Muon Collider

J. Pasternak,

Imperial College London/RAL STFC

Outline

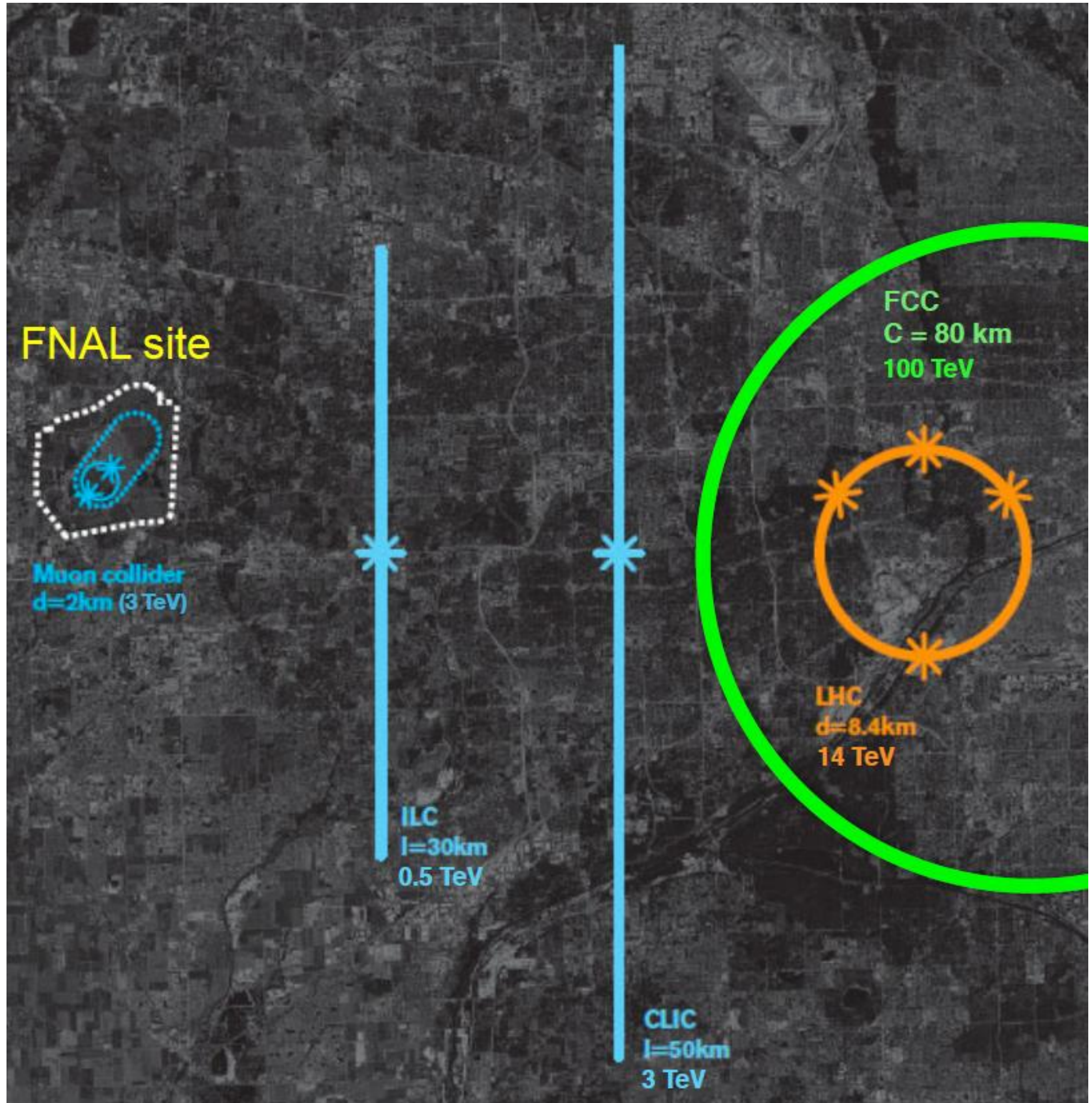
- Motivations for using muon beams for particle physics
- Challenges of manipulating muon beams
- Neutrino Factory as a front end of Muon Collider
- Muon Collider Studies by MAP
- State of art of R&D for selected subsystems
- MICE - Key technology demonstration
- Summary

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

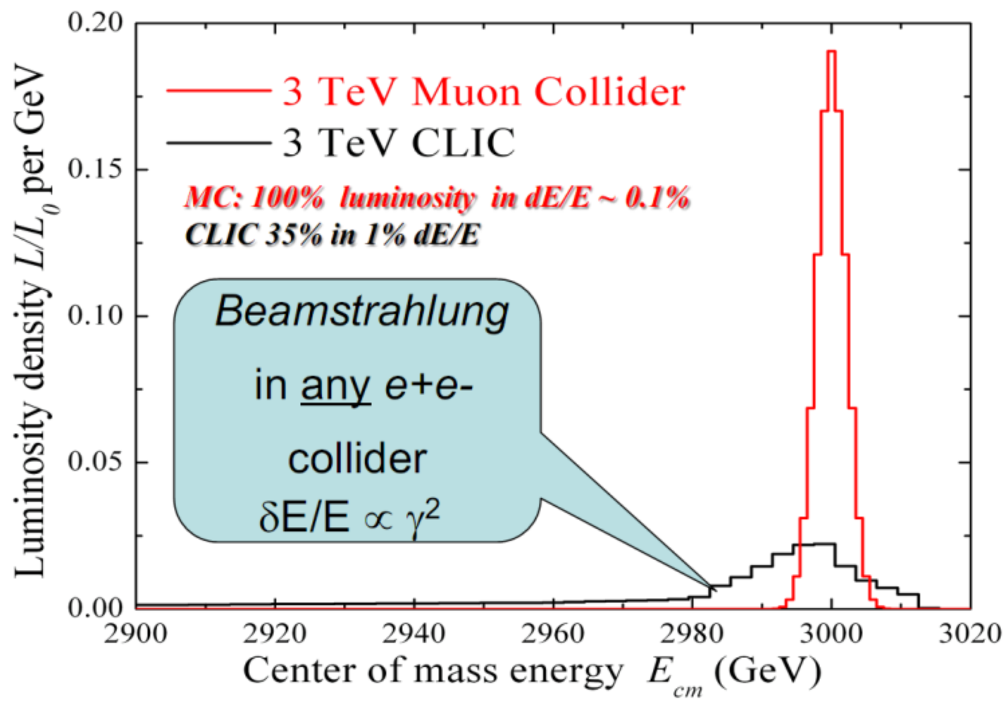
Sizes of various proposed colliders versus FNAL site

Only Muon Collider would fit into existing lab boundaries.



Motivations for using muon beams (2)

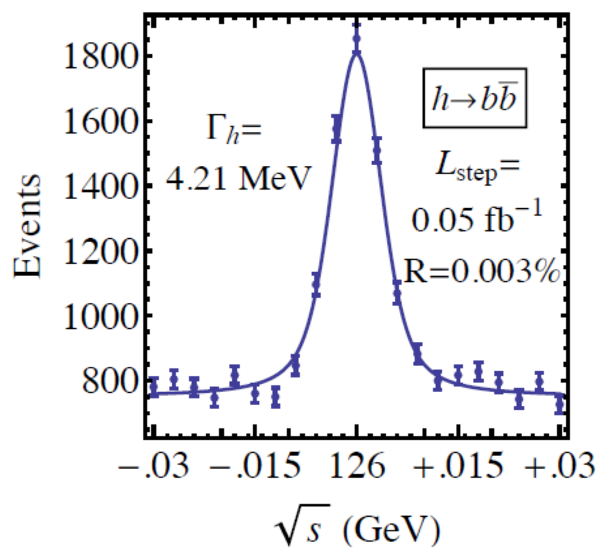
- This also suppresses beamstrahlung -> allows to preserve the high quality beam at collision energy with very small momentum spread

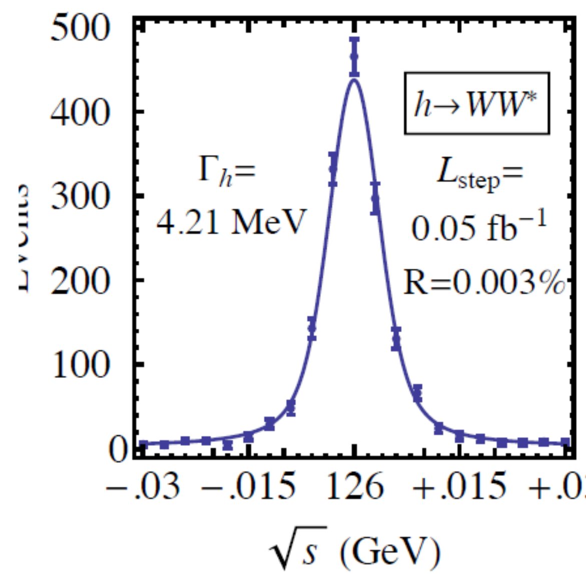


Motivations for using muon beams (3)

- 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
  - Anomaluos 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)
  - All beam manipulations (capture, cooling, acceleration, collisions) have to be made very fast
- Muons are produced as tertiary beam (p$\longrightarrow\pi\longrightarrow\mu$)
  - Initial intensity and beam quality is rather weak

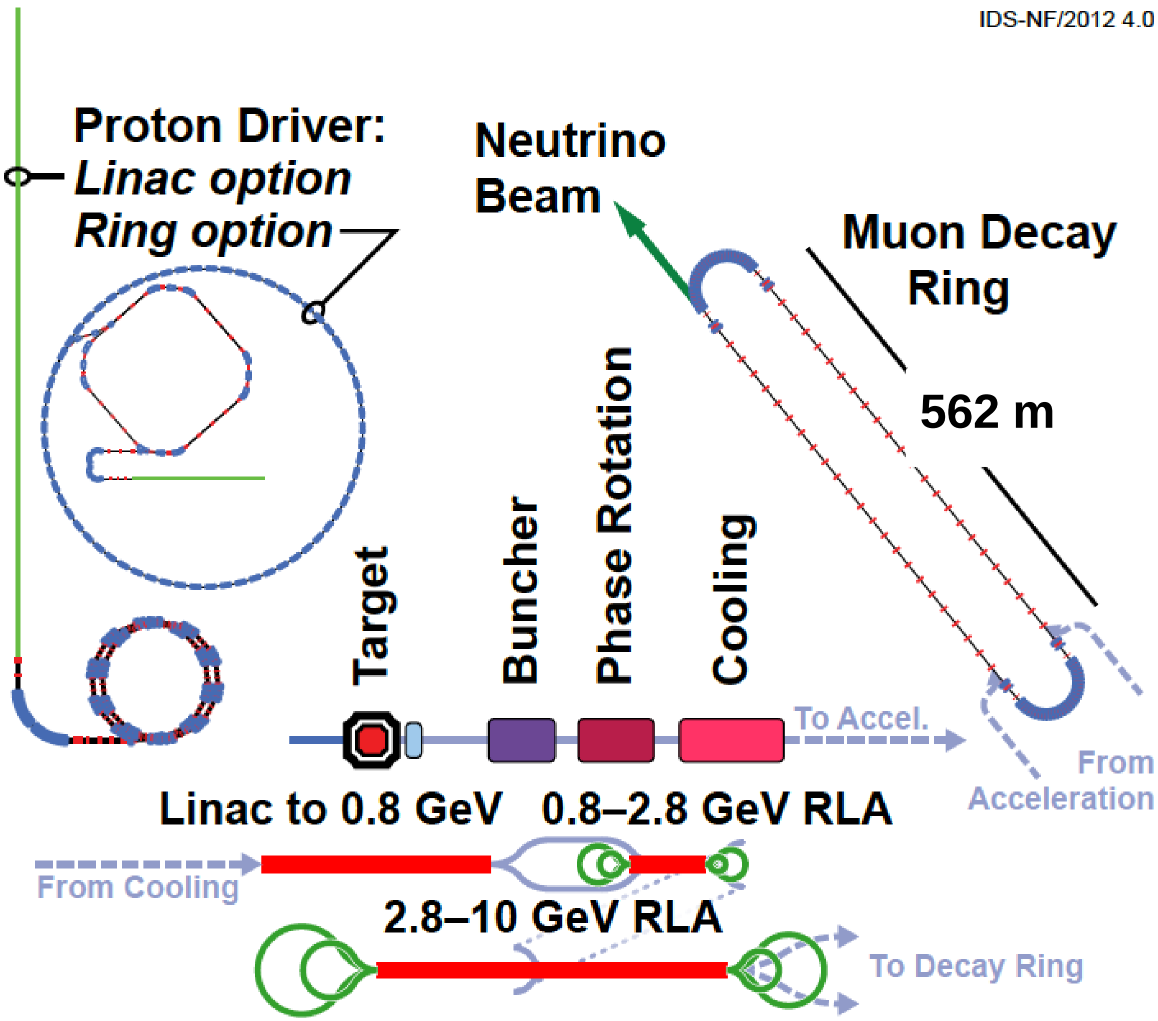
Challenges for using muon beams (solution)

