# Production of a High Quality Beam for the Muon Collider

International
MUON Collider
Collaboration

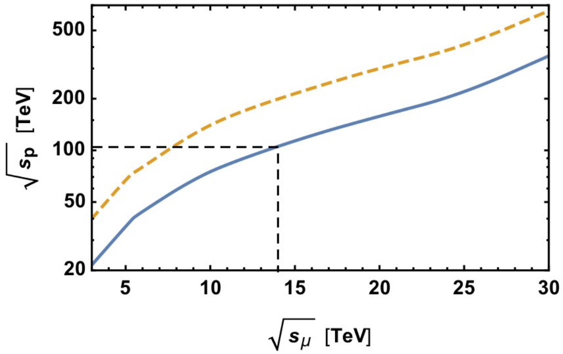
Science & Technology Facilities Council
ISIS Neutron and Muon Source

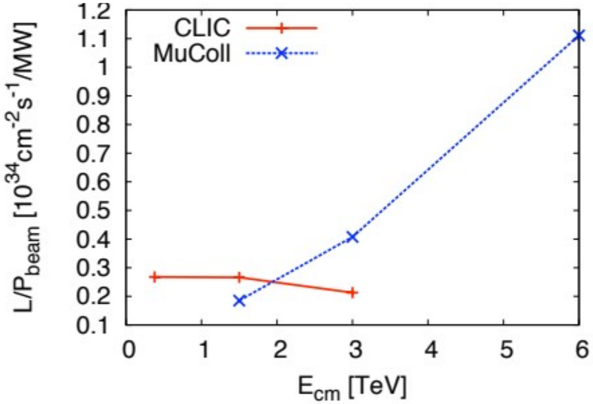
C. T. Rogers on behalf of the Muon Collider Collaboration
ISIS
Rutherford Appleton Laboratory

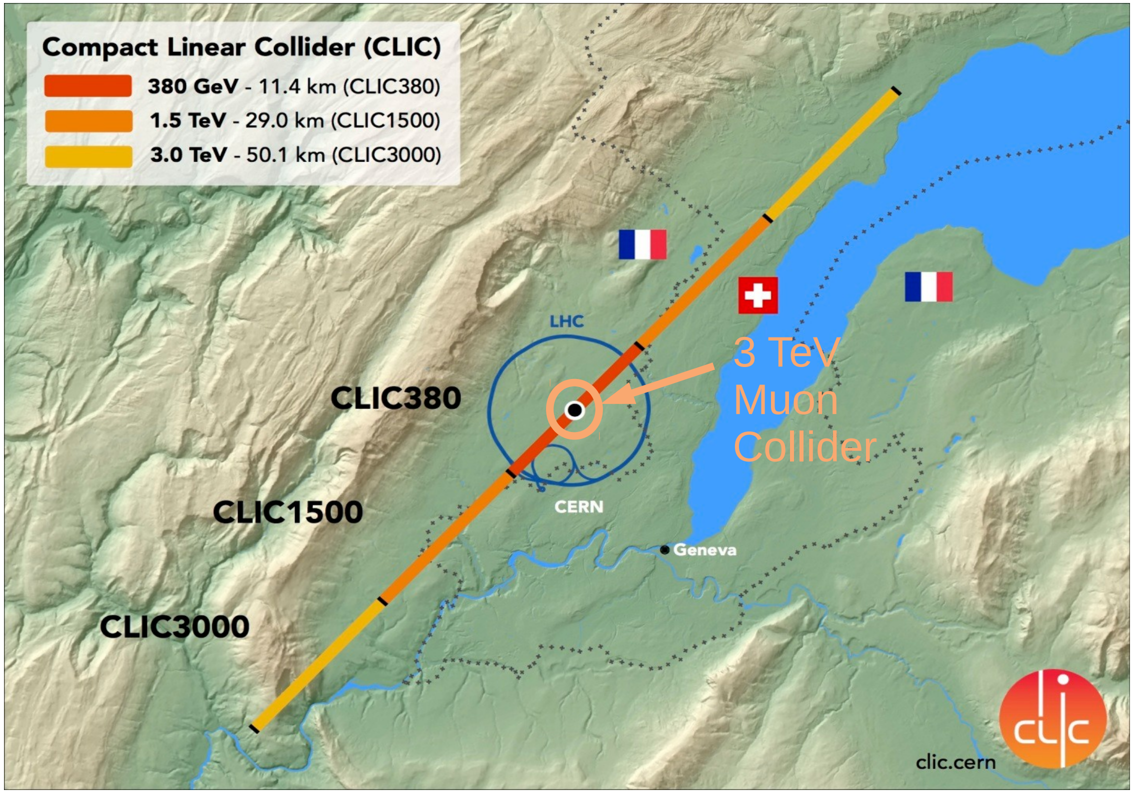
# Muon Collider

International MUON Collider Collaboration

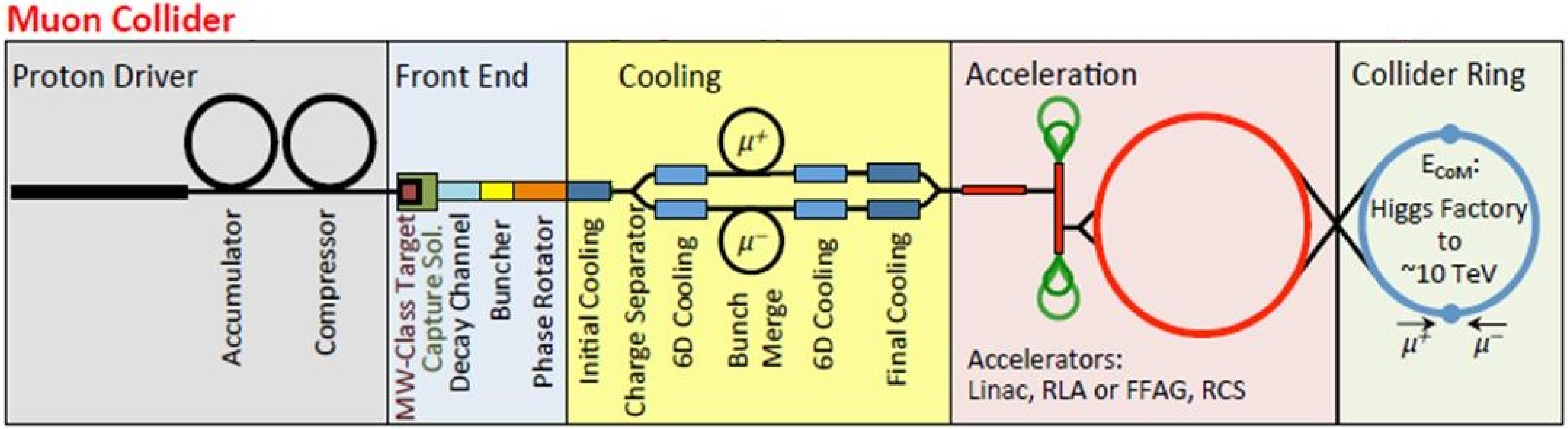
- Growing interest in muon collider as a future facility in Europe
  - Only lepton collider with potential to go beyond 3 TeV
  - At ~14 TeV, physics reach comparable to 100 TeV protons
  - Compact footprint
  - Efficient electrical power consumption even at high energy
  - Potential for phased construction with physics at each stage







# Muon Collider Facility



- Reminder – muon collider facility (proton-based)
  - Protons on target in high-field solenoid → pions, muons et al.
  - **Clean up beam impurities**
  - **Capture muons longitudinally**
  - **Transverse and longitudinal cooling**
  - Acceleration
  - Collider ring

# A little history

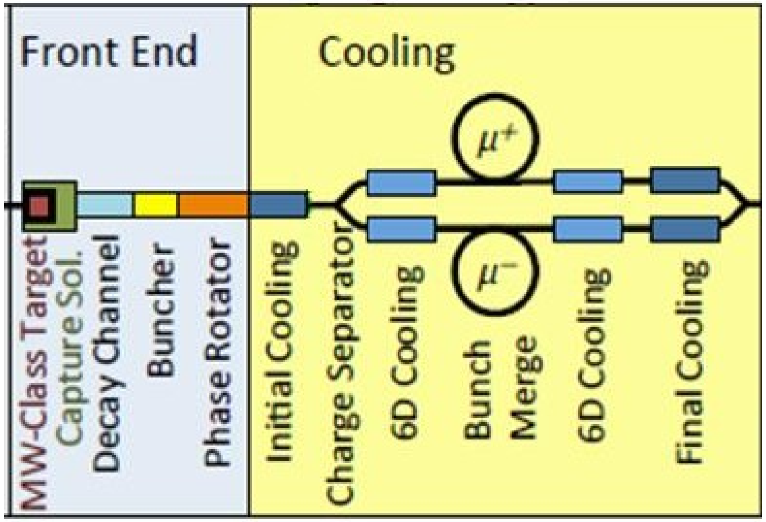
- Theoretical studies demonstrated essential feasibility to build a muon collider
  - Target design
  - Beam clean up
  - Practical cooling options to high luminosity
  - Assessment of neutrino radiation issues
  - Understanding of collider backgrounds
  - Demonstration of high field RF necessary for muon cooling
- Hardware work to demonstrate key technologies
  - Studies of high power targetry
  - Muon Ionisation Cooling Experiment
  - Demonstration of high gradients in NC RF cavities
  - EMMA test for rapid acceleration
  - Synchrotron magnet studies

