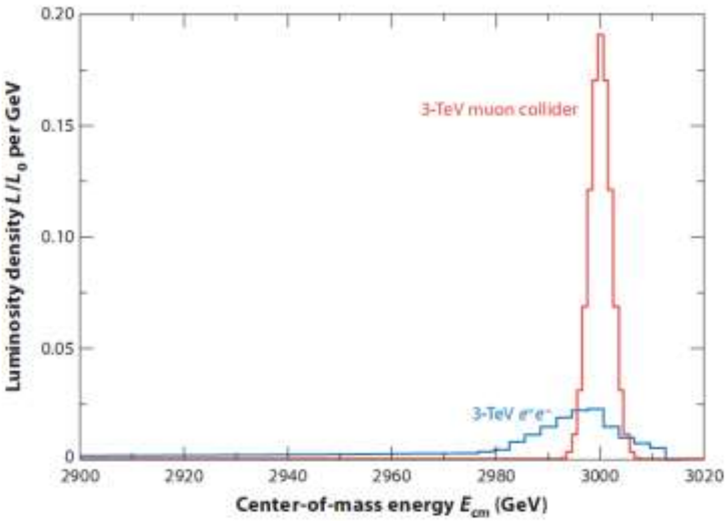
Muon Collider Design Status

Y. Alexahin

Physics Case for a Muon Collider

First (published) considerations:

F.F. Tikhonin, On the Effects with Muon Colliding Beams, JINR Report P2-4120 (Dubna, 1968).



Energy spread in high-luminosity lepton colliders (V. Shiltsev)

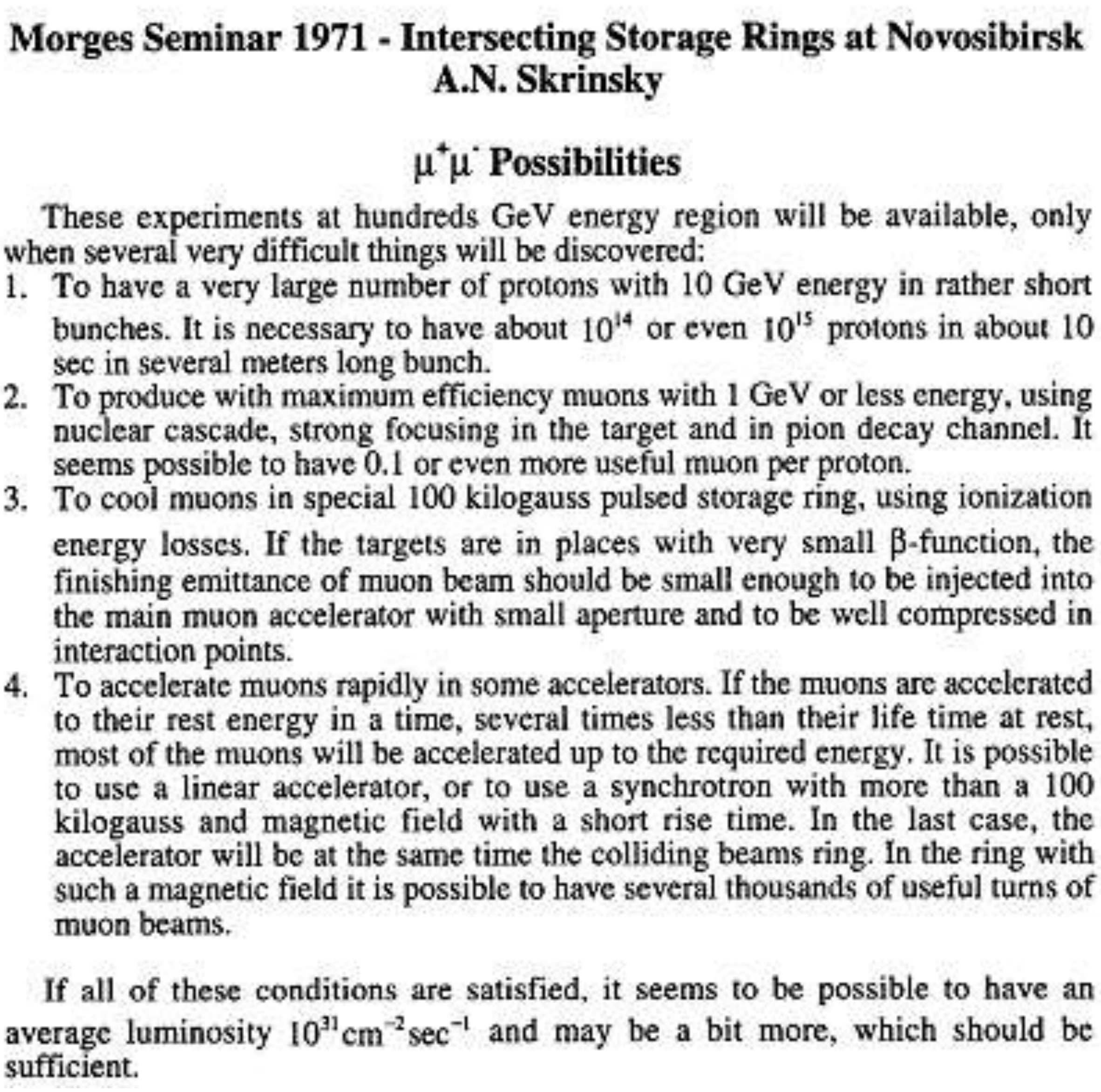
As compared to e+e- collider (CLIC), a muon collider will profit from:

- $(m_\mu / m_e)^2 \sim 4\cdot10^4$ times larger cross-section of s-channel production of scalar particles (including Higgs)
- much smaller c.o.m. energy spread - which will further increase production rate of narrow resonances - thanks to practical absence of
  - beamstrahlung - radiation in coherent EM field of opposing bunch
  - quantum fluctuations of bremstrahlung in the field of interacting particle
- much smaller size for the same energy – will fit in the existing sites
- theorists give a lot of arguments which are far beyond my comprehension!

First public mentioning of work on the Muon Collider idea:

G.I. Budker, VII International Conference on High Energy Accelerators (Yerevan, 1969)

Four Cornerstones of a Muon Collider



Morges Seminar 1971 - Intersecting Storage Rings at Novosibirsk
A.N. Skrinsky

$\mu^+\mu^-$ Possibilities

These experiments at hundreds GeV energy region will be available, only when several very difficult things will be discovered:

1. To have a very large number of protons with 10 GeV energy in rather short bunches. It is necessary to have about 10^{14} or even 10^{15} protons in about 10 sec in several meters long bunch.
2. To produce with maximum efficiency muons with 1 GeV or less energy, using nuclear cascade, strong focusing in the target and in pion decay channel. It seems possible to have 0.1 or even more useful muon per proton.
3. To cool muons in special 100 kilogauss pulsed storage ring, using ionization energy losses. If the targets are in places with very small β-function, the finishing emittance of muon beam should be small enough to be injected into the main muon accelerator with small aperture and to be well compressed in interaction points.
4. To accelerate muons rapidly in some accelerators. If the muons are accelerated to their rest energy in a time, several times less than their life time at rest, most of the muons will be accelerated up to the required energy. It is possible to use a linear accelerator, or to use a synchrotron with more than a 100 kilogauss and magnetic field with a short rise time. In the last case, the accelerator will be at the same time the colliding beams ring. In the ring with such a magnetic field it is possible to have several thousands of useful turns of muon beams.

If all of these conditions are satisfied, it seems to be possible to have an average luminosity 10^{31}cm^{-2}sec^{-1} and may be a bit more, which should be sufficient.

p-driver

Front-end

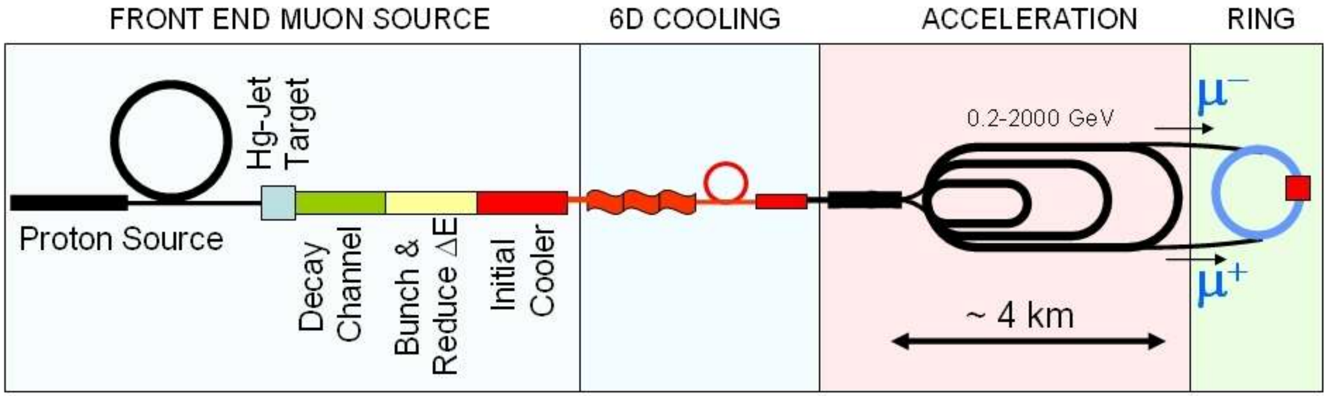
6D ionization cooling followed by final cooling

Muon accelerator

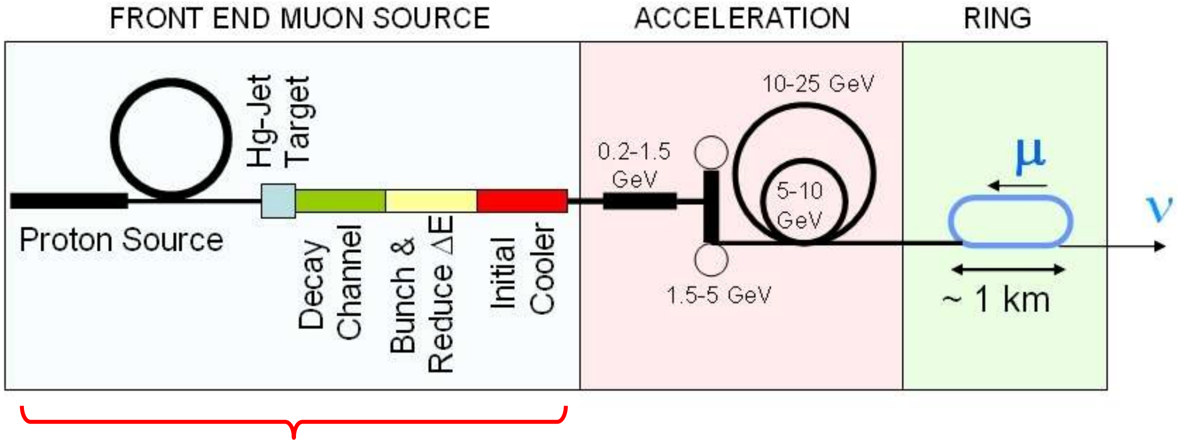
Now we are bold enough to speak about 10^{34}cm^{-2}s^{-1} for 1.5TeV c.o.m. energy

Muon Collider & Neutrino Factory Schemes

MC



NF



Courtesy
of S.Geer

In present baseline design, the NF Front End is ~ same as for MC, otherwise NF is much simpler than MC so I will speak mostly about MC.

