NEW CAVITY SHAPE DEVELOPMENTS FOR LOW BETA APPLICATIONS *

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Abstract

There is an increasing interest world wide in proton and ion linear accelerators for the low and medium energy range. Many of these accelerators will be operated at high duty cycles up to 100%. Superconducting cavities are favourable or sometimes even technologically necessary. Using conventional low beta cavities (quarter wave, half wave) leads to a large number of cavities and subsystems because of the small number of accelerating cells per cavity. The recently developed superconducting CH-cavity is the first multi-cell cavity for low beta applications. A prototype cavity (19 cells, β=0.1) has been tested with effective gradiends of 7 MV/m. Presently two optimized CH-cavities are under construction (β=0.15, 325 MHz, 7-cell and β=0.059, 217 MHz, 15 cells). Both cavities will be fully equipped with cryo-module, tuning systems and high power couplers. It is planned to test both cavities with beam at GSI, Darmstadt. The paper covers the development of the superconducting CH-cavity, different applications and future plans.

INTRODUCTION

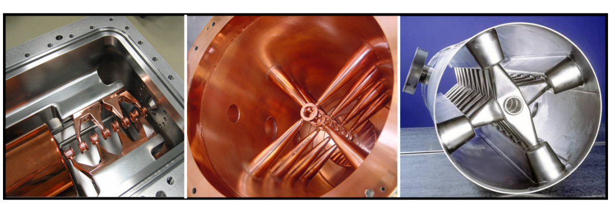

Figure 1: Different H-mode drift tube cavities: 217 MHz IH-cavity (left), 340 MHz room temperature CH-cavity (center), 360 MHz superconducting CH-cavity (right).

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 this reduces the filling factor significantly as cavities with a small number of cells imply a lot of drift spaces and increase the mechanical complexity of the linac significantly.

The CH-structure is a multi-cell cavity and belongs to the family of H-mode cavities which are operated in an H_{n1}-mode [1] (see Fig. 1). This new structure has been named CH-structure because of its cross-bar geometry and the H_{21}-mode [2, 3]. The CH-structure can be used between 150 MHz and 700 MHz. The usable energy range of the superconducting CH-structure is between 1.4 AMeV and 100 AMeV depending on frequency, beam current and charge-to-mass ratio.

CH-structures and multi-spoke cavities have some common properties like the cross-bar geometry. Main differences are the "drift tube in stem concept" where drift tubes with different lengths are welded into the stems to achieve a flat field distribution and to make allowance for increased particle velocity within the CH-cavity. Additionally, CH-cavities have girders which reduce the magnetic peak fields and give better possibilities for coupling and tuning [3].

SEMI-ANALYTICAL APPROACH

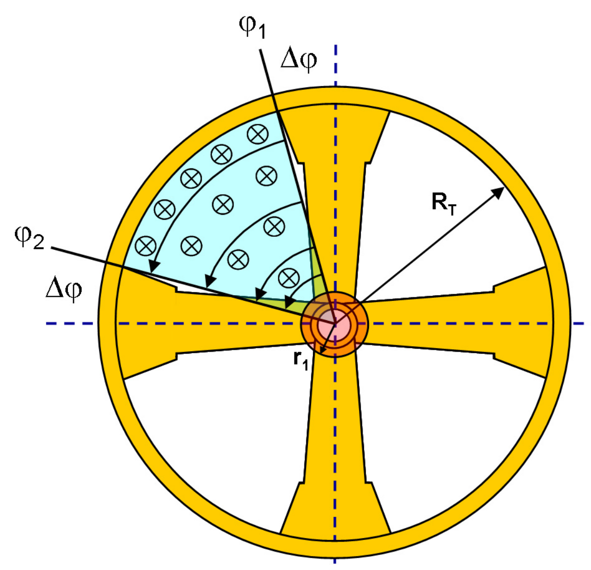

Figure 2: Equivalent geometry of a CH-cavity.

