Development, construction and testing of a room temperature CH-DTL

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Abstract

The CH-DTL is a novel structure operated in the $H_{21(0)}$ mode which shows a large potential for ion acceleration between 5 and 150 AMeV. In order to demonstrate the feasibility of this kind of cavities in terms of construction, alignment, cooling and copper plating, IAP started an intensive R&D campaign which has resulted in the construction of an eight cells model which can also stand high RF power. This paper describes in detail the construction strategy and, finally, presents the results of the RF test performed with a 2kW, cw amplifier.

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Introduction: the Proton Injector for FAIR

A significant part of the experimental program at FAIR [1] is dedicated to antiproton physics which requires of up to $7 \cdot 10^{10}$ cooled pbar/h. Taking into account the pbar production and cooling rate, this is equivalent to a primary beam of $2 \cdot 10^{16}$ protons/h which has to be provided by a dedicated proton linac and by the two synchrotrons SIS18 and SIS100 (Fig. 1).

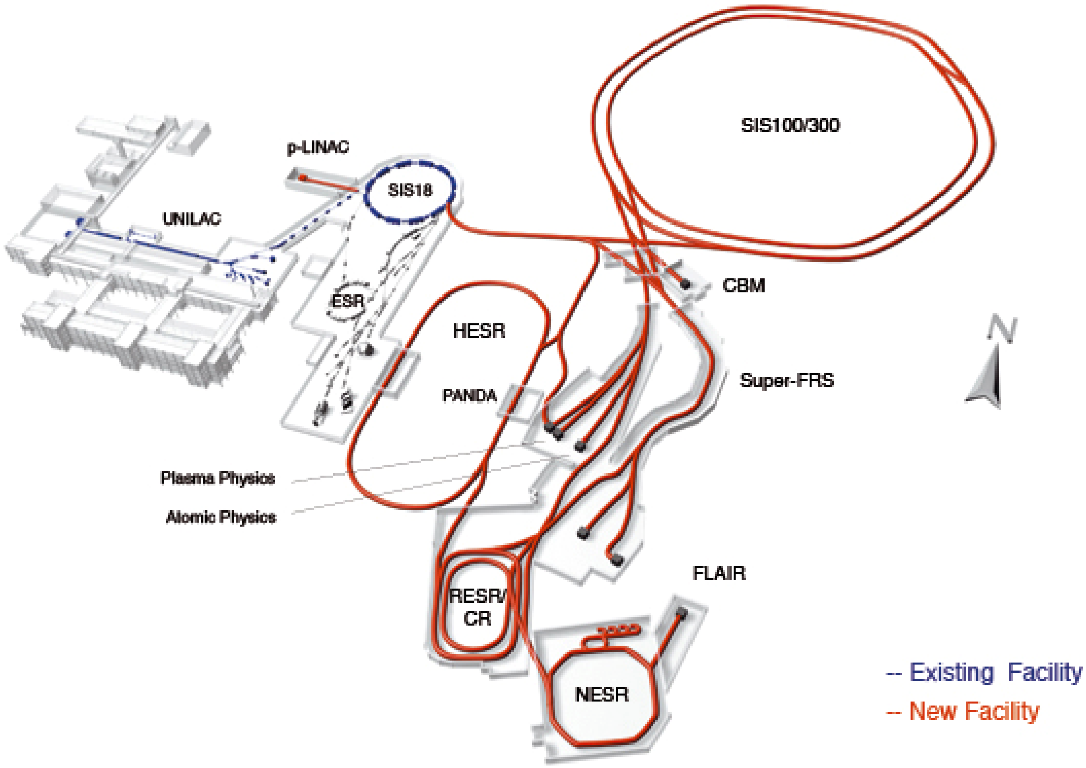

Fig.1: Layout of the FAIR Project showing the existing GSI and the proposed ion and antiproton research facility.

This new linac injector has to provide 70 MeV proton beams with a final current and emittance determined by the acceptance and by the injection scheme into SIS18. Finally, it was decided to apply a 10 turn injection at a beam current of 70 mA with a transversal emittance less than 7 π mm-mrad. In this way the space charge limit of the SIS18 is reached while the added beam emittance sums up to about half of the synchrotron's acceptance (150 π mm-mrad).

Initially, it was decided to operate the new proton injector at a frequency of 352 MHz because of the avaibility of the 1.1 MW LEP Klystrons and, because the LEDA project in Los Alamos had successfully demonstrated the proton acceleration at beam currents up to 100 mA with a 350 MHz linac (see e.g. [10]).

Nevertheless, after the LINAC 06 Conference it was decided to operate the machine at 325 MHz for the following reason:

- The market offers a great avaibility of 325 MHz, 2.5 MW amplifiers, which are well suited for p-linacs.
- Using 6 Klystrons at 2.2 MW instead of 12 at 1.1 results in considerable cost savings
- Most of the recent worldwide projects are based on this frequency (JPARC, ISIS, KAERI, FNAL P-Driver, BSNS)
- 325.244 is exactly three times the operational frequency of the 108 MHz UNILAC which most probably will be updated in end energy within the next years.

- Construction of 4-rod RFQ's gets easier at lower frequencies.

Finally, as discussed later in this paper, the avaibility of more than 2 MW from a single RF amplifier has pushed to develop a coupled structure to match the linac with those power supplies.

1. The H-Mode Family and the main features of the CH-DTL

H-type cavities are characterized by the direction of the RF magnetic field which is oriented parallel and antiparallel with respect to the beam axis. Closed field loops are provided by connecting field lines with opposite orientation at the cavity ends. At present RFQ and DTL versions exist for the H_{110}-mode as well as for the H_{210}-mode (Fig. 2).

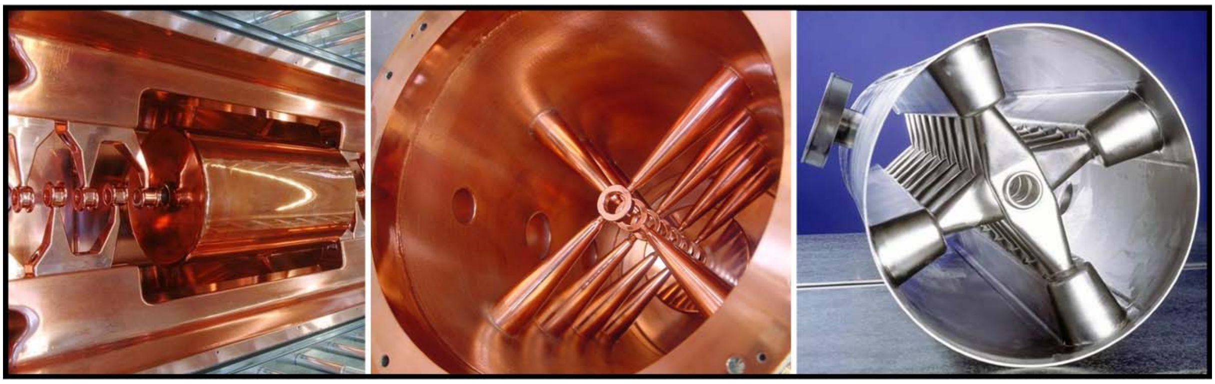

Fig.2: The Family of H-Mode DTL. On the left the IH, in the middle the cooper plated room temperature CH, and, on the right, the bulk niobium prototype for the superconducting CH.

The Interdigital H-type drift tube structure (IH, H_{110}-mode) was mentioned as an attractive solution for proton acceleration up to 30 MeV already at the 1956 CERN Symposium by J.P. Blewett [2]. Important improvements and innovations were achieved during the design phase of many H-linac projects [3-9], including the RFQ development from the early beginnings. H-type cavities are characterized by a high capacitive load contribution of the accelerating electrodes, which are providing the longitudinal electric field components for beam acceleration. To minimize the electric capacitance for H-DTL's, the beam dynamics KONUS was developed which allows the design of lens free multi gap sections followed by quadrupoles triplet. The thin drift tubes have a small ratio between the outer and inner diameter (less than 1.4) to reduce the capacitive load. On the other hand, it was demonstrated that these geometries can stand very high RF fields in routine operation [11].

