The Neutrino Factory

EUROnu and IDS-NF

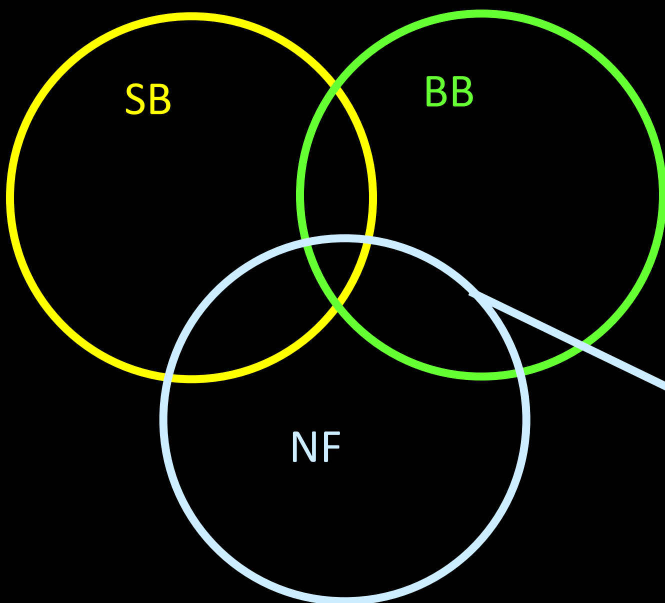
K. Long, 10 May, 2011

Imperial College London

EUROnu and the IDS-NF

- EUROnu is the European contribution to the IDS-NF

EUROnu



IDS-NF

- The Americas
  - Canada
  - USA
- Asia
  - Japan
  - India
  - (in the future: China …)
- Europe
  - EUROnu

IDS-NF mandate from NuFact07:

International Design Study of the
Neutrino Factory

17 January 2007

Principal objectives

The principal objective of the International Design Study of the Neutrino Factory (the IDS) is to deliver a design report in which:

- The physics performance of the Neutrino Factory is detailed and the specification of each of the accelerator, diagnostic, and detector systems that make up the facility is defined;
- The schedule for the implementation of the Neutrino Factory facility is presented;
- The cost of the Neutrino Factory accelerator, the diagnostics, and the detector systems are presented at a level of accuracy appropriate for the report to inform a decision to initiate the Neutrino Factory project; and
- The outstanding technical and financial uncertainties are documented and an appropriate uncertainty-mitigation plan is presented.

This report, the Reference Design Report (RDR), is required in 2012/13. As a step on the way, an Interim Design Report (IDR) is required in 2010/11. The purpose of this note is to define the terms RDR and IDR.

The Interim Design Report

The Interim Design Report has three functions: it marks the point in the IDS at which the focus turns to the engineering studies required to deliver the RDR; it documents the baseline for the accelerator complex, the neutrino detectors, and the instrumentation systems. It also defines example sites to be taken forward in the RDR; and it forms the basis of the proposals required to deliver the RDR. The IDR must therefore contain engineering designs of each of the accelerator, diagnostic, and detector systems that make up the facility together with estimates of the cost and schedule accurate at the 50% level. In addition, the IDR must contain a detailed, precisely-costed, plan of the work required to deliver the RDR. This plan must include a description of the hardware R&D work required to address any outstanding technological or systems-integration issues that must be addressed before the RDR can be completed. To avoid the additional cost incurred unnecessary engineering multiple designs, the transition from IDR phase to the RDR phase implies the implementation of an appropriate change-control procedure.

The Reference Design Report

The Reference Design Report is conceived as the basis on which a request for the resources to carry out the first phase of the Neutrino Factory project can be made. The Neutrino Factory project necessarily encompasses detailed design work, a continuing R&D programme by which the technical and cost uncertainties are managed, and the initial stages of the construction of the facility itself.

For the RDR to be used to support such a proposal requires that the cost and schedule estimates must be robust, accurate at the 30% level, and that an appropriate evaluation of contingency has been carried out. The RDR must therefore contain sufficient engineering detail on each subsystem to demonstrate that the cost and schedule estimates are robust at this level.

International Design Study for the Neutrino Factory

IDS-NF-020

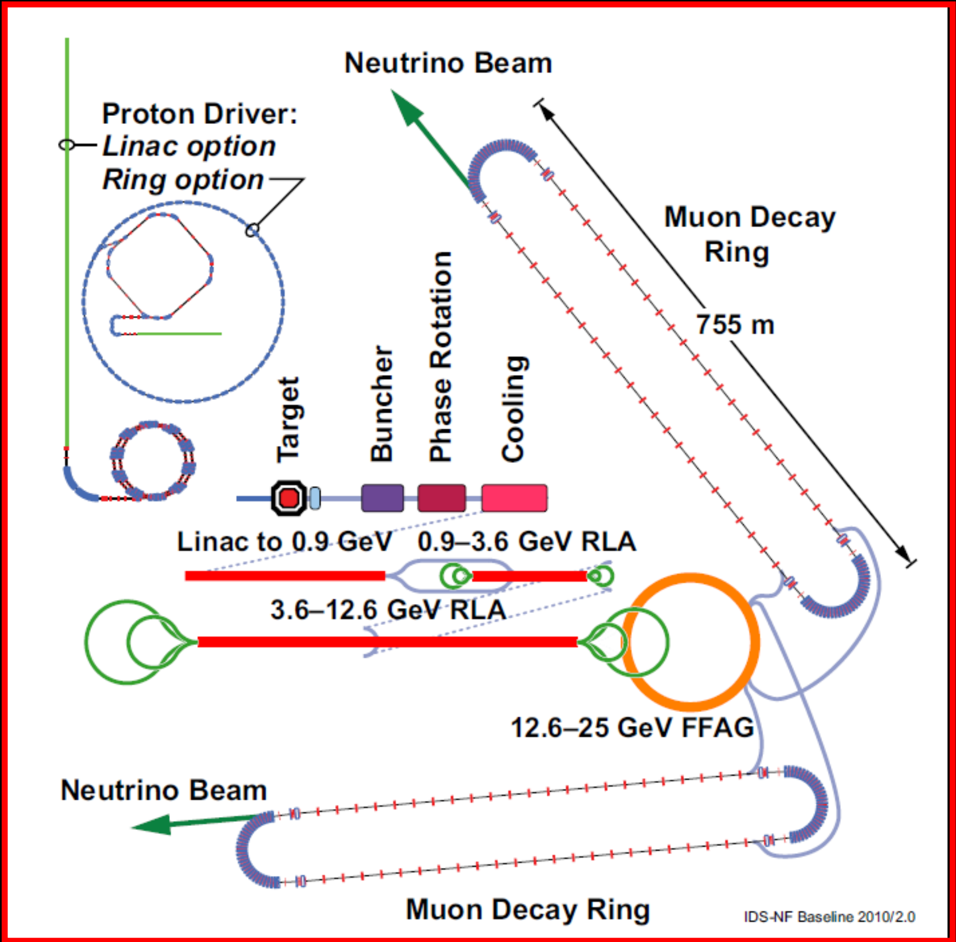
Interim Design Report

The IDS-NF collaboration

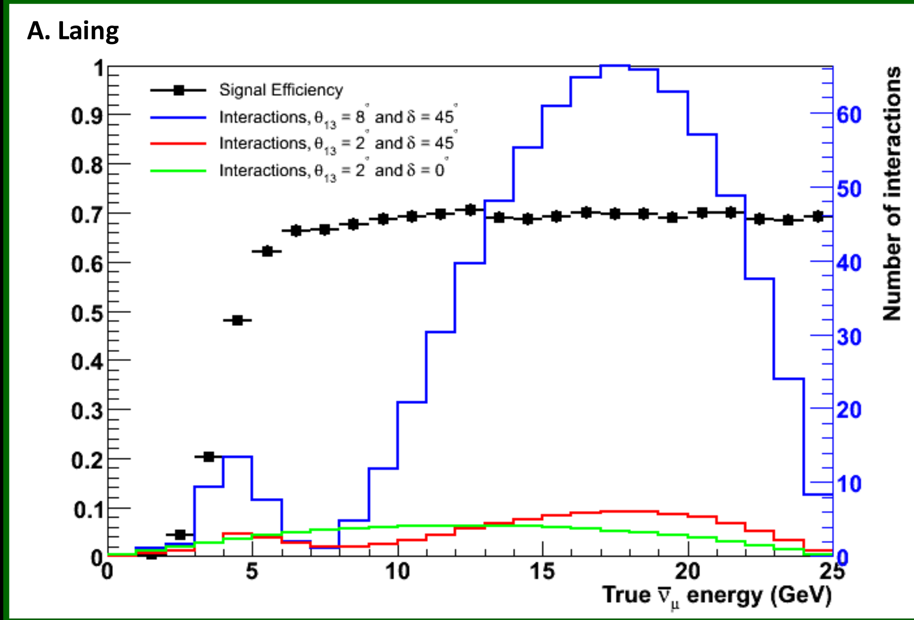
March 26, 2011

Bulgaria	University of Sofia
France	IPHC Strasbourg
Germany	MPI Heidelberg, MPI Munich, Fakultät für Physik und Astronomie Würzburg
India	HCRI Allahabad, SINP Kolkata, TIFR Mumbai
Italy	Milano Bicocca, Universita di Napoli Federico II, Universita di Padova and INFN Padova, Sezione INFN Roma Tre
Japan	Kyoto University RRI, University of Osaka, Tokyo Metropolitan University
Spain	UAM and IFT Madrid, UV/CSIC and IFIC Valencia
Russia	INRR Moscow
Switzerland	CERN, University of Geneva
UK	Brunel University, Daresbury Laboratory, Glasgow University, Imperial College London, IPPP Durham, Oxford University, Rutherford Appleton Laboratory, Sheffield University, Warwick University
USA	Brookhaven National Laboratory, Fermi National Laboratory, Jefferson Laboratory, Laurence Berkeley National Laboratory, University of Mississippi, Michigan State University, Muons Inc., Northwestern University, Oak Ridge National Laboratory, Princeton University, University of California at Riverside, Stony Brook University, University of South Carolina, Virginia Polytechnique Institute, University of California at Los Angeles

Progress highlights: accelerator:



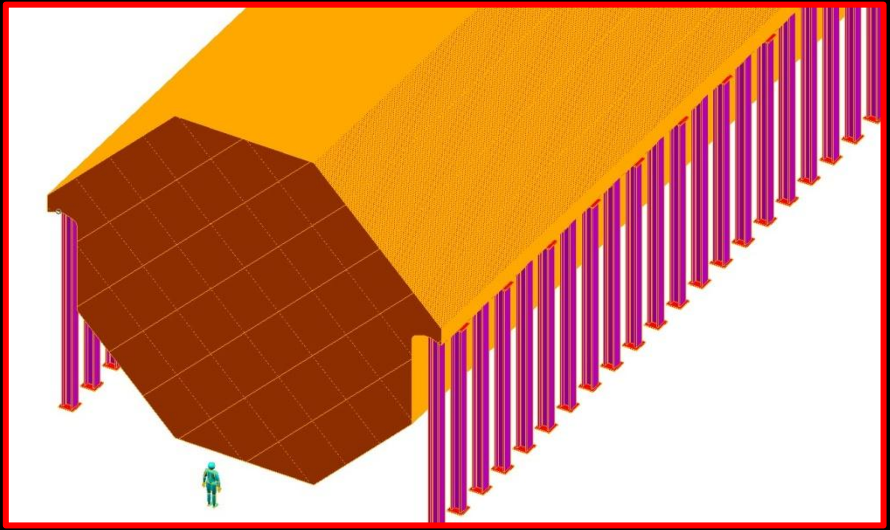
$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$	$\mu^- \to e^- \bar{\nu}_e \nu_\mu$	
$\bar{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance
$\bar{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	appearance (challenging)
$\bar{\nu}_\mu \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	appearance
$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$	disappearance
$\nu_e \to \nu_\mu$	$\bar{\nu}_e \to \bar{\nu}_\mu$	appearance: "golden" channel
$\nu_e \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$	appearance: "silver" channel



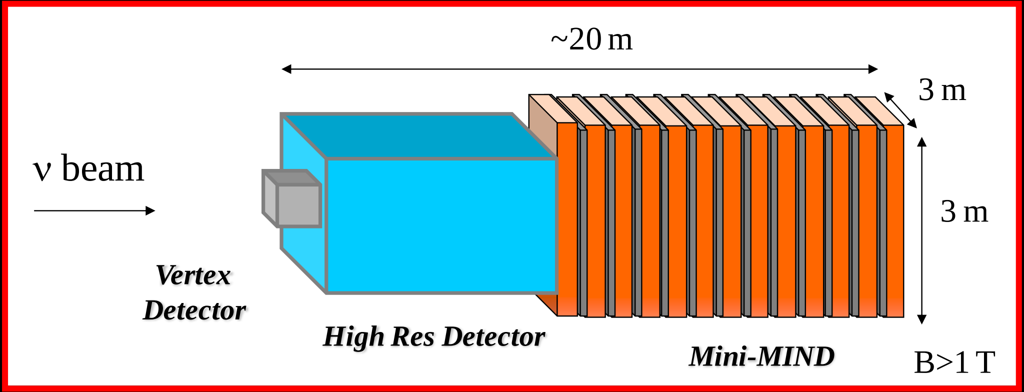
- Substantial improvements in:
  - Target, front-end and muon acceleration sub-systems
- Other sub-systems have undergone incremental improvement
  - Indicative of the degree of maturity of the design

Progress highlights: detector:

- **MIND:**
  - Re-optimised sampling fraction
  - Cuboid in 1 T dipole field
    - More realistic field configuration in hand
  - Detector mass:
    - Intermediate detector [2500—5000 km]: 100 kT
    - Far detector [7000—8000 km]: 50 kT

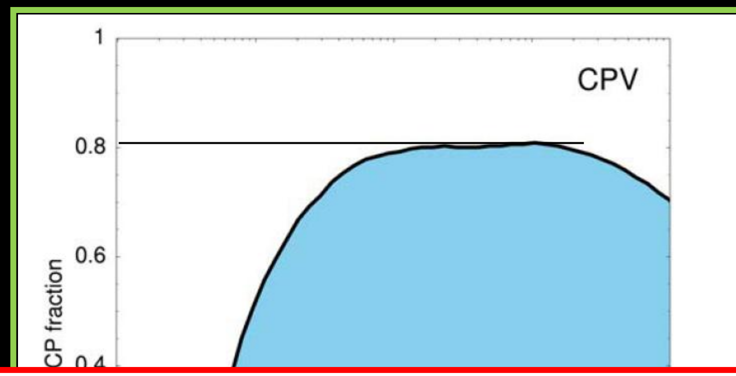


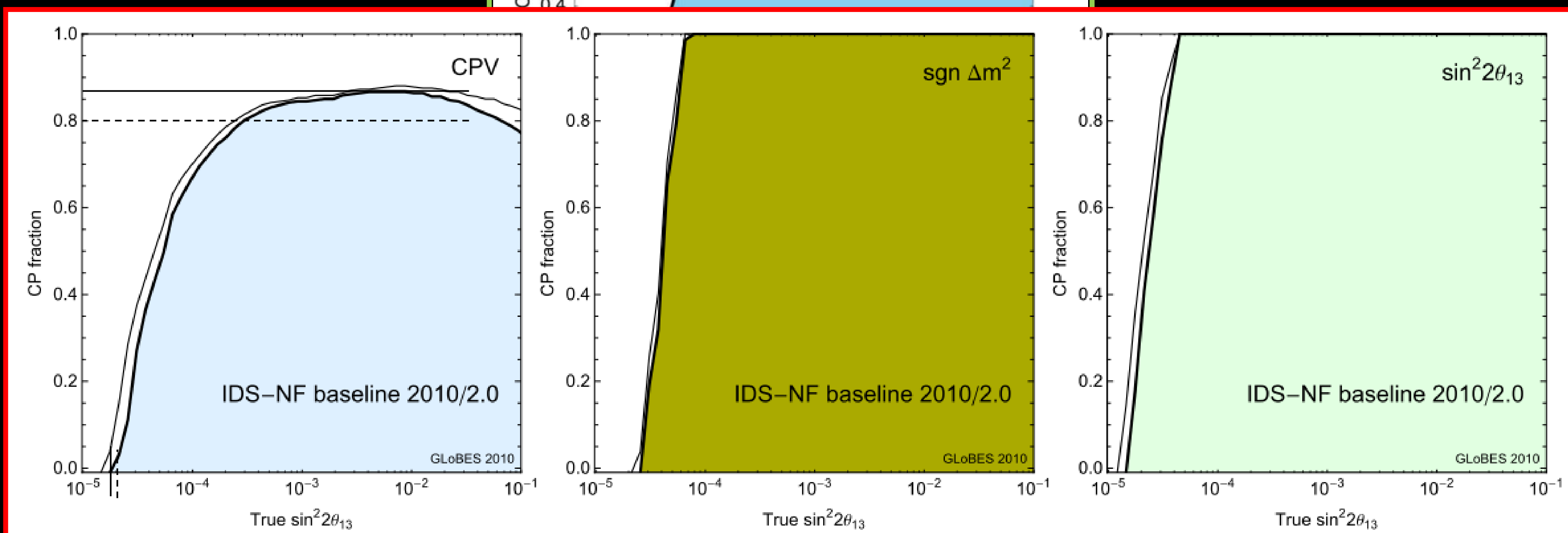
- **Near detector:**
  - No near detector specified in initial IDS-NF baseline [i.e. ISS Detector W/g report]:
    - Known to be a shortcoming
  - IDS-NF near detector concept (baseline 2010/2.0)



IDS-NF baseline 2010-2.0:

- **Migration matrices (see IDR):**
  - **Significant improvement over IDS-NF baseline 2007/1.0**

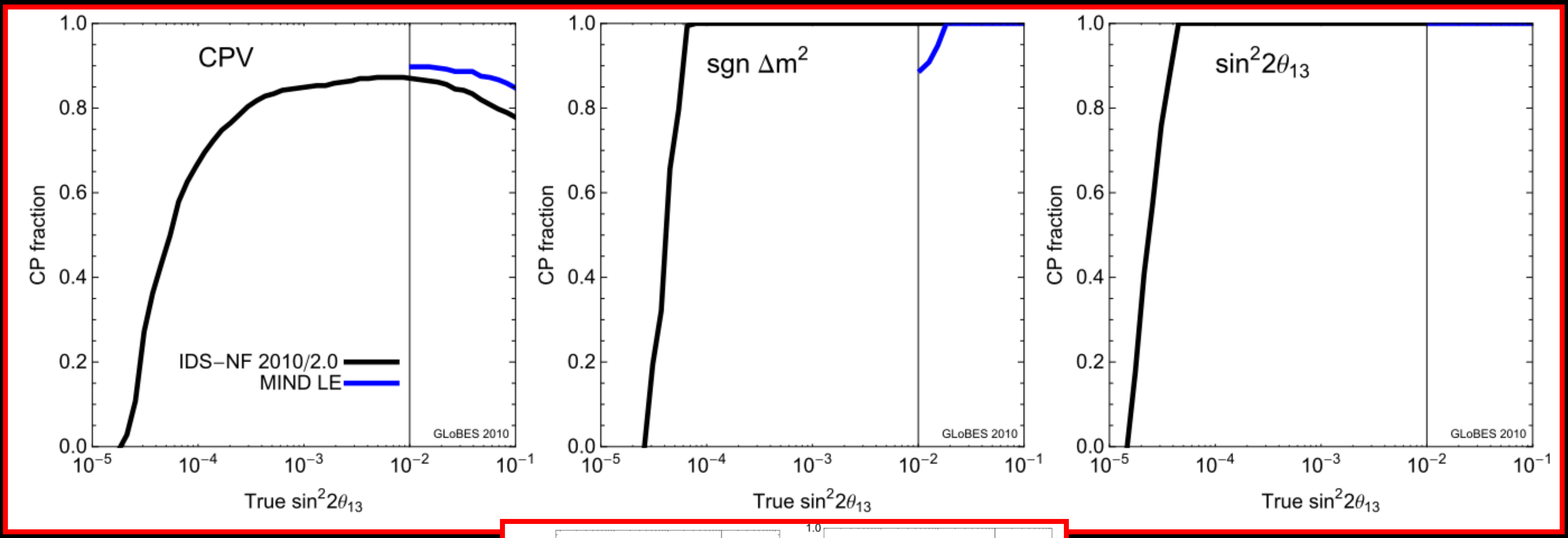


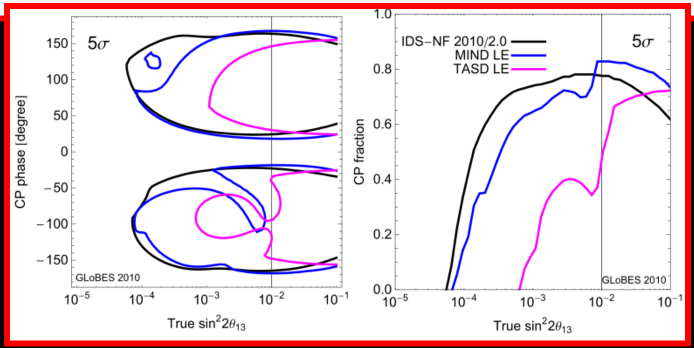


Neutrino Factory performance:

- Discovery reach at 3σ extends down to $\sin^2 2\theta_{13} \sim 5 \times 10^{-5}$
  - Should θ_{13} to be shown to be > 0 before start of Neutrino Factory project:
    - Re-optimisation of baseline:
      - 10 GeV muon energy serving a single 100 kTon MIND at a baseline of 2000 km