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

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

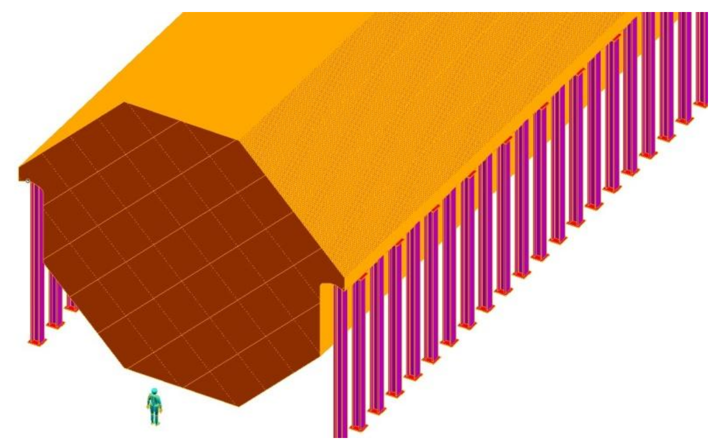
IDS-NF Neutrino Factory Baseline

Work was also supported by EUROnu project



Baseline reviewed 2012: from 25 GeV to 10 GeV muons (v4.0), one storage ring with detector at 2000 km, due to large θ_{13} results

- Magnetised Iron Neutrino Detector (MIND):
  - 100 kton at ~2000 km

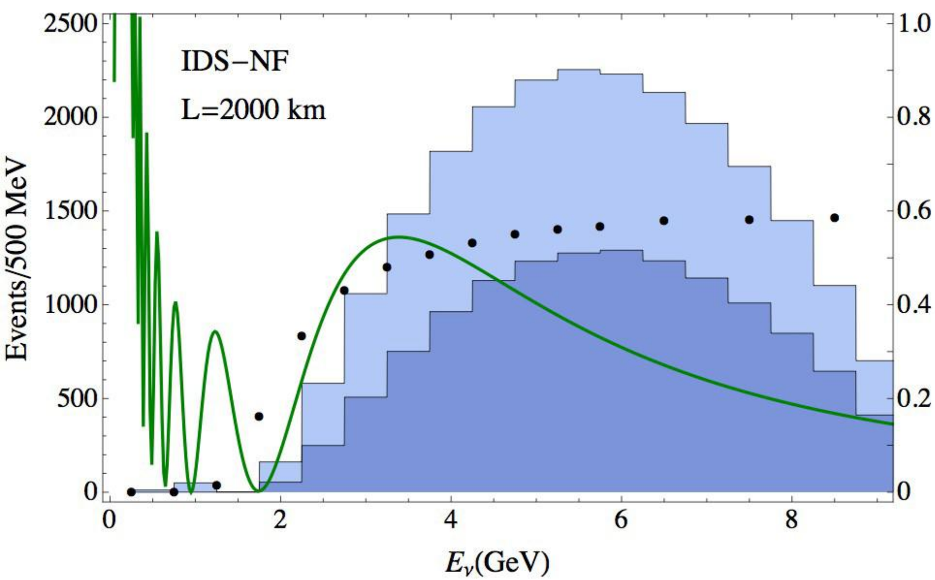


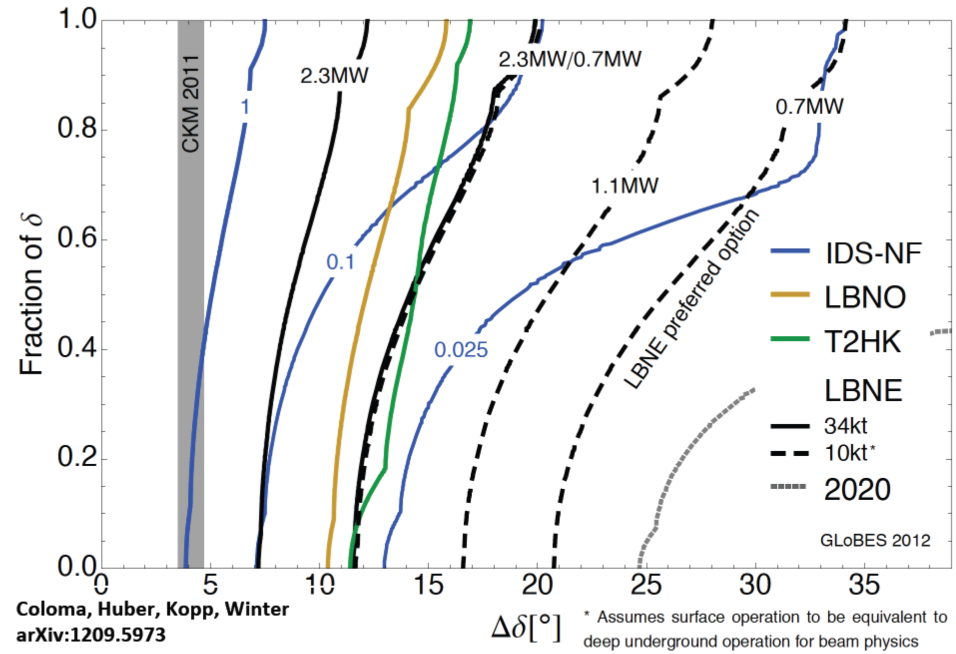
The NF can be used as the front end for a Muon Collider!

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





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

High Power Proton Driver

- Requirements:

  arXiv:1112.2853

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

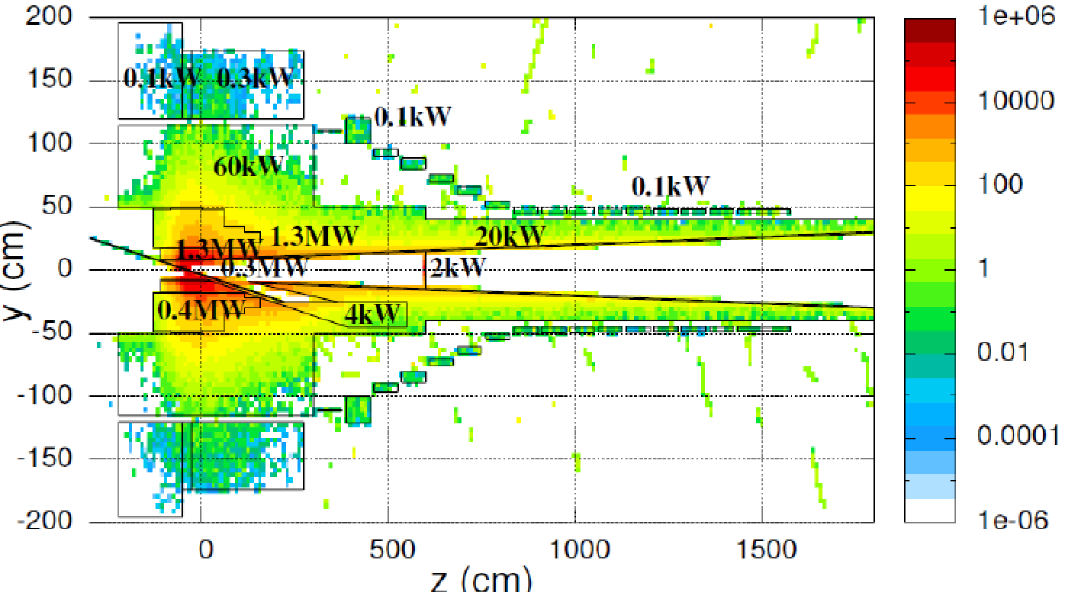
- Site specific solutions

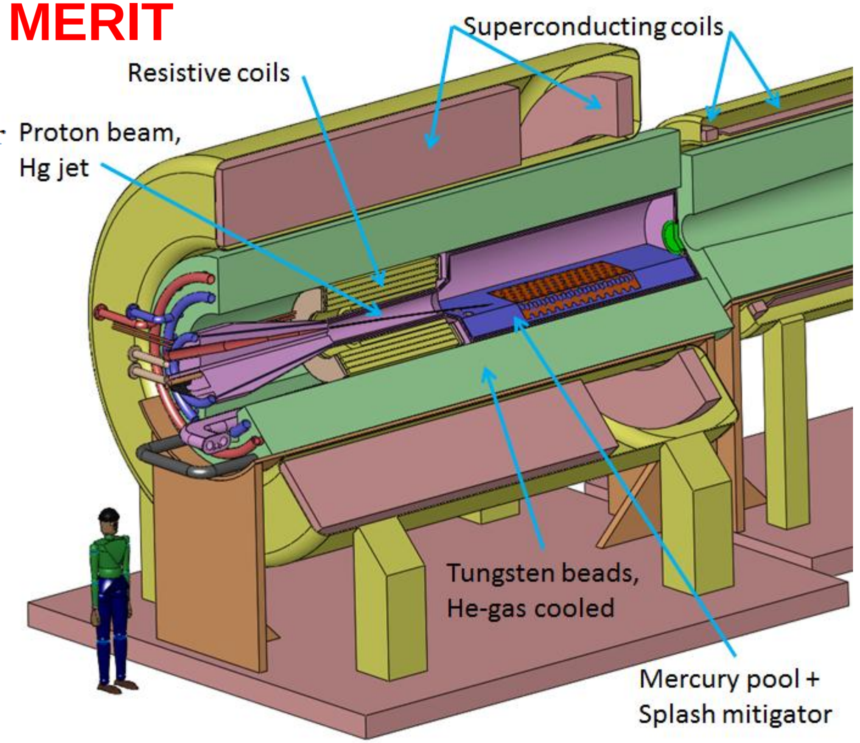
  - LINAC based (SPL) proton driver at CERN
  - Synchrotron(s)/FFAG based proton driver (green field solution) – studied at RAL.
  - PIP based solution at Fermilab.

High power target

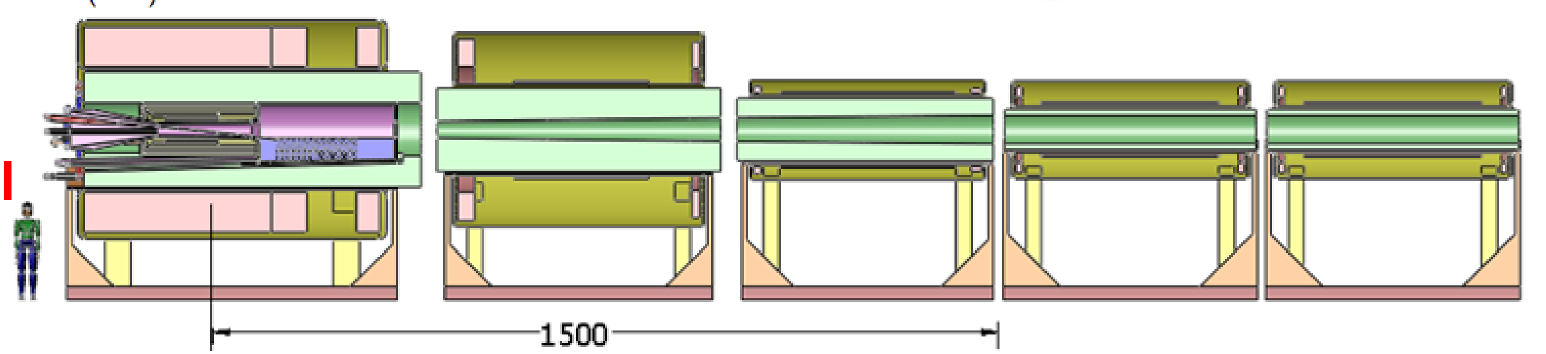
- Radiation shielding in solenoid surrounding the target station is essential

