THE NEW HIGH CURRENT ION ACCELERATOR AT GSI AND PERSPECTIVES FOR LINAC DESIGN BASED ON H-MODE CAVITIES

U. Ratzinger, GSI Darmstadt, Planckstr. 1, D-64291 Darmstadt, Germany
New address: IAP, Goethe Universität Frankfurt, Robert-Mayer-Str. 2-4, 60325 Frankfurt, Germany

Abstract

In 1999 a new High Current Injector HSI was installed to replace the Wideröe section of the Unilac. Designed for a high mass-to-charge ratio $A/q \leq 65$ it additonally provides high ion beam currents, e.g. U^{4+}-ions up to 15 mA. The new linac has an RFQ section, which is 9.4 m long and uses mini-vanes inside an IH-cavity. It is followed by a 20 m IH drift-tube linac with the KONUS beam dynamics layout as used for instance for the CERN lead injector. This concept provides rf-acceleration within lens-free drift tube sections and at a strongly reduced defocusing action of the rf-fields. For the first time this concept was tested with high beam currents at a large tune depression of $\sigma/\sigma_0 \sim 0.70$.

The application of H-mode cavities in the design of high-current proton and heavy ion linacs will be discussed on a more general base. For the energy range from 5 to 150 MeV, that is the first part of a high intensity proton machine behind the RFQ section, a new DTL concept based on Cross-Bar CH-cavities (H_{210}-mode) is proposed. This CH structure can be designed for operation at about 350 MHz in the first section and at twice the frequency in the main section. CH-designs for room temperature and for superconducting operation will be discussed, as well as a 45 MeV, 100 mA proton linac design with a total length of 8.5 m.

1 INTRODUCTION

Heavy ion beams are provided from a combination of an ECR-ion source, an RFQ and an IH-type DTL with high reliability since a couple of years at GSI and at CERN [1,2]. A new goal at GSI was envisaged in 1994: Filling of the synchrotron SIS 18 up to its space charge limit for all ions including Uranium. The original Unilac, consisting of Penning ion sources, a Wideröe DTL section up to 1.4 MeV/u and a gas stripper, followed by an Alvarez DTL up to 11.4 MeV/u, failed that goal so far by more than two orders of magnitude at mass numbers above 150. The needed beam intensities can be provided by existing ion sources for low charge states only. The strategy for the Unilac rebuilt was to increase the voltage gain of the prestripper linac by a factor of 2.5 [3, 4]. This allows for example to accelerate intense U^{4+}-beams out of MEVVA-type ion sources instead of U^{10+} from Penning sources. Assuming a 20 turn injection into the horizontal SIS phase space and two stripping processes at 1.4 MeV/u (gasjet) and 11.4 MeV/u (carbonfoil with beam sweeper) the linac has to deliver $4 \cdot 10^{10}$ U^{73+}-particles during

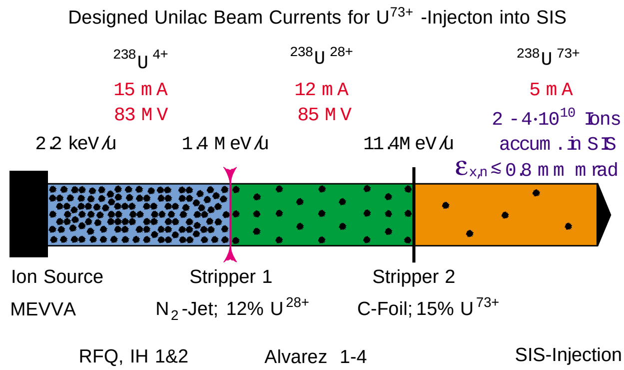

Fig. 1: Uranium injection into SIS.

