

# PRELIMINARY REPORT ON A 500-MeV LINAC-POWERED RACE-TRACK MICROTRON FOR THE UNIVERSITIES OF NORTHWEST ITALY

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The electron beams required nowadays for nuclear research must offer high intensity in a narrow energy bin at high duty cycle. In order to get these characteristics within cost limits consistent with University budgets, we decided for a machine long since proposed (in more or less detail)<sup>(1-4)</sup> but newer yet built: a recycled linac or linac-powered race-track microtron, consisting essentially of a linac section placed between two constant-field magnets so as to drive the electrons through  $n$  cotangential race-track orbits (Fig. 1).

The system is a transformer multiplying by  $n$  the rated energy of the linac and dividing by  $n$  its rated current; but, moreover, the recycling magnets endow the linac with a strong phase focusing, analyzing the beam at each turn, so that the machine yields the energy of a  $n$ -section linac with a much better spectrum. This spectrum compaction is not obtained by simply throwing away part of the electrons against energy-defining slits, but by keeping them all to oscillate very close to a "synchronous" value of the accelerating voltage,  $\Delta V_s = N\lambda Bc/2\pi^{**}$ , determined by the magnetic field and independent of the external or internal fluctuations of the linac peak voltage  $\Delta V_p$ . Therefore, in principle, with a well-centered injection bunch the whole rf power transferred to the beam is spent on the utilized electrons, which fact, added to the drastic reduction in copper losses with respect to a  $n$ -section linac, ma-

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\*\*  $\lambda$ =rf wavelength;  $N$ =differential harmonic number, the harmonic number of the  $n^{\text{th}}$  orbit being given by  $N_n = N_0 + nN$ .

kes for installation and operation costs much lower than those required by a beam with the same energy and current within the given narrow energy bin, obtained with a conventional linac and its analyzing magnet. Indeed, the efficiency of the rf power transfer to precise output beams may be measured by the average input rf power required per unit average beam power within a 0.1% energy bin; this figure is 56—65 for the design data of the MIT linac<sup>(5)</sup>, while a sample computation with tentative parameters for our machine (with out attempts to optimization and beam loading compensation) yields a value 16, which (we think) will be reduced to about 8, in view of the results of other sample computations<sup>(3)</sup>. Another figure of merit is the beam power lost on the energy-defining slits per unit of beam power within a 0.1% energy bin, which is a measure of the high-energy background at the entrance of the beam transport system: this is 7 for the quoted data on the MIT linac and 0.5 for our sample computation, and we think it can be still reduced to the level of the low-energy background of the machine.

The parameters of the machine are not yet definitely decided: we are thinking to an output of about 500 MeV, with average useful beam power of 10—20 kW at 3% duty cycle, to be reached in 25—30 orbits with a magnetic field of about 1.5 Wb/m<sup>2</sup>, an injection energy of 12—20 MeV, and a gain per turn of 15—20 MeV, obtained with two conventional L-band linac sections excited with two 75-kW klystrons. The duty cycle is limited by the cooling system and the available klystron power; of course a superconducting linac could yield unit duty cycle, but we decided to stick to conventional structures and aim at lower values, because the development of a cryogenic linac can be tackled with only in a technological climate, as highly sophisticated as in the USA. We choose an external high-energy injection in order to exploit the higher beam-loading tolerance that seems allowed for work at  $N=1$  (a low-energy injection is possible only with  $N \geq 2$ ) and to make available the injection linac (casily overdesigned) as an independent tool for extra-nuclear research, since interdisciplinary activities are highly desirable in a University Laboratory.

The design of the machine does not call for major physical or technological breakthroughs: it is not matter of a new acceleration method as much as of a new optimal arrangement of well-known devices. The main design problem consists in determining the focusing parameters in space and phase, where many questions require particular attention since the adiabatic conditions no longer obtain, which in conventional cyclic machines allow to write differential linearized equations.

