mrad and $K \approx 1.2 \cdot 10^{-8}$. This yields the value of zero-current β-function ("coherent" β-function) $\lambda_0 \approx a/\sqrt{2K} \approx 130$ m. The value of "incoherent" β-function is much larger ($\approx a^2/\epsilon \approx 1000$ m) due to defocusing effect of the space-charge itself.

2 Coherent effects

2.1 The beam-wall interaction

We begin our analysis of the coherent beam stability with a simplified system of round uniformly charged electron beam in a perfectly conductive vacuum chamber.

The electric image of the electron beam is then offset from the center of the vacuum chamber by distance b:

$$b = \frac{a_{ch}^2}{x}, \tag{7}$$

where x is displacement of the beam centroid from the vacuum chamber center and a_{ch} is the inner chamber radius. The value of the transverse electric field from this image charge is:

$$E_{\perp} = \frac{2\pi ena^2}{b} = \frac{2\pi ena^2}{a_{ch}^2} x, \tag{8}$$

where n is the electron beam density.

The equation of motion of the electron beam centroid can be written as:

$$\frac{d^2x}{ds^2} = \frac{2\pi r_e na^2}{\gamma\beta^2 a_{ch}^2} x, \tag{9}$$

where $r_e = e^2/mc^2$ is the classical electron radius. One can show that this defocusing force produces exponential deflection of the beam as $cosh(s/\lambda)$ with

$$\lambda^{-1} = \sqrt{\frac{2\pi r_e na^2}{\gamma\beta^2 a_{ch}^2}}. \tag{10}$$

For the FERMILAB cooler $a = 2$ cm, $a_{ch} = 5$ cm, $I_e = 0.2$ A, $\gamma \approx 10$, $\beta \approx 1$ and $n \approx 3.3 \cdot 10^6$ cm^{-3} we have $\lambda \approx 32.8$ m.

In addition to image effects, charge neutralization effects are also of concern. The electron beam produces ions by ionization of the residual gas in the vacuum chamber. These ions are easily accumulated in the potential well produced by the electron beam space charge. The electric field of these ions has an effect on the electron beam γ^2 times greater then its own space charge. The transverse electric field from the stored ions is equal to:

$$E_{\perp} = 2\pi e\alpha nx, \tag{11}$$

which yields the electron beam oscillation wave length of

$$\lambda_i^{-1} = \sqrt{\frac{2\pi nr_e\alpha}{\gamma\beta^2}}, \tag{12}$$

where $\alpha = n_i/n$ is the ratio of the ion density to the electron density. For $\alpha = 1$ and $I_e = 0.2$ A we have $\lambda_i = 14$ m which shows how dangerous these ions are.

2.2 Fire-hose instability

This instability is driven by the dipole oscillations of magnetized electron beam with respect to the non-magnetized ion background. Here we present a qualitative picture of such instability. Consider for simplicity that the space charge of electron beam is fully compensated by the residual gas ions and the longitudinal magnetic field H is strong enough to magnetize electrons: $\rho_{larmor} \ll a$. We will limit our consideration to the long wavelength $k \approx 1/l$, where l is the length of the ion column. In this case the displacement x of the electron beam with respect to the center of the ion column results into the electric field, given by Eq. (11). The electric field will cause drift with the drift velocity $v_d = cE_{\perp}/H$. Angular frequency of electron beam rotation around the center of the ion column is then $\omega_d = v_d/x = (2\pi n\alpha ec)/H$. This displacement propagates together with electron beam with the typical phase velocity of $\omega/k = v$. Resonant amplification of this displacement can take place if $\omega_d \approx \omega = kv$. Using $k \approx 1/l$ one obtains an approximate limit on the electron beam current density j (for $\alpha = 1$):

$$j \approx \frac{Hv^2}{2\pi cl}. \qquad (13)$$

This result is a factor of $8/(2\pi)$ greater than the current limit obtained by the more careful analysis of the electron beam stability.

If we now try to calculate the tune shift of the transverse electron beam oscillation frequency, the result in a smooth approximation looks as following:

$$2\omega\Delta\omega = \frac{2\pi n\alpha e^2}{\gamma m}, \qquad (14)$$

where ω is an unperturbed betatron frequency of electron beam in a focusing system with β-function: $\lambda_0 = v/\omega$. To obtain the value of the betatron tune shift after the electron beam passes the ion column of length l we will write:

$$\Delta\nu = \frac{\Delta\omega l}{2\pi v} = \frac{n\alpha r_e \lambda_0 l}{2\gamma\beta^2} \qquad (15)$$

For weak focusing (when $\lambda_0 = 200m$) needed to insure parallel electron beam in cooling region we have from Eq. (15): $\Delta\nu = 8.4\alpha$. To provide stability in this case we need ion clearing efficiency of better than $\alpha < 0.01$ in order to keep $\Delta\nu \approx 0.08$. Let us also rewrite this equation as a limit for a maximum current density for a case of the magnetic field focusing $\lambda_0 = \gamma\beta mc^2/(eH)$:

$$j_{max} = 2\Delta\nu_{max}\frac{Hv^2}{cl}. \qquad (16)$$

As easy to see by comparing this equation with Eq. (13), the maximum available tune shift is not more than $\Delta\nu \approx 1/16 \approx 0.06$: more or less typical value for beam-beam interaction. It means that this instability develops not only in the case of magnetic field focusing but also in any other focusing system.

3 Focusing system with periodic focusing elements

One of the possible cooling region designs is a periodic focussing channel consisting of weak solenoids with focal length F spaced distance L apart. The cooling region is preceded by two solenoids which provide the two needed degrees of freedom to specify the beam size and divergence at the entrance to this confinement system. Each solenoid provides just enough focussing to locally correct the electron beam expansion primarily due to its space charge and, at low beam currents, its emittance. The divergence θ of the electron beam near the entrance into the focusing solenoid is

$$\theta = \frac{a}{2F}. \tag{17}$$

The rms beam divergence in this case is $\theta_{rms} = \frac{a}{\sqrt{12}F}$. According to the introduction section we would like to keep this angle below 40 μrad or $F > 144$ m.

Taking into account the beam-wall interaction, described in the section 2.1, we can write the Twiss matrix M of the element of periodicity as:

$$M = \begin{pmatrix} 1 & 0 \\ -\frac{1}{2F} & 1 \end{pmatrix} \begin{pmatrix} cosh(L/\lambda) & \lambda sinh(L/\lambda) \\ \frac{1}{\lambda} sinh(L/\lambda) & cosh(L/\lambda) \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{2F} & 1 \end{pmatrix} \tag{18}$$

After performing the matrix multiplication we obtain:

$$M = \begin{pmatrix} cosh(L/\lambda) - \frac{\lambda}{2F} sinh(L/\lambda) & \lambda sinh(L/\lambda) \\ \left(\frac{1}{\lambda} + \frac{\lambda}{4F^2}\right) sinh(L/\lambda) - \frac{1}{F} cosh(L/\lambda) & cosh(L/\lambda) - \frac{\lambda}{2F} sinh(L/\lambda) \end{pmatrix} \tag{19}$$

The stability condition for the transverse beam oscillations is:

$$cos(\mu) = \frac{1}{2} Tr(M) = cosh(L/\lambda) - \frac{sinh(L/\lambda)}{2F/\lambda} < 1 \tag{20}$$

Condition on the focal length F ($L \ll \lambda$):

$$F < \lambda \frac{sinh(L/\lambda)}{2(cosh(L/\lambda) - 1)} \approx \frac{\lambda^2}{L} \tag{21}$$

The value of beta function λ_0 for this type of focusing structure (FOFO) in the case when $L \ll F$ can be written as:

$$\lambda_0 \approx \sqrt{FL} \tag{22}$$

Using Eq. (21) one can notice that stability condition is $\lambda_0 < \lambda$. For $I_e = 0.2$ A and $L = 2$ m we have: $F < 538$ m and $\lambda_0 < 32.8$ m. This last inequality contradicts our numerical estimates, given at the end of the introduction, where we determined that in the space charge dominated regime $\lambda_0 \approx 130$ m. Making the beta-function λ_0 smaller (< 32.8 m) will provide stability but will result in the beam radius of ≈ 0.5 cm and angular spread unacceptable for cooling.

4 Beam transport with longitudinal magnetic field

Using the longitudinal magnetic field can help to suppress the transverse coherent motion without increasing the angular spread of the electron beam. In such a system electrons move along the magnetic field line and increase in the value of magnetic field does not increase the transverse velocity of the individual particle. This is different from the standard focusing channel where increase in the focusing strength of a separate element will increase the velocity of transverse motion for a given beam size.

