Laser and Particle Beams (2003), *21*, 627–632. Printed in the USA.

DOI: 10.1017/S0263034603214221

High current ion beam RF acceleration and perspectives for an inertial fusion driver

U. RATZINGER,[1] H. LIEBERMANN,[1] O. MEUSEL,[1] H. PODLECH,[1] R. TIEDE,[1]
W. BARTH,[2] AND W. VINZENZ[2]
[1]Institute for Applied Physics, J.W. Goethe-Universität, Frankfurt am Main, Germany
[2]Gesellschaft für Schwerionenforschung, Darmstadt, Germany

(Received 28 February 2003; Accepted 16 September 2003)

Abstract

The actual situation with respect to the use of an RF linac driver for heavy ion inertial fusion (HIF) is discussed. At present, there is no high current heavy ion linac under construction. However, in the course of linac projects for e^-, p, d, or highly charged ions several developments were made, which may have some impact on the design of a HIF driver. Medium- and low-β superconducting structures suited for pulsed high current beam operation are actually designed and investigated at several laboratories. A superconducting 40 MeV, 125 mA cw linac for deuteron acceleration is designed for the Inertial Fusion Material Irradiation Facility (IFMIF). The Institute for Applied Physics (IAP) is developing a superconducting 350-MHz, 19-cell prototype CH-cavity for $\beta = 0.1$. The prototype cavity will be ready for tests in 2004. A superconducting main HIF driver linac would considerably reduce the power losses. Moreover, it would allow for an efficient linac operation at a higher duty factor.

The 1.4-AMeV room-temperature High Current Injector HSI at Gesellschaft für Schwerionenforschung (GSI) has been in routine operation for more than 2 years now. With a mass-to-charge ratio of up to 65, a current limit of 15 mA for U^{4+}, and an energy range from 2.2 AkeV up to 1.4 AMeV, this linac is suited to gain useful experience on the way toward the design of a HIF RF driver. The status and technical improvements of that $A/q \leq 65$, 91-MV linac are reported. Beam dynamics calculations for Bi^{1+}-beams show that powerful focusing elements at the linac front end are the bottleneck with respect to a further increase in beam current. Besides superconducting and pulsed wire quadrupoles, the potential of the Gabor-plasma lenses is investigated.

Keywords: Beam focusing; Gabor plasma ions; H-type multicell cavities; Ion beams; Linear accelerator; Low β superconducting cavities

INTRODUCTION

There is a long tradition of shortly pulsed, low repetition rate, room temperature (r.t.) synchrotron injector linacs for protons and H^- with beam currents up to 300 mA. The development of superconducting (s.c.) linac structures since the mid-1960s has been strongly motivated by high duty cycle applications. Elliptical multicell cavities for velocities $\beta \geq 0.5$ as well as single-, two-, and three-cell structures for low- and medium-β profiles are available now (Padamsee, 2001). After the successful development of input power couplers, up to 400 kW, RF power can be fed into a s.c. cavity by one feeder in cw operation (Schmierer *et al.*, 2001; Campisi, 2002).

Pulsed operation of s.c. multicell structures became possible through the use of mechanically stabilized cavities equipped with fast tuners and with powerful digital controls (Simrock, 2002; Vardanyan *et al.*, 2002).

Recently, the development of multicell s.c. activities for the fusion-driver-relevant β-range has started (Eichhorn *et al.*, 2002; Zaplatin *et al.*, 2002). It may lead to a very compact and power-efficient driver linac solution at beam energies above 5 AMeV. The s.c. multicell CH-linac development at IAP is reported in this article.

A very flexible cw ion linac design for ions ranging from 1-GeV protons to 400-AMeV uranium is investigated at the Argonne National Laboratory (ANL) and at Michigan State University (MSU) within the Rare Isotope Accelerator (RIA) project. An interesting feature is the simultaneous acceleration of multiply charged ions after stripping processes (Ostroumov, 2001). Up to the heaviest elements, a total transmission of 80% should be reached by accepting two

---

Address correspondence and reprint requests to: U. Ratzinger, Institute for Applied Physics, J.W. Goethe-Universität, Robert-Mayer-Str. 2-4, Frankfurt am Main, Germany. E-mail: u.ratzinger@iap.uni-frankfurt.de

charge states from the Electron Cyclotron Resonance (ECR) ion source and including two stripping processes at 12.3 AMeV and at 85.5 AMeV. Although the application of such a concept on a future fusion driver scenario is not obvious to date, it could have an impact on the design of shortly pulsed high current heavy ion injectors.