A number of focusing devices (edges and quadrupoles) may be used on each orbit to achieve spatial focusing. On the basis of the similar and simpler synchrotron beam stability problem we worked a generalization suitable to our case, obtaining betatron beam oscillations of limited extent (Fig. 2). Requirements on the one-turn transfer matrices to get a first-order separation between the spatial and the phase focusing

problems were also imposed. First order computer calculations show that the spatial focusing is achieved with (quadrupole gradients lower than 300 Gauss/cm and with edge angles smaller than  $20^\circ$ ). Tolerances of the order of  $0.5\%$  on all the calculated values are possible.

For the phase focusing, the first problem is to find size and position of the injection buckets, i. e. the range of phase and energy within which an electron must be injected in order to get, through the  $n$  orbits, a gain-perturb close enough to  $\Delta V_s$  not to be stopped by the energy-defining slits on the magnet edges; these buckets are found to be different in size and shape at different values of the „synchronous phase”  $\varphi_s = \sin^{-1}(\Delta V_s / \nabla V_p)$  of the accelerating voltage, and to overlap only partially (Fig. 3) (a behaviour quite unlike that offered by conventional „adiabatic” machines); as  $\varphi_s$  changes during the acceleration, owing to the variations of  $\Delta V_p$  caused by the power fluctuations and the beam load, the useful injection bunch must be limited to the overlapping portion of the buckets corresponding to a given excursion of  $\Delta V_p$ , i. e. to a given beam load in presence of given external fluctuations. First results show that injection at bunches  $N=15^\circ$  wide, with fair to large energy tolerance, can be accelerated without losses through  $\Delta V_p$  excursion allowing for a substantial beam load (the higher the injection precision, the higher the allowed beam power); at  $N=2$  the buckets overlap only for small variations of  $\Delta V_p$ , and to such a limited extent that only  $2^\circ-3^\circ$  injection bunches can be accommodated (Fig. 4)\*. With the wide energy-defining slits used in this sample computation, the energy spread of the whole accelerated bunch, jittering through the whole injection tolerance, keeps within  $\pm 0.07-0.12\%$ . One can reasonably expect still better values with optimized parameters and an external compensation of the beam-loading build-up during the machine filling time.

Some interesting interface problems are yet to be solved, but they are well defined and present at first approximation a comfortable margin of safety.

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\* Computation parameters:  $V_s=16$  MV;  $n=30$ ;  $\lambda = 23.8$  cm; linac length:  $4.3$  m magnet distance:  $5.25$  m; beam loading parameter:  $250\%/A$ ; external fluctuation  $\sigma$ ;  $V_p: 1\%$ ; hard-edge magnetic field.

Table 1

Efficiency comparison between multisection linacs and linac-powered race-track microtrons

Machine:	LINACS				COMPUTATION ON MICROTRONS		
	Saclay		MIT(5)		Wik Wilson (3)		N. W. *) Italy
Mode	A	B	A	B	A	B	
Energy at full load, MeV	500	340	396	198	414	595	500
Duty cycle %	1	2	1,8	5,8	3	6	3
Klystrons: $n^\circ \times KW_{ave}$	15×55		10×80	10×65	2×75	2×300	2×75
Total average rf power input	825		800	650	150	600	150
Beam total output average power	100		114	80	18	60	14
Energy bin %	1		0,4	0,4	0,1	0,1	0,15
Fraction of beam in the energy bin %	50		50	50	100	100	100
Input rf power per unit beam power within 0,1 % energy bin	165		56	65	8,33	10	16
Beam power dissipated on the analyzing slit:							
for the design bin	50		57	40	—	—	—
for a 0.1% bin	95		100	70	—	—	—
Beam power dissipated on the analyzing slit per unit beam power within 0.1 % energy bin	19		7	7	—	—	0,5