For the design of modern RF cavities powerful codes like Microwave Studio [4] are used to reach reasonable accuracy with respect to frequency and field distribution. However, sometimes it is from interest to estimate basic parameters like frequency, shunt impedance or Q-value from a semi-analytical model. Even if this model is not able to deliver such parameters with the same accuracy as numerical

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simulations it delivers scaling laws how these parameters scale with the frequency or with β.

The drift tube structure of a CH-cavity changes the field distribution significantly compared to an empty cylindrical cavity. The tank wall is at ground potential because the radial component E_r of the electric field vanishes at $r = R_T$ where R_T is the tank radius. In the first approximation the only existing component of the electric field is $E_\varphi(r)$ with $E_\varphi(R_T) = 0$. Within a radius r_1 the electric field is almost constant. It turned out that the longitudinal magnetic field $B_z(r)$ which is responsible for charging the drift tubes is approximately given by [5]

$$B_z(r) = B_0\left(1 - \frac{(R_T - r)^2}{R_T^2}\right) \qquad (1)$$

These considerations lead to a simplified equivalent geometry (see Fig. 12. Knowing the electromagnetic fields in the cavity it is possible to calculate the stored energy of the electric and magnetic field W_e and W_m. Using $W_e = W_m$ we obtain the resonance frequency ω [5]:

$$\omega \approx c\sqrt{\frac{0.73}{R_T^2\left(\frac{25}{144} + \frac{25}{72}\ln\left(\frac{R_T}{r_1}\right) - 0.5\right)}} \qquad (2)$$

In case of the superconducting prototype cavity R_T was 0.136 m and r_1 was 0.02 m. This gives a frequency f of 375 MHz. The measured frequency was 360 MHz. After calculating the specific inductance and capacitance and the required power we obtain the Q-value and the shunt impedance Z_0 [5]:

$$Q_0 \approx \frac{\mu_0 c\sigma\delta\left(\frac{\pi}{2} - 2\Delta\varphi\right)\overline{\beta}R_T\omega}{5(\pi c\overline{\beta} + \omega\Delta\varphi R_T)} \qquad (3)$$

$$Z_0 \approx 1.3\cdot 10^{-14}\frac{\omega^{7/2}R_T^3\left(\frac{\pi}{2} - 2\Delta\varphi\right)^2}{\overline{\beta}(15\pi c\overline{\beta} + 16\omega\Delta\varphi R_T)}\ (\Omega/m) \qquad (4)$$

σ is the conductivity, δ the skin depth and $\overline{\beta}$ is the average geometrical β along the cavity which can be calculated knowing the input and output values β_i and β_f:

$$\overline{\beta} = \left(\frac{\beta_i^3 + \beta_f^3}{2}\right)^{1/3} \qquad (5)$$

360 MHz CH-PROTOTYPE

A superconducting CH-prototype cavity with 19 accelerating cells, β=0.1, f=360 MHz has been developed and tested in Frankfurt [3]. Figure 3 shows the cavity before the final welding of the end cells and Figure 4 shows the experimental setup for the vertical tests. The cavity has been fabricated from RRR=250 bulk niobium at ACCEL GmbH (now renamed to Research Instruments RI). Table 1 summarizes the main parameters of this cavity. At the beginning the gradient was limited to values of 4.7 MV/m because of a field emission induced quench. Strong X-ray emission could be observed [3]. After a detailed analysis of the X-ray distribution using Thermo-Luminescence Dosemeters (TLD) a single emission spot could be identified. After an additional surface preparation including a mild BCP and HPR an effective gradient of 7 MV/m could be achieved (see Fig. 5). This corresponds to an effective voltage of 5.6 MV [5]. In the framework of the HIPPI