Proof-of-principle: MERIT





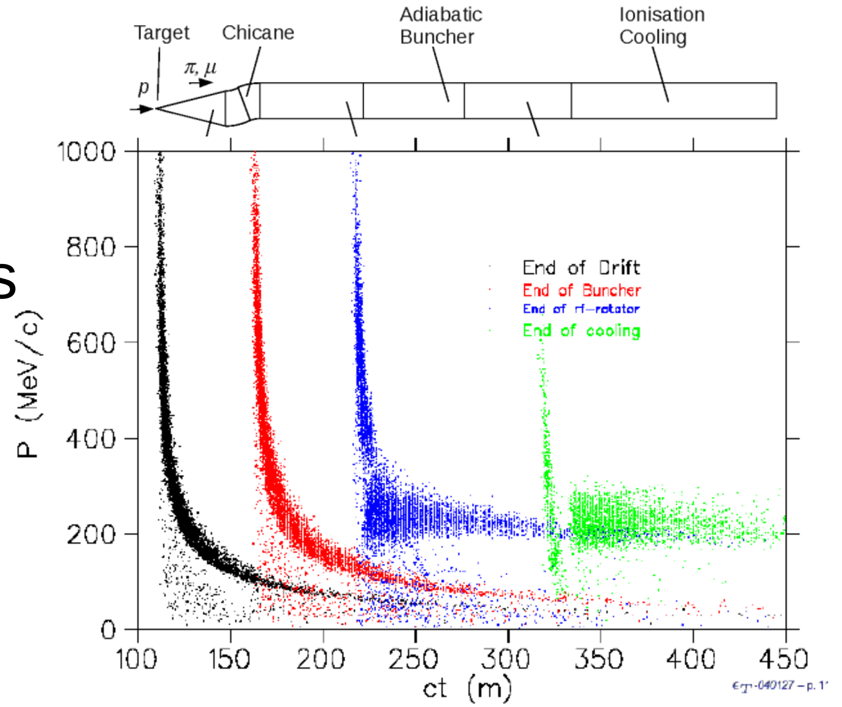
Target station and start of decay channel

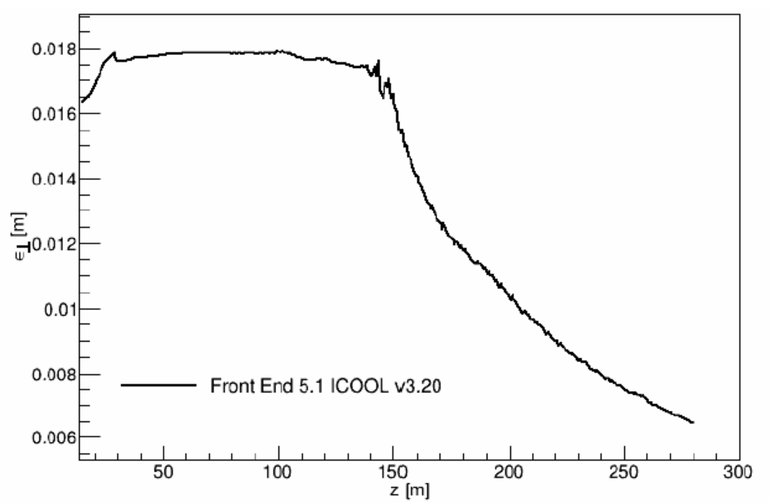


Project could start with Graphite target at reduced power.

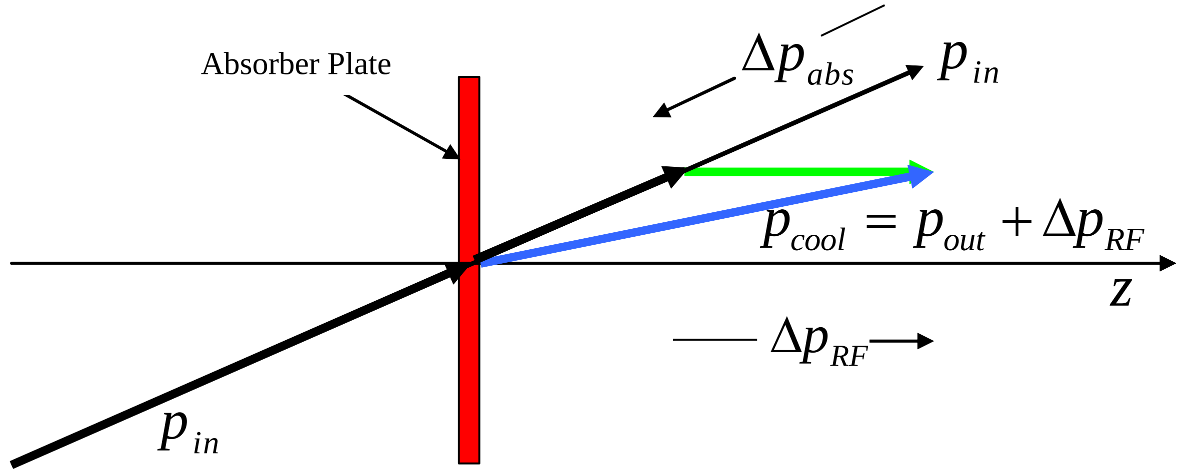
Muon Front End

- Adiabatic B-field taper from Hg target to longitudinal drift
- Added chicane to remove protons
- Drift in ~1.5 T, ~60 m solenoid
- Adiabatically bring on RF voltage to bunch beam
- Phase rotation using variable frequencies
  - High energy front sees -ve E-field
  - Low energy tail sees +ve E-field
  - End up with smaller energy spread
- Ionisation Cooling
  - Try to reduce transverse beam size





Basics of ionization cooling

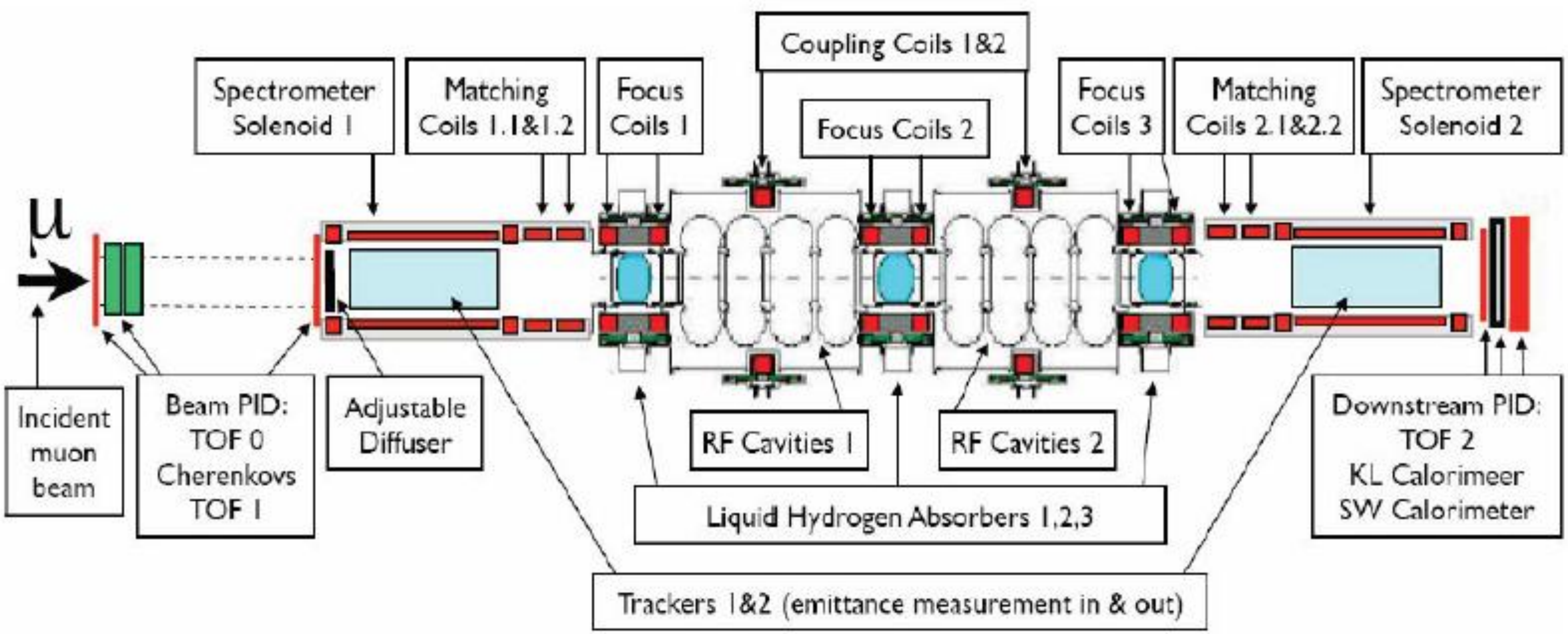


- Muons pass trough absorber (liquid hydrogen) and acelerating cavity (RF).
- As a net effect transverse momentum id reduced.
- Strong focusing (using solenoids), low Z material as absorber and high RF gradient are necessary.
- ...However is still needs to be demonstrated experimentally

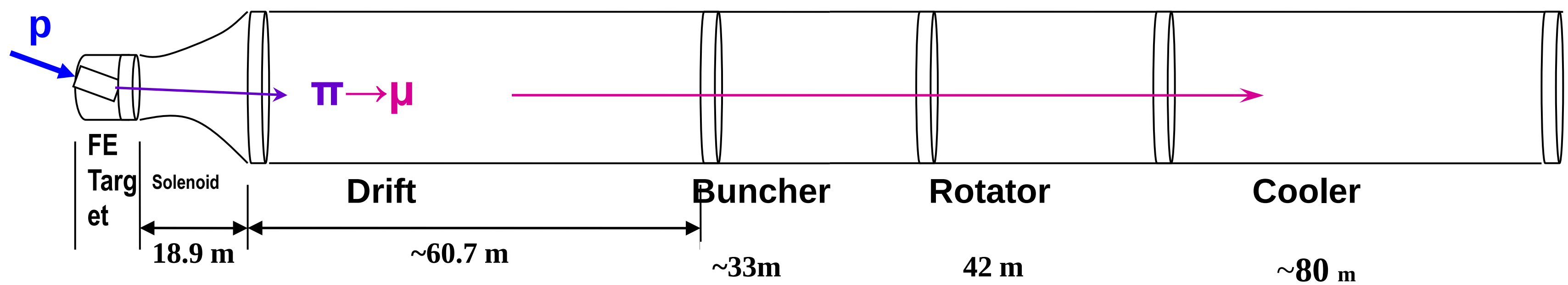
MICE

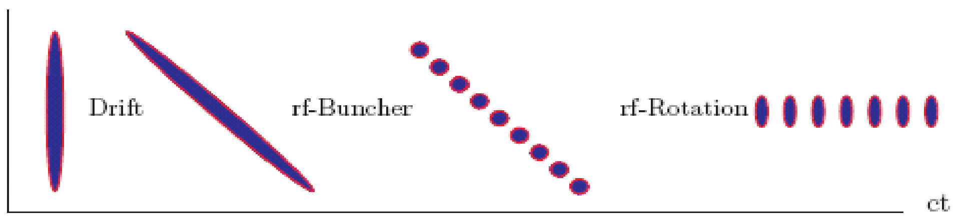
Muon Ionization Cooling Experiment

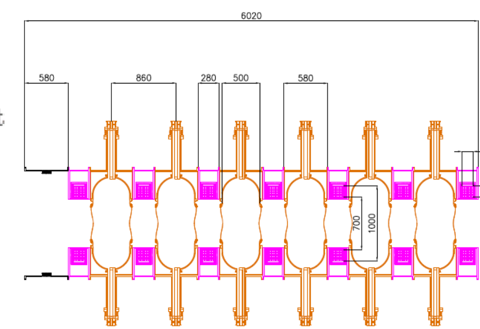
- World first ionisation cooling device
  - Unique high acceptance solenoidal focussing lattice
  - Choice of Lithium Hydride or liquid Hydrogen emittance absorbers
  - High gradient 201 MHz RF system
  - Advanced diagnostic system to measure full 6D phase space of beam
  - Under construction at Rutherford Appleton Laboratory
  - Essential for the Neutrino Factory and Muon Collider.