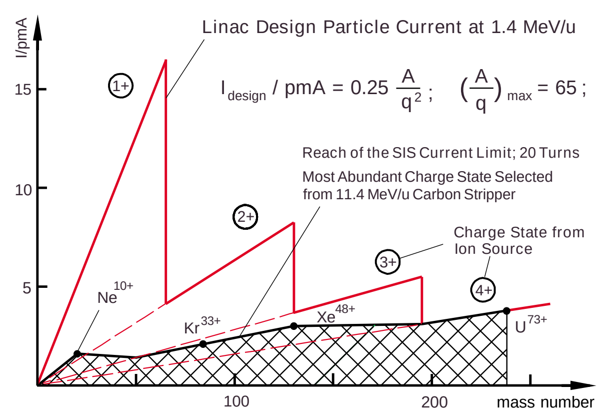

Fig. 2: Current limit of the new injector for the whole mass range and requirements for synchrotron injection (hatched region).

about 100 µs. The demanded horizontal beam emittance at synchrotron injection is $\varepsilon_{n,tr} \leq 0.8\ \pi$ mm mrad. Fig. 1 shows some key design numbers along the upgraded Unilac in case of an Uranium beam. Fig. 2 shows the current limit of the new 1.4 MeV/u linac as well as the demanded beam currents at 1.4 MeV/u with respect to maximum SIS needs. It becomes obvious that only in case of ions with charge state 4+ ($A \geq 180$) the linac has to be operated close to the current limit, while for light ions – especially up to mass 60 – there is a pronounced surplus in the beam current capabilities of the linac. The costs of the project were minimized by keeping the length of the new 91 MV linac within the length of the 34 MV Wideröe section – that means about 30 m. By choice of the IH-type DTL with an averaged effective voltage gain of 4.2 MV/m there was enough space left for the additional installation of a 9.4 m long RFQ at the front end which provides the bunch formation at 2.2 keV/u as well as an acceleration up to 120 keV/u (Fig. 3).

LORASR beam simulations showed, that the postulated beam intensities, which cause significant space charge effects, can be accelerated with high transmission and beam quality. Results from beam experiments with Ar^{1+} are in good agreement with the predictions.

The GSI High Current Injector has demonstrated, that H-type DTLs with KONUS beam dynamics are attractive high current structures. Tune depressions down to 0.70 in all three phase space planes have been demonstrated successfully.

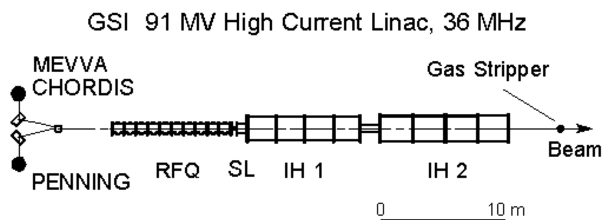

Fig. 3: General drawing of the new linac

A next goal is the technical realization of the CH-DTL (H_{210}-mode), which could become especially attractive as a link between RFQ and CCL (Coupled Cavity Linac) for future proton high current accelerators [5]. Of course it is at the same time a candidate for heavy ion acceleration up to 150 MeV/u. Room temperature as well as superconducting versions of that structure are envisaged.

2 LINAC LAYOUT

The HSI is fed by two ion source terminals, one for short high intensity pulses at low charge states (MUCIS- and MEVVA-type sources) and one for 5 ms, 50 Hz rep. rate pulses at intermediate charge states (Penning ion source), respectively [6,7]. The linac design current for short pulses (≤ 1 ms, ≤ 20 Hz rep. rate) in emA is 0.25 · A/q with A/q ranging up to 65. Operation at 30 % duty cycle is claimed for A/q-values up to 26. Switching of all linac settings between left- und right-hand terminal operation is possible on a pulse to pulse basis (20 ms).

At maximum current, the low energy beam transport depends on a space charge compensation above the 95 % level by electrons out of the residual gas. The beam is focused into the RFQ by a quadrupole quartet. A beam chopper with a rise time of about 0.6 µs is located in front of that pronounced waist. The RFQ beam dynamics was designed at IAP, Goethe-Universität Frankfurt. The PARMTEQ code was used for multiparticle simulations [8]. The development of the new IH-type RFQ-cavity and the mini-vane design were done at GSI [9].

The matching between RFQ und DTL is accomplished by a compact low aperture quadrupole doublet followed by the Superlens – a novel large aperture, 11 cell RFQ-design which allows 3-dimensional focusing into the DTL [10]. The 83 MV IH-DTL is the first high current linac which is based on the KONUS beam dynamics [11].

