Overview of Past Muon Accelerator R&D

Daniel M. Kaplan

Muon Accelerator Program

ILLINOIS INSTITUTE OF TECHNOLOGY
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Workshop on Muon Collider Testing Opportunities
Zoom-land
25 March 2021

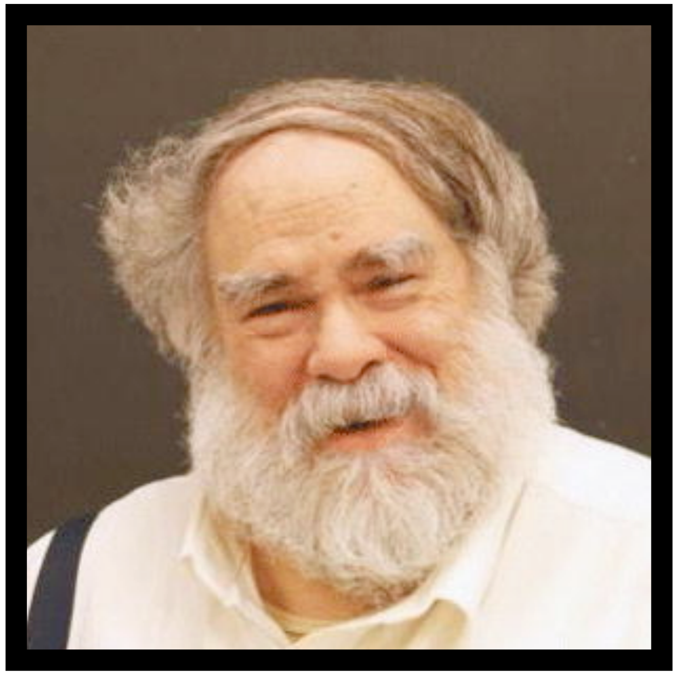
Outline

- Brief history
- R&D overview
- Technology Demonstrations
- Summary

R.I.P.

Yuri Alexahin
1948–2020

Don Summers
1951–2021



"A Brief History of Muons"

(See also https://puhep1.princeton.edu//mumu/physics/index.html)

- Muon storage rings: an old idea
  - Charpak et al. (g – 2) (1960), Tinlot & Green (1960), Melissinos (1960)
- Muon colliders suggested by Tikhonin (1968), Neuffer (1979)
- But no concept how to achieve high luminosity until ionization cooling proposed
  - O'Neill (1956), Lichtenberg *et al.* (1956)
  - for muon cooling: Skrinsky & Parkhomchuk (1981), Neuffer (1983)
- Realization (Neuffer & Palmer) high-luminosity muon collider might be feasible stimulated workshops & formation (1995) of (Neutrino Factory and) Muon Collider Collaboration (NFMCC)
  - subsequently grew to 47 institutions and >100 physicists
- Snowmass Summer Study (1996):
  - feasibility study of a 2+2 TeV Muon Collider [Fermilab-conf-96/092]

"A Brief History of Muons"

- Neutrino Factory suggested by Geer (1997) at Workshop on Physics at the First Muon Collider and the Front End of the Muon Collider [AIP Conf. Proc. 435; Phys. Rev D 57, 6989 (1998) [D59:039903,1999(E)]; also CERN Neutrino Factory yellow report (1999) [CERN 99-02, ECFA 99-197]
- Formation of ICAR (1998) and Muons, Inc. (2002)
- Muon Ionization Cooling Experiment (MICE) proposed (2003)
- Fermilab Muon Collider Task Force (MCTF) established (2006)
- At DOE request, NFMCC & MCTF consolidated (2012) into Muon Accelerator Program (MAP)
- MAP terminated (2017) by DOE (P5 report, 2013)
- MICE observed cooling (2018)
- European work resumed (2019) – LEMMA,…
- European Strategy endorsed MC R&D (2020)

Muon Accelerator (partial) Timeline

- 1960-80: Early ideas
- '81-3: Ionization Cooling proposed
- 1995: Muon Collider Collab. formed
- '96: **Snowmass96 MC Feas. Study report**
- 1997: Neutrino Factory conceived, MCC renamed NFMCC
- '99: Eur. NF Feas. Study; annual NuFact work-shops begin
- 2000: **(Fermilab-led) NF Feasibility Study (I)**
- '01: **(BNL-led) NF Feasibility Study II**; Feasibility study of a Neutrino Factory in Japan
- '03: MICE approved; (UK-led) ISS/IDS NF Feasibility Study; **MERIT shows 8 MW target capability**
- '06: Fermilab MCTF formed; MAP formed
- '11: **Practical 6D cooling lattice designs found**
- '14: MAP ramp-down starts
- '15

Muon Accelerator (partial) Timeline

1997 '99 2000 '01 '03 '06 '11 '14 '15 '17 '18 '19 '20 '21

Neutrino Factory conceived, MCC renamed NFMCC

ss96 Study t

Eur. NF Feas. Study

annual NuFact work-shops begin

(Fermilab-led) NF Feasibility Study (I)

(BNL-led) NF Feasibility Study II

Feasibility study of a Neutrino Factory in Japan

(UK-led) ISS/IDS NF Feasibility Study

MICE approved

Fermilab MCTF formed

MERIT shows 8 MW target capability

MAP formed

Practical 6D cooling lattice designs found

MAP ramp-down starts

RF in B field problem solved

MICE completes data-taking

MICE observes cooling

1st Eur. MC work-shop

LEMMA proposal

50 MV/m @ 3T vac. RF PRAB paper

ESG endorses MC R&D

MICE Nature article

Some MC/NF source material:

- **Neutrino Factory Feasibility Study II report** [BNL-52623 (2001)]
- **Recent Progress in Neutrino Factory and Muon Collider Research within the Muon Collaboration,** M. Alsharo'a et al., Phys. Rev. ST Accel. Beams 6, 081001 (2003)
- APS Multidivisional Neutrino Study [www.aps.org/neutrino/ (2004)]
- Recent innovations in muon beam cooling, R. Johnson *et al.*, AIP Conf. Proc. 821, 405 (2006)
- Muon Colliders and Neutrino Factories, S. Geer, Annu. Rev. Nucl. Part. Sci. 59, 347 (2009)
- **International Design Study for the Neutrino Factory**, Interim Design Report [IDS-NF-20, BNL-96453-2011, CERN-ATS-2011-216, EURONU-WP1-05, FERMILAB-PUB-11-581-APC, RAL-TR-2011-018, FERMILAB-DESIGN-2011-01], arXiv:1112.2853 [hep-ex]
- **Muon Colliders,** R.B. Palmer, Rev. of Accel. Sci. and Tech. 7 (2014) 137–159
- map.fnal.gov; www.cap.bnl.gov/mumu/; mice.iit.edu; proj-hiptarget.web.cern.ch
- **JINST Special Issue on Muon Accelerators** [iopscience.iop.org/journal/1748-0221/page/extraproc46]

Repository for archival MAP and MICE papers

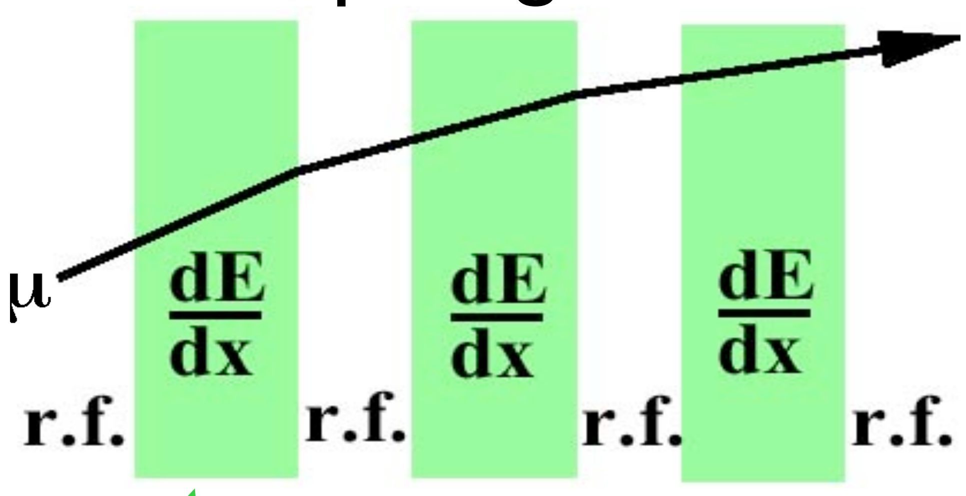
- The future prospects of muon colliders and neutrino factories, M. Boscolo, J.-P. Delahaye, M. Palmer, Rev. of Accel. Sci. and Tech. 10 (2019) 189-214

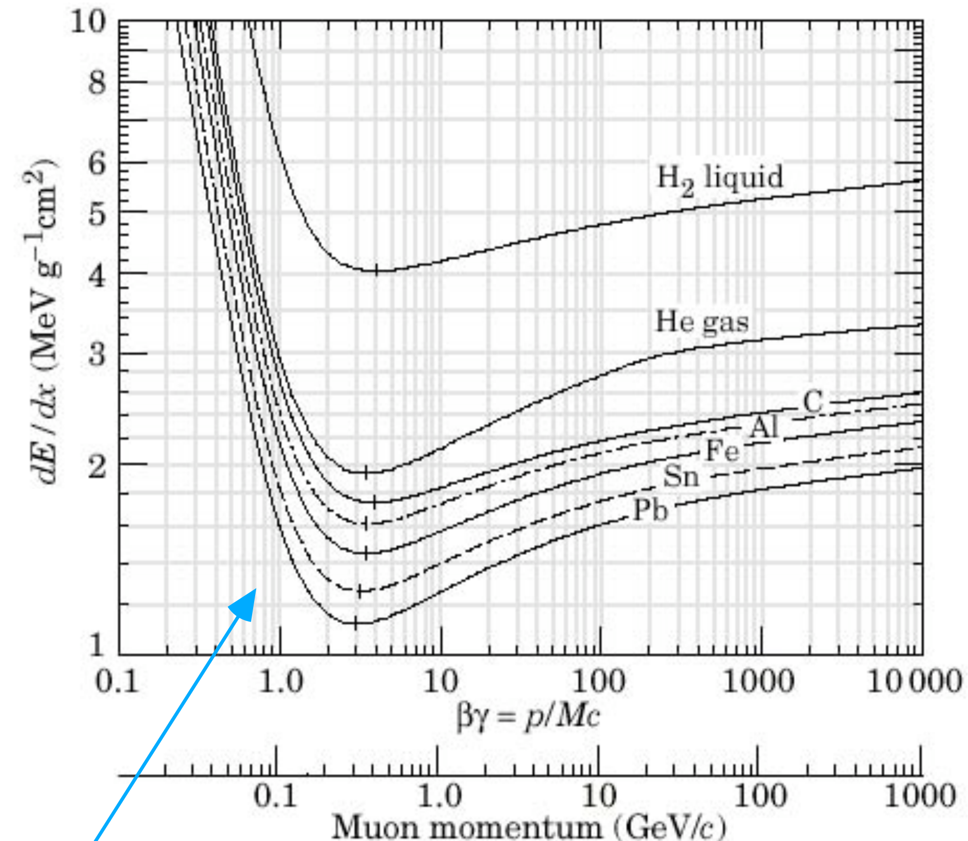
Challenges:

- High power beam & target
- Rapid, 6D muon cooling
- Final cooling to extreme emittance
- Rapid muon acceleration
- High-field low-β storage ring
- (neutrino radiation)

Ionization Cooling

- Two competing effects:





  – Absorbers:

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

ionization energy loss

multiple Coulomb scattering

  – RF cavities between absorbers replace ΔE
  – Net effect: reduction in muon $\Delta p_{\perp}$ at constant $p_{||}$, i.e., transverse cooling

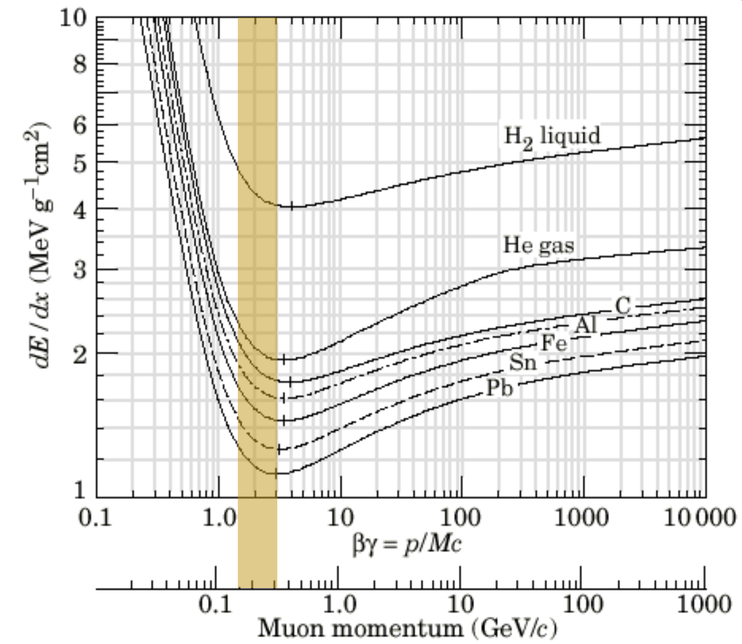
$$\frac{d\epsilon}{ds} \approx -\frac{1}{\beta^2}\left\langle \frac{dE_\mu}{ds} \right\rangle \frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\,\text{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$

