Imperial College
London

Towards muon colliders: single particle emittance measurement in MICE cooling experiment at RAL

J. Pasternak

06/02/2015, Advanced Optics Control workshop, CERN

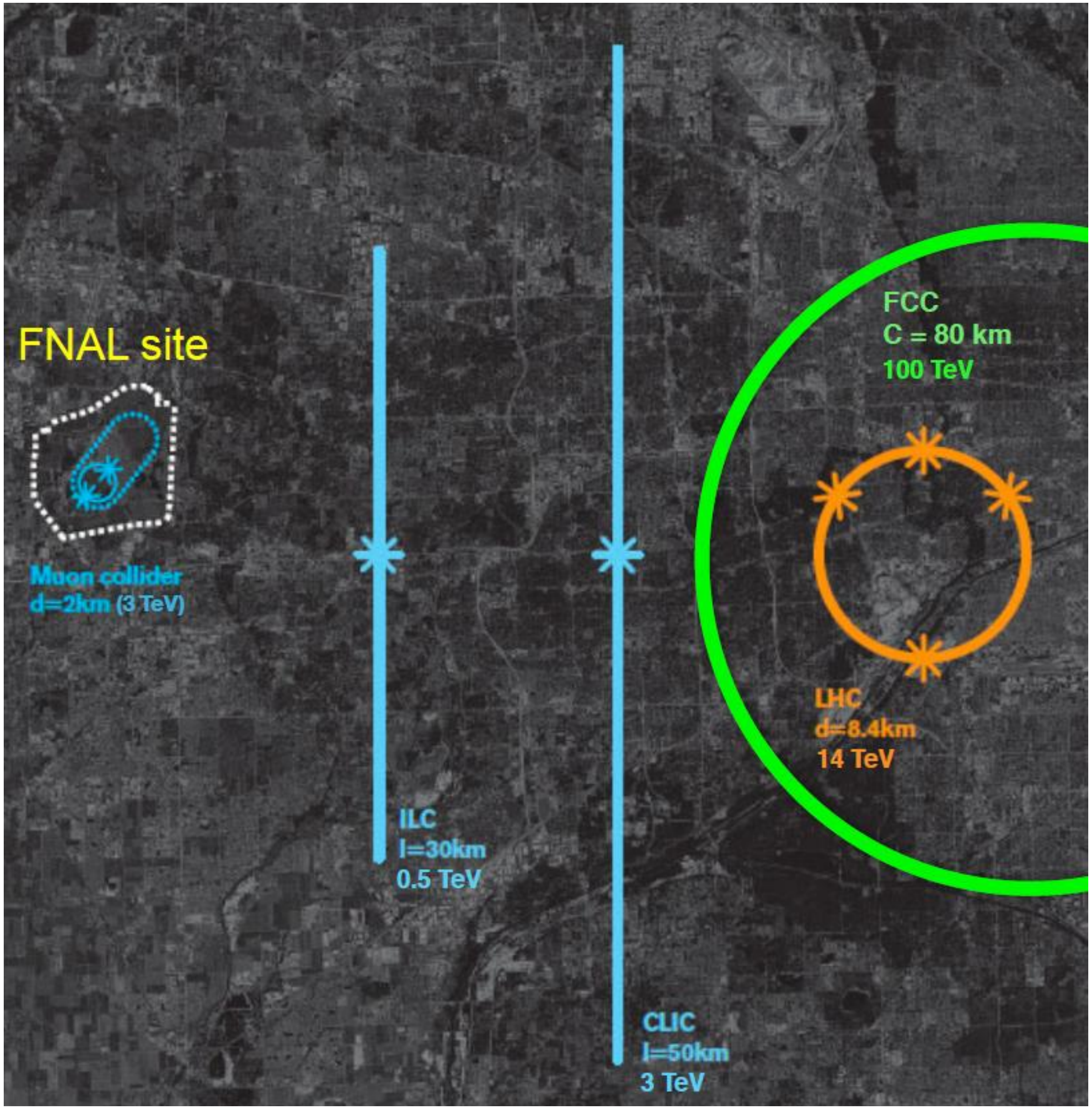
Outline

- Motivations for using muon beams for particle physics and their challenges
- Overview of the Neutrino Factory and a Muon Collider designs
- MICE and its unique single particle emittance measurement
- Summary

Motivations for using muon beams (1)

- Muons as elementary leptons ~200 times heavier than electrons offer possibility to be used for colliding beam experiments
  - Allowing to avoid a large QCD background known in hadron colliders
  - Offering a full CM energy for creating new states (in contrary to hadron colliders)
  - Rate of emission of synchrotron radiation is highly suppressed -> allows to build compact collider facility

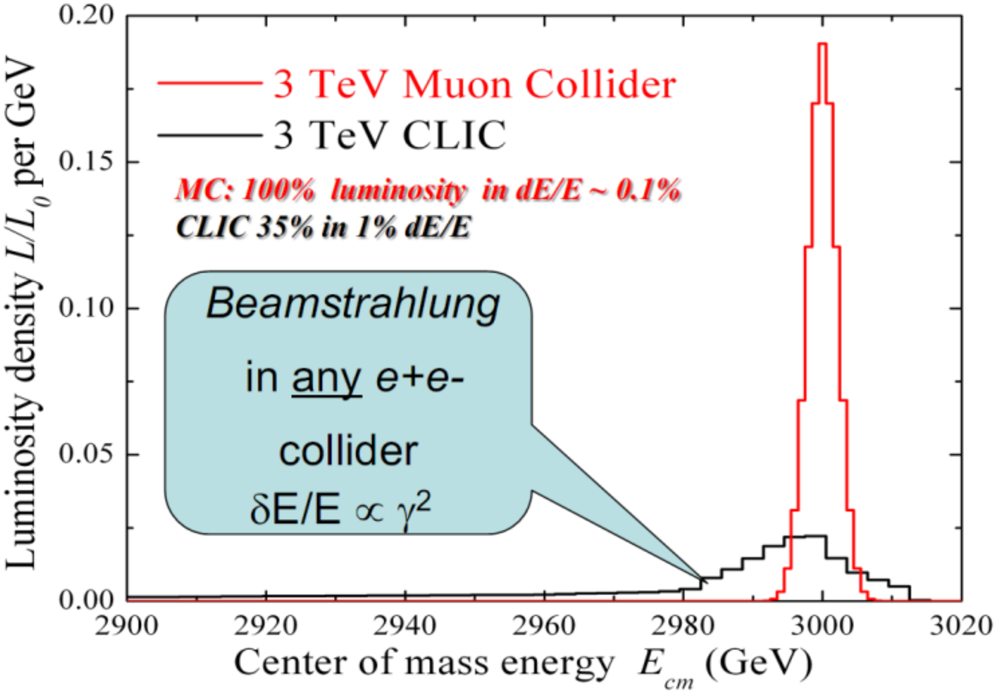
Sizes of various proposed colliders versus FNAL site



Only Muon Collider would fit into existing lab boundaries.

Motivations for using muon beams (2)

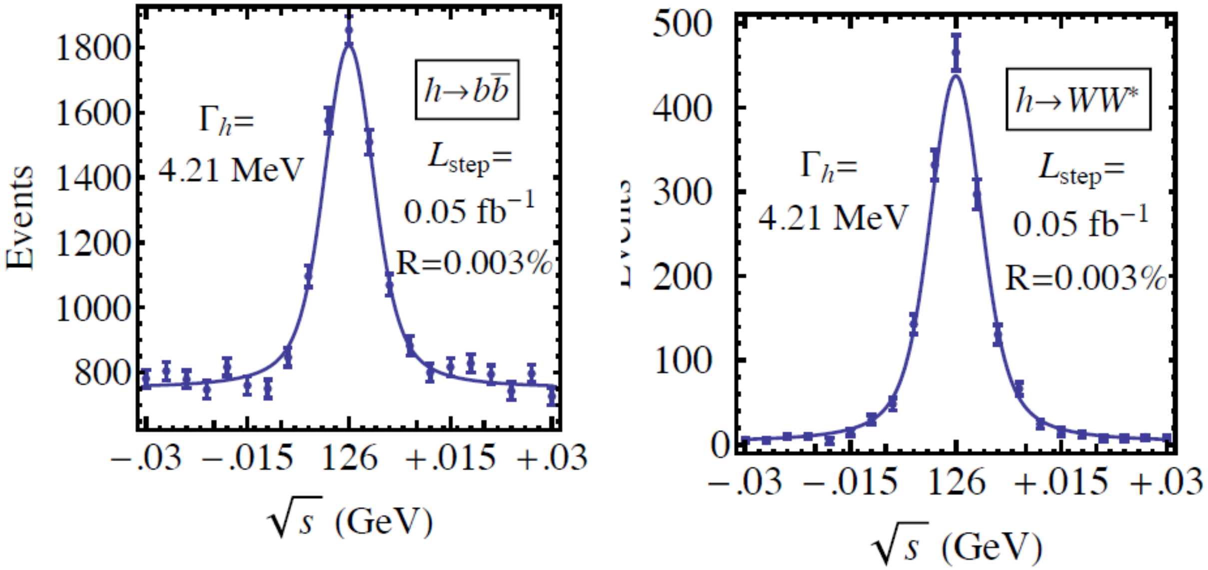
- This also suppresses beamstrahlung -> allows to preserve the high quality beam at collision energy with very small momentum spread



Motivations for using muon beams (3)

- Large m_μ / m_e ratio not only allows to suppress the synchrotron radiation emission, but also provides large coupling to the Higgs mechanism.
- This allows for the resonant Higgs production at the s-channel

Studies indicates capabilities to measure Higgs mass to 60 keV and its width to 150 keV.



T. Han and Z. Liu [arXiv:1210.7803]

Motivations for using muon beams (4)

- Muon beams are important for particle physics
  - Anomalus magnetic moment (g-2) – a possible sign of BSM physics
  - Searches for Lepton Flavour Violation -> complementary test of SM at a very high mass scale
  - Provide a high quality neutrino source -> the Neutrino Factory

Challenges for using muon beams

- Muon beams are unstable (muon lifetime at rest ~2.2 μs)
- Muons are produced as tertiary beam (p$\longrightarrow\pi\longrightarrow\mu$)

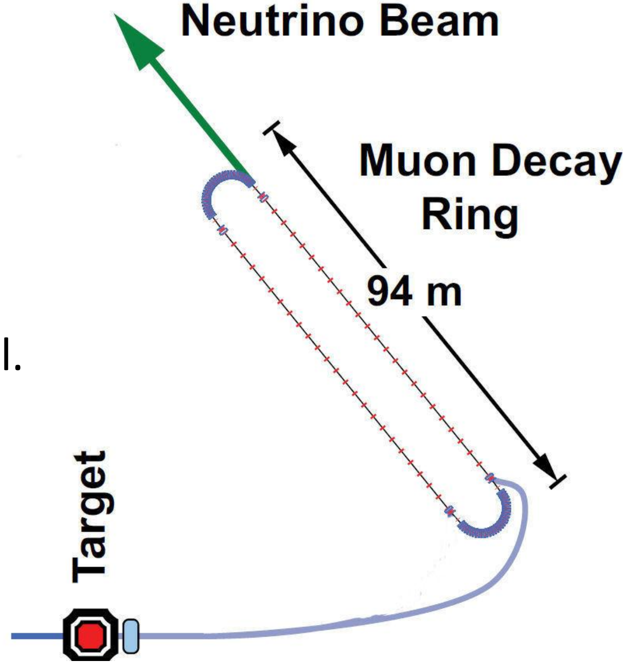
Solutions

- Use ionization cooling, which is fast enough!
- Use high power proton driver
- Develop rapid accelerators

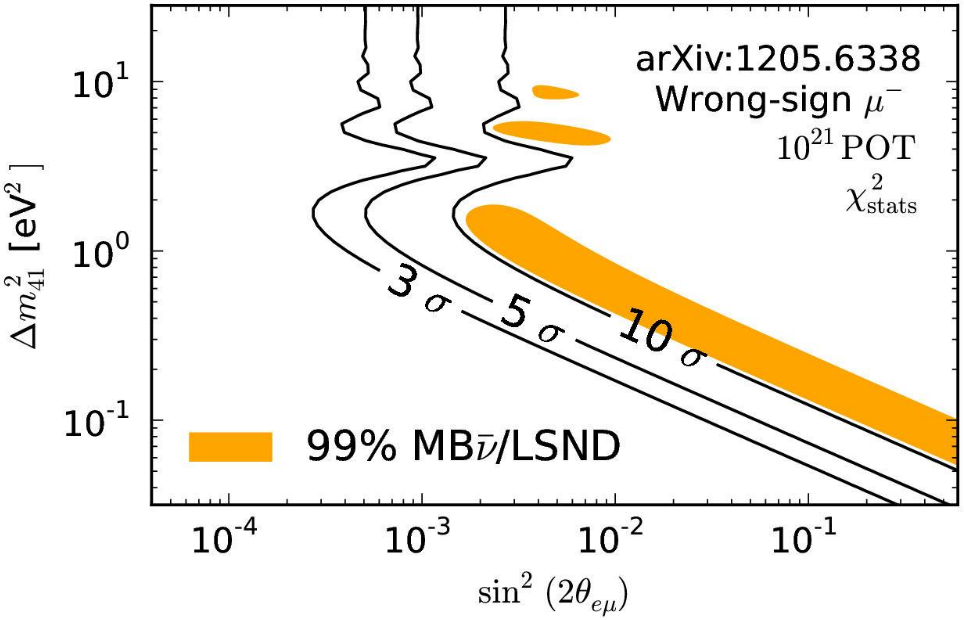
nuSTORM - Mini-neutrino factory

(low energy/intensity storage ring for short baseline neutrino oscillation physics and measurement of cross-sections)

nuSTORM Concepts



A. Bross et al.



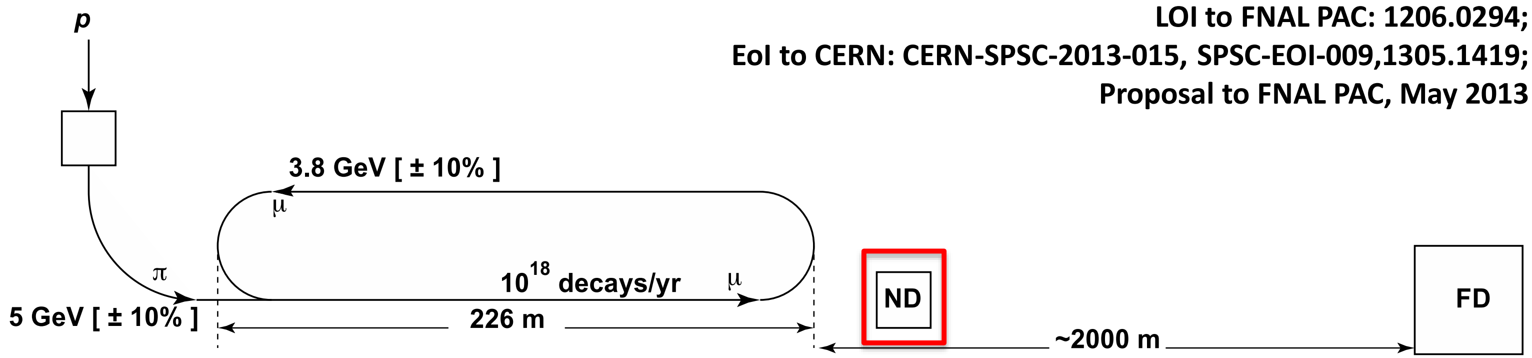
Sensitivity to test the MiniBoone/LSND anomaly

Mu-storage ring presents only way to measure ν_μ & ν_e & anti- (ν_μ & ν_e) x-sections in the same experiment.

It seems to fit into current budgetary climate.

