Imperial College London

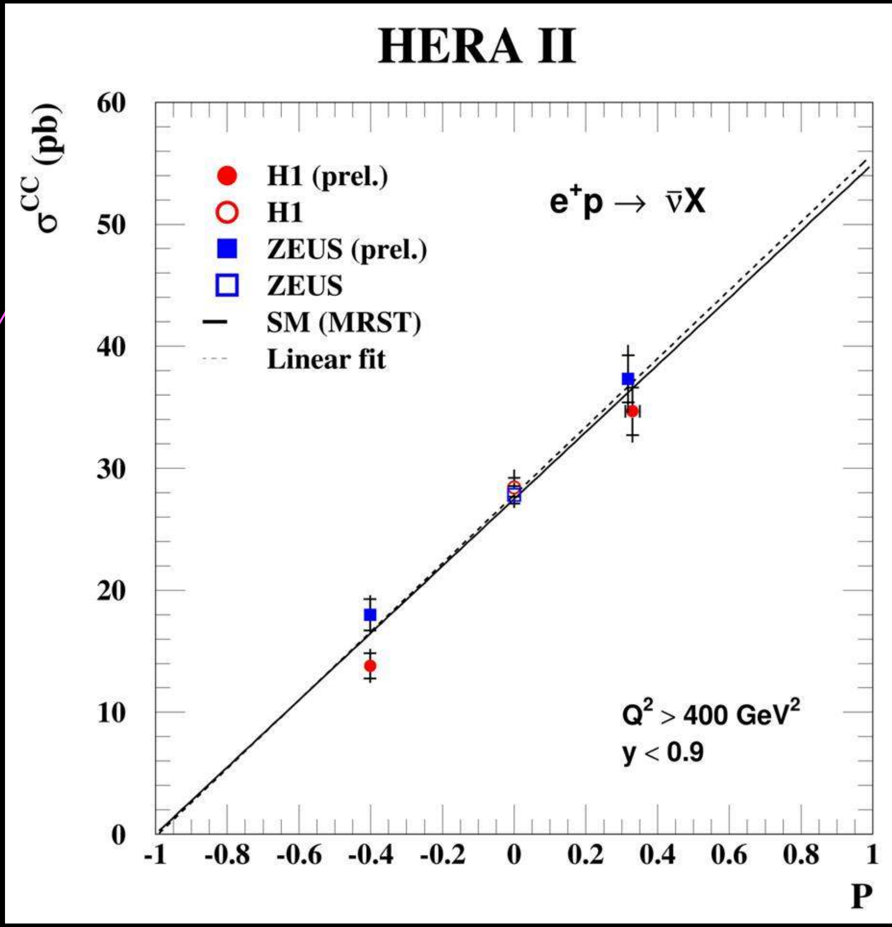
K. Long, 14. Dezember 2005

MICE, in preparation for the Neutrino Factory

Neutrinos in the Standard Model

- Standard Model neutrino:
  - Mass = 0
  - Dirac spinor
    - ν_L and $\bar{\nu}_R$ present (ν_R and ν *not* present)
  - Quantum numbers:
    - Weak isospin – ½

    No conserved quantum numbers
  - Only ν_L and $\bar{\nu}_R$ interact
    - Quantum numbers such that ν_R and $\bar{\nu}_L$ are sterile



Standard neutrino Model (SνM)?

- The observation of neutrino oscillations implies:
  - Mass $\neq 0$ *and* neutrino masses not equal
  - $\bar{\nu}_L$ and ν_R present
    - and can interact
  - No conserved quantum numbers and mass $\neq 0$
    - Dirac spinor
    - Majorana spinor
      - Neutrino could be its own antiparticle
  - Mass states mix to produce flavour states

CP violation

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

Plan:

- Motivation
- Sources for era of precision & sensitivity
- Neutrino Factory R&D
  - MICE
- Conclusions

Motivation: understanding the mixing matrix

- **Present knowledge of the parameters:**

$$\delta m^2 = 7.92\,(1^{+0.09}_{-0.09}) \times 10^{-5}\ \mathrm{eV}^2$$

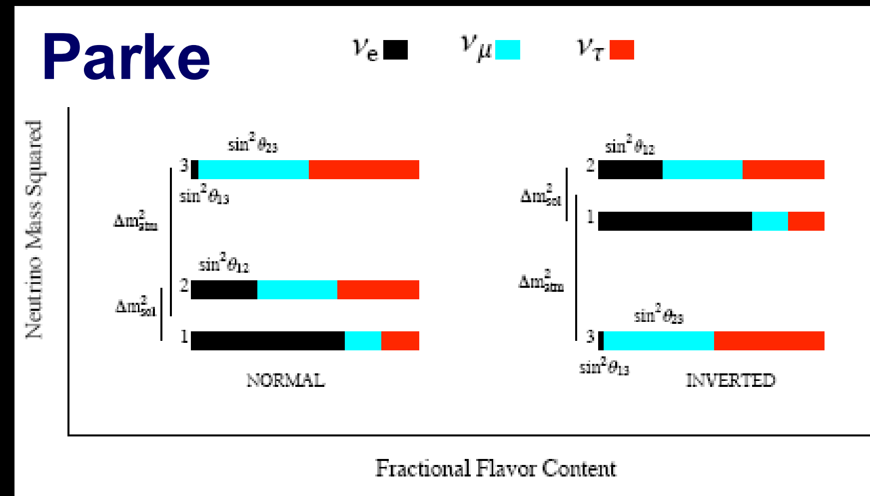
$$\Delta m^2 = 2.4\,(1^{+0.21}_{-0.26}) \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\theta_{12} = 0.314\,(1^{+0.18}_{-0.15})$$

$$\sin^2\theta_{23} = 0.44\,(1^{+0.41}_{-0.22})$$

$$\sin^2\theta_{13} < 3.2 \times 10^{-2}$$

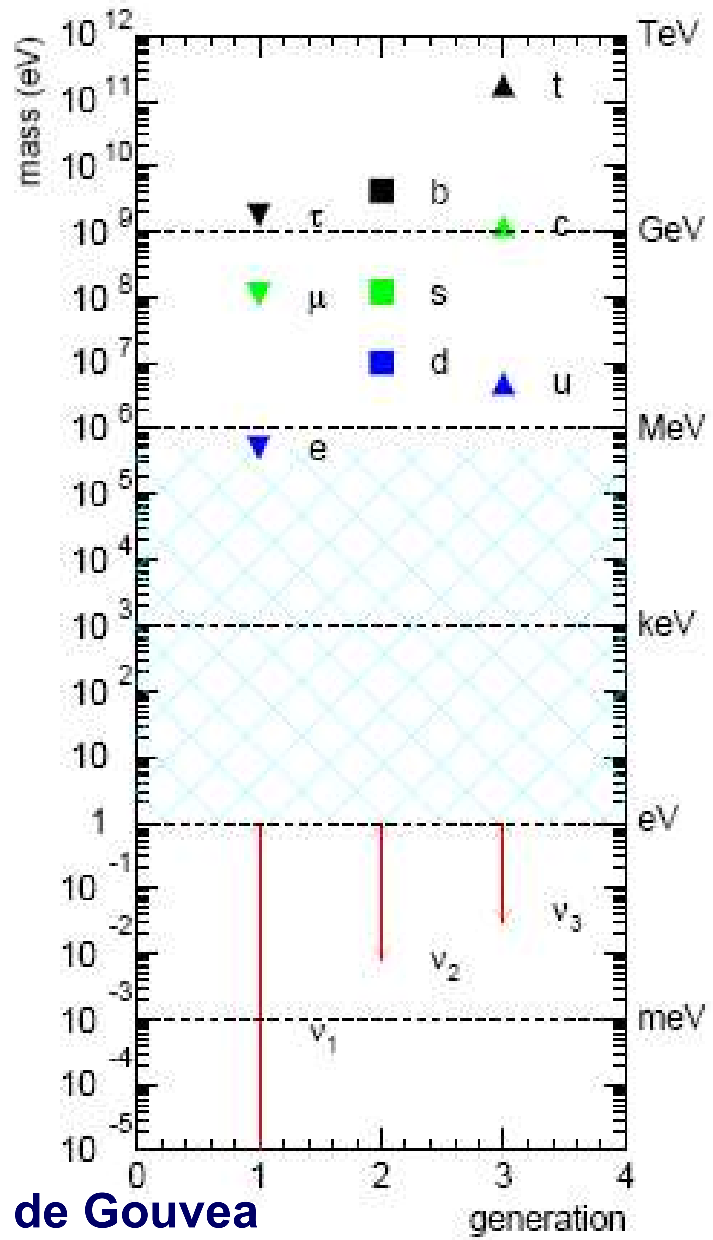
Lisi



- **Presently unknown:**
  - Sign of Δm^2_{23} – discovery
  - Precision determination of θ_{13}
  - Search for non-zero δ – discovery
- **As important as study of CKM matrix**

Motivation: key issues in particle physics

- The origin of mass
  - Neutrino mass very small
    - Different origin to quark and lepton mass?



de Gouvea

Motivation: key issues in particle physics

- The origin of mass
  - Neutrino mass very small
    - Different origin to quark and lepton mass?
- The origin of flavour
  - Neutrino mixing different from quark mixing
    - 'Natural' explanation in 'see-saw' models?

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

$[|(V_{MNS})_{e3}| < 0.2]$

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

de Gouvea

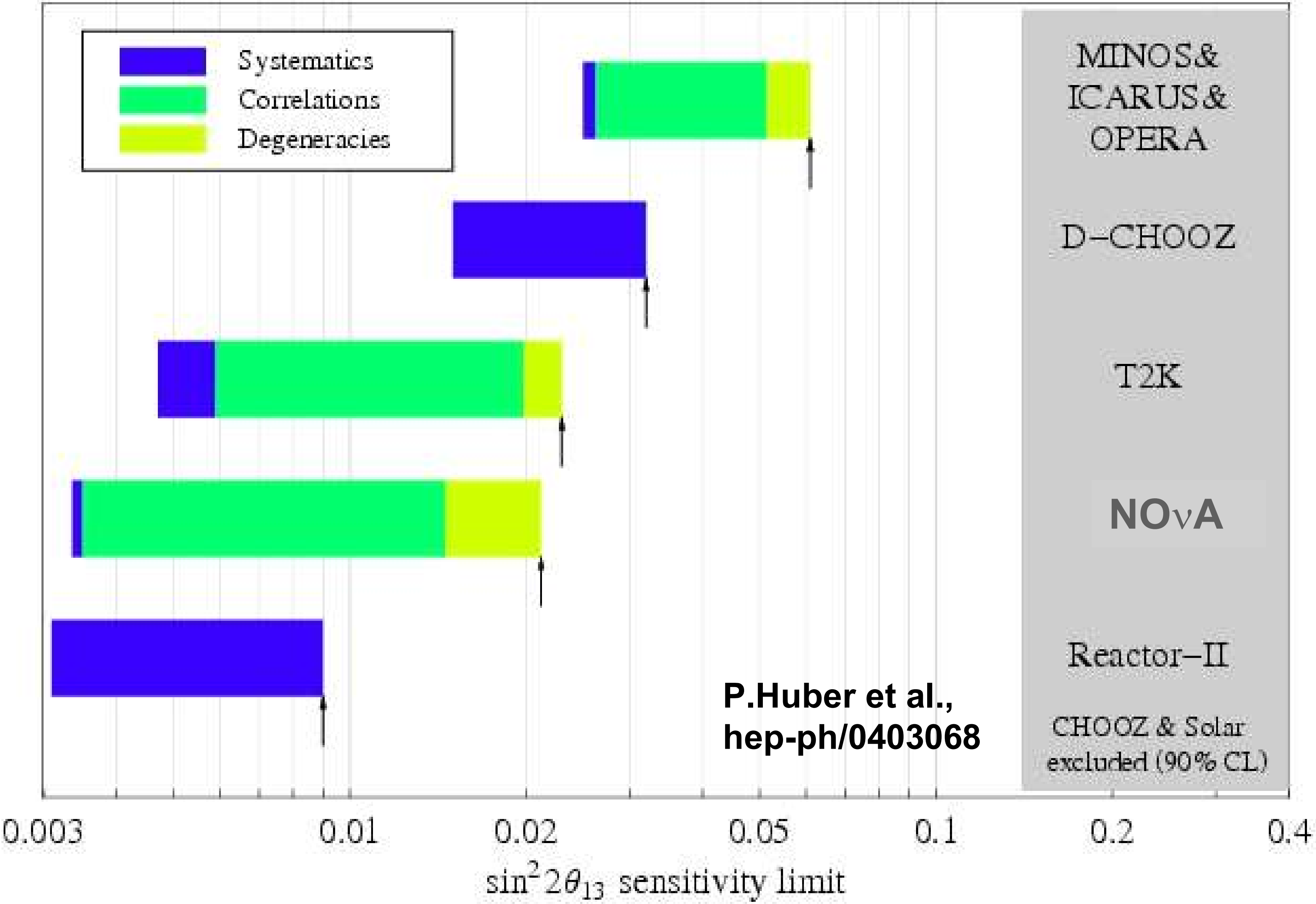
Motivation: key issues in particle physics

- The origin of mass
  - Neutrino mass very small
    - Different origin to quark and lepton mass?
- The origin of flavour
  - Neutrino mixing different from quark mixing
    - ‘Natural’ explanation in ‘see-saw’ models?
- The quest for unification
  - ‘Unified’ theories relate quarks to leptons
    - Generating relationships between quark and lepton mixing angles

Motivation: key issues in particle physics

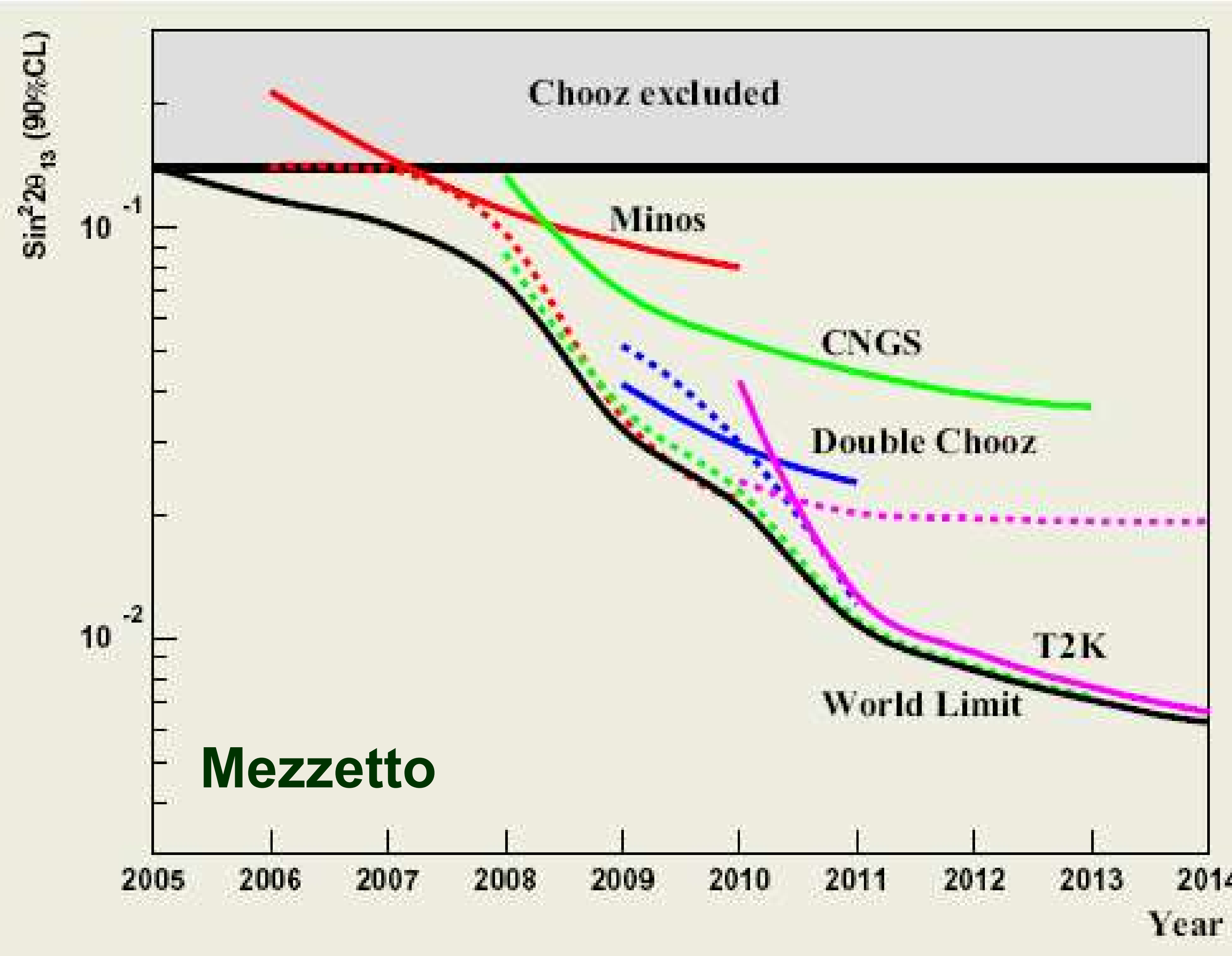
- The origin of dark matter & dark energy
  - ~96% of matter/energy is not understood
  - Neutrinos:
    - Contribution as large as baryonic matter?
    - In some models neutrinos impact on dark energy
- The absence of anti-matter
  - CP violation in lepton sector underpins removal of anti-matter
    - 'Dirac' phase, δ, not directly responsible, but,
    - Relationship of relevant (Majorana) phases to δ is model dependent
- Explanation of (absence of) large-scale structure
  - Neutrino interacts only weakly – possible means of communication across large distances?
  - In some models, super-symmetric partner to neutrino may be responsible for inflation

Motivation: the next generation



P.Huber et al., hep-ph/0403068

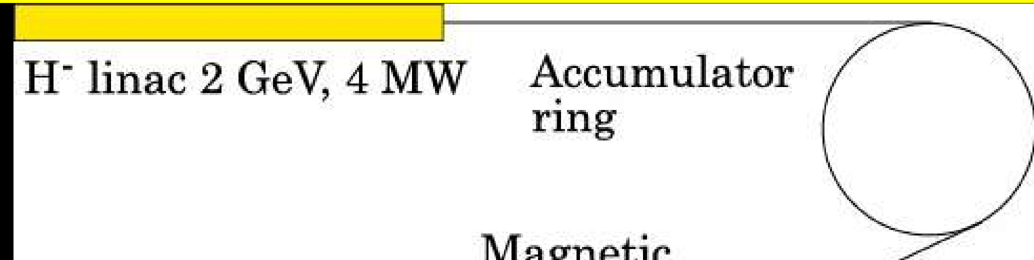
Motivation: timescales

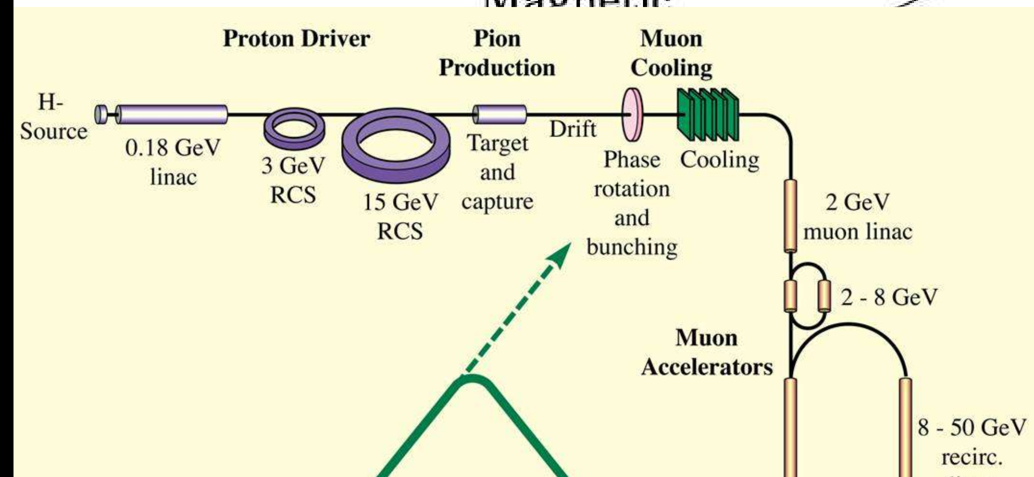


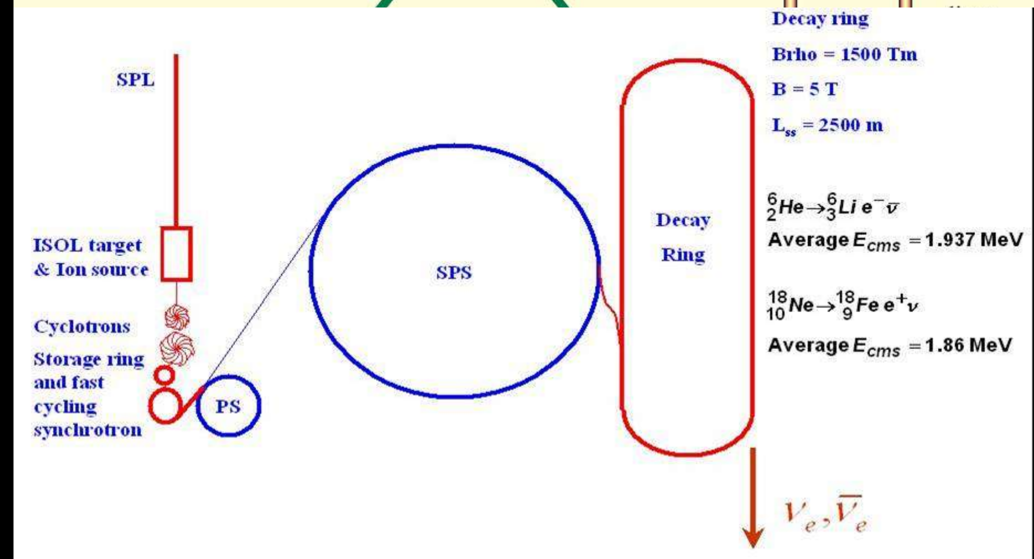
Require 2nd generation facility in second half of next decade

Neutrino source – options:

- Second generation super-beam
  - CERN, FNAL, BNL, J-PARC II
- Neutrino Factory
- Beta-beam

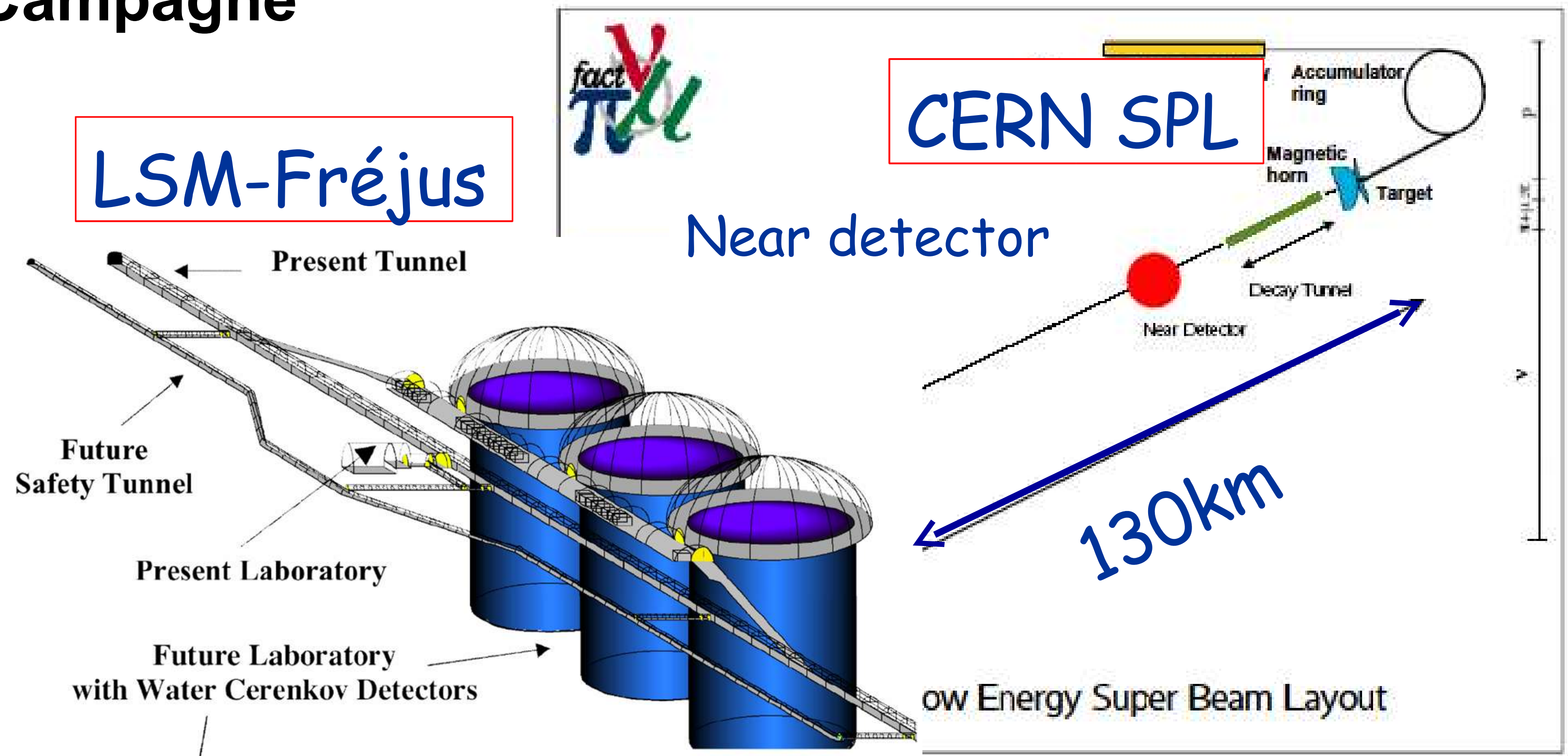






Super-beams: SPL-Frejus

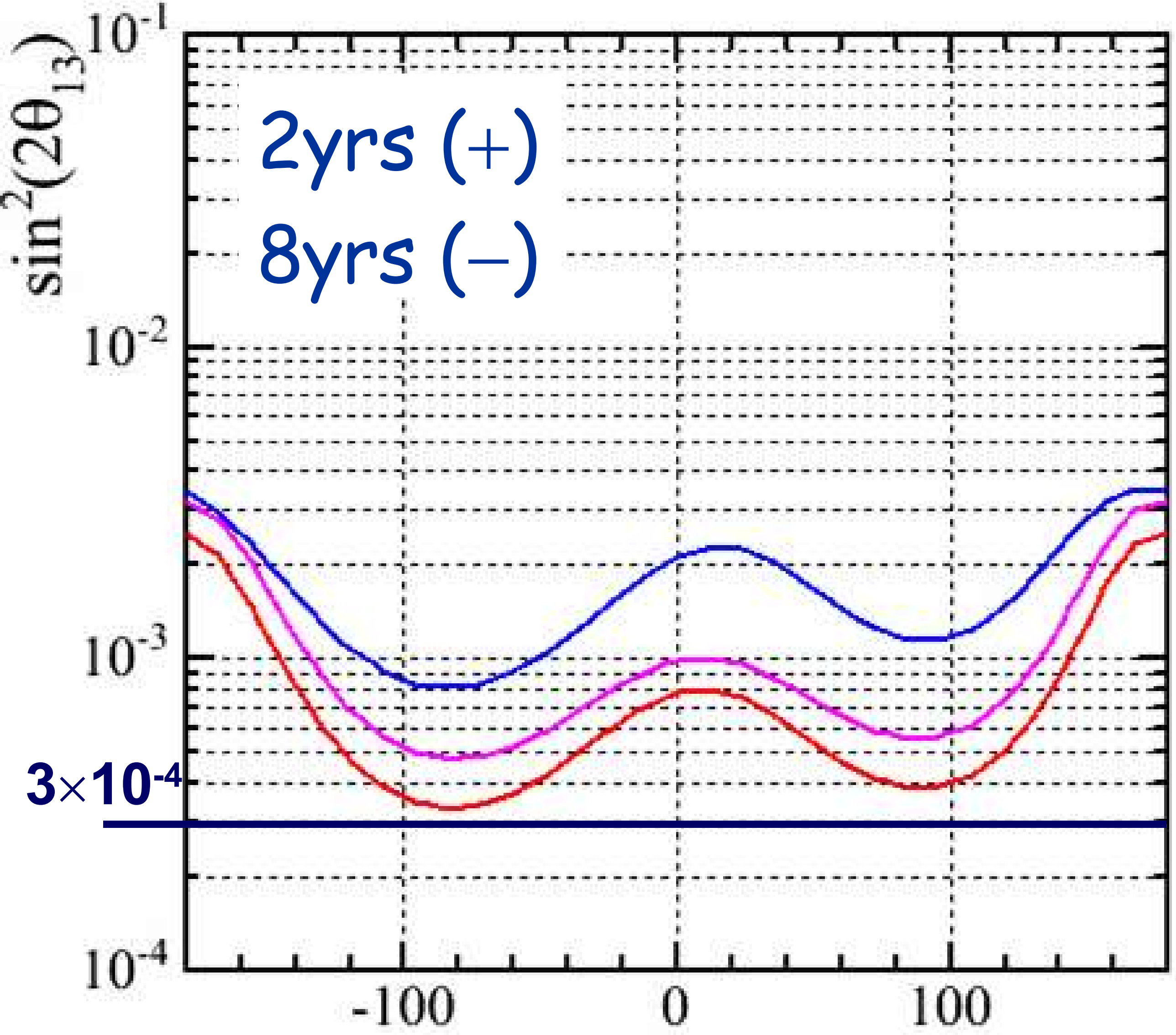
Campagne



- New optimisation: 4 MW; 440 kTon H_2O
  - Energy: 3.5 GeV
  - Particle production
  - Horn/target
  - Decay tunnel

