DEVELOPMENT OF H-MODE LINACS FOR THE FAIR PROJECT*

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Abstract

H-mode cavities offer outstanding shunt impedances at low beam energies and enable the acceleration of intense protons and ion beams. Crossed-bar H-cavities extend these properties to energies even beyond 100 MeV. Thus, the designs of the new injector linacs for FAIR, i.e. a 70 MeV, 70 mA proton driver for pbar-production and a cw intermediate mass, superconducting ion linac are based on these novel cavities. Several prototypes (normal and superconducting) have been built and successfully tested. Moreover, designs for a replacement of the 90 MV Alvarez section of the GSI - Unilac will be discussed to improve the capabilities as the future FAIR heavy ion injector.

INTRODUCTION

The scientific program of FAIR requires the construction of a new 70 MeV, 325 MHz proton injector [1] for the SIS18. This machine will provide at least 35 mA of protons at a repetition rate of 4 Hz.

Beside the new proton linac, FAIR also requires a massive upgrade of the GSI UNILAC linear accelerator [2].

The UNILAC started operation in 1975 and it is one of the eldest DTL still active. Almost 40 years of high duty factor operation (up to 25 %) led to the increasing number of failures occurred in the last years. That represents a strong reliability issue for the new FAIR facility.

Additionally, the Alvarez-DTL is equipped with DC quadrupoles, which is a disadvantage for short pulse operation and limits the machine flexibility in case of the multibeam operation (different ion beam with specific magnetic rigidities and beam currents). That constraint, together with the challenging requirements of 15 mA of U^{28+}, favours the replacement of the existing DTL section by a new high energy linac with short beam pulses at low repetition rate (HE-Linac).

The linac upgrade program will be completed by a new superconducting cw heavy-ion linac [3] with an adjustable energy from 3.5 to 7.3 AMeV for the super heavy elements program (SHE-Linac).

The choice of the RF cavity type represents the most critical key for such a massive upgrade. The experience with high current operation at the HSI and HLI led to the natural decision to base the UNILAC replacement on IH-DTL cavities. On the other hand, the successful R&D performed at the Frankfurt University on room temperature [4] and superconducting CH-DTL [5] justifies the use of that kind of structures for the new proton linac and for the cw SHE linac.

H-MODE CAVITIES

H-Mode cavities are characterized by a slim tube geometry resulting in a high shunt impedance and a uniform power loss distribution (see Fig.1). Beam dynamics is designed according to an asynchronous injection energy lattice like the KONUS [6] or the EQUUS [3]. Alternatively an APF [7] lattice can be used.

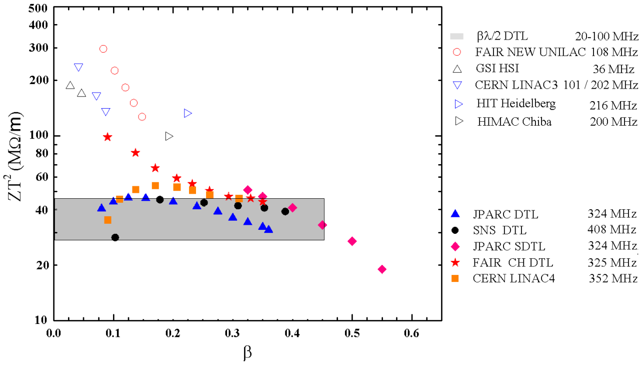

Figure 1: Effective shunt impedance of several ion and proton accelerators as function of the velocity profile.

The IH-DTL, exited in the $TE_{11(0)}$ mode is by far the most efficient RF structure in the β range from 0.01 to 0.2. For $\beta \leq 0.1$ it is competitive with superconducting structures, concerning the plug power demand, even at cw operation. Several IH-DTL are routinely in operation and this structure has established as standard solution for heavy ion in the frequency range between 30 and 200 MHz.

The CH-structure, exited in the $H_{21(0)}$ mode has a larger diameter for a given frequency compared with the IH-structure. Cavities with frequencies from 150 MHz to 3 GHz can be realized, making the CH-structure feasible for proton and ion acceleration up to 100 AMeV. Additionally, the crossbar geometry is so robust to ensure the mechanical stability required for superconducting operation. At present, the s.c CH-DTL is the only multi gap superconducting structure available at low energy.

