Measurement of Muon Cooling for a Future Neutrino Factory

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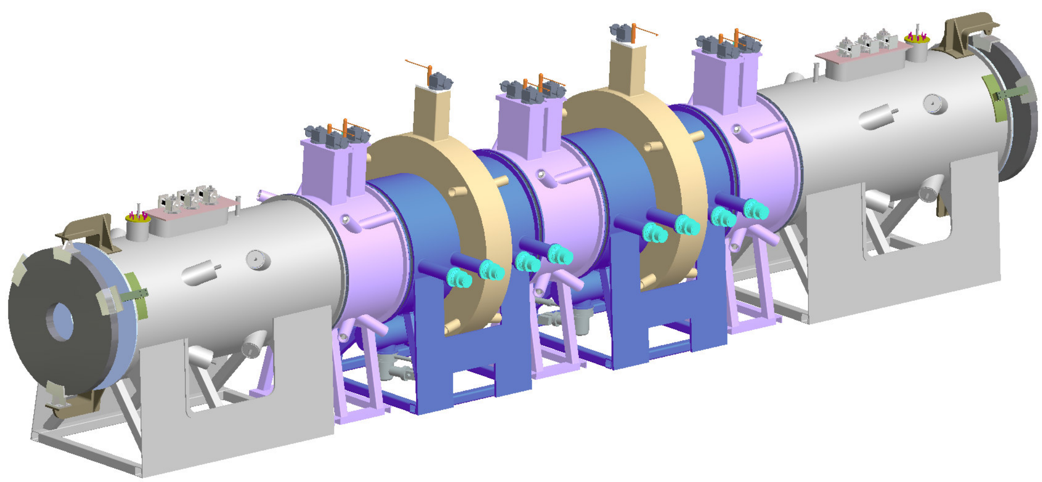
Imperial College London,
on behalf of the MICE Collaboration

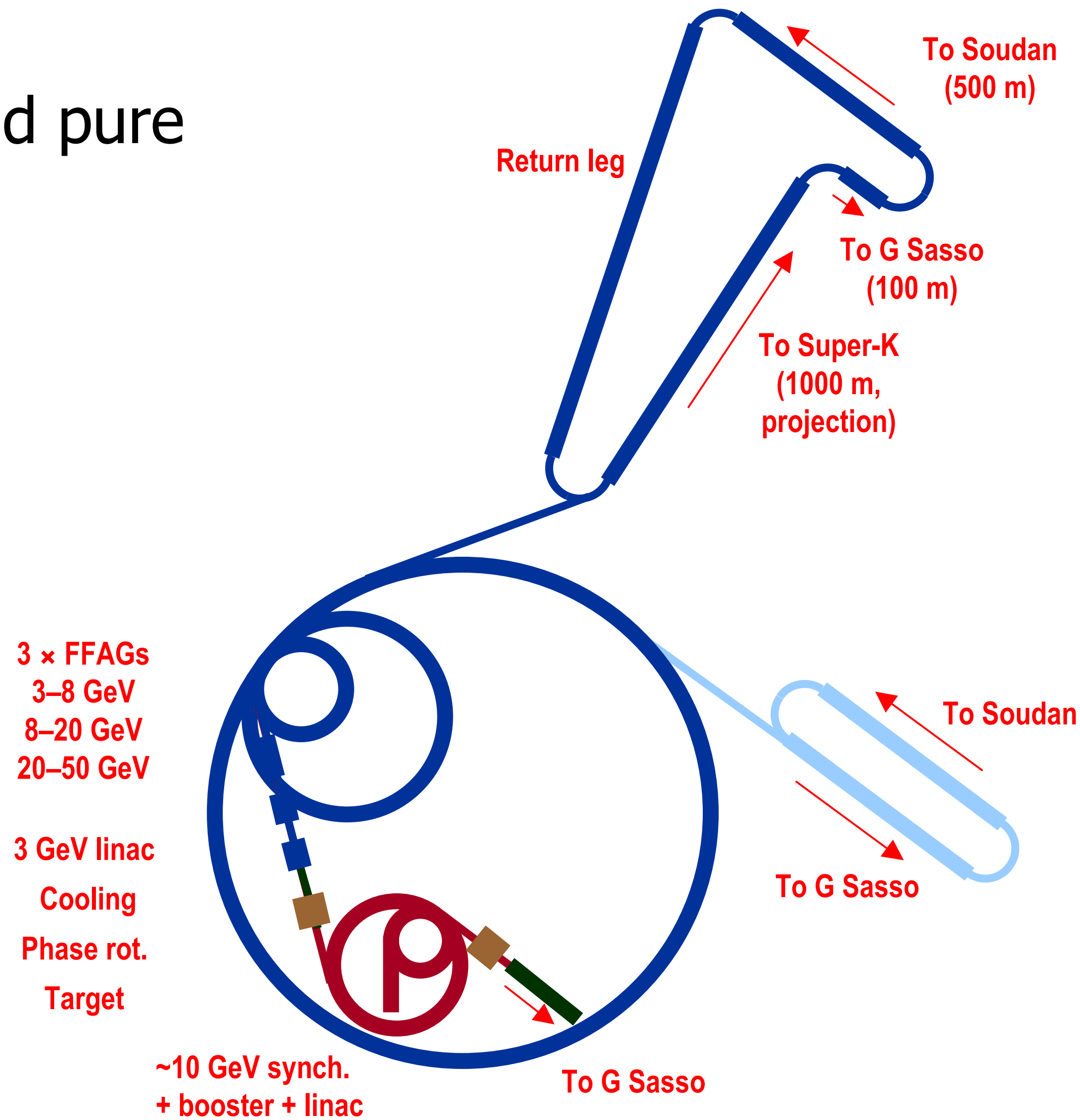
Overview

- MICE and muon cooling
- Accelerator simulation
  - Solenoids
  - Liquid Hydrogen
  - RF Cavities
- Simulated transverse emittance resolution



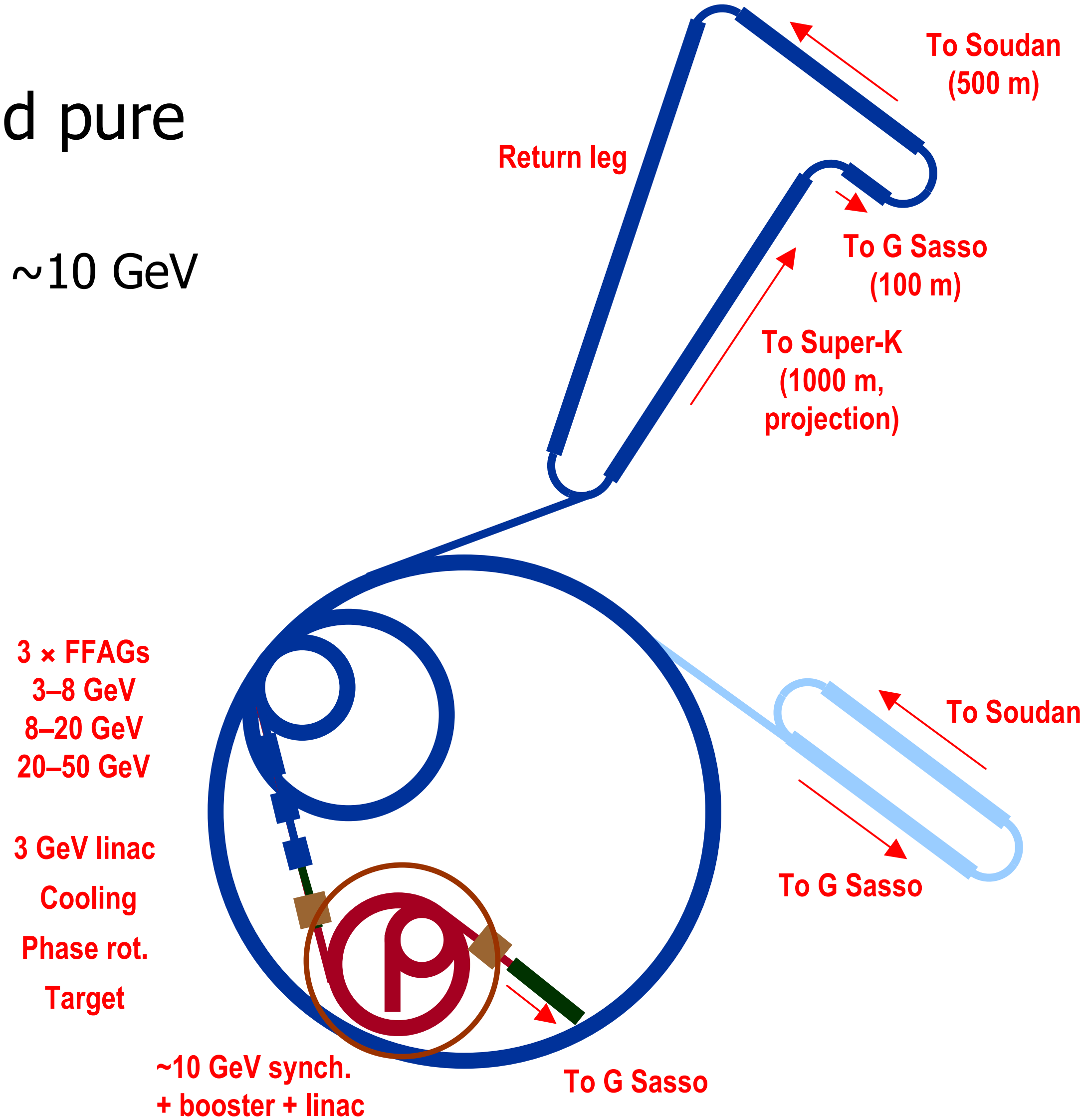
Neutrino Factory

- Intense, high energy and pure source of neutrinos



Neutrino Factory

- Intense, high energy and pure source of neutrinos
  - Proton beam accelerated to ~10 GeV



