Imperial College London

K. Long, June 08, 2004

The international Muon Ionisation Cooling Expt

– status and prospects

Contents

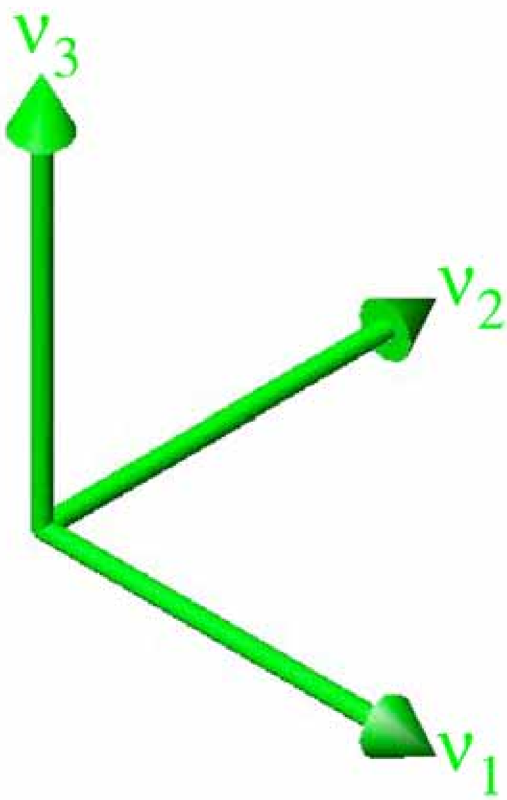
- Motivation: high-sens^{ty} studies of ν-osc^{tions}
- Neutrino Factory machine: overview
- Ionisation cooling: principle
- Muon Ionisation Cooling Experiment
- Conclusions

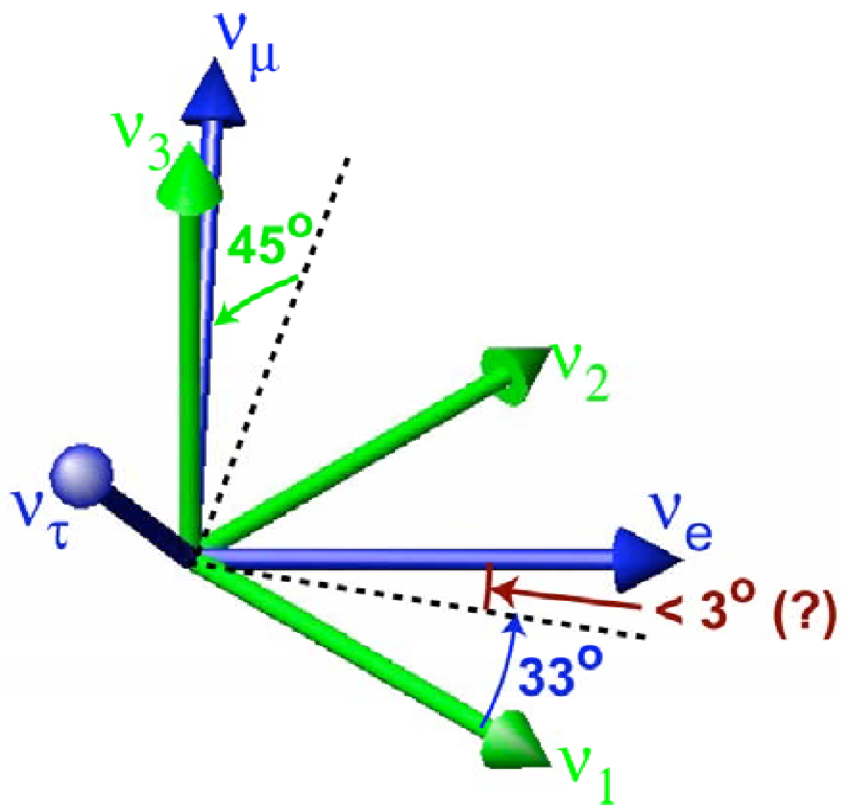
Motivation: headlines

- Neutrino oscillations – established exp^{tly}
- Implications for particle physics:
  - Neutrino mass > 0
  - Neutrinos violate matter-antimatter symmetry?
  - New state of matter (Majorana?)
- Impact on astrophysics and cosmology:
  - Origin of matter (leptogenesis)
  - Dark matter
- Require dedicated expt^{l} programme to:
  - Search for matter-antimatter symm^{y} violation
  - Precisely measure parameters

Motivation: phenomenology

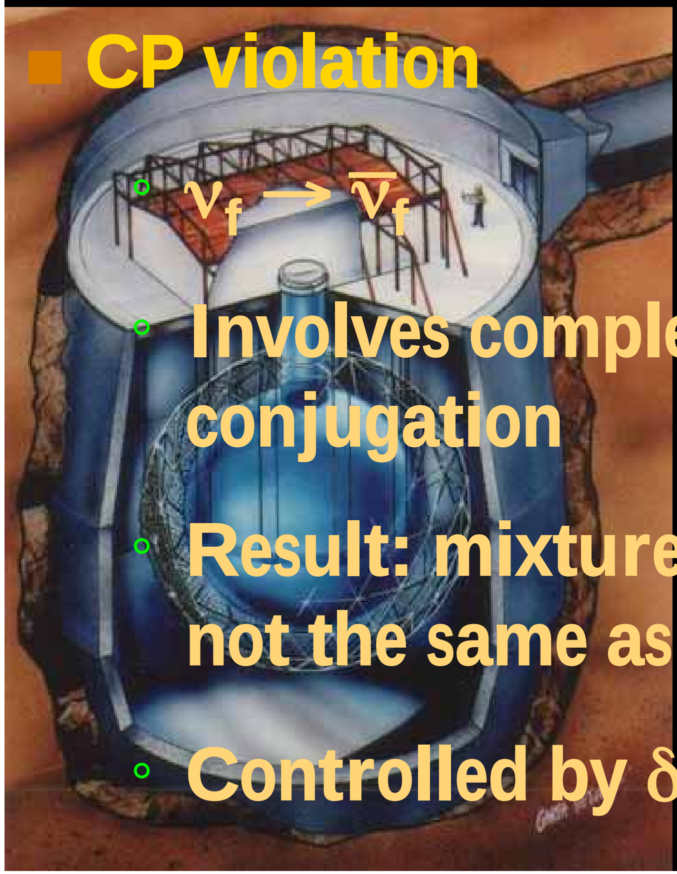
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{i\delta}\\0&1&0\\-s_{13}e^{-i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



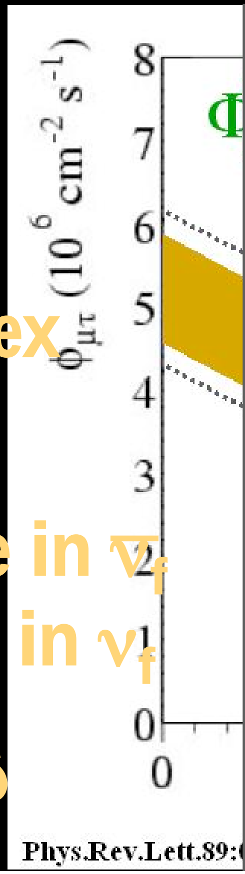


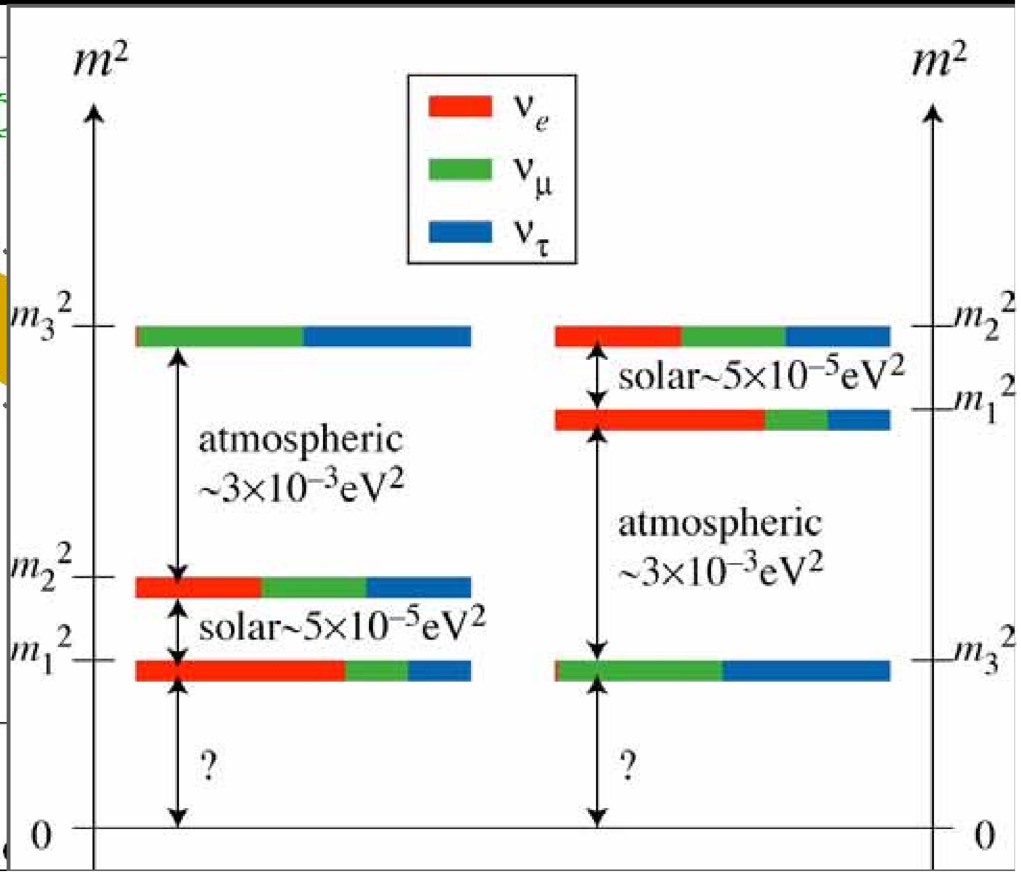
Motivation: phenomenology

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \quad \text{Solar} \qquad\qquad \text{eric} \quad \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



- CP violation
  - $\nu_f \rightarrow \overline{\nu}_f$
  - Involves complex conjugation
  - Result: mixture in $\overline{\nu}_f$ not the same as in ν_f
  - Controlled by δ





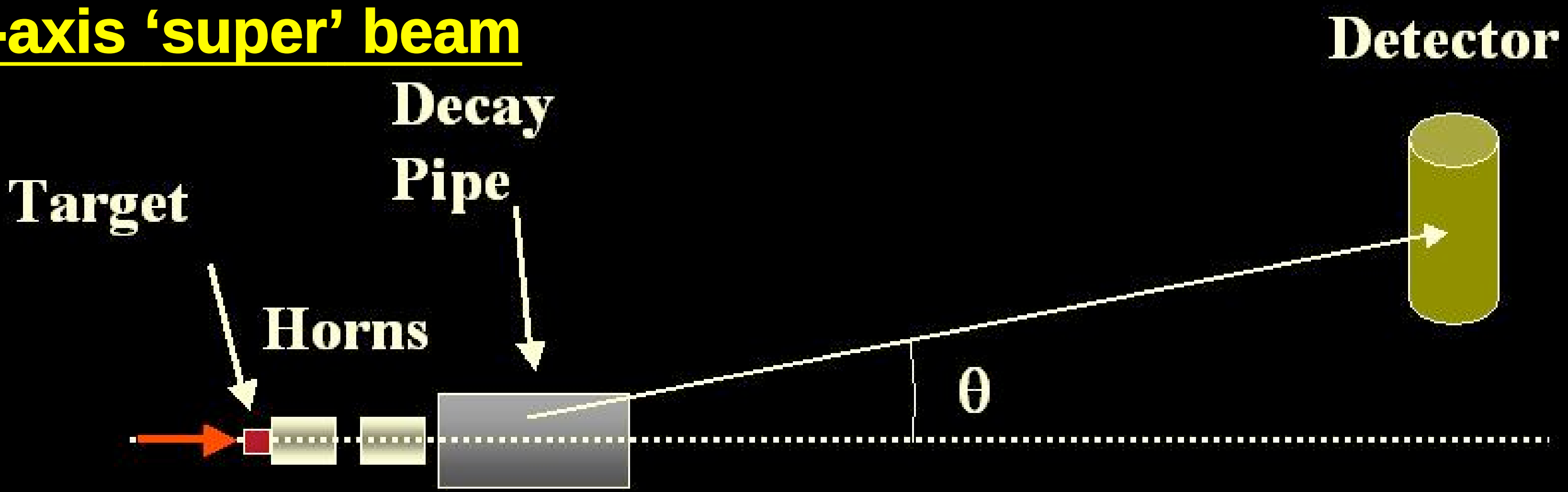
Programme of measurement

$\sin^2\theta_{13}$	δ	Δm^2_{23}

Programme of measurement

$\sin^2\theta_{13}$	δ	Δm^2_{23}

Off-axis 'super' beam



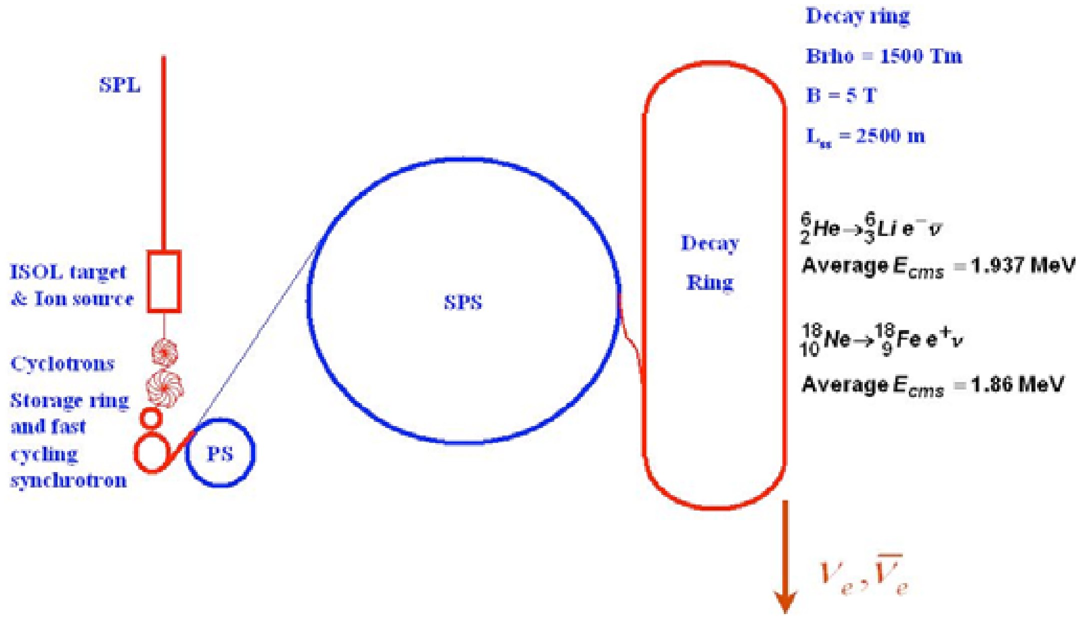
- **Low-energy ν_μ beam:**
  - **Water Cherenkov detector**
  - **Short (~300 km) baseline ideal**
- **Several experiments planned, or proposed:**
  - **Japan: T2K**
  - **US: NuMI off axis**
  - **CERN: SPL $\rightarrow$ Frejus**

Programme of measurement

$\sin^2\theta_{13}$	δ	Δm^2_{23}

Beta beam

- $^6He \rightarrow \bar{\nu}_e$
- $^{18}Ne \rightarrow \nu_e$
- Low-energy
  - Water Cherenkov
  - Short (~300 km) baseline indicated
- Possible sites:
  - CERN → Frejus
  - US? (APS Study IIa)



Some sensitivity to δ

Beta beam

Programme of measurement

$\sin^2\theta_{13}$	δ	Δm^2_{23}

Neutrino Factory

- $\mu^- \rightarrow \nu_\mu + \bar{\nu}_e$
- $\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e$

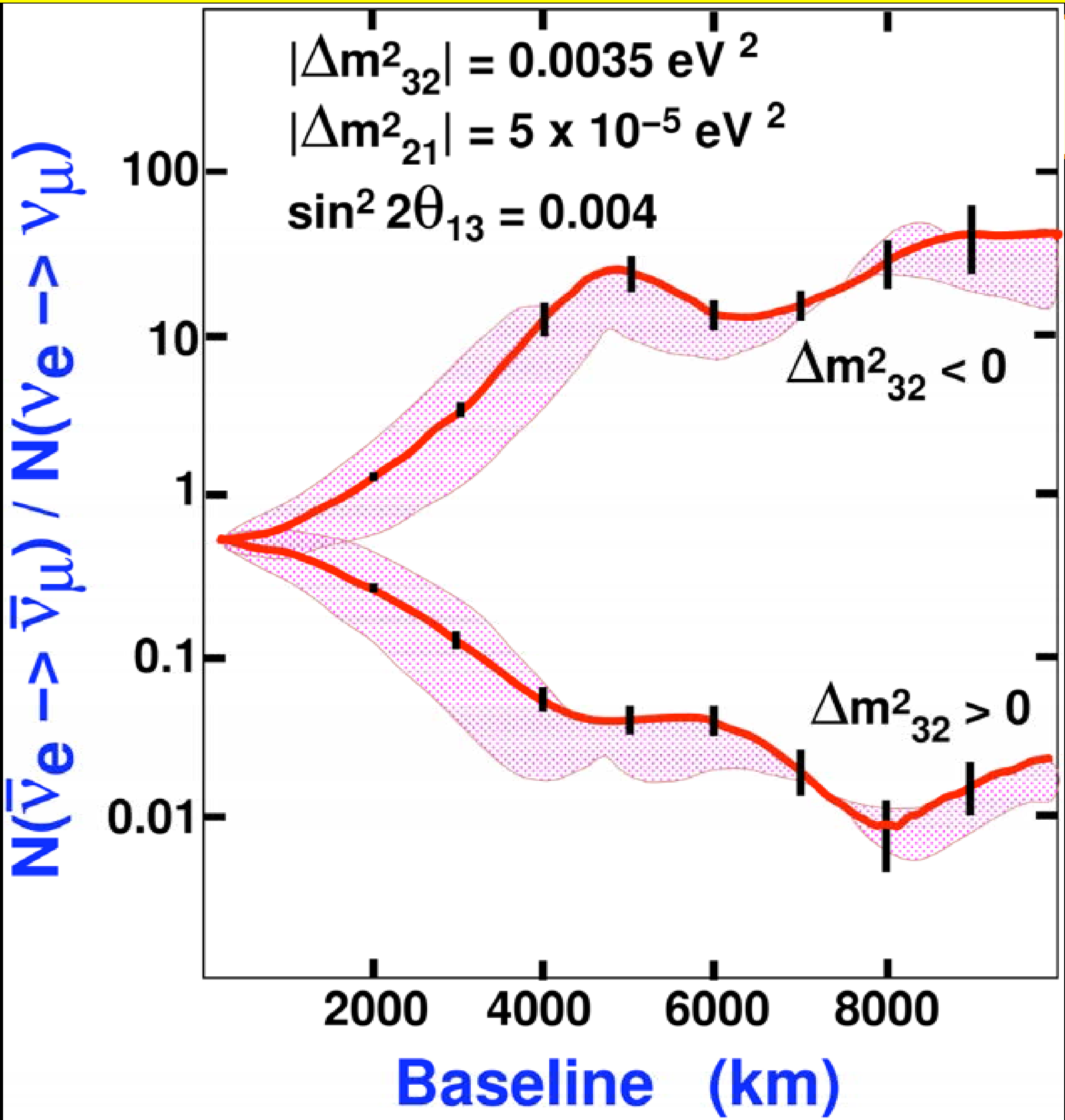
- High-energy
  - Require 'tracking' detector
  - Long (~n × 1000 km) baseline indicated

Features:

- Beam composition known
- Energy spectrum known
- Neutrino flux measured
- 1,000 times more intense than conventional beams

