NuSTORM, Muon Cooling and its Demonstration

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ISIS Neutron and Muon Source

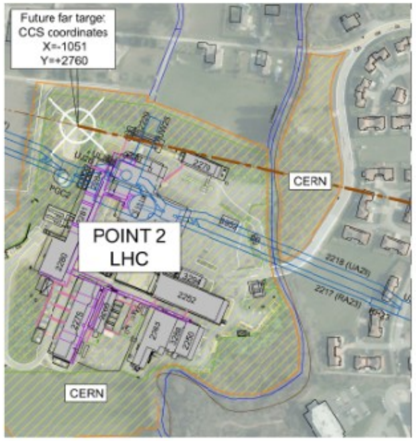
C. T. Rogers

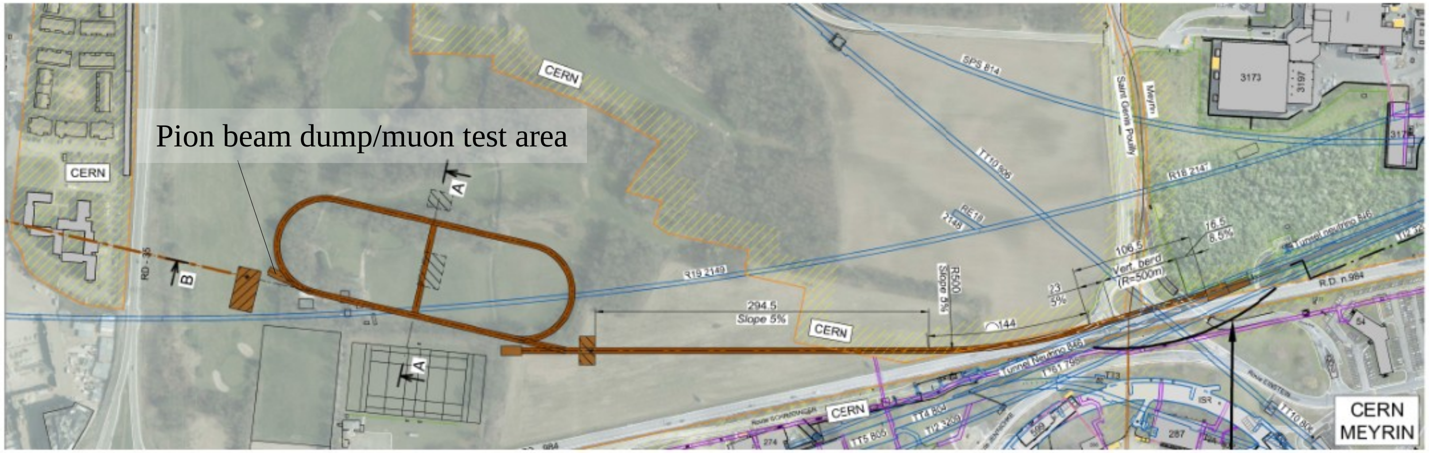
NuSTORM and muon collider

- nuSTORM facility aims to
  - Measure neutrino scattering cross sections
  - Search for sterile neutrinos and other BSM physics
  - **Provide a technology test-bed for the muon collider**
- What is the nuSTORM muon facility?
- Why – and how - is it related to muon collider?

nuSTORM facility

- What is the nuSTORM facility?

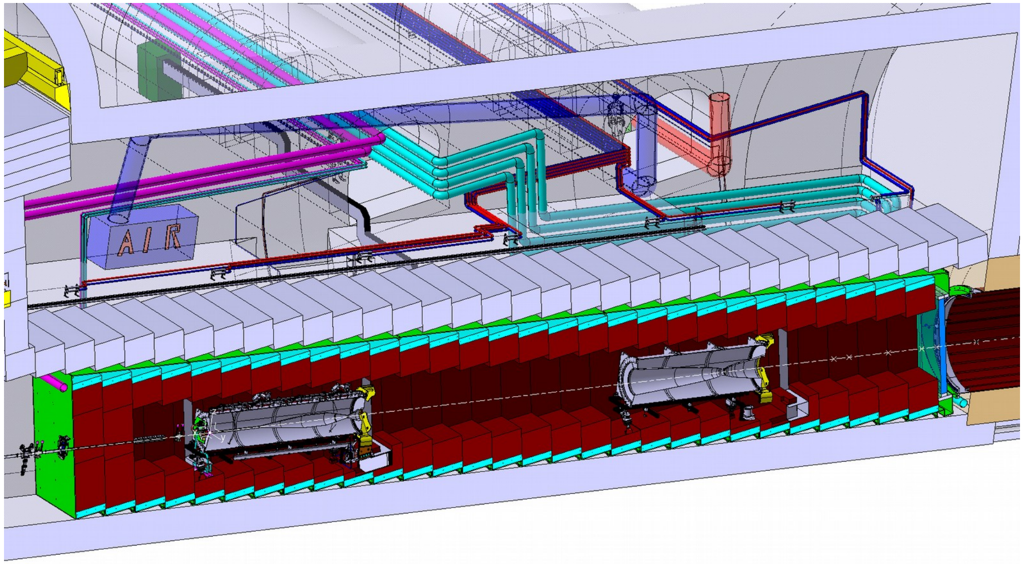




nuSTORM at CERN – Feasibility Study, Ahdida et al, CERN-PBC-REPORT-2019-003, 2020

- Main features
  - ~250 kW target station
  - Pion transport line
  - Stochastic muon capture into storage ring
  - Option for conventional FODO ring or high aperture FFA ring