The IH has been successfully employed in many projects such as the HLI and HSI at GSI, the LINAC 3 at CERN, the ISAC at Triumph and, it will be employed as Carbon Injector in the cancer therapy projects HICAT and CNAO.

For frequencies higher than 250 MHz the IH tends to become transversally extremely small and, for this reason, cannot be employed there as a multicell structure: on the other side, due to the cross sectional geometry the CH-DTL can be operated successfully up to 700 MHz, while for frequency lower than 250 MHz, the capacitive load between the stems would drastically reduce the shunt impedance when compared with the IH-alternatives.

Moreover, CH Cavities in combination with the KONUS [6] beam dynamics show around 300 MHz and within the energy range of 3 – 70 MeV many advantages against the classical Alvarez structure based on a FODO lattice. The shunt impedance of H-mode cavities in general can be significantly improved by reducing the capacity between the drift tubes: long sections made by slim tubes without any internal focusing elements allow to reach high effective field gradients (up to 10 MV/m [12]) and to use a higher resonance frequency already at low beam energies. The transverse focusing is provided by quadruple lenses (triplets) placed at the end of every drift tube section. In this way effective shunt impedances around 100 MΩ/m can be reached in the 10 MeV energy region. All these reasons give motivation to propose the CH-DTL for the next generation of proton injectors, like requested for FAIR. Recently it was proposed at Fermilab and ANL [13] as well.

Finally, thanks to its geometry, which makes the cooling design easy together with a strong mechanical robustness, the CH can be operated in superconducting and/or continuous wave mode.

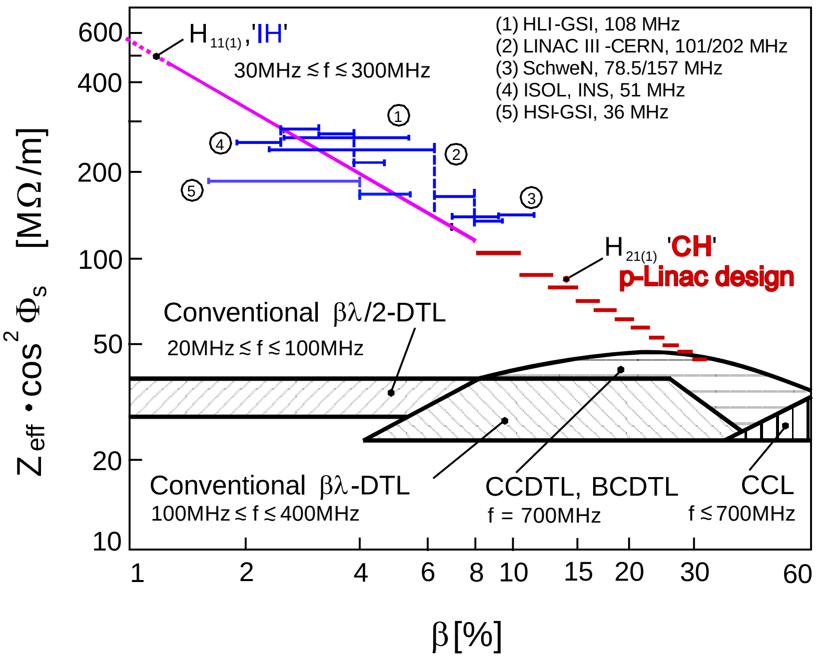

Fig.3: Effective Shunt Impedance as function of the beta profile for existing IH structures (blue lines), for conventional DTL's and for the new GSI CH-Proton Injector (red line, estimated)

2. The Mechanical Model

In order to improve the technical experience on such a new cavity a model made of 8 gaps with period βλ/2 of 45 mm was built; this corresponds to a total inner length of 60 cm which will be approximately the total length of the first tank of the GSI Proton Injector. To reduce the budget an existing stainless steel cylinder of 332 mm inner diameter was taken. Even if with this radius we will be not able to match the resonance frequency of the Proton Injector the aim of this model was to test all the fabrication steps and to find out technical solutions in order to show the feasibility of cross-bar cavities with respect to mechanical construction and copper plating. Finally, during the construction, a high power amplifier became avaible at IAP: for this reason an intensive high level RF investigation was performed on the model going much further than the original aim.

2.1 Early Design Phase

In a first step the geometry was optimized to get the higher shunt impedance: the shape of the stems was based on the existing IH cavities and adapted to the cross bar geometry. Two examples of those early geometries are shown in Fig.4 while, in Fig. 5, a technical design of the high energy side is presented.

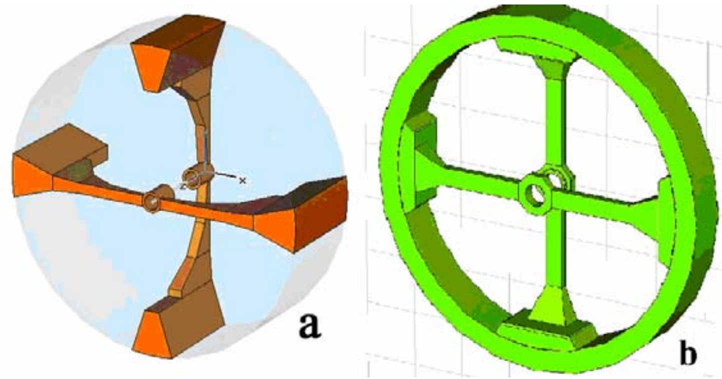

Fig.4: on the left side the first design of the proton injector: on the left, a version with simplified water cooled stem (note the central corona to cool the drift tube)

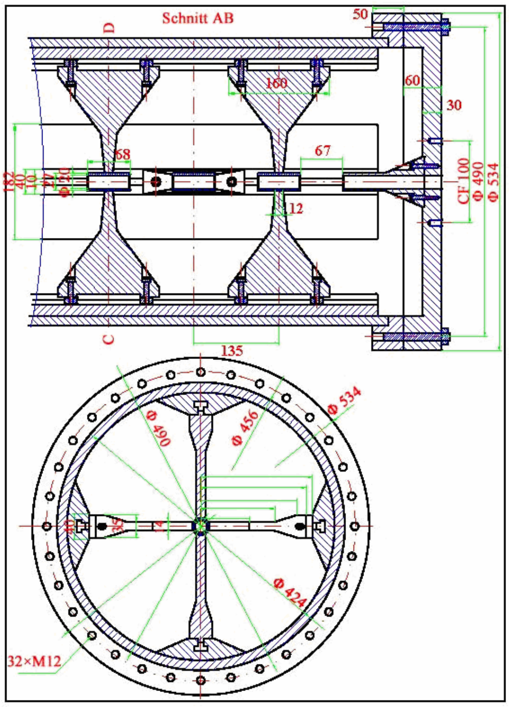

Fig. 5 :a technical drawing showing the early design of the high energy side of the proton linac

Since the beginning it was decided to build the tank in stainless steel and then to copper plate it at the GSI galvanic workshop. There are several motivations for this choice with respect to a bulk copper model: at first, the mechanical stress on copper stems tends to become very fast unbearable as the tank's radius increases with energy. On the other side the large and successfull experience in copper plating at GSI could be used resulting in a considerable cost saving.

2.2 Concept and Design of the model

With respect to the first proposed design shown in the previous section, the geometry of the cavity has been modified in order to optimise the cooling capabilities of the stems, to reduce the potential misalignment of the drift tubes and, finally, optimised end half drif tubes were developed to approximate the "zero" mode.