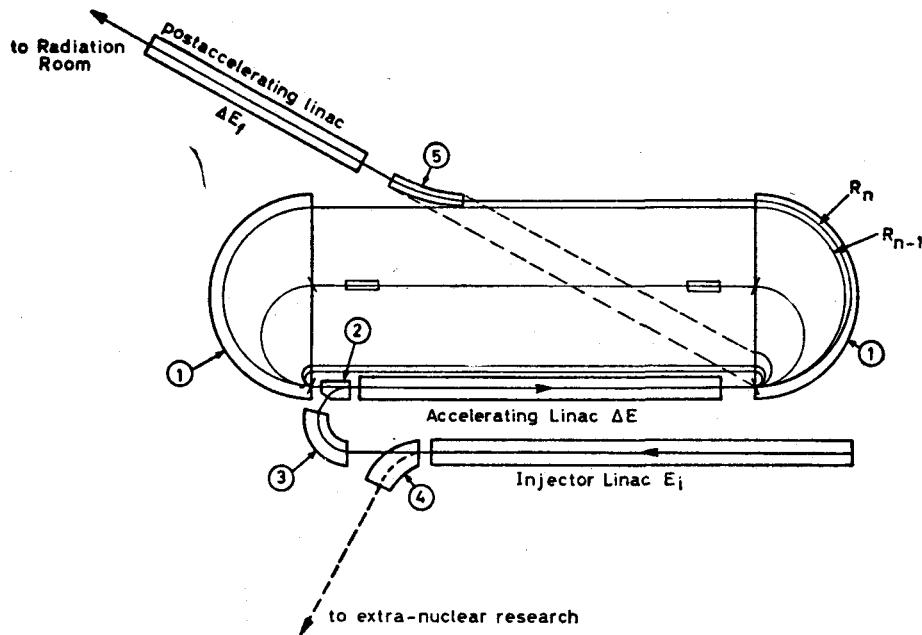


Fig. 1. Schematic Layout.

\*) First computations, without optimization nor beam-loading compensation.

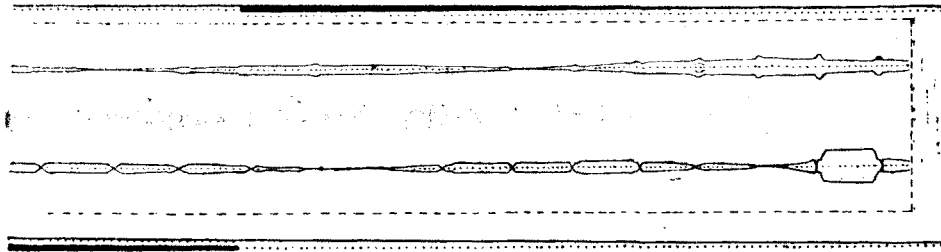


Fig. 2.

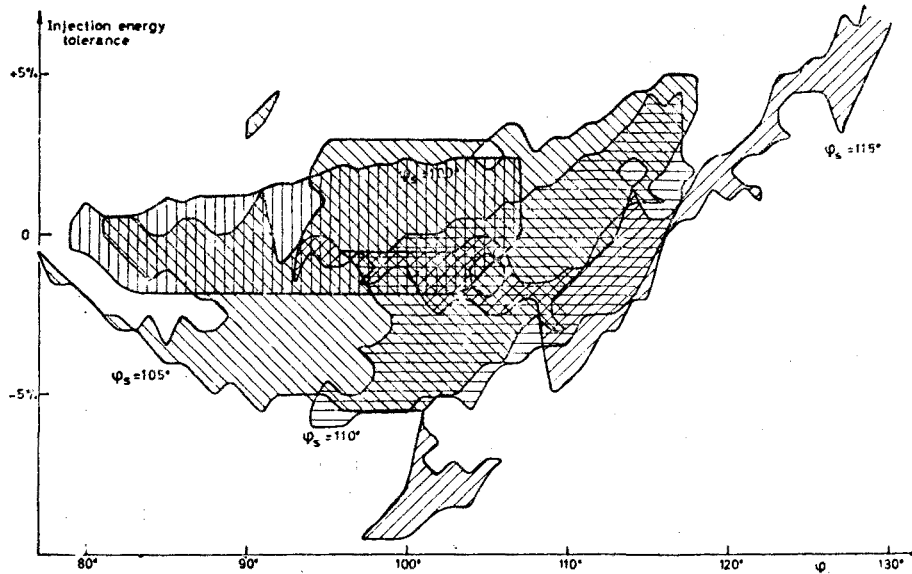


Fig. 3. Injection buckets at four values.