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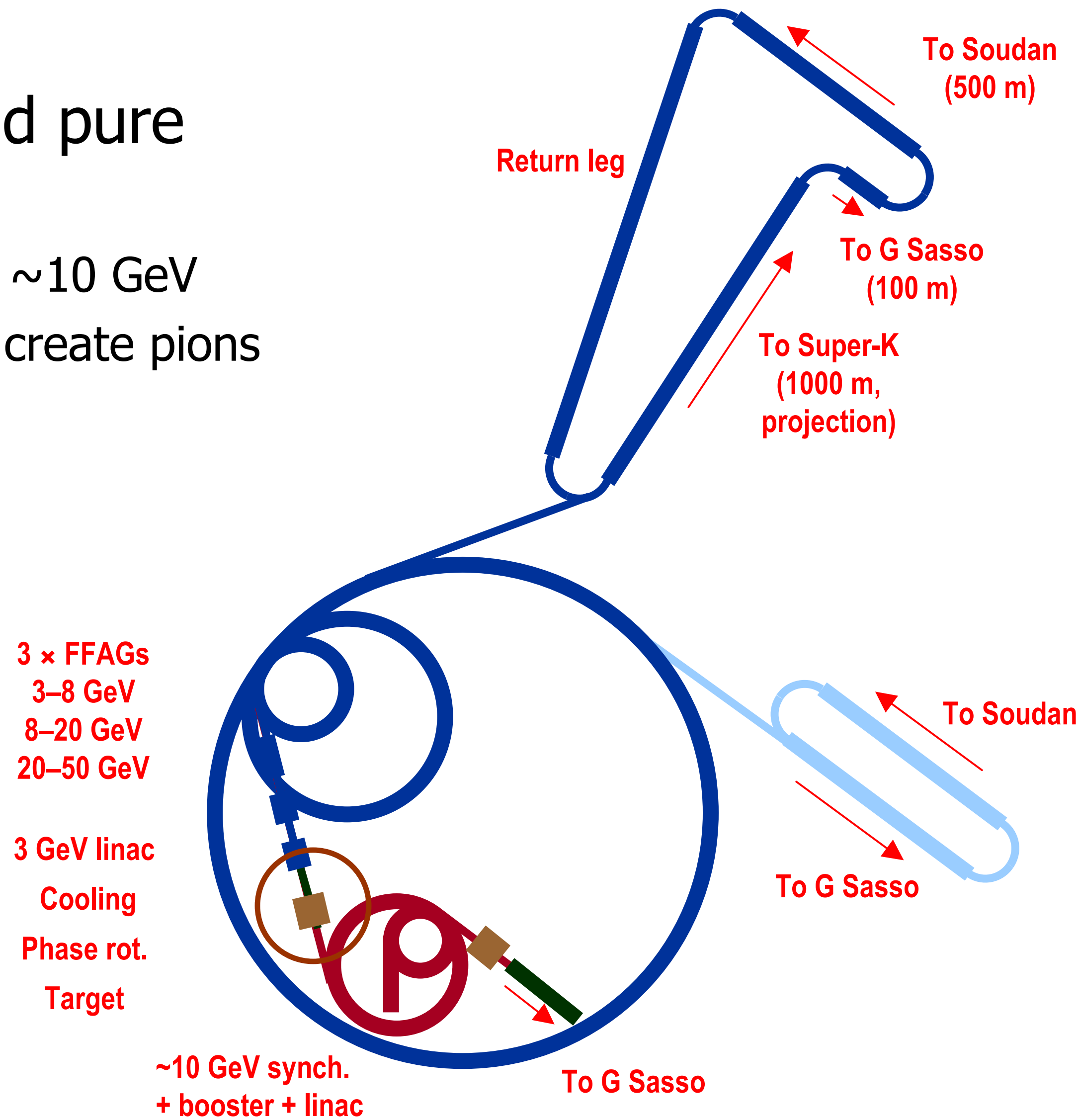
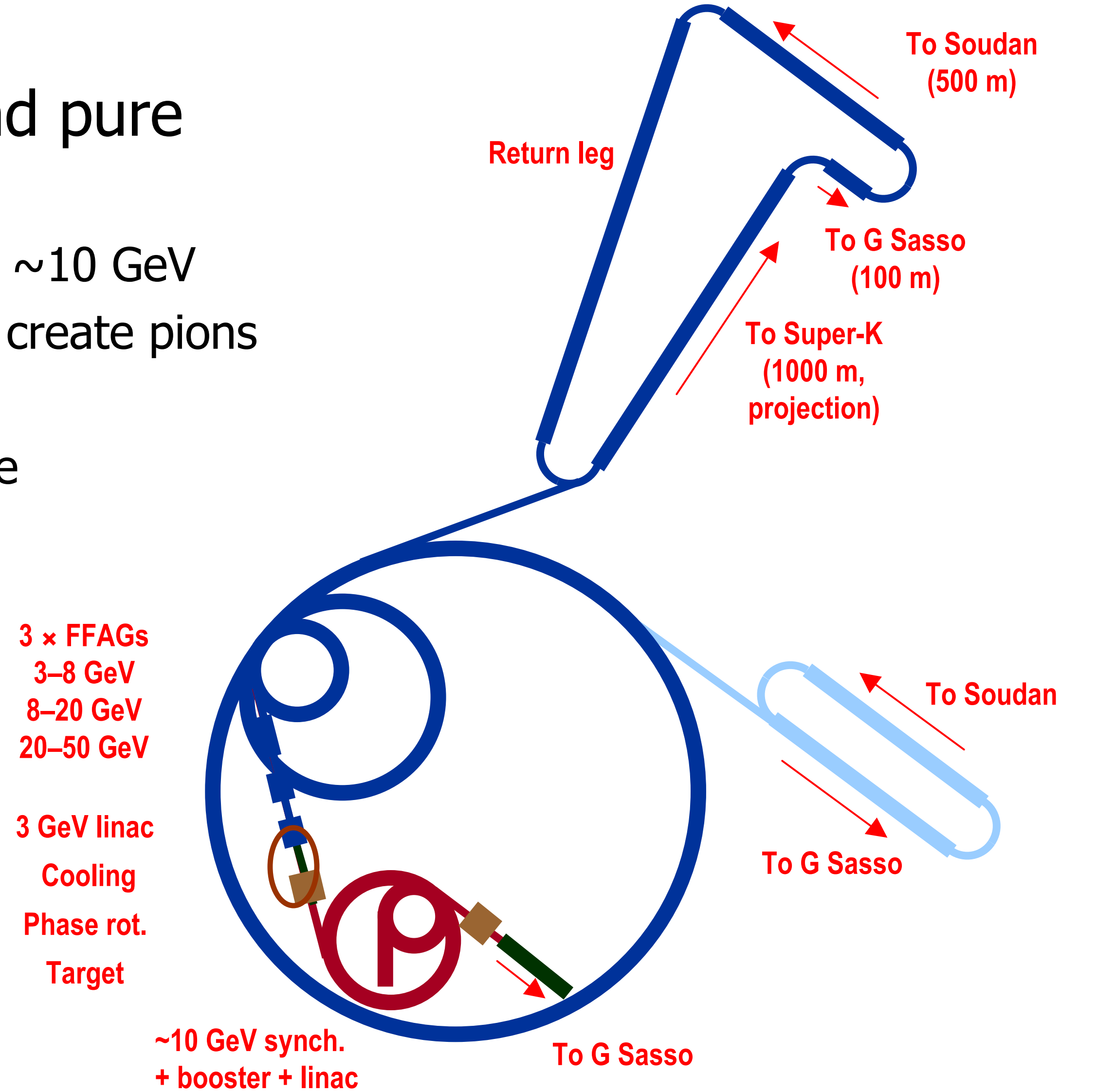
  - Protons fired onto target to create pions



Neutrino Factory

- Intense, high energy and pure source of neutrinos
  - Proton beam accelerated to ~10 GeV
  - Protons fired onto target to create pions
  - Pions decay to muons
    - Muon beam is very large



