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CAVEL: a simulation program for electrons in RF cavities

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The program CAVEL simulates the motion of electrons inside an RF cavity. The cavity is assumed to be azimuthally symmetric and may be immersed in a 2D or 3D external magnetic field. The cavity boundary coordinates and RF fields are taken from SuperFish. Secondary emission of electrons may also be simulated.

1. Introduction

The breakdown of room-temperature RF cavities in magnetic fields is an important issue for the development of neutrino factories or muon colliders [1]. The breakdown may limit the useable field gradient, which has implications on cooling efficiency and facility cost. The motion of emitted electrons from high electric field locations in the cavity is thought to play an important role in the breakdown process. The program CAVEL was written to help understand this aspect of breakdown. The cavity boundary and RF fields are described using a SuperFish model. In order to reproduce the conditions found in muon ionization cooling lattices the cavity fields may be superimposed with 2D or 3D external static magnetic fields.

The coordinate system used in the program has the z axis along the axis of the cavity. Particles are normally launched in the y-z plane, in which case the radial direction is y. Adaptive stepsize control is very important in a code like this since the field seen by a particle during a time step may vary by up to ~7 orders of magnitude.

The parameters described in this note refer to version 1.20 of the code. The latest version of the program can be found at http://pubweb.bnl.gov/people/fernow/cavel/.

2. RF cavity model

The RF cavity is modeled in CAVEL using the program SuperFish. This restricts the code to analysis of axially symmetric cavities. The cavity boundary shape is taken from a table in the SuperFish OUTAUT.TXT file. The boundary is assumed to follow straight lines between the points (typically many hundred) in this table. The RF fields inside the cavity are taken from the SuperFish Parmela T7 postprocessor file. Input parameters related to the RF cavity are listed in Table 1.

Table 1. RF cavity input parameters

ASCRF	specifies left-right symmetry of SuperFish cavity model
BNDNAME	name of SuperFish boundary file
RFNAME	name of SuperFish RF field file
RFNRM	normalization of RF field strength

Detailed specifications about these and other input parameters can be found in the CAVEL Reference Manual.

3. External static magnetic field

The external magnetic field is described by a 2D or 3D static magnetic field map. Input parameters related to the external field are listed in Table 2.

Table 2. External field input parameters

CSCALE	normalization factor for external field
MAGDIM	specifies symmetry of external field
MAGNAME	name of external field file
ROBTH	polar rotation angle of external field from y axis
ROBPHI	azimuthal rotation angle of external field from y axis
ZOFF	axial offset of cavity with respect to external field

4. Primary electron generation

A number of parameters control the initial launch of the primary electrons. One can launch primary electrons from the peak electric field point on the cavity boundary, from a specified location, or from a list of boundary points. Input parameters related to the primary electron launch conditions are listed in Table 3.

Table 3. Primary electron input parameters

LAUNCH	specifies launch category
NPHI	number of initial RF launch phases
NTEMP	number of random surface temperatures
OFFLAUN	displacement from boundary surface
OTHERSIDE	force launch from high field point on opposite side
PHILO	starting RF launch phase angle
PHISTP	step in RF launch phases
PSURF	initial momentum perpendicular to surface
PYLAUNCH	specified initial momentum along y
PZLAUNCH	specified initial momentum along z
RLAUNCH	specified initial radius
SIGP	width of Gaussian momentum distribution at surface
ZLAUNCH	specified initial axial position

5. Program execution

A number of parameters control the tracking of electrons in the cavity. Tracking is done using a 4th order Runge-Kutta algorithm with adaptive stepsize control. Input parameters related to the program execution are listed in Table 4.

