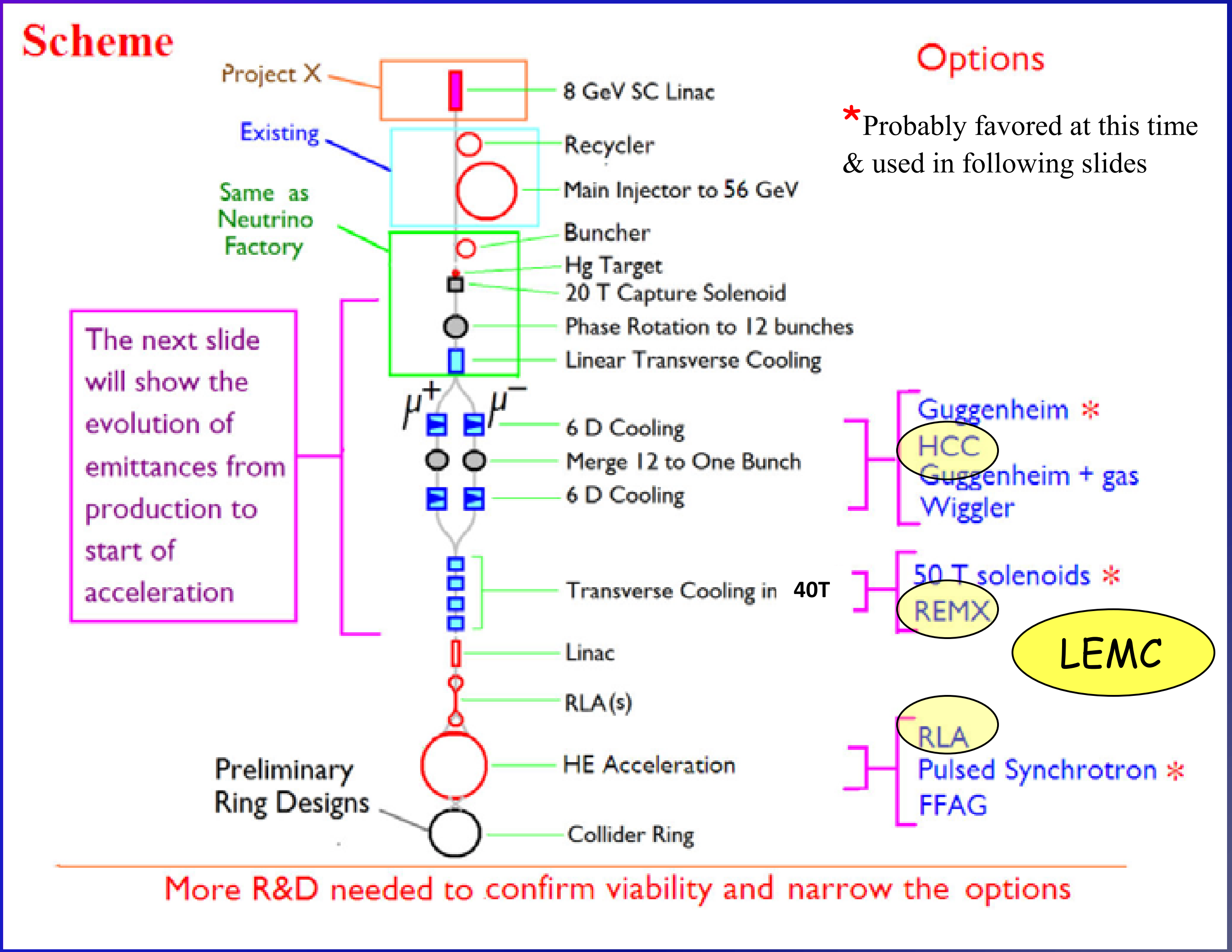
Muon Cooling R&D for the Muon Collider

Alan Bross

Muon Collider 2011

Telluride, CO

Muon Collider Facility
from Bob's talk yesterday



Muon Ionization Cooling

Basics and R&D Program

MC – Design Options

- From the MC facility slide, you see that there are many options for the cooling *(well, also for acceleration, but that is mostly cost optimization).*
  - Why?
- Because, at present there is no current solution for one technical issue for the cooling prior to final cooling
  - Operation of RF in High (3-10T) Magnetic Field
    - Max stable Operating gradient drops rapidly in B
- And for the final cooling the need for
  - Very High Field (≈ 40T) Magnets are extremely challenging
- These issues drive, for the most part, our hardware R&D program

Muon Ionization Cooling - Transverse

- 2D Transverse Cooling

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

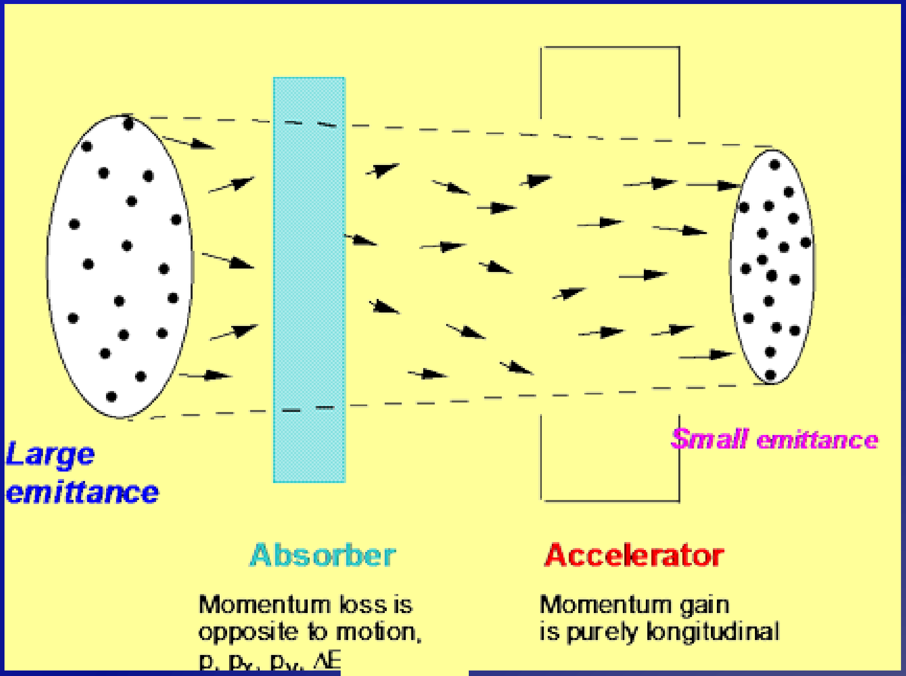
and

$$\epsilon_{N,\min} = \frac{\beta_\perp (14\ \mathrm{MeV})^2}{2\beta m_\mu \frac{dE_\mu}{ds} L_R}$$

- Figure of merit: $M=L_R dE_\mu/ds$

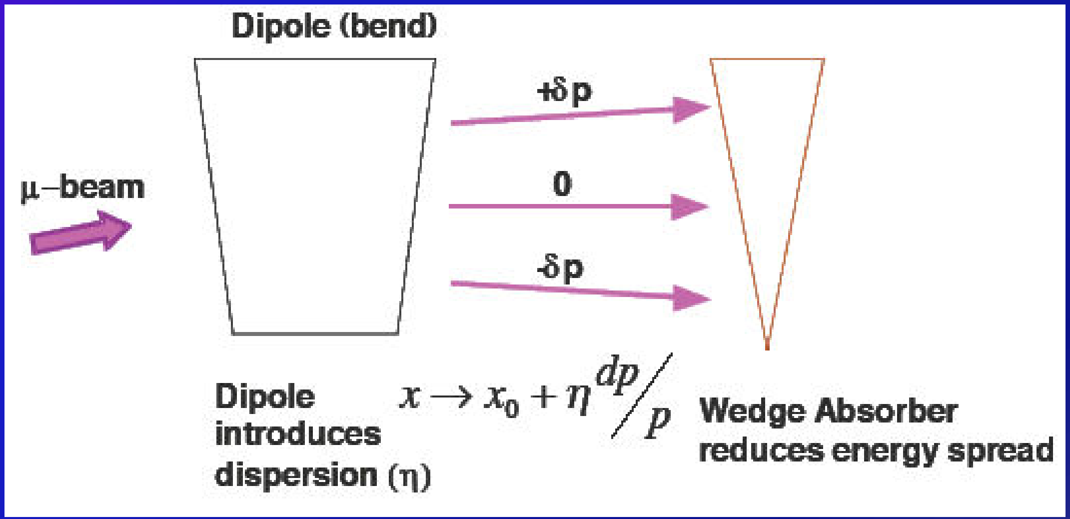
M^2 (4D cooling) for different absorbers

Material	$\langle dE/ds \rangle_{\min}$ (MeV g^{-1}cm^2)	L_R (g cm^{-2})	Merit
GH_2	4.103	61.28	1.03
LH_2	4.034	61.28	1
He	1.937	94.32	0.55
LiH	1.94	86.9	0.47
Li	1.639	82.76	0.30
CH_4	2.417	46.22	0.20
Be	1.594	65.19	0.18



Tom Roberts
See his detailed talk in WG2

Muon Ionization Cooling – Longitudinal *Emittance Exchange*



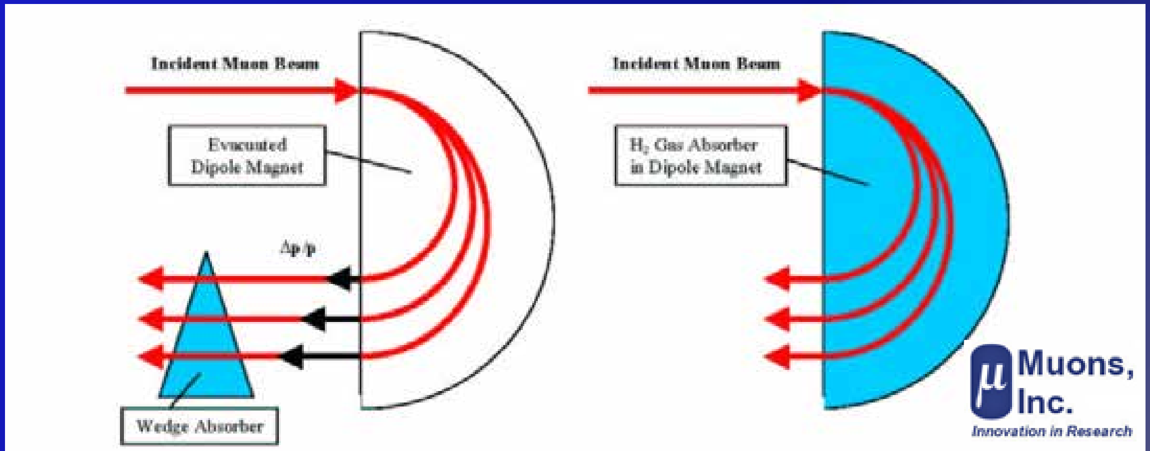
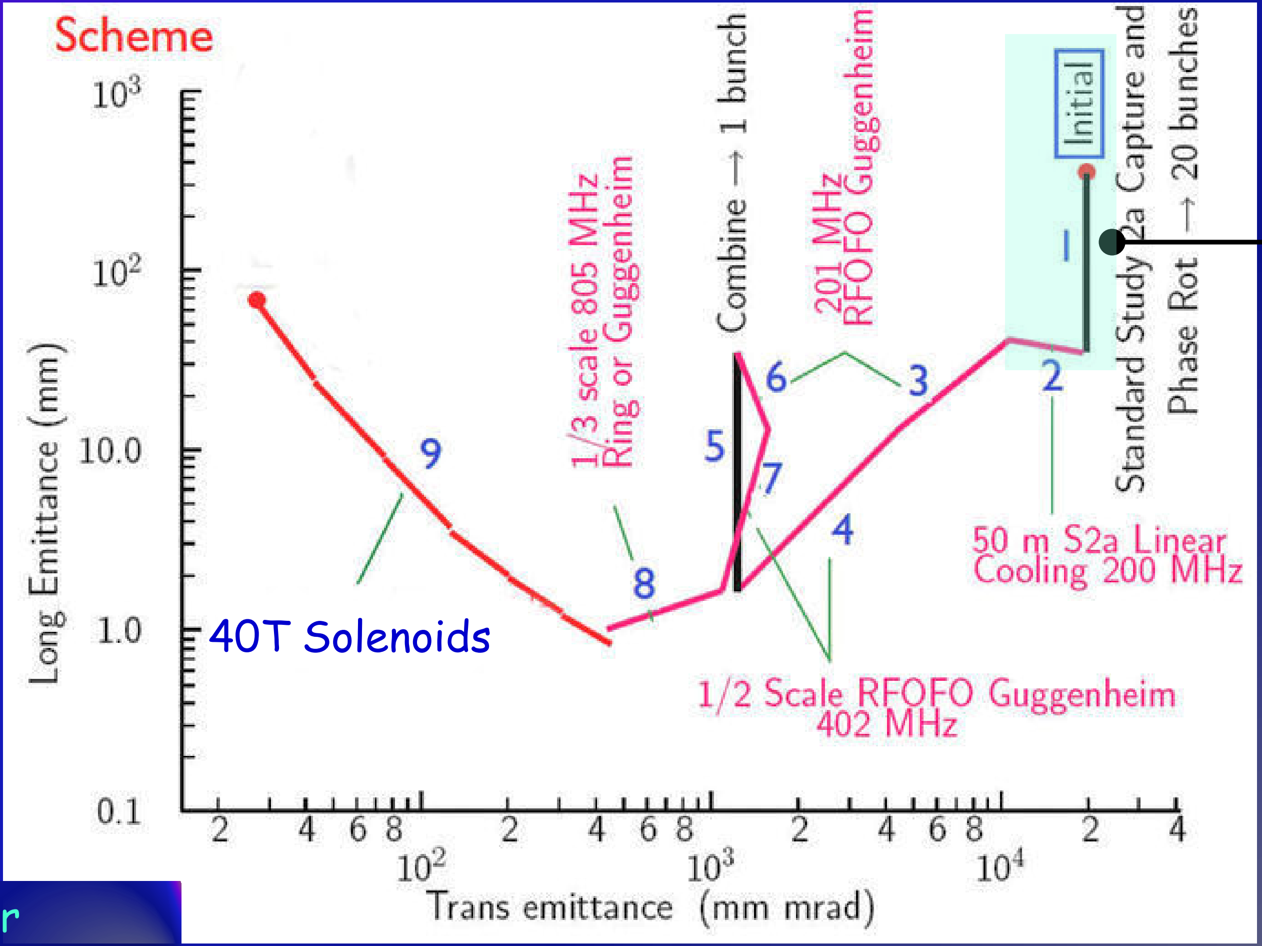


Figure 1. Use of a Wedge Absorber for Emittance Exchange

Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

A Muon Collider Cooling Scenario

Fernow-Neuffer plot



NF FRONT END?