Tank 1 contains 3 internal quadrupole triplets and 4 accelerating sections, respectively, while tank 2 has two sections, coupled by one internal triplet. The intertank section consists of a pair of xy-steerers, a diagnostic box, and another quadrupole triplet.

A new aspect in the technical design of an IH-DTL is the integration of voluminous, lens housing drift tubes on the bottom girder. The geometry was optimized in detail and for the complete tanks by MAFIA calculations as well as by rf model measurements [12]. All cavity components were copperplated in the GSI galvanic workshop. Metal sealings (Cu und Al) are used exclusively. Without rf power the vacuum pressure is better than $2\cdot10^{-8}$ hPa in all cavities. The new linac is operated at 36 MHz, that is one third of the Alvarez frequency. This choice resulted from beam dynamics calculations (one frequency along the whole prestripper linac gives best performance under space charge conditions) and from arising cavity sizes mainly [13]. To achieve a matching into the Alvarez section at high beam current the beam transport und the charge separator behind of the gasstripper had to be rebuilt [14].

3 RF EQUIPMENT

The choice of the new Unilac frequency 36 MHz made a new design of the reference system necessary [15]. Additionally the phase and amplitude controls along the whole Unilac were rebuilt to prepare the operation with beam load including significant intensity variations. The new controls provide a bandwidth of 500 kHz to achieve this goal.

The five 200 kW amplifiers were built by Thomcast AG, Turgi, Switzerland. Three of them are used as driver units for the 2 MW end stages which were developed at GSI [16]. They are powered by the Siemens tetrode RS2074 SK. The 2 MW amplifiers are feeding the RFQ as well as IH1 and IH2. All 36 MHz power amplifiers were provided in time and show a very reliable operation. At full power the duty cycle can be as high as 5 % (50 Hz, 1 ms).

4 TUNING AND POWERING OF THE CAVITIES

The voltage distributuion along the 9,2 m long RFQ-electrodes is flat within ± 1 %. The plungers provide a frequency tuning range from - 0.2 ‰ to + 1 ‰. The IH1 cavity has a ramped voltage distribution due to the massive change in beam velocity. Within each of the 4 accelerating sections of IH1, the voltage deviation from the design value is within ± 0.5 %. Single gap voltage deviations are up to ± 4 % [17].

All cavities came on rf power after about 2 days of preconditioning, where only some 10 Watts were accepted. At voltage amplitudes above the 75 % design level dark current contributions occur at the RFQ and the Superlens mainly. IH1 shows modest dark current contributions while IH2 seems to become completely free of that effect after some more operation time. So far U^{4+}-levels can be provided reliably by the HSI.

5 HSI BEAM COMMISSIONING

RESULTS

The linac assembly and commissioning was done stepwise in the period from March to September '99. In each case a 5 m long beam diagnostics setup was installed behind the structure to be investigated. The instrumentation consisted of 4-segmented capacitive pick-up probes, beam transformers, slit-grid as well as single shot, pepper pot-structured emittance measurement devices, and of diamond detectors for bunch length detection [18]. In each step well detectable bunch signals and correct beam energies (TOF) were received immediately after first beam injection. Fig. 4 shows as an example the signals of two phase probes mounted in a well known distance from each other and connected to the oscilloscope by paths having identical delay times. This measurement was taken behind of IH2 at 1.4 MeV/u, where the pick-up signals contain 13 higher harmonics. The signal FWHM of 1.8 ns corresponds to a bunch length of 1.0 ns in this case. The measurement error in $\Delta W/W$ is around $\pm 1\cdot10^{-3}$.

