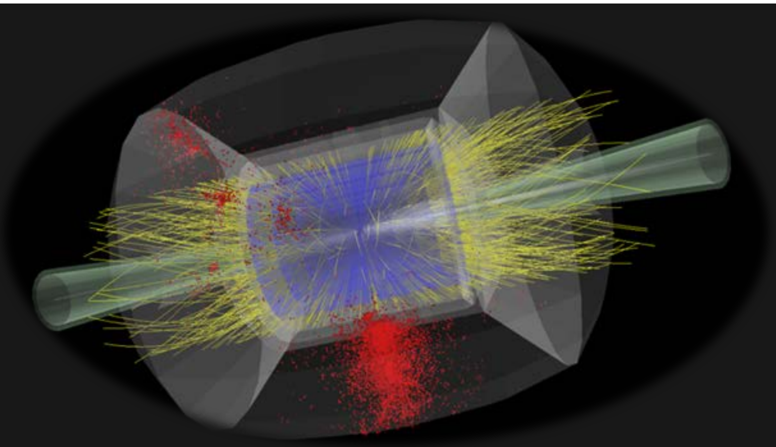
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), July 2022.
Plenary presentation PL4 given at MT27, 15-19 November 2021, Fukuoka, Japan.



Muon Colliders & Their Magnet Technology Needs

Mark Palmer
Brookhaven National Laboratory

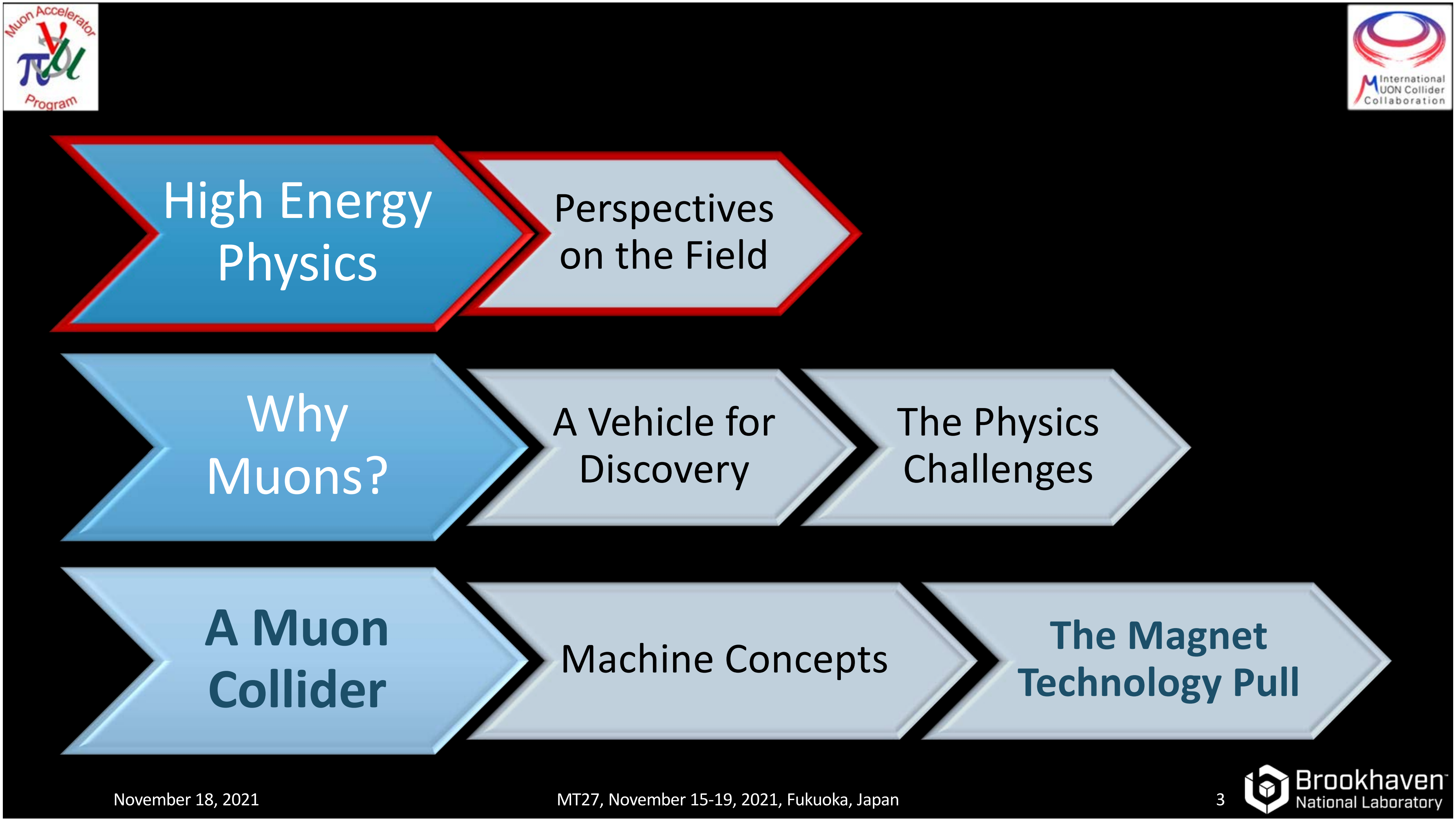
Drawing on work conducted by:
the US Muon Accelerator Program (MAP),
the International Design Study for a Neutrino Factory (IDS-NF),
the International Muon Ionization Cooling Experiment (MICE) and
the International Muon Collider Collaboration

U.S. DEPARTMENT OF ENERGY | Office of Science

Brookhaven National Laboratory

Themes of this Talk

- High Energy Physics
  - Perspectives on the Field
- Why Muons?
  - A Vehicle for Discovery
  - The Physics Challenges
- **A Muon Collider**
  - Machine Concepts
  - **The Magnet Technology Pull**



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A Muon Collider
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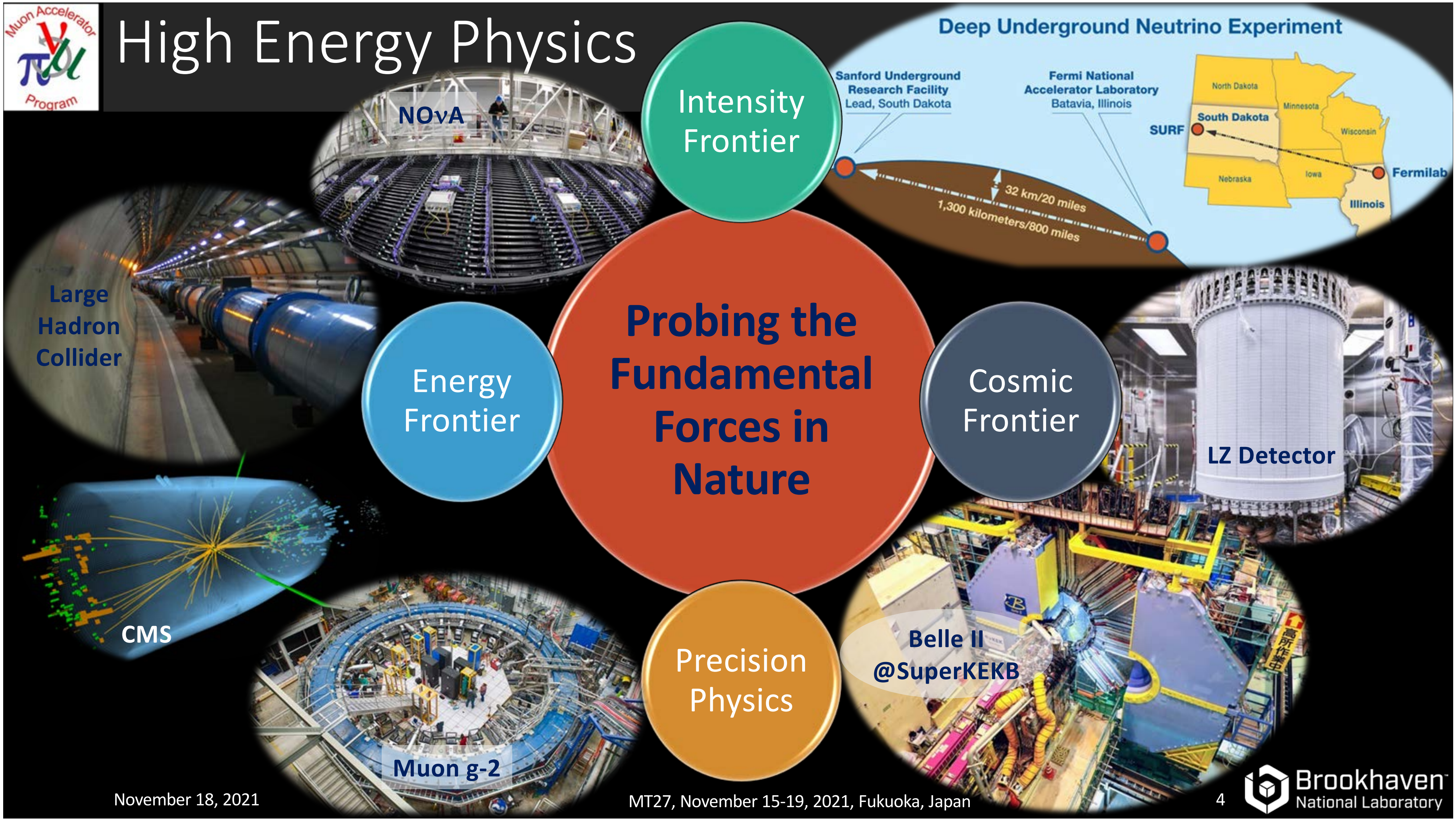
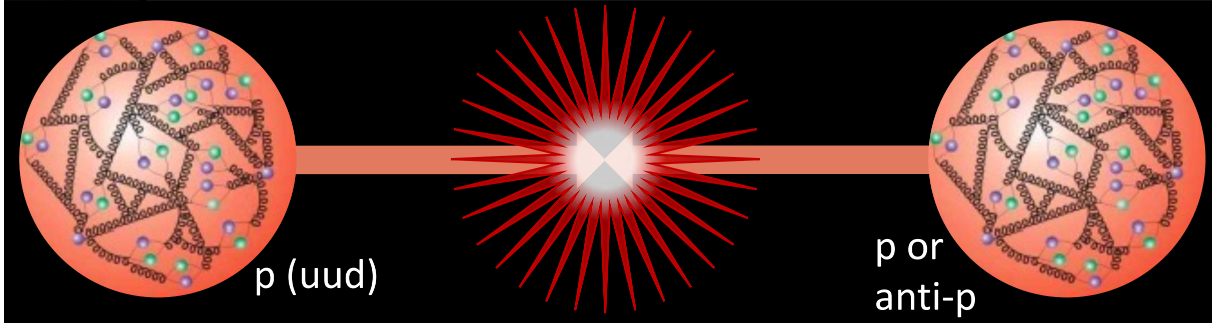


High Energy Physics

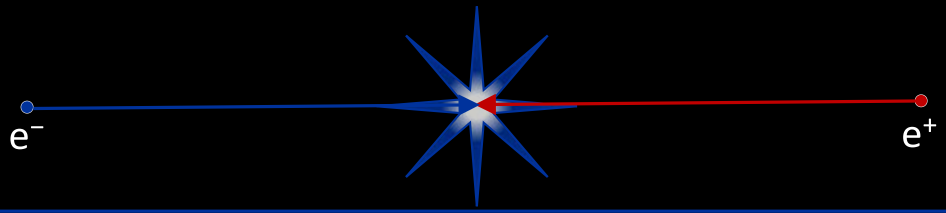
Probing the Fundamental Forces in Nature