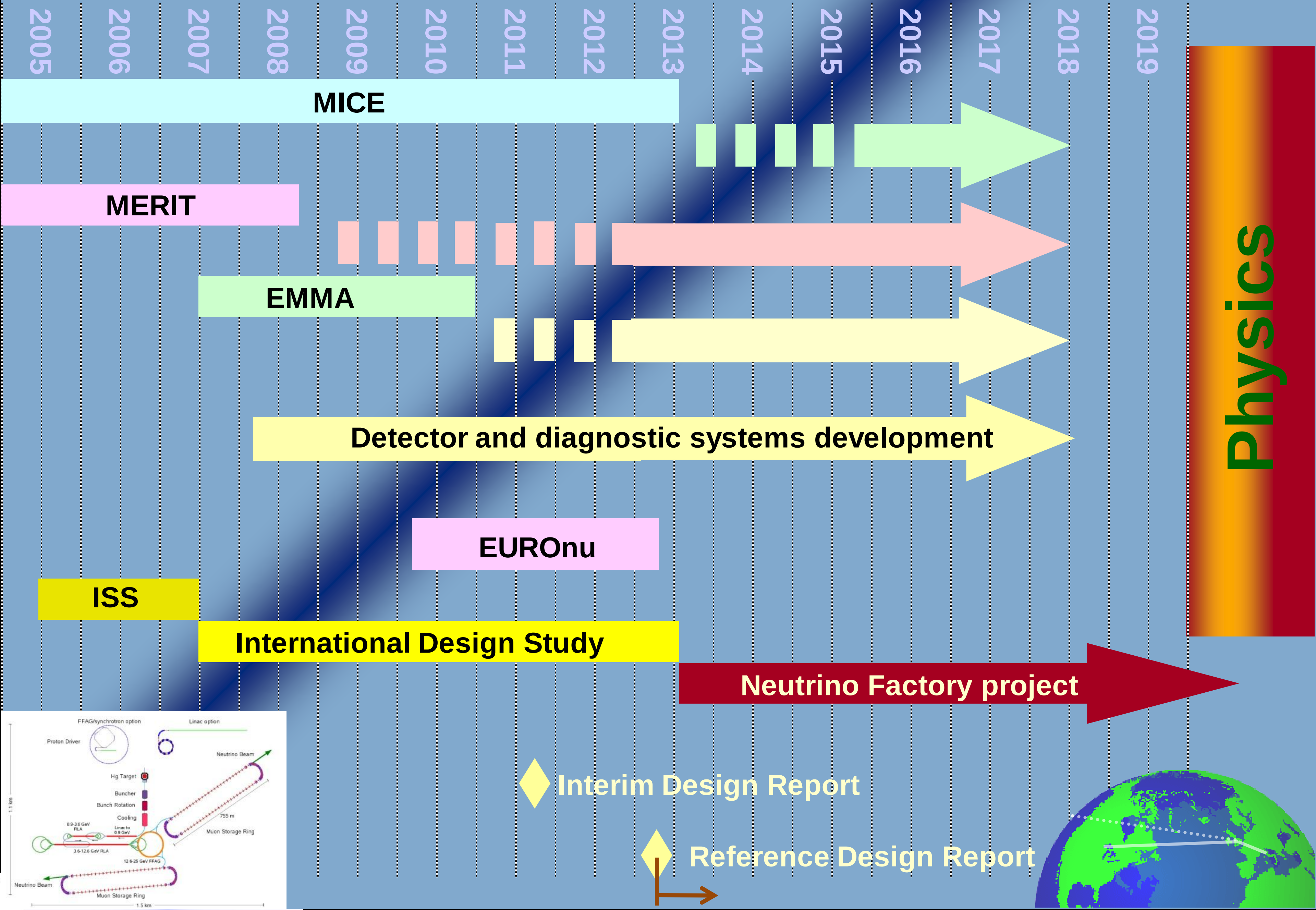
    gives excellent performance





07Mar10

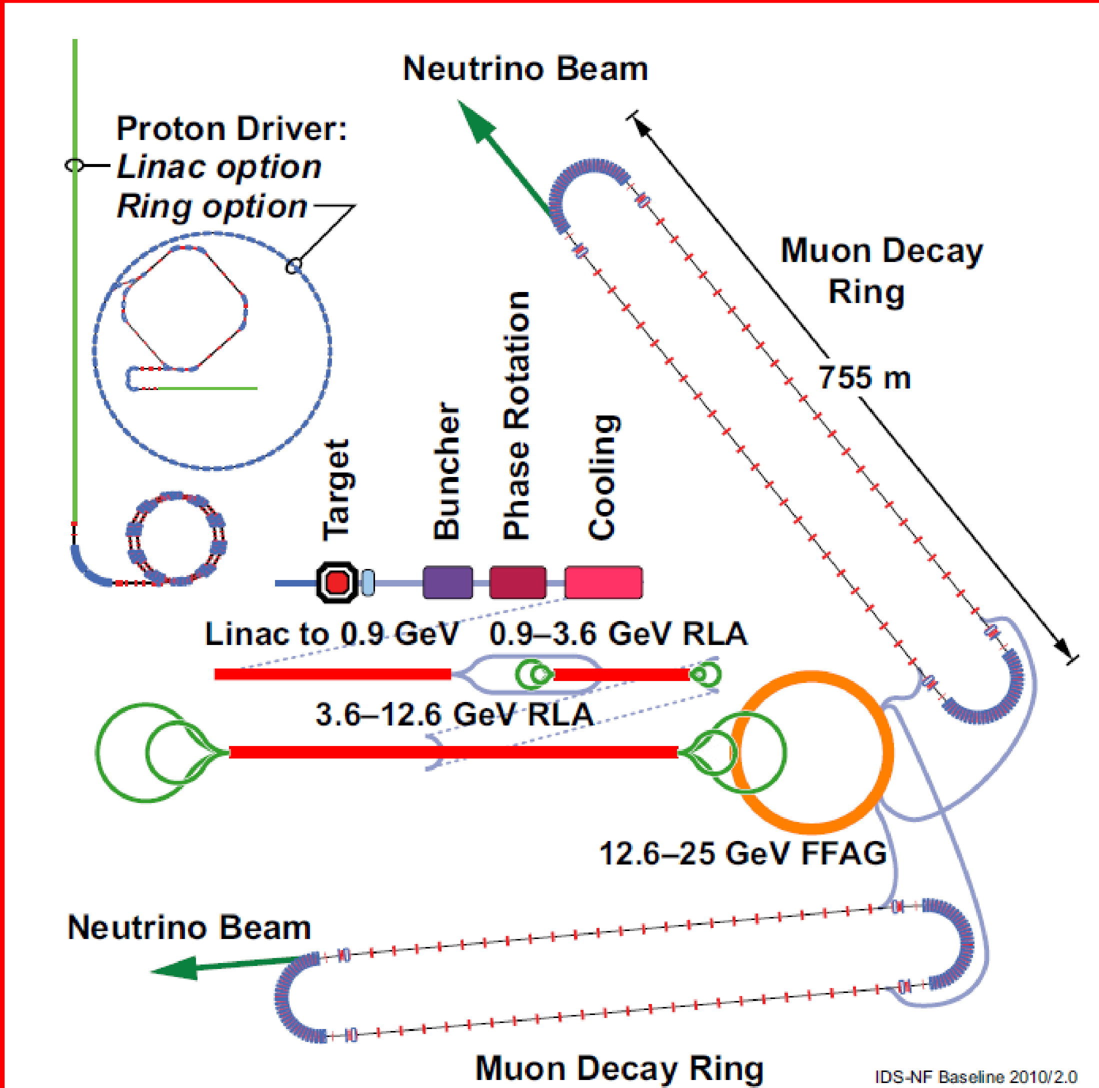
Neutrino Factory roadmap



The Neutrino Factory:

Accelerator facility:

Parameter	Value
Muon total energy	25 GeV
Production straight muon decays in 10^7 s	10^{21}
Maximum RMS angular divergence of muons in production straight	$0.1/\gamma$
Distance to intermediate baseline detector	3 000–5 000 km
Distance to long baseline detector	7 000–8 000 km



Garoby, Gollwitzer, Thomason

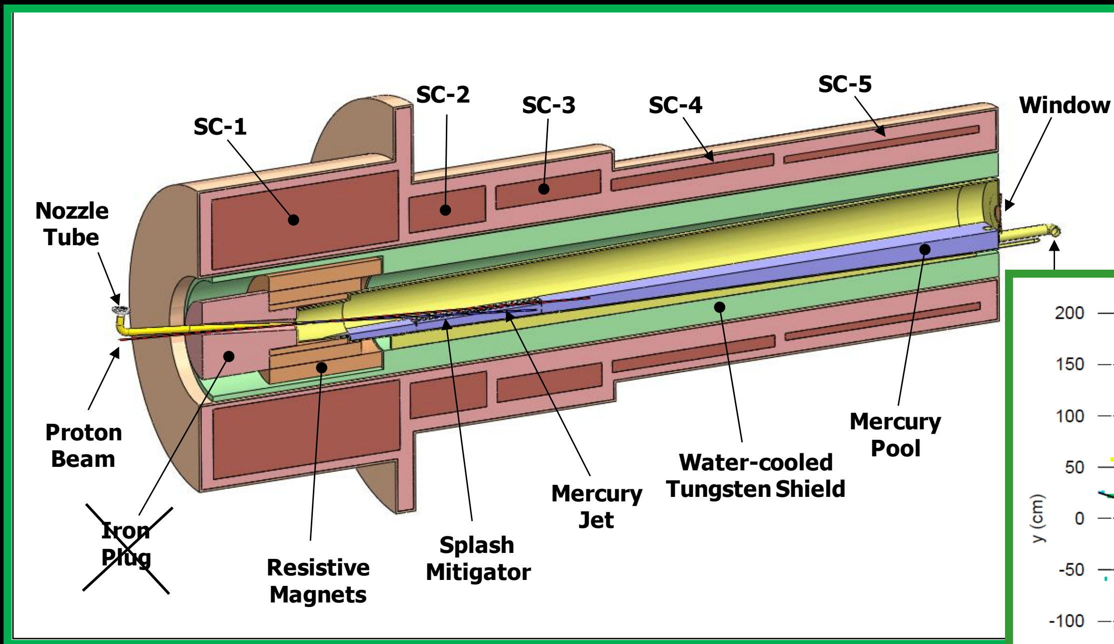
Proton driver:

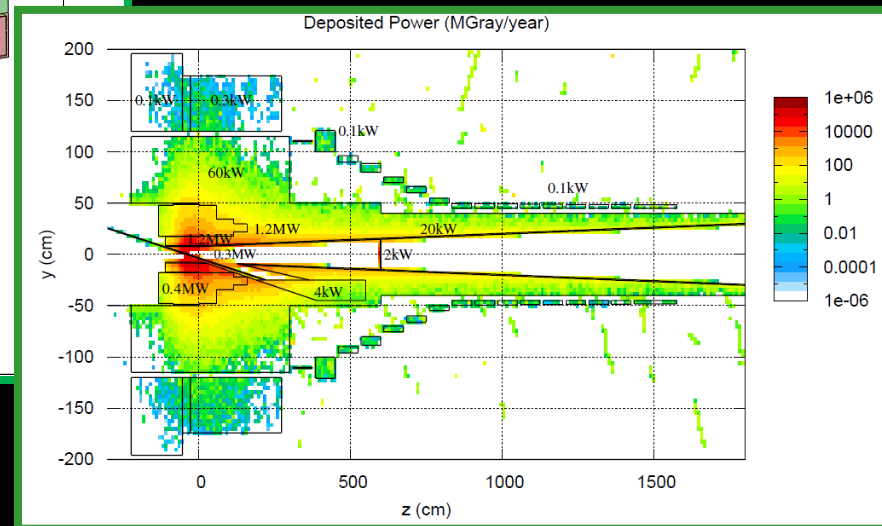
- Challenges:
  - High power; short proton-bunch length at ~10 GeV
- IDS-NF approach:
  - Consider two 'generic' options:
    - LINAC:
      - Possible development option for SPL (CERN) or Project-X (FNAL)
      - Requires accumulator & compressor rings
    - Rings:
      - Development option for J-PARC or RAL or possible 'green-field' option
      - Requires bunch compression

Parameter	Value
Kinetic energy	5–15 GeV
Average beam power	4 MW
	(3.125×10^{15} protons/s)
Repetition rate	50 Hz
Bunches per train	3
Total time for bunches	240 μs
Bunch length (rms)	1–3 ns
Beam radius	1.2 mm (rms)
Rms geometric emittance	< 5 μm
β^* at target	≥ 30 cm

Target/capture:

IPAC10: WEPE101, THPEC092





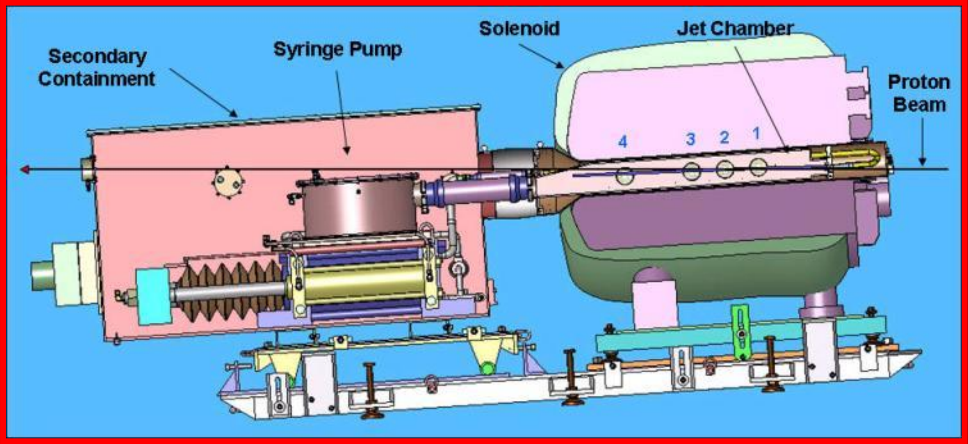
- **Baseline:**
  - Mercury jet, tapered solenoid for pion capture:
    - 20 T tapering to 1.5 T in ~13 m
- **Radiation shielding:**
  - Found to be inadequate
  - Progress towards improved design being made
- **Alternatives:**
  - Solid and powder jet maintained to mitigate technical risk

Parameter	Value
Target type	Free mercury jet
Jet diameter	8 mm
Jet velocity	20 m/s
Jet/solenoid axis angle	96 mrad
Proton beam/solenoid axis angle	96 mrad
Proton beam/jet angle	27 mrad
Capture solenoid (SC-1) field strength	20 T
Front-end π/μ transport channel field strength	1.5 T
Length of transition between 20 T and 1.5 T	15 m

Kirk, Densham, Back, Graves

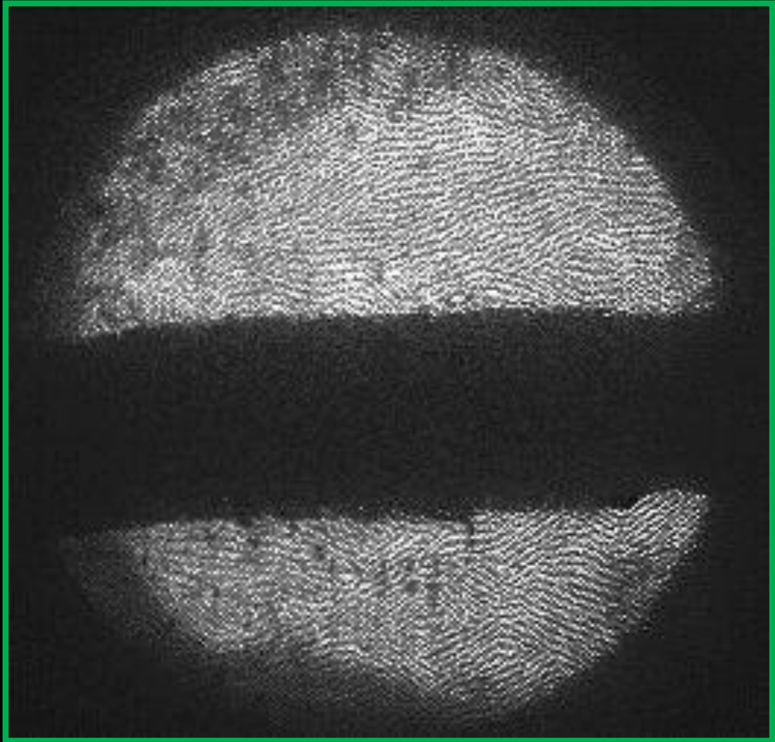
Baseline target: proof of principle: MERIT:

IPAC10: WEPE078



- 'Disruption length': 28 cm
- 'Refill' time: 14 ms
  - Corresponds to 70 Hz
- Hence:
  - Demonstrated operation at:
    - 60 kJ × 70 Hz = 8 MW

- 20 m/s liquid Hg jet in 15 T B field
- Exposed to CERN PS proton beam:
  - Beam pulse energy = 115 kJ
  - Reached 30 tera protons at 24 GeV