(emittance change per unit length)

Note: It's "just Maxwell's equations," so in principle it *has* to work!
But complicated in practice… *so a test was essential!* → ***MICE***

Comments on Ionization Cooling

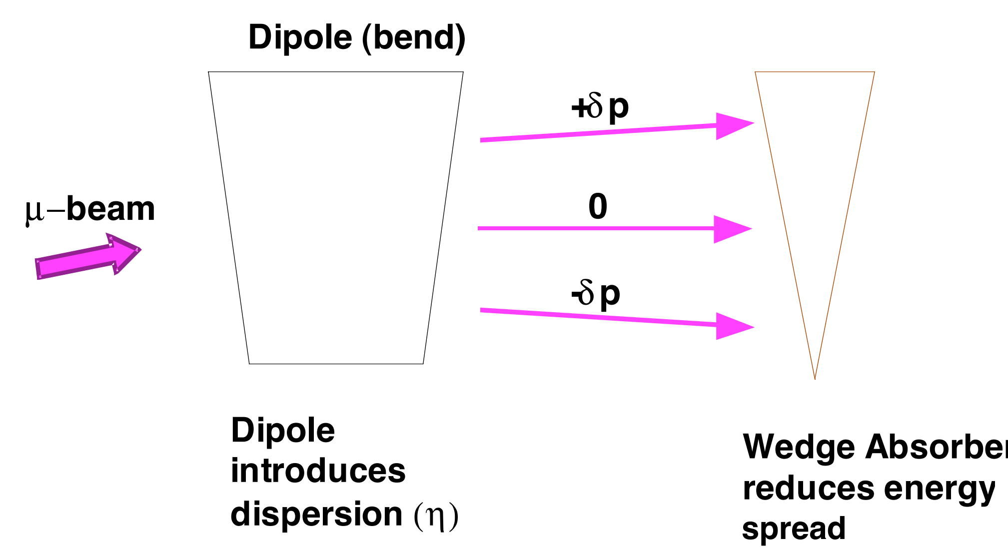
1. Effect is transverse only
   - might hope to cool longitudinally via dE/dx curve's slight positive slope above ionization minimum
   - but dE/dx "straggling" tail causes heating



2. To optimize cooling requires:
   - low $\beta_\perp$ (via, e.g., SC solenoids)
   - large-X_0 (low-Z) absorber material
   - low E_μ (typ. $150 < p_\mu < 300$ MeV/c)

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

3. Can "rotate" portion of effect into longitudinal phase plane via "emittance exchange"
   - allows cooling of all 6 phase-space dimensions

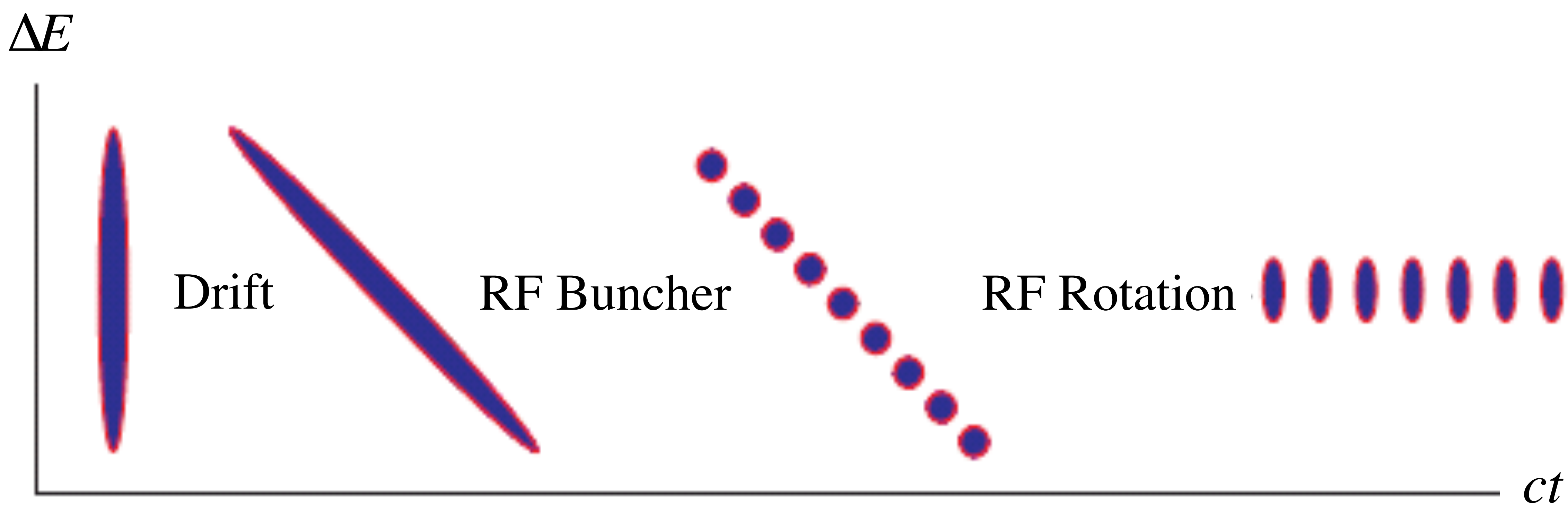


$$x \rightarrow x_0 + \eta\, {}^{dp}\!/_{p}$$

Preparing for Ionization Cooling: Phase Rotation

Example: International Scoping Study (ISS) νF design [JINST 4, P07001 (2009)]

- Muons born with small Δt but large ΔE
- 1st bunch, then phase-rotate:



Bunching via RF "vernier" [D. Neuffer]

D. Neuffer *et al*. 2017 *JINST* **12** T11007

– uses several RF frequencies, starting at ≈ 300 MHz, decreasing to ≈200 MHz

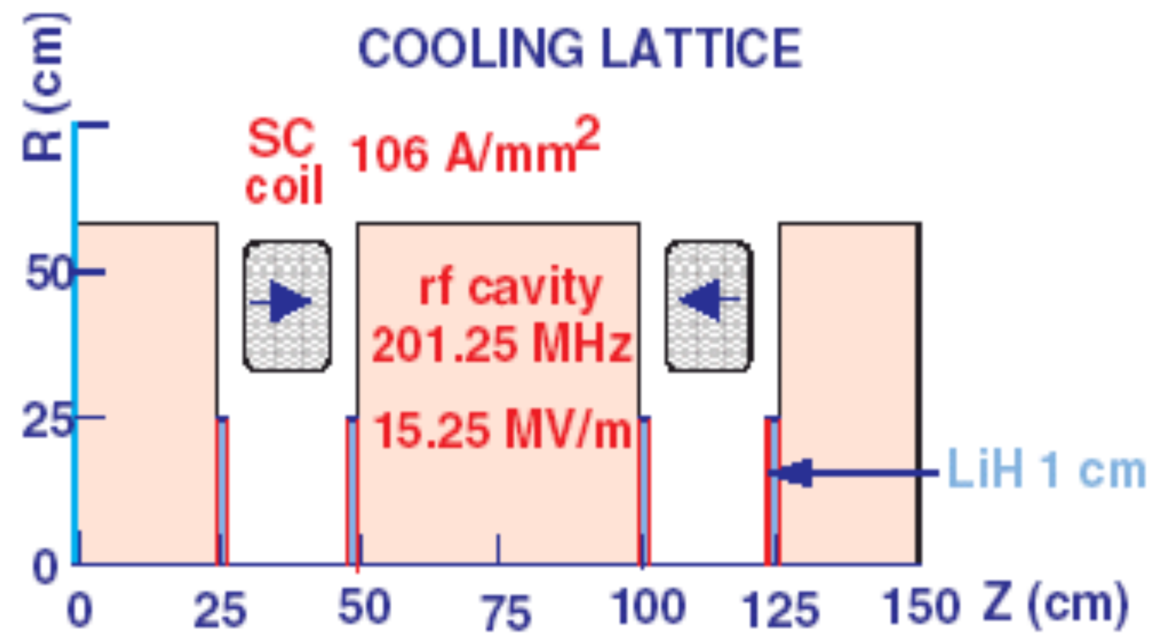
– works for both signs at once → train of alternating μ^+ and μ^- bunches

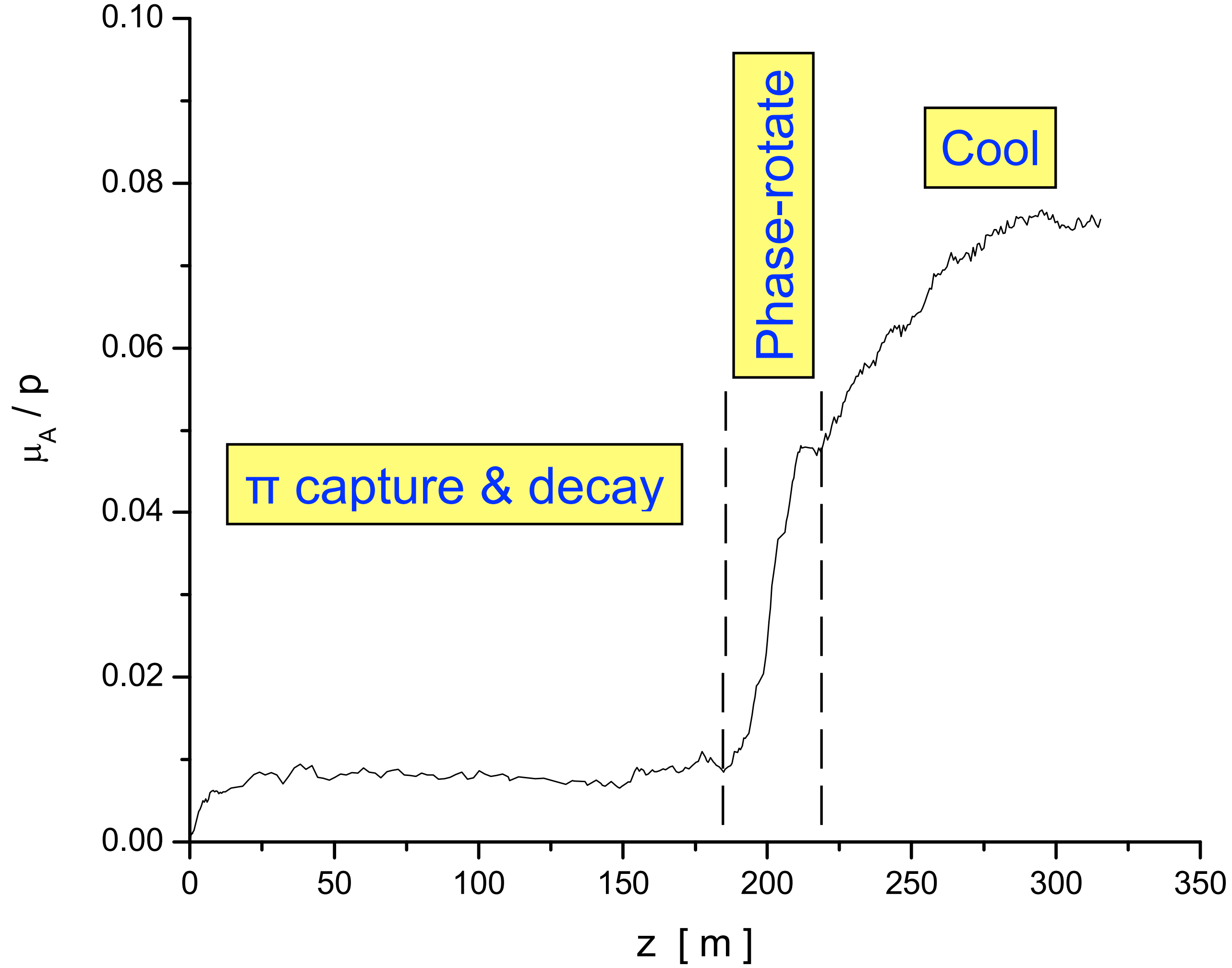
Transverse Ionization Cooling

ISS scheme:

[M. Apollonio et al., JINST 4, 7 (2009) P07001]

- Cost-effective alternating-solenoid lattice
- Thin, Be-coated LiH absorbers double as RF-cavity windows



