Imperial College London

K. Long, 8 April, 2004

The Neutrino Factory

– motivation and machine

Contents

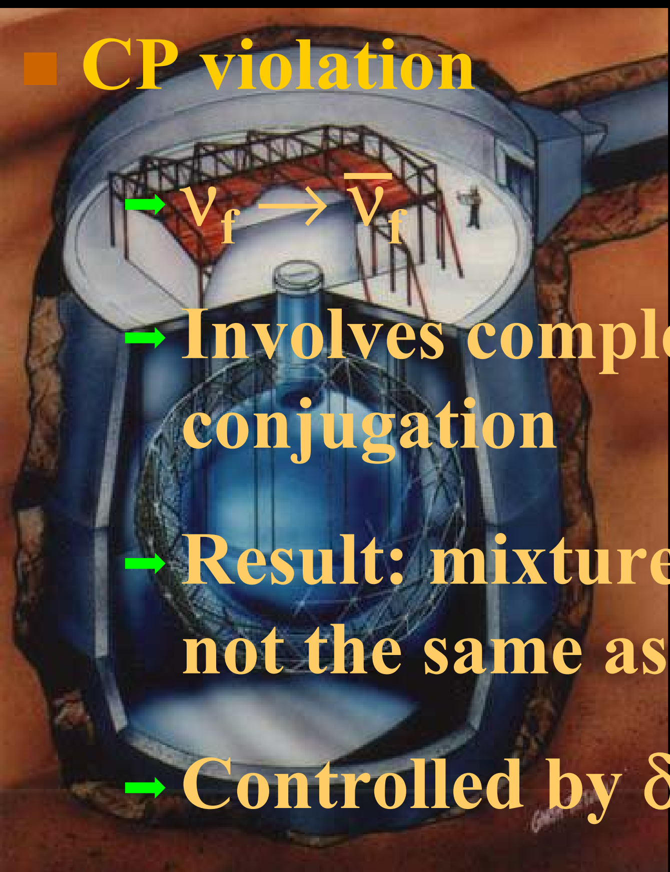
- Motivation: high-sens^{ty} studies of ν-osc^{tions}
- Neutrino Factory machine: overview
- Accelerator R&D programme: highlights
- International Ionisation Cooling Experiment
- Conclusions

Motivation: headlines

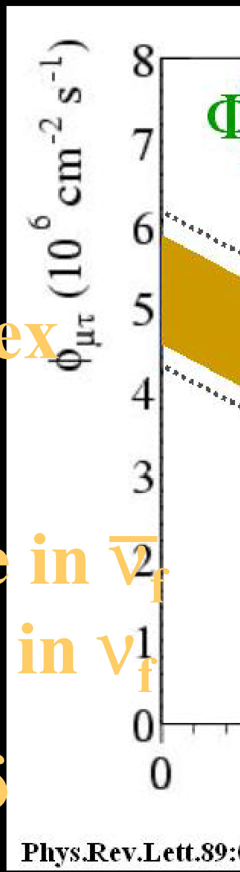
- Neutrino oscillations – established exp^{tly}
- Implications for particle physics:
  - Neutrino mass > 0
  - Neutrinos violate matter-antimatter symmetry?
  - New state of matter (Majorana?)
- Impact on astrophysics and cosmology:
  - Origin of matter (leptogenesis)
  - Dark matter
- Require dedicated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

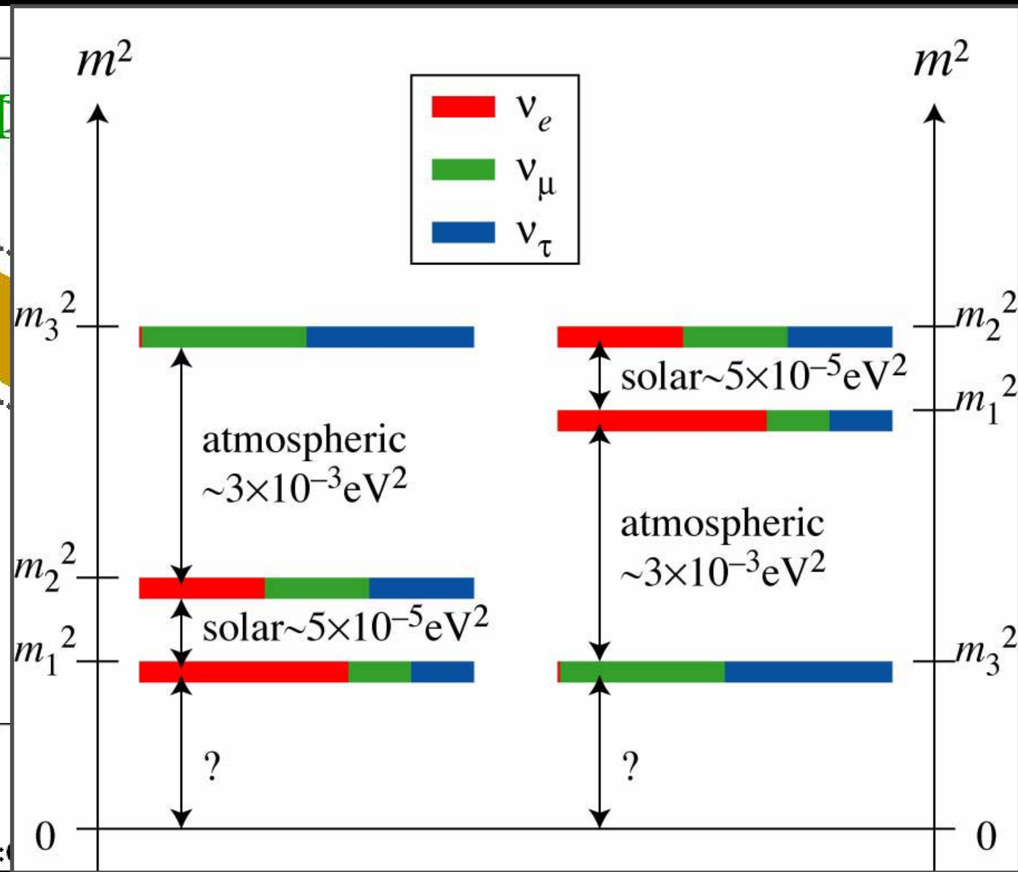
Motivation: phenomenology

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



- 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





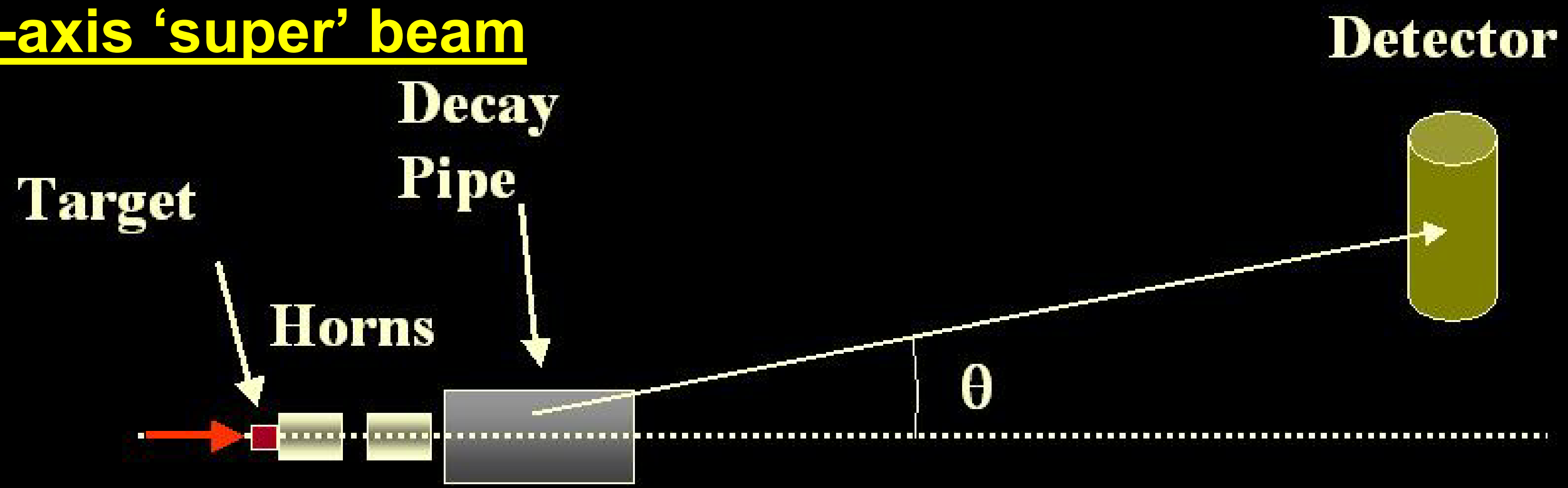
Programme of measurement

$\sin^2\theta_{13}$	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

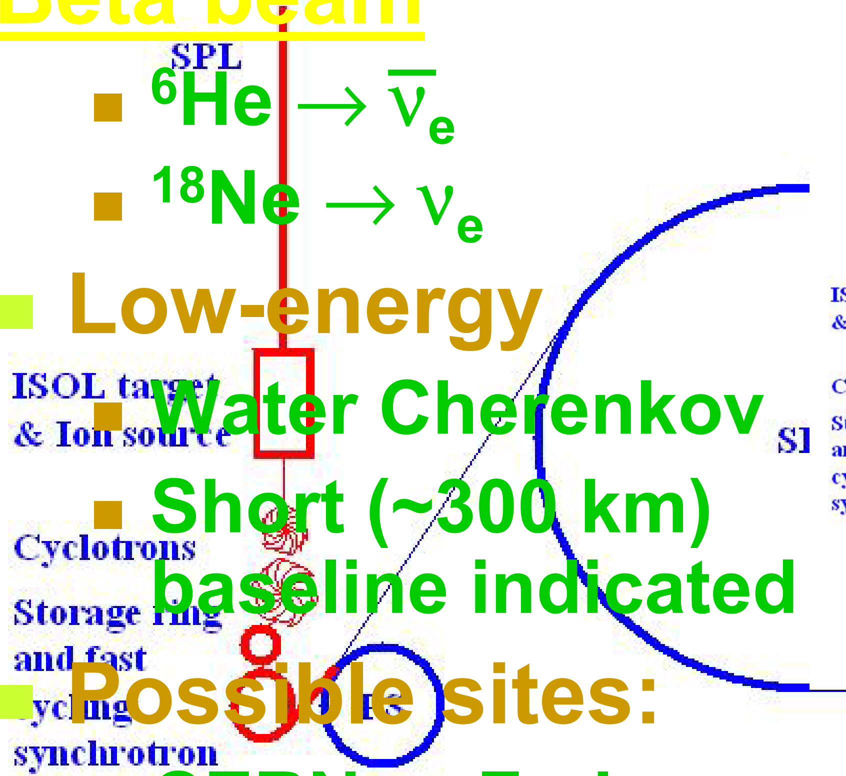
Programme of measurement

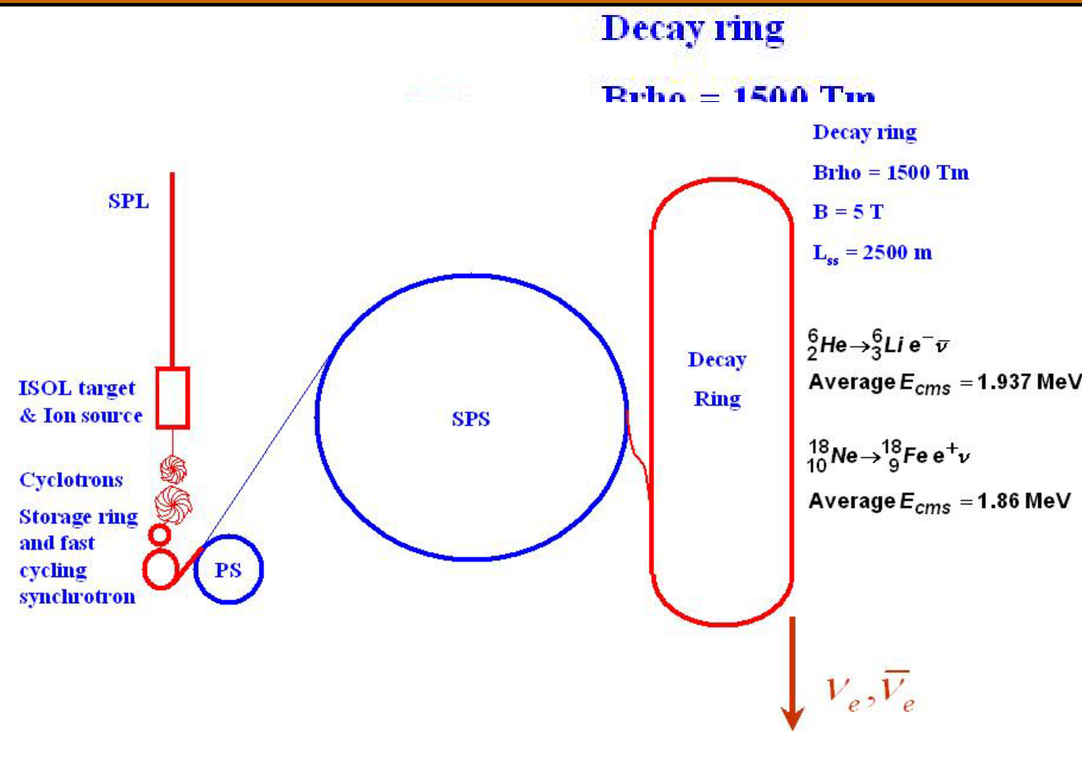
$\sin^2\theta_{13}$	δ	Δm^2_{23}

Beta beam

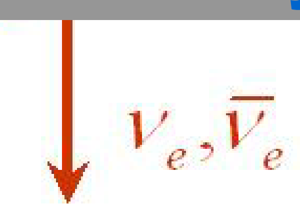
- $^6He \rightarrow \overline{\nu}_e$
- $^{18}Ne \rightarrow \nu_e$

- 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

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

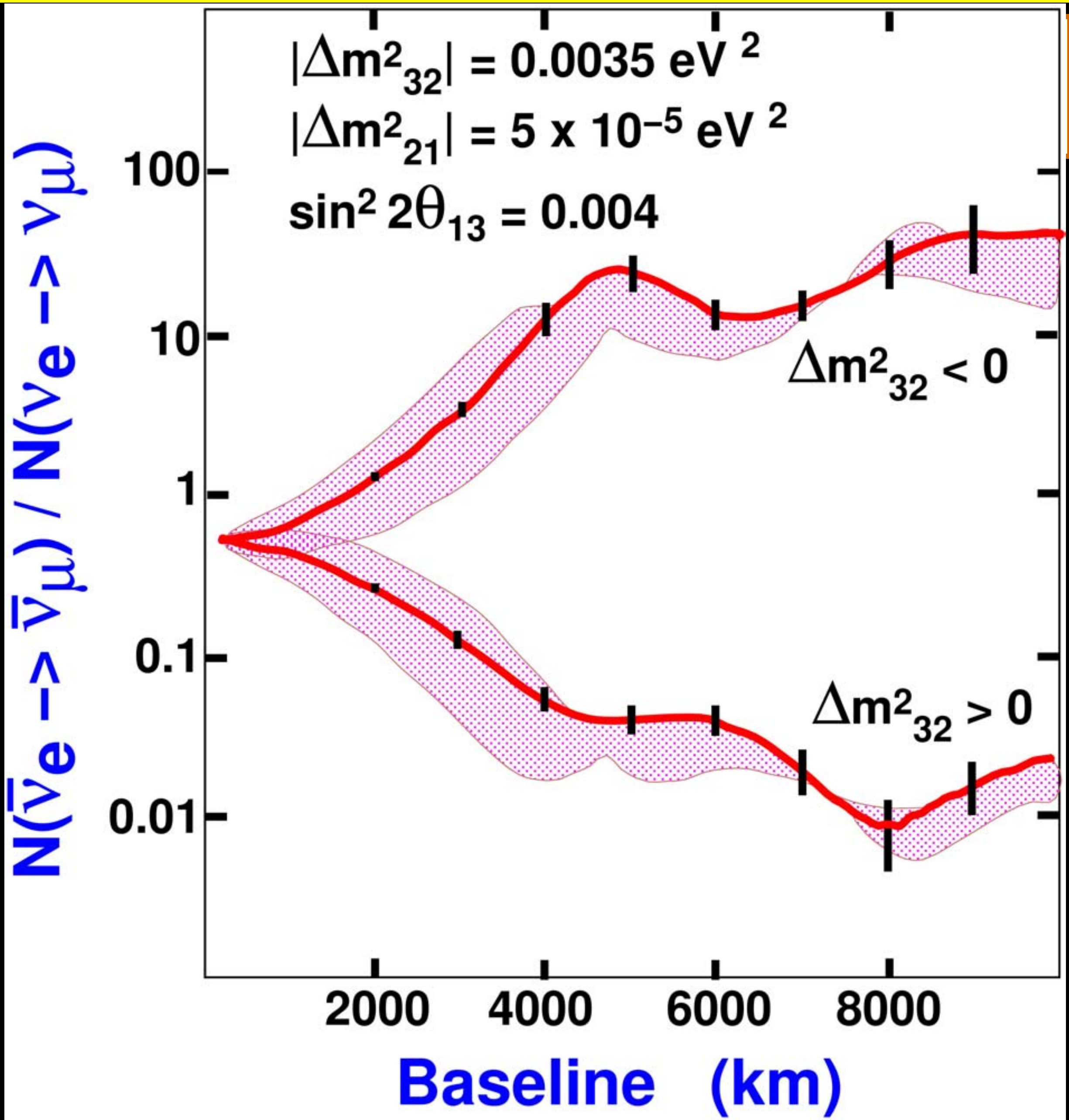
- High-energy
  - Require 'tracking' detector
  - Long ($\sim n \times 1000$ km) baseline indicated
- Possible sites:
  - BNL, CERN, FNAL …
  - RAL

