Muon Cooling Progress and Prospects for an S-channel Muon Collider Higgs Factory

Muons, Inc.

M. A. Cummings ••• Muons, Inc. ••• August 5, 2015 ••• DPF 2015
Ann Arbor, MI

…or, one highly possible, desirable facility that could illuminate the nature of the recently discovered Higgs Boson on the once and future path to the energy frontier that runs productively through the peculiar and unique capabilities of Fermilab:

- Muon storage rings as high precision neutrino sources.
- A Z’ Factory
- **A Higgs Factory** ←
- A Muon Collider is an ideal technology for a TeV or multi-TeV collider.

P5 Goals: Long-Range Accelerator R&D

- “For e^+e^- Colliders the primary goals are:
  - Improving the gradient and lowering the power consumption”
    - **P5, Building for Discovery , p. 19 (May 2014)**

- Both goals are achieved by increasing the mass of the electrons
  - Higher mass electrons will not radiate ($\sim m^{-4}$); enabling multipass acceleration; gradient is improved by number of turns
  - Non-radiating electrons, multipass acceleration, consume less power

- Changing the electron mass … (m_e is quantized)
  - 0.511, **105.6**, 1777 **MeV**

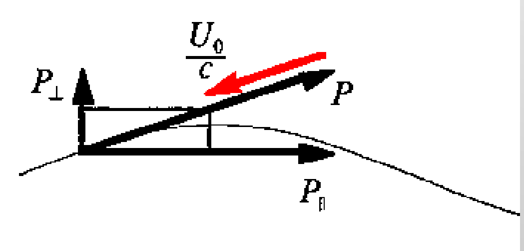
- 105.6 MeV is optimum for next generation e^+e^- Colliders
  - requires $E' \gg m_e / c\tau_e = 0.16$ MV/m

High-Luminosity Lepton Colliders Need Cooling

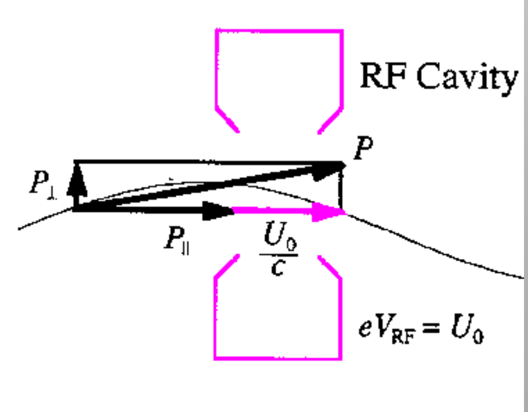
Light e$^-$:

- **radiation damping**

1. Lose $P_{e,t}$ in bends - synchrotron radiation



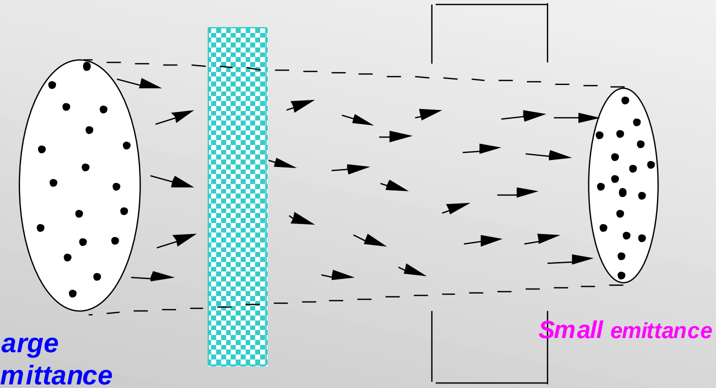
2. Regain only P_z in RF



Heavy e$^-$:

- **"ionization cooling" ....**

1. Lose $P_{l,t}$ in material –



Large emittance

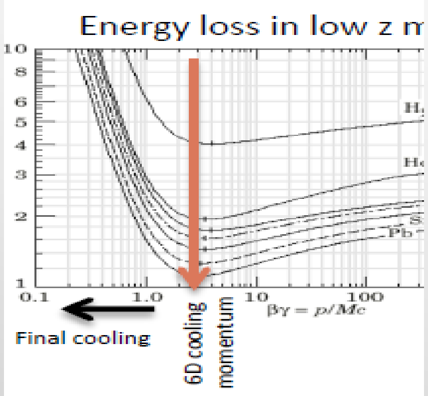
Small emittance

Absorber

Momentum loss is opposite to motion, p, p_x, p_y, ΔE decrease

Accelerator

Momentum gain is purely longitudinal



2. Regain only P_z in RF

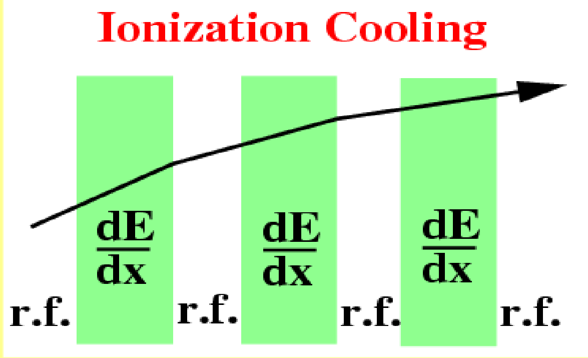
$$\frac{d\varepsilon_N}{ds} = -\frac{1}{P_\ell}\frac{dP_\ell}{ds}\varepsilon_N + \frac{\beta_\perp E_s^2}{2\beta^3 m_\ell c^2 L_R E}$$

