Overview of Muon Cooling

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COOL'15
Jefferson Lab
28 September 2015

Outline

- Brief Motivation
- Muon Collider and Neutrino Factory concepts
- Need for muon cooling
- Ionization cooling
- Rubbia's vision
- Frictional cooling
- R&D overview
- Summary

Thank you!

- to the organizers
- and
  - Yuri Alexahin, Chuck Ankenbrandt, Valeri Balbekov, Alain Blondel, Dave Cline, J-P Delahaye, Slava Derbenev, Rick Fernow, Juan Gallardo, Steve Geer, Gail Hanson, Rol Johnson, Yoshi Kuno, Ken Long, Yoshi Mori, Dave Neuffer, Bob Palmer, Mark Palmer, Tom Roberts, Carlo Rubbia, Andy Sessler, Sasha Skrinsky, Pavel Snopok, Diktys Stratakis, Don Summers, Yagmur Torun, Katsuya Yonehara, Mike Zisman…
- and, of course,
  - DOE, NSF, STFC…

Muon Accelerators in a Nutshell

☞As the first speaker on muon cooling, let me briefly summarize its motivation:

- High-energy e^+e^- colliders radiatively limited $\propto m^{-4}$

  ⟹ need *heavier* fundamental fermions — i.e., muons

  - *and* an effective cooling scheme for them

- Muon storage rings could then serve as uniquely powerful $\ell^+\ell^-$ colliders
  - e.g., for sensitive Higgs studies

- *And* neutrino sources

- *And* potentially, improved low-energy muon experiments

C. Rubbia, "A Complete Demonstrator of a Cooled-Muon Higgs Factory," https://indico.fnal.gov/conferenceDisplay.py?confId=9752

- Only a muon collider can *definitively* investigate Higgs physics

Some History

Late 1970s – early 1980s: Muon Collider concepts proposed (Skrinsky, Parkhomchuk, Neuffer)

1995: Muon Collider Collaboration (later, NFMCC) formed (Snowmass96)

- comprising over 140 scientists at labs and universities in U.S. and abroad

1998 – 2004: CERN muon cooling studies

1999: Neutrino Factory Feasibility Study I

2001: Neutrino Factory Feasibility Study II

2003: MICE approved

2004: Neutrino Factory Feasibility Study 2a

2006: Fermilab Muon Collider Task Force formed to study site-specific MC design

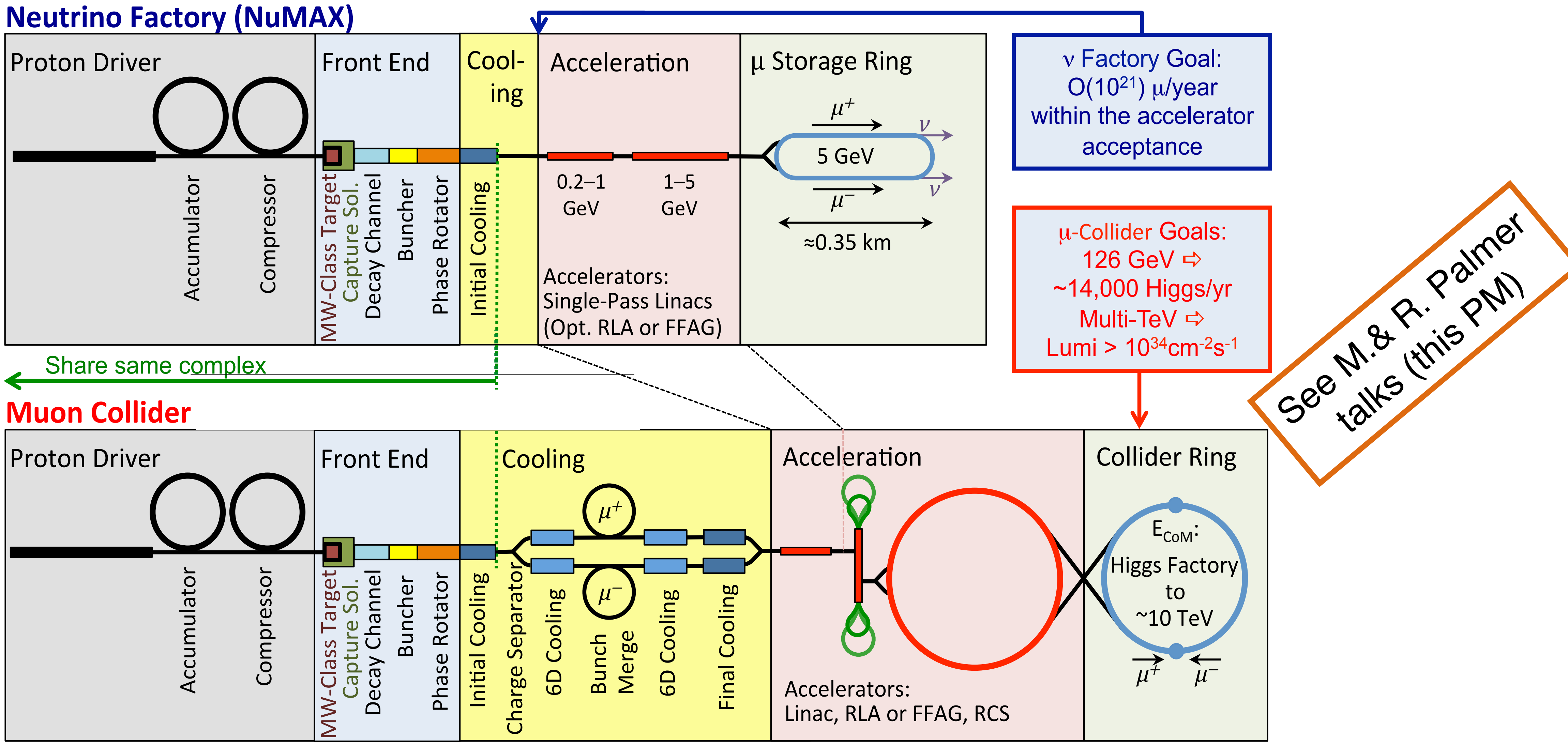
2010: (On DOE initiative) NFMCC and MCTF join forces → interim MAP & proposal to DOE

2011: MAP formally approved

2014: Start of MAP rampdown in response to P5 advice

νF and μC

- Recent MAP designs:



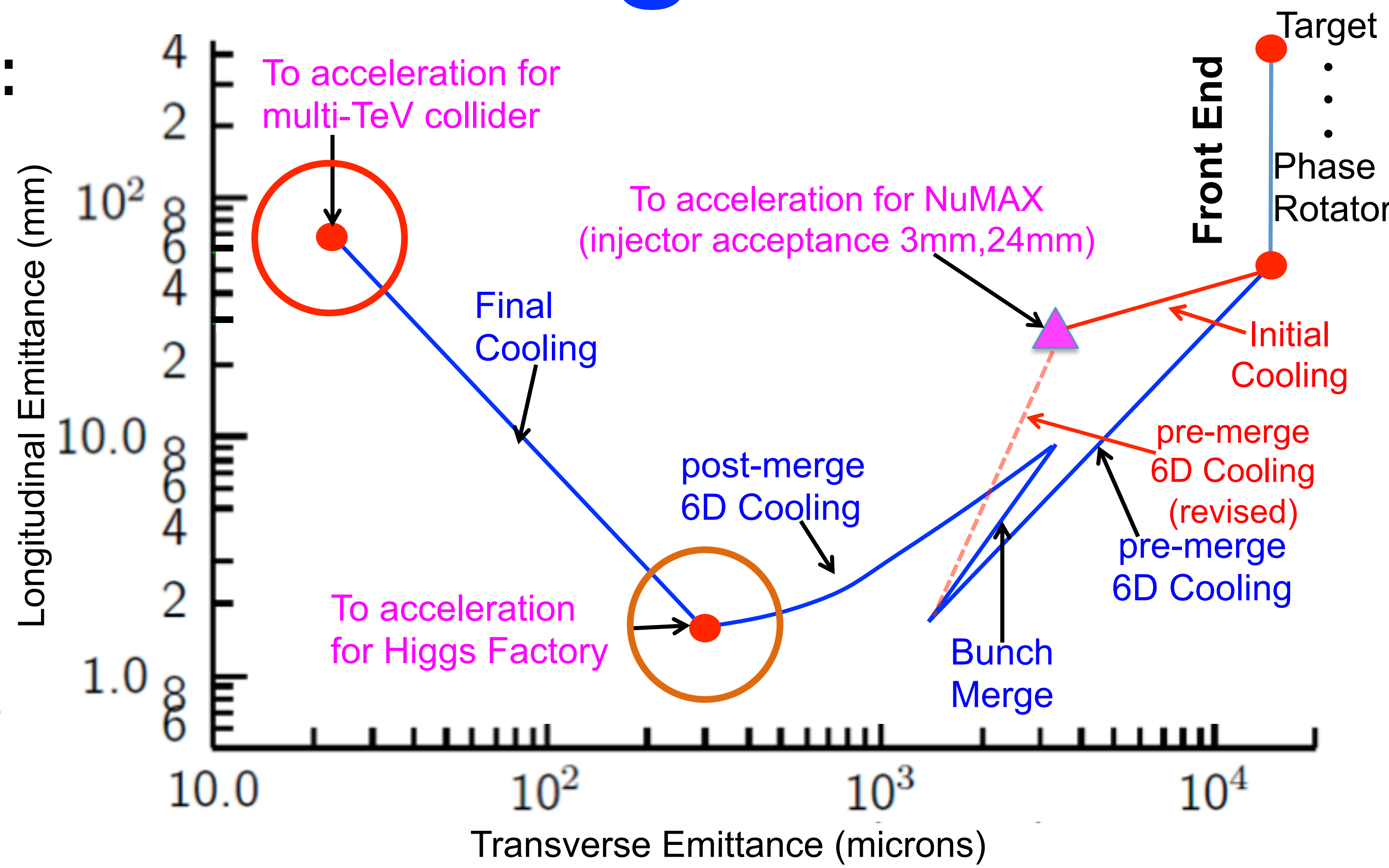
- Note strong similarities! (Front ends very similar)
  - both start with ~ MW p beam on high-power tgt → π → μ, then cool, accelerate, & store

Muon Cooling

- Desired evolution of ϵ_n:
- Physics of multi-TeV lepton collisions calls for $\mathcal{L} > 10^{34}$ cm^{-2} s^{-1}

$\Rightarrow$ must cool both $\epsilon_\perp$ & $\epsilon_{||}$

- need factor ~10^6 in total 6D emittance reduction:
  $\epsilon_\perp \approx 25$ μm, $\epsilon_{||} \approx 60$ mm



- Higgs physics requires $\mathcal{L} \sim 10^{32}$ and $\Delta p/p \sim 10^{-5}$
  - $\epsilon_\perp \leq 200$ μm, $\epsilon_{||} \approx 1.5$ mm

Suggests staging plan!

- Neutrino factory (with "dual-use" linac) requires more modest, ~ 10 6D cooling factor

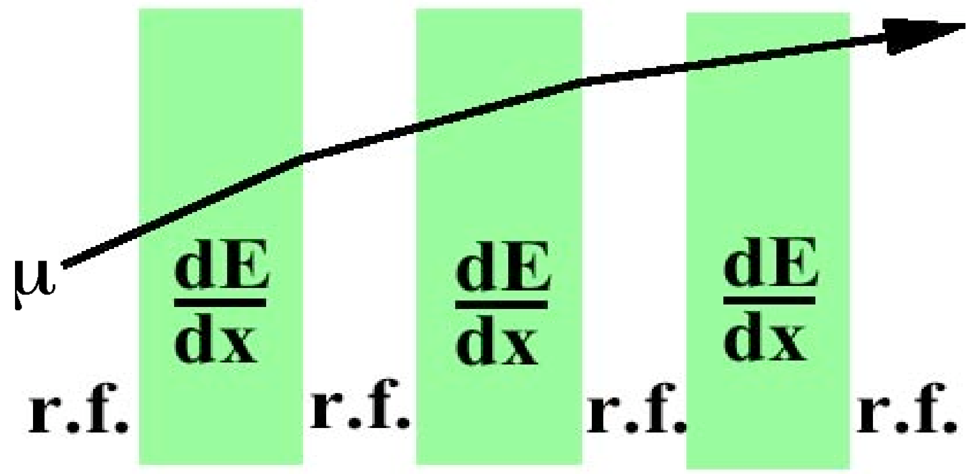
The Challenge:

$$\tau_\mu = 2.2\ \mu s!$$

Q: What cooling technique works in microseconds?