SPL-Frejus: performance

Campagne



T2K×10, 5 yrs

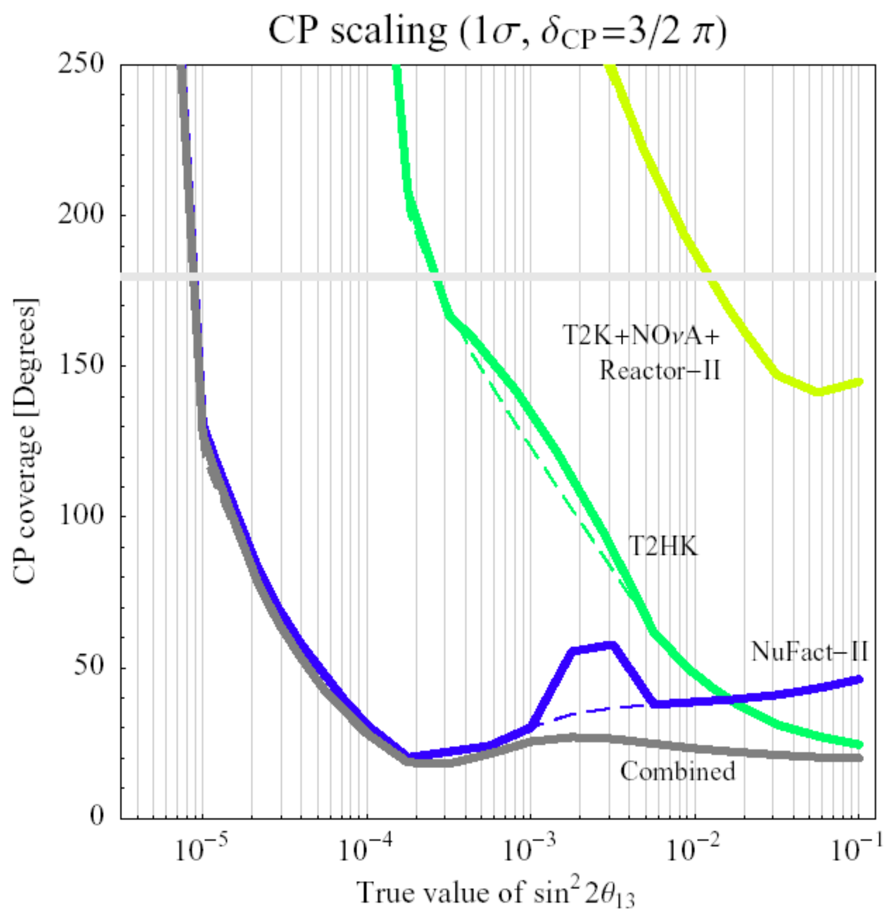
'Old' (2.2 GeV)

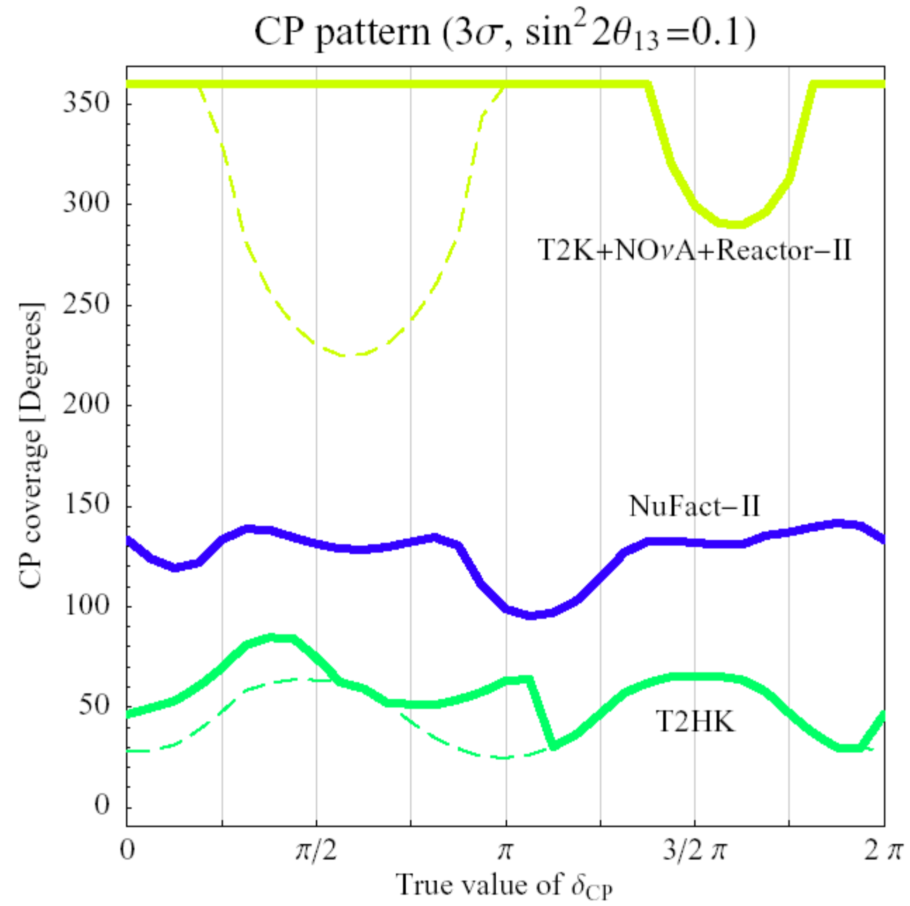
Rates

Rates and energy spectrum

Assumes 2% systematic uncertainties

Neutrino Factory: sensitivity





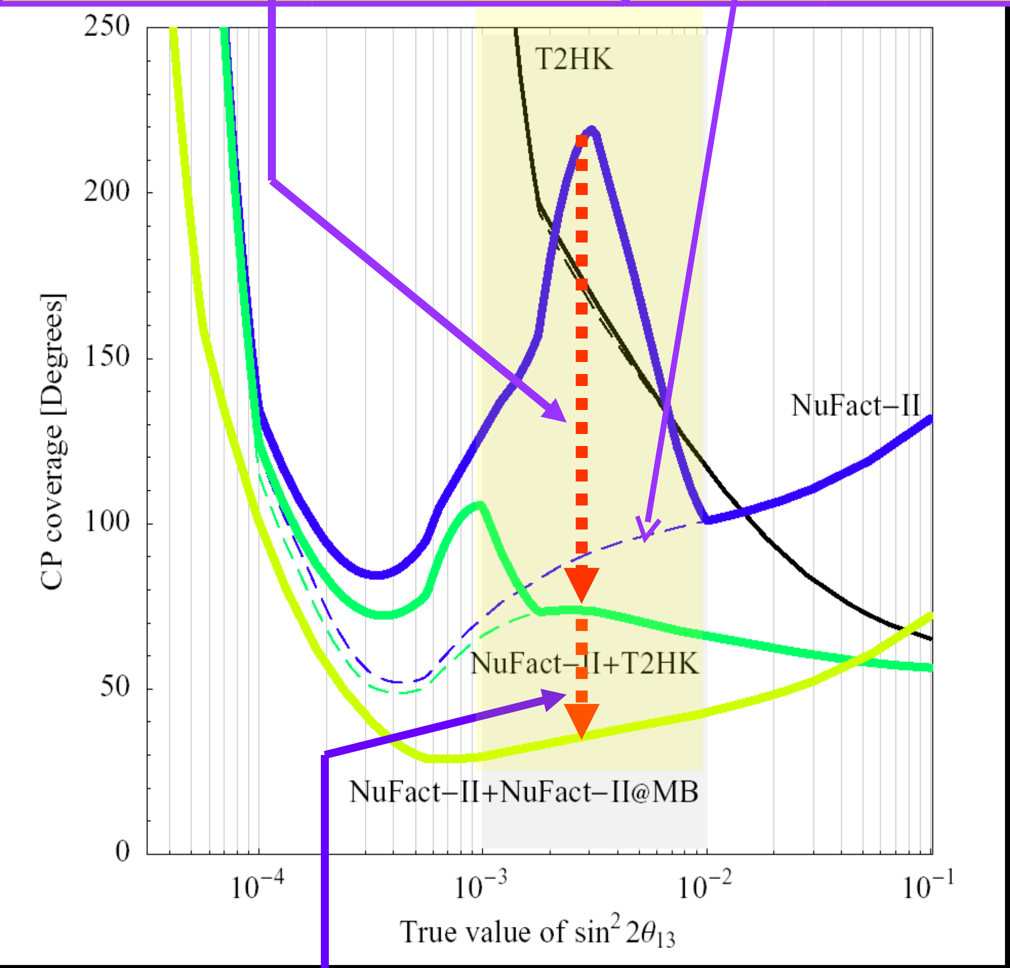
- Neutrino Factory: 10^{21} decays/year; 50 GeV
- 50 kTon magnetised iron calorimeter
  3000 km base line

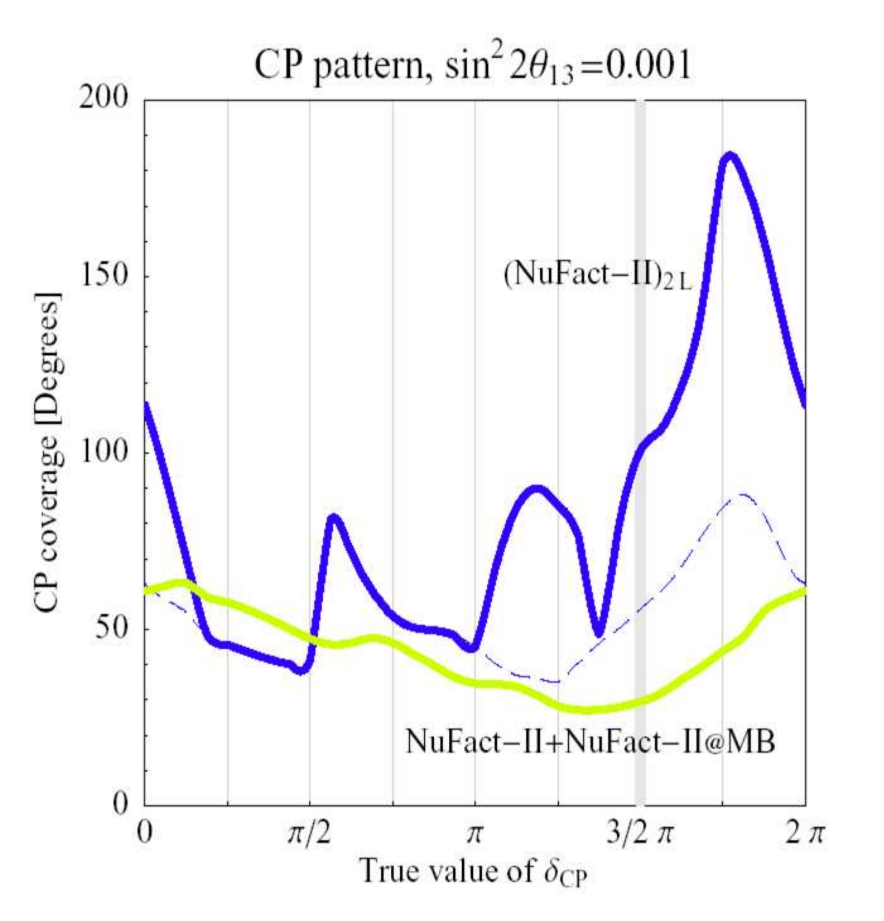
P.Huber et al., hep-ph/0412199

Neutrino Factory: sensitivity

Synergy of NuFact-II(3000 km)+T2HK

mass hierarchy removed

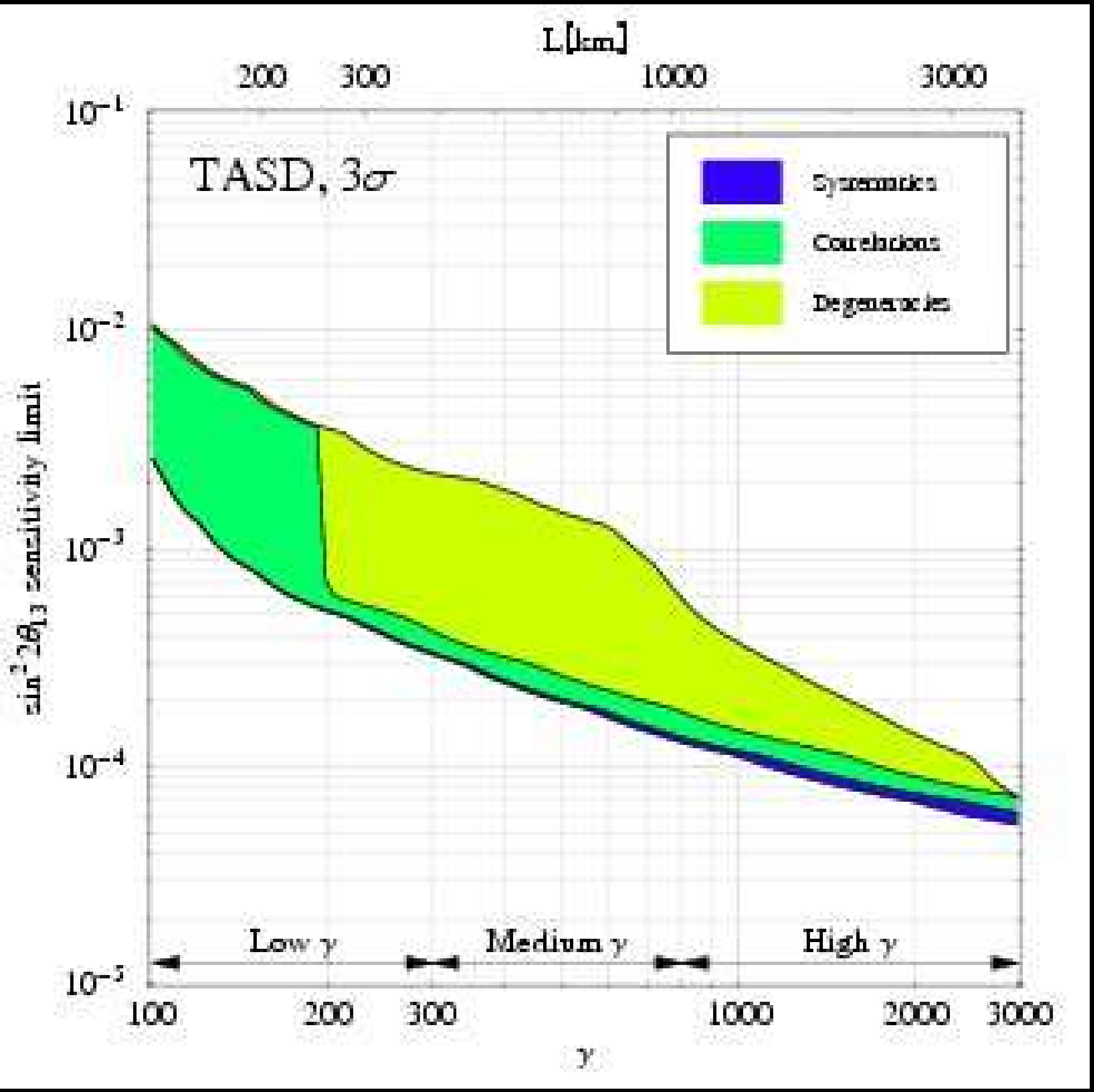




2nd L at MB=Magic Base Line(7500km)

P.Huber et al., hep-ph/0412199

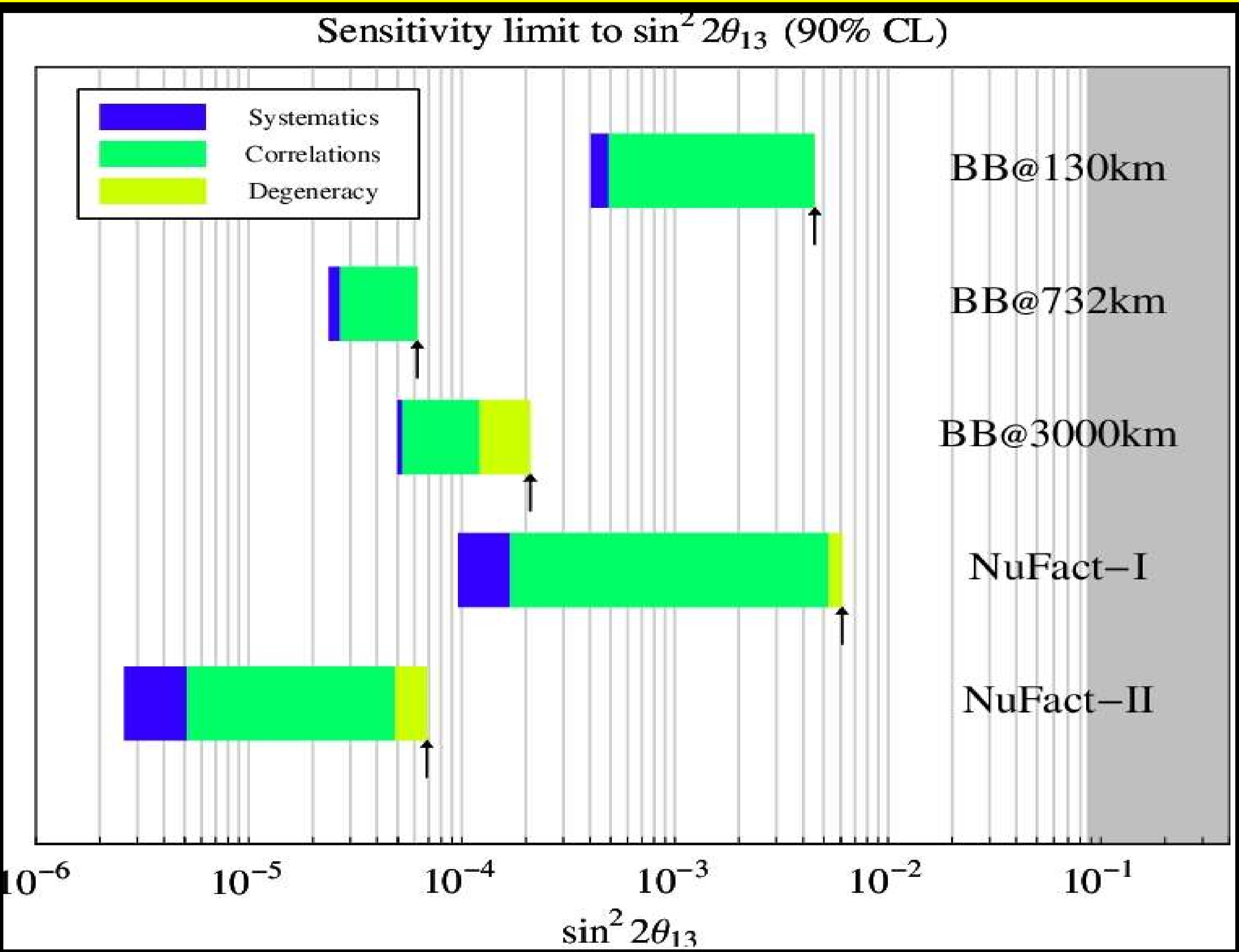
Beta-beam



- **Optimisation**
  - **Beam energy (γ)**
  - **Detector:**
    - **H_2O Ckov**
    - **TASD**

  considered

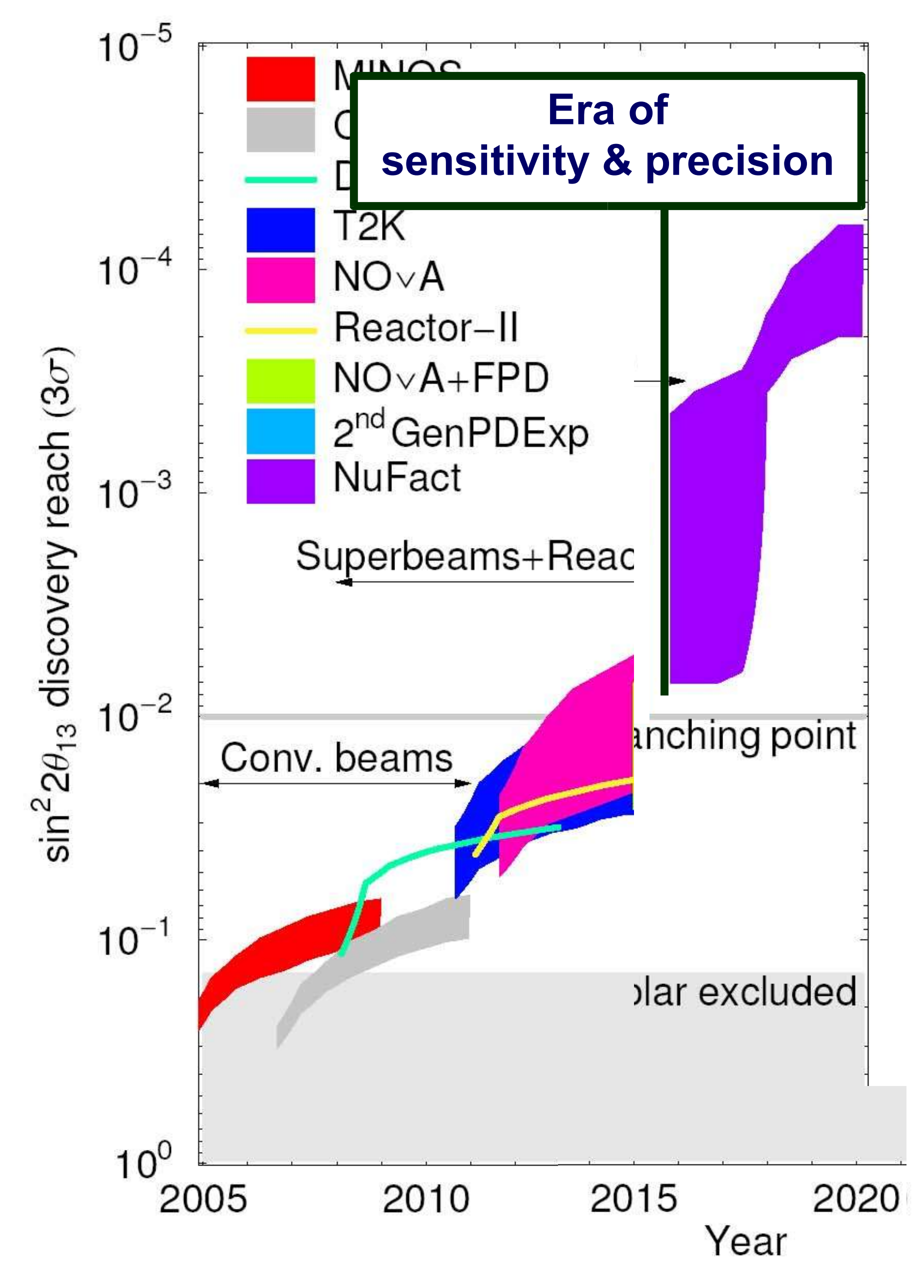
Neutrino Factory / beta-beam



Super-beam/beta-beam/Neutrino Factory

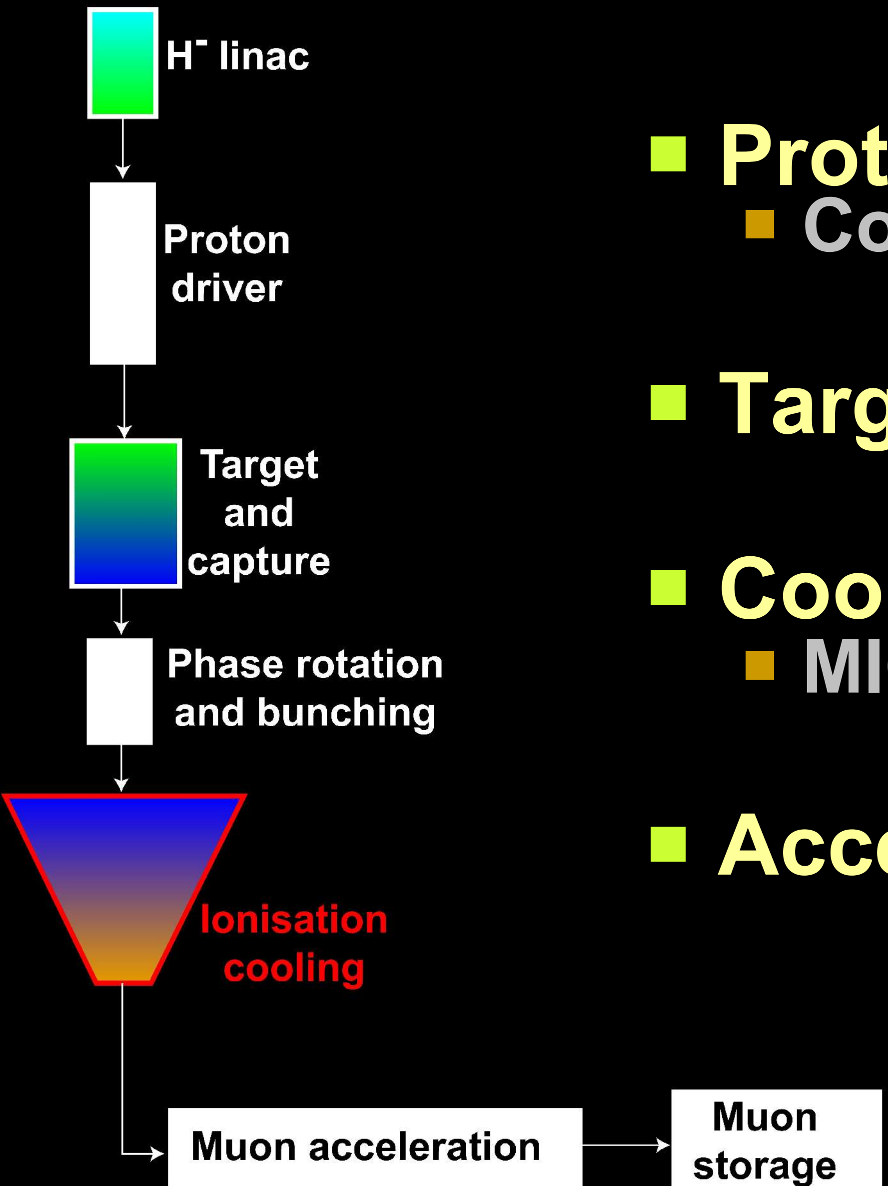
- Neutrino Factory offers best performance
  - Best sensitivity to δ
    - Unless $\sin^2 2\theta_{13}$ is large
      - NF optimisation for large $\sin^2 2\theta_{13}$ to be reviewed
  - Best 'discovery reach' in $\sin^2 2\theta_{13}$
- High-γ beta-beam competitive
  - $\gamma \sim 350$ requires '1 TeV proton machine'
- High-performance super-beam has $\delta \neq 0$ discovery potential if $\sin^2 2\theta_{13}$ is large
  - Multi-megawatt class proton source
  - Megaton scale H_2O Cherenkov

The challenge: time-scales

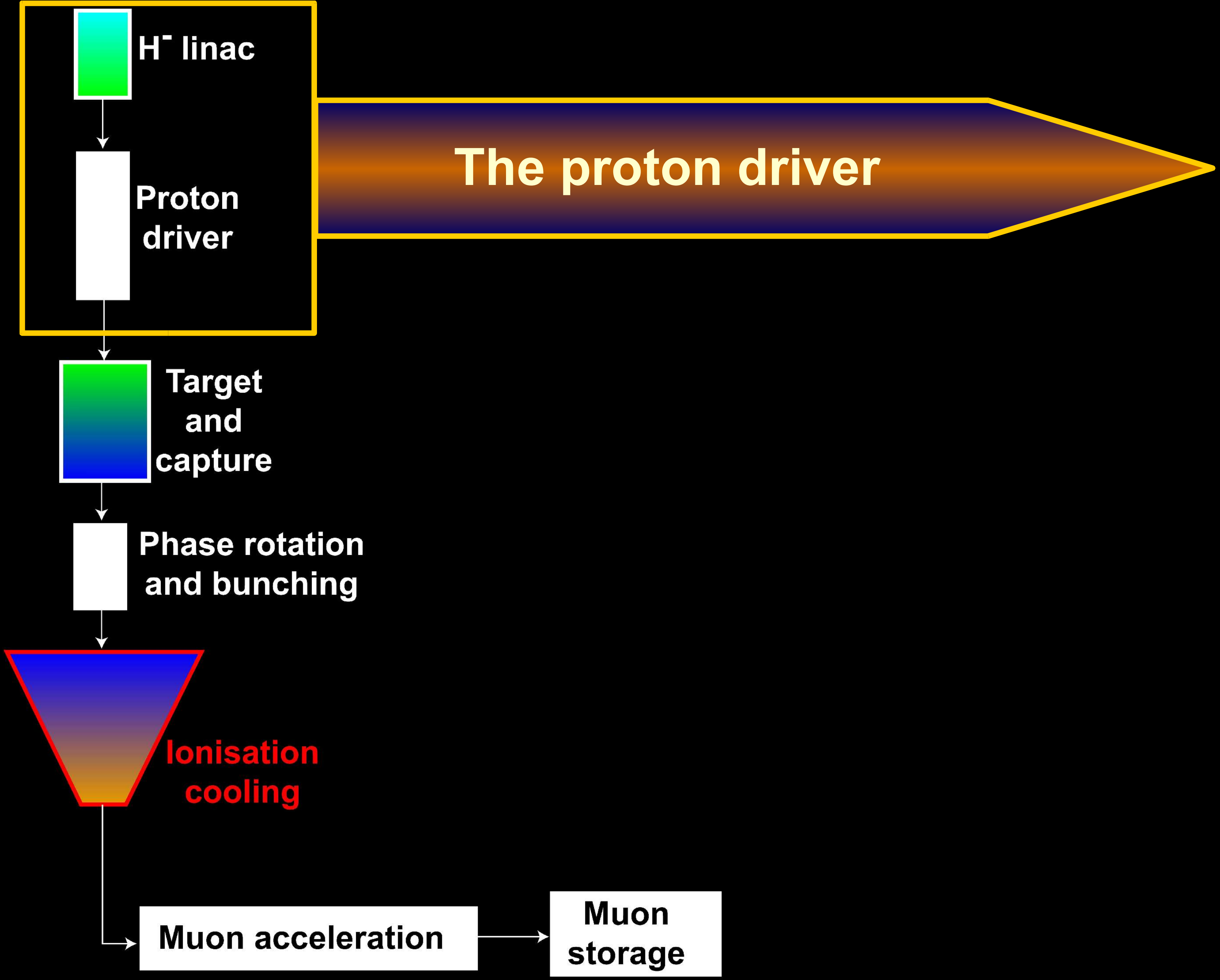


- **Optimum schedule**
  - Science driven
  - Potential match to funding window
- **Challenge:**
  - To make the case!
- **International scoping study**
  - 1-year study of Neutrino Factory and super-beam facility
  - … a step on the way?