Heating by multiple scattering

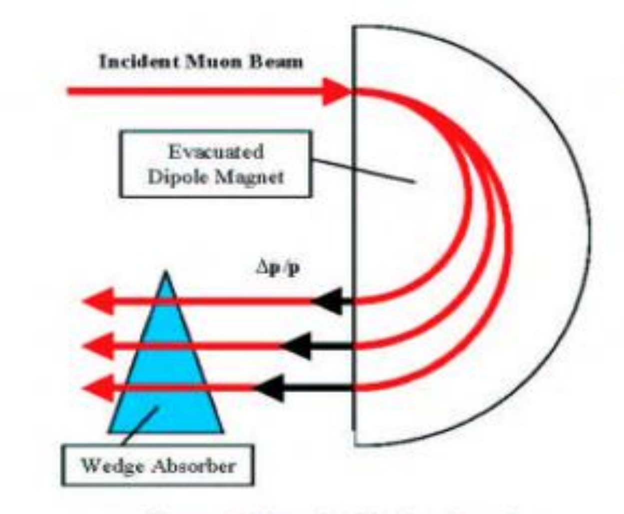
Dave Neuffer

6 D Ionization Cooling and Emittance

1. Neutrino source: 4-D cooling

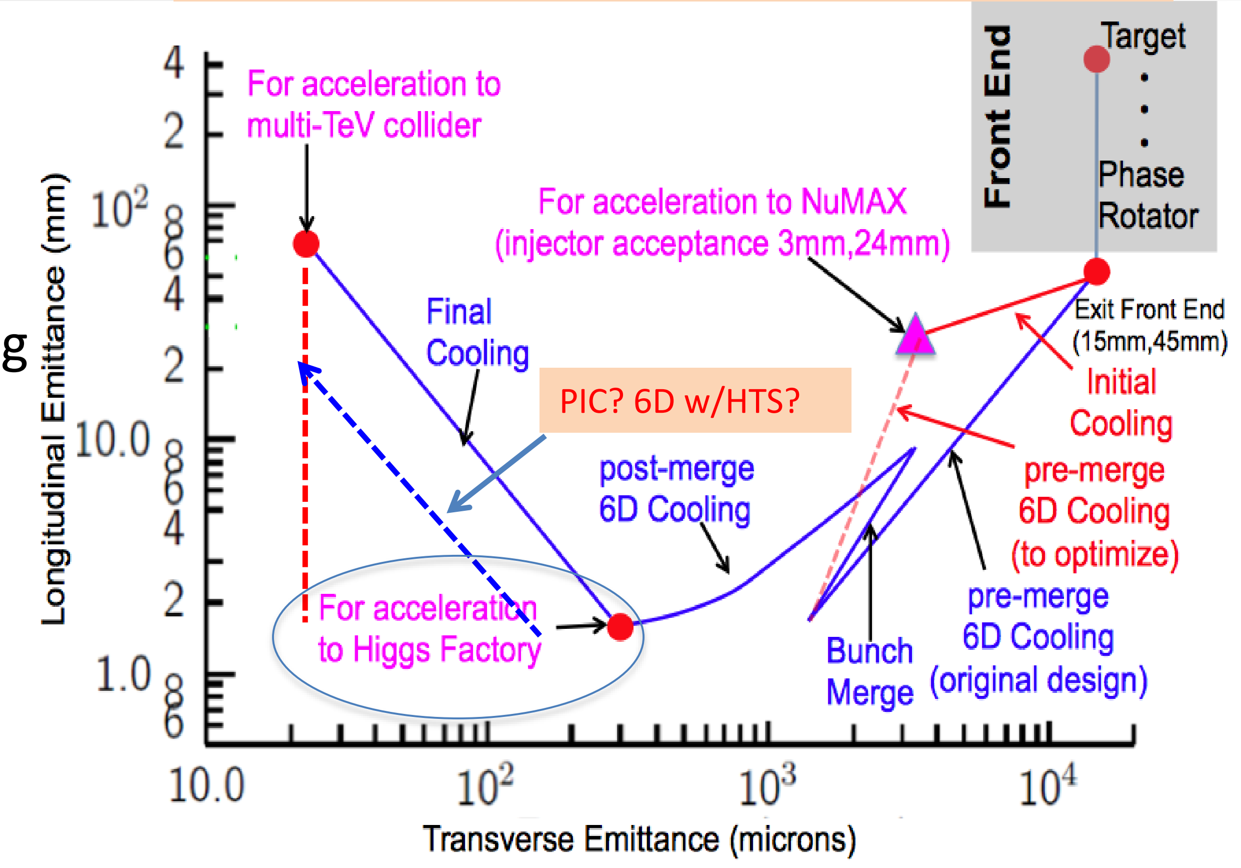


2. Muon collider: 6-D cooling

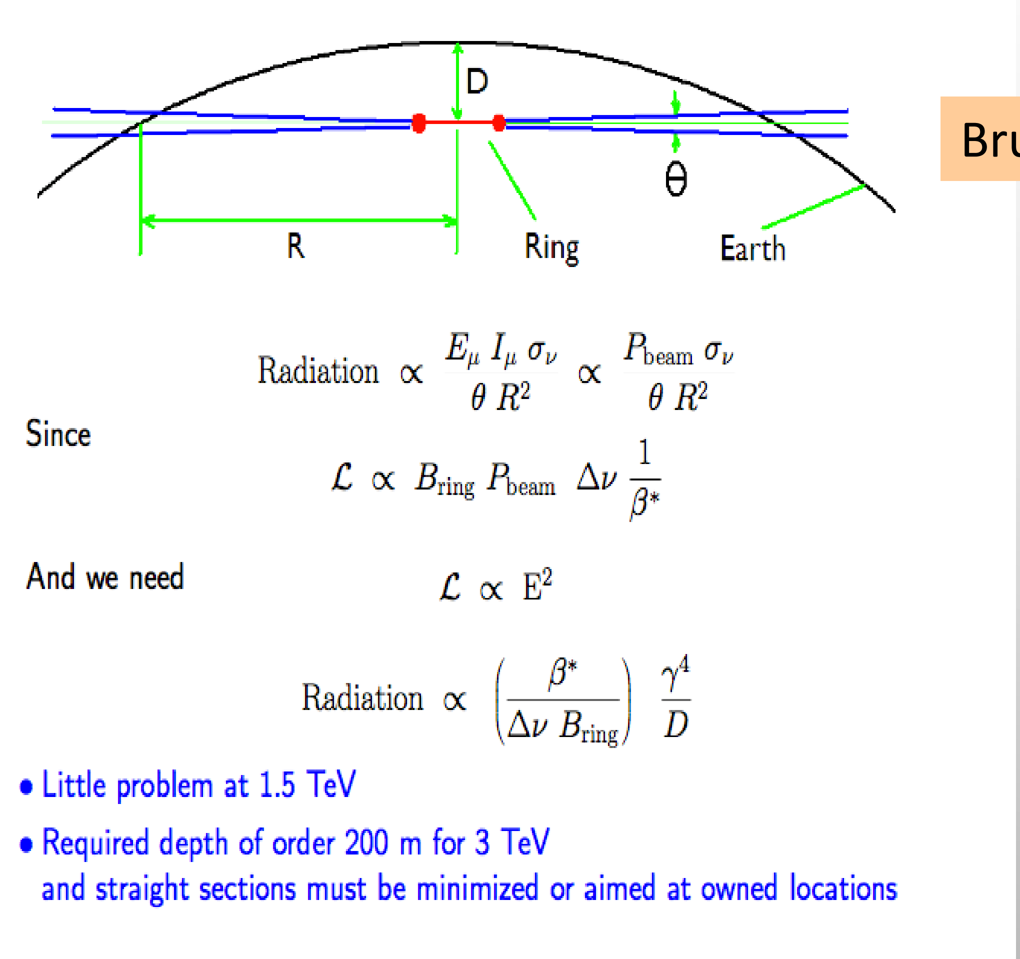


Emittance exchange:
exploits “dispersion”: *x(s) = D(s)*Δp/p*

Emittance evolution in a cooling channel



Neutrino Radiation Problem Inspires New Source



$$\text{Radiation} \propto \frac{E_\mu\, I_\mu\, \sigma_\nu}{\theta\, R^2} \propto \frac{P_{\text{beam}}\, \sigma_\nu}{\theta\, R^2}$$

Since

$$\mathcal{L} \propto B_{\text{ring}}\, P_{\text{beam}}\, \Delta\nu\, \frac{1}{\beta^*}$$

And we need

$$\mathcal{L} \propto E^2$$

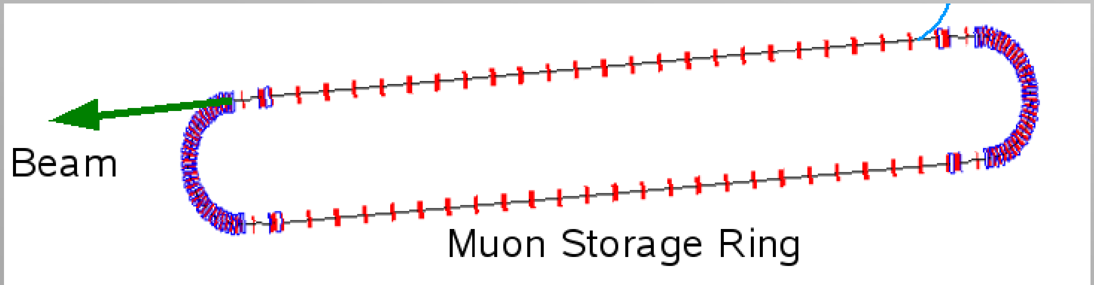
$$\text{Radiation} \propto \left(\frac{\beta^*}{\Delta\nu\, B_{\text{ring}}}\right) \frac{\gamma^4}{D}$$

- Little problem at 1.5 TeV
- Required depth of order 200 m for 3 TeV and straight sections must be minimized or aimed at owned locations

Bruce King, 2000

Since muons live 100 times longer than charged pions, to be efficient a linear muon decay channel would have to be tens of km long, hence:

Neutrino Factory



“Heavy Electron” Accelerators

Advantages

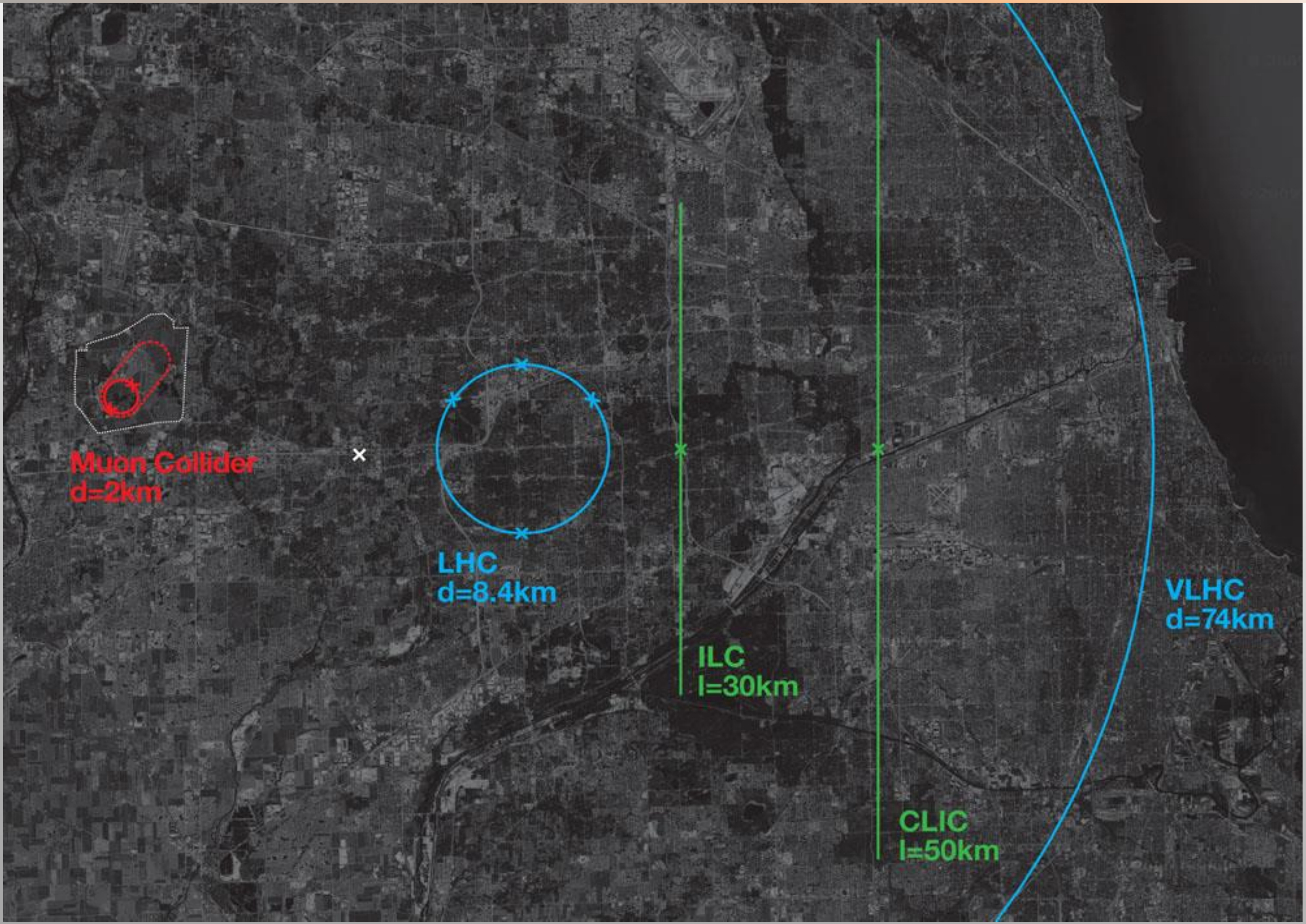
- Larger couplings to Higgs-like particles - possible low energy Higgs Factory, Z’
- Narrower energy spread – precision measurements
- Easier acceleration
- Smaller machine footprints

Challenges

No show-stoppers…

- Production is into diffuse phase space
  - Tertiary beam: $\mathbf{p \rightarrow \pi \rightarrow \mu\, \nu}$
  - Need to capture and focus quickly
  - Ion. cooling necessary – but now a **developing technology**
- Have very short lifetimes: $\mu \rightarrow e\, \nu_e\, \nu_\mu$
  - Acceleration must be rapid
  - Backgrounds from decays
  - Concern over neutrino radiation (**mitigated by extreme cooling, flat and or undulating beams…**)

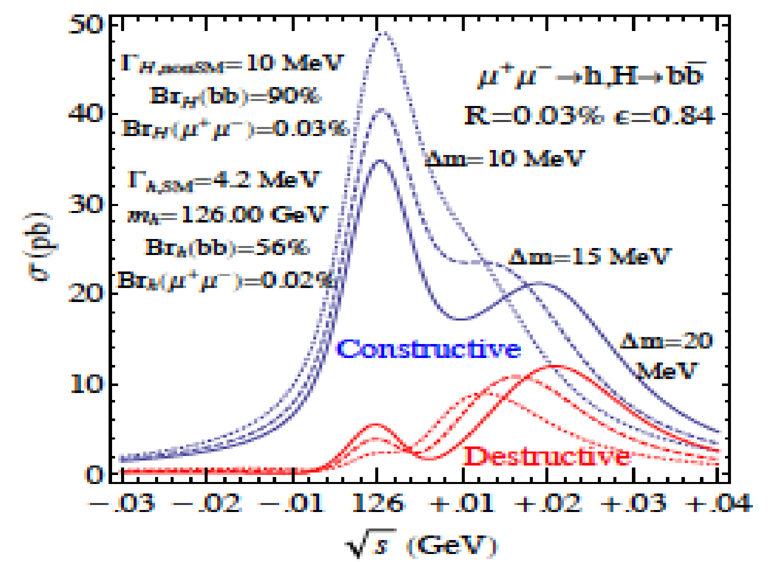
Muon (heavy electron) Colliders are compact

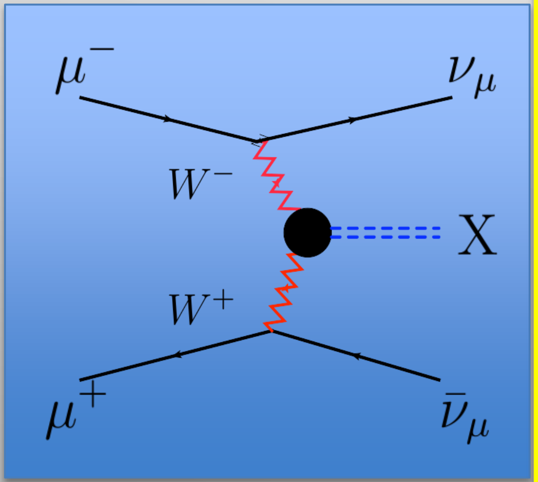


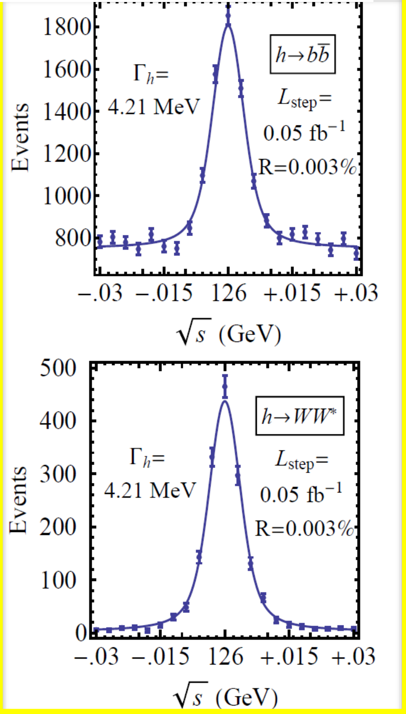
Features of the “Heavy Electron” Collider

- Superb Energy Resolution
  - SM Thresholds and s-channel Higgs Factory operation
- Multi-TeV Capability (≤ 10TeV):
  - Compact & energy efficient machine
  - Luminosity > 10^{34} cm^{-2} s^{-1}
  - Option for 2 detectors in the ring
- For √s > 1 TeV: Fusion processes dominate
  - an Electroweak Boson Collider
  - a discovery machine complementary to a very high energy pp collider