Muon Collider Tentative Parameters

$\sqrt{s}$ (TeV)	1.5	3
Av. Luminosity / IP (10^{34}/cm^2/s)	1.25	4
Max. bending field (T)	10	14
Circumference (km)	2.5	4
No. of IPs	2	2
Repetition Rate (Hz)	15	12
Beam-beam parameter / IP	0.09	0.09
β^* (cm)	1	0.5
Bunch length (cm)	1	0.5
No. of bunches / beam	1	1
No. of muons / bunch (10^{12})	2	2
Norm. Trans. Emit. (μm)	25	25
Energy spread (%)	0.1	0.1
Momentum compaction factor	-1.5e-5	
μ+ in collision / 8 GeV proton	0.01	0.008
8 GeV proton beam power (MW)	4	4

$$\langle \mathcal{L} \rangle = f_0 \frac{n_b N_\mu^2}{4\pi\varepsilon_\perp \beta^*} h \times \frac{1}{2}\tau f_{rep} \sim \frac{P_\mu \xi}{C\beta^*} h\tau$$

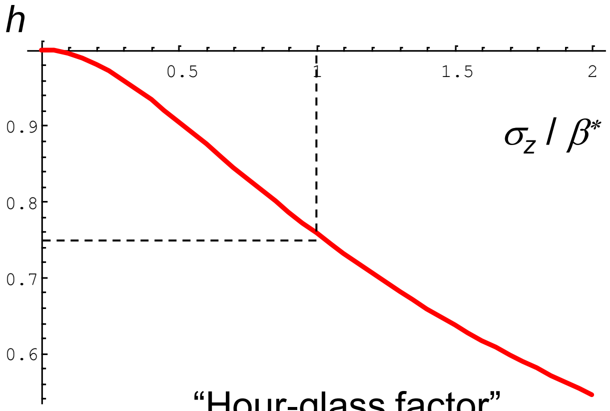
P_μ – average muon beam power (~ γ)

$$\xi = \frac{r_\mu N_\mu}{4\pi\gamma\varepsilon_\perp}$$ – beam-beam parameter

C – collider circumference (~ γ if B=const)

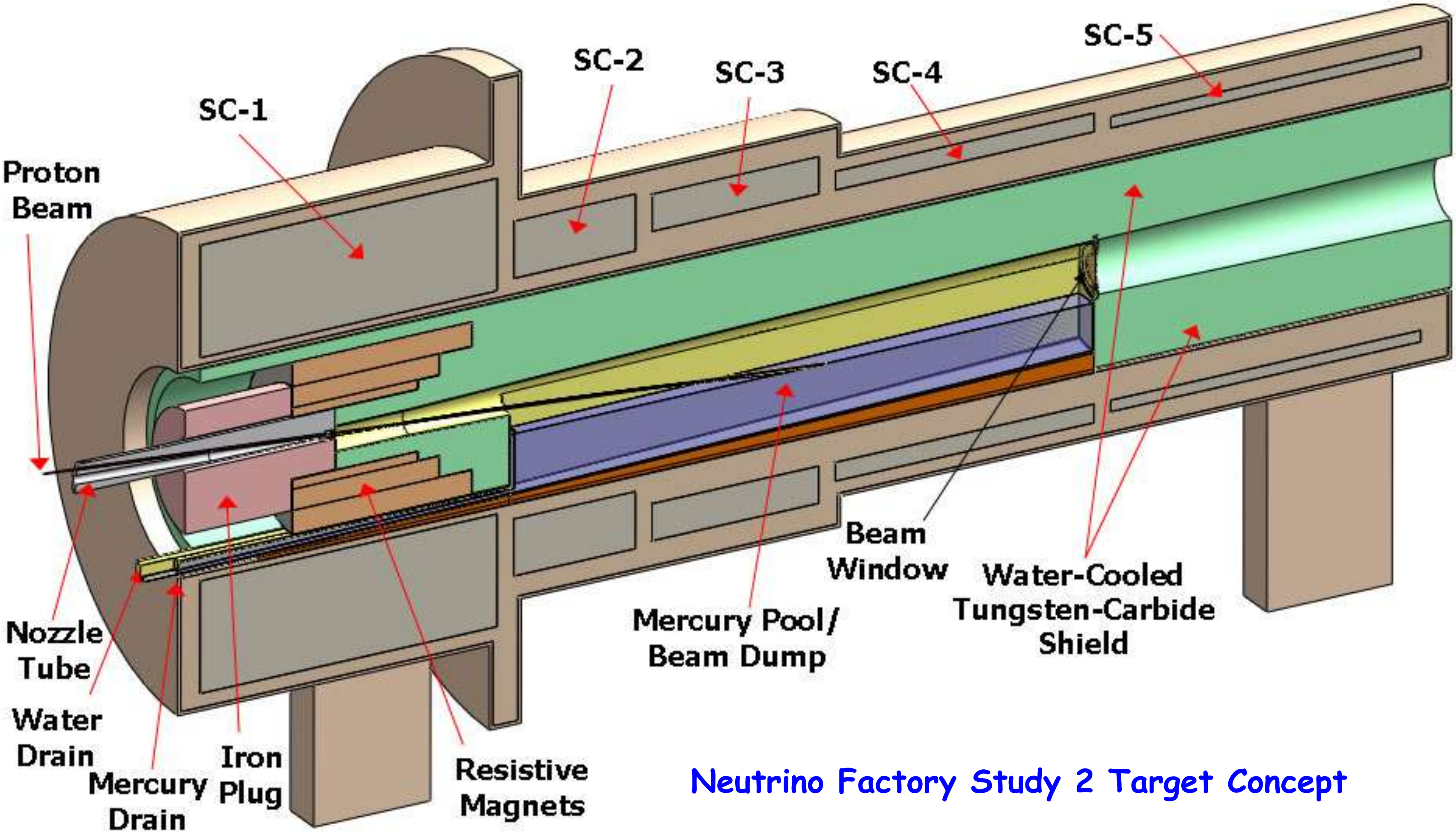
τ – muon lifetime (~ γ)

β^* – beta-function at IP



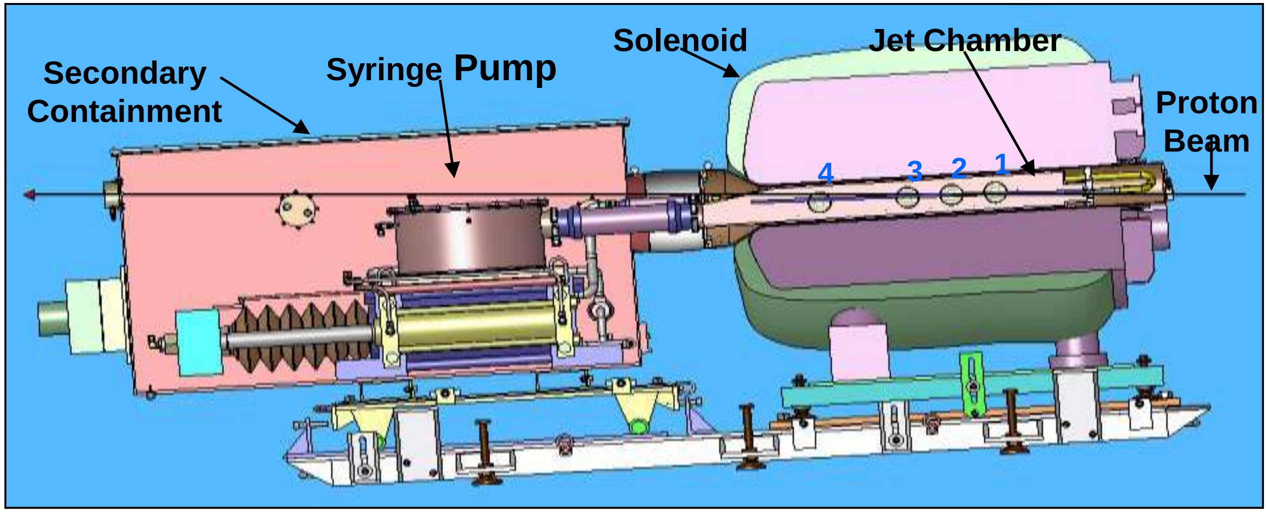
“Hour-glass factor”

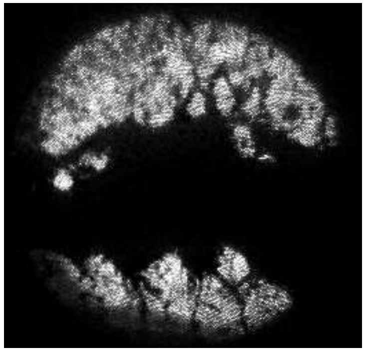
Pion Production



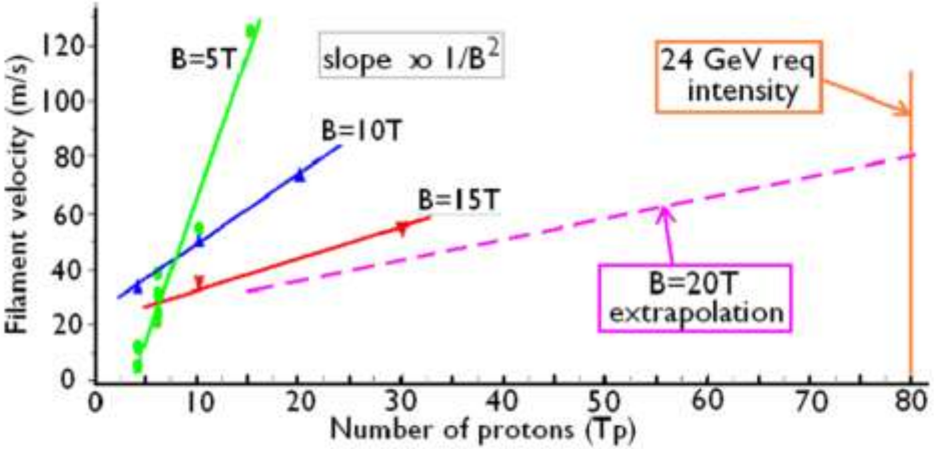
Neutrino Factory Study 2 Target Concept

MERIT Experiment @ CERN (2008)



