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ELECTRON BEAM DRIVEN CAVITIES

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Abstract

State of the art high power feeder for RF cavities used as accelerators generally require RF amplifiers consisting of a vacuum tube, such as a klystron or Grid Tubes. In addition, a number of cost intensive RF auxiliary devices are needed: Modulator, waveguides, circulator, power dump and couplers. The equipment requires significant floor space within the linac building. Alternatively, we propose a direct driven system. A micro bunched electron beam is injected directly into the cavity. A high perveance bunched electron beam can be generated by a standard electron gun combined with a deflecting beam chopper [1], an off-the-shelf IOT or klystron, respectively. The pulse rate is determined by the resonance frequency of the cavity. The resonator hereby acts like the output cavity of a klystron: Within its propagation through the cavity the beam is decelerated increasing the stored energy of the accelerator. We present 3D particle PIC simulations evaluating the geometry and beam properties in order to optimize the coupling efficiency and cavity excitation of state-of-art CH particle accelerator structures.

INTRODUCTION

The direct driven system consists of the following three components: The RF accelerating cavity, an electron beam source and the modulator powering the electron source. The electron beam can be provided by a standard off-the-shelf IOT (Input Output Tube), which is typically operated in the range of 200 – 500 MHz up to 200 kW. The accelerator itself serves as the output cavity comparable to a klystron. The energy of the electron beam is hereby directly transferred into the cavity. The simulations examined in this study have been performed with a 325 MHz CH accelerating structure, which is a broadly used frequency for hadron accelerators [2].

ELECTRON SOURCE

The power for the cavity is provided by the electron beam of an IOT. The IOT is flanged directly to the cavity and the electron beam is directed through the accelerator. The principle is similar to a standard coupling loop inducing a magnetic field and delivering the power needed for acceleration. On the other side of the cavity, the electron beam is absorbed by an electron catcher / beam dump. The advantage of IOT's are both reasonable costs as well geometric sizes. Detailed studies on chopping a high brilliance electron beam can be found in [1, 3, 4]. The first step towards particle simulations is to define the general parameters of the electron beam. If not stated otherwise, the parameters used for the simulations are summarized in Table 1. The bunch distance is defined by the frequency of the cavity:

Table 1: Physical Parameters of the Electron Beam

Beam Energy	50 keV
Beam Current	5 A
Bunch Distance	3.127 ns
Bunch Length	0.31 ns
Duty Cycle	10%
Beam Power	250 kW
Av. Beam Power	25 kW
CH frequency	325 MHz

$$T_{bunch} = \frac{1}{f} = \frac{1}{325\,\mathrm{MHz}} \approx 3\,\mathrm{ns}. \tag{1}$$

If the cavity ought to be excited at its maximum, the frequency has to be kept in a small range of approximately the FWHM (frequency width at -3 dB), which can be calculated by the intrinsic Q factor. That means, the bunch distance has to be kept in a very in a small range of $2 \cdot 10^{-4}$ ns:

$$\Delta T_{bunch} = \frac{1}{f_0} - \frac{1}{f_0 + \frac{f_0}{Q_0}} \approx 0.0002\,\mathrm{ns}. \tag{2}$$

In order to optimize and evaluate the excitation, we have to sweep the bunch distance in small steps over a range of approx. 0.01 ns.

CH-MODEL

Resonating in the $H_{21(0)}$-mode, the CH (Crossbar H-mode) structure is suitable in the frequency range between 200 MHz and 400 MHz. The magnetic field points parallel to the beam direction, opposing in neighbouring quadrants. For the following simulations the high field cavity at 325 MHz is used. The cavity has been designed, built and tested by IAP, Frankfurt, during 2015 and 2017, being now ready for further variations and experiments (see Fig. 1). Frequencies of 325 MHz and 350 MHz are nowadays broadly used in hadron linear accelerators as this frequency range is a perfect trade-off between feasible geometric sizes for manufacturing, yet reducing the overall linac length compared to lower frequencies.

