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MuCoL

A Design Study for a Muon Collider complex at 10 TeV centre of mass

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DELIVERABLE REPORT

PRESENTATION OF COOLING CELL CONCEPTUAL DESIGN

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MuCol Consortium, 2024
For more information on MuCol, its partners and contributors please see https://mucol.web.cern.ch/

Delivery Slip

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Executive summary

[This text (in italics for emphasis) needs to summarise the entire milestone document in a clear, succinct form.

It could have short paragraphs, each paragraph summarising the content of one section in the document, so that the main points are covered.

Please note that this milestone report will be publicly available on the MuCol website and will also be sent to the European Commission]

1. INTRODUCTION

MuCol aims to advance the design of a Muon Collider Complex, to clarify the parameters of the entire complex of accelerators and to propose new designs for the most challenging components. WP8 in particular focuses on the design and integration of the Cooling Cell (CC). The purpose of a cooling cell is to reduce the transverse emittance of the muon beam which is generated by the collision of a proton beam with a production target, which results in a shower of pions that will then decay into muons. Pions are generated with a large angular spread and a large momentum spread. The capture and cooling section will maximize the number of particles captured and reduce their transverse momentum by interacting with a low-Z material which will reduce both the longitudinal and the transverse momentum. A Radio-Frequency (RF) cavity will re-accelerate the particles to restore their longitudinal momentum. Through this, the beam is cooled, meaning the particles decrease their transverse energy and also their energy spread with respect to the reference energy. Strong superconducting solenoids are present throughout the beam trajectory to maintain its focus around the reference trajectory. The cooling performance is critical for the luminosity of the machine, which is one of the key performance indicators of the whole machine.

A preliminary layout, based on a series of cells with RF cavities resonating at 352 MHz, in the first part, and at 704 MHz in the rest of the cooling section (see Table X), is described in [1] and is based on the previous work of the US – MAP (Muon Accelerator Program) group.

The cooling cells (CC) are complex mechanical assemblies consisting of high fields, large radius superconducting solenoids, high gradient RF cavities and their ancillaries (tuners, power couplers) operating in magnetic field, and varies types of absorbers, all tightly integrated in order to reduce as much as possible any free space. Given the difficulty of such integration it is considered critically important to demonstrate that it is possible to integrate efficiently all the components, with a realistic layout, without compromising the performance of the CC.

This report provides a conceptual design of the Cooling Cell and the motivations for the selection of one among the different types of cells in order to proceed with the complete 3D mechanical integration.

Content, heading level 1

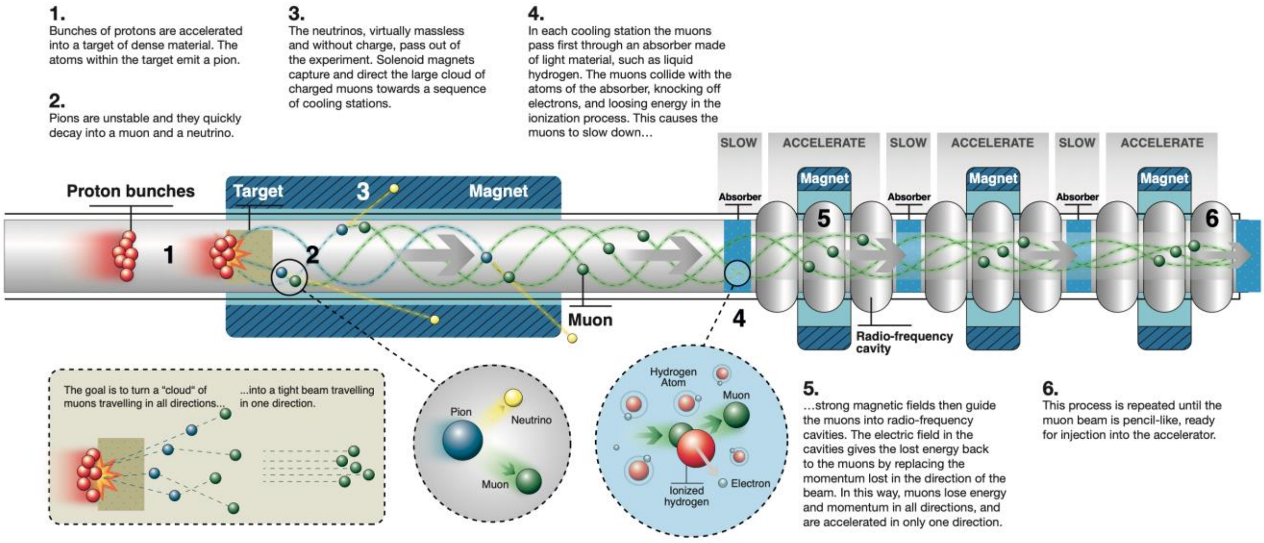
1.1. CONTENT HEADING LEVEL 2

2. MUON PRODUCTION AND COOLING

2.1. THE TENTATIVE LAYOUT OF THE MUON PRODUCTION AND COOLING SECTION

The muon production and cooling system comprises of several subsystems. The protons provided by the proton complex intersect a target to produce pions. The target is immersed in a 20 T solenoid field, yielding a high pion flux. The field is rapidly tapered to 1.5 T. Pions and muons traverse a solenoid-focused chicane where high momentum beam impurities are removed followed by a Beryllium absorber which ranges out remnant low energy protons. The remaining beam passes through a longitudinal drift where any remaining pions decay. The beam is then captured longitudinally. A multi-frequency RF system that captures the beam into 21 bunches is required, owing to the initially large longitudinal beam emittance. Another solenoid chicane system splits the beam by charge species, in preparation for the ionisation cooling system.

The ionisation cooling system comprises of a series of solenoids, which focus the beam onto energy absorbers where the beam momentum is removed. The momentum is restored longitudinally using RF cavities, resulting in a reduction of the beam's emittance (volume in position-momentum space). An initial rectilinear cooling system reduces the beam emittance sufficiently that the many initial bunches can be merged into one single bunch. The beam is then cooled further to the final emittance, using a continuation of the rectilinear cooling system followed by a sequence of high field solenoids operated ultimately with a low momentum (non-relativistic) beam. The beam is finally reaccelerated to relativistic speeds via the pre-accelerator so that it can be delivered to the acceleration system.


1.
Bunches of protons are accelerated into a target of dense material. The atoms within the target emit a pion.

2.
Pions are unstable and they quickly decay into a muon and a neutrino.

3.
The neutrinos, virtually massless and without charge, pass out of the experiment. Solenoid magnets capture and direct the large cloud of charged muons towards a sequence of cooling stations.

4.
In each cooling station the muons pass first through an absorber made of light material, such as liquid hydrogen. The muons collide with the atoms of the absorber, knocking off electrons, and loosing energy in the ionization process. This causes the muons to slow down...

5.
...strong magnetic fields then guide the muons into radio-frequency cavities. The electric field in the cavities gives the lost energy back to the muons by replacing the momentum lost in the direction of the beam. In this way, muons lose energy and momentum in all directions, and are accelerated in only one direction.

6.
This process is repeated until the muon beam is pencil-like, ready for injection into the accelerator.

The goal is to turn a "cloud" of muons travelling in all directions...

...into a tight beam travelling in one direction.

Fig. 1: it would be nice to have a picture of the conceptual cooling layout. Is this ok?

Within the two main sections: 6D rectilinear cooling and final cooling, there are about 20 different types of cells with various geometry, length, electric field, magnetic field strength and frequency starting at 352 MHz and continuing with harmonics (704 MHz). In order to decide which one is the more interesting to be designed in detail, one has to look not only at scientific considerations, but also to practical aspects that would ensure the maximum result for the required investment.

