RF LINAC FOR HEAVY ION FUSION DRIVER

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1. Introduction

For a number of years ITEP has been engaged in feasibility studies for ICF power facility with heavy ion driver. The proposed driver scheme will include RF linac followed by systems for beam storage, compression and transport [1].

Estimates made in ITEP [2] show that RF linac has to provide a possibility to hit fusion target with 20 GeV Bi beams and to deliver to it total energy of 9 MJ (400 TW total power). To attain this goal RF linac should have the following parameters:

Bi^{2+} beam energy	20 GeV
Pulse beam current	500 mA
Pulse duration	2 ms
Momentum spread	$\pm 3 \cdot 10^{-5}$
Normalized emittance	0.2 cm·mrad

For a driver being coupled with four fusion reactors the linac will consump 810 MW, assuming linac efficiency to be about 50%. The proposed block-diagram of RF linac and its performance are discussed below. Also, some experimental results obtained during start up of the first section prototype with 5 mA Xe^{2+} beam accelerated from 130 keV to 1.35 MeV are presented.

2. RF linac block-diagram

Main advantages of linacs in obtaining ion beam with predetermined kinetic energy, as compared to cyclic accelerators, are:

- possibility of accelerating beams of any desired pulse duration;
- relative simplicity of distributed RF power feeding and heat removal;
- and, finally, simple and reliable collimation and total beam extraction at all energy levels.

Difficulties in accelerating high current low charged ion beams are primarily caused by low intensity of ion sources, low ion velocity during injection and low acceptance of accelerating section. These difficulties were overcome after invention in the USSR of RFQ-principle and introduction in our country and abroad of multibeam array for initial part, in which the number of beam-lines decreases with particle energy increase.

It is expected that in each of 16 injection beam-lines 50 mA ion beam of Bi^{2+} will be obtained. Initial acceleration up to energy of 10 MeV will take place in the RFQ at frequency of 6 MHz. Design and performances of the prototype of such a section (6 m long) tested at nominal RF field levels are discussed below. It seems that the results of beam parameter studies and of accelerating sections investigations obtained for the initial part will permit to judge upon the validity of accelerator scheme as a whole because the design of the subsequent sections has been tested at operating facilities for ions with higher charge states.

Main parameters list for the RF linac (see Fig.1) is given in Table 1 [3].

All beam-lines of the first three sections can be located in one vacuum tank. According to estimates 30 mA beam would be captured for acceleration in each beam-line of the first section. In the main part not less than 500 mA pulse beam will be accelerated, each second separatrix being filled. It should be noted that relatively high output ion energy requires to increase acceleration rate; this leads to momentum spread increase. As in the main part only each second separatrix is filled, debunching at the output can be improved. In principle, doubling of the number of beam-lines in each section of the initial part could allow to increase mean beam current at the output of linac, but the momentum spread will increase accordingly.

Table 1. Main parameters list for RF linac.

Parameter	Initial part				Main part
	Section I	Section II	Section III	Section IV	
Number of beam-lines	16	8	4	2	1
f (MHz)	6.19	12.39	24.78	99.10	198.2
RF structure	Spirals	Spirals	Wideröe	Alvarez	Alvarez
Focusing system	RFQ	RFQ	REC-quadrupoles	REC-quadrupoles	REC-quadrupoles
Input ion energy	200 keV	10 MeV	50 MeV	600 MeV	2.5 GeV
Output ion energy	10 MeV	50 MeV	600 MeV	2.5 GeV	20 GeV
Mean current per beam-line	32 mA	64 mA	128 mA	256 mA	512 mA
Section length	16.4 m	62.7 m	360 m	360 m	3296 m

Frequency of accelerating field in resonators is optimized according to ion velocities. Exact frequency values in various sections are chosen in such a way as to use in the main part of linac the frequency established for the first part of meson factory being constructed by the Academy of Science of the USSR.