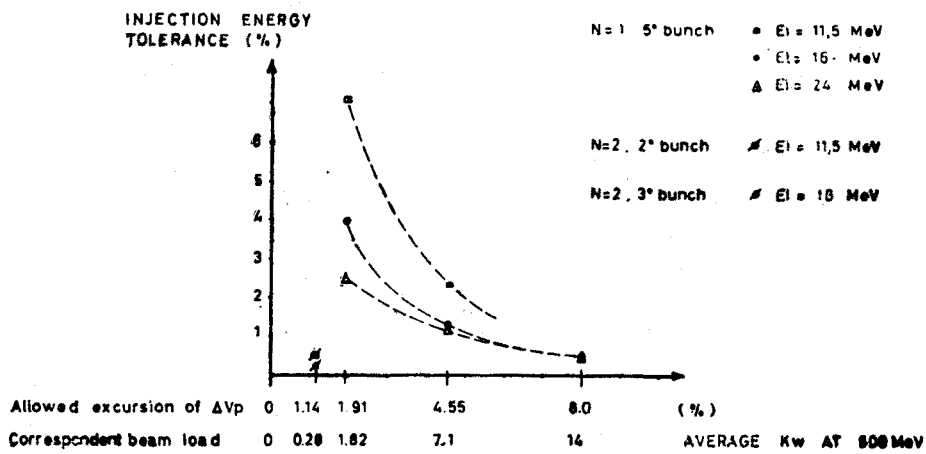


Fig. 4. Injection tolerance for given variations of peak accelerating voltage,

## ДИСКУССИЯ

**Беловинцев:** Вопрос к Чижову и д-ру Хансону. Предусматривается ли возможность регулировки фазы прохождения электронов через линейный ускоритель на первых орбитах?

**Чижев:** Никакой регулировки для фазового дрейфа нет, хотя её легко сделать в случае необходимости.

**Hanson:** For an energy of 20 to 30 MeV it is not necessary to make adjustments of the phases at individual orbits. Below this energy some adjustment of the separation between magnet or in the length of the low energy return paths will be necessary.

**Сидоренко:** Вопрос к д-ру Хансону. Допускается ли возможность потерь пучка на диафрагмах сверхпроводящего ускорителя?

**Hanson:** We expect to have very small beam losses in the superconducting accelerator section. The largest deviation from the axes are calculated to be about 0,5 cm while the smallest aperture in the accelerator section will have a radius of 1,3 cm.

**Чижев:** Вопрос к д-ру Хансону. Какова технология ниобиевых резонаторов?

**Hanson:** The technology for the fabrication of the superconducting sections is that which has been developed at Stanford University and will be discussed in another paper.

**Haimson:** I have a general question regarding the superconducting microtron projects. All the discussions and the calculations shown to date have been associated with steady-state operation. Have any numerical analyses been conducted on the transient beam loading effects of long accelerating structures in relation to the multiple orbit build-up, and secondly, have the effects of possible small transverse beam displacement due to BBU (beam break-up) been studied? I see here several people from Stanford. They can answer this question.

**Suelzle:** Transient beam loading should not be a problem in this case since one can use feedback to stabilize the amplitude and phase of the fields in the accelerating structure. At Stanford University during tests on a lead-plated accelerator with amplitude and phase feedback control the transient beam loading effect was less than 0,1% amplitude change. No beam instabilities were observed during the transient build up period nor at any other time.

**Мочешников:** Вопрос ко всем трем докладчикам. Когда Вы надеетесь увидеть свои проекты осуществленными?

**Hanson:** We are now constructing one of the two linac section which should be completed early next year. We have not received money for the complete facility. If funds become available soon we could have the microtron operating in 1971.

**Чижев:** Такую машину можно построить за 2,5—3 года.

**Gonella:** The funds for the whole project, which also requires building a new laboratory, are allocated in the 1970-74 Five-Year Plan of the INFN, but we do

not know when they will be available, because this plan has not yet been examined by the Government. We are thinking of a three-step construction schedule: first we shall test the low orbits with small end-magnets, exiting the two linac sections with one klystron at low duty cycle; then adjust the full magnetic system at low duty cycle; finally assemble the full power, high duty cycle klystron units.