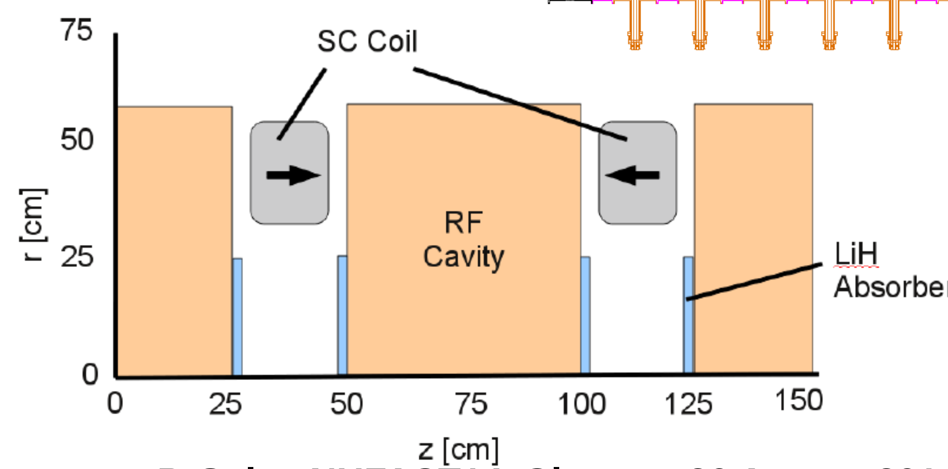
Muon Front End





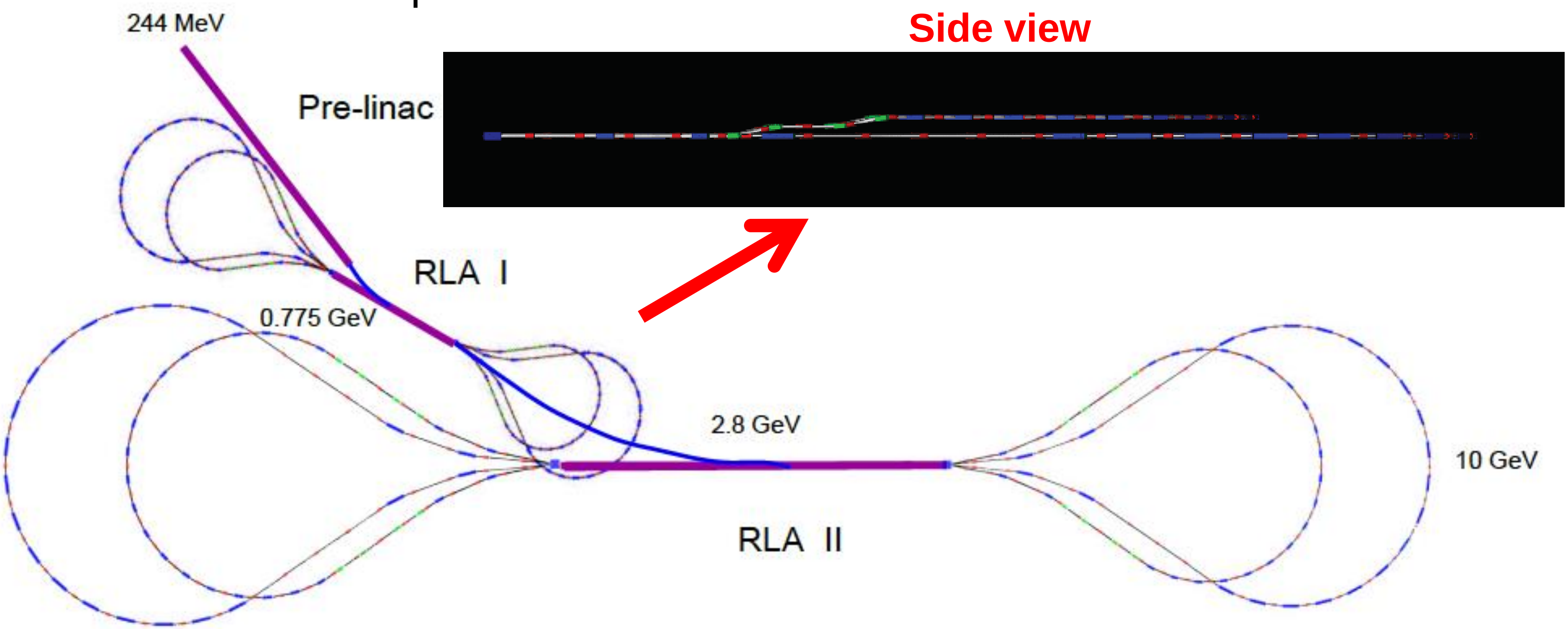


- Cooling channel:
  - 100 cells of 0.75 m length ➔0.86 m
  - Total length: ~80 m
  - 100 normal conducting RF cavities with SC coils
  - RF frequency 201.25 MHz
  - Gradient 15 MV/m
  - LiH absorbers (1.1 cm)



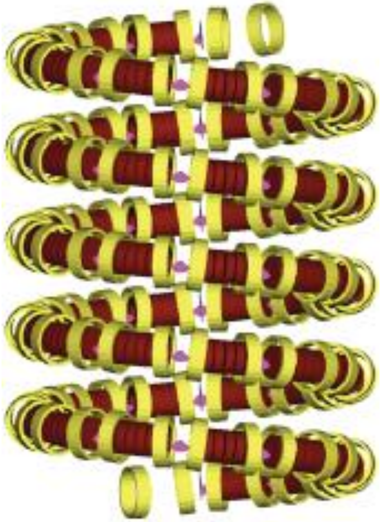
Rapid Acceleration

- IDS-NF baseline of 10 GeV consists of:
  - Pre-linac with solenoidal focusing (up to 0.8 GeV)
  - Baseline: two “dog-bone” Recirculating Linear Accelerators (RLA)
  - First RLA up to 2.8 GeV
  - Second RLA up to 10 GeV



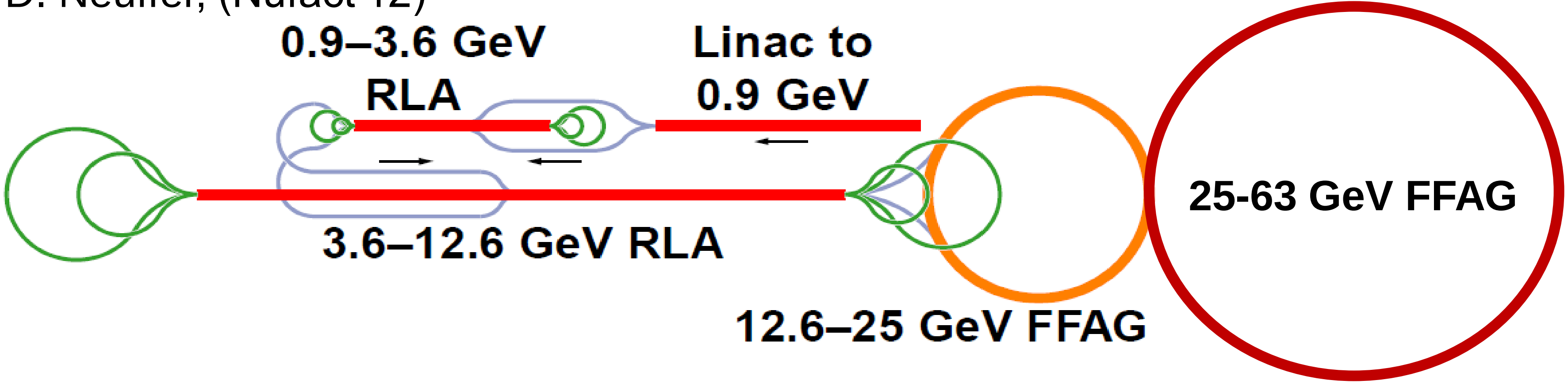
Higgs Factory at 125 GeV COM

•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).

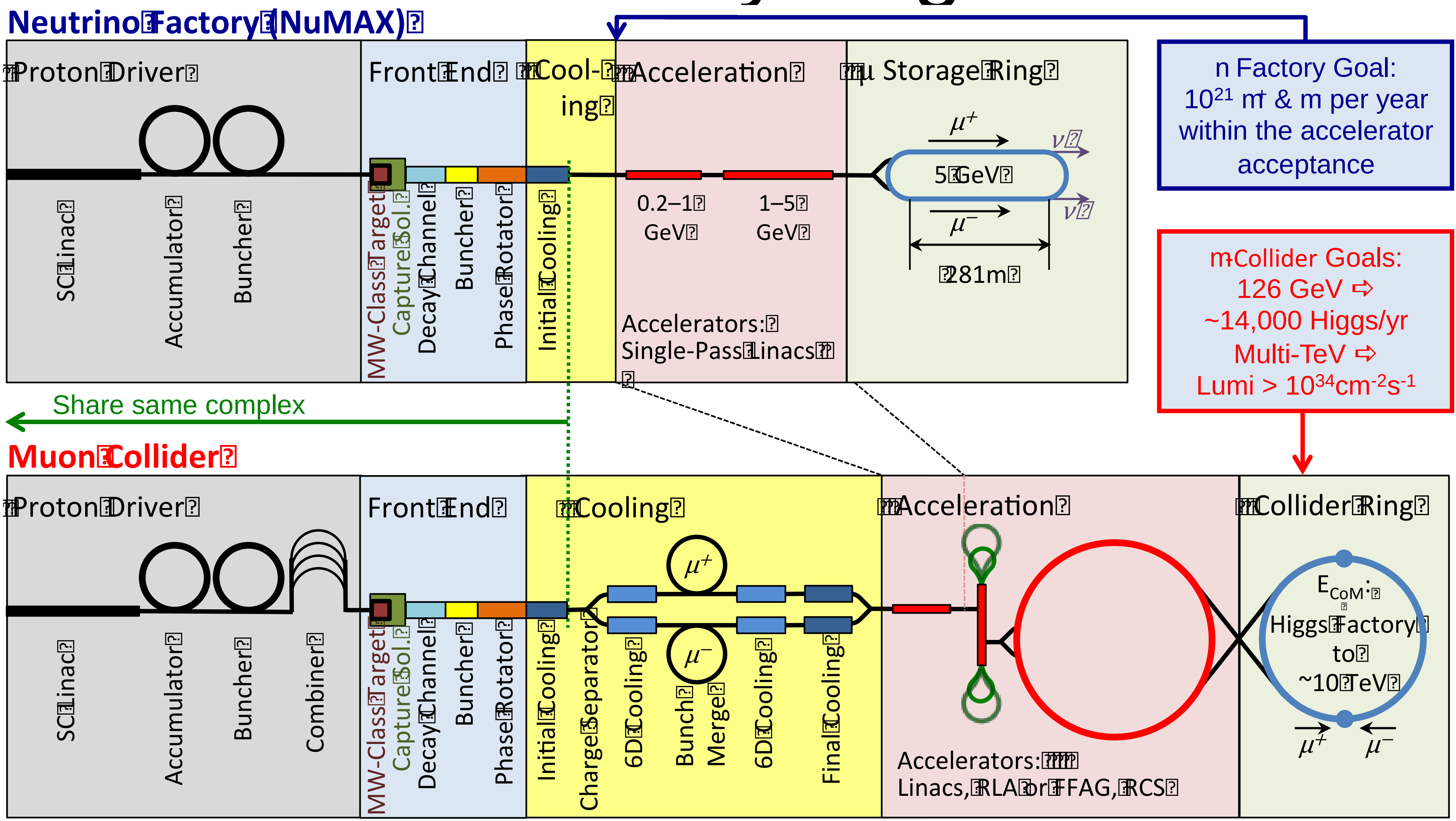


One of the proposed 6D cooling channels

Acceleration scenario for Higgs Factory,
D. Neuffer, (Nufact'12)



NF/MC Synergies



14.11.2014, UK HEP Forum,
Abingdon, Cosener's House

Muon Accelerator Program (MAP)

- Mission Statement:
  - "The mission of the Muon Accelerator Program (MAP) is to develop and demonstrate the concepts and critical technologies required to produce, capture, transport, accelerate, and store intense beams of muons for Muon Colliders and Neutrino Factories"
  - "The goal of MAP is to deliver results that will permit the high-energy physics community to make an informed choice of the optimal path to a high-energy lepton collider and/or a next-generation neutrino beam facility"

The Staging Study (MASS)

Enabling Intensity and Energy Frontier Science with a Muon Accelerator Facility in the US - http://arxiv.org/pdf/1308.0494

The plan consists of a series of facilities with increasing complexity, each with performance characteristics providing unique physics reach:

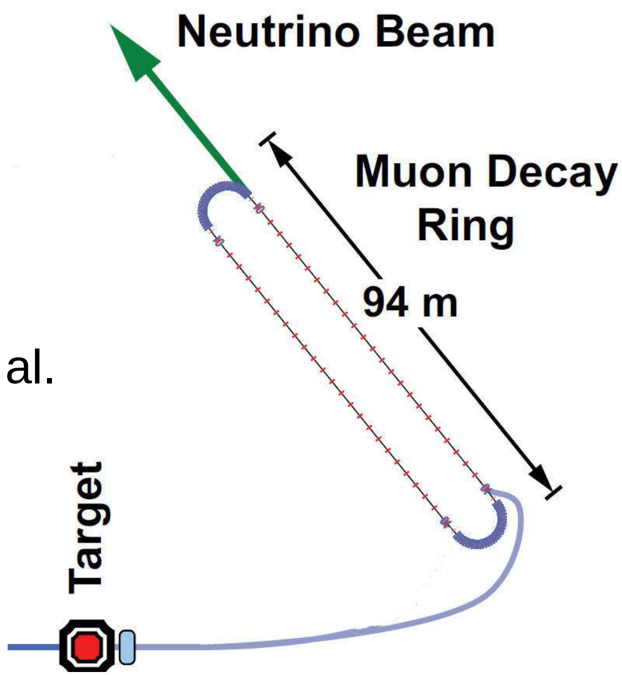
- nuSTORM: a short-baseline Neutrino Factory-like ring enabling a definitive search for sterile neutrinos, as well as neutrino cross-section measurements that will ultimately be required for precision measurements at any long-baseline experiment.
- NuMAX: an initial long-baseline Neutrino Factory, optimized for a detector at SURF, affording a precise and well-characterized neutrino source that exceeds the capabilities of conventional superbeam technology.
- NuMAX+: a full-intensity Neutrino Factory, upgraded from NuMAX, as the ultimate source to enable precision CP-violation measurements in the neutrino sector.
- Higgs Factory: a collider whose baseline configurations are capable of providing between 3500 (during startup operations) and 13,500 Higgs events per year (10^7 sec) with exquisite energy resolution.
- Multi-TeV Collider: if warranted by LHC results, a multi-TeV Muon Collider likely offers the best performance and least cost for any lepton collider operating in the multi-TeV regime.