THE CH-DTL FOR FAIR

The FAIR requirement of a dedicated proton injector pushed an intensive R&D activity in order to explore the capabilities of the room temperature CH-DTL. In 2006 a first test model was successfully built at the University of Frankfurt and later copper plated at the galvanic workshop of GSI. This 340 MHz cavity comprises eight equidistant cells of length $\beta\lambda/2$=45 mm, and was used to test all fabrication steps including welding, copper plating and designing of an efficient cooling system. Moreover, a tuning strat-

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egy based on exchangeable drift tubes was adopted, and a new geometry based on larger half drift tube was developed to tune the end cells (see Fig.2). This cavity was successfully tested with a 2 kW, cw amplifier.

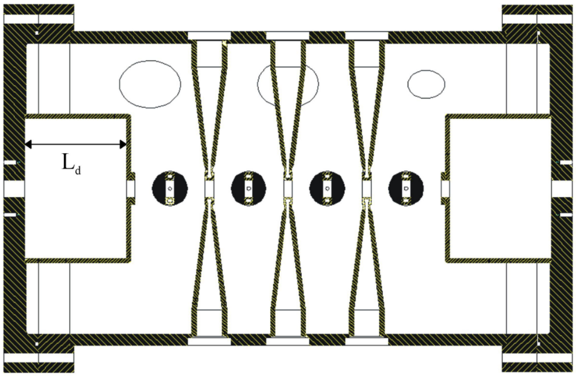

Figure 2: The geometry of the first room temperature CH-DTL.

Later on, the 3 MW 324 MHz klystron developed for JPARC opened new perspectives for the optimization of the CH-DTL. At low energy, the KONUS beam dynamics requires short sections in contrast with the high shunt impedance which favours longer cavities . To overcome this problem a coupling scheme to match one klystron to two CH sections have been developed [8].

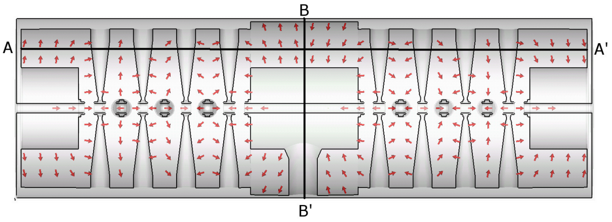

Figure 3: The electric field on the axis of a coupled CH-DTL.

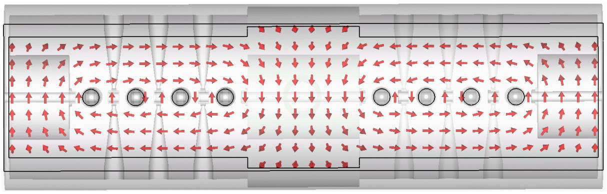

Figure 4: The magnetic field orientation inside a coupled CH. Field is shown in the plane A-A' of Fig.3.

The coupled structure consists of two CH-DTL connected through a single cell resonator. This intertank section oscillates in the Alvarez mode and the large drift tube houses an electromagnetic quadrupole triplet. The radius of the single cell resonator has to be adjusted so that the resonance frequency of this unit matches the adjacent CH cavities. RF simulations have proven that an effective coupling is achieved with this geometry. Fig. 3 and 4 show the distribution of the electric and magnetic field along the coupled structure. In particular, Fig.5 shows how the coupling cell oscillates in a TM mode like the standard DTL.

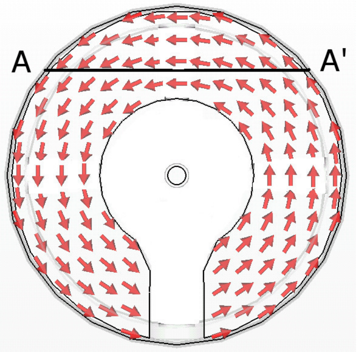

Figure 5: The magnetic field orientation inside the coupling cell. Field is shown along plane B-B' of Fig.3

Successful RF measurements on the scaled model of the second cavity of the FAIR proton injector was the milestone for the construction of the full scale prototype [9].

The main parameter of this structure are listed in Tab.1

Table 1: Main Properties of the second resonator of the FAIR Proton Linac. * indicates that calculation have been performed with a 15% reduced σ.

Energy Range (MeV)	11.7-24.4
RF frequency (MHz)	325.2
Effective Voltage (MV)	13.5
Beam Aperture (mm)	20
Magnet Aperture (mm)	30
Length (m)	2.7
RF Losses*	1.34

The cavity was delivered at the university of Frankfurt in late 2011. In a first step dummy stems and exchangeable drift tube made of Aluminum were mounted inside the cavity. Seventeen provisional tuners were installed along the structure, six in the fist CH, one in the intertank section and ten in the second CH, respectively.