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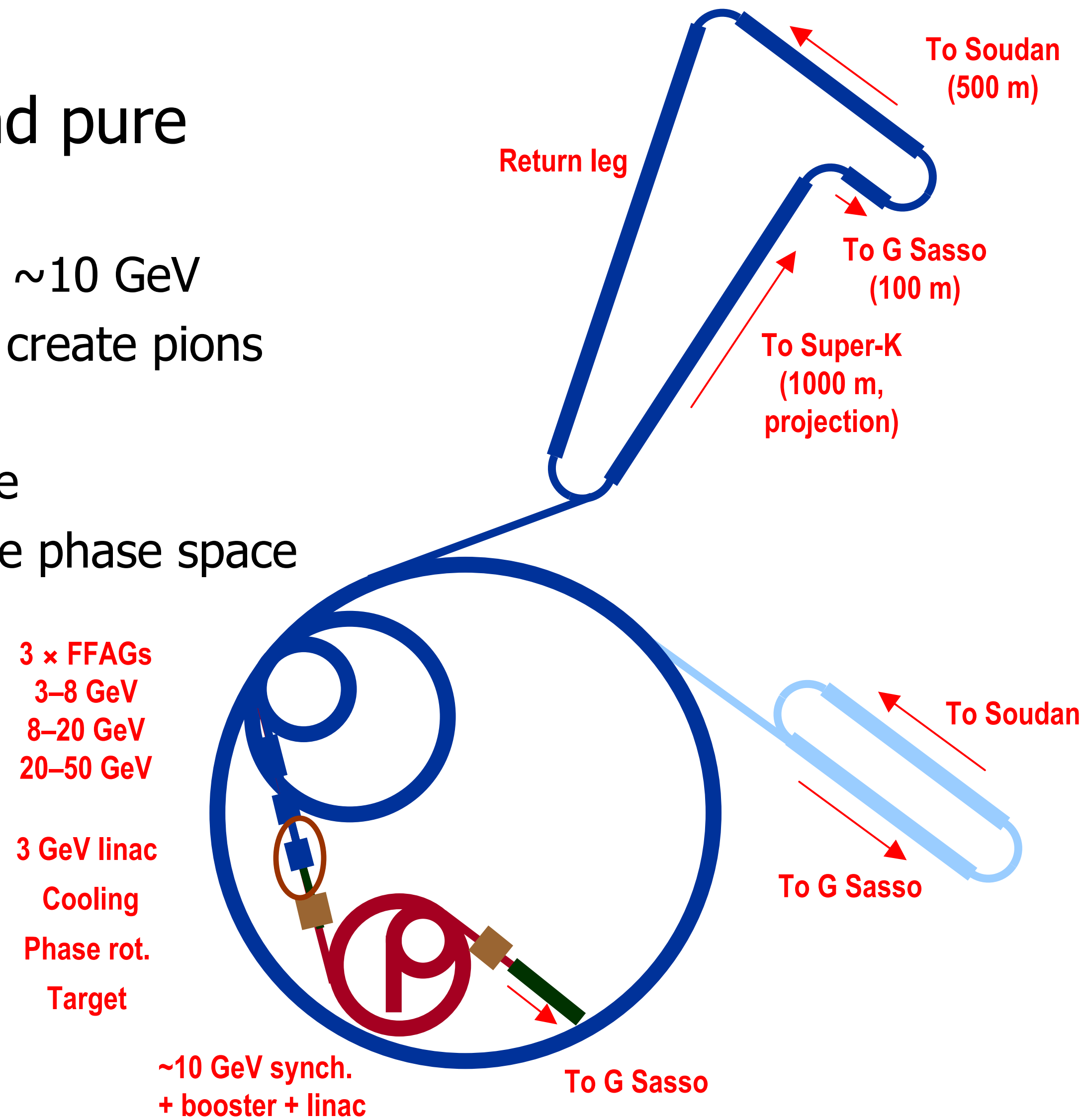
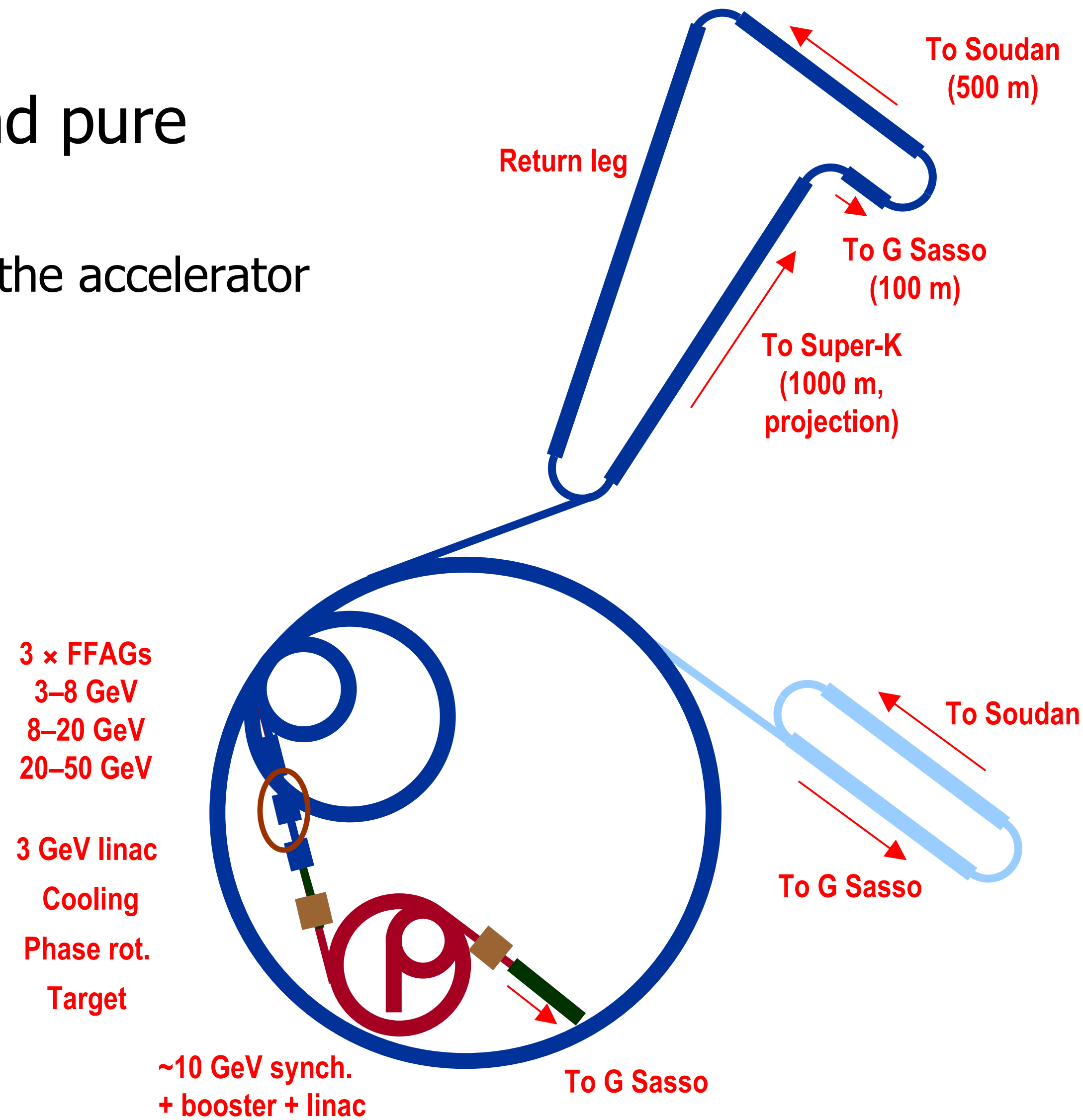
    - Muon beam is very large
  - Beam rotated in energy-time phase space to fit into cooling section



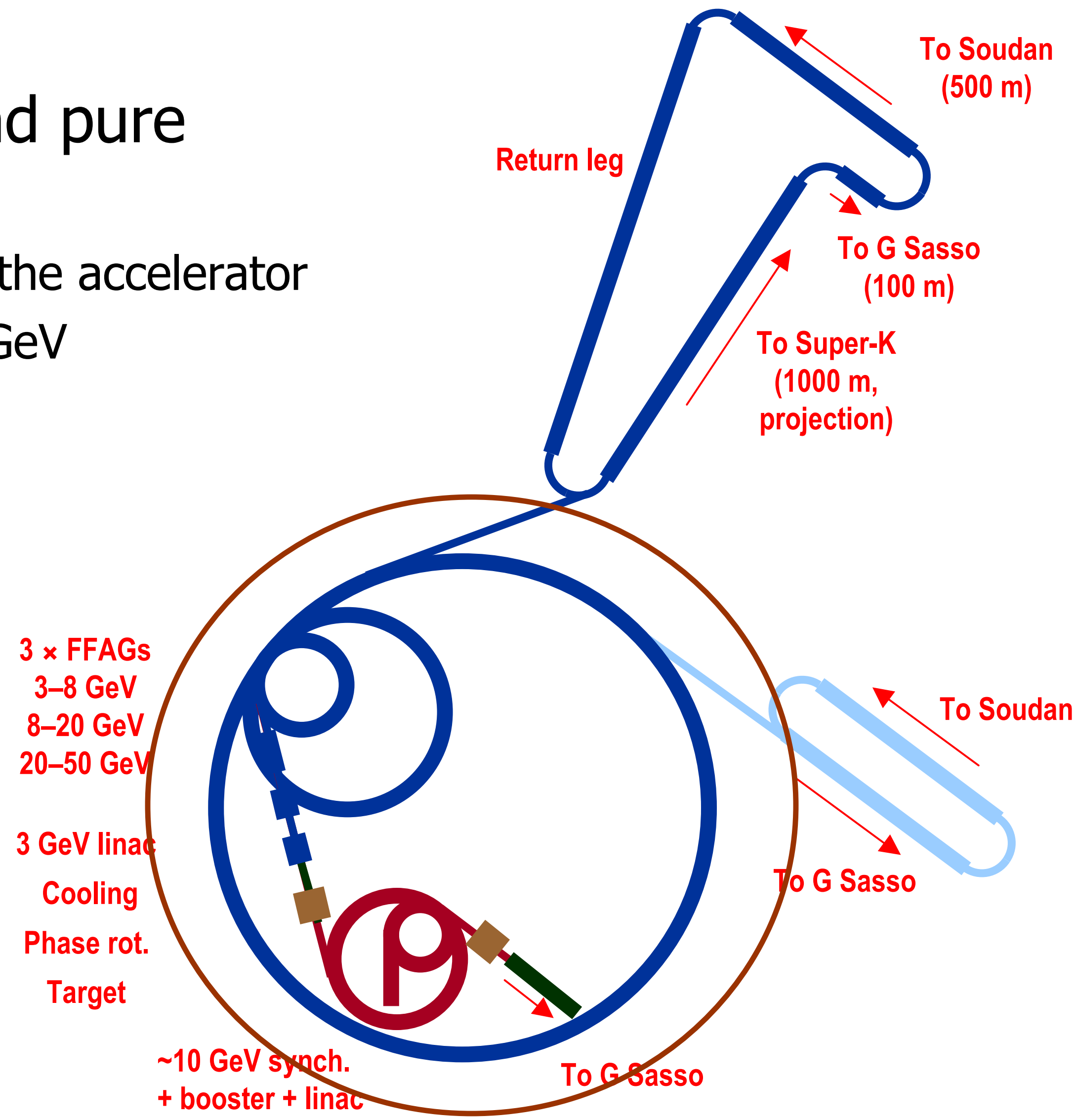
Neutrino Factory

- Intense, high energy and pure source of neutrinos
  - Muon beam cooled to fit in the accelerator