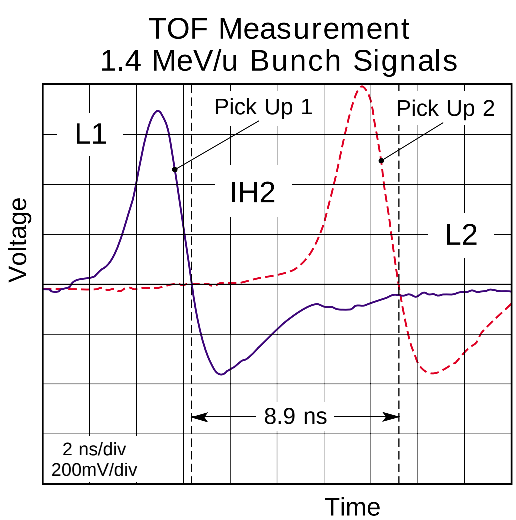

Fig. 4: Two phase probe signals for energy measurement at 1.4 MeV/u.

The transverse emittance areas along the linac were measured during different commissioning steps. For the 2.2 keV/u Ar^{1+} beam, the normalized 90 % emittance areas are around 0.3 π mm mrad at beam currents below 10 mA and correspond to the RFQ acceptance. At 20 mA $\varepsilon_{n,90\ \%} \simeq 0.45\ \pi$ mm mrad are measured in front of the quadrupole quartet which focuses into the RFQ. This explains partly, why the RFQ design output current of 10 mA Ar^{1+} was reached only at a low beam transmission value of 50 %. A reduction of the injected beam current by cutting the horizontal beam emittance with slits results in transmission values for the complete linac close to 100 %. Down to the RFQ exit the slit grid emittance device could be used (Fig. 5a). At higher beam energy and high current only single shot measurement techniques can be used. For the pepper pot based single shot device it was detected, that the divergence on the low intensity level is measured too large (about ± 2 mrad in Fig. 5b). The reasons for that effect are still under investigation. For the 7.5 mA Ar^{+} beam behind IH2 the measured 80 % emittance areas are well contained within the 90 % areas simulated by LORASR, after the systematic measuring error is subtracted.

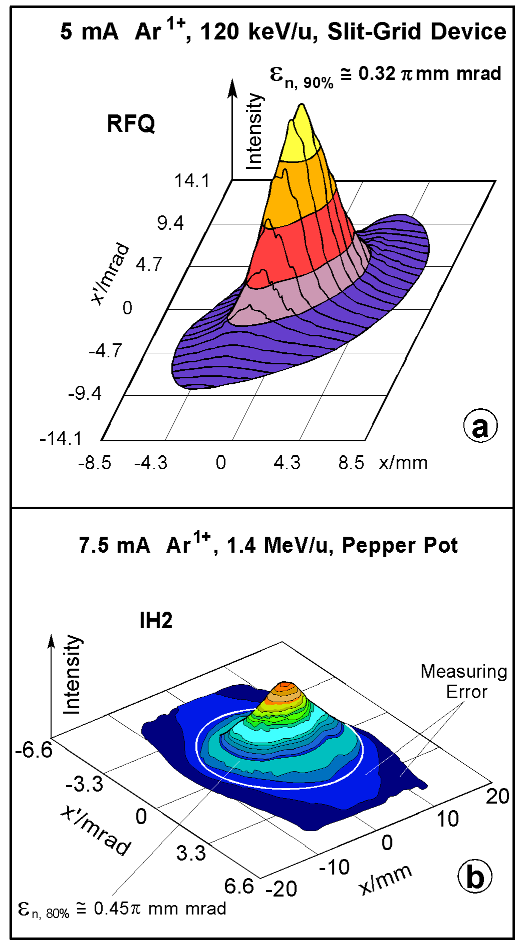

Fig. 5: Horizontal emittance measurements taken during different commissioning steps behind of the RFQ (a) and behind of IH2 (b).

A high current case for the whole linac is documented by the beam transformer signals in Fig. 6. 18 mA from the LEBT result in 9 mA behind of the RFQ and in 7.5 mA behind of the IH-DTL (8 mA Ar^{1+} at 1.4 MeV/u was the maximum so far). The LEBT relies on a space charge compensation above 95 % by electrons out of the residual gas at high beam currents and is very sensitive to electric potentials.

