RECENT STUDIES OF LINAC FOR PRODUCTION OF RADIOACTIVE BEAMS IN THE INR*

I.N.Birukov, I.V.Gonin, D.V.Gorelov, A.N.Iljinov, V.A.Moiseev, P.N.Ostroumov
Institute for Nuclear Research, 117312 Moscow, Russia
A.V.Tiunov, Moscow State University, Moscow, Russia

I. INTRODUCTION*

Accelerators for the production of radioactive ion beams have been proposed by many laboratories. A wide range of researches in nuclear physics can be carried out with a 6-10 MeV/n radioactive beam. For the ion source to produce high intensity beams, the initial charge-to-mass ratio must be as low as possible, 1/60, for instance; but the cost of a linac for these beams becomes high. Recently at TRIUMF a 1.5 MeV/n linear accelerator accepting ions with q/A=1/30 has been proposed [1]. Possessing the feature of variable energy, this linac can provide for various experiments in astrophysics. A similar project is under consideration at INR. Below we describe the optimized design of the linac for the energy range 2 keV/n to 1.76 MeV/n, calculation of the rf power consumption in the accelerating structures by MAFIA code and end-to-end beam dynamics simulation in the realistic rf field distribution.

II. ACCELERATOR STRUCTURE

The linac comprises five parts: 1) prebuncher; 2) RFQ; 3) prestripper linac (PSL); 4) matching and stripping section (MSS) at beam energy 357 keV/n and 5) poststripper linac (POSL). The linac layout is shown in fig. 1.

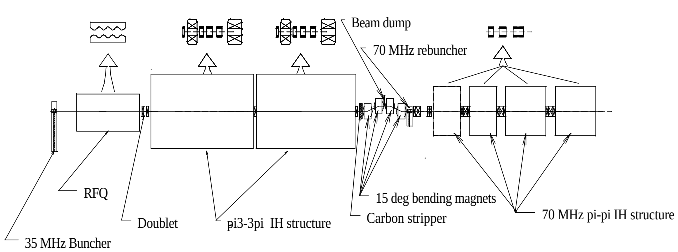

Fig. 1 Linear accelerator layout.

The linear accelerator is characterized with the following properties:

- The 98.6% capture of the 2 keV/n cw ion beam with q/A=1/30 and acceleration up to the energy 1.76 MeV/n;
- Extremely low rf power consumption which allows to operate in cw mode for the all ion species with q/A=1/30 and mass number up to 240. According to simulation by MAFIA code, the required rf power is ~140 kWt for the whole linac;
- The accelerator includes a spectrometer magnet to separate and dump the parasitic ions formed downstream of the stripper which mades the linac radiation free;
- Despite the very low q/A and frequency (35 MHz) the RFQ is short enough (3.9 m) to have just one tank; the RFQ has been designed to provide longitudinal matching to the following accelerating structure without an additional rebuncher;
- There is an essential rf power saving due to the use of IH type accelerating structure beginning from the very low beam energy (60 keV/n);
- The stripping energy 357 keV/n allows to keep all possible ion species on high intensity level; the linac can be upgraded to higher energies by the addition of further accelerating structures;
- Smooth energy variation in the range 0.2-1.76 MeV/n. In the range 0.2-0.5 MeV/n the rms energy spread is $(\Delta W/W)_{rms} < 0.5\%$, for the higher energies $(\Delta W/W)_{rms} < 0.2\%$; as a rule, the energy spread on the base is $\pm 3\cdot(\Delta W/W)_{rms}$.
- Due to the negligible transverse emittance growth on the stripper (30%-50% for the most of ion species) the aperture diameter is equal to 2 cm throughout the linac accelerating structures. The transverse normalized acceptance for the whole linac is $0.8\pi\cdot$mm$\cdot$mrad which is 3 times larger than expected 2 keV/n beam emittance.

The main parameters of the linac are listed in the table 1.

