Univ. & INFN Napoli,
Italy

MICE
…and the next generation of muon beams for particle physics

Contents

- Muon beams for particle physics
- Ionization cooling
- Muon Ionization Cooling Experiment (MICE)
- Vision for a cold, bright future for muon beams
- Conclusions

MICE and the next generation of muon beams for particle physics

MUON BEAMS
FOR PARTICLE PHYSICS

Muon rings have the potential to

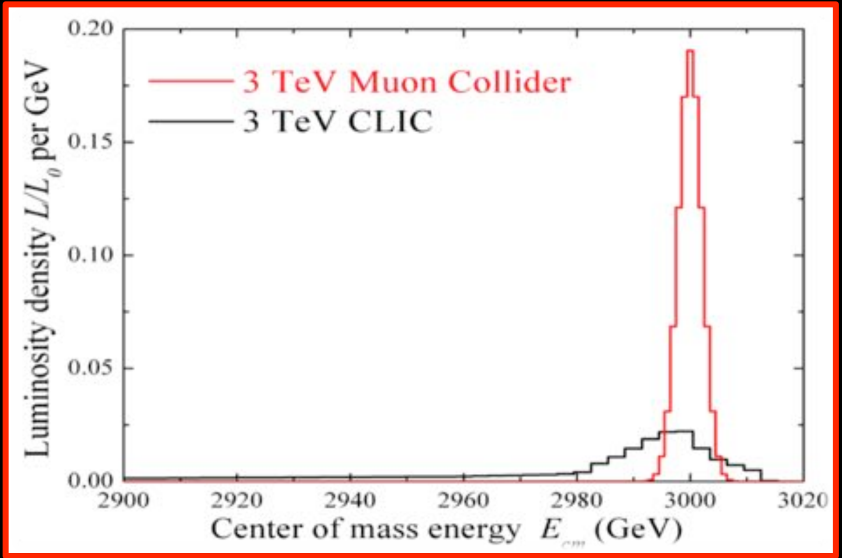
- Serve neutrino physics with intense beams that have:
  - BOTH 50% (anti) muon and 50% electron neutrinos
  - Precisely known flavour content
  - Precisely known energy spectrum

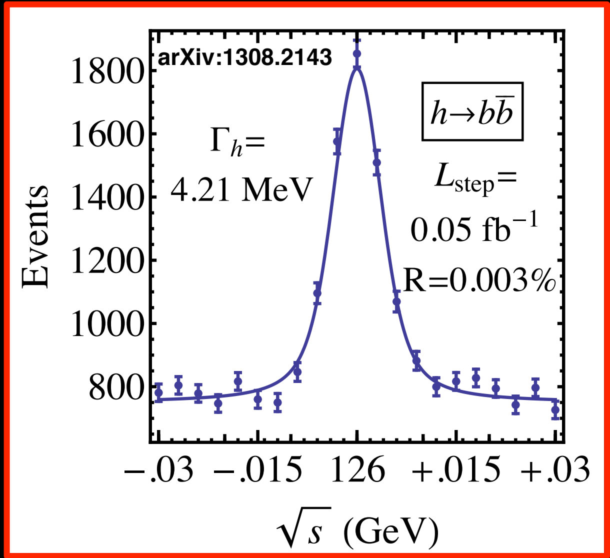
- Provide multi-TeV lepton-anti-lepton collisions:
  - With extremely small energy spread;
  - Most cost-effective means to achieve E_{CM} > 1. TeV

- and sub-TeV lepton-anti-lepton Higgs factories

Muon beams; basis of advantages

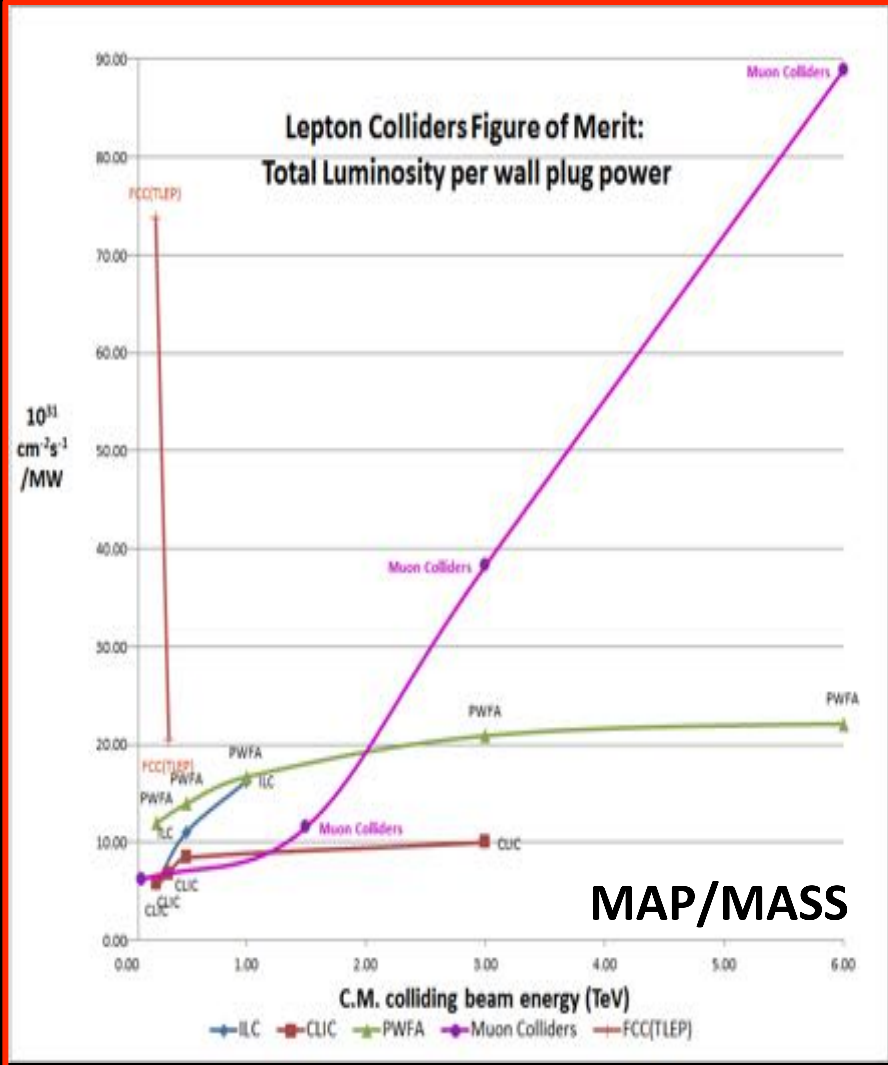
- **Muon mass:**
  - m_μ = 106 MeV/c^2 ≈ 200 * m_e
- **Consequences:**
  - Negligible synchrotron radiation during acceleration:
    - Rate ∝ m^{-4} ⇒ reduction of factor 5 × 10^{-10} over e
  - Strong coupling to Higgs:
    - Production rate ∝ m^2 ⇒ enhancement 5 × 10^4 over e^+e^-





Muon Collider:

- **Optimum route to multi-TeV lepton-anti-lepton collisions:**
  - **Muon mass; 200 times that of the electron mitigates:**
    - **Synchrotron radiation;**
    - **Beamsstrahlung**
  - **Muon rigidity allows efficient acceleration**
    - **Results in cost-efficient acceleration to very high energy**
- **Luminosity critical:**
  - **Muon-beam cooling essential**



A COMPLETE DEMONSTRATOR OF A
COOLED-MUON HIGGS FACTORY

Monday, 18 May 2015 at 3:30 pm
Fermilab, Ramsey Auditorium

In analogy with the discovery of the W and Z with hadrons and the subsequent study of the Z resonance in the pure s-state with LEP, the recent discovery of the Higgs particle of 125 GeV has revived the interest in the so-called second generation Higgs factory. However the direct production of the H^0 scalar resonance in the s-state has a remarkably small, narrow width, since $\Delta E/E < 4$ MeV / 125 GeV = 3.2×10^{-5}. We describe here a $\mu^+\mu^-$ collider at a modest energy of 62.5 GeV and the adequate cooled muon intensity of about 6×10^{12} muons of each sign, a repetition rate of 15-50 p/s and $L = 10^{32}$ cm^{-2} s^{-1}, corresponding to about 10'000 H^0 for each detector x year. Its partial widths can be studied with remarkable accuracies. With the help of the decay frequency of the polarized muon decay electrons, the H^0 mass itself can also be measured to about ±100 keV, i.e. $\Delta m/m \approx 10^{-6}$.

The next modest step, prior to but adequate for the subsequent H^0 physics programme, could be the practical realization of an appropriate muon cooling demonstrator. Starting from a conventional pion beam, the required longitudinal and transverse emittances are achieved with a cascade of two unconventional but very small muon rings of few meters radius. Low momentum muons of about 250 MeV/c, initially with $\Delta p/p \approx 0.1$, are cooled in a first ring, extracted and ionization cooled to about 70 MeV/c, and cooled ultimately in a second small ring up to a longitudinal momentum spread of 0.7 MeV/c r.m.s. The operation of the demonstrators may be initially explored and fully demonstrated with the help of a modest muon beam already available in a number of different accelerators.

The additional but relatively conventional components necessary to realize the facility with the appropriate muon current and luminosity should then be constructed only after this initial cooling experiment has been successfully demonstrated. The ultimate $\mu^+\mu^-$ collider for a Higgs Factory may be situated within the existing CERN site or elsewhere.

Nobel Laureate
Prof. Carlo Rubbia

Muon Accelerator Program

U.S. DEPARTMENT OF ENERGY | Office of Science

Fermilab

http://map.fnal.gov/events/CarloRubbia.shtml

Muon beams; basis of advantages

- **Muon decay described precisely by SM**

μ

$J = \frac{1}{2}$

Mass $m = 0.1134289267 \pm 0.0000000029$ u
Mass $m = 105.6583715 \pm 0.0000035$ MeV
Mean life $\tau = (2.1969811 \pm 0.0000022) \times 10^{-6}$ s
$\tau_{\mu^+}/\tau_{\mu^-} = 1.00002 \pm 0.00008$
$c\tau = 658.6384$ m
Magnetic moment anomaly $(g-2)/2 = (11659209 \pm 6) \times 10^{-10}$
$(g_{\mu^+} - g_{\mu^-})\ /\ g_{\text{average}} = (-0.11 \pm 0.12) \times 10^{-8}$
Electric dipole moment $d = (-0.1 \pm 0.9) \times 10^{-19}$ e cm

Decay parameters [b]

$\rho = 0.74979 \pm 0.00026$
$\eta = 0.057 \pm 0.034$
$\delta = 0.75047 \pm 0.00034$
$\xi P_\mu = 1.0009^{+0.0016}_{-0.0007}$ [c]
$\xi P_\mu \delta/\rho = 1.0018^{+0.0016}_{-0.0007}$ [c]
$\xi' = 1.00 \pm 0.04$
$\xi'' = 0.7 \pm 0.4$
$\alpha/A = (0 \pm 4) \times 10^{-3}$
$\alpha'/A = (-10 \pm 20) \times 10^{-3}$
$\beta/A = (4 \pm 6) \times 10^{-3}$
$\beta'/A = (2 \pm 7) \times 10^{-3}$
$\overline{\eta} = 0.02 \pm 0.08$

PDG 2014

- **Charge to mass ratio favourable:**
  - **Readily tune neutrino-beam energy**

Neutrino Factory

- **Optimise discovery potential for CP and MH:**
  - Requirements:
    - Large ν_e ($\bar{\nu}_e$) flux
    - Detailed study of sub-leading effects
- **Unique:**
  - Large, high-energy ν_e ($\bar{\nu}_e$) flux
    - Muon-beam cooling huge advantage
  - Optimise event rate at fixed L/E
    - Optimise MH sensitivity
    - Optimise CP sensitivity

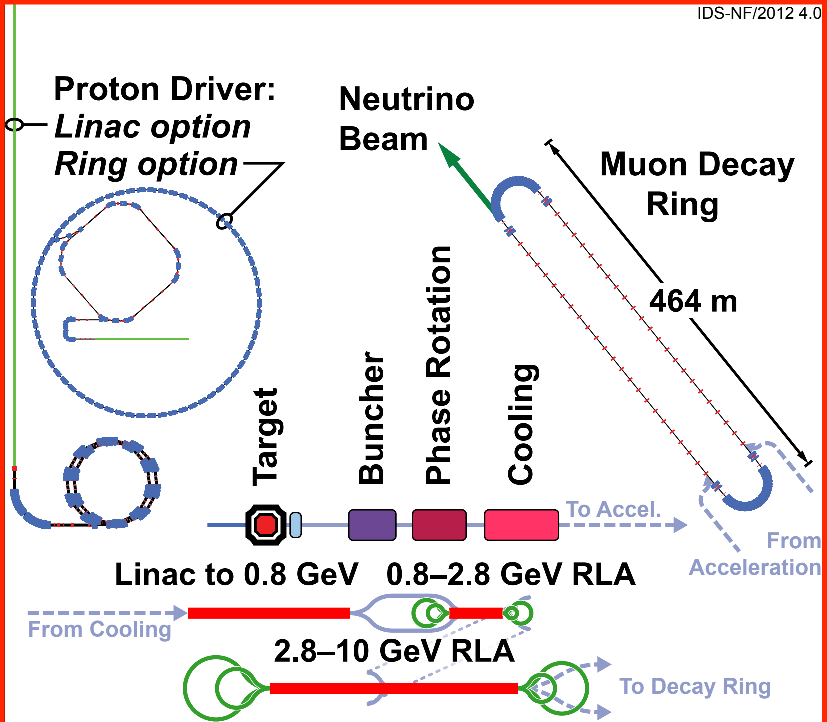
	Appearance $\nu_\alpha \to \nu_\beta \quad \bar{\nu}_\alpha \to \bar{\nu}_\beta$
CPT:	$P(\nu_\alpha \to \nu_\beta) = P(\bar{\nu}_\beta \to \bar{\nu}_\alpha)$; $P(\nu_\alpha \to \nu_\alpha) = P(\bar{\nu}_\alpha \to \bar{\nu}_\alpha)$
CPiV:	$\frac{P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}$
MH:	$P(\nu_\alpha \to \nu_\beta)$; $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ $[P(\nu_\alpha \to \nu_\alpha)]$
$(\theta - \frac{\pi}{4})$:	$P(\nu_\alpha \to \nu_\beta)$; $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ and $P(\nu_\alpha \to \nu_\alpha)$

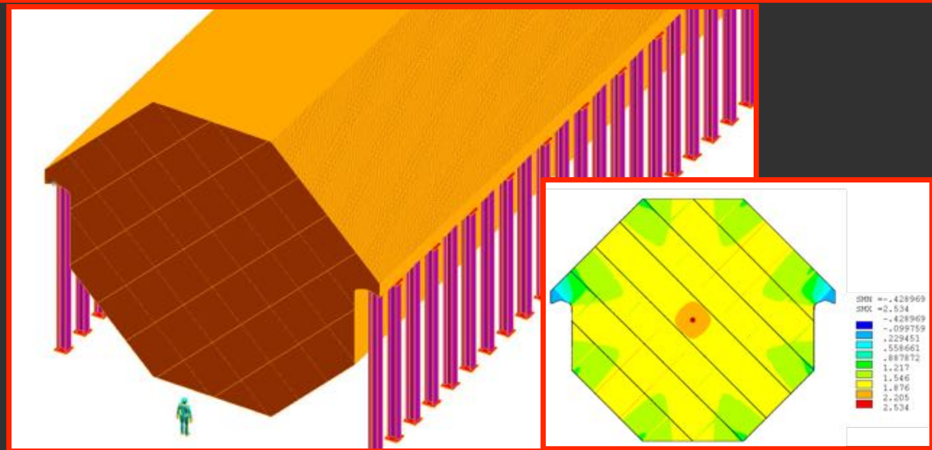
arXiv:1112.2853

Neutrino Factory:

- Two approaches:
  - Optimise *L* and *E* to match magnetised Fe/scintillator
    - IDS-NF approach:
      - 1.4% signal
      - 20% background

	Value
Accelerator facility	
Muon total energy	10 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 long-baseline neutrino detector	1 500–2 500 km





- Magnetised Iron neutrino Detector (MIND): 100 kton
- Octagonal plates and toroidal field (as in MINOS)
- Magnetic field 1.2-2.2 T from 100 kA current