Target Station



J. Alabau-Gonsalvo et al, Laguna-lbno design study

- Baseline is for a conventional target horn arrangement
  - Talk by Ilias

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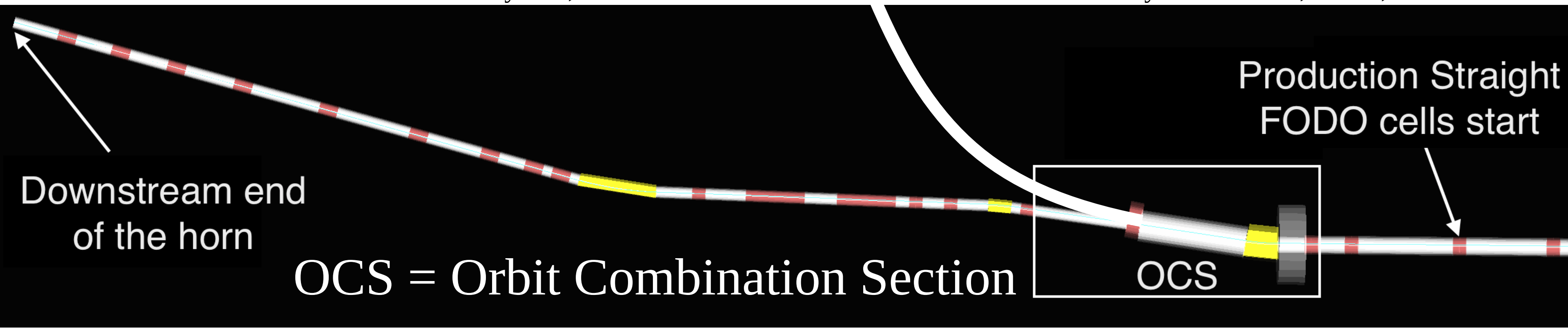
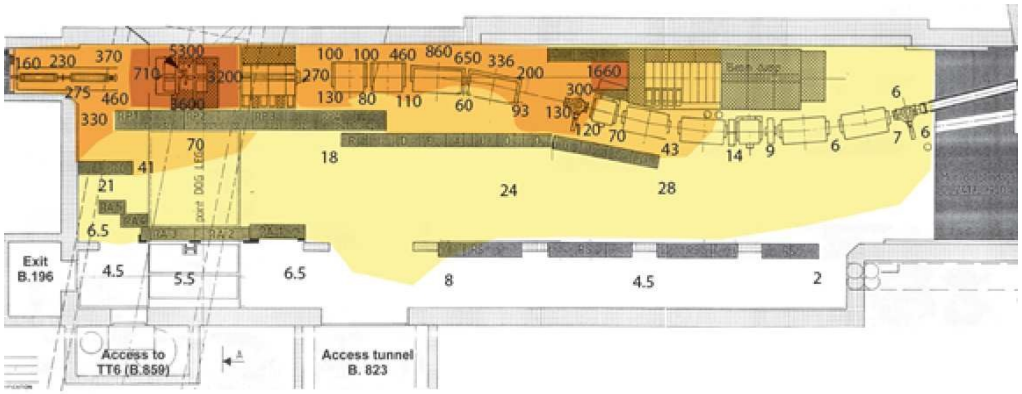
Pion Transport Line

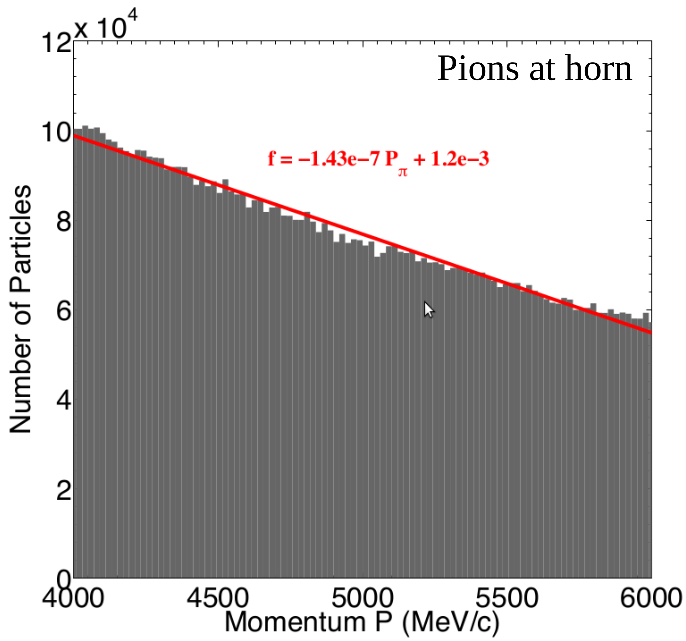
A. Liu et al, Design and Simulation of the nuSTORM Pion Beamline, NIM A, 2015
D. Adey et al, Overview of the Neutrinos from Stored Muons Facility – nuSTORM, JINST, 2017

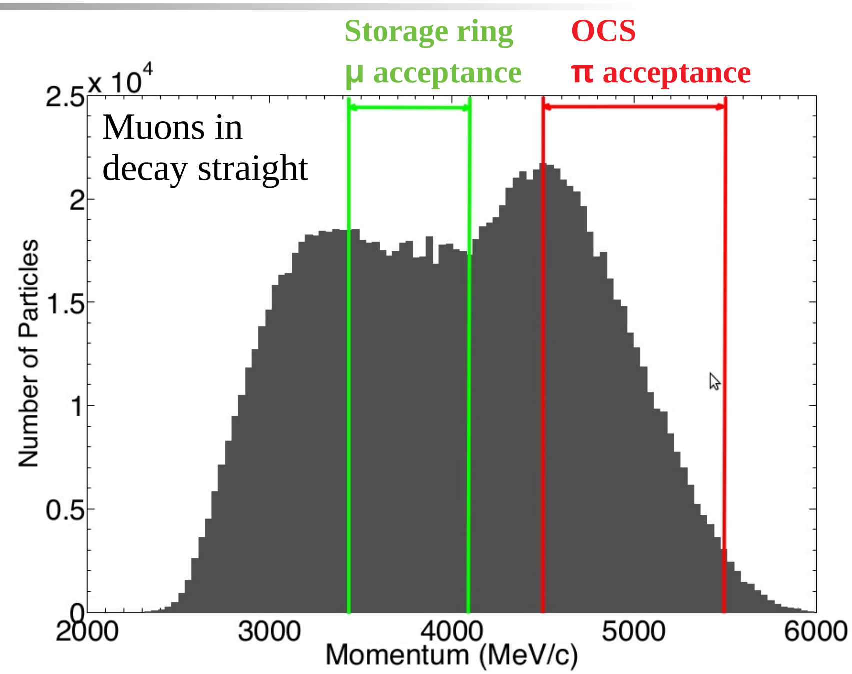




- Pion transport line
  - Proton beam dump
  - Momentum selection
  - Active handling

Stochastic Muon Capture





- Pions injected into the decay ring
- Capture muons that decay backwards in pion CoM frame
- Undecayed pions and forwards muons diverted into muon test area
  - Extraction line at end of first decay straight

