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UPGRADE OF HEAVY ION INJECTOR I-3 AT ITEP

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Abstract

Heavy ion injector I-3 represents two-gap 2.5 MHz resonator with accelerating voltage 2x2 MV. It's used with laser ion source (LIS) for acceleration of ions in wide range of charge to mass ratio. As a result of modernization, injector structure will be supplemented by the second two-gap resonator, RF voltage will be increased to 3x4 MV and accelerated beam structure has to be improved by increasing accelerating frequency to 5 MHz. Design features of upgraded linac I-3M and peculiarity of beam dynamics for different types of ions are presented.

INTRODUCTION

Linac I-3 with laser ion source LIS100, constructed on the base of 100 J CO_2 laser, had been used many years as the ion injector for booster synchrotron UK of proton-ion accelerator-accumulator facility ITEP-TWAC [1, 2]. Generated at the output of injector I-3 ion, such as C^{4+}, Al^{11+}, Si^{10+}, Fe^{16+}, Cu^{17+}, Ag^{19+} etc., with energy of 4Z MeV had been accelerated in UK ring up to the energy of several hundred MeV per nucleon with intensity limited by high charge density of 2 MHz bunch structure of injected beam. Upgraded structure of I-3M is optimized for acceleration of heavy ions with A/Z in the range from 3 to 10. For acceleration of protons and light ions, injectors I-2 [3, 4] and I-4 [5] are used. The energy of accelerated in I-3M ions increased by factor of three at some improvement of beam density uniformity will allow to raise the intensity of accelerated in booster ring beam by more than an order of magnitude.

Increasing of accelerating voltage in I-3M is achieved by optimizing the configuration of accelerating electrodes, which will reduce the maximum electric field strength on the surfaces of electrodes that will allow to raise by half the amplitude of operating voltage on the accelerating gaps to 3 MV. The structure of two two-gap phased resonators allows having an accelerated voltage close to maximum of up to 12 MV for ions with variable charge-to-mass ratio.

OPTIMIZATION OF ACCELERATING ELECTRODES CONFIGURATION

Maximum amplitude of voltage 2 MV on the accelerating gaps in existing construction of resonator is limited by electric field strength on the localized areas of the electrode surfaces. Maximum electric field strength on the surface of electrodes as the function of relevant parameters shown in Figure 1 allows optimizing the shape of electrodes providing to reduce electric field strength on the surface of electrodes at a given voltage value at the accelerating gap. The optimum shape of the electrodes, providing extreme voltage value on the accelerating gap, is characterized by a minimum radius of surface curvature of 60 mm at the electrode diameter value of 600 mm.

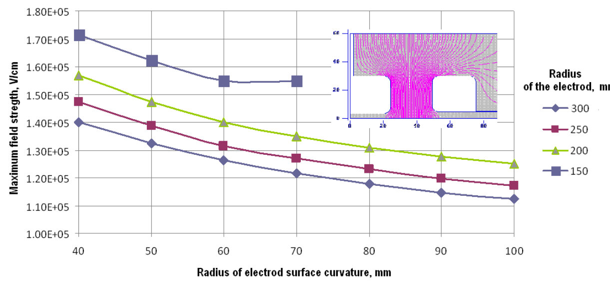

Figure 1: Maximum electric field strength on the surface of electrodes as the function of relevant parameters.

ACCELERATING STRUCTURE

Layout of the injector I-3M accelerating structure is shown in Figure 2, comparison parameters of both I-3 and I-3M injectors are given in Table 1. The length of drift tubes 0.5 m and 1.4 m in resonators is optimized for acceleration of heavy ions with A/Z=6.

The initial beam is formed at the output of the 50 kV gap that breaks the laser plasma generated in the target chamber of LIS100. In the matching channel of I-3M, the beam is focused by three electrostatic lenses and bunched at the input of the first accelerating resonator using the 10x2 kV, 5 MHz, two-gap buncher. Additional transverse focusing of the bunched beam of high charge density is provided in the first accelerating gap by optimized configuration of axially symmetric nonlinear RF field.

