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Low energy DTL sections for intense Bi^{1+} beams

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Abstract

The beam dynamics design of the low energy DTL section of a fusion driver linac based on the IH-structure is presented. The acceleration of a $^{209}Bi^{1+}$ beam by an IH-DTL operated at 27 MHz (54 MHz) is investigated for two specific injection energies at 60 A keV and at 200 A keV, respectively. Both cases are optimized separately, with the goal to find out the maximum achievable acceleration gradient, beam current, as well as the most attractive field strength range of the quadrupole lenses. Calculations are performed on one beamlet, but the results can be applied to build up multibeam cavities. H-mode cavities are very well suited for this purpose and provide high acceleration efficiency, especially at low particle velocity. In addition, the "Combined 0° structure" ("Kombinierte Null Grad Struktur–KONUS") beam dynamics concept allows grouping into modular units consisting of short, simple rf cavities and of multiaperture quadrupole triplet lenses located in the intertank sections.

Keywords: Acceleration gradient; Beam current; Low energy DTL; Quadrupole lenses

1. INTRODUCTION

Challenging criteria which have to be imposed on a fusion driver DTL in order to make it competitive and feasible on an industrial scale are:

- High acceleration efficiency resulting in a reduced overall linac length.
- Robustness and simplicity of the main components.
- Limited total number of accelerating and focusing elements.

A DTL design based on the IH structure together with the "Combined 0° structure" beam dynamics concept is well suited to meet these criteria.

The Gesellschaft für Schwerionenforschung (GSI) High Current Linac (HSI) injector has been routinely operated since 1999, providing an average acceleration gradient of 5.4 MV/m and a maximum surface field of 400 kV/cm for the design particle with $A/q = 65$, at the resonance frequency of 36 MHz (Ratzinger, 2001). High power tests performed on the 202-MHz IH 2 tank of the Centre Européen pour la Recherche Nucléaire (CERN) Lead Injector showed the feasibility of peak surface fields of up to 540 kV/cm, corresponding to an effective acceleration gradient of 10.7 MV/m (Broere *et al.*, 1998).

The simplicity and robustness of the accelerating structures is given by the fact, that the IH drift tubes carry no internal focusing elements (quadrupole lenses). For further simplification, a modular setup was proposed, where the focusing elements should always be placed in the intertank regions (Ratzinger & Tiede, 1998). Additionally, the use of multibeam IH-DTLs was suggested, as H-type resonators are very much suited for this purpose (linear voltage increase along the drift tube supporting stems and reasonable tank diameters at low frequencies because of the high capacitive load; see also Ratzinger *et al.*, 1998).

Based on this experience, the design of two $^{209}Bi^{1+}$ IH-DTL sections with injection energies of 60 A keV (200 A keV), and operated at 27 MHz (54 MHz) has been worked out. The input energies are corresponding to the stages between funnel sections as defined by the Heavy Ion Driven Inertial Fusion (HIDIF) study (Hofmann & Plass, 1998) and the resonance frequencies are related to the GSI accelerator facility.

The main goal of the present study is to establish the significant beam and cavity parameters—this is why only short sections, each consisting of four tanks and four triplet lenses, were investigated to characterize the whole lattice.

2. MULTIBUNCH CAVITIES

In Figure 1a, the whole funnel tree as proposed by the HIDIF study is shown, to illustrate the "working scope" chosen for the present design study. At the input energy of 60 A keV, a beam current of 50 mA is required for each branch. This value was chosen as reference for our beam dynamics calculations. A substantial simplification of the cavity and rf

