CSS2013 Colloquium:
Opportunities with High Intensity Accelerators Beyond the Current Era

Technologies for Intensities Beyond the Current Era

Patrick Hurh, Bob Kephart, *Mark Palmer*

August 4, 2013

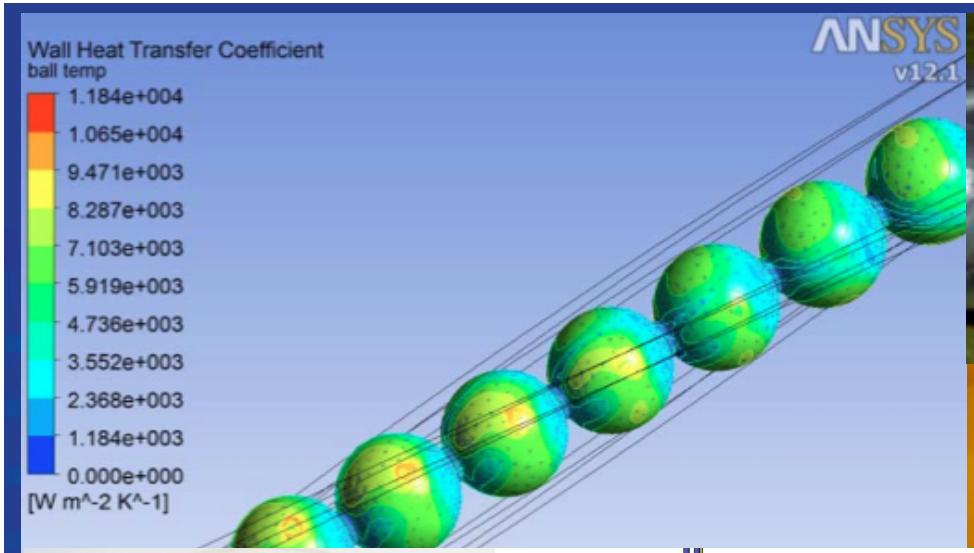
Snowmass on the Mississippi

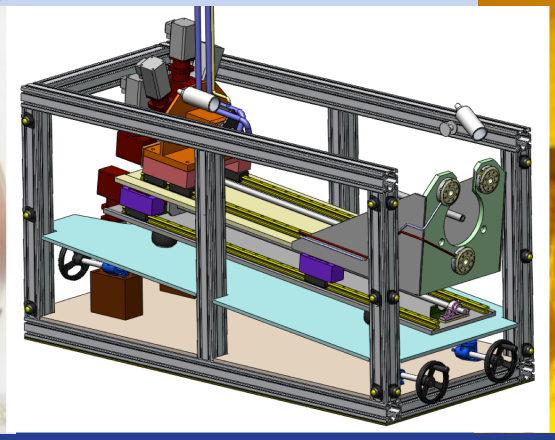
Fermilab

Outline

Accelerator Technologies to ***Move Beyond the State of the Art***

- High Power Targetry
- High Intensity Muon Beams
  - Including Muon Cooling
- Ongoing SRF Needs





HIGH-POWER TARGET FACILITIES: CHALLENGES AT ≥4 MW

Acknowledgments to Patrick Hurh (FNAL)

Critical Issues: High Power Target Facilities

- Target and Window Design Challenges
  - Heat removal
  - Thermo-mechanical integrity (beam induced stresses)
  - Radiation damage
  - Optimization for science yield

- Facility Design Challenges
  - Radiation protection and remote handling
  - Radiation accelerated corrosion
  - Optimization for science yield

Target Challenges

Heat Removal

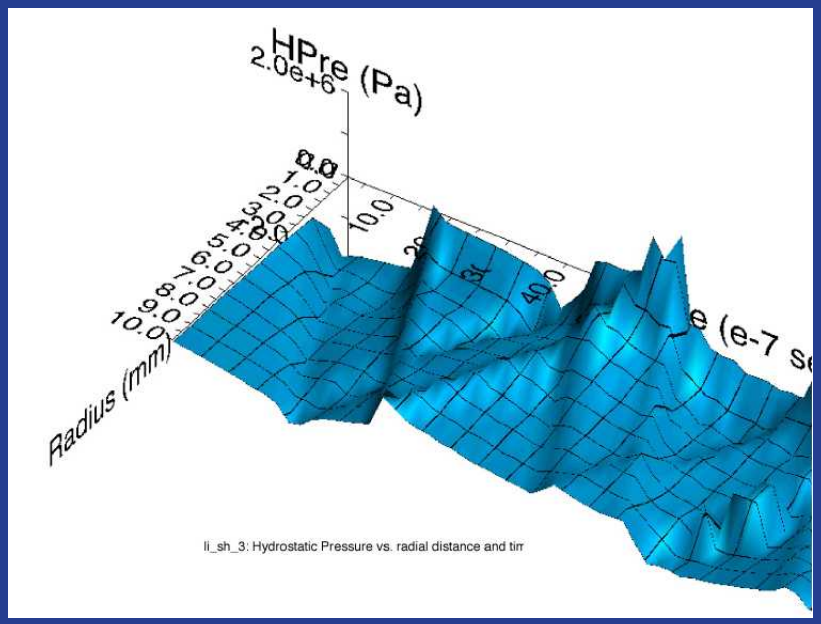
At ≥4 MW

- Different target applications require *very different cooling capacity*
  - Neutrino production target: 1-2% of beam power left in target
  - Spallation neutron target: 95-100% of beam power left in target
- Stopping targets & conventional target geometries:
  - Approach material limits for solid, static targets

Target Challenges

Thermal Shock (Stress Waves)

Ta-rod after irradiation with 6E18 protons in 2.4 μs pulses of 3E13 at ISOLDE (photo courtesy of J. Lettry)



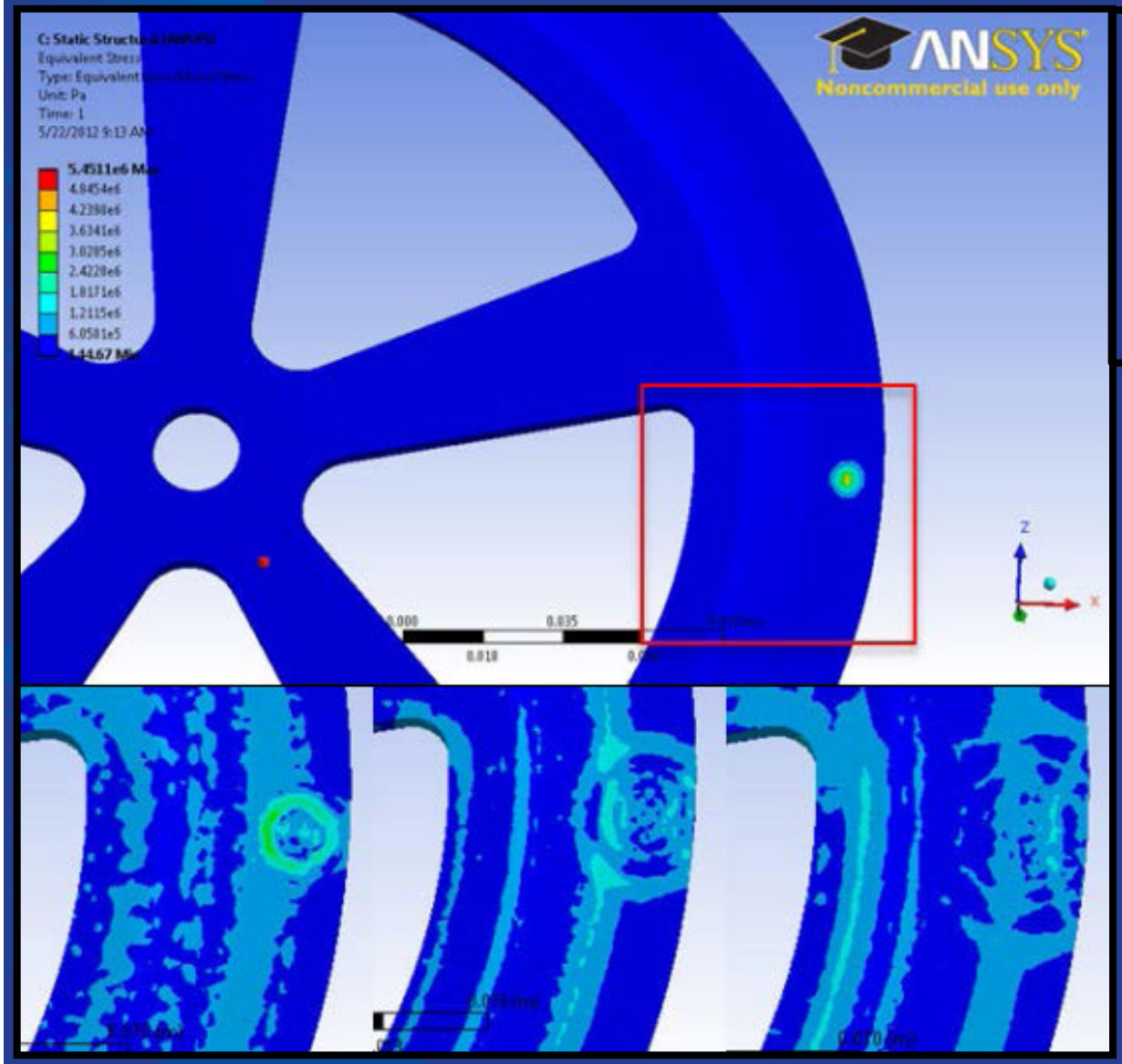
Simulation of stress wave propagation in Li lens (pbar source, Fermilab)

- Fast expansion of material surrounded by cooler material creates a sudden local area of compressive stress
- Stress waves (not shock waves) move through the target
- Plastic deformation or cracking can occur

- Mitigating thermal shock:
  - Material Selection
  - Segment target length
  - Manipulate beam parameters (spot size, intensity)
- Also impacts liquid and rotating targets
  - Cavitation in liquid metal (SNS)
  - Rotating target in CW beam (FRIB)

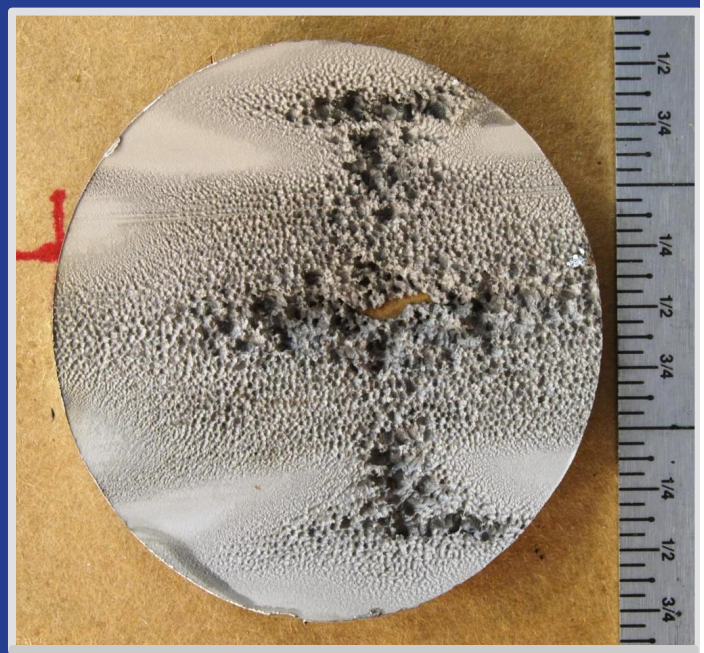
Target Challenges

Thermal Shock (Stress Waves)



Stress developing:
0 μs (top), 1.8 μs, 4.2 μs and 6 μs. Unit is Pa
Stress wave from the beam pulse is seen

