DEVELOPMENT OF THE SUPERCONDUCTING CH-CAVITY AND APPLICATIONS TO PROTON AND ION ACCELERATION

H. Podlech, A. Bechtold, M. Busch, H. Klein, H. Liebermann, U. Ratzinger
Institut für Angewandte Physik (IAP), University of Frankfurt, Germany

Abstract

The Crossbar-H-mode (CH)-structure which has been developed at the IAP in Frankfurt is a multi-cell drift tube structure for the efficient acceleration of low and medium energy protons and ions [1, 2]. A superconducting CH-cavity with 19 cells (f=360 MHz, β=0.1) has been built and tested successfully (see fig. 1) [2, 3]. After the localization of a field emission site an additional surface treatment has been performed. Recent tests showed a significant increase in performance. A gradient of 7 MV/m in cw operation has been reached, corresponding to an effective voltage gain of 5.6 MV in that cavity. This shows that high real estate gradients can be achieved in superconducting low energy mulit-cell cavities. Several projects like IFMIF or EUROTRANS/ADS with fixed velocity profile driver linacs could profit from this development.

INTRODUCTION

The CH-cavity is operated in the H_{21}-mode and belongs to the family of H-mode cavities like the IH drift tube cavity and the 4-vane RFQ. Due to the mechanical rigidity of the CH-cavity room temperature (r.t.) as well as superconducting (s.c.) versions can be realized [1, 2]. For example, the new 70 MeV, 70 mA proton injector for the FAIR project will consist of 6 r.t. CH-cavities operated at 325 MHz with a low duty cycle [4]. For higher duty cycles or even cw operation superconducting solutions become more favourable because of a lower plug power consumption and higher achievable gradients. In many cases the rf linac efficiency can be increased significantly by the use of multi-cell cavities. For instance, in case of actual projects involving proton and light ion driver linacs with rf frequencies between 175 and 350 MHz there is an obvious lack of efficient superconducting low-β cavities. In these cases efficient means a high energy gain per cavity which leads to a low total number of individual cavities and rf systems. Due to the rf frequency and to the RFQ voltage gain which is typically between 1 MV and 5 MV the cell length $\beta\lambda/2$ is around 40 mm at the superconducting DTL front end. Using conventional superconducting 2-gap cavities reduces the filling factor significantly as cavities with a small number of cells imply a lot of drift spaces. The required higher number of components increase the complexity of the linac significantly which can have a strong impact on the system reliability.

The realization of long multi-cell cavities in the low and medium energy range requires a special beam dynamics (KONUS) to reduce the transverse RF defocusing [5]. The linac is separated into several KONUS-periods. Each period consists of a few rebuncher gaps operated at negative synchronous phase (-25° to -35°) followed by the main accelerating section (0°). The KONUS-period ends with a transverse focusing element like a quadrupole triplet or a solenoid. This accelerating scheme has been demonstrated with beam very successfully at several laboratories around the world [6, 7]. The KONUS dynamics is also capable to accelerate high current beams [5]. Room temperature H-mode cavities with up to 54 gaps have been built and put into routine operation successfully [8].

CAVITY DEVELOPMENT

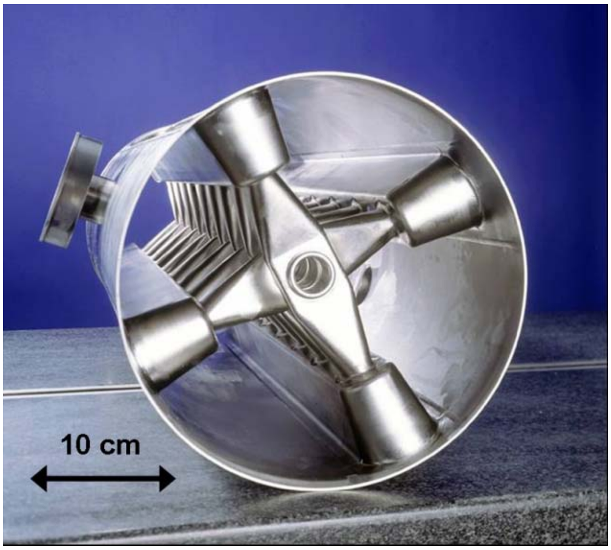

Figure 1: Superconducting CH-prototype cavity with 19 accelerating cells, β=0.1, f=360 MHz (ACCEL GmbH).