But what is minimum value the longitudinal magnetic field for suppression the coherent instability? The equation of motion for the relativistic electron beam can be written as:

$$\frac{d^2x}{ds^2} = x\frac{1}{\lambda^2} + \frac{dy}{ds}\frac{1}{\lambda_H}, \tag{23}$$

$$\frac{d^2y}{ds^2} = y\frac{1}{\lambda^2} - \frac{dx}{ds},\frac{1}{\lambda_H} \tag{24}$$

where $\lambda_H = pc/eH$ is a Larmor length, x and y are transverse particle coordinates. If we introduce a new coordinate $z = x + iy$ we can simplify this set of equations:

$$\frac{d^2z}{ds^2} + i\frac{dz}{ds}\frac{1}{\lambda_H} + z\frac{1}{\lambda^2} = 0 \tag{25}$$

Using ansatz $z = z_0 exp(iks)$ we have the following equation for the wave vector k :

$$k^2 - \frac{1}{\lambda_H}k + \frac{1}{\lambda^2} = 0 \tag{26}$$

The solution for k is:

$$k = \frac{1}{2\lambda_H} \pm \sqrt{\frac{1}{4\lambda_H^2} - \frac{1}{\lambda^2}} \tag{27}$$

We can easily see that for suppression of coherent instability we have condition:

$$\lambda_H < \frac{\lambda}{2} \tag{28}$$

And equation for the minimum value of magnetic field to suppress instability can be written as:

$$H > \frac{2\gamma\beta mc^2}{e}\sqrt{\frac{2\pi r_e n a_o^2}{\gamma\beta^2 a^2}} \approx 10G \cdot \sqrt{I_e/(0.2A)}. \tag{29}$$

The second condition on the value of magnetic field for suppression of the drift motion caused by space charge is:

$$H > \frac{2\pi nea}{\gamma^2(\Delta p_\perp/p)} \approx 2G\frac{I_e}{0.2A}, \tag{30}$$

where $\Delta p/p$ is the value of the relative drift velocity.

And finally we will write the condition that the radius of Larmor rotation in the beam frame should be less then the distance between particles to provide good magnetization:

$$H > \frac{mcv_{\perp e}}{e}n^{1/3} \approx 250G(\frac{I_e}{0.2A})^{1/3}, \tag{31}$$

where $v_{\perp e}$ is the thermal velocity of electrons in the rest frame. Numerical values used for the calculations are ($\Delta p/p = 10^{-4}$, a=2 cm, and $T = 0.12$ eV).

As easy to see, the condition of good magnetization is the hardest but the question whether to use this magnetized regime needs some computer simulations.

5 Numerical estimates

Now we try to design both systems for electron current $I_e = 0.2$ A and kinetic energy of 4.4 MeV. If we clear all ions and have only interaction with vacuum chamber wall, the coherent increment wave length will be about 32 m. Both systems should have beta-function equal or smaller than that: $\lambda_0 \leq 32$ m.

5.1 Periodic focusing system

The equilibrium beam radius for the space charge dominated regime from Eq. (5) is: $a = \lambda_0\sqrt{2K} \approx 0.5$ cm. For the distance between lenses of $L = 2$ m the focal length should be $F = 512$ m. For space charge dominated regime the rms angle excited by these lenses is $\theta_{rms} \approx 3 \cdot 10^{-6}$.

How does the lens with $F = 512$ m look like? If we take the length of this lens to be l_l=0.2 m we have the focusing length:

$$F \approx \frac{4}{l_l}(\frac{pc}{eH})^2 \tag{32}$$

and need $H \approx 30$ G.

5.2 Solenoidal focusing system

For the solenoidal focusing we need $H > 10$ G. For the solenoid with radius 15 cm and cooper wall $\Delta = 0.3$cm, length 130 m , mass of copper is 2.6 T and required power will be 516 W. If we introduce good cooling in this solenoid it is easy to have 400 G but power will increase to 0.8 MW.

Limitations on the Applicability of FODO Lattices for Electron Cooling

Assuming a KV beam distribution (a uniform distribution over an elliptical region of transverse phase space), the beam envelope equations are (Humphries, p. 410):

$$\frac{d^2X}{dz^2} = -\kappa_x X + \frac{2K}{X+Y} + \frac{\varepsilon_x^2}{X^3} \qquad 1)$$

$$\frac{d^2Y}{dz^2} = -\kappa_y Y + \frac{2K}{X+Y} + \frac{\varepsilon_y^2}{Y^3} \qquad 2)$$

where X and Y are the transverse beam sizes, κ is the lens strength, K is the generalized beam perveance, and ε is the beam emittance.

If we further assume operation in a space-charge dominated regime, the right most term can be ignored in each equation. In this case, particle flow will be laminar, and the above equations not only describe the envelope of the beam, but also the trajectory of the outermost particles.

Weak, Thin Lenses

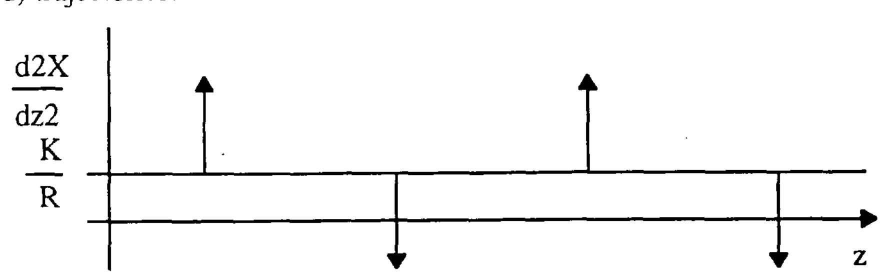
If the beam envelope remains at a fairly constant radius (which will be true if lenses are weak enough and spaced closely enough), the space charge terms (the second terms on the right in eqs 1 and 2) are approximately constant. Furthermore, if thin lenses are assumed, the strength constant κ is zero everywhere except at the thin lenses, where it becomes infinite and causes instantaneous changes in *dX/dz* and *dY/dz*. In this approximation, eqs 1 and 2 become, in the drift spaces between the thin lenses:

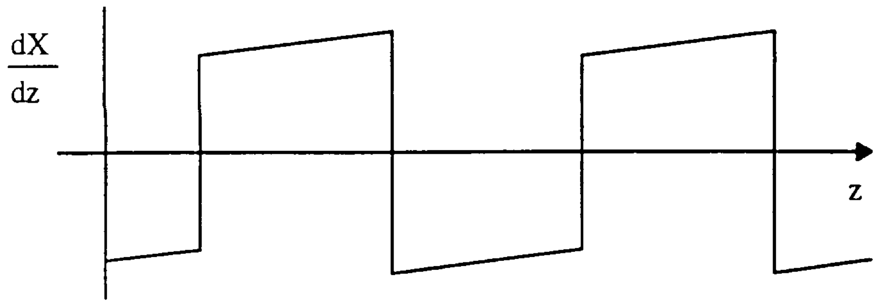
$$\frac{d^2X}{dz^2} \cong \frac{K}{R} \qquad 3)$$

$$\frac{d^2Y}{dz^2} \cong \frac{K}{R} \qquad 4)$$

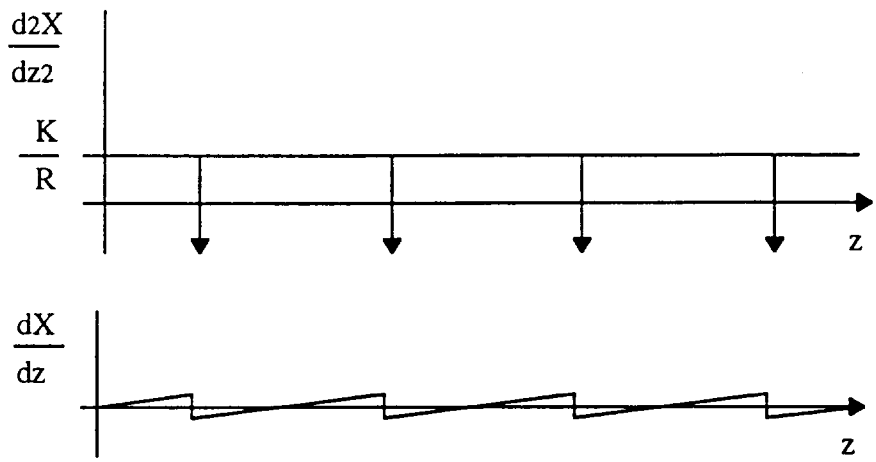
where it is assumed that $X \sim Y \sim R$.

For a matched FODO lattice, this can be integrated, leading to the following (exagerated) trajectories:





In comparison, the trajectories for a transport system using short solenoids are:



Thus, for a given space-charge condition, beam in a FODO channel will inherently have much larger angles than it would in a periodic solenoidal focusing channel. For transverse electron cooling, the angle dX/dz must be small, and a FODO channel may not be appropriate.

The dependence of this angle on K, R, and lens spacing d may be easily calculated subject to the above assumptions. In the following, the operator d/dz will be denoted by a prime, and the subscripts d and f will be used to denote parameters at the defocusing and focusing lenses respectively.

FODO Lattice Calculations

For a FODO lattice (with equal focussing and defocussing lens strengths), the angular kick at each lens is simply proportional to beam size. Thus:

$$\frac{X'_d}{X_d} = \frac{X'_f}{X_f}$$

From the geometry of the sketch of X' (above), it may be seen that:

$$X'_f = X'_d + \frac{Kd}{R}$$

Based on the beam matrix for a drift space, we may approximate that:

$$X_f \cong X_d + \frac{(X'_d + X'_f)}{2} d$$

We may approximate R as:

$$R \cong \frac{(X_d + X_f)}{2}$$

Putting all of these equations together, we may eliminate X_d, X_f, and X'_d, and find that the maximum angle, X'_f, at a focusing lens is given by:

$$X'_f \cong \frac{Kd}{2R} + \sqrt{K}$$

This maximum angle is clearly always larger than $\sqrt{K}$.

The generalized perveance, K, is defined as (Humphries, p. 212):

$$K = \frac{eI_0}{2\pi\varepsilon_0 m_0 (\beta\gamma c)^3}$$

For electrons having $\beta\gamma \sim 10$, this results in:

$$K \cong \frac{I_0}{8.5\text{MA}}$$

$$X'_f > \sqrt{\frac{I_0}{8.5\text{MA}}}$$

Thus, if it is desired to limit the maximum angle to 50μrad (a typical parameter under discussion for electron cooling at FNAL), the electron current must be less than 21mA! This is an order of magnitude below the lowest current considered for electron cooling at Fermilab. FODO channels are not appropriate for the electron cooling parameters under discussion for Fermilab.