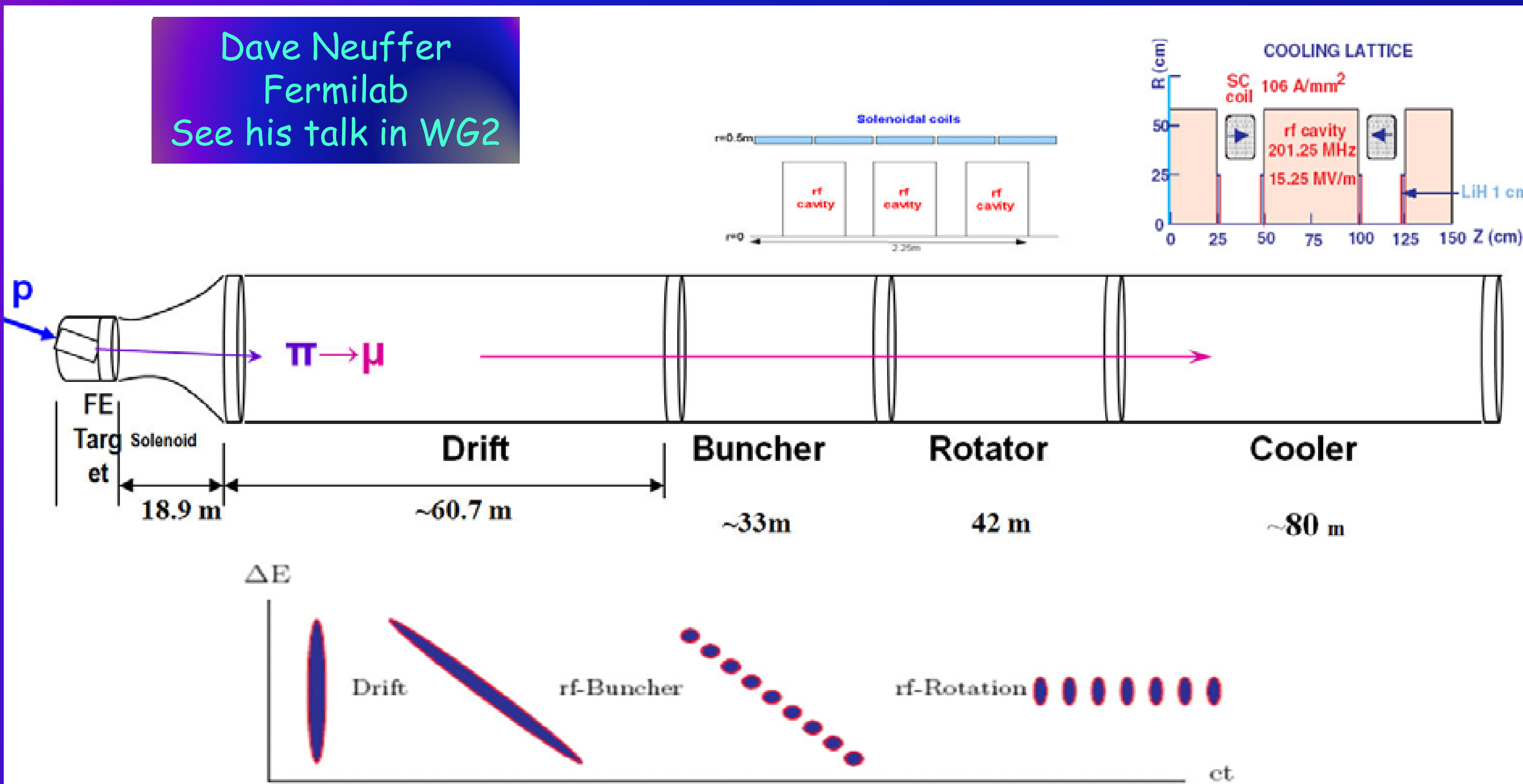
Note, for clarity, the details regarding the bunch merging are not shown

Bob Palmer
MC Ambassador at Large

Front-End

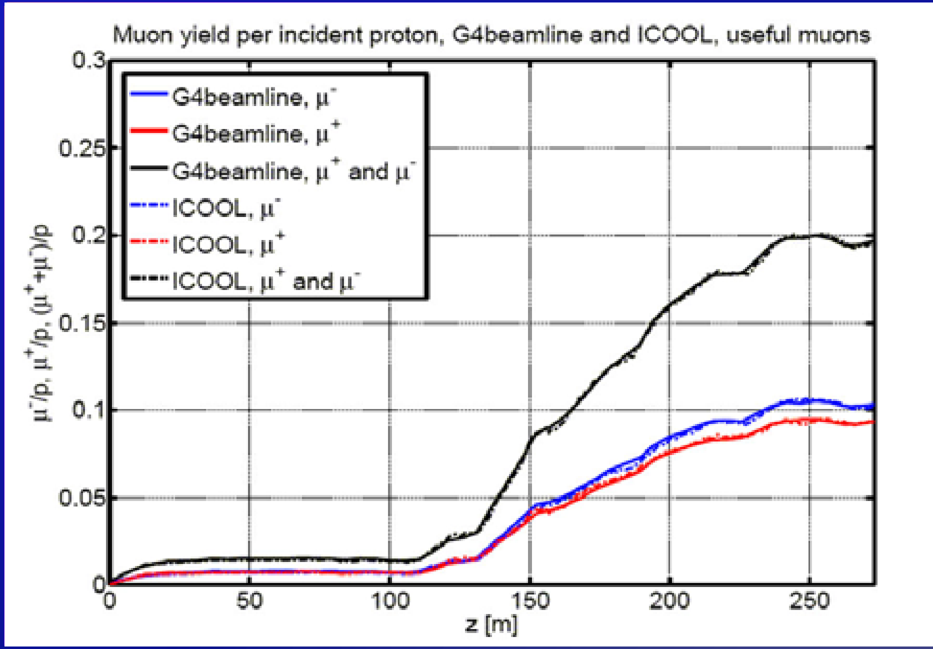
Production, Capture, Bunch, Rotate & Cool

Dave Neuffer
Fermilab
See his talk in WG2



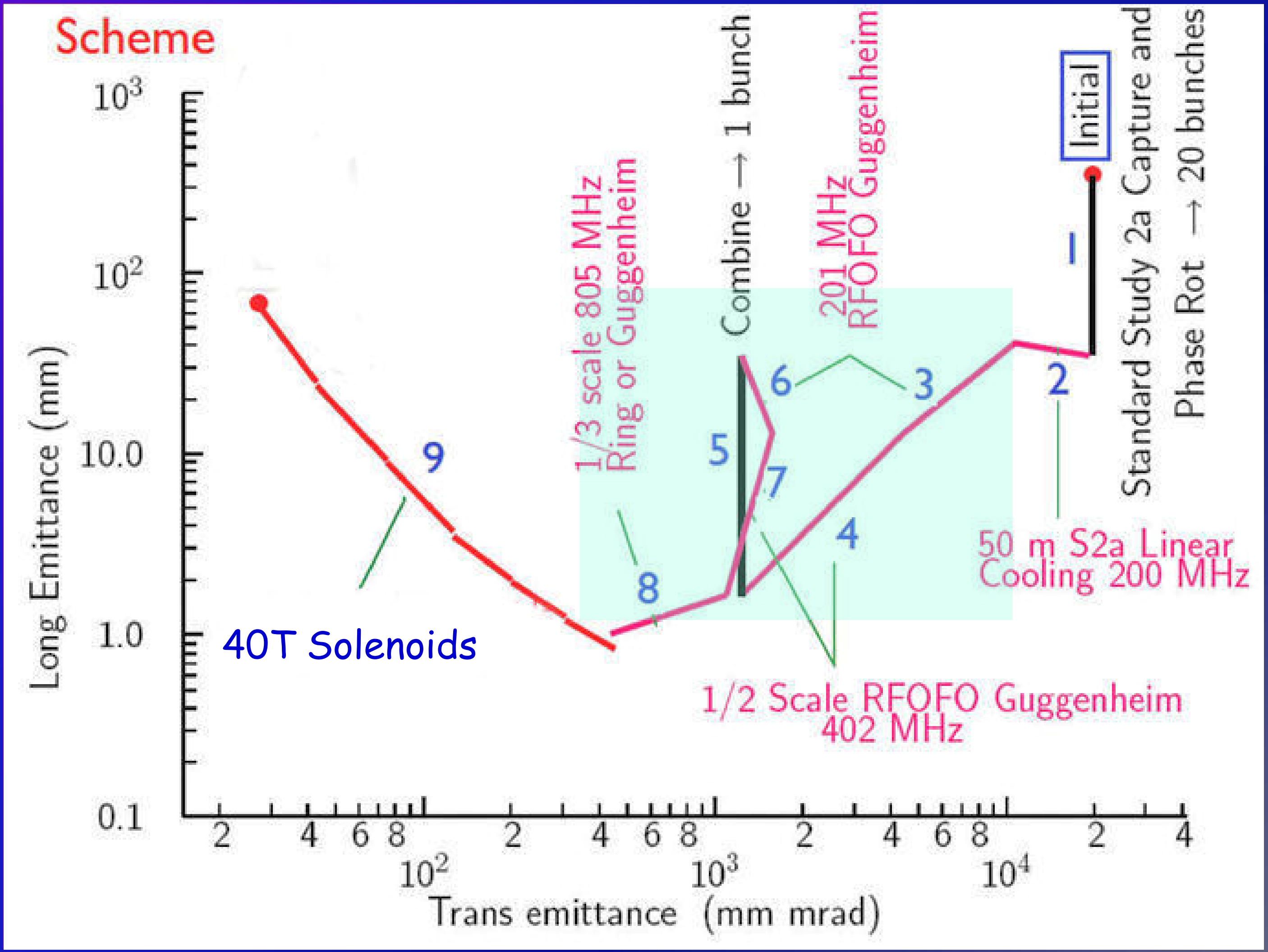
4D Cooling Channel

- Performance quite good
  - 0.11 μ/p (each sign)
- Technology
  - Vacuum RF (gradients to 16MV/m)
  - SC solenoids (1.5T)
  - LiH absorbers
- MC Optimization is somewhat different
  - 230 → 275 MeV/c
  - 150m → 120m
  - 9/12/15 MV/m → 12.5/15/18
  - 1.5T → 2T
  - 0.15 μ/p (each sign)



R&D Issues for 4D Cooling
RF Operation in B
Beam Losses

6D Cooling

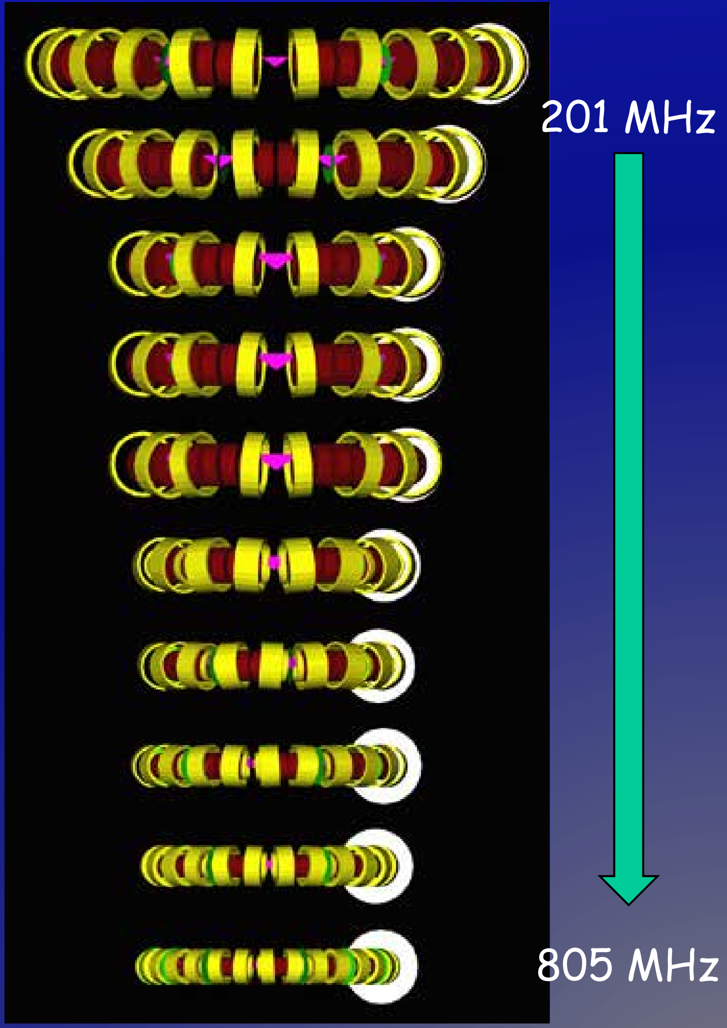


Scheme
Long Emittance (mm)
10^3
10^2
10.0
1.0
0.1
Trans emittance (mm mrad)
2 4 6 8
10^2
10^3
10^4
40T Solenoids
9
8
1/3 scale 805 MHz
Ring or Guggenheim
Combine → 1 bunch
5
6
7
3
4
201 MHz
RFOFO Guggenheim
Initial
1
2
Standard Study 2a Capture and
Phase Rot → 20 bunches
50 m S2a Linear
Cooling 200 MHz
1/2 Scale RFOFO Guggenheim
402 MHz

