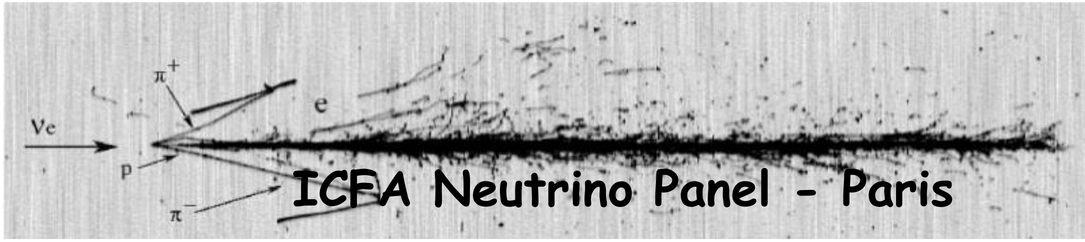


MICE : the International Muon Ionization Cooling Experiment

MICE Collaboration

M. Bonesini

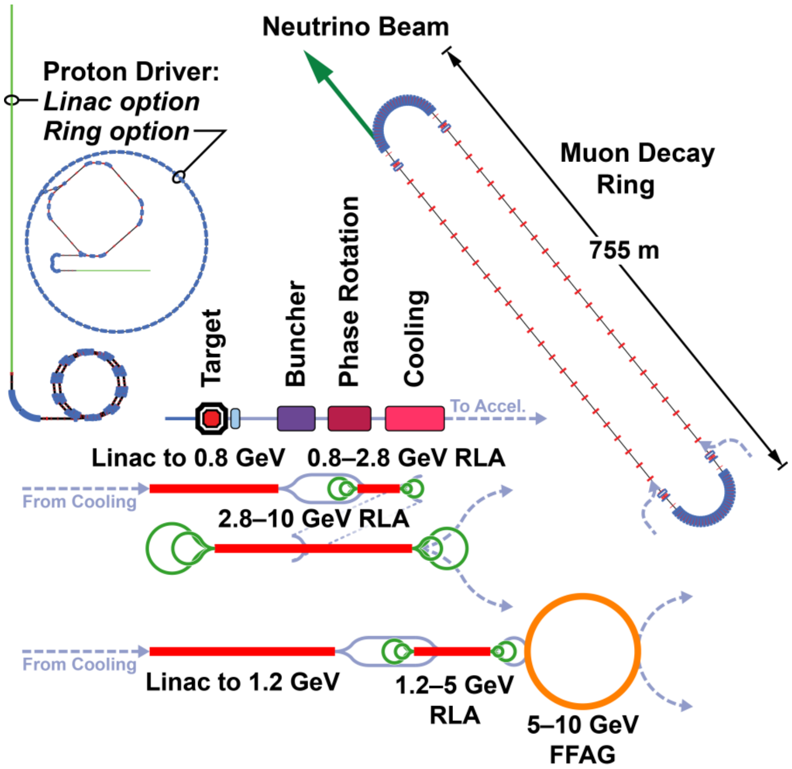
INFN, Sezione di Milano Bicocca

Dipartimento di Fisica G. Occhialini, Milano Bicocca

Milano Italy

Neutrino Factory

International Scoping Study baseline



S.Choubey et al., Design Study, IDS-NF-20 (arXiv:1112.2853) and updates

neutrino factory:
accelerate muons and store to produce neutrinos

$$\boxed{\mu^+ \longrightarrow e^+ \nu_e \overline{\nu}_\mu}$$

- Flux known to 1% or better
- High energy electron neutrinos

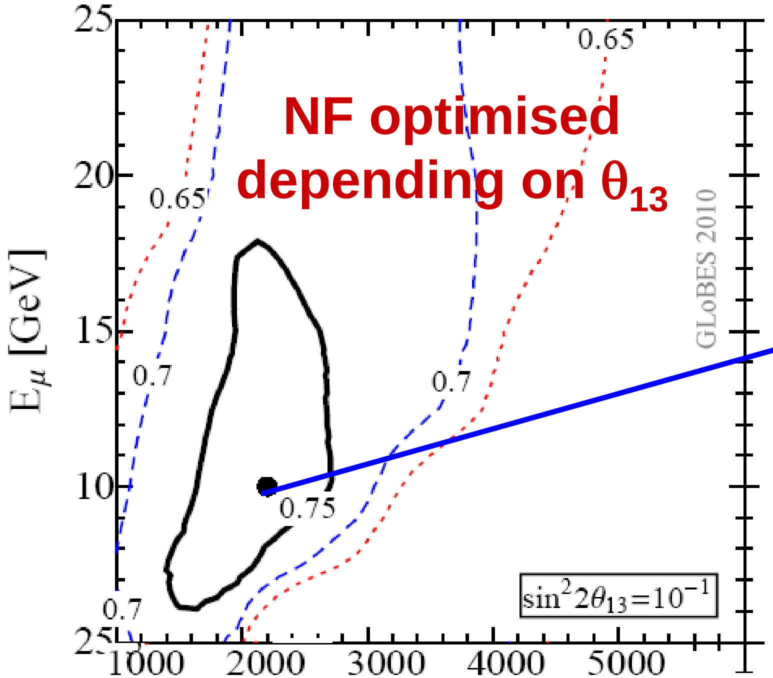
Golden Channel:
long baseline oscillation manifests itself by wrong sign muons:

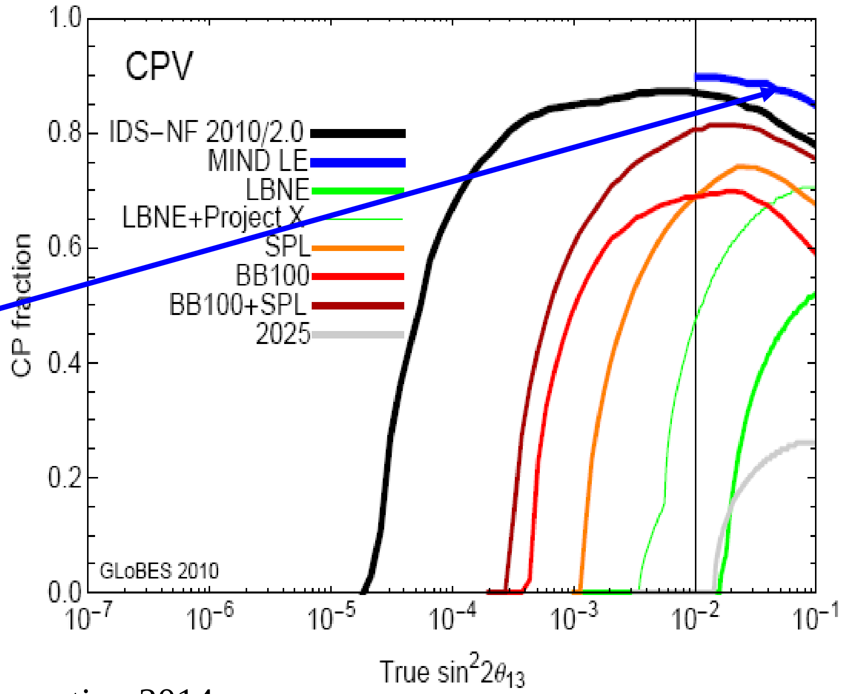
$$\boxed{\nu_e \rightarrow \nu_\mu \,;\, \nu_\mu + N \longrightarrow \mu^- + X}$$

Large (100 kton) magnetized iron detector
Unique ability to test $\nu_e \rightarrow \nu_\tau$

Neutrino Factory optimisation

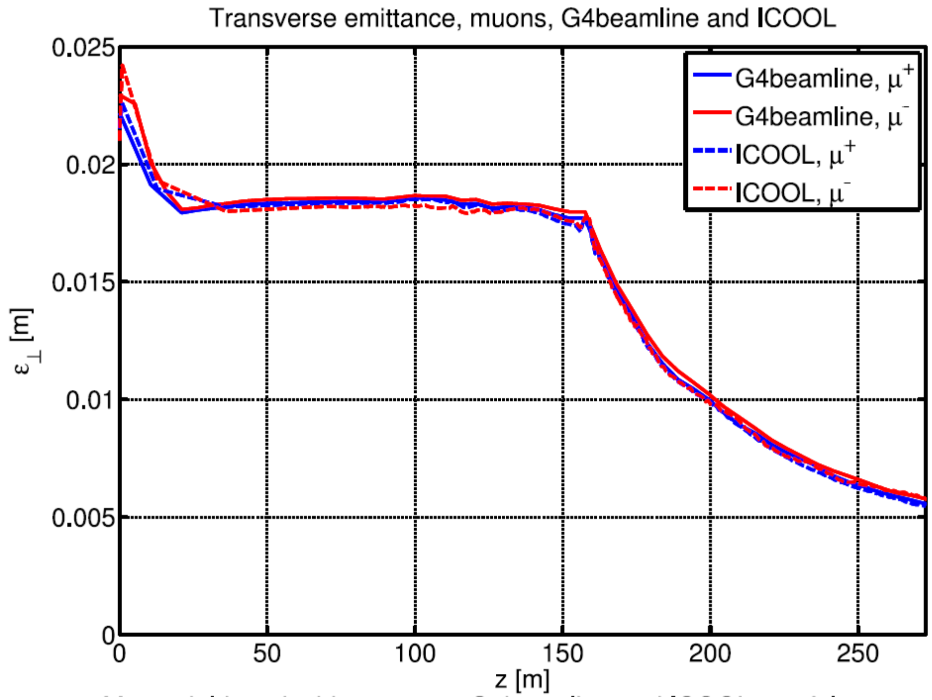
- Neutrino Factory optimisation depends on value of θ_{13}
- At $\sin^2 2\theta_{13}$~0.1 optimum is ~10 GeV NF with ~2000 km baseline
- Neutrino Factory offers best sensitivity and smallest $\Delta\delta_{CP}$ ~ 5^o out of all future facilities