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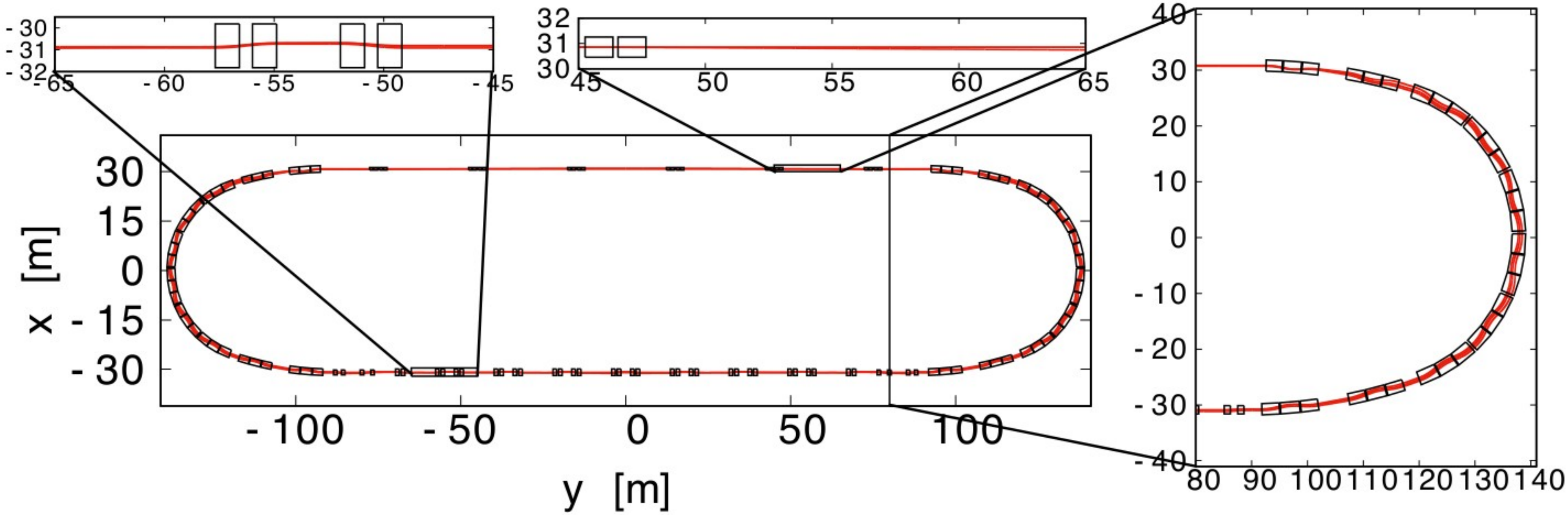
Storage Ring

nuSTORM at CERN – Feasibility Study, Ahdida et al, CERN-PBC-REPORT-2019-003, 2020

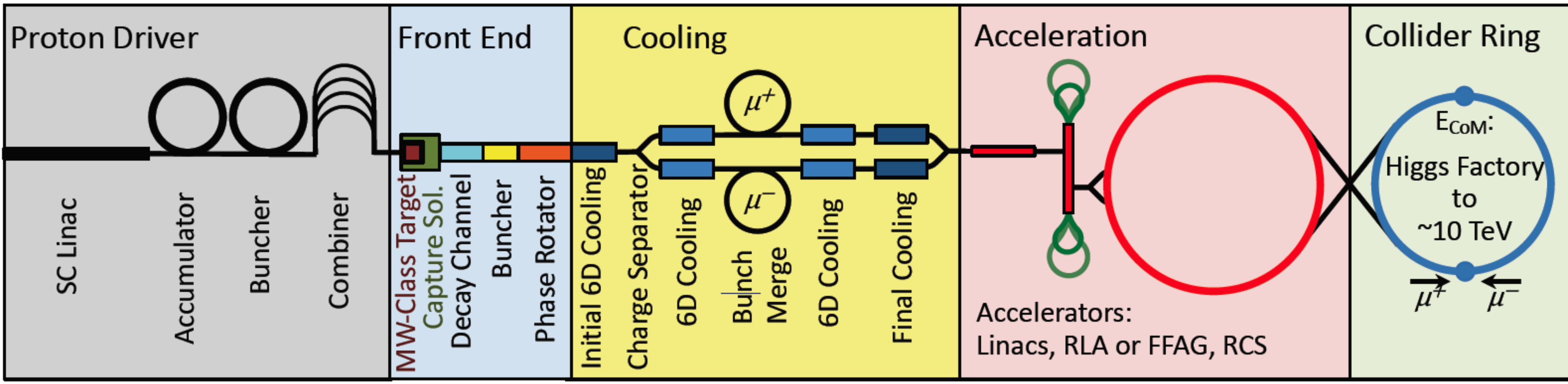


- Storage ring
  - Either conventional FoDo ring
  - Or high acceptance FFA ring
  - (Talk by Jaroslaw)

Muon Collider

- Why – and how - is nuSTORM related to muon collider?
- **Muon beam physics** highlighted as **high priority initiative** by European strategy update
  - ~10 TeV Muon Collider has **physics reach comparable to FCC-hh**
  - **Footprint** is considerably **smaller**
- CERN-led Muon Collider Collaboration formed in June
- Some discussion of making a “demonstrator”
  - Demonstrate some of the beam physics concepts
  - Address some of the technical issues

Muon Collider Facility



- Proton based Muon Collider (MC) facility
  - Protons on target → pions, muons et al.
  - Transverse and longitudinal capture
  - Transverse and longitudinal cooling
  - Acceleration
  - Collider ring

Muon Collider Facility

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

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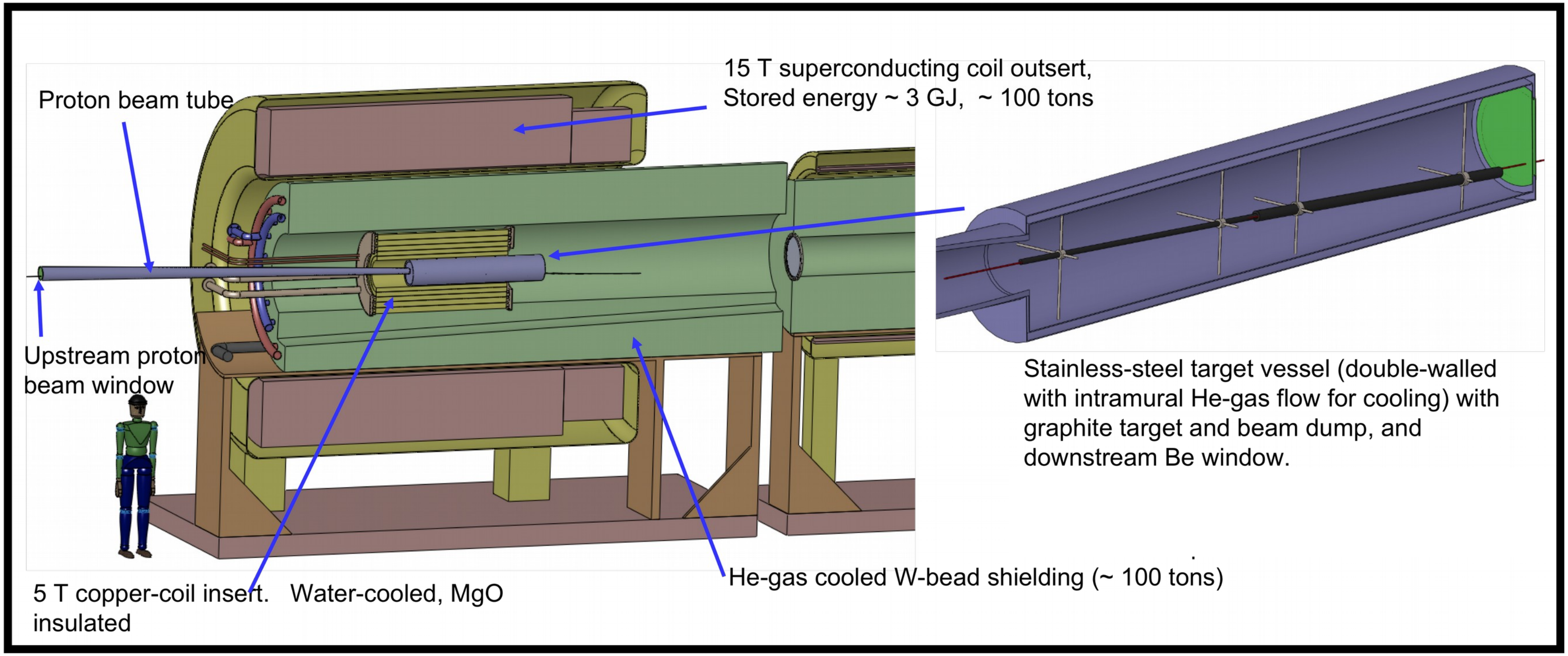
MC Target