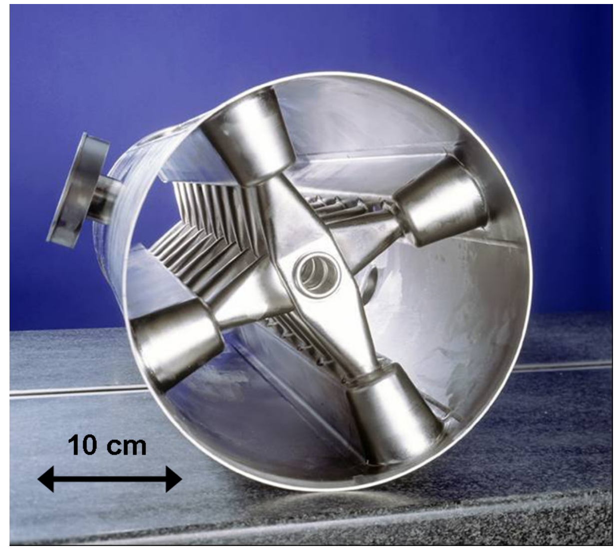

Figure 3: Superconducting 360 MHz, β=0.1 CH-prototype cavity.

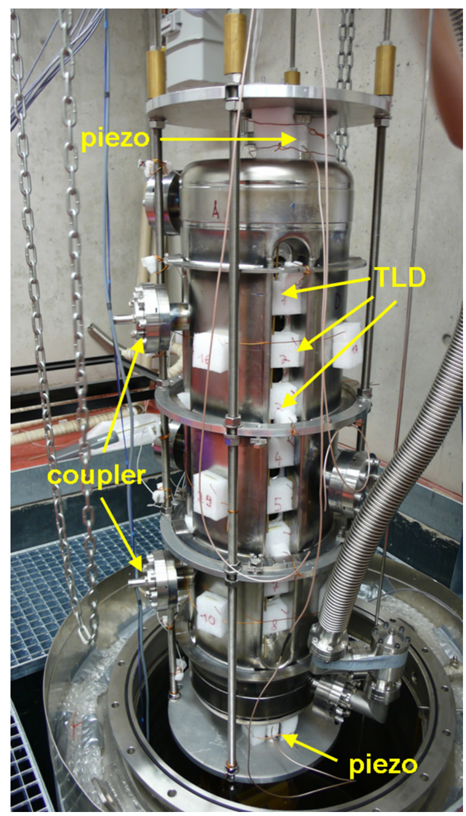

Figure 4: Experimental setup for vertical tests.

Table 1: Parameters of the Superconducting CH-prototype

cavity type	Crossbar H-mode (CH)
β	0.1
f (MHz)	360
cells	19
length (mm)	1048
diameter (mm)	272
G (Ω)	56
Q_0 (measured)	$6.8 \cdot 10^8$
R_a/Q_0 (Ω)	3180
R_a/Q_0 per cell (Ω)	167
R_aR_s (Ω^2)	178000
E_p/E_a	5.2
B_p/E_a (mT/(MV/m))	5.7
W/E_a (mJ/(MV/m))	92

(High Intensity Pulsed Proton Injectors) research program a tuning system has been developed [6]. The frequency of the cavity is changed by pushing the end-cells. This results in a change in capacitance and finally in a frequency shift. Measurements at room temperature showed a sensitivity of 400 kHz/mm (per end cell) (see Fig. 6). The prototype

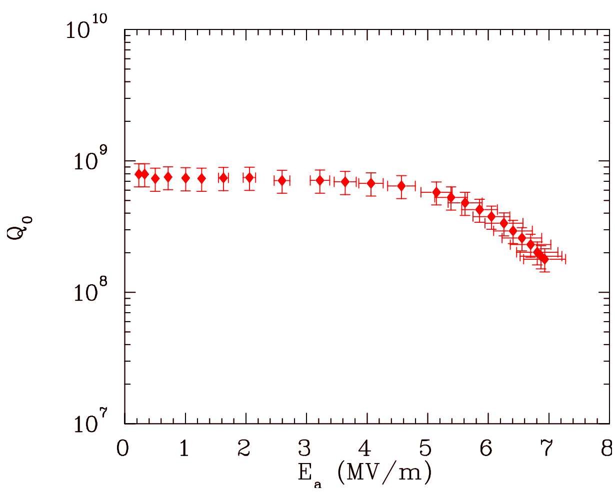

Figure 5: Measured Q-value as function of the gradient for the 360 MHz CH-prototype cavity.