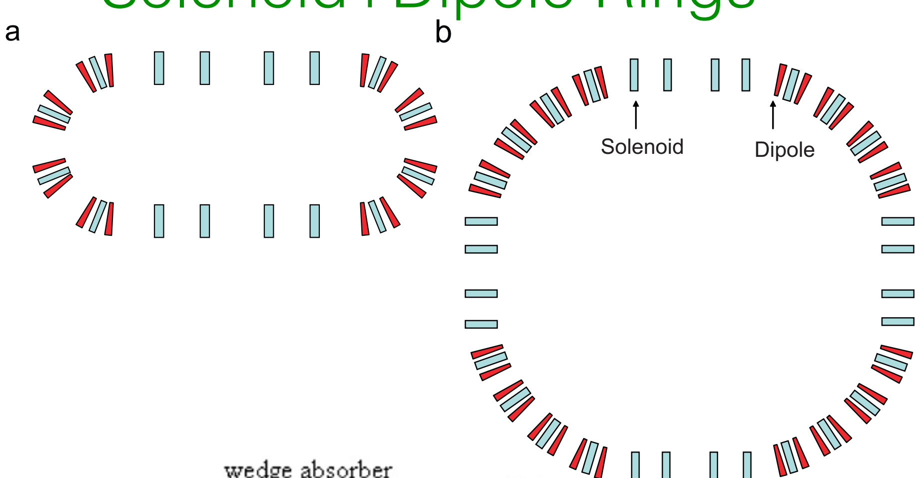


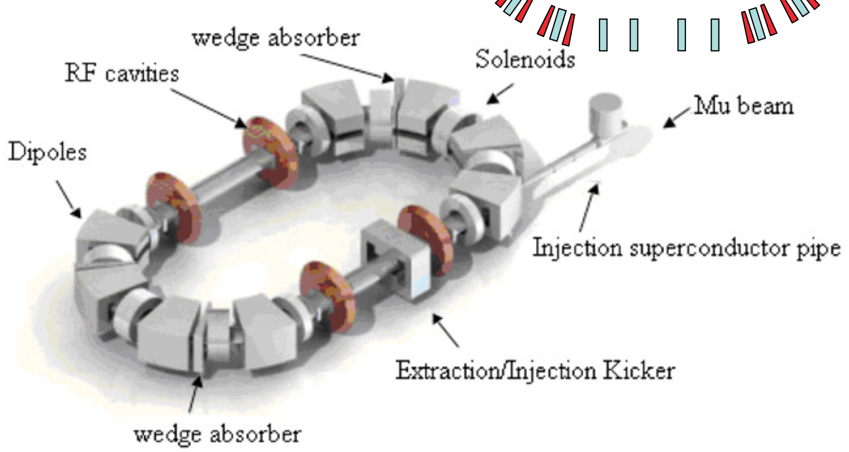
- 80m-long cooling channel increases muon intensity × 1.6
  - less expensive than higher-intensity proton driver and target
- Accepts and cools μ^+ and μ^- simultaneously
- Superseded by Alexahin 6D scheme…

6D Cooling Approaches

- Transverse ionization cooling self-limiting due to longitudinal-emittance growth, leading to particle losses
  - – caused by energy-loss straggling plus channel's finite ΔE acceptance
  - ⇒ *need* longitudinal cooling for muon collider (also helpful for NF)
- Variety of cooling ring, wedge-absorber, & spiral lattices explored:

Solenoid+Dipole Rings





A. Garren, D Cline, et al. (UCLA-BNL)

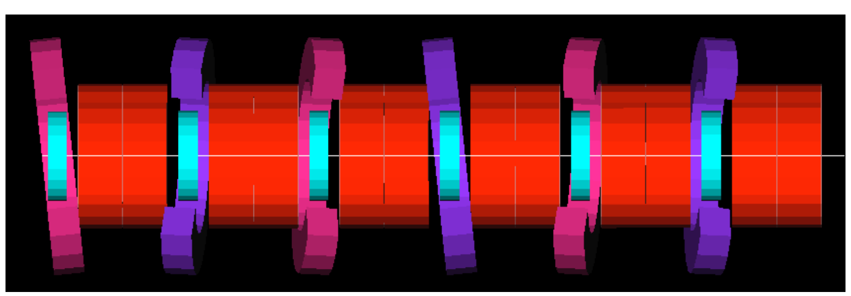
A. Garren *et al.*, NIM A 654 (2011) 40-44

Helical Solenoid

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

K. Yonehara 2018 *JINST* **13** P09003

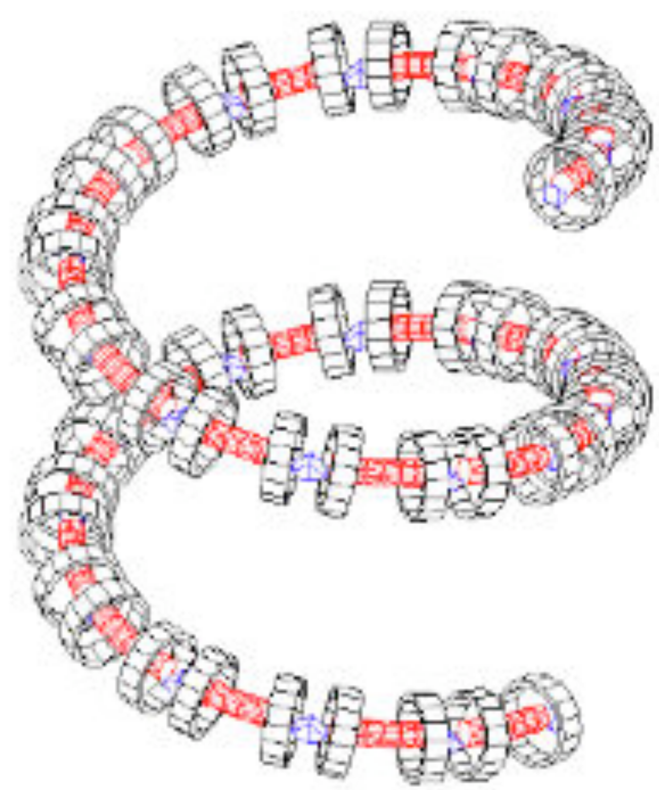
Helical FOFO "Snake"



Y. Alexahin (FNAL)

D. Neuffer *et al*. 2017 *JINST* **12** T11007

RFOFO "Guggenheim"



etc…

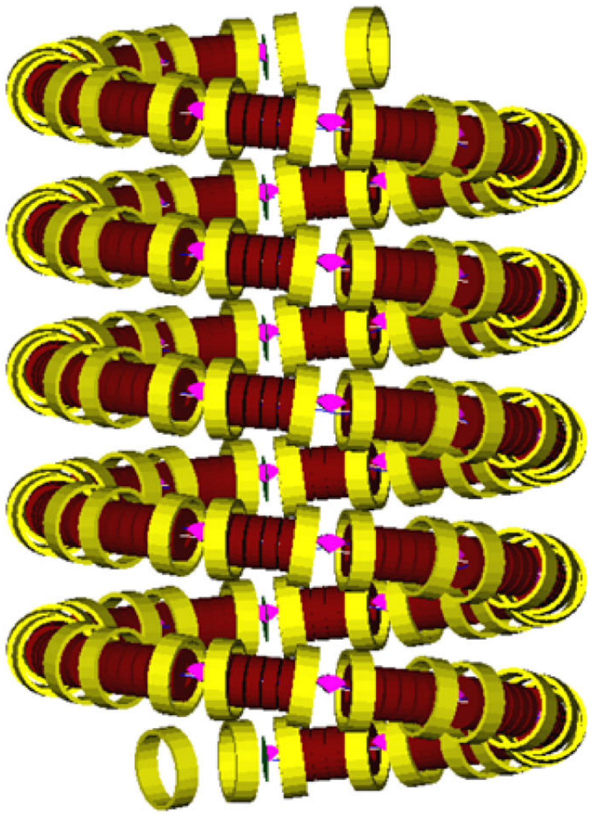
P. Snopok (UCR/IIT) et al.

P. Snopok, G. Hanson, A. Klier, IJMP A 24 (2009) 987–998

⟶ Helices avoid injection/extraction kickers & allow matching of β to $\epsilon(s)$…

6D Cooling Approaches

- Guggenheim and HCC emerged as most practical
  - ring might still make cost-effective 6D demo
- But Guggenheim hard to engineer
- V. Balbekov realized it could be straightened into a "rectilinear FOFO" (R_FOFO) channel without performance loss
  - cools in 6D x10^5 with $\beta^* \downarrow$ 3 cm



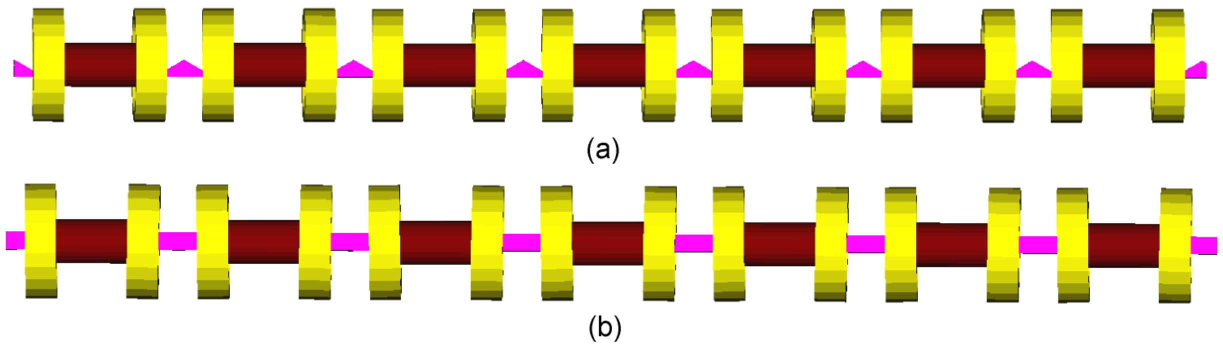
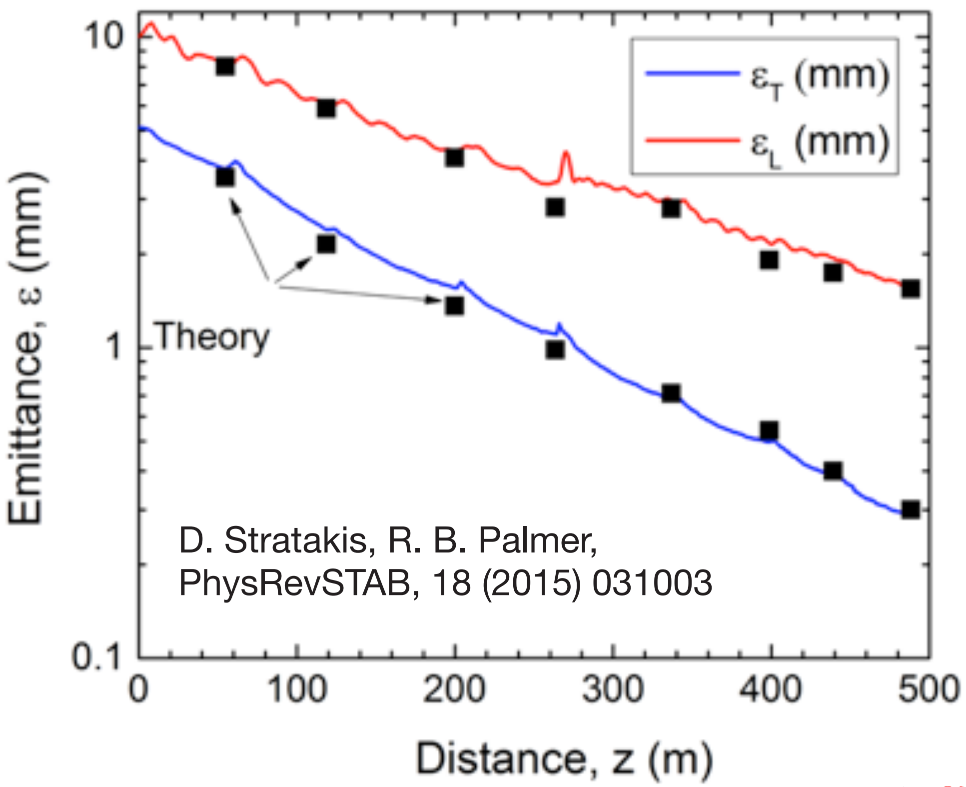


FIG. 2. Conceptual design of a rectilinear channel: (a) top view; (b) side view.