From M. Palmer, nufact'14

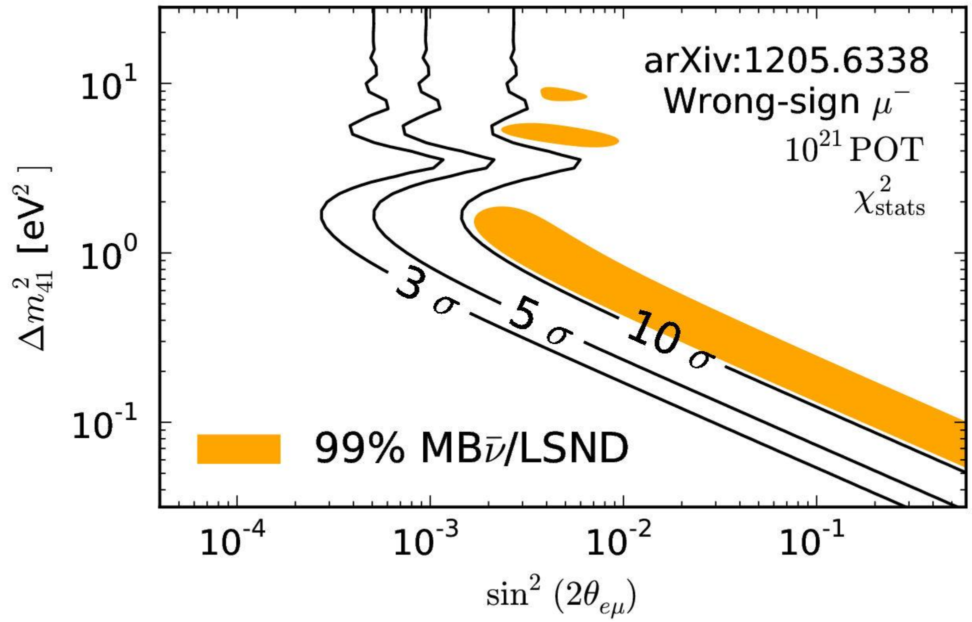
nuSTORM - Mini-neutrino factory

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

nuSTORM Concepts



A. Bross et al.



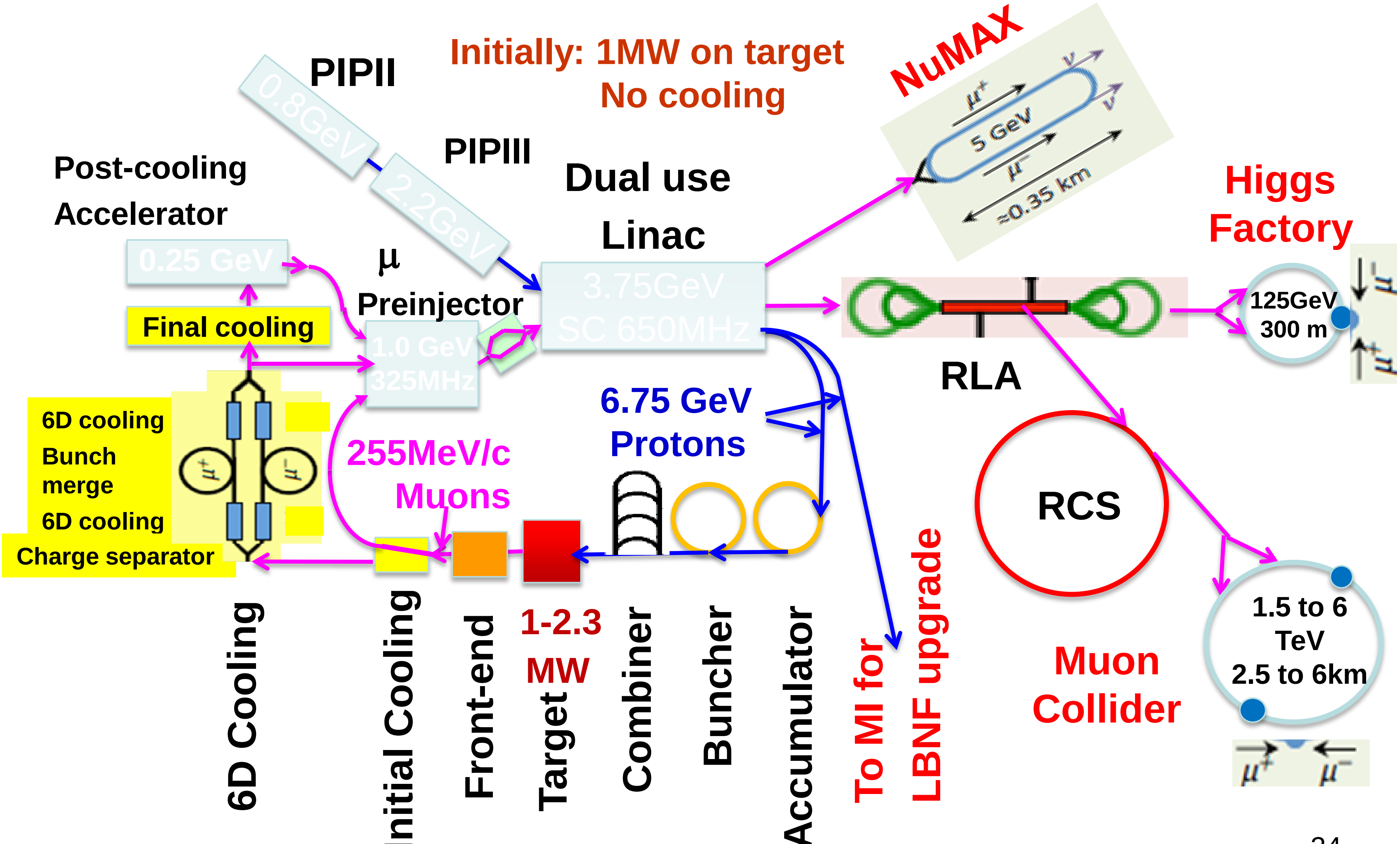
Sensitivity to test the MiniBoone/LSND anomaly

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 – however not supported by P5.

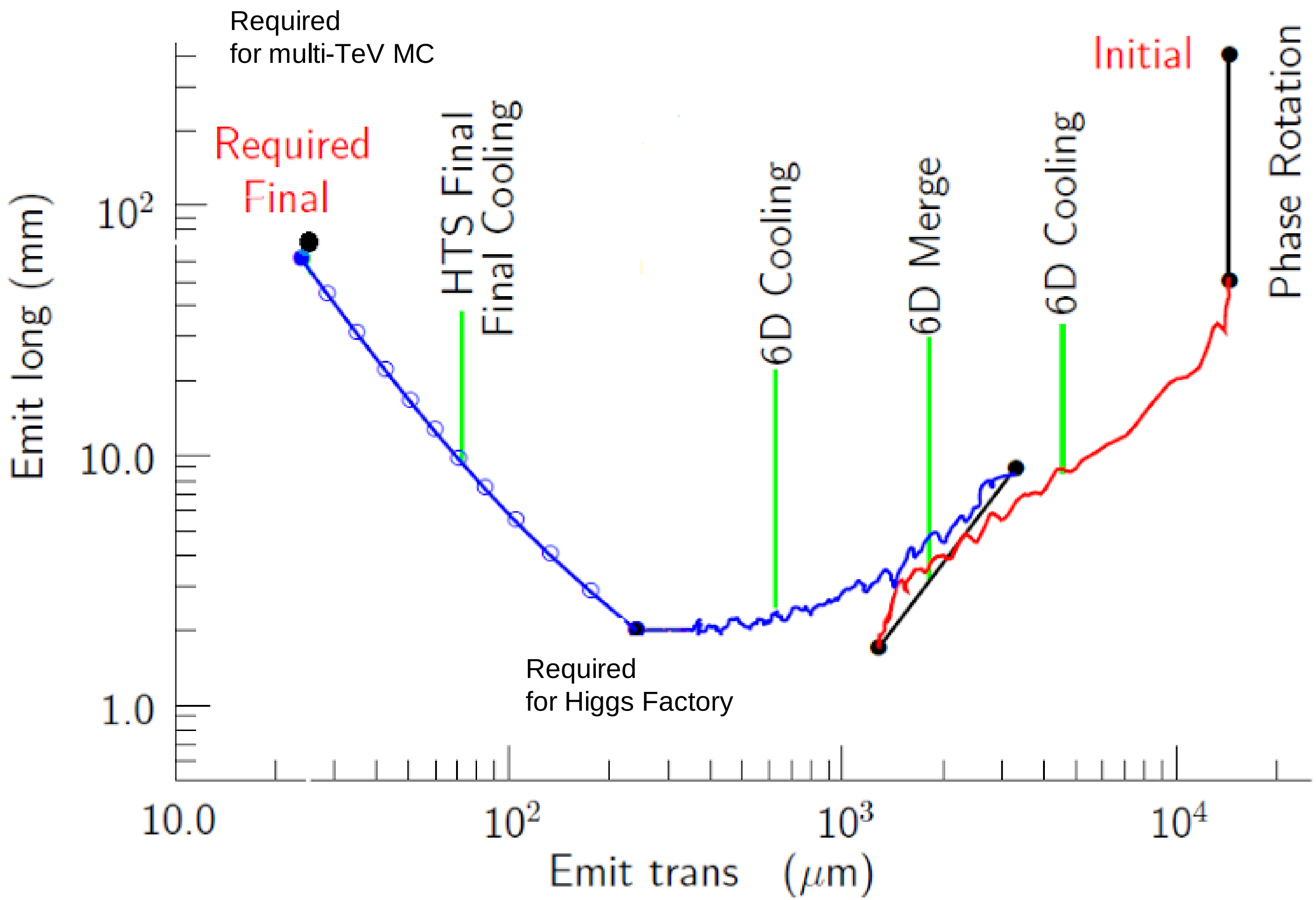
It may serve as a demonstration of the Neutrino Factory Concept.

Staging Scenario at FNAL under MAP



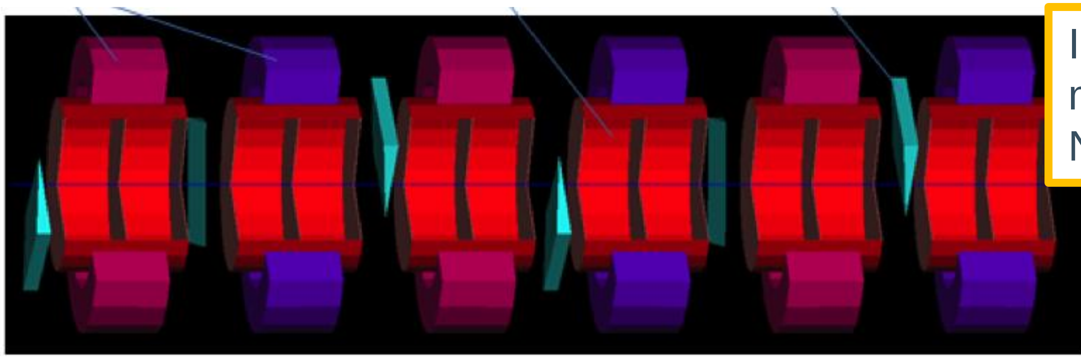
From J.-P. Delahaye | DOE
Review of MAP (BNL, August 12-