# Task – muon capture and cooling

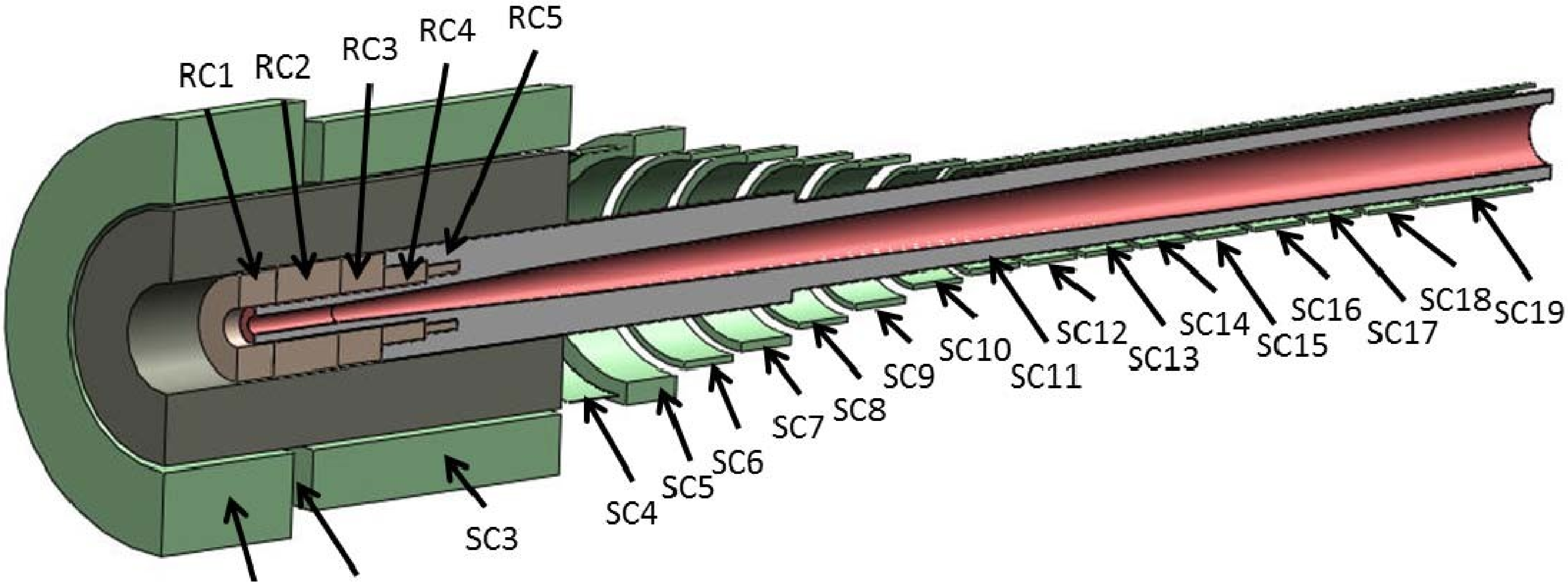
- Establish a single baseline cooling lattice
  - Optimise the existing designs
  - Support and integrate novel technologies
- Build on MICE, MuCOOL and targetry R&D
  - Prototyping of realistic RF cavities and operation in fields
  - Engineering and construction of more challenging cooling cell
  - Demonstrate 6D cooling, reacceleration and multiple cooling cells
  - Understand effects of beam on target and required radiation shielding of magnets
- Outline our baseline
- Highlight some new ideas
  - Many are work in progress!

# Task – muon capture and cooling

- Baseline concept
  - Heavily influenced by previous studies (MAP, NF)!
- Graphite target in high field solenoid
  - Target horn(s) as backup
- Chicane and proton absorber to clean beam
- Buncher and phase rotation to make bunches
- Initial dual-sign cooling
- Charge separator
- Rectilinear 6D cooling
- Bunch merge
- Rectilinear 6D cooling
- Final cooling



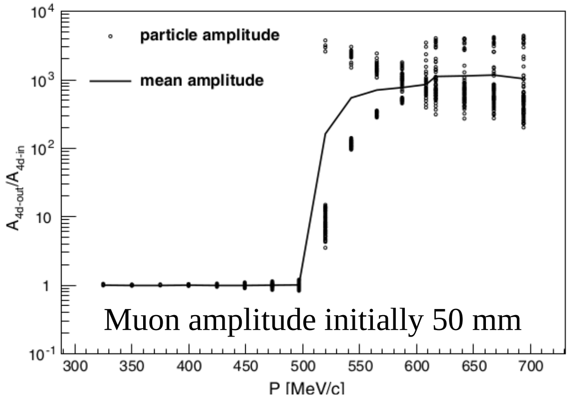
# Target



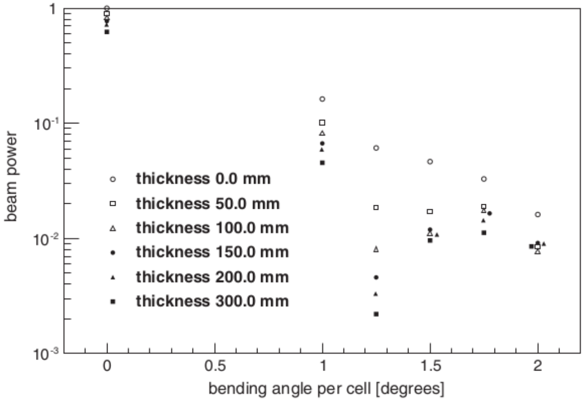
- 15 m long high field solenoid
  - 15-20 T pion capture region tapering to 1.5 T
  - Shielding is very challenging
- Graphite target
  - Multi-MW proton beam with ~ ns bunch length → shock load

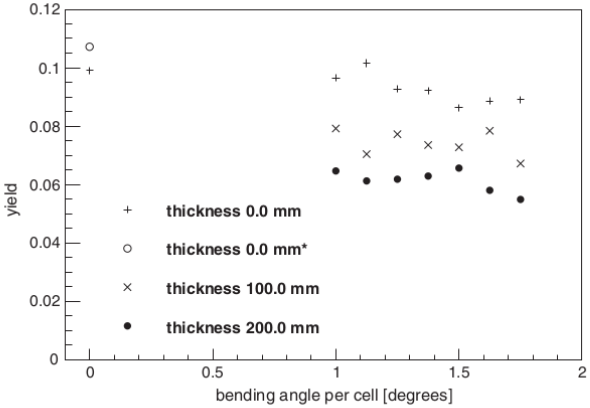
# Particle selection

- Reject beam impurities
- Solenoid chicane
  - Reject high momentum particles
  - Extremely good acceptance below threshold
- Beryllium absorber
  - Absorbs low momentum protons
  - Muons relatively unperturbed



