Muon Accelerator Program R&D

Diktys Stratakis
Brookhaven National Laboratory

Nufact Workshop, Glasgow, UK
August 28, 2014

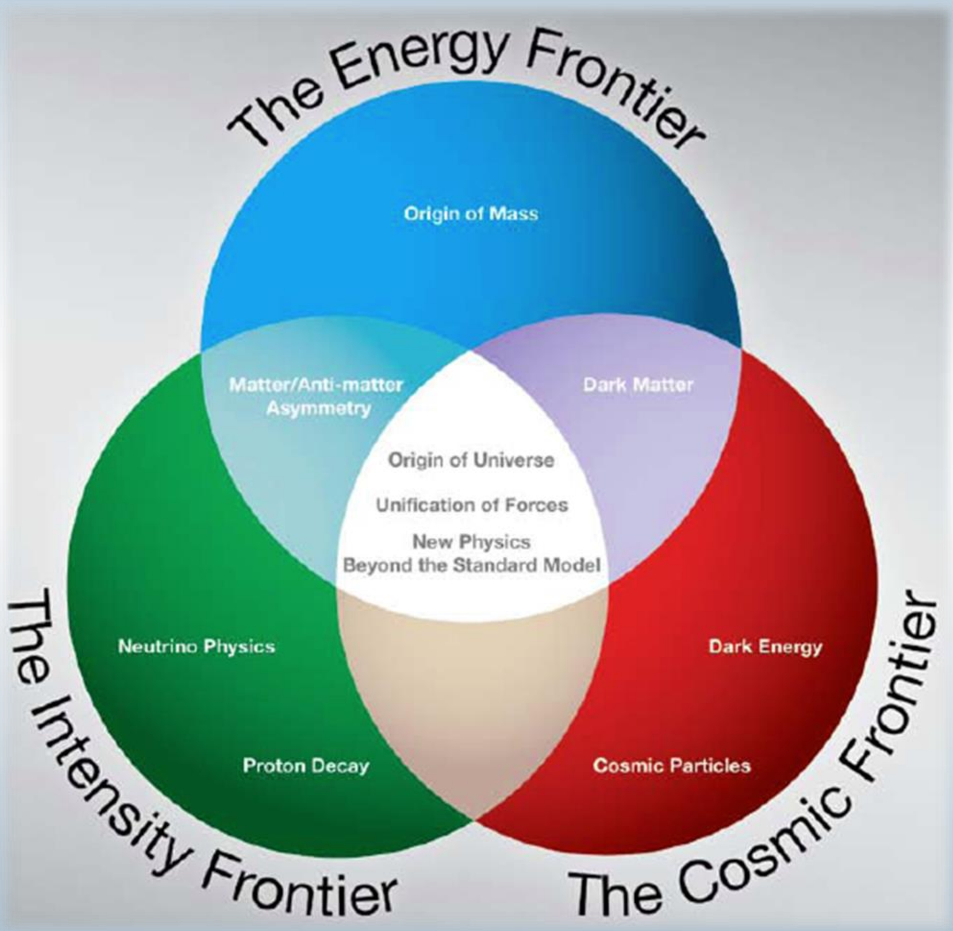
Introduction

- 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"

Source: www.map.fnal.gov

Aim of the MAP effort

- MAP accelerator R&D can address critical questions extending two frontiers:
  - **Intensity frontier**: with a Neutrino Factory producing ν beams for high-sensitivity studies
  - **Energy Frontier:** with a Muon Collider capable of reaching multi-TeV CoM energies



History of MAP

May 2008	P5 Report
August 2010	DOE Review: MAP Proposal
March 2011	Approval of national program: US MAP
January 2012	Director Appointed
August 2012	DOE Review: MAP Project-like reorganization R&D Status and plans
March 2013	DOE Review: MAP Progress on reorganization monitored
February 2014	DOE Review: MAP Program Execution Plan endorsed Plan for Feasibility Assessment endorsed
May 2014	New P5 Report *"Reassess the Muon Accelerator Program…"*
August 2014	DOE Review: US MAP Reassessment

Not discussed in this talk

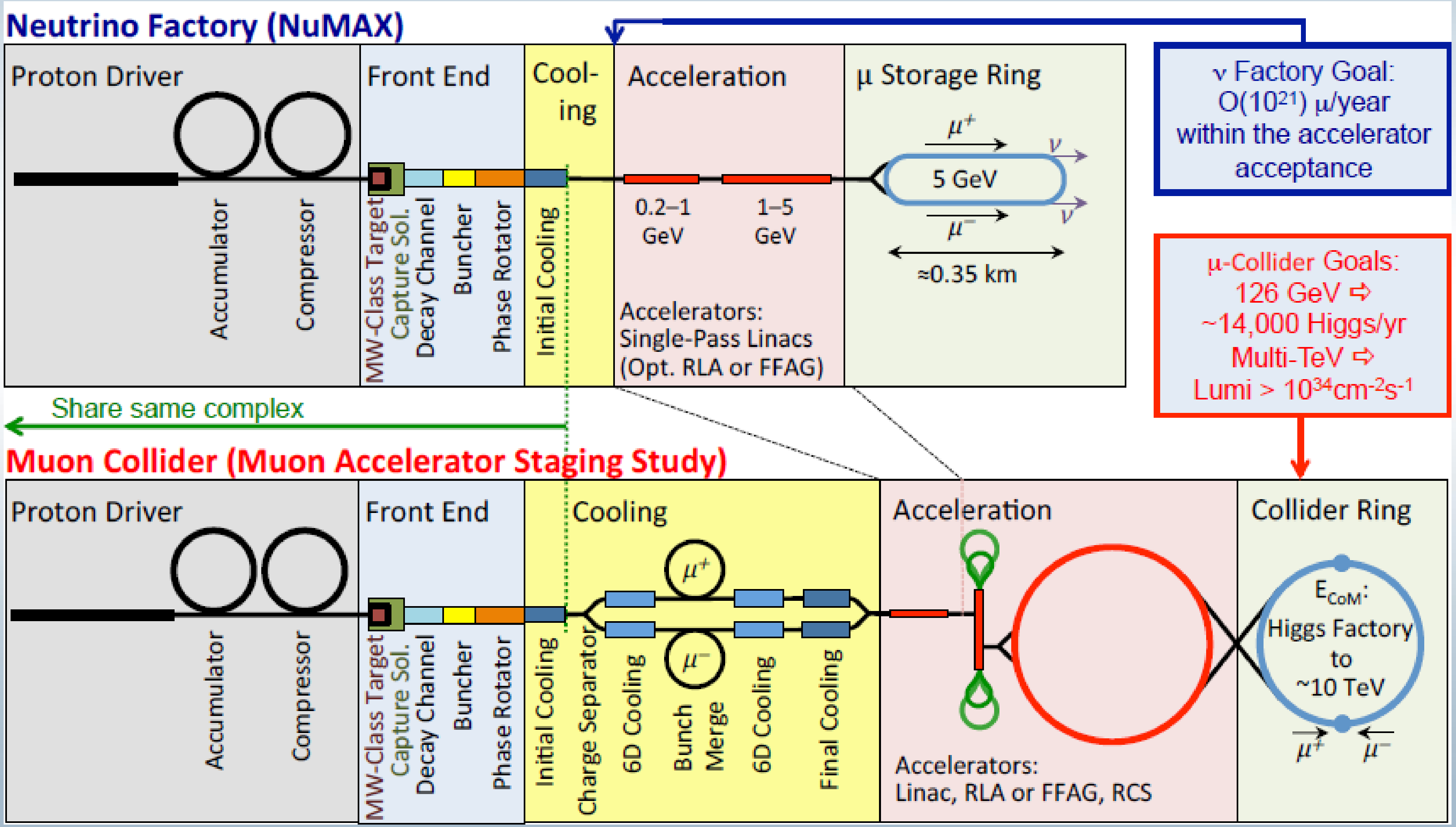
Physics motivations

- Muon – an elementary charged lepton:
  - 200 times heavier than the electron
  - 2.2 μs lifetime at rest
- Large mass strongly suppresses synchrotron radiation
  - Muons can be accelerated and stored using rings at much higher energy than electrons
  - Higher quality colliding beam with reduced beamstrahlung
    - Therefore, a muon collider would offer a precision leptonic probe of fundamental interactions
- Muon beams, can provide equal fractions of muon and electron neutrinos at high intensity for studies of neutrino oscillations → Neutrino Factory concept

Muon challenges

- Muon beams are born as tertiary beams
  - Protons → pions → muons
  - Challenge: capture & transport
- Muons are born within a large phase-space
  - To obtain luminosities O(10^{34}) $cm^{-2}s^{-1}$ need to reduce the initial phase-space by 6 orders of magnitude
  - Challenge: Phase-Space manipulation
- Muon decay fast (~ 2 µs at rest)
  - Challenge: Everything must be done fast
  - Must deal with high momentum protons, electrons…

