MICE:
Muon Ionisation Cooling Experiment

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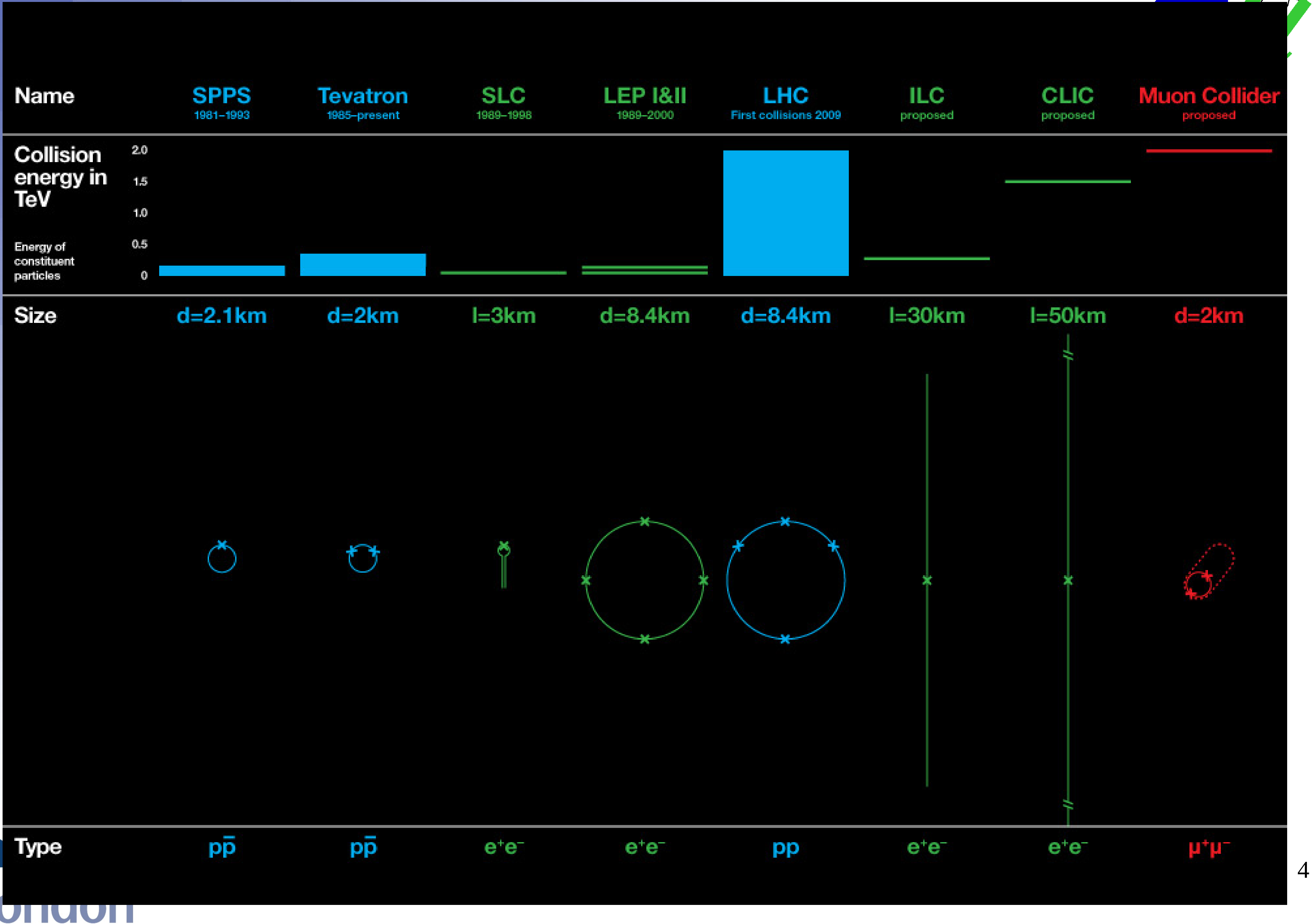
Overview

- Motivation
- Design
- Stages of development and hardware implementation
- A tour of MICE
- Analysis so far (beam)
- This year
- The future

Motivation: Muon Colliders

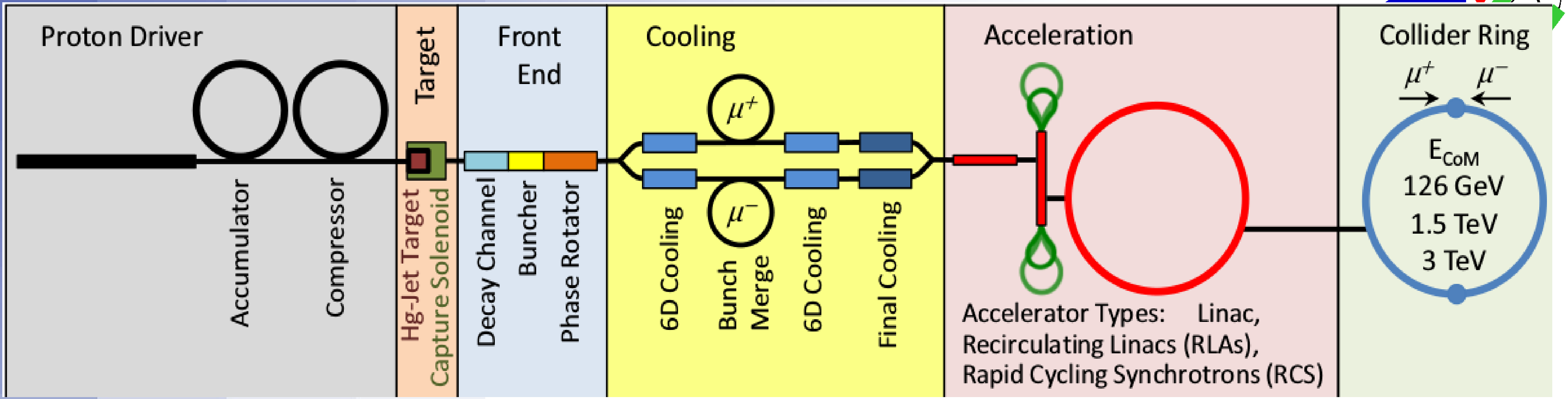
- Muons have many important advantages over electrons for high-energy lepton colliders:
  - suppression of radiative processes as $m_\mu = 207 * m_e$
  - enables the use of storage rings and recirculating accelerators
  - “Beamsthralung” effects, (radiation due to beam-beam interactions), much smaller in a muon collider than an e^+e^- machine
    - Circular e^+e^- colliders are energy limited and linear colliders are long and expensive.
  - The centre of mass energy of the collision can be precisely adjusted and the resonance structures and threshold effects studied in great detail in a muon collider.
  - Can sit on existing laboratory sites.

Size Comparison of Colliders



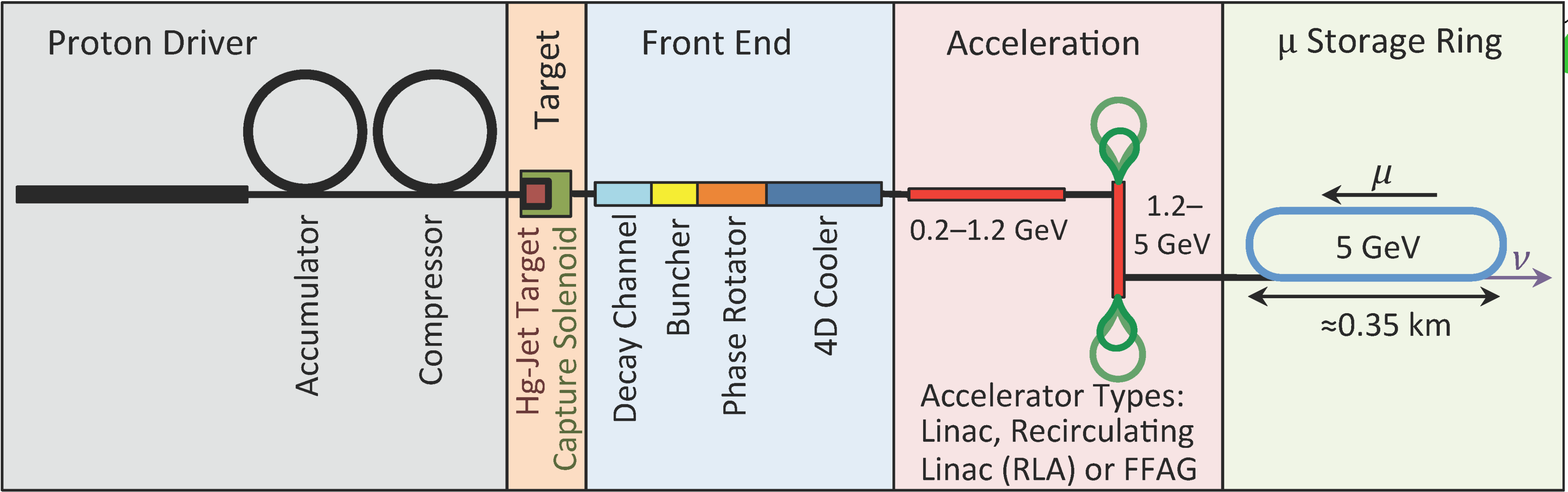
Name	SPPS 1981–1993	Tevatron 1985–present	SLC 1989–1998	LEP I&II 1989–2000	LHC First collisions 2009	ILC proposed	CLIC proposed	Muon Collider proposed
Size	d=2.1km	d=2km	l=3km	d=8.4km	d=8.4km	l=30km	l=50km	d=2km
Type	$p\bar{p}$	$p\bar{p}$	e^+e^-	e^+e^-	pp	e^+e^-	e^+e^-	$\mu^+\mu^-$

Motivation: Muon Colliders



- μ/e cross-section ratio for s-channel annihilation to Higgs boson, $(m_\mu/m_e)^2 = 4.3\times10^4$
  - gives the muon collider unique access to precision Higgs measurements *[http://www-bd.fnal.gov/icfabd/HF2012.pdf, Nucl. Phys. B (Proc. Suppl.) 51A (1996) 13, SNOWMASS-2001-E110, AIP Conf. Proc. bf 1507,p. 849 (2012)]*
  - e.g., at the ≈ 126 GeV/c^2 mass measured by ATLAS and CMS, only a muon collider can directly the observe the (4 MeV) width and lineshape of a Standard Model Higgs boson.
- Furthermore, should the Higgs have closely spaced supersymmetric partner states at higher mass, only a muon collider has the mass resolution required to distinguish them. (The same argument applies as well to closely spaced scalar states in any other new-physics scenario.)

Motivation: Neutrino factory



- A muon storage ring is an ideal source for long-baseline neutrino-oscillation experiments: via $\mu^- \rightarrow e^- \nu_\mu \nu_e$ and $\mu^+ \rightarrow e^+ \nu_\mu \nu_e$
- Provides collimated, high-energy neutrino beams with well-understood composition and properties.
- Clean identification of final-state muons in far detectors enables low-background appearance measurements using ν_e and $\bar{\nu}_e$ beams.
- Non-zero θ_{13} neutrino mixing angle measured
  - observing or ruling out neutrino CP violation becomes highest priority in neutrino physics, from which the needed neutrino factory performance follows.

A Brief History of Muons

- Muon storage rings are an old idea:
  - Charpak et al.(g– 2)(1960), Tinlot & Green (1960), Melissinos (1960)
- Muon colliders suggested by Tikhonin (1968)
- But no concept for achieving high luminosity until ionisation cooling
  - O'Neill (1956), Lichtenberg et al. (1956), applied to muon cooling by S krinsky & Parkhomchuk (1981) and Neuffer (1979, 1983)
- The realisation (Neuffer and Palmer) that a high-luminosity muon collider might be feasible stimulated a series of workshops & formation (1995) of the Muon Collaboration
  - has since grown to 26 institutions and >100 physicists
- Snowmass Summer Study (1996)
  - study of feasibility of a 2+2 TeV Muon Collider [Fermilab-conf-96/092]
- Neutrino Factory suggested by Geer (1997) at the Workshop on Physics at the First Muon Collider and the Front End of the Muon Collider [AIP Conf. Proc.435] also CERN yellow report (1999) [CERN 99-02, ECFA 99-197]

See also: "Muon Colliders and Neutrino factories" [arXiv:1412.3487]; "Status of Muon Collider Research and Future Plans" [PRSTAB2:081001(1999)]; Neutrino Factory Feasibility Study I (2000) and II (2001) reports; "The Program in Muon and Neutrino Physics" [hep-ex/0108041]; www.fnal.gov/projects/muon_collider

Motivation: Summary

- Muon colliders and neutrino factories are attractive options for future facilities aimed at achieving the highest lepton-antilepton collision energies and precision measurements of parameters of the Higgs boson and the neutrino mixing matrix.
- Performance and cost depends on how well a beam of muons can be “cooled”.
- MICE has developed and will test a full or partial cooling cell, a series of which would be used to produce the collider or factory.
- Recent progress in muon cooling design studies and prototype tests nourishes the hope that such facilities can be built during the coming decade.

Muon Ionisation Cooling Experiment MICE

- Ionisation cooling is the process of reducing the beam emittance (phase space) while maintaining the longitudinal momentum of the beam.
- Necessary for a Muon Collider or neutrino factory.
- Short lifetime of muon means that
  - traditional beam cooling techniques which reduce emittance cannot be used.
  - ionisation cooling is the only practical solution to preparing high intensity muon beams for use in these facilities.
- MICE is currently the only experiment studying ionisation cooling of muons.

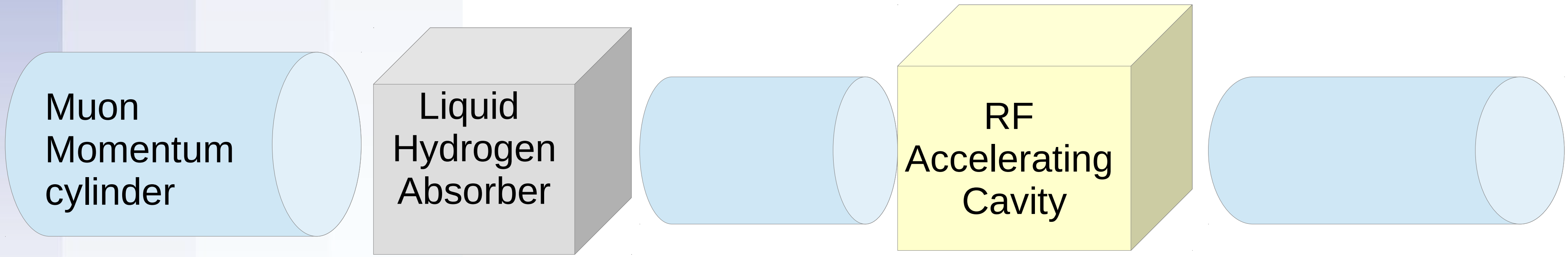
MICE: Muon Ionisation Cooling Experiment

MICE: Collaboration

Over 100 collaborators from >10 countries and ~30 institutes.

What is Muon Ionisation Cooling?

- Muons are passed through a liquid hydrogen `absorber' where they lose both longitudinal and transverse momentum as they ionise the hydrogen.
- A proportion of the lost longitudinal momentum is then restored by RF cavities.
- The result is a beam of muons with reduced transverse momentum.



Muon Momentum cylinder

Liquid Hydrogen Absorber

RF Accelerating Cavity

- However, this process also causes some heating so the net cooling is a delicate balance between these two effects

Muon Ionisation Cooling

- Muon beam loses both transverse and longitudinal momentum by ionisation cooling when passed through an 'absorber'.

- Longitudinal momentum is restored by two 201 MHz RF cavities.

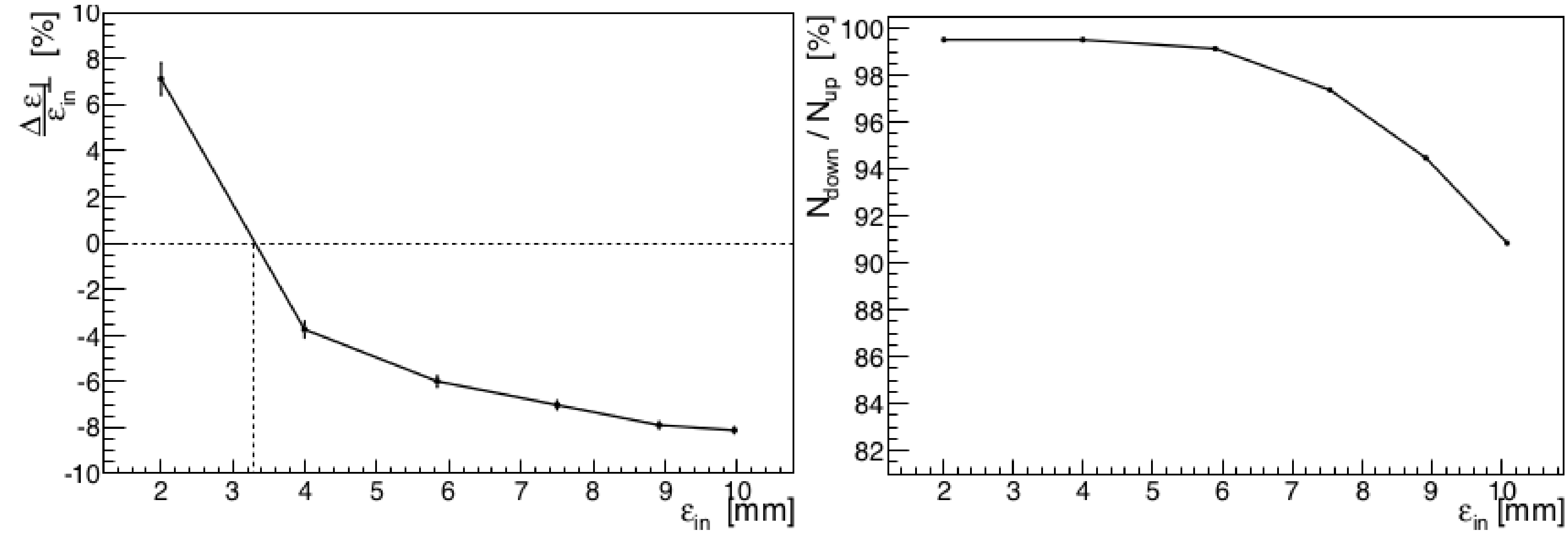
$$\frac{d\epsilon_n}{ds} \simeq \overbrace{-\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_n}{E_\mu}} + \underbrace{\frac{1}{\beta^3}\frac{\beta_\perp(0.014\mathrm{GeV})^2}{2E_\mu m_\mu L_R}}$$

$D\varepsilon_n/ds$ is the rate of change of normalised-emittance within the absorber;
β, E_μ and m_μ the muon velocity, energy, and mass respectively;
$\beta_\perp$ is the lattice betatron function at the absorber;
L_R is the radiation length of the absorber material.

