End-to-end design of 6D muon ionization cooling

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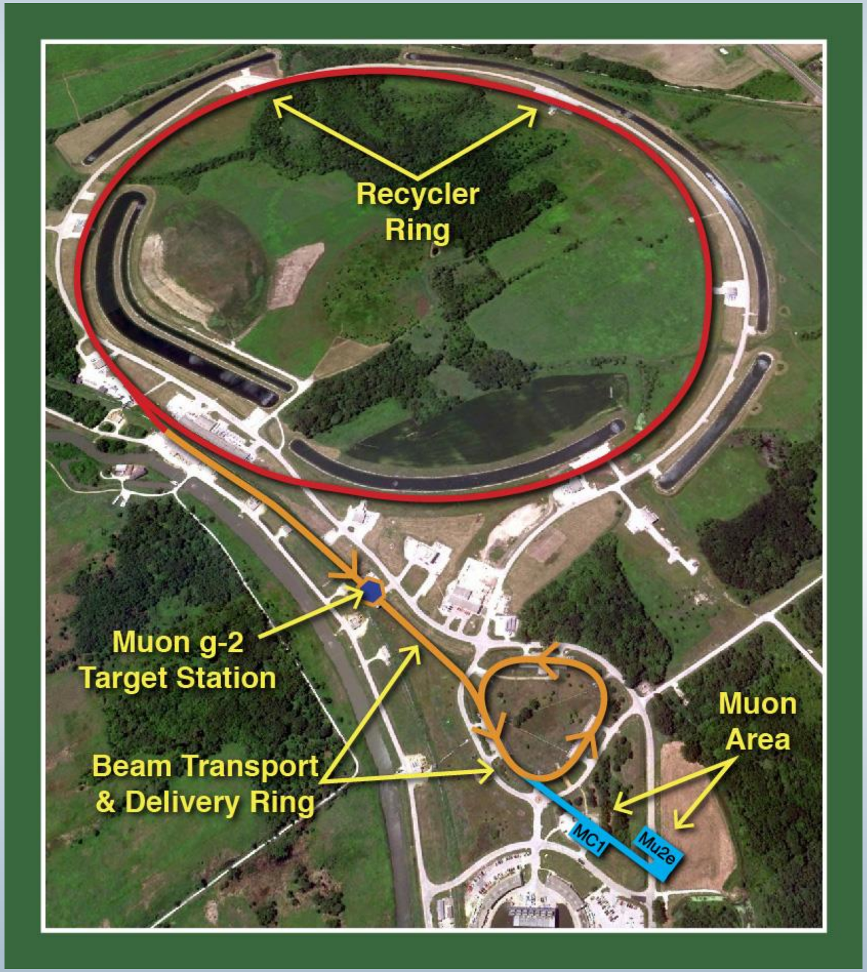
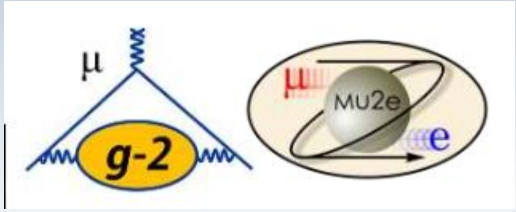
Why muons?

- Carry the same electrical charge as electrons
- Like electrons, muons are elementary particles and thus can produce “clean collisions”
- Muons are 207 times heavier than electrons making it more sensitive to the discovery of new physics
- Unlike electrons, they can be accelerated and stored in circular rings at very high (~TeV) energies by taking advantage of their larger mass

Current activity: Muon campus @ Fermilab



http://muon.fnal.gov/



- **Mu2e**: The Mu2e experiment attempts to detect charged lepton flavor violation
- **g-2**: Precision measurement of magnetic properties of muons

Far future (?): Towards a Muon Collider

- Some benefits…
  - Large muon mass suppresses synchrotron radiation
  - Muons can be accelerated and stored using rings at much higher energy than electrons
  - As with an e^+e^- collider, a $\mu^+\mu^-$ collider would offer a precision probe of fundamental interactions

