PARAMETER STUDY FOR A HIGH CURRENT HEAVY ION LINAC*

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Abstract

In present scenarios of a heavy ion inertial fusion facility, a combination of linacs and storage rings has been proposed as a driver. After some funnelling steps, the main linac has to accelerate and focus an intense heavy ion beam (e.g. Bi^+, 400 mA) to a final energy of 10 GeV.

Using well known analytical formulae an attempt has been made to find a range of beam and structure parameters (e.g. frequency, shunt impedance, beam current, emittances, focusing scheme), in which the requirements on a DTL can be fulfilled. Beam dynamics aspects have been checked by numerical simulations.

1 INTRODUCTION

Since about 20 years, studies have been performed on inertial confinement fusion for potential application in energy production. Laser facilities, light and heavy ion accelerators and storage rings have been investigated as drivers; one study for a heavy ion driven fusion power system (HIBALL) was completed in the 1980's already [1]. Main progress has been achieved during the last years in the understanding of pellet dynamics after ignition, i.e. in the physics of extremely hot and dense matter, leading to new conditions for pellet ignition which impose also new requirements on the layout of the driver accelerator facilities. Progress and changes can nicely be seen in the proceedings of the Symposia on Heavy Ion Inertial Fusion, held every two years at different places, e.g. [2,3,4].

2 THE HIDIF STUDY

A combination of linacs and storage rings has been proposed by a European study group as an rf approach of a driver for a Heavy Ion Driven Ignition Facility (HIDIF) [5]. The scheme is shown in Fig. 1.

For pellet ignition, a beam energy of 3 MJ must be brought to the pellet within 5 ns, focused to spot sizes of about 1.7 mm radius. The ion species is Bi^+, the final ion energy was fixed to 10 GeV. These requirements determine mainly the driver layout and the beam parameters like beam current, beam emittance and pulse duration.

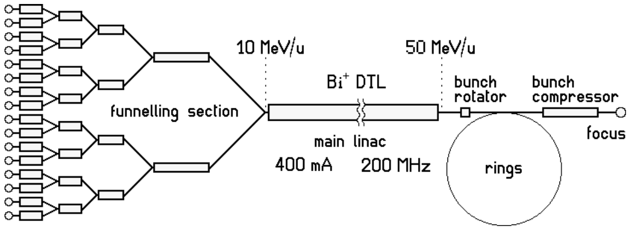

Figure 1: Scheme of the heavy ion driven ignition facility.

Since the capability of high current acceleration in a rf linac is limited, an array of rings and bunch compressors will be needed for the necessary current multiplication and pulse compression for the final focus. By tracking back the parameters needed at the final focus, limits on output conditions at the linac end are pre-given: beam current of 400 mA in a total transverse emittance of 4 π mm mrad, and longitudinal maximum momentum spread of $\pm 2\times 10^{-4}$ for 99% of the particles after bunch rotation for tolerable losses at ring injection. Following the scheme of funnelling [6] (already proposed for HIBALL) and taking some measured values for ion source currents and emittances, there are only few degrees of freedom for the choice of parameters in the layout of the main linac.

3 LAYOUT OF THE MAIN LINAC

Existing ion sources are not able to produce a current of 400 mA Bi^+: for a seven hole extraction, values up to 70 mA have been recently reported; with a lower extraction voltage, a 21 mA beam has been achieved within an emittance of 0.065 π mm mrad (80% rms, norm.) [7]. Moreover, RFQs cannot accept such a high current; then beams from several sources must be extracted, accelerated and merged in a funnel tree as indicated in Fig. 1. In each funnel step the frequency of the linac and the current are doubled: assuming 3 funnel steps and including some losses at beam formation, an ion source current of 60 mA is required; for 4 funnel steps it is lowered to 30 mA.

The first accelerator will be an RFQ, which is able to capture, focus and bunch the beam even at high space charge forces. Its frequency is chosen with respect to the input ion velocity: an appropriate choice is 12.5 MHz, since one has about 1.2–1.5 keV/u Bi^+ with a dc post-acceleration of 250–300 kV after extraction; 60 mA are still accepted but already close to the RFQ current limit.

In the RFQ the dc current is formed to bunches of about $\pm 30^{\circ}$ phase width. Due to the high space charge forces in the beam, the initial bunch length will nearly stay constant, i.e. before the frequency can be doubled in the next step the ion energy should be increased by a factor of four to avoid dilution in the longitudinal phase space. With these assumptions one ends up, after 3 funnel steps, with 100 MHz for the main linac and an injection energy of about 3 MeV/u; or, after 4 funnel steps,

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with 200 MHz and about 12 MeV/u. The standard formulae of Mittag [8] show that in both cases the longitudinal acceptance is large enough to capture a beam with an rms emittance of 0.2 π°MeV/u without filamentation in the following acceleration to a final energy of 50 MeV/u.