The superconducting CH-prototype cavity has been optimized using MicrowaveStudio [9]. One main focus during the design of the cavity was the creation of a flat electric field distribution along the beam axis. The voltage U_i in the i^{th} gap can be derived from the induction law:

$$U_i = -\dot{\Phi} = -\int_{\text{quad}} \dot{B}_z \, dA \tag{1}$$

The integration has to be done over one quadrant. Without end cells the resulting sinoidal dependence of the longitudinal magnetic field in z-direction leads directly to a sinoidal electric gap field and voltage distribution, respectively. The electric field could be enhanced by using an end-cell geometry with longer half drift tubes. This decreases the resonance frequency of the end-cells. Figure 2 shows the electric field distribution for different lengths of the end cell. In the upper part a constant gap to cell length ratio (g/L) of 0.5 has been used, in the lower part optimized and variable g/L ratios have been used. An important feature of the superconducting CH-structure are the girders. Girder can help to optimize the electric field distribution as shown in figure 3. The electric field is plotted along the beam axis for three different girder heights. The field quality is improved with larger girders. Additionally, simulations have shown that girders can reduce the magnetic peak fields significantly. The girders are a broad common extension of the stems. This reduces the surface currents and consequently the magnetic fields. Figure 4 shows the magnetic and electric peak fields as function of the girder height. Using a girder height as in the prototype cavity the magnetic peak field can be reduced by about 30%. Table 1 summarizes the main parameters of the superconducting CH-prototype cavity.

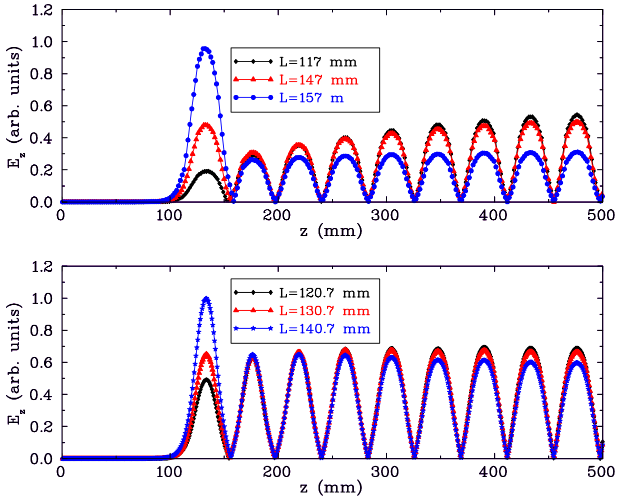

Figure 2: Top: Electric field distribution for different end cell lengths with a constant g/L-ratio of 0.5. Bottom: Electric field distribution for different end cell lengths with a variable and optimized g/L-ratio. The prototype cavity has been realized with that g/L-ratio.

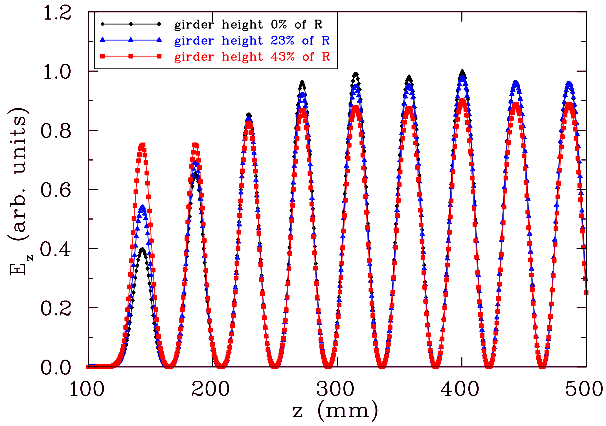

Figure 3: Electric field along the beam axis using different girder heights. A larger girder enhances the field flatness.

