Ionization cooling scheme for a Muon Collider

Diktys Stratakis
Brookhaven National Laboratory

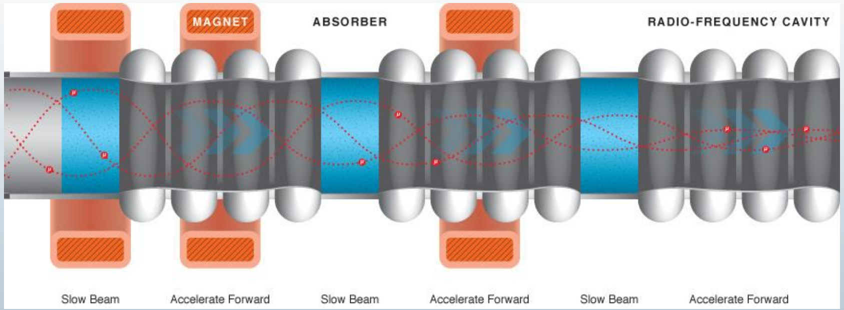
MAP Winter Meeting, SLAC, Menlo Park, CA
December 04, 2014

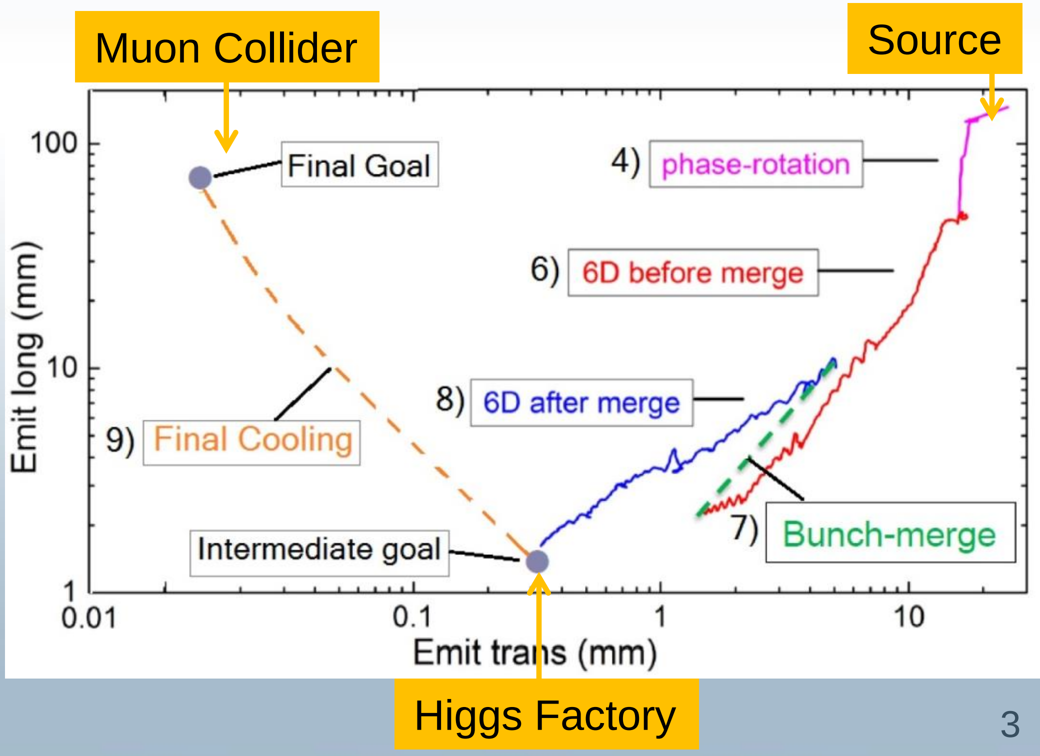
Introduction

- Muons have relative immunity to synchrotron radiation due to their large rest mass
- Have applications to fundamental research as well as to various industrial applications:
  - Muon radiography
  - Medical and material detection applications
  - Neutrino Factory and Muon Collider [This talk]
- But there are some challenges:
  - Short lifetime (~2 μs in rest)
  - Initial muon beam is huge: enormous 6D emittance and very large momentum spread

Motivation

- Muon Collider final 6D emittance is 5-6 orders of magnitude less to the emittance of the born muon beam
- Beam cooling (i.e. reduction of phase-space volume) is necessary → **ionization cooling**!