cavity has been prepared for tests in a horizontal cryo module (Fig. 7). In a first step the slow tuner has been tested. The tuning range could be validated with 400 kHz/mm. In a next step the fast tuner system which is based on piezo technology will be tested [6].

325 MHz CH-CAVITY

Recently the construction of a new superconducting 325 MHz, β=0.15 CH-cavity with optimized geometry has started. The new geometry is optimized for high power applications like EUROTRANS [7] or IFMIF [7, 9]. The stem base geometry has been changed to house larger power couplers. This gives also the possibility to use larger static

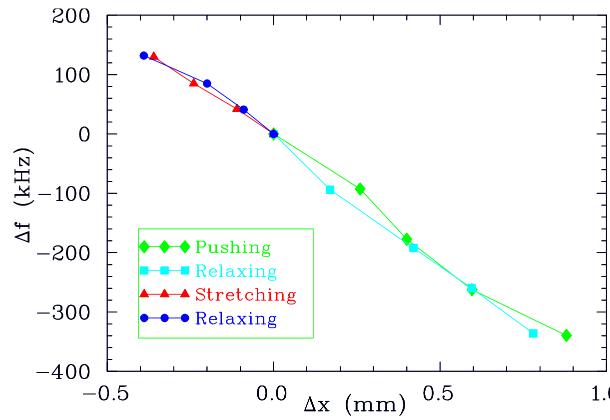

Figure 6: Measured frequency shift by changing the end cell length. Negative values mean stretching and positive values pushing the end cells.

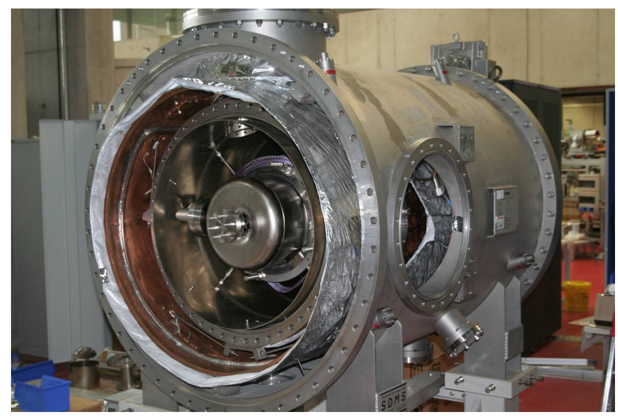

Figure 7: 360 MHz CH-cavity in the horizontal cryo module.

tuners to correct the frequency during the fabrication process. In total three different kinds of tuners are foreseen. The principle of static tuners has been demonstrated already with the 360 MHz superconducting CH-prototype cavity [3]. After the fabrication movable cylindrical brass tuners are screwed into the girder of the cavity. Moving the tuners into the cavity leads to a decrease of the frequency because of the capacitive effect. After fixing all tuner heights the brass tuners are removed and replaced by niobium cylinders which will be welded into the girder. The new cavity will use 4 static tuners with a diameter of 30 mm and a height between 0 and 60 mm. Figure 8 shows the frequency as function of the tuner height using all four tuners. A new slow and fast tuner system has been developed for this cavity. While the first CH-prototype cavity was tuned by pushing the end-cells from outside the new cavity will use bellow tuners inside the cavity. One bellow tuner will act as slow tuner while the second tuner will use a piezo to correct fast frequency variations due to microphonics and Lorentz-force detuning. One big advantage of the new tuner system is that there is no additional longitudinal space required for mechanical installations.