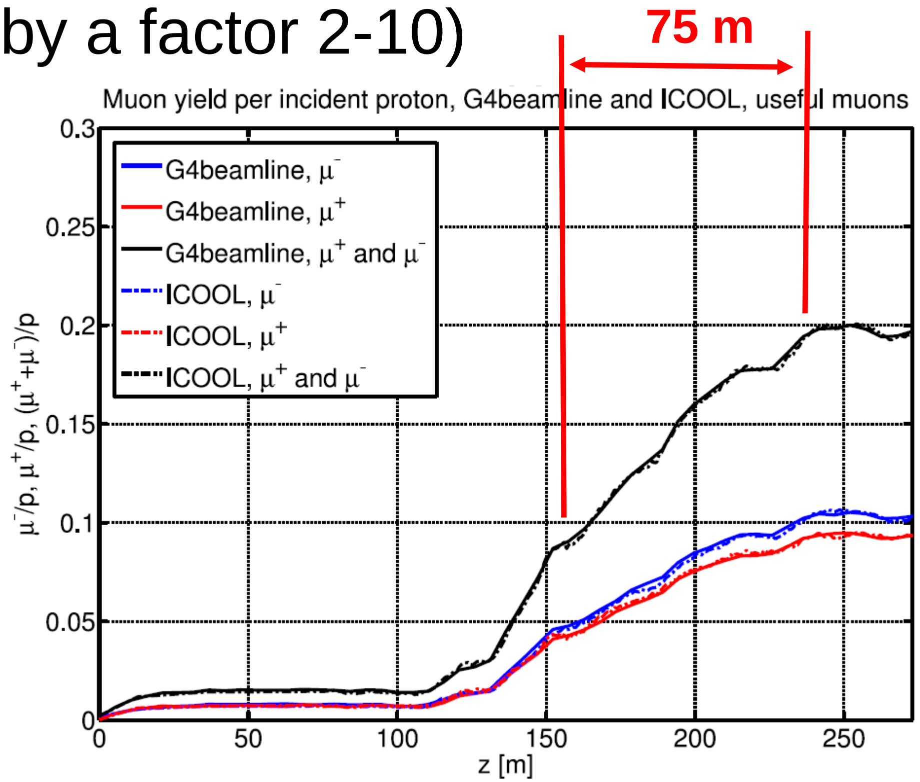




Neutrino Factory: cooling reqs.

- Cooling important to deliver Neutrino Factory performance (increase by a factor 2-10)



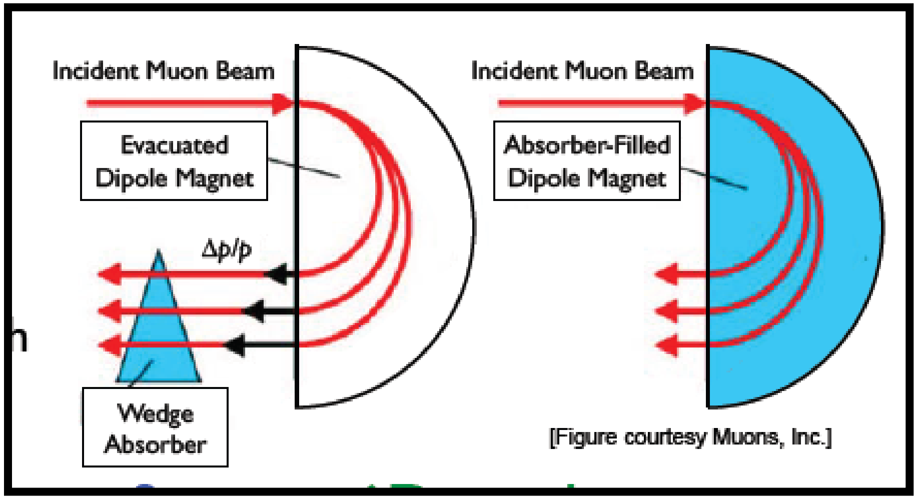


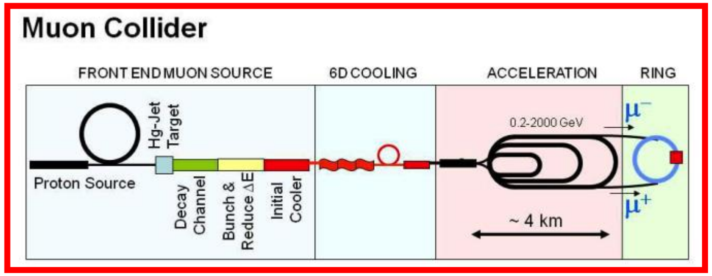
Emittance: 18 mm rad → 7.5 mm rad **Muon yield: 0.08 μ/p.o.t. → 0.19 μ/p.o.t.**

IDS-NF design ncrease in performance: 2.4

μ-collider : cooling reqs.

- Cooling essential for Muon Collider performances (a factor ~10^6 needed)
- 6D cooling via emittance exchange





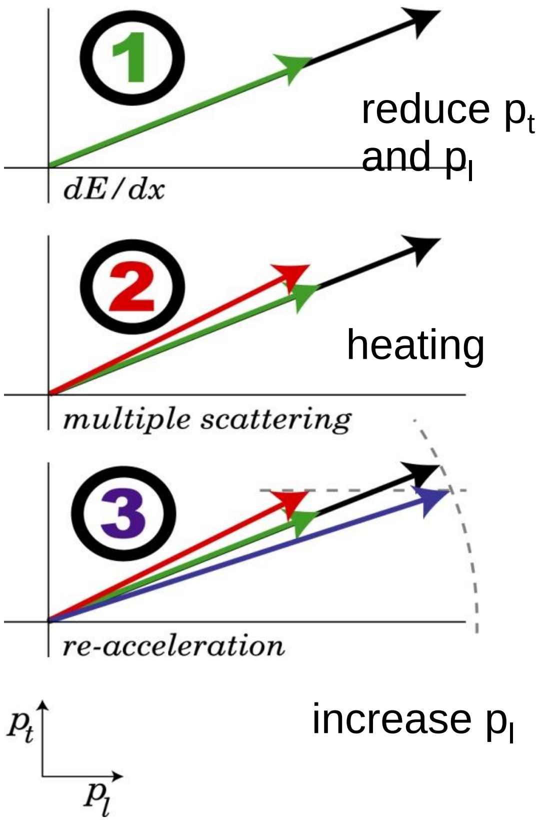
- Negligible synchrotron radiation (and beamstrahlung)
- Precise det of E_{beam} (0.003%)
- Strong coupling to the Higgs

- Ionization cooling is not directly effective for longitudinal emittance
- Two approaches to longitudinal cooling via emittance exchange (cool ε_t , exchange ε_t & $\varepsilon_{||}$)
- A wedge shaped dE/dx absorber is introduced, to increase (decrease) ionization losses for faster (slower) particles

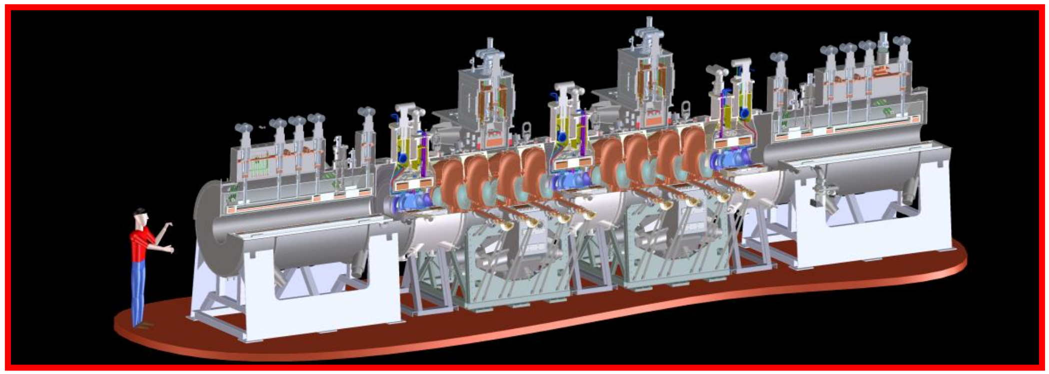
Muon ionization cooling

Stochastic cooling is too slow.
A novel method for μ+ <u>and</u> μ- is needed: **ionization cooling**

principle



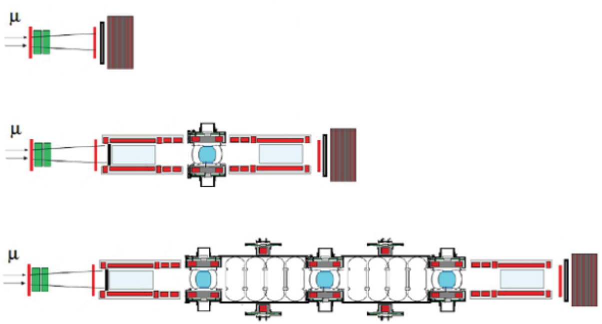
reality including beam diagnostics(simplified)



- Build a section of cooling channel long enough to provide measurable cooling (10%) and short enough to be affordable and flexible
- Wish to measure this change to 1%
- Requires measurement of emittance of beams into and out of cooling channel to 0.1% !
- Cannot be done with conventional beam monitoring device
- Instead perform a single particle experiment:
    - High precision measurement of each track (x,y,z,px,py,pz,t,E)
    - Build up a virtual bunch offline
    - Analyse effect of cooling channel with bunches of different emittances
    - Study cooling channels parameters over a range of initial beam momenta and emittances

MICE installation status

- Target
- Beamline
- PID detectors (CKOV, TOF,KL, EMR)



Step I
(completed)