**Гришаев:** В линейных ускорителях можно легко изменять энергию пучка путем изменения количества ускоряющих секций и регулированием ускоряющего напряжения. Каким образом это будет осуществляться в обсуждаемых проектах?

**Gonella:** The beam energy can be varied either by changing together the linac voltages and the magnetic fields, or by extracting from different orbits with a sliding magnet (in which case the beam power may be held constant); if the coordinated variation of the voltages and fields were found out to be too critical, one might fix a few set values for them, and use for the fine variations between the energies of successive orbits a "post acceleration" linac (fig. 1) excited with the residual r. f. power of the injector.

**Капица:** Я предлагаю произвести сравнение этих трех проектов рейстрек микротронов между собой и с линейными ускорителями.

Ускоритель	Стоимость млн. долларов	Средн. мощн. квт	Энергия Мэв	Монохроматичность $\Delta E/E$	Коэффициент использования рабочего времени
Линейный ускоритель МТИ	6	100	400	0,5%	1,8% (максим 6,5%)
Линейный ускоритель в Сакле	8	100	500 (при импульсном токе 20 ма)	0,5%	1-2%
Итальянский проект рейстрек микротрона		20	500	0,1%	3%
Иллинойский проект	2	6	600	0,01%	10%
Проект ЛФТИ	3 млн. руб. (вкл. здание и физическое оборудован.)	250	400	0,05%	10%
Линейный ускоритель в Амстердаме (проект)	6	100	500	0,3%	10% (250 Мэв) 2,5% (501 Мэв)

**Haimson:** The cost is not the only important issue since the initial requirements for a given facility must depend principally on the intended physics program. It seems that the expenditure of a large sum of money to obtain a medium energy machine with low beam power capability only is hardly justifiable when planning a flexible, broad front experimental facility. This is especially the case today, the increasing interest in future meson physics programs is quite evident. Of the various microtron proposals discussed here it seems that the Leningrad proposal is the only one with a beam power comparable to the high duty cycle linacs. However, it is not clear how the necessary temperature-phase stability is to be maintained with 100 KW average RF power dissipated in the waveguide.

**Чижов:** В нашем проекте ускорителя предусматривается большой ток (средний) при малой скважности импульсов. Импульсный циркулирующий ток с длительностью импульса 15 мксек, сложенный из сгустков электронов от всех 30 орбит равен 200 ма. Более 70% этого тока составляют электроны с энергией от 100 до 400 Мэв. Длина ускоряющей структуры с постоянным градиентом  $-2\text{м}$ ,  $\lambda=25\text{ см}$ . Известно, что в коротких структурах получают импульсные токи до 3а с длительностью импульса 10 мксек. Такие токи без развала пучка получает, в частности, д-р Хаймсон. На этом основании наш импульсный ток можно считать малым, т. е. не приводящим к эффекту развала пучка. В проекте заложен "тяжелый, тепловой режим работы структуры, в стенках которой будет выделяться около 100 квт тепла. Однако, нас опять-таки вдохновляют работы д-ра Хаймсона. В МИТ от структуры отводят 30 квт тепла и достигают стабильности температуры  $0,1^\circ\text{C}$  при малом изменении фазовой скорости волны на длине структуры. В нашем ускорителе нет необходимости устанавливать одинаковую фазовую скорость волны по длине структуры так как устойчивое фазовое движение достигается путем подбора длин орбит электронов. Кроме того, нам необходимо обеспечивать стабильность температуры с точностью не  $0,1^\circ\text{C}$ , а около  $1^\circ\text{C}$ .

**Gonella:** We do not think of our machine as a meson factory. For the physics we aim to do the power level indicated is more than plenty. Certainly a machine of our type cannot compete with a multisection linac in total beam power, but when a very narrow energy spread is desired, we think it better to recycle the linac and enjoy the benefits of the phase focusing rather than waste expensive beam power on energy-defining slits.