Big picture

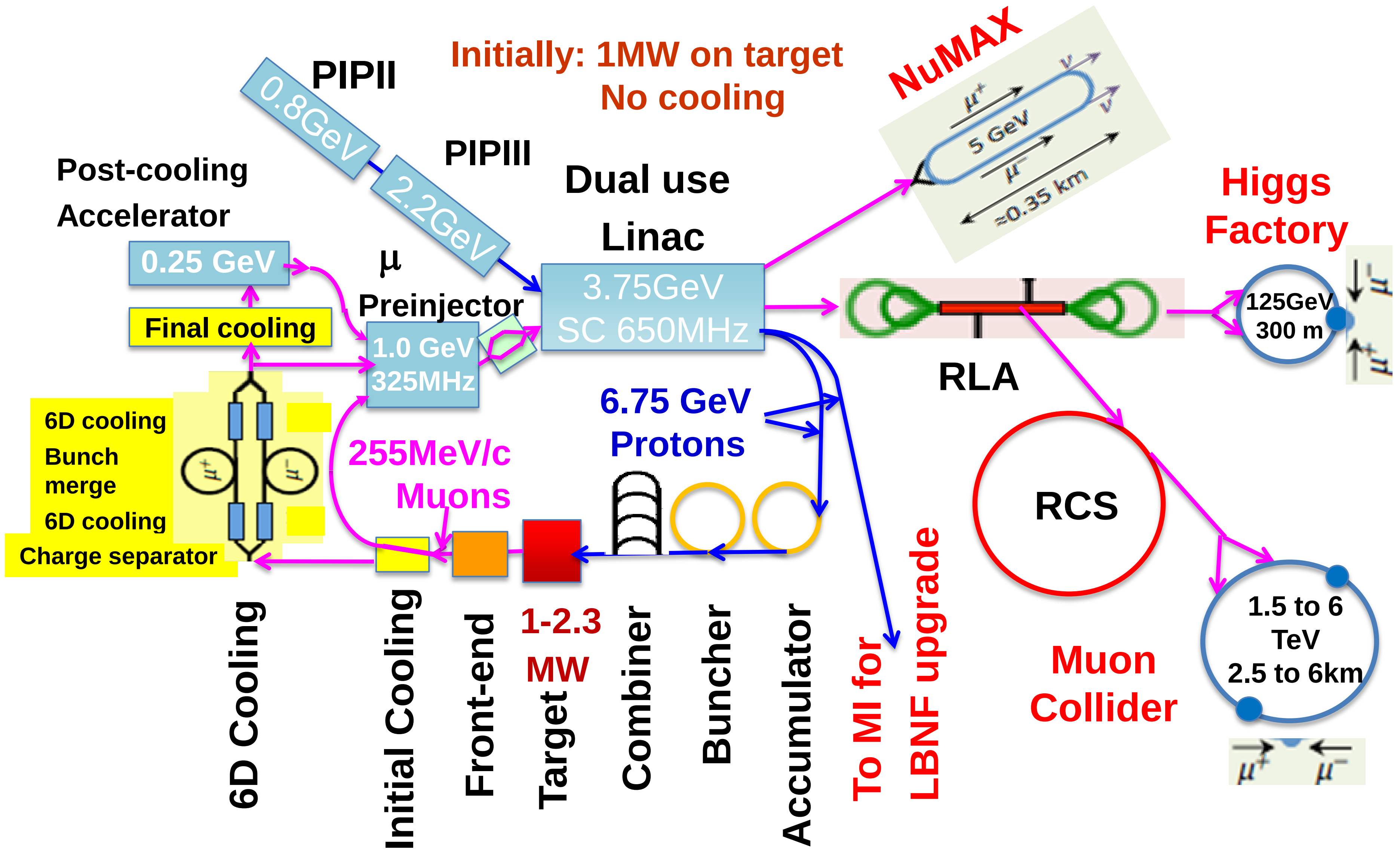


Neutrino Factory (NuMAX)
Proton Driver
Accumulator
Compressor
Front End
MW-Class Target
Capture Sol.
Decay Channel
Buncher
Phase Rotator
Cool-ing
Initial Cooling
Acceleration
0.2–1 GeV
1–5 GeV
Accelerators: Single-Pass Linacs (Opt. RLA or FFAG)
μ Storage Ring
5 GeV
≈0.35 km
ν Factory Goal: O(10^21) μ/year within the accelerator acceptance
μ-Collider Goals: 126 GeV ⇨ ~14,000 Higgs/yr Multi-TeV ⇨ Lumi > 10^34cm^-2s^-1
Share same complex
Muon Collider (Muon Accelerator Staging Study)
Proton Driver
Accumulator
Compressor
Front End
MW-Class Target
Capture Sol.
Decay Channel
Buncher
Phase Rotator
Cooling
Initial Cooling
Charge Separator
6D Cooling
Bunch Merge
6D Cooling
Final Cooling
Acceleration
Accelerators: Linac, RLA or FFAG, RCS
Collider Ring
E_CoM: Higgs Factory to ~10 TeV

Approach

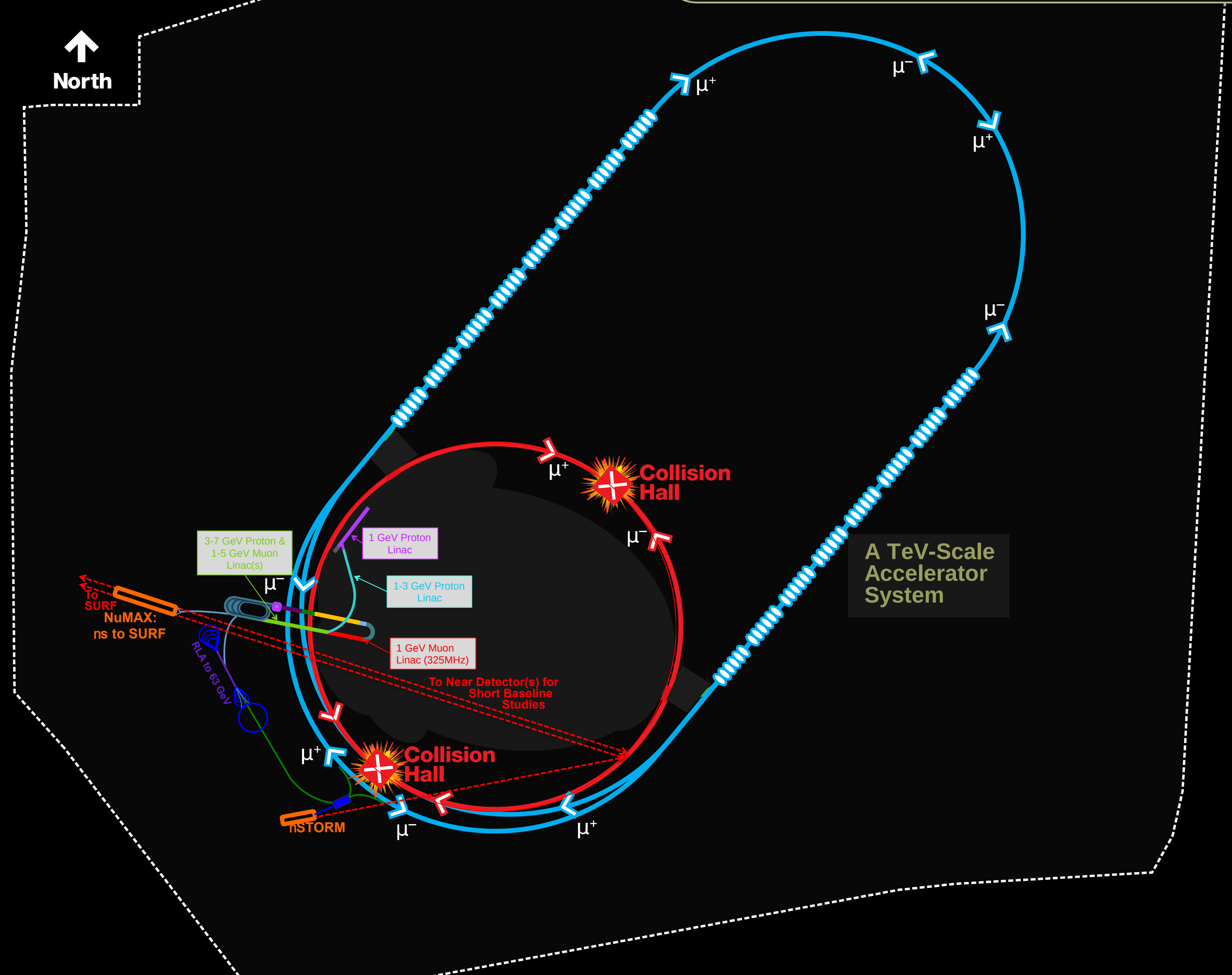
- Three critical program elements
- MASS: The Accelerator Staging Study
  - Provides a new prospective on how to deploy muon accelerator technologies and keep them as economical as possible
- IBS: The Initial Baseline Selection Process
  - Provides a structured approach to clearly identifying the concepts and basic parameters of the required machine elements
- The R&D Demonstrations (focus of this talk)
  - Demonstrate critical concepts

Staging Scenario under MAP



A Potential Muon Accelerator Complex at Fermilab:

➔ Multi-TeV Collider



Accelerator R&D effort

Design and Simulation Studies

- Proton Driver
- Front-End
- Cooling
- Acceleration and Storage
- Collider
- Machine-Detector Interface

Technology R&D

- MW class target & absorbers
- RF in magnetic fields (MTA)
- High field magnets
  - Utilizing HTS technologies
- Rapid-cycling magnets for the ultra-fast muon acceleration chain