- Intensity Frontier
- Energy Frontier
- Cosmic Frontier
- Precision Physics

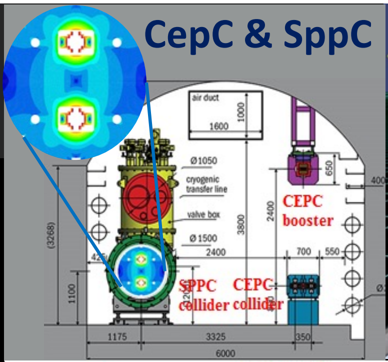
HEP Particle Colliders

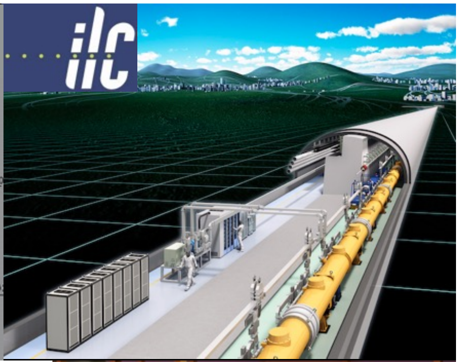


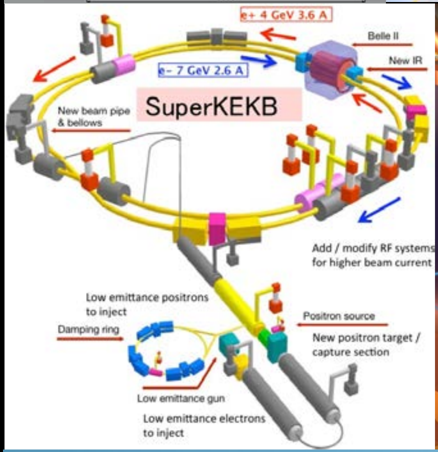
Proton-proton (or anti-proton) Collisions:
- Offer highest achievable center-of-mass collision energies
- Collisions of composite particles
- Discovery potential via Electroweak and Strong Interactions

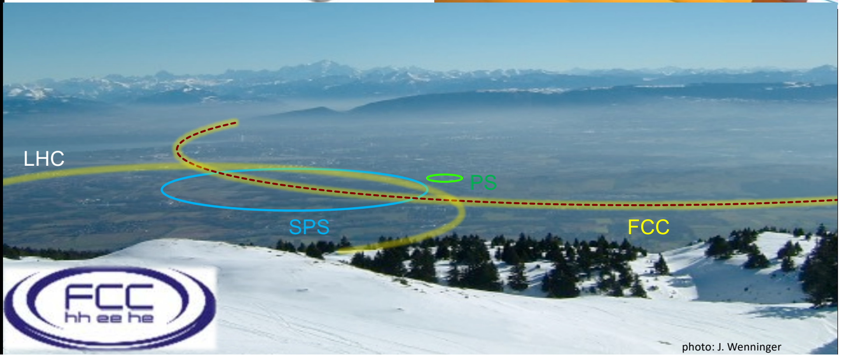


Electron-Positron Collisions:
- Collision of point-like fermions with well-defined initial state
- Precision measurements via Electroweak Interactions

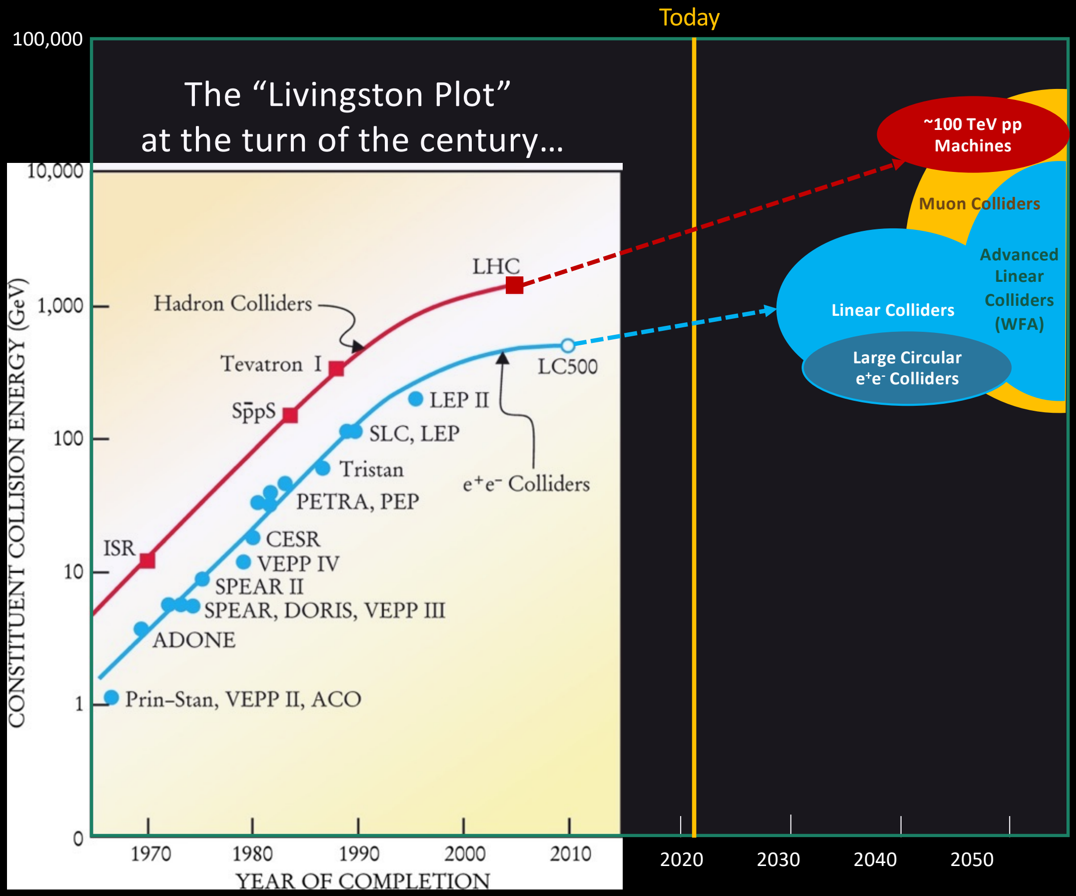








A Look at Where We Are



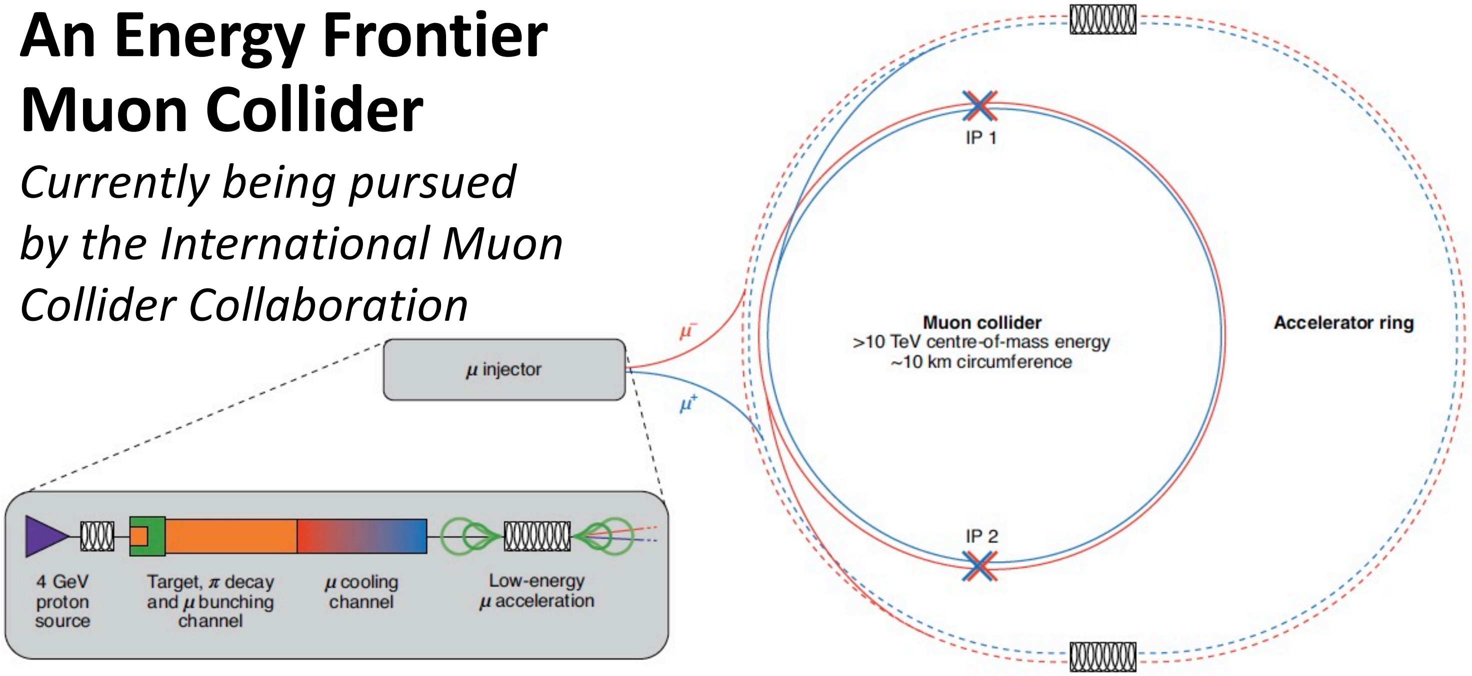
- Livingston Plot in 2001
  [M. Tigner, Physics Today 54 , 1, 36 (2001)]
  - Through the 1900s, progress driven by critical technology developments for many decades (1940s –)
  - CoM Energies increasing by ***~2 orders of magnitude*** every ***25 years***
- Where are we now?
  - Progress has become much more challenging
    - Machine Complexity
    - Costs (R&D and capital)
  - ***What are our options and priorities for the next HEP machine?***

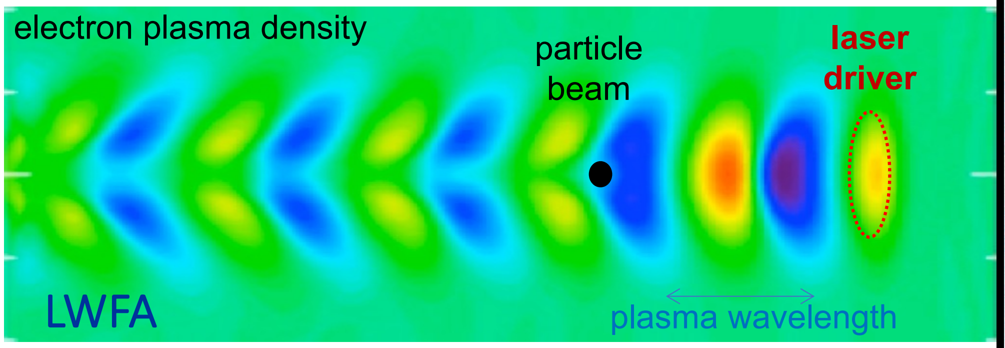
Advanced Concepts

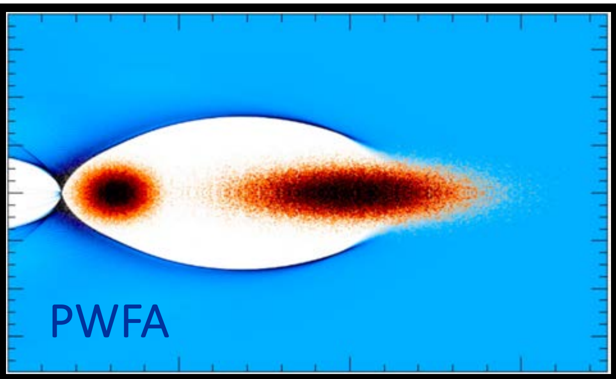
- Emerging Options
  - Muon Collider with strong dependence on advanced magnet technology
  - Wakefield Acceleration
    - Laser-Driven Plasma
    - Beam-Driven Plasma
    - Beam-Driven Structure