Features:

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

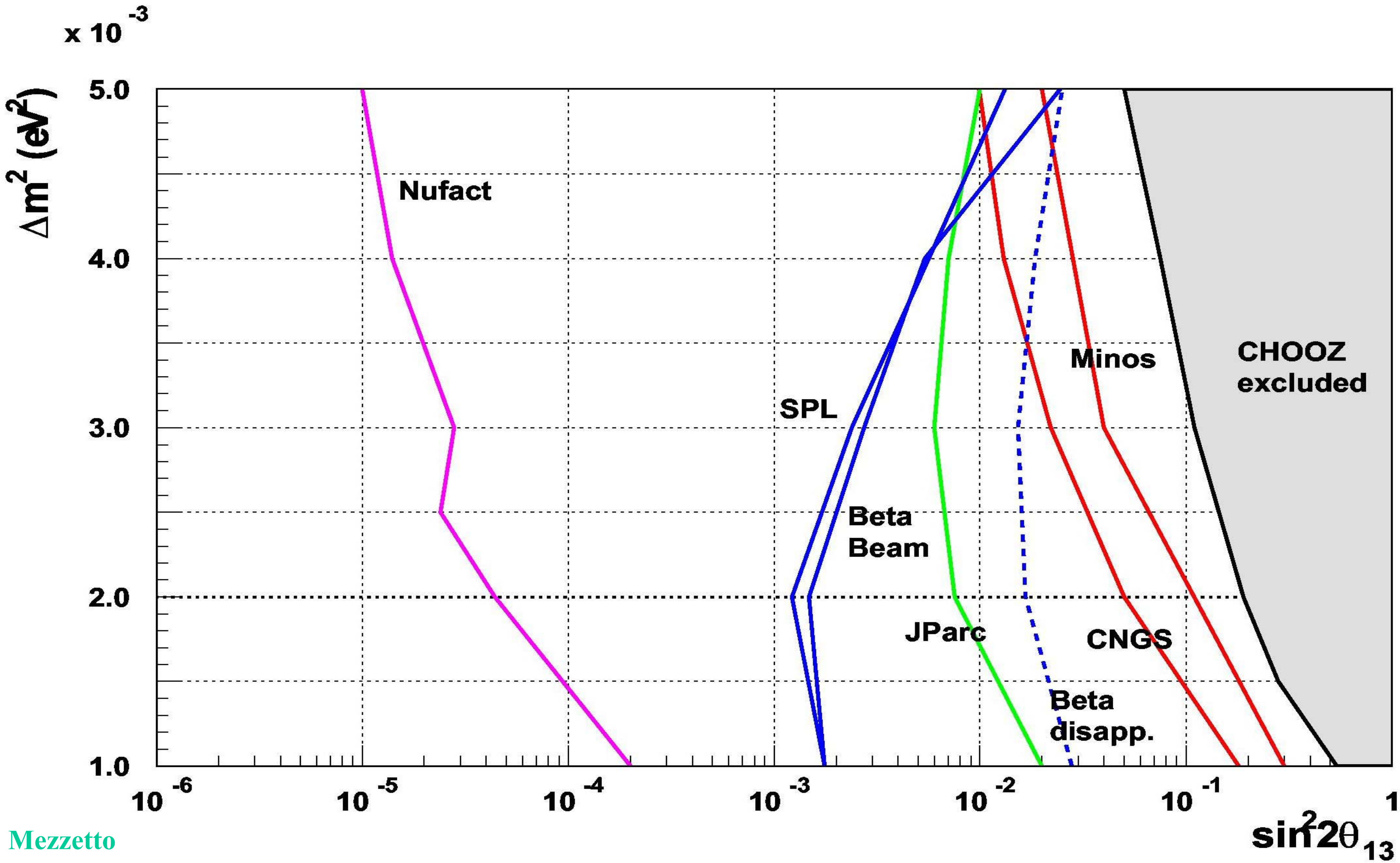
$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$	
Disappearance	**Appearance**
$\bar{\nu}_e \rightarrow \bar{\nu}_e \rightarrow e^+$	$\bar{\nu}_e \rightarrow \bar{\nu}_\mu \rightarrow \mu^+$ $\bar{\nu}_e \rightarrow \bar{\nu}_\tau \rightarrow \tau^+$
$\nu_\mu \rightarrow \nu_\mu \rightarrow \mu^-$	$\nu_\mu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

Performance: unique



Δm^2_{23}

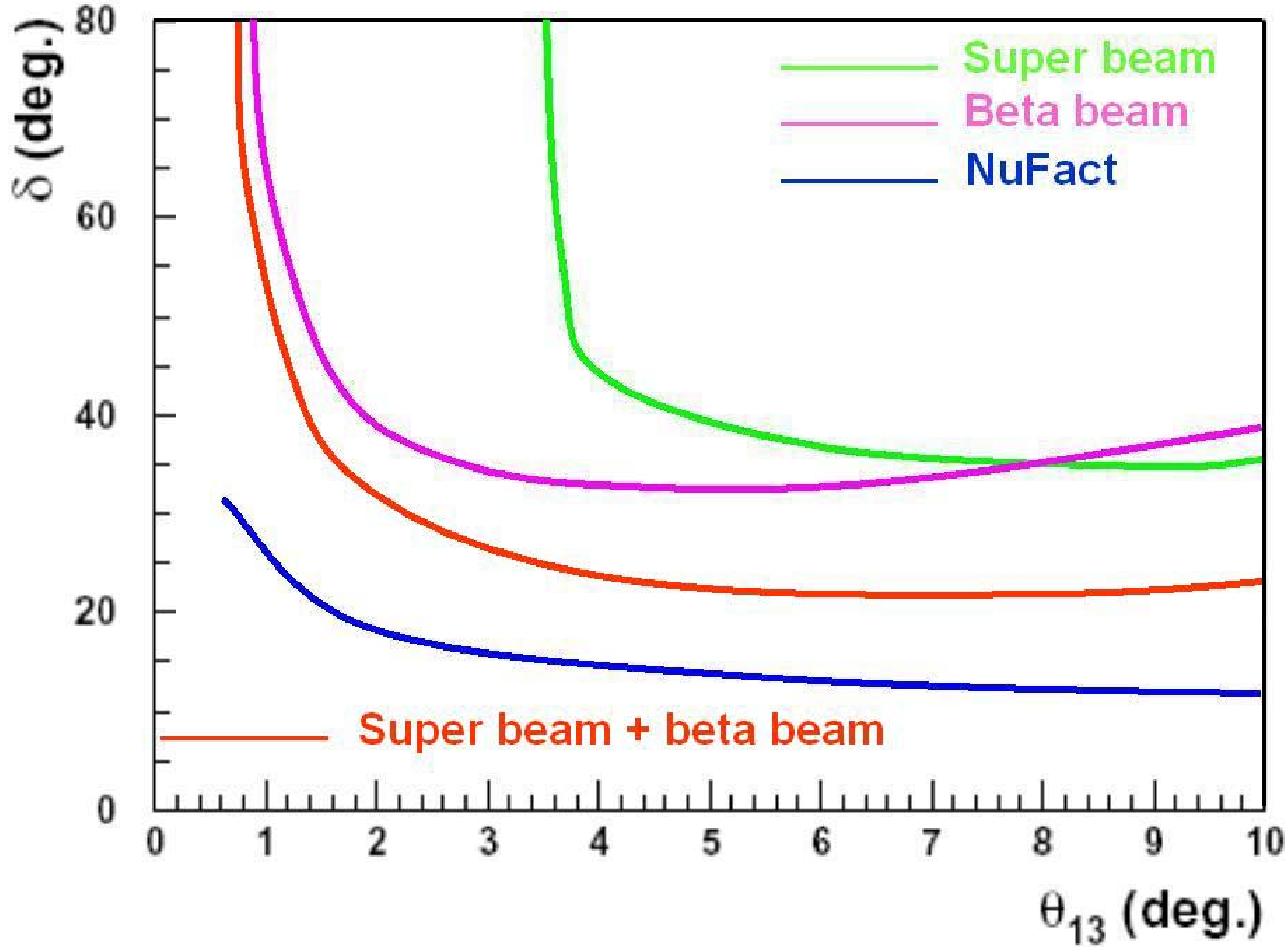
Performance: comparison



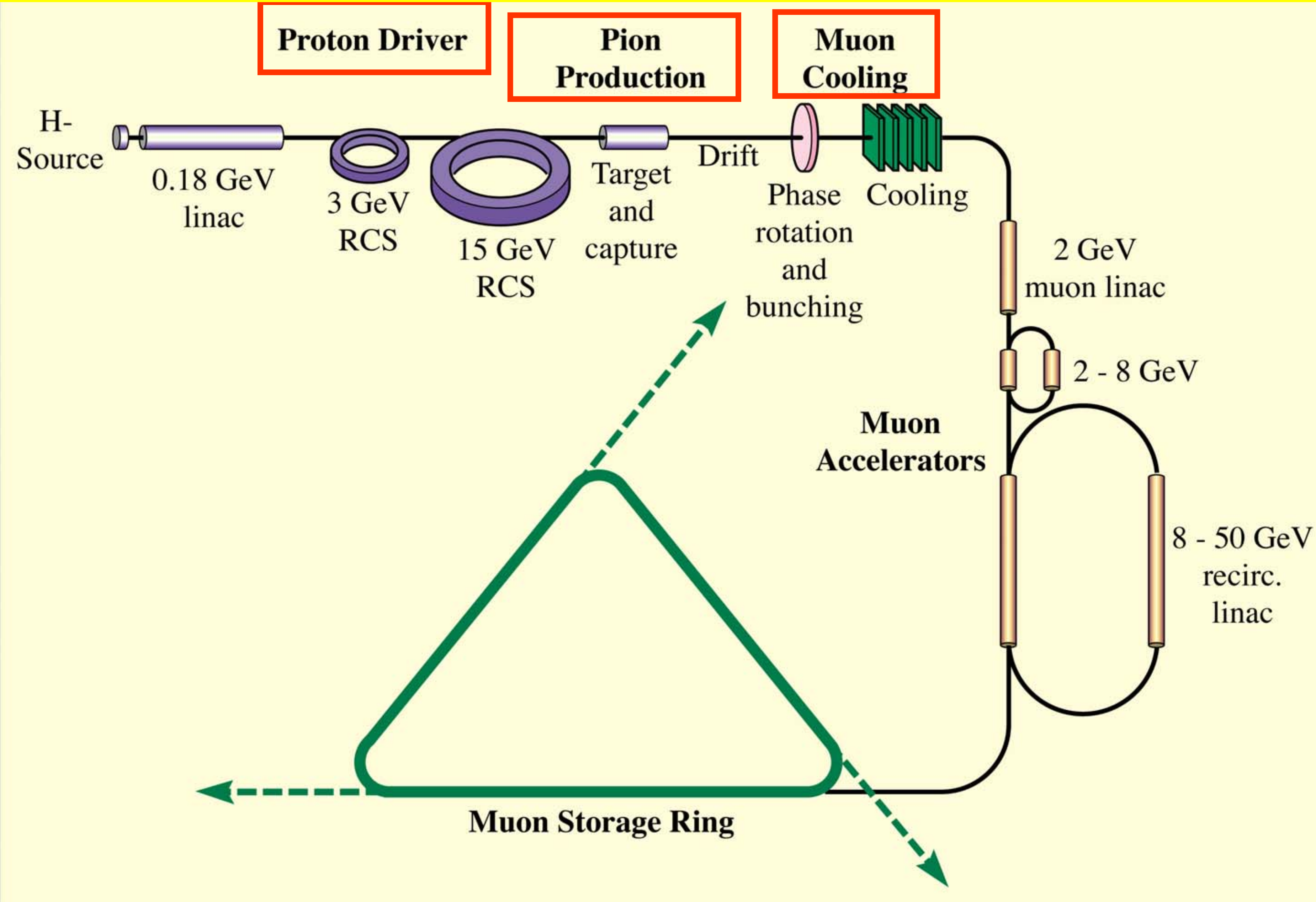
Mezzetto

Performance: comparison

3 sigma sensitivity



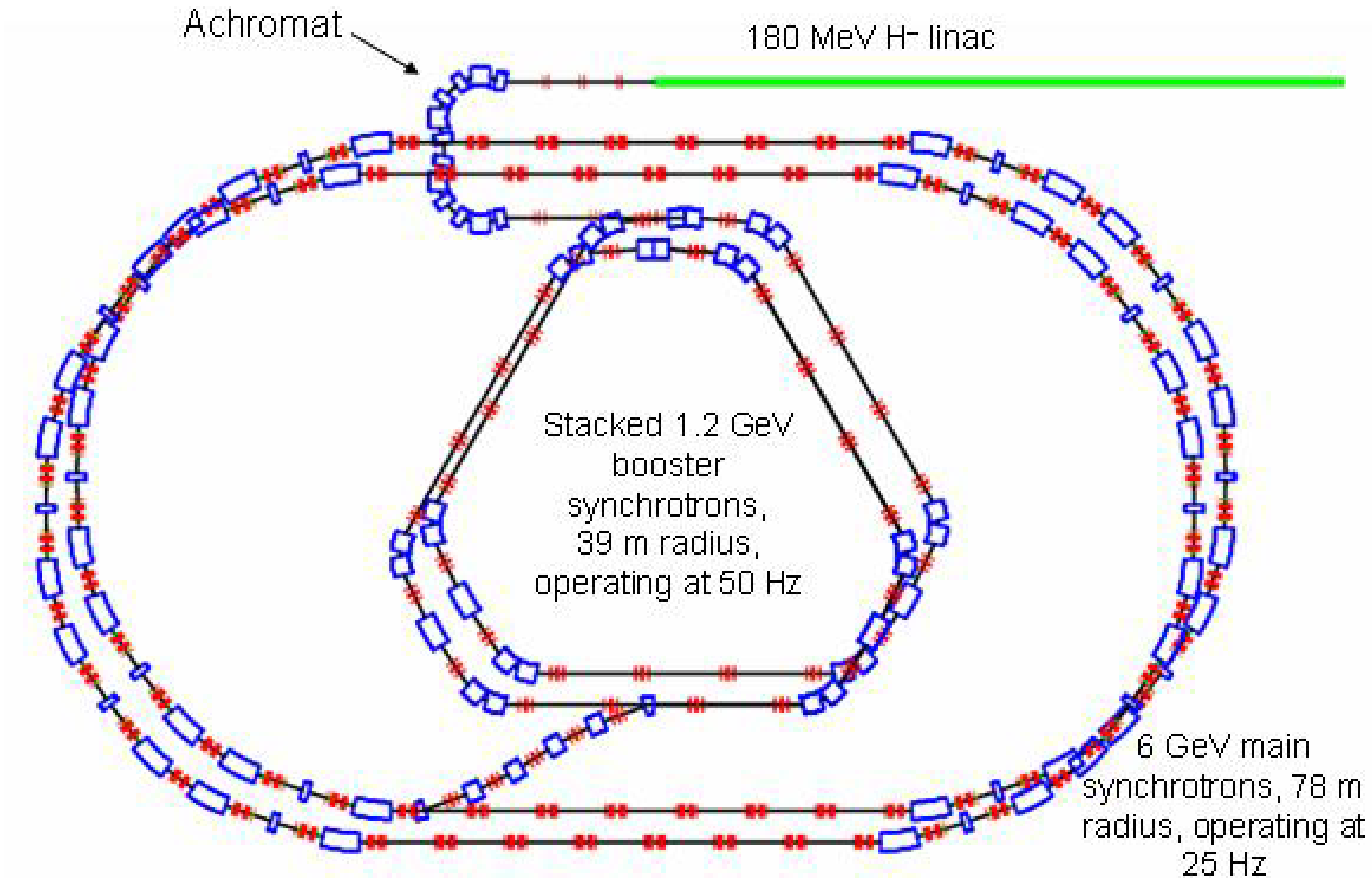
Neutrino Factory: the machine



Proton driver

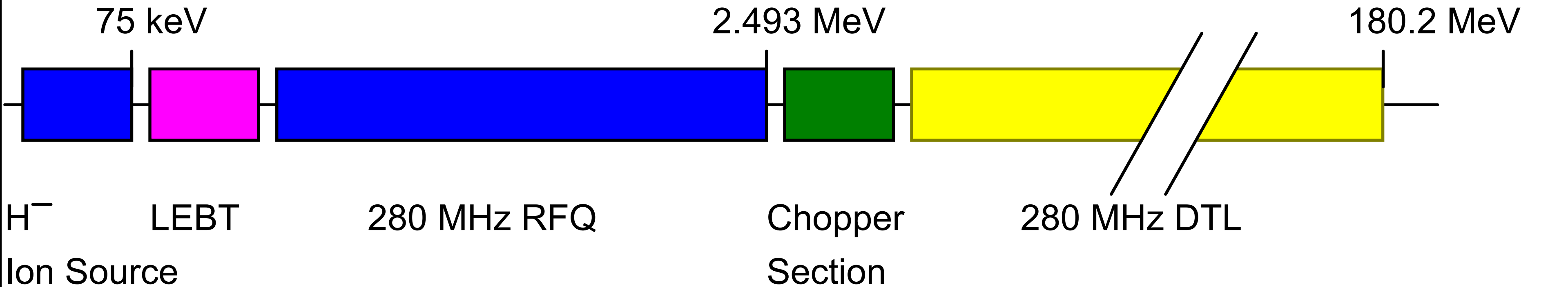
RAL

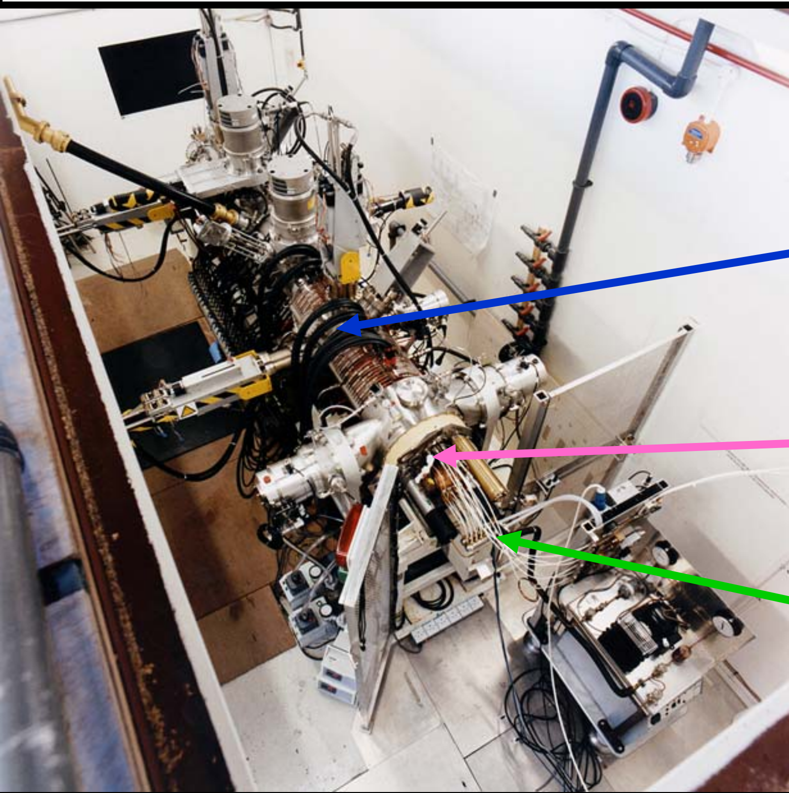
5 MW proton driver developed from ISIS synchrotron



