A 70-MEV PROTON LINAC FOR THE FAIR FACILITY BASED ON CH – CAVITIES*

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Abstract

Future ion accelerators for fundamental and for applied research will need a significant improvement in injector capabilities. While the pulsed acceleration of intense proton beams has a long tradition, a reduction of linac faults as well as an increase in beam transmission, stability and brilliance is needed for new facilities.

The international FAIR facility at GSI Darmstadt will include a antiproton research program. The needed intensities can be provided only by adding a high current proton injector to the existing synchrotron SIS 18. This injector is designed for 70 MeV end energy at a current limit of 70 mA. A 350 MHz, 3 MeV RFQ will inject into the 350 MHz CH – DTL, which will accelerate the protons to 70 MeV within about 22 m. 6 commercial 3 MW klystrons will feed the CH-DTL. Each RF amplifier drives one resonator consisting of two CH-modules coupled by a short central coupling module. This concept led to a significant cost reduction for RF equipment and accelerator fabrication. One coupled cavity structure is under design and will be fabricated and RF power tested within the next two years.

At the same time superconducting CH-cavity development is progressing at IAP Frankfurt. First tests with a 19 cell cavity from bulk Nb were quite successful. This development will allow to shift the transition energy from r.t. to s.c. RF structures significantly further down towards the low energy end for future linacs operated at high duty factors.

INTRODUCTION

The general layout of the FAIR 70 MeV proton injector and the status are described in ref. [1] within these proceedings. Beam injection into the synchrotron SIS 18 via multiturn injection through an electrostatic septum is practised since many years for intense ion beams. Using the same techniques for proton beams excludes the application of H^- - injection. There was a discussion about the optimum number of injected turns. The 15 turn beam injection as practised for heavy ions tends to show increased capture losses during the last turns. So it was decided to foresee some intensity reserves for the proton injector: While 35 mA, 36 µs long pulses will suffice to fill SIS 18 up to the space charge limit by a 15 turn injection, a linac design current of 70 mA was chosen.

A 100 mA proton source (ECR-type or Duoplasmatron) will inject at 95 keV into a 350 MHz, 3 MeV RFQ (4-rod or 4-window-type alternatively, to be decided during this year). After a 0.6 m long matching section the beam will be accelerated up to 70 MeV by a 350 MHz DTL.

There is a long experience at GSI with the UNILAC-DTL consisting of a 36 MHz, 80 MV IH-DTL (H_{110}-mode), a 108 MHz, 10 MV IH-DTL and a 108 MHz, 85 MV Alvarez-DTL. It was decided to aim on an H-type linac for the new FAIR proton injector: at a given RF frequency this structure is cost efficient, robust and compact in its transverse and longitudinal dimensions.

The CH-type drift tube structure and its integration into the H-type linac family are described in ref. [2]. At beam energies up to 100 AMeV the CH-DTL promises to be a good choice. The cross bar structure with stems crossing the cavity along the tank diameter at a sequential rotation of the stem direction by 90 deg is mechanically quite robust and easy to cool by water. In fact this geometry allows also the realization of multi cell superconducting (s.c.) cavities. This development at IAP in Frankfurt is described in the last chapter.