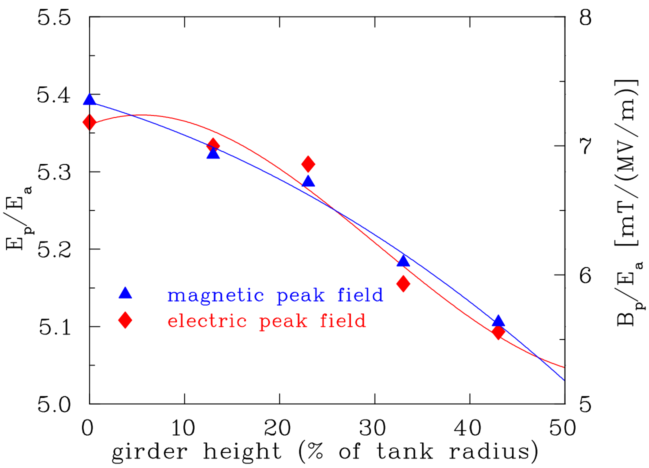

Figure 4: Electric and magnetic peak fields as function of the girder height. The magnetic peak field can be reduced by about 30%.

Cavity type	Crossbar-H-mode
β	0.1
Frequency (MHz)	360
Accelerating cells	19
Material	bulk niobium
RRR	250
Total length (mm)	1048
Diameter (mm)	274
G (Ω)	56
Q_0 (BCS)	$1.3 \cdot 10^9$
R_a/Q_0 (Ω)	3180
R_a/Q_0 per cell (Ω)	167
GR_a/Q_0 (kΩ^2)	178
E_p/E_a $\beta\lambda$-def.	5.2
B_p/E_a $\beta\lambda$-def. [mT/(MV/m)]	5.7
E_p/E_a total length	6.6
B_p/E_a tot. length [mT/(MV/m)]	7.3
W/E_a [mJ/(MV/m)^2]	92 ($\beta\lambda$-def.)
E_a exp. (MV/m)	7
U_a exp. (MV)	5.6
E_p exp. (MV/m)	36
Q_0 exp. low level	$6.8 \cdot 10^8$

Table 1: Parameters of the superconducting CH-protoype cavity.

TEST RESULTS

Several cryogenic tests have been performed since 2005 in Frankfurt. Before the second surface treatment gradients of 4.7 MV/m have been achieved [2, 3]. This corresponds to electric peak field of 25 MV/m. Above peak fields of 20 MV/m strong field emission ocurred. A detailed analysis of the X-ray distribution have been performed to localize a possible emission site. 30 X-ray TLD-detectors (Thermoluminescence Dosimeter) have been placed along the cavity to measure the dose. Figure 5 shows the measured dose along the cavity. The measurement showed a very strong radiation level close to the cavity center which indicates a single field emitter [2]. It has been decided to send the cavity to ACCEL for an additional Buffered Chemical Polishing (BCP) and High Pressure Rinsing (HPR). The cavity then has been tested in September 2007. Figure 6 shows the cavity prepared for the test. 40 TLD-detectors have been used to measure the X-ray dose. Additionally two piezos have been placed close to the end-cells to measure the mechanical spectrum at 4 K and to measure the VCO-(Voltage controlled Oscillator)-signal as response of the perturbation due to the piezo. After the surface preparation the performance of the cavity increased significantly. A gradient of 7 MV/m has been achieved. This corresponds to an effective voltage of 5.6 MV and to electric peak fields of 36 MV/m, figure 7 shows the Q_0 versus E_a-curve for different test. It shows clearly the improvement.

