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DESIGN OF THE TWO-GAP SUPERCONDUCTING RE-BUNCHER*

M. Gusarova[1†], MEPhI National Research Nuclear University, 115409 Moscow, Russia
W. Barth[2,3], S. Yaramyshev[3], GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany, M. Miski-Oglu, HIM Helmholtz Institute Mainz, 55099 Mainz, Germany
M. Basten, M. Busch, IAP University of Frankfurt, 60438 Frankfurt am Main, Germany
[1]also Joint Institute for Nuclear Research, Dubna, Russia
[2]also HIM Helmholtz Institute Mainz, 55099 Mainz, Germany
[3]also MEPhI National Research Nuclear University, 115409 Moscow, Russia

Abstract

A new design of a spoke cavity for low relative velocities of heavy ions has been elaborated. Simulation results for a 2-gap spoke cavity with a resonance frequency of 216.816 MHz and a relative velocity of 0.07c are presented.

INTRODUCTION

The ongoing UNILAC upgrade program at GSI has to provide for high current heavy ion beams [1-4] as well as proton [5] beams for the Facility of Antiproton and Ion Research (FAIR) [6] at Darmstadt. Due to the low duty factor requirements for FAIR injector operation, a use of the UNILAC for super heavy element (SHE) research at GSI will be strongly limited.

The dedicated standalone superconducting (sc) continuous wave (cw) Linac HELIAC (HElmholtz LInear ACcelerator) is assumed to meet the demands of the experimental program best. The cw mode of the machine operation significantly increases the SHE production rate. The beam dynamics concept [7-9] for the HELIAC is based on multi cell CH-DTL cavities, operating at 216.816 MHz. The first superconducting CH-DTL cavity of HELIAC was successfully commissioned with beam [10,11] at GSI in summer 2017. Figure 1 shows the layout of the first cryo module [12, 13], which comprises three CH-DTL cavities, two solenoids and a short re-buncher-cavity. In this paper the design of a two-gap spoke re-buncher cavity with geometrical limitations of length and diameter is presented.

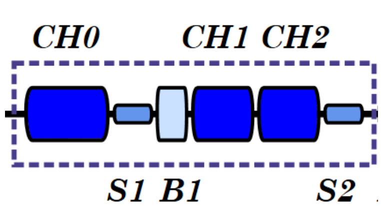

Figure 1: Layout for the first HELIAC cryo module with three CH-DTLs, two solenoids and one re-buncher cavity. The total length is 4.5 m.

RF DESIGN AND RF OPTIMIZATION

The main parameters of the re-buncher (Table 1) are determined by the fixed operating frequency of 216.816 MHz and the space limitation inside the given cryostat layout.

Table 1: Required Re-Buncher Parameters

Parameter	Designation	Value
Frequency	f, MHz	216.816
Rel. Velocity	β	0.07
Number of gaps	N_g	2-3
Drift tube aperture	R_a, mm	30-35
Length	L, mm	<300
Diameter	D, mm	410-500

According to Fig. 2 for the given parameters, the use of a quarter-wave structure is effective, however, in order to unify the existing equipment of the first HELIAC cryo module (cryostat, frequency-tuning elements, etc.), the possibility of creating a compact two-gap spoke re-buncher that allows the use of already developed devices is being considered. As illustrated in Fig.2, the superconducting spoke resonators are usually used as accelerating structures for particle velocities above 0.2c and up to 0.7c in the frequency range from 300 MHz to 900 MHz [14]. The main features of the newly developed design are the low frequency f = 216.816 MHz and the low relative velocity β = 0.07c, which are below the typical values.

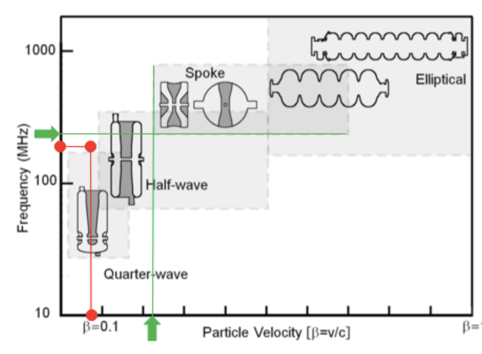

Figure 2: Practical superconducting cavity geometries spanning the full range of velocities.

The shape of the spoke and the length of the accelerator gap (g) is chosen to adjust the frequency of the cavity to 216.816 MHz, while the cavity diameter D is limited to 410 mm and the overall length L to 300 mm.

Figure 3 shows classical shapes of spokes for RF-cavities. At first these resonators were designed with a cylindrical spoke (see Fig. 3(a)). When the diameter of the spoke became comparable to the aperture, the spokes design was equipped with a flattening (Fig. 3(b)) [15].

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† MAGusarova@mephi.ru

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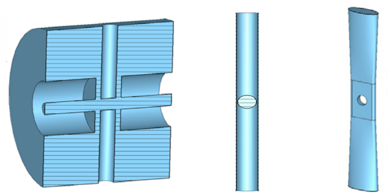


(a) (b) (c)

Figure 3: Cross section of a simple two-gap spoke cavity structure (a) and two versions of the spoke geometry (b), (c).

According to [16] the optimal ratio of the length of the accelerating gap *g* and the length between the gaps of the two-gap cavity $d=\beta\lambda/2$ (in order to obtain the maximum transmission factor at the dedicated speed) is g/d = 0.3; the gap length g is 16 mm. For the cylindrical spoke (b), the CST studio [17] calculation of electromagnetic fields results in a drift tube aperture which is close to the diameter of the spoke. The variant with an elliptical spoke exceeds the resonance frequency of 216.816 MHz for the given geometrical constrains.

To reduce the operating frequency, the inductance L or the capacitance C has to be increase:

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (1).$$

Figure 4 shows the proposed geometry of the outer tank and the spoke: strong limitations in diameter *D* of the structure and the top area of the spoke (parameters *a* and *b*) prohibit a further increase of the inductance. An increase of the capacitance could be performed by reducing the accelerating gap width below 16 mm and by increasing the surface area in transversal direction (parameter *x*).

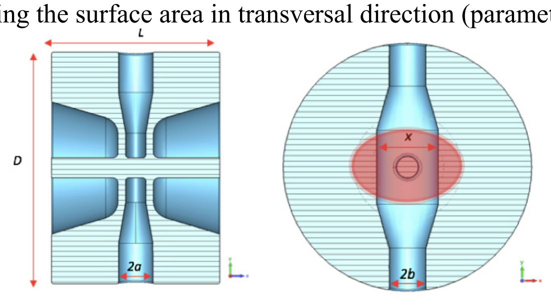
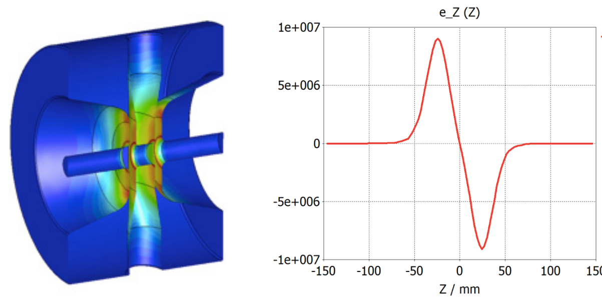


Figure 4: Proposed tank geometry of the two-gap spoke cavity; with parameters a, b and x.

A parametric study of the structure with an increased capacitance has been performed, taking the minimization of the peak values of the electric and magnetic fields on the surface of the structure into account. In Fig. 5 CST studio simulations of the el. field distribution (a), as well as the longitudinal field $E_z(z)$ along the beam axis z (b) is depicted. Table 2 summarizes the main RF parameters of the two-gap spoke re-buncher, designed for a resonance frequency of 216.816 MHz and for a rel. velocity of 0.07c.



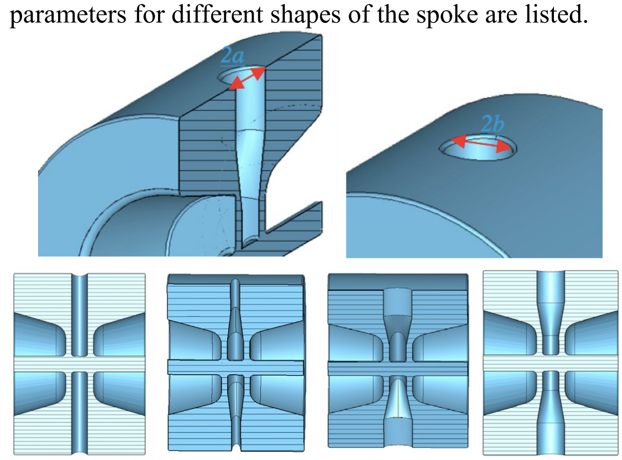
(a) (b)

Figure 5: CST studio simulation of the el. field in the cross section of the two-gap spoke re-buncher (a), and E_z(z) (b).

Table 2: RF parameters of the two-gap spoke re-buncher, calculated with a stored energy of 1 Joule.

***a* = *b*, mm**	**30**	**29**
f, MHz	217.9	216.8
U, kV	391	396
E_p, MV/m	27	27.5
B_p, mT	38	40
$E_{acc}= U_{total}/ \mid \lambda$, MV/m	4	4
E_p/E_{acc}	6.6	6.5
B_p/E_{acc}, mT/[MV/m]	9.5	10
R/Q	110	114

The dependence of frequency and B_p/E_{acc} on the form of the top of the spoke has been investigated, as shown in Fig.6 for different shapes. In Table 3 dimensions and RF parameters for different shapes of the spoke are listed.



(a) (b) (c) (d, e)

Figure 6: Different shape of the top of the spoke.

Table 3. Geometrical Dimensions for Different Shapes of the Top of the Spoke and RF Parameters

	(a)	**(b)**	**(c)**	**(d)**	**(e)**
a, mm	17.7	10	30	30	25
b, mm	50	30	10	30	25
B_p/E_{acc}, mT/[MV/m]	17.9	24.2	21.4	9.4	10
f, MHz	225	206	203	218	212

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As depicted in Table 3, acceptable values of B_p/E_{acc} are achieved using a cylindrical shape of the top of the spoke (variants d and e).

SIMULATIONS OF TUNING SYSTEMS

The dynamic tuner (Fig.7), positioned perpendicularly to the beam direction, provides for frequency tuning during operation. The geometrical design of the bellow is comparable to the dynamic tuner for the CH- cavities of HELIAC [18]. Table 4 summarizes the calculations of the resonance frequency for different tuner lengths h and corresponding values of E_p/E_{acc}.

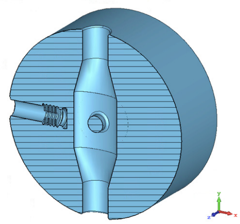


Figure 7: Tuner with bellow.

Table 4: Dependence of Frequency f and E_p/E_{acc} on the Length h of the Tuner

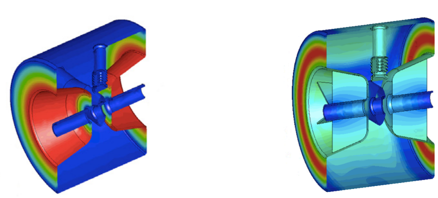
h, mm	**120**	**125**	**130**	**135**	**140**	**145**
f, MHz	217.8	217.7	217.6	217.3	216.4	213.8
E_p/E_{acc}	6.7	6.8	6.5	6.7	9.4	18.2

A tuner with a length of 134 mm provides for a frequency shift of 80-90 kHz/mm, while the minimum ratio of $E_p/E_{acc} \sim 6.6$ is maintained.

MECHANICAL SIMULATIONS

The primary estimation of the frequency shift due to pressure and cooling to temperature 4.2 was carried out by an iterative method using the electromagnetic and mechanical solvers of the CST Studio [17]. The frequency shift with a uniform increase in the vacuum volume of the structure by 0.1 mm was 750 kHz. This means that the structure will have a high sensitivity to etching. The largest contribution to the frequency shift is made by the change in the size of the accelerating gap. The frequency shift during cool down to 4.2 K is about 2 MHz. As a boundary condition this study of mechanical properties was carried out with the fixed drift tube.

The simulations of the pressure sensitivity *df/dp* stiffeners are shown in Fig. 8, data are presented in Table 5.



(a) (b)

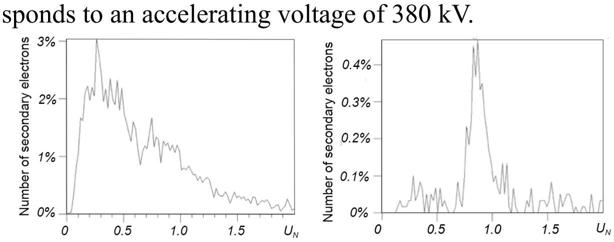
Figure 8: Max. displacement (a) without stiffeners; (b) with stiffeners.

Table 5: Max. Displacement, Max. Mechanical Stress and *df/dp*

	Max. displacement, mm	Max. Stress, MPa	*df/dp*, Hz/mbar
without stiffeners (a)	0.400	219	608.0
with stiffeners (b)	0.047	63	58.7

MULTIPACTING ANALYSIS

Computer simulations of the multipacting discharge have been performed by means of the MultP-M code [19] without taking additional tuners into account. The tuner is potentially a source of multipactor barriers at low field values, due to narrow gaps inside the bellow . The long narrow accelerating gap is another risk of multipacting at low field levels. Fig. 9 illustrates the growth rates of secondary electrons after 10 (a) and 40 (b) RF periods for a voltage level U_N from 0 to 1. The value U_N =1 corresponds to an accelerating voltage of 380 kV.



(a) (b)

Figure 9: Number of secondary electrons after 10 (a) and (40) RF periods for different value U_N.

The multipactor trajectories are located on the outer surface of the structure for a wide range of accelerating voltages, while the trajectories are damped. As shown in [15, 20] for similiar spoke cavities multipacting barriers potentially could be overcome by a dedicated RF-conditioning process.

CONCLUSION

The possibility of creating a two-gap compact rebuncher of the spoke design, calculated for a frequency of 216.816 MHz with tuning by an internal dynamic tuner, has been presented. This work is important for the cw linac HELIAC at GSI, which is one of the new developments in accelerators [21 - 27]. The two-gap compact rebuncher of the spoke design simultaneously ensure the preservation of the minimum length of the first module, and to reduce the costs associated with the development of the cryostat for designs of other types and frequency tuning systems.

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