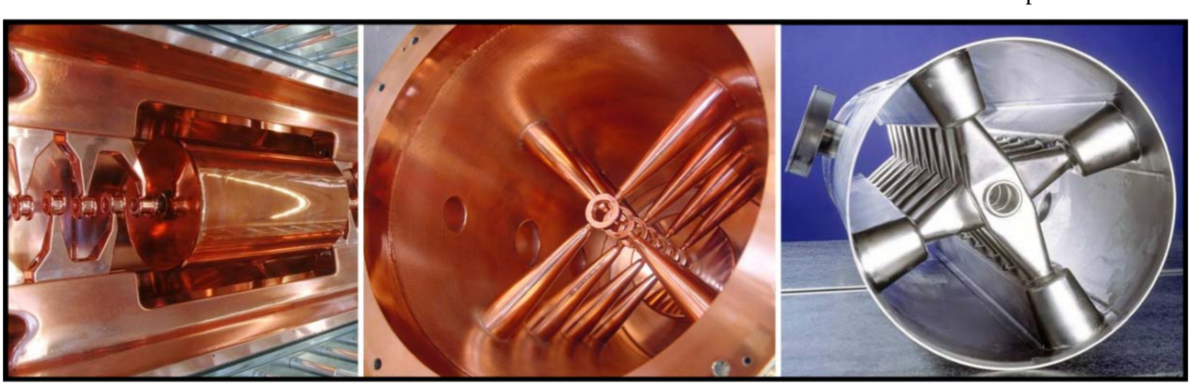

Figure 1: The family of H-mode DTLs. From left to right: r.t. IH, r.t. CH and bulk Nb s.c. CH-cavity.

*Work supported by BMBF (contr. no. 06F134I), GSI and the EU (CARE, cont. no. RII3-CT-2003-506395)

Besides careful beam dynamics investigations with the LORASR-code [3], a big progress was made by developing RF coupled CH-cavities which can be fed by one power klystron. This technique allows to match available amplifier power classes efficiently to the linac. The coupling cell layout is very robust and can contain a magnetic lens within the corresponding drift tube. The RF coupling as well as the mechanical concept are explained.

Finally, results from measurements of the s.c. 19 cell prototype CH-cavity and envisaged next steps are described.

LORASR CODE DEVELOPMENT

For the beam dynamics design of the 70 MeV FAIR proton injector DTL the LORASR code is used. It provides the single particle tracking along drift tube sections, quadrupole lenses, short RFQ sections including fringe fields and dipole magnets.

The code can treat all kinds of drift tube structures (e.g. Alvarez-type DTL based on FODO lattices), but it is specialized on the beam dynamics design of Separate Function DTL's based on the 'Combined Zero Degree Structure (KONUS)' beam dynamics concept.

Recent code developments are focused on the implementation of a new PIC 3D FFT space charge routine, allowing for time-efficient simulations with up to 10^6 macro particles routinely, as well as of tools for error studies and loss profile investigations.

The new LORASR space charge solver takes advantage of the speed of the FFT algorithm, reducing the number of arithmetic operations from the order N^2 to the order $N \bullet \log_2 N$. Presently an algorithm using closed boundary conditions (Dirichlet cond. for the potential at the surface of a rectangular pipe, up to 128 x 128 x 128 grid points, up to 1 million macro particles) is implemented.

The performance of the new algorithm has been systematically investigated. From theory [4] the following dependence of the processing time T on the particle number N_P and on the grid number N_G is expected:

$$T = T_1 + T_2 = C_1 \cdot N_P + C_2 \cdot N_G \cdot \log_2 N_G \quad (1)$$

This dependence has been checked by LORASR runs using $N_P = 10^3$; 10^4; 10^5; 5×10^5 and 10^6 for 3 different grid numbers (N_G = 32^3; 64^3 and 128^3; respectively). In fig. 2 the results from LORASR simulations are shown. These are in perfect agreement with the predictions as defined by eq. (1). The coefficients C_1 and C_2 were determined by fits on the simulation data. It turns out that C_1 has nearly the same value for the 3 different grid point numbers (see Table 1). Thus the processing time is linearly depending on the particle number $T_1 = C_1 \cdot N_P$, with an additional, constant value T_2 depending on N_G. T_2 scales as follows for different grid numbers:

$$T_{2,32} = T_{2,128} \cdot \frac{32^3 \cdot \log_2(32^3)}{128^3 \cdot \log_2(128^3)} \quad (2)$$

Table 1: Resulting parameters of the LORASR code performance test, see eq. 1

	32^3-grid	**64^3-grid**	**128^3-grid**
C_1	8.13×10^{-6} s	8.11×10^{-6} s	8.02×10^{-6} s
C_2	5.41×10^{-8} s	8.06×10^{-8} s	10.97×10^{-8} s
T_2	0.009 s	0.127 s	1.611 s