In order to focus the effort, one has to identify the main goals of the design exercise. We have therefore listed the main motivations to design, and in the future build and test a cooling cell:

- Previous studies on Muon Colliders have never gone through a thorough exercise of 3D mechanical integration of the components (RF, magnets, absorber). Given the fact that the performance required is very demanding for each of the components, it is important to be able to provide a very compact design, minimizing the dead spaces that reduce the real estate gradients, i.e. the average electric field over the whole cavity length. It is therefore important to understand how much the technical systems (water cooling, power feed, cryostat and cryogenic cooling etc…) impact the compactness of the assembly.
- Concerning the ***magnets***, the last technology programme for the Muon Collider (US-MAP) ended in 2016. Since then High Temperature Superconductors (HTS) are more affordable and more reliable, allowing reasonably higher fields at a relatively low cost. For this reason, we chose to use HTS (High Temperature Superconductors) in form of REBCO tapes as superconductor to wind the solenoids of the cooling cell, rather than Nb_3Sn as in the US-MAP design. Although REBCO has been tested in a few prototypes to produce even higher fields than those required for ionization cooling (20T and more, though only one magnet is operational), there is still little experience in Europe and in particular in the accelerator community. Therefore, it is necessary to foresee the design of a magnet that is not too challenging yet not too easy. A solenoid generating a field between 5T and 10T on its axis is significant if it can be subjected to extensive testing. In addition, it is worth noticing that the solenoids, profiting of the main property of HTS (i.e., the high critical temperature) will be designed to operate at 20 K, by use of cryocoolers. The choice to go for higher temperature in the cooling cell is a novelty introduced in the IMCC/MuCol design study mainly driven by energy saving and sustainability (helium is becoming rare) considerations. We believe that for the muon collider (and any other future large accelerator for the post-LHC era), it is fundamental to confirm that such a high operational magnet temperature concept is feasible.
- For the ***RF structure*** there are still many open questions. The role of RF in ionisation cooling is to transfer longitudinal momentum to muons in the fastest possible way. This means in practice that we must provide the highest possible voltage, with a reasonable value for the real estate RF gradient (total RF voltage divided by the length of the cooling cell, therefore including eventual drift space and the absorber) up to around 40 MV/m at 704 MHz. Such value is limited by the power that would be necessary to be fed into the cavity, and on the necessity to limit field emissions at high field. Open topics includes the cell to cell coupling, the mode of resonance, the number of power couplers, the space necessary for the couplers and the other ancillaries, the availability of a klystron etc…
- Regarding the ***absorbers***, the best performance would be provided by liquid Hydrogen. There are unfortunately a number of drawbacks, such as the peak of overpressure that would be instantly generated by the energy peak deposed by the beam passing inside the liquid, the fact that hydrogen is highly flammable and therefore specific safety measures have to be studied and the hazards well understood before being able to commit on such

solution. Lithium Hydride is also a candidate material, providing a degradation in performances yet to be quantified, but since it is in solid phase and with limited safety hazards, it is considered a good choice for the first 3D integration exercise.

- Several ancillary issues have to be looked at, for instance the effect of the solenoids of adjacent cells on each cell, for instance to understand whether they increase the stress on the mechanical parts of adjacent cells. It has to be understood whether it is worth including the solenoids of the adjacent cells in the design of a single cooling cell , how to deal with the magnetic forces that will be generated in order to start analyzing the powering schemes, the necessary protections, and the most convenient cryostat configuration. The assembly scenario is also part of this exercise, to discuss what is the best assembly sequence, intervention scenarios following eventual failures, analysis of the most credible incident scenario etc…

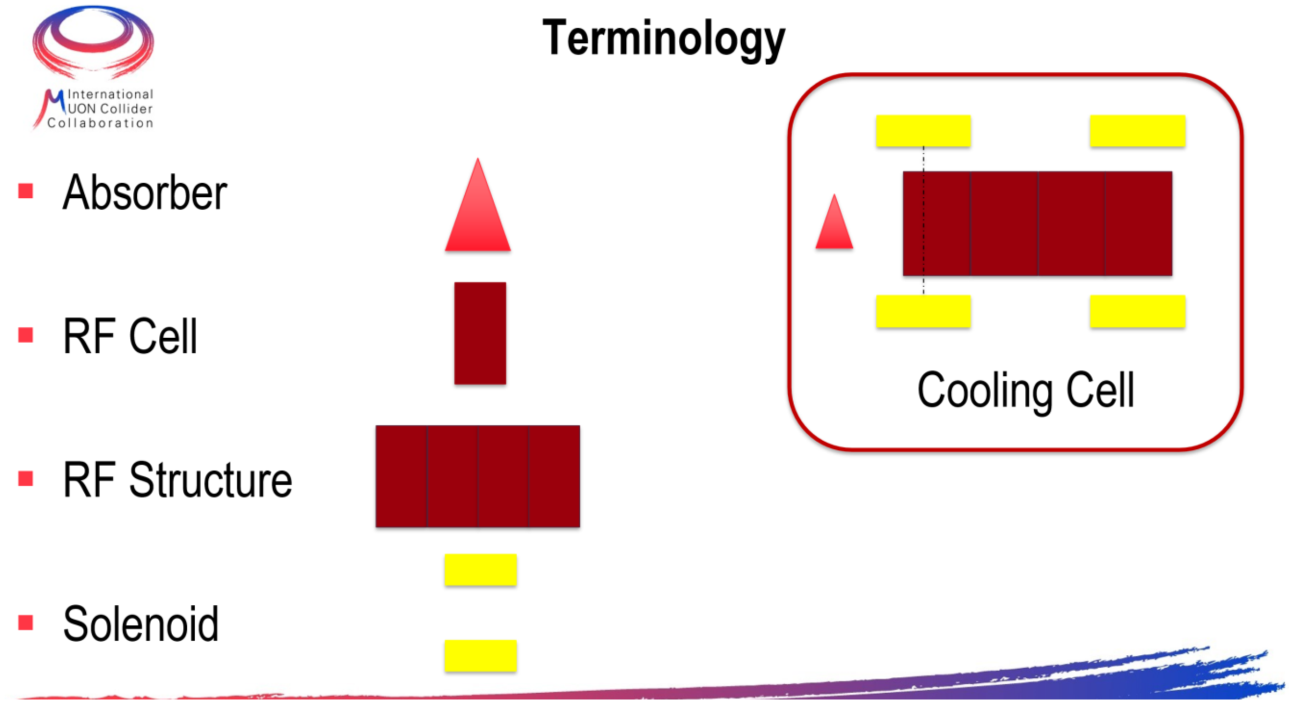
Within the framework of MuCol, a workshop was organized in January 2024 [2] to collect information from various experts and members of both MuCol and the International Muon Collider Collaboration (IMCC), and more discussions were organized at the annual MuCol and IMCC annual meeting [3]. A consensus was found around the design of a Cooling cell of the type B5 [naming from previous MAP configuration], or S5 in the new naming convention recently adopted [ref. Interim report] however simplified to two solenoids, a multicell RF structure and an absorber in LiH. The different components will be described in the following paragraph.

3. TECHNICAL CONSIDERATIONS ON THE COOLING CELL

3.1. COMPONENTS OF A COOLING CELL

A cooling cell is composed of two or more solenoids, an RF Structure made of one or multiple RF cells, and one or two absorbers made of low-Z materials.

The Collaboration adopts the terminology in fig. 2 to designate the elements of a cooling cell.



Terminology

- Absorber
- RF Cell
- RF Structure
- Solenoid

Fig. 2: Terminology for the cooling cell. It is important to underline that in this convention RF Structure and RF Cavity are synonym. The two solenoids of a cooling cell are sometime indicated as a solenoid pair or a split coil.

3.1.1. Absorbers

Several low-Z materials have been considered for the absorbers, with two options preferred over the others:

- ***Liquid Hydrogen***: the best from the point of view of the performances, minimising the total interception of particles in the absorber and still providing sufficient absorption of the momentum of the particles.
- ***Lithium Hydride***: Easier to use since it is solid at room temperature, presents no particular hazards, and is relatively easy to machine, however provides a lower effective yield.

3.1.2. Solenoids

Cells are being designed with just two solenoids, one at each end of the cooling cell. Simulations of beam dynamics in the cooling section are still in progress and it is not excluded that in order to improve the performances some cells might have to include more solenoids (4, 6 or more, as shown in fig. 5 of [2]).

- For the purpose of performing the first exercise of design and integration of a cooling cell, we will consider only a cell design based on two solenoids. The design of Muon collider solenoids is based on the technology of High Temperature Superconductors (HTS) compared to Low Temperature Superconductors for several reasons:Higher critical field
- Better critical current in high Magnetic fields
- Higher operational temperature leading to:

  - The possibility of operating at 20 K (increasing the thermodynamic CoP by a factor 10 with respect to the 2K used for LHC Nb-Ti magnets and for HL-LHC Nb3Sn magnets);
  - increased temperature and energy margin to quench; though a protection system will be necessary, for safety reason, we believe that after initial training an HTS solenoid will be quench-free in operation.
- Minimisation of operational costs and maintenance time (no use of LHe or HEII).

The IMCC collaboration is therefore working in the hypothesis that all magnets for the cooling sections of the future Muon Collider will be based on HTS, in particular on REBCO tapes. It is assumed that by having just one type of superconductor, or one family of superconductors, economy of scale will bring an overall cost reduction for the production of the REBCO tapes. On this material there is also a very interesting synergy with the world of nuclear fusion as they have already chosen REBCO as the material for future fusion projects, and this will bring additional economies of scale, and will provide opportunities for the exchange of know-how that will benefit both communities.