6D cooling requirements

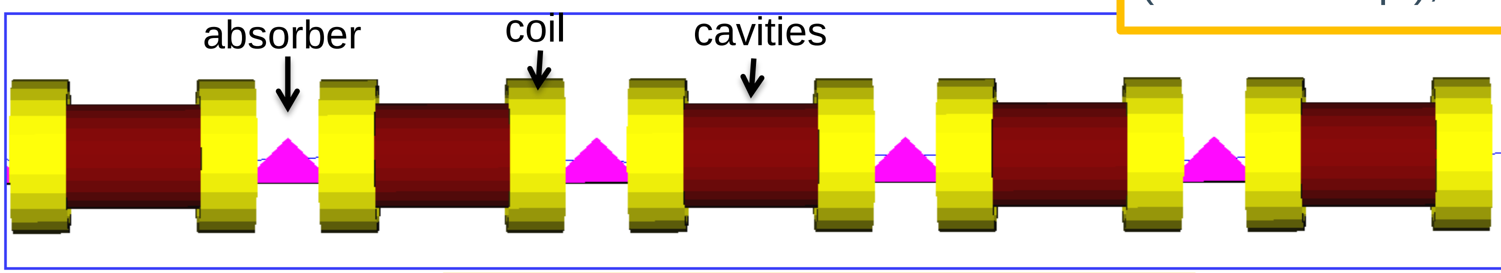


6D Cooling channel concepts

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

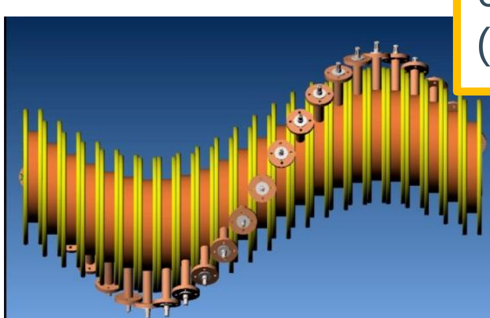


Initial Cooling: Cools both mu signs, suitable for NuMAX (Alexahin)



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

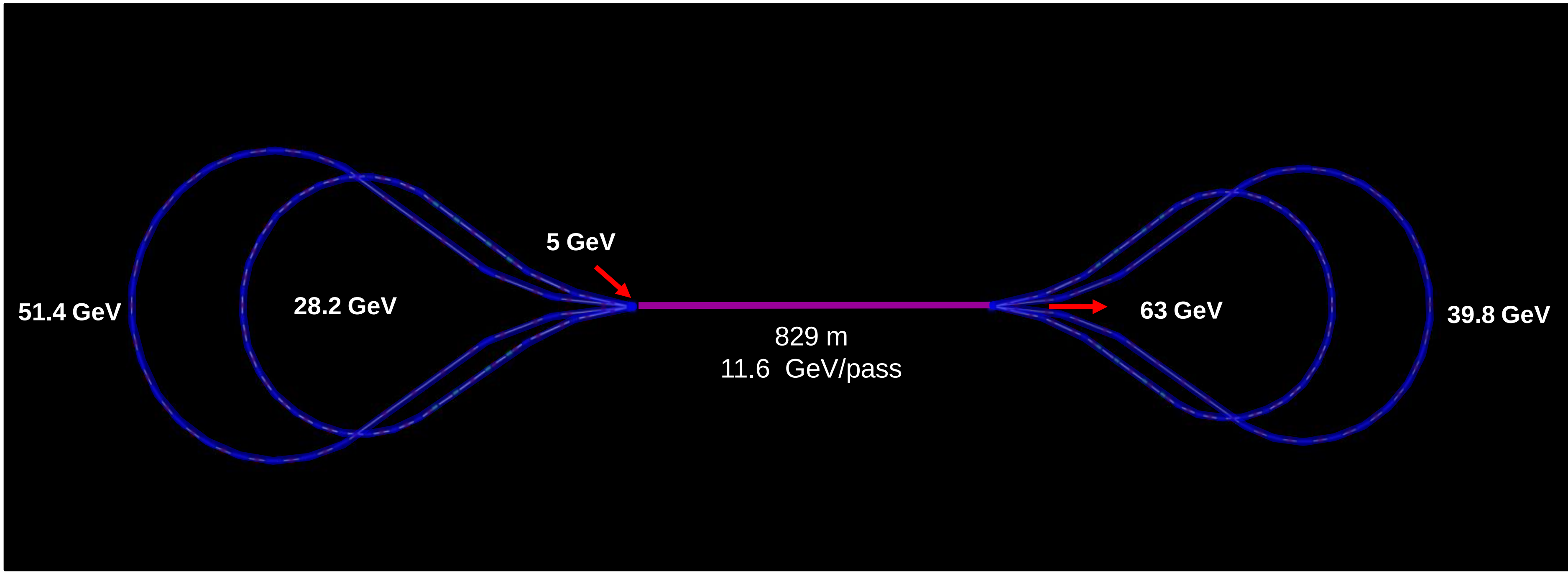
6D Cooling with gas-filled rf cavities (**HCC** Concept), K. Yonehara



- Delivered a complete cooling scheme!

High Energy Acceleration

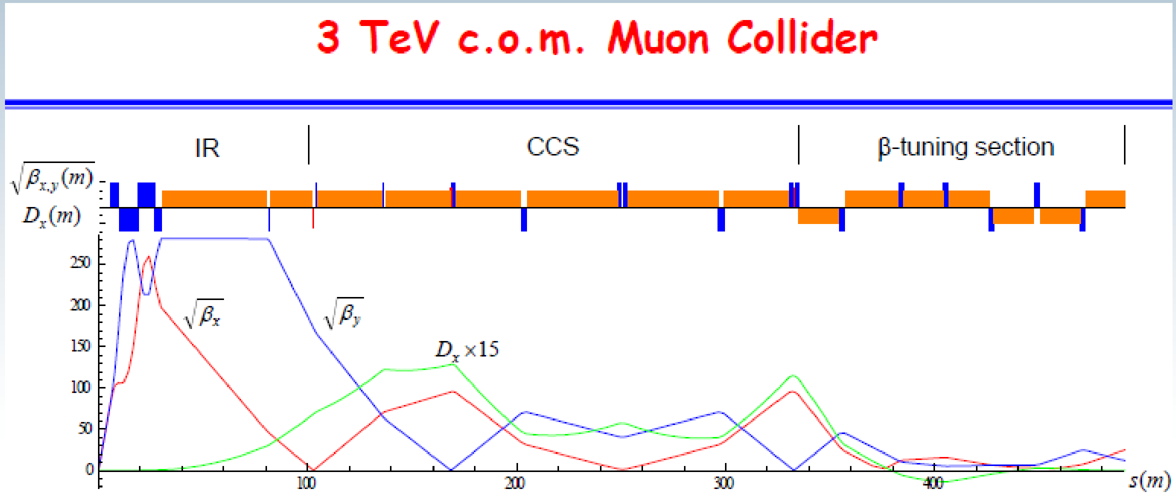
5-pass RLA 5–63 GeV



Higher energy systems may include:

- RLAs
- Fixed Field Alternating Gradient (FFAG) solutions
- Very Rapid Cycling Synchrotrons (VRCSs)

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…

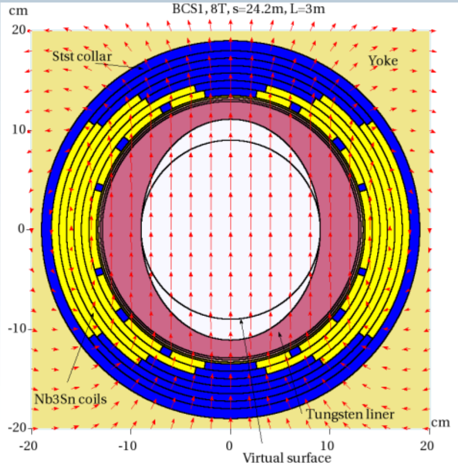
High Energy MC parameters	
Collision energy, TeV	3.0
Repetition rate, Hz	12
Average luminosity / IP, 10^{34}/cm^2/s	4.4
Number of IPs	2
Circumference, km	4.5
β^*, cm	0.5
Momentum compaction factor, 10^{-5}	-1
Normalized emittance, π·mm·mrad	25
Momentum spread, %	0.1
Bunch length, cm	0.5
Number of muons / 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

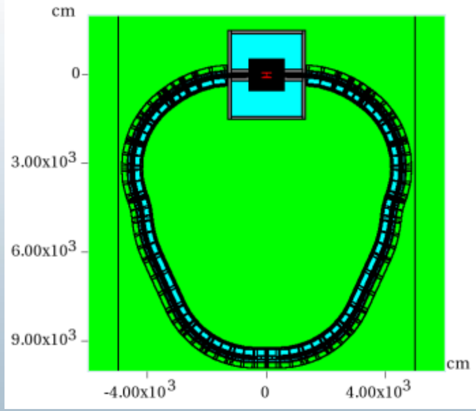
From D. Stratakis, nufact'14

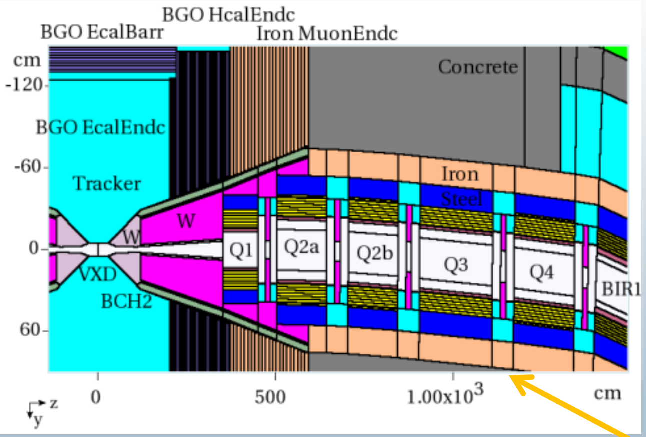
From D. Stratakis, nufact'14

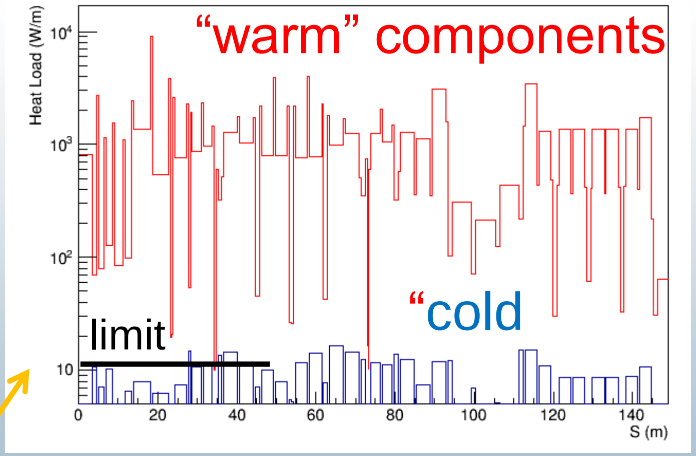
Backgrounds in the collider ring

- High field dipoles and quadrupoles must operate in high-rate muon decay backgrounds
- A sophisticated radiation protection system was designed for the Higgs Factory (HF) collider ring