X. Ding et al, Carbon and Mercury target system for muon colliders and neutrino factories, IPAC16



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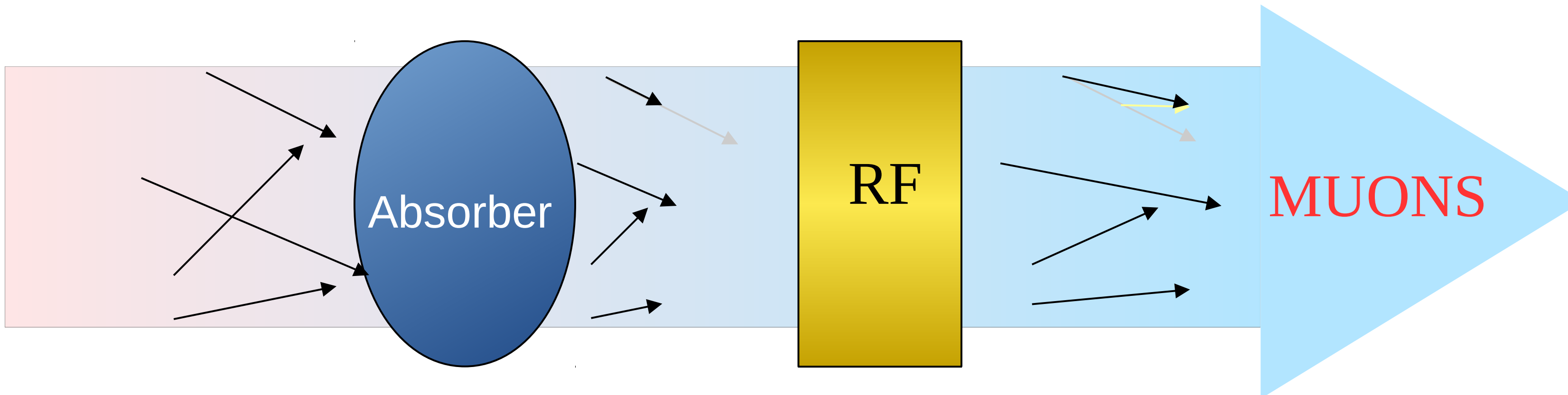
MC Accelerator/Collider Ring

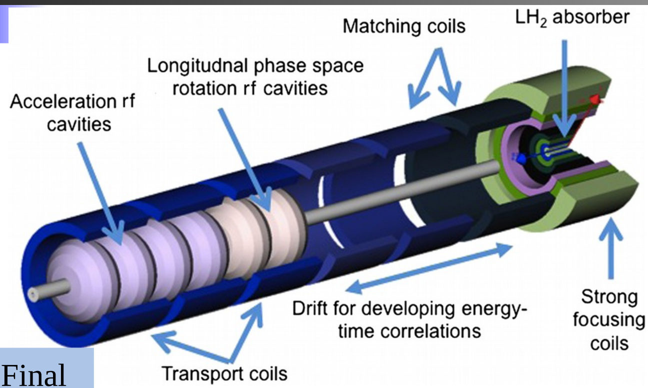
- RCS concept
  - Hybrid superconducting/normal conducting RCS
- FFA concept
  - Fixed field accelerator
  - Use vertical orbit excursion
    - Constant path length at different energy
    - “Relativistic cyclotron”

Ionisation Cooling

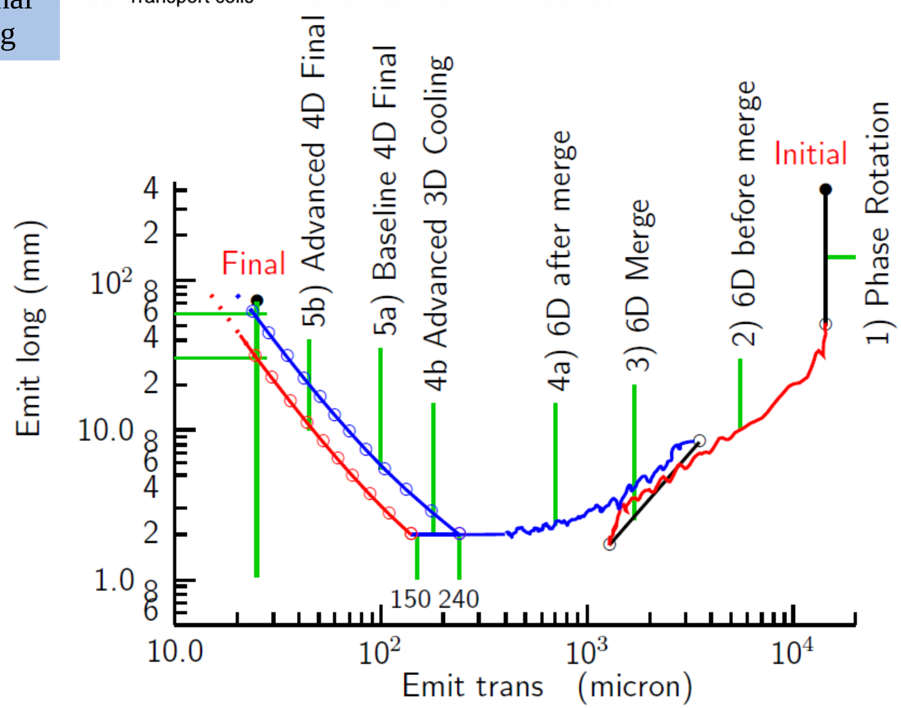


- Beam loses energy in absorbing material
  - Absorber removes momentum in all directions
  - RF cavity replaces momentum only in longitudinal direction
  - End up with beam that is more straight
- Multiple Coulomb scattering from nucleus ruins the effect
  - Mitigate with tight focussing
  - Mitigate with low-Z materials
  - Equilibrium emittance where MCS completely cancels the cooling