3. Ion source

For linac injector duopigatron ion source is developed. The main feature of its design is vacuum separation of duoplasmatron and duopigatron chambers by pulse electromagnetic valve (shutter), which opens only for a period necessary for penetration of ions and electrons from one chamber to another. Similiar valve is used for connection of pigatron chamber with vacuum chamber of the injector. Because of the valves injection of vapours and gases into each chamber can be made independently. So ballast gas can be injected into duoplasmatron chamber while Bi vapours will occupy pigatron chamber. Among the elements which has $A \geqslant 200$ Bi is the most suitable as working medium in the source. Pressure in each chamber can be set practically independently. Valve opening is 3.5 mm in diameter, delay time - 3 ms, holding time in opened position - 1-3 ms. Besides axial magnetic field there is an opportunity to apply periferial magnetic field in pigatron chamber. Estimates show that at the source output we can expect to have Bi^{2+} beam with current up to 50 mA and normalized emittance E_N = 0.03 cm•mrad. At present the source is being prepared for tests.

At the first stage it was decided to test RFQ-structure with Xe^{2+} beam. These ions were produced in duoplasmatron designed to use noble gases as a working medium. Main features of the source design are cold cathode in a form of hollow cylinder[4] and pulse shutter[5]. The main advantage of cold cathode is long life time (many thousands hours) that permits, inter alia, to maintain stable injection conditions for a long time. Output valve allows to receive desired high density of working gas in discharge chamber and at the same time to minimize inleakage into high vacuum chamber of linac. For the purpose of time-of-flight analyses ion optic system was equiped with control grid. High voltage short front pulses provided ion pulses of duration from 0.5 to 10 μs. Charge state of ions was determined by measuring transit time of base space between beam transformer and Faraday cup. Xe^{+}, Xe^{2+} and Xe^{3+} ions at 65 kV injector output (100 kV for Bi) were reliably determined, unspite the fact that each peak on the oscillogram corresponded to $Xe^{129-136}$ mixture. Beam transportation through matching channel and test run of RFQ structure were performed on 16 mA beam and later on 28 mA beam measured at the injector output.

4. RFQ structures

As is known, the increase of average ion current leads to substantial sparking limit decrease in accelerating tube (column) of electrostatic injector. Because of these voltage limitations the velocity of low charged heavy ions at linac input is so low that to use magnetic focusing is practically impossible. RFQ is the most effective in this case. Beam accelerated in RFQ structure can be bunched so as it is required for the most effective capture in Wideröe and Alvarez structures.

Our estimates show that in order to obtain 30 - 40 mA accelerated Bi beam with phase density j = 0.3 A/cm•mrad working frequency should be chosen about 6 MHz. As it can be seen from Table 1, the frequency of accelerating field in the first RFQ section with lumped resonant elements [6] was chosen to be quite low (6.19 MHz) that permited to optimize focusing regime and to inject Bi^{2+} ions at so low voltage as 100 kV. Main RFQ parameters are given in Table 2.

The first section of the initial part consists of three parts: shaper, buncher and accelerator. In the second RFQ section beam is accelerated at constant synchronous phase. Rigidity of quadrupole channel is proportional to wave-length of accelerating field [7] :

$$K = \frac{\lambda}{2a}\sqrt{\varkappa \frac{Z e U_L}{A \mathcal{E}_0}}$$

For accelerating part of the first RFQ section we have K^2 = 2.19 and defocusing factor γ_S = 0.092. This permits to attain optimum values for transverse oscillation frequencies.

As to sparking limit of the gaps, it was found [8] that break-down levels determined during test held on vacuum gaps in the frequency range of 25-150 MHz. Break-downs on copper, aluminum and duraluminum electrodes began at exactly the same levels of electric field strength E_s = 200 kV/cm that is 2.5 times higher those corresponding to Kilpatrik criterium for 6.2 MHz. For stainless steel electrodes E_s was found to be 1.5 times higher (for titanium - 3-4 times) than for copper ones. RF training of copper electrodes permited to increase E_s up to 500 kV/cm and even higher. As for titanium electrodes training doesn't lead to any increase and to reach $E_{s\,max}$ level after the first break-down is impossible.

A number of problems has arised in the development of accelerating structure. It was impossible to use split coaxial resonator (for λ = 50 m) because of its insufficient stiffness. Indeed, the quarter-wave vibrators, fixed at one end, should be of 5-6 m long and half-wave vibrators, fixed at both ends, should be of 10-12 m. It was also impossible to use coaxial stub as a support structure, method widely used in Wideroe-type resonators, because of their length. That's why a possibility to use lumped inductions (flat or cylindrical spirals) was investigated.