After several consultings with mechanical engineers the girder, which had to be used as cooling channel, was eliminated from the design: in fact, welding this long bar on the outer cylinder would have certainly distorted the external structure even if electron beam welding would have been used.

For this reason, completely new solutions have been adopted: the stems enter directly the outer cylinder and they are welded from inside; all stems are hollow and connected to an individual water source to ensure optimal cooling all across the cavity. Finally, the outer cylinder is cooled down by four independent external pipes.

Already from this short description, it emerges clearly one of the main features of this design: the number of screws inside the cavity is strongly reduced and, they are used only to fix the end flanges: in this way the RF losses inside the cavity are strongly reduced, as demonstrated in the next sections where all the components and the experimental results are illustrated.

2.2.1 The Stems

In H-Mode structure the stems carry currents to the drift tubes to create the axial electric field needed for the particles acceleration, as explained by Fig.6

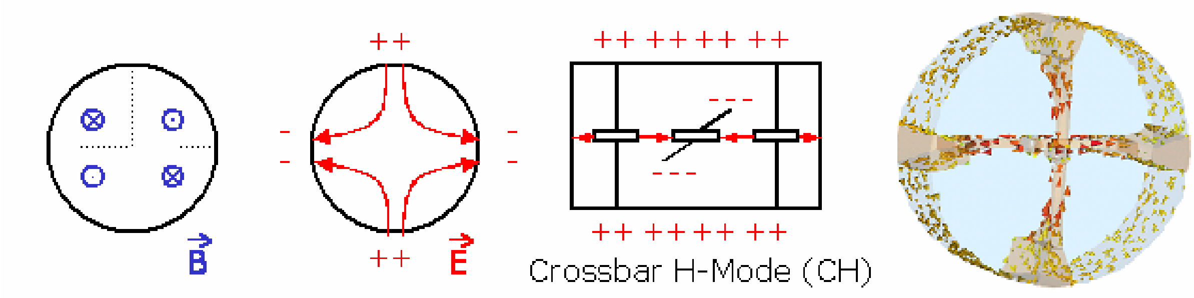

Fig.6: The $H_{21(0)}$ Mode and its application into the CH. Each stem connects the cavity walls at same potential: by orientating each stem 90° each other, the accelerating axial electric field is generated. The generated currents flow from one stem to the next across the outer cylinder.

From this picture it emerges clearly how the stems are responsible for the mechanical stability of the machine as well, and how they bear the higher current density of the whole structure: for this reason, their design must be enough robust and a water channel must be located inside them. On the other side, the stems should not be too large otherwise the shunt impedance would be reduced as a consequence of the higher capacitive load between each couple of stems.

To take into account those necessities, as one can see from Fig.7 a conical geometry ending with 2 cylinders was adopted; the central ring will let the water flow from one side to the other and, will host the drift tube as explained in the next section.

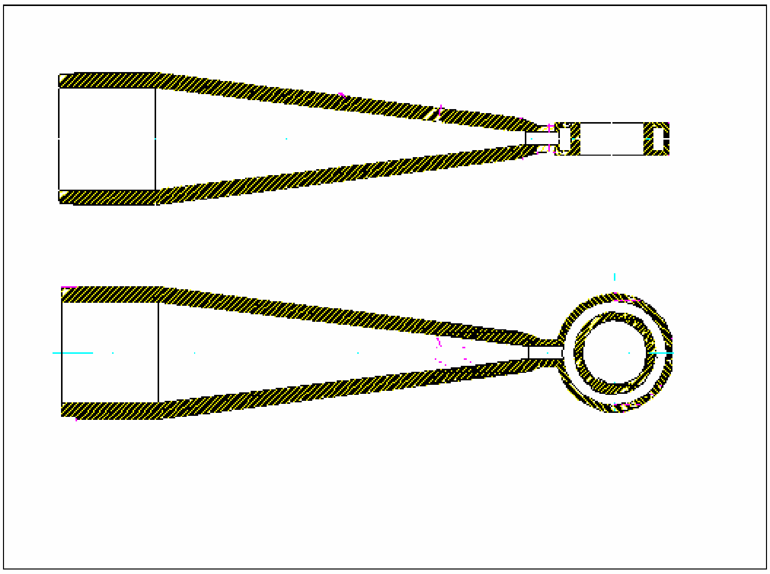

Fig.7: half stem geometry including the water cooling system

There are several reasons for this choice:

- A conical shape allows larger stem radius in the contact point with the outer cylinder, where the welding takes place: this ensure a higher mechanical stability.
- The contact points between the stems and the outer cylinder bears a strong current density and should be large enough to avoid overheating during RF operation.
- The reduction of the radius along the stems corresponds to a reduction in the mutual capacitance between each couple of stems avoiding a reduction in the efficiency of the machine.
- The small neck on the contact point with the central ring is necessary to reduce the potential misalignments of the drift tube: this is especially true at low beta profile.
- With respect to any solutions with sharp edges, the copper plating becomes much easier.

The production of the stems ended in spring 2005: after successful leak test they were mounted in the cavity and welded into the outer stem, as shown from Fig. 8 to Fig. 10

Fig.8: a view of one stem with the central rings: it is possible to notice the aperture for the cooling water.

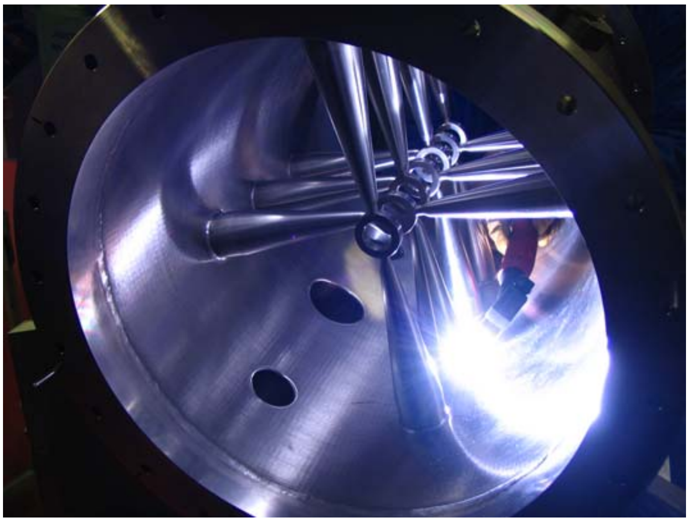

Fig.9: the welding of the stems into the outer cylinder

Fig.10: The inner part of the cavity after welding.

Unfortunately, the thickness of the central ring wasn't big enough and a small deformation was observed after the welding operations. This situation represents a serious problem with respect to the insertion of the drift tubes as explained in the next section

2.2.2 The drift tubes

One of the main features of the H-structure is the possibility to locally tune the cavity: local gap voltage changes in the range ± 20 % can be achieved by varying the gap / period length-ratio, as demonstrated in the tuning of the existing IH resonators.

