Progress Toward a Higgs Factory

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Physics Motivations

- Muon beams offer enormous potential for high energy physics
  - Tests of Lepton Flavor Violation (Mu2e)
  - Anomalous magnetic moment – hints of new physics (g-2)
  - Equal fractions of electron and muon neutrinos for high intensity neutrino experiments

$$\mu^{+} \rightarrow e^{+}\ \nu_{e}\ \bar{\nu}_{\mu} \qquad\qquad \mu^{-} \rightarrow e^{-}\ \bar{\nu}_{e}\ \nu_{\mu}$$

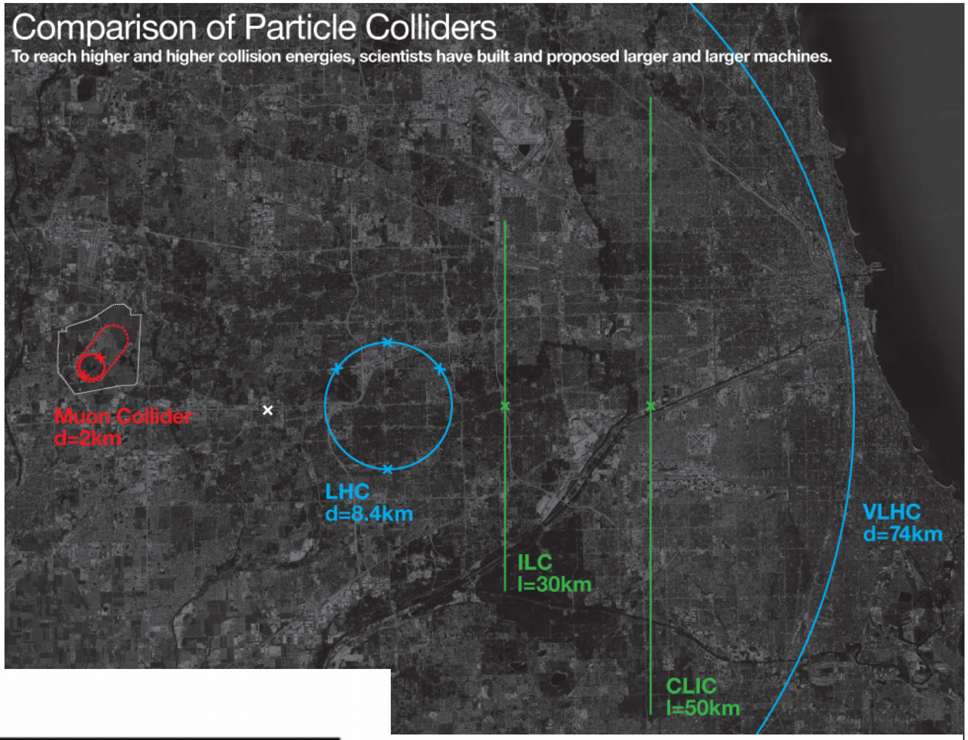
  - **Large coupling to the Higgs mechanism**

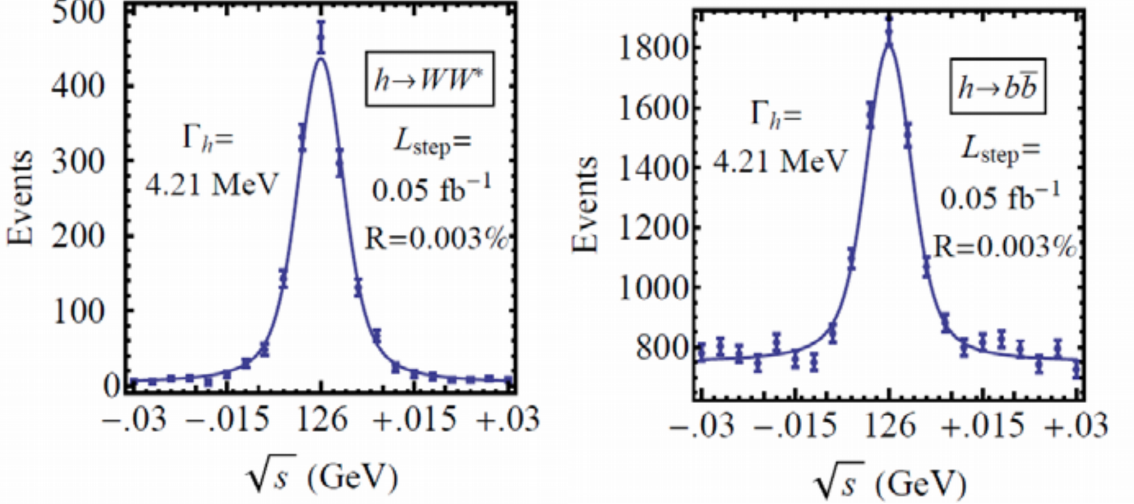
$$\sigma \propto \left(\frac{m_{\mu}^{2}}{m_{e}^{2}}\right) \approx 4\,x\,10^{4}$$

  - Extremely precise probe of fundamental interactions (as with $e^{+}e^{-}$ colliders, as opposed to hadron colliders)

Higgs Factory Advantages

- So far, the Higgs boson appears to be fairly plain
    - What if nothing “exciting” is seen at the LHC?
- A μ^+/μ^- collider allows probing of Higgs with unparalleled precision
    - ~0.004% energy resolution
    - Significantly smaller backgrounds than LHC
- Compact (~100 m diameter)
- Acceleration in rings
- Upgradeable to >1 TeV





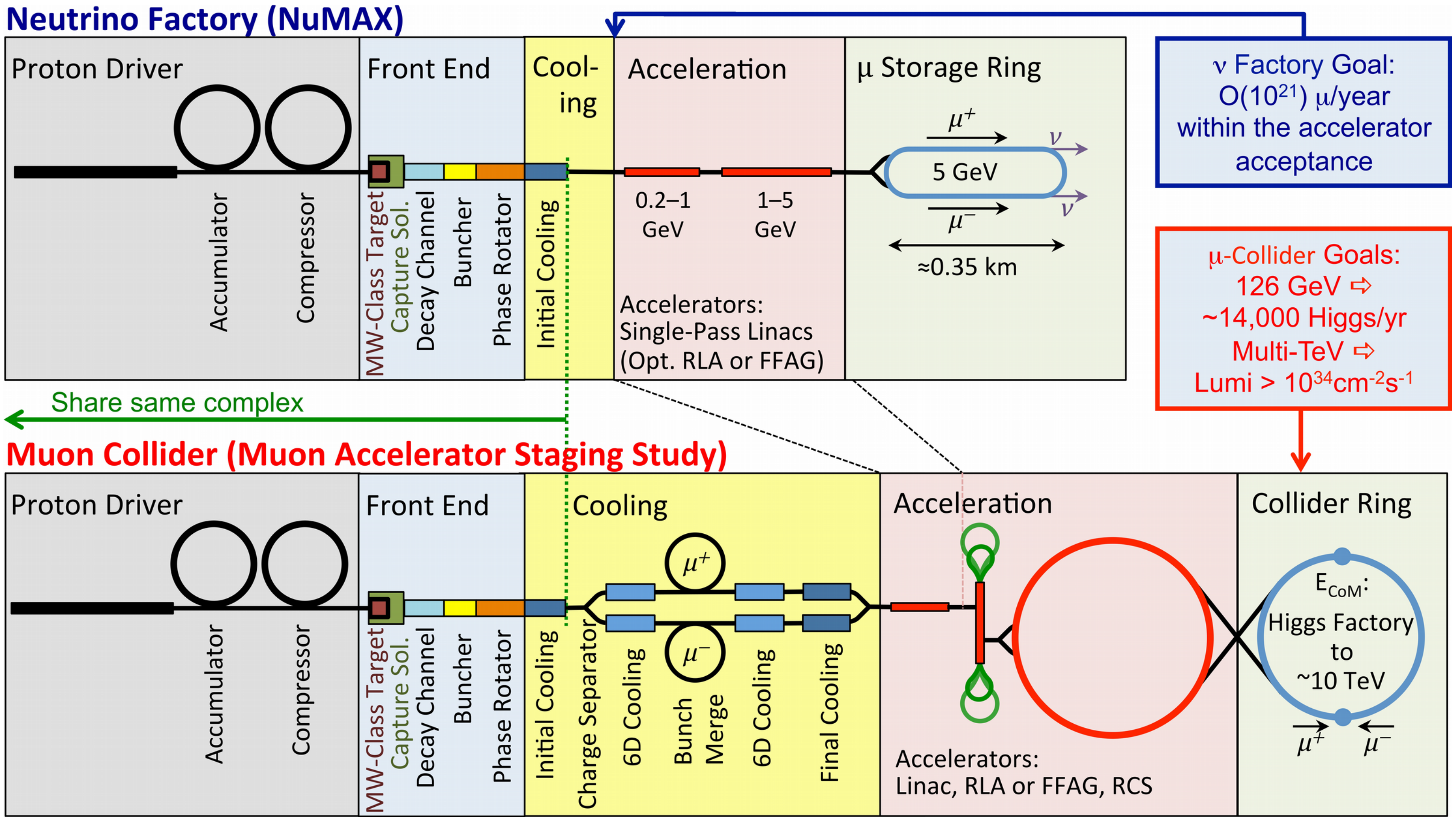
Muon Collider Parameters

		Higgs	**Multi-TeV**		
Parameter	***Units***	*Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	**0.126**	**1.5**	**3.0**	**6.0**
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^{7}sec		13,500	37,500	200,000	820,000
Circumference	km	0.3	2.5	4.5	6
No. of IPs		1	2	2	2
Repetition Rate	Hz	15	15	12	6
β^*	cm	1.7	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1.5	70	70	70
Bunch Length, σ_s	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