The currently most powerful heavy ion linac, UNILAC, at GSI, has a beam transmission of only around 1.5% for uranium through the inclusion of two stripping processes at 1.4 AMeV and at 11.4 AMeV, and the acceptance of one charge state per section only. In 1999, the 1.4-AMeV Wideroe section was replaced by the 91-MV High Current Injector HSI to increase the heavy ion beam current by more than two orders in magnitude (Ratzinger, 2001; Barth, 2002). This 15-mA, U^{4+} injector consists of a 120-AkeV RF Quadrupole (RFQ) followed by a 11-cell RFQ “Superlens” matching the beam to the Interdigital H-type Drift Tube Linac (IH-DTL). This article will describe the HSI status and planned activities for further improvement.

The suitability of H-type structures to accelerate intense Bi^{1+}-ion beams was discussed earlier (Ratzinger & Tiede, 1998). A detailed beam dynamics study with respect to the H-DTL front end shows that the key elements are the transversely focusing lenses. The requested parameters are quite similar to those of the induction linac approach, where promising results have been obtained already with s.c. quadrupole prototypes (Faltens *et al.*, 2002).

H-type structures offer attractive features for high current heavy ion acceleration like the small transverse dimensions at a given resonance frequency, the option to realize multi-aperture cavities, and the chance for innovative RF powering concepts (Setzer *et al.*, 2000).

2. SUPERCONDUCTING CAVITY DEVELOPMENT AND CONSEQUENCES FOR A HIF DRIVER LINAC

At beam velocities $\beta > 0.5$, several coupled cavity structures have been developed successfully. Typically four to six elliptical cells are coupled in the π-mode through the aperture and are tuned to a constant voltage profile (Ciovati *et al.*, 2001). The 350-MHz linac within the CERN-LEP ring was operated with great success in the cw mode. For a high beam load, powerful RF input couplers are already available (Schmierer *et al.*, 2001; Campisi, 2002), and the present power limit of around 400 kW per coupler in cw operation does not seem to be a final technical limit. After a careful analysis of mechanical cavity resonances along with the increasing capabilities of digital controls, it became possible to operate s.c. cavities reliably at well-defined pulsed time structures (Simrock, 2002). At the velocity range of interest for a heavy ion fusion driver with $\beta \leq 0.35$, there are no well-tested multicell s.c. cavities existing so far. Only two-, three- and four-gap s.c. cavities have been successfully operated for many years at nuclear research facilities, where variable beam energies are needed (Fortuna *et al.*, 1996). It seems unreasonable to base a fixed velocity, 10-GV linac on about 12,000 low-β s.c. cavities. On the other hand, by using multicell cavities, one could aim to keep the total number of cavities below 2000. At present, two types of multicell cavities for a β-range from about 0.1 to 0.5 have been developed: the CH cavity and the multicell versions of the spoke cavity (Shepard *et al.*, 1998; Zaplatin *et al.*, 2002). IAP has designed a 1.05-m-long 350-MHz, 19-cell prototype CH cavity (see Fig. 1) in collaboration with industry (ACCEL Company, Bergisch-Gladbach, Germany) and has equipped a cryolaboratory with a vertical cryostat ($\phi_i \sim 600$ movement, H = 3 m) and with a class 100 laminar flow box to perform test runs with that cavity. First results are expected in 2004. Moreover IAP is designing s.c. 175-MHz CH cavities for high current applications at the HIF-relevant velocity range (Sauer *et al.*, 2002). Table 1 shows the characteristic parameters of the prototype cavity, resulting from Microwave Studio calculations. The low maximum magnetic field levels at a given effective voltage gain are prom-

