QUADRUPOLE FOCUSING LENSES FOR HEAVY ION LINAC

Vl. Skachkov, A. Kozlov, G. Kropachev, T. Kulevoy, D. Liakin, O. Sergeeva, Vic. Skachkov, Yu. Stasevich
Institute for Theoretical and Experimental Physics (ITEP – NRC "Kurchatov Institute") Moscow, Russia

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 on 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

Ions kind	Na ÷ Bi
Mass-to-charge ratio A/Z	4 ÷ 8
Output energy,MeV/nucleon	4
Ion current (for $^{209}Bi^{27+}$),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. Focusing channel electromagnetic quadrupoles (EMQ) design should meet requirements on gradient integrals at severe restrictions on aperture, geometrical length, and tolerances on non-linearity and accuracy of magnetic field as well.

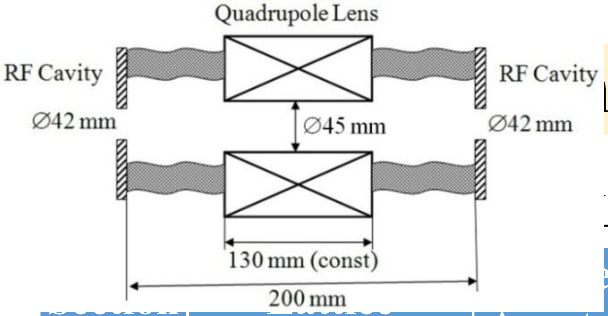
REFERENCES

[1] L. Arnaudon*et al.*, "Linac4 Technical Design Report", Editors: F. Gerigk, M. Vretenar, CERN, Geneva, Switzerland, Rep. CERN.AB.2006.084 ABP/RF, CARE-Note-2006-022-HIPPI, Dec. 2006.

[2] K. M. Polivanov, *Ferromagnetics*, Moscow, Leningrad, USSR: GosEnergoIzdat,1957.

[3] A. M. Kozodaev, N. V. Lazarev, V. S. Skachkov, and S. V. Skachkov, "The System of Magnetic Pulse Commutation of the Linear Accelerator I-2 Beam", Preprint ITEP-52, Moscow, USSR, 1976.

[4] Yu. B. Stasevich and A. V. Kozlov, "Generator of Current Pulses with Flat Top for Electromagnetic Lenses", *Voprosy Atomnoy Nauki I Tekhniki*, issue: 2(28), 1-81, Moscow, USSR, pp.44-45, 1986.



el structure

L Focusing Channel

		eam Aperture, mm	Lens length, mm
DTL	FODO	≥∅45	≤130

Table 3: Evaluated DTLs Focusing Channel Parameters

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

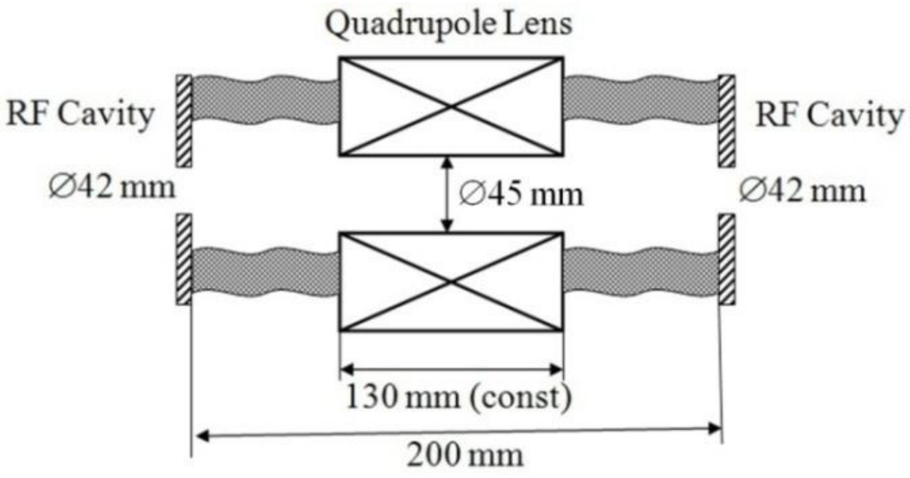


Figure 1: Quadrupole arrangement between RF cavities.

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 that establishes preconditions to seek unified solution for a quadrupole lens design.

40 quadrupoles should be installed in focusing channels of DTLs with parameters shown in Table 3, which follows 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 $^{209}Bi^{26+}$ has been chosen for the DTL channel development.