During the commissioning the chopper had not yet reached the optimum performance: typical beam transformer signals with rise times of around 50 µs are shown by Fig. 6. After installing screening electrodes with voltages between -1 kV and -2 kV close to both ends of the chopper and after reaching the chopper voltage design levels of up to ± 15 kV, pulse rise times of around 5 µs are reached now as shown qualitatively by the dashed curves in Fig. 6. This value is much closer to the chopper rise time of 0.6 µs. The measured curves in the same figure show the quality of the flat top as well as the conservation of the beam pulse shape along the linac. This demonstrates at the same time that the rf control loops act very well with respect to beam loading of the cavities while working close to the design current level of 10 mA Ar^{+}. A further optimization including the tuning of the control loops will follow as a next step to optimize the beam pulse shaping. The rise time defines the minimum amount of beam energy to be handled while machine parameters have to be changed or optimized. It has to be noted that the HSI beam power at 1.4 MeV/u is up to 1300 kW which can cause melting and evaporation of hit material after a few µs due to the short ion penetration depth of around 10 µm only.

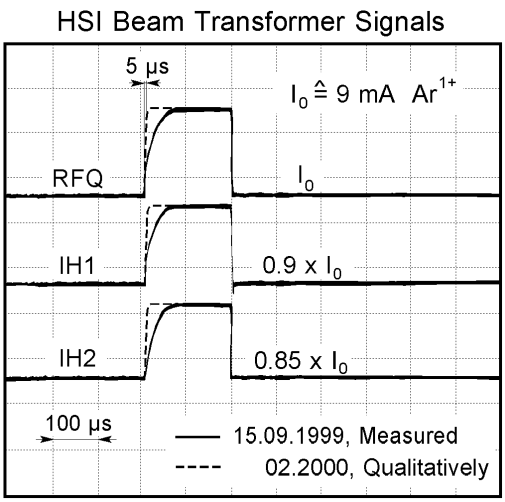

Fig. 6: Beam transformer signals along the new linac (dashed line corresponds to an improved chopper performance achieved after the commissioning).

Bunch shape measurements were done by using diamond detectors which were hit by Rutherford scattered ions out of a Au-target [19]. It was possible to verify the pronounced space charge dependent differences in the RFQ longitudinal emittance area as predicted by PARMTEQ simulations. In February 2000, U^{4+} from the MEVVA-source was accelerated successfully to 1.4 MeV/u. The beam current was 5.5 mA at injection and 3 mA at the linac exit [20].

6 CH-CAVITY DEVELOPMENT

At beam velocities $\beta \geq 0.15$ a 4 chamber H-type structure (H_{210}-mode, Fig. 7) has advantages when compared to the IH-DTL:

- At a given frequency and velocity profile the transverse cavity dimensions become significantly larger. This effect is reducing the capacitive load between cavity walls and drift tubes.
- CH-cavities for resonance frequencies up to around 700 MHz can be realized. This allows to close the velocity gap with respect to attractive structures at the low energy end of Coupled Cavity Linacs CCL.
- Combining both aspects mentioned above in a CH-cavity design, the shunt impedance can be improved by about a factor $\sqrt{2}$ relatively to the IH-structure.
- The CH-cavity exceeds by far the mechanical rigidity of IH-tanks. This opens the possibility to develop superconducting multi-cell cavities [21]. So far only 2- and 3-cell sc structures were realized for low beam velocities.

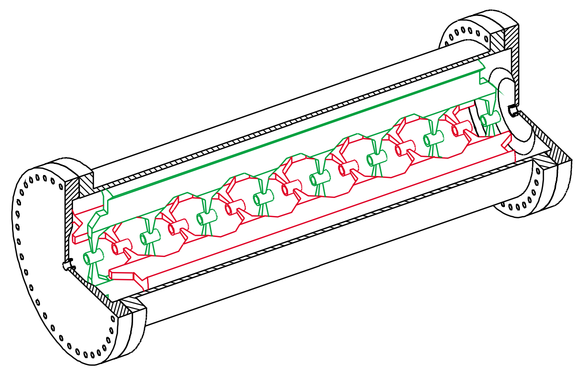

Fig. 7: 3-dim view on the CH cavity with one quarter of the outer wall removed..