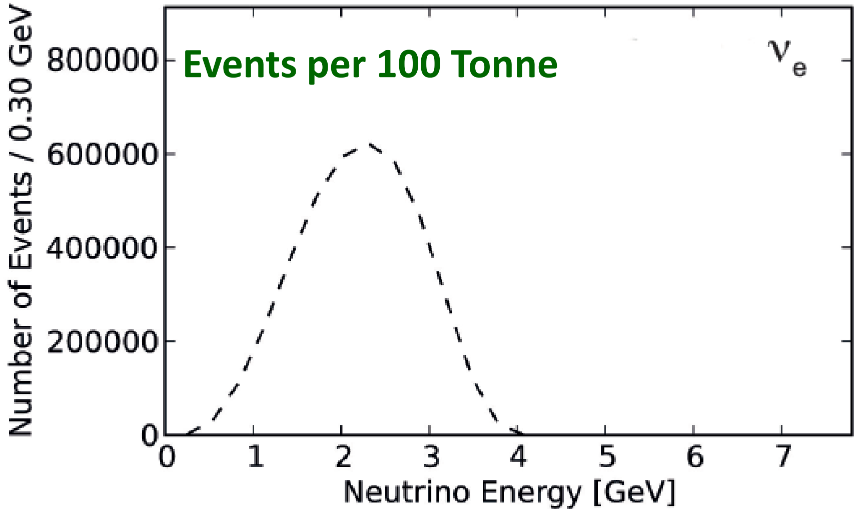
It may serve as a demonstration of the Neutrino Factory Concept.

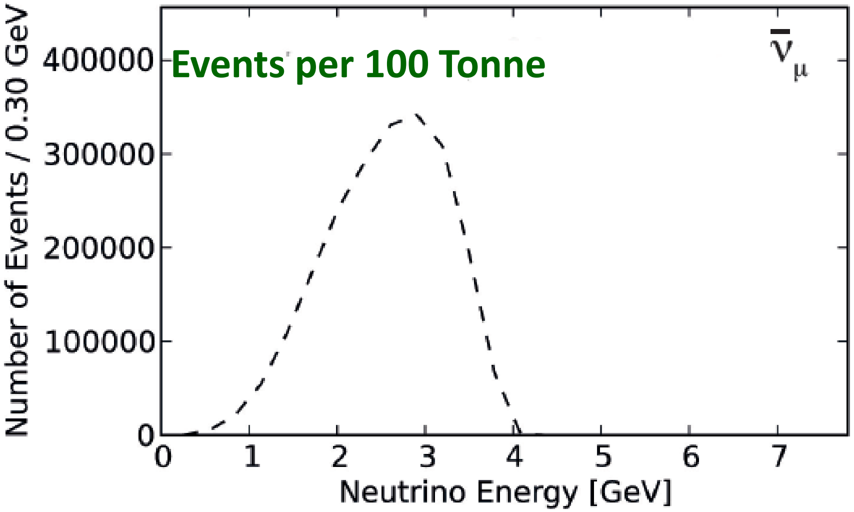
nuSTORM and cross section



LOI to FNAL PAC: 1206.0294;
EoI to CERN: CERN-SPSC-2013-015, SPSC-EOI-009,1305.1419;
Proposal to FNAL PAC, May 2013

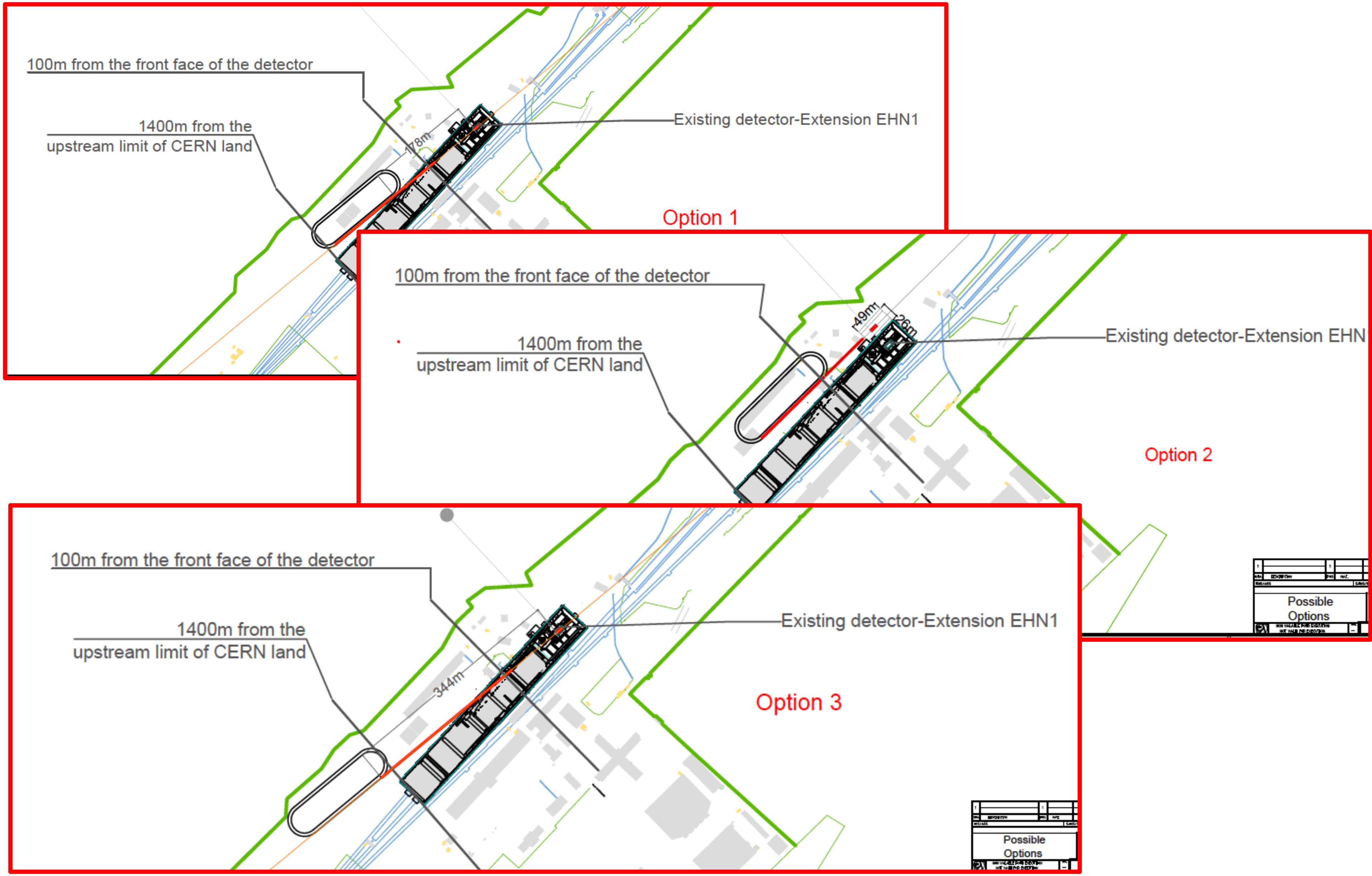
- nuSTORM event rate is large:
  - Statistical precision high:
    - Can measure double-differential cross sections





nuSTORM serving the CERN Neutrino Platform

under study; M. Nessi et al

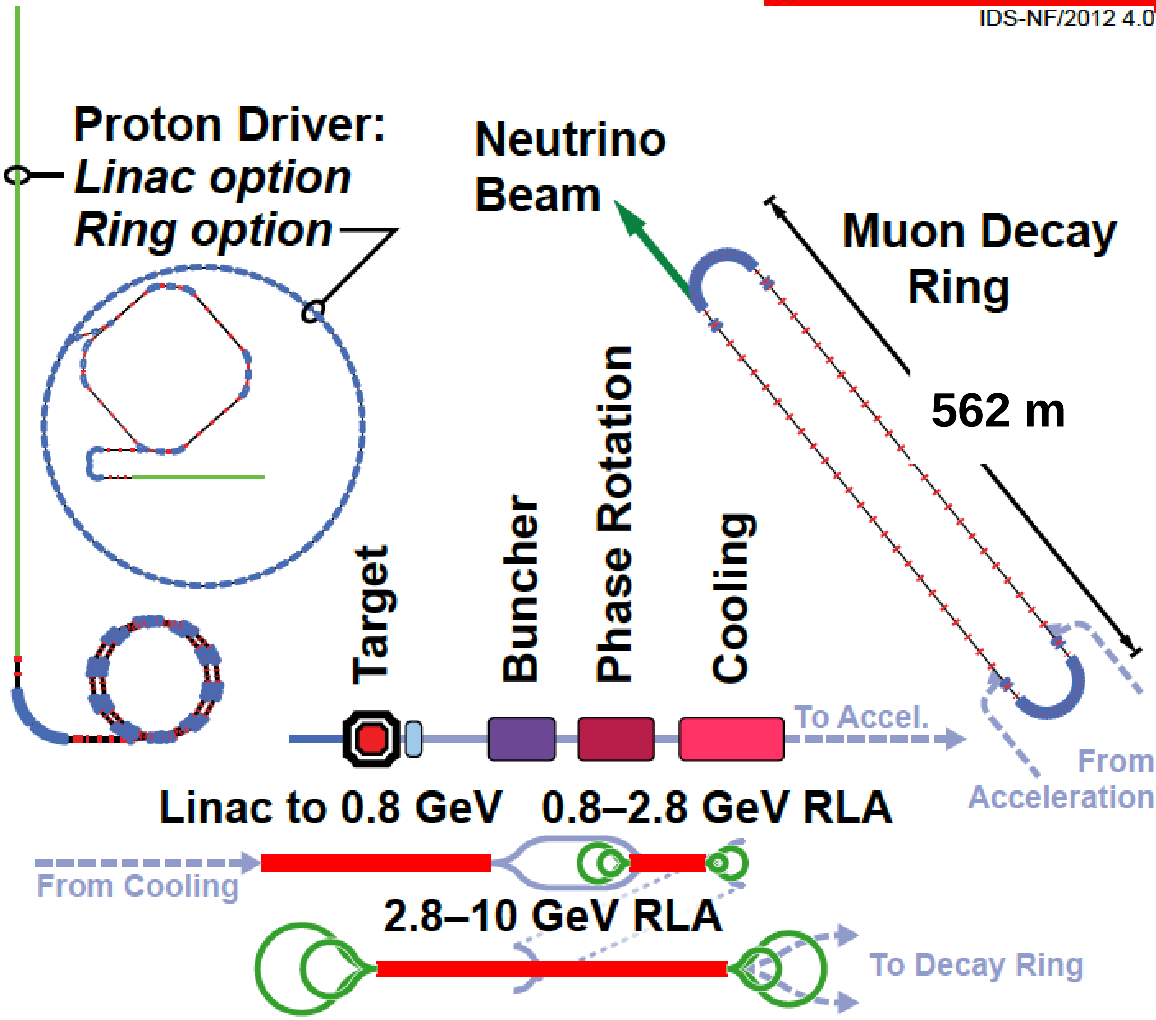


Neutrino Factory, IDS-NF Design

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

IDS-NF/2012 4.0

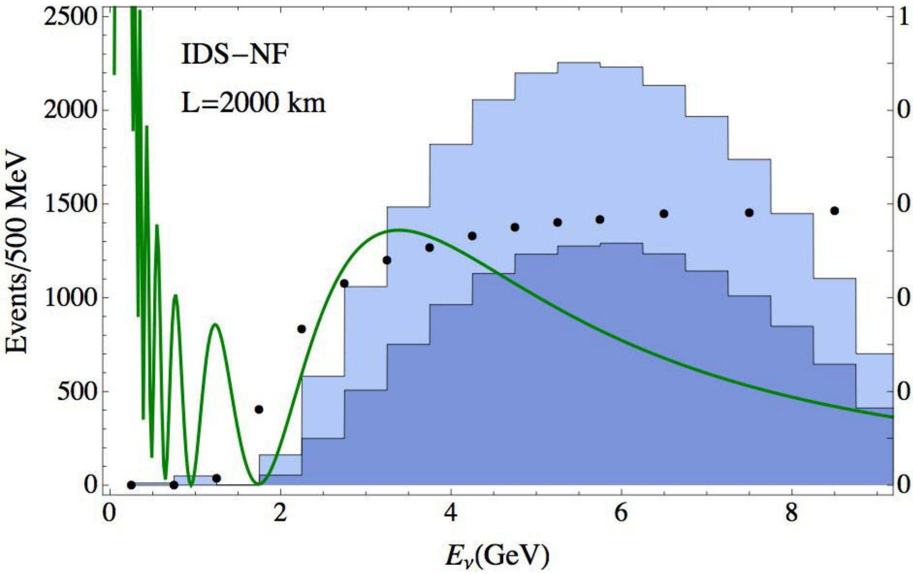
- Provide 10^{21} muon decays per year toward a far detector
- Decays from 10 GeV muon beam
- Angular divergence below
- Beam directed toward detector 2000 km away
- Ionization cooling channel is an essential ingredient of the facility in order to obtain high intensity keeping the accelerator aperture reasonable in size.

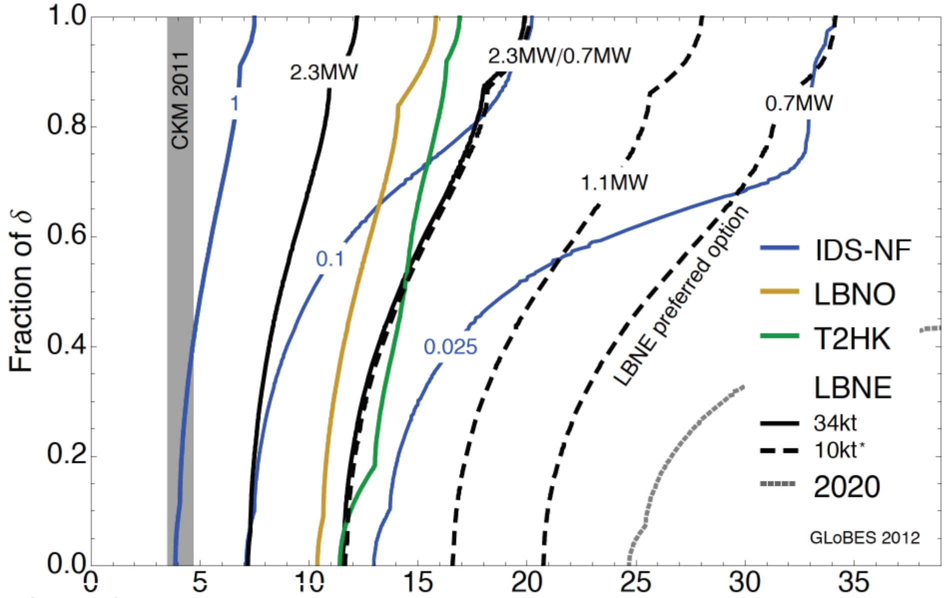


Performance 10 GeV Neutrino Factory

- Systematic errors: 1% signal and 20% background
- Results 10 GeV Neutrino Factory, 10^{21} μ/year for 10 years with 100 kton MIND at 2000 km gives best sensitivity to CP violation
- This provides best sensitivity out of all future proposed facilities