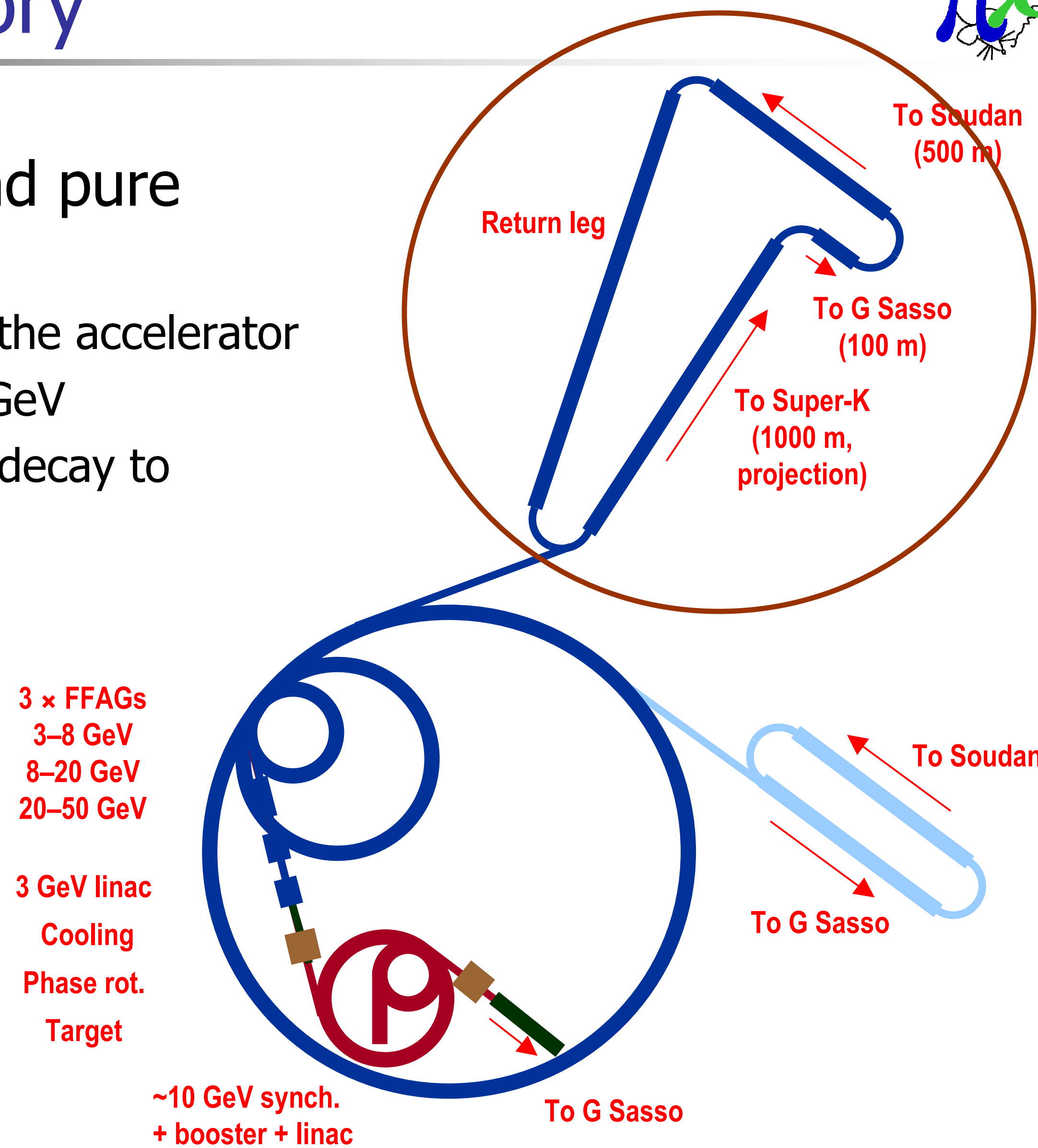
Neutrino Factory

- Intense, high energy and pure source of neutrinos
  - Muon beam cooled to fit in the accelerator
  - Muons accelerated to ~50 GeV



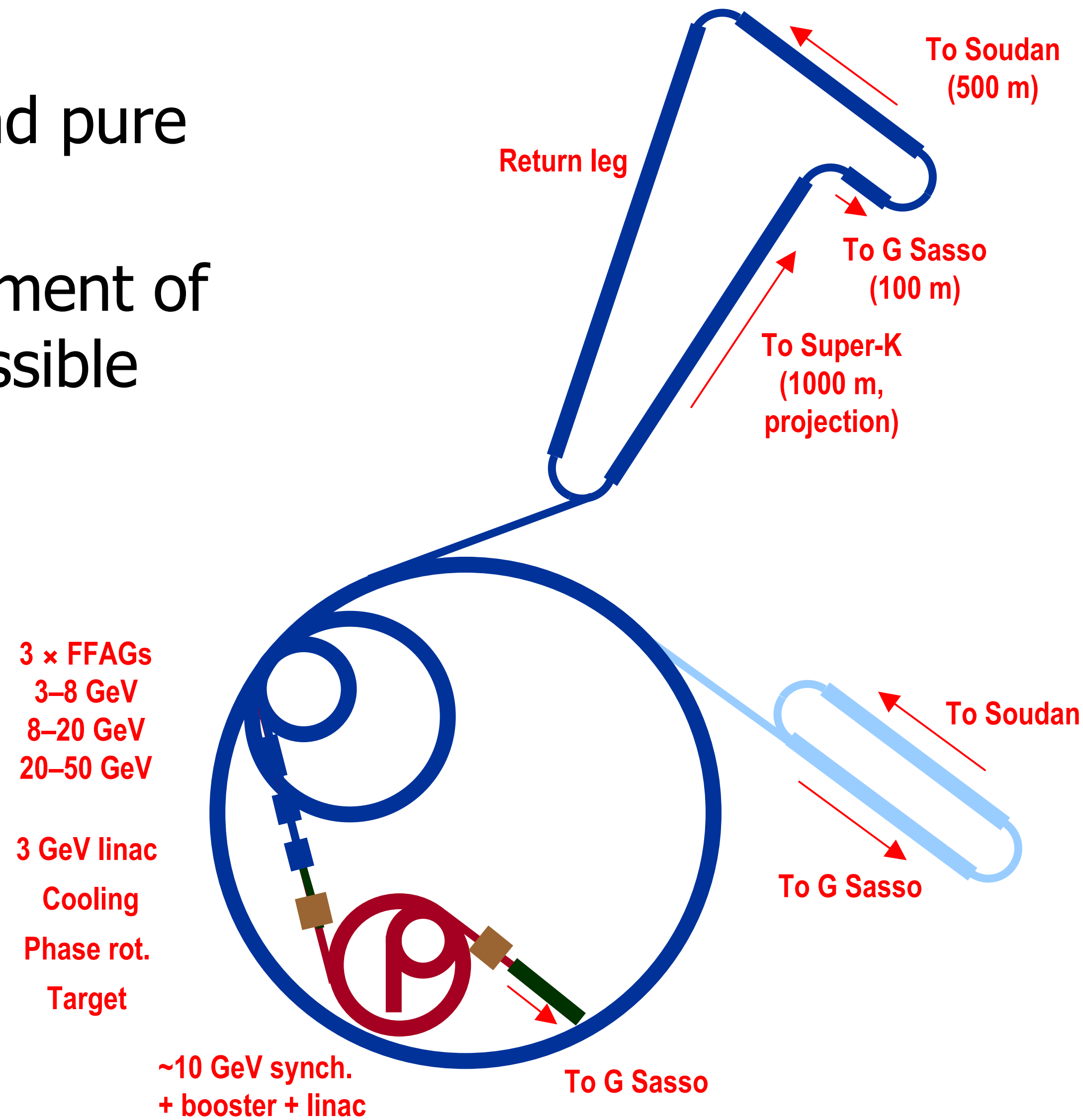
Neutrino Factory

- Intense, high energy and pure source of neutrinos
  - Muon beam cooled to fit in the accelerator
  - Muons accelerated to ~50 GeV
  - Muons stored in a ring and decay to neutrinos in long straights



Neutrino Factory

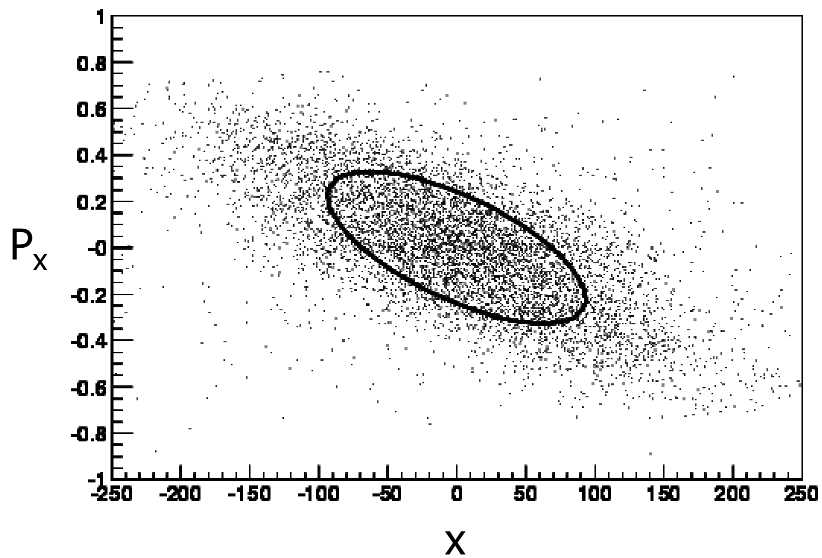
- Intense, high energy and pure source of neutrinos
- High precision measurement of neutrino mixing and possible leptonic CP violation