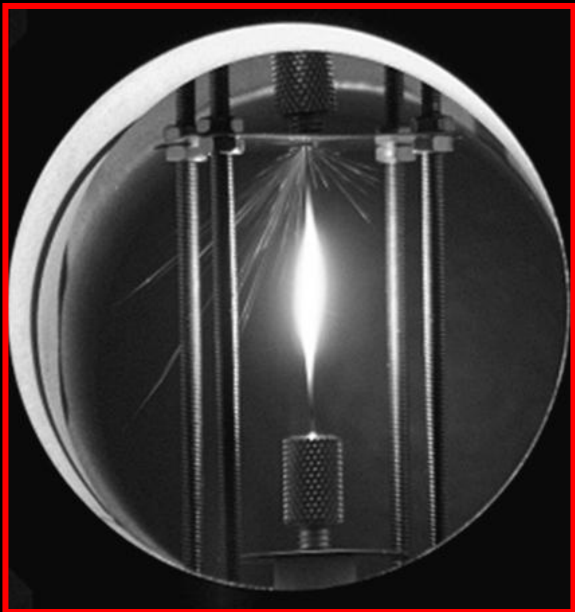


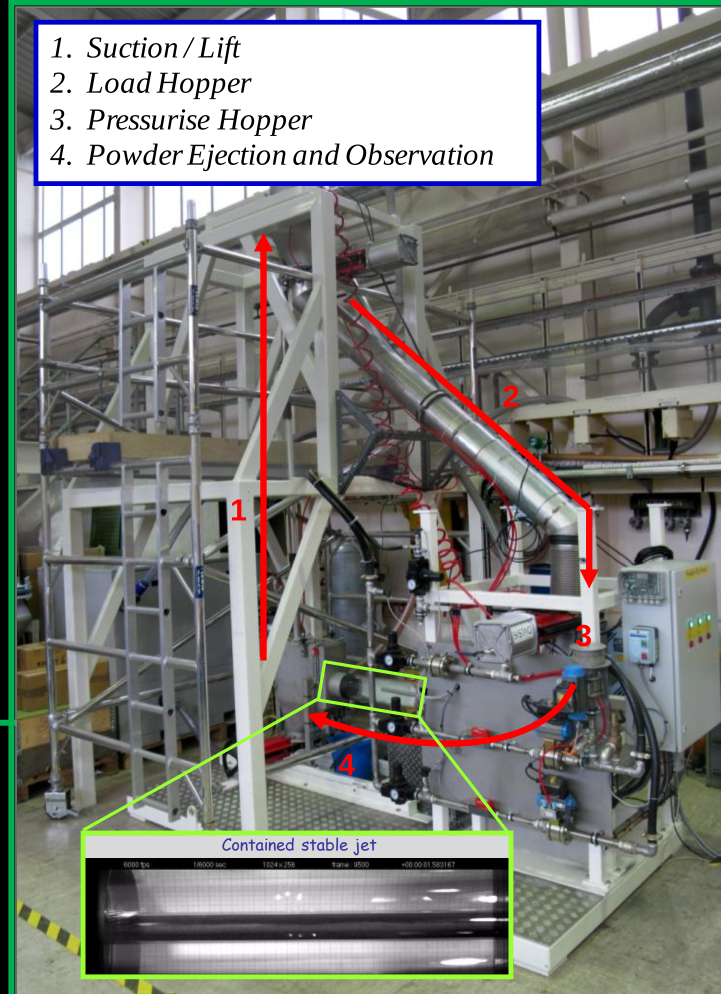
IPAC10: THPEC089, THPEC091

Solid and powder jet-targets:

- **Solid target:**
  - Lifetime limitation from beam-induced shock:
    - Investigated using rapid rise-time (kicker) power supply and thin wire
  - Measurements imply:
    - 2 cm diameter tungsten rod will survive > 10 yrs
  - Measurements of properties of W and Tn being prepared for publication
  - Working on rod-exchange mechanism

R. Edgecock, R. Bennett, G. Skoro





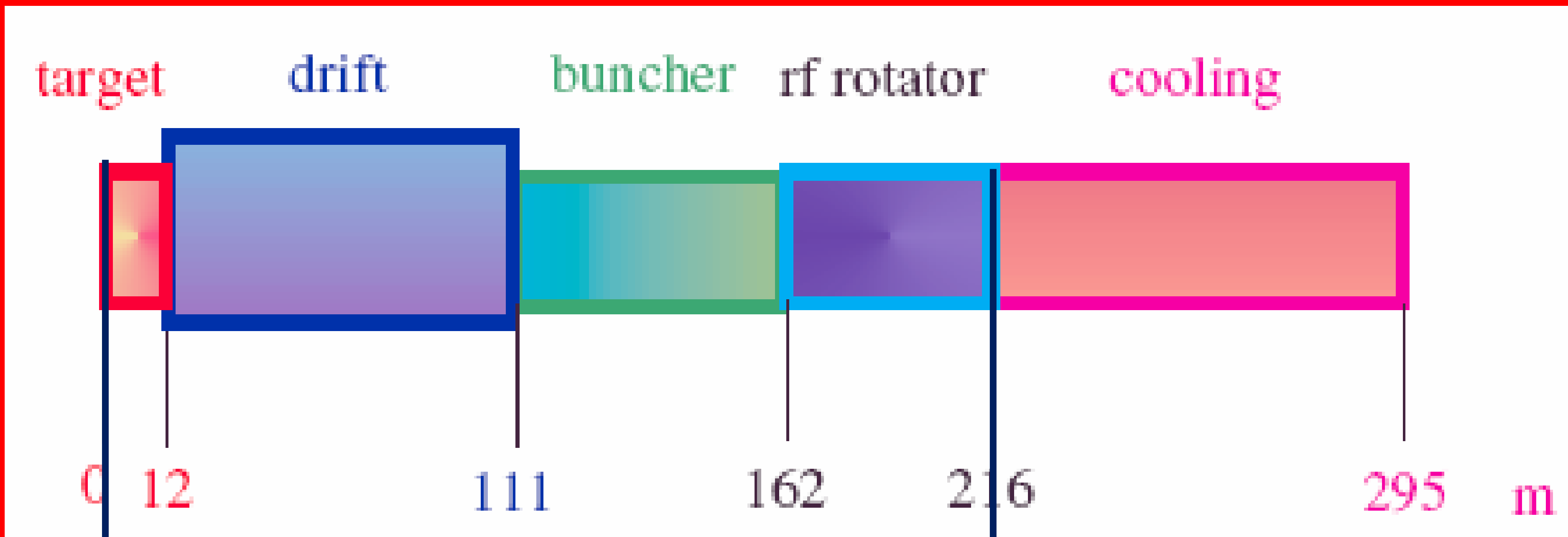
- **Tungsten-powder jet:**
  - (Jet) advantage:
    - Avoids issue of shock
  - (Solid) advantage:
    - Avoids issue of Hg handling
  - 'Bench-test' system under evaluation
  - Proof of principal system under consideration

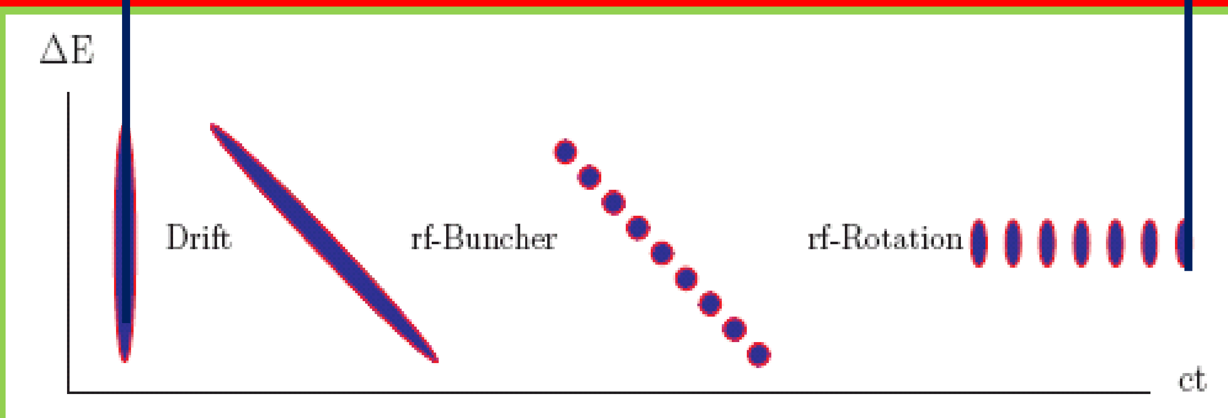
C. Densham et al.

Neuffer, Rogers

Muon front-end:

IPAC10: WEPE050, WEPE051, WEPE068, WEPE074, WEPE076





Key R&D:

- **Ionisation cooling:**
  - **MICE; proof of principle**
- **RF in magnetic field:**
  - **MuCool in MTA at FNAL**

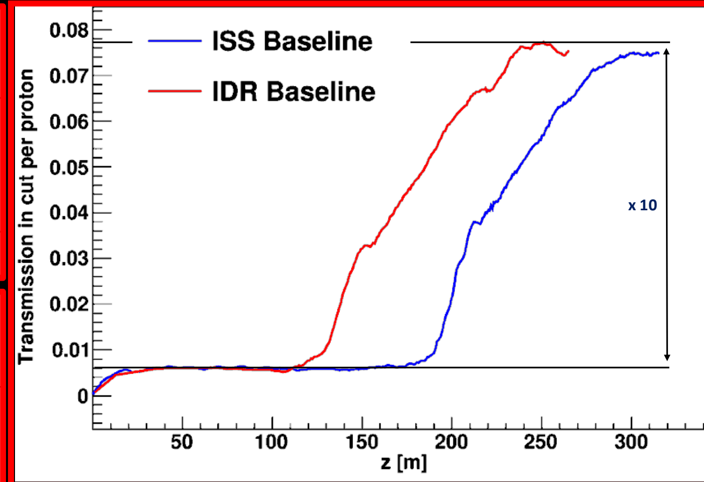
Neuffer, Rogers

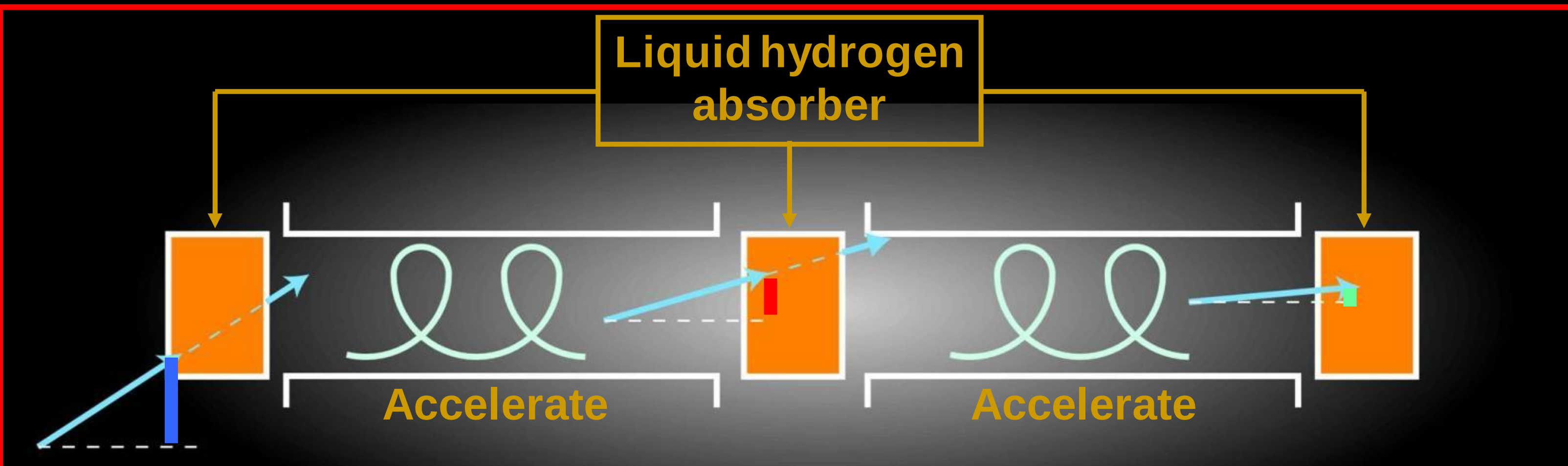
Muon front-end:

- Optimised bunching, phase-rotator, and ionisation-cooling lattice is reduced

	Length [m]	Number of cavities	Frequencies [MHz]	Number of frequencies	Peak gradient [MV/m]	Peak power requirements
Buncher	33	37	319.6 to 233.6	13	4 to 7.5	1–3.5 MW/freq.
Rotator	42	56	230.2 to 202.3	15	12	2.5 MW/cavity
Cooler	75	100	201.25	1	15	4 MW/cavity
Total	150 m	193	319.6 to 201.25	29	1000 MV	550 MW

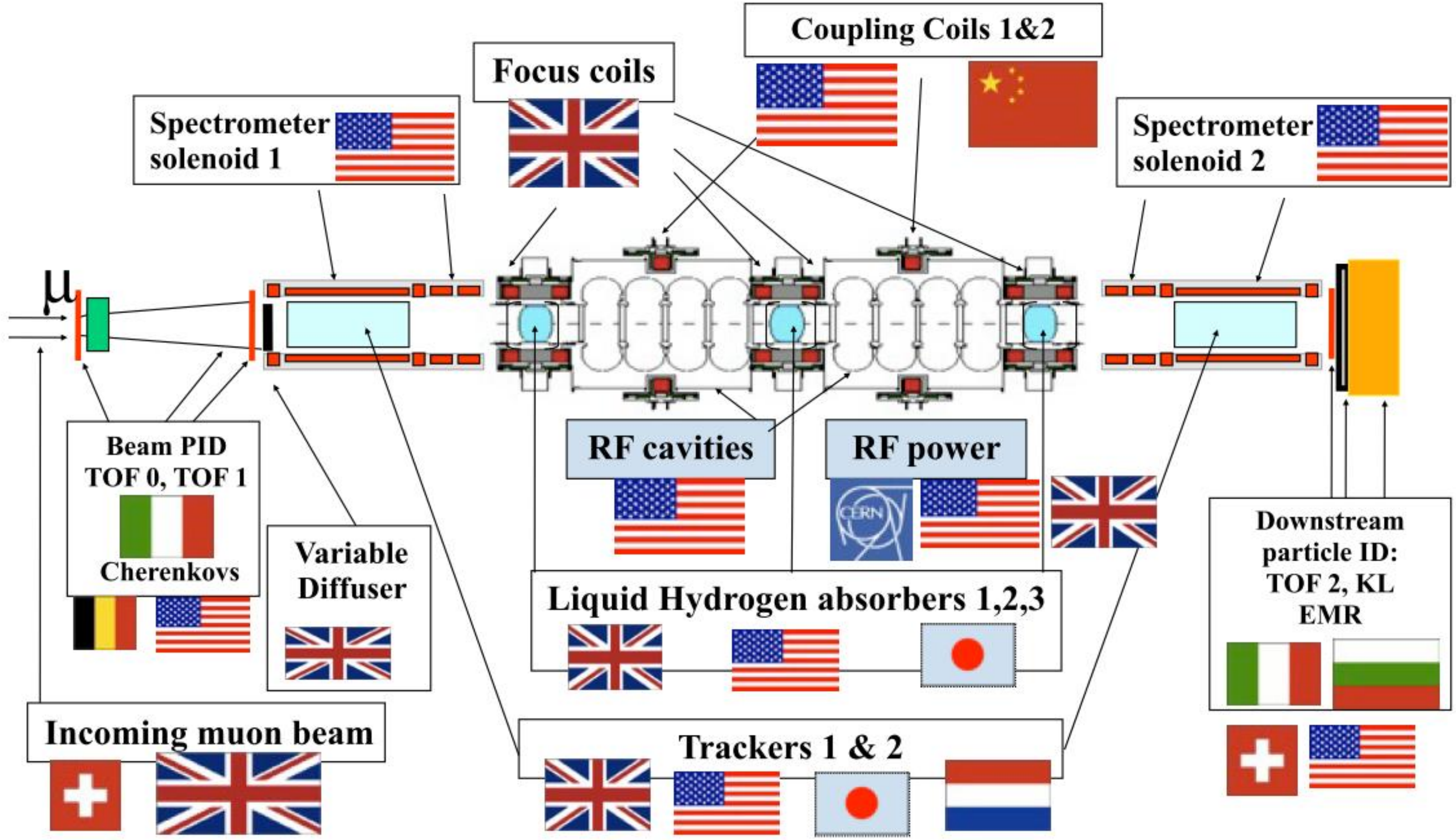
	Length [m]	Inner radius [m]	Radial thickness [m]	Current density [A/mm^2]	Number
Initial transport	0.5	0.68	0.04	47.5	180
Cooling channel	0.15	0.35	0.15	±107	100





