An Update on the 6D Muon Cooling Demonstrator

NuFact 2024

Argonne National Laboratory

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Rohan Kamath

On behalf of the IMCC

Funded by the European Union

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Introduction

- Muon colliders are seen as a promising candidate for the next generation of particle colliders because:
  - They are lepton colliders which provide the same physics reach as hadron colliders at a lower CoM energy.
  - They can do this in a much smaller footprint compared to electron-positron colliders due to the lack of synchrotron radiation.
- Momentum has been building in muon collider research, with the 2020 update to the European Strategy for Particle Physics endorsing R&D for muon colliders as part of its accelerator roadmap.
- In 2023, the P5 report outlined the need for a “aggressive R&D program to determine the parameters for a muon collider test facility”, working towards the goal of a 10TeV pCoM collider that could fit in the Fermilab campus.
- The report called this a “Muon Shot”.

Introduction

symmetry follow

topics

Illustration by Sandbox Studio, Chicago with Steve Shanabruch

A trio of paths toward the discovery machine of the future

03/19/24 | By Kimberly Hickok

The New York Times

Particle Physicists Agree on a Road Map for the Next Decade

A "muon shot" aims to study the basic forces of the cosmos. But meager federal budgets could limit its ambitions.

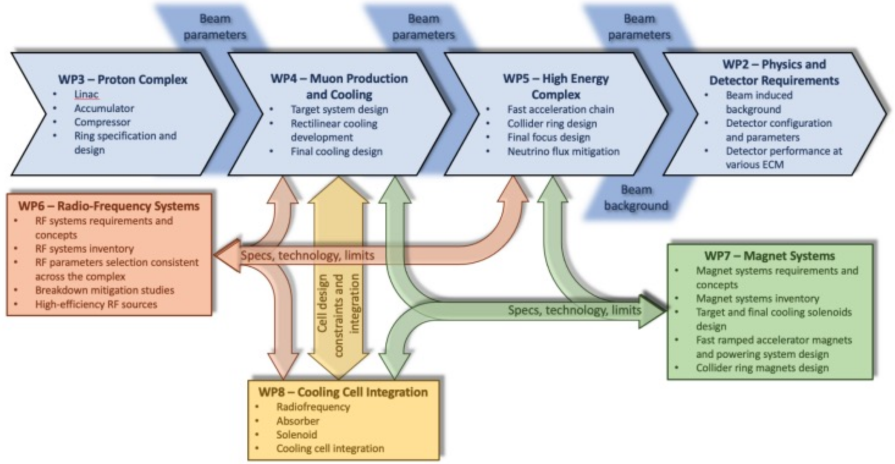
Science

THE DREAM MACHINE

An accelerator known as a muon collider could revolutionize particle physics—if it can be built

28 MAR 2024 • 2:00 PM ET • BY ADRIAN CHO

International Muon Collider Collaboration



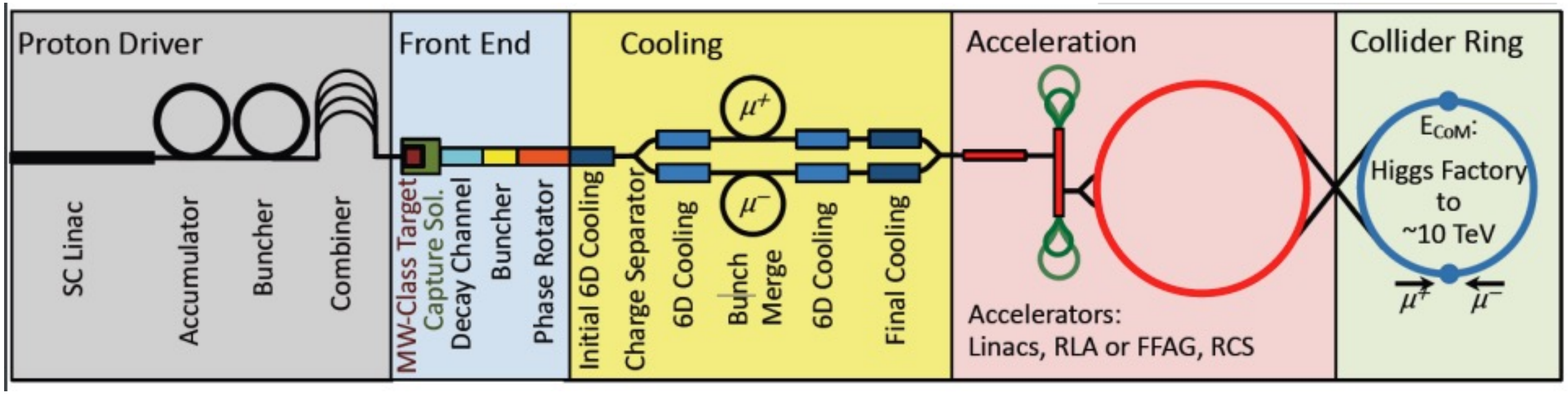
[Submitted on 17 Jul 2024]

Interim report for the International Muon Collider Collaboration (IMCC)

C. Accettura, S. Adrian, R. Agarwal, C. Ahdida, C. Aimé, A. Aksoy, G. L. Alberghi, S. Alden, N. Amapane, D. Amorim, P. Andreetto, F. Anulli, R. Appleby, A. Apresyan, P. Asadi, M. Attia Mahmoud, B. Auchmann, J. Back, A. Badea, K. J. Bae, E. J. Bahng, L. Balconi, F. Balli, L. Bandiera, C. Barbagallo, R. Barlow, C. Bartoli, N. Bartosik, E. Barzi, F. Batsch, M. Bauce, M. Begel, J. S. Berg, A. Bersani, A. Bertarelli, F. Bertinelli, A. Bertolin, P. Bhat, C. Bianchi, M. Bianco, W. Bishop, K. Black, F. Boattini, A. Bogacz, M. Bonesini, B. Bordini, P. Borges de Sousa, S. Bottaro, L. Bottura, S. Boyd, M. Breschi, F. Broggi, M. Brunoldi, X. Buffat, L. Buonincontri, P. N. Burrows, G. C. Burt, D. Buttazzo, B. Caiffi, S. Calatroni, M. Calviani, S. Calzaferri, D. Calzolari, C. Cantone, R. Capdevilla, C. Carli, C. Carrelli, F. Casaburo, M. Casarsa, L. Castelli, M. G. Catanesi, L. Cavallucci, G. Cavoto, F. G. Celiberto, L. Celona, A. Cemmi, S. Ceravolo, A. Cerri, F. Cerutti, G. Cesarini, C. Cesarotti, A. Chancé, N. Charitonidis, M. Chiesa, P. Chiggiato, V. L. Ciccarella, P. Cioli Puviani, A. Colaleo, F. Colao, F. Collamati, M. Costa, N. Craig, D. Curtin, L. D'Angelo, G. Da Molin, H. Damerau, S. Dasu, J. de Blas, S. De Curtis, H. De Gersem et al. (287 additional authors not shown)

arXiv:2407.12450

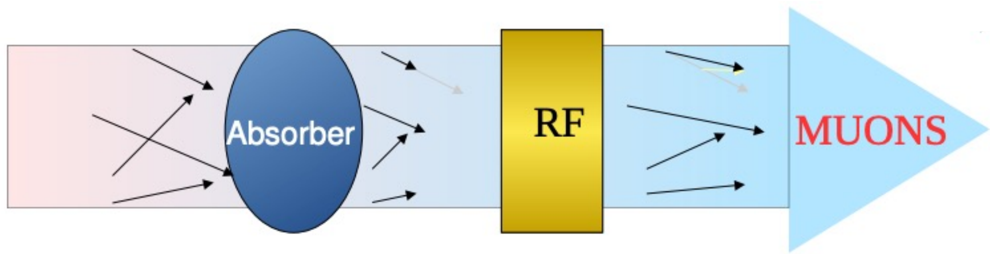
Schematic

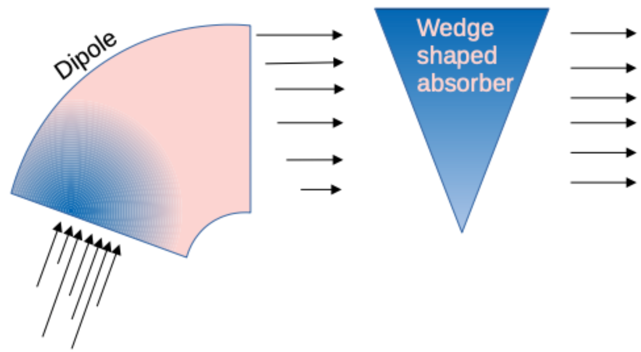


- A muon collider which uses existing proton driver schemes would create muons from pion decay.
- As tertiary particles, these muons occupy a large volume in phase space, having a high emittance.
- This requires muon cooling before accelerating the muons to collision energy. Since traditional cooling methods, such as synchrotron radiation damping, are impractical for muons, a technique called ionisation cooling has been proposed for the muon collider.