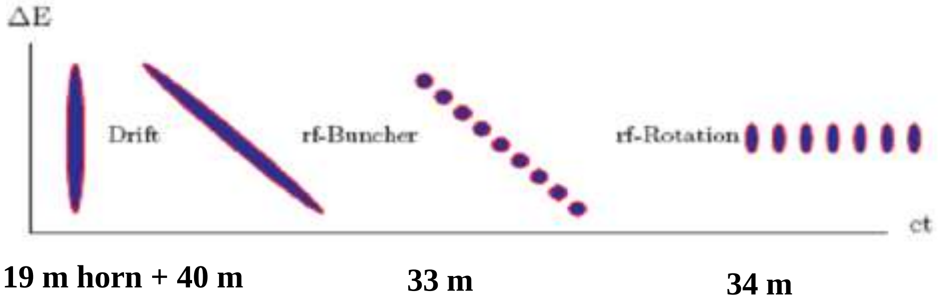


Hg jet @WP4 after impact of 8e12 24GeV protons in 10T field



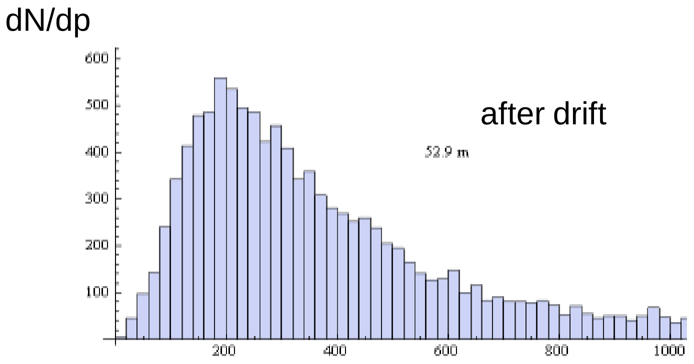
Observed Hg filament velocities and extrapolation to 20T field

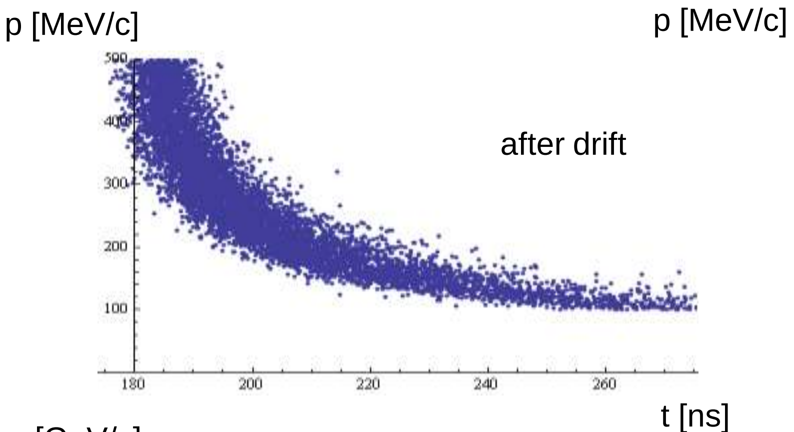
Front End Scheme (D. Neuffer)

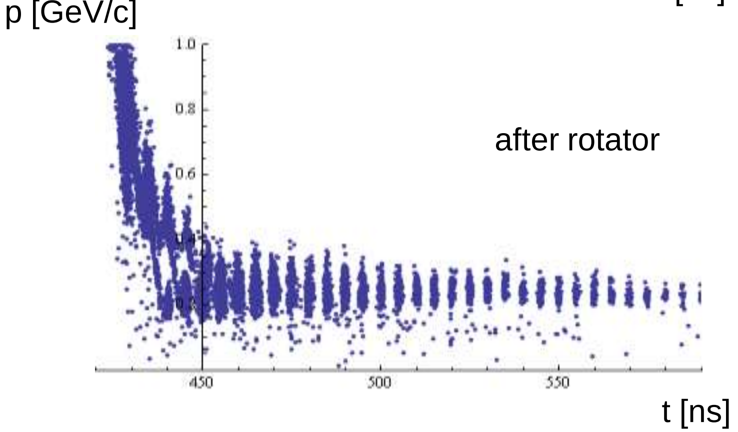


RF phase velocity in buncher and rotator varies with time – achieved by using RF cavities of ~30 different frequencies (360MHz → 201.5MHz)

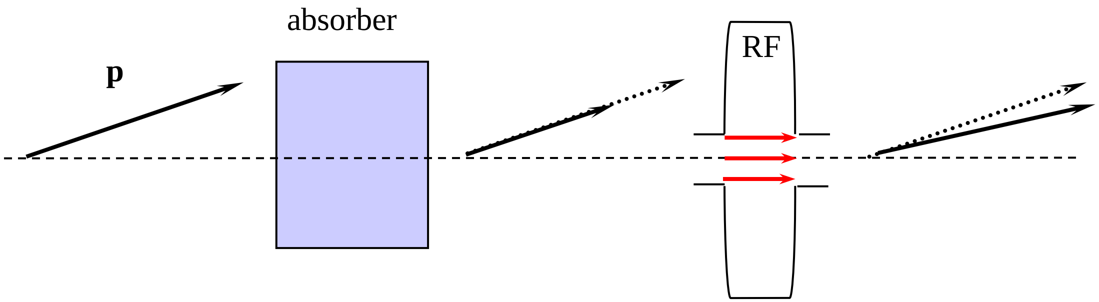
The front end yield in 150 MeV/c < p < 300 MeV/c is ~ 0.2 μ+ / 8GeV p in all bunches, number of μ- is slightly higher

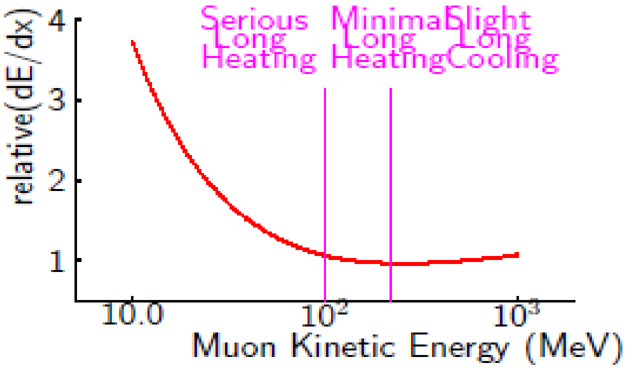




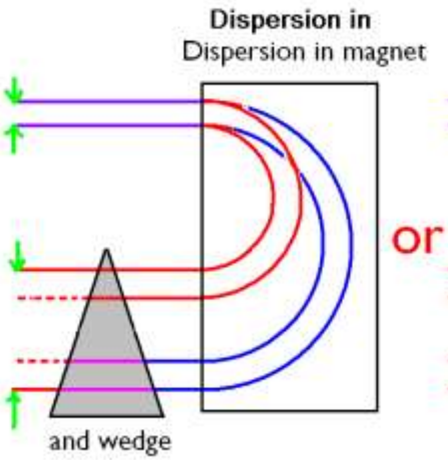


Principle of Ionization Cooling

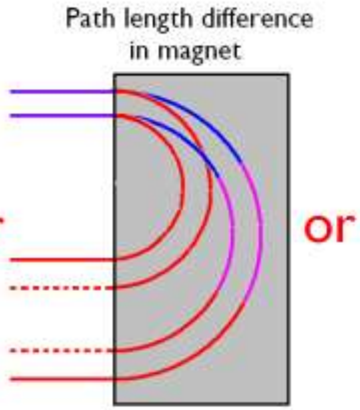




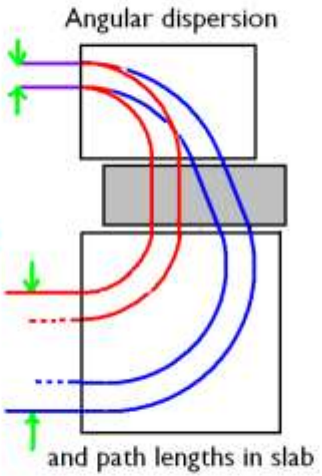
At p < 300MeV/c only transverse cooling naturally happens (4D cooling), longitudinal cooling can be obtained by curving the trajectories:



“Guggenheim”

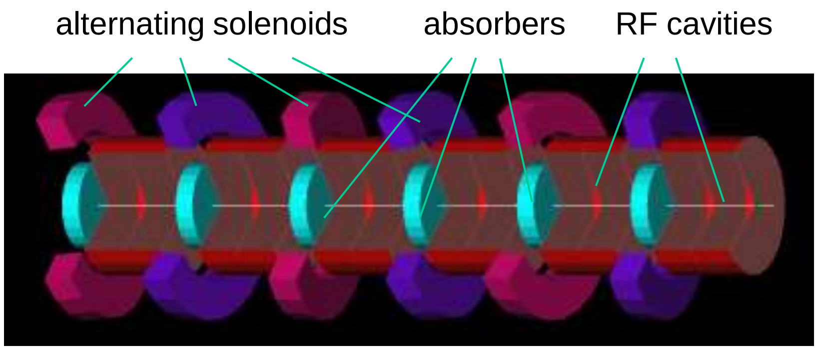


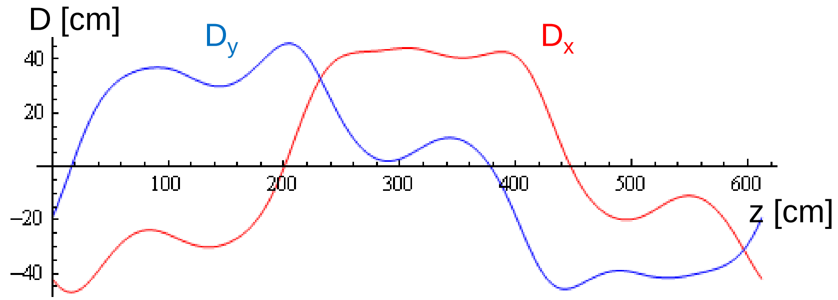
Helical Cooling Channel

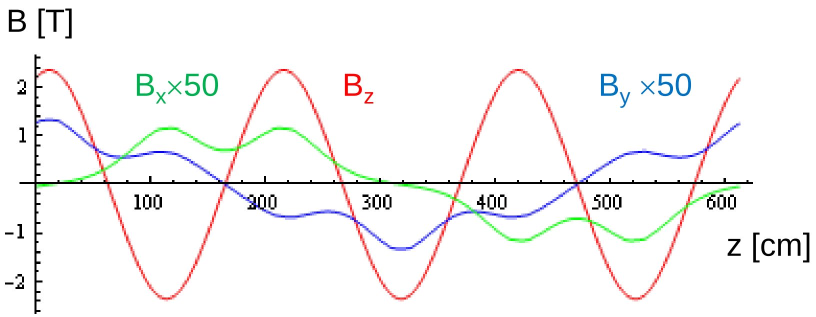


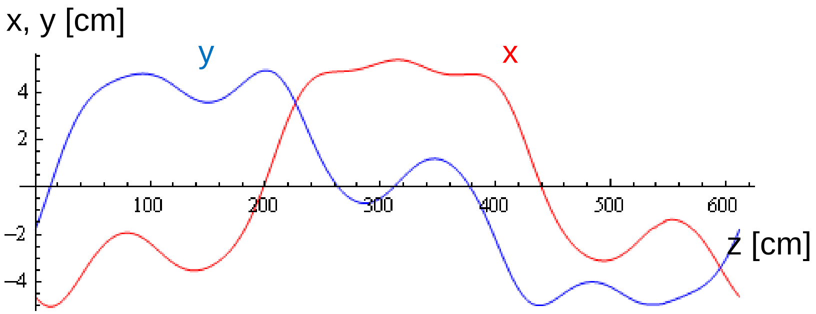
FOFO snake

FOFO Snake – Initial 6D Cooling (Y.Alexahin)

