

QUADRUPOLE FOCUSING LENSES FOR HEAVY ION LINAC

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Abstract

Simulation results of pulsed current electromagnet quadrupoles with integral of the magnetic field gradient up to 7 T are presented. Magnets for the DTL and MEBT focusing channels are designing for the heavy ion linac in Institute for Theoretical and Experimental Physics (ITEP–NRC “Kurchatov Institute”). Appropriate conditions which promise getting the magnetic lens parameters required at restrictions on the overall length ≤ 130 mm as well as on the beam aperture $\geq \varnothing 45$ mm are defined. It is shown that the channel acceptance to beam emittance ratio desired not less than 3 can be provided by conventional low-carbon steel up to magnetic aperture of $\varnothing 50$ mm while beyond this size permendur is out of competition. Some aspects of the pulsed power supply system are considered and main parameters of the pulse current generator (PCG) are given.

INTRODUCTION

High-energy heavy ion beams are the unique tool that allows investigating the radiation resistance of materials. The scope of the R&D is defined by the variety of physics tasks, for example such as the radiation resistivity of reactor materials and space electronic devices.

The Heavy Ion Linac-2 (HIL-2) being under development in ITEP will provide the initial acceleration of following ions Na, Al, Si, P, Ca, Ti, Fe, Zn, Nb, Ag, Pr, Yb, Bi for target irradiations aimed at material engineering and studies of the radiation effects on the space devices. It should meet the requirements shown in Table 1.

Table 1: HIL-2 Characteristics

Type of ion	Na÷ Bi
Mass-to-charge ratio A/Z	4÷8
Output energy, MeV/nucleon	4
Ion current (in case: $^{209}\text{Bi}^{27+}$), mA	3
Beam pulse duration, μs	5
Repetition rate, Hz	1
Beam intensity, ions/pulse	$10^4 \div 3 \cdot 10^9$
Operation mode	pulsing

The goal of the project: front-end physical design of HIL-2 magnetic optics to provide required beam dynamics for maximally compact machine. Electromagnetic quadrupole (EMQ) design should meet requirements on gradient integrals at severe restrictions on aperture, geometrical length, tolerances on non-linearity and accuracy

of magnetic field. These cause the hardest lenses in the channel to produce high magnetic fields in their magnetic steel core and also cause substantial power consumption.

FOCUSING CHANNEL STRUCTURE

Focusing channel of HIL-2 with FODO lattice has to obey the requirements mentioned in Table 2. Focusing channel period has been chosen to be invariable over each DTL section. This establishes preconditions that are used to seek unified solution for a quadrupole lens design.

Table 2: Restrictions to DTL Focusing Channel

Section	Lattice	Beam Aperture, mm	Lens length, mm
DTL	FODO	$\geq \varnothing 45$	≤ 130

The drift tube linac is divided into two parts with different frequencies 81.25 MHz (DTL1) and 162.5 MHz (DTL2). 40 quadrupoles should be installed in focusing channels of DTLs. The parameters shown in Table 3 follow from dynamics simulation results for ions with mass-to-charge ratio of $A/Z = 8$ up to output energy 4 MeV/nucleon. The most rigid ion $^{209}\text{Bi}^{26+}$ has been chosen for the DTL channel development. The calculations were fulfilled under the constraint that normalized acceptance to beam emittance ratio is not less than 3 confined throughout the accelerator.

Table 3: Evaluated DTLs Focusing Channel Parameters

Section	Lens number	Gradient G , T/m	$ Gdz $, T
DTL1	12	$32.5 \div 39.5$	$4.4 \div 5.3$
DTL2	28	$40.7 \div 45.5$	$5.5 \div 6.1$

According to our scheme each quadrupole is installed between flanges of each neighbor pairs of RF cavities seen in Fig.1 within 200 mm length.

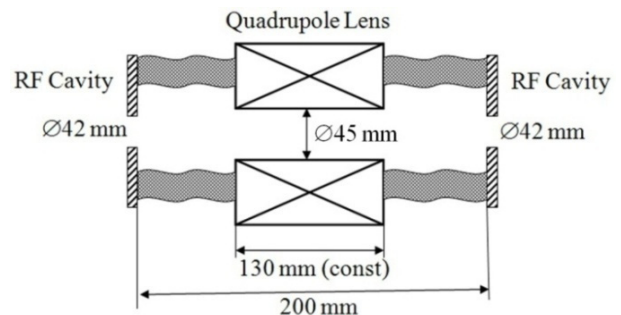


Figure 1: Quadrupole arrangement between RF cavities.

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Since the regular channel gradient range is rather low: $\Delta G/G_{av} = \pm 17\%$ in both DTLs (see Table 3) and depth of gradient change at channel retune for another type of ion in routine linac operation is not greater than 2 (see Table 1) unique type-design for quadrupole lens has been chosen for the whole DTL focusing channel. Besides in adapted design version the kind of magnetically soft steel has been also unified.