Beam Emittance

- Define “beam size” in a 2N dimensional phase space by quantity called beam emittance, ε_n
  - Volume of an ellipse aligned with beam at 1 rms

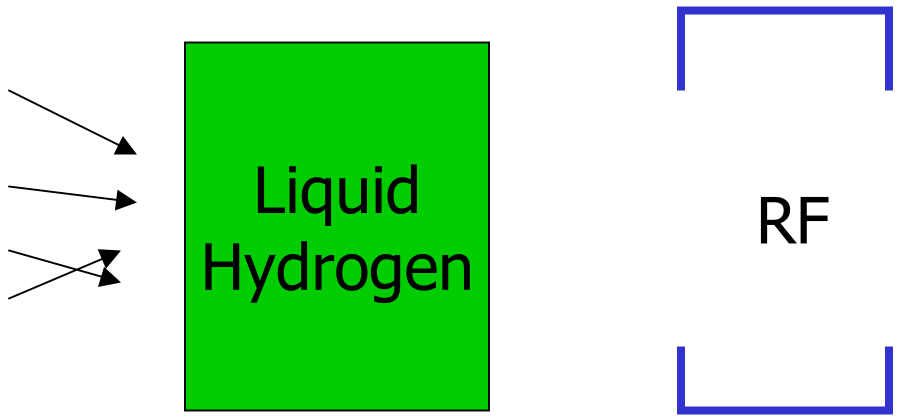
$$\varepsilon_n = \frac{\sqrt[2N]{|V|}}{m}$$



- Where **V** is the covariance matrix of canonical phase space coordinates e.g. x, y, p_x, p_y

Muon Cooling

- Muon cooling increases beam phase space density using material placed across the beamline



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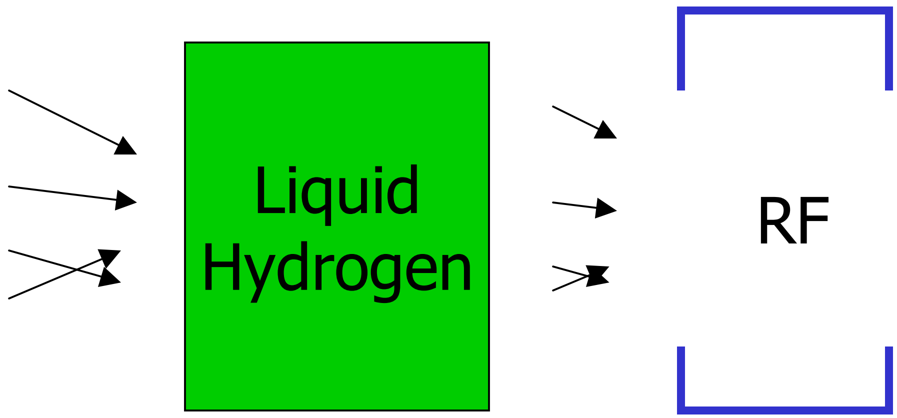

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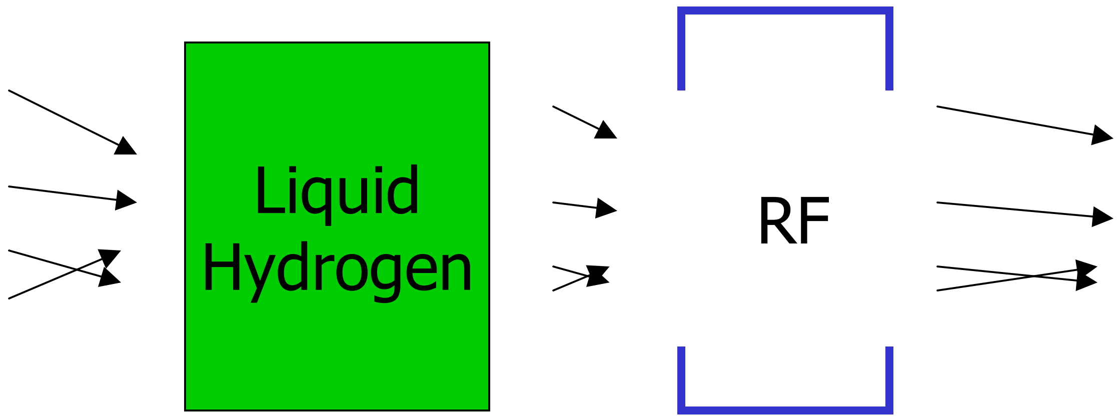

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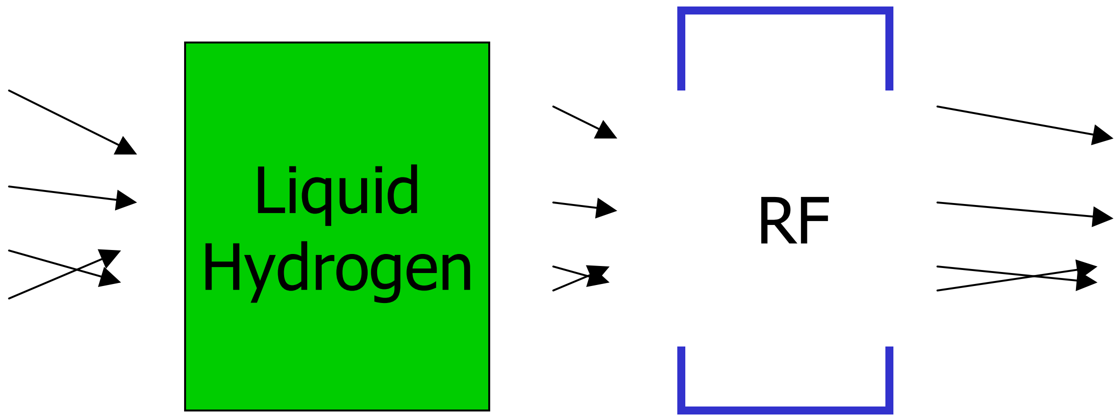
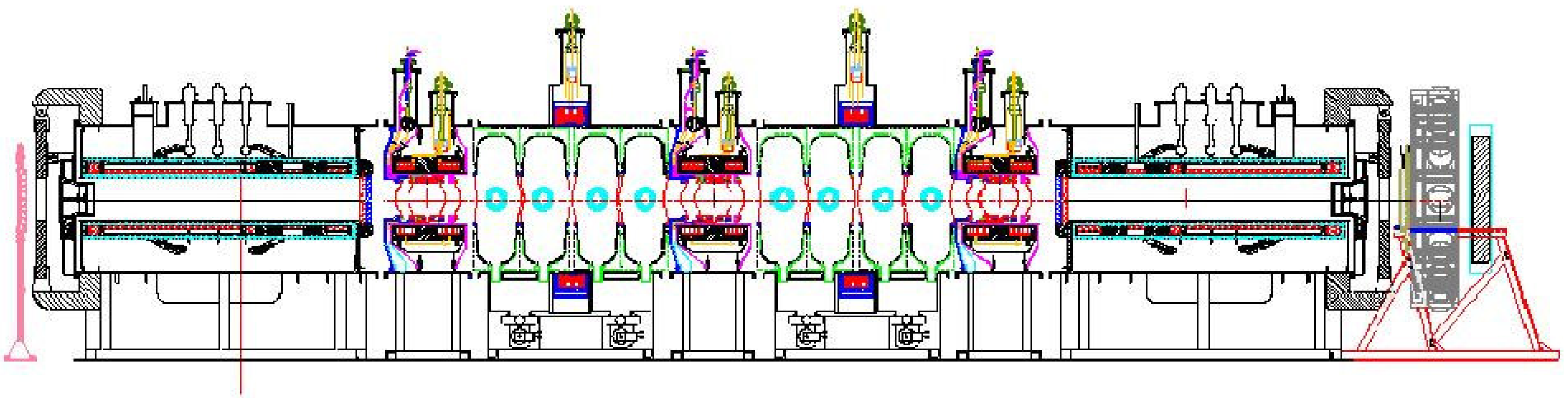