- Heating through multiple scattering

MICE aims to reduce the transverse emittance of the beam and measure the normalised emittance reduction with a precision of 0.1%.

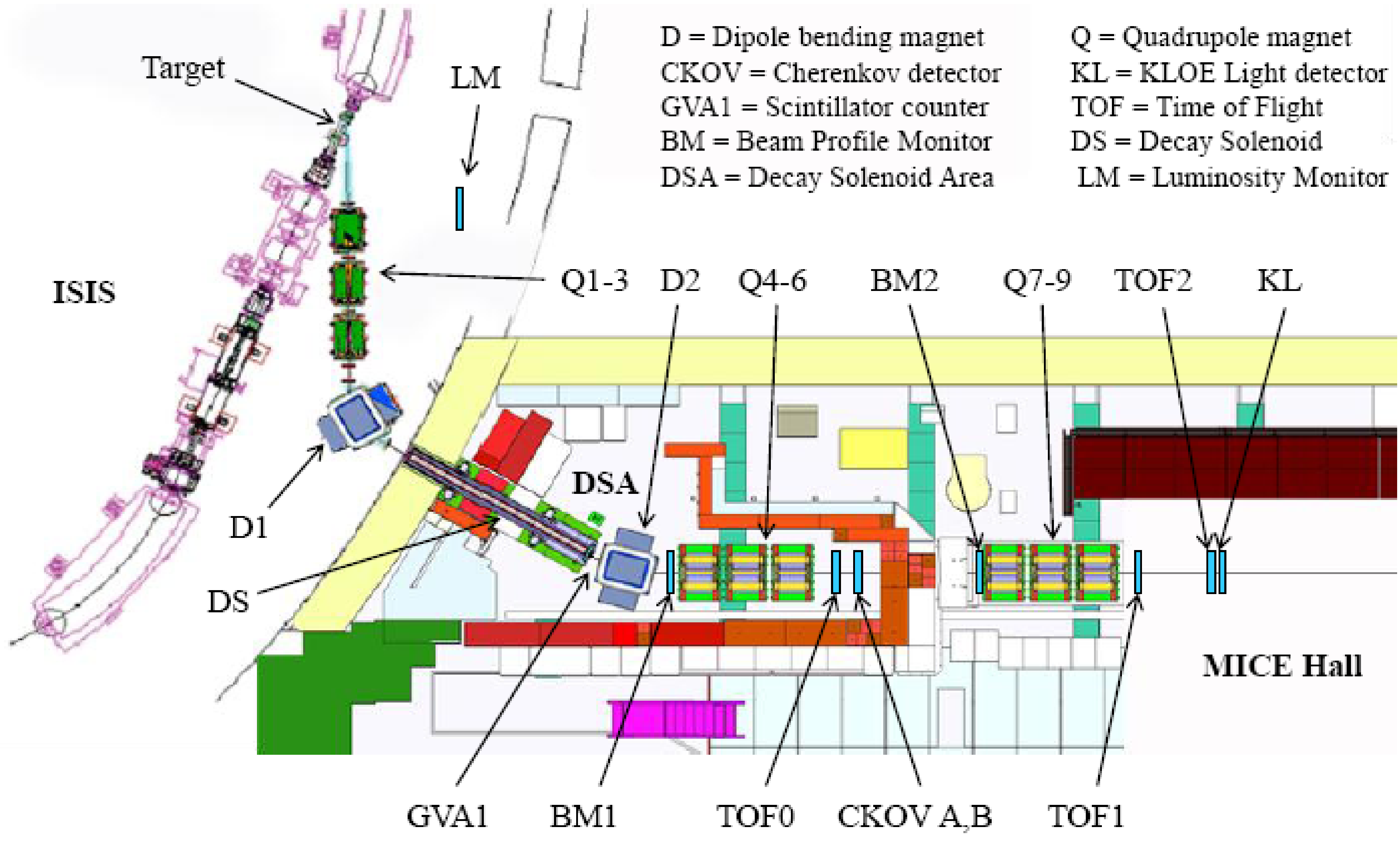
MICE: The trade off



(left) Change in emittance, and (right) beam transmission (both in percent), vs. input emittance.

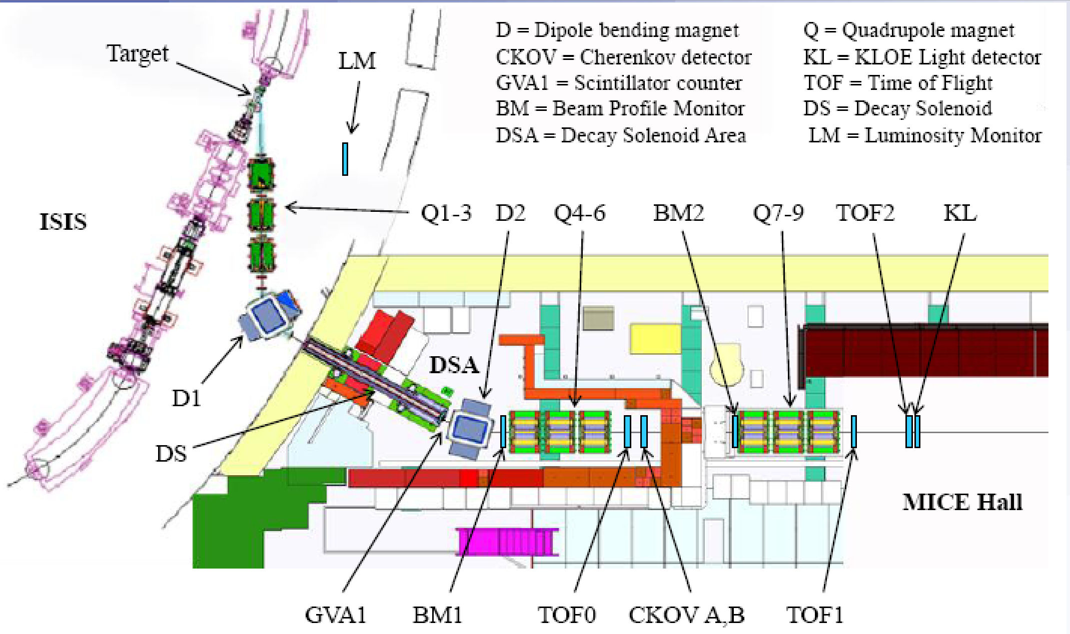
- The effect of the heating & cooling terms is an equilibrium emittance $\varepsilon_{n,eq} \propto \beta_\perp / \beta X_0 \langle dE_\mu /ds \rangle$ below which the beam cannot be cooled.
- However, as input emittance increases, beam scraping results in increased loss.
- MICE will study this in order to obtain a complete experimental characterisation of the cooling process.
- (Since a typical cooling channel will employ dozens to hundreds of cooling lattice cells, the precision with which even the tails of distributions can be predicted will have important consequences for the performance of the channel.)

MICE: Beam Production



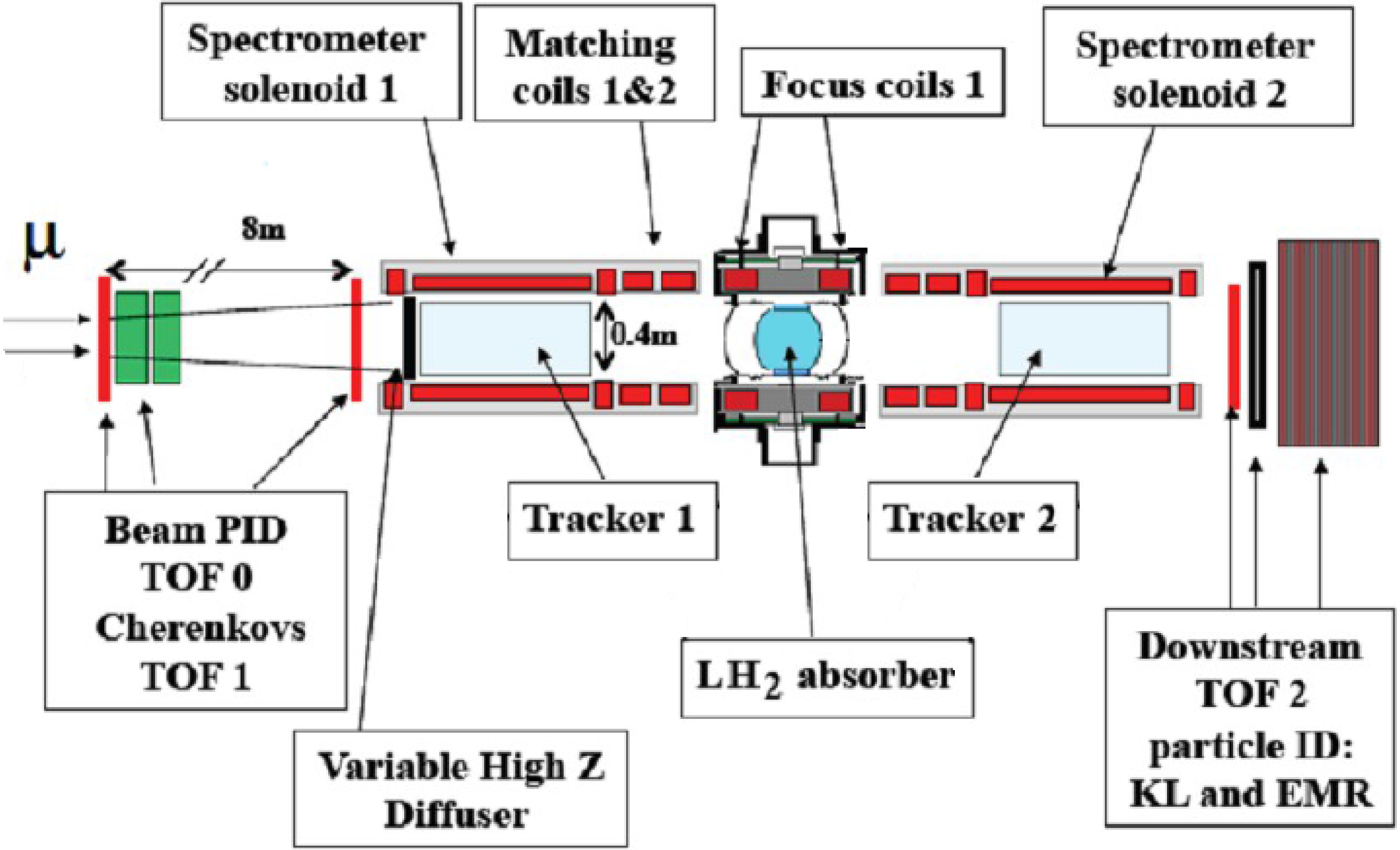
Far left shows part of the ISIS accelerator which serves as a proton driver, with a titanium target used to generate pions by intercepting the circulating proton beam.

The Beam

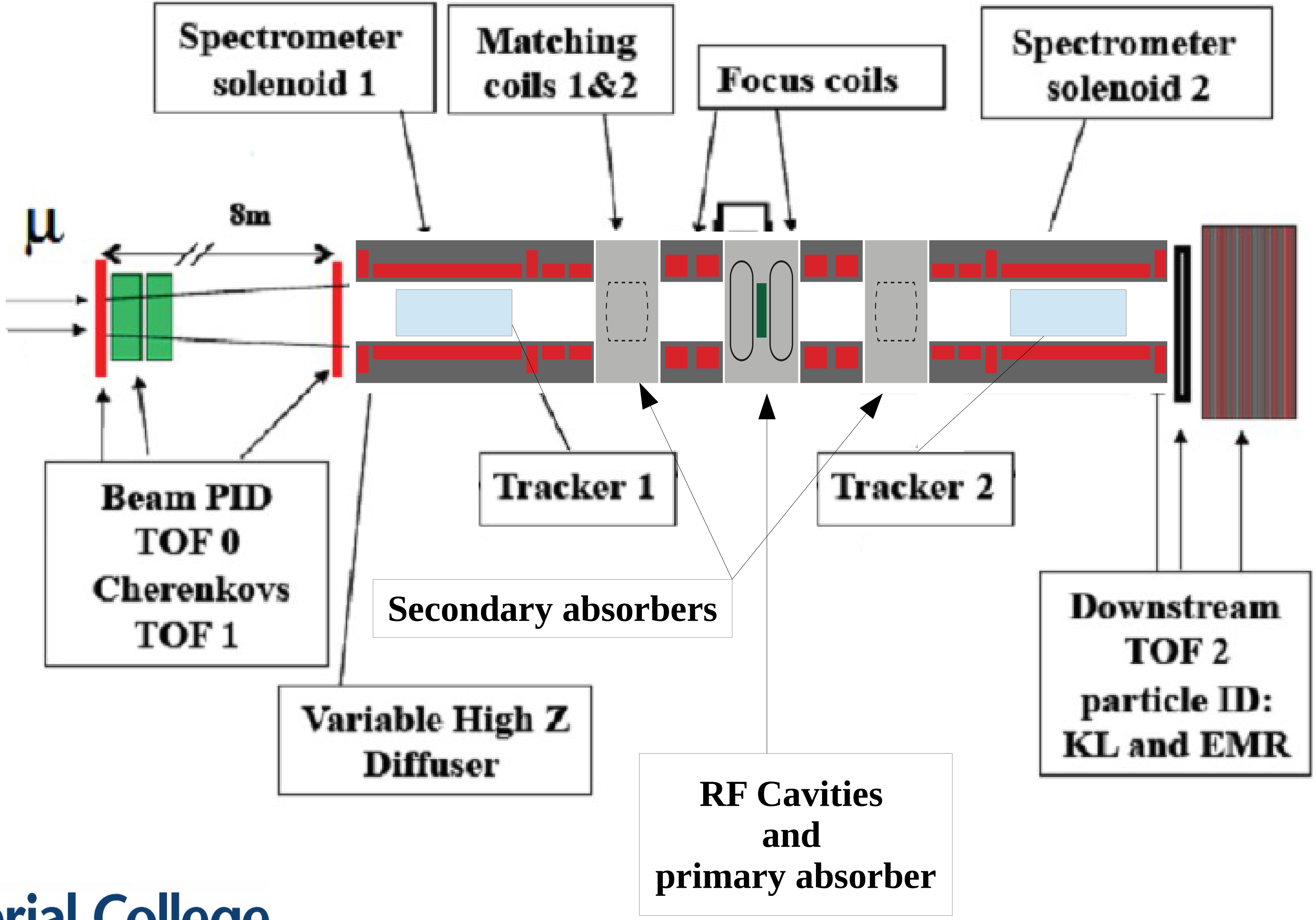


- ISIS 800 MeV proton beam.
  - delivering 4 μC of protons
  - in two 100 ns long pulses
  - With mean current of 200 μA.
- Titanium target is dipped into ISIS beamline.
- Pions (π^+) produced in target decay to muons of lower momentum.
- Beam can be prepared as a π beam or μ beam with momenta between 140-450 MeV/c.
- Dip rate: 1 dip/2.56s
- Max Particle rate (for 1 dip/2.56s):
  - μ^+ ~120 μ/dip
  - μ^- ~20 μ/dip
- Most efficient usage delivers 850 μ/s at 1 Hz.
- Final μ beam: 1ms wide spill in 2 100ns long bursts every 324 ns.

MICE: This Year



MICE: Full System (2017)



Secondary absorbers

RF Cavities
and
primary absorber

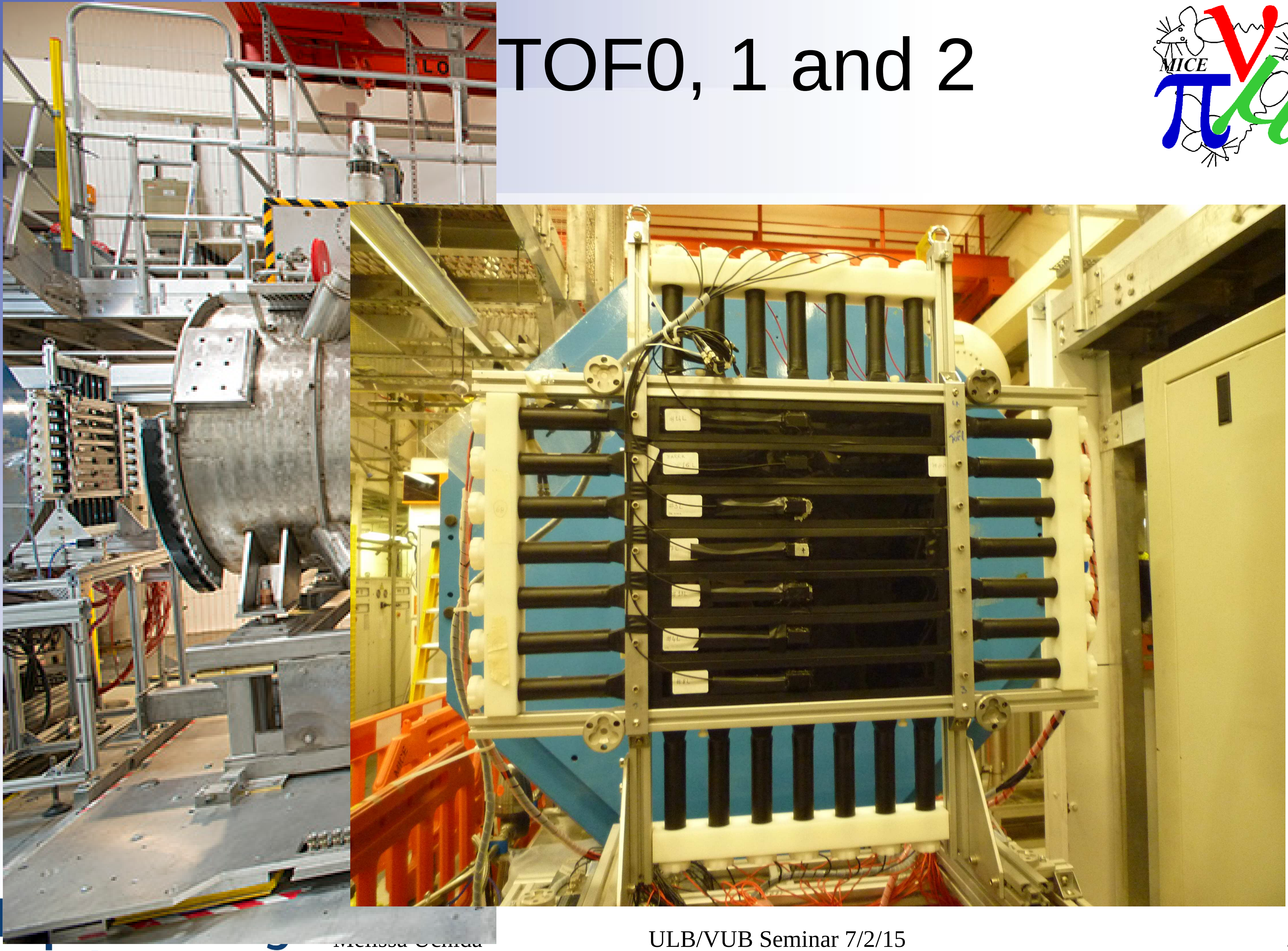
The Detectors

- Time Of Flight: TOF0, TOF1 and TOF2
  - precise timing measurements correlate time of incoming beam muons to the phase of the accelerating field in each RF cavity.
  - PID obtained US by TOF0 & TOF1 and 2 threshold Cerenkov counters, that will provide π/μ separation up to 300 MeV/c.
- Identification of downstream particles is obtained by adding (TOF2) and an electromagnetic calorimeter (EMC) made up of:
- Electron Muon Ranger: EMR
  - to separate muons from decay electrons in collaboration with the..
- KLOE-Light: KL
  - based on the Kloe calorimeter design
- Cerenkov: CkoVa CKoVb
  - Threshold Cerenkov counters (CKOVa and CKOVb), with TOF0 and TOF1 to provide π/μ separation up to 300 MeV/c.
- Trackers
  - 2 Tracker detectors upsteam and downstream of cooling section, each immersed in a uniform magnetic field of 4T.
  - Measure the normalised emittance reduction with a precision of 0.1% (beam emittance measured before and after cooling).