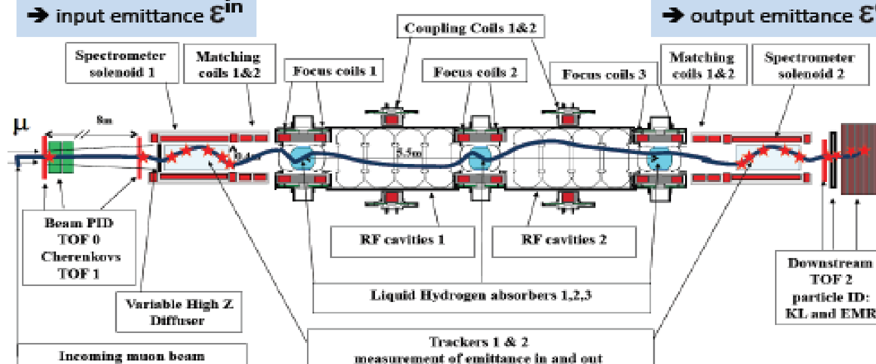
Step IV
(2015-2016)

Step VI (2019)

Measure input particle
x,x',y,y', t, t'=E/Pz
➔ input emittance ε^{in}

COOLING CHANNEL

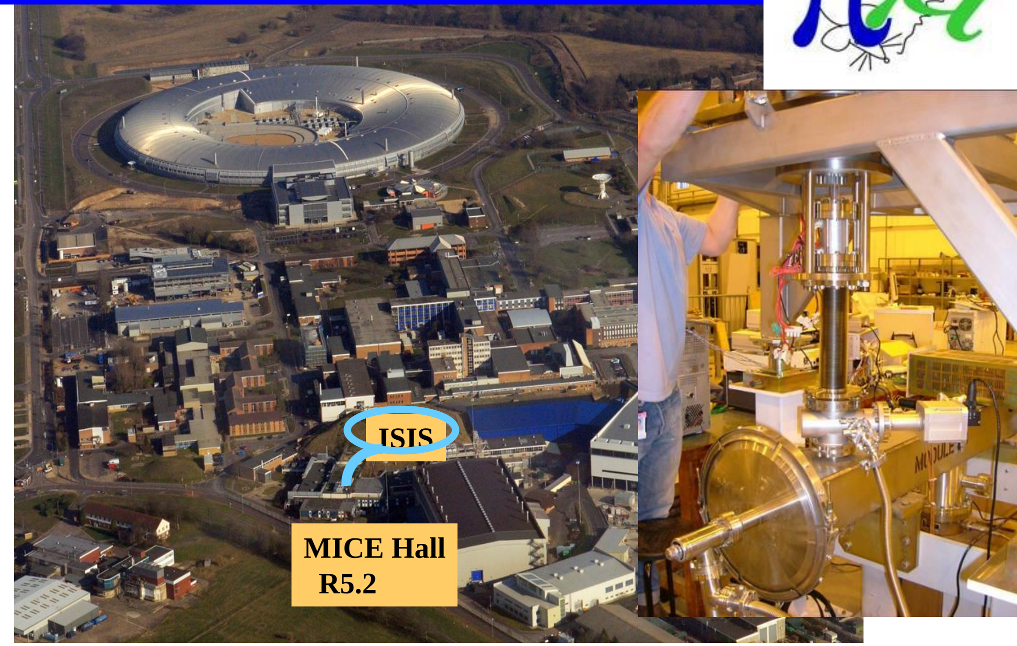
Measure output particle
x,x',y,y', t, t'=E/Pz
➔ output emittance ε^{out}

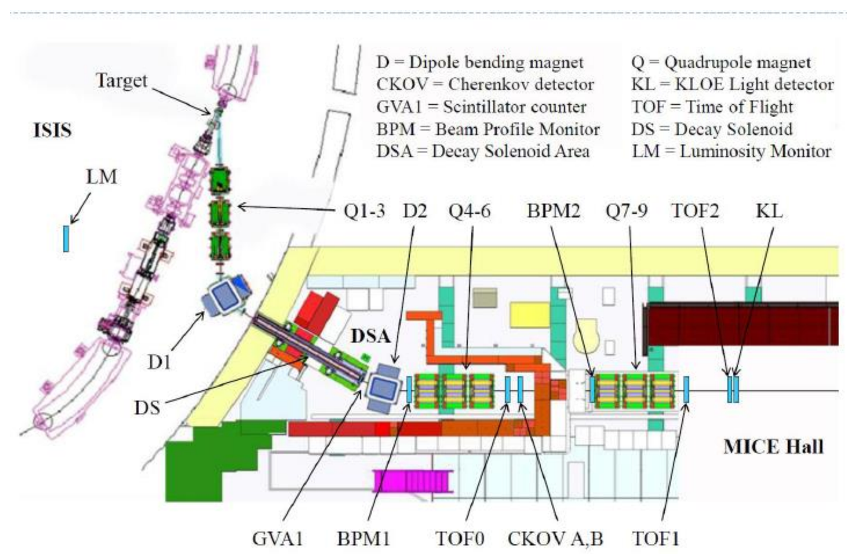


MICE in STEPS

STEP I: MICE Beamline

- ISIS 800 MeV proton synchrotron at RAL
- Titanium target, dipping rapidly into ISIS beam
- π captured by quad triplet and momentum selected by dipole (D1)
- Followed by 5T decay superconducting solenoid (5 m long): contain π and decay μ
- Second dipole momentum select muons (D2)
  - $p_{D1} \sim 2 \times p_{D2}$ μ beam
  - $p_{D1} \sim p_{D2}$ e/π calib beam





M. Bonesini – ICFA meeting 2014

MICE beam instrumentation

- **Particle identification: TOF, CKOV, Calorimeter**
  important to insure high μ purity for muon cooling measurement.
  - Upstream:
    - Time of Flight TOF0 + TOF1 x/y hodoscopes
    - 2 Aerogel Cherenkov detectors (n=1.07 and 1.12)

    ➔ π/μ separation up to 360 MeV/c

    ➔ Beam purity better than 99.9%

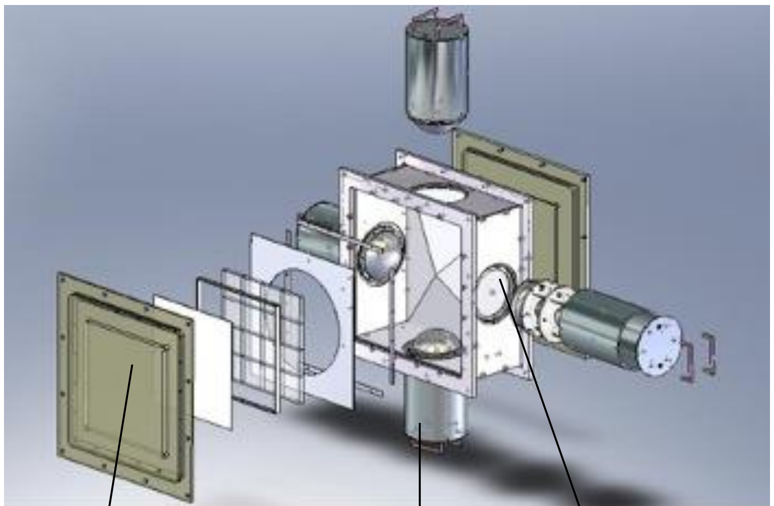
  - Downstream:

  0.5% of μ s decay in flight: need electron rejection at 10^{-3} to avoid bias on emittance reduction measurement
    - TOF2 x/y hodoscope
    - EMC Calorimeter
      - Kloe-like (KL) Lead-scintillating fiber sandwich layer
      - Electron-Muon Ranger (EMR)
        » $1m^3$ block extruded scintillator bars
        » Also measure muon momentum

- Particle tracking
  - Scintillating Fiber trackers
  - Measure position and reconstruct momentum