Taking into account a 100 MHz DTL structure, the shunt impedance, which is a measure of the efficiency, drops already to the end of the linac. To improve the efficiency, a frequency jump in the main linac would be necessary, leading to a higher peak current and empty rf buckets. For a 200 MHz Alvarez type structure the effective shunt impedance changes only slightly in the whole velocity range; the technology is well proven in different laboratories. Therefore a preliminary layout for a 200 MHz DTL from 10 to 50 MeV/u has been made; the main parameters are summarized in Table 1.

The effective accelerating field E_oT is 2.8 MV/m; the average shunt impedance is 26 MΩ/m. For a total voltage gain of 8.4 GV, the length of the linac sums up to 3.4 km.

Table 1: Linac and beam parameters.

Mass number	209 (Bi+)	
Frequency	200.0	MHz
Current	400	mA
Number of cells	9775	
Total length (10-50 MeV)	3383	m
Min. aperture radius	1.6	cm
Max. pole tip field	1.15	Tesla
Electric field amplitude E_oT	2.80-2.88	MV/m
Total energy gain	40.0	MeV/u
Peak beam power, 60% chopping	690	kW/m
Peak dissipated power	320	kW/m
Average shunt impedance	26	MΩ/m
Transv. rms norm. emittance	0.176-0.183	π mm mrad
Long. rms norm. emittance	1.66-1.83	π ns keV/u

4 BEAM DYNAMICS ASPECTS

When generating the linac geometry, a drift tube aperture of about 1.6 cm radius came up; with a maximum pole tip field of 1 Tesla the transverse focusing turned out to be too weak for the FD or FFDD quadrupole configuration normally used. Going to a FFFFFDDDDD scheme, as proposed in [9], resulted in a maximum pole tip field of 1.16 T and a transverse phase advance of 35°–55° per period. Schemes from 3F3D to 7F7D seem to be possible too; no optimization has been done for these. In Fig. 2 the focusing scheme is plotted, showing a low flutter factor.

The normalized transverse emittance for proper ring injection of 1.3 π mm mrad is rather small. Assuming a safety factor of 10 between full and rms emittance, to reduce the risk of particle losses and structure activation, the required value of 0.13 π mm mrad has to be compared to the value of 0.06 π mm mrad measured directly at the ion source. This allows only a factor of 2 for the unavoidable emittance growth along the whole linac complex.

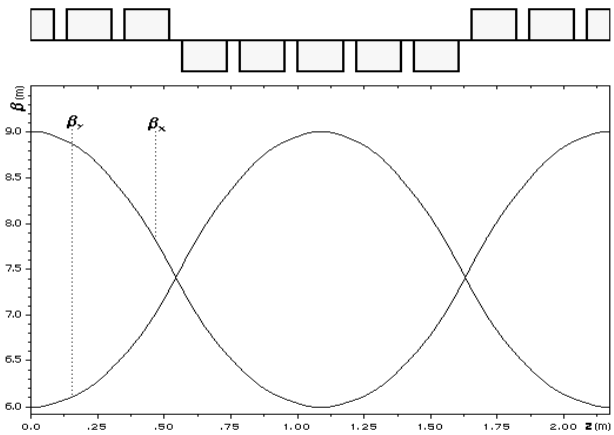

Figure 2: Chosen focusing scheme: plot of β_x and β_y.

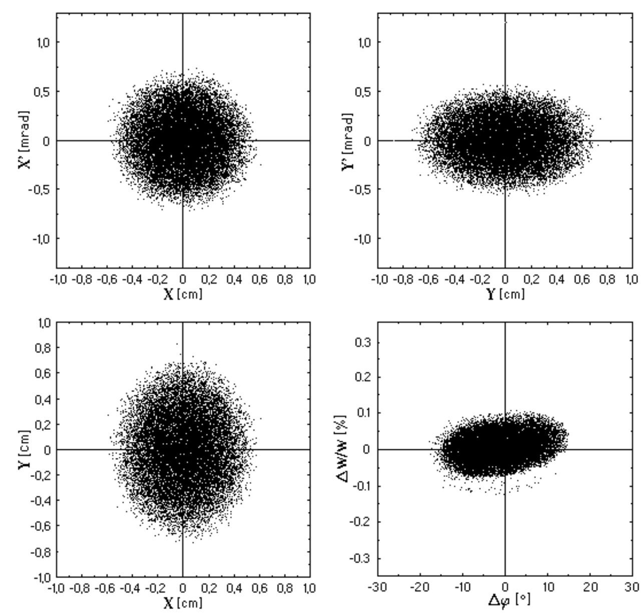

Figure 3: Output distribution at the linac end for 20,000 particles; 6D waterbag input, phase and amplitude errors.