  → 5TeV: Higgs self-coupling resolution <10%





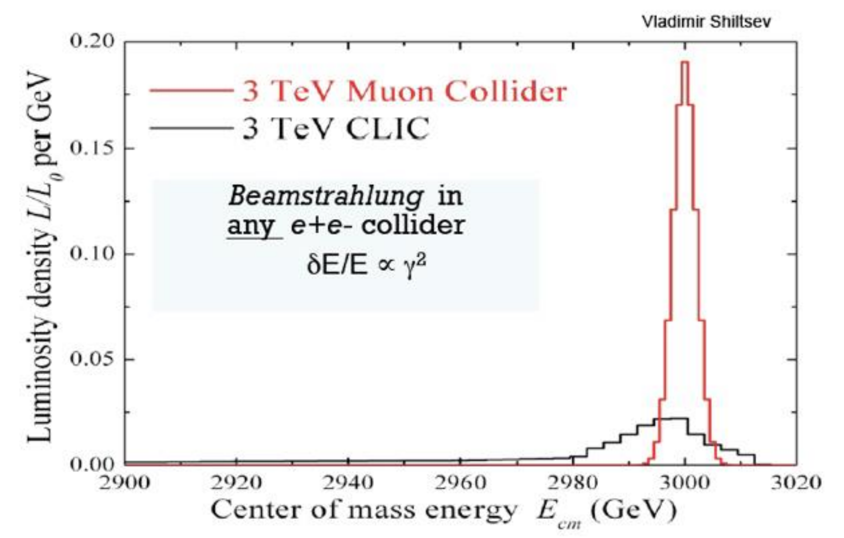


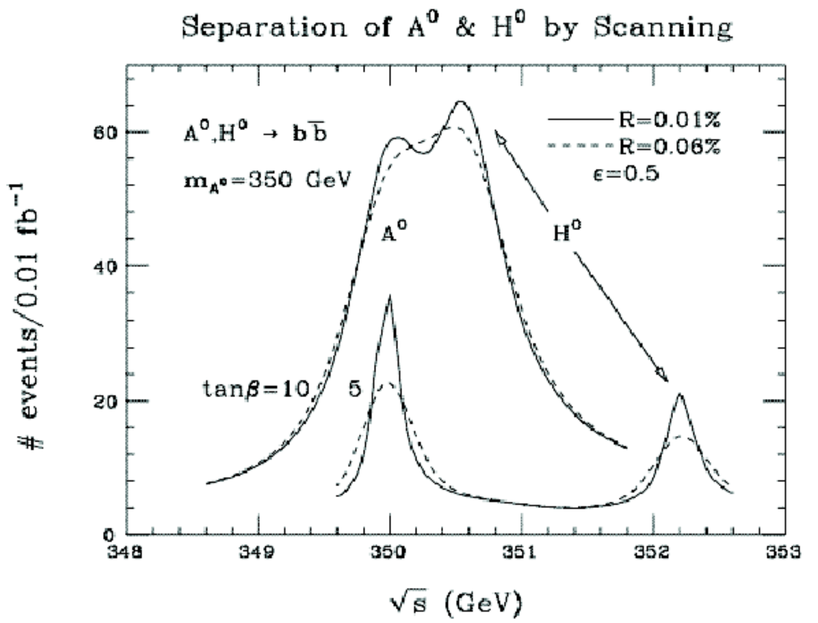
A 10 TeV $\mu^+\mu$□ collider has similar discovery reach as a 100 TeV pp machine!

Heavy vs. Light Lepton Physics Capability

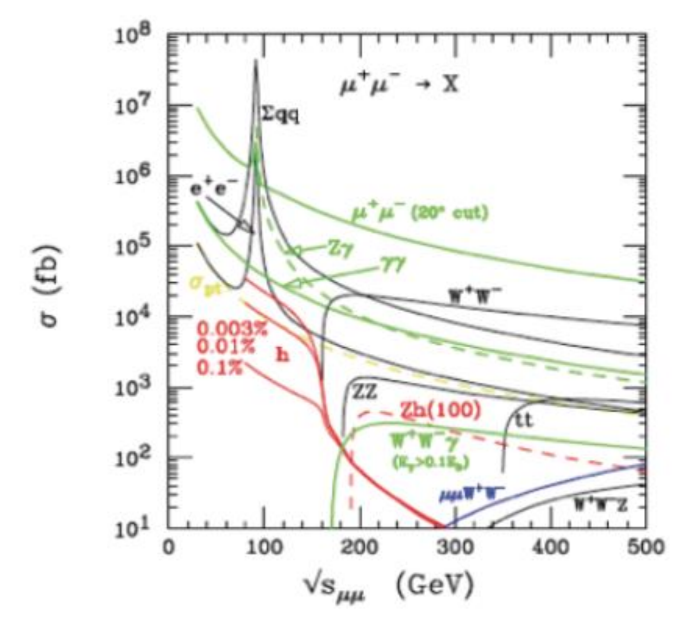
Superb Energy Resolution

- MC: 95% luminosity in dE/E ~ 0.1%
- CLIC: 35% luminosity in dE/E ~ 1%

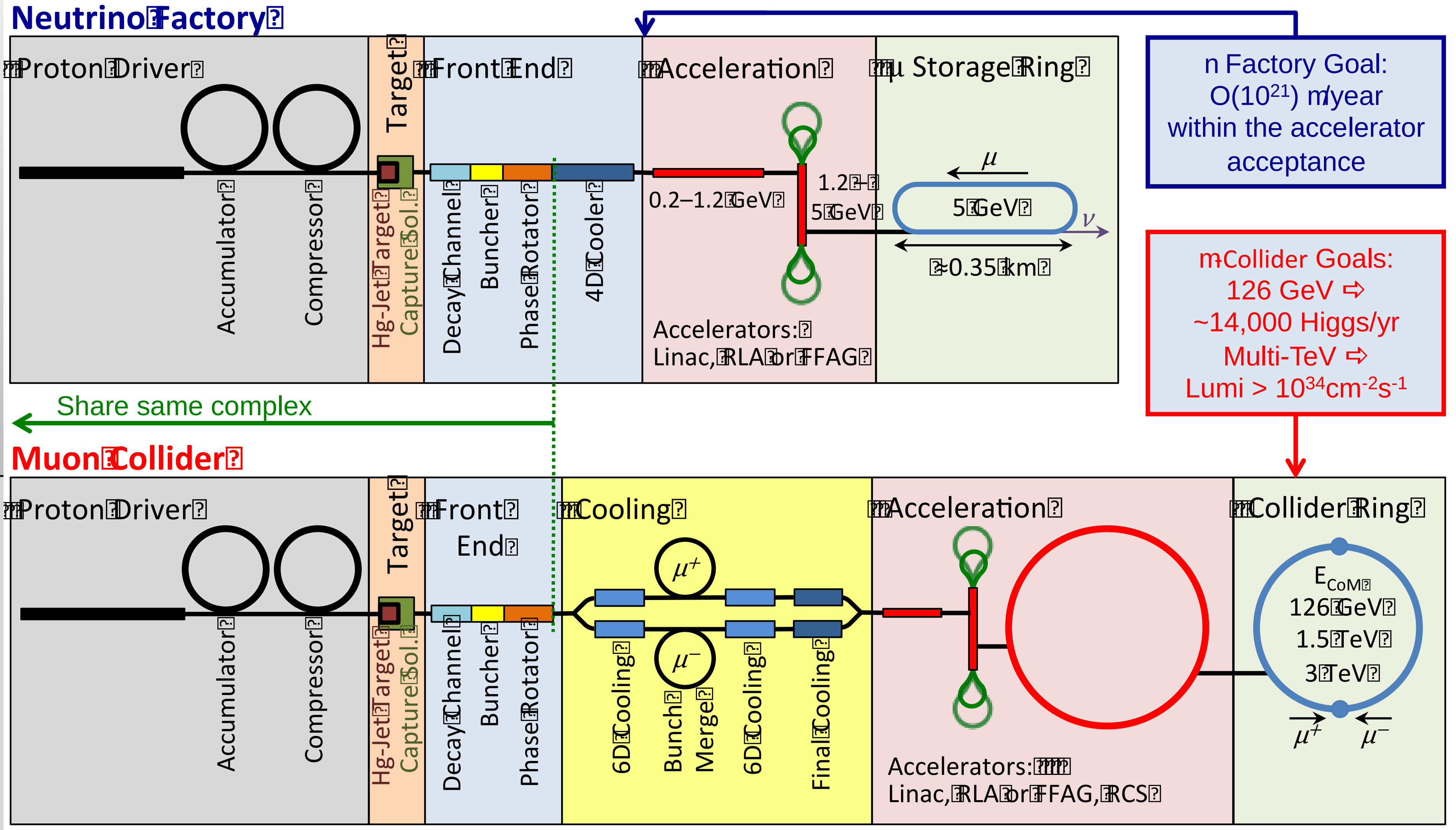




Gunion and Berger, 2000



Muon Collider Functional Layout



n Factory Goal:
O(10^{21}) m/year
within the accelerator
acceptance

m-Collider Goals:
126 GeV ⇨
~14,000 Higgs/yr
Multi-TeV ⇨
Lumi > 10^{34}cm^{-2}s^{-1}

Shared front ends - means a staged approach possible

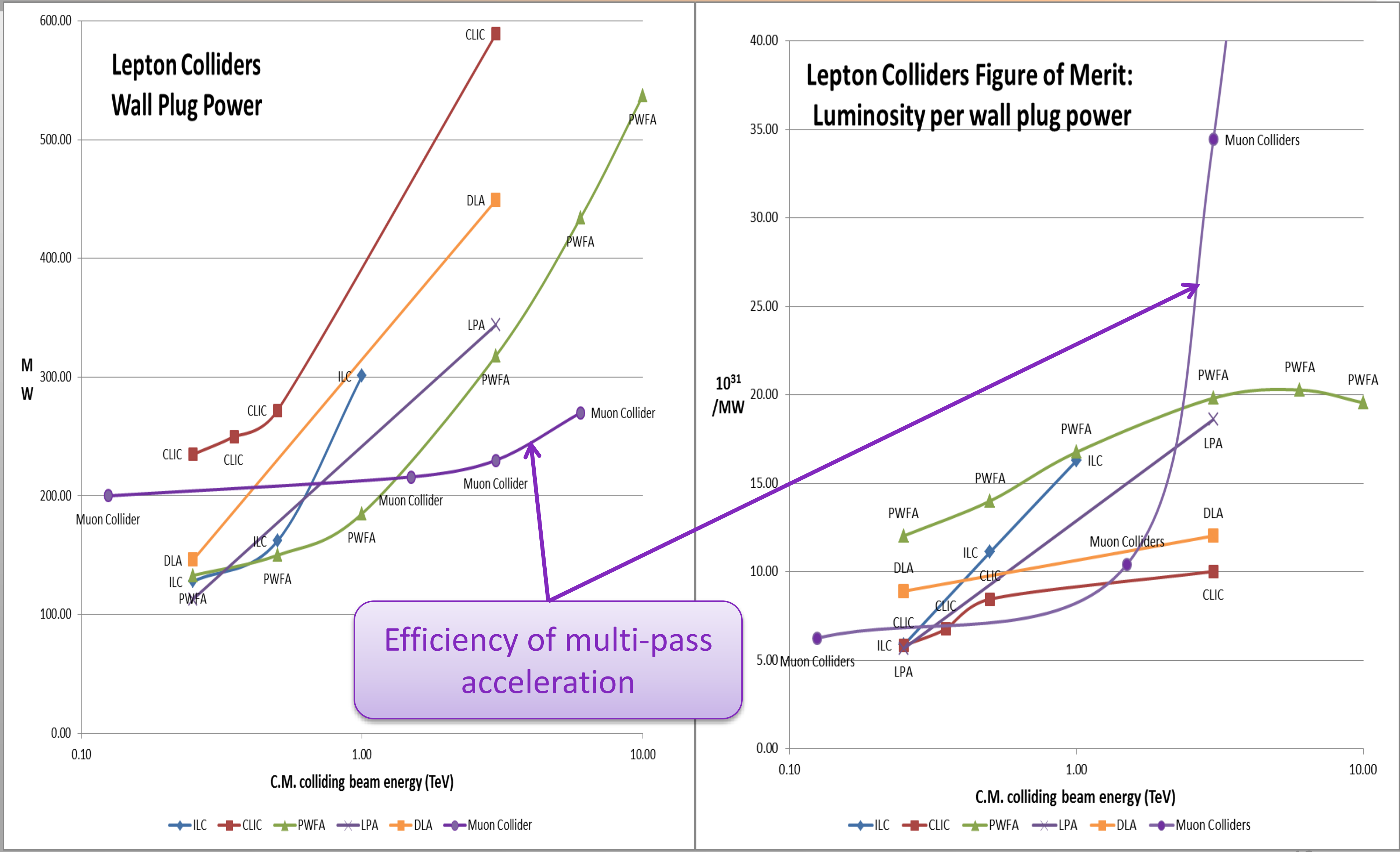
Lepton (Muon) Collider Parameters

		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
b*	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, e_{TN}	p mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, e_{LN}	p mm-rad	1.5	70	70	70
Bunch Length, s_{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 ⇨ several ↙ 10^{32}

Lepton Colliders – Efficiency at Multi-TeV Scale



Efficiency of multi-pass acceleration

New Ideas from Muons, Inc.