Table 4. Program execution input parameters

EPSSTEP	required stepping accuracy
MAXSTEPS	maximum number of steps allowed in each track
NFIX	maximum number of fixed steps near cavity boundary
RNSEED	random number seed
STEP	initial time step
STEPMAX	maximum allowed time step
STEPMIN	minimum allowed time step

Given a boundary described by a table of boundary points, it is non-trivial to determine when a track moves from the inside to the outside of the cavity. We consider this to be the end point of the track, where in reality it would plow into the cavity surface. The most successful algorithm that we were able to develop is: 1) Determine the nearest boundary point (nbp) to the current location of the electron. 2) Using the nbp as the vertex, compute the angles to the track (T) and to the neighboring boundary points (P and M). 3) Determine whether the track is inside or outside the cavity by comparing the angles T, P and M.

6. Program output

CAVEL produces two output files. Most of the important information is summarized in the LOG file. This file contains the input parameters used in the simulation and the cavity boundary points. The starting and ending points of all tracks are also given, as well as any error messages. The DAT file contains detailed information about the actual trajectories taken by every particle. Input parameters related to the program execution are listed in Table 5.

Table 5. Input parameters controlling the program output

RSKIP	number of track steps to skip between writes to DAT file
RTUPLE	specifies whether to create a DAT file

7. Secondary emission model

It is also possible to model secondary electron emission using CAVEL. Input parameters related to secondary emission are listed in Table 6.

Table 6. Input parameters controlling secondary emission

SECEM	controls type of simulation
SEDELM	parameter δ_{max}* for calculating secondary emission yield
SEEMAX	parameter E_{max}* for calculating secondary emission yield
SEEPS0	parameter ε_o for calculating secondary emission yield
SEFANG	parameter α for calculating secondary emission yield
SEMXDAU	maximum number of daughter particles in an interaction
SEMXGEN	maximum number of secondary generations

SECEM=1 calculates the secondary emission yield at the end of each primary track. SECEM=2 creates secondary electrons at the end point of each primary electron and tracks them through the cavity. The program allows a maximum of 8 secondary particles to be created at the end of each track. The program will follow the secondary cascade for a maximum of 8 generations. The maximum number of produced secondaries for a given primary parent particle is 99.

The secondary emission yield SEY(0) for normal incidence is calculated using the model given in R. Cimino et al. [2].

$s = 1.35$
$x = E_{kin} / E_{max}^*$
$\delta_{true} = \delta_{max}^* \; s\, x / (s-1.+x^s)$
$t_1 = \sqrt{(E_{kin})}$
$t_2 = \sqrt{(E_{kin} + \varepsilon_o)}$
$\delta_{elas} = (t_1-t_2)^2 / (t_1+t_2)^2$
$SEY(0) = \delta_{true} + \delta_{elas}$

The total yield is assumed to be the sum of contributions from “true” secondaries and an elastic scattering peak. We next correct the yield SEY(θ) for the actual angle of incidence of the primary electron on the cavity wall [3].

$$SEY(\theta) = SEY(0) \exp[\alpha(1-\cos(\theta)]$$

The program uses the default values E_{max}*=160 eV, δ_{max}*=2, ε_o=150 eV, and α= 0.45.

When SECEM=2 the value of SEY(θ) is used generate a number of secondary tracks determined from a Poisson distribution. The generated polar angle comes from a cosine distribution and the azimuthal angle comes from a uniform distribution [4]. The energy distribution comes from a Gaussian due to true secondaries centered at 5 eV, a Gaussian due to elastic scattering centered at the energy of the parent particle, and a constant background at all energies. The relative height of the two Gaussians is adjusted depending on the parent energy, roughly in accord with Fig. 1 in reference [2]. Conservation of energy is enforced in the secondary production.

References

[1] R. Palmer et al, RF cavity breakdown in external magnetic field, Proc. 10th International Workshop on Neutrino Factories, Superbeams, and Beta Beams, Valencia, Spain, PoS (NuFact08) 081, 2008.

[2] R. Cimino et al, Can low-energy electrons affect high-energy physics accelerators?, Phys. Rev. Lett. 93:014801, 2004.

[3] R. Kirby & F. King, Secondary electron emission from accelerator materials, SLAC-PUB-8380, Feb. 2000.

[4] M. Furman & M. Pivi, Probablistic model for the simulation of secondary electron emission, PRSTAB 5:124404, 2002, p. 4.