Neutrino Factory R&D: highlights

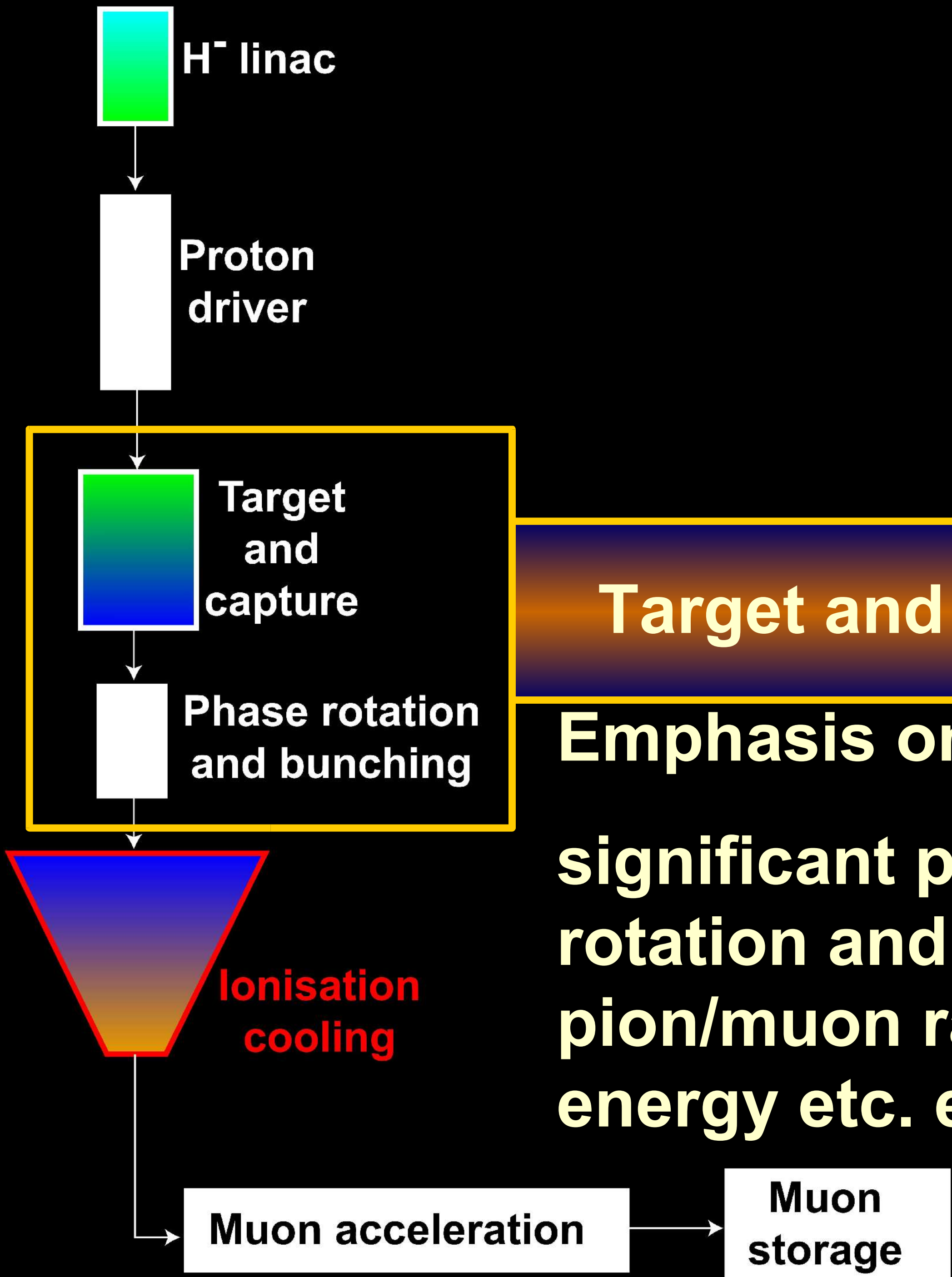


- Proton driver
  - Comment on front end
- Target and capture
- Cooling
  - MICE
- Acceleration


H⁻ linac
Proton driver
The proton driver
Target and capture
Phase rotation and bunching
Ionisation cooling
Muon acceleration
Muon storage

Proton driver & its front end

- Proton labs all have proton-driver plans
  - … too much detail to cover here!
- Importance to inject ‘good’ beam:
  - Parallel front-end developments (in Europe):
    - CERN: 3 MeV test place; Linac 4; SPL
    - CCLRC: Front-end test stand; 180 MeV linac
    - CEA: SPES-1
    - INFN: Incipit
    - CNRS, IPN, IN2P3, Eurotrans: PDS-XADS
    - Eurisol, HIPPI
    - …
  - Synergy!
    - Breadth of applications is a great strength



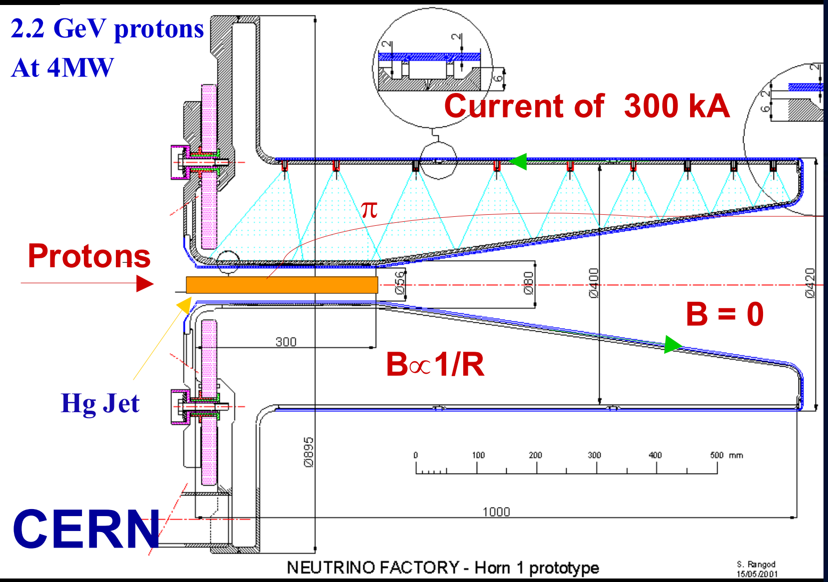
Target and capture

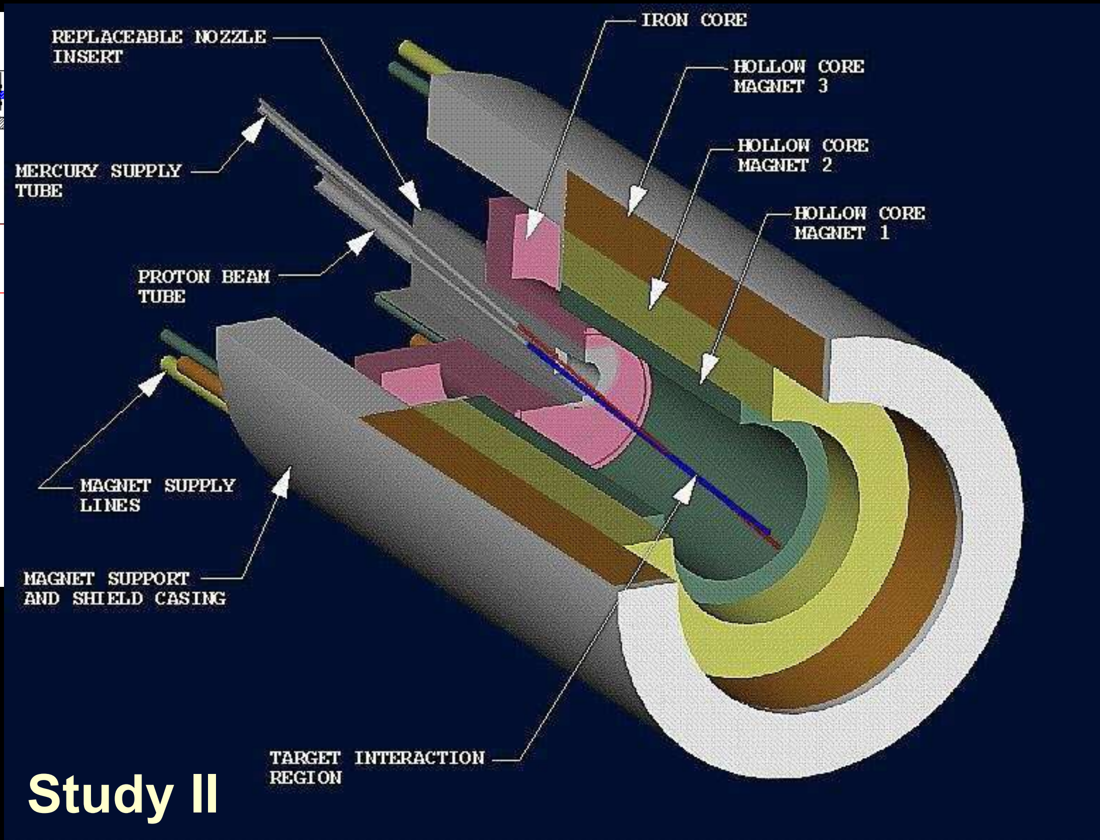
Emphasis on target work, but

significant progress in phase-rotation and bunching schemes pion/muon rates vs proton energy etc. etc.

Target and capture

- Two schemes:
  - Horn: good match to super-beam
  - Tapered solenoid: possible to capture μ^+ and μ^- simultaneously (US Study IIa)

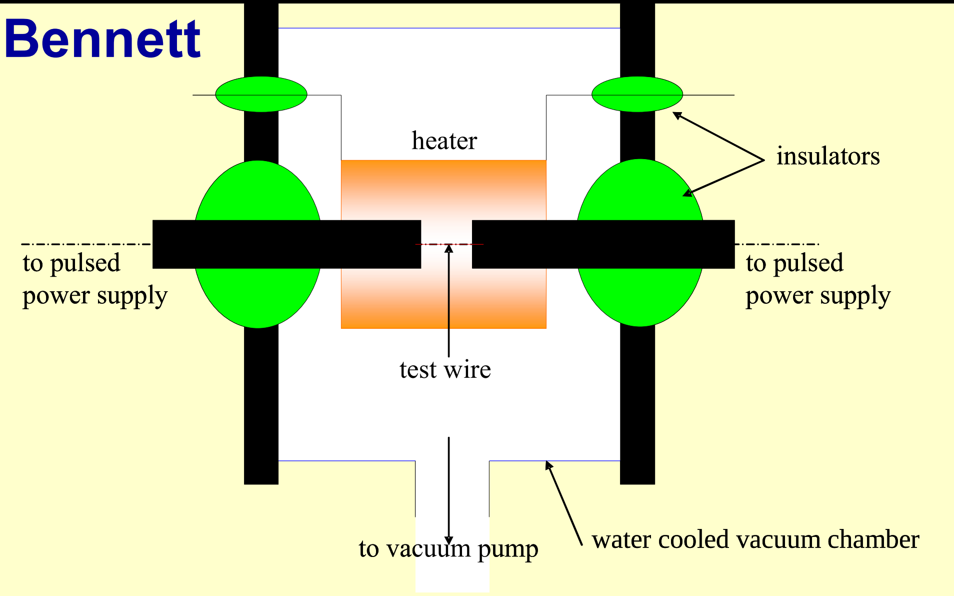




Target: evaluation of options

- Solid target:
  - Lifetime: beam-induced shock leads to fracture
  - Irradiation tests:
    - Exposure of various candidate materials to pulsed proton beam at BNL and at CERN
    - Annealing of target material through 'baking' also being studied
  - Shock test (UKNF):
    - Current pulse to simulate heating
    - Thin (tantalum wire)
    - Numerical models (LS-Dyna) being studied

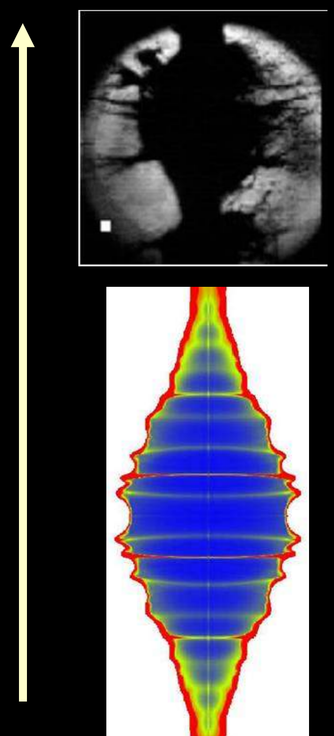
Bennett

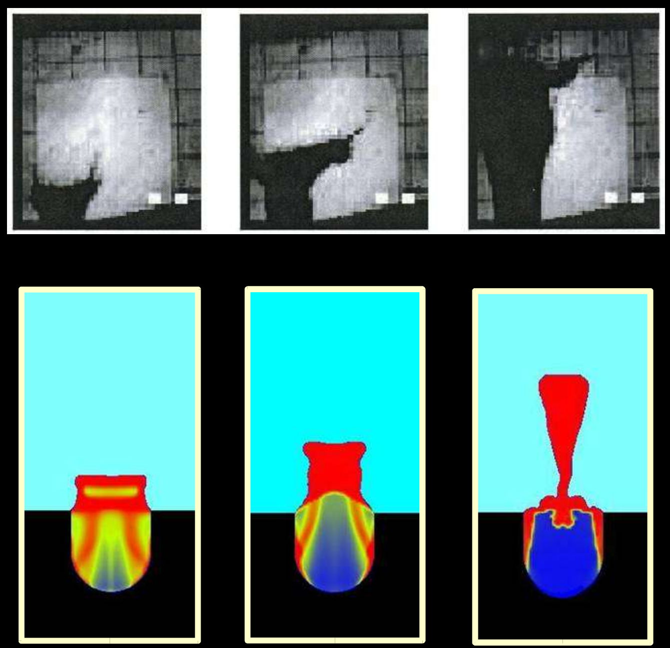


Schematic diagram of the test chamber and heater oven.

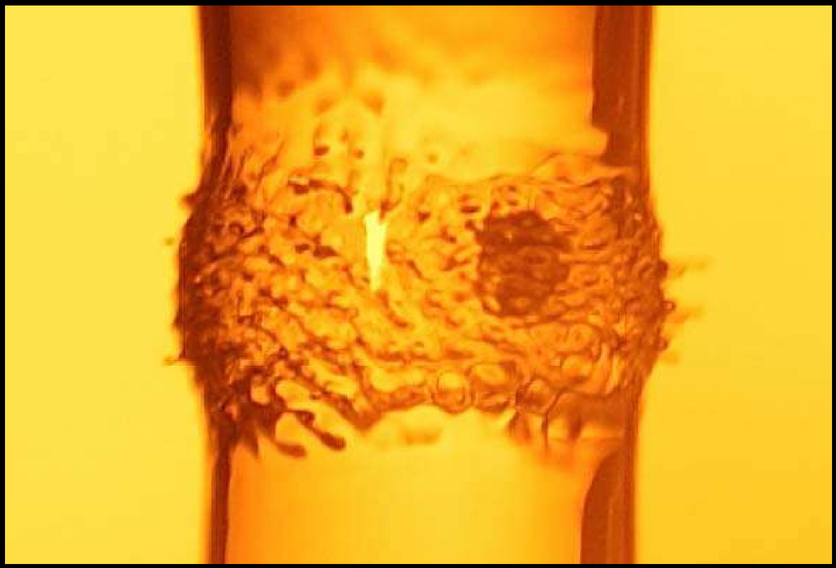
Target: evaluation of options

- **Liquid-mercury jet:**
  - To date, have tested:
    - Effect of beam on jet without magnetic field
    - Development of jet in a solenoidal magnetic field
  - Progress in modelling results





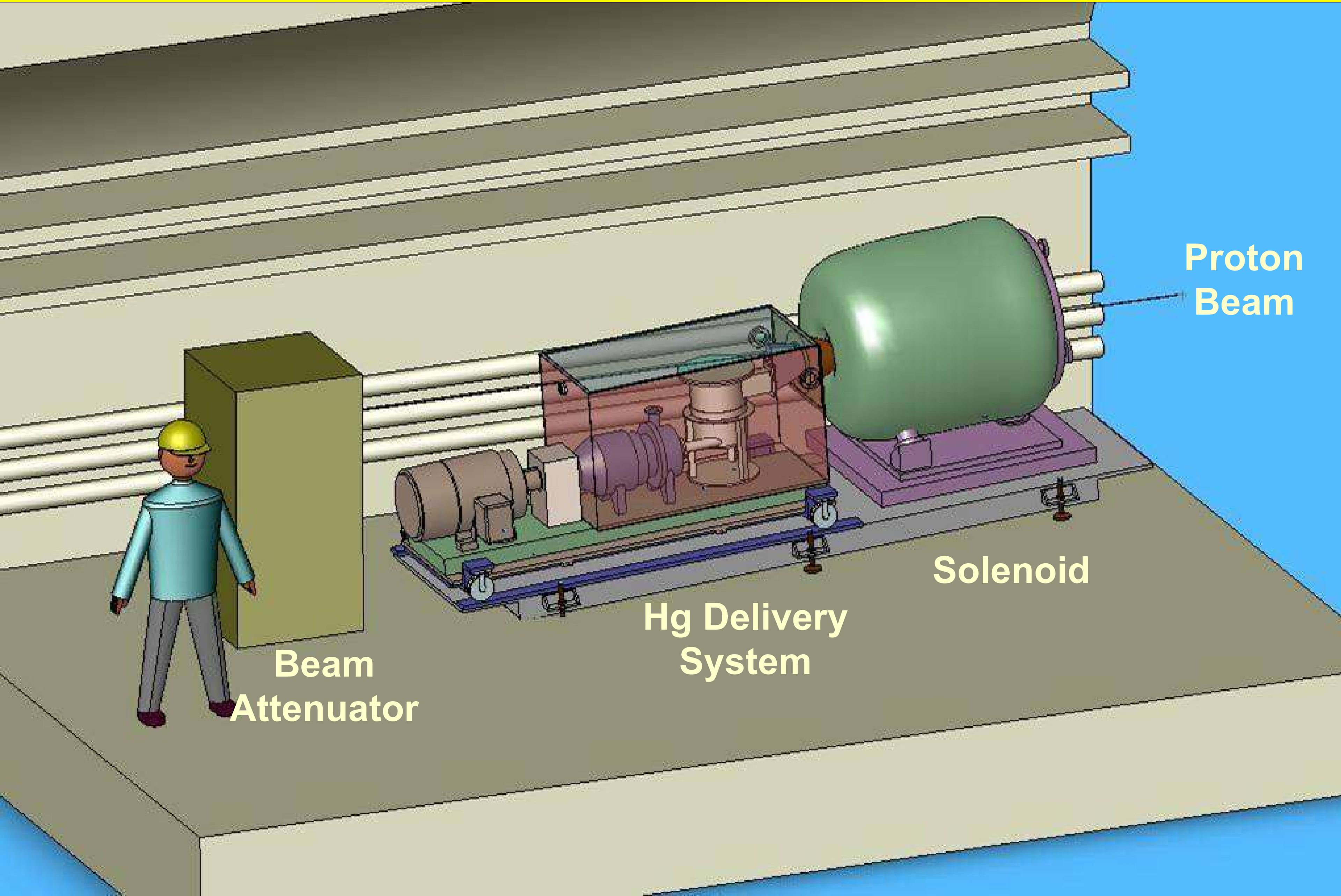
Samulyak



Lettry/Robert: laser ⊕ water jet

Cavitation, surface ripples

High-power target experiment



High-power target experiment

- Proposal to CERN ISOLDE/nTOF committee

  Studies of a target system for a
  4 MW, 24 GeV proton beam

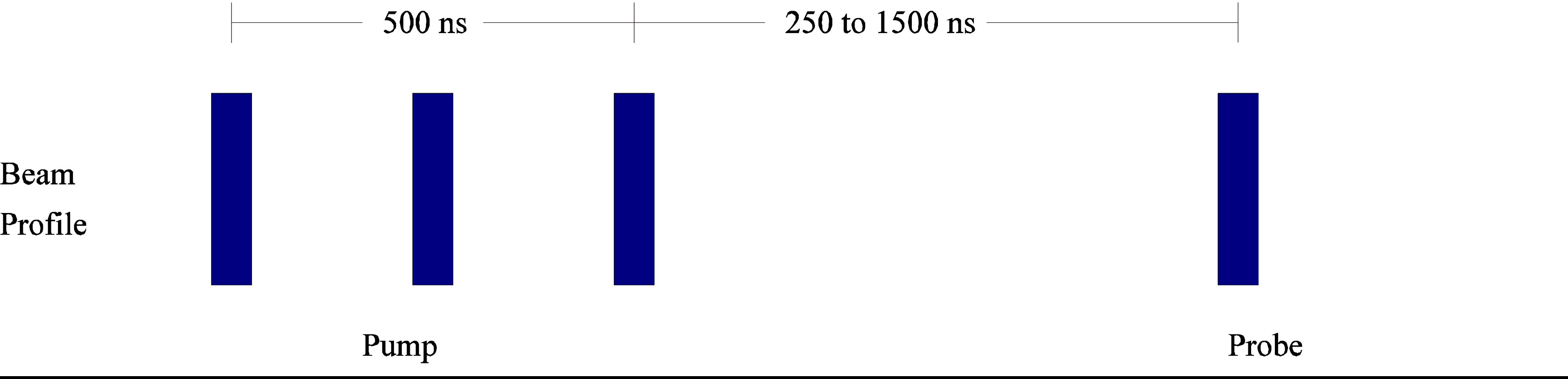
  Spokespersons: H.Kirk (BNL), K.McDonald (Princeton)

  APPROVED! MERIT (nTOF11)

- Participating institutes:
  - BNL, CERN, KEK, ORL, Princeton, RAL
- Mercury jet:
  - 1 cm diameter; 20 m/s
- PS delivers:
  - $10^{12} – 10^{13}$ protons per 2 μs spill in 4 bunches
  - Beam spot ~3 mm diameter

MERIT: objectives

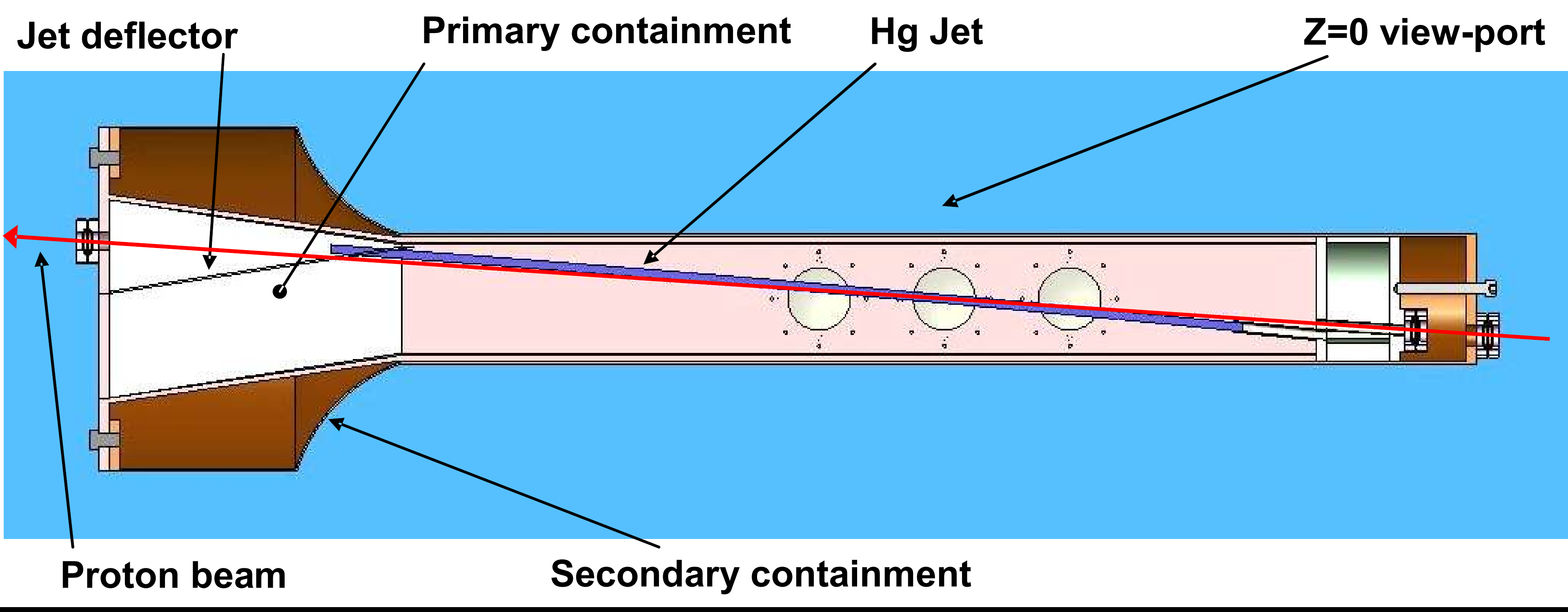
- Effect of increasing charge density:
  - 7×10^{12} – 28×10^{12} protons per spill
- Effect of magnetic field on jet dispersal:
  - 0 – 15 T
- Cavitation:



- 50 Hz operation

MERIT: preparations

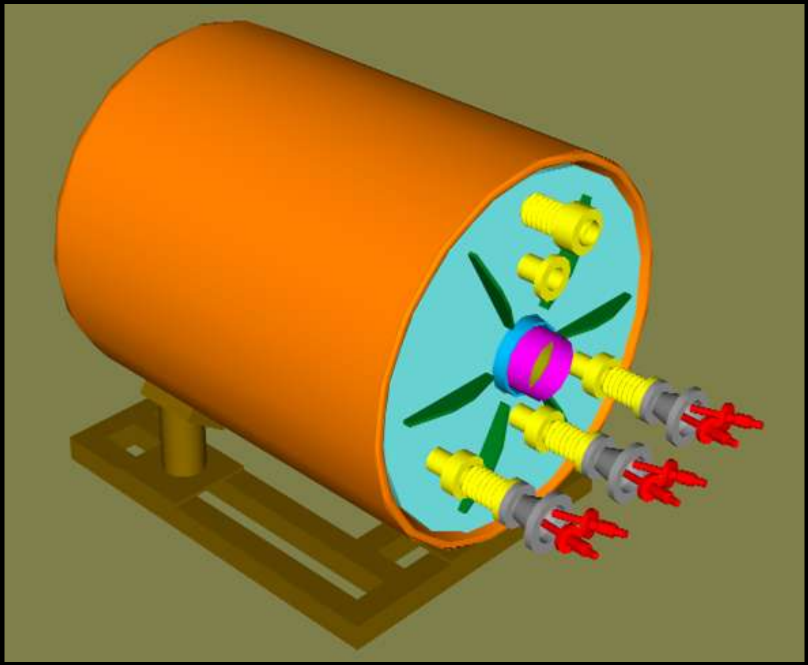
- Target:



- Viewing system under development
- Mercury pump system under development

MERIT: preparations

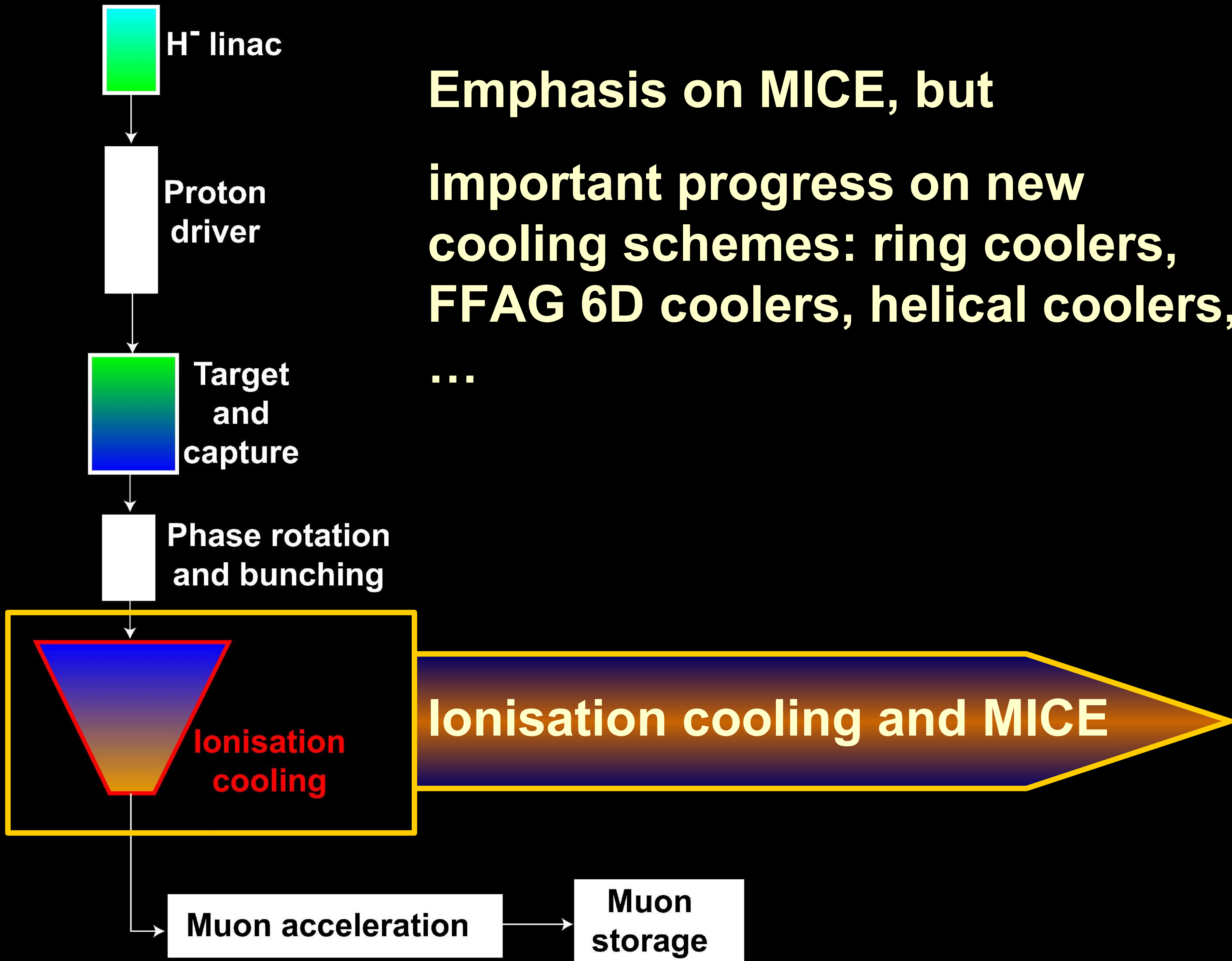
- Magnet:



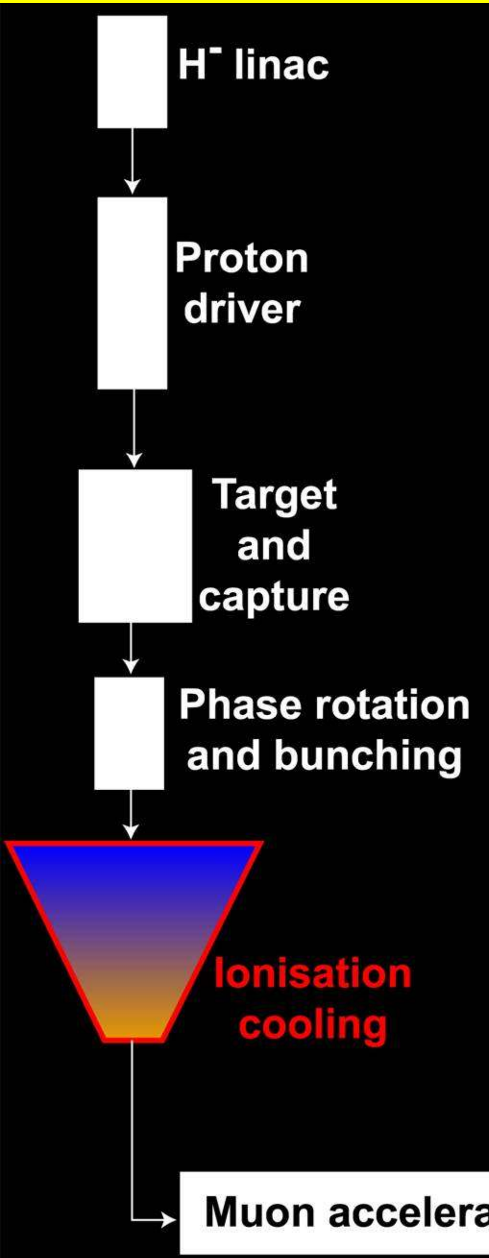
- LN_2 Operation
- 15 T (5.5 MW pulsed power)
- 15 cm warm bore
- 1 m long beam pipe

nTOF11: schedule

- **2005**
  - March — nToF11 approved
  - Spring — solenoid construction completed
  - Summer — solenoid tests
  - Winter — construction of Hg system
- **2006**
  - April — solenoid test finished
  - June — solenoid shipped to CERN
  - autumn — integrated test at CERN
  - December — fully ready for beam
- **2007**
  - April — final run at PS start-up


H⁻ linac
Proton driver
Target and capture
Phase rotation and bunching
Ionisation cooling
Muon acceleration
Muon storage
Emphasis on MICE, but
important progress on new cooling schemes: ring coolers, FFAG 6D coolers, helical coolers, …
Ionisation cooling and MICE

Cooling and the Neutrino Factory

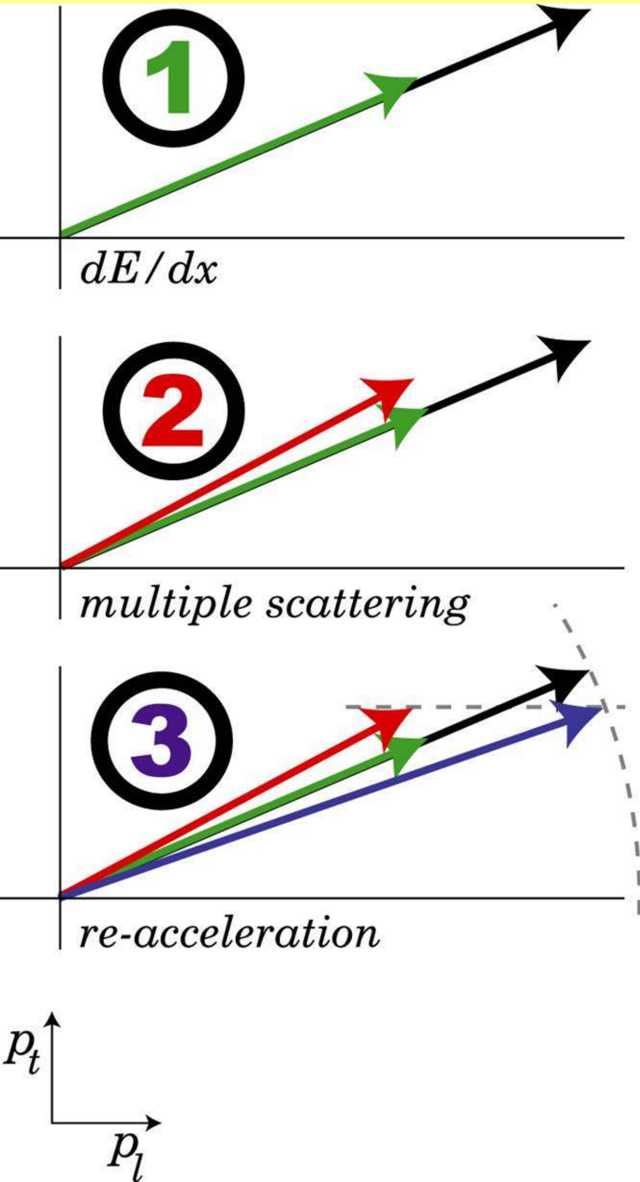


Ionisation cooling survey

Design	Number of cooling cells	Gain factor	Cooling per cell (%)	Comment
US Study II	26	6	7	Increase in phase-space density in acceptance of downstream accelertor
US Study IIa	26	2	2	Increased acceptance in muon acceleration section; use of FFAGS. Lithium-hydride absorber.
CERN	36	10	7	Increase in muon yield at 2 GeV over optimised NF without cooling
Japan	-	> 1.5 - 2		Acceleration based on FFAGs. Performance improvement may be possible with cooling. Possible transverse and longitudinal cooling using FFAGs.

Ionisation cooling

Principle



Practice

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 collaboration

Universite Catholique de Louvain **Belgium**

INFN: Bari, Frascati, Genova, Legnaro, Milano, Napoli, Padova, Trieste
ROMA TRE university, **Italy**

KEK, Osaka University **Japan**

NIKHEF **The Netherlands**

CERN

Geneva, PSI **Switzerland**

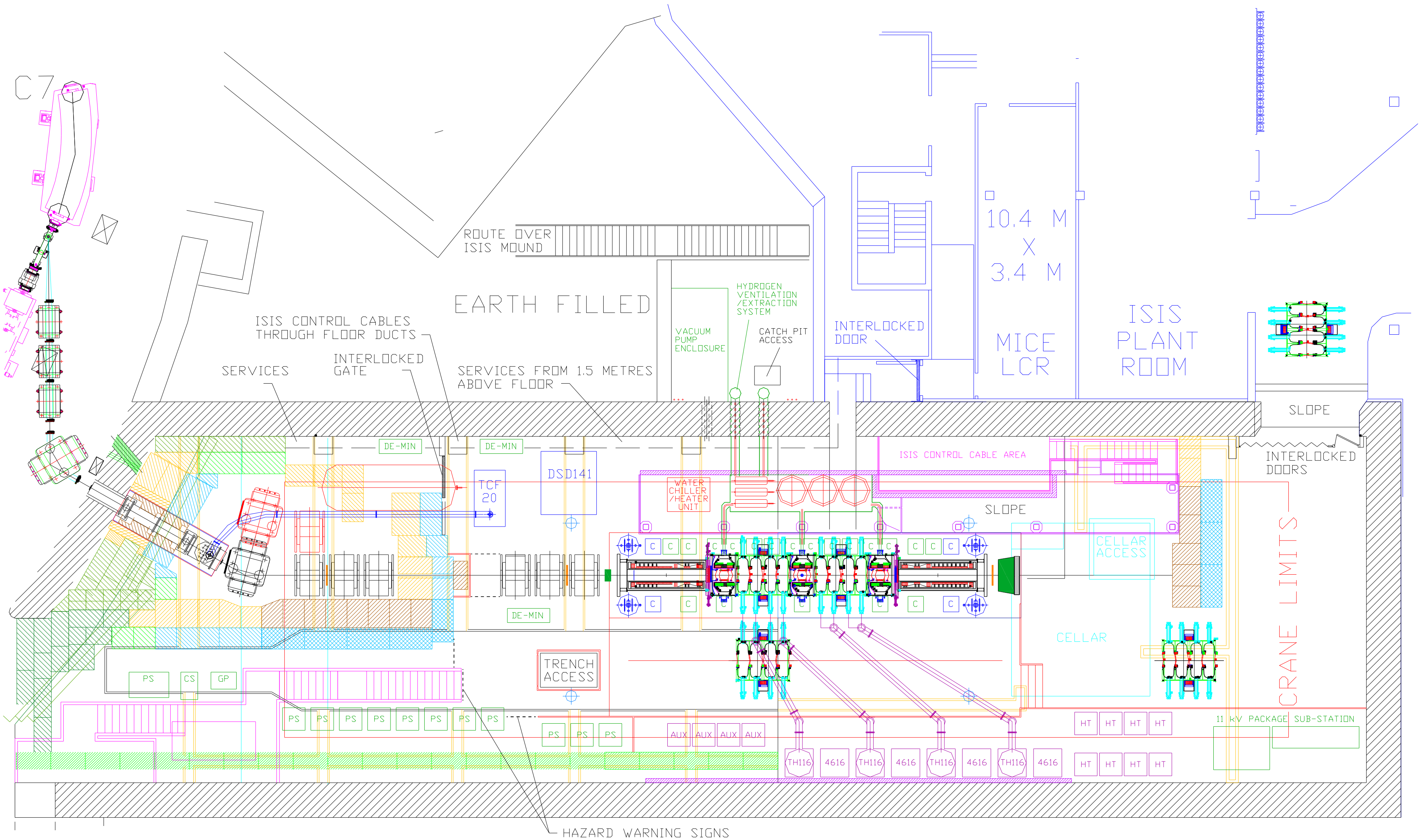
Brunel, Edinburgh, Glasgow, Liverpool, Imperial, Oxford, RAL,
Sheffield **UK**

ANL, BNL, FNAL, JLab, LBNL,
Universities of Fairfield, Chicago, UCLA Physics, Northern Illinois,
Iowa, Mississippi, UC Riverside, Illinois-UC
Enrico Fermi Institute, Illinois Institute of Technology **USA**

THE MICE COLLABORATION
3 continents
7 countries
40 institute members
140 individual members
- Engineers & physicists (part. & accel.)

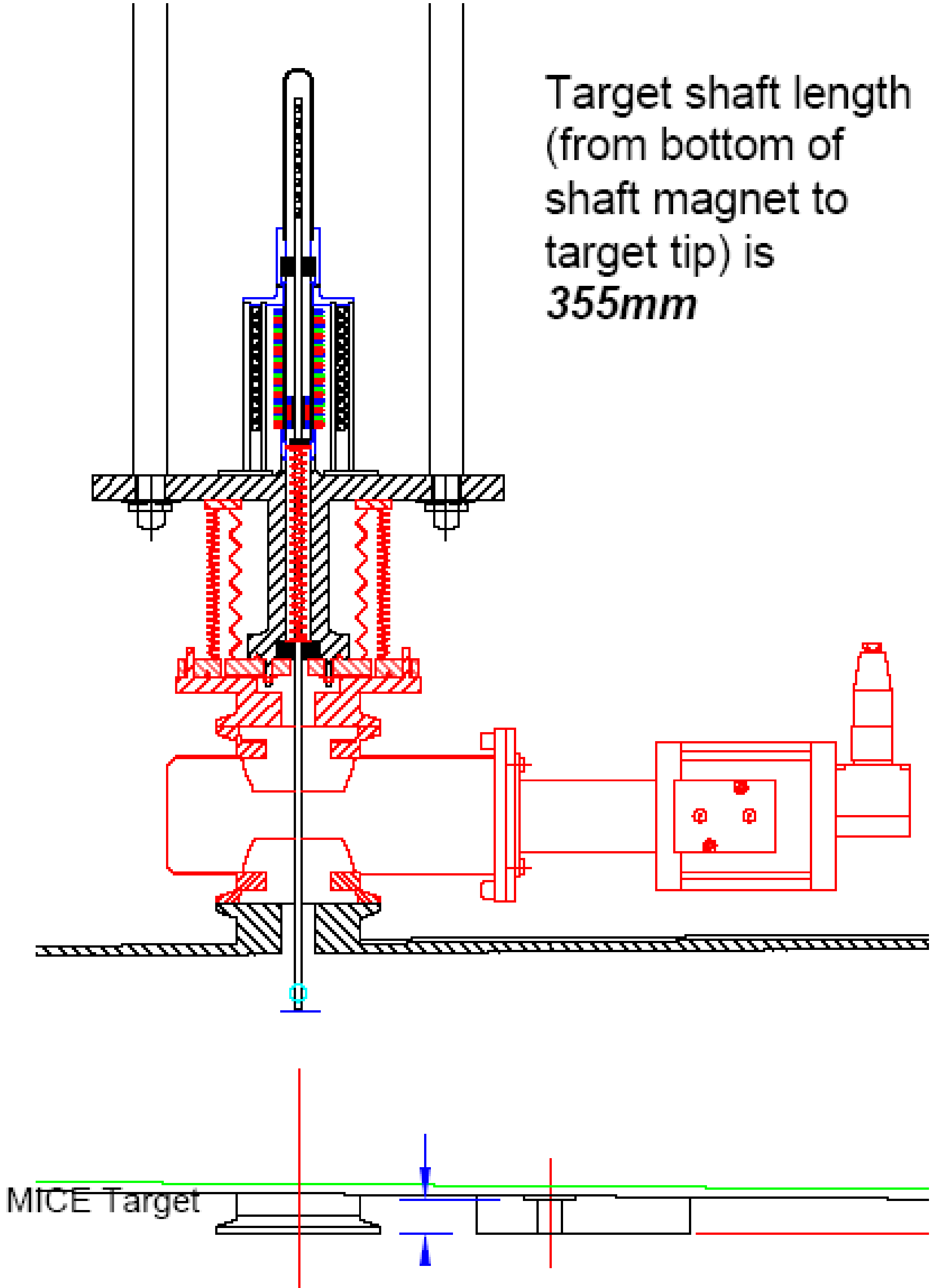
Spokesman:	**A.Blondel (GVA)**
Deputy:	**M.Zisman (LBNL)**
Proj. Man.:	**P.Drumm (RAL)**

MICE on ISIS at RAL



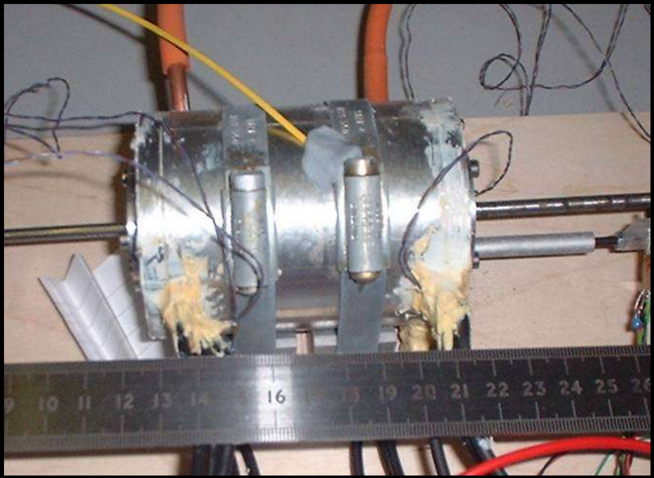
MICE Target

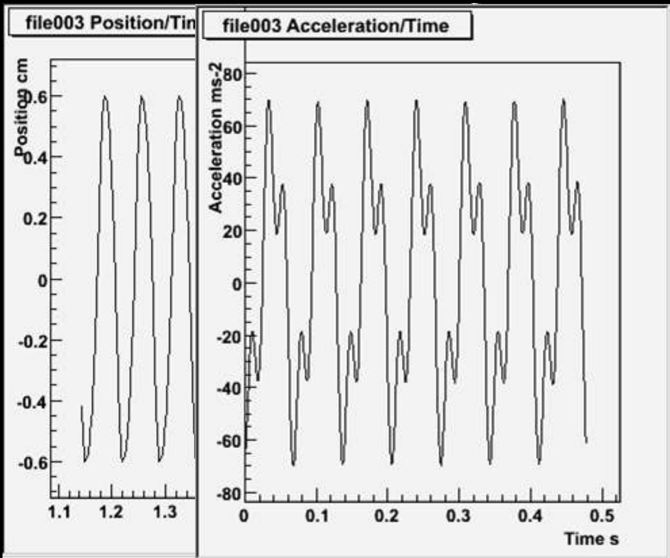
- **Concept:**
  - **Target dips into halo of ISIS beam**
    - **On demand**
    - **1 – 3 Hz operation**
- **Engineering:**
  - **Require to separate vacuum surrounding target mechanism from ISIS machine vacuum**



MICE Muon Beam: target

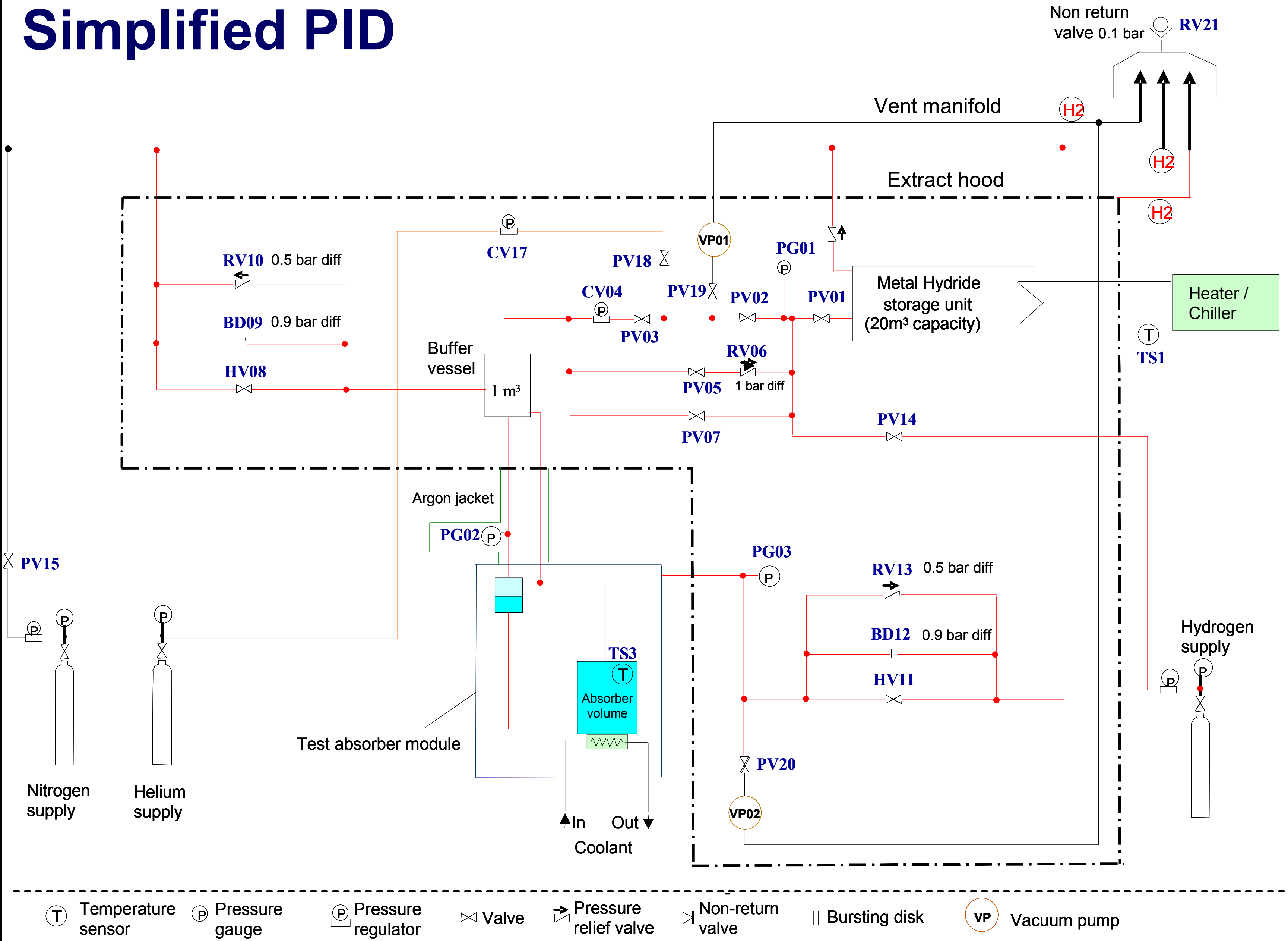
- **Pre-prototype:**
  - Gain experience with construction and operation



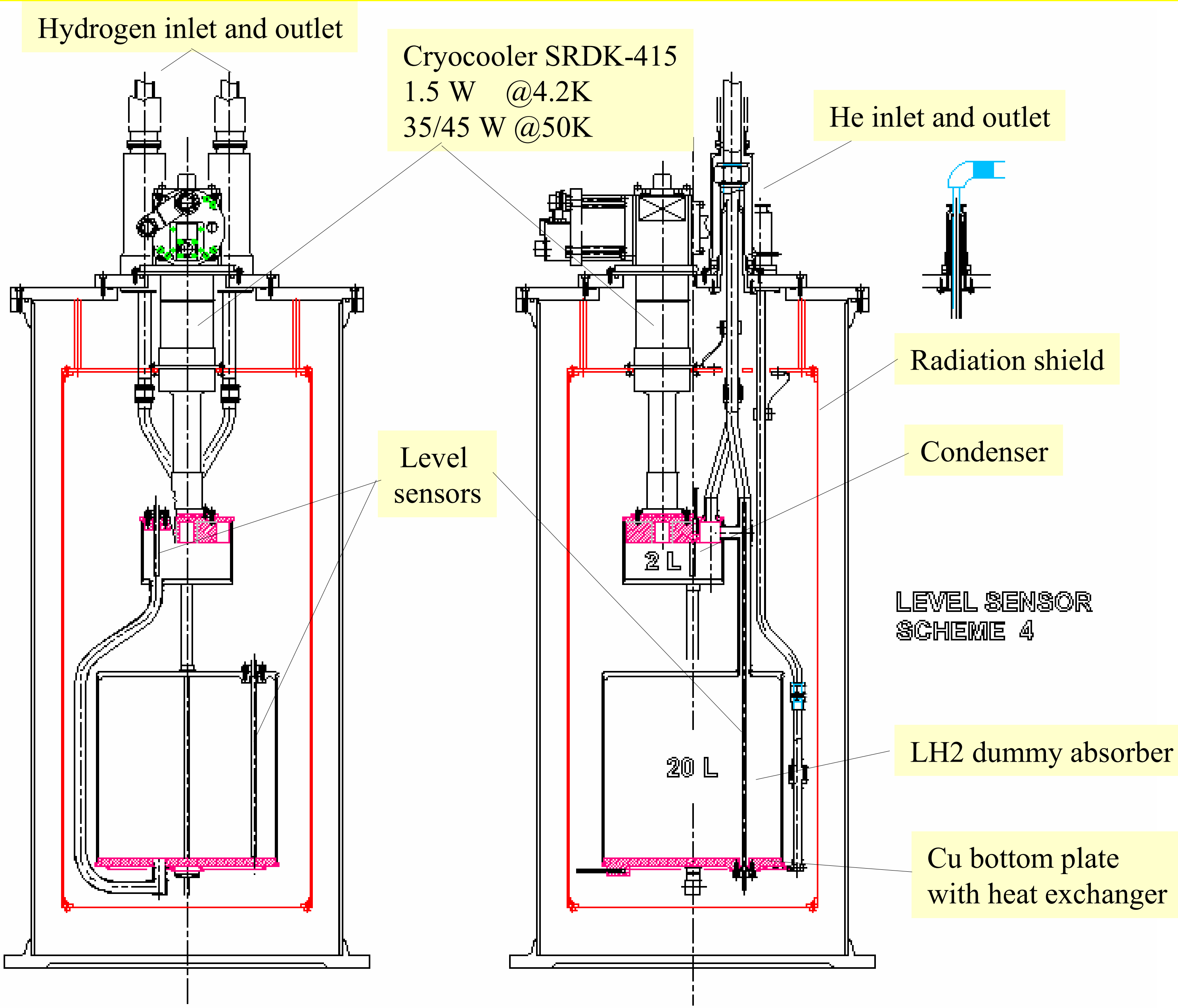


MICE Hall: hydrogen-system R&D

Simplified PID

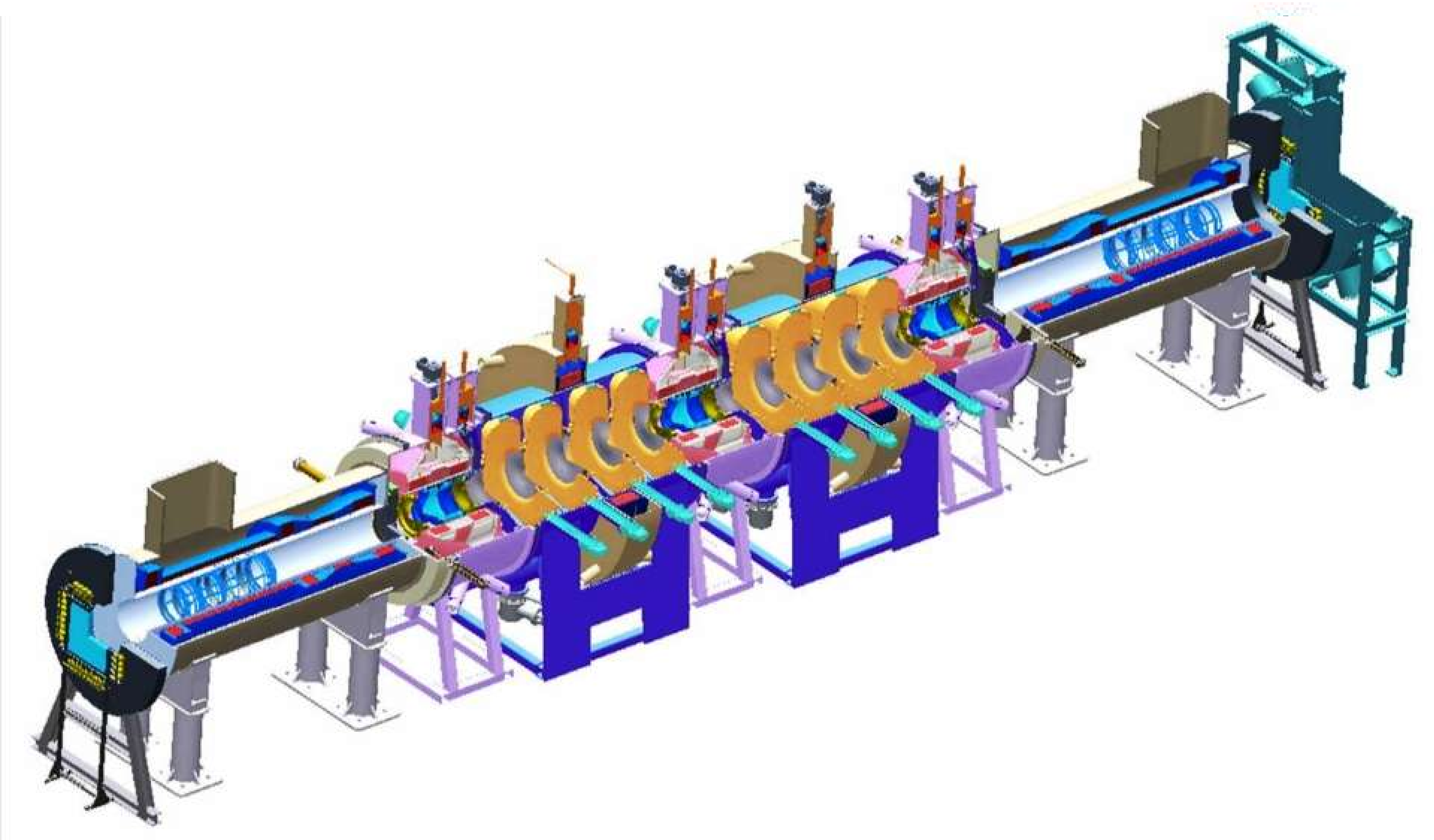


MICE Hall: hydrogen-system R&D



Dummy absorber and cryostat

Muon Ionisation Cooling Experiment



MICE: cooling performance

- **Transverse emittance:**

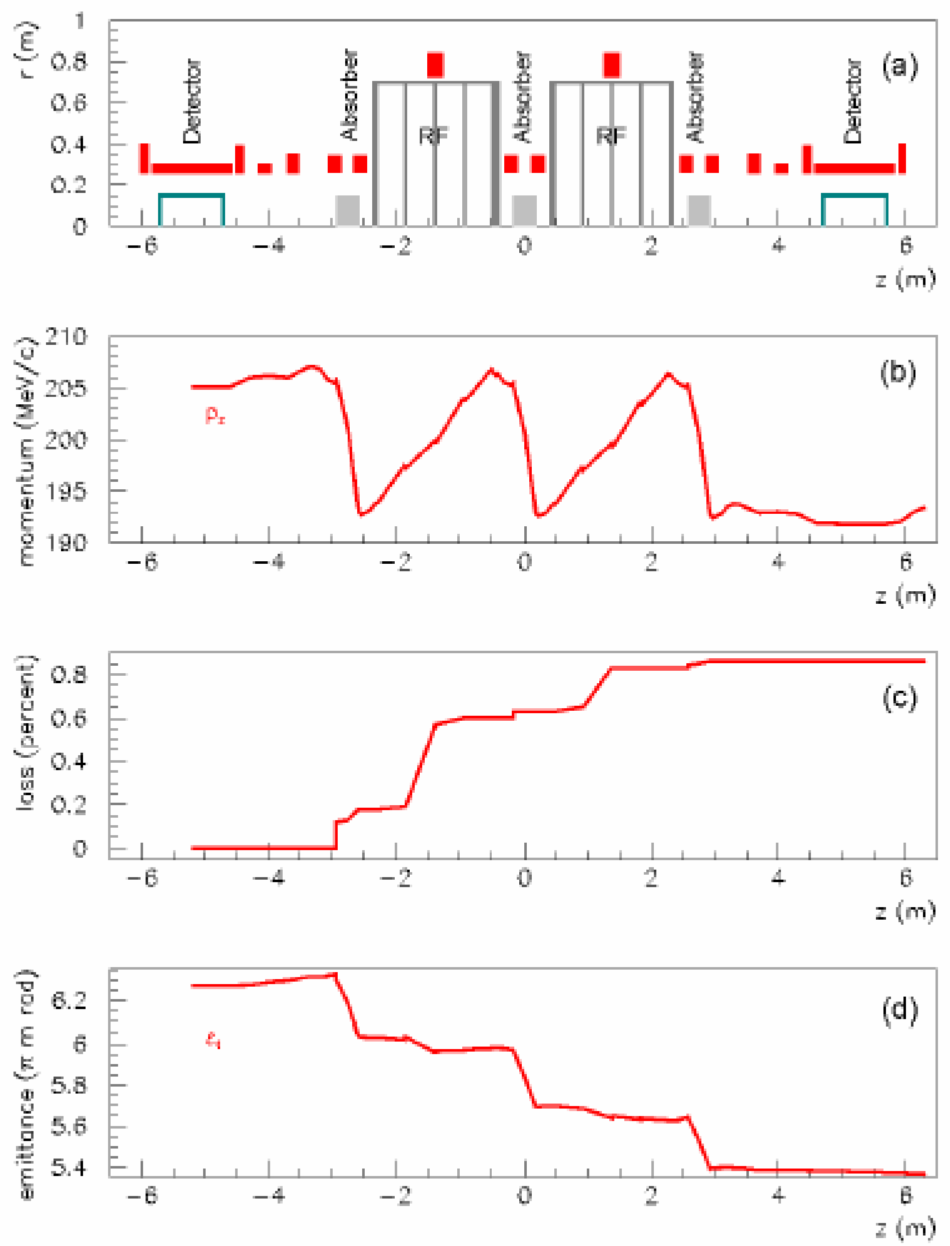
$$\varepsilon_T = \frac{1}{m_\mu}\sqrt[4]{V}$$