Muons, Inc.

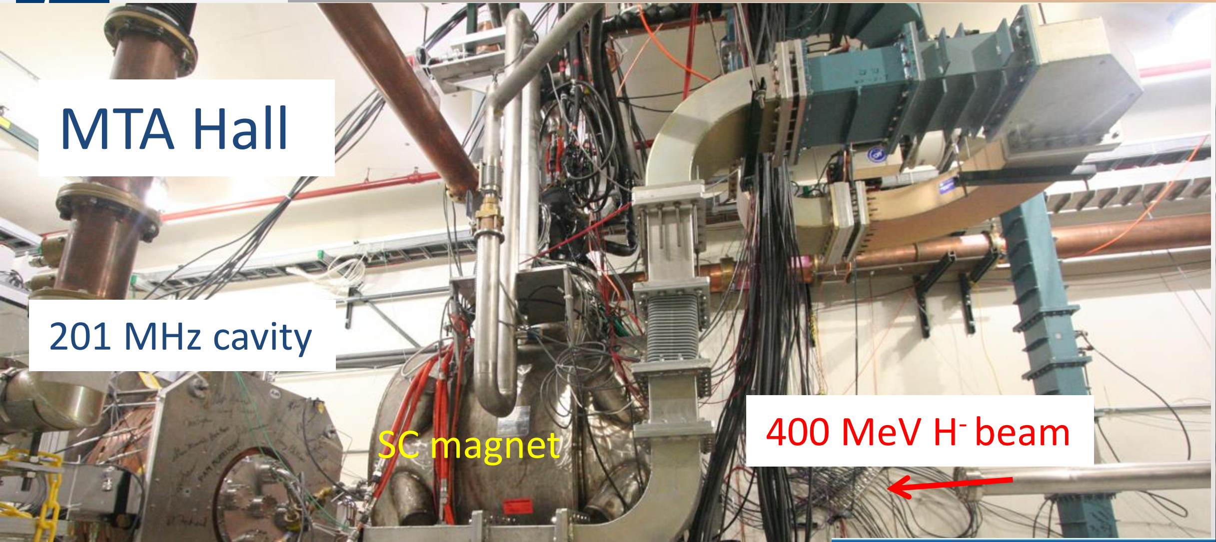
Private company funded primarily through DOE SBIR/STTR program
Rolland Johnson, founder and president

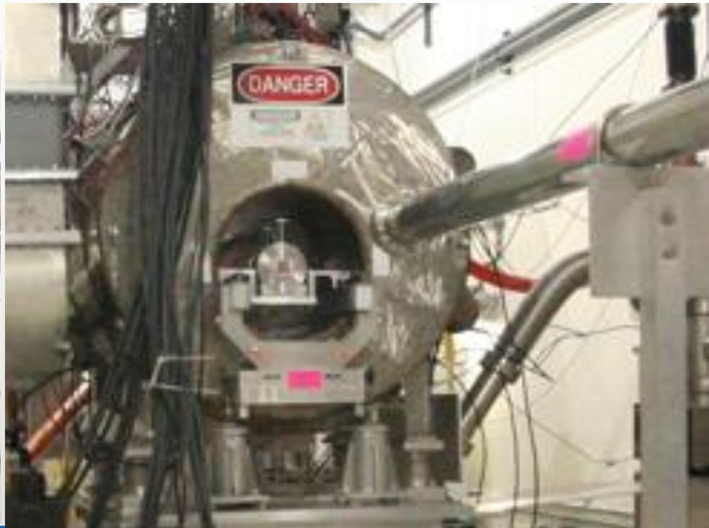
1. **The idea of a gaseous energy absorber enables new technology to generate high accelerating gradients for muons by using the high pressure region of the Paschen curve: High Pressure RF Cavity (HPRF) TESTED!**

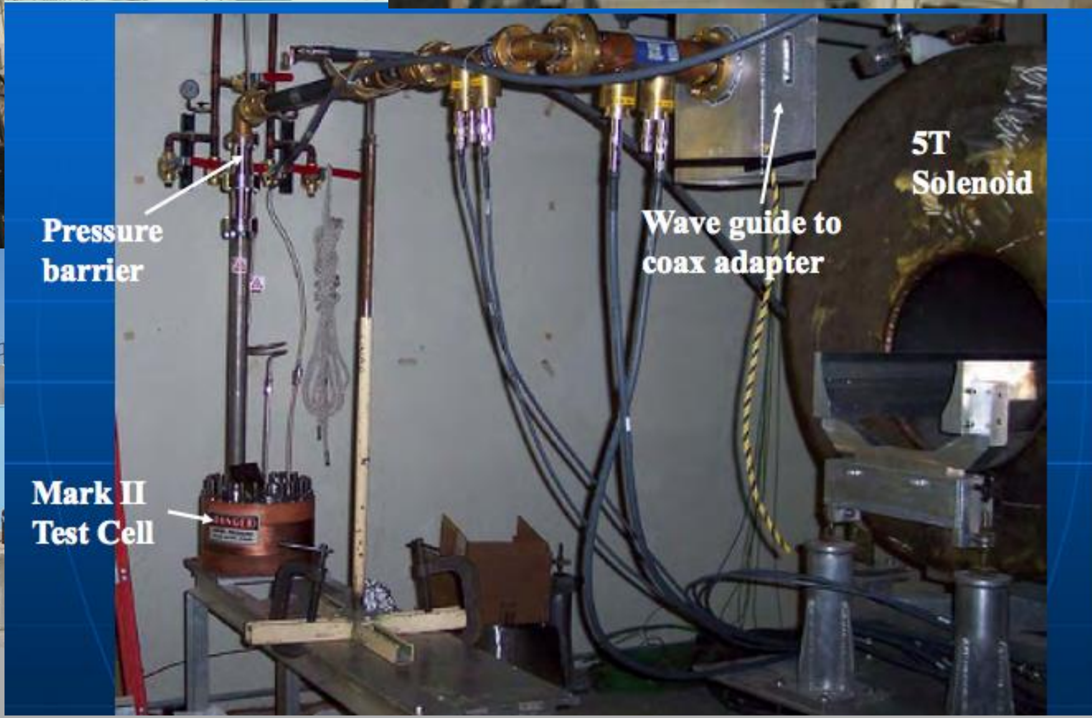
2. **Concept of a cooling channel filled with continuous homogenous absorber to provide longitudinal cooling by exploiting the path length correlation with momentum in a magnetic channel with positive dispersion: Helical Cooling Channel (HCC). COMPLETE END-END SIMULATION.**

3. **Parametric Resonance Ionization Cooling (PIC) concepts are being developed that can decrease emittance by factor of 10 beyond the "equilibrium emittance" of current cooling techniques. STILL DEVELOPING**

Mucool Test Area (MTA)

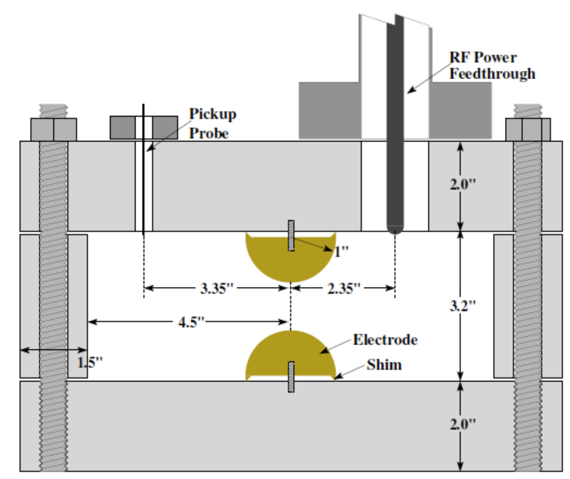






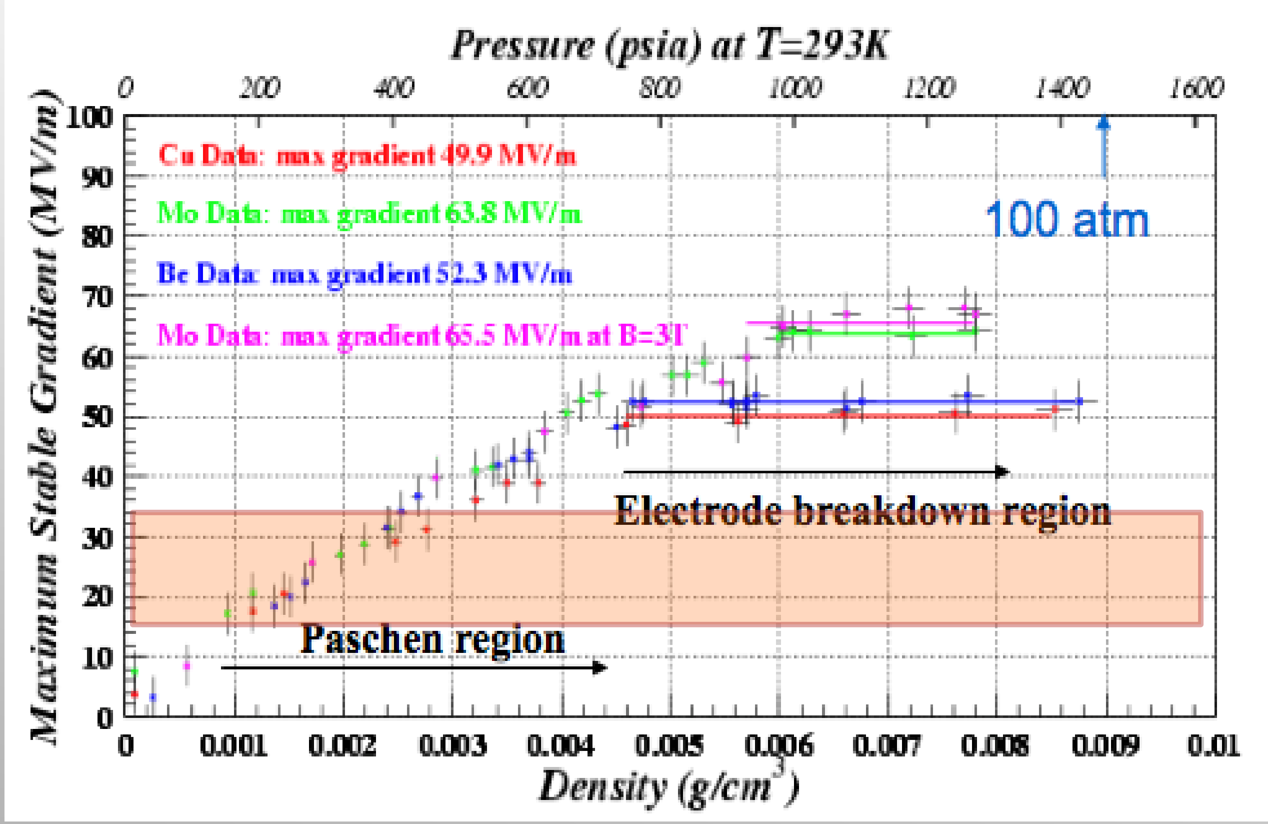
High Pressure RF Test Cell

Can moderate dark current and breakdown currents in magnetic fields



Schematic view of HPRF cavity

Paschen curve verified!