K.J. Bertsche

2-22-96

Workshop on Medium Energy Electron Cooling

Proceedings of the Working Group on Guns and Collectors

Thomas K. Kroc

The Group: Bill Herrmannsfeldt - chair

Thomas Kroc - secretary

Dave Anderson

Xiaojian Kang

Alex Shemyakin

Anatoly Sharapa

An outline of the discussion of the working group was created jointly by B. Herrmannsfeldt, T. Kroc, A. Shemyakin, and A. Sharapa. This is an expansion of that outline. Because the Fermilab design is relatively new, much of this discussion is broadly conceptual and even tutorial in character.

I. The Issues:

a Gun Design

b Collector Design

c Current Control

d Modulation

e Stability

f Stray Magnetic Fields

g Solenoids on Gun and Collector

II. Gun Design

The components of an electron gun are noted in figure 1.

This design is based on the Pierce geometry. The potential fields generated by this geometry create a laminar beam with little emittance growth.

The cathode is the surface from which the electrons are emitted. The cathode is heated and the electrons emerge by thermionic emission. As the temperature is increased, the emitted current increases. This dependence is called the temperature limited regime. As the emitted electrons accumulate above the cathode surface, and before they are carried away by the electric field, they build up a repulsive force that inhibits the further emission of electrons. As the emission current increases, the current may decrease below what would be allowed by thermionic emission alone. This is the space charge limited regime. The cathode may be flat or spherical depending on desired geometrical and beam effects.

The focus electrode surrounds the cathode and is generally cup shaped. It helps shape the fields around the cathode surface and is part of the Pierce geometry.

The modulating electrode stands part way between the cathode and the anode; typically closer to the cathode. It shapes the equipotential distribution above the cathode. Its profile should be as sharp as possible. This allows it to guide the equipotential fields. If it is flat or blunt, the equipotentials would flow around its surface and cause a bowing one way or the other. This electrode can be used to vary the current emitted by the cathode. The equipotentials between it and the cathode control the space charge effects directly above the cathode. It therefore can also be used to turn the gun on and off.

The anode is at the exit of the gun and its potential is that of the final kinetic energy of the electron beam. If the difference between the anode and the modulating electrode is too great, the potential lines near the modulating electrode can be distorted. To counter this, one or more gradient electrodes, similar to the modulating electrode, can be added. This will help regulate the distribution of the potentials and allow the modulating electrode to be varied enough to vary the current and turn the gun on and off.

Principal points of concern in gun design:

- Try to achieve uniform current density on cathode. The space charge of the emitted beam will then be most uniform. Also, when the cathode starts to fail, the areas of higher emission will fail first but not in an azimuthally symmetric way. Beam stability will then degrade very rapidly. The greater the non-uniformity, the faster the decay.
- Avoid emission from the cathode edge. Attention must be paid to the joint between the cathode and the focus electrode. Avoid virtual cathodes and emission from the sides of the cathode.
- Use the modulating anode to control the current.
- If one uses a multi-element cathode then one looses the advantages of the Pierce geometry.

Items specific to Fermilab application:

- Flat cathode will probably be adequate.
- One additional gradient electrode will probably be needed in addition to the modulating electrode.
- Cathode can be of similar diameter as the final beam. This should allow current density and perveance to be in acceptable range.
- Compression or expansion of the beam is not necessary. We can concentrate on matching to the accelerator column transport.

III. Current Control / Modulation

Perveance is defined as $k = I/V^{3/2}$. Normally perveance is considered to be a geometrical factor. If one wanted to vary the perveance of the gun, one would have to vary the geometry of the design. However we can redefine to perveance to use the potential difference between the cathode and anode for the voltage. Now we can vary the voltage of the modulating electrode to vary the current emitted by the cathode. This can be used to turn the gun on and off. It can also vary the gun current by approximately an order of magnitude

IV. Pulsed vrs. Continuous Operation

This pertinent for commissioning. The question is how to turn on a high current device for the first time and commission the beamline. Naively one can think of two methods: turn up the current gradually or start with short pulses and gradually lengthen them. Other working groups will address other aspects of the question but an issue pertinent to gun design came up in this group.

If the gun is suddenly switched on at full operating parameters, the fields have not yet equilibrated with respect to the space charge. The initial emission from the cathode will be temperature limited, not space charge limited. It will produce a current higher than the steady state current. This will then decay to the steady state current as the fields adjust for the space charge. This will give a transient that, at least at the start of commissioning, will be of a length similar to the initial pulse.

For low current operation, the cathode can be run in the temperature limited regime for commissioning. As the system is tuned up, the current can be raised and space charge will come to dominate in a more controlled way.

V. Collector Design

For the collector, we define the perveance as $k = I/E_{beam}^{3/2}$. The critical issue here is to keep the perveance below 2 until the beam is inside the collection element.

If the collector is more positive than the gun cathode, the beam will be accelerated into the collector and any ions and secondaries will be collected.

An asymmetric (not cylindrically symmetric) collector will also reduce the chance of secondaries re-entering the deceleration column.

If a symmetric collector is used then one will probably want a crossed magnetic field to divert electrons moving in the opposite direction into the wall.

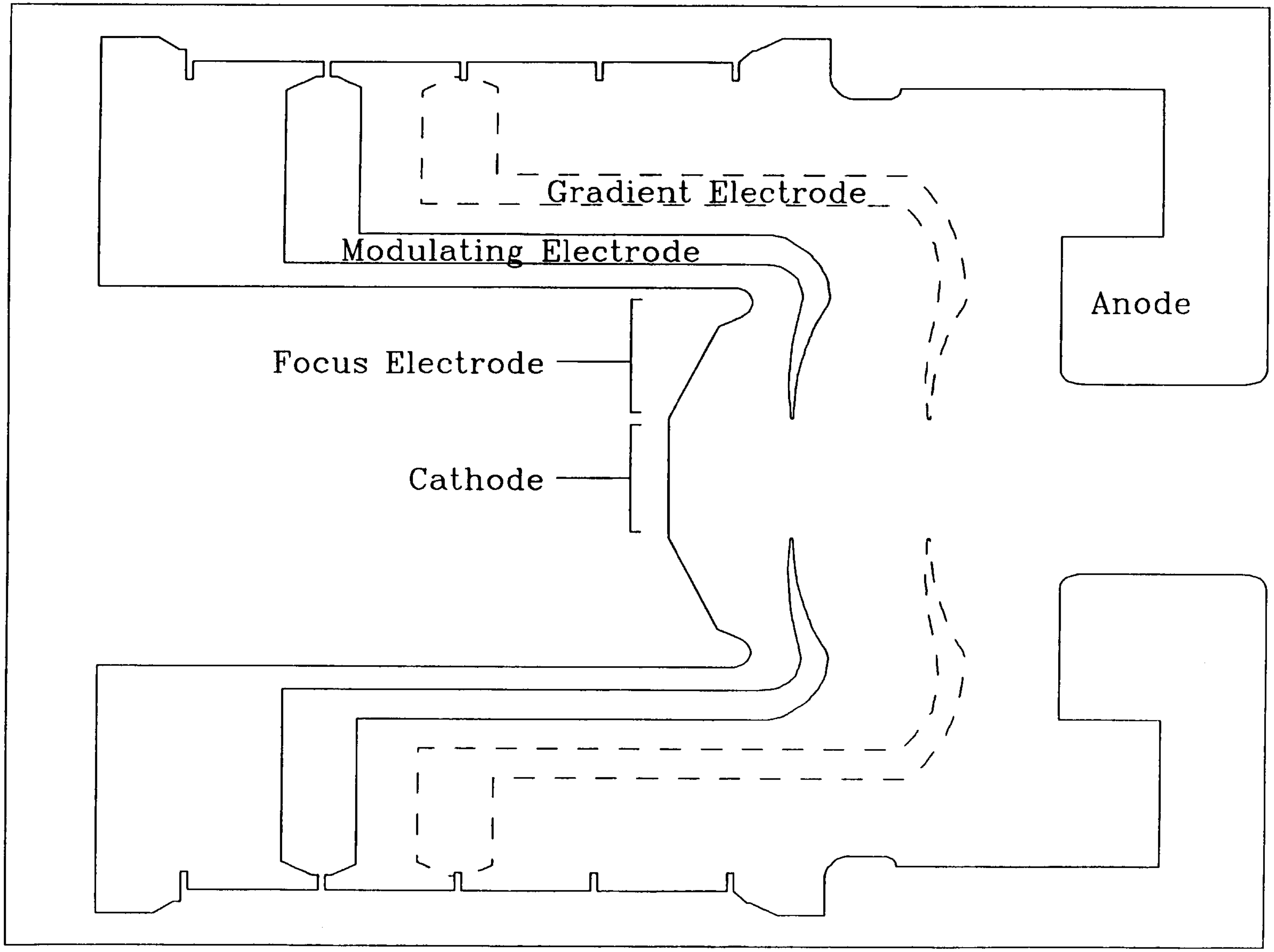
Plasma neutralization is not advisable for the applications discussed here.

VI. Subjects that are technically not covered by guns and collectors but that were discussed in the working group.

- Magnetic Field shielding - It is the experience of B. Herrmannsfeldt that one can not use shielding metals to achieve greater than a 90% reduction in static magnetic fields. Since we need much greater reduction we will probably need to use active control such as helmholtz coils. We will need to wait until we can map out the magnetic fields in the cooling area and then determine the number of segments needed. Since the fields will be time varying, the suppression will also need to vary.