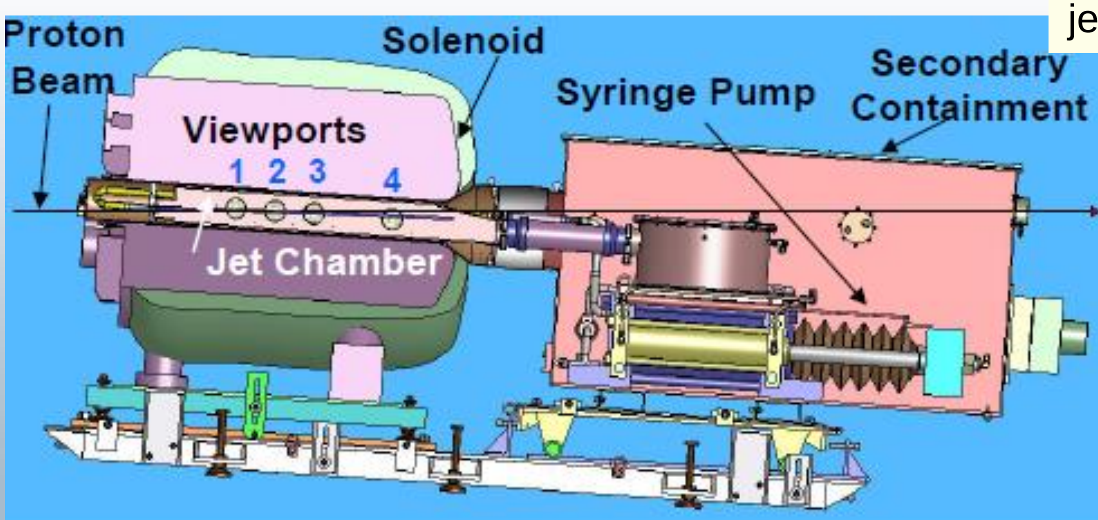
Muon Ionization Cooling Experiment (MICE)

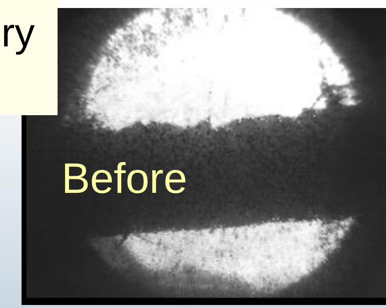
- Major system demonstration
- US effort to provide key hardware: RF cavities and couplers, spectrometer solenoids, coupling coil(s), partial Yoke
- Experimental and Operation support

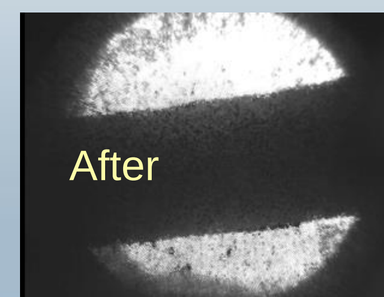
Target concept

- MERIT Experiment at CERN (2007):
  - Proof-of-principle demonstration of a mercury jet target in a strong magnetic field, with proton bunches of intensity equivalent to a 4 MW beam

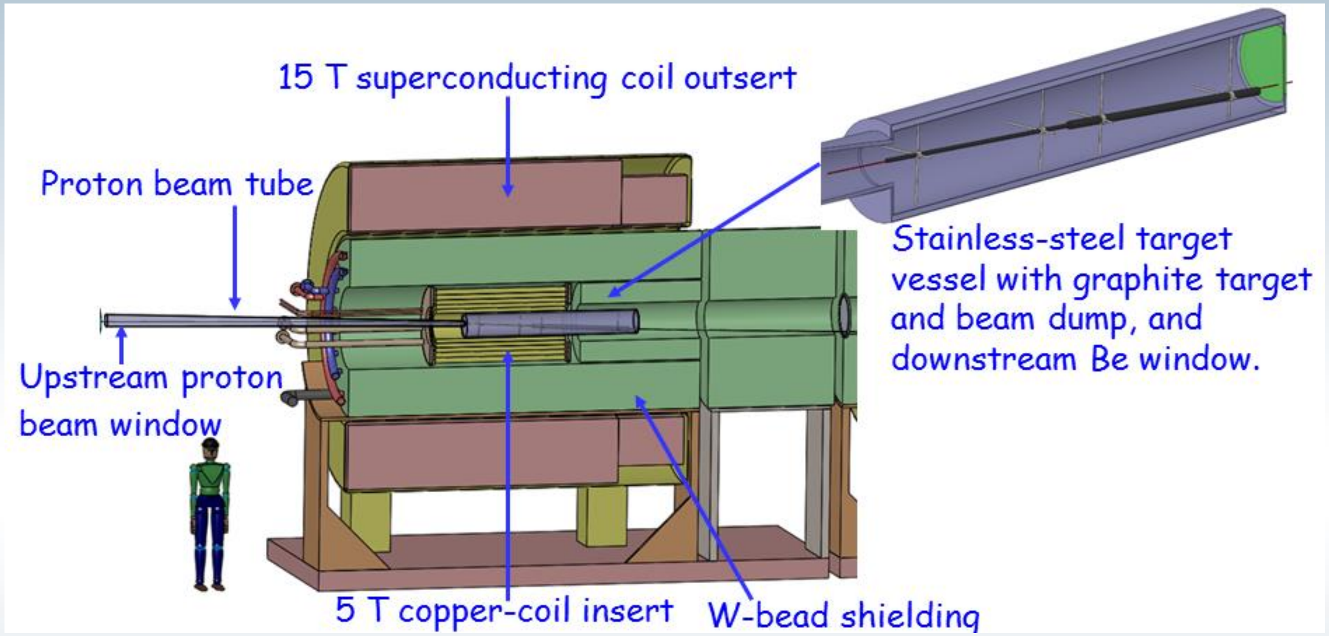
24 GeV, 10×10^{12} proton pulse impact a Hg mercury jet in 10 T field.







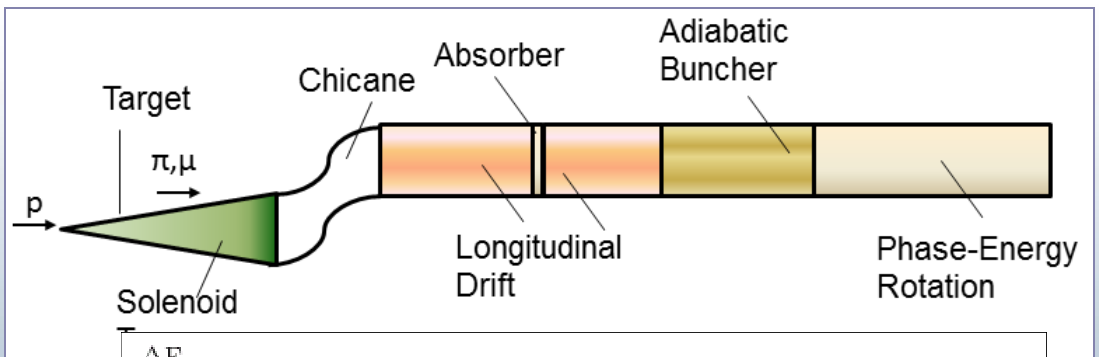
Target and capture system

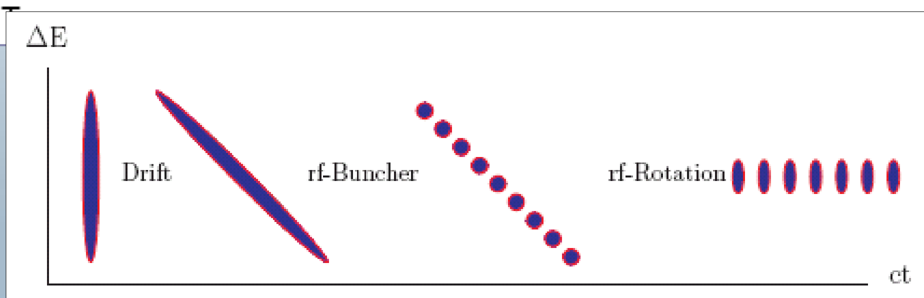


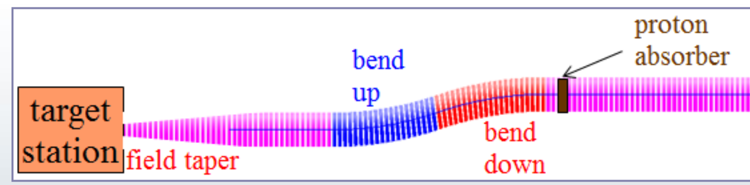
- Graphite target, 1 MW initial beam power, upgradable to 2.3 MW
- Removes technical risks and will benefit from developments at other facilities (e.g. spallation sources)
- More details: Targetry session 11:00-12:30 (Friday)