First frequency measurements were in good agreement with simulations. The experimental value of 323.7 MHz is very close to the expected one of 324.4 MHz. The cavity was designed at a lower value with respect the operational frequency of 325.2 MHz to take into account the inductive effect of the tuners.

A measured field distribution along the beam axis is shown in Fig.8 while, Figs.9 and 10 compare the measured voltage with the reference one calculated with LORASR.

At present, stainless steel stems are ready for being welded inside the cavity. Copper plating will be performed in early 2013. The prototype will be then tested with a 3 MW klystron in the dedicated test bench recently built at GSI.

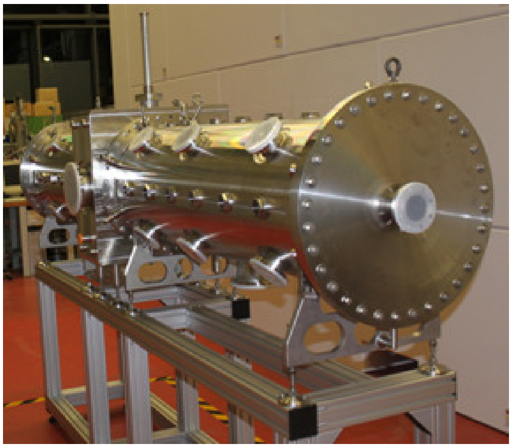

Figure 6: The second resonator of the FAIR proton linac.

Figure 7: The dummy drift tubes.

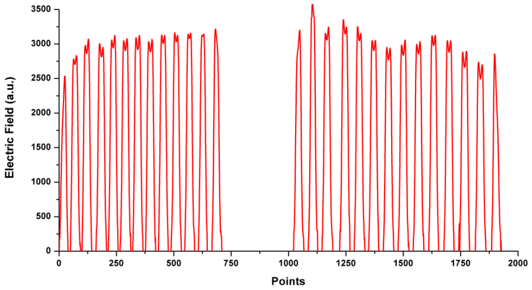

Figure 8: The measured field distribution on the axis.

The Proton Linac

The design of the FAIR proton injector is sketched in Fig.12: up to 100 mA of proton will be extracted from an ECR ion source at 95 keV. The beam is first accelerated by an RFQ to the energy of 3 MeV. After a matching section, the beam enters the first part of the drift tube linac, composed of three pairs of coupled CH-DTLs. At the energy of 37 MeV a 1.6 meter long dedicated diagnostic section is installed.

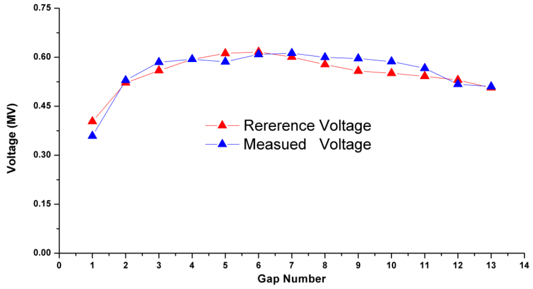

Figure 9: The voltage distribution in the first CH section.

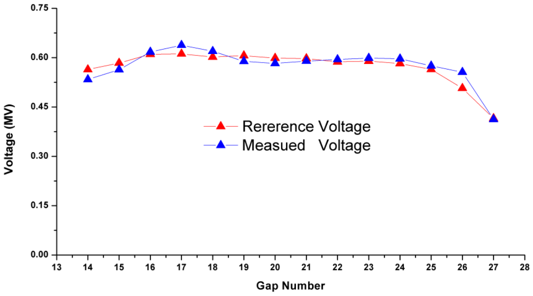

Figure 10: The voltage distribution in the second CH section.

At that energy, space charge effects are reduced and the KONUS offers the possibility to build long lens free sections. For that reason, the high energy section is based on standard lens free CH cavities with slightly larger beam aperture at each cavity ends. In this way the number of quadrupole triplets is reduced and the mechanical and RF design is simplified. Electromagnetic 3D simulations showed that three CH-DTL made of 21 gaps each could cover the energy range from 37 to 70 MeV within an rf power demand around 1 MW per individual cavity.