Ionisation Cooling

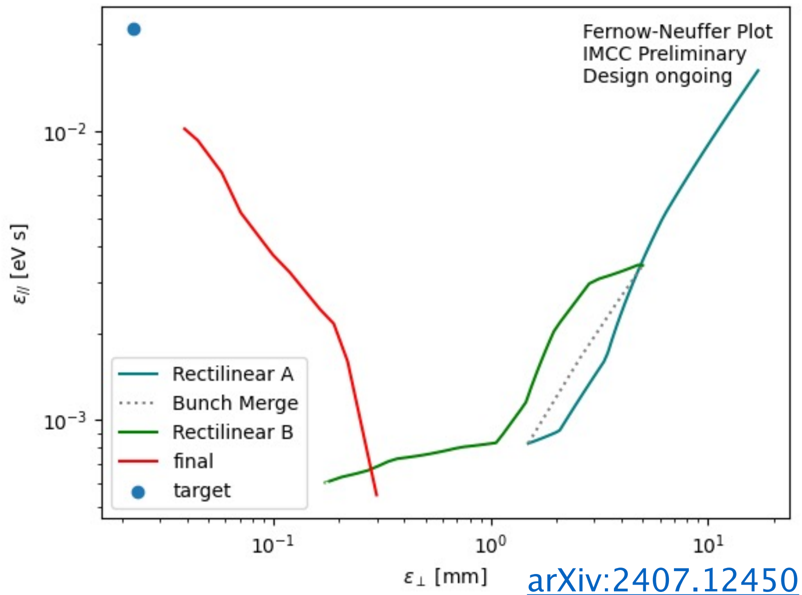
- Ionisation Cooling involves passing the beam through an absorber.
- The beam loses momentum in all direction as it ionises the absorber.
- An RF cavity restores momentum in a single direction.
- Multiple coulomb scattering from the nucleus is mitigated using low-Z materials and having tight focussing using solenoids.
- Having a dipole and a wedge-shaped absorber allows us to cool in all 6 dimensions.





Cooling Stages

- In the muon collider, first 6D (rectilinear) cooling is done to reduce emittance in all directions.
- This is followed by 4D (final) cooling, which involves cooling only in the transverse direction at the cost of longitudinal emittance.



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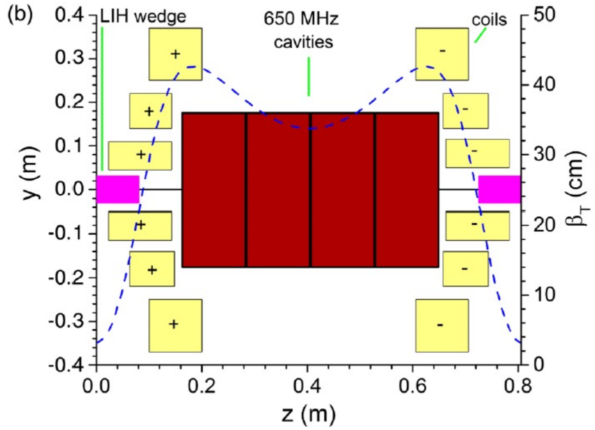
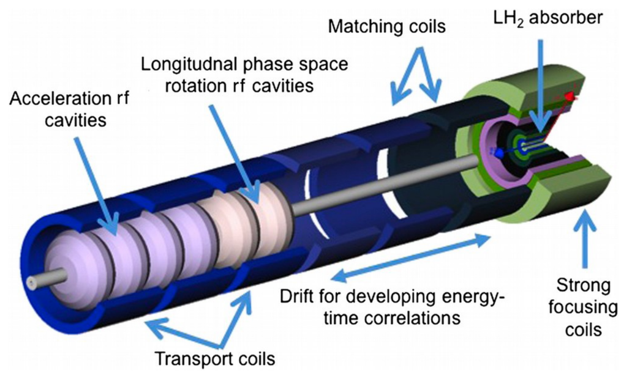


An example of a rectilinear cooling cell



An example of a final cooling cell

Rectilinear Cooling Simulations

R. Zhu

Design of two rectilinear cooling channels before and after bunch merging

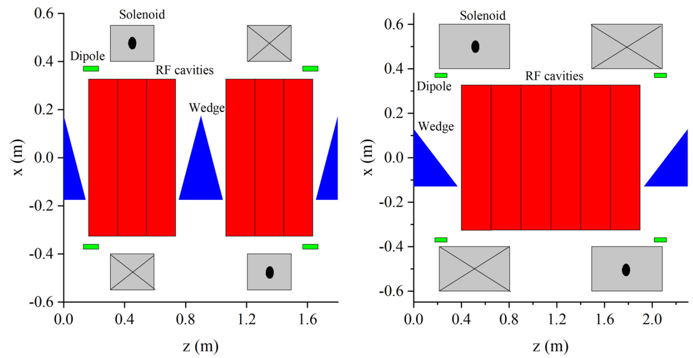
Pre-merging cooling

- 4 stages
- 362.8 m in length
- 49.6% in transmission including decay
- $\varepsilon_\perp$: 16.96 to 1.24 mm
- $\varepsilon_\parallel$: 45.53 to 1.74 mm

Post-merging cooling

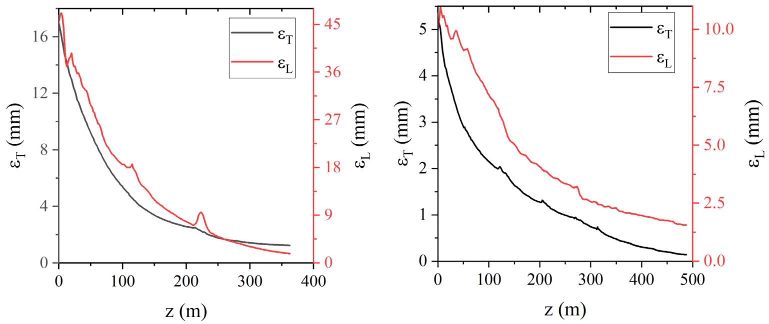
- 10 stages
- 487.26 m in length
- 28.5% in transmission including decay
- $\varepsilon_\perp$: 5.13 to 0.14 mm
- $\varepsilon_\parallel$: 9.99 to 1.56 mm

Cooling cell layout



A-type (pre-merging) B-type (post-merging)