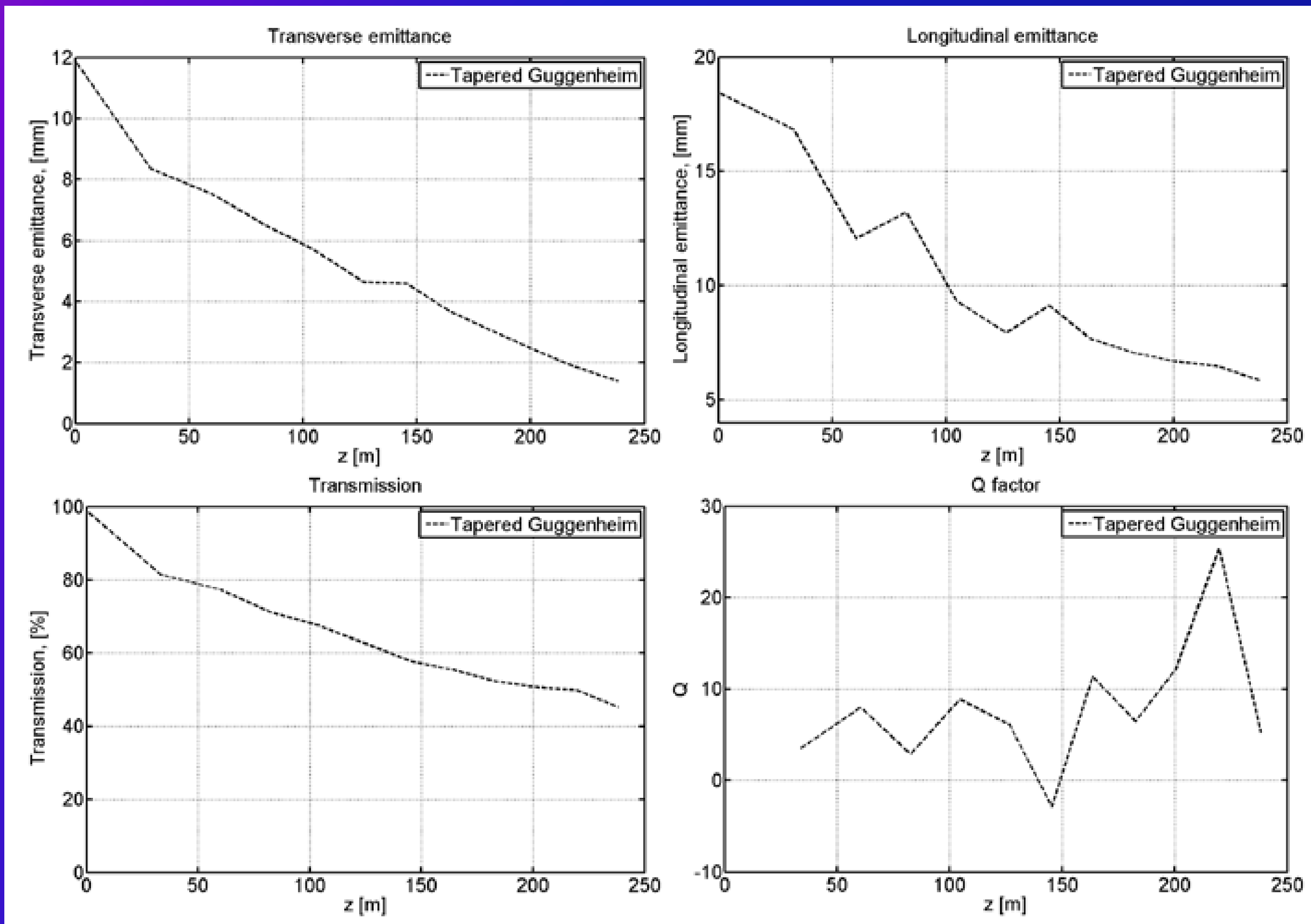
6D Cooling with tapered *Guggenheim*

- **Notes**
  - This sim is approximation to the helix
    - *Individual rings*
    - *Coil tilt to generate bending field*
    - *Coil displacement to control vertical orbit*
- **14 Stages**
- **Total Length = 321m**
- **Height(depth) ≈ 45m**
- **RF**
  - 201 → 805 MHz
  - Gradient: 16MV/m
- **Max B on axis**
  - 2.3T → 10.6T
- **LH_2 wedge absorbers**

Pavel Snopok
IIT/Fermilab



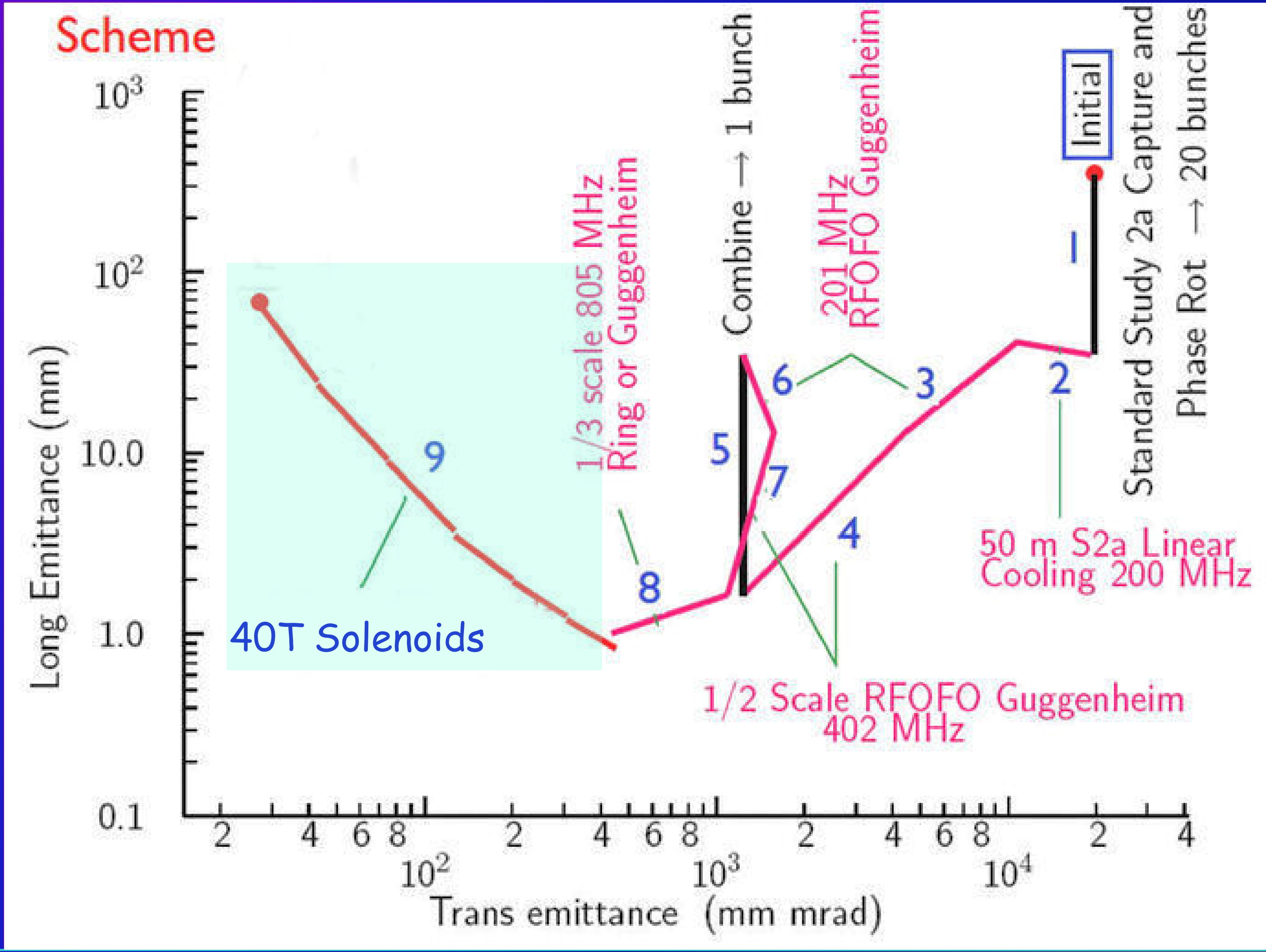
Tapered Guggenheim *Performance*



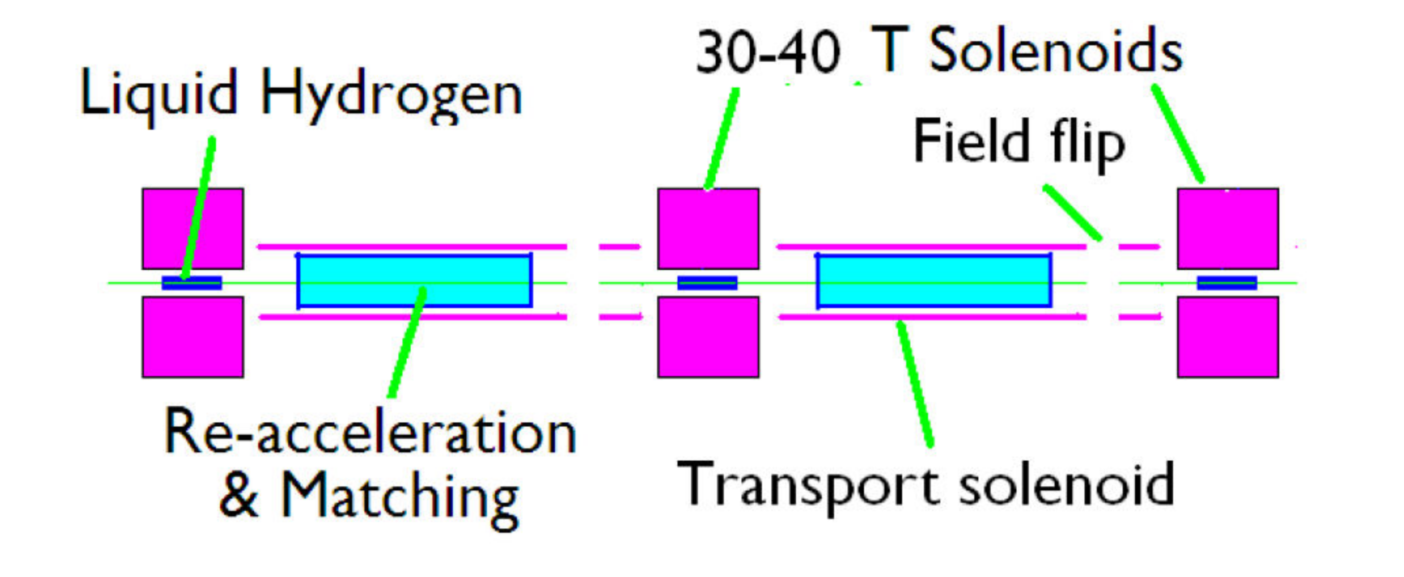
$$Q = \frac{d\epsilon^N_{6D}/ds}{dN/ds}\,\frac{N(s)}{\epsilon^N_{6D}(s)}$$

Total reduction in 6D emittance ≈ 230 with ≈ 45 % transmission. The Q factor compares the rate of change of emittance to the particle loss

Final Cooling



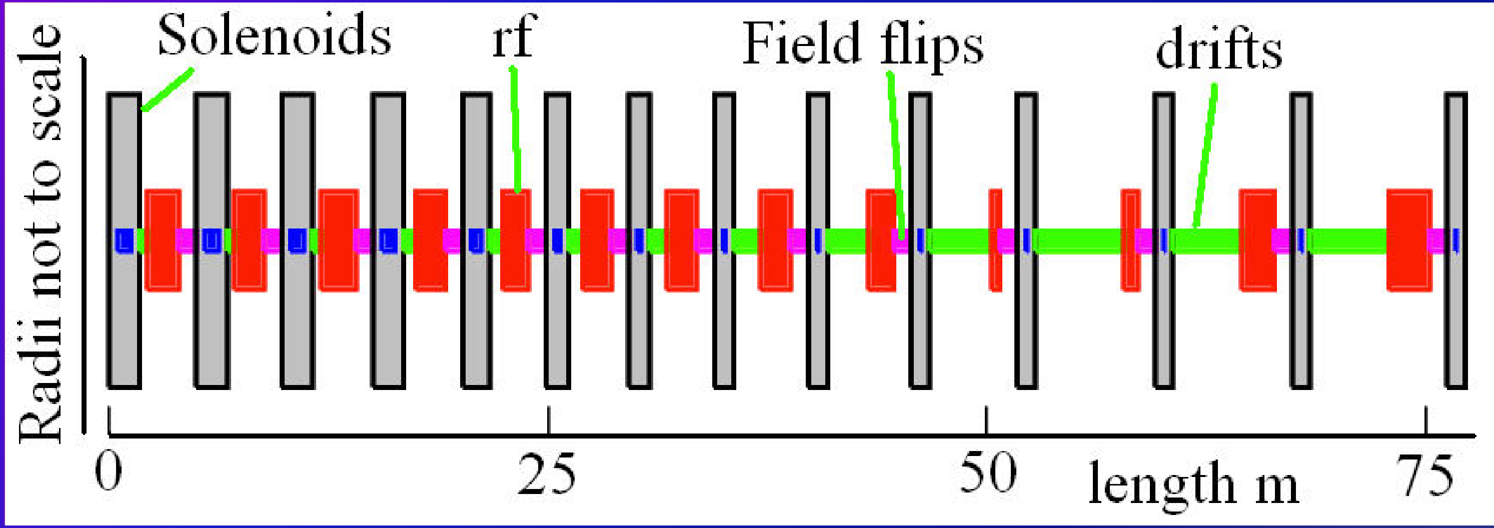
Final 4D cooling



- 13 Stages
- 30-40T HTS magnets
  - Operating @ 4K
- RF cavities & Induction linacs needed
- LH_2 forced-flow absorbers
  - SLAC E158
- Only candidate that has demonstrated 25 μm $\varepsilon_\perp$