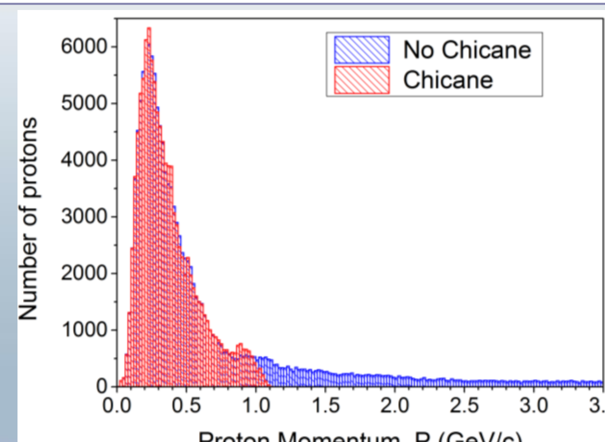
Front-End

- Front-End concept developed & simulated
  - Redesigned for a 325 MHz base frequency
- One challenge is the energy deposition from unwanted particles in the accelerator components
  - Concepts to mitigate this, have been identified

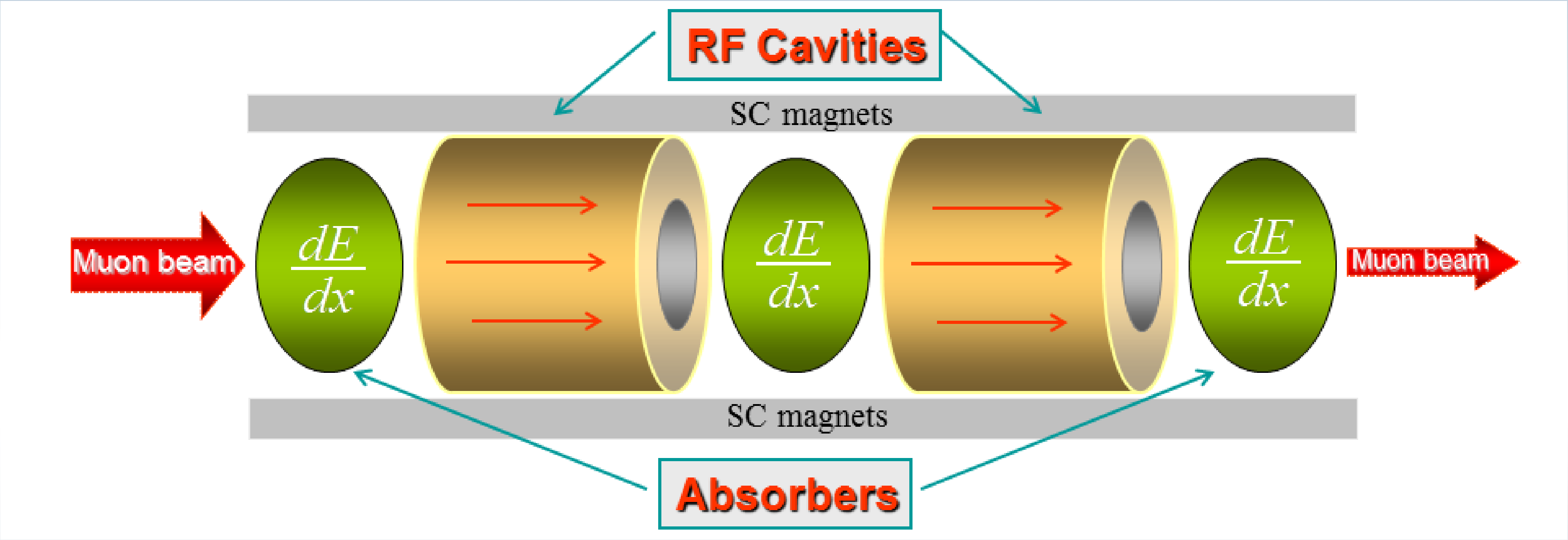








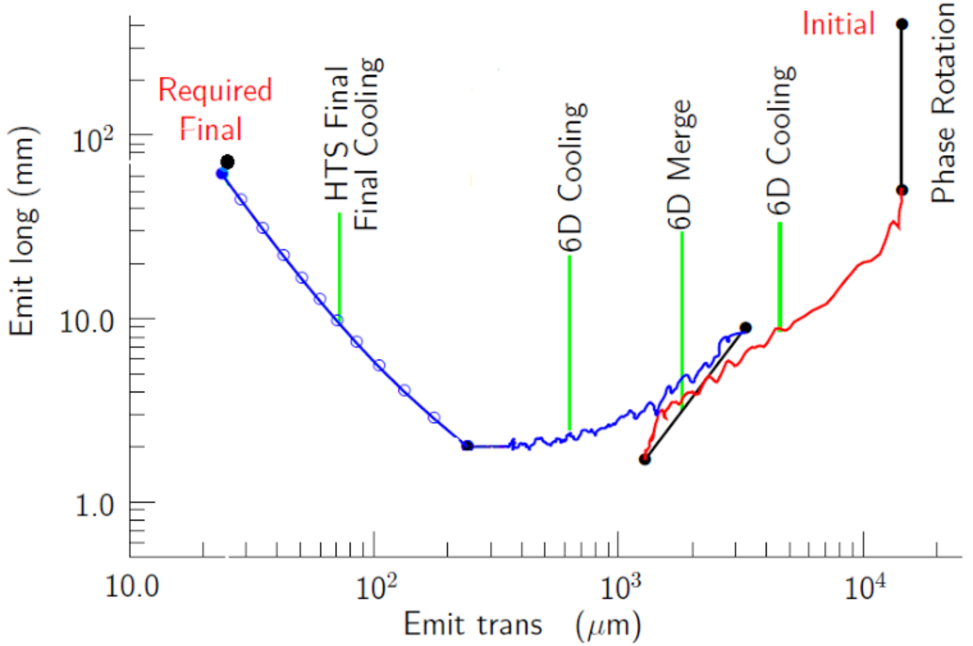
Ionization cooling concept



- Energy loss in discrete absorbers
- rf cavities to compensate for lost longitudinal energy
- Multi-tesla magnetic field to confine muon beams

Cooling for Muon Accelerators

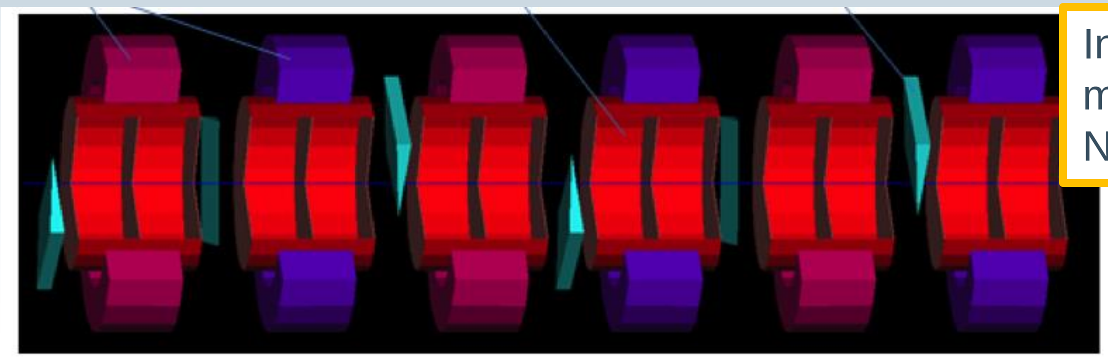
- Neutrino Factory: "NuMAX with a limited amount of cooling affords a cost-effective, precise and well-characterized neutrino source" (MASS study)
- Muon Collider: Development of a cooling channel design to reduce the 6D phase-space by a factor of 10^6 → MC luminosity of 10^{34} cm^{-2} s^{-1}



- Some challenges:
  - Very high field solenoids > 30 T
  - High gradient rf cavities in multi-Tesla fields

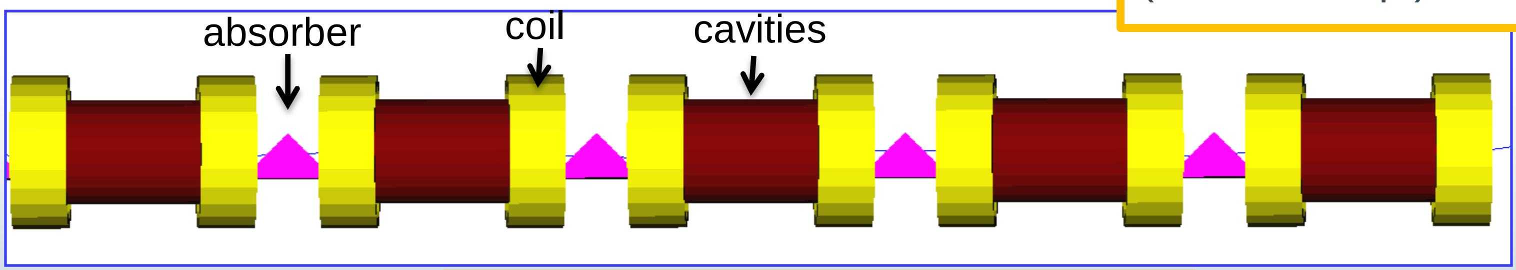
6D Cooling channel concepts

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

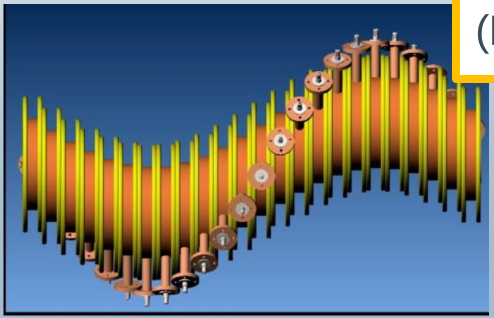


Initial Cooling: Cools both mu signs, suitable for NuMAX (Alexahin)