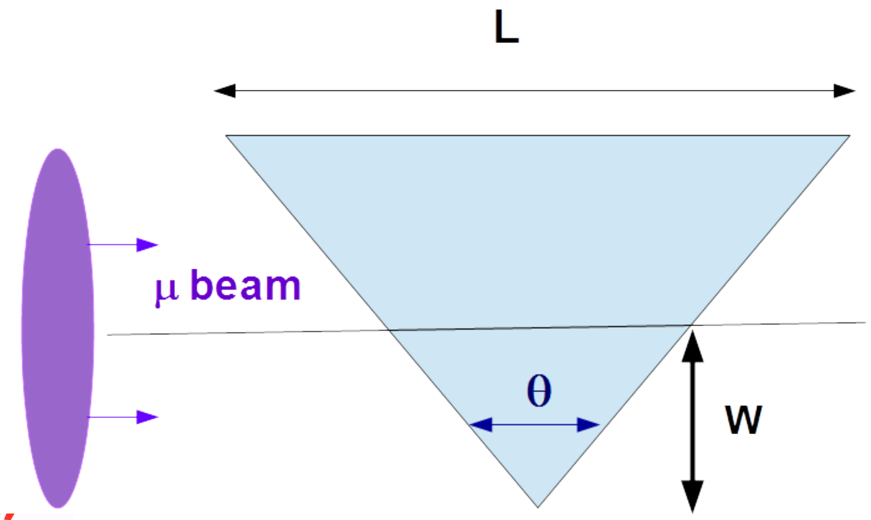
Final Cooling

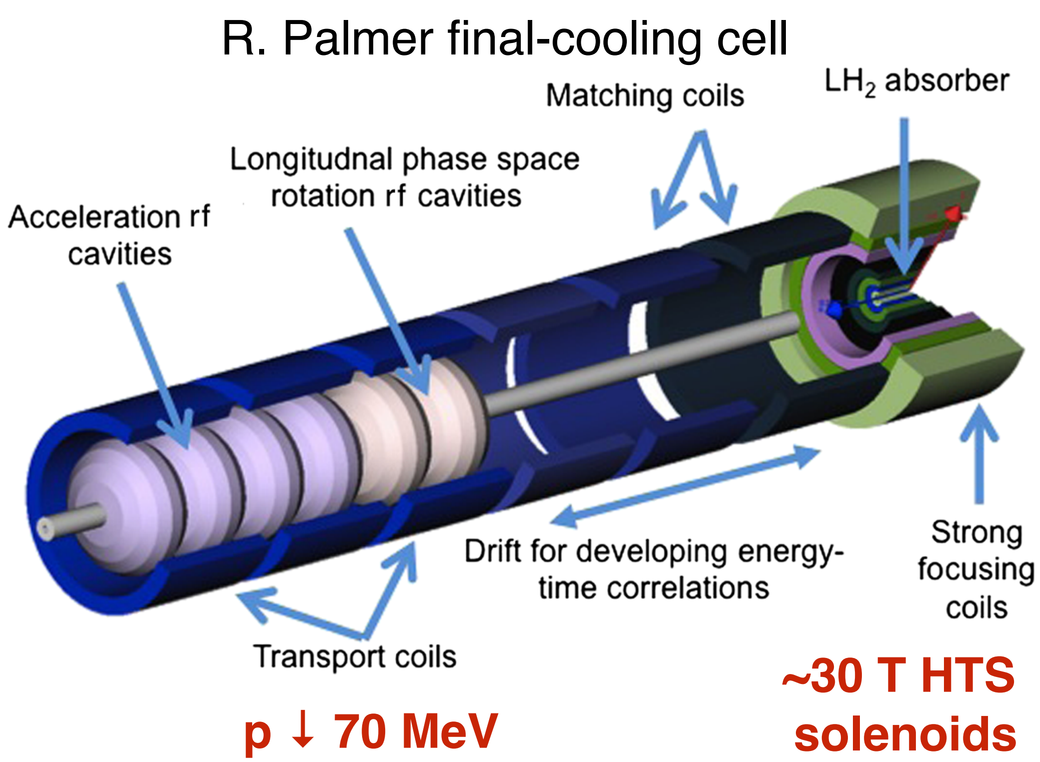
- HFOFO snake + R_FOFO → good (10^{32}) luminosity and superb (4×10^{-5}) energy spread needed for "Higgs Factory"

- For high-luminosity ($>10^{34}$) multi-TeV MC need more ⊥ & less || cooling

⇒ use reverse emittance exchange, ideally with some ⊥ cooling?

⇒ or just wedge absorbers?

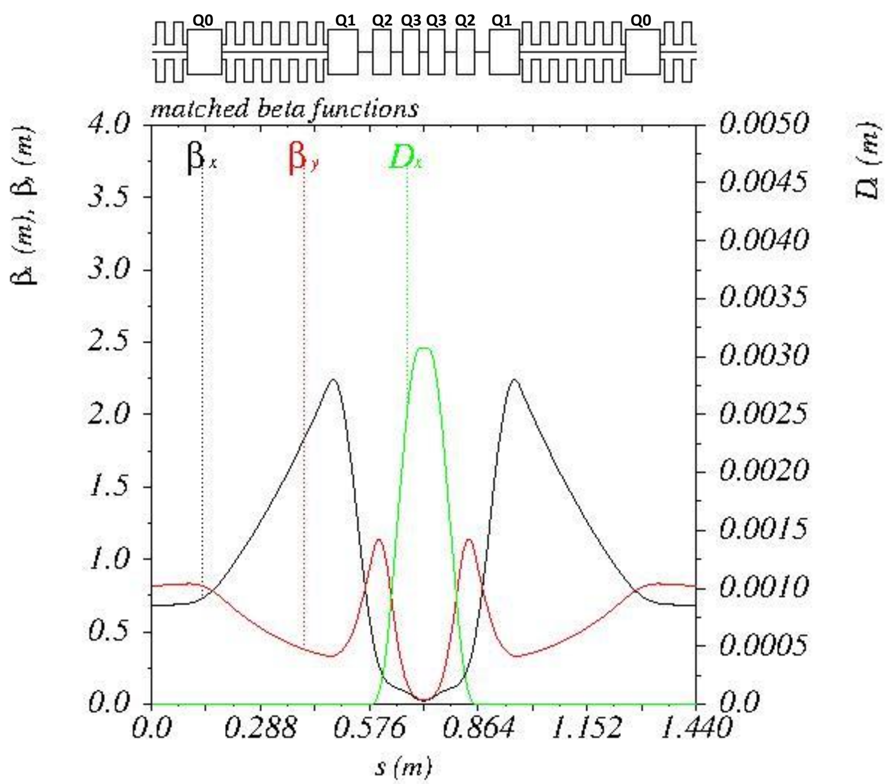




⇒ or quadrupole-focused cooling channel?

Final Cooling

- Can quad focusing reach lower β than SC solenoids?
  - cf. collider final-focus optics
  - recently revisited* by D. Summers *et al.*



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Muon Accelerators for Particle Physics — MUON

Unconventional ideas for ionization cooling of muons

JINST 15 (2020) P03004

T.L. Hart,[a] J.G. Acosta,[a] L.M. Cremaldi,[a] D.V. Neuffer,[b] S.J. Oliveros,[a] D. Stratakis,[b] D.J. Summers[a,1] and K. Yonehara[b]

[a] *Department of Physics and Astronomy, University of Mississippi-Oxford, University, MS 38677, U.S.A.*

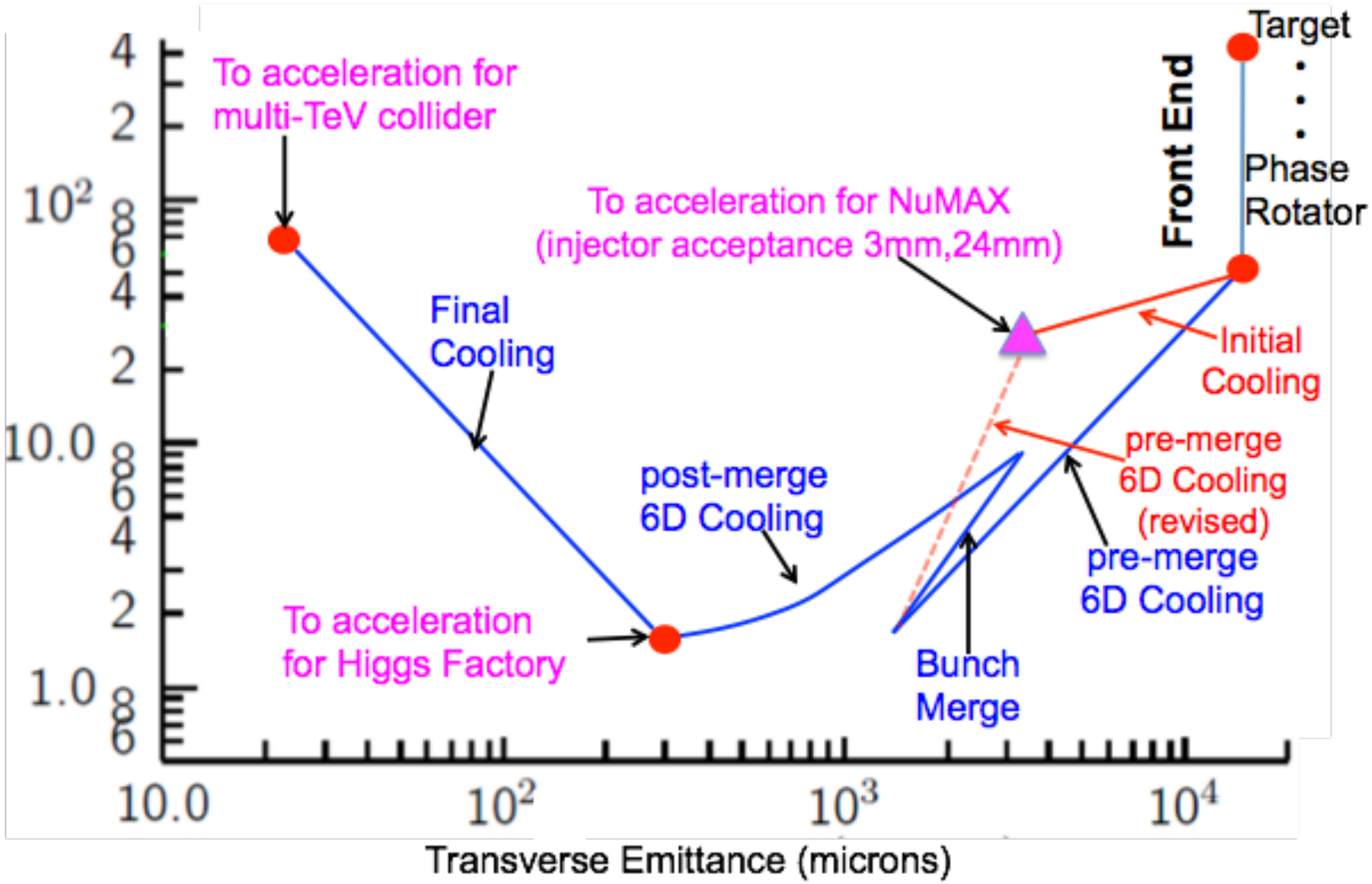
[b] *Accelerator Division, Fermi National Accelerator Laboratory, Batavia, IL 60510, U.S.A.*

E-mail: summers@phy.olemiss.edu

- SC-quad + wedge approach proposed for x5 reduction in final 6D emittance

* cf. C. Johnstone, M. Berz, D. Errede, K. Makino, NIM A 519 (2004) 472-482

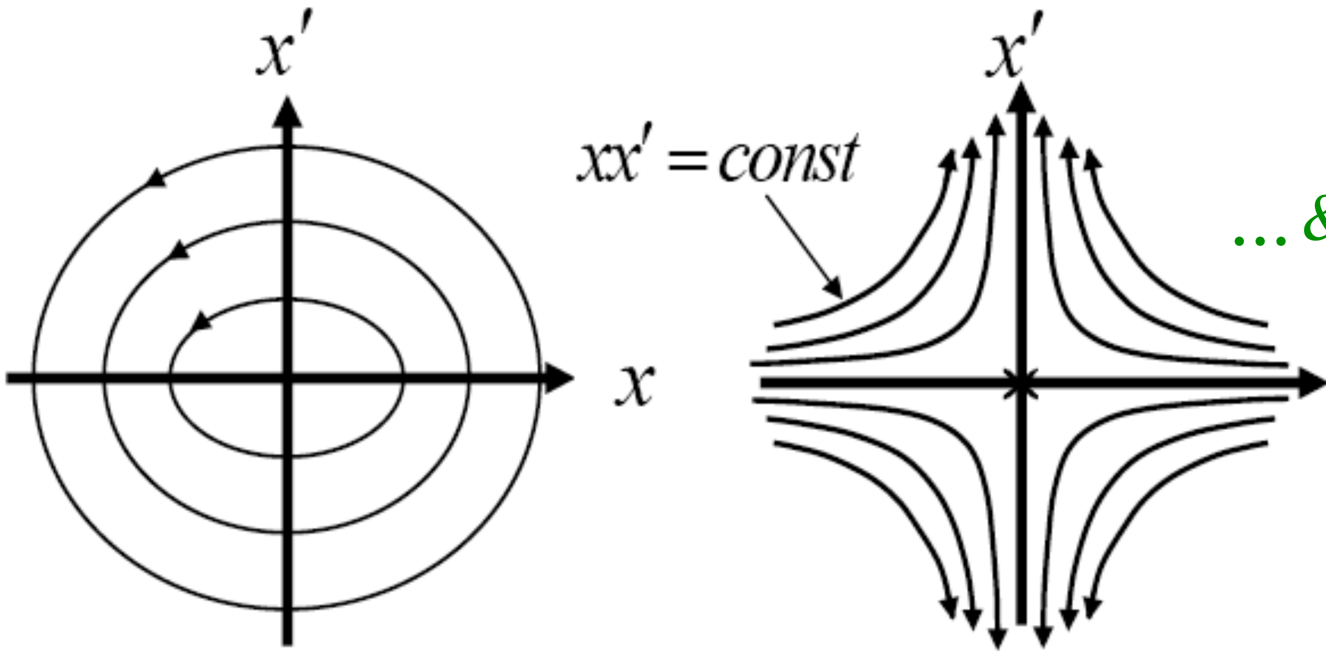
Muon Collider Cooling Scheme

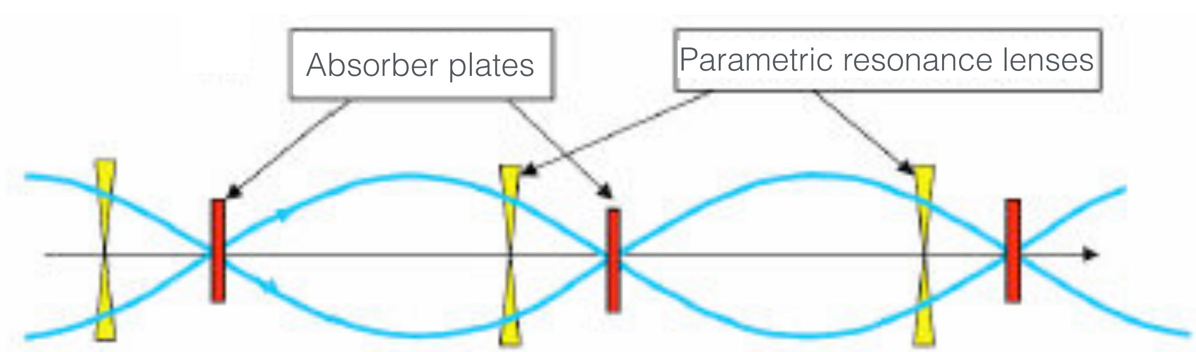


"Extreme Cooling"