$$\frac{d\varepsilon_n}{dX} = \frac{-\varepsilon_n}{\beta^2 E}\left\langle \frac{dE}{dX} \right\rangle + \frac{\beta_t (0.014\ \mathrm{GeV})^2}{2\beta^3 E m_\mu X_0}$$

MICE Collaboration



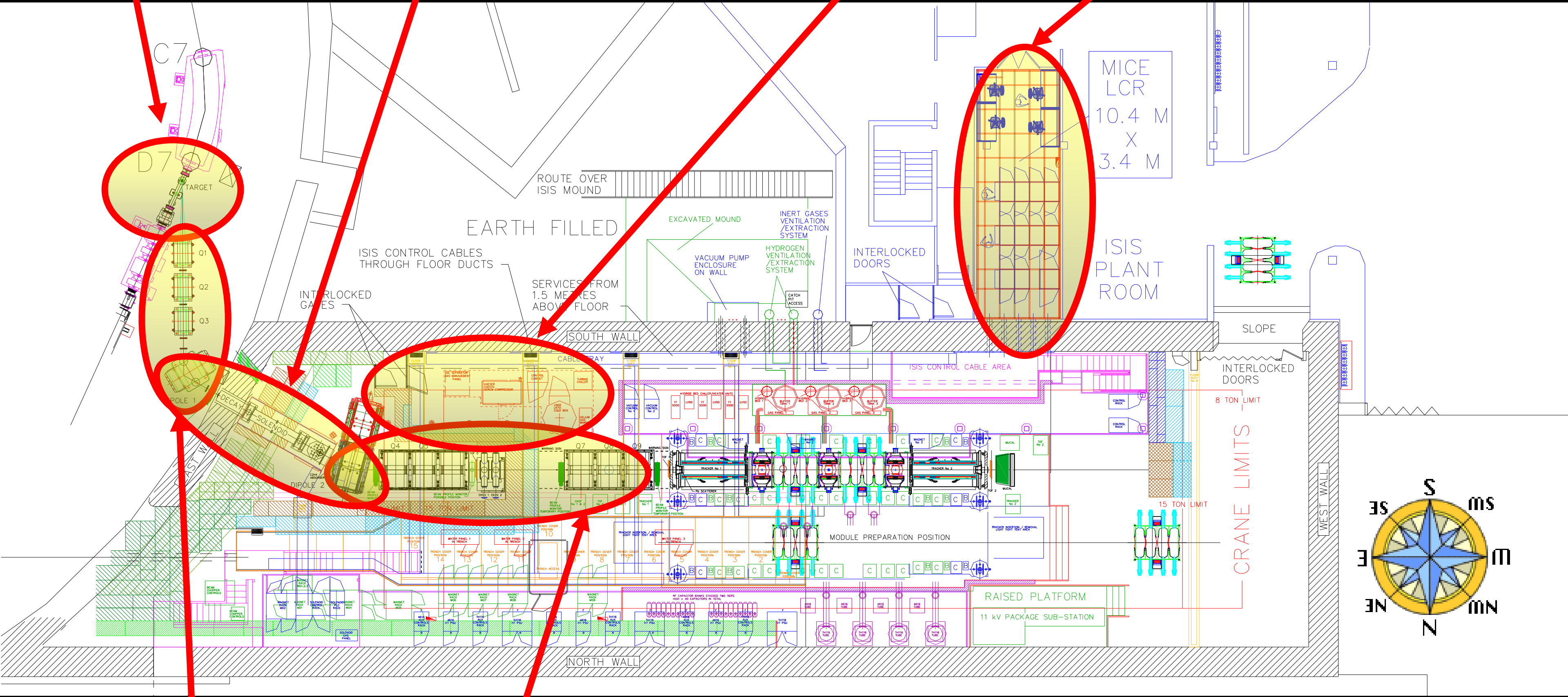
Status of MICE:

Target

Decay solenoid

Linde refrigerator

MICE Local Control Room



Upstream beam line

Downstream beam line

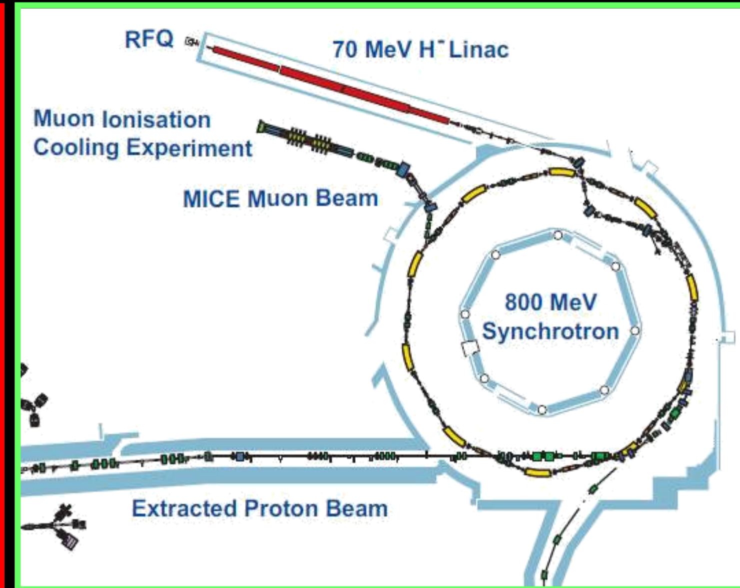
Instrumentation in place:

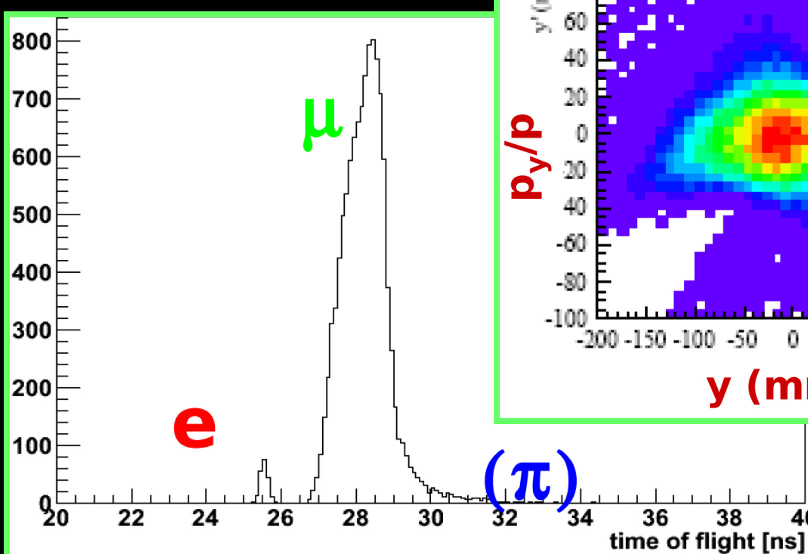
Beam profile monitors

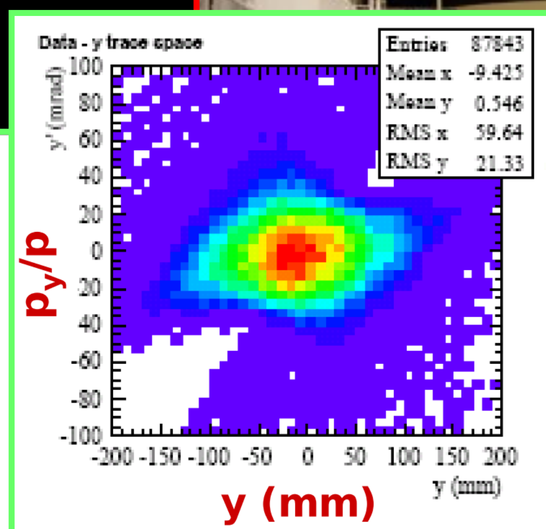
Trigger/rate scintillators

CKovA&B, TOF0,1, & 2, KL

- **MICE: proof of principle:**
  - Design, build, commission and operate a realistic section of cooling channel
  - Measure its performance in a variety of modes of operation and beam conditions
    - Results will allow Neutrino Factory complex to be optimised

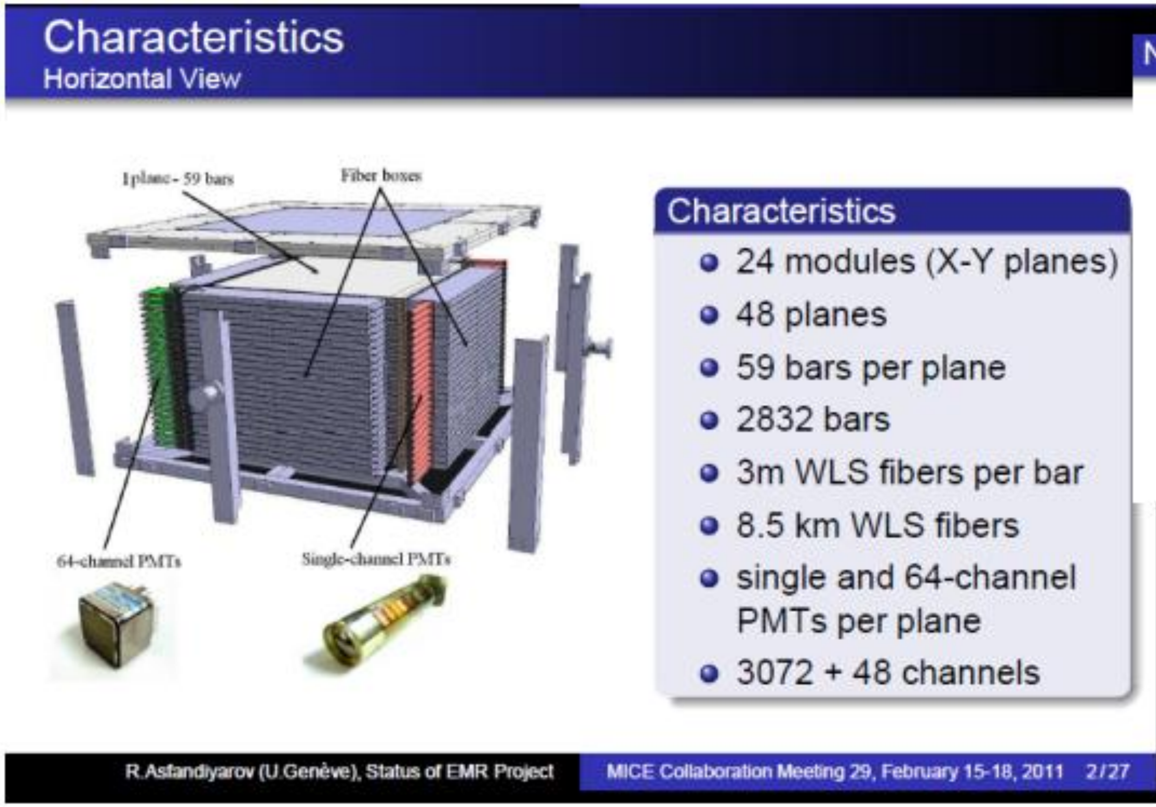


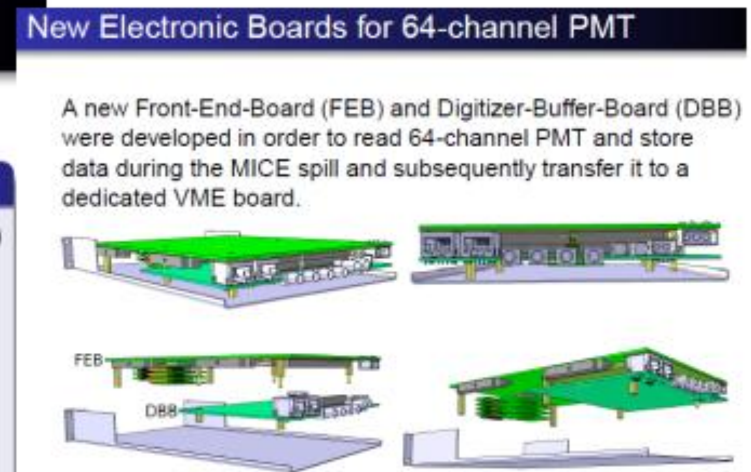




Electron Muon Ranger (EMR):