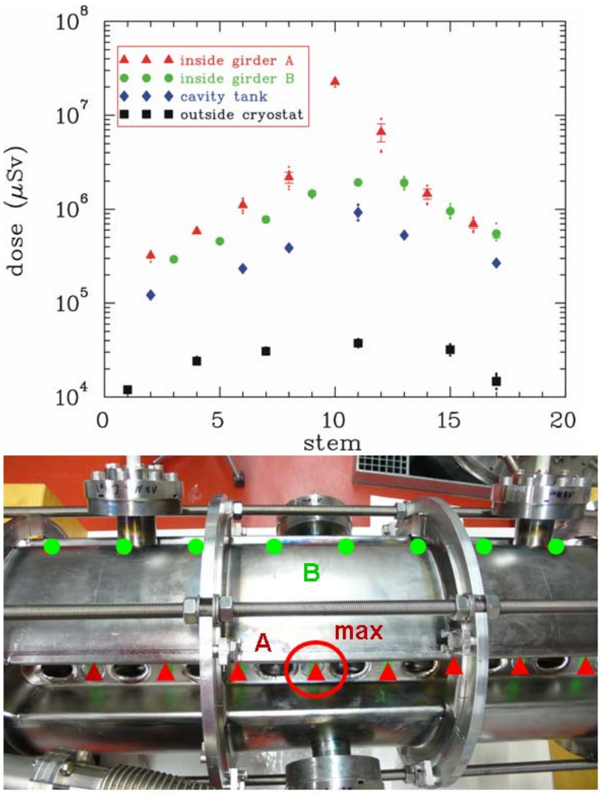

Figure 5: Top: Measured x-ray dose along the CH-cavit. Bottom: Position of the x-ray TLD-detectors inside the girders.

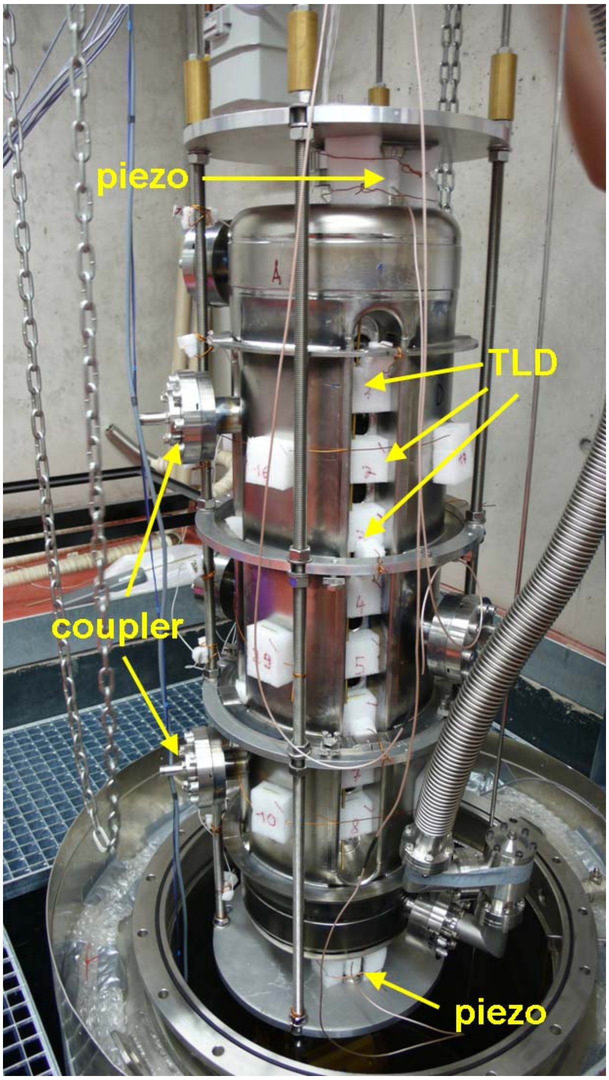

Figure 6: CH-cavity during the preparation for the last cryogenic test.