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

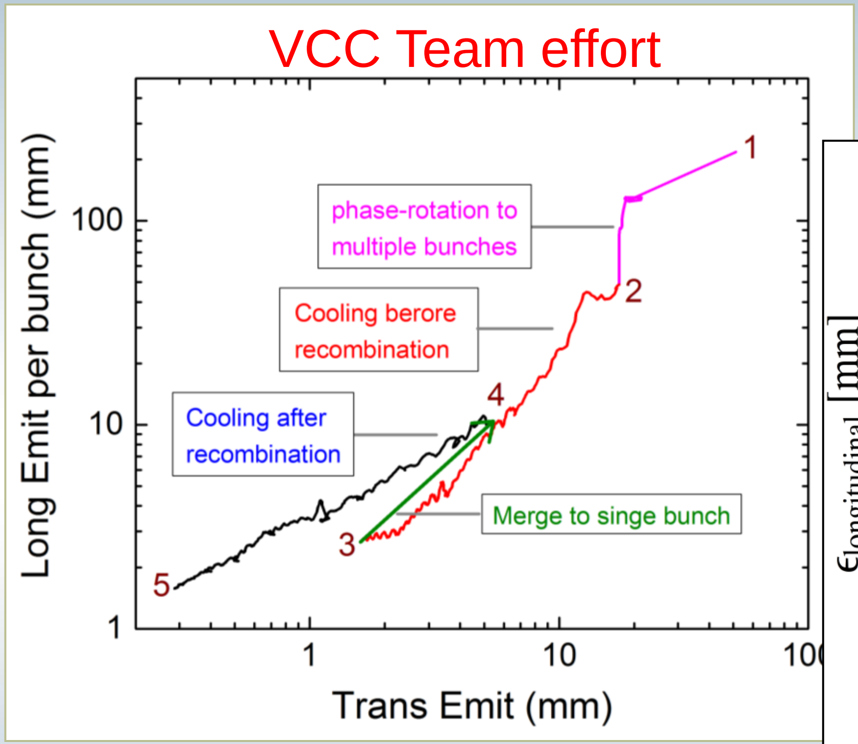


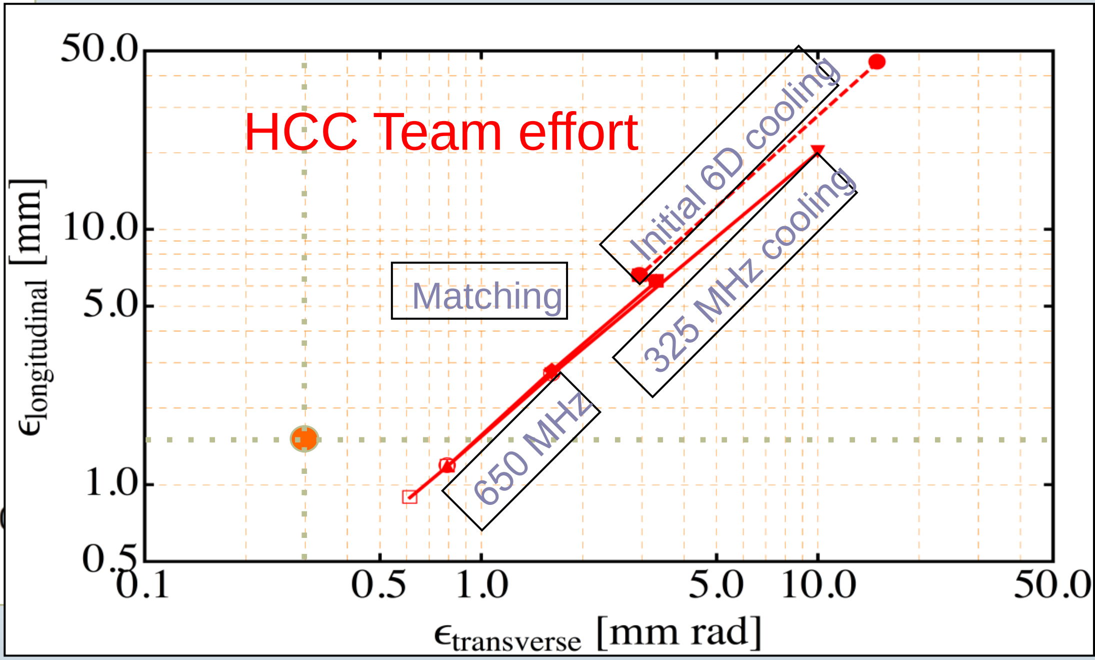
6D Cooling with gas-filled rf cavities (**HCC** Concept), K. Yonehara



- Delivered a complete cooling scheme!

Complete "end-to-end" simulation

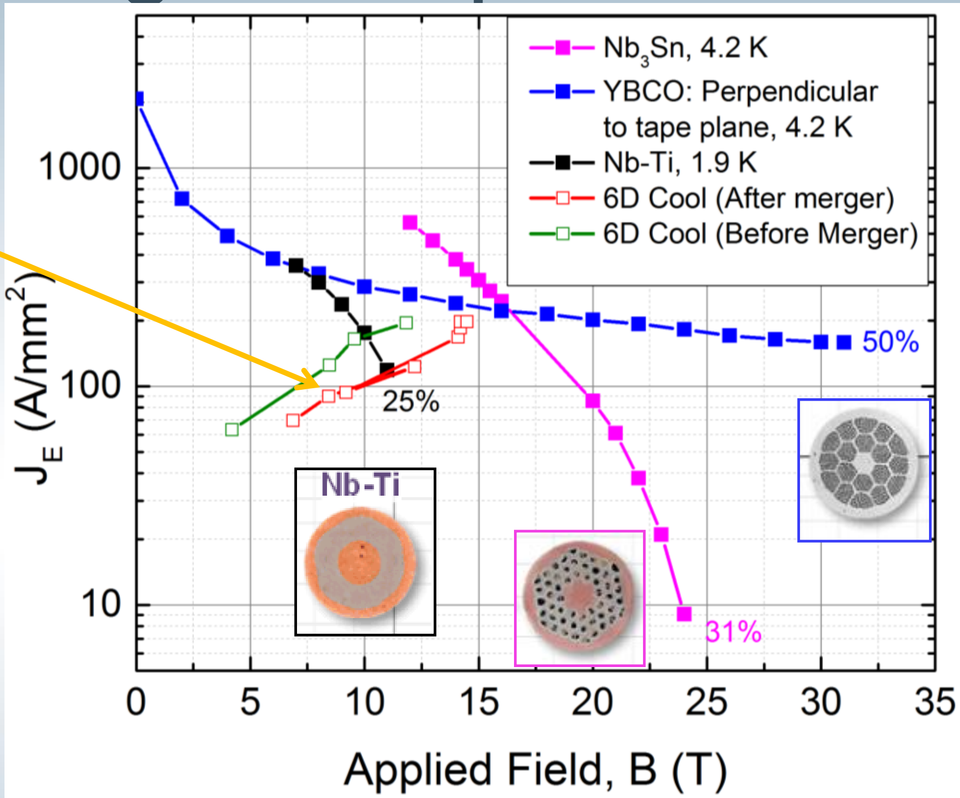




- End-to End simulation starting from the Front-End
- 6D cooling by 5 orders of magnitude achieved!
- More details: WG3, 2:00-3:30 pm (Friday)

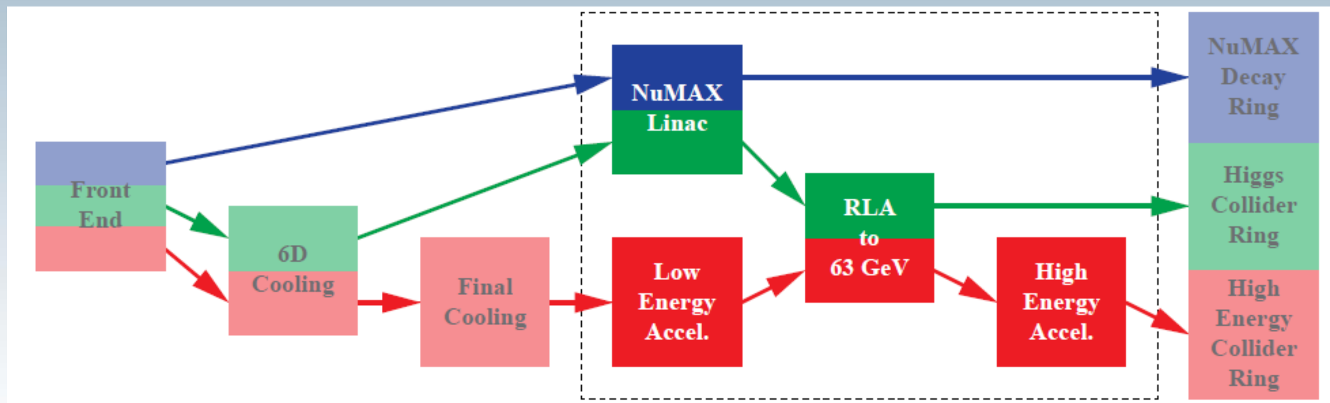
Magnet requirements

6D cooling magnet requirements within Nb_3Sn technology

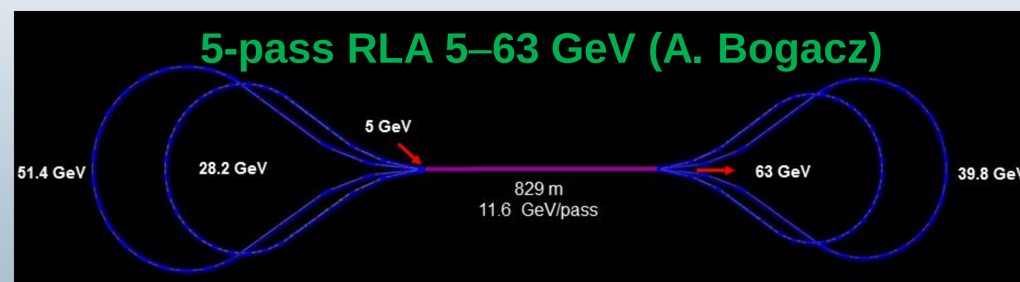


- Last stages 6D cooling stages are close to the Nb_3Sn limit
- A path towards a Multi-Tev Collider requires utilizing HTS
  - 15 T on-axis field with YBCO superconductor has achieved
  - Very promising performance with BSCCO-2212 conductor