3.1.3. RF Structures

A decision on the type of RF structure that will have to be integrated in the cell requires taking into account a number of parameters that includes:

- the required real estate gradient of the electric field in a cell vs. the peak gradient achievable in the RF structure,
- the available or realistically feasible power sources,
- the space available to fit ancillaries (e.g. tuners, power couplers, cooling pipes etc…), considering the tight interference with the cryomagnetic system,
- the type of RF coupling from cell to cell,
- the RF frequency,
- expected breakdown rate and eventual mitigation strategy, especially in the high magnetic field and high magnetic gradient they experience.

Most of the parameters used for simulations of the entire cooling section are at the edge or beyond the present state-of-the-art, therefore require careful evaluation of the feasibility of the corresponding technological solution. This is a strong motivation to design a structure in a frequency range where power sources exist to equip a test stand where one could push such an RF structure to the limits of its performance. In the following chapters we will analyse the availability of RF sources and provide a justification for the choice of the frequency to be used for the design.

3.1.4. RF Power sources (Alexej/Dario/Graeme)

Analysis of klystrons on the market, concluding that the only available klystron is the 1 GHz CLIC one

3.2. VARIETY OF COOLING CELLS (CHRIS)

In this paragraph we want to provide some more details about the different types of cooling cells that are presently under study. It should contain a table with main parameters useful for electromagnetic and mechanical design, such as:

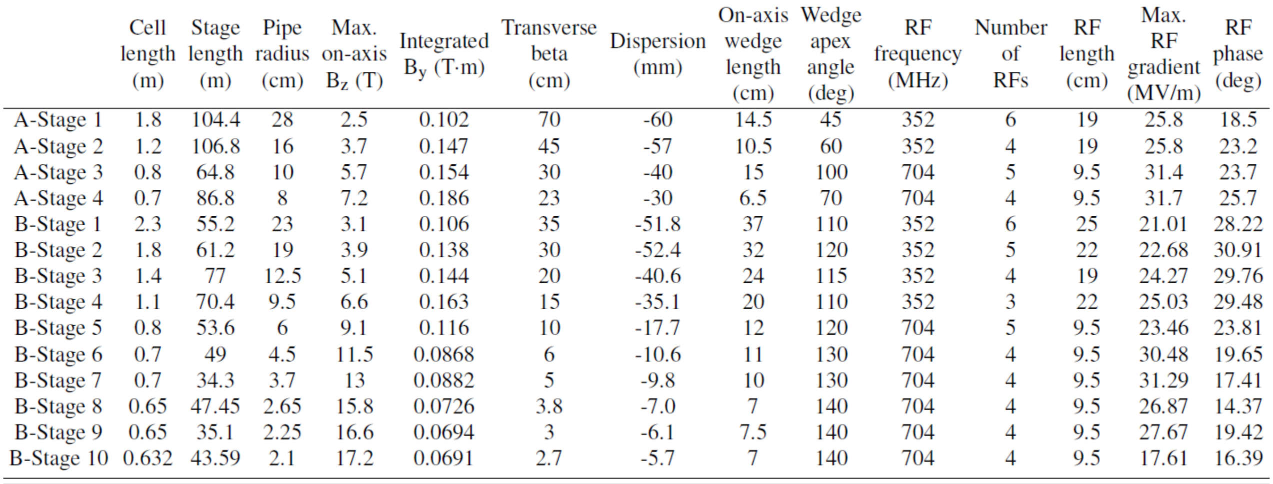
The layout of the muon production system is shown in [figure]. While there is a rich history of different sorts of muon beams cooling systems, the IMCC has selected rectilinear and final cooling systems for the facility design and the rectilinear cooling system has been selected for the cooling cell.

The rectilinear cooling system is comprised of many highly compact cooling cells, containing a mix of high gradient RF cavities and relatively high field superconducting solenoids. Two systems are required, one for each charge species with each planned to be about 1 km in length. Each system is divided into two sections, distinguished by the cell tune (number of betatron oscillations) per cell. The initial cooling is performed by ‘Type A’ cooling cells that operate with a cell tune below 1. This operating point is chosen as the lattice can accept a beam with a higher emittance, suitable for the initial beam arising from the capture system.

The bunches are then merged before being cooled in ‘Type B’ cooling cells that operate with a cell tune between 1 and 2. Operating at a higher tune causes cooling cells to have tighter focusing, and so yield lower emittances. The cost of this is that the cooling cells do not accept such high emittances, and in particular have a limited momentum acceptance owing to stopbands at the integer resonances.

Proposed parameters, under review by IMCC, are shown in Table X. The earlier stages have weaker solenoidal (Bz) magnetic fields and longer cooling cells, while the later stages have stronger fields. WP7 is reviewing the limits of achievable solenoid field. This design employs liquid hydrogen absorbers. The heat load on these absorbers, especially when the beam is narrow in the later stages, may cause undesirable effects in the hydrogen necessitating the use of lithium hydride absorbers. In these cells the RF cavities are assumed to be independently phased; this would require a complicated power feed. Alignment and beam instrumentation systems have not been studied and there is very little space that would enable installation of such a system.

Table 1: Parameters under consideration by IMCC for the rectilinear cooling system.



	Cell length (m)	Stage length (m)	Pipe radius (cm)	Max. on-axis B_z (T)	Integrated B_y (T·m)	Transverse beta (cm)	Dispersion (mm)	On-axis wedge length (cm)	Wedge apex angle (deg)	RF frequency (MHz)	Number of RFs	RF length (cm)	Max. RF gradient (MV/m)	RF phase (deg)
A-Stage 1	1.8	104.4	28	2.5	0.102	70	-60	14.5	45	352	6	19	25.8	18.5
A-Stage 2	1.2	106.8	16	3.7	0.147	45	-57	10.5	60	352	4	19	25.8	23.2
A-Stage 3	0.8	64.8	10	5.7	0.154	30	-40	15	100	704	5	9.5	31.4	23.7
A-Stage 4	0.7	86.8	8	7.2	0.186	23	-30	6.5	70	704	4	9.5	31.7	25.7
B-Stage 1	2.3	55.2	23	3.1	0.106	35	-51.8	37	110	352	6	25	21.01	28.22
B-Stage 2	1.8	61.2	19	3.9	0.138	30	-52.4	32	120	352	5	22	22.68	30.91
B-Stage 3	1.4	77	12.5	5.1	0.144	20	-40.6	24	115	352	4	19	24.27	29.76
B-Stage 4	1.1	70.4	9.5	6.6	0.163	15	-35.1	20	110	352	3	22	25.03	29.48
B-Stage 5	0.8	53.6	6	9.1	0.116	10	-17.7	12	120	704	5	9.5	23.46	23.81
B-Stage 6	0.7	49	4.5	11.5	0.0868	6	-10.6	11	130	704	4	9.5	30.48	19.65
B-Stage 7	0.7	34.3	3.7	13	0.0882	5	-9.8	10	130	704	4	9.5	31.29	17.41
B-Stage 8	0.65	47.45	2.65	15.8	0.0726	3.8	-7.0	7	140	704	4	9.5	26.87	14.37
B-Stage 9	0.65	35.1	2.25	16.6	0.0694	3	-6.1	7.5	140	704	4	9.5	27.67	19.42
B-Stage 10	0.632	43.59	2.1	17.2	0.0691	2.7	-5.7	7	140	704	4	9.5	17.61	16.39

