TRAVELING WAVE RF SYSTEMS FOR HELICAL COOLING CHANNELS*

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Abstract

The great advantage of the helical ionization cooling channel (HCC) is its compact structure that enables the fast cooling of muon beam 6-dimensional phase space. This compact aspect requires a high average RF gradient, with few places that do not have cavities. Also, the muon beam is diffuse and requires an RF system with large transverse and longitudinal acceptance. A traveling wave system can address these requirements. First, the number of RF power coupling ports can be significantly reduced compared with our previous pillbox concept. Secondly, by adding a nose on the cell iris, the presence of thin metal foils traversed by the muons can possibly be avoided. We show simulations of the cooling performance of a traveling wave RF system in a HCC, including cavity geometries with inter-cell RF power couplers needed for power propagation.

INTRODUCTION

A muon collider has been proposed as the next generation collider to explore the energy frontier beyond the LHC. Because the muon is unstable, a compact muon accelerating and phase space cooling system is required. To this end, a Helical ionization beam phase space Cooling Channel (HCC) has been proposed [1] and studied [2]. It consists of a helical dipole, helical quadrupole, and solenoid magnetic components, and a dense hydrogen gas is continuously filled in a helical beam path for ionization beam cooling. A high pressure hydrogen gas filled RF (HPRF) cavity [3,4] will be used for compensation of the energy loss in the ionization beam cooling process.

Practical RF structures are now being modeled for the HCC, which is inherently compact yet requires relatively low frequencies. Here we consider a traveling wave structure, which seems preferable to the pillbox approach that has been studied before because the number of power coupler ports can be significantly reduced.

RF FIELDS IN HCC SIMULATIONS

Figure 1 shows a typical muon beam phase space evolution of transverse and longitudinal planes in the phase space cooling channels for muon colliders. Solid lines represent simulated results with realistic helical magnetic fields. Broken lines represent cooling channel sections in which the simulations have not yet been done with any realistic fields.

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After the 6D HCC sections, even smaller emittances may be achieved using techniques such as Parametric-resonance Ionization Cooling or Reverse Emittance Exchange with very high field magnets [5].

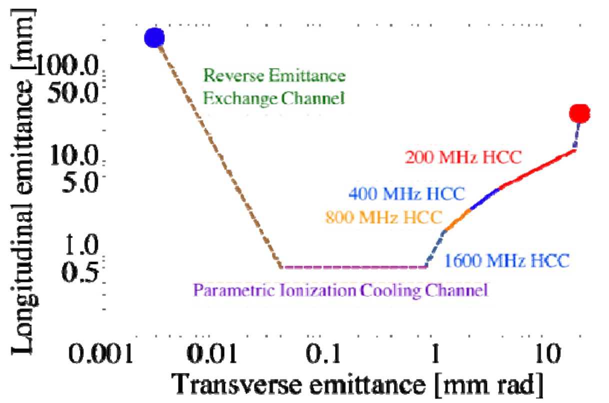

Fig. 1: Fernow-Neuffer plot of emittance evolution for a muon collider. Dashed lines represent parts yet to be simulated, solid lines are simulated with realistic magnetic fields generated by practical current conductors but not practical RF solutions.

HCC simulation studies have been done in simple RF structures, where the RF field distribution is represented as an ideal pillbox cell oriented along the axis of the HCC structure. This RF field direction is then at an angle relative to the helical beam path, and only the strong coupling between transverse and longitudinal momenta in the helical magnet prevents this situation from causing unwanted beam heating. Table 1 shows the designed RF field parameters in a series of HCCs simulation with discrete RF frequencies.

Table 1: Designed RF parameter in simulation

parameter	unit	Value
Mean energy loss rate	MeV/m	10.3
Field gradient (E_0)	MV/m	16.1
Tentative frequency	MHz	200, 400, 800, 1600
Tentative cell length	mm	200, 100, 50, 25

HCC TRAVELING WAVE RF DESIGN

In this study, large iris-loaded RF cells have been investigated as shown in Figure 2. The RF traveling wave is injected from one end of the helical RF structure. The phase velocity (0.92c) is tuned by adjusting the cell outer radius (~ 25 cm for 400 MHz). Unfortunately an excessive propagating RF power of ~ 2.5 GW is needed through these large cells to produce the specified gradient even with a field gradient of E_0 = 12 MV/m, which is 75% of the original value in Table 1.

