SIMULATION OF RF CAVITY DARK CURRENT IN PRESENCE OF HELICAL MAGNETIC FIELD*

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Abstract

In order to produce muon beam of high enough quality to be used for a Muon Collider, its large phase space must be cooled several orders of magnitude. This task can be accomplished by ionization cooling. Ionization cooling consists of passing a high-emittance muon beam through low Z material and accelerating RF cavities within a multi-Tesla focusing channel. First high power tests of RF cavity in solenoidal magnetic field showed a dramatic drop in accelerating gradient. It has been concluded that solenoidal magnetic fields make dark currents focused at field emission sites, and RF breakdowns are initiated by that. However, magnetic field in Helical Cooling Channel has a strong dipole component in addition to solenoidal one. The simulation of dark current dynamic in HCC performed with CST Studio Suit is presented in this paper.

INTRODUCTION

The concept of a Muon Collider and ionization cooling has been under study internationally for a number of years. There are several designs of ionization cooling channels, and Helical Cooling Channel (HCC) is one of them. Important to any demonstration of muon ionization cooling is the accelerating cavity technology. Some specific muon beam parameters make closed-cell RF cavity more effective to use in cooling channels. But first high power tests of closed RF cavity with beryllium windows in solenoidal magnetic field showed a dramatic drop in accelerating gradient due to RF breakdowns [1]. It has been concluded that external magnetic fields parallel to RF electric field significantly modifies the performance of RF cavities by deflecting and focusing electrons coming off the surface at field emission sites or shaping any plasma that might form near the surface. That is a serious problem for cooling schemes similar to MICE in which RF cavities are inside big solenoids. However, magnetic field in Helical Cooling Channel has a strong dipole component in addition to solenoidal one. The dipole component of magnetic field in HCC affects strongly the electron motion in a cavity, so one may expect quite different dark current dynamic. The study of the dark current features in HCC performed with CST Studio Suite is presented in the paper.

CST STUDIO SUITE MODEL

The helical field concept for muon cooling was proposed and described in [2]. Helical cooling channel consists of a magnet system with superimposed solenoid and helical dipole and quadrupole fields. The dark current study has been performed for two alternative designs of HCC magnet system proposed in [3]. The first system has a large bore superconducting solenoid with outer helical dipole and quadrupole coils. The second is a system of short superconducting coils shifted in the transverse direction to generate simultaneously solenoidal, helical dipole and helical quadrupole field components (see Fig. 1). Since the results for both systems are quite similar we chose the second one for the paper. The study of large bore helical channel can be found in [4].

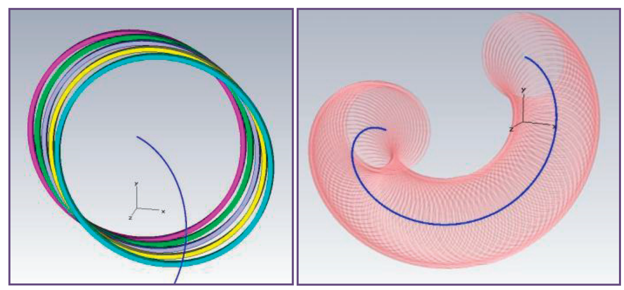

Figure 1: Left – layout of SC coils along equilibrium helix orbit (coils are coloured for better view), right – complete helical period arrangement.

The parameters of HCC version used in this paper are:

Table 1: HCC Parameters

Helix Parameters	Value
Period of Helix	1.6 m
Helix pitch	1.0
Coil inner diameter	0.4 m
Equilibrium orbit radius	0.255 m
Current×turns	9.7 kA×10
Coil max flux density	7.0 T
Helical dipole field	1.75 T

CST model of the helical solenoid consists of 82 superconducting coils that make a full 1.6 m period of helix channel. The magnetic field distribution within the HCC was calculated with CST electromagnetic solver. To verify the model the muon tracking in the fields of design magnitude has been performed. Fig. 2 shows the trajectories of muons with nominal energy of 212±10% MeV. The muons move along stable helical trajectories with specified period, pitch and radius.

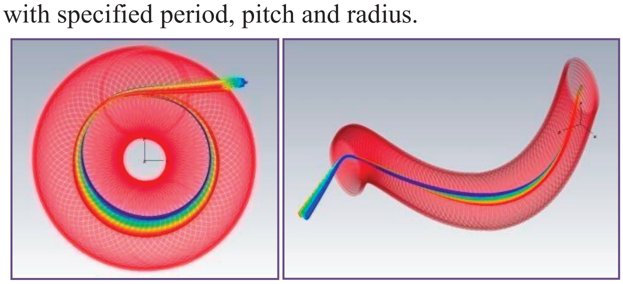

Figure 2: Muon trajectories in HCC. Color indicates muon energy – blue is for the lowest one.

* Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.
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ISBN 978-3-95450-115-1

An 805 MHz RF cavity with beryllium (Be) windows for a muon cooling experiment has been designed, built and tested at high power [5]. This cavity fits HCC under consideration quite well for simulation since we need to use RF volume only (see Fig. 3).

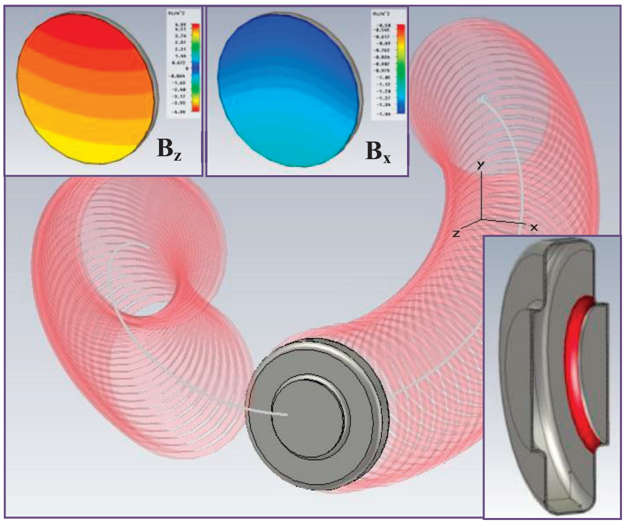

Figure 3: Solid model of 805 MHz RF cavity model closed with beryllium windows inside HCC. Some coils are removed for clear view. A particle source that simulates high field emission area shown in red.

RF fields in the cavity have been simulated, and the accelerating gradient of 30 MV/m has been set for further simulation of electron motion inside the cavity. CST Particle Studio offers advanced model of high field emission. But to simulate high field dark current emission we simply assigned a particle source with fixed emission properties to the iris area. This particle source produces a burst of electrons at the moment of highest electric field. The emitted electrons are uniformly distributed over the iris, with initial energy uniformly distributed from 0 to 4 eV, and uniform angular spread within normal and 45°.

DARK CURRENT IN UNIFORM SOLENOIDAL FIELD

Simulation of dark current in RF cavity in presence of uniform solenoidal field is useful by three reasons: 1) this is an important real case; 2) the dark electron trajectories can be easily checked analytically and therefore the model can be verified; 3) the case is a good reference point for understanding of dark current particle dynamic.

First let us have a look at dark current dynamic with RF filed without any static magnetic field (see Fig. 4). During the first RF period, just after the initial emission, electrons are moving in more or less compact group. When they hit opposite iris and wall some of them are re-diffused and elastically back scattered. The electrons are mostly backscattered because the probability for generation of true secondaries is very low, since the average energy of electrons at the first hit is rather high ≈1.1 MeV. The reflected electrons acquire angular (0-45°) spread and significant energy spread from zero to the maximum of incident energy. So, the electrons of second generation are already very much dispersed and motion of the next electron generations is completely chaotic. It is important to notice that some of the elastically scattered electrons are accelerated up to 4.4 MeV, and therefore they are more capable to damage the copper surface.

The simulations show that starting with solenoidal field of 1 T, the dark current electrons move strictly along magnetic lines of force and hit practically mirror image spot on the opposite iris (see Fig. 5). Moreover the backscattered electrons move back along solenoidal field due to very strong focusing in spite of angular and energy spread, and they hit the original emission site. Number of backscattered electron drops very quickly during 3-4 RF periods. But the primary electrons are originated at each half of RF period, so the total dark current may even increase in time. The average impact energy is 0.4 MeV, while some elastically scattered electrons reach maximal impact energy of ≈2-3 MeV.

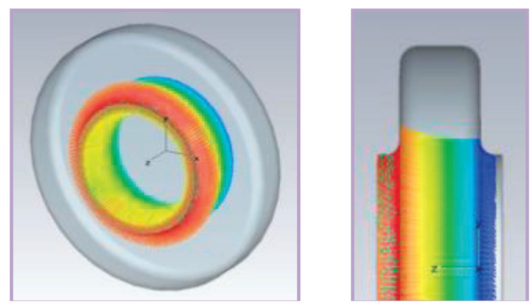

Figure 4: Dispersed electrons trajectories without static magnetic field.

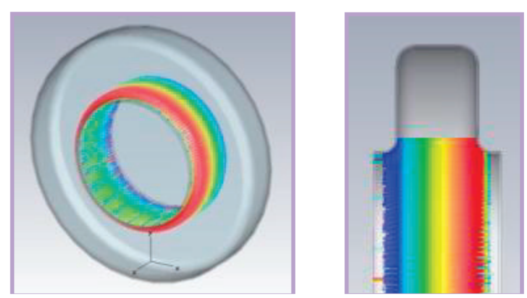

Figure 5: Focussed electron trajectories in presence of 5.7 T uniform solenoidal field and RF fields.