**C. de Vries:** I would like to make some comments on the problem dealing with linear accelerators versus racetrack-microtrons. First I would like to point out that the prime motivation for any type of machine should come from the physicists. As I mentioned before in Amsterdam we have turned in a proposal for a MIT-type accelerator. Our motivation is to nuclear physics with electrons and the secondary  $\pi$ - and  $\mu$ -beams coincidence type experiments. I believe that an energy resolution of one part in  $10^3$  as possible with modern linacs is highly satisfactory. Moreover if one likes to do the very high resolution type of experiments for which energy spreads of  $1:10^4$  are needed, one can either use slits to improve the energy spread of the accelerator beam or still better apply an energy-loss spectrometer like planned at MIT. In the latter case one has the additional advantage of spreading the primary beam in an energy-position correlated way over the target, which reduces the heating problem. Obviously for the use of the secondary beams, the energy spread of the initial beam is completely indifferent, but one needs high beam power. Linacs are likely to be the better machines in this respect. According to me the sole but important reason for racetrack microtrons is the first column, where comparison is made of the different budgets.

Finally I would like to point out that the excellent performances of the Saclay machine and the design studies made at MIT, makes it very clear that, at least at present, the risk involved in the construction of the racetrack microtrons is higher than for the linacs.

**Haimson:** Since my work has been quoted I would like to classify several points regarding beam break-up and waveguide dissipation. Firstly, the 2,5 а peak current, 8  $\mu\text{sec}$  pulse operation mentioned above was achieved with quite different design parameters than those quoted for the Leningrad microtron waveguide. For example, two short 2856 MHz waveguides (the first a buncher and the second a  $v_p=c$  section) were used compared to the proposal single section 1200 MHz waveguide. Also, the guides were specifically designed to suppress BBU and a much higher electric field strength was used than that proposed for the microtron. The transmission of only 200 mA (15  $\mu\text{sec}$  pulses) through a 2 meter 1200 MHz waveguide can readily be achieved, however, by suitably varying the impedance of the structure. It seems to me that a major problem for the microtron project is the effect of high

dissipation in the structure and the sensitive relationship between temperature of the cavities and the integrated phase shift through the structure. It is true that up to 30 kW of average dissipation occurs in the MIT short waveguide structures but these are provided with 0,1°C sensitive automatic temperature-phase control systems. In addition, the seriousness of loss of phase during initial tuning in a linear array of multiple waveguides is not as great as when using a single section with phase dependent re-cycling, since in the case of the linac the beam still traverses the entire machine can be readily analysed and re-phased. I feel that the temperature-phase control problem is very important for the success of the Leningrad microtron proposal and would recommend that the phase fulcrum point on the waveguide be temperature controlled within a 0,2°C bin. This then will automatically take into account beam loading effects.

**Gonella:** The phase shift between the electron and the travelling wave does not matter too much as long as the total accelerating voltage does not go too far from the synchronous value. The phase focusing provided by the recycle magnet is very strong; we found in simple computations that it can absorb quite easily phase kicks of 15° at each passage through the linac.

**Чижов:** Необходимо стремиться к мощным пучкам с большим коэффициентом заполнения и хорошей монохроматичностью. Например, для исследований магнитного рассеяния электронов ядрами (рассеяние на 180°) нужны энергии 400—600 Мэв, токи более 100 мкА и разрешающая способность  $10^{-4}$ . При рождении  $\pi$  и  $\mu$ -мезонов монохроматичность не нужна, нужна малая скважность, что позволит выполнять такие эксперименты, которые нельзя осуществить на машинах с большой скважностью. Интенсивность  $\pi$  и  $\mu$ -мезонов низких энергий будет достаточно велика.

**Капица:** Обсуждавшиеся здесь проекты представляют собой дальнейшее развитие микротонов. При этом теряются основные качества, присущие обычному микротрону, — простота и изящество. Однако возможности, которые могут открыть эти ускорители, представляются очень существенными. Такие ускорители могут дать новые перспективы для физических исследований, некоторые из этих возможностей сейчас еще даже трудно предвидеть.