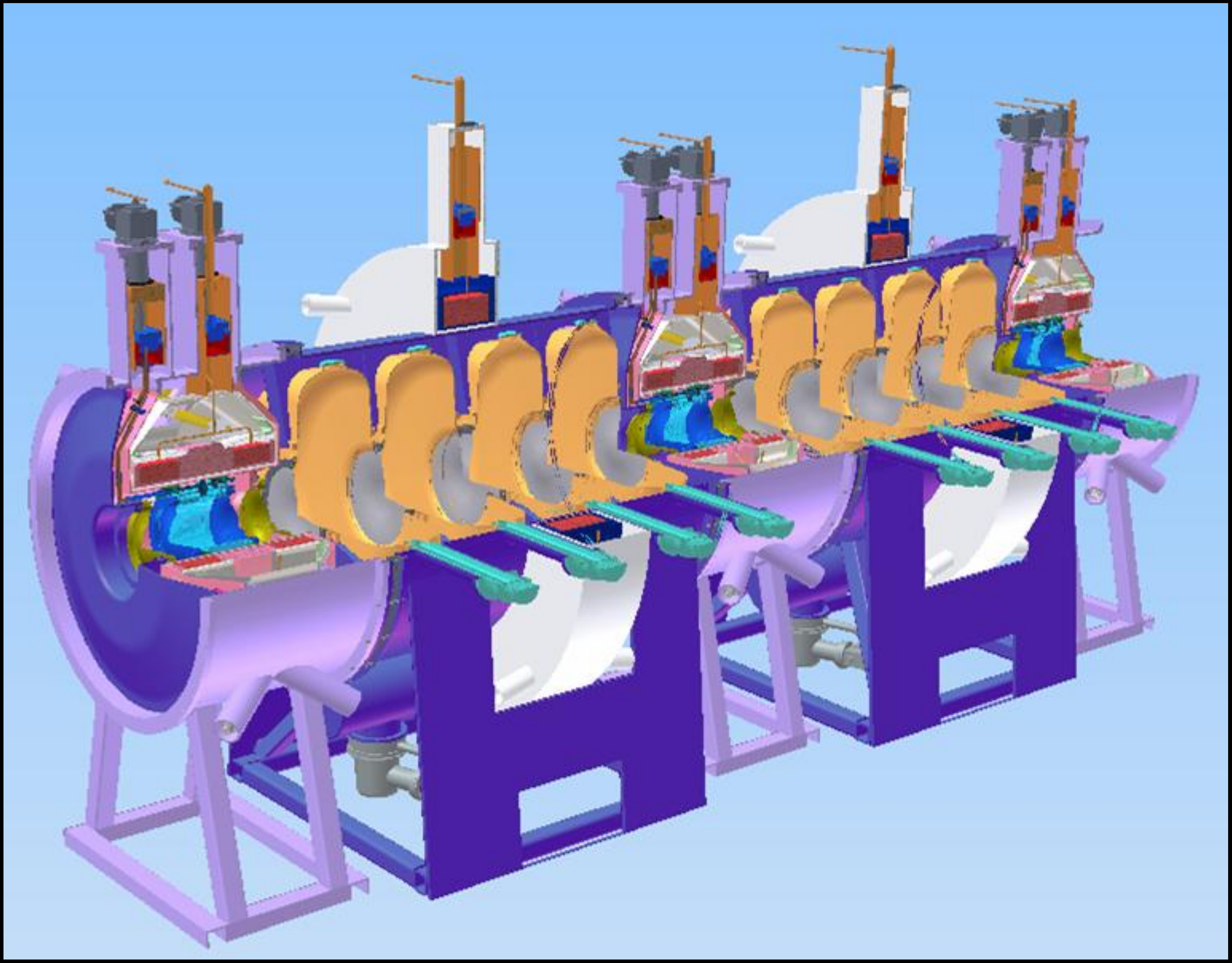
[Geneva, FNAL, Trieste/Como]





- Under construction at U Geneva
- Prototype to be tested at MICE this summer

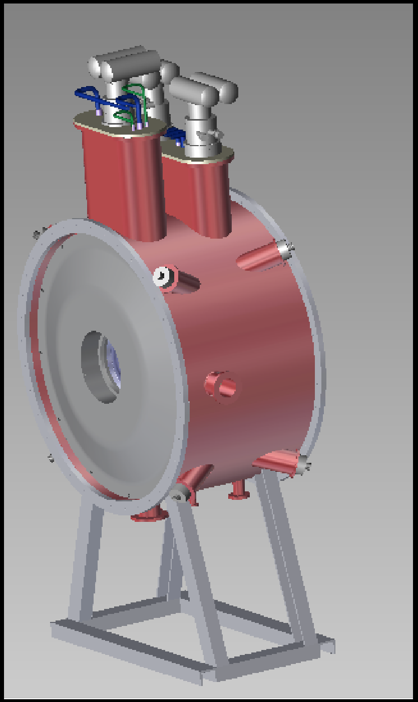
Cooling channel:

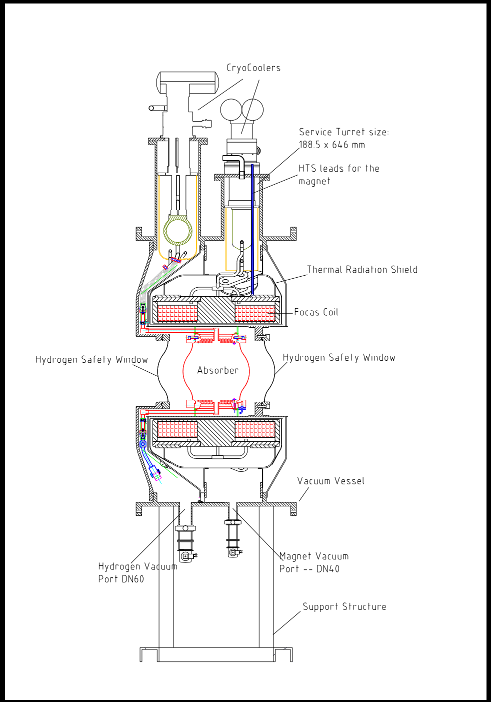


Oxford, RAL,
KEK, Mississippi

Absorber/focus-coil module:

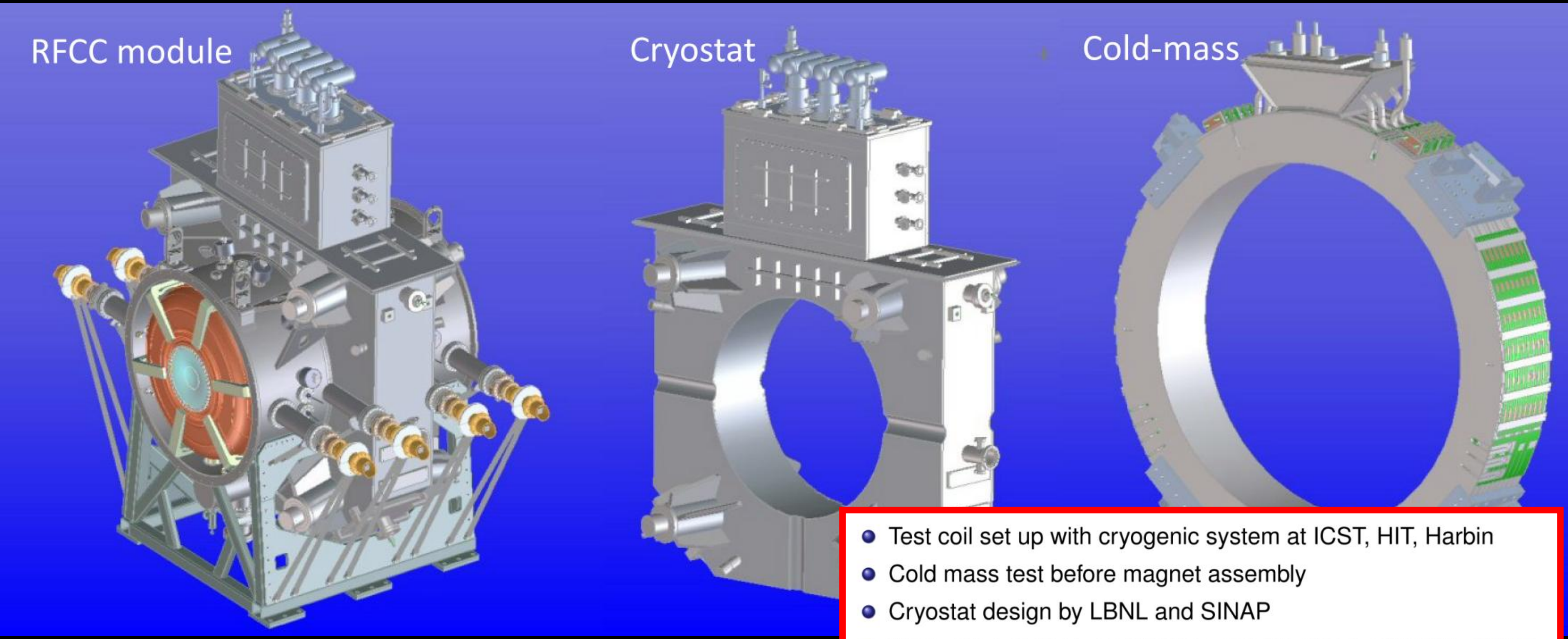
- Focus coil module:
  - Under construction at TESLA
  - Presently preparing for winding first set of coils
  - First module, Q3 2011
- Absorber:
  - Prototype tested at KEK
  - Production underway:
    - Will match (be ahead of!) focus-coil schedule
  - Windows in production at Mississippi



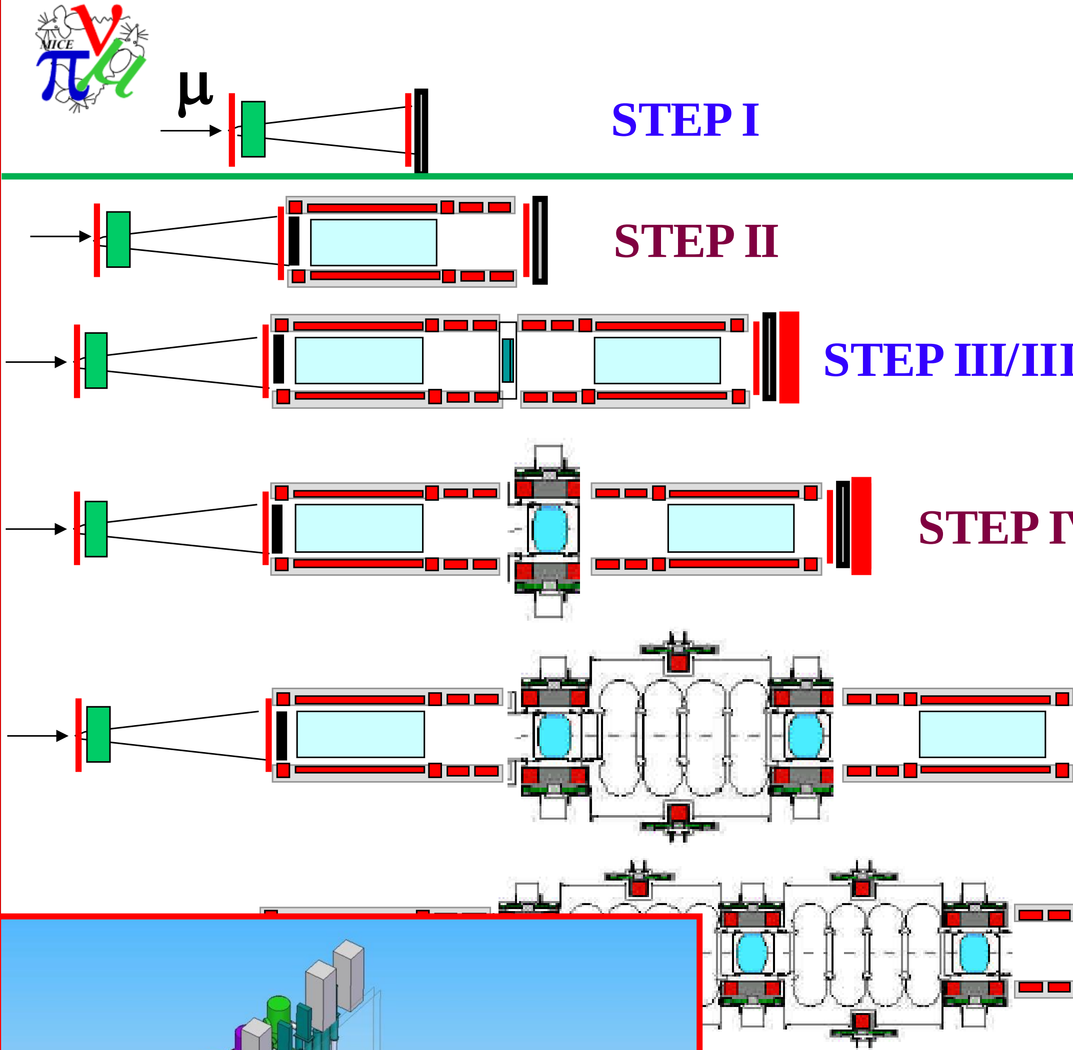


LBNL

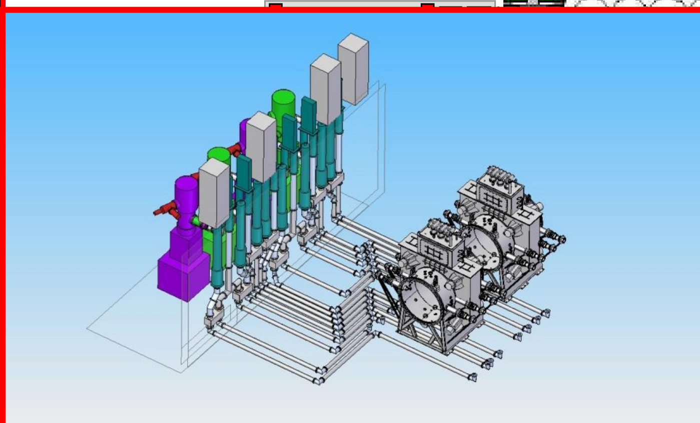
RFCC module: cavities:



- Test coil set up with cryogenic system at ICST, HIT, Harbin
- Cold mass test before magnet assembly
- Cryostat design by LBNL and SINAP
- Production at Qi Huan (Beijing); 1st (MuCool) coil 2011, MICE coils 2012

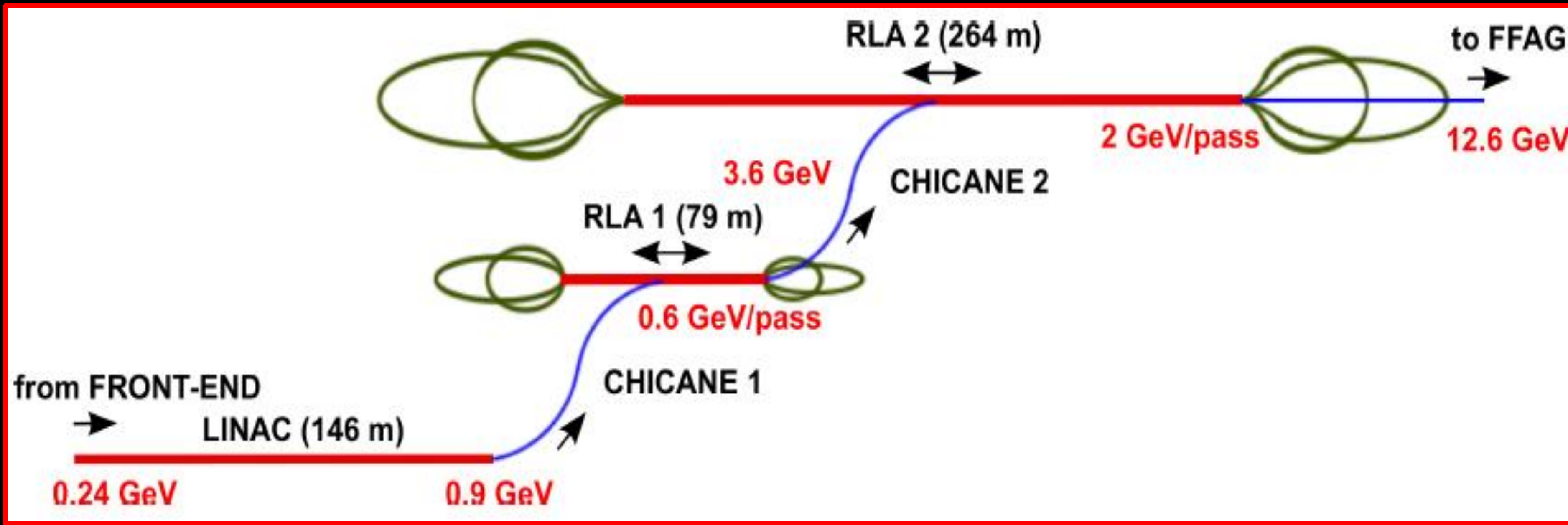


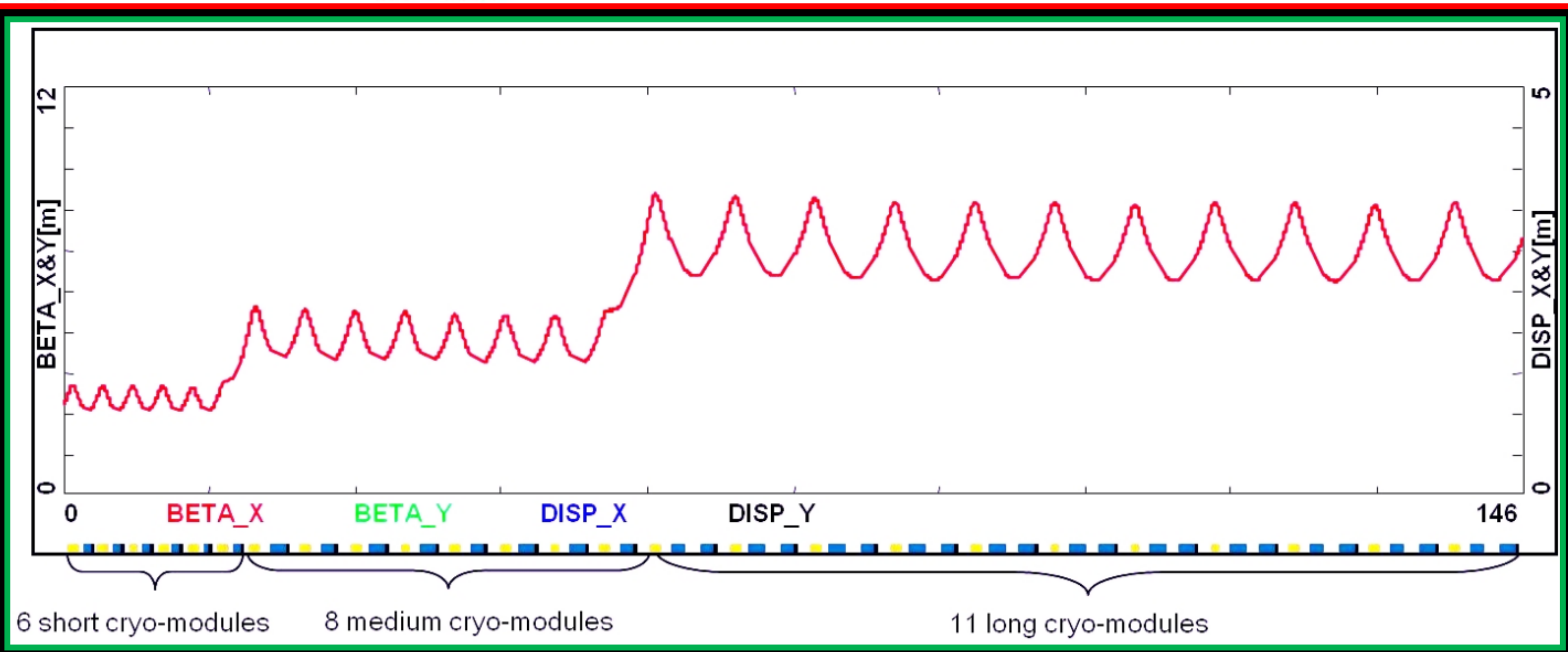
Step IV:
2 solenoids,



Rapid acceleration!

Muon acceleration: [1]:

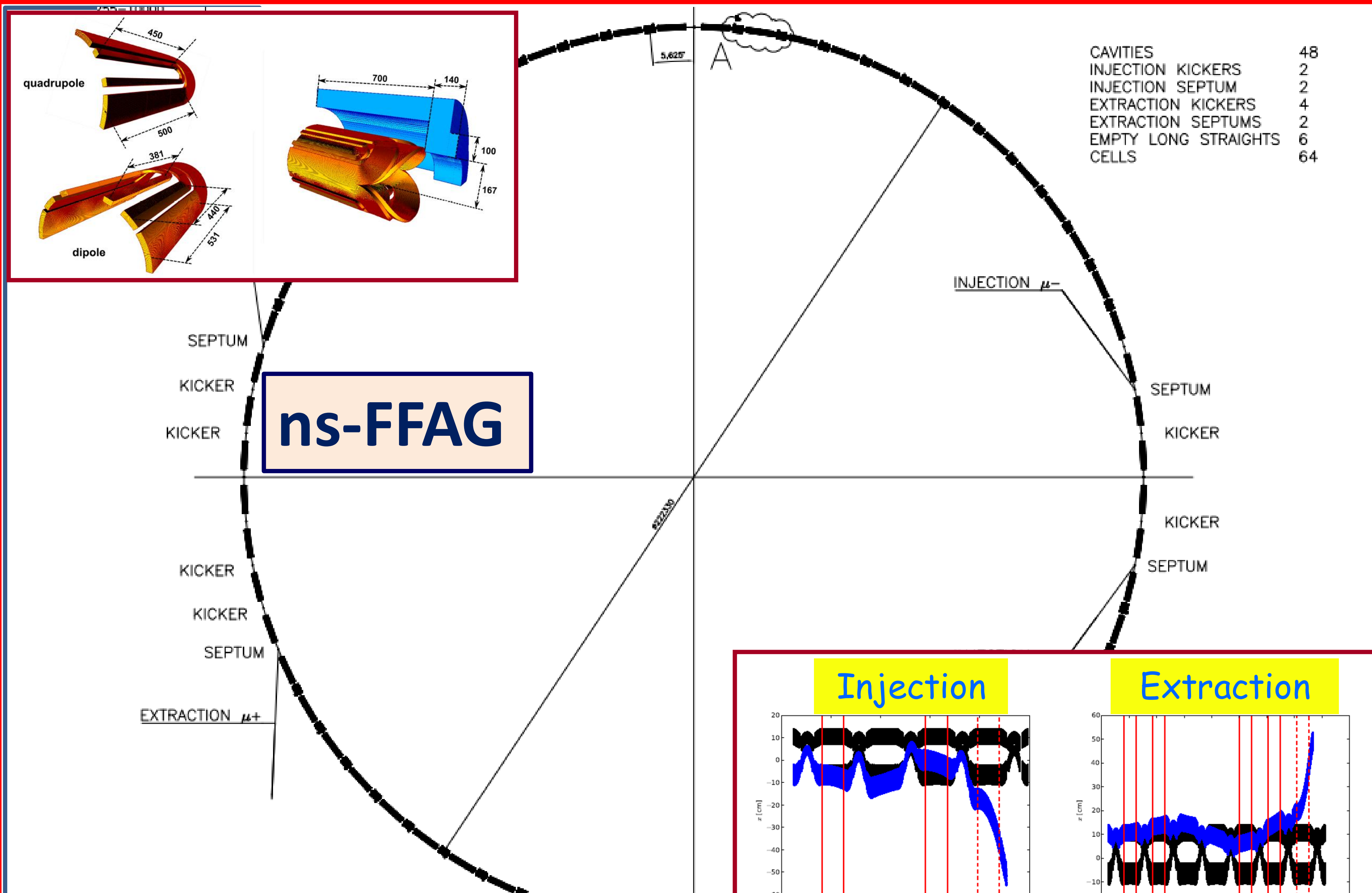




Bogacz, Bontoiu, Pozimski

Rapid acceleration!