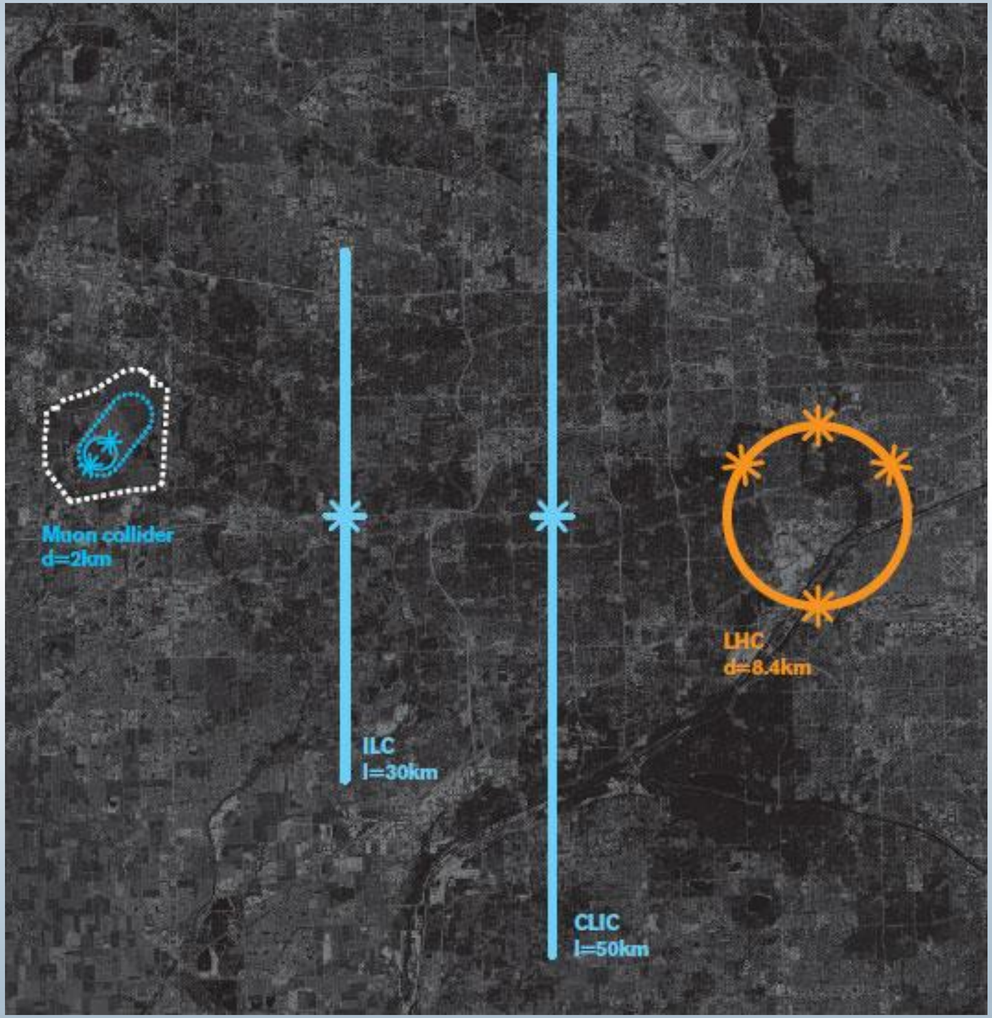


Image: www.map.fnal.gov

Muon Collider (MC) components

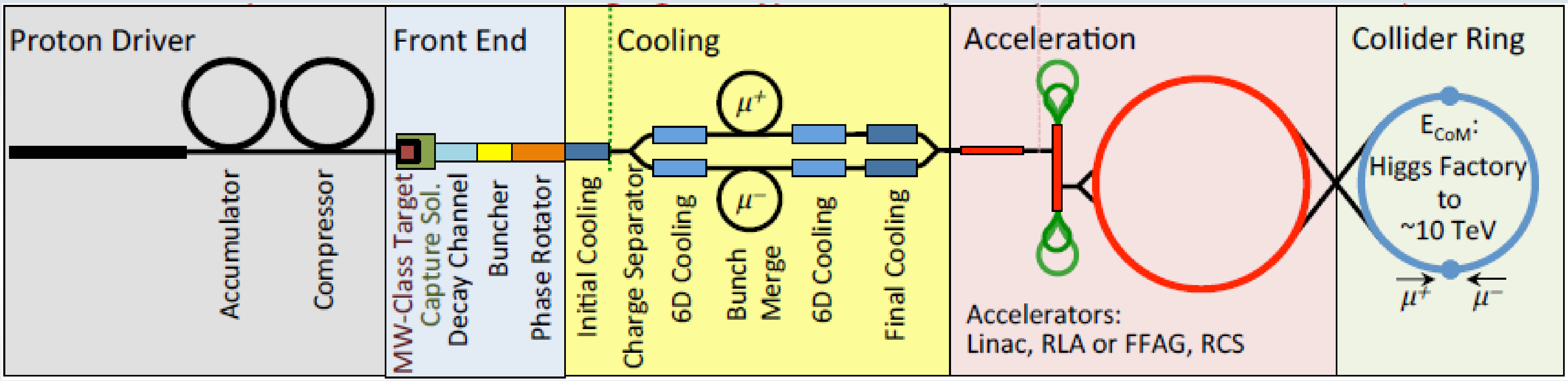
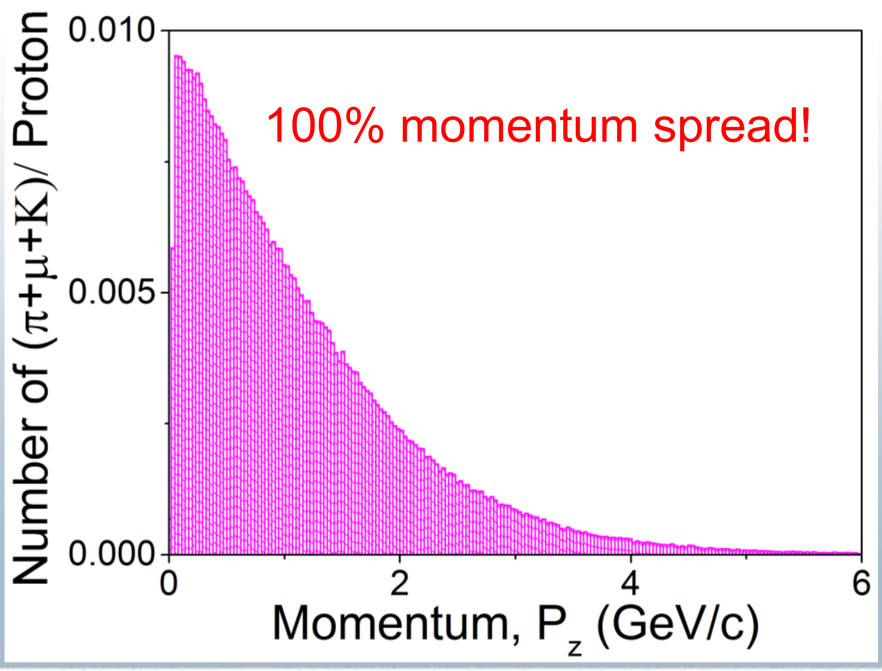


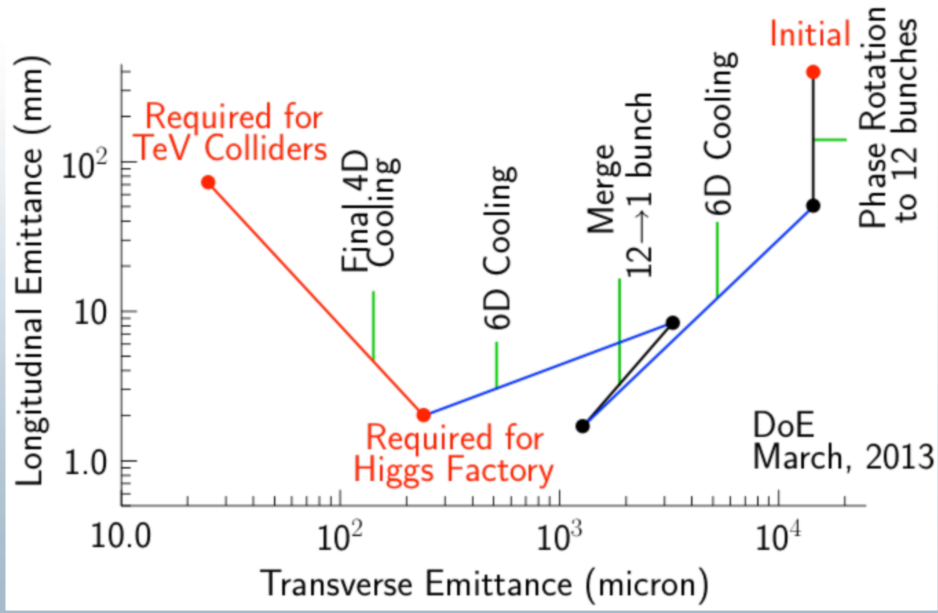
Image: www.map.fnal.gov

- The desired average luminosity of a MC is $O(10^{34})$ $cm^{-2}s^{-1}$

Challenge

- The produced muon beam has a huge energy spread!
- To obtain luminosities O(10^{34}) $cm^{-2}s^{-1}$ we need to reduce the initial phase-space by several orders of magnitude
- How can we cool the beam fast?

