EU contract number RII3-CT-2003-506395

CARE Conf-04-011-HIPPI

DEVELOPMENT OF ROOM TEMPERATURE AND SUPERCONDUCTING CH-STRUCTURES

H. Podlech
IAP, Universität Frankfurt/Main, Germany

Abstract

Abstract
In the last decades several types of H-mode cavities have been developed for a wide range of applications. Several drift tube cavities (IH-structure) are in routine operation [1][2]. At the IAP (University of Frankfurt, Germany) a new type of H-mode cavity, the Cross-Bar-H-mode or CH-structure is presently under development. This multicell drift tube cavity is operated in the $H_{21(0)}$-mode. The CH-structure is an excellent candidate for high power proton accelerators in the energy range from 3 to 100 MeV. We present the status of the room temperature (r.t.) CHcavity development for a dedicated 70 MeV proton injector for the international accelerator facility FAIR at GSI [3]. Due to its mechanical rigidity this cavity can be realized not only for room temperature but also for superconducting (s.c.) operation. To prove the very promising properties of superconducting CH-structures obtained by simulations, a 352 MHz prototype CH-cavity has been designed. Presently, this cavity is in the final stage of production. We present recent results of the s.c. cavity development and different applications which could take advantage of the s.c. CH-structure (XADS, IFMIF, cw-linac for the production of superheavy elements).

Contribution to the conference LINAC 04, Lübeck, Germany

Work supported by the European Community-Research Infrastructure Activity under the FP6 “Structuring the European Research Area” programme (CARE, contract number RII3-CT-2003-506395).

DEVELOPMENT OF ROOM TEMPERATURE AND SUPERCONDUCTING CH-STRUCTURES

H. Podlech
IAP, Universität Frankfurt/Main, Germany

Abstract

In the last decades several types of H-mode cavities have been developed for a wide range of applications. Several drift tube cavities (IH-structure) are in routine operation [1][2]. At the IAP (University of Frankfurt, Germany) a new type of H-mode cavity, the Cross-Bar-H-mode or CH-structure is presently under development. This multicell drift tube cavity is operated in the $H_{21(0)}$-mode. The CH-structure is an excellent candidate for high power proton accelerators in the energy range from 3 to 100 MeV. We present the status of the room temperature (r.t.) CH-cavity development for a dedicated 70 MeV proton injector for the international accelerator facility FAIR at GSI [3]. Due to its mechanical rigidity this cavity can be realized not only for room temperature but also for superconducting (s.c.) operation. To prove the very promising properties of superconducting CH-structures obtained by simulations, a 352 MHz prototype CH-cavity has been designed. Presently, this cavity is in the final stage of production. We present recent results of the s.c. cavity development and different applications which could take advantage of the s.c. CH-structure (XADS, IFMIF, cw-linac for the production of superheavy elements).

INTRODUCTION

A common property of all H-mode cavities is the high shunt impedance and the uniform power loss distribution which simplifies the cooling, especially at higher duty factors or cw operation . Figure 1 shows the effective shunt impedance as function of the particle velocity for different kinds of drift tube cavities. The well known IH-structure ($TE_{11(0)}$-mode) has no competitor in the low β-range from 0.01 to 0.1. The main reason for the high shunt impedance is the low capacitive load by using slim drift tubes without transverse focusing elements inside the tubes. Very high accelerating gradients up to 10.7 MV/m have been achieved in pulsed operation [1], and cw operation has been realized successfully, too [4][5]. Limitation of IH-structures are the lack of mechanical stability for s.c. operation and the upper operation frequency of about 300 MHz. Above this frequency the tank diameter becomes unreasonable small.

The CH-structure which is operated in the $H_{21(0)}$-mode has a larger diameter for a given frequency compared with the IH-structure. Cavities with frequencies from 150 to 800 MHz can be realized. This means that the CH-structure fits well to the popular frequency of proton drivers at around 350 MHz.