arXiv:1209.5973





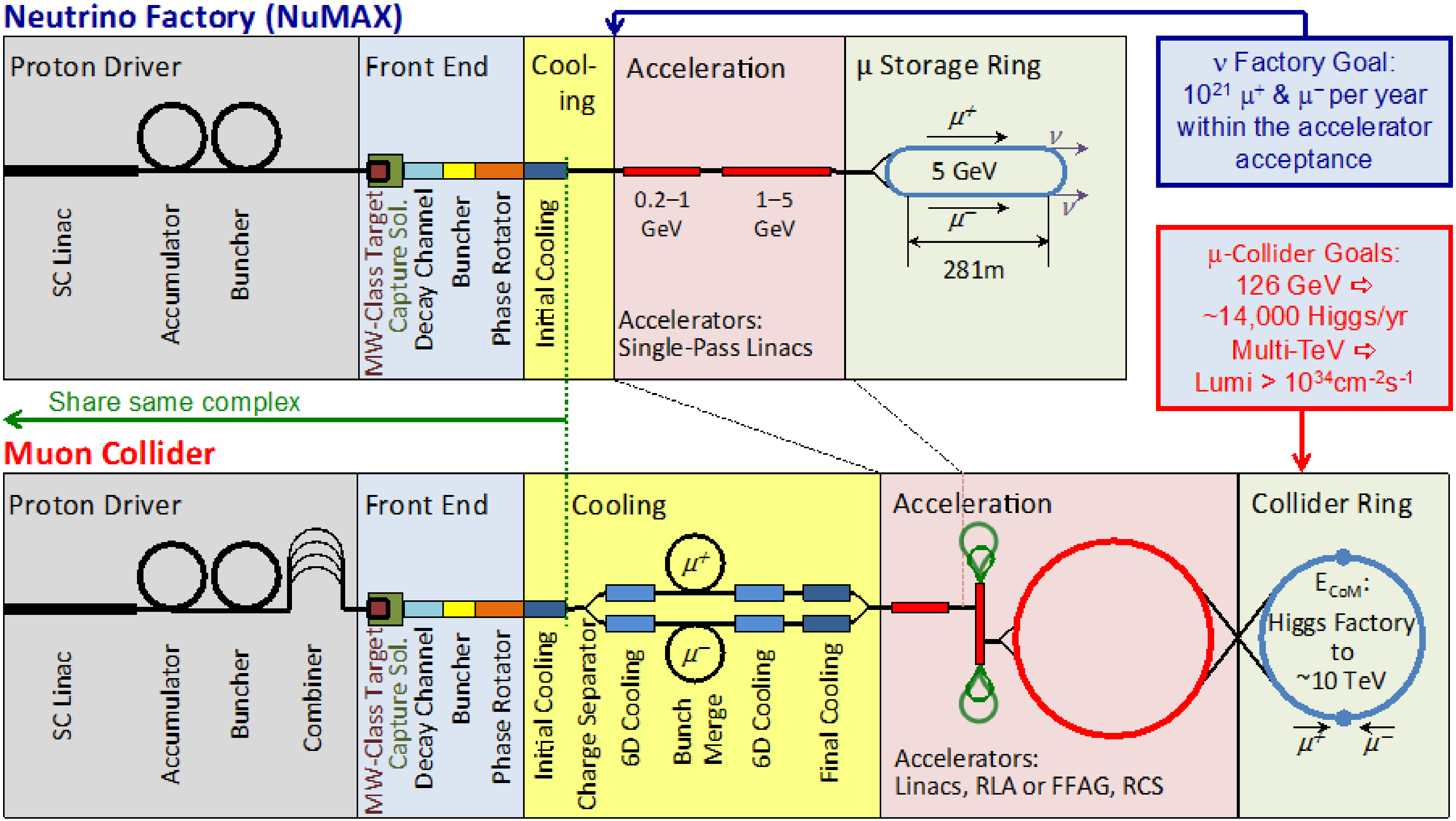
Coloma, Huber, Kopp, Winter
arXiv:1209.5973

* Assumes surface operation to be equivalent to deep underground operation for beam physics

CP violation 5σ coverage is 85% (ie. 85% probability of CPV discovery!)

P. Soler, NUFACT14, Glasgow 26 August 2014

Neutrino Factory/Muon Collider Synergies



Neutrino Factory (NuMAX)

ν Factory Goal:
10^{21} μ^+ & μ^- per year
within the accelerator acceptance

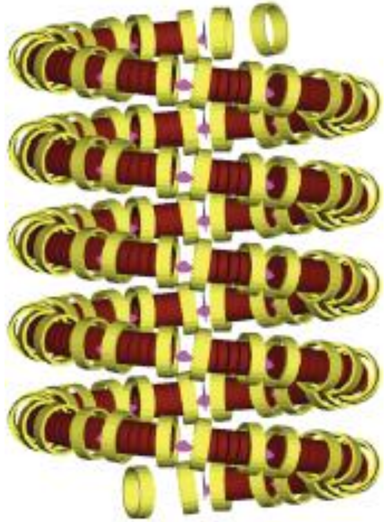
μ-Collider Goals:
126 GeV ⇨ ~14,000 Higgs/yr
Multi-TeV ⇨ Lumi > 10^{34}cm^{-2}s^{-1}

Share same complex

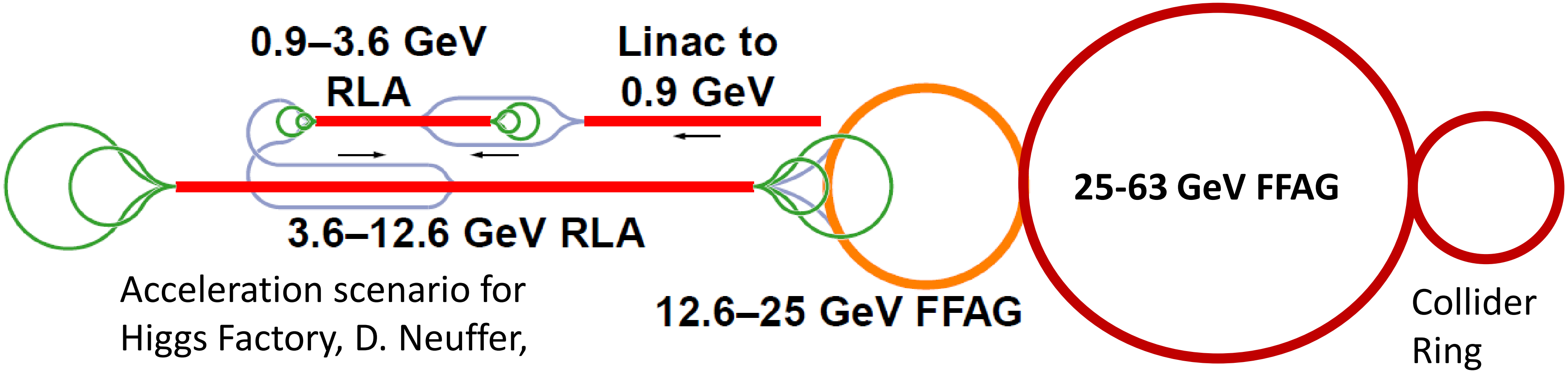
Muon Collider

Higgs Factory at 125 GeV COM

- Discovery of Higgs-like boson at LHC opens a possibility to use muon collisions at the resonance for Higgs production.
- Required collider ring could be very compact (C=350 m).
- Still substantial beam cooling is required. MICE results are essential and R&D studies beyond MICE are needed.
- Acceleration can be based on straightforward extrapolation from the Neutrino Factory and will use RLAs and NS-FFAGs (EMMA results are essential).

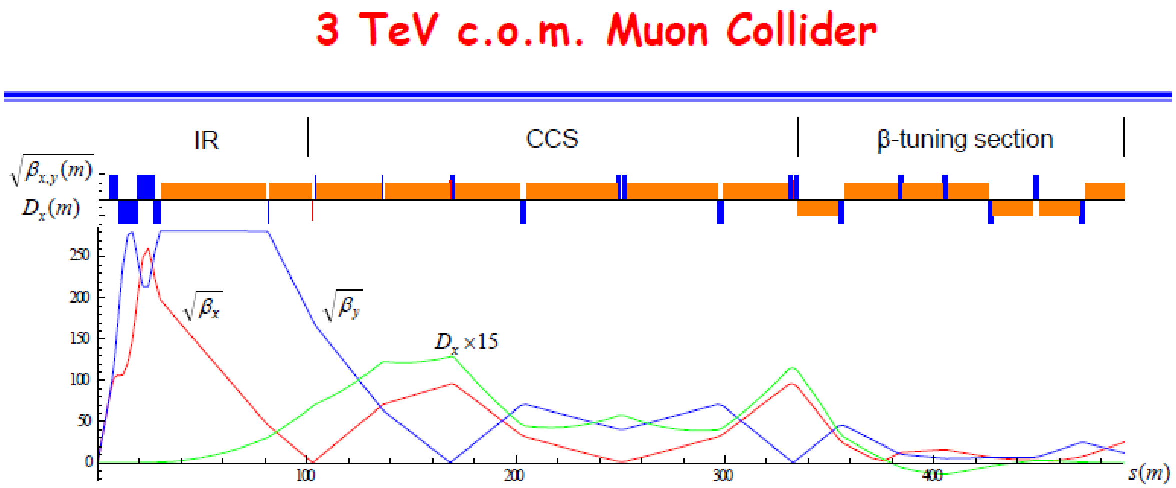


One of the proposed 6D cooling channels



Acceleration scenario for Higgs Factory, D. Neuffer,

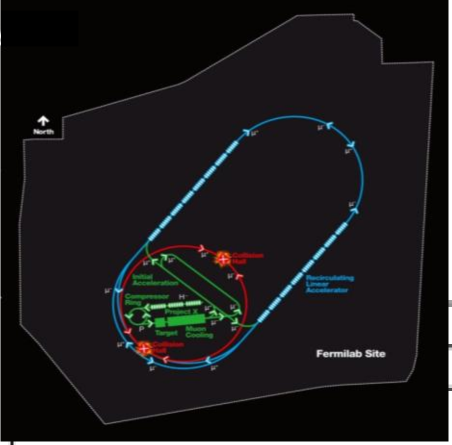
Multi-Tev Collider – 3.0 TeV Baseline



- Lattices for 63 GeV Higgs Factory, 1.5 TeV MC have been designed & simulated
- New: 3.0 TeV MC baseline
- Design Goals
  - High luminosity, acceptable detector backgrounds, manageable magnet heat loads…

High Energy MC parameters	
Collision energy, TeV	3.0
Repetition rate, Hz	12
Average luminosity / IP, 10^{34}/cm^2/s	4.4
Number of IPs	2
Circumference, km	4.5
β*, cm	0.5
Momentum compaction factor, 10^{-5}	-1
Normalized emittance, π·mm·mrad	25
Momentum spread, %	0.1
Bunch length, cm	0.5
Number of muons / bunch, 10^{12}	2
Number of bunches / beam	1
Beam-beam parameter / IP	0.09
RF voltage at 1.3 GHz, MV	150
Proton driver power (MW)	4

From D. Stratakis, nufact'14



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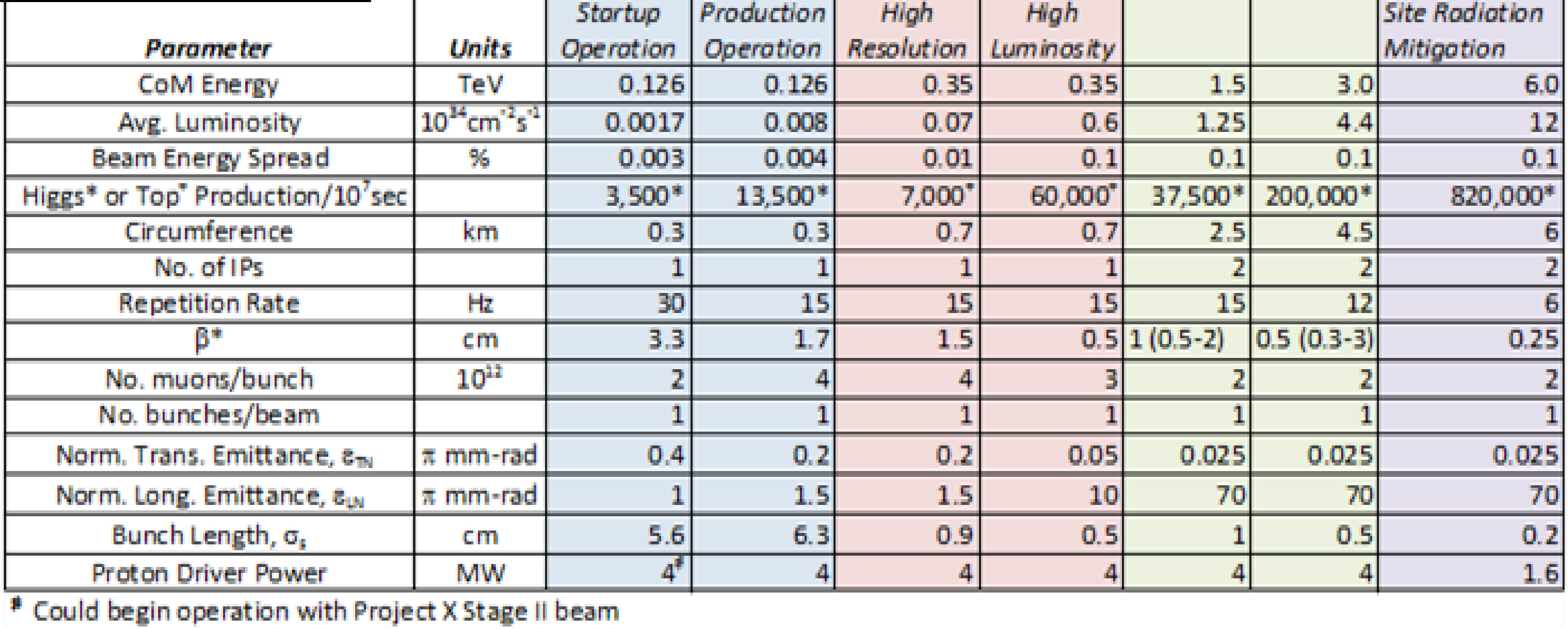
Muon Collider Parameters