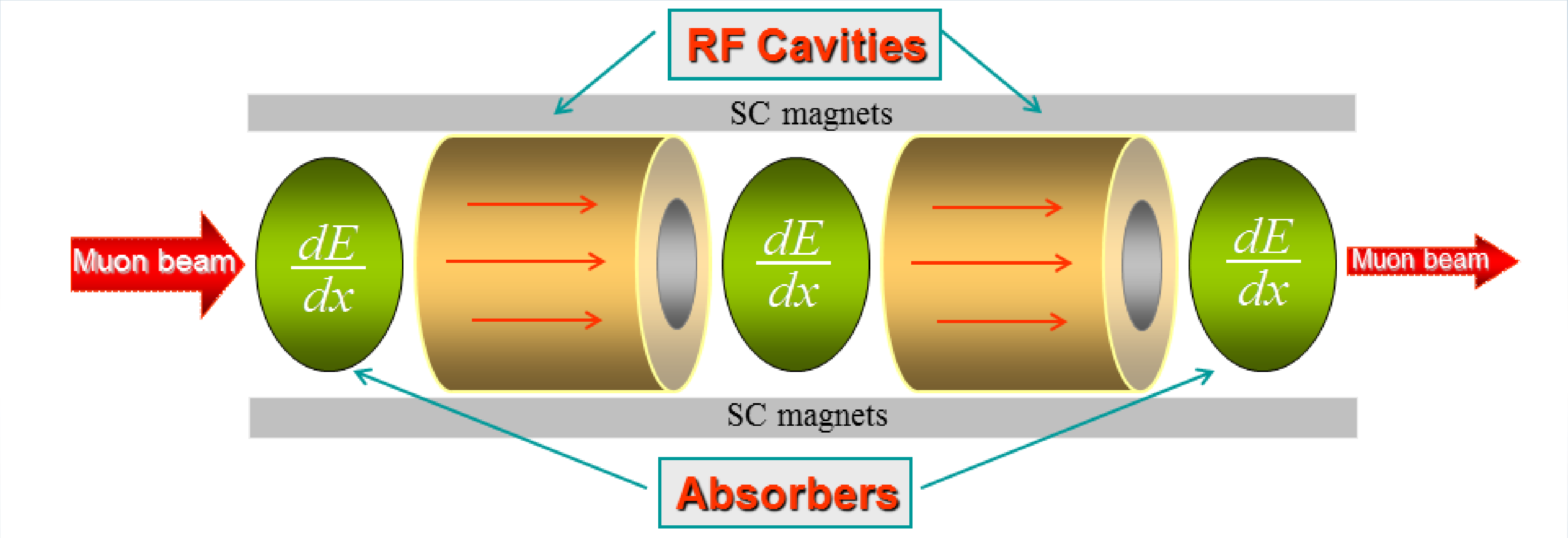




Purpose of this work

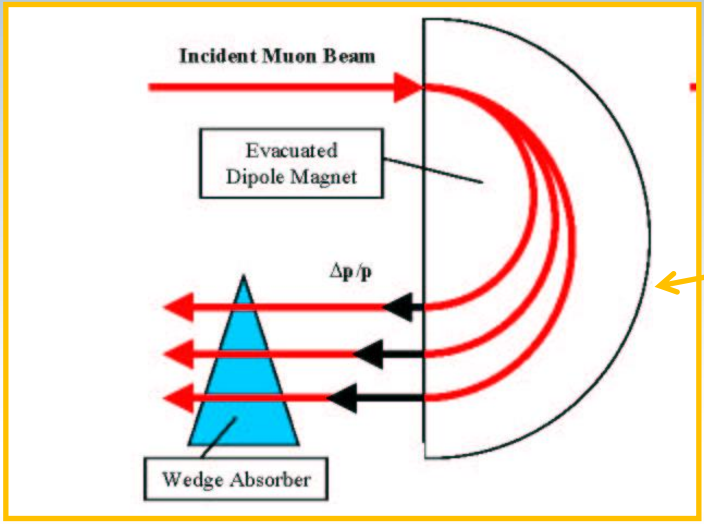
- Present a simple scheme to cool the 6D emittance of a muon beam
- Simulate the aforementioned concept and present the results
- Discuss challenges and provide solutions
  - Space-charge issues
  - Magnet requirements
  - Gas filled cavities
- Summary & future study

Ionization cooling



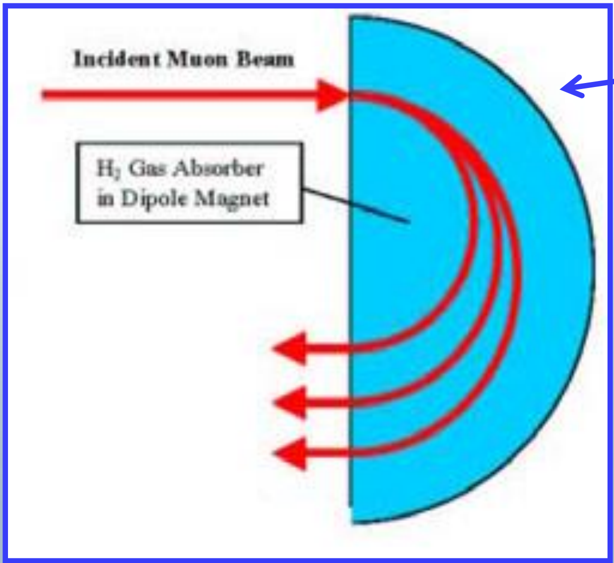
- Energy loss through ionization in absorbers
- rf cavities to compensate for lost longitudinal energy
- Note: This process cools the beam transversely, only!

Emittance exchange for 6D cooling



Concept 1: Generate dispersion and cool via emittance exchange in a wedge absorber

Concept 2: Energy loss dependence on path length in a continuous absorber



- Two concepts, same principle
- Dispersion is introduced to spatially separate muons of different momenta
- This study focuses on channels with discrete absorbers only!

Ionization cooling basics

- In the absorber: Energy loss is causing **cooling**, BUT multiple scattering is causing **heating**.
- A balance between the two processes gives:

$$\varepsilon_T^{\mathrm{eq}} = \left(\frac{dE}{ds}\right)^{-1} \frac{\beta_T (13.6\ \mathrm{MeV})^2}{2\beta m_\mu c^2 L_R}$$