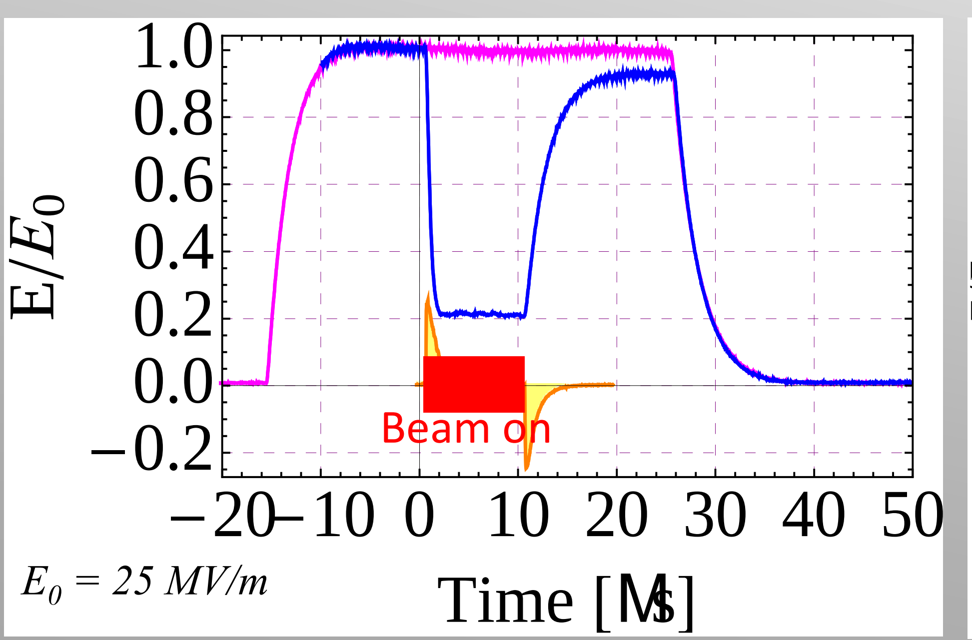
- Maximum gradient limited by breakdown of metal.
- Cu and Be have same breakdown limits (~50 MV/m), Mo(~63MV/m), W(~75MV/m).
- Results show no B dependence, much different metallic breakdown than for vacuum cavities.

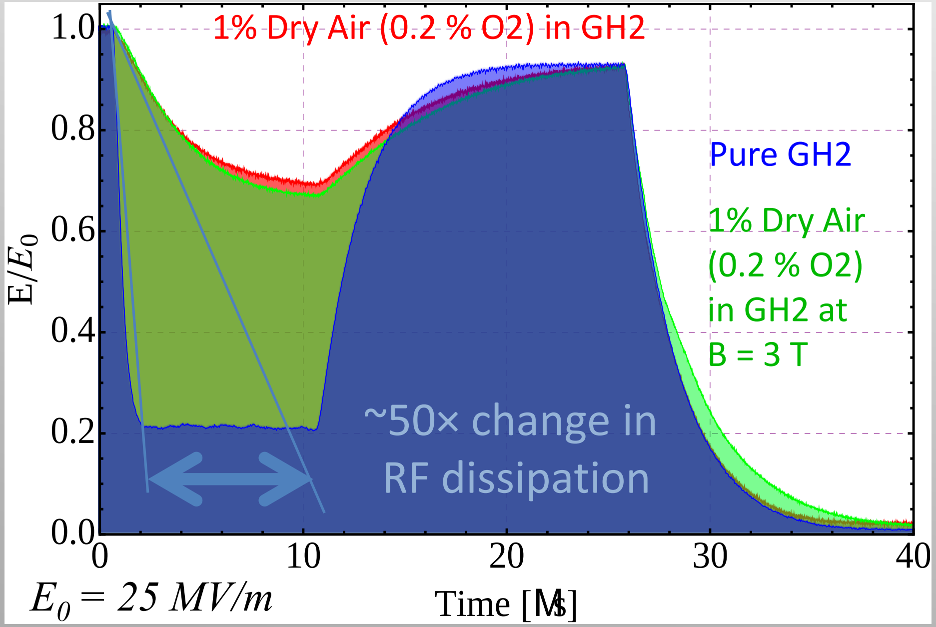
High Pressure RF with Beam

Does intense beam induce an electric breakdown? → **No!**

- Gas-filled cavity
  - Moderates dark current and breakdown currents in magnetic fields
  - Contributes to cooling
  - Is loaded, however, by beam-induced plasma

- Electronegative Species
  - Dope primary gas
  - Can moderate the loading effects of beam-induced plasma by scavenging the relatively mobile electrons





Helical Cooling Channel Magnet

Dipole ➔ Dipole + Solenoid (+Quad for stability)

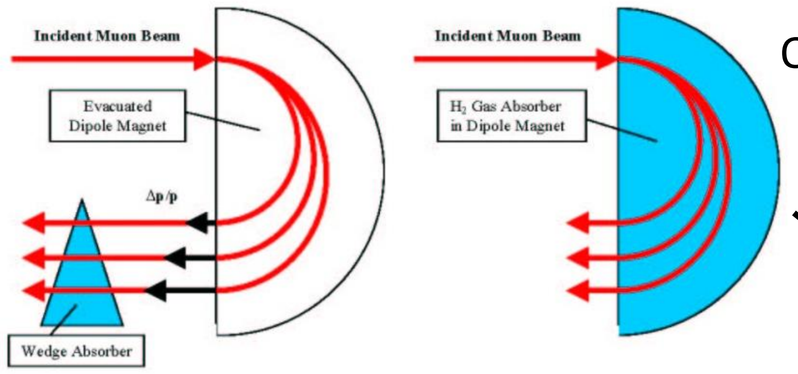


Figure 1. Use of a Wedge Absorber for Emittance Exchange

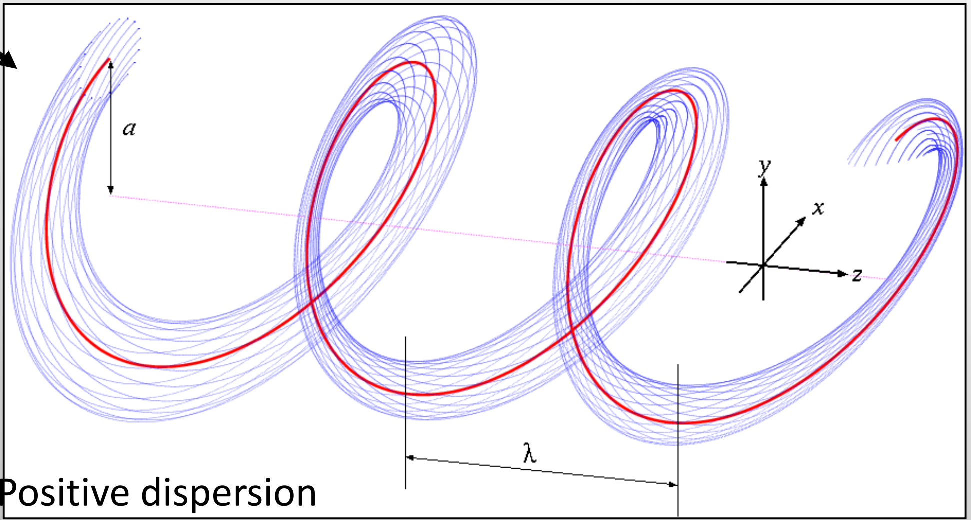
Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

Opposing radial forces:

$$F_{h-dipole} \approx p_z \times B_\perp; \quad b \equiv B_\perp$$

$$F_{solenoid} \approx -p_\perp \times B_z; \quad B \equiv B_z$$

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



Positive dispersion

Red: Reference orbit

Blue: Beam envelope

Transforming to the frame of the rotating helical dipole leads to a time and z –independent Hamiltonian, can form relation:

$$p(a) = \frac{\sqrt{1+\kappa^2}}{k}\left[B - \frac{1+\kappa^2}{\kappa} b\right]$$

Manipulate values of parameters to change performance

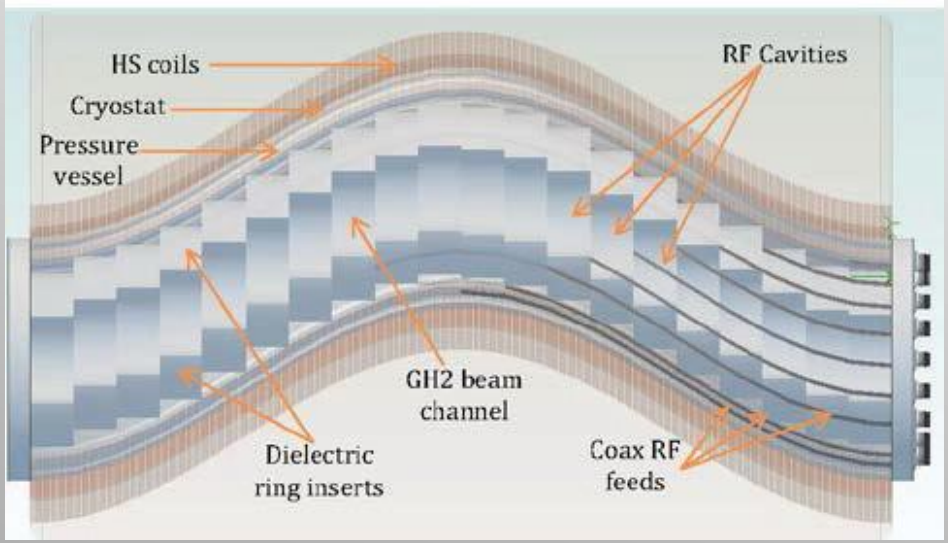
Dispersive component makes longer path length for higher momentum particles and shorter path length for lower momentum particles.