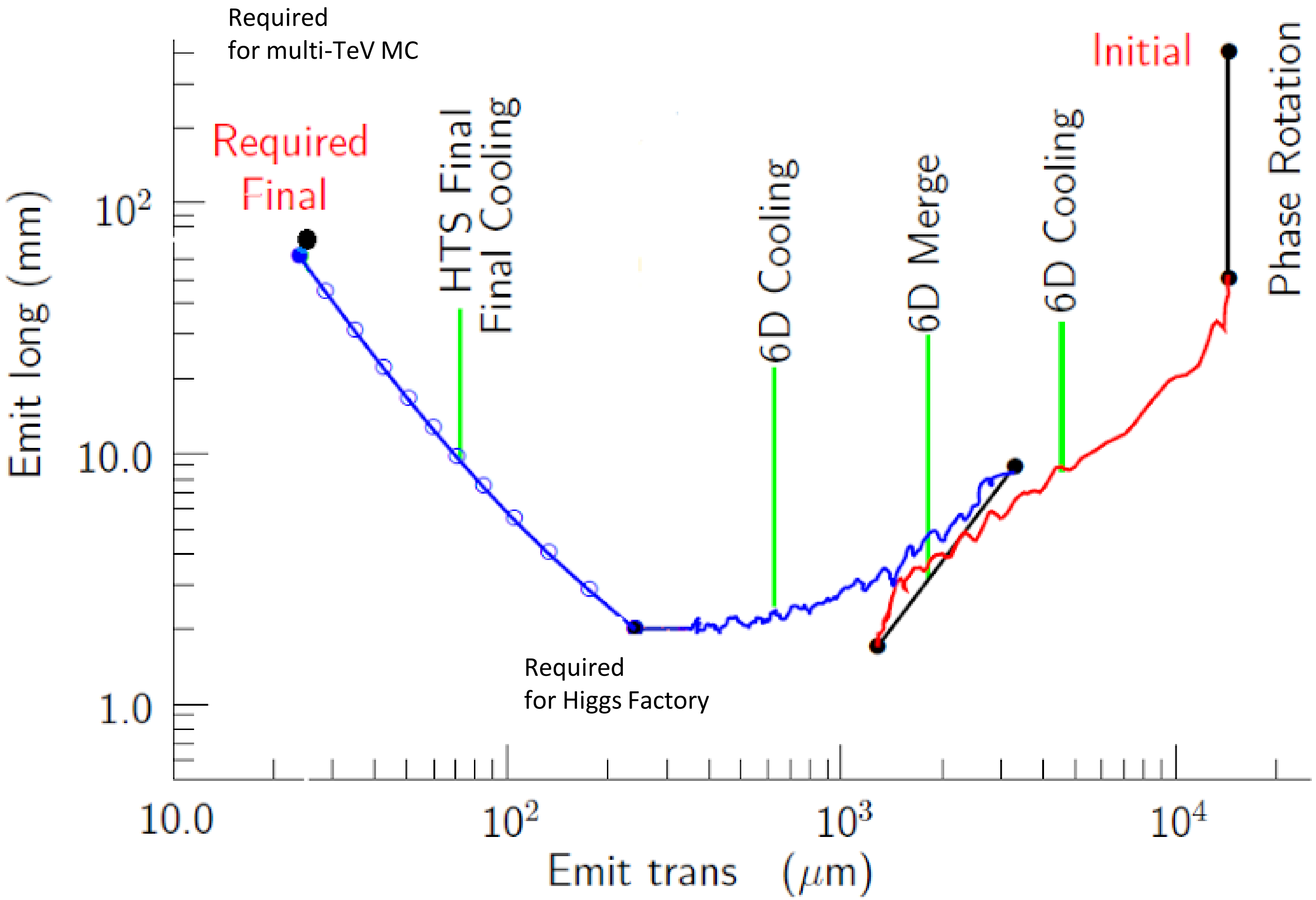
Muon Collider Parameters								
		Higgs Factory		Top Threshold Options		Multi-TeV Baselines		
Parameter	*Units*	*Startup Operation*	*Production Operation*	*High Resolution*	*High Luminosity*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	0.126	0.126	0.35	0.35	1.5	3.0	6.0
Avg. Luminosity	10^{34}cm^{-2}s^{-1}	0.0017	0.008	0.07	0.6	1.25	4.4	12
Beam Energy Spread	%	0.003	0.004	0.01	0.1	0.1	0.1	0.1
Higgs* or Top† Production/10^7sec		3,500*	13,500*	7,000†	60,000†	37,500*	200,000*	820,000*
Circumference	km	0.3	0.3	0.7	0.7	2.5	4.5	6
No. of IPs		1	1	1	1	2	2	2
Repetition Rate	Hz	30	15	15	15	15	12	6
β^*	cm	3.3	1.7	1.5	0.5	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	2	4	4	3	2	2	2
No. bunches/beam		1	1	1	1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.2	0.05	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	1.5	10	70	70	70
Bunch Length, σ_z	cm	5.6	6.3	0.9	0.5	1	0.5	0.2
Proton Driver Power	MW	4#	4	4	4	4	4	1.6

Could begin operation with Project X Stage II beam

MAP Result

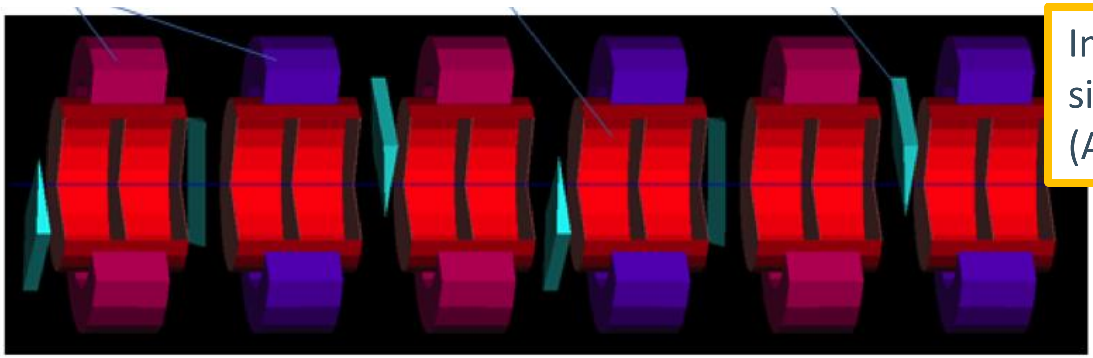
M. Palmer, NuFACT 2014

6D cooling requirements for MC



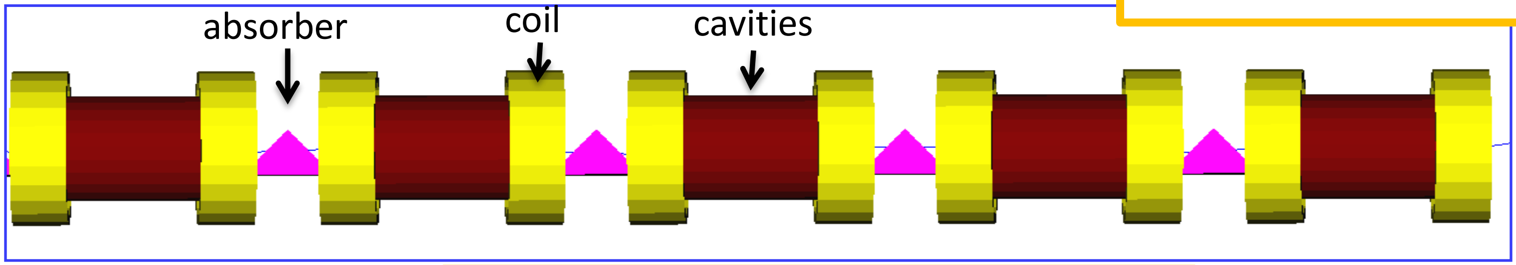
6D Cooling channel concepts

- Great progress on D&S over the last year:

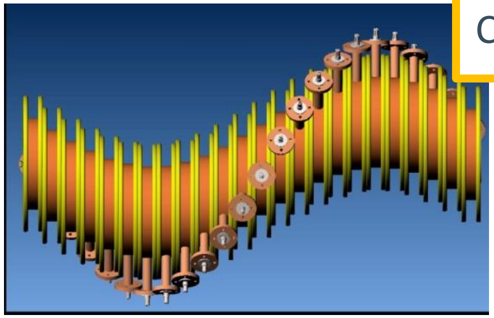


Initial Cooling: Cools both mu signs, suitable for NuMAX (Alexahin)

6D Cooling with vacuum rf cavities (**VCC** Concept), D. Stratakis



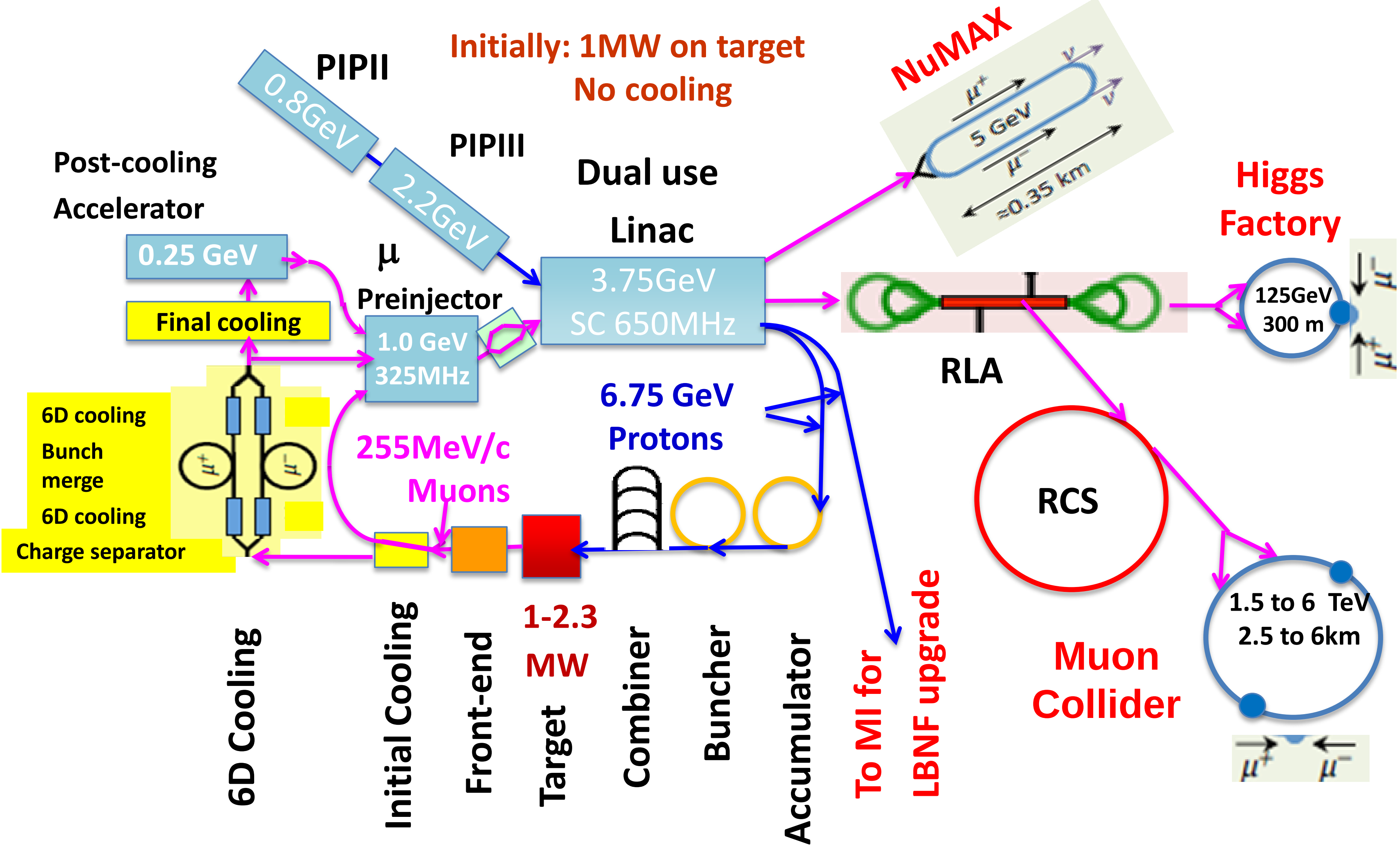
6D Cooling with gas-filled rf cavities (**HCC** Concept), K. Yonehara



- Delivered a complete cooling scheme!

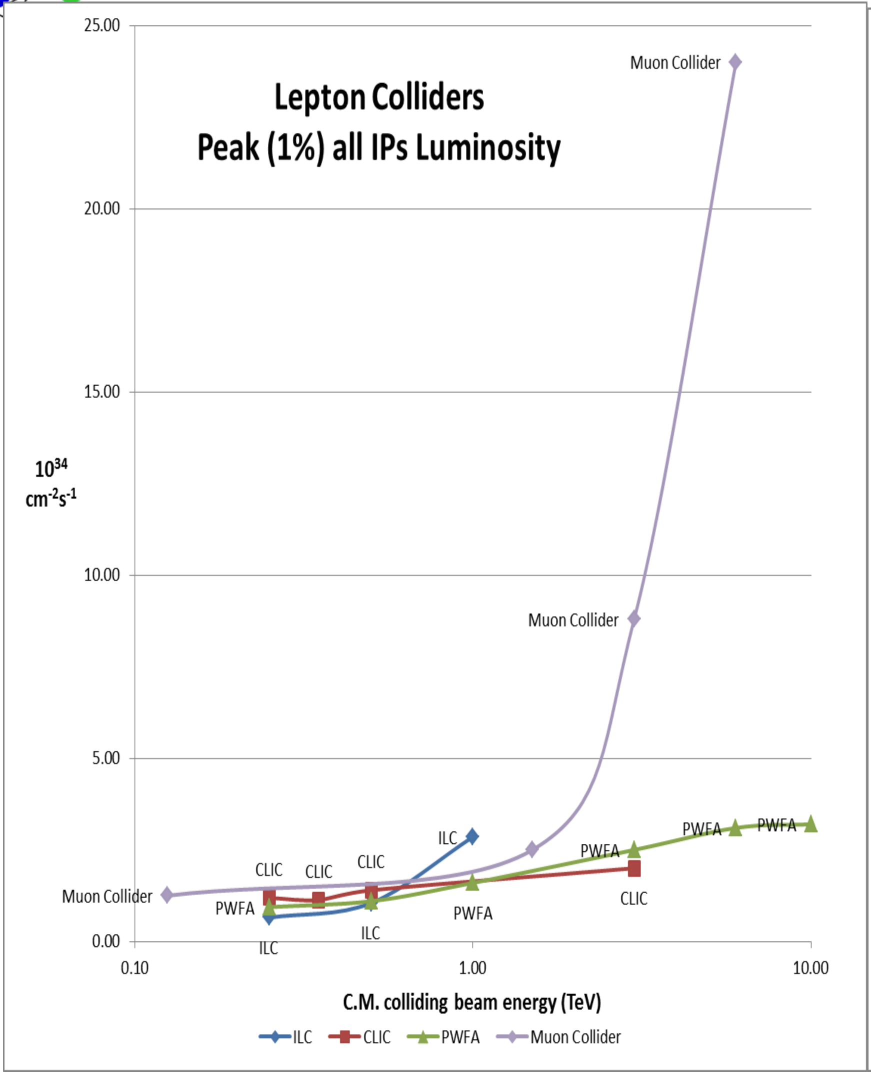
All developed by MAP

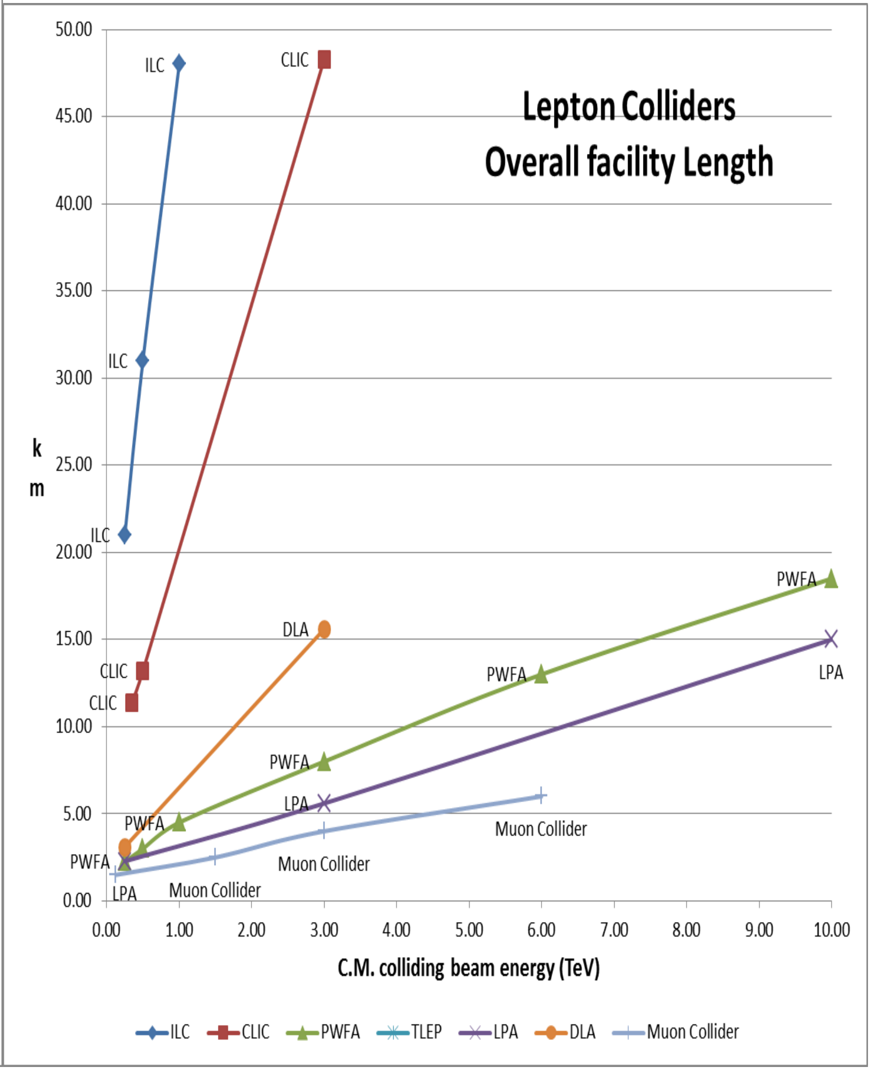
Staging Scenario at FNAL under MAP



From J.-P. Delahaye | DOE Review of MAP
(BNL, August 12-14, 2014)