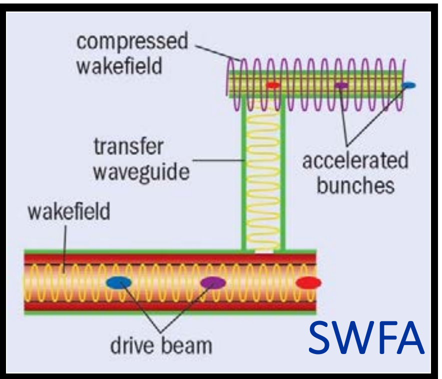
An Energy Frontier Muon Collider

Currently being pursued by the International Muon Collider Collaboration







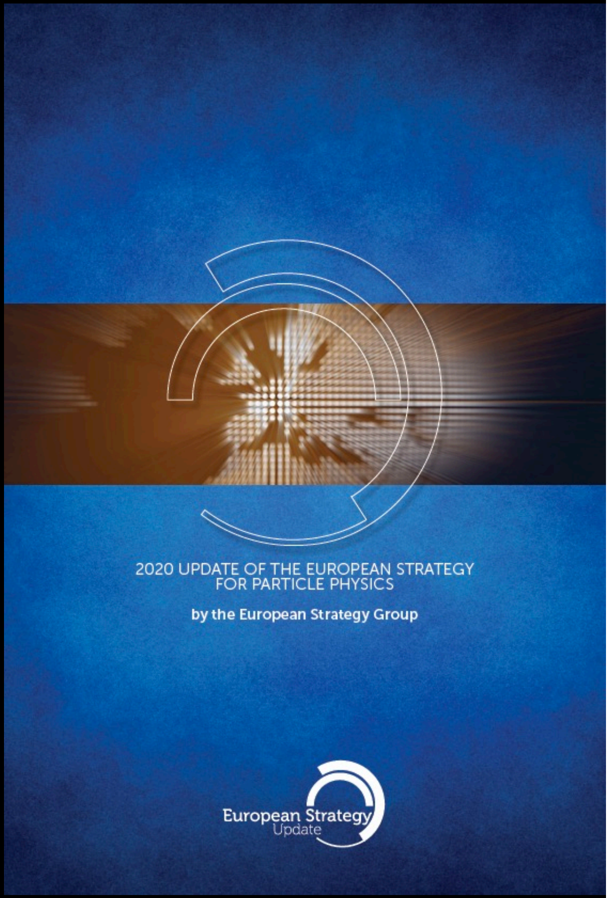


Perspectives

- Community planning processes are underway around the world
  - 2020 Update of the European Strategy for Particle Physics
    - European Strategy Update
    - European Accelerator R&D Roadmap presently in preparation
  - US Snowmass Community Planning Process will continue through mid-2022
    - Snowmass

Snowmass 2021

A major focus of each effort is the technology required to deliver an Energy Frontier discovery machine by roughly the middle of the century!



2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

European Strategy Update

High Energy Physics

- Perspectives on the Field

Why Muons?

- A Vehicle for Discovery
- The Physics Challenges

A Muon Collider

- Machine Concepts
- **The Magnet Technology Pull**

Why Muons?

Physics Frontiers

- **Intense and cold muon beams ⇨ unique physics reach**
  - Tests of Lepton Flavor Violation
  - Anomalous Magnetic Moment (g-2)
  - Precision sources of neutrinos
  - Next generation lepton collider

$$m_\mu = 105.7\,MeV/c^2$$
$$\tau_\mu = 2.2\,\mu s$$

Colliders

- **Opportunities**
  - s-channel production of scalar objects ⇨ strong coupling to Higgs → $\sim\left(\frac{m_\mu^2}{m_e^2}\right) \cong 4\times10^4$
  - Strong coupling to particles like the Higgs
  - Reduced synchrotron radiation (E^4/m^4) ⇨ multi-pass acceleration feasible
  - Beams can be produced with small energy spread
  - Beamstrahlung effects suppressed at the collider IP
- ***BUT* the accelerator complex and detector must be able to handle the impacts of μ decays**

Collider Synergies

- High intensity beams required for a long-baseline Neutrino Factory are readily provided in conjunction with a Muon Collider Front End
- Such overlaps offer unique staging strategies to guarantee physics output while developing a muon accelerator complex capable of supporting collider operations

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

$\mu^+\mu^-$ Collider Luminosity

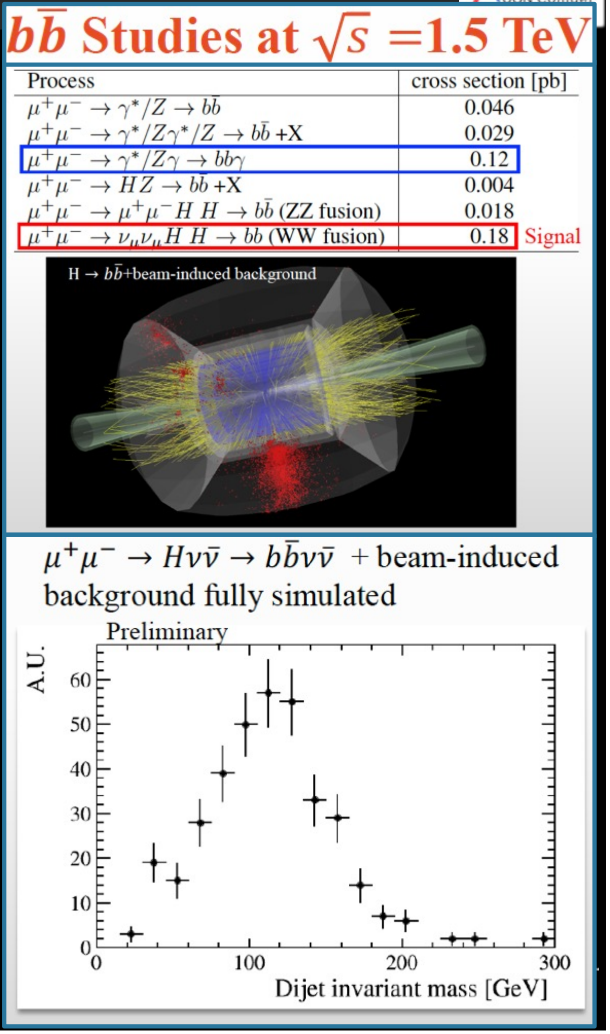
Detector and Physics Performance at a Muon Collider
N. Bartosik et al 2020 JINST 15 P05001

- For a muon collider, we can write the luminosity as:

$$\boxed{\mathcal{L} = \frac{N^2 f_{coll}}{4\pi\sigma_x\sigma_y} = \frac{\left\langle N^2\right\rangle_{n_{turns}} n_{turns} f_{bunch}}{4\pi\sigma_\perp^2}}$$

- For the 1.5 TeV muon collider design, we have
  - N = 2×10^{12} particles/bunch
  - $\sigma_{x,y}$ ~ 5.9 μm, β^* = 10 mm, $\varepsilon_{x,y}(norm)$ = 25 μm-rad
  - n_{turns}~1000 ∝ 150 ⟨B[T]⟩
  - f_{bunch}=15 Hz (rate at which new bunches are injected)

$$\boxed{\mathcal{L} \approx \frac{N_0^2 n_{turns} f_{bunch}}{4\pi\sigma_\perp^2} \approx 1.4\times10^{34}\, cm^{-2}s^{-1}}$$



$b\bar{b}$ Studies at $\sqrt{s}$ =1.5 TeV

Process	cross section [pb]	
$\mu^+\mu^- \to \gamma^*/Z \to b\bar{b}$	0.046	
$\mu^+\mu^- \to \gamma^*/Z\gamma^*/Z \to b\bar{b}$ +X	0.029	
$\mu^+\mu^- \to \gamma^*/Z\gamma \to bb\gamma$	0.12	
$\mu^+\mu^- \to HZ \to b\bar{b}$ +X	0.004	
$\mu^+\mu^- \to \mu^+\mu^- H\ H \to b\bar{b}$ (ZZ fusion)	0.018	
$\mu^+\mu^- \to \nu_\mu\nu_\mu H\ H \to bb$ (WW fusion)	0.18	Signal

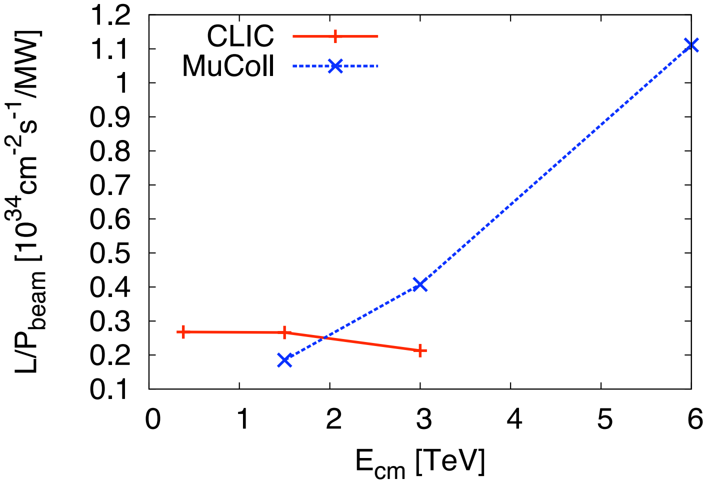
H → $b\bar{b}$+beam-induced background

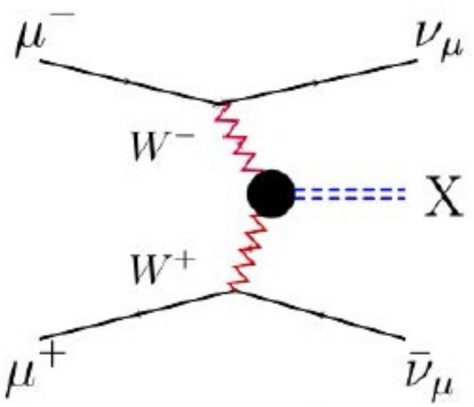
$\mu^+\mu^- \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$ + beam-induced background fully simulated