Y. Derbenev and R. Johnson, Phys. Rev. ST –Accelerators and Beams 8 (2005) 041002

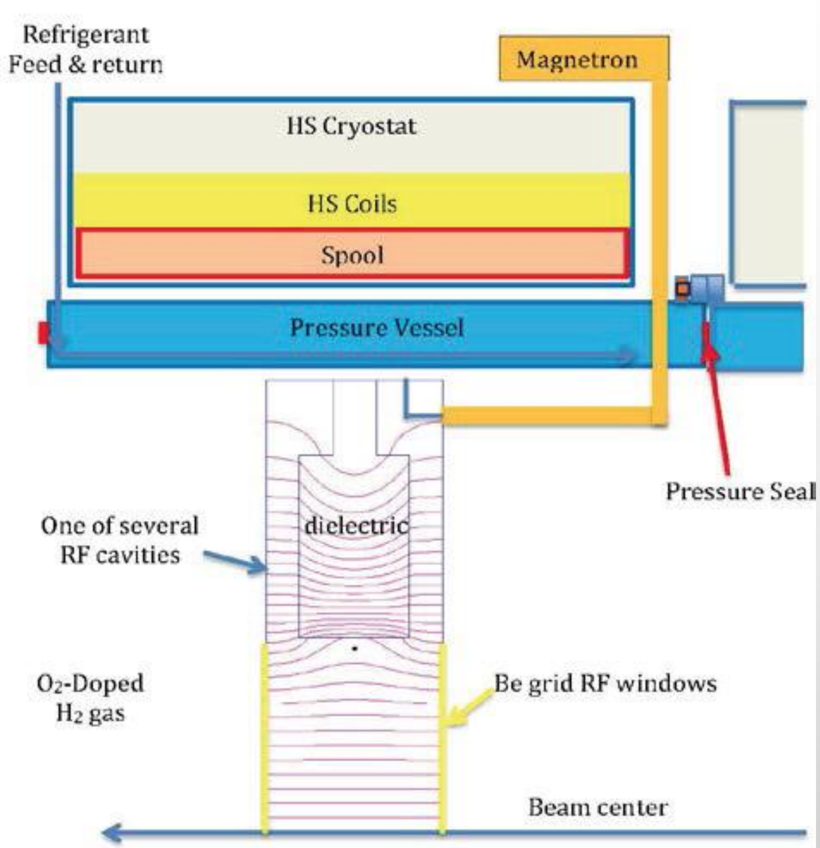
HCC Engineering Design

RF Cavities:

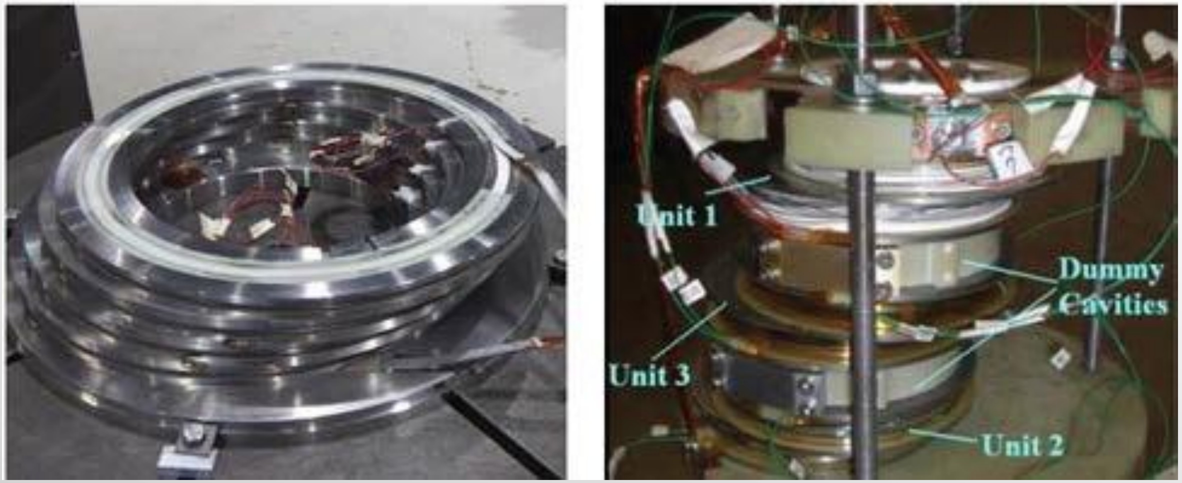
1 Pressurized
2 Dielectric Loaded
3 Positioned inside HS Coils
4 Powered by Magnetrons



Conceptual diagram of an HCC module, showing dielectric-loaded RF cavities enclosed in a pressure vessel that “screws” into the HS cryostat. The pressure vessel contains tubes for water or LN2 refrigerant.



Helical Solenoid Magnet – Muons, Inc. and Fermilab



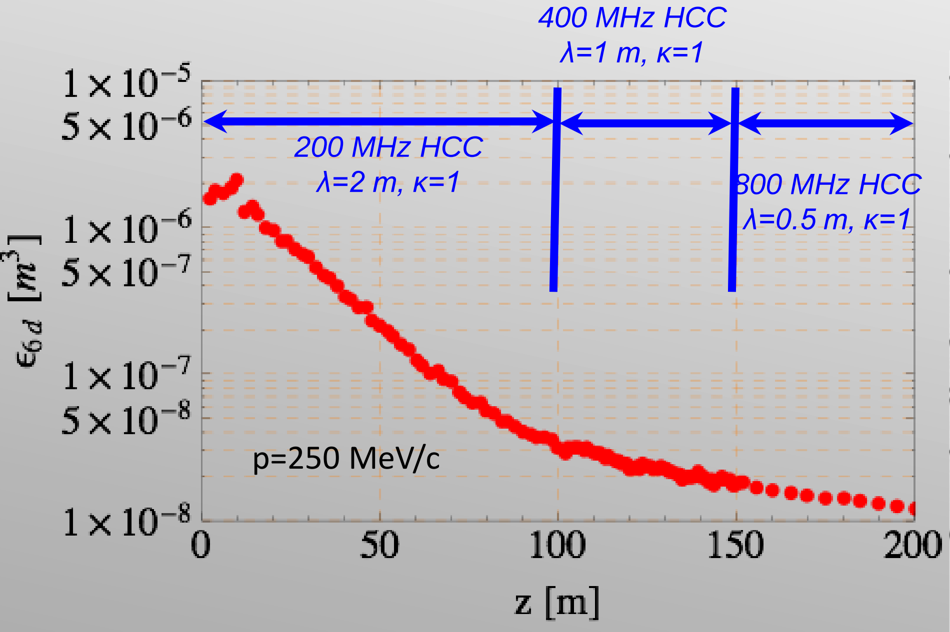
Previous HS fabrication projects: (left) NbTi HS and (right) YBCO HS

Conceptual drawing (left) and 3d printer version (right) of the Nb3 Sn HS spool and conductor that will be fabricated and tested in the Fermilab Vertical Magnet Test Facility. The test will use two layers of cable.

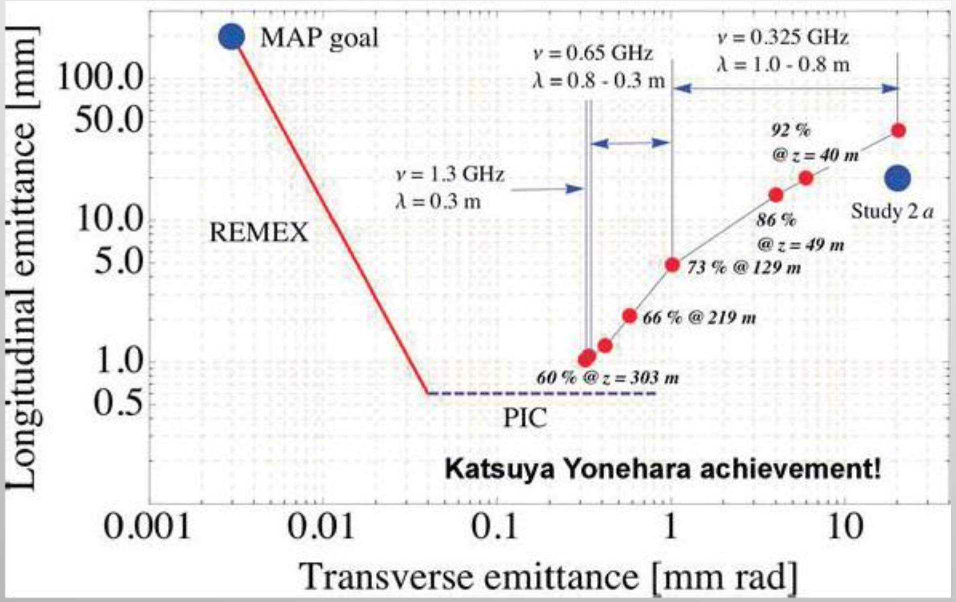
Muons, Inc.

Simulation study of HCC for Muon Collider (MC)

Goal for low emittance MC design



6D Phase space evolution in current HCC, by Katsuya Yonehara

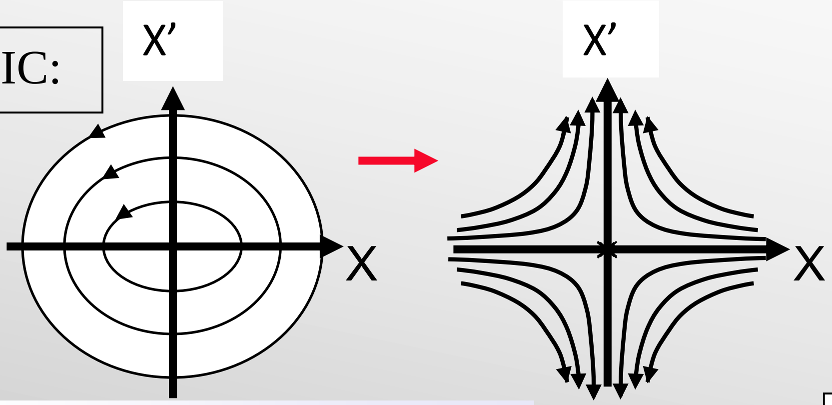


Phase space evolution for Low Emittance Muon Collider

(solid line: complete simulation, dashed line: in progress)

Extreme Cooling: PIC and HCC

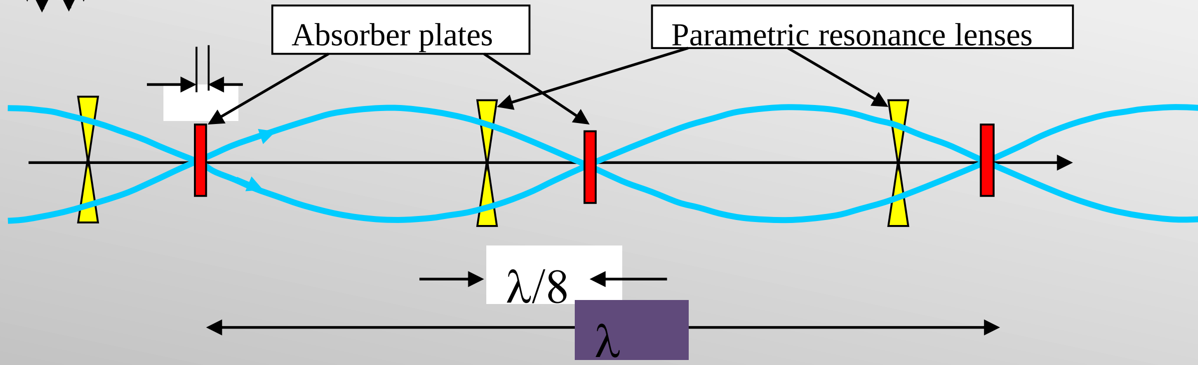
Old PIC:



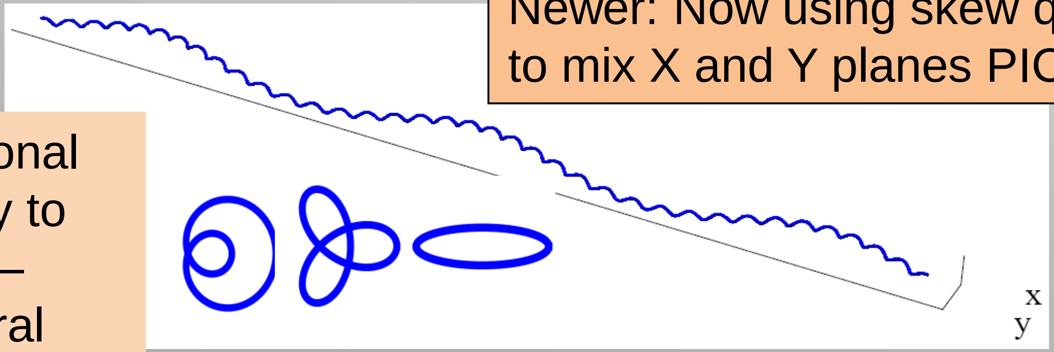
$$M = \begin{pmatrix} e^{-\lambda\Lambda_d}\cos\psi & g\sin\psi \\ -\frac{1}{g}\sin\psi & e^{\lambda\Lambda_d}\cos\psi \end{pmatrix}$$

$\sin\Psi = 0$ decouples x and x’

PS area is reduced in x due to the dynamics of the parametric resonance and reduced in x’ by ionization cooling.