L_R: Radiation length

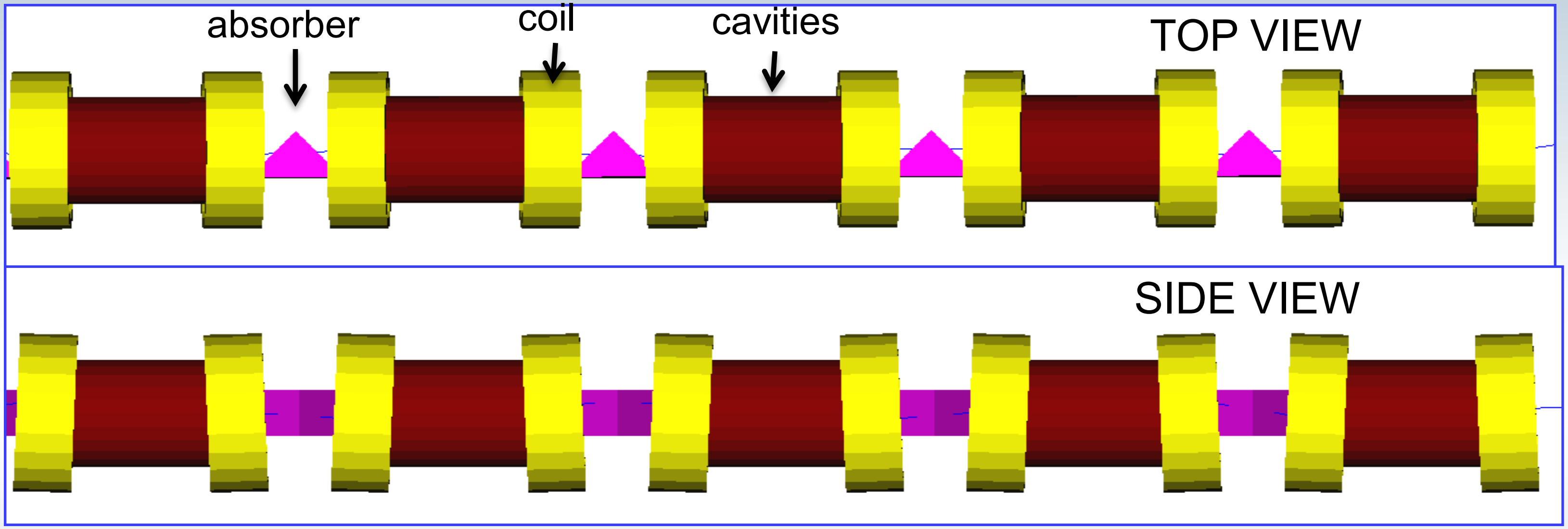
E: Muon energy

β_T: Transverse beta function

$\frac{dE}{ds}$: Energy loss

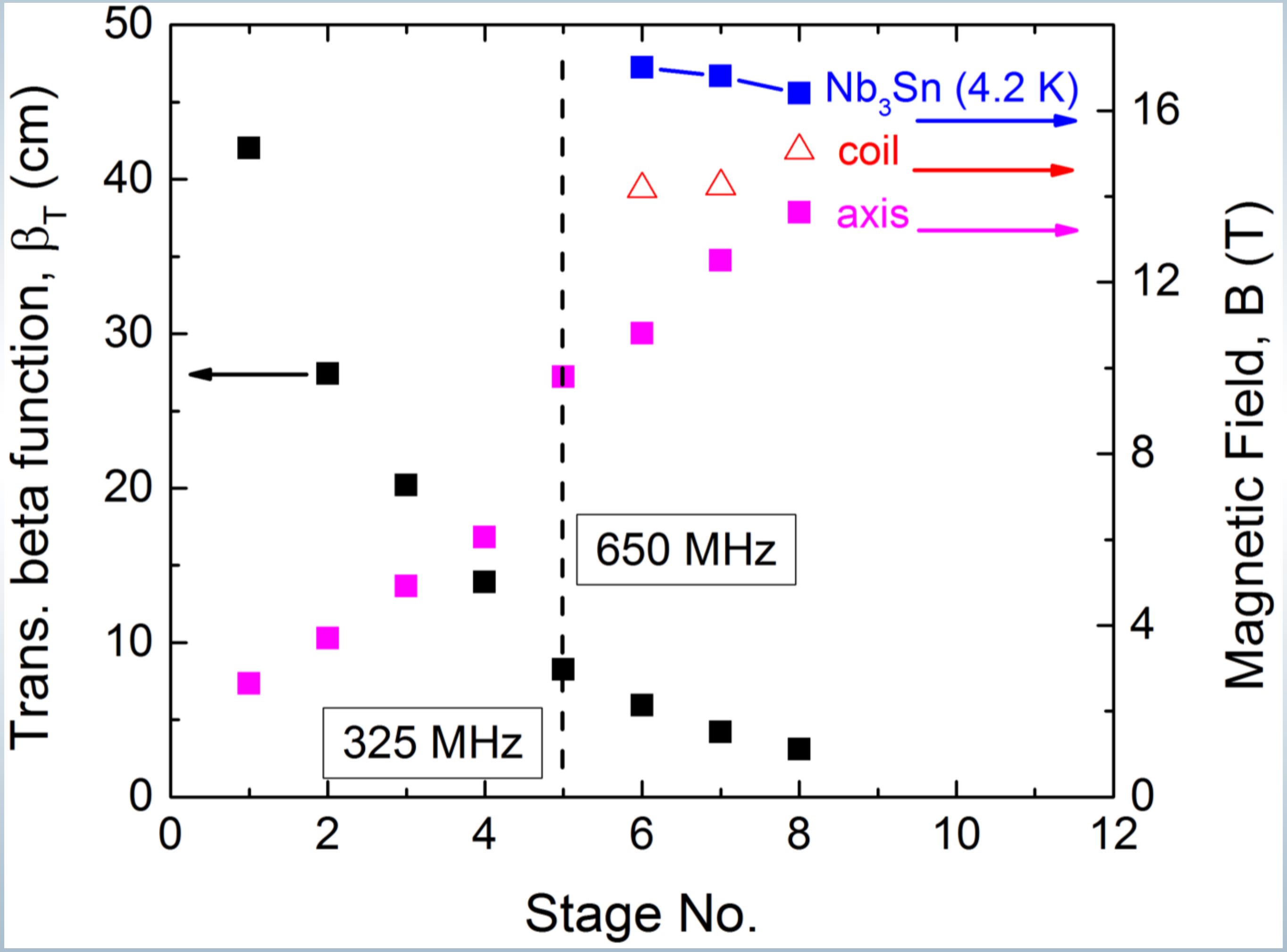
- Emittance can be controlled by:
  - Material: Product of L_R and dE/ds should be large.
  - Magnet strength: Transverse beta function must be small. Thus, we progressively taper the magnetic field towards higher values

Proposed cooling channel



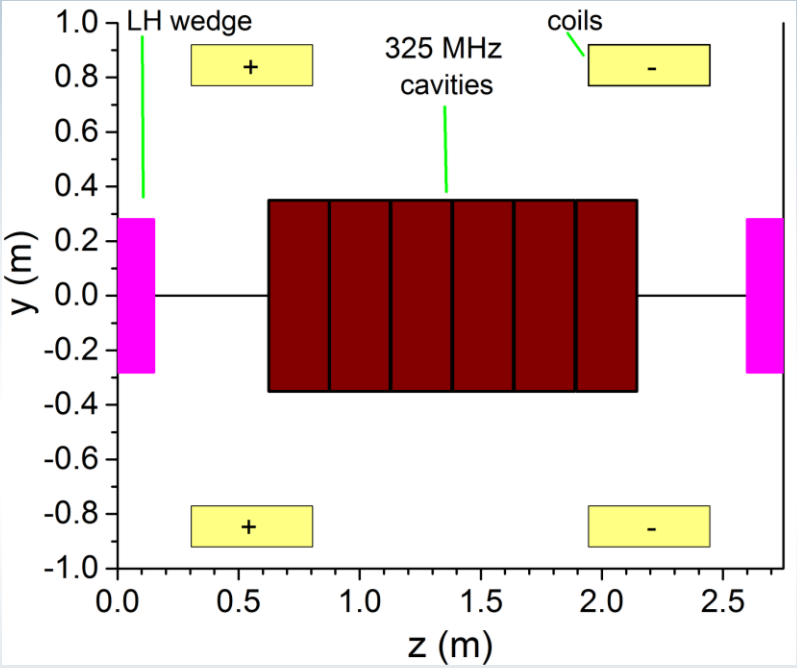
- We considered a straight cooling scheme for a MC
- Idea originally proposed by Valeri Balbekov (Fermilab)
- Its simple geometry avoids several engineering challenges of previously considered schemes (rings or helix)

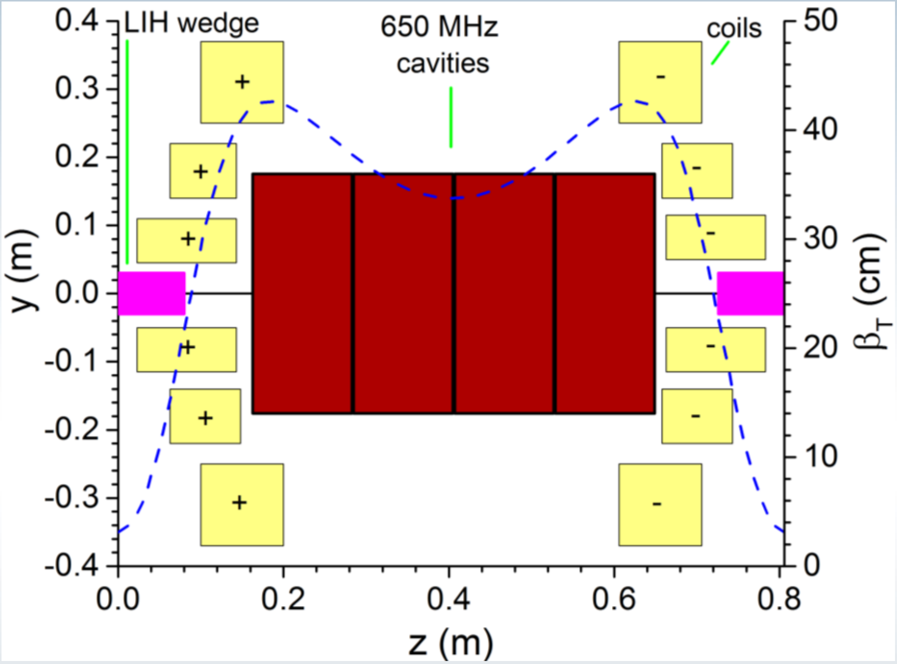
Tapered lattice design: 8 stages



Magnet limits:
https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

Two extremes: First & last cooling stage





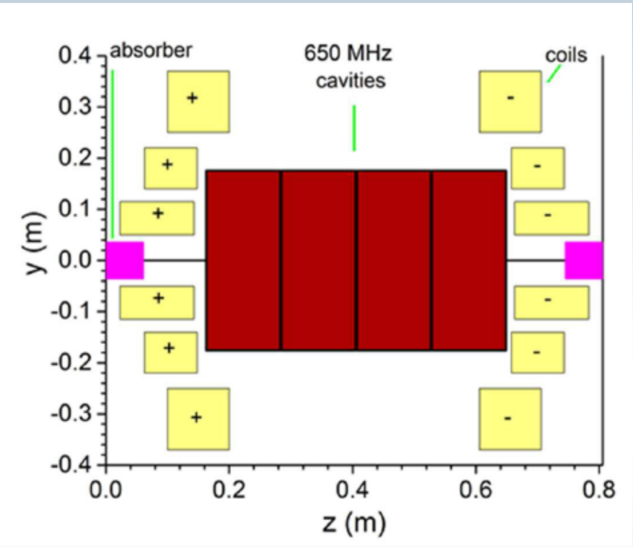
EARLY STAGE OF COOLING

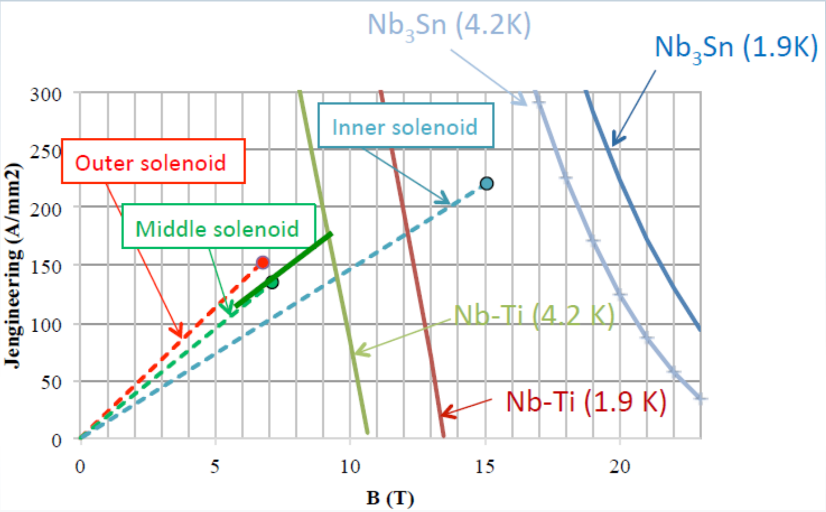
- 275 cm long
- Coils far
- 325 MHz
- Axial B ~ 3 T
- Beta ~ 40 cm