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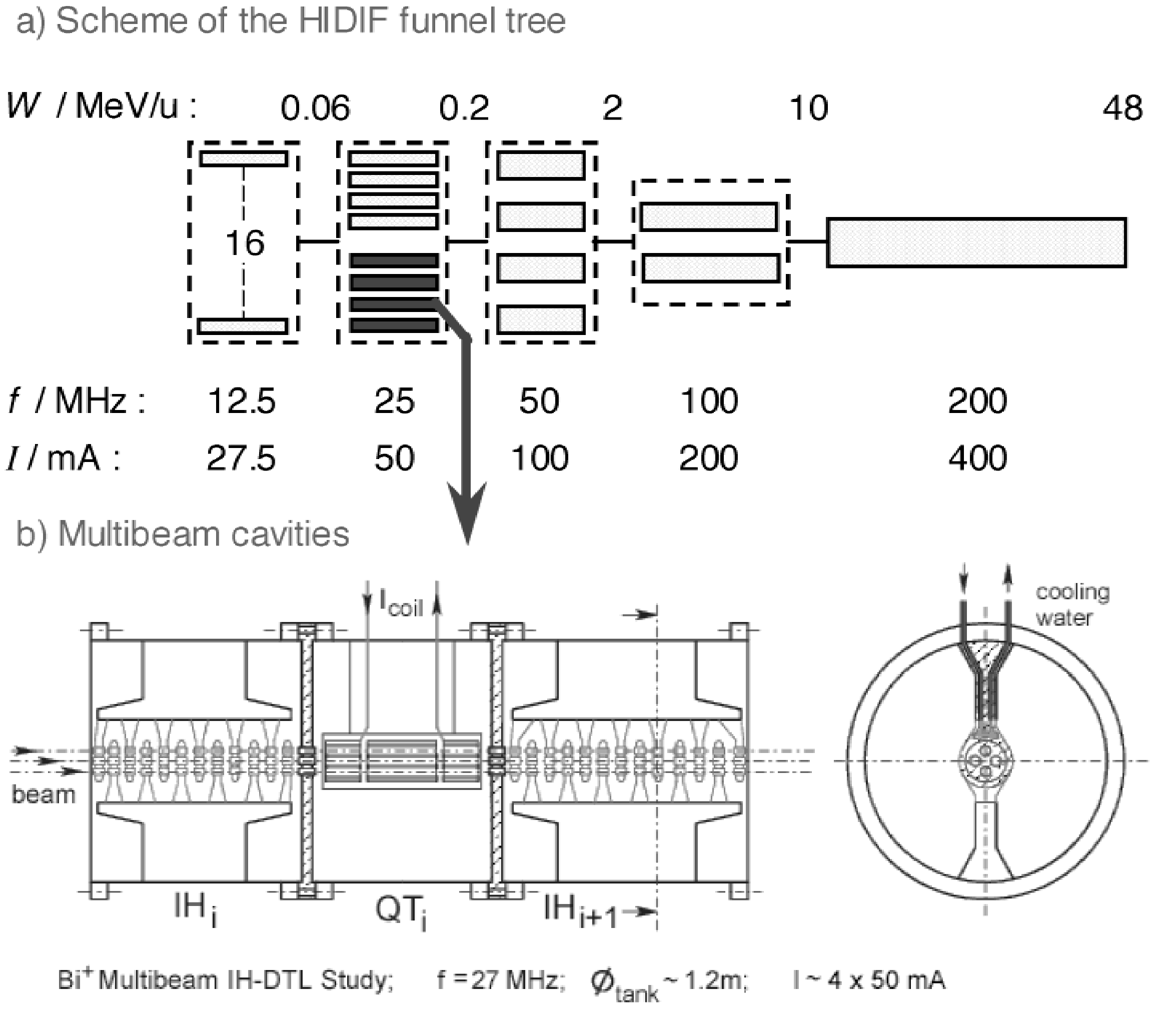

Fig. 1. Illustration of the classic fusion linac concept based on funnelling (HIDIF) and suggested cavity reduction by multibeam IH structures.

amplifier array could be achieved if four beamlets could be grouped into one cavity, as shown in Figure 1b. Then the cavity would carry a total beam current of 200 mA, which is still feasible for short cavities with respect to beam loading and power supply needs.

For the input energy of 200 A keV, again a design current of 50 mA per beamlet was chosen, to show the effect of the particle velocity and resonance frequency on the beam behavior and on the emittance growth especially (each bucket filled).

3. BEAM DYNAMICS RESULTS

3.1. Layout of the 27 MHz, 60–150 keV/u section

In Figure 2 the transverse and longitudinal beam envelopes for one beamlet at the design current of 50 mA are shown. Table 1 contains the cavity, beam, and quadrupole lens parameters.