Success of advanced cooling concepts a several × 10^{32}

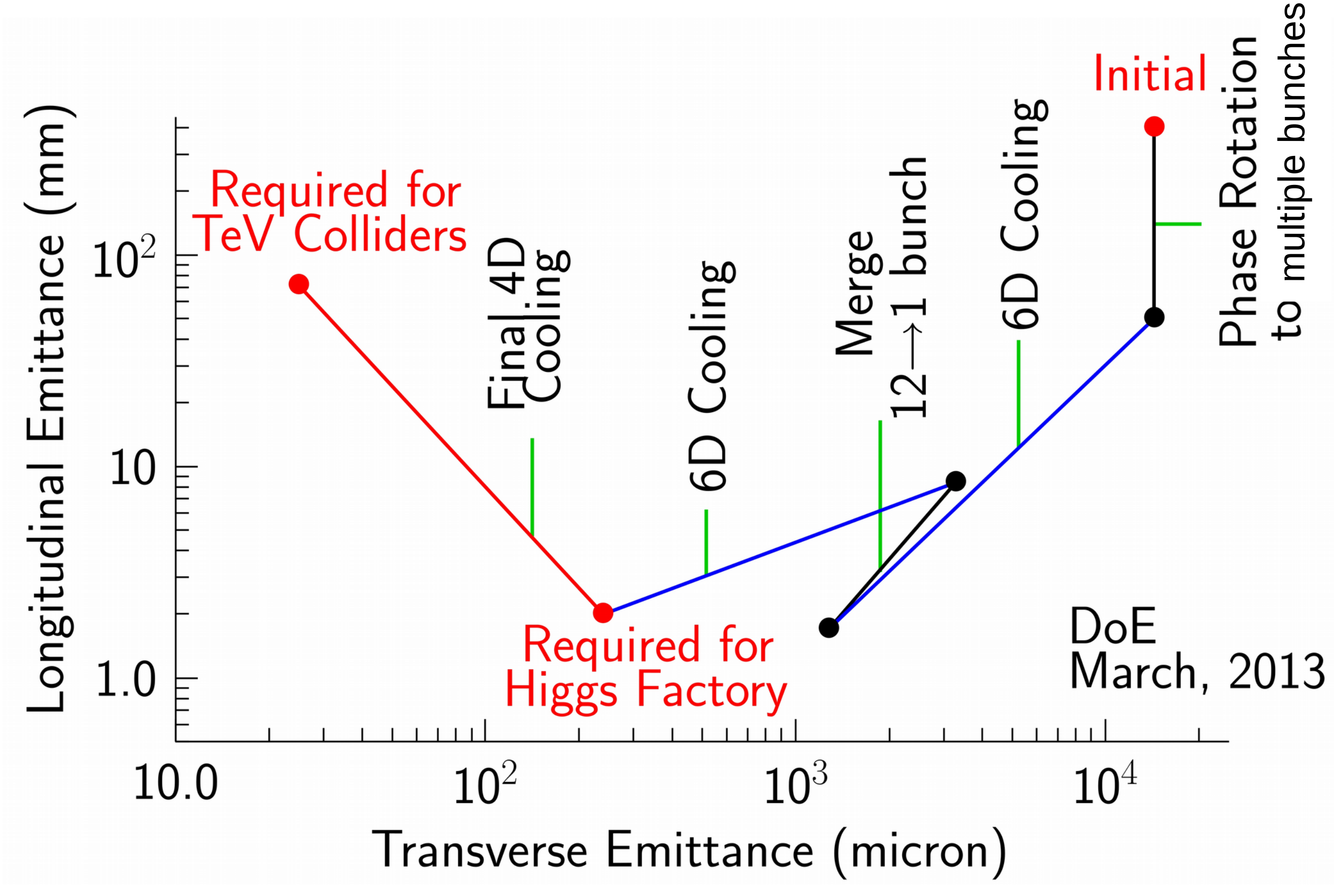
A Muon Accelerator



- Producing high quality muon beam challenging
  - Proton driver
  - Target
  - Cooling
  - Acceleration

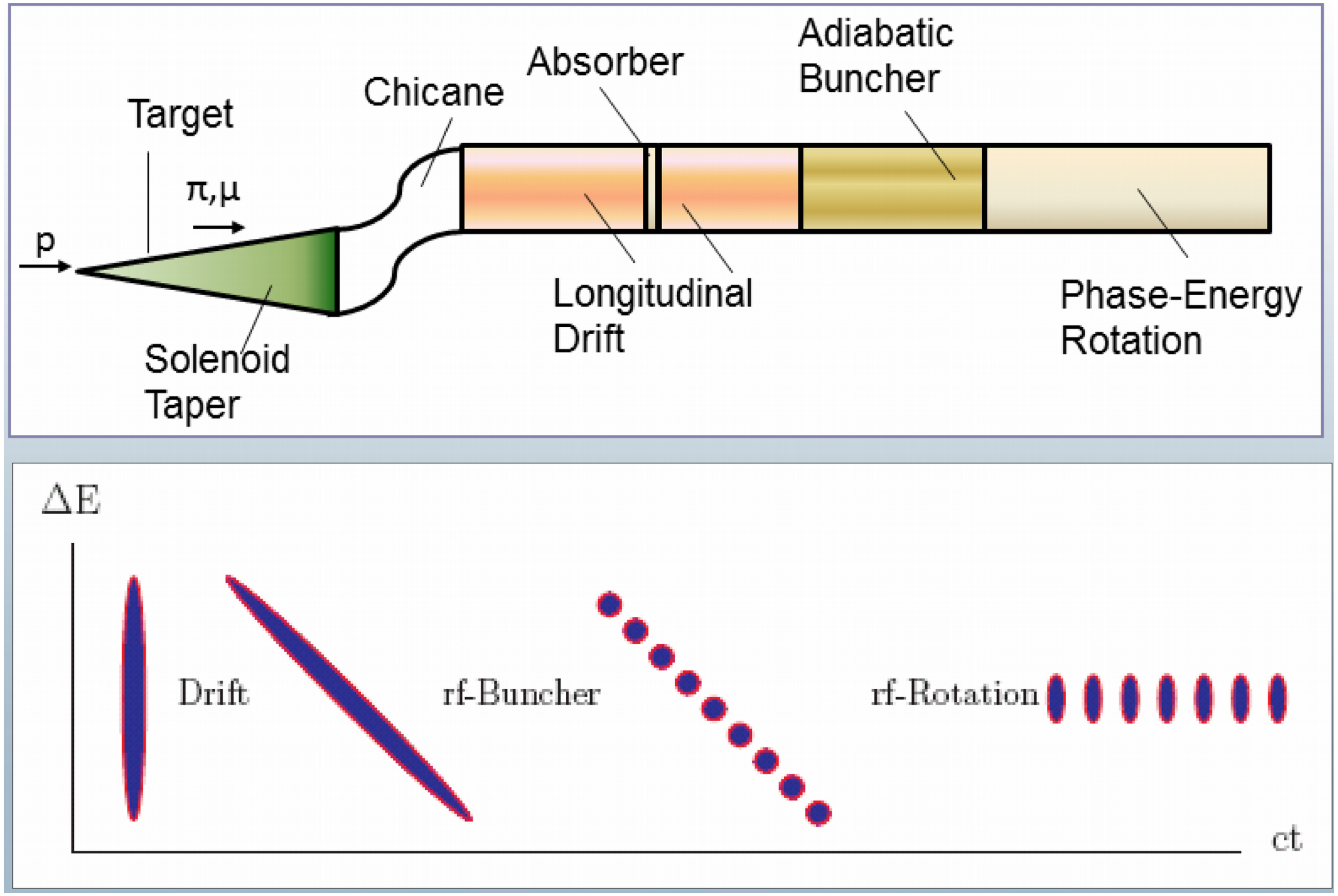
Emittance

- The initial emittance is much too large to attain the desired luminosity
- For a Higgs Factory, a momentum spread on the order of 10^{-5} mandates small longitudinal emittance