- Solenoids on guns and collectors - B. Herrmannsfeldt was of the opinion that we might be able to use a combination of discrete focusing elements and long solenoids for controlling the cooling beam. This would involve immersing the gun and collector in solenoidal fields. Frequent but discrete, thin coils down the accelerating and decelerating columns and then a long continuous solenoid in the cooling section. This could be done if the magnetic fields required are on the order of 100 G. During the wrapup, P. Colestock mentioned that permanent magnets might be useful in the columns.

Example Gun Design



Electron guns and collectors developed at INP for electron cooling devices

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April 4, 1996

1 Introduction

Institute of Nuclear Physics (INP) has a rich experience in designing electron guns and collectors for electron cooling devices. This paper is a review of the experience of several INP research groups in this field. Some results obtained at INP for systems without a guiding magnetic field are also discussed.

2 Systems with longitudinal magnetic field

All existing electron cooling devices are based on a longitudinal magnetic field confinement. Their guns and collectors have the same main principles as the gun and collector, which have been first developed and tested at INP.

2.1 Traditional guns

The main requirement to a gun of an electron cooling device is to minimize transverse electron velocities in the beam. These velocities can increase due to transverse electric field E_r in the gun (so called "anode lens effect"). The first gun for the electron cooling [1] was made at INP for the NAP-M cooler in 1969 (Fig.1). To suppress "the anode lens effect", the NAP-M gun was designed to use resonant optics. The idea was to create a quasi-rectangular E_r distribution in the gun with the width of this distribution being equal to an electron gyroperiod (Fig.2). The first electron cooling experiments were successfully performed with this gun.

Attempts to obtain the explicit resonance optics helped to understand that the most sequential approach is to form a maximally smooth E_r distribution in the gun

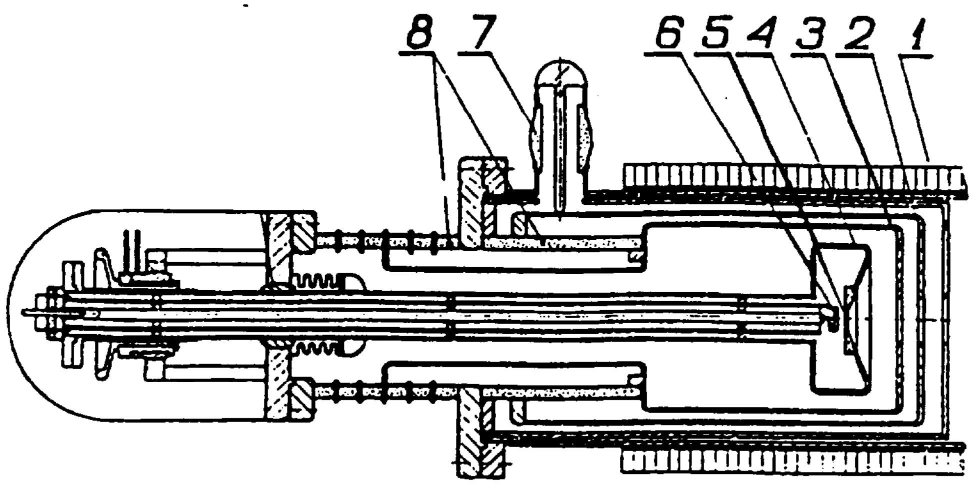

Figure 1: The NAP-M electron gun. 1,2,3 - anodes, 4- Pierce electrode, 5- LaB_6 cathode, 7,8- high voltage insulators.

(adiabatic gun) [2]. The smoother this distribution is, the less magnetic field strength is required to produce a beam with low transverse velocities (Fig.3).

Such an approach was first applied for the development of the gun for the MOSOL facility [3] in 1985 (Fig.4).

The measurements carried out on MOSOL showed that the electron transverse energy was approximately equal to the thermal one, i.e. "the anode lens effect" was negligible. These results were used in designing other coolers. All the guns of the modern electron cooling devices use an adiabatic gun regime (see, for instance [4], [5]). Partly, the adiabatic gun for LEAR was produced by the Lipetsk branch of INP [6]. Presently, the gun for GSI SIS cooler is being manufactured at INP.

2.2 Traditional collectors

There are two main requirements to an electron beam collector:

• to decrease the dissipated power, *i.e.*, to decrease the product of collector voltage with respect to the gun cathode, U_{coll}, and beam current, I. This requirement is normally characterized by the value of the collector perveance P_{coll}:

$$P_{coll} = \frac{I}{U_{coll}^{\frac{3}{2}}}$$

• to suppress secondary electron flux from the collector. The ratio of this flux to

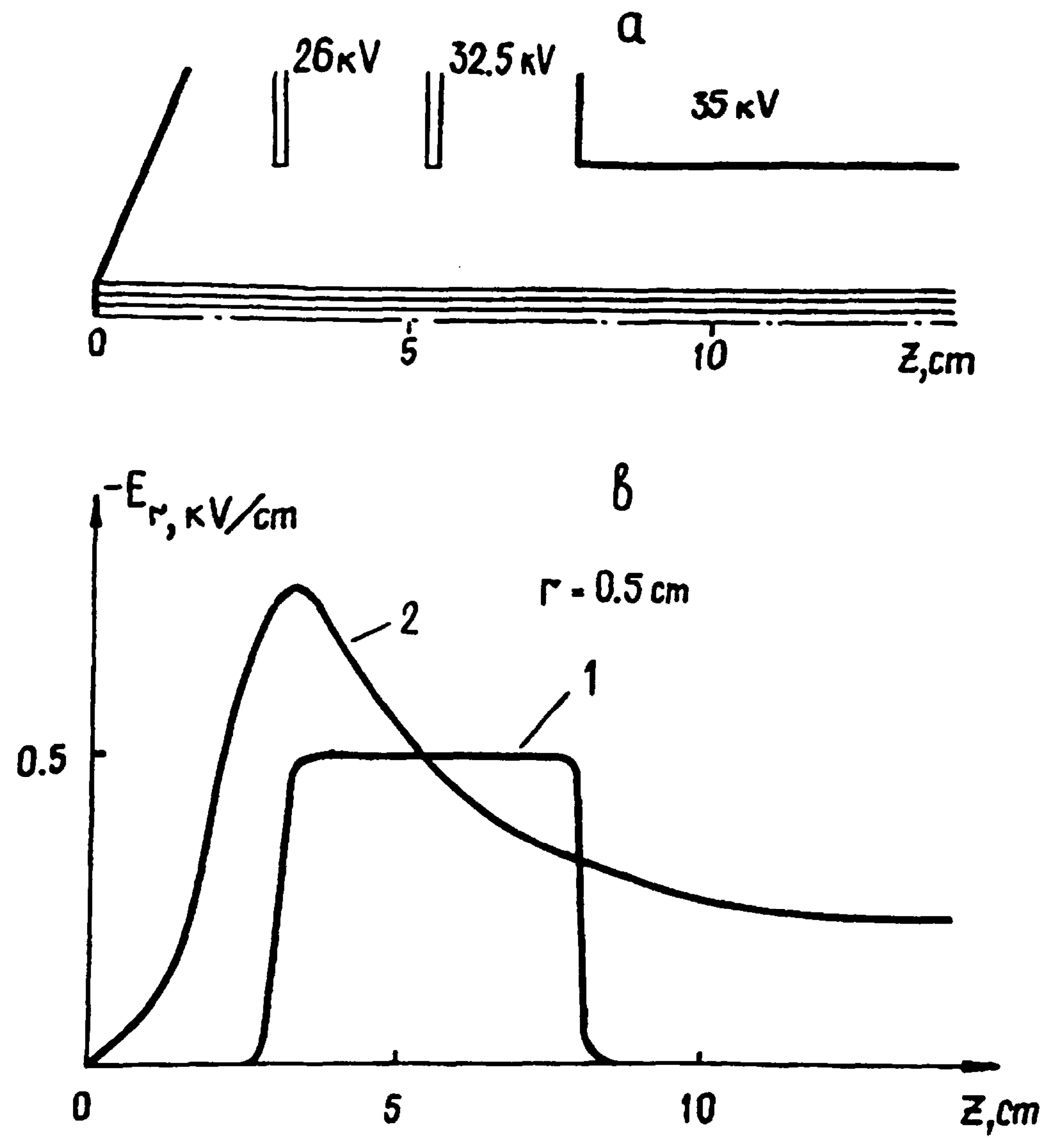

Figure 2: a) The NAP-M gun, b) E_r distribution along Z-axis: Curve 1 shows the "resonant optics" and curve 2 is the calculated field distribution.