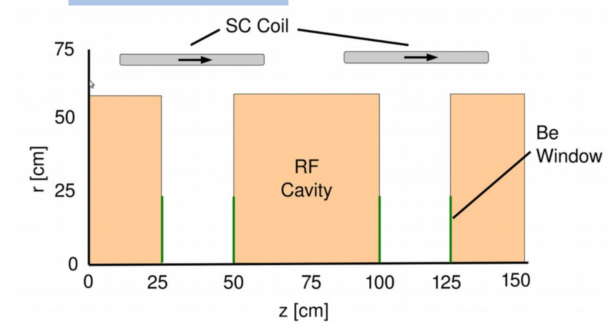
Muon Cooling



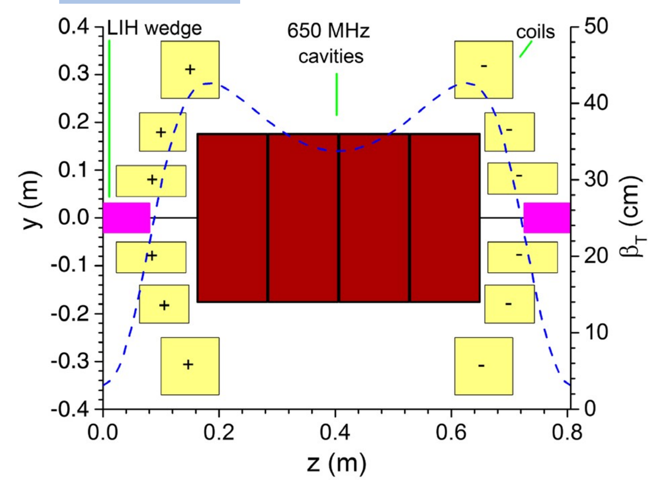
4D Final cooling



Phase rotation



6D cooling



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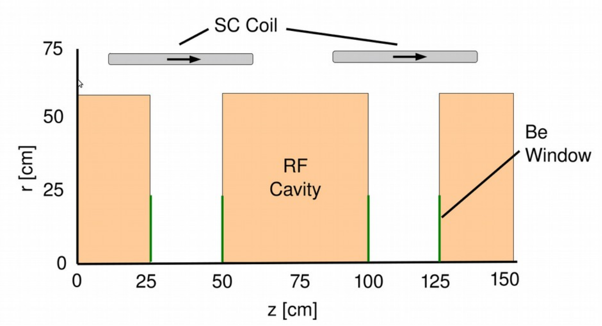
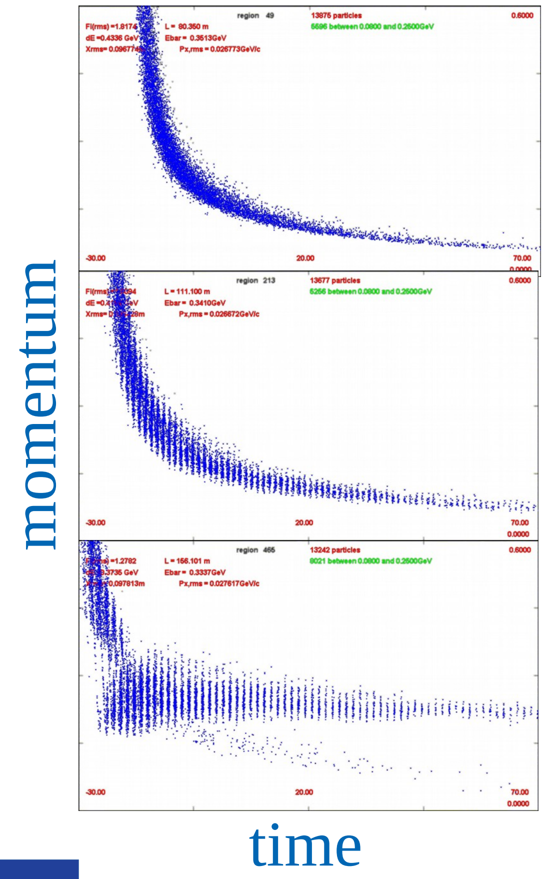
Buncher/Phase Rotator

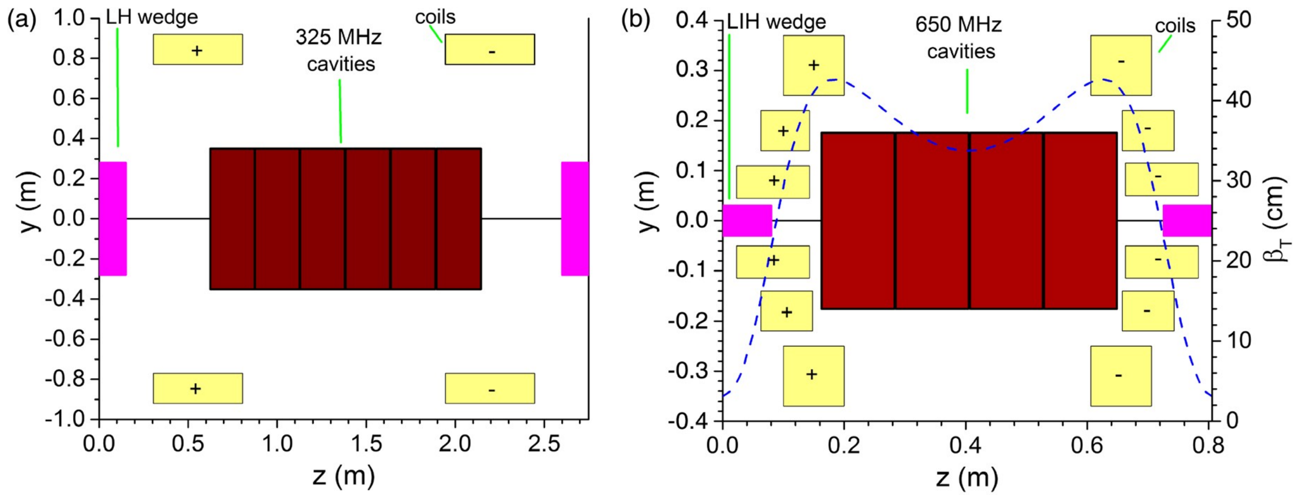
- Drift to develop energy-time relation
- Buncher adiabatically ramp RF voltages
- Phase rotator misphase RF
  - High energy bunches decelerated
  - Low energy bunches accelerated
- Many RF frequencies required
  - Bunch separation changes along the length of the front end
- Nb: plots to right were made without chicane
  - This would remove the high p muons
- Uniform solenoid field
  - Transport very high emittance muon beam





