Cooling Simulations for the Muon Collider, Neutrino Factory and MICE

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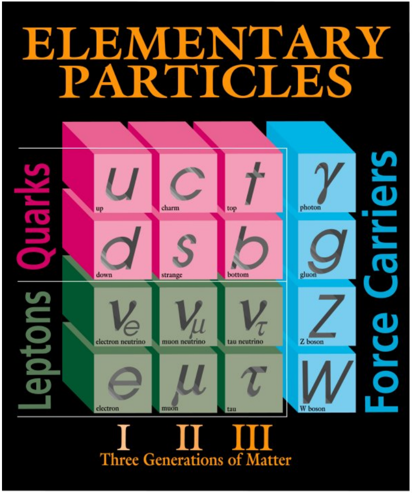
University of California Riverside

September 14, 2010

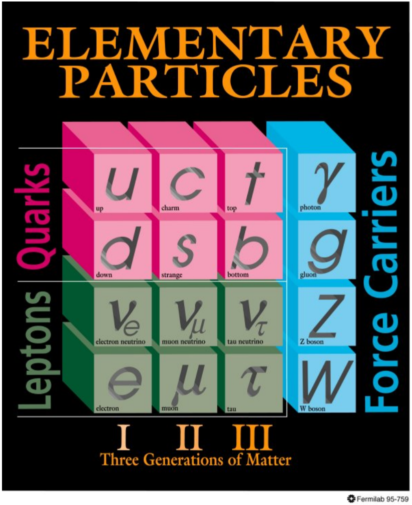
Muons/neutrinos: quick reference



Fermilab 95-759

Building blocks of the Standard Model

- Muon—elementary particle with properties similar to those of electrons.
- Muon is heavier than electron.
- Muon is unstable, 2.2 μs half-life.
- Neutrinos are nearly massless particles, electrically neutral.



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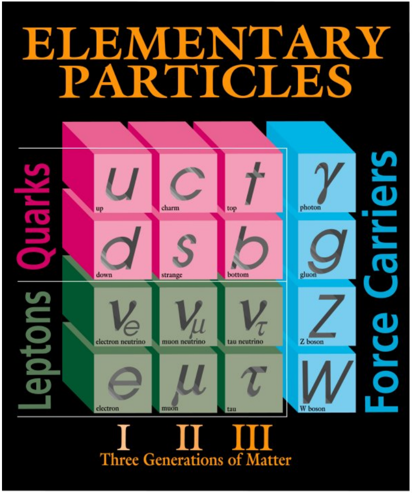

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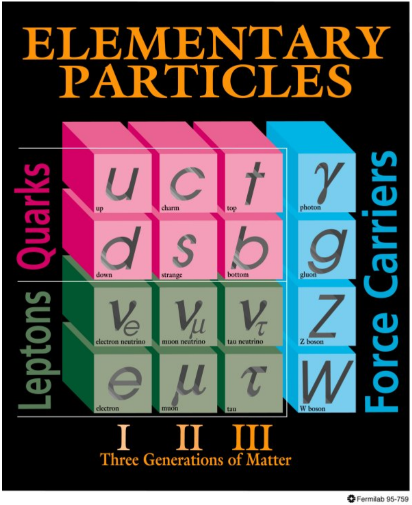

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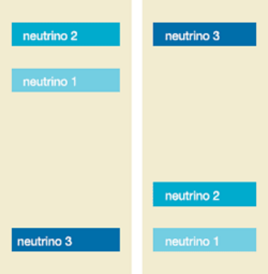
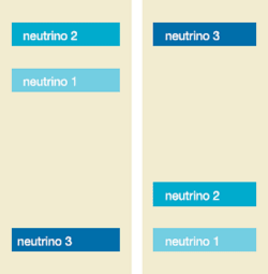


Neutrino hierarchy diagram

- Neutrino masses are unknown.
- It is theorized that the two masses are close together, but it is not known what the hierarchy of masses is (usually expressed in terms of $\text{sgn}(\Delta m^2_{31})=\text{sgn}(m_3^2 - m_1^2)$.
- Neutrinos that we commonly observe come in three "flavors": ν_e, ν_μ, ν_τ, which are superpositions of mass states.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \approx \frac{\sqrt{2}}{2} & \approx -\frac{\sqrt{2}}{2} & \sin\theta_{13} e^{i\delta} \\ \approx \frac{1}{2} & \approx \frac{1}{2} & \approx -\frac{\sqrt{2}}{2} \\ \approx \frac{1}{2} & \approx \frac{1}{2} & \approx \frac{\sqrt{2}}{2} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- It is vital to determine the values of θ_{13} and δ (CP-violation factor) as precisely as possible.



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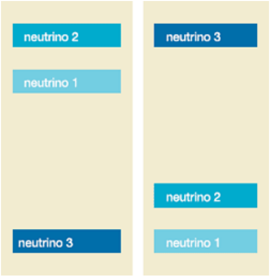

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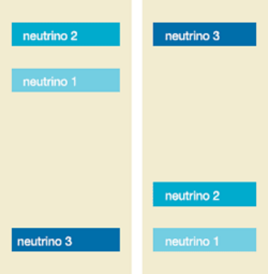

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Why do we want to accelerate muons?

- Muons are ≈200 times heavier than electrons ⇒ can be accelerated in circular channels, synchrotron radiation is negligible, collision energy is not limited by radiative effects, compact footprint.
- Muons are elementary particles in the framework of the Standard Model ⇒ clean collisions, particle energy is utilized fully.
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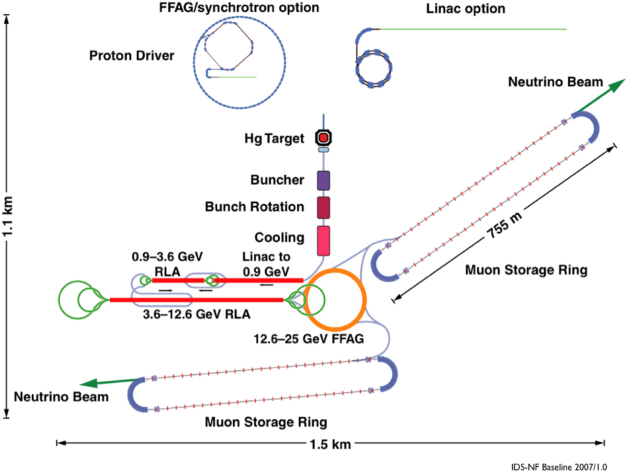
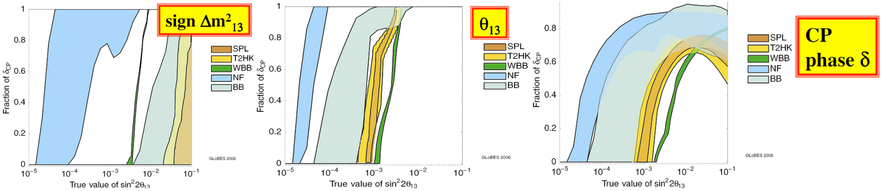
Neutrino Factory