- **Cooling effect:**
  - Cooling term
  - Heating term

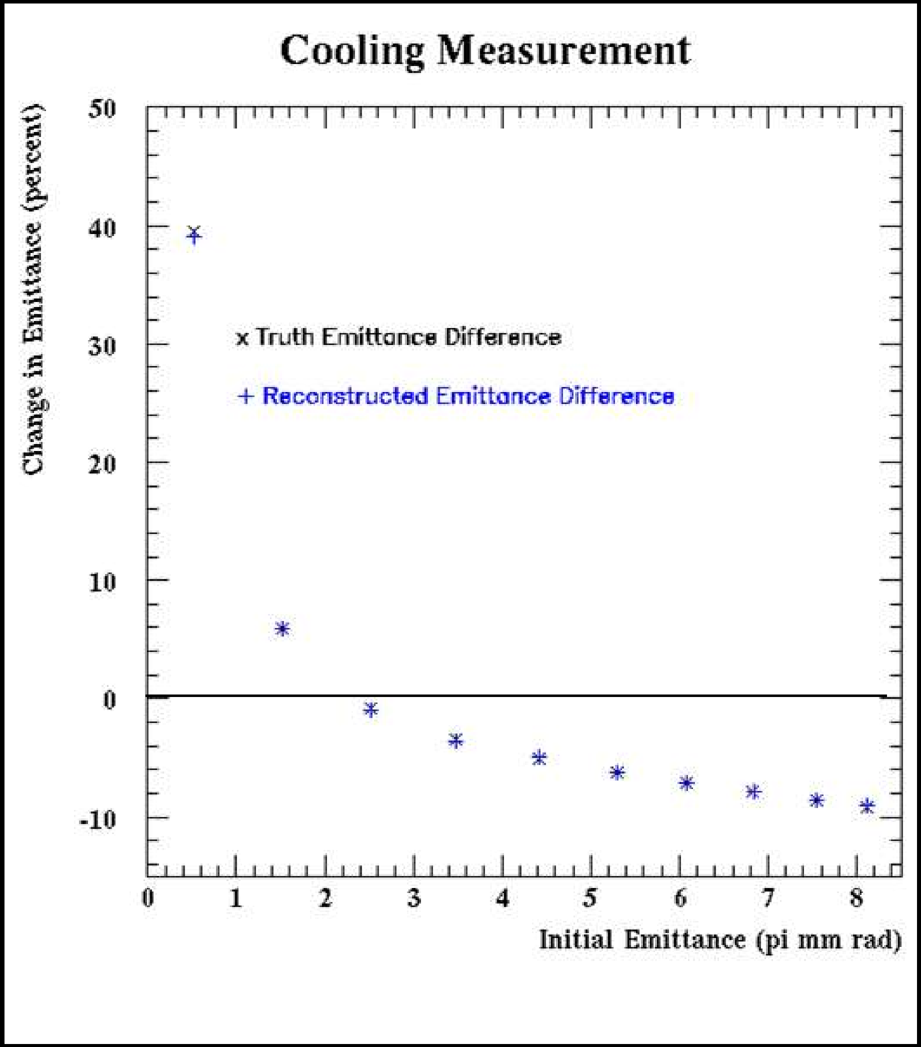
$$\frac{d\varepsilon_T}{dz} = \frac{-\varepsilon_T}{\beta^2 E}\left\langle\frac{dE}{dz}\right\rangle + \frac{\beta_T(0.014\,\mathrm{GeV})^2}{2\beta^3 E m_\mu X_0}$$

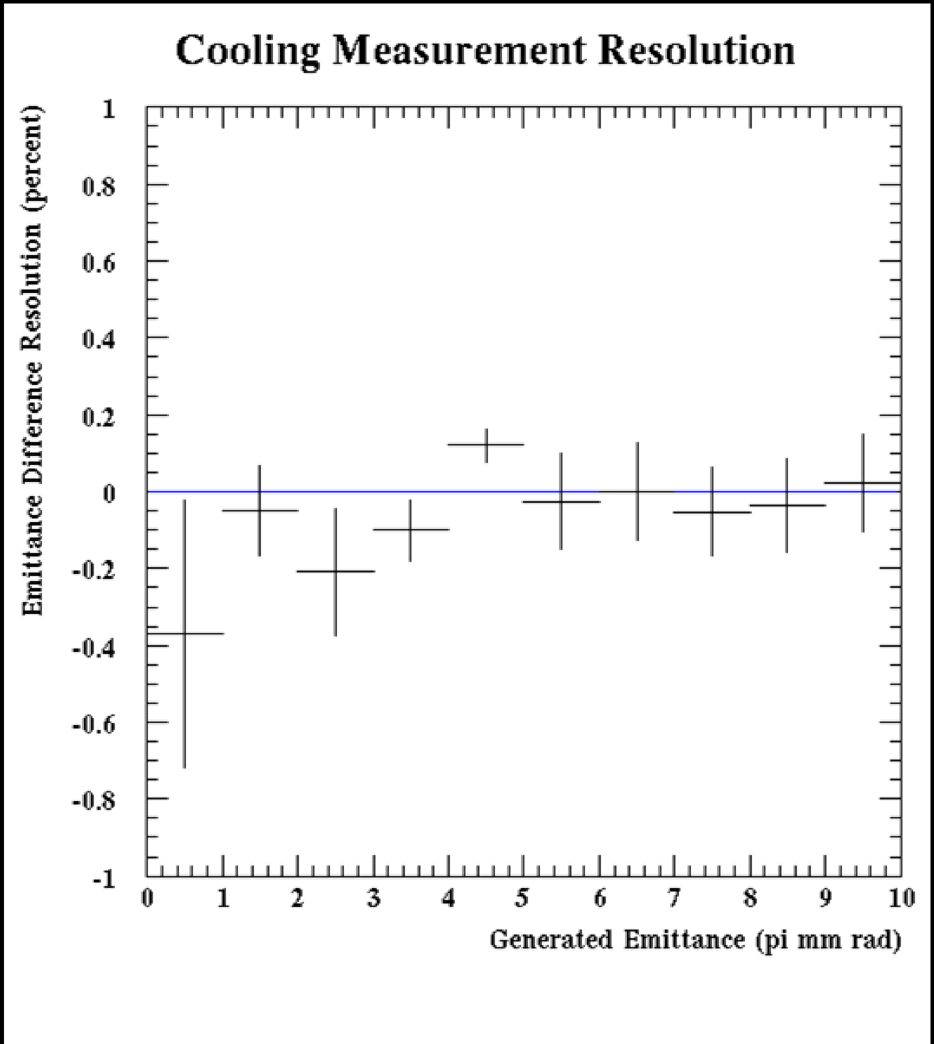
- **For MICE:**
  - Liquid hydrogen only:

Initial emittance 6π mm	Final emittance πmm	%
One absorber	5.7	94.9
Full MICE	5.1	84.6



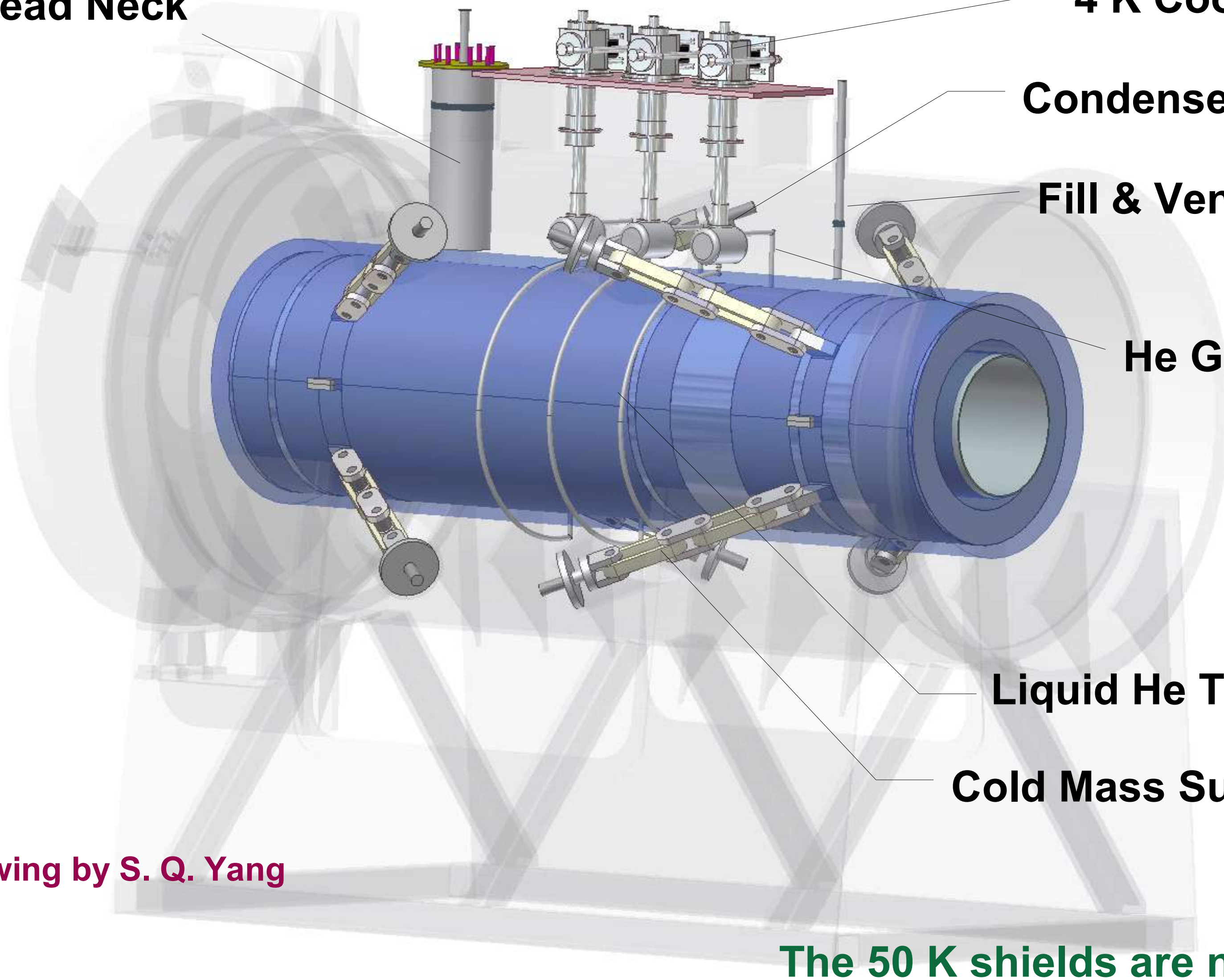
Cooling Measurement





Spectrometer: solenoid

LBNL



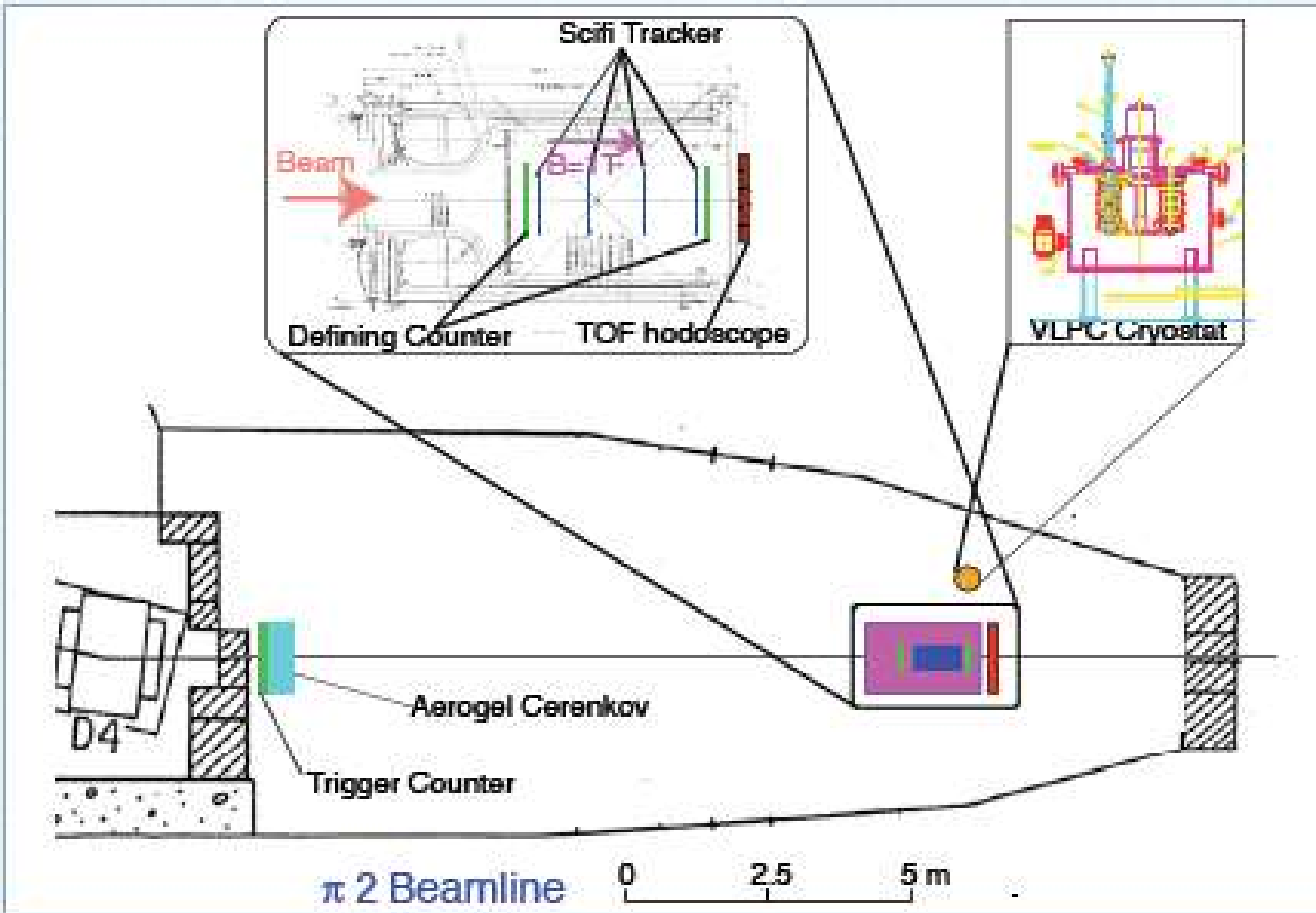
Drawing by S. Q. Yang

The 50 K shields are not shown.

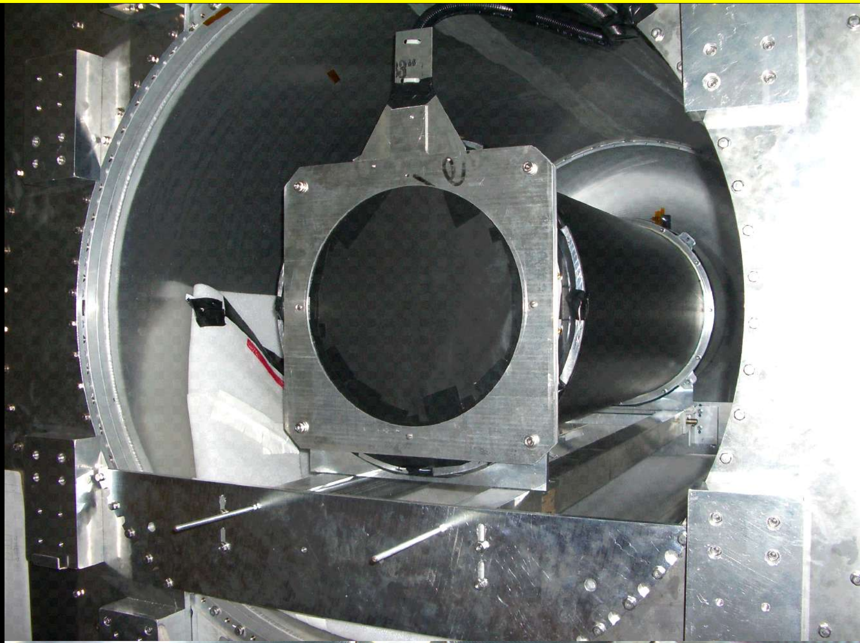
Spectrometer: tracker

- KEK test: 30Sep05 – 07Oct05

Brunel, Edinb'gh, FNAL, Gva, IIT, Imperial, KEK, Liverpool, Osaka, Riverside, UCLA



Spectrometer: tracker

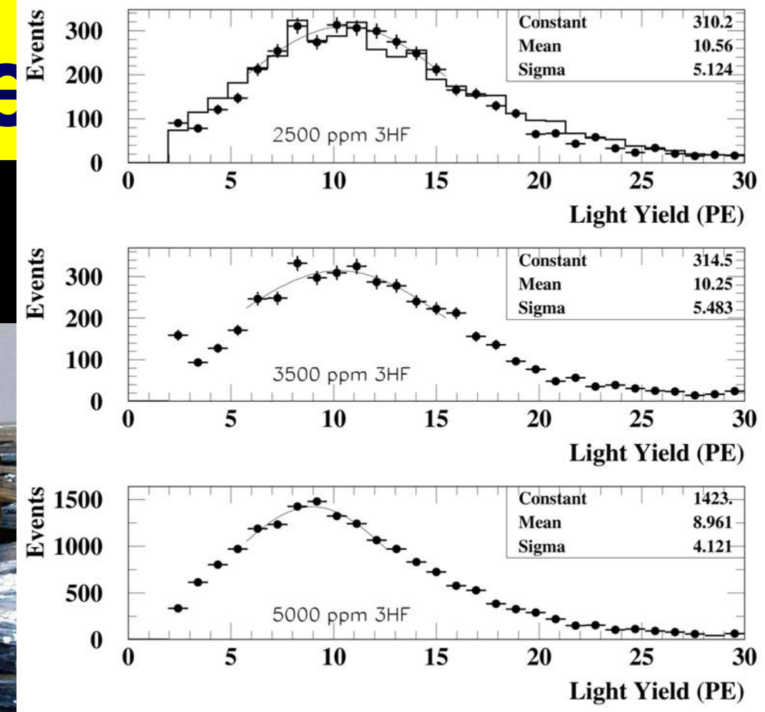


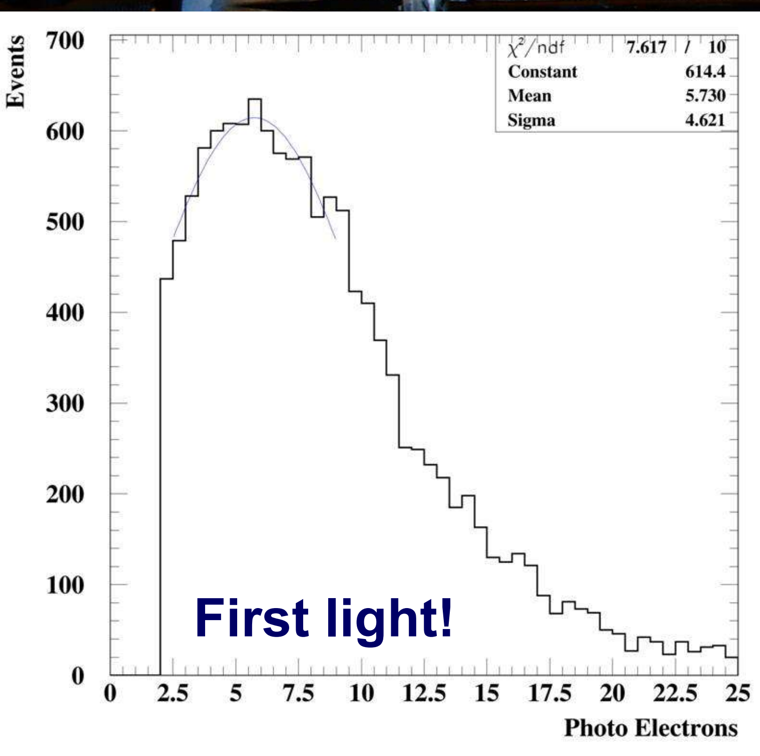
Spectrometer: tracker; electronics

- Two VLPC cassettes borrowed from D∅
- Prototype AFE II boards borrowed from D∅
  - Some MICE specific interface boards
- Cryostat design/built for MICE
  - Cryocooler for refrigeration
- Commissioning of AFE II – FNAL experts:
  - Require expertise in tracker team

Spectrometer: tracke

- Prototypes:

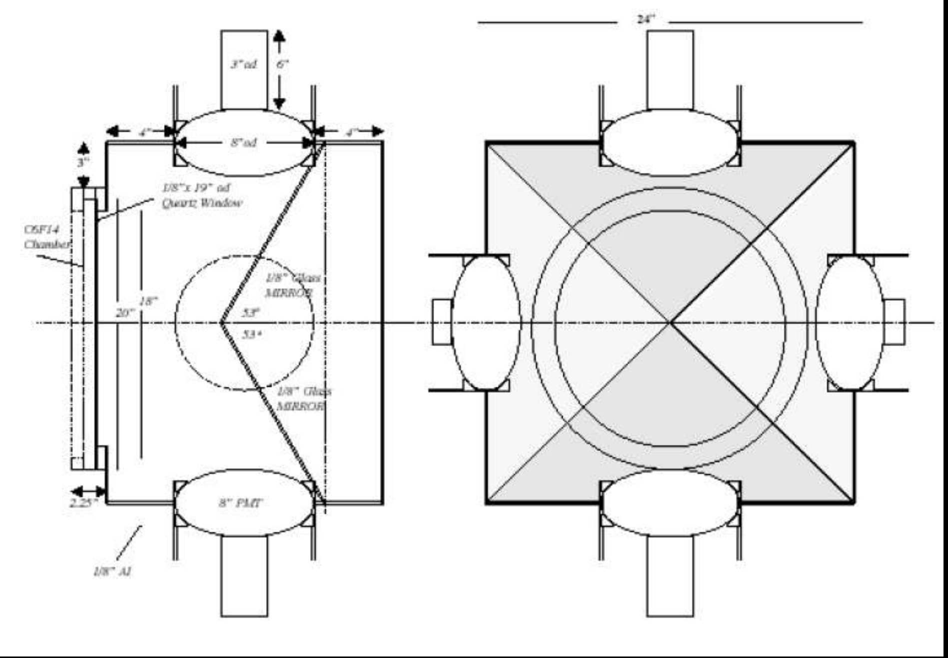


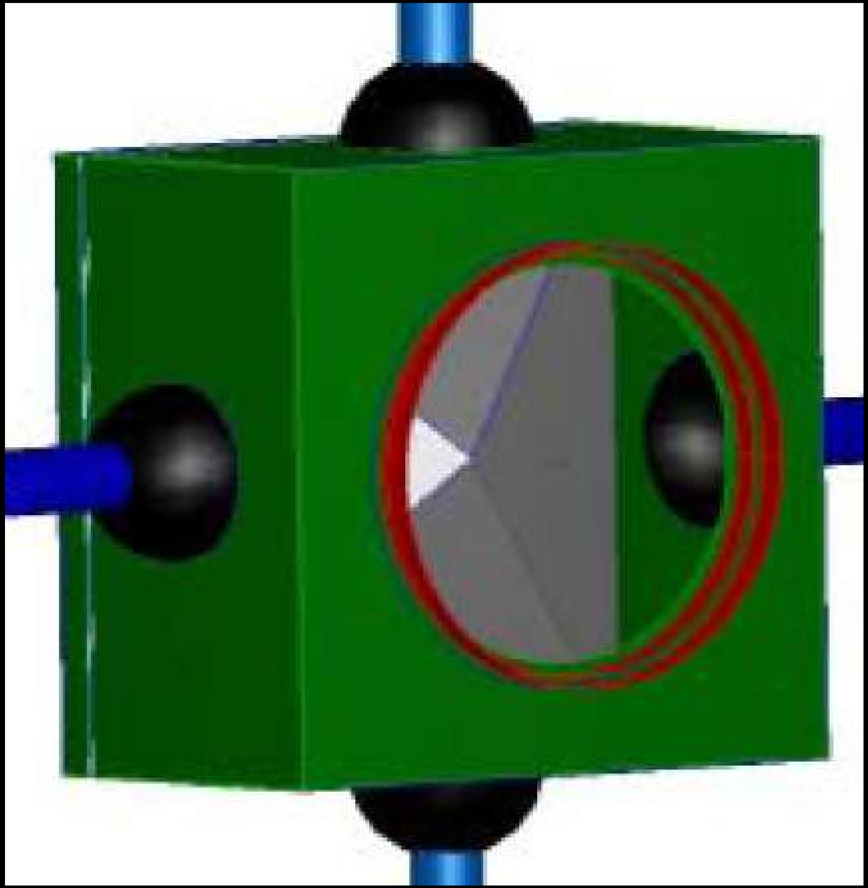


Upstream Cherenkov

Mississippi

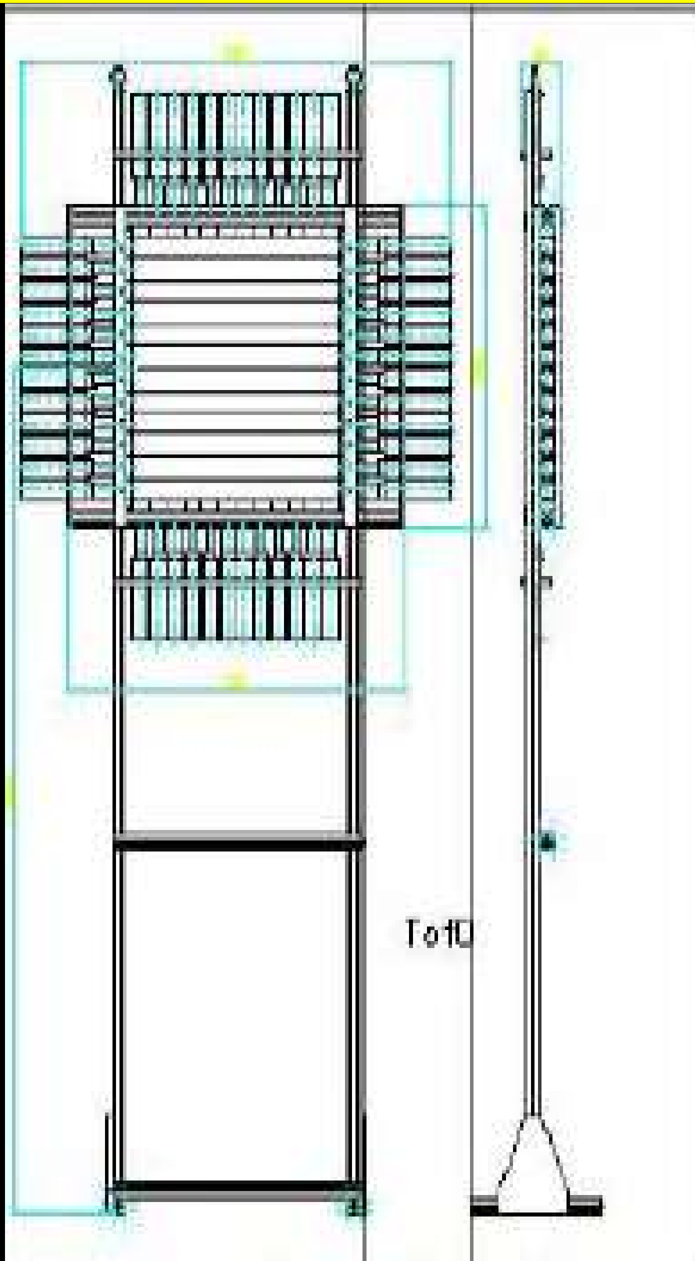
- Upstream Ckov
  - C_6F_{14} radiator with n=1.25
  - 4 PMTs
    - 2 on top, 2 on bottom.
  - Threshold cherenkov:
    - 0.7 MeV for electrons
    - 140 MeV for muons
    - 190 MeV for pions