Proton driver test stand

RAL: 180 MeV H- linac



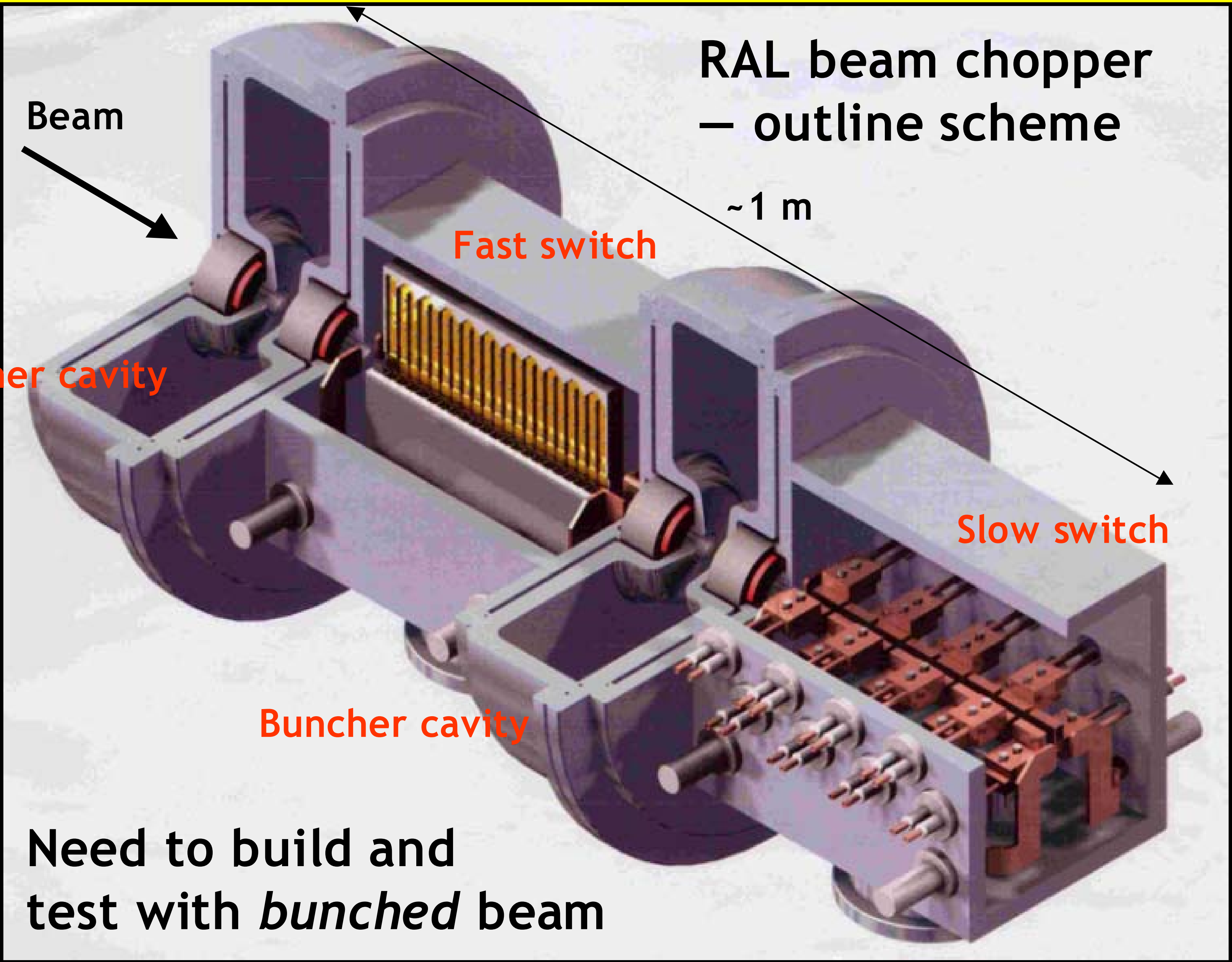


Radio-freq. quadrupole

Low energy beam transp^{t}

Ion source

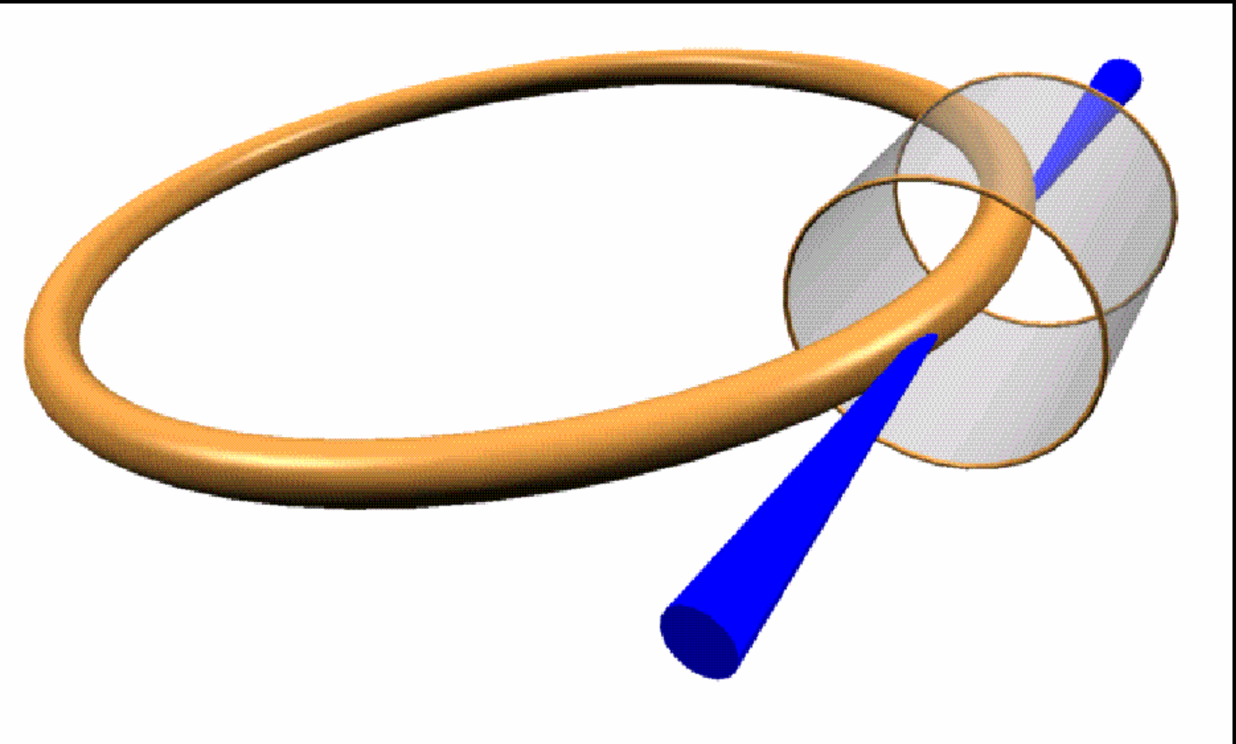
Proton driver test stand: chopper



Need to build and
test with *bunched* beam

Pion-production target

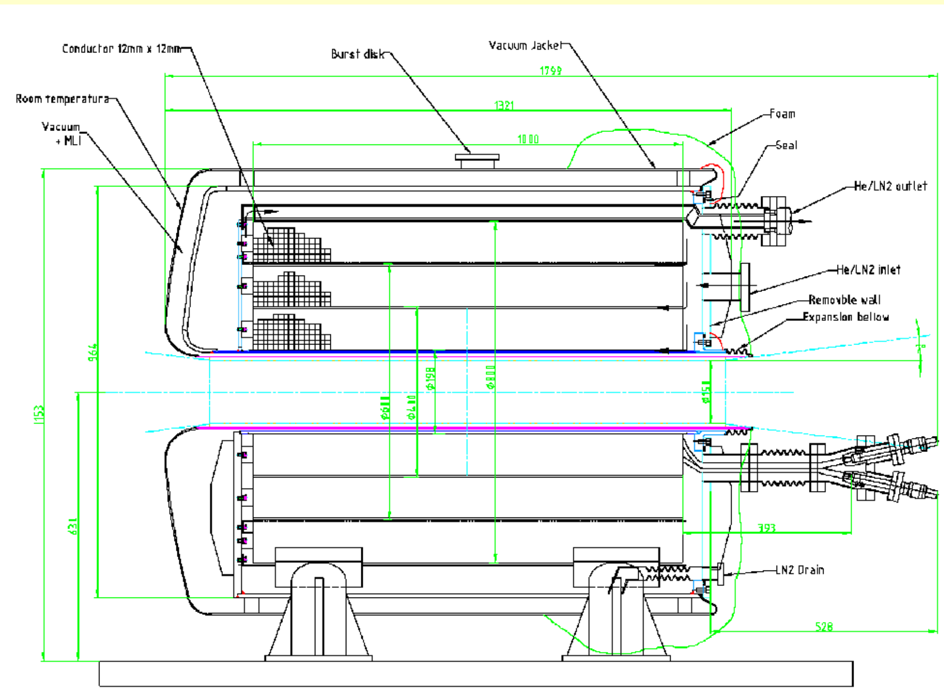
- Options:
  - Liquid metal – mercury (currently preferred)
  - Solid metal:
    - Tantalum balls cooled with inert gas (CERN)
    - Solid band cooled by radiation (RAL)

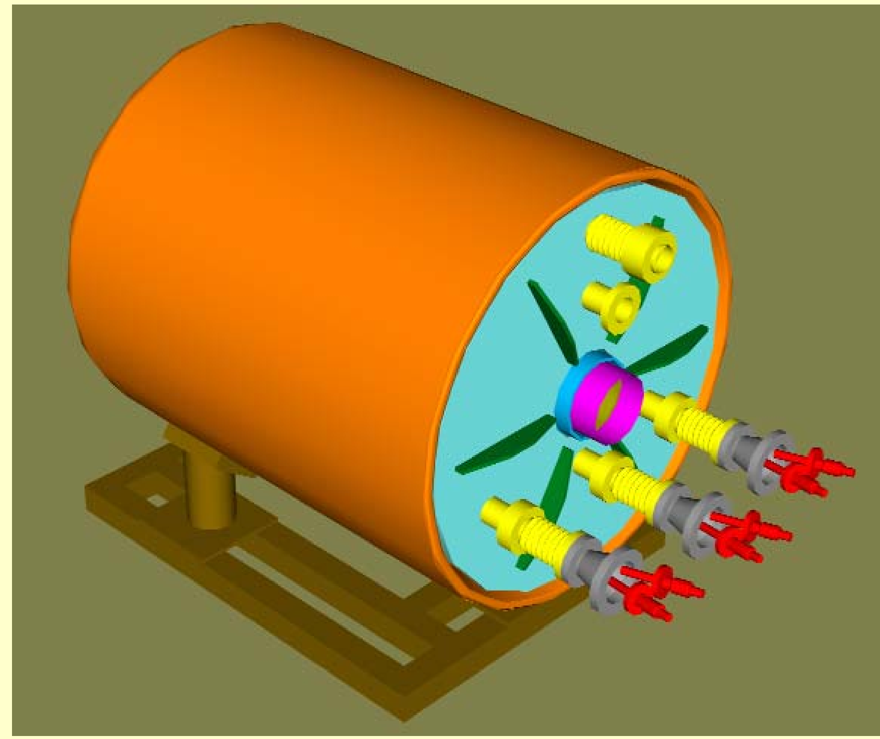


Key problem: thermal shock

Target: liquid metal target exp^{t}

CERN-INTC-2003-033
INTC-I-049
23 October 2003
Updated: 31 Oct 2003

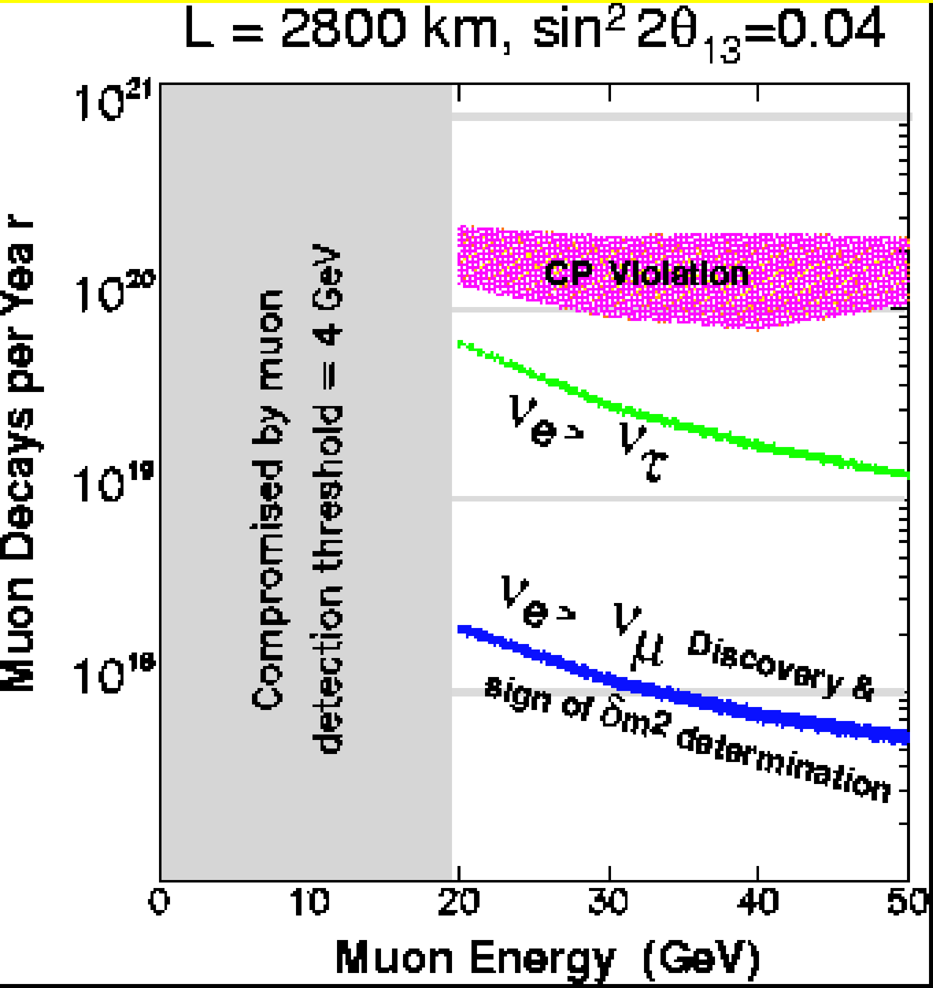




- 70º K Operation
- 15 T with 4.5 MW Pulsed Power
- 15 cm warm bore
- 1 m long beam pipe