Potential as an Energy Frontier Discovery Machine

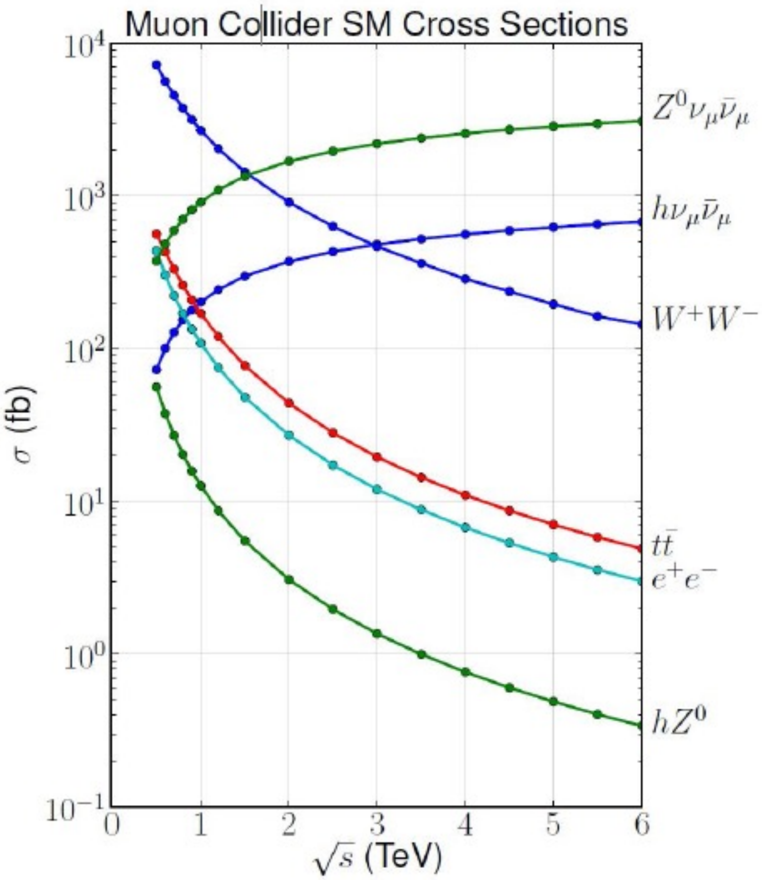
High Energy Collisions

- At √s > 1 TeV: Fusion processes dominate
  - An Electroweak Boson Collider
  - Disscovery machine complementary to high energy pp collider
- At >5TeV: Higgs self-coupling resolution <10%
- Luminosity scaling at multi-TeV energies is favorable when compared to e^+e^-



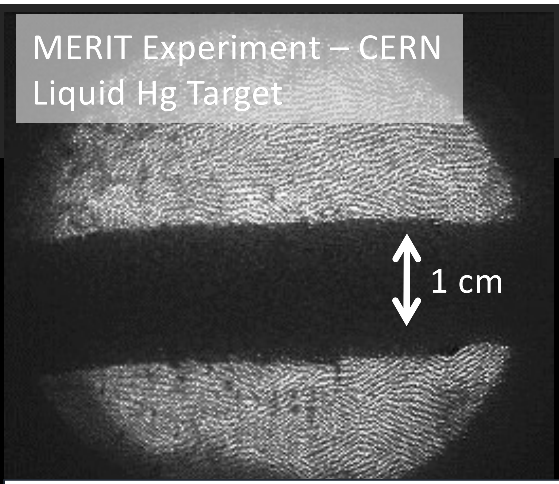


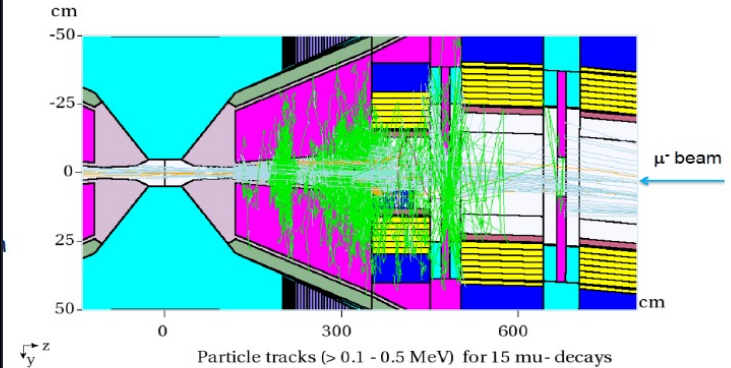
$$\sigma(s) = C \ln\left(\frac{s}{M_X^2}\right) + \ldots$$



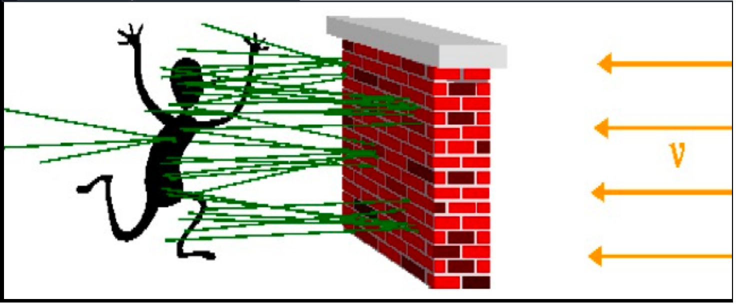
The Physics Challenges

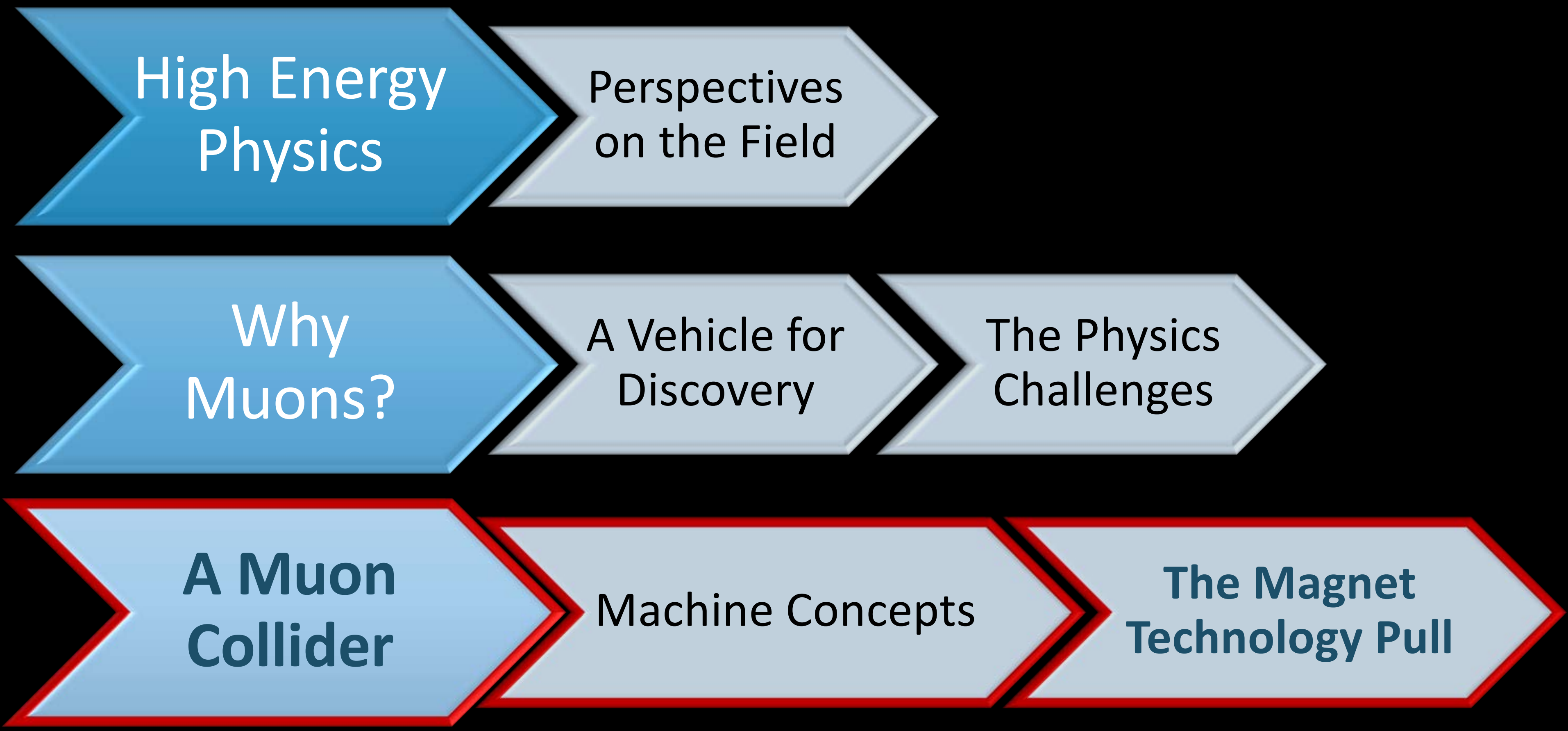
- Muons are difficult to produce
  - Most effective route is tertiary production from a multi-MW proton beam on a target: **p** → π → μ
  - Beams must be bunched and cooled to produce luminosity in a collider
- Muons decay
  - All beam manipulations must be rapidly carried out to deliver useable beams to a collider
    - Bunching
    - Cooling
    - Acceleration
  - Electrons from the muon decays deposit significant energy in the accelerator components and physics detector
  - Neutrinos from the muon decays can produce ionizing radiation far from the accelerator complex


MERIT Experiment – CERN
Liquid Hg Target



Particle tracks (> 0.1 - 0.5 MeV) for 15 mu- decays





High Energy Physics → Perspectives on the Field

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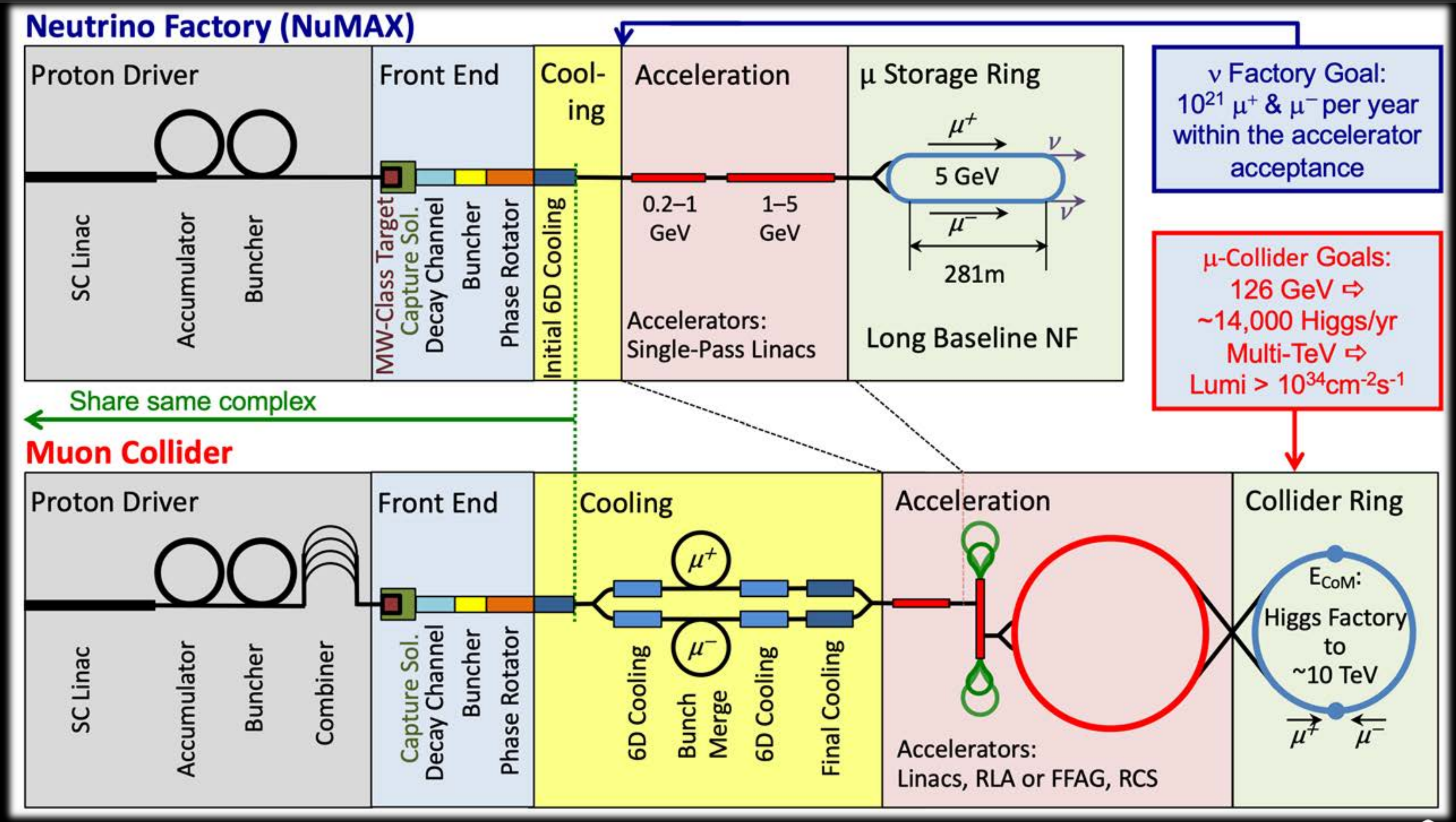
Elements of a Muon Collider (and ν Factory)