Two aerogel Ckov counters: CKOV a/b

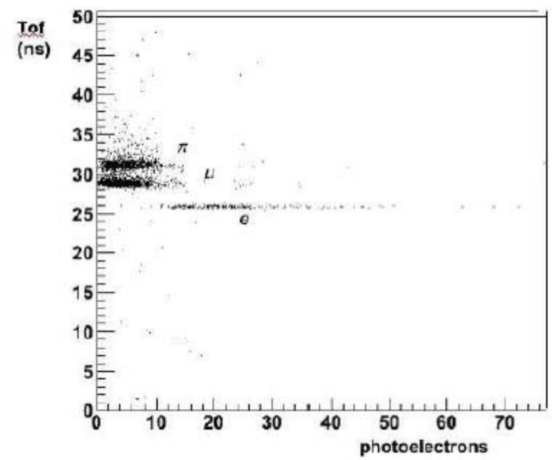
Aereogel Cherenkov detector blowup



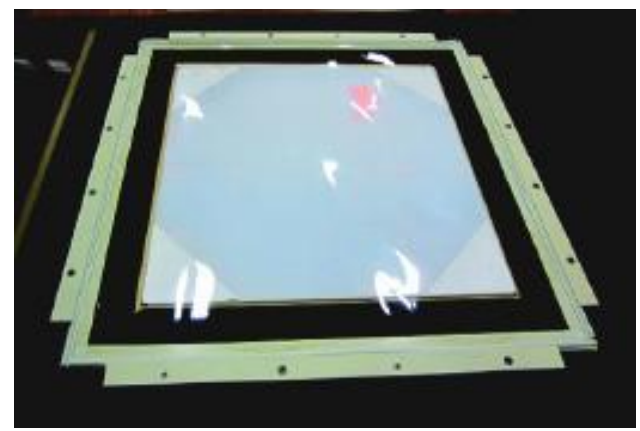
radiator

Reflector Panels

8" PMT port

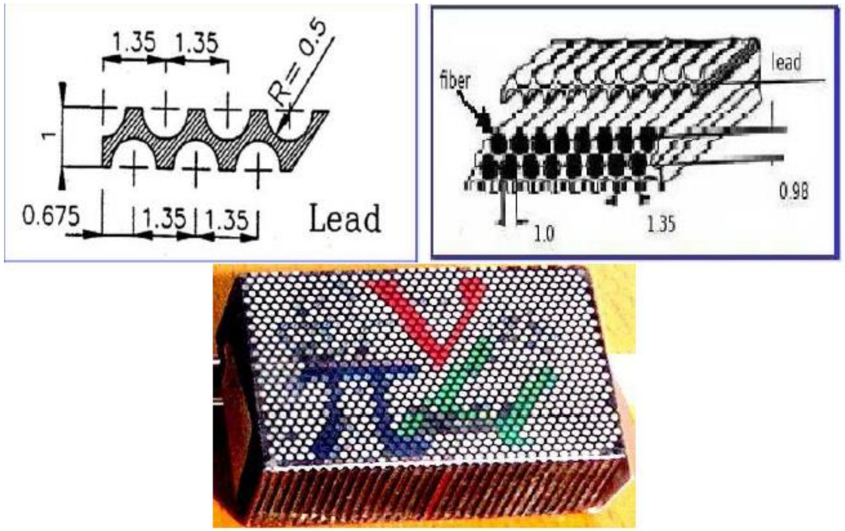


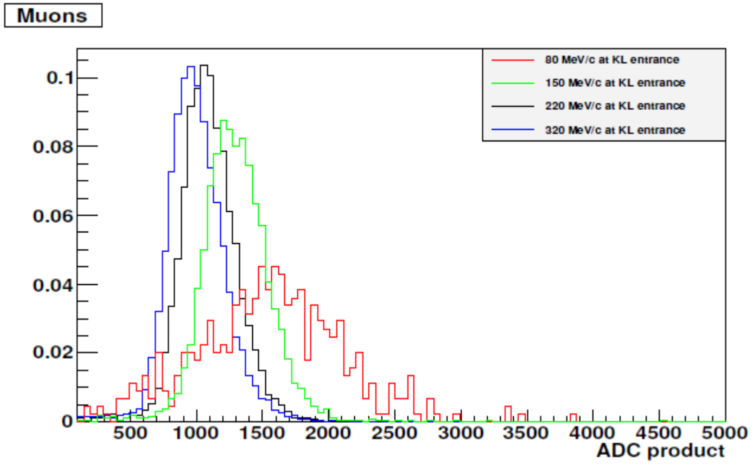
Ckov vs TOF measurement



Aerogel

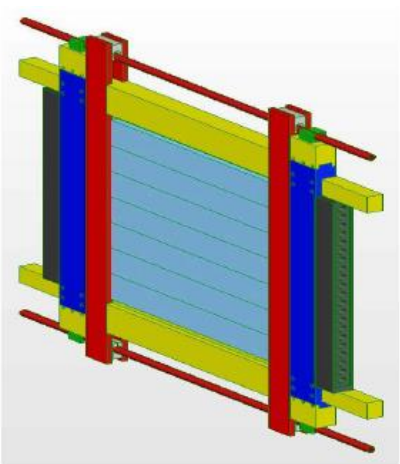
KLOE-type sampling calorimeter (KL)



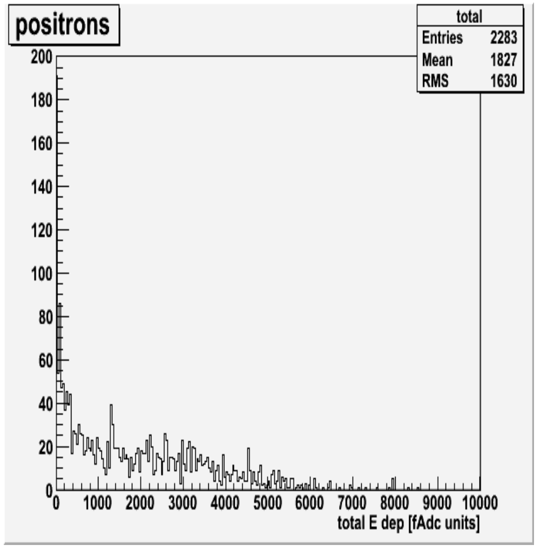


KL response to muons

Schematic layout of KL extruded fibers and lead



KL response to 100 MeV e^+ beam



TOF system requirements

- Exp trigger, upstream/downstream PID and measure of t vs RF
- Work in a harsh environment (high incoming particle rate, high fringe fields from solenoids, X rays from converted e^-)

Tof resolution can be expressed as:

$$\sigma_t = \sqrt{\frac{\sigma^2{}_{scint} + \sigma^2{}_{PMT} + \sigma^2{}_{pl}}{N_{pe}} + \sigma^2{}_{elec}}$$

with good timing performances (σ_t~50 ps)

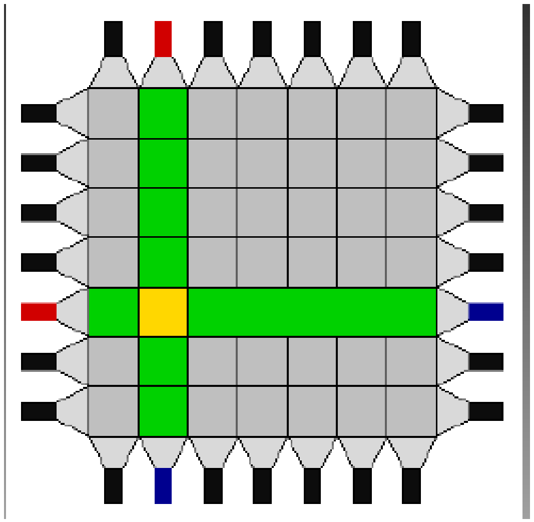
Some points to look at to have high resolution TOFs

- σ_{pl} **dominated by geometrical dimensions ~√(L/Npe)**
- σ_{scint} ~ **50-60 ps (mainly connected with produced number of γ's fast and scintillator characteristics, such as risetime)**
- σ_{PMT} **PMT TTS (typically 150-300 ps)**

+

- **HARSH Environment (shielding from B, RF noise, high particle rate)**

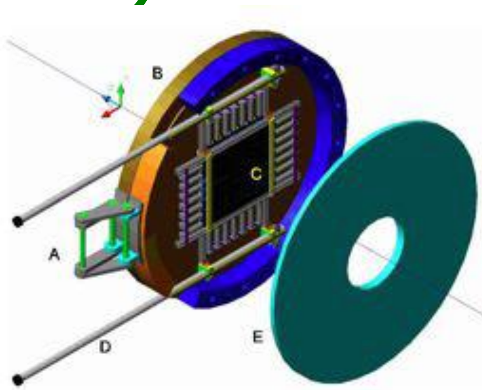
TOF system



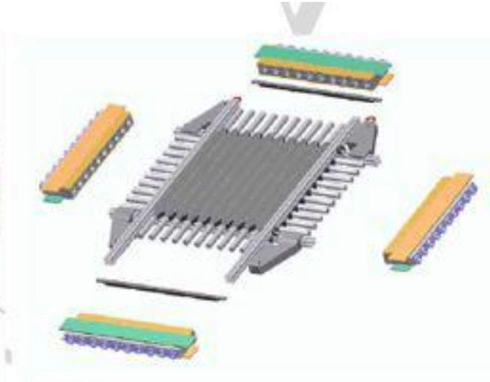
(for more details see R. Bertoni NIM A615 (2010) 14)

- X/Y scintillator hodoscopes
- Hamamatsu R4998 PMTs
- CAEN V1724 FADC + V1290 TDC
- time resolution σ_t ~50 ps **meets reqs.**

•**problems:** high incident particle rate (1 MHz) and solenoid fringe field (up to 1kG)

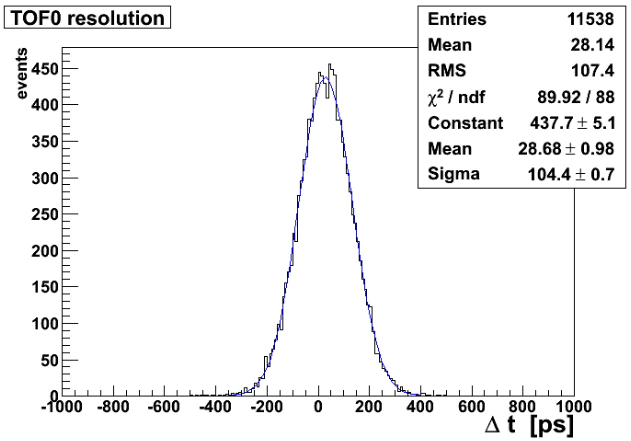


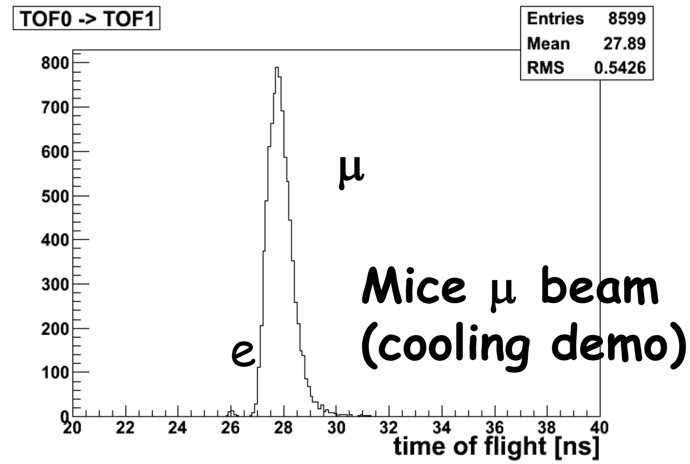
External B-field Shielding via global cage: TOF1