Neutrino Factory baseline lattice

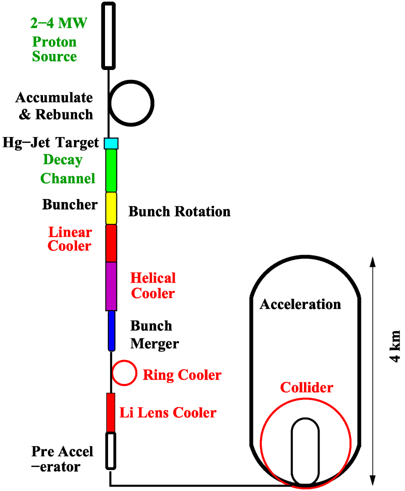
Why do we need a Neutrino Factory?

- Neutrino mass hierarchy ($\text{sgn}(\Delta m^2_{31})$).
- Neutrino mixing parameters: θ_{13} and δ—how close to zero are they?
- Neutrino Factory physics reach:



NF discovery reach compared to other experiments. Source: International Scoping Study 2007 (ISS). The NF curves show the NF performance before (worst) and after (best) the ISS improvements.

Muon Collider



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- High energy, high luminosity.
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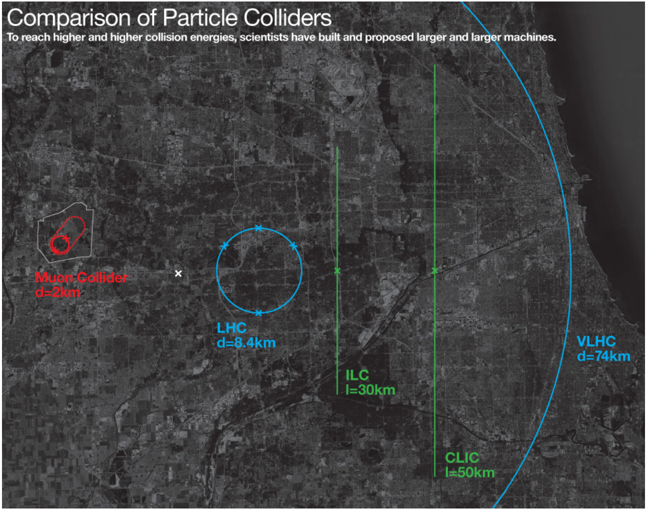
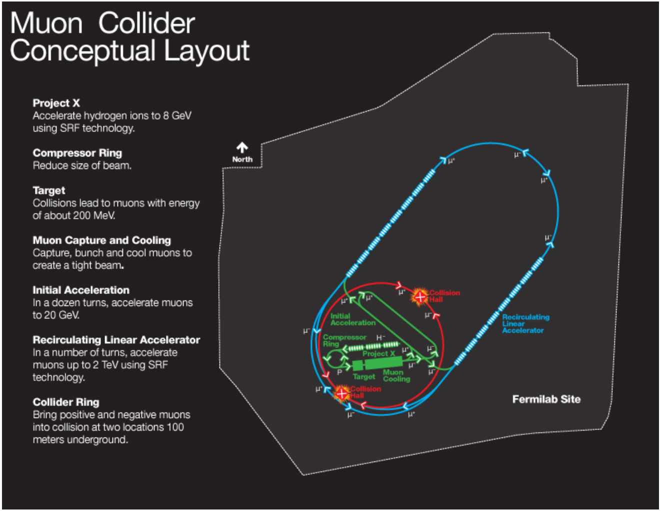
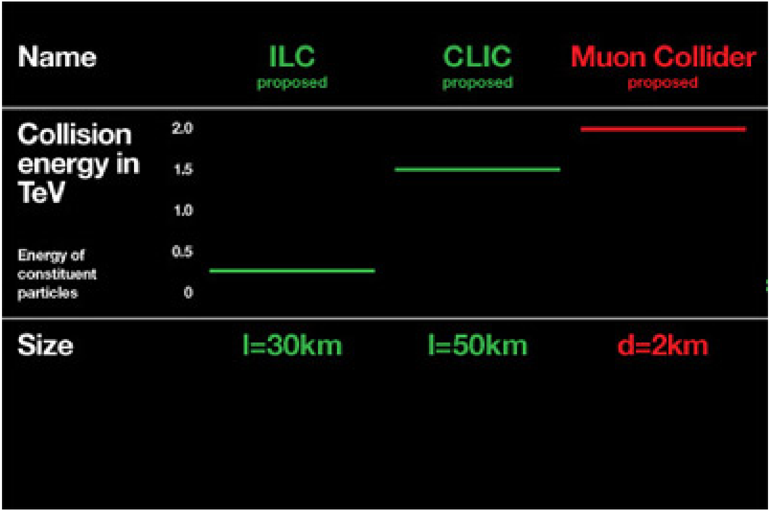


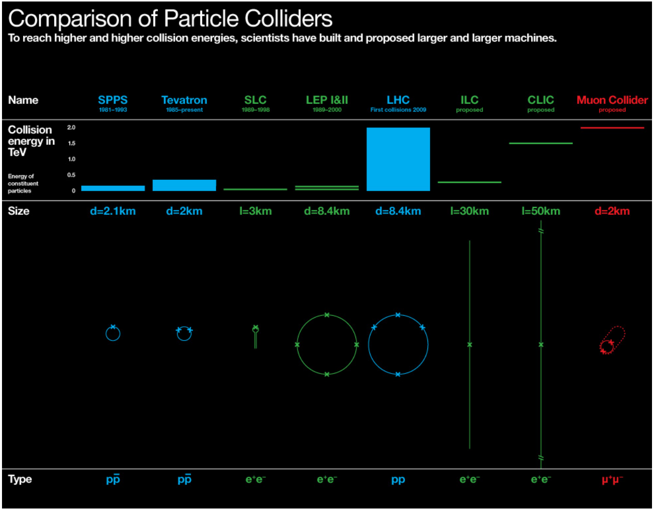
Sizes of various high energy colliders compared with the Fermilab site.



Muon Collider accelerator chain shown on the Fermilab site.

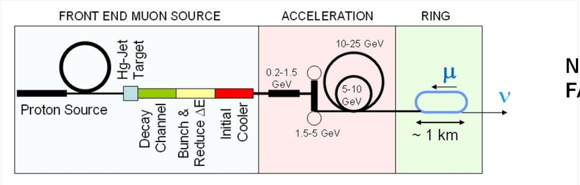


Collision energy comparison: ILC, CLIC, Muon Collider.