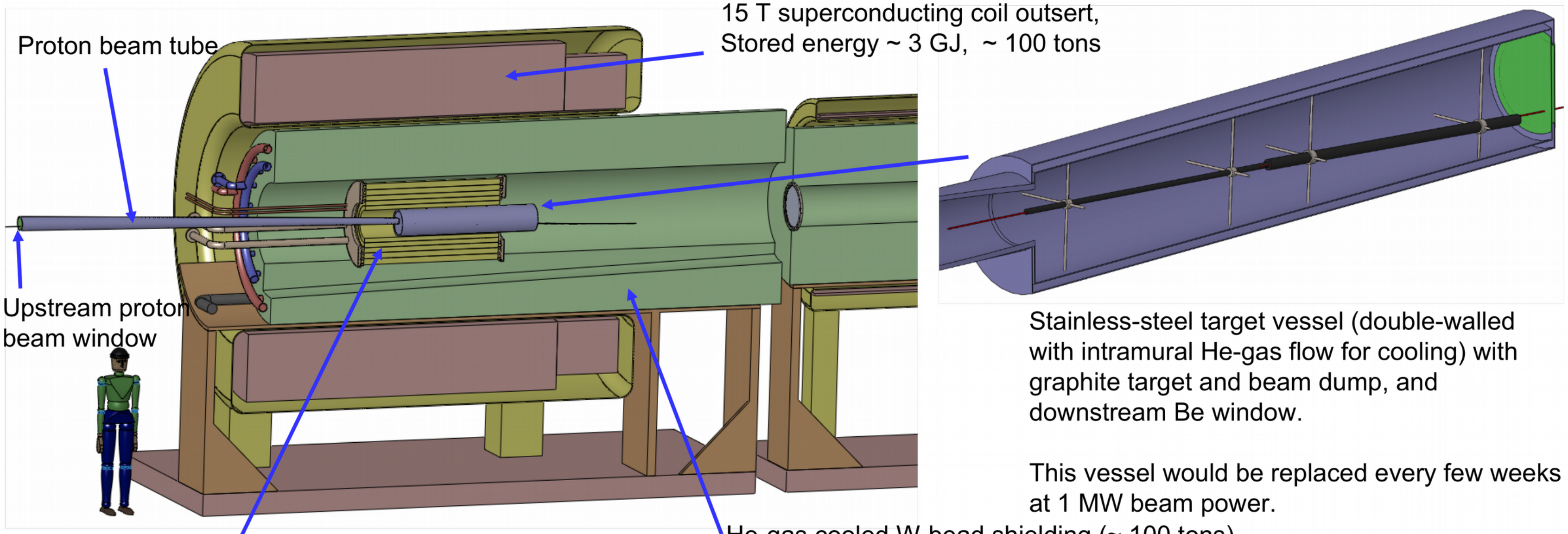


Front End

- Target → Chicane → Decay Channel → Buncher → Phase rotator



Target



Proton beam tube

15 T superconducting coil outsert, Stored energy ~ 3 GJ, ~ 100 tons

Upstream proton beam window

Stainless-steel target vessel (double-walled with intramural He-gas flow for cooling) with graphite target and beam dump, and downstream Be window.

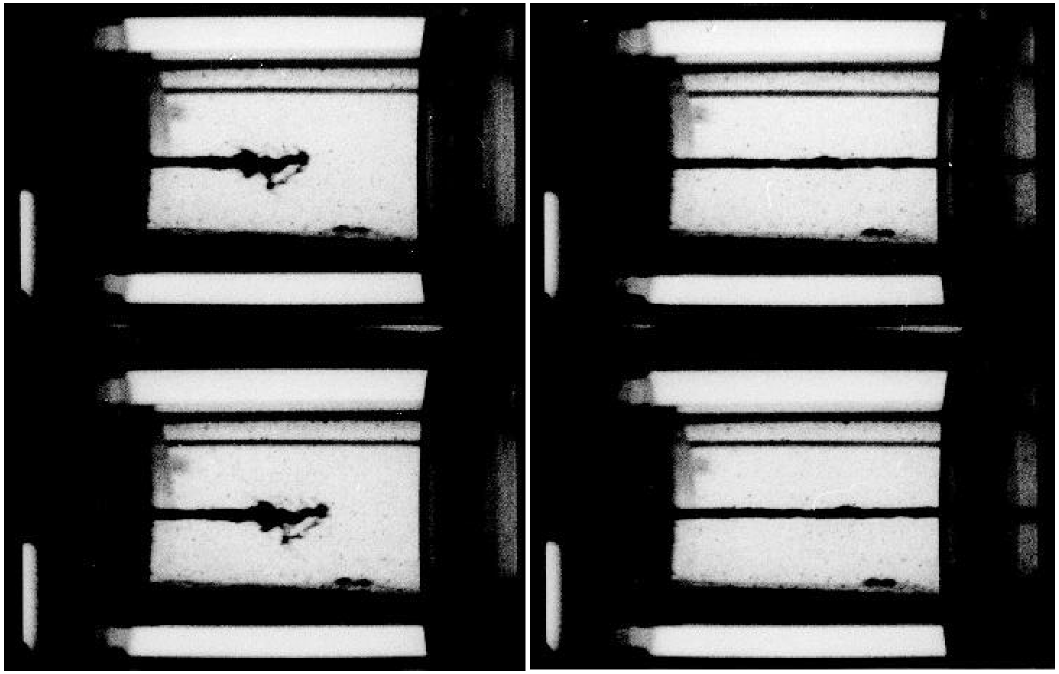
This vessel would be replaced every few weeks at 1 MW beam power.

He-gas cooled W-bead shielding (~ 100 tons)

5 T copper-coil insert. Water-cooled, MgO insulated

- Two target options:
  - Solid carbon
    - 6.75 GeV protons, 1 MW beam power, 20 T → 2 T over 5 m
  - Liquid mercury
    - 8 GeV protons, 4 MW beam power, 15 T → 2 T over 5 m

Target Technology



High-speed photographs of mercury jet target for CERN-PS-AA (laboratory tests)

4,000 frames per second, Jet speed: 20 ms-1, diameter: 3 mm, Reynold's Number:>100,000

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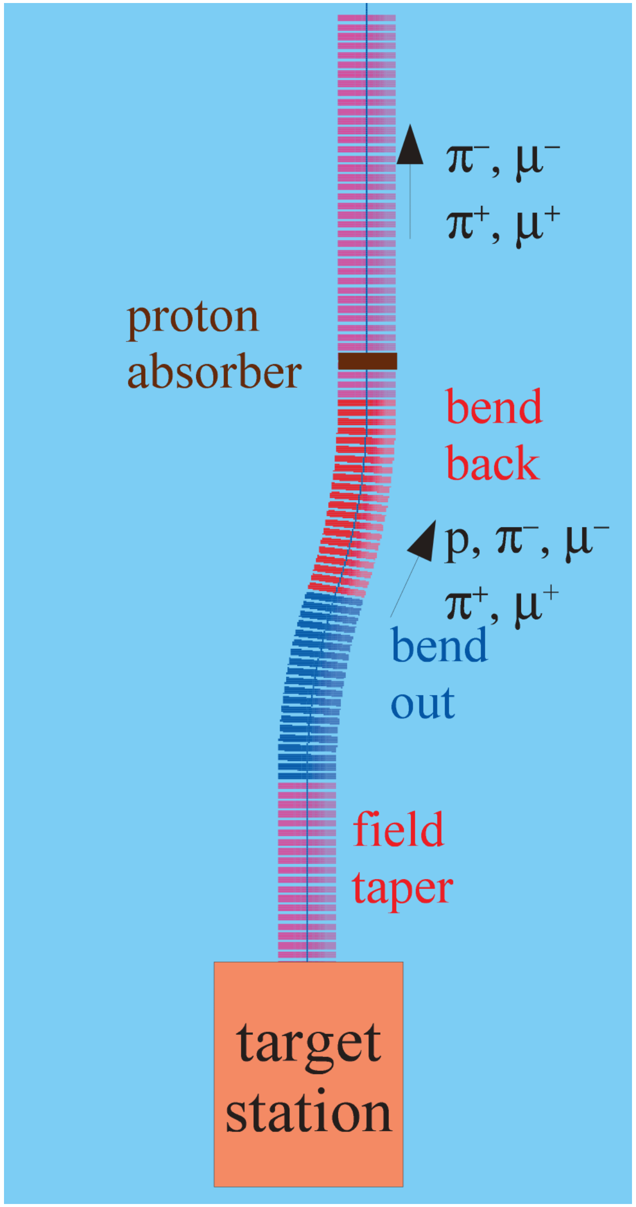
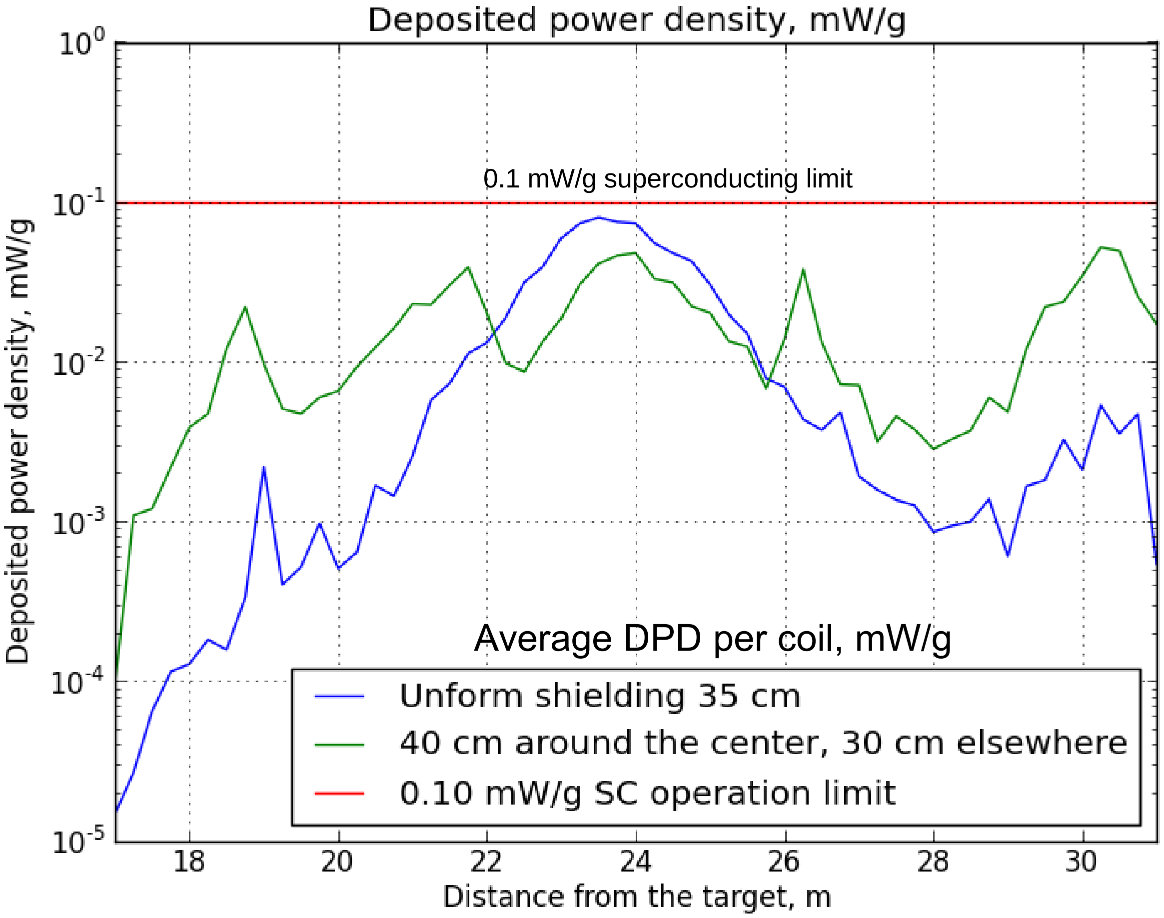
- Liquid Mercury target experiment (MERIT) demonstrated
  - Pulsed 4 MW proton beam
  - 15 T magnetic field
- Magnets around target need significant radiation shielding