The electron beam is herby led through one quadrant from the vertical tube suspension to the horizontal suspension maximising the enclosed magnetic field between the electron beam and the cavity (see Fig. 2). In the transversal cut section, the magnetic field is perpendicular to the plane surrounded by the electron beam and cavity. Depending on the overall geometry of the cavity the electron beam could also be used within two neighboured quadrants. Therefore, the

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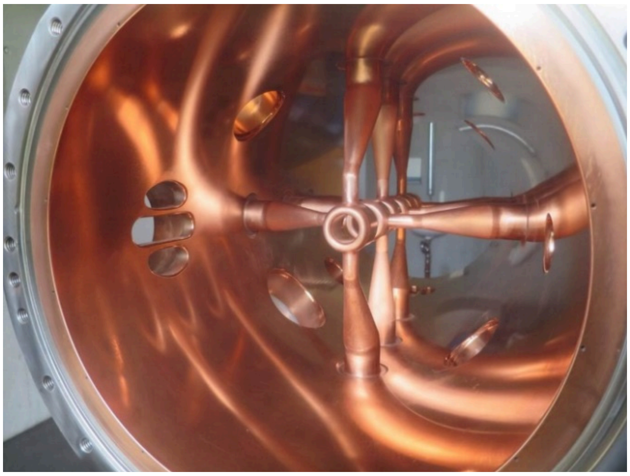

Figure 1: 325 MHz CH cavity used as a simulation model [2].

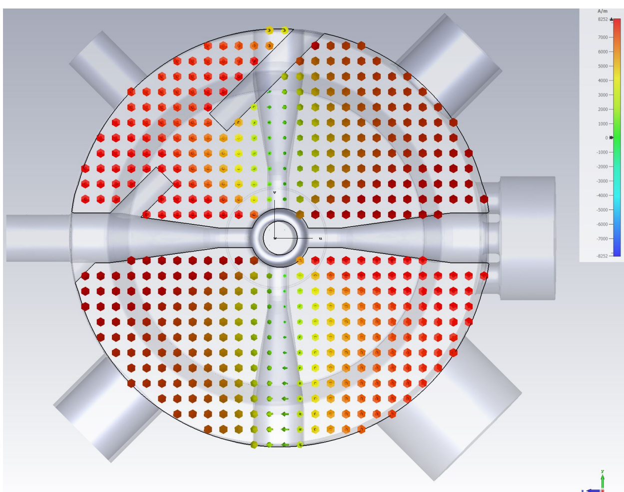

Figure 2: Magnetic Field of the transversal plane.

gap mid distance would have to be $\beta\lambda/2 = c/2f \approx 46\,\mathrm{cm}$, which exceeds the diameter of that cavity. During the propagation of the beam in the cavity, the electrons are decelerated transferring its energy into the field of the cavity.

SIMULATIONS

All simulations are performed by the CST Microwave Studio. The first step is to find the exact frequency with the RF eigenmode solver for the current geometry. Due to the additional internal electron beam pipe, the actual frequency slightly differs from the original operating frequency of 325 MHz. The second step is the simulation of the electron beam excitation using the CST PIC solver. The total simulation time has to be several decay times τ in order to see full excitation:

$$\tau = Q_0/\omega. \tag{3}$$

The average power of the electron beam is mainly defined by the beam energy, current and the bunch length, which is 10% of the bunch distance in our case:

$$P_{beam} = E \cdot I \cdot 0.1 = 25\,\mathrm{kW}. \tag{4}$$

The allowable bandwidth in the bunch distance for a successful excitation is depicted in Fig. 3. In contrast to the theoretical limit calculated above, the simulations show that the maximum deviation from perfect excitation is approximately one order higher, limited by 0.001 ns. If the behaviour of the current geometry or beam parameter were to be studied, the exact bunch distance has to be found in advance. Therefore, all simulation setups are to be swept in 1 ps steps.

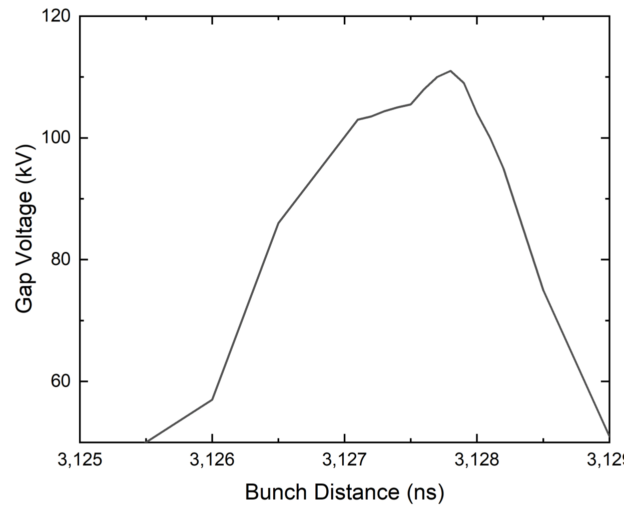

Figure 3: Excitation in dependence of the bunch distance.