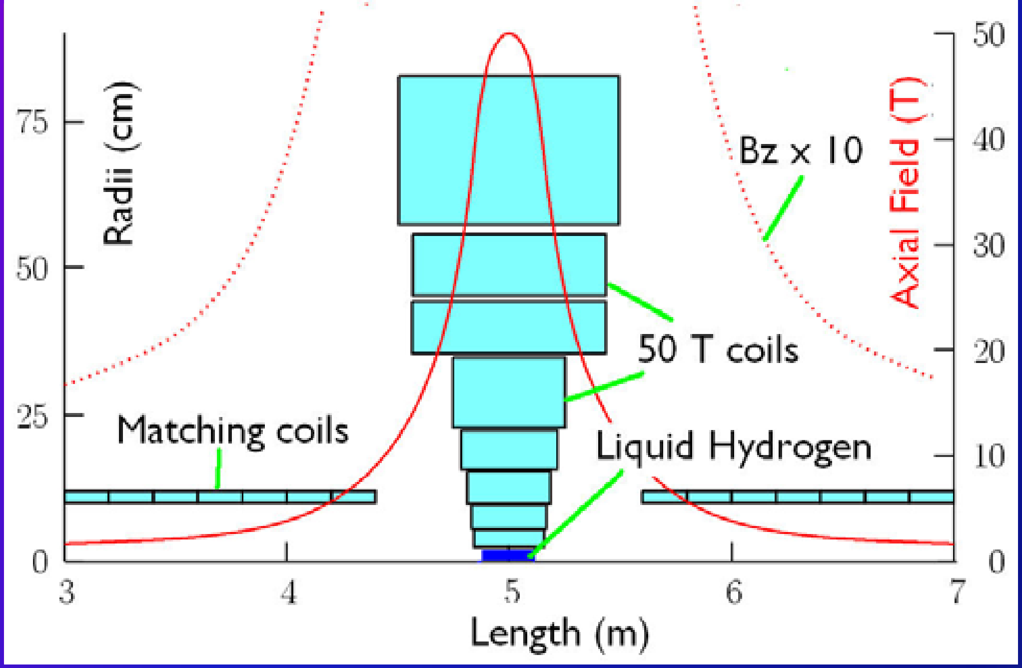
Bob Palmer
MC Ambassador at Large

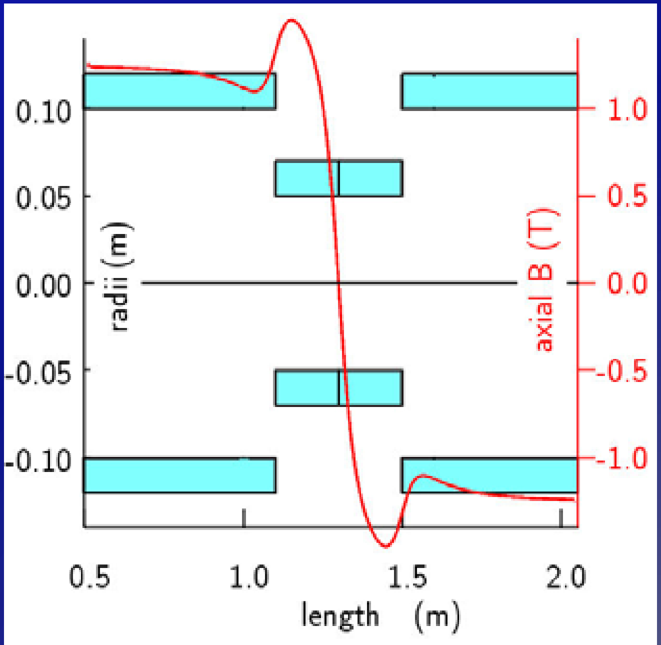
Final Cooling II



- Bunch length rises from 5 cm-400 cm.
- Energy falls from 66 MeV to 5 MeV.
- $H2$ absorber length falls from 77 cm to 11 cm.
- Beta is reduced to 1.5 cm w/RMS beam size of 0.6 mm.
- dE/dx rises
- For bunches larger than 0.75 m, induction linacs were assumed with gradients of 1 MV/m

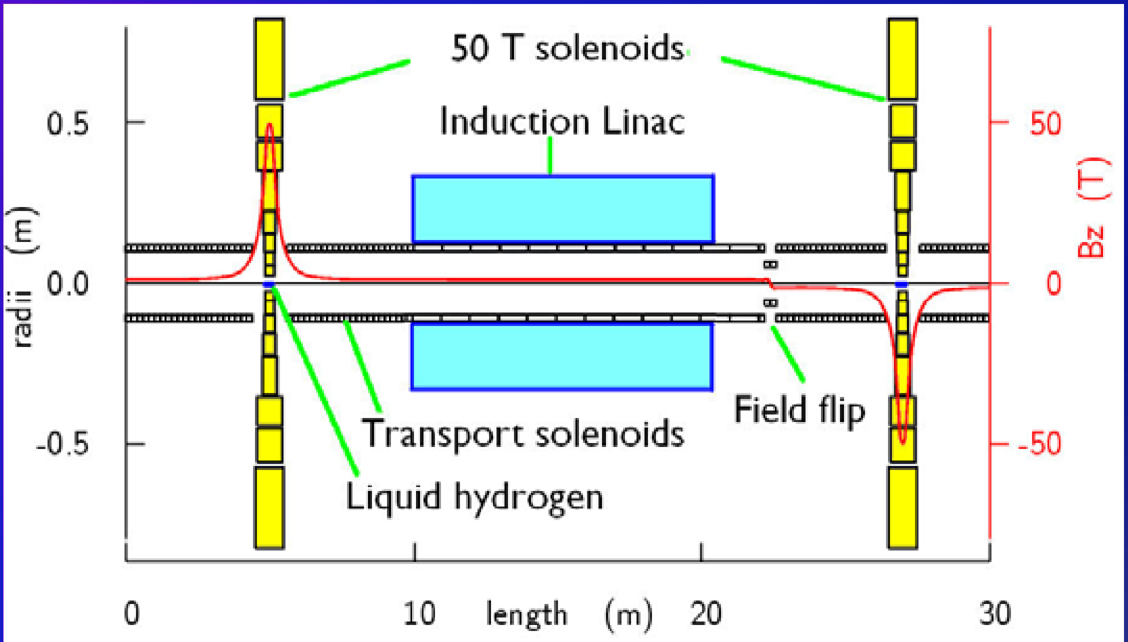
Final Cooling III





Field Profiles

Final Cooling IV



- Detailed simulation of last two stages
- RF – Induction Linac
- Bunch L = 3 m
- The muon energy falls in conjunction with rising dE/dz,
  - Energy falls from 66 MeV to 5 MeV in full final cooling channel
- min $\varepsilon_\perp$ can fall below 25 μm

Jon Lederman
BNL/UCLA

Cooling Options

- What I have described is what we believe is the most promising approach, at this time, to muon cooling for a high luminosity Muon Collider
  - And meets the required specification [at the current level of the simulation and our understanding of the systems]
- However, there are other approaches being investigated
  - To a large degree, driven by the "*RF problem*"

So, First

Cooling Hardware R&D Program

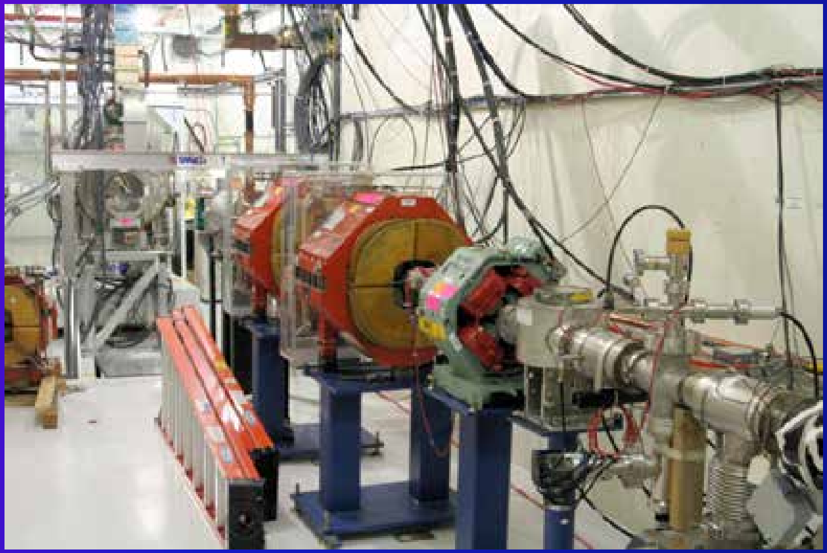
MuCool
Component R&D

Yagmur Torun
IIT/Fermilab
See his talk in WG2

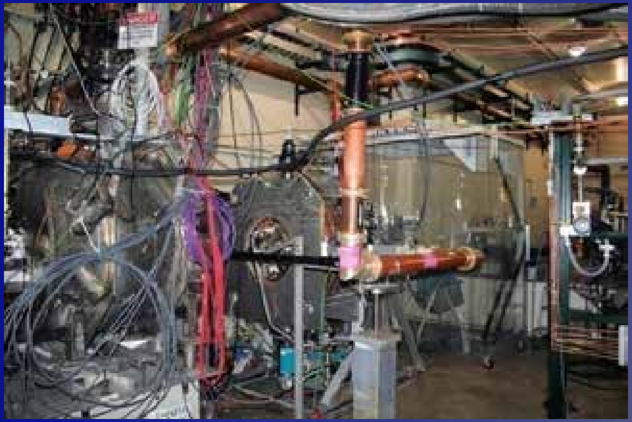
- **MuCool**
  - Component testing: RF, Absorbers, Solenoids
    - With High-Intensity Proton Beam
  - Uses Facility @Fermilab (MuCool Test Area –MTA)
  - Supports Muon Ionization Cooling Experiment (MICE)

50 cm ∅ Be RF window

MTA proton beam line



MuCool
201 MHz RF Testing



MuCool
LH_2 Absorber
Body

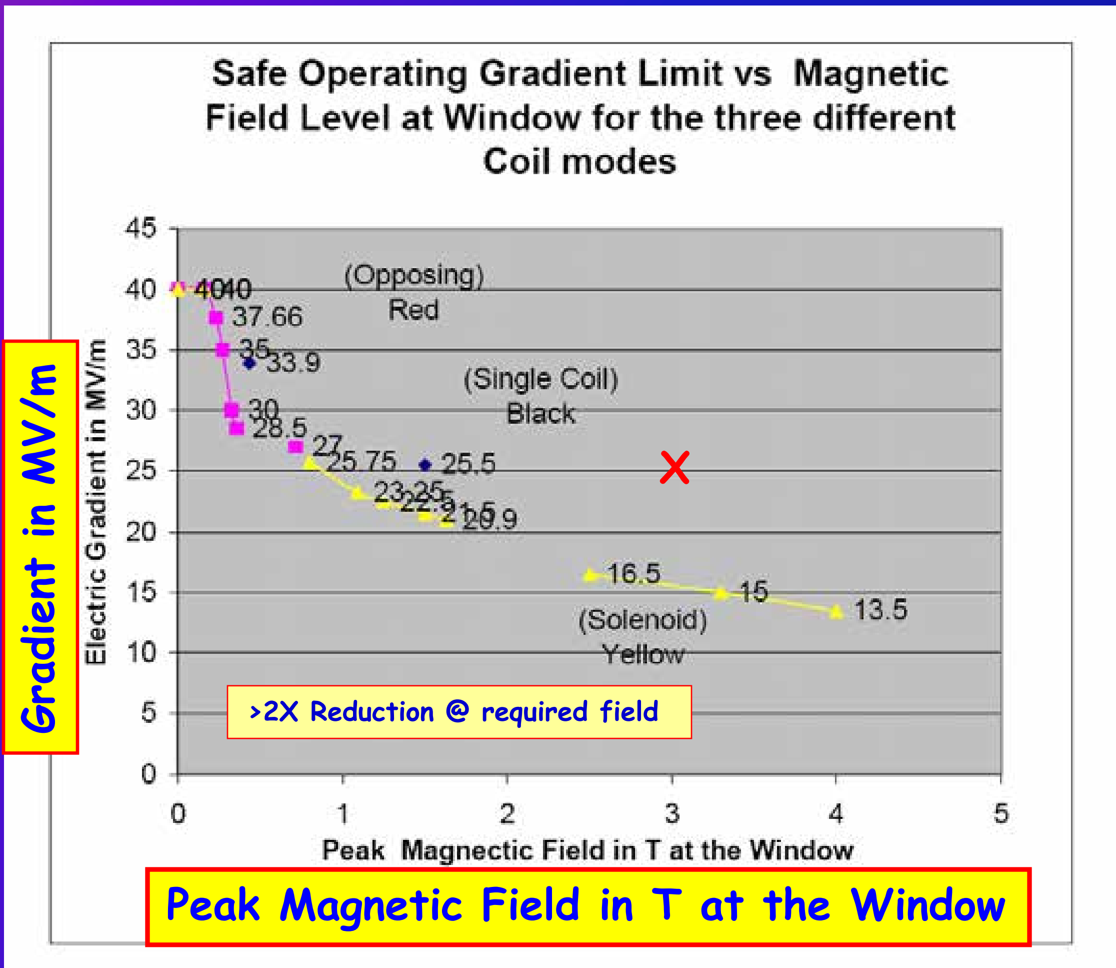
RF Test Program

- MuCool has the primary responsibility to carry out the RF Test Program in the Muon Accelerator Program
- Study the limits on Accelerating Gradient in NCRF cavities in magnetic field
- Fundamental Importance due to the use of high-gradient RF in a magnetic field in muon capture, bunching, phase rotation and cooling

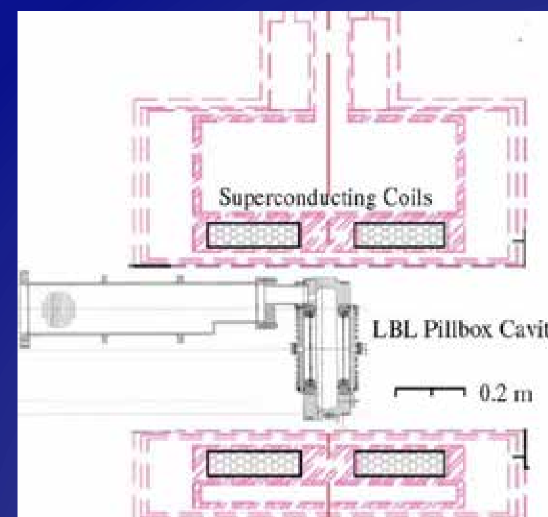
It can be argued that this is the single most critical Technical challenge for the Muon Collider