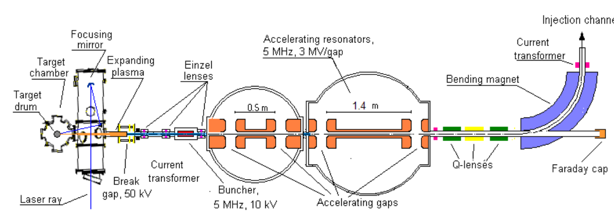

Figure 2: Acceleration structure of I-3M.

Table 1: Comparison Parameters of I-3 and I-3M

Injector	I-3	I-3M
Accelerating frequency, MHz	2.5	5.0
Number of resonators	1	2
Accelerating gaps	2	4
Accelerating voltage, MV	4	12
Bunching voltage, kV	10x2	
Accelerating ions. A/Z	2÷5	3÷10
Injection energy, kV	50	
Trans. acceptance, π mm mrad	>1000	
Momentum spread, Δp/p, %	up to ±2.5	
Transmission factor, %	~50	

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MODEL OF THE FIRST RESONATOR

The resonator is a circuit with concentrated in the solenoid inductance and capacity distributed inside of the resonator volume. The 3D model of the first resonator with drift tube length of 0.5 m is shown in Figure 3. Main modes of resonant frequency are given in Table 2. The resonant frequency tuner (Figure 4), which is moved inside the solenoid in the displacement range up to 100 mm, allows to adjust the resonant frequency according to the frequency signal of the second resonator within 100 kHz.

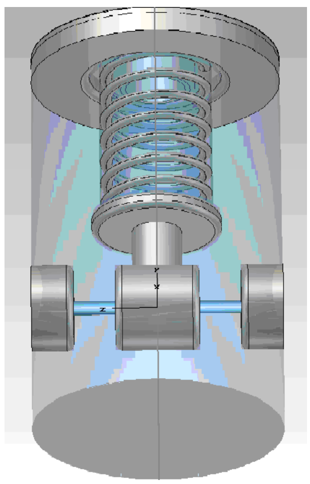

Figure 3: The 3D model of the first resonator.

Table 2: Resonant Mode of the First Resonator

Mode	1	2	3
Frequency, MHz	4.940	19.471	30.364

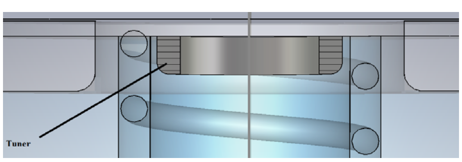

Figure 4: Frequency adjuster tuner core.

The calculated quality factor of the resonator is estimated by the value of Q=5500.

Distribution of power dissipated in the resonator at the maximum amplitude of the accelerating voltage of 3 MV per gap is given in Table 3. The largest amount of dissipated power (78.5%) is concentrated in the water-cooled spiral.

Table 3: RF Power Losses in the First Resonator

Component	Loss/W(peak)	Loss/%
Enclosure	336	2.83
Spiral	9328	78.5
Top	631	5.31
Drift tube	7	0.08
Spiralbott	623	5.24
Solid7	11	0.1
Spiraltopcyl	943	7.94
Sum	11879	100%

MODEL OF THE SECOND RESONATOR

The existing construction of the I-3 resonator is used in I-3M as the second resonator in which the spiral and the accelerating structure are modified. The 3D model of the second resonator with drift tube length of 1.4 m is shown in Figure 5. Main modes of resonant frequency for this resonator are given in Table 4. The second resonator operates in the autogenerator mode. The calculated quality factor of the second resonator is estimated by the value of Q=5520, distribution of power dissipated in the resonator by the components of its construction at the maximum amplitude of the accelerating voltage of 3 MV per gap is similar to that shown in Table 3 for the first resonator.