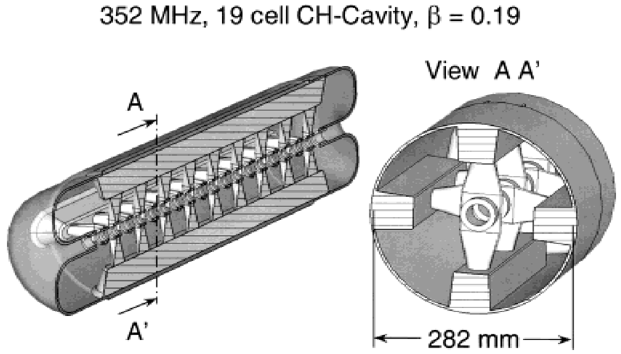

Fig. 1. Superconducting prototype CH cavity, designed by IAP, University of Frankfurt (supported by BMBF, contract no. 06F134I, and by IFMIF) and under construction at ACCEL Instruments GmbH, Bergisch-Gladbach, Germany.

Table 1. *Characteristic parameters of the s.c. prototype cavity*

f (MHz)	352
β	0.1
Length (mm)	1048
Diameter (mm)	280
Number of gaps	19
R_a/Q_0 (Ω)	3220
$G = R_S Q_0$ (Ω)	56
E_p/E_a	6.59
B_p/E_a (mT/(MV/m))	7.29
E_p (MV at $E_a = 3.2$ MV/m)	21
B_p (mT at $E_a = 3.2$ MV/m)	23.3
$W/(E_a)^2$ (mJ/(MV/m)^2)	154
W (J at $E_a = 3.2$ MV/m)	1.58
Q_0 (BCS = 40 nΩ, 4K)	1.6×10^9
Q_0 ($R_s = 140$ nΩ)	4.6×10^8
P at 3.2 MV/m, $R_S = 140$ nΩ (W)	9

ising. The ratio between the magnetic and the electric peak field B_p/E_p is 7.3 mT/(MV/m). This value is about one-third lower than for typical spoke resonators. On the other side, the electric peak field is relatively high ($E_p/E_a = 6.59$). This means that the s.c. CH cavity will most likely be limited by field emission. An effective acceleration gradient of 3.2 MV/m leads to a peak field of 21 MV/m, which still seems to be a moderate value. Tests will show whether the relatively high electric peak fields localized at the drift tube ends are tolerable. Alternatively the drift tube geometry must be modified in a next step.

3. STATUS OF THE GSI HIGH CURRENT INJECTOR

The new 1.4-AMeV, 36-MHz High Current Injector has replaced the Wideroe section of UNILAC and has been in routine operation since October 1999 (Ratzinger, 2001). The beam current design limit of the linac was reached by delivering 10 mA of Ar^{1+}. From a total U^{4+} beam current of 11 mA in front of the quadruplet focusing into the RFQ, 6 mA were accelerated by the HSI and delivered to the gas stripper at the beginning of the year 2003. This was a factor of 2.5 below the U^{4+} current limit. Improvements of the MEVVA-ion source, of the electrostatic acceleration geometry, and of the low energy beam transport section as well as of the RFQ front end are under investigation to reach the design current of 15 mA for U^{4+} (Barth, 2002). Based on the newest emittance measurements on U^{4+} beams at 2.2 AkeV just behind the high voltage gap, it seems realistic to achieve up to 11 mA at the HSI exit after minor hardware changes.

3.1. Superlens and RFQ

The Superlens (Ratzinger, 2001), which is a short, 11-cell, 36-MHz IH-RFQ, showed an intolerably high dark current load, when operated at U^{4+} levels. During the 2001/02 winter shut down, the mechanically polished RFQ electrodes from bulk Oxygen-Free High Conductivity (OFHC) copper were replaced by galvanically copper-plated ones and the electrode distances towards the end walls were increased from 7 mm to 12 mm, as the dark currents were concentrated at the electrode ends. As a consequence, the dark currents are substantially reduced now (see Fig. 2). A voltage level of 212 kV at a minimum vane–vane distance of 8.3 mm is reached easily. This corresponds to A/q = 65 or to 9 V in arbitrary units as used in Figure 2. An input RF power of 100 kW has been measured, which results in a dark current contribution of 20 kW at a neglectable level of reflected power. This is acceptable at low duty cycle operation.