Emittance reduction

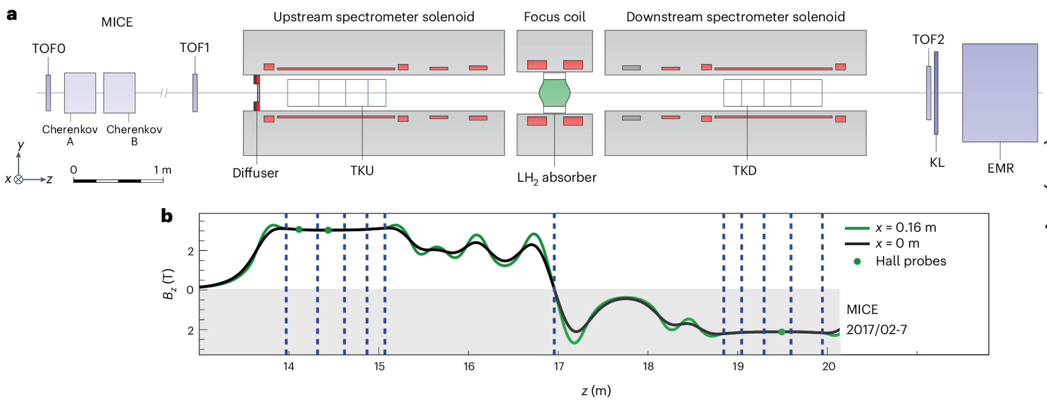


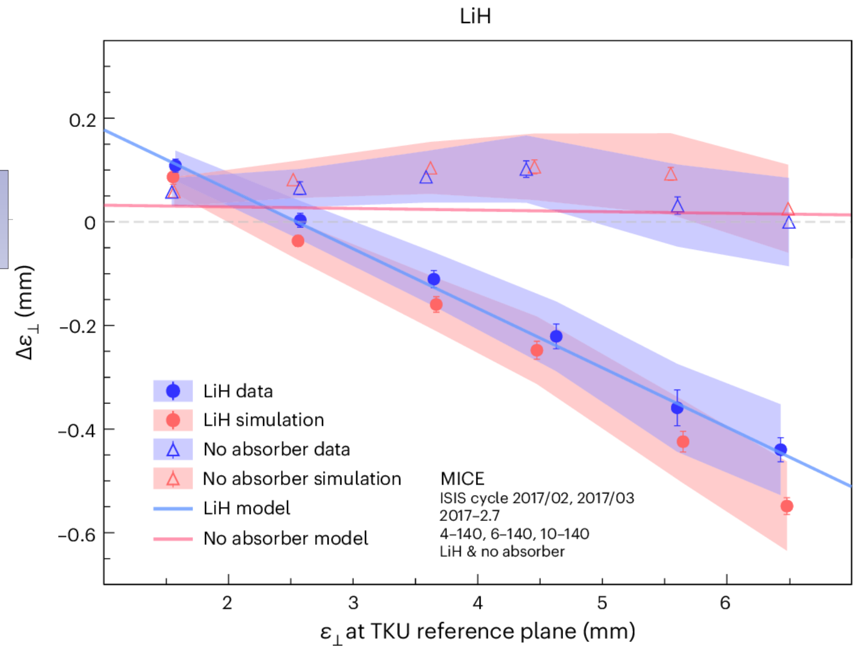
pre-merging post-merging

MICE

P. Jurj et. al

- Muon cooling through ionisation was tested at the Muon Ionisation Cooling Experiment (MICE) which was built at the Rutherford Appleton Laboratory.
- Using muons from the ISIS Neutron and Muon Source, MICE successfully showed the reduction of transverse (4D) emittance.
- Can we extend this to 6D?



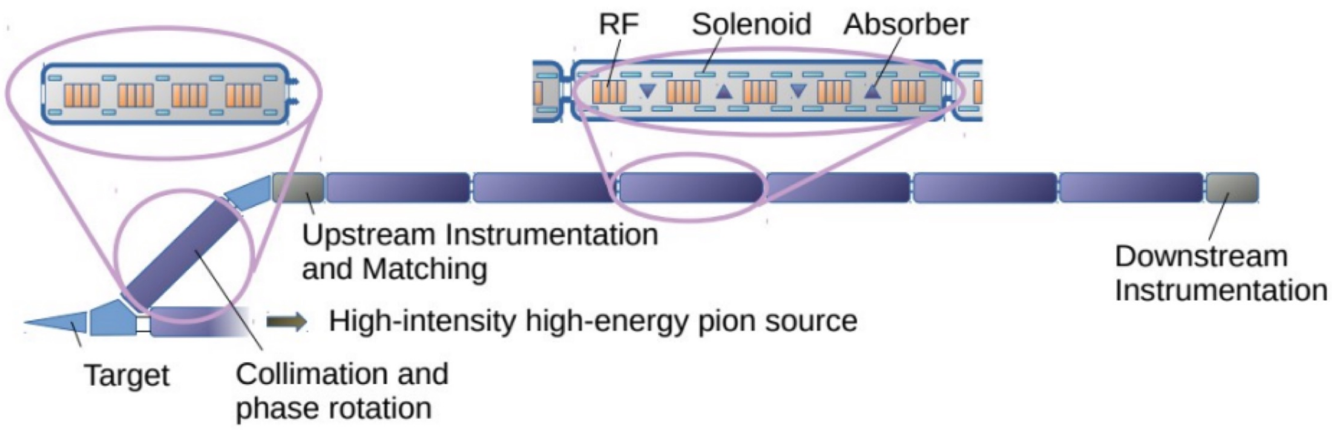


Nat. Phys. (2024). https://doi.org/10.1038/s41567-024-02547-4

6D Cooling Demonstrator

Attribute	MICE	6D Cooling Demonstrator
Cooling Type	4D (Transverse)	6D
Absorbers	Single Absorber	Many Absorbers
Cooling Section	Section of a single cell	Many cooling cells
Acceleration	No reacceleration	RF cavities
Beam	Single Particle Beam	Bunched beams
Instrumentation	HEP style	Multiparticle Style

Layout



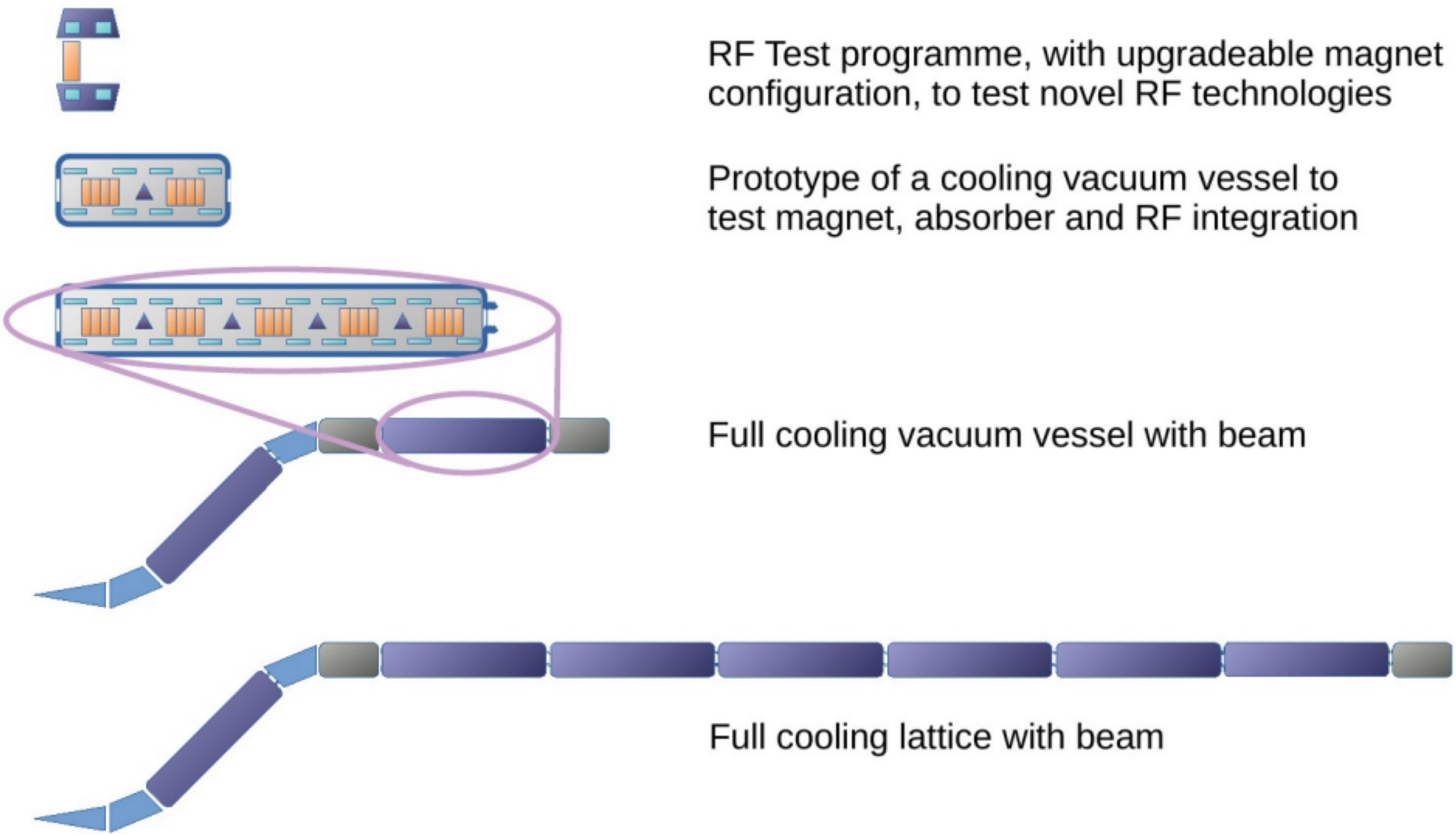
- The demonstrator would be designed like above, with a proton driver and target scheme.
- A high energy pion source could also be achived, allowing the demonstrator to share a target with another experiment like nuSTORM.
- The cell which would be demonstrated would be similar to the parameters of the B5 cell in the muon collider.