Therefore particle dynamics calculations have been done with a 6D waterbag distribution including rf field amplitude and phase errors with an rms input emittance of 0.176 π mm mrad, allowing for some more emittance growth in the front part. It could be demonstrated that the requirements for ring injection can be fulfilled [10,11].

As an example, in Fig. 3 the output emittances at the linac end are plotted for the nominal design, including rf phase and amplitude errors. There is only a slight increase of beam size in the real transverse space. The energy spread in the longitudinal phase space is smaller than $\pm 4\times 10^{-4}$ after debunching.

5 LINAC OPTION FOR TELESCOPING

An additional complication for the layout of the linac is the need to accelerate ions of different masses to the same momentum, to allow for "telescoping" of the different bunches in the final transport line. Telescoping is a non-Liouvillean method: bunches with different ion species but same momentum are started with an appropriate delay time in a single beam line. The delay time and the velocity difference have to be chosen in such a way that the bunches fully overlap in real and momentum space at the end of the final transport, i.e. when hitting the pellet [12].

In the present scheme a mass difference of ±10% is required, which would correspond to the ions ^{187}Re, ^{209}Bi, ^{232}Th [5]. In Fig. 4 kinetic energy versus momentum is plotted for different masses for the velocity range of the main linac. At the design output energy for Bi (50 MeV/u) the momentum is 64 GeV/c; to get the same momentum, the kinetic energy for Re and Th must be 61 and 40 MeV/u.

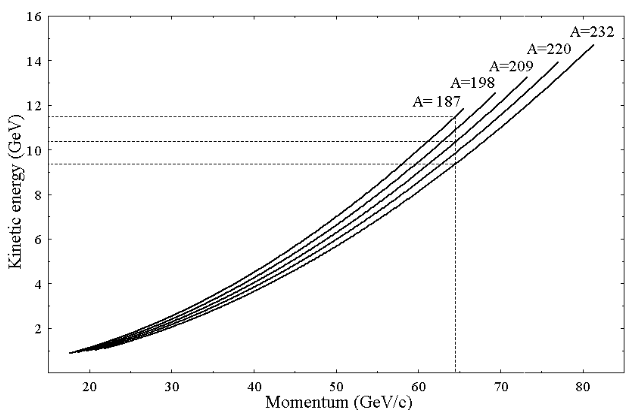

Figure 4: Energy vs. momentum for different masses.

But a DTL has a fixed velocity profile, accelerating all ions from the same specific input energy to the same specific output energy when the voltage is scaled accordingly to the mass ratios. Different velocity profiles can be obtained only if the frequency can be adjusted to the change in ion velocity, to fulfill the condition for synchronous acceleration. A large frequency variation of ±10% for an Alvarez type structure seems not to be realistic. Therefore the following concept has been investigated:

- the linac length has to be increased to accelerate the lightest ion to the higher required energy;
- the design mass has to be transported through the additional part only, keeping the beam bunched;
- the heaviest ion (which reaches the lower required energy already before the linac end) has to be transported through the rest of the main linac and the additional part.

For a mass 10% lighter than the design mass (ion energy difference of 20%) the linac becomes 20% longer; Th must be accelerated with a higher electric field E_oT of 3.1 MV/m and then transported without loss of beam quality through 1.6 km.

Preliminary beam dynamics calculations indicate that the beam can be transported through several DTL cells, when single resonators are installed in between the tanks, acting as rebuncher [11]. The time for switching all parameters between two pulses with different ion species is 0.075 ms. Any reduction in the required mass differences would simplify also the linac architecture and operation.

Table 2: Change of linac parameters for telescoping.

Mass numbers	187 (Re), 209 (Bi), 232 (Th)	
Number of new cells	1540	
Additional length	760	m
Electric field amplitude E_oT	2.4-3.1	MV/m
Momentum at output	64.3	GeV/c

5 CONCLUSIONS

From the point of view of particle dynamics, a conventional Alvarez type DTL can serve as main linac in the present HIDIF scheme. Some critical points exist: the alignment of drift tubes and quadrupoles in a 3 km long linac, the acceleration of ions with different masses to the same momentum at the linac end, the required peak power of about 1.1 MW/m. A higher beam current, as discussed for energy production, or a higher acceleration rate would increase this value. Beam dynamics calculations including errors and tolerances gave good results for the design ion Bi^+ and the linac layout of Table 1. The telescoping option must still be reconsidered.

6 ACKNOWLEDGEMENTS

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