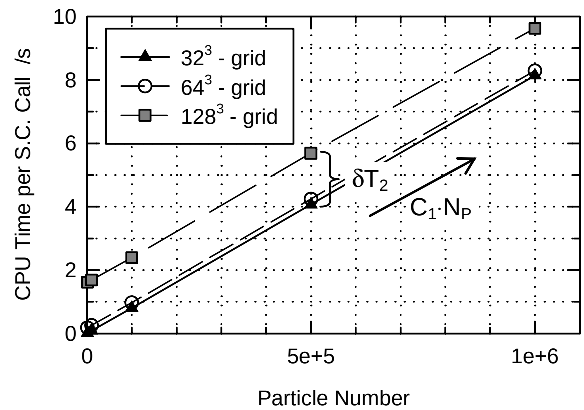

Figure 2: Performance test of the new LORASR 3D FFT space charge solver: Calculated processing times for single space charge calls on a PC with a 3 GHz CPU.

According to the results shown in fig. 2 and Table 1, an adaptive fitting of the mesh point number is the right solution, as it is already implemented in LORASR: a 32^3 grid is used for $N_p \leq 10^4$, 64^3 for $N_p \leq 10^5$ and 128^3 for $N_p \leq 10^6$, respectively.

Due to the efficiency of the new s.c. routine, validation runs with 10^6 macro particles are now routinely available in LORASR, resulting in total CPU times below 4 hours on a modern PC with a 3 GHz CPU for the given GSI Proton Linac example (≈ 1000 s.c. calls in total).

The LORASR code was successfully validated within the European 'HIPPI' Project activities [5]: The new space charge routine was tested within the Poisson solver benchmarking programme, showing good agreement with the results from other codes like 'IMPACT', 'HALODYN', 'DYNAMION' and 'TOUTATIS'. Additionally a tracking comparison was performed on the 1.4 – 11.4 AMeV GSI UNILAC Alvarez DTL, where apart from the codes already mentioned also 'PARMILA', 'PATH' and 'PARTRAN' were included. The level of agreement between the results is encouraging. As a consequence, we consider LORASR as an authorized tool for future DTL beam dynamics designs.

MATCHING SECTION RFQ - CH-DTL

Main components are a xy-steerer at the RFQ exit followed by a quadrupole singlet and a diagnostic box with current transformer and phase probe. It was shown that a 2 gap rebuncher with RF voltage amplitudes of 190 kV is the best choice. A 4-gap rebuncher would take too much space and by this would cause emittance growth. Finally, a quadrupole triplet will match the beam well into the acceptance of the CH-linac. The layout as well as the beam envelopes along the matching section are shown by fig. 3. The rms emittance growth rates in all three phase space planes are kept well below 10%, depending on the details of the chosen RFQ exit distribution. This is true for 100% of simulated beam particles reaching the RFQ exit. The missing part is not within the specified longitudinal phase space area and will be lost. Detailed loss studies along the linac with the LORASR code will be started soon.

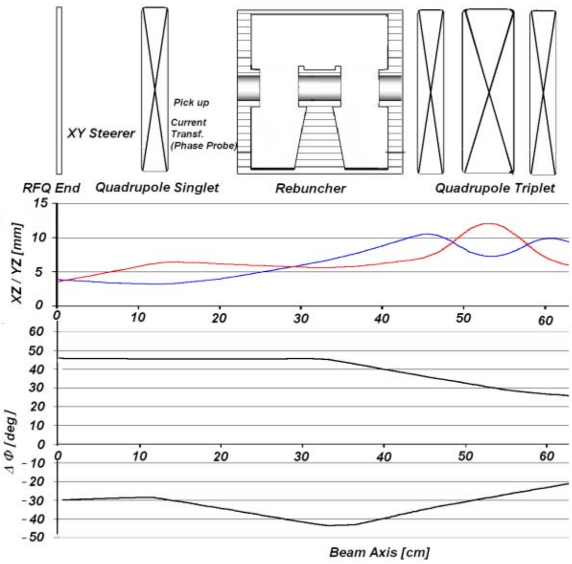

Figure 3: Matching section between RFQ and CH-DTL.