Muon amplitude initially 50 mm

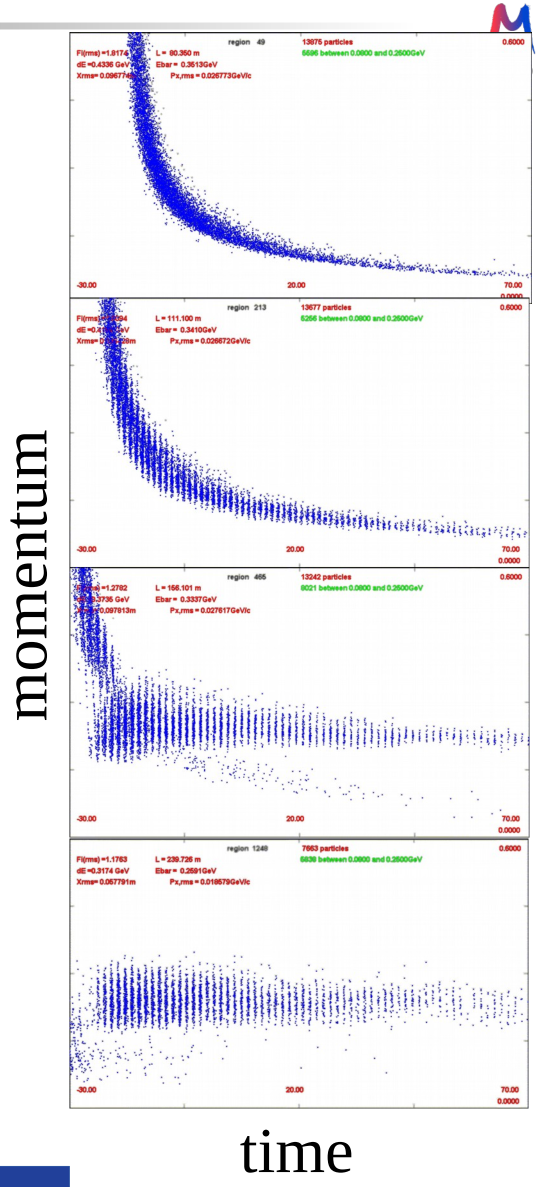




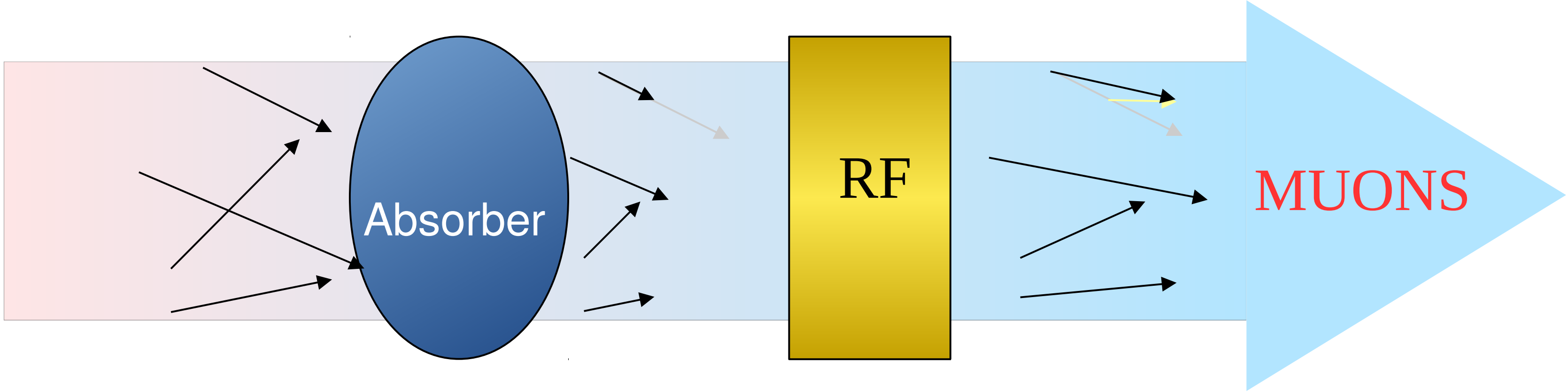
https://map-docdb.fnal.gov/cgi-bin/ShowDocument?docid=4355 (D. Neuffer)
Proc. IPAC2014 TUPME022 (S. Berg)
https://journals.aps.org/prab/pdf/10.1103/PhysRevSTAB.16.040104 (C. Rogers et al)

# 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

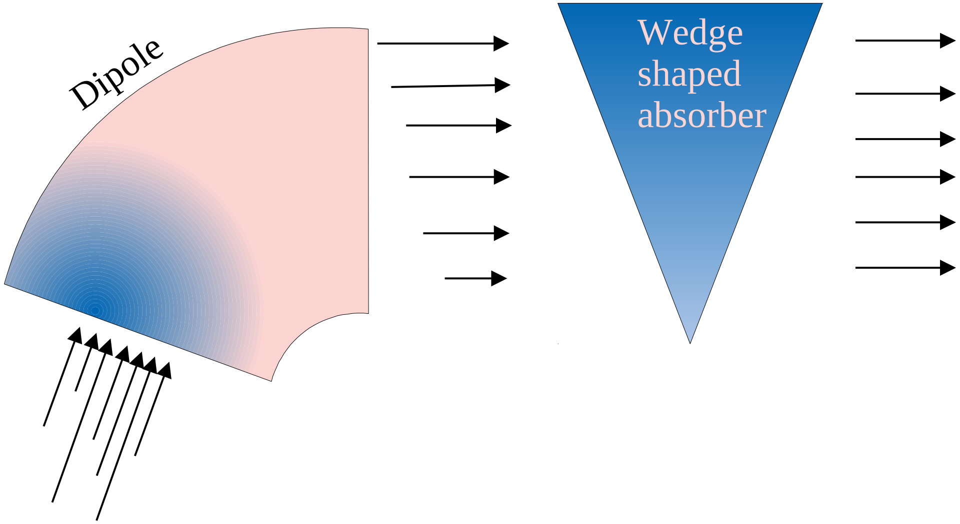


# 4D Ionisation Cooling



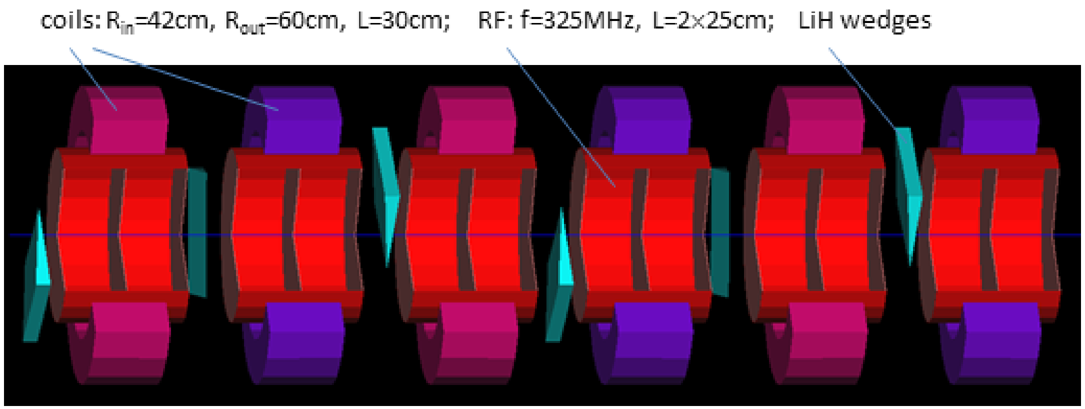
- Beam loses energy in absorbing material
  - Absorber removes momentum in all directions
  - RF cavity replaces momentum only in longitudinal direction
  - End up with beam that is more straight
- Multiple Coulomb scattering from nucleus ruins the effect
  - Mitigate with tight focussing
  - Mitigate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

# 6D Ionisation Cooling

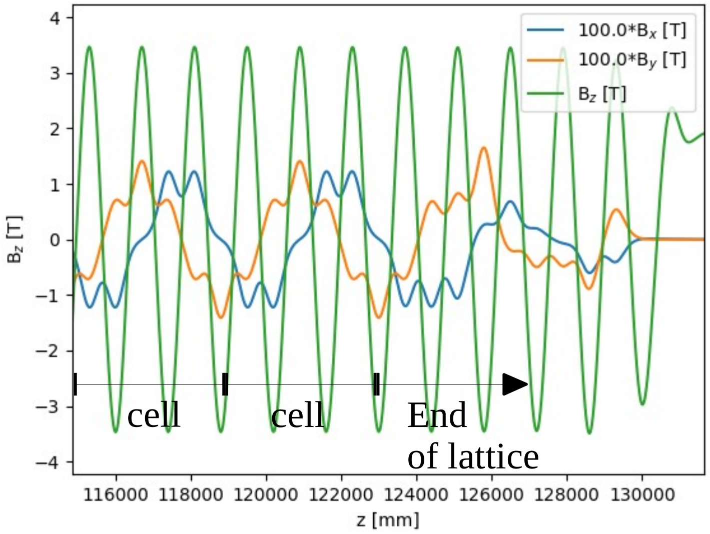


- Initial beam is narrow with some momentum spread
  - Low transverse emittance and high longitudinal emittance
- Beam follows curved trajectory in dipole
  - Higher momentum particles have higher radius trajectory
  - Beam leaves wider with energy-position correlation
- Beam goes through wedge shaped absorber
  - Beam leaves wider without energy-position correlation
  - High transverse emittance and low longitudinal emittance

# Initial Cooling



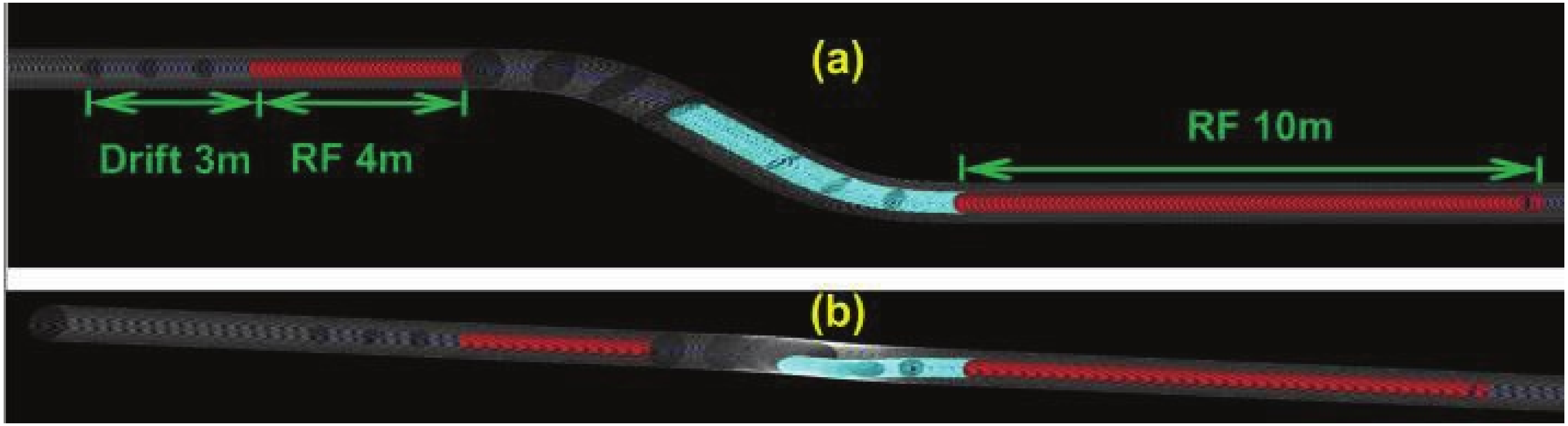
coils: $R_{in}$=42cm, $R_{out}$=60cm, L=30cm; RF: f=325MHz, L=2×25cm; LiH wedges