Acceleration

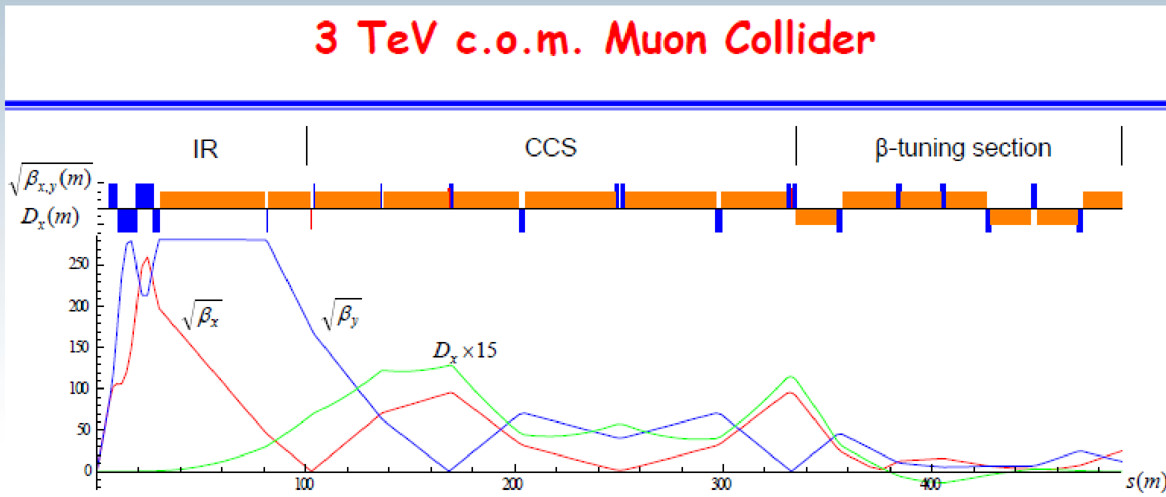


- Three classes of machines
  - 1) NUMAX: neutrino factory to 5 GeV, 2) Higgs Factory: 63 GeV collider, 3) High energy coliders:1.5, 3, 6 TeV
- Four acceleration subsystems
  - Linacs for NuMAX
  - RLA to reach 63 GeV
  - Low energy for colliders
  - High energy acceleration beyond 63 GeV: pulsed synchrotrons



- More details: 2:00-3:30 pm (Tuesday)

Multi-Tev Collider – 3.0 TeV Baseline

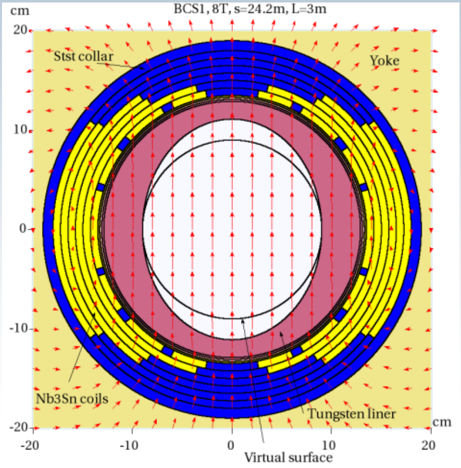


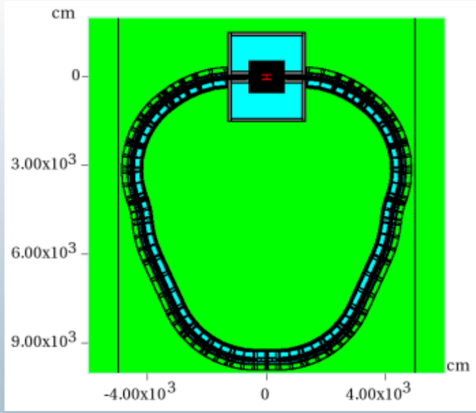
- Lattices for 63 GeV Higgs Factory, 1.5 TeV MC have been designed & simulated
- New: 3.0 TeV MC baseline
- Design Goals
  - High luminosity, acceptable detector backgrounds, manageable magnet heat loads…

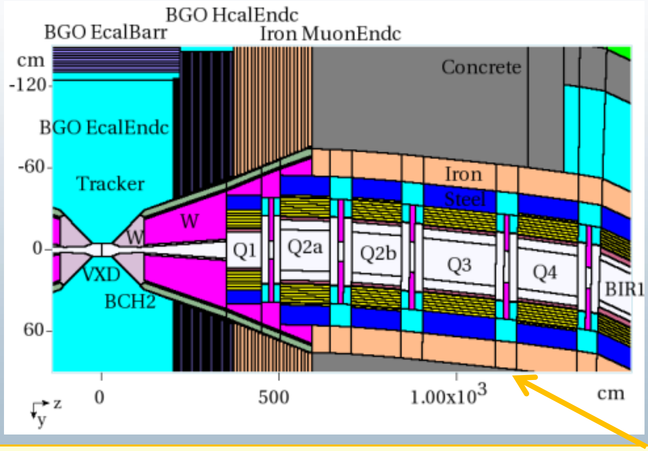
High Energy MC parameters	
Collision energy, TeV	3.0
Repetition rate, Hz	12
Average luminosity / IP, 10^{34}/cm^2/s	4.4
Number of IPs	2
Circumference, km	4.5
β*, cm	0.5
Momentum compaction factor, 10^{-5}	-1
Normalized emittance, π·mm·mrad	25
Momentum spread, %	0.1
Bunch length, cm	0.5
Number of muons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

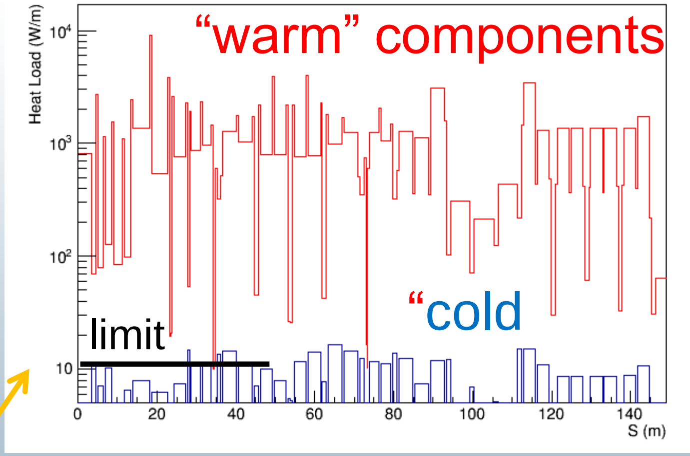
Backgrounds in the collider ring

- 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



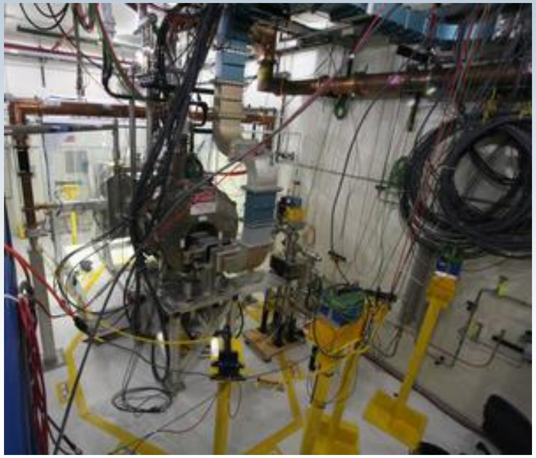




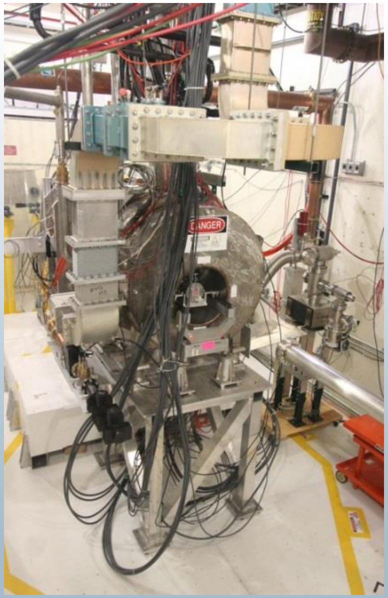


Model of entire HF ring including, magnet, detector, machine-detector interface has been built in MARS15