BEAM DYNAMICS ALONG THE CH-DTL

The KONUS ('Combined Zero Degree Structure') beam dynamics is used and imbedded in a quadrupole triplet channel with FDF 0 DFD 0 polarity grouping. After 6 accelerator sections there will be an extended drift to house beam diagnostics devices like profile monitors, current transformer and phase probes. After 6 more sections the end energy is reached. Two neighboured drift tube sections are RF coupled like shown in figs. 4 and 5. By this technique the needed drift space around the quadrupole triplet lens is minimized. By coupling two CH-modules in that way the distance between the gap centres in front and behind of the coupling drift tube is fixed by the beam dynamics to lengths of about ($N \times \beta\lambda - 0.1\ \beta\lambda$) due to the synchronous RF phases of 0° and -35°, respectively. The resulting design values for the p-linac are N_1 = 3, $N_{2\text{-}6}$ = 2. As the length conditions become quite relaxed towards the high energy end, alternative solutions will be investigated for the last 3 resonators (see below).

The envelopes resulting from a 100000 particle run with a realistic input particle distribution from RFQ-PARMTEQ simulations are shown in fig. 4. One can see that aperture radii of 10 mm along the accelerator structure and of 15 mm along the lenses are quite convenient. At the present layout magnetic field gradients are ranging up to 65 T/m.

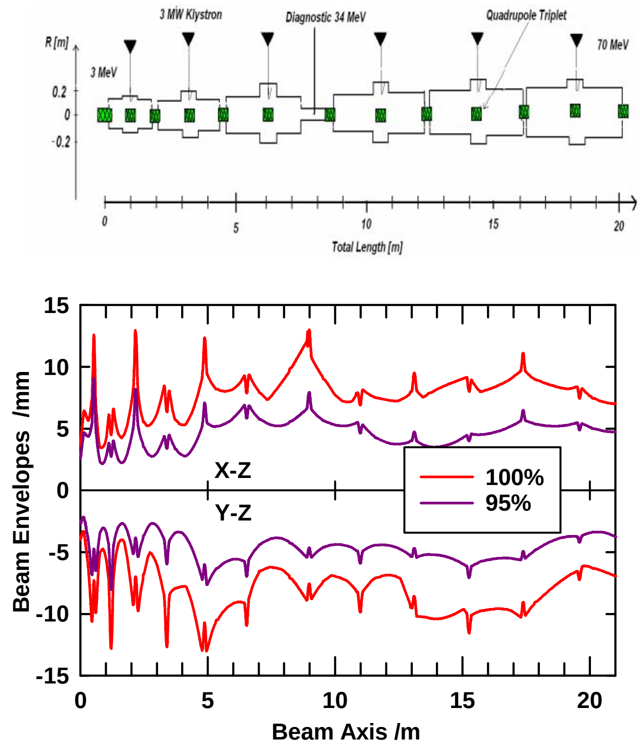

Figure 4: The GSI 3-70 MeV, 70 mA Proton Linac DTL calculated with a simulated RFQ output distribution (100000 particles in total).

COUPLED CH-CAVITY

4-Vane-RFQ's are operated in the H_{210}-mode like CH-cavities and are using vane undercuts for resonant end tuning [6]. One main difference between both resonators is the capacitive load per unit length which is higher by factors 4-6, typically for RFQ's. Resonant end tuning for CH-cavities is possible by half drift tubes with adequate length and diameter [7], mounted at the end walls. The field distribution and geometry at the CH-cavity ends are then similar to reentrant cavities.

By putting two CH-cavities of that type together and by replacing the inner endwalls by a radial stem, one is approaching the coupled CH-cavity geometry as proposed in this article for the first time. Taking the coupling tank diameter as well as the drift tube outer diameter as variables one finally gets resonant coupling of both CH-cavities. The field distributions in the coupling cell were investigated by MWS field simulations and are shown in Fig. 6. The large coupling drift tube is capable to house a magnetic quadrupole triplet and/or diagnostics instrumentation as well as a water cooled beam collimator. A robust radial stem is well suited for tube adjustment. Moreover, it allows comfortable access to feed all installations within the coupling tube.