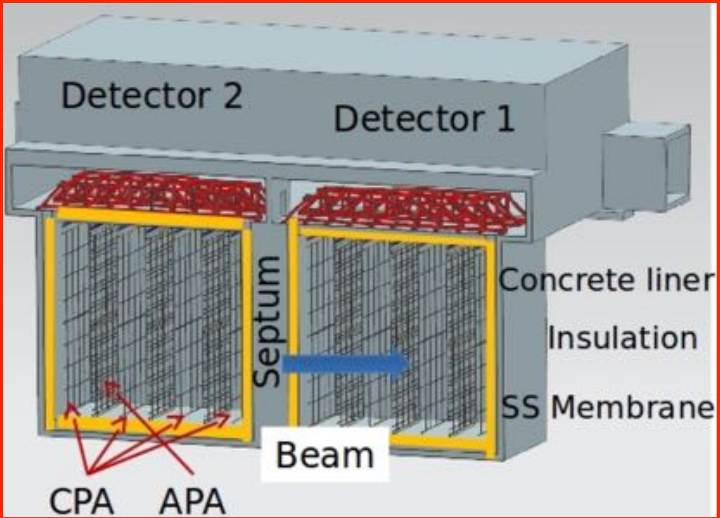
arXiv:1112.2853; 1308.0494v1

Neutrino Factory

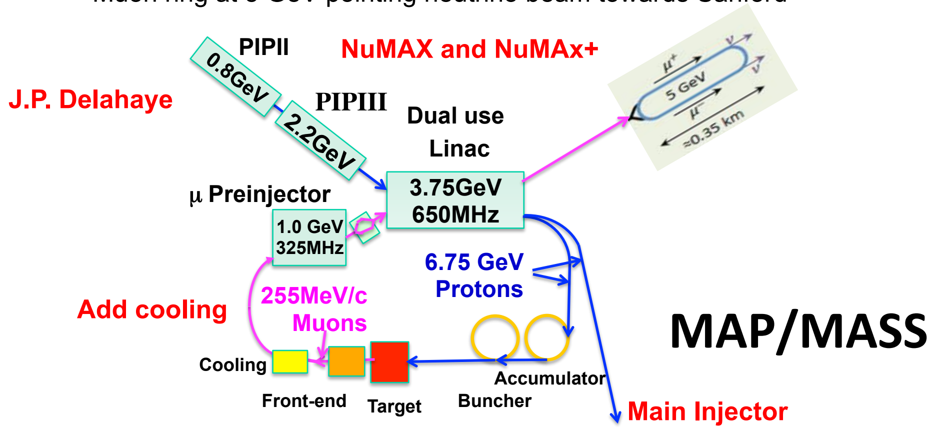
- **Two approaches:**
  - **Optimise *L* and *E* to match detector threshold**
    - **IDS-NF approach:**

	Value
Accelerator facility	
Muon total energy	10 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 long-baseline neutrino detector	1 500–2 500 km

  - **Exploit LAr detector sited 1300 km from FNAL**
    - **MAP/MASS approach:**

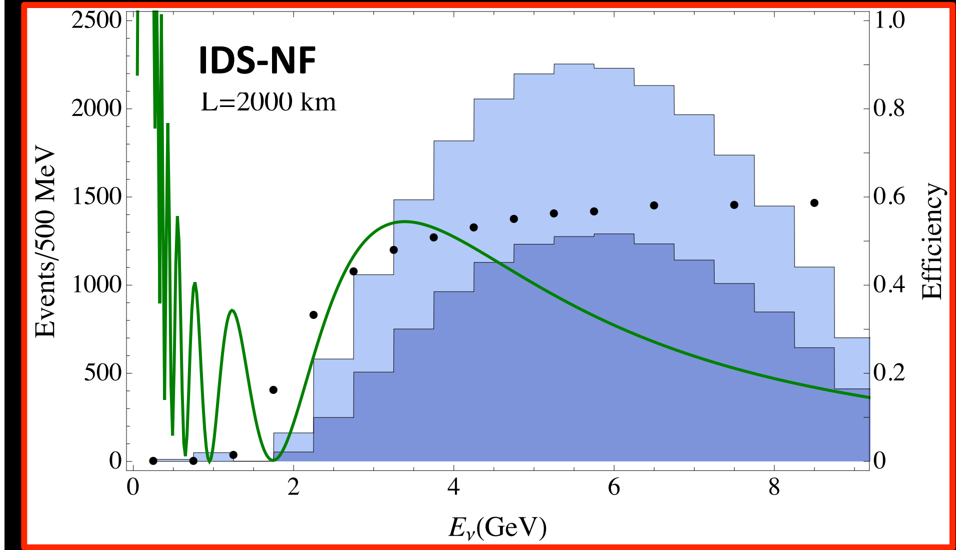


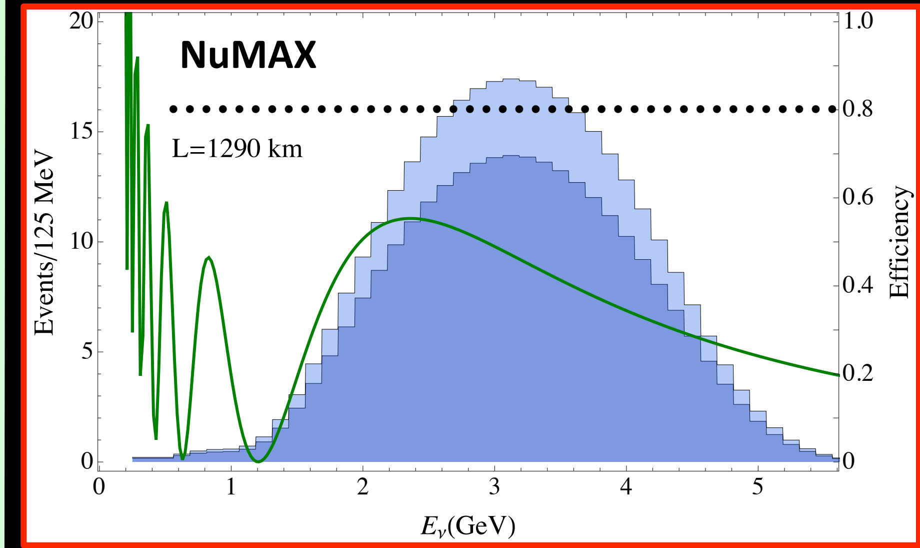
- Neutrinos from a Muon Accelerator CompleX (NuMAX)
  - Add small amount of 6D cooling
  - Neutrino Factory with 5×10^{20} straight muon decays/year @ 5 GeV
  - Muon ring at 5 GeV pointing neutrino beam towards Sanford

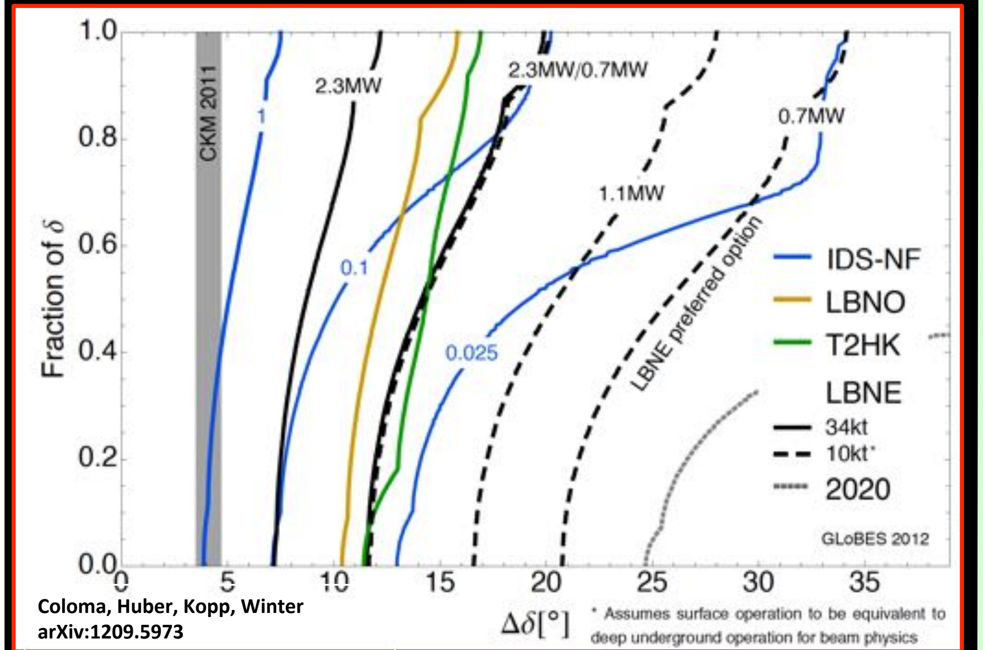


Bayes, Coloma, Huber

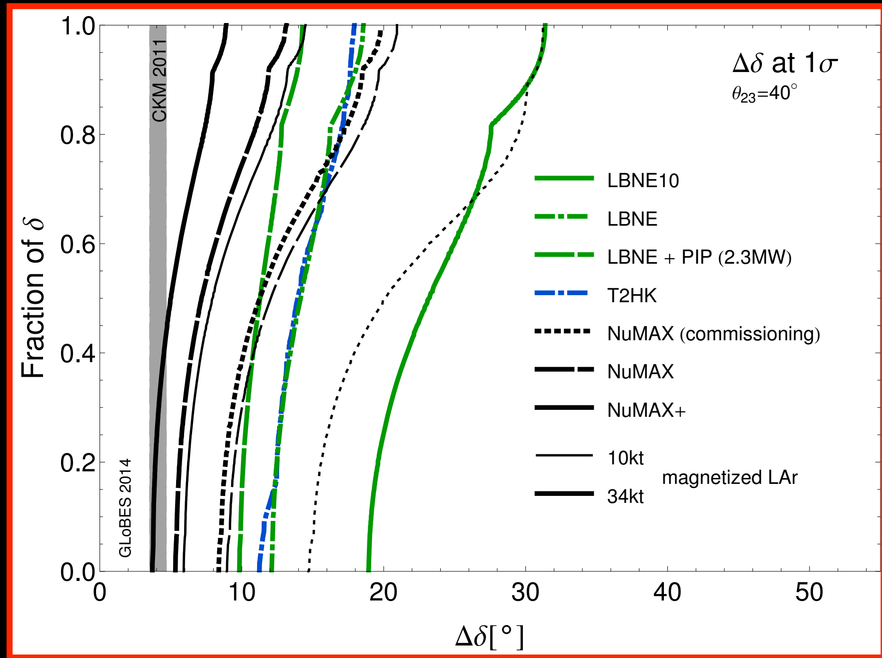
Neutrino Factory



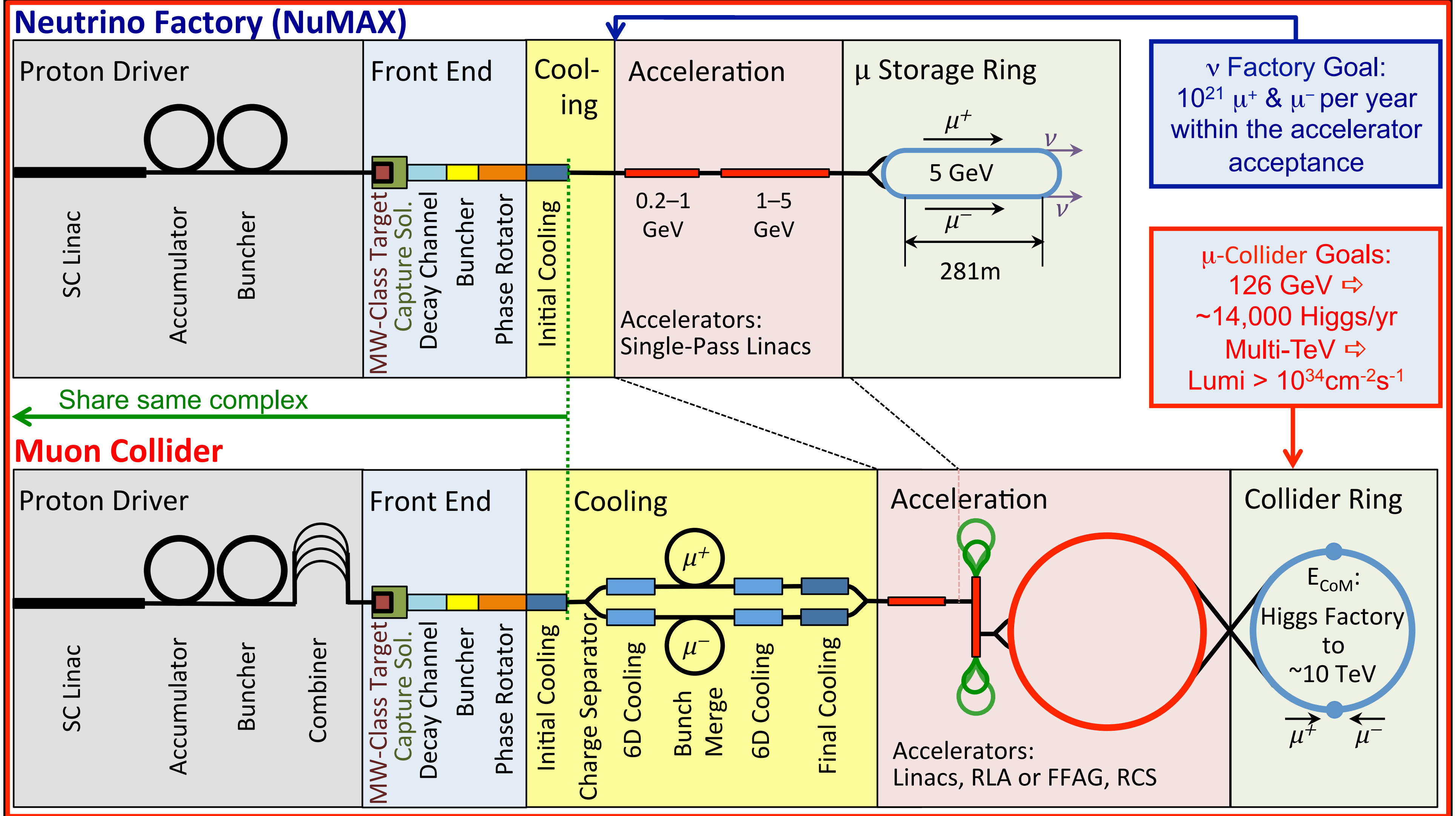




Coloma, Huber, Kopp, Winter
arXiv:1209.5973



Neutrino Factory & Muon Collider concept

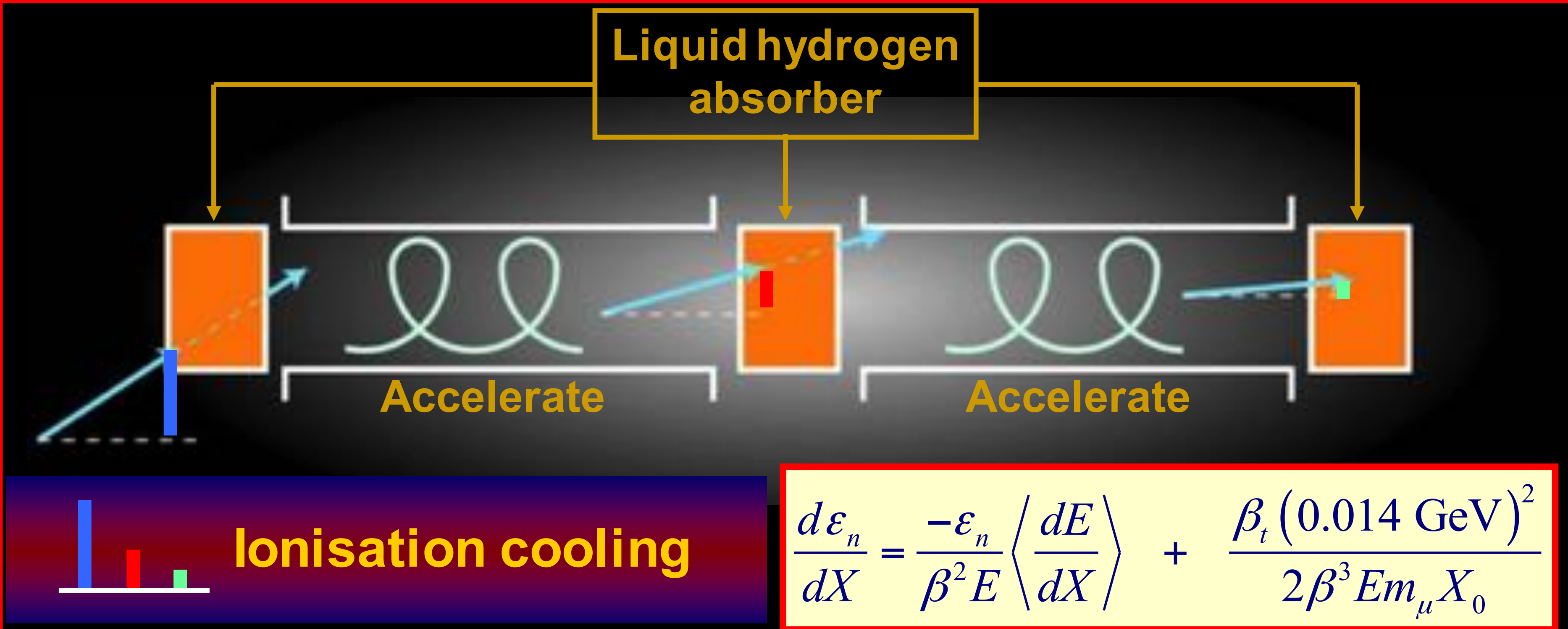


Accelerator challenges

- **High-power, pulsed proton driver:**
  - **Development of high-power, pulsed proton source underway at proton labs**
- **Pion-production target:**
  - **MERIT experiment**
    - **Proved principle of mercury jet target**
- **Muon front end:**
  - **MuCool programme at FNAL:**
    - **Study of effect of magnetic field on high-gradient, warm, copper cavities;**
  - **MICE experiment at RAL:**
    - **Proof of principle of ionization-cooling technique**
- **Rapid acceleration:**
  - **EMMA experiment at DL:**
    - **Proved principal of non-scaling FFAG technique**