Rectilinear Cooling

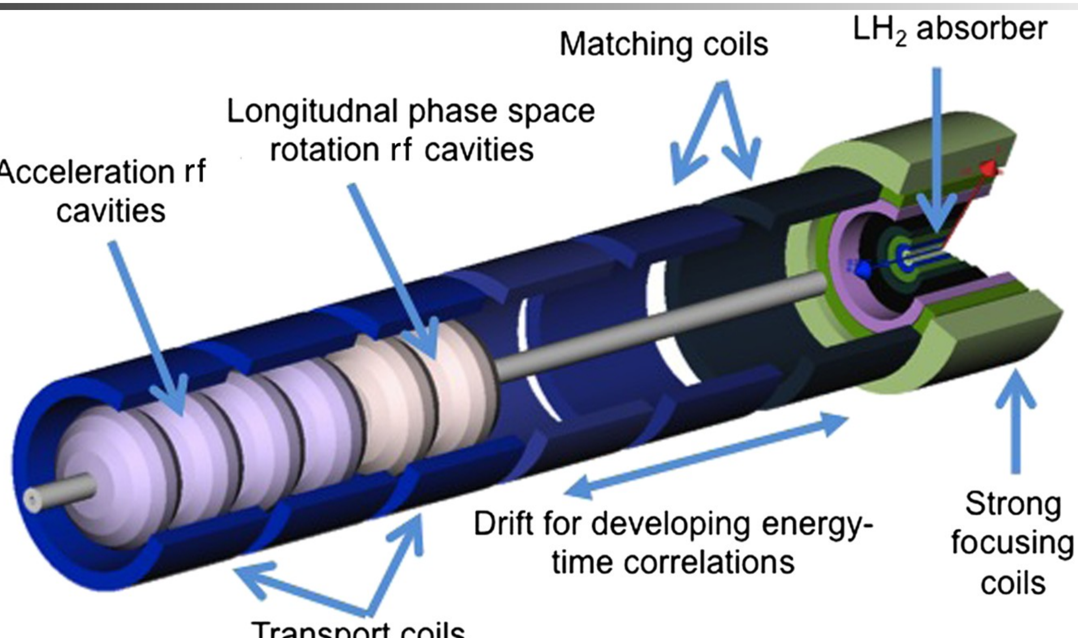
Beam



D. Stratakis and R. Palmer, Rectilinear six-dimensional ionization cooling channel for a muon collider: A theoretical and numerical study, Phys. Rev. ST Accel. Beams 18, 2015

- 6D Cooling
  - Combined function dipole-solenoid magnets
  - Compact lattice – RF integrated into magnet cryostat
  - Lithium Hydride or lH2 absorbers
  - Careful field shaping to control position of stop-bands

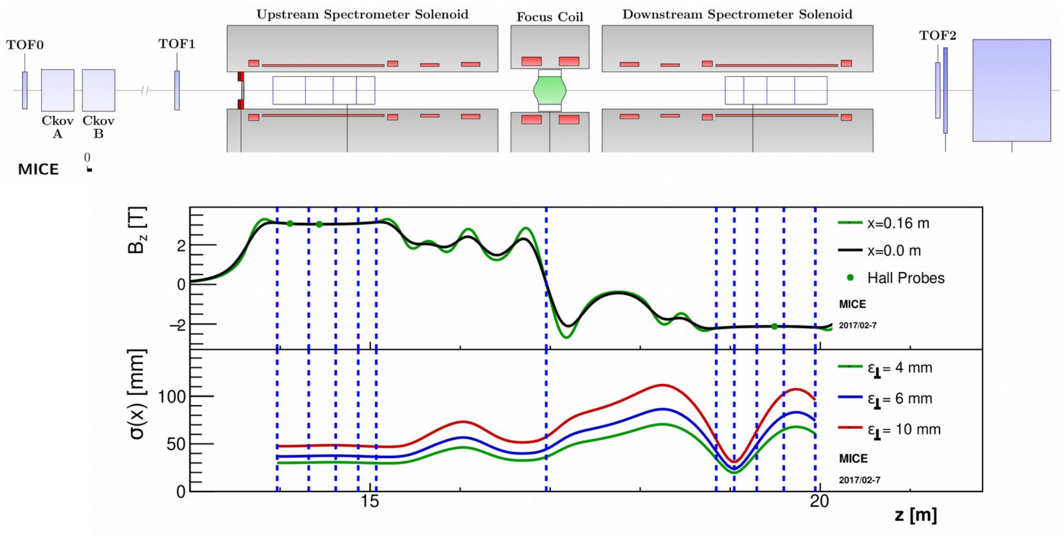
Final cooling

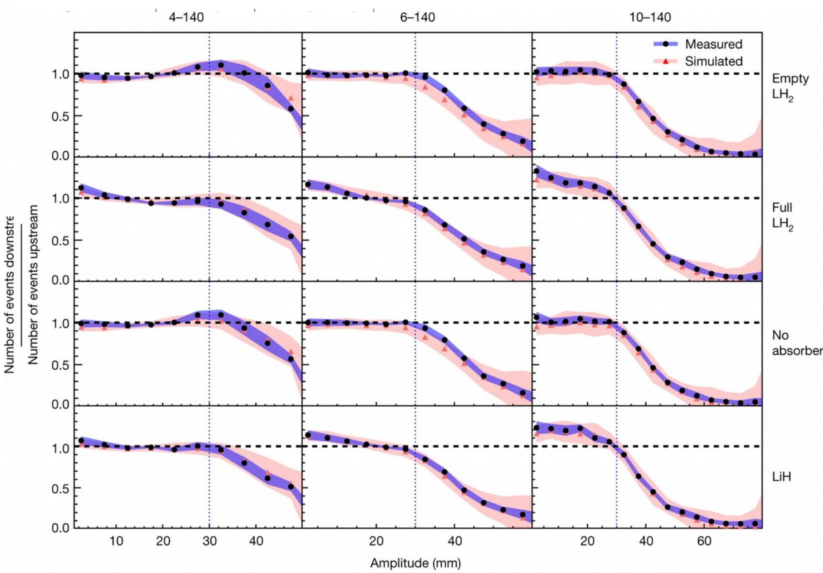


H. Sayed et al., High field – low energy muon ionization cooling channel, Phys. Rev. ST Accel. Beams 18, 2015

- Challenge is to get very tight focussing
- Go to high fields (~30 T) and lower momenta
  - Causes longitudinal emittance growth
  - Chromatic aberrations introduce challenges
    - Elaborate phase rotation required to keep energy spread small
    - Move to low RF frequency to manage time spread

MICE





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Demonstration of cooling by the Muon Ionization Cooling Experiment

MICE collaboration

Nature **578**, 53–59(2020) | Cite this article

- Muon ionisation cooling has been demonstrated by MICE
  - Muons @ ~140 MeV/c
  - Transverse cooling only
  - No re-acceleration
  - No intensity effects