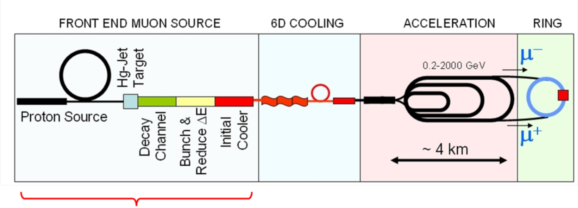


Collision energy comparison: SPPS, Tevatron, SLC, LEP, LHC, ILC, CLIC, Muon Collider.

Common features of NF and MC



NEUTRINO FACTORY



MUON COLLIDER

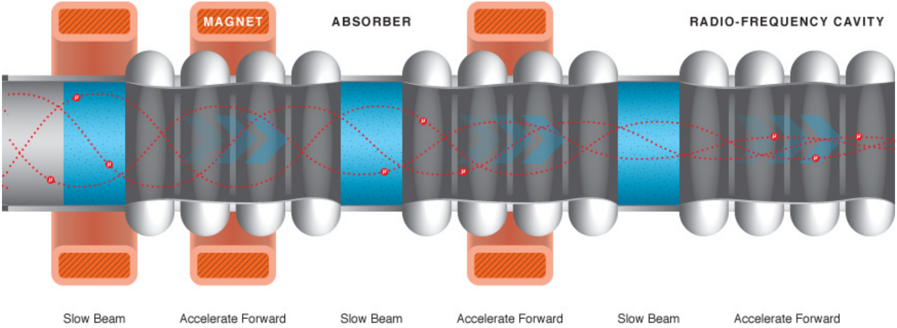
In present MC baseline design, Front End is same as for NF

Side-by-side comparison of NF (top) and MC (bottom) baseline lattices. Common frontend: proton source (protons), target (p$\rightarrow \pi$), decay channel ($\pi \rightarrow \mu$), buncher, phase rotator and initial transverse cooling channel (μ).

Why cool?

- Both MC and NF are tertiary beam machines (p $\rightarrow \pi \rightarrow \mu$). Beam sizes (=emittances) coming out of the target are very large.
- Need intense μ beam $\Rightarrow$ need to capture as much as possible of the initial large emittance.
- Large aperture acceleration systems are expensive $\Rightarrow$ for cost-efficiency need to reduce emittances prior to accelerating ("cool the beam").
- NF only requires a modest amount of cooling, predominantly in the transverse plane. However, NF could benefit from full 6D cooling.
- Current MC design assumes significant ($O(10^6)$) six-dimensional cooling.
- Need to act fast since muons are unstable. The only feasible option is ionization cooling.

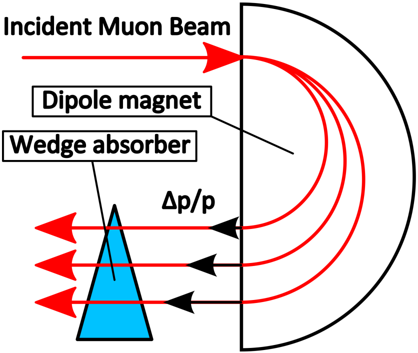
Ionization cooling principle



Ionization cooling principle:

- Let particles go through material (absorbers, blue).
- Let them regain energy in longitudinal direction only (RF cavity, white).
- Keep focusing particles using solenoidal magnets (orange).

Emittance exchange or “How to cool in 6D”



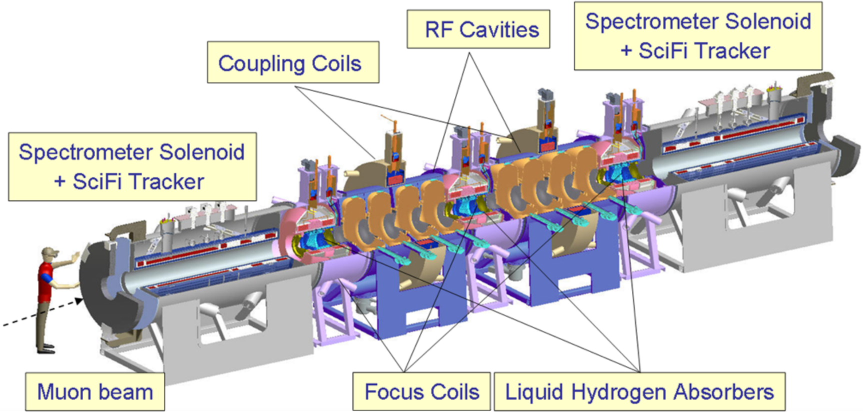
Emittance exchange principle: let the particles with higher energy pass through more material and loose more energy, thus reducing the beam spread in the longitudinal direction.

Theoretical vs practical

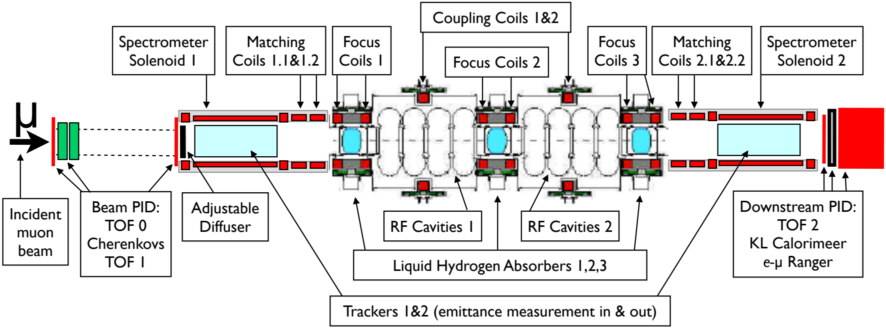
- Ionization cooling principles were established in 1970's[1].
- Cooling, especially for muons, has not been demonstrated experimentally.
- Lots of subtleties $\Rightarrow$ experiment is essential.
- One of the main aims of the international Muon Ionization Cooling Experiment (MICE) is to demonstrate ionization cooling.

[1] G.I. Budker, in: Proceedings of 15th International Conference on High Energy Physics, Kiev, 1970 A.N. Skrinsky, Intersecting storage rings at Novosibirsk, in: Proceedings of Morges Seminar, 1971 Report CERN/D.PH II/YGC/mng.