Peter Titus, MIT

Ionisation cooling

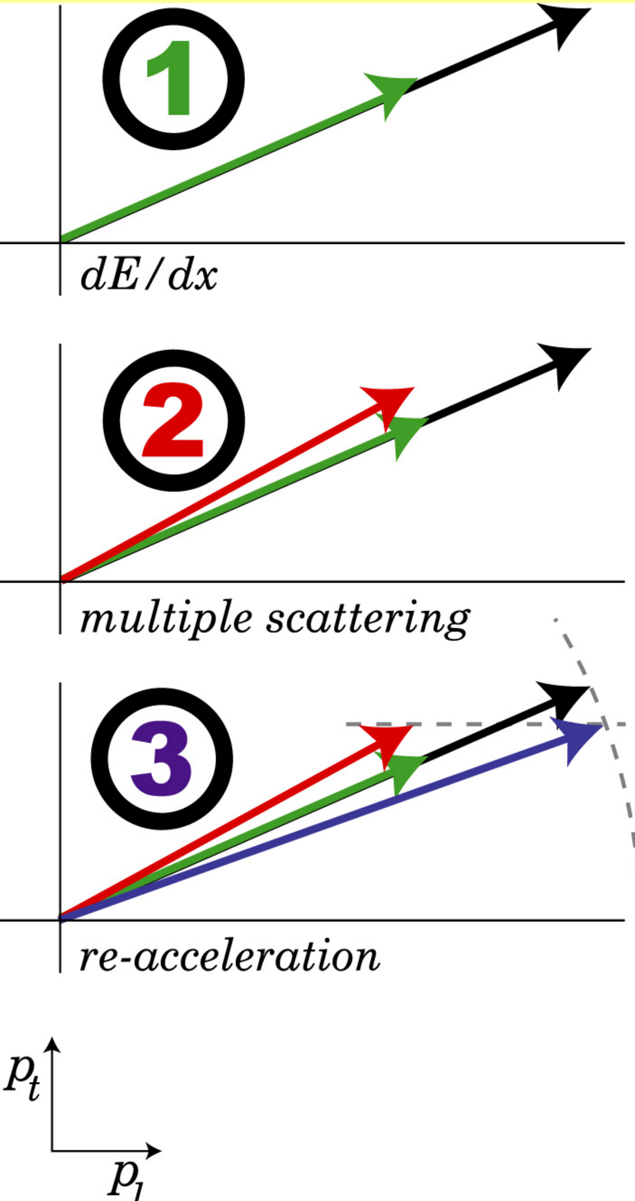


- **Physics reach increases with neutrino flux**
- **Maximise stored muon intensity**
- **Implies:**
  - **Require to capture and store as many of the 'decay' muons as possible**
    $\Rightarrow$ ***Cool muon beam***

Short muon lifetime requires novel technique:
IONISATION COOLING

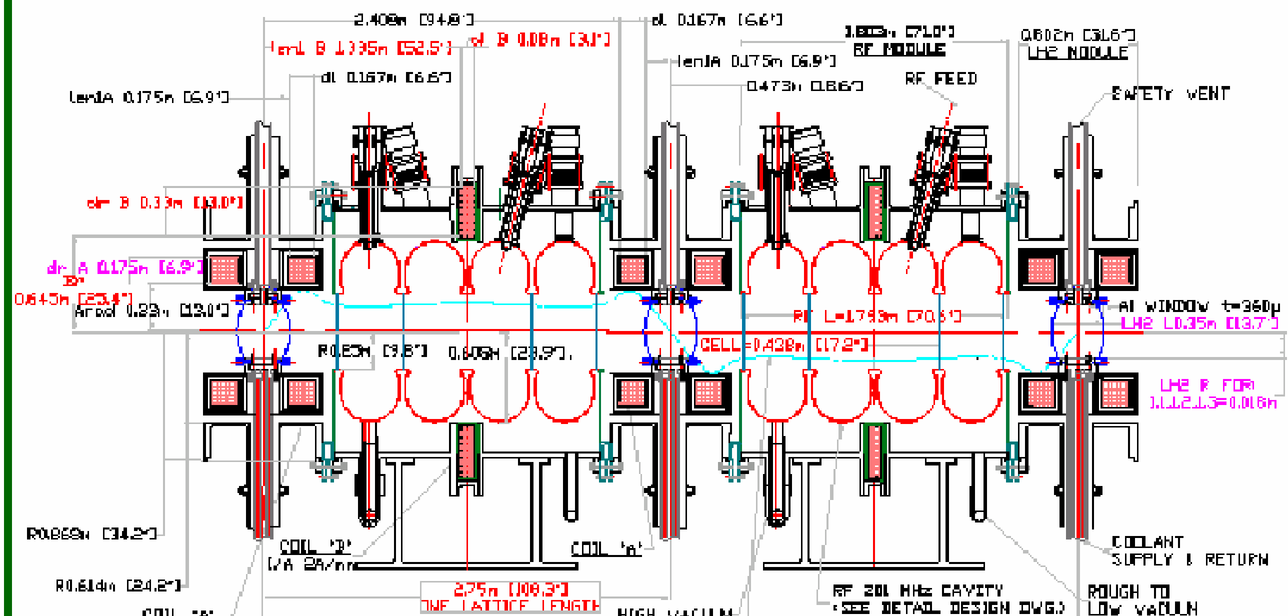
Ionisation cooling: technique

Principle



Practice

Study II

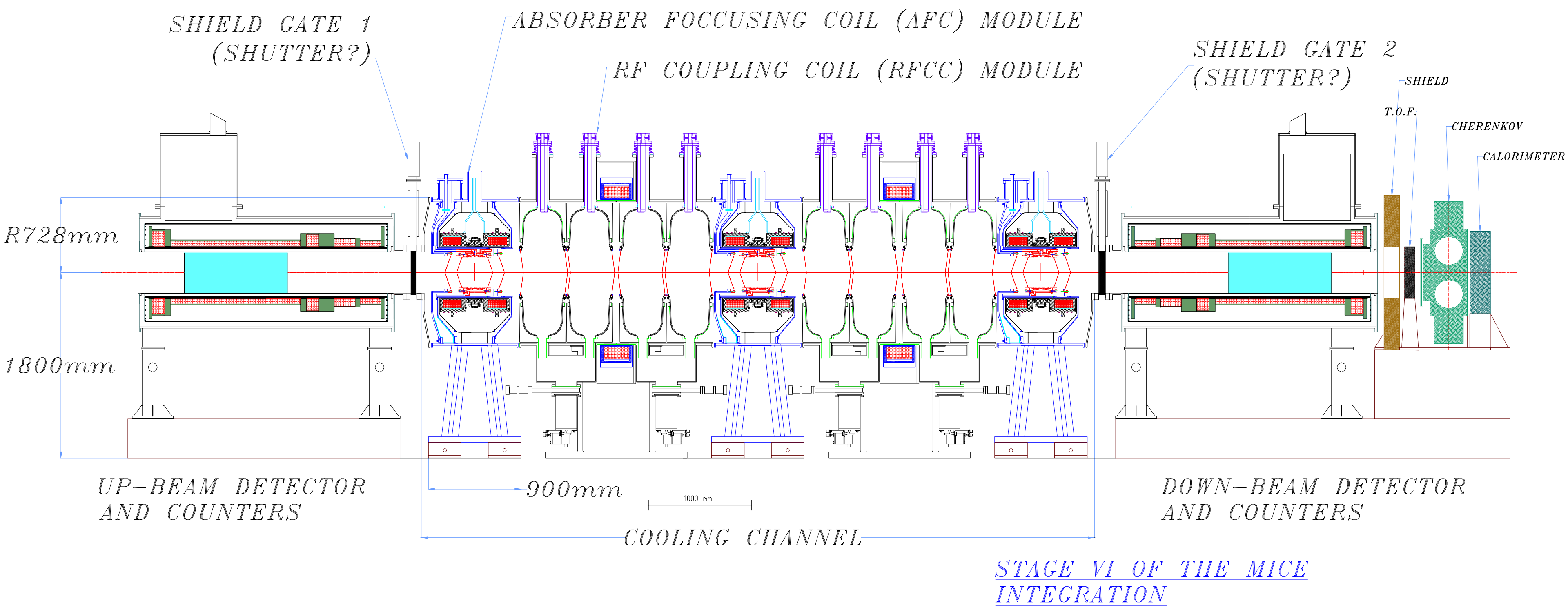


International Muon Ionisation Cooling Exp^t **(MICE):**

- **Design, build, commission and operate a realistic section of cooling channel**
- **Measure its performance in a variety of modes of operation and beam conditions**

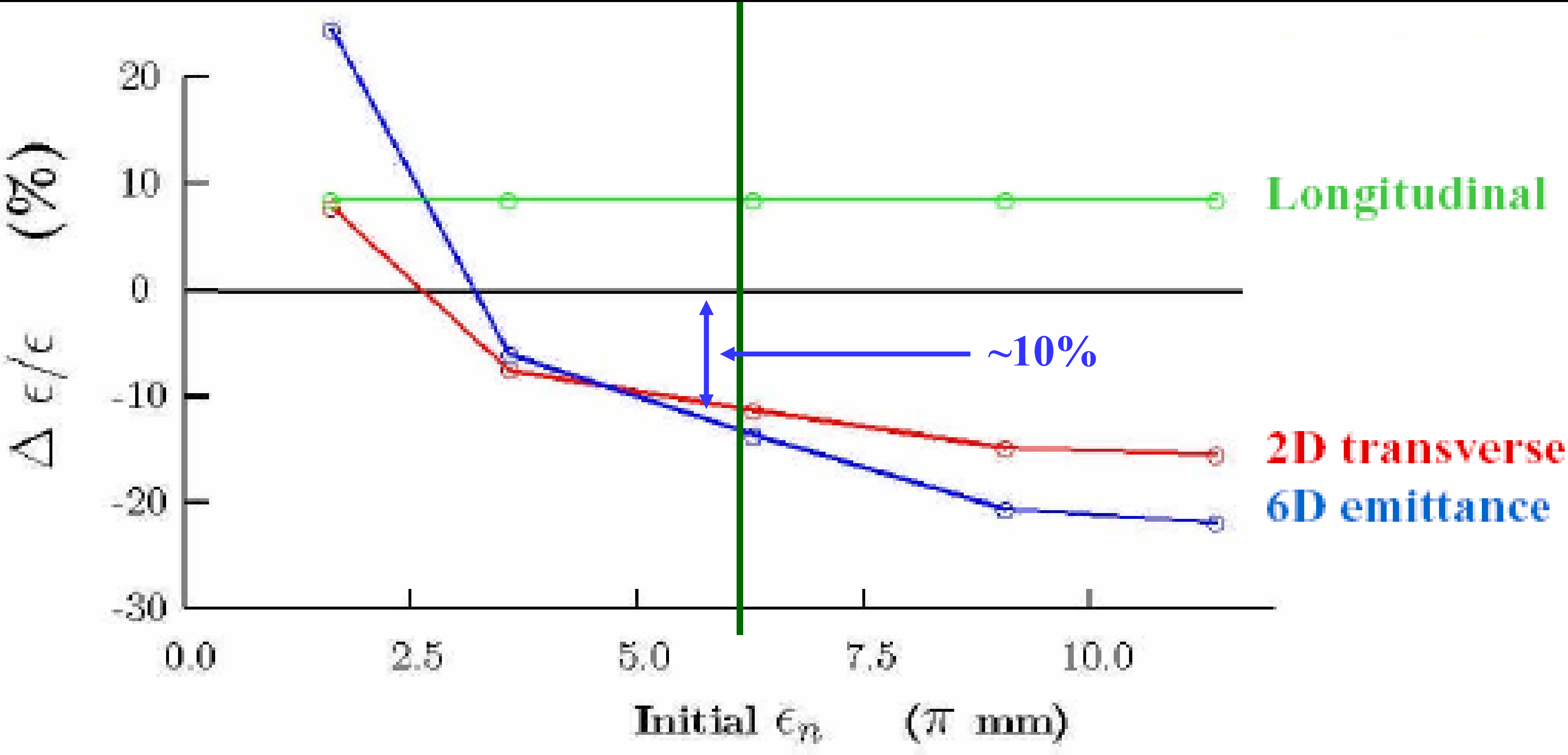
i.e. results will allow NuFact complex to be optimised

MICE: experiment



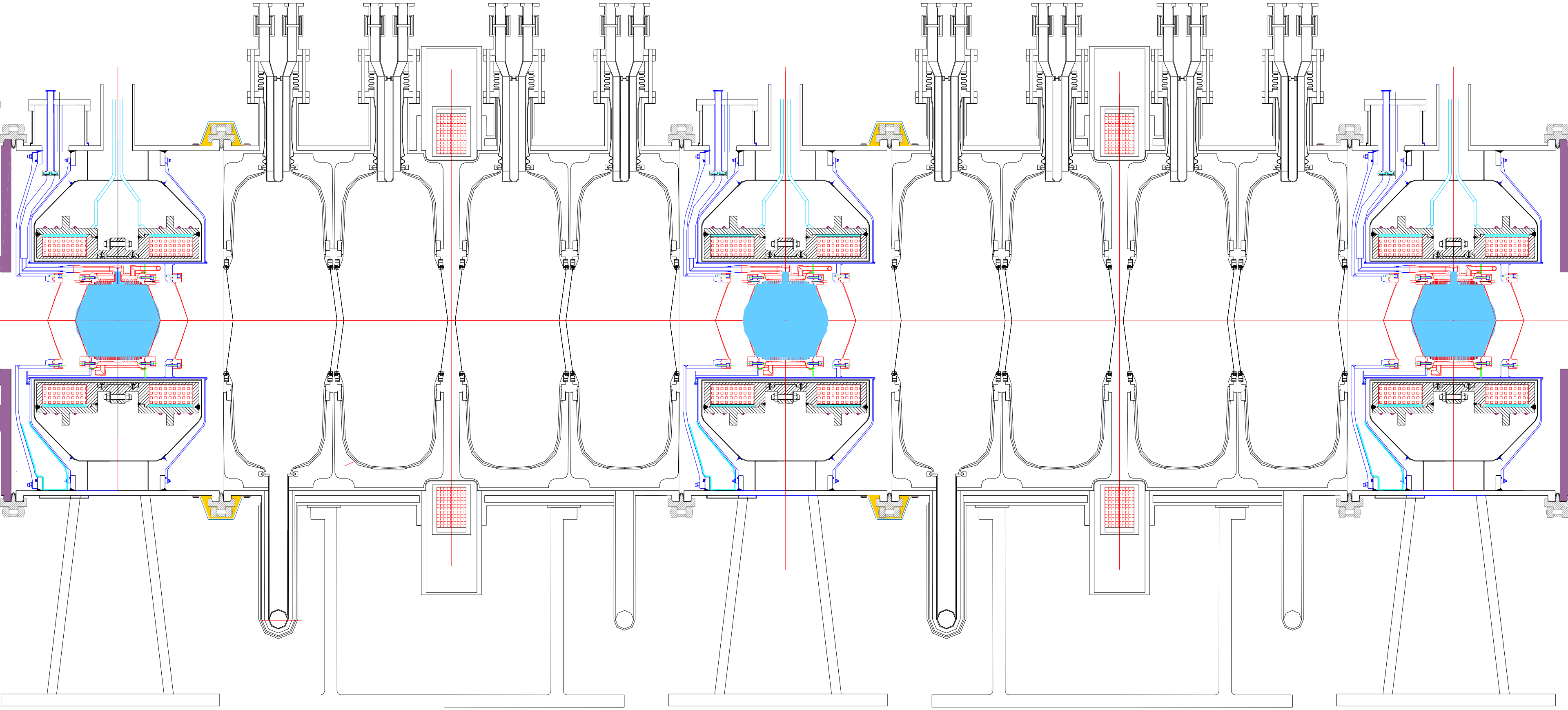
- Single particle experiment
- Cooling channel sandwiched between two 'identical' spectrometers