When compared to the main IH-RFQ (9.4 m long, 356 cells, mechanically polished electrodes), the dark current contributions per unit length at similar electrode surface fields are now lower at the Superlens. There is some evidence that it is advantageous to copperplate (20 μm thick, typically) the RFQ electrodes. Moreover, no significant reduction of dark current contributions was seen at the RFQ during several months of operation at a high RF voltage level, while the Superlens after a few hours of operation reached the performance as plotted in Figure 2.

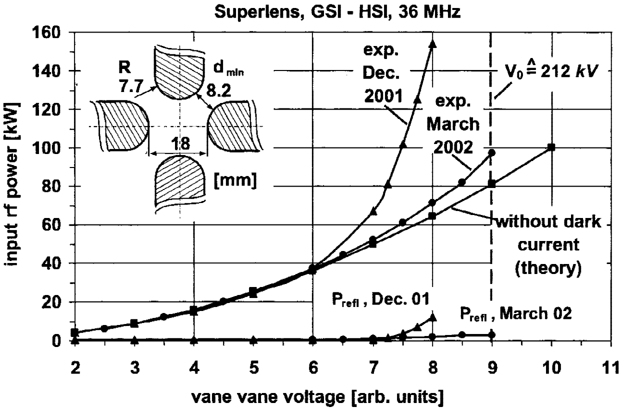

Fig. 2. Reduction of the dark current contributions to the total RF power losses by enlarging the distance of the quadrupole electrode ends toward the cavity and flanges. Additionally, the minivans are electrolytically copperplated now. The nominal vane–vane voltage for U^{4+} corresponds to 194 kV (8.2 V in arb. units).

3.2. IH-DTL

The 40-MV IH1 cavity contains three internal quadrupole triplet lenses (Ratzinger, 2001). During shut-down inspection in January 2002 serious damage at the lens housing of the first triplet was found. It is suspected that in the case of special two-beam operation modes (50-Hz operation with 5-ms pulses at reduced RF level and 1-ms pulses at high RF level in parallel), a well-localized electron current toward a neighboring drift tube caused local overheating and, as a consequence, melted the copperplated stainless steel end plate. This damage happened twice at exactly the same position. As the maximum heat load without dark current contributions was estimated to remain below 0.05 W/cm^2, direct water cooling was provided only for the cylindrical surfaces but not for the end plates of the lens housings. Air cooling is applied to the inner housing surfaces (including the beam tubes).

Meanwhile, a second generation of IH internal lenses with directly water cooled lens end plates was fabricated and the first lens of IH1 was exchanged in January 2003.

The geometry of the damaged asymmetric cell in tank IH1 was modified (Lieberman *et al.*, 2002) by reducing the surface peak field at the drift tube after the lens housing (Fig. 3, pos. B). Perturbation measurements show that this was the absolute IH1 peak field so far (Ratzinger *et al.*, 1999).

There are some indications now, that an RF-power-level-dependent vacuum leak in the tank end flange water circuit caused that drastic lens damage described above. Meanwhile, such a leak was detected and eliminated.

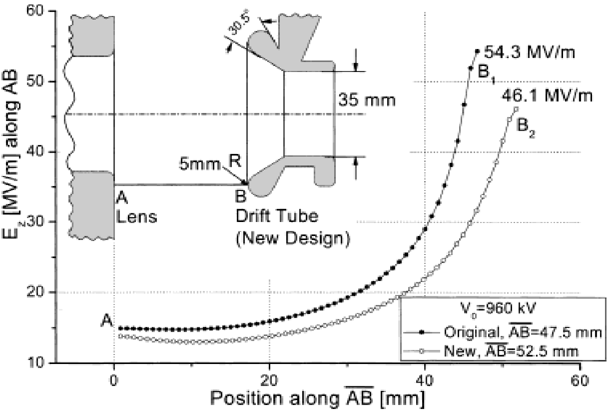

Fig. 3. Longitudinal electric field distribution along path AB in gap no. 10 of the HSI-IH1 cavity. The drift tube (bulk copper) behind of the quadrupole triplet lens was shortened by 5 mm, the end curvature was increased from 3 mm to 5 mm radius, and the electric capacity between lens and drift tube stem was reduced by a diminished stem geometry.