With resonance frequencies at or above 300 MHz, the CH-cavites have inner diameters below 0.5 m, typical inner drift tube diameters for room temperature versions will be around 20 mm. That means the geometry is attractive for the realization of tanks with lengths ranging from 0.5 m to about 3 m. A simple analytical model for the estimation of H-cavity geometries was derived [22]. This gives a first idea of useful parameter ranges. Detailed design work has to be based on 3-dim. codes for electromagnetic field computation and/or on rf model measurements. Important is the application of the KONUS beam dynamics which results in long, lens free accelerating sections housed in individual cavities. This additionally opens the superconducting option, as the cavity internal magnetic quadrupole field can not be easily shielded well enough to avoid frozen current contributions.

7 PROTON ACCELERATION BY CH-CAVITIES

At present the main activities stimulating the further development of proton and H^{-}-linacs are: injector linacs for synchrotrons, effective production of radioisotopes, driver linacs for spallation neutron sources, for nuclear waste transmutation and for tritium production.

A CH-structure design for high current proton acceleration is discussed now. Table 1 lists the main parameters.

Table 1: Parameter list of the 433 MHz p-DTL study

Energy range /MeV	7.0 – 45.0
Total length /m	8.7
Drift tube aperture /mm	20-30
Lens aperture /mm	30
Total rf losses /MW	3.0
Current limit /mA	300
norm. input emitt. / π mm·mrad	2
long. input emitt. / π keV·ns	4.6

Fig. 8a shows the resulting compact linac. The first cavity contains an internal quadrupole triplet lens. All other lenses are installed in the intertank sections. The settings are optimized for a beam intensity of 150 mA. Emittance growth numbers and averaged phase advances along one section (between the mid planes of two neighboured triplet lenses) are shown by Fig. 8b. Only the rf voltage amplitude was varied by up to + 1.5 % at beam intensities above 150 mA, all other settings remained constant.

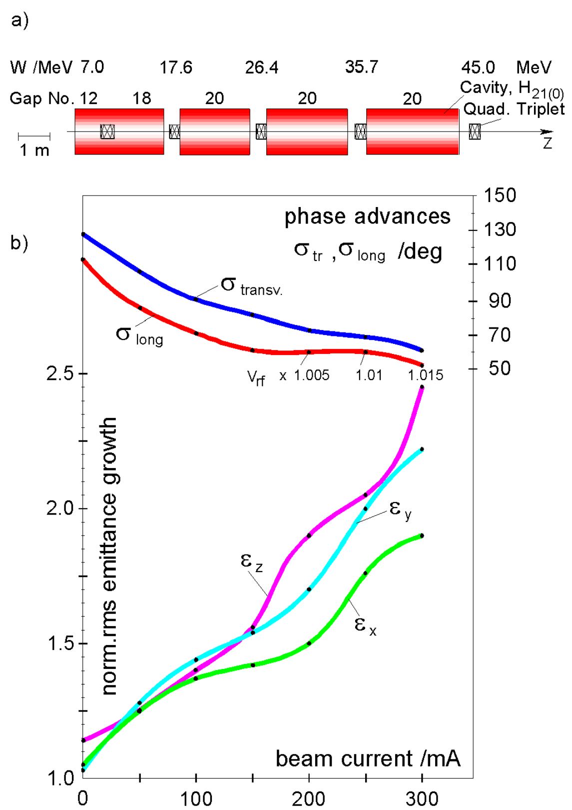

Fig. 8: Layout of a 45 MeV high current proton linac consisting of 4 CH-cavities (a) and dependance of beam dynamics parameters on beam current (b).

8 CONCLUSIONS

The new High Current Linac at GSI was commissioned successfully. A/q-values up to 60 can be provided so far. For this application, the capability of the IH-DTL to provide a high voltage gain per unit length was a great advantage. A new utilization of H-type strucures is very promising, namely the acceleration up to 150 MeV/u by CH-cavities.

Two RFQ-versions as well as two DTL-versions operated in the H_{110}- and in the H_{210}-mode, respectively, are available now and will provide attractive solutions for numerous future linac projects.

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