Muon Colliders extending high energy frontier with potential of considerable cost savings





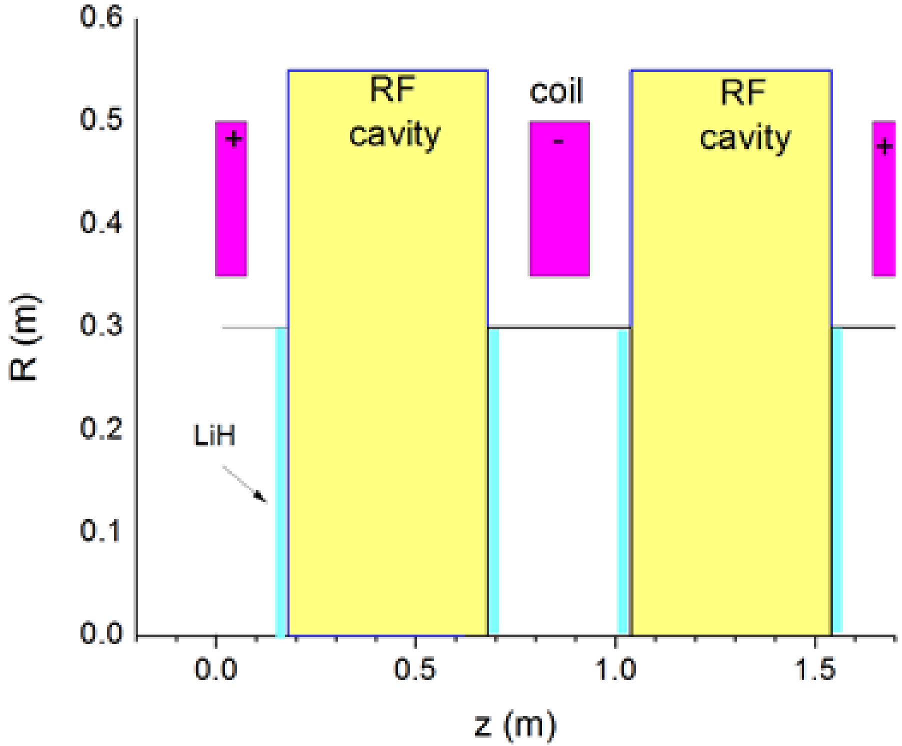
J-P. Delahaye, *et al.* [arXiv:1308.0494]

NF Cooler parameters

D. Stratakis

- Cooler (~100 m long)
  - 0.75 m cell length
  - 201.25 MHz
  - RF voltage: 16 MV/m
  - 2.8 T peak field on axis
  - 2.7 T field on the iris
  - Lithium Hydride absorber
  - 4D cooling only

Two cooler cells:



Parameters of the cell (RF gradient, solenoidal field, engineering constraints are challenging and the ionization cooling has never been demonstrated!

What is MICE?

M*uon*

I*onization*

C*ooling*

E*xperiment*

MICE **is a proof of principle experiment to demonstrate that we can “cool” a beam of muons.**

MICE collaboration

Bulgaria	University of Sofia
Italy	Sezione INFN Milano Bicocca Sezione INFN Napoli and Dipartimento di Fisica Sezione INFN Pavia and Dipartimento di Fisica Nucleare e Teorica Sezione INFN Roma Tre e Dipartimento di Fisica
Japan	High Energy Accelerator Research Organization (KEK) Kyoto University, Reactor Research Institute Osaka University, Graduate School of Science, Department of Physics
Netherlands	NIKHEF
CERN	CERN
Switzerland	DPNC, Section de Physique, University of Geneve
UK	Brunel University The Cockcroft Institute STFC Daresbury Laboratory School of Physics and Astronomy, University of Glasgow Department of Physics, Imperial College London Department of Physics, University of Liverpool Department of Physics, University of Oxford STFC Rutherford Appleton Laboratory Department of Physics and Astronomy, University of Sheffield Department of Physics, University of Strathclyde Department of Physics, University of Warwick
USA	Brookhaven National Laboratory Fermi National Laboratory Lawrence Berkeley National Laboratory, Berkeley, CA, USA Illinois Institute of Technology, Chicago, IL, USA University of Mississippi University of New Hampshire Department of Physics and Astronomy, University of Iowa University of California, Riverside

3 regions

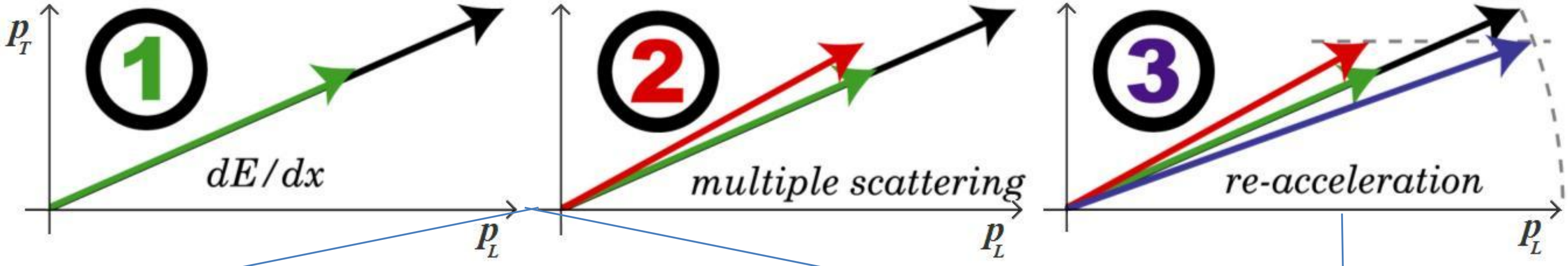
8 countries

30 institutes

63 PhD-level physicists/ engineers *

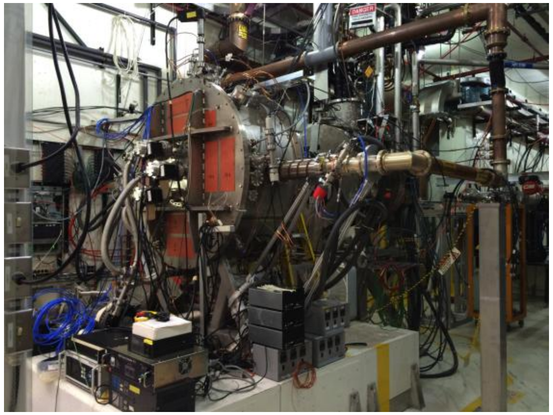
* Common Fund levy

Basics of ionization cooling



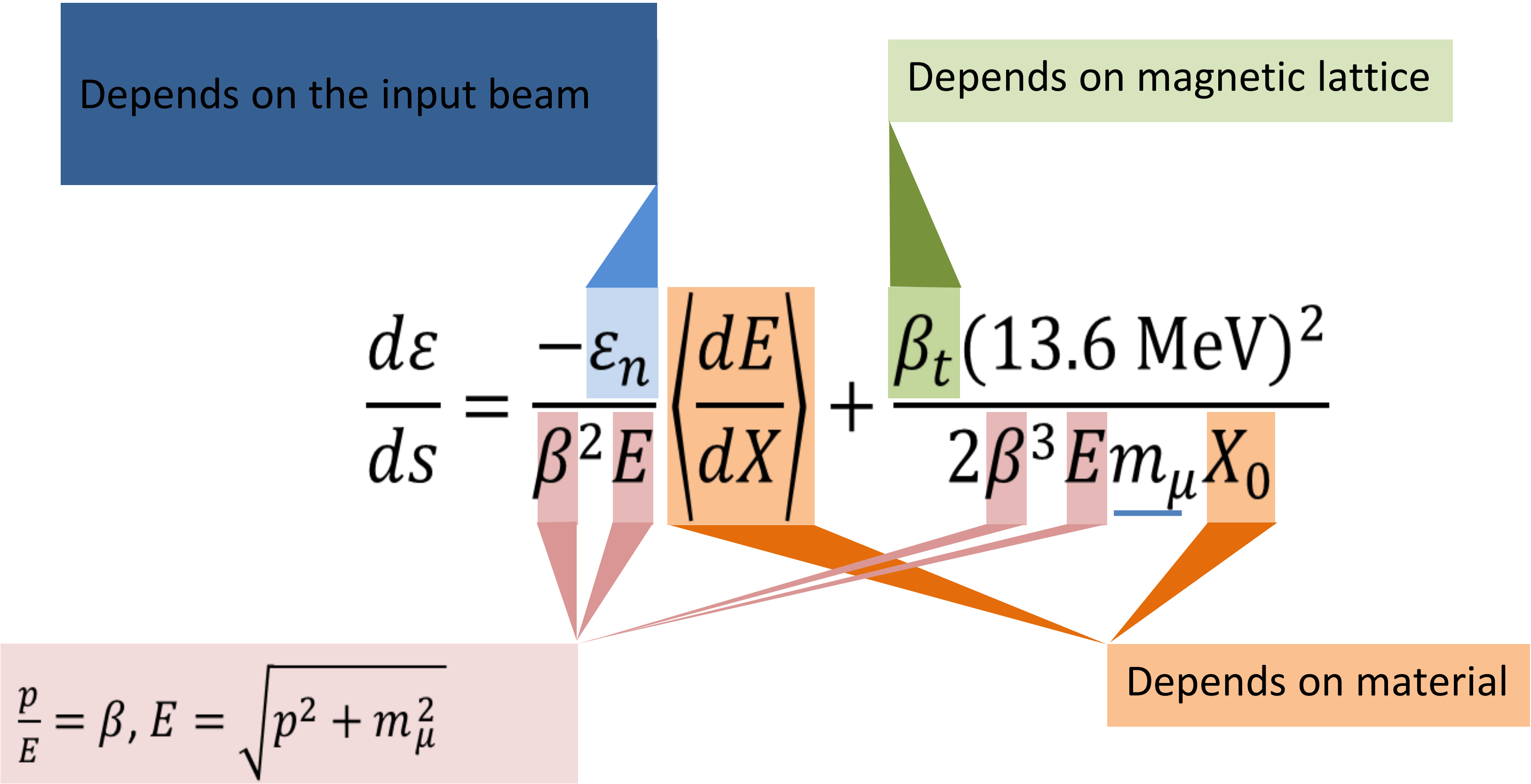
LiH disk

LH2 system



Single Cavity Test Stand
(SCTS) at MTA, FNAL

Ionization cooling equation



Depends on the input beam

Depends on magnetic lattice

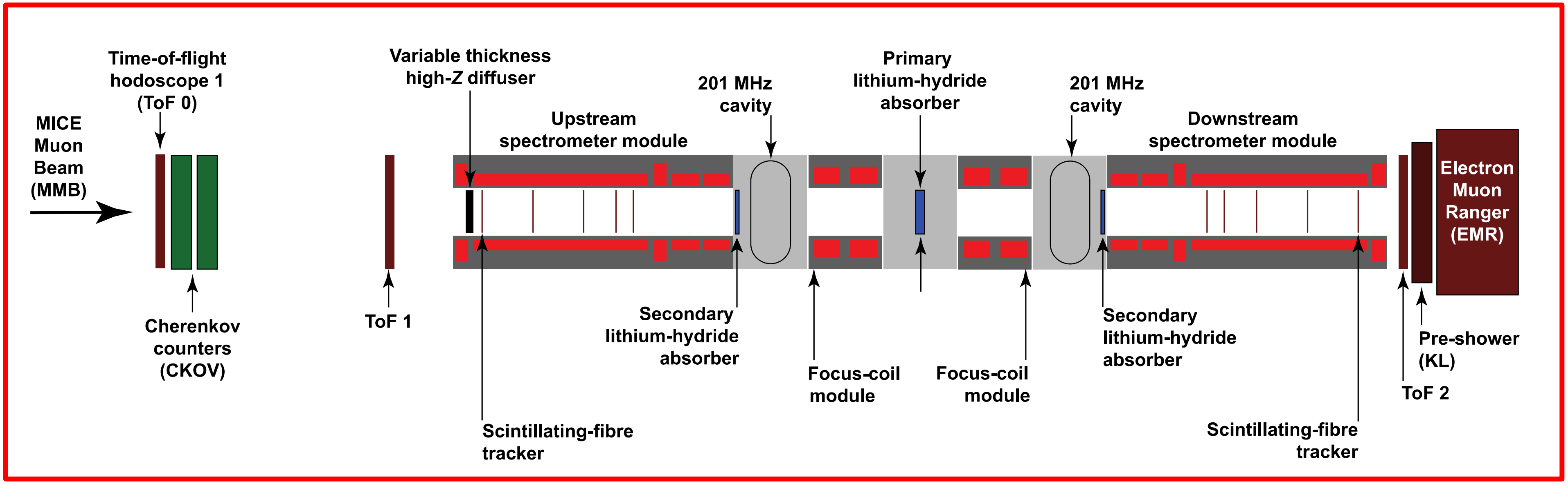
$$\frac{d\varepsilon}{ds} = \frac{-\varepsilon_n}{\beta^2 E}\left\langle\frac{dE}{dX}\right\rangle + \frac{\beta_t (13.6\ \mathrm{MeV})^2}{2\beta^3 E m_\mu X_0}$$

$$\frac{p}{E} = \beta, E = \sqrt{p^2 + m_\mu^2}$$

Depends on material

This equation is derived assuming several approximations and the real emittance evolution expected to deviate from its predictions can only be assessed experimentally.