Resonant structures of both sections are specially modulated four-wire lines (80 pF/m specific capacity) which are fixed on spirals made of copper tubes (see Fig.2). These inductive support elements have a form of symmetric triangular star that ensures mutual compensation of ponderomotive forces arising in spirals. Damping of swinging forces is essential because the frequency of mechanical resonance of the structure and the proposed linac repetition rate are quite close. A certain part (6 m long, 1.2 m in diameter) of the first section was manufactured and tested (see Fig.3). At resonance frequency of 6.19 MHz the structure parameters are the follows: quality factor - 800; shunt impedance - 20 kOhm. Mechanical parameters are: stiffness - 1500 N/mm; frequency - 9 Hz; quality factor - 400.

Table 2. Main RFQ parameters

Parameter	Symbol	The first RFQ section			The 2nd RFQ section
		Shaper	Buncher	Accelerator	
Input energy	$W_s(inp)$	196 keV	204 keV	1.6 MeV	10 MeV
Output energy	$W_s(out)$	204 keV	1.6 MeV	10 MeV	50 MeV
Voltage between adjacent electrodes	U_L	190 kV	190 kV	190 kV	320 kV
Surface electric field strength (max)	E_s	122 $\frac{kV}{cm}$	122 $\frac{kV}{cm}$	122 $\frac{kV}{cm}$	250 $\frac{kV}{cm}$
Average radius	R_o	8.5–2.2	2.2 cm	2.2 cm	1.8 cm
Aperture	a	8.5–2.1	2.1–1.47	1.47 cm	1.44 cm
Modulation depth	m	1–1.095	1.095–2.0	2.0	1.5
Absolute equilibrium phase	$\lvert\varphi_s\rvert$	90°–85°	85°–35°	35°	37°
Rigidity of the focusing channel	K	0.396–1.536	1.536–1.490	1.490–1.460	1.197–1.193
Transit time factor	T	0–0.0317	0.0317–0.432	0.432–0.465	0.288–0.299
Focusing efficiency	$\varkappa$	1–0.915	0.915–0.420	0.420–0.403	0.620–0.616
Transversal phase advance on period	μ		1.02–0.938	0.938–0.981	0.622–0.645
Minimal transversal frequency in scale of τ	ν_φ		0.58–0.55	0.55–0.59	0.45–0.47
Acceptance	V_k	cm·mrad	0.53–0.25	0.25–0.26	0.39–0.40
Relative frequency of the phase oscillations	$\frac{\Omega}{\omega}$		0.097	0.097–0.040	0.046–0.021

After the section was evacuated to a pressure of $5\cdot 10^{-6}$ Torr RF power was supplied and voltage between the electrodes reached 210 kV without breakdowns while for acceleration of Bi^{2+} ions calculated value was 190 kV.

At the start-up ion optics was tuned so that the crossover of Xe^{2+} beam was located at the inlet of 2 m matching channel equipped with two electrostatic lenses and two steering devices. During first experiments we have reseived 7 mA beam at the inlet of RFQ section. After threshold level of RF field was overreached main fraction of Xe^{2+} peak ($>$95%) measured at the output of RFQ section shifted for 5 μs that corresponds to acceleration of these ions to calculated energy of 1.35 MeV. Output current was about 5 mA i.e. capture factor was close to 70%. Further researches to be held with the first part of 6 m long RFQ structure will allow to define more exactly parameters of the second part of 6.2 MHz RFQ and of further parts of the driver prototype.

5. Sections with quadrupole magnet focusing

Consideration of low charged heavy ion focusing features show that transversal stability should be provided by rather large number of one sign lenses in focusing period. That's why acceptance of the channel would be rather low. Nevertheless as Coulomb repulsion in $Z/A \ll 1$ ion beams is low it is possible to reach rather high value of beam current limit.

As is shown in Table 1 we are planning to use rare-earth qadrupoles in Wideröe and Alvarez structures.