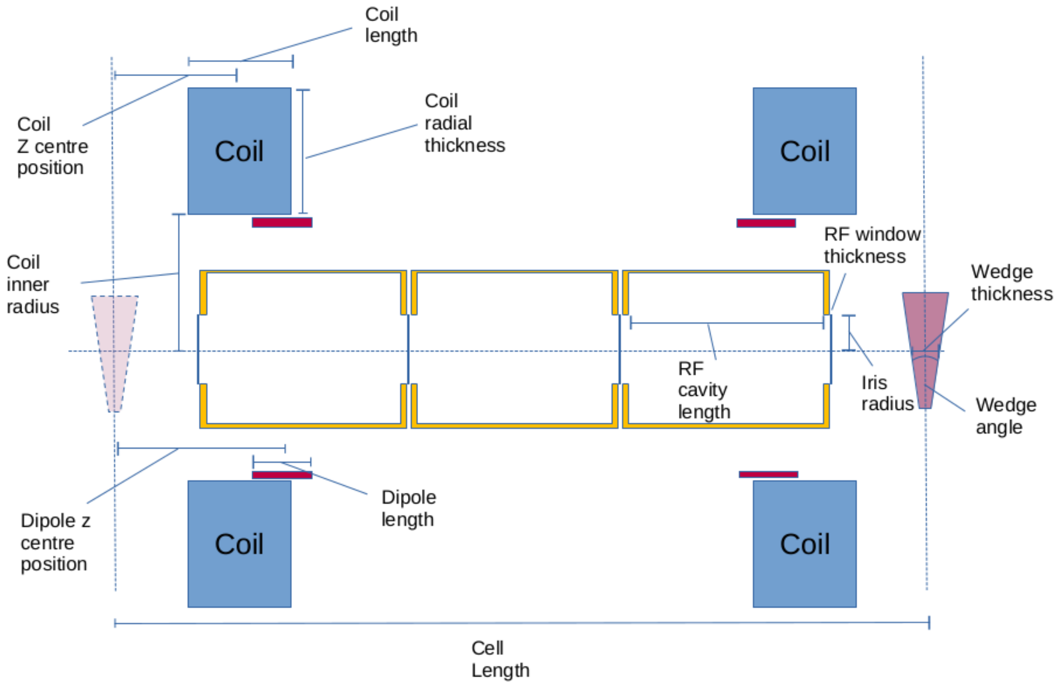
The ‘Type B’ cells have been initially chosen for more detailed study as they are physically and optically more demanding. Optically they require a careful balance between focusing strength, control over the location of the stop bands, and acceptance. The RF and absorbers must be carefully controlled to ensure that the RF does not accelerate particles into the stop bands while maintaining sufficient acceptance to control the beam. The B5 cell provides a good balance of demanding magnets, high acceptance and low emittance.

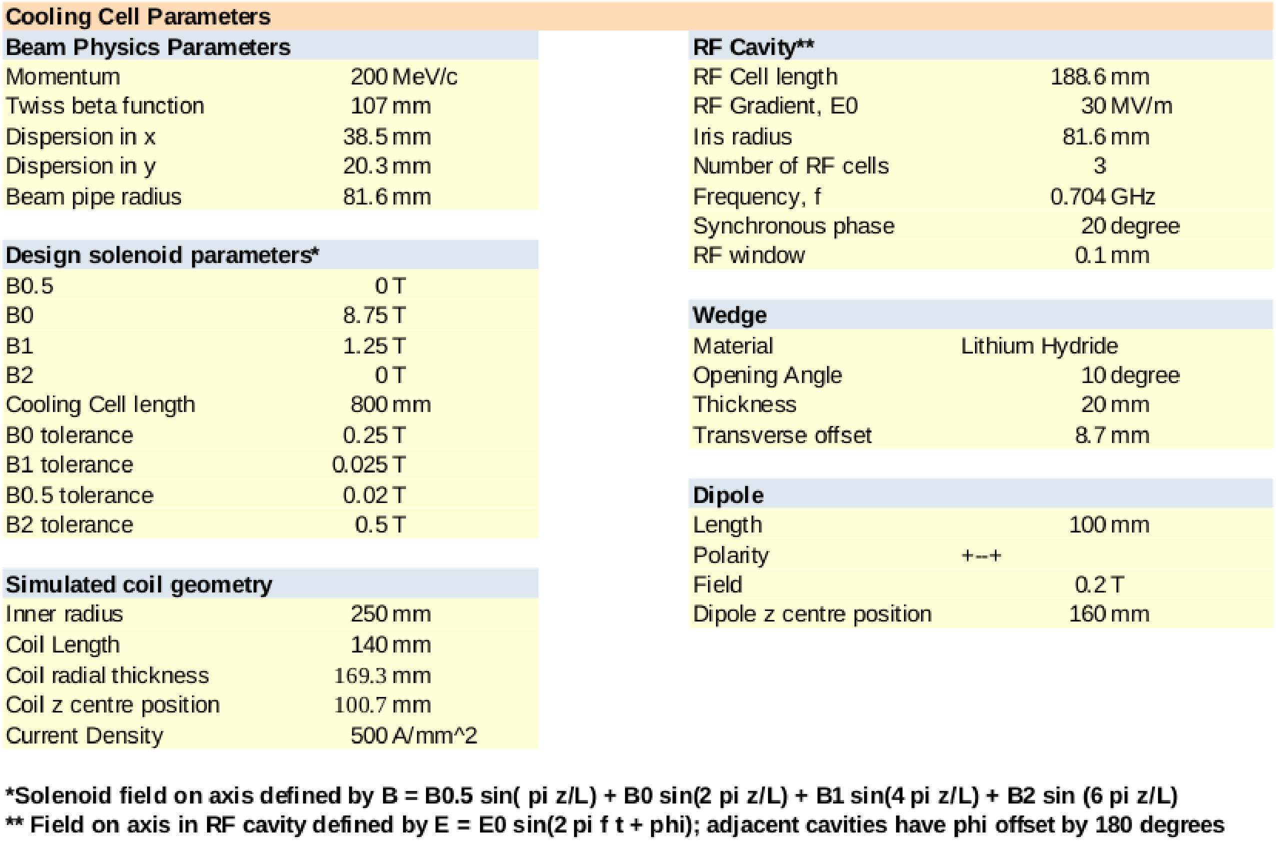
3.2.1. Design of a Cooling cell of type S5

A cooling cell has been designed based on the design for the B5 cell described above, but taking several approaches which may facilitate the cell construction. The cooling cell schematic, as simulated in G4Beamline, is shown below. The lattice was simulated using G4Beamline v3.08. Lattice files are available in the Work Package 4 area on github in the MuonCollider-WG4/cooling_demonstrator repository with the version branch ‘2024-05-23-prerelease'. Parameters for the cooling cell are described in Table X.

In order to generate the simulation, a solenoid lattice was generated using an ideal solenoid field based on a sum of harmonic components. This ideal field, described as the “Design solenoid parameters” was used to calculate optical functions in order to estimate cooling performance. A coil geometry was generated, in order to calculate a 3D field map which could be used for tracking in G4Beamline. Dipoles were added enabling calculation of dispersion. The dipoles were treated as a vertical field that filled the transverse aperture of the beam pipe and had a hard edge that did not reflect a realistic fringe field; subsequent iterations of the design may include a realistic fringe field model when a dipole arrangement becomes known.

RF cavities and absorbers were added in order to estimate the energy change and ultimately the cooling performance. The RF cavities were treated as ideal cylindrical pillboxes with an electric field that was uniform longitudinally and a Bessel function in transverse. A matching magnetic field, out of phase with the RF, was also included in the simulation. Thin windows were used to terminate the RF cavities, which had the effect of increasing the available accelerating gradient at the expense of introducing scattering and potentially degrading the cooling performance. For this reason thin windows were used to minimise scattering.





Cooling Cell Parameters

Beam Physics Parameters	
Momentum	200 MeV/c
Twiss beta function	107 mm
Dispersion in x	38.5 mm
Dispersion in y	20.3 mm
Beam pipe radius	81.6 mm

Design solenoid parameters*	
B0.5	0 T
B0	8.75 T
B1	1.25 T
B2	0 T
Cooling Cell length	800 mm
B0 tolerance	0.25 T
B1 tolerance	0.025 T
B0.5 tolerance	0.02 T
B2 tolerance	0.5 T