A: There is only one, and it works only for muons:

Ionization Cooling

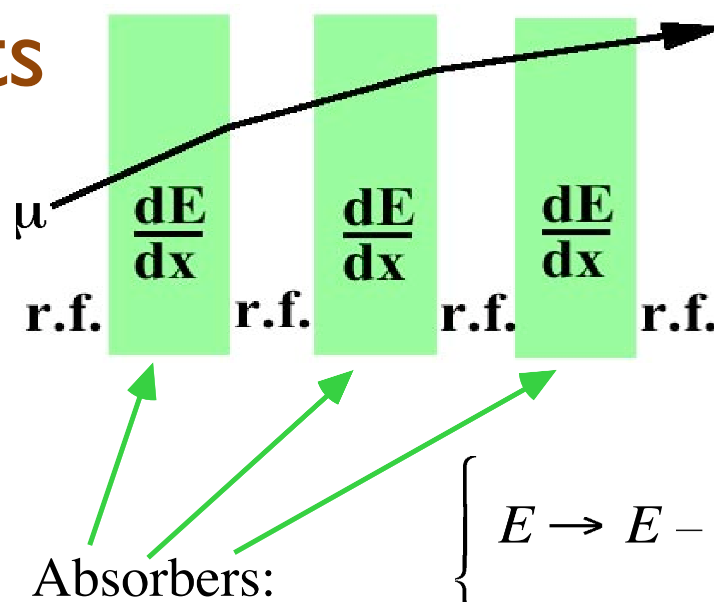


G. I. Budker and A. N. Skrinsky, Sov. Phys. Usp. **21**, 277 (1978)
A. N. Skrinsky and V. V. Parkhomchuk, Sov. J. Part. Nucl. **12**, 223 (1981)

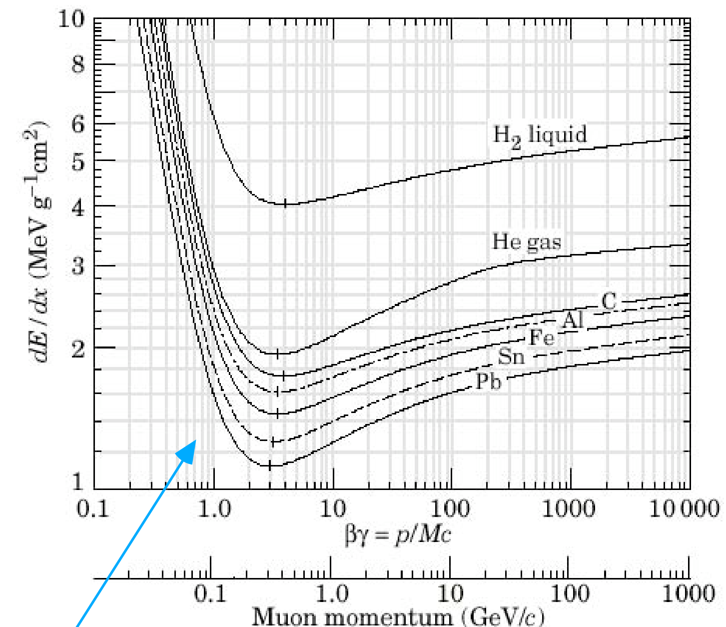
A *brilliantly* simple idea!

Ionization Cooling:

- Two competing effects
  - (cf. synch. rad. damping, opposed by quantum fluctuations)



$$\begin{cases} E \rightarrow E - \left\langle \frac{dE}{dx} \right\rangle \Delta s \\ \theta \rightarrow \theta + \theta^{rms}_{space} \end{cases}$$



ionization energy loss

multiple Coulomb scattering

- How it works:
  - Absorbers reduce $\vec{p}_\mu$
  - RF cavities replace $p_{||}$
  - Reduction in muon $p_\perp$ at constant $p_{||}$ is transverse cooling:

$$\frac{d\epsilon}{ds} = -\frac{1}{\beta^2}\left\langle \frac{dE_\mu}{ds} \right\rangle \frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\,\mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$

(emittance change per unit length)

Note: It's "just Maxwell's equations," so in principle it *has* to work!

But in practice it's subtle and complicated...

so a test is essential!

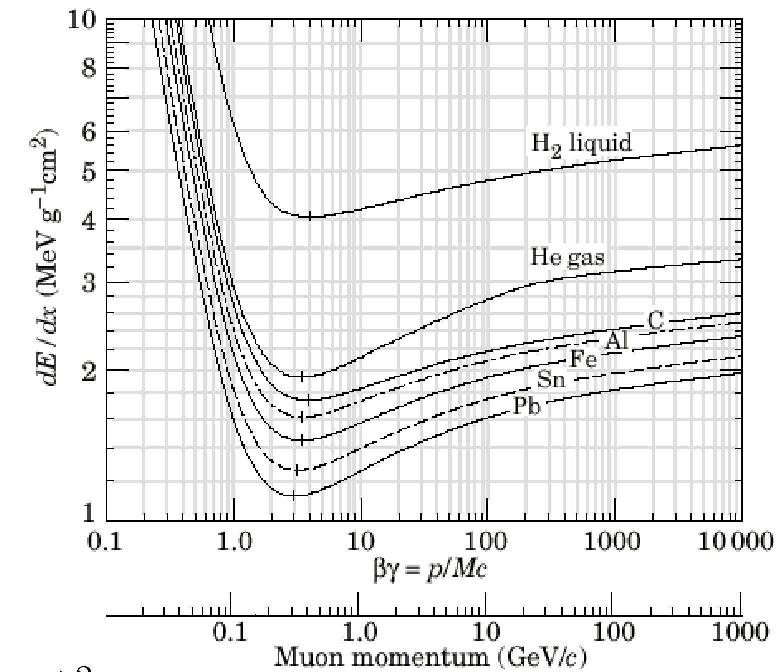
⇒ **MICE** [C. Rogers talk (Tuesday)]

Some Ionization Cooling Details

1. Effect is transverse only

– might hope to cool longitudinally via *dE*/*dx* curve's slight positive slope above ionization minimum

– but *dE*/*dx* "straggling" tail leads to heating



2. Optimal cooling requires:

– low $\beta_\perp$ at absorber

– large absorber X_0 (low Z)

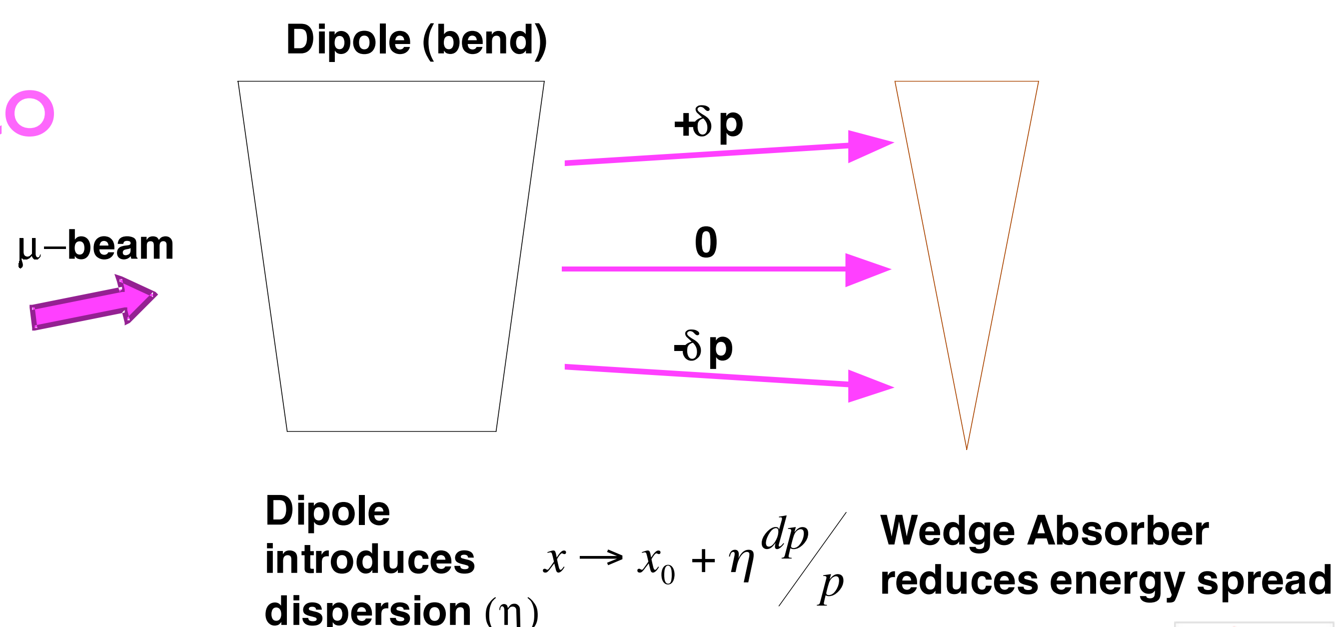
– low E_μ (typ. $150 < p_\mu < 400$ MeV/c)

$$\frac{d\epsilon}{ds} = -\frac{1}{\beta^2}\left\langle \frac{dE_\mu}{ds} \right\rangle \frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\,\mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$

3. Can couple cooling effect into longitudinal phase plane via emittance exchange

– allows all 6 phase-space dimensions to be cooled

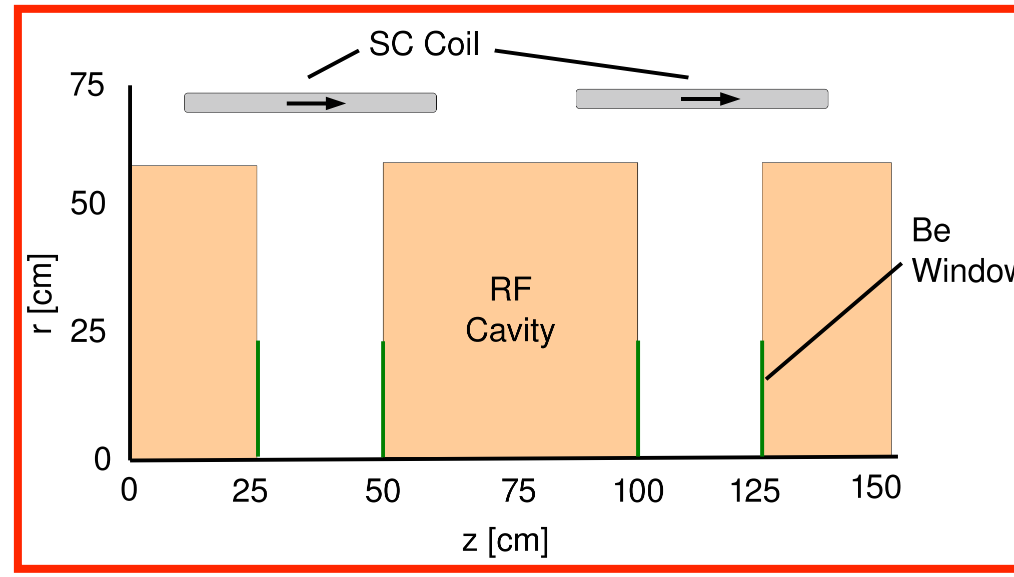
Emittance exchange example (D. Neuffer):

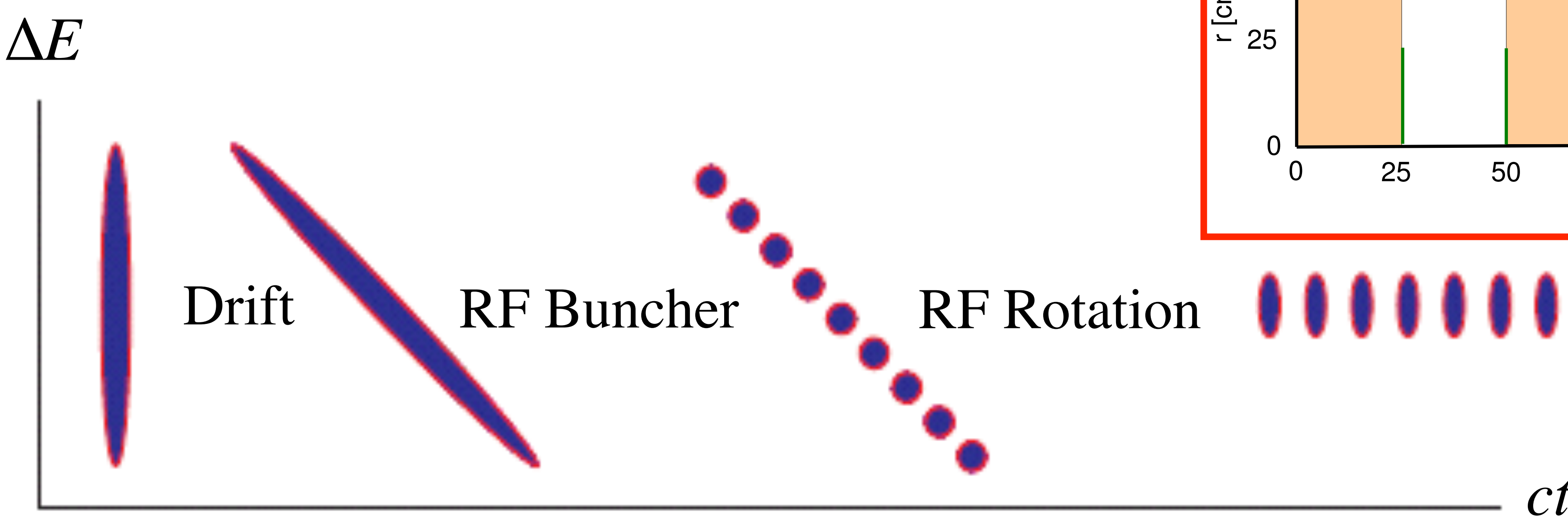


Preparing for Ionization Cooling

Example: International Design Study (IDS) νF design [hep-ex/1112.2853]

- Ionization cooling requires bunched beam with $dp/p \lesssim 10\%$
  - μ "born" with small Δt but large ΔE
  - first, bunch, then phase-rotate:





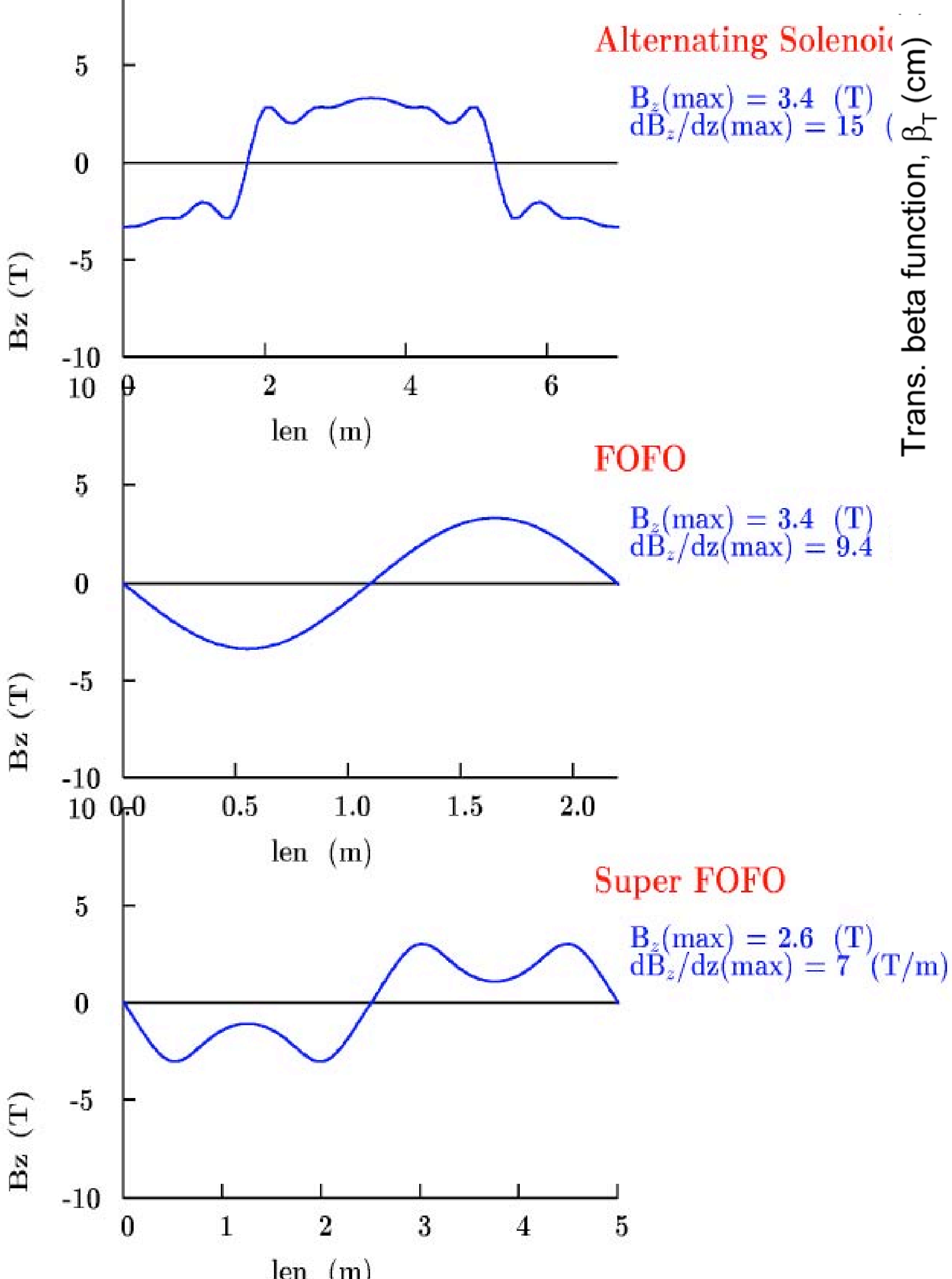
Neuffer talk (Thursday)

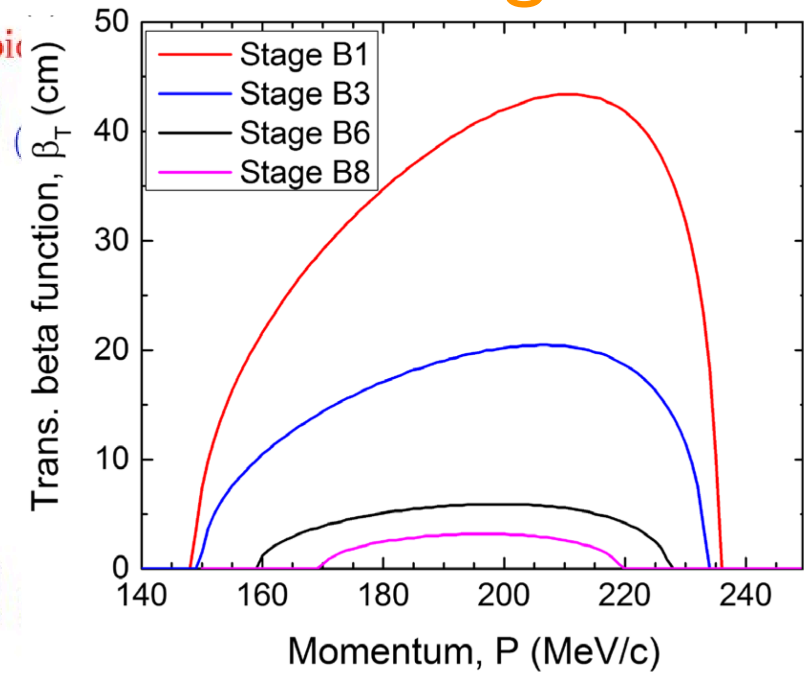
  - efficient bunching via RF "vernier" [D. Neuffer]
    - uses several RF frequencies starting at ≈ 500 MHz, decreasing to 325

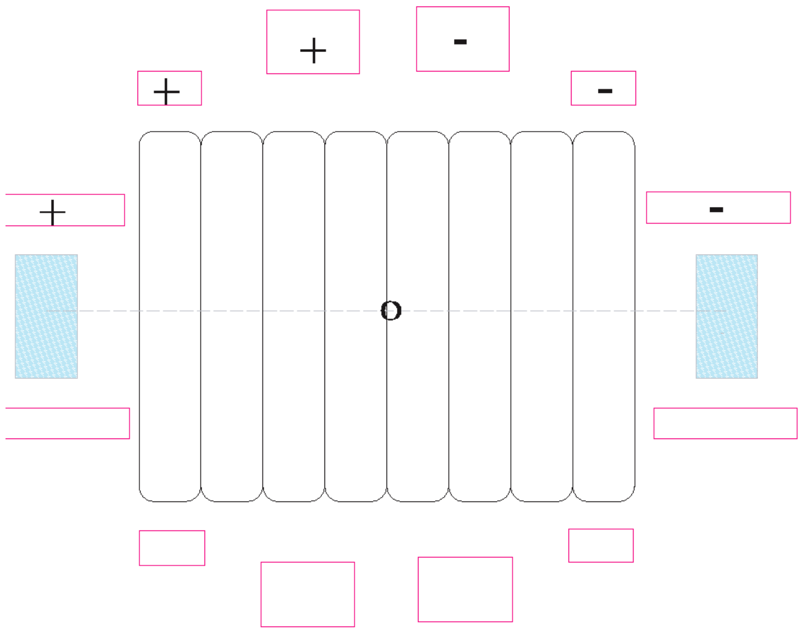
Alternating-Gradient Lattices

R. Palmer (BNL) et al.

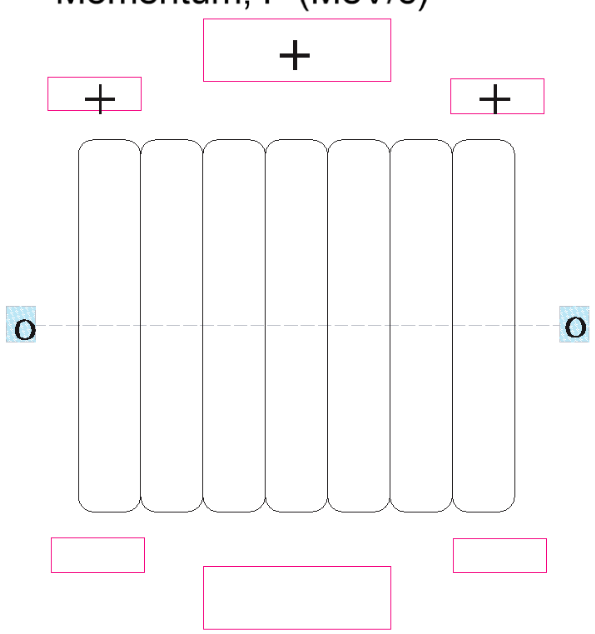
- With thick- or thin-solenoid focusing



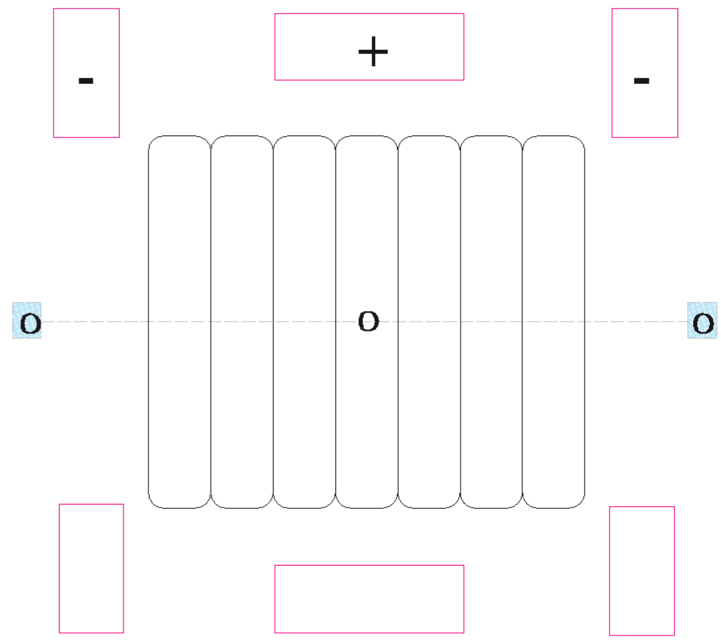




Alternating solenoid



FOFO



Super-FOFO

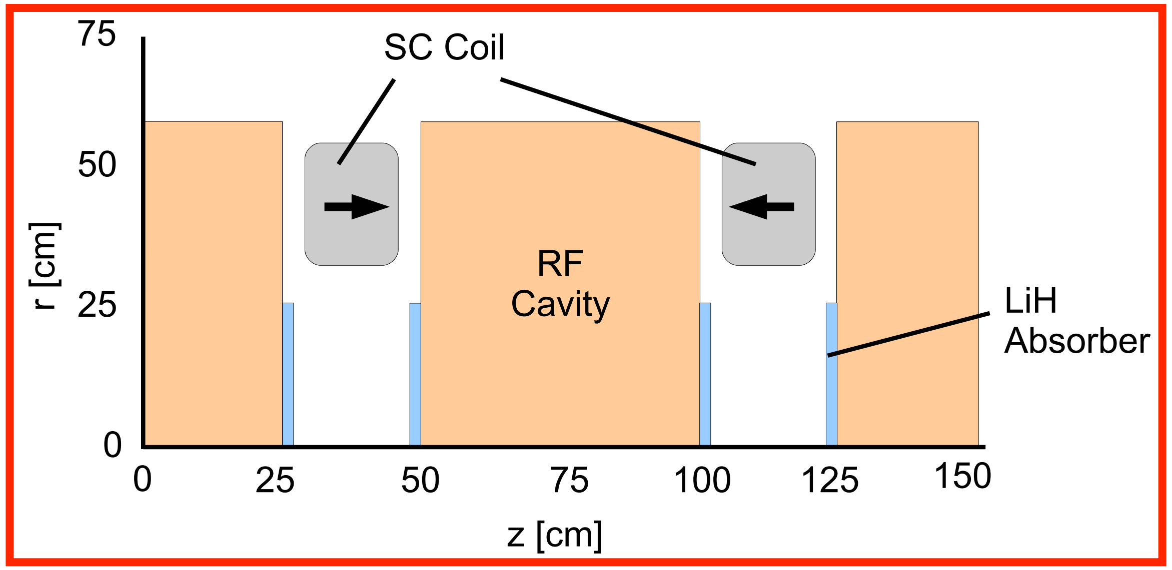
+ RFOFO, DFOFO, ...

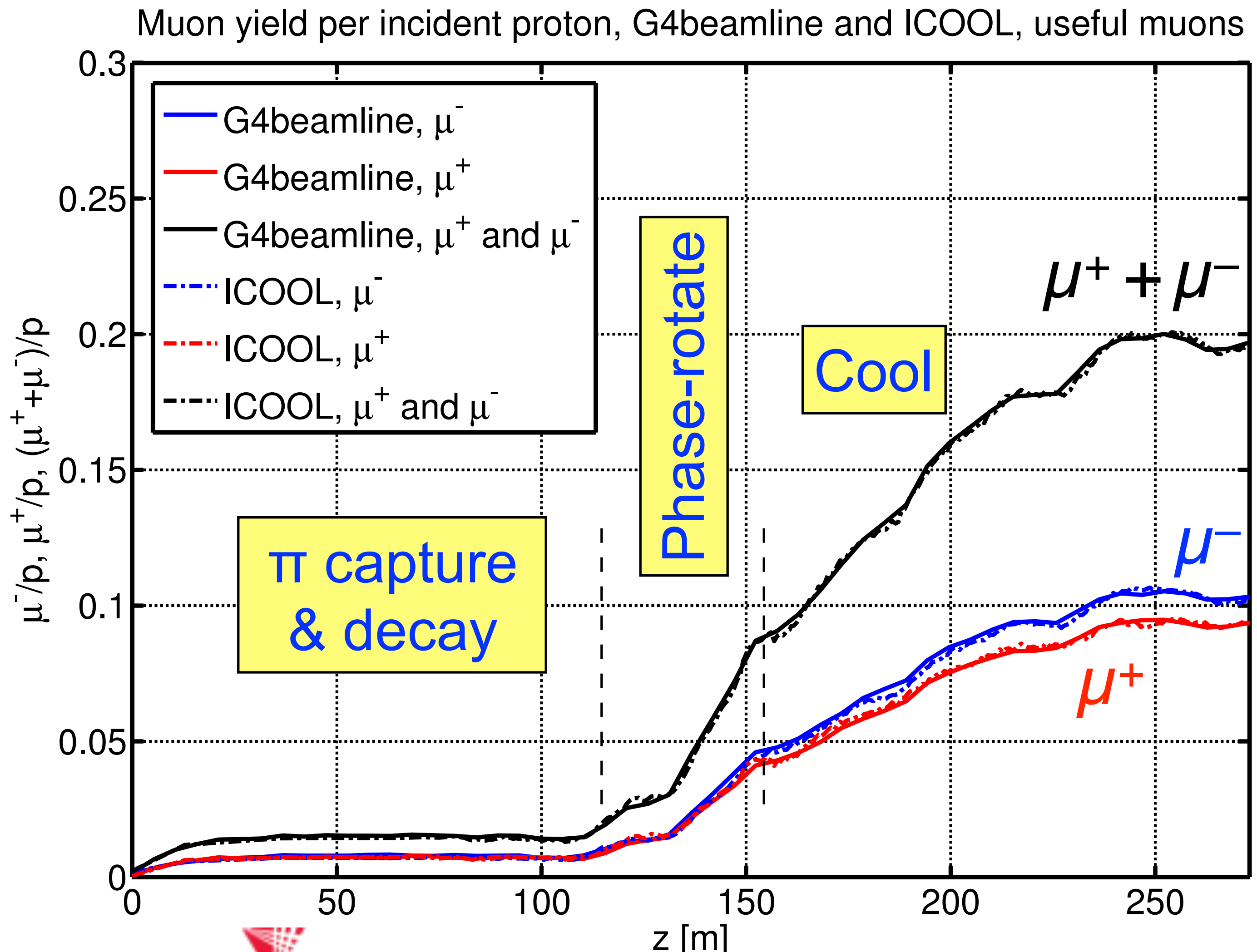
- Resonances → low β with less superconductor