MICE:
Muon Ionization Cooling Experiment



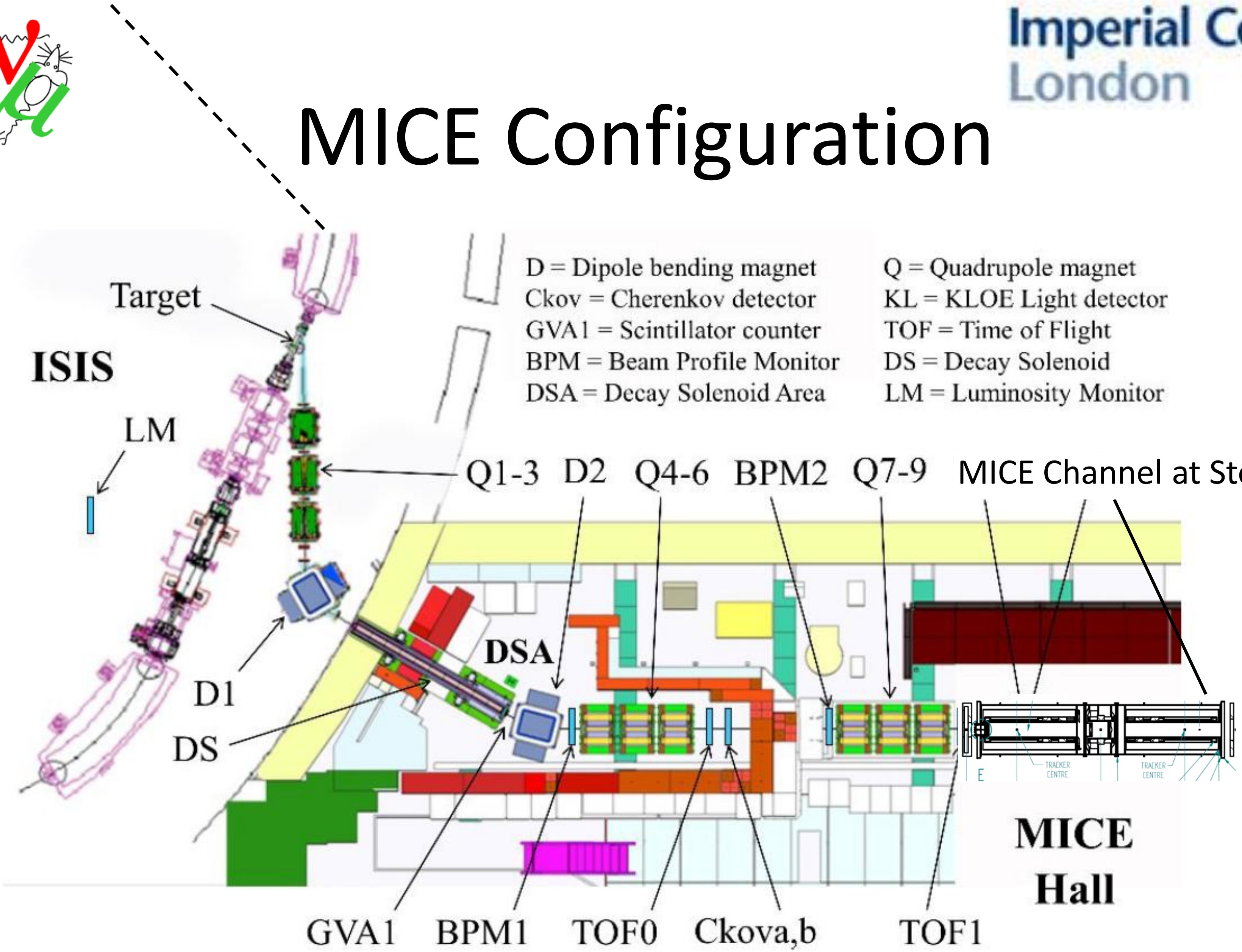
- **MICE Goals:**
  - **Design, build, commission, and operate a realistic section of cooling channel**
  - **Measure its performance in a variety of modes of operation and beam conditions**

…results will be used to optimize Neutrino Factory, Muon Collider and future high brightness muon beam designs.

MICE Configuration

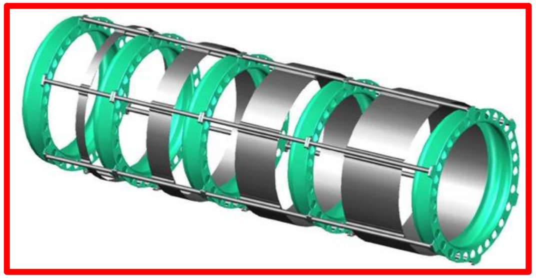
D = Dipole bending magnet
Ckov = Cherenkov detector
GVA1 = Scintillator counter
BPM = Beam Profile Monitor
DSA = Decay Solenoid Area

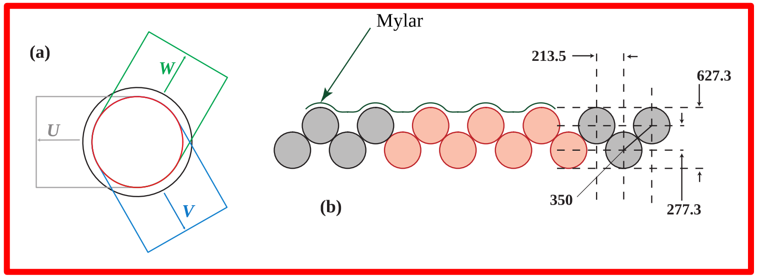
Q = Quadrupole magnet
KL = KLOE Light detector
TOF = Time of Flight
DS = Decay Solenoid
LM = Luminosity Monitor

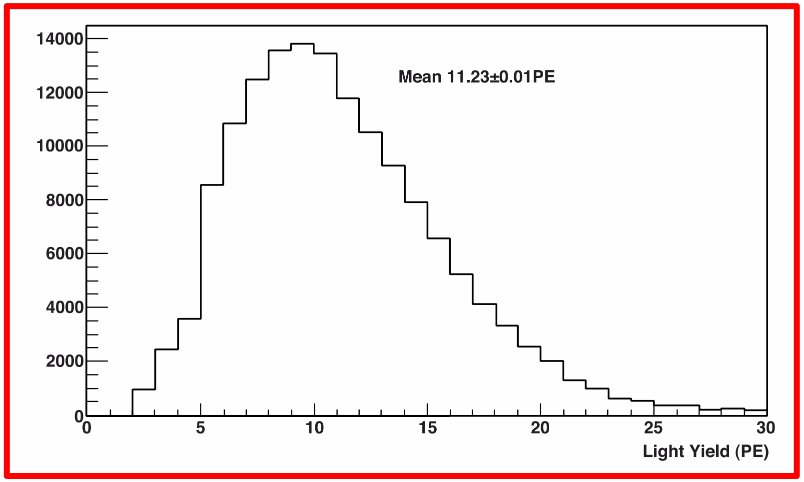


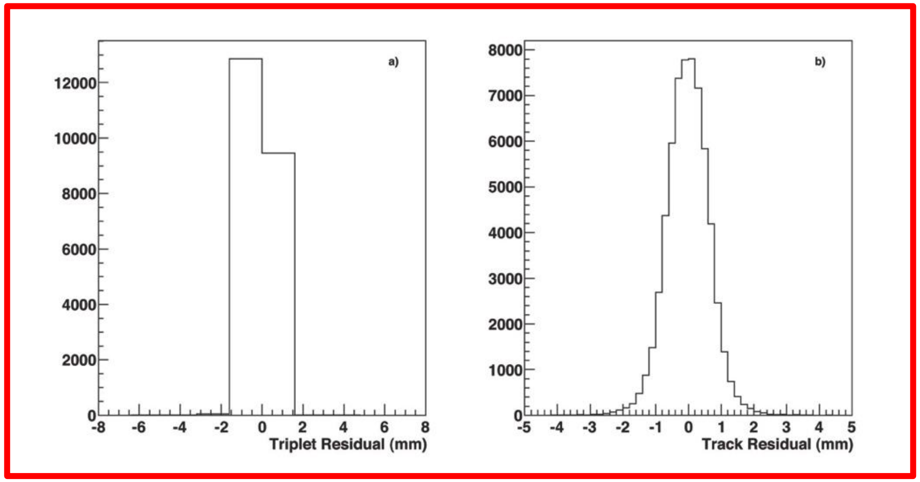
MICE trackers

Nucl.Instrum.Meth. A659 (2011) 136-153

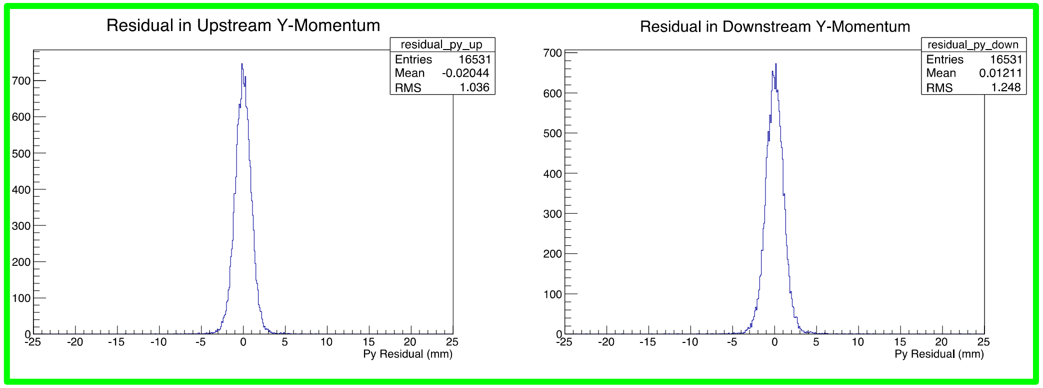




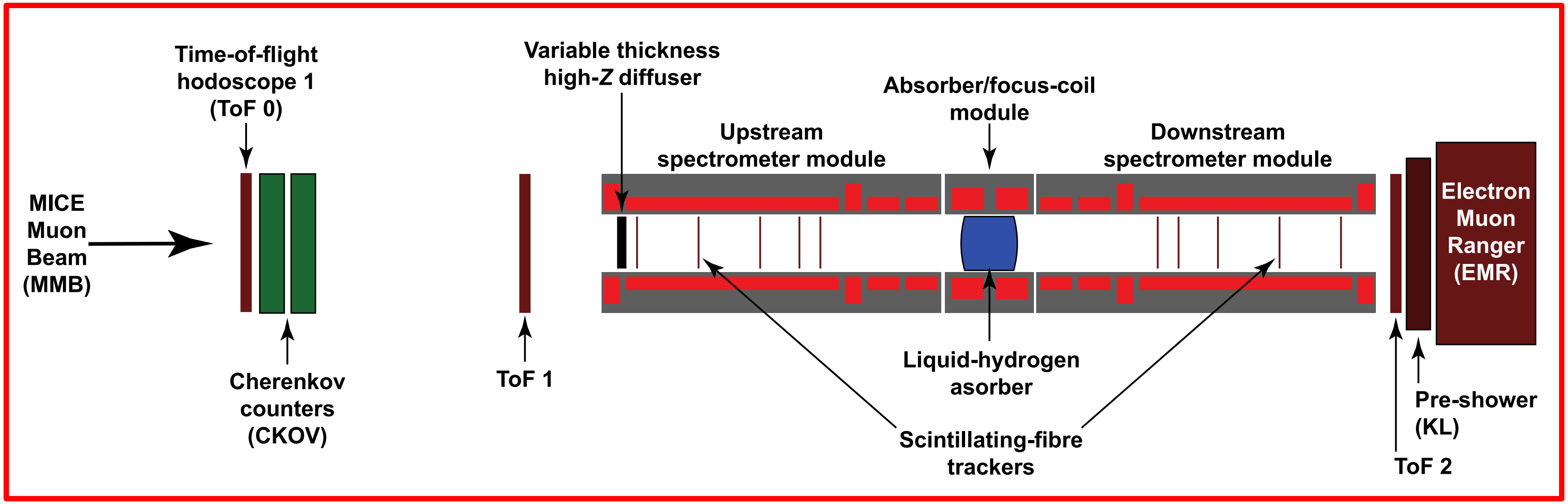




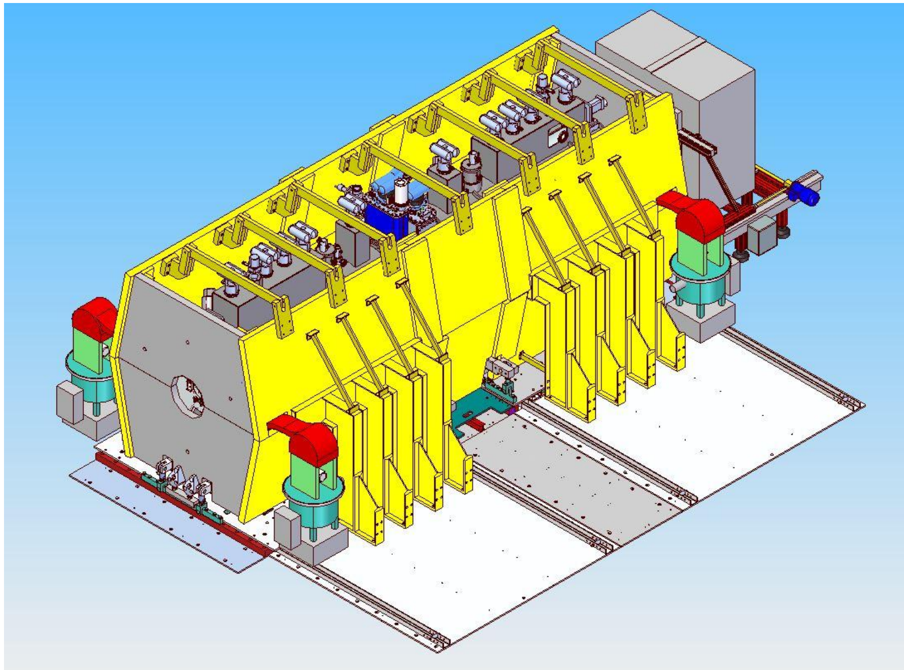
- 350 µm scintillating-fibre tracker:
  - 10 p.e./mip demonstrated with cosmics
  - 470 µm intrinsic resolution per plane
- MC: delivers per-mille level emittance measurement particle by particle



"Step IV"; data taking 2015/16



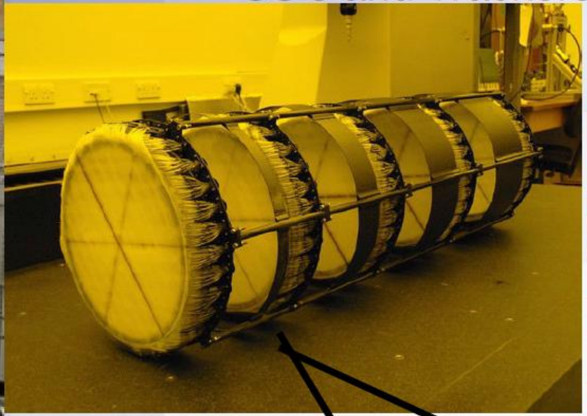
- Optimised for the study of material properties that affect cooling

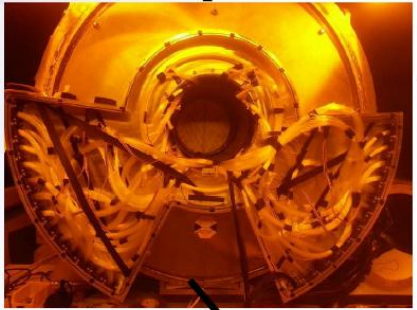


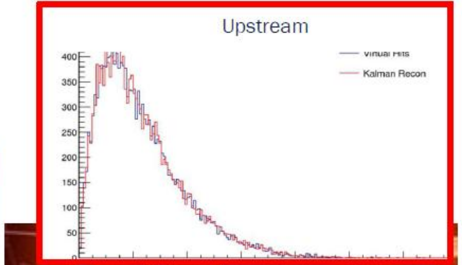
MICE Step IV inside
the Partial Return Yoke