MICE and the next generation of muon beams for particle physics

IONIZATION COOLING



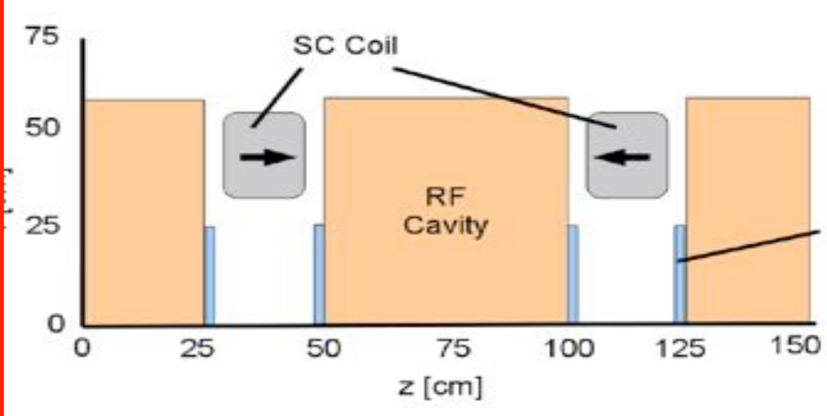
$$\frac{d\varepsilon_n}{dX} = \frac{-\varepsilon_n}{\beta^2 E}\left\langle\frac{dE}{dX}\right\rangle + \frac{\beta_t (0.014\ \mathrm{GeV})^2}{2\beta^3 E m_\mu X_0}$$

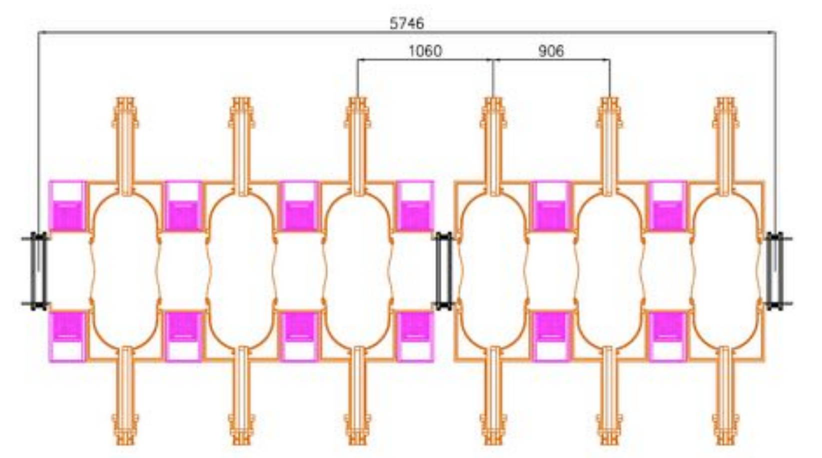
- **Competition between:**
  - dE/dx [cooling]
  - MCS [heating]
- **Optimum:**
  - Low *Z*, large X_0
  - Tight focus

	Z	FoM	Rel. 4D cooling
H	1	252.6	1.000
He	2	182.9	0.524
Li	3	130.8	0.268
C	6	76.0	0.091
Al	13	38.8	0.024

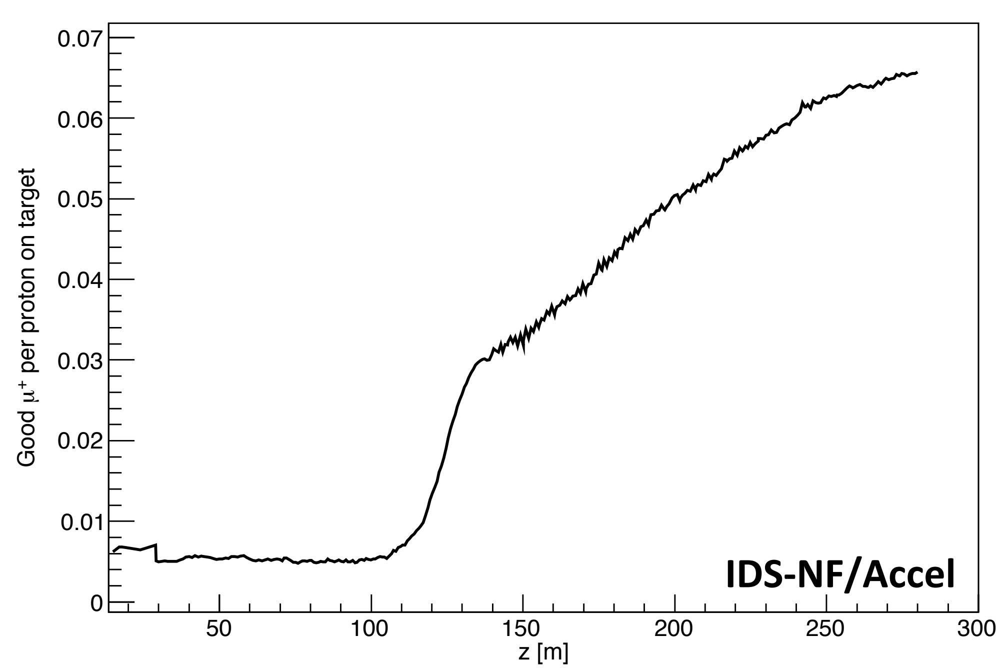
Neutrino Factory

- **Requirement is to maximise rate:**
  - – Transverse (4D) cooling sufficient



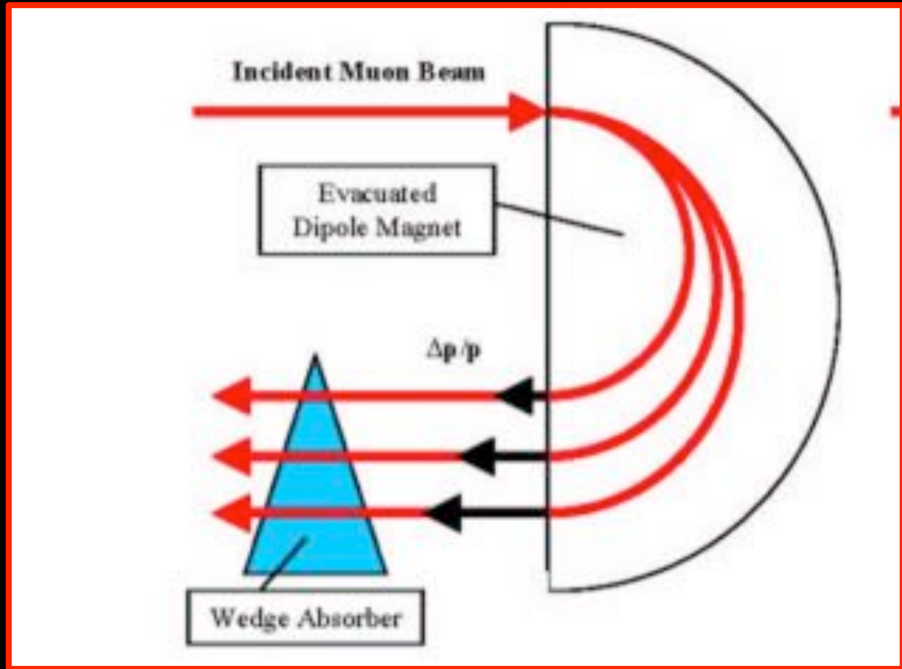


Combined Cooling Cell Sections 1 & 2
Contains 6coils & 6 cavities = total length 5.746m

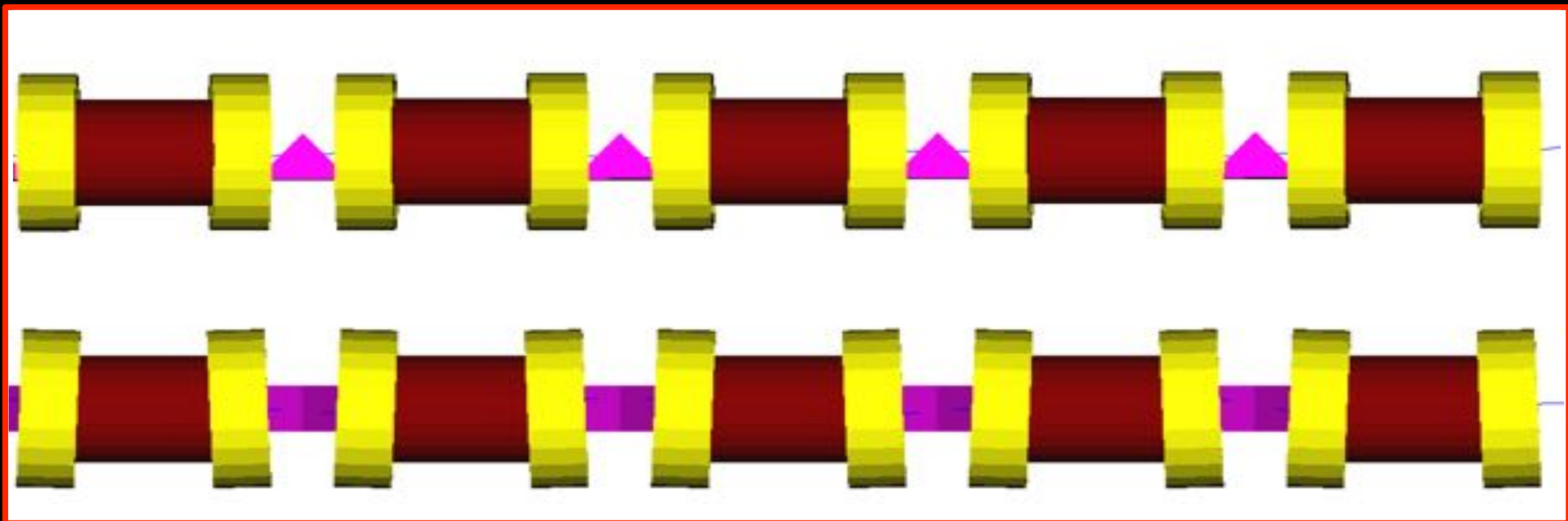


Muon Collider

- **Requirement is tiny emittance**
  - **6D cooling essential**



MAP

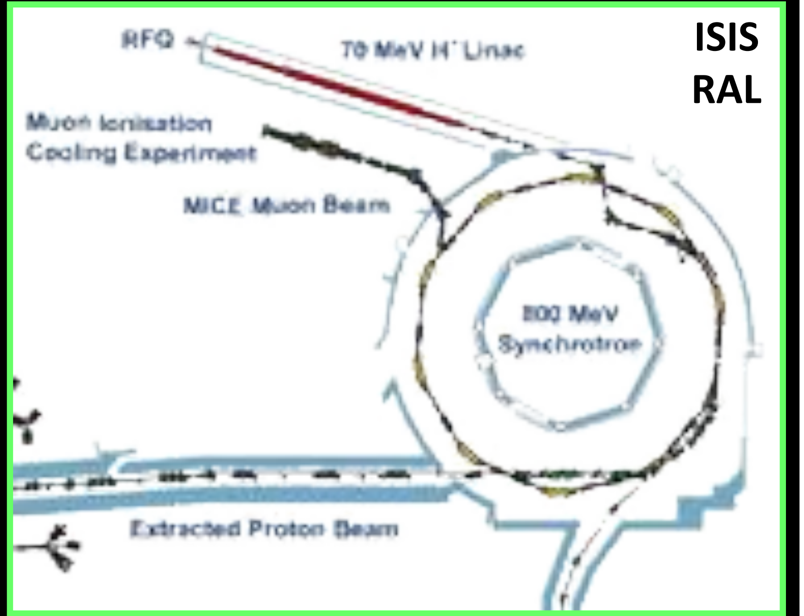


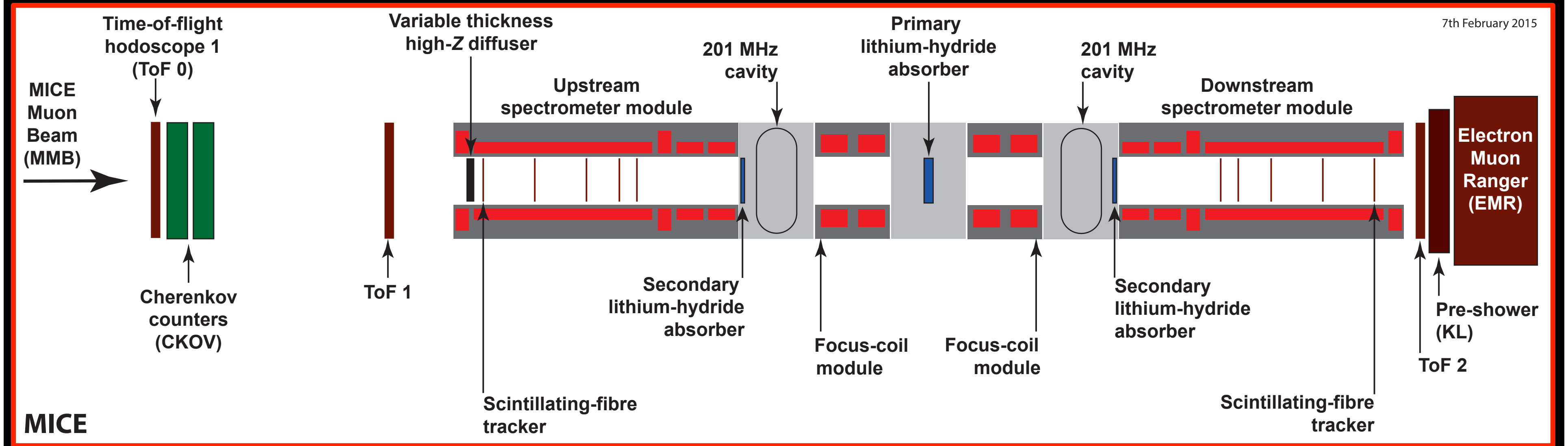
MICE and the next generation of muon beams for particle physics

MUON IONIZATION COOLING EXPERIMENT … MICE

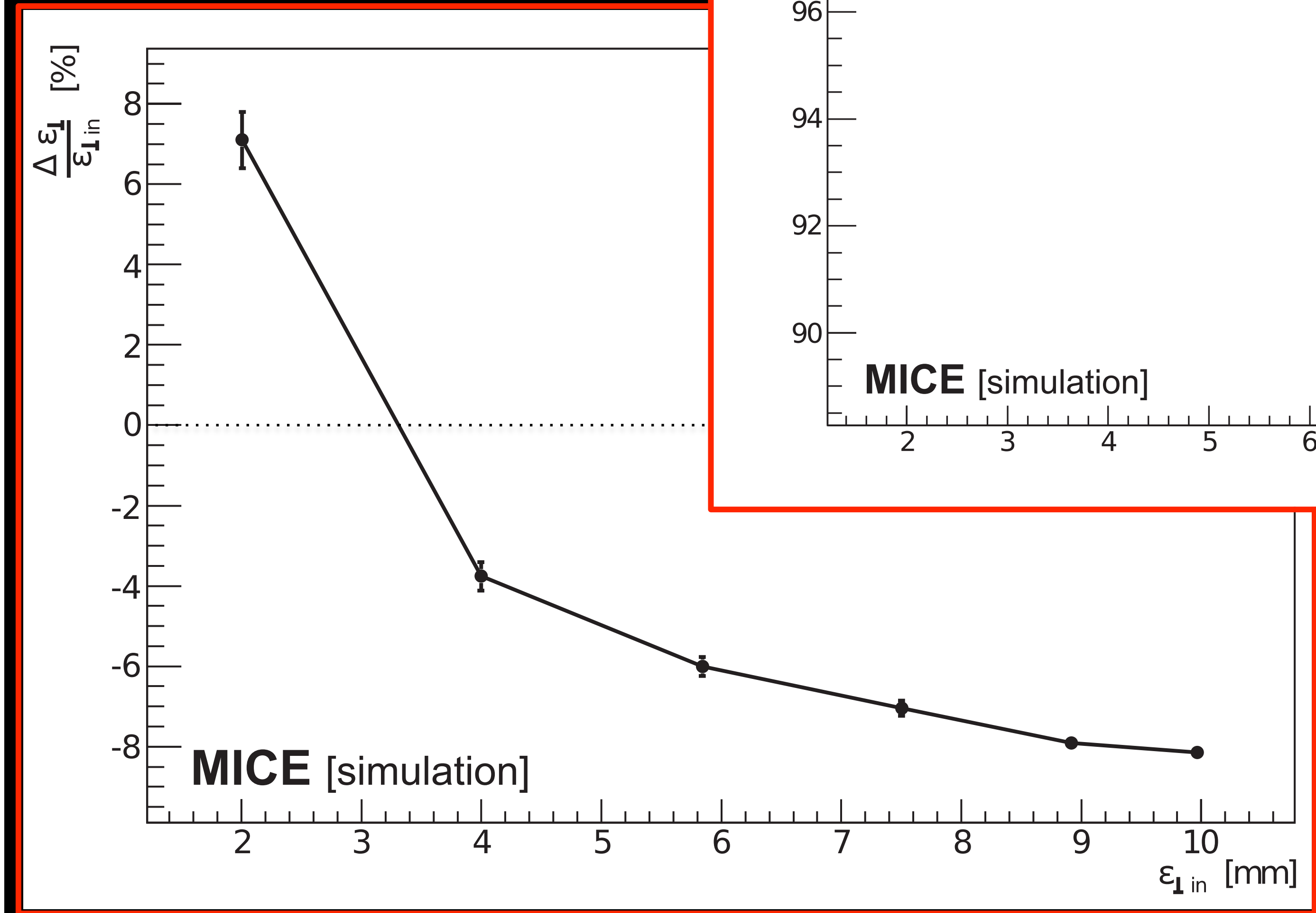
MICE:

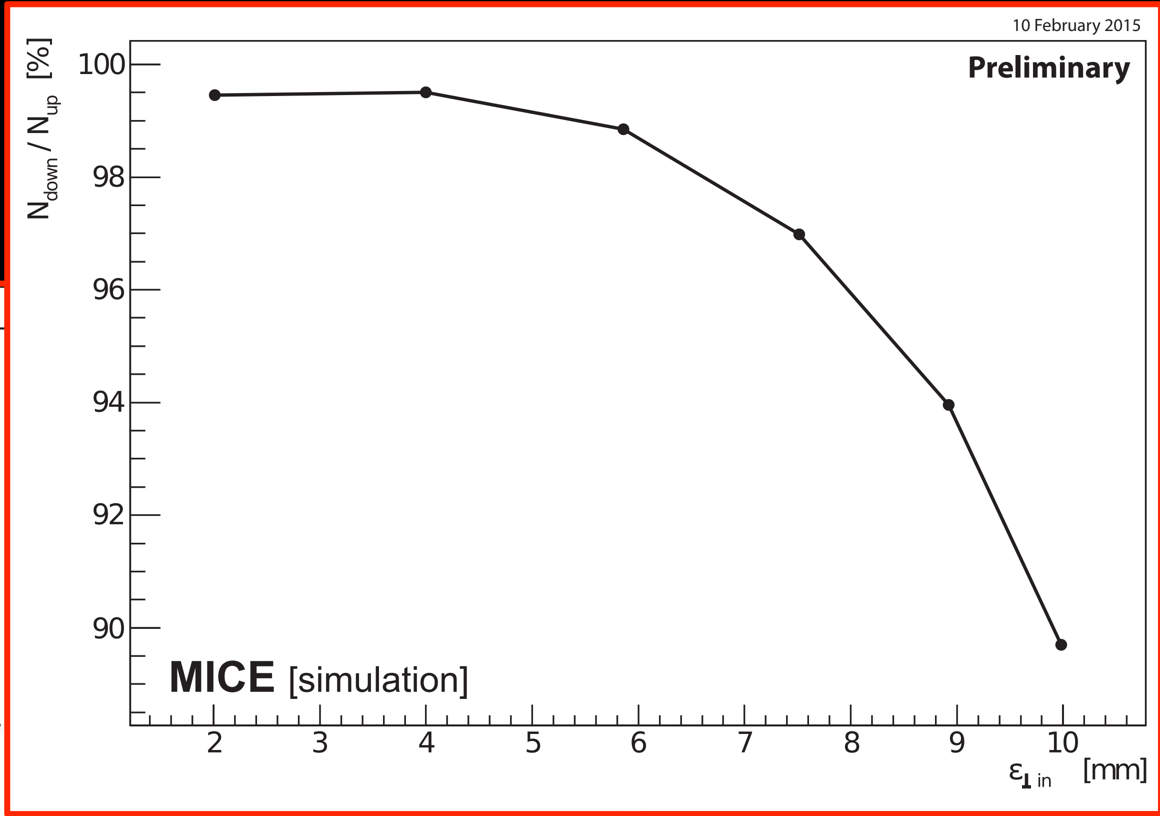
- MICE approved to:
  - Design, build, commission and operate a realistic section of cooling channel
  - Measure its performance in a variety of modes of operation and beam conditions
    - Results will allow Neutrino Factory [and Muon Collider] complex to be optimised
- Requirements:
  - Normalised transverse emittance: 0.1%
    - Requires selection of 99.9% pure muon sample



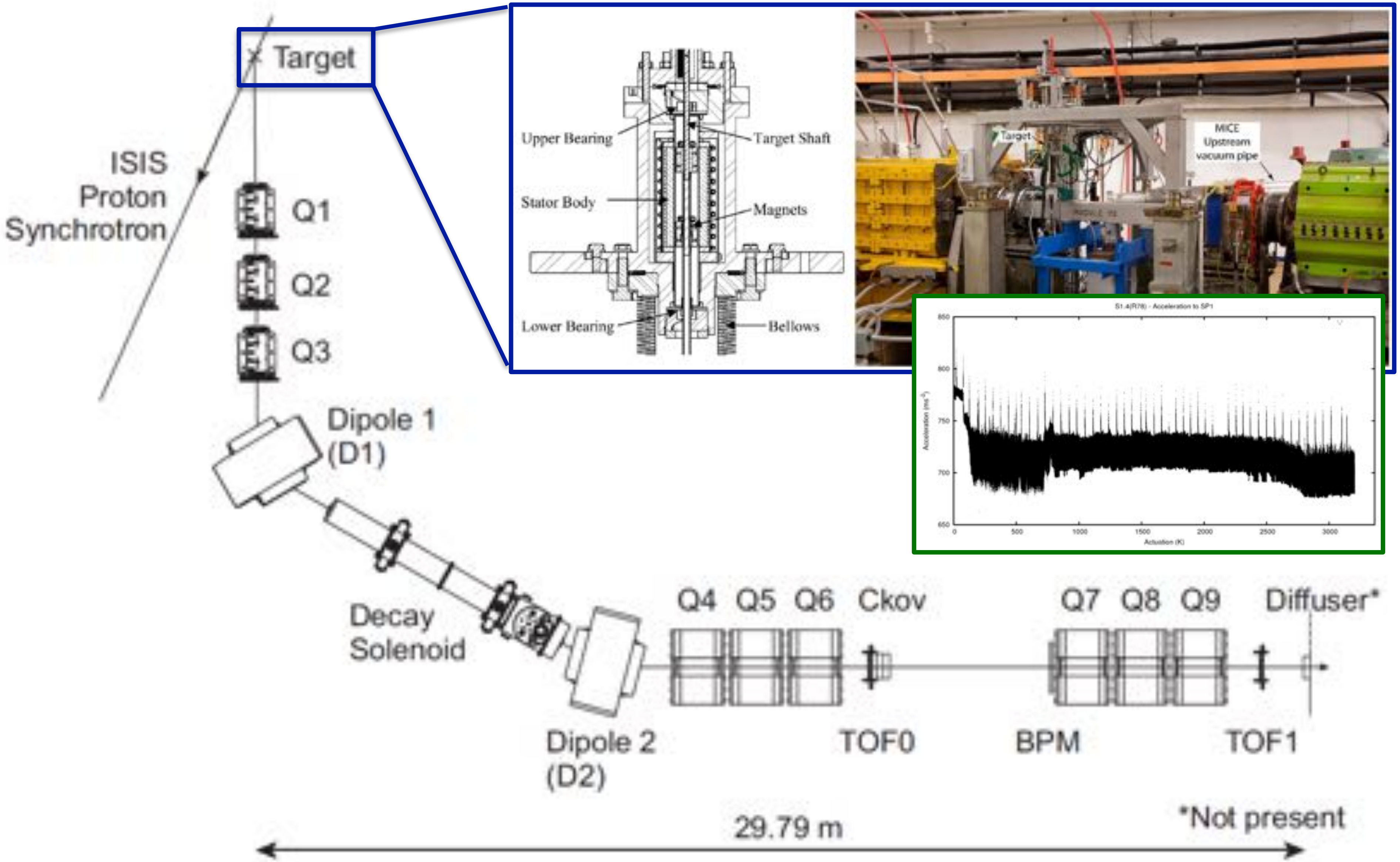


Cooling demonstration; performance:

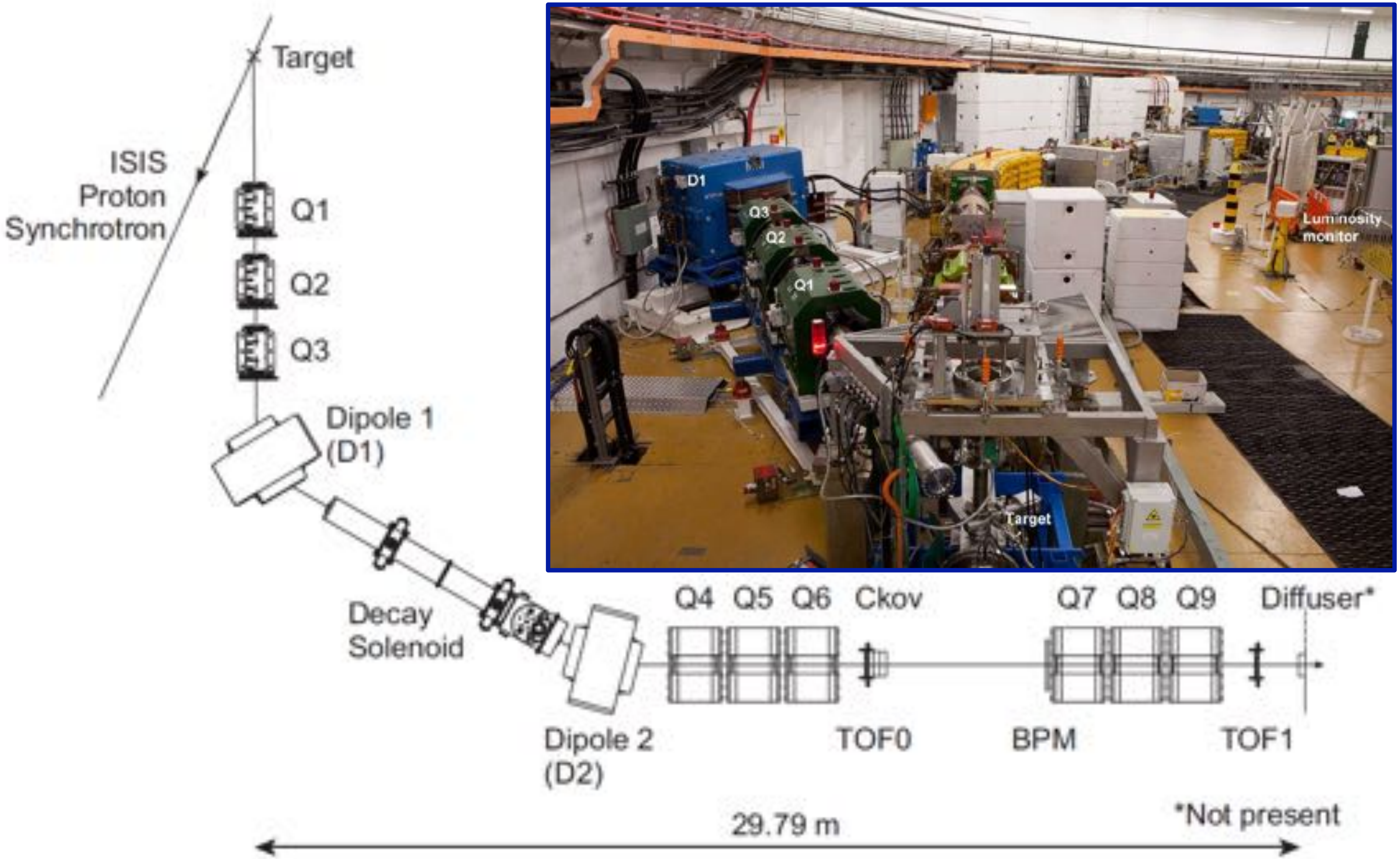




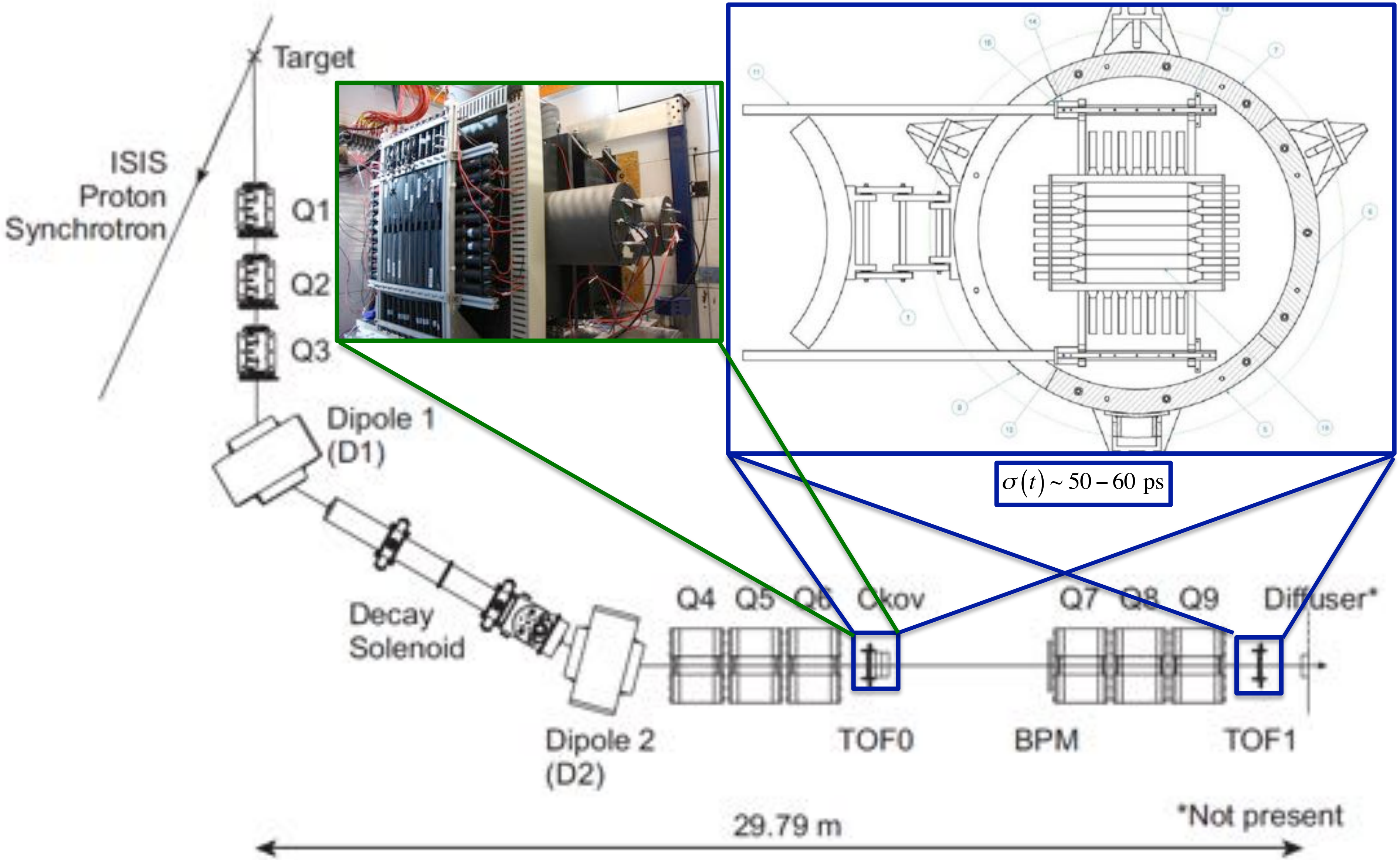
MICE Muon Beam



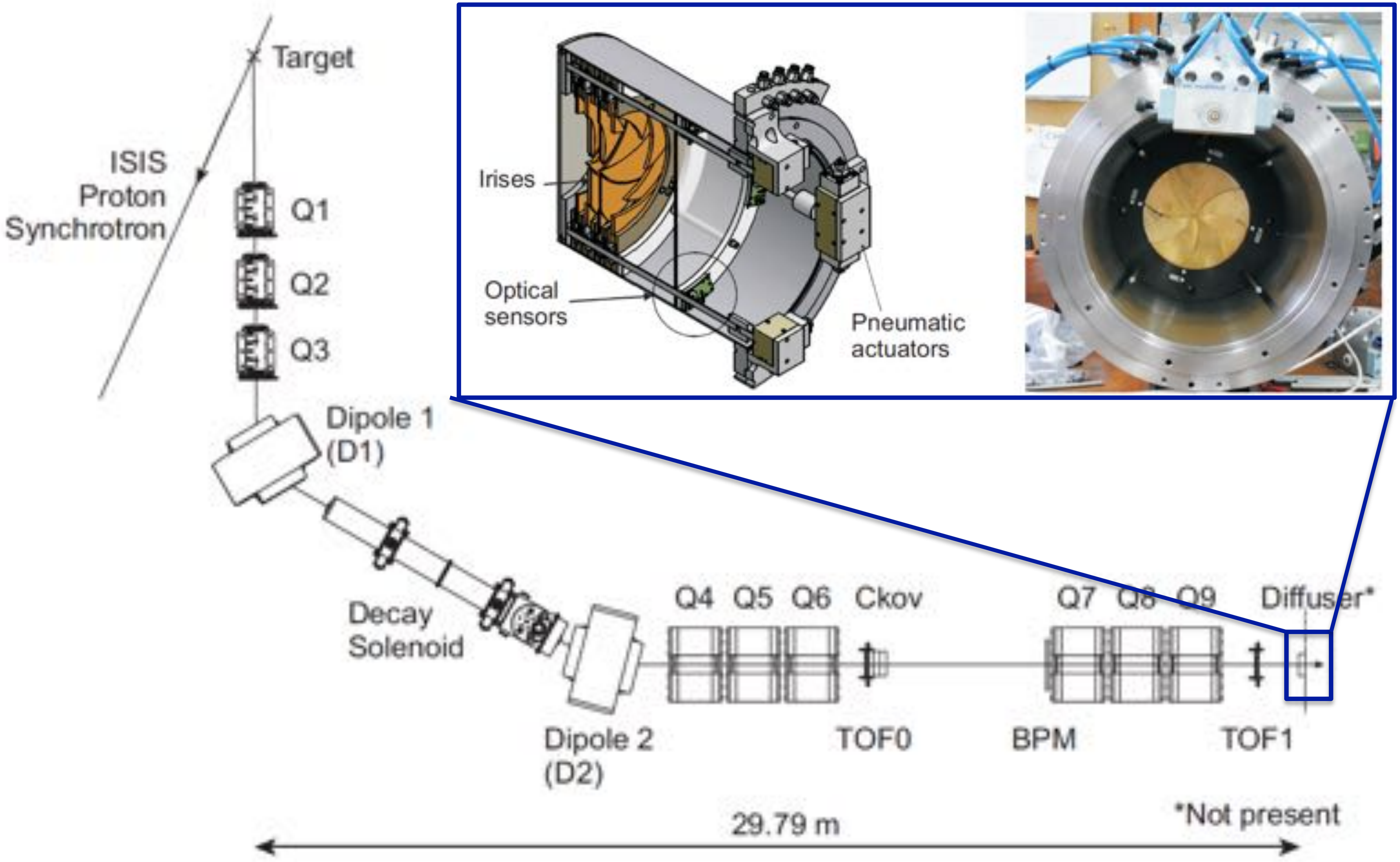
MICE Muon Beam



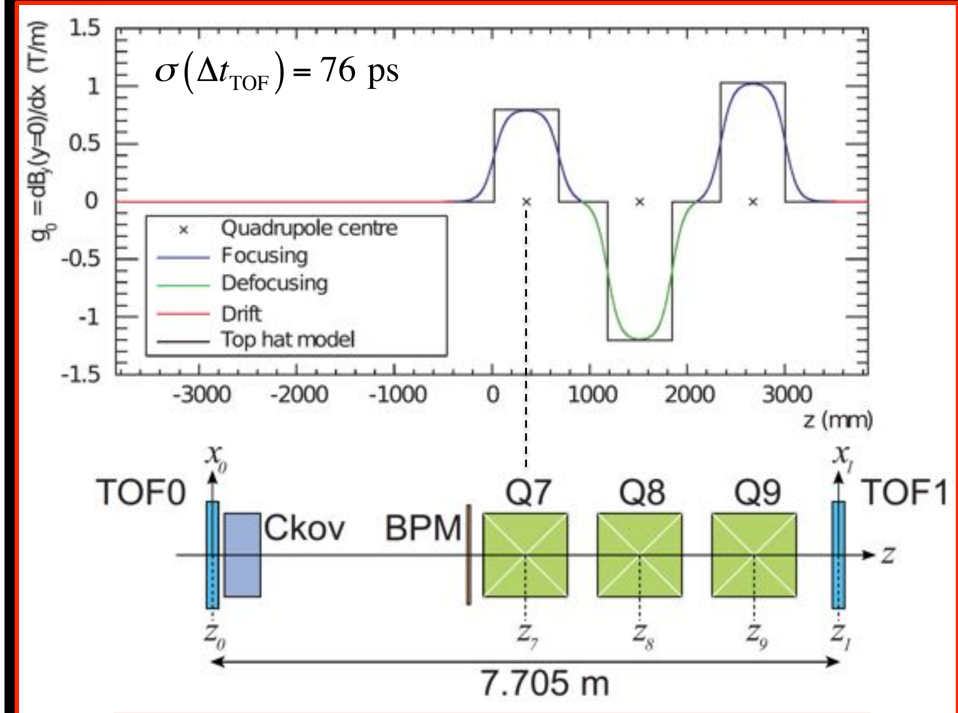
Beam-line instrumentation



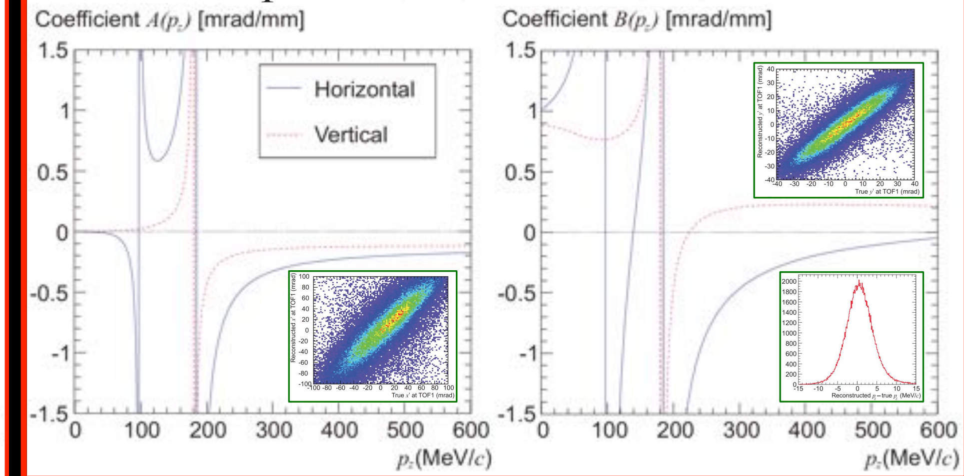
MICE Muon Beam



Characterisation of the MICE Muon Beam

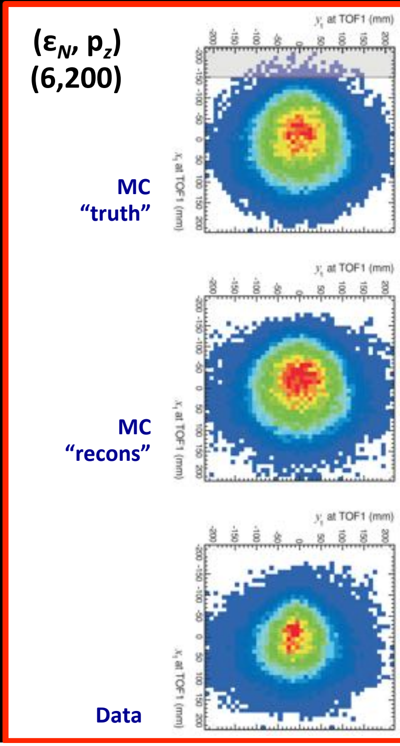


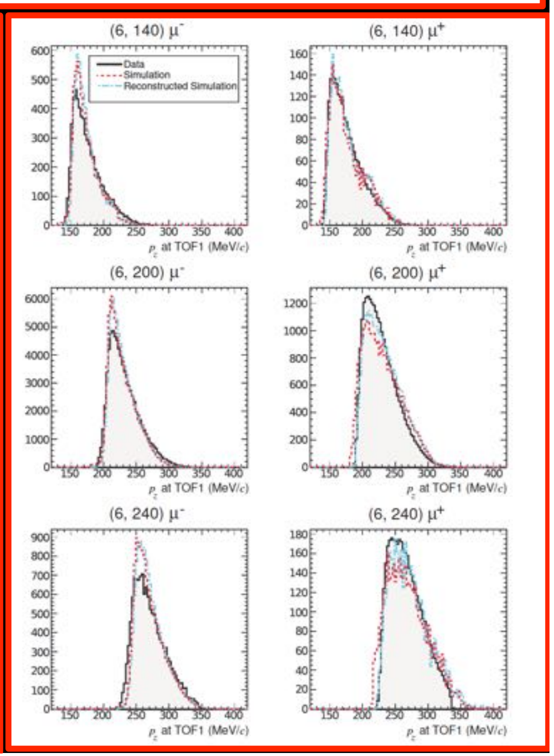
$$x'_1 = A(p_z)x_0 + B(p_z)x_1$$



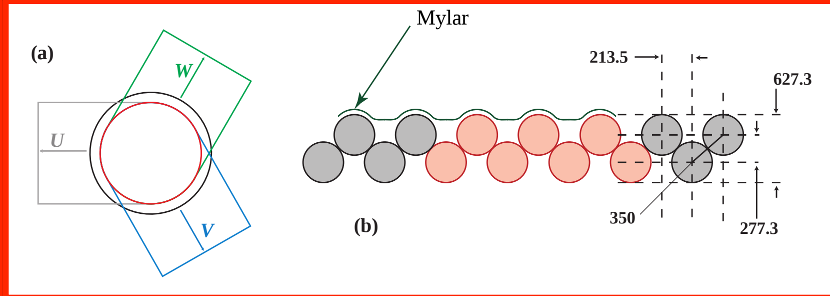
$$\begin{pmatrix} x'_0 \\ x'_1 \end{pmatrix} = \frac{1}{M_{12}} \begin{pmatrix} -M_{11} & 1 \\ -1 & M_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \end{pmatrix}$$

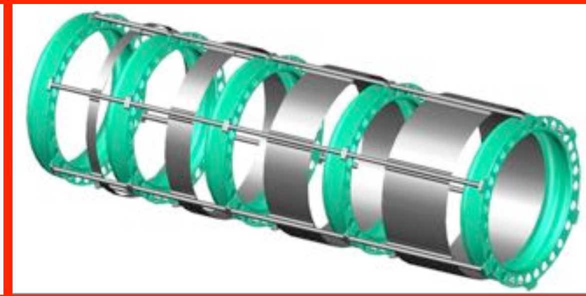
- Iterate to determine trace-space parameters:
  - Initial estimate of p_z from TOF
  - (x_0,y_0), (x_1,y_1) and $M_{x,y}(p_z)$ used to determine trace-space parameters
  - Updated estimate of p_z from trace space parameters
- Corrections applied for energy loss in air and material