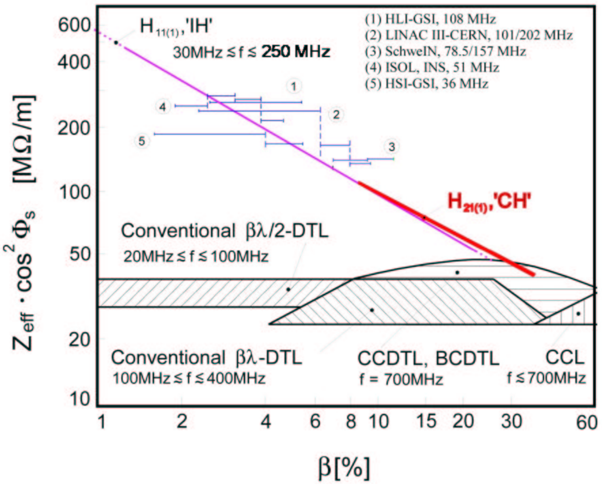

Figure 1: Effective shunt impedance as function of β for different rf structures. The horizontal blue bars represent existing IH-structures and the red line is the expected shunt impedance of the designated CH-proton linac for FAIR/GSI.

Unlike cavities with only two gaps as half wave or spoke resonators which cover typically a broad velocity range, the CH-structure is a multi cell cavity with a fixed velocity profile. Therefore this cavity has a constant high transit time factor larger than 0.8. Additionally, the KONUS beam dynamics (Kombinierte Null Grad Struktur) [1] is used to optimise the individual cavity cells. Due to the reduced transverse rf defocusing, long lens free sections can be realized even at high beam currents. This results in very high real estate gradients

R.T. CAVITY DEVELOPMENT FOR THE GSI PROTON-INJECTOR

The existing Unilac at GSI is a fixed velocity heavy ion linac and can fill the synchrotron SIS12 only to about a few percent of the space charge limit for protons [1]. For the physics program, especially for the antiproton producton at FAIR, it is required to increase the proton current by a factor of 70 compared with the present capabilities. This can only be fulfilled by a dedicated proton injector. The key parameters are the final energy of 70 MeV, the neccessary peak current of 70 mA and the rf frequency of 352 MHz.

A combination of a 4-rod-RFQ [6] and of a CH-linac consisting of 11 r.t. CH-cavities is planned [7]. The design goal

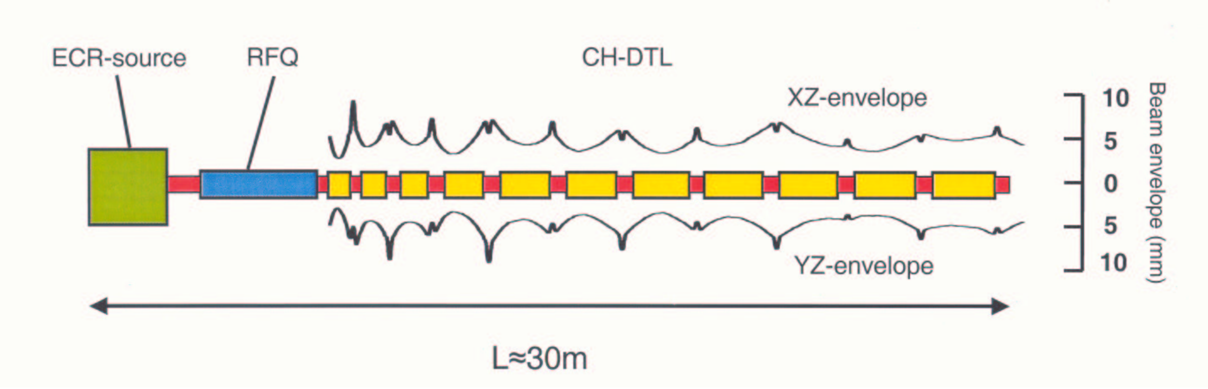

Figure 2: Principal layout of the FAIR proton linac with an ECR-source, a 4-rod-RFQ and 11 r.t. CH-cavities.

is to realize a proton injector which is efficient with respect to capital costs, maintainance and rf power consumption. Figure 2 shows a scheme of the the proposed proton linac. Additionally, the 99% beam envelopes derived from multi particle simulations are plotted along the CH-DTL [8]. The LEP klystrons will be used as rf drivers for all cavities including the RFQ. The maximum pulsed power per cavity varies between 500 and 1100 kW with beam loading [7].
The main concern regarding the cavity rf design was to maximise the shunt impedance by lowering the capacitive load without loosing mechanical stability. Therefore thin slices with only one accelerating cell have been optimised using Microwave Studio [9]. The effective shunt impedance $Z_{eff} = Z_0 T^2$ ranges from 100 to 45 MΩ/m [7] which are competitive values compared with conventional rf structures like the Alvarez-DTL. Fig. 3 shows a design study of the r.t. CH-structure for the FAIR proton injector. Each stem is cooled by water. ANSYS-simulations [10] have been performed to determine the mechanical stress and the deformation of the drift tubes under pressure due to thermally induced variations of the stem length. These results are in good agreement with experimental tests.