The propagation of an electron bunch at the beginning of the simulation is visualized in Fig. 4. The initial beam energy is 50 keV. With the growth of the energy stored in the resonator, the electron beam is decelerated almost completely and can be dumped in a beam catcher on the opposing side of the beam entry.

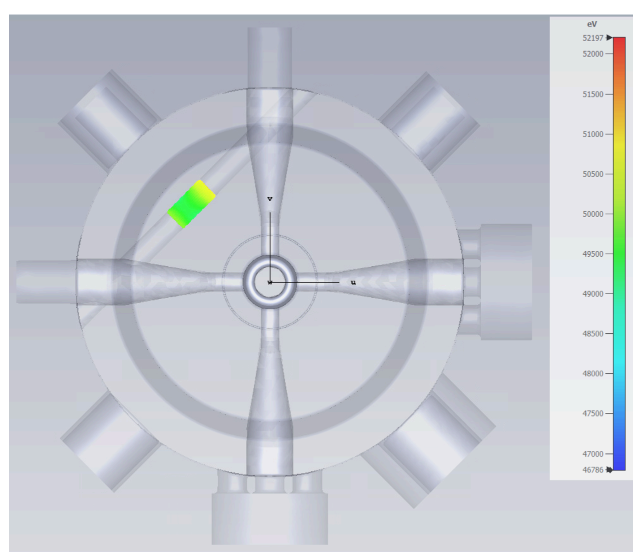

Figure 4: Electron beam propagating through the cavity.

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The most comfortable parameter to recognize the success of the simulation is to monitor the gap voltages between the drifttubes. By monitoring both amplitude and sign of all gap voltages, one can determinate the correct field mode of the cavity, which is $H_{21(0)}$ in case of the CH. The maximum gap voltage after a simulation time of 15 µs the gap voltage has reached approx. 200 kV (see Fig. 5). In comparison, the maximum gap voltage according to RF losses of 25 kW is 166 kV.

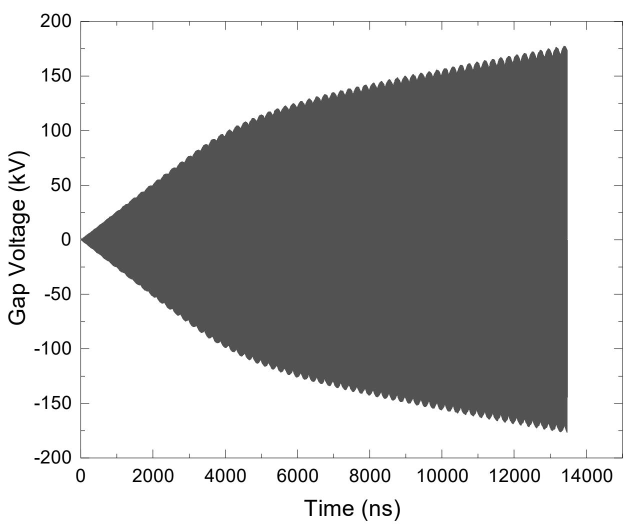

Figure 5: Voltage in drift gap number four of the CH with a simulation time of 15 µs.

The excitation in dependence of the electron beam current and energy are shown in Figs. 6 and 7, respectively. Up to a certain threshold of approx. 5 A and 50 keV the excitation increases linearly with the beam power. For higher beam currents and energies the power transfer is further increased, yet less effective. Beside from the physical beam parameters, Fig. 8 shows the dependence of the excitation from the geometrical position of the electron beam pipe. The distance of the accelerator's beam axis to the electron beam (black curve) has a maximum around 90 – 95 mm which is slightly beyond half the radius (17 cm). For larger distances the excitation decreases equally to the enclosed magnetic field. The gap length of the electron beam pipe shows a similar behaviour with a maximum at 50 – 60 mm.