MICE: Muon Ionization Cooling Experiment



MICE 3D layout



MICE layout scheme

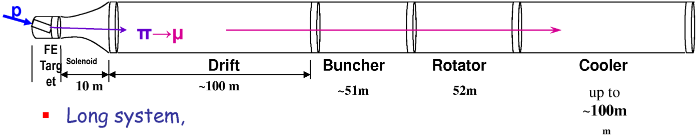
MICE objectives

- Design, engineer and fabricate a section of cooling channel capable of giving the desired performance for NF.
- Place the cooling apparatus in a muon beam and measure its performance in various modes of operation and beam conditions, thereby investigating the limits and practicality of ionization cooling.
- Measure a 10% reduction in emittance (size) of the beam with a precision of 1%.
- Develop and thoroughly test simulation and data analysis software.

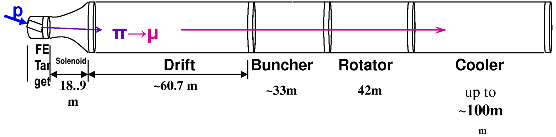
Simulation efforts

Neutrino Factory frontend simulations in G4beamline

- **ISS study based on n_B = 18 (280 MeV/c to 154 MeV/c)**
  - Buncher 0 to 12MV/m; Rotator 12.5MV/m, B=1.75T (**201.25 MHz**)



  - Long system,
- **Try shorter version - n_B = 10 (233 MeV/c to 154 MeV/c)**
  - slightly lower fields (1.5T, 15MV/m)
  - Buncher 0 to 9 MV/m, Rotator 12MV/m
  - Shorter bunch train



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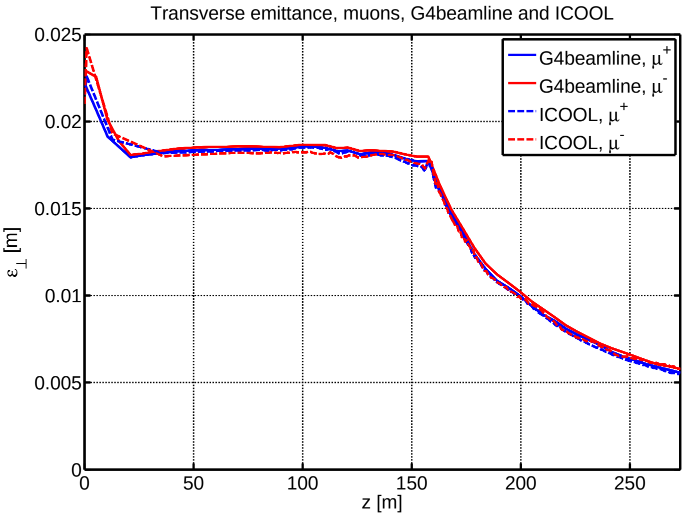
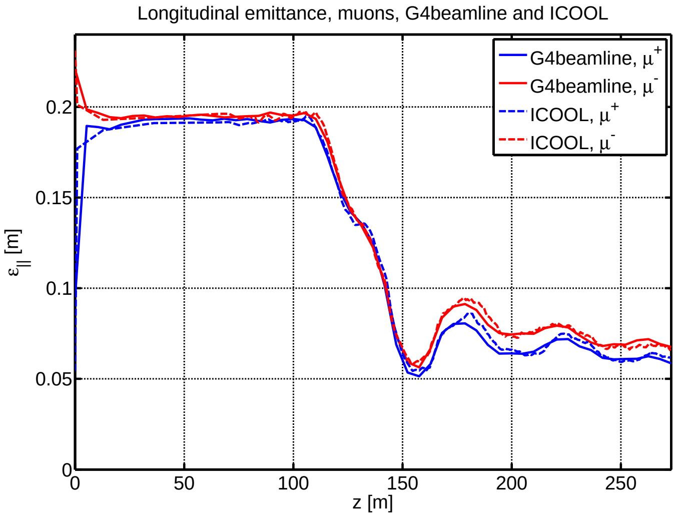
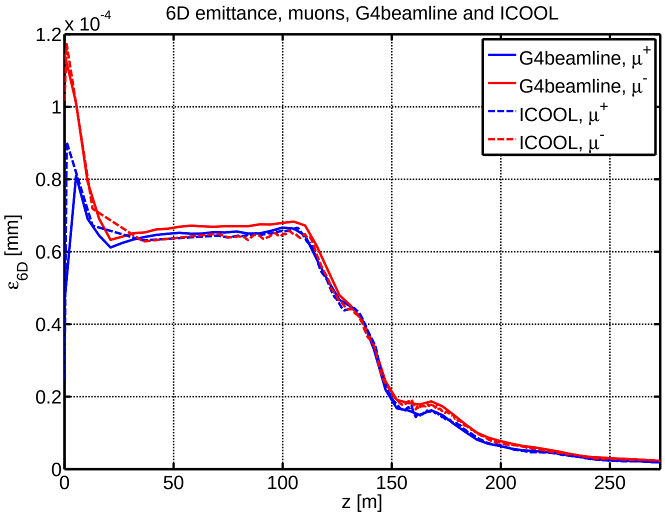
Study of the Neuffer's front end in G4beamline, comparison to ICOOL: underway.



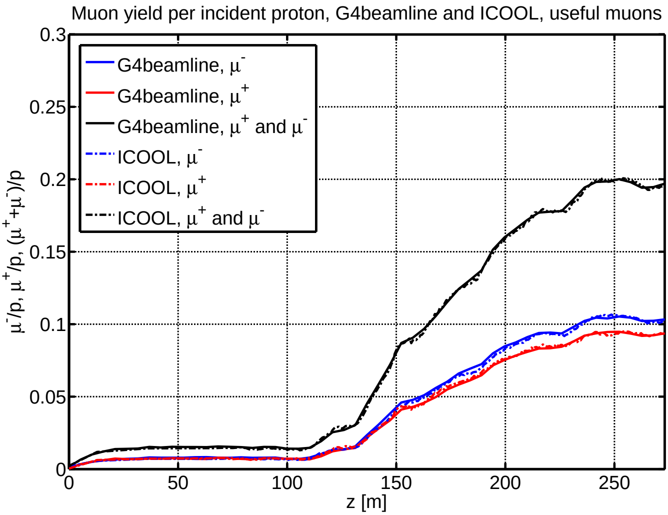
Transverse emittance shrinks in the cooler, as expected.