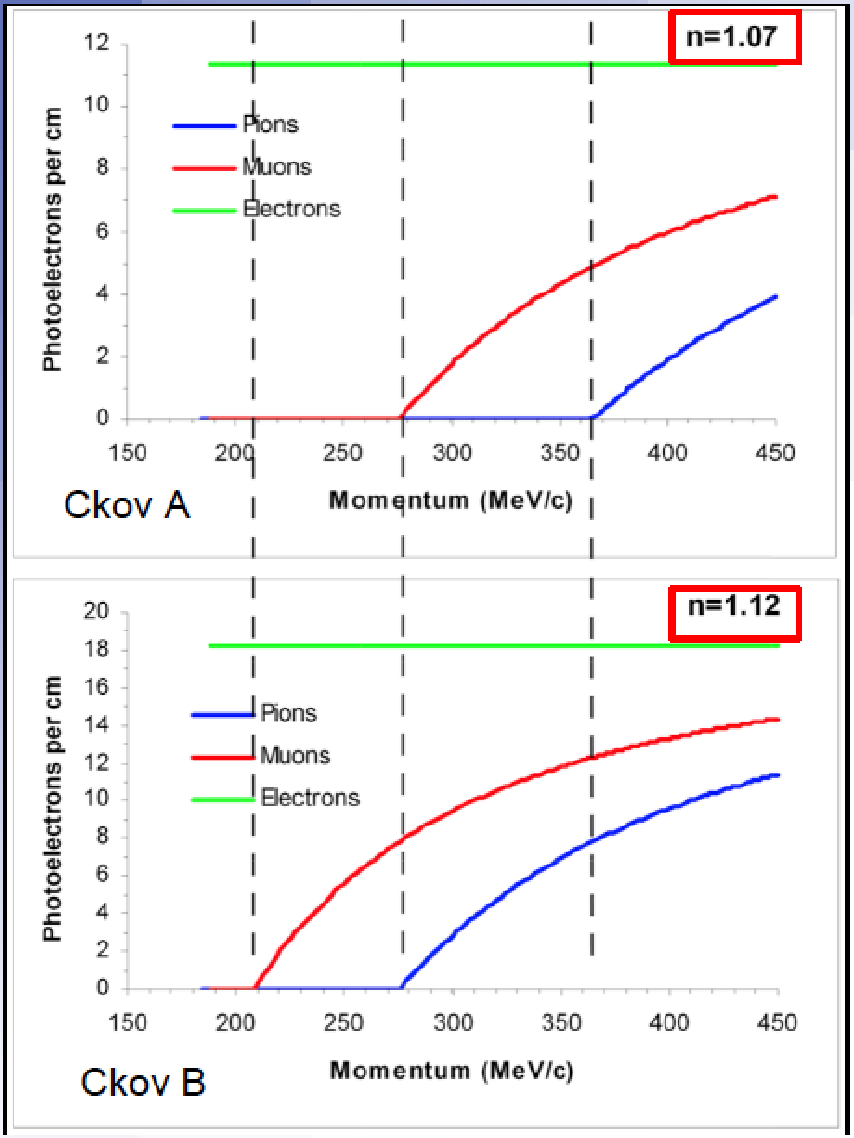
TOF0, 1 and 2

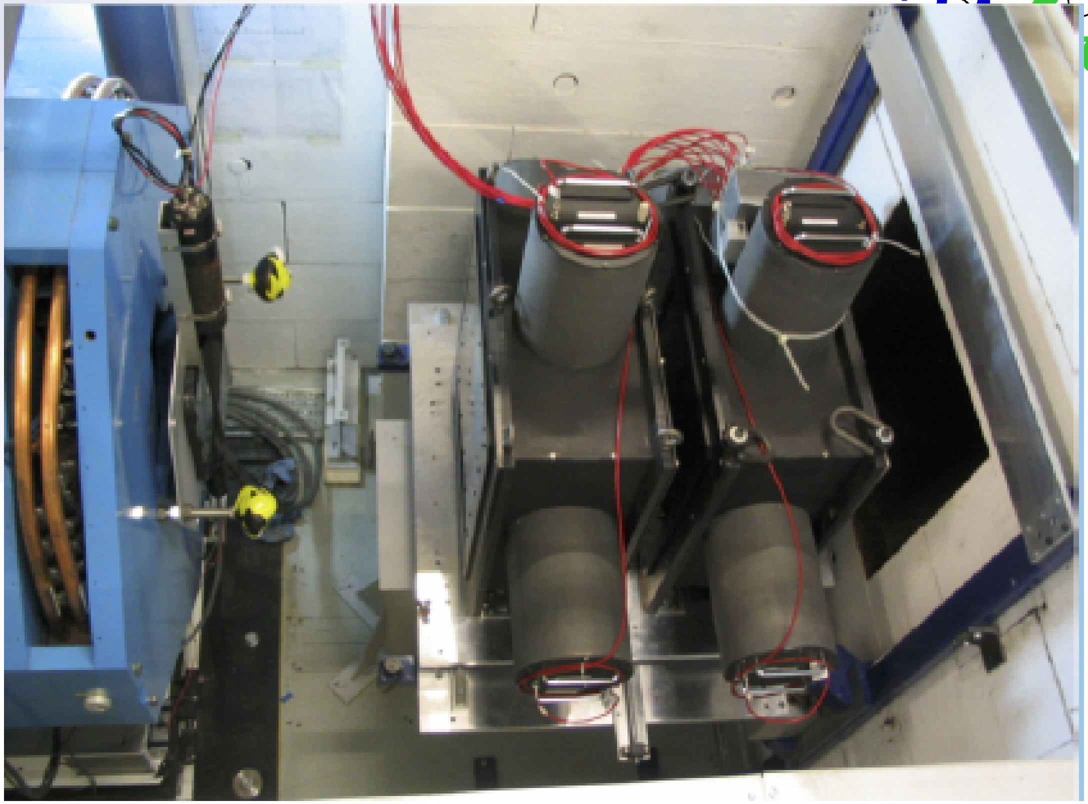
- All TOF stations share a common design off 2.5x4cm (TOF0 and TOF1) 2.5x6cm (TOF2) thick slabs of fast scintillator material.
- Each TOF has two planes, x and y orientations (to increase measurement redundancy) and are read out at both ends by R4998 Hamamatsu fast photomultipliers (rise time 1ns).
- Active areas:
  - TOF0 400x400mm
  - TOF1 and TOF2 420x420mm
- Each (following refurbishments in 2011) have timing resolution of ~ 50 ps.
- Allows muon momentum to be determined with resolution 3.7 MeV/c (in collab. with Trackers)

TOF0, 1 and 2



CKoV

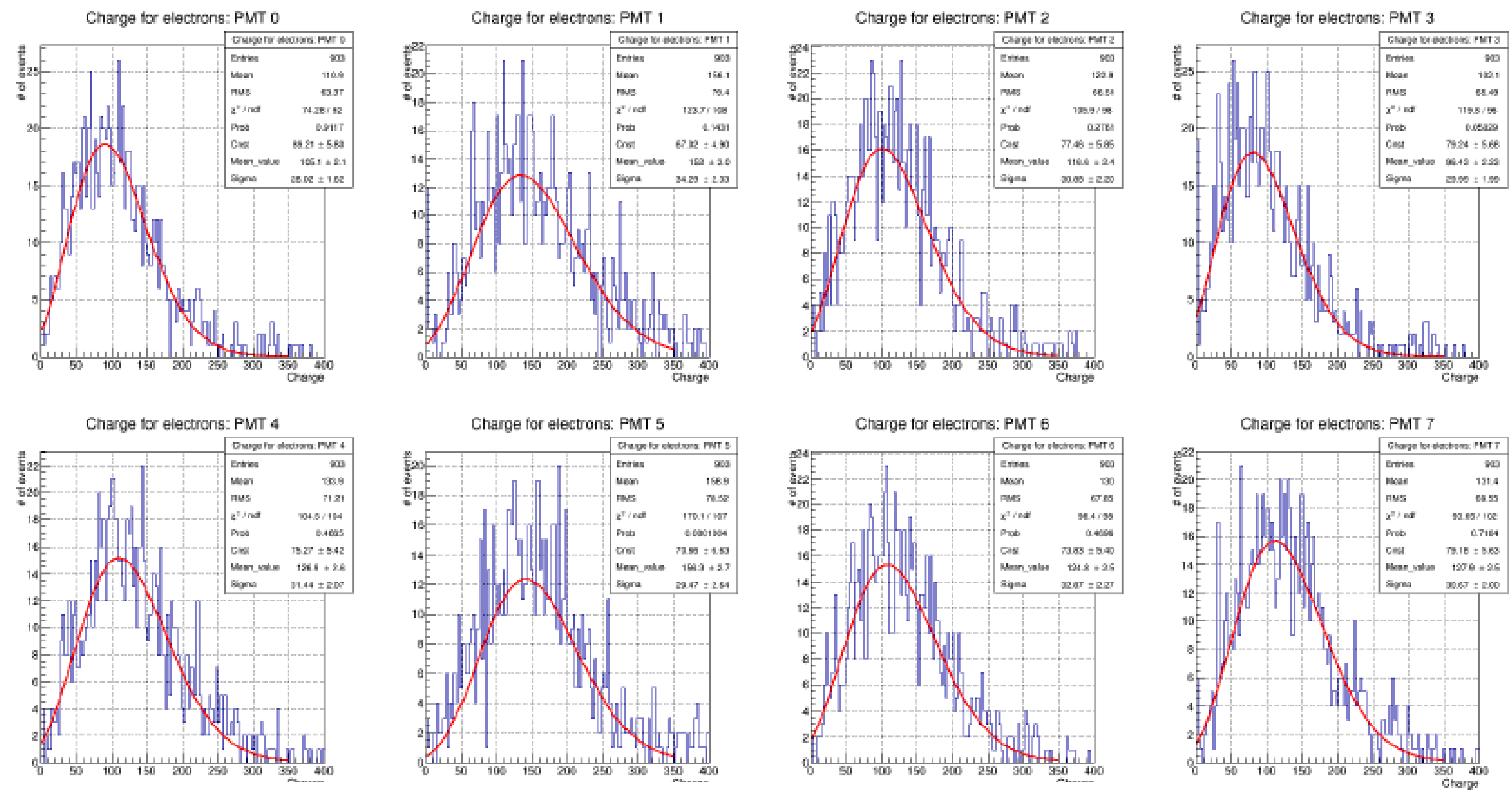




- Use 8″ photomultiplier tubes
- π/μ separation
- Installed
- Calibrated
- Tested on data and MC.

CKoV

Electron charge seen by each of the 8 PMTs

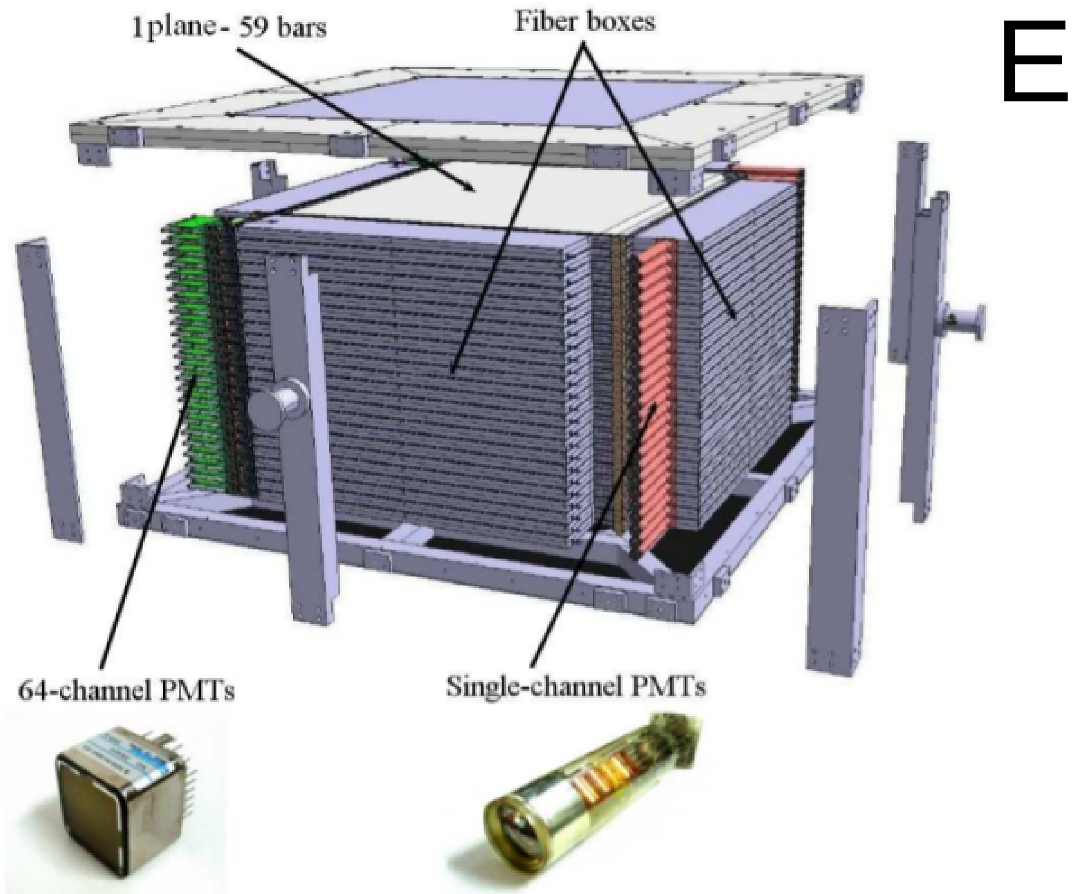


This procedure was tested in June 2014 run

EMR

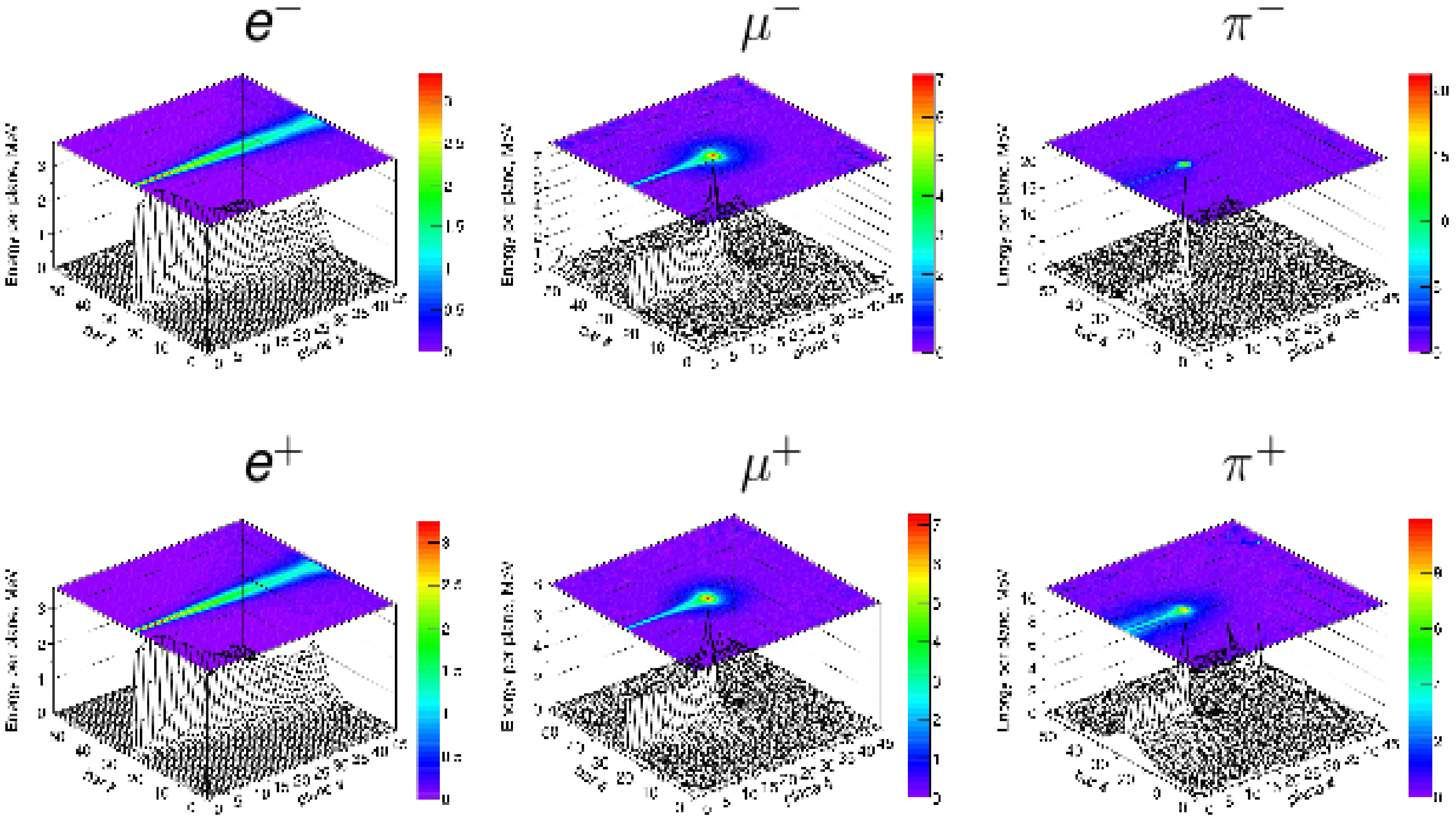
- A totally active scintillating calorimeter and tracking detector for low energy muons and electron.
- 48 planes made up of 59 scintillating bars per plane. The planes are installed perpendicular to each other in an x-y arrangement.
- A wavelength shifting bar is glued inside each bar, and connects to waveguides and photomultiplier tubes (PMTs) on each side.
- On one side of each plane, the bars are connected to a 64 channel PMT which provides a readout of each individual bar.
- On the other side, the waveguides from every bar are sent to a single channel PMT.
- Signals from the single channel PMTs are read out by a CAEN V1731 Flash Analogue to Digital Converter.
- This readout is then used to measure the total energy deposited per plane.