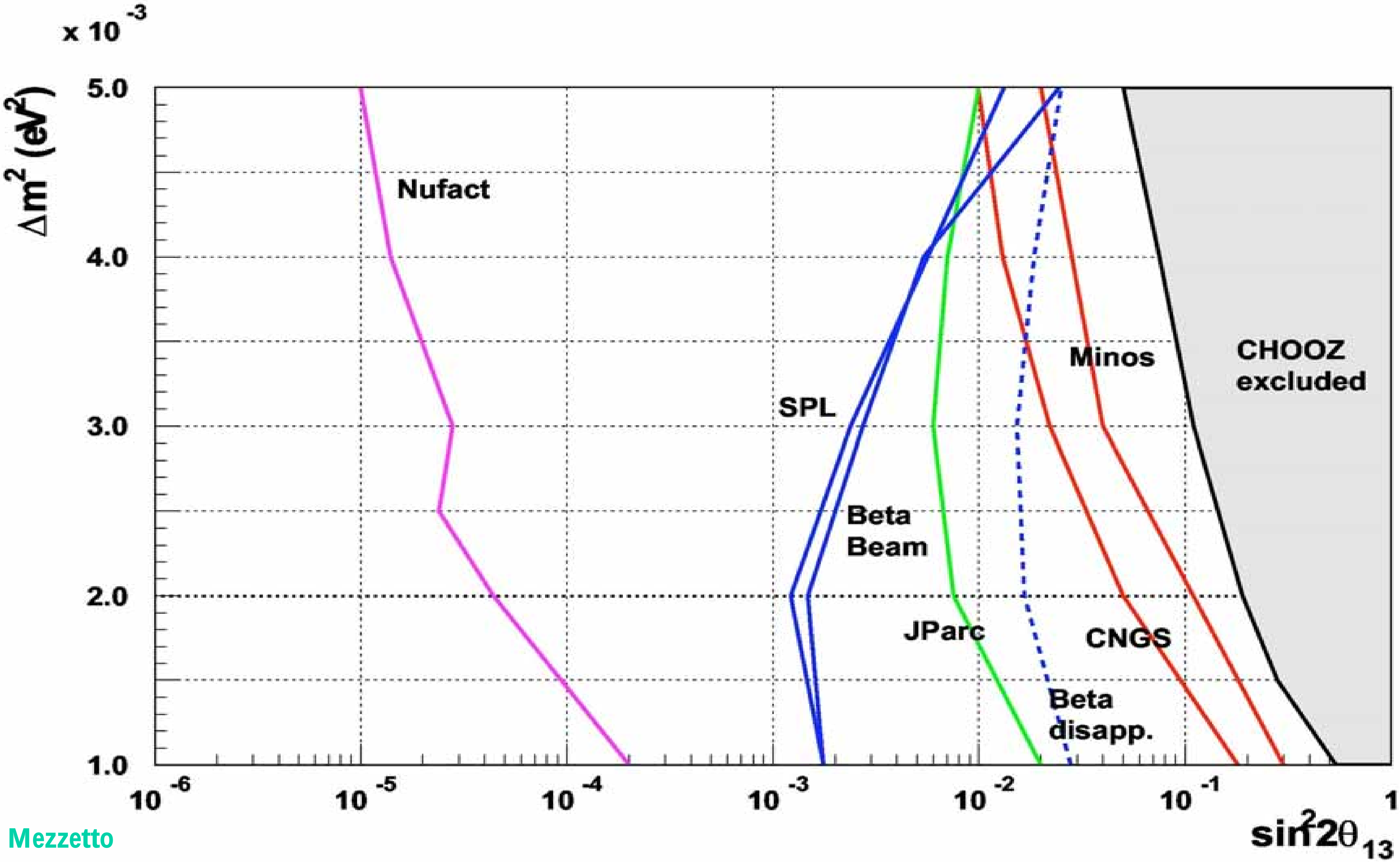
DisappearanceAppearance	
$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$	
$\bar{\nu}_e \rightarrow \bar{\nu}_e \rightarrow e^+$	$\bar{\nu}_e \rightarrow \bar{\nu}_\mu \rightarrow \mu^+$ $\bar{\nu}_e \rightarrow \bar{\nu}_\tau \rightarrow \tau^+$
$\nu_\mu \rightarrow \nu_\mu \rightarrow \mu^-$	$\nu_\mu \rightarrow \nu_e \rightarrow e^-$ $\nu_\mu \rightarrow \nu_\tau \rightarrow \tau^-$

Performance: unique



Δm^2_{23}

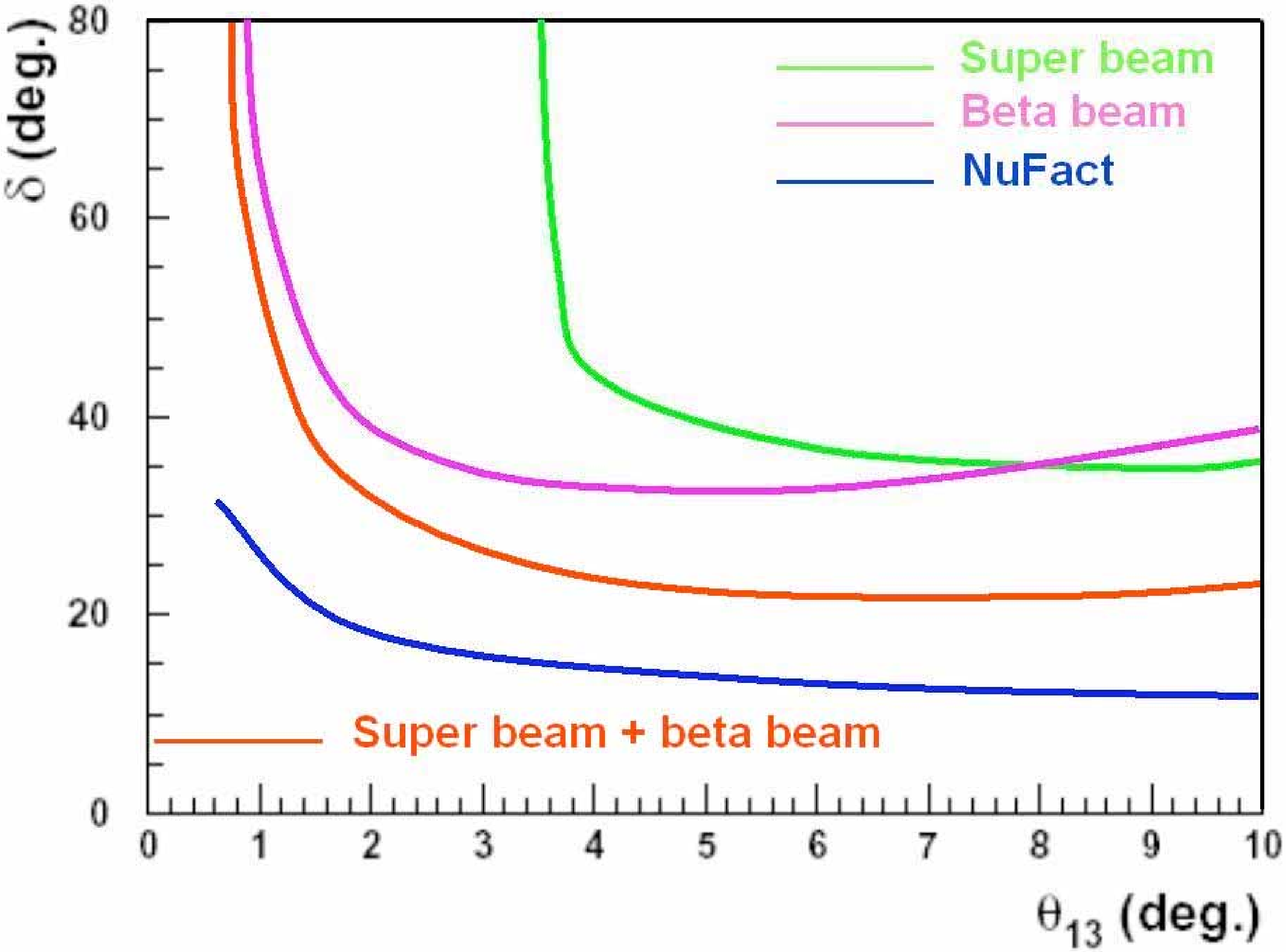
Performance: comparison



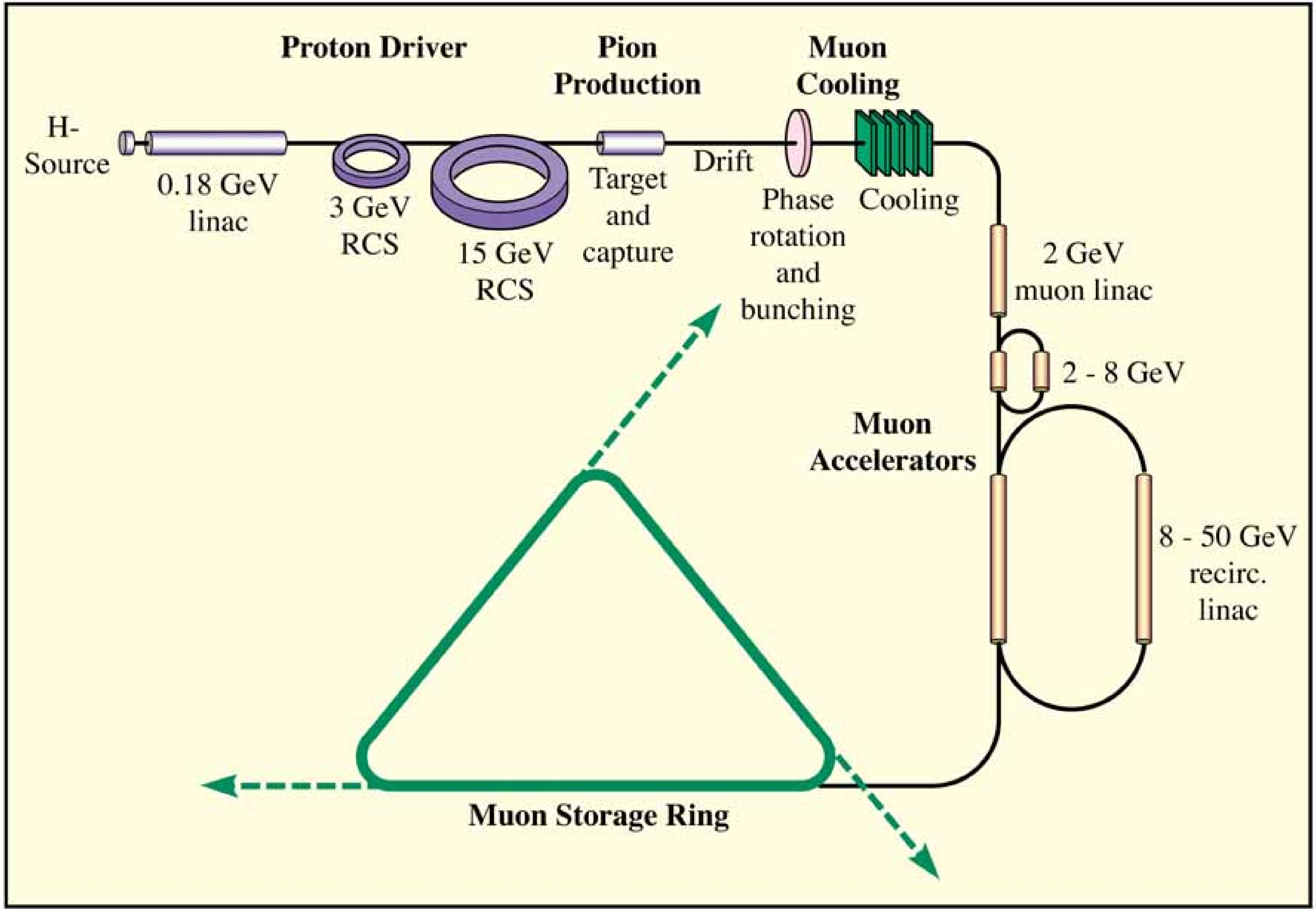
Mezzetto

Performance: comparison

3 sigma sensitivity

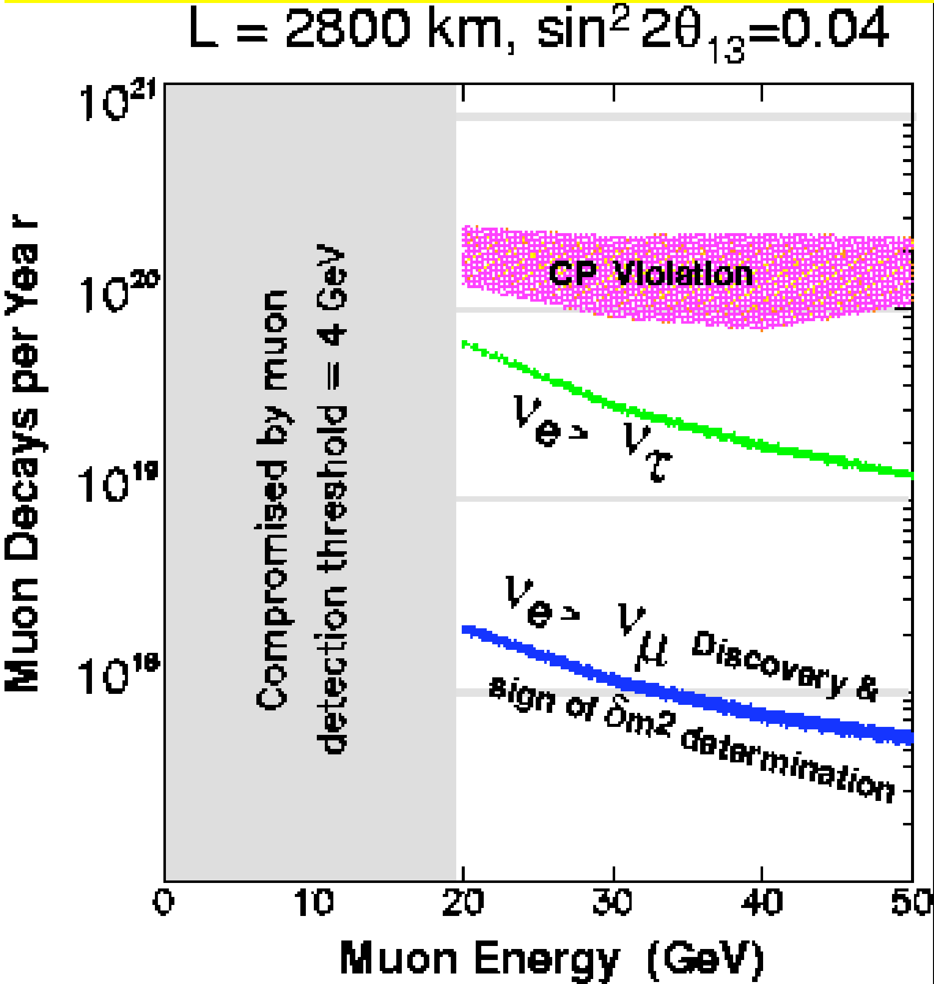


Motivation: NF concept



Neutrino Factory at RAL

Motivation: ionisation cooling

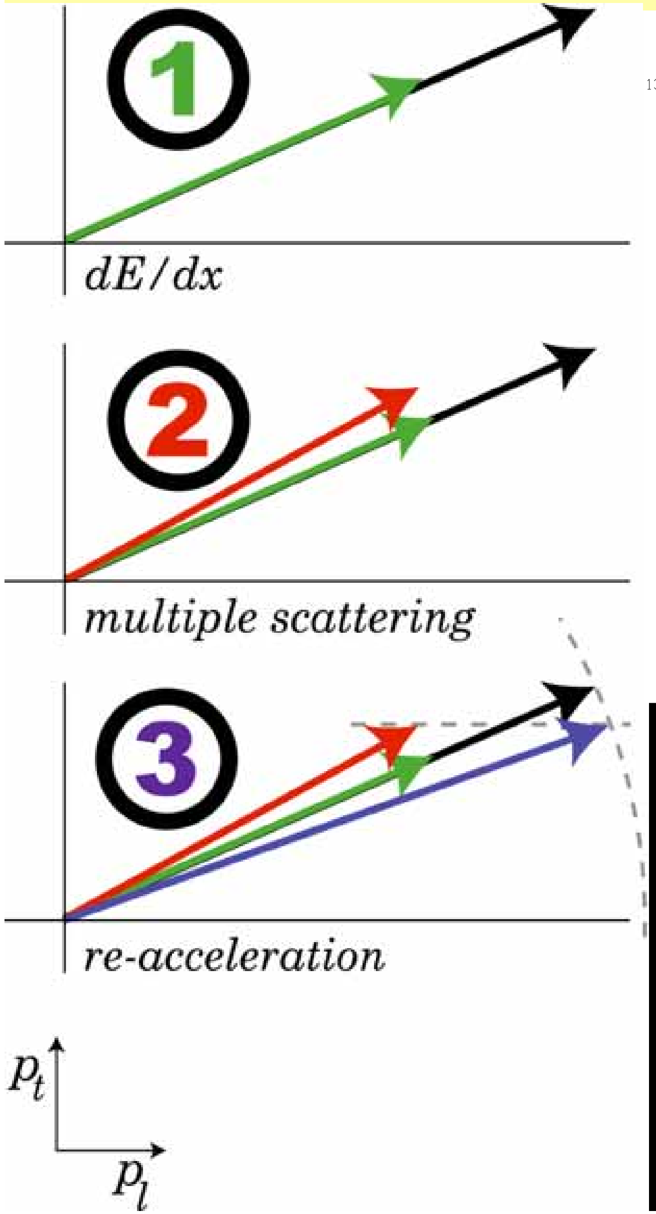


- Physics reach increases with neutrino flux
- Maximise stored muon intensity
- Implies:
  - Require to capture and store as many of the 'decay' muons as possible
    $\Rightarrow$ ***Cool muon beam***

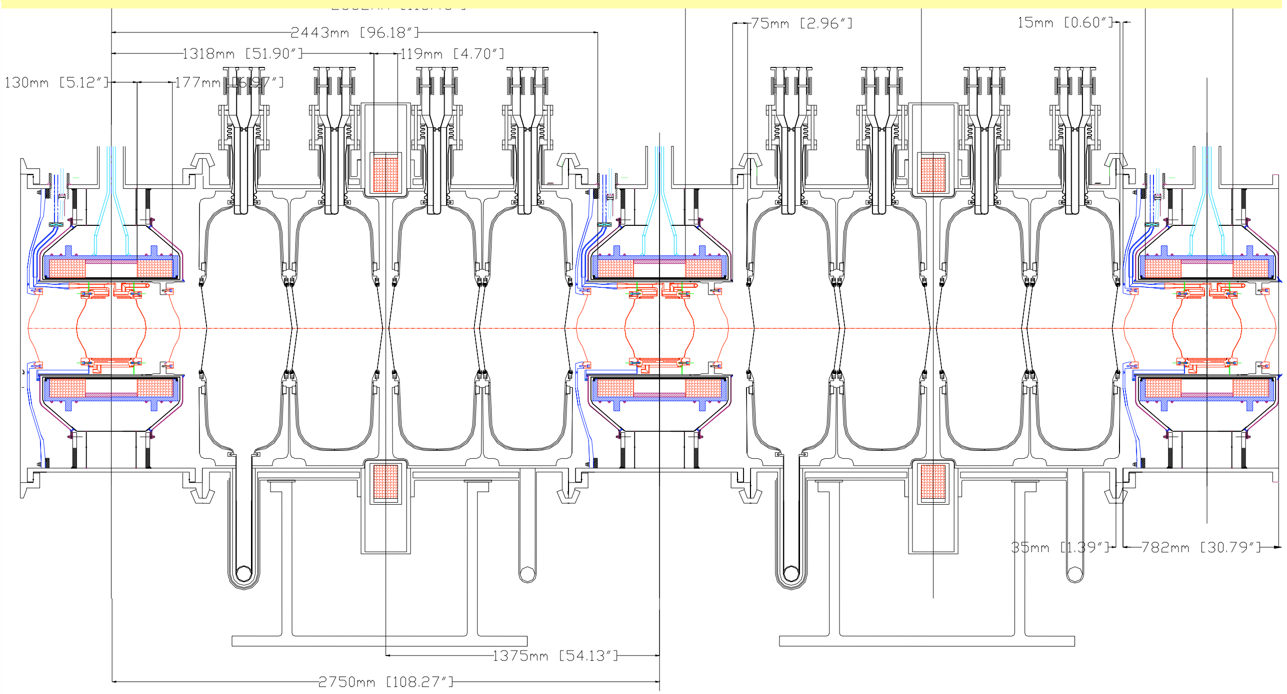
Short muon lifetime requires novel technique:
IONISATION COOLING

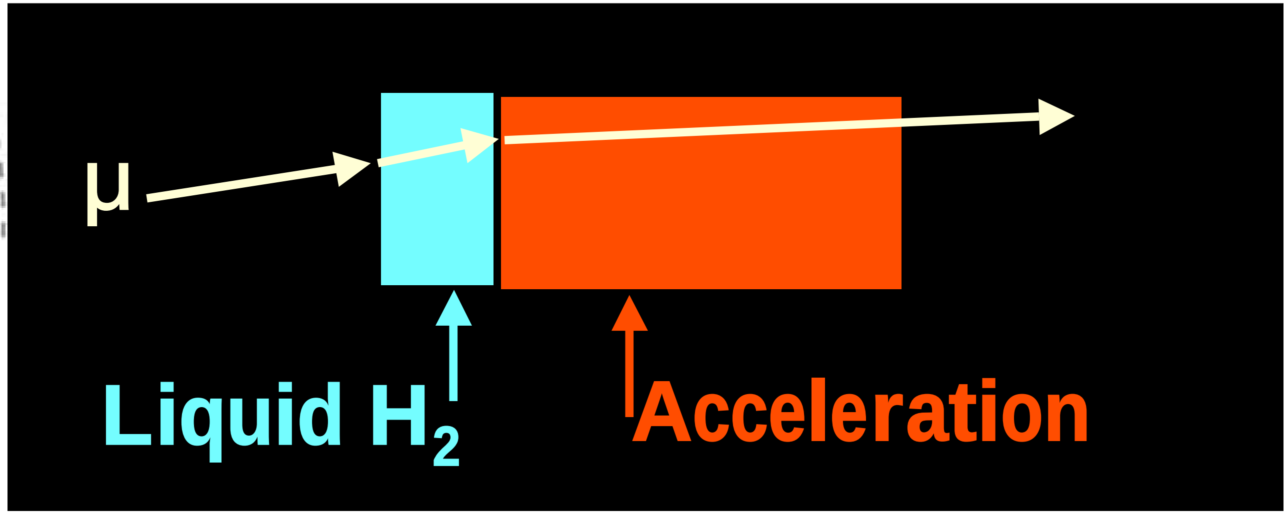
Motivation: cooling technique

Principle



Practice

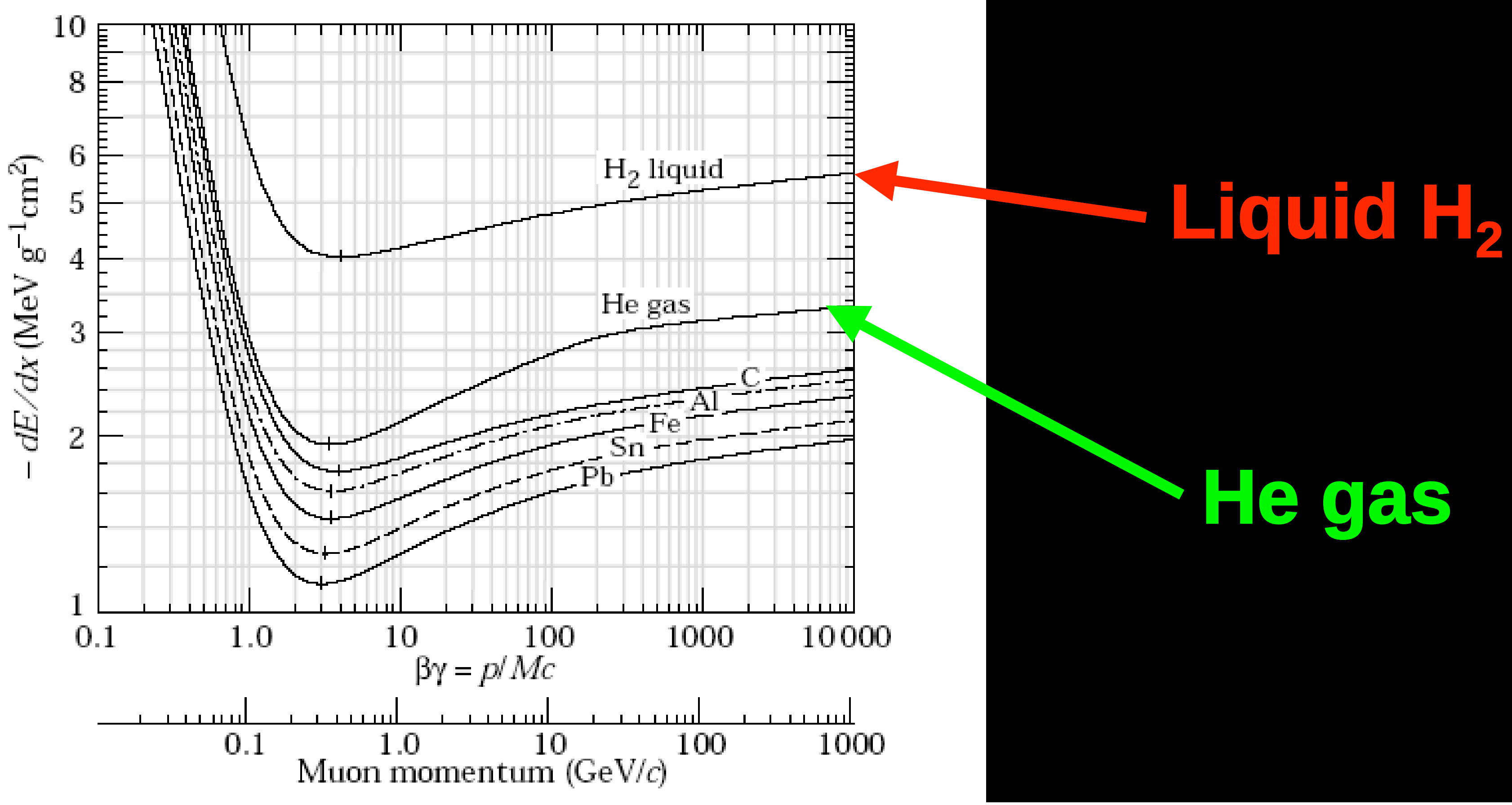




Ionisation cooling: 'theory'