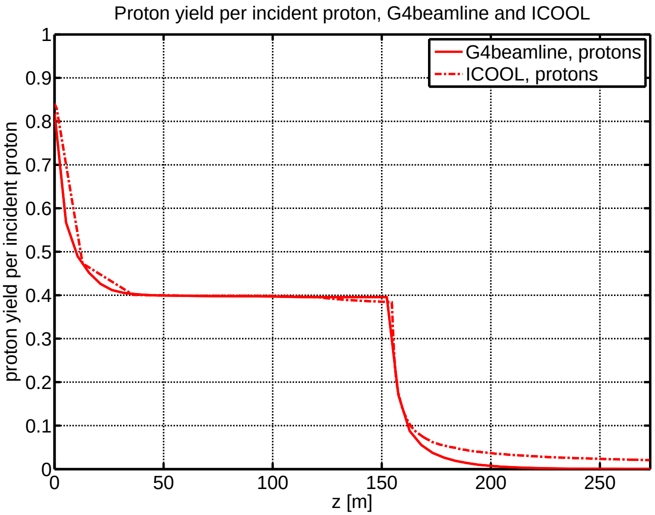
Longitudinal emittance oscillates, but does not change much.



The overall six-dimensional emittance shrinks.



Useful muons ($p \in [100, 300]$ MeV/c + certain range of amplitudes)



There is still lots of undesired background that needs to be addressed.

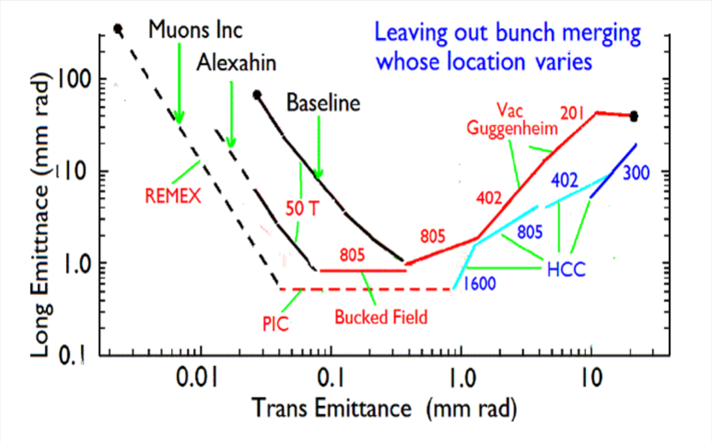
6D Cooling Simulations for the Muon Collider

6D cooling channels for the Muon Coolider

- RFOFO ring / Guggenheim helix / Tapered Guggenheim
- modification: Open cavity lattice
- Helical cooling channel (Muons, Inc.)
- FOFO Snake (Y. Alexahin)

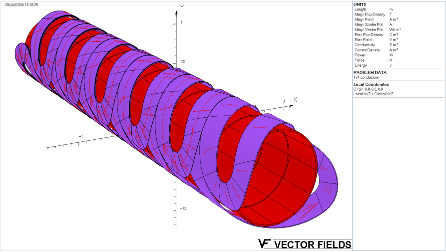
I will mention the HCC and the FOFO Snake layouts briefly and concentrate on the RFOFO-based channels.

Muon Collider cooling schemes

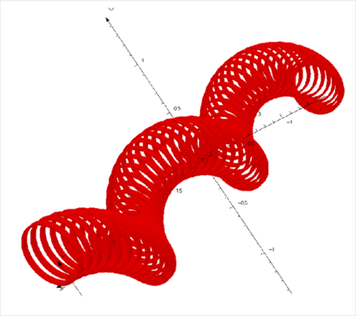


Various proposed cooling channels

Helical cooling channel I (HCC)



- Consists of 4 layers of helix dipole to produce tapered helical dipole fields.
- Coil diameter is 1.0 m.
- Maximum field is more than 10 T.



- Consists of 73 single coils (no tilt).
- Maximum field is 5 T.
- Coil diameter is 0.5 m.

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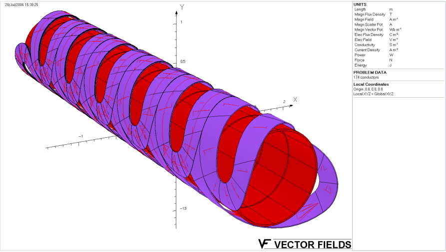

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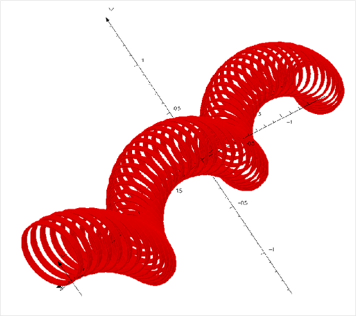

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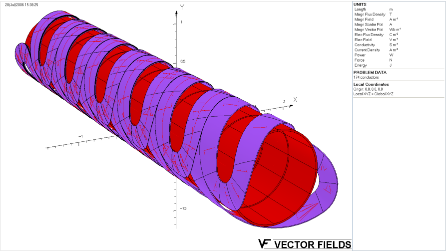

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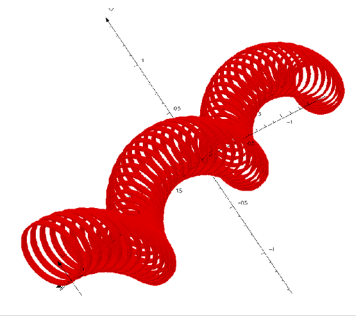

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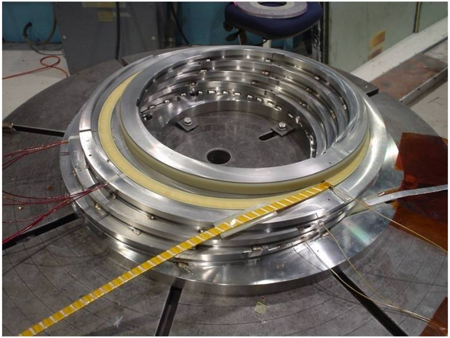
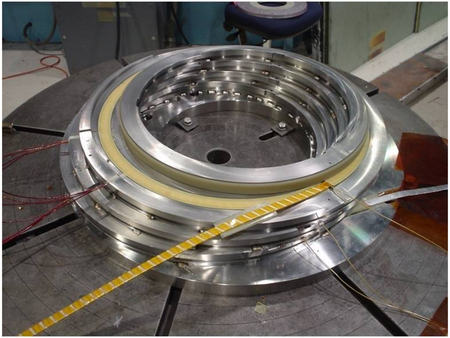
Helical cooling channel II



- Engineering of the test section (4-coil SC assembly) is complete.
- RF: still an issue, especially in the magnetic field.
- Absorber: continuous, homogeneous, pressurized H_2 gas.