Simple Transverse Cooling Scheme

IDS design [hep-ex/1112.2853]:

- Alternating-solenoid ("RFOFO") focusing (Study 2a)
- Thin, Be-coated LiH absorbers double as RF-cavity windows





- Performance:
  - $\approx$ 100-m-long cooling channel $\approx$ doubles muon intensity
  - accepts and cools μ^+ and μ^- simultaneously, in interspersed RF buckets

6D Cooling Approaches

- Effective transverse ionization cooling designs proposed ~2000
- 6D harder – many lattices explored to find current, successful ones:

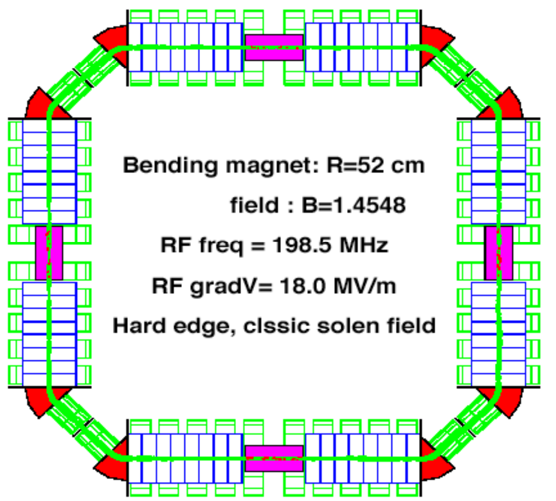
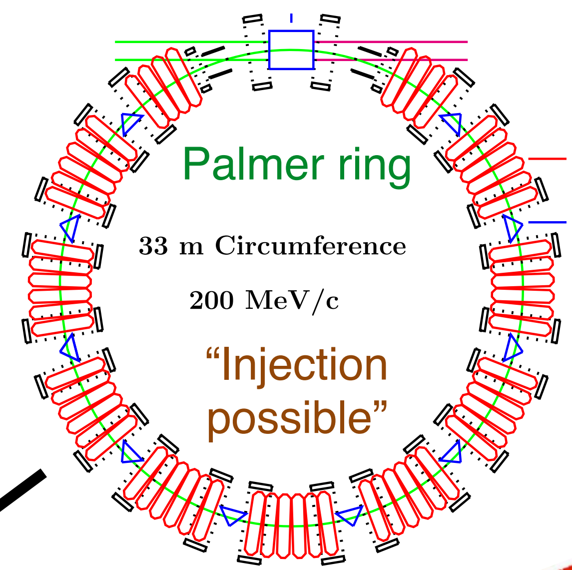
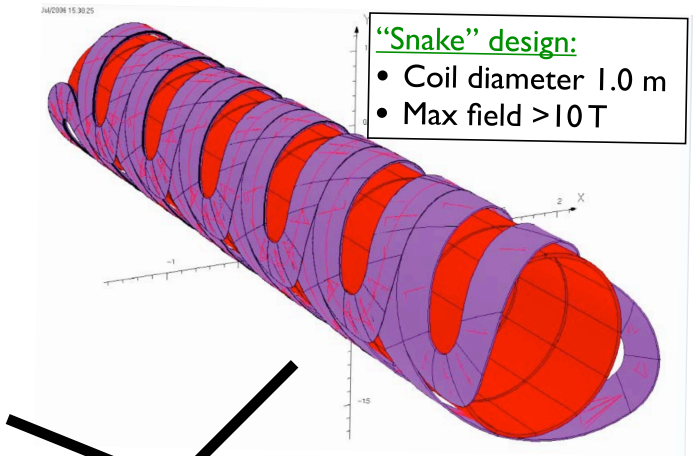


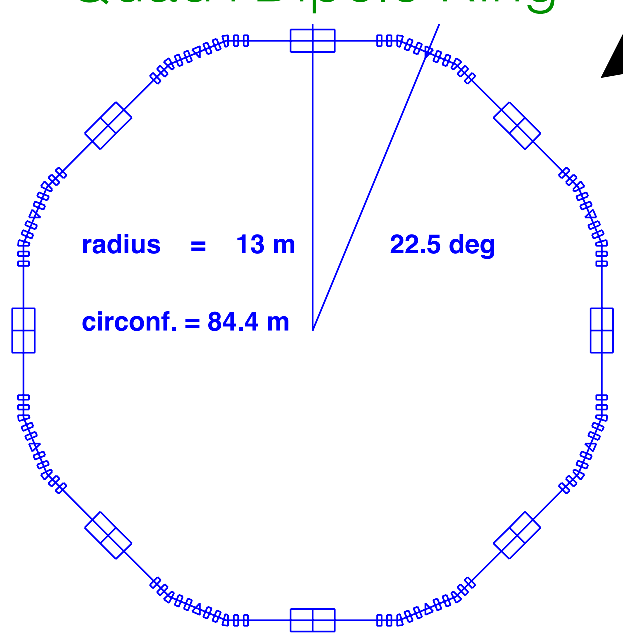
Fig. 5: Schematic of Balbekov ring cooler





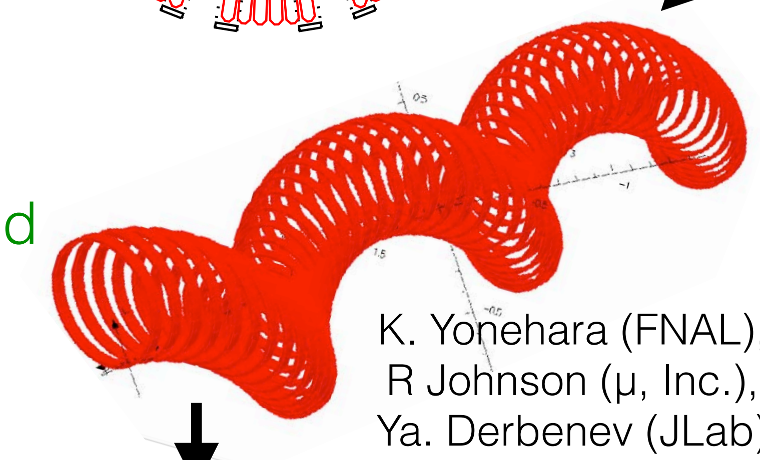
RFOFO "Guggenheim"

Quad+Dipole Ring



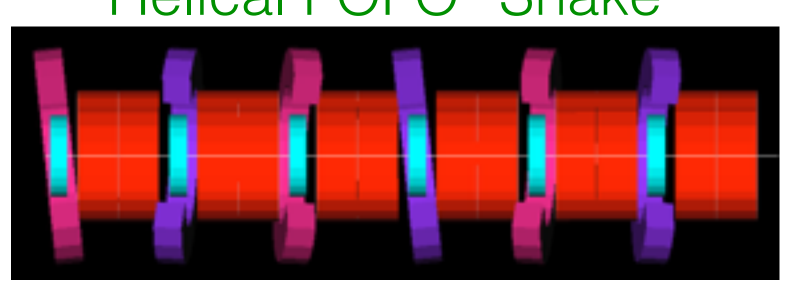
A. Garren, D. Cline (UCLA), H. Kirk (BNL)

Helical Solenoid (HCC)

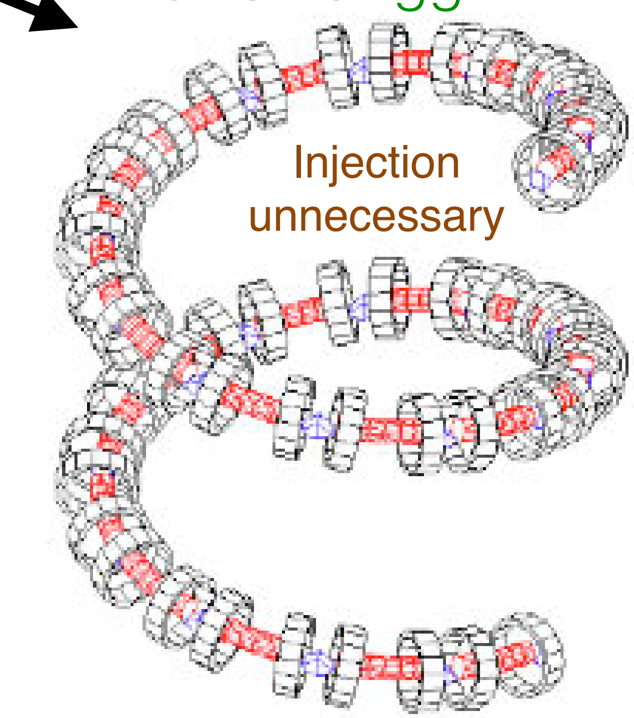


K. Yonehara (FNAL), R Johnson (μ, Inc.), Ya. Derbenev (JLab)

Helical FOFO "Snake"



Y. Alexahin (FNAL)



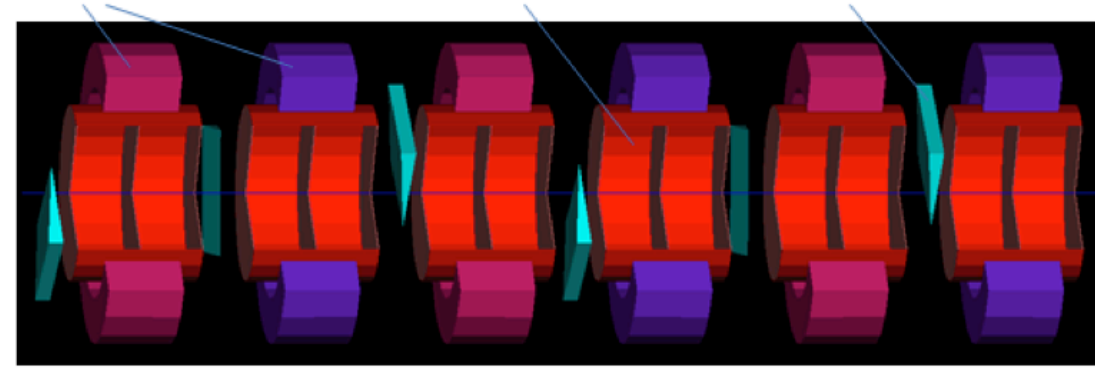
. . .

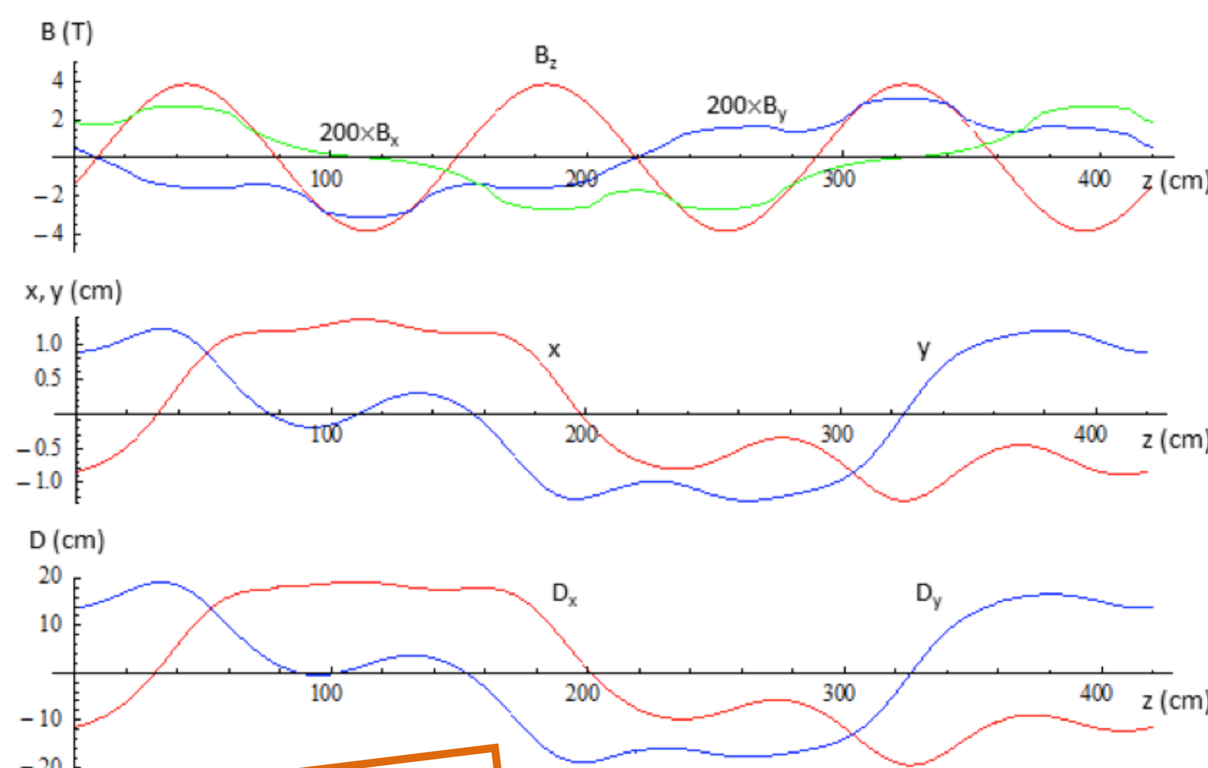
R. Palmer, D. Stratakis (BNL), A. Klier, G. Hanson (UCR), P. Snopok (UCR/IIT)