The Basic Problem – B Field Effect

805 MHz Studies



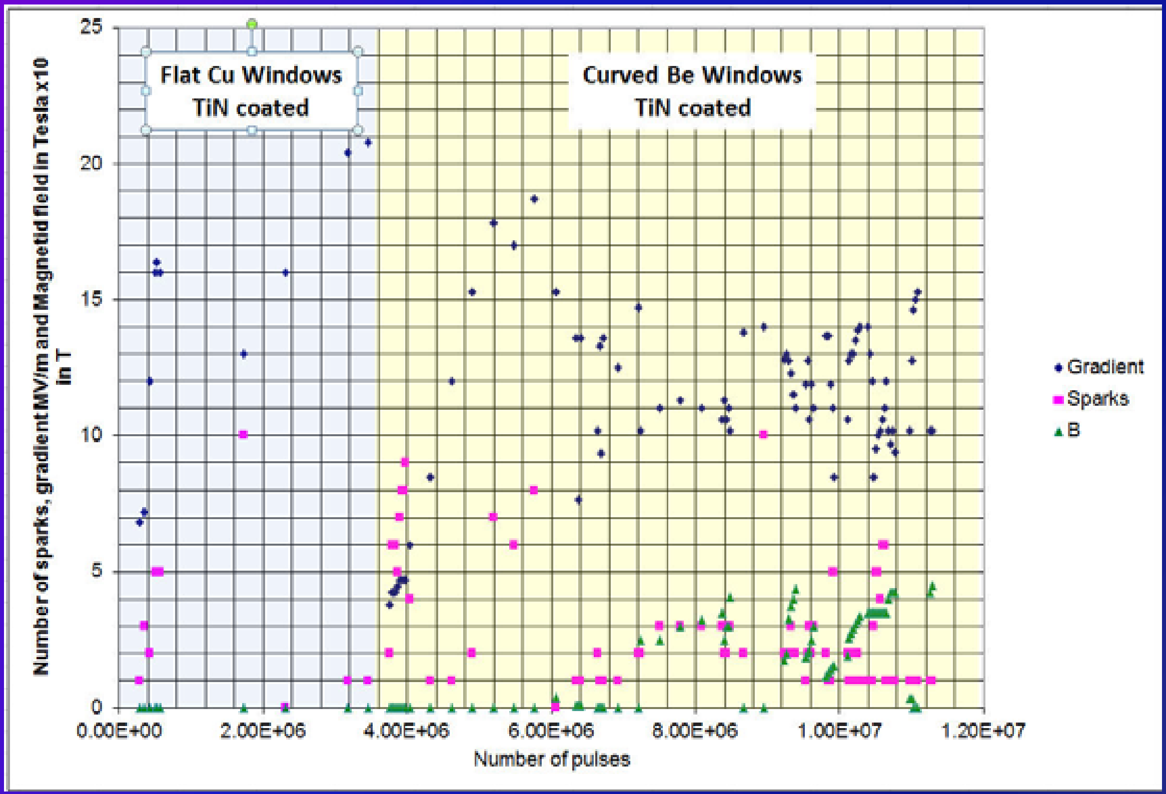
- Data seem to follow universal curve
  - Max stable gradient degrades quickly with B field
- Re-measured
  - Same results

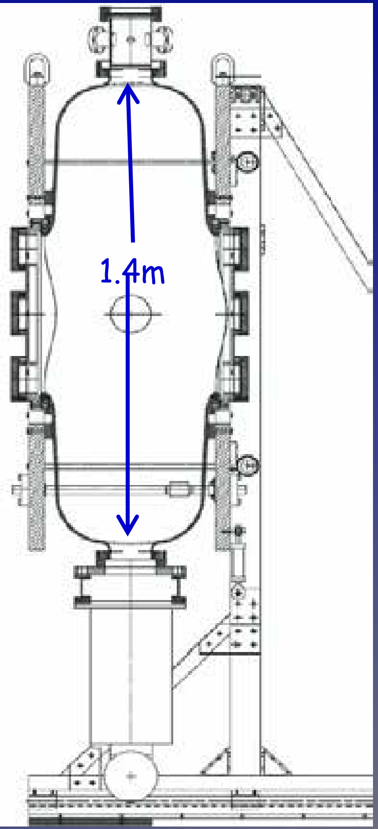


RF R&D – 201 MHz Cavity Test

Treating NCRF cavities with SCRF processes

- **The 201 MHz Cavity – *21 MV/m* *Gradient Achieved*** (Design – 16MV/m)
  - *Treated at TNJLAB with SCRF processes – Did Not Condition*
- **But exhibited Gradient fall-off with applied B**



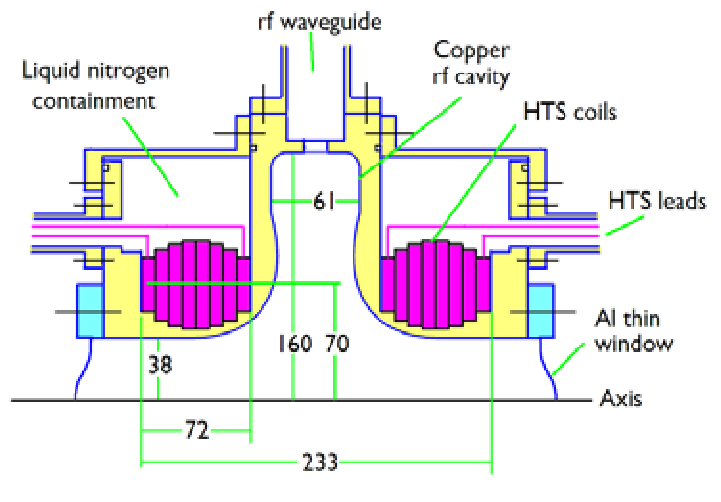


Facing the RF B Field Challenge

- We are pursing multiple solutions
  - Reduce/eliminate field emission
    - Process cavities utilizing SCRF techniques
    - Surface coatings
      - Atomic Layer Deposition (Jim Norem (ANL)
  - Material Studies
      - Non-Cu bodies (Al, Be)
        - Mitigate the effect of B field emission on breakdown
  - RF cavities filled with High-Pressure gas (H_2)
    - Utilize Paschen effect to stop breakdown
  - Magnetic Insulation
    - Eliminate magnetic focusing
      - Promising results with first test
        - Box cavity with $E \perp B$
      - See Yagmur Torun's talk in WG2

See Diktys Stratakis' Talk in WG2

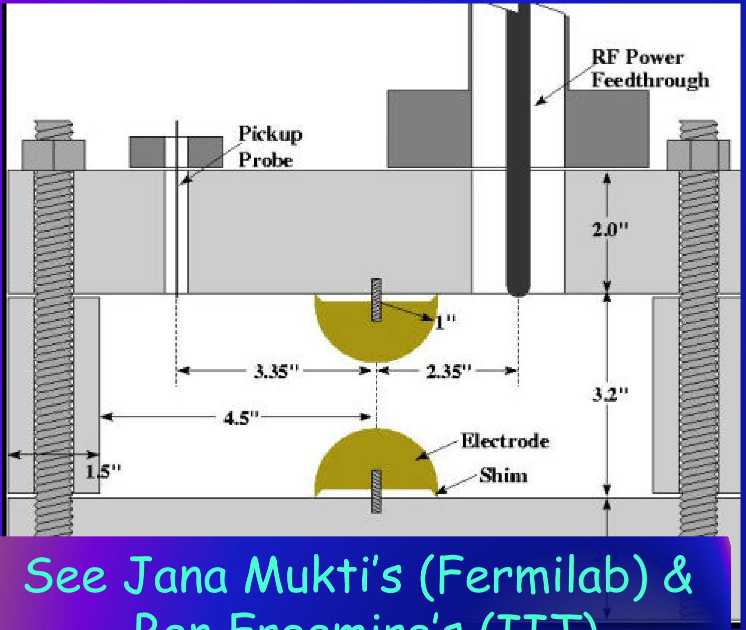
Palmer & Stratakis BNL



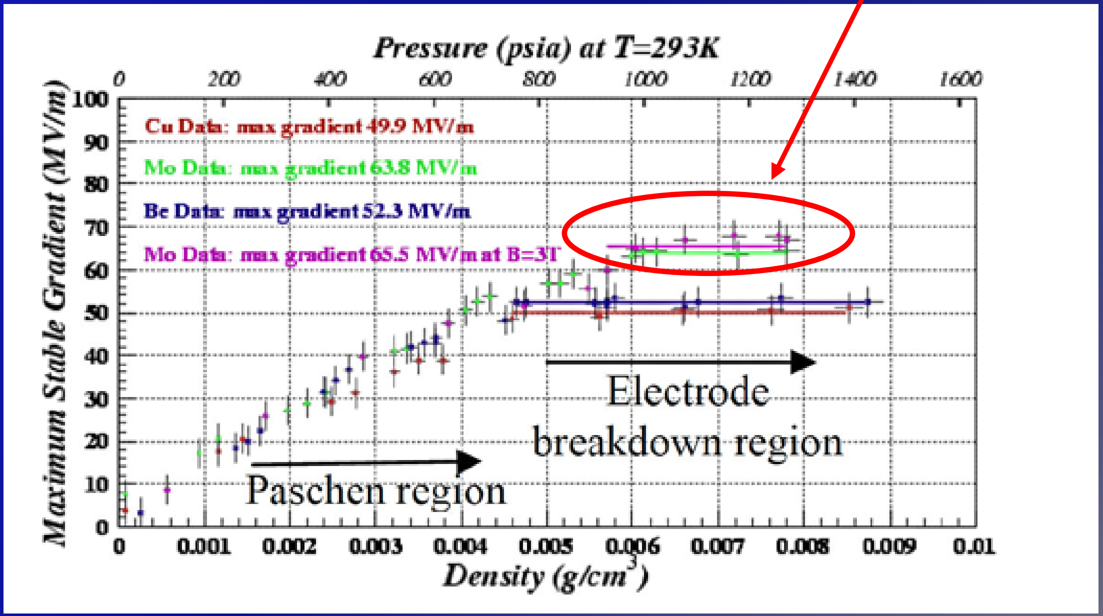
High Pressure H_2 Filled Cavity Work *with Muons Inc.*

- High Pressure Test Cell
- Study breakdown properties of materials in H_2 gas
- Operation in B field
  - No degradation in M.S.O.G. up to ≈ 3T
- Next Test – Repeat with beam

No Difference B=0 & B=3T



See Jana Mukti's (Fermilab) & Ben Freemire's (IIT) Posters



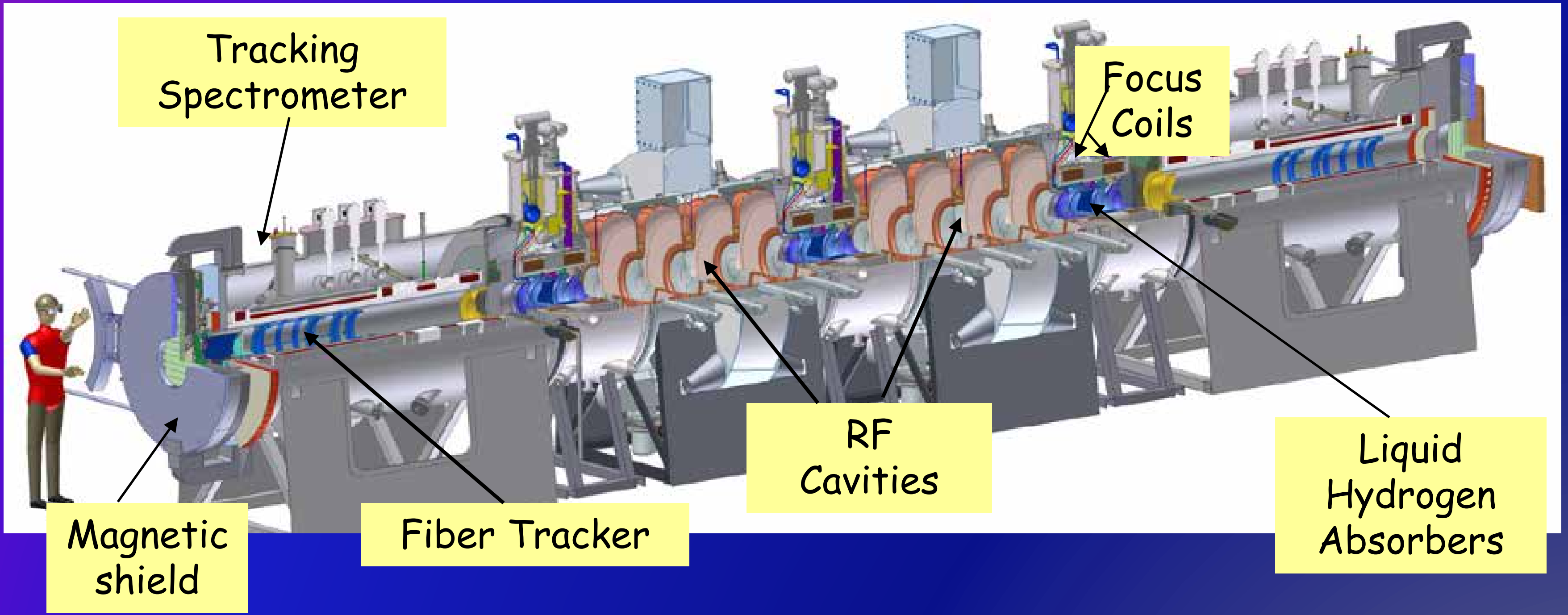
RF Program (next 2 years)