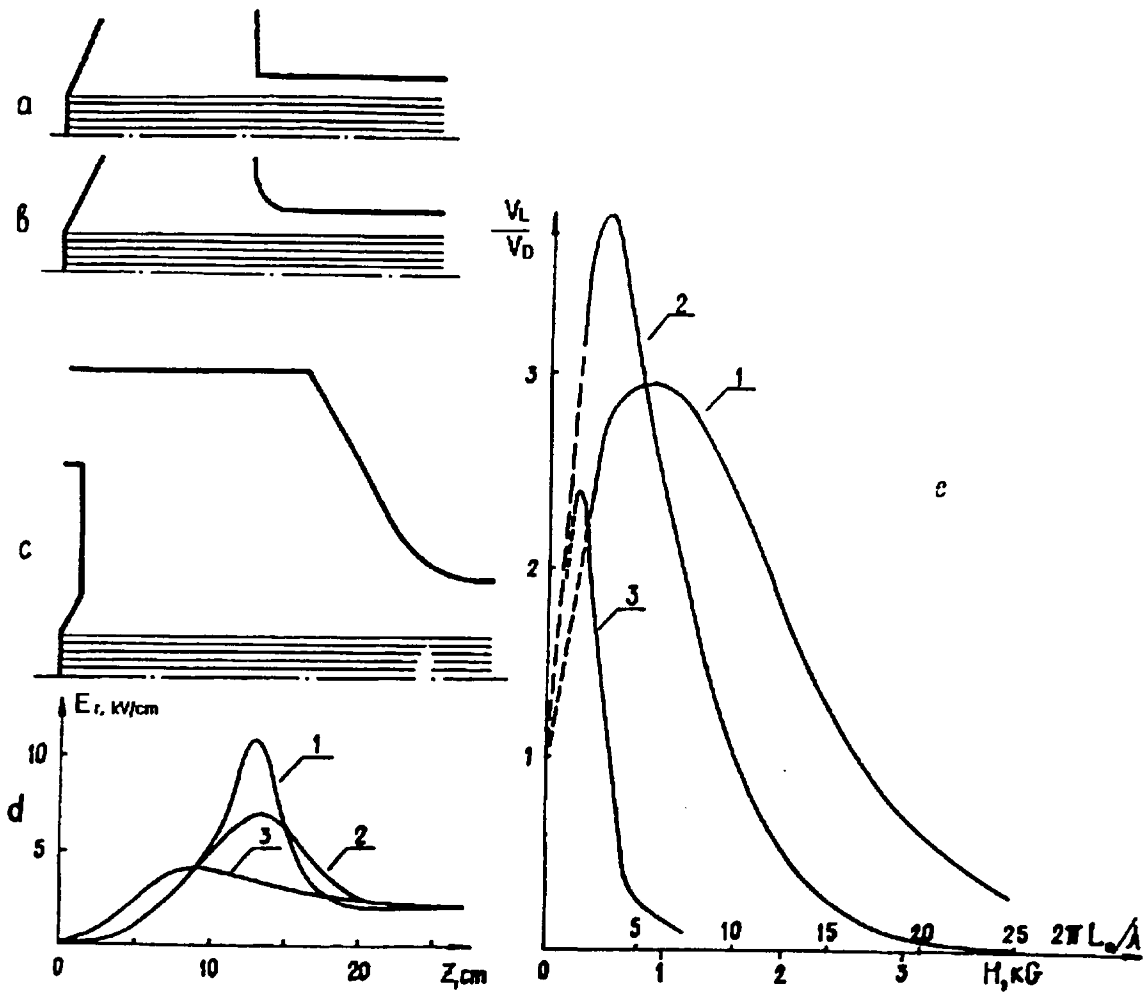

Figure 3: Three diode guns of various smoothness (a,b,c) and their characteristics: d- E_r distributions, e- transverse velocity V_L due to the gun optics. Perveances of all guns are equal, the results are obtained for equal currents. The transverse velocity is shown in units of a drift velocity V_D of a boundary electron around the beam in an equipotential space: $V_D = (2Ic)/(V_0 rB)$, I is the beam current, V_0 and c are the electron and the light speed, correspondingly, r is the beam radius, B is the magnetic field strength. L is a characteristic gap in the gun, $\lambda = (2\pi V_0 mc)/(eB)$, m is an electron mass.

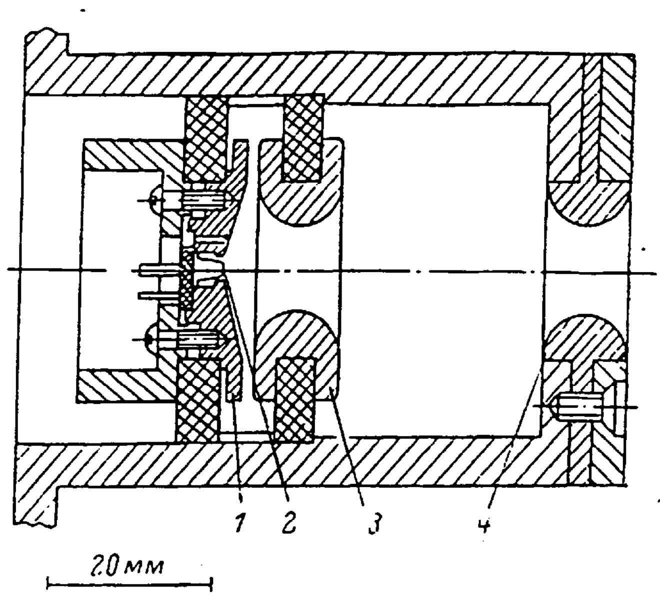

Figure 4: The MOSOL electron gun. 1- Pierce electrode, 2- cathode, 3- first anode, 4- grounded anode.

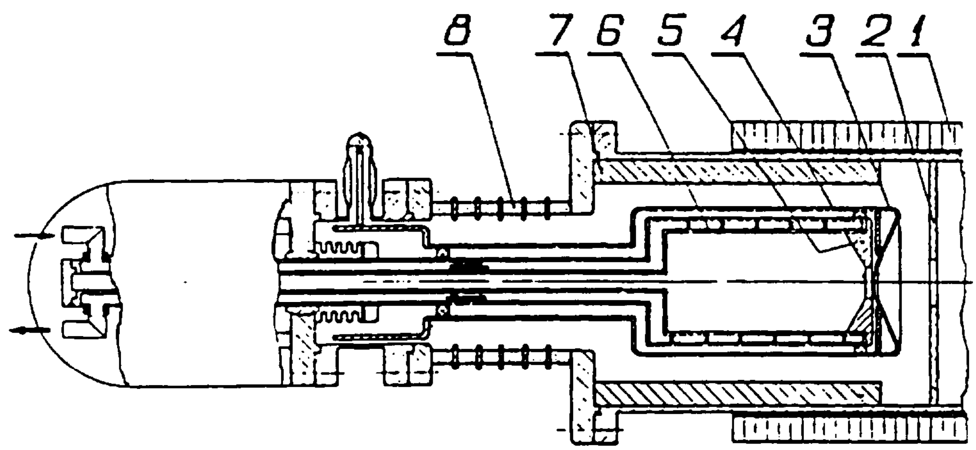

Figure 5: The NAP-M collector. 1- solenoid, 2- collector anode, 3- suppressor, 4,7- magnetic screens, 5,6- collector surface, 8- high voltage insulator.

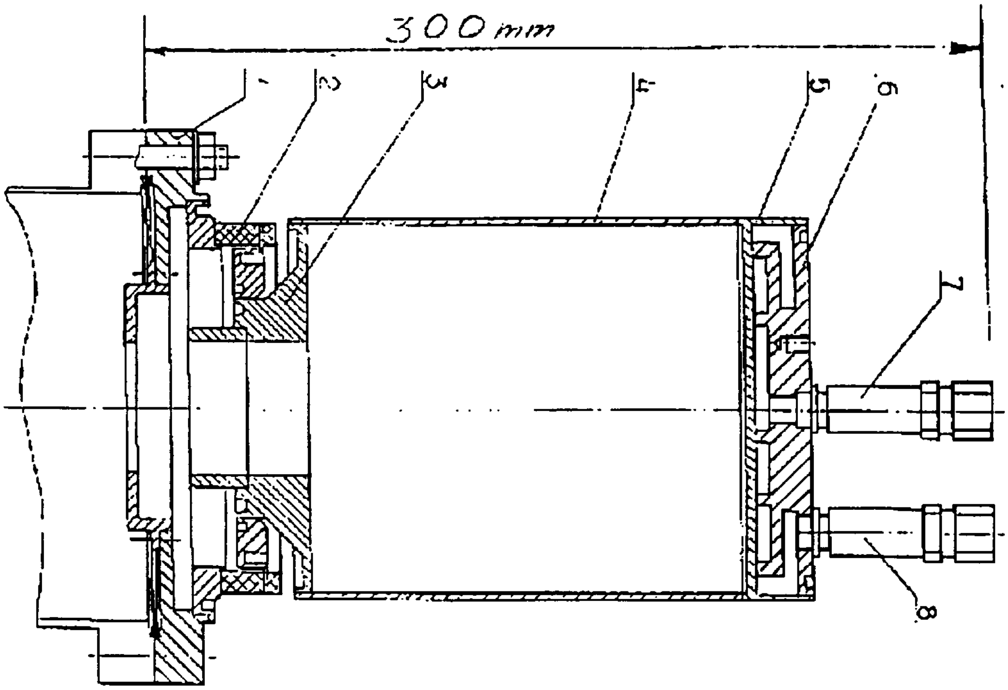

Figure 6: The CELSIUS collector. 1- suppressor, 2- insulator, 3,4,5- collector surface, 7,8- water input and output.

the beam current is called the collector secondary emission coefficient σ_{coll} and is a characteristic of the efficiency of the collector itself[7]. Typically, only a fraction of the escaped secondary electrons reach grounded electrodes, thus contributing to the total high voltage power supply current. This secondary electron current is called current loss, δI. It is more traditional to talk about the collector efficiency in terms of the relative current loss $\delta I/I$, although this value depends on the device properties as a whole.

The first collector intended for electron cooling was the NAP-M collector (Fig.5), developed at INP in 1969 [1]. It is a Faraday cup with decreasing magnetic field inside, which creates a magnetic mirror for secondary electrons. A special electrode (suppressor) placed near the collector entrance produces a potential barrier for these secondaries. This collector operated successfully at currents up to 1 A and $\delta I/I = 10^{-4}$, P_{coll}=15 $\mu A/V^{3/2}$.