In the case of U^{4+}, the dark current contributions to the RF power losses are about 25% for IH tank 1 and 15% for IH tank 2. Dark current contributions are clearly detected at operation above 60% of the U^{4+} power levels.

The operation experience after these changes is quite promising. The HSI is providing again simultaneous two-beam operation at power levels and duty cycles corresponding to U^{10+} (30% d.c.) and U^{4+} (2% d.c.).

4. DEVELOPMENTS WITH RESPECT TO THE Bi^{1+} LINAC FRONT END

The high A/q ratio in combination with the high beam intensity makes the development of new concepts and components necessary, especially along the linac front end and up to the last funnel section.

4.1. Bi^{1+} test injector

It is obvious that a high terminal voltage eases the beam transport from the ion source to the RFQ. It was envisaged to base the Bi^{1+} ion source development at IAP on a 500-kV platform (Ratzinger, 2001). As an intermediate step, a 300-kV platform is under construction at GSI. At that test stand, IAP plans to continue the development of an extraction and acceleration geometry fitting to the Bi^{1+} plasma generator. The plasma generator itself will be further optimized at an IAP test stand. The Bi^{1+} fraction of the full beam from the IAP volume source is 93%, which is favorable for a compound extraction and postaccelerator setup. A powerful slit-grid emittance measurement device was constructed (PET, Darmstadt) and has been successfully tested with beam at IAP.

Low energy beam measurements by CCD cameras will be further improved (Jakob *et al.*, 2002). The aim is to develop a destruction-free emittance measurement, which will no longer influence the conditions of space charge compensation as conventional detectors do.

4.2. Investigations on Gabor lenses

Gabor lenses (GLs) are very powerful in focusing low energy heavy ion beams (Mobley *et al.*, 1979; Meusel *et al.*, 2000). The positive ion beam is passing an electron space charge cloud, which is stabilized within an insulated beam tube on positive voltage V_a by superposition of a longitudinal magnetic field B_Z. Gabor related the transverse cloud confinement to the condition for Brillioun flow. This results in the following equation for the electron density n:

$$n_{\text{rad}} = \frac{\varepsilon_0 B_Z^2}{2m_e}. \tag{1}$$

Longitudinal confinement is provided by the electrostatic potential. The space charge limit is reached in that direction when the on-axis potential within the tube is decreased to zero by adding the space charge potential to V_a. Assuming a tube filled homogeneously with electrons up to the aperture radius a leads to a corresponding electron density:

$$n_{\text{long}} = \frac{4\varepsilon_0 V_a}{ea^2}. \tag{2}$$

The longitudinal confinement in praxis depends on the longitudinal electron temperature as well as on the real radial density distribution of the cloud that defines the useful lens aperture. In the IAP-type GL, the electron production is accomplished by a gas discharge (typical current range 0.1 mA to 10 mA) and by beam collisions with the rest gas. No heated cathode is used. A filling factor is defined by relating the electron density prediction of Eq. (1) to the experimental result:

$$\kappa = \frac{n_{\text{ex}}}{n_{\text{rad}}}. \tag{3}$$

At IAP, a test stand for GLs was constructed. A 14-keV, 10-mA He^+ beam is matched by two GLs ($B_Z = 7.8$ mT, $V_a = 1850$ V, $l_{1,2} = 0.1$ m, $r_a = .03$ m) to a 108-MHz RFQ. The measured focal length of 0.33 m for each of these lenses corresponds to a filling factor of about 0.32.