In addition, two piezos have been placed at the end cells to measure the microphonics spectrum at cryogenic temperatures. One piezo excited the cavity with a white noise signal. The other piezo acts as sensor. The signal has been transformed into a frequency spectrum with a FFT algorithm. The VCO-signal from the phase detector which measures the shift in rf resonance frequency has been measured also. Figure 8 shows the mechanical spectrum and the rf response to the perturbation. Several mechanical resonances have been found which do not influence the frequency of the cavity. The Q-value of the mechanical resonances have been measured, typical values are between 30 and 50. Additionally, the response of the phase detector signal due to a harmonic perturbation of the cavity with one piezo has been measured. Figure 9 shows the signal of the second piezo and the VCO-signal from the phase probe. It showed that the control system behaves as expected. In a next step the piezo will be driven by the VCO-signal to keep the cavity on a fixed frequency.

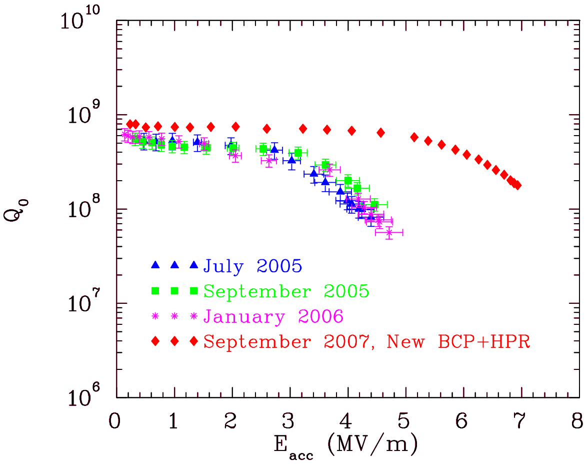

Figure 7: Measured Q-value as function of the accelerating gradient E_a. In former tests the cavity was limited to gradients of about 4.7 MV. After a surface preparation at ACCEL the performance increased significantly.

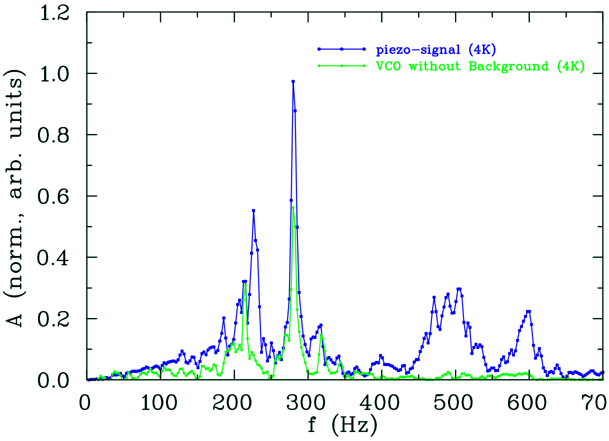

Figure 8: Mechanical mode spectrum of the CH-prototype cavity. The cavity has been mechanically excited by a piezo with a white noise. A second piezo measured the response of the cavity. The phase detector signal of the control system measured the shift in rf frequency.

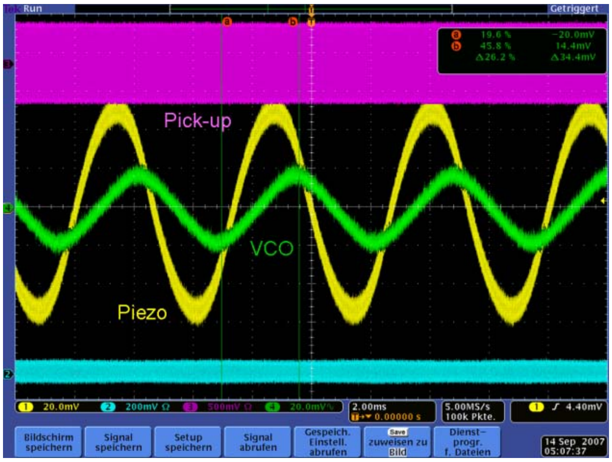

Figure 9: One piezo drives a harmonic perturbatiuon of the cavity. The VCO signal of the phase detector is proportional to the shift in resonance frequency.