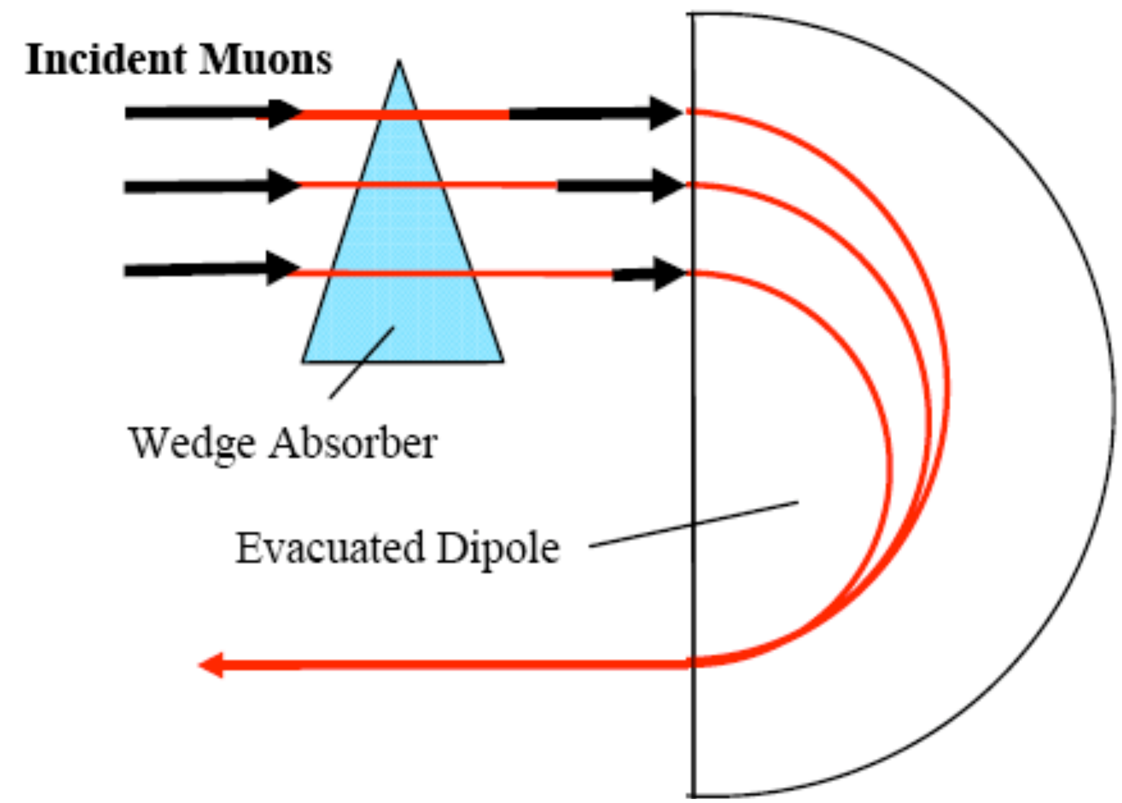
Ya. Derbenev (JLab), R. Johnson (Muons, Inc.)

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

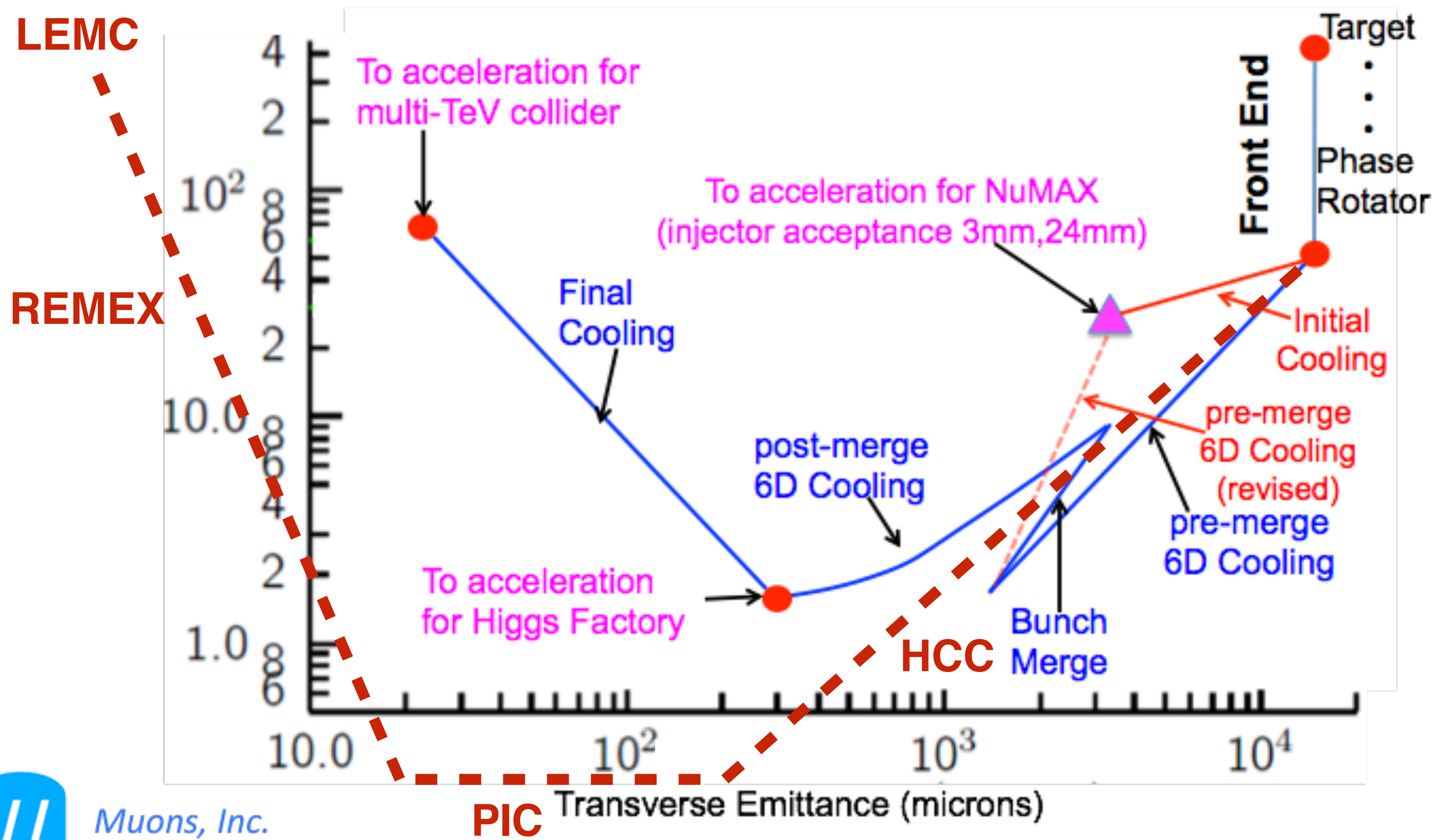




... & Reverse Emittance Exchange (REMEX):



Muon Collider Cooling Scheme



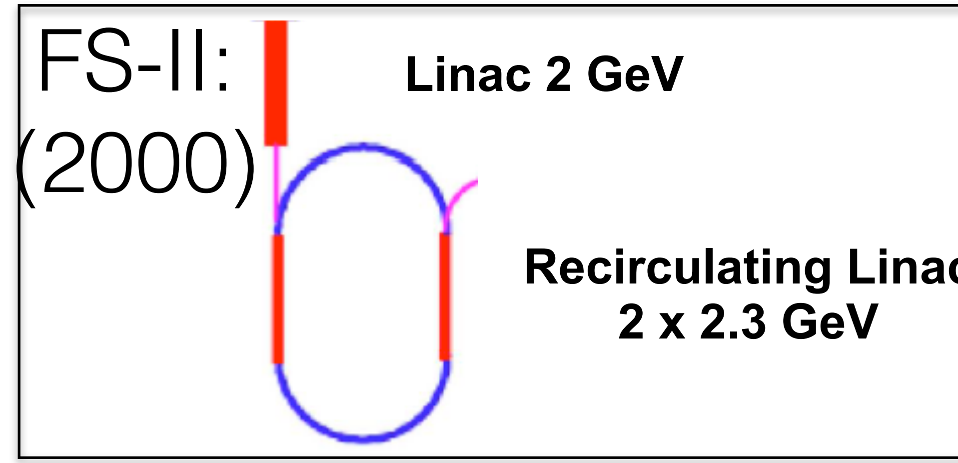
Muons, Inc.
Innovation in Research

→ More than one way to skin this cat...

Rapid Muon Acceleration

- Conventional synchrotrons far too slow!
- After cooling, muons at ≈ 200 MeV/c

  ⇒ must start with linac
- Subsequent stages:
  - previously (FS-I and -II) racetrack RLAs
  - better: dogbone RLAs (D. Summers idea) and novel, non-scaling FFAGs



— and *very*-RCS:

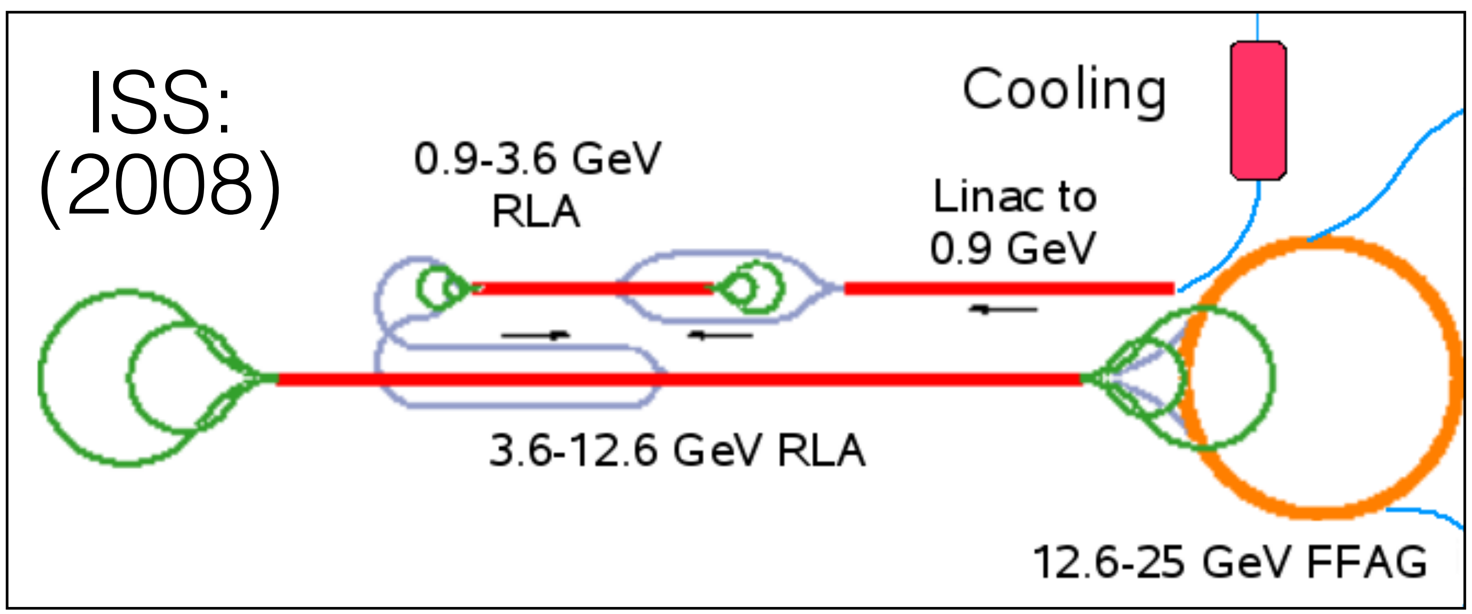
Modify the 400 GeV Main Ring

- 70 → 750 GeV in 68 orbits (1.4 ms). 10 GeV of 1.3 GHz, 30 MV/m SRF. Muon Survival = 79%. r = 1000 m.
- FODO Lattice 30.45 m Long Half Cell. 3.3 m, 160 Hz, 30 T/m Quadrupoles. 3.2 m, 8 Tesla Superconducting Dipoles. 5.7 m, 360 Hz, ∓1.8 Tesla Dipoles. Dipoles oppose, then act in unison. Eddy Currents: Thin copper wire and .28mm grain oriented Si steel laminations.

Q F	∓1.8T Dipole	+8T Dip.	∓1.8T Dipole	+8T Dip.	∓1.8T Dipole	Q D

- 1.5 TeV $\mu^+\mu^-$ Collisions in the MI Tunnel. Little civil construction. Existing tunnels.