In order to apply this feature to the CH, the original idea was to use the so called "Press Fit Technique": a bulk copper drift tube is cooled down into liquid nitrogen and then inserted into the central ring of the stainless steel stem. The successive thermal dilation would have created a strong contact between the drift tube and the stem: this idea was checked with the ANSYS code as shown in Fig.11

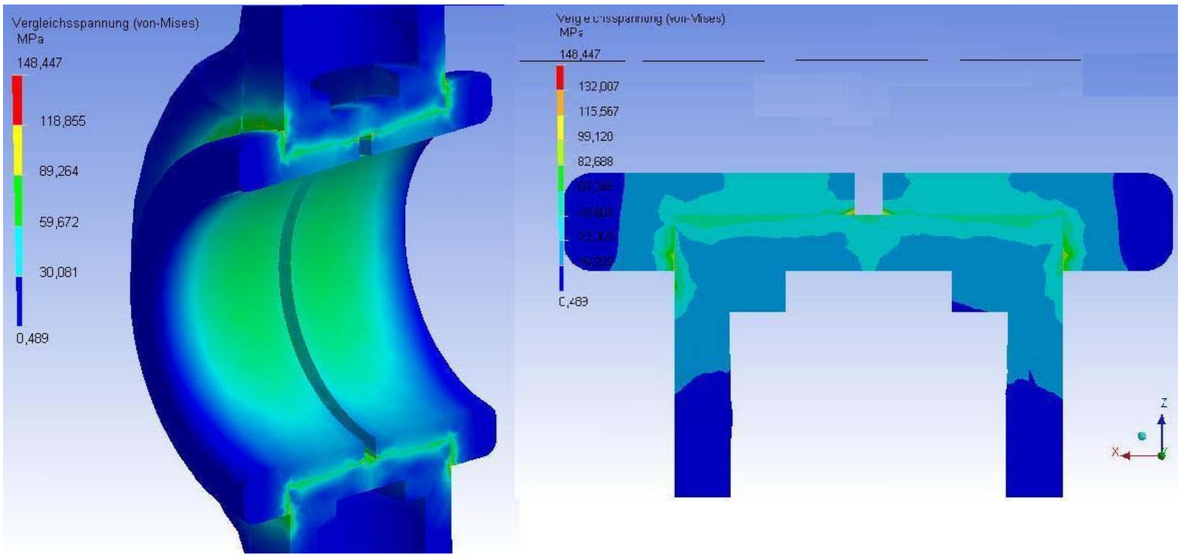

Fig.11: an ANSYS simulation showing the press-fit technique. The thermal dilatation of the drift tube creates a strong pressure on the stem ensuring both good mechanical and RF contacts

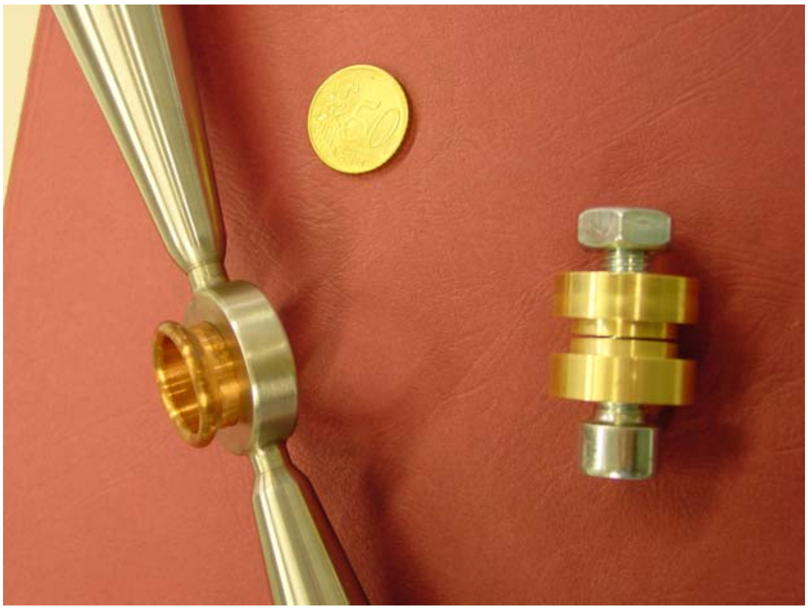

Fig.12: The stem and the half drift tube which had to be press-fitted.

Unfortunately, as explained in the previous section, tube deformation induced by the welding would result in a bad RF contact between the drift and the stem. For this reason, it was decided to abort this idea and to test further the cavity without the drift tubes. The effect of this choice on the RF parameters of the cavity will be explained in the fourth section of this paper.

Nevertheless the aim of this model was to test all the fabrication steps: from this accident we learnt now, that the central ring of the stem must be very thick to bear the stress during the welding operation. This experience will then be transferred in the next future to the production of real GSI P-Injector cavities.

2.2.3 The Water cooling.

We already discussed how the cross geometry of the CH is suitable for an optimum cooling of the stems and of the drift tubes: on the other side, currents flow on the surface of the outer tank which needs to be cooled as well (see Fig.6): since we cannot use and internal girder, as explained in sect 3.2, some new solutions have to be found.

There were two feasible possibilities:

- 4 water pockets are mounted on the outer wall

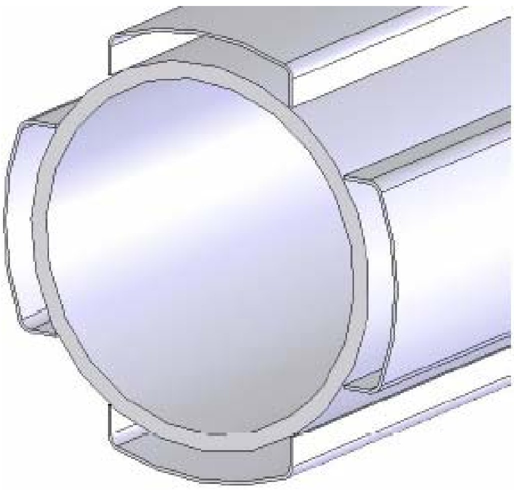

Fig.13: the first proposal for the cooling system of the outer cylinder

- A double walled outer cylinder

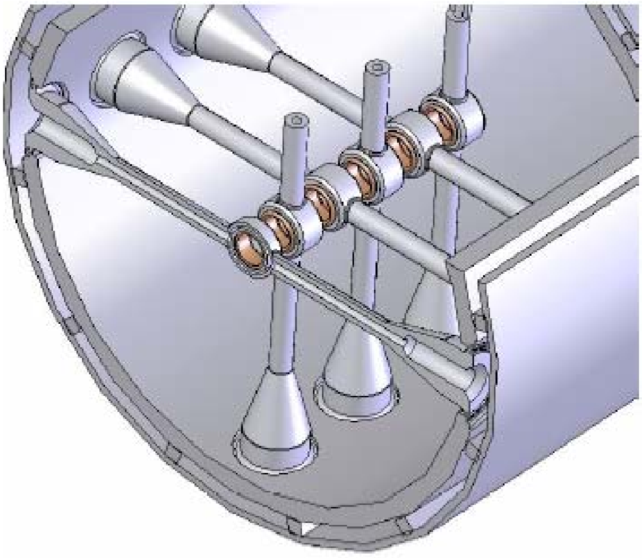

Fig.14: the second proposal for the cooling of the outer tank

This last solution has the main advantages that the stems and the outer cylinder would be cooled by the same channel but, on the other side it is much more complicated and expensive.

