Muon Cooling, Muon Colliders, and the MICE Experiment

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ILLINOIS INSTITUTE OF TECHNOLOGY
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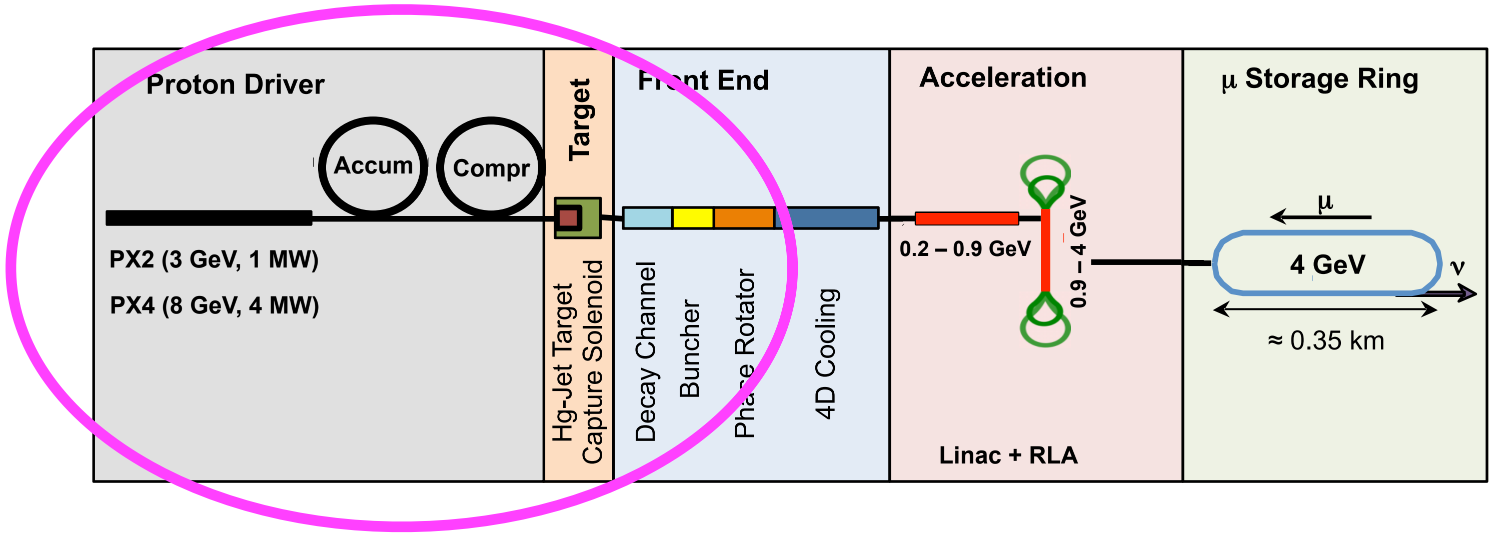
COOL'13
Mürren, Switzerland
10 June, 2013

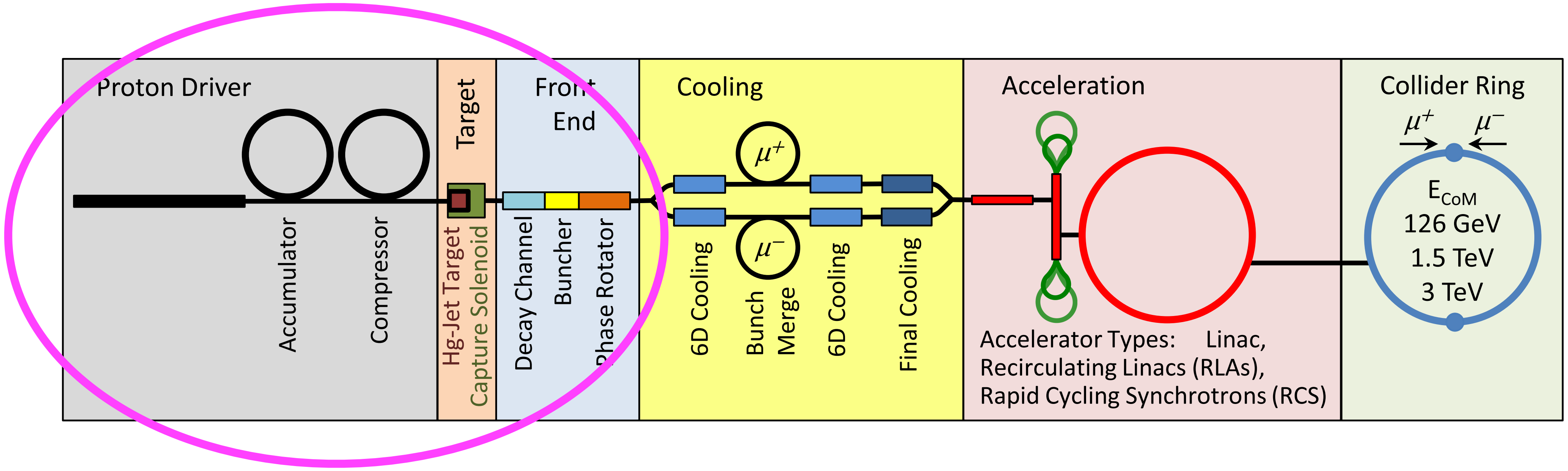
Outline

- Neutrino Factories and Muon Colliders
- Muon cooling
- MICE
- Conclusions

νF and μC



~ 10^{21} ν/year to remote detectors

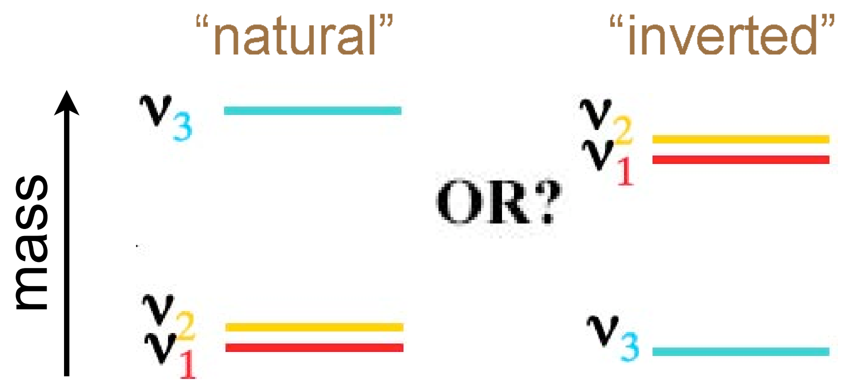


$\mathcal{L} \sim 10^{34}\ \mathrm{cm^{-2}\ s^{-1}}$

- Strong similarities! (Upstream ends nearly identical)
  - both start with ~MW *p* beam on high-power tgt → π → μ, then cool, accelerate, & store

Neutrino Factory Physics

1. What is the neutrino mass hierarchy? [sgn(Δm^2_{31})]



2. Why is pattern of neutrino mixing so different from that of quarks?

CKM matrix:

$\theta_{12} \cong 12.8°$
$\theta_{23} \cong 2.2°$
$\theta_{13} \cong 0.4°$
} **hierarchical & nearly diagonal**

PMNS matrix:

$\theta_{12} = 30°$ (solar)
$\theta_{23} = 45°$ (atmospheric)
$\theta_{13} \approx 9°$ (Daya Bay + Reno + Double Chooz...)

$$\begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin\theta_{13} e^{i\delta} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2} \end{pmatrix}$$

3. How close to zero is the PMNS phase δ?

➡ Does neutrino mixing violate *CP*, as required for Leptogenesis?

4. Is 3-generation mixing the whole story?

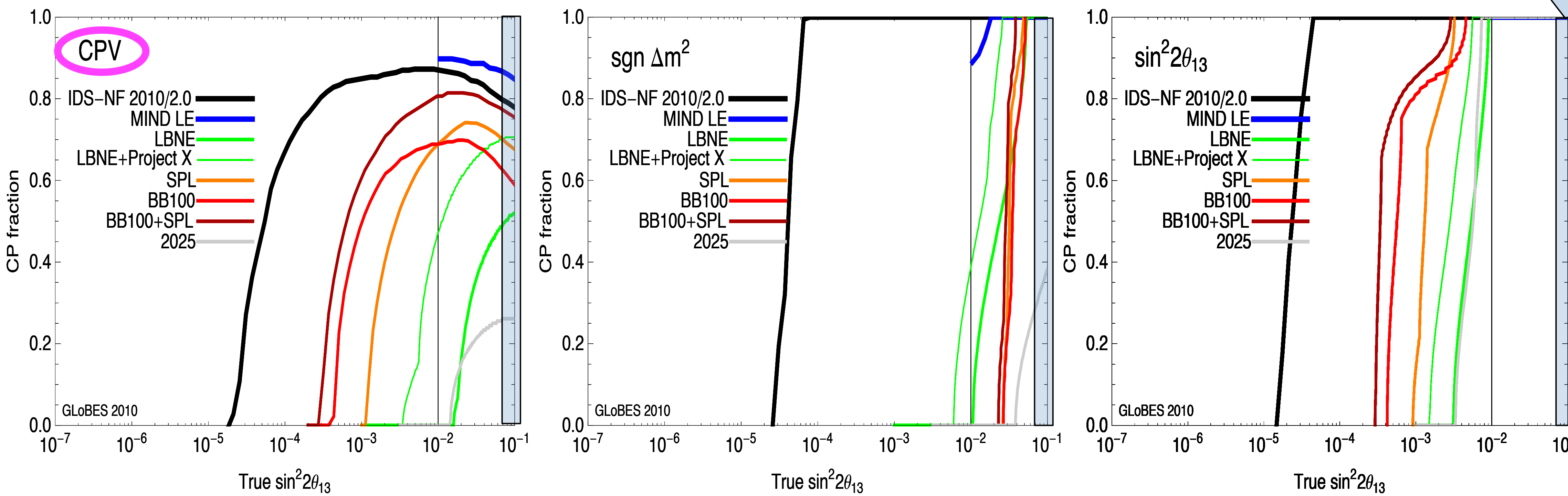
⟹ Need to measure PMNS matrix as precisely as possible.

Neutrino Factory Physics

From IDS-NF Interim Design Report (Oct. 2011):
[S. Choubey *et al.*, arXiv:1112.2853]

Daya Bay et al.: You are here!

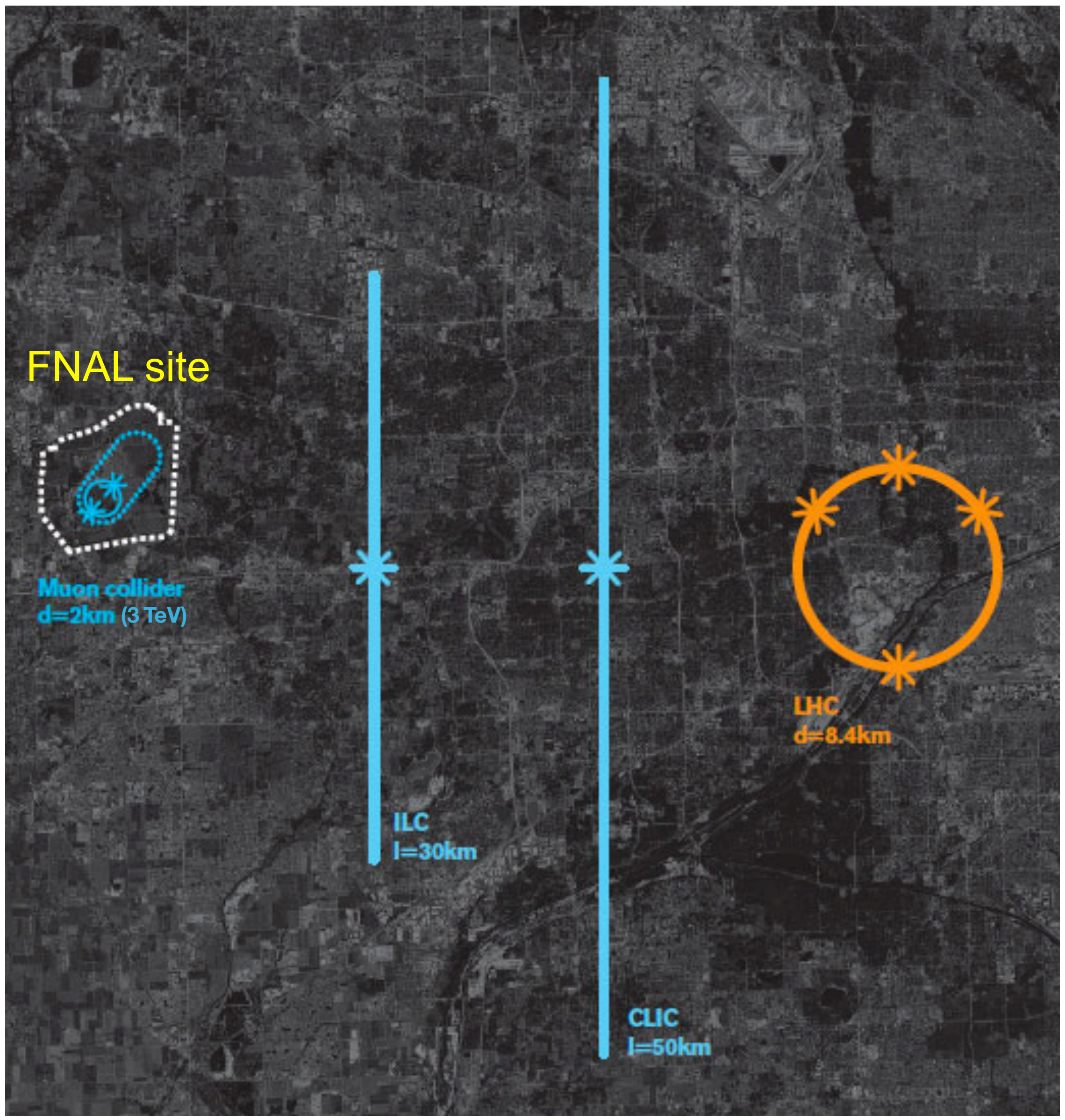
- νF compared with other facilities:



➡ νF has greatest reach and will ultimately be required

Muon Colliders

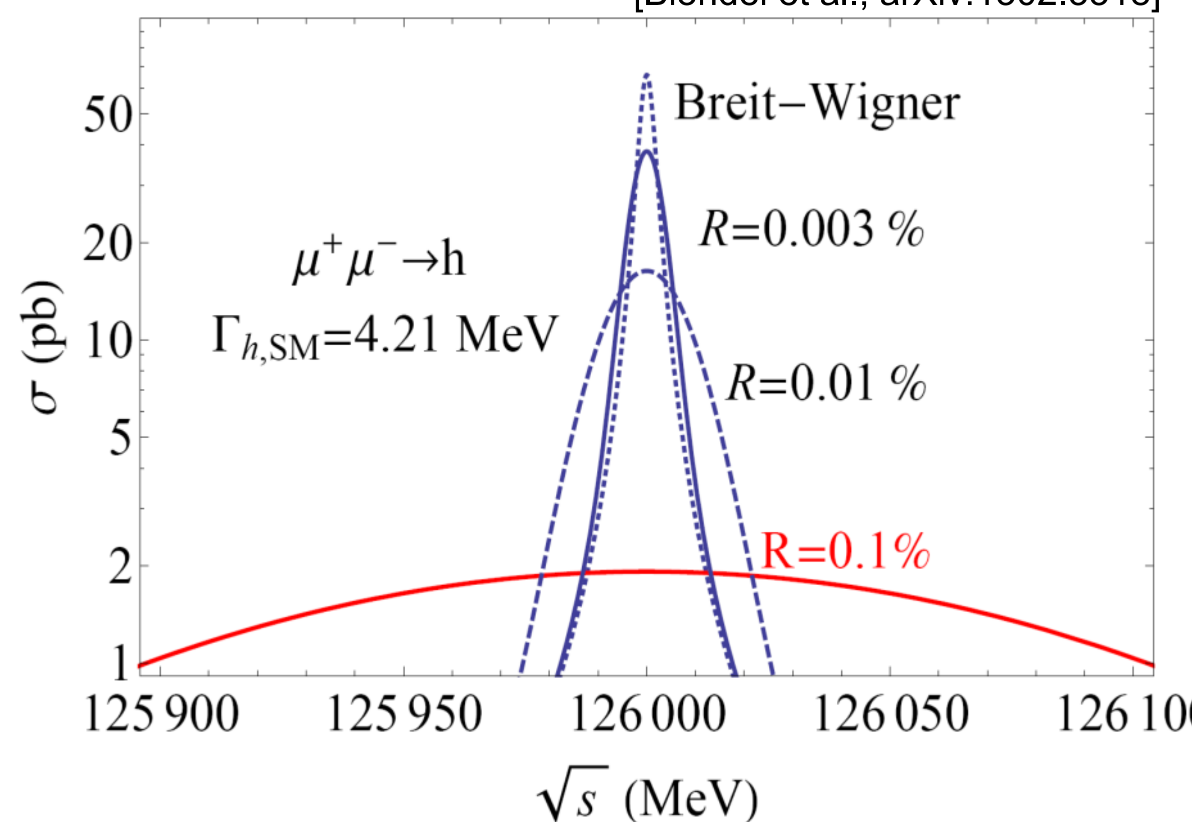
- An option for *high-energy* lepton colliders
  - unlike e^+e^-, $\sqrt{s}$ not limited by radiative effects
  - ➡ a μC can fit on existing laboratory sites even for $\sqrt{s} > 3$ TeV:



➡ Likely to be cost-effective! i.e., ~ \$(LHC)

- Also,
  - s-channel coupling of Higgs to lepton pairs $\propto m_{\text{lepton}}^2$
  - ➡ μC resolution can uniquely
    - measure Higgs width & shape

[Blondel et al., arXiv:1302.3318]



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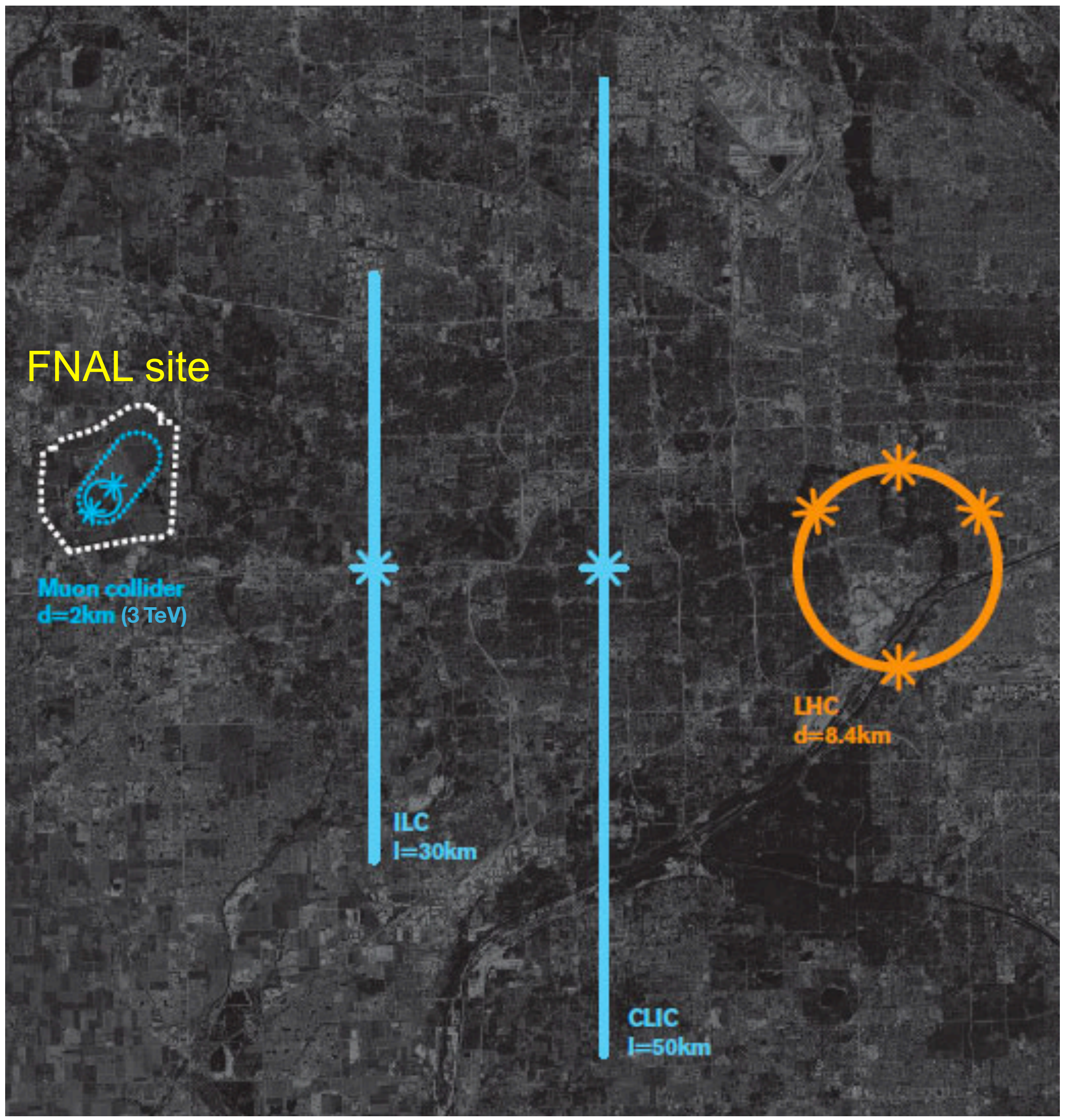

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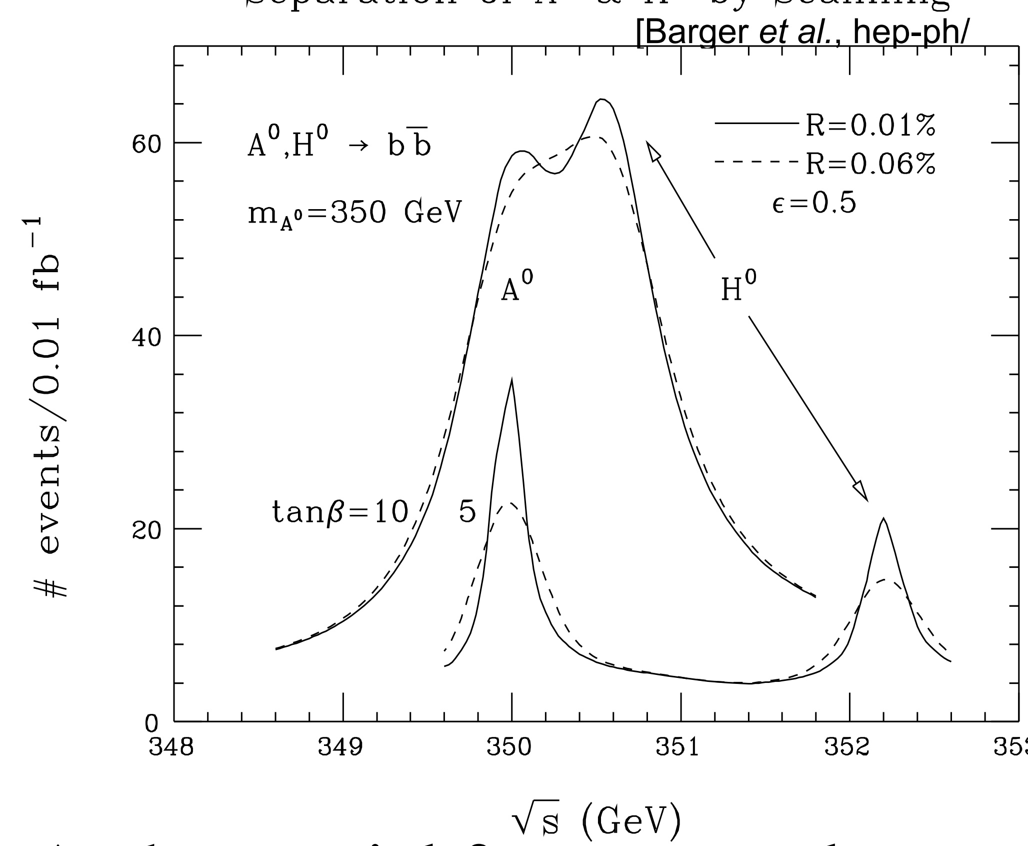
- Also,
  - s-channel coupling of Higgs to lepton pairs $\propto m_{\text{lepton}}^2$
  - ➡ μC resolution can uniquely
    - measure Higgs width & shape
    - separate near-degenerate scalar and pseudo-scalar Higgs states of high-tan β SUSY

Separation of A^0 & H^0 by Scanning



- And potential for spectacular signatures, e.g., if ∃ Z' or Kaluza-Klein resonances of ED models