M. Avilov, FRIB, 06/14/2012

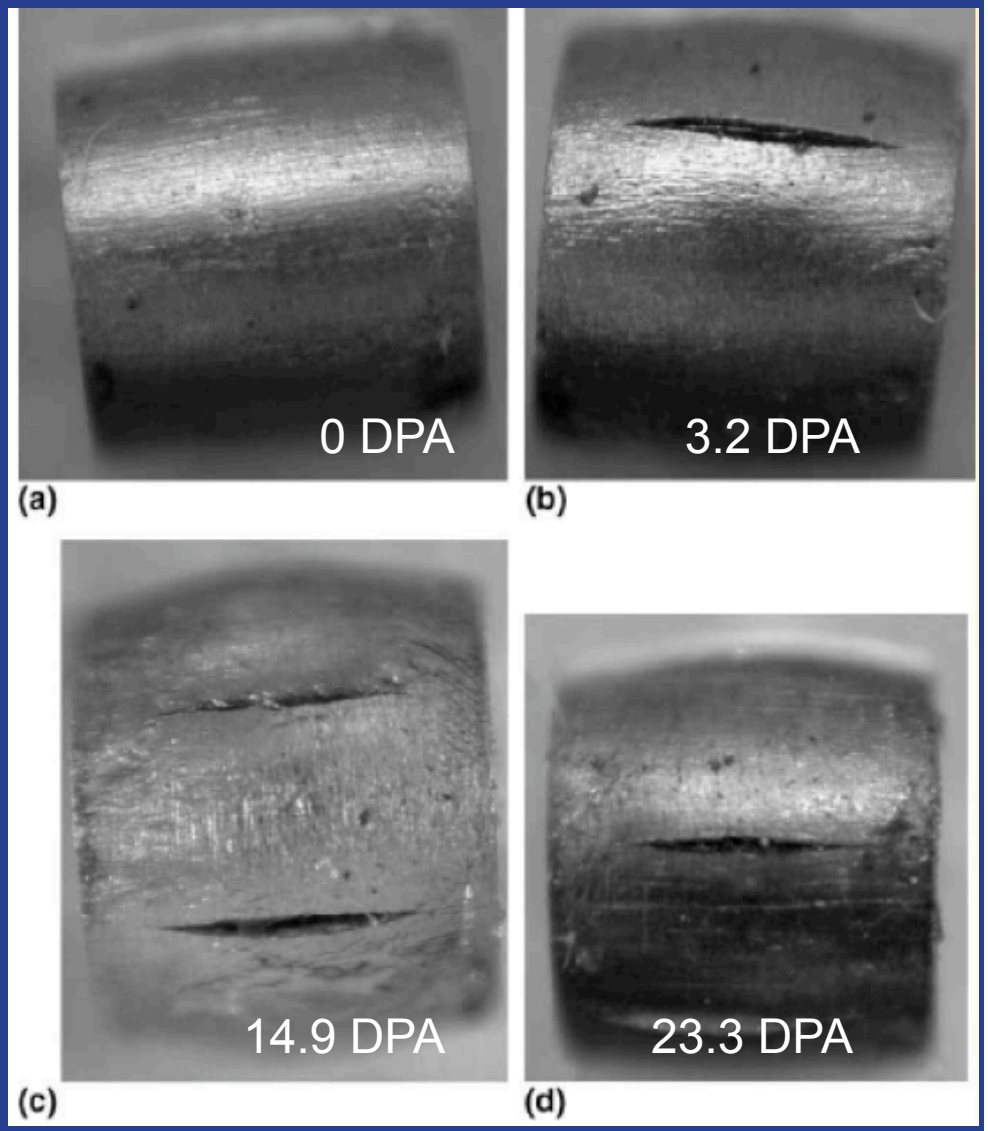


Beam induced cavitation damage in SNS target. B. Riemer for PASI 2012

Target Challenges

Radiation Damage

- Displacements in metal crystal lattice
  - Embrittlement
  - Creep
  - Swelling
  - Fracture toughness reduction
  - Thermal/electrical conductivity reduction
  - Coefficient of thermal expansion changes
  - Accelerated corrosion
  - Transmutation products (impurities, gas production)
- Very dependent upon irradiation conditions (eg. temperature)



S. A. Malloy, et al., Journal of Nuclear Material, 2005. (LANSCE irradiations)

Radiation Damage

n ≠ p
1-14 MeV 100+ MeV

Irradiation Source	DPA rate (dpa/s)	He gas production (appm/DPA)	Irradiation Temp (°C)
Mixed spectrum fission reactor	3e-7	0.1	200-600
Fusion reactor	1e-6	10	400-1000
High energy proton beam	6e-3	100	100-800

Effects from low energy neutron irradiations do not equal effects from high energy proton irradiations. Table compares typical irradiation parameters.

R a D I A T E Collaboration

Radiation Damage In Accelerator Target Environments

Broad aims are threefold:

- to generate new and useful materials data for application within the accelerator and fission/fusion communities
- to recruit and develop new scientific and engineering experts who can cross the boundaries between these communities
- to initiate and coordinate a continuing synergy between research in these communities, benefitting both proton accelerator applications in science and industry and carbon-free energy technologies

Fermilab

UNIVERSITY OF OXFORD

BROOKHAVEN NATIONAL LABORATORY

Pacific Northwest NATIONAL LABORATORY

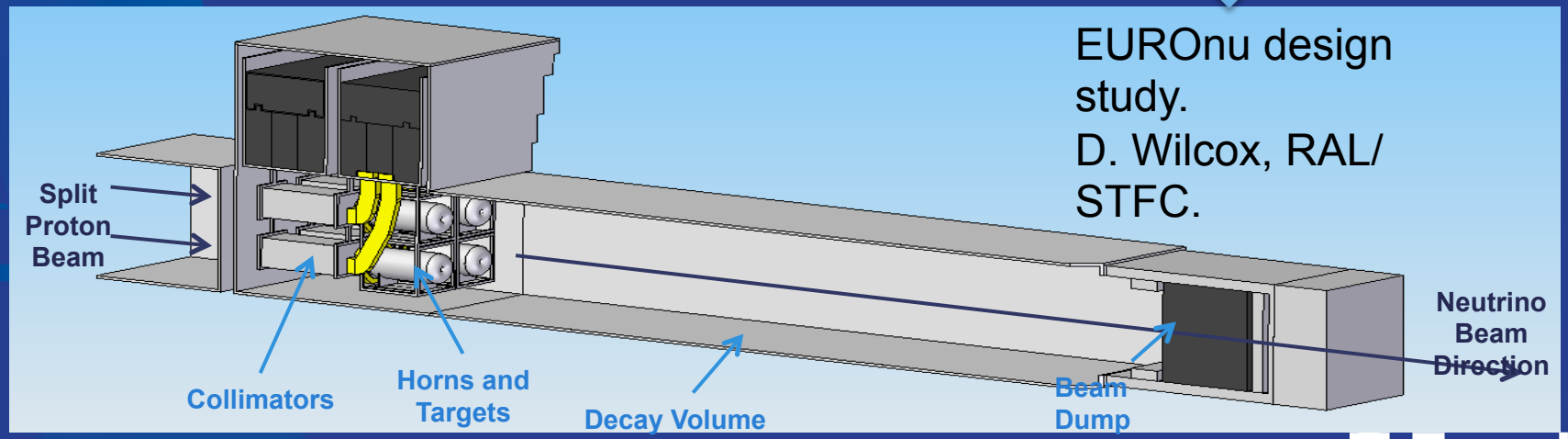
Science & Technology Facilities Council

Optimization for Science

Target Challenges

- 3 major challenges are helped by spreading the beam out
  - Decreases peak temp and stresses
  - Increases surface area for cooling
  - Reduces DPA rate/Increases useable life
- Typically reduces science yield per incident particle
  - Extensive analysis required to optimize yield (also target lifetime)
  - Some novel solutions exist

- Some options:
  - Liquid metal jets
  - Powdered metal jets
  - Rotating solid discs
  - Multiple targets in one shield pile:



EUROnu design study.
D. Wilcox, RAL/ STFC.

Facility Challenges

Radiation Protection

- Typically:
  - 50-75% of the cost of a new target facility is in the civil construction and radiation protection
  - 75% of the cost of maintaining operations of a target facility is associated with systems and staff to work with radioactive materials
- Facility design highly dependent on full life-cycle planning (including disposition of spent radioactive materials)

- ≥4 MW vs. 1-2 MW:
  - Prompt Dose Shielding – minor differences
    - Increased shielding thickness
    - Increased cooling capacity for shielding
  - Remote Handling – nearly identical:
    - Increased shielding in casks/hot cells
    - Increased cool-down times
  - Some previously minor problems could have new significance
    - Off-gas systems (esp. for liquid metal targets) will need significant attention
    - Loss of coolant scenarios more severe due to possible decay heat issues

Facility Challenges

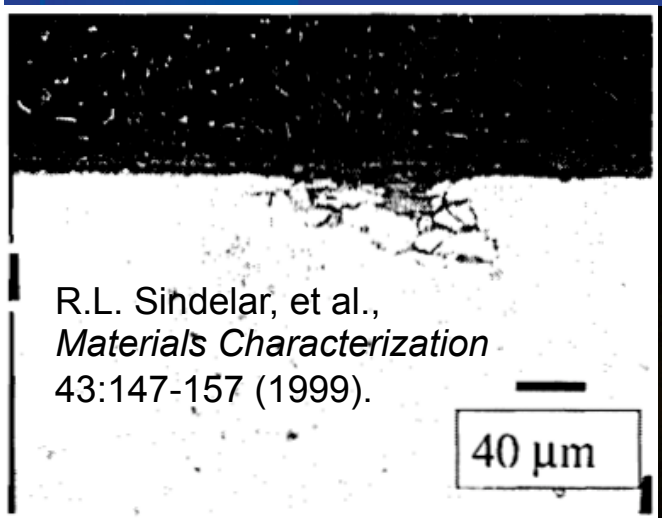
Radiation Protection

- Must apply lessons learned from 1 – 2 MW era:
  - Air activation must be carefully assessed and addressed in civil construction plans
  - Tritium production in shielding and component materials migrates readily and systems must be incorporated to isolate/collect and dispose of tritium safely (and legally)
  - Flexibility must be built into remote handling aspects of the facility design to handle off-normal events
  - Single event upsets can take down entire control systems if not shielded appropriately
  - Radiation can accelerate corrosion effects significantly; especially hi-strength steels exposed to activated, humid air

Facility Challenges

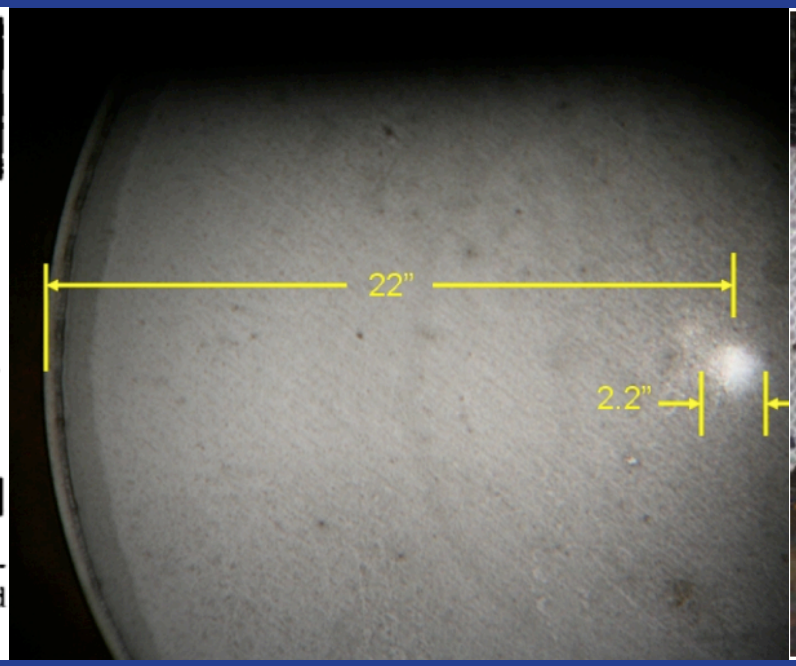
Radiation Accelerated Corrosion

- Al 6061 samples:
  - Displayed significant corrosion after 3.6 Grad
  - NuMI target chase air handling condensate with pH of 2
  - NuMI decay pipe window concerns
- Photograph of NuMI decay pipe US window showing corroded spot corresponding to beam spot
- MiniBooNE 25 m absorber HS steel failure
  - Hydrogen embrittlement from accelerated corrosion.



R.L. Sindelar, et al., *Materials Characterization* 43:147-157 (1999).

FIG. 8. Localized corrosion on 6061 Al sample exposed 12 weeks to saturated water vapor at 200°C and gamma irradiation.



Facility Challenges

Optimization for Science

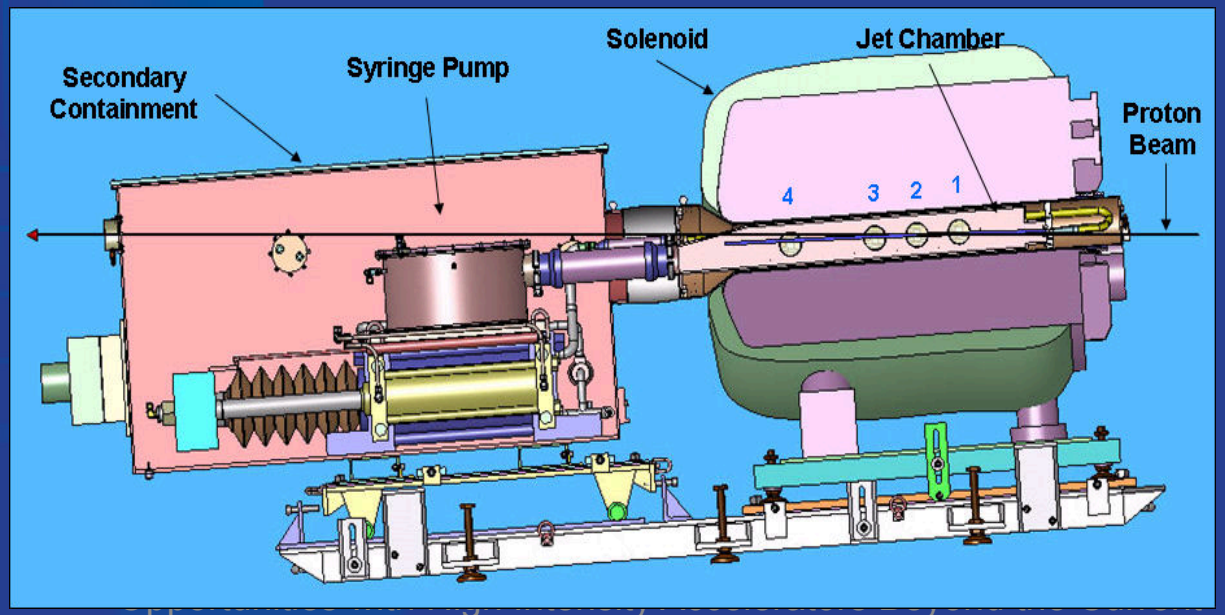
- As with the target design, facility design must be optimized considering the following competing parameters:
  - Cost (both construction and operational)
  - Reliability/availability
  - Flexibility
  - Science yield
- General engineering consensus is that spending more on a reliable, high availability facility that is flexible enough to service several experimental needs will maximize science yield per $ in the long term