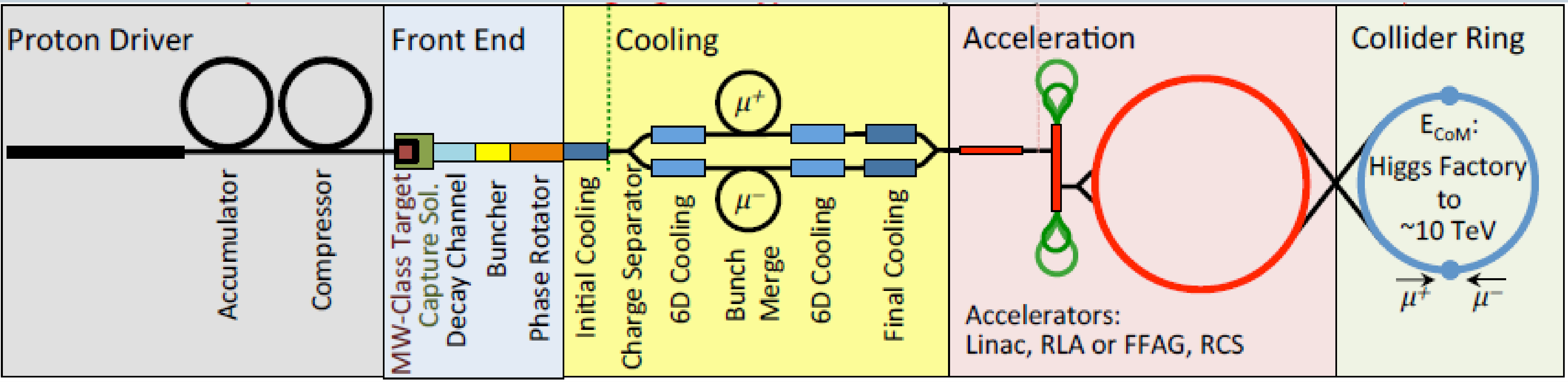




Purpose of this work

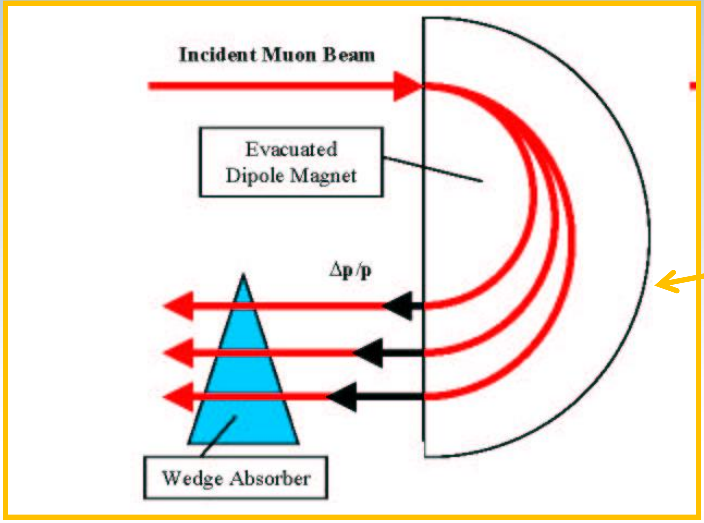
- Describe a novel rectilinear cooling scheme for a MC
- Review the theoretical framework to predict the behavior of a ionization cooling channel and apply it to our case
- Present the first end-to-end simulation of a rectilinear channel and show a notable 6D emittance reduction by at least 5 orders of magnitude
- Discuss key challenges
  - Space-charge, Magnet feasibility, RF in magnetic fields…
- Future steps & Conclusion
- Note: I will talk only about lattices with discrete absorbers!

Cooling scheme for a Muon Collider



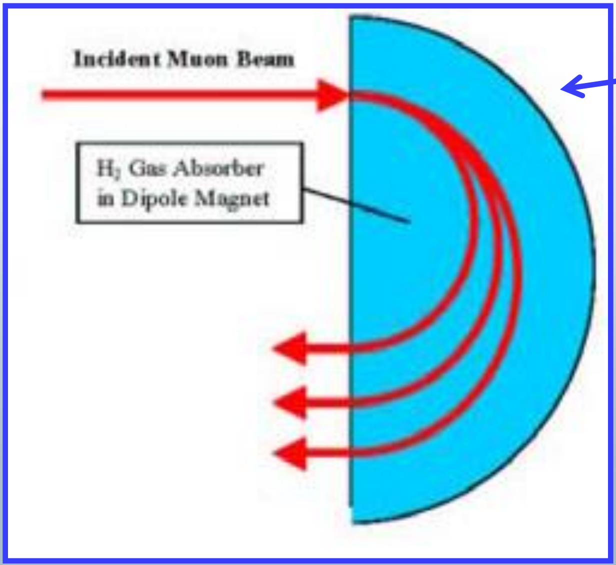
- Front-end produces 21 well aligned muon bunches
- Two sets of 6D cooling schemes
  - One before recombination (trans ε≈1.5 mm)
  - One after recombination (trans ε≈ 0.50 mm or less)
- Final cooling (if necessary)

Emittance exchange for 6D cooling



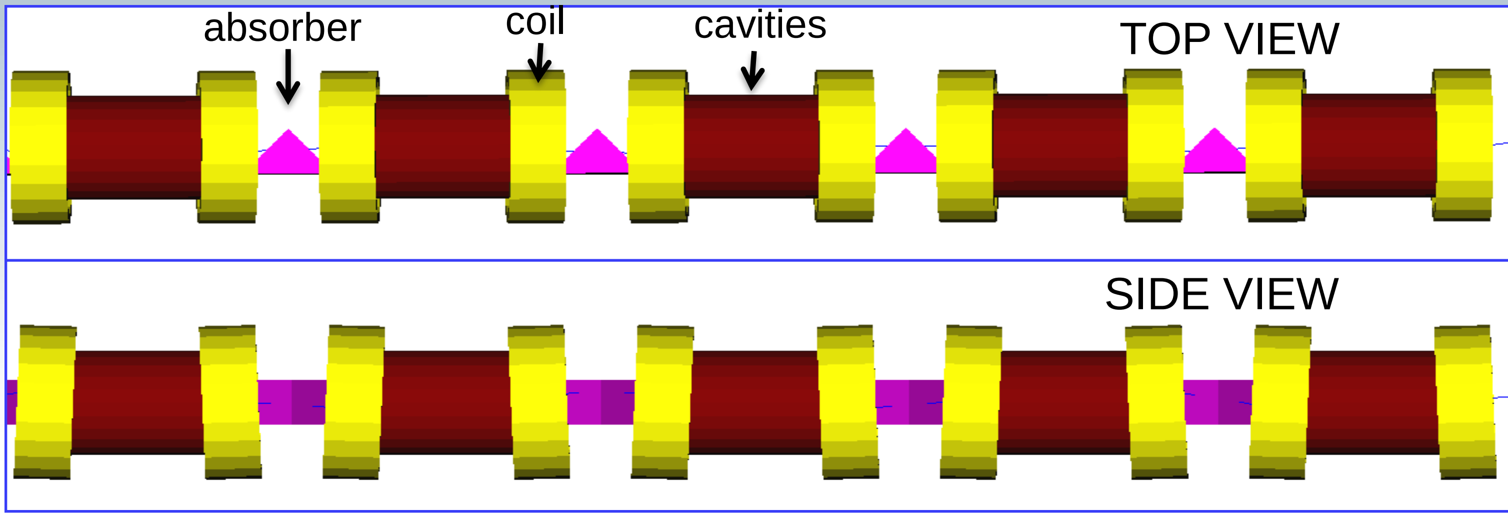
Concept 1: Generate dispersion and cool via emittance exchange in a wedge absorber

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!

Tapered rectilinear channel



- Offers several advantages for cooling over previously consider helical schemes (idea proposed by V. Balbekov)
- Multiple stages with different cell lengths, focusing fields, rf frequencies to ensure fast cooling

R_FOFO snake channel for 6D muon cooling
("R" can be interpreted as "rectilinear")
V. Balbekov, MAP Friday Meeting 02/01/2013 (edited 06/01/13)

Proceedings of IPAC2014, Dresden, Germany TUPME020

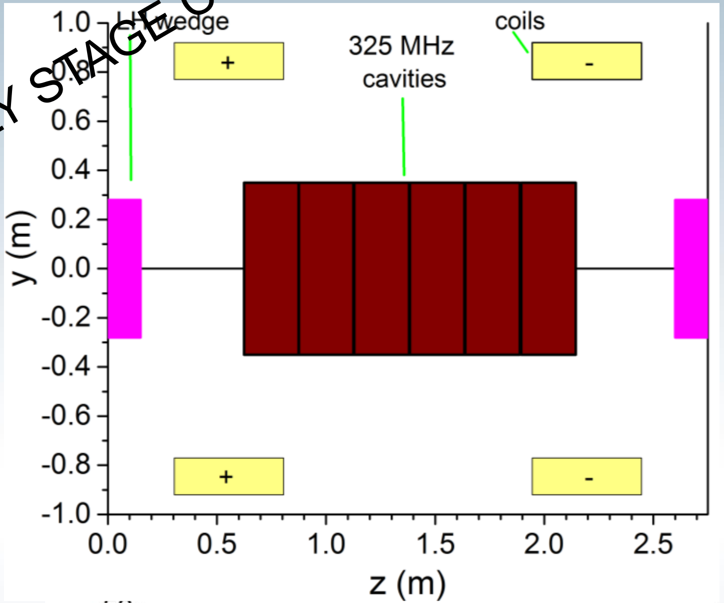
COMPLETE 6-DIMENSIONAL MUON COOLING CHANNEL FOR A MUON COLLIDER*