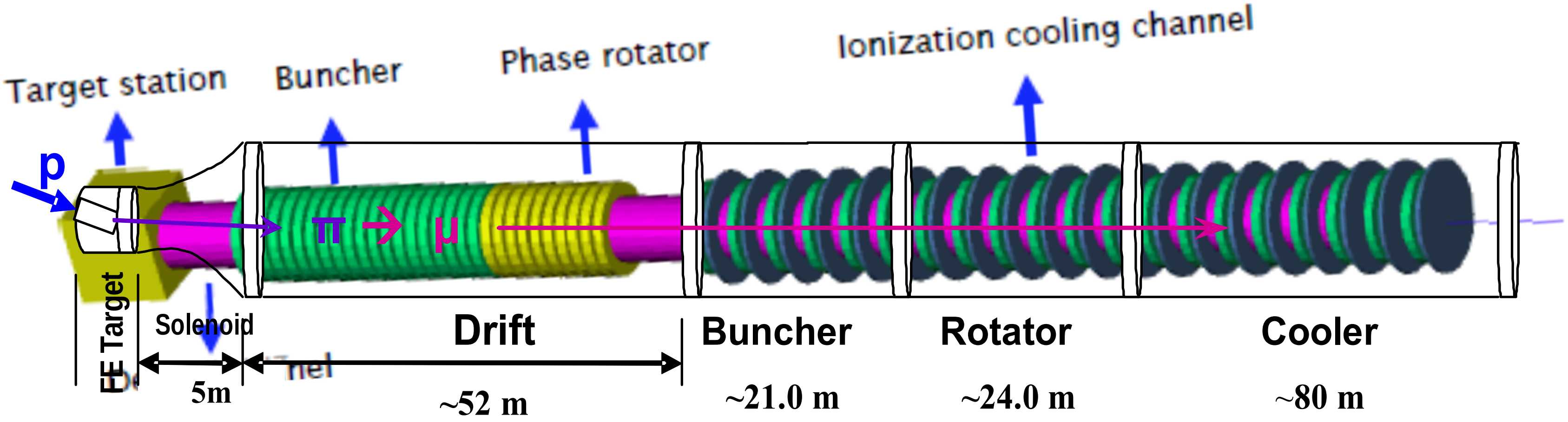
Chicane



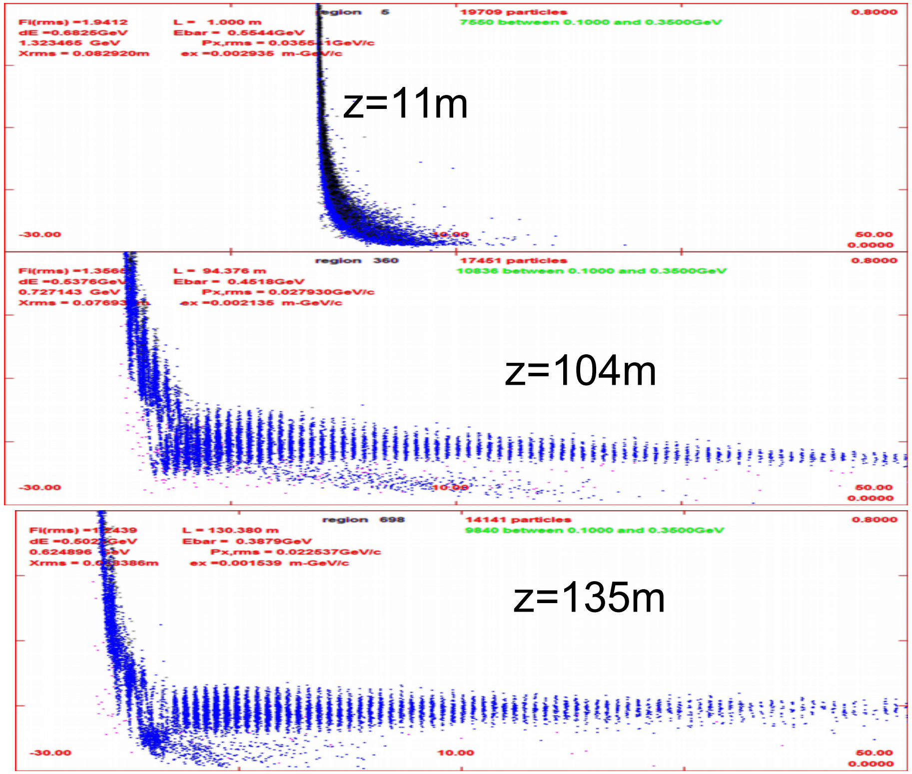
- Uniform 35 cm shielding (tungsten beads) added to minimize energy deposition in superconducting coils



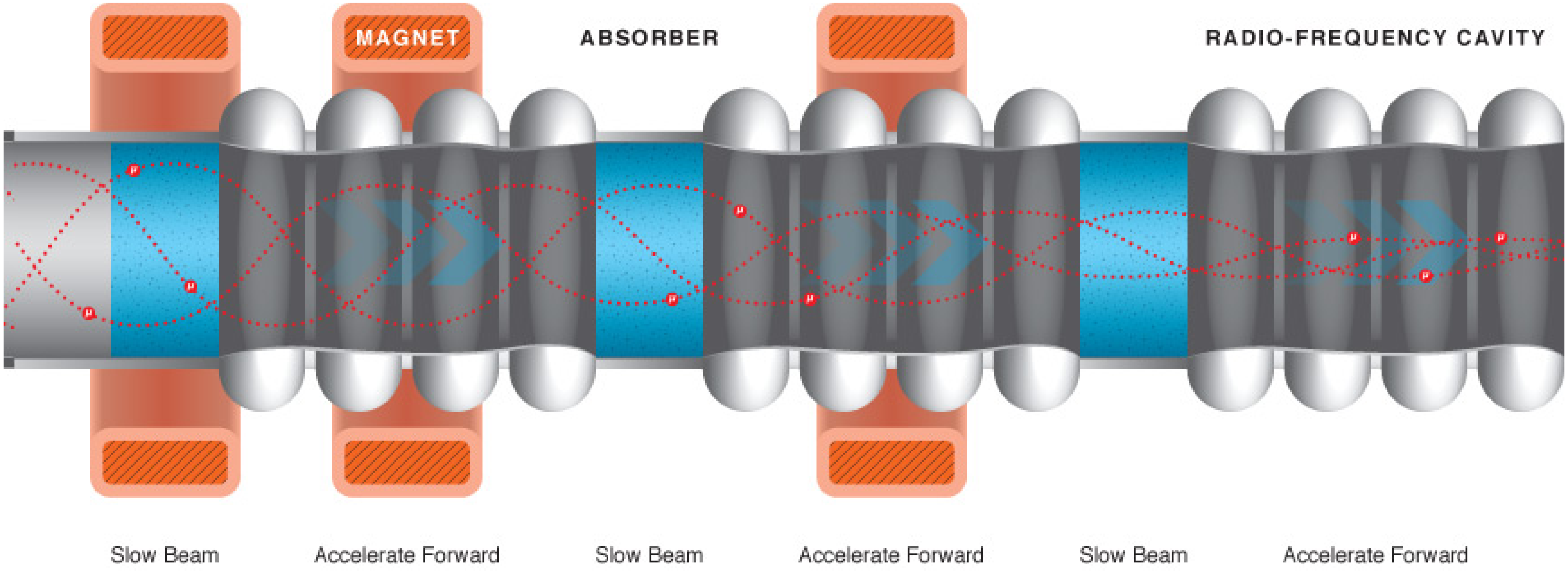
Front End Simulation



- 8 GeV protons on mercury target
  - 0.0756 μ^+/p, 0.0880 μ^-/p
- 6.75 GeV protons on carbon target
  - 0.0613 μ^+/p, 0.0481 μ^-/p
- 490 → 365 MHz in buncher
- 364 → 326 MHz in rotator
- Adding 34 atm H_2 gas decreases production by 10%
  - 17 atm consistent with baseline



