PARTICLE DYNAMICS DESIGN ASPECTS FOR AN IFMIF D^+ RFQ[1]

D. Li[*], R. A. Jameson[**], H. Deitinghoff, H. Klein
Institut für Angewandte Physik der J-W-Goethe Universität
Robert-Mayer-Str. 2-4, D-60054 Frankfurt/M, Germany
[*] on leave from Institute of Heavy Ion Physics,
Peking University, Beijing 100871, China
[**] Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Abstract

A conceptual design activity for an International Fusion Material Irradiation Facility (IFMIF) has been started to investigate the feasibility of an intense D-Li neutron source. As injector of the acceleration system, a RFQ is required to accept, bunch and accelerate a 125 mA D^+-beam to 8 MeV with a very good beam quality for low losses in the following main accelerator part. To fulfill these severe requirements, extensive numerical calculations of the particle dynamics in the RFQ have been performed, with special emphasis on the equipartitioning design strategy, in which the temperatures in the transverse and longitudinal directions are balanced to prevent possible coupling resonances caused by the strong non-linear space charge forces. Design aspects and the resulting beam behaviours are presented.

1 INTRODUCTION

The D-Li neutron source concept has been adopted in the IFMIF project. Deuterons of a few hundred mA are accelerated to 30, 35, or 40 MeV, and directed on a molten lithium target to generate a fusion-like neutron spectrum through the Li(d,n) nuclear stripping reaction.

The accelerator system consists of two 125mA accelerator modules operating in parallel[1]. Each module is comprised of a sequence of beam transport and acceleration stages. Dual ion sources (operating and standby) generate a cw 140 mA deuteron beam at 100 keV. A low-energy-beam-transport (LEBT) guides the deuteron beam from the operating source to a RFQ which bunches and accelerates the beam to 8 MeV. The 8 MeV beam from RFQ is injected directly into a drift-tube-linac (DTL) of the conventional Avarez type, where it is accelerated to the desired energies.

The key requirement for the accelerators is extremely low beam losses to allow hands-on maintenance. It has been demonstrated that if the beam is not in thermal equilibrium, the equipartitioning process caused by the strong coupling between the transverse and longitudinal motions can lead to emittance growth and halo formation. Hence we study the ability of the RFQ to prepare an equipartitioned beam. According to the most prevailing design methods of RFQs [2,3,4], the transverse phase advance at zero current, σ_0^t , is kept approximately constant or varied adiabatically. As a result, with the increase of the energy, the transverse beam size becomes smaller while the bunch length becomes larger. Such a beam is not equipartitioned. Therefore a new design strategy is adopted, in which the parameters are chosen to form the beam to be equipartitioned by the end of the RFQ, with different ratios of emittances in transverse and longitudinal directions.

2 EQUIPARTITIONING DESIGN STRATEGY

An equipartitioned beam has equal transverse and longitudinal temperatures, $T_t = T_l$. Theoretically, for matched bunches in a smooth-focusing system, the temperatures can be related to the beam widths and normalized emittances in form of [5]:

$$\frac{T_l}{T_t} = \frac{\varepsilon_{ln}^{\;2}}{\varepsilon_{tn}^{\;2}} \cdot \frac{a^2}{(\gamma b)^2}\,, \qquad (1)$$

where ε_{tn}, ε_{ln} denotes the full 100% normalized emittance of a uniform beam distribution, a, b the full beam radius, in the transverse and longitudinal direction respectively. γ is the relativistic energy factor. For a matched beam the rate of change of divergence is zero in the envelope equations. Accordingly, the following two relations can be deduced:

$$\varepsilon_{tn} = \frac{a^2 \sigma_t \gamma}{\lambda} \qquad (2)$$

$$\varepsilon_{ln} = \frac{b^2 \sigma_l \gamma^3}{\lambda} \qquad (3)$$

where σ_t, σ_l denotes the phase advance in transverse and longitudinal directions respectively, while λ stands for the wavelength.

[1] Work performed under constract no. ERB500 CT950013NET

On the other hand, following the smooth approximation theory, σ_t, σ_l can be related to the external focusing forces (expressed as σ_0^t,σ_0^l) and the beam itself in form of:

$$\sigma_t^2 = \sigma_0^{t2} - \frac{I\lambda^3 k(1-ff)}{a^2(\gamma b)\gamma^2} \quad (4)$$

$$\sigma_l^2 = \sigma_0^{l2} - \frac{2I\lambda^3 kff}{a^2(\gamma b)\gamma^2} \quad (5)$$

where $k = \frac{3\times10^{-6} z_0 q}{8\pi m_0 c^2}$, with z_0 = 376.73 Ω, and ff = ellipsoid form factor, ~ $a/3\gamma b$ for $0.8 \le \gamma b/a \le 5$.