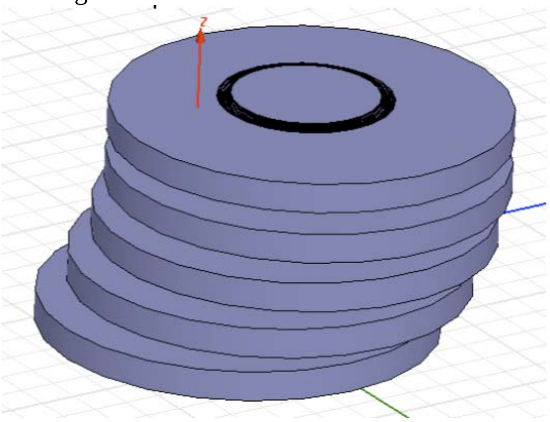

Fig.2 Forward-wave structure oriented in the helix axis direction

To reduce this huge RF power requirement, two peripheral holes are made on the disks. This eliminates the large iris in the middle but has the drawback that thin foils are needed that have to be traversed by the muons. Figure 3 shows this second concept of the helical RF structure. The two holes provide magnetic coupling between cells inducing a negative group-velocity (backward wave). Since the holes need not satisfy any beam-aperture specification, they are kept small; the required propagating RF power can be significantly reduced to, say, 43 MW at E_0 = 12 MV/m. After 40 cells of wall losses (Cu, 300^{o} K), the gradient will be reduced by sqrt(1/e). The accelerating field is hardly changed with respect to the simple pillbox case.

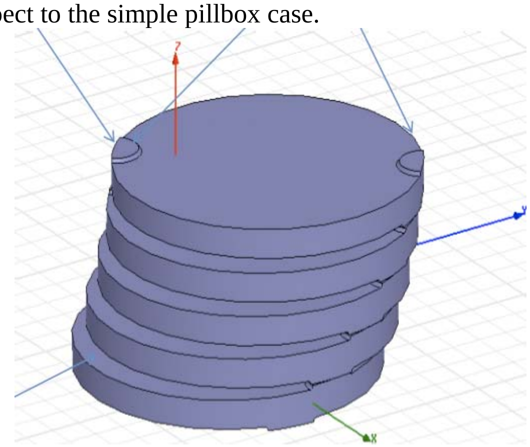

Fig. 3 Backward-wave structure oriented in the helix axis direction

MOTIVATION OF WEDGE-SHAPED RF CELL

In cylindrical cells as shown above, when the phase and particle velocities are equal to the speed of light, the acceleration is independent of transverse position over the complete beam aperture. Furthermore, according to the Panofski-Wenzel theorem, there are no net transverse kicks given by a cell if the acceleration is independent of transverse position. *Note that the previous (side-coupled) cell example with foil end plates (having no beam aperture) does not offer this advantage.*

Properly tuned cylindrical HCC cells would almost satisfy the requirements above with $\beta_{particle}$ = 0.92, β_{phase} = 0.92 and ε_{rel}=1.32. A more economical cell, with factor of about 2 less RF power, could be obtained by directing the cell in the beam direction instead of parallel to the helix axis. For this the RF structure must be based on wedge shaped cells to generate the quasi-helical electric accelerating field that would follow the helical beam path. As seen below, a wedge-shaped cell is not worse than a cylindrical cell in terms of homogeneity or transverse kicks. Further, the radial accelerating field variation of the standing-wave pillbox, proportional to the J_0 Bessel function, should thus be practically overcome by the traveling.-wave approach as shown in figure 5.