- Initial cooling to get muon beam to “manageable” emittance
- Simultaneously cool mu- and mu+ in the same lattice
  - Initially too high emittance to split charges
  - This is quite a challenge
- Rotating dispersion vector

https://map-docdb.fnal.gov/cgi-bin/ShowDocument?docid=4377 (Y. Alexahin)

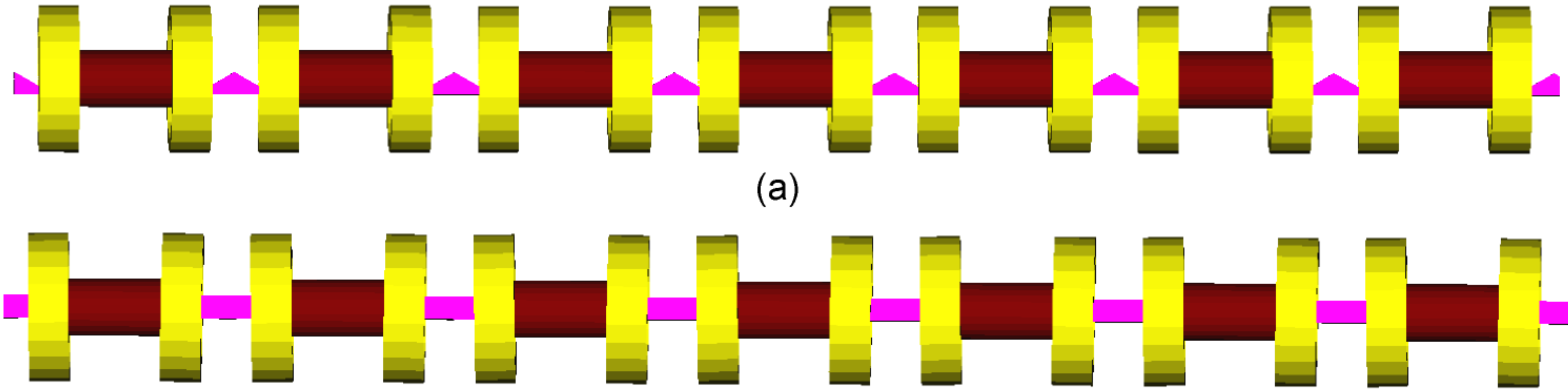
# Charge Separation



- Further cooling (and the collider) requires separation of mu+ and mu-
  - Basic concept is to use a bent solenoid to introduce vertical dispersion
    - Just like in the particle cleaning
    - But now we must maintain the bunch structure

https://www.osti.gov/biblio/1113648 (C. Yoshikawa)

# Rectilinear cooling channel



(a)

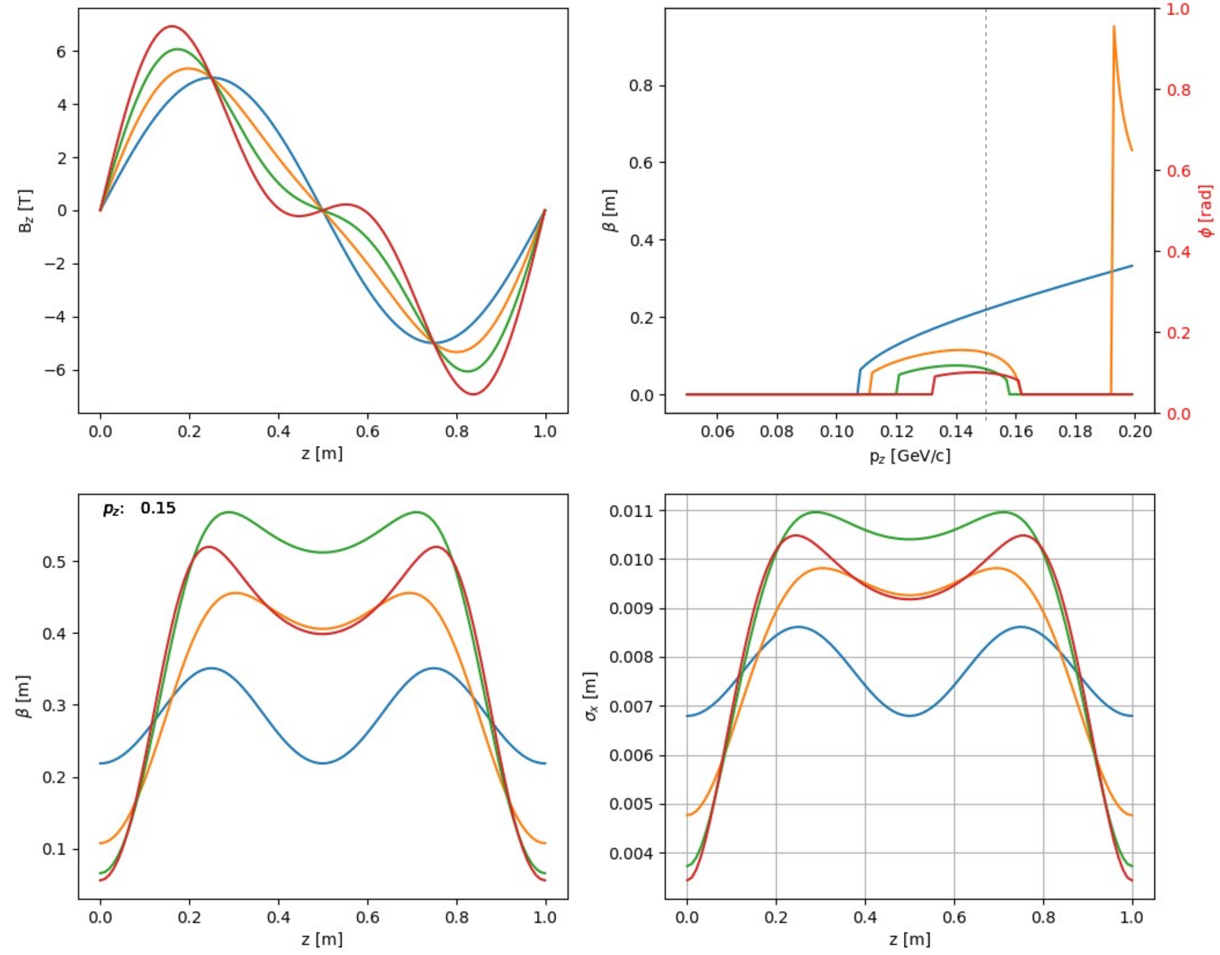
(b)

- “Tilted solenoids” to induce dispersion
  - Solenoids with added dipole coils might be more tunable
- Wedge-shaped absorbers
- Magnetic Fields up to ~ 14 T
- RF gradients up to ~30 MV/m at 650 MHz

https://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.18.031003 (D. Stratakis et al)

# Effect of harmonics

$$B_z = B_0\sin(kz) + B_1\sin(2kz)$$



Mixing different harmonics of $B_z$

Cooling:

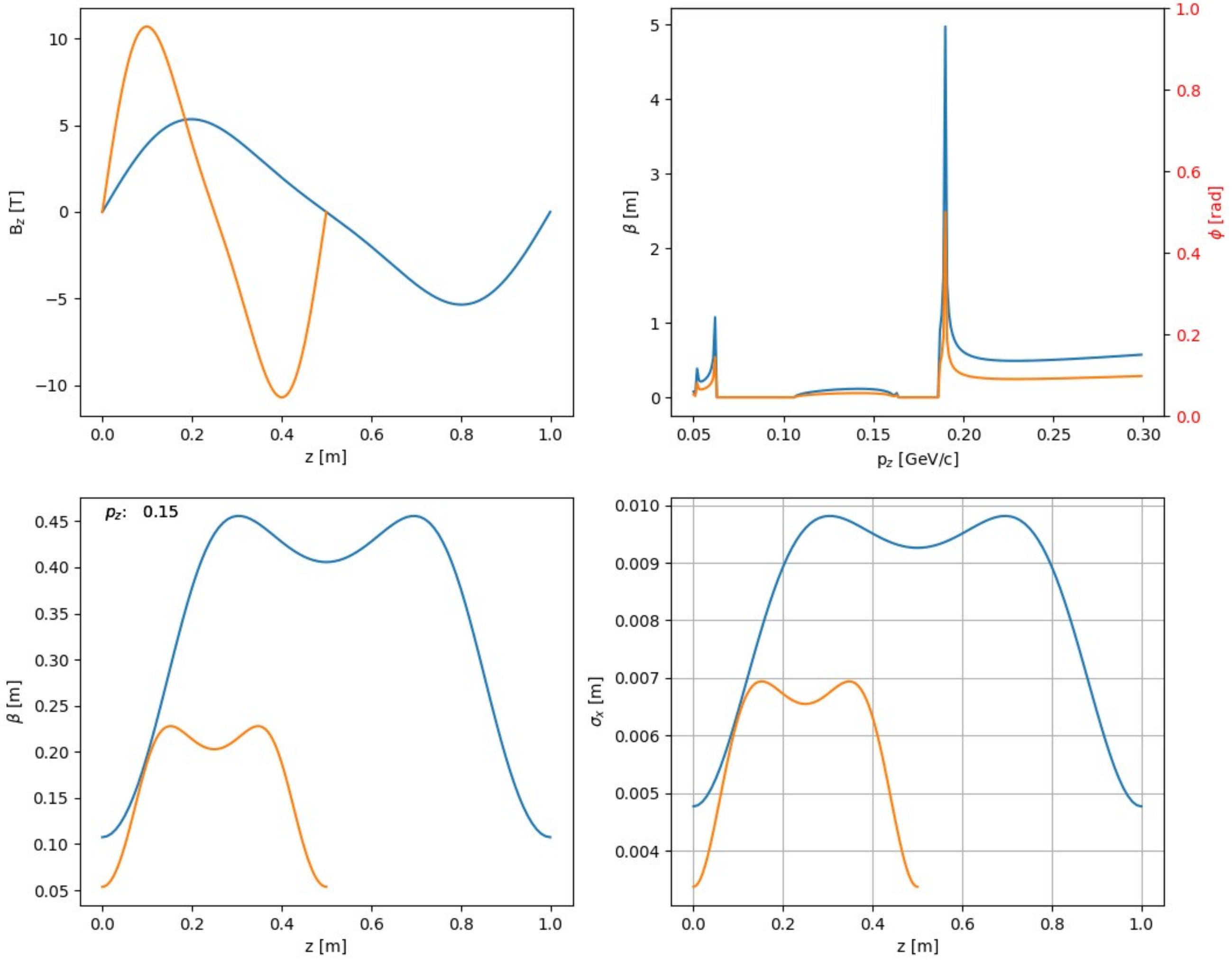
$\varepsilon_{min} \sim \beta_{min}$

Aperture:

$\varepsilon_{max} \sim \beta_{max}$

# Scaling

$$B_z = B_0 \sin(kz) + B_1 \sin(2kz)$$



$B_0 \rightarrow 2B0$

$B_1 \rightarrow 2B1$

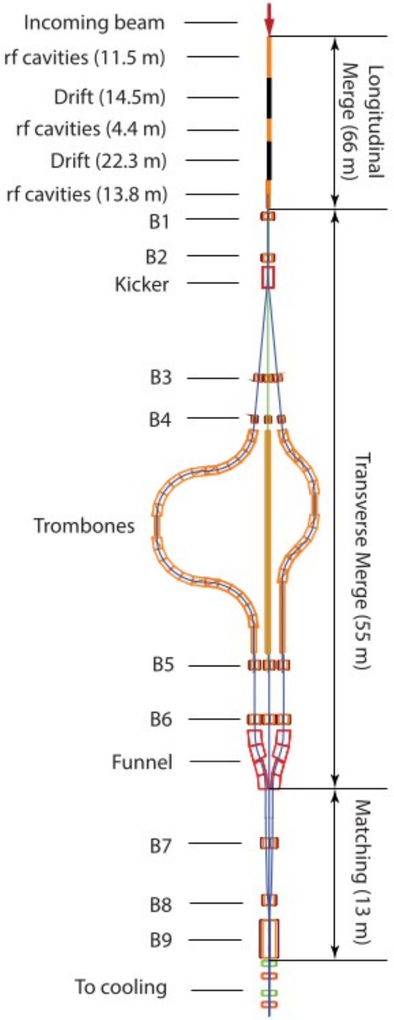
$k \rightarrow 2k$

Question: How short can we make the cells? How high field?

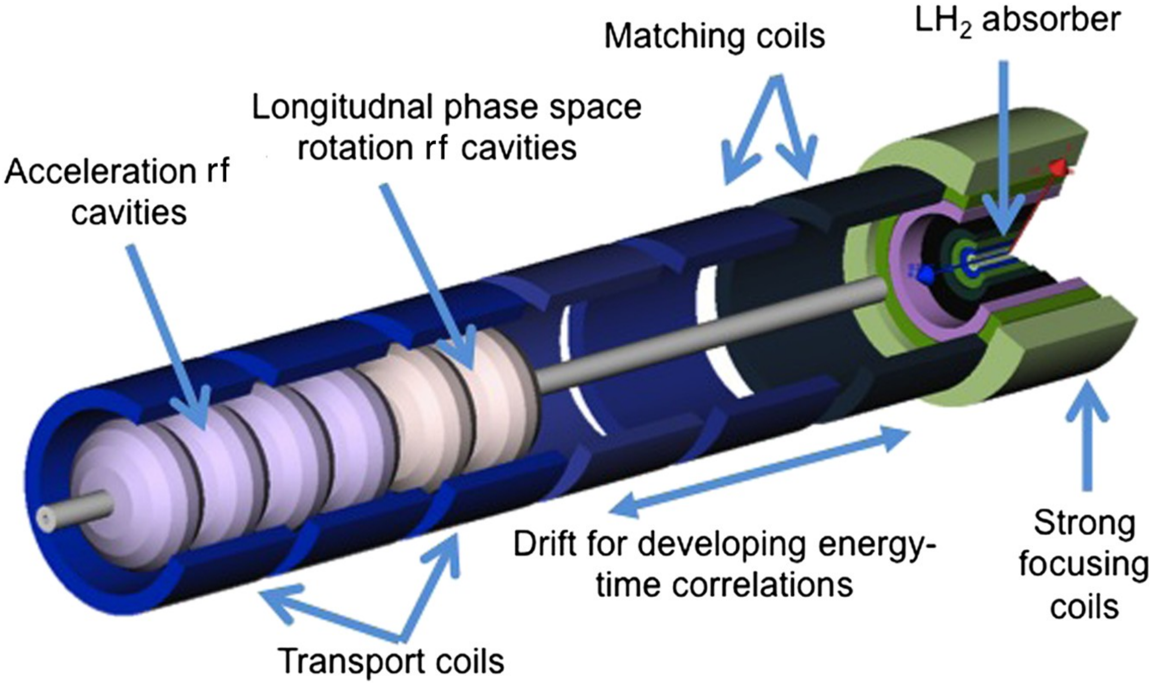
# Bunch merge

- Remember, the buncher/phase rotator made a bunch train of 21 bunches (or so)
- Combined longitudinal and transverse merge
  - RF cavities do phase rotation on 21 bunch train to make 7 bunches
  - Kick each bunch into 7 separate “trombone” arc
    - Only 3 are shown
  - Funnel bunches together transversely to make a single bunch

https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.19.031001 (Yu Bao)