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.

Since the regular channel gradient range is rather low: $\Delta G/G_{av}$ = ±17 % in both DTLs (see Table 3) and depth of gradient change at channel retune for another ion kind 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.

QUADRUPOLE LENS DESIGN

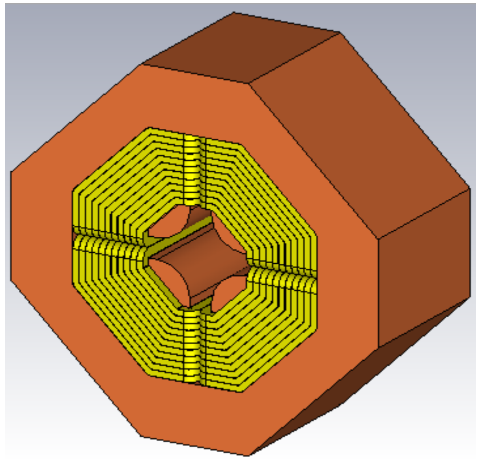


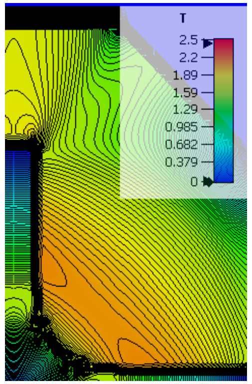
Figure 2: Quadrupole for DTL.

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.

Such lens, shown in Fig. 2, with calculated magnetic parameters listed in Table 4 ensures gradient integral range required but for reduced aperture ∅ 47 (severe duty, compare with [1]).

Table 4: DTL Quadrupole Parameters

Steel type (over entire lens)	**Steel-3408**
Magnetic aperture, D_{ap}, mm	∅ 47
Pole profile	Hyperbolic
$L_{pole}\times L_{geom}\times L_{effect}$, mm	114×130×133
Current, kA/pole	13.5
Current density, A/mm²	26
Fill coefficient	0.95
Fields: $B_{pole}\times B_{core}\times B_{yoke}$, T	1.1×1.9×1.9
G × ∫Gdz, T/m×T	49 × 6.5
Field nonlinearity @75 %D_{ap}, %	≤ 0.7
Layers × Turns/layer	2×11
R×L×τ, mOhm×mH×ms	28×3×105
I_{nom} × U × P, A×V×kW	614×17×11
Overall dimensions, mm	360×360×130



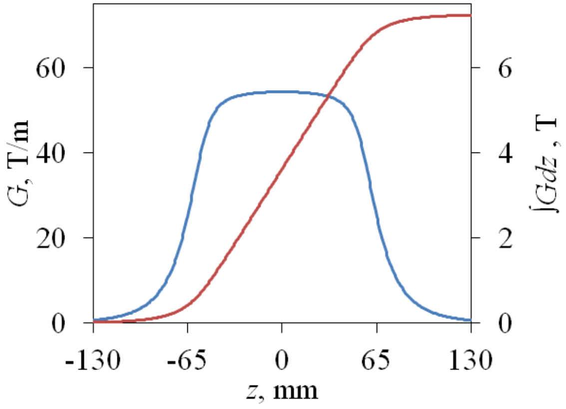


Figure 3: Field distribution in the central lens cross-section – (a) and (b) – longitudinal distributions of the gradient (bell-like curve) and of gradient integral.

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 till breaking point of hyperbolic profile . The lens provides $\int Gdz$ >7 T at fill coefficient of 1.0 (Fig. 3b).

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

MAGNETIC FLUX INCREASING

One of the most critical tasks at lens design development is always choice of appropriate lamination thickness to blade up a magnetic core. We considered two types of the laminated magnetic materials: permendur (Fe-Co alloy with 2% V) and low-carbon electric steel (type 3408).

Aresponse of a lamina with its ρ, $\mu$and l_{p} – specific electric resistance, relative magnetic permeability, and thickness, respectively, on ideal step-like increasing of external magnetic field is magnetic flux increasing in the lamina which can be described by simplified equation (full boundary problem solution can be found in [2])

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

where Φ_∞ – equilibrium magnetic flux, μ_0 – magnetic constant. Time constant τ_{skin} of magnetic flux increasing 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 δ_{tol}= 0.3% then delay is of order $5\tau_{\mathrm{skin}} \approx$ 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. In practice Pulse Current Generator with special flat top in current pulse is widely used for such regime realization.