“epicycle HCC” PIC

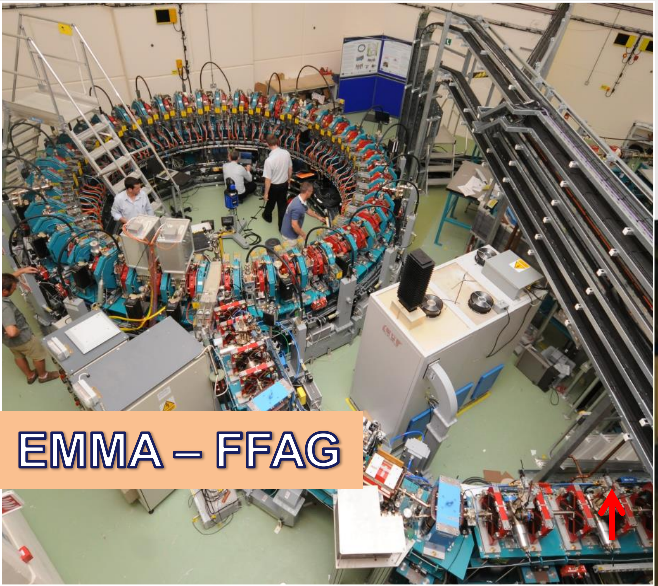


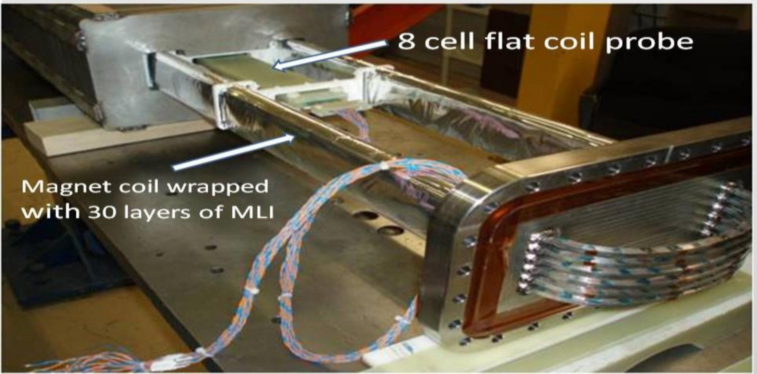
Newer: Now using skew quads to mix X and Y planes PIC

HCC with 2 periods: an additional helical field of opposite helicity to create alternating dispersion – modified orbit from simple spiral

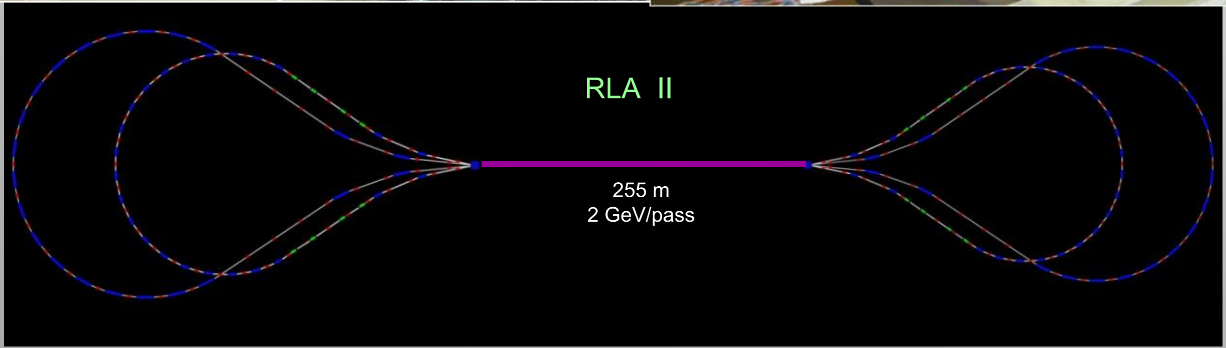
Technology Challenges - Acceleration

- **Muons require an ultrafast accelerator chain, that is just beyond "standard" machines**
  - Superconducting Linacs (NuMAX choice)
  - Recirculating Linear Accelerators (RLAs)
  - Fixed-Field Alternating-Gradient (FFAG) Rings
  - Rapid Cycling Synchrotrons (RCS)





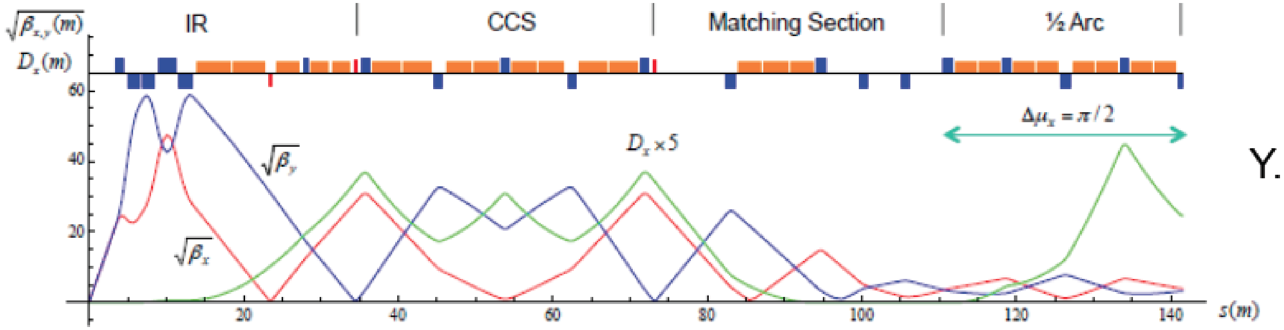
RCS requires 2 T p-p magnets at f ≥ 400 Hz (U Miss, BNL & FNAL)



JEMMRLA Proposal: JLAB Electron Model of Muon RLA with Multi-pass Arcs

- **RF power sources: Muons, inc. phase and frequency locked magnetrons can provide a cheaper, more robust alternative to klystrons .**

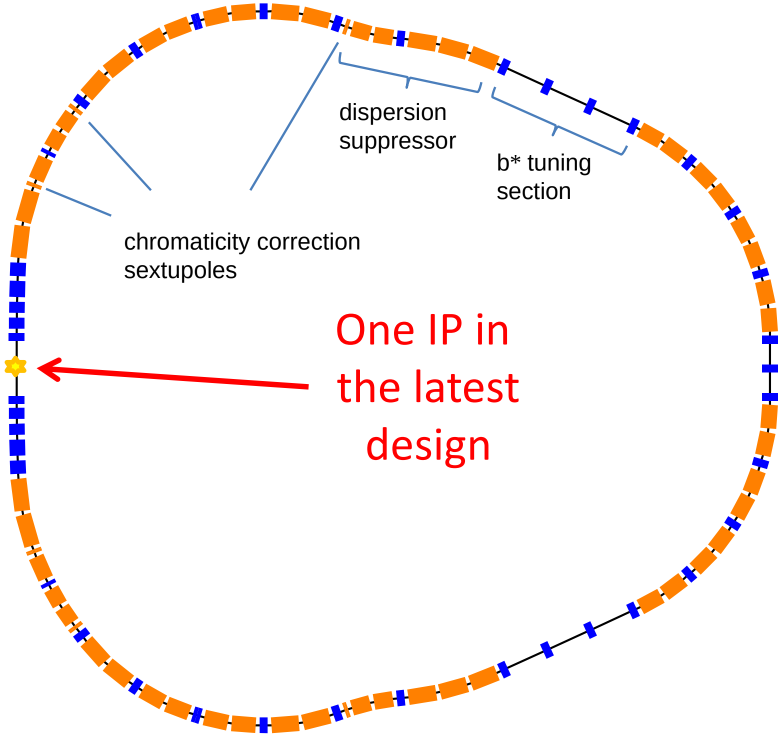
Updated 63 x 63 GeV Lattice



Optics functions in half ring for β*=2.5cm

Y. Alexahin

Parameter			
Beam energy	GeV	63	63
Average luminosity	10^{31}/cm²/s	1.7	8.0
Collision energy spread	MeV	3	4
Circumference, C	m	300	300
Number of IPs	-	1	1
β*	cm	3.3	1.7
Number of muons / bunch	10^{12}	2	4
Number of bunches / beam	-	1	1
Beam energy spread	%	0.003	0.004
Normalized emittance, $\varepsilon_{\perp N}$	π·mm·rad	0.4	0.2
Longitudinal emittance, $\varepsilon_{\parallel N}$	π·mm	1.0	1.5
Bunch length, σ_s	cm	5.6	6.3
Beam size at IP, r.m.s.	mm	0.15	0.075
Beam size in IR quads, r.m.s.	cm	4	4
Beam-beam parameter	-	0.005	0.02
Repetition rate	Hz	30	15
Proton driver power	MW	4	4



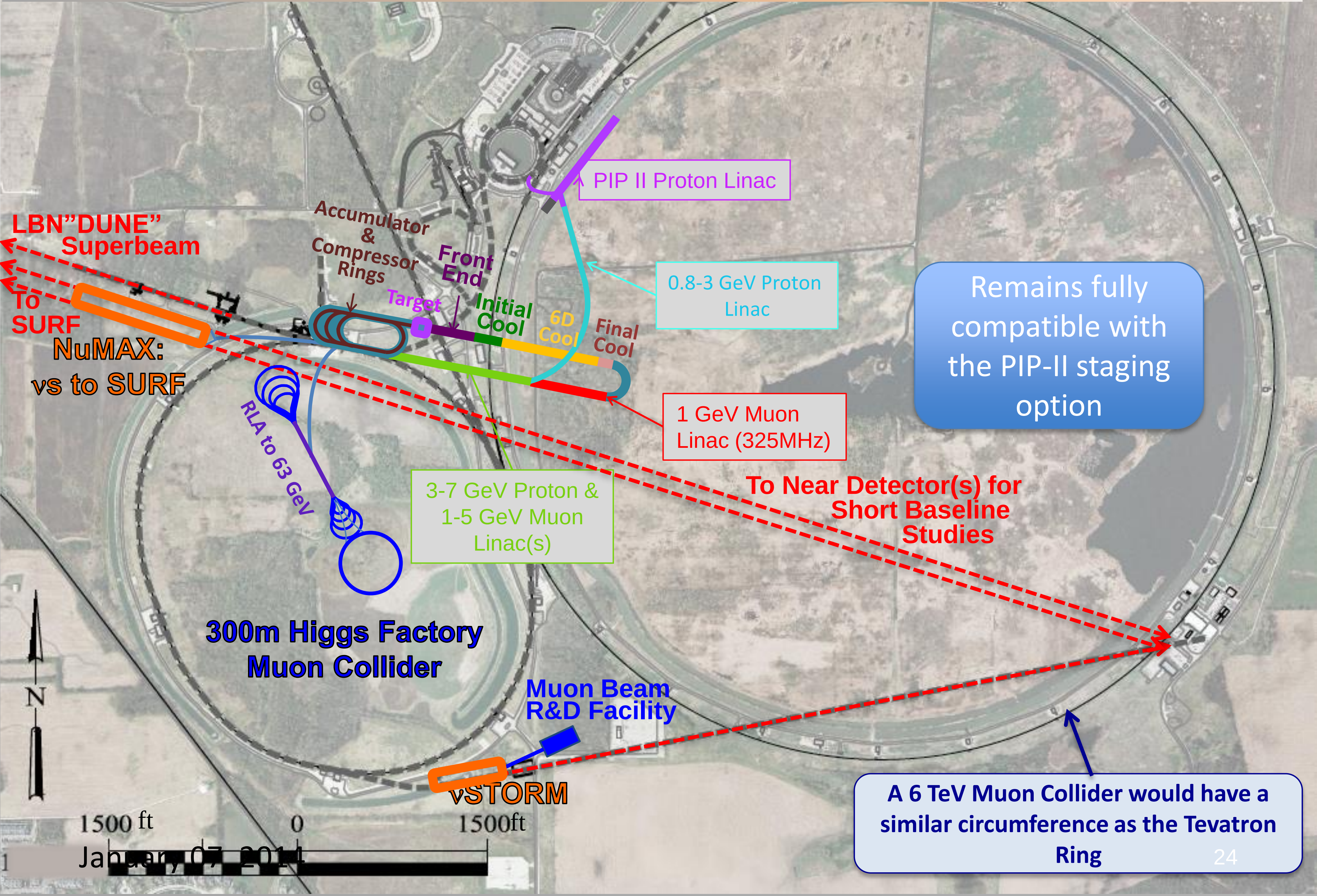
dispersion suppressor

b* tuning section

chromaticity correction sextupoles

One IP in the latest design

Heavy Lepton Acceleration Program at Fermilab



PIP II Proton Linac

0.8-3 GeV Proton Linac

1 GeV Muon Linac (325MHz)

3-7 GeV Proton & 1-5 GeV Muon Linac(s)