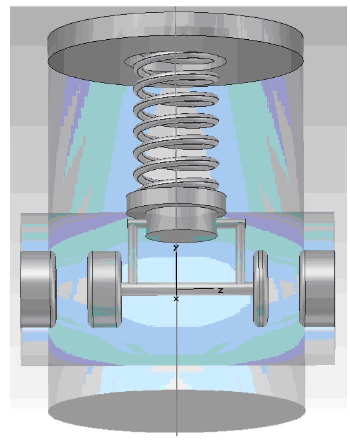

Figure 5: The 3D model of the second resonator.

Table 4: Resonant Mode of the Second Resonator

Mode	1	2	3
Frequency, MHz	4.971	20.974	32.250

BEAM DYNAMICS IN THE ACCELERATING STRUCTURE OF I-3M

Transmission of the beam in the accelerating structure of I-3M is determined by both: limited range of RF phase providing particle acceleration in the first acceleration gap, and Coulomb forces of particles repulsion in the high density beam bunch at the input of the first accelerating gap. Accelerating structure of I-3M has been optimized for acceleration of beam in the range of A/Z from 3 to 10 with current of several tens of mA at transmission of ~50%. The maximum total transmission of the beam with input current of 50 mA at A/Z=6 is estimated as ~58%, herewith the energy spread of accelerated beam is ±5%. The decrease in the energy spread of the beam up to ±2% reduces the transmission of the beam to~53%.

Longitudinal acceptance of I-3M for particles with variable value of A/Z is shown in Figure 6. The diagrams in the same figure show dependences of transmission factors for the beam with input current of ~50 mA on the amplitude of bunching voltage. It can be seen that optimum bunching voltage is sufficiently high and creates a large energy spread of the beam which reaches ±40%.

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The nonlinear field in the buncher can significantly increase the transverse emittance of the beam.

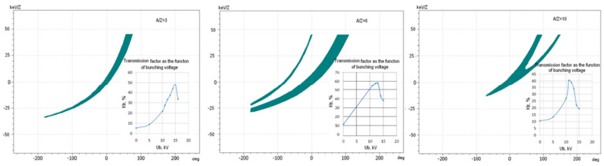

Figure 6: Longitudinal acceptance of I-3M for particles with A/Z=3, 6, 10.

Transverse acceptance of the I-3M accelerating structure at low beam current and optimal phases of accelerated voltage in both resonators is so great as ~8000 π mm mrad. Coulomb forces in bunched beam cardinally increases the transverse emittance of the beam and actually make the effective acceptance of the channel highly dependent on the beam current.

The envelope of the beam in the accelerating structure is limited by the effective aperture of beam line ∅90 mm, as shown in Figure 7. The maximum transmission of the beam is achieved by its sharp focusing at low energy on the input of the first accelerating gap, the optimal focusing properties of which are formed by the position of the grid in the inside of the resonator input electrode.

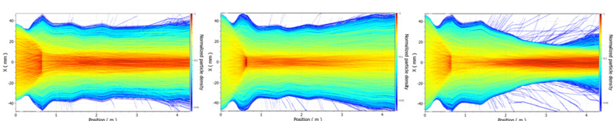

Figure 7: Envelope of 50 mA beam for A/Z=3, 6, 10.

Phase portraits of the accelerated beam at A/Z=6 and the input beam current 50 mA is shown in Figure 8. The energy spread of particles ±2% fits into the beam transverse emittance of 140 π mm mrad. The bunch length of accelerated beam is estimated by the value of 15^0 or 8 ns, duty factor of pulses is more than 20, herewith the amplitude of bunch current reaches 5÷6 A.

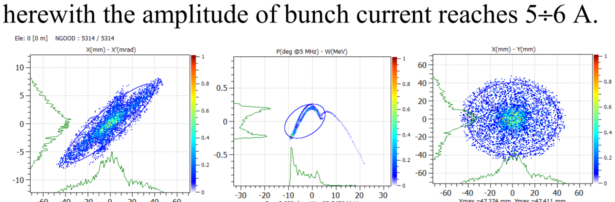

Figure 8: Phase portraits and cross-section of accelerated beam at A/Z=6 and beam current 50 mA.