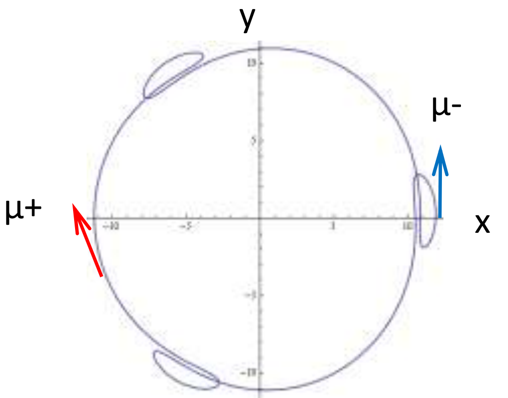




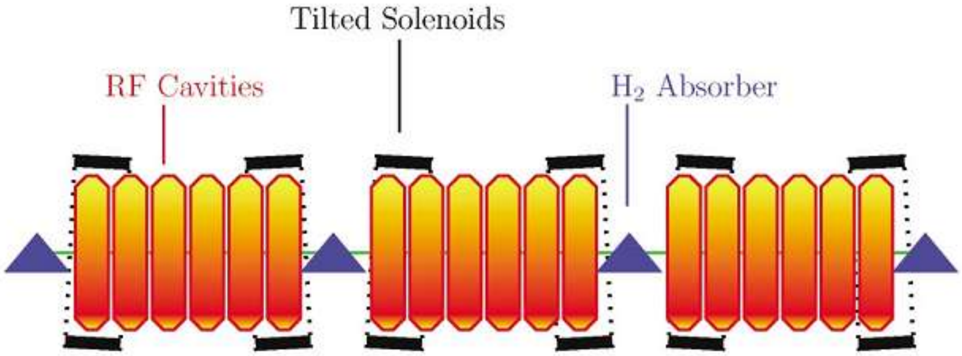


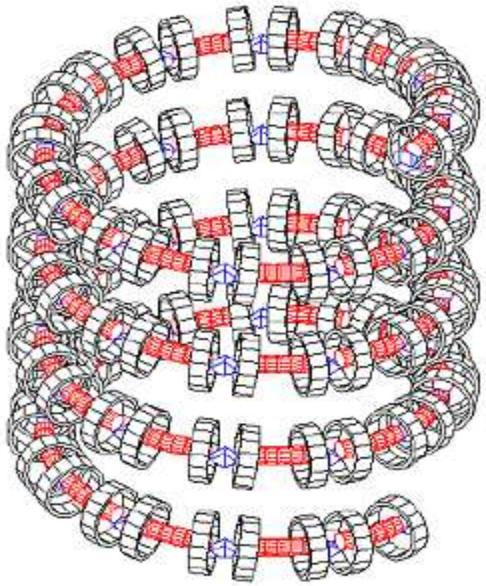


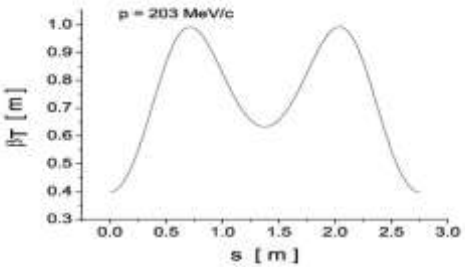
- Cools both μ+ and μ- simultaneously
- Large at $< \beta_\perp >$ ~ 70cm at absorbers →
- 1st stage gives $\varepsilon_\perp$ = 6 mm, $\varepsilon_{||}$ = 10 mm
- 2nd stage can give $\varepsilon_\perp$ = 4 mm, $\varepsilon_{||}$ = 6 mm

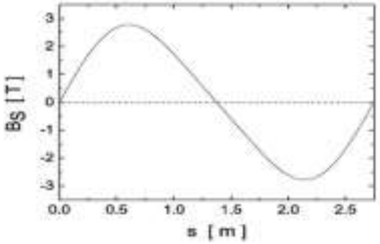


"Guggenheim" RFOFO Channel (V. Balbekov, R. Palmer)





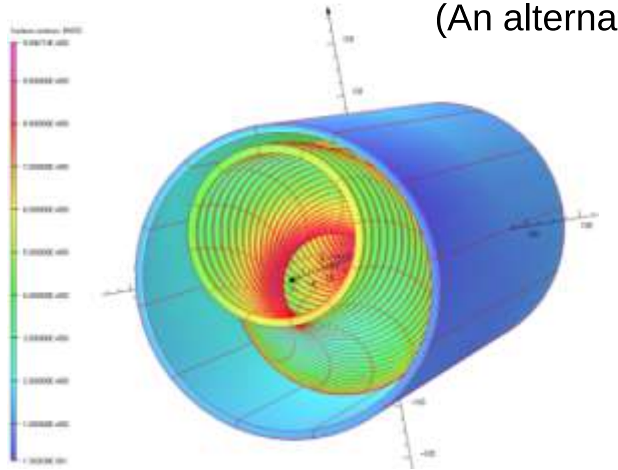




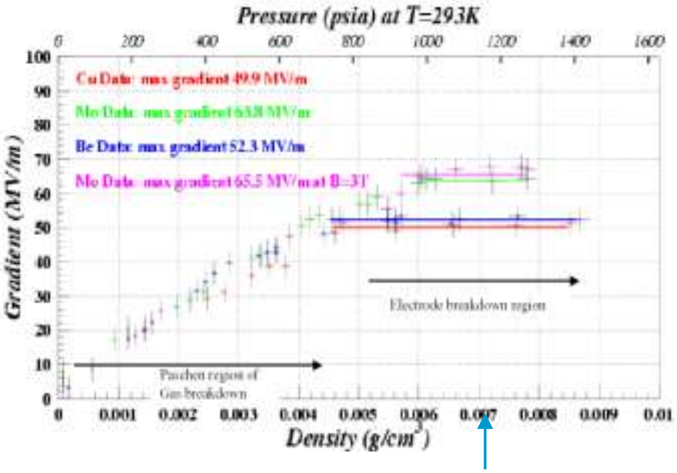
- μ+ and μ- cooled in separate channels
- 3 stages (200, 400 and 800 MHz) give $\varepsilon_\perp$ = 0.4 mm, $\varepsilon_{||}$ = 1 mm
- Transmission ~ 30% (including recooling after merging)
- MICE (4D cooling in straight channel) is under construction at RAL
- Requires RF is strong magnetic field (15MV/m in 3T for 200 MHz)

Helical Cooling Channel (Y. Derbenev, R. Johnson)

(An alternative to Guggenheim RFOFO)

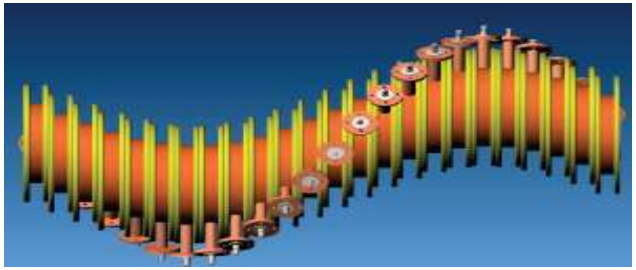


Two opposing solenoids – helical and straight – provide a right combination of longitudinal and rotating dipole fields



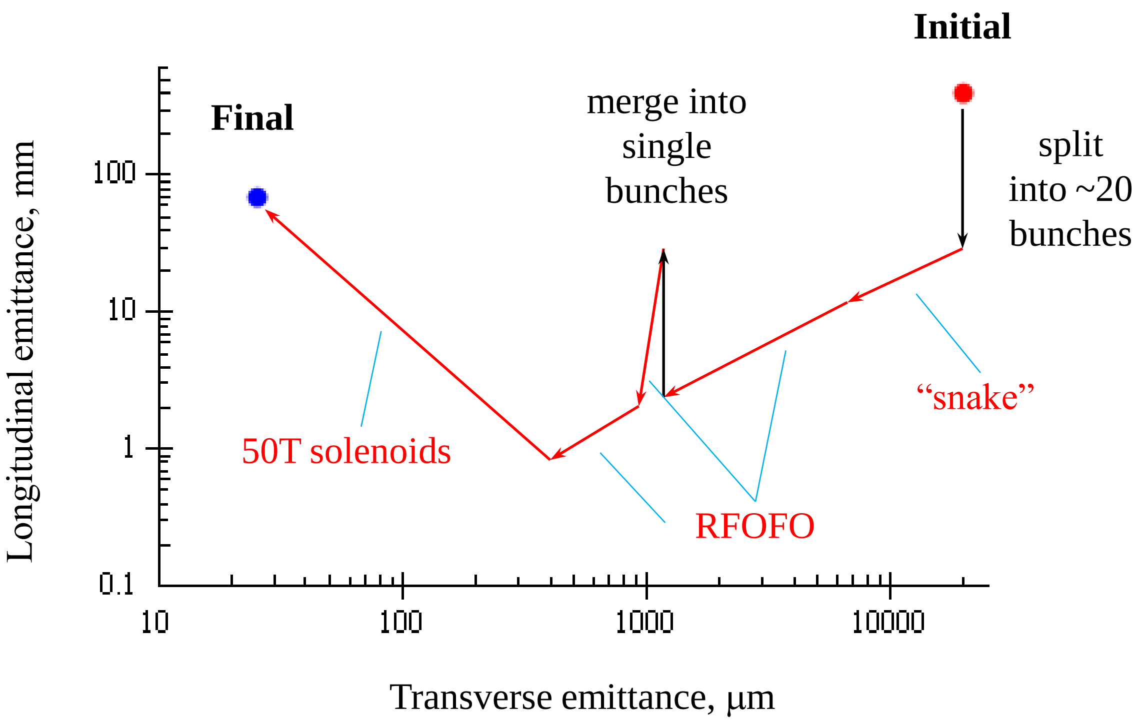
10% of liquid H_2

- No polarity flips:
  - higher average Bz → low < $\beta_\perp$ >
  - resonance-free → better transmission
- Cooling by homogeneous H_2 → RF breakdown suppressed
- 3 stages give $\varepsilon_\perp$ = 0.35 mm, $\varepsilon_{||}$ = 1 mm
- Gas filled RF in presence of strong ionization – will SF_6 help? Experiment is planned for next year.