Challenges

The following challenges need to be addressed:

- Demonstration of dispersion and closed orbit control
- Reliable RF operation and suppression of RF breakdown, as muons have seldom been accelerated in a conventional RF cavity
- Magnet engineering, including integration with RF cavities and absorbers
- Managing collective effects such as space charge, beam loading, and heating
- Mitigating the radiation load from decaying muons on the magnets

Staging



RF Test programme, with upgradeable magnet configuration, to test novel RF technologies

Prototype of a cooling vacuum vessel to test magnet, absorber and RF integration

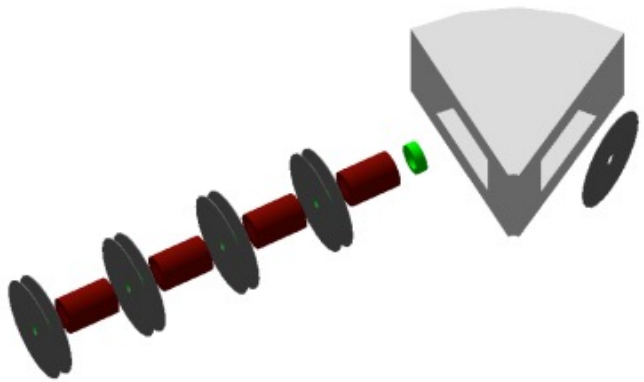
Full cooling vacuum vessel with beam

Full cooling lattice with beam

Beam Preparation

C. Rogers

- The cell design chosen to be demonstrated requires a 100ps pulsed muon beam with low emittance, relative to the muons produced from the target.
- We get momentum collimation from the switchyard.
- Using a series of collimators and RF cavities, the beam achieves transverse collimation and longitudinal phase rotation.

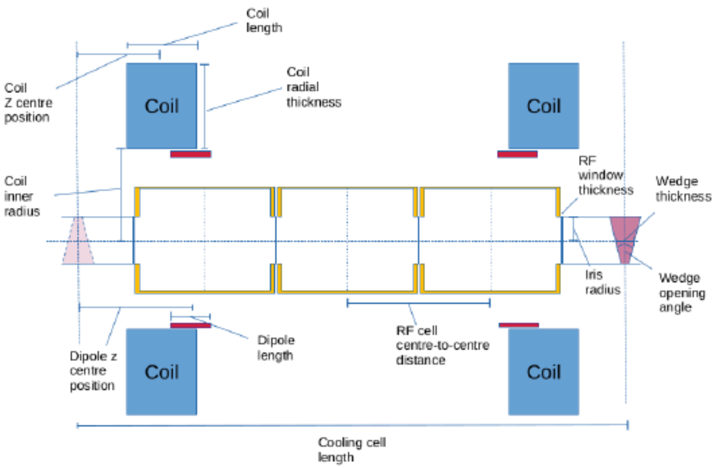


Beam Preparation System

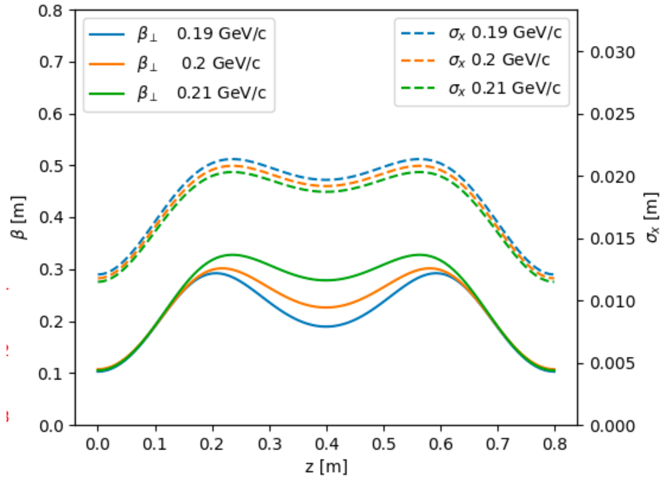
Parameter	Value
Cell length	1 m
Peak solenoid field on-axis	0.5 T
Collimator radius	0.05 m
Dipole field	0.67 T
Dipole length	1.04 m
RF real estate gradient	7.5 MV/m
RF nominal phase	0° (Bunching)
RF frequency	704 MHz