Mucool Test Area

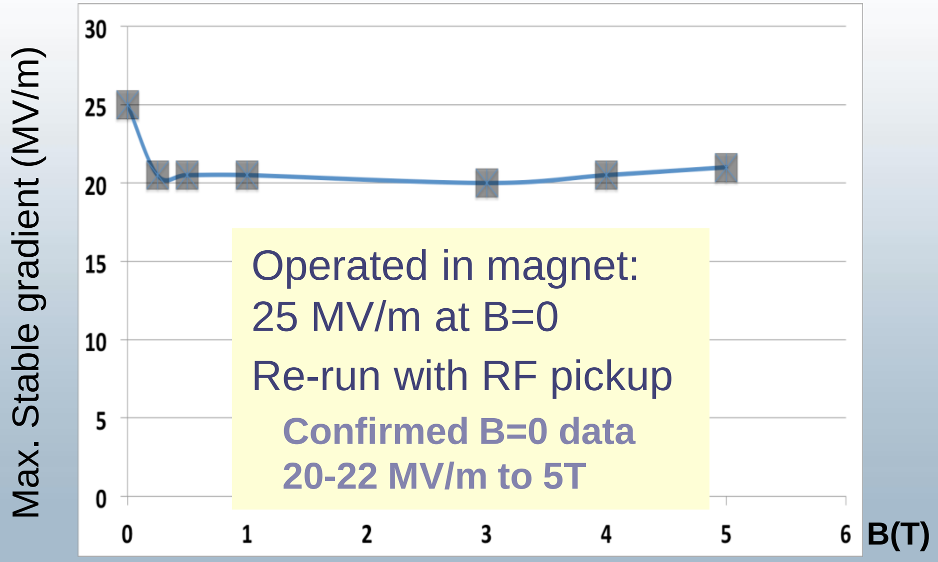


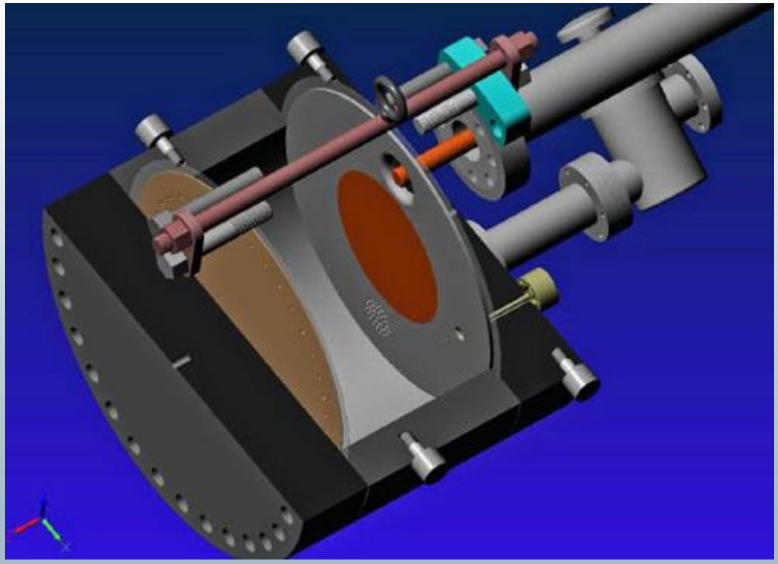
- Dedicated facility for muon cooling R&D
  - RF power at two frequencies (201/ 805 MHz)
  - Large-bore 5 T SC magnet
  - Extensive diagnostics for RF cavity tests
  - 400-MeV H- beamline
  - Unique in the world!



RF in magnetic fields

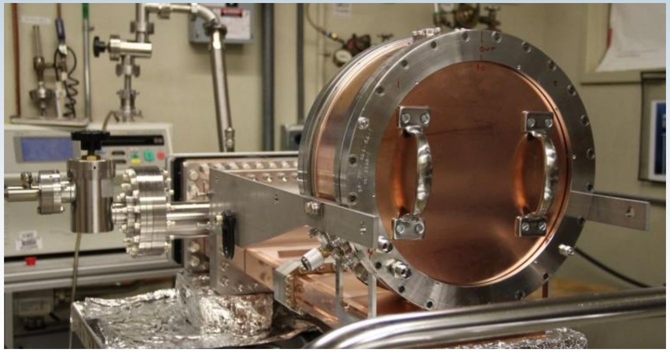
- Is the RF problem in magnetic fields solved?
- Study a new structure: All seasons Cavity
  - Modular pillbox with replaceable end plates
  - 805 MHz frequency
- Significant improvement over old 805 MHz cavity results

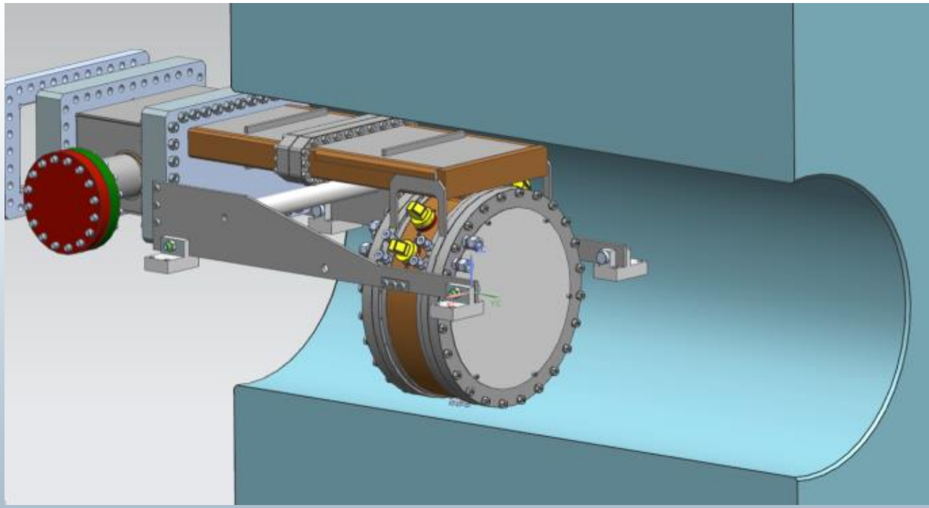




New 805 MHz modular cavity

- Significant improved over older designs
  - Removable endplates (initially Cu; Be, other material, treated surfaces)
  - Coupling iris moved to center ring anf field reduced (more realistic to a cooling channel)
  - RF design validated through simulation
- Begin tests within FY 14





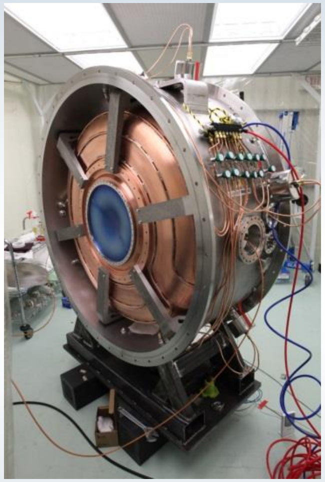
MTA: MICE support

Muon Ionization Cooling Experiment

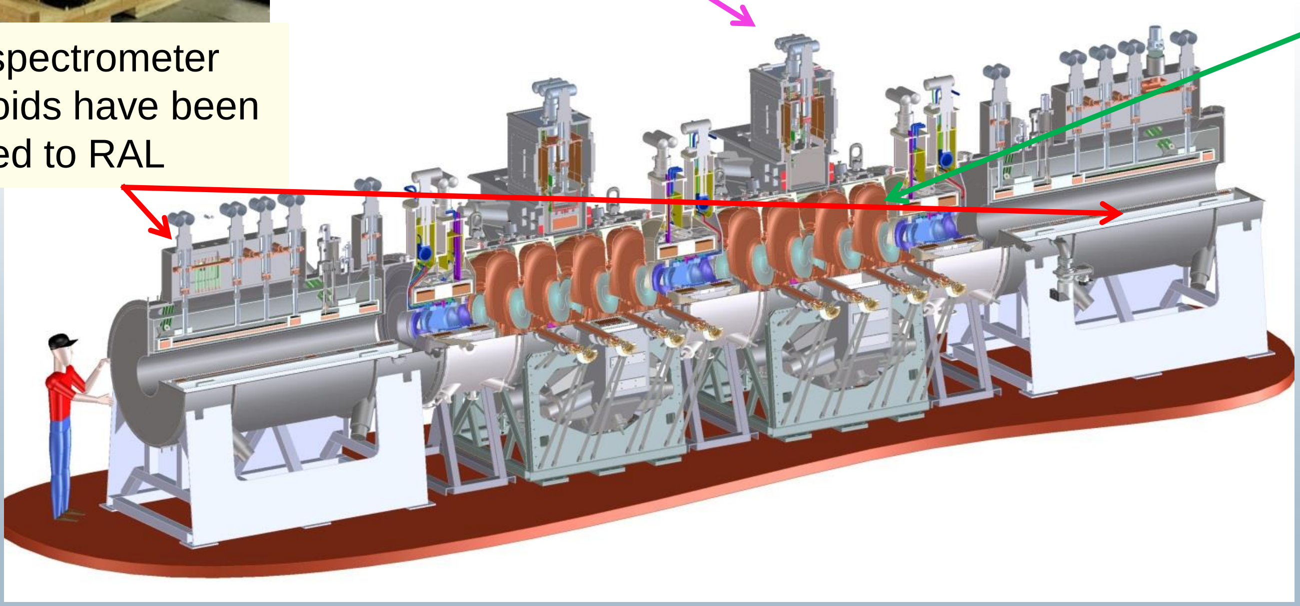
- MICE will demonstrate muon ionization cooling and validate simulation models