QUADRUPOLE LENS DESIGN

Electromagnet calculations of EMQs with magnetic aperture beyond $\varnothing 50$ mm and comparative analysis of their results showed there are no alternative to lens with permendur within ranges specified in Tables 2-3. Due to 15% higher saturation magnetization ensuring by this material compared to conventional non-alloy low-carbon steel such lens produces up to 7.0 T gradient integral at magnetic aperture of $\varnothing 50.4$ mm. This solution has about 10% supply desired to cover technologic corrections.

In order to satisfy traditional technique of EMQ production and to get a low-cost design the preference was given to steel kinds, such as widely used steel-3408.

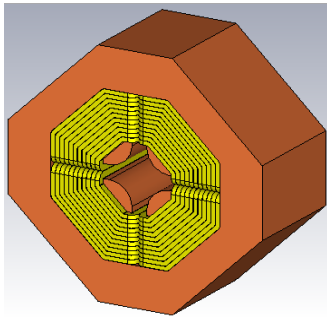


Figure 2: Quadrupole for DTL.

Such lens, shown in Fig. 2, with calculated magnetic parameters listed in Table 4 ensures gradient integral range required but for reduced aperture (much severe duty, compare with [1]).

Table 4: DTL Quadrupole Parameters

Steel type (over entire lens)	Steel-3408
Magnetic aperture, D_{ap} , mm	$\varnothing 47$
Pole profile	Hyperbolic
$L_{pole} \times L_{geom} \times L_{effect}$, mm	$114 \times 130 \times 133$
Current, kA/pole	13.5
Current density, A/mm ²	26
Fill coefficient	0.95
Fields: $B_{pole} \times B_{core} \times B_{yoke}$, T	$1.1 \times 1.9 \times 1.9$
$G \times [Gdz, T/m \times T]$	49×6.5
Field nonlinearity @75 % D_{ap} , %	≤ 0.7
Layers $\times$ Turns/layer	2×11
$R \times L \times \tau$, mOhm $\times$ mH $\times$ ms	$28 \times 3 \times 105$
$I_{nom} \times U \times P$, A $\times$ V $\times$ kW	$614 \times 17 \times 11$
Overall dimensions, mm	$360 \times 360 \times 130$

Dynamics calculations for focusing channel at 3D magnetic field distribution proved compliance with requirements of minimal beam emittance growth at normalized acceptance to beam emittance ratio being not less than 3 in our case.

The electromagnet simulation results are depicted in Fig. 3 and show the operational state of the lens core corresponds to a boundary on magnetization curve (Fig. 3a) where Steel-3408 approaches to saturation. Nevertheless entire pole surface remains far from saturation until the breaking point of hyperbolic profile. Further enlarging of the lens excitation in current-carrying wires results in additional losses in field linearity. The lens provides $\int Gdz > 7$ T at fill coefficient of 1.0 (Fig. 3b).

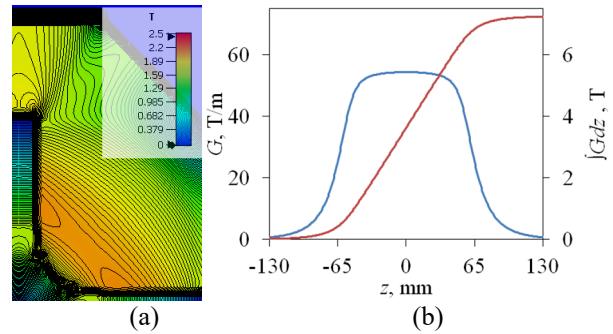


Figure 3: Field distribution in the central lens cross-section – (a) and (b) – longitudinal distributions of the gradient (bell-like curve) and of gradient integral.

Ambient environmental equipment materials, fallen into quads fringe field at its pulse operation in focusing channel, should be carefully chosen to reduce additional losses in gradient integral. So it is necessary to avoid good conductors or to minimize their thickness especially near resonator or drift tube surface that decreases losses in magnetic flux generated by the focusing lens.

Thus quadrupole lens described here is preferable for our purposes in the aggregate of parameters of estimation.

MAGNETIC FLUX INCREASING

To make the focusing channel operation more effective we decided to accept a pulsing mode which follows naturally from relatively small ($< 10^{-4}$) beam pulse duration in comparison with minimal beam repetition period (see Table 1). The most suitable excitation pulse duration is of order of several milliseconds. The choice of appropriate lamination thickness to blade up a magnetic core is always one of the most critical tasks at lens design development. We considered two types of the laminated magnetic materials: permendur (Fe-Co alloy with 2% V) and low-carbon electric steel (type 3408).