EUROTRANS

For future accelerator driven systems (ADS) efficient and reliable high power proton drivers have to be developed. Within the XADS-project (eXperimental ADS) the feasibility of an ADS for nuclear waste transmutation has been studied [10]. EUROTRANS is the continuation of XADS and it has been launched by the EU in 2006. One goal of EUROTRANS is to build, to test and to assess different accelerator structures for a driver linac of an European Transmutation Demonstrator (ETD). The linac parameters are mainly inspired from the MYRRHA-project [11]. The beam current is 3.5 mA with a final proton energy of 600 MeV. The beam with a power of 2 MW will hit a spallation-target within in a sub-critical core. The most challenging feature of the transmuter driver linac is the extremely high reliability requirement. Beam trips longer than 1 s will cause severe stress in the material of the target and of the core due to thermal shocks. Therefore the number of trips with t>1 s has to be limited to about 10 per year for an ETD. In case of a future industrial transmuter with a beam power of 25 MW (25 mA, 1 GeV) the number of beam trips should not exceed 3 per year. Beam trips will most likely be caused in the low and intermediate energy part of the linac. At higher energies (i.e. several 10 MeV) the failure of a cavity or magnet will not cause a beam trip: It is planned to raise the field and to re-adjust the phases in the cavities neighbouring a failing cavity. But even using redundancy with respect to power supplies, control systems and amplifiers it seems to be questionable to fulfil the reliability requirements for the low energy part. Therefore a possibility is to use two identical injectors up to a certain energy, which may be 17 MeV or higher. Injector 1 delivers the beam while injector 2 is on-line and ready to deliver the beam in case of a failure in injector 1.Due to the required cw operation the main part of the linac will be superconducting. In the design which has been proposed by IAP the beam will be delivered by an ECR source followed by a 352 MHz 4-vane RFQ with a final energy of 3 MeV. A r.t CH-structure accelerated the beam to 5 MeV. The energy range between 5 and 17 MeV could be covered by 4 superconducting 352 MHz CH-cavities. The energy gain in each cavity is typically 3 MeV. For transverse focusing s.c. solenoids are foreseen between the cavities. The total length of the superconducting CH-linac is about 6 m. The average beam load in case of the ETD is between 7.5 and 12 kW per cavity depending on the beam current. A detailed beam dynamics study has been performed. It shows an excellent beam quality and a very moderate emittance growth of 10% in the whole CH-linac. Table 2 summarizes some parameters of the CH-cavities for EUROTRANS. Figure 10 shows the schematic layout of the EUROTRANS driver accelerator.

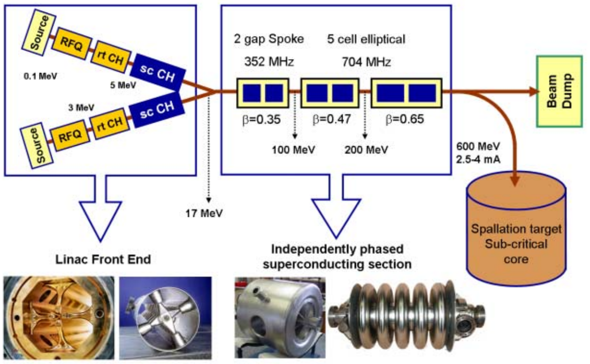

Figure 10: Present reference design of the EUROTRANS driver linac. Due to reliability reasons two injectors with an energy of 17 MeV are foreseen. Each injector consists of an ECR source, a 4-vane RFQ, a r.t. CH-cavity and 4 s.c. CH-cavities.

cavity type	r.t. & s.c. CH-DTL
Particles	protons
Beam current (mA)	2.5-4.0
Duty cycle	100%
Frequency (MHz)	352
RFQ energy (MeV)	3
r.t. CH energy (MeV)	3-5
E_a r.t. CH (MV/m)	2.7
s.c. CH-energy (MeV)	5-17
No. of sc CH-cavities	4
E_a s.c. CH (MV/m)	4
Electric peak fields s.c. (MV/m)	< 22
Magnetic peak fields s.c. (mT)	< 25
RF losses per s.c. cavity (W)	< 25

Table 2: Design parameters of the CH-injector for EUROTRANS.