LATE STAGE OF COOLING

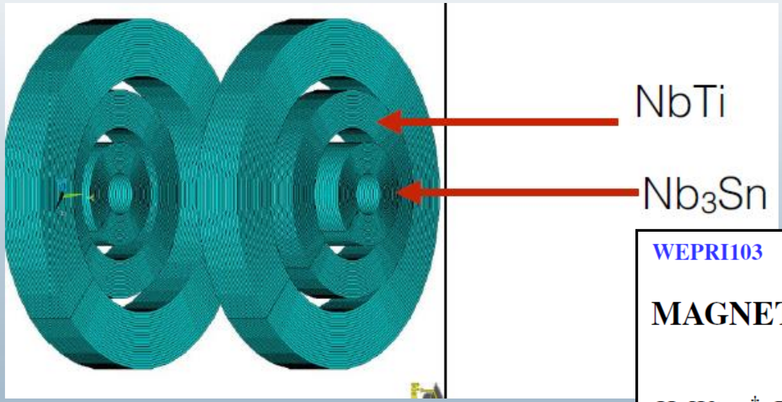
- 80 cm long
- Coils near axis
- 650 MHz
- Axial B ~ 12 T
- Beta ~ 3 cm

Magnet feasibility studies (last stage)





	% of the load line at operational current		
	Inner solenoid	Middle solenoid	Outer solenoid
Nb-Ti @ 4.2 K	-	76%	74%
Nb-Ti @ 1.9 K	-	59%	58%
Nb3Sn @ 4.2 K	88%	-	-
Nb3Sn @ 1.9 K	81%	-	-



WEPRI103 Proceedings of IPAC2014, Dresden, Germany

MAGNET DESIGN FOR A SIX-DIMENSIONAL RECTILINEAR COOLING CHANNEL - FEASIBILITY STUDY*

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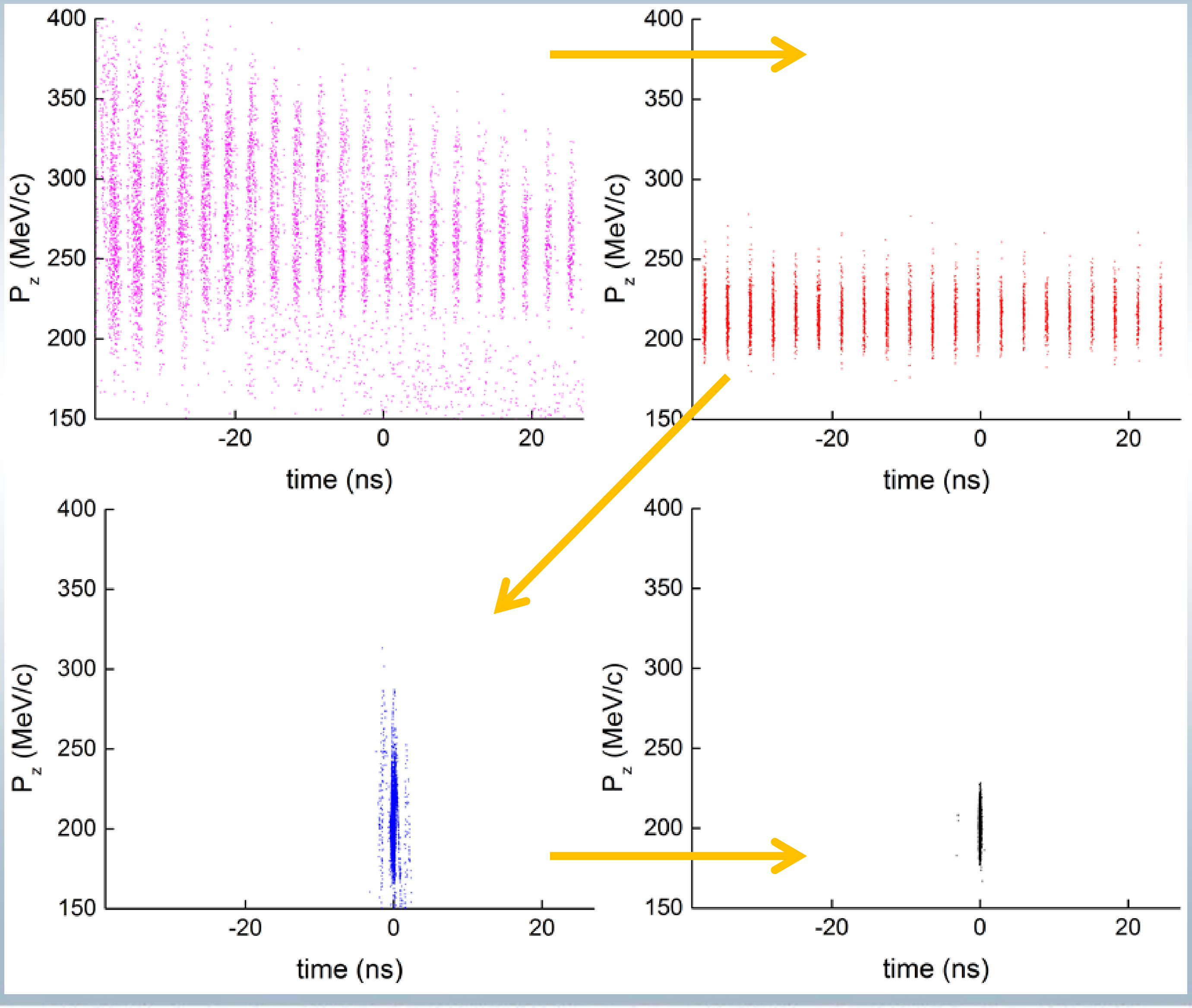
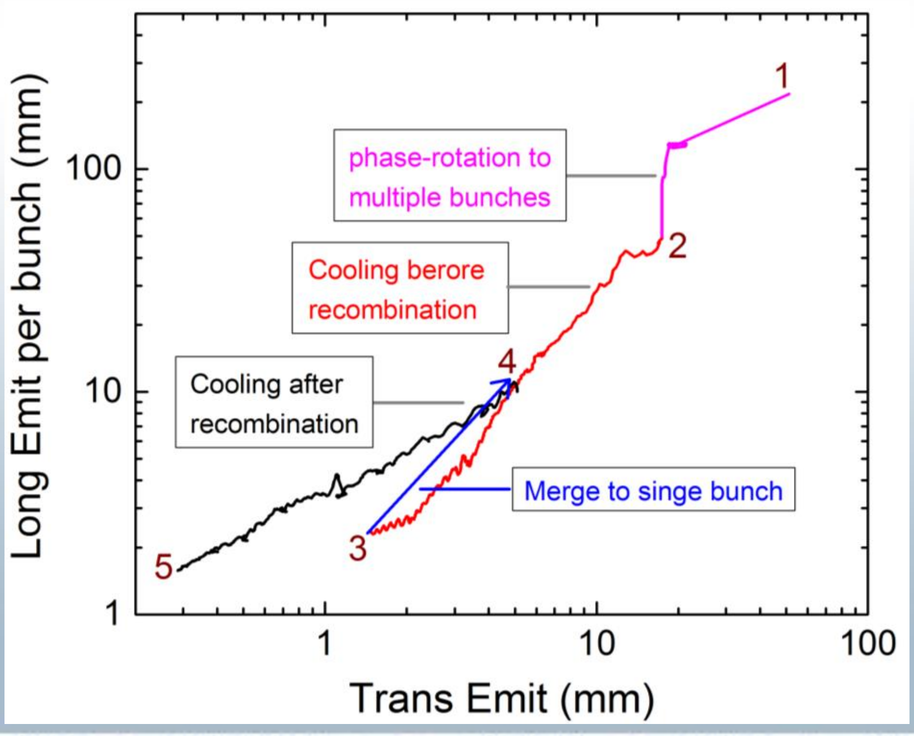
Simulation results (1)