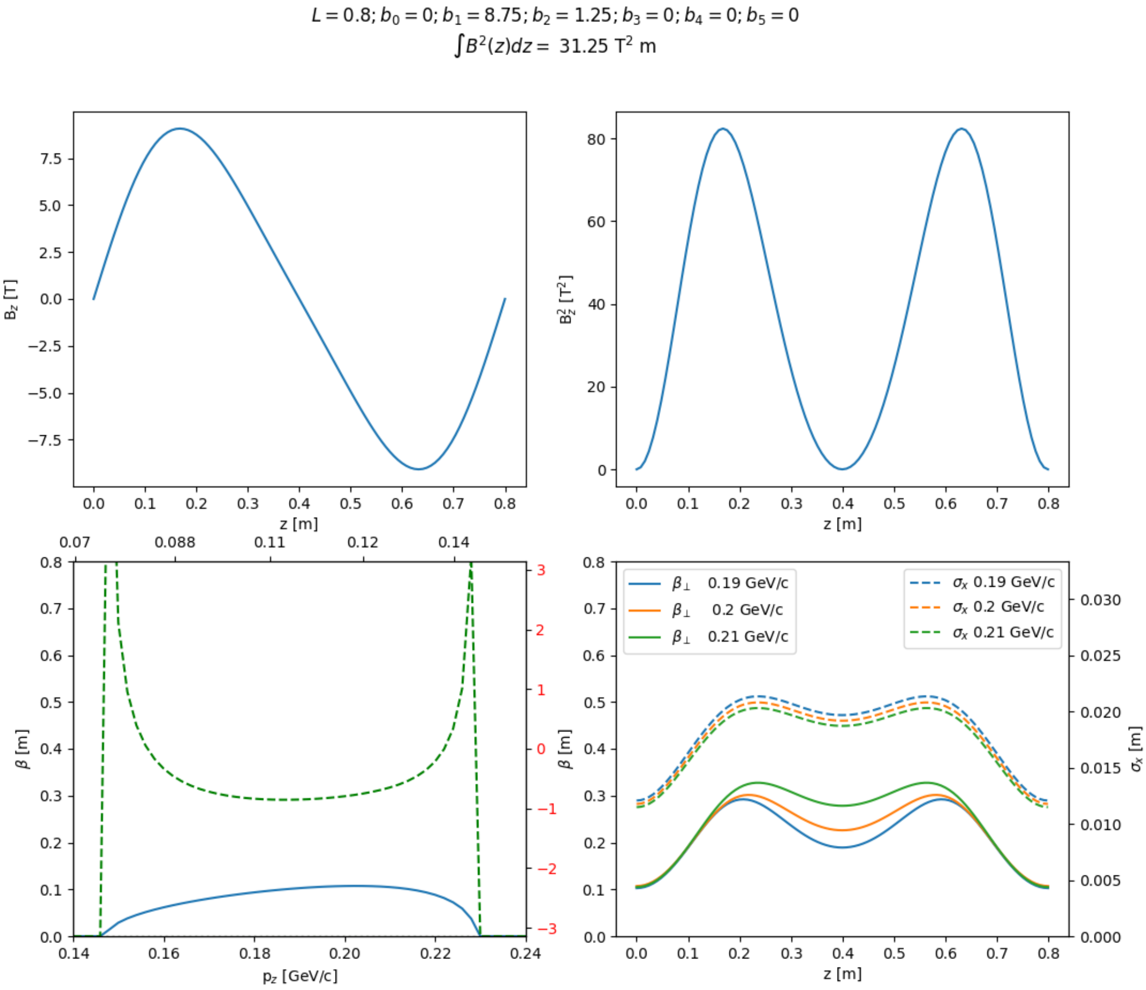
Simulated coil geometry	
Inner radius	250 mm
Coil Length	140 mm
Coil radial thickness	169.3 mm
Coil z centre position	100.7 mm
Current Density	500 A/mm^2

RF Cavity**	
RF Cell length	188.6 mm
RF Gradient, E0	30 MV/m
Iris radius	81.6 mm
Number of RF cells	3
Frequency, f	0.704 GHz
Synchronous phase	20 degree
RF window	0.1 mm

Wedge	
Material	Lithium Hydride
Opening Angle	10 degree
Thickness	20 mm
Transverse offset	8.7 mm

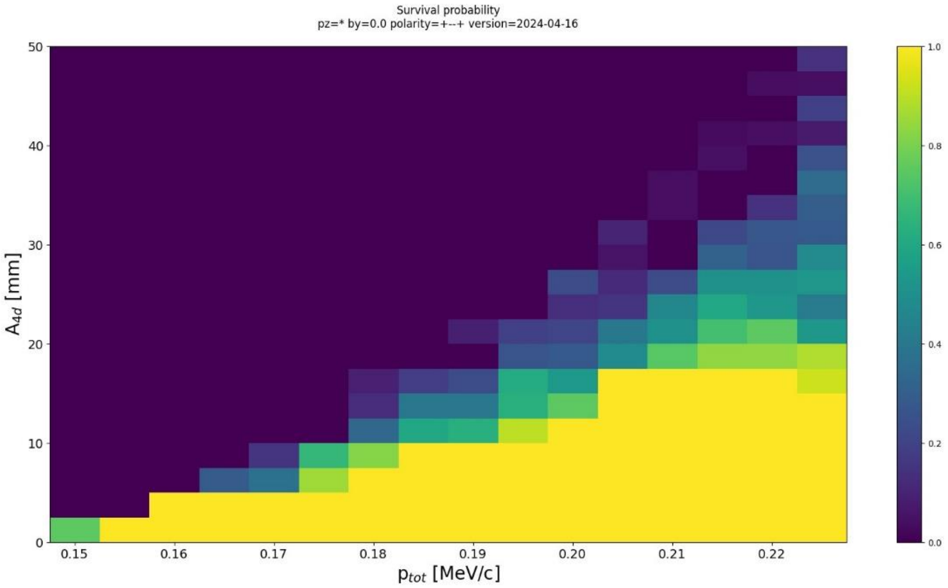
Dipole	
Length	100 mm
Polarity	+--+
Field	0.2 T
Dipole z centre position	160 mm

***Solenoid field on axis defined by B = B0.5 sin(pi z/L) + B0 sin(2 pi z/L) + B1 sin(4 pi z/L) + B2 sin (6 pi z/L)**
**** Field on axis in RF cavity defined by E = E0 sin(2 pi f t + phi); adjacent cavities have phi offset by 180 degrees**

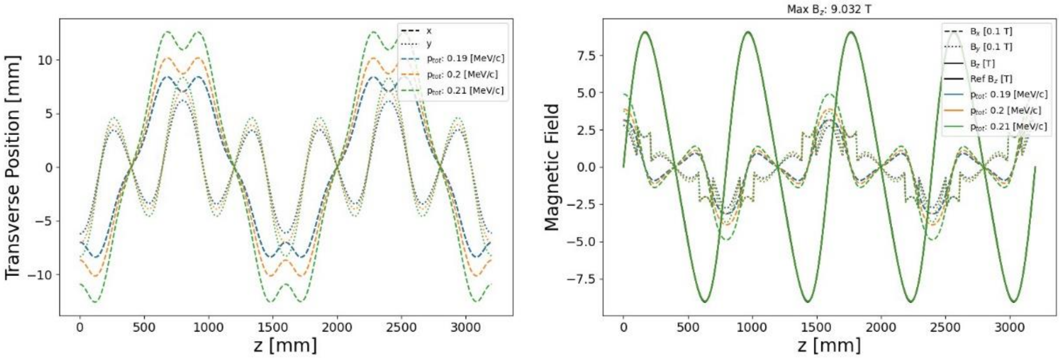


The ideal solenoid parameters are shown in fig. X. The top left plot shows the on-axis field, while the top right plot shows the square of the field, proportional to the solenoid focusing strength. The bottom left plot shows the optical beta function at the focus and anti-focus as a function of moment in the pass band of interest. The bottom right plot shows the optical beta function and beam radius at one standard deviation for a beam having 2.5 mm transverse normalised emittance, for a selection of momenta. The lattice yields stopbands at around 140 MeV/c and 230 MeV/c, showing the maximum momentum acceptance of the magnetic lattice. The beam size at 1 standard deviation is 11.5 mm at the focus and about twice that at the maximum extent.

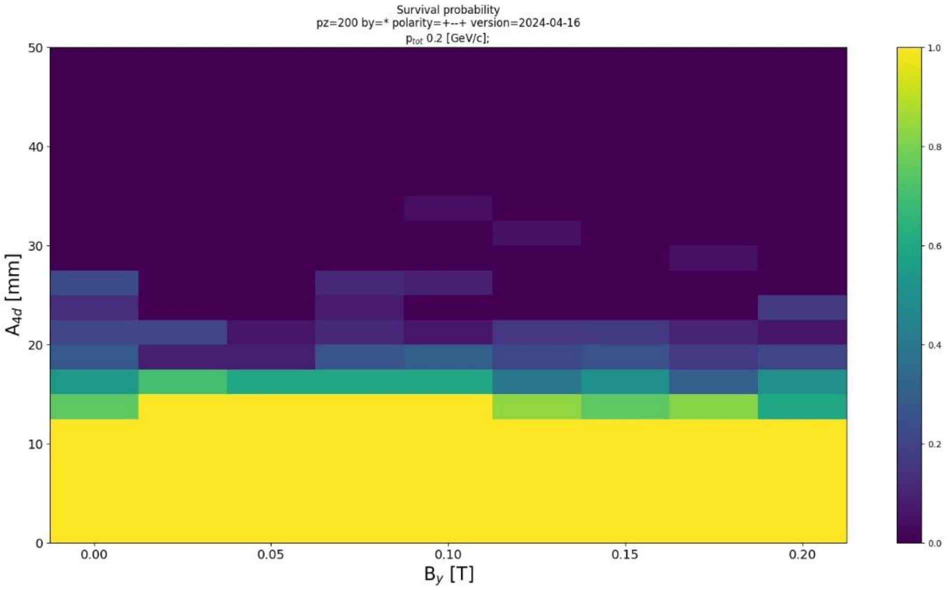
The transverse acceptance was calculated by tracking a beam of muons uniformly distributed in x and y actions and angles. The muons were generated at the field flip so the average angular momentum of the beam was set to 0. This process was repeated for a number of different momenta. The resulting survival probability after traversing 80 m was calculated and is shown in Fig. Y. The solenoids exhibit an octupole-like behaviour that gives excess focusing for high amplitude particles, increasing their tune towards 2. This yields a worse dynamic acceptance for the low momentum particles.



