Cooling Code Benchmarking

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Abstract

The aim of this document is to specify a set of common beam elements and lattices to enable a good comparison of different codes. Subsequent versions may include the actual benchmarking plots - depending on how things go.

Please feel free to comment if you don't feel that the comparisons are valid or the input parameters are not correct.

1 Introduction

In recent times European teams have become more involved in muon collider development. Meanwhile new models are required to account for collective effects. For this reason two relatively untested codes, BDSIM and RFTrack have been introduced to model cooling systems. These codes should be benchmarked against the existing and well-established G4Beamline and ICOOL codes. It is probably beneficial to recheck the existing codes as well, in the light of new versions of Geant4 etc.

2 Checklist

Several sets of studies should be performed. First we check single-element differences between codes using single particles. For absorbers this is performed with a million particles with the same initial coordinates to handle the stochastic effects. Once each component is compared separately a cooling cell consisting of a combination of the three can be tested with a full initial beam. A summary of the different proposed studies is listed below. The tracking studies are described in more detail in later sections.

- Absorber
  - ☐ Distribution of particles in x' for different momenta
  - ☐ Distribution of particles in energy for different momenta
- Solenoid
  - ☐ Trajectories as a function of radial offset.
- RF Cell - TM_{010}
  - ☐ Trajectories as a function of radial offset.
  - ☐ Trajectories as a function of time offset.
- Cooling Cell, no absorber
  - ☐ Optical beta function

  - ☐ Kinetic angular momentum
  - ☐ Transverse emittance conservation
  - ☐ Longitudinal emittance conservation
  - ☐ profile in x, p_x, y, p_y, t, kinetic energy

- Cooling Cell, absorber
  - ☐ Optical beta function
  - ☐ Kinetic angular momentum
  - ☐ Momentum distribution
  - ☐ Transverse emittance change
  - ☐ Longitudinal emittance change
  - ☐ Transmission
  - ☐ profile in x, p_x, y, p_y, t, kinetic energy

3 Standalone Tests

The benchmarking will be based on the `2024-05-24-release` Demonstrator lattice, described in [Losito et al, Presentation of cooling cell conceptual design, DOI:10.5281/zenodo.11402736]. For now, 6D cooling equipment (dipoles, wedge-shaped absorbers) will not be included; they may be added at a later date. This is both for clarity and because some codes can't model the 6D cooling equipment.

Absorber benchmarking will use the MICE absorbers, where good experimental data is available, and an additional thin absorber to benchmark low momenta characteristic of the Final Cooling system.

3.1 Absorber

Parameter	Unit	Magnitude
Material		LiH
Thickness	mm	65.37
Density	g cm^{-3}	0.69
Li6 Fraction	by mass	0.814
Li7 Fraction	by mass	0.043
H Fraction	by mass	0.143
Momenta		171.55, 199.93, 239.76
Material		liquid H_2
Thickness	mm	349.6
Density	g cm^{-3}	0.07053
Momenta	MeV c^{-1}	164.9, 199.0, 237.1
Material		liquid H_2
Thickness	mm	10
Density	g cm^{-3}	0.07053
Momenta	MeV c^{-1}	30
Number of particles		10^6

Table 1: Reference absorbers and associated momenta.

The proposed reference absorbers are listed in table 1. Momenta have been selected to match the momenta used in MICE. These absorbers will stop low momentum particles, so an additional ‘low momentum’ absorber is included to study the material processes in this regime. The MICE liquid hydrogen absorber is described in [Performance of the MICE diagnostic system, 2021 JINST 16 P08046] and the Lithium Hydride absorber is described in [Multiple Coulomb scattering of muons in lithium hydride, Phys. Rev. D 106, 092003]

In all cases, distributions should be produced in kinetic energy and x' for particles initially travelling along the axis with the listed momenta.