Remains fully compatible with the PIP-II staging option

A 6 TeV Muon Collider would have a similar circumference as the Tevatron Ring

Parting Thoughts – Thinking Bigger

- Despite (consistent with) the current P5 priorities, a staged muon (heavy electron) acceleration program at Fermilab is a viable path to a Higgs factory and a possible energy frontier future. Starting with what we already have - planned and present.
- Cooling is a standard practice in accelerator science, ionization is settled physics and the **essential technology** for ionization cooling has now been proven **viable**. Necessary accelerator and magnetic field gradients have already been demonstrated.
- Some elements of these future machines will be built in the current “future” LBN(E,F,DUNE) neutrino program. A muon storage ring source of neutrinos could be a viable upgrade. Consistent with the “megascience”, international character of our aspirations at Fermilab.
- In particular, Muons, Inc. cooling and other accelerator technologies are making bright muon beams (and beams of any flavor) more **affordable** and **viable**.
- Great synergies with the Fermilab Program: Before the ultimate energy frontier machine, it offers possible upgrades to both current muon and neutrino programs. Staged implementation with **accruing** savings.

Some Important Relationships

Hamiltonian Solution

$$p(a)=\frac{\sqrt{1+\kappa^2}}{k}\left[B-\frac{1+\kappa^2}{\kappa}b\right] \qquad k=2\pi/\lambda \qquad \kappa=ka$$

Equal cooling decrements

$$q\equiv\frac{k_c}{k}-1=\beta\sqrt{\frac{1+\kappa^2}{3-\beta^2}} \qquad k_c=B\sqrt{1+\kappa^2}/p$$

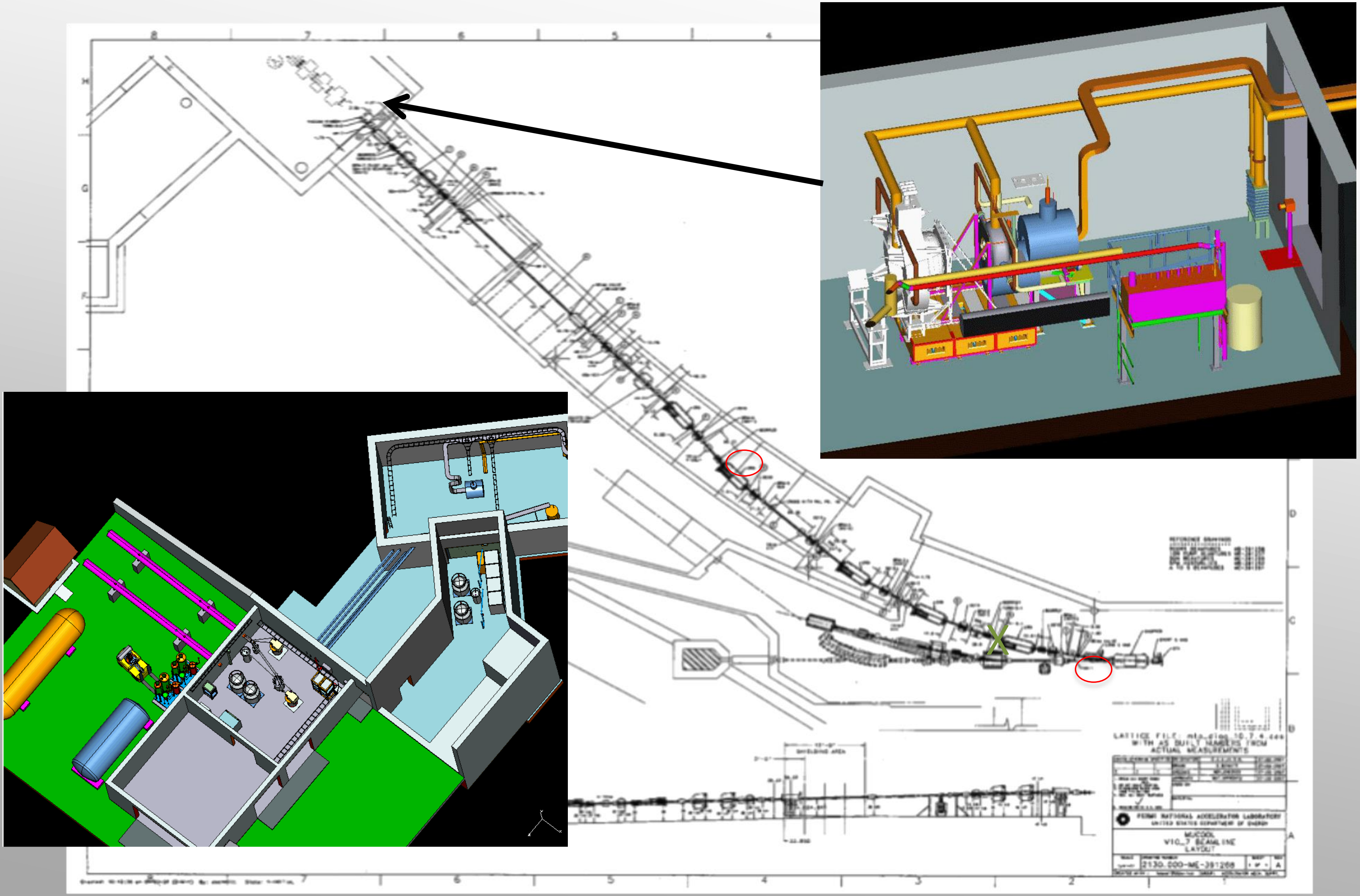
Longitudinal cooling only

$$\hat{D}\equiv\frac{p}{a}\frac{da}{dp}=2\frac{1+\kappa^2}{\kappa^2} \qquad q=0$$

~Momentum slip factor

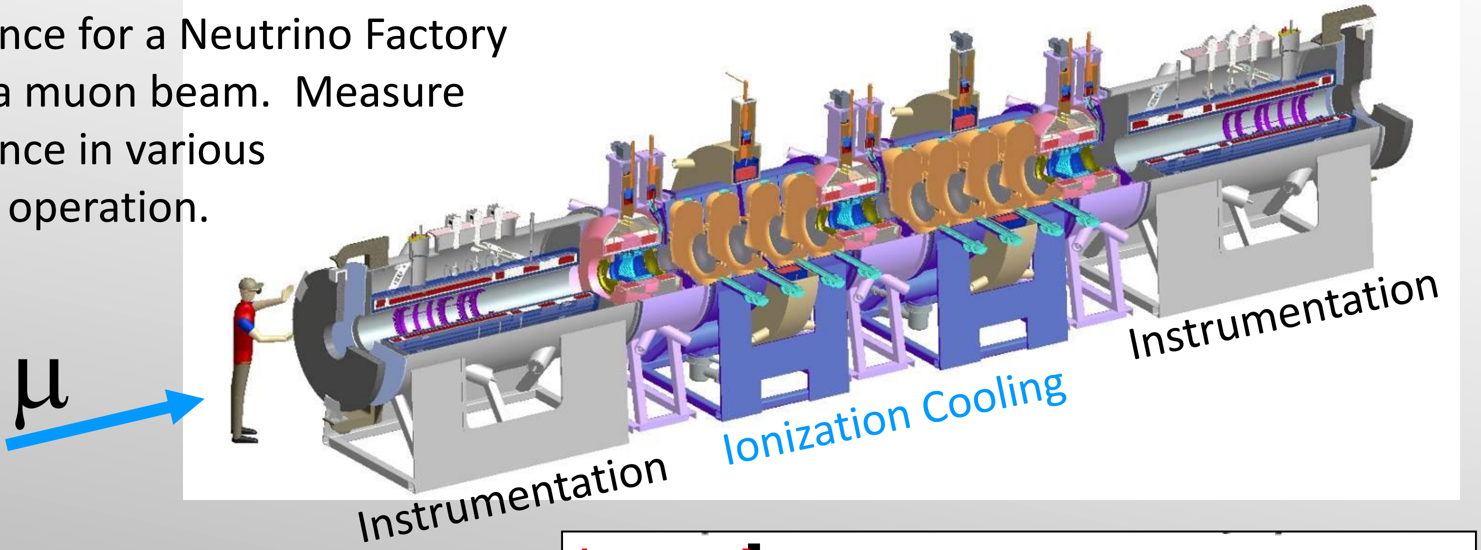
$$\eta=\frac{d}{d\gamma}\frac{\sqrt{1+\kappa^2}}{\beta}=\frac{\sqrt{1+\kappa^2}}{\gamma\beta^3}\left(\frac{\kappa^2}{1+\kappa^2}\hat{D}-\frac{1}{\gamma^2}\right) \qquad \frac{\kappa^2}{1+\kappa^2}\hat{D}\sim\frac{1}{\gamma^2_{transition}}$$

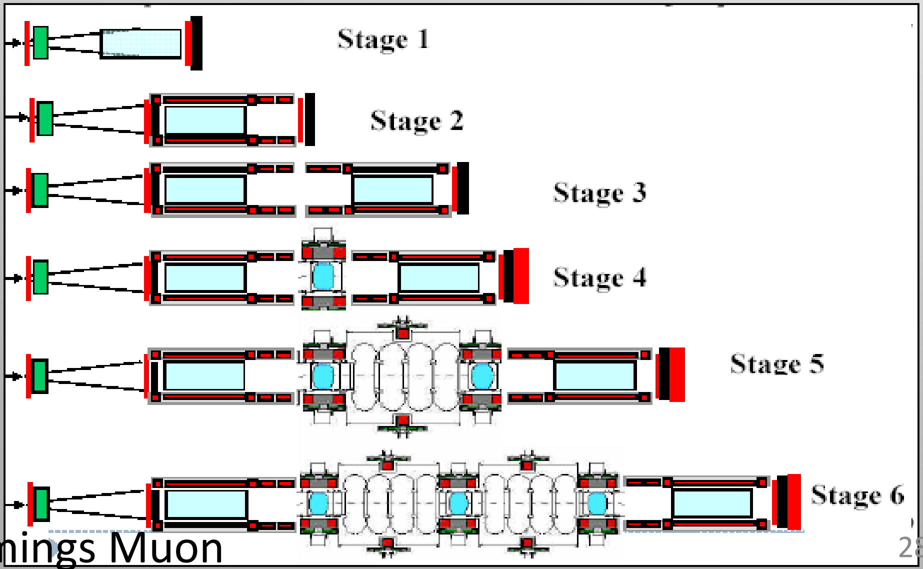
MTA Beamline



Ionization Cooling Experiment: MICE

GOALS: Build a section of cooling channel capable of giving the desired performance for a Neutrino Factory & test in a muon beam. Measure performance in various modes of operation.





- *Multi-stage experiment.*
- *First stage being commissioned now.*
- *Anticipate final stage complete by ~2015*