Ionization Cooling



- Only means of cooling a muon beam fast enough is ionization cooling
- Beam passes though absorbing material, losing energy
- RF cavities replace lost longitudinal momentum to maintain energy along beam path, while losing energy transversely
- Repeated many times, this reduces transverse emittance (4D cooling)

Maximizing Cooling

Change in normalized emittance:

$$\frac{d\epsilon_n}{ds} = \boxed{\frac{1}{\beta^3}\frac{\beta_\perp (0.014)^2}{2E_\mu m_\mu X_0}} - \boxed{\frac{1}{\beta^2}\left\langle \frac{dE_\mu}{ds} \right\rangle \frac{\epsilon_n}{E_\mu}} \qquad \beta_\perp = \frac{\pi\sigma_\perp^2}{\epsilon_\perp}$$

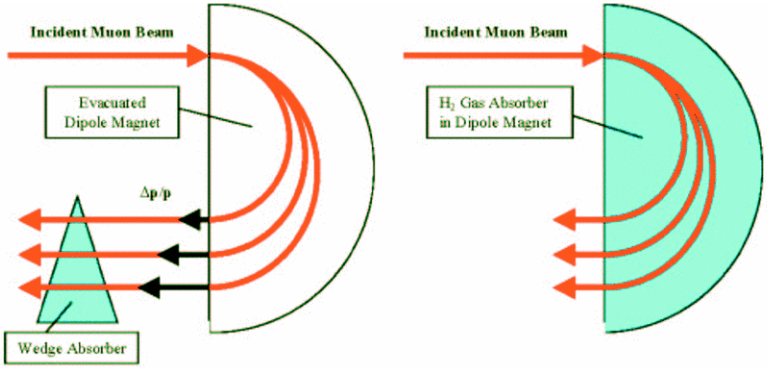
Heating

Cooling

- To minimize heating:
  - Small beta function
    - Strong magnetic field
  - Large radiation length
- To maximize cooling:
  - Large stopping power (dE/ds)
- Hydrogen provides ideal radiation length and stopping power

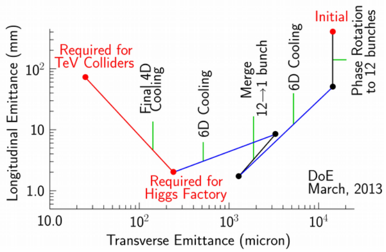
6D Cooling

- Emittance exchange must be introduced to cool in 6D
  - Two schemes

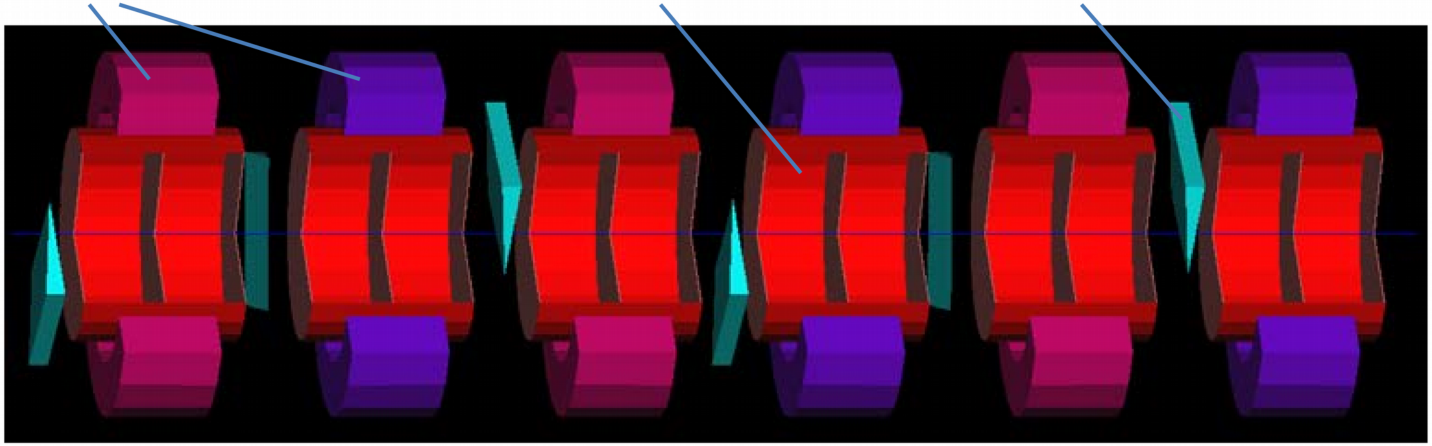


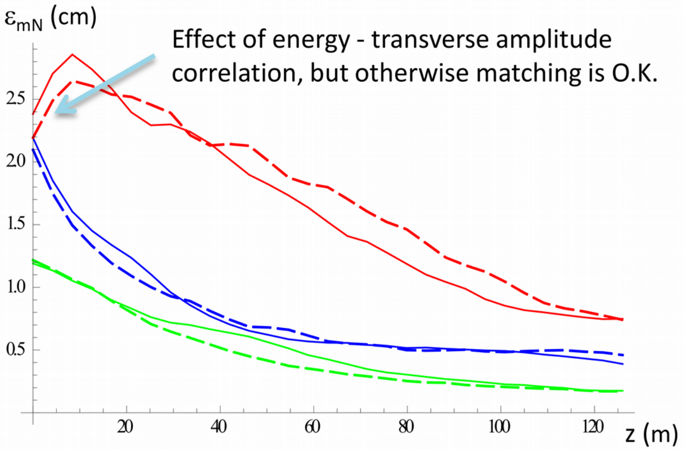
- 6D cooling channels under consideration
  - Rectilinear Cooling Channel
    - Vacuum RF cavities, tilted solenoids, wedge absorbers
  - Helical Cooling Channel
    - Gas filled RF cavities, helical solenoids, homogeneous H_2 absorbers
  - Hybrid Cooling Channel
    - Gas filled RF cavities, tilted solenoids, wedge absorbers

Initial Cooling



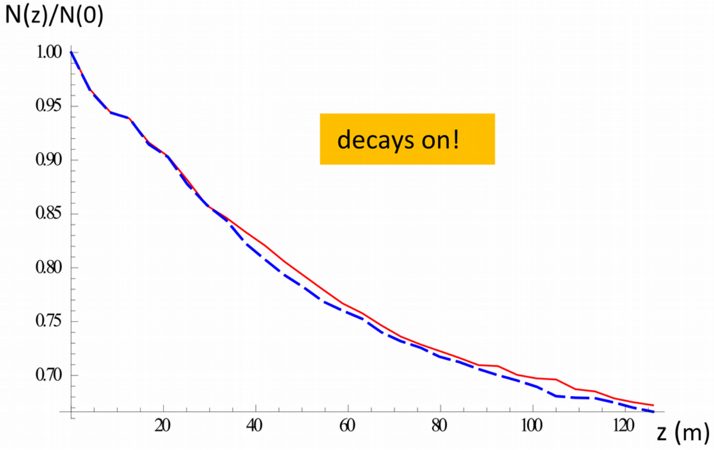
coils: R_{in}=42cm, R_{out}=60cm, L=30cm; RF: f=325MHz, L=2×25cm; LiH wedges





Effect of energy - transverse amplitude correlation, but otherwise matching is O.K.

Normalized emittances (cm) from Gaussian fit: μ^+ - solid lines, μ^- - dashed lines.

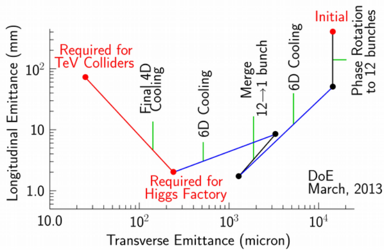


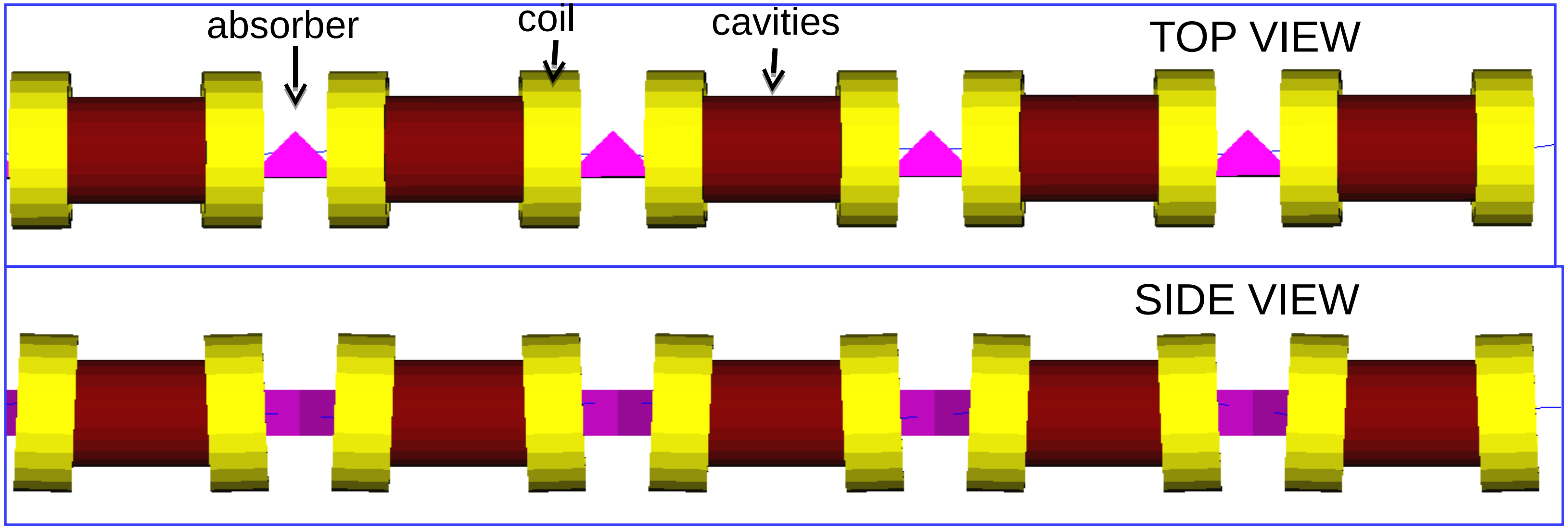
decays on!