Table 1

Tank	RFQ	IH-1	IH-1	IH-3	IH-4	IH-5	IH-6
q/A	1/30	1/30	1/30	1/9	1/9	1/9	1/9
f, MHz	35	35	35	70	70	70	70
φ_S , deg		-25	-25	-25	-25	-25	-25
$W_{out.}$ MeV/n	0.06	0.199	0.357	0.582	0.90	1.297	1.755
L, m	3.89	4.55	4.34	1.02	1.28	1.56	1.92
D, m	1.0	1.8	1.8	1.0	1.0	1.0	1.0
R_{eff}, MOm/m	500[1]	278	196	310	245	202	164
P, kWt	31.5	8.3	16.6	8.0	15.8	24.7	32.8

[1]) The characteristic resistance [kOm·m].

A. RFQ

The geometry generation of the RFQ has been done following ref. [2]. However the shaper has been replaced by a klystron buncher and an external prebuncher has been added one meter upstream the RFQ. During the beam dynamics study the Yamada's design procedure has been slightly modified in order to minimize longitudinal emittance. The

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RFQ resonator is followed by the IH structure and between the RFQ and IH tank there is 53 cm space for two matching quadrupoles. To provide longitudinal matching, a bunch rotator containing 10 cells of unmodulated electrodes and four cells of modulated electrodes with $\phi_s = -90°$ has been inserted into RFQ. The RFQ output energy has been chosen from the analysis of the efficiency of RFQ and IH structures [3]. The variation of the main RFQ parameters with respect to the cell number are shown in fig. 2. The evolution of the beam image in longitudinal phase space is shown in fig. 3. The bunch rotator forms a converging beam in longitudinal phase space that allows to have a long drift space between RFQ and IH structure. The beam phase portrait at the entrance of the IH structure is shown in fig. 3b .

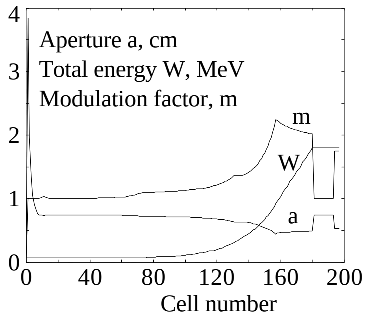

Fig. 2. RFQ parameters VS cell number

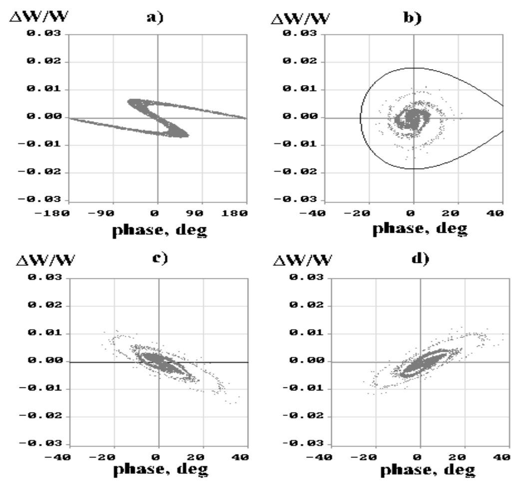

Fig. 3. Beam image evolution in longitudinal phase space a) RFQ entrance, b) Output of the cell #180 - the end of acceleration, c) Output of the cell #193 - the end of longitudinal drift, d) Output of the RFQ, after bunch rotator.

B. Prestripper Linac

As a prestripper linac in the energy range 60 keV/n to 360 keV/n the IH structure with FODO focusing has been proposed. The use of the FODO focusing structure simplifies the transverse matching between RFQ and IH structure. Having just one qaudrupole lens inside the drift tubes per four accelerating gaps, the modified IH structure consumes very low rf power. The superperiod of the accelerating structure consists of 3 accelerating cells with $3\cdot\pi$ phase advance of the rf field and a long drift tube containing the quadrupole lens and a gap with additional $3\cdot\pi$ phase advance. A superperiod of the structure is shown in fig. 4 as it is used for the MAFIA simulation. The total power consumption and effective shunt impedance have been found from the simulation of several superperiods of the whole tank.