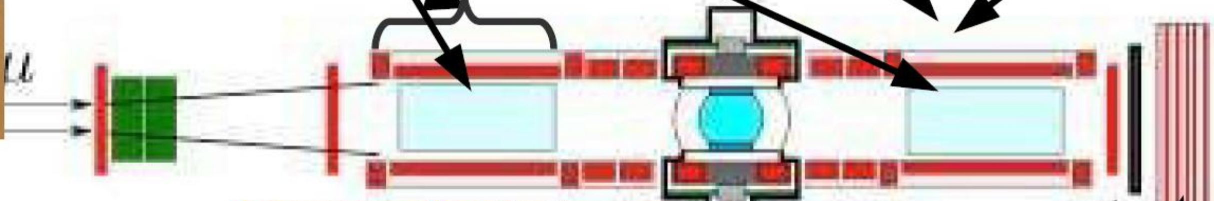
Step IV

SS's and Trackers









EMR

AFC

TOF/KL

Racks

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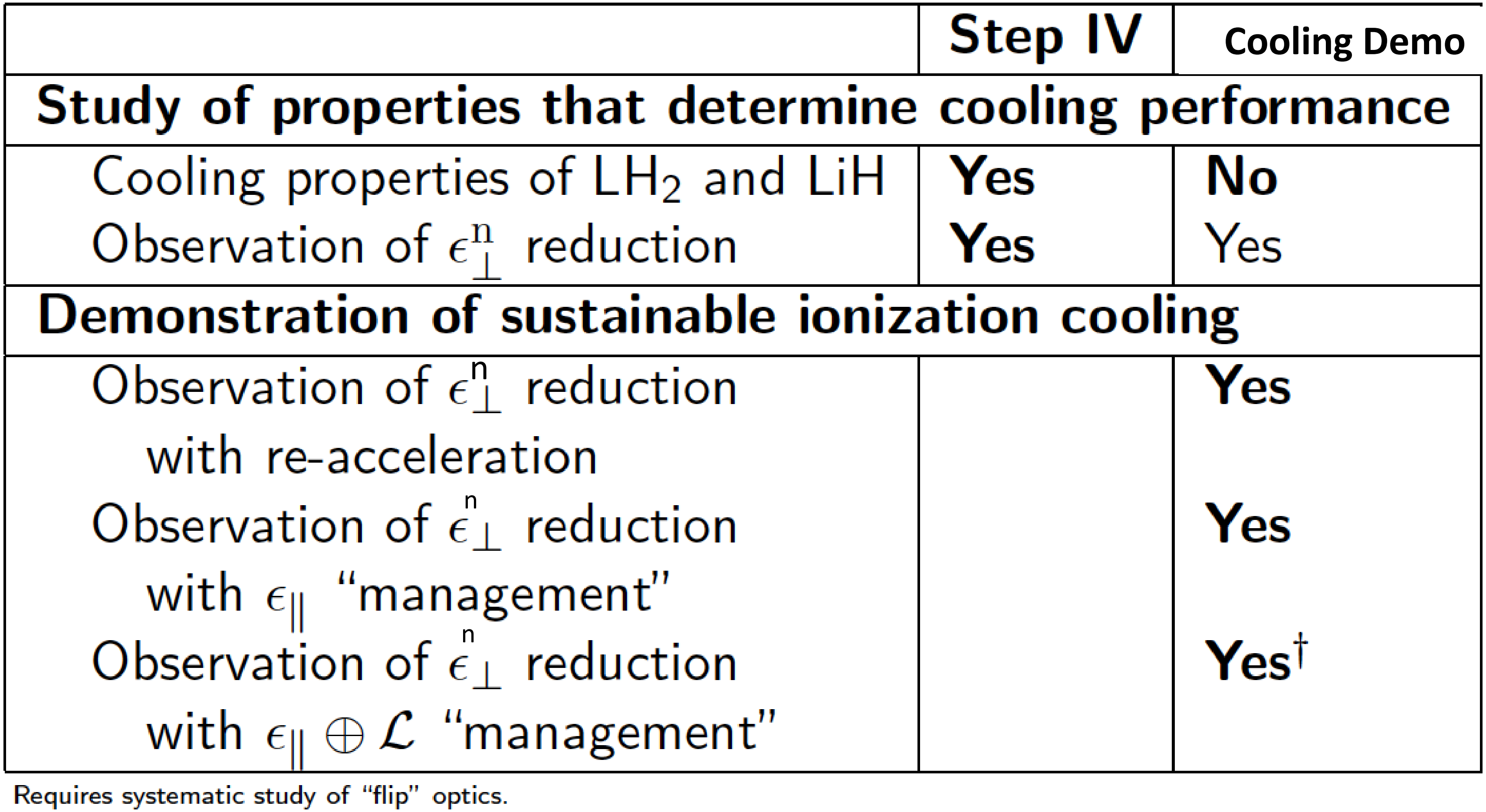
MICE Hall

MICE goals

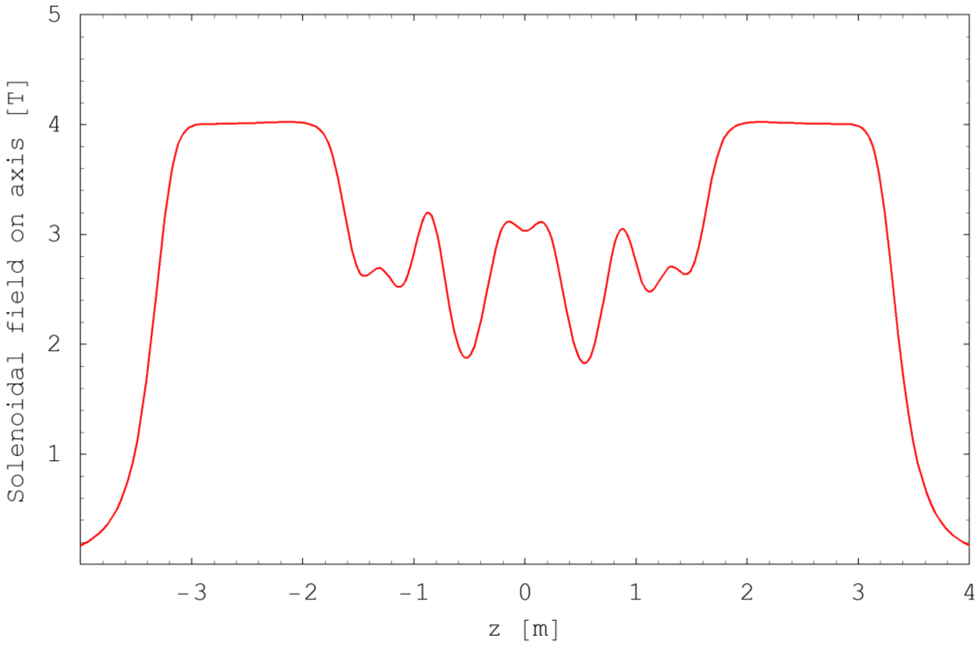


	Step IV	Cooling Demo
Study of properties that determine cooling performance		
Cooling properties of LH_2 and LiH	**Yes**	**No**
Observation of $\epsilon_\perp^n$ reduction	**Yes**	Yes
Demonstration of sustainable ionization cooling		
Observation of $\epsilon_\perp^n$ reduction with re-acceleration		**Yes**
Observation of $\epsilon_\perp^n$ reduction with $\epsilon_\parallel$ "management"		**Yes**
Observation of $\epsilon_\perp^n$ reduction with $\epsilon_\parallel \oplus \mathcal{L}$ "management"		**Yes**[†]

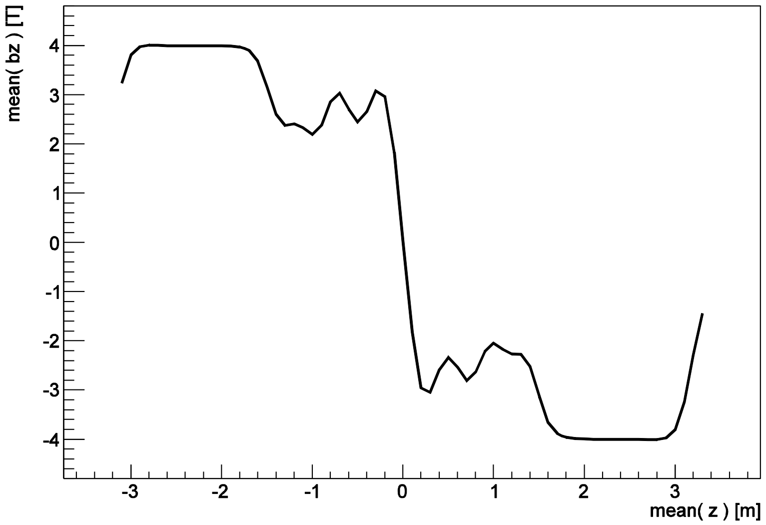
[†] Requires systematic study of "flip" optics.

The cooling channel for the NF may contain ~100 cells, so to predict the cooling performance of the entire channel you need to measure emittance reduction in MICE very precisely.
We aim for the very difficult precision level of 0.1%, which is challenging (alignment errors, resolution limitations), but is believed to be possible!

“Solenoid” and “Flip” magnetic configurations



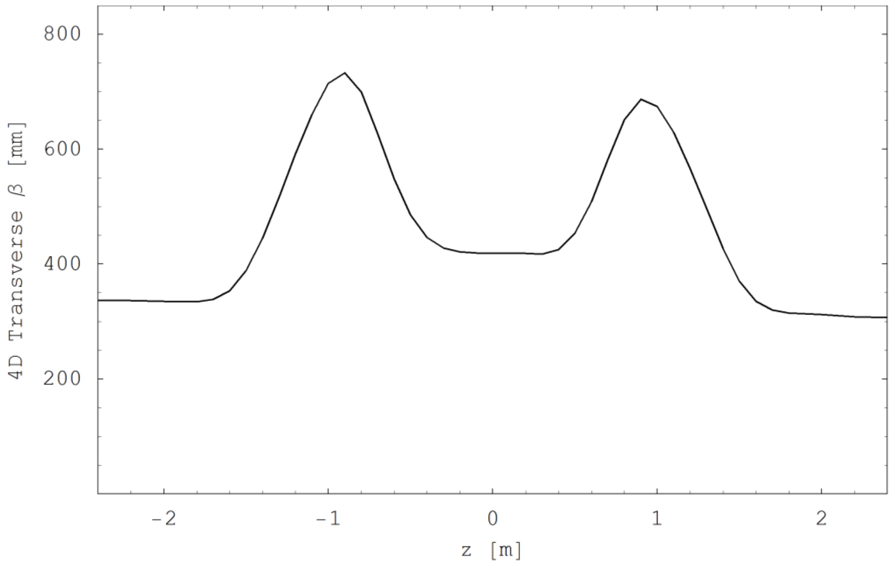
Solenoid mode

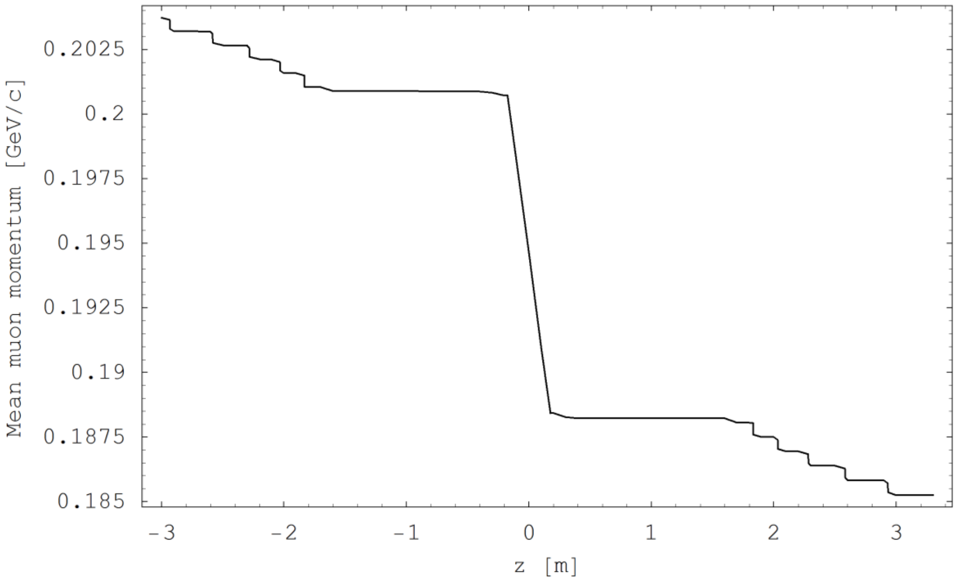


Flip mode

Experimentation in both modes is foreseen and necessary in order to study the evolution and effects associated with canonical angular momentum.

Optics and MC studies in Solenoid Mode



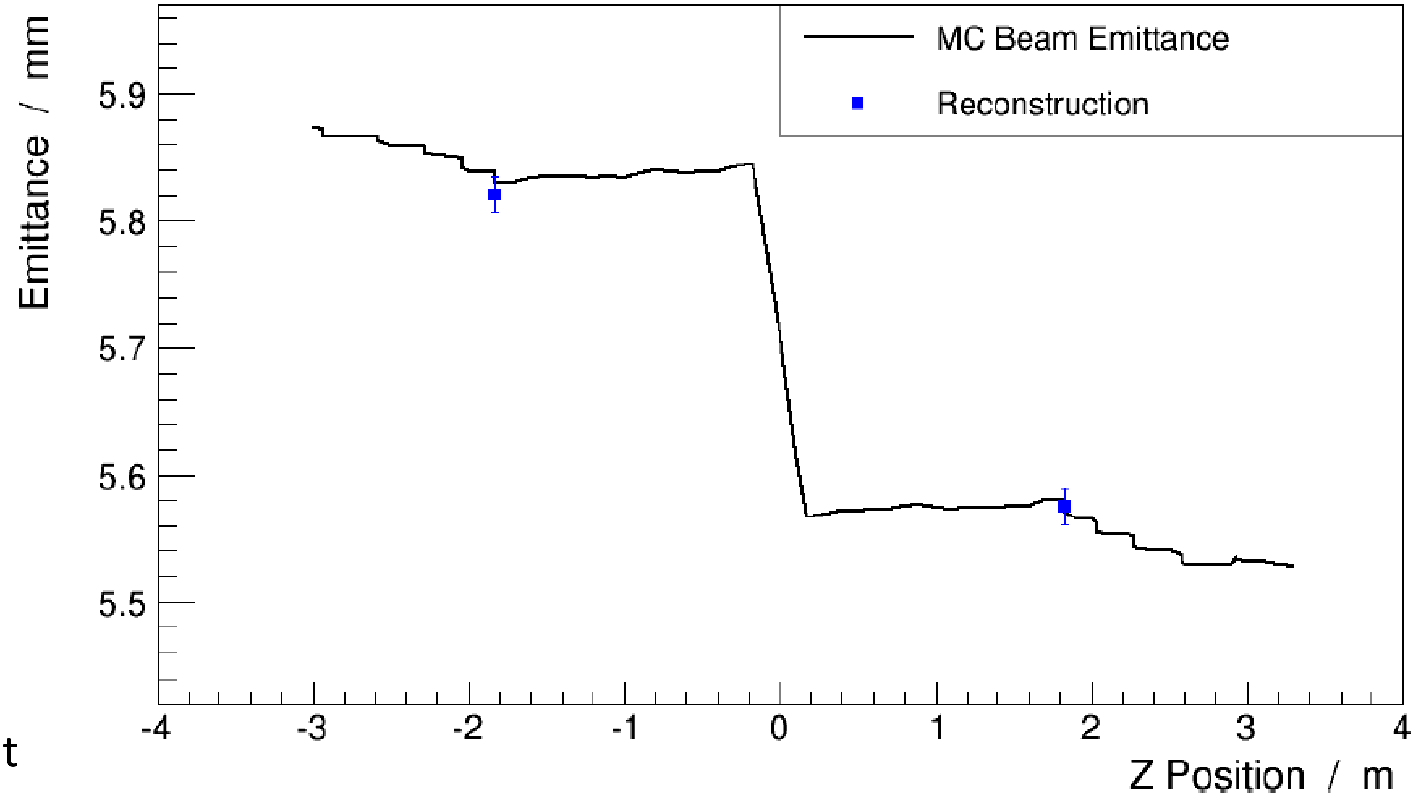


Betatron function is not exactly
Symmetric due to asymmetry in momentum, however matching conditions are preserved

The effect of absorber and Tracker planes in both Trackers can be clearly seen

Emittance Reconstruction at Reference Plane

Approx 80,000 Muons - With Covariance Matrix Corrections

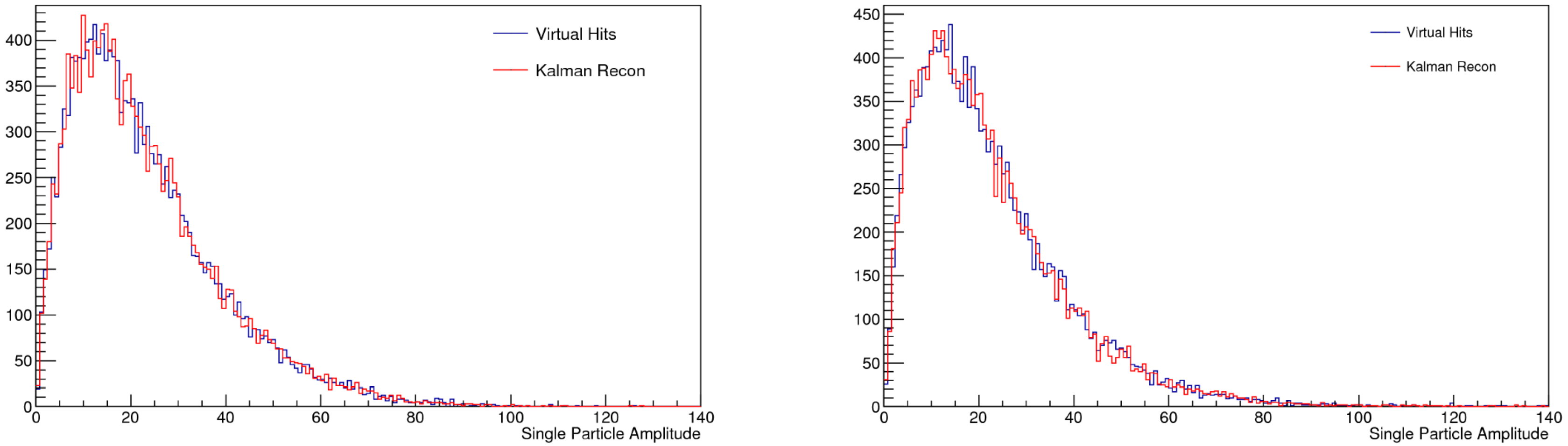


C. Hunt

A 6πmm at 200MeV/c Positive Muon Beam using a Step IV Cooling Channel Geometry

Single particle emittances

Comparison between pure MC data with Tracker reconstruction which simulates the real measurement using the detector algorithms.