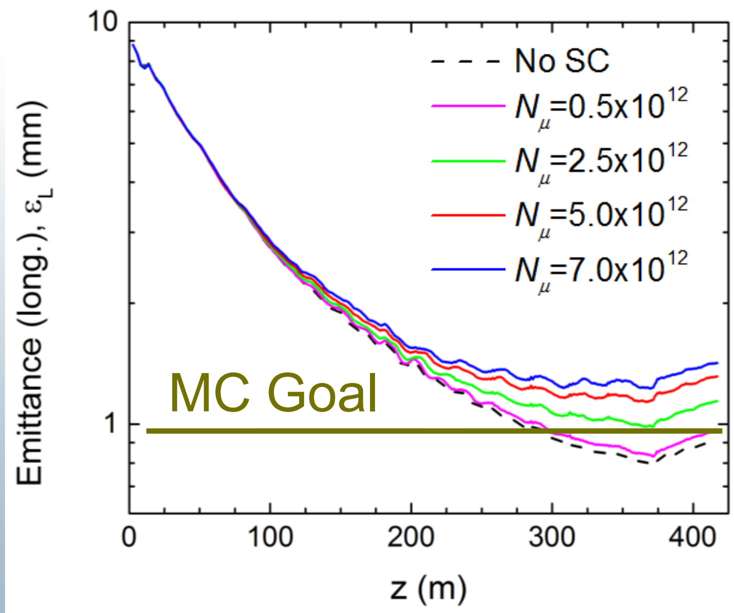
Simulation results (2)

- End-to-end simulation starting from the target (point 1)
- Reduction of the 6D emittance by FIVE orders of magnitude (point 5)
- Desired emittances for a Higgs factory delivered!

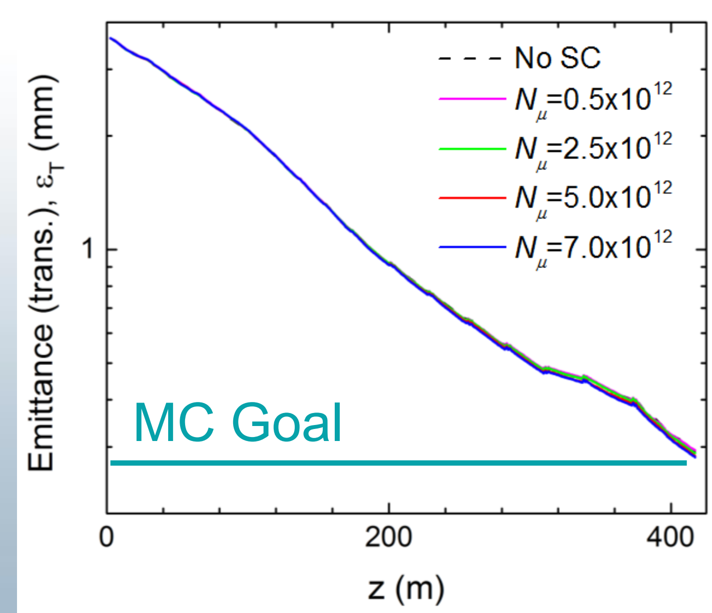


Influence of space-charge (SC)

- At the end of cooling, 5x10^{12} muons are squeezed within a 2 cm rms bunch length. There is a concern for SC effect
- We examined the influence of SC fields on cooling
- SC causes particle loss & longitudinal emittance growth

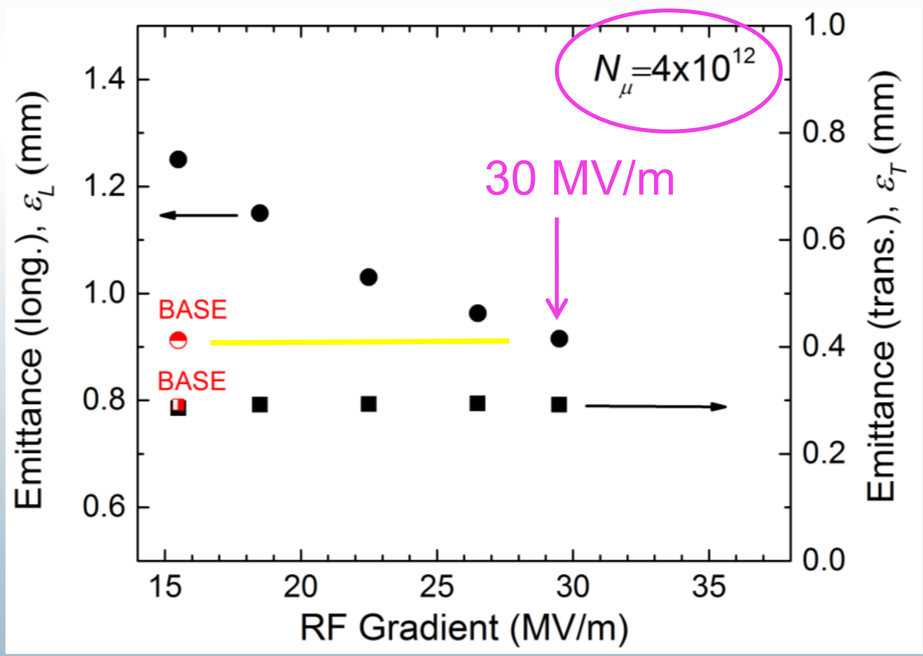


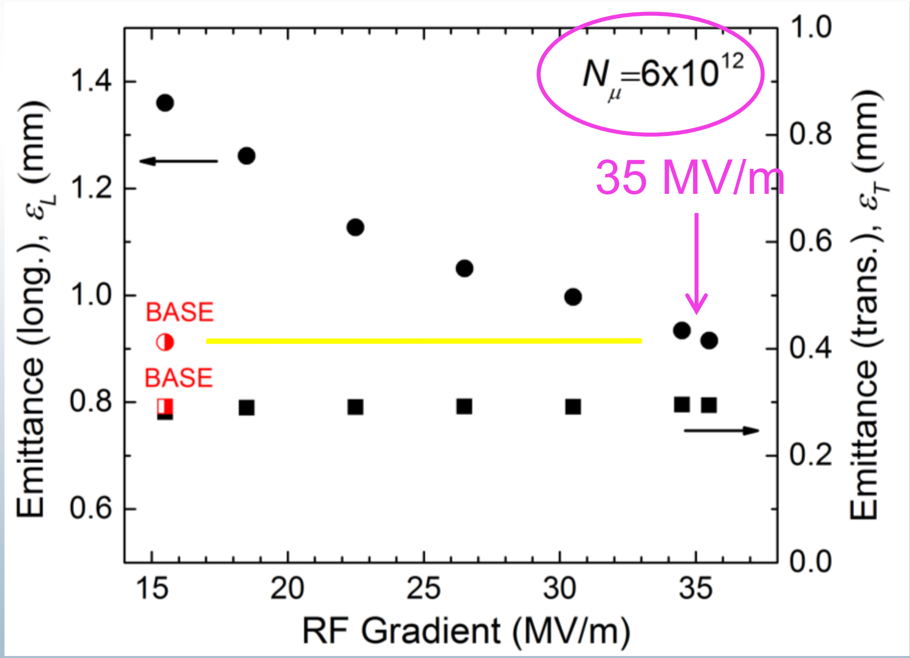
WARP Simulation



Space-charge compensation (1)