Technical Challenges

1. High-power (≈4 MW) *p* beam and target
   - Hg jet feasible (MERIT@CERN, 2007)

   e.g., SNS, Project X SC Linac

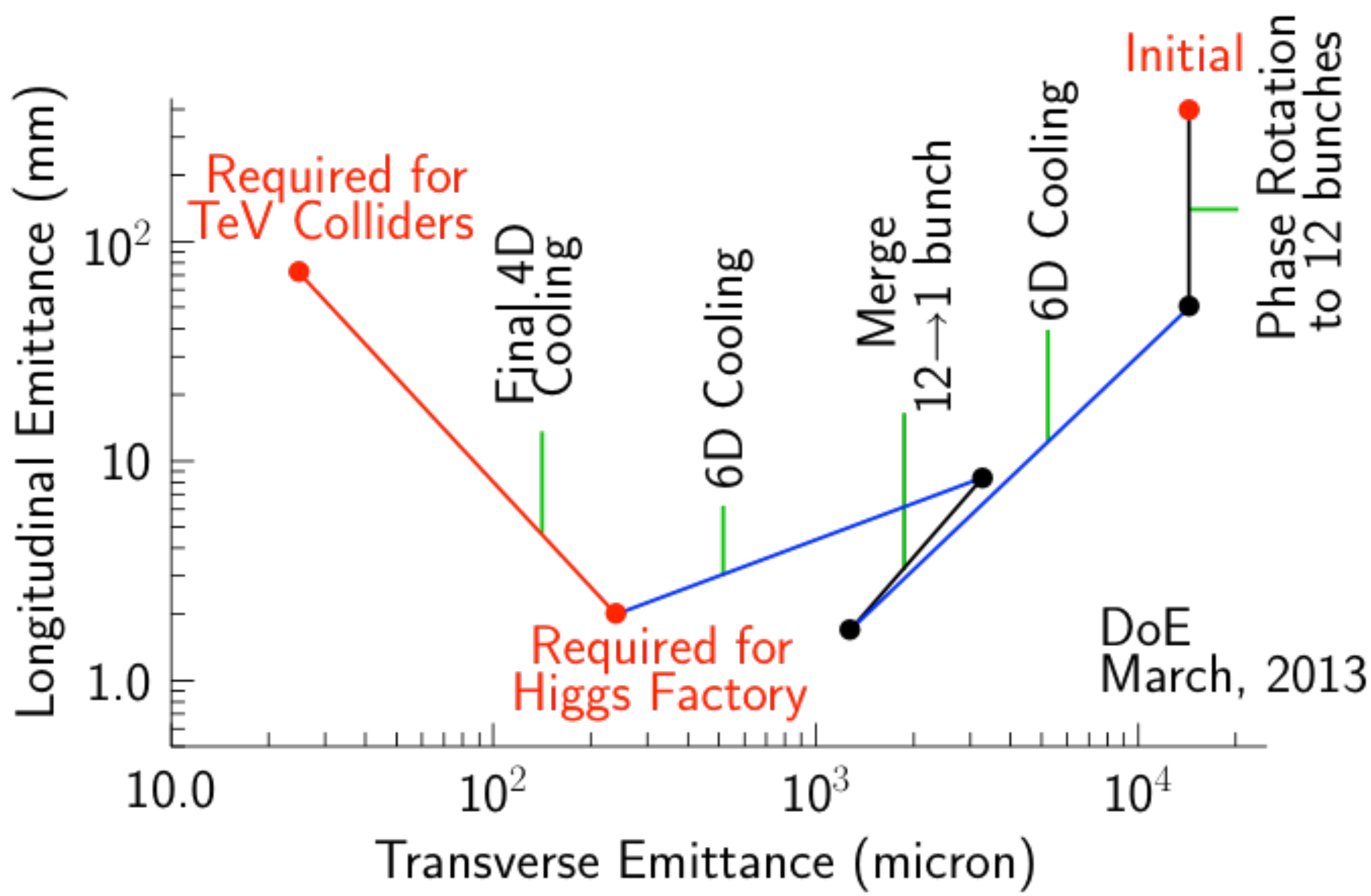
2. Muon beam cooling in (for μC) all dimensions
   - μ unstable, τ_μ = 2.2 μs ⇒ must cool quickly!...

3. *Rapid* acceleration
   - Linac–RLAs–(FFAGs)–RCS
     (EMMA@DL, 2011; proposed JEMMRLA@JLab)

4. High storage-ring bending field (to maximize # cycles before decay) and small $\beta_\perp$, for high $\mathcal{L}$
   - Solution devised, B ~ 10 T, β ~ 1 cm

Muon Cooling

- Physics of multi-TeV lepton collisions calls for $\mathcal{L} \sim 10^{34}$ cm^{-2} s^{-1}
- Higgs physics requires $\mathcal{L} \sim 10^{32}$ and $\Delta p/p \sim 10^{-5}$
- How to get there: (one scenario)
  - must cool both $\epsilon_{\perp}$ and $\epsilon_{||}$
  - need factor 10^6 total 6D emittance reduction



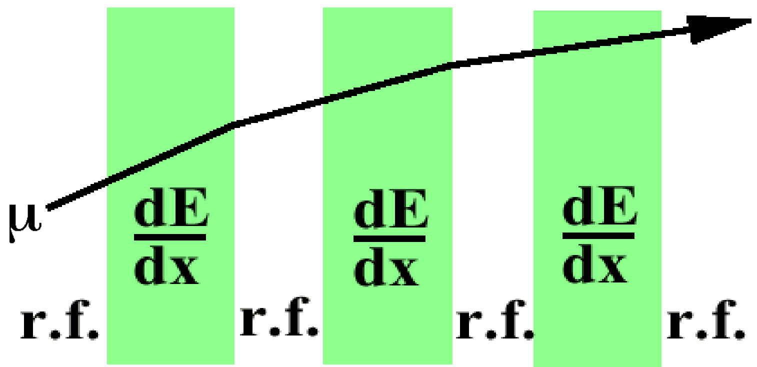
How cool muons?

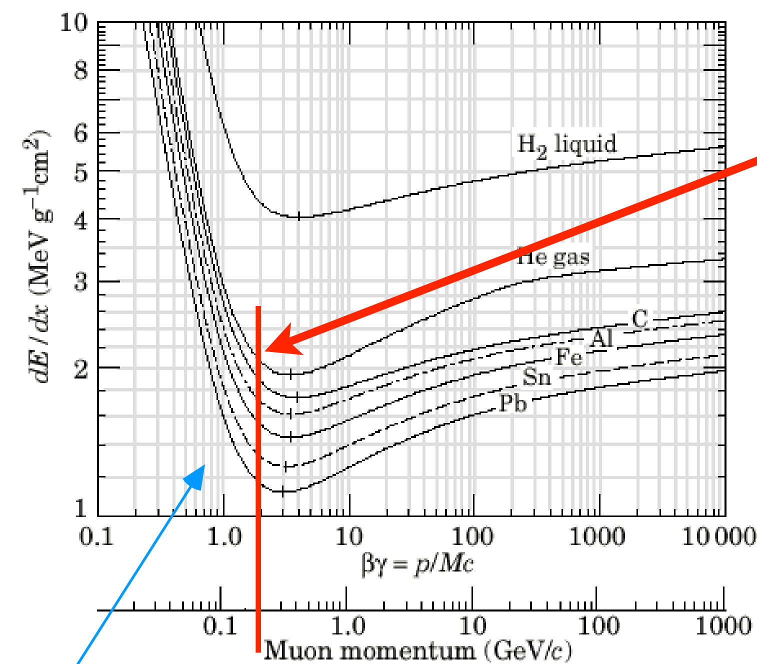
- Problem: Average lifetime at rest = 2.2 μs
- But established cooling methods (stochastic, electron, laser) take seconds to hours!

- What cooling method can work in ≪ 2.2 μs?

Ionization Cooling!

- Muons cool via dE/dx in low-Z medium:





- optimal working point is ≈ ionization minimum

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

ionization energy loss

multiple Coulomb scattering

  – RF cavities between absorbers replace ΔE

  – Net effect: reduction in $p_\perp$ at constant $p_\parallel$, i.e., transverse cooling

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

(emittance change per unit length)

- 2 competing effects
  $\Rightarrow$ equilibrium emittance:
  $\varepsilon_0 \propto \beta_\perp / \langle dE/ds \rangle X_0$

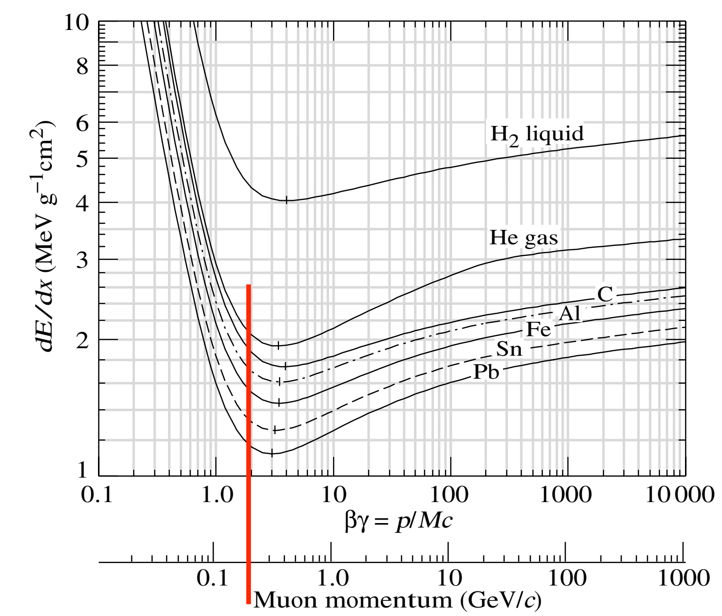
- Only* practical way to cool within μ lifetime

- Expt'l demo in progress...

*Optical stochastic cooling?

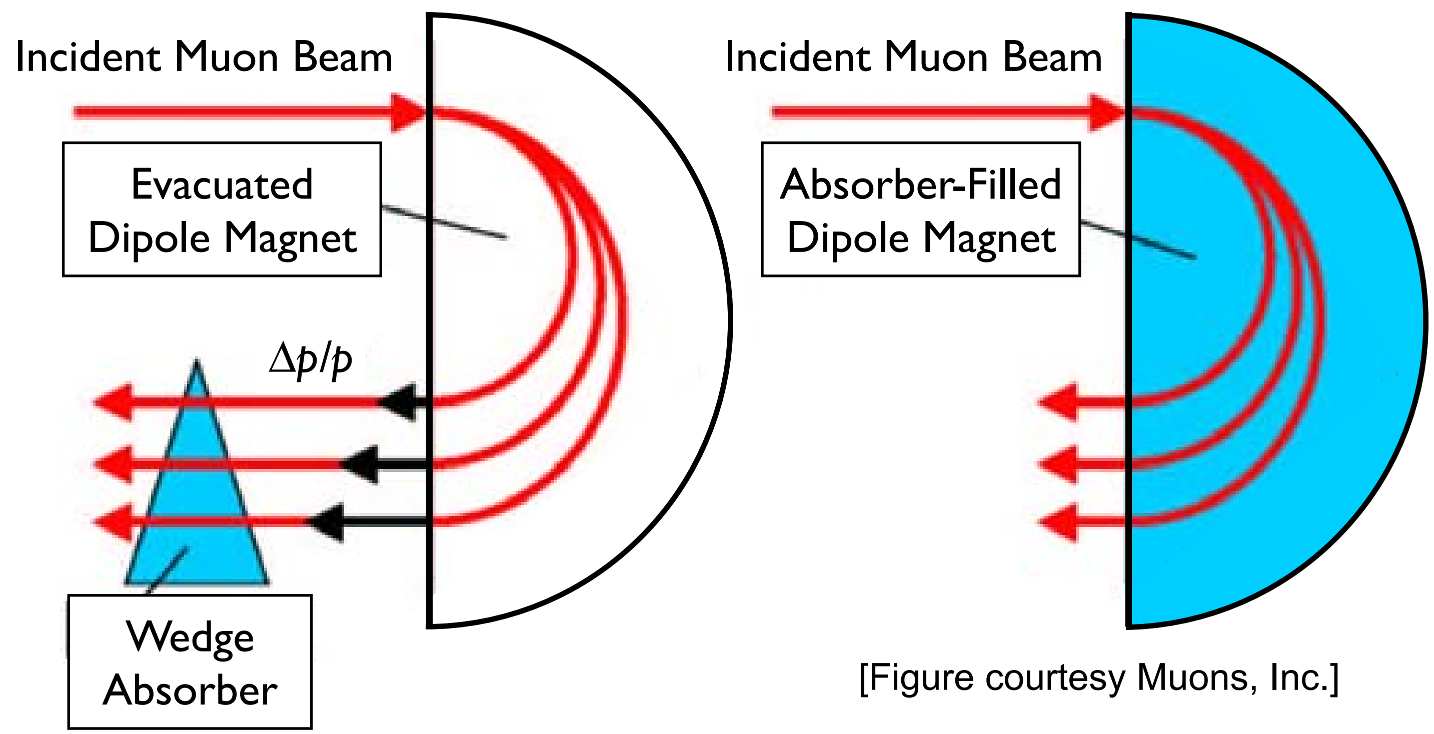
How to cool in 6D?

- Work above ionization minimum to get negative feedback in p_z?
- No – ineffective due to straggling



$\Rightarrow$cool longitudinally via *emittance exchange*:

- use dispersion to create appropriate correlation between momentum and position / path length



[Figure courtesy Muons, Inc.]

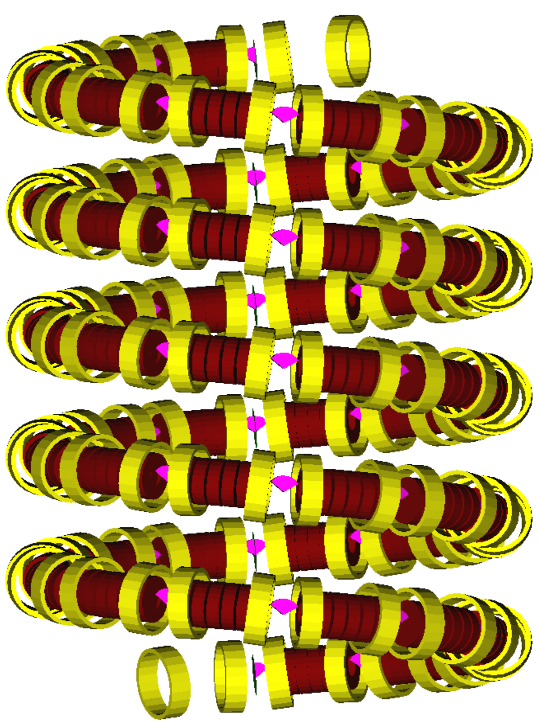
- Cool $\epsilon_\perp$, exchange $\epsilon_\perp$ & $\epsilon_{||}$ → 6D cooling

How to cool in 6D?