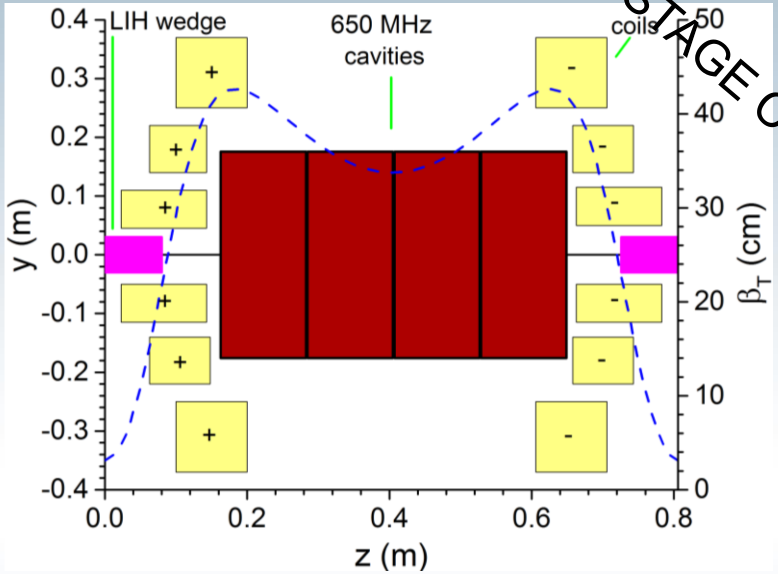
D. Stratakis,# R. B. Palmer, J. S. Berg, and H. Witte, Brookhaven National Laboratory, Upton, NY

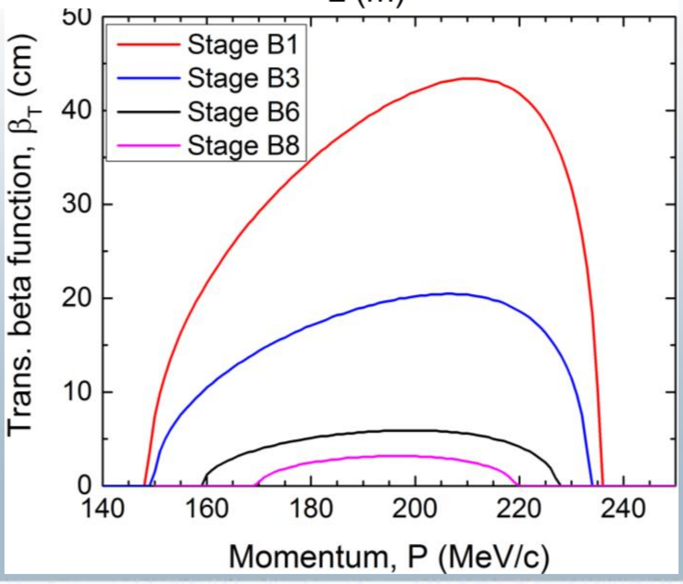
Lattice design

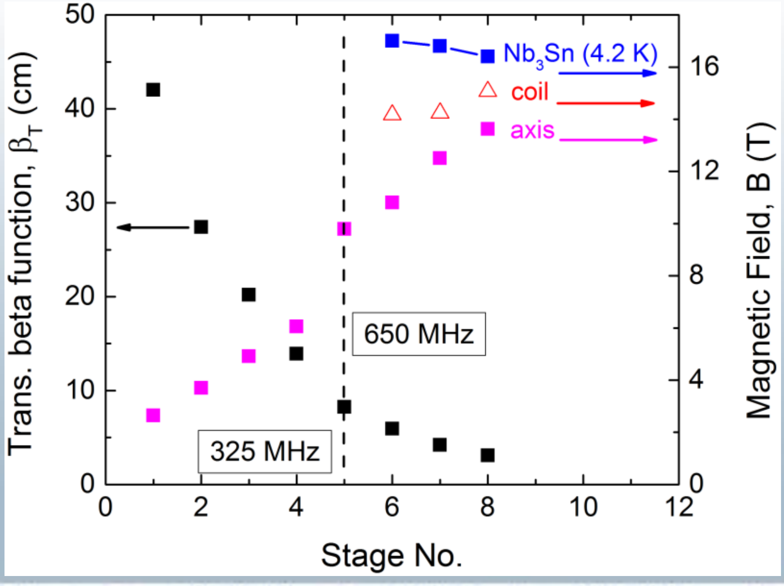
EARLY STAGE COOLING

LATE STAGE COOLING









Ionization cooling theory (Neuffer)

- Transverse Cooling:

$$\frac{d\varepsilon_T}{ds} = -\frac{g_T}{\beta^2 E}\frac{dE}{ds}\varepsilon_T + \frac{\beta_T E_s^2}{2\beta^3 m_\mu c^2 L_R E}$$

$$g_T = 1 - D/w$$

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

- Longitudinal Cooling:

$$\frac{d\varepsilon_L}{ds} = -\frac{g_L}{\beta^2 E}\frac{dE}{ds}\varepsilon_L + \frac{\beta_L}{2}\frac{d<\Delta E^2>}{ds}$$

$$g_L = \frac{2\gamma^2 - 2\ln[K(\gamma^2-1)]}{\gamma^2 \ln[K(\gamma^2-1)] - (\gamma^2-1)} + \frac{D}{w}.$$

$$\varepsilon_L^{\mathrm{eq}} = \left(\frac{dE}{ds}\right)^{-1} \frac{\beta^2 E \beta_L}{2 g_L}\frac{d\langle \Delta E^2\rangle}{ds}$$

- Emittance evolution:

$$\varepsilon^{\mathrm{calc}}(s) = \varepsilon^{\mathrm{eq}} + (\varepsilon^0 - \varepsilon^{\mathrm{eq}})\exp\left(-\frac{s}{s^{\mathrm{calc}}}\right)$$

$$s_T^{\mathrm{calc}} = \frac{\beta^2 E}{g_T}\langle\frac{dE}{ds}\rangle^{-1} \qquad s_L^{\mathrm{calc}} = \frac{\beta^2 E}{g_L}\langle\frac{dE}{ds}\rangle^{-1}$$

TUPME021 Proceedings of IPAC2014, Dresden, Germany

THEORETICAL FRAMEWORK TO PREDICT EFFICIENCY OF IONIZATION COOLING LATTICES*

Diktys Stratakis#, Brookhaven National Laboratory, Upton, NY, USA
David Neuffer, Fermi National Accelerator Laboratory, Batavia, IL, USA

Numerical study with ICOOL

- No *a priori* assumption of the initial beam distribution!
- End-to-end simulation starting from the post-phase-rotation beam (point 2)
- 6D emittance reduction by > 5 orders of magnitude
- Higgs factory emittances delivered!