Demonstrator Cell Design

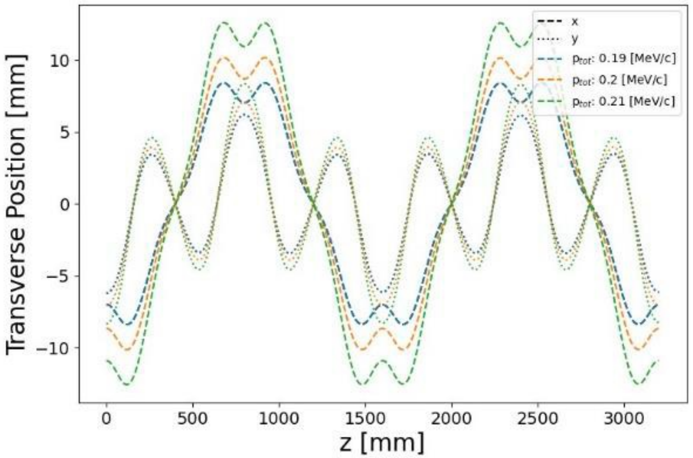
C. Rogers



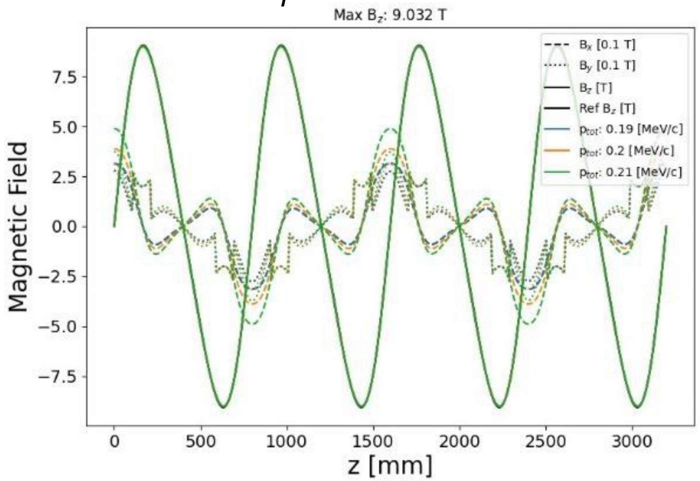
Cooling Cell Design



β and 1-σ beam size



Transverse position of reference and off momentum particles



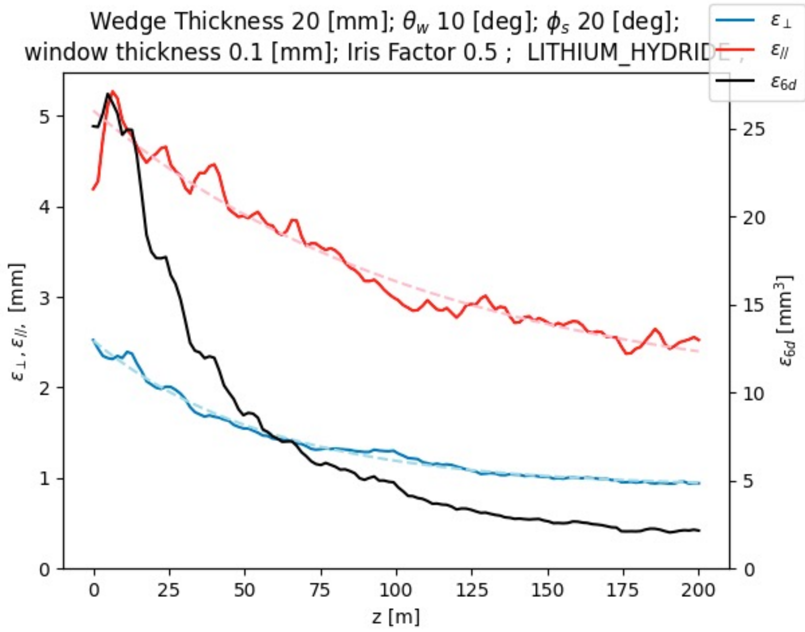
Magnetic field strength

PRESENTATION OF COOLING CELL CONCEPTUAL DESIGN
DELIVERABLE: D8.1
10.5281/zenodo.11402737

Absorber and RF Material Performances

C. Rogers

- We use Beryllium for the RF cavity walls.
- We use LiH absorbers
- Simulations show good cooling performance
- Optimisation is still on going, and further work is being done on matching.



PRESENTATION OF COOLING CELL CONCEPTUAL DESIGN
DELIVERABLE: D8.1
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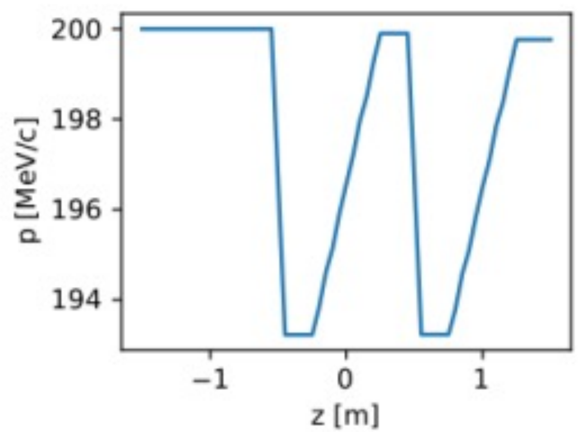
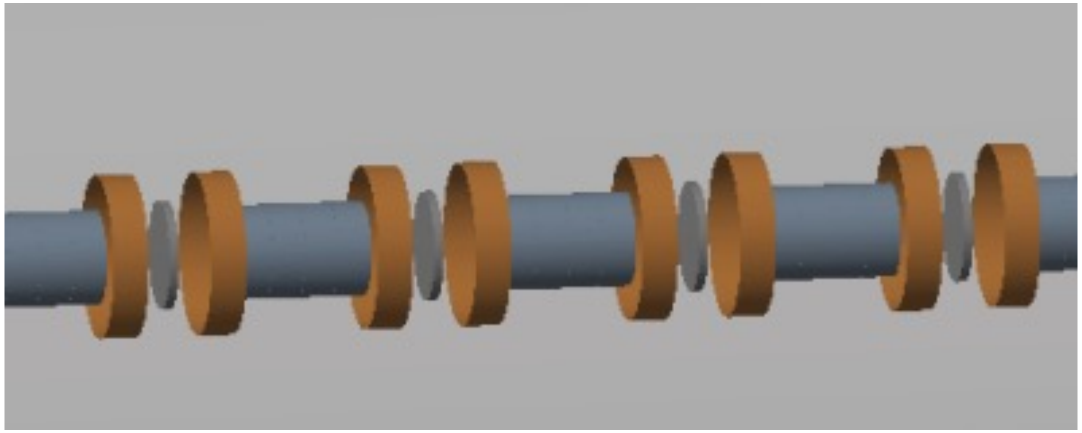
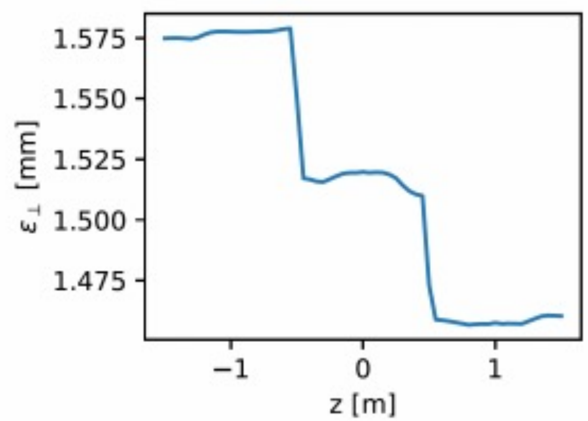
BDSIM Simulations

P. Jurj, R. Kamath, C. Rogers

- Simultaneously, efforts are underway to implement the cooling channel in BDSIM – a GEANT4 based lattice simulator.
- The solenoid, RF, and absorber models in BDSIM have been validated, and 4D cooling has been successfully simulated.
- Ongoing work focuses on extending these simulations to 6D cooling using a dipole model.







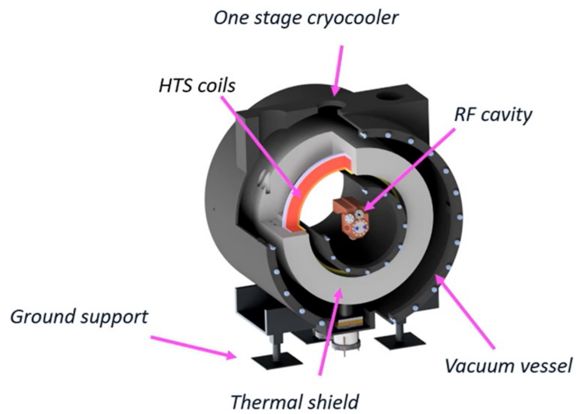
Magnets

M. Castoldi, S. Fabbri, G. Scarantino, M. Statera

Magnet studies focus in finding a viable solution for the design of two main cell prototypes:

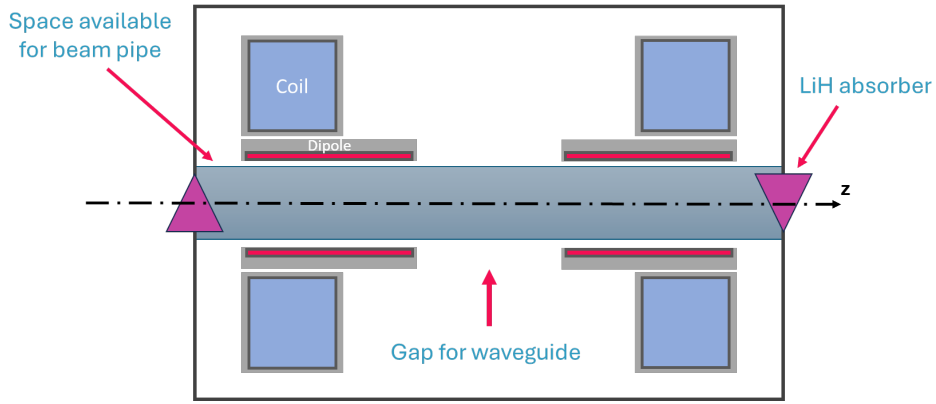
Test facility for RF cavity

- Cell-like configuration to test the breakdown limit of RF cavities under high background fields (7 T).
- Engineering design under way, aim to commission the facility by 2027.



