DEVELOPMENT OF A SUPERCONDUCTING H-MODE CAVITY FOR THE LOW-BETA REGIME

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Abstract

Normal conducting H-mode cavities have become standard for accelerating all types of ions with velocities between 0.002 c and 0.1 c. These structures show a high shunt impedance, they allow the acceleration of very intense beams and provide high accelerating gradients. Together with the KONUS (Kombinierte Null Grad Struktur) beam dynamics the required transversal focusing elements, i.e. quadrupole triplets can be placed outside of the resonator. This allows the design of superconducting H-type cavities for high current proton and ion linac applications. The design principles of the resonator, possible fabrication options and a status report will be given.

1 INTRODUCTION

Linacs based on normal conducting H-mode structures are estimated to be efficient in the velocity range from β=0.002 up to β=0.5. RF power tests show the capability of IH-cavities to stand about 25 MV/m on axis field. Beside these high accelerating gradients the H-mode cavities allow the acceleration of intense beams. Many future projects (the Accelerator Driven Transmutation Project ADTP[1], the European Spallation Source ESS[2] or the Heavy Ion Inertial Fusion HIIF [3]) are based on the availability of accelerating cavities with these properties that additionally could be operated in cw mode. It is commonly accepted that above an energy of 200 MeV/u superconducting cavities are superior to their normal conducting analogons. By combining the advantages of the H-mode cavities with the benefits of superconductivity, effective acceleration of all types of ions including protons down to an energy of 10 MeV/u could be possible. To study this option is part of the work at GSI started recently.

This paper examines some aspects of H-mode cavities and describes results achieved with normal conducting resonators. As a key to the design of the superconducting H-mode cavity, the essentials of the 'Combined 0° Structure KONUS' beam dynamics will be reported, which allows to place the magnetic quadrupoles necessary for the transversal focusing of the beam outside the resonator. First results of the numerical simulation of an $H_{21(0)}$-type cavity covering the energy range form 10.9 to 17.6 MeV for protons will be shown.

2 NORMAL CONDUCTING H-MODE CAVITIES

Fig. 1 shows the family of H-mode linac cavities. The 4 vane-RFQ (H_{210}-mode) is well established for protons and light ions acceleration [4].

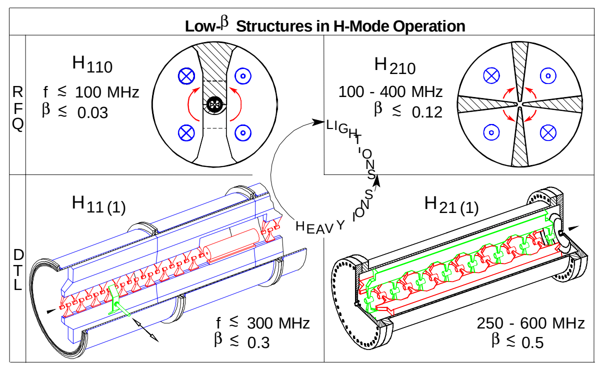

Figure 1: The H-mode structure family: The main direction of the magnetic RF field is oriented parallel and anti parallel with respect to the beam axis.

The IH-DTL (Interdigital H-mode or $H_{11(0)}$) has become a standard solution for heavy ion accelerating. The CERN Pb-injector installed in 1994 [5] is one example. The new high current injector at GSI [6] consists of the first IH-DTL designed for very heavy ions with A/q = 65 including space charge effects of considerable strength at the design current of I/emA = 0.25·A/q.

The important property of the H-mode DTLs is their high acceleration efficiency, especially at β-values up to 0.2. This can be quantified in terms of two constituents:

- The RF wall losses P_{loss} expressed by the formula

$$P_{loss} = \frac{V_{eff}^2}{Z_{eff} \cos^2 \phi_s L} \quad (1)$$

are low, where V_{eff} is the effective voltage gain of a particle along the cavity $(W_{out}-W_{in})/q$. L denotes the axial length of the cavity between end flanges and Φ_s the averaged RF phase angle of the bunch at the gap centres.