- Tricky beam dynamics: must handle dispersion, angular momentum, nonlinearity, chromaticity, & non-isochronous beam transport

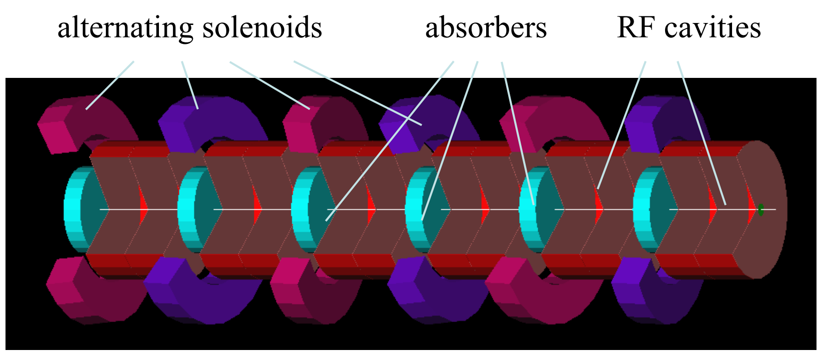
- 3 types of solutions viable in simulation:

RFOFO "Guggenheim"



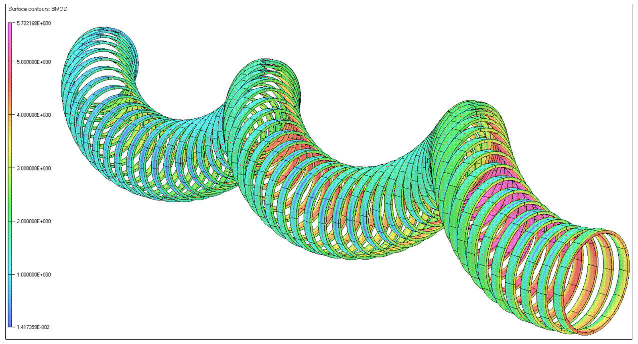
UCR, BNL, IIT

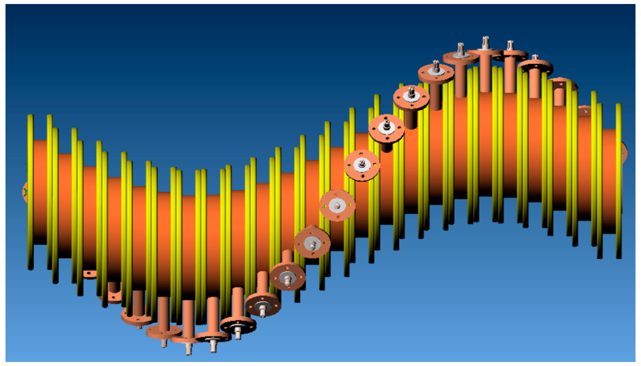
FOFO Snake



Y. Alexahin, FNAL

Helical Cooling Channel





Muons, Inc. & FNAL

How to cool in 6D?

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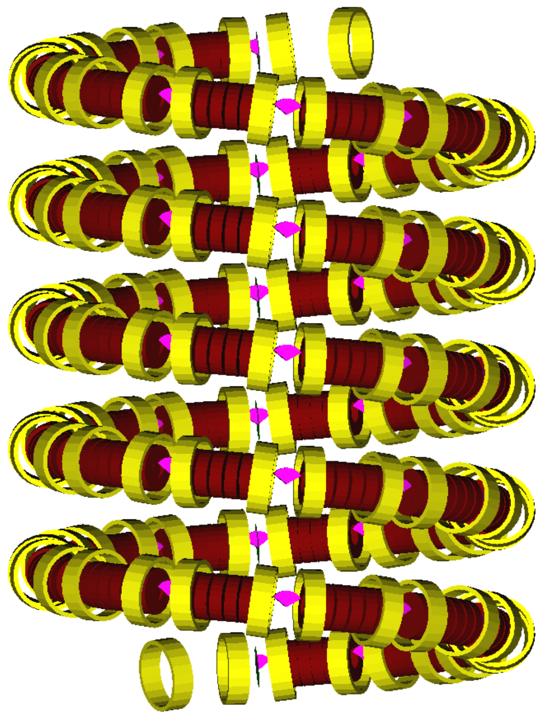

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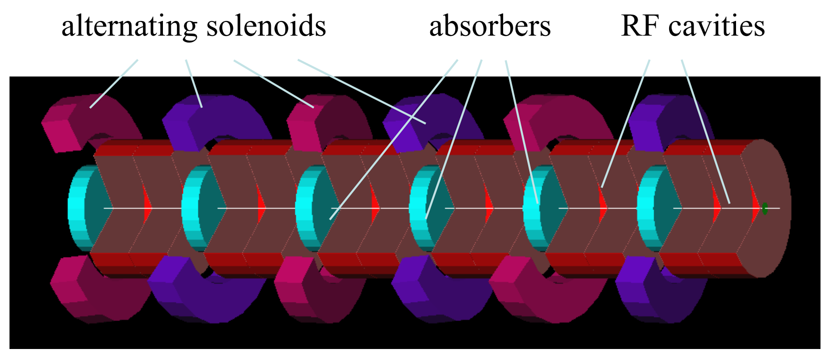

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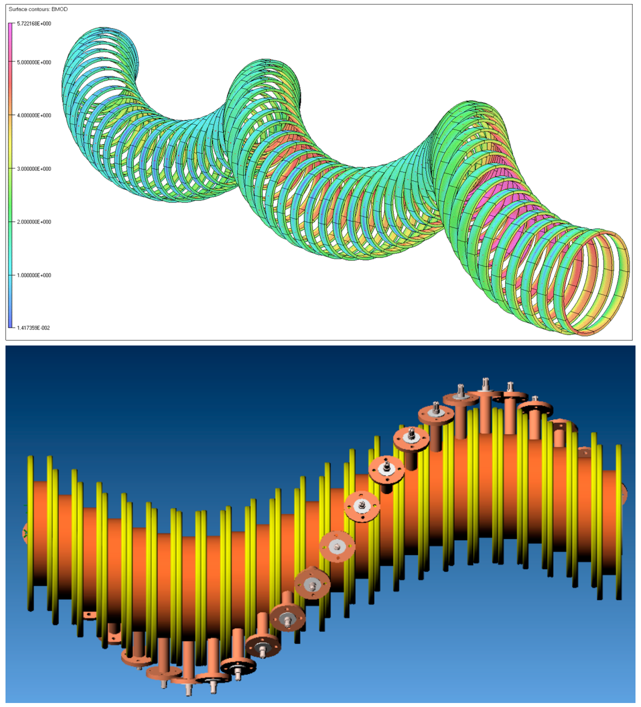
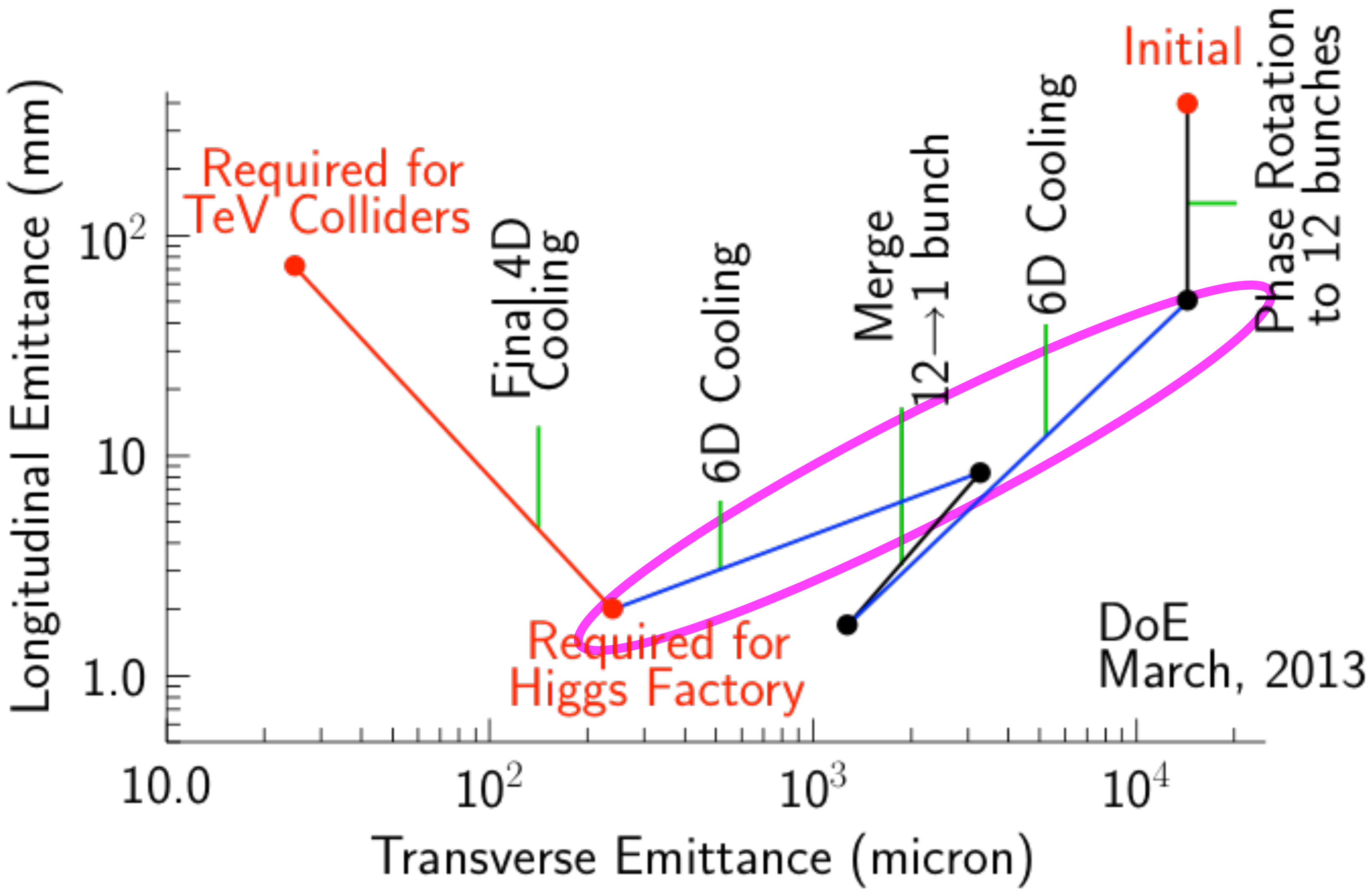


Muons, Inc. & FNAL

- FOFO Snake can cool both signs at once but may be limited in $\beta_{\perp,min}$ $\Rightarrow$ may be best for initial 6D cooling
- HCC may be most compact
- Performance limits of each not yet clear, nor which is most cost-effective

How to cool in 6D?

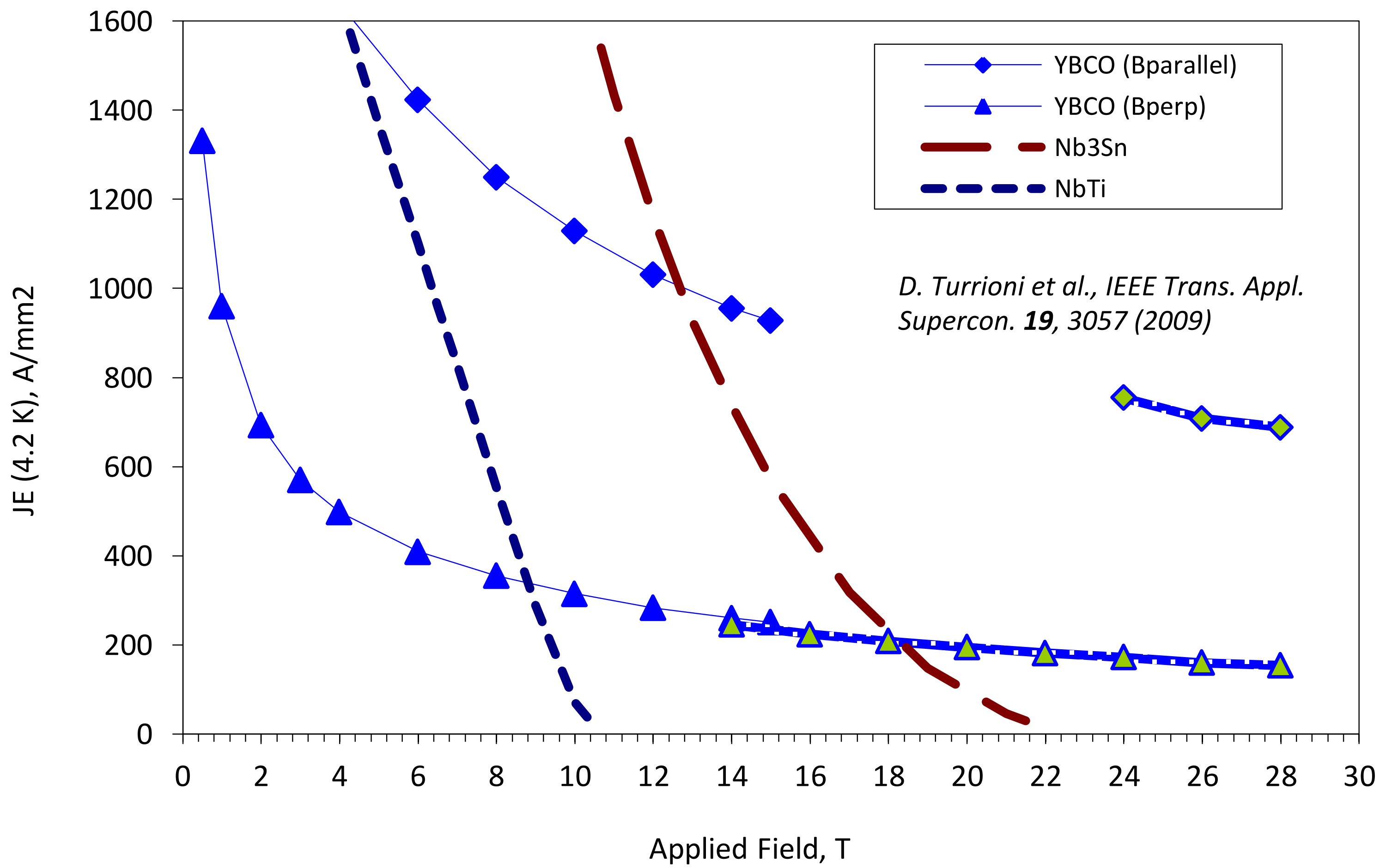
- Guggenheim simulation example:



Beyond 6D Cooling

- To reach ≤25 μm transverse emittance, must go beyond 6D cooling schemes shown above
- One approach (Palmer "Final Cooling"):
  - cool transversely with *B* ~ 40 T at low momentum
  - gives lower β & higher *dE/dx*:

$$\beta_\perp \sim \frac{p}{B}$$



- Lower-*B* options under study as well (Derbenev "PIC/REmEx," lithium lenses)

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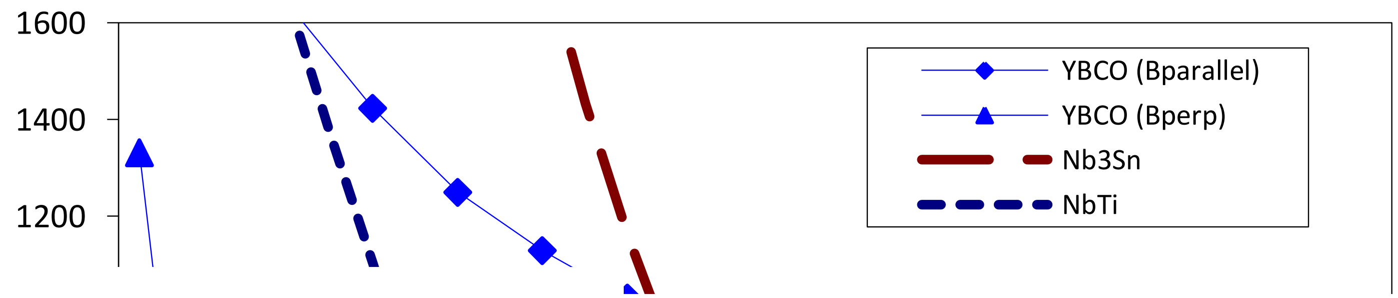
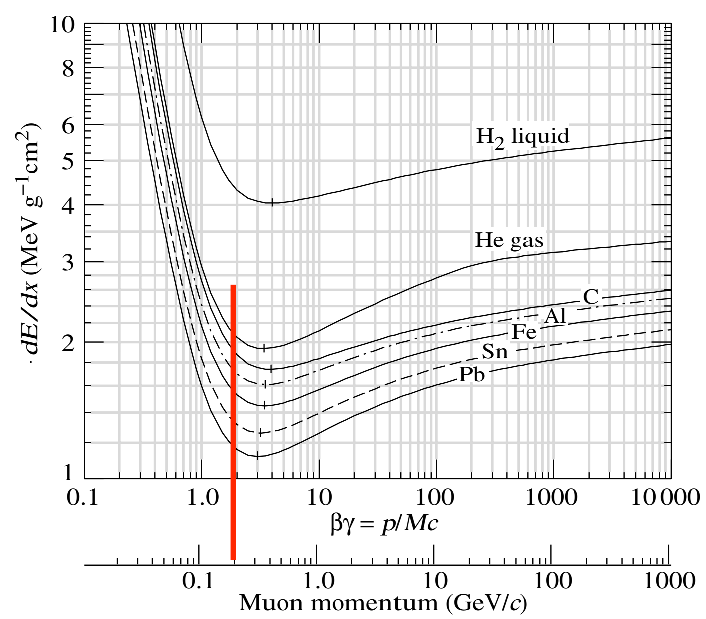
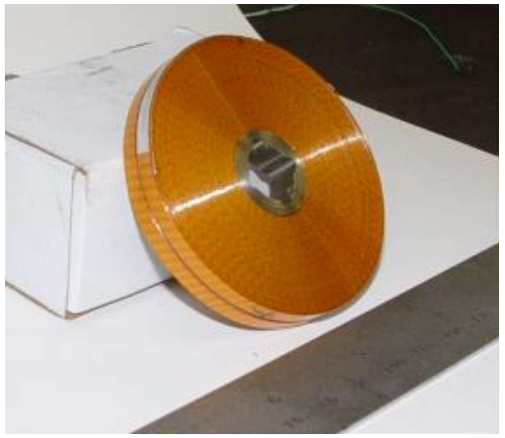






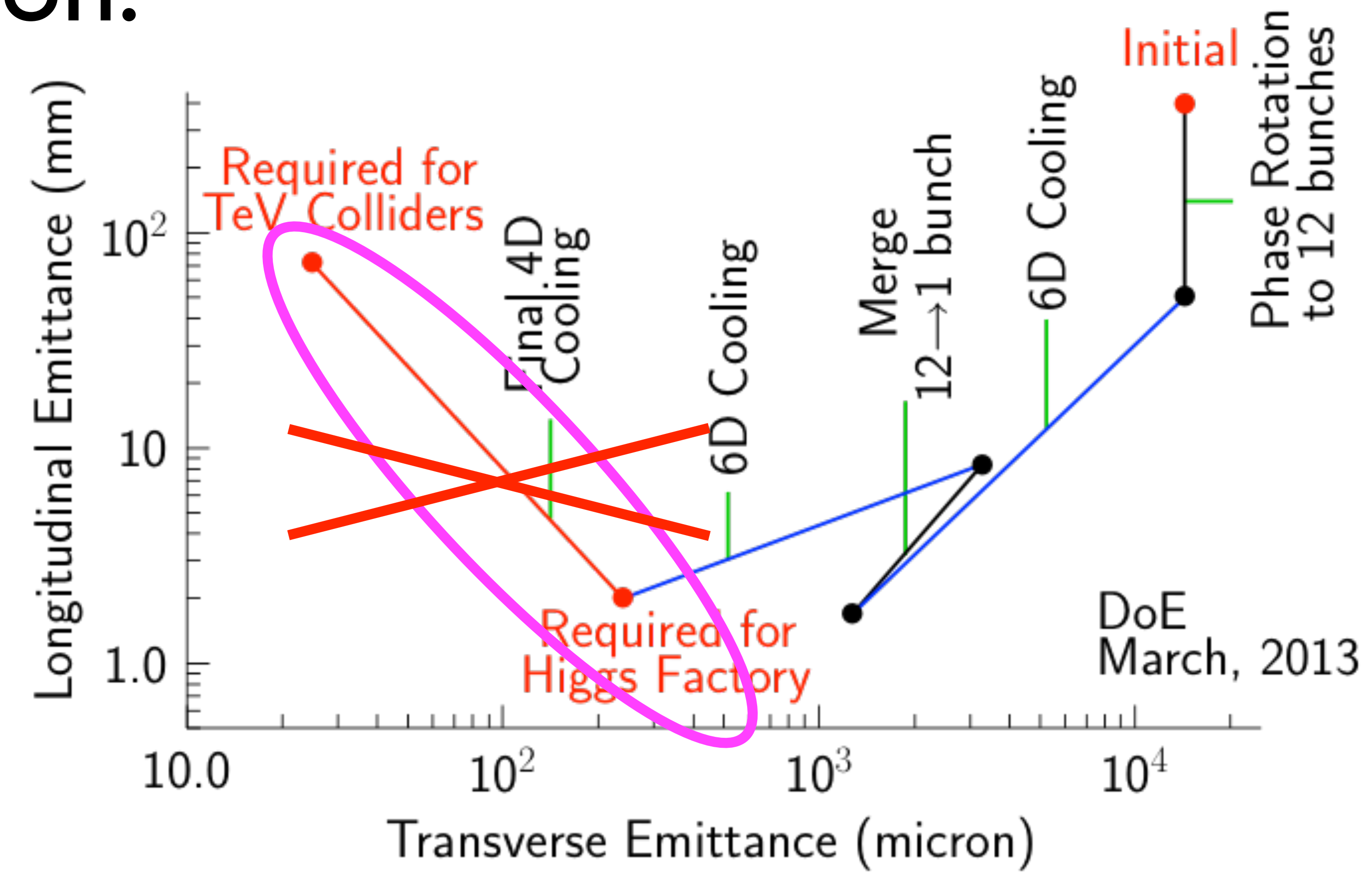
High-field YBCO solenoid (BNL/Particle Beam Lasers, Inc.)

- Lower-*B* options under study as well (Derbenev "PIC/REmEx," lithium lenses)

Higgs Factory Cooling

- $\mu^+\mu^-$ Higgs Factory requires exquisite energy precision:
  - use $\mu^+\mu^- \to h$ s-channel resonance, $dE/E \approx 0.003\% \approx \Gamma_h^{SM} = 4$ MeV

⟹ omit final cooling



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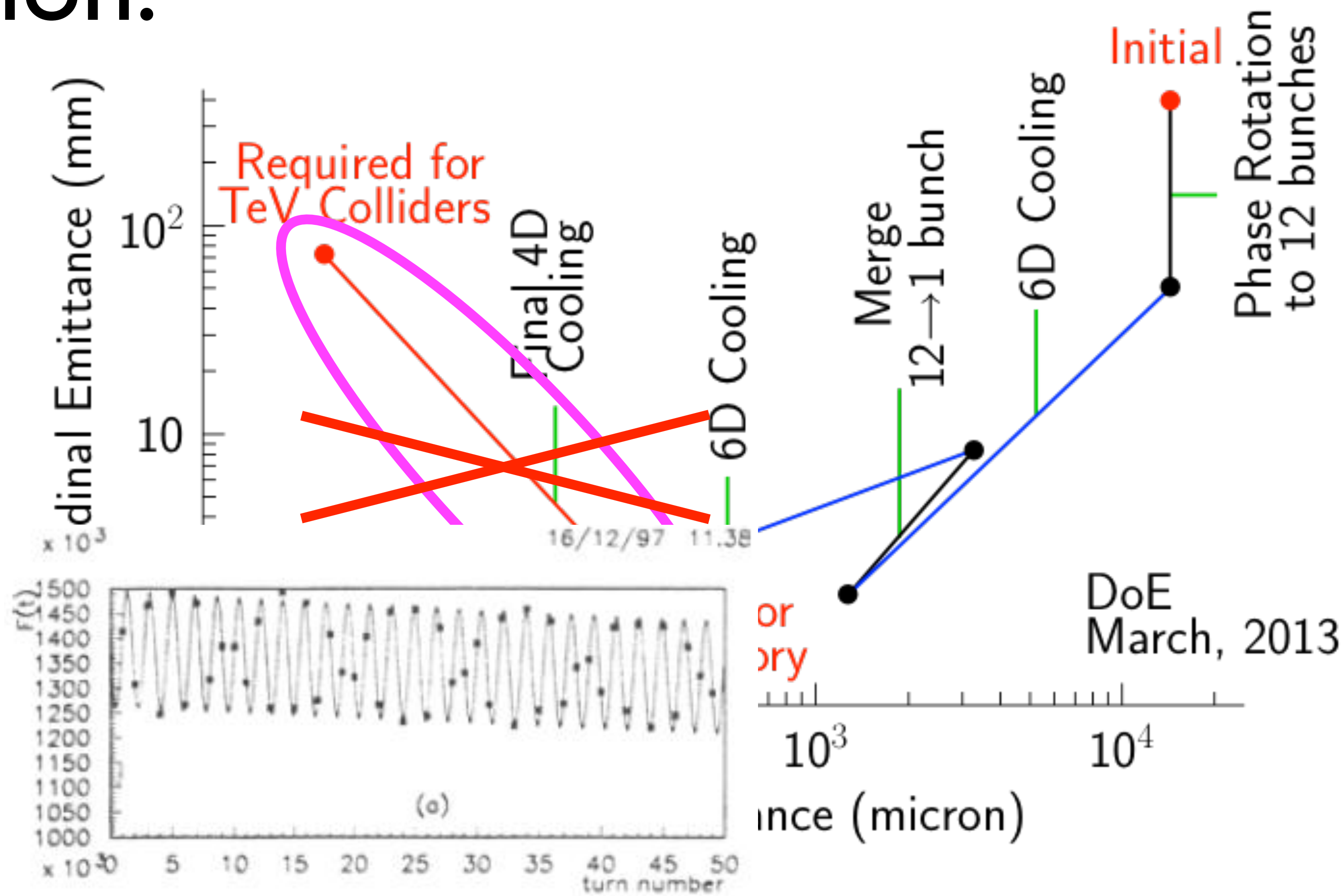
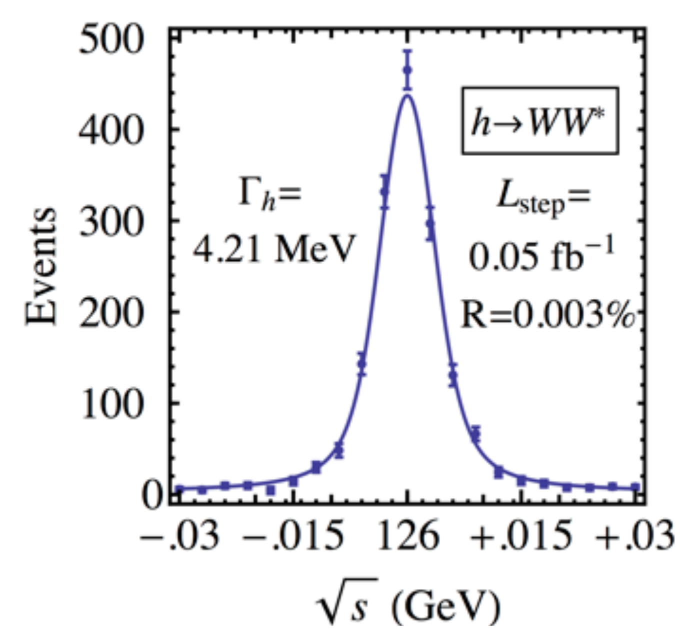
    ⇒ omit final cooling