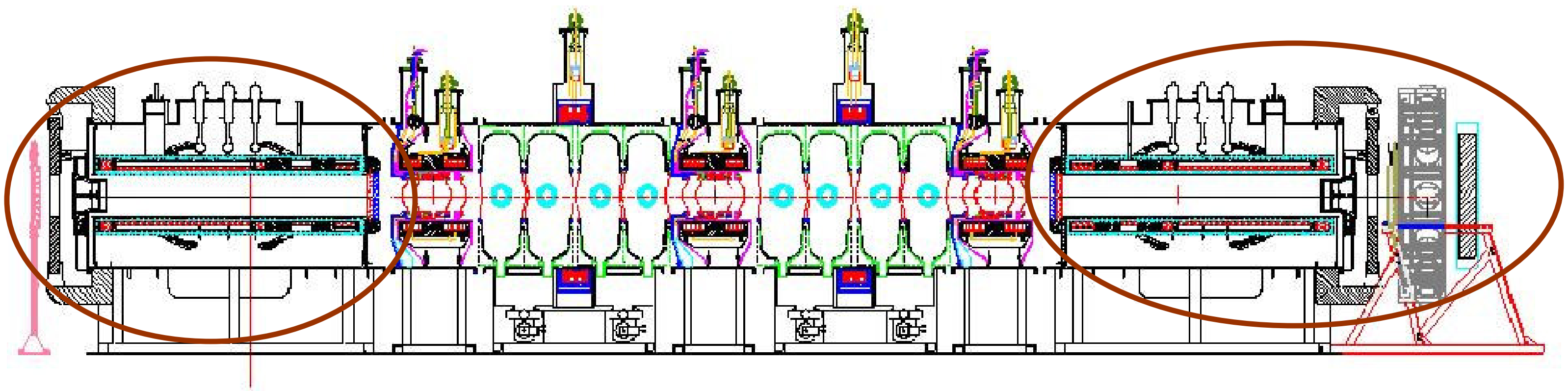
- By cooling we can fit more muons into our accelerator and improve the neutrino rate
- Liquid Hydrogen is the optimal material to use
  - Multiple scattering heats the beam
  - Liquid Hydrogen has more dE/dx vs multiple scattering

Muon Ionisation Cooling Experiment



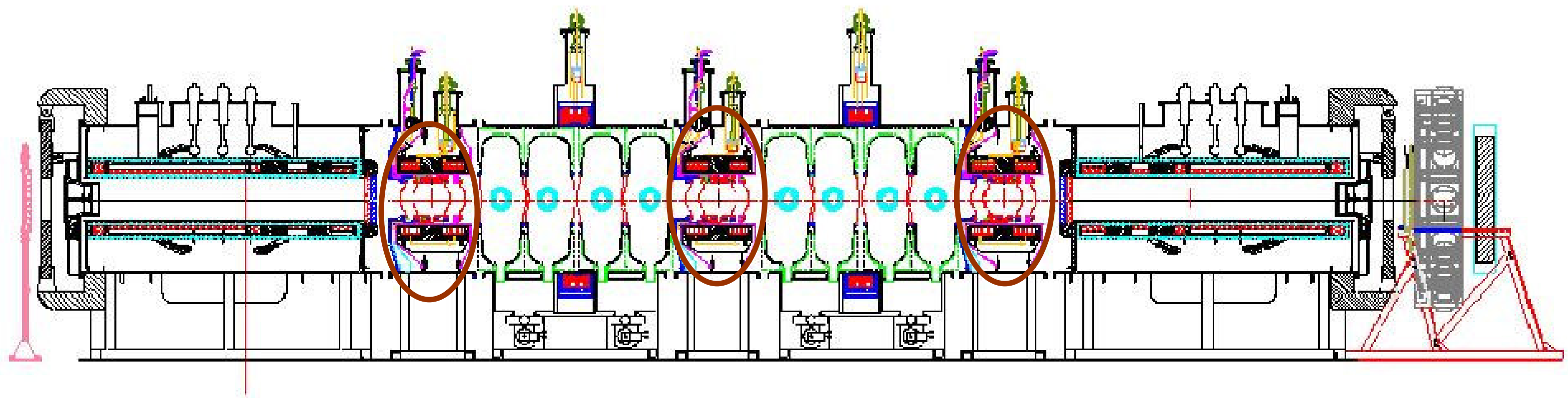
- Aim is to measure reduction in beam emittance over a cell of a cooling channel

Muon Ionisation Cooling Experiment



- Aim is to measure reduction in beam emittance over a cell of a cooling channel
  - Detectors measure phase space vector of particles and distinguish muons from pions and electrons

Muon Ionisation Cooling Experiment



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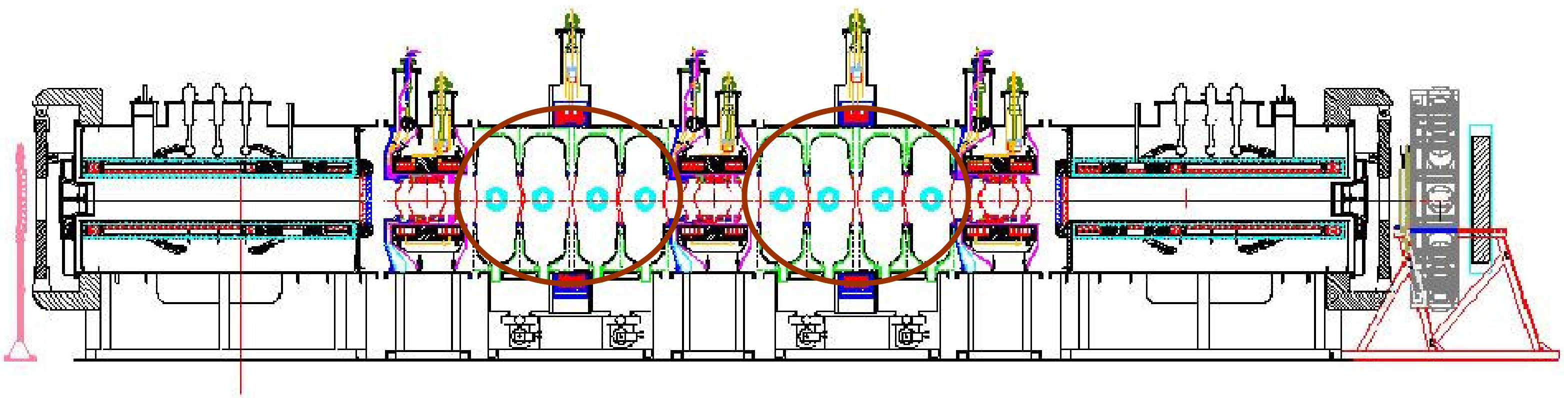
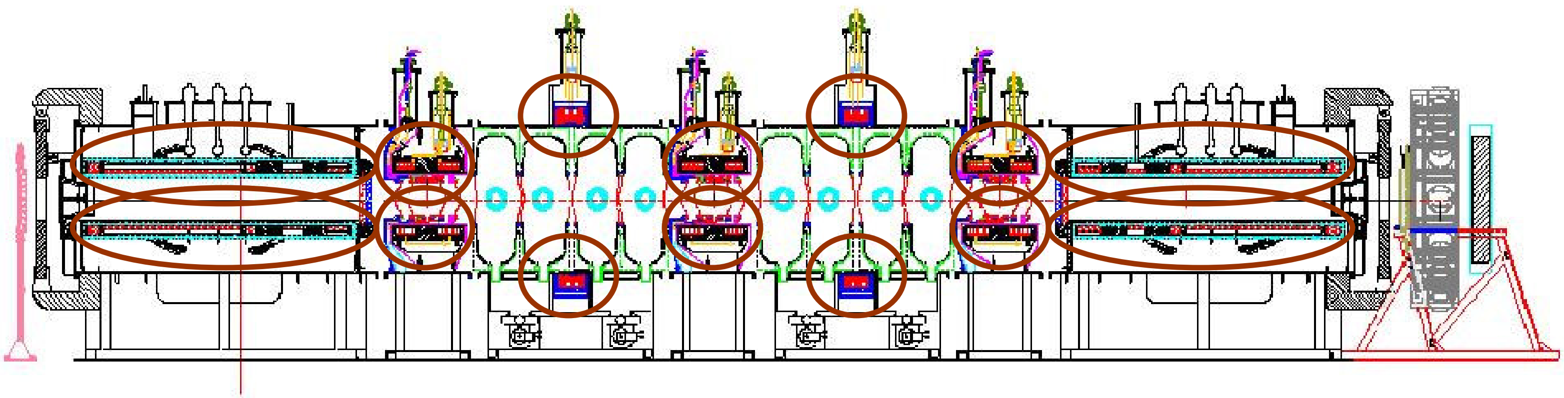


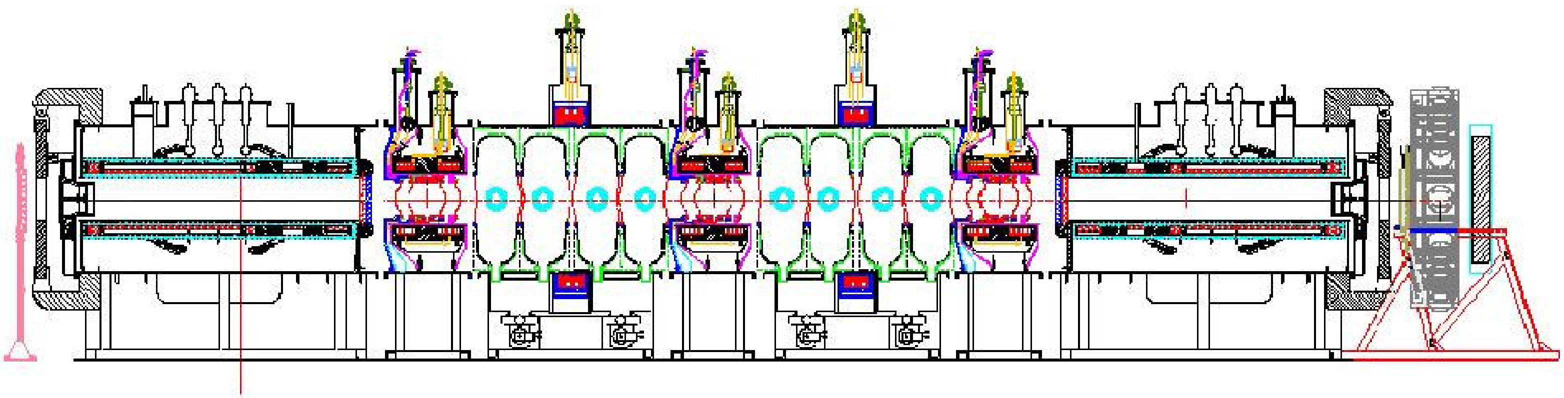
- Aim is to measure reduction in beam emittance over a cell of a cooling channel
    - Detectors measure phase space vector of particles and distinguish muons from pions and electrons
    - Liquid Hydrogen absorbers provide cooling
    - RF Cavities keep beam momentum ~ constant