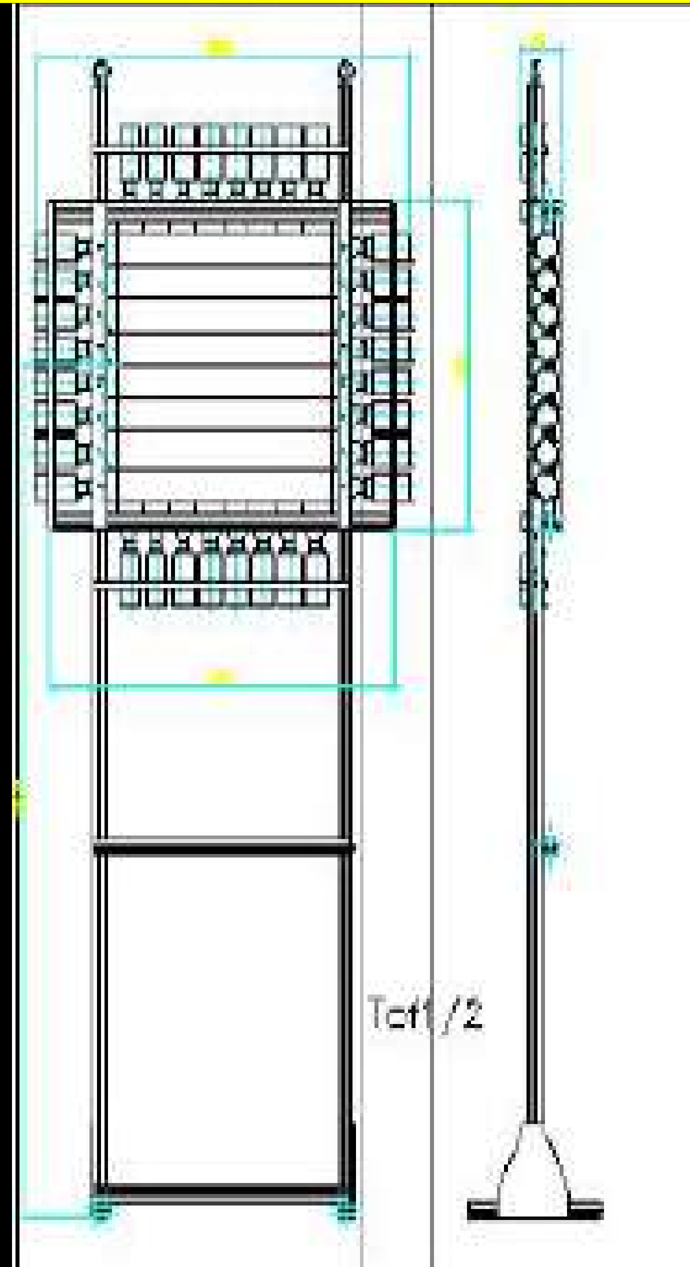
Time-of-flight/trigger

Milan/Pavia



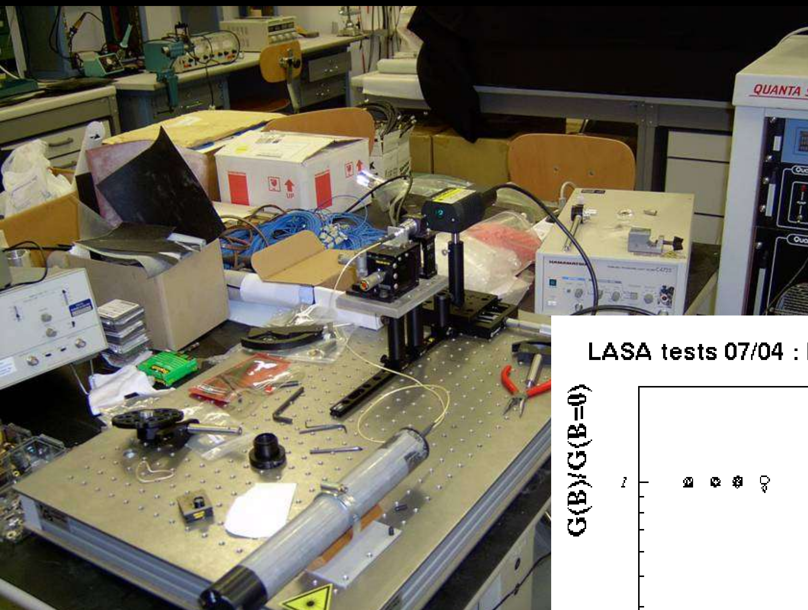
R4998 TOF0

fine mesh R7761 TOF I & II

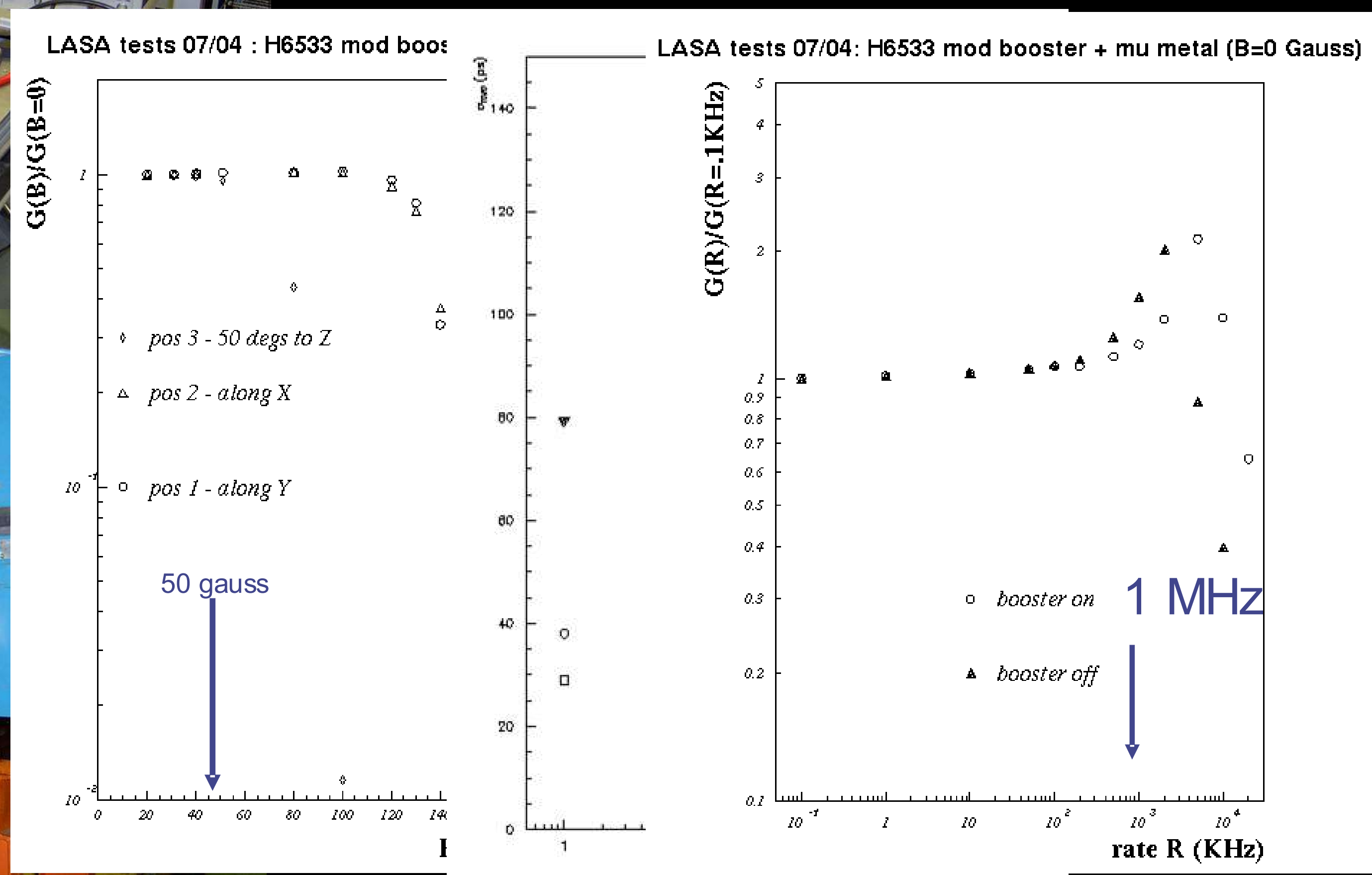


ToF/trigger

- Prototype development/performance tests

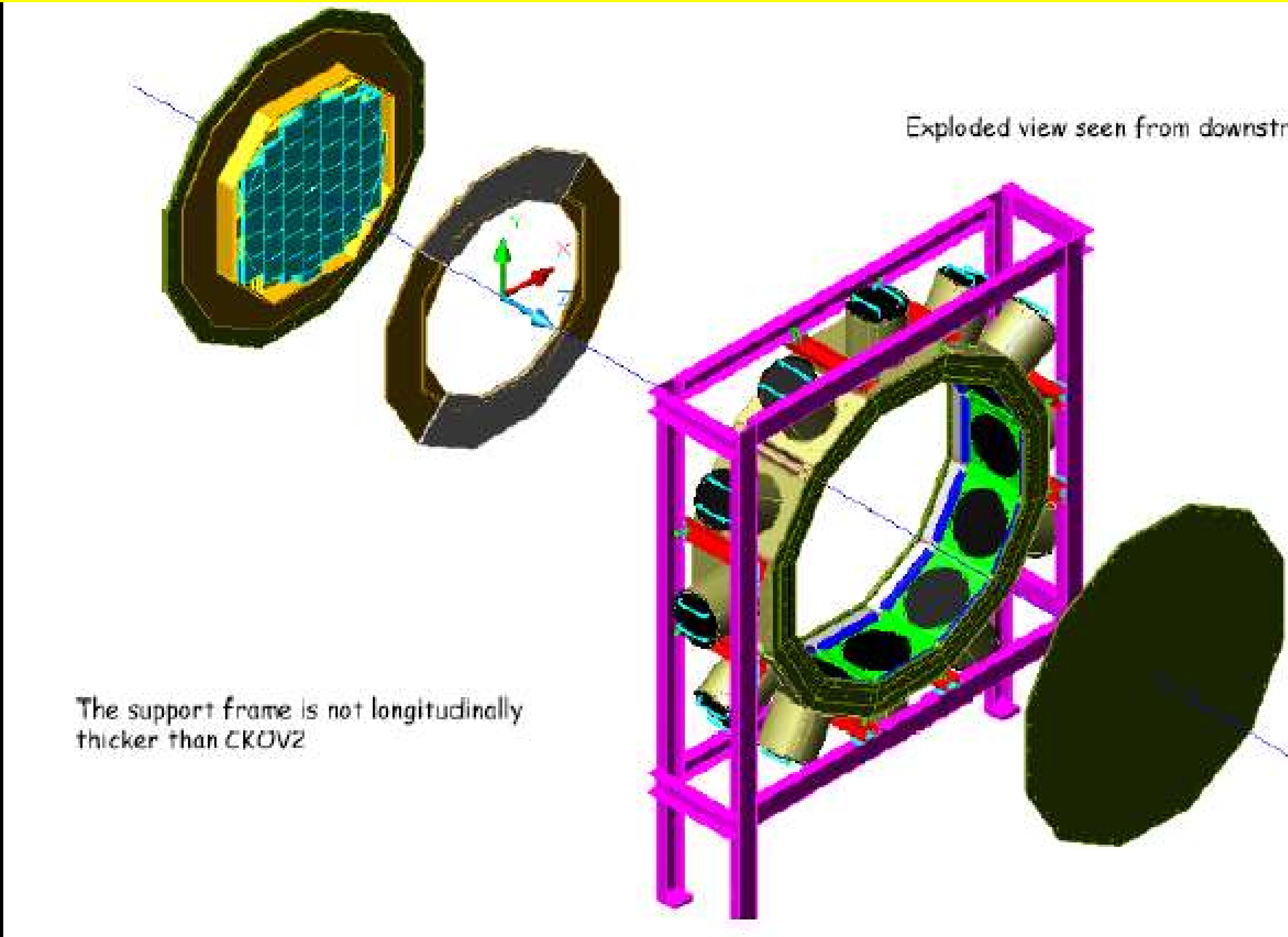


- Issues:
  - Rate (especially ToF0)
  - Operation in magnetic field



Downstream Cherenkov

Louvain

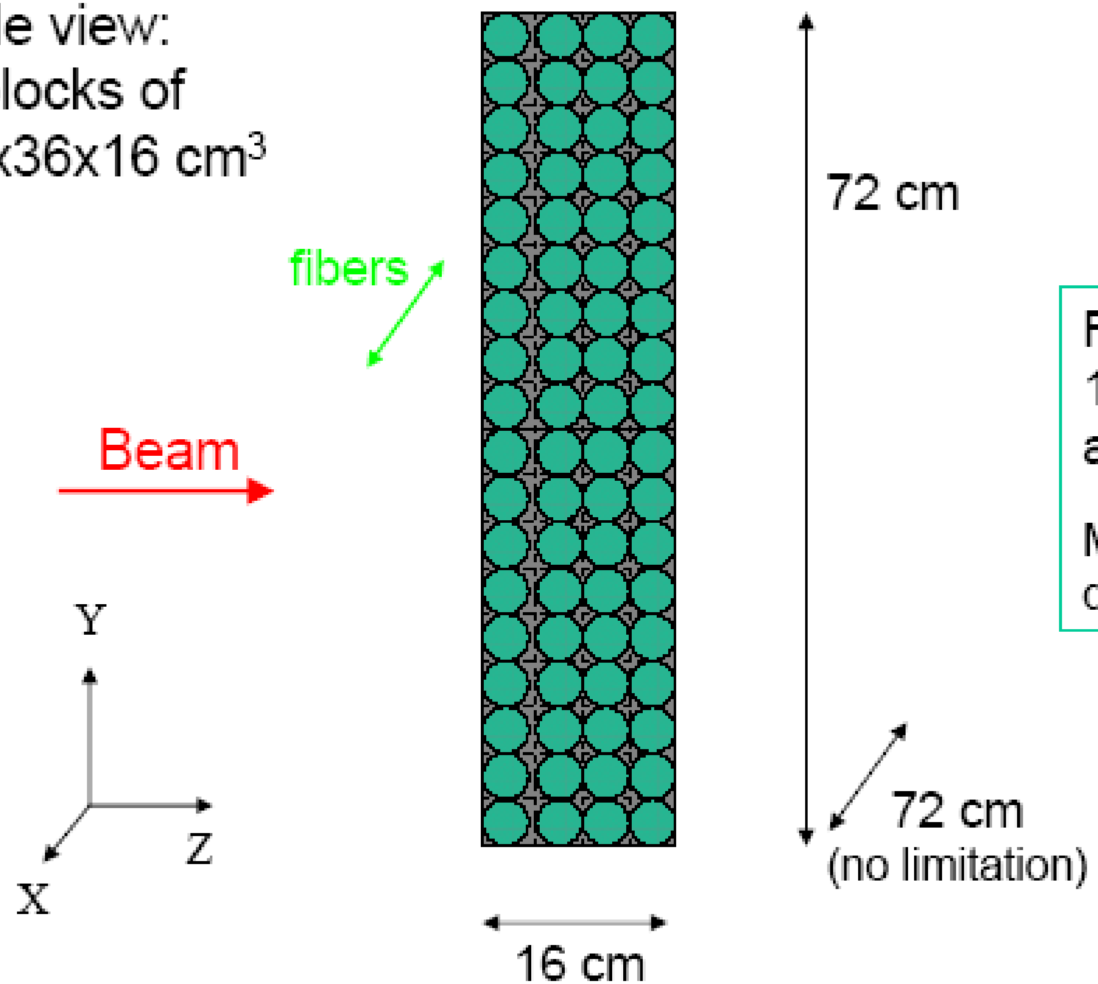


Muon calorimeter:

- **Task: μ/e separation** **Rome III, Trieste**

Scintillating fibers embedded in grooved lead layers

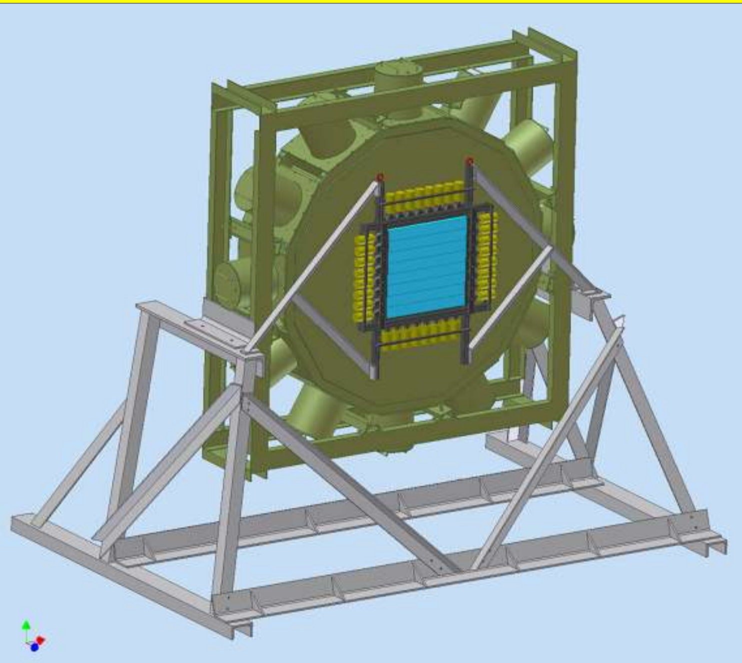
Side view:
2 blocks of
$72 \times 36 \times 16\ cm^3$

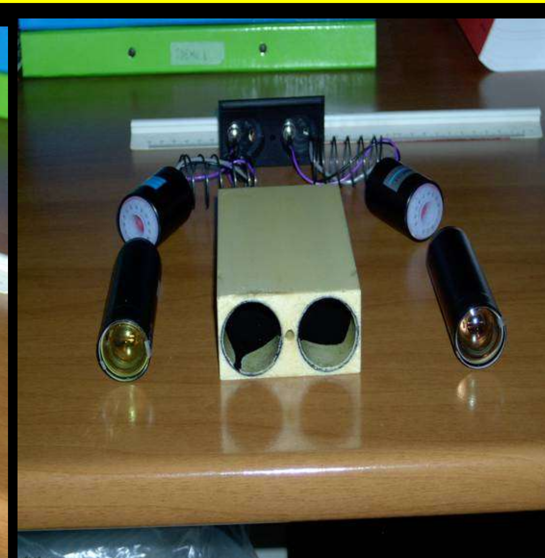


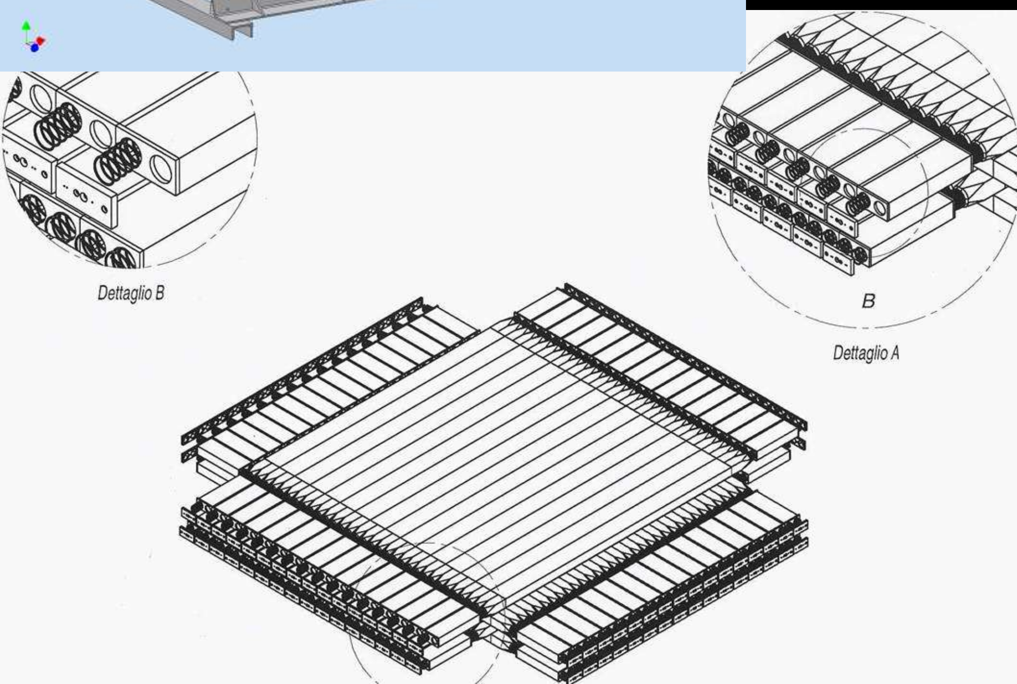
Readout:
18 PMTs per layer
at both ends

Minimum cell size $4 \times 4 cm^2$
due to PMT support

Muon calorimeter: development

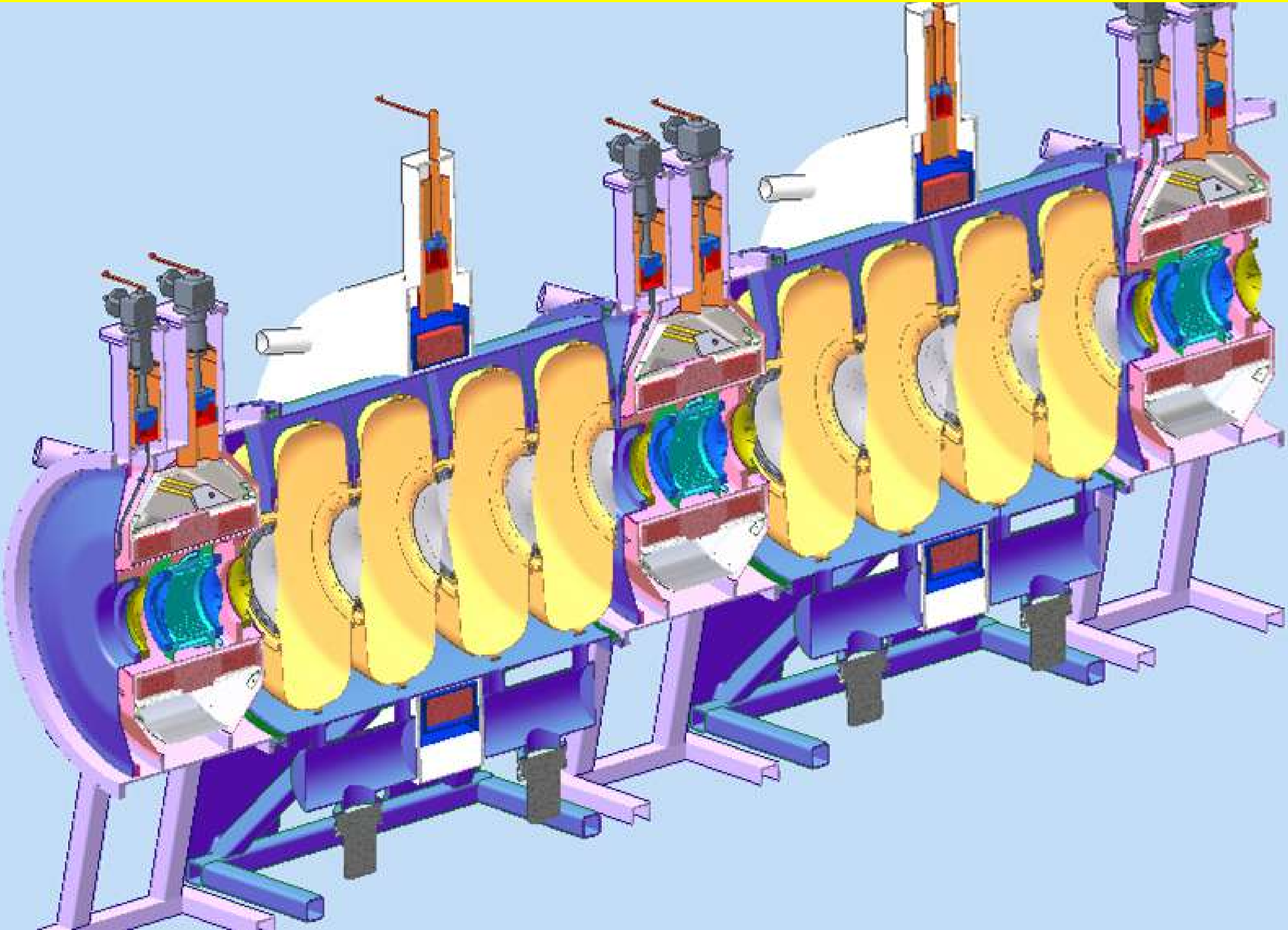




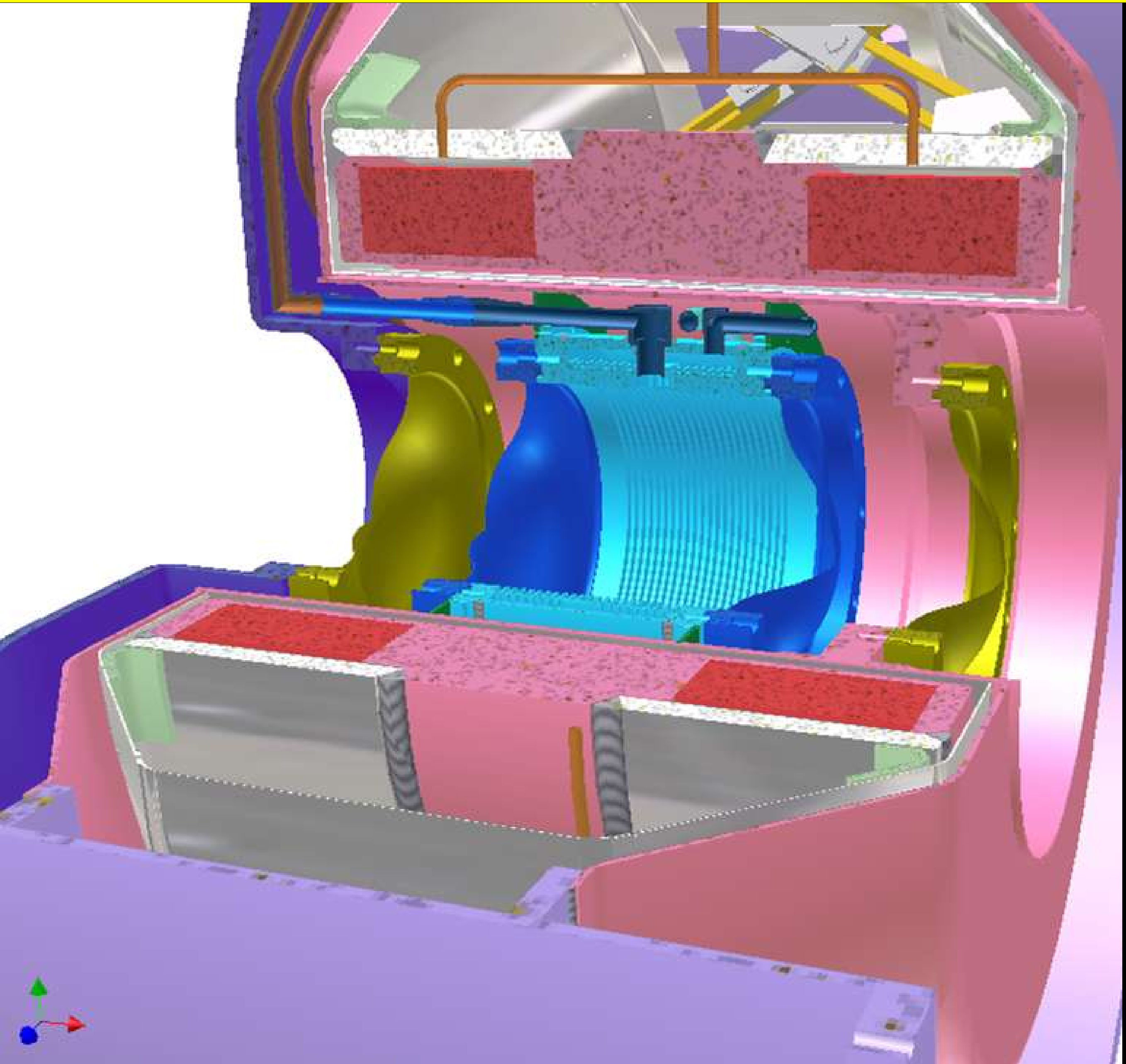


- Base line design complete
- Testing of components underway

MICE: cooling channel



Focus-coil module:



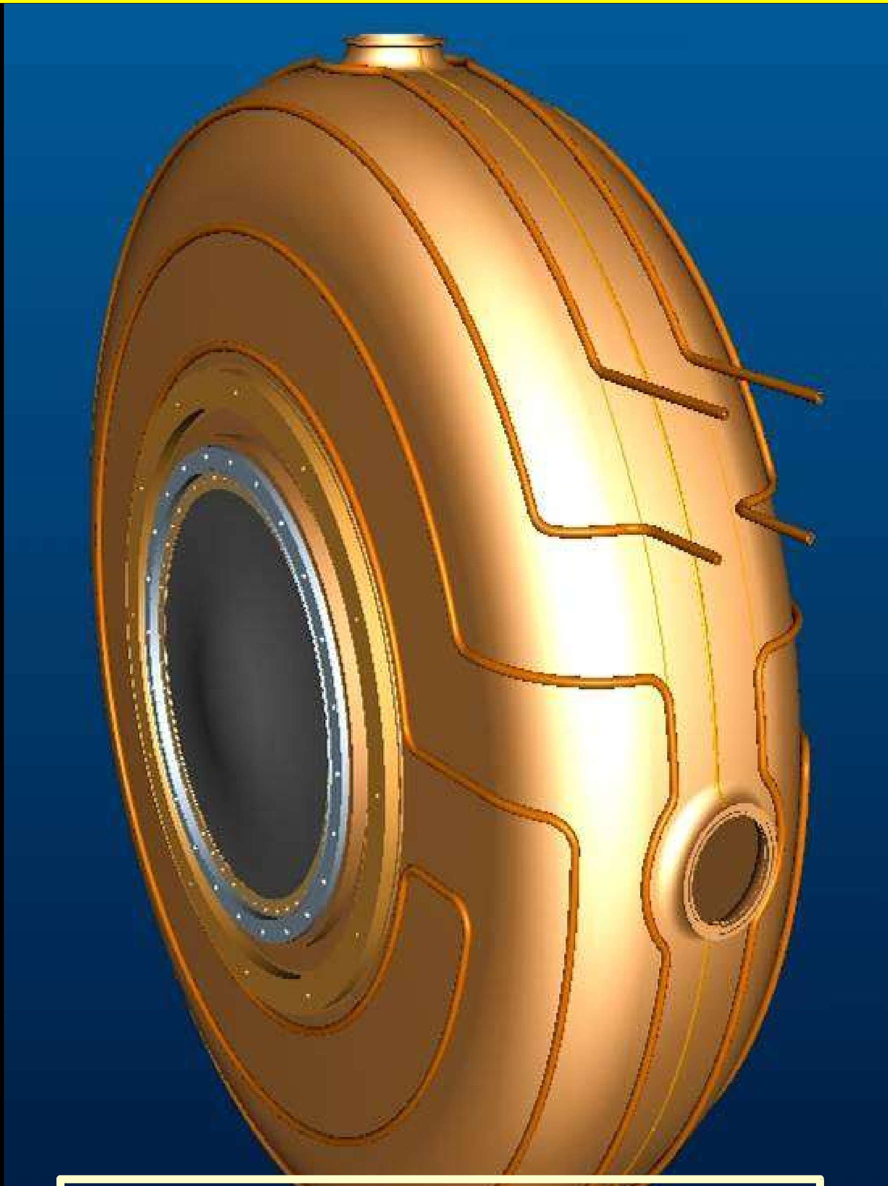
- Focus-coils:
  - 5 T
  - Field flip (focus)
  - Conceptual & now detailed design of magnets
  - Safety analysis