EMR


1plane - 59 bars
Fiber boxes
64-channel PMTs
Single-channel PMTs

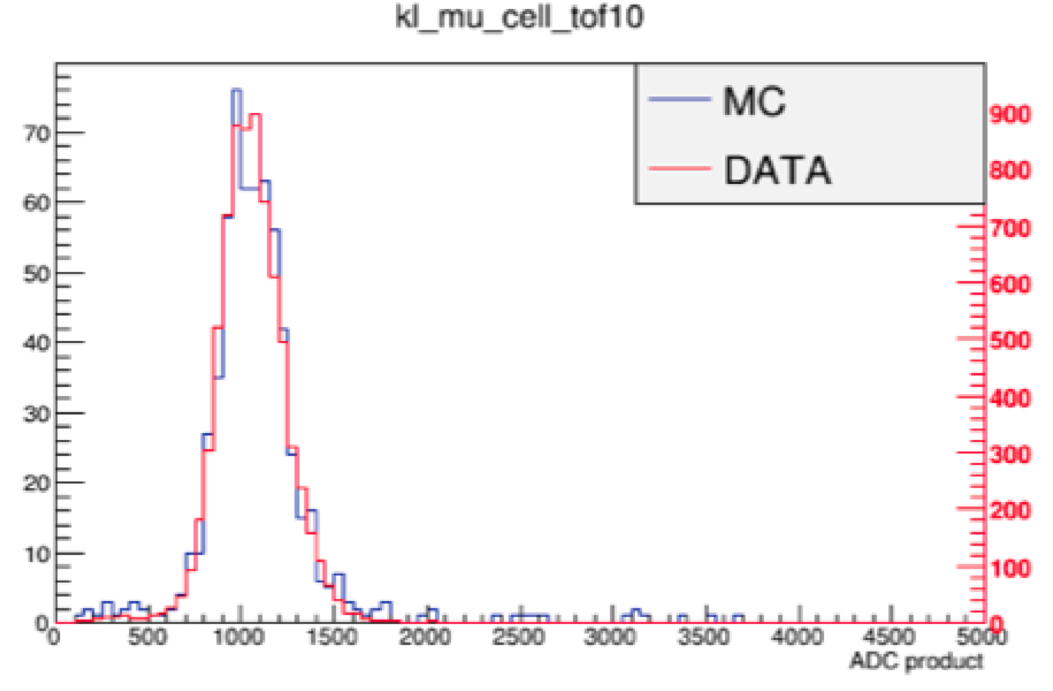
Simulation

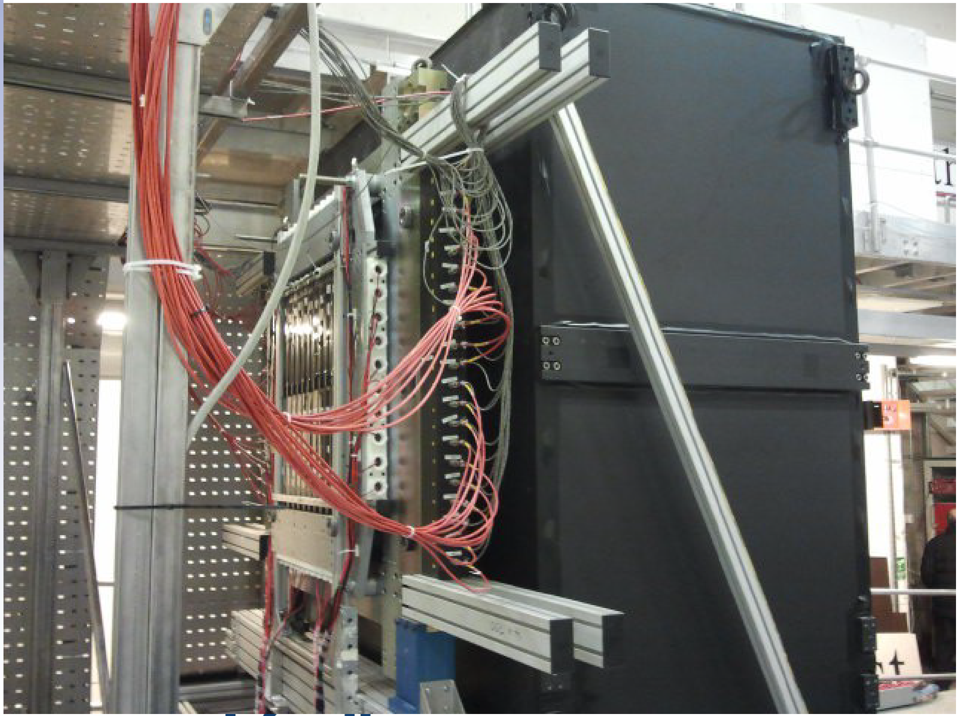
EMR



Interaction of Low Energy Particles with EMR simulation of 200 MeV/c π^+, π^-, μ^+, μ^-, e^+, e^- beams (showing energy in MeV per plane and bar)

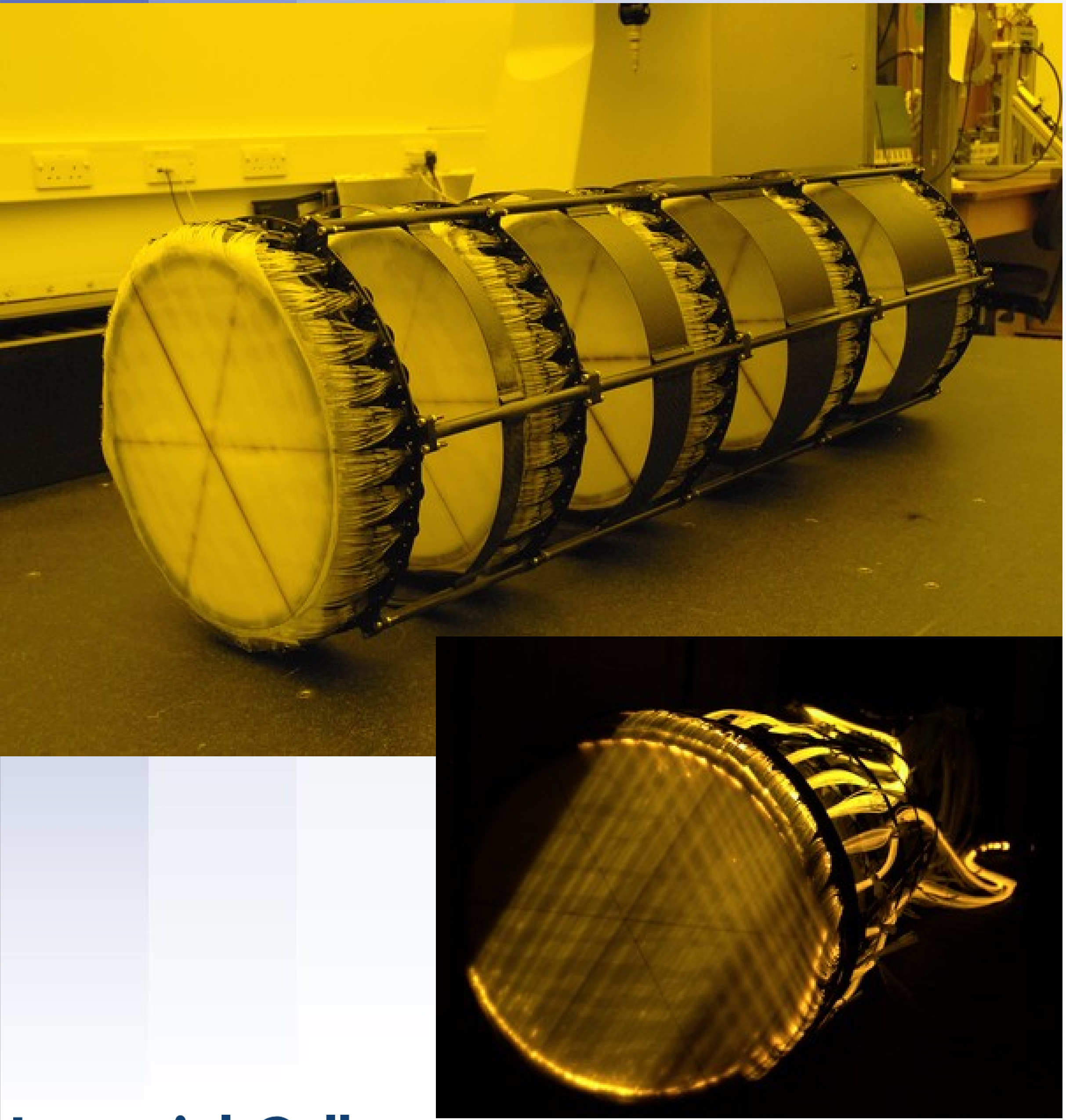
KL





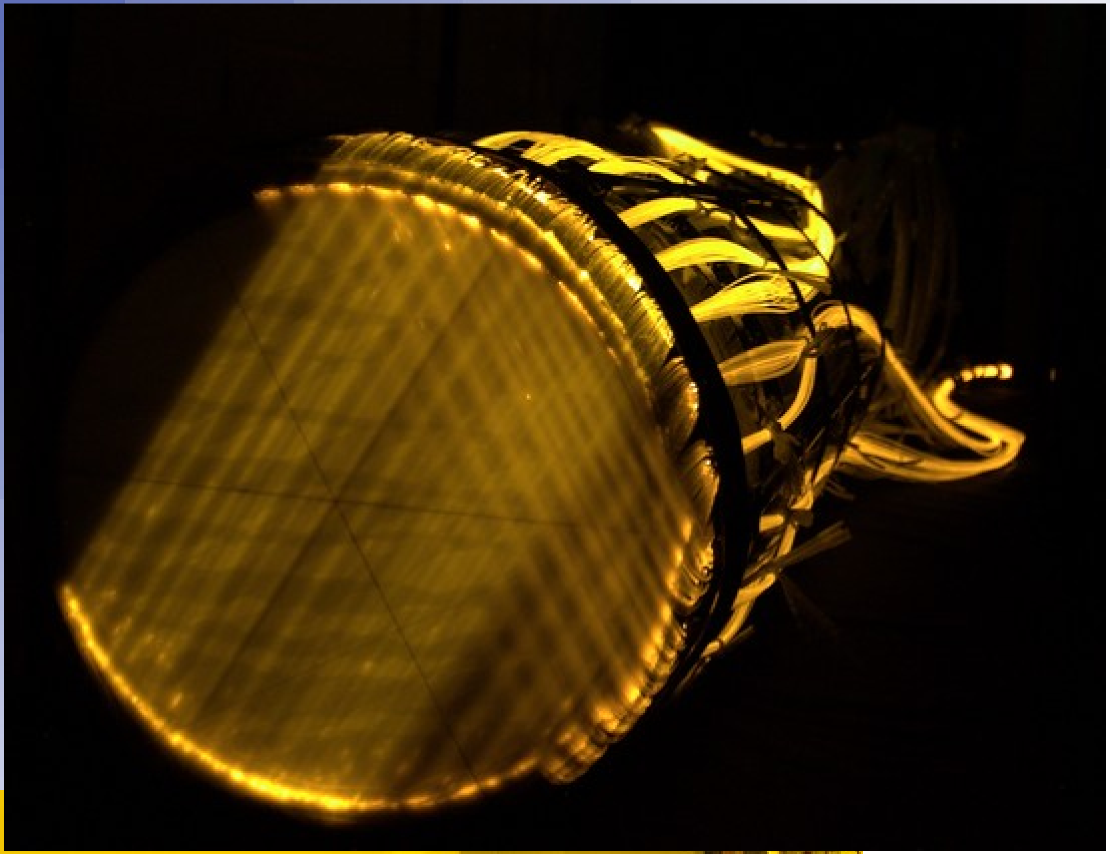
- Based on the design of the KLOE calorimeter.
  - F. Ambrosino et al. “Calibration and performances of the KLOE calorimeter”, Nucl.Instrum. Meth. A598, 239, 2009
  - Made up of a series of lead scintillating fibres.
- Works with the TOFs to perform PID providing π/μ separation up to 300 MeV/c.

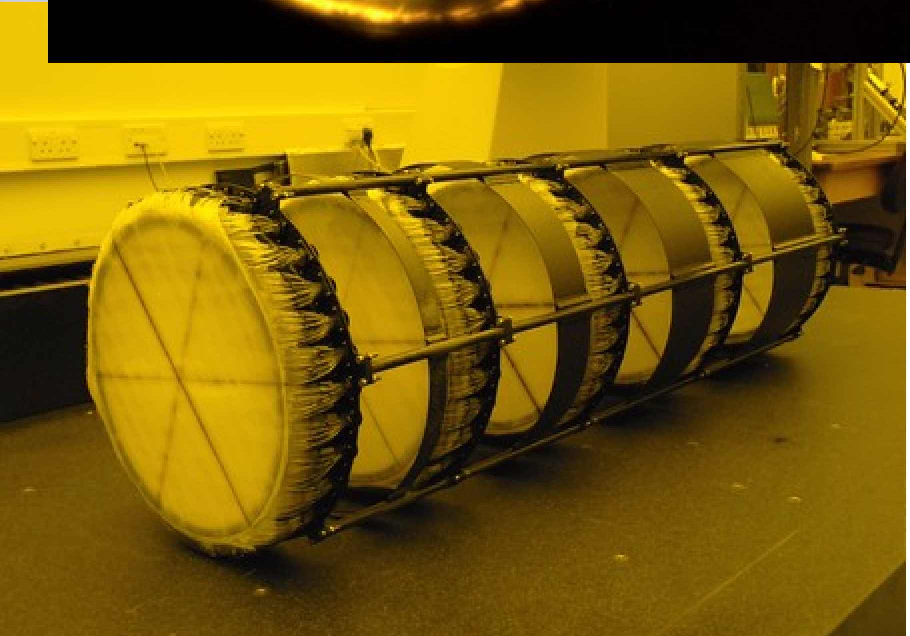
The Trackers



- Two scintillating fibre trackers, one upstream, one downstream of the cooling channel.
- Each within a spectrometer solenoid producing a 4T field.
- Each tracker is 110 cm in length and 30 cm in diameter.
- 5 stations per tracker at varying separations in z between 20 and 35 cm.
- LED calibration system.
- Hall probes.

The Trackers

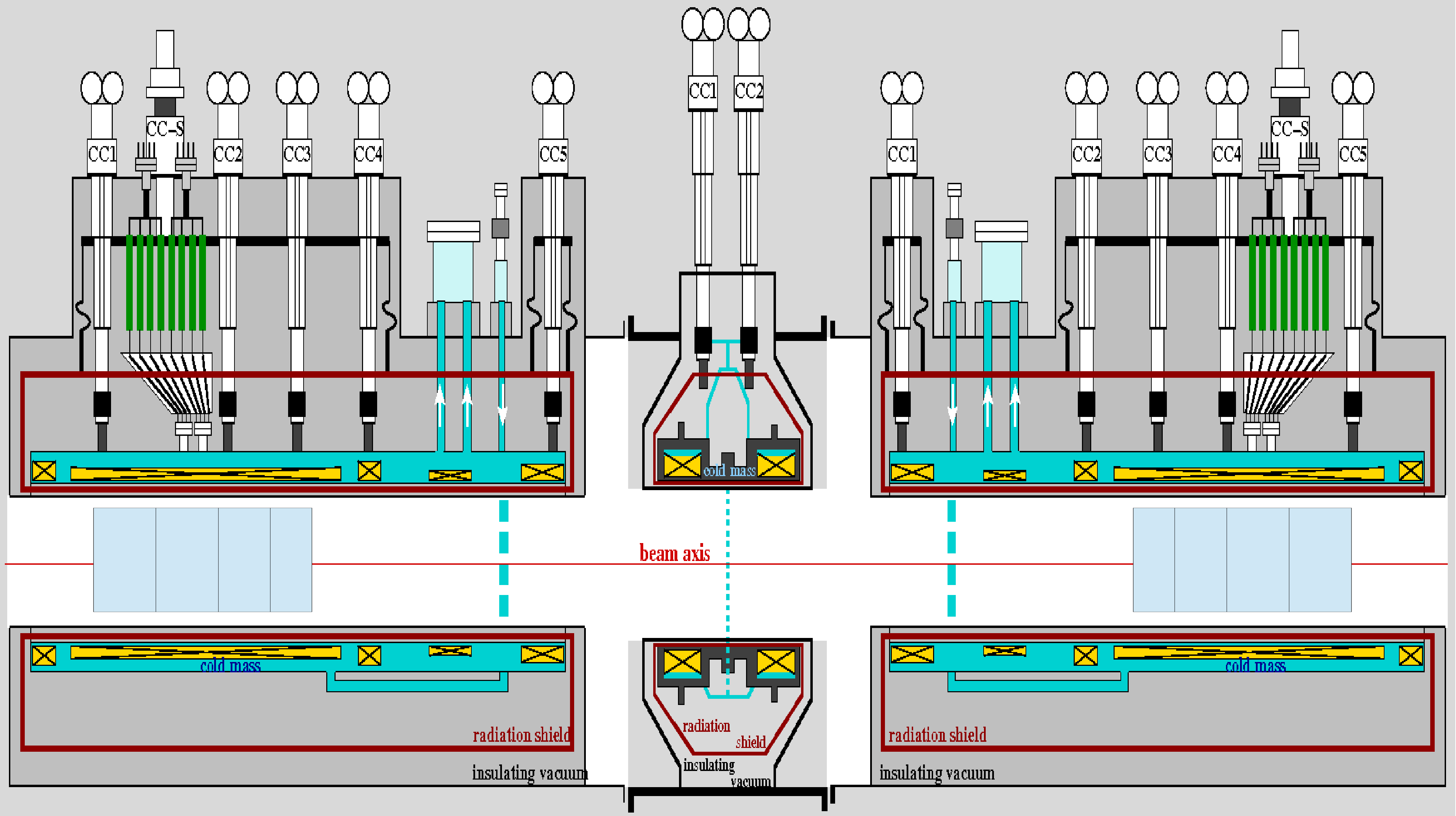




- 350 µm scintillating fibres are glued into doublet layers with a thickness of 627µm.
- 7 fibres are grouped into a single readout channel. (This reduces the number of readout channels, while maintaining position resolution).
- 3 doublet layer fibre planes per station, each offset by 120 deg.
- Position resolution of 470 µm per doublet layer.
- Fibres readout by Visible Light Photon Counters, operating at liquid He temperatures.
- Digitised by FPGA based system from D0.