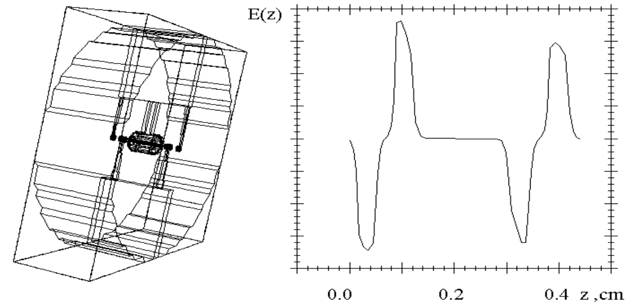

Fig. 4. Superperiod of the π3-3π IH structure and accelerating field distribution $E_Z(z)$.

Tuning the accelerating field along the IH structure and the mechanical design of the tank can both be simplified if the gap voltage is accepted to be constant along the tank (except the end cells). To keep high accelerating gradients two IH tanks with the total length ~9 m have been chosen. The gap voltages are 120 kV and 215 kV in the first and second tank accordingly. For the design of the focusing structure a standard procedure based on the analysis of the transport matrices of the focusing period has been used. The strengths of the focusing gradients satisfy the transverse effective emittance preservation condition $\sigma_T > 0.7\sigma_L$. Where σ_T and σ_L are phase advances of the particle motion per focusing period on transverse and longitudinal phase plane accordingly.

C. Matching/Stripping Section

The matching and stripping section consists of: a carbon stripper, four 15° rectangular bending magnets; 70 MHz rebuncher, one qaudrupole triplet and two single lenses, beam dumps for the parasitic ion species.

The carbon stripper is installed at the output of the PSL (fig. 1). Due to the relatively high stripping energy all radioactive ion species with mass number up to 240 will be kept. The transverse rms emittance growth due to stripper is ~30%-50% for the most of ion species. The additional rms energy spread contributed by the stripper is ~0.1%-0.2% which slightly increases longitudinal emittance. Four bending magnets allow to separate all radioactive ions with non-equilibrium charge state. The beam dumps installed at the high dispersion points safely absorb parasitic radioactive ions and provide radiation free linac.

D. Poststripper Linac

The π-π IH type accelerating structure for the POSL has been considered most suitable. Operating at fields well below breakdown, the POSL accepts all ion species produced downstream of the stripper with q/A as low as 1/9. The use of lower accelerating gradients promotes lower rf power consumption as well as lower energy spread of the accelerated beam. Main specification to the POSL is the possibility of the smooth energy variation in the range 0.2-1.76 MeV/n. Therefore the POSL comprises several tanks powered separately. In order to provide maximal shunt resistance, focusing elements are not included inside the tanks. The criteria to choose the tank length are following: short enough to provide transverse beam dynamics stability as well as smooth energy variation keeping energy spread small, long enough in order to avoid a low shunt resistance.

From studies with the MAFIA code as well as beam dynamics code, a 15 gap IH accelerating tanks have been selected. The beam focusing is provided by triplets installed between the tanks. The lengths of the triplet quadrupoles are 9.2 and 16 cm which have been optimized in order to have lowest focusing gradients. The bore radius for all quadrupoles is 1.5 cm and the focusing gradients are in the range 4.1-5.6 kGs/cm for the lowest value of q/A.

The diameter of all four IH tanks of the POSL are equal to one meter. In order to tune to the resonant frequency and desired voltage distribution along the tank, the magnetic flux inducer size, ridge-to-ridge distance as well as cell parameters will be fitted.