KEK, IIT, FNAL, RAL, Oxford, Missippi

201 MHz Cavity Ingredients

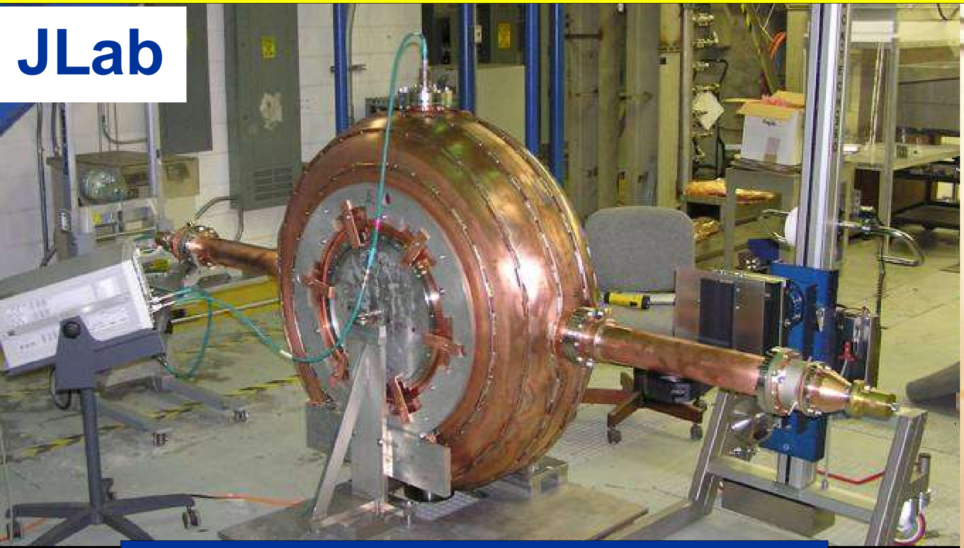
LBNL

- Cavity body + water cooling lines
- Ports and flanges
- RF loop couplers
- Cavity support structure
- Cavity tuners
- Ceramic RF windows (~4”)
- Curved Be windows
- MICE specifics
  - Tuners
  - Integration
    - joints and flanges
  - Possible LN_2 operation



Layout of cooling lines

Cavity prototype: MuCool

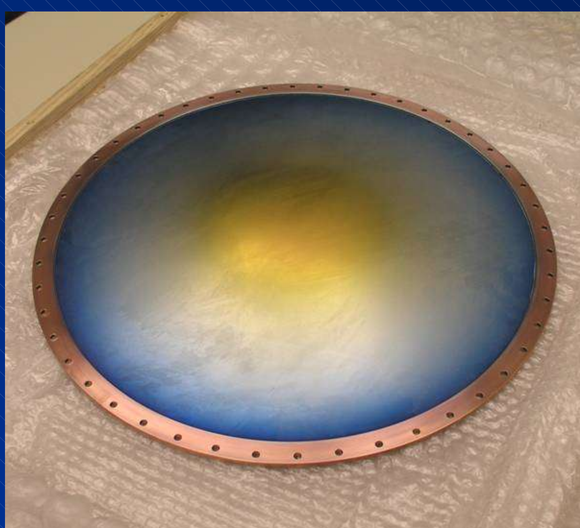


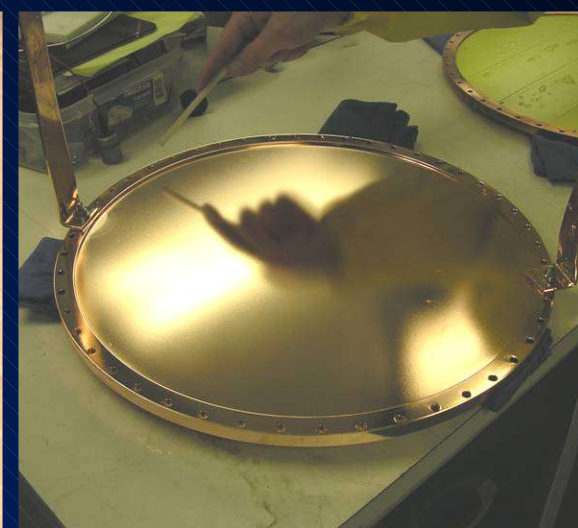
- ✓ E-beam welding
- ✓ Ports
- ✓ Water cooling lines
- Couplers assembled first time (mid-April-2005)
- First low power measurement
  - frequency ~ 199.5 MHz
  - coupling ~ 5 (max)
  - Q ~ 5000

- **Now, preparing to condition in MTA at FNAL**

Curved Be windows

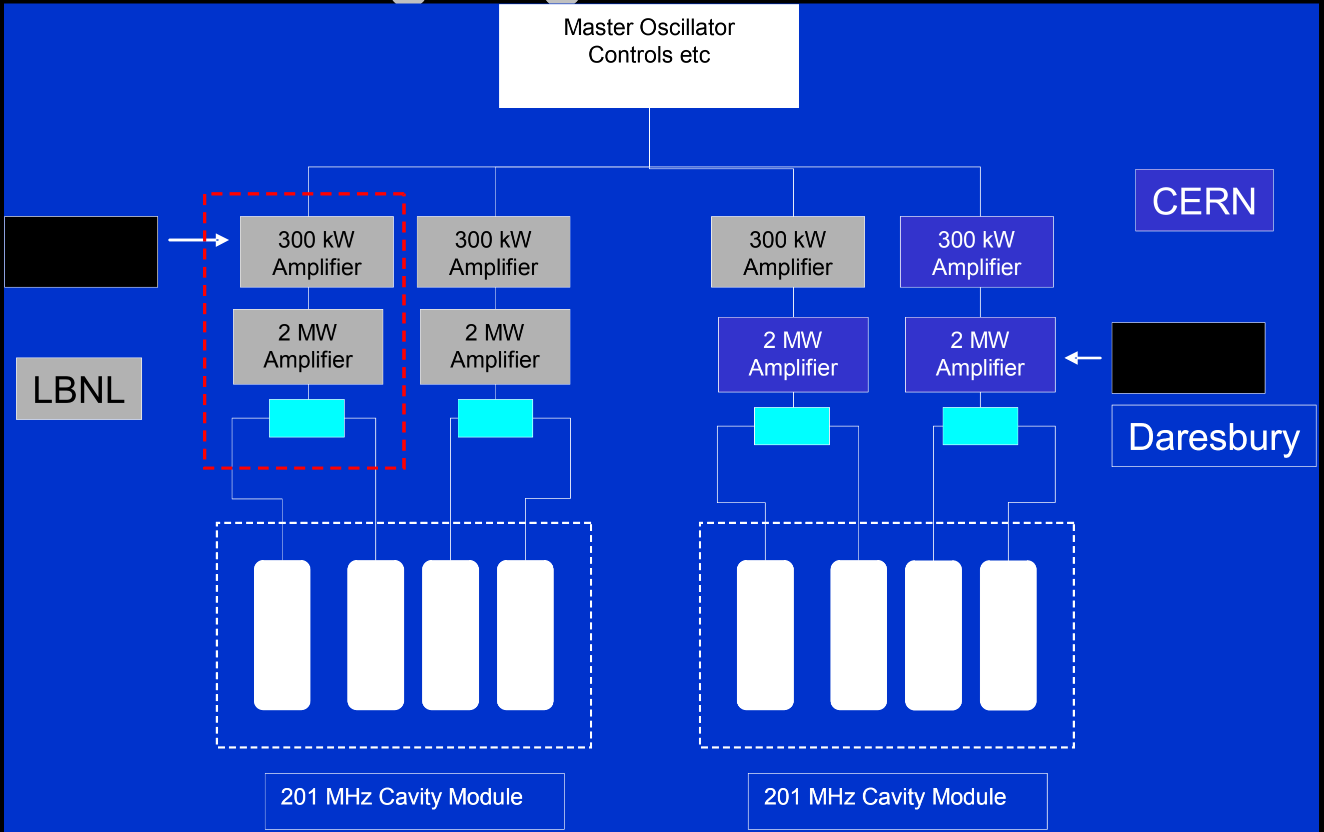
- Each cavity will require a pair of 0.38 mm thick pre-curved beryllium windows with Ti-N coating
- Double-curved shape prevents buckling caused by thermal expansion due to RF heating
- Thermally induced deflections are predictable
- A die is applied at high temperature to form window
- Copper frames are brazed to beryllium windows in a subsequent process





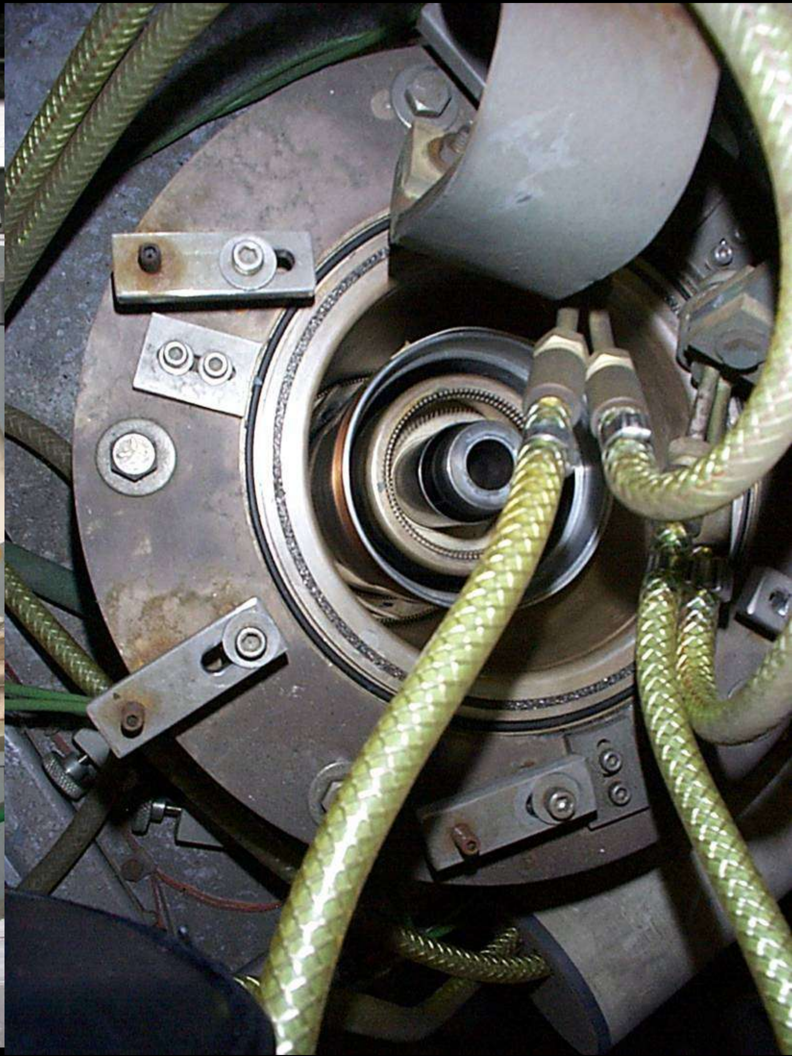
Cooling channel: RF power

- Require 1 MW/cavity to produce 8 MV/m
- Will use 4 × 2.5 MW amplifiers
  - 2 circuits from LBNL
  - 2 circuits being negotiated from CERN

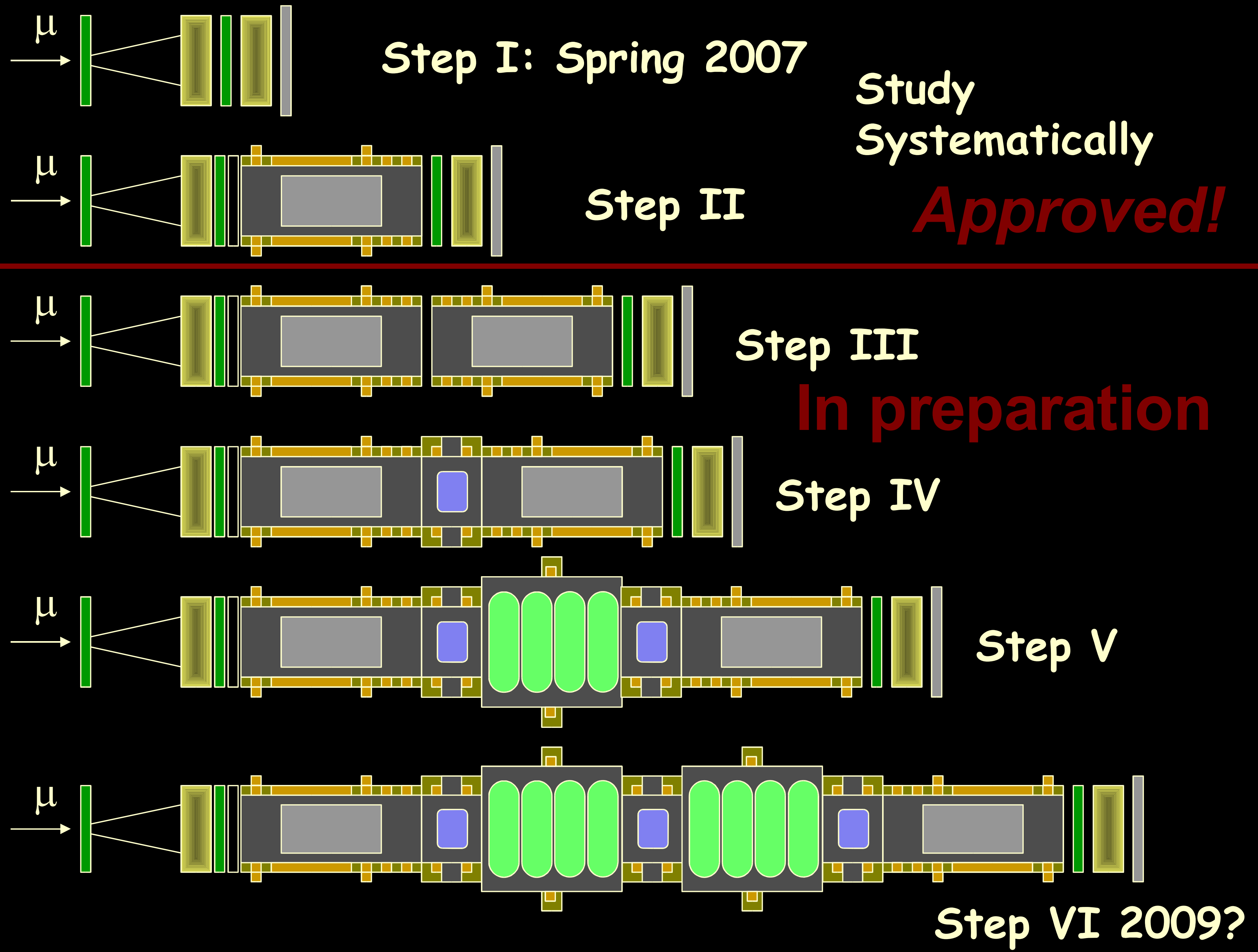


Cooling channel: RF power

- **Refurbishment has begun:**

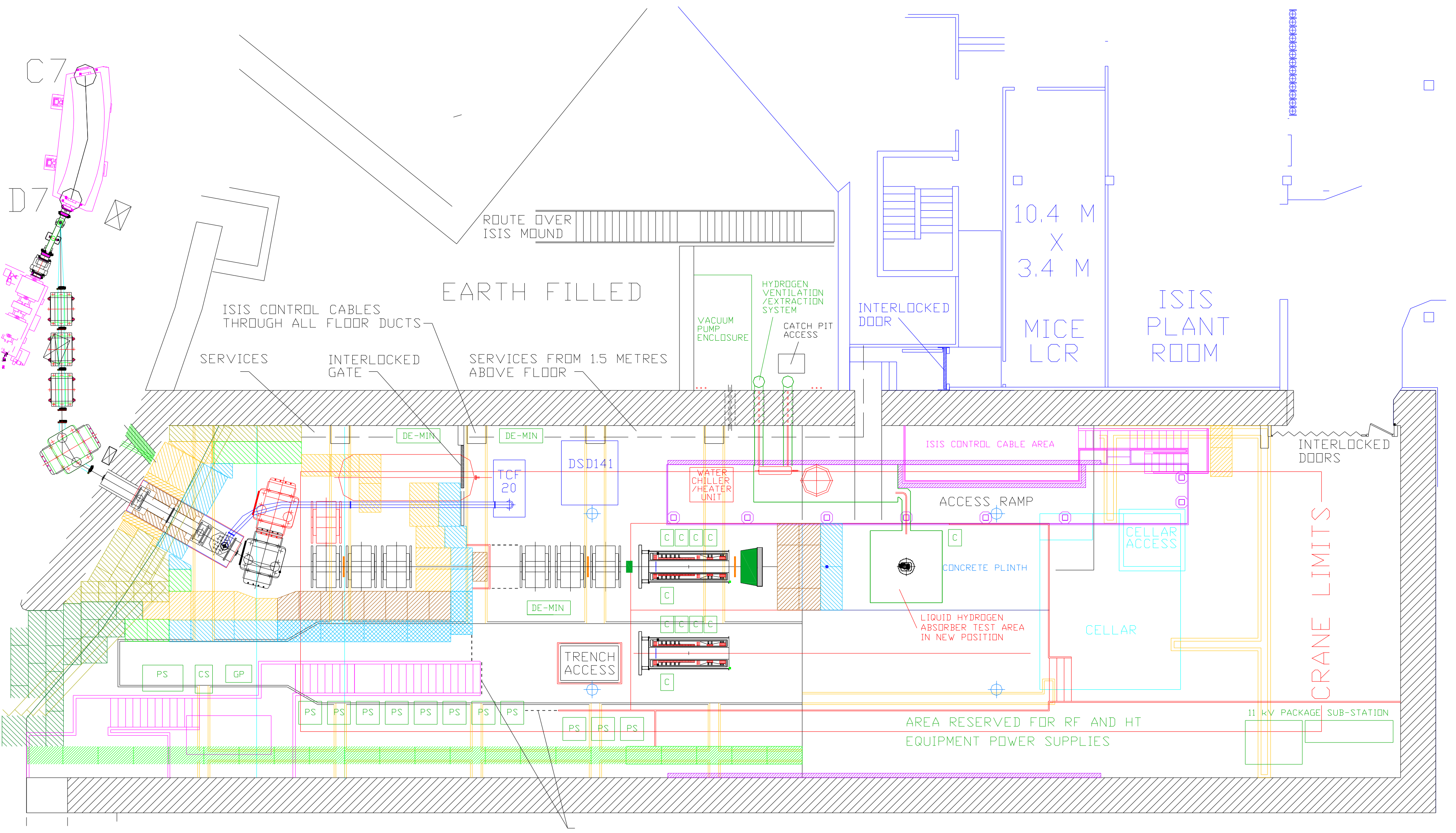


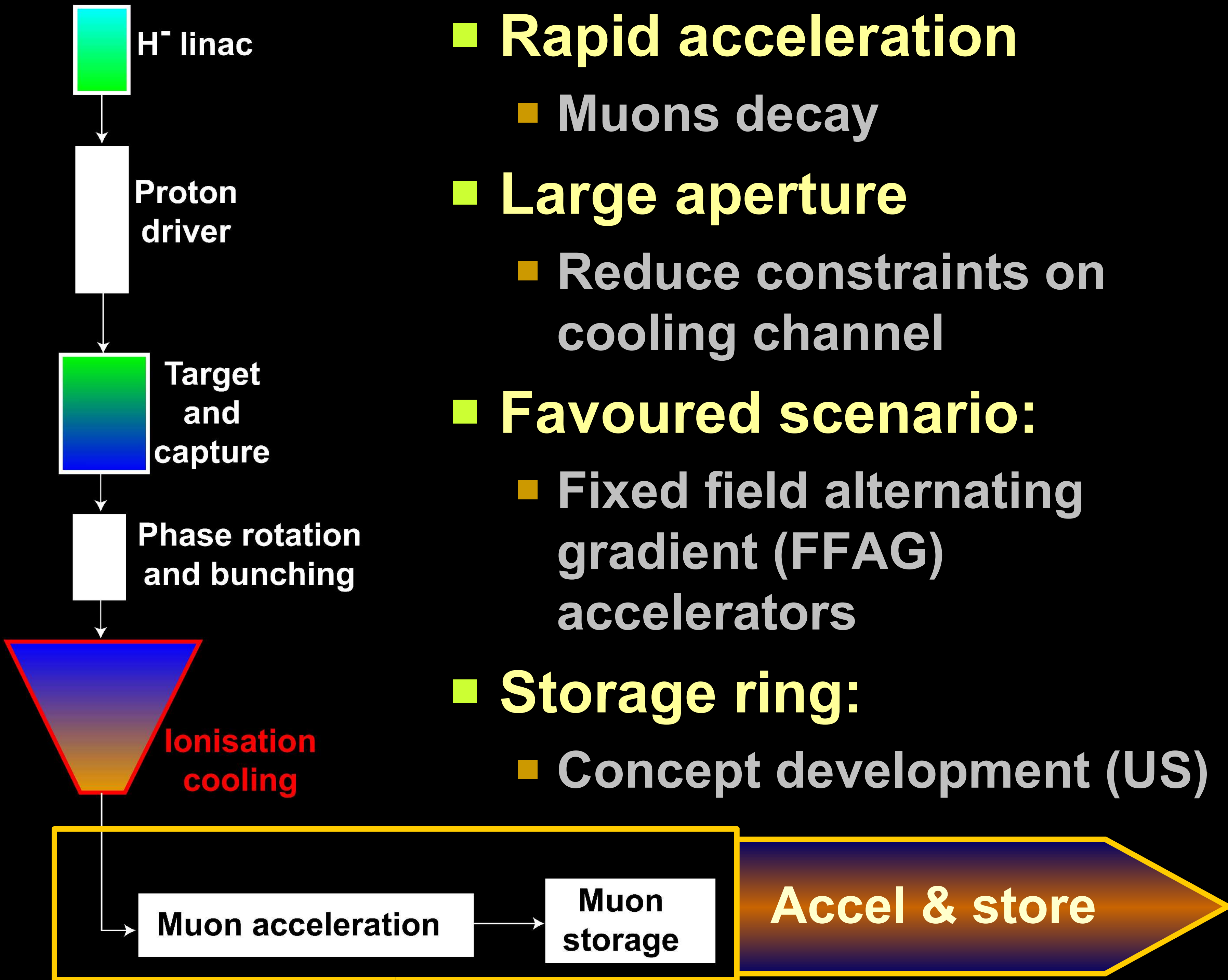
- **Risk: supply of components**



μ
Step I: Spring 2007
Study
Systematically
Step II
Approved!
Step III
In preparation
Step IV
Step V
Step VI 2009?

MICE Phase I on ISIS at RAL

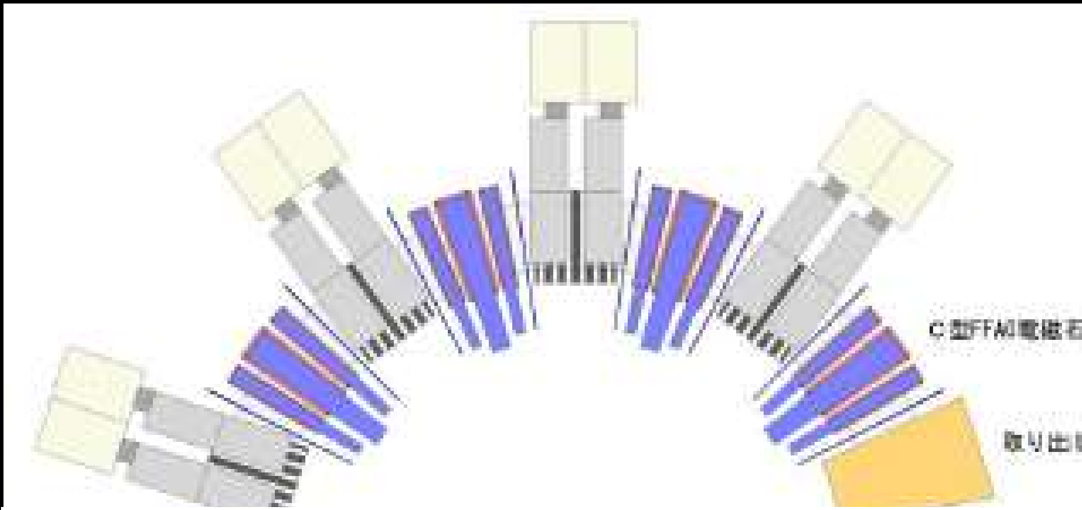




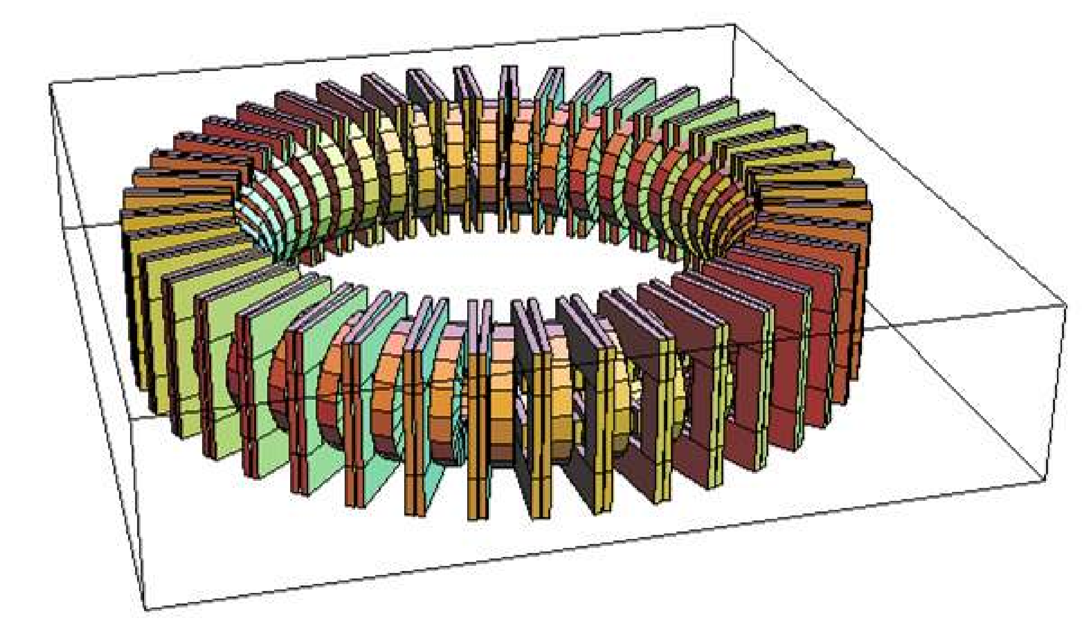
- Rapid acceleration
  - Muons decay
- Large aperture
  - Reduce constraints on cooling channel
- Favoured scenario:
  - Fixed field alternating gradient (FFAG) accelerators
- Storage ring:
  - Concept development (US)

FFAG R&D

- **PRISM: culmination of Japanese scaling-FFAG R&D**
  - Built on success of POP machines



- **International activity developing non-scaling FFAG concept**
  - Electron model:
    - POP machine for non-scaling FFAG



Comments and conclusions

- Several studies at the turn of the century
  - US Studies I and II
  - ECFA/CERN Study
  - NuFact-J Study

  established feasibility & R&D programme
- R&D programme is now maturing:
  - International Muon Ionisation Cooling Experiment
  - International high-power targetry experiment
  - International rapid acceleration (FFAG) programme
- In parallel, continued concept development

Desirable timescale

2005 MINOS, MiniBOONE, CNGS, KamLAND, SK, T2K, …

T2K/NOνA start

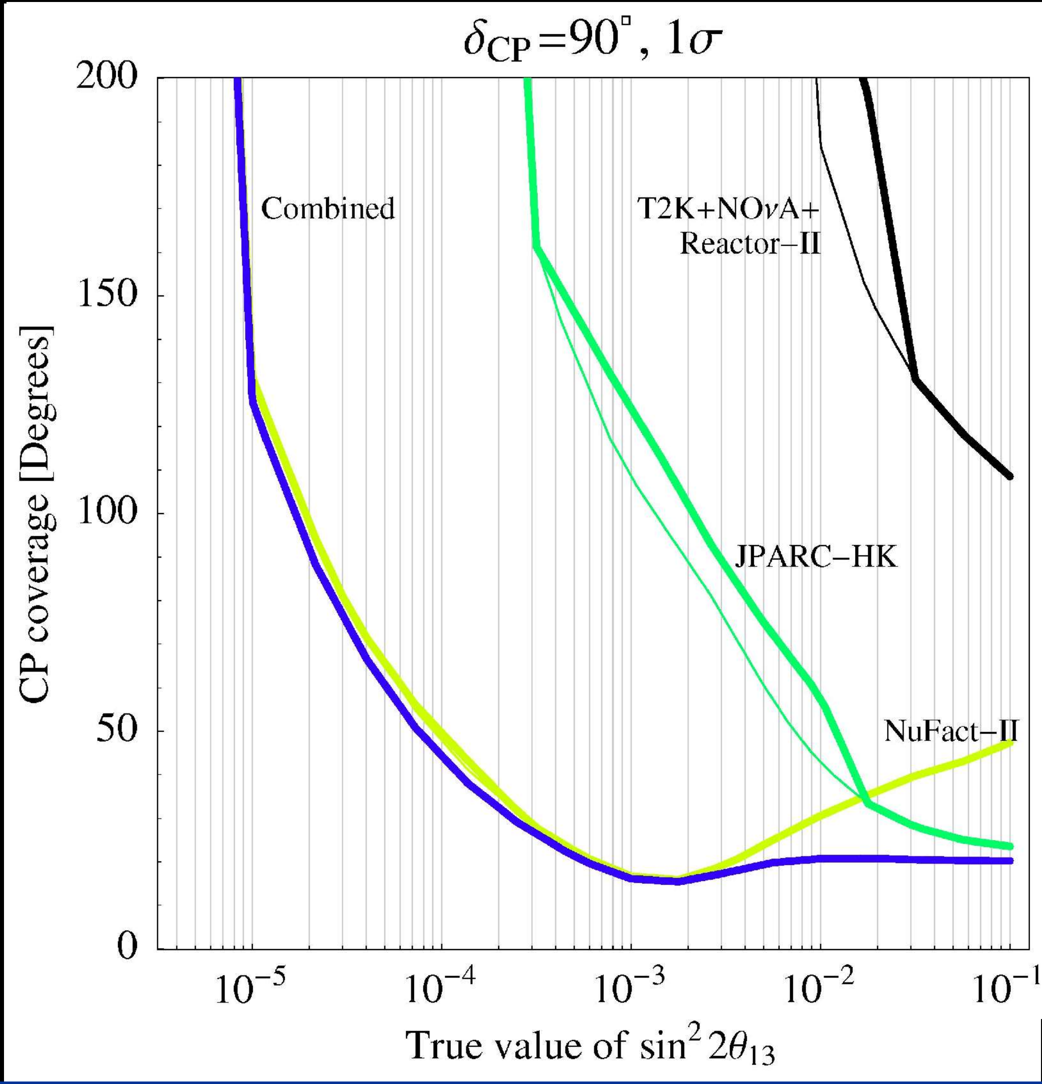
2010

First $\sin^2\theta_{13}$?