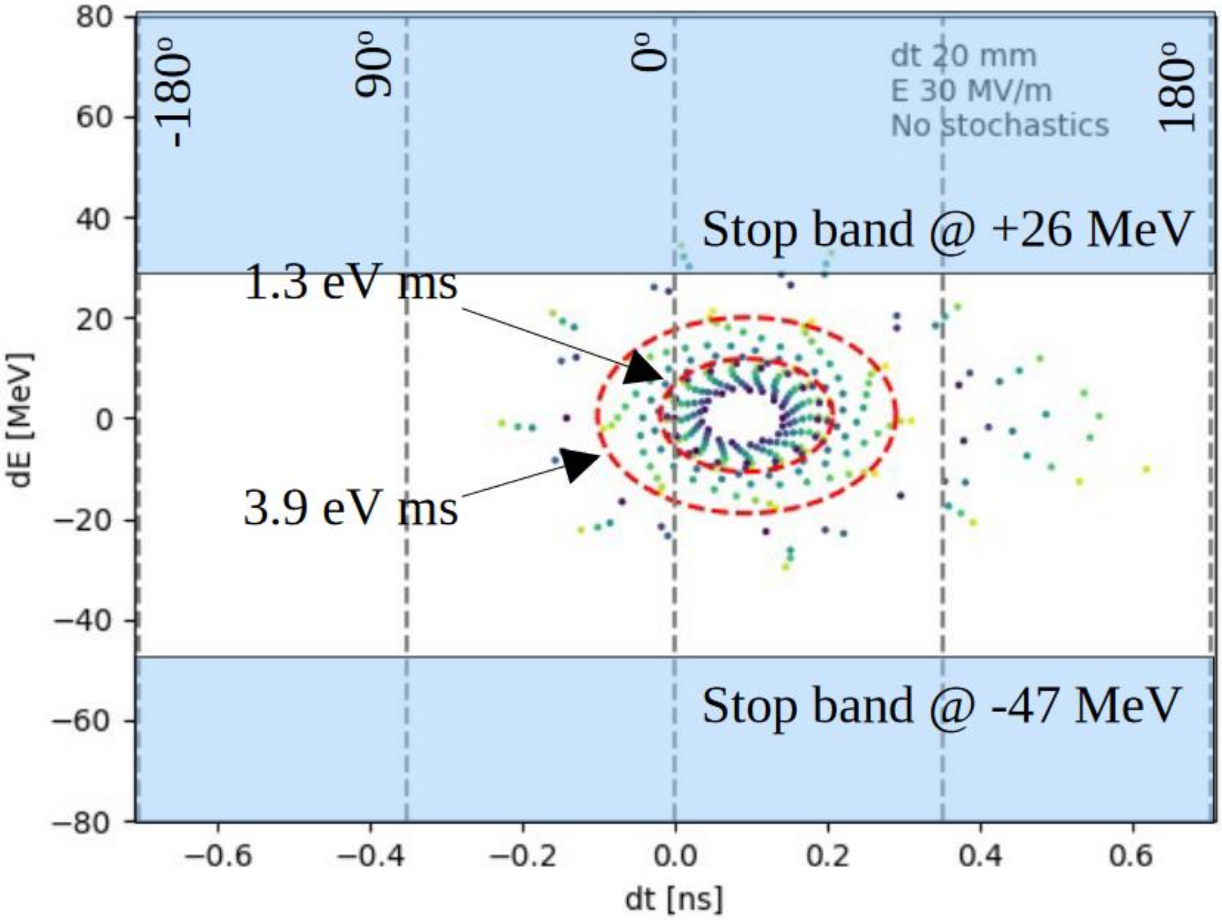
Dispersion was introduced by adding dipole fields to the lattice. By flipping the dipoles in every other cell, significant dispersion can be produced. The dispersion that is produced is shown



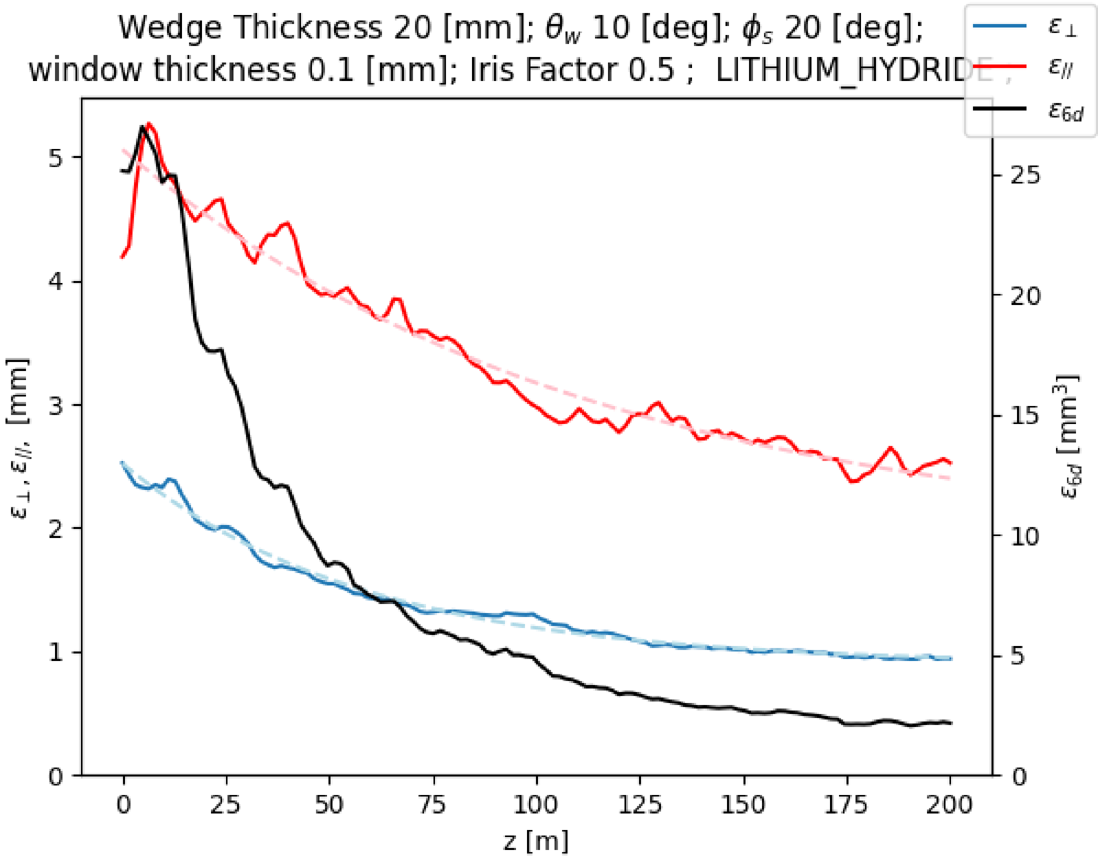
Dipoles 0.1 m long of 0.2 T were introduced with the dipole field flipping in adjacent cells. The closed orbit distortion that this creates is shown in fig X (left) and the resultant field along the closed orbit is shown in fig. X (right). The dipole field strength was ramped between 0 and 0.2 T to explore the impact on dynamic aperture, calculated in the same was as described above. Negligible reduction in DA was observed.



RF cavities were introduced to the lattice. Three RF cells were simulated in each 0.8 m period of the solenoid lattice. Each RF cell was 188 mm long. Adjacent cells were simulated 180 degrees out of phase with respect to each other. This arrangement may enable a single power feed to the central cavity and inductive or capacitative coupling to bring power to the end cells, which is likely to be more practical than individual power feeds to each cell. The RF cavities were modelled with 30 MV/m and 0.704 GHz RF frequency, which is the expected achievable voltage that may be possible for this cooling system, depending on RF tests. A LiH wedge absorber was also introduced and the thickness adjusted so that the RF bucket could comfortably accommodate a beam having 1.3 eV ms longitudinal emittance, which was the target longitudinal emittance for this lattice. 20 mm was found to be a suitable wedge thickness on the closed orbit. Time-energy trajectories of some nominal particle tracks are shown in fig. X, where the energy of the stop bands and typical beam emittances at 1 and 3 standard deviations are also shown.