Spectrometer Solenoids

Not to scale

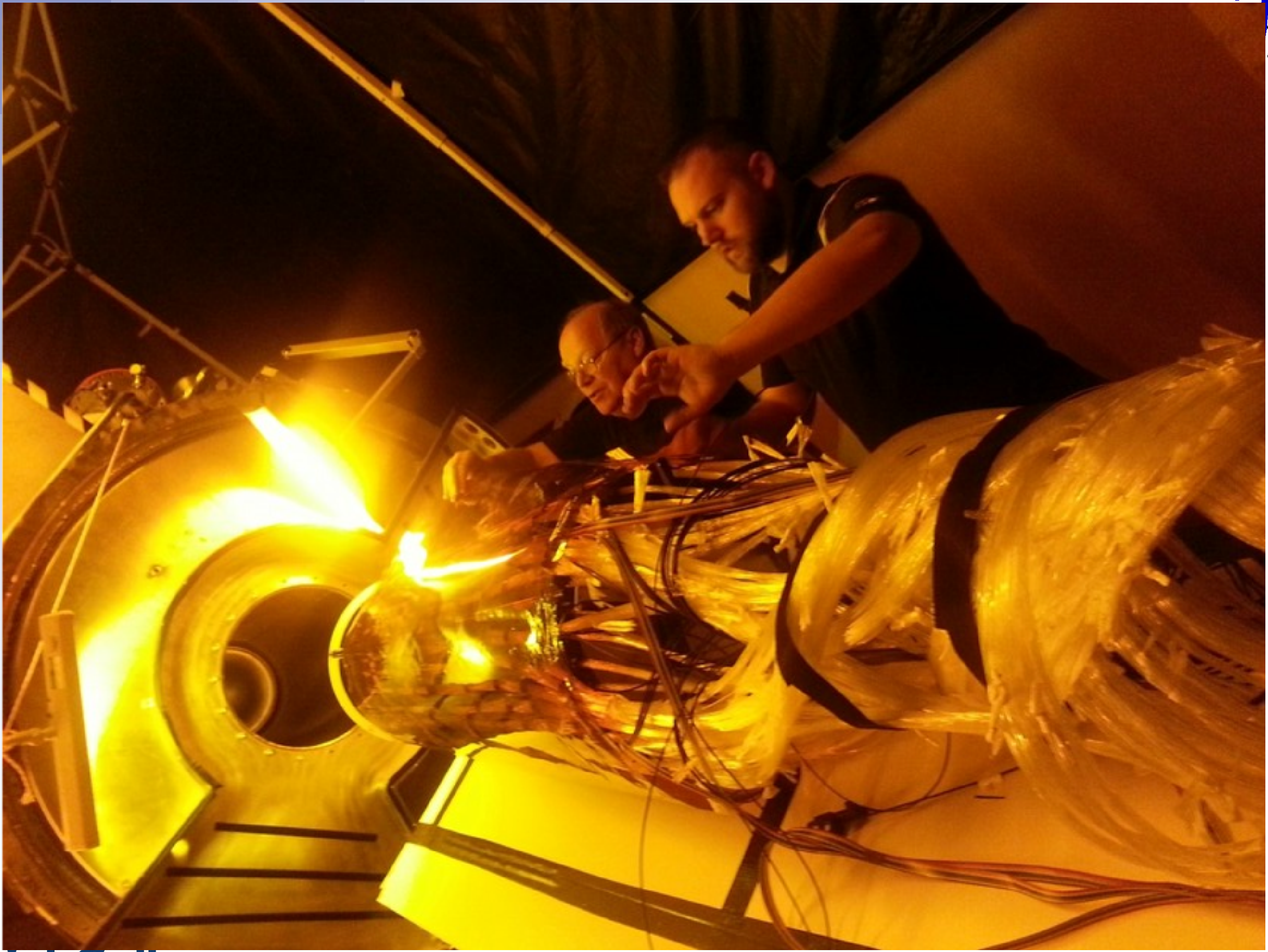


Tracker Installation

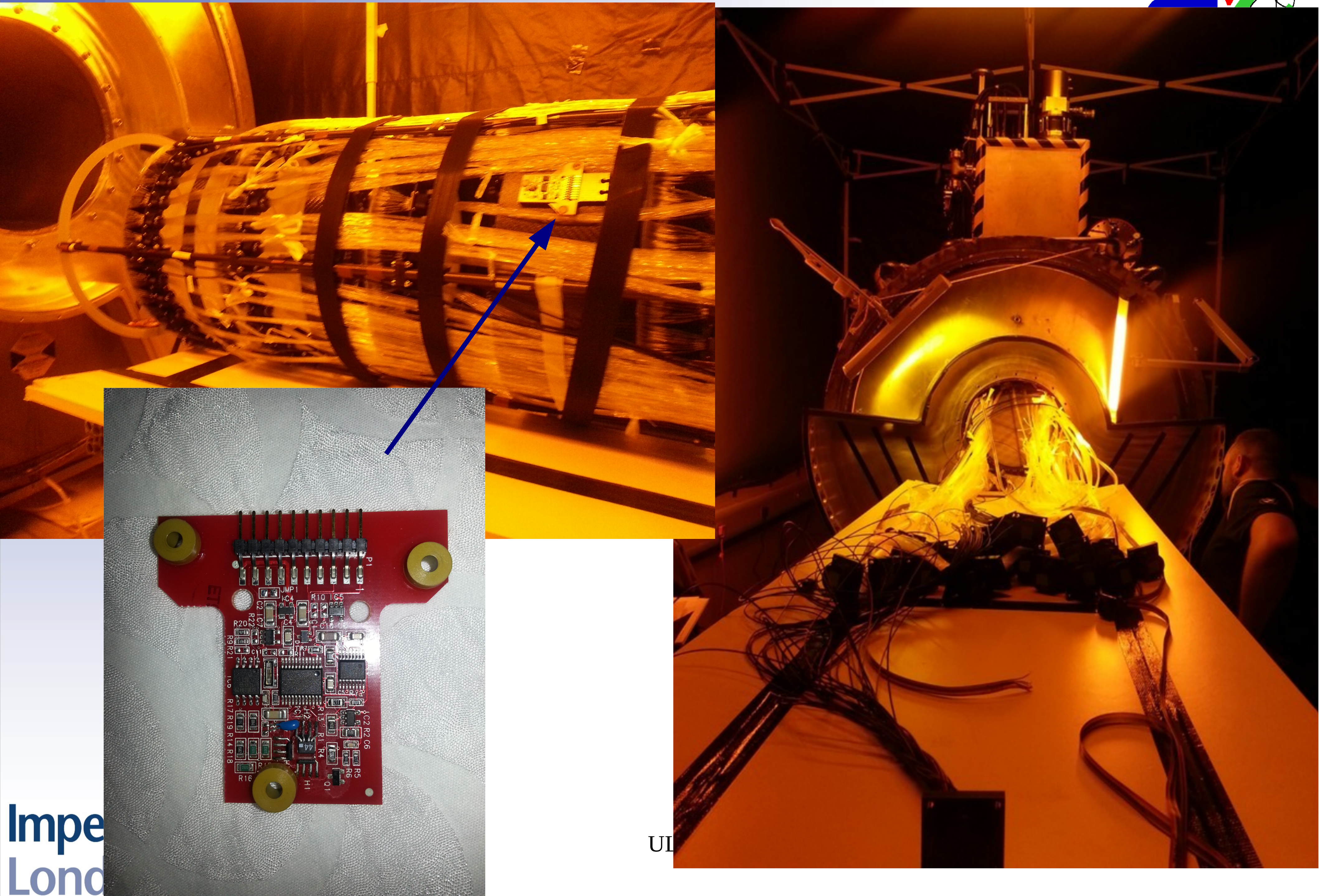
Tracker Installation

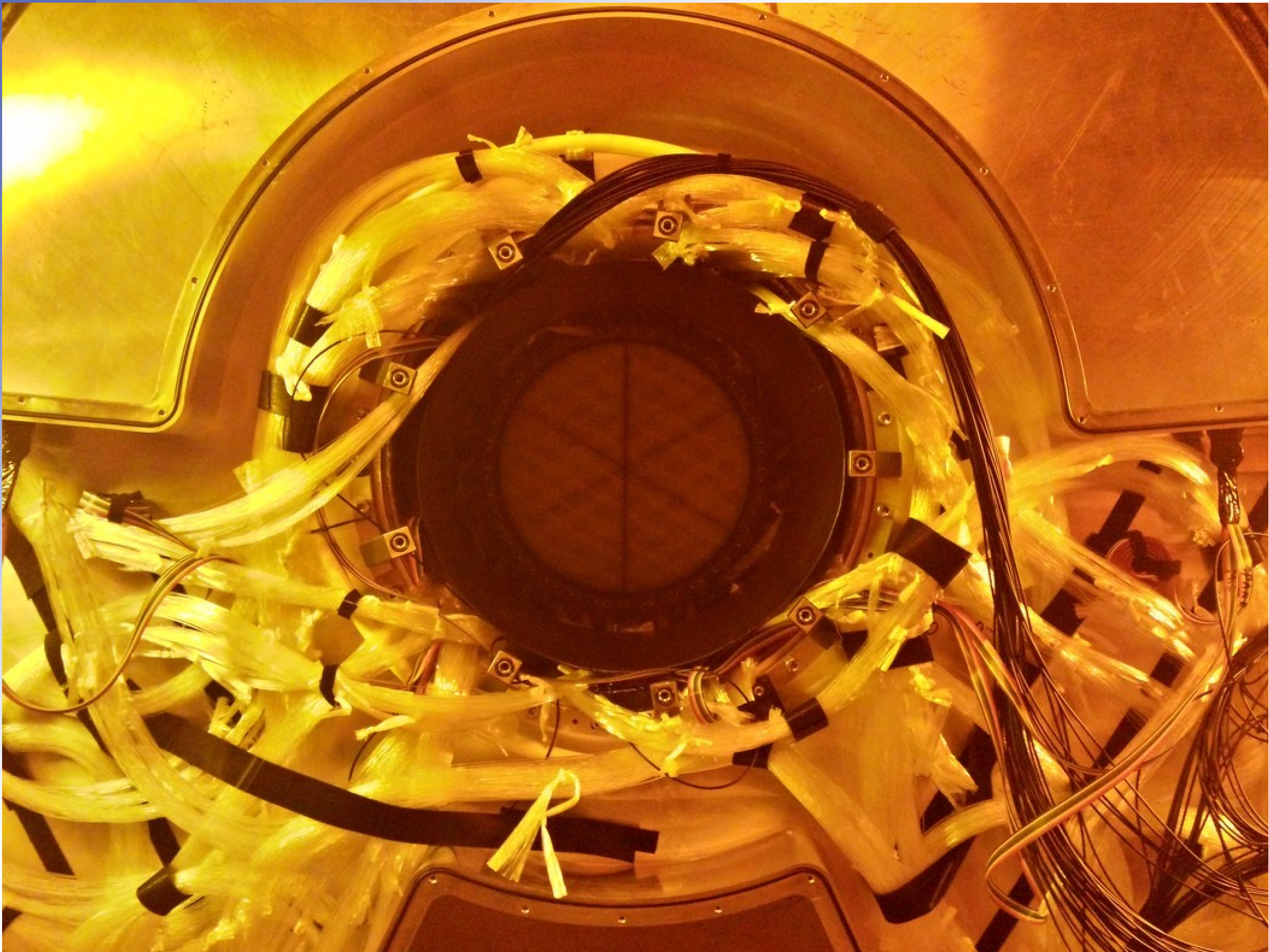
Trackers are sensitive to light < 450 nm....