Complete phase 1?

2015

Next generation facility



Era of precision and sensitivity

Desirable timescale

2005

Super-beam | Neutrino Factory | Beta-beam

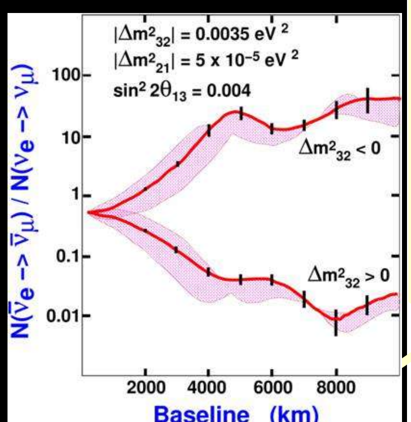
Concept development (design studies)

leading to consensus programme

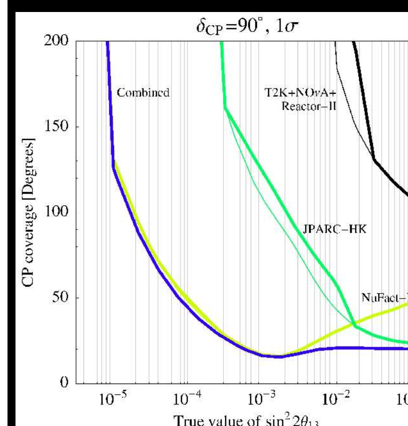
2010

Build

2015



Next generation facility



Era of precision and sensitivity

Conclusion:

- Clear programme:
  - Present experiments to:
    - Tie down θ_{12}, θ_{23}, Δm_{12}^2, Δm_{23}^2
  - Next generation of experiments to:
    - Make first measurement of θ_{13} (or set limit)
    - Begin search for leptonic CP violation
  - Energetic programme of R&D by which to:
    - Arrive at a consensus programme for the era of precision and sensitivity
    - Options:
      - Second-generation super-beam
      - Beta-beam
      - Neutrino Factory

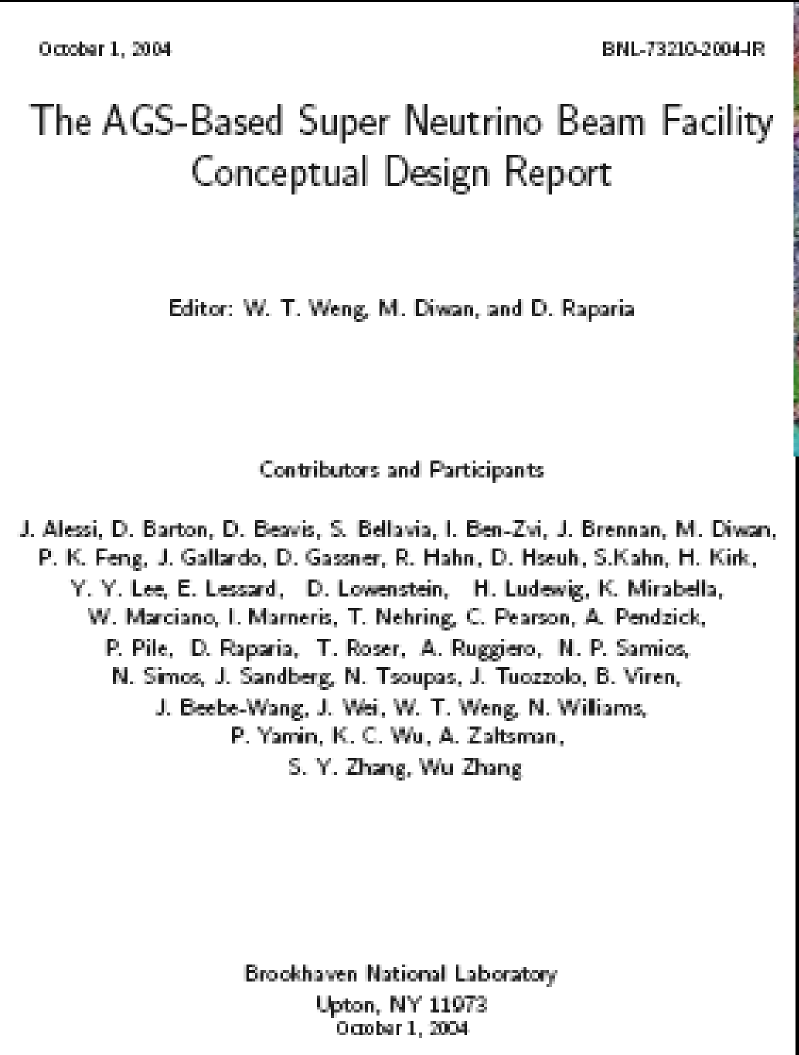
      alone or in combination
- A fantastic programme!

Backup slides

BNL-VLBL

Viren

- Upgraded AGS at 28 GeV
  - Replace booster with 1.2 GeV SC linac



October 1, 2004 BNL-73210-2004-IR

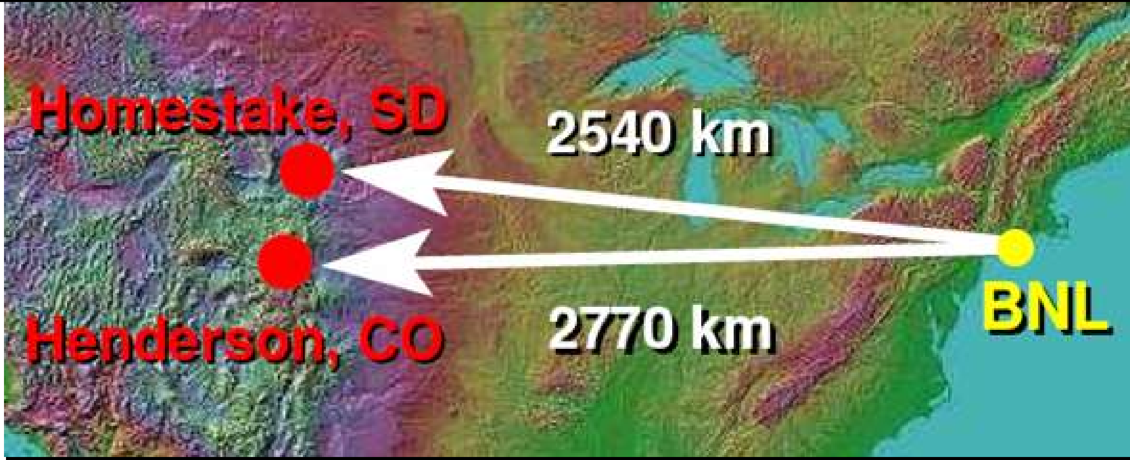
The AGS-Based Super Neutrino Beam Facility Conceptual Design Report

Editor: W. T. Weng, M. Diwan, and D. Raparia

Contributors and Participants

J. Alessi, D. Barton, D. Beavis, S. Bellavia, I. Ben-Zvi, J. Brennan, M. Diwan, P. K. Feng, J. Gallardo, D. Gassner, R. Hahn, D. Hseuh, S.Kahn, H. Kirk, Y. Y. Lee, E. Lessard, D. Lowenstein, H. Ludewig, K. Mirabella, W. Marciano, I. Marneris, T. Nehring, C. Pearson, A. Pendzick, P. Pile, D. Raparia, T. Roser, A. Ruggiero, N. P. Samios, N. Simos, J. Sandberg, N. Tsoupas, J. Tuozzolo, B. Viren, J. Beebe-Wang, J. Wei, W. T. Weng, N. Williams, P. Yamin, K. C. Wu, A. Zaltsman, S. Y. Zhang, Wu Zhang

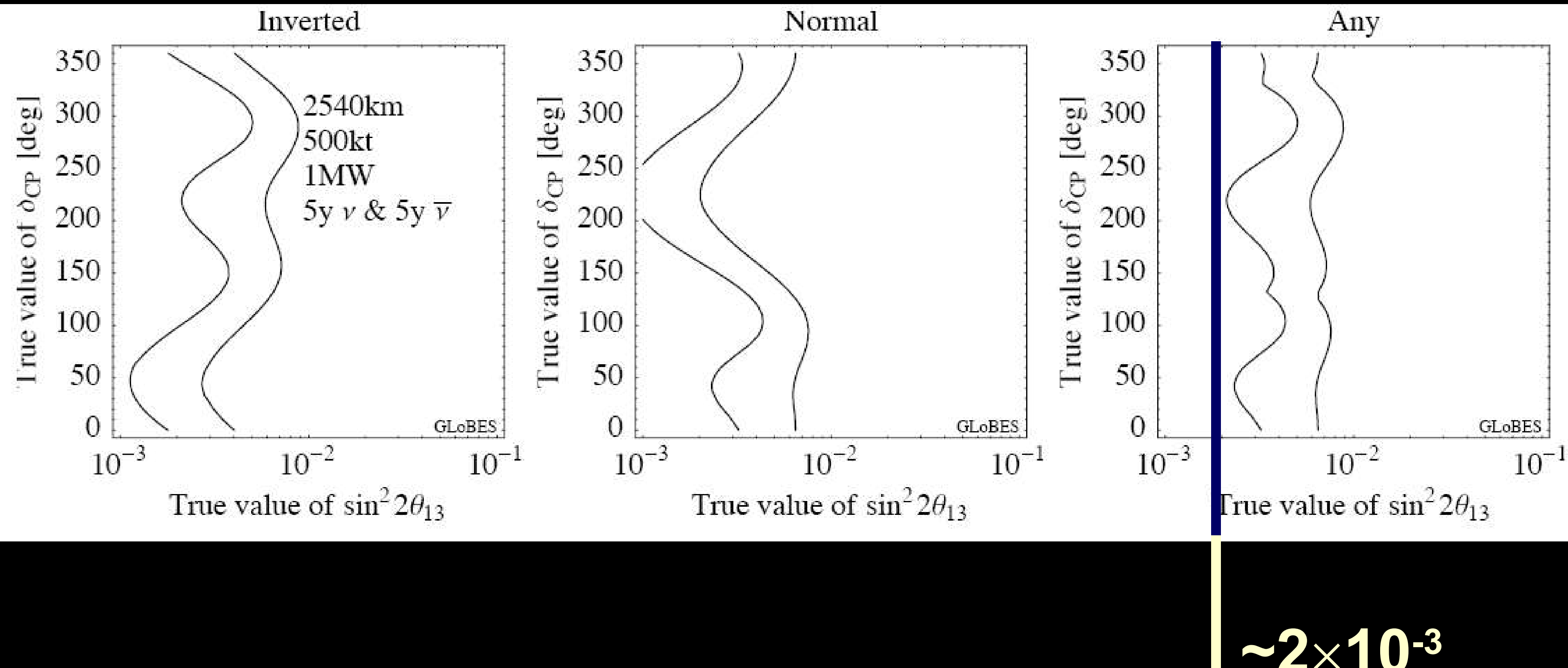
Brookhaven National Laboratory
Upton, NY 11973
October 1, 2004



- Assume UNO: 500 kTon H_2O
- Running assumptions:
  - ν: 1 MW, 5 yrs
  - $\bar{\nu}$: 2 MW, 5 yrs
- Performance updated:
  - Example only →

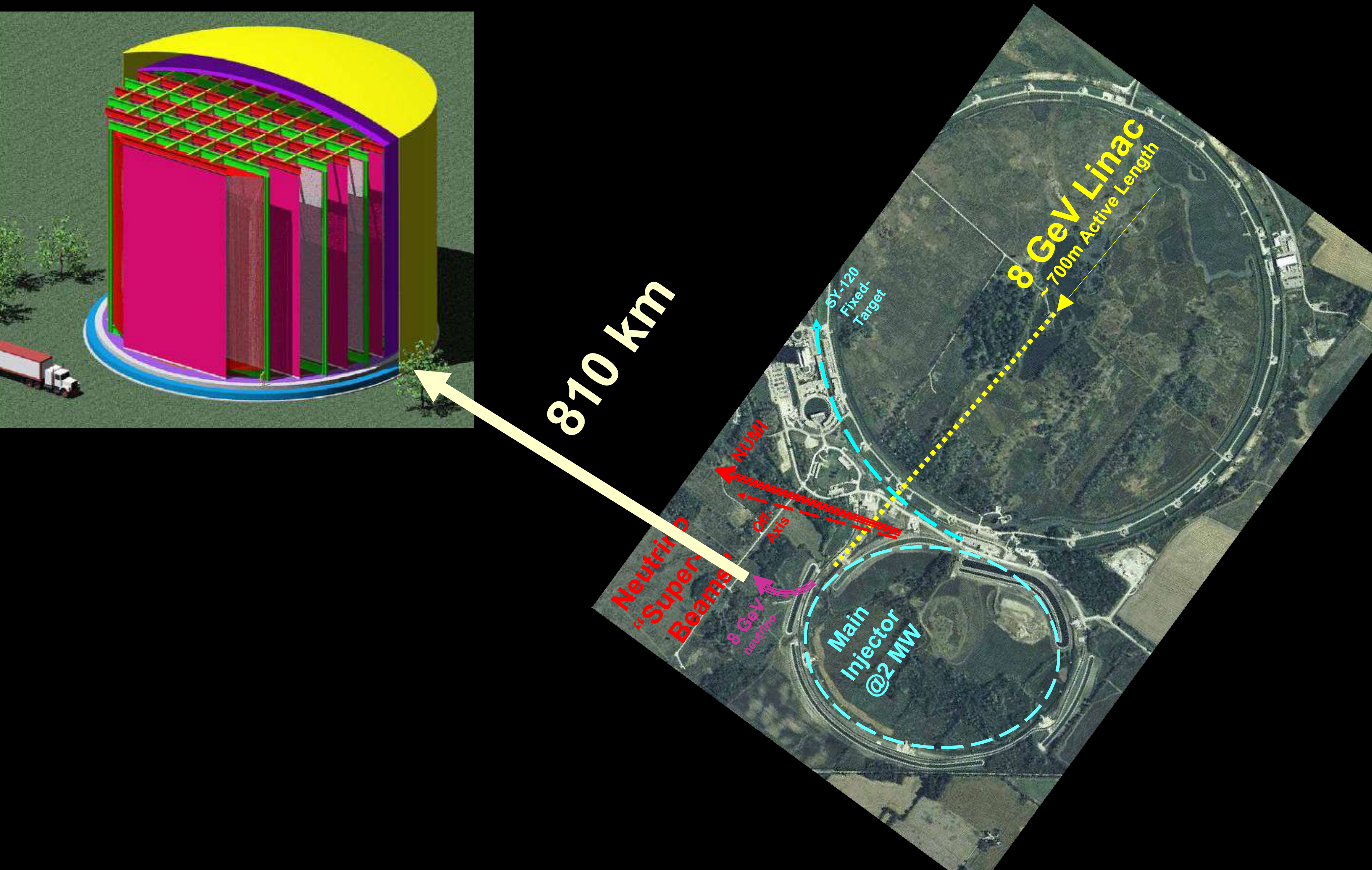
BNL-VLBL: sensitivity

Viren



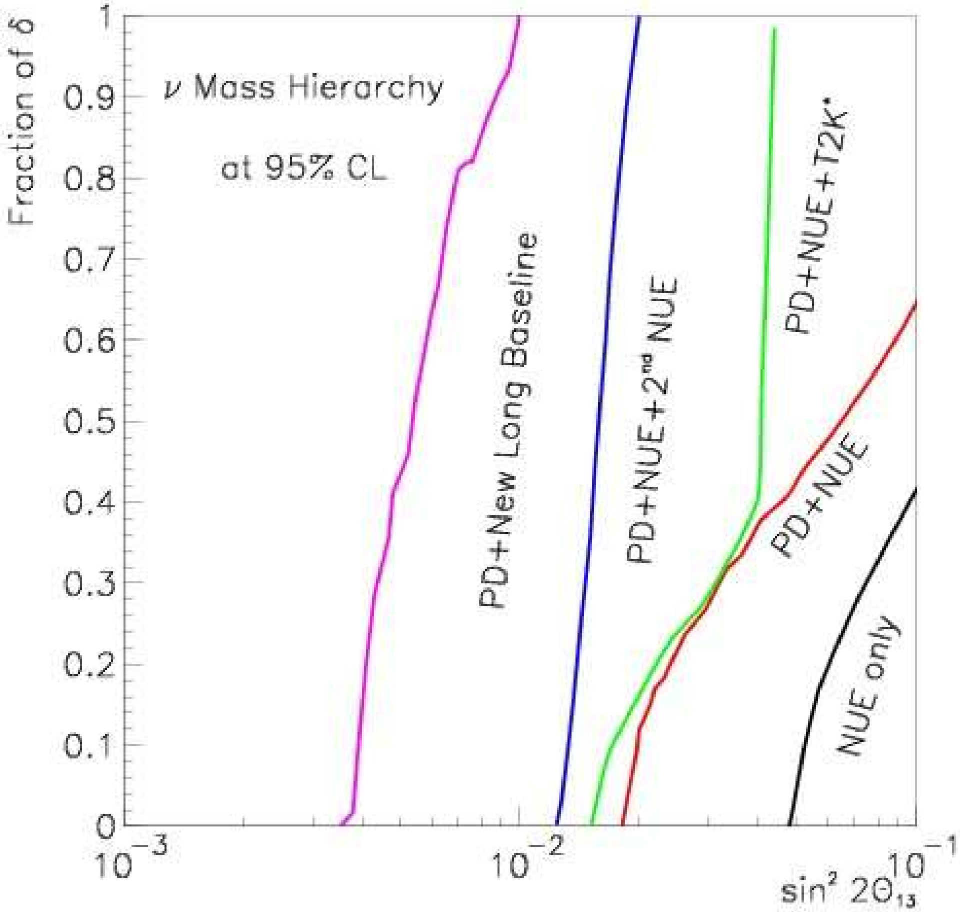
- **Very long baseline:**
  - **Sensitivity to Δm_{23}^2 from matter effects**

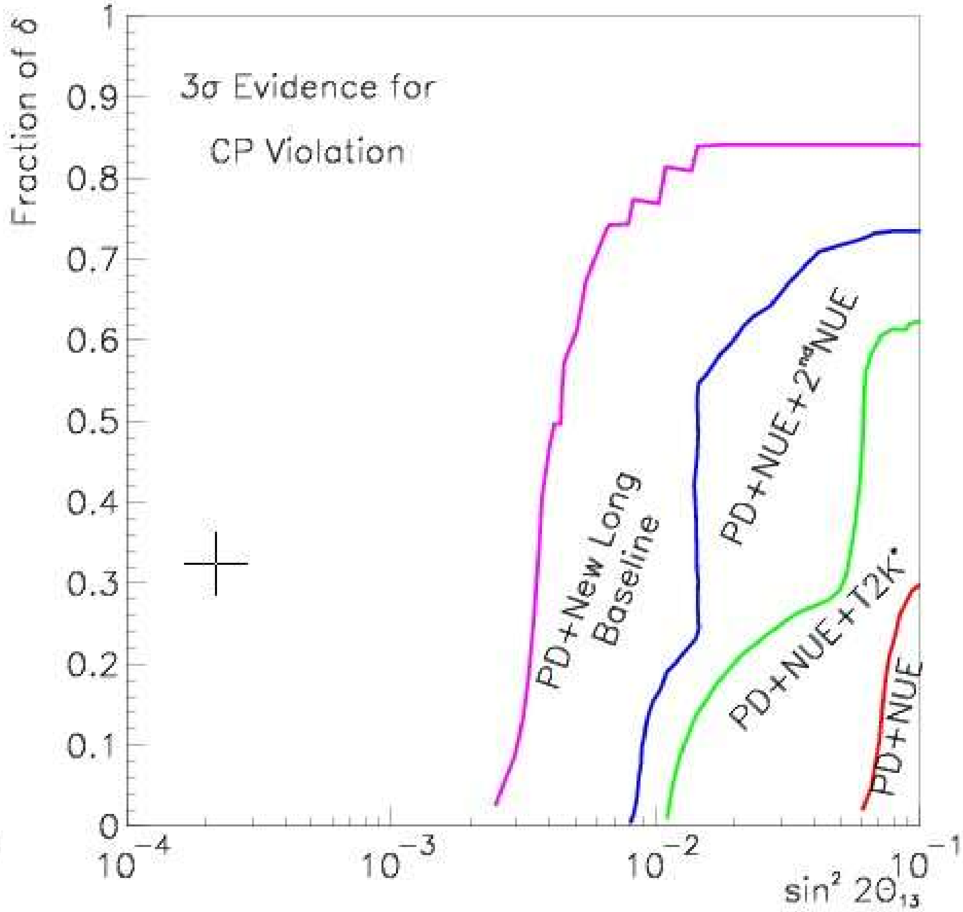
Super-NOνA


810 km
8 GeV Linac
~700m Active Length
SY-120
Fixed-
Target
NUMI
Off-
Axis
Neutri
“Super-
Beams
8 GeV
neutrino
Main
Injector
@2 MW

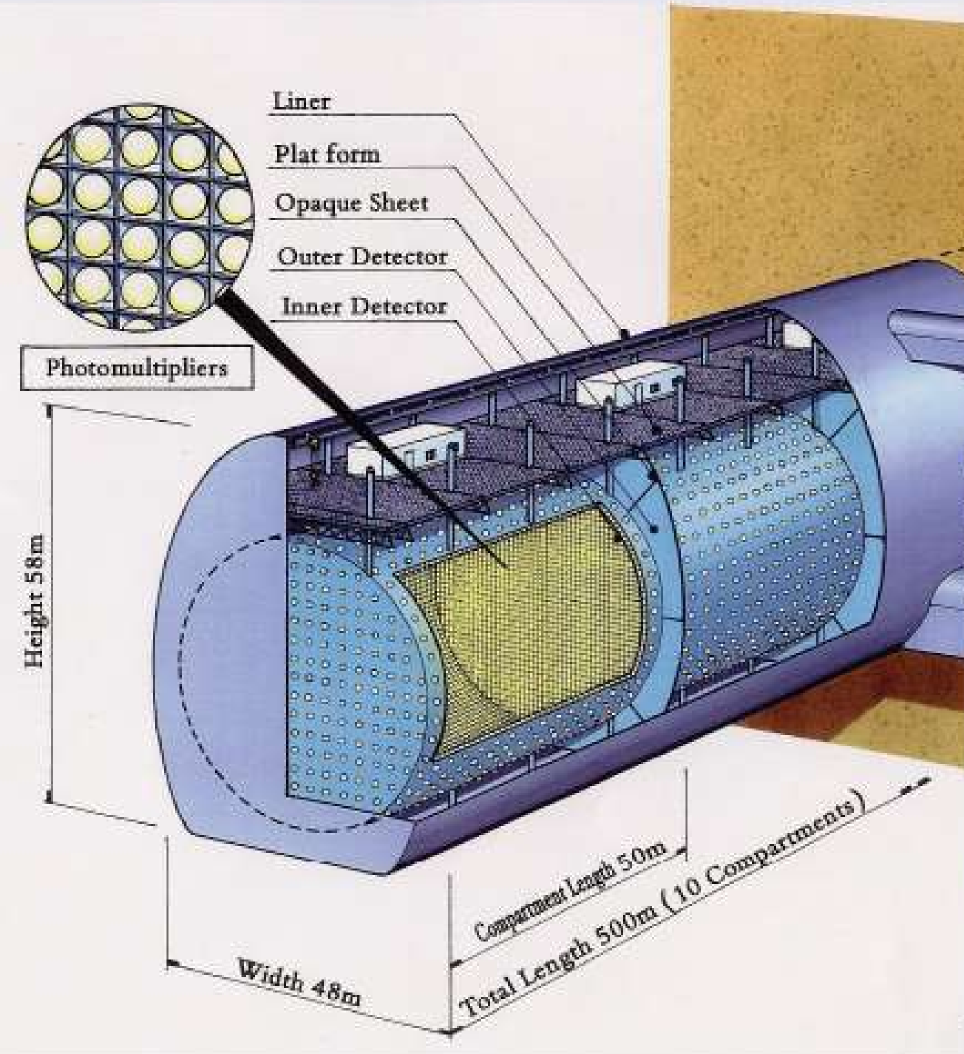
Supa-NOνA: sensitivity

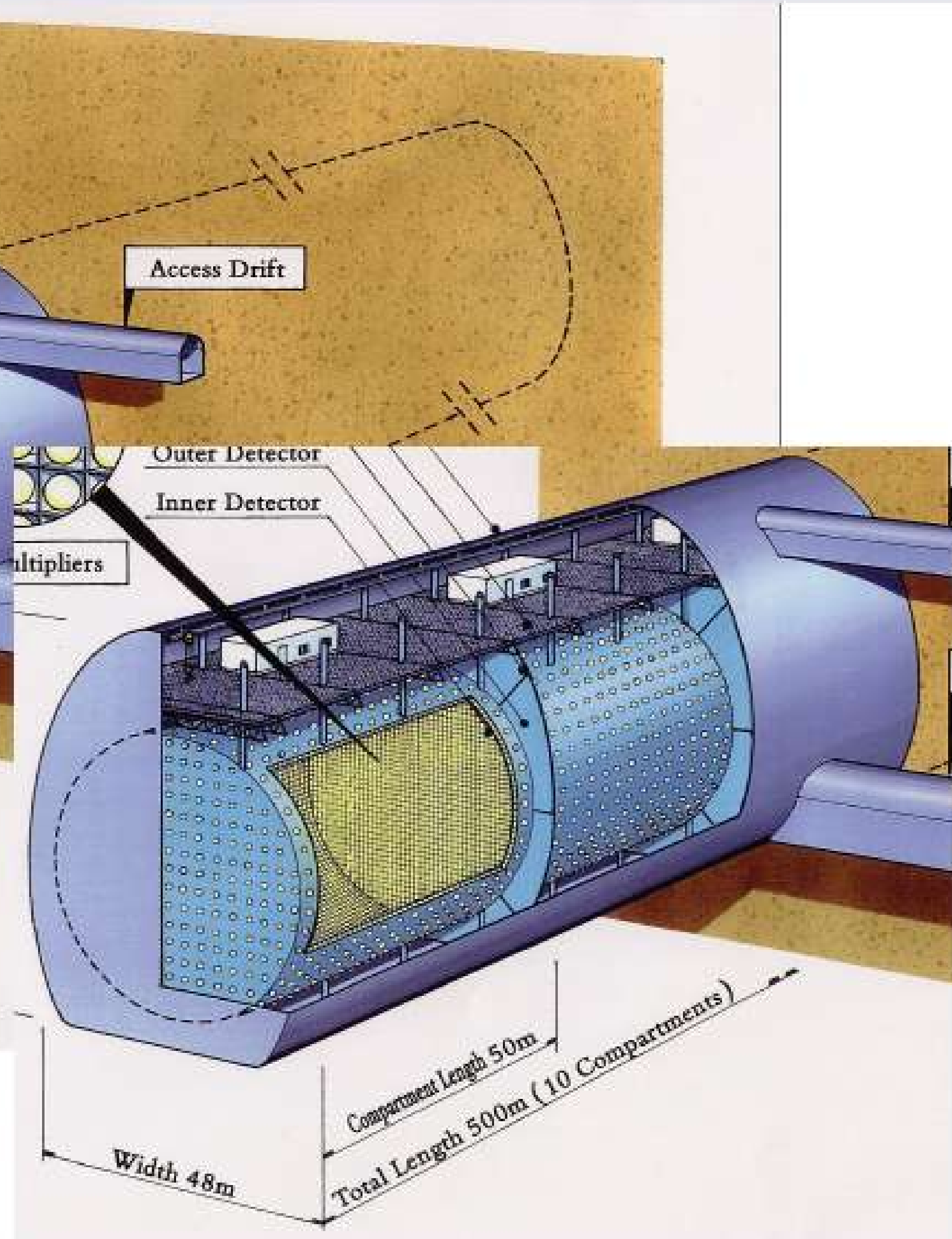
Winter





Hyper-Kamiokande





2 detectors 48m x 50m x 250 m

1 Mton total mass

T2K II sensitivity