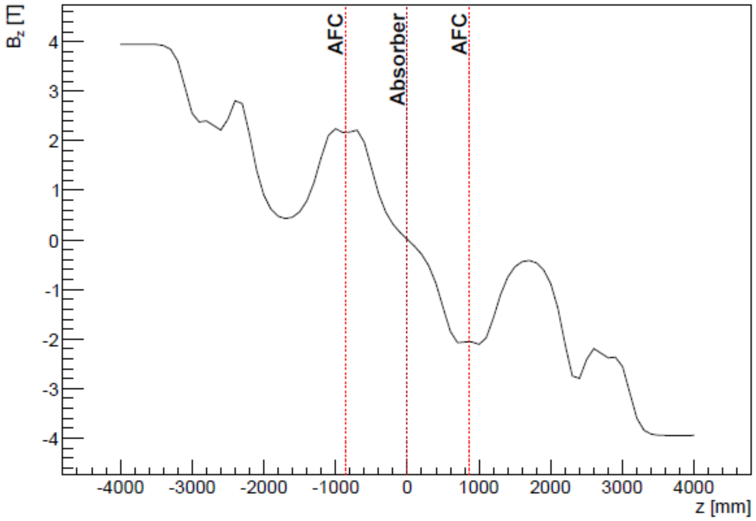
Upstream

Downstream

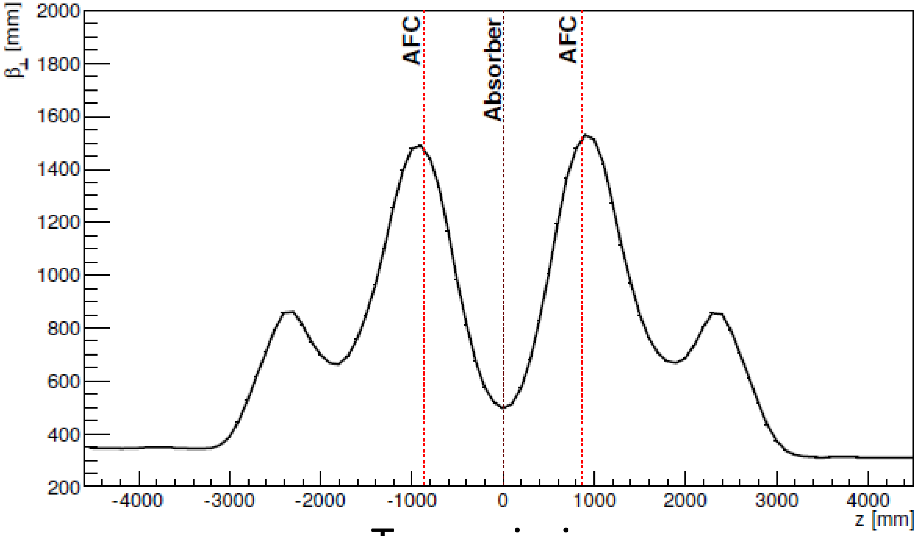
Convenient way to visualise the beam is to calculate single particle emittances for each particle.

Optics and performance of the Cooling Demonstration Step

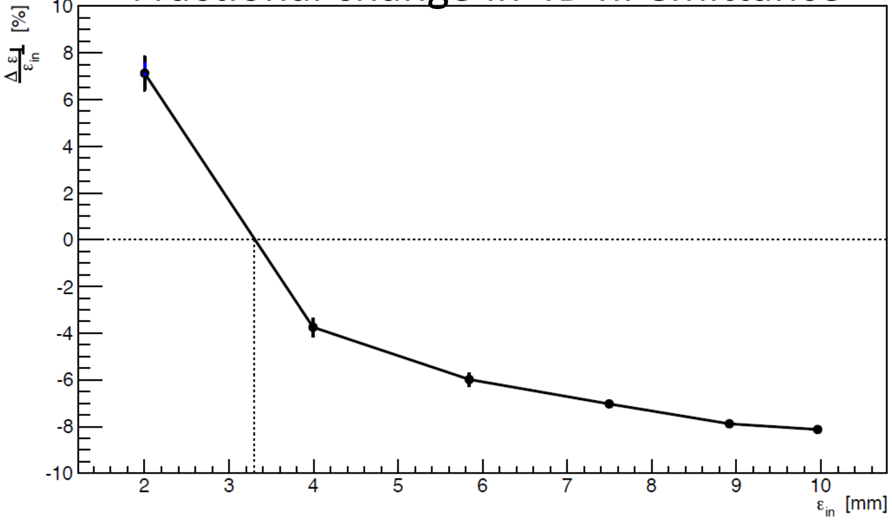
Magnetic field on axis



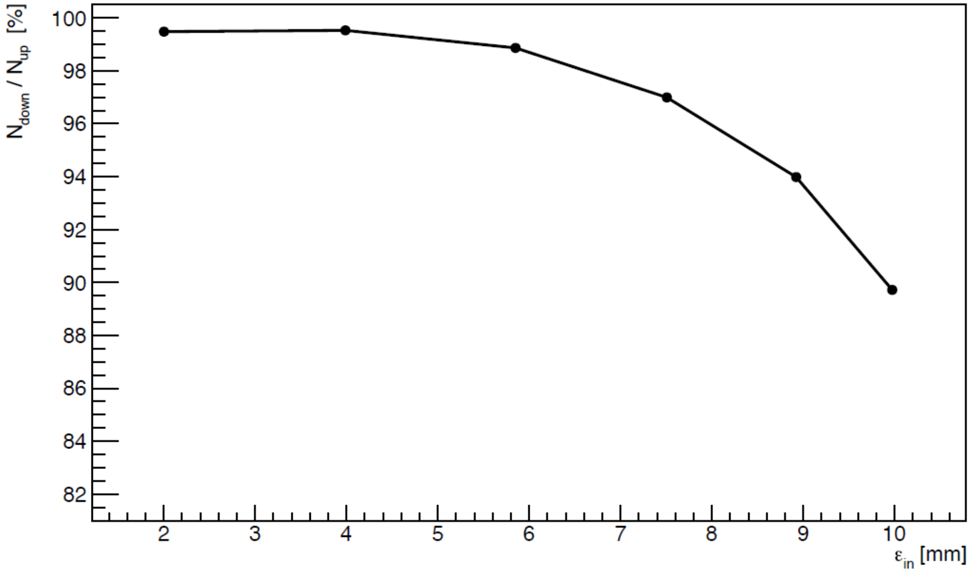
4D betatron function



Fractional change in 4D n. emittance

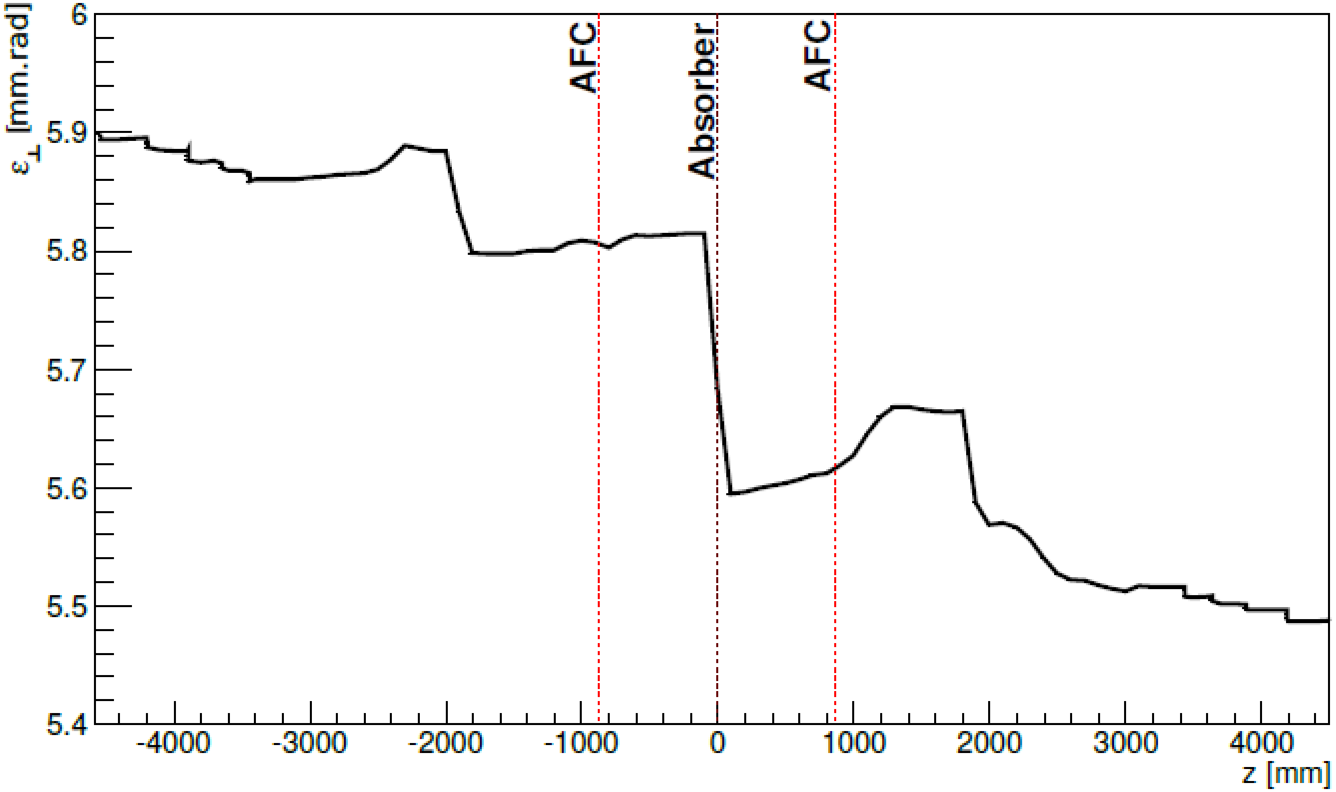


Transmission



Emittance evolution

Emittance evolution in the Demonstration of Ionization Cooling

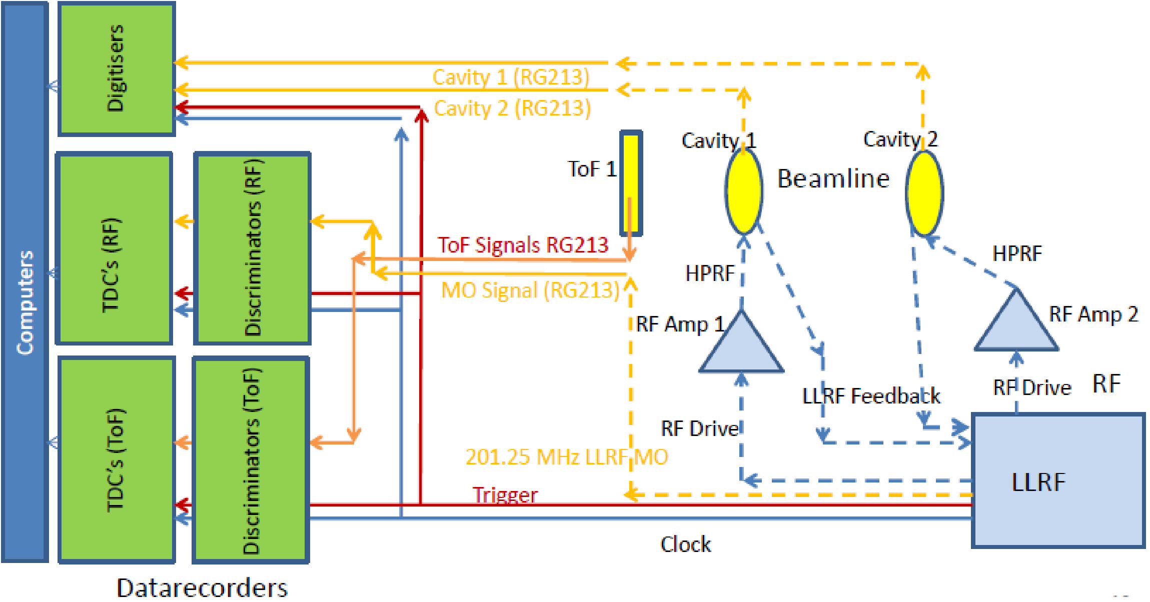


MC simulations show indication for some nonlinear emittance growth, which needs to be properly understood to maximise the performance of cooling channels, but also to understand properly MICE measurements and to ensure its precision (0.1%).

MICE Opportunities and Challenges

- Unique single particle measurements of MICE offers possibilities to study beam dynamics like nonlinear effects, influence of canonical angular momentum, material effects etc. in a novel approach.
- This may provide new insight and allow for code benchmarking.
- The inclusion of longitudinal plane into the analysis requires a precise measurement of muon RF phase. This will allow to study 6D effects.
- The principle system for muon RF phase measurement has been proposed, but it is still in an early stage.

New collaborators would be very welcome!



Conclusions

- Muon accelerators have the potential to:
  - Revolutionise the study of the neutrino
  - Provide a route to multi-TeV lepton-antilepton collisions

- MICE:
  - Will prove the essential ionization-cooling technique
  - Rapidly progressing towards its two Steps
    - Study of the factors that affect ionization cooling (Step IV):
      - Construction complete: Spring 2015
      - Data taking: Summer 2015—June 2016
    - Demonstration of ionization cooling:
      - Construction complete: Early 2017
      - Data taking start: Spring 2017

- Poised to deliver the demonstration of ionization cooling