On the other side the first proposal is very easy, cheap and doesn't require any further welding since the channel can be screwed on the top of the cavity. In this case each stem will have its own water connection, ensuring in this way an optimal cooling system all along the machine. For this reason this solution was preferred and a complete illustration is presented from Fig. 15 to Fig. 16

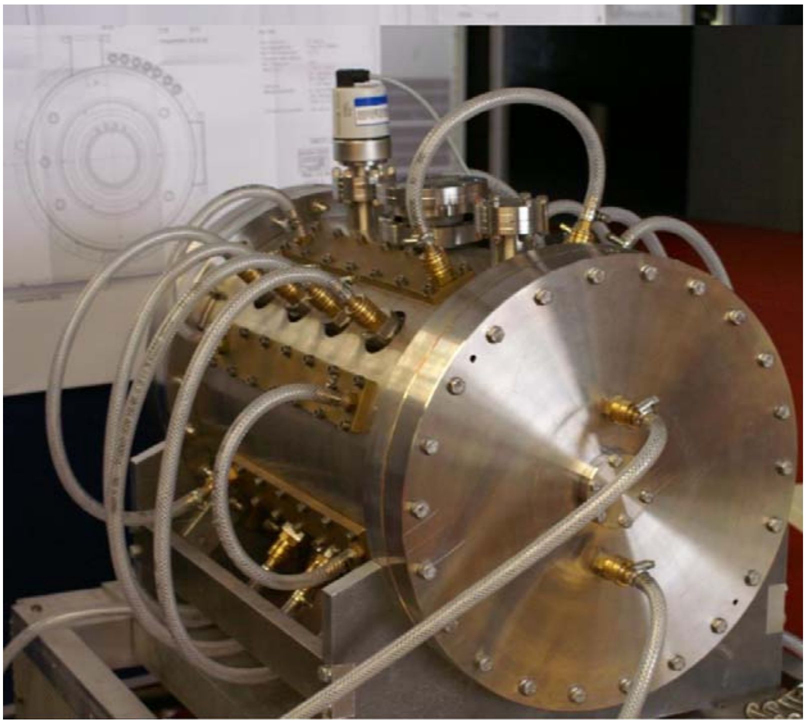

Fig.15: the cooling system of the CH

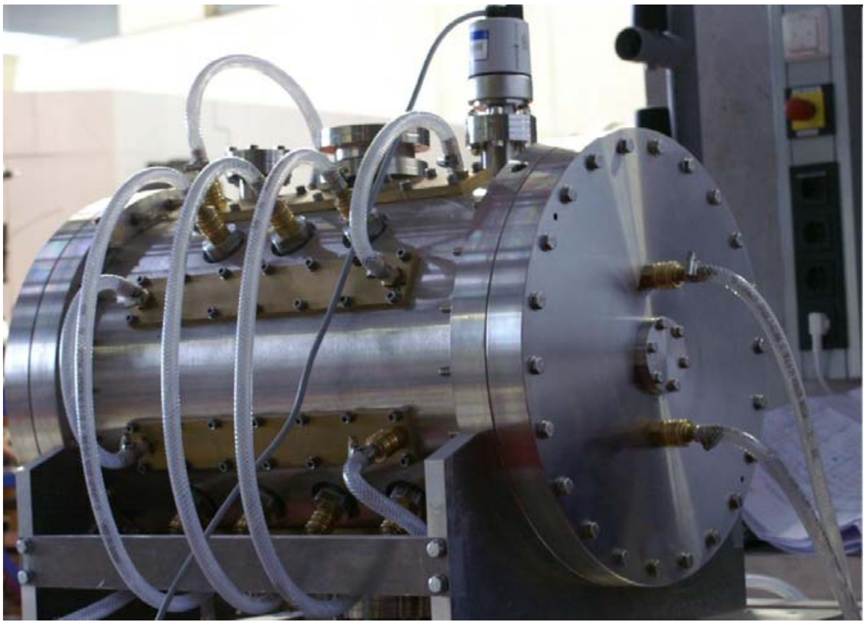

Fig.16: a detail of the cooling system: the water connections of each stem and the cooling pockets from braze on the outer cylinder can be seen.

Finally, to complete the design six flanges were located on the outer cylinder: we opted for 3 CF 63, one for the power incoupling, one for pumping and one as spare part, and 3 smaller CF 35, two of them for the outcouplings and 1 to measure the vacuum pressure. The location of those flanches are illustrated in Fig.17

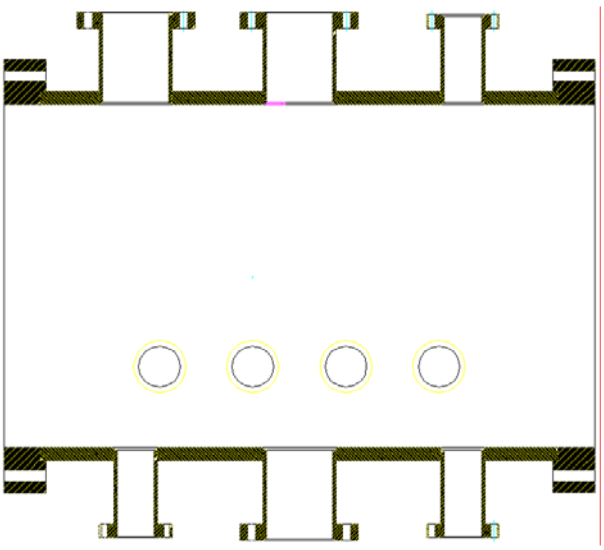

Fig.17: the location of the external flanches with respect to one row of stems.

3 Results from Microwave Studio

The RF properties of the cavity were investigated with CST Microwave Studio. In the following section the most important parameters of the structure such us shunt impedance, Q Value, resonance frequency and axial electric field distribution will be presented and commented.

3.1 The End Cell

Both IH and CH show naturally a cosine distribution of the electric field due their real resonant modes, respectively H_{111} and H_{211}: in order to approximate the "zero mode" a tuning method has to be found.

In IH, for instance large undercuts are created in the girder at the cavity ends: this geometry (compare Figs.2 and 18) is most suited to create the zero mode. The short circuit-action of the end walls with respect to H-modes is suppressed by that geometry if the undercuts are getting large enough.

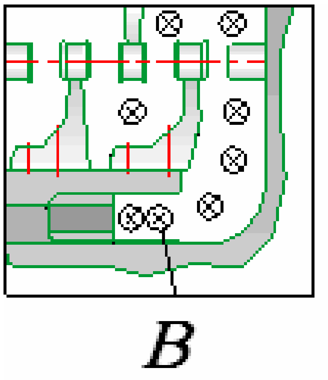

Fig.18: the undercuts used in the IH to get the "zero mode"

In the CH, as already explained in sect. 3.2.2, no girder can be located inside the cavity and the tuning method must necessarily act on the end half drift tube. Infact, lengthening the last half drift tube leads to an increase of the magnetic flux at the cavity end making the end cell resonant: on the other hand, if also its radius is increased, we will get a design where the last half drift tube make the end cell resonant and, at the same time, could host the magnetic lens needed for particles focusing and some diagnostics devices, such as a phase probe or a beam current transformator. A scheme of the cavity is shown in Fig 19 where this concept becomes clear.