IFMIF

Future fusion reactors using the D-T-reaction need inner walls which can stand very high fluxes of fast neutrons of up to 14 MeV. This is especially true for the first wall of the vacuum chamber. A certain fraction of this flux will be absorbed in the material causing displacements of lattice atoms. This will result in a fatigue of the used material. To extend the lifetime and to limit the activation damages of the first wall it is necessary to find new alloys with sufficient robustness against neutron radiation. Presently there is not any high flux source of fast neutrons which can probe the conditions in future reactors. The International Fusion Material Irradiation Facility IFMIF which is under design will provide the neutron flux needed to develop new reactor materials [12].

cavity type	s.c. CH-DTL
β	0.1-0.2
Frequency (MHz)	175
No. of sc CH-cavities	8
No. of couplers per cavity	2
Frequency (MHz)	175
Beam current (mA)	125
Duty cycle	100%
Electric peak fields (MV/m)	< 22
Magnetic peak fields (mT)	< 30
RF losses per s.c. cavity (W)	< 30
Aperture diameter (mm)	50-80

Table 3: Design Parameters of the superconducting IFMIF-CH cavities.

The neutrons will be produced from a 40 MeV Deuteron beam hitting a liquid lithium target. The total required beam current is 250 mA in cw operation delivered by two linacs in parallel operation. The beam power is 10 MW. The loss rate along the accelerator must be very low, in the order of 1 W/m to avoid activation and to guarantee hands-on-maintenance. The front-end of each IFMIF accelerator will consist of an ECR-source injecting into a 175 MHz 4-vane-RFQ. The reference design of the DTL is an Alvarez-type accelerator. The IAP Frankfurt has proposed an alternative DTL concept using room temperature and superconducting CH-structures. Within this concept the beam will be accelerated after the RFQ from 2.5 AMeV to 4.7 AMeV by a 175 MHz r.t. IH-structure. A following chain of s.c. CH-structures accelerates the beam to the final energy of 20 AMeV. The superconducting part of the linac consists of 4 cavity doublets each corresponding to one KONUS period. One main advantage of the superconducting option are significantly higher accelerating fields, as the limiting cooling power aspect is not valid here. Additionally, larger apertures of up to 8 cm diameter become possible which gives an additional safety margin against particle losses. A third surplus is the significant saving in electricity costs. The rf power for the two Alvarez type linacs is estimated to 4.1 MW without beam loading. Assuming an amplifier efficiency of 60% the required plug power due to Ohmic losses in the DTL is 6.2 MW. The two r.t. IH-cavities need 240 kW rf power and 400 kW plug power, respectively. A conservative estimation for the rf power in one superconducting cavity is 30 W and addtional 30 W of static losses. Both s.c. linacs require then less than 1 kW at 4.5 K. The plug power is typically 300 times higher because of the efficiency of the cryogenic system. The total plug power for two CH-linacs is about 0.7 MW. Assuming 8000 hours of operation time per year a s.c. solution could save 44 million kWh per year. The accelerating gradient in the superconducting linac will be 4 MV/m. This results in moderate electric peak fields of about 22 MV/m and in magnetic peak fields below 35 mT. Figure 11 shows a possible superconducting CH-linac for IFMIF. Because of the high beam current and because of the large energy gain the beam loading per cavity is about between 450 and 500 kW. Therefore two power couplers per cavity are foreseen. Table 3 summarizes the parameters of the superconducting CH-linac for IFMIF. Concerning the focusing scheme there are different options. One possibility is the use of quadrupole triplets which leads already to a good beam quality. Presently an IFMIF layout is being optimized using s.c. solenoids. Because solenois can be built more compact than triplets it is expected that the beam dynamics is easier compared with quadrupoles. Figure 12 and 13 show a possible test setup to test a superconducting CH-structure during the IFMIF-EVEDA phase under realistic conditions with full beam current.