To achieve a flat field distribution the first prototype had long end cells. This resulted in an additional drift space of about 25% of the total cavity length. The drift space reduced the real estate gradient and it can have a negative impact on the longitudinal beam dynamics, especially in case of high current. The new design has inclined stems in the end cells to increase the inductance in that region. The result is a very compact cavity with flat field distribution. The disadvantage of the new stem geometry is an increased magnetic peak field.

The new cavity will be fully equipped with power couplers and helium vessel and it will be tested in a horizontal cryomodule together with two superconducting solenoids. In addition it is planned to test the cavity with beam at GSI. The 108.48 MHz Unilac linear accelerator will deliver a 10 mA Uranium beam with an energy of 11.4 AMeV which corresponds to a β of 0.158. The cavity will have 7 accelerating cells and should provide an effective voltage of 3 MV. It is expected to test the cavity in 2011-2012. Figure 9 shows the geometry of the new 325 MHz cavity and Table 2 summarizes the main parameters.

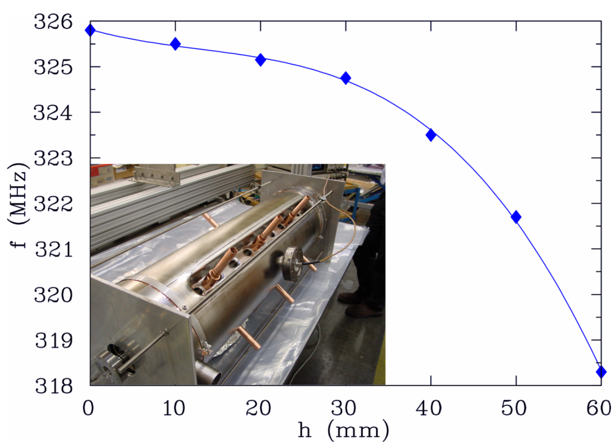

Figure 8: Frequency shift using 4 static tuners with a diamter of 30 mm.

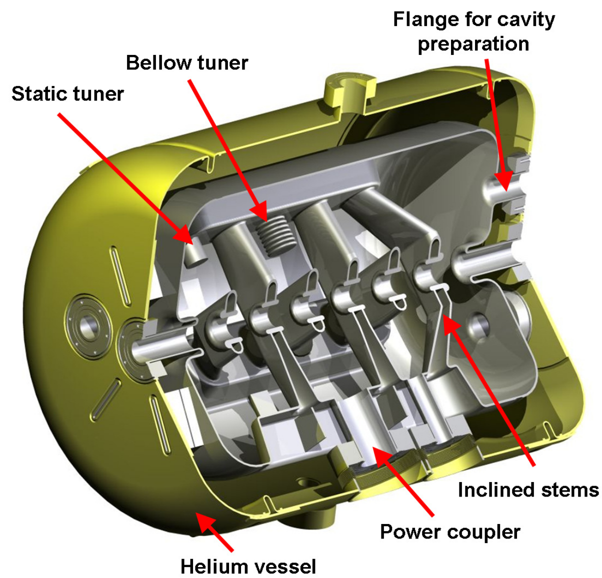

Figure 9: Layout of the superconducting 325 MHz CH-cavity with helium vessel.

Table 2: Parameters of the 325 MHz Superconducting CH-cavity

cavity type	Crossbar H-mode (CH)
$\overline{\beta}$	0.15
f (MHz)	325
cells	7
length (mm)	550
diameter (mm)	356
static tuner	4
bellow tuner	2
G (Ω)	64
R_a/Q_0 (Ω)	1250
R_a/Q_0 per cell (Ω)	179
R_aR_s (Ω^2)	80000
E_p/E_a	5.1
B_p/E_a (mT/(MV/m))	13