  - 10^{-6} energy calib. via $(g-2)_\mu$ spin precession!
  - measure Γ_h, lineshape (& m_h) via $\mu^+\mu^-$ resonance scan
    - the only way to do so!
    - and a key test of the SM

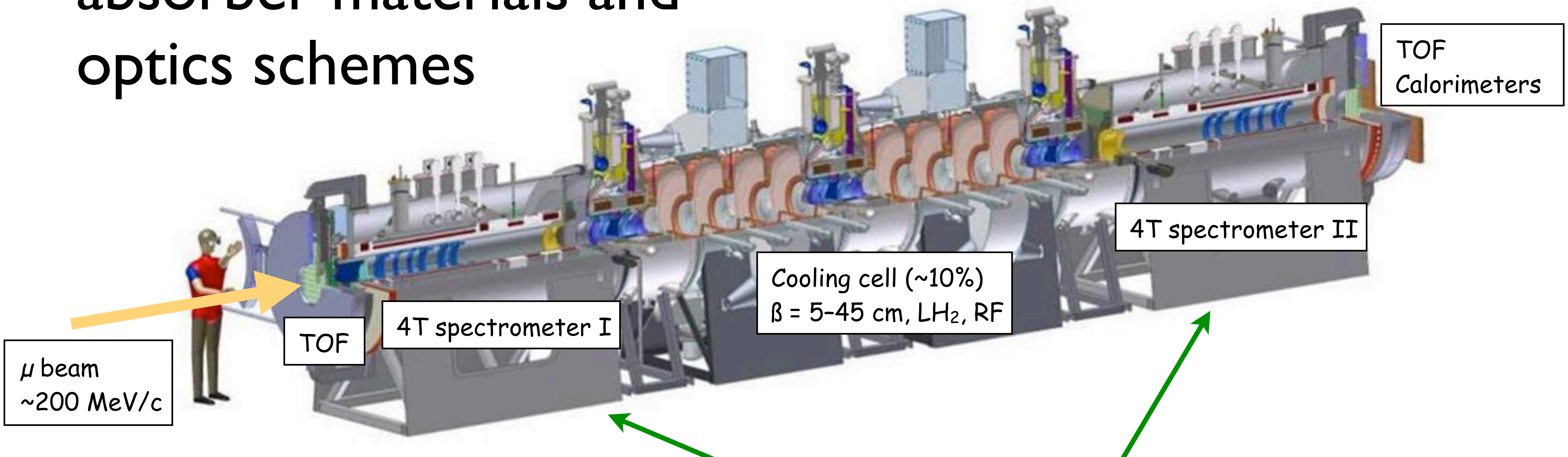




[P. Janot, HF2012]

MICE

- International Muon Ionization Cooling Experiment at UK's Rutherford Appleton Laboratory (RAL)
- Flexibility to test several absorber materials and optics schemes



SciFi solenoidal spectrometers measure emittance to 1‰ (muon by muon)

- Status: under construction, program complete by ~2020

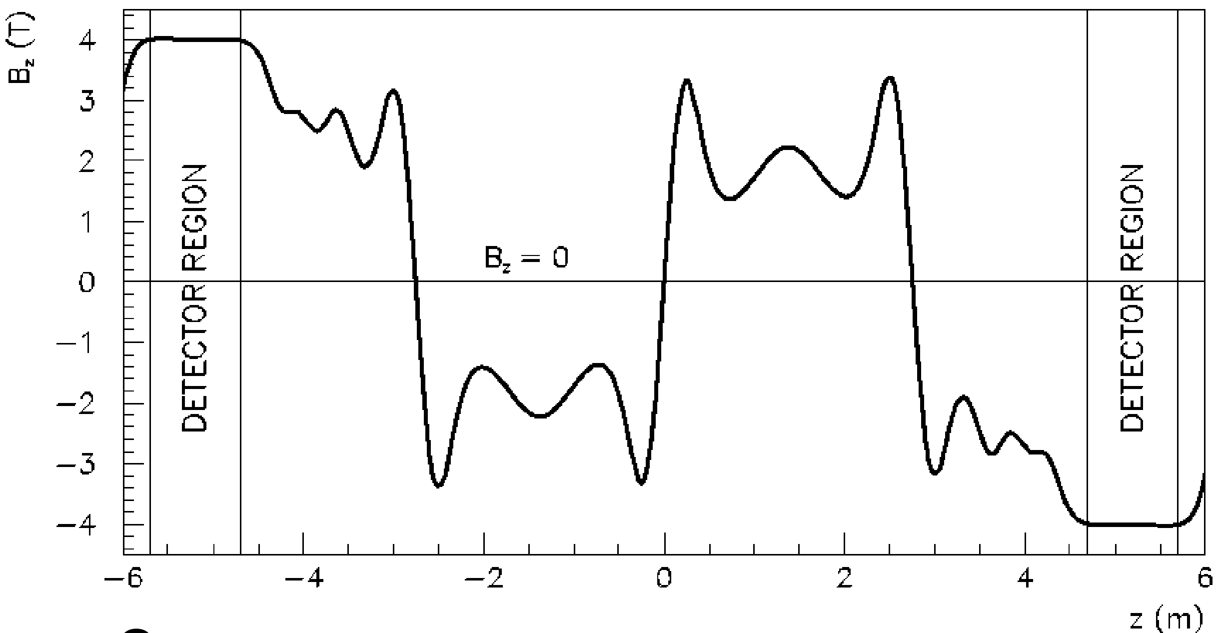
Principles of MICE

- Build minimum cooling channel that suffices
  - one complete lattice cell → ≈10% cooling effect
- Measure emittance with 0.1% precision
  - allows even small cooling effects near equilibrium emittance to be well measured

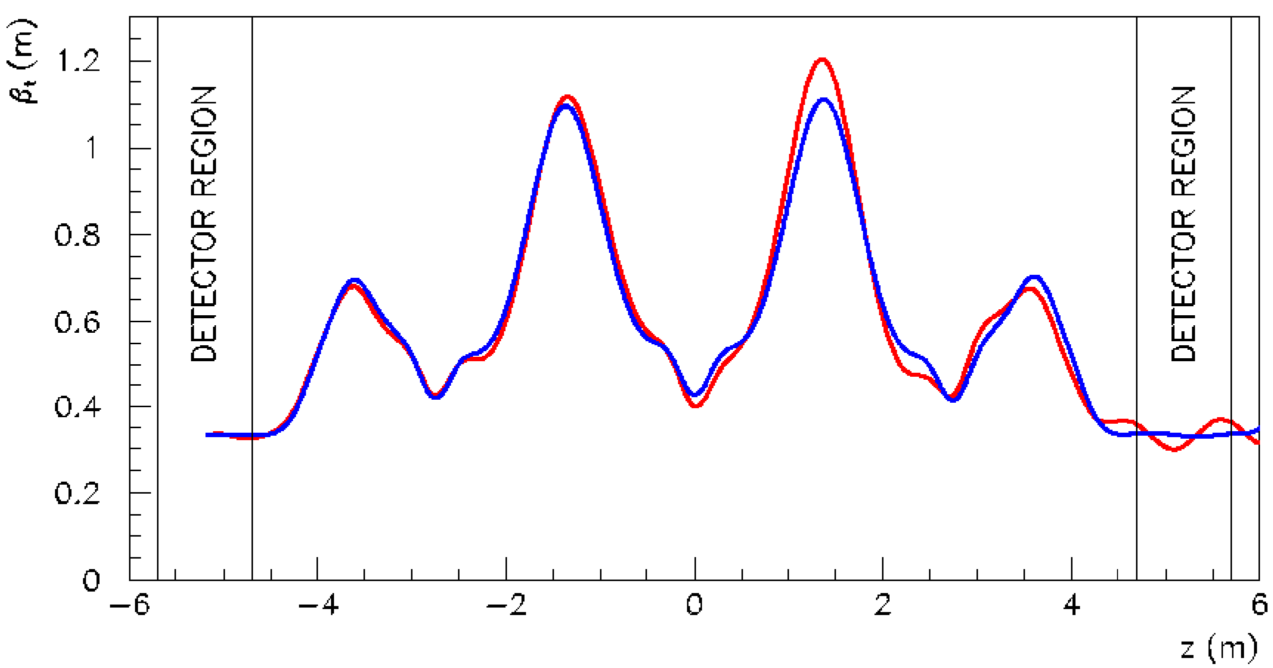
  ⇒ need to measure muon beam one muon at a time
- Vary all parameters to explore full performance range, validate simulation tools

Principles of MICE

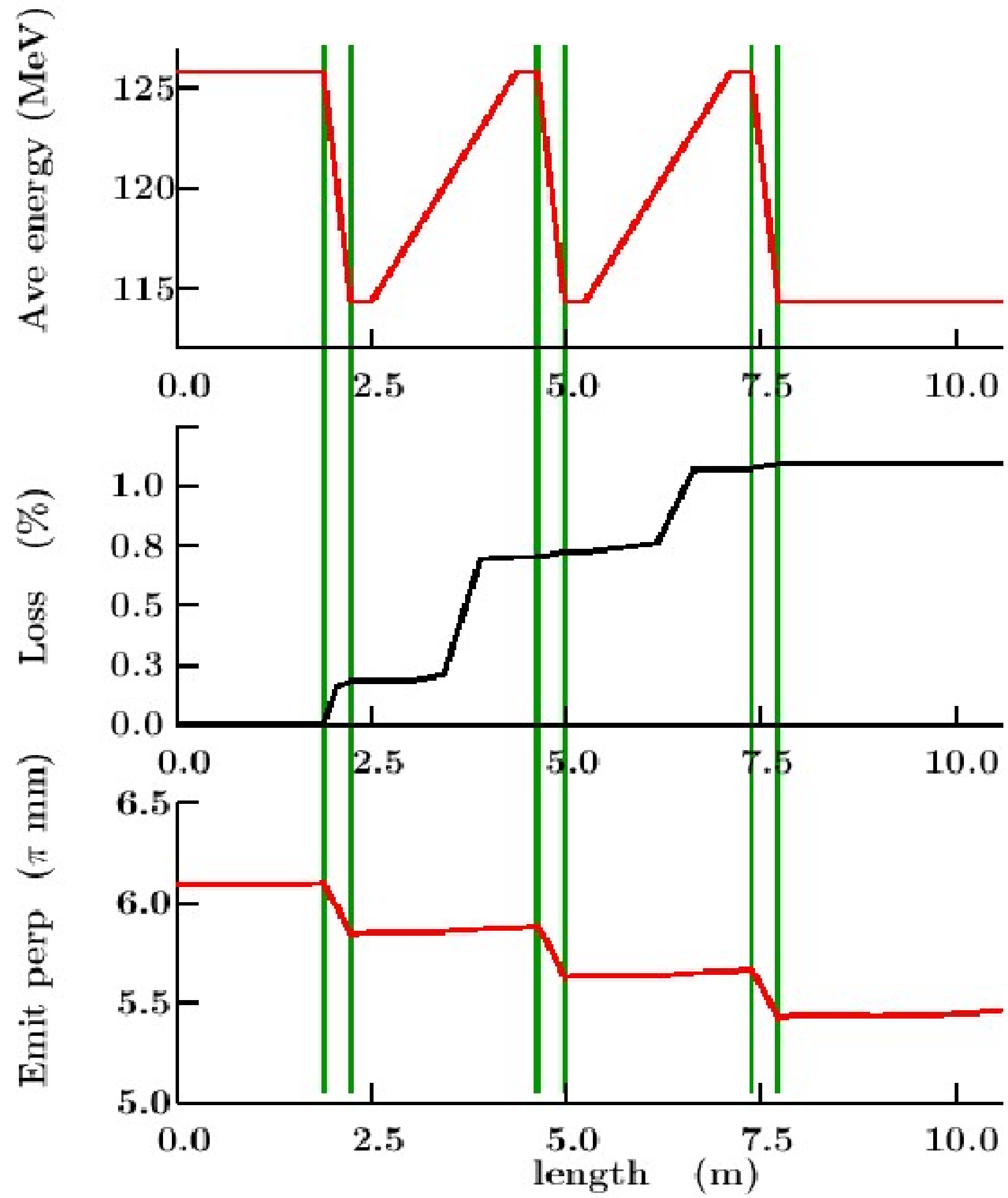
- B_z vs. z (nominal, 200 MeV/*c*):