- Beam tests of high pressure H_2 filled cavity
- Be materials tests
  - Button cavity test
  - Be wall cavity
- Complete tests on Magnetic Insulation
  - Box with orientation $E \parallel B$
- New tests with 201 MHz cavity
  - Redesigned couplers
  - Tests in higher B field
    - Need new SC magnet (2.5T, 1.5m bore)

Muon Ionization Cooling Experiment

Transverse cooling system test

Muon Ionization Cooling Experiment

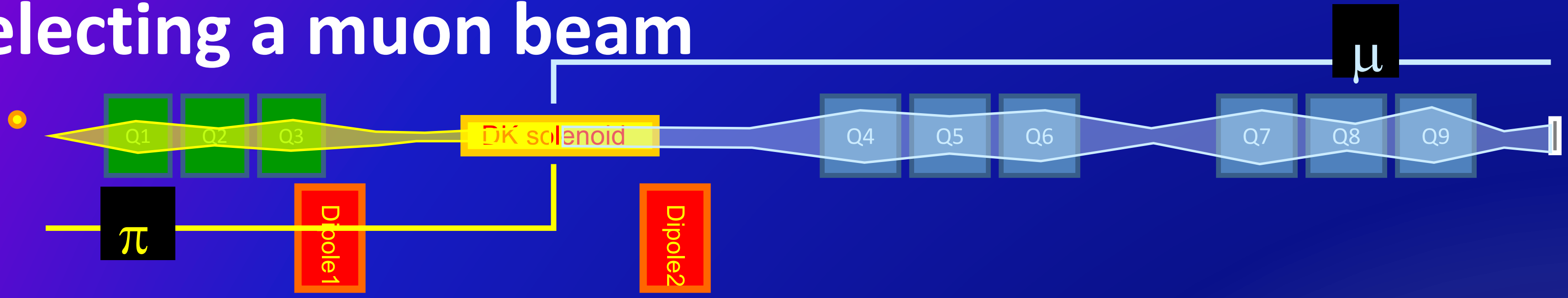


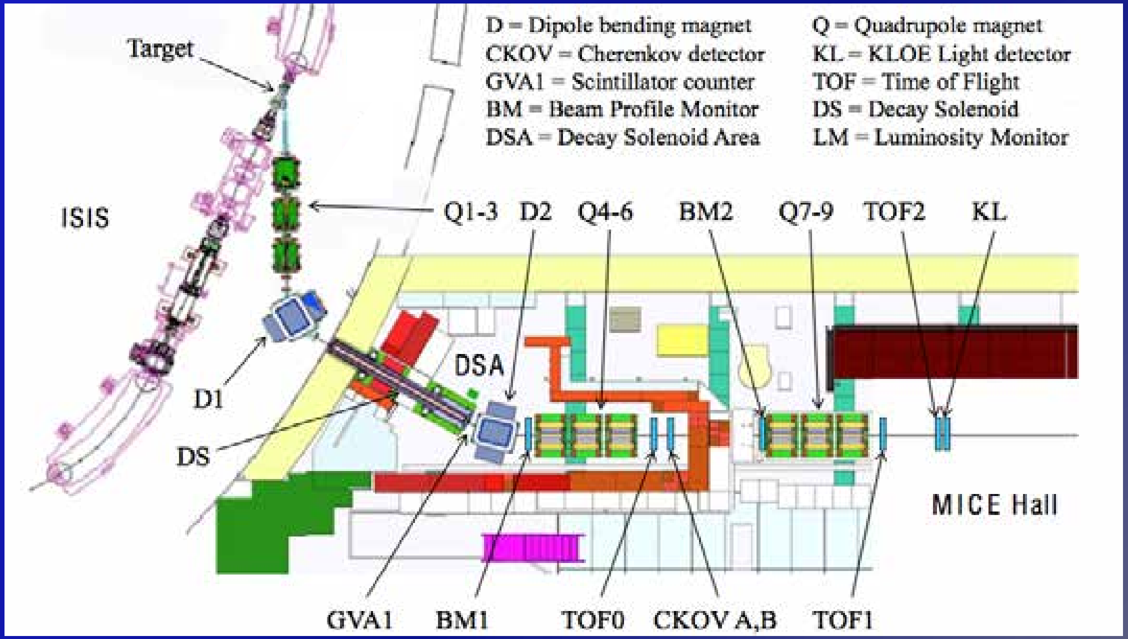
- **Measure transverse (4D) Muon Ionization Cooling**
  - 10% cooling – measure to 1% (10^{-3})
- **Single-Particle Experiment**
  - Build input & output emmittance from μ ensemble

Linda Coney
UCR
See her talk in WG2

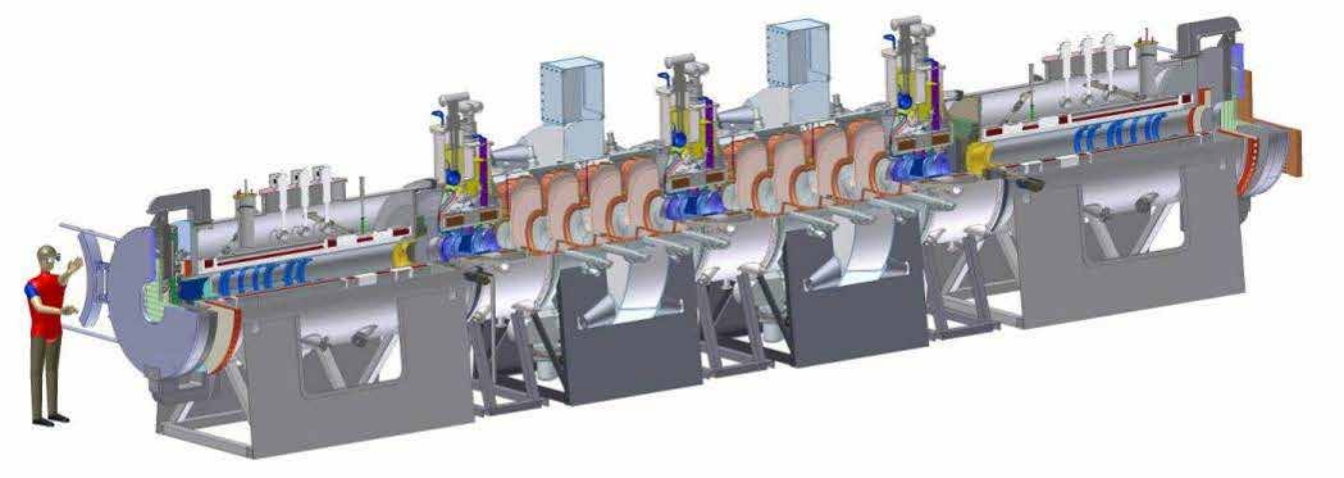
μ Beam Creation

Selecting a muon beam





MICE Future Program?



- Although MICE is testing a cooling channel design that is not currently envisioned for either the Neutrino Factory or Muon Collider, the components under test are used in muon capture, bunching & rotation, 4D cooling (modified channel) and in the initial sections of the tapered Guggenheim
  - 201 MHz cavities
  - 2-3T large aperture solenoids
  - LH_2 absorbers
- Much will be learned regarding the operation of these components
- Finally, the MICE components could, in principle, be reconfigured to simulate sections of the Guggenheim or RFOFO Snake.

Magnet R&D
Addressing the needs in cooling

- **HTS solenoid R&D to assess the parameters that are likely to be achieved**
  - What is the highest practical achievable solenoid field & what is the R&D required before these solenoids can be built?
- **HCC magnet R&D to assess the feasibility of this type of cooling channel and**
  - Eventually build a demonstration magnet for a HCC test section (dependent on success of HP RF tests)

The VHFSMC Collaboration

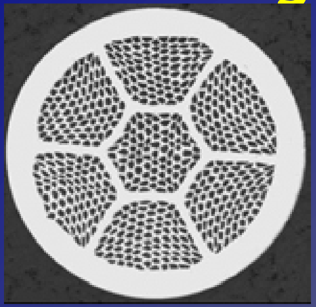
Focusing on BiSCO2212 technology.

HTS: $Bi_2Sr_2CaCu_2O_x$
BSCCO 2212

- J_e of 2212 has increased to 600 A/mm^2 at 4.2 K, 20 T.
- Given this increase, paths to 30+ T all superconducting magnets based on 2212 open up
  - And actually have design credibility
- Strong collaboration and synergy between VHFSMC and MAP will be important in bringing technology forward.

A round-wire conductor is preferred for HEP magnet applications.

- Allow Rutherford cable and 20+ T dipoles



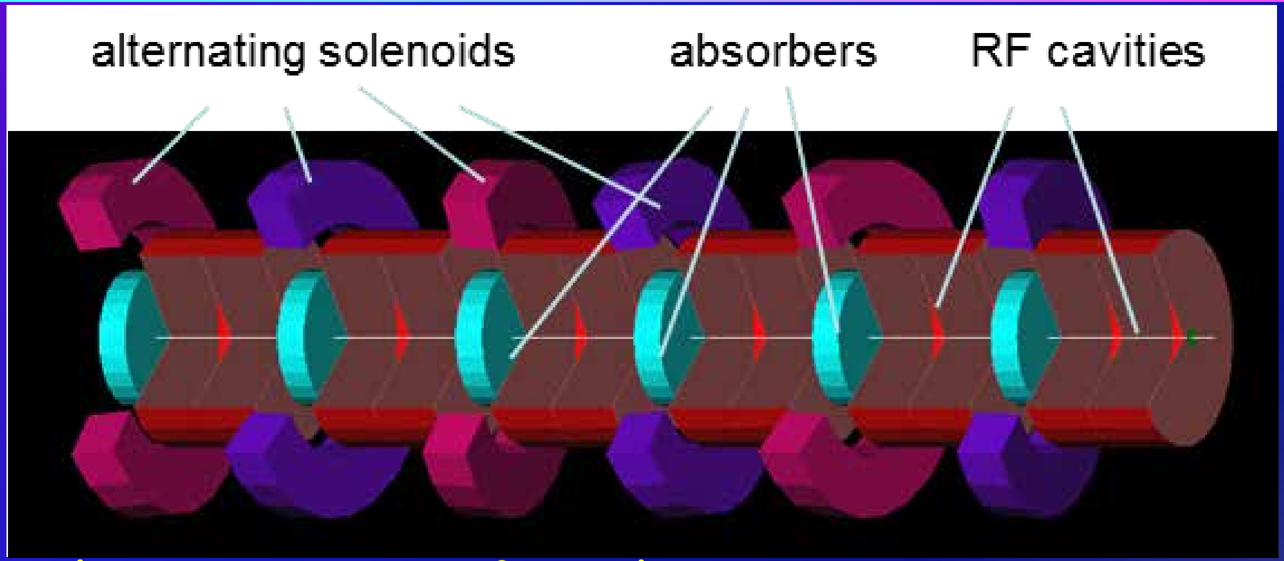
Ramesh Gupta (BNL), Vito Lombardo (Fermilab)
See their talks in WG2

Tengming Shen
Fermilab
See his talk in WG2

Cooling Channel Options

A few cases

Helical FOFO Snake

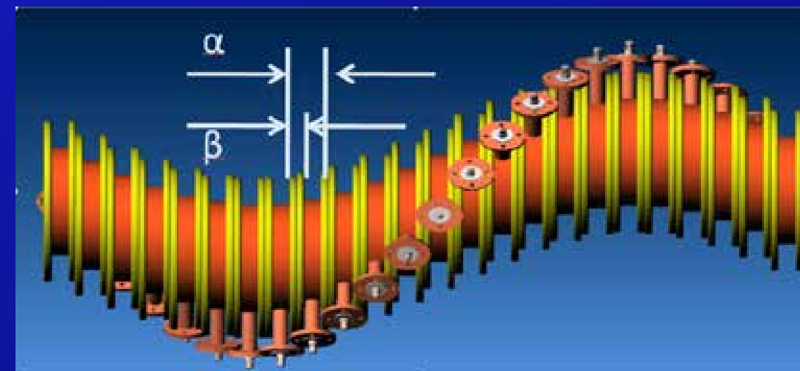


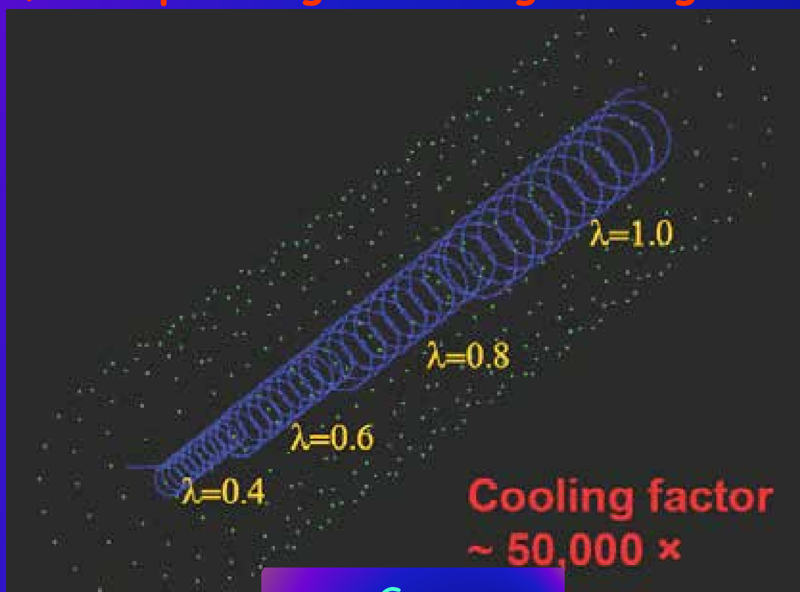
- Uses similar components to Guggenheim
  - RF pillbox cavities
  - Solenoids
    - Tilted in order to introduce dispersion
  - LH_2 absorbers
    - Planar
- Advantage
  - Cools μ^+ and μ^- in same channel
- Gives reasonable performance even with known matching problems
  - Appreciable transverse and longitudinal cooling with transmission ~55%

Yuri Alexahin
Fermilab

Helical Cooling Channel

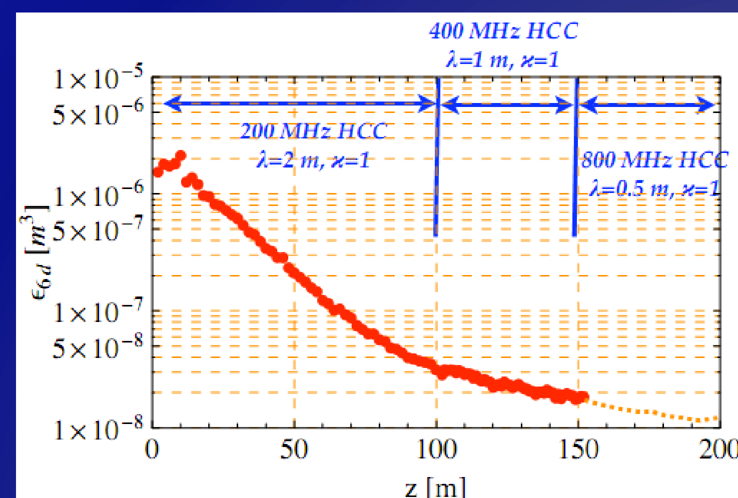
- Magnetic field is solenoid B0+ dipole + quad
- System is filled with H_2 gas, includes rf cavities (absorber & RF together)
- Cools in 6D (large E means longer path length)
- But, incorporating RF is Engineering challenge!