The product $Z_{eff} \cdot \cos^2 \Phi_s$ is plotted in fig. 2 for multigap structures in the interesting frequency range.

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The curves for IH and CH cavities are an estimation valid for short high current cavities containing no quadrupole lenses and using the KONUS beam dynamics, which will be explained later on. Compared with conventional DTLs of the $\beta\lambda/2$ and $\beta\lambda$-type there is a P_{loss}-reduction by factors ranging from 4 to 10 at β-values below 0.1.

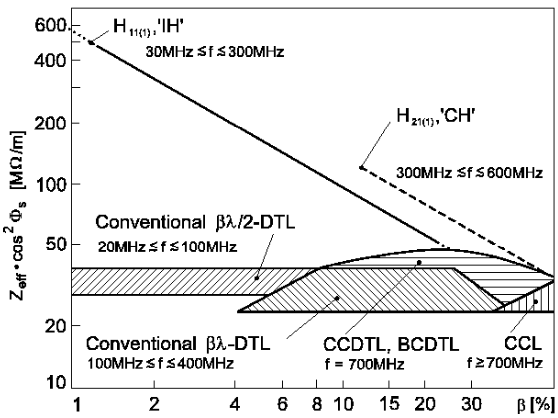

Figure 2: Comparison of the RF power efficiencies for several DTL cavities.

- The IH-cavity containing slim drift tubes made from bulk copper is very resistant against voltage break down. At one 202 MHz IH cavity of the CERN lead injector power tests up to 1.3 MW were performed successfully [7]. The averaged effective voltage gain between tank end flanges was as high as 10.7 MV/m.

A competitive H-mode cavity in the velocity range from β = 0.1 to 0.5 may become the $H_{21(1)}$-mode CH structure, which can be deduced from the 4-vane RFQ by cutting down the vanes around the aperture and replacing the electrodes by drift tubes connected by two stems with girders of the same RF potential (see fig. 1). The dipole mode that usually causes trouble during the tuning procedure of the 4-vane RFQ is short-circuited in this DTL version along the whole cavity. The analytically estimated shunt impedance assuming slim drift tubes without quadrupoles is about a factor 1.5 higher as compared to the IH-cavity (see fig. 2).

3 THE KONUS BEAM DYNAMICS

Conventional drift tube linacs are operated at negative synchronous RF phase to provide linear longitudinal focusing. The transversal focusing is done by placing quadrupole singulets in every (or every n^{th}) drift tube thus forming a FODO channel. This arrangement of magnetic elements inside the resonator has to be avoided when designing superconducting cavities.

By introducing a modified beam dynamics (KONUS), the quadrupoles can be placed outside the resonator. The principle of this dynamics is explained in fig. 3. A detailed description can be found in ref. [8].

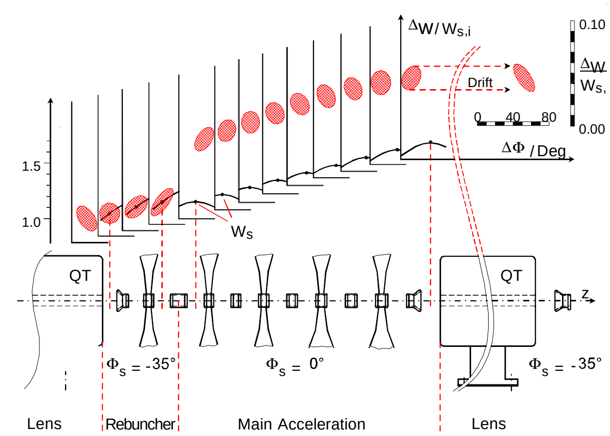

Figure 3: Principle of the KONUS beam dynamics: The particle bunch is focused transversally by quadrupole triplets that can be placed outside of the resonator. Rebunching features are implemented in the tank entrance gap section.

The main accelerating section consists of typically 10 to 30 drift tubes without any transverse focusing elements. The particle pulse is injected into this 0° section asynchronously with a surplus in energy. In the subsequent section, the beam is focused transversally by a quadrupole triplet, that is kept as short as possible, to keep the phase spread of the particle pulse low. In front of the succeeding accelerating section, a -35° rebunching section formed by 3 to 7 drift tubes typically matches the beam longitudinally. The capability of this dynamics has been proved on several machines, including a high current application [5,6].