- $\beta_\perp$ vs. z (nominal, 200 MeV/*c*):

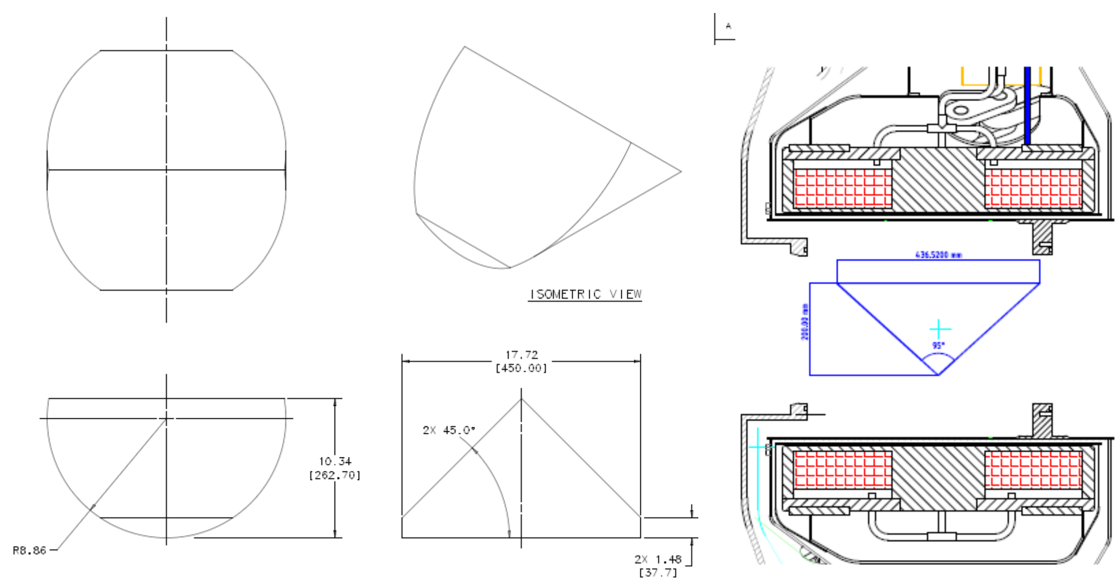


- Beam behavior vs. z:



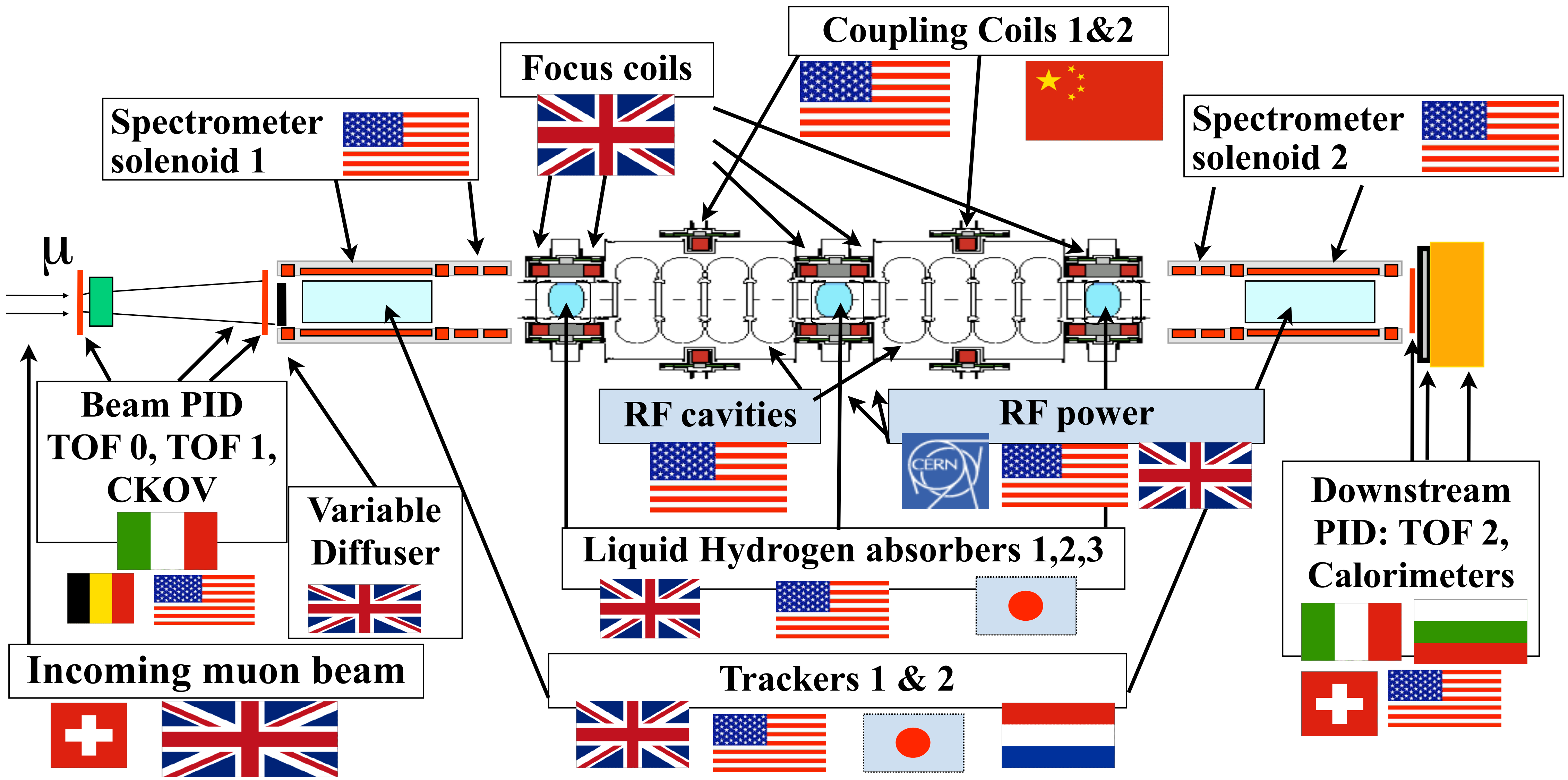
1st 6D cooling test:

- Some aspects of 6D cooling / emittance exchange can also be tested, by inserting wedge absorbers in MICE
- Part of MICE program
  - LiH wedge in fabrication:



MICE

- International collaboration:



MICE

- Quick tour:

MICE

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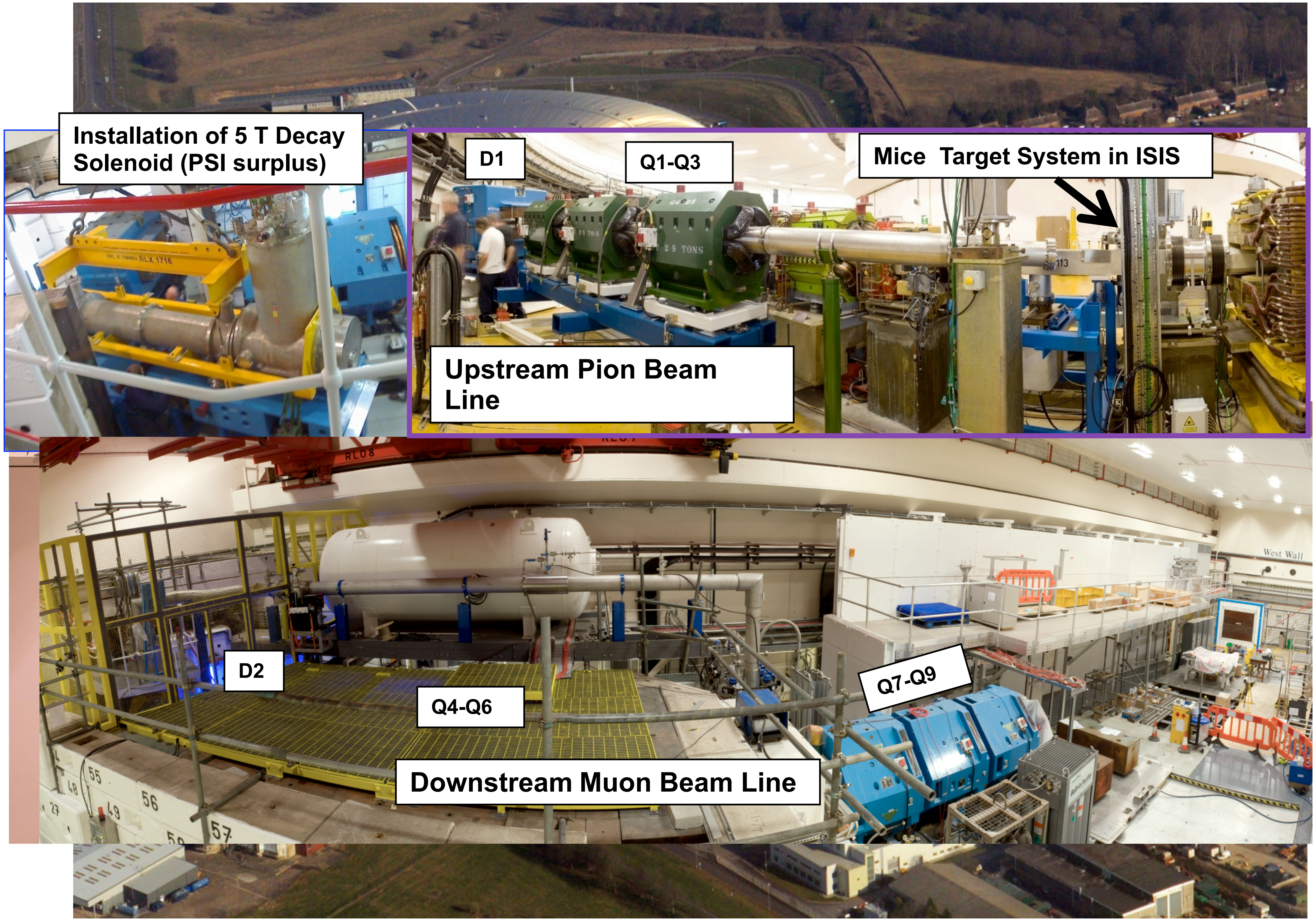
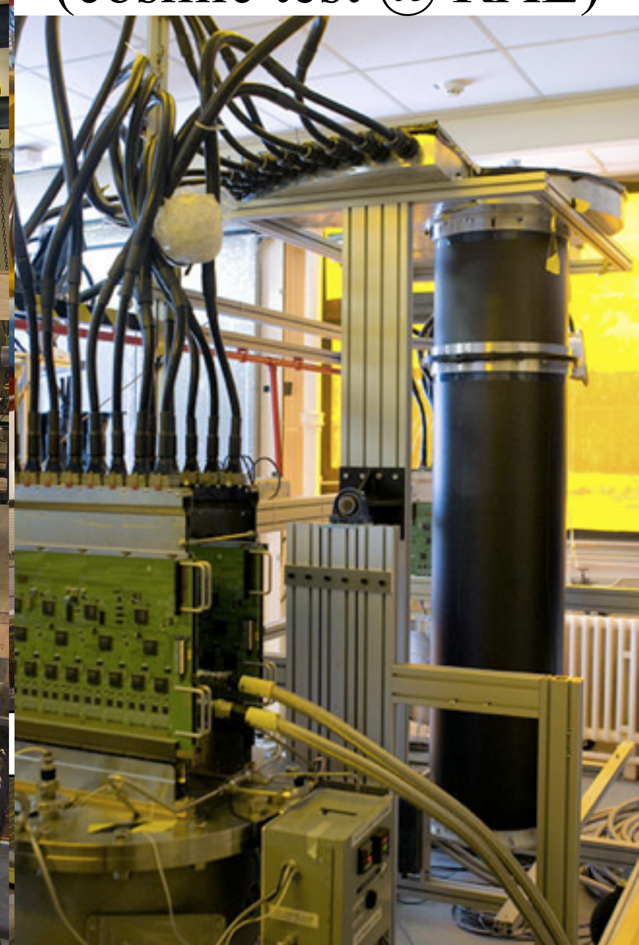


MICE

- Quick tour:

Spectrometer Solenoids (at vendor)

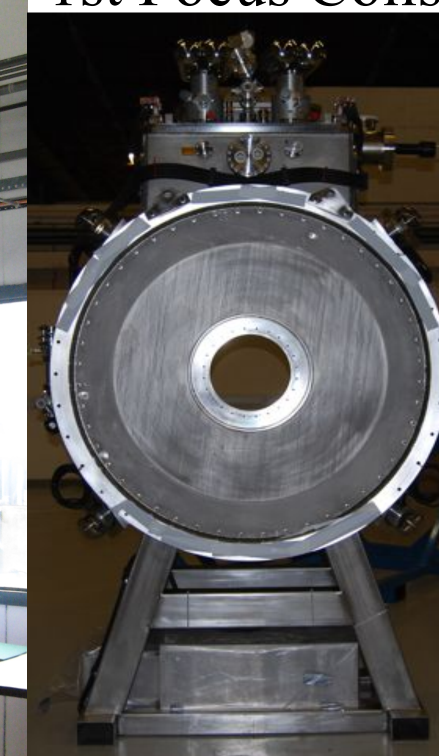
SciFi Trackers (cosmic test @ RAL)