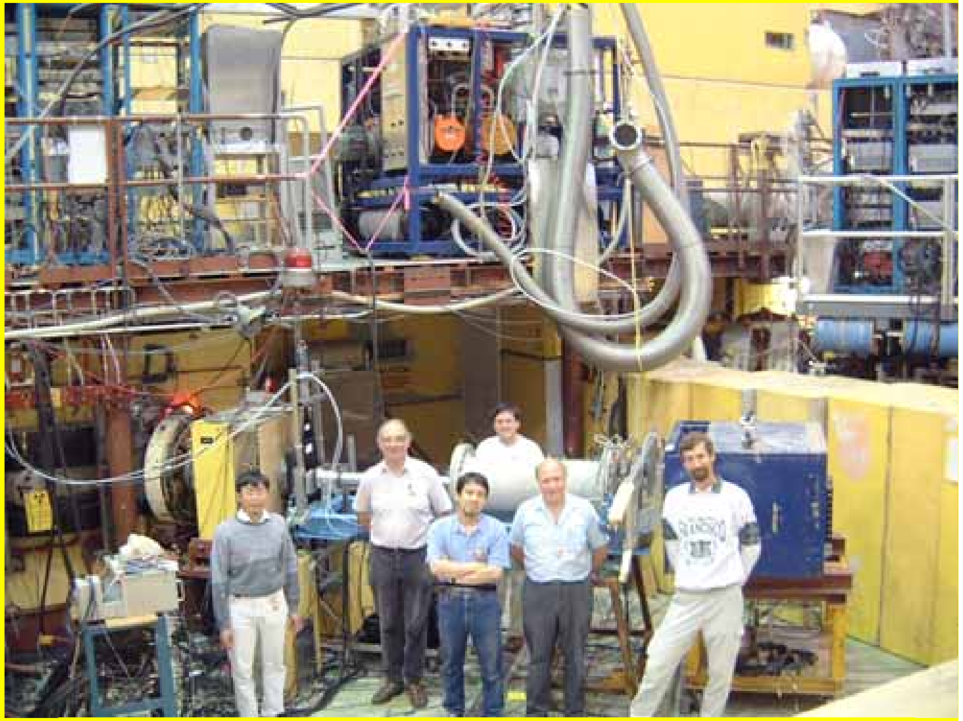
- Rate of change of emittance:

$$\frac{d\varepsilon_N}{ds} = -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\varepsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\,\mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$



Ionisation cooling

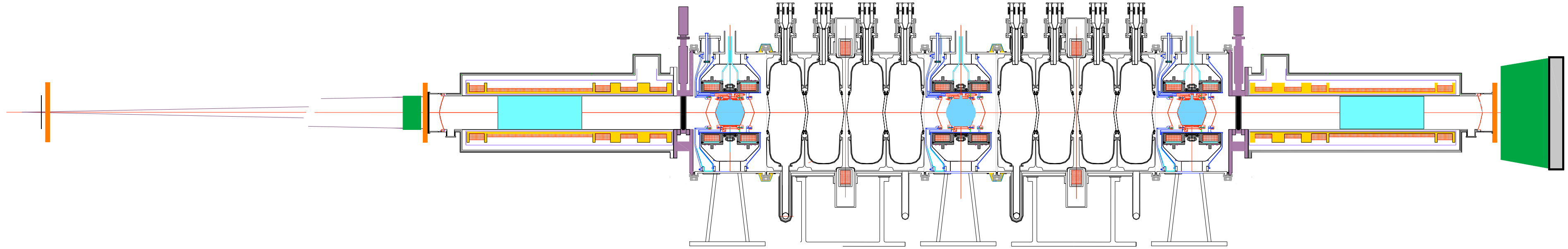
- **Ionisation cooling:**
  - **Principle:**
    - **MuScat:** Measure MCS distributions
    - **I/p to simulation of heating term**



Data taking complete

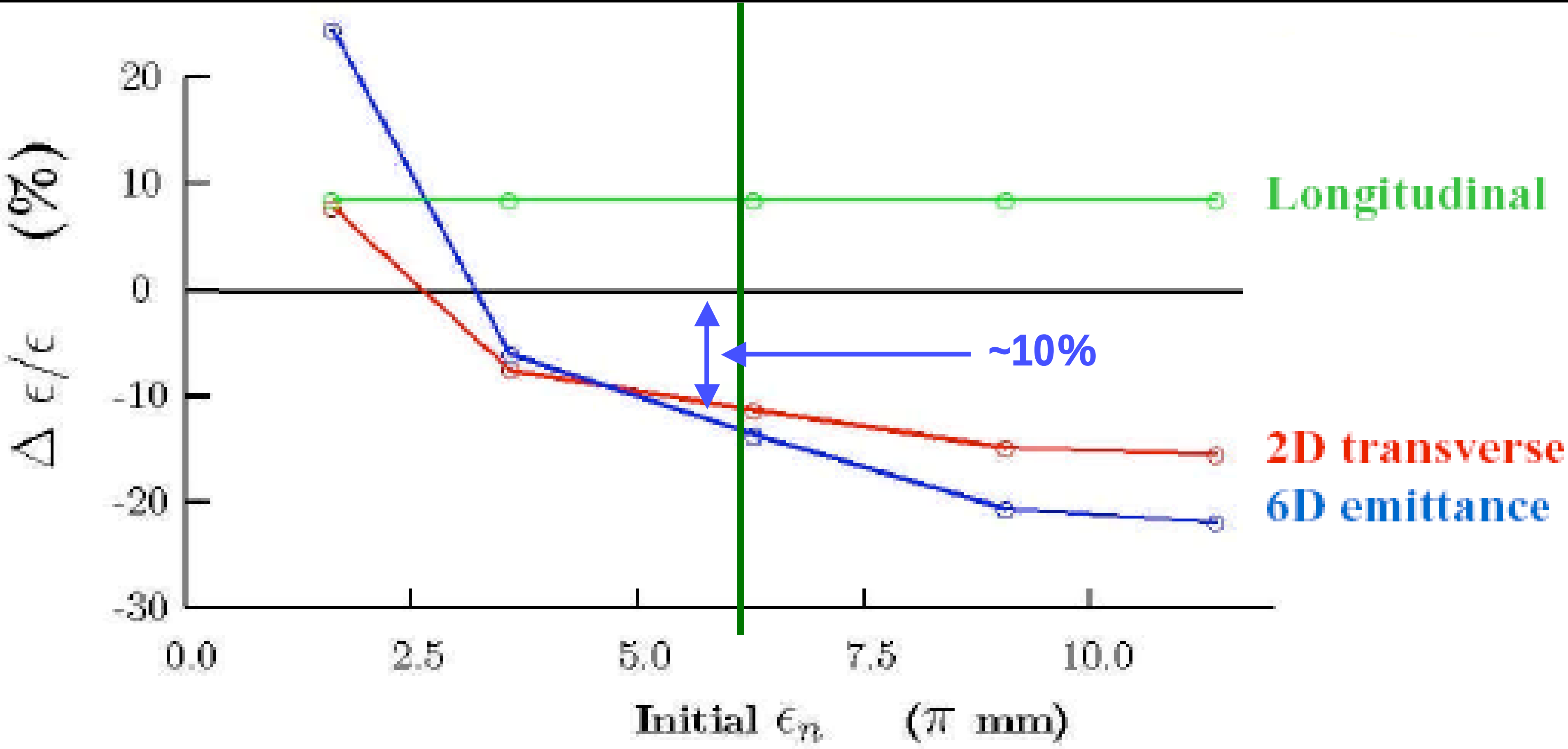
  - **Engineering demonstration:**
    - **Muon Ionisation Cooling Experiment (MICE)**

Muon Ionisation Cooling Exper^{mnt}



- MICE:
  - Design, build, commission and operate a realistic section of cooling channel
  - Measure its performance in a variety of modes of operation and beam conditions
- i.e. results will allow NuFact complex to be optimised

Motivation: measure^{ment} precis^{ion}



$$\Rightarrow \sigma\left(\frac{\Delta\varepsilon}{\varepsilon_{in}}\right) << 0.1 \qquad \text{Goal}: \sigma\left(\frac{\Delta\varepsilon}{\varepsilon_{in}}\right) = 0.001$$

Approval and funding: status

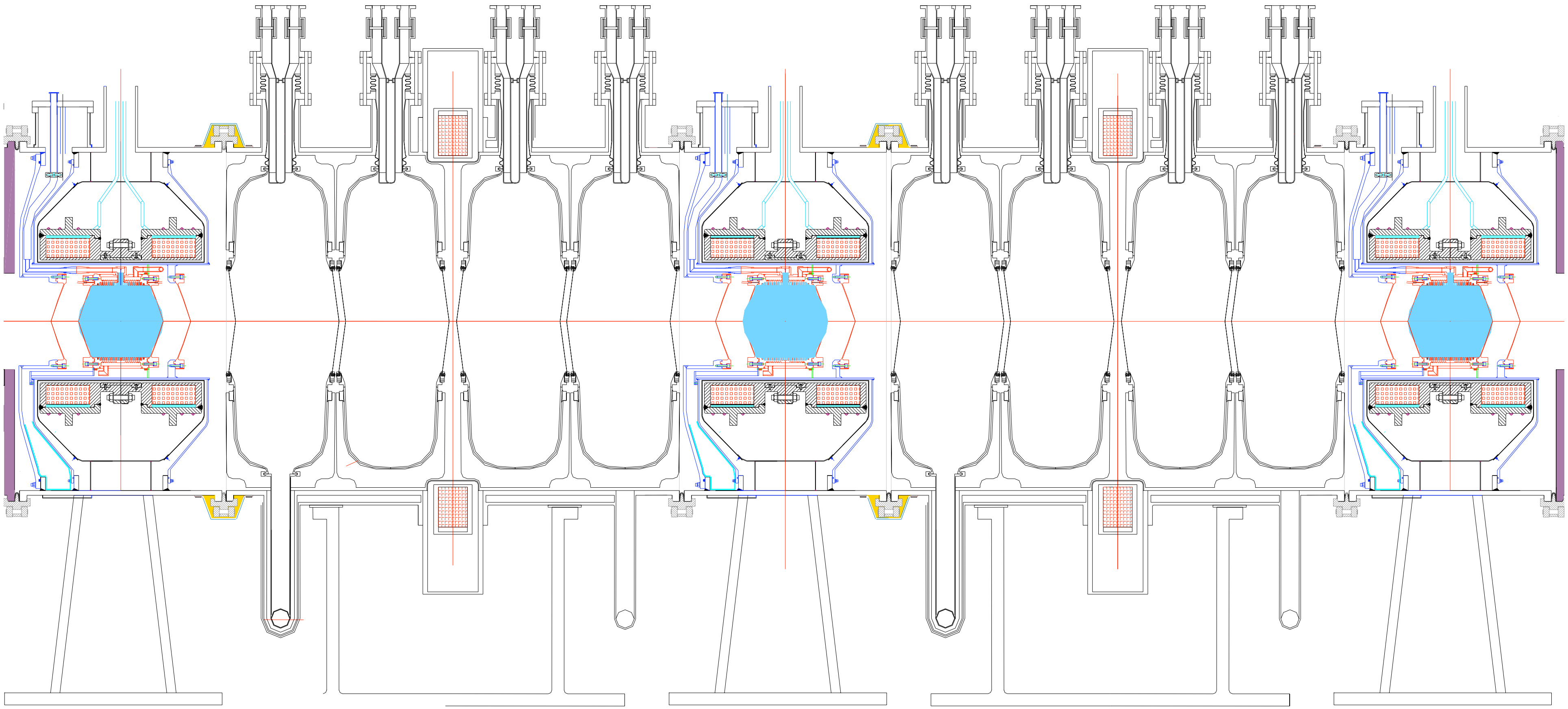
- Proposal:
  - Submitted to CCLRC and PPARC 10 January 03
- Peer review:
  - International Peer Review Panel (Chair Astbury):
    Report of IPRP 20May03:
    'strongly recommends approval of the project'
  - UK: PPARC Projects Peer Review Panel:
    03Jun03:
    Recommended appropriate funding for UK contribution
- Research Councils UK:
  - Allowed project to proceed to Gateway Process

Approval and funding: status

- CCLRC (24Oct03; J. Wood, Chief Exec.):
  - 'Accepts the strong endorsement of the proposal by the Astbury panel and consequently considers the proposal to have full scientific approval'
  - 'Approves the project subject to satisfactory passage through the Gateway'
- Office of Science and Technology:
  - Gateway Process (UK procedure for large capital projects):
    - Gateway 0: 'Business need' – passed
    - Gateway 1: 'Business case' – passed on amber
    - Gateway 2/3: 'Procurement strategy' – goal summer/fall 04; requires indications that international funding will be forthcoming

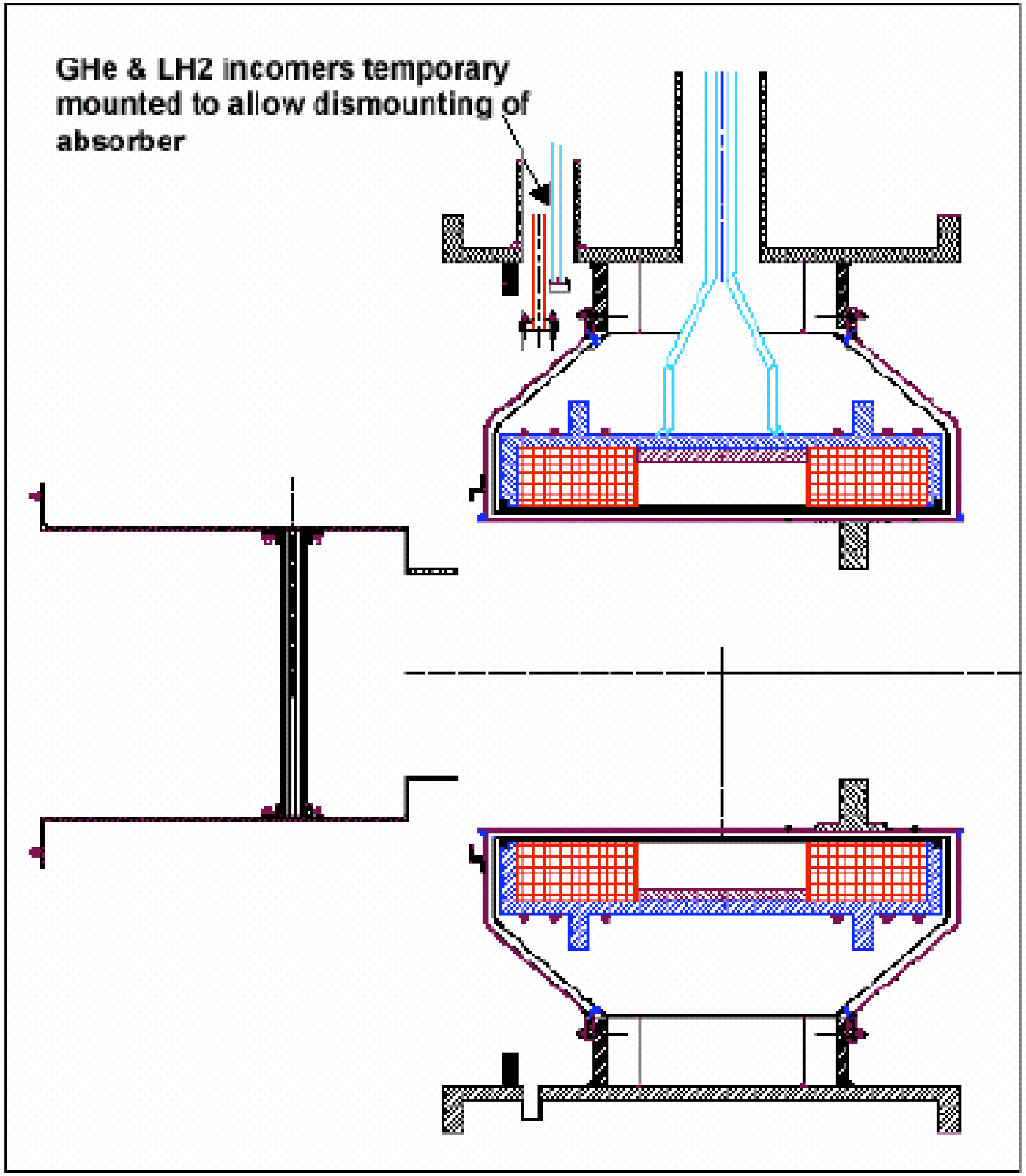
Apparatus: cooling channel

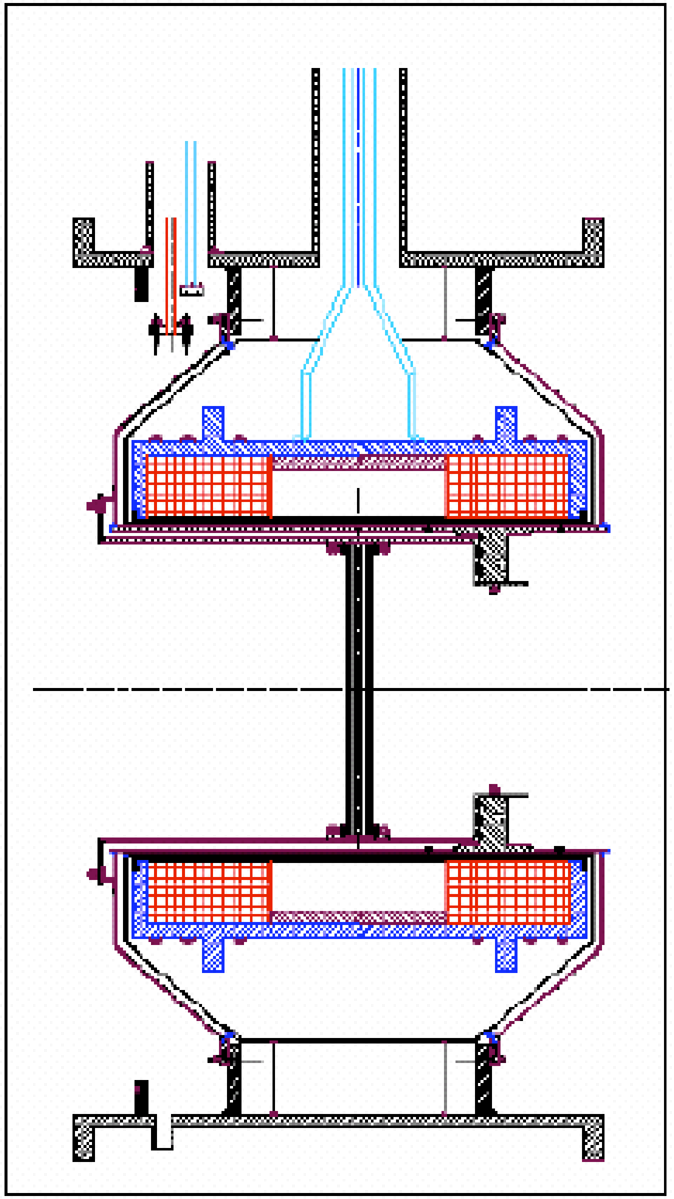
[redacted]



[redacted]