3.2 Solenoid

Parameter	Unit	Magnitude
Coil inner radius	mm	250.0
Coil radial thickness	mm	169.3
Coil outer radius	mm	419.3
Coil length	mm	140.0
Current density	A/mm^2	500.0
Particle species		$\mu+$
Particle momentum	MeV/c	200.0
Particle z start	mm	-500.0
Particle z end	mm	500.0
Particle radial step	mm	10.0
Particle maximum radius	mm	200.0

Table 2: Coil and test particles.

The solenoid will be modelled by a single cylindrically symmetric block of current as described in Table 2. Tracking will be performed by a set of μ^+ test particles initially 500 mm upstream of the solenoid centre and the particle positions will be studied at a plane in z 500 mm downstream of the solenoid centre. Initially particles will have 200 MeV/c momentum in the z-direction. Particles will be placed every 10 mm radially.

The aim is to sample the magnetic field and check that tracking is correct through the field map. Self-consistency studies e.g. convergence over a range of step sizes are valuable.

3.3 RF Cell

Parameter	Unit	Magnitude
Frequency	MHz	704.0
Peak electric field	MV/m	30.0
Length	mm	183.6
Window thickness	mm	0.0
Phase relative to bunching mode	°	0.0
Particle species		$\mu+$
Particle momentum	MeV/c	200.0
Particle z start	mm	-500.0
Particle z end	mm	500.0
Particle radial step	mm	10.0
Particle maximum radius	mm	200.0
Particle time step	ns	0.1/0.704
Particle maximum time	ns	1/0.704

Table 3: RF Cell and test particles.

The RF cell will be a single pillbox represented by a TM010 mode cylindrically symmetric field. The parameters are shown in Table 3. The cell should be phased so that a particle starting at $t = 0$ ns passes through the cell when it is in bunching mode. A grid of particles in (x, t) space should be used.

4 Cooling Cell

A full simulation of a realistic muon beam travelling through a cooling cell is also proposed. In order to check for correct modelling of linear beam optics, a low emittance beam will be studied traversing a cooling cell with no absorbers present. Subsequently a nominal emittance beam will be studied, to validate emittance change and transmission modelling. For simplicity cylindrical absorbers will be used and dipoles will be entirely omitted.

A schematic of the cooling cell is shown in fig. 1. The cell consists of a pair of oppositely polarised solenoids, a three-cell RF cavity and absorbers at both ends of the cell.

In order to correctly model the field from a long cooling line of such solenoids, several coils should be modelled upstream and downstream of the tracking region. This is so that the overlapping fringe fields of the solenoids are correctly represented.

A three-cell RF cavity should be modelled. In the proposed cooling scheme, adjacent cavities are phased 180° relative to the adjacent cavities.

An absorber should be placed at either end of the cooling channel. The absorber should be half the length of the nominal Demonstrator thickness so that overall the beam passes through one full absorber length.

The parameters are listed in tables 4 and 5.

Parameter	Unit	Magnitude
Beam pipe radius	mm	81.6
Cooling cell length	mm	800.0
RF Cavity as Table 3		
Phase relative to bunching mode	°	20.0
RF cell separation	mm	5
RF centre-to-centre distance	mm	188.6
Iris radius	mm	81.6
Solenoid as Table 2		
Coil Z centre position	mm	100.7
No absorber		
Beam momentum	MeV/c	200.0
Beam distribution		Gaussian
Beam longitudinal emittance	eV ms	1.3×10^{-3}
Beam transverse emittance	mm	2.5×10^{-3}
σ_t	ns	0.003532
σ_E	MeV	0.3692
Beam $\beta_\perp$	mm	107
Beam $\alpha_\perp$		0
Beam L_{kin}	mm MeV/c	0

Table 4: Cooling Cell definition - with a low emittance beam.