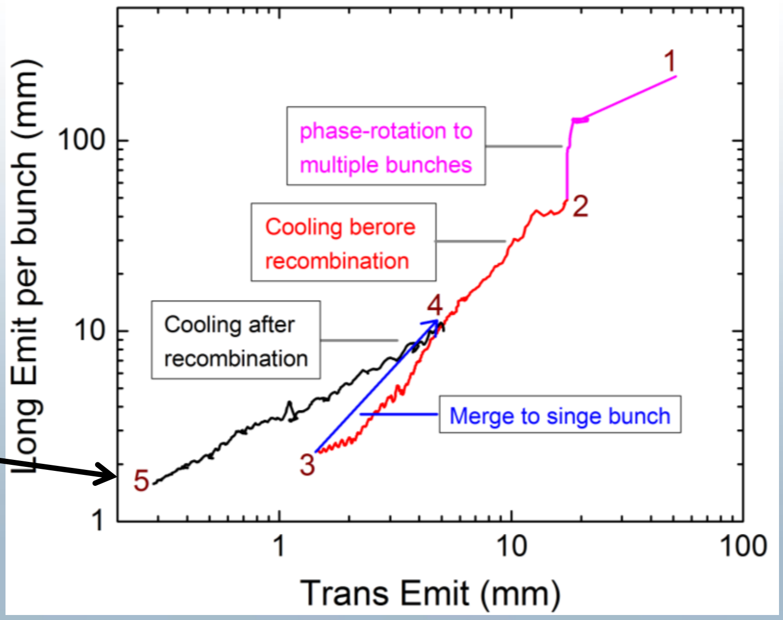
Initial Baseline Selection Criteria of 6D cooling scheme Feb 10, 2014

Criteria for Comparing and Assessing 6-D Cooling Channels

by the Muon Cooling Advisory Committee[1]

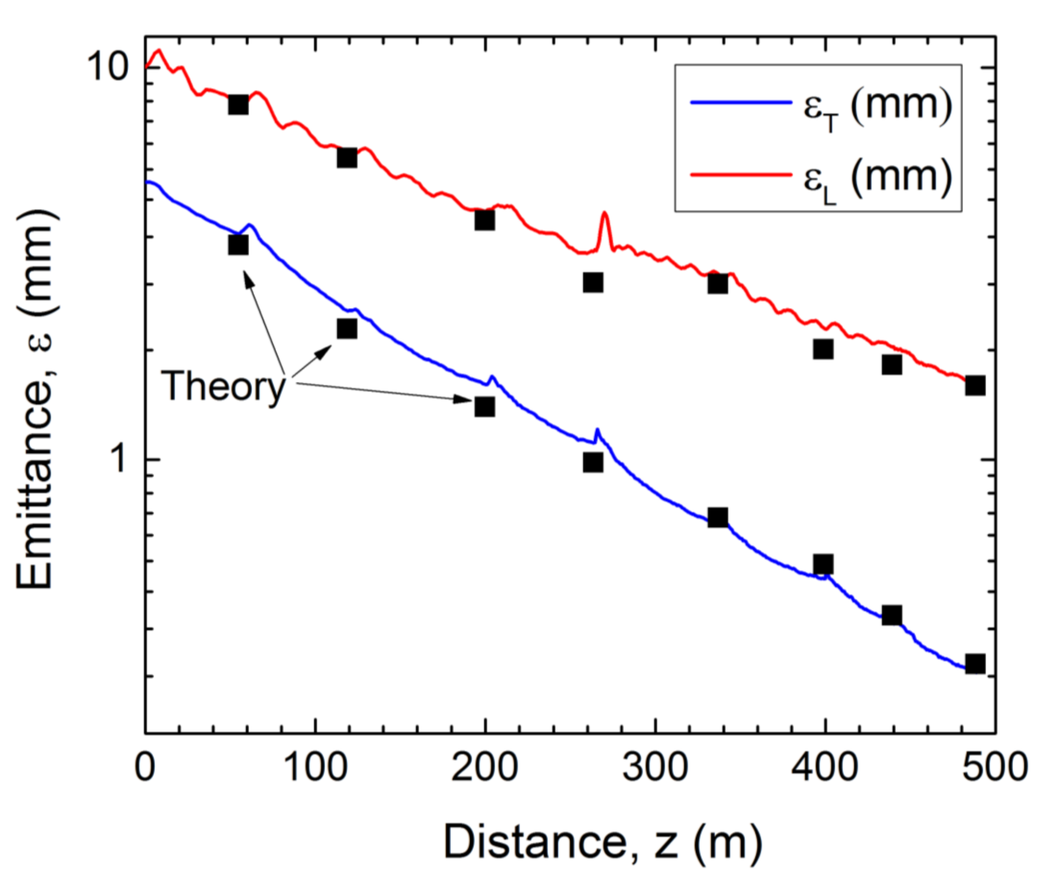
Quantity	Value
RMS Normalized Transverse Canonical Emittance (projected onto each plane)	0.3 mm[4]
RMS Normalized Canonical Longitudinal Emittance	1.5 mm

Cooling criteria satisfied!