(from D. Summers, "Muon Acceleration to 750 GeV in the Fermilab Tevatron Tunnel," NFMCC mtg, UCLA, 2/1/07)

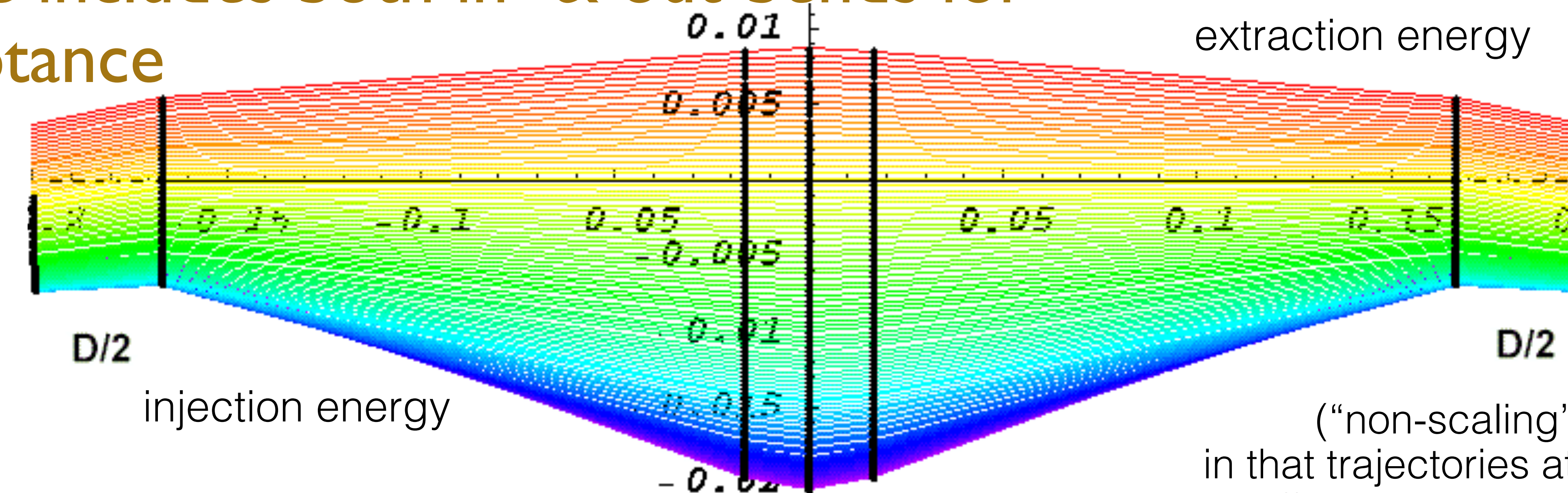


Or the LHC? D. Neuffer, V. Shiltsev, "On the feasibility of a pulsed 14 TeV c.m.e. muon collider in the LHC tunnel," *JINST* **13** (2018) 10, T10003

Non-Scaling FFAG Acceleration

J. S. Berg (BNL), C. Johnstone (FNAL)

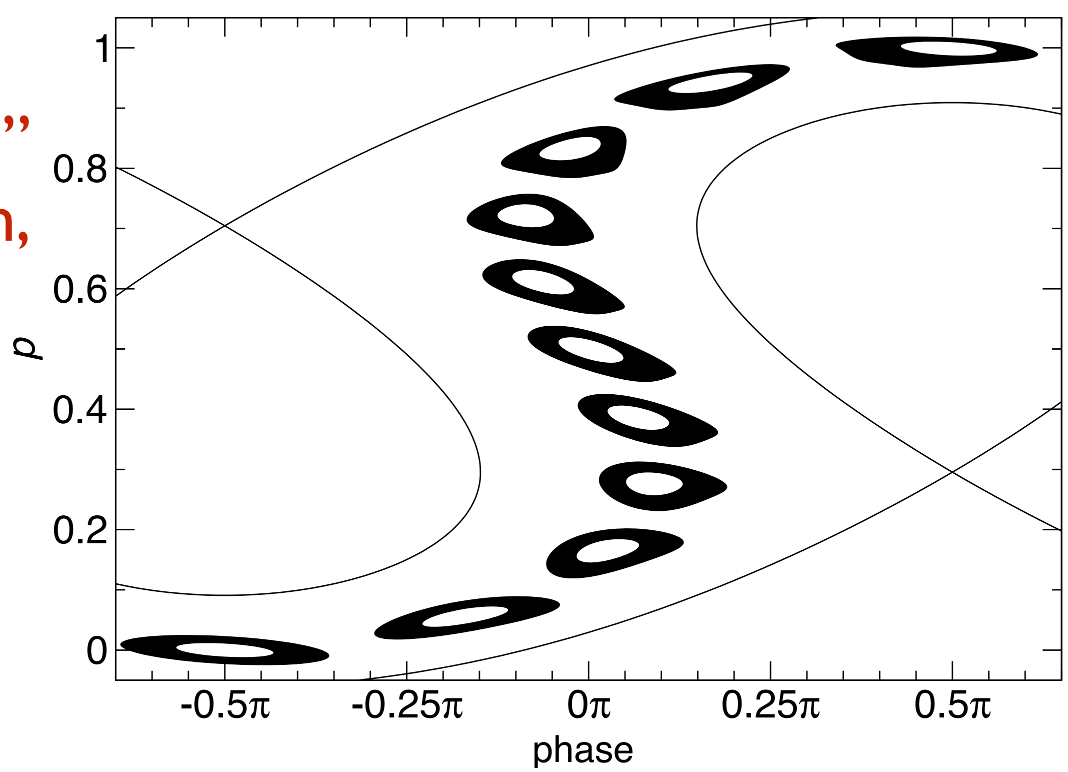
- Fixed-field lattice includes both in- & out-bends for large $\Delta p/p$ acceptance
  - beam trajectories move from inside ring at injection to outside at extraction
  - seems lower-cost than other approaches

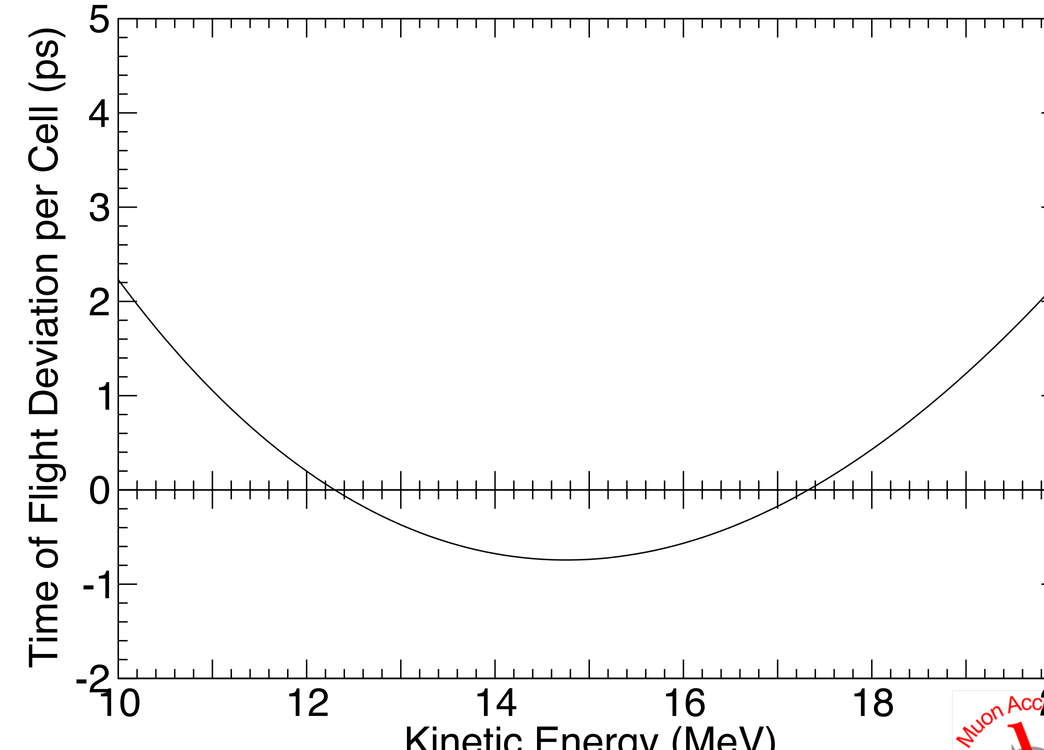


(“non-scaling” in that trajectories at different momenta are dissimilar)

- Beam timing could make synchronization with RF buckets impractical

$\Rightarrow$ could use “serpentine” acceleration, *between* buckets

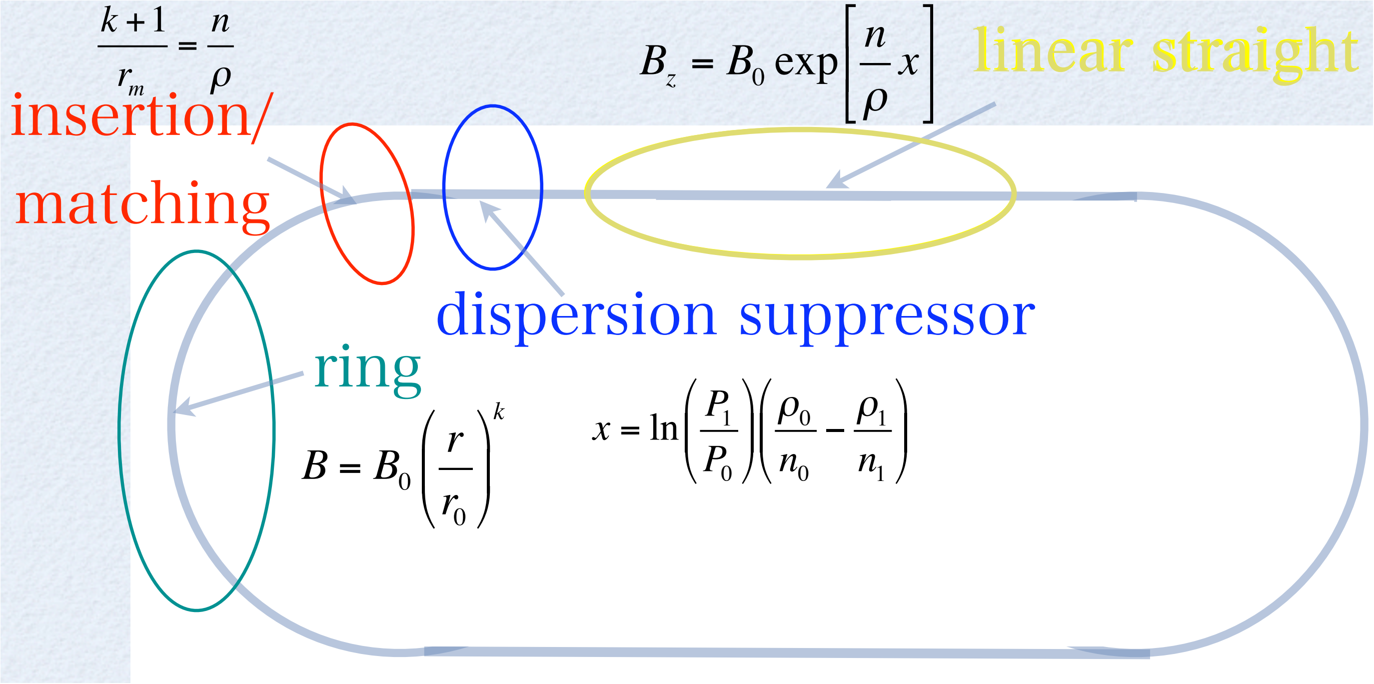




"Advanced FFAG" Idea (2009)