Finally the cooling channel was simulated with a full beam. The initial beam was a multivariate gaussian. The performance of the cooling channel is shown in fig. X. An over long cooling channel was simulated so that the full range of emittances from injection to equilibrium could be observed. A significant mismatch was observed in longitudinal phase space despite a reasonable attempt at linear matching. This was accompanied by beam loss. A better matching procedure will be needed and is under study. After the initial mismatch, performance is acceptable.



3.2.2. Mechanical Design of a Cooling cell of type S5

The starting point for the conceptual design of the cooling cell of type S5 is its frequency, which fixes the radius of the internal RF surface of the cavity.

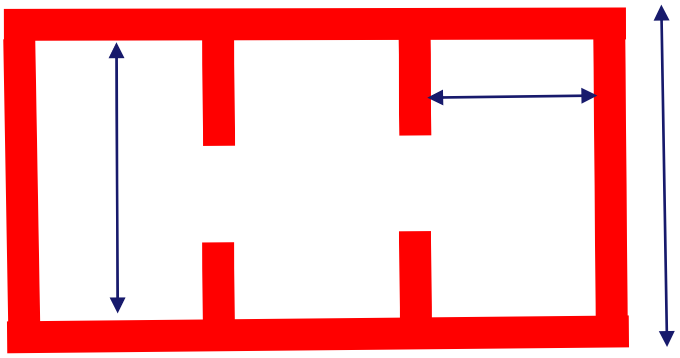


Fig. 1: Dimensions of the RF structure

At 704 MHz the internal diameter will be order of 360 mm, to which one has to add about 50 mm of thickness for the copper structure.

The Solenoids cryostats will therefore have a free bore diameter, at room temperature, of **470 mm** leading to a bore for the HTS solenoids of about **550 mm.**

We will refine the numbers then scale down to 1 GHz linearly.

Coupling will be through the center cell. The RF structure will be constituted of 3 cells if we stay below 0.8 m, and 5 cells if we decide to go for 1.2 m. The solenoids will have separate cryostats so that eventually one could test 2 structures, one with three cells and one with 5 cells later on.

Technical details to be added…..

4. THE MAGNET SYSTEM OF THE RFMF TEST FACILITY AS GUIDELINE DESIGN FOR THE COOLING CELL

The IMCC collaboration considers the construction of a facility to test RF single cell cavities in high magnetic field as a primary objective of the R&D phase toward a muon collider. Among various options, INFN is proposing to design and build a facility called RFMFTF (Radio Frequency in Magnetic Field Test Facility). The facility consists of a split coil (coil pair) capable to generate both uniform and gradient magnetic field in order to study the behaviour of various RF structures in magnetic field condition similar to the one experienced in the cooling cells, see Fig 4.1. The size of the coil pair is such that will allow testing of room temperature cavities of frequency approximately higher than 1.3 GHz, in magnetic field up to 7 Tesla. In particular the INFN project is, in a first step, aimed at testing 3 GHz RF cavities: in this case the room inside the bore is not an issue and the service can come longitudinally, along the axis of the magnet or beam direction.

Fig. 4.1

A second scope of the RFMFTF is to be a first and significant prototype of the cooling cell magnet technology. Therefore, even if the field level would allow to use Nb-Ti, it will be designed and built in HTS for operation at 20 K. The cooling method is still to be decided. It might be cooled by means of a flow cold He gas at 20 K, as is most likely for the cooling cell of the Muon Collider, or can be cooled without any cryogenic fluid, by means of cryocooler. In any case the coil will be cooled via solid conduction, i.e., it will be a cryogen-free coil.

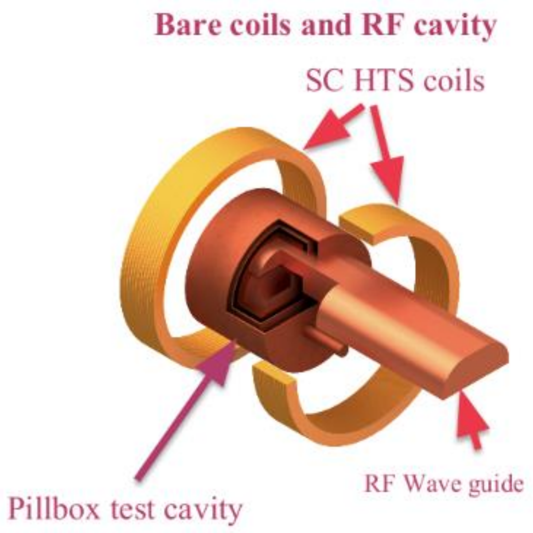
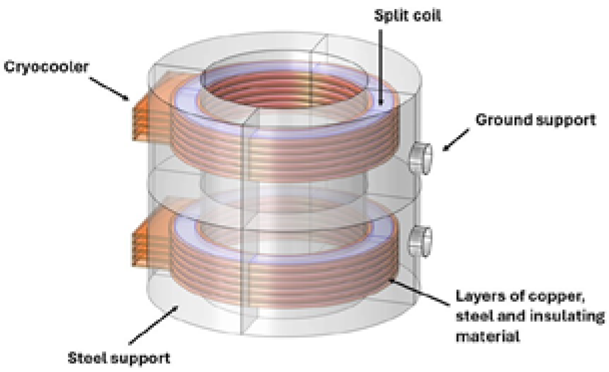


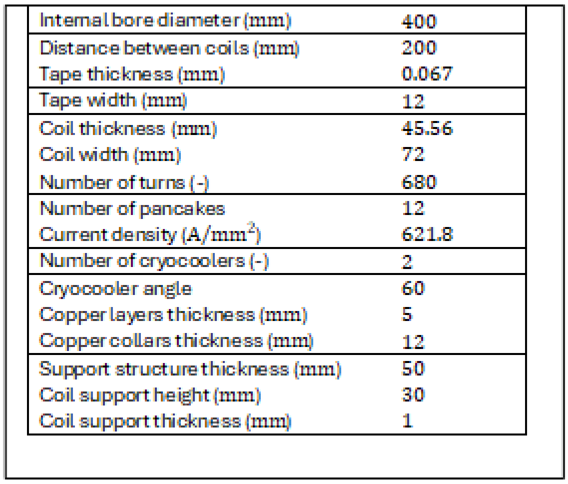
Fig.4.1 Sketch of the RFMFTF as proposed by INFN. For a coil radius of 200 m the effective free bore for the RF system is about 300-320 mm

Here in this chapter we make a short description of the RFMFTF magnet as a contribution to the preliminary design of the magnet of the cooling cell. The criteria of magnet design of the cooling cell will follow the RFMFTF.

4.1. COIL DESIGN

Each coil of the pair is composed of six flat pancakes wound with flat HTS tape, see Fig.4.2 where the structure of the coil is shown with the table of main parameters. Those parameters would allow 7 T field to be generated in a room temperature free bore of 300-320 mm.





Internal bore diameter (mm)	400
Distance between coils (mm)	200
Tape thickness (mm)	0.067
Tape width (mm)	12
Coil thickness (mm)	45.56
Coil width (mm)	72
Number of turns (-)	680
Number of pancakes	12
Current density (A/mm^2)	621.8
Number of cryocoolers (-)	2
Cryocooler angle	60
Copper layers thickness (mm)	5
Copper collars thickness (mm)	12
Support structure thickness (mm)	50
Coil support height (mm)	30
Coil support thickness (mm)	1

Fig. 4.2. Left: split coil structure. Right: main parameters list.

The coils are submitted to a large radial force and hoop stress, so they need a robust support of 316 LN austenitic steel, about 50 mm restraining the coils expansion, see Fig. 4.3. In the same figure it can be appreciated that the coils are kept in a unique cod mass that helps to support the strong forces between coils. Because the system is designed both for opposite and same current polarity in the coil (to create a gradient field – like in the cooling cells – or a uniform flat field inside the coils), we have opted for integrating the coils in a unique mechanical structure, abandoning the initial system where two separate coils were supported by tie-rods.