420 MHz WEDGE-SHAPED RF CELL

A novel idea by one of us (L.T.) to overcome the huge power requirement for the HCC at low frequencies, combines a large iris (to avoid foils) with 4 peripheral coupling holes such that both forward and backward waves propagate to result in a reduced net RF power flux. This structure is shown in figure 4. Depending on the peripheral hole size, the net power flux can be forward, backward or even zero. In all cases the specified forward phase velocity (0.92c) is maintained. Obviously, the provided RF power must at least cover the wall losses.

Figure 5 shows other important parameters such as the accelerating field homogeneity (integrated E_z×dz) along the local cell length (10 cm length at the cell center) for various positions in the beam aperture. The E-field enhancement (with respect to the specified gradient of 8.5 MV/m) is ~2.3 (with 20 MV/m maximum surface gradient on the iris torus).

615 MHz WEDGE-SHAPED RF CELL

A 14 cm long cell for 615 MHz with 160 mm diameter beam aperture needs ~83 MW transmitted power with peripheral backward coupling holes. The power dissipation is high: 970kW/cell and the maximum surface field is 26 MV/m, corresponding to an enhancement of about 3.0. The beam aperture is offset by 1.7 cm with respect to the outer mantle to lower the transverse kicks and to make the acceleration more uniform. Figure 7 shows how wedge-shaped cells are combined. Figure 8 shows the field uniformity for the 615 MHz case.

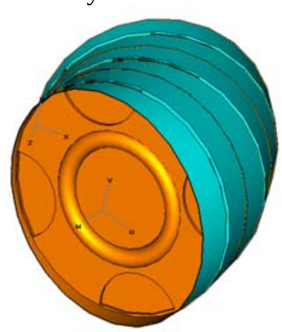

Fig. 4: Hybrid travelling wave cell with forward (single central opening) and backward (4 peripheral openings) for power coupling, yielding a reduced net RF power flux.

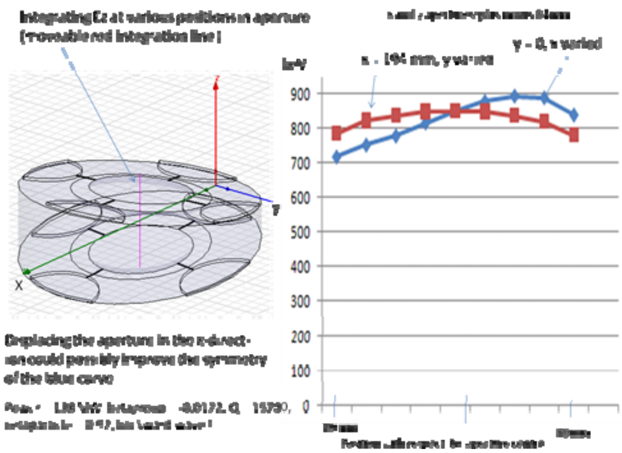

Fig.5: Integrated single-cell acceleration field variation.

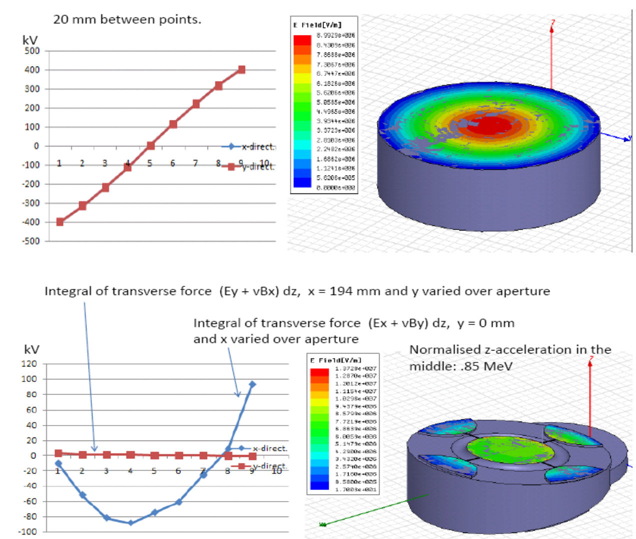

Fig.6: Comparison of integrated transverse kicks between a cylindrical pillbox and the wedge shaped cell (containing a small asymmetric. alcove to reduce the kick in the x-direction at the aperture middle. Offsetting the beam aperture with respect to the cell wall does the same).