Table 1: Main parameter of the FAIR proton injector (CH-DTL)

Frequency	352 MHz
rf pulse length	1 ms
Repetiton rate	5 Hz
Macro pulse length	100 μs
Current (design/operation)	90/70 mA
Energy range	3-70 MeV
Nr. of CH-cavities	11
Length	22 m
Single tank length	0.6-2.2 m
Accelerating gradient	6.3-2.7 MV/m
Nr. of gaps/cavity	12-17
Effective shunt impedance	100-45 MΩ/m
rf power per cavity	600-1100 kW

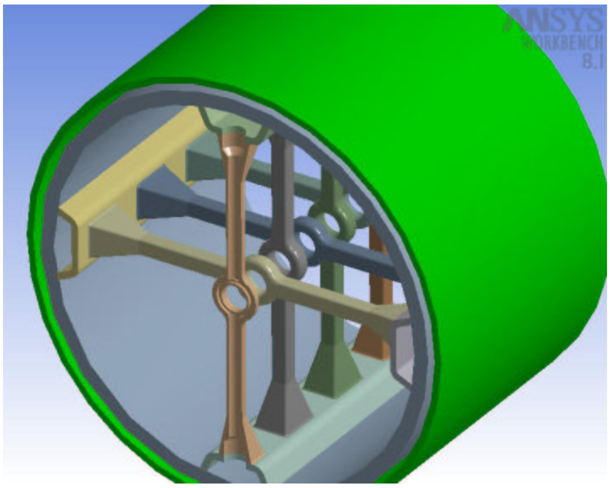

Figure 3: Three-dimensional view of the first CH-cavity for the FAIR proton linac.

SUPERCONDUCTING CH-CAVITIES

For accelerators operated with high duty cycles or even cw it is often advantageous to use superconducting cavities to reduce the overall power consumption. Additonally, s.c. cavities can have much larger apertures than r.t. cavities. This reduces particle losses and activation which is especially important if the linac should be a hands-on maintainance system.
For higher beam energies above around 100 AMeV s.c. elliptical cavities seem to be the best choice. These very efficient s.c. rf structures provide high gradients and a large voltage gain per cavity. Different projects will use or consider elliptical cavities [11][12][13].
In the case of s.c. low and medium β-cavities the situation is not as clear as for the high energy part. Many different cavities for ion and proton acceleration have been developed since the late 1960's. Even after the development of half wave and spoke resonators which have demonstrated very high gradients in recent tests [14][15] there is still a lack of efficient s.c. low and medium β cavities with frequencies of around 350 MHz whereas “efficient” means

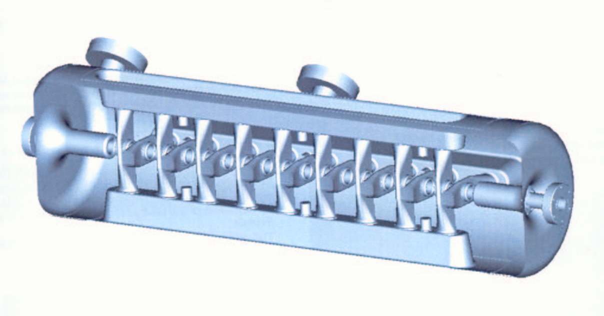

Figure 4: The superconducting CH-prototype.

high real estate gradient and large voltage gain per cavity. If energy variability is not an issue as for fixed velocity driver accelerators it is very reasonable to use multi cell cavities. If reliability is an issue it is clear that a multi cell cavity has to be designed very carefully with enough safety margin. This is in particular true for the peak fields.
The CH-structure will be the first s.c. multi cell cavity for the low and medium energy range. Due to the crossed stem construction this cavity has a very high mechanical rigidity which is needed for superconducting operation. The CH-structure has some common features with the multi-spoke resonator. But the CH-structure uses girders to connect the stems which decreases the transverse dimensions of the cavity and results in lower magnetic peak fields. The use of the KONUS beam dynamics increases the number of possible acceleration cells without transverse focusing. Together with a velocity profile this leads to high real estate gradients between 3 and 4 MV/m which is much higher than in typical low β 350 MHz spoke cavities running with higher nominal gradients.

Figure 5: Some of the niobium parts of the s.c. CH-cavity which is in the final stage of production.