Initial Cooling

- Helical (Guggenheim etc.) channels need μ^+/μ^- charge separation – hard at large emittance
  - Y. Alexahin Helical FOFO "Snake" accepts *both* signs, via rotating, tilted solenoids giving (small) rotating dipole
    - like synchronizing traffic lights on 2-way street!
  - 3 120° orientation steps give isomorphic μ^+ and μ^- orbits with half-period offset

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

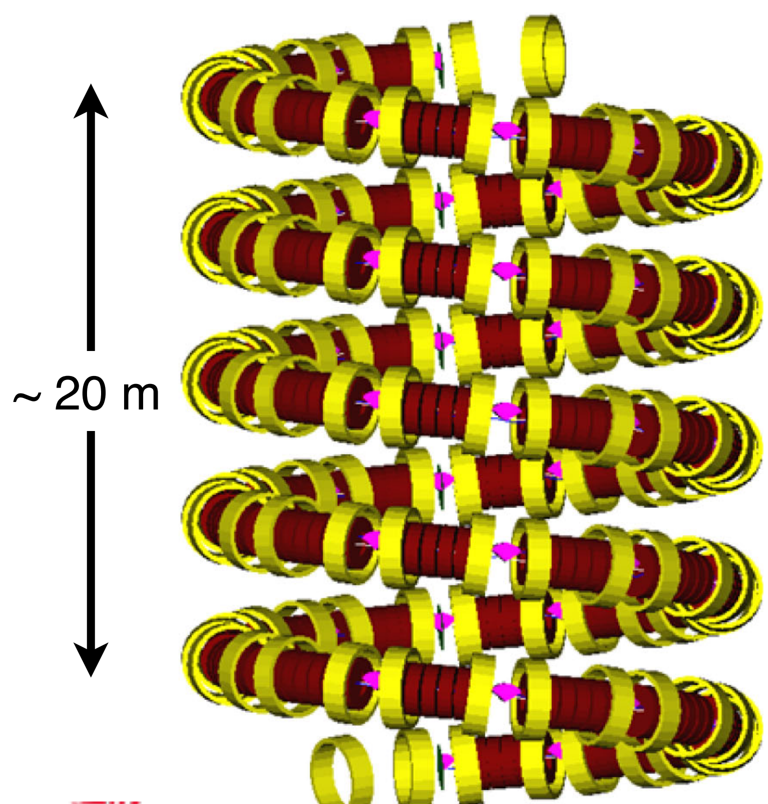




Neuffer talk (Thursday)

Current 6D Schemes

- Guggenheim scheme neatly avoided difficult injection and allowed tailoring of $\beta_\perp$ to ϵ
  - but engineering looked hard!
- V. Balbekov (2013): "R_FOFO snake channel for 6D muon cooling," http://map-docdb.fnal.gov/cgi-bin/ShowDocument?docid=4365



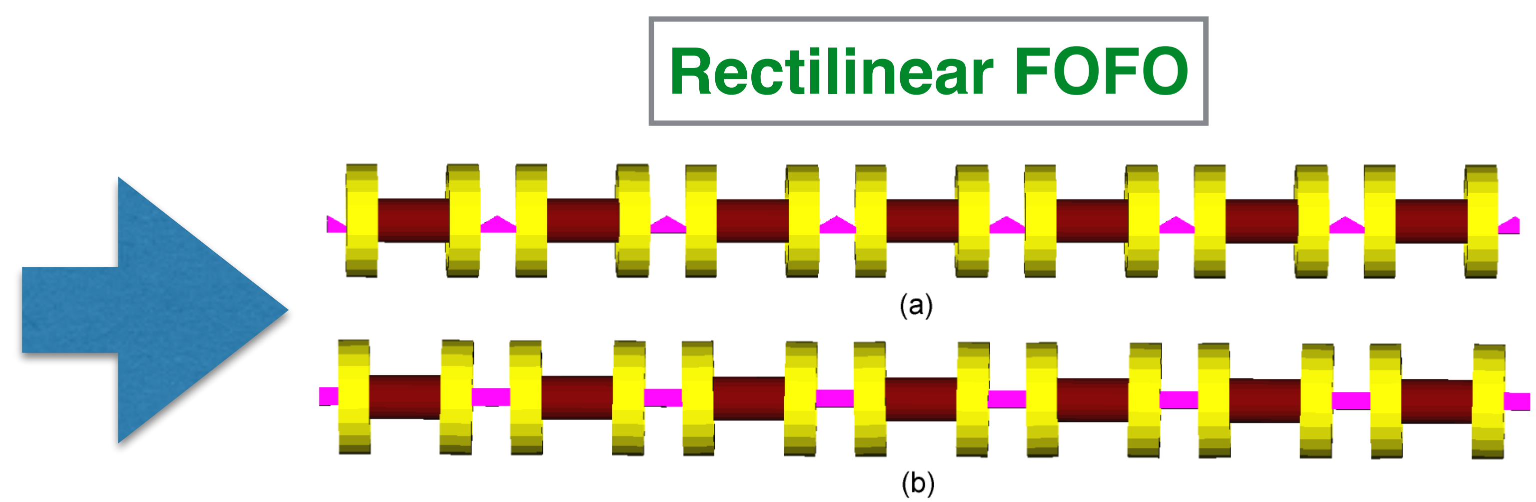
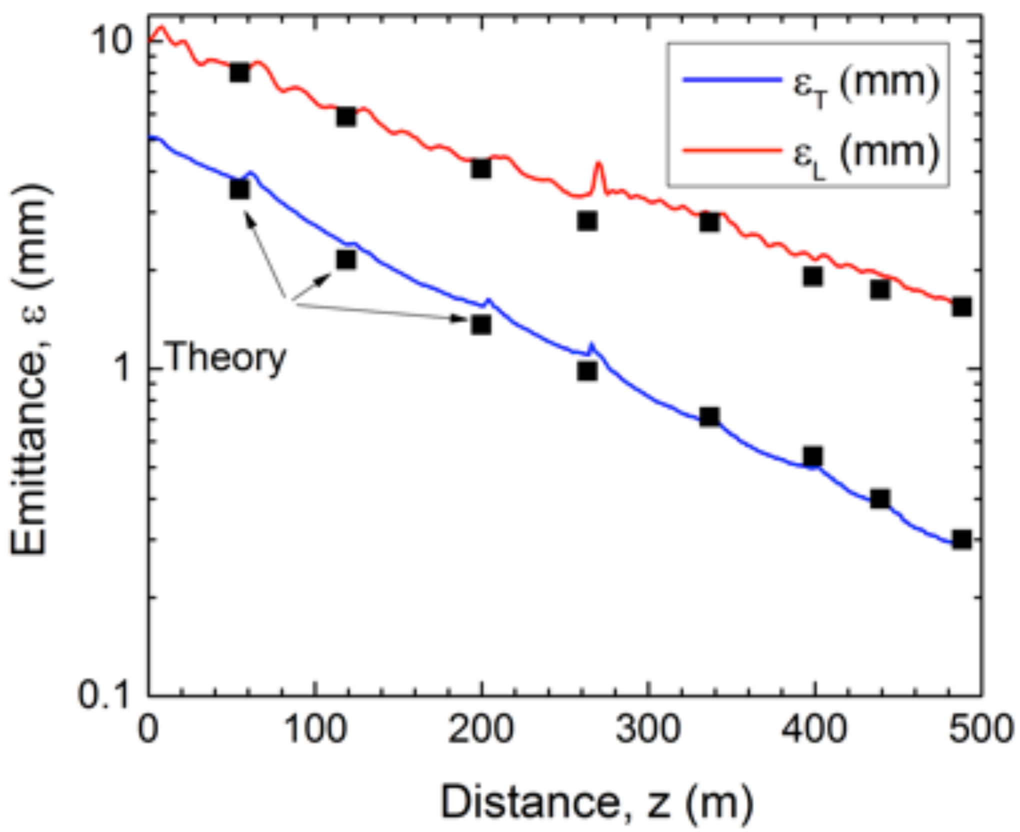


FIG. 2. Conceptual design of a rectilinear channel: (a) top view; (b) side view.

[D. Stratakis, R. Palmer, PRSTAB 18, 031003 (2015)]

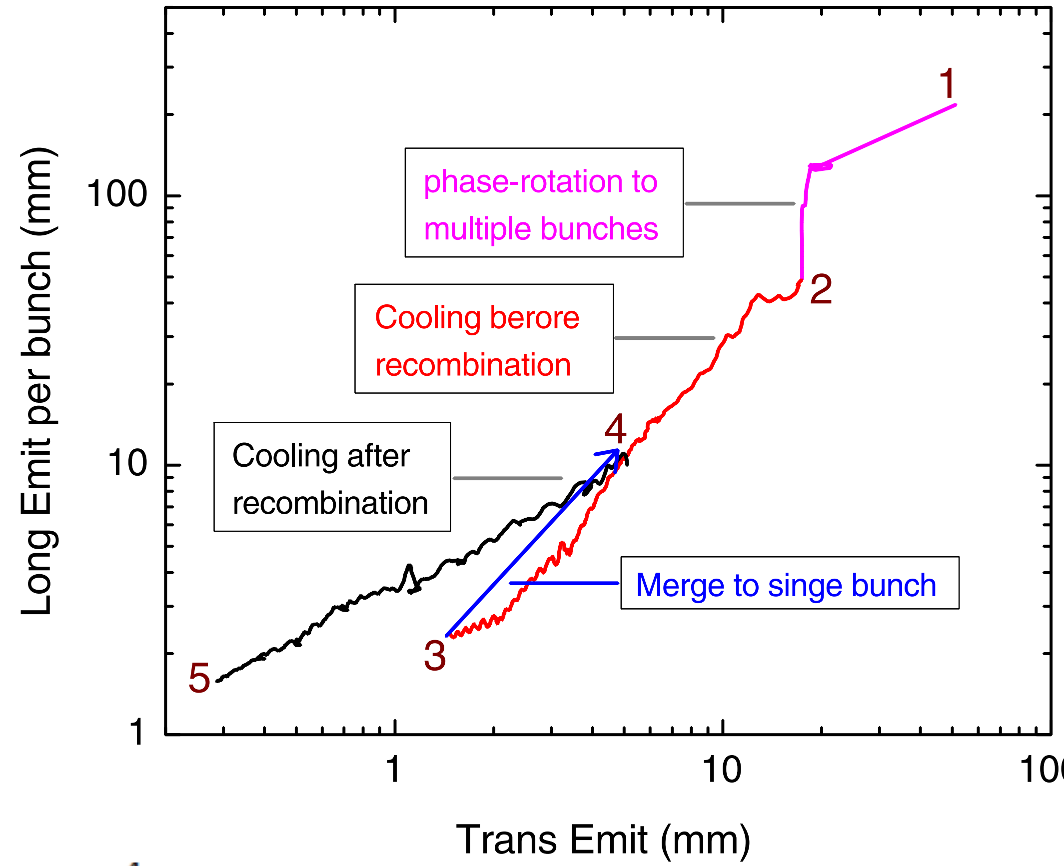
Current 6D Schemes

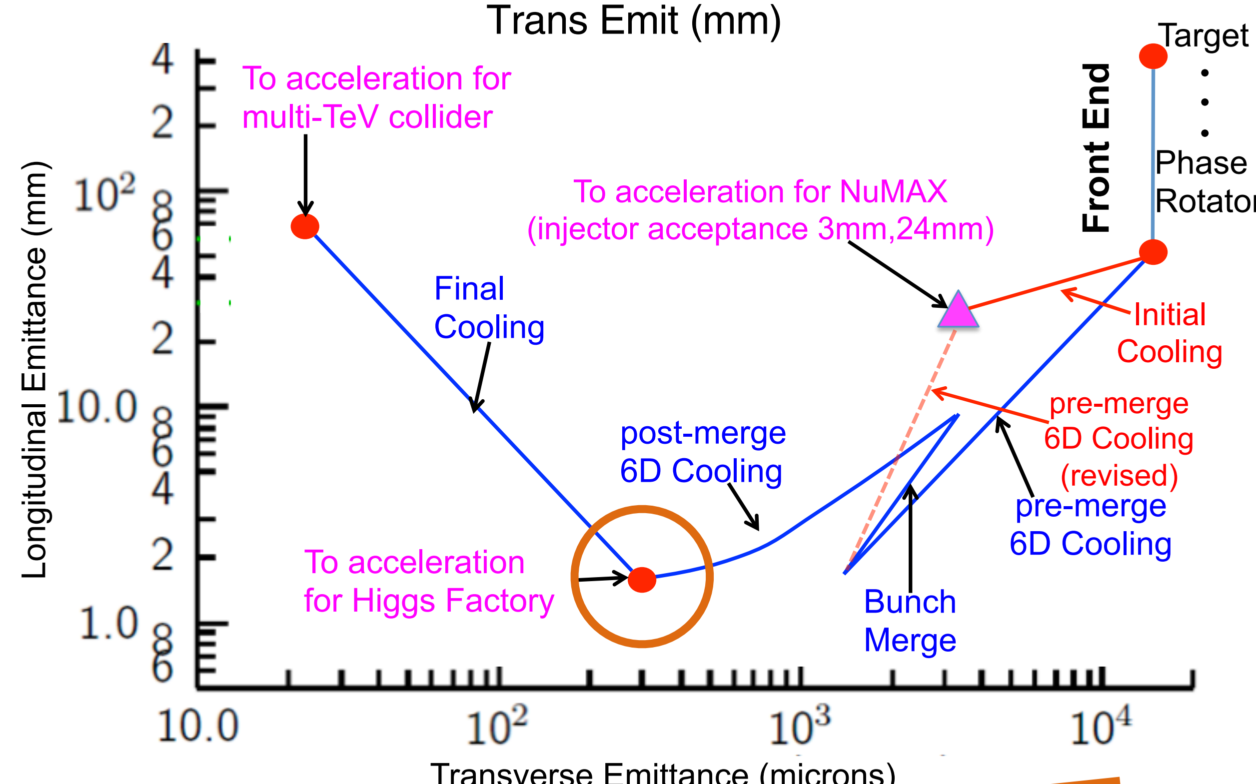
- R_FOFO performance: 12 stages → x 10^{-5} in 6D emittance in 500 m