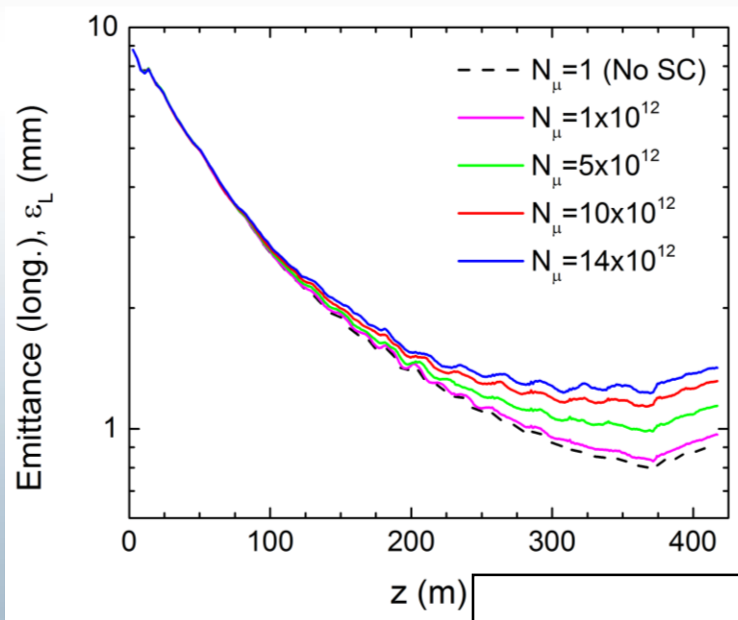
Theory and simulation

- Found good agreement between theory and simulation

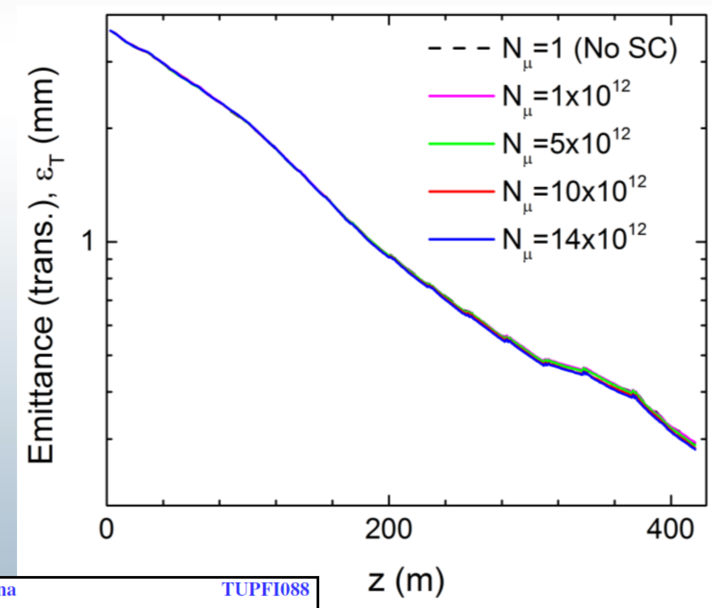


Influence of space-charge (Grote)

- For the first time, the influence of space-charge on the cooling process of muon beams was examined
- Used WARP, a well established code for SC effects
- SC causes particle loss and longitudinal emittance growth



WARP Simulation



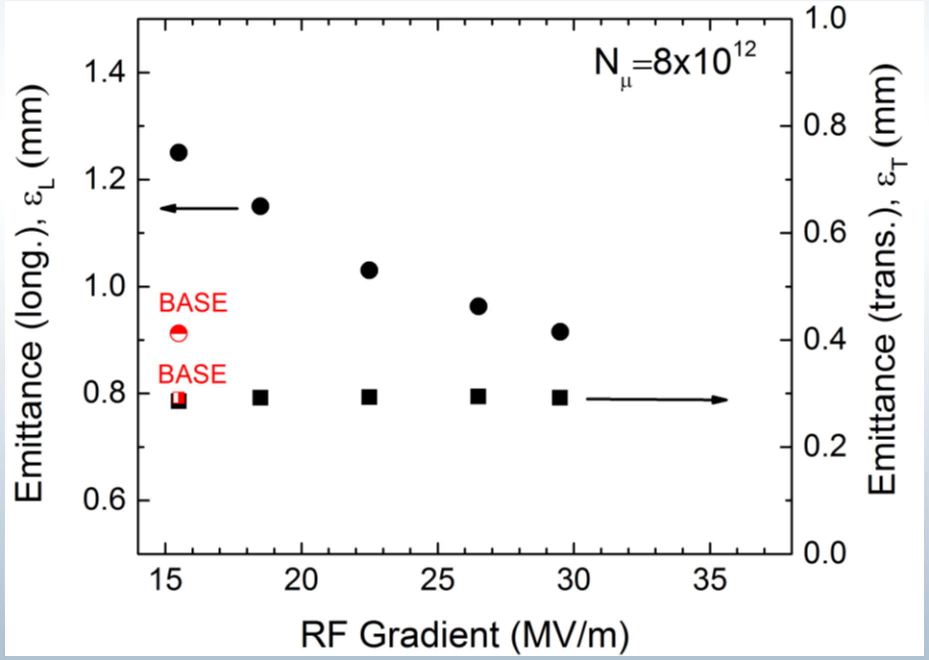
Proceedings of IPAC2013, Shanghai, China TUPFI088

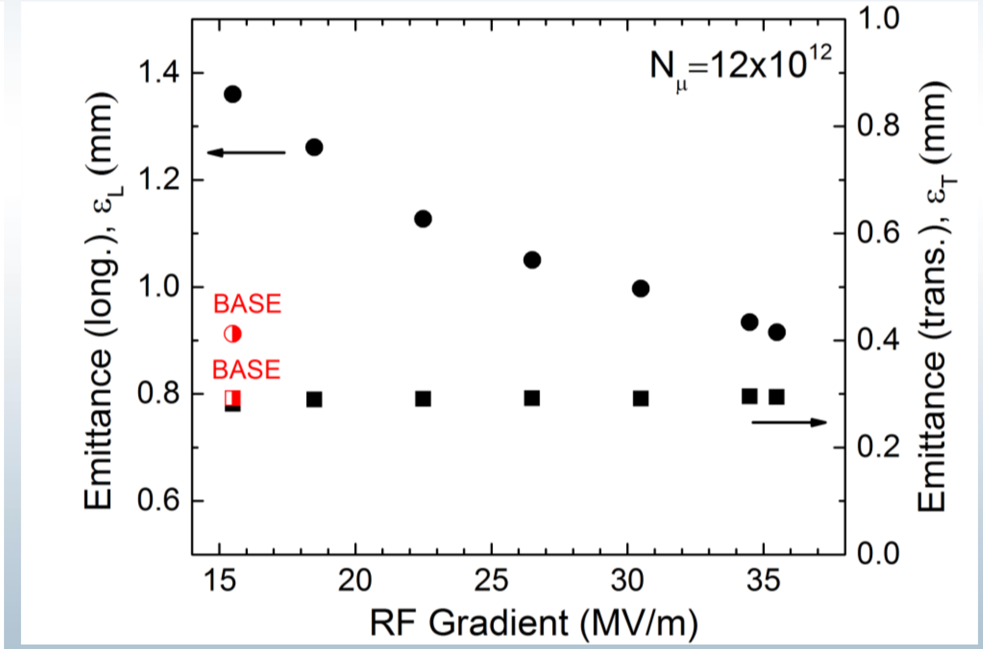
SPACE-CHARGE STUDIES FOR IONIZATION COOLING LATTICES *