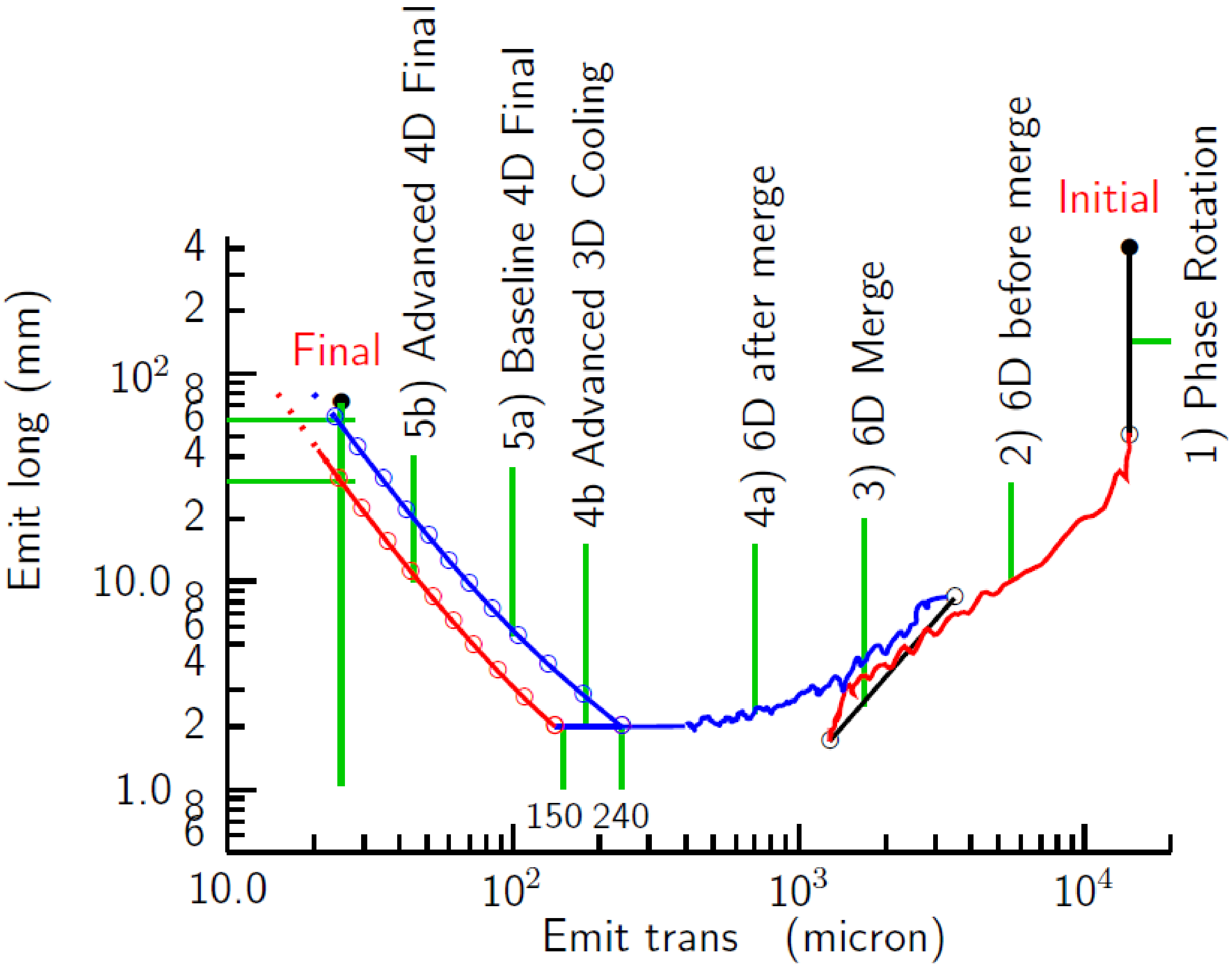
# Final cooling



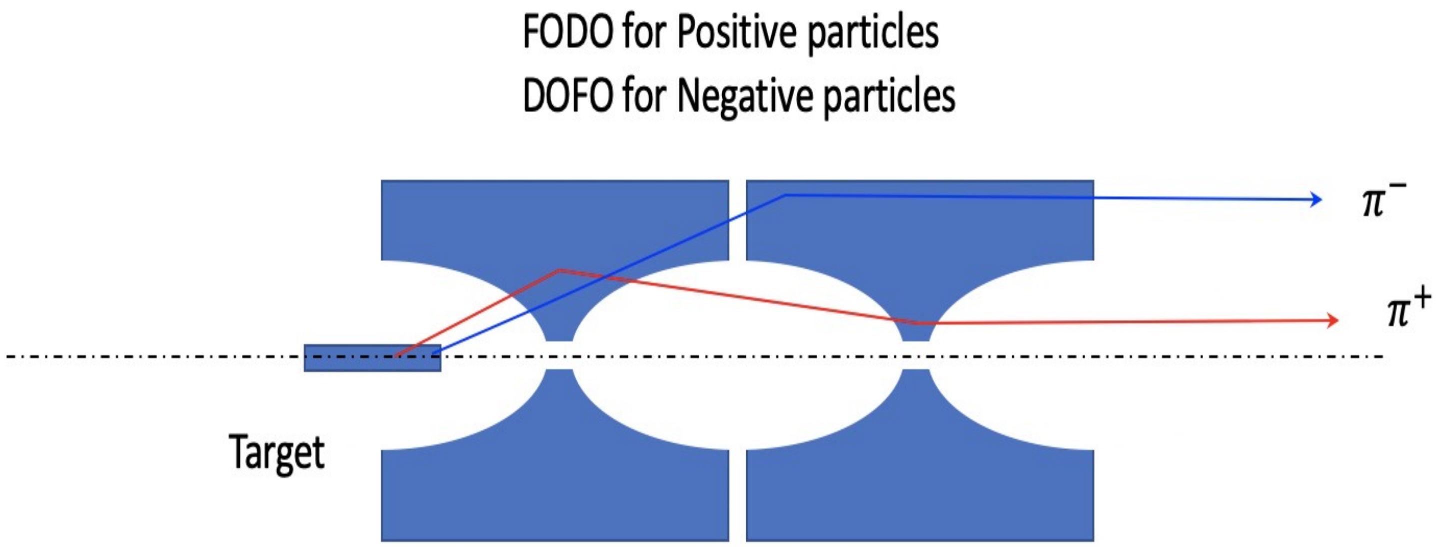
- Challenge is to get very tight focussing
- Go to higher fields and lower momenta
  - Causes longitudinal emittance growth
  - Chromatic aberrations introduce challenges
    - Elaborate phase rotation required to keep energy spread small
    - Move to low RF frequency to manage time spread

https://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.18.091001 (H. Sayed et al)

# Emittance path

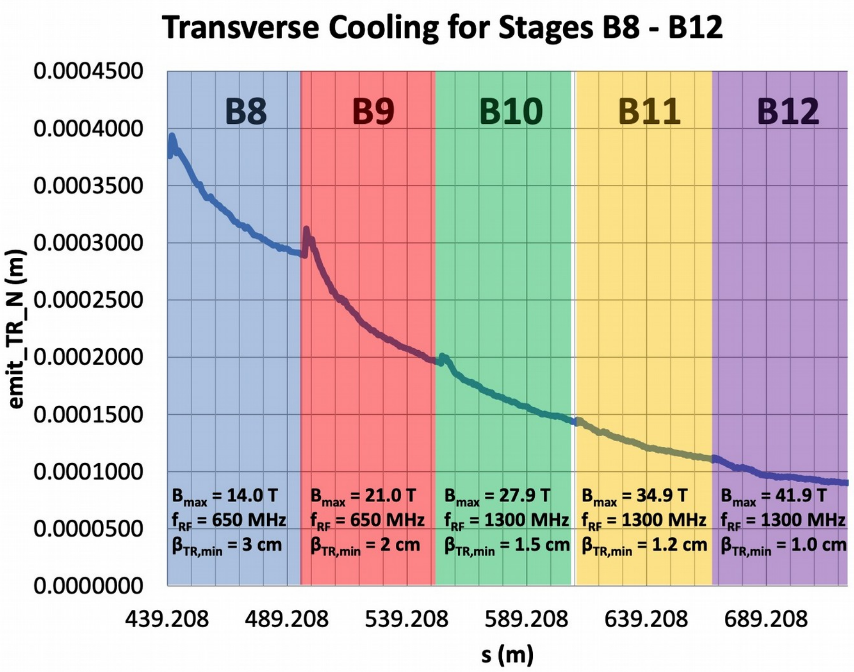


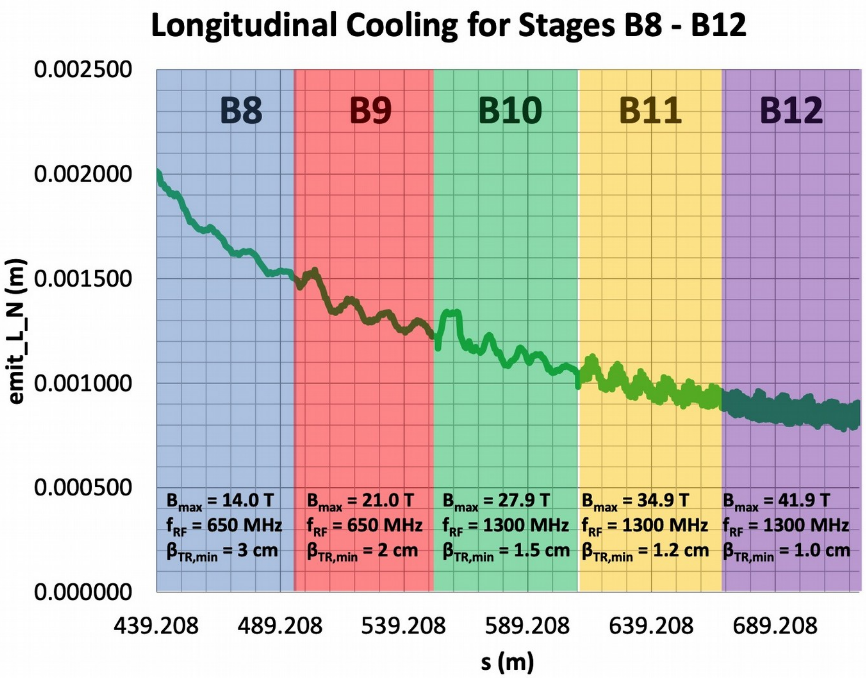
# Dual-sign horn (K. Yonehara)