After acceleration to 440 keV, the bunched He beam will again be focused by a powerful Gabor lens with the design values $B_Z = 0.2$ T, $V_a = 65$ kV, $l = 0.3$ m, r_a variable up to about 80 mm (O. Meusel, pers. comm.). One GL of that type was constructed (see Fig. 4) and will be commissioned with beam during 2004. A second one is under construction. It is envisaged to test this lens also at the GSI high current test injector with 150 keV U^{4+} beams. Figure 4 shows a cross-sectional view of the lens and a photo of the completed setup.

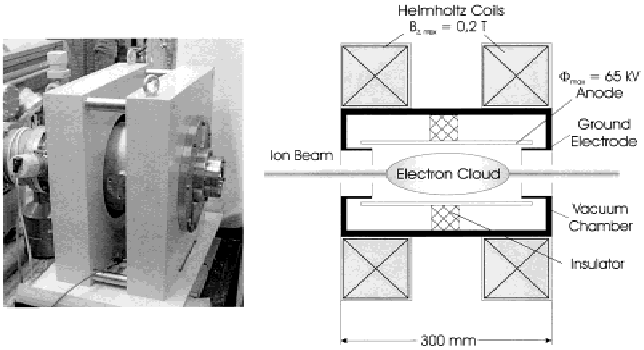

Fig. 4. Photo and scheme of the new Gabor lens at IAP.

Table 2 compares field levels of conventional lenses with the GL in case of Bi^{1+} and He^{1+} beams. The thin lens approximation was used (Wangler, 1998). In each case, the lens system has a total axial length of 0.3 m. It should be noticed that the GL enables the transport of space charge compensated beams: As mentioned above, the beam axis is kept on zero potential, while off axis, a decompensation at the lens end regions is strongly hindered by the action of the magnetic fringing fields. In contrast to GLs and to the magnetic lenses, the space charge compensation by electrons is heavily distorted in the case of electric quadrupole focusing. The comparison made in Table 2 clearly demonstrates the efficiency of Gabor lenses—even at an assumed filling factor of 0.32.

4.3. IH-type structure for beam acceleration behind the RFQ

The capabilities of H-type structures were described earlier (Ratzinger & Tiede, 1998). At beam energies up to about 5 AMeV, r.t. IH-type cavities will be preferable to any s.c. alternatives, because of their excellent shunt impedance and because of the expected higher rate of particle losses within that energy range.

The KONUS beam dynamics for 20-MHz IH-type cavities at injection energies of 60 AkeV and at 200 AkeV have now been studied in more detail (see Ratzinger & Tiede, 2002). It is clearly recognized that the needed axial length of the transversely focusing elements sets an upper limit for the beam current to be accelerated at acceptable emittance growth rates.

The development of powerful focusing elements will become a key issue. At Lawrence Livermore National Laboratory quite attractive s.c. quadrupoles are being developed at present within the induction linac approach (Faltens *et al.*, 2002). The capability of Gabor lenses to focus bunched low energy beams will be investigated experimentally (see Sect. 4.2).

5. CONCLUSIONS

Superconducting cavities for low- and medium-energy beams are under development in several laboratories. Pulsed operation of superconducting structures has been developed successfully for $\beta = 1$ structures. The concepts and principles can be applied to the pulsed operation of low- and medium-β structures. As a consequence, an RF driver linac scenario without funnel sections and operated at a higher duty factor becomes attractive: It is in combination with accumulator ring schemes filling the longitudinal phase space between linac bunches and including multiturn injection.

The GSI High Current Injector HSI has been operated successfully at the nominal field levels with A/q values ranging up to 60. The current limit of 0.25 A/q in units of milliamperes was demonstrated successfully for Ar^{1+} beams. In the case of U^{4+}, further improvements including the ion

Table 2. *Comparison of different lens systems with identical geometric and focal lengths applied on 2.5-AkeV Bi^{1+} and 110-AkeV He^{1+} beams.*