  - reaches $\epsilon_\perp \approx 280$ μm, $\epsilon_{||} \approx 1.6$ mm

[D. Stratakis, R. Palmer, PRSTAB 18, 031003 (2015)]



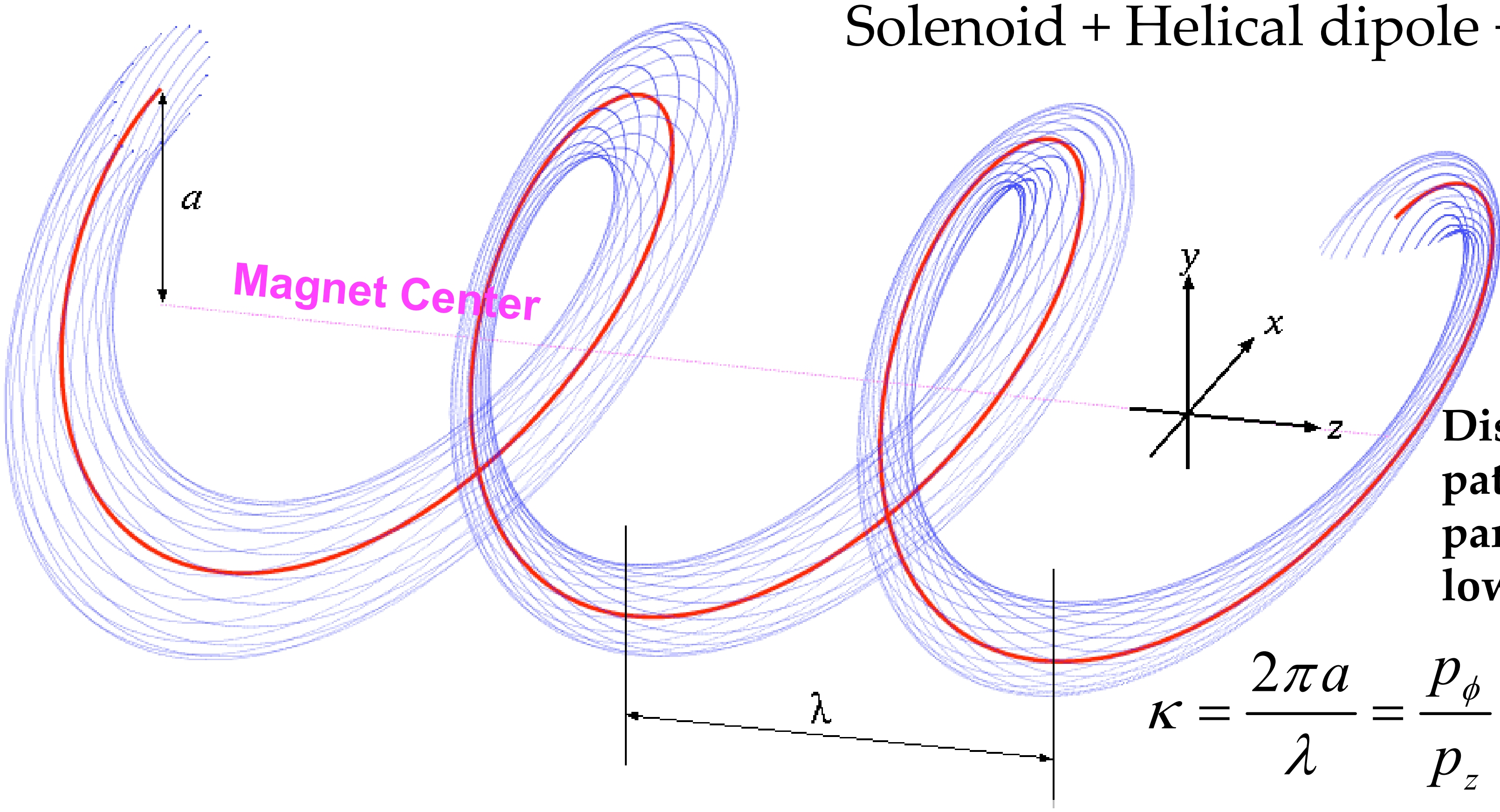


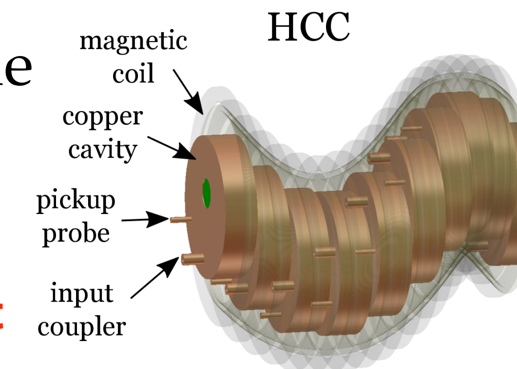
Stratakis talk (Thursday)

Helical-Channel Dynamics

[Ya. Derbenev, R. Johnson, PRSTAB 8, 041002 (2005)]

Solenoid + Helical dipole + Helical Quadrupole





Red: Reference orbit

Blue: Beam envelope

Dispersive component makes longer path length for higher momentum particle and shorter path length for lower momentum particle.

$$\kappa = \frac{2\pi a}{\lambda} = \frac{p_\phi}{p_z}$$

- *Continuous* focusing & (high-pressure-gas) absorber

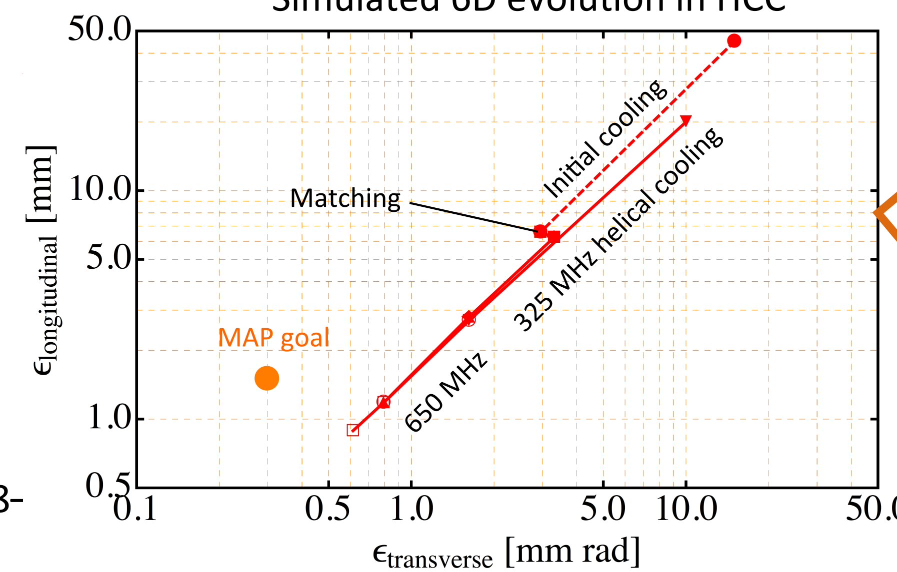
$f_\uparrow \propto b_\varphi \cdot p_z$	Repulsive force
$f_\downarrow \propto -b_z \cdot p_\varphi$	Attractive force

$$f_{central} = \frac{e}{m}(b_\varphi \cdot p_z - b_z \cdot p_\varphi)$$

- HCC performance:
  - reaches $\epsilon_\perp \approx 600$ µm, $\epsilon_{||} \approx 0.9$ mm

[K. Yonehara, ICFA BD Newslett. 65, 63 (2015)]

Simulated 6D evolution in HCC



Johnson & Yonehara talks (Tuesday)

“Last Mile” Problem

Alija/E+/Getty Images

The Last Mile Problem

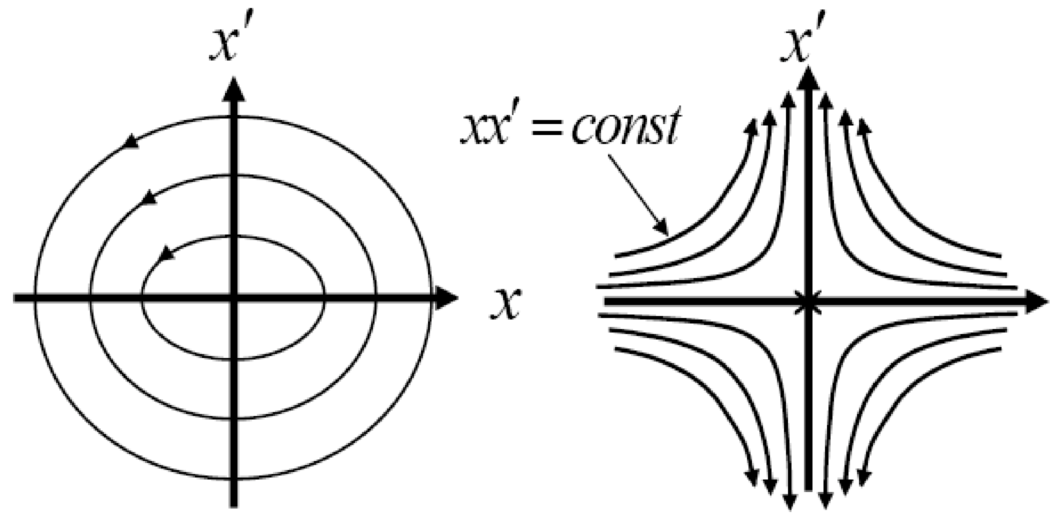
While rapid transit solutions such as light rail, heavy rail, commuter rail, and bus rapid transit (BRT) are popular ways to increase a particular area's transit network coverage, the fact that they stop only every mile on average to maintain a high average speed means that many residences and businesses lay beyond an easy walking distance to a station [……] a barrier to better utilization of a rapid transit network.

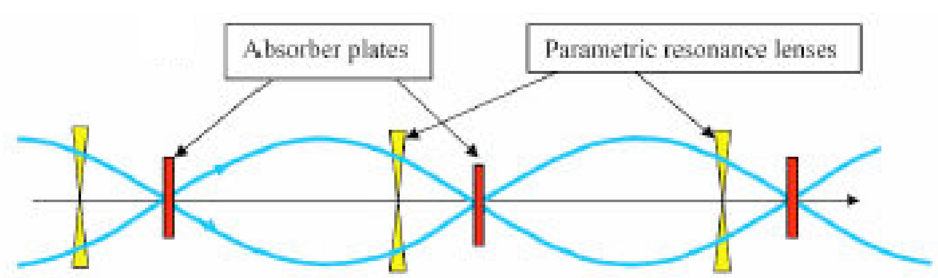
- But we have a different “last mile” problem
  - we’ve shown how to get within an order of magnitude of the desired 6D emittance!
    - what about that last factor of 10???

“Beyond” 6D Cooling

Ya. Derbenev (JLab), R. Johnson (Muons), R. Palmer, H Sayed (BNL)

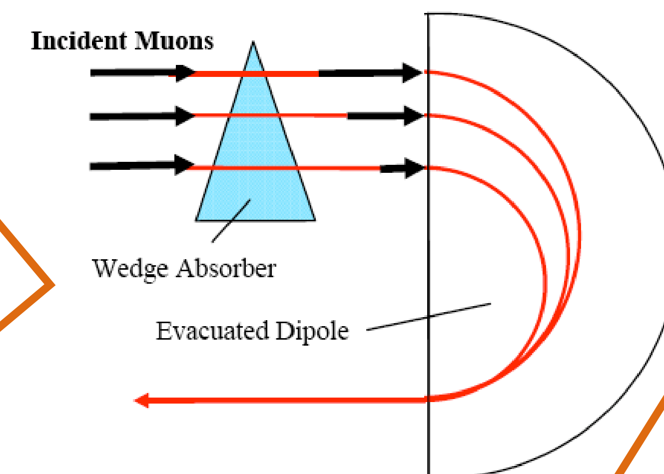
- Can cool beam yet further with new approaches:
  - Parametric-resonance Ionization Cooling (PIC)...