Some important design features are as follows:

- The whole array is very compact—a overall length of about 7 m is sufficient to cover the energy range of 60–150 keV/u (it is 22.1 MV effective accelerating voltage).
- Both the transverse and the longitudinal beam envelopes indicate a safe design—there are no big fluctuations and the transverse beam radii are less than 10–13 mm within the resonators and up to 20 mm within the lenses.
- The features mentioned above could only be achieved by rather high acceleration (and longitudinal focusing) gradients (6.5 MV/m without lenses) and by extremely high magnetic quadrupole fields (5 T on the pole tip).

The extremely tough requirements for the transverse focusing system (caused by $A/q = 209$) can especially be seen from the lens density along the channel—the added lengths of the triplets correspond to the total length of the cavities (see also the discussion of the results in Section 4).

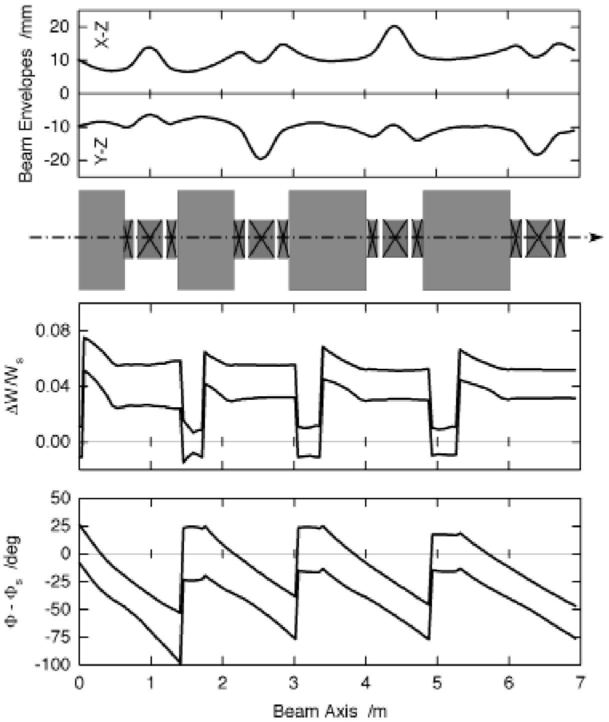

Fig. 2. Beam envelopes of the 60–150 A keV design ($I_{beam} = 50$ mA).

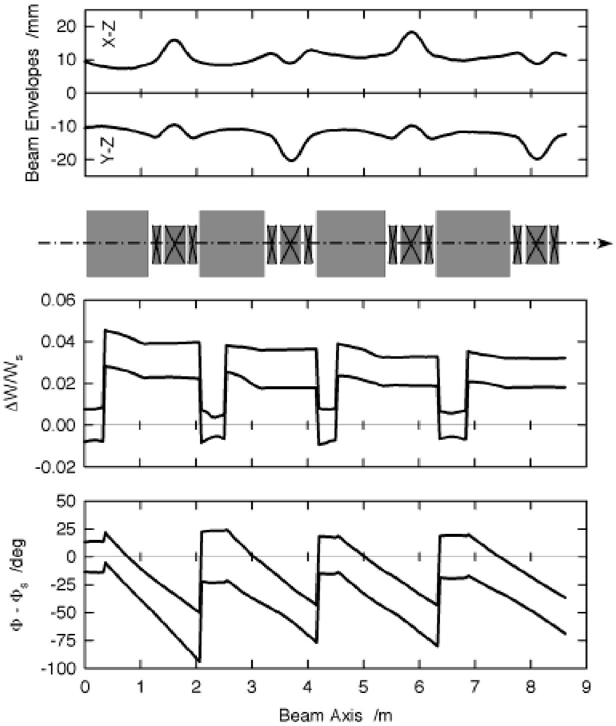

Fig. 3. Beam envelopes of the 200–325 A keV design ($I_{beam} = 50$ mA).