To prove the promising properties of s.c. CH-structures a 352 MHz β=0.1 CH-cavity with 19 gaps has been designed (see. fig.4) [16]. Table 2 summarises the main parameters of the CH-prototype cavity. The electric peak fields in CH-structures are higher compared with half wave or spoke resonators whereas the magnetic peak fields are lower. The ratio E_p/E_a is 6.59 and B_p/E_a is 7.29 mT/(MV/m) in the case of the CH-prototype cavity. This means that this cavity will be limited most likely by field emission. A gradient E_a=3.2 MV/m leads to an electric peak field of 21 MV/m and to a magnetic peak field of 23 mT. With an assumed intrinsic Q-value of 3.7·10^8 (R_s=140 nΩ) an rf power of 9 W is required to reach the gradient of 3.2 MV/m and the effective voltage gain of 3.4 MV, respectively. After a study had shown the technical feasibility of producing s.c. CH-structures the fabrication of this prototype cavity has been started in 2003 by the company ACCEL (Bergisch-Gladbach, Germany). The

Table 2: Parameters of the superconducting CH-cavity prototype

f	MHz	352
β		0.1
length	cm	104.8
diameter	cm	28
number of gaps		19
R_a/Q_0	Ω	3220
G	Ω	56
$(R_a/Q_0) \cdot G$	Ω^2	180000
E_p/E_a		6.59
B_p/E_a	mT/(MV/m)	7.29
E_p @ E_a=3.2 MV/m	MV/m	21
B_p @ E_a=3.2 MV/m	mT	23.3
W	mJ/(MV/m)^2	155
W @ E_a=3.2 MV/m	J	1.58
Q_0 (BCS, 4.2K)		1.5·10^9
Q_0 (R_s=140 nΩ)		4·10^8
P @ E_a=3.2 MV/m	W	9
material		bulk niobium
RRR		250
sheet thickness	mm	2-3

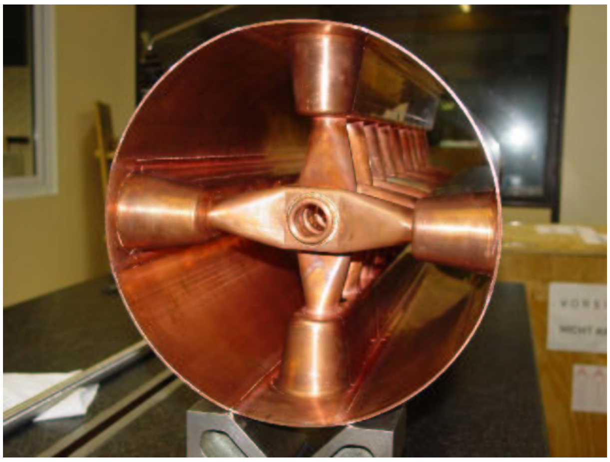

Figure 6: The full scale CH-prototype in copper.

cavity parts are produced with 2-3 mm thick high RRR bulk niobium sheets by deep drawing and spinning. Because of the very complex geometry many procedures of the production had to be developed first. Each production step has been performed in copper including the electron beam welding. Then the same step has been performed with niobium. Presently the niobium cavity is in the final stage of production (fig.5) whereas the copper version is already finished (see fig.6). The CH-prototype cavity will then be chemically treated with Buffered Chemical Polishing (BCP) and High Pressure Rinsing (HPR).

To test superconducting cavities at the IAP in Frankfurt, a cryogenic laboratory has been established recently. The laboratory has been equipped with a 3 m long vertical cryostat, a magnetic shielding (shielding factor 30), two transport dewars for LHe, a class 100 laminar flow box and the necessary rf equipment including the control system. The cryogenic laboratory has been already put into operation. Cold tests of a 176 MHz half wave resonator built by ACCEL have started and the cavity has been operated in a phase locked loop mode.

There are different possibilities to couple rf power to a s.c. CH-cavity. To study different coupling methods MWS simulations have been performed [17]. For the first cryo tests it is foreseen to couple electrically with a coaxial coupler through the girder (see. fig. 7). The simulations of the external Q-value could be reproduced by measurements very well (see. fig. 8).