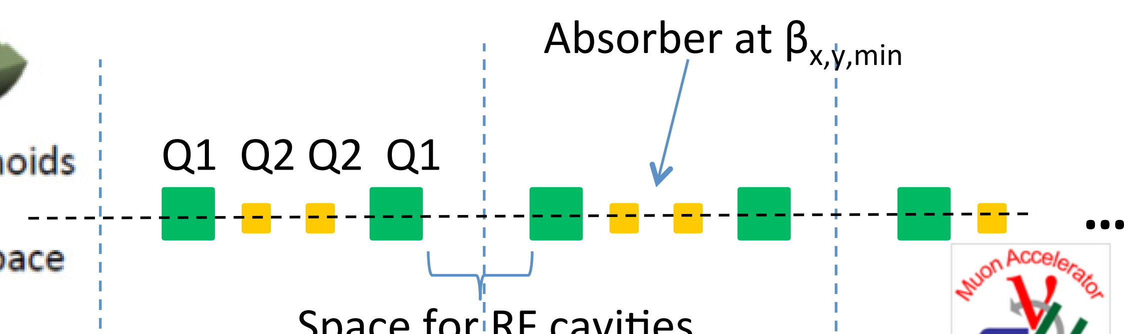
Morozov talk (Tuesday)

… & Reverse Emittance Exchange (REMEX):

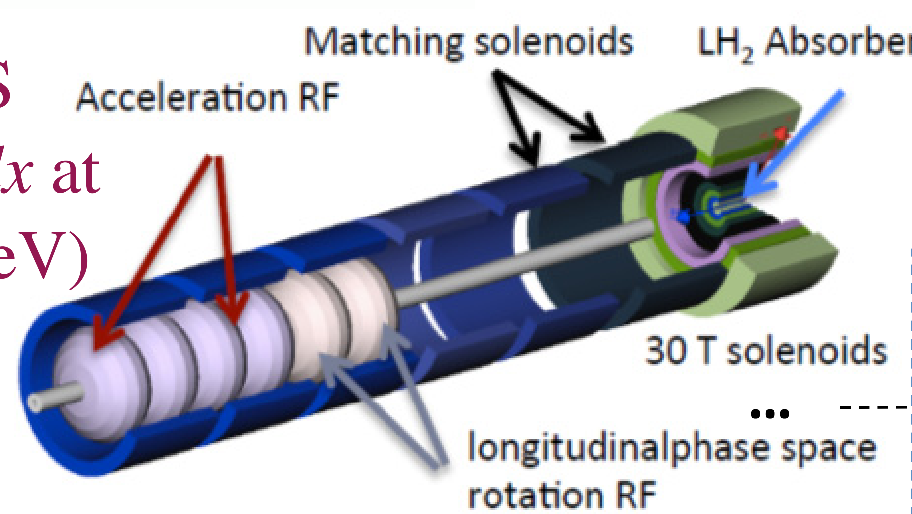


Acosta & Neuffer posters (this PM)

  - or with quad-focused channel and reverse emittance exchange? …



  - or with ~ 30 T HTS solenoids and *dE/dx* at low energy (~ 5 MeV)



R. Palmer talk (this PM)

“Rubbia Vision”

[see e.g. C. Rubbia, “A complete demonstrator of a muon cooled Higgs factory,” arXiv:1308.6612; http://tinyurl.com/oe9yesf]

- Higgs physics is best done at muon collider!
  - scan Higgs resonance with precision and *precisely* ($\leq 1\%$) measure branching ratios

    $\Longrightarrow$ *s*-channel $\mu^+\mu^-$ Higgs Factory: E = 126 GeV ± ε

    - want $\mathcal{L} > 10^{32} \rightarrow \sim$ 50,000 Higgs/yr/detector

      $\Longrightarrow$ need new (“beyond 6D”) cooling technique
  - must also go above 2-Higgs production threshold and measure Higgs self-coupling

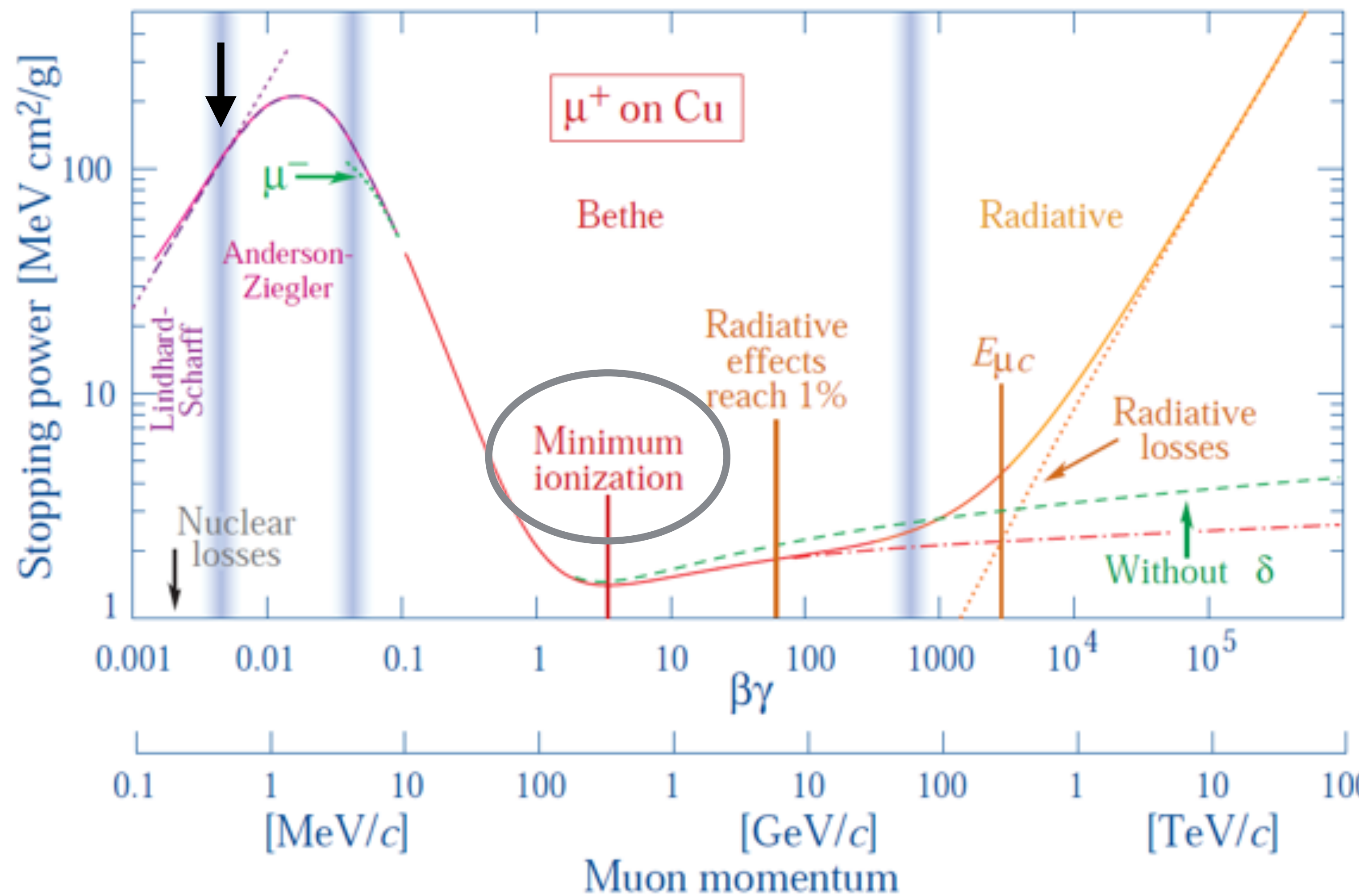
    $\Longrightarrow$ TeV muon collider upgrade
  - “no other” approach is as capable!

necessary in order to rule out, or confirm, alternatives to SM Higgs

need to reinforce R&D effort (CERN?)

Frictional Cooling

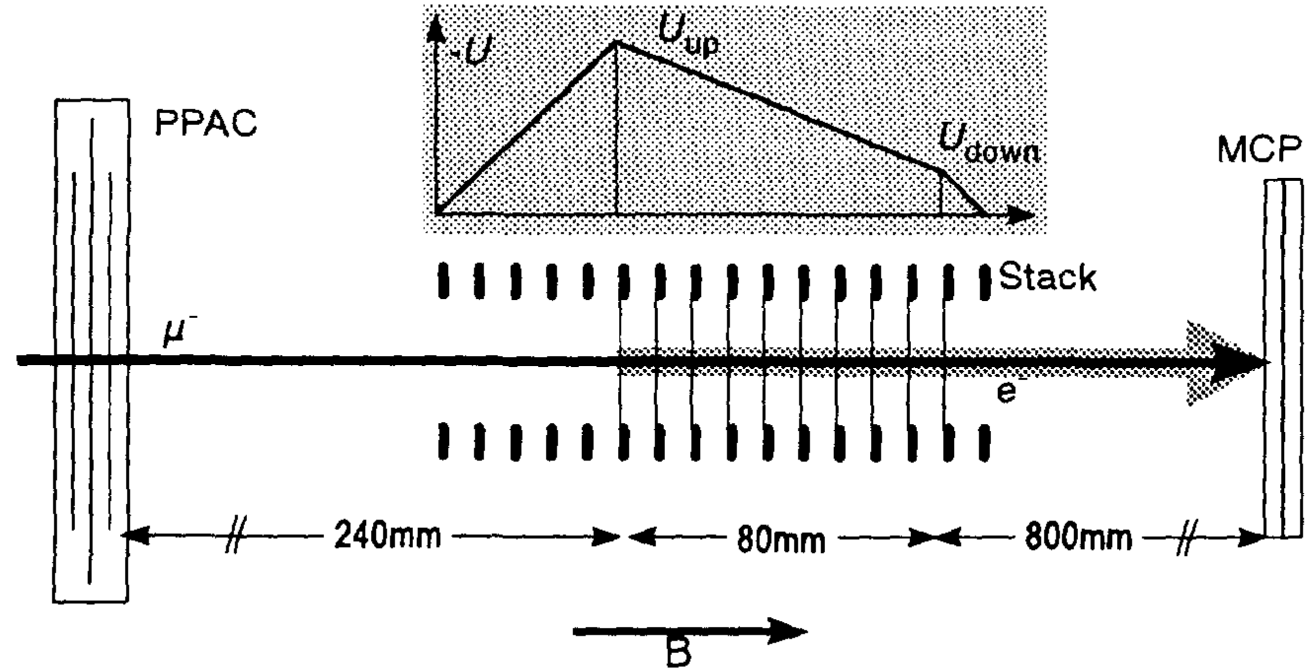
- Conventional ionization cooling works at the ionization *minimum*!



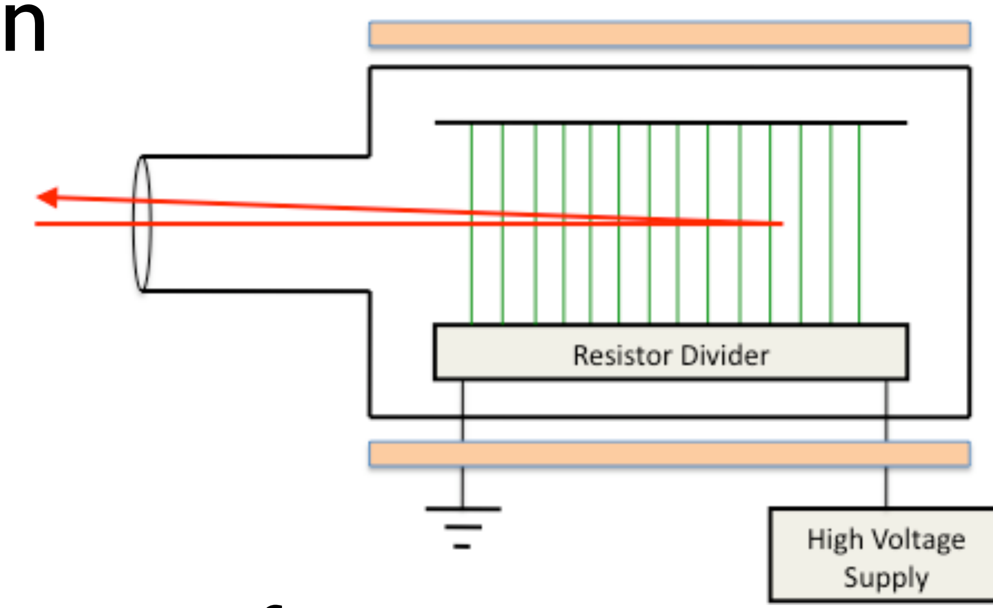
- Why not work where *dE*/*dx* is 2 orders of magnitude *larger*, and → – feedback?
  - answer: momentum acceptance ≲ 10 keV
  - but still of interest for low-energy applications

Frictional Cooling

- Can use foil stacks (or gas, but sparks)
- Idea to increase momentum acceptance: "Particle Refrigerator" (possible use: cooled-muon cargo-container scanning?)
- Planned surface-muon-beam application:
  - increase phase-space density of stopping muon beam @ PSI

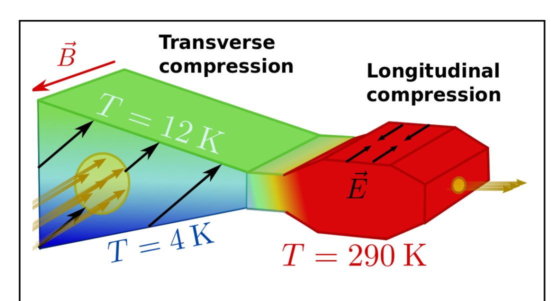


[M. Mühlbauer et al., Nucl. Phys. B Proc. Suppl. 51A, 135 (1996)]



T. Roberts, Muons, Inc.

[T. Roberts, D. M. Kaplan, PAC2009, WE6PFP096]



Knecht talk (Thursday)

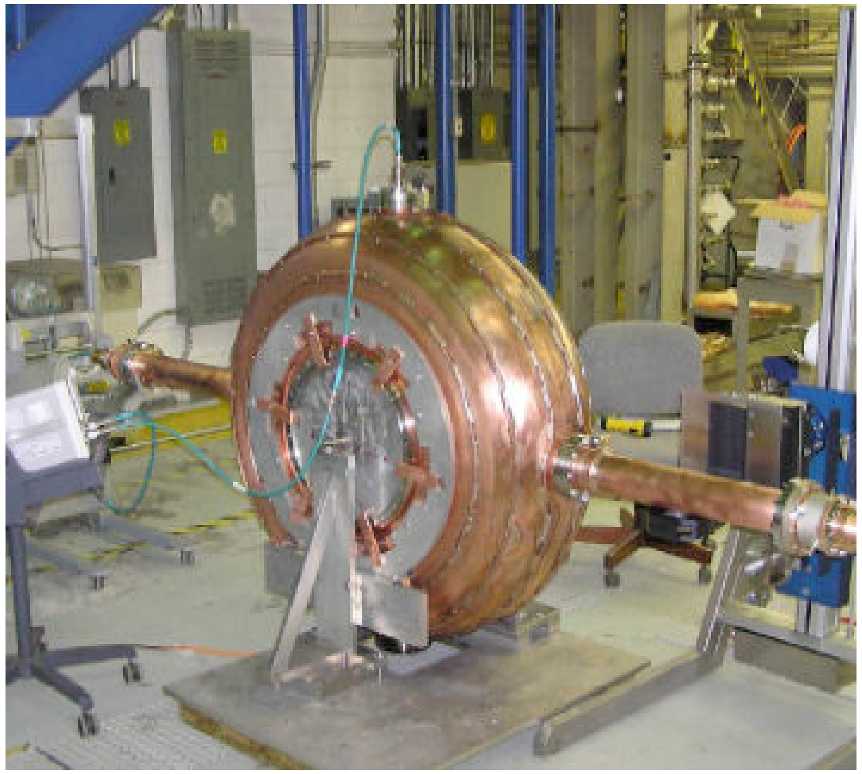
Muon Cooling R&D

- MICE: build and test a section of cooling channel
- Efficient ionization-cooling channel requires high-gradient RF cavities in strong focusing fields