Transmission as a ratio of the number of muons in the Gaussian core: red solid line - μ^+, blue dashed line - μ^-.

- 325 MHz cavities filled with H$_2$ gas, 25 MV/m
- Be windows, radius 30 → 20 cm, thickness 120 → 70 μm
- LiH absorbers with tapered wedge angle 0.17 → 0.2 rad, placed at $\beta_\perp$ minimum
- Solenoid pitch 2.5 mrad, tapered B_z 3.9 → 3.5 T, coil inner radius 42 cm
- 6D emittance reduced by factor ~110 for both μ^+ and μ^-
- Transmission ~67% for core of beam

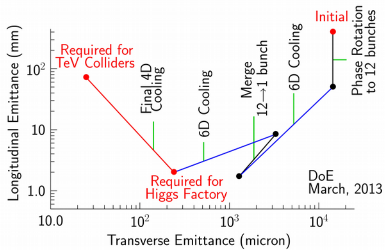
Rectilinear Cooling Channel



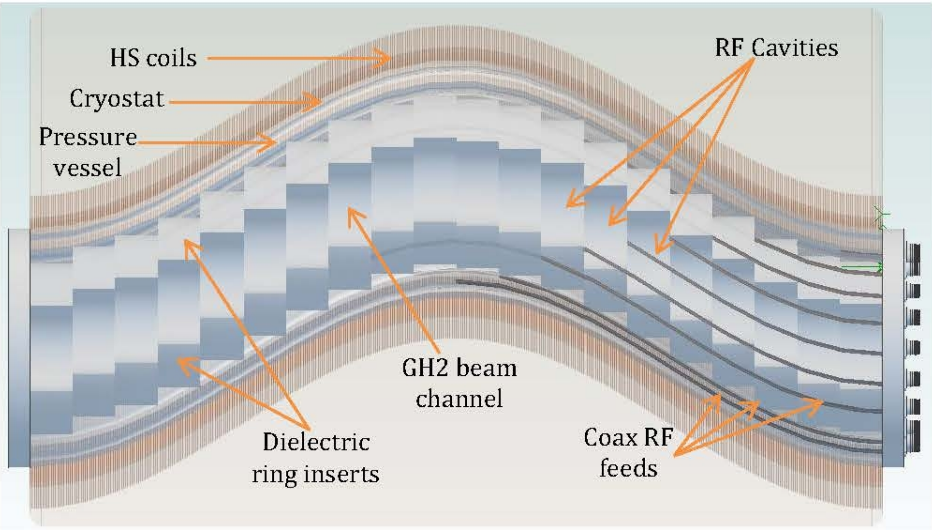


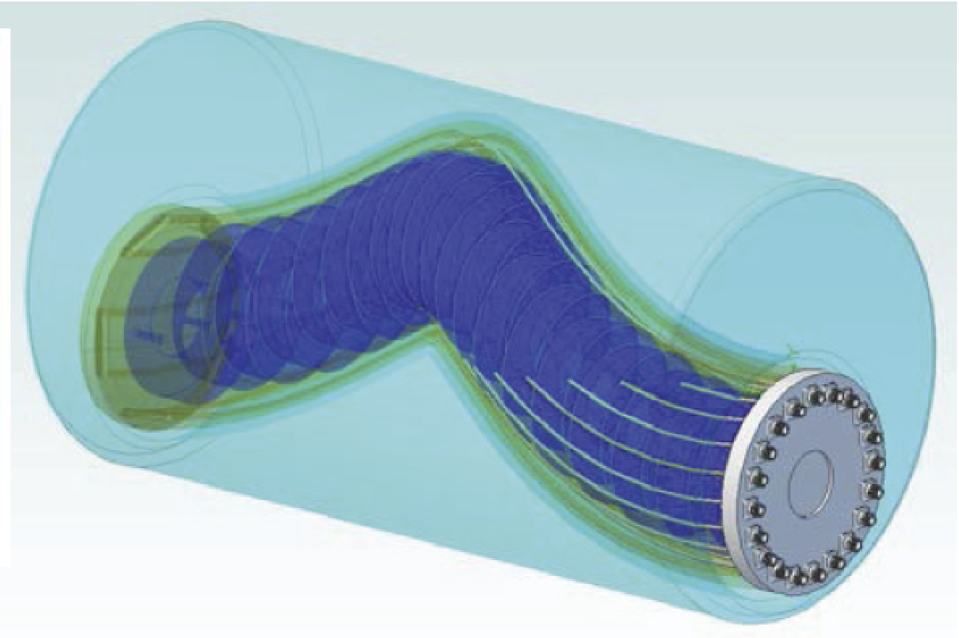
- Tilted magnet coils generate dispersion
- Absorbers are discrete LH_2 & LiH wedges
- Axial magnetic field in RF cavities 2.4 → 15 T for 325 MHz and 650 MHz

Helical Cooling Channel



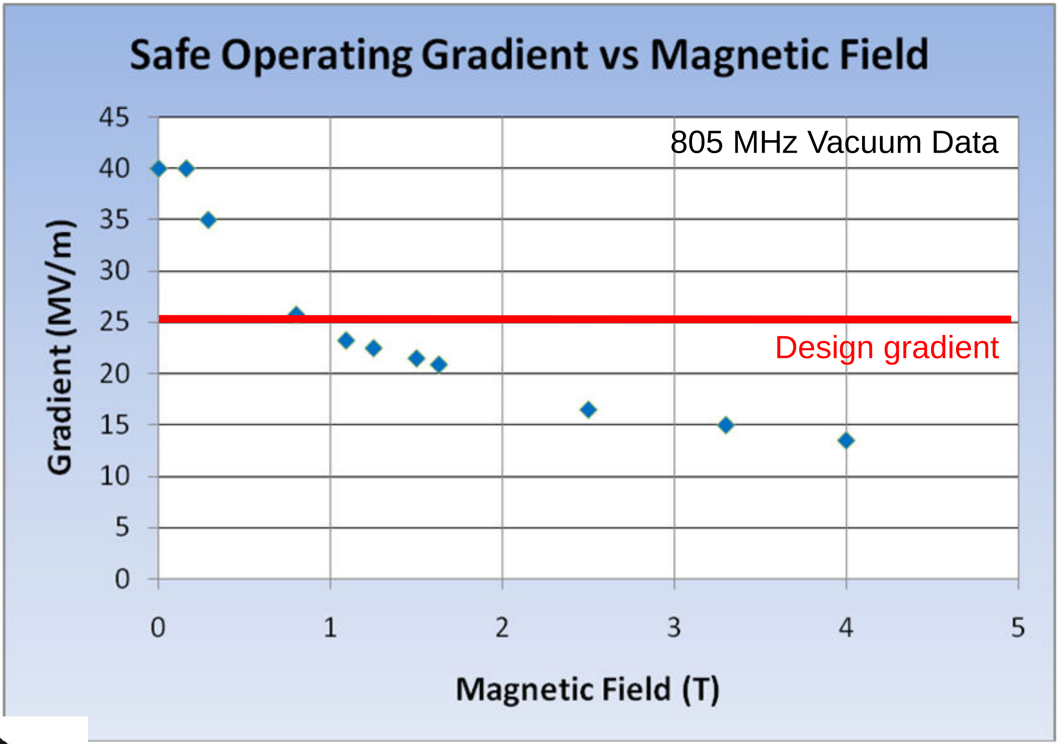
- Helically arranged magnets produce solenoidal and helical dipole and quadrapole fields
- Homogeneously distributed H_2 filled RF cavities placed along particle orbit



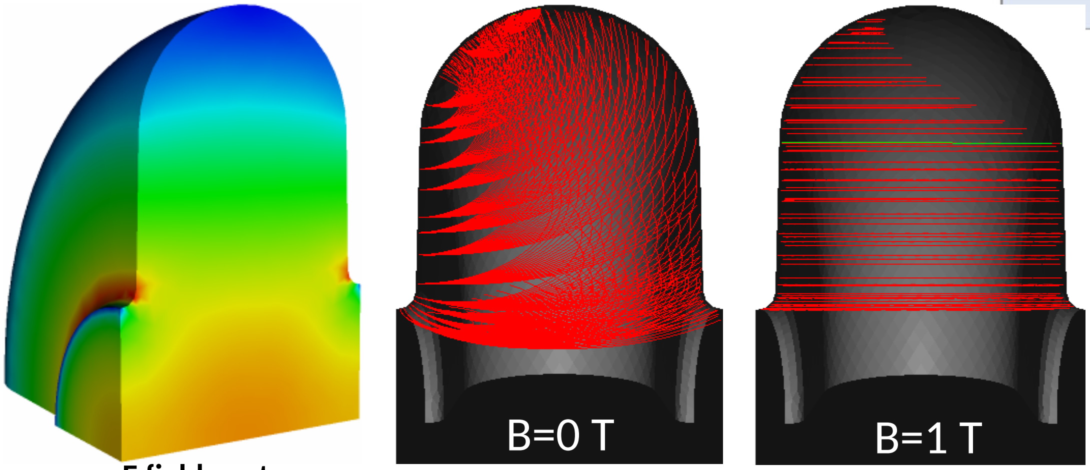


RF Cavities in Magnetic Fields

- Early results have shown vacuum pillbox RF cavities break down in strong external magnetic fields
- Likely due to field emission electrons being focused onto small region of opposing wall