Collectors of all existing coolers employ the same principles: they are Faraday cups with a magnetic mirror and suppressor. For example, Fig.6 shows the CELSIUS cooler collector, developed at INP in 1993 [8]. Another example is the CERN LEAR collector, which was manufactured at the Lipetsk branch of INP [9].

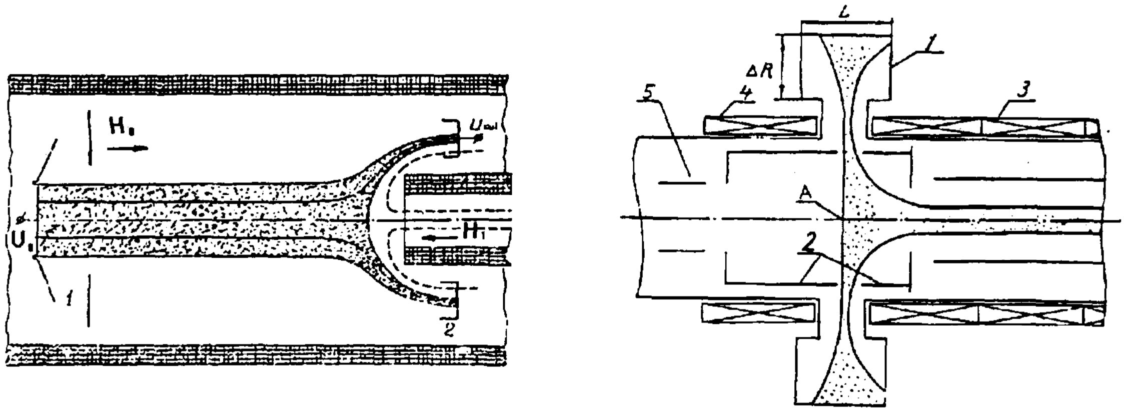

Figure 7: The experiments on the beam shape transformation. The left hand picture shows the transformation into the tube beam. 1- electron gun, 2- collector. The right hand picture illustrates the transformation into a disk beam. 1- collector surface, 2- additional collector, 3- main solenoid, 4- solenoid creating a cusp field, 5- reflector.

2.3 Systems with a beam shape transformation

The two tasks for the collector mentioned above (namely, an increase in the collector perveance (a) and decrease in the current loss(b)), are in contradiction to each other [10]. It is difficult to collect the beam with the current of over several amperes with the low enough current loss and a reasonable value of the dissipated power. The solution for the energy recovery of such beams is a beam shape transformation. This transformation was performed at INP in 1979 by the magnetic field of two oppositely polarized solenoids. Two transformation schemes were successfully tested. In the first one [11] the solenoid with colliding field was placed inside the main solenoid, and the beam was transformed into a tube (Fig.7). The value of the collector perveance 500 $\mu A/V^{3/2}$ was achieved with the relative current loss of 10^{-3}. For the maximum tested beam current of 4 A, the adequate power dissipated in the collector was 200 W.

The second scheme uses solenoids with equal diameters producing a disk-shaped beam [12]. The experimental results are similar to those for the first design.

This last transformation can be inverted, so that the disk-shaped beam emitted from an inner surface of a cylinder is transformed into a solid beam. The gun of this type was tested at INP for first time in 1990 [13]. It has no electrodes on the axis and can be used for an electron cooling device without toroids, in which the axis of the cooled beam coincides with those of the gun and collector [14]. (Fig.8).

The advantages of this device are the absence of an asymmetric impact by the transverse component of the toroid magnetic field on the cooled beam, shorter total

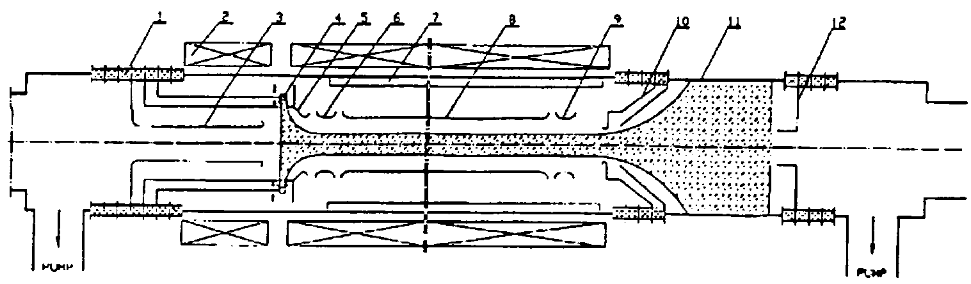

Figure 8: Electron cooling device without toroids. 1- high voltage insulator, 2- solenoid forming the cusp magnetic field, 3- gun reflector, 4- cathode, 5- anode, 6,8,9- drift tube, 7- NEG pumps, 10- suppressor, 11- collector, 12- collector reflector.

length for the same cooling section length, and significantly lower cost. A prototype of such a device is under investigation at INP within the framework of the CRYSTAL storage ring project[15]. The gun of the prototype is shown in Fig.9. The main beam characteristics of this gun were measured [16]. They are approximately the same as those for traditional guns, except for the small region near the beam axis (a disturbance region). Some beam parameters are listed below.

Parameters of the beam generated by the hollow cathode gun.

Energy	0.1- 20	keV
Beam current	0.01- 1	A
Beam diameter	30	mm
Disturbance region diameter for I=0.1 A, B=2 kG	3.5	mm

2.4 Model of the high voltage electron cooling device

In 1986 the model of the high voltage electron cooling device (SILUET) was tested at INP [17]. The layout of the SILUET installation is shown in Fig.10. It consists of three tanks and a beam line. The central tank is a standard 1 MV power supply of an INP industrial accelerator ELV. Two other stainless steel tanks contain acceleration and deceleration columns with a gun and collector, respectively. Conical solenoids situated outside them create the magnetic field of up to 1 kG. The gun and collector are connected with the high voltage terminal by tubes.

In this setup, the recirculation of 1 MeV, 1 A DC beam was reliably performed [18]. For the collector perveance of $P_{coll} = 5\mu A/V^{3/2}$ the relative current loss was measured to be $\delta I/I = 10^{-3}$.

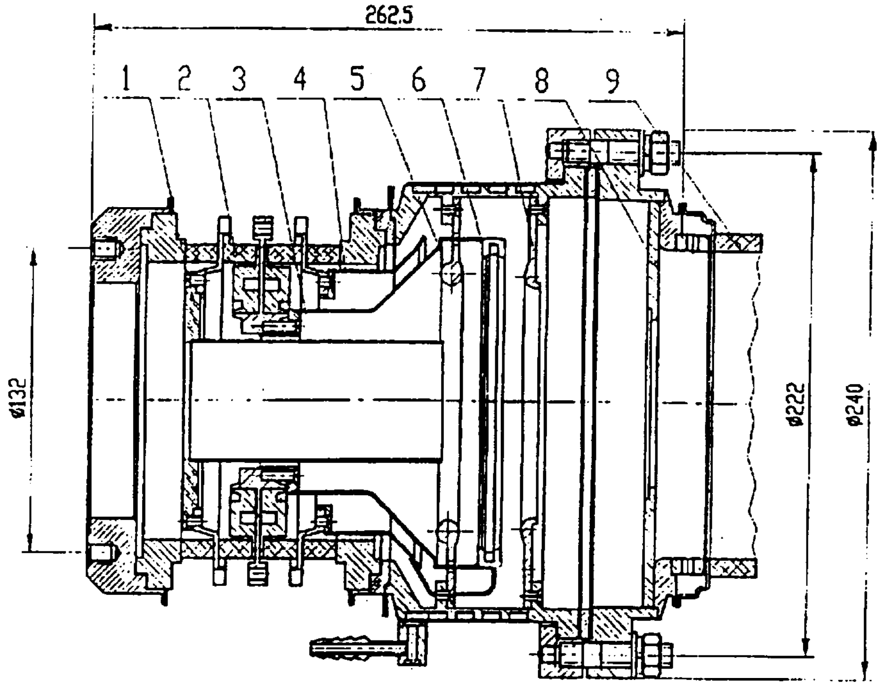

Figure 9: The hollow cathode gun. 1- gun reflector, 2- insulator, 3- cathode feedthrough, 6- cathode, 7,8- anode, 9- high voltage insulator.