Cooling demonstrator

- B5-cell prototype magnets aiming to reproduce the full lattice.
- Consider the integration of absorbers, RF cavities and magnets (solenoids + dipoles).
- Design currently under way.

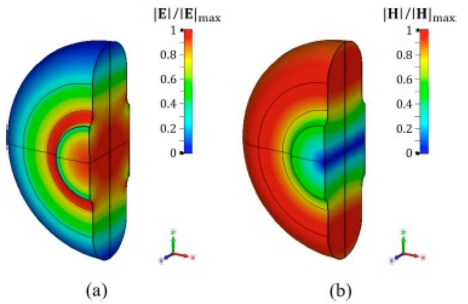


IPAC24 – WEPR38

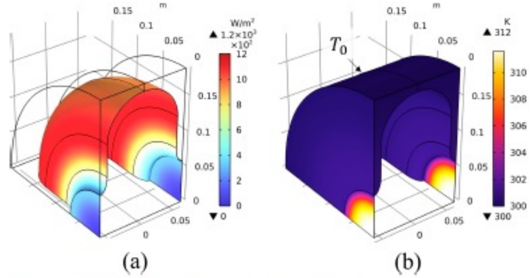
RF Cavity Design

C. Barbagallo, D.A. Giove,
A. Grudiev, R. Losito

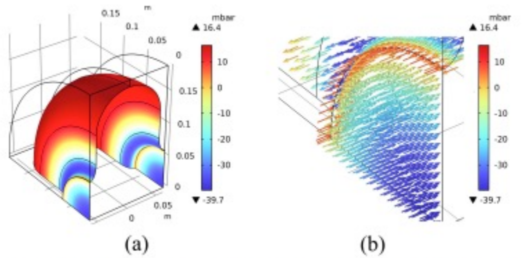
- A 704MHz cavity has been designed and optimized, to enable operation at gradients of up to 44 MV/m within strong solenoidal magnetic fields of up to 7.2 T.
- The RF eigenmode simulations and optimisations were conducted in CST and coupled RF and thermo-mechanical simulations are performed in COMSOL.



(a) Normalised E and (b) B fields of the cavity



(a) Dissipated power and (b) Maximum Temperature on the cavity and window walls



RF pressure on (a) cavity and (b) window walls

Parameter	Unit	Value	Description
f_0	MHz	704	Operating frequency
Q_0	1	2.83×10^4	Intrinsic quality factor
R/Q	Ω	166.69	Geometric shunt impedance
$R/Q \cdot Q_0$	MΩ	4.72	Shunt impedance
P_{diss}	MW	4.43	Peak dissipated power
DF	1	5.48×10^{-5}	Beam duty factor
P_{ave}	W	242.91	Average power
E_{peak}	MV/m	45.45	Peak surface electric field
B_{peak}	mT	100.03	Peak surface magnetic field

Figures of Merit of the cavity design

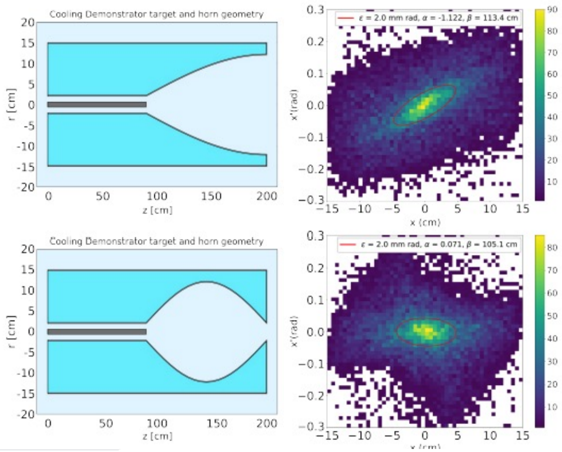
IPAC24 – WEPR25

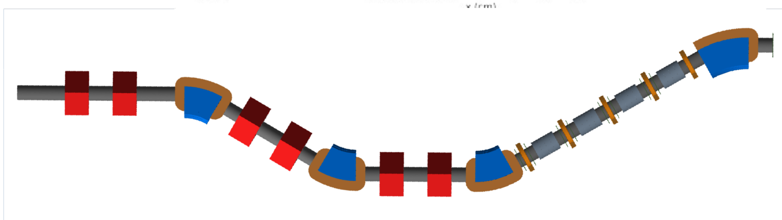
Siting: CERN

P. Jurj

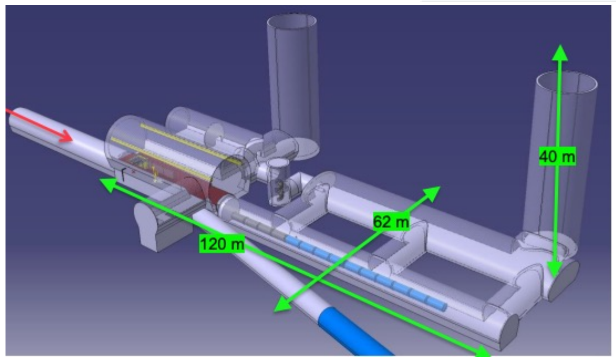
Two sites have been proposed for the Demonstrator

- TT7:
  - This option involves the demonstrator to be in the TT7 extraction line within the ISR complex at CERN.
  - This would be close to the surface level, a beam power of 10kW, with a PS beam energy of 14GeV has been proposed due to radiation and safety concerns.



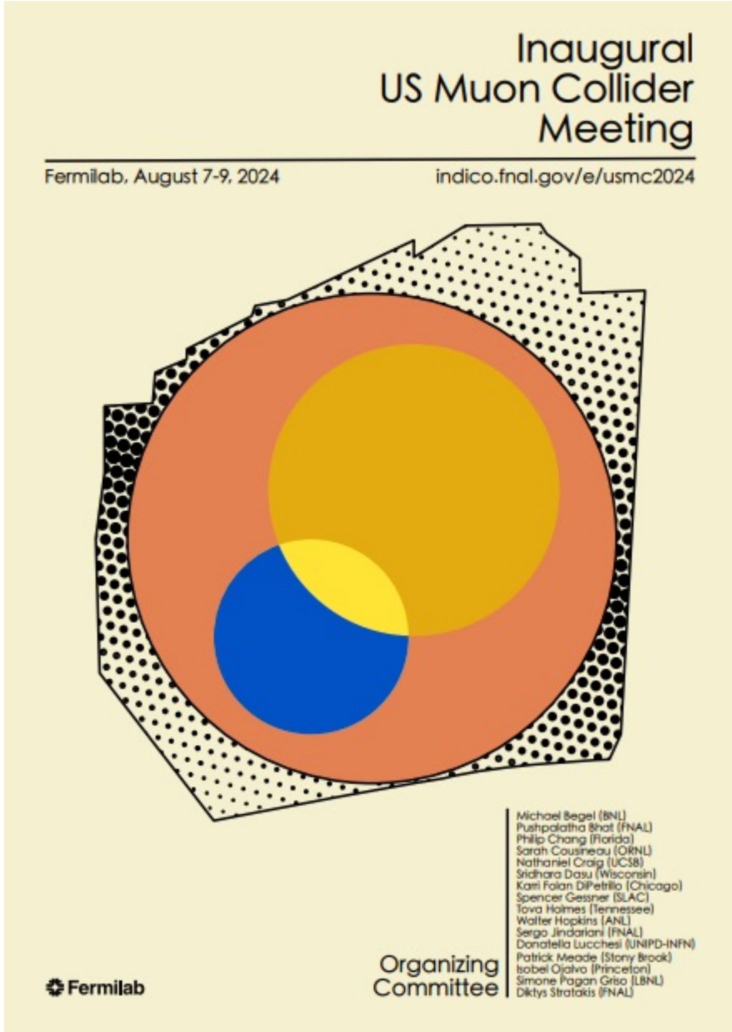


- TT10
  - This involves a bespoke cavern allowing a full energy (26 GeV) PS beam of 80kW
  - This could be potentially upgraded to a 100GeV SPS beam.