D. Stratakis# and R.B. Palmer, Brookhaven National Laboratory, Upton, NY 11973, USA
D. P. Grote, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

Space-charge compensation

- Space-charge compensation with rf gradient possible
- Compensation gradient is coupled to the beam intensity



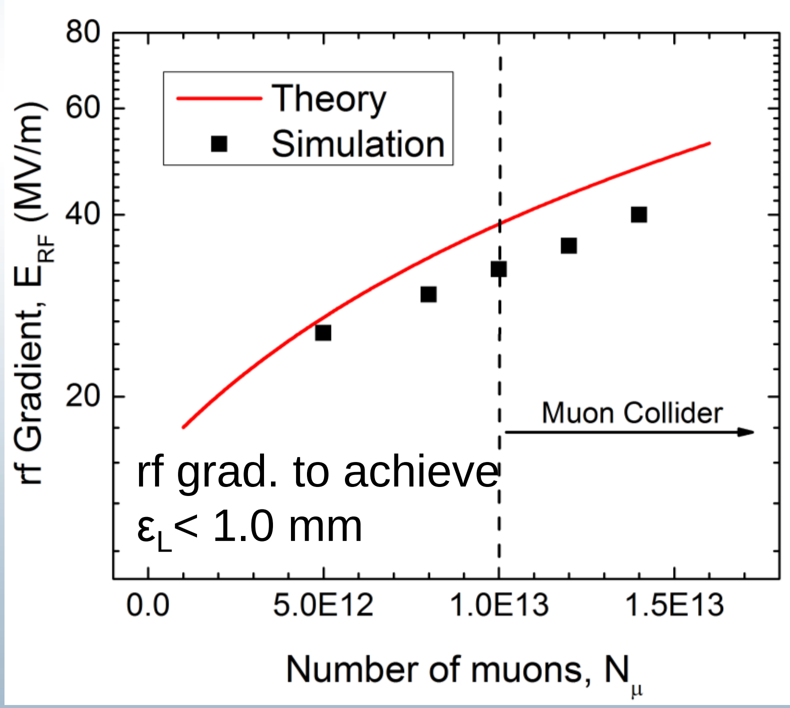


Space-charge compensation

- For a Muon Collider in order to obtain a longitudinal emittance < 1.0 mm the rf gradient of a 805 MHz cavity needs to surpass the demanding value of 32.5 MV/m

- Theory (Palmer et al.):
  - Compensation gradient strongly correlated to bunch charge
  - Avoid long. cooling to < 1.3 mm

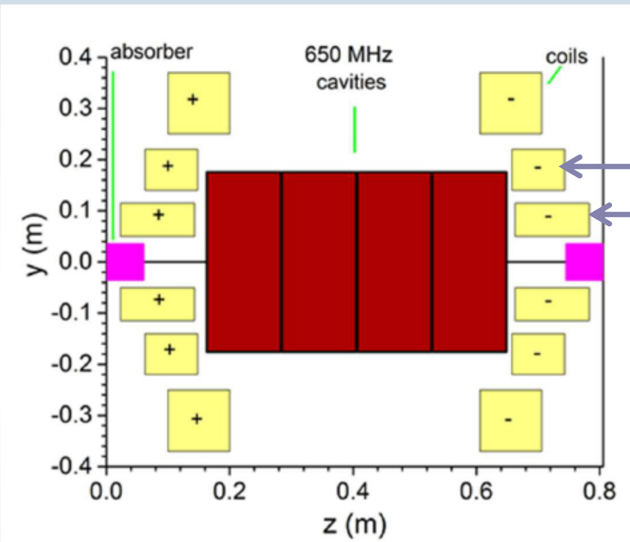
$$\xi = 1 + \frac{Q g_0 c}{4\pi\varepsilon_0\sqrt{2\pi}\gamma^2\sigma_z^3(2\pi f E n cos\varphi)}$$



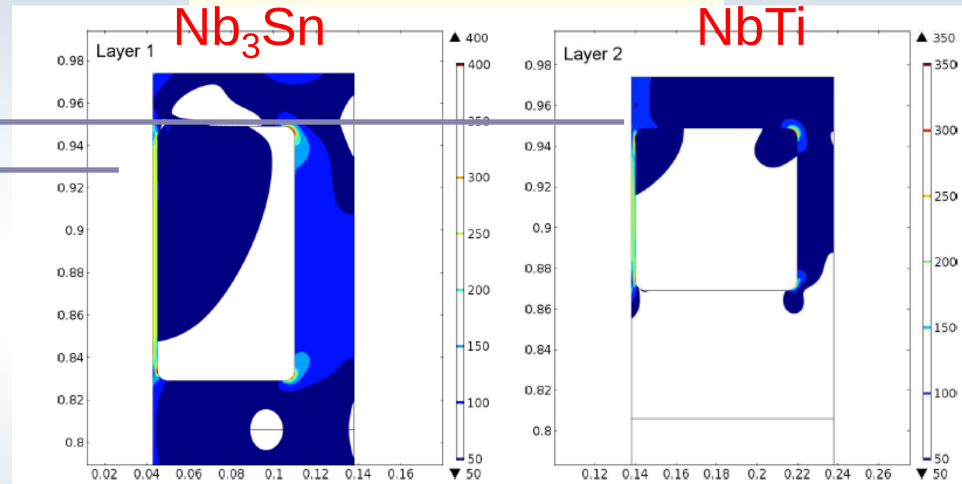
Stratakis et al. PRST-AB (submitted)