Tracker Installation

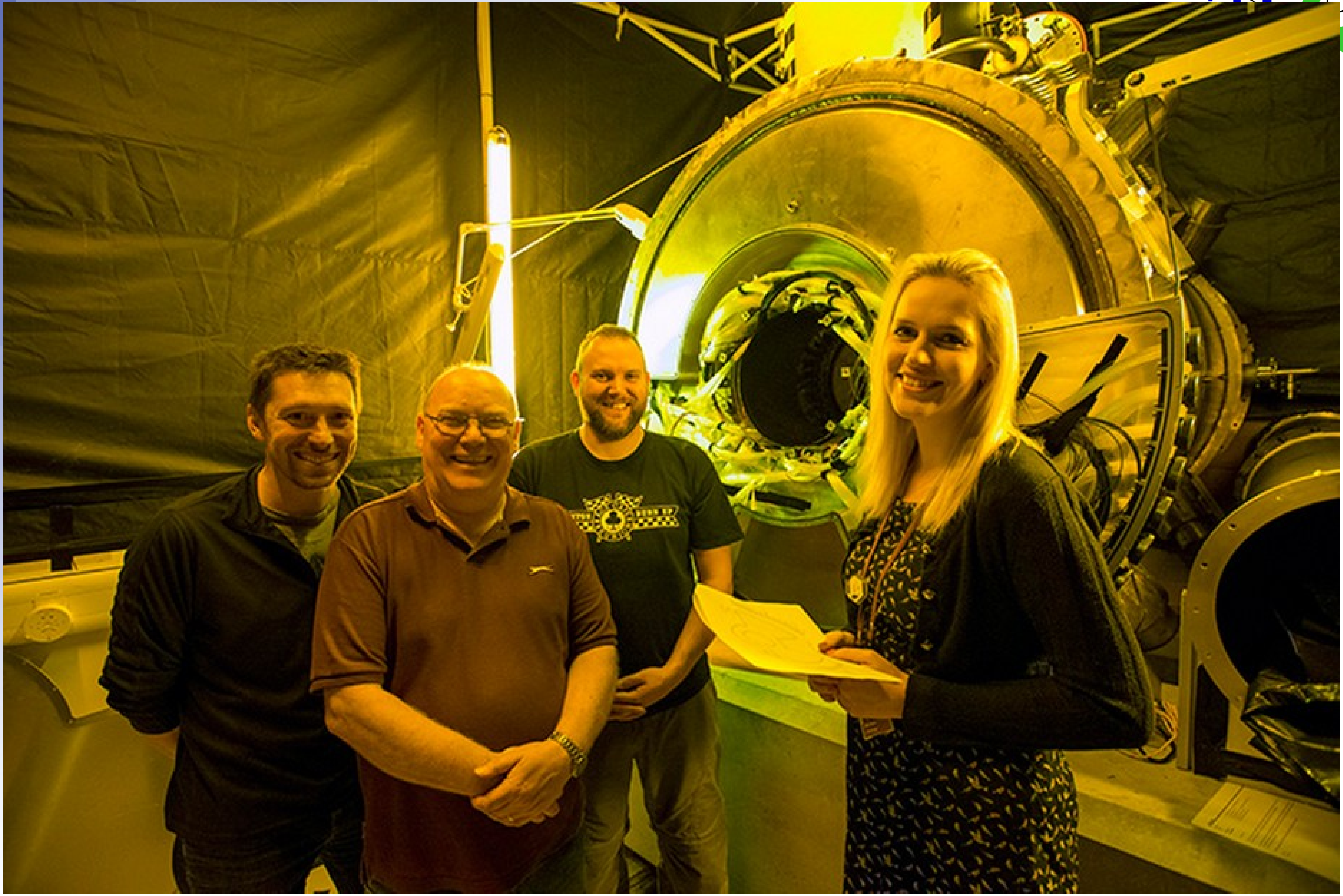


Tracker Installation

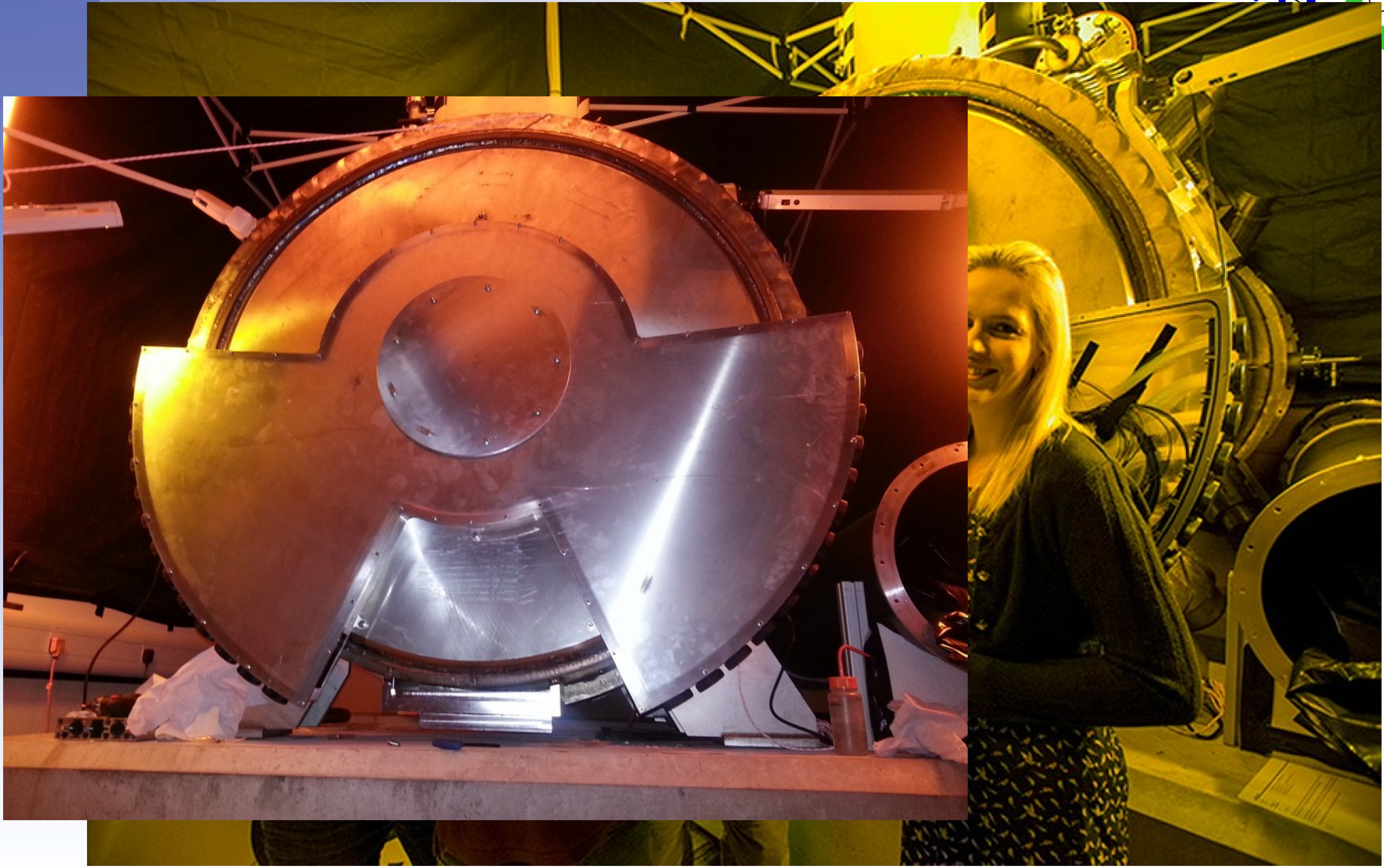




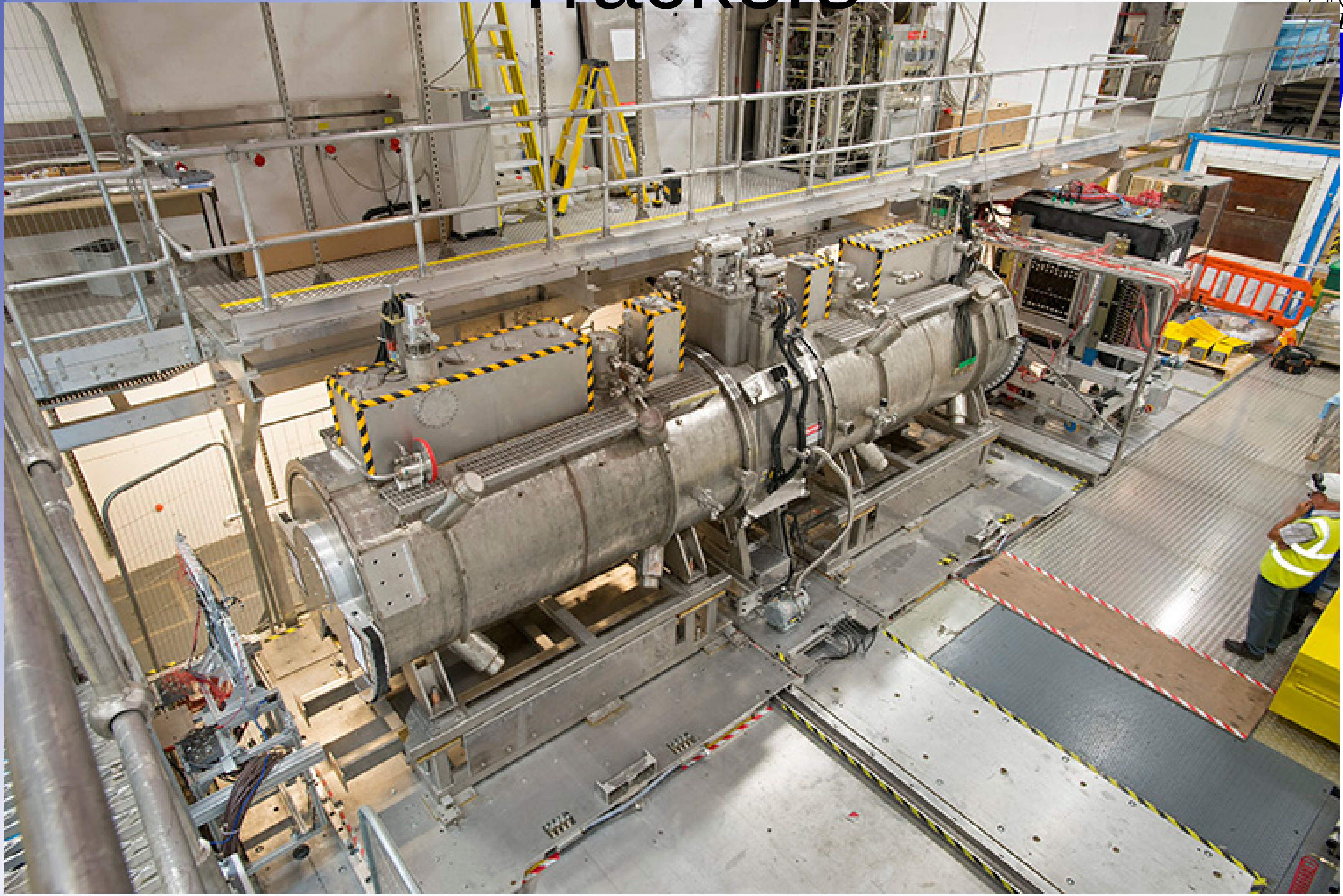
Tracker Installation



Tracker Installation



Trackers



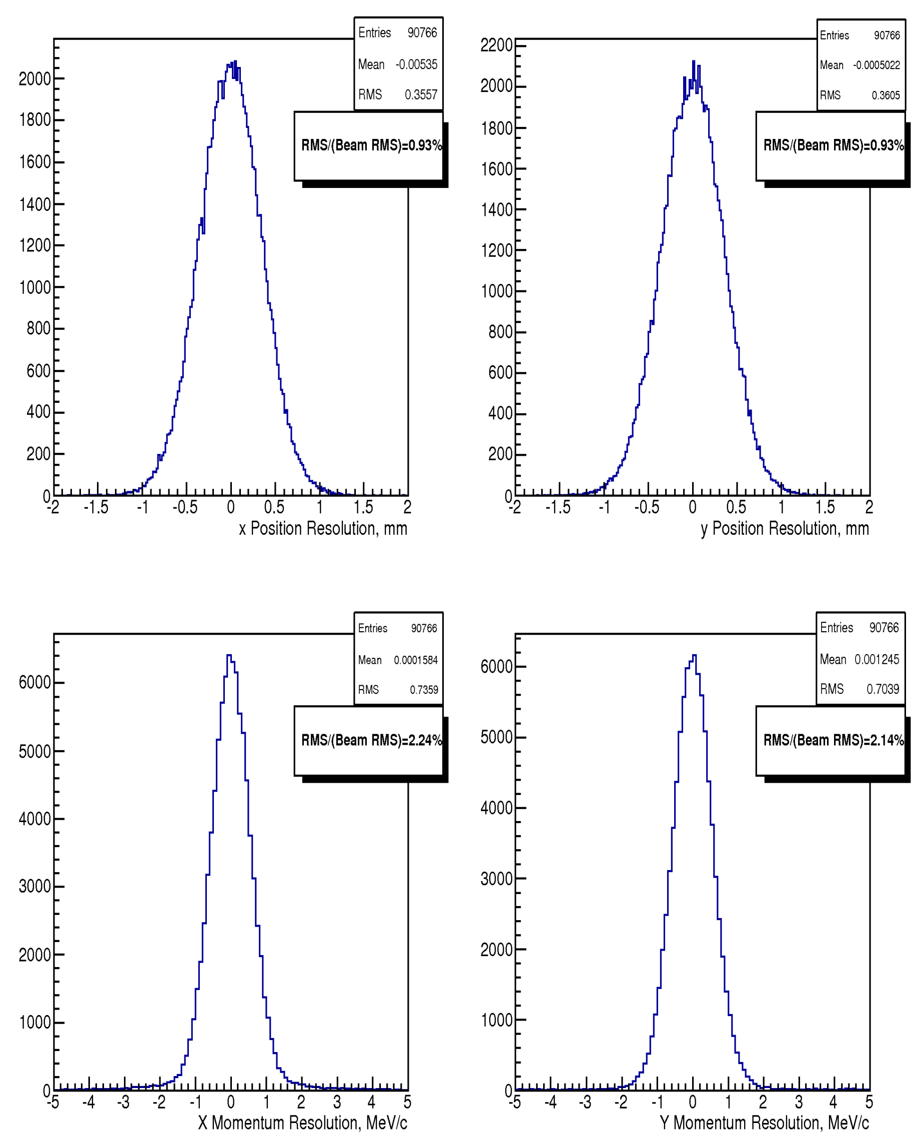
Installed, cosmics tested, QA'd commissioning in progress, mock data challenge tested.

Tracker Software: Reconstruction

- **Digitisation** – unpack the real data or digitise MC data.
- **Clustering** – look for adjacent channel hits and group them.
- **Spacepoints Reconstruction** – look for intersecting clusters on different planes.
- **Pattern Recognition** – use a linear least squares circle fit in x-y, and straight line fit in s-z to associate spacepoints with tracks.
- **Final track fit** – use a Kalman fitter.
- **Online Reconstruction** – Performs spacepoint and digit checks per station and tracker and has a real time event display.

Tracker Software

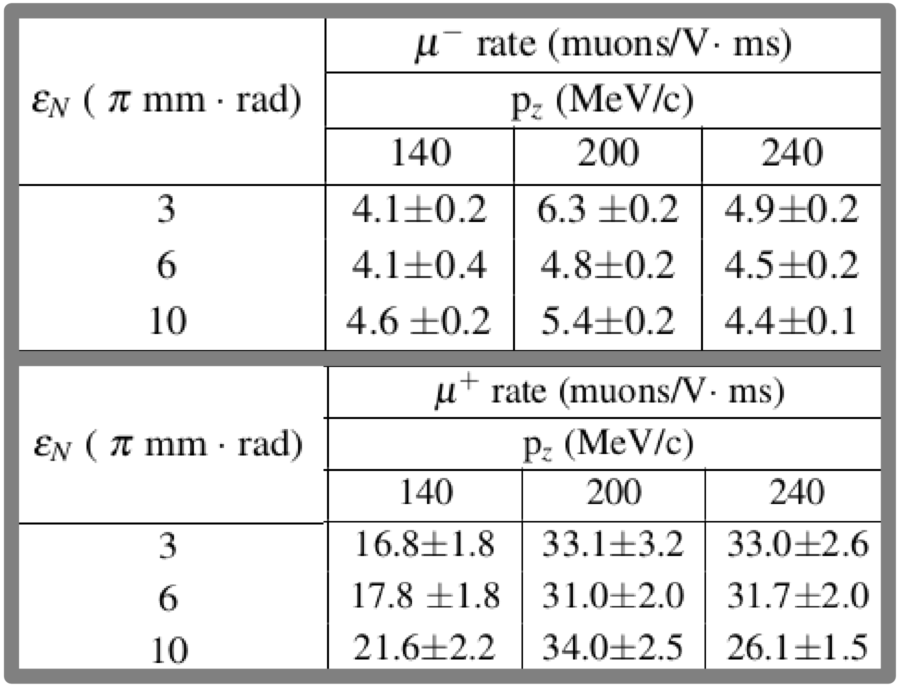
Reconstruction



- Resolution of the track parameters computed as the difference between MC truth and reconstruction values.
- The distribution RMS to be RMS ratio is shown.
- Requirement of being able to measure 10% change in beam emittance to 1% accuracy means that transverse momentum resolution must be better than 10% of the beam RMS.
- **Results show we are well within this requirement!**

Step I

Muons per MICE target dip (spill) as a function of ISIS beam loss



μ^-

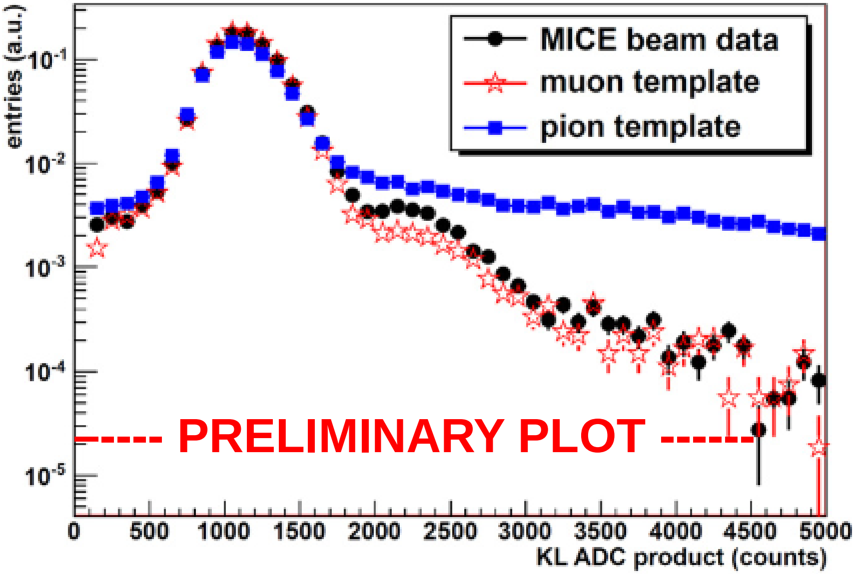
ε_N (π mm · rad)	μ^- rate (muons/V· ms)		
	p_z (MeV/c)		
	140	200	240
3	4.1±0.2	6.3 ±0.2	4.9±0.2
6	4.1±0.4	4.8±0.2	4.5±0.2
10	4.6 ±0.2	5.4±0.2	4.4±0.1

μ^+

ε_N (π mm · rad)	μ^+ rate (muons/V· ms)		
	p_z (MeV/c)		
	140	200	240
3	16.8±1.8	33.1±3.2	33.0±2.6
6	17.8 ±1.8	31.0±2.0	31.7±2.0
10	21.6±2.2	34.0±2.5	26.1±1.5

- Observed particle rates in TOF0 and TOF1 detectors were recorded and time-of-flight used to select good μ tracks.
- The rates are found to be linear with the ISIS beam loss/target depth.
- Errors mainly due to the time-of-flight cuts used to define a muon.
- Muons per spill is presently limited by the tolerance of the irradiation caused in ISIS by protons and secondary particles produced in the MICE target.
- Rates obtained are sufficient to collect the ~10^5 muons necessary to perform a relative measurement of cooling with a precision of 1%, in maximum one day.

Ref. ArXiv:1203.4089

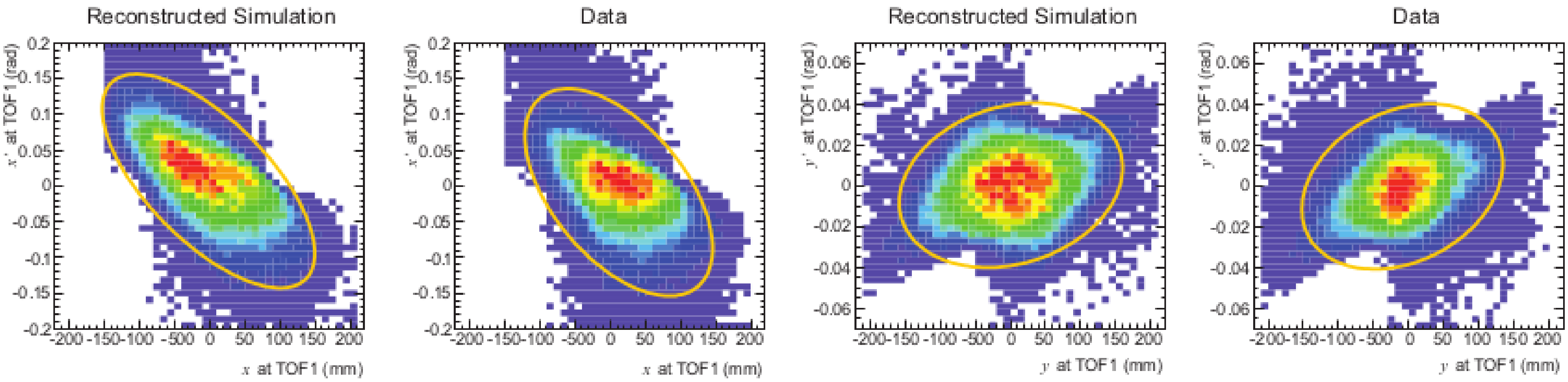


MICE Muon beam contamination

- Determination of MICE muon beam purity using the KL detector. A pion contamination in the muon beam at or below the 1% level (<5% for μ^+) is determined.

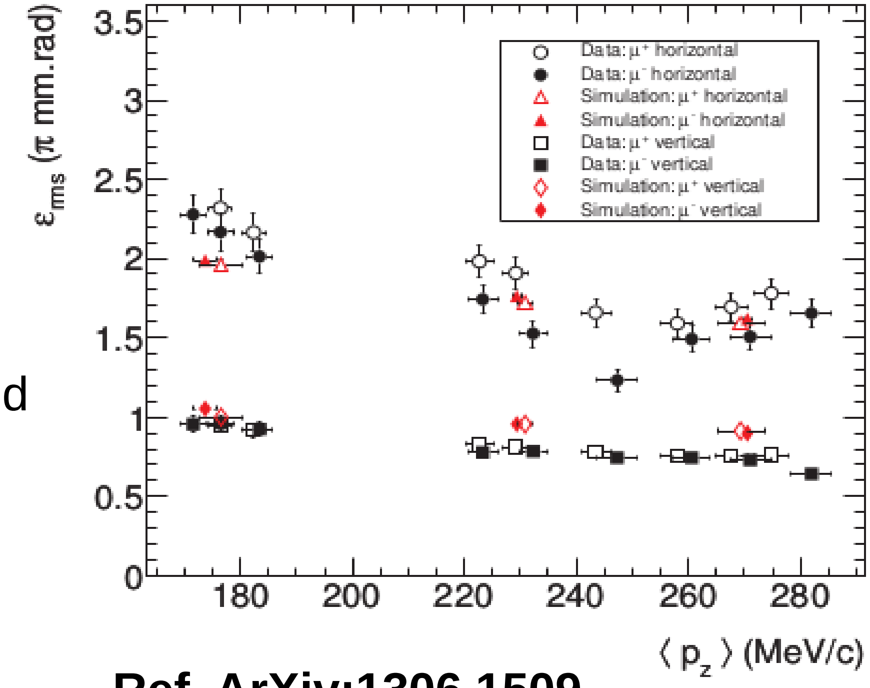
Step I

Reconstructed horizontal and vertical trace-space in simulation and data.