- Idea to capture both pion signs using horns
  - Horn is well-understood technology
  - No need for SC magnets near to radiation source

# Improved Rectilinear Cooling
D Summers et al

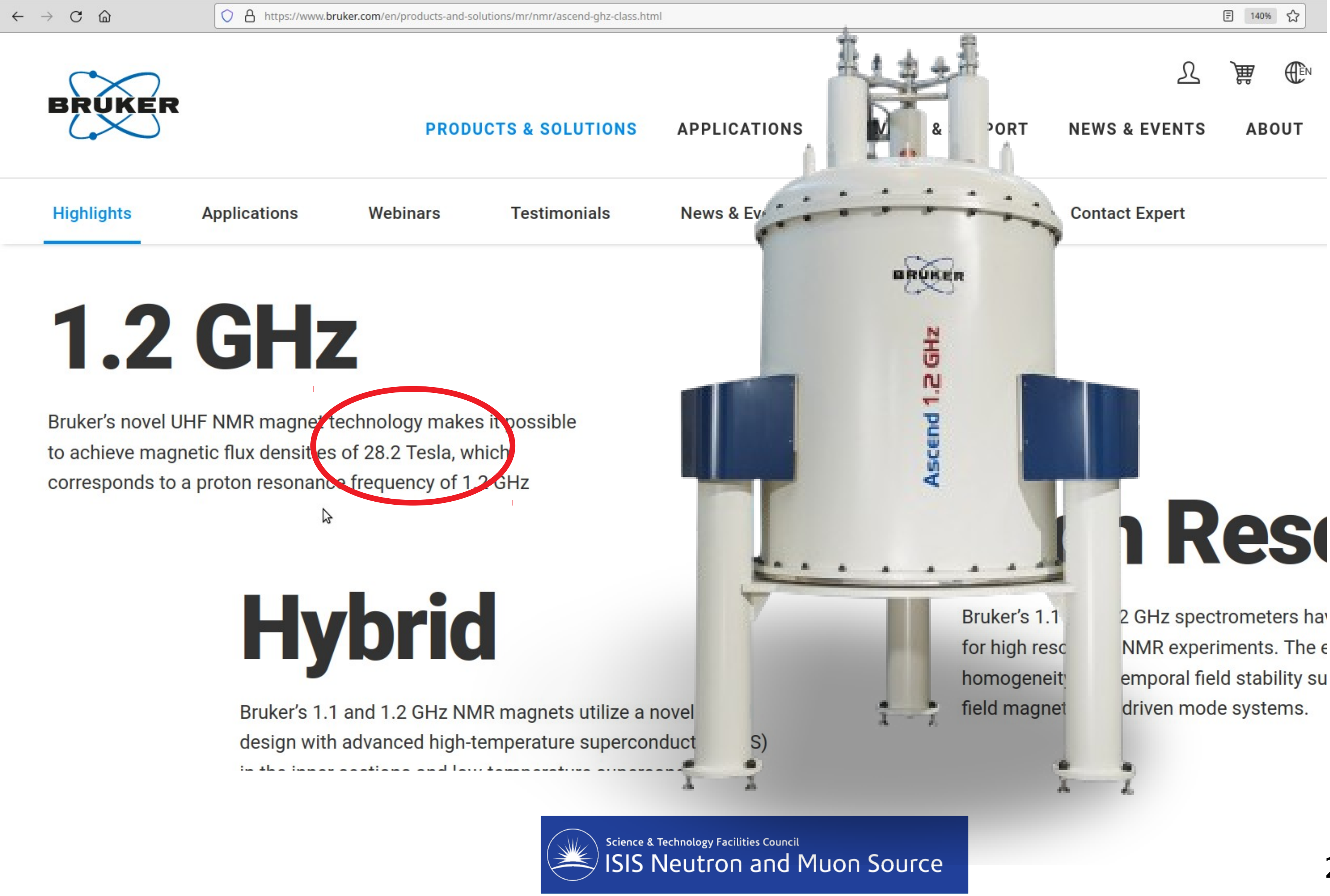

Transverse Cooling for Stages B8 - B12


Longitudinal Cooling for Stages B8 - B12

- Add extra rectilinear cooling stages
  - Fields are still rather challenging
  - Cell length is very short → rapidly varying fields

# Improved Final Cooling

B. Stechauner, E. Fol



1.2 GHz

Bruker's novel UHF NMR magnet technology makes it possible to achieve magnetic flux densities of 28.2 Tesla, which corresponds to a proton resonance frequency of 1.2 GHz

Hybrid

Bruker's 1.1 and 1.2 GHz NMR magnets utilize a novel design with advanced high-temperature superconduct S)

n Res

Bruker's 1.1 2 GHz spectrometers ha
for high reso NMR experiments. The e
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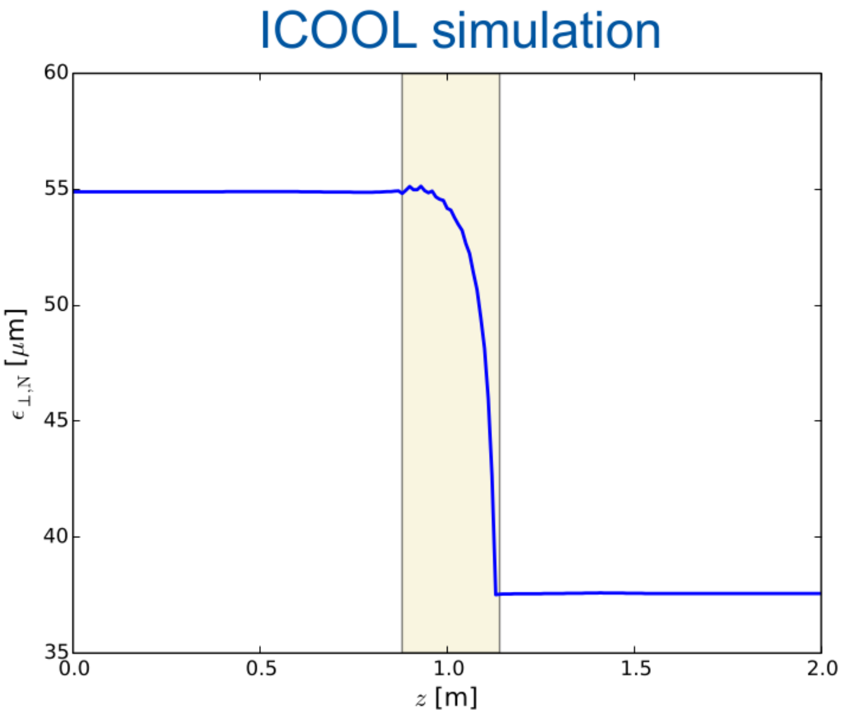
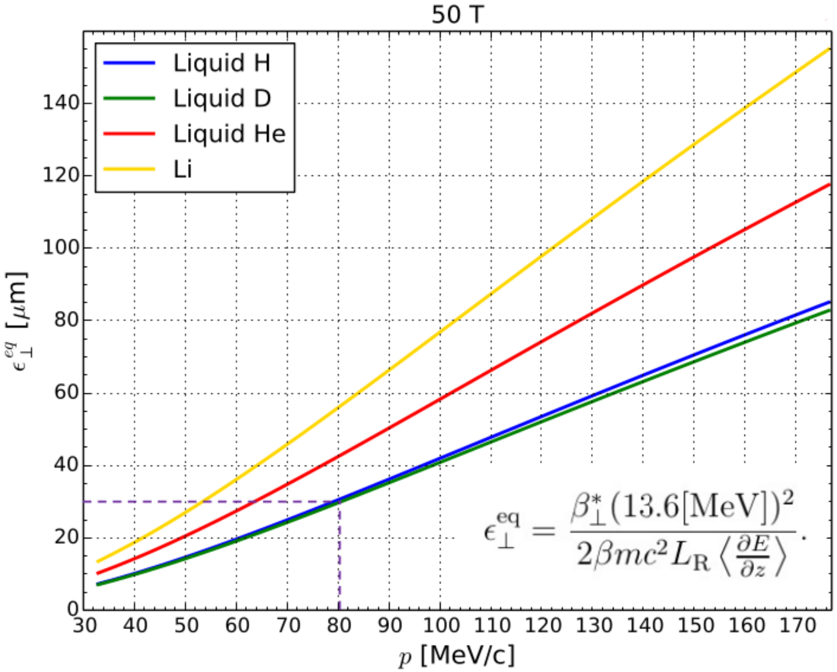
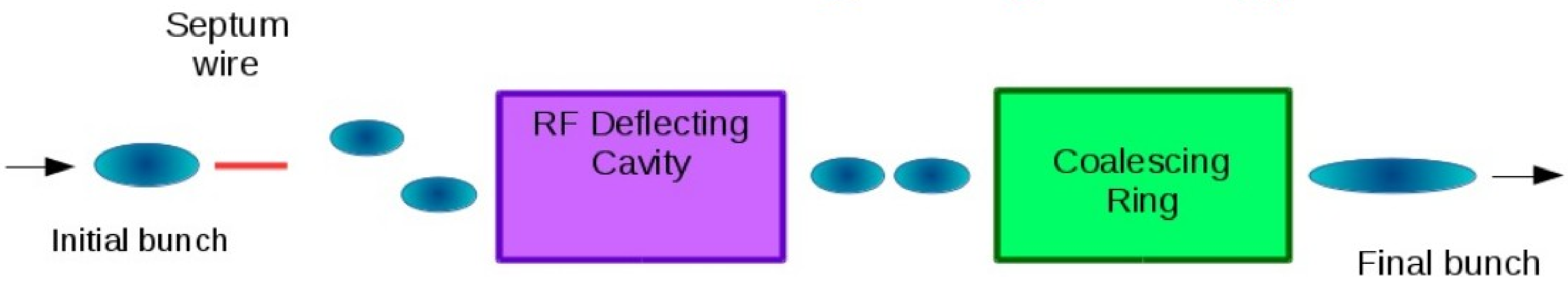
# Improved Final Cooling
## B. Stechauner, E. Fol





- More aggressive final cooling should be possible!