Helical cooling channel II



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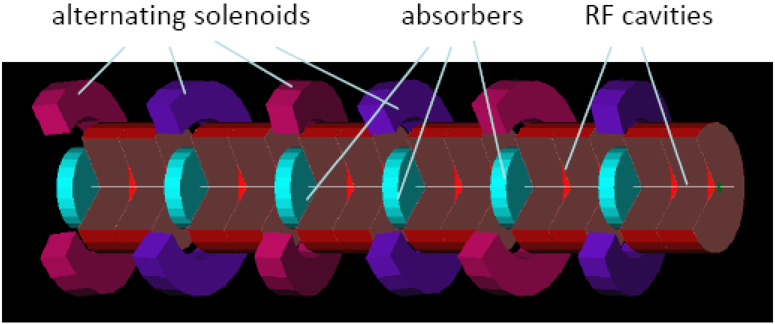
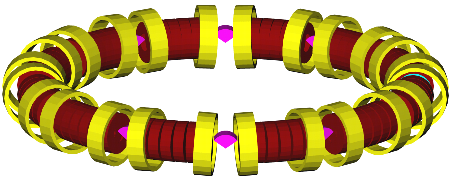


FOFO snake lattice layout.

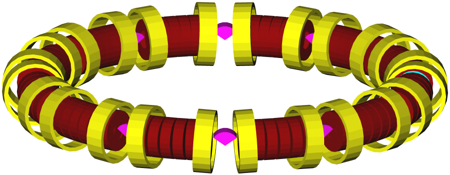
RFOFO ring



RFOFO ring

- Yellow: tilted magnetic coils that guide and focus particles.
- Magenta: wedge absorbers for cooling and emittance exchange.
- Brown: RF cavities to restore energy lost in the absorber (longitudinal direction only).

RFOFO ring



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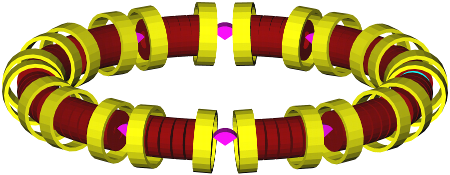

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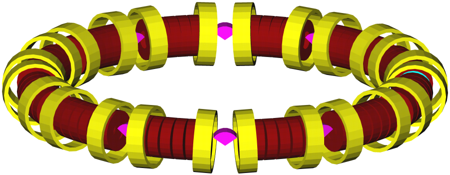
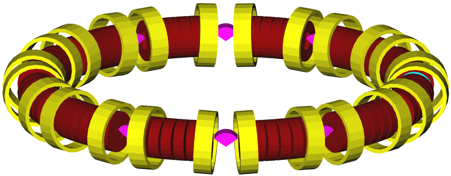
RFOFO ring



RFOFO ring

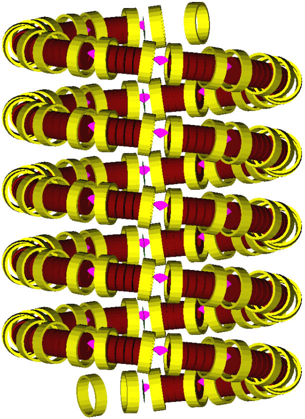
- Yellow: tilted magnetic coils that guide and focus particles.
- Magenta: wedge absorbers for cooling and emittance exchange.
- Brown: RF cavities to restore energy lost in the absorber (longitudinal direction only).

RFOFO ring and Guggenheim helix



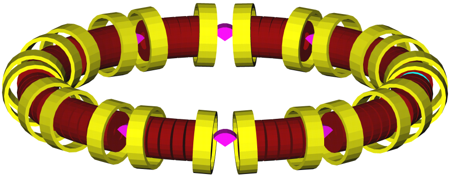
RFOFO ring

- Advantages: fast cooling, compact design, RF reuse.
- Challenges: absorber overheating, injection/extraction, continuous operation.



RFOFO-based Guggenheim helix

RFOFO ring and Guggenheim helix



RFOFO ring

- Advantages: fast cooling, compact design, RF reuse.
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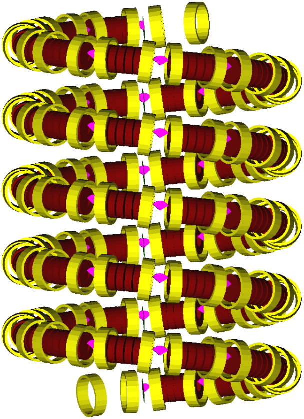
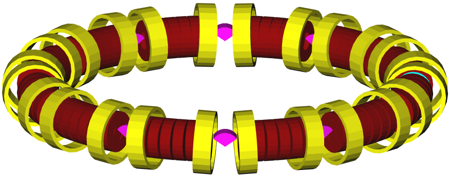


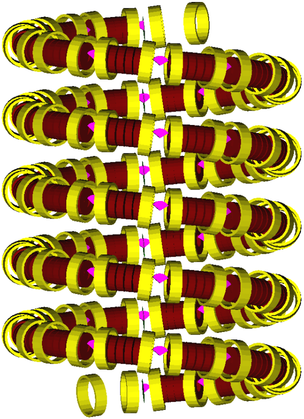
RFOFO-based Guggenheim helix

RFOFO ring and Guggenheim helix



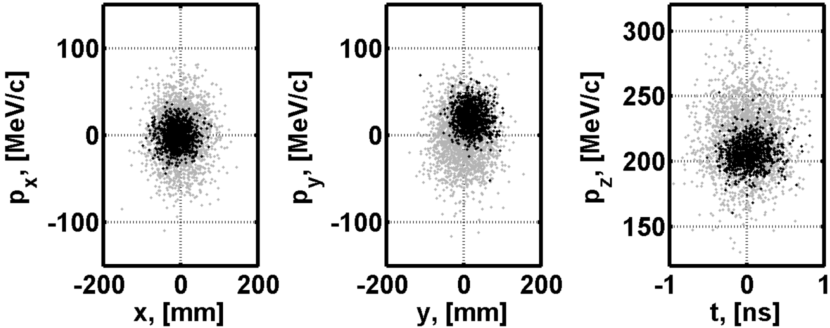
RFOFO ring

- Advantages: fast cooling, compact design, RF reuse.
- Challenges: absorber overheating, injection/extraction, continuous operation.



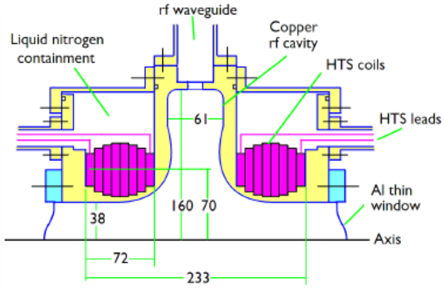
RFOFO-based Guggenheim helix

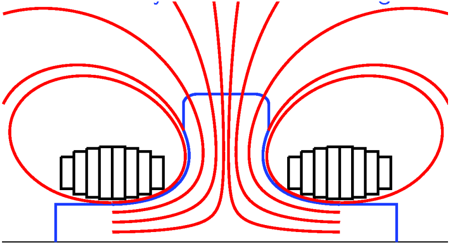
Phase space reduction



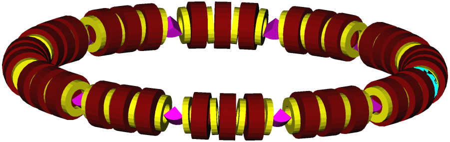
- Gray: initial particle distribution.
- Black: final particle distribution.
- Beam size reduction in all six dimensions.