Apparatus: Absorber/focus coils



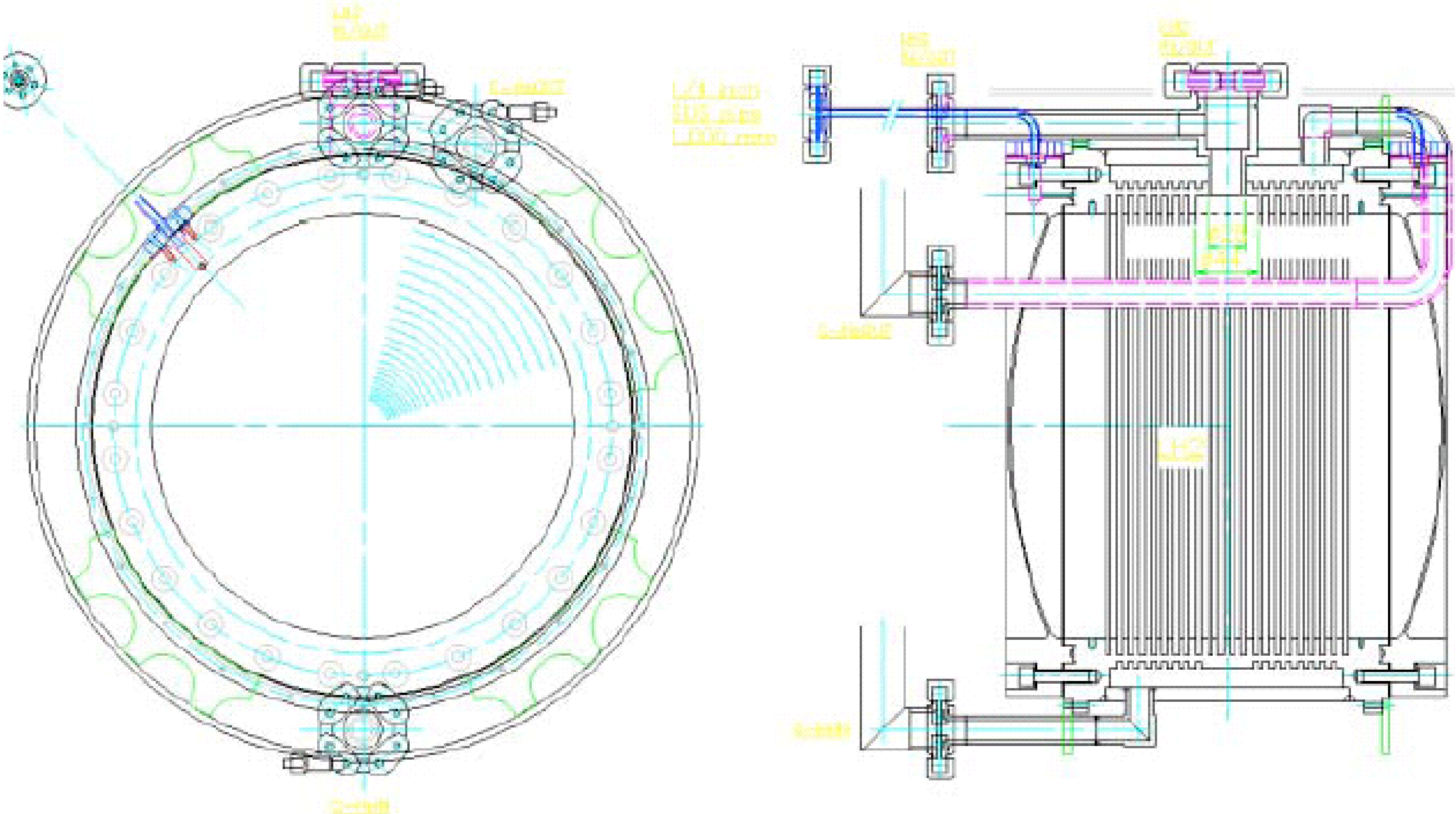


Apparatus: AFC safety – 1st review

- First review of safety of MICE: Dec. 2003
  - Internal review reporting to MICE management
  - International panel chaired by John Weisend
- Focus: hydrogen safety – largest hazard
- Review panel conclusions:
  - Complementary about MICE approach to safety
  - Three areas requiring development high-lighted:
    - Hydrogen gas handling and venting system
    - Metal-hydride system R&D
    - Window development
  - All issues (including other more minor issues) being addressed

Apparatus: Liquid H_2 vessel

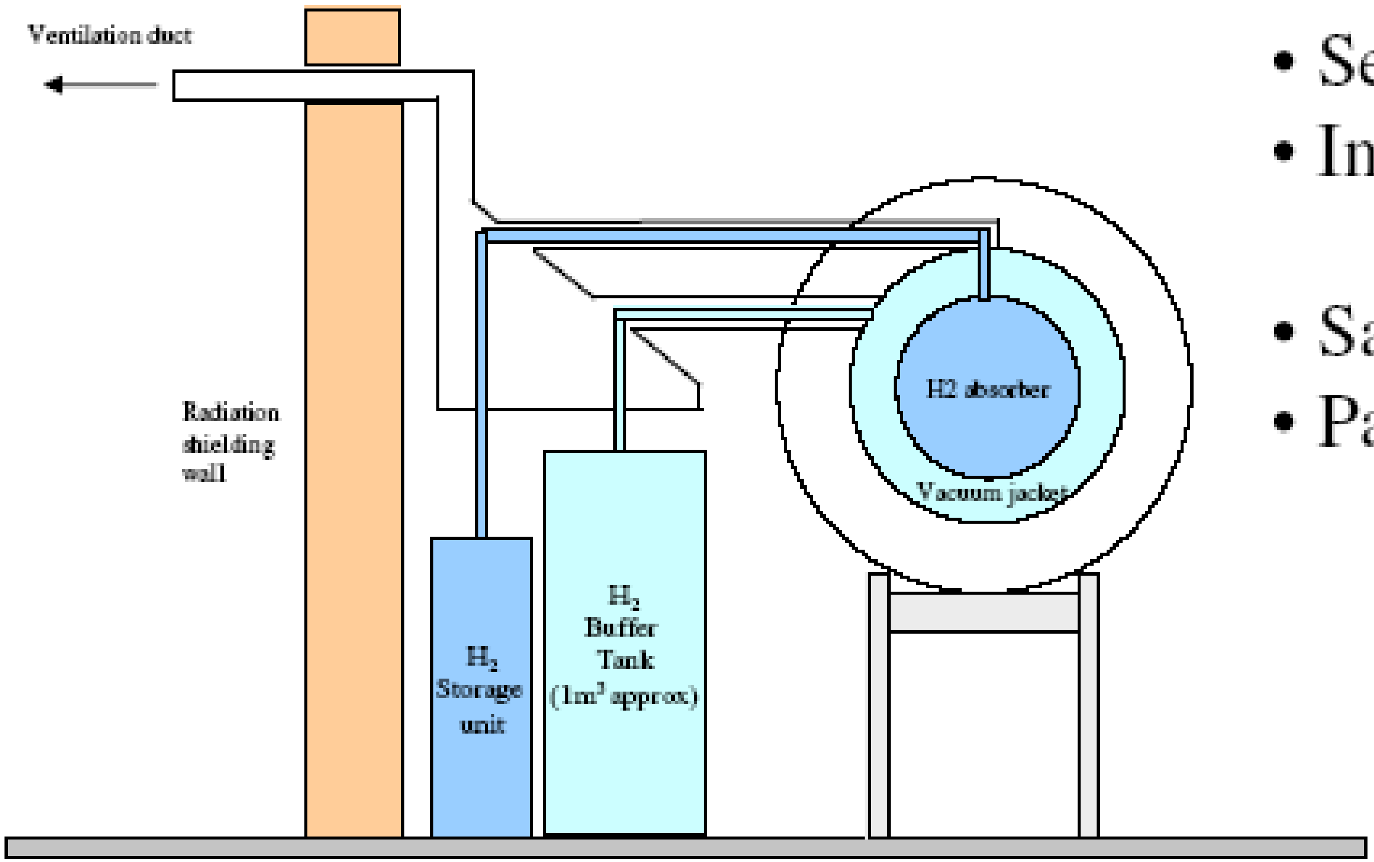
MICE Absorber Design



Apparatus: absorber development

- Build 3 – 5 absorbers:
  - Bodies at KEK
  - Windows US
- First absorber test with gaseous helium at 20 K later this year

Hydrogen-storage system

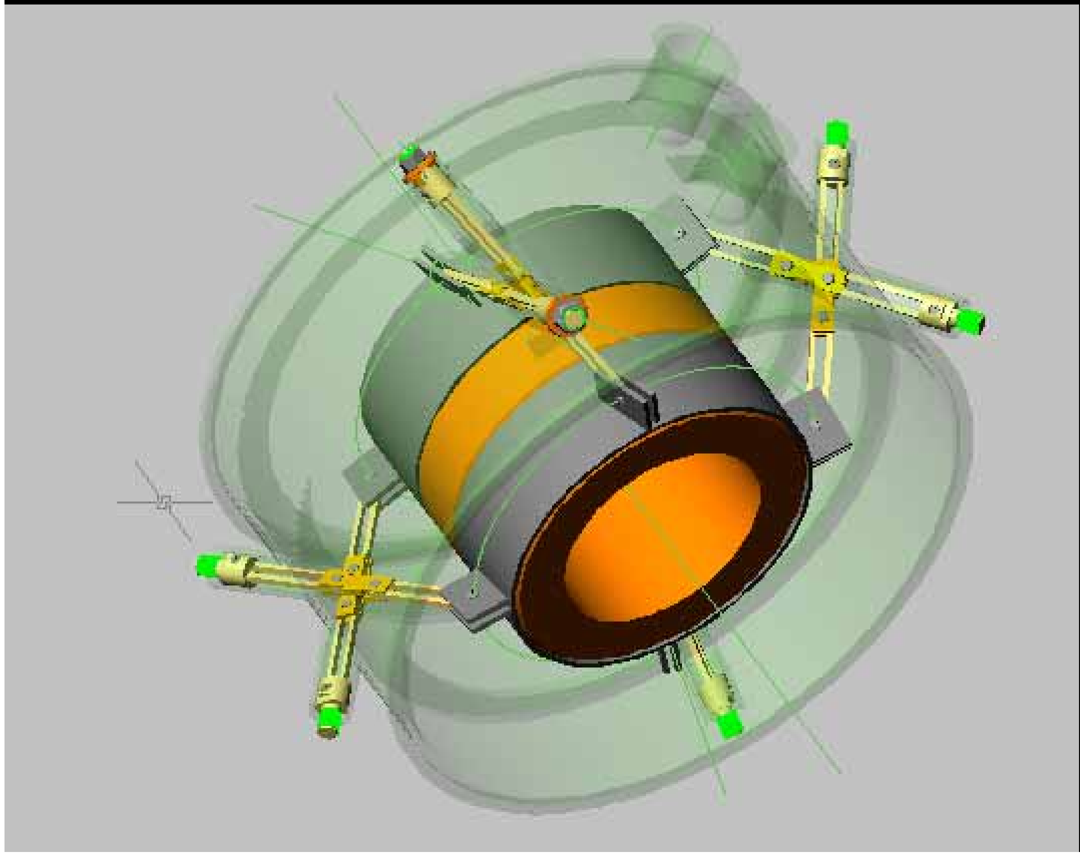


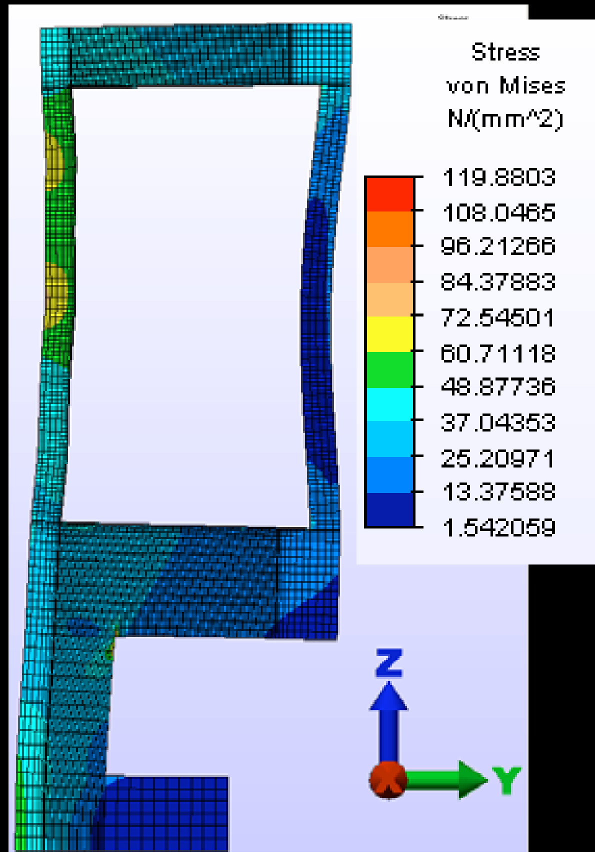
- Innovative!
- Separate systems
- Incremental

- Safe Storage
- Passive

Apparatus: focus coils

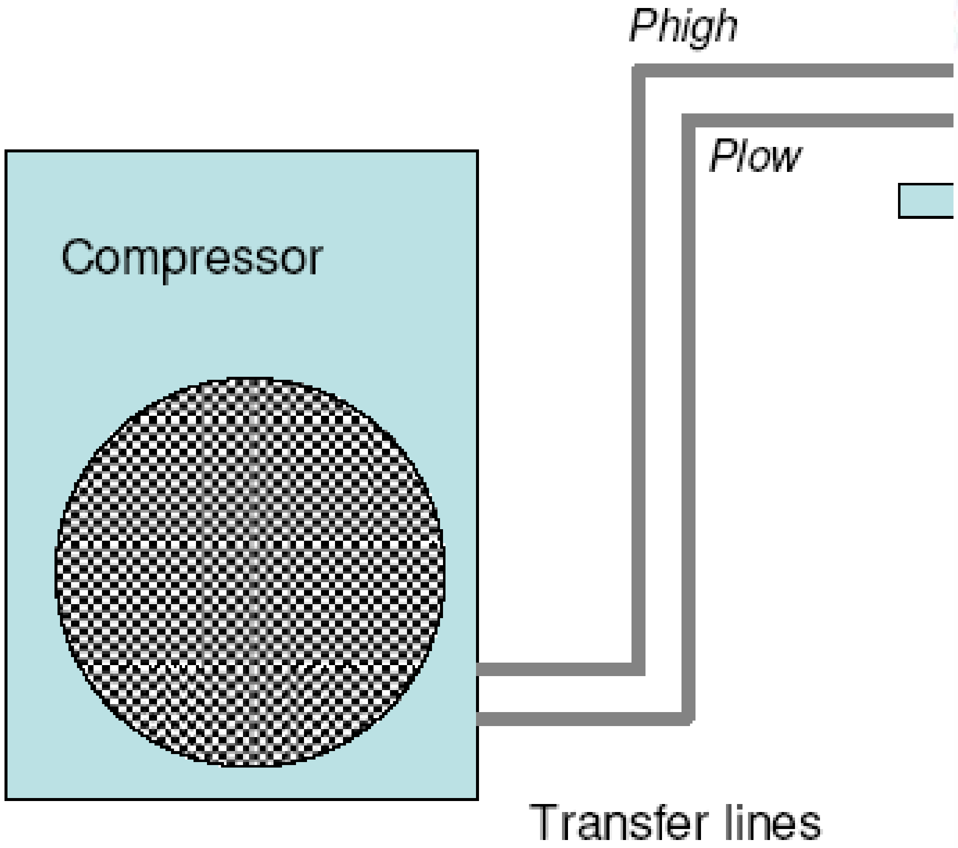
- **Detailed design:**
  - **Cold mass support and forces**
  - **Coil support tube including thermal and stress analysis**





Cryogenic systems

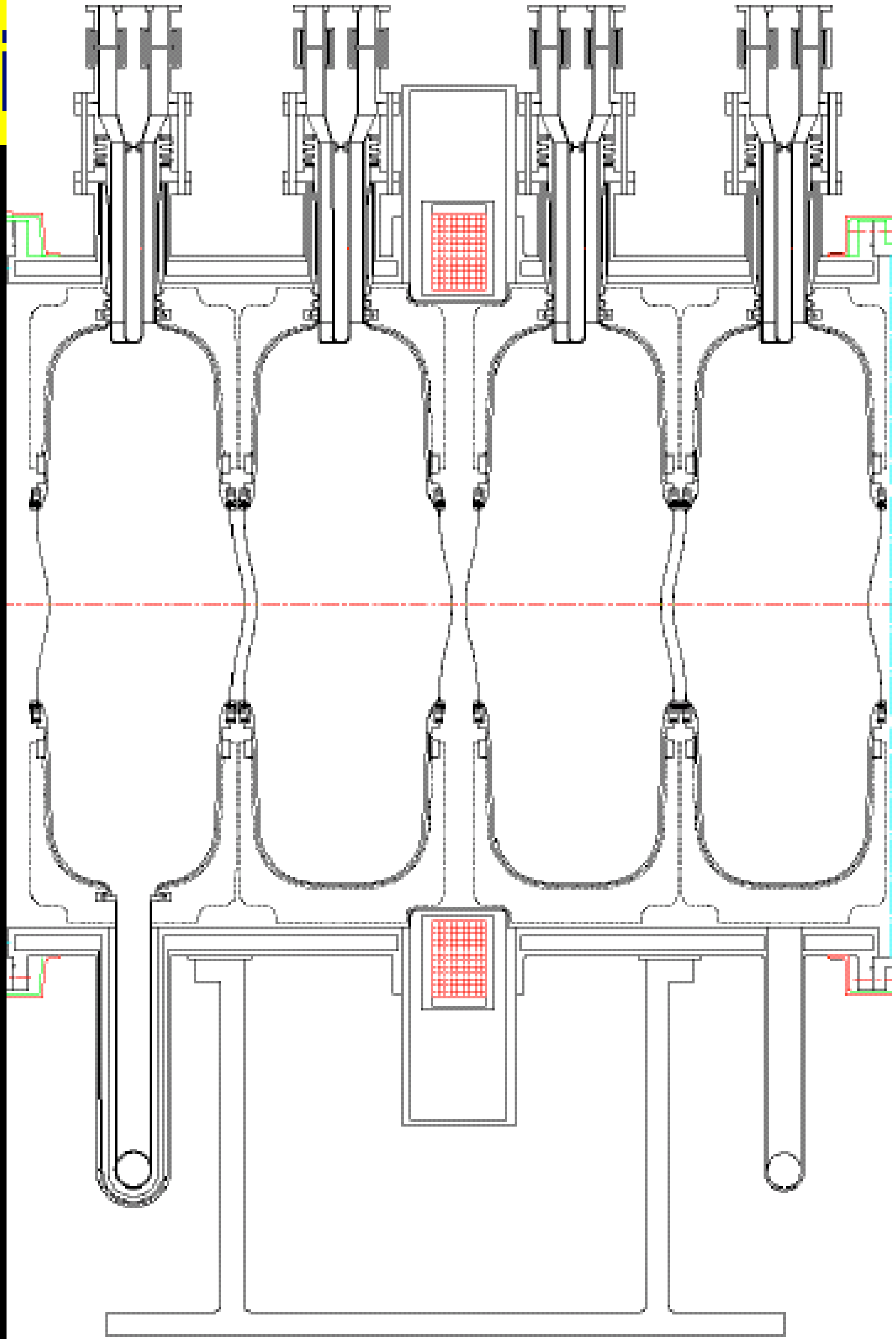
Cryocoolers are closed cycle cooling systems that generally only require electrical input power to produce refrigeration.



 Compressor

Apparatus: Caviti

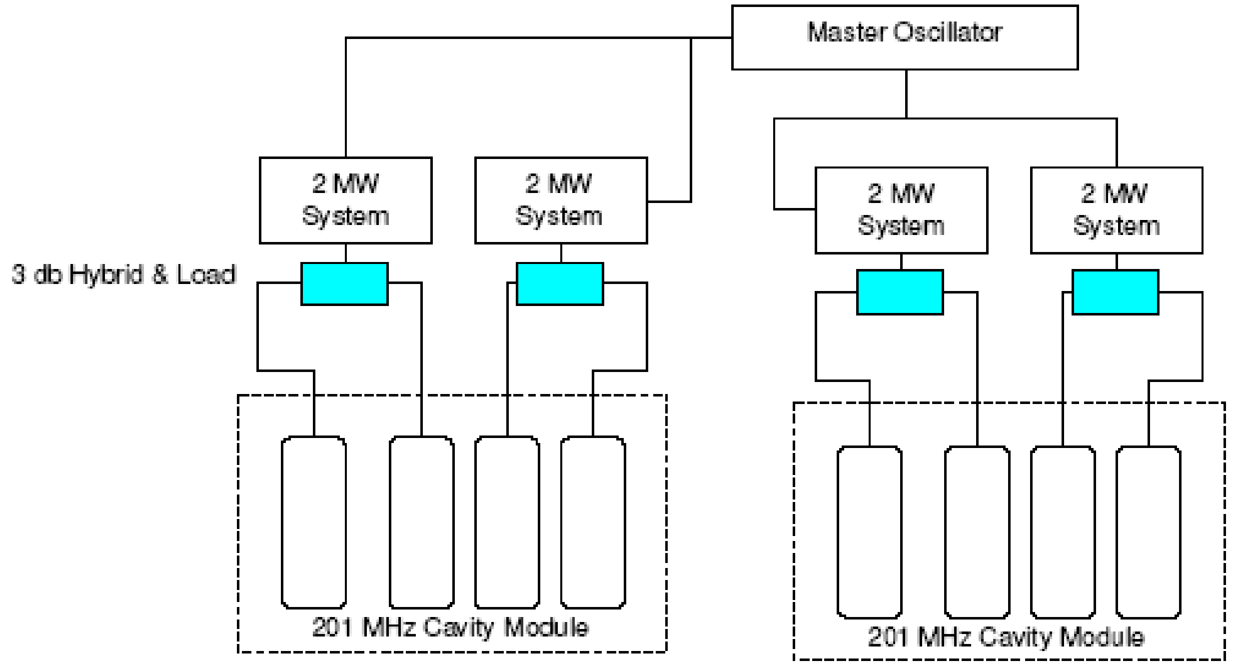
- Specification: 201.25 MHz; 8 MV/m
- Principal challenges:
  - Operation in strong magnetic field
  - Large aperture; require window



Apparatus: Prototype cavity

To be tested in MTA (FNAL) 4th quarter 2004

Apparatus: RF power sources

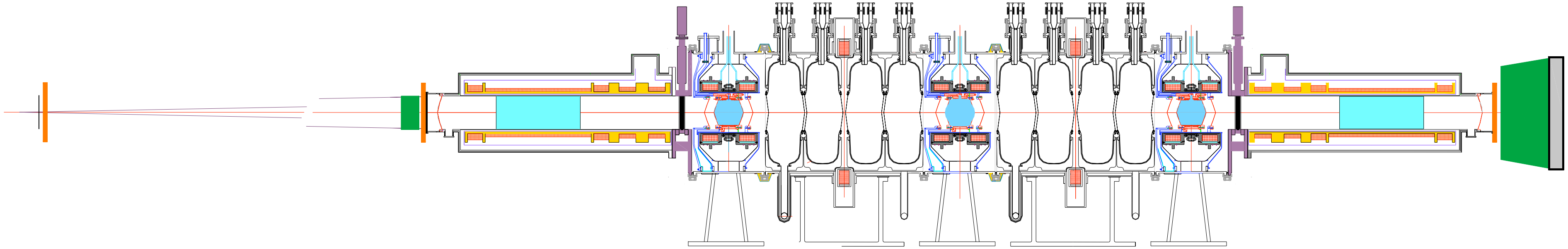


… potential supply problem with tubes @ 4MW
… stock of ISIS TH116 tubes 2MW max…

Scheme: work in progress.