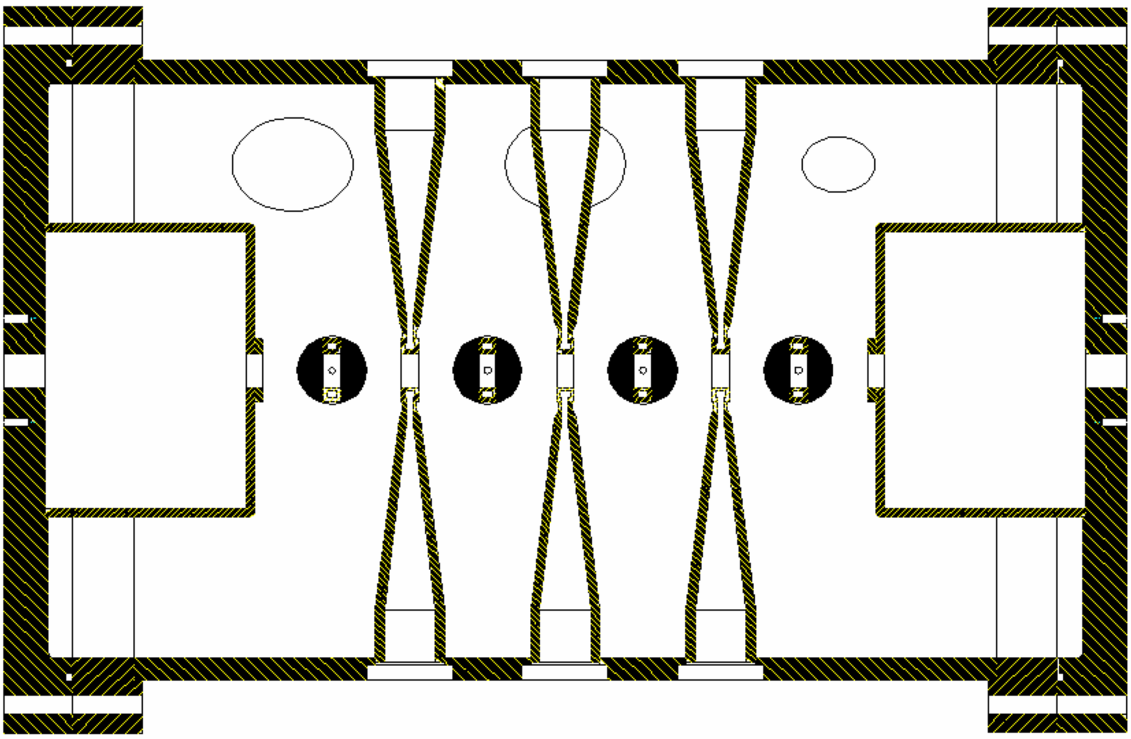

Fig.19: a schematic cut of the cavity along the beam axis: the big end cells are used to approximate the "zero mode" and, at the same time, they will host magnetic lenses and diagnostics devices.

In order to check the validity of this concept we studied the influence of the length of the half drift tubes on the RF parameters of the cavity. From Fig. 20 one can see how an increase of around 25 % in the electric field of the last cells can be achieved varying the length of the big drift tube in general the axial electric field tends to become flat approximating the "zero mode".

In order not to exceed with the dimension of the cavity we decided to set the length at 120 and, in Tab.1 one can observe the dependency of the main RF parameters from this length. For all case a g/l of 0.5 was used and the copper conductivity was set to its ideal value

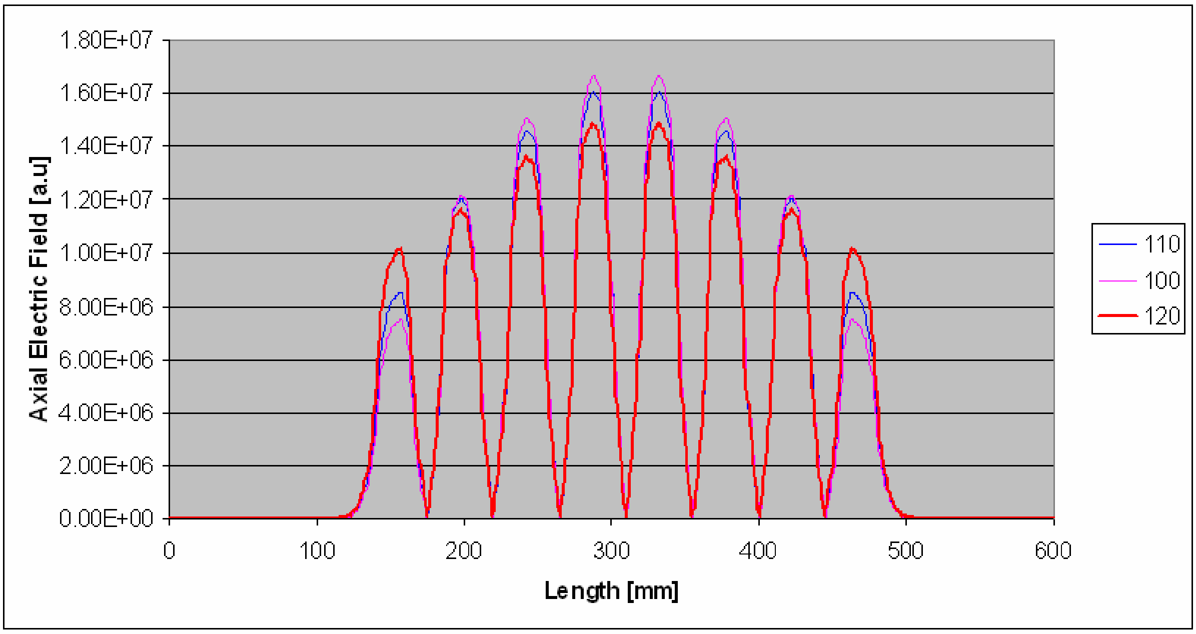

Fig.20: The axial electric field for different length of the big end drift tube: the g/l was set at 0.5 for all cases.

Length [mm]	Q-Value	Frequency [MHz]	Loss* [W]
80	12974	328.06	158900
100	13000	327.35	158200
110	13168	326.32	155700
120	13255	324.54	153845

Tab.1: dependency of the RF parameters from the length of the big end drift tube.
* The loss value assumes 1 J of energy inside the cavity.

3.2 RF Parameters

After fixing the geometry of the end cells the cavity was tuned changing the gap/length ratio all around the structure. The simulated frequency became 323.3 MHz with a Q-value of 13115. The axial field distribution is shown in Fig.21 and the Effective Shunt Impedance is around 80 MΩ/m, in good agreement with the prevision on the GSI Proton Injector.

Finally, since it was decided to test the cavity without the drift tube, this "naked" version of the cavity was investigated with Microwave studio: the main difference between the two versions is the capacitive load which results now strongly decreased: as a consequence the resulting frequency became 338.7 MHz and Q-value encreas up to 13675. On the other side is very interesting to observe the axial field distribution, shown in Fig. 22: the field distribution is peacked now at the cavity's extreme. This is due to the high capacitive load now between the end cells and the last stems which concentrates the electric field at the ends of the cavity.

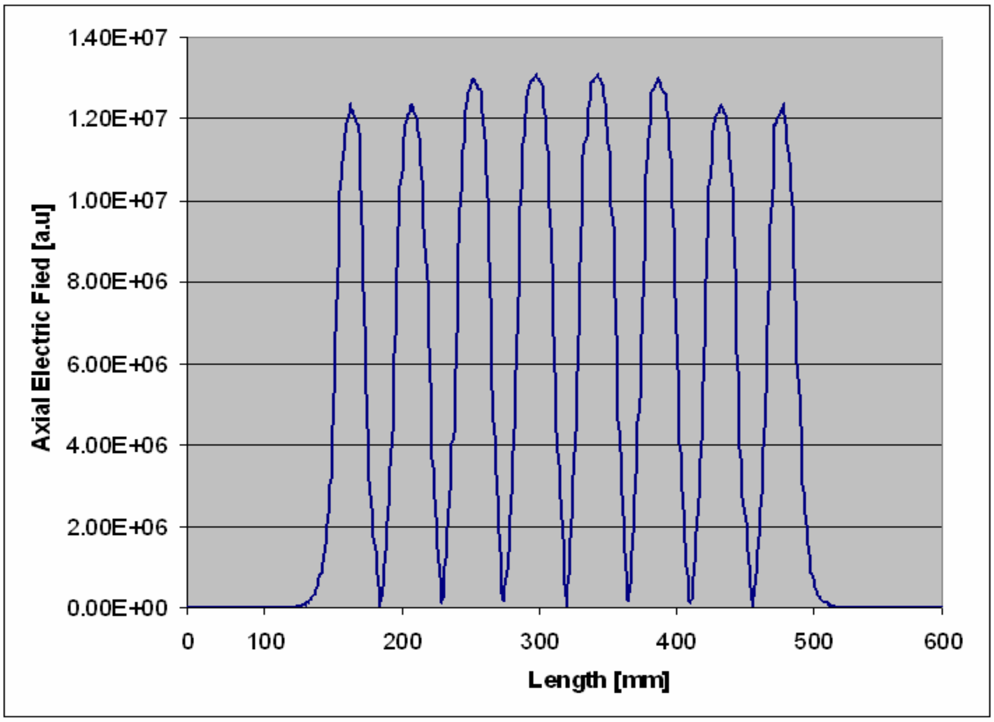

Fig.21: the axial electric field for the tuned cavity.