Simulation

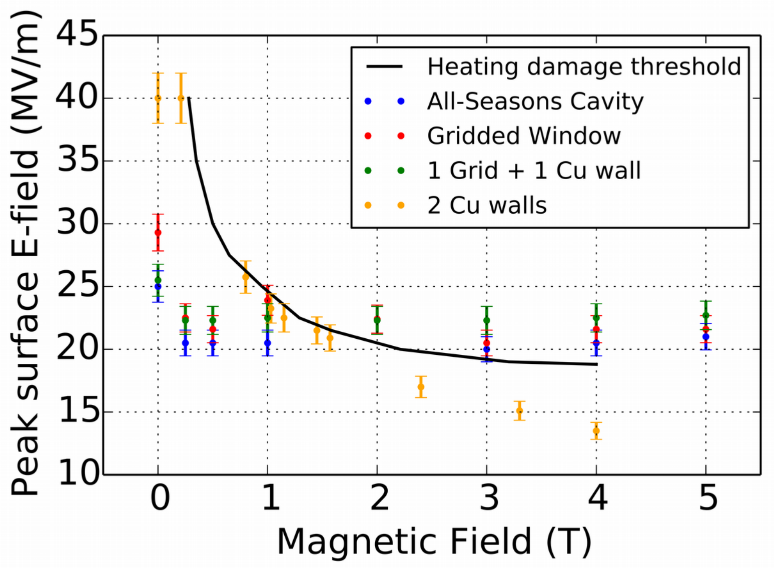


E field contour

- Two ways to combat this
  - Limit field emission
  - Limit the effect of field emission

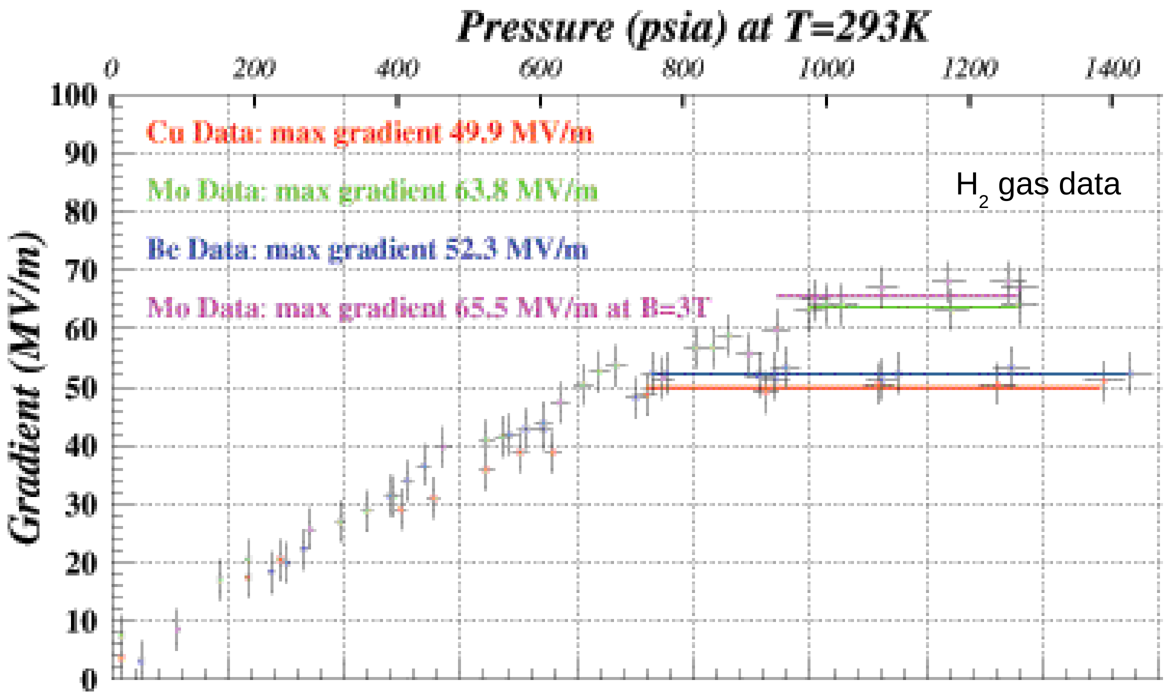
Vacuum Cavities

- Recent results indicate innovative design/surface preparation may improve performance in external magnetic fields
  - Cavity length → minimize electron impact energy
  - Window material → increase radiation length
  - Surface preparation (electropolishing, TiN coating, …) → minimize dark current / multipacting
- New vacuum cavity data out soon – stay tuned!



Gas Filled Cavities

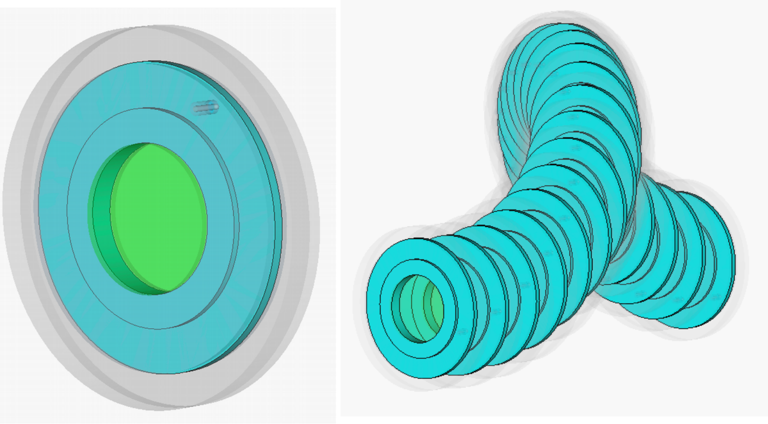
- Gas limits mean free path of free electrons
- Increasing the gas pressure increases the breakdown gradient
- Metal limits gradient above some gas pressure
- Results show virtually no difference in breakdown gradient between no magnetic field and 3 T

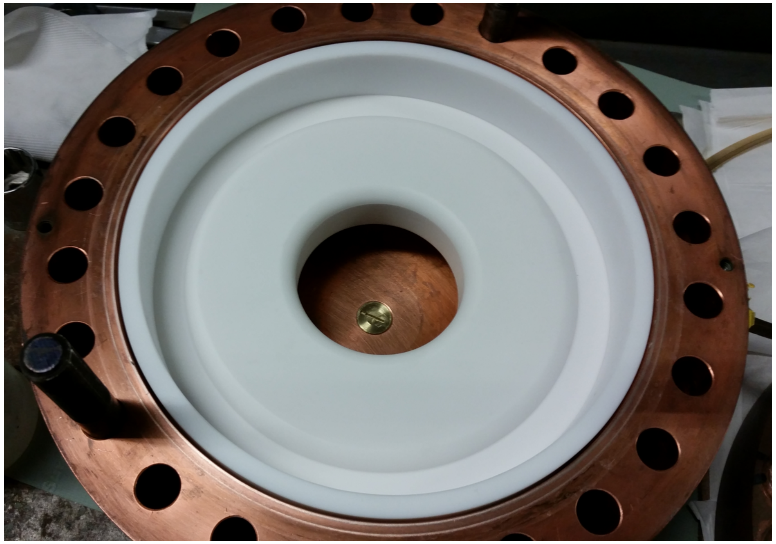


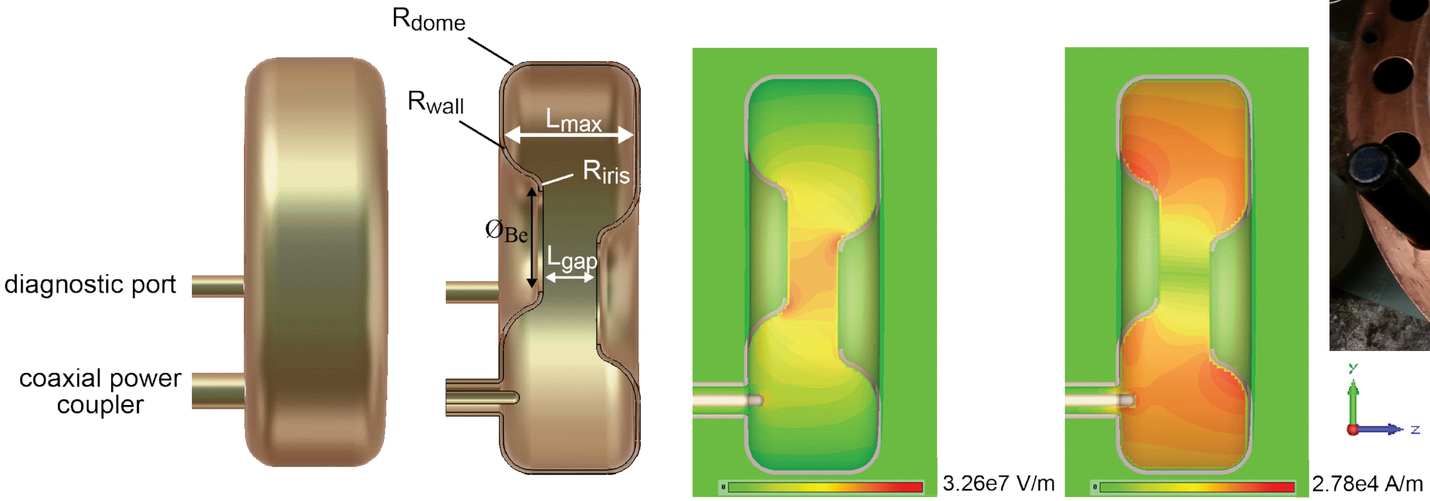
P. Hanlet et al, Proceeding of EPAC '06, TUPCH147