MC Parameters as Developed by MAP

RAST, Vol 10, No. 01, pp. 189-214 (2019)

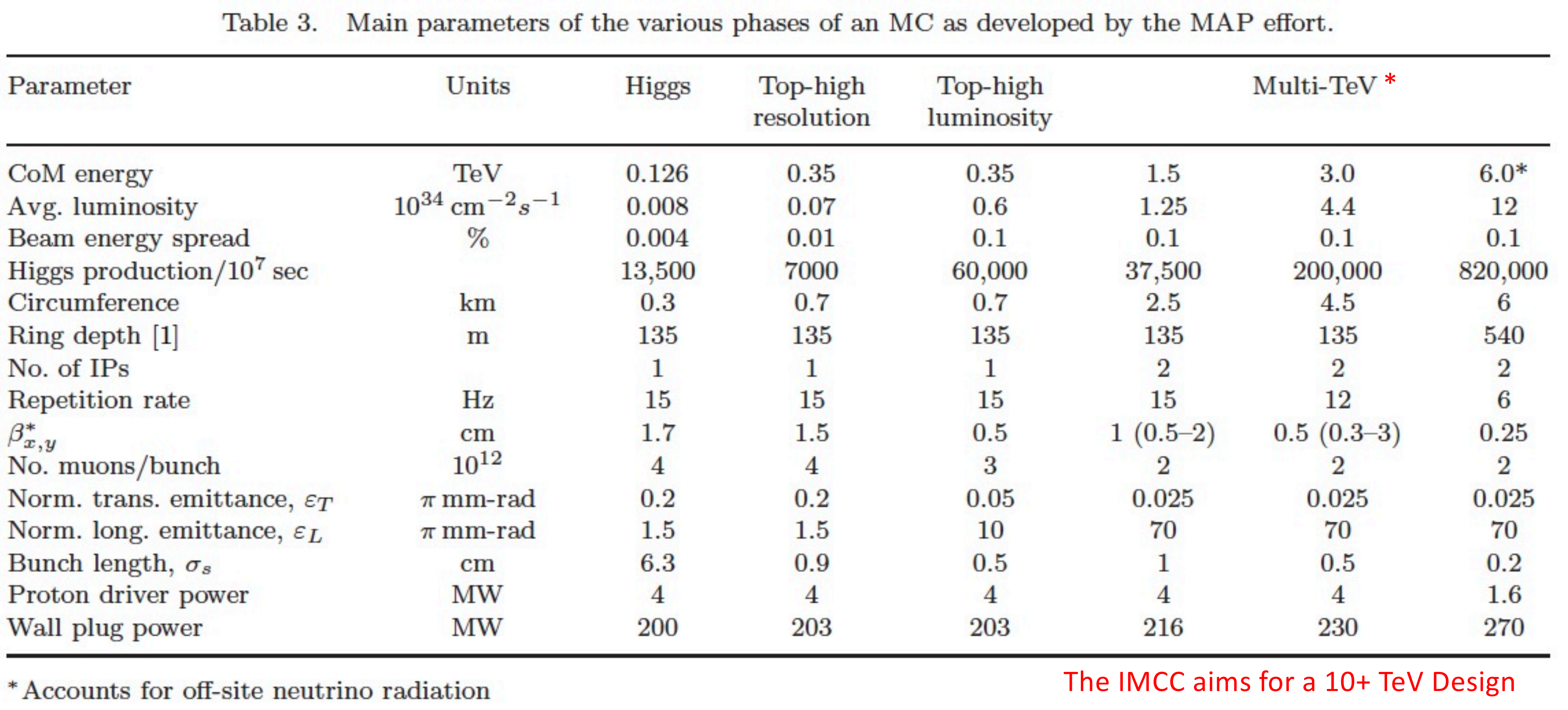


Table 3. Main parameters of the various phases of an MC as developed by the MAP effort.

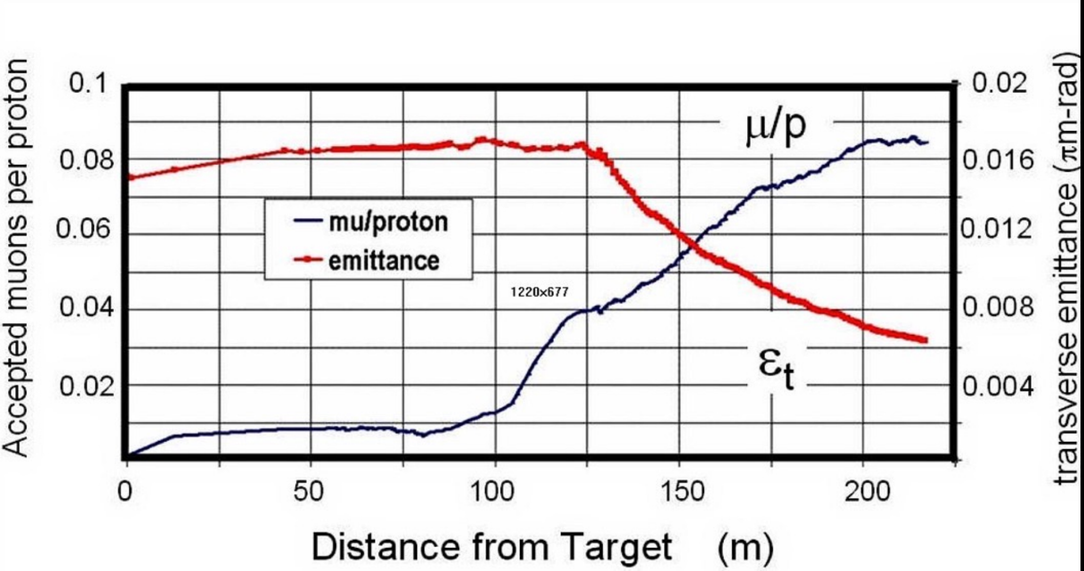
Parameter	Units	Higgs	Top-high resolution	Top-high luminosity	Multi-TeV *		
CoM energy	TeV	0.126	0.35	0.35	1.5	3.0	6.0*
Avg. luminosity	$10^{34}\ \mathrm{cm}^{-2}s^{-1}$	0.008	0.07	0.6	1.25	4.4	12
Beam energy spread	%	0.004	0.01	0.1	0.1	0.1	0.1
Higgs production/10^7 sec		13,500	7000	60,000	37,500	200,000	820,000
Circumference	km	0.3	0.7	0.7	2.5	4.5	6
Ring depth [1]	m	135	135	135	135	135	540
No. of IPs		1	1	1	2	2	2
Repetition rate	Hz	15	15	15	15	12	6
$\beta^*_{x,y}$	cm	1.7	1.5	0.5	1 (0.5–2)	0.5 (0.3–3)	0.25
No. muons/bunch	10^{12}	4	4	3	2	2	2
Norm. trans. emittance, ε_T	π mm-rad	0.2	0.2	0.05	0.025	0.025	0.025
Norm. long. emittance, ε_L	π mm-rad	1.5	1.5	10	70	70	70
Bunch length, σ_s	cm	6.3	0.9	0.5	1	0.5	0.2
Proton driver power	MW	4	4	4	4	4	1.6
Wall plug power	MW	200	203	203	216	230	270

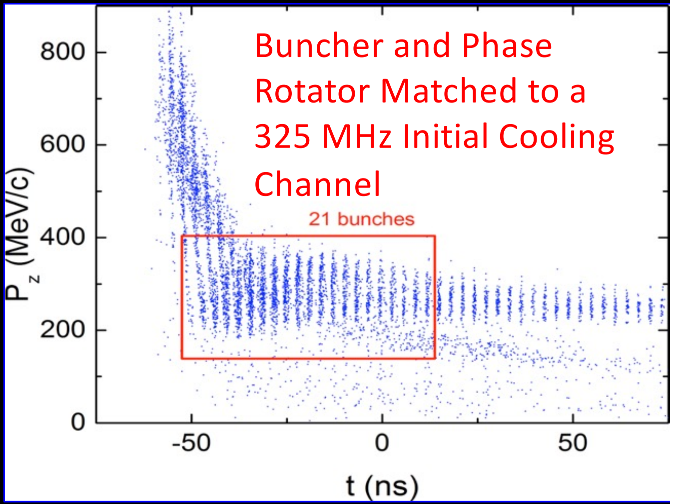
* Accounts for off-site neutrino radiation

The IMCC aims for a 10+ TeV Design

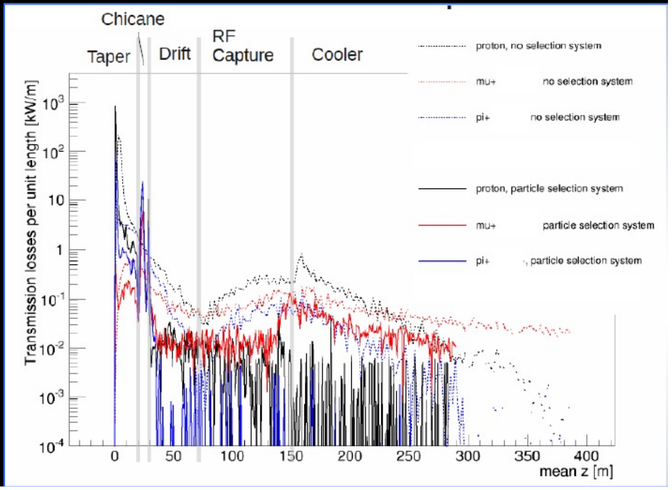
Target & Capture System

- Produce muons through tertiary production from protons on target
- Prepare the beams for the ionization cooling channel
- Requires significant radiation protection of all system components