- Increasing the rf gradient can compensate SC effect
- The needed compensation gradient is coupled to the beam intensity

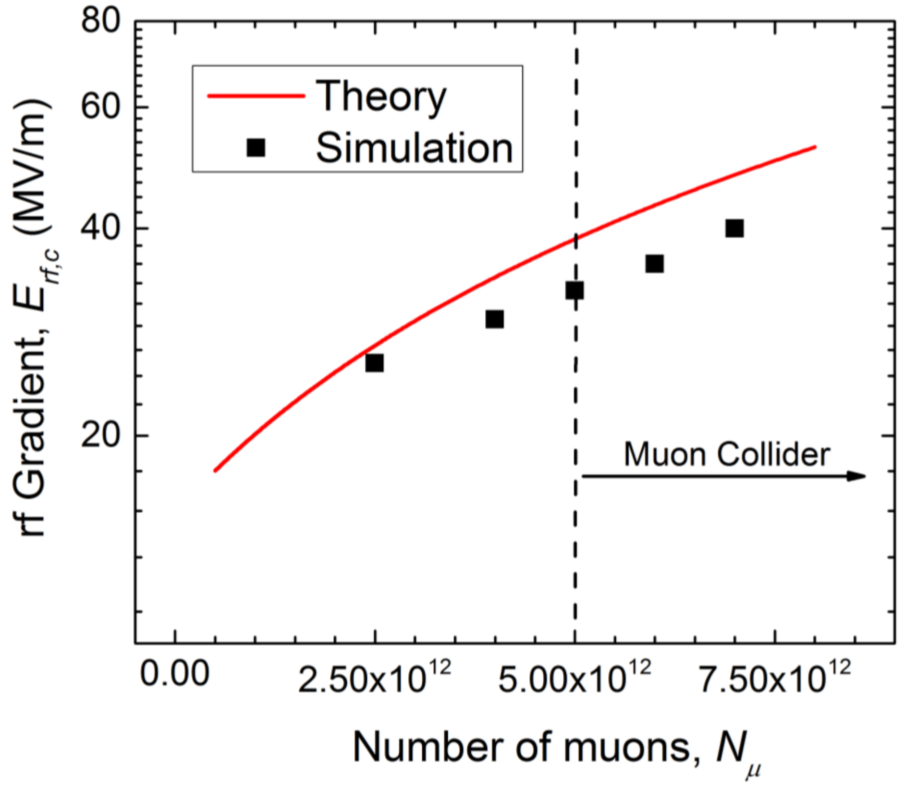




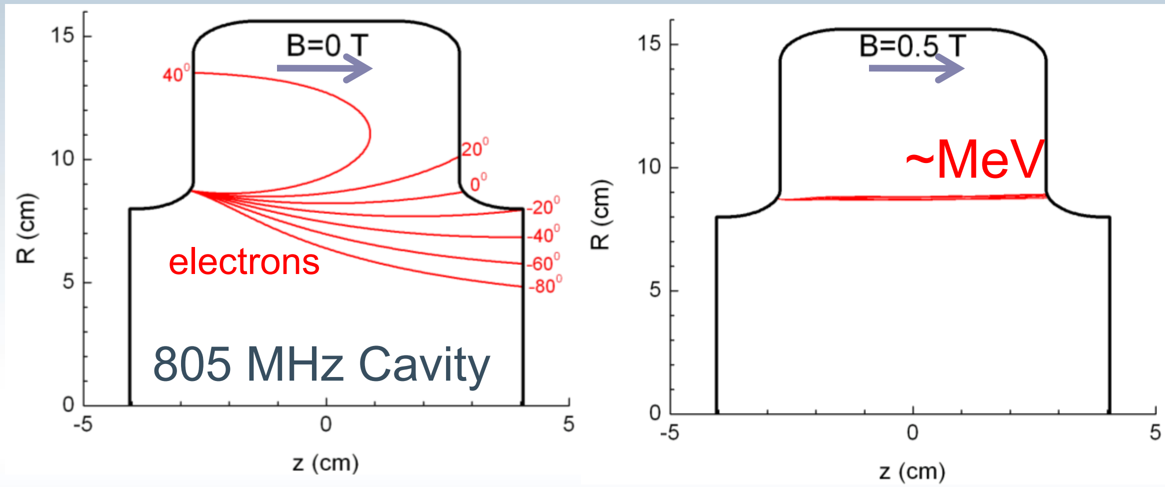
Space-charge compensation (2)

- For a MC to obtain a ε_L< 1.0 mm the rf gradient of a 805 MHz cavity needs to surpass 32.5 MV/m
- Can be a problem (next slide)
- Required compensation gradient from theory:

$$E_{rf,c} = \frac{eN_0 g_0 c}{4\pi\varepsilon_0\sqrt{2\pi}\gamma^2\sigma_z^3(2\pi f n \cos\varphi)^2}$$



Cavity operation in magnetic fields



- Numerical simulations predict that the copper surfaces of a rf cavity may damaged when B> 1T

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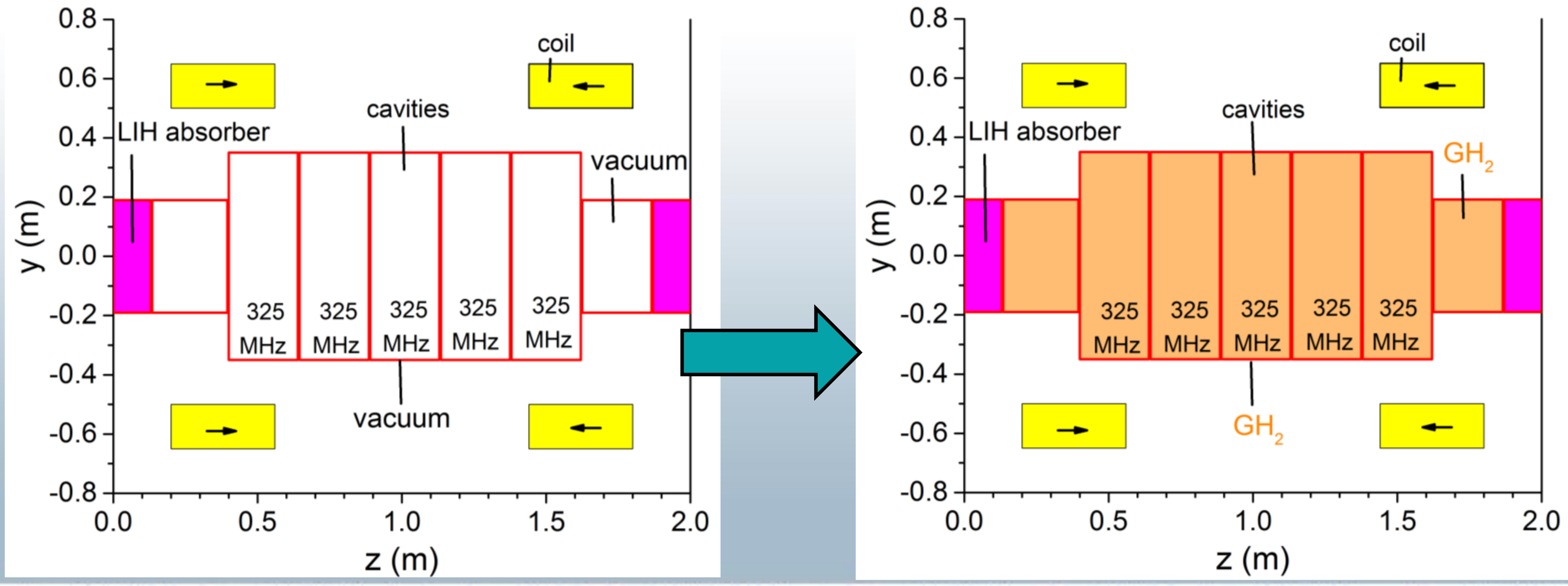
Effects of external magnetic fields on the operation of high-gradient accelerating structures