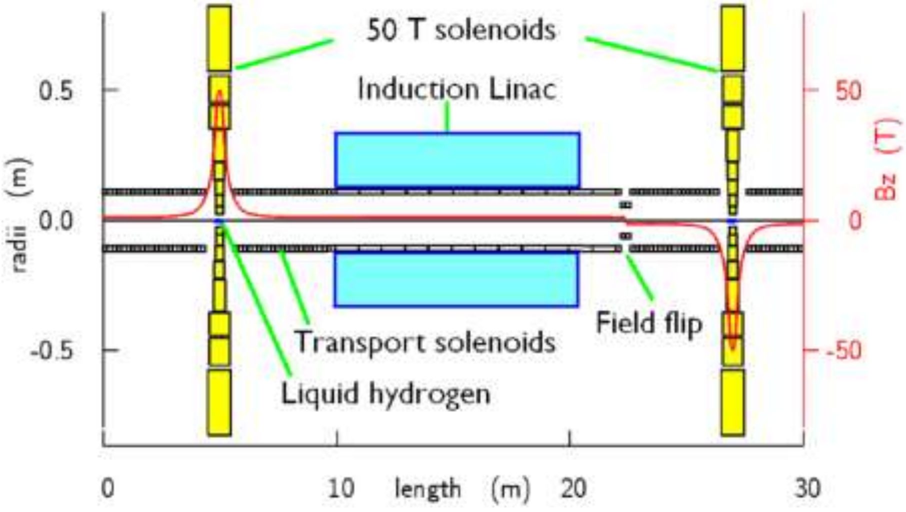
Incorporating RF into the helical solenoid is a major problem

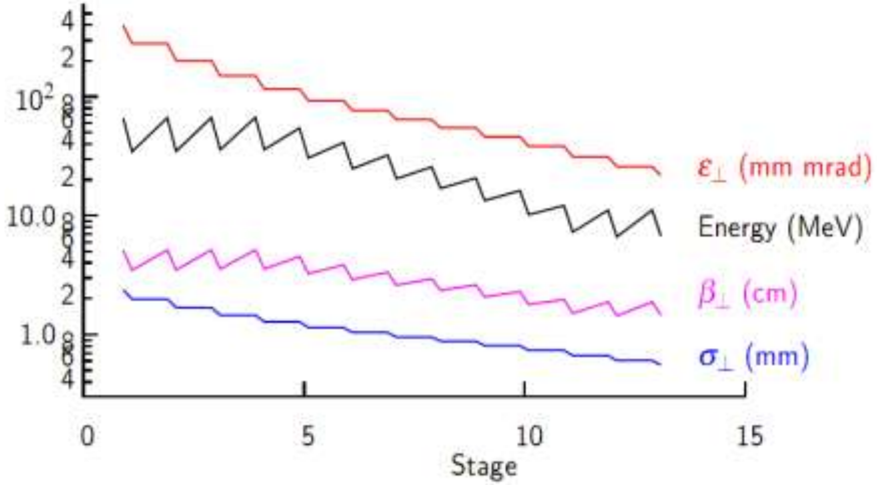
Emittance Evolution

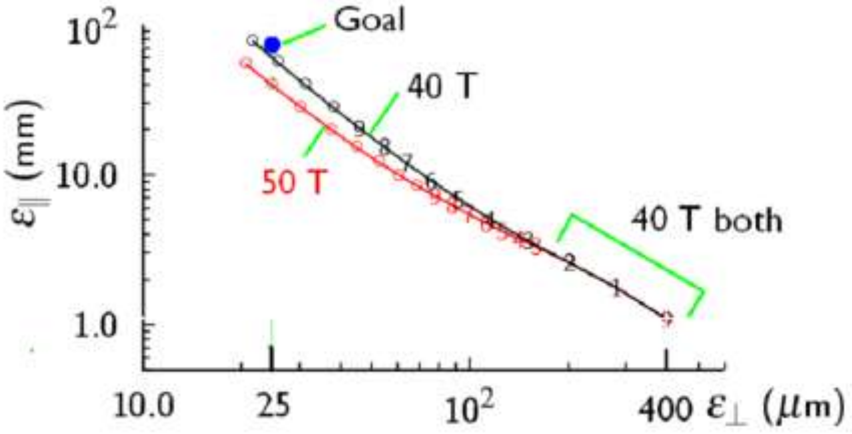


Final normalized emittances:
$\varepsilon_{\perp}$ = 25 µm, $\varepsilon_{||}$ = 70 mm

Final Cooling in 50T Solenoids (R. Palmer)



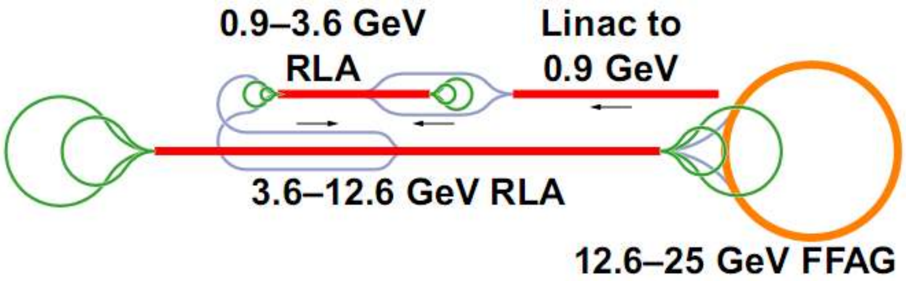




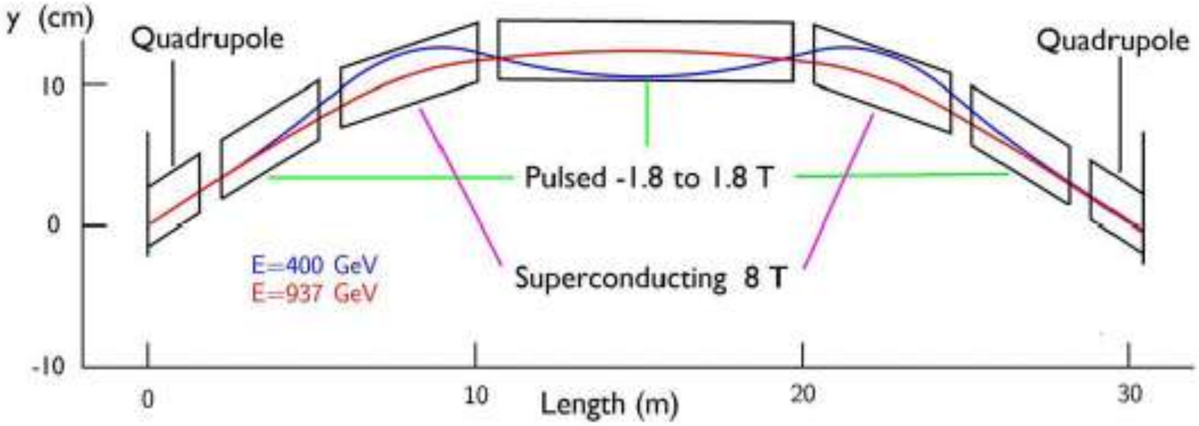
Very low energy (<10 MeV) is necessary to attain low emittance → Landau tails

40 T is sufficient to achieve the goal, but higher B → higher energy → better transmission

Muon Acceleration

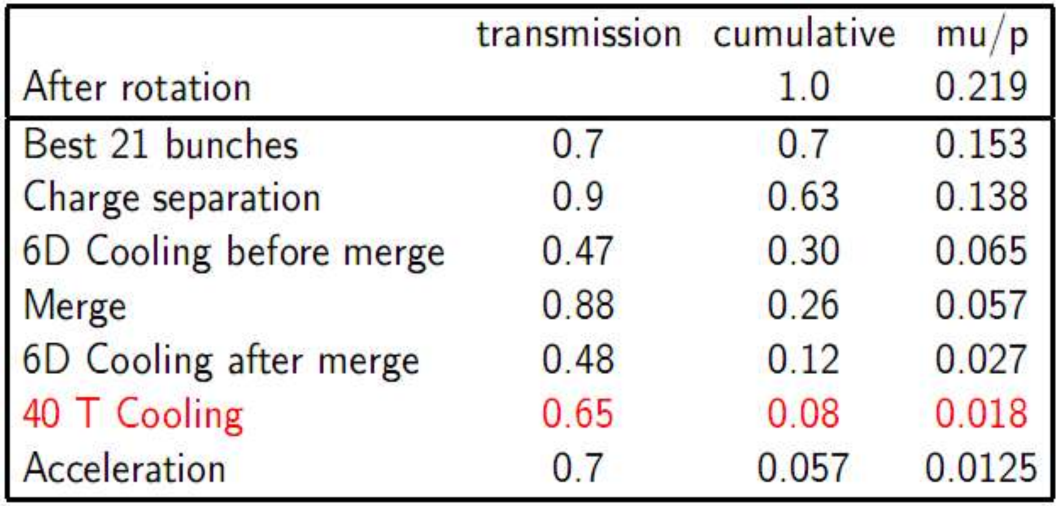


NF accelerator chain



Half-cell of RCS lattice for high-energy acceleration in MC

Efficiency of Different Stages (R.Palmer)



	transmission	cumulative	mu/p
After rotation		1.0	0.219
Best 21 bunches	0.7	0.7	0.153
Charge separation	0.9	0.63	0.138
6D Cooling before merge	0.47	0.30	0.065
Merge	0.88	0.26	0.057
6D Cooling after merge	0.48	0.12	0.027
40 T Cooling	0.65	0.08	0.018
Acceleration	0.7	0.057	0.0125

Based on simplified simulations the required p-driver power is 3.1MW

Muon Collider Ring Challenges

What we would like to achieve compared to other machines:

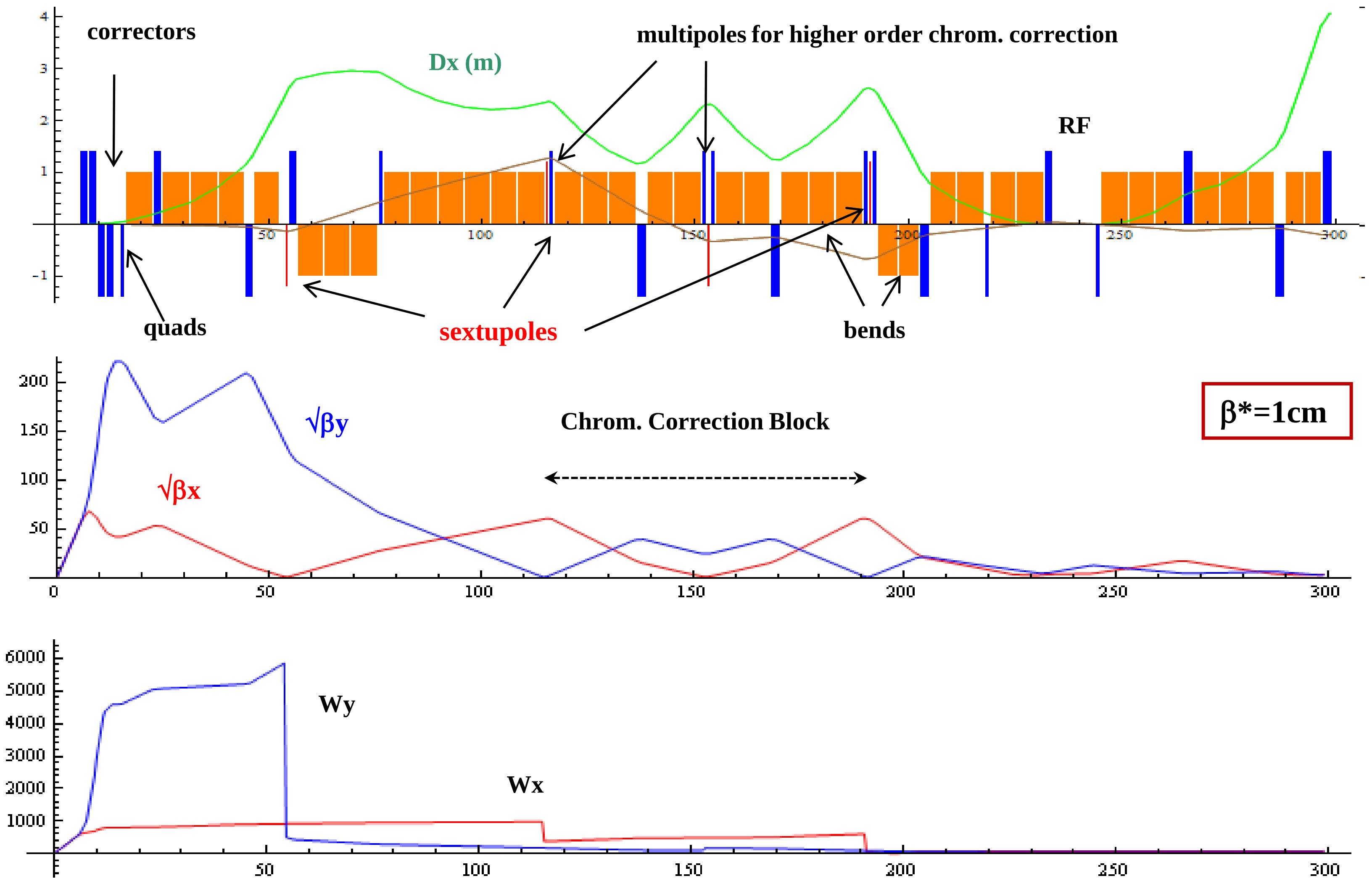
	MC	Tevatron	LHC
Beam energy (TeV)	0.75	0.98	7
β^* (cm)	1	28	55
Momentum spread (%)	0.1	<0.01	0.0113
Bunch length (cm)	1	50	15
Momentum compaction factor (10^-3)	0.015	2.3	0.322
Geometric r.m.s. emittance (nm)	3.5	3	0.5
Particles / bunch (10^11)	20	2.7	1.15
Beam-beam parameter, ξ	0.1	0.025	0.01