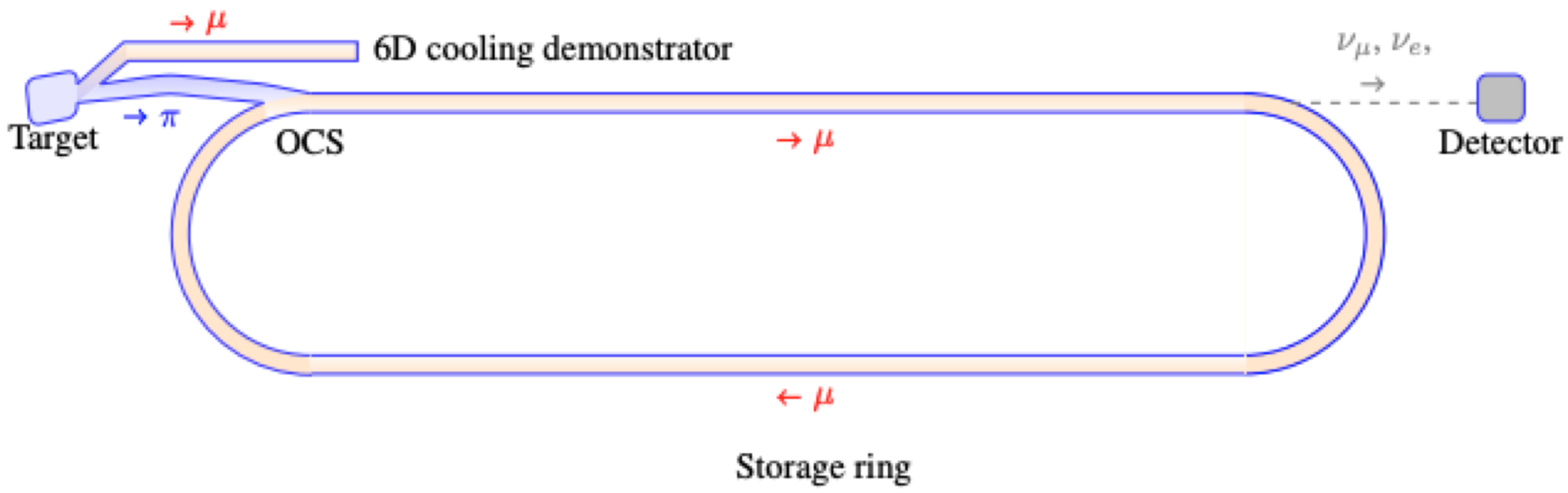
Siting: Fermilab

- The muon campus in FNAL would be an excellent plausible location for the 6D cooling demonstrator.
- A workshop has been planned at the end of next month to explore this further!



Synergies:nuSTORM

- nuSTORM is an experiment that aims to create a neutrino flux with %-level precision from muon decay in a racetrack shaped storage ring.
- The ring can be tuned to accept muons with momenta in the 1-6GeV/c $\pm$ 16% range which consequently decay into electrons, muon and electron neutrinos.
- Along with providing a test bed for muon collider technologies, this would also help cross section analysis and be sensitive to BSM physics.
- Stay tuned for my next talk for more information ;)



Conclusion

- The muon collider stands as a strong candidate for a 10 TeV pCoM collider within a comparatively smaller footprint.
- However, it necessitates advancements in muon production, cooling, and detection technologies.
- This talk highlighted the proposed 6D cooling demonstrator, addressing key aspects of beam physics, RF systems, and magnet design.
- Additionally, potential locations for the demonstrator were discussed, along with its synergies with other particle physics experiments, such as nuSTORM.

Thank you

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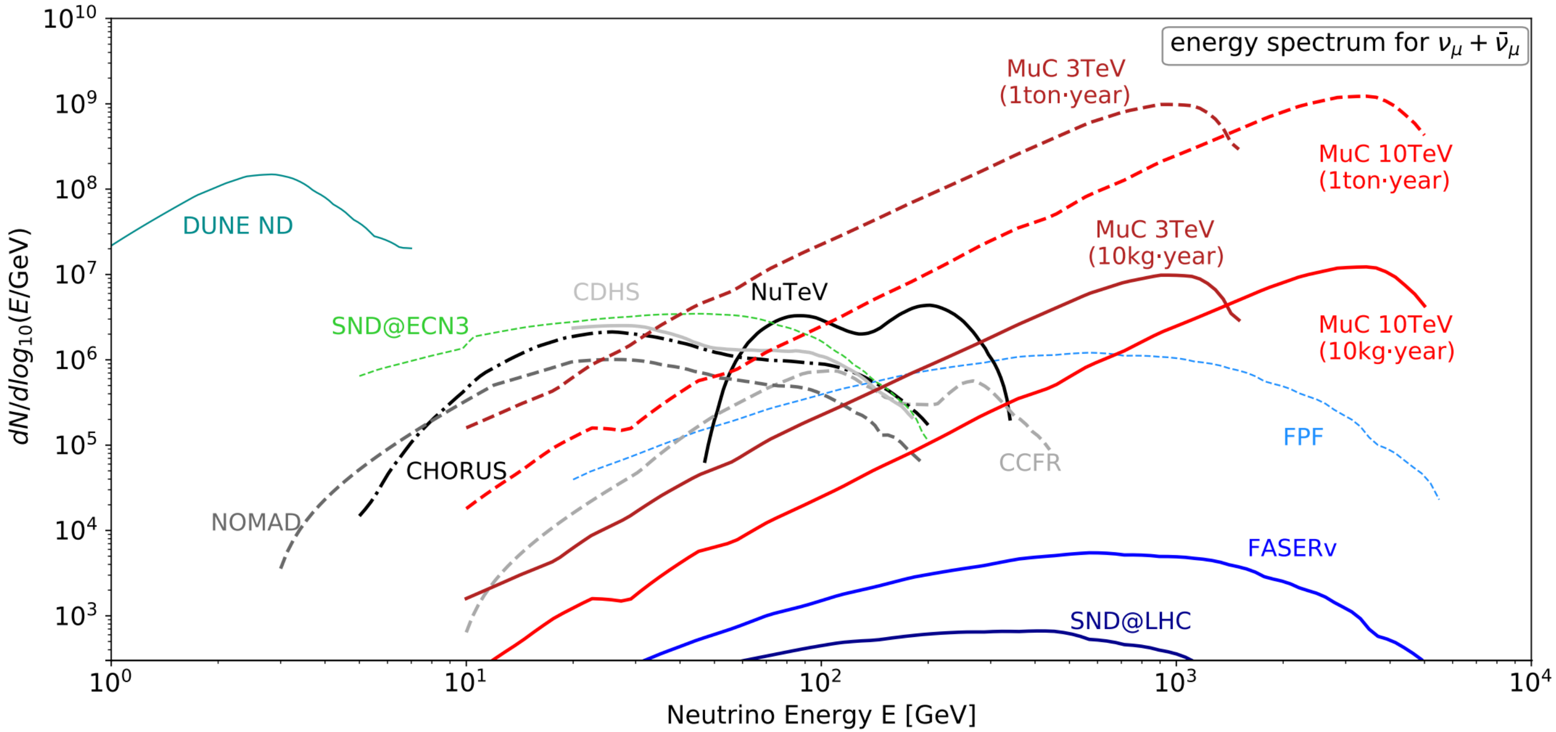
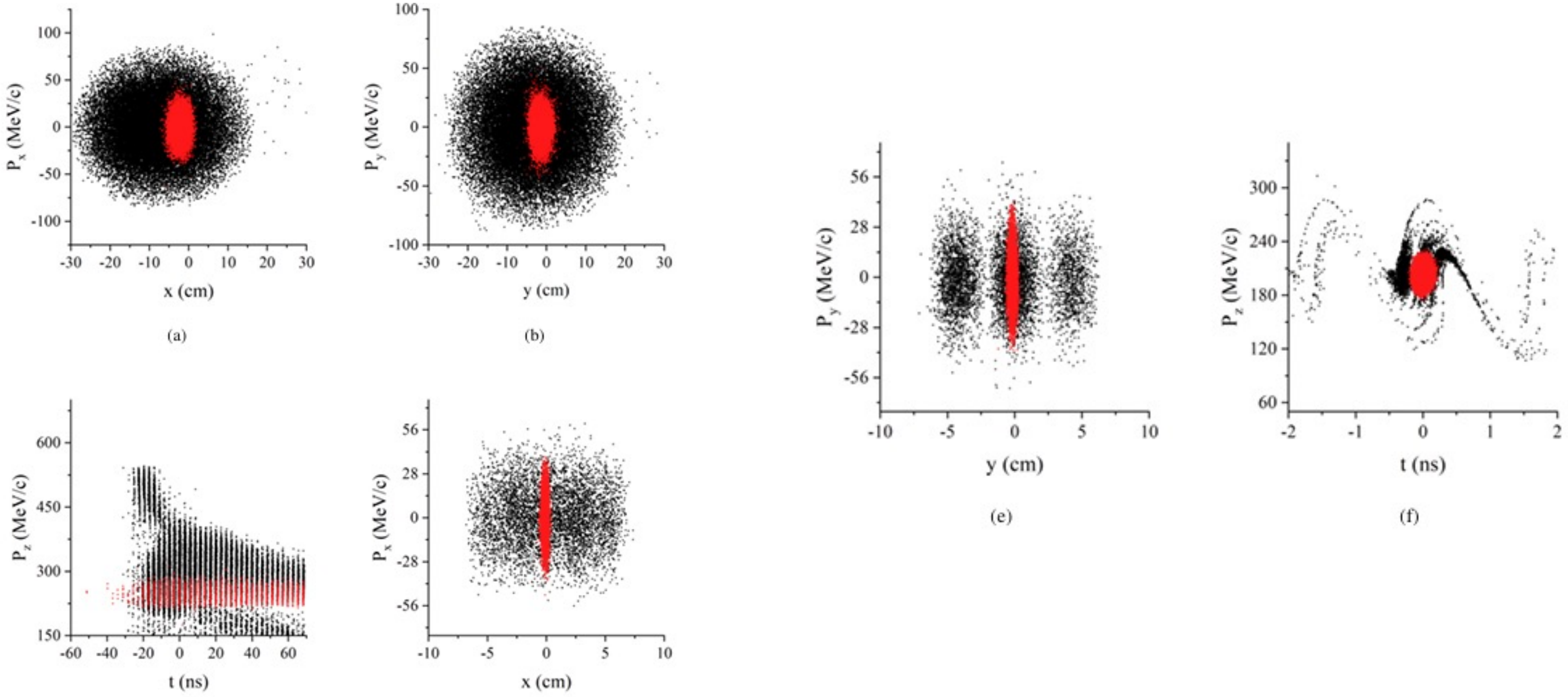
Back Up