CURRENT PULSE SHAPE

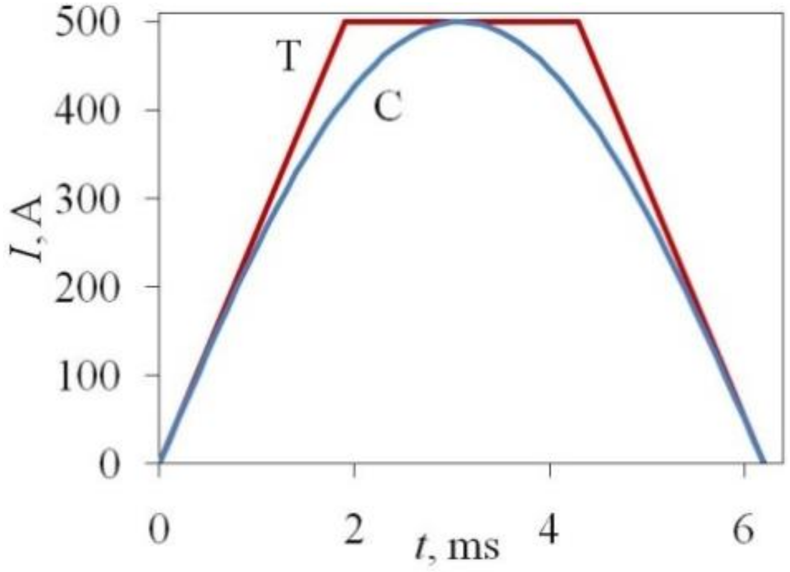


Figure 4: Excitation current pulse at resonance discharge (C) and of trapezoidal shape (T) with flat top.

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 dampen, prevailing factor).

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

We prefer the pulse of trapezoidal shape seen in Fig. 4. With active switches in electronic commutator one can vary arbitrarily initial voltage on a capacitor and thus disable DF2. From the other hand it can be actively reduced a delay till the moment when excitation current in all 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, in particular, to make the system 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.

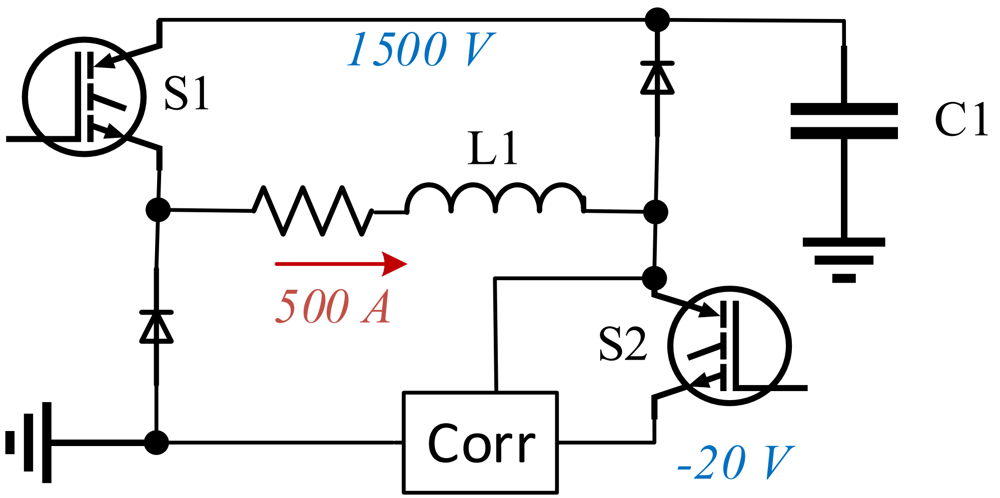


Figure 5: The model of PCG with a flat top option.

The electromagnetic regime study at different discharging circuit parameters showed that in ranges R=30-40 mOhm, L=3-4 mH it is reasonable to choose capacitor on C ≈2 mF. Then current of 500-600 A could be achieved at initial voltage U_{C0}=1-1.5 kV through t_{nom} ≈1.5-2 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 lamina of 0.3 mm thick. At such a regime it is possible to reduce the power of more than 10 kW (at DC mode, see Table 4) down to P_{imp} ≈6 kW (averaged over current pulse), whereas power $\langle P \rangle$ ≈30 W averaged over minimal beam repetition period. In this case water cooling of quads is unnecessary.

THANKS FOR ATTENTION

Reporter: Gennady Kropachev
ITEP, Moscow, Russia
May, 2021