MICE: performance specification

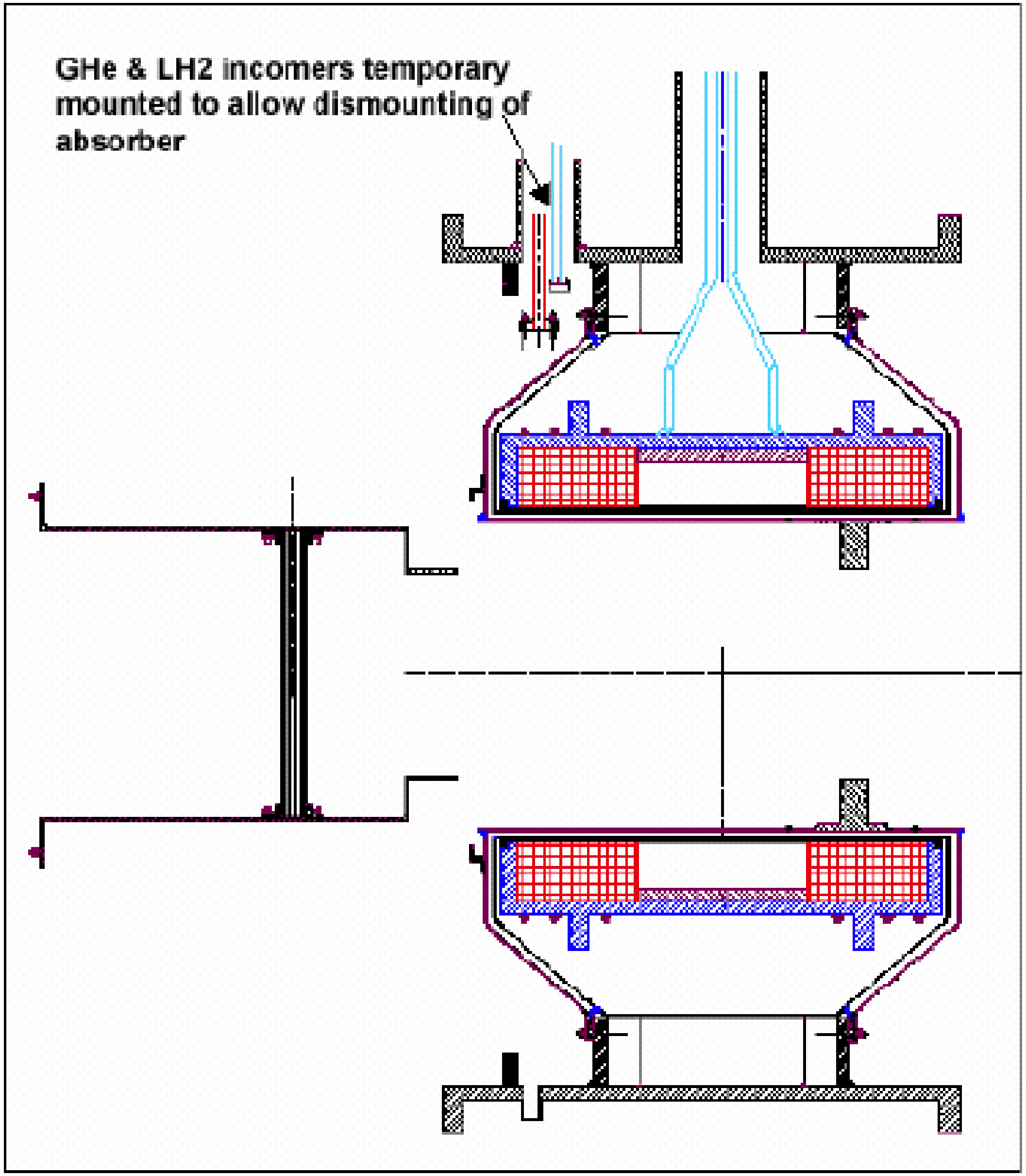


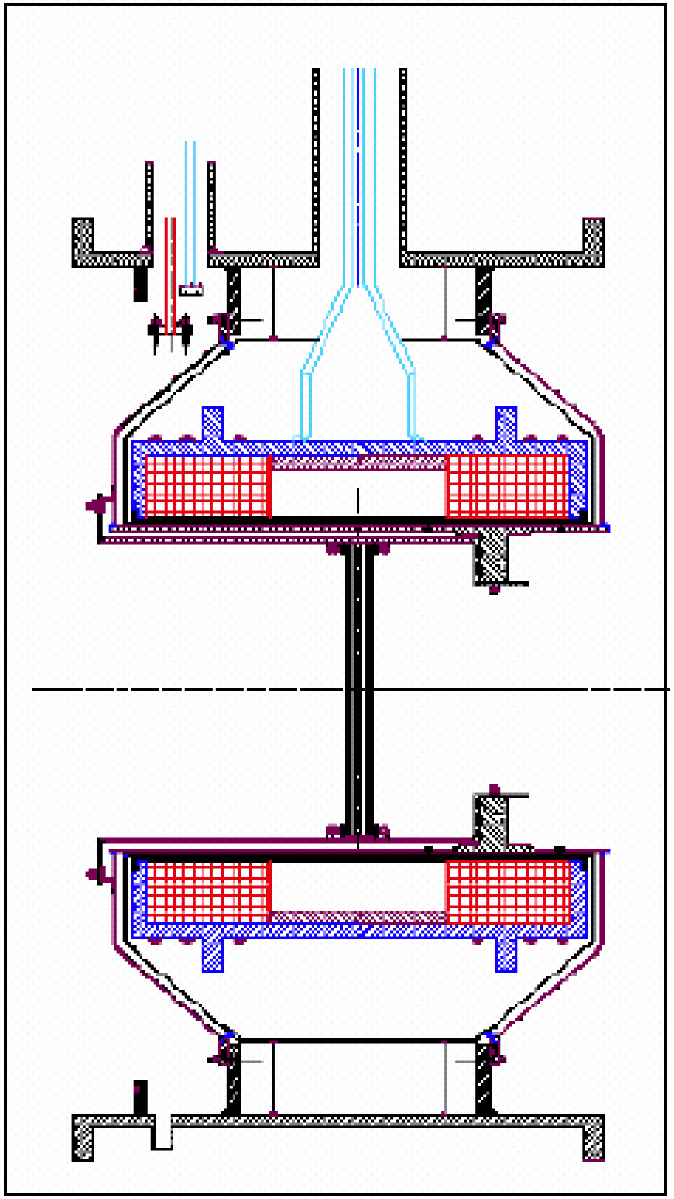
$$\Rightarrow \sigma\left(\frac{\Delta\varepsilon}{\varepsilon_{in}}\right) << 0.1 \qquad \text{Goal}: \sigma\left(\frac{\Delta\varepsilon}{\varepsilon_{in}}\right) = 0.001$$

MICE: cooling channel



MICE: absorber/focus coils ass^{bly}

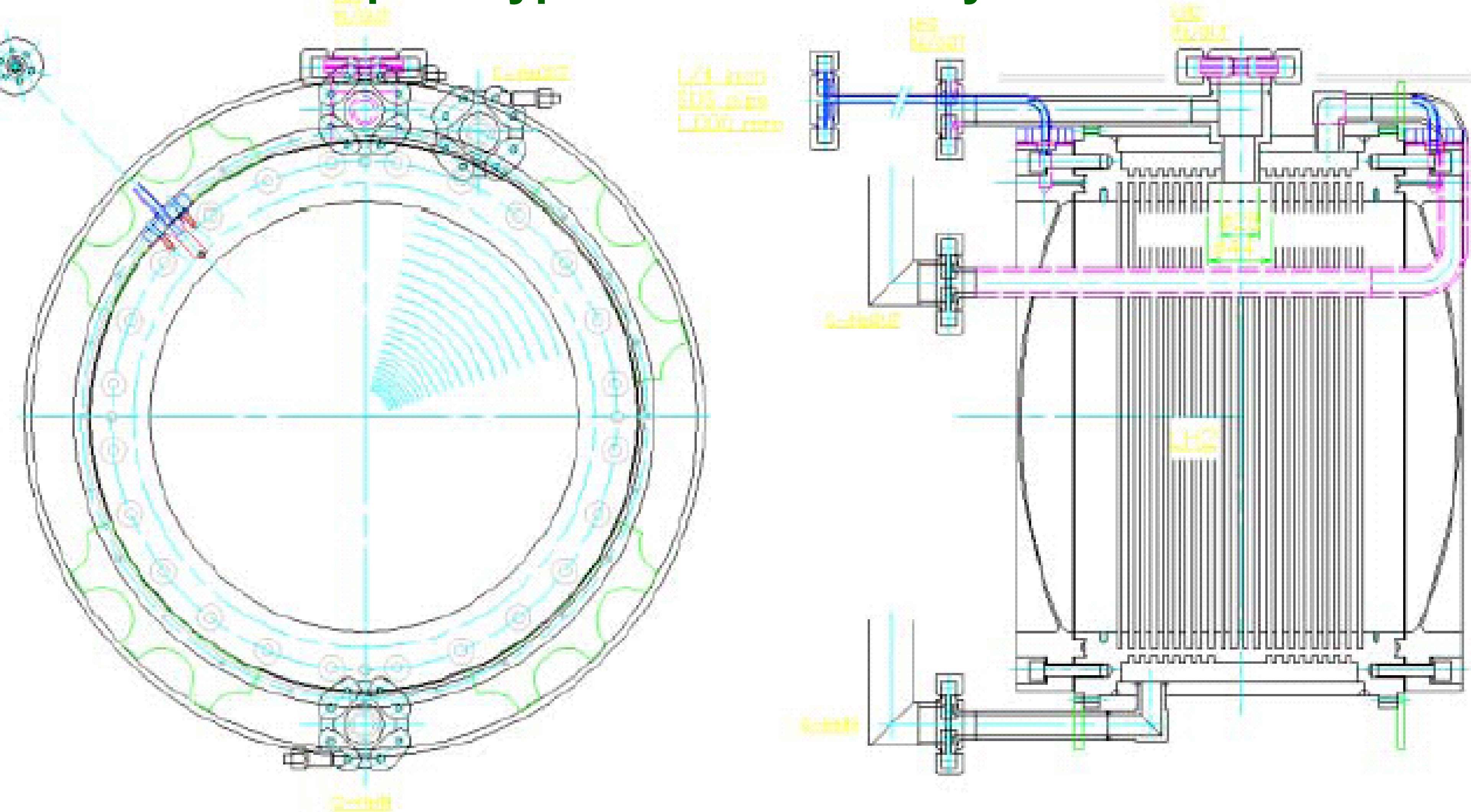




MICE: liquid hydrogen absorber

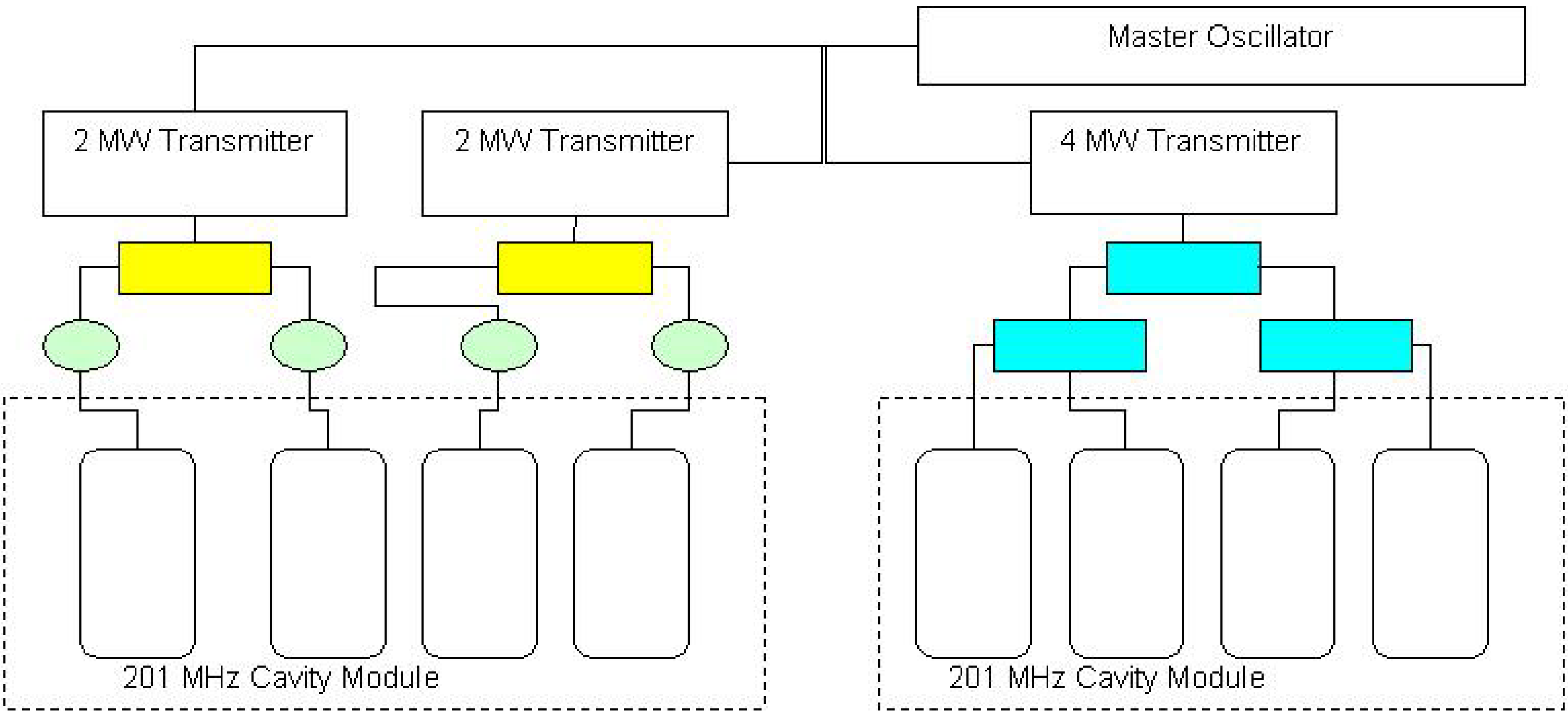
MICE Absorber Design

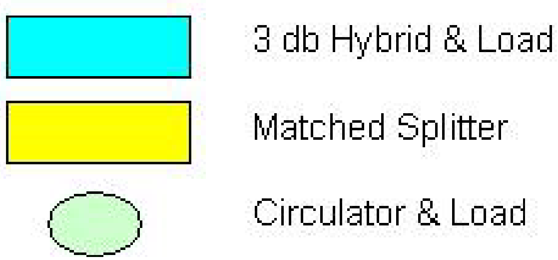
Plan: fabricate prototype III and test this year



Cavity fabrication in progress: ready for test in MTA (FNAL) 4th quarter 2004

MICE: RF power sources

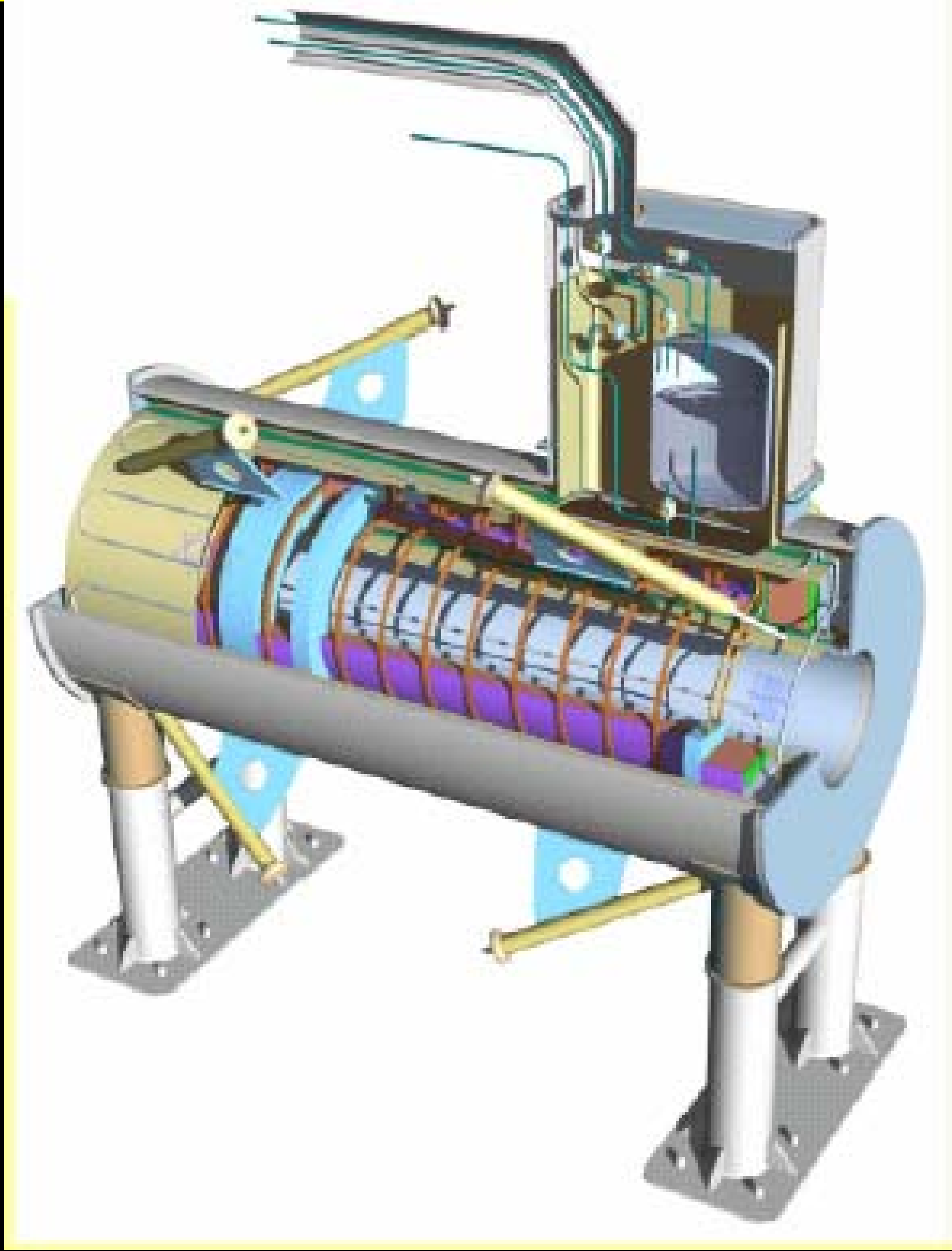




RF amp test stand to be established at Daresbury Laboratory this year. Equipment to be shipped from LBNL for refurbishment.