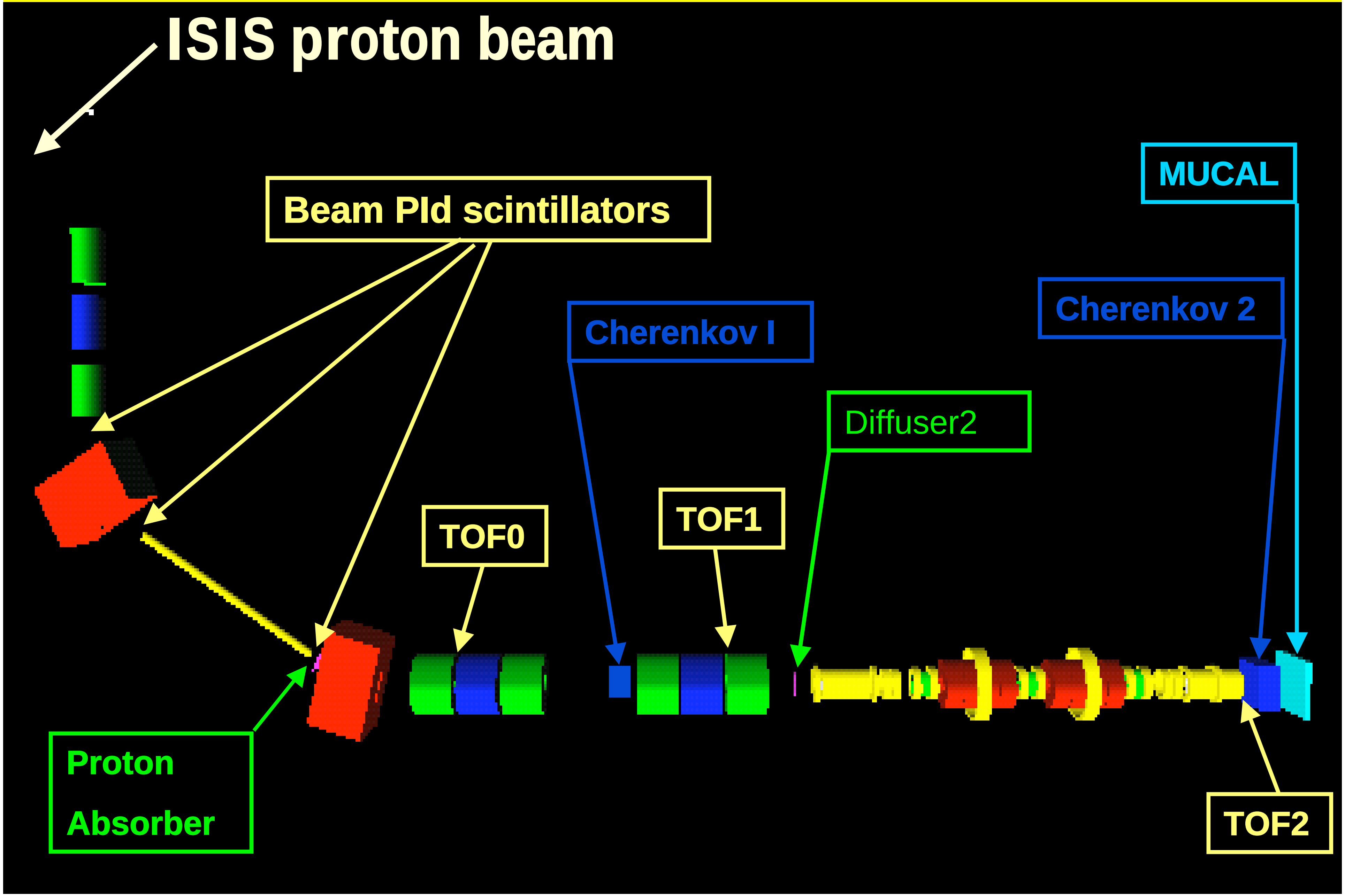
RF amp test stand to be established at Daresbury Laboratory this year. Equipment to be shipped from LBNL for refurbishment.

Apparatus: instrumentation



- Particle identification
  - Upstream: $\pi - \mu$ separation
    - Time-of-flight measurement
    - Cherenkov
  - Downstream: $\mu - e$ separation
    - Cherenkov
    - Electromagnetic calorimeter
- Spectrometers:
  - Position, momentum, emittance measurement

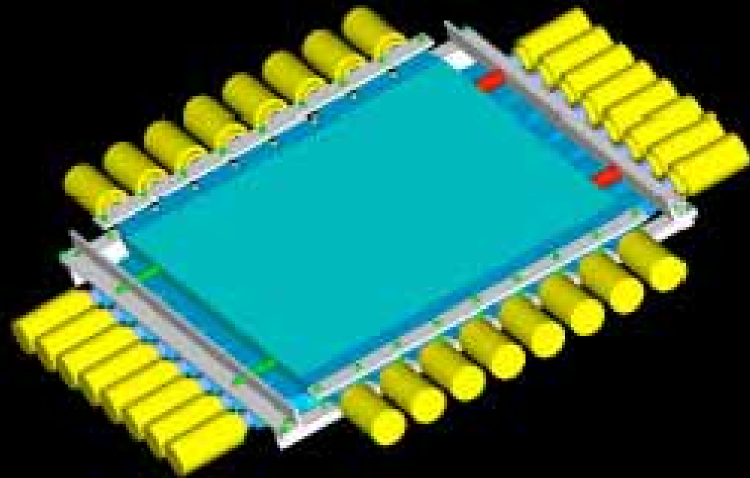
Apparatus: PId – overview



Apparatus: PId: Time of flight

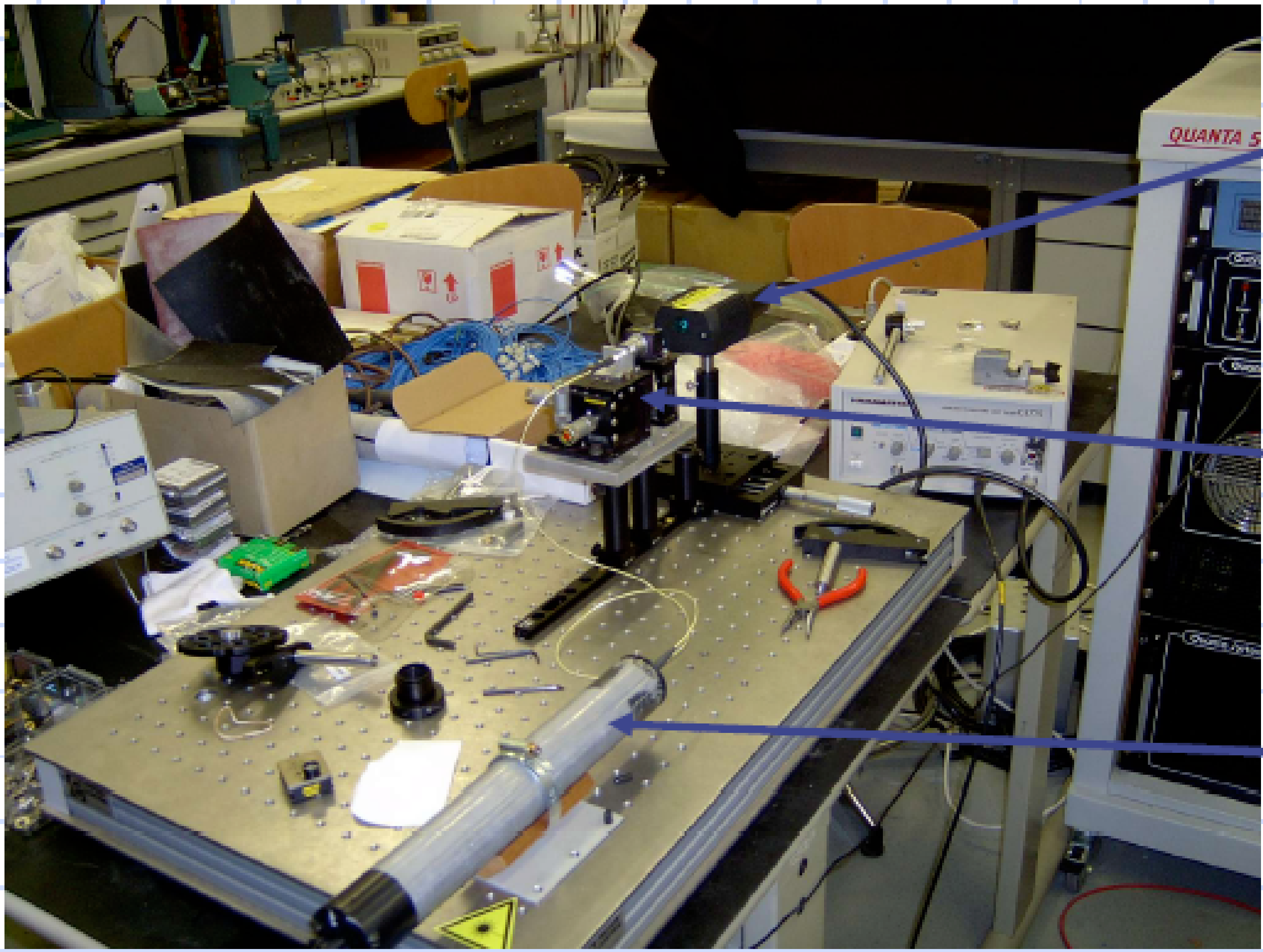
Milan

- Specification: time-difference resolut^n 70ps
- Tasks:
  - TOF0 – TOF1: π/μ separation
  - TOFs: measurement of muon phase w.r.t. RF
  - Trigger and trigger time
- Principal challenges:
  - Rate in upstream TOFs
  - Time-difference resolution



Apparatus: PId: ToF R&D

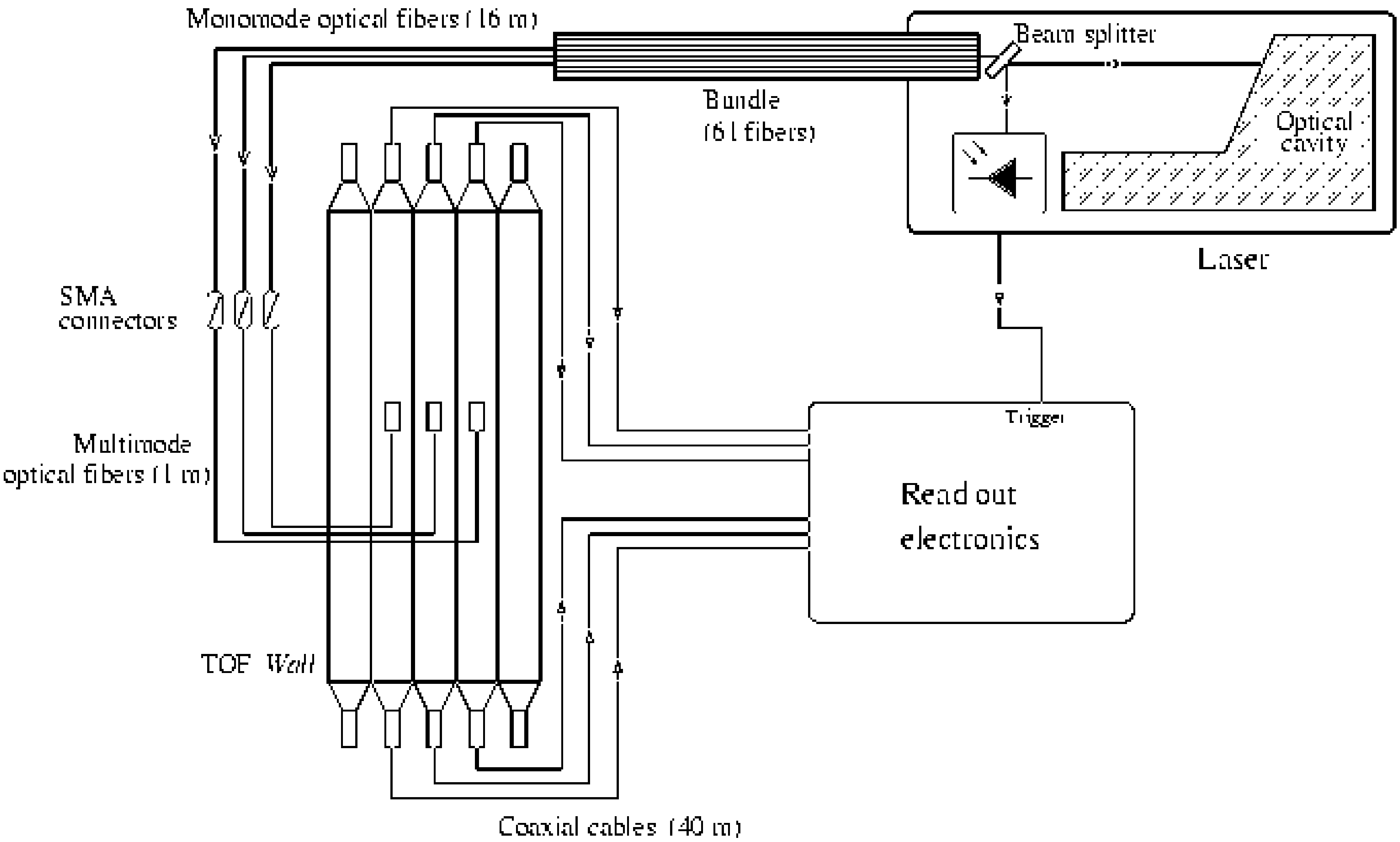
Test setup for study of rate effects



- Light source: Hamamatsu fast laser ($\lambda \approx 405$ nm, FWHM 35 ps, .17 mW power)
- Optical system: x,y,z micrometric movement to inject light into a CERAM/OPTEC multimode fiber (spread 14 ps/m)
- PMT under test (R7761, ...), output to SILENA MCA
- All tests to be redone at LASA with B-field

Apparatus: PId: ToF calib^{n} syst.

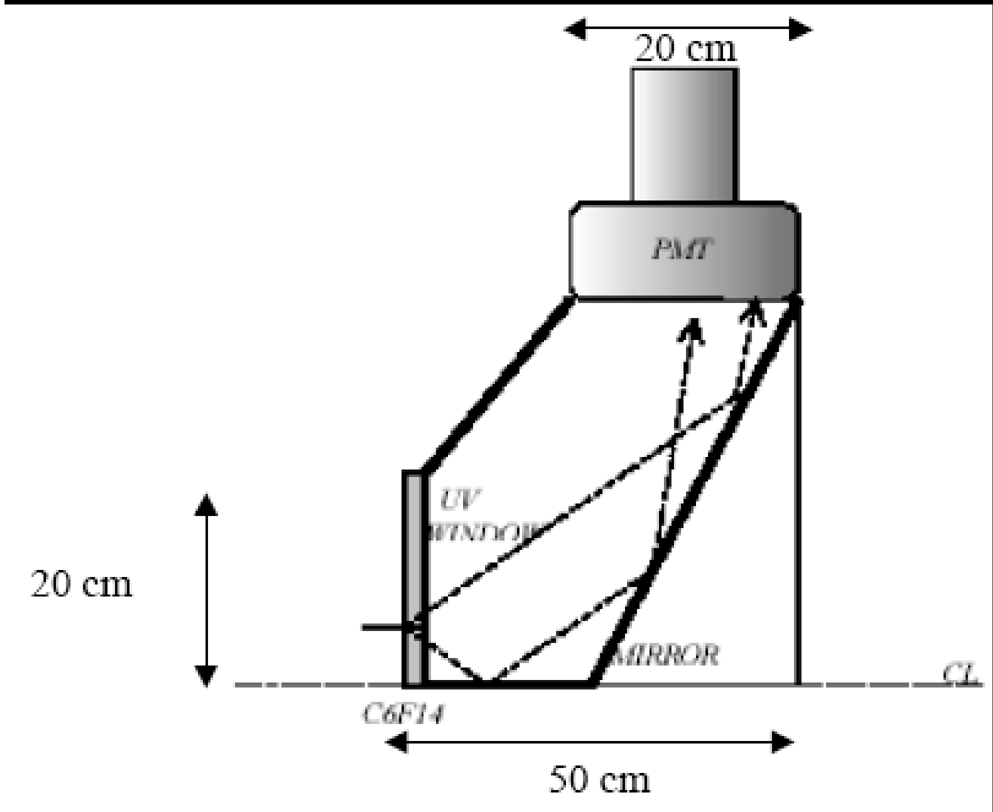
Calibration: tracks in overlaps plus laser system