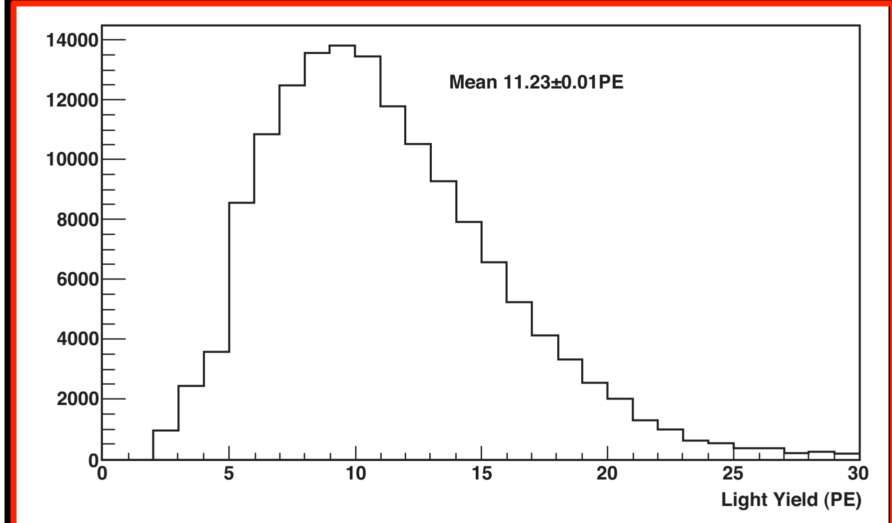


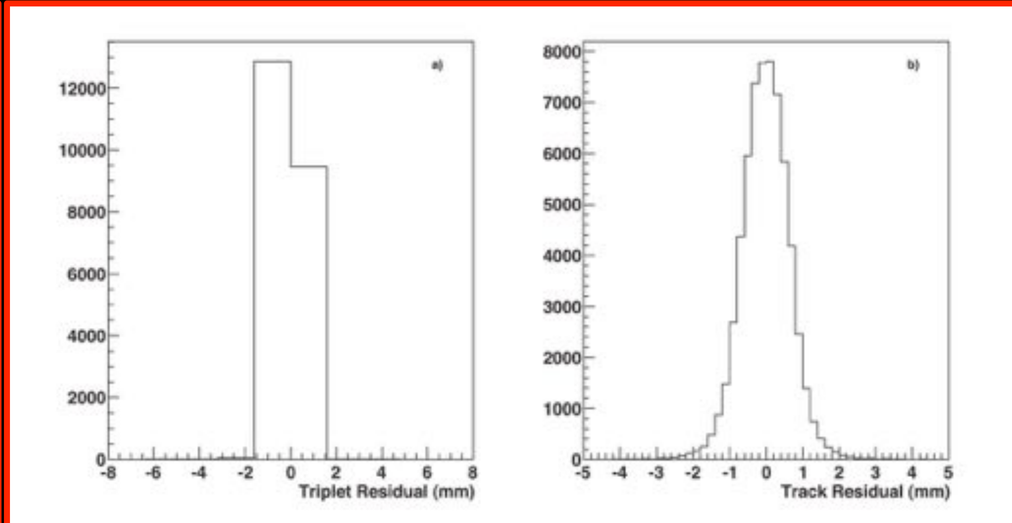


MICE trackers

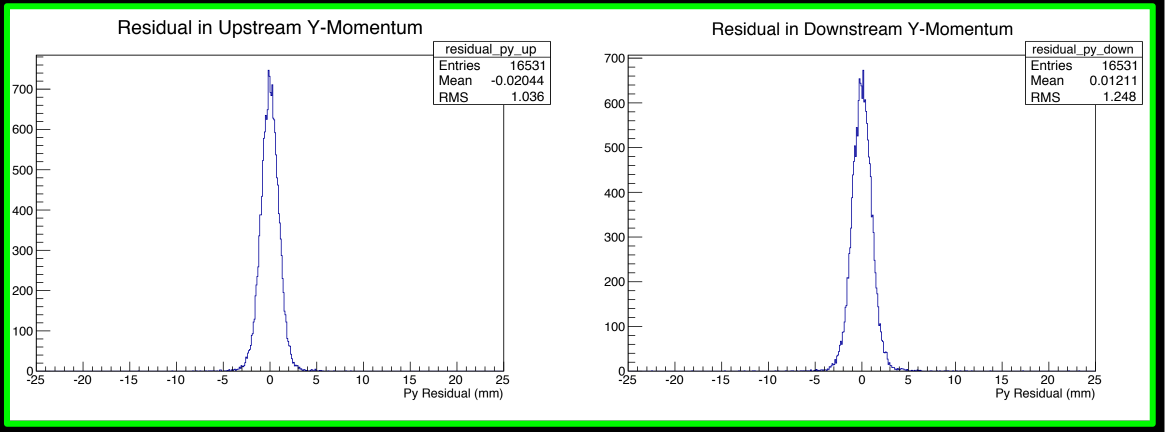




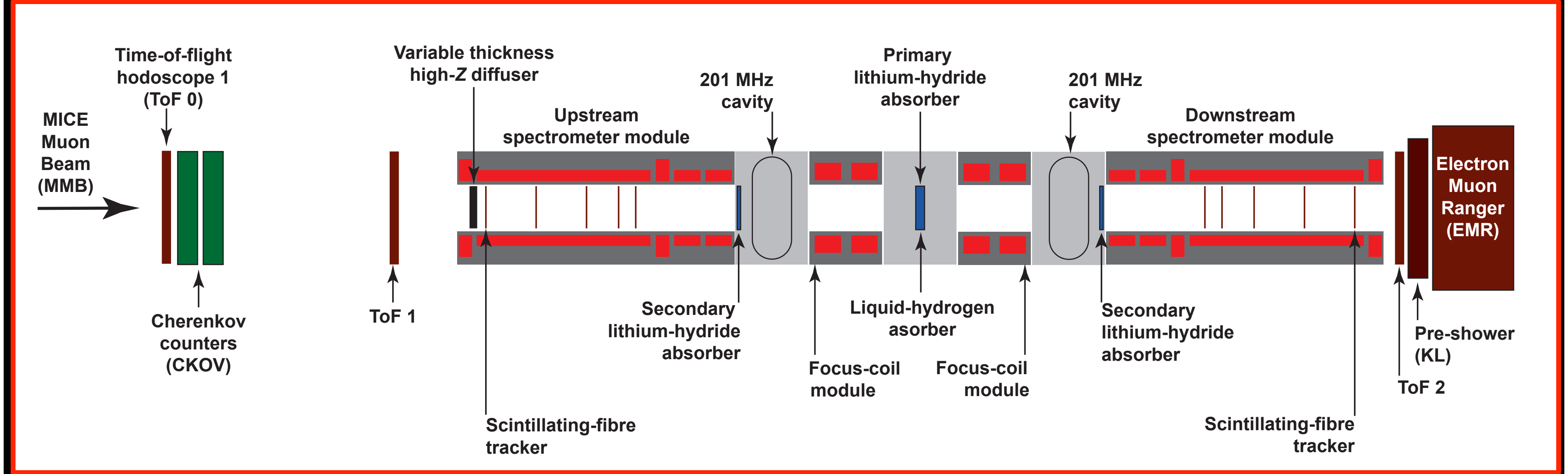


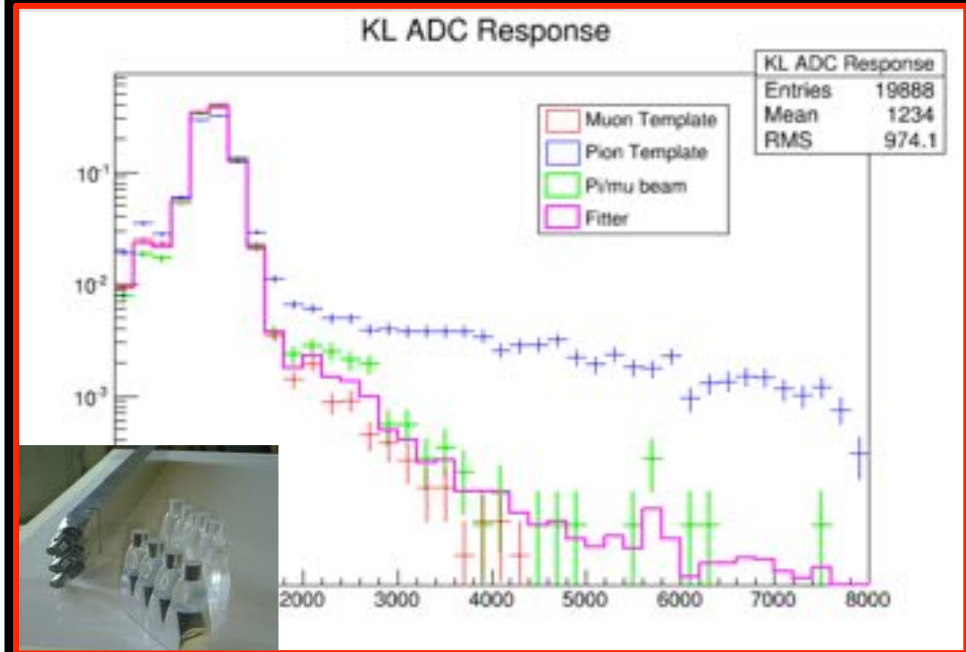


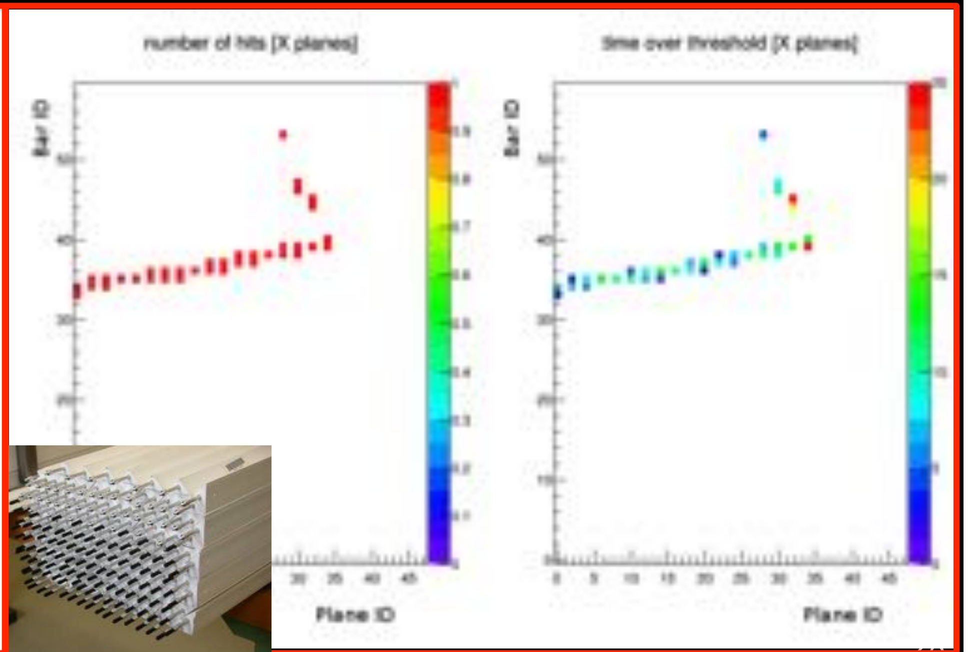
- **350 μm scintillating-fibre tracker:**
  - **10 p.e./mip demonstrated with cosmics**
  - **470 μm intrinsic resolution per plane**
- **MC: delivers per-cent level emittance measurement**



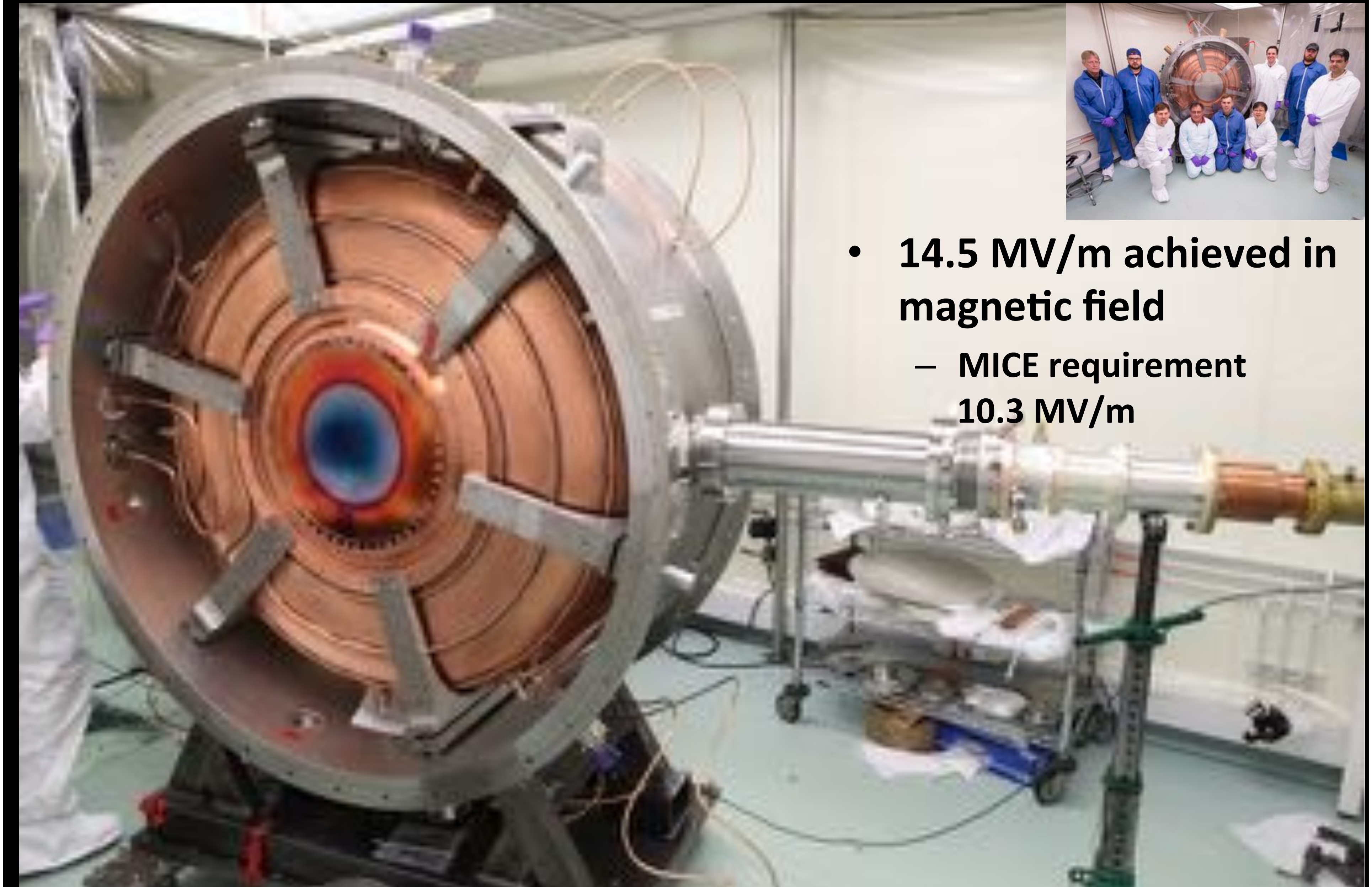
Calorimetry







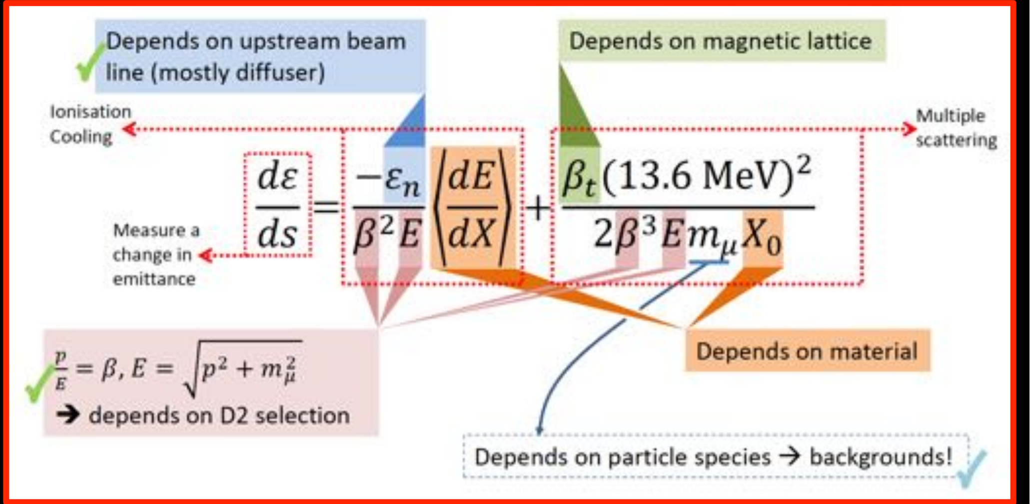
Single cavity modules

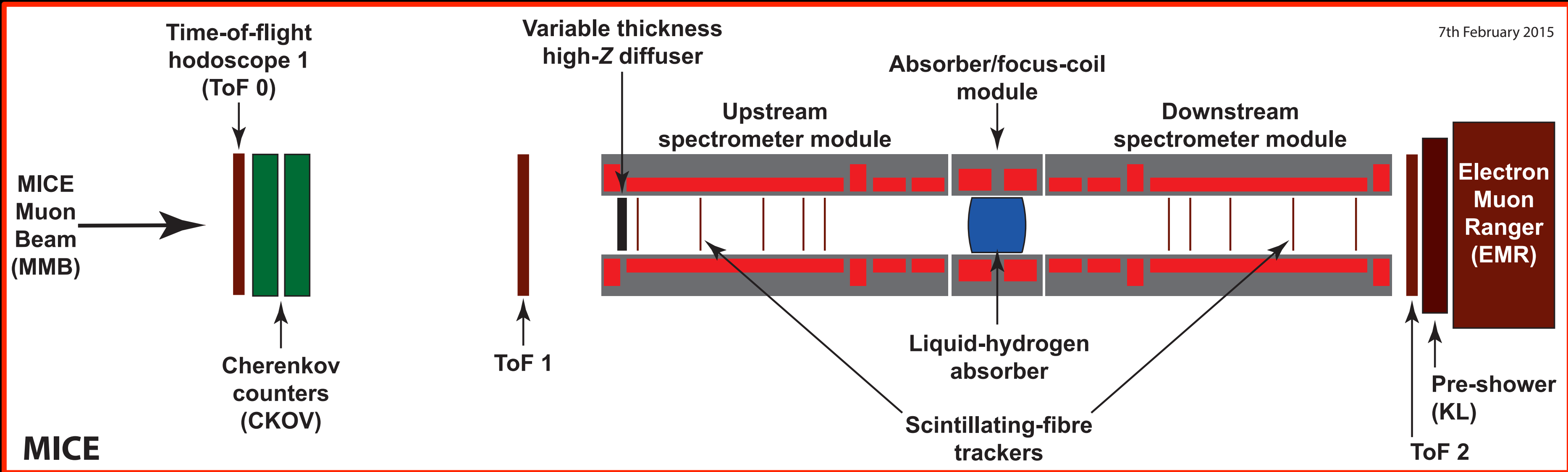


- **14.5 MV/m achieved in magnetic field**
  - **MICE requirement 10.3 MV/m**

Study of factors that affect cooling:

- **Emittance:**
  - MICE Muon Beam optics and diffuser settings
- **Material:**
  - Absorber change (LH2; LiH);
- ***p*, *E* and β:**
  - Vary beam momentum, optics

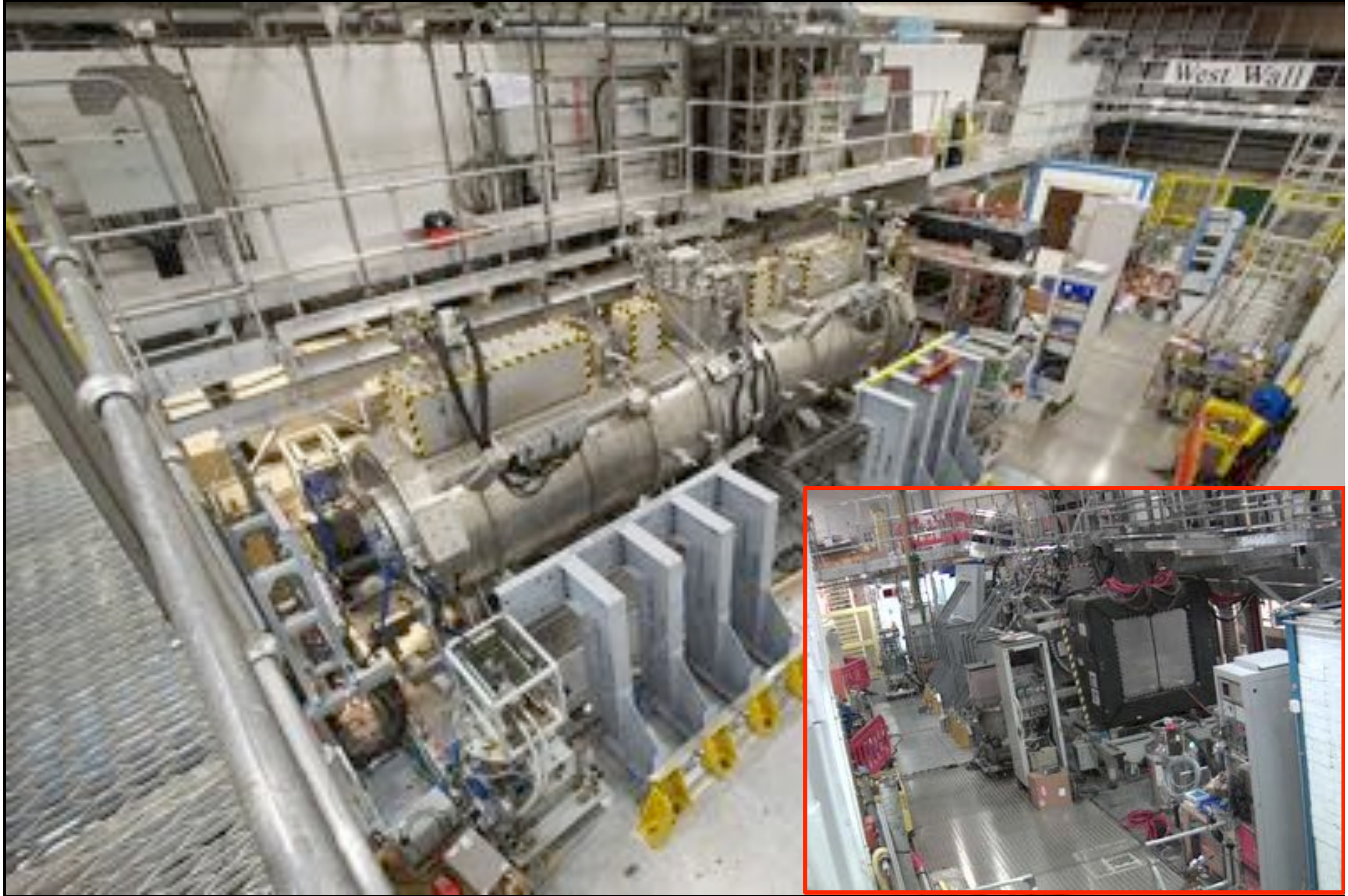




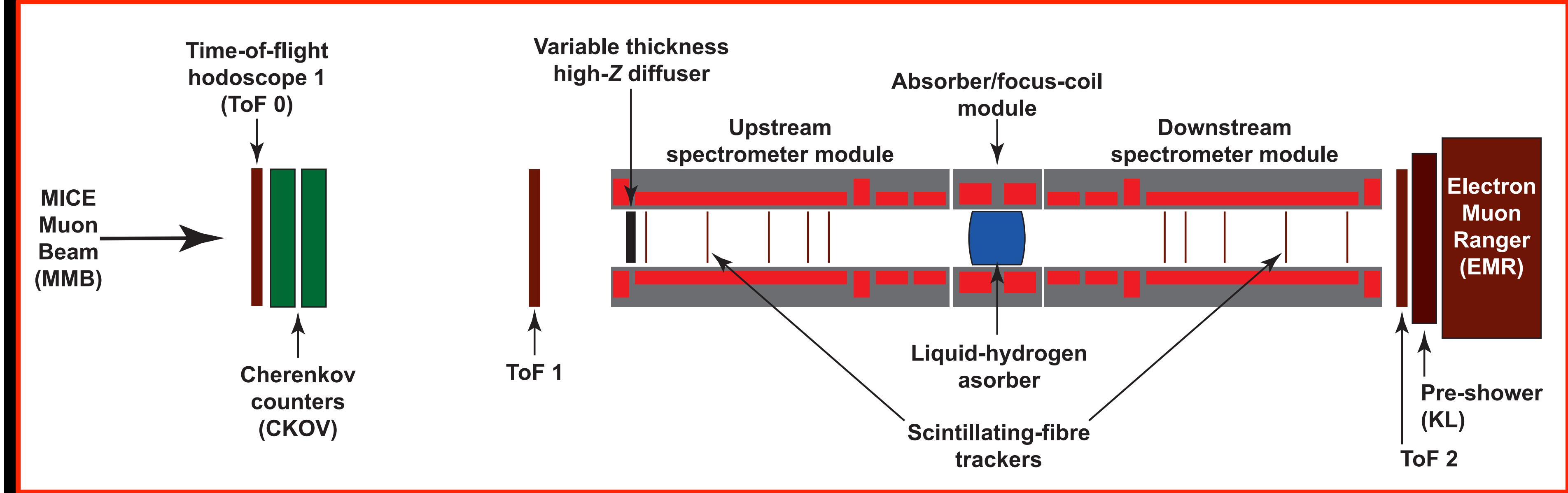
Data taking: summer 2015 to summer 2016

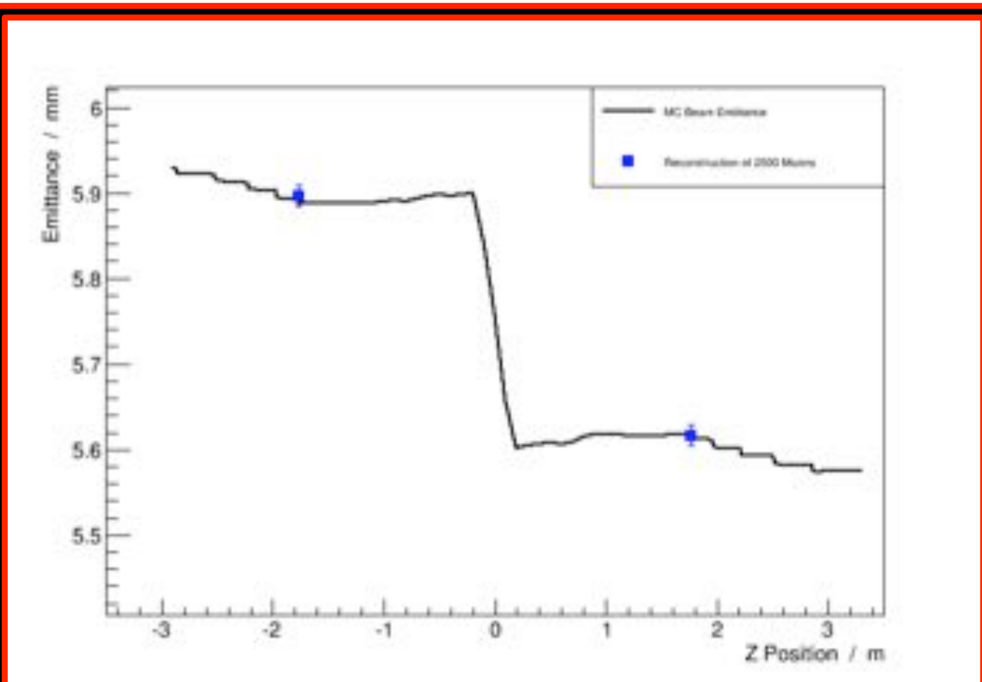
Commission has started (in parallel to completion of the build)