Gas Filled Cavity R&D

- Gas filled cavities must fit within magnet bores
- Reentrant and dielectric loaded concepts being studied
- Dielectric loaded tests with high purity alumina encouraging
  - Realistic design seems feasible



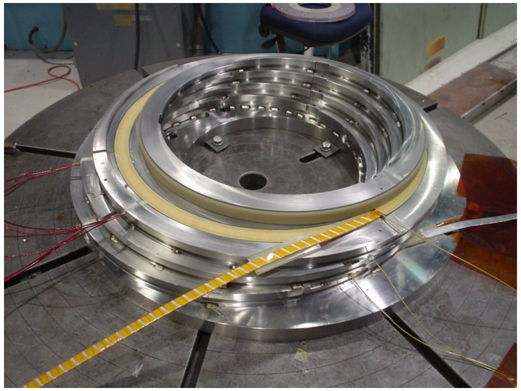


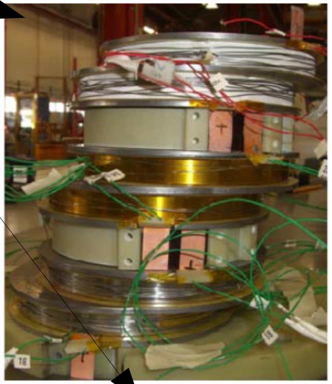


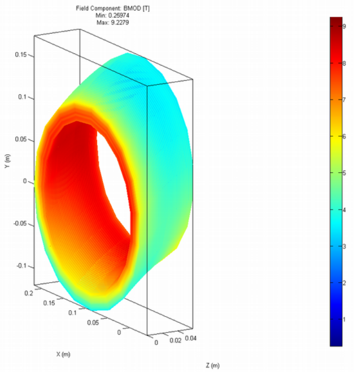
side view cross section electric RF field contours magnetic RF field contours

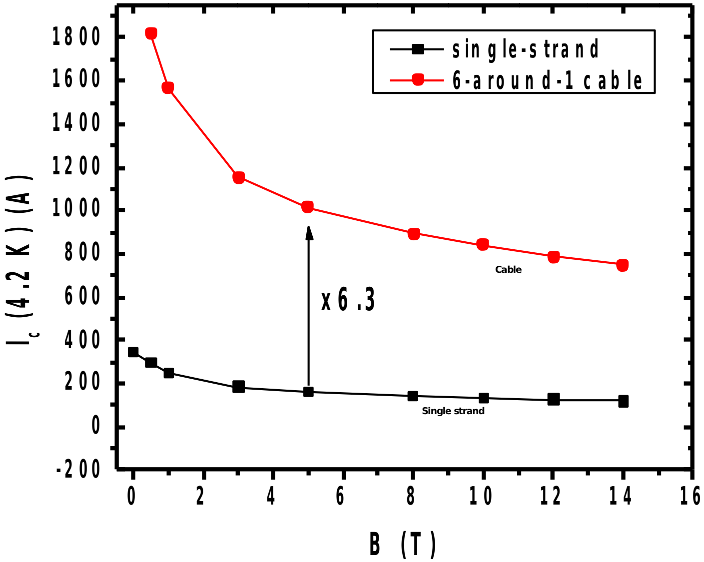
Magnet Progress

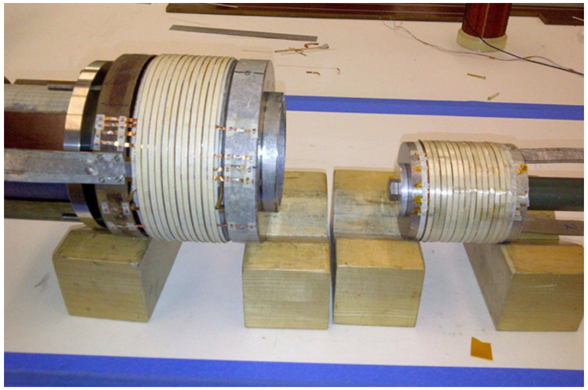
- Higgs Factory baseline does not require HTS magnets
- A number of prototypes have been built & tested
  - NbTi (2 models, 4 coils each)
  - YBCO Tape (3 double pancakes)
- Nb_3Sn with continuous coil geometry design
- HTS only coil, 15 T on axis (16 T on coil)
- HTS cable matches strand performance





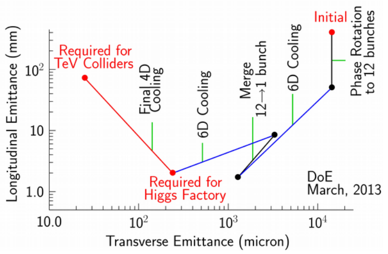




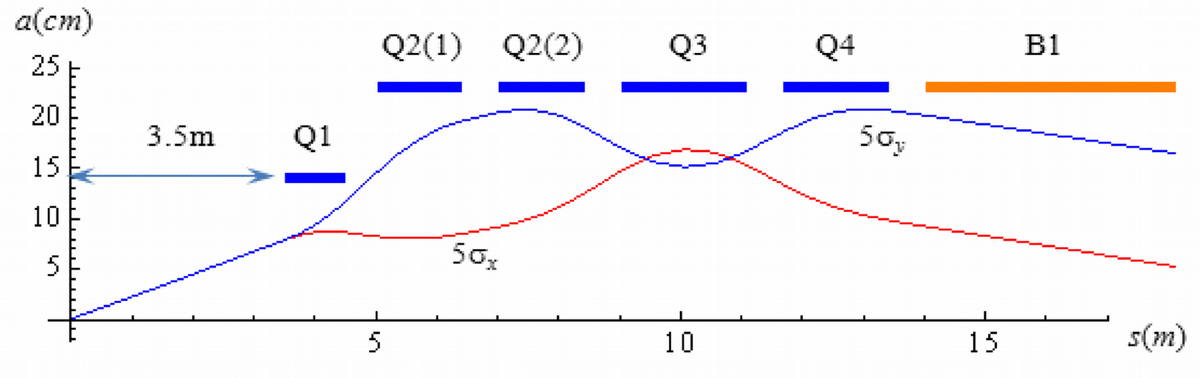


Collider Ring Design

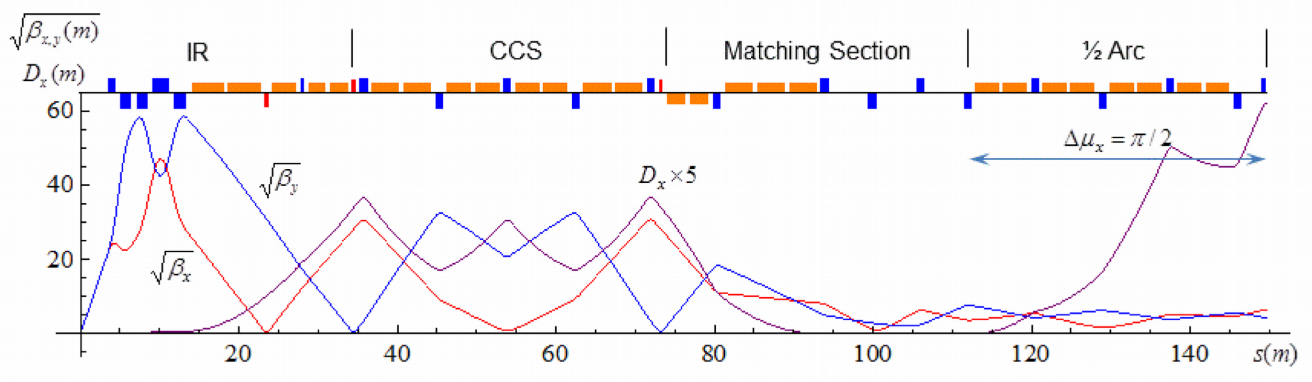
- Large transverse emittance dictate β ~ few cm at IP
  - Large beam size in final focus quads
- Large aperture magnets in IR (muon decay protection)



- Quadruplet final focus and 3 sextupole chromaticity correction scheme



- IR quadrupole aperture and 5σ beam envelopes for β* = 2.5 cm



- Optics functions in half ring for β* = 2.5 cm
- Momentum acceptance > ±5%

Remarks

- A Muon Accelerator could offer excellent physics results
  - Neutrino Factory
  - Higgs Factory / multi-TeV Collider
- Significant progress made in many subsystems
  - Target
  - Beamline
  - Cooling
- Demonstration of cooling concept and technology encouraging
  - RF cavities in magnetic field work!
  - Engineering challenges being addressed