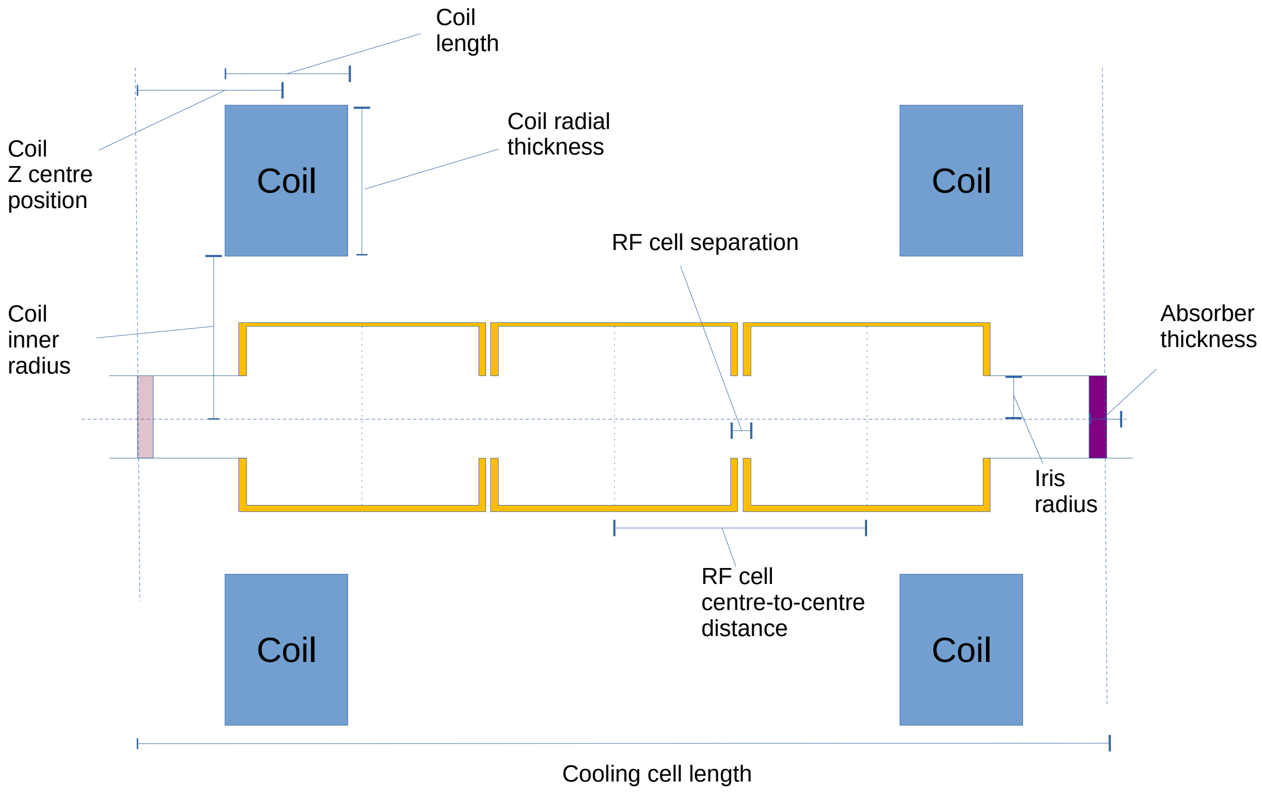

Figure 1: Schematic of the cooling cell to be simulated.

Parameter	Unit	Magnitude
Cooling cell as Table 4 except absorber and beam		
Absorber as LiH from Table 1 except thickness		
Thickness	mm	10
Beam momentum	MeV/c	200.0
Beam distribution		Gaussian
Beam longitudinal emittance	eV ms	1.3
σ_t	ns	0.1117
σ_E	MeV	11.68
Beam transverse emittance	mm	2.5
Beam $\beta_\perp$	mm	107
Beam $\alpha_\perp$		0
Beam L_{kin}	mm MeV/c	0

Table 5: Cooling Cell definition - with a high emittance beam.