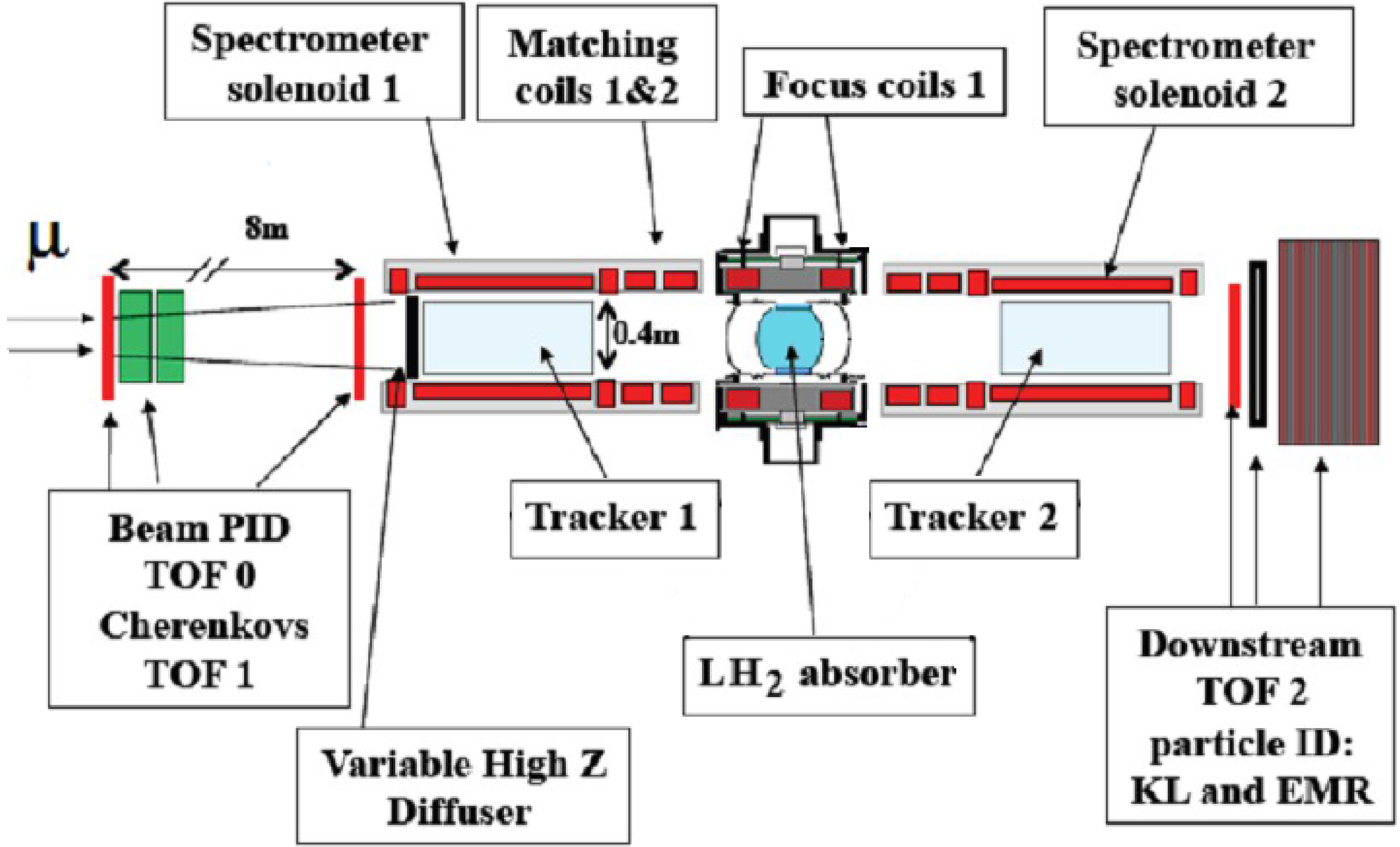
Horizontal and vertical RMS emittance in data and simulation.

A novel technique based on time-of-flight counters was used to establish that the beam emittances are in the range 0.6–2.8 π mm-rad, with central momenta from 170–280 MeV/c, and momentum spreads of about 25 MeV/c.

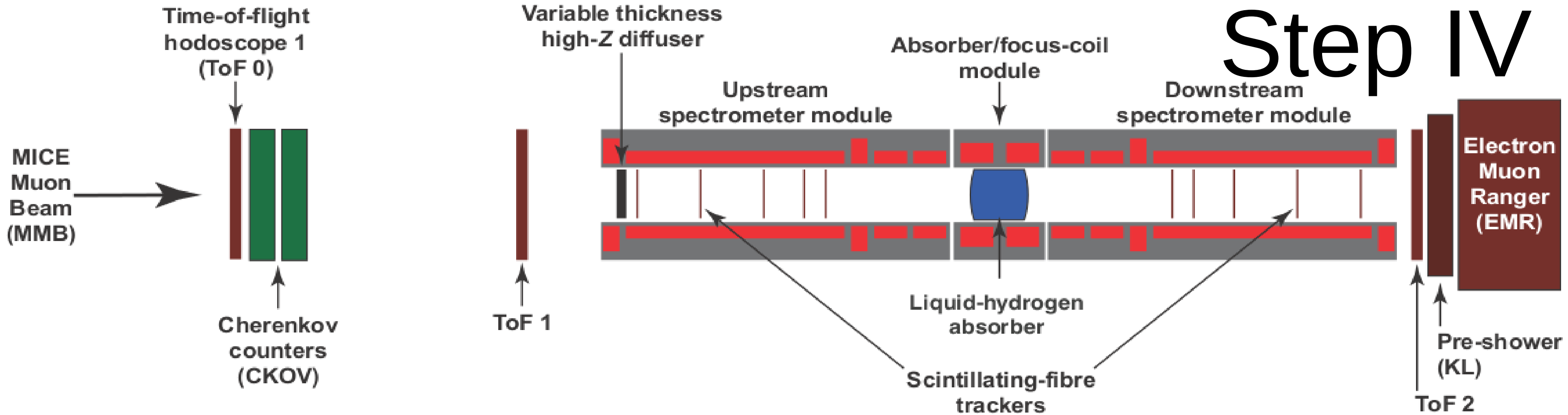


Ref. ArXiv:1306.1509

MICE: Step IV This Year



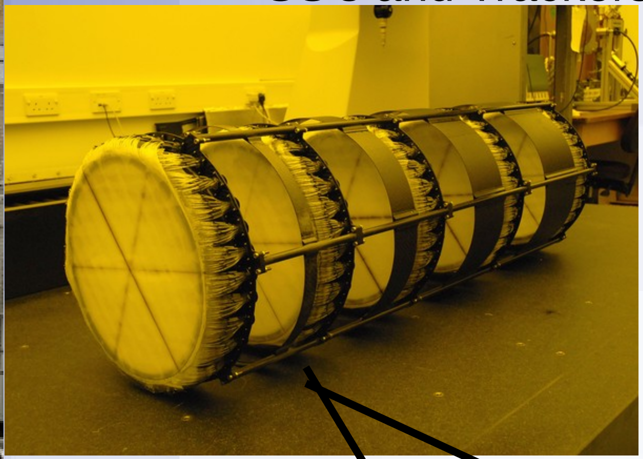
Step IV

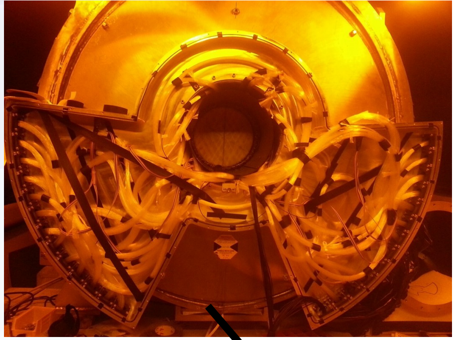


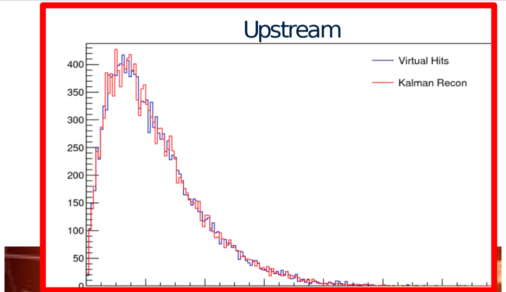
- Includes the two solenoidal spectrometers, a pair of alternating focus coils, and an absorber;
- it will allow the change in emittance of the beam passing through a single liquid-hydrogen or solid absorber to be measured,
- over a range of momenta and under a variety of focusing conditions.
- However, it will lack the crucial RF re-acceleration required for “sustainable” cooling, where the lost energy is restored so that the cooling process can be iterated.
- The muons will be measured in the two spectrometers before and after the absorber.
- Step IV will provide valuable data for validating the multiple scattering and energy loss models used in ionisation-cooling simulation codes.
- Data taking begins in a few months.

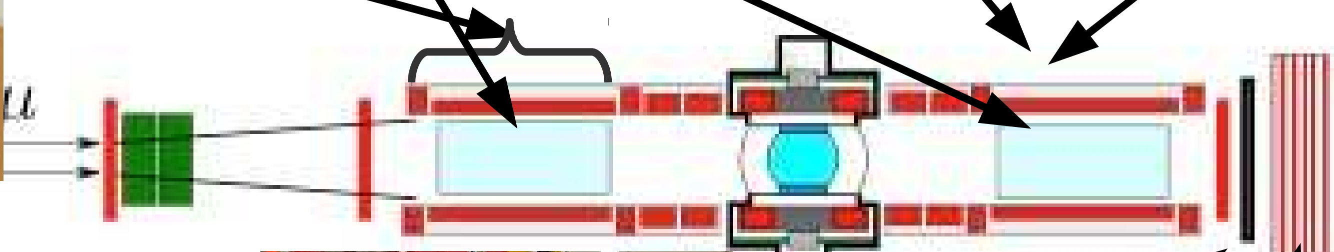
Step IV

SS's and Trackers





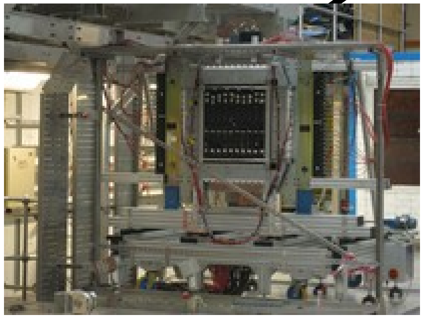




Racks

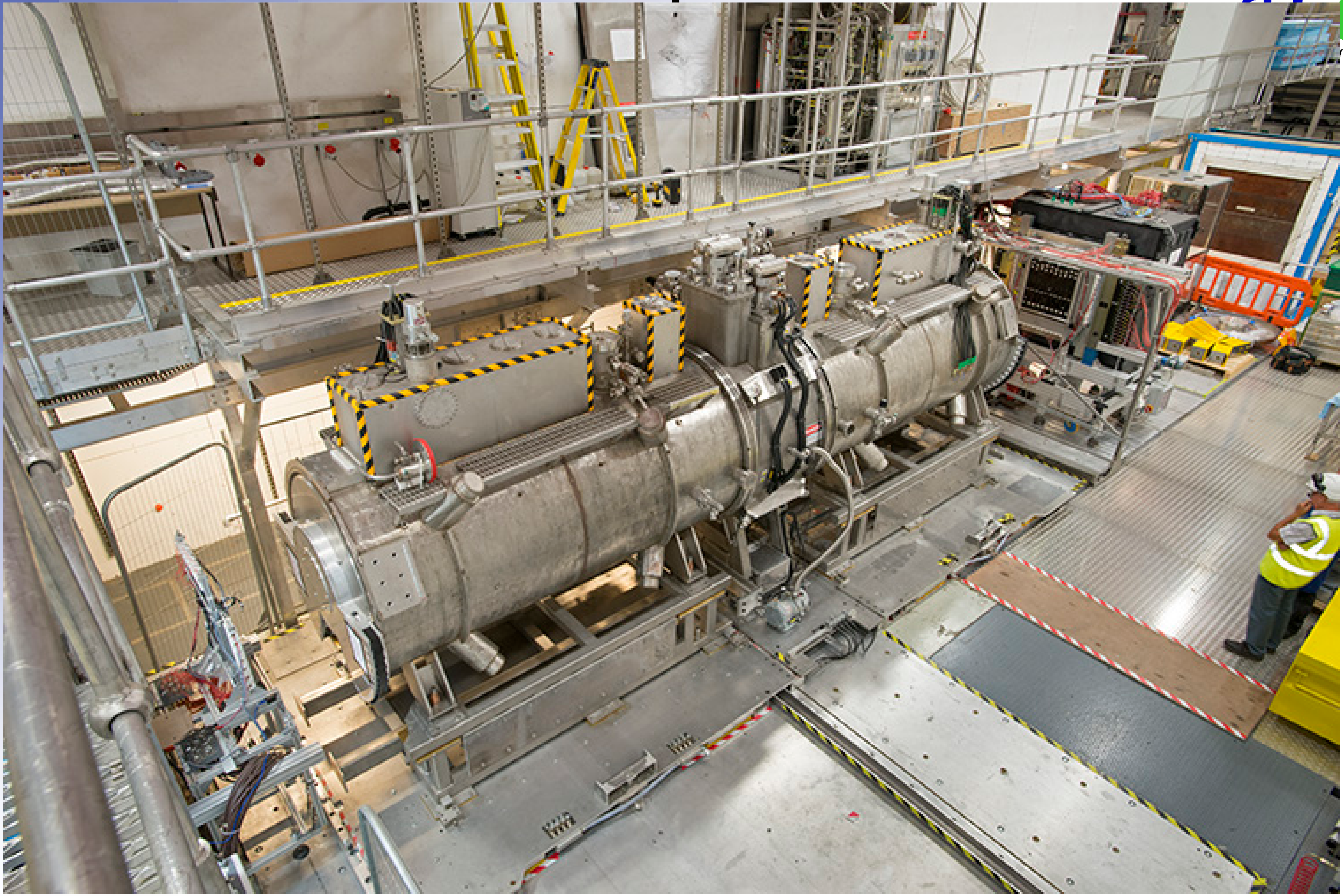
AFC

TOF/KL

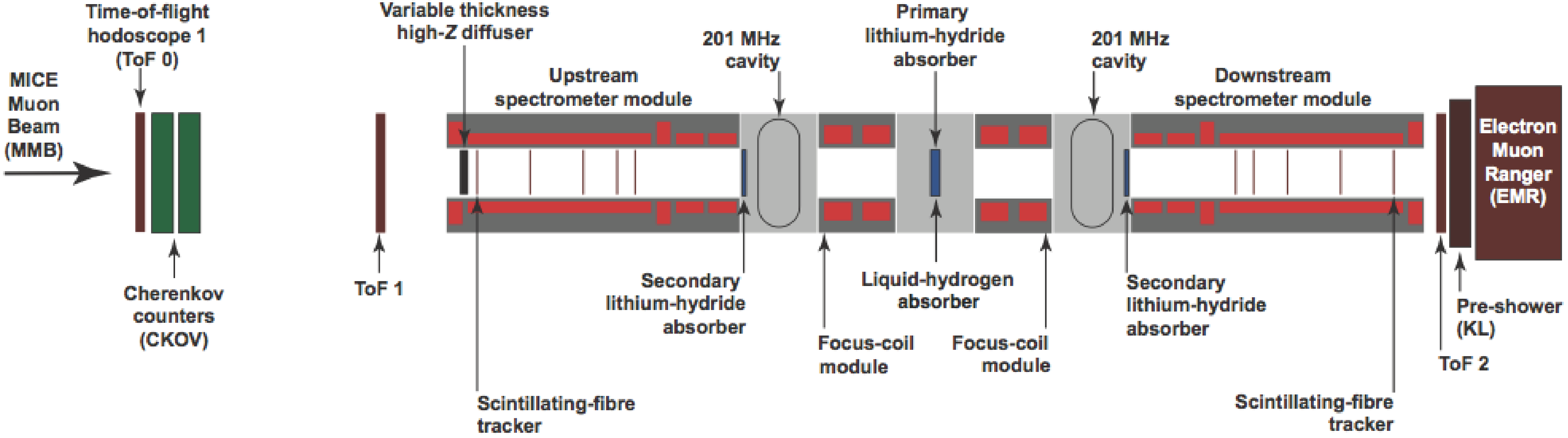


EMR

Step IV



MICE: Demonstration of Ionisation Cooling (2017)