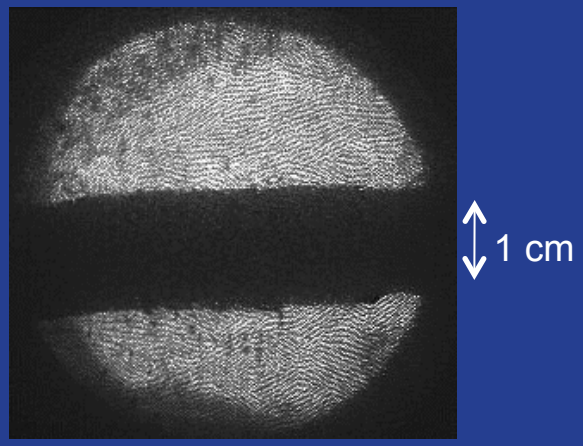
For neutrino factories, colliders and other applications

HIGH INTENSITY MUON BEAMS

Key Technologies - Target

- The MERIT Experiment at the CERN PS
  - Demonstrated a 20m/s liquid Hg jet injected into a 15 T solenoid and hit with a 115 KJ/pulse beam!
    - ⇨ Jets could operate with beam powers up to **8 MW** with a repetition rate of 70 Hz
- MAP staging aimed at initial 1 MW target





Hg jet in a 15 T solenoid with measured disruption length ~ 28 cm

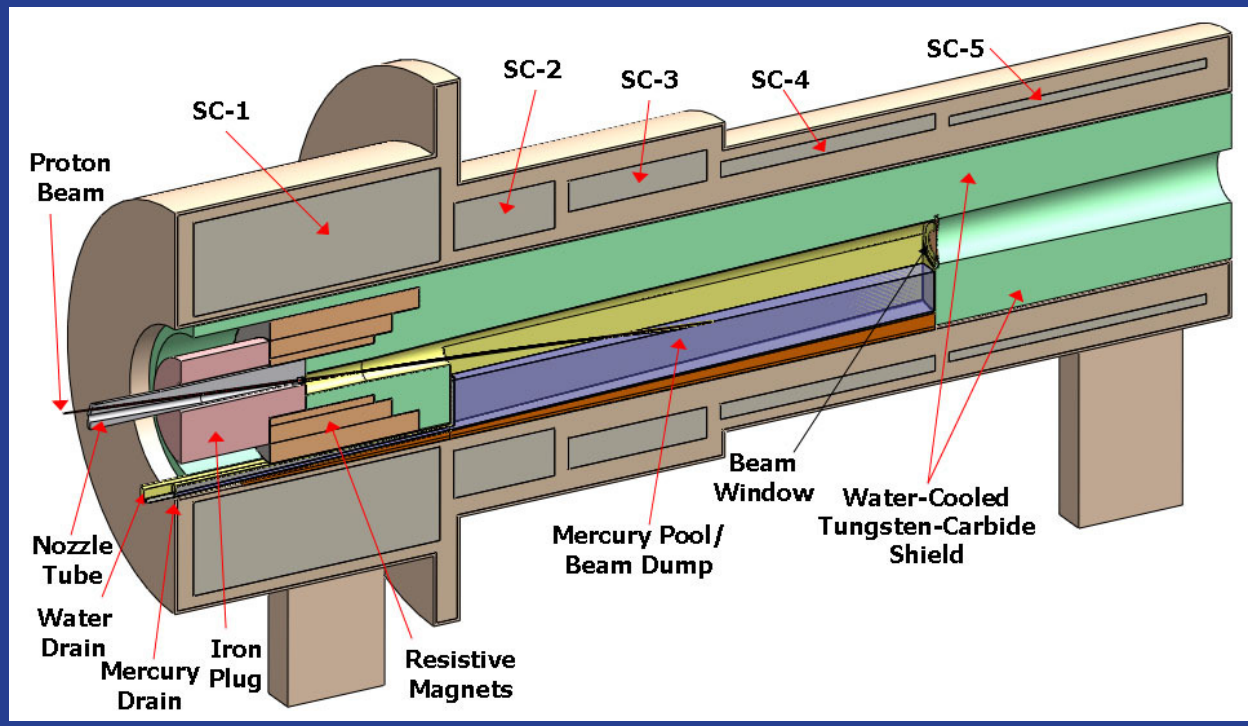
Technology Challenges – Capture Solenoid

- A Neutrino Factory and/or Muon Collider Facility requires challenging magnet design in several areas:
  - Target Capture Solenoid (15-20T with large aperture)

E_{stored} ~ 3 GJ

O(10MW) resistive coil in high radiation environment

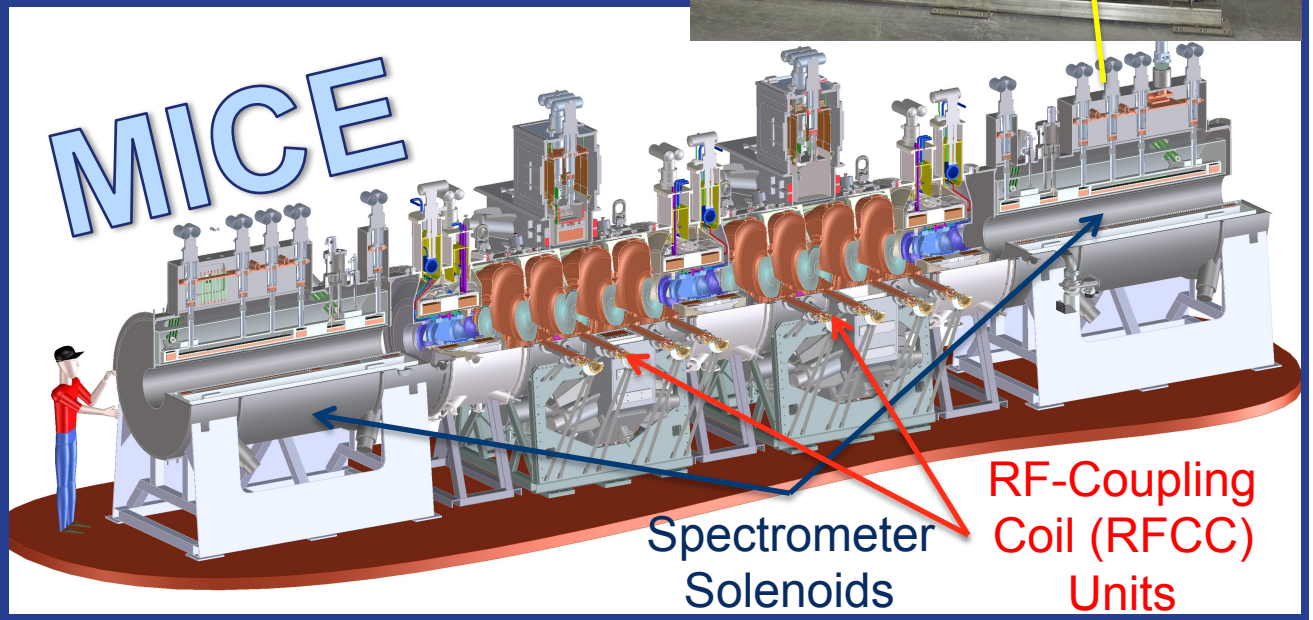
Possible application for High Temperature Superconducting magnet technology



Technology Challenges - Cooling

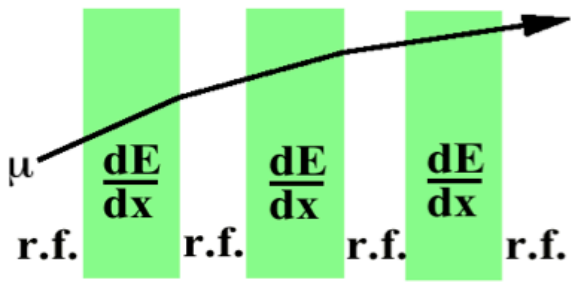
- Tertiary production of muon beams
  - Initial beam emittance intrinsically large
  - Cooling mechanism required, but no radiation damping
- Muon Cooling ⇨ Ionization Cooling
  - dE/dx energy loss in materials
  - RF to replace p_{long}

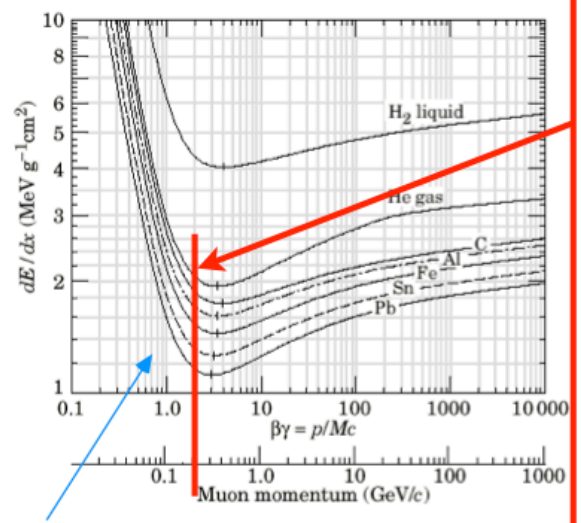
The Muon Ionization Cooling Experiment: Demonstrate the method and validate our simulations



Ionization Cooling

- Muons cool via dE/dx in low-Z medium





- ionization minimum is ≈ optimal working point:
  - longitudinal +ive feedback at lower p
  - straggling & expense of reacceleration at higher p

– Absorbers:

$$\begin{cases} E \rightarrow E - \left\langle \frac{dE}{dx} \right\rangle \Delta s \\ \theta \rightarrow \theta + \theta^{rms}_{space} \end{cases}$$

ionization energy loss

multiple Coulomb scattering

- 2 competing effects ⇒ ∃ equilibrium emittance

– RF cavities between absorbers replace ΔE

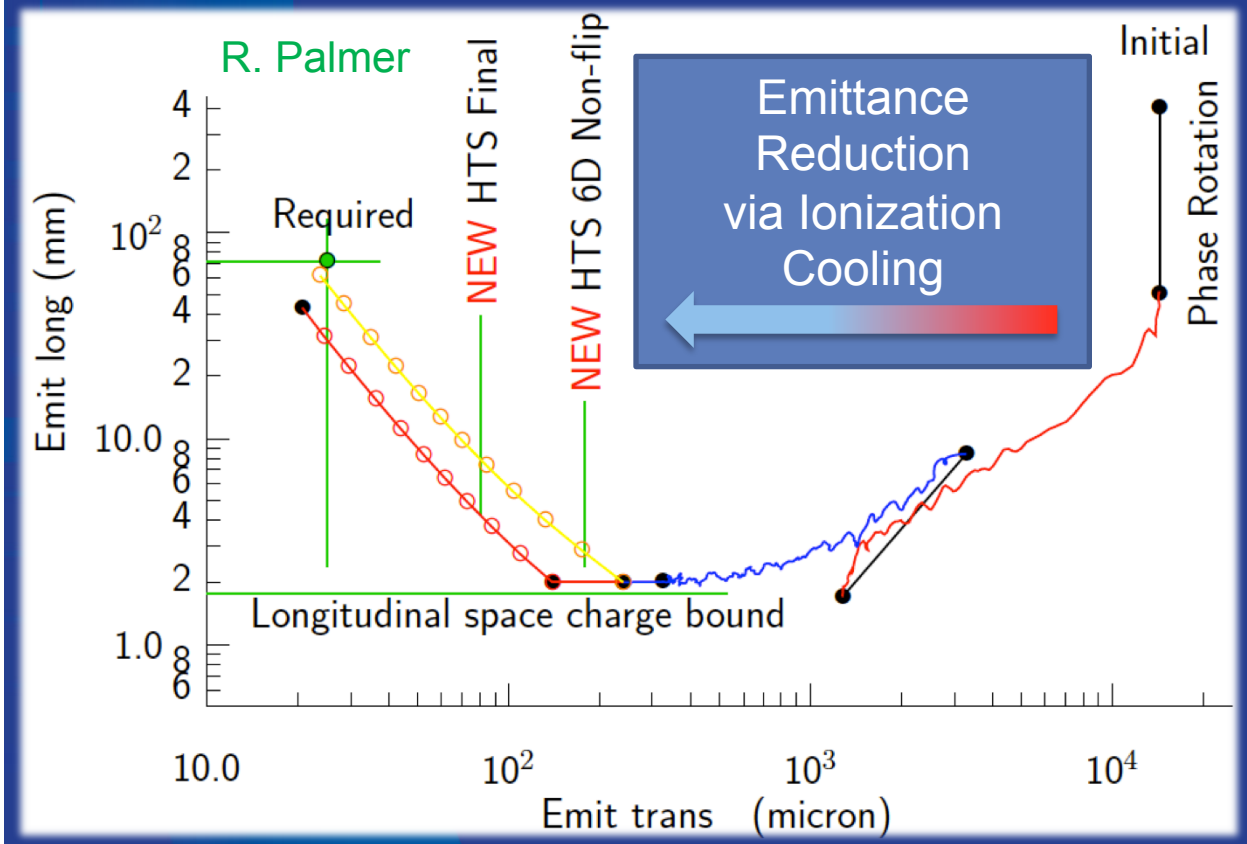
– Net effect: reduction in $p_\perp$ at constant $p_\parallel$, i.e., transverse cooling

$$\frac{d\epsilon_N}{ds} \approx -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\ \text{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$