The design of resonant structure in Wideröe section is similiar to the design developed for appropriate section of UNILAC facility. After 600 MeV level is reached it is possible to use Alvarez resonators which allow to increase acceleration rate.

RF linac should contain about 9450 drift tubes. Each electromagnetic quadrupole will dissipate approximately 2 kW. It means that iv total 20 MW would be needed not taking into account rectifiers efficiency and power consumed by water cooling system. Rather high duty factor and strict requirements to gradient stability of magnetic lenses make pulse power supply uneffective. Rare-earth quadrupoles would permit to exclude the stabilized power supply as a whole from scheme of focusing channels, to avoid related operational difficulties and to save above mentioned 20 MW. In order to reduce the costs of focusing channel it is reasonable to use samarium-cobalt alloy only for some lenses and for most of them to use alnico alloy which is cheaper.

6. RF power supply

Active RF losses in resonators were estimated in ITEP by following methods:

a) For RFQ sections - experimental data obtained for real resonators were used;

b) For Wideröe sections - transformed data on active losses in appropriate UNILAC sections were used;

c) For Alvarez sections - developed in ITEP codes were used in which specific coductivity of copper was taken equal to $5.71\cdot 10^7$ $Ohm^{-1}m^{-1}$.

Table 3. The data on pulse losses, RF power and number of generators for linac

Parameter		RFQ-1	RFQ-2	Wideröe	Alvarez I	Alvarez II
Accelerating field frequency	MHz	6.19	12.39	24.78	99.1	198.2
Active losses per beam-line	MW	2.0	15.0	8.0	68	1080
Number of beam-lines		16	8	4	2	1
Total active losses	MW	32	120	32	136	1080
RF power for beam	MW	2.56	10.24	140.8	486.4	4480
Total pulse RF power	MW	34.6	130	173	622	5560
Generator pulse power	MW	10	10	5	5	5
Number of generators		4	13	35	125	1112

Data on pulse active RF losses, pulse RF power delivered for beam acceleration and number of generators are given in Table 3.

Total pulse RF power delivered for beam acceleration will be 5120 MW and total pulse losses - 1400 MW. Thus electronic efficiency of the linac will be 79%. If to assume generator efficiency to be equal to 65%, RF system efficiency as a whole will be 50%.

For a driver coupled with one reactor average RF power consumed by linac at the repetition rate of 10 Hz and pulse duration of 2 ms will be 130.4 MW and total average power consumed by power supply system taking into account generator efficiency - 200 MW.

Power consumption by other technological systems is rather negligible in comparison with RF system so total linac-driver efficiency could be approximately 50%.

One linac could ensure irradiation of targets in 4 or 5 reactors in turn if the repetition rate and power supply would be increased (this, of course, should be provided in RF system design).

7. Conclusion

Wide-range researches in several accelerator centers allowed to determine base scheme of RF linac designed for a driver. Main tasks involved in the development of the scheme proposed in ITEP are:

a) Further optimization of accelerating and focusing structures at the frequencies of 6-25 MHz;

b) Development of 50 mA Bi^{2+} injector with beam emittance of about 0.02 cm·mrad;

c) Development of injector-linac matching scheme;

d) Development of funneling scheme without beam losses and emittance growth;

e) Further development of effective rare-earth quadrupoles for drift tubes;

f) Development of high reliable high power RF generators and RF power supply equipment for resonators.

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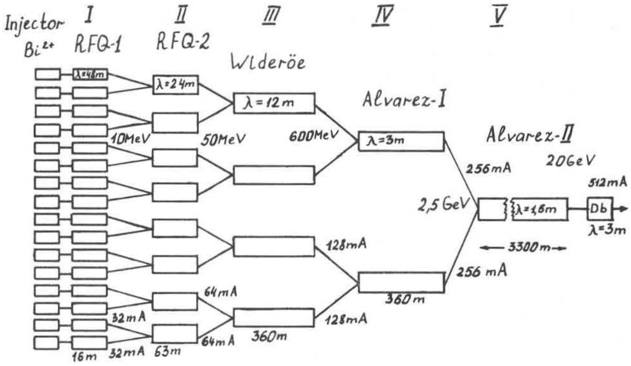

Fig. 1. Block-scheme of Linac proposed for HIF Driver in ITEP.