Local magnetic ARMCO Shielding: TOF2

TOF performances



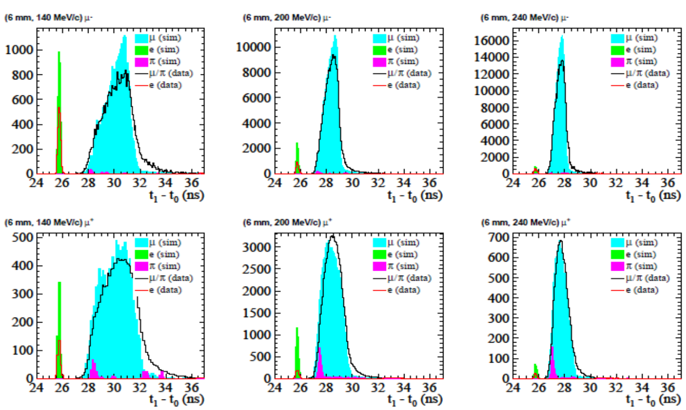


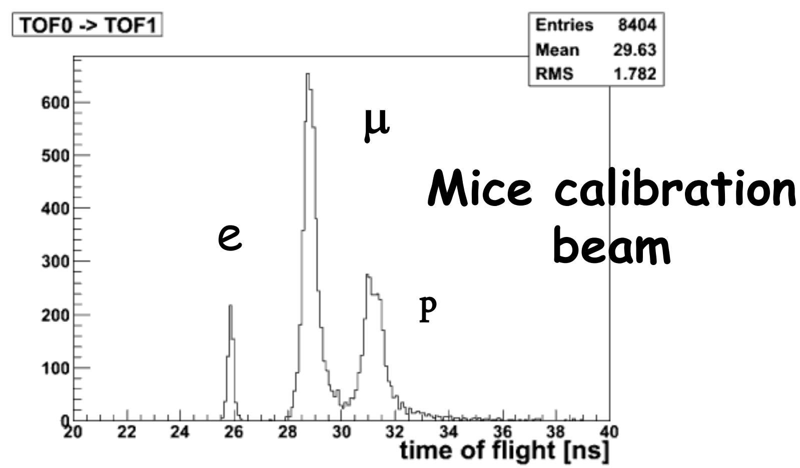
- Time resolution after calibration:

TOF0 – 51ps; TOF1 – 53ps; TOF2 – 52ps.

TOF distribution

Comparison data-MC

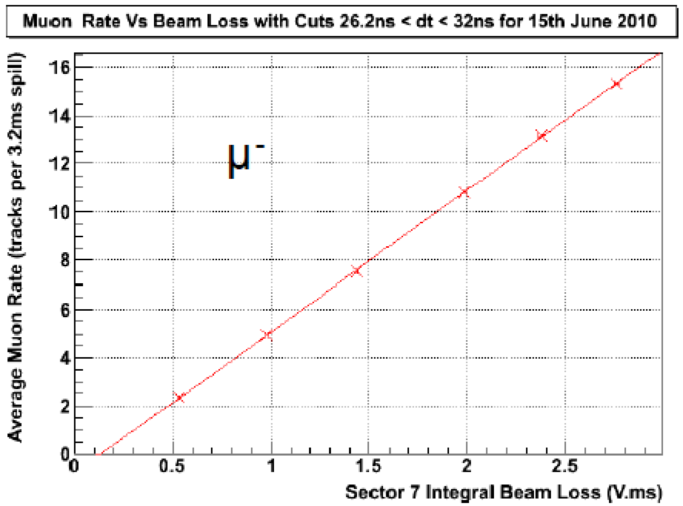




Beamline Commissioning

- The beamline has been operated over a range of momenta, producing electron, proton and muons
- TOF detectors used for PID and record beam profiles
- TOF have been used for a preliminary measure of emittance

(for more details see M. Bogomilov et al., JINST7 (2012) P05009)



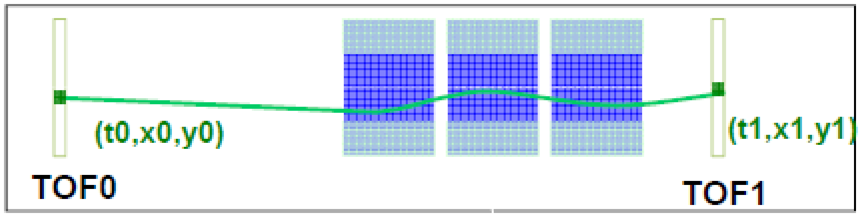
μ rate related to ISIS beam losses

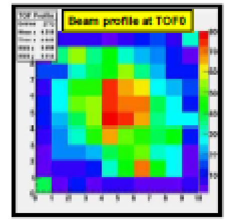
Momentum (MeV/c)

emittance	140		200		240	
3	39	80	58	171	57	237
6	98	207	112	527	85	198
10	95	183	78	200	89	174

Data collected in STEP I (in 1kevt) (+ve in black): out of 18 beams 17 measured

Emittance measurement with TOF



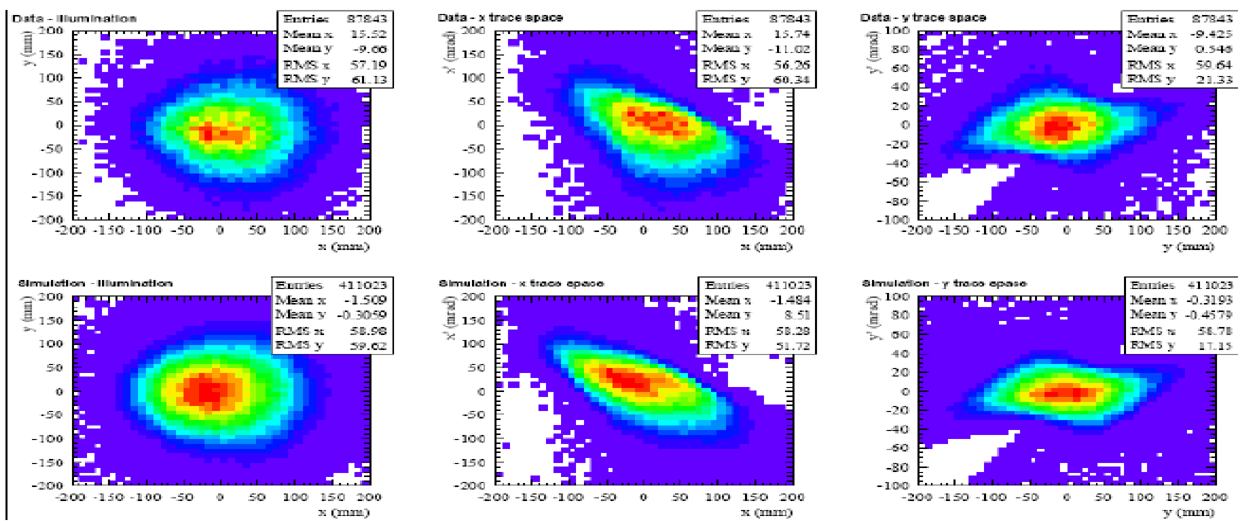


Momentum-dependent matrix relates: $(t_0,x_0,y_0,t_1,x_1,y_1) \rightarrow (t_1,p,x_1,x'_1,y_1,y'_1)$ solved by iteration