Muon collider is by far more challenging:

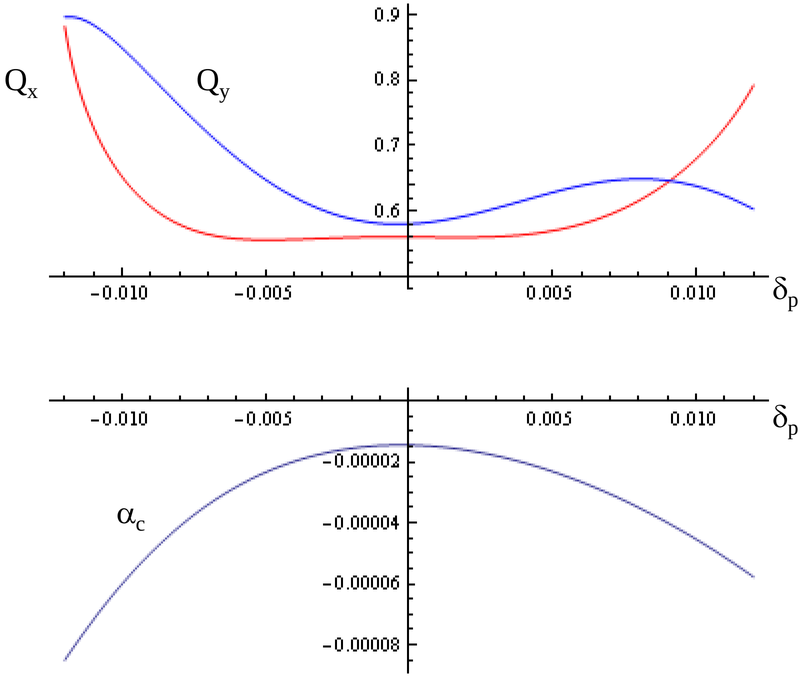
- much larger momentum acceptance with much smaller β^*
- ~ as large Dynamic Aperture (DA) with much stronger beam-beam effect

\- **New ideas for IR magnets chromaticity correction needed!**

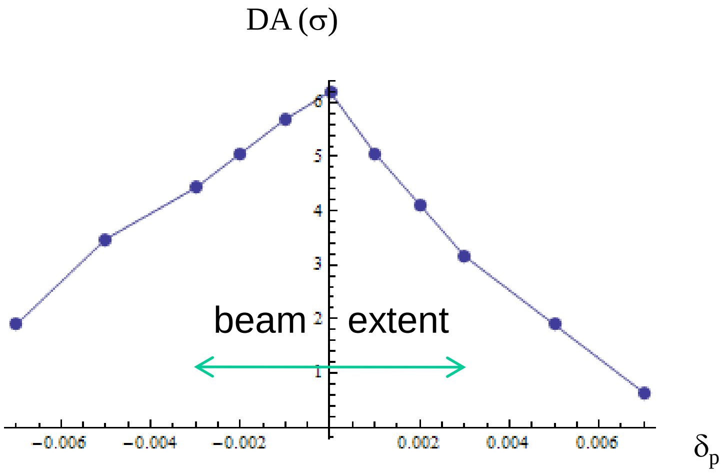
Muon Collider IR



Muon Collider Lattice Performance



Fractional parts of the tunes and momentum compaction factor vs. momentum deviation



“Diagonal” Dynamic Aperture (Ax=Ay) vs. (constant) momentum deviation in the presence of beam-beam effect (ξ = 0.09/IP) for normalised emittance $\varepsilon_{\perp N}$=25 μm

Only muons at bunch center tracked !

US National Muon Accelerator Program

- “A concerted national R&D program that addresses the technical challenges and feasibility issues relevant to … future Neutrino Factory and multi-TeV Muon Collider facilities” was created in 2010
- 214 participants at birth (~31 FTE) from 14 institutions:
  - ANL, BNL, FNAL, Jlab, LBNL, ORNL, SLAC, Cornell, IIT, Princeton, UCB, UCLA, UCR, U-Miss
- Milestones :
  - Neutrino Factory RDR (Reference Design Report) in 2013
  - Muon Collider Initial Configuration in 2012
  - MC Interim Design Feasibility Study Report in 2014
  - end-to-end simulation of a MC complex, and a MC feasibility assessment and cost range in 2016
- Fermilab is the leading laboratory which will host the complex
- Funding request ~15 M$/year (up from 10 M$ in FY2010)
- DoE review in August 2010 approved the MAP proposal

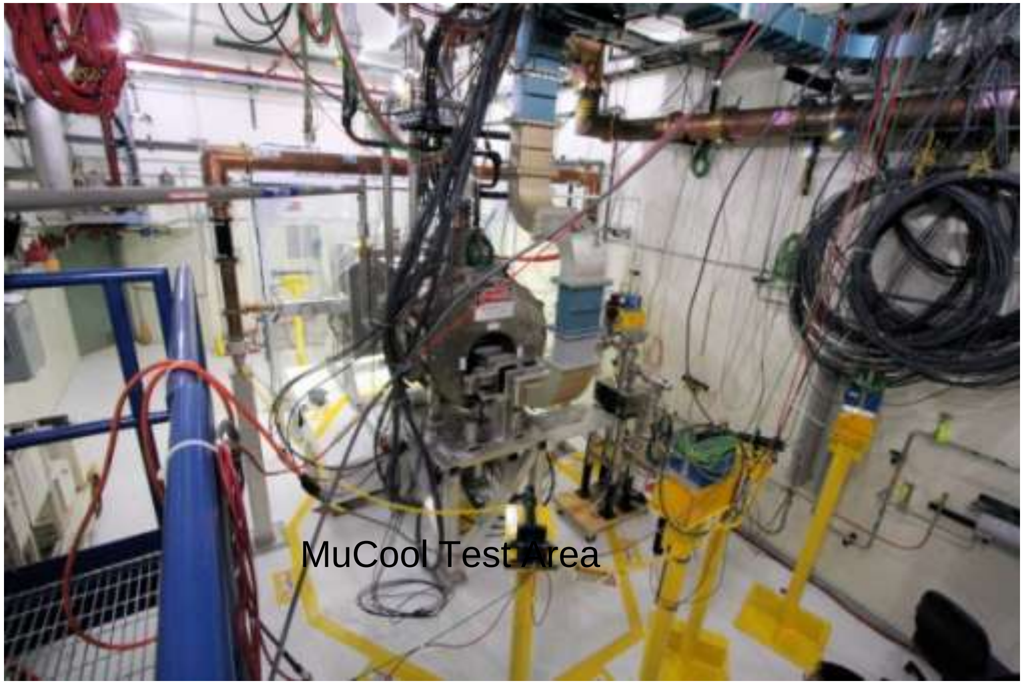
http://map.fnal.gov/

Critical Issues and R & D Activities

To prove the MC feasibility MAP must solve the problems with

- High-gradient RF in strong magnetic field
  - experiments are underway at Fermilab MuCool test area
- Magnets:
  - HTS for 50T Final Cooling Solenoids and 20 T capture solenoids - VHFSMC
  - Open midplane IR dipoles (arc dipoles?) - Fermilab & BNL
  - 1.8 T fast ramping magnets for RCS - U_Miss
- LH2 absorber @ high beam energy deposition - MICE collaboration

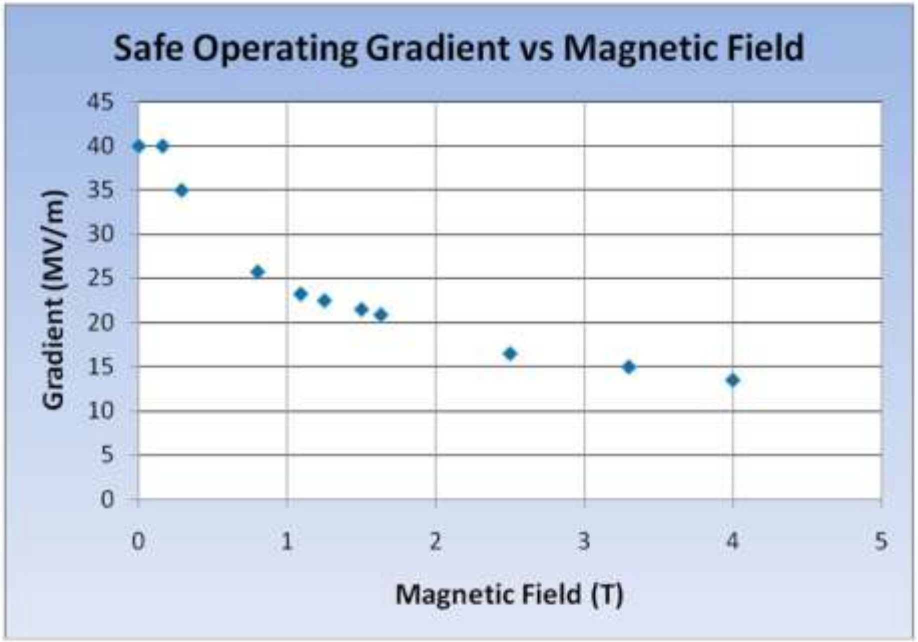
RF Test Facility @ Fermilab



- RF Power:
  - 201 MHz (5 MW)
  - 805 MHz (12 MW)
- Class 100 clean room
- Instrumentation
  - Ion counters, scintillation counters, optical signal, spectrophotometer
- 4T SC Solenoid
  - 250W LHe cryo-plant
- 400 MeV p beam line