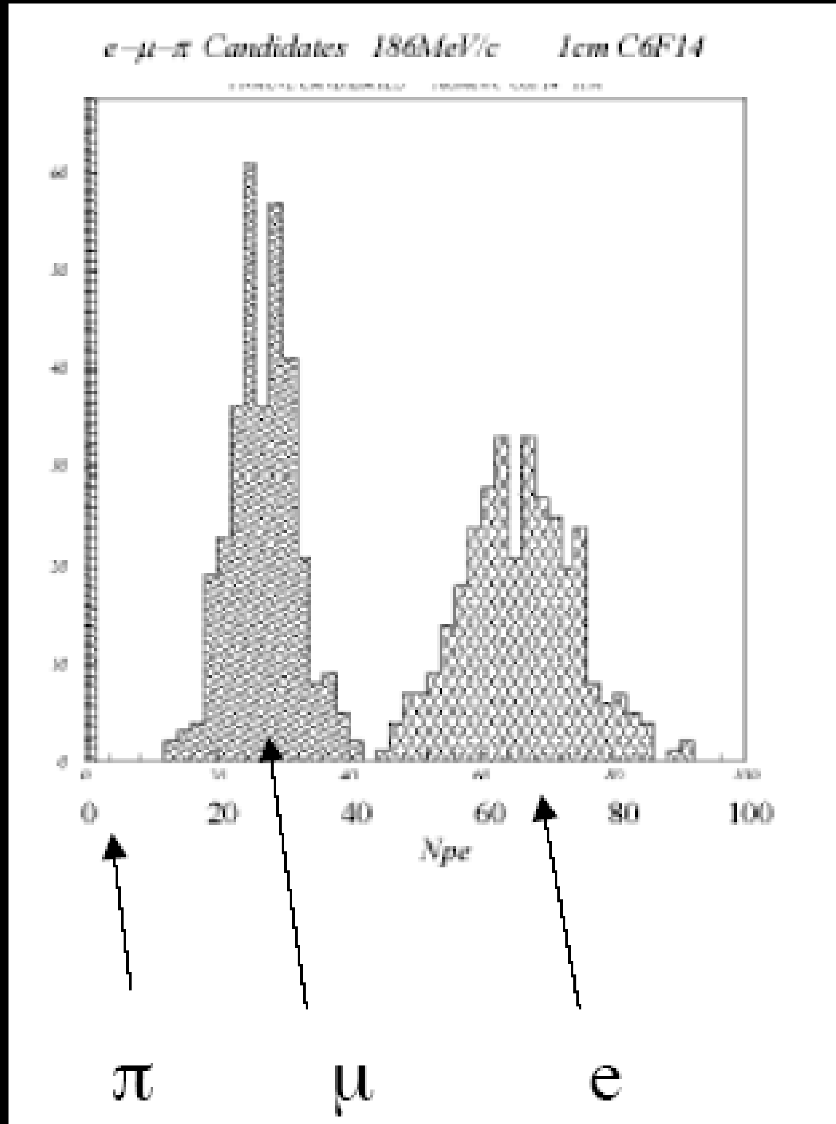


Apparatus: PId: up^{strm} Cherenkov

U-Mississippi

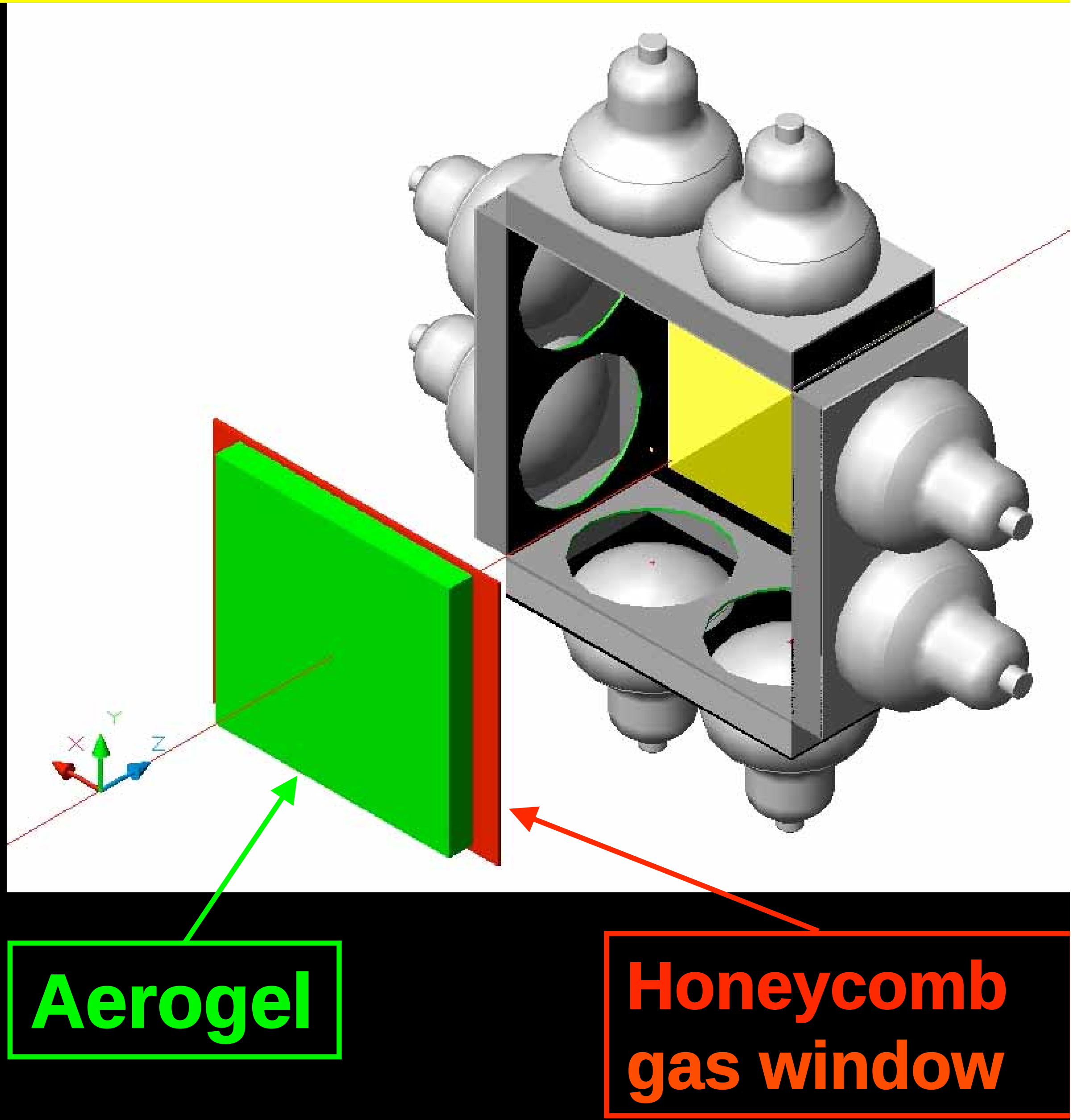
- Tasks:
  - π/μ separation





Apparatus: PId: dn^{strm} Cherenkov

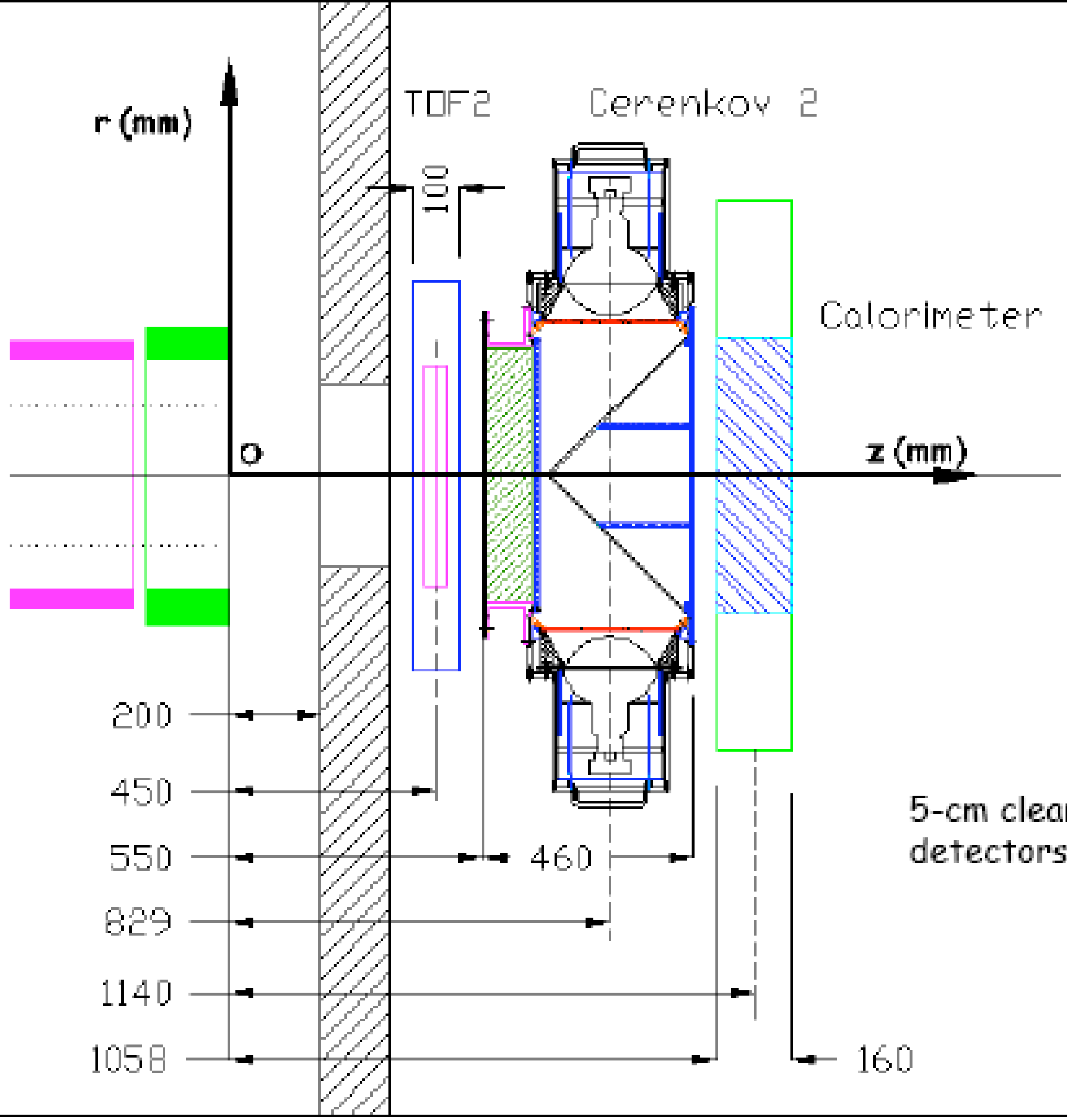
- **Task:**
  - **μ/e separation**
- **Challenge:**
  - **Operation in fringe field of detector solenoid**

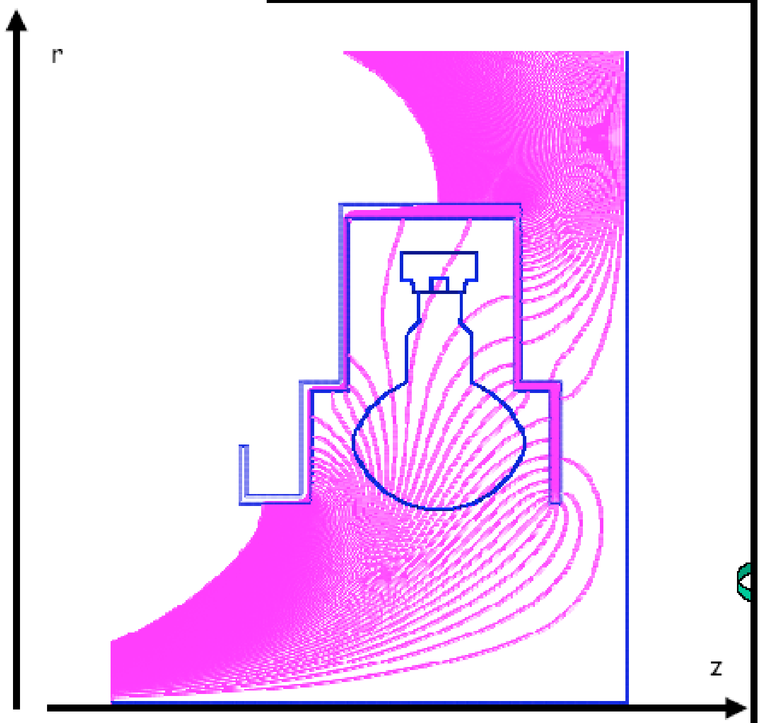


Louvain

Apparatus: PId: dn^{strm} Cherenkov

- Layout and magnetic shielding



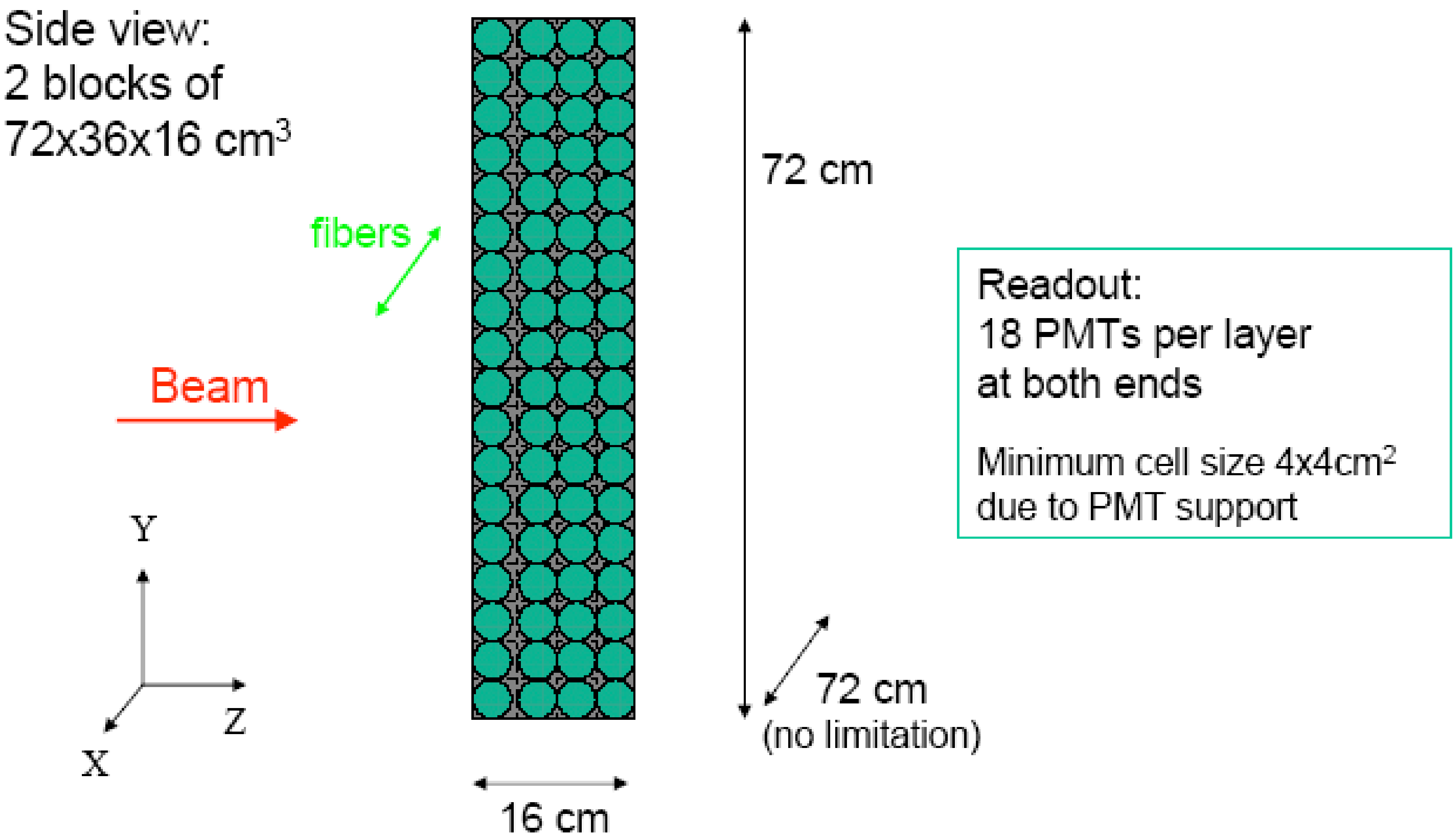


Apparatus: PId: MUCAL

■ Task: μ/e separation

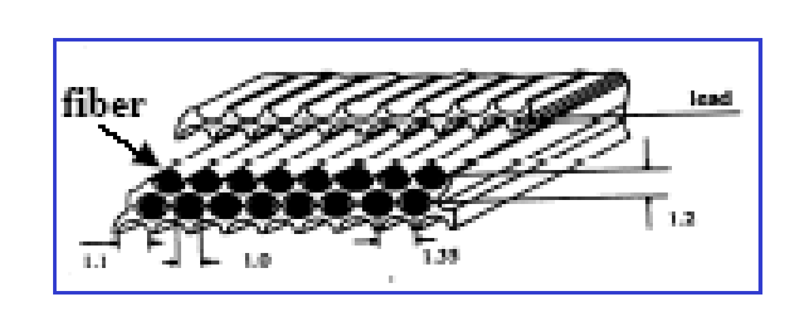
Rome III

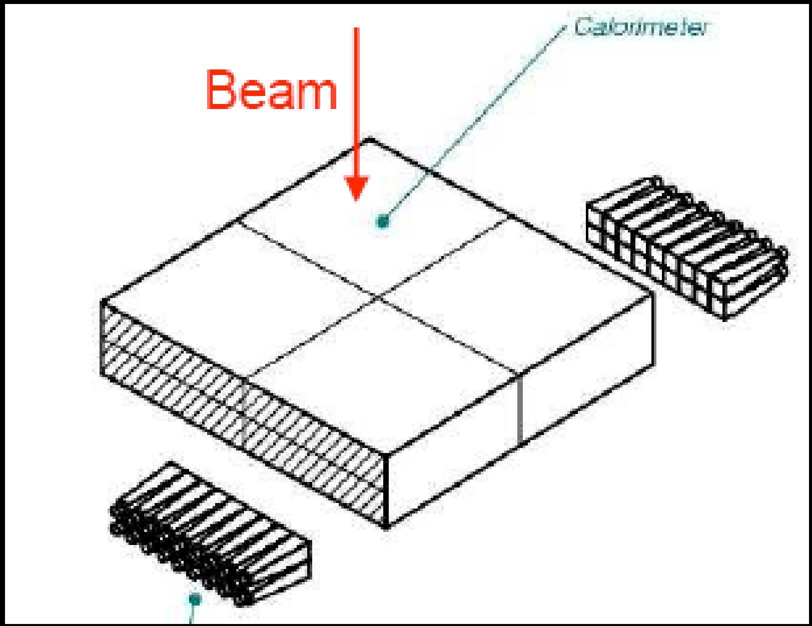
Scintillating fibers embedded in grooved lead layers