(emittance change per unit length)

Technology Challenges - Cooling

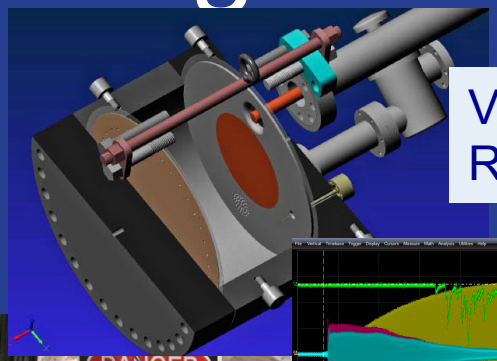
- Development of a cooling channel design to reduce the 6D phase space by a factor of $O(10^6)$ $\rightarrow$ MC luminosity of $O(10^{34})$ cm^{-2} s^{-1}

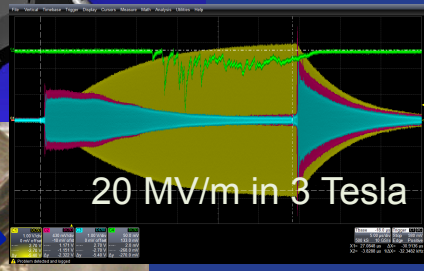


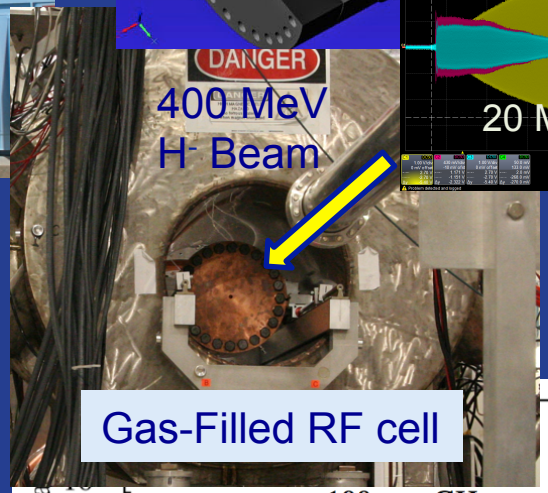
- Some components beyond state-of-art:
  - Very high field HTS solenoids (≥30 T)
  - High gradient RF cavities operating in multi-Tesla fields

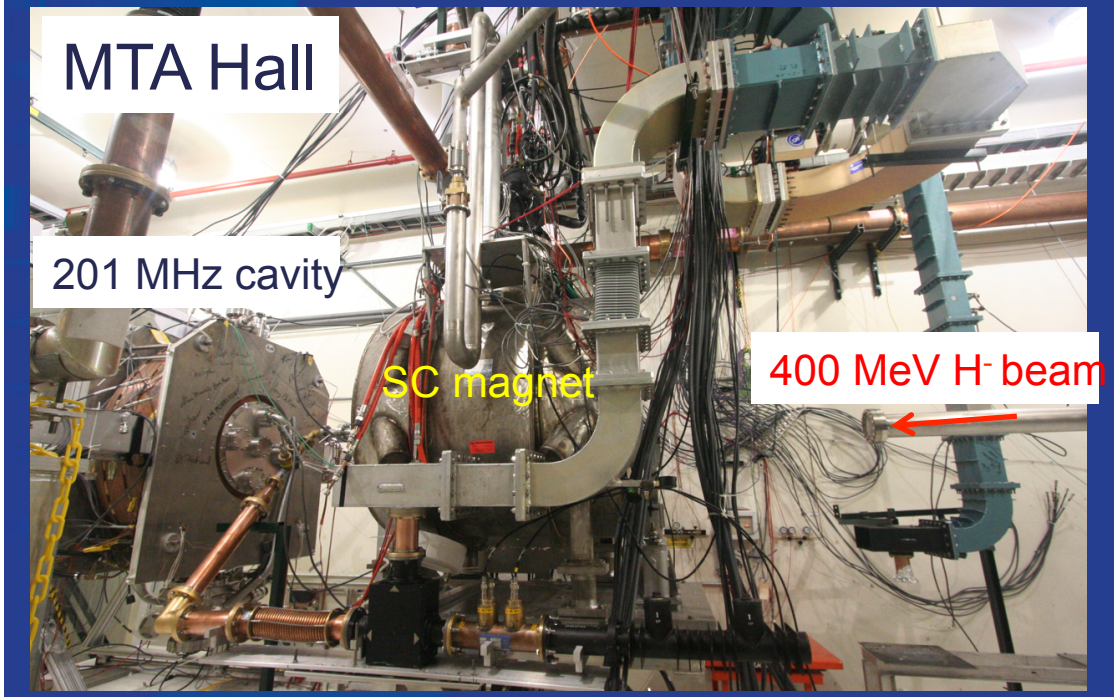
The program targets critical magnet and cooling cell technology demonstrations within its feasibility phase.

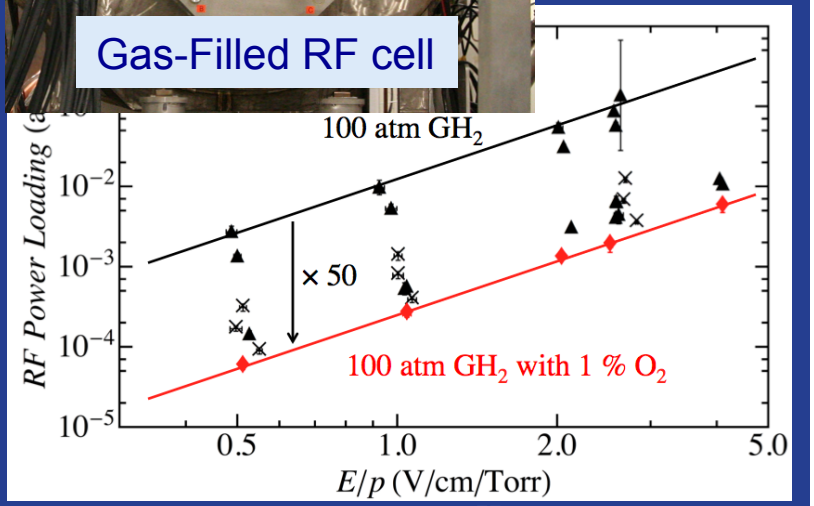
Elements of the R&D Program



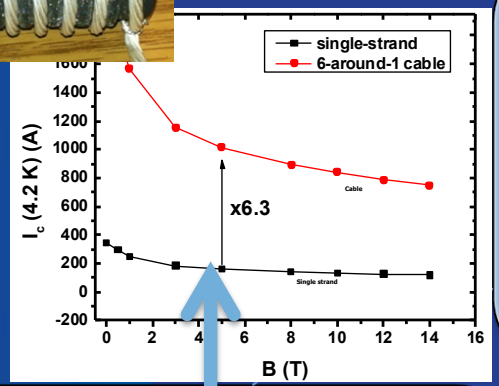






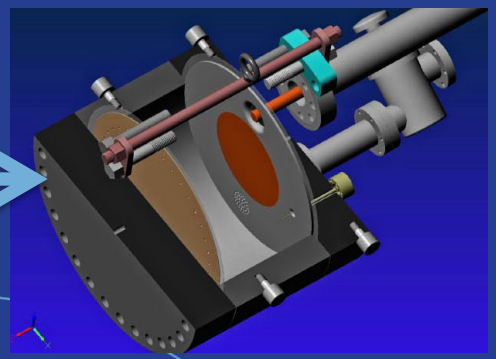


Cooling Channel R&D Effort



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

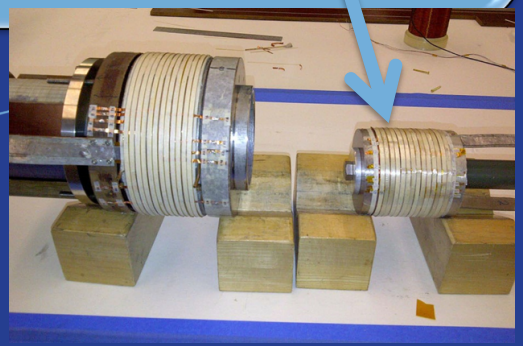
FNAL-Tech Div
T. Shen-Early Career Award

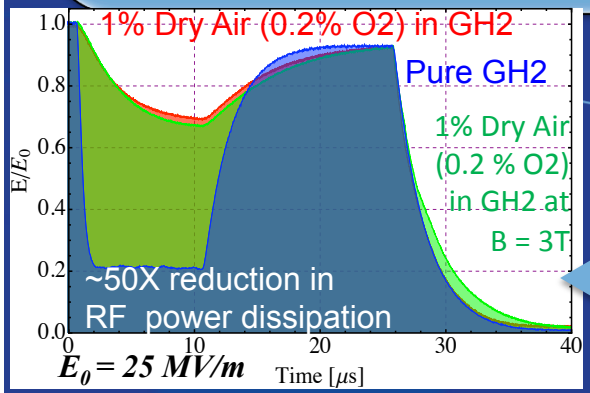
The Path to a Viable Muon Ionization Cooling Channel

World Record HTS-only Coil

15T on-axis field
16T on coil

PBL/BNL





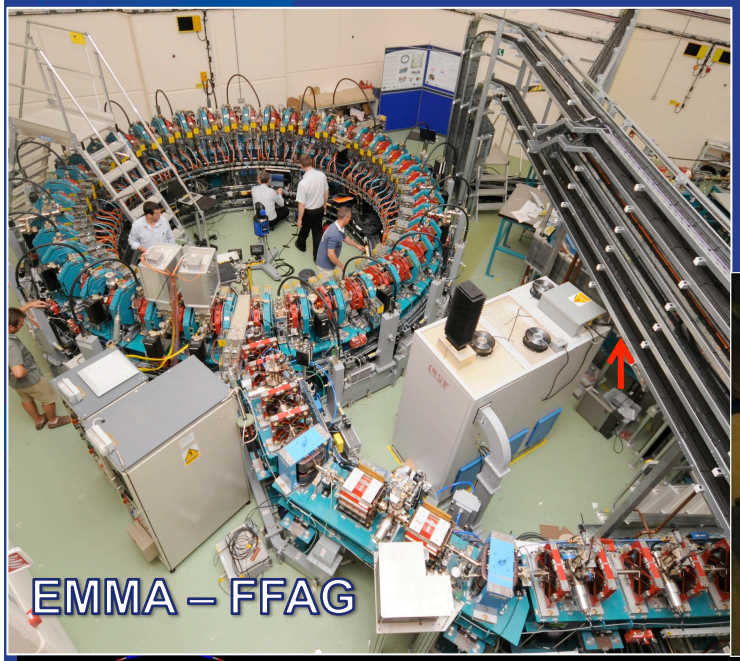
Demonstration of High Pressure RF Cavity in 3T Magnetic Field with Beam

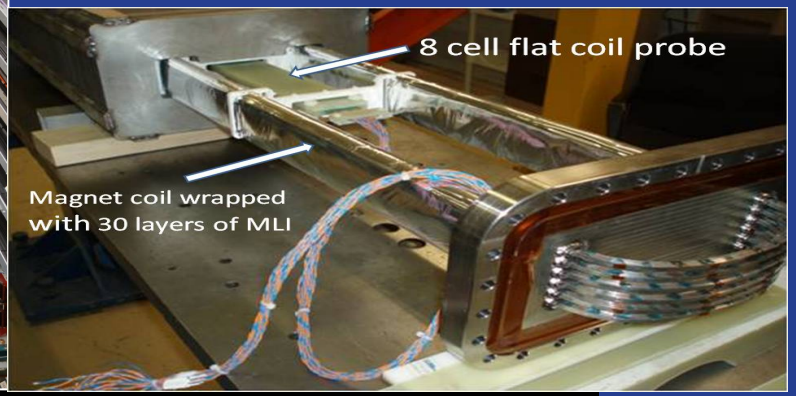
Extrapolates to
μ-Collider Parameters

MuCool Test Area

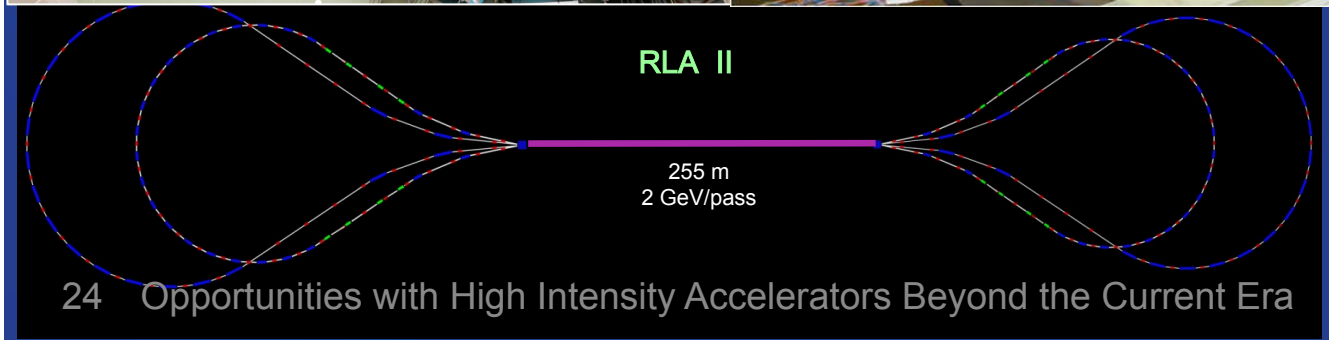
Technology Challenges - Acceleration

- Muons require an ultrafast accelerator chain
  - ⇨ *Beyond the capability of most machines*
- Solutions include:
  - Superconducting Linacs
  - Recirculating Linear Accelerators (RLAs)
  - Fixed-Field Alternating-Gradient (FFAG) Machines
  - Rapid Cycling Synchrotrons (RCS)