Diktys Stratakis *, Juan C. Gallardo, Robert B. Palmer

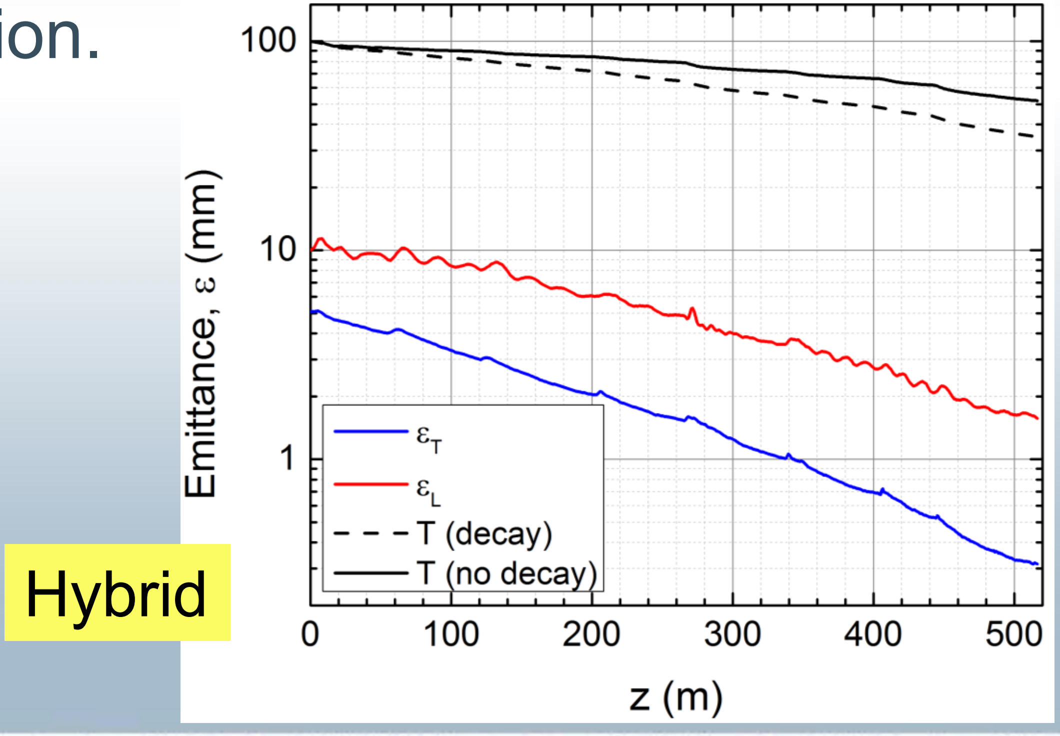
Hybrid cooling solution

- The gradient of a gas filled cavity showed no magnetic field dependence in a solenoidal field up to 3 T.
- Key Idea: Utilize gas filled cavities in a rectilinear channel. Majority of cooling in LiH and use gas only to protect rf cavity from the high-field.



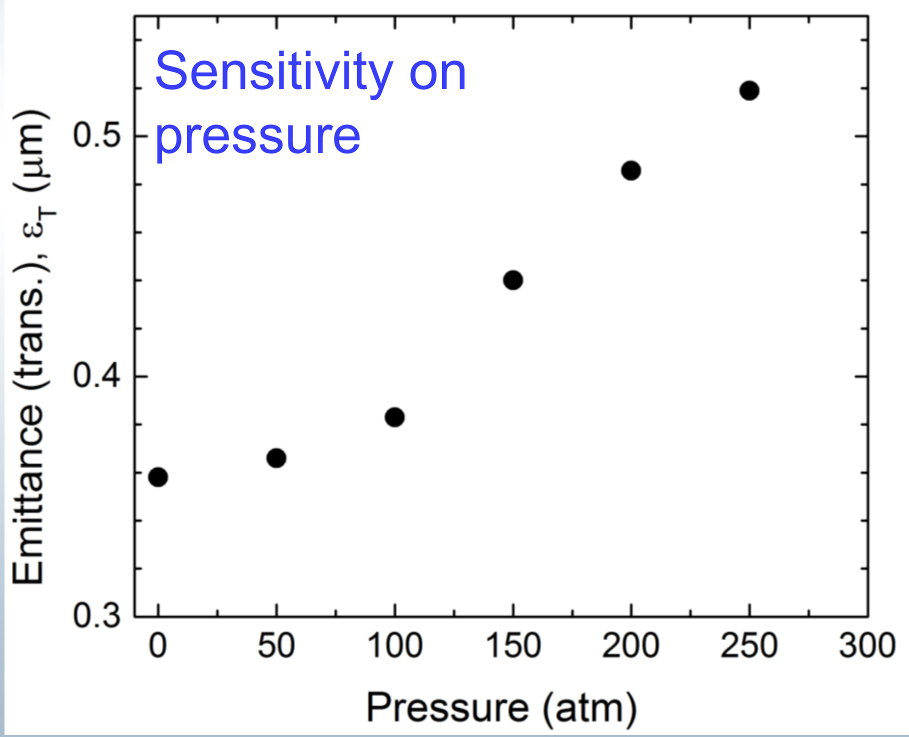
Lattice performance

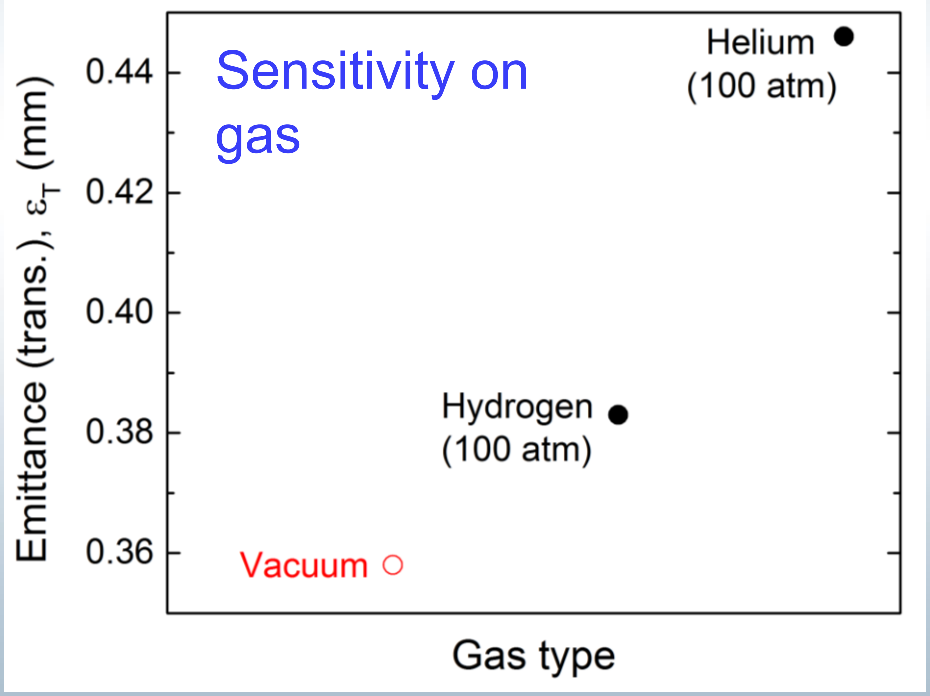
- Essentially, the same performance as an equivalent channel with vacuum cavities
- BUT there remains considerable work to do before a hybrid channel can be considered a validated cooling channel option.



Sensitivity to pressure & gas

- Final transverse emittance is correlated to the gas pressure and the type of gas





Summary

- Presented a simple scheme for ionization cooling
- Simulations predict that is capable to reduce the 6D emittance by at least five orders of magnitude thus satisfying the needs of a Higgs factory.
- The influence of space-charge fields on the cooling process was thoroughly examined
- A hybrid solution with gas filled cavities was presented
- The performance of a gas filled channel is essentially the same as the equivalent vacuum channel assuming a pressure of 34 atm (at room T)

Acknowledgement

- Special thanks to all members of the Muon Accelerator Program community

Future work – Open problems

- Improve design of muon capture channel
  - Increase performance
- Reduce length of the cooling channel
  - Existing channel for a MC is 900 m ...
- Physics problems
  - Wakefields, absorbers, plasma loading
- Engineering problems
  - Magnets, windows for pressurized cavities, …