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RF-ACCELERATION STUDIES FOR THE HBS-LINAC APPLYING ALTERNATING PHASE FOCUSING CONCEPTS*

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Abstract

The recent layout of the Jülich High Brilliance Neutron Source (HBS) driver linac is based on short crossbar H-mode (CH) cavities operated at a fixed synchronous phase. In the last decades the computing power for the development of linacs, available to physicists and engineers, has been increased drastically. This also enabled the accelerator community to finally carry out the required R&D to generate further the idea of drift tube linacs with alternating phase focusing (APF) beam dynamics, originally proposed in the 1950s. This focusing method uses the electric fields in between the drift tubes (i.e., gaps) to provide subsequent transverse and longitudinal focusing to the beam along multiple gaps. The beam focusing properties within each gap are adjusted individually by means of the synchronous phase. As a result of the alternating phase focusing method, these linacs can operate completely without internal magnetic lenses. The R&D-program for the high brilliance neutron source HBS offered the opportunity to investigate the APF concept further in order to open this advanced concept for high duty-factor, high intensity hadron beam acceleration. Besides, a prototype APF-interdigital H-mode (IH)-cavity has been designed and is going to be build and tested in the next future.

INTRODUCTION

The Jülich High Brilliance Neutron Source (HBS) is currently developed to provide high-power neutron beams for scientific fields of physics, biology, chemistry geology, as well as material and engineering science [1, 2]. In order to provide high-power beams for various applications, normal conducting cavities capable for sustaining high thermal loads beyond 20 kW/m need to be designed and developed. As state-of-the-art normal conducting cavities, for 1 % to 10 % of speed of light interdigital H-mode (IH) cavities, and for 10 % to 50 % the speed of light, crossbar H-mode (CH) cavities are available, achieving high shunt impedance of up to 700 MΩ/m [3]. Challenges in cooling and dynamic tuning are addressed within the HBS Innovation Pool Project for safe and reliable routine operation of energy-efficient H-Type cavities [1–6].

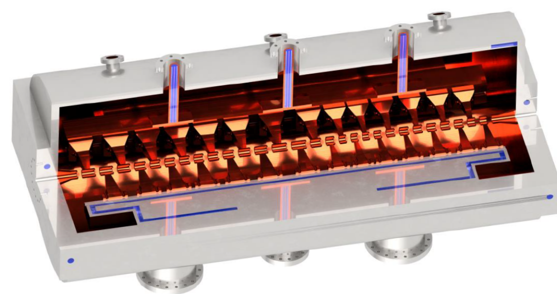

Figure 1: Conceptual drawing of an high power interdigital H-mode cavity with alternating phase focusing beam dynamics; cooling water supply system inside girder is shown in purple color.

At the GSI Helmholtz Centre for Heavy Ion Research (GSI) and the Helmholtz Institute Mainz (HIM) a continuous wave IH cavity has been developed applying alternating phase focusing (APF) in order to obtain elongated cavities without internal quadrupoles for simplified fabrication and stable operation (see Fig. 1 and Table 1). The thermal load of these cavities reaches up to 23 kW/m [4]. The HBS project will benefit from research on the subject of compact, thermal-loaded cavities, whereas the IH cavities will be employed in a different accelerator: the new heavy ion GSI continuous wave linear accelerator Helmholtz Linear Accelerator (HELIAC) [7, 8]. The HELIAC will meet the demand for continuous wave beams of the superheavy element synthesis and material research community, whereas the existing UNIversal Linear ACcelerator (UNILAC) will be upgraded for pulsed high peak-current applications for the Facility for Antiproton and Ion Research at Darmstadt (FAIR) [9].

METHOD

The concept of alternating phase focusing (APF) was originally suggested (to the best of the authors knowledge) by

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Table 1: Design parameters of interdigital H-mode cavities, foreseen to be employed in the HELIAC injector.

Ion mass/charge ratio	1 to 6
Max. beam current	1 mA
Repetition rate	continuous wave
Frequency	108.408 MHz
Energy range	300 keV/u to 1400 keV/u

J. Adlam [10] and M. Good [11] in 1953 and independently by I. Fainberg [12] in 1956. The theoretical framework was elaborated in the following years by I. M. Kapchinsky [13]. Yet, the first actual operation of an APF-linac was reported by Y. Iwata *et al.* [14] in 2007 (see Table 2). It appears that the APF method of beam focusing and acceleration was not used extensively because the computational capabilities required to construct this type of cavity were not available.