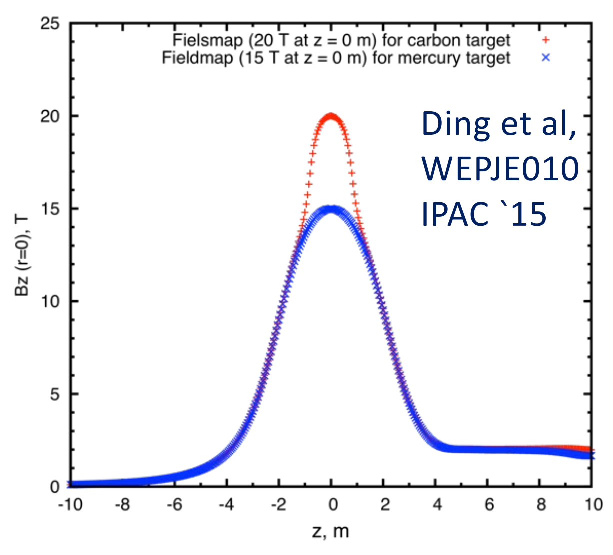


Buncher and Phase Rotator Matched to a 325 MHz Initial Cooling Channel

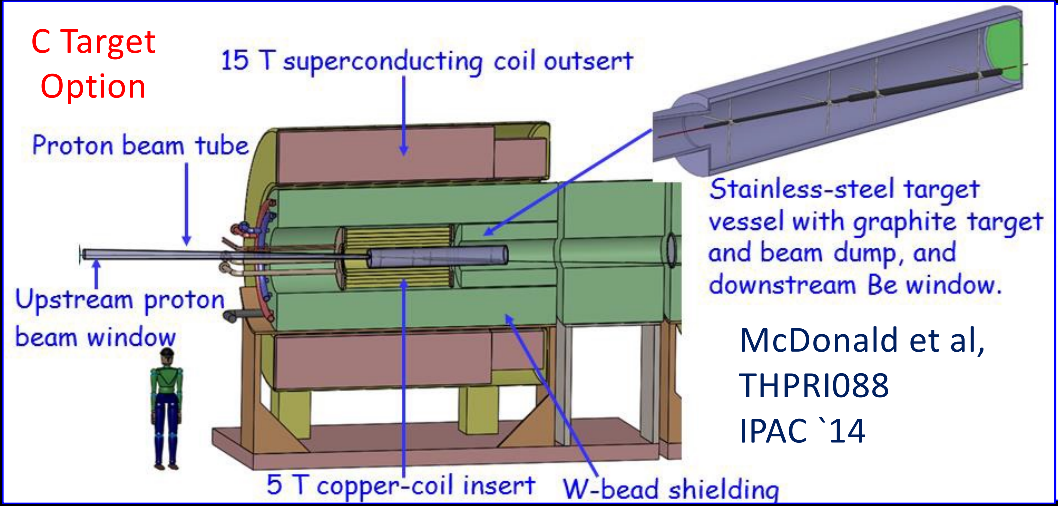


Target & Capture Magnets

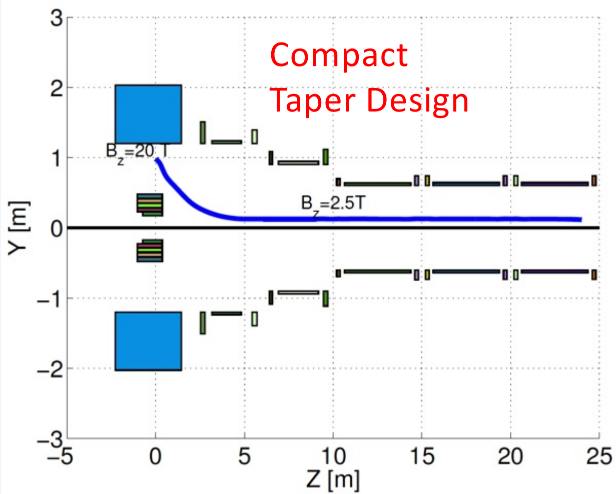
- 20T Capture Solenoid
  - Solenoid allows capture of both signs of pions
    - Initially operate with graphite target module
    - Upgrade to highest power using a liquid metal target
  - Magnet
    - 15T SC Outsert (3 GJ, 100 tons)
    - 5 T Insert: Copper ⇨ HTS?
  - Very high radiation environment
    - Possible use of CICC technology
    - Internal shielding required
- Solenoid Decay channel ⇨ taper to ~2.5T guide field



Ding et al,
WEPJE010
IPAC `15

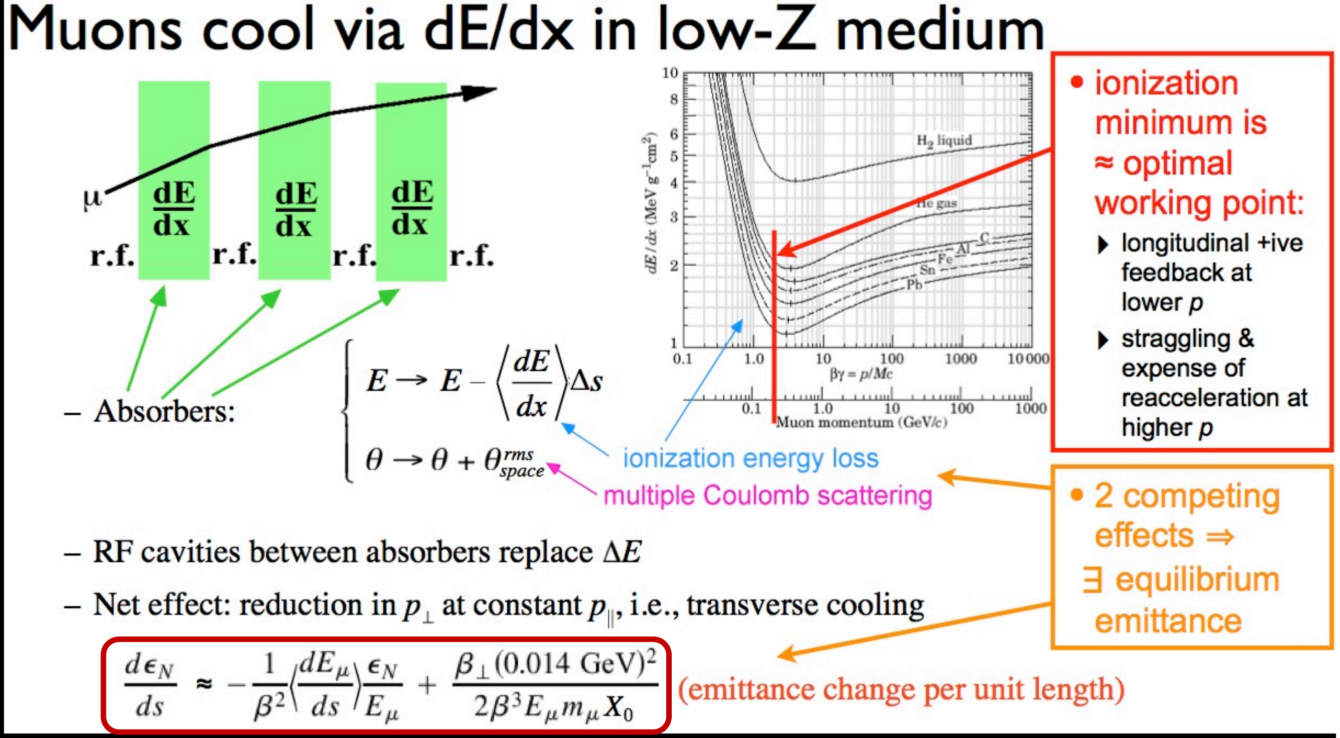


McDonald et al,
THPRI088
IPAC `14



Cooling Methods

- Muon Cooling
  - Must take place very quickly
  - ⇨ Utilize energy loss in materials with RF re-acceleration
  - Operating in a solenoid-based guide field
- Equilibrium emittance in the solenoid-based lattice
  - $\varepsilon_{equilib} \propto \beta_{\perp} \propto B^{-1}$
  - Large aperture HTS magnets desirable for 6D Cooling
  - Ideally 50-60 T in Final Cooling channel
    - Aperture ~50 mm (dia)
    - Synergistic with Very High Field User Magnet development



Muons cool via dE/dx in low-Z medium

– Absorbers:

$$\begin{cases} E \to E - \left\langle \dfrac{dE}{dx} \right\rangle \Delta s \\ \theta \to \theta + \theta_{space}^{rms} \end{cases}$$

ionization energy loss

multiple Coulomb scattering

– RF cavities between absorbers replace ΔE

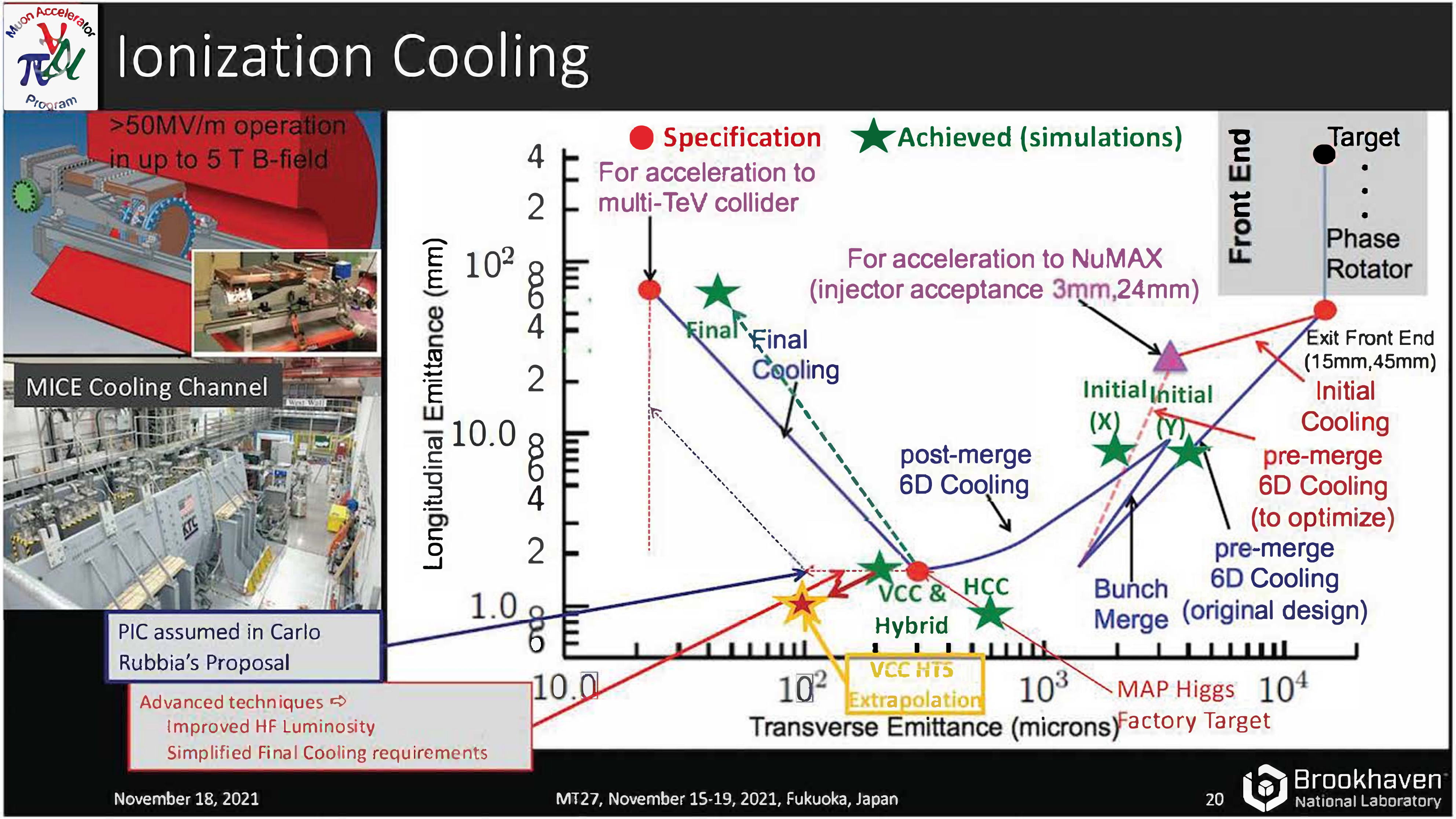
– Net effect: reduction in $p_{\perp}$ at constant $p_{\parallel}$, i.e., transverse cooling