Muon Ionisation Cooling Experiment



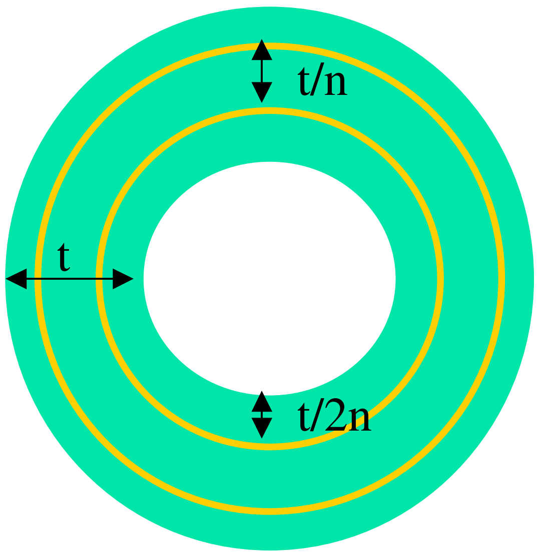
- Aim is to measure reduction in beam emittance over a cell of a cooling channel
  - Detectors measure phase space vector of particles and distinguish muons from pions and electrons
  - Liquid Hydrogen absorbers provide cooling
  - RF Cavities keep beam momentum ~ constant
  - Coils provide transverse focusing

Muon Ionisation Cooling Experiment

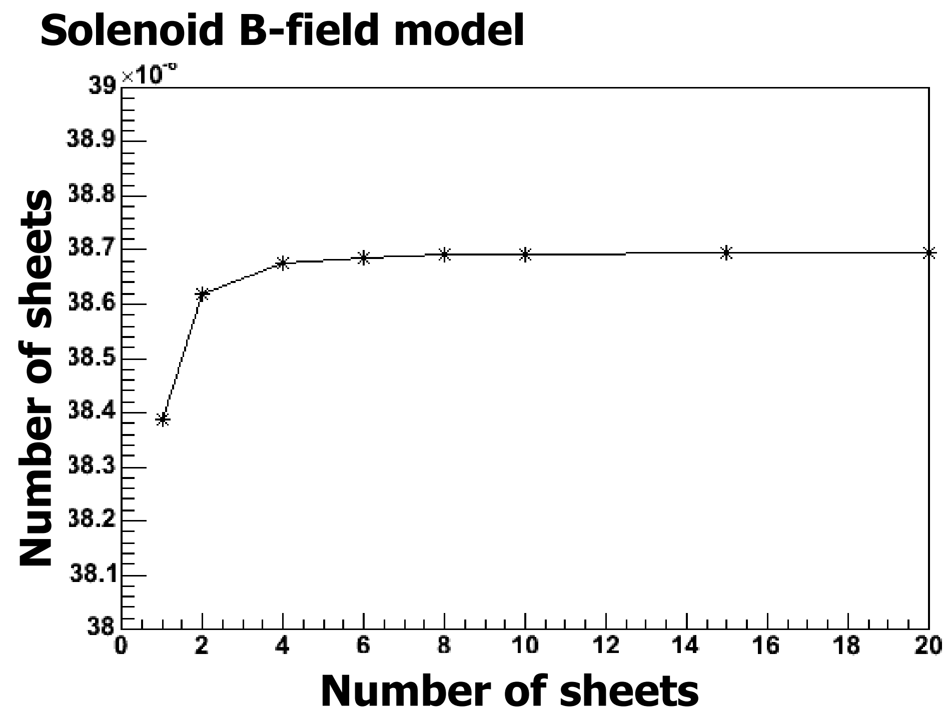


- Aim is to measure reduction in beam emittance over a cell of a cooling channel
- Challenging to build
- Ionisation cooling has never been demonstrated
- Reproduce and measure emittance to unprecedented 0.1% precision
- Simulated in MICE's customised accelerator, detector and beam optics package G4MICE, based in GEANT4

Solenoid Simulation



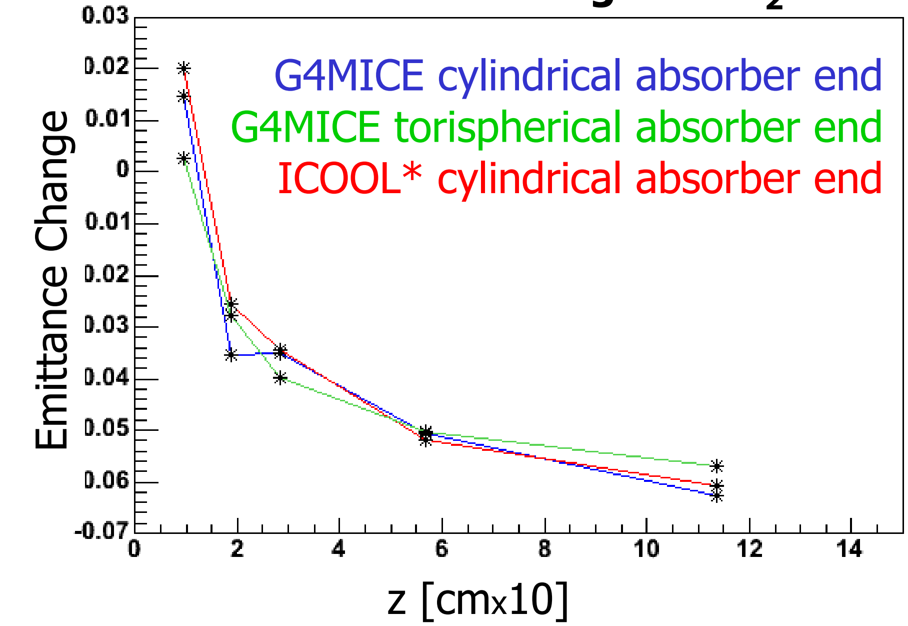
n = number of sheets
t = thickness



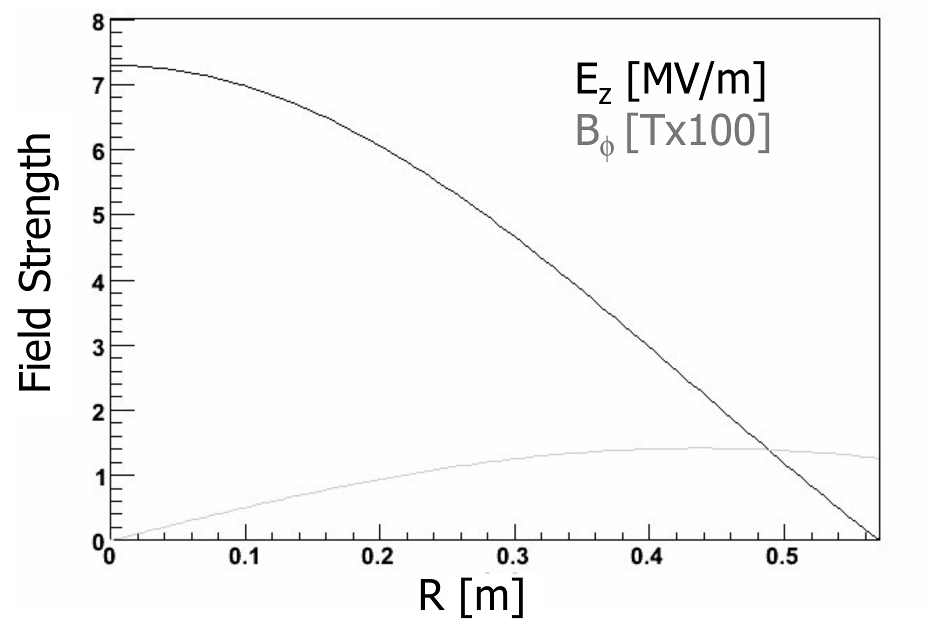
- Solenoid simulated using concentric cylindrical current sheets
  - Analytical model for one sheet is well known
  - In the limit of a large number of sheets, expect to achieve good field model
  - We will measure the fields and compare with this model

Liquid Hydrogen and RF Simulation

Transverse emittance change in LH_2



Fields in RF cavity

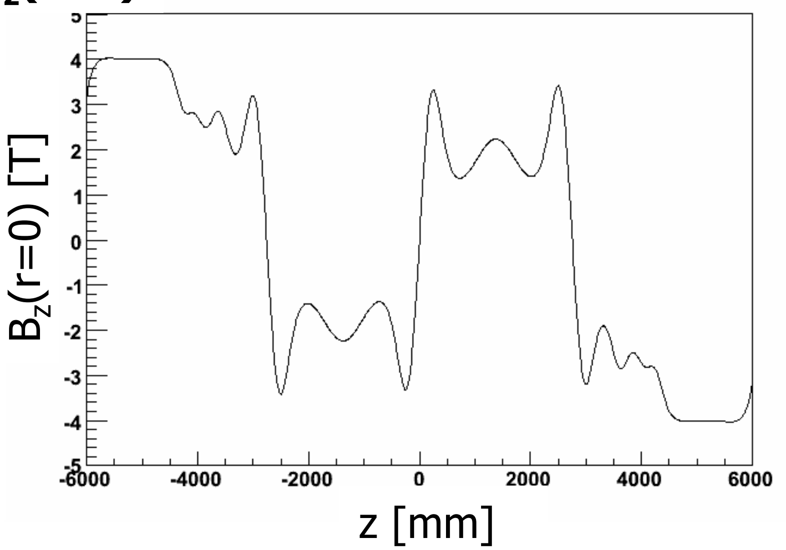


- Simulated cooling power for a typical MICE beam in a liquid Hydrogen absorber
  - Compare G4MICE with a well known software package
  - Compare realistic absorber with cylindrical absorber
- Simulated accelerating field in a MICE RF Cavity