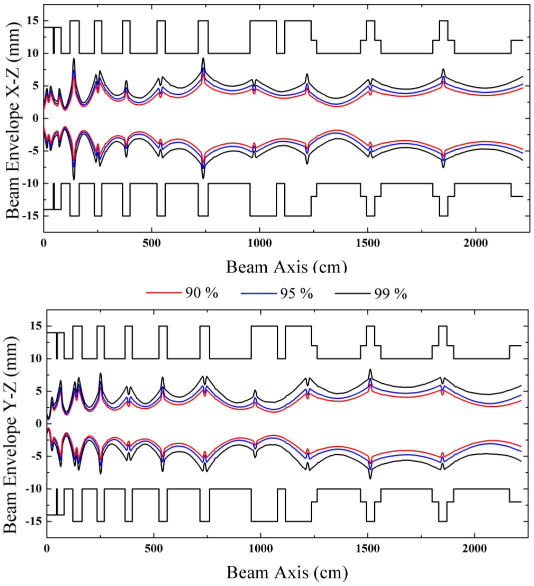

Figure 11: Beam envelope for the FAIR proton linac when 70 mA are injected in the DTL section.

The linac was designed assuming an RFQ output current ranging from 45 to 70 mA using the LORASR code. The

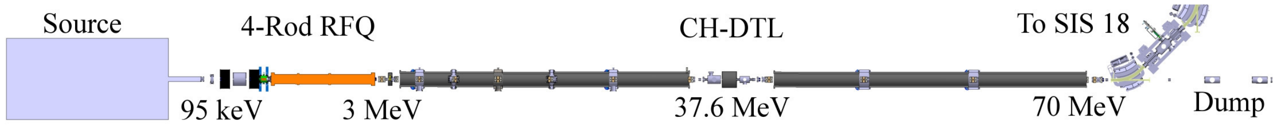

Figure 12: The schematic view of the FAIR proton linac.

Table 2: Beam Evolution of the FAIR proton injector at 70 mA

RFQ Output 95% ϵ X-X', norm. (mm mrad)	1.22
RFQ Output 95% ϵ Y-Y', norm. (mm mrad)	1.14
RFQ Output 95% ϵ ΔW-Φ (keV ns)	9.01
DTL Output 95% ϵ, norm. X-X'(mm mrad)	2.35
DTL Output 95% ϵ, norm. Y-Y' (mm mrad)	2.68
DTL Output 95% ϵ ΔW-Φ (KeV ns)	17

beam envelopes, shown in Fig.11, for the design current of 70 mA shows a large safety margin against beam losses.

Fig.13 presents the emittance including the current stated along the abscissa at the injection point. The red curve is the upper limit for the emittance that the injector, at given current, must provide. This limit is obtained from the foreseen multi-turn scenario and it depends mainly on several synchrotron parameters, such as circumference, injection energy, acceptance and filling factor. For a proper injection the linac emittance must remain below the straight line. This brilliance analysis shows that the best window for an effective injection would be around 55 mA.

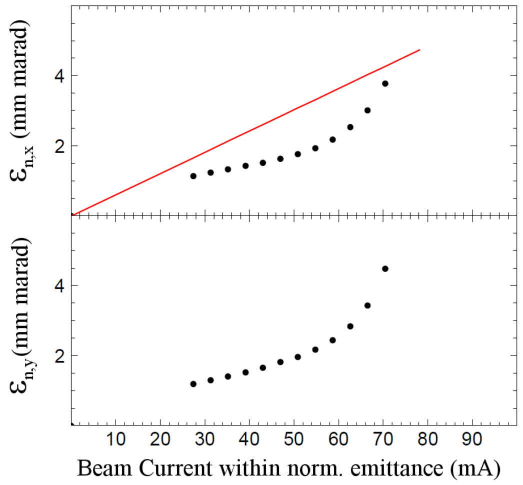

Figure 13: Brilliance analysis at the end of the proton linac in comparison with the synchrotron acceptance.

Finally, Tab.2 shows the beam evolution to the final energy of 70 MeV.

THE CW SHE LINAC

All chemical elements from 107 to 112 have been discovered at GSI.

Table 3: Main parameter of the s.c. cw SHE LINAC

A/q	6
Frequency (MHz)	217
Max. Beam Current (mA)	1
Injection Energy (AMeV)	1.4
Output Energy (AMeV)	3.5-7.3
Length (m)	13

To keep the Super Heavy Element (SHE) program at a competitive level an upgrade of the High Charge Injector (HLI) is ongoing, including a new 28 GHz ECR source and a new cw four-rod RFQ [10].At present, behind the new RFQ the existing IH-DTL injects a 1.4 AMeV beam inside the Alvarez DTL section of the UNILAC.