Combining Eqs. (2)-(5), one can numerically solve for the beam sizes. To solve the independent parameters $a(z)$, $m(z)$, $\varphi_s(z)$, we use a nonlinear solver. By equating Eq. (1) to 1, we get the object function. As constraint functions we have

$$-90° \le \varphi_s \le \text{e.g. } -30°;$$
$$1.0 \le m \le \text{e.g. } 2.0;$$
$$\sigma_0^t, \sigma_0^l \le 90°;$$
$$\sigma_t / \sigma_l \ne n \text{ or } 1/n \ (n = 1,2,\cdots);$$
$$\sigma_t / \sigma_0^t, \sigma_l / \sigma_0^l > 0.4.$$

By using this method, the parameters in the gentle buncher and accelerator sections can be properly fixed. As for the shaper section, we follow the normal way to choose the parameters as linear functions of z, but note that an appropriate length should be chosen to minimize emittance growth. A too short shaper will cause larger transverse emittance growth, while a too long one will lead to the extension of the beam in the longitudinal direction[6].

3 NUMERICAL SIMULATIONS

Choosing the ratio $\varepsilon_{ln}/\varepsilon_{tn}$ = 2.0, we have generated parameters of the IFMIF RFQ according to the method described above. Another strategy that has been used is that the intervane voltage is ramped with the increase of the energy, which has also been adopted by Lloyd Young of LANL, so that the 1.8 times Kilpatrick limit is kept along the whole structure. The parameters are plotted in Fig. 1 and enumerated in Table 1. As can be seen from them, σ_0^t is varied from some 45° at the beginning of the shaper to about 15° at the end of the RFQ, and the voltage is ramped from 100kV to 190kV.

Numerical simulations of the beam dynamics have been performed with the program PARMULT from LANL. The initial particle distribution is waterbag in the transverse direction, with a normalized rms emittance of 0.2 π mm mrad, and dc in the longitudinal direction. The output transverse and longitudinal normalized rms emittance is 0.3 and 0.57 π mm mrad respectively in case of 140mA. Fig. 2 shows the particle trajectories through the RFQ, in which a gradually increasing transverse beam size after the end of the gentle buncher is observed. These results have been confirmed by the latest version of PARMTEQM at LANL [7]. Comparisons with the RFQ generated by the traditional method with the same initial conditions have been done [6], which show that the equipartitioning design procedure can give good energy balance between transverse and longitudinal direction, resulting in smaller longitudinal emittance growth and less beam losses in the high energy end. Moreover, the overall length of the equipartitioned RFQ is obviously shorter than the conventional one.

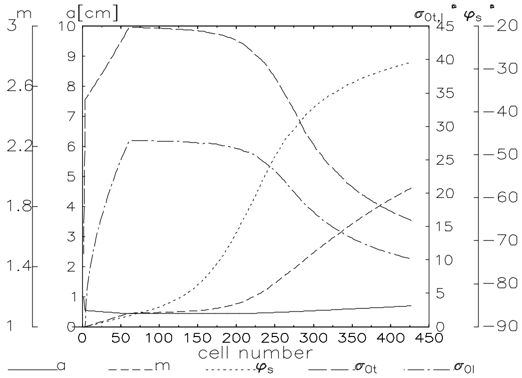

Fig. 1. Plot of the dynamics parameters of the equipartitioned D^+ RFQ .

Table 1. Equipartitioned D^+ RFQ parameters

Ion	D^+
Frequency [MHz]	175
Input / Output Energy [MeV]	0.1 / 8.0
Voltage [MV]	0.1-0.19
Cell / Length [m]	427 / 11.5
Aperture Radius [cm]	0.55-0.69
Input Beam Current [mA]	140
Transmission Efficiency	95.8%
Input / Output Tran. Norm. rms Emit. [π mm mrad]	0.2 / 0.30
Input / Output Long. Norm. rms Emit. [π mm mrad]	0 / 0.57

The behaviours of the ratios $\varepsilon_{ln}/\varepsilon_{tn}$, σ_t/σ_l , $\gamma b/a$ and $\varepsilon_{ln}*\sigma_l/\varepsilon_{tn}*\sigma_t$ are illustrated in Fig. 3, where the quantities were calculated from the results of the PARMULT and only those particles that are transported to the end of the RFQ were used for the computations. To observe the tendency of the variation of the ratios, the RFQ was 'extended' to 16MeV. It shows that all of the three ratios converge approximately to the designed value of 2 at the high energy end. More interesting, the ratio $\gamma b/a$ is kept obviously constant at 2 from the beginning of the gentle buncher. Simulations with the $\varepsilon_{ln}/\varepsilon_{tn}$ ratio equal to 1.0, 1.25, 1.5, 1.75, 2.25, 2.5 etc. have also been carried out, which show that although the $\varepsilon_{ln}/\varepsilon_{tn}$ and σ_l/σ_t ratios deviate somewhat from the designed values, the $\gamma b/a$ ratio comes out close to the designed values. Fig.4 gives an example (calculated also up to 16 MeV), where the dynamics parameters were generated with $\varepsilon_{ln}/\varepsilon_{tn}$ equal to 1.5 .