CONCLUSIONS

The HCC has a large transverse acceptance which need not deteriorate the cooling performance. The coupling strength between transverse and longitudinal momenta is adjustable by tuning the helical dipole and solenoid field. The search for optimum parameters will be done by numerical cooling simulations.

The helical wedge-cell structure (compared with the pillbox one) requires less power and provides more constant acceleration across the aperture with smaller transverse kicks that can heat the beam. Furthermore, with a thick-torus shaped iris the beam-traversing foils should be avoidable at the expense of a moderate E enhancement factor (~2-3). Hopefully, future RF simulation work will lead to better compromises between group-velocity, cell coupling-hole geometries, and cell length.

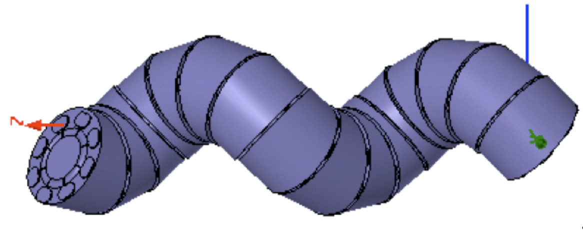

Fig. 7: Combined 615 MHz cells

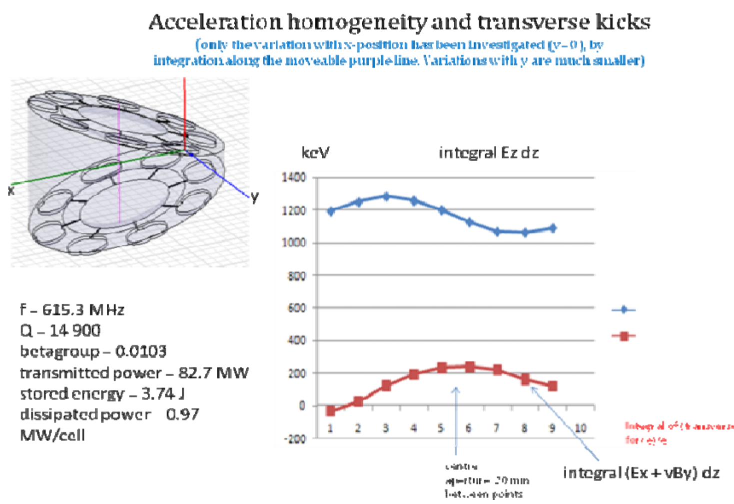

Fig. 8: 615 MHz single-cell: integrated acceleration and transverse kicks in the x-direction.

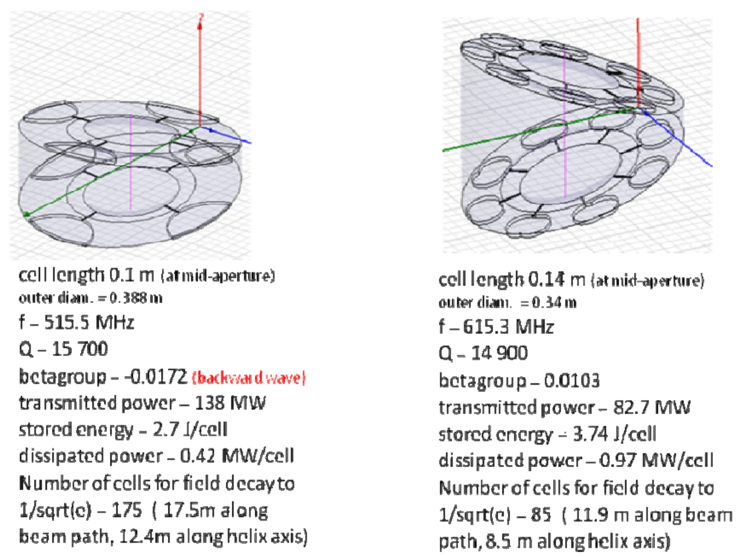

Fig. 9: Summary of the main cell properties

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