		Bi^{1+} 2.5 A·keV (HIF)		He^{1+} 110 A·keV (IAP)	
System	Focusing strength	Mag. Field [T]	Voltage [kV]	Mag. Field [T]	Voltage [kV]
Solenoid	$k = \frac{qB}{2mv}$	5.52	—	0.7	—
Elec. quad.* doublet	$k = \frac{\sqrt{V_q}}{\sqrt{V_{ex} a^2}}$	—	9.5	—	8.02
Mag. quad.* doublet	$\mathrm{k} = \frac{\sqrt{qB}}{\sqrt{mva}}$	0.9	—	0.12	—
Gabor lens*	$\mathrm{k} = \sqrt{\frac{\kappa e B^2}{8 V_{ex} m_e}}$	0.016	4.9	0.014	4.14

Each lens system has an effective length of 0.3 m and a focal length of 1 m.
*aperture $a = 0.03$ m; $L_{\mathrm{Solenoid}} = L_{\mathrm{Gabor}} = 0.3$ m; $\kappa = 0.32$ assumed filling factor of the Gabor lens; $L_{\mathrm{EQS}} = L_{\mathrm{MQS}} = 0.15$ m; $V_{\mathrm{ex}} = \mathrm{W/q}$ (beam energy divided by the electric charge).

source, LEBT, the whole linac, and down to the synchrotron injection are needed. The 36-MHz HSI has successfully demonstrated that averaged effective voltage gains of up to 8 MV/m along drift tube sections can be reached at RF frequencies as low as 36 MHz. This is again an indication that there is a rather weak dependence of maximum RF field levels from the RF frequency below 300 MHz. This is of great importance for an attractive HIF RF driver design. In a next step, the HIF specific linac development has to be focused on the design of powerful transversely focusing elements along the full energy range. IAP will investigate the Gabor lens capabilities in focusing intense low-energy d.c. and bunched beams.

ACKNOWLEDGMENT

This work was supported by BMBI (contract number: 06F134I and EU-IFMIF).

REFERENCES

Barth, W., Dahl, L., Glatz, J., Groening, L. & Richter, S. (2002). Experiences during operation with high current U^{4+} beams in the new GSI high current injector. *Proc. of the 2002 LINAC Conf.*, Gyeongju, Korea, pp. 349–351.

Campisi, I.E. (2002). State of the Art Power Couplers for Superconducting RF Cavities. *Proc. of the 2002 EPAC Conf.*, Paris, pp. 144–148.

Ciovati, G., Kneisel, Brawley, P.J., Bundy, R., Campisi, I.E., Davis, K., Macha, K., Machie, D., Mammosser, J., Morgan, S., Sundelin, R., Turlington, L., Wilson, K.M., Sekutowicz, J., Barni, D., Pagani, C., Parodi, R., Pierini, P., Matsumoto, K., Mitchell, R., Schrage, D.L., Doleans, M., Kim, S.H., Mangra, D. & Yläoijala, P. (2001). Superconducting prototype cavities for the spallation neutron source (SNS) project. *Proc. of the 2001 PAC*, Chicago, pp. 484–486.

Eichhorn, R., Ratzinger, U. & Liebermann, H. (2002). Superconducting CH-cavities for low- and medium beta ion and proton accelerators. *Proc. of the 2002 LINAC Conf.*, Gyeongju, Korea, pp. 481–483.

Faltens, A., Lietzke, A., Sabbi, G., Seidl, P., Lund, S., Manahan, B., Martovetsky, N., Gung, C., Minervini, J., Schultz, J., Myatt, L. & Meinke, R. (2002). Progress in the development of superconducting quadrupoles for heavy ion fusion. *Laser Part. Beams* **20**, 617–620.

Fortuna, G., Lombardi, A., Bassato, G., Battistella, A., Bellato, M., Bezzon, G., Bisoffi, G., Canella, S., Cavenago, M., Cervellera, F., Chiurlotto, F., Comunian, M., Cortese, R., Facco, A., Favaron, P., Moisio, M.F., Palmieri, V., Pengo, R., Pisent, A., Poggi, M., Porcellato, A.M. & Ziomi, L. (1996). The new superconducting positive ion injector for the Legnaro ALPI booster. *Proc. of the 1996 LINAC Conf.*, Geneva, pp. 125–127.