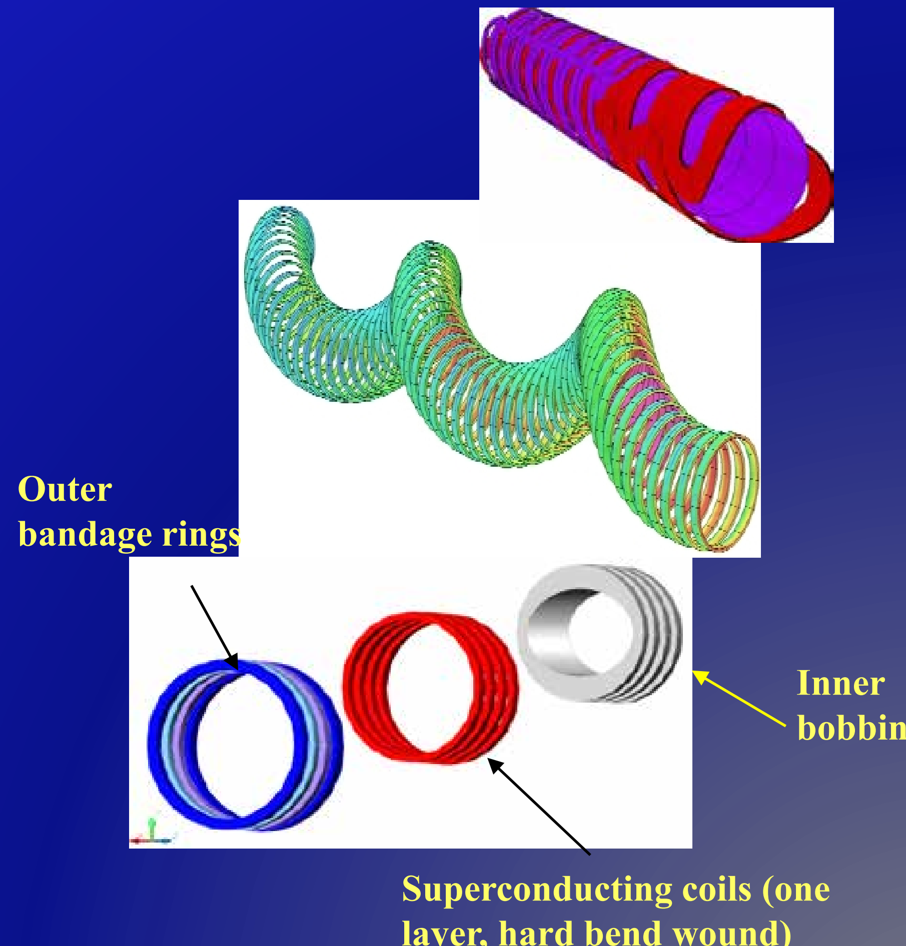
See K. Yonehara's Poster

Muons, Inc.
Innovation in Research



HCC Hardware R&D
Magnet Design & Prototyping

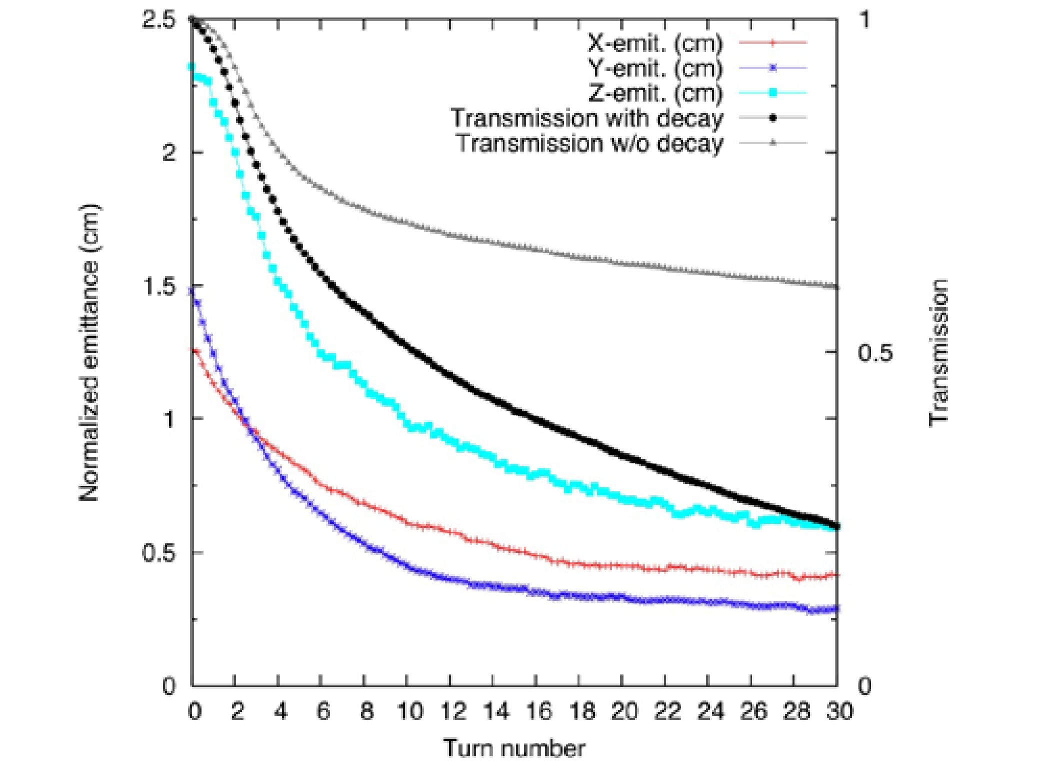
- **Helical solenoid (HS): Smaller coils than in a "snake" design**
  - Smaller peak field
  - Lower cost
- **Field components in HS determined by geometry**
  - Over constrained
  - Coil radius is not free parameter
- **4 Coil Demonstration Models have been built**
  - Validate mechanical structure and fabrication methods
  - Study quench performance and margins, field quality, quench protection
  - Use SSC conductor

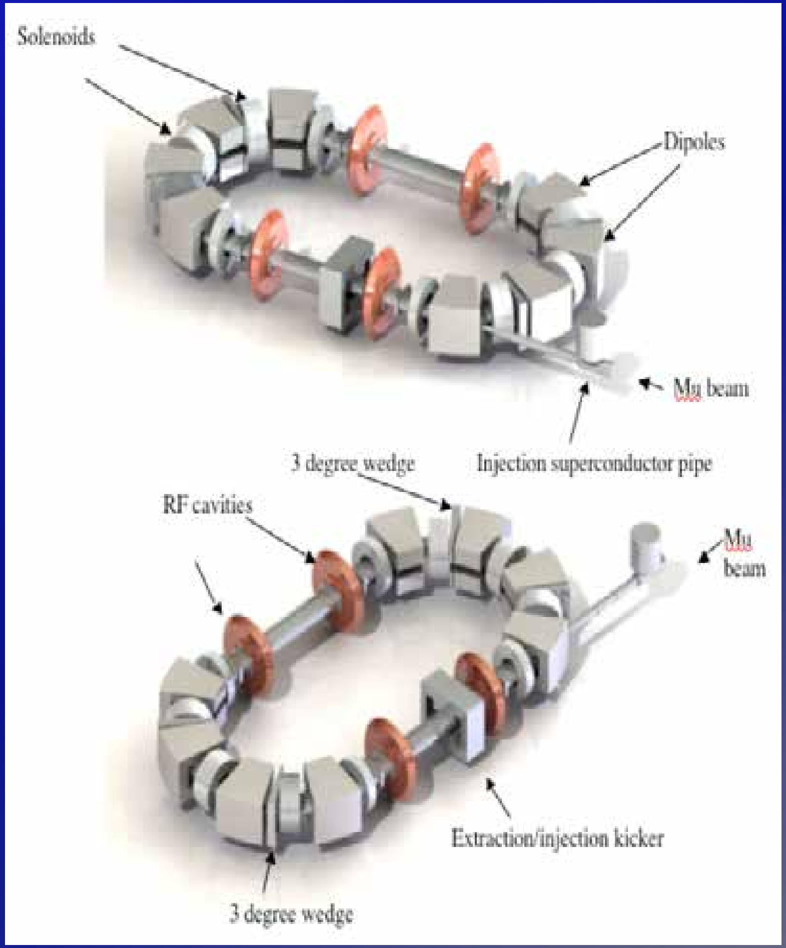


Solenoid-Dipole Ring Cooler

Garren, Berg, Cline, Ding and Kirk

NIMA



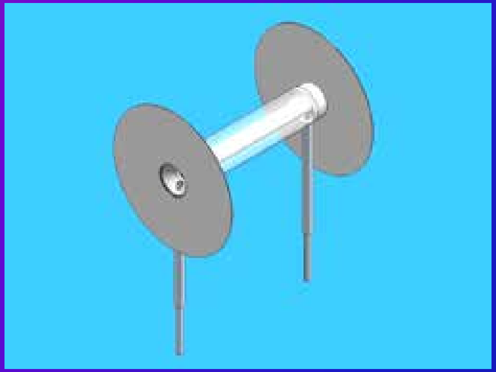


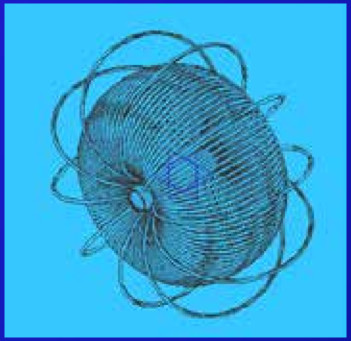
Final Cooling

Very brief description of options

Lithium Lens for Muon Final Cooling

Initial Design of Liquid Li Lens

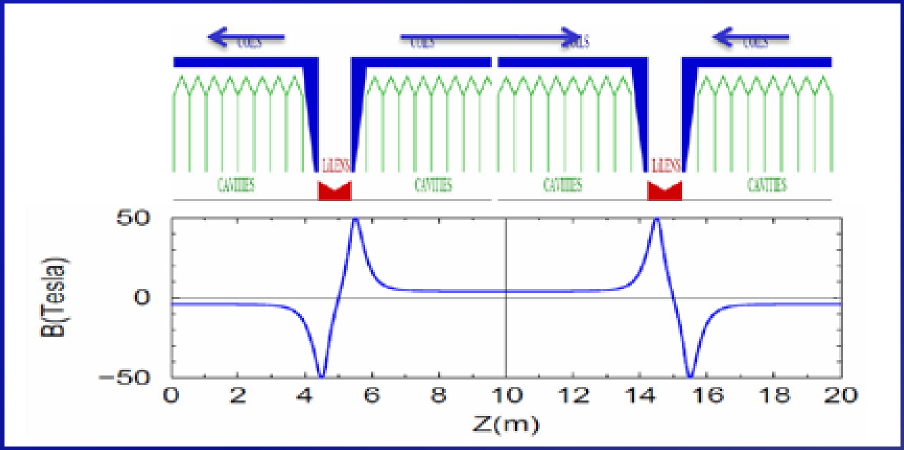




- Lens assembly w/ current discs and the primary and secondary coils
- Li D = 2.54 cm; L = 30.0 cm
- Some cooling achieved in sim, but
- Much more work to be done

Kevin Lee *et al.*
UCLA

Li Lens with high-field solenoids



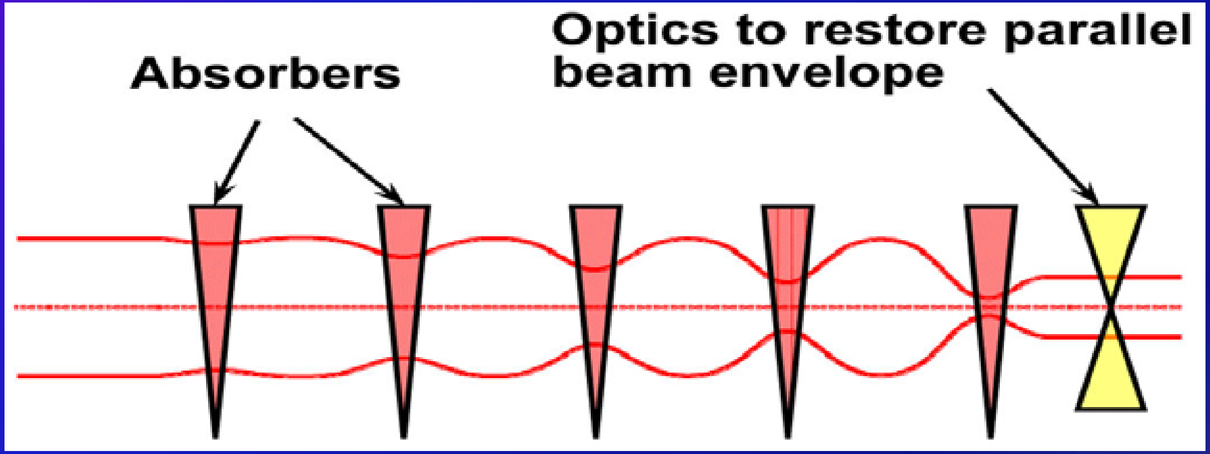
Red - Li lenses for cooling.