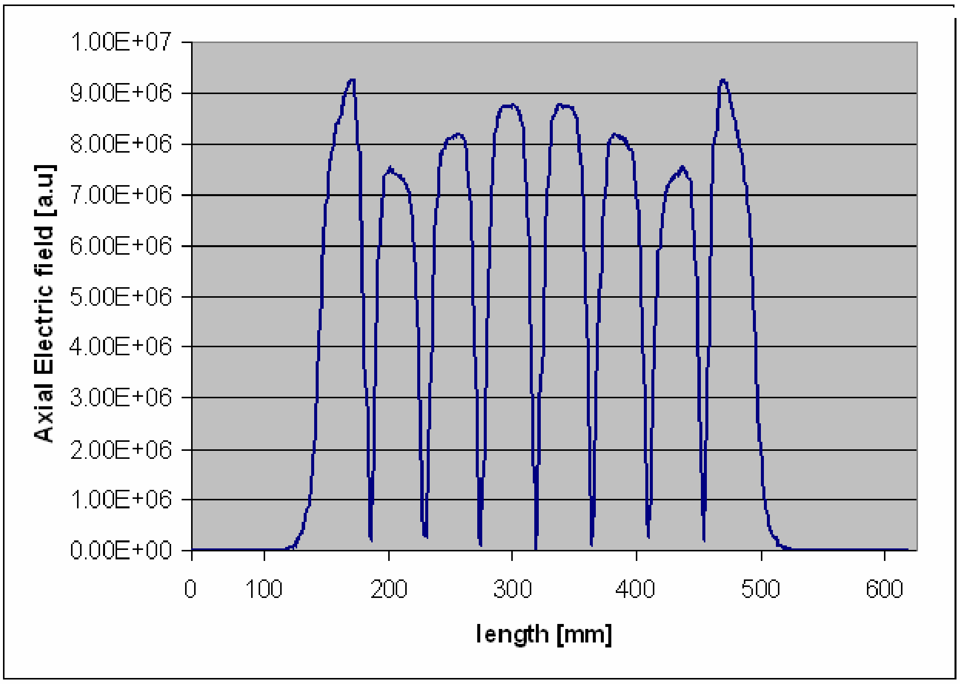

Fig.22: the field distribution without drift tube.

Parameter	*Model with drift tube inserts*	*Model without drift tube inserts*
Frequency [MHz]	***323.3***	***338.7***
Q-Value	***13115***	***13675***
Shunt Impedance [MΩ/m]	***144***	***128***

Tab.2: the effect of the drift tube on the main RF parameters of the cavity.

3.3 Copper Plating

After construction at IAP, the cavity was transferred to GSI where it was copper plated: in order to get a uniform layer the thickness of copper was around 60 µm on the outer cylinder, and around 30 µm on the stems.

The copper plating was considered as a major topic during the development of CH-type because of the complexity of the cross bar geometry. The excellent result in such a complex operation represents a milestone since this demonstrates finally the feasibility of the CH under all mechanical aspects.

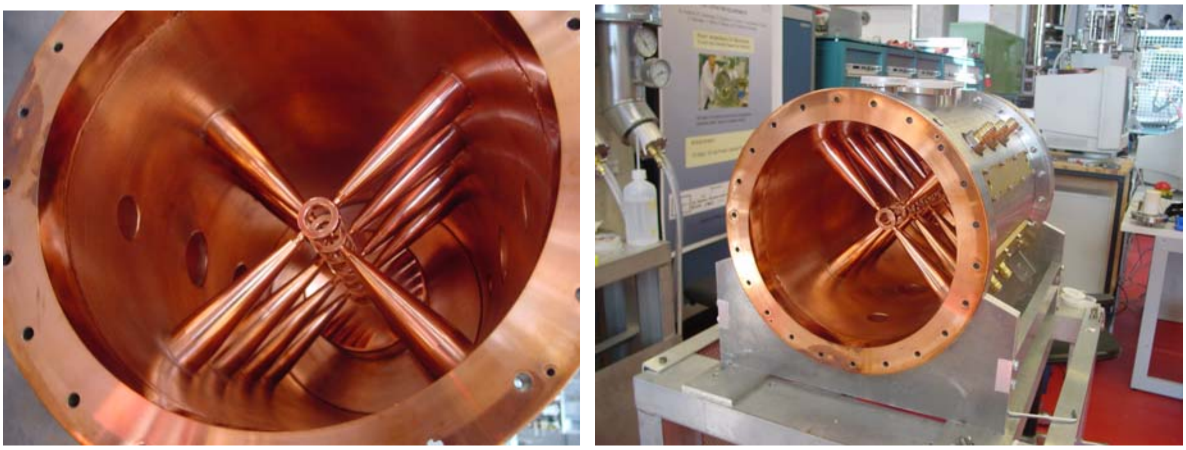

Fig.23: The cavity after copperplating

4 Experimental Results

After copper plating the cavity was ready for the RF measurements, including a power test performed with the 2 kW, cw amplifier avaible at IAP.

In a first step, the basic parameters were measured and compared with the simulated values from Microwave Studio: as one can see from Tab.3 there is a very satisfyng agreement between the measurements and the expected value.

	Measurements	**Computed value**	**% Difference**
Frequency	340.05	338.7	0.3
$\mathbf{Q_0}$	13675	13000	5

Tab3: Comparison for frequency and Q-value between measurements and expected value.

It is particularly interesting to note the good agreement on the Q-value, since MWS tends to overestimate this parameter by 10-20 %, typically; most probably, this is due to the presence of screws and contact in the cavities which results in a higher level of electrical losses. At this point the advantages of the construction concept used for this CH-model becomes obvious: welding the stems into the outer cylinder results infact in a considerable reduction of screws which are used only to fix the end flanges to the cavity. In this way we get rid of a possible source of RF losses increasing the capabilities of the structure.

Finally, to test the capabilities of the cooling system, the cavity was connected to the 2 kW cw amplifier available at IAP: the experimental setup is shown in Fig.24.