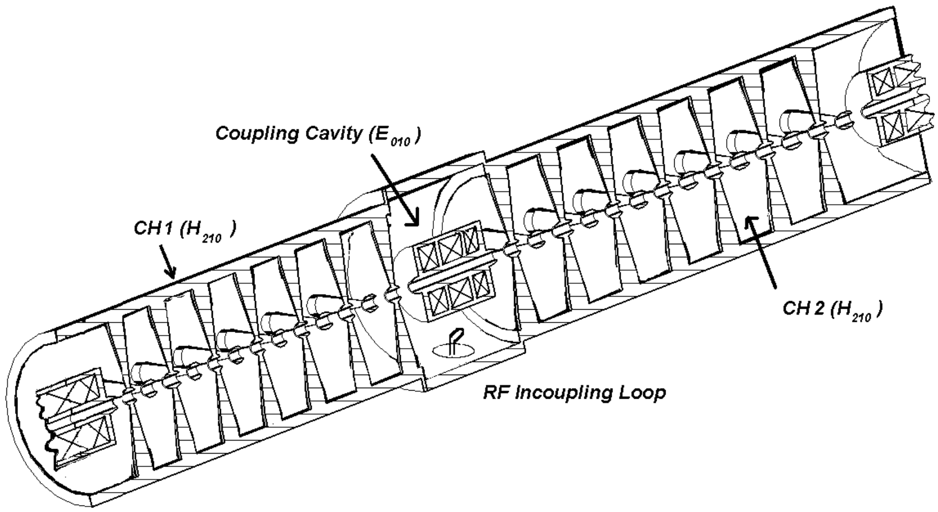

Figure 5: The coupled CH-cavity. Detailed view on resonator 2 from fig. 4.

There is a long experience with this kind of tube installations in IH-cavities [8]. While the RF situation in IH-cavities is quite different from the CH coupling cell, the mechanical concept can be partly adapted. Fig.5 shows resonator no. 2 of the 70 MeV p-linac. After investigation on a 1:2 scaled RF model this resonator will be built at the IAP and RF power tested at GSI within the next two years.

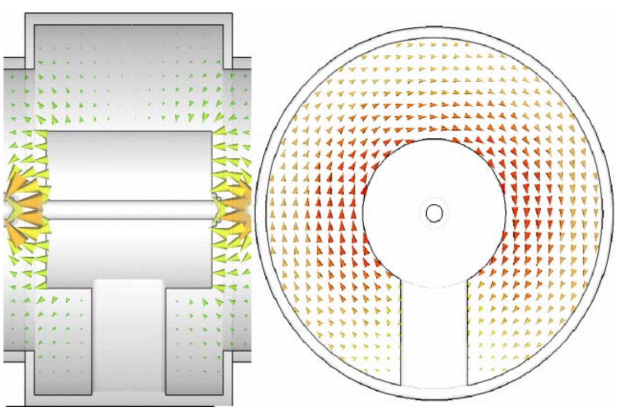

Figure 6: Coupling section between CH cavities with electric field distribution (left, yz-plane) and magnetic flux (right, xy-plane).

COUPLED CAVITY CH-DTL

It turned out from the beam dynamics design of the FAIR p-injector that voltage gains of 3-6 MeV along 10 to 16 gaps can be achieved between neighboured quadrupole triplet lenses. Assuming a beam current of 70 MeV and an effective shunt impedance ranging from 100 down to 45 MΩ/m this results in total RF power needs below 1 MW per individual CH cavity. On the other hand there are klystrons of the 3 MW class avaible which would allow quite cost saving solutions if an optimum matching to the linac could be achieved.

By coupling two CH modules with a coupling cell along the beam axis as described in the previous chapter it became possible to match the power needs of this coupled cavity system to the avaible 3 MW klystrons. The first three resonators of that type will accelerate the beam up to 34 MeV within a length of 8.2 m. After passing a 0.6 m long drift needed for diagnostics and a quadrupole triplet, 3 more coupled cavities will accelerate the beam up to 70 MeV. In this design the 21 m long CH-DTL will contain 12 triplet lenses (see Fig. 4).