II. BEAM DYNAMICS SIMULATION

For the design and simulation of the RFQ the beam dynamics code DESRFQ has been developed which runs on an IBM PC computer. In addition to standard procedures associated with design and simulation procedure in the RFQ, DESRFQ allows to animate the beam images on the phase planes during the simulation; which is very helpful for the beam parameters optimization. The particle coordinates output from the RFQ are accepted by LANA code [4] in order to simulate the beam dynamics in the PSL, MSS (including a stripper) and POSL. The LANA code produces drift tube geometry using two dimensional realistic electric field distribution $E_z(r,z)$, $E_r(r,z)$ along the tank axis.

The beam envelope taken for all particles accepted by the RFQ (98.65%) along the IH linac is shown in fig. 5. The normalized acceptance of the whole linac is 0.8 π·mm·mrad which is safe enough in order to avoid any particle losses.

A. Beam energy variation

The beam energy variation can be produced by changing phase (φ) or/and amplitude (E) of the rf field in the IH tanks. The energy adjustment procedure does not increase transverse emittance and produces the intermediate beam energies without any degradation of the energy spread. As it follows from beam dynamics simulation, there is an optimal path in the plane (E, φ) in order to obtain minimal energy spread during the procedure of the energy variation. The families of curves obtained by the variation of rf field level in the range (0.4-1.0)·E_0 as well as rf phase in the range (0,-200°) in each four tanks are shown in fig. 6. The envelope curve shows minimal energy spread which can be obtained for the certain beam energy selecting rf phase and amplitude on the tank being adjusted. To transport a beam with intermediate energy to the accelerator end the focusing triplets must be retuned.

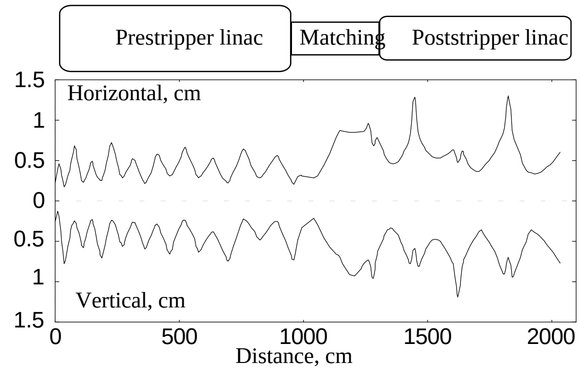

Fig. 5. Beam envelope (100% particles) along the IH linac.

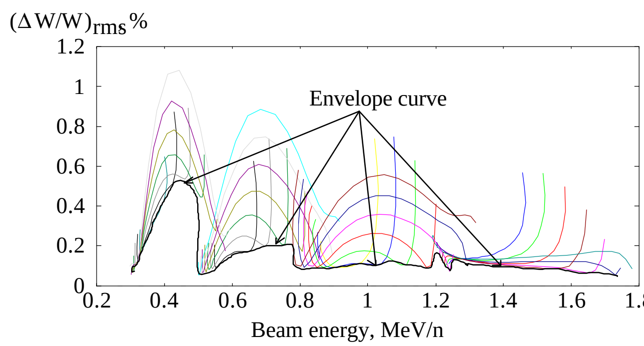

Fig. 6. Beam energy spread as a function of the beam energy obtained by the phase variation in the tanks of the poststripper linac. The parameter is the rf field level in the range (40-100)% of the nominal level.

III. ACKNOWLEDGMENT

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IV. REFERENCES

[1] P.G.Bricault et al. ISAC-1: Radioactive Ion Beam Facility in TRIUMF, RPG12, this proceedings.
[2] S.Yamada. Buncher Section Optimization of Heavy Ion RFQ Linacs. Proc. of the 1981 Linac Conf. Santa-Fe, 1981.
[3] P.N.Ostroumov. Choice of Transition Energy Between RFQ and IH Structure in Radioactive Beam Linac. Preprint INR, 1995.
[4] D.V.Gorelov and P.N.Ostroumov. The LANA Computer Code for the Beam Dynamics Simulation in Multi-Cavity Linacs. INR internal report, 1993-1994.