MICE: spectrometer

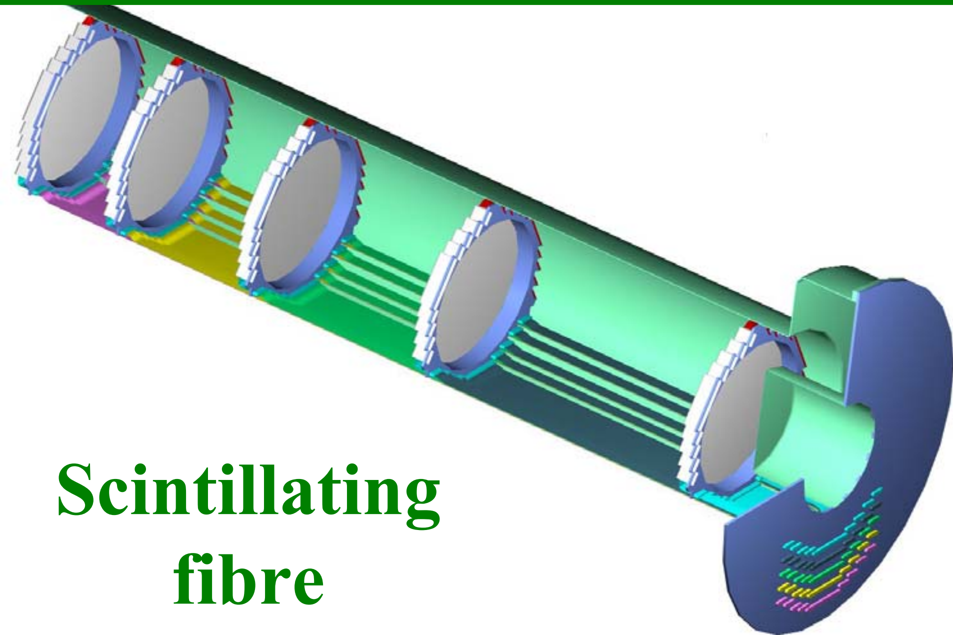
- 4 T field, 40 cm bore
- Cryostat contains matching coils at each end
- Design allows for installation next to focus coils and tracker services

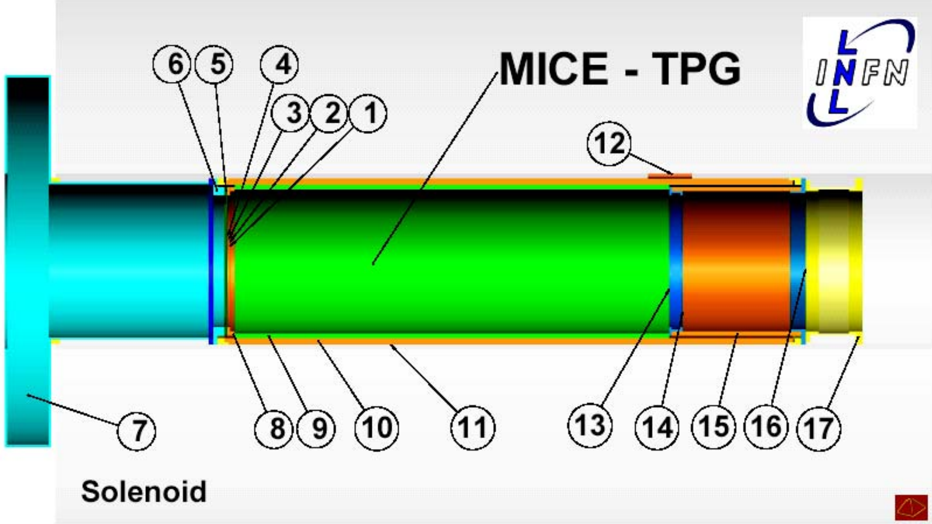


Genoa

MICE: tracker

Baseline	Alternative/fallback



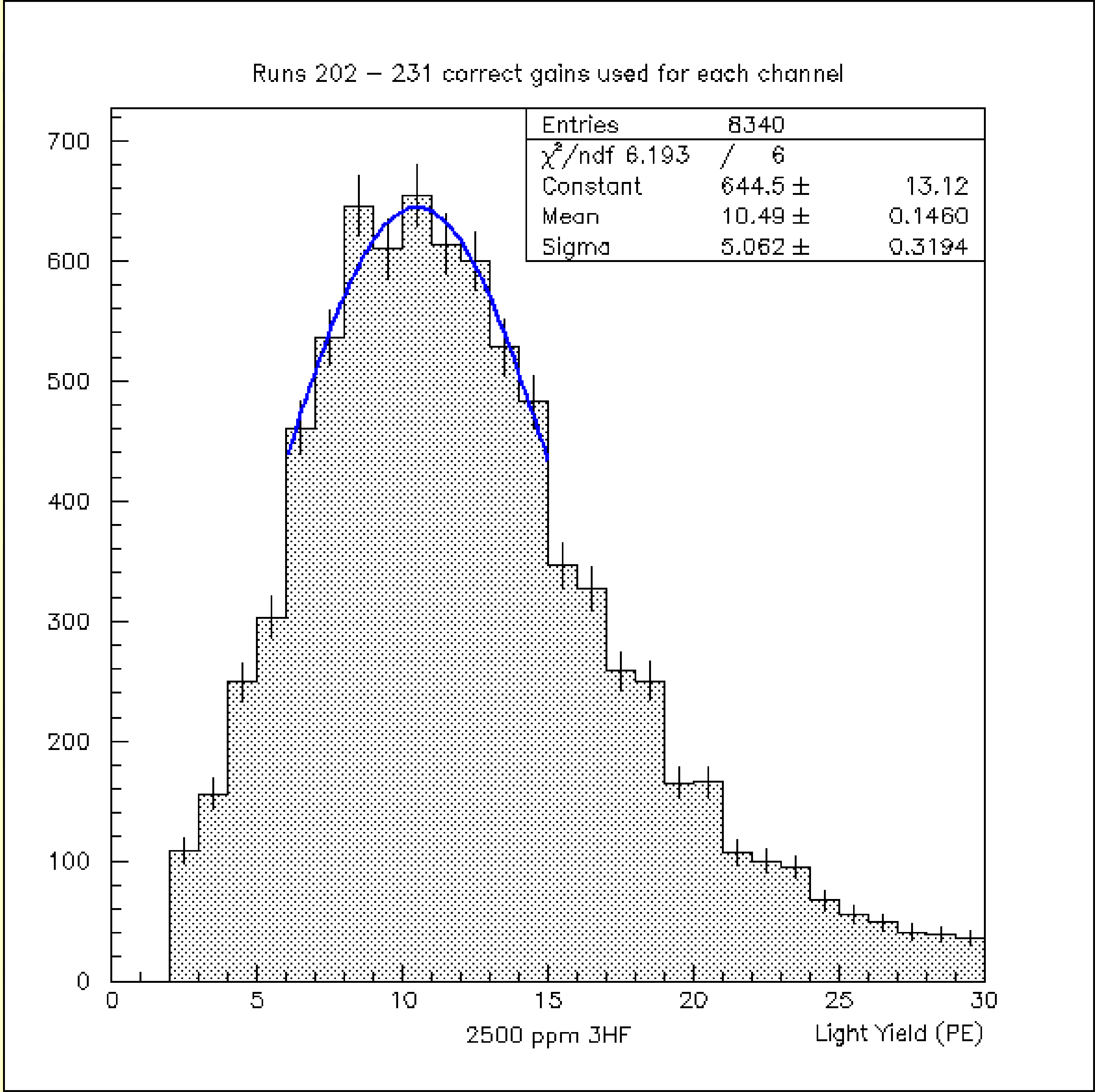


TPG – TPC with GEM readout

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

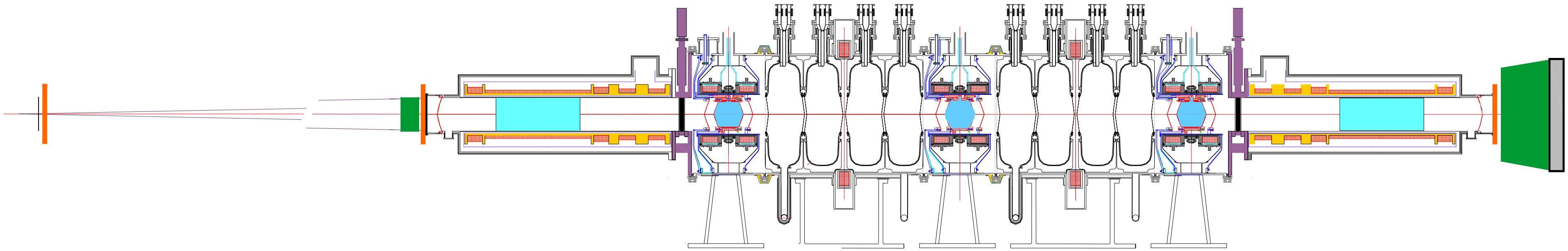
- Light gas (0.15% X_0)
- Many points per track
- High precision track rec^n possible
- Large integration time
- Effect of X-rays on GEMs

MICE: tr



Runs 202 – 231 correct gains used for each channel
Entries 8340
χ²/ndf 6.193 / 6
Constant 644.5 ± 13.12
Mean 10.49 ± 0.1460
Sigma 5.062 ± 0.3194
0
100
200
300
400
500
600
700
0
5
10
15
20
25
30
2500 ppm 3HF
Light Yield (PE)

MICE: particle identification



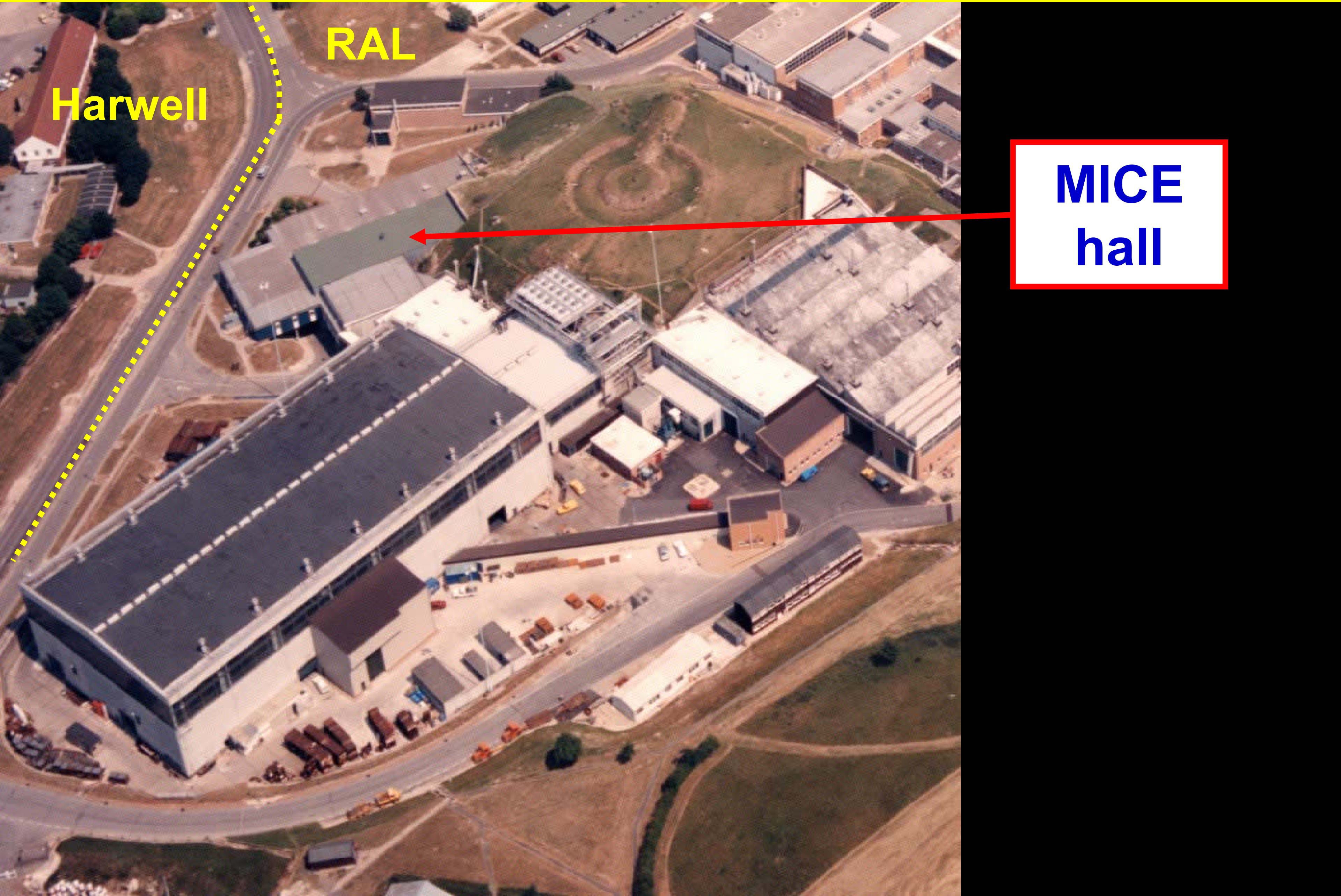
<u>Upstream</u>

- TOF: Milan: 70 ps resolution
  - PId, trigger, timing with respect to RF phase
- Cherenkov: U.Miss: Pi/Mu separation

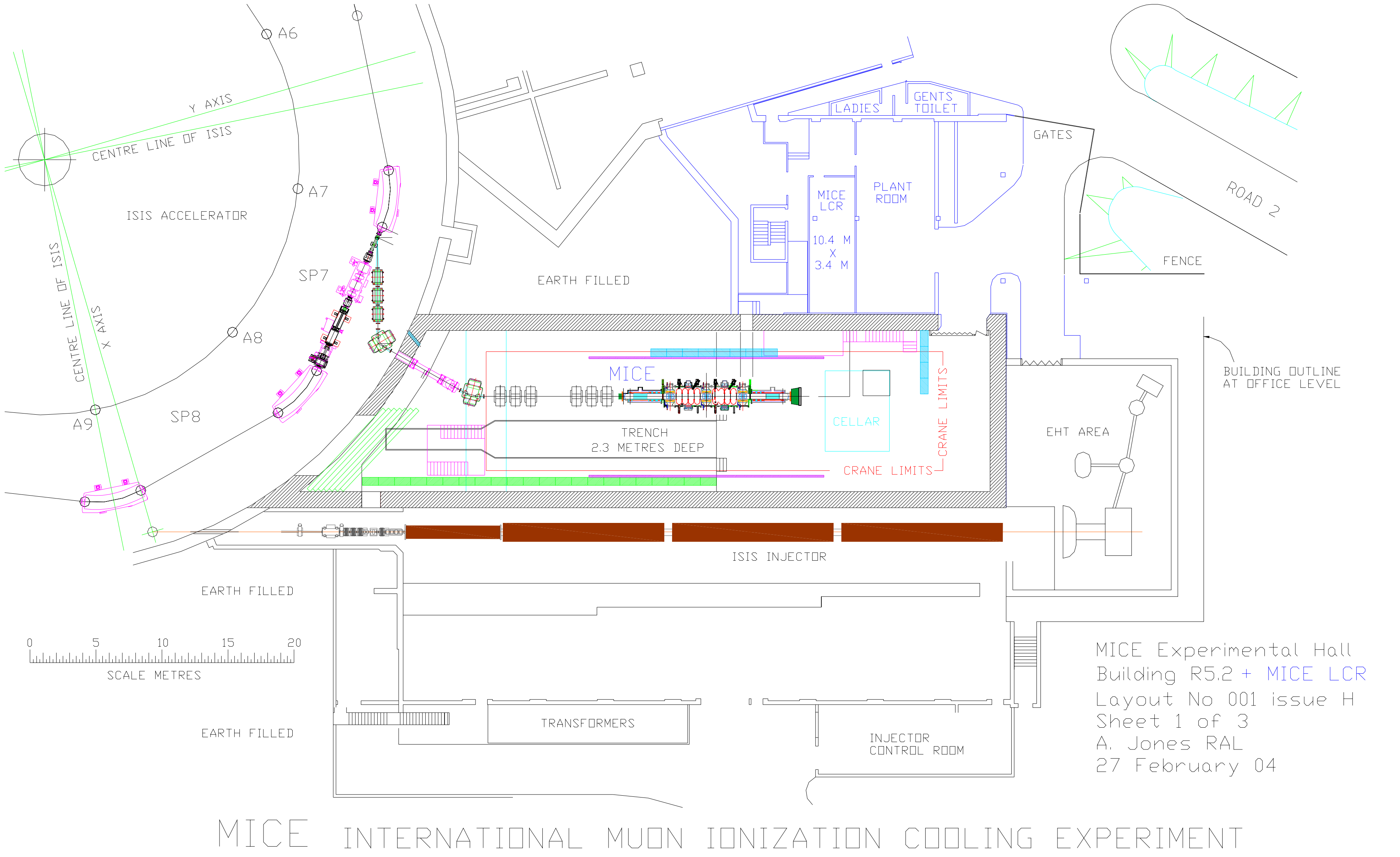
<u>Downstream</u>

- Cherenkov: Louvain: Mu/electron separation
- EM calorimeter: Rome III: Mu/elec. separat^{n}