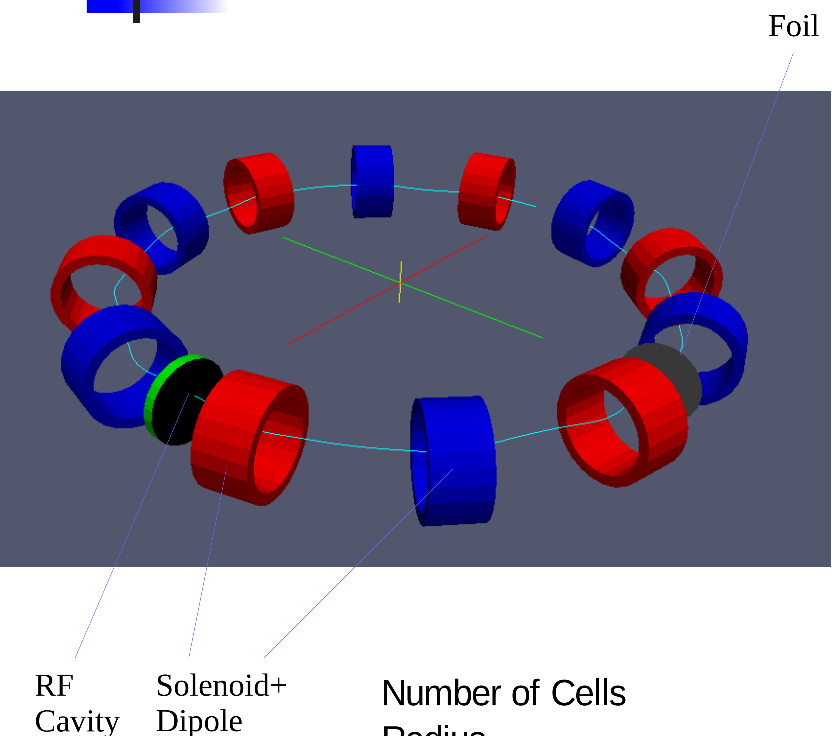
Muon Cooling Issues

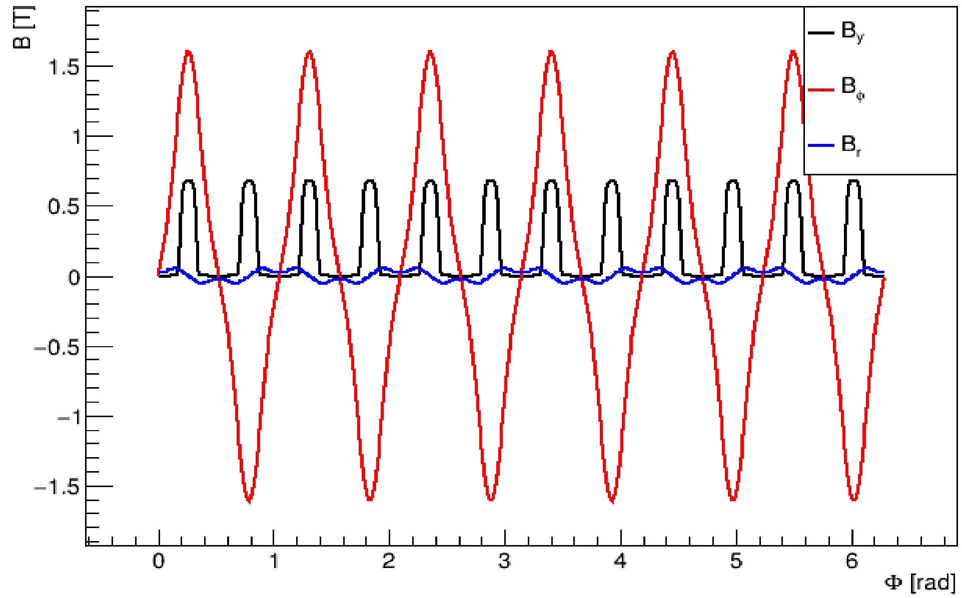
- Longitudinal cooling has not yet been demonstrated
- Cooling in regime of tight focussing/low emittances has not been demonstrated
- Integration of very high field solenoids with RF and beam may be challenging
- “Conventional” intensity effects
- Novel intensity effects
  - Absorber heating
  - Plasma loading of cavities
- Day-to day operation
- ...

Cooling - Beam Tests

- Single-pass (linac) prototype
  - Measurement of cooling challenging
- Ring prototype
  - Multi-turns → bigger cooling signal
  - May be more expensive
- Muons
  - Difficult to get to high intensities
- Protons
  - High intensities available
  - Energy loss regime is quite different → thin absorbers
  - Nuclear effects may also contribute
- Don’t consider electrons
  - e^- energy loss is primarily through Bremsstrahlung
- **Phased approach** may be productive
  - Build a ring segment for protons; add more segments for muons

Solenoid Cooling Ring (Protons)



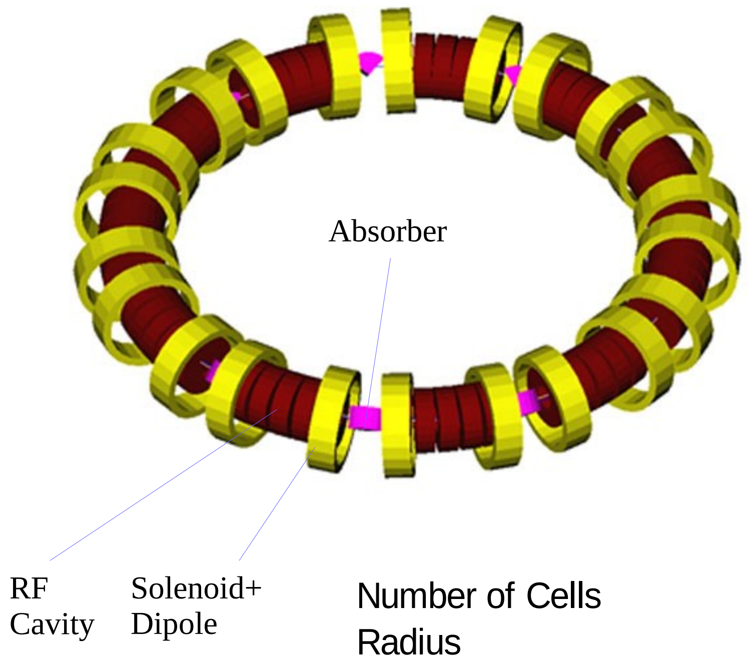


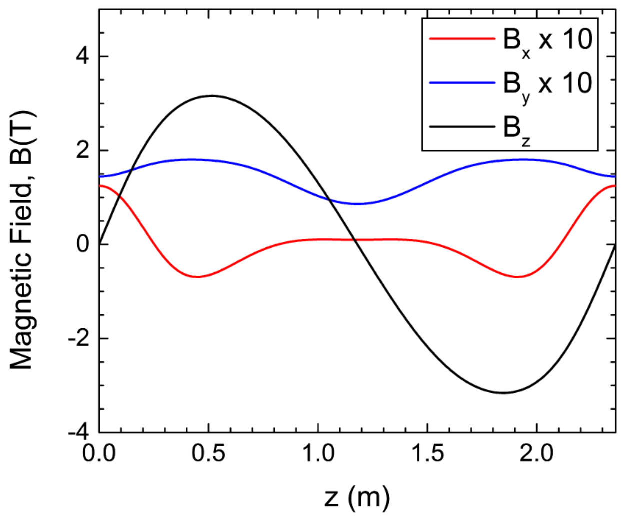
Number of Cells	12
Radius	3 m
Energy range	6-15 MeV
Solenoid field	1.6 T
Dipole field	0.68 T
Magnet Length	500 mm
Bore Radius	400 mm