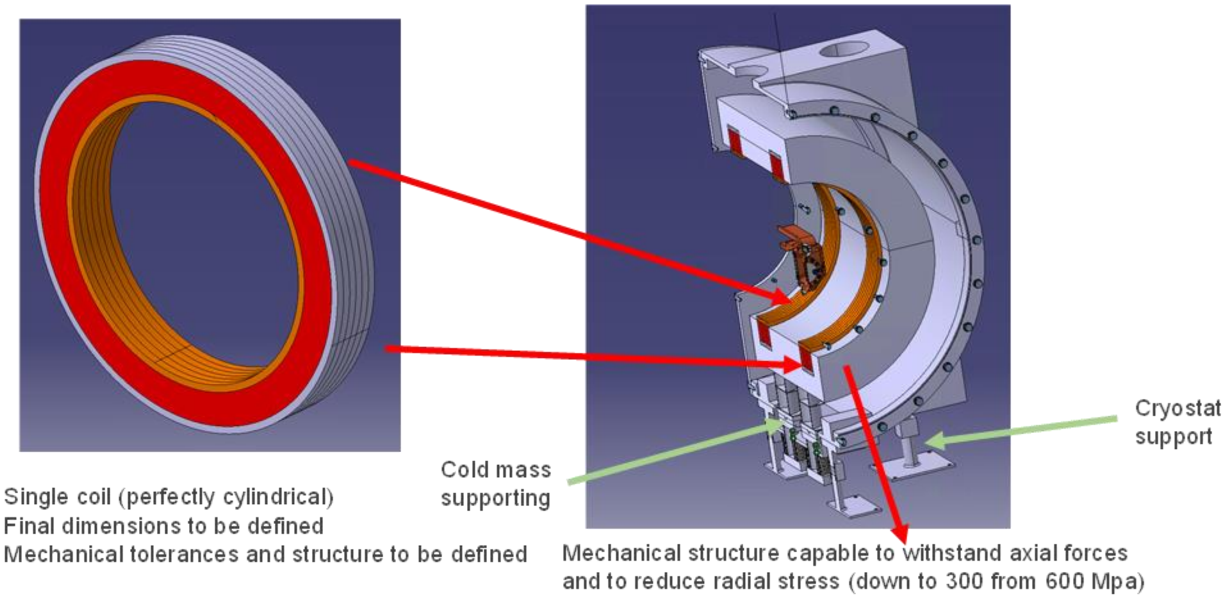


Fig. 4.3 : RFMFTF structural design with single cold mechanical structure for force support

The drawback of the system is that it requires a single cryostat embracing both coils and making it difficult to have radial access. This is the only difference between the magnetic system of the RFMFTF and the one of the cooling cell that will have a room temperature vertical passage to serve for the RF power coupler and other possible RF auxiliary equipment. It is worth emphasizing that the most important parameter inferred from the RFMFTF design is that the distance that one must take from the inner edge of the coil and the outside of the vacuum vessel at room temperature **is 40 mm** (strictly speaking 38 mm). This is the space required for vacuum insulation (the 300 K of the vacuum vessel, to the 60 K thermal shield and from this one to the 20 K coil) and for the thickness of the vacuum vessel wall and thermal shield. This dictates the minimum coil diameter, which is 80 mm larger than the minimal radius that must be kept for the RF system, as it is reported in 3.2.1 section, if the RF system goes inside the coil cryostat. In addition, since the actual cooling cell must have vertical room temperate bore between the two coils, as above mentioned, this 40 mm clearance between coil and room temperature equipment must apply to any warm-cold interface

In Fig. 4.4 a view of the test facility with inside (in scale) a 3 GHz RF cell with the waveguide (without its support system) is shown.

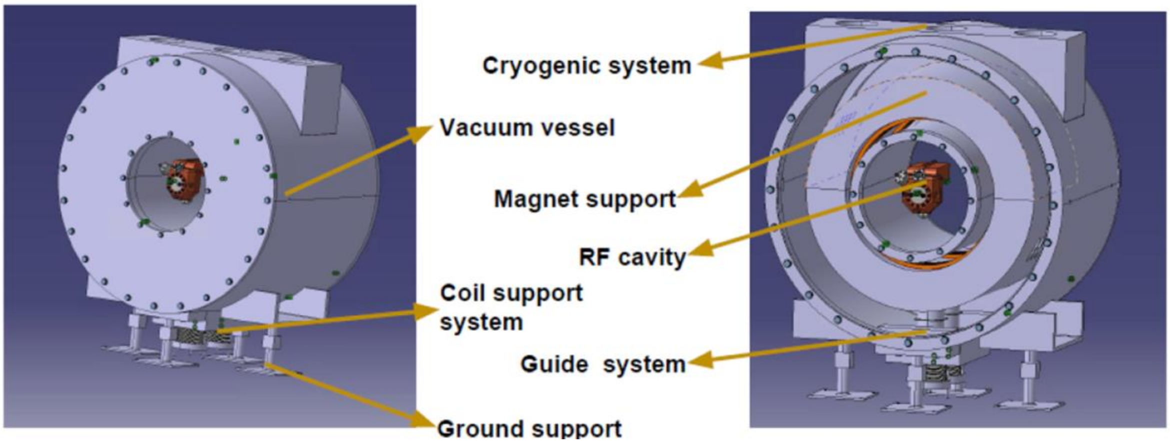


Fig. 4.4. Global view of the RFMFTF magnetic system with a 3 GHz Cavity inside (w/o support)

5. MORE CONTENT

5.1. MORE CONTENT HEADING LEVEL 2

[Text]

5.1.1. More content heading level 3

5.1.1.1. Heading level 4

Heading level 5

Heading level 6

Heading level 7

Heading level 8

Heading level 9

6. FUTURE PLANS / CONCLUSION / RELATION TO OTHER MUCOL WORK

[Text to end the document, either mentioning future plans, some sort of conclusion or how this work relates to other work within the MuCol project. Use your judgement to find a suitable heading for a short end-section for the deliverable]

7. REFERENCES

MUCOL references are based loosely on the Harvard System of referencing. In the text, references should be marked by numbers in square brackets [x]. Then in this "references" section, they are listed by number using the following styles:

JOURNAL ARTICLES:

[x] Author's surname, Author's initials. (Year of publication) Article title, *Journal title*, volume (issue), page numbers.

e.g. [1] Katz, U.F. (2006) KM3NeT: Towards a km3 Mediterranean neutrino telescope, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 567 (2), pp 457-461.

CONFERENCE PAPERS

[x] Author's surname, Author's initials. (Year of publication) Title of contribution. In: Editor of Conference proceeding (Initials, Surname with ed(s) if relevant/available). *Title of Conference proceeding*, date and/or place of conference. Place of publication: Publisher (if known), Page(s) of contribution if available.

e.g. [2] Medjoubi, K. et al. (2011) Performance and Applications of the CdTe- and Si-XPAD3 photon counting 2D detector. In: *Journal of Instrumentation (JINST) Open Access Conference Proceedings of 12th International Workshop on Radiation Imaging Detectors (IWORLD)*, 11-15 July 2010, Cambridge, UK. UK: Institute of Physics (IOP), 6 C01080 http://iopscience.iop.org/1748-0221/6/01/C01080/

REPORTS

Author's surname, Author's initials, (Year of report) *Title in italics*, Issuing organisation, report number, pages.

e.g. [3] SuperB Collaboration (2007) *Super-B, a High Luminosity Super Flavour Factory, Conceptual Design Report*, INFN/AE - 07/2, SLAC-R-856, LAL 07-15 http://arxiv.org/abs/0709.0451v2

BOOKS:

[x] Author's surname, Author's initials. (Year of publication) *Title in italics*. Edition (if not the first). Place of publication: Publisher.

e.g. [4] Grupen, C. and Shwartz, B. (2011) *Particle Detectors (Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology)*, Paperback, 2 edition, UK: Cambridge University Press

EDITED BOOKS

[x] Author's surname, Author's initials. (Year of publication) Title of chapter. In Editor's surname, Editor's initials (ed.) *Title in italics*. Edition (if not the first). Place of publication: Publisher, Page numbers of chapter.

e.g. [5] Charpak, G. (2010) Particle detectors and society. In Cashmore, R., Maiani, L. and Revol, J-P (eds.) *Prestigious Discoveries at CERN: 1973 Neutral Currents. 1983 W & Z Bosons*, Paperback, Germany: Springer, pp. 135-146.

WORLD WIDE WEB DOCUMENTS

Author's surname, Author's initials. (Year) *Title or main heading of web page in italics* [online]. Available from: URL. [Accessed date].

The URL should be given to the specific page, not a generic website for the organisation.

If an author is not available it is common to use the organisation name e.g. BBC or Anon.

e.g. [6] Wyles, N. (2011) *AIDA - Advancing European particle detector research* [online]. Available from: http://www.alphagalileo.org/ViewItem.aspx?ItemId=94835&CultureCode=en [Accessed 18 February 2011].

NEWS ARTICLE

Author's surname, Author's initials. (Year of publication) Title of Article. *Title of Newspaper in italics*. Day published, page number (if available).

e.g. [7] Wyles, N. (2011) AIDA – pushing the boundaries of European particle detector research, *CERN Bulletin*, 11 February 2011, p. 6.

ANNEX: GLOSSARY

Acronym	**Definition**
xxx	Definition of xxx