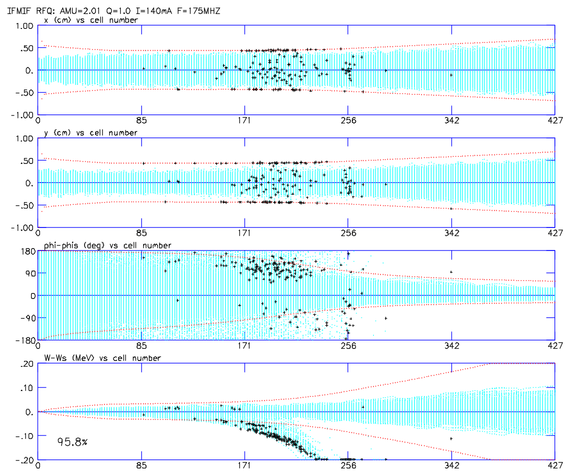

Fig. 2. Particle trajectories in the equipartitioned RFQ in case of 140mA.

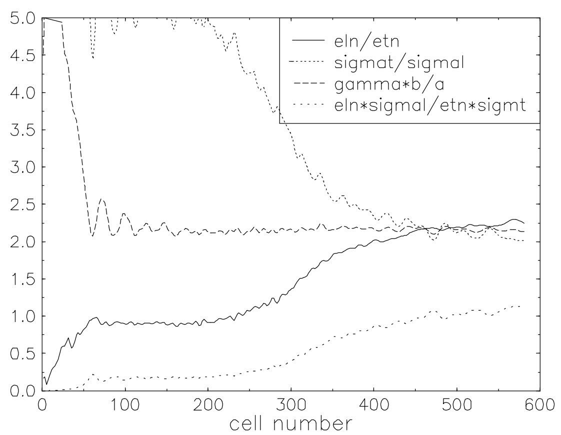

Fig. 3. Equipartitioning ratios of the D+ RFQ generated with $\varepsilon_{ln} / \varepsilon_{tn}$ = 2.

With PARMULT, multipoles associated with the deviations of the electrode pole-tips from the theoretical one can be evaluated. Calculations show that if the ratio of the radius of the pole-tip to the aperture radius in the middle of the acceleration cell is not smaller than 0.9, the influences of the multipoles can be neglected[6]. Hence all of the above calculations have been done with the ratio being 1.0.

4 CONCLUSION

The equipartitioning design procedure of RFQ linacs and its application in the IFMIF D+ RFQ have been presented, which demonstrates that such a method is successful in decreasing the emittance growth and beam halo, and hence the beam losses. The RFQ overall length can be shorten since the ramping of the voltage is possible because of the decrease of the transverse phase advance. Moreover, through proper choice of the ratio of the emittances, one can form the equipartitioned output bunches to have different ratio of bunch sizes, which can probably ease the transition to the next accelerator stage.

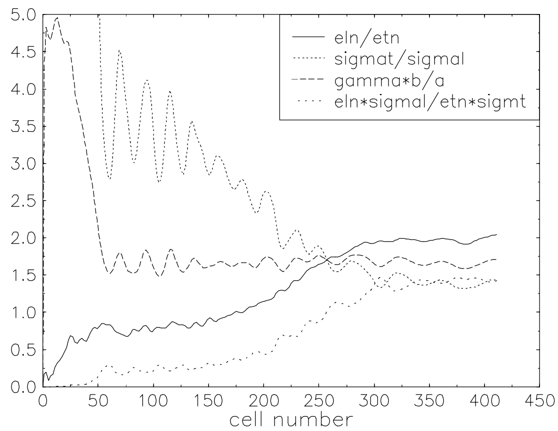

Fig. 4. Equipartitioning ratios of the D+ RFQ generated with $\varepsilon_{ln} / \varepsilon_{tn}$ = 1.5.

ACKNOWLEDGEMENTS

We gratefully acknowledge the supports of the Deutsche Forschungsgemeinschaft, the Alexander von Humboldt-Stiftung and the Computer Center of the Frankfurt University, and valuable discussions with Dr. I. Hofmann and Prof. Dr. A. Schempp.

REFERENCES

[1] R. A. Jameson, ‘SF Meeting Summary’, 11-13 Sep. 1995, Sante Fe, New Mexico, USA.
[2] I. Kapchinskiy, V. A. Teplyakov, Prib. Tekh. Eksp. 2, 18-22(1970).
[3] K. R. Crandall, R. H. Stokes, T. P. Wangler,BNL-Report(1979) p205.
[4] A. Schempp, EPAC88, World Sci.(1988) p464.
[5] R. A. Jameson, “Equipartitioning in linear accelerators”, Proc. 1981 Linac Conf. , Santa Fe.
[6] D. Li, Ph.D. Thesis, Uni-Frankfurt and Peking(1996).
[7] R. A. Jameson, IFMIF Accelerator Technical Memorandum 3-9-96: RFQ Design, AOT-1:96-077, March 1996.