As the UNILAC should be operated as injector for FAIR, a strong limitation of the beam time for the SHE program is expected. To offer and adequate beam time for the nuclear chemistry program a dedicated linac is request by many scientific users. The design of a low energy cw linac would considerably profit from a multigap superconducting structure. At present, the CH-DTL is the only multigap structure which can be operated as superconducting DTL.

For that reason, a collaboration between GSI, IAP Frankfurt and HIM Mainz worked out a conceptual design based on s.c CH-DTL.

That new linac consists of nine superconducting CH-cavities operated at 217 MHz. The first three cavities accepts the beam from the HLI and perform the first stage of acceleration to 3.5 AMeV. At this point, the energy variable part begins and the final energy can be adjusted up to 7.3 AMeV within an energy spread of ± 3 AkeV. Beam focusing is provided by seven superconducting solenoids. The general parameters are listed in Table 3.

The demonstrator

The so called *Demonstrator* project includes the construction of the first s.c CH cavity with the s.c. solenois at the cavity ends, and the assembly of the components in the cryostat. A full performance beam test is foreseen at the HLI within 2014 at earliest [11].

The s.c. 217 MHz CH-structure [12] consists of 15 equidistant gaps for a gradient of 5.1 MV/m. The structure, shown in Fig.14, has inner total length is 0.69 m. Optimized field distribution is shown in Fig.15

Nine static tuners, one slow and two fast bellow tuners, will be mounted to ensure the proper frequency matching.

Further rf, mechanical and multipacting simulations are

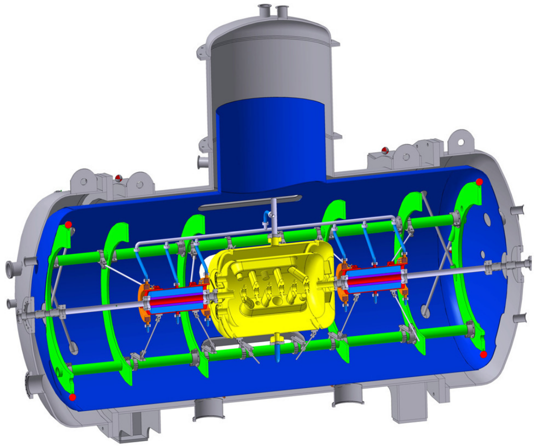

Figure 14: The demonstrator project.

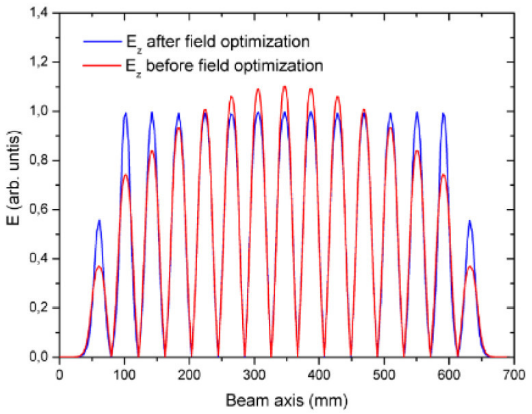

Figure 15: Field distribution of the demonstrator CH-DTL.

in progress at the moment to determine the final geometry of the dynamic bellow tuners.

THE HE LINAC

A new High Energy Linac (HE-LINAC) is presently under discussion at GSI. This new machine has to replace the 90 MV DTL section of the UNILAC.

A first proposal [13] was to increase the prestripper energy to 3 AMeV with 3 IH-DTL. The higher energy would allow generation of U^{37+} which would be further accelerated to 11 AMeV by another 4 IH-DTL.

Recently a less ambitious solution, consisting in the replacement of the Alvarez DTL, is under investigation. Six IH cavities would cover the energy up to 11.4 AMeV in approximatly 25 meter including a new matching section behind the charge separator.

This solution is more cost effective compared to the previous one, and will leave plenty of space available for a future linac upgrade. At the energy of 11.4 the frequency can be raised to 325 MHz and CH cavities could be used to increase the energy. Additionally, alternative solutions to the present gas stripper, like a C-foil or a plasma stripper are under investigation in order to generate higher charge states.

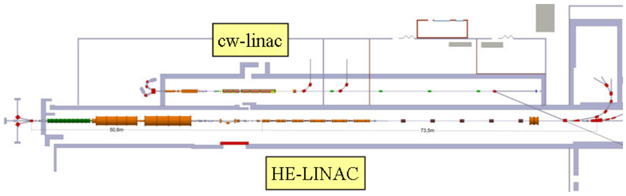

Figure 16: The proposed upgrade of the UNILAC insludig the new HE and SHE linac.

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