Muon Collider Neutrino Events



arXiv:2407.12450

Phase Space Distributions



Particle distribution in phase space: (a), (b), (c), pre-merging; (d), (e), (f) , post-merging.
(black dots: initial, red dots: final)

Cooling Cell Parameters

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	
Coil 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

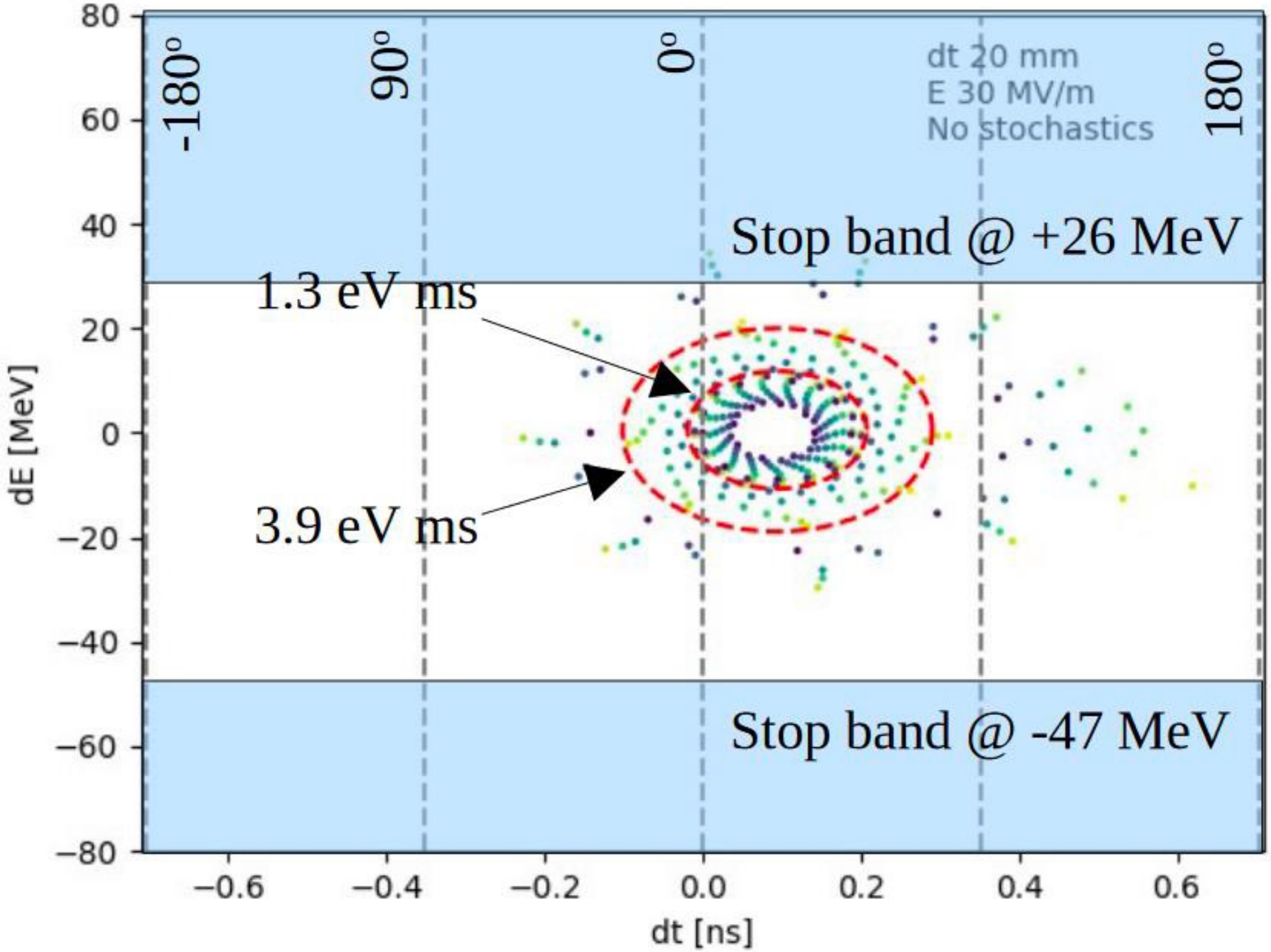
RF Cavity**	
RF cell centre-to-centre distance	188.6 mm
RF Gradient, E0	30 MV/m
Iris radius	81.6 mm
Number of RF cells	3
Frequency, f	0.704 GHz
Synchronous phase	20 degree
RF window thickness	0.1 mm

Wedge	
Material	Lithium Hydride
Wedge opening angle	10 degree
Wedge thickness	20 mm
Wedge alignment	Horizontal

Dipole	
Dipole length	100 mm
Polarity	+ - - +
Field	0.2 T
Dipole z centre position	160 mm
Dipole field direction	Vertical

***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**

RF bucket



dt 20 mm
E 30 MV/m
No stochastics
-180°
90°
0°
180°
Stop band @ +26 MeV
1.3 eV ms
3.9 eV ms
Stop band @ -47 MeV
dE [MeV]
dt [ns]
80
60
40
20
0
−20
−40
−60
−80
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6