MICE: implementation at RAL



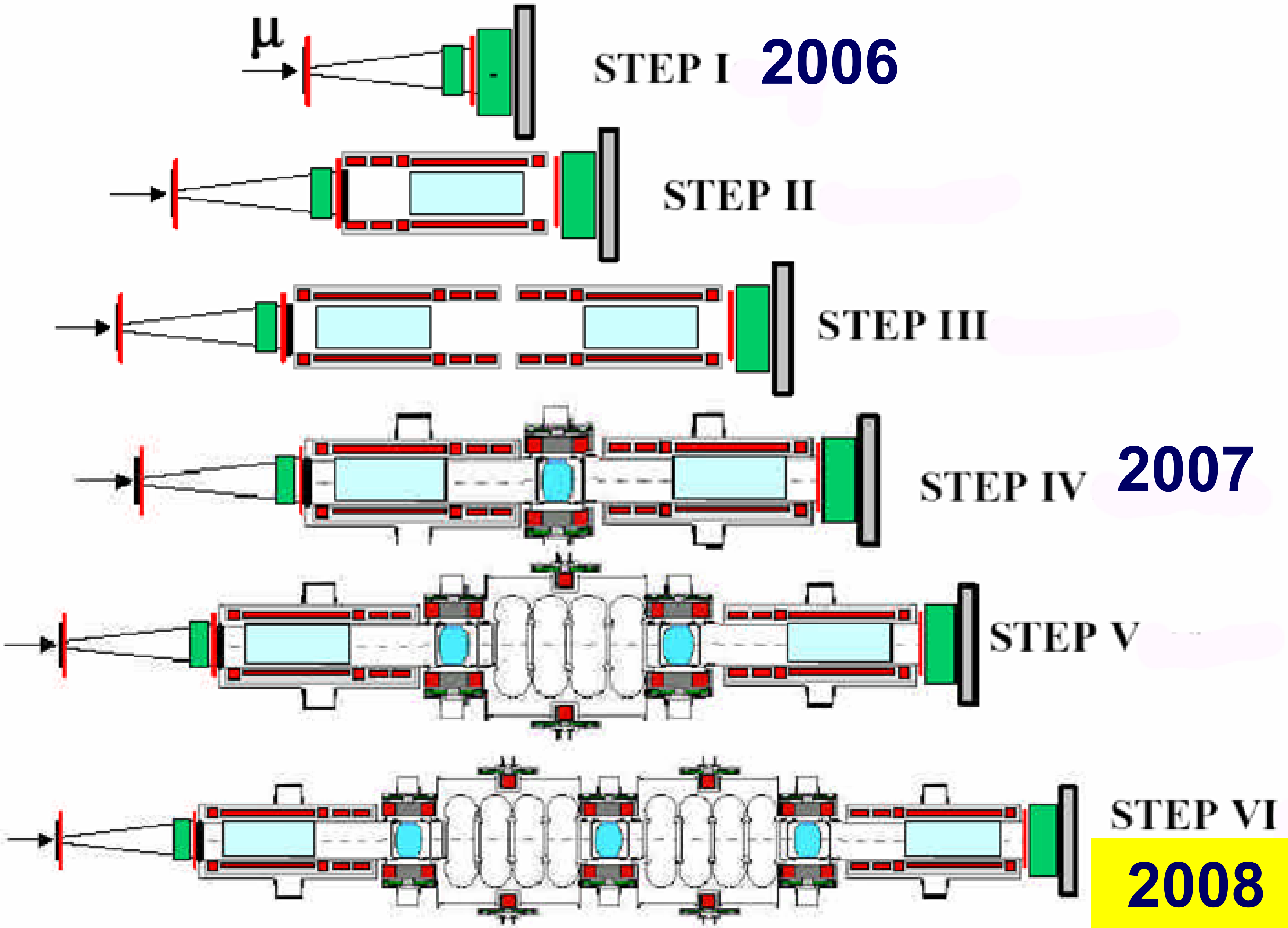
MICE: layout



A6
A7
A8
A9
Y AXIS
CENTRE LINE OF ISIS
X AXIS
CENTRE LINE OF ISIS
ISIS ACCELERATOR
SP7
SP8
EARTH FILLED
LADIES
GENTS TOILET
GATES
MICE LCR
PLANT ROOM
10.4 M x 3.4 M
ROAD 2
FENCE
BUILDING OUTLINE AT OFFICE LEVEL
MICE
CELLAR
CRANE LIMITS
CRANE LIMITS
EHT AREA
TRENCH
2.3 METRES DEEP
ISIS INJECTOR
EARTH FILLED
0 5 10 15 20
SCALE METRES
EARTH FILLED
TRANSFORMERS
INJECTOR CONTROL ROOM
MICE Experimental Hall
Building R5.2 + MICE LCR
Layout No 001 issue H
Sheet 1 of 3
A. Jones RAL
27 February 04
MICE INTERNATIONAL MUON IONIZATION COOLING EXPERIMENT


WT17 TON
M105
WT17T

MICE: timescales

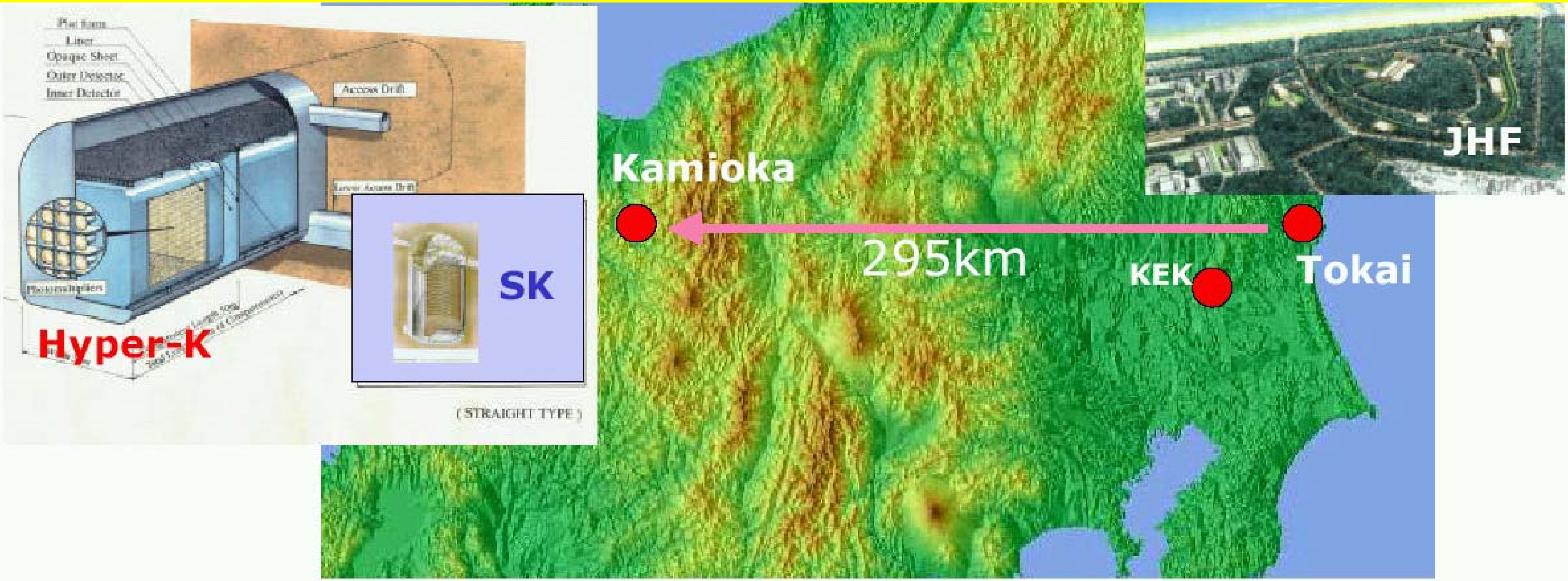


Conclusions

- 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: Proton driver, target, ionisation cooling – MICE
    - Develop conceptual design of entire facility
- Overall a *fantastic* programme!

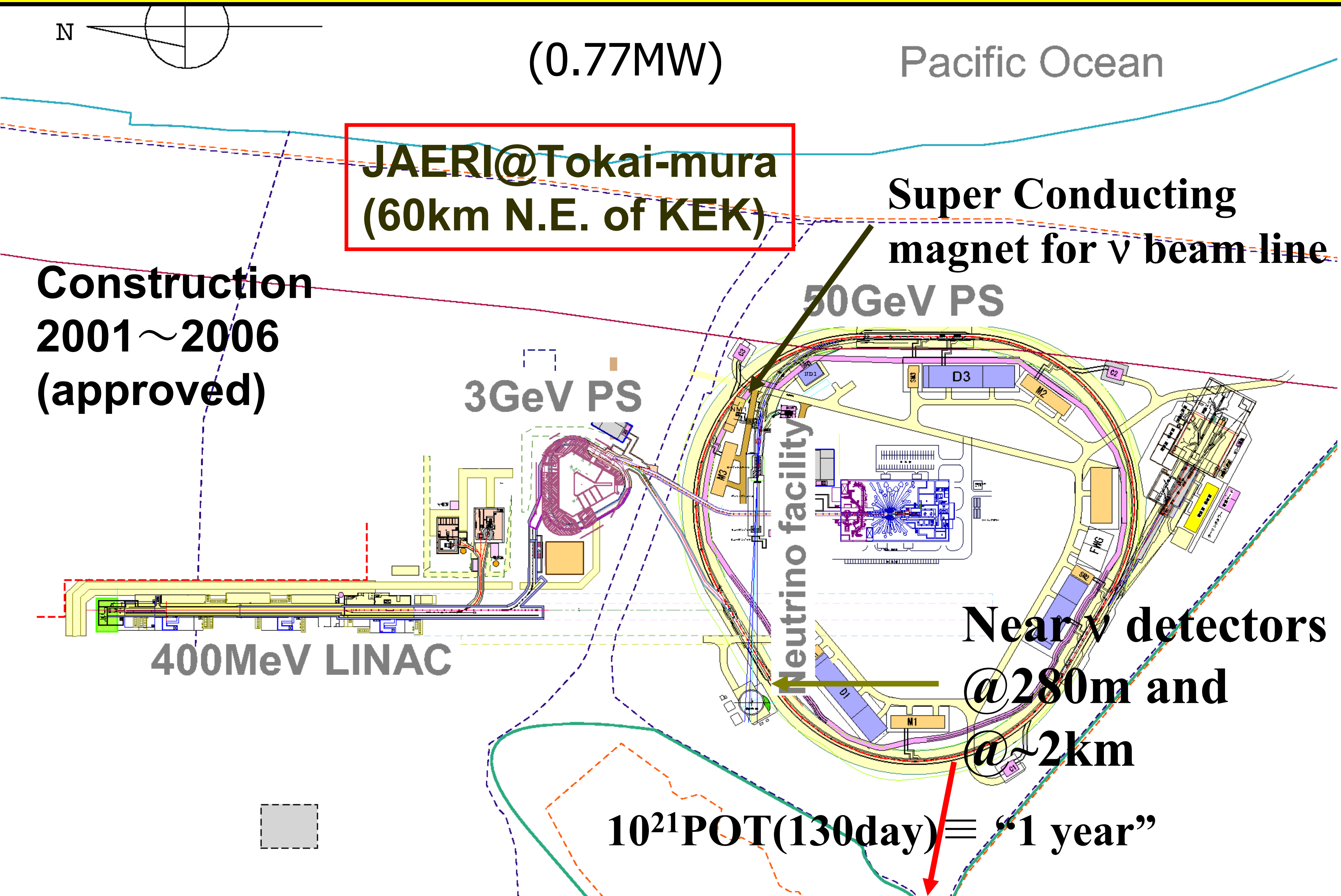
Backup slides

J-PARC to Super-Kamiokande

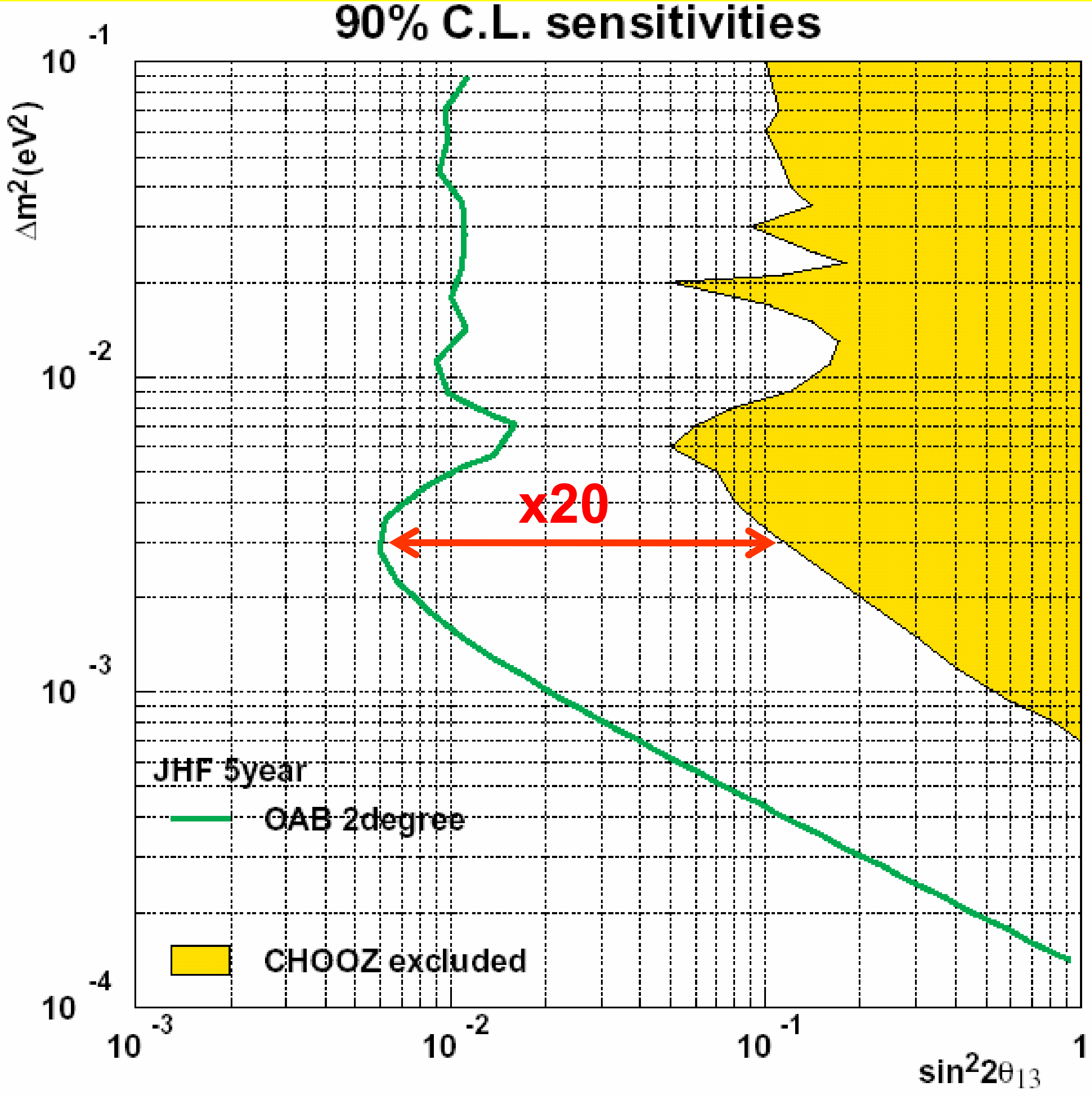


- Phase I: 2007$_{(?)}$~201x
  - ~1MW 50GeV PS $\rightarrow$ 22.5kt detector (Super-Kamiokande)
    - $\nu_\mu \rightarrow \nu_x$ disapp., $\nu_\mu \rightarrow \nu_e$ app., NC measurement
- Phase II: 201x(?)~202y(??)
  - ~4MW 50GeV PS $\rightarrow$ ~1Mt detector (Hyper-Kamiokande)
    - CPV search, Proton Decay, . . .