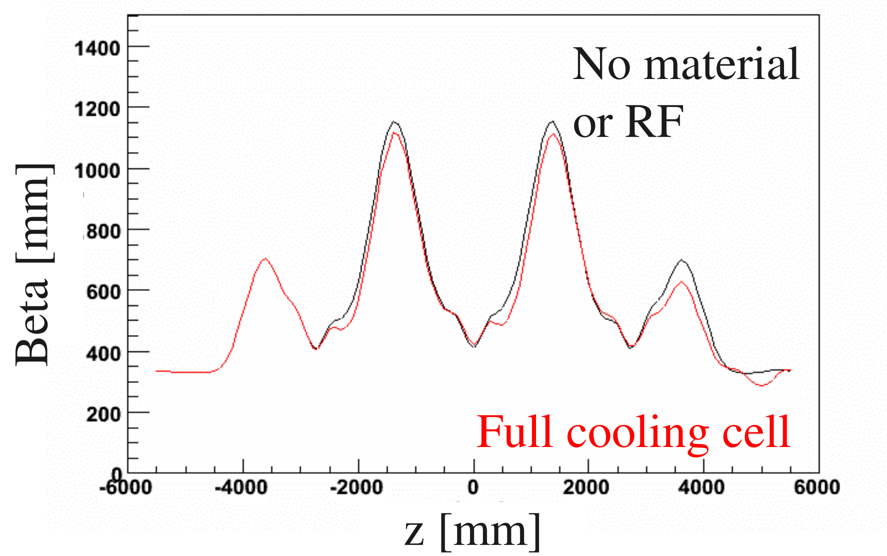
*ICOOL simulation code, Fernow, Proc. Particle Accelerator Conference 1999

MICE Baseline Magnetic Lattice

$B_z(r=0)$

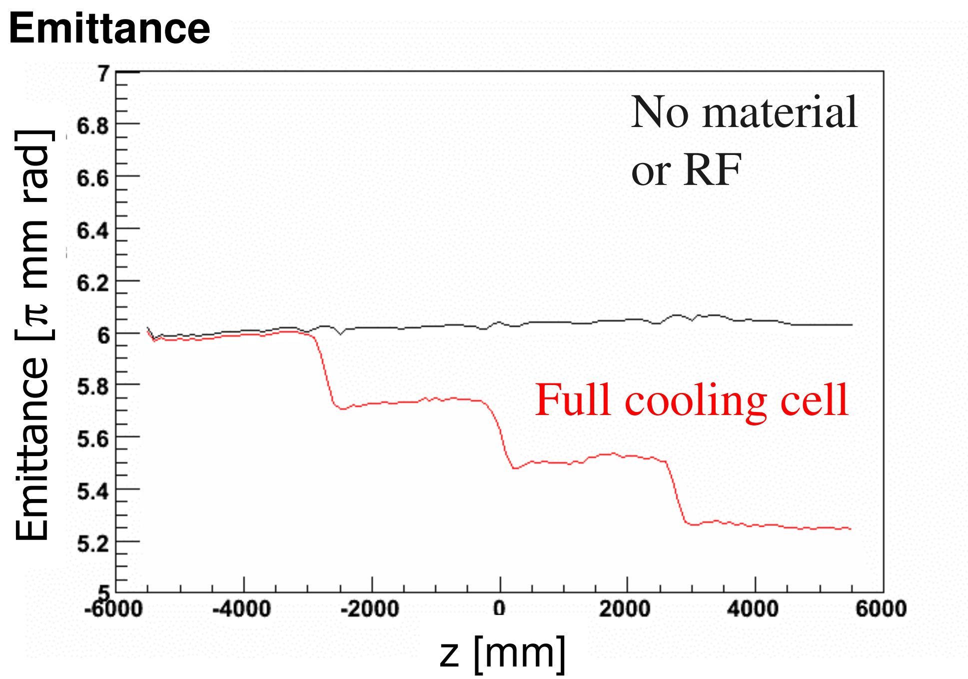


Beta function



- 8 coils of cooling lattice chosen to:
  - Maximise beam accepted into cooling channel
  - Focus muons at the absorbers
  - Minimise scraping
- 6 coils in Spectrometer solenoids provide up to 4T field constant to 1% over fiducial volume
- 4 matching coils control beam from spectrometer to cooling lattice

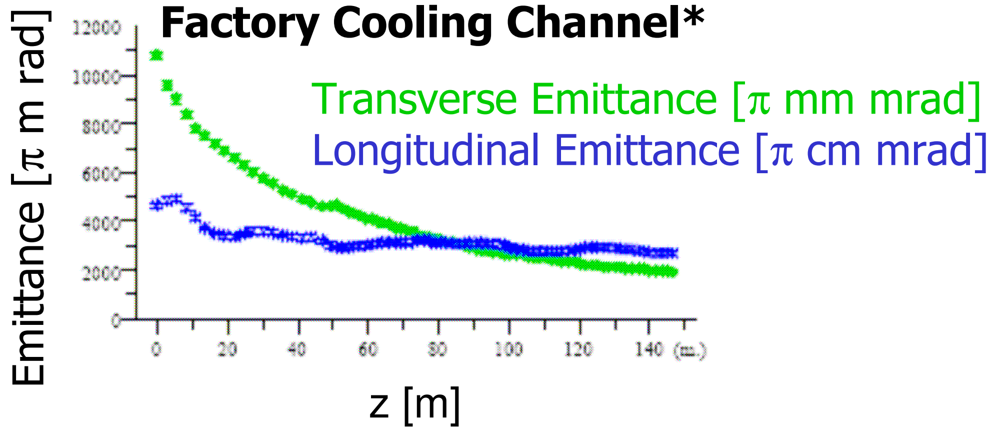
Simulated Cooling Performance



- Simulated cooling performance for typical beams
  - Simulated using MICE's customised beam tracking, detector modelling and beam optics analysis package based on GEANT4
  - Simulated for a typical MICE case
    - MICE is designed to run with many different input emittances and input momenta

Measurement Requirement

Emittance through a Neutrino Factory Cooling Channel*

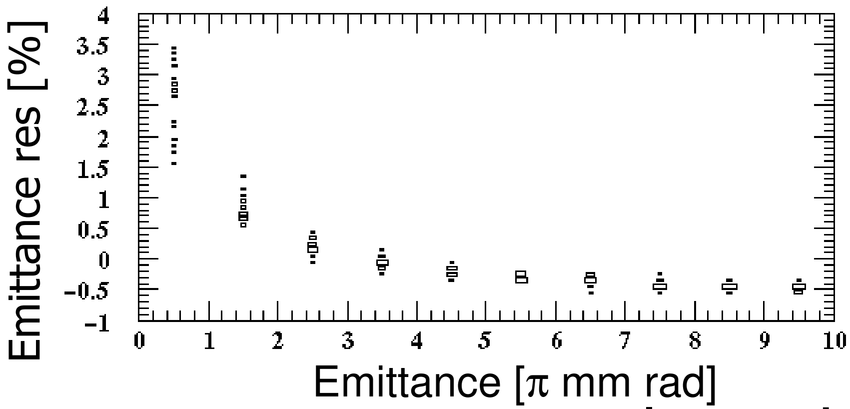


- Desire to extrapolate measurement from 1 cell to many
- Small error on a single cell measurement has a significant impact on prediction of emittance for many cells
- In practice several measurements will be made with different emittance beams for a given setting
  - But the errors will not be independent

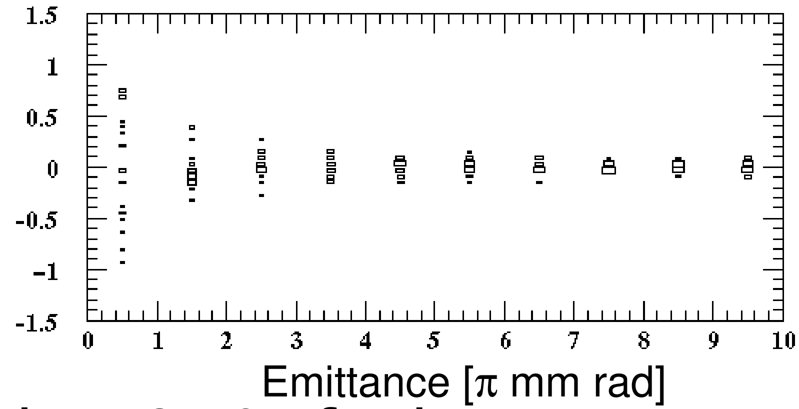
*Feasibility Study II of a Muon Based Neutrino Source, 2001, ed. Ozaki, Palmer, Zisman, Gallardo

Simulated Transverse Emittance Resolution

Emittance Resolution without calibration*



Emittance Resolution with ideal calibration*



- Emittance resolution better than 0.5% for beam emittances in the region of interest
- Most of the error can be removed by careful calibration
  - Emittance resolution limited by statistics for a given measurement given a very precise calibration
  - Even if we can only estimate the resolutions to ~10%, we can still measure emittance to the desired precision

*C.Rogers, M. Ellis, Proc. Particle Accelerator Conference 2005, MPE013

Summary

- MICE looking to measure emittance to high precision
  - Unprecedented precision for emittance measurement
- Detector design is approaching completion
  - High resolution tracking and time of flight measurements
  - Precise particle identification
- Construction of MICE has begun
- First beam October 2007