RF Power Supplies (at Daresbury Lab)

LH_2 Absorber

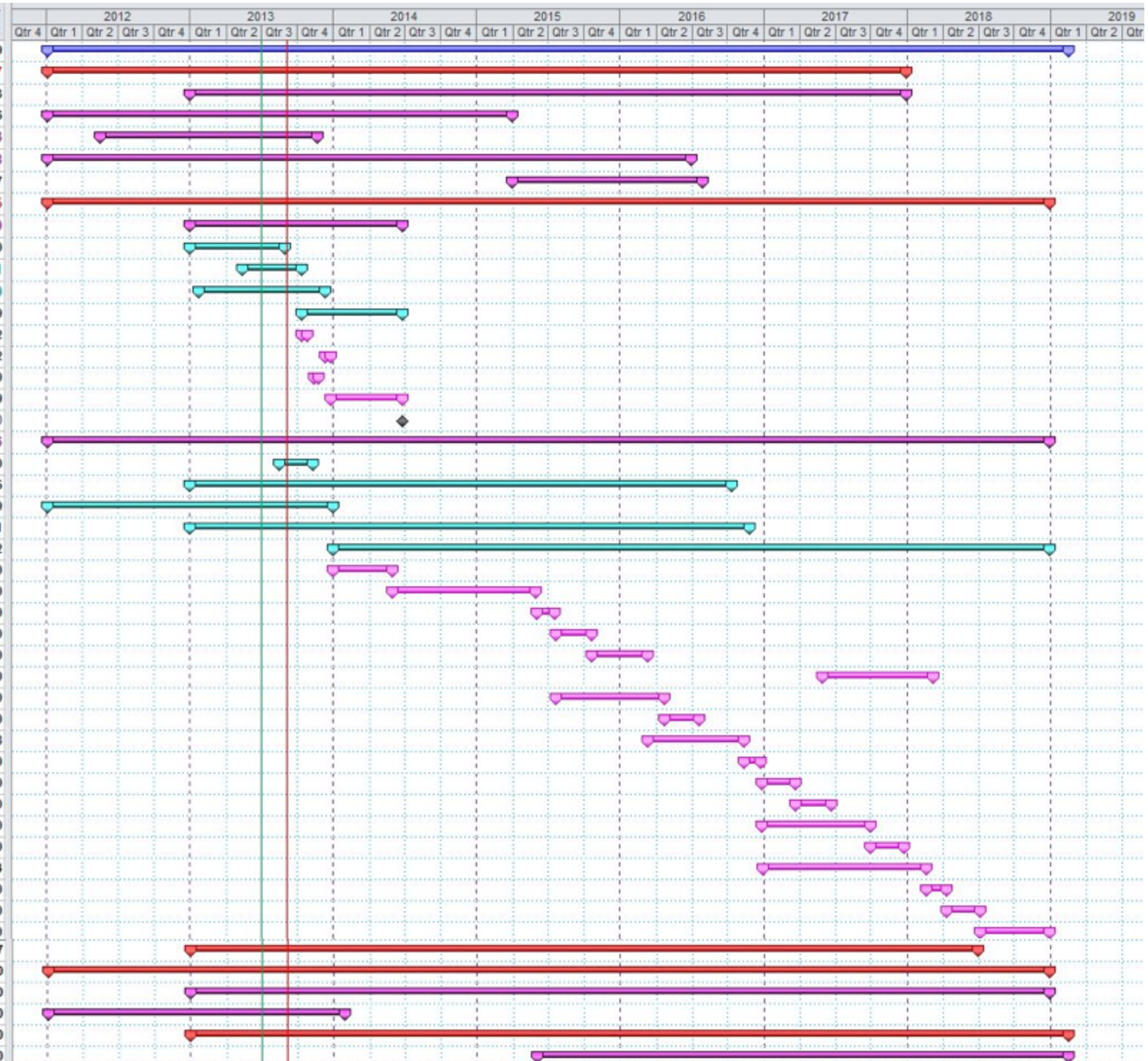
1st Focus Coils



1st RF Cavity

MICE Construction Schedule

Name	Start	Finish	Project Contingency (Other Institutions)
⊟ MICE Construction	Aon 10/3/11	Fri 11/16/18	3637157.89
⊟ MICE RF Design, Fabrication and Testing	on 10/3/11	Fri 9/29/17	1099241.57
⊞ MICE Engineering Oversight	Aon 10/1/12	Fri 9/29/17	154326.23
⊞ MICE RFCC Component Design	Aon 10/3/11	on 12/29/14	34327.86
⊞ MICE RF Cavity Fabrication (Prototype)	ed 2/15/12	ue 8/20/13	29283.03
⊞ MICE RF Cavity Fabrication (Production)	on 10/3/11	ue 3/29/16	723213.48
⊞ MICE RFCC Vacuum Vessel Fabrication	ue 12/30/14	Thu 4/28/16	158090.97
⊟ MICE Magnet Design, Fabrication and Testing	on 10/3/11	hu 9/27/18	2043875.05
⊟ MICE Spectrometer Solenoids	on 10/1/12	ed 3/26/14	266008.49
⊞ Spectrometer Solenoid Controls Upgrade & Validatic	Aon 10/1/12	Ved 5/29/13	0
⊞ Spectrometer Solenoid 2	on 2/11/13	ed 7/10/13	48817.21
⊞ Spectrometer Solenoid 1	n 10/22/12	Aon 9/9/13	165650.79
⊟ Spectrometer Solenoid Delivery, Installation, Commi	Thu 7/11/13	Ved 3/26/14	51540.49
⊞ SS#2 Shipment to UK	Thu 7/11/13	Ved 7/24/13	6162
⊞ SS#1 Shipment to UK	Tue 9/10/13	Aon 9/23/13	6162
⊞ Prepare and Ship Field Mapping Equipment from |	Aon 8/12/13	Fri 8/23/13	0
⊞ SS#1 and SS#2 Installation and Commissioning	Tue 9/24/13	Ved 3/26/14	39216.49
L4 - SS#1 & SS#2 Spectrometer Solenoids Ready for Oı	Ved 3/26/14	Ved 3/26/14	0
⊟ MICE Coupling Coils (CC)	on 10/3/11	hu 9/27/18	1777866.56
⊞ MICE Test Facility Contributions (FNAL)	Ved 5/15/13	Thu 8/8/13	0
⊞ CC Cold Mass Preparation	Aon 10/1/12	Aon 7/11/16	202901.15
⊞ CC Cryostat Design	Aon 10/3/11	Aon 9/30/13	71627.09
⊞ CC Cryostat Fabrication	Aon 10/1/12	Fri 8/26/16	1165040.61
⊟ CC Magnet Assembly	Tue 10/1/13	Thu 9/27/18	338297.72
⊞ CC Assembly Area Preparation	Tue 10/1/13	Ved 2/26/14	0
⊞ CCM Prototype Assembly at FNAL	Fri 2/28/14	Fri 2/27/15	0
⊞ CCM Prototype Test at FNAL	Mon 3/2/15	Fri 4/17/15	0
⊞ CCM Prototype Moved to MTA	Aon 4/20/15	Aon 7/20/15	0
⊞ RFCC Prototype Test (RFCC_Lite - Single Cavity)(1	Tue 7/21/15	hu 12/10/15	0
⊞ Optional: RFCC Prototype Integration	Tue 2/28/17	Tue 12/5/17	0
⊞ CCM#1 Assembly at FNAL	Aon 4/20/15	Ved 1/20/16	0
⊞ CCM#1 Testing at FNAL	Thu 1/21/16	Tue 4/19/16	0
⊞ RFCC#1 Integration	Fri 12/11/15	Thu 8/11/16	204182.58
⊞ RFCC#1 Preparation for Shipment to RAL	Fri 8/12/16	Fri 9/23/16	0
⊞ RFCC#1 Shipping to RAL	Aon 9/26/16	ue 12/20/16	0
⊞ RFCC#1 Installation & Commissioning at RAL	ed 12/21/16	Tue 3/21/17	0
⊞ CCM#2 Assembly at FNAL	Aon 9/26/16	Ved 6/28/17	0
⊞ CCM#2 Testing at FNAL	Thu 6/29/17	Fri 9/22/17	0
⊞ RFCC#2 Integration	Fri 9/30/16	Fri 11/17/17	134115.14
⊞ RFCC#2 Preparation for Shipment to RAL	on 11/20/17	Mon 1/8/18	0
⊞ RFCC#2 Shipping to RAL	Tue 1/9/18	Tue 4/3/18	0
⊞ RFCC#2 Installation & Commissioning at RAL	Wed 4/4/18	Thu 9/27/18	0
⊞ MICE Magnetic Shielding	Aon 10/1/12	Fri 3/30/18	494041.27
⊟ MICE Detector Design, Fabrication and Testing	Aon 10/3/11	Fri 9/28/18	0
⊞ MICE Detectors (US Contributions)	Aon 10/1/12	Fri 9/28/18	0
⊞ MICE Absorbers (US Contributions)	Aon 10/3/11	on 10/28/13	0
⊟ MICE US Component Integration	Aon 10/1/12	Fri 11/16/18	0
⊞ MICE-US RF Component Integration	Mon 3/2/15	Fri 11/16/18	0

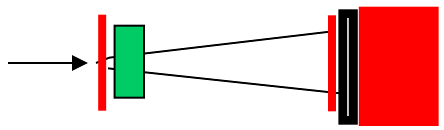


MICE Running Schedule

μ

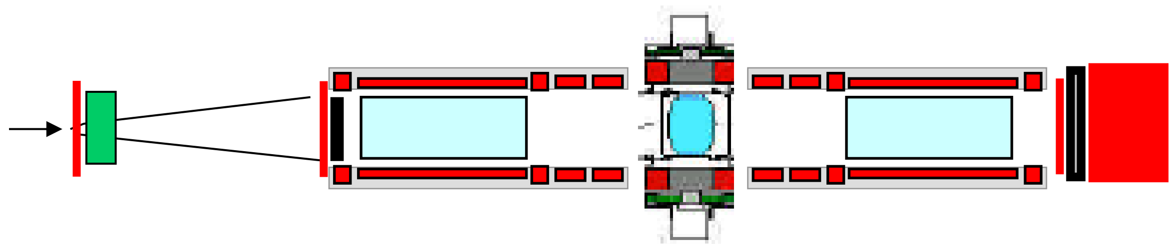
Provisional MICE SCHEDULE update: May 2013

Run date:



STEP I

EMR run July 2013

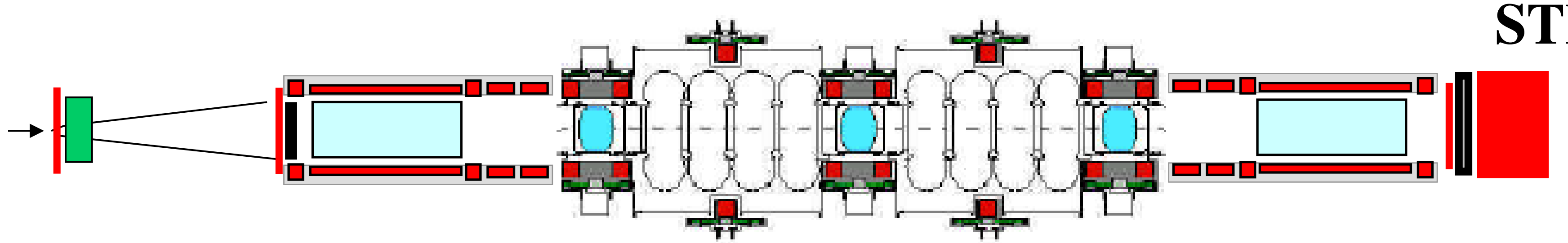


STEP IV

(Q2 2014, no field)
Q1 2015
to Q1 2016

1st μ cooling demonstration!

Under construction:



STEP VI

Thorough investigation of μ cooling and MC validation

Possible Step V run Q4 2017
Step VI 2019

May 2013 MICE Status Alain Blondel

Current MICE Status

- EMR calorimeter in final assembly for installation @ RAL & beam test later this year
- Both SS completed @ vendor, one in field-mapping, other in cooldown for training
- 1st AFC in training at RAL
- 1st (MuCool) CC cold mass under test @ FNAL
- Plan:
  - Step IV running in 2015 following long ISIS shutdown
  - Steps V/VI running 2017–19

Conclusions

- Higgs and θ_{13} discoveries have set the stage for stored-muon facilities
- 10^{21} ν/year Neutrino Factory feasible S. Choubey *et al.* [IDS-NF collaboration], Interim Design Report, arXiv:1112.2853 [hep-ex]

  → world's best measurements of neutrino oscillation parameters

- High-$\mathscr{L}$ Muon Collider looks feasible
  - possibly buildable as Neutrino Factory upgrade
  - Higgs Factory could be important step(s) on the way!
- Muon Collider technology selection & feasibility assessment are main goals of MAP 6-year R&D program [M. Palmer, next talk]

  ➡ 1st Muon Collider could be under construction by late 2020s