CONCLUSION AND OUTLOOK

The simulations have shown the proof-of-principle for a successful excitation of an H-type cavity as used for ion and proton acceleration. Furthermore, the achievable gap voltage has been studied for various geometric designs of the electron beam pipe as well as the physical parameters of the electron beam itself. The next step is to add electron beam pipes to the CH and directly attach an IOT in order to measure the RF properties and to compare the results with simulations.

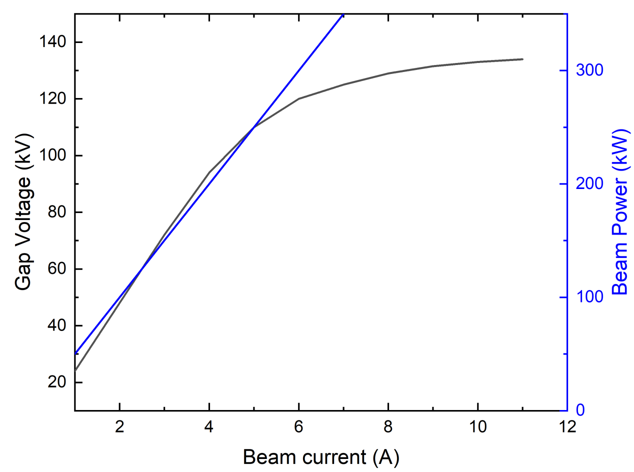

Figure 6: Gap Voltage in dependence of the electron beam current. The beam energy is kept constant at 50 keV.

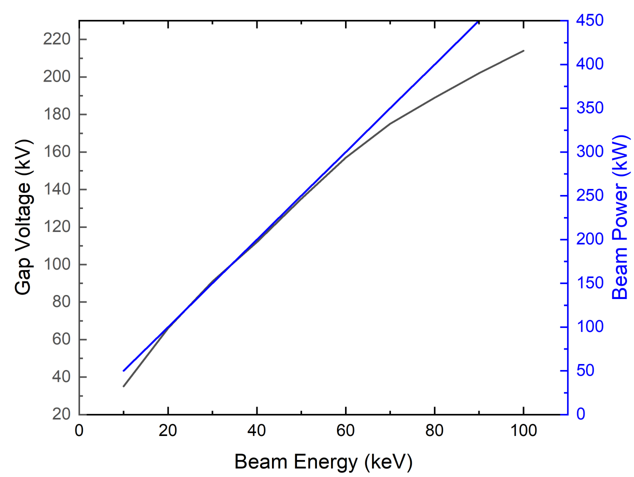

Figure 7: Gap Voltage in dependence of the electron beam energy. The beam current is kept constant at 5 A.

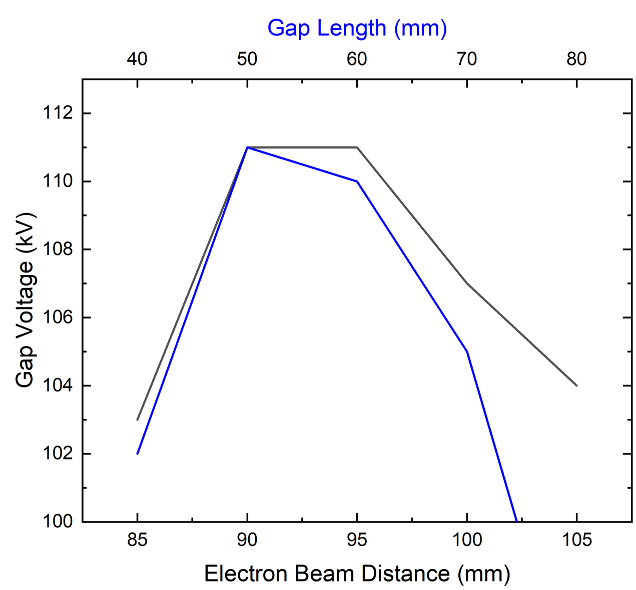

Figure 8: Gap Voltage in dependence of the electron beam distance (black) and the length of the electron beam gap (blue).

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