If the input beam current increases to 100 mA, Coulomb forces don't allow to form an optimal beam configuration at the input to the first accelerating gap, that leads to decrease in transmission to ~40% and increase in emittance of accelerated beam to ~180 π mm mrad. Emittance of the beam can be reduced by factor of 1.5 at a slight decrease in beam transmission (2÷3%) by adjusting the phase difference between the bunching and accelerating voltage. The radical reduction of the accelerated beam emittance can be achieved by eliminating the transverse nonlinearity of the field in the accelerating gaps of the buncher.

CONCLUSION

The upgraded injector I-3M with the laser ion source LIS100 allows to extend a set of ions accelerated in synchrotron up to uranium. Table 5 shows the parameters of some types of heavy ions generated in LIS100 with different A/Z ratio and ionization potential up to ~1 kV after acceleration in I-3M. As can be seen from the table, the effective accelerating voltage of the I-3M structure is reduced at the edges of A/Z operating range by ~10%. The intensity of the accelerated beam given in the Table 5 corresponds to the findings of the ion source LIS100 taking into account the beam transmission factor in I-3M.

Table 5: Parameters of Heavy Ions at the Output of I-3M

A/Z	10(U^{24+})	9(U^{28+})	8(Au^{25+})	7(Ta^{26+})	6(Ag^{19+})	5(Ag^{22+})	4(Fe^{16+})	3(Ni^{18+})
U_{ion}, eV	600	836	763	789	512	974	506	624
m/Z, MeV	9315	8392	7452	6520	5589	4657	3726	2794
Δφ, rad	1.1	1.3	1.9	2.3	2.8	3.2	3.5	3.8
p/Z, MeV/c	440	426	411	390	357	323	283	240
V/Z, MV	10.4	10.8	11.3	11.6	11.4	11.2	10.7	10.3
E, MeV/u	1.0	1.2	1.4	1.6	1.9	2.2	2.6	3.4
β	0.046	0.051	0.055	0.059	0.064	0.069	0.075	0.085
N, p/p	$1.3x10^{10}$	$1.1x10^{10}$	$1.2x10^{10}$	$1.2x10^{10}$	$1.6x10^{10}$	$1.4x10^{10}$	$1.9x10^{10}$	$1.7x10^{10}$

Upgraded heavy ion injector I-3M is included in the project of Multipurpose Hadrons Facility (MHF) proposed at ITEP [6]. The key objectives of the MHF mission are the following: effective using and further development of accelerator technologies mastered in ITEP [7]; maintenance, improvement and expanding of the ITEP accelerator facility infrastructure as the basis of scientific and technological developments; fundamental and applied research with proton and ion beams at energy to 10 GeV for protons and to 5 GeV/u for ions; fundamental and applied research, technological development and industrial application with proton and ion beams at energy to 1 GeV/u; technological research and development in the field of generation, acceleration, accumulation, cooling, compression, extraction and sharp focusing of high intensity hadrons beams; expansion of scientific and educational activity in the areas of nuclear technologies. In particular, MHF will allow performing full-scale tests of radiation resistance of modern electronic components intended for use in the space environment. Beams of upgraded linac I-3M will be used also to expand research in the field of materials science and technology in the application to nuclear power and semiconductor industries.

REFERENCES

[1] N.Alexeev *et al.*, Let. of JETP, vol.77-3, p.149.
[2] N.Alexeev, *et al.*, in *Proc. RuPAC'12*, pp.112-116.
[3] I.M.Kapchinsky *et al.*, Preprint IHEP, pp. 67-38, 1967.
[4] V.I.Bobylev, *et al.*, in *Proc LINAC'72,* pp. 275-278.
[5] V. Andreev, *et al.*, in *Proc. IPAC'10*, pp. 801-803.
[6] N.Alexeev *et al.*, in *Proc. RuPAC'16*, pp. 73-77.
[7] N.Alexeev *et al.*, in *Proc. RuPAC'14*, pp. 34-38.