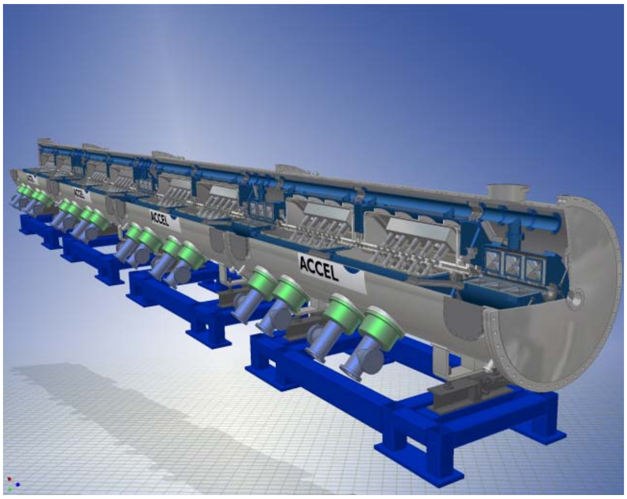

Figure 11: Design study of a superconducting CH-linac for IFMIF.

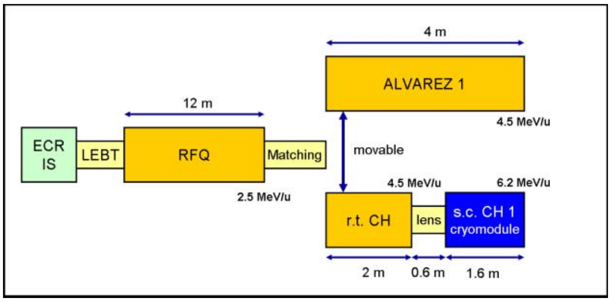

Figure 12: Possible test setup to test different design options of the drift tube linac.

SUMMARY AND OUTLOOK

The superconducting CH-cavity is the first low energy multi-cell structure which has been developed and tested. After detection of an emission site and a following chemical treatment a high gradient of 7 MV/m has been achieved. This corresponds to an effective voltage of 5.6 MV, the highest value ever reached in a s.c. low energy cavity. The optimization of the cavity geometry with respect to high power applications as EUROTRANS and IFMIF has already started. A room temperature model is under fabrication. In a next step the prototype cavity will be tested in a horizontal cryostat with a slow and a fast piezo tuner.

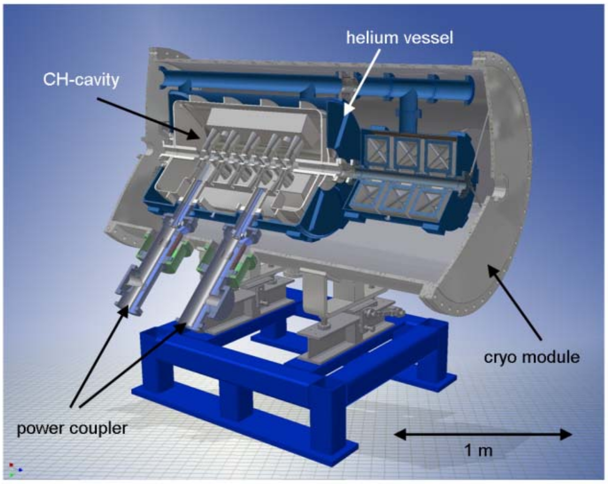

Figure 13: Cryo module with one s.c. CH-cavity equipped with two power couplers. This figure shows a quadropole triplet for transverse focusing. A scheme using superconducting solenoids is presently under investigation.

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