Magnet feasibility studies

- Last (and most challenging) 6D cooling stage



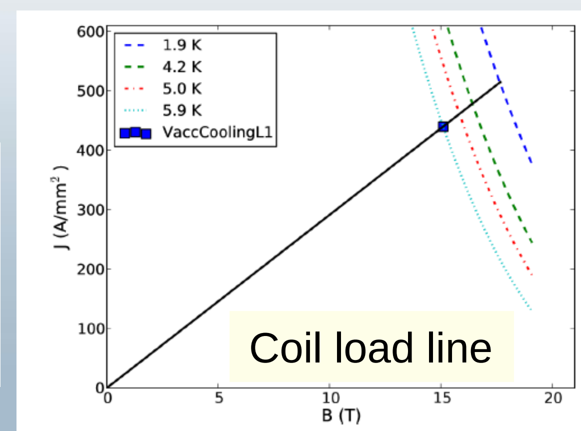
Von-Mises stress analysis



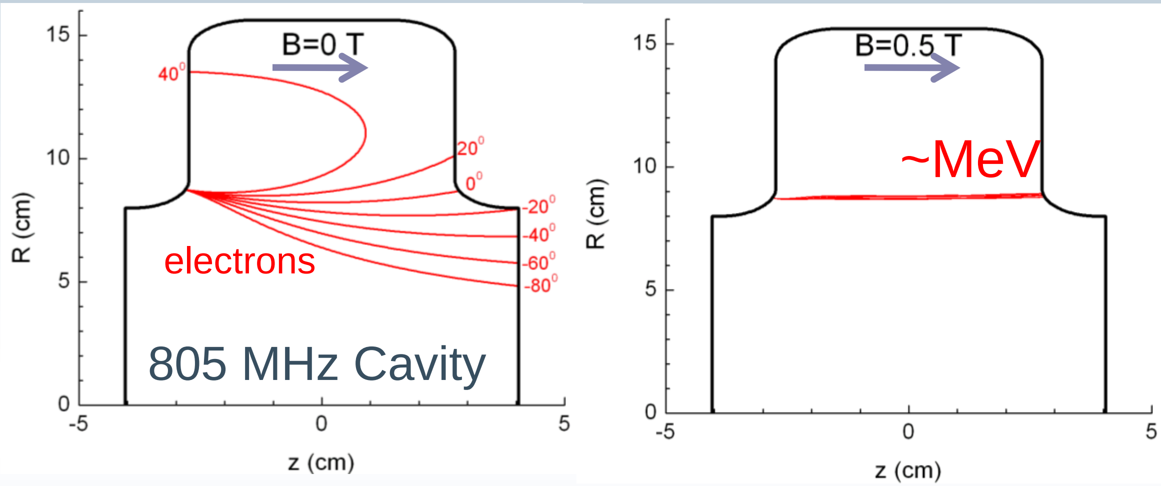
WEPRI103 Proceedings of IPAC2014, Dresden, Germany

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

H. Witte†, D. Stratakis, J. S. Berg, R. B. Palmer, Brookhaven National Laboratory, Upton, NY, USA
F. Borgnolutti, Lawrence Berkeley National Laboratory, Berkeley, CA, USA



The bad news: rf problems in B-fields



Damage on a 805 MHz rf cavity immersed in a multi-T magnetic field.

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

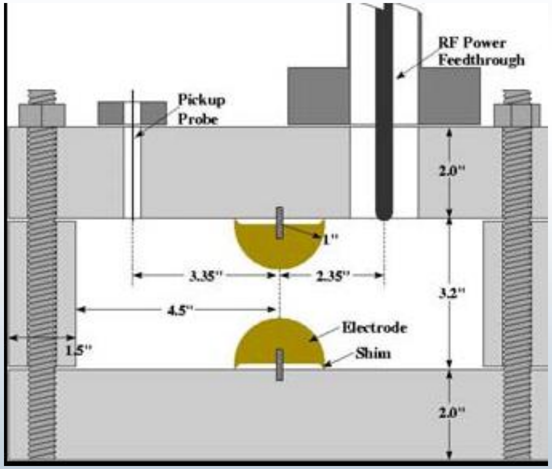
Contents lists available at ScienceDirect
Nuclear Instruments and Methods in Physics Research A
journal homepage: www.elsevier.com/locate/nima
ELSEVIER

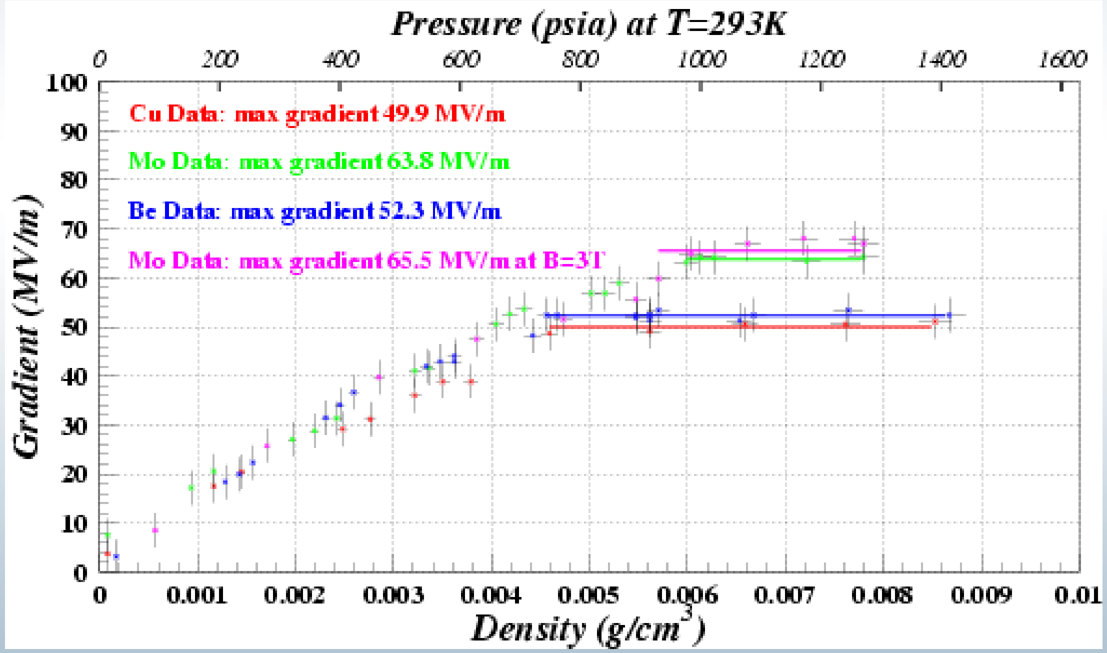
Effects of external magnetic fields on the operation of high-gradient accelerating structures

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

The good news: Gas-filled cavities

- The gradient of a gas filled cavity showed no magnetic field dependence in a solenoidal field up to 3 T.