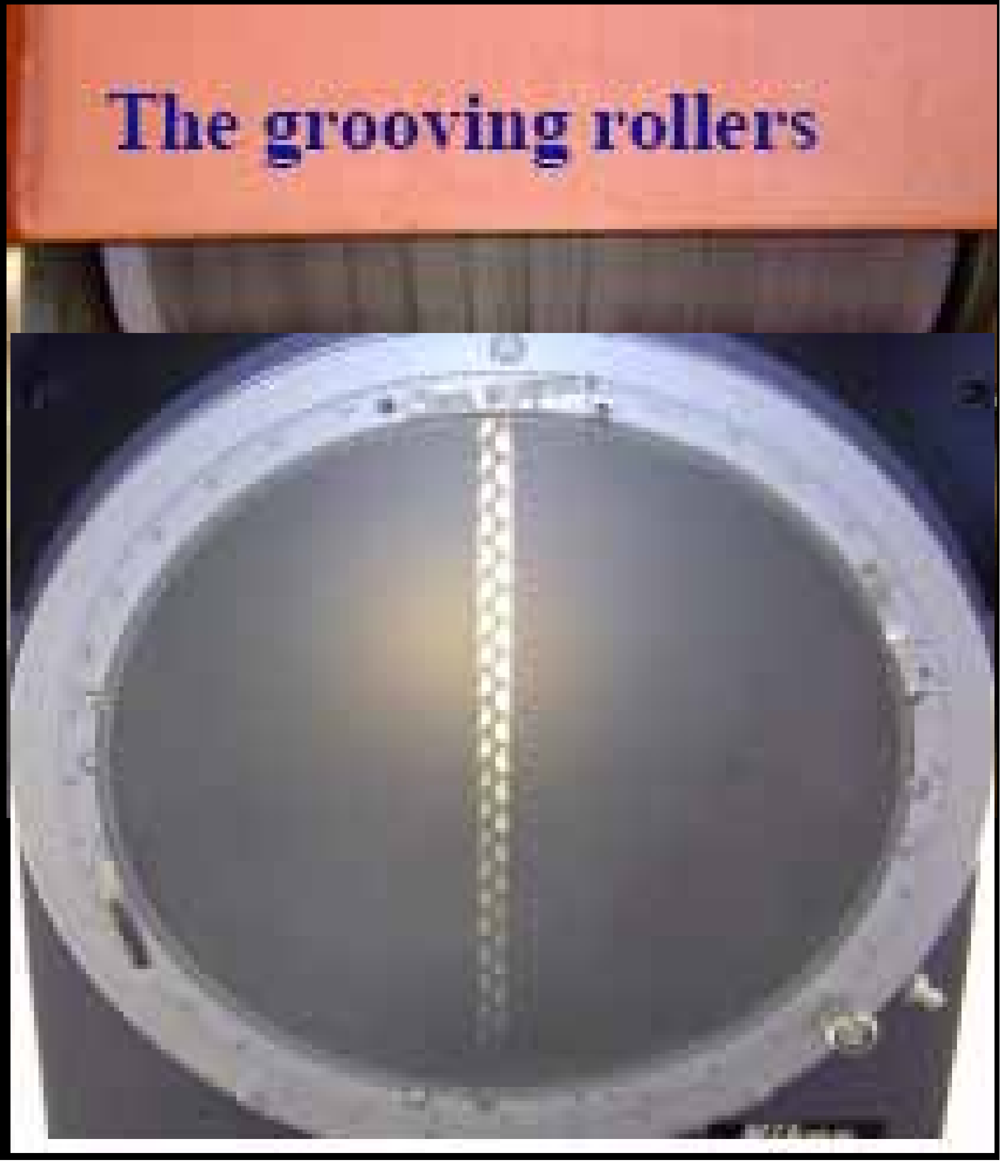


Apparatus: PId: MUCAL

- Construction: 0.3 mm lead; 1 mm fibre

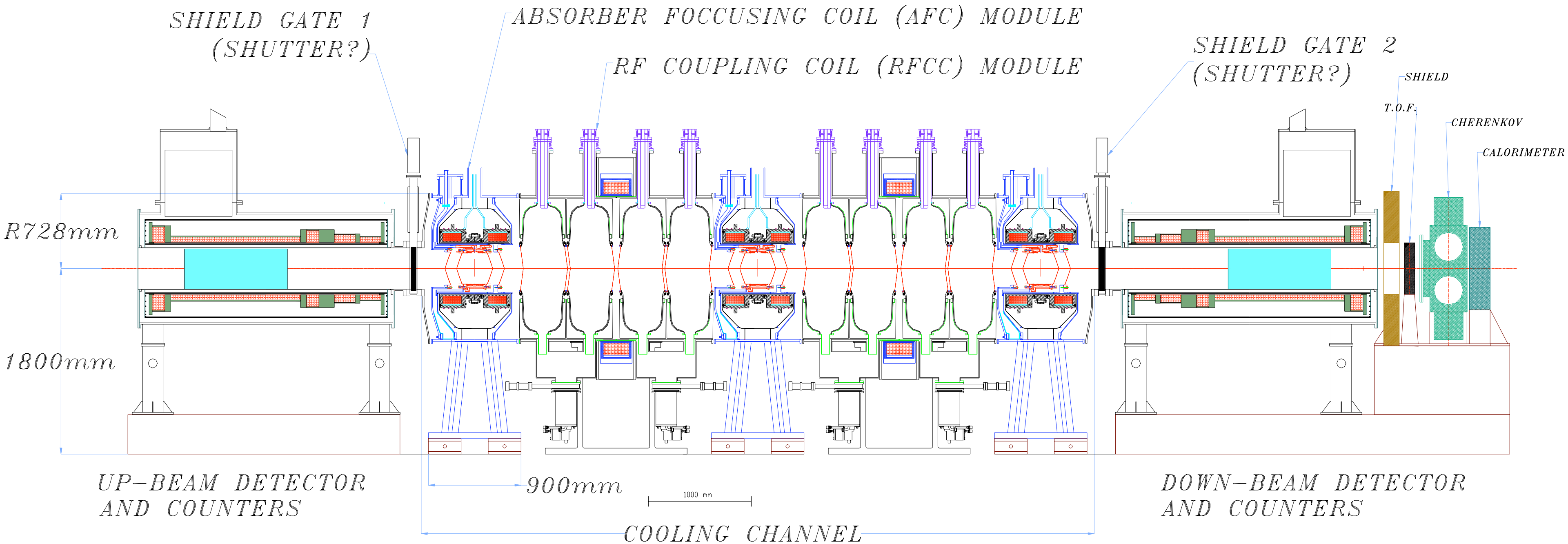






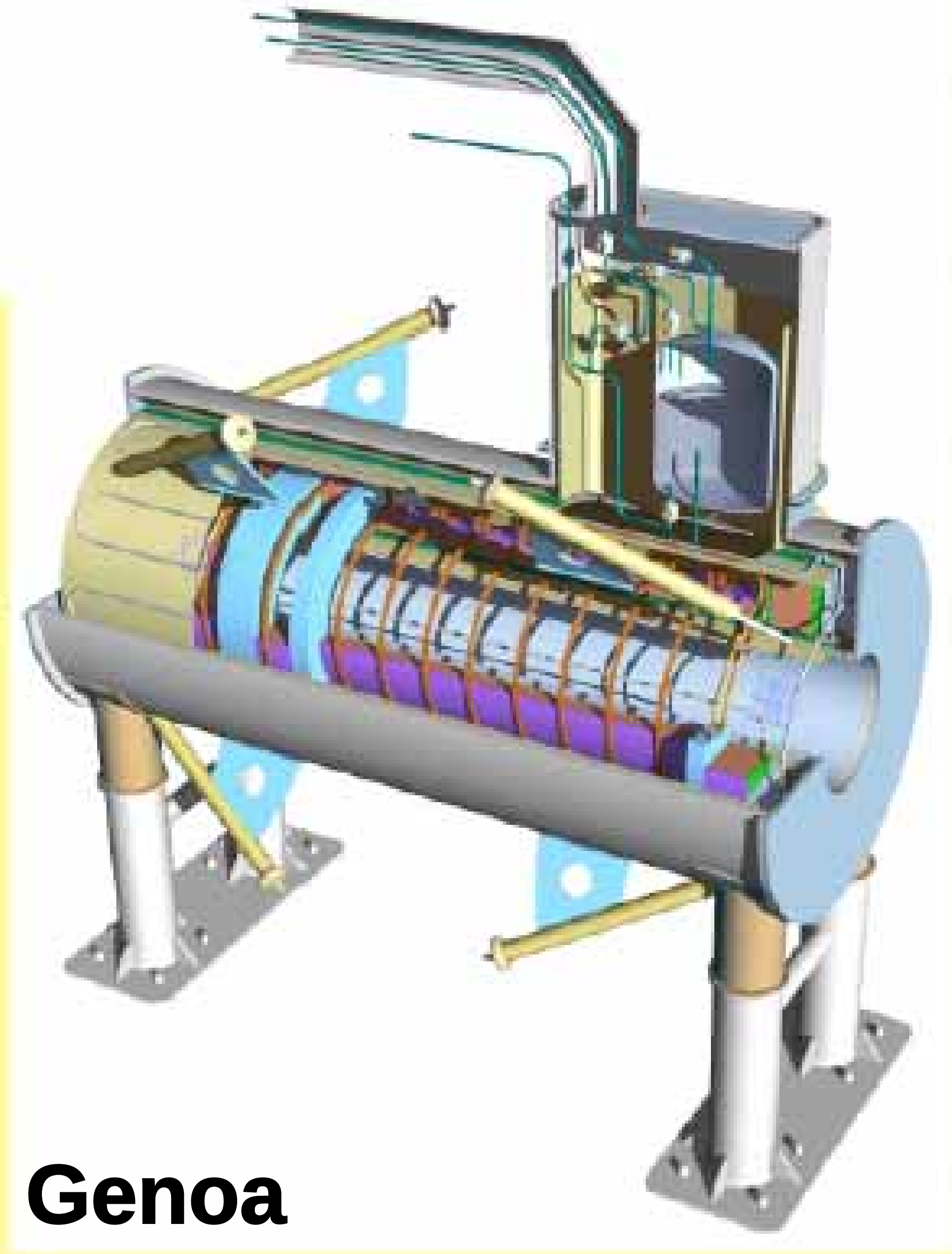
Apparatus: spectrometers

- Tasks:
  - Muon momentum (energy) and position (time)
  - Emittance



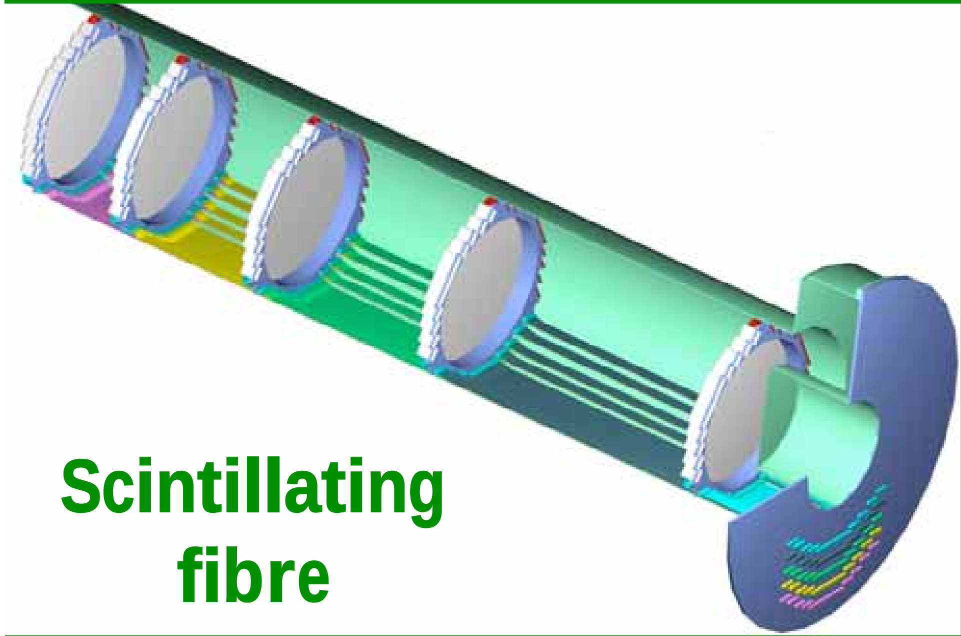
Apparatus: spectr^{mtr}: solenoid

- Specification:
  - 4 T field, 40 cm bore
- Challenges:
  - Many coils; one cryostat
    - Matching coils at each end of solenoid
  - Tracker services; magnetic field monitoring

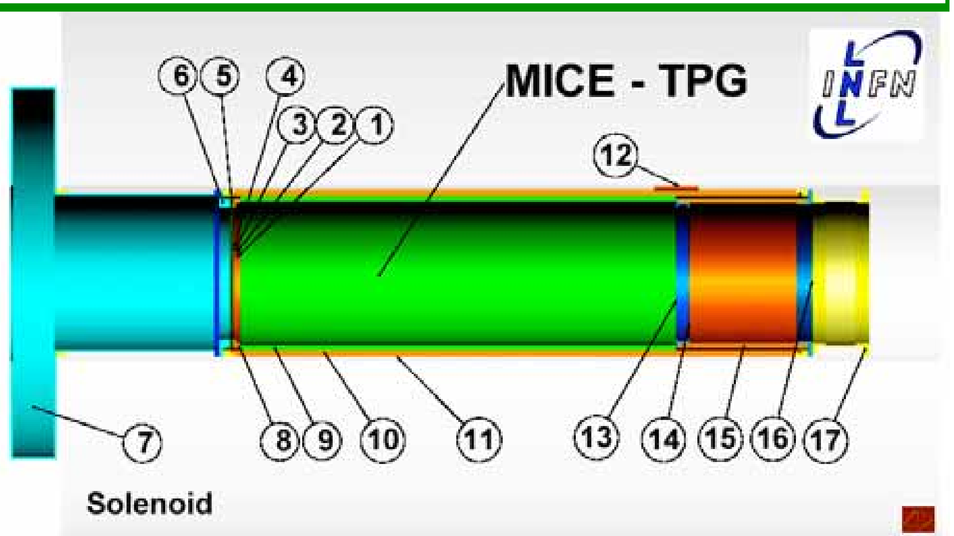


Apparatus: spectr^{mtr}: tracker

Baseline	Fallback



Scintillating fibre



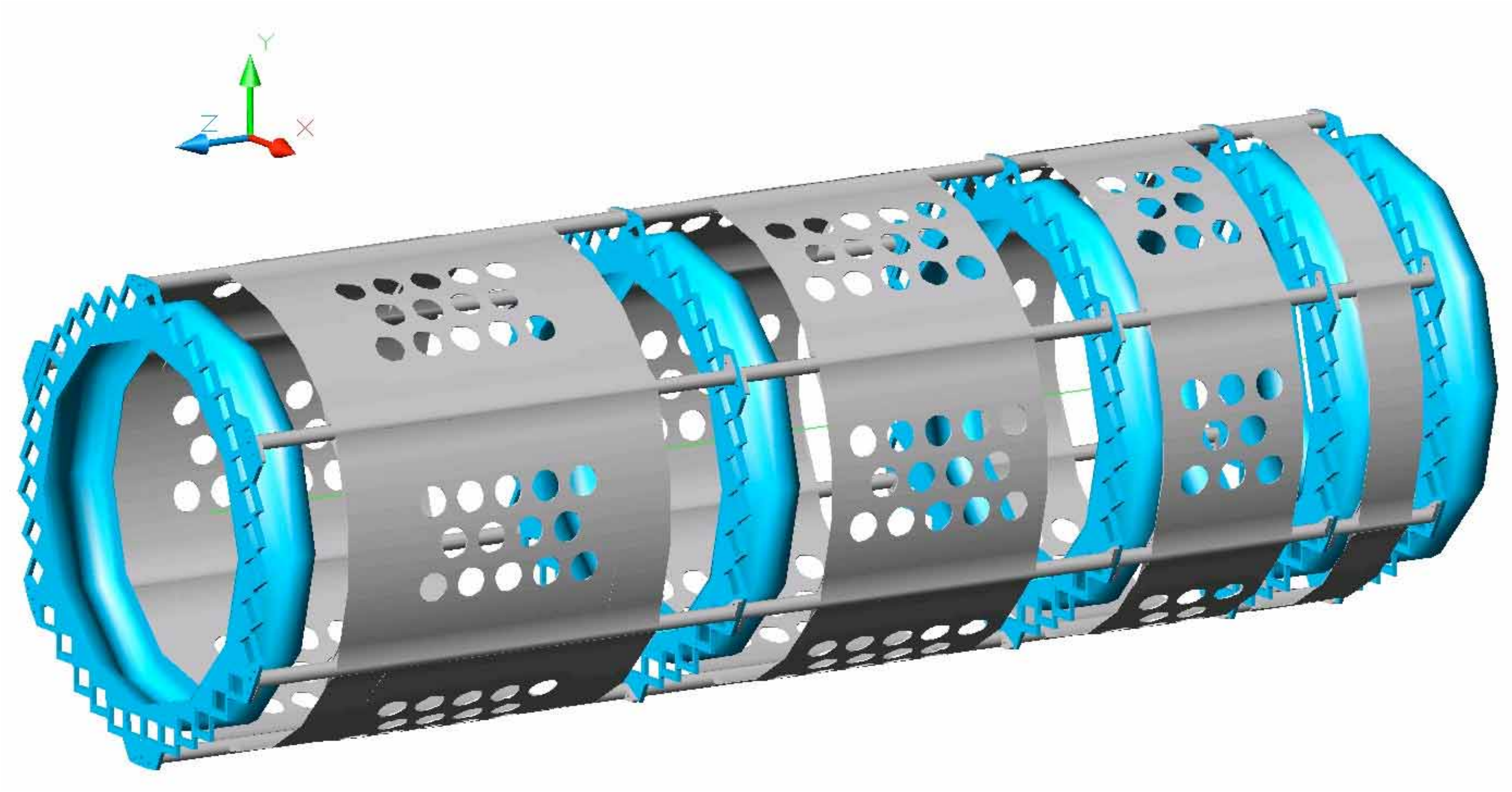
TPG – TPC with GEM readout

- No active electronics/HV close to liquid hydrogen absorber
- No copper close to RF (no pickup)
- 350 μ fibre: 3-fold doublet; 0.35% X_0
- VLPC read-out: high quantum-efficiency, high gain

- Light gas (0.15% X_0)
- Many points per track
- High precision track rec^n possible
- Large integration time
- Effect of X-rays on GEMs

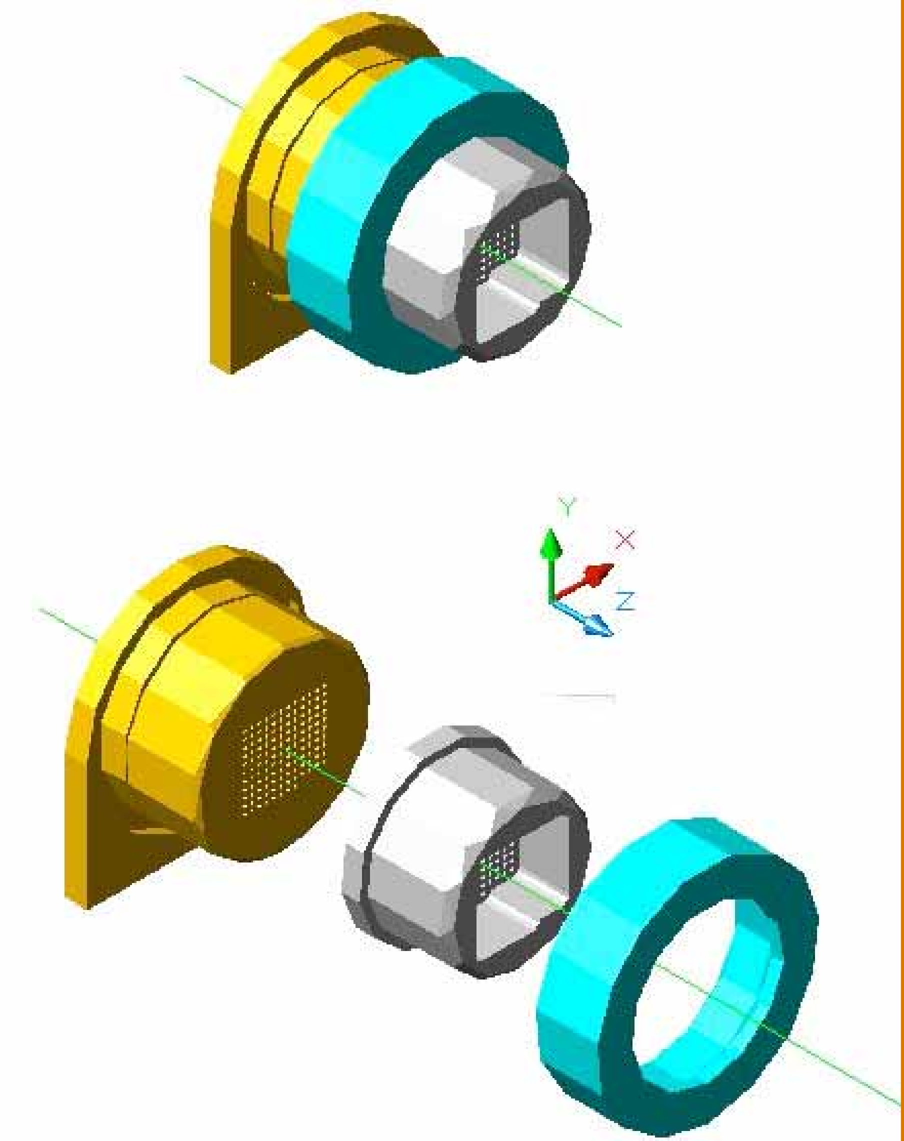
Apparatus: spectr^{mtr}: tracker

■ Mechanical design: status



Apparatus: spectr^{mtr}: tracker

- **Optical connectors:**



Bulkhead connector

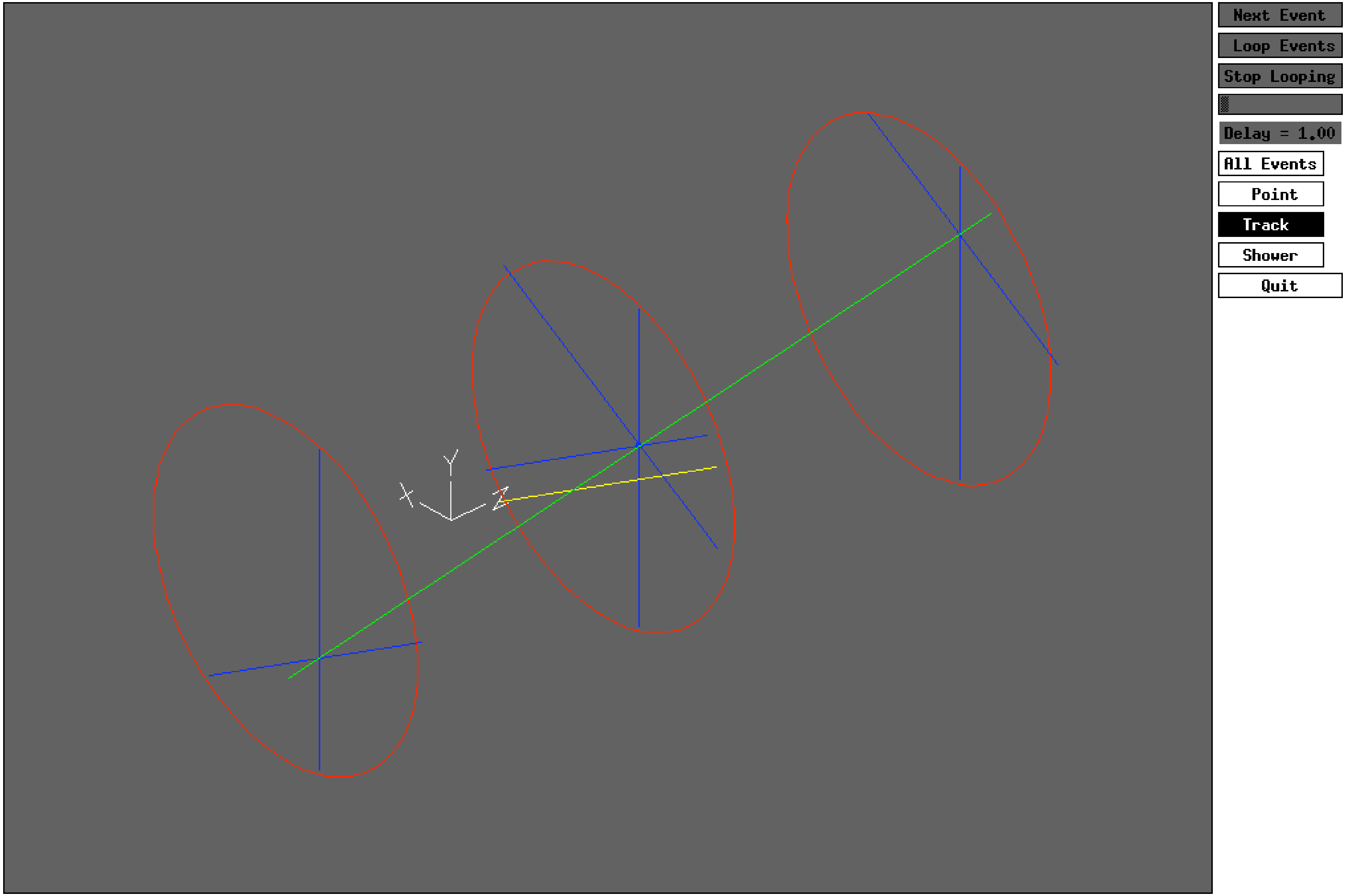
Station connector

Seven 350 μm scint. fibres read out through one 1 mm clear fibre

7-fold reduction in channel count ⇒ significant cost saving

Apparat

Runs 202 – 231 correct gains used for each channel



Apparatus: spectr^{mtr}: tracker

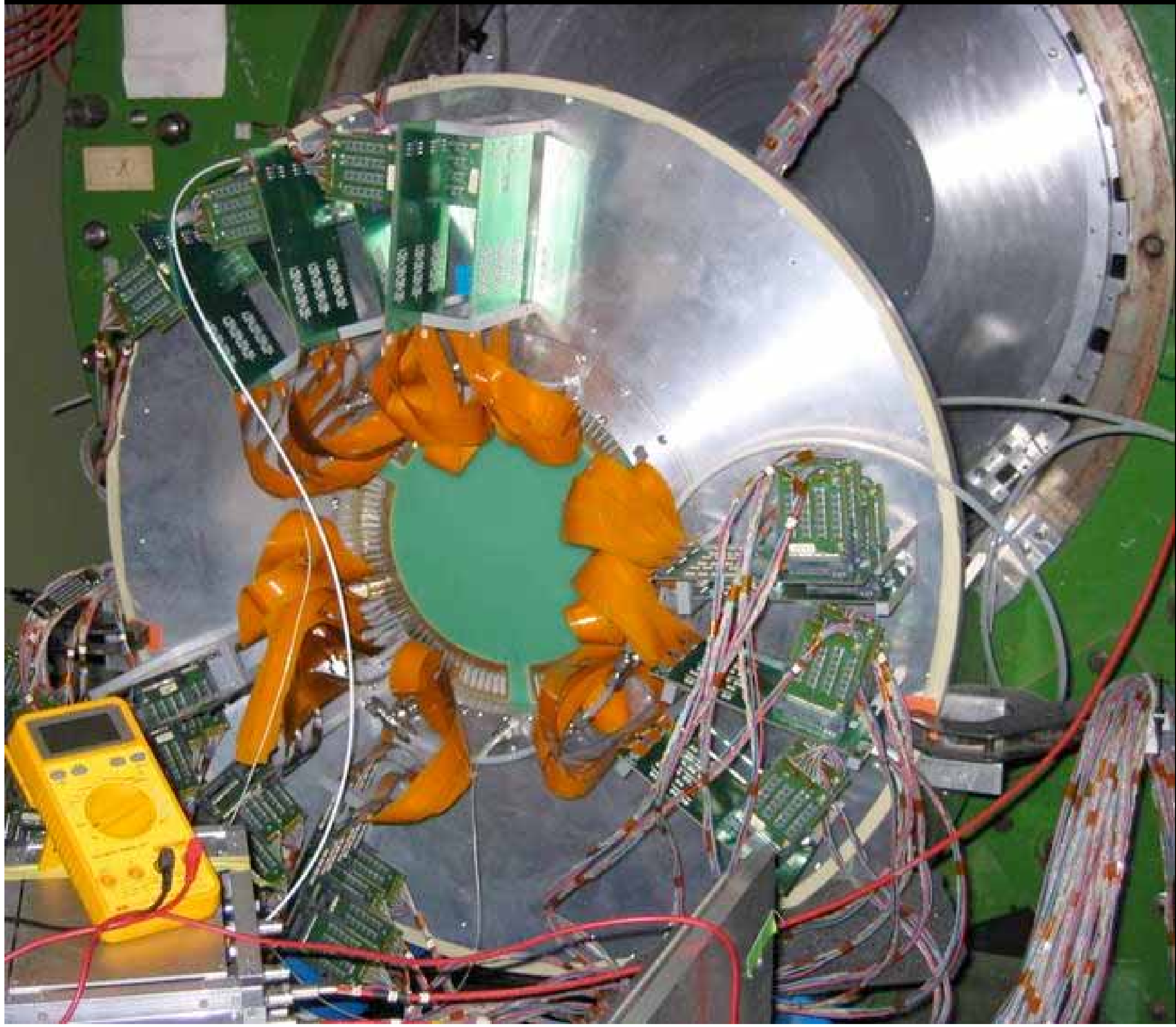
- Prototype performance:
  - Most probable light yield: 10.5 – 11 p.e.
    - Expectation based on D0 experience ~10
  - Resolution: 442 ± 4 (stat) ± 27 (syst) μm
    - Expectation from fibre geometry: 424 – 465 μm (single fibre bunch or two fibre bunch)
  - Efficiency: (99.7 ± 0.2)%
    - Poisson expectation for 10 p.e. signal 99.7%
  - Dead channels 0.2% (two channels)
    - 0.25% assumed in G4MICE simulation based on D0 experience
- Planning test beam at KEK (then RAL):
  - Additional station – finalise fabricat^{n} techniques
  - Magnetic field: verify pattern recognition and momentum measurement