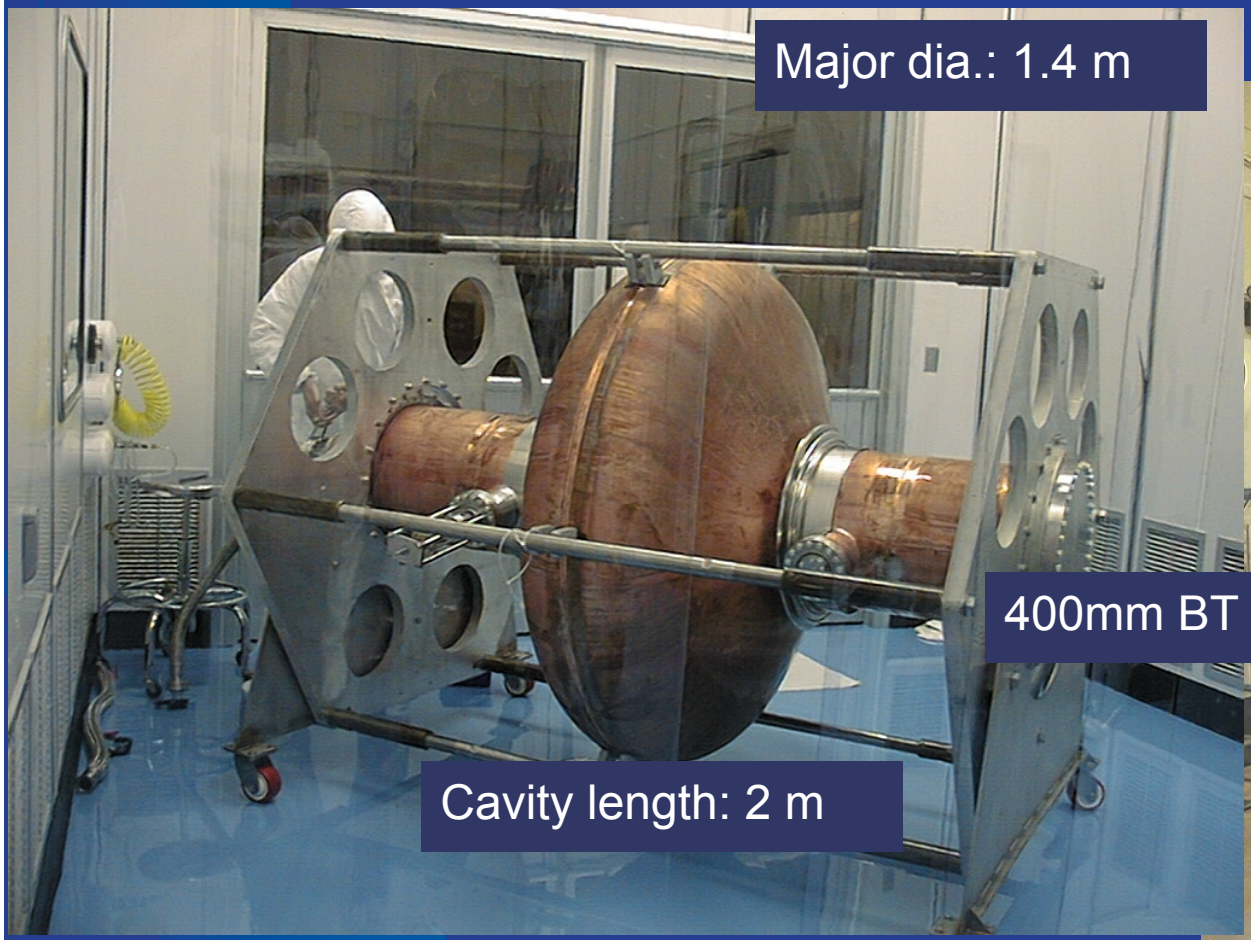
RCS requires 2 T p-p magnets at f = 400 Hz (U Miss & FNAL)

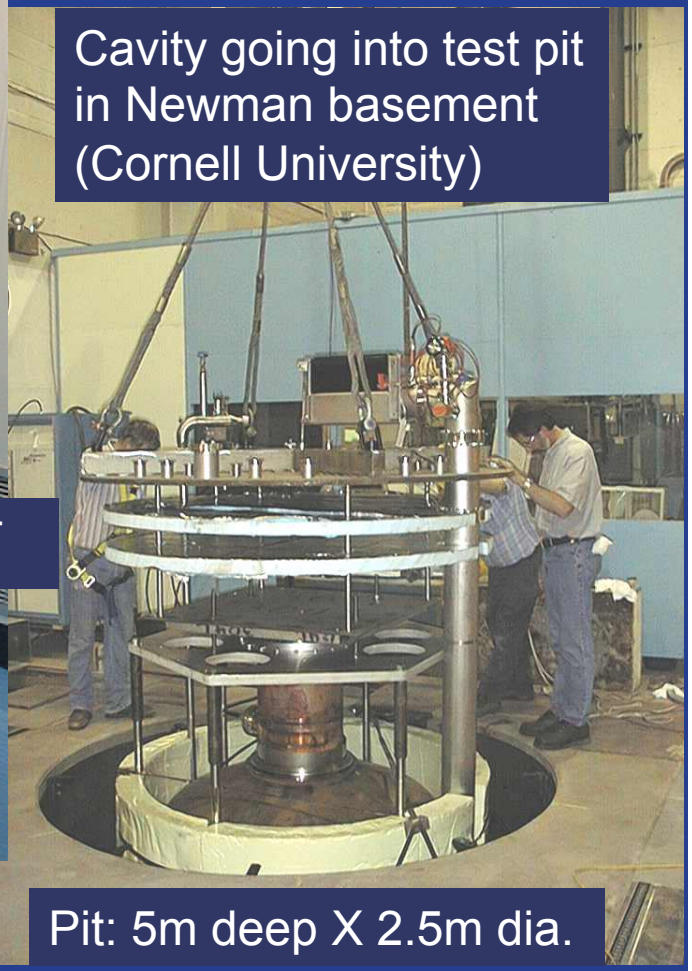


JEMMRLA Proposal: JLAB Electron Model of Muon RLA with Multi-pass Arcs

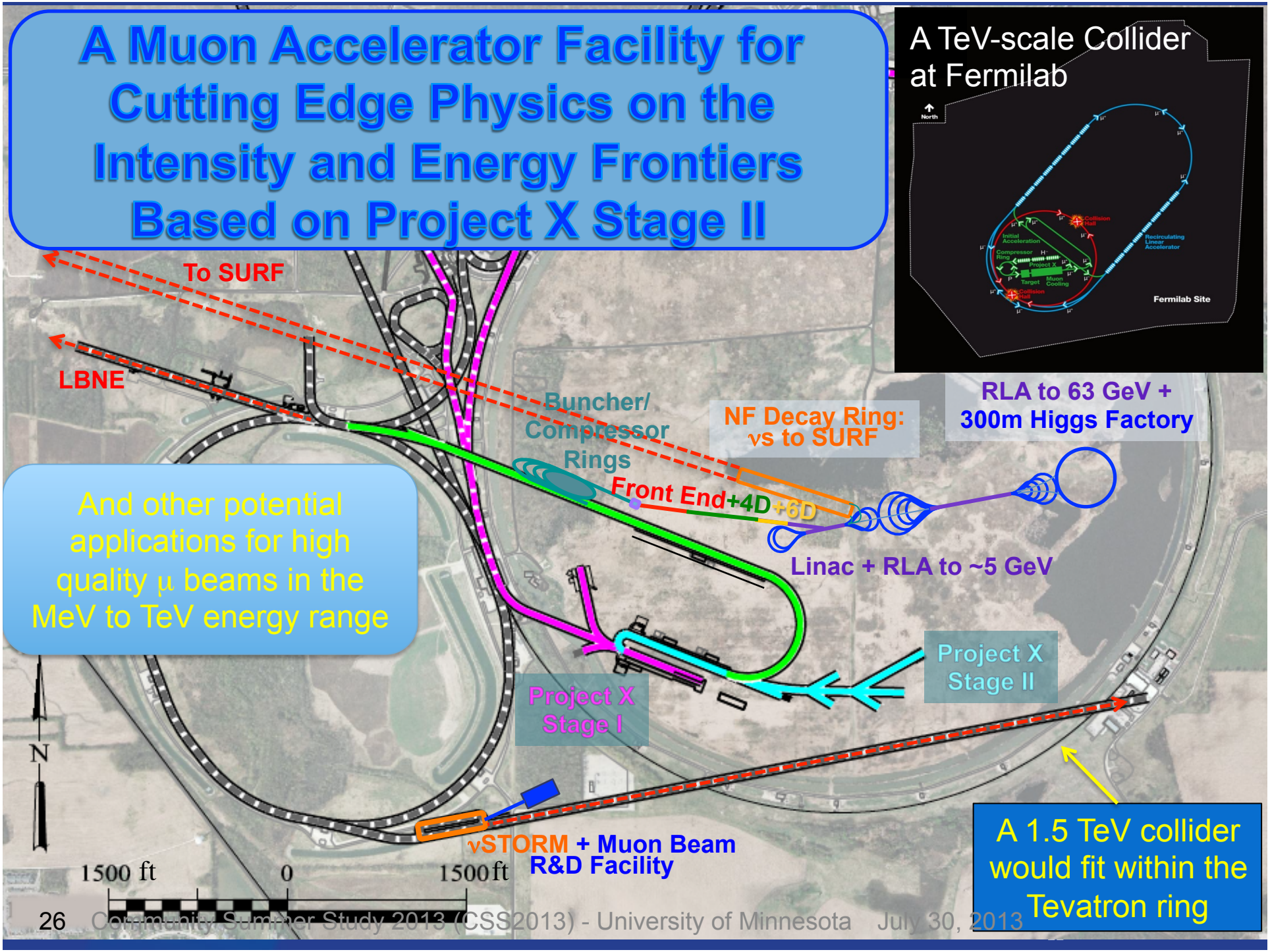
Superconducting RF Development

201 MHz SCRF R&D





A Muon Accelerator Facility for Cutting Edge Physics on the Intensity and Energy Frontiers Based on Project X Stage II



And other potential applications for high quality μ beams in the MeV to TeV energy range

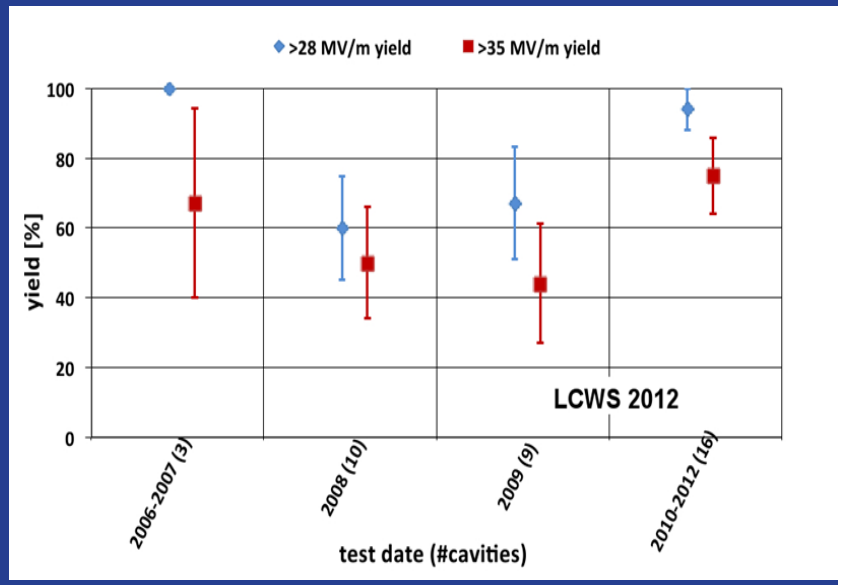
A 1.5 TeV collider would fit within the Tevatron ring

ONGOING SRF NEEDS

Acknowledgments to Bob Kephart (FNAL)

SRF Today: Bulk Nb Cavities

- Cavities based on bulk Nb have already reached performance values > 40 MV/m Eacc that approach the theoretical limits of Nb at ~ 180 mT for 1300 MHz cavities
- R&D has also led to surface processing that is cheaper and requires little or no Chemistry (e.g. Centrifugal Barrel Polish)
- Improved High Pressure Rinse and assembly techniques mean that Field emission is now often not a limitation
- JLAB 12 Gev Upgrade Cavities consistently ~ 25 MV/M
- ILC cavity yields > 90% at ~30 MV/M
  $Q_0 = 10^{10}$ seems achievable
- Key technologies for ILC or PX
  ⇨ ~in place
- But… high purity Nb is expensive
  ⇨ ~ 40% of the cavity cost
- So are cryomodules & big cryogenic refrigerators



What is possible in the future?