Table 2: Designed, planned or operational alternating phase focusing drift tube linacs. An extended table can be found in Ref. [15].

Project Name	**Cavity Commissioning**	***A/Z***
J-PARC muon linac [16, 17]	2022 [17]	0.1[a]
HELIAC injector — two cavity design [4, 7]	(ordered 2022)	1 to 6
325 MHz proton medical accelerator [18]	(design proposed 2019)	2
Compact IH [19]	2015	2
HIMAC medical synchrotron injector [14]	2007	3
HELIAC injector — single cavity design [15]	no	1 to 6
108 MHz medical synchrotron injector [20]	no	3

[a] Due to Muon mass

The principle of APF was extensively discussed in literature [13, 15, 20]. To give a review of the basic concept, consider a standard drift tube linac. It comprises a lattice of tubes, which change their distance concerning the beam velocity. The radio frequency (RF) phase (synonimous with the time when the beam center enters the gap center) is in each gap the same, usually $\phi = -30°$. This results in longitudinal focusing and transverse defocusing. The latter is usually required to be counteracted by magnetic focusing elements. The energy gain achieved is given by $\Delta W = U_{\text{eff}} \cos(\phi)$, according to the effective voltage U_{eff} applied in the RF-gap. In contrast, alternating phase focusing (APF) cavities have an adjusted tube-gap geometry to yield a different RF phase ϕ_i of the synchronous particle in each gap center, thus the cell length has to be altered in accordance with the desired phase:

$$L_{\text{cell}} = \frac{\beta\lambda}{2} + \beta\lambda\frac{\Delta\phi}{360°} \ , \qquad (1)$$

using the relative velocity $\beta = v/c$, RF wavelength λ, and change of synchronous phase in between two neighboring gaps $\Delta\phi = \phi_{i+1} - \phi_i$. The electric focusing strength k is proportional to $k_z \propto \sin(\phi)$ longitudinally and $k_{x,y} \propto -1/2\sin(\phi)$ transversely. A set of phases has to be found to provide for desired focusing properties along the cavity. In the APF approach, positive, as well as negative phases are applied in order to focus the beam alternating in the transverse and longitudinal direction. The additional transverse focusing (compared to the standard constant-phase approach) yields elongated cavities, without additional magnetic lenses. This can simplify the production of such cavities, positively impacting the price tag and reliability of an accelerator unit.

A crucial factor for designing APF cavities is the harmonization of structural computer-aided design (CAD) and beam dynamics layout, as both scopes influence each other. The CAD software must be regularly updated with the desired tube/gap lattice, and the realistically calculated voltages from the 3D geometry must be reiterated in the beam dynamics software.

A lower threshold for the application of APF cavities is the ratio of the cell length to the beam aperture. A too low ratio will not yield a significant electric field on the beam axis. Additionally, at a low beam energy the cell length is too short and the production of DTL structures is impeded. An upper threshold for the use of APF cavities is derived from beam velocity. At higher beam velocities, magnetic focusing becomes preferable over electric focusing, as the Lorentz force in contrast to the Coulomb force scales with the beam velocity. The upper threshold is thus comparable to those of radio frequency quadrupoles (RFQs) at a kinetic energy of several MeV/u. Thus, APF cavities potentially offer an energy-efficient (high shunt impedance) alternative to the high-energy part of RFQs [18].

RESULTS

In the frame of the HBS Innovation Pool Project, two IH cavities for continuous wave (CW) acceleration of heavy ions has been developed, foreseen in the second step to be operated as part of the HELIAC injector linac. Detailed information on the beam dynamics design [7] and on the RF and thermal design [4] has been published. An overview of relevant RF cavity properties of Cavity-1 and Cavity-2 is displayed in Table 3.

Two separate APF IH cavities, separated by a quadrupole triplet, have been designed. This robust and reliable design has been preferred over a design using only one long cavity without any additional focusing element (see Table 2). Nevertheless, the dedicated APF beam dynamics provides additional transversal beam focusing within the two cavities, so that the cavity length could be increased in contrast to a

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Table 3: Interdigital H-Mode RF Design Parameters [4]

Property	Cavity-1	Cavity-2
Number of gaps	29	27
Effective length L_{eff}	1.31 m	1.75 m
Length (outer cavity)	1.5 m	2.0 m
Quality factor Q_0	19000	22000
Shunt impedance Z_0	690 MΩ/m	425 MΩ/m
RF-Power (CW)	20 kW	48 kW
Max. temperature	≈ 413 K	≈ 441 K
Accelerating gradient	3.0 MV/m	3.1 MV/m
Electric peak field	28.9 MV/m	29.5 MV/m
Drift tube aperture radius	9 mm	9 mm
Drift tube outer radius	14 mm	17 mm