Both spectrometer solenoids have been shipped to RAL

CC cold mass under test at Fermilab

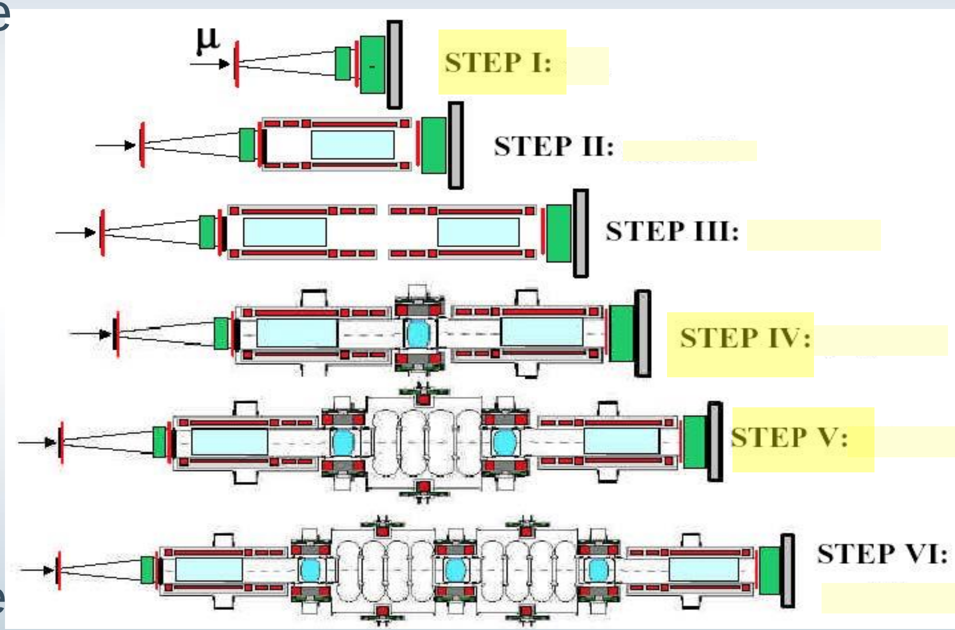


First MICE RF cavity tested at MTA: Conditioned at B=0, reached 8 MV/m



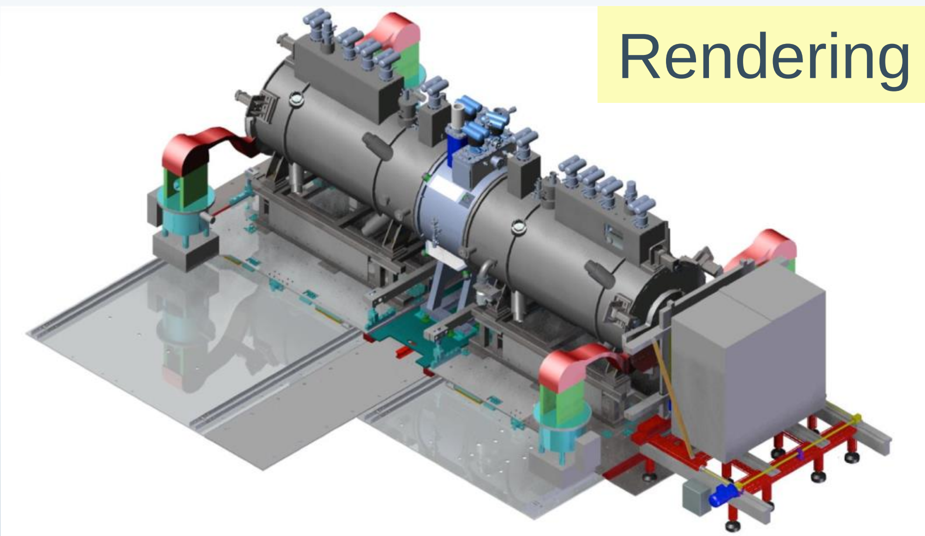
MICE

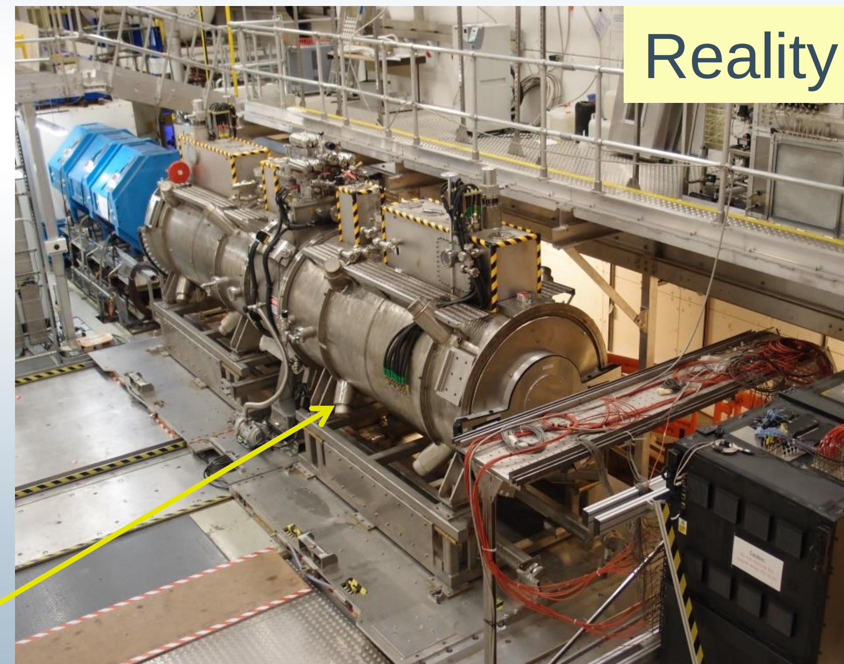
- The MICE run plan evolved from 6 “Steps” to 3.
  - Step I: Construct muon beam line and characterize with TOF and particle ID detectors - COMPLETE
  - Step IV: Study the cooling equation in the context of energy loss and straggling
    - Measure multiple coulomb scattering, dE/dx, ie, muon interaction physics in appropriate absorbers: LH_2 and LiH
  - Step V: Demonstrate the ability to do cooling with reacceleration between steps.



MICE construction

- We are well on our way to deploying MICE Step IV
- Magnets delivered, Partial yoke fabrication underway, experimental preparations well advanced





Spectrometer Solenoids with Trackers installed in MICE Hall

- More Details: MICE Session 2:30-4:00 pm (Monday)

Summary

- The unique feature of muon accelerators is the ability to provide cutting edge performance on both the Intensity and Energy Frontiers
- For the last 3 years US Muon Accelerator Program has pursued options to deploy muon accelerator capabilities
  - Near term (NuSTORM)
  - 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

Extra Material

Neutrino Factory Stagging

System	Parameters		Unit	nuSTORM	NuMAX	NuMAX+	IDS-NF
Perfor-mance	**Stored μ+ or μ-/year**			8×10^{17}	2×10^{20}	1.2×10^{21}	1×10^{21}
	ν_e or ν_μ to detectors/yr			3×10^{17}	8×10^{19}	5×10^{20}	5×10^{20}
Detector	***Far Detector:***		Type	SuperBIND	MIND / Mag LAr	MIND / Mag LAr	MIND
	Distance from Ring		km	1.9	1300	1300	2000
	Mass		kT	1.3	30 / 10	100 / 30	100
	Magnetic Field		T	2	0.5-2	0.5-2	1-2
	Near Detector:		Type	SuperBIND	Suite	Suite	Suite
	Distance from Ring		m	50	100	100	100
	Mass		kT	0.1	1	2.7	2.7
	Magnetic Field		T	Yes	Yes	Yes	Yes
Neutrino Ring	**Ring Momentum (P_μ)**		GeV/c	3.8	5	5	10
	Circumference (C)		m	480	600	600	1190
	Straight section		m	185	235	235	470
	Arc Length		m	50	65	65	125
Acceleration	**Initial Momentum**		GeV/c	-	0.22	0.22	0.22
	Single-pass Linac		GeV/pass	-	0.95	0.95	0.56
			MHz	-	325	325	201
	4.5-pass RLA	**RLA I**	GeV/pass	-	0.85	0.85	0.45
			MHz	-	325	325	201
		RLA II	GeV/pass	-	-	-	1.6
			MHz	-	-	-	201
Cooling				No	No	4D	4D
Proton Source	**Proton Beam Power**		MW	0.2	1	3	4
	Proton Beam Energy		GeV	120	3	3	10
	Protons/year		1×10^{21}	0.1	41	125	25
	Repetition Frequency		Hz	0.75	70	70	50

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^{7}sec		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)	2.5
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	2
Proton Driver Power	MW	$4^{\sharp}$	4	4	4	4	4	1.6

$^{\sharp}$ Could begin operation with Project X Stage II beam