Y. Mori, T. Planche, J.-B. Lagrange, *et al.* (Kyoto U.)

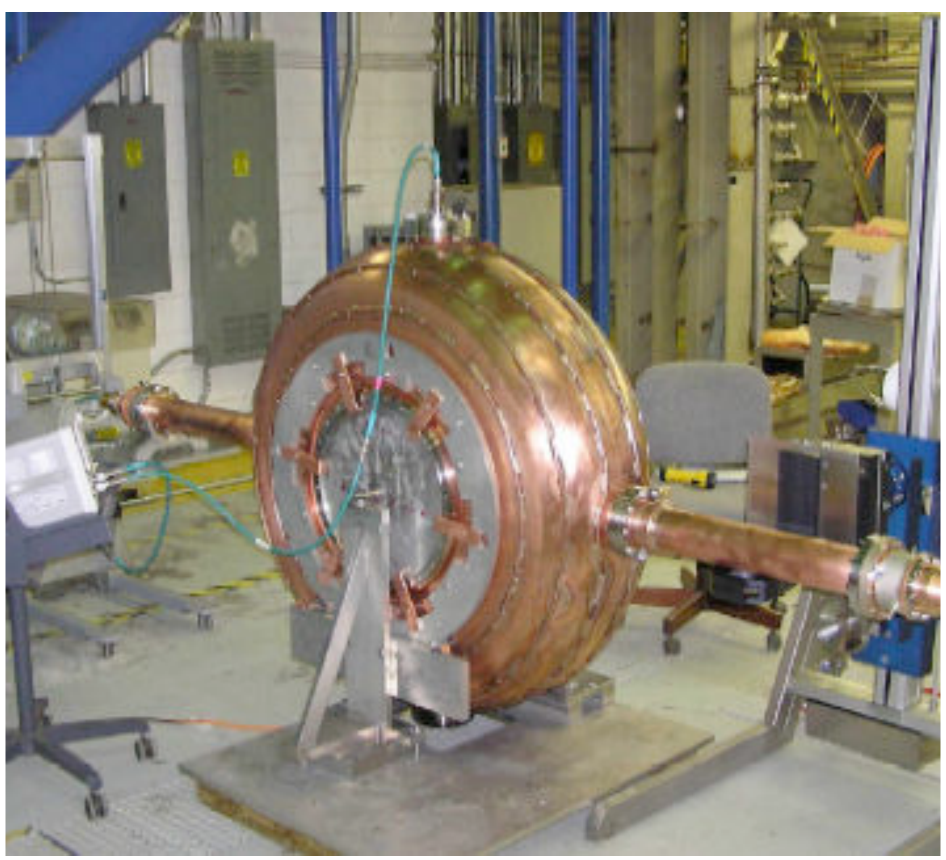
- Scaling FFAGs have attractive features
  - fixed field ⇒ no ramping, allows rapid acceleration
  - zero chromaticity ⇒ constant tunes
- But also drawbacks: large dispersion ⇒ large orbit excursion
  - large-aperture magnets & RF cavities ⇒ low RF frequency
  - short straight section ⇒ injection/extraction difficult
  - limited space for cavities
- "Advanced" scaling FFAGs:
  - sol'n for straight insertion with dispersion suppression
  - eases above problems
  - allows harmonic-number-jump instead of serpentine acceleration



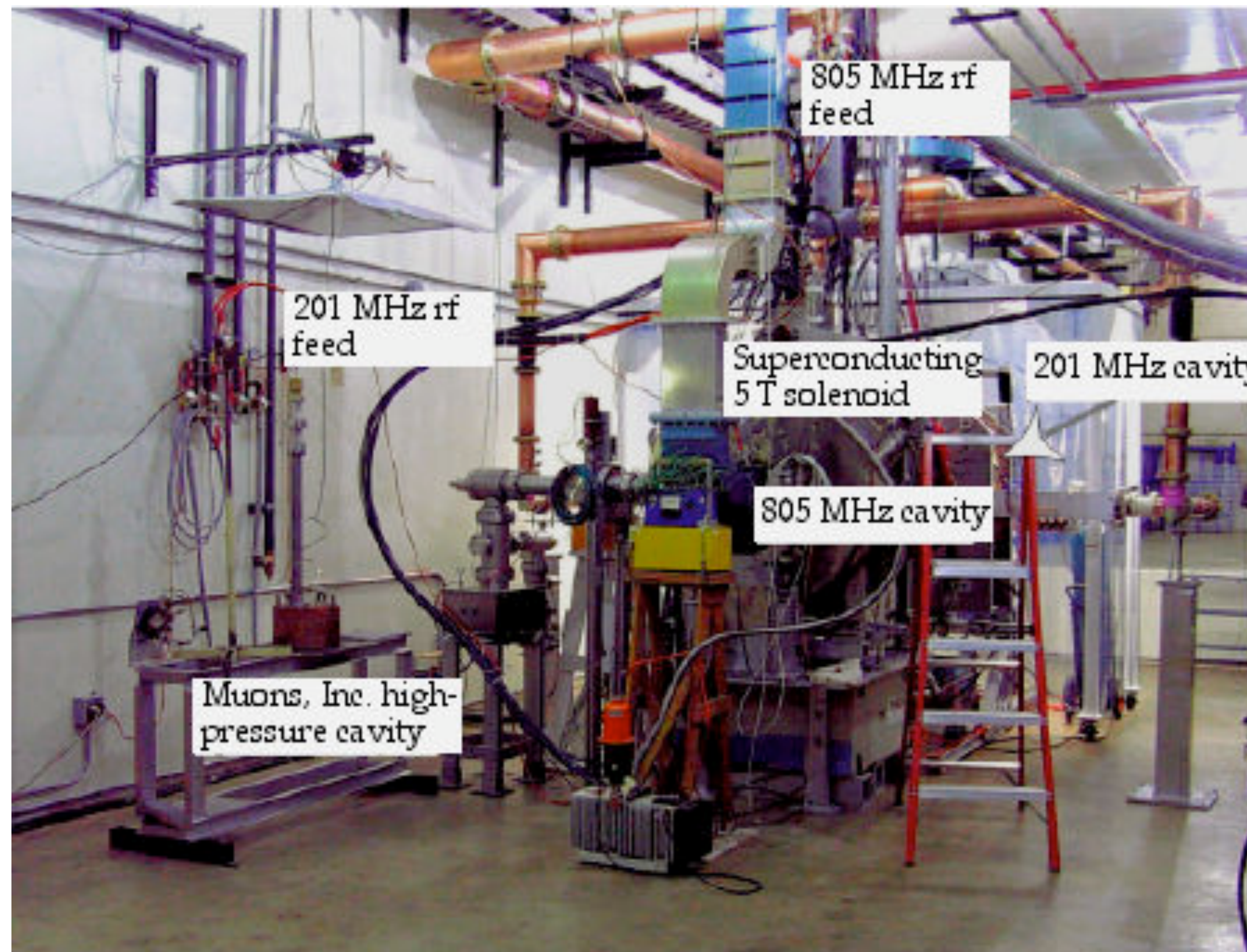
R&D Efforts

*(<u>not</u> muCool - that's an effort at PSI on cooling a very low-energy μ^+ beam)

- MuCool*: Operation of high-gradient RF cavities in strong solenoidal fields Focused dark currents tend to cause breakdown
  - — to cool large initial μ beam, want high-gradient, moderate-frequency, normal-conducting RF cavities operable in high magnetic focusing fields
  - — tests at FNAL MuCool Test Area (≈2005–17) – 2 solutions found:
    - Vacuum RF cells closed with thin Be windows (for higher on-axis field)
      D. Bowring *et al.*, PRAB 23 (2020) 7, 072001
    - H_2-pressurized cavities
      B. Freemire *et al.*, PRAB 19 (2016) 6, 062004



Prototype 201-MHz cavity



Muon Facility Feasibility Demonstrations

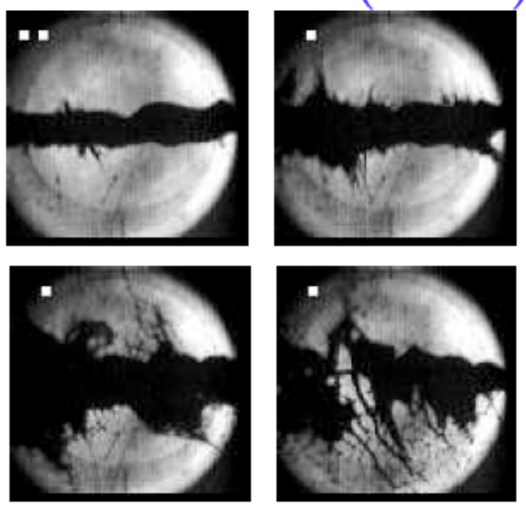
- Multi-MW targets: MERIT @ CERN nTOF facility
- Transverse ionization cooling: MICE @ RAL ISIS synchrotron
- Non-scaling FFAG acceleration: EMMA @ DL
- 6D helical cooling: MANX proposal (not approved)

MERIT (MERcury Intense Target):

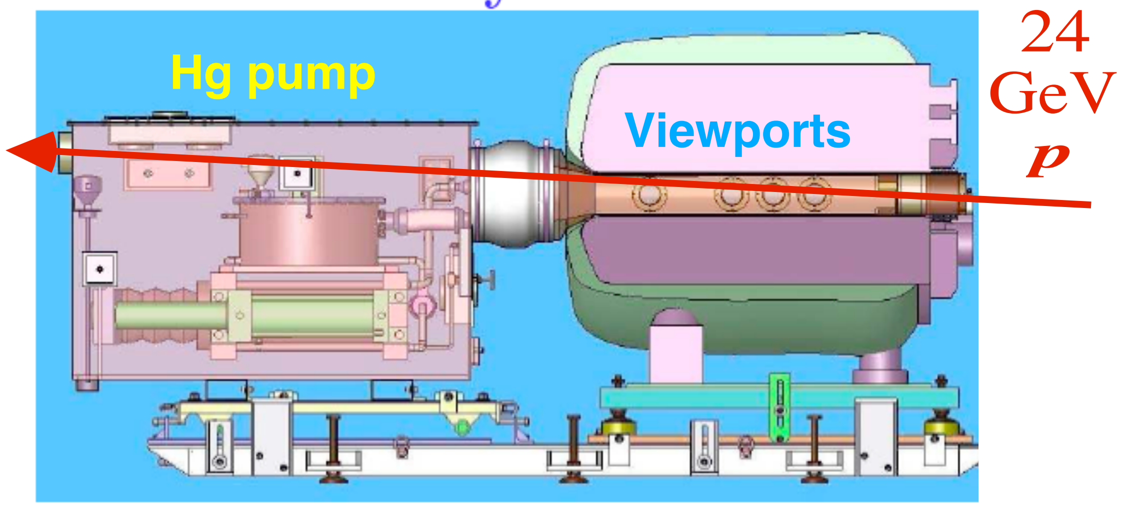
H. Kirk (BNL), K. McDonald (Princeton), I. Efthymiopoulos (CERN), *et al.*

- Proof-of-principle demonstration of Hg-jet target for 4 MW proton beam, contained in a 15 T solenoid for maximal collection of soft secondary pions

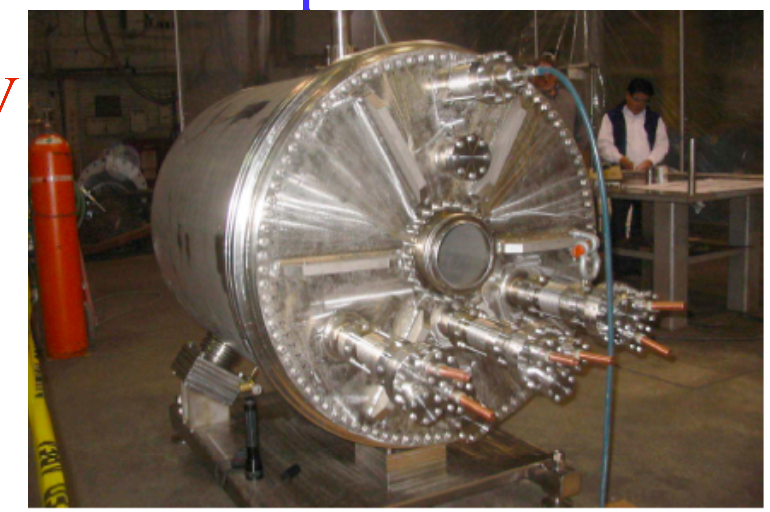
BNL E-951 (2001)



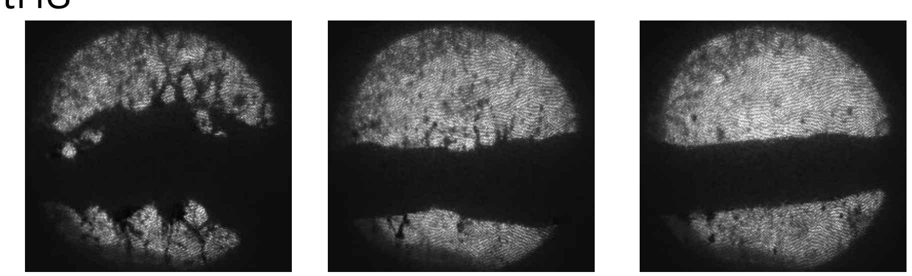
MERIT cutaway view:



15-T NC pulsed solenoid:



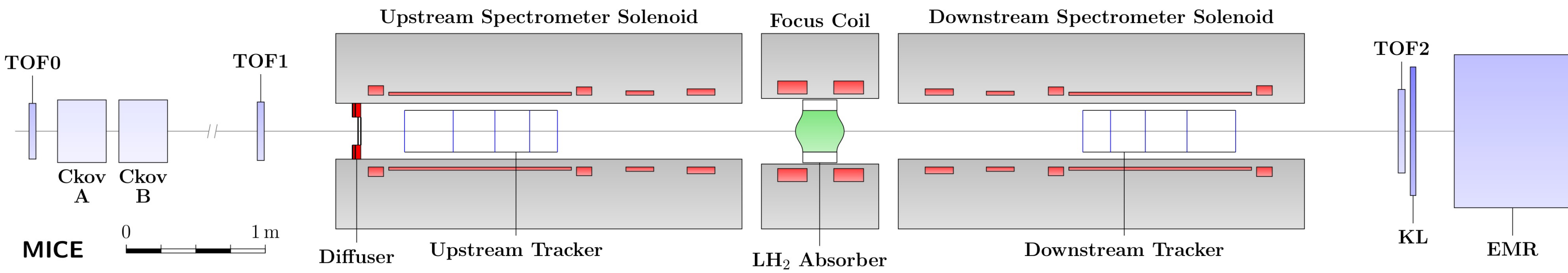
- Key parameters:
  - Used CERN PS *p* beam 2 14 & 24 GeV, up to 3 × 10^{13} *p* / 2 μs spill in ≤ 8 bunches ("pump/probe")
  - σ_r of proton bunch ≤ 1.5 mm, beam axis at 67 mrad to magnet axis
  - Hg jet of 1 cm diameter, v = 20 m/s, jet axis at 33 mrad to magnet axis
  - Each proton intercepts Hg jet over 30 cm = 2 interaction lengths
- Ran Oct. 22 – Nov. 12, 2007; conclude:

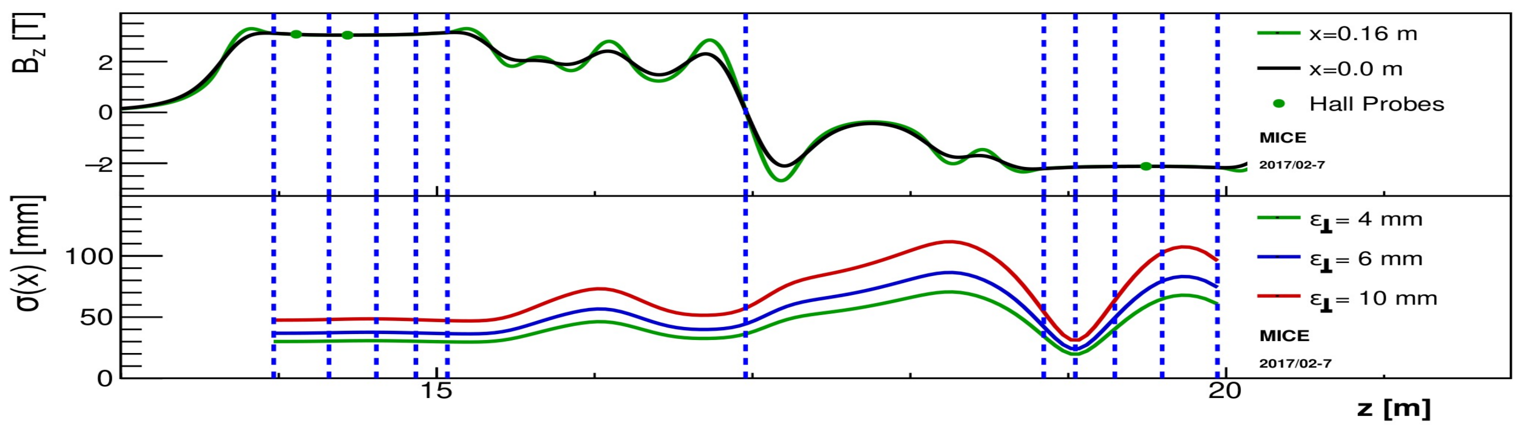


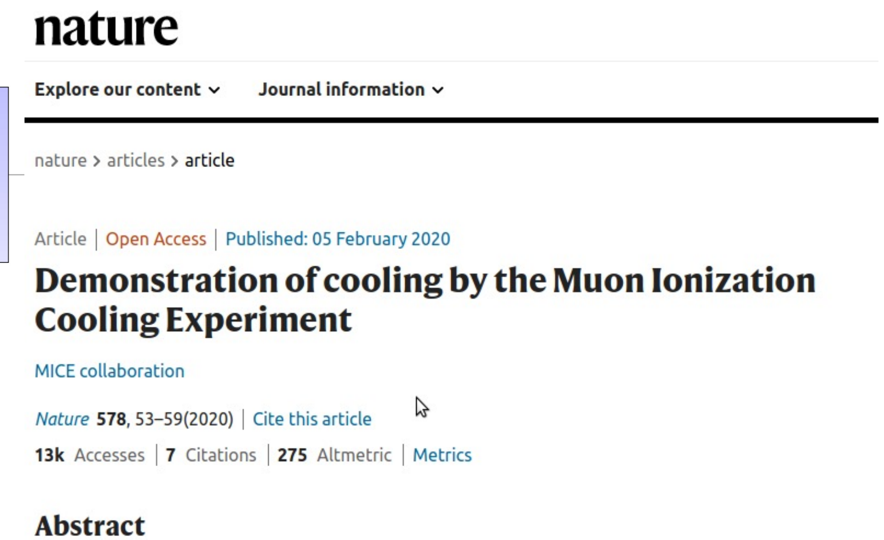
  - Hg jet disruption mitigated by magnetic field
  - Hg ejection velocities reduced by magnetic field
  - Pion production remains viable up to 350 μs after previous beam impact
  - 170 kHz operation possible for sub-disruption-threshold beam intensities
  - 20 m/s operations allows 70 Hz operations
  - 115 kJ pulse containment demonstrated

} ⇒ 8 MW capability demonstrated!

Muon Ionization Cooling Experiment (MICE)



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Article | Open Access | Published: 05 February 2020

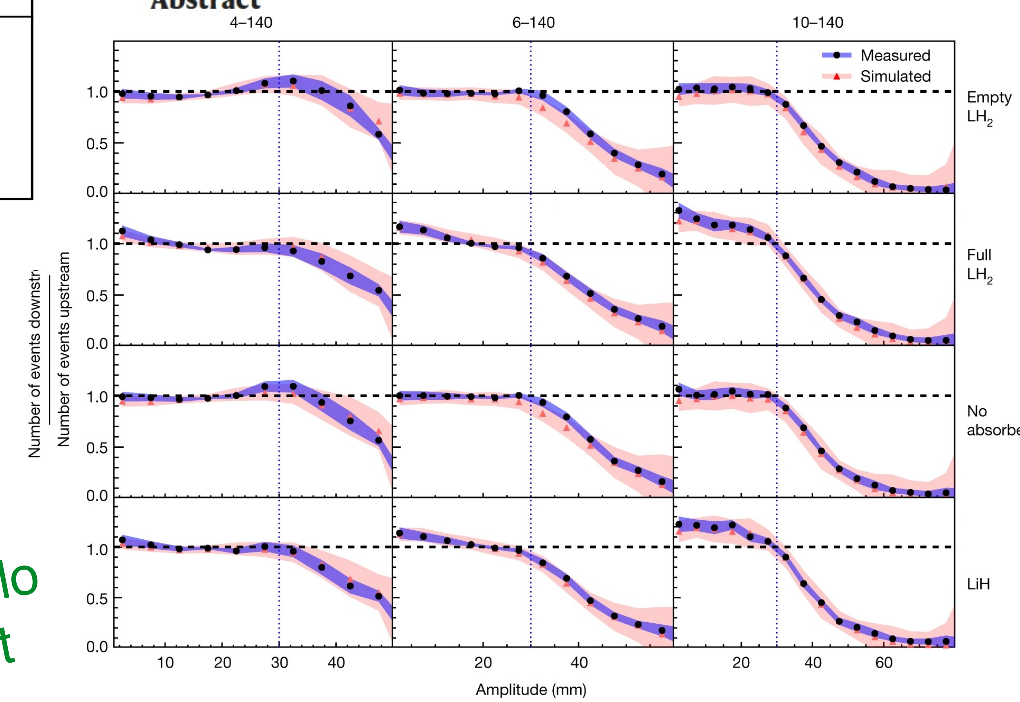
Demonstration of cooling by the Muon Ionization Cooling Experiment

MICE collaboration

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

13k Accesses | 7 Citations | 275 Altmetric | Metrics

Abstract



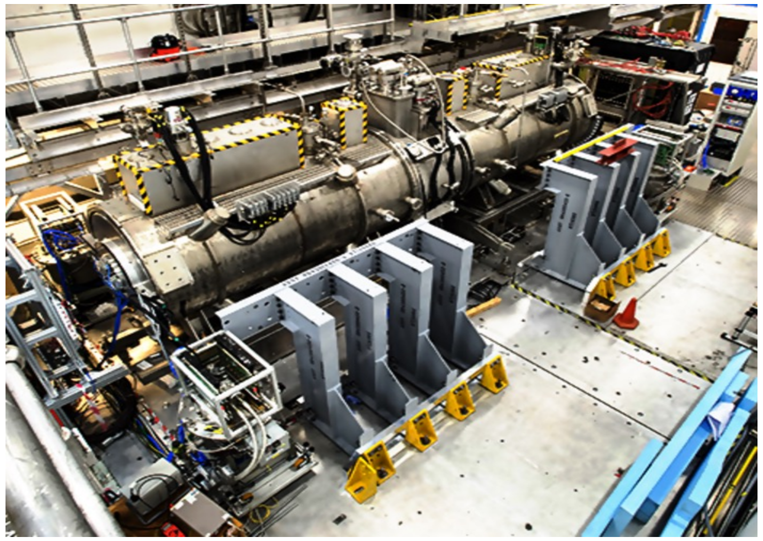
- Muon ionization cooling has been demonstrated by MICE @ RAL

Asia/Europe/U.K./
U.S. collaboration

  - with muons @ ~140 MeV/c
  - each muon individually measured

Data and Monte Carlo
in good agreement

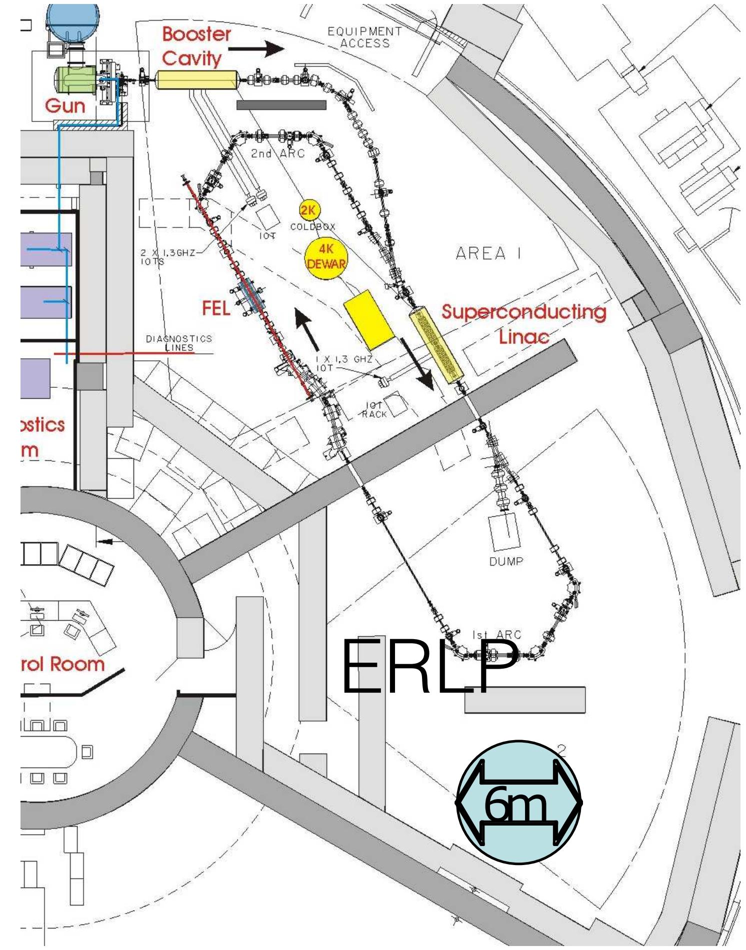
- But
  - transverse cooling only
  - no re-acceleration
  - no intensity effects
  - larger-emittance beams (≥ 4 mm·rad)



- Further analyses in progress

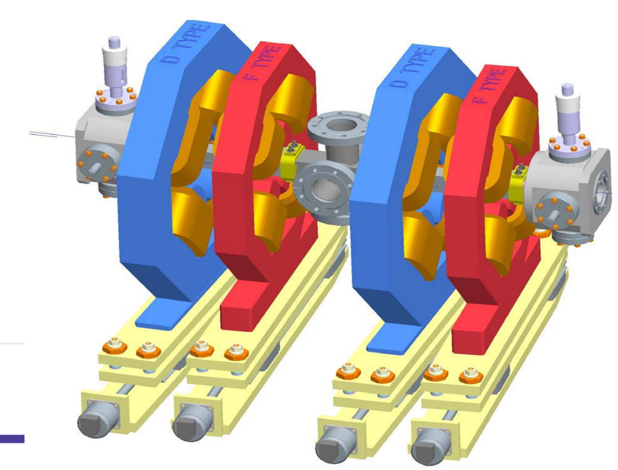
EMMA (Electron Model ~~of Muon Accelerator)~~ for Many Applications

R. Edgecock, S. Machida (RAL), *et al.*



- Proof of principle demo of non-scaling FFAG using electron beam
- Applications envisioned in muon acceleration, cancer therapy,...
- Ran at Daresbury Lab (2011)
- Verified novel acceleration, including rapid resonance crossing
- Int'l collaboration:

  AU/CA/CERN/UK/US



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Published: 10 January 2012

Acceleration in the linear non-scaling fixed-field alternating-gradient accelerator EMMA

S. Machida, R. Barlow, [...] T. Yokoi

Nature Physics **8**, 243–247(2012) | Cite this article

288 Accesses | **36** Citations | **28** Altmetric | Metrics

Summary

- U.S.-led muon collider & neutrino factory R&D ran vigorously ("on a shoestring") until DOE cut off funding
- Identified and explored the key technological challenges
- Developed key, innovative ideas
- Demonstrated there are no showstoppers