SRF Today: Surface R&D

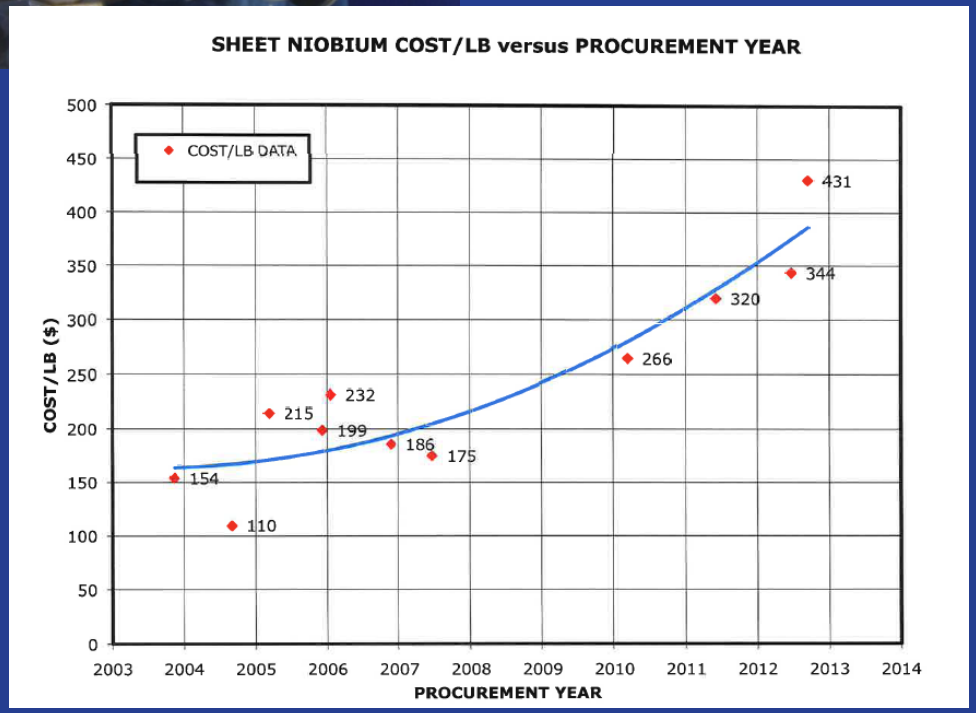
- Already a lot of effort in this direction
- Determine what matters at an SRF surface and control it!
  - Bad topography or particulates
    - ➔ Field emission or quenches
    - ➔ losses
    - ➔ need smooth clean surfaces
  - Impurities (e.g. precipitates, oxides, bulk contamination)
    - ➔ lower Q0
    - ➔ cryogenic load
  - Need surfaces with well controlled properties
  - But we don't always know what matters
- Performance is steadily getting better
- Well established techniques, useable for machines

But…

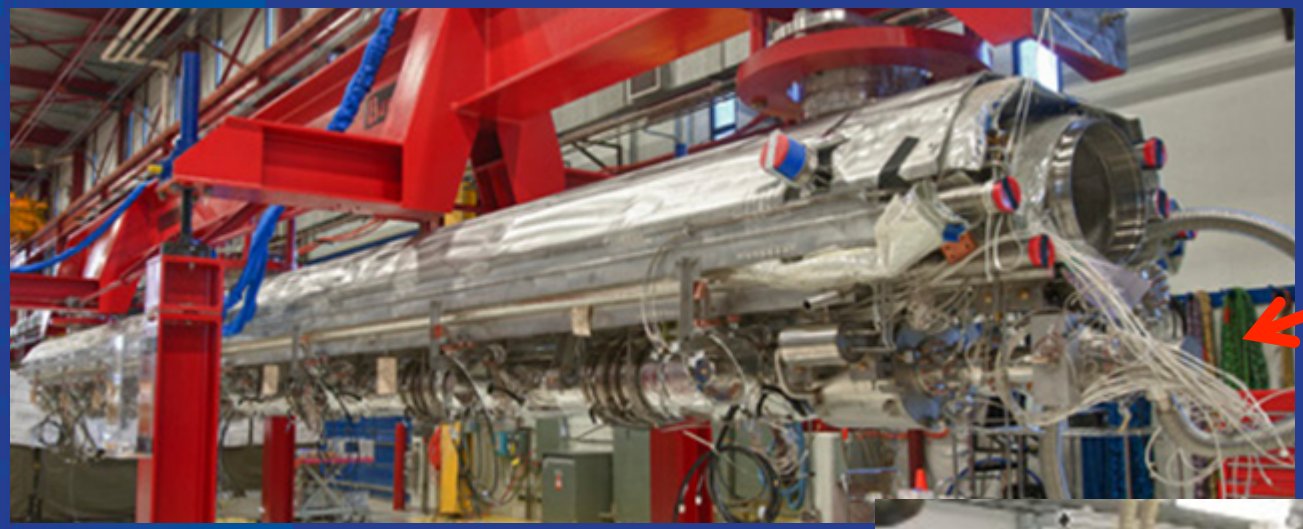
- It is unlikely that bulk Nb cavities built with high purity material and with anything like current processing are going to get a lot cheaper with time!

Bulk Nb Cavities

- Industrial fabrication technology in hand but cost of bulk Nb material is growing



Current Cryomodules (ILC, XFEL, CBEAF)



ILC/XFEL type cryomodule at Fermilab

- 2 K cryogenic systems
- RF distribution
- Complicated!
- Expensive!

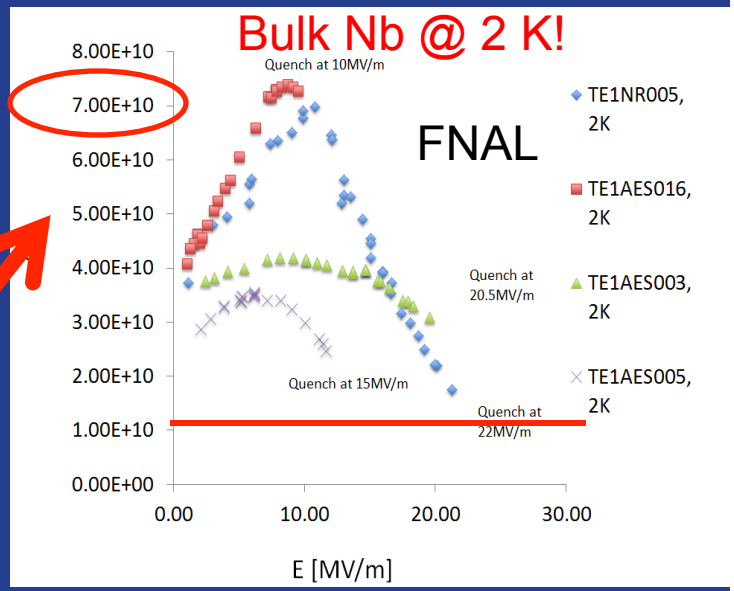
SRF: Its all about the surface!

- SRF currents flow only in the top 100 nm of a cavity surface

➔ We pay for a lot of expensive high purity Nb that we do not use!

- Q_0 is often determined by surface impurities such as hydrides or defects.
- New surface treatment (e.g. Nitrogen or Argon treatment @FNAL) show world record Q_0 at gradients of interest for CW HEP accelerators (e.g. Project X)

➔ Lower cryogenic costs

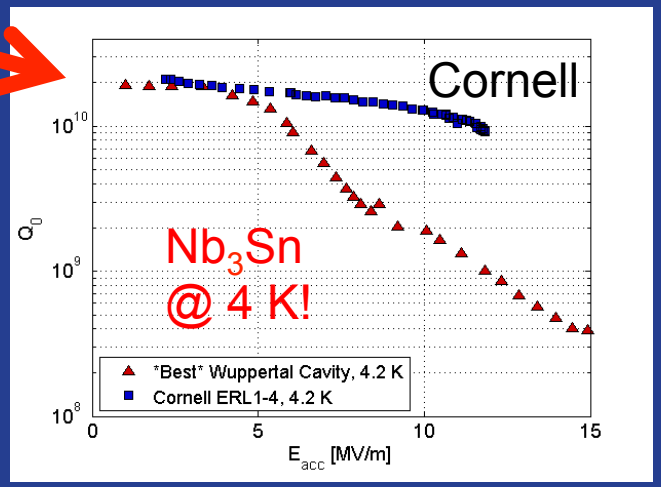


- Deposited films may allow the use of higher Tc materials resulting high Q_0 at higher temps.

- Thin films on e.g. Copper substrate are demonstrated to work. (e.g. LEP)

➔ Could save a lot of money but performance of SRF films are not yet as good as e.g. bulk Nb

➔ Thin film R&D could have a big pay off



The Future of SRF? Lower the Cost!

- Low-cost cavities with deposited SRF films
  - Bulk material is cheap (e.g. copper or aluminum)
  - High Tc film SRF surfaces, better methods ➔ higher gradients
  - High Q_0 ➔ enables CW operation

- Low-cost cryomodules
  - Operate cavities at 4 K or above via conduction or tube cooling
  - Equip each cryomodule with cryo-coolers
    - ➢ No big cryogenics plant or large He inventory!
    - ➢ No Helium vessels!
    - ➢ Much cheaper cryomodule, perhaps even more reliable!

- Low cost, high efficiency RF
  - Solid State or Magnetron based

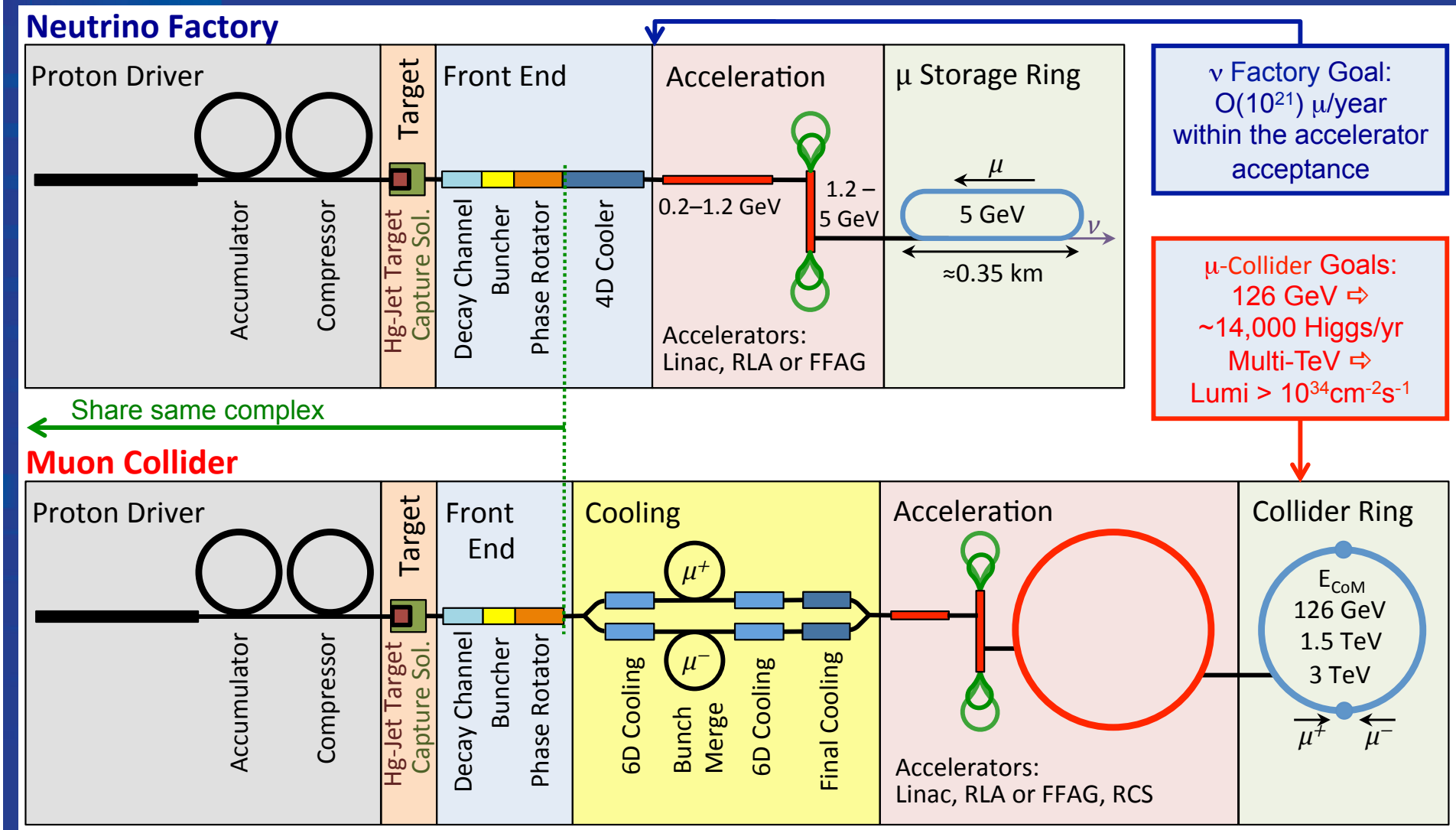
⇨ Goal: an SRF Linac for HEP built at well below ILC costs
  - Seems achievable, and has lots of synergy with industrial use of SRF
  - Steady R&D support needed to make this possible