Magnetic insulation





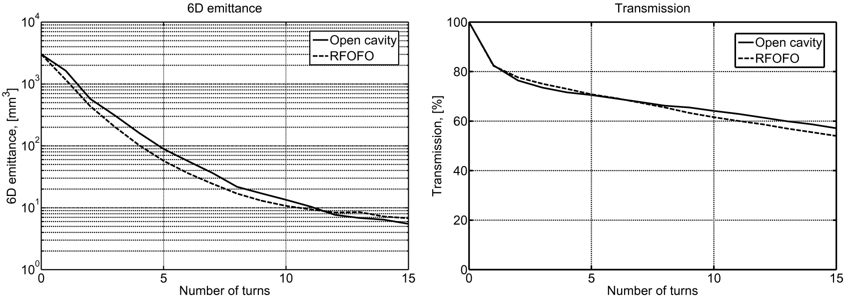
- Issue: RF breakdown in the magnetic field.



One of the proposed solutions:

- Open cavity lattice.
- Coils in the irises.
- Cavity wall shape follows the magnetic field lines.

Performance comparison: RFOFO vs. open cavity

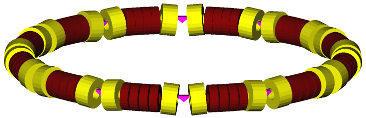


Performance of the open cavity lattice *vs.* the RFOFO lattice with decay and stochastic processes. Solid line—open cavity lattice, dashed line—RFOFO lattice.

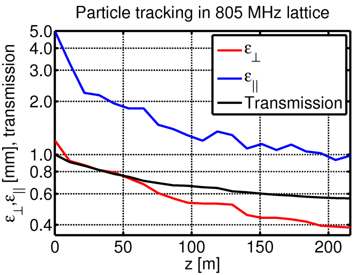
805 MHz lattice

- After a certain number of turns in the 201.25 MHz RFOFO ring/helix cooling stops (the equilibrium emittance is achieved).
- It is necessary to change the parameters of the channel in order to boost cooling efficiency.
- It was proposed to scale the original RFOFO ring/helix in size and use stronger magnetic fields and 402.5 MHz frequency cavities, then scale again and use 805 MHz cavities.
- A 402.5 MHz lattice was simulated previously using both ICOOL and G4beamline, but the 805 MHz lattice has never been simulated in G4beamline.

805 MHz lattice



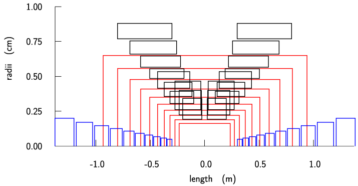
- Very small ring ($C = 10.8$ m), very little space for wedges.
- Magnetic coils have very small radius and very high field, cannot be placed over the RF cavities $\Rightarrow$ moved into the space between the cavities.
- In the simulation assumed a uniform dipole field over the ring instead of tilting the coils.

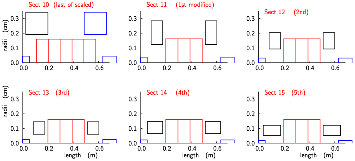


- Initial and final emittances correspond to that of the ICOOL simulation.
- Transmission is 56% in G4beamline, 55% in ICOOL (decay and stochastic processes on).

Tapered channel

R. Palmer proposed the following:

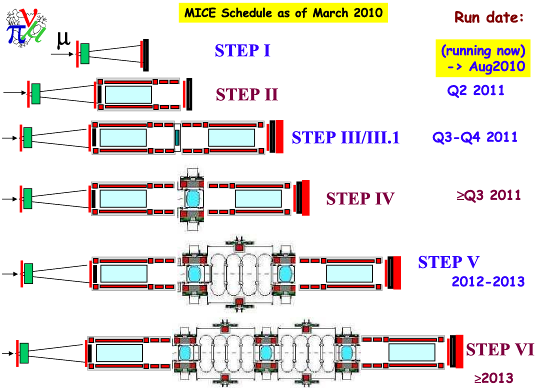




- First 10 cells of the cooling channel are scaled versions of the original RFOFO lattice.
- Frequency changes continuously.
- Last 5 cells have the same length with coils between cavities.
- Liquid hydrogen absorbers are replaced with solid LiH.
- TODO: full tapered helix simulation in G4beamline.

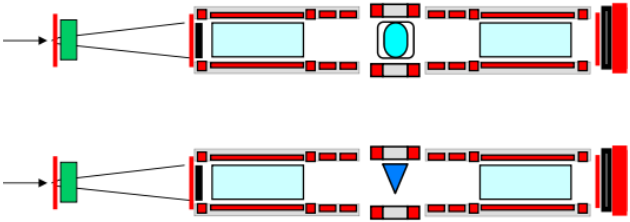
Wedge absorber in MICE: emittance exchange demonstration

MICE step-wise implementation



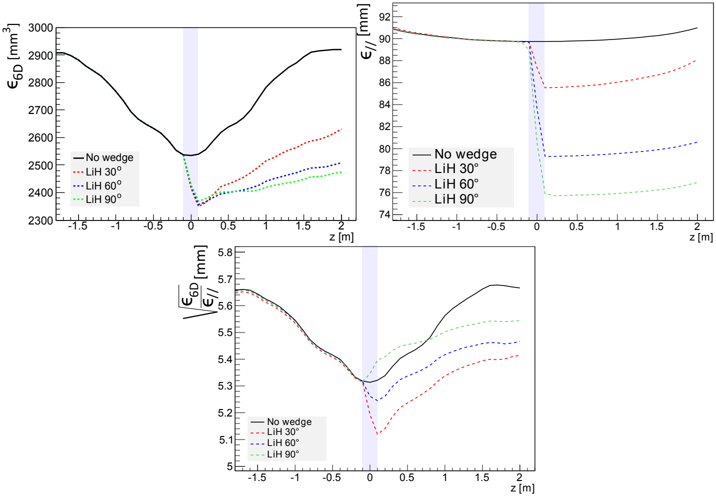
MICE implementation schedule, we are interested in Step IV

MICE wedge



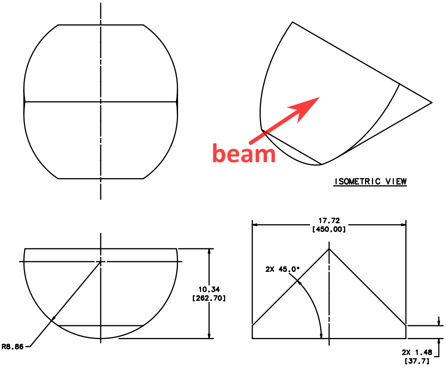
- Top: MICE Step IV with a liquid hydrogen absorber. MICE is a 4D cooling experiment: transverse emittance is reduced while longitudinal emittance stays the same or increases slightly due to stochastic processes in the energy loss.
- Bottom: LH_2 absorber is replaced with a solid LiH absorber. This way emittance exchange can be observed if the beam is properly matched (dispersion is introduced).