Muon acceleration: [2]:

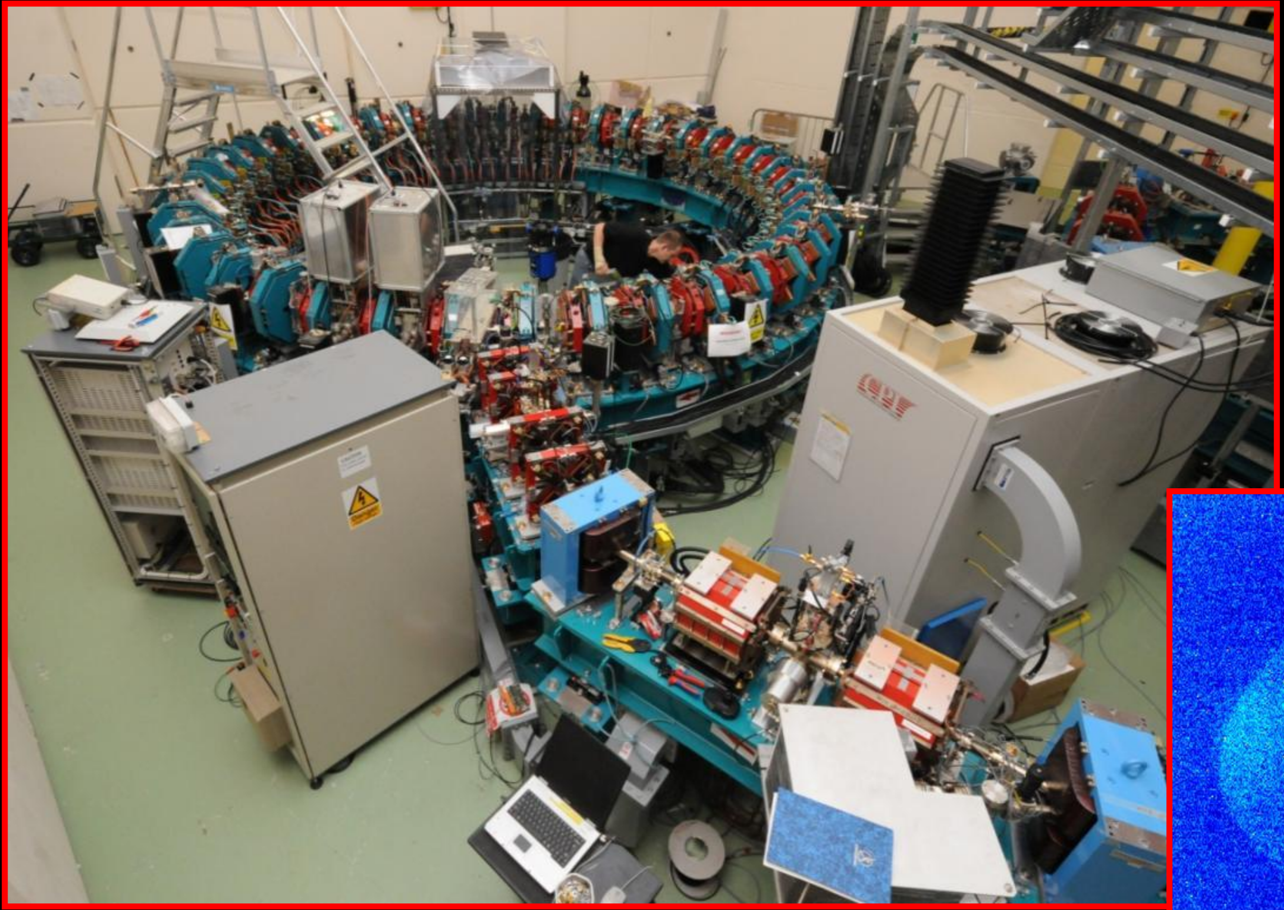


Berg, Machida, Kelliher, Pasternak

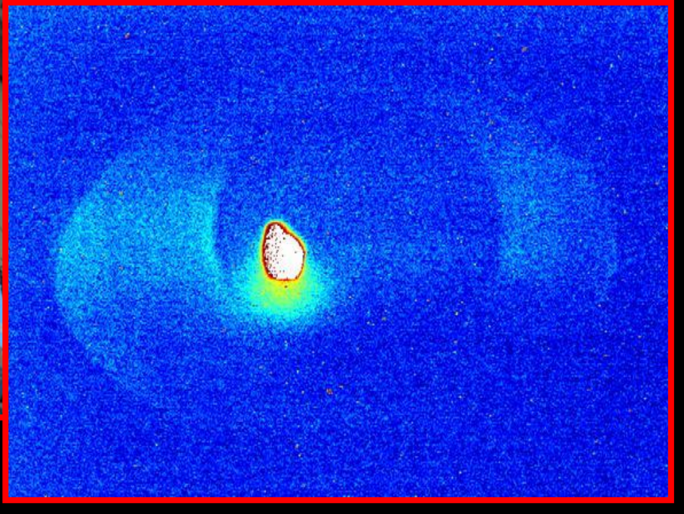
Muon acceleration: proof of principle:

- EMMA; almost complete at Daresbury Lab.
  - Electron Model of Muon Acceleration
    - Aka:
      - Electron Model of Many Applications

DL, RAL, CI, BNL, TRIUMF, FNAL, JAI CERN, GRENOBLE

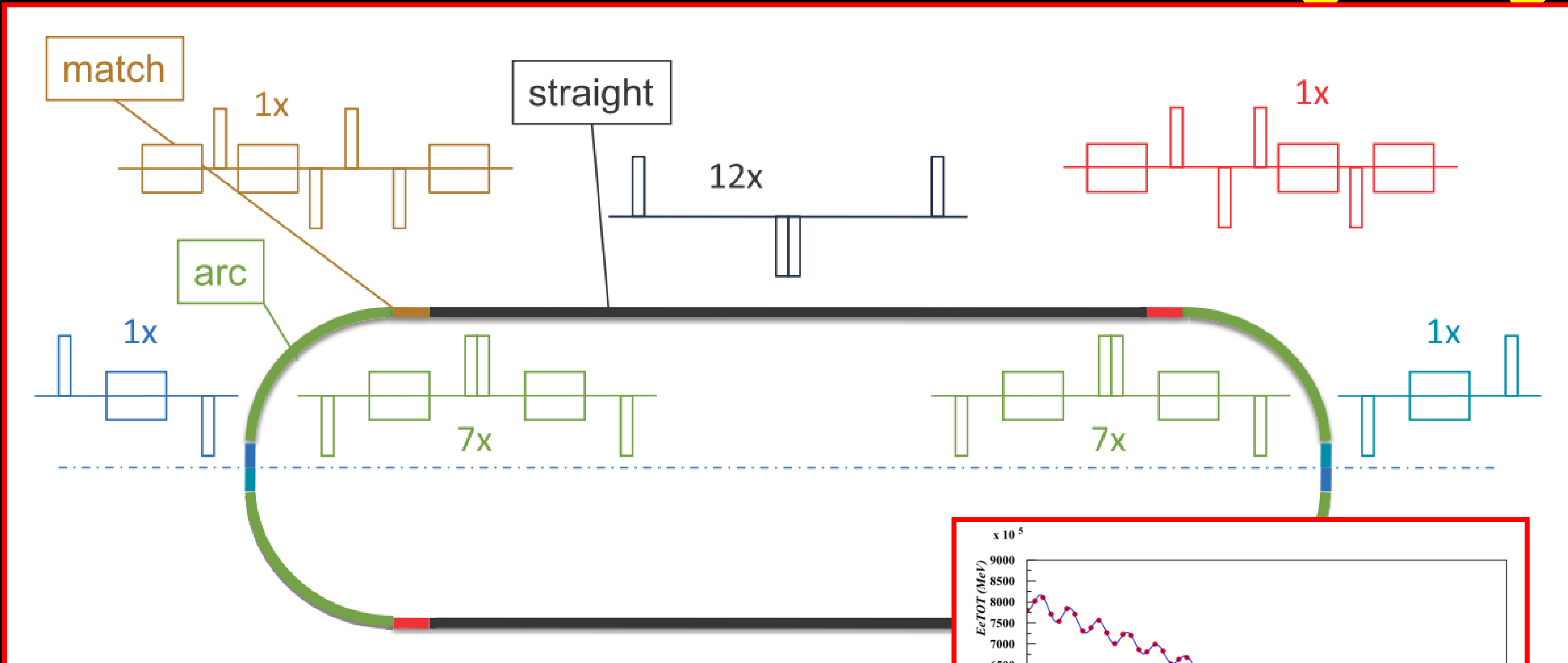


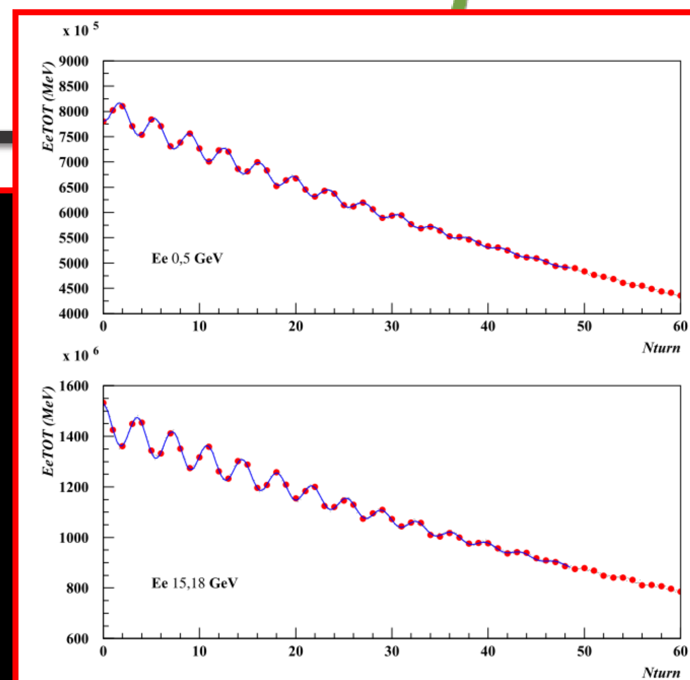
- Installation complete;
- Commissioning underway
- First extracted beam: 15Mar11



Apollonio, Johnstone, Prior

Muon storage ring:

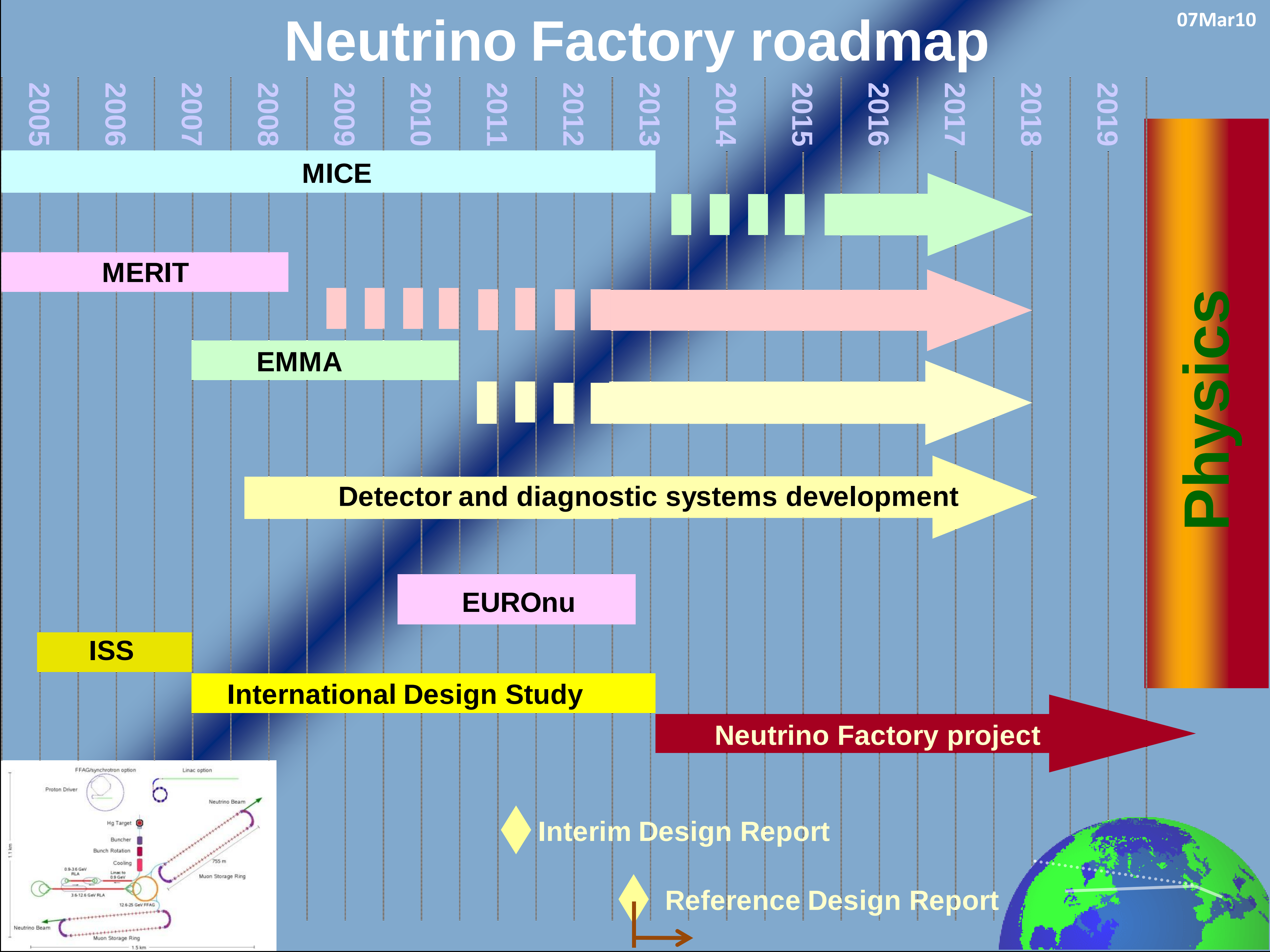




- Detailed studies of:
  - Dynamic aperture
  - Instrumentation:
    - Stored muon energy measurement via beam polarisation;
    - Divergence and current

Neutrino Factory:

Conclusions:


07Mar10
Neutrino Factory roadmap
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
MICE
MERIT
EMMA
Detector and diagnostic systems development
EUROnu
ISS
International Design Study
Neutrino Factory project
Physics
Interim Design Report
Reference Design Report
FFAG/synchrotron option
Linac option
Proton Driver
Neutrino Beam
Hg Target
Buncher
Bunch Rotation
Cooling
755 m
Muon Storage Ring
0.9-3.6 GeV RLA
Linac to 0.9 GeV
3.6-12.6 GeV RLA
12.6-25 GeV FFAG
Neutrino Beam
Muon Storage Ring
1.5 km
1.1 km

Conclusions:

- The Neutrino Factory:
  - Best discovery reach
  - Best precision:
    - But need to define agreed figure of merit
  - Best sensitivity to non-standard interactions
- The International Design Study for the Neutrino Factory:
  - Collaboration energetic and ambitious!
    - IDR 2011; RDR 2012/13
  - EUROnu: encompasses and coordinates European contributions
- Baseline established and documented in the IDR
  - Alternatives to baseline retained to mitigate risks
- Scientific imperative:
  - Make the Neutrino Factory an option for the field!