Conclusion

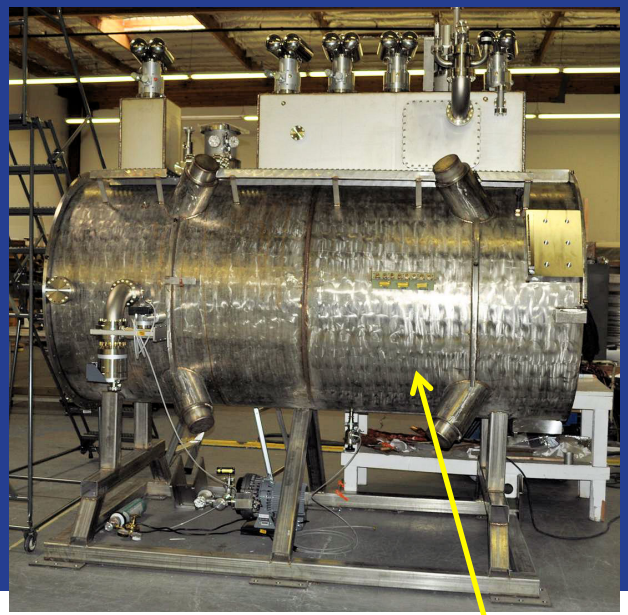
- High power targetry will be a crucial element of the accelerators needed for the 21st century
  - Considerable R&D is required
  - The time for investment is now
- Muon accelerators offer potentially unique capabilities for HEP
  - A vibrant R&D program needs further support to develop this potential
- SRF will be central to a broad range of accelerator applications on the horizon
  - Can we develop more cost effective implementations to leverage our HEP aspirations?

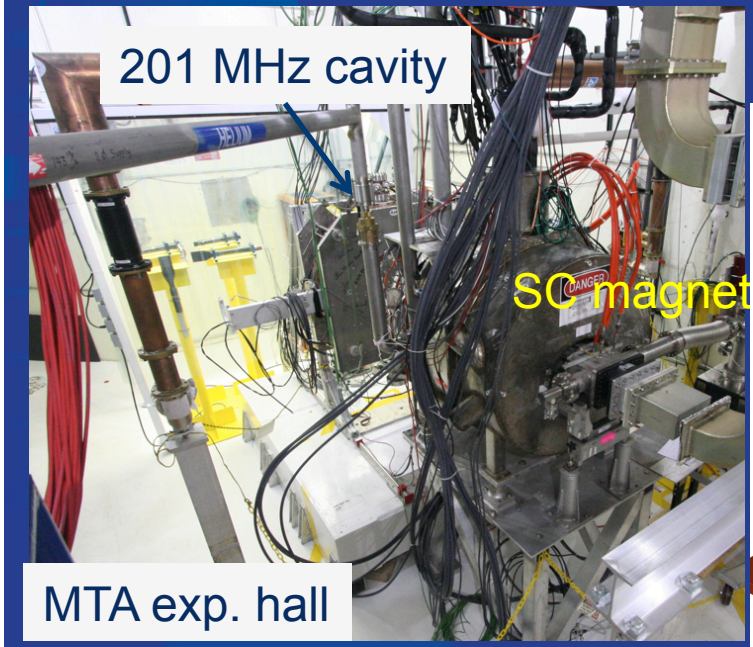
BACKUP SLIDES

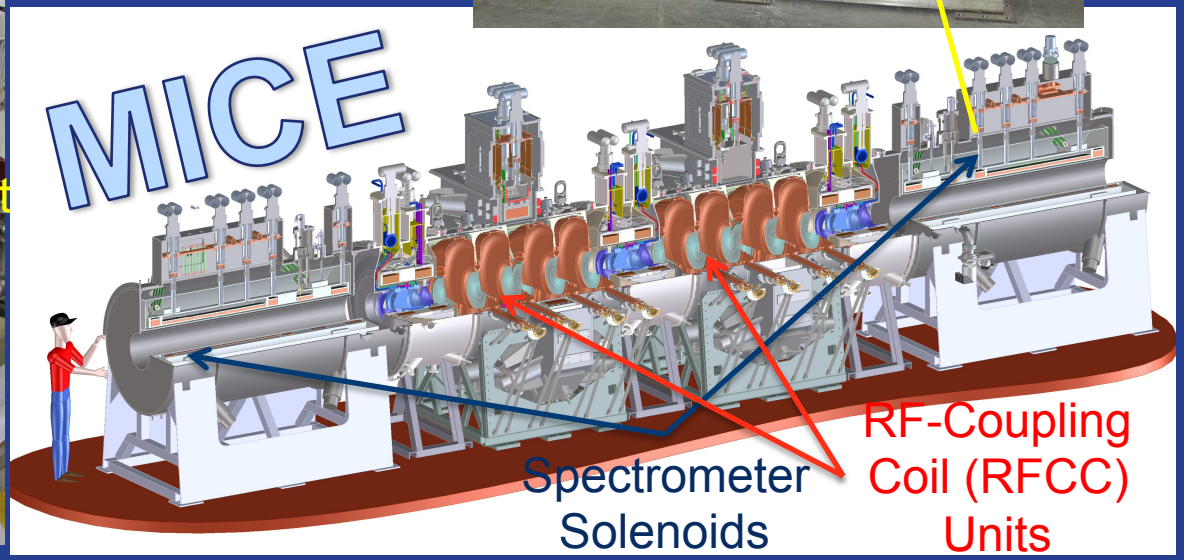
The U.S. Muon Accelerator Program



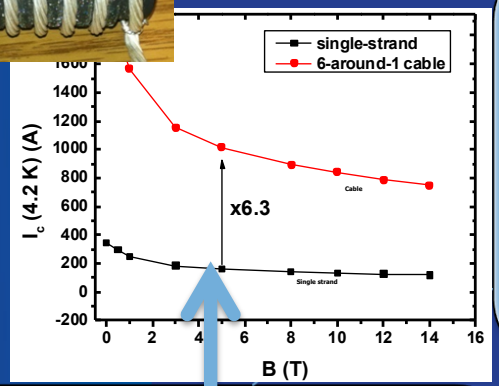
Elements of the R&D Program





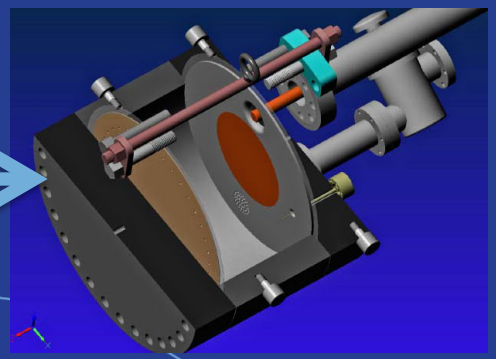


Cooling Channel R&D Effort



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

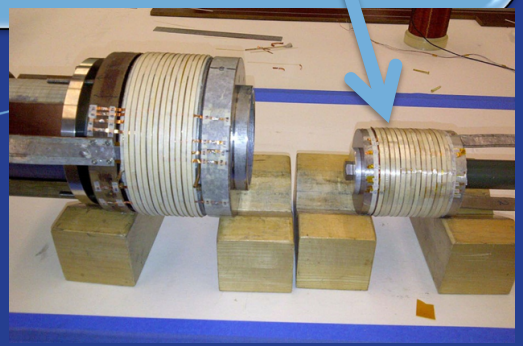
FNAL-Tech Div
T. Shen-Early Career Award

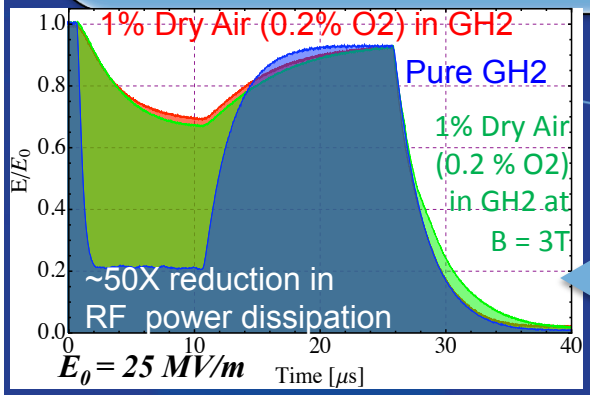
The Path to a Viable Muon Ionization Cooling Channel

World Record HTS-only Coil

15T on-axis field
16T on coil

PBL/BNL





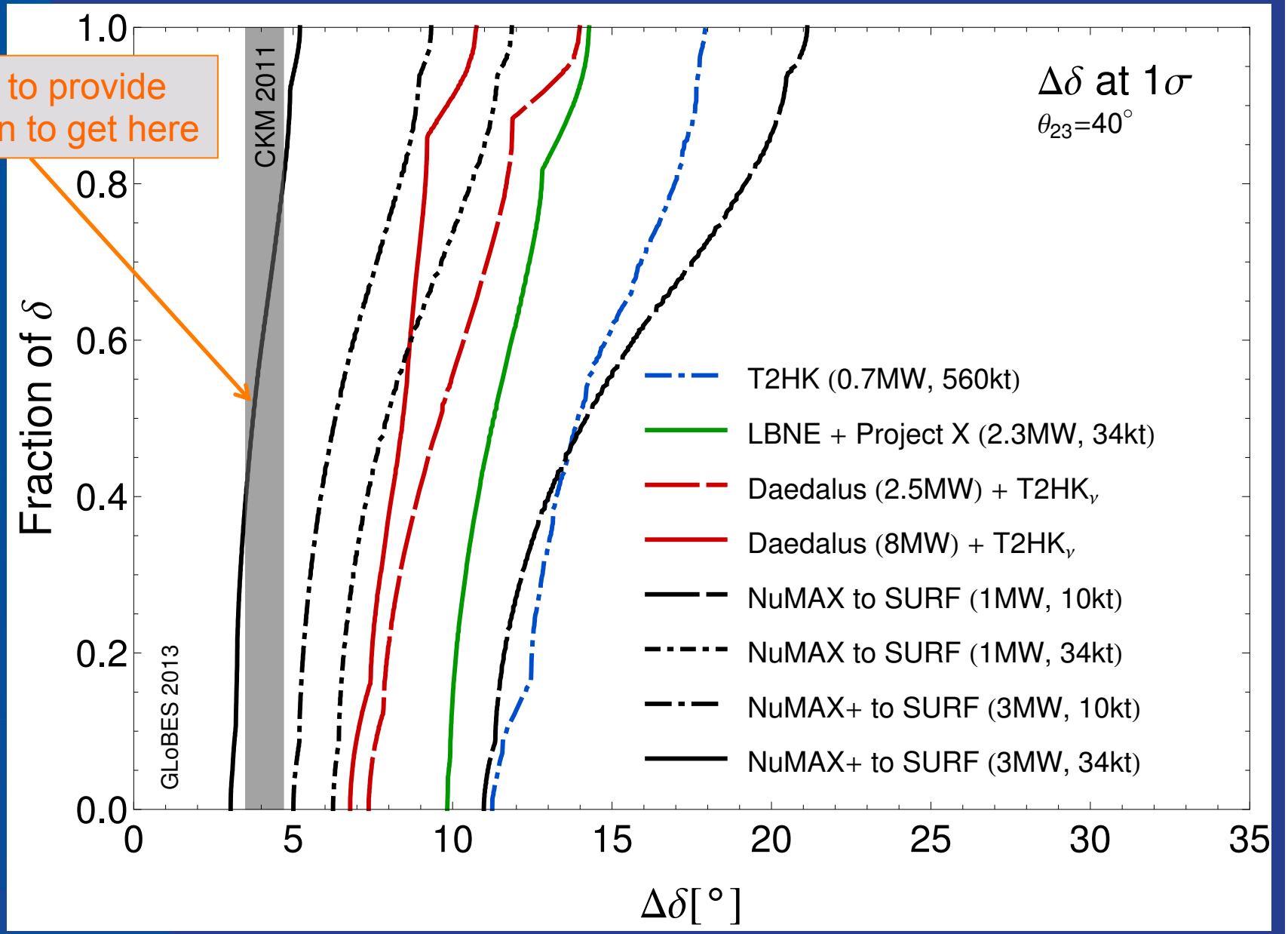
Demonstration of High Pressure RF Cavity in 3T Magnetic Field with Beam

Extrapolates to
μ-Collider Parameters

MuCool Test Area

The ν Sector

We want to provide the option to get here



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)	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, 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_s	cm	5.6	6.3	0.9	0.5	1	0.5	2
Proton Driver Power	MW	4$^\#$	4	4	4	4	4	1.6