Cooling signal



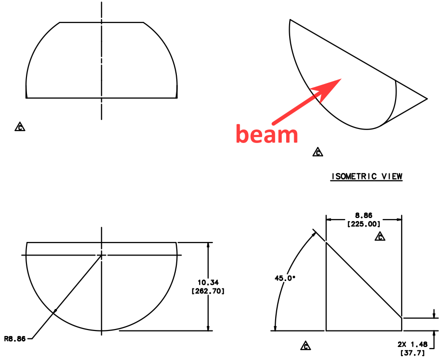
Cooling effect observed for LiH at different angles

Wedge geometries



- Two wedge shapes were chosen to request a quote from Y12: 90° LiH wedge as an overall best performer, and 30° LiH wedge that covers the whole aperture.
- In addition to the LiH wedge it would be good to have a set (90°, 60°, and 30°) of plastic wedges to test properties of different materials (time permitting).

Wedge geometries



- Good news: a 90° LiH wedge has been ordered (consisting of two parts for cost reduction).
- Beam behavior with a 45° half-wedge needs to be simulated.

Summary

- NF front end simulation in G4beamline is underway, comparison of two independent codes shows a very good agreement in results.
- MC 6D cooling simulations progress toward a complete tapered channel implementation in both ICOOL and G4beamline.
- Various options for the MICE wedge were studied, engineering drawings were prepared, a 90 degree two-part absorber was ordered.

Useful links

- `http://indico.fnal.gov/conferenceDisplay.py?confId=3474` – Muon Accelerator Program review reports and DOE comments.
- `http://www.fnal.gov/muoncollider/` – Fermilab Muon Collider webpage.
- `http://mice.iit.edu/` – Muon Ionization Cooling Experiment portal.
- `https://www.ids-nf.org/wiki/FrontPage` – International Design Study for the Neutrino Factory webpage.

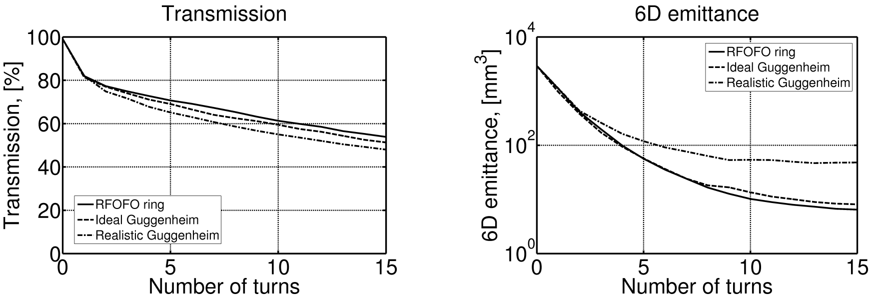
Thank you!

Extra Slides

Parameter and performance comparison

	RFOFO/Guggenheim
Circumference, [m]	33.00
RF frequency, [MHz]	201.25
RF gradient, [MV/m]	12.835/12.621
Maximum axial field, [T]	2.80
Pitch, [m]	0.00/3.00
Pitch angle, [deg]	0.00/5.22
Radius, [mm]	5252.113/5230.365
Coil tilt (wrt orbit), [deg]	3.04
Average momentum, [MeV/c]	220
Reference momentum, [MeV/c]	201
Absorber angle, [deg]	110
Absorber thickness on beam axis, [cm]	27.13

Performance comparison



- 6D emittance is reduced by a factor of 2.76 per plane in the RFOFO ring or a factor of 2.66 per plane in the Guggenheim helix (495 m),
- or by a factor of 1.98 per plane in a realistic simulation with windows in the RF cavities and absorbers.

Open cavity and RFOFO parameters

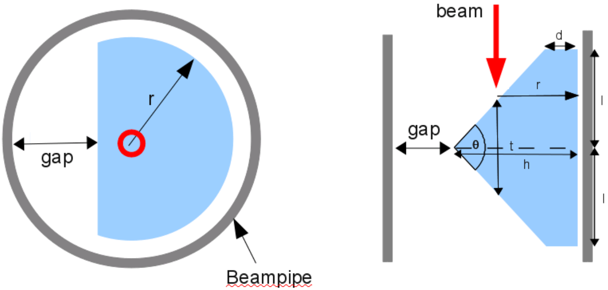
Parameter	Unit	Open cavity	RFOFO
Number of cells		12	12
Circumference	[m]	30.72	33.00
Radius	[m]	4.889	5.252
RF frequency	[MHz]	201.25	201.25
RF gradient	[MV/m]	16.075	12.835
Maximum axial field	[T]	3.23	2.80
Reference momentum	[MeV/c]	214	201
Coil tilt	[deg]	4.90	3.04
Number of coils per cell		4	2
Current densities	[A/mm^2]	[63,45,-45,-63]	[95,-95]
Number of RF cavities		3	6
Length of each RF cavity	[mm]	385	282.5
Absorber angle	[deg]	90	110
Absorber vertical offset	[cm]	12.0	9.5
Absorber axial length	[cm]	24.00	27.13

Quantitative analysis of open cavity lattice vs. RFOFO

Structure	$\varepsilon_\perp$ [mm]	$\varepsilon_\parallel$ [mm]	ε_{6D} [mm^3]	Transmission [%]
Initial	12	19	3000	100
Open cavity (15 turns)	1.5	2.3	5.5	57
RFOFO (14 turns)	1.7	2.5	7.2	56
RFOFO (15 turns)	1.6	2.4	6.7	54

Table: Parameters of the open cavity ring compared to the RFOFO ring.

Wedge schematic



- Wedge absorber = cylinder intersected with a triangular prism.
- One of the typical sizes: opening angle = 90°, on-axis length = 75.4 mm (corresp. to 12 MeV energy loss at 200 MeV), radius $>$ 150 mm.