Alternatively, the beam dynamics allows for longer lens free sections along the high energy part of this linac. As the drifts through the coupling cell when corresponding to (2 - 0.1) βλ are getting quite long it will be checked in a further optimisation step whether long, simple CH-cavities could be an alternative. The total number of quadrupole triplets would be reduced to 9 only in that case, at slightly increased apertures along the high energy section.

THE SUPERCONDUCTING CH-STRUCTURE

Several future projects (EUROTRANS, IFMIF, RIA, …) will require high duty cycles or even cw operation. Superconducting solutions seem to be favourable above a certain duty cycle because of higher reliability and lower operational costs when compared to room temperature linacs. If energy variability is not an issue as in driver accelerators with a fixed velocity profile it is advantageous to use multi-cell cavities which can increase the real estate gradient significantly while the total number of cavities with their support systems is reduced significantly. Although many types of superconducting cavities have been developed in the past there was still a lack of efficient cavities in the low energy regime whereas efficient means a large energy gain per cavity. The development of efficient superconducting DTL front ends with high real estate gradients have motivated the design, construction and test of the superconducting CH-structure (see fig. 7).

A 19-cell, β=0.1 CH-prototype cavity has been built at ACCEL Company *) and cold tests at IAP have started in July 2005. The cavity has a length of 105 cm and a diameter of 28 cm. The cavity has been fabricated from 2 mm thick bulk niobium sheets (RRR=250). After fabrication and surface treatment several tests have been performed in the new cryogenic rf laboratory in Frankfurt [9]. Figure 8 shows the measured unloaded Q versus the effective accelerating gradient E_a. The gradient is based on the βλ-definition.

Figure 7: The Superconducting CH-cavity, β=0.1, f=360 MHz.

The maximum gradient which has been achieved so far was 4.6 MV/m. This corresponds to an effective accelerating voltage (including T=0.8) of 3.8 MV. The electric peak field was 25 MV/m and the magnetic peak field was 26 mT, respectively. The Q-value at low field level was 5.7E8 which gives a total surface resistance of 96 nΩ. The residual resistance is 43 nΩ.

The development of a mechanical tuner has started. Presently the cavity is being prepared for cryogenic tests in a horizontal cryostat.

At higher field levels (E_p>20 MV/m) strong field emission has been observed. Depending on a detailed analysis of x-ray profile measurements performed during July 2006, the cavity will undergo an additional surface preparation.

OUTLOOK

H-mode structures are used routinely now at low beam energies (4 vane-RFQ and IH-DTL, respectively). It is intended to make use of the advantages given by H-mode structures at beam energies up to around 100 AMeV in future, by the development of r.t. and s.c. CH-DTL's. The FAIR project is well suited to push this program.

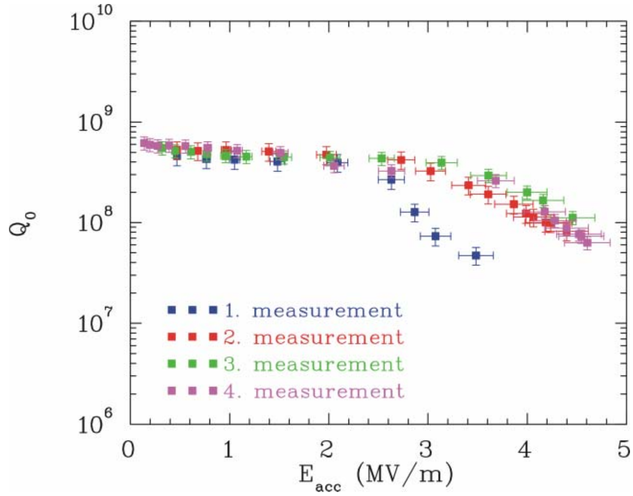

Figure 8: Measured unloaded Q-value versus the effective accelerating gradient.

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