Reconstructed transverse phase space of the baseline MICE beam (6-200) at TOF1

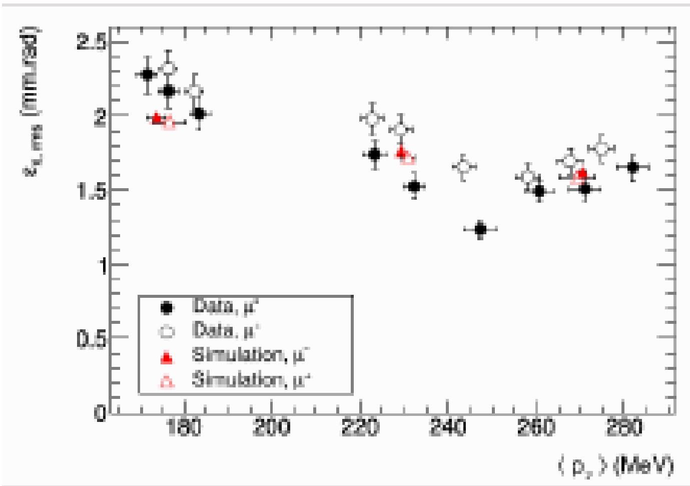
data

MC

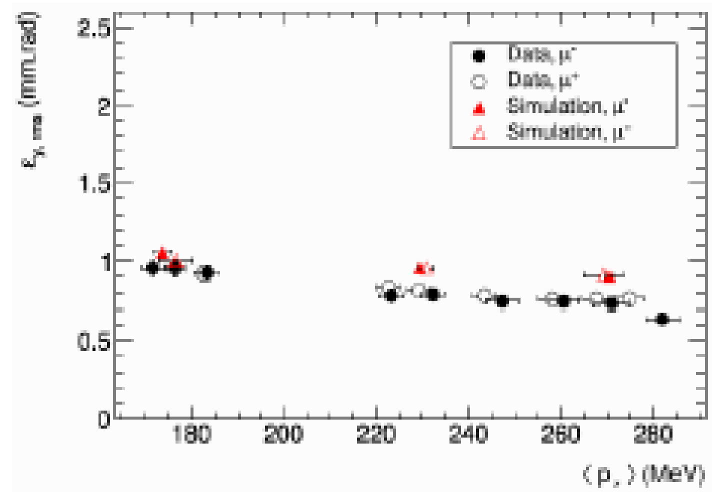


y(mm) vs x(mm) **x' (mrad) vs x (mm)** **y'(mrad) vs y (mm)**

Beam emittance: MC vs Data



Horizontal emittance

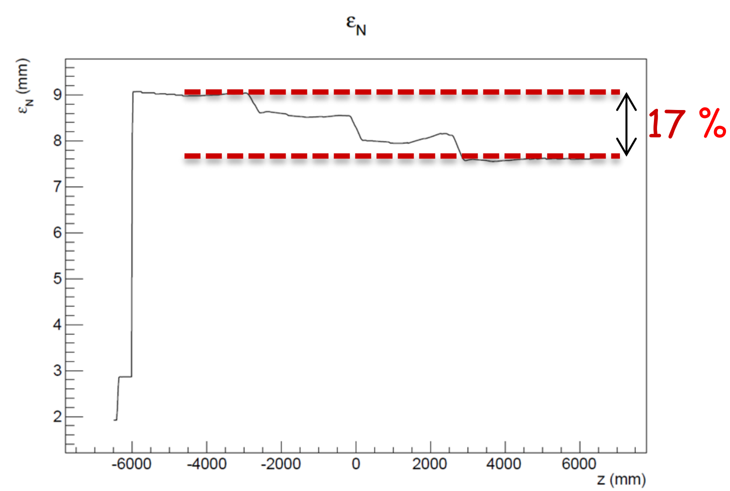


Vertical emittance

Expected Performance of the Cooling Channel

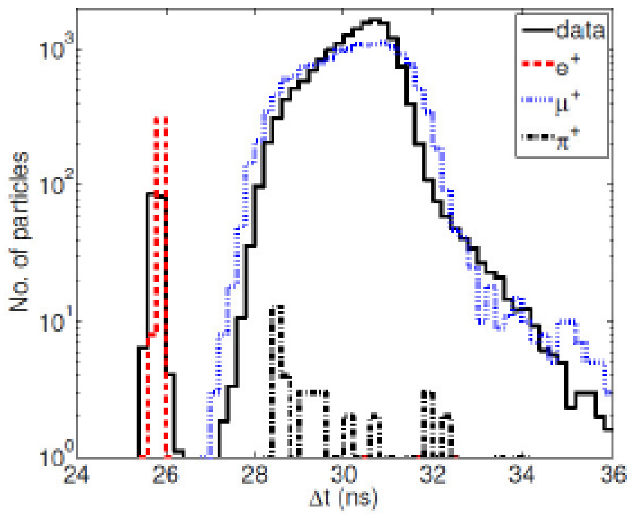
Measured beams are propagated forward through full simulated cooling channel

(More details in D. Adams et al, EPJC73 (2013) 2582)

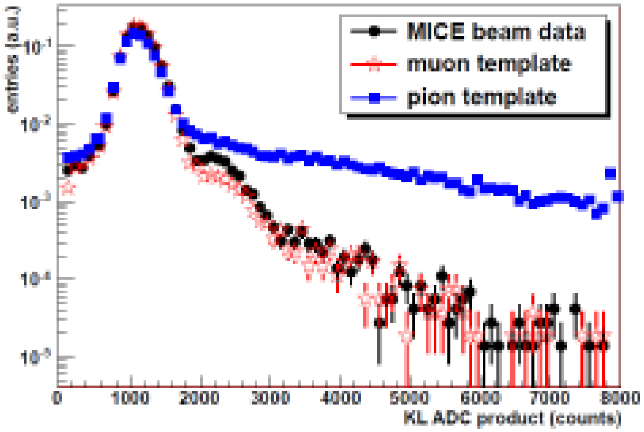


Pion contamination study

Simulation (6,140)



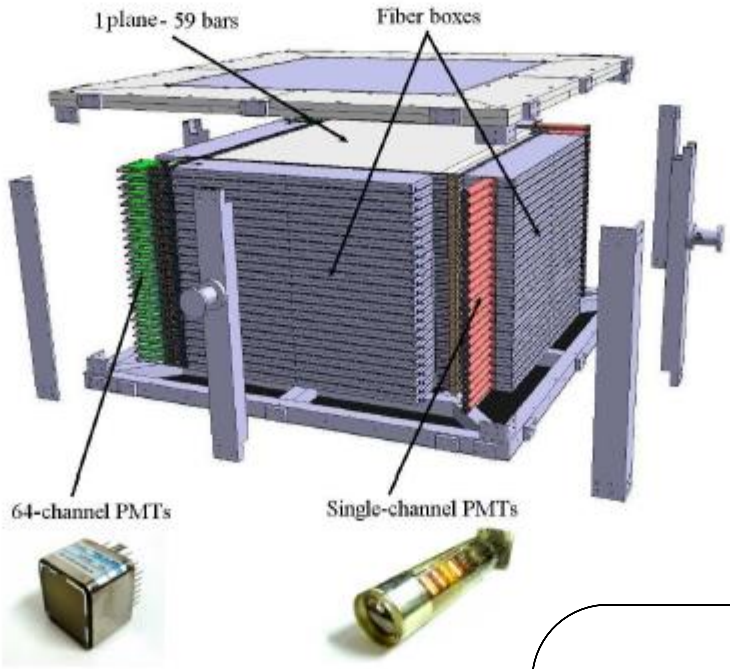
KL data



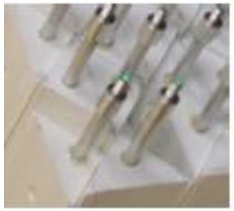
- **Pion contamination in MICE muon beam determined via TOF & KL at < 1%**
  - Muon and pions templates in KL from calibration data
  - Data & MC in agreement with pion contamination < 1% at the entrance of the cooling channel

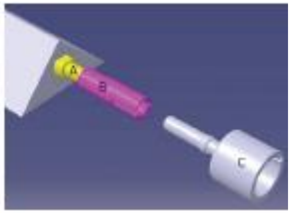
(more details in M. Bogomilov et al., MICE-NOTE 416 (2013))

Electron-Muon ranger (PID upgrade)



- 24 modules (X-Y planes)
- 48 planes
- 59 bars per plane
- 2832 bars
- 3m WLS fibers per bar
- 8.5 km WLS fibers
- single and 64-channel PMTs per plane
- 3072 + 48 channels





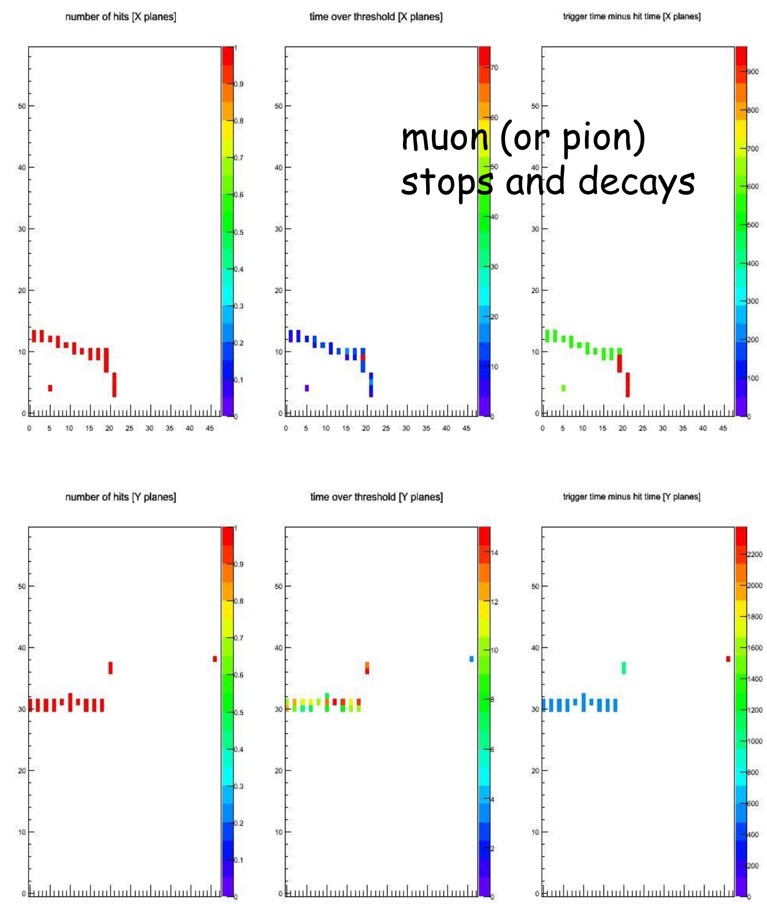
Discriminate muons from electrons.

- ❑ **Track Properties:**
  - *Muons show tracks;*
  - *Electrons converted in EM showers in KL show scattered hits*
- ❑ **dE/dx along Z**
  - *Muons have constant dE/dX up to the Bragg peak*
  - *Electrons have large fluctuations in Energy loss which tends to decrease with Z*

Data-taking in October 2013

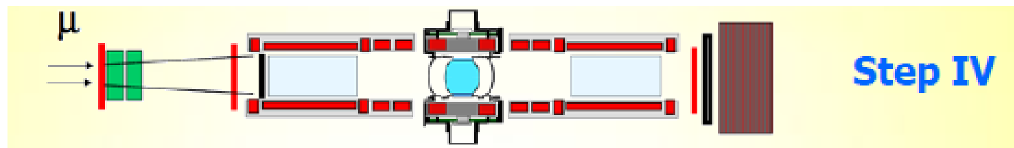
- Succesful run in October 2013
- but statistics limited by absence of Decay Solenoid

MICE beam

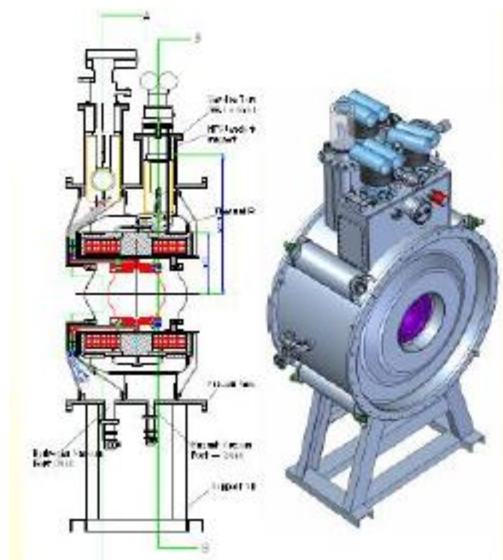


STEP IV overview

The addition of the SC spectrometer solenoids (US) and the first absorber module will enable first emittance reduction measurement using full MICE in 2015. Detector instrumentation will be completed with trackers and EMR.