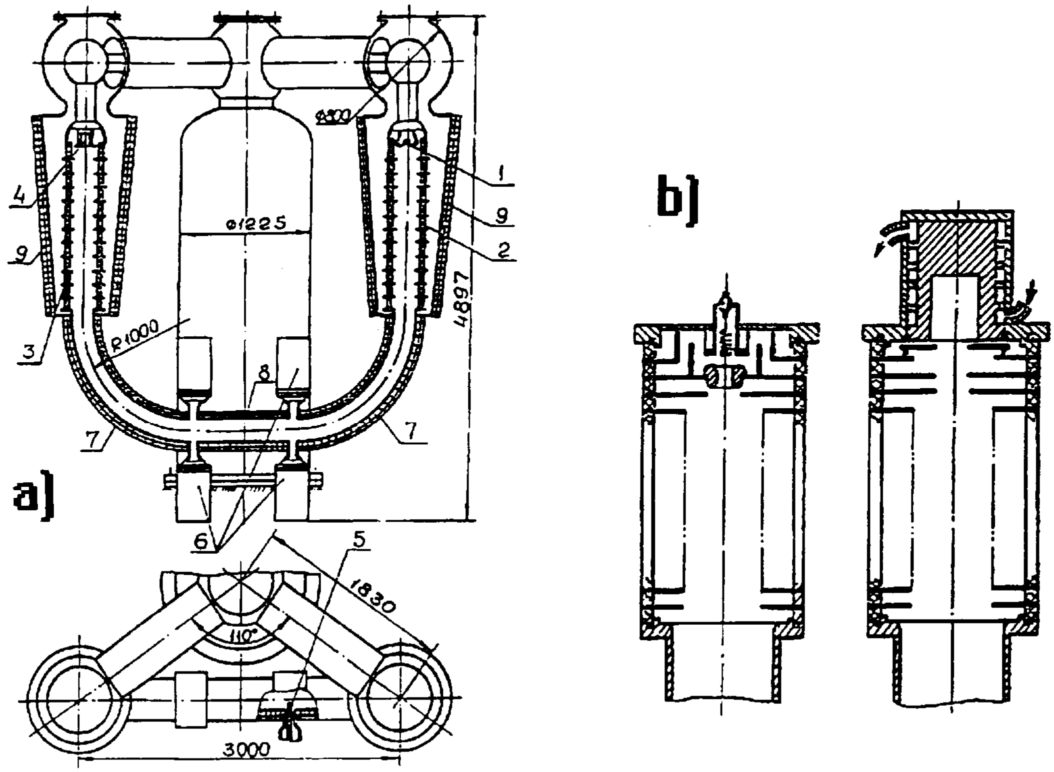

Figure 10: (a)The SILUET installation: (1) cathode, (2) accelerating column, (3) decelerating column, (4) collector, (5) secondary electron collector, (6) ion pumps, (7),(8),(9) solenoid. (b)Gun and collector of SILUET setup.

Note, that one of the reason for the relatively high value of the current loss was large diameter of the electrode holes near the collector (considerably exceeding the beam diameter, see Fig.10b). The diameters of these holes were chosen by taking into account the beam movement during the operation due to the instability of the high voltage power supply.

3 Systems without a guiding magnetic field

INP also has a rich and varied experience in designing and producing systems for generation, transport, and energy recovery of electron beams without the longitudinal magnetic field.

3.1 Prototype of a high voltage switch tube

Approximately at the same time when the electron cooling device for the NAP-M installation was developed, an efficient recovery of the intensive electron beam energy in a device with a cathode and collector arranged outside the magnetic field was performed [19]. It was the prototype of a high voltage switch tube, developed at INP in 1970 (Fig.11). In this device, the relative current loss of $\delta I/I=10^{-3}$ at the average beam current of 8 A, collector perveance of 30 $\mu A/V^{3/2}$, and electron energy of 100 keV was achieved. Note, that the beam is transported by a periodic permanent magnet focusing system and all the electrons escaping the collector are lost.

3.2 Experiments on loss decrease for the industrial accelerator gun

INP successfully produces and sells industrial accelerators of ELV series [20]. They are the powerful electron electrostatic accelerators for the electron energy of up to 2.5 MeV and beam power of up to 100 kW.

At the beginning of the eighties, one of the problems for a reliable operation of the accelerator was the breakdowns. It was found, that the breakdowns take place, if the current loss, i.e. the electron current to the column electrodes, exceeds one microampere level. To find the reasons for this loss, special experiment was performed at INP in 1983. Fig.12 shows the scheme of this experiment. The electron beam is generated by the gun analogous to the ELV accelerator gun, passes through the system of grounded electrodes and is received by the collector. With a suppressed potential at the electrode before the collector, the secondary flow from the collector is less than $\delta I_{coll} \leq 10^{-5}$, so that the current loss to the grounded electrodes is due to a halo around the primary beam only.

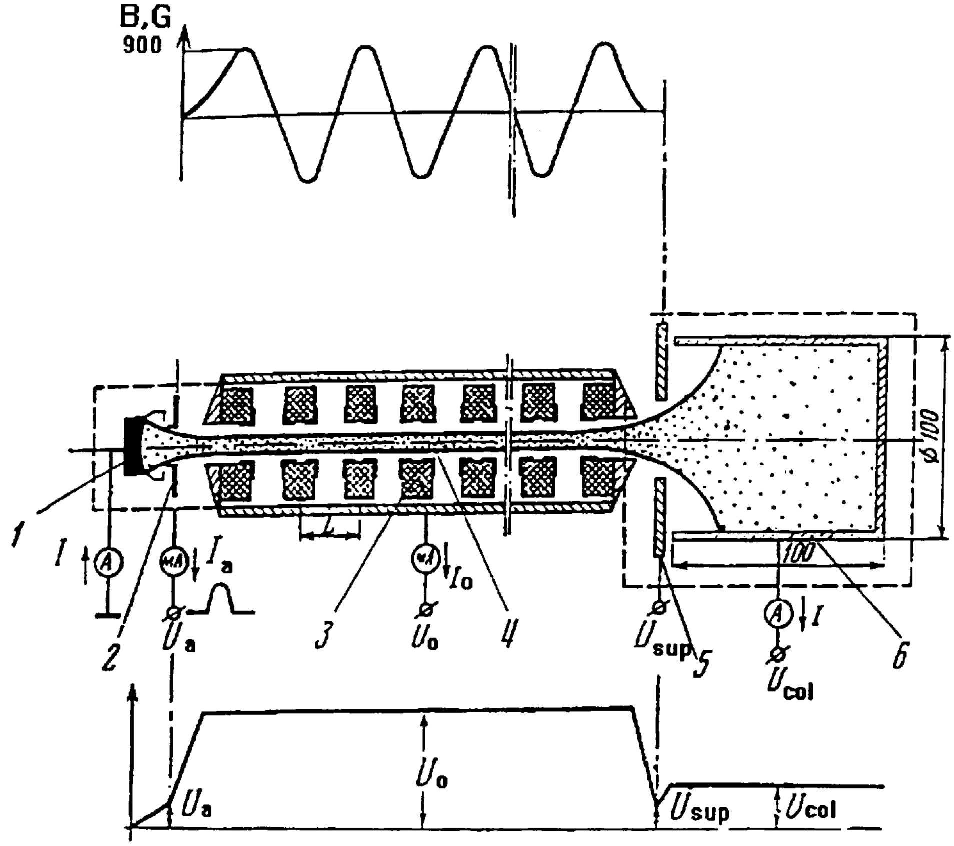

Figure 11: High voltage switch tube prototype. 1- cathode, 2- anode, 3- permanent magnet lens, 4- electron beam, 5- suppressor, 6- collector.

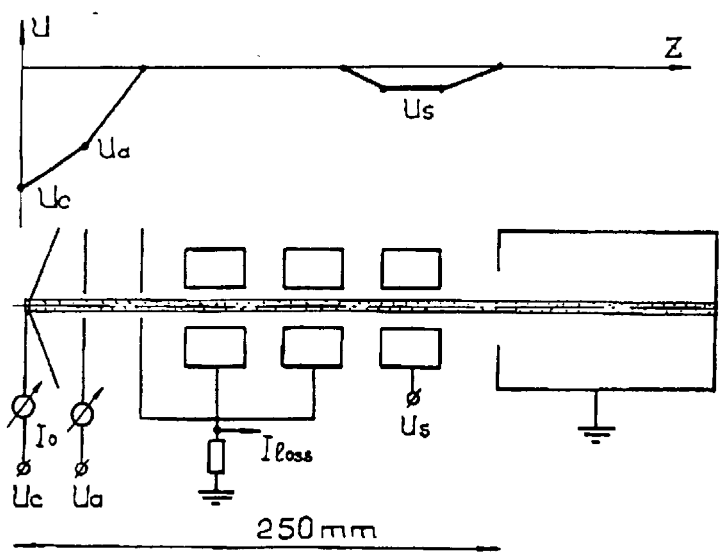

Figure 12: Experiment with the ELV accelerator gun.

The most important characteristic of a gun is the dependence of the current loss on the beam current.In our measurements, the beam current was changed by the first anode potential or by the cathode heater power for the fixed cathode potential with respect to ground.

Typical picture of such a function is illustrated in Fig.13. For low (high) enough current, the beam converges (diverges), such that it cannot pass through the column: a part of the primary beam goes to the grounded electrodes and creates a high current loss. In the optimal parameter region, the beam with approximately parallel trajectories is generated and reaches the collector. In such a regime, the main source of the current loss is the beam halo, created in the gun region.

The main conclusions made by the results of these measurement are the following:

1) For all the guns tested, there exists an area of the beam current where the grounded electrode current is relatively low ($\delta I/I <<1$), i.e. the loss of the primary beam is close to zero.

2) The computer simulation describes well the behavior of the primary beam part, for instance, the boundary of the low loss area of the beam current. However, in the cases, where a low current of electrons hitting the accelerating column is necessary, the conventional computer trajectory analysis gives only a first order approximation.

3) In the low loss regime ($\delta I/I < 10^{-4}$), the experiments showed a strong dependence of the loss in the accelerating column on the vacuum, cathode temperature, and specific design of the cathode unit.