RF Breakdown Studies

- 201 MHz Cavity:
  - Achieved 21 MV/m (limited by available RF power)
  - Design – 16MV/m
  - At 0.75T reached 10-12 MV/m (no damage observed)
- 805 MHz Cavity:



Mitigation strategies:

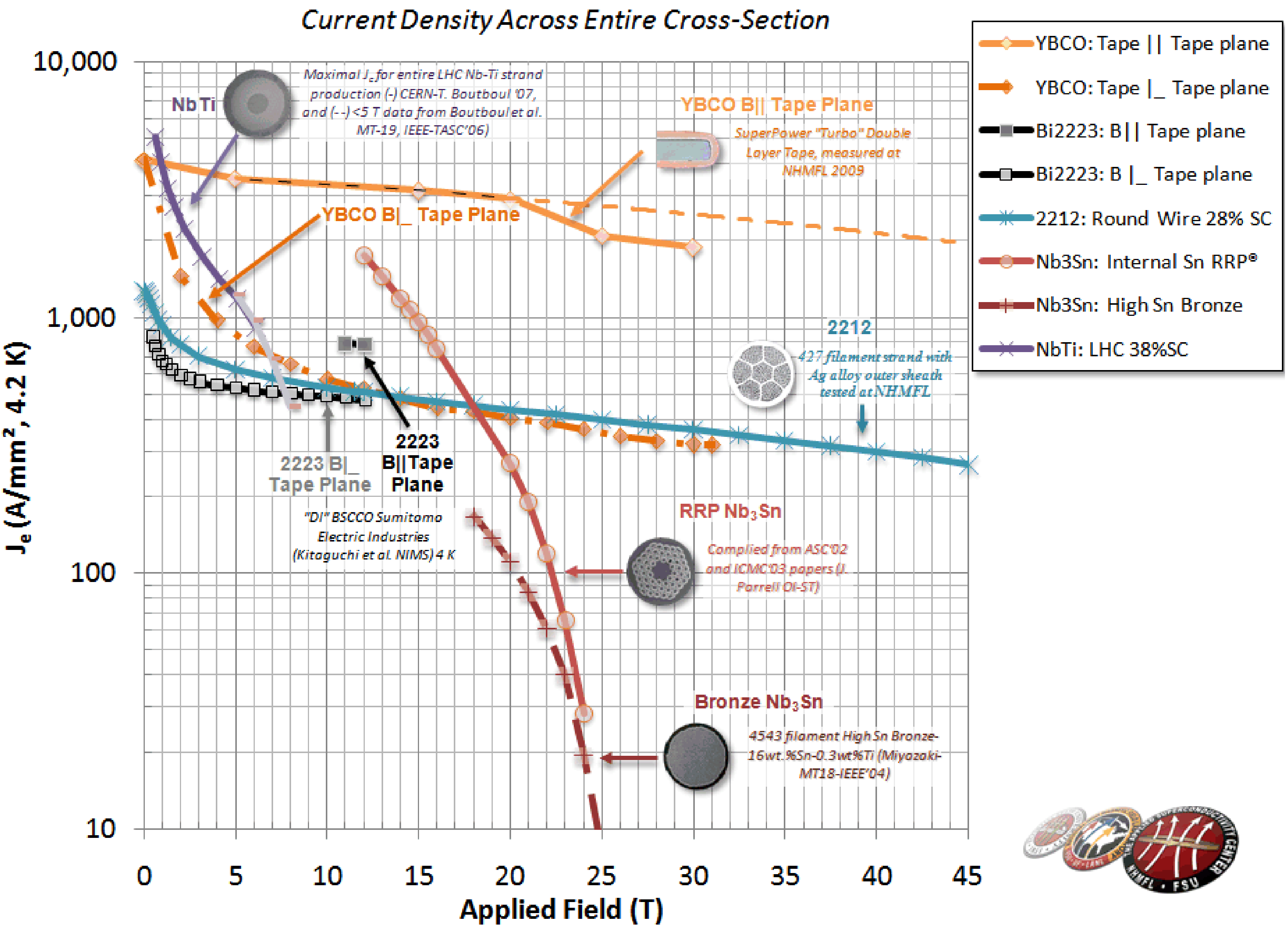
- Be cavity
- Magnetic insulation (~ done)
- Electropolishing & ADL (Atomic Layer Deposition)
- High-pressure H_2-filled cavities

Very High Field Superconducting Magnet Collaboration

National High Magnetic Field Laboratory, Florida State University

- The world’s highest DC magnetic fields
  - 45T DC in hybrid, 32 mm warm bore (28 MW insert providing 34 T)
  - Purely resistive magnets: 36T in 32 mm warm bore, 31 T in 50 mm bore and 19T in 195 mm warm bore (28 MW per magnet may allow 40T)
- 20 MW resistive magnet ~$1000/hr at full power

Current Density in Superconductors vs Magnetic Field



Maximal J_c for entire LHC Nb-Ti strand production (-) CERN-T. Boutboul '07, and (- -) <5 T data from Boutboul et al. MT-19, IEEE-TASC'06)

SuperPower "Turbo" Double Layer Tape, measured at NHMFL 2009

427 filament strand with Ag alloy outer sheath tested at NHMFL

"DI" BSCCO Sumitomo Electric Industries (Kitaguchi et al. NIMS) 4 K

Complied from ASC'02 and ICMC'03 papers (J. Parrell OI-ST)

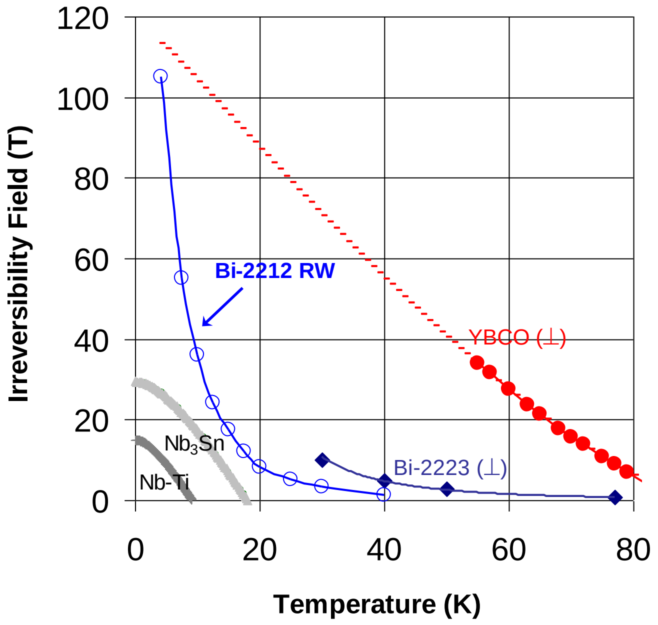
4543 filament High Sn Bronze-16wt.%Sn-0.3wt%Ti (Miyazaki-MT18-IEEE'04)

High-Field Solenoid R&D

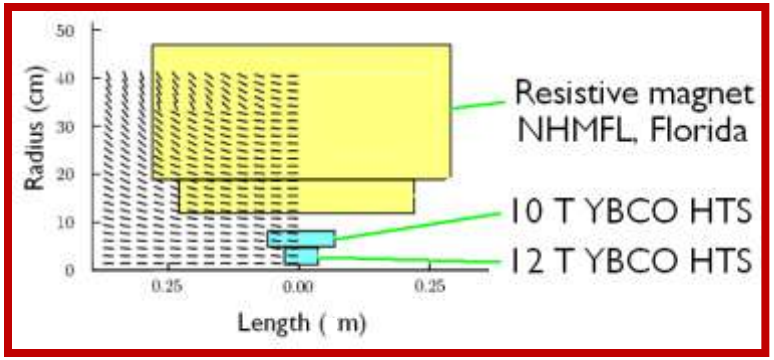
YBCO HTS Solenoid at ~40 T - BNL, PBL (Particle Beam Lasers)

The program

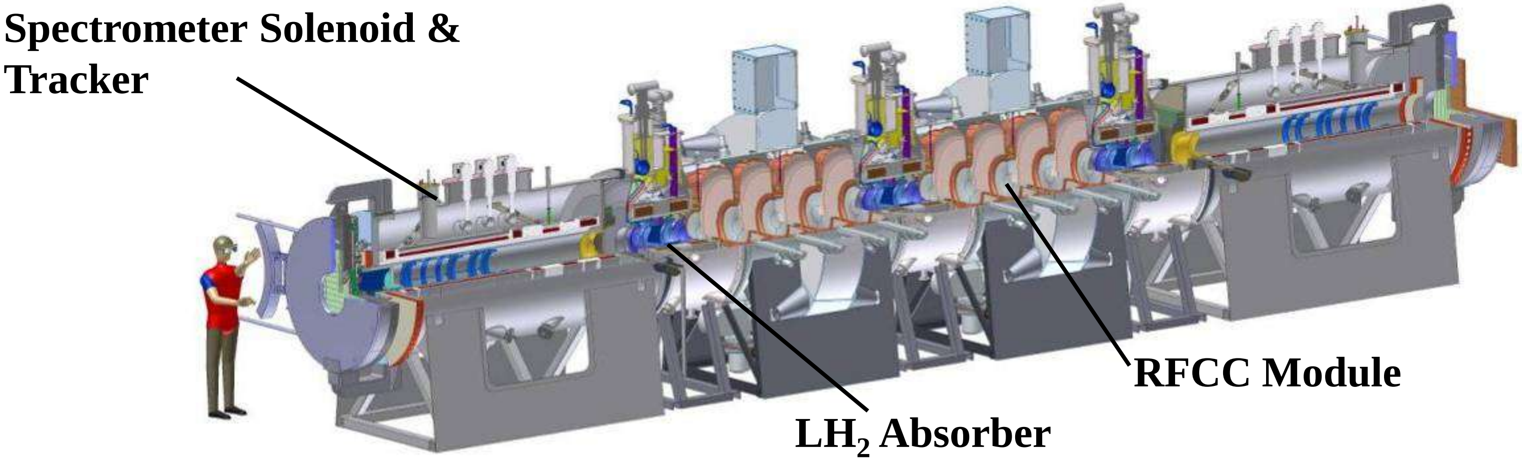
- First Phase 2 SBIR
  - Build 10 T Solenoid 10 cm diameter bore
  - Chose to use YBCO to explore very high current densities – compact
- Second Phase 2 SBIR
  - Build 12 T YBCO Solenoid 2.5 cm diameter bore that fits inside #1
  - Test both solenoids in 19 T magnet at NHMFL