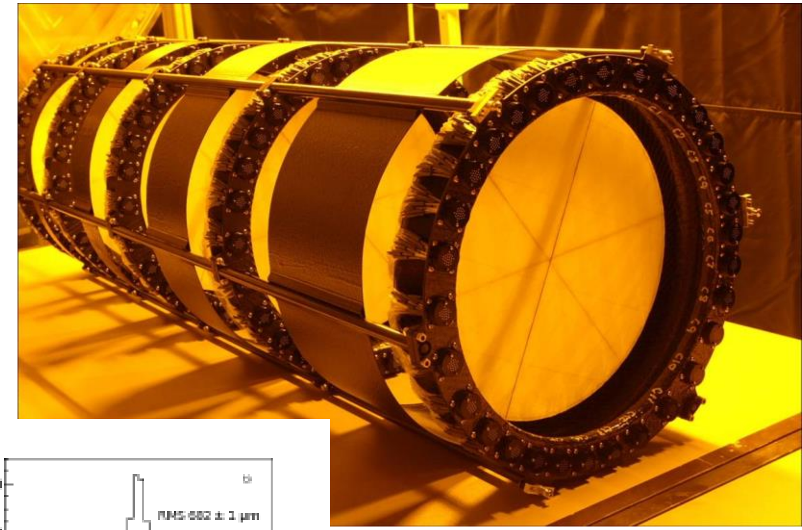


4T SC solenoids. Trackers inside.



Absorber-Focus-Coil modules

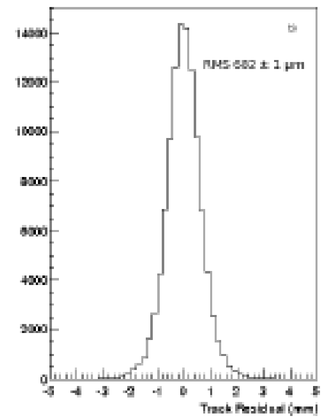
STEP IV : MICE Trackers installation



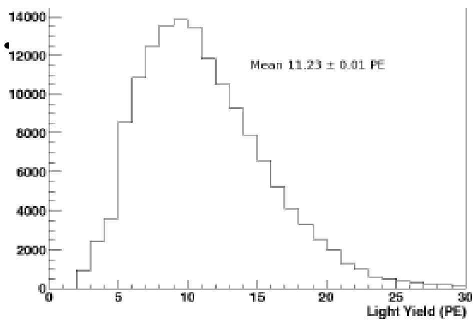
- **Scintillating fiber trackers**
  - Determine x,x',y,y' and momentum
  - Space resolution ~0.5 mm

- **Design**
  - 350 μm scintillating fiber doublet layers
  - Active area has diameter of 30 cm
  - 5 measurement "stations" with 3 planes for each tracker
  - In 4T superconducting solenoids with cryocoolers
  - Readout via VPLC (low band-gap avalanche devices, QE~80%)

(for more details M. Ellis et al. NIM A465 (2011) 136)

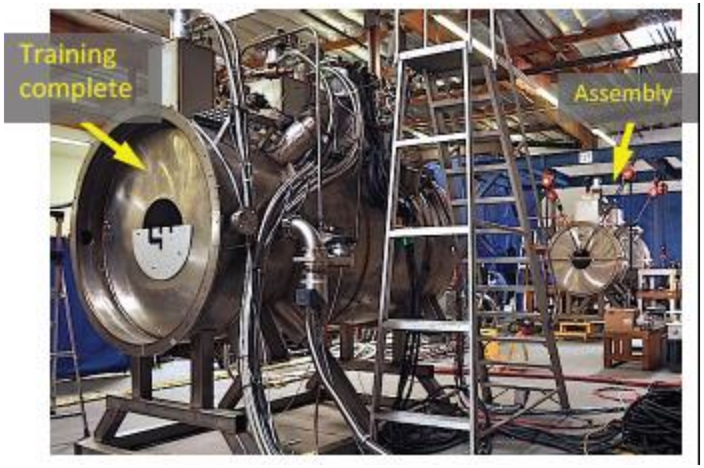


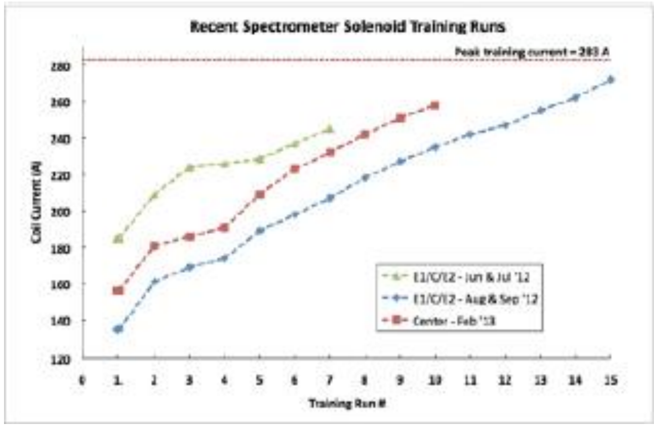
Performances with cosmics:
- **RMS of residual distribution 682+-1 μm**
- **MEAN number of P.E. 11.23+-0.01**



SC magnets: solenoids

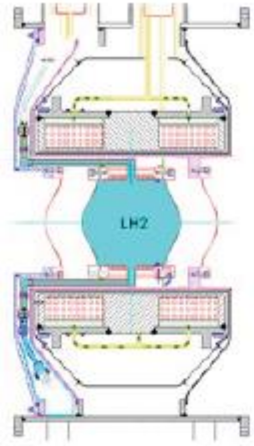
- Two 4T solenoids with 0.1% field quality, each with 5 NbTi coils
- Built by Wang NMR, under LBNL supervision
- 1^{st} magnet shipped to RAL after training, mapping and debug, 2^{nd} soon

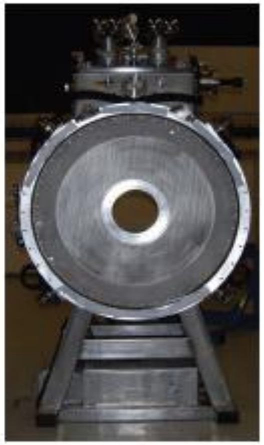


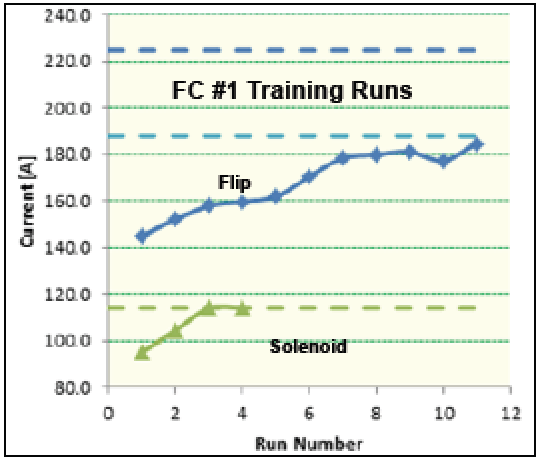


SC magnets: FC coils

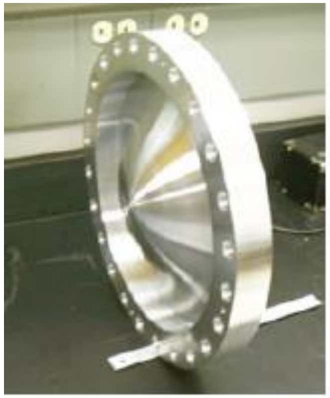
- Three 3T solenoid pairs to provide low β at absorbers in both gradient (“flip”) and solenoid modes
- Design Uni Oxford/RAL, built by Tesla Eng.
- 1st delivered and successfully trained in solenoid mode (only one needed for STEP IV), flip mode training goes slowly
- 2nd delivered in October at RAL

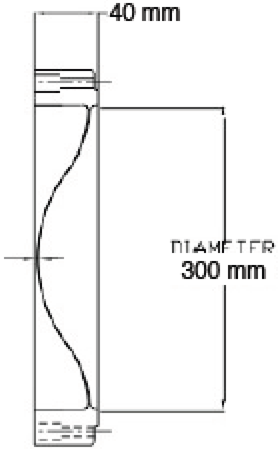






Absorbers



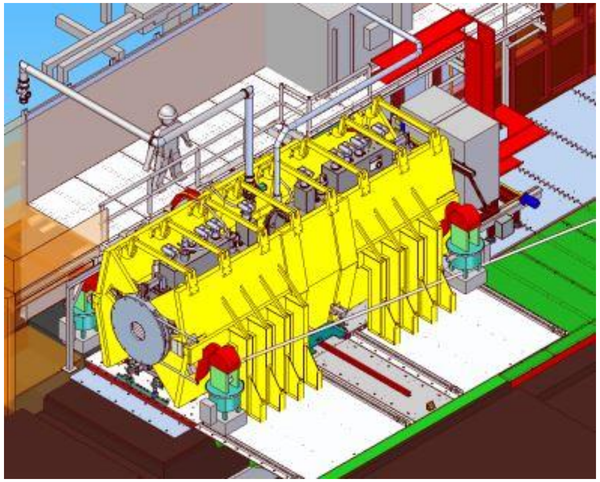


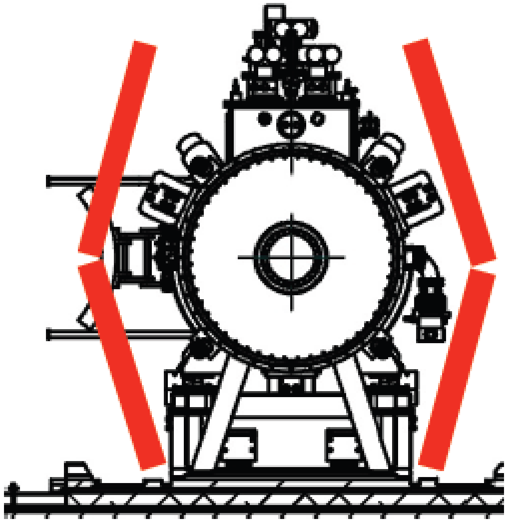
LH2 absorbers:
- One required for STEP IV (two out of three built so far)
- Thin (180 μm) tapered Al-alloy windows (IIT-U.Miss-Oxford)
- May be used also for LHe
- LH2 system successfully tested at RAL