APPLICATIONS

EUROTRANS

Accelerator Driven Systems (ADS) for nuclear waste transmutation require proton drivers with energies between 600 and 800 MeV and beam currents of several mA for demonstrators and up to 25 mA for a large industrial systems. The required operation is continuous wave (cw) which prefers superconducting cavity technology. One major issue of these accelerators is reliability and fault tolerance to reduce the number of unwanted beam trips. Additionally, beam losses have to be minimized to avoid activation of the machine. The European activities are focused in the EUROTRANS project. The EUROTRANS driver linac has to deliver a 600 MeV proton beam with a maximum beam current of 4 mA but it is capable to accelerate up to 25 mA. The present reference design for the EUROTRANS proton driver linac is shown in Figure 10.

In order to improve the overall reliability two 17 MeV, 352 MHz injectors are foreseen. Each injector consists of a 3 MeV RFQ, two room temperature CH-cavities and four superconducting (sc) CH cavities. The intermediate energy section (17-100 MeV) consists of independently phased superconducting spoke cavities. It is followed by a high energy section with two groups of superconducting elliptical 5-cell cavities. Both front ends are in operation with the nominal beam current. But only one injector delivers the beam to the main linac. In case of a beam trip in this injector which can not be handled within a given time (t<1s) the second injector will deliver the beam. The main acceleration of the front end will be provided by four supercon-

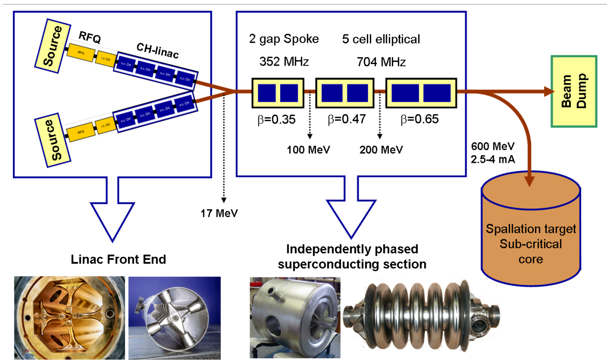

Figure 10: Reference design of the EUROTRANS 600 MeV proton driver linac.

ducting CH-cavities. The design goal is 3.9 MV/m with a Q-value of $2 \cdot 10^8$. Figure 11 shows a scheme of the 17 MeV EUROTRANS front-end and Table 3 summarizes the main parameters of the first superconducting CH-cavity for EUROTRANS (Fig. 12). The cavity will provide 2.5 MV effective voltage and will require a power of 18 W at the design Q-value of $2 \cdot 10^8$ without beam.

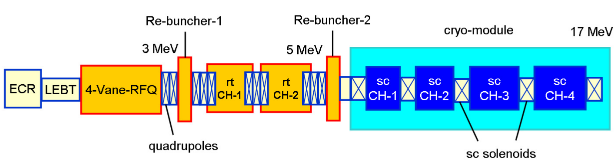

Figure 11: Layout of the 17 MeV EUROTRANS front-end consisting of four 352 MHz superconducting CH-cavities.

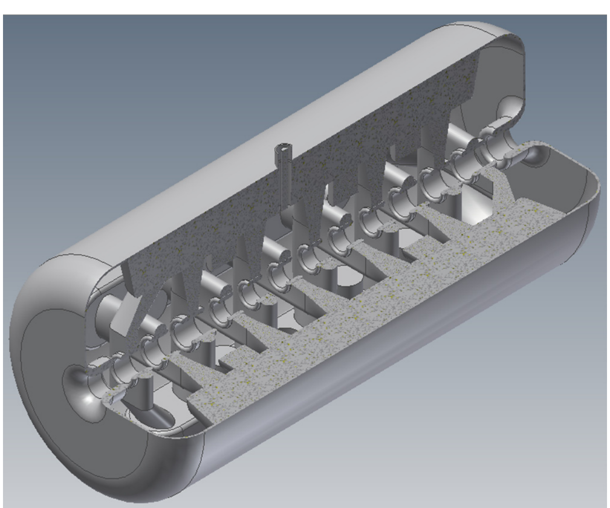

Figure 12: The first superconducting CH-cavity of the EUROTRANS front-end.