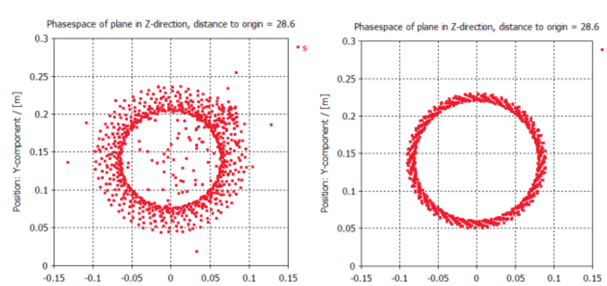

Figure 6: Electron impact coordinates in transverse XY plane without (left) and with solenoidal magnetic field.

The principal difference between the two dark current dynamics is that the impacts are spread over larger area in the absence of solenoidal field, while with magnetic field the impacts are focused to small spots, which are actually initial electron emission sites. The difference is illustrated in Fig. 6, where the impacts are shown in XY phase plane in the location of iris for both cases.

A number of models have been proposed for RF breakdown with and without a magnetic field present. All models consider high field emission intense bombardment near a field emission site with high surface field as a most probable trigger for breakdown or at least as an essential component of breakdown mechanism [6].

DARK CURRENT IN HCC

In HCC the electrons after emission also move along magnetic force lines, but now the lines are bent in spiral, so the trajectories look as it is shown in Fig. 7.

The impact coordinates in the transverse phase plane show that dark current is still well focused, but misses opposite iris almost completely (Fig. 8).

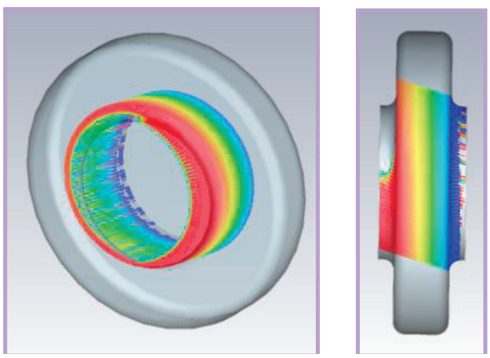

Figure 7: Dark current electron trajectories in presence of HCC magnetic fields and RF fields.

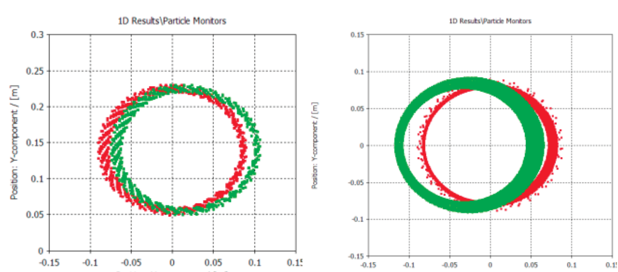

Figure 8: Electron emission (red) and impact (green) coordinates in transverse XY plane in presence of HCC fields (left) and in presence of tilted uniform solenoidal field (20° tilt).

This is an important change in dark current dynamic since now there is no high field emission intense bombardment near a field emission site with high RF electric surface field. The dark current electron energy reaches 1-3 Mev, when they hit the walls, and the electrons still can damage the surface, creating craters and asperities. But the locations of such damages are at low gradient areas, so there is neither immediate breakdown nor dark current increase.

Another effect may reduce dark current generation. Approximately 50% of dark current electrons generated at the iris hit the beryllium window. The beryllium windows have TiN coating and therefore reduced true secondary emission yield. The coating eliminates very effectively low energy multipacting that is based on true electron re-emission. If the TiN coating also reduces the elastic scattering, which dominates in our case, then it could be an additional dumping of dark current generation. Unfortunately no data on elastic scattering of TiN has been found to make more definite conclusion.

The simulations show specific dark current dynamic in HCC. Notably the high field emitted primary electrons miss opposite irises almost completely as opposed to uniform solenoidal field. That is a reason to expect some improvement in high power cavity performance. But the high energy elastically backscattered focused electrons; remaining overlapped areas of bombardment and possible one side multipacting in low field areas create certain doubts. A high power test of the cavity in the fields that produce similar dark current dynamic can give us a final answer. Such test could be done in an uniform solenoidal field, while the angle between the cavity axis and the solenoid changes up to 20°, Simulations show that dark current dynamic in this configuration is very similar to that in HCC (see Fig. 8).

CONCLUSION

The dark current in the RF accelerating cavity in Helical Cooling Channel has been simulated. The simulation of electron motion in combined RF, magnetic solenoidal and dipole fields, revealed the qualitative change in the dark current dynamic in compare to pure solenoidal magnetic field. In case of the HCC the dark current is still well focused, but it misses cavity opposite iris almost completely. Therefore there is no high field emission intense bombardment near field emission sites that have high RF electric surface field. That can diminish the problem of RF breakdowns in accelerating cavities in HCC.

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ISBN 978-3-95450-115-1