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

(emittance change per unit length)

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

- 2 competing effects ⇒ ∃ equilibrium emittance



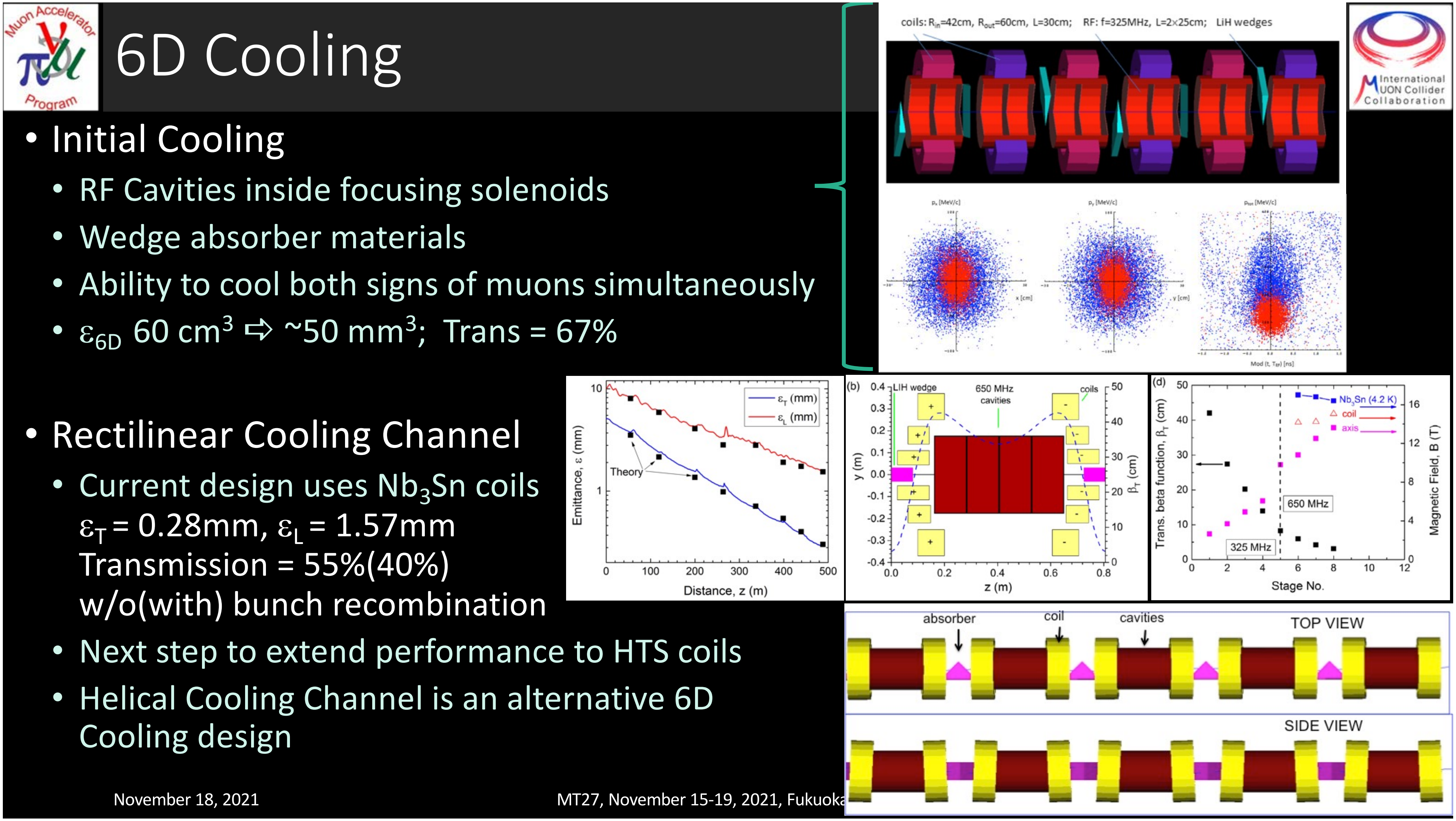
Ionization Cooling

>50MV/m operation
in up to 5 T B-field

MICE Cooling Channel

PIC assumed in Carlo Rubbia's Proposal

Advanced techniques ⇨
Improved HF Luminosity
Simplified Final Cooling requirements



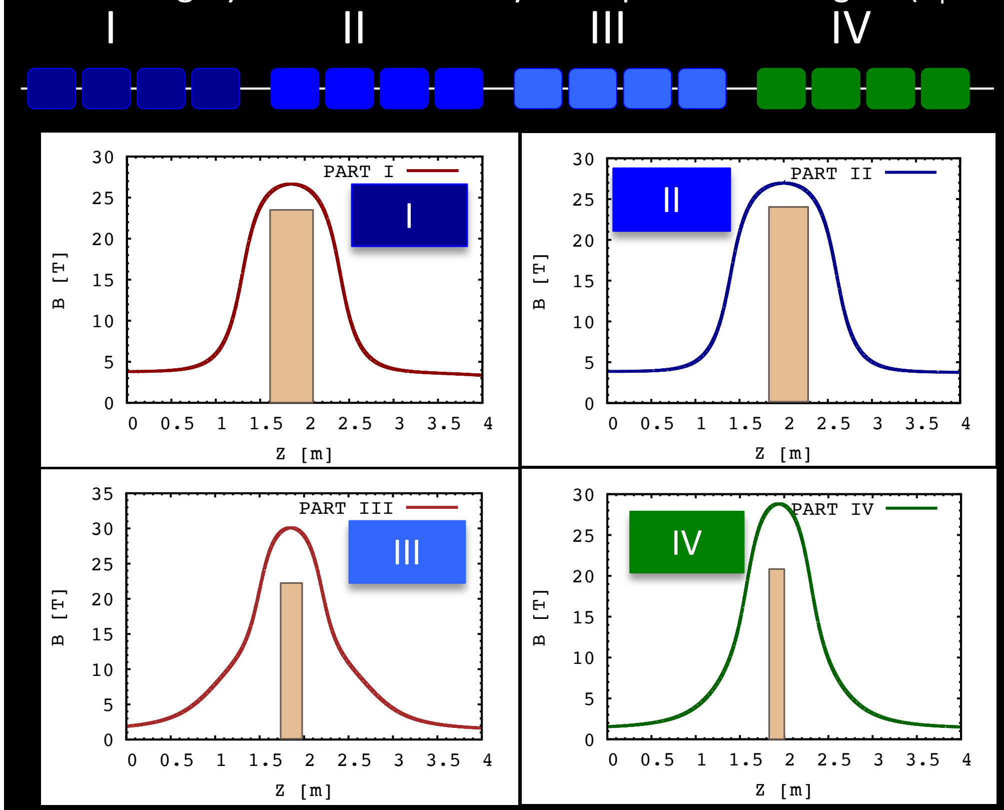
6D Cooling

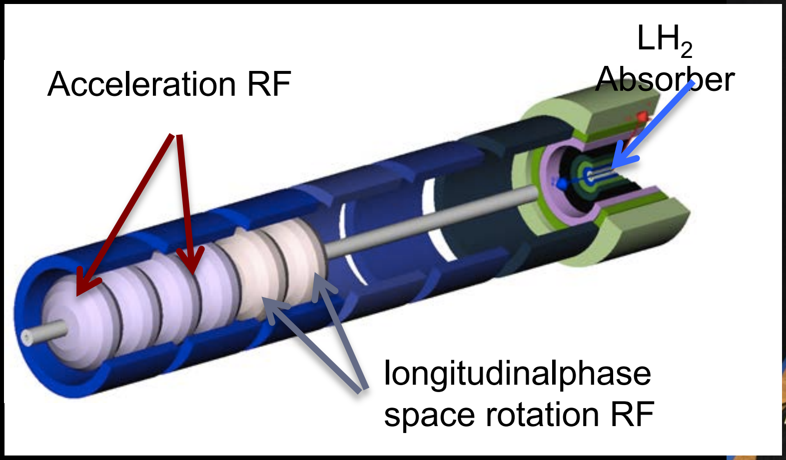
- Initial Cooling
  - RF Cavities inside focusing solenoids
  - Wedge absorber materials
  - Ability to cool both signs of muons simultaneously
  - ε_{6D} 60 cm^3 ⇨ ~50 mm^3; Trans = 67%

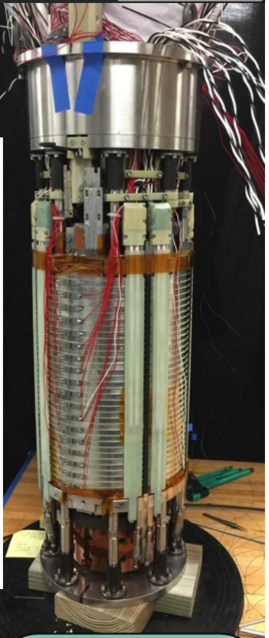
- Rectilinear Cooling Channel
  - Current design uses Nb_3Sn coils
    $\varepsilon_T = 0.28$mm, $\varepsilon_L = 1.57$mm
    Transmission = 55%(40%)
    w/o(with) bunch recombination
  - Next step to extend performance to HTS coils
  - Helical Cooling Channel is an alternative 6D Cooling design

Final Cooling

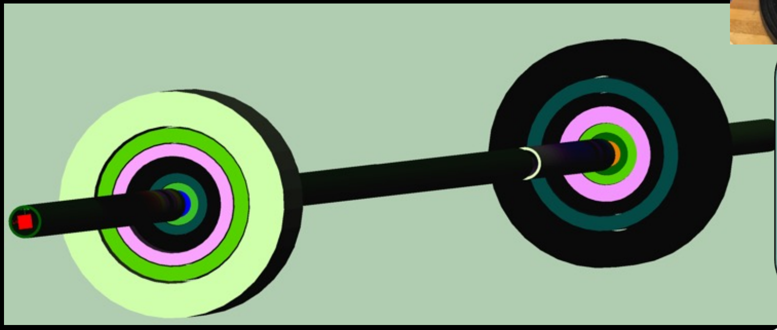
- Performance studies with ~30 T limit
- Roughly a factor of 2 away from performance goal (ε_T = 55µm, ε_L = 75mm)







World Record LTS-HTS Hybrid Magnet
32T on-axis field
NHFML



Cooling Channel Magnet Pull

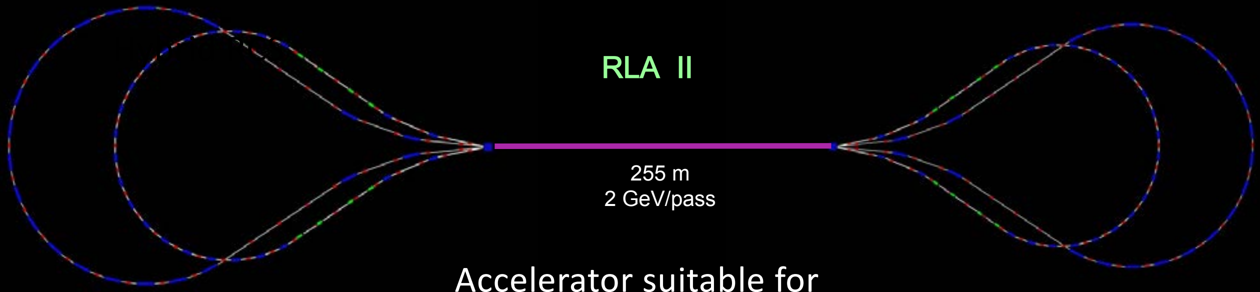
- 6D Cooling Requires:
  - Large-bore high field magnets
    - RF cavities must fit within the magnet structure
    - Space required for cryogenic design
  - HTS Solenoid development will directly enable higher performance
  - Structural engineering of cryomodules will be challenging
- Final Cooling:
  - Magnets are separated from acceleration elements
  - Bores of ~50mm diameter required
  - Very high field solenoid development improves performance linearly with field
  - Ideal range to deliver MC parameter sets: 50-60 T [30-40 T acceptable]