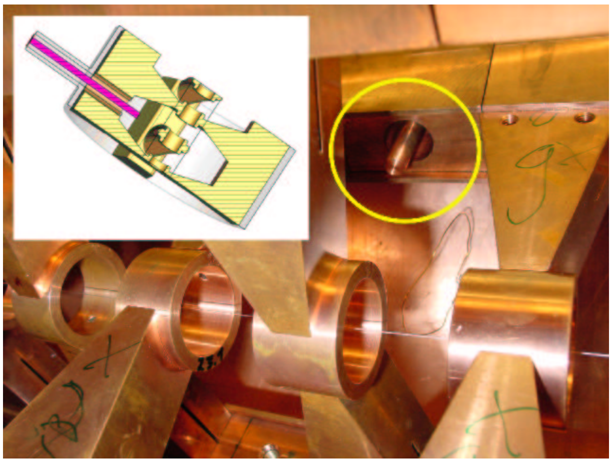

Figure 7: It is planned to couple with a coaxial coupler (yellow circle) through the girder to the electric field.

APPLICATIONS OF S.C. CH-STRUCTURES

XADS

XADS (**Ex**perimental **A**ccelerator **D**riven **S**ystem) is a nuclear waste transmutation project [18]. A superconducting driver linac delivers a cw 10 mA, 600 MeV proton beam to a subcritical core with a liquid metal spallation target. The main concern of this linac is the reliability because only a few beam trips (t>1 s) per year are allowed. Therefore it is considered to build two identical injectors up to an energy of about 35 MeV. Above this energy the linac is expected to be more robust against parameter deviations. Superconducting CH-structures could be used for the injector part from the RFQ energy (5 MeV) to the transition energy. This would reduce the number of cavities significantly compared with the use of 2-gap spoke resonators. In particular, the real estate gradient of low energy 2-gap spokes is very small because of a short cell length, long drift sections, a small number of cavities per focusing lattice and partially low transit time factors. Table 3 shows a comparison between a CH-linac and a spoke linac based on β=0.15 spoke cavities in the low energy range from 5 to 18 MeV [19].

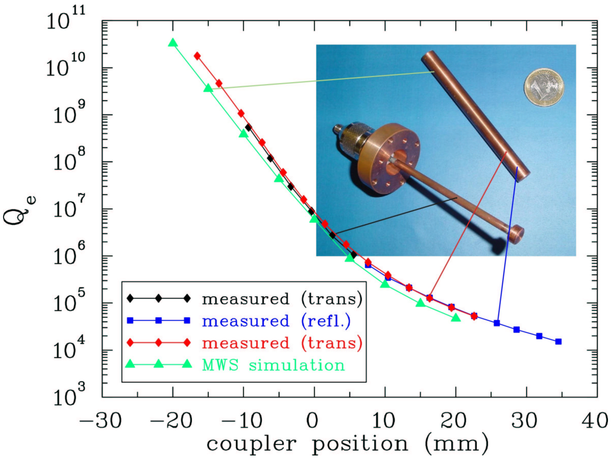

Figure 8: Different capacitive couplers have been used for model measurements. It could be demonstrated that sufficient coupling ($Q_e \approx 2 \cdot 10^8$) can be provided. A positive position means that the coupler protrudes from the girder.

Table 3: Comparison of a CH-linac and a 2-gap spoke linac for XADS in the energy range from 5 to 18 MeV [19].

parameter	CH-linac	spoke linac
number of cavities	4	30
β	0.1-0.2	0.15
gradient at β_{opt}	3 MV/m	6.3 MV/m
gradient (cavity length)	3 MV/m	2.5 MV/m
real estate gradient	1.62 MV/m	0.33 MV/m
energy gain per cavity	3-3.5 MeV	0.16-0.42 MeV
E_p at design gradient	19.5 MV	25 MV
B_p at design gradient	22 mT	50 mT
total length (m)	8	40

IFMIF

The **IFMIF** project (**I**nternational **F**usion **M**aterial **I**rradiation **F**acility) is planned as a high flux source of fast neutrons to develop appropriate wall materials for future fusion reactors [20]. The facility has to provide a 250 mA, 40 MeV, 10 MW deuteron beam accelerated by two 175 MHz linacs to a liquid Li target. In the reference design, a r.t. Alvarez-DTL is foreseen [20]. But because of the required cw operation it is attractive to use superconducting cavities to reduce the overall plug power and to avoid thermal problems in the r.t. Alvarez-type drift tube structures. At the IAP a linac for IFMIF has been proposed consisting of a r.t. IH-structure followed by a chain of 7 s.c. CH-structures [21].

CW linac for production of superheavy elements

At GSI and IAP a new linac for A/q=7 has been proposed for the production of superheavy elements [22]. Up to an energy of 1.4 AMeV the linac would consist of an ECR-source, a 4-rod-RFQ and an IH-structure. Due to the high duty cycle (cw) superconducting operation of the following cavities is advantageous. Therefore 8-10 s.c. CH-structures are foreseen to accelerate the beam up to an energy of 7.5 AMeV. The final energy would be continiously varied by using several s.c. 2-gap half wave resonatos.