3.2. Layout of the 54-MHz, 200–325-keV/u section

The results obtained for the scenario with higher input energy (200 A keV/u) are shown in Figure 3 and Table 2. The main design features correspond to the 60 keV/u lattice. The lower quadrupole lens density and the more relaxed tuning conditions, which correspond with a smaller relative emittance growth, are obvious.

4. DISCUSSION OF THE CRITICAL DESIGN PARAMETERS

4.1. Acceleration gradients

The design values for the acceleration gradient (6.5 MV/m) averaged along the cavities and the maximum surface field

Table 1. *Design parameters of the 27-MHz, 50-mA section*

	IH cavities			
	IH 1	IH 2	IH 3	IH 4
Tank length (m)	0.63	0.85	1.12	1.25
No. of gaps	8	10	12	12
Drift tube aperture (mm)	16	18	20	20
Max. eff. gap voltage (kV)	500	555	625	680
Energy rante (keV/u)	60	72	93	121
	72	93	121	151
Beam emittance (rms)	Input			Exit
transverse (π mm mrad)	0.15			0.20
longitudinal (π keV/u ns)	0.28			0.50
	Quadruple triplet lenses			
	QT 1	QT 2	QT 3	QT 4
Total length (m)	0.90	0.90	0.90	0.90
Aperture (mm)	30	30	30	30
Eff. pole length (mm)	156/260/156			
Field gradient (T/m)	150–163			

Table 2. *Design parameters of the 54-MHz, 50-mA section*

	IH cavities			
	IH 1	IH 2	IH 3	IH 4
Tank length (m)	1.06	1.14	1.21	1.29
No. of gaps	18	18	18	18
Drift tube aperture (mm)	20	20	20	20
Max. eff. gap voltage (kV)	430	460	480	508
Energy range (keV/u)	200	224	256	290
	224	256	290	325
Beam emittance (rms)	Input			Exit
transverse (π mm mrad)	0.27			0.30
longitudinal (π keV/u ns)	0.28			0.41
	Quadruple triplet lenses			
	QT 1	QT 2	QT 3	QT 4
Total length (m)	1.00	1.00	1.00	1.00
Aperture (mm)	30	30	30	30
Eff. pole length (mm)	176/310/176			
Field gradient (T/m)	155–160			

(300 kV/cm) are quite high, but when compared to the second section of the GSI High Current Injector (7.9 MV/m and 400 kV/cm at 36 MHz), these values seem to be feasible.

A test simulation based on a "conventional," 3.0 MV/m average acceleration gradient design showed that not only the acceleration efficiency is decreased in this case, but also the longitudinal focusing is too weak, so that no stable longitudinal beam dynamics could be provided.

4.2. Quadrupole field strengths

It turned out that the most challenging design parameter is the extremely high quadrupole lens strength—about 150 T/m is needed, which is 5 T on the pole tip. The state of the art with conventional techniques (pulsed iron yoke multibeam array) comes to the limits of around 38 T/m and 1.9 T pole tip field (Faltens *et al.*, 1999). This is why alternative techniques should be considered. The most promising seem to be

- Pulsed, iron-free wire lenses. For very short pulses this lens type can be competitive. Field gradients of 150 T/m have been demonstrated on triplet lens configurations with small aperture (Spiller *et al.*, 1993).
- Space charge lenses (Gabor lens). At IAP, Frankfurt University there is long-term experience in the design and application of Gabor plasma lenses as a component of low energy beam transport sections (Meusel *et al.*, 2000). At present, further investigations are needed to check the ability of this lens type to replace the conventional intertank quadrupole triplets.

5. CONCLUDING REMARKS

A compact design for the low energy range of a $^{209}\mathrm{Bi}^{1+}$ fusion DTL driver was investigated. The capabilities of this alternative DTL concept based on the IH structure together with the KONUS beam dynamics depends upon the technical feasibility of (short) lenses with sufficient focusing power.

Beam dynamics calculations showed that, at least for the KONUS beam dynamics, there is no chance to reduce the critical parameters magnetic field strength and acceleration gradient. Reducing the magnetic field strength means longer triplet lenses, which completely disturb the longitudinal beam dynamics. Low acceleration gradients increase the number of gaps (and the tank length) for a given energy gain, resulting in big transverse beam envelopes.

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