4) The gun modification made in accordance with the results of these experiments

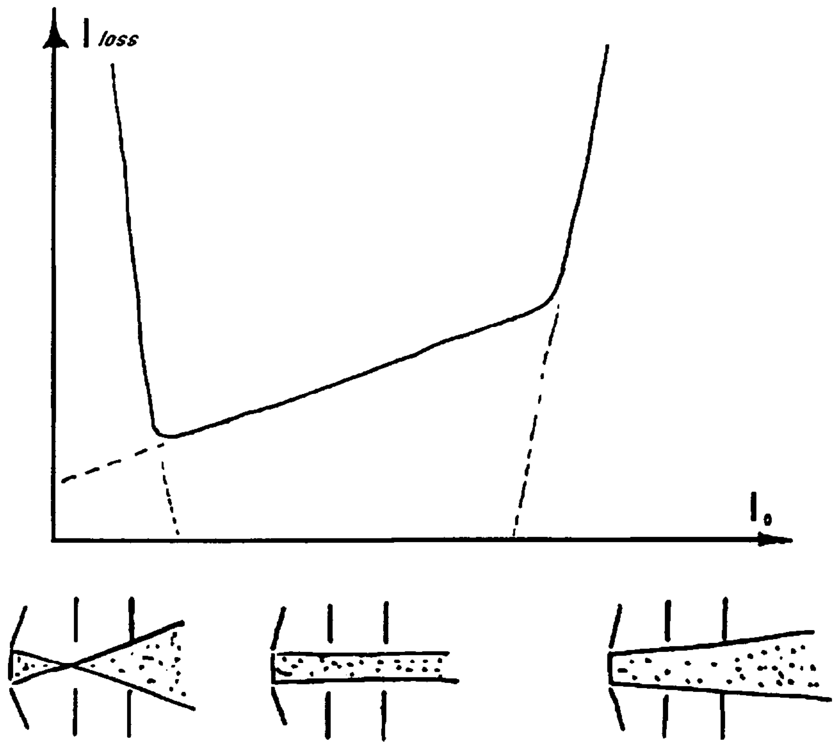

Figure 13: Illustration of the current loss as a function of the beam current.

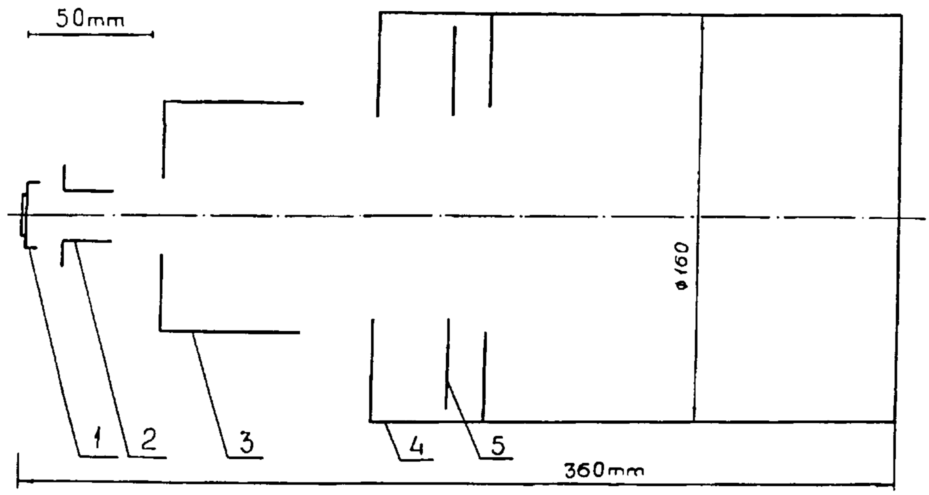

Figure 14: Scheme of measurements. 1- gun, 2,3- anode, 4- collector, 5- suppressor.

gave the loss decrease down to the value of $\delta I/I < 10^{-5}$.

3.3 Model of the collector for the SSC MEB EC project

When the SSC MEB EC project was under development at the Indiana University Cyclotron Facility [21], a model of the collector appropriate to use in this cooler was tested at INP. The scheme of measurements is shown in Fig.14. The beam current was up to 0.3 A, the collector and anode voltages with respect to the cathode were, correspondingly, 0.1 - 1 kV and 0.3 - 6 kV. The main task of this development was to decrease the current loss down to values suitable for the use in a cooler based on the Pelletron as a high voltage power supply, i.e. $\delta I/I < 10^{-4}$. The relative current loss as a function of the collector perveance is shown in Fig.15 for several runs.

In our opinion, there are some conclusion from these results, which are general for all Faraday cup collectors:

1. The current loss increases with the collector perveance. The low current loss ($\delta I/I < 10^{-4}$) can be achieved only for low values of the collector perveance ($P_{coll} < 10\mu A/V^{3/2}$).

2. At this level, the current loss depends also on the gun characteristics and can be defined by the beam halo.

3. The secondary electron flow from the collector depends on the vacuum and the collector surface condition.

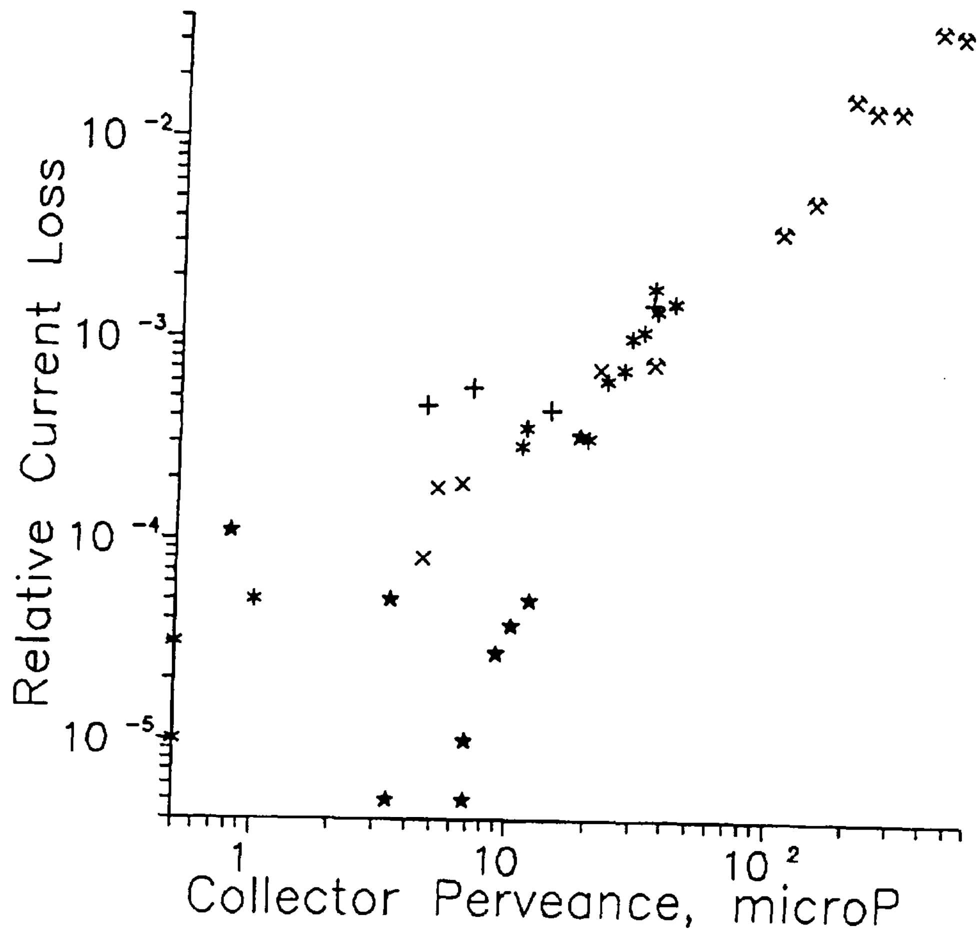

Figure 15: Relative current loss as a function of the collector perveance.

4 Conclusion

• Solutions for the guns generating the beams with low transverse velocities and parameters typical for the electron cooling devices (i.e. I = 1A, B= 1 kG) are known, such guns work successfully in many coolers.

The generation the beam with an emittance equal to the thermal one in the guns without the magnetic confinement is also possible, as have been shown by the simulation and experiments made for FEL systems [22].

Contrary to the FEL, the electron cooling device should work in a DC regime, so that the very low current loss is necessary. Apparently, the main problem of the gun for cooling is the beam halo created near the cathode.

• The prediction of the main collector characteristics, first of all, the current loss, is more complicated.

Collectors for systems with a longitudinal magnetic field could be compared with those, used in the electron cooling devices under operation. But all of these devices work with presence of a strong magnetic field (about 1 kG) and at electron energy not exceeding 300 kV. In this case, the current loss is determined not only by properties of the collector itself, but also by the system configuration and the magnetic field strength. As a rule, only small part of all electrons, knocked by the primary beam from the collector surface and escaping from the collector, reach the grounded electrodes. Other electrons, kept by the strong magnetic field, travel to the gun, reflect, return into the collector and are captured like the primary beam. As a result, the current loss can be much smaller than the total flow of secondaries from the collector, $\sigma_{coll} >> \delta I/I$.

For intermediate energy devices, the magnetic field cannot keep secondaries at bends, and in this case $\sigma_{coll} = \delta I/I$, i.e. the current loss will by far exceed those for the same collector in a low energy cooler.

Another probable difficulty may arise due to an intrabeam scattering inside the electron beam, increasing the width of the electron distribution over the energy. Electrons from far enough tails of this distribution are repelled from the potential minimum at the collector entrance and can noticeably increase the current loss, as is shown by the estimation.

Hence, the requirements to the collector are more severe for the devices operating at a beam energy over $1MeV$ in comparison with currently operating coolers. Nevertheless, our experience gives us a hope for the success in development of collectors appropriate for the intermediate energy electron cooling device.

• From our point of view, the scheme analogous to the SILUET one would be preferable for an intermediate energy electron cooling device with a guiding magnetic field, because it can use a standard high voltage power supply separated from the columns.

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