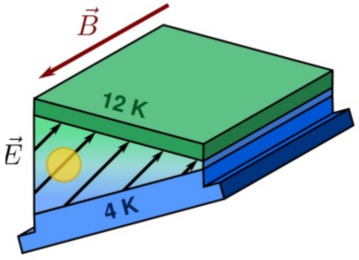
# “Potato slicer” - D. Summers et al

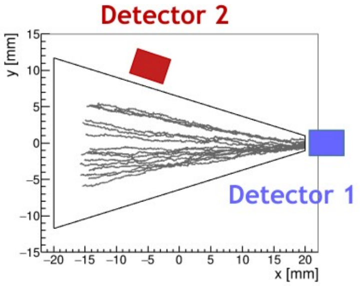


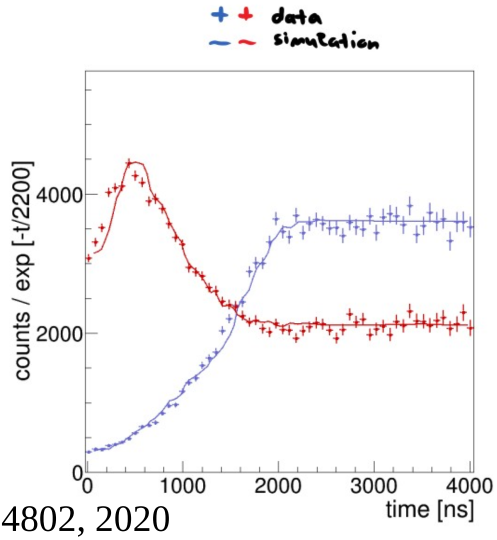
- Use septa to split one $\epsilon_{xyz} = (90, 90, 850)$ micron bunch into 16 $\epsilon_{xyz} = (25, 25, 850)$ micron bunches.
  Fermilab fixed target switchyard used 8 electrostatic septa
- Use RF deflector cavities to form a 3.7 m long bunch train
  Follow CLIC test experience
- Snap bunch coalesce 16 bunches into one in a 21 GeV ring
  Rotate over a quarter synchrotron period and then drift
  Capture in a short wavelength RF bucket
  87% longitudinal packing may be possible. Chandra Bhat
  Follow Tevatron experience

# Frictional Cooling Scheme

- Novel frictional cooling scheme constructed at PSI
    - Yields very small emittances
- Rough estimate that transverse acceptance is ~ high enough
    - More quantitative estimate would be beneficial
- Need to check time spread of beam
    - Can we recapture in RF?
- Overall do we get required bunch compression?
    - Qualitatively looks promising

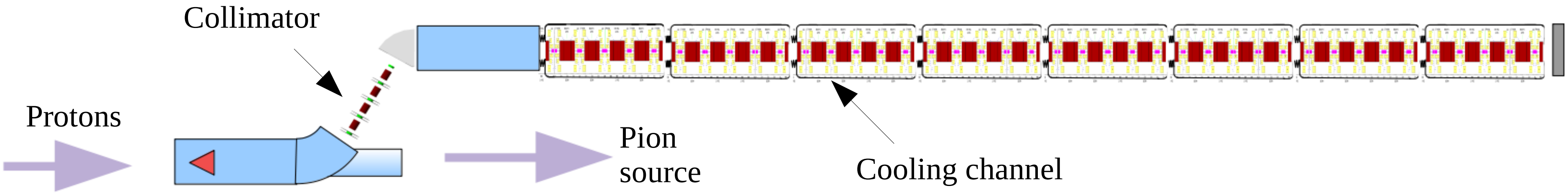






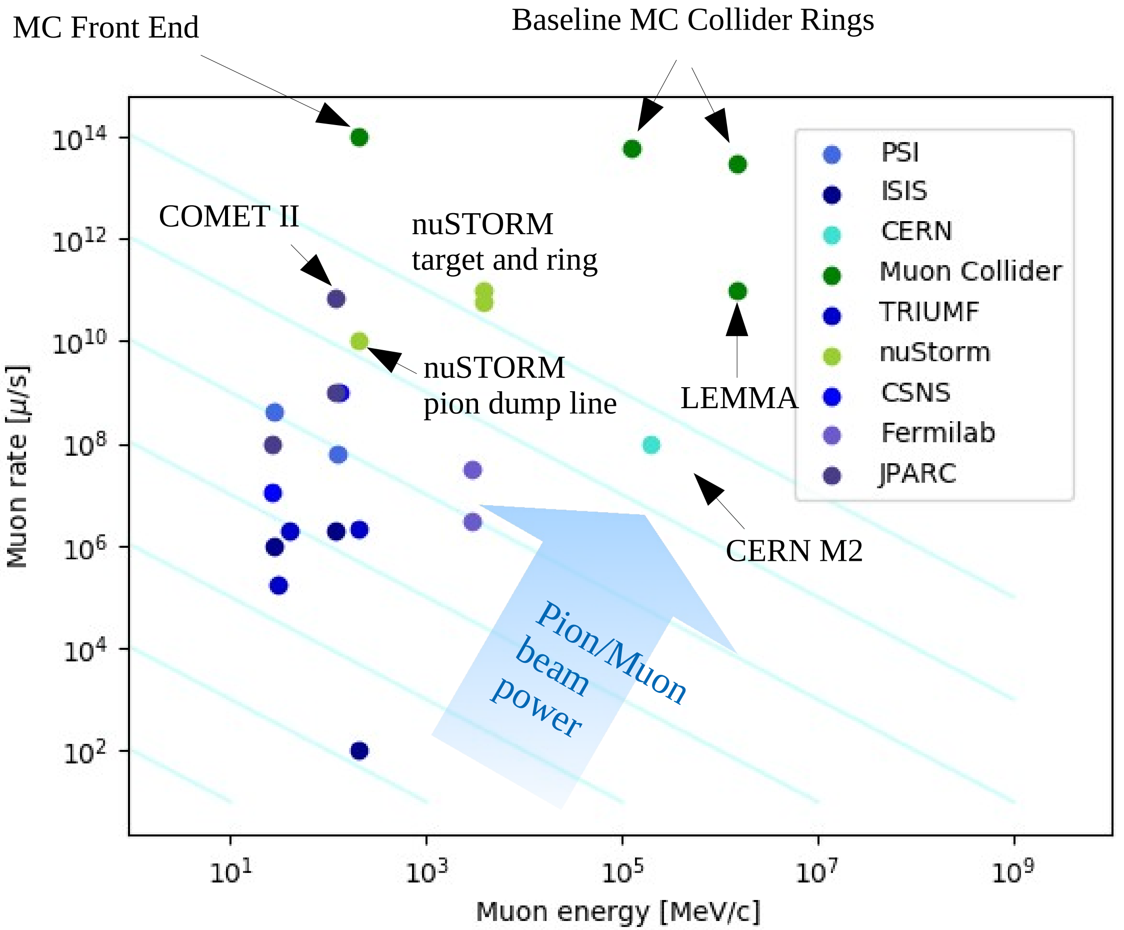
Angela Papa (PSI) et al, Phys. Rev. Lett. 125, 164802, 2020

# Cooling demonstrator



- Need for a technology demonstrator
  - MICE showed engineering integration
  - Demonstrated cooling principle in a single absorber with tight focus
  - Seek now to concatenate several cooling cells
  - Seek to demonstrate reacceleration
  - Seek to demonstrate 6D cooling at low emittance

# Survey of Muon Beamlines



- Existing and proposed
- nuSTORM would be highest current high-energy muon beam

# Conclusions

- Muon production for the muon collider has now a number of conceptual solutions
- Demonstration of the principle of ionisation cooling in MICE
- Seek to
  - optimise the designs
  - Integrate into a single baseline
  - Demonstrate integration of components
  - Demonstrate cooling suitable for low emittance beams