Foil thickness	10 micron
Foil material	Be
Voltage/turn	250 kV
RF phase	11 degrees
RF freq	2.452 MHz

Solenoid Cooling Ring (Muons)

R, Palmer et al, Phys. Rev. ST Accel. Beams 8, 061003 (2005)

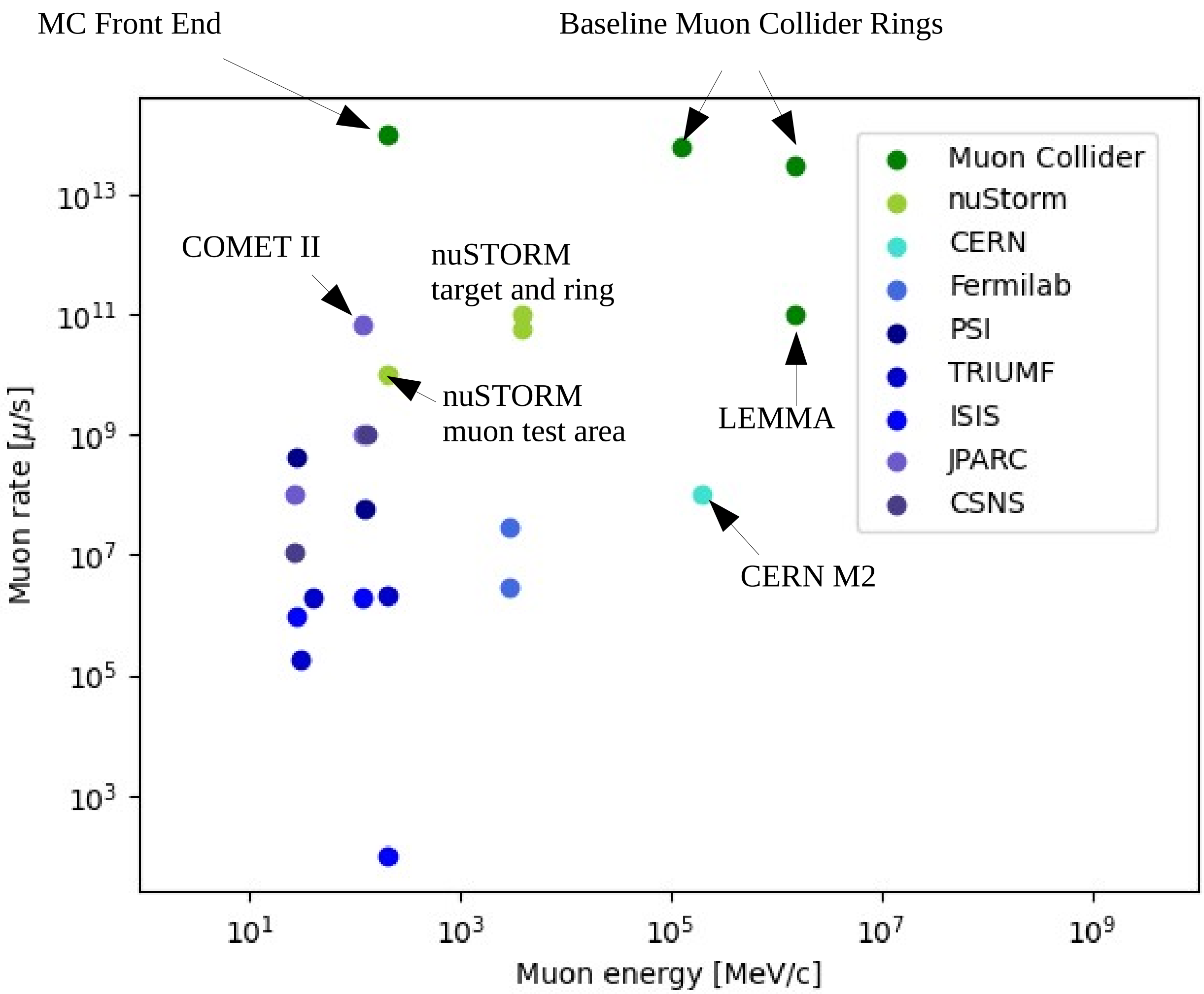




(b)

Number of Cells	12	Abs thickness	28 cm
Radius	5 m	Abs material	liquid H2
Energy	250 MeV	Voltage/turn	~120 MV
Solenoid field	2.8 T	RF phase	25 degrees
Dipole field	0.15 T	RF freq	201 MHz

Survey of Muon Beamlines



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Cooling - Questions

- Cooling considerations
  - Benefits of high intensity muons
    - Can we design an “affordable” lattice with strong enough cooling signal that conventional diagnostics are convincing
    - Or do we need to do single particle experiment like MICE
  - Is it easy to get a high intensity source of protons at nuSTORM?
    - Can we interleave proton/muon tests?
      - Excite collective effects with protons and test with muons?
      - Pump probe
    - What proton momentum is desired for physics tests?

LDG and PPTAP Panels

- (European) LDG Process
  - Lab Directors’ Group called panels to coordinate R&D based on European Strategy
  - Muon LDG panel led by D. Schulte
- (European) ECFA Process
  - Support detector R&D
- (UK) PPTAP Process
  - Produce UK position on R&D Roadmaps for European Strategy
  - Seek to establish UK priorities
    - Where is there expertise? Where are there gaps? How does it tie in to other UK priorities (e.g. non-HEP)
  - Rogers – contact for muon beam physics
  - Palladino – contact for Gas/Liquid detectors
  - https://stfc.ukri.org/about-us/how-we-are-governed/advisory-boards/pptap/
- (UK) PPAP process
  - Set overall UK physics priorities

Summary

- NuSTORM can be a stepping stone on the way to a muon collider
- A number of issues that will be faced by muon collider can be addressed at nuSTORM
- In particular, nuSTORM would provide the highest rate high energy muon beam line