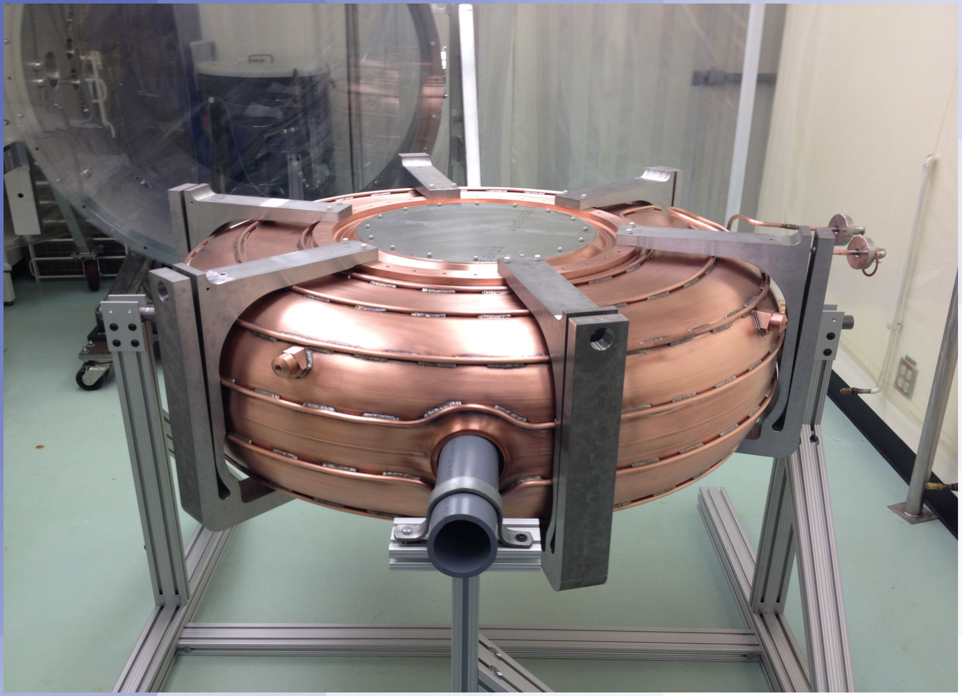


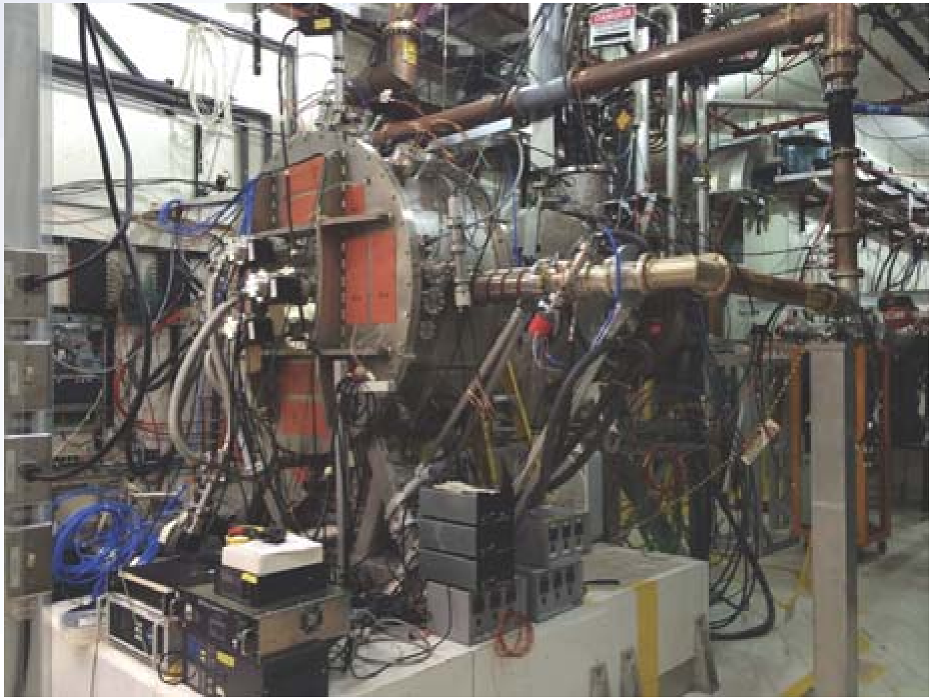
- The cooling section contains one full absorber, plus two secondary absorbers which protect the tracking devices from radiation emitted by the RF cavities and also increase the measured cooling factor.
- The baseline magnetic configuration of the cooling section is referred to as "FOFO" and is such that the magnetic field reverses ("flips") at the centre of the central absorber.
  - Periodic field reversal is essential for a full-length cooling channel in order to simultaneously reduce both the rms divergence and size of the beam.

Demonstration of Ionisation Cooling

- Will vary the absorber material, magnetic focusing strength (typically 5 settings), polarity and optics configuration, beam momentum (3 settings) and emittance (3 settings)
- Absorber materials: LH 2 , empty, LiH, and possibly plastic.
- Muon momenta: 140, 200, and 240 MeV/c.
- Emittance: 3,6 and 10 π mm.rad
- At each momentum, it is important to study a variety of beam emittances and β ⊥ values, so as to sample typical cases along the length of an ionization cooling channel.
- Varying the muon polarity will also be valuable as a systematics check (most of the data points will be taken with positives).
- Muons rate reduced as synchronised to the RF waveform.

RF

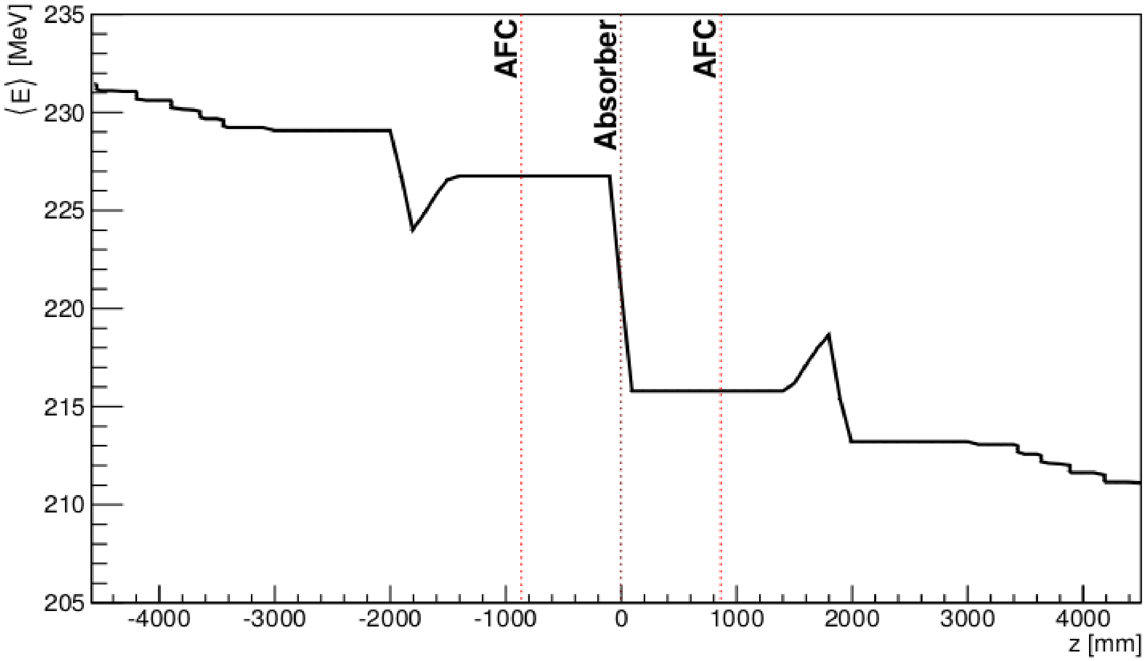




First MICE RF cavity (left) with tuners attached, and (right) installed in its Single-Cavity Module in the Fermilab MuCool Test Area.

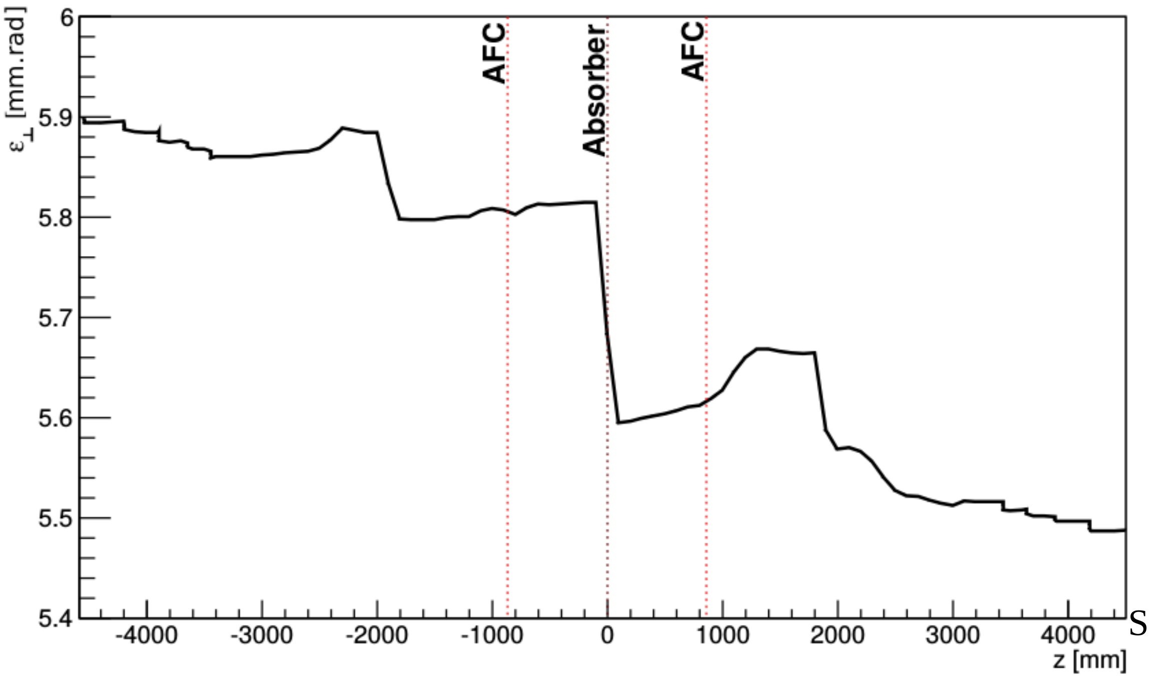
- The 201 MHz RF RF cavities have been assembled and the first is being tested in the Fermilab MuCool Test Area (MTA).
- One 201 MHz power source has been refurbished at Daresbury Laboratory and tested to above (2.08 MW) its specified (2 MW) output power. Refurbishment of a second supply is in progress.
- One supply will power each cavity, permitting a maximum accelerating gradient of 10.3 MV/m.

(ε, p_z) = (6, 200) beam with re-acceleration.



Mean beam energy

Energy is lost in the upstream tracker and first (secondary) absorber before being partially restored in the first RF cavity (z ≈ −2000 mm). Further energy is lost in the primary absorber, partially restored in the second RF cavity, and then lost in the final (secondary) absorber.



Emittance reduction

The beam is subject to non-linear effects in regions of high $\beta_\perp$, which causes emittance growth in both cases. Nonetheless, a reduction in emittance is observed between the up- and downstream trackers (z ≈ ±4000 mm) ≈ 7 %.

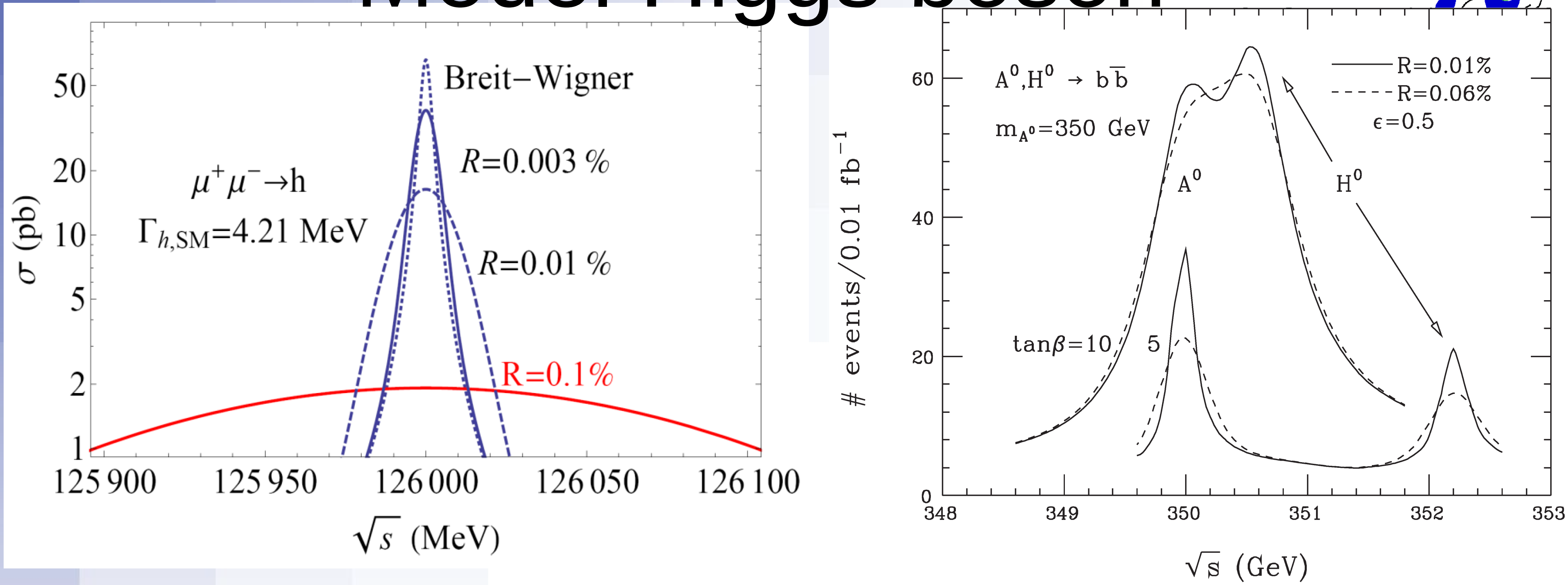
My Personal Hopes for An Extended Future

- RF Upgrades
  - The current power supplies used to power the RF cavities could be upgraded to beyond 2 MW output power. Potentially increasing the maximum accelerating gradient of 10.3 MV/m to 14MV/m.
  - This work is not on the agenda but I personally believe would be a relatively inexpensive yet valuable upgrade.
- There is the potential to test more absorbers and absorber positions than the three currently planned. Again an interesting and valuable extension, but again this is not currently on the cards.

Conclusions

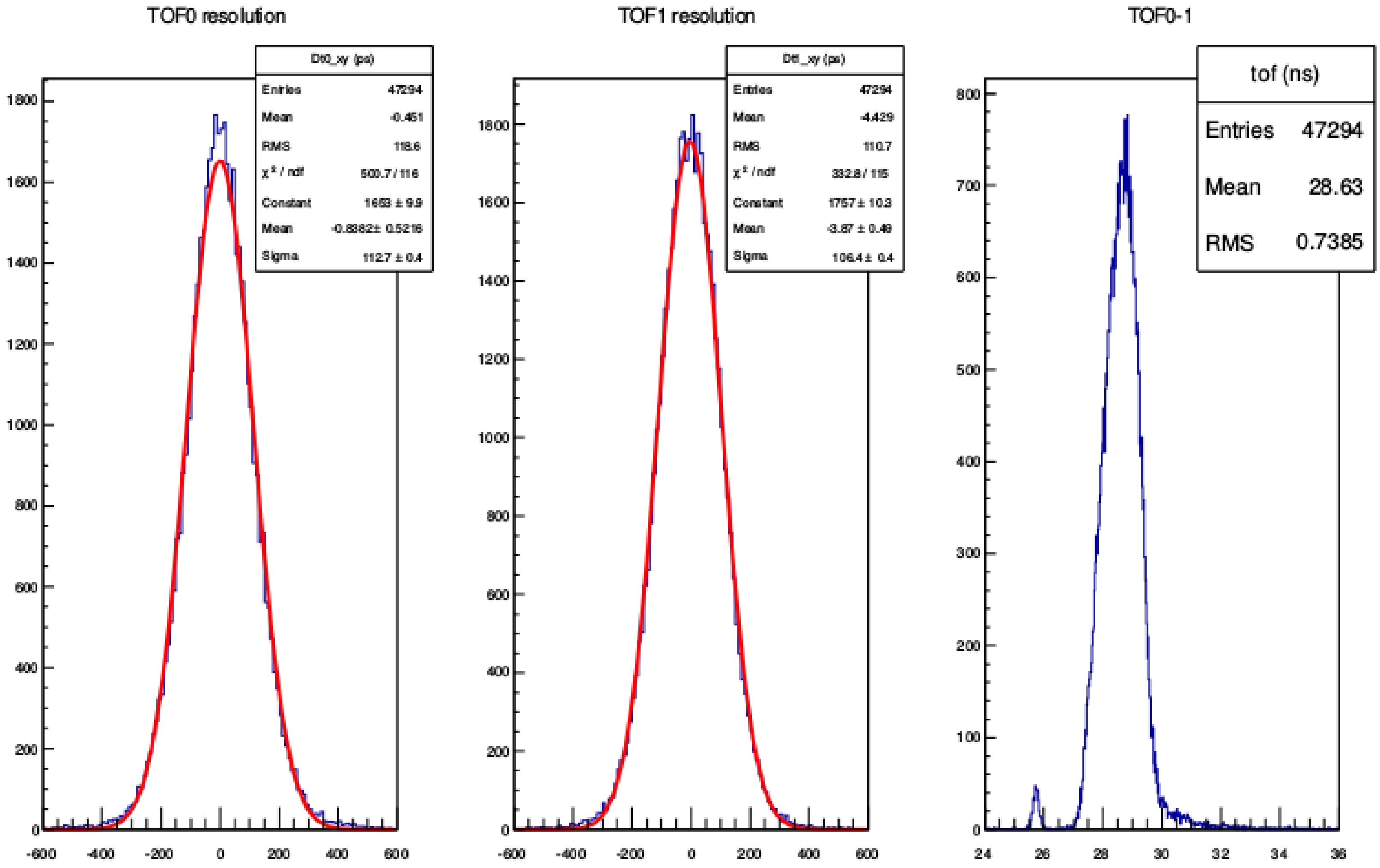
- The MICE experiment aims to reduce the transverse emittance of a muon beam and will measure the normalised emittance reduction with a precision of 0.1%.
- Has already shown that it is using a suitable beam and instrumentation to achieve its physics goals.
- Step IV will perform ionisation cooling but without beam re-acceleration. Therefore, it will not be “sustainable” cooling, and the cooling process can be iterated. It will provide valuable data for validating the multiple scattering and energy loss models used in ionisation cooling simulation codes, Construction is nearing completion and data taking will begin in the next few months.
- The demonstration of Ionisation cooling will demonstrate sustainable ionisation cooling for the first time and hence will be a major step in the development of a muon collider or neutrino factory. Data taking due to begin in mid 2017.

Width & Lineshape of Standard Model Higgs boson



(left) Standard Model Higgs line shape compared with three scenarios for muon collider energy resolution [4]; (right) resolving scalar and pseudoscalar supersymmetric Higgs partners for two possible values of the supersymmetric parameter tan β.

TOF 0 and 1



Left and middle panel: time difference Δt_{xy} between vertical and horizontal slabs in TOF0 and TOF1 after the refurbishing of TOF0 and TOF1, done in late 2010 and early 2011. Right panel: time of flight between TOF0 and TOF1. The trigger is on TOF1 and the run is a typical muon beam run (run 3407)