LiH absorbers:
- Under production at Oak Ridge

Other solid absorbers under consideration (C, Al, polyethylene, …)

B-Field mitigation





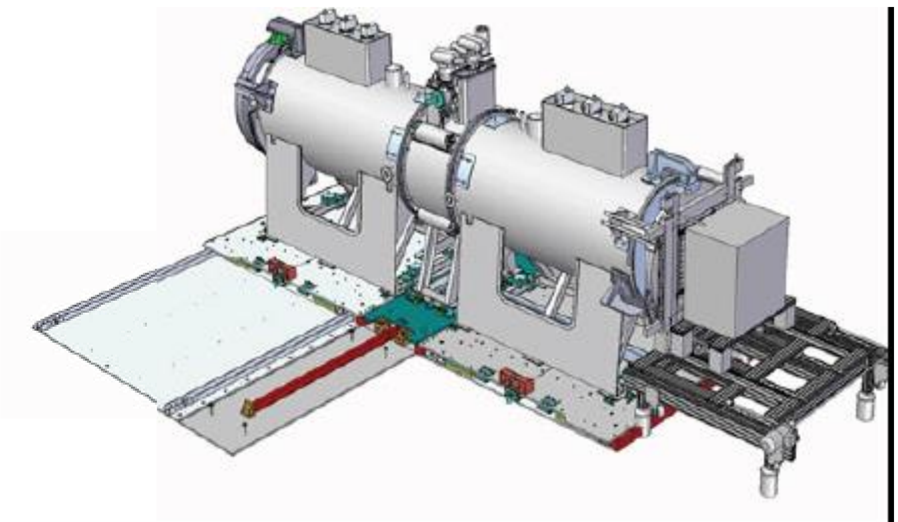
(not to scale)

Need to reduce fringe fields for detector operation and sensitive components in MICE Hall.

Two solutions:

- Local shielding (TOF, KL,EMR)
- Partial return yoke (PRY) for other sensitive components
  - Shielding plates thickness > 10 cm; 35 t weight
  - Reduce stray fields to 5-10 G

Step IV plans

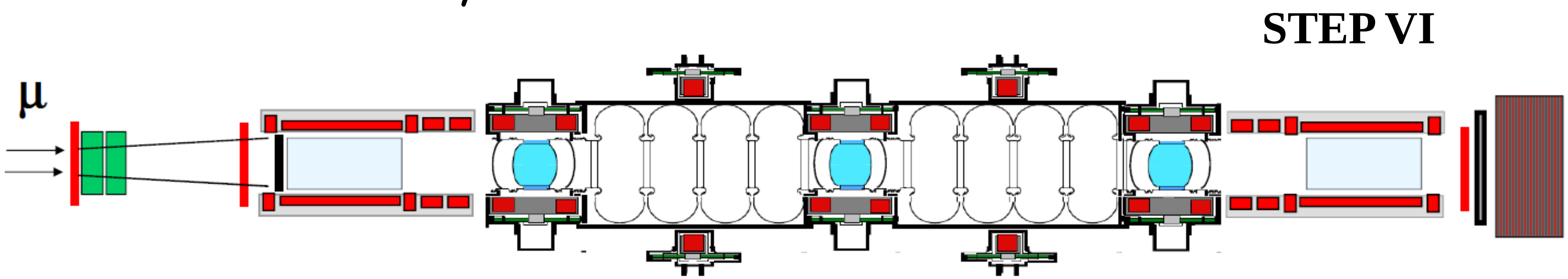


MICE STEP IV "deliverables":

- Calibration of emittance measurement to 10^{-3}
- Measure equilibrium emittance of a given absorber and for a given beta function
- First test of longitudinal cooling (with wedge absorbers)
- Precision measurements of multiple scattering and energy loss straggling

… and to completion: STEP VI

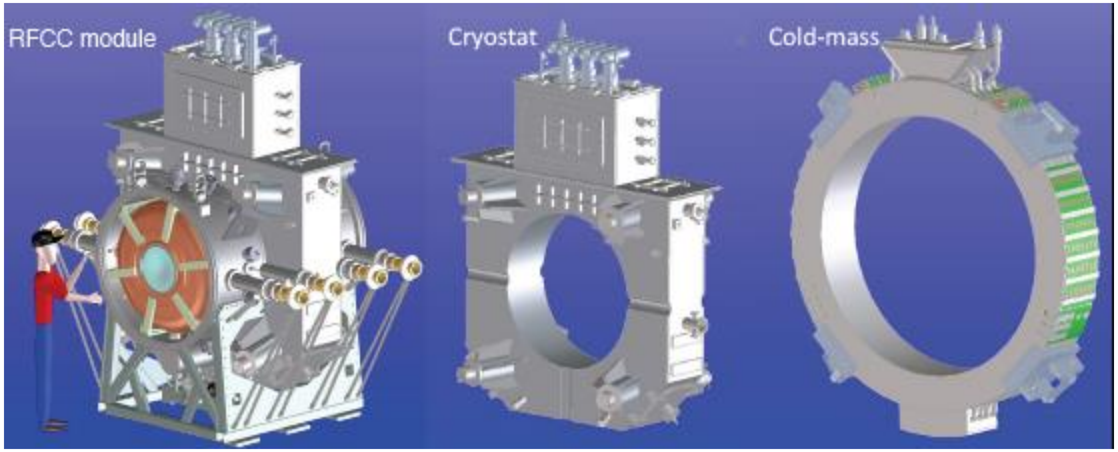
The addition of RF cavities (built) and absorber modules will permit an emittance reduction of ~10% to be measured to an absolute accuracy of 0.1%



201-MHZ RF cavities RF amplifier RF power coupler CC cold mass

RF: cavities & power

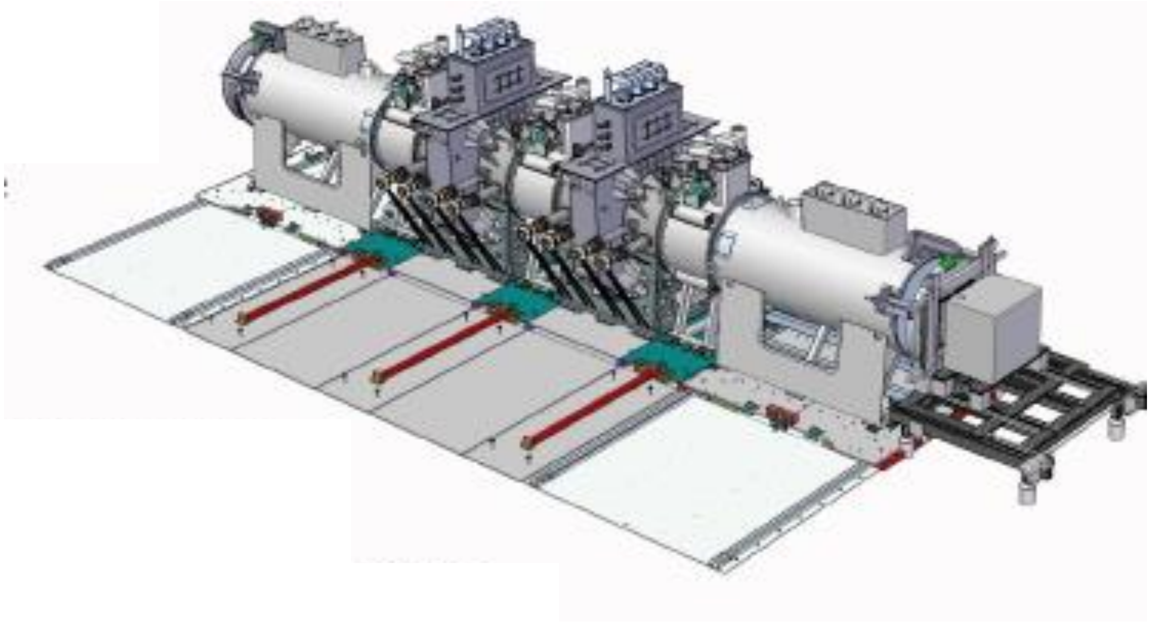
- 2 RFCC modules (LBNL,U. Miss.) needed for STEP VI
- novel Be cavity windows double accel gradient for a given power (MuCool)
- RFCC modules designed, cavities built
- Coupling coils fab in China (HIT,SINAP) led by LBNL
- 4 recycled (LBNL,CERN) 2 MW triode power supplies for RF (refurbished at DL)



STEP VI plans

Step VI deliverables:

- Full cooling cell in operation with RF cavities
- Exact replenishment of energy possible
- Precise measurement of equilibrium emittance for various optical and absorber configurations
- Benchmark for future cooling-channel options



Step V, with ½ lattice cell, possible as intermediate STEP, but not current baseline

Conclusions

- The MICE experiment is an essential R&D milestone towards a Neutrino Factory and a Muon Collider
- MICE beamline in place and commissioned: over 13×10^{6} triggers collected in STEPI
- PID detectors (upstream: TOF0,TOF1,CKoV, downstream: TOF2,KL,EMR) installed and working well
- Preliminary emittance measurement with TOF only
- STEP IV under installation and ready to take data (possibly 2014 w/o fields and 2015 with fields, due to ISIS long shutdown) with addition of trackers+EMR to instrumentation
- Components for STEP VI under construction