4 DESIGN OF A SUPERCONDUCTING CH-MODE CAVITY

As mentioned before, the acceleration of ions using H-mode type resonators is practicable starting from particle energies of some 100 keV/u up to about 100 MeV/u, depending on the choice of the operating frequency and the drift tube geometry. The prototype cavity discussed now is one part of an accelerator design proposed for a high current proton linac. The parameters of this prototype cavity are summarized in tab.1.

The RF behavior of the resonator is studied with an analytical model [9] that allows an extensive optimization of the cavity parameters. The consequent numerical simulation of the resonator is done using the MAFIA package [10]. As a first step, only two accelerating gaps have been computed (see fig. 4). The results of this calculation are given in tab. 2. Further steps in optimizing will be performed. All parameters predicted with the analytical model were found within 10 % deviation. When compared to other types of cavity [11], the normalized shunt impedance (R/Q) of the CH-mode cavity is higher indicating the high accelerating efficiency.

Table 1: Parameters of the superconducting CH-mode prototype cavity.

Particle type	Proton
Energy range	10.9 - 17.6 MeV
Frequency	433 MHz
Mode	$H_{21(0)}$ (CH)
No. Gaps	18
Cavity length	1.01 m
Drift tube aperture	17 - 25 mm
Transit time factor	0.8 - 0.85
Tank radius	125 mm
Current limit	300 mA

Table 2: Expected parameters of the superconducting CH-mode prototype cavity.

Stored energy	4.1 J
E_{max} (E_{acc} = 6.7 MV/m)	38 MV/m
B_{max} (E_{acc} = 6.7 MV/m)	70 mT
Norm. shunt impedance	3.6 kΩ/m
Geometric factor	110 Ω
Unloaded Q-value (4K,Pb)	$1.2\cdot10^9$
Dissipated power (4K,Pb)	9.6 W
Unloaded Q-value (4K,Nb)	$2\cdot10^9$
Dissipated power (4K,Nb)	5.8 W

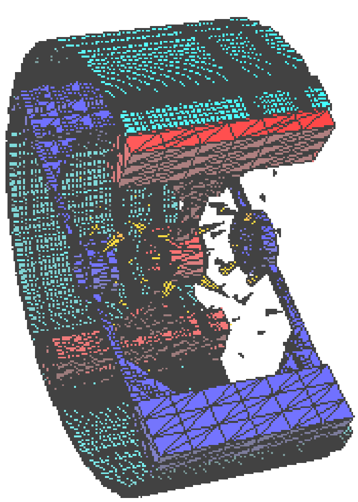

Figure 4: Electric field distribution in a two gap segment of the prototype CH-mode cavity calculated with MAFIA.

Figure 4 gives an impression of the resonator geometry. The electric field is concentrated between the drift tubes while the rest of the resonator is mainly field free. The dipole admixture to the field between the drift tubes is well below 10^{-6}.

5 FABRICATION OPTIONS

Like the normal conducting IH-mode resonators we plan to fabricate the drift tubes and the stems out of bulk copper. After mounting the drift tubes, the whole cavity will be electroplated with oxygen free copper to get a clean and smooth surface. Concerning the deposition of the superconducting surface layer two options are favored at present. One is to sputter the cavity with niobium. Though the behavior of thin niobium films is well known and would fit very well to the requirements, it might need much effort for sputtering this complex geometry with the needed precision. The second option is electrolytic lead plating. The experience made elsewhere [12] is very promising and the surface preparation is easier compared to the sputtering process. The considerably lower quality (tab. 2) factor of the later process seems to be acceptable.

6 CONCLUSION

The normal conducting H-mode cavities showed their suitability for ion acceleration in many projects. First investigations indicate that H-mode cavities may be well suited to design superconducting resonators. The results of the numerical simulation of such a cavity are very promising. Using state of the art technology the fabrication of a superconducting CH-mode cavity should be possible.

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