Table 3: Parameters of the First EUROTRANS CH-cavity

cavity type	Crossbar H-mode (CH)
β	0.116
f (MHz)	352
cells	13
static tuner	7
bellow tuner	3
length (mm)	703
diameter (mm)	286
G (Ω)	56
Q_0 (goal)	$2 \cdot 10^8$
R_a/Q_0 (Ω)	1775
R_a/Q_0 per cell (Ω)	137
R_aR_s (Ω^2)	99000
E_a (MV/m)	3.9
U_a (MV)	2.5
E_p (MV/m)	26.5
B_p (mT)	40
P_c @Q_0=$2 \cdot 10^8$ (W)	18

SHE cw Heavy Ion Linac

At GSI (Darmstadt, Germany) the design effort for a cw operated heavy ion linac has started. This dedicated linac will be used for the production of super heavy elements. The linac has to provide ion beams with a A/q of up to 6 and with energies up to 7.3 AMeV. Above an energy of 3.5 AMeV the linac is fully energy variable. Due to the required cw operation the main linac will be superconducting. The front end is the existing high charge injector (108.48 MHz, 1.4 AMeV) which is presently being upgraded for the required duty cycle. The main acceleration of about 35 MV will be provided by the superconducting linac consisting of 9 CH-cavities operated at 217 MHz. The first superconducting CH-cavity is under design and it is planned to test it with beam in 2012. Each cavity is powered by a 5 kW solid state amplifier. The different CH-cavities are optimized for a different geometrical β. To simplify the production and to reach full energy variability the cell length within one specific cavity is kept constant (**EQUUS**-concept=**EQU**idistant m**U**lti-gap **S**tructure). Transverse focusing between the cavities will be provided by superconducting solenoids. Figure 14 shows the layout of the superconducting part of the new heavy ion linac. Although the gradient is moderate with 5.1 MV/m the real estate gradient is very high compared with conventional 2-gap structures. This results in a compact linac with a length of about 10 m.

SUMMARY AND OUTLOOK

The superconducting CH-cavity is an excellent candidate for proton and ion acceleration in the low and medium energy range. The major advantage is the large energy gain per cavity which leads to high real estate gradients and to a significant reduction of required accelerator components.

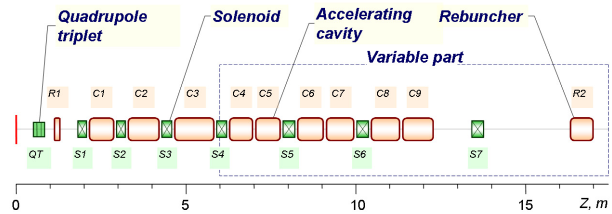

Figure 13: Layout a cw heavy ion linac for the production of super-heavy elements (SHE) consisting of nine 217 MHz CH-cavities.

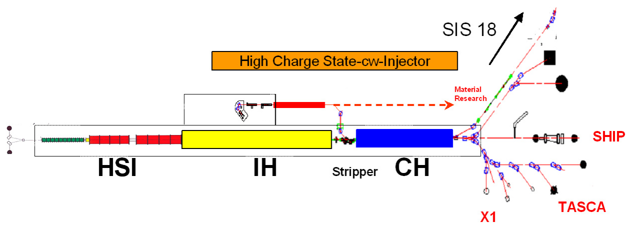

Figure 14: Location of the new cw heavy ion linac which will be built parallel to the existing Unilac at GSI.

A first prototype cavity has been tested with gradients of 7 MV/m. Presently two more cavities (325 MHz, β=0.158 and 217 MHz, β=0.06) are under construction. Both cavities will be tested with beam at GSI.

ACKNOWLEDGEMENT

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