CONCLUSIONS AND OUTLOOK

The CH-structure is a new multi cell drift tube cavity with promising properties. It can be applied in room temperature as well as in superconducting linacs for the acceleration of protons and ions in the low and medium energy range. A high current proton linac for FAIR at GSI consisting of r.t. CH-structures is presently under development. A protoype cavity will be built and tested with high power.
Several future projects as IFMIF or XADS could take advantage of s.c. CH-cavities. A s.c. prototype cavity is in the final stage of production and will be tested this year. The development of a mechanical tuner for the CH-structure and a structural analysis using ANSYS has started.

ACKNOWLEDGEMENT

The author would like to thank U. Ratzinger, H. Klein, H. Deitinghoff, the members of the Linac group, and the technical staff of the IAP.
This work has been supported by GSI, BMBF contr. No. 06F134I. and EU contr. No. EFDA/99-507ERB5005 CT990061. We acknowledge also the support of the European Community-Research Infrastructure Activity under the FP6 ”Structuring the European Research Area” program (CARE, contract number RII3-CT-2003-506395)

REFERENCES

[1] U. Ratzinger, Habilitationsschrift, Universität Frankfurt, 1998

[2] U. Ratzinger, The New High Current Ion Accelerator at GSI and Perspectives for Linac Design Based on H-Mode Cavities, Proceedings of the EPAC 2000, p.98, Vienna, Austria

[3] W. Henning, The Future GSI Facility: Beams of Ions and Antiprotons, Proceedings of the PAC 2003, p.16, Portland, OR; USA

[4] E. Nolte et. al., The Munich Heavy Ion Post Accelerator, Nucl. Instr. and Meth. 1979, vol.158, p.311

[5] R. Laxdal et al., Beam commissioning and first operation of the ISAC DTL at TRIUMF, Proceedings of the PAC 2001, p3942, Chicago, IL, USA

[6] A. Schempp et al., Design of a 352 MHz Proton-RFQ for GSI, these Proceedings

[7] Z. Li et al., Design of the r.t. CH-Cavity and Perspectives for a New GSI Proton Linac, these Proceedings

[8] R. Tiede et al., KONUS Beam Dynamics Design of a 70 mA, 70 MeV Proton CH-DTL for SIS at GSI, these Proceedings

[9] http://www.cst.com

[10] http://www.ansys.com

[11] M. White, The Spallation Neutron Source (SNS), Proceedings of the LINAC 2002, p.1, Gyeongju, Korea

[12] J.A. Nolen, The U.S. Rare Isotope Accelerator Project, Proceedings of the LINAC 2002, p.29, Gyeongju, Korea

[13] J-L. Biarrotte, High Intensity Driver Accelerators for EURISOL, Proceedings of the EPAC 2002, p.1007, Paris, France

[14] G. Olry et al., Recent Developments on Superconducting β=0.15 and β=0.35 Spoke Cavities at IPN for Low and Medium Energy Sections of Proton Linear Accelerators, Proceedings of the EPAC 2004, Lucerne, Switzerland

[15] T. Tajima et al., Test Results of the LANL 350 MHz, β=0.175, 2-Gap Spoke Resonator, Proceedings of the LINAC 2002, p.228, Gyeongju, Korea

[16] H. Liebermann et al., Design of a Superconducting CH-Cavity for Low- and Medium Beta Ion and Proton Acceleration, Proceedings of the PAC 2003, p.2820, Portland, OR; USA

[17] H. Liebermann et al., Status of the Coupler Development for the 352 MHz Superconducting CH-Cavity, these Proceedings

[18] “A European Roadmap for Developing Accelerator Driven Systems (ADS) for Nuclear Waste Incineration”, April 2001, ENEA, Italy

[19] J.-L. Biarrotte et. al., High Intensity Proton SC Linac Using Spoke Cavities, Proceedings of the EPAC 2002, p.1010, Paris, France

[20] IFMIF Conceptual Design Report

[21] A. Sauer et al., Beam Dynamics Design of a Superconducting 175 MHz CH-Linac for IFMIF, Proceedings of the EPAC 2002, p.1404, Paris, France

[22] R. Eichhorn, RF Structures for Linear Acceleration of Radioactive Beams, Proceedings of the PAC 2001, p.495, Chicago, IL, USA