J-PARC – the facility



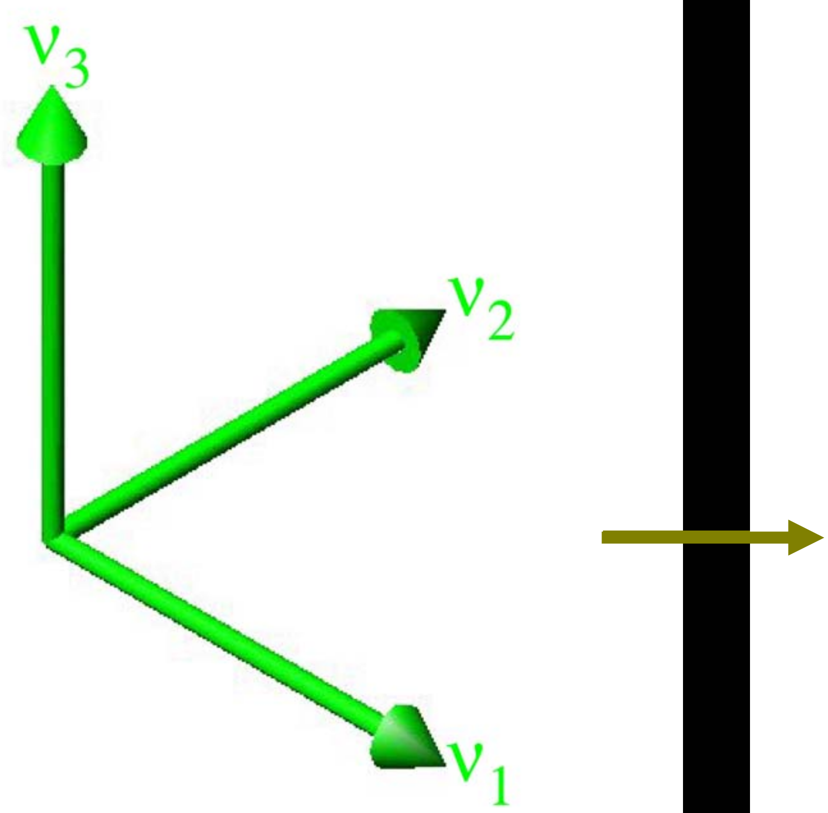
J2KOA sensitivity

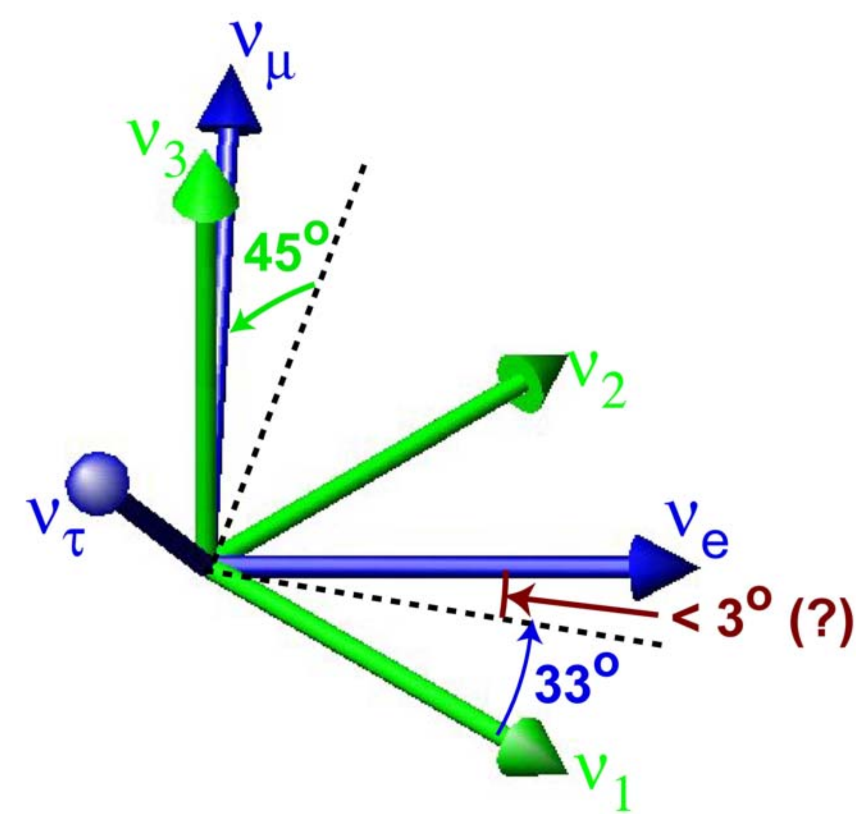


Hayato: EPS03

Motivation: phenomenology

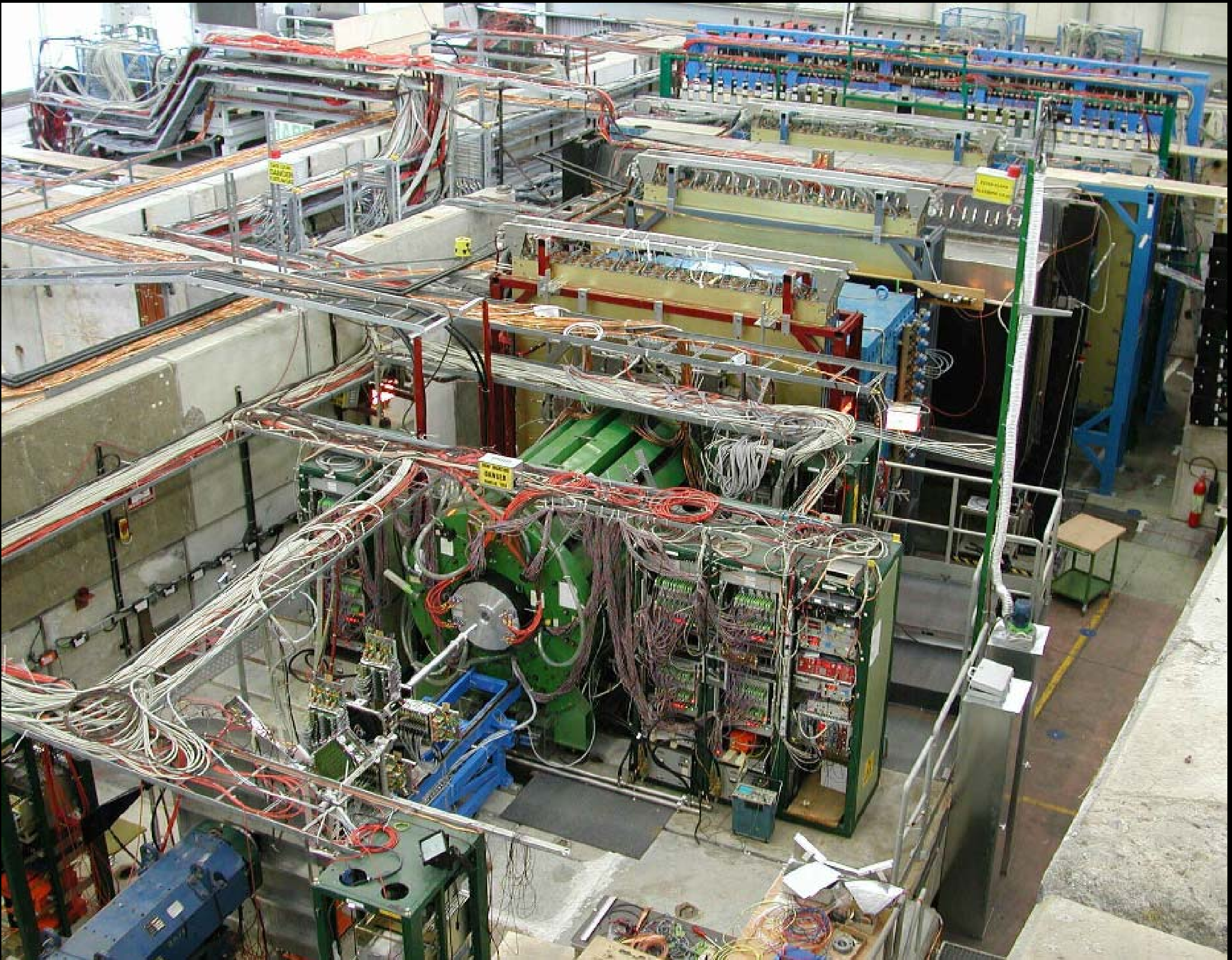
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{i\delta}\\0&1&0\\-s_{13}e^{-i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\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





Target syst^{m}: π prod^{n} and capture

- **Measurement of particle spectra:**
  - **HARP (CERN): E_p=2-15 GeV; range of materials**

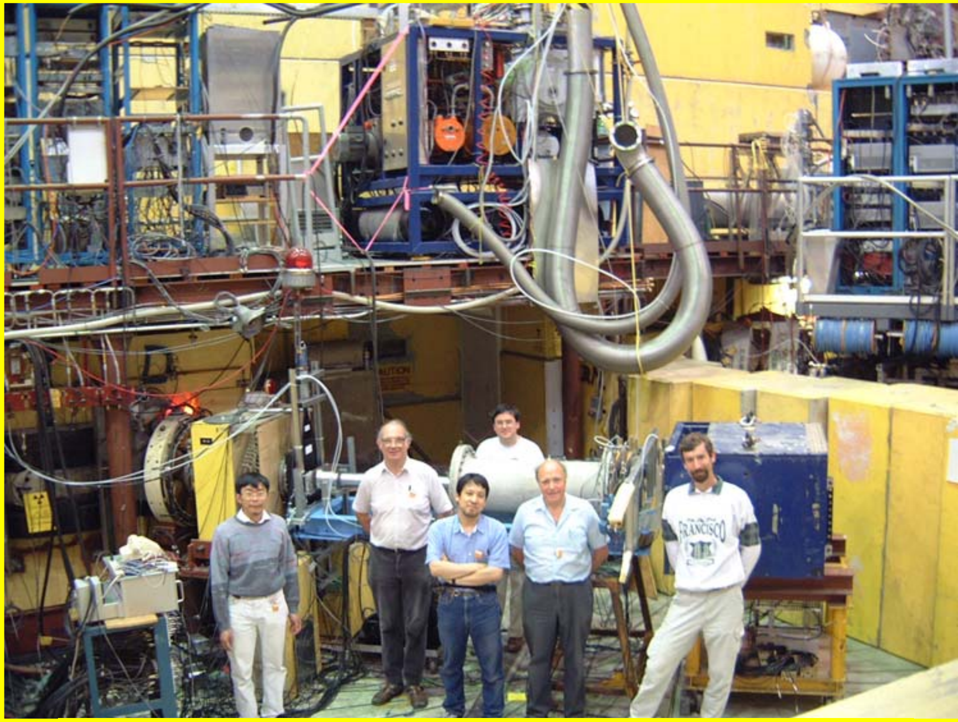


Data taking complete

Results will come 2004

Ionisation cooling

- **Ionisation cooling:**
  - **Principle:**
    - **MuScat:** Measure MCS distributions



Data taking complete

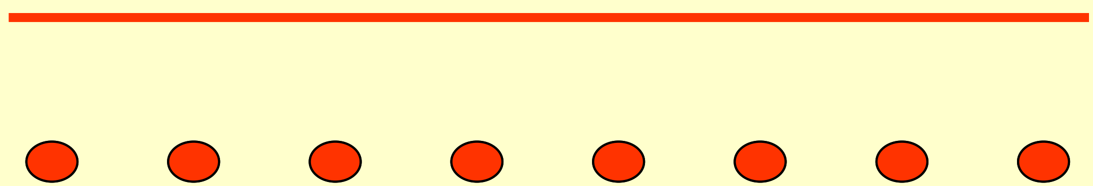
  - **Engineering demonstration:**
    - **Muon Ionisation Cooling Experiment (MICE)**

Proton driver test stand: chopper

Chopper performance required

DC accelerator

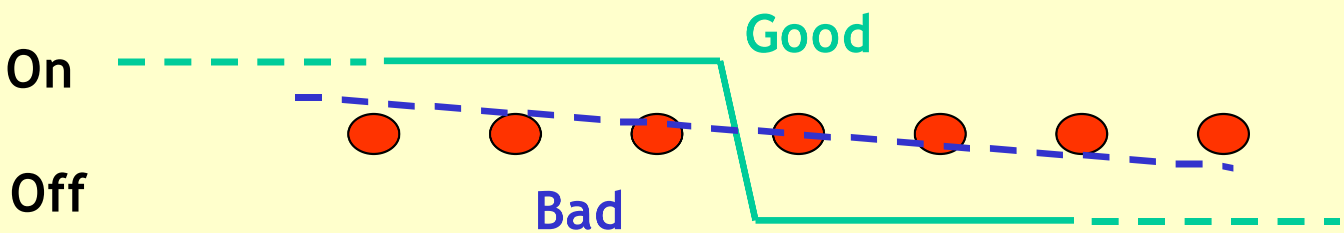
RF accelerator



ns - μs spacing

UKNF: 280 MHz, bunch spacing 3.57 ns

Switch between bunches

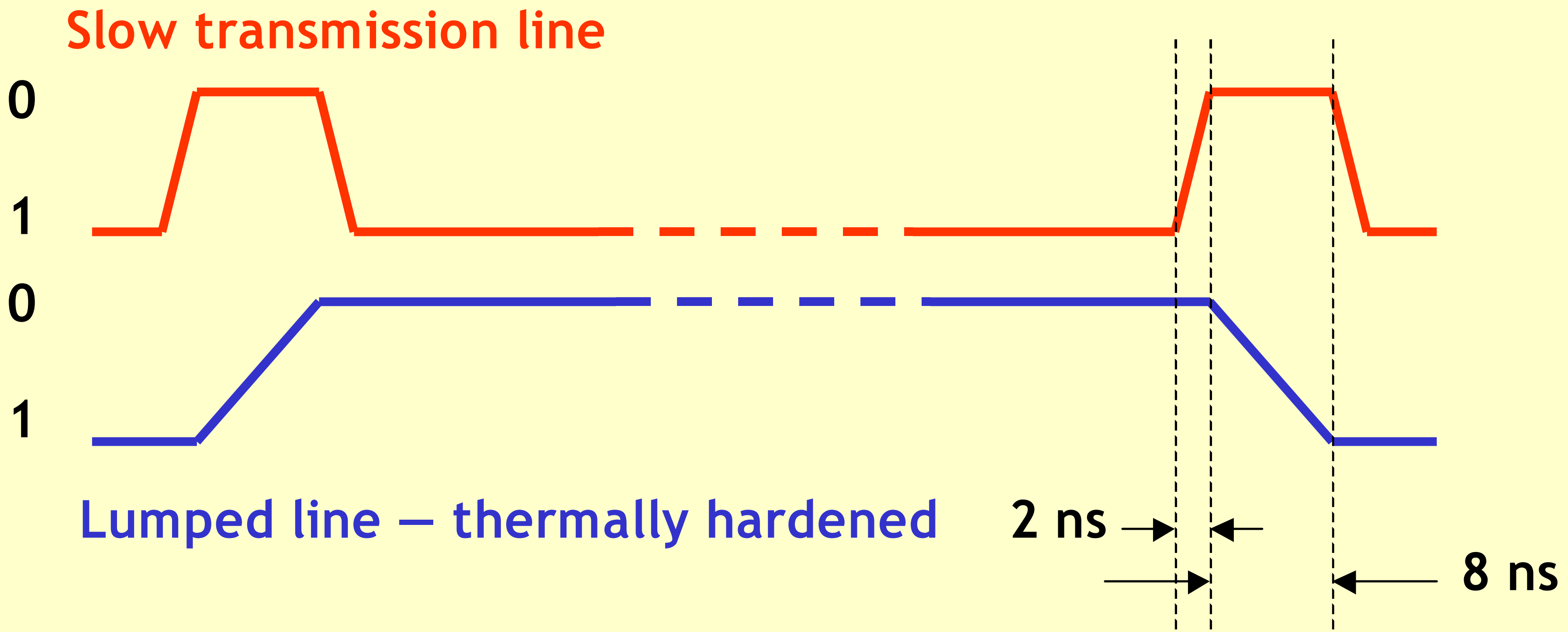


Partially chopped bunches a problem!

Proton driver test stand: chopper

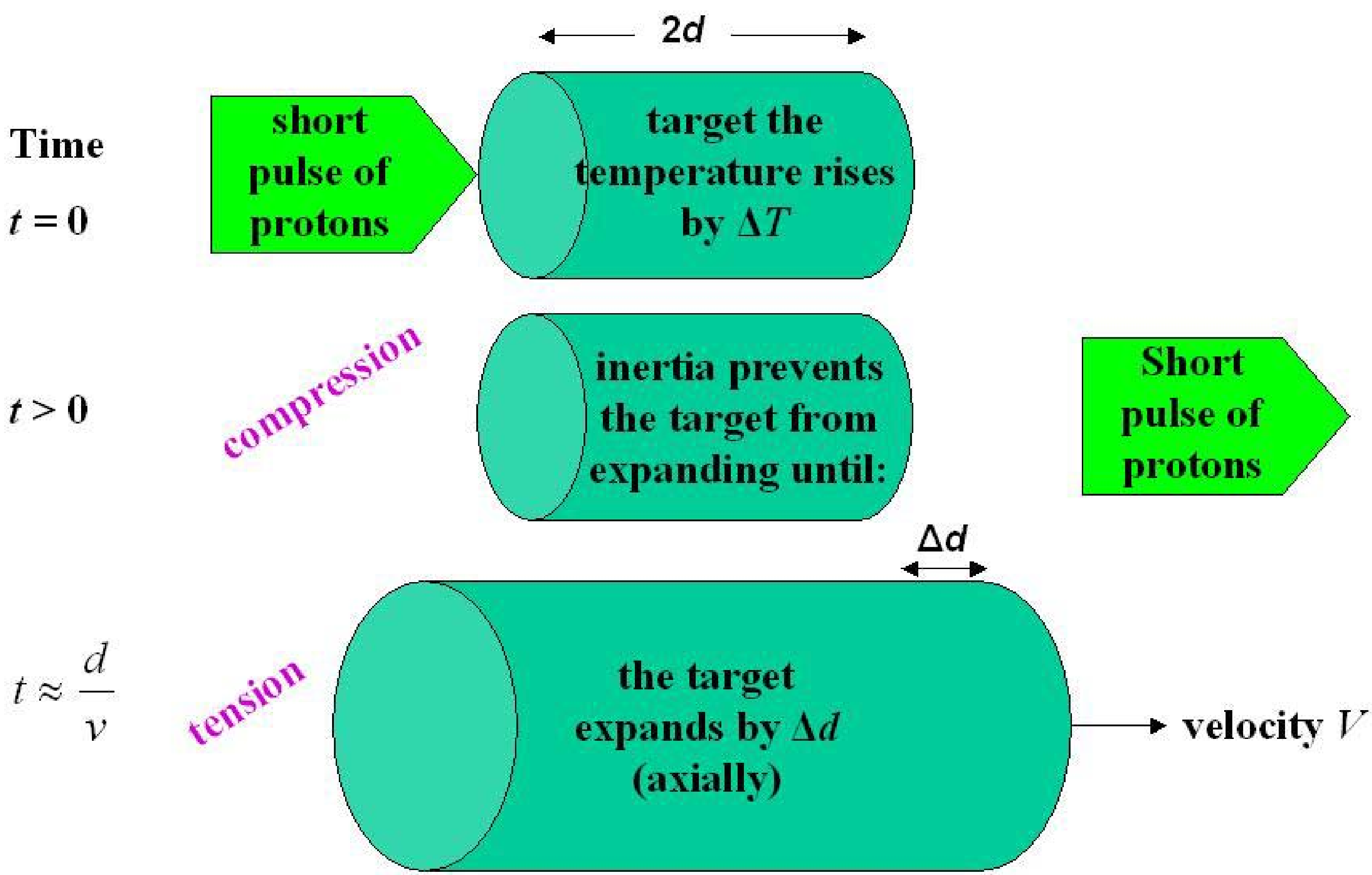
RAL aspiration:
switch in 2 ns and dissipate ~3-4 kW when "off"

2-stage process



Target: UKNF thermal-shock stdy

Simple explanation of shock waves



v is the velocity of sound in the target material.

Proton driver

- Specification:
  - Beam power 1 – 4 MW
  - Bunches ~few ns
  - Modest energy (5 – 25 GeV)
  - Schemes at AGS, CERN, FNAL, J-PARC
  - UKNF: RCS ISIS upgrade option
- Proton driver front end:
  - Challenge: high-quality pulsed beam
  - Common to CERN, FNAL, ISIS proton-driver upgrade plans
  - EU FP6 'HIPPI' programme
  - UKNF: Proton driver test stand development

A roadmap for neutrino physics?

- **US: APS initiated 'Study IIa'**
  - **Considering super beams, beta beams and Neutrino Factory**
- **Europe: EMCOG initiating roadmap discuss^n**
  - ***Context:*** **CERN SPL; Frejus Underground Lab.**
  - ***FP6 Network:*** **Beams for European Neutrino Experiments (BENE) to study:**
    - **Super beam; Beta beam; Neutrino Factory**
- **UK:**
  - ***Present:*** **SNO, MINOS**
  - ***Next generation:*** **T2K, NOVA**
  - ***Future:*** **Neutrino Factory R&D**
  - **Time to work through arguments for ourselves!**