Jakob, A., Gabor, C., Klein, H., Meusel, O., Pozimski, J. & Ratzinger, U. (2002). H^--LEBT in Frankfurt. *Proc. of the 2002 EPAC Conf.*, Paris, pp. 1906–1908.

Liebermann, H., Ratzinger, U. & Vinzenz, W. (2002). Redesign of a voltage limiting gap at the GSI-HSI. *GSI Scientific Report 2002*, GSI 2003-01. Darmstadt, Germany: Gesellschaft für Schwerionenforschung.

Meusel, O., Pozimski, J., Jakob, A., Lakatos, A. & Klein, H. (2000). Low energy beam transport for heavy ions using space charge lenses. *Proc. of the 2000 EPAC Conf.*, Vienna, Austria, pp. 2258–2260.

Mobley, R.M., Gammel, G. & Maschke, A.W. (1979). Gabor lenses. *IEEE Trans. Nucl. Sci.*, **NS-26**, 3112–3114.

Ostroumov, P.N., Pardo, R.C., Zinkann, G.P., Shepard, K.W. & Nolen, J.A. (2001). Simultaneous acceleration of multiply charged ions through a superconducting linac. *Phys. Rev. Lett.* **86**, 2798–2801.

Padamsee, H. (2001). Superconducting RF-mew dorectopms/ *Proc. of the 2001 PAC Conf.* Chicago, pp. 468–472.

Ratzinger, U. (2001). Commissioning of the new GSI high current linac and HIF related RF linac aspects. *Nucl. Instrum. Methods A*, **464**, 636–645.

Ratzinger, U., Gaiser, H., Kaspar, K., Minaev, S. & Krietenstein, B. (1999). Status of the 36 MHz linac cavities for the GSI high current injector. *Proc of the 1999 PAC*, New York, pp. 3552–3554.

Ratzinger, U. & Tiede, R. (1998). Status of the HIIF RF linac study based on H-mode cavities. *Nucl. Instrum. Methods A*, **415**, 229–235.

Ratzinger, U. & Tiede, R. (2002). Low energy DTL sections for intense Bi^{1+} beams. *Laser Part. Beams* **20**, 447–450.

Sauer, A., Deitinghoff, H., Klein, H., Ratzinger, U., Tiede, R. & Eichhorn, R. (2002). Beam dynamics design of a superconducting 175 MHz CH-Linac for IFMIF. *Proc. of the 2002 EPAC Conf.*, Paris, pp. 1404–1406.

Schmierer, E.N., Chan, K.C.D., Gautier, D.C., Gioia, J.G. Haynes, W.B., Krawczyk, F.L., Lujan, R.E., Madrid, M.A., Schrage, D.L., Smith, B.G., Waynert, J. & Rusnak, B. (2001). Results of the APT RF power coupler development for superconducting linacs. *Proc. of the 2001 PAC Conf.*, Chicago, pp. 1110–1112.

Setzer, S., Weiland, T., Ratzinger, U. & Minaev, S. (2002). A chopped electron beam driver for H-type cavities. *Proc. of the 2000 LINAC Conf.*, Monterey, pp. 1001–1003.

Shepard, K.W., Kedzie, M., Delayen, J.R., Piller, C. & Porcellato, A.M. (1998). Development of niobium spoke cavities for a superconducting light-ion linac. *Proc. of the 1998 LINAC Conf.*, Chicago, pp. 956–958.

Simrock, S.N. (2002). Lorentz force compensation of pulsed SRF cavities. *Proc. of the 2002 LINAC Conf.*, Gyeongju, Korea, pp. 556–560.

Vardanyan, A., Ayvazyan, V. & Simrock, S.N. (2002). An analysis tool for RF control for superconducting cavities. *Proc. of the 2002 EPAC Conf.*, Paris, pp. 1673–1675.

Wangler, T. (1998). *Principles of RF linear accelerators*. New York: John Wiley & Sons.

Zaplatin, E., Braeutigam, M., Pop, M., Skrobucha, M. & Stassen, R. (2002). Low-beta SC H-cavity for ESS. *Proc. of the 2002 EPAC Conf.*, Paris, pp. 2300–2301.