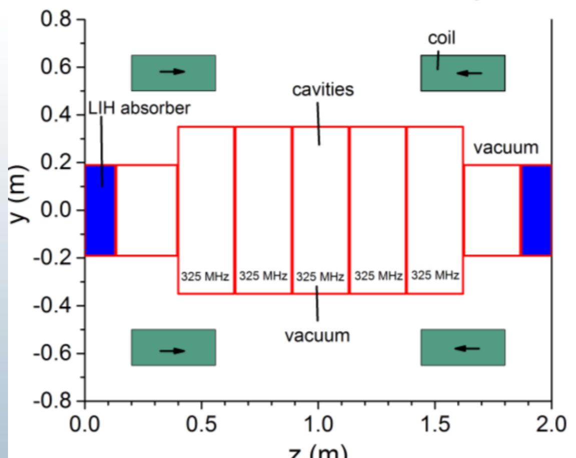


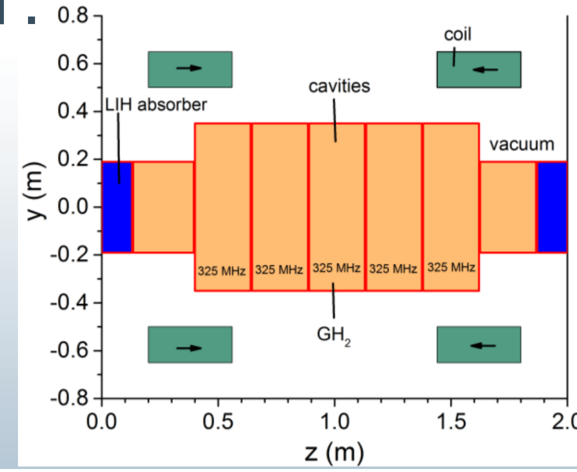


P. Hanlet et al., EPAC 2006, p. 1364 (2006)
M. Chung et al., PRL 111, 184802 (2013)

Hybrid solution

- Key Idea: Utilize gas filled cavities in a rectilinear channel
- Majority of cooling will be done in LiH and use gas only to protect the cavity from the high-field. Similar idea was used in the past for 4D cooling (Gallardo & Zisman, Nufact09)
- We assume 34 atm of gas, at room T.





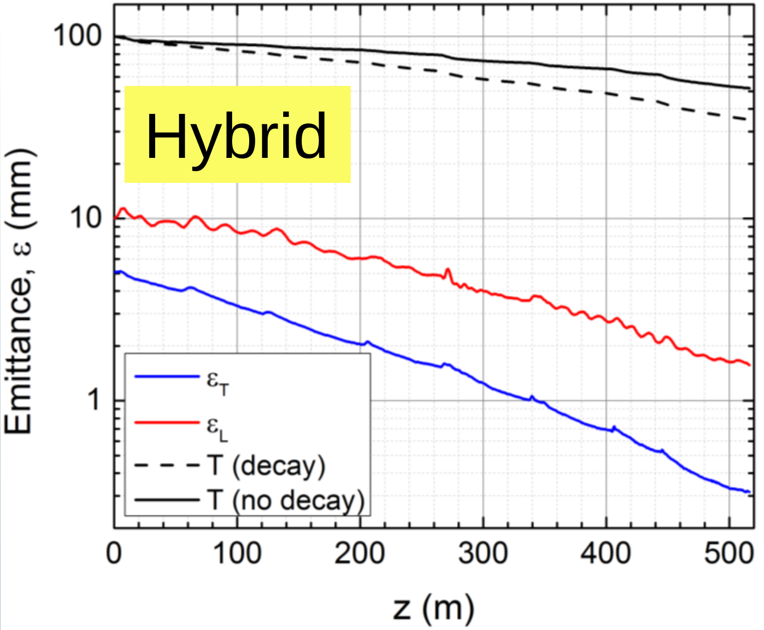
Proceedings of IPAC2014, Dresden, Germany TUPME024

A HYBRID SIX-DIMENSIONAL MUON COOLING CHANNEL WITH GAS FILLED CAVITIES.*

Diktys Stratakis#, Brookhaven National Laboratory, Upton, NY, USA

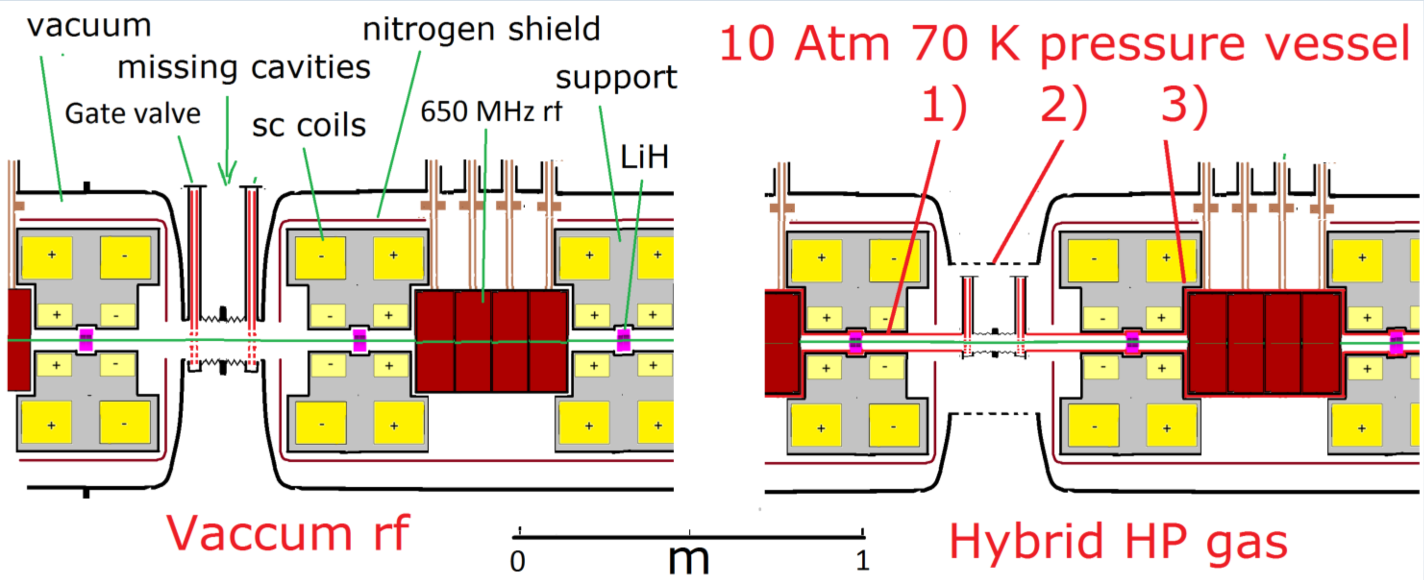
Lattice performance

- Final emittances are 0.30 mm (trans.) and 1.5 mm (long.) with a transmission of 50 % (no decays)
- This work is a “proof-of-principle” numeric study only!
- There remains considerable work to do before a hybrid channel can be considered a validated cooling channel option.



Challenges for a hybrid cooler

- Late evening discussion with Bob Palmer…



Problems

1) No space between beam and inner coil
2) How does one open vacuum to get at gate HP valves
3) HP flange will be thick

Pressure vessel must be built to code for HP inflamable

Making room will hurt performance

Summary

- We have presented a conceptual design of a rectilinear channel that in view its simple geometry may offer several technological advantages (compared to a helix or a ring)
- Showed reduction of 6D by at least 5 orders of magnitude.
- Numerical results agree well with theory
- For the first time the influence of space-charge fields on the cooling process was thoroughly examined
- Presented first results on magnet feasibility with encouraging results
- A hybrid solution with gas filled was presented