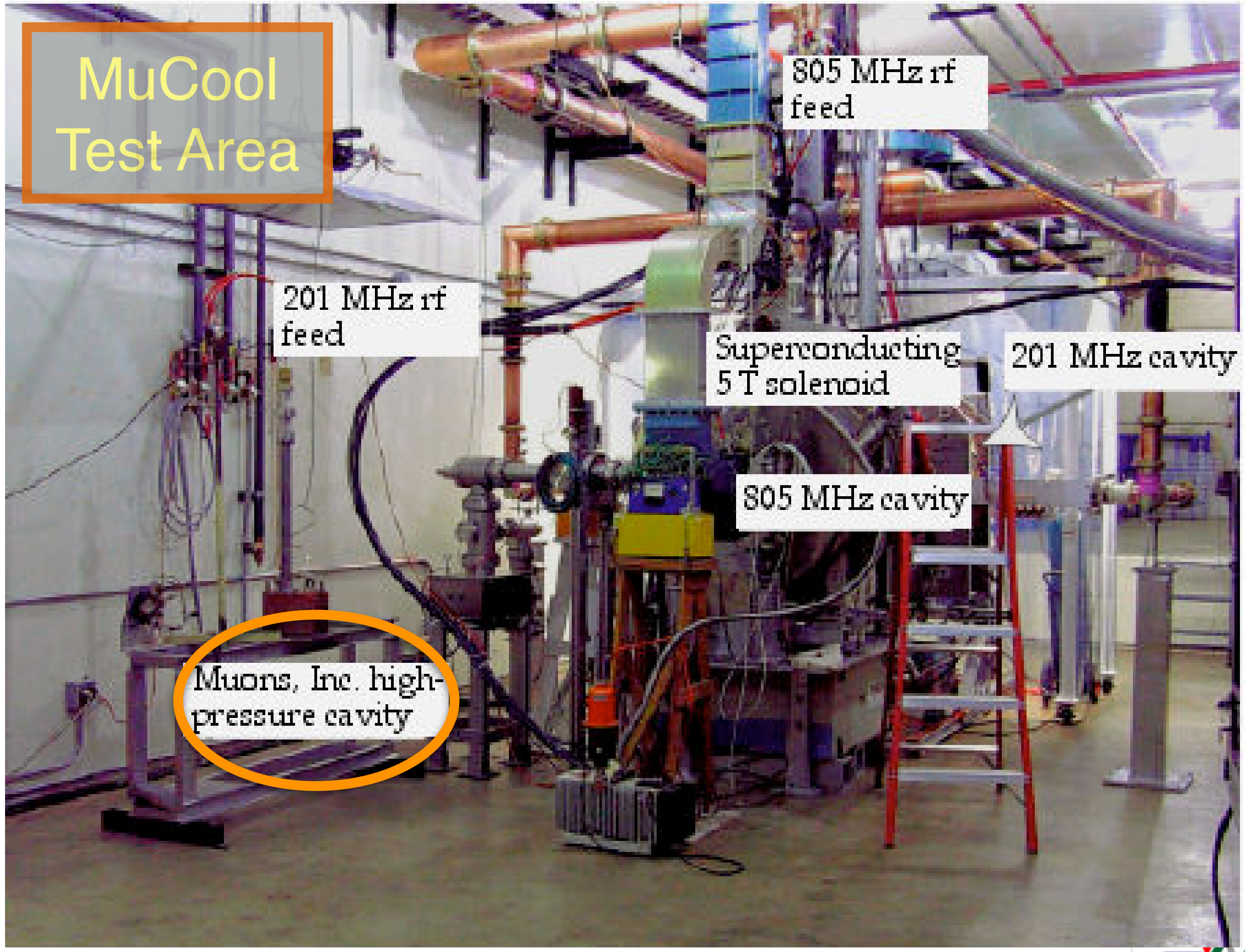
Rogers talk (Tuesday)

⟶ high-gradient NC cavity studies at Fermilab

  - large beam ⇒ low RF freq. (now 325/650 MHz)



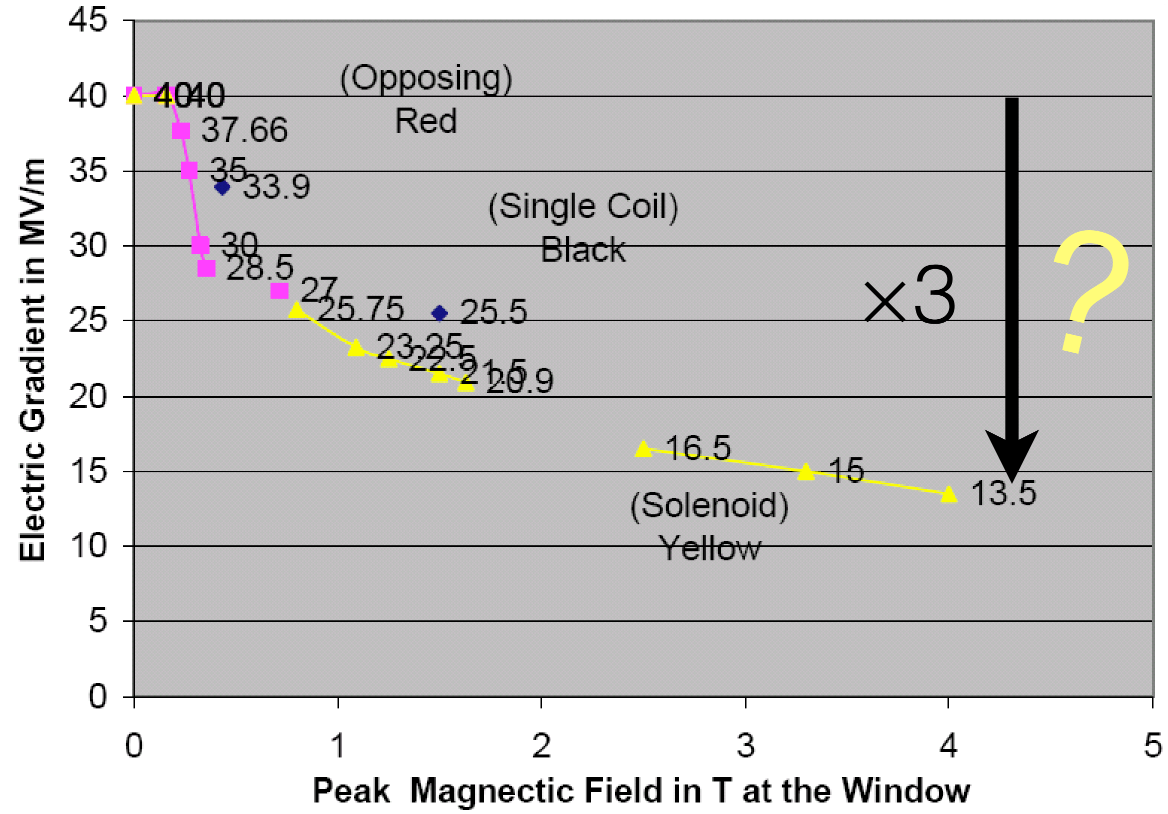
Prototype MICE 201-MHz cavity



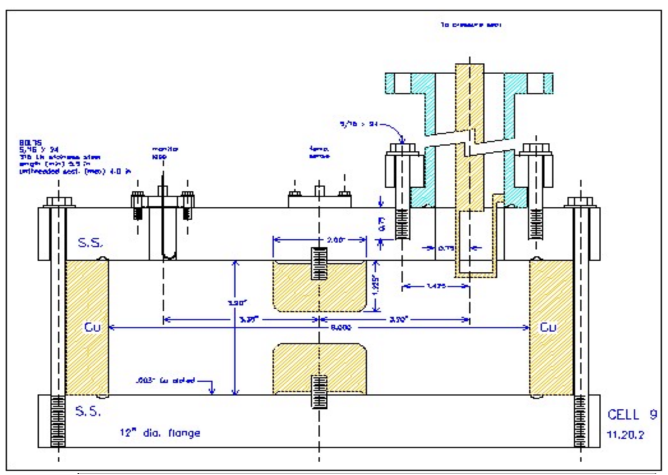
Freemire talk (Thursday)

RF Cavity R&D

- Early work showed strong spark-probability increase with *B*-field
  - suppressed by high-pressure H_2 fill



805 MHz Test Cell

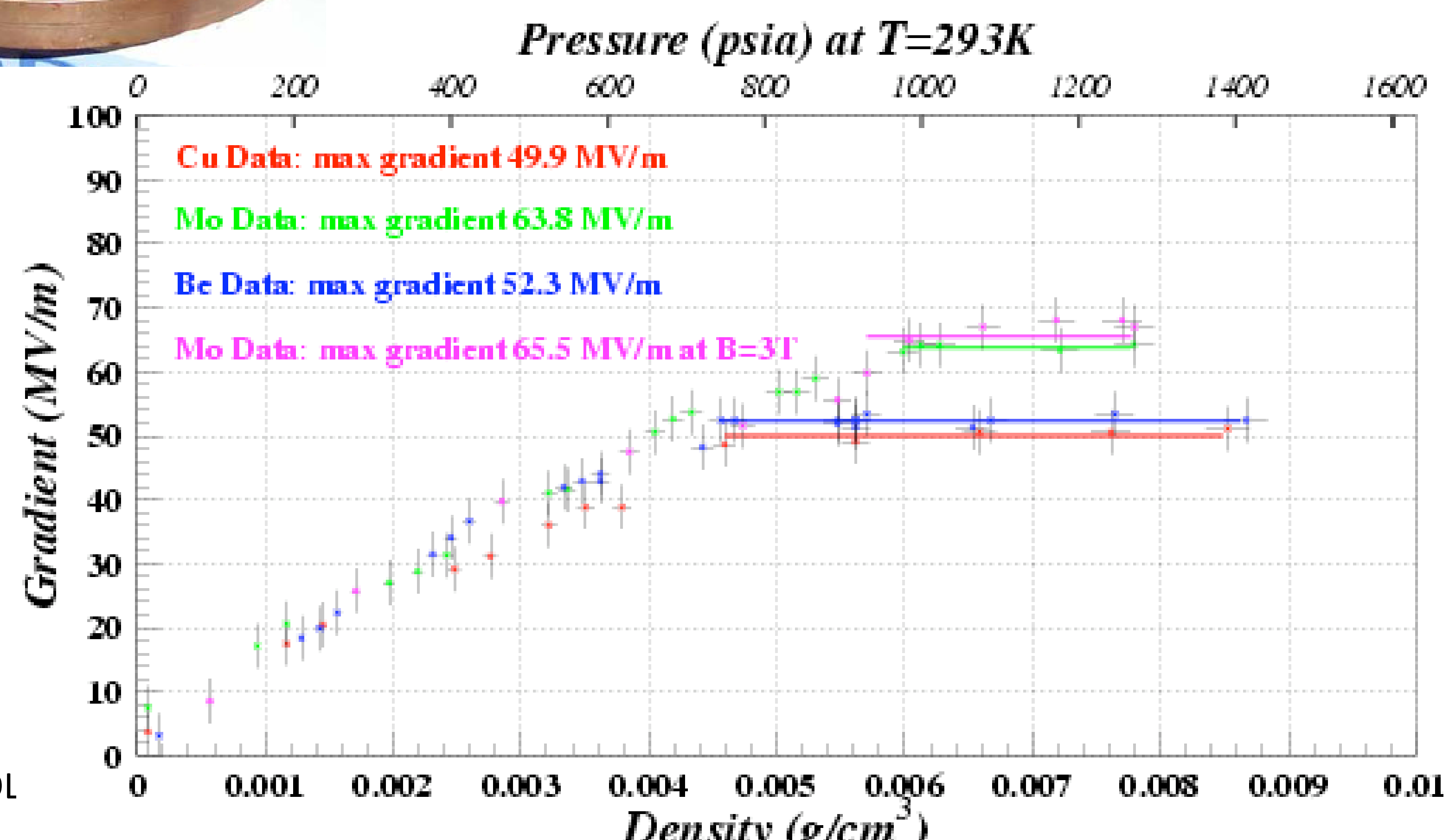


High-P Electrode Structure

- Newer vacuum cavities perform better

Freemire talk (Thursday)

and M. Palmer talk (this PM)



Summary

- Muon cooling looks feasible
- Promising facility designs conceived
- Neutrino Factory: best future ν facility
- "Heavier electron" colliders remain compelling
  - cf. C. Rubbia, "A complete demonstrator of a muon cooled Higgs factory," arXiv:1308.6612; http://tinyurl.com/oe9yesf
- Appealing solutions to "last mile" problem proposed
- See coming talks…

In Memoriam

- We lost three pioneering leaders this year

Andy Sessler,
1928–2015

Dave Cline,
1933–2015

Mike Zisman
1944–2015

- All made important contributions to muon collider R&D
- We will miss them!