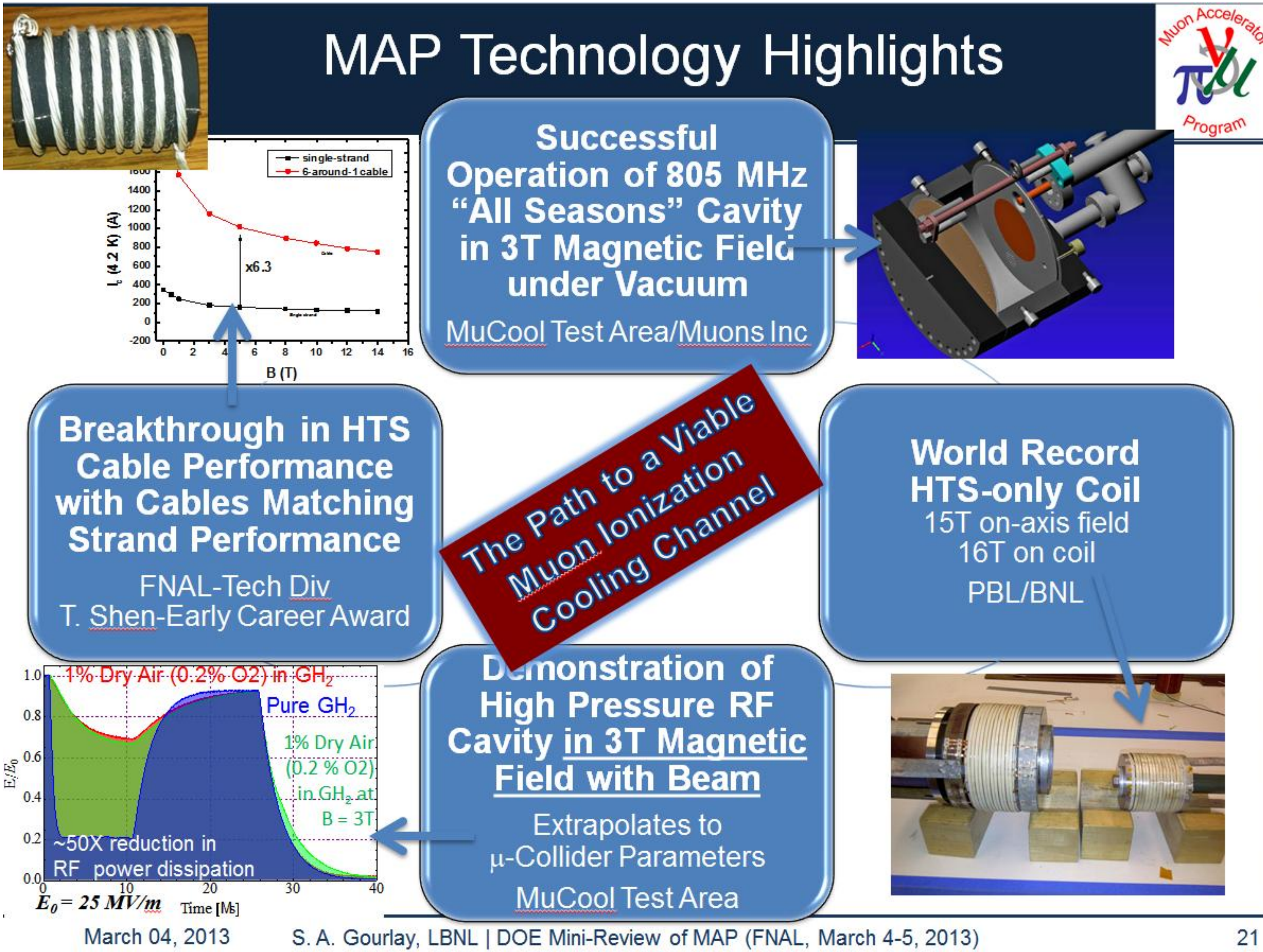






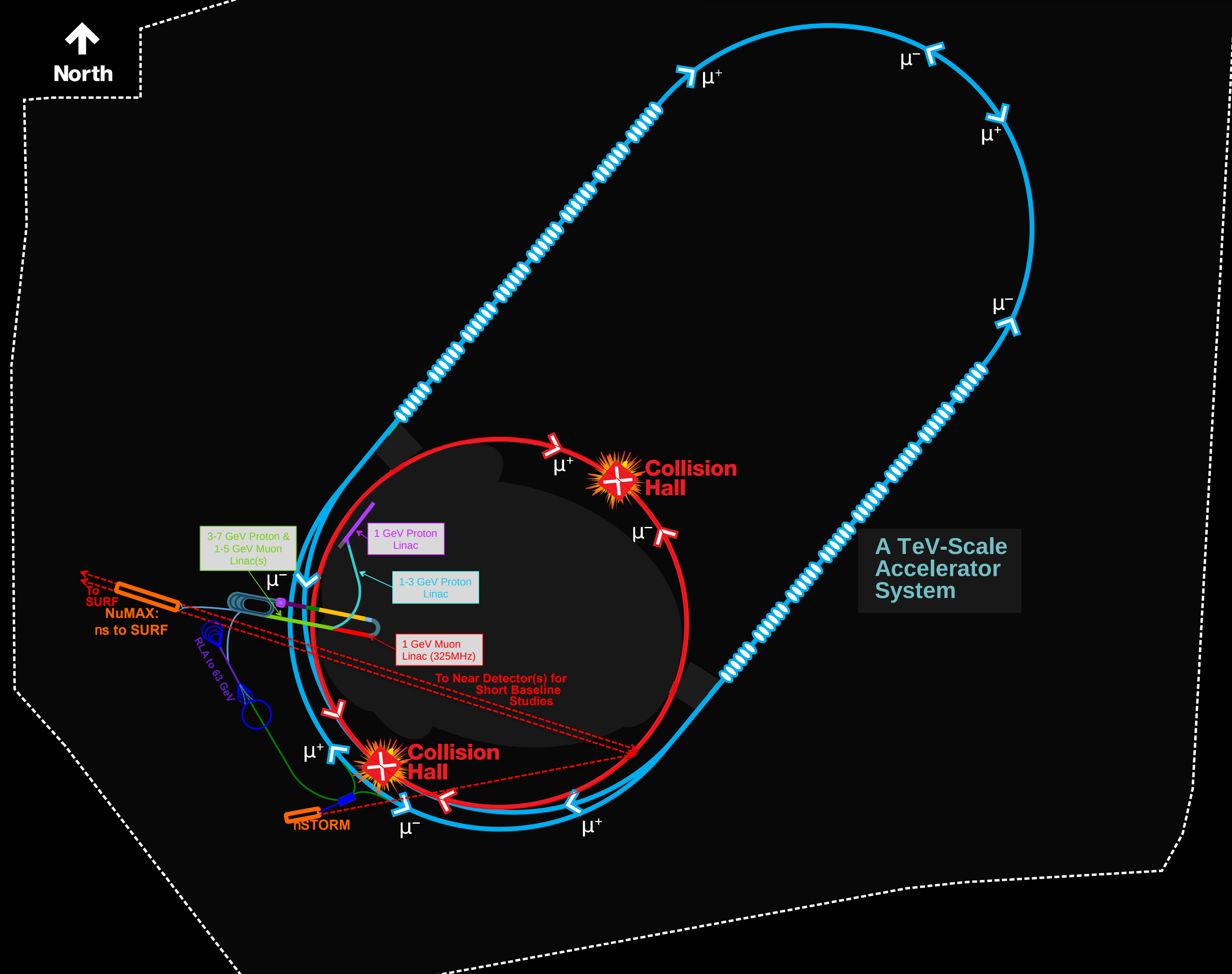


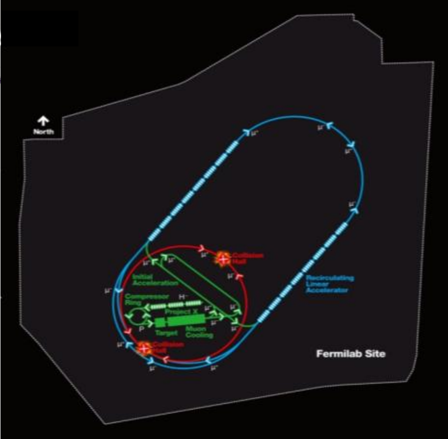
Model of entire HF ring including, magnet, detector, machine-detector interface has been built in MARS15


MAP Technology Highlights
Muon Accelerator Program
single-strand
6-around-1 cable
I_c (4.2 K) (A)
B (T)
x6.3
Successful Operation of 805 MHz "All Seasons" Cavity in 3T Magnetic Field under Vacuum
MuCool Test Area/Muons Inc
Breakthrough in HTS Cable Performance with Cables Matching Strand Performance
FNAL-Tech Div
T. Shen-Early Career Award
The Path to a Viable Muon Ionization Cooling Channel
World Record HTS-only Coil
15T on-axis field
16T on coil
PBL/BNL
1% Dry Air (0.2% O2) in GH_2
Pure GH_2
1% Dry Air (0.2 % O2) in GH_2 at B = 3T
~50X reduction in RF power dissipation
E_t/E_0
E_0 = 25 MV/m
Time [μs]
Demonstration of High Pressure RF Cavity in 3T Magnetic Field with Beam
Extrapolates to μ-Collider Parameters
MuCool Test Area
March 04, 2013
S. A. Gourlay, LBNL | DOE Mini-Review of MAP (FNAL, March 4-5, 2013)
21

A Potential Muon Accelerator Complex at Fermilab:

→ Multi-TeV Collider





Muon Collider Parameters

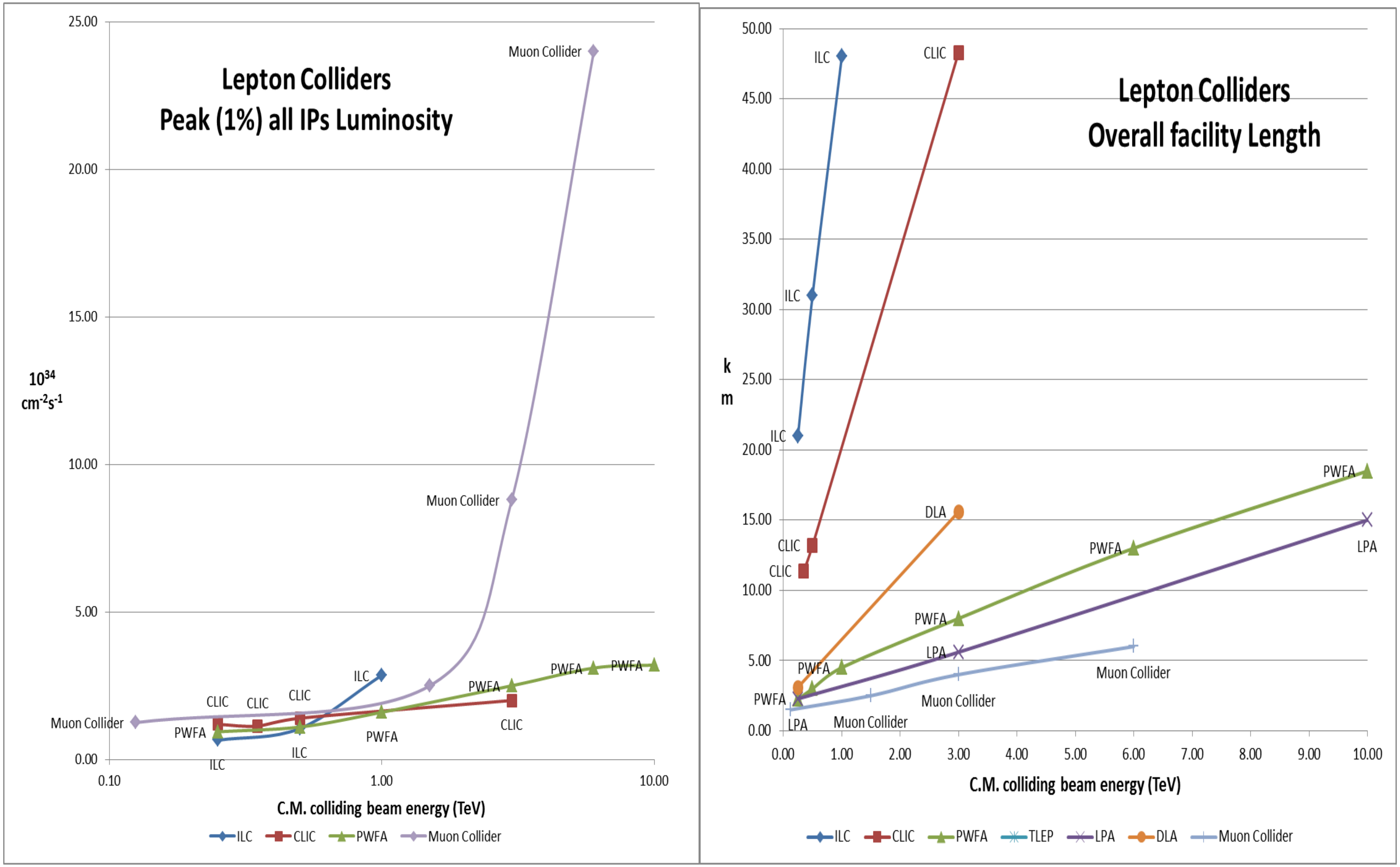
Imperial College London

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
b*	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, e_{TN}	p mm-rad	0.4	0.2	0.2	0.05	0.025	0.025	0.025
Norm. Long. Emittance, e_{LN}	p mm-rad	1	1.5	1.5	10	70	70	70
Bunch Length, s_s	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

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

Imperial College London



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

P5 Effect

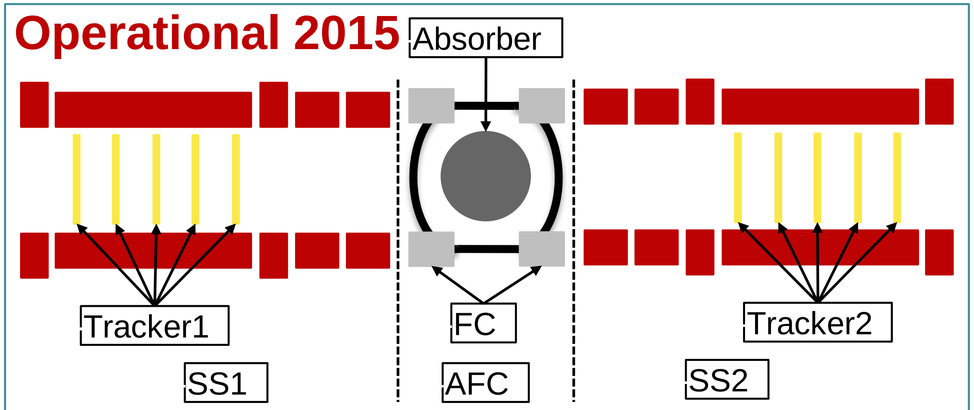
- For the last 3 years US Muon Accelerator Program has pursued options to deploy muon accelerator capabilities
  - Near term (νSTORM)
  - Long term (NuMAX)
  - Along with the possibility of a follow-on muon collider option
- In light of the recent P5 recommendations that this directed facility effort no longer fits within the budget-constrained US research portfolio, the US effort is entering a ramp-down phase

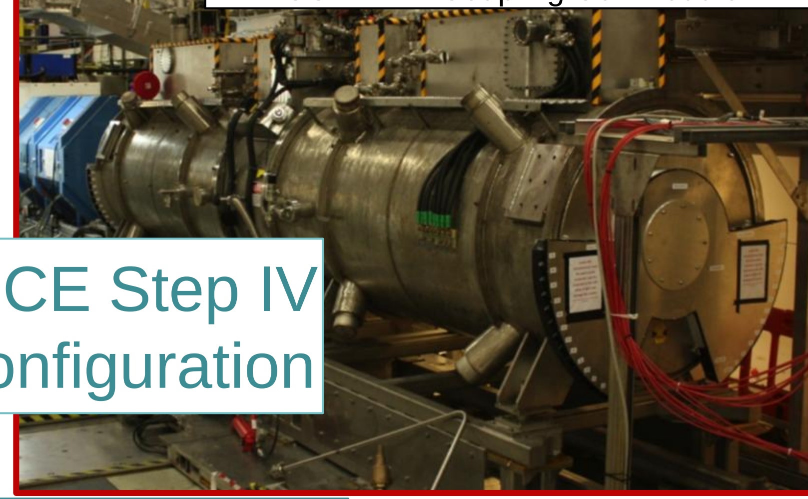
- Budgetary constraints also affect MICE experiment!