Acceleration

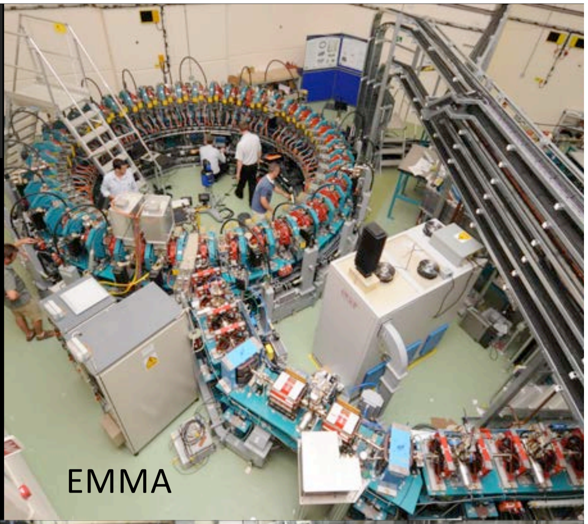
- Technologies Include:
  - Superconducting Linacs
  - Recirculating Linear Accelerators (RLAs)
  - Fixed-Field Alternating-Gradient Rings (FFAs)
  - Hybrid Rapid Cycling Synchrotrons (magnetic field ramps with RF acceleration)

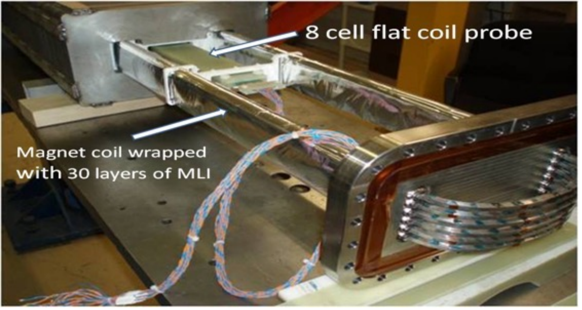
Designs to 125 GeV CoM

Needed for Multi-TeV Scale



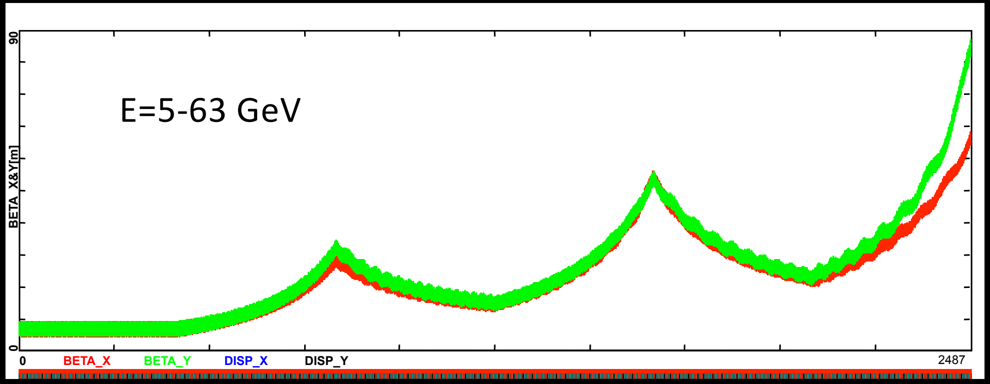
Accelerator suitable for
Neutrino Factory Applications



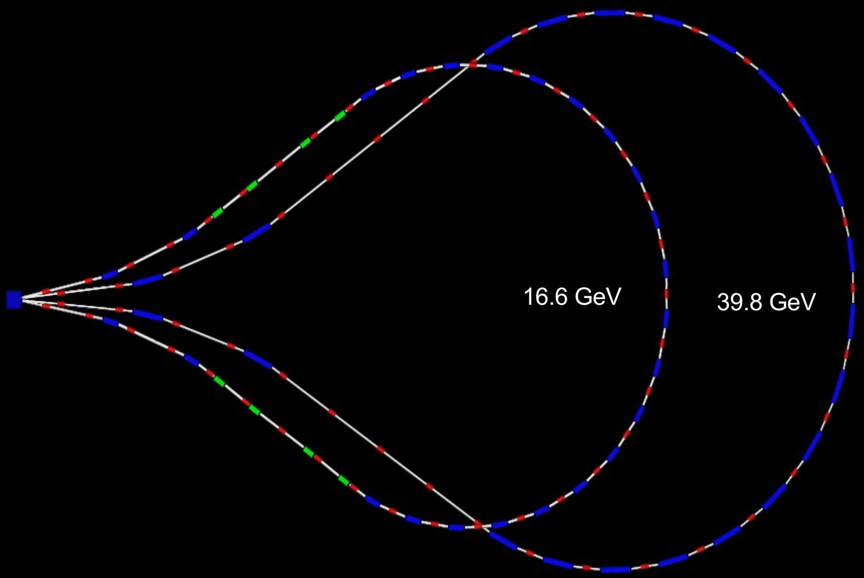


Acceleration to 125 GeV Center-of-Mass

Magnet Pull: Arcs benefit from application of FFA concepts to maximize energy bandwidth See, for instance: [CBETA: First Multipass Superconducting Linear Accelerator with Energy Recovery](#) Phys. Rev. Lett. 125, 044803, July 2020

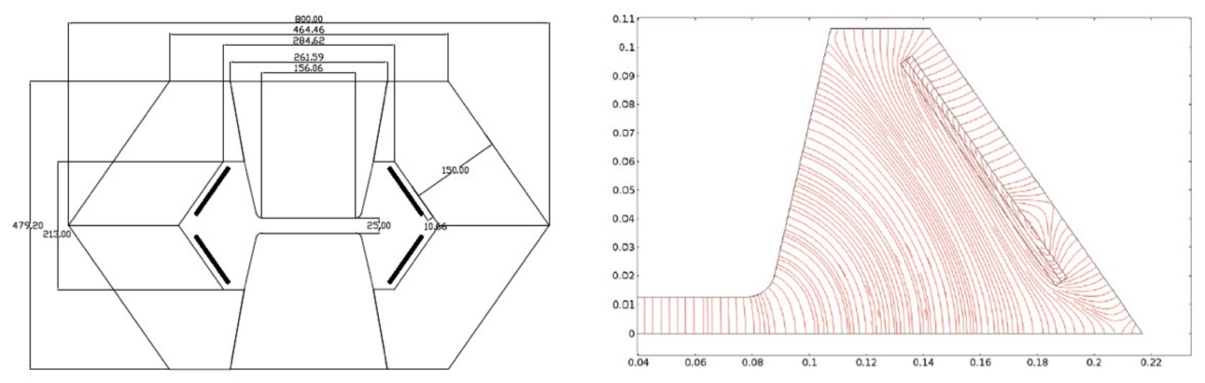


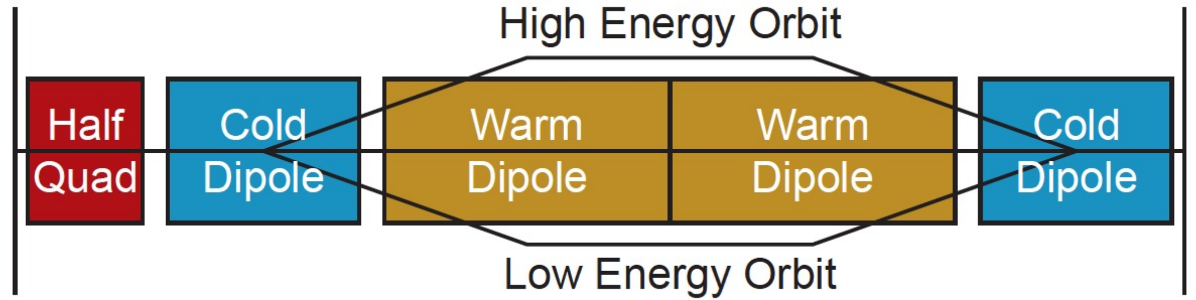
RF: f = 650 MHz cells/cavity = 5 Gradient = 25 MV/m phase = 22°



TeV-Scale Acceleration

- Challenges:
  - Large energy bandwidth lattice at high energies
  - Fast-ramping magnets
    - Grain-oriented silicon steel can support ramp rates at the kT/s level
      - Modeling remains a challenge
        - Eddy currents
        - Anisotropy
    - Power supply system efficiency at high ramp rates must be demonstrated




High Energy Orbit

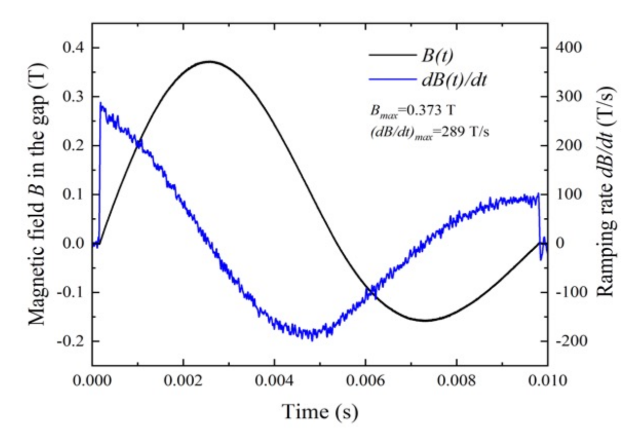
Half Quad | Cold Dipole | Warm Dipole | Warm Dipole | Cold Dipole

Low Energy Orbit

Hybrid Rapid Cycling Synchrotron Cell Concept

Advances in Fast Ramping HTS Magnets

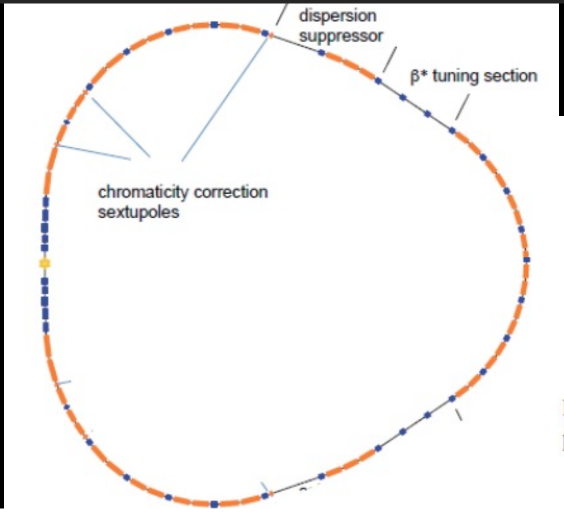
- dB/dt = 289 T/s demonstrated (H. Piekarz, this conference)
- TeV-class muon acceleration ideally wants >1000 T/s (E. Barzi, this conference)
- Power system with acceptable dissipation also challenging



1 – Magnet, 2- Current leads, 3- Power supply, 4 – Control electronics, 5- Liquid Helium flow lines

Higgs Factory (125 GeV) Lattice Design

MC Higgs Factory:
MAP design
with a single IP



Alexahin, et al., JINST 13 P11002