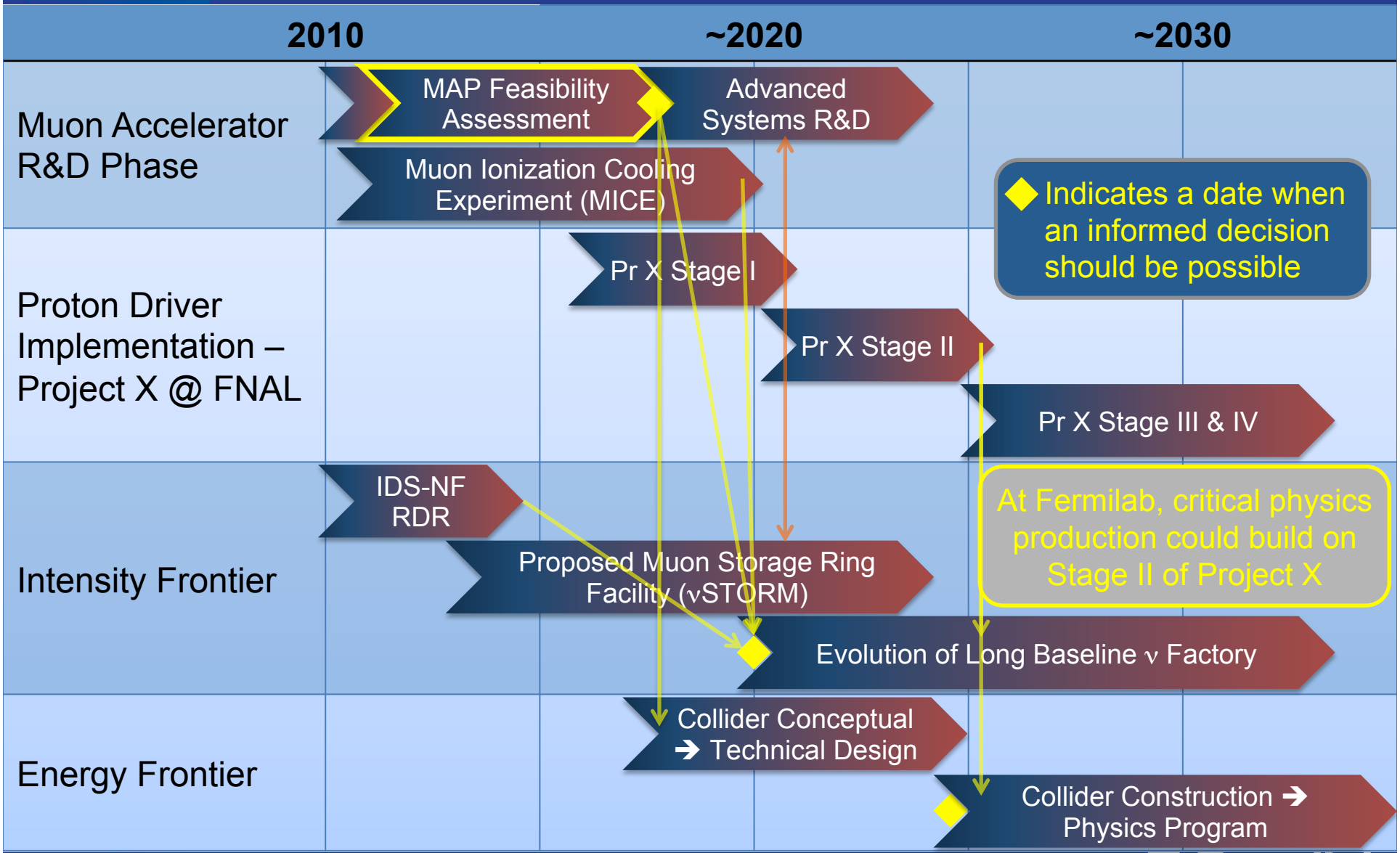
$^\#$ Could begin operation with Project X Stage II beam

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

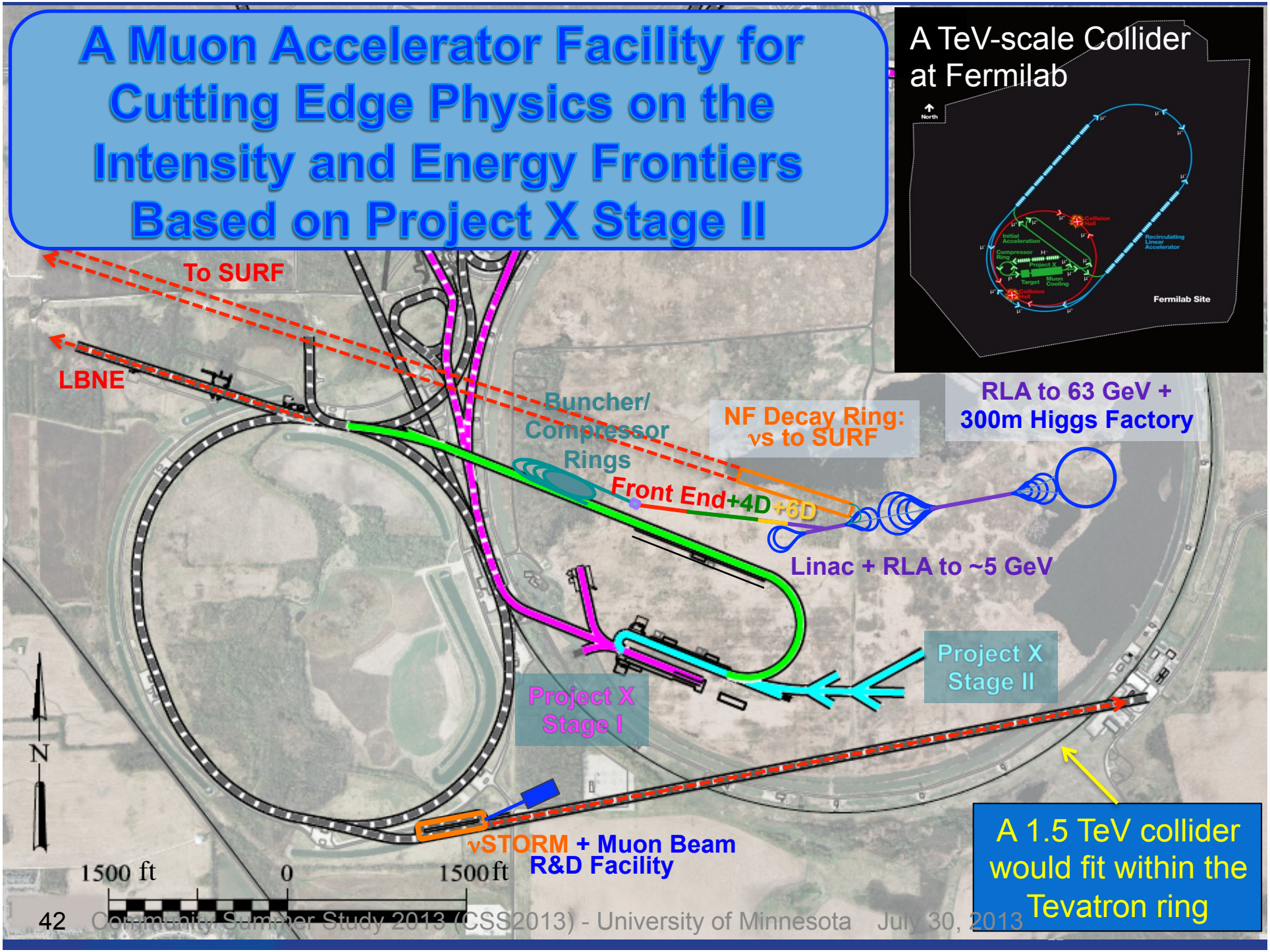
Success of advanced cooling concepts ⇨ several × 10^{32}

Site Radiation mitigation with depth and lattice design: ≤ 10 TeV

MAP Timeline



A Muon Accelerator Facility for Cutting Edge Physics on the Intensity and Energy Frontiers Based on Project X Stage II

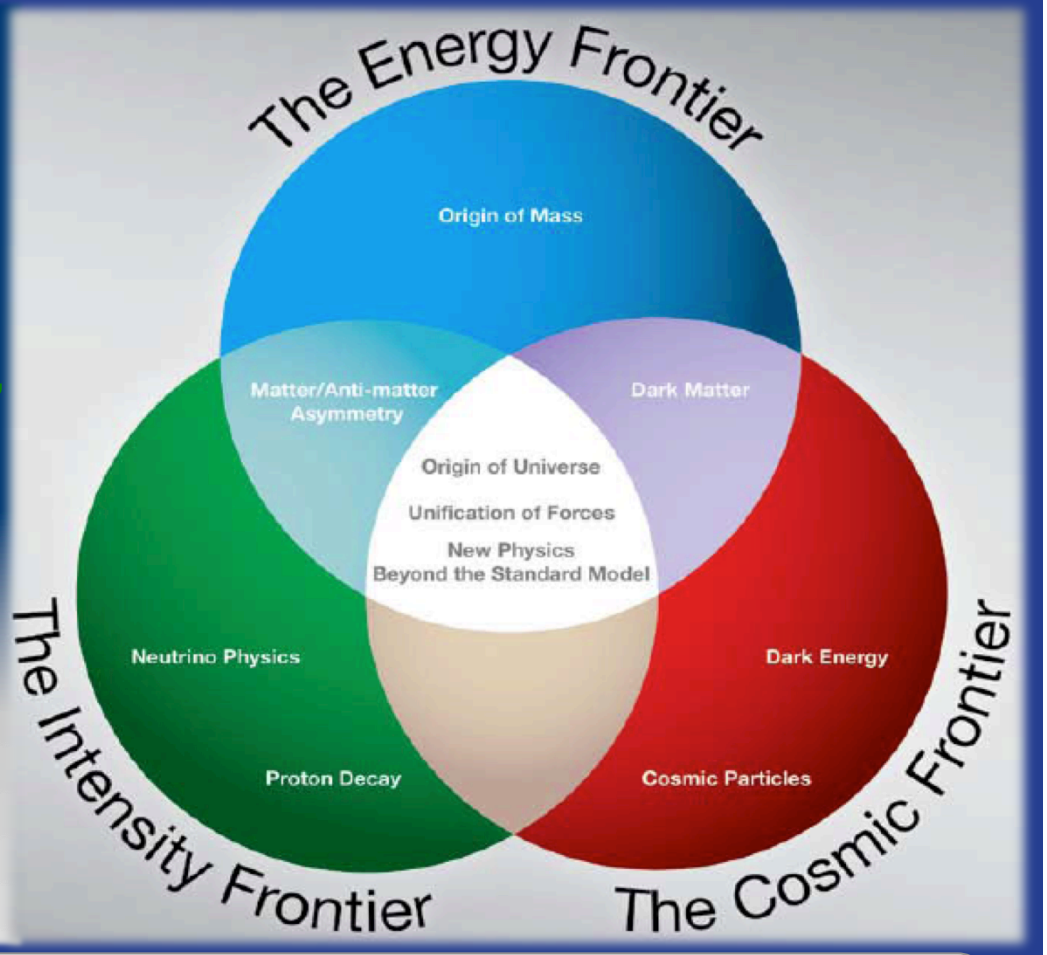


The Aims of the Muon Accelerator Program

Muon accelerator R&D is focused on developing a facility that can address critical questions spanning two frontiers…

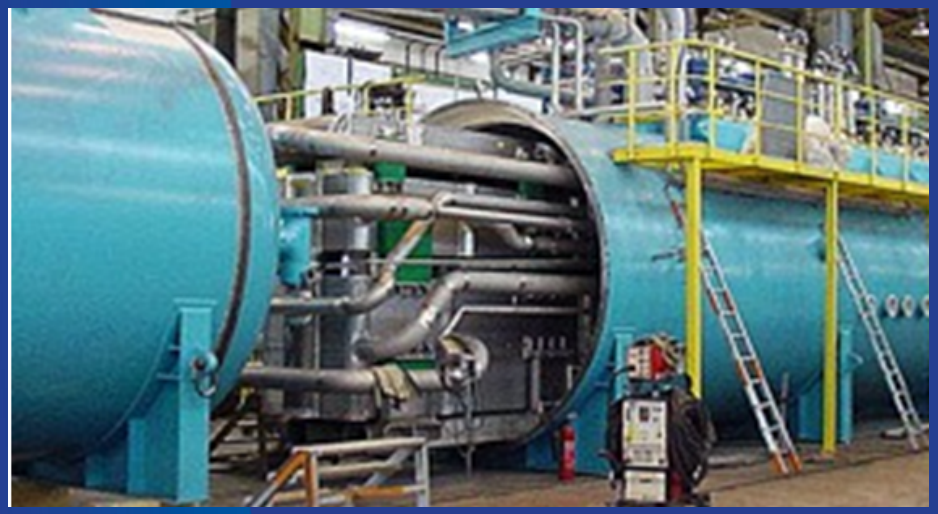
The Intensity Frontier:
with a ***Neutrino Factory*** producing well-characterized ν beams for precise, high sensitivity studies

The Energy Frontier:
with a ***Muon Collider*** capable of reaching multi-TeV CoM energies
and
*a **Higgs Factory** on the border between these Frontiers*



The unique potential of a facility based on muon accelerators is physics reach that SPANS 2 FRONTIERS

The Future of Cryogenics for HEP?



LHC Cryo-Plant (1of 6)

LHC Helium storage

Cryomodule mounted Cryo-coolers
Compact, NO Liquid Helium!
But…. don't work well at 2 K