MICE Steps IV & V

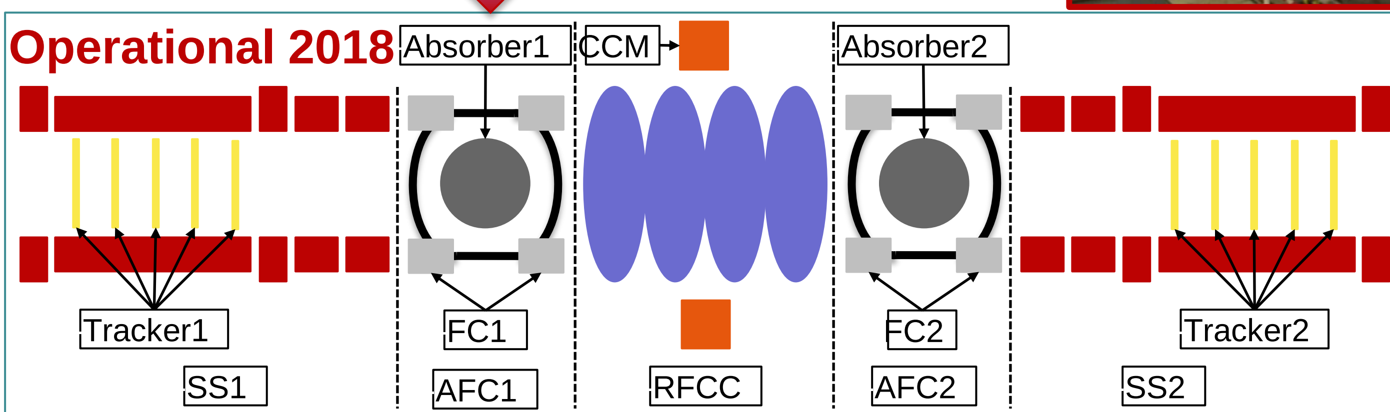
Plan endorsed by MICE Project Board in April 2014

Legend:
SS = Spectrometer Solenoid
FC = Focus Coil
AFC = Absorber-Focus Coil Module
CCM = Coupling Coil Magnet
RFCC = RF-Coupling Coil Module





MICE Step IV Configuration



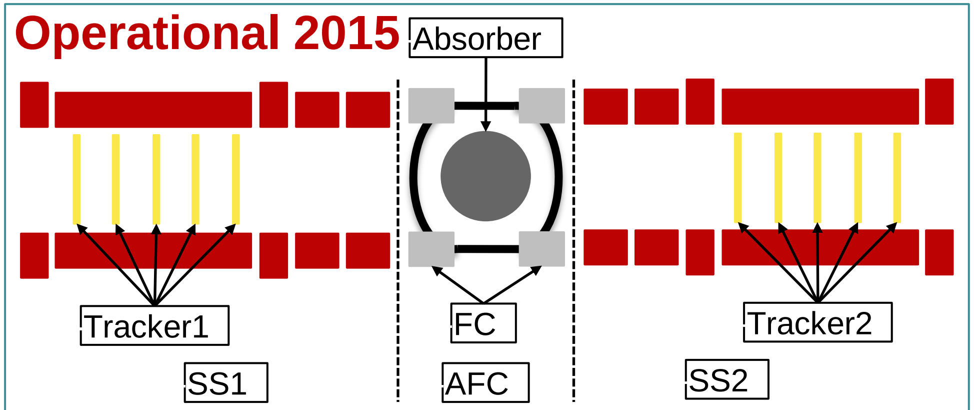
MICE Step V Configuration

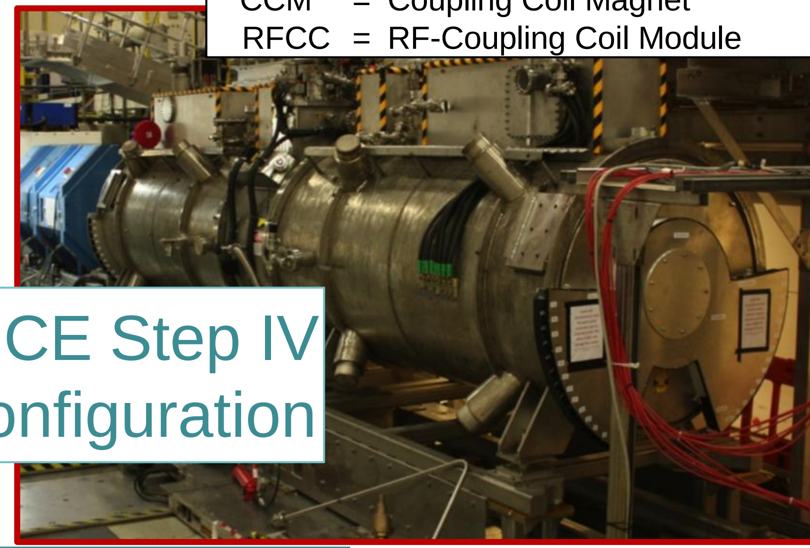
MICE Steps IV & V

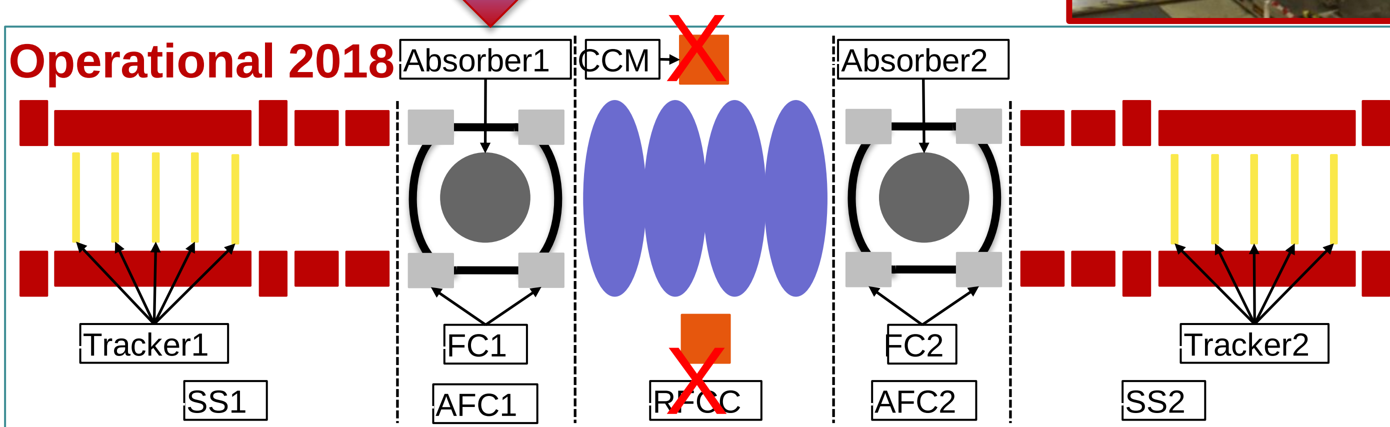
Plan endorsed by MICE Project Board in April 2014

Legend:

SS	=	Spectrometer Solenoid
FC	=	Focus Coil
AFC	=	Absorber-Focus Coil Module
CCM	=	Coupling Coil Magnet
RFCC	=	RF-Coupling Coil Module



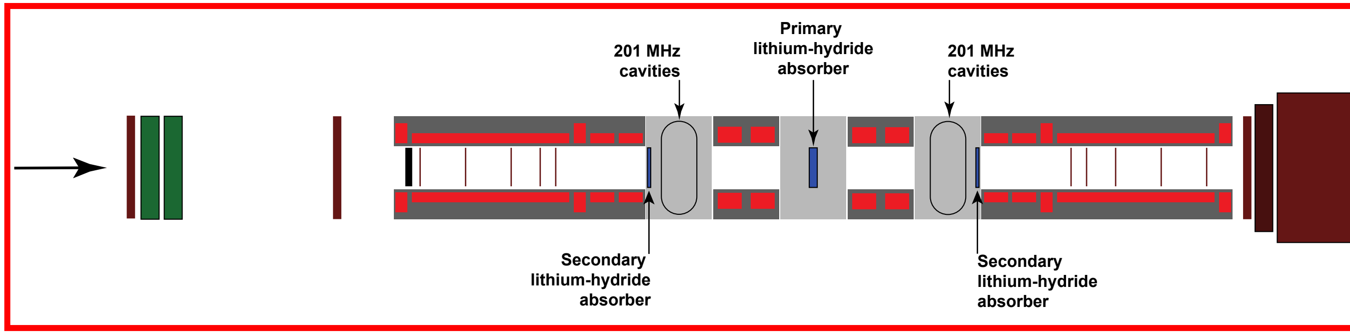




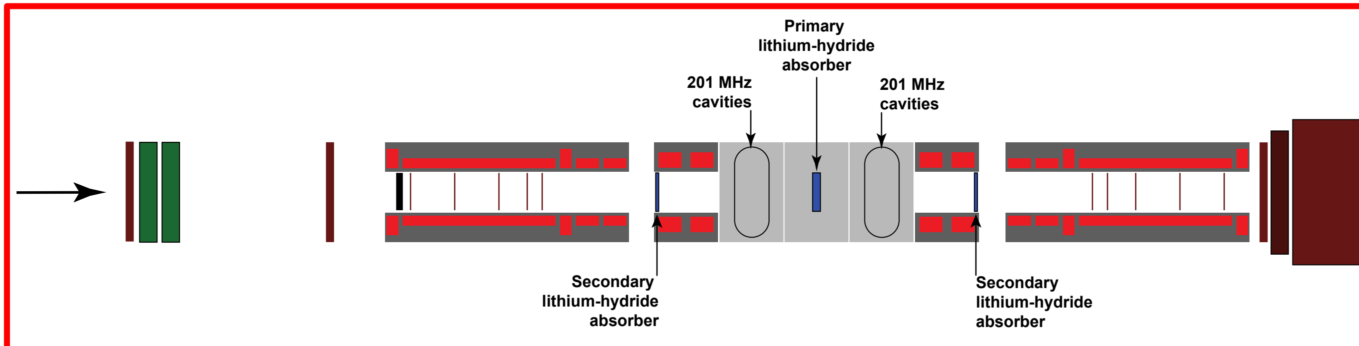
Unfortunately CC and RFCC are no longer on our plan (the DOE decision)

MICE: Demonstration of Ionization Cooling with RF re-acceleration

Reference solution:



Alternative solution:



- Both produce measurable cooling
- Both use existing magnets at RAL and substantially reduce risks.
- Chosen solution will allow to perform the full demonstrate of ionization cooling with RF re-acceleration in 2017!

Summary

- Thanks to the international R&D effort (IDS-NF, EUROnu, MAP) a substantial progress was achieved towards realising the Neutrino Factory and a Muon Collider.
- Muon Collider is capable to extend the energy frontier with compact footprint and considerable cost saving.
- Key technology demonstration of the ionization cooling is essential and MICE aims to deliver it in 2017 (current focus of the UK and the US efforts).
- R&D studies will continue (GARD in the US).
- Let’s hope the key demonstrations and designs will be ready for the decisions, when LHC provides new data and HEP community may need a Muon Collider.