Consider a response of a lamina with its ρ , μ and l_p – specific resistance, relative magnetic permeability, and thickness, on ideal step-like increase of external magnetic field. Then magnetic flux in the lamina as a function of time can be described by the following simplified equation (full boundary problem solution can be found in [2])

$$\frac{\Phi(t)}{\Phi_{\infty}} \cong 1 - \frac{8}{\pi^2} \exp\left(-\frac{t}{\tau_{\text{skin}}}\right); \quad \tau_{\text{skin}} = \frac{\mu\mu_0 l_p^2}{\pi^2 \rho}, \quad (1)$$

where Φ_{∞} – equilibrium magnetic flux, μ_0 – magnetic constant. Parameter τ_{skin} in approach (1) can be accepted as time constant of magnetic flux increasing. It is quadratic function of lamina thickness l_p . Time delay is necessary to dissipate eddy currents energy and for flux increasing up to nominal. It depends on accuracy on the magnetic field; for example, if tolerance given on the field instability is $\delta_{\text{tol}} = 0.3\%$ then delay is of order $5\tau_{\text{skin}} \approx 1$ ms at $l_p = 0.3$ mm. Such substantial delay of availability for service does not permit to accept current in the lens and magnetic field excited by the lens being of the same shape at pulse duration of order of several milliseconds. In practice PCG with special flat top in current pulse is widely used for such regime realization.

CURRENT PULSE SHAPE

The automatic control of the channel power supply is more flexible when independent pulse generators carry quads individually. We plan to organize a control system of such very wide network in the following manner: current state monitoring over the system, PCGs operation regimes (in-tolerance) verification, and signals producing for caution, warnings, recommendations for operator, as well as overall routine adjustment.

Traditionally they form a current pulse by capacitor discharge on electromagnet in resonant mode (see Fig. 4, curve C). In this case the useful part of the pulse near its top satisfying tolerance on instability δ_{tol} is of several percent of pulse duration and insufficient for eddy currents dissipation (passive dampening, prevailing factor).

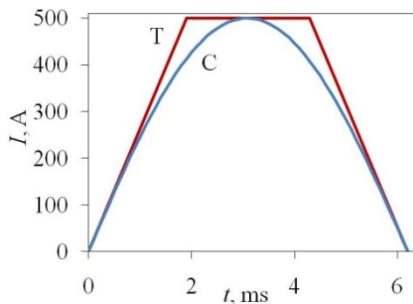


Figure 4: Excitation current pulse at resonance discharge (C) and of trapezoidal shape (T) with flat top.

Besides it should be taken into account all concurrently existing destabilization factors (DF) that magnetic field accuracy experiences; their action should be also suppressed or neutralized at all actively:

1. Eddy currents in laminated quadrupole core and in environment equipment of accelerator.
2. Initial voltage instability on capacitor.
3. PCG activation time instability.
4. Electric parameters of discharge loop variations.

5. Accompanying oscillations attributed to parasitic impedance components of electronic discharge circuit, which occurs at fast transition processes.

ACTIVE FLAT TOP FORMATION

To make the situation controllable we prefer the pulse of trapezoidal shape seen in Fig. 4. With active switches in electronic commutator one can vary initial voltage on a capacitor arbitrarily and thus disable DF2.

Due to such pulse shape a delay can be actively reduced till the moment when excitation current in all (and each) quads in the channel increases up to the nominal level because of both PCG activation time instability and spread of discharging circuit elements parameters. These permit to neutralize factors DF3 and DF4 and to make the system, in particular, insensitive to thermal shifts, electric/magnetic aging, capacitors renovation etc.

Figure 5 demonstrates the PCG operation principle. Chain C1-S1-L1-S2-Corr serves to ensure rapid leading pulse edge while energy recuperation goes through two passive switches like in thyristor/diode H-Bridge [3] or active ones if 4 IGBT modules are applied [1]. When current has reached the nominal level, then the S1 is switched off and circuit L1-S2-Corr maintains the current until the damping transient in the lens core is relaxed. There are another ideologies of flat top formation also effective for pulse currents of up to 1 kA and flat top duration up to 10 ms (see, for example, [4-5]).

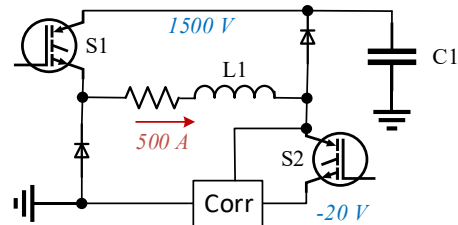


Figure 5: The model of PCG with a flat top option.

The electromagnetic regime study at different discharging circuit parameters showed that in ranges $R = 30\text{--}40$ mOhm, $L = 3\text{--}4$ mH it is reasonable to choose capacitor on $C \approx 2$ mF. Then the current of 500-600 A can be achieved at initial voltage $U_{C0} = 1\text{--}1.5$ kV through $t_{\text{nom}} \approx 1.5\text{--}2$ ms. So the pulse duration of 4-6 ms is sufficient to form flat top duration of 1-2 ms that could be sufficient to dissipate eddy currents energy, dominated DF in 0.3 mm thick lamina. According to (1) active flat-top formation permits to move the magnetic flux $\Phi(t)/\Phi_{\infty}$ into tolerance belt of order 0.3 %. So it is possible to reduce the power of more than $P_{\text{DC}} \approx 10$ kW (at DC mode, see Table 4) down to $P_{\text{imp}} \approx 6$ kW (averaged over current pulse), whereas power $\langle P \rangle \approx 30$ W averaged over minimal beam repetition period. In this case water cooling of quads is unnecessary.

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