Blue - Solenoid coils and field for adiabatic matching.

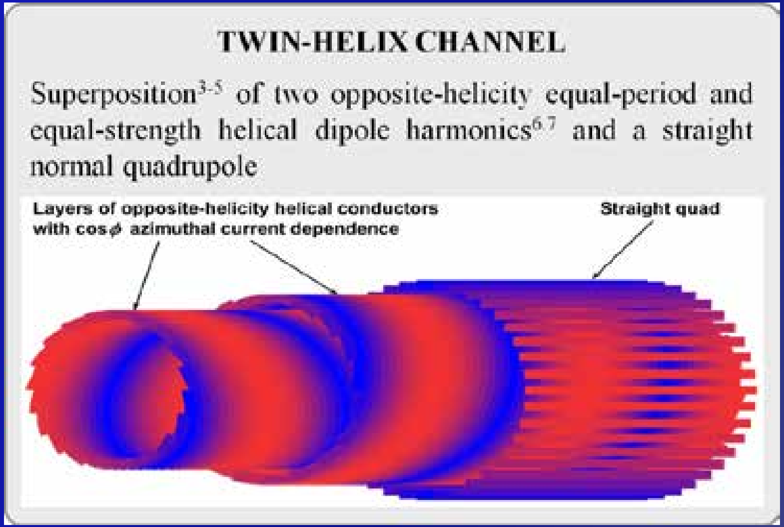
Green - RF cavities (linac) of 100 – 200 MHz, 10 – 12 MeV/m.

Valeri Balbekov
Fermilab
See his poster

Epicyclic twin-helix channel



- Outgrowth/extension of the concept of Parametric-Ionization-Cooling (PIC) for final cooling
- Includes LH_2 wedge absorbers
- Short RF cavities after wedges



For the details see Vasiliy Morozov's (JLAB) poster

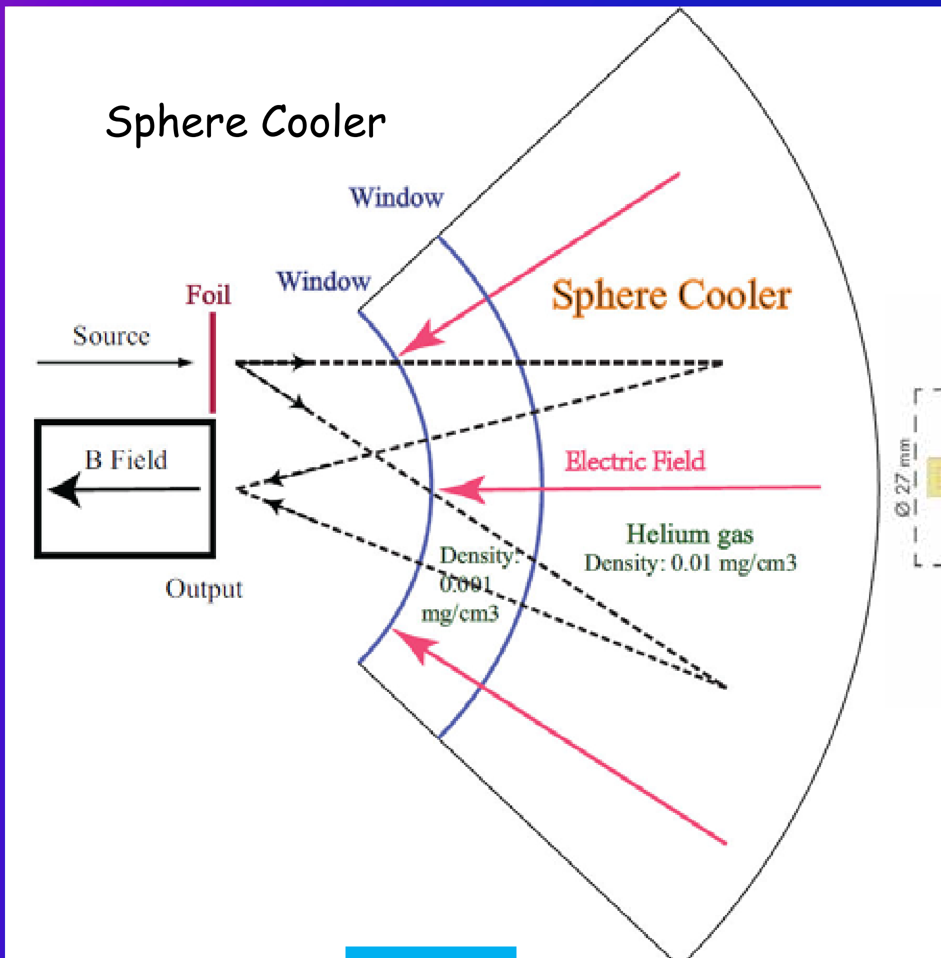
A different cooling Paradigm

Frictional Cooling

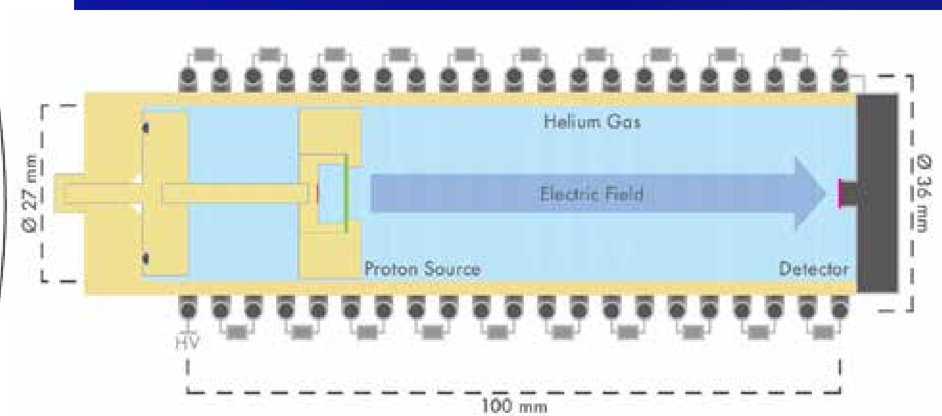
Frictional Cooling

- Frictional cooling has long been known to be capable of producing very low emittance beams
- The problem is that frictional cooling only works for very low energy particles, and its input acceptance is quite small in energy:
  - Antiprotons: KE < 50 keV
  - Muons: KE < 10 keV
- Key Idea:
- Make the particles climb a few Mega-Volt potential, stop, and turn around into the frictional cooling channel. This increases the acceptance from a few keV to a few MeV.
- So the particles enter the device backwards; they come back out with the equilibrium kinetic energy of the frictional cooling channel regardless of their initial energy.
- Particles with different initial energies turn around at different places.
- The total potential determines the momentum (energy) acceptance.

Frictional cooling cell concepts of Caldwell & *Bao*



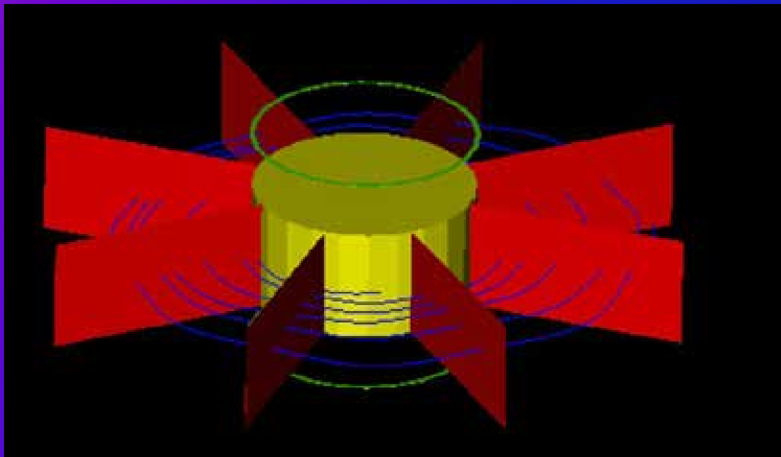
PAC 11



arXiv:1012.3946v1

Muon Cooling With an Inverse Cyclotron

G4beamline model

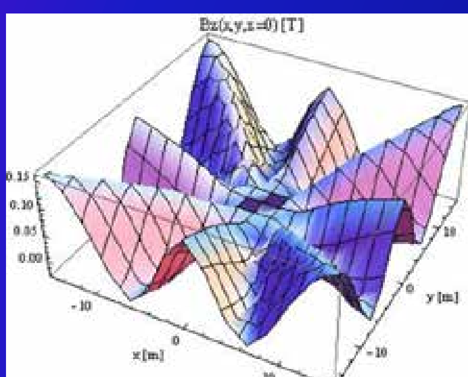


LiH wedges r=15m
He: r = 5m

- Single turn energy loss injection
- Muons spiral in and stop
- - LiH wedges
- - 0.1 bar helium

- Extract muons from helium
  - 0.5 MV/m electric field along +z
- Accelerate muons to 100 MeV
  - 1 MV/m over 100 meters through two guiding solenoids

- Results: See Terry Hart's poster



Outer B Field:
8-sector strong focus

Conclusions

- Although the technological challenges of muon ionization cooling for the muon collider are daunting, they are not overwhelming
  - A complete scheme does exist
    - Its performance, based on the assumption that a few technical problems can be solved, is acceptable
  - And the assumption above is not outrageous: The basic technical problems are limited
    - High-gradient RF operation in magnetic field
      - Note: The required RF gradient is easily met in the absence of B in all sections of the cooling system
    - Development of 30-40T solenoids
      - Much progress in the last few years

Conclusions II

Once we solve the RF problem

- The Devil will be in the Details
  - Space charge, collective effects in general
    - Tune shifts
    - Beam loading, etc.
  - Bunch Coalescing in the 6D cooling section
  - Detailed studies of matching in all sections

END

But, their timing could have been better

I find I'm so excited I can barely sit still or hold a thought in my head.
I think it's the excitement only a free-thinking man can feel,
a free-thinking man at the start of
a long journey whose conclusion is uncertain.*

We just missed both the "Pinhead Institute meeting on the Science of Cocktails" and the Telluride Wine Festival

...in MAP for all
...conversations I
...subject
...k the co-Chairs:
...en, Robert Palmer

Thank You

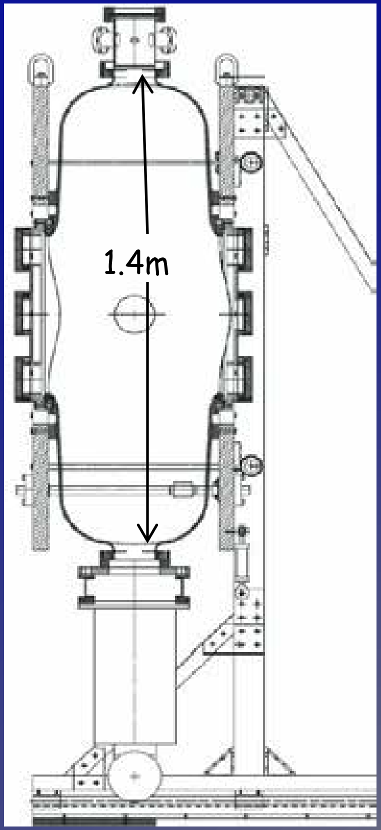
*Apologies to Steven King

Back Up Slides

RF R&D – 201 MHz Cavity Test

Treating NCRF cavities with SCRF processes

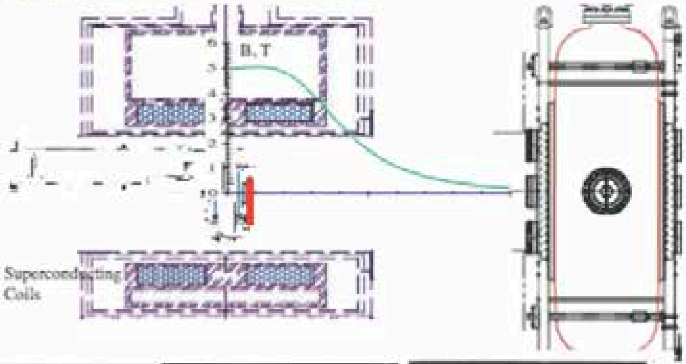
- **The 201 MHz Cavity – *21 MV/m* *Gradient Achieved*** (Design – 16MV/m)
  - *Treated at TNJLAB with SCRF processes – Did Not Condition*



805 MHz Imaging

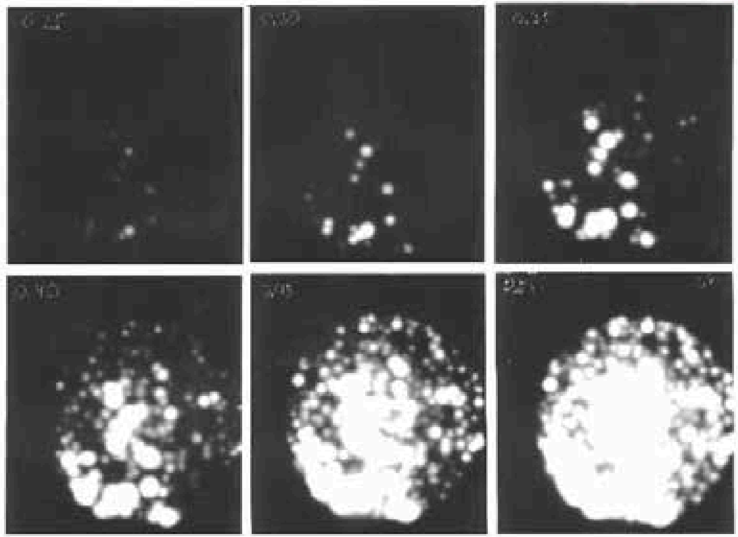
Polaroid Pictures of Field emitters

- Inserting polaroids near the window,



- Gives a picture of how the field emitters change with rf field.

  8.8 - 17.6 MV/m



Quick Overview of Bi 2212
Why the excitement?