MICE Step IV



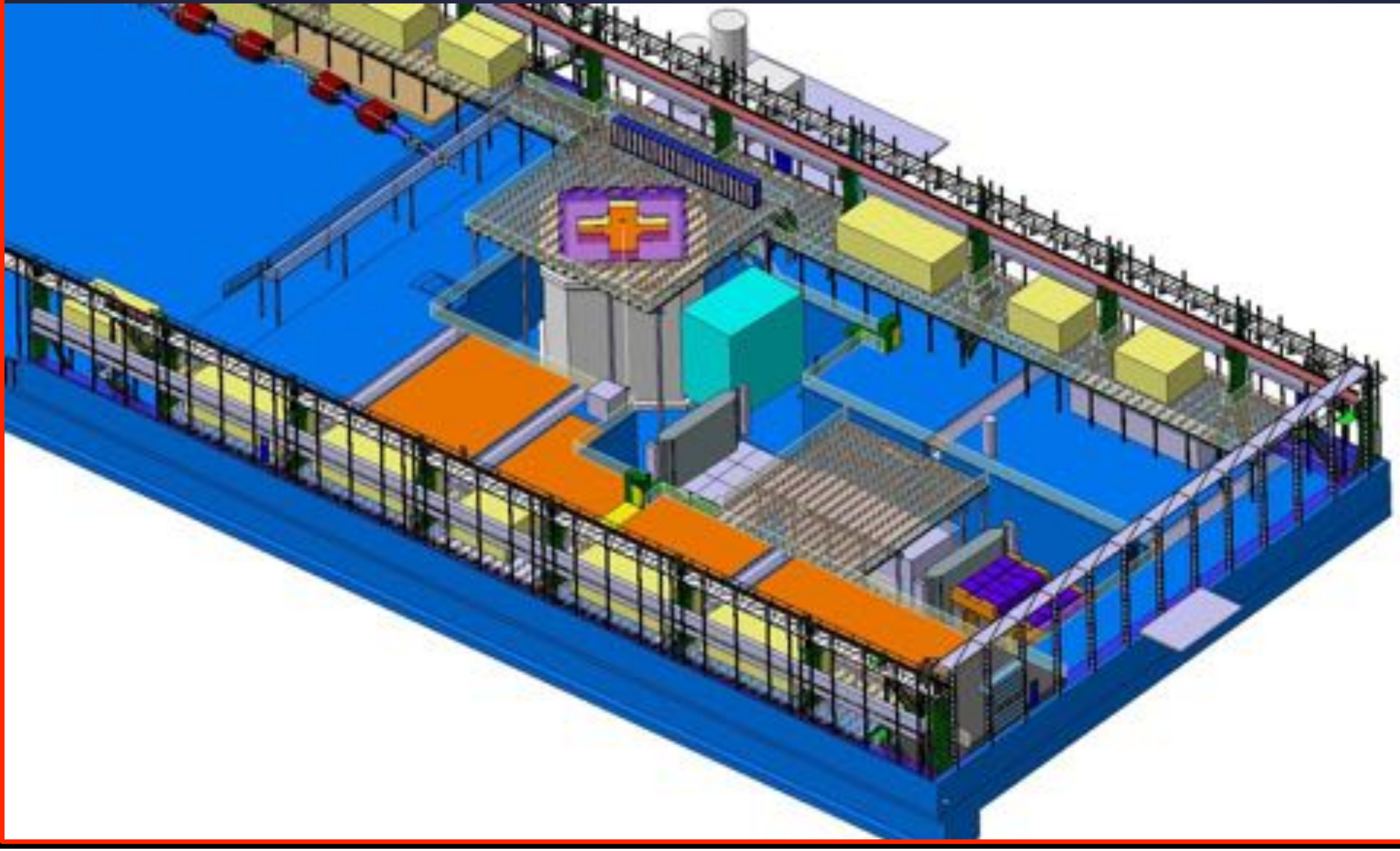
"Step IV"; 2015/16





Innovation in detectors

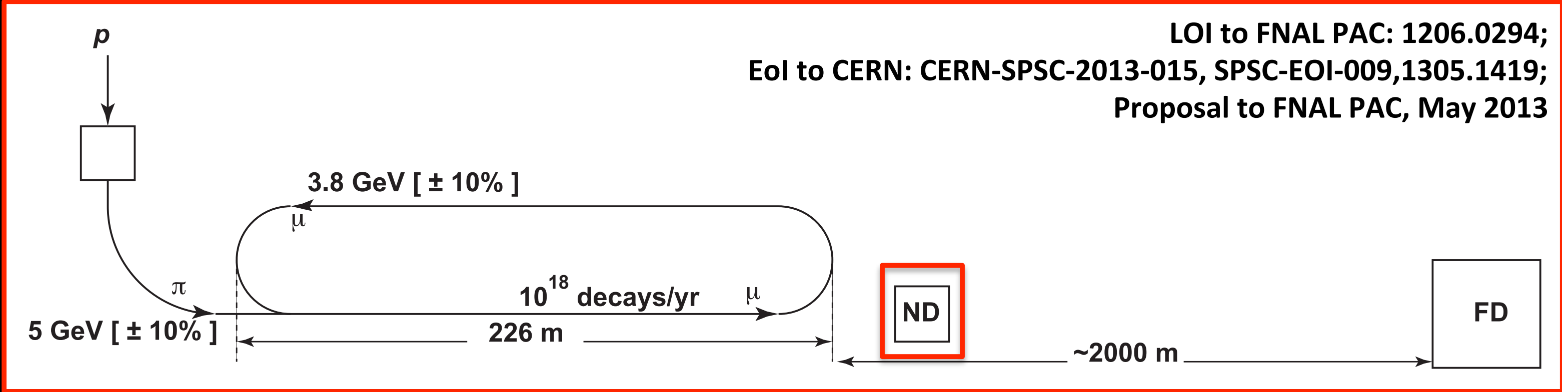
Neutrino extension



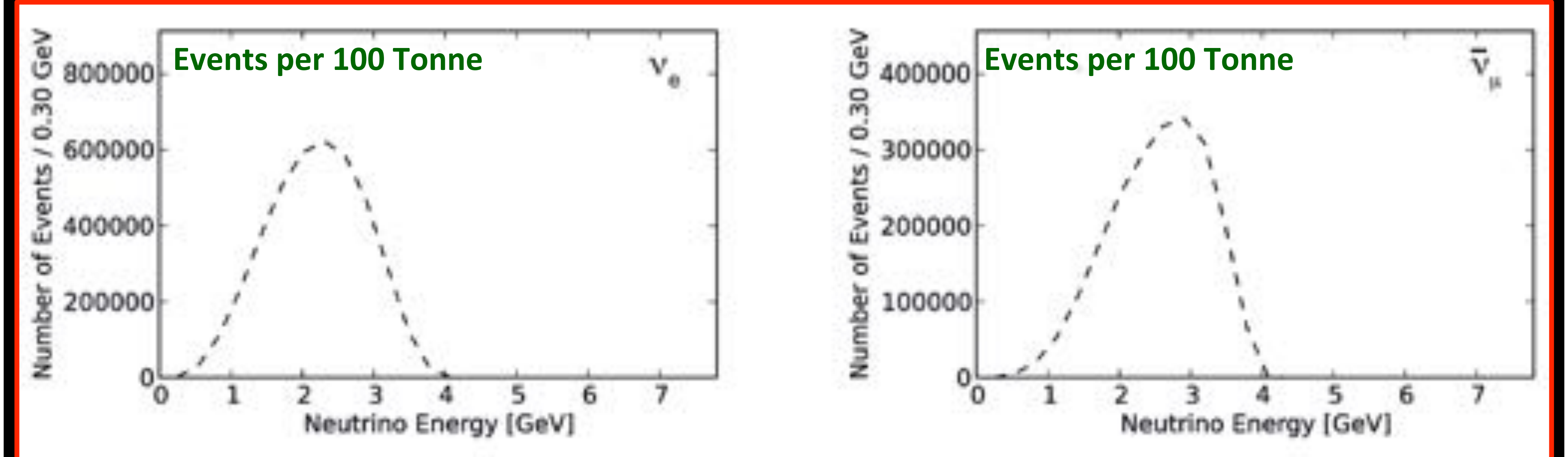
MICE and the next generation of muon beams for particle physics

VISION FOR A COLD, BRIGHT FUTURE FOR MUON BEAMS

nuSTORM and cross section measurement:

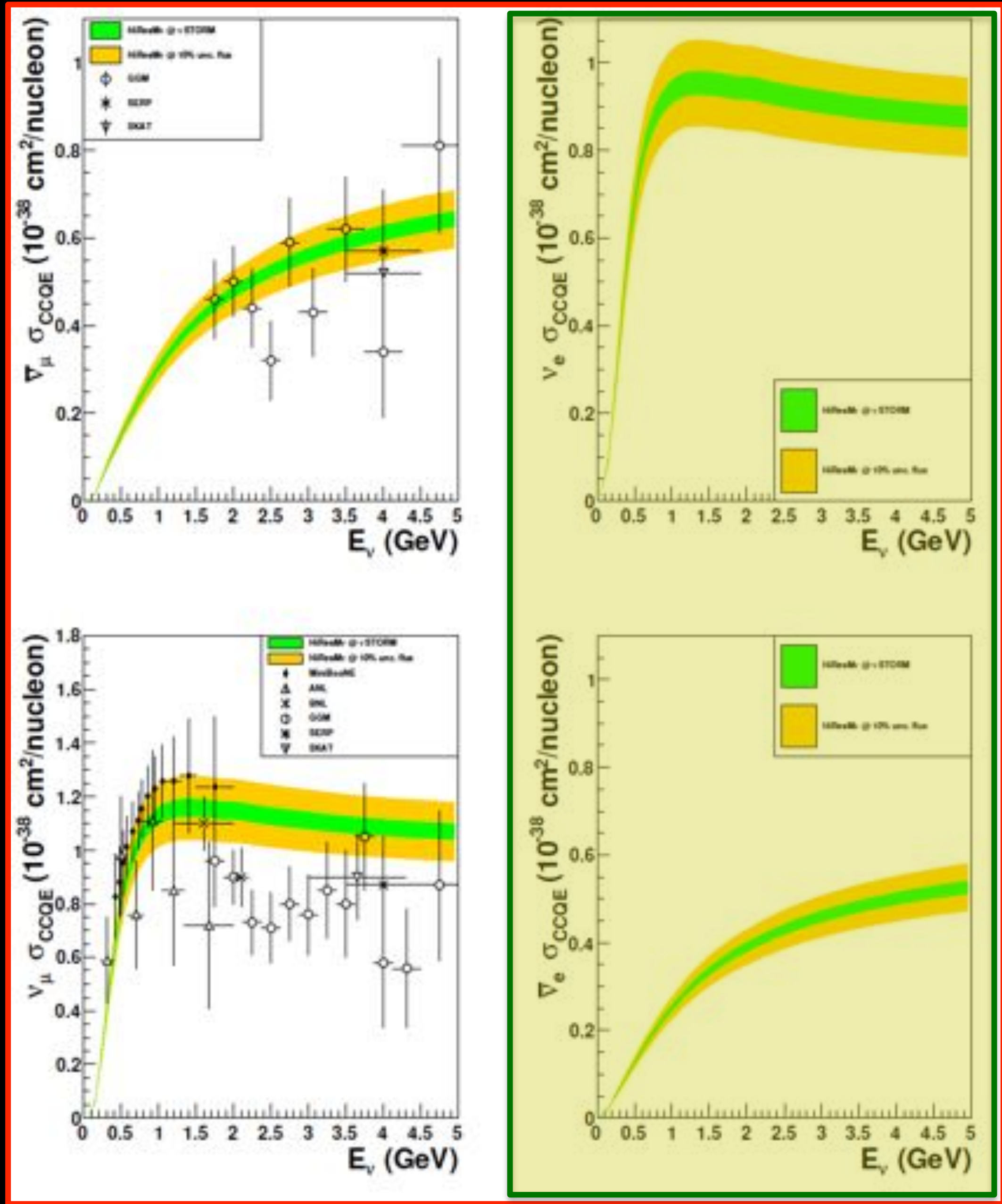


- nuSTORM event rate is large:
  - Statistical precision high:
    - Can measure double-differential cross sections



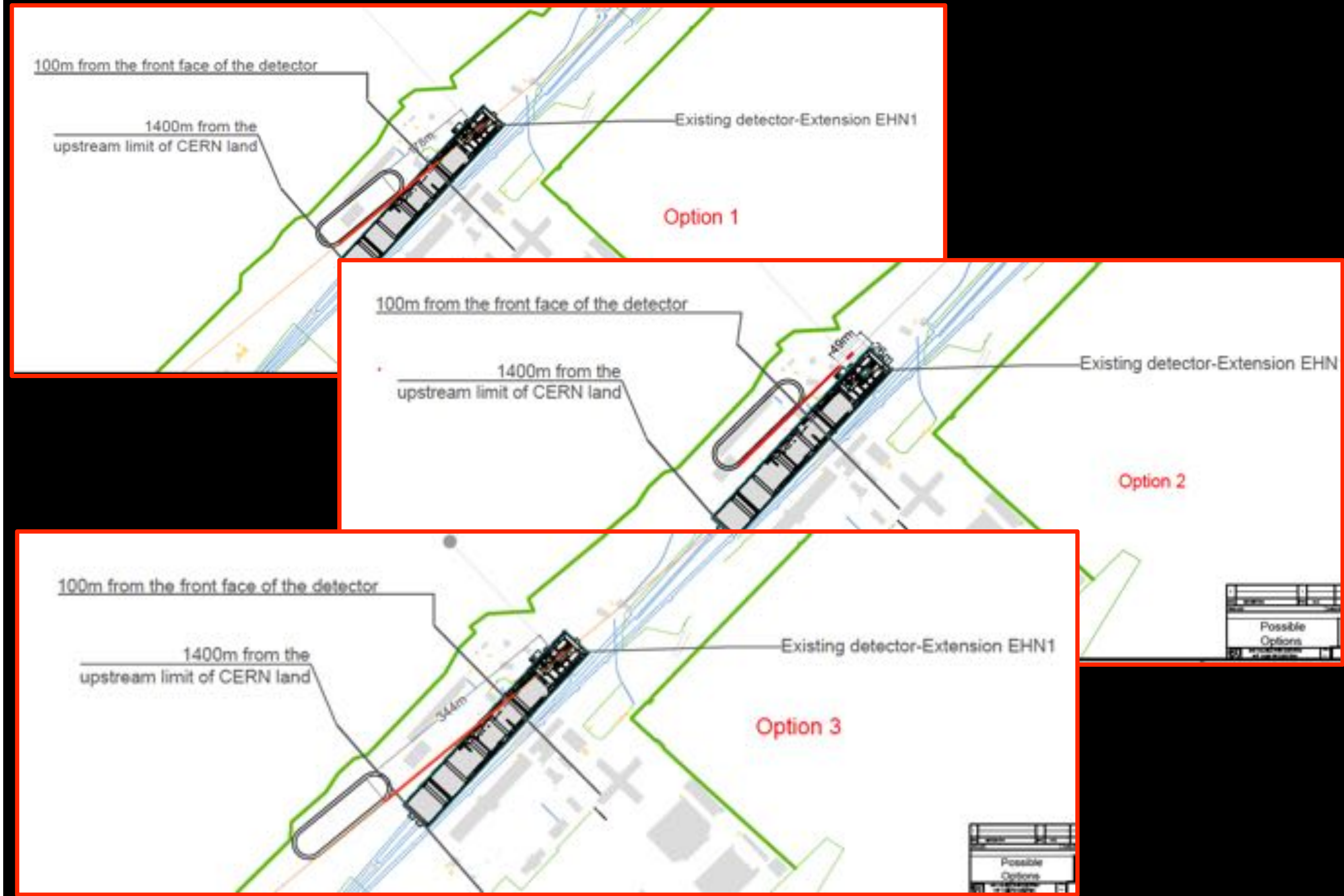
CCQE cross section measurement:

- **Systematic uncertainties for CCQE measurement at nuSTORM:**
  - **Six-fold improvement in systematic uncertainty compared with “state of the art”**
  - **Electron-neutrino cross section measurement unique**

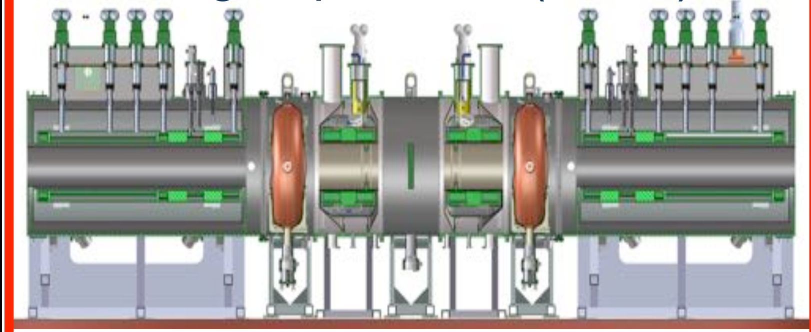


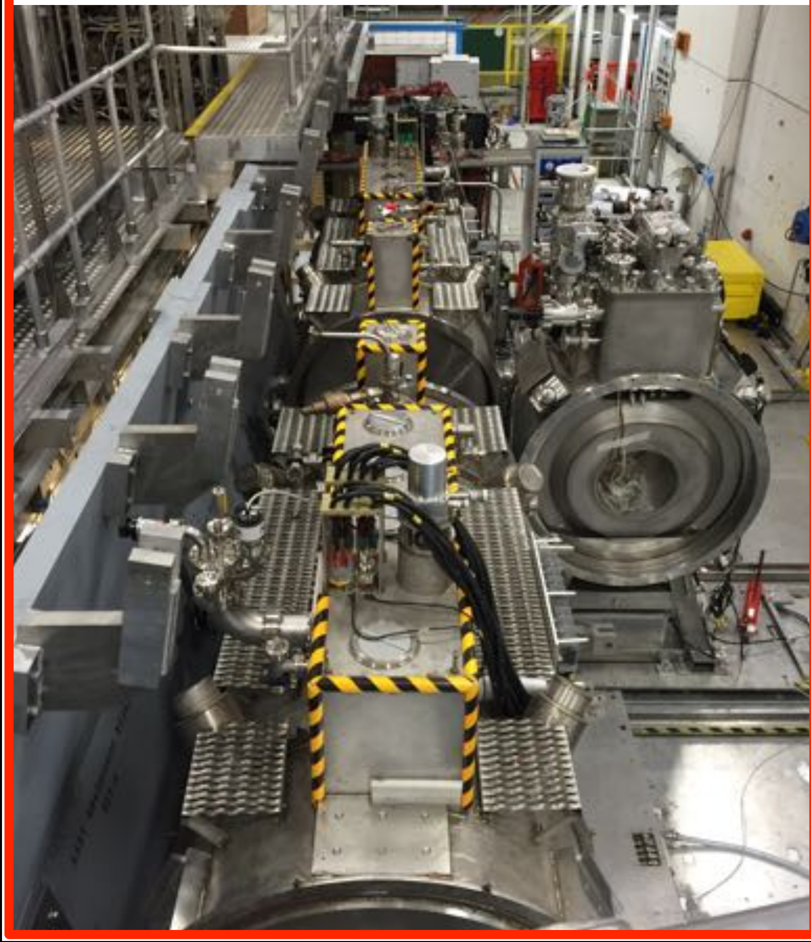
nuSTORM serving the CERN Neutrino Platform

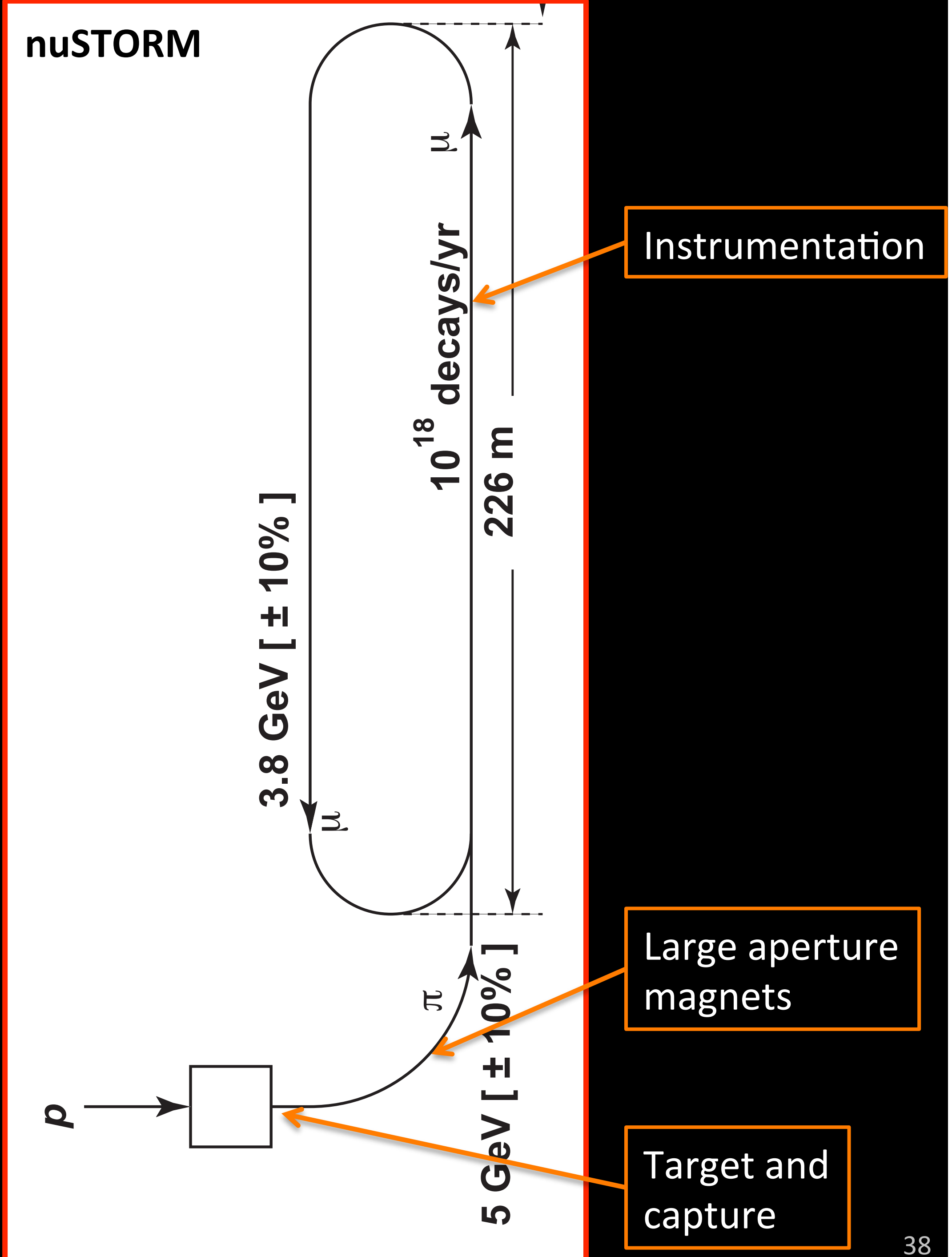
under study; M. Nessi et al



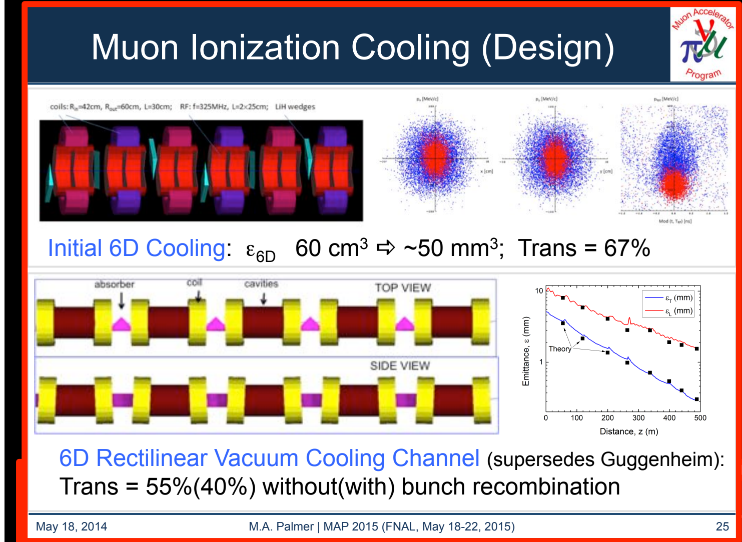
International Muon Ionization Cooling Experiment (MICE)

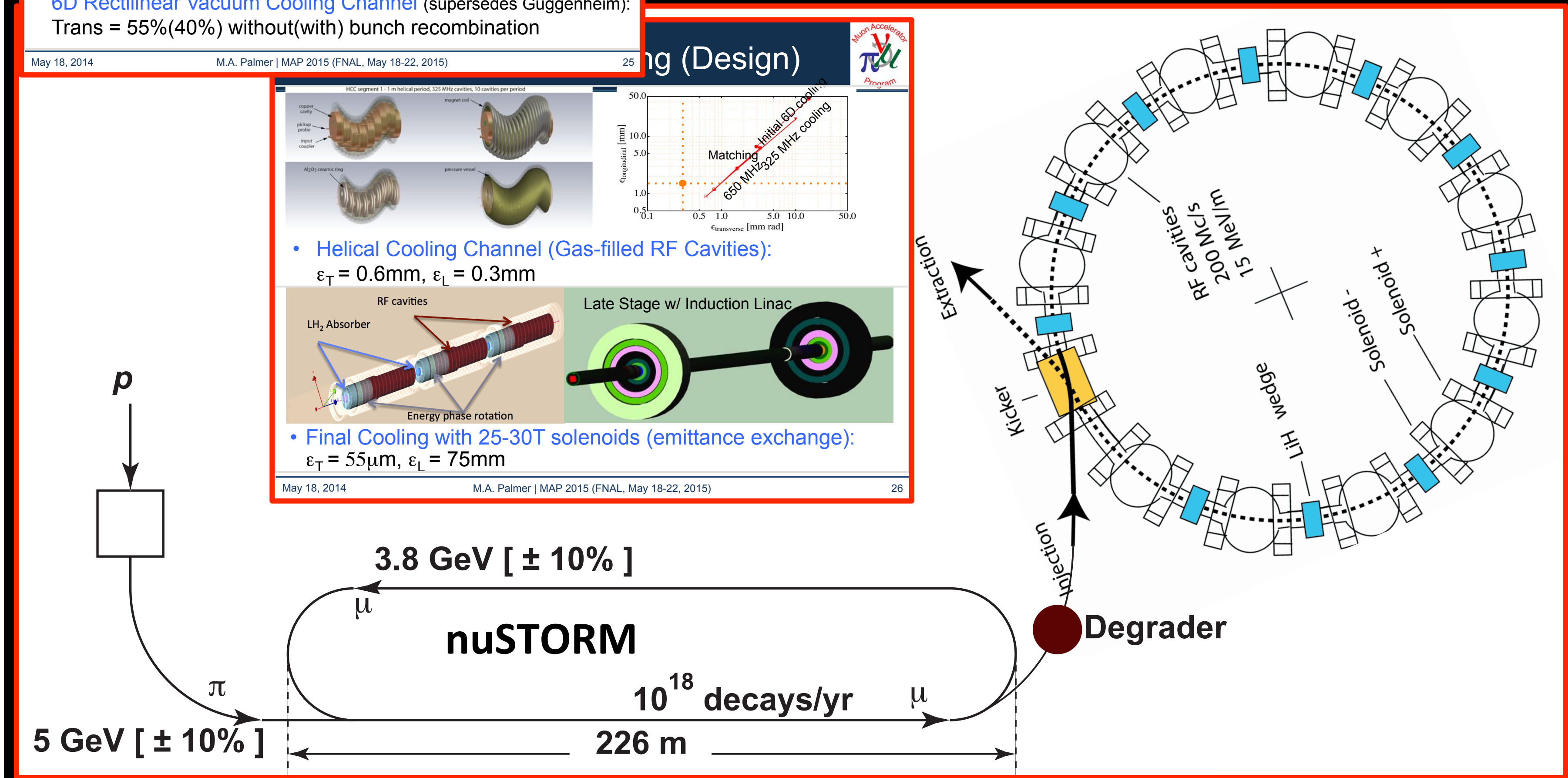






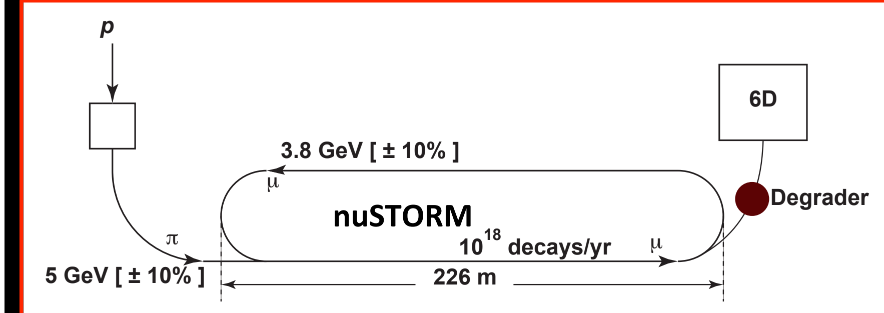
6D cooling demonstration





Vision

- **Posit #1:**
  - %-level measurement of ν_eN cross sections will be required
- **Posit #2:**
  - Neutrino Factory capability likely required
- **Posit #3:**
  - Capability to deliver multi-TeV l^+l^- colissions likely required



A proposal for discussion:

- It is proposed to develop an international team with the aim of designing, financing and constructing the above described cooling muon ring for the Initial Cooling Experiment.
- A campaign of extensive measurements, hopefully confirming the expectations of muon cooling theory could then be performed, starting for instance with a single proton bunch and the CERN-PS accelerator.
- Alternatively, this experiment might be realized either at the Fermilab Booster, at the BNL-AGS or even elsewhere (UK, Switzerland).

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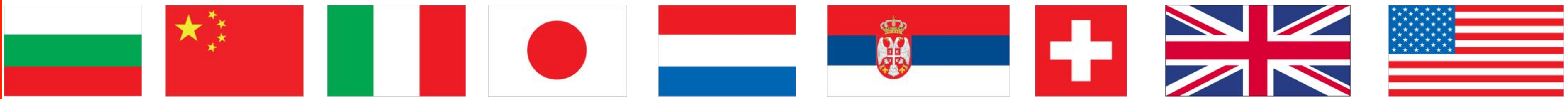
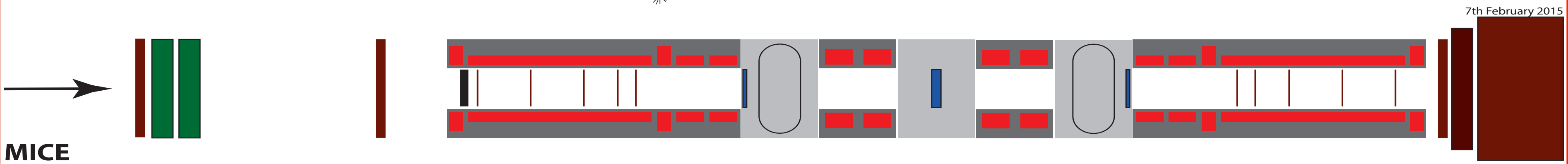


MICE



MICE and the next generation of muon beams for particle physics

CONCLUSIONS

Muon accelerators and MICE

- **Muon accelerators have the potential to:**
  - **Serve the next generation long- and short-baseline programmes by:**
    - **Making precise measurements of *electron-* and muon-neutrino nucleus cross sections**
  - **Revolutionise the study of neutrino oscillations:**
    - **And make searches for sterile neutrinos of exquisite sensitivity**
  - **Provide a route to multi-TeV lepton-antilepton collisions;**

- **Development of the capability to deliver the Neutrino Factory is required:**
  - **To study CP-invariance violation in detail if it is discovered; or**
  - **To continue the search of it is not; and**
  - **To deliver precision sufficient to elucidate the underlying physics**

- **MICE will unlock the exploitation of muon accelerators by providing the essential demonstration of ionization cooling:**
  - **Starting *now*:**
    - **Investigation of the effect of material, emittance, momentum on the cooling effect**
  - **Starting 2017:**
    - **Demonstration of ionization cooling;**
    - **Systematic study of factors that affect cooling performance**

- **Basis for executing the vision!**