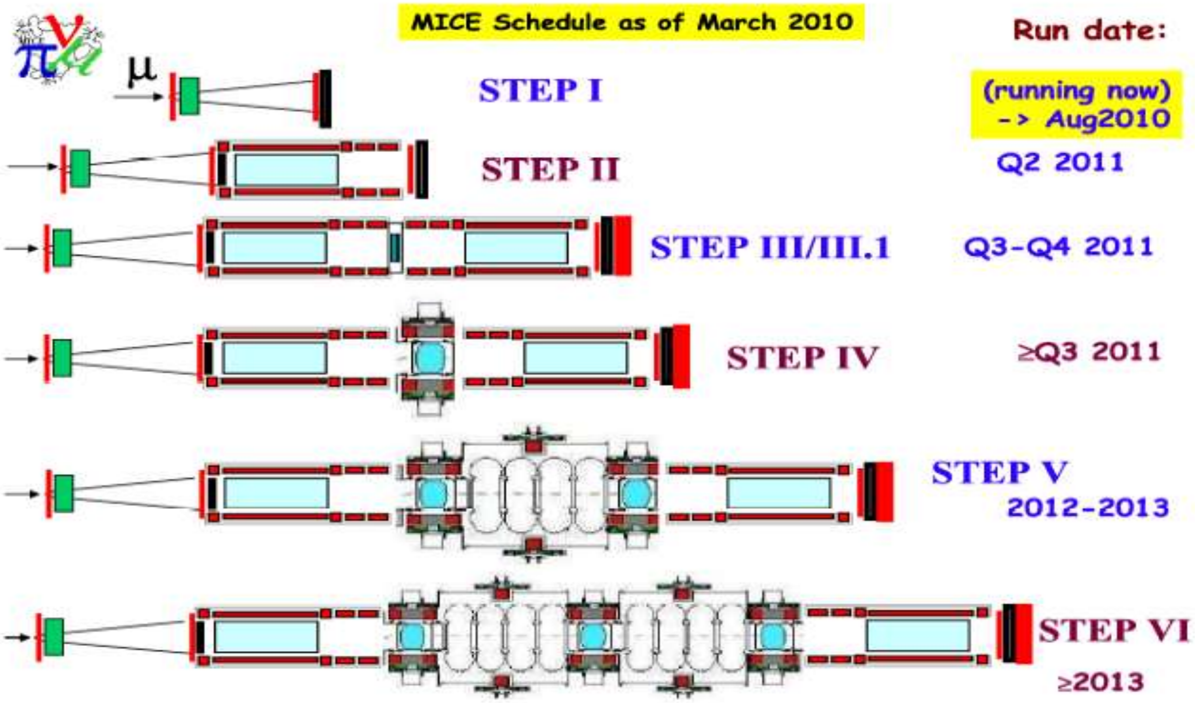


Tests are planned for 2012, if successful – proceed with fully SC magnet design



Muon Ionization Cooling Experiment (MICE)

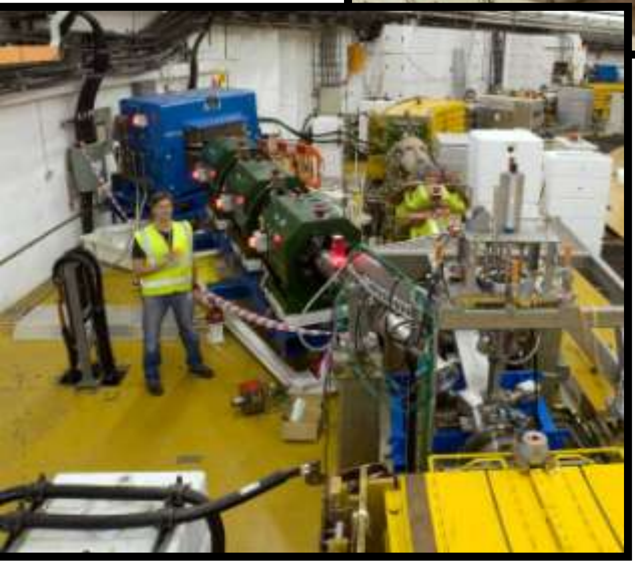


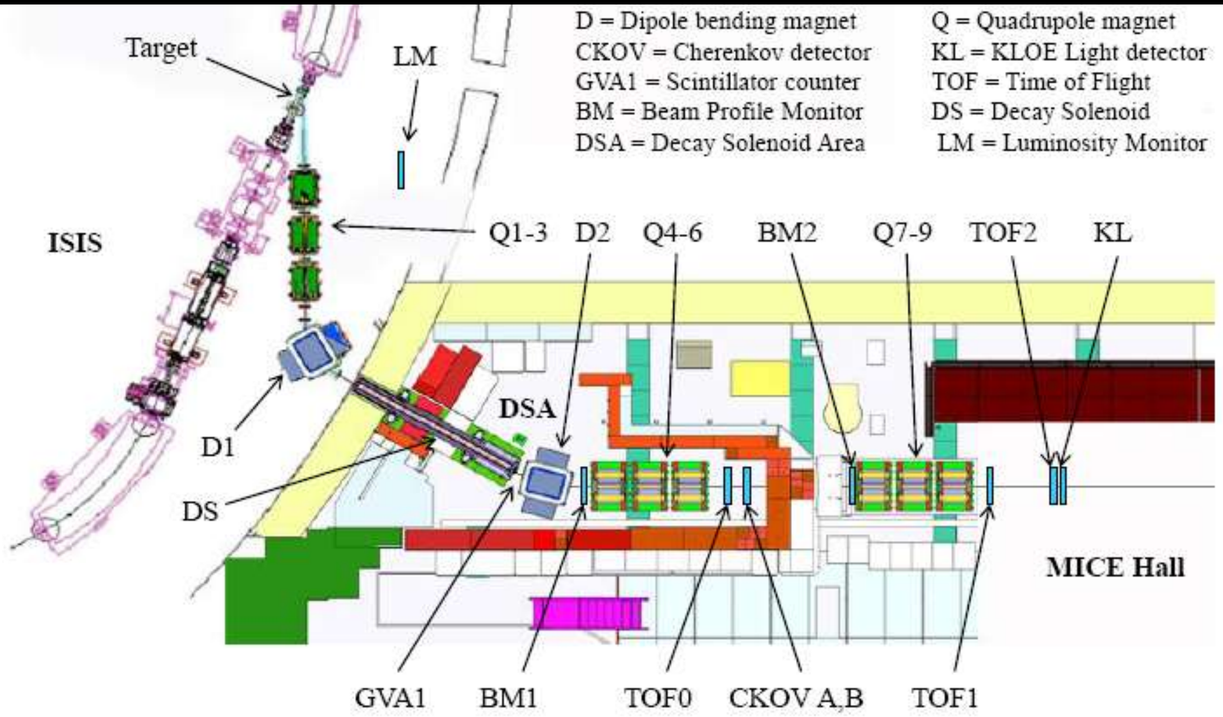


MICE Schedule as of March 2010

	Run date:
STEP I	(running now) -> Aug2010
STEP II	Q2 2011
STEP III/III.1	Q3-Q4 2011
STEP IV	≥Q3 2011
STEP V	2012-2013
STEP VI	≥2013

MICE Beamline

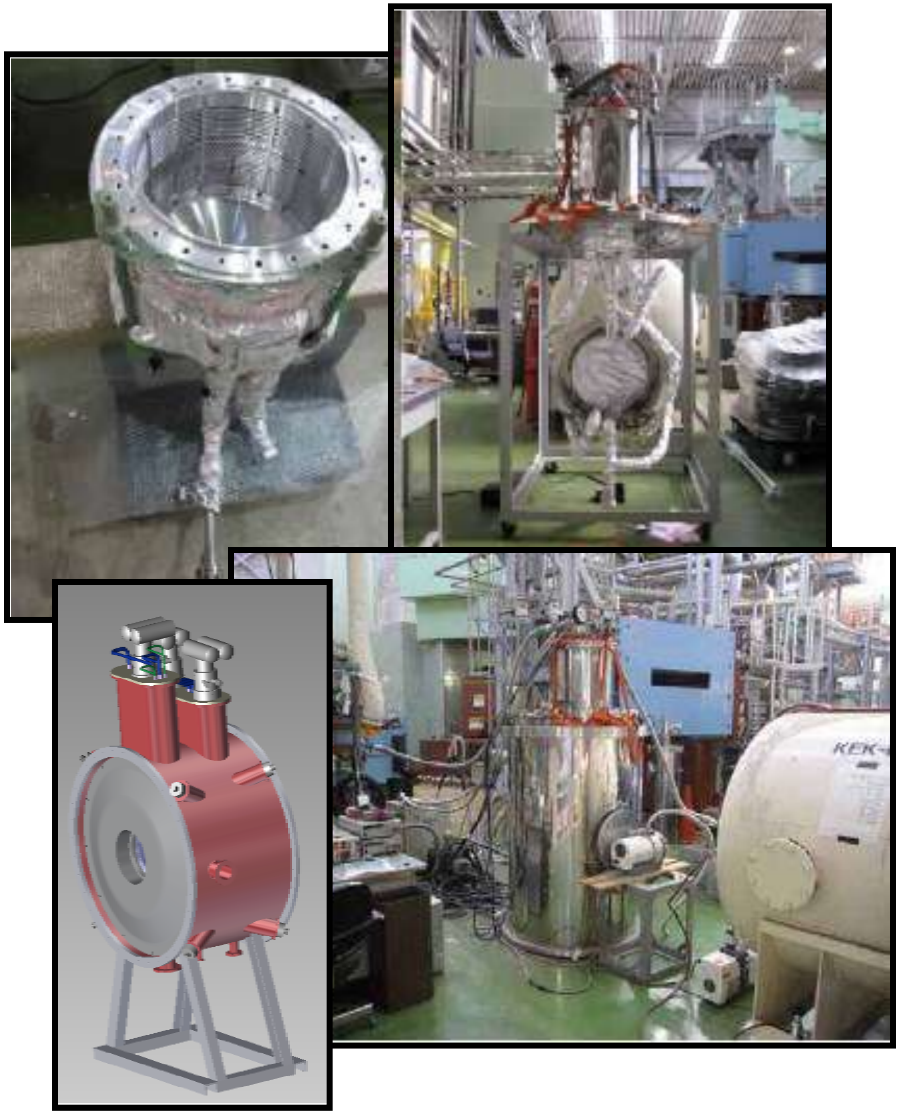




D = Dipole bending magnet
CKOV = Cherenkov detector
GVA1 = Scintillator counter
BM = Beam Profile Monitor
DSA = Decay Solenoid Area

Q = Quadrupole magnet
KL = KLOE Light detector
TOF = Time of Flight
DS = Decay Solenoid
LM = Luminosity Monitor

MICE LH2 Absorber



- ***Absorber-Focusing Coil – AFC***
  - ***LH$_2$ absorbers inside Absorber-Focus-Coil (AFC) module with superconducting coils to provide strong focus for muon cooling***
  - ***3 modules by Step VI***
- ***LH2 Absorber (KEK)***
  - *20.7 liters LH2*
  - *LiH absorber will also be tested*
  - *35 cm long on beam axis*
  - *15 cm radius*
- ***Focusing Coils (UK)***
  - ***2 coils***
  - ***26.3 cm inner radius***
  - ***4 T in solenoid mode***

4 TeV Muon Collider @ Fermilab