Apparatus: spectr^{mtr}: tracker

- **Fallback:**

Bari, Legnaro, Napoli, Trieste, Geneva

  - **Time-projection chamber with GEM readout**



Test of TPG head using HARP TPC field cage

<u>Operation:</u>

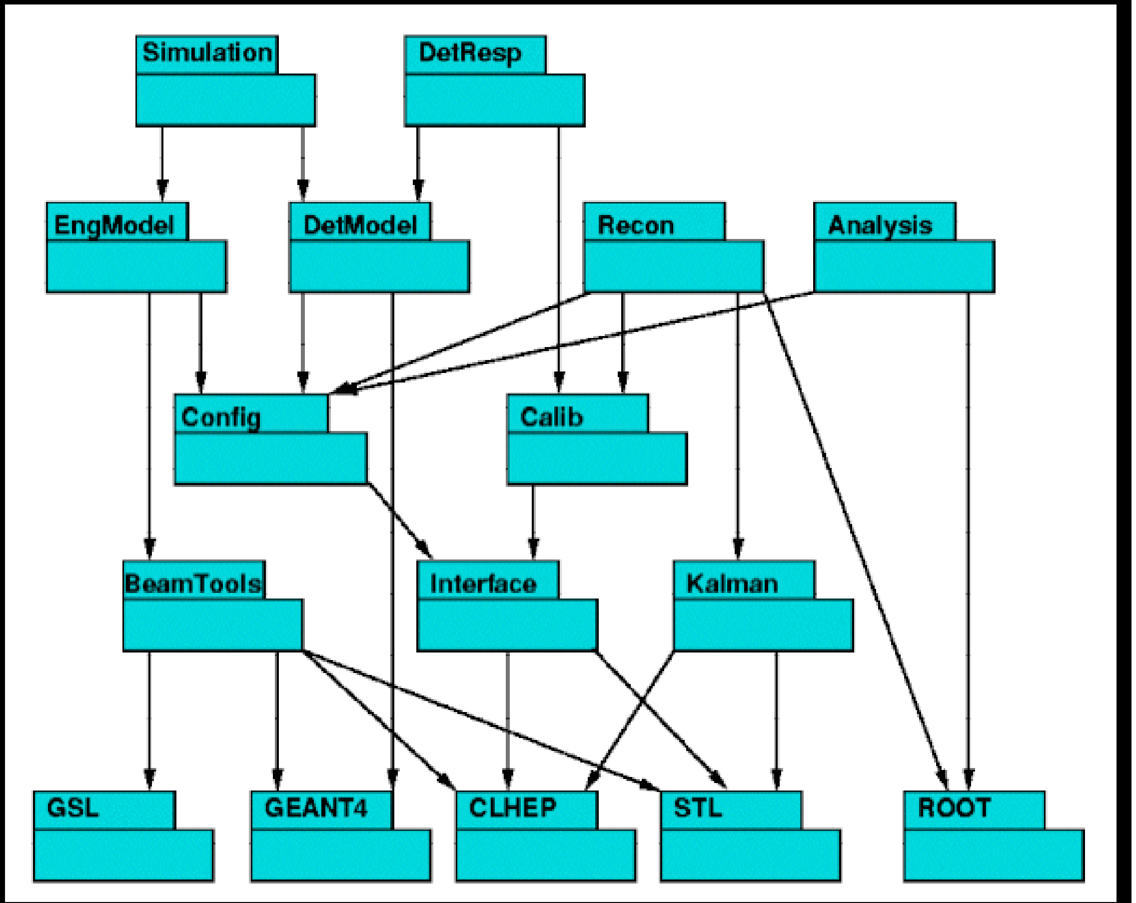
with cosmics March 2004

with beam May 2004

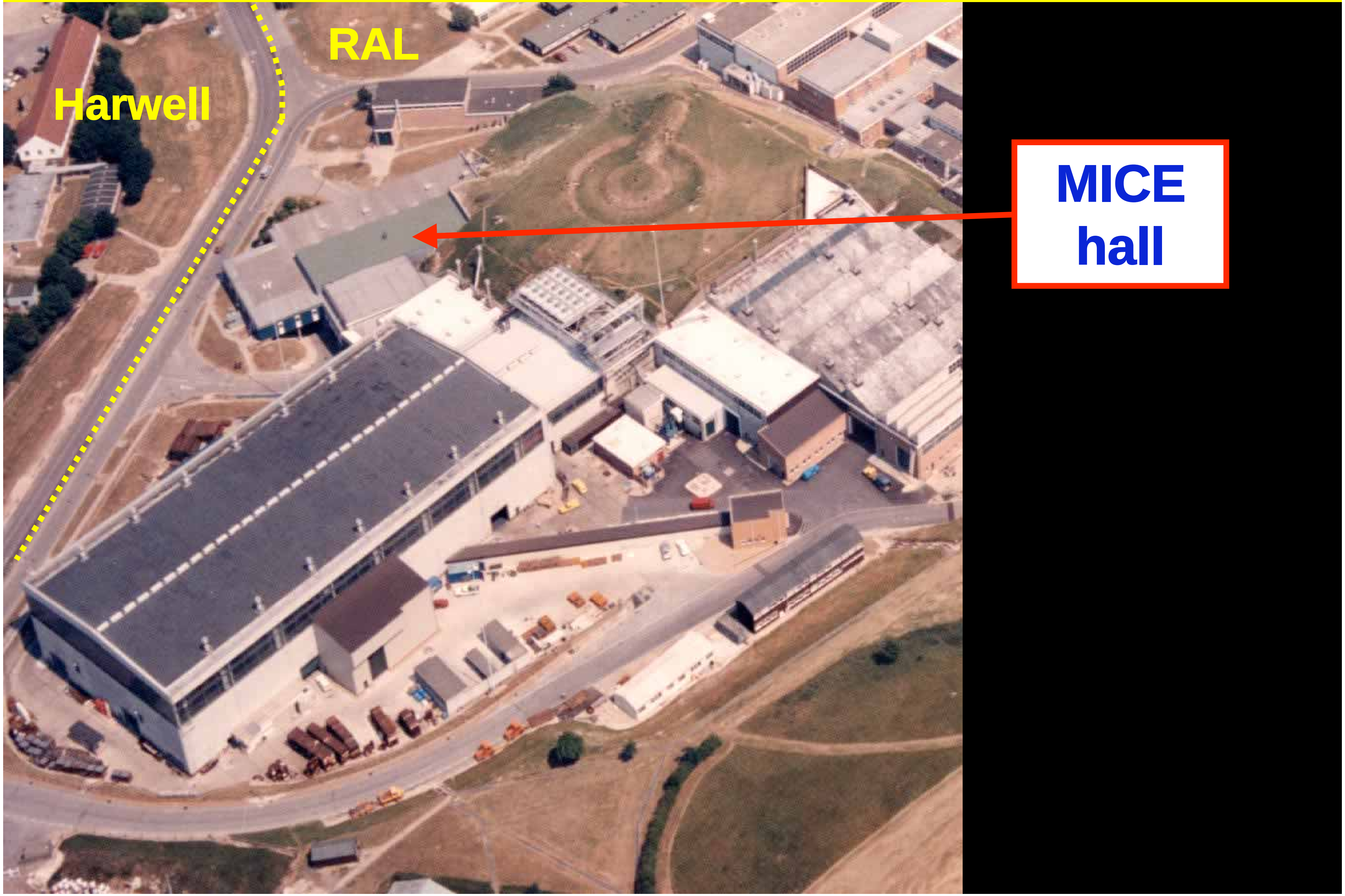
Apparatus: softwaren – G4MICE

– Contributions from EU, Jp, US and UK

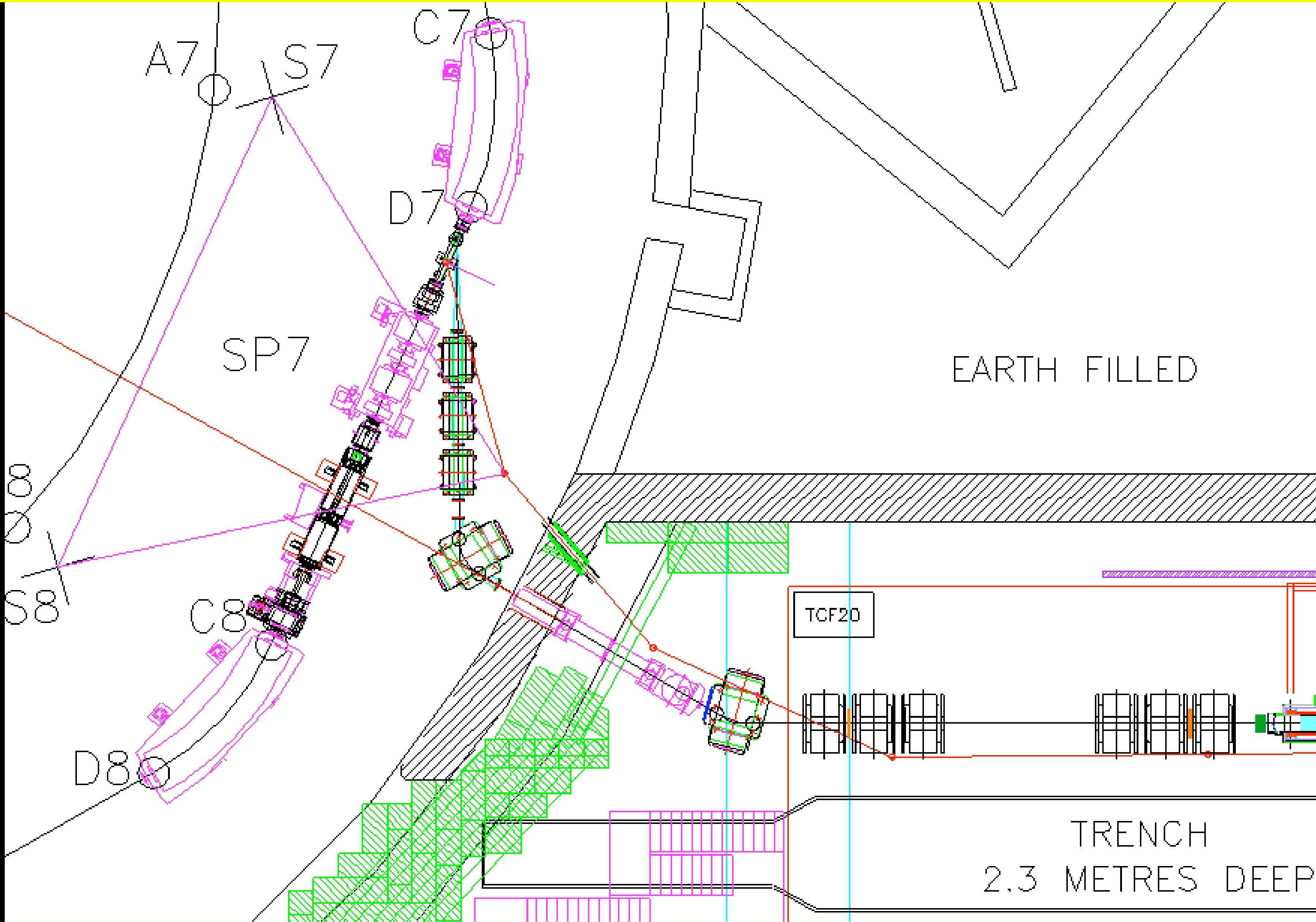
- Beam line and MICE simulation in Geant
- Presently in transition phase:
  - S/w required to:
    - meet requir^{ments} of component design and optimisation;
    - evolve into final product^{n} framework.



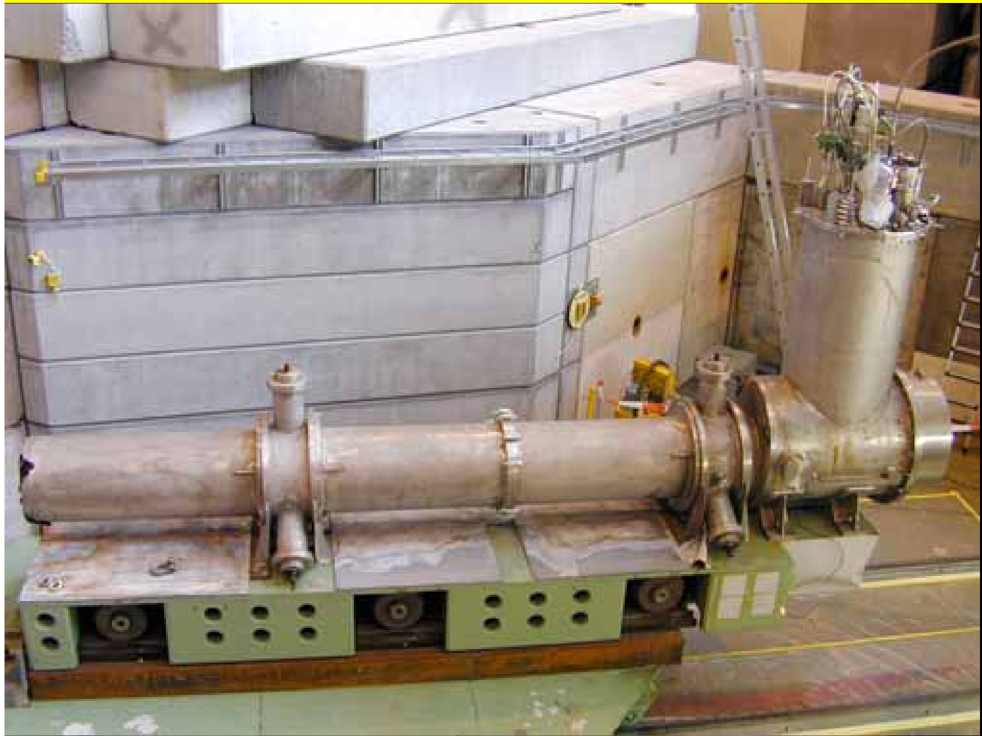
MICE: implementation at RAL



MICE Muon Beam



Muon decay solenoid: PSI

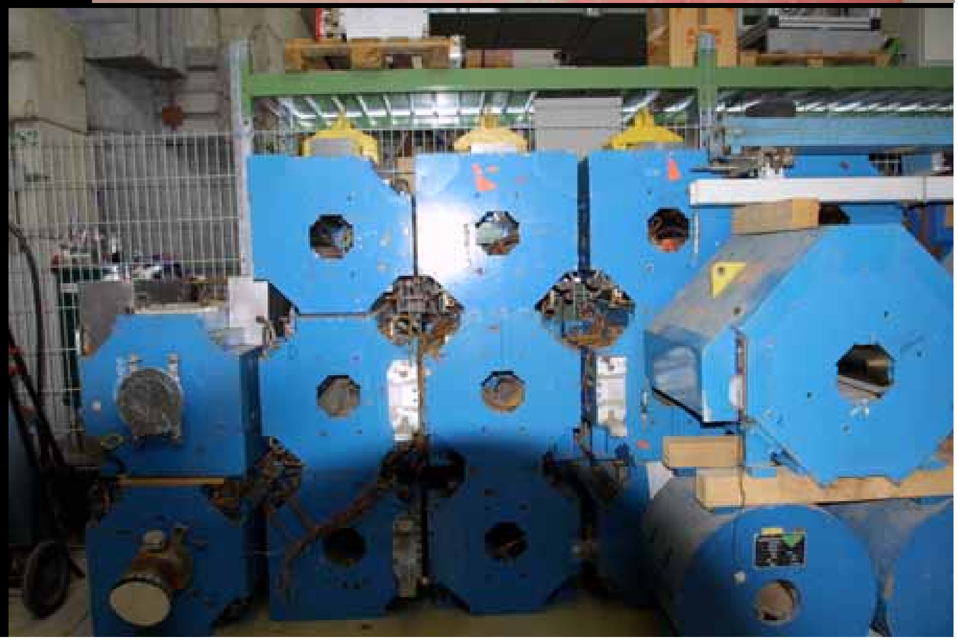


Solenoid
Power Supply
Cryo Control System

Active
- remake hot parts

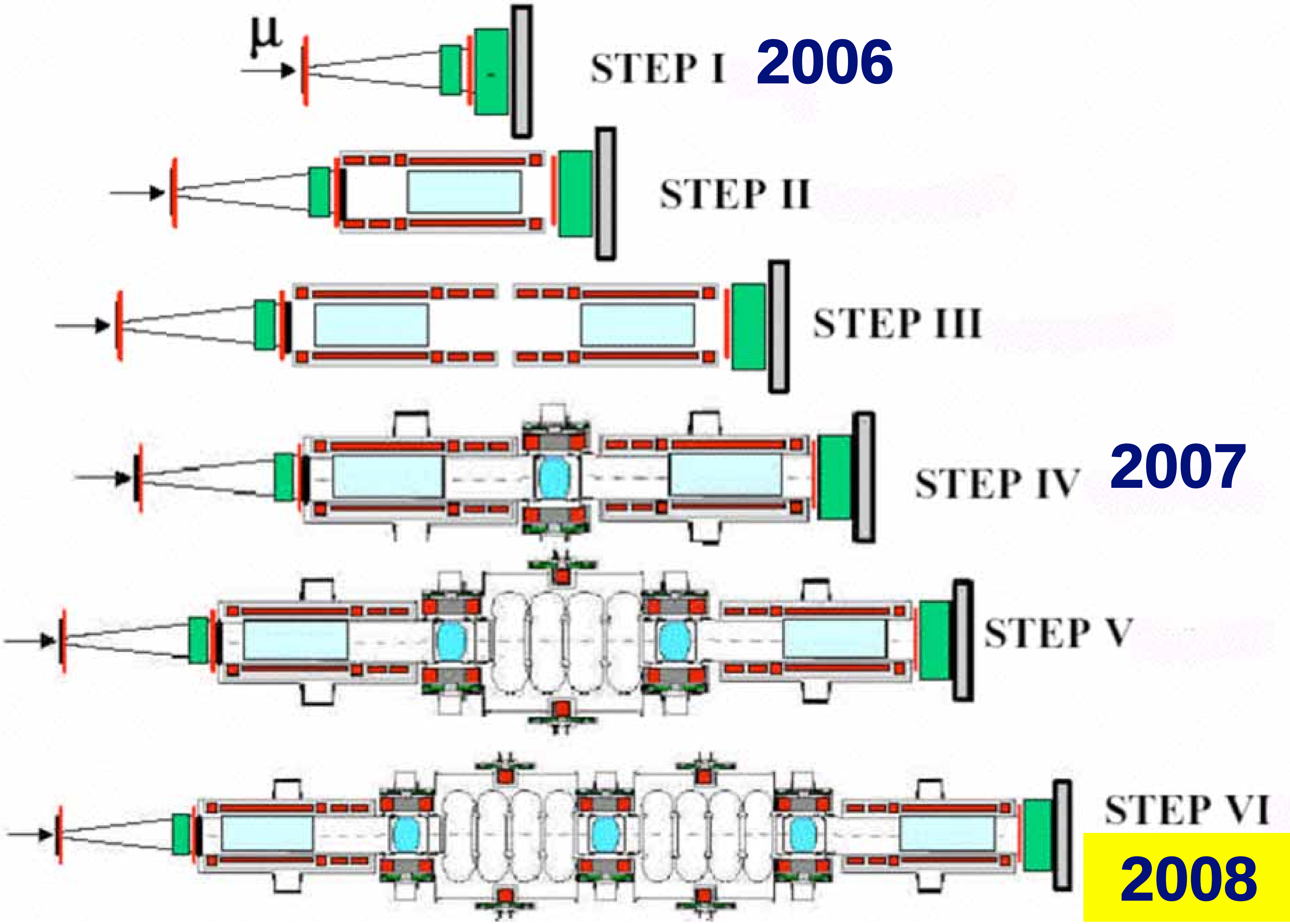
Sign MoU in October

Beam-line elements



- **MICE Muon Beam Line:**
  - **Shielding to be re-installed**
  - **Prepare beam line for installation in next long ISIS shutdown – early (?) 2006**

Outlook:



Conclusions

- Experimental study of neutrinos:
  - Origin of matter
  - Contribution to dark matter
  - New theory of fundamental particles
- Near/medium term programme:
  - Present generation: K2K, SNO, MINOS, CNGS
  - Next generation: J2K, NuMI off axis (+ …)
- Opportunity for the future:
  - Establish NF R&D programme:
    - Key technologies: ionisation cooling – MICE
proton driver, target
    - Develop conceptual design of entire facility
- Overall a *fantastic* programme!