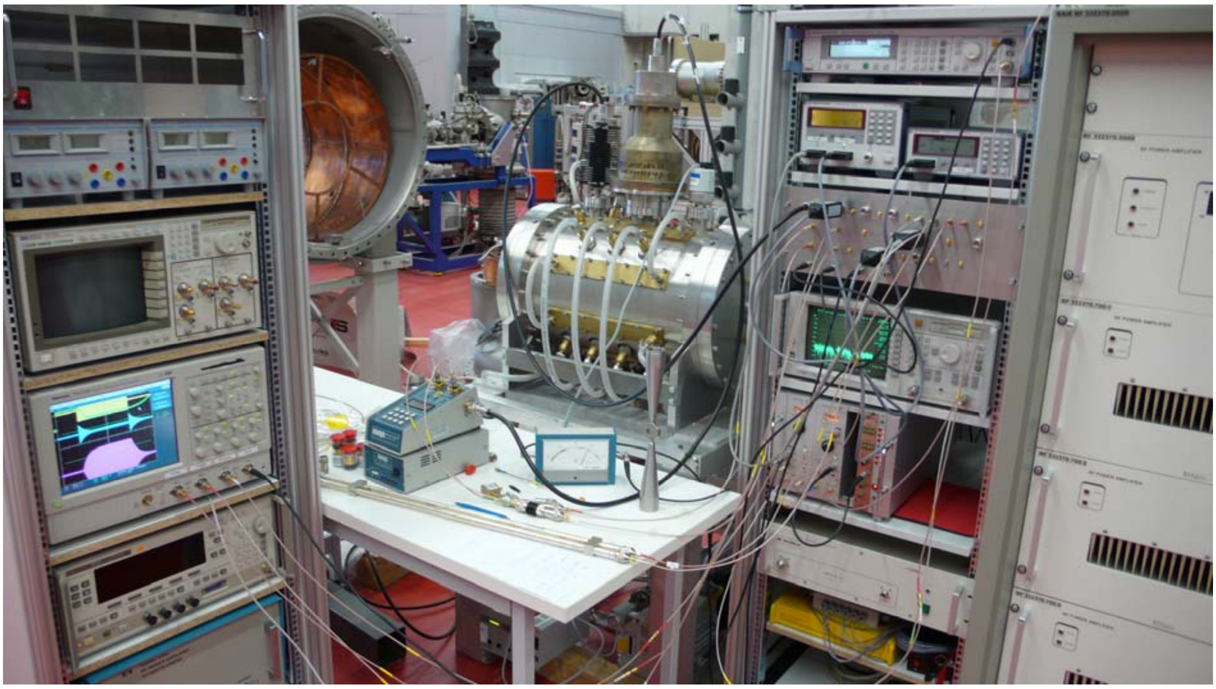

Fig.24: The experimental setup for the high power test at IAP. The CH cavity with power coupler is at the centre of the figure, while on the right the 2 kW amplifier is partly shown.

In a first step the cavity was tested up to 1 kW, corresponding to a total voltage inside the cavity of ~ 220 kV: this level was achieved very fast, around 20 minutes, and no significant multipacting was observed: this phenomenon happened only one and disappeared just after few seconds. The temperature on the outer cylinder was extremely stable showing the efficiency of the cooling system.

Finally, the cavity was brought to 2 kW (corresponding to ~ 304 kV inside the cavity) without any need of conditional time; again, no significant shift of the cavity frequency was observed confirming the capability of the designed cooling system.

5 Next Steps in CH-Cavity development: a coupling scheme for the new Proton Injector based on CH-DTL's.

As discussed in the first section, the avaibility of high power klystrons pushed into the direction of couple 2 tanks in order to match the big power availabe from each sender to a single resonator via a single coupling loop.

We already discussed how one can make resonant end cells of a CH by half drift tubes with adequate length and diameter. Another advantage of this solution is that it leads naturally to a coupling scheme between two neighbor cavities, as illustrated in the following.

By putting two CH-cavities together and by replacing the inner endwalls by a radial item, one is approaching the coupled CH-cavity geometry as proposed for the first time in [16]. Taking the coupling tank diameter as well as the drift tube outer diameter as variables one finally gets a resonant coupling between CH-cavities by means of the intertank section which resonates in the classical E_{010} mode. 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 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.

There is a long experience with this kind of tube installations in the IH-cavities. While the RF situation in IH-cavities is quite different from the CH coupling cell, the mechanical concept can be partly adapted. Fig.25 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.

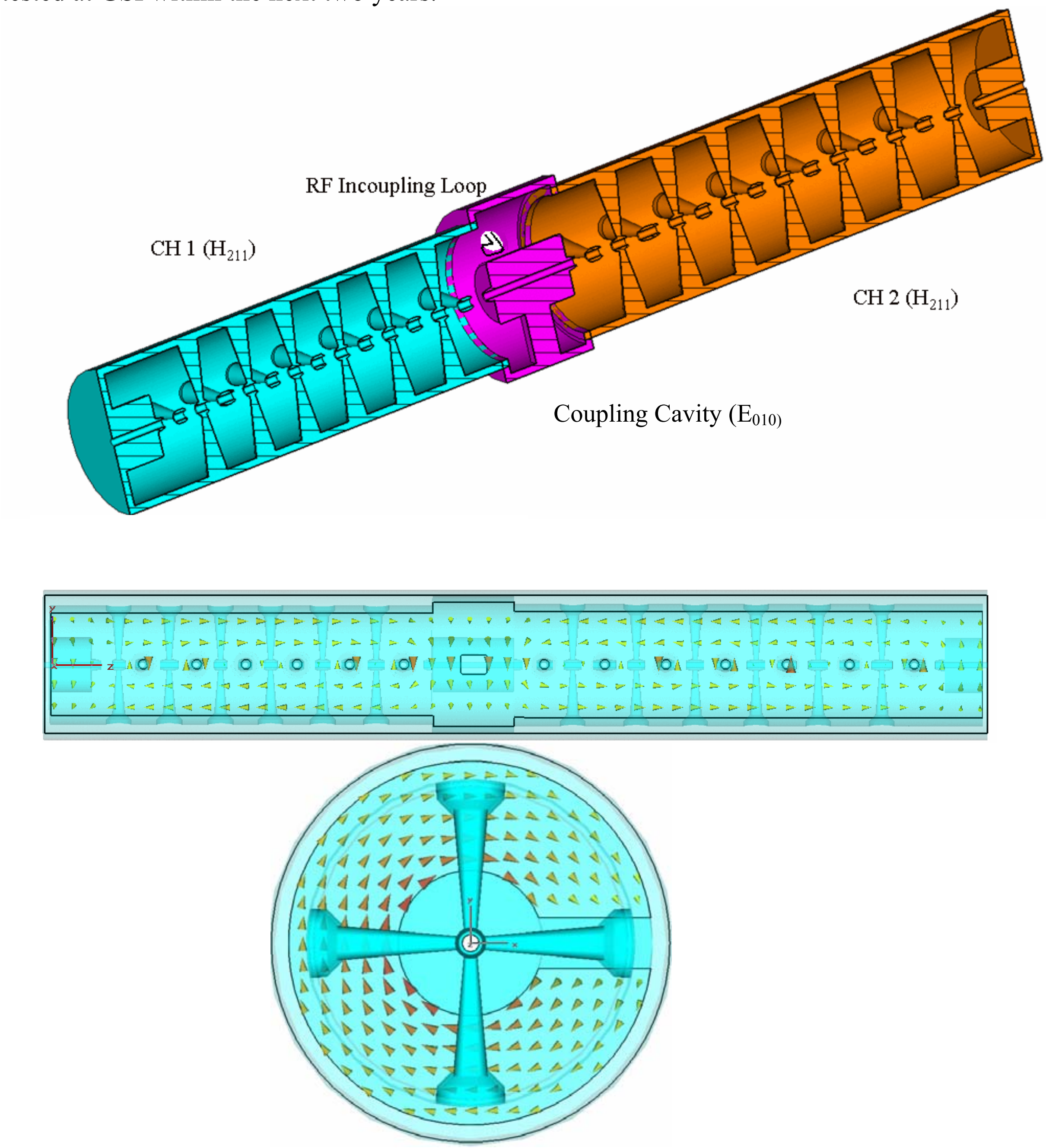

Fig.25: The proposed Coupled CH. On top a representation of the second resonator of the GSI Proton Injector (Tank 3 and 4), and, on bottom the distribution of magnetic field in a longitudinal plane parallel to the beam axis and in the transvers plane of the coupling cell. From this picture one can understand the coupling mechanism based on a coupling cell oscillating in the classical E_{010} Mode.

6 Conclusions

A new room temperature linac structure is under development at IAP in Frankfurt in close collaboration with GSI and the FAIR project. A first 325 MHz, 8 cells model CH-cavity was built within CARE-HIPPI. This model has demonstrated the feasibility of the main fabrication steps like stainless steel welding concept, galvanic copper plating and drift tubes to stems connections. Due to no screwed components, with the only exception of the cavity end flanges, the measured Q-value of more than 13000 was very close to the theoretical value.

Actually, the Fermi National Accelerator Laboratory, FNAL, is including the CH-structure in their design of a powerful new proton linac.

In a recent step, IAP is developing a Coupled Cavity concept for the CH-structure to match the linac efficiently to the available 2.5 MW power klystrons.

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