DTL with constant synchronous phase. The synchronous phase within Cavity-1 oscillates from −90° to 90° in order to accelerate the beam from 300 keV/u to 700 keV/u. Cavity-2 provides for beam acceleration to the final energy of 1.4 MeV/u and additional beam focusing in all directions. A matching section, consisting of two quadrupole multiplets and two rebunchers, refocuses the beam to the entrance of the superconducting (SC) HELIAC (see Fig. 2).

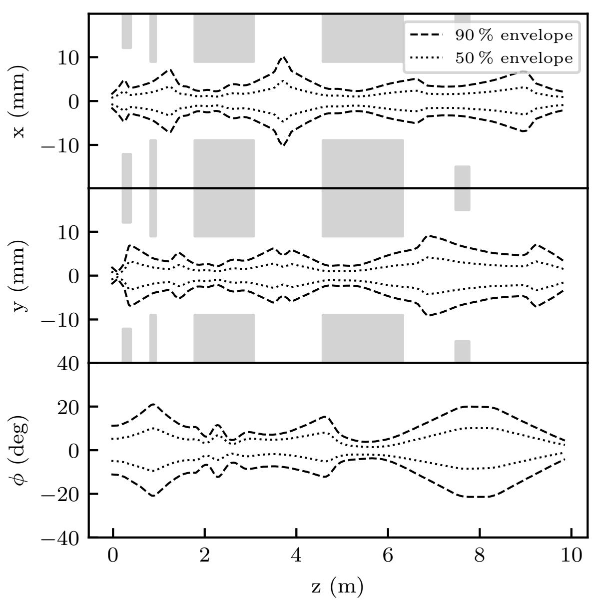

Figure 2: Beam envelopes along the accelerator from RFQ output to SC HELIAC input. The apertures are indicated in gray; the two gray blocks indicate the apertures of Cavity-1 and -2.

The thermal load on the cavities, with copper stems/tubes and copper-plated mild steel frames, reaches up to 48 kW (see Table 3). The cavities were therefore designed to absorb the dissipated power by water cooling (see Fig. 1). The remaining heat load leads to elastic deformation of the cavity and thus a shift of its resonance frequency. Three parallel-operated frequency tuners, mounted on step motors, are used to mitigate the frequency shift during high-power operation. The tuners are capable of tuning the frequency by 1 MHz. The movement of the tuners furthermore causes a deformation of the electromagnetic field inside the cavity, which could lead to a decreased beam quality. The tuner positioning and dimensions were optimized to keep the change of the electric field on the beam axis below 2 % (see Fig. 3).

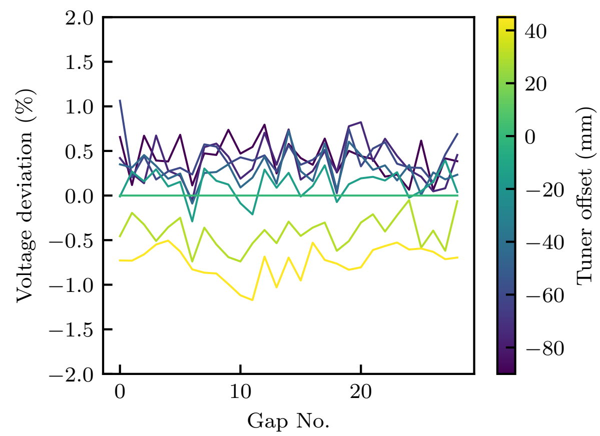

Figure 3: Simulated voltage deviation caused by frequency-tuner operation in Cavity-1.

CONCLUSION

In the frame of the HBS Innovation Pool Project [2], two interdigital H-mode cavities have been developed, capable to serve also for continuous wave acceleration of heavy ions, potentially foreseen to be operated as part of the Helmholtz Linear Accelerator injector linac. The cavities operate with a voltage of 3.9 MV and 5.4 MV and withstand a heat load of about 48 kW each. To the best knowledge of the authors, the designed interdigital H-mode cavities are the first ones applying alternating phase focusing for a heavy ion beam within a section length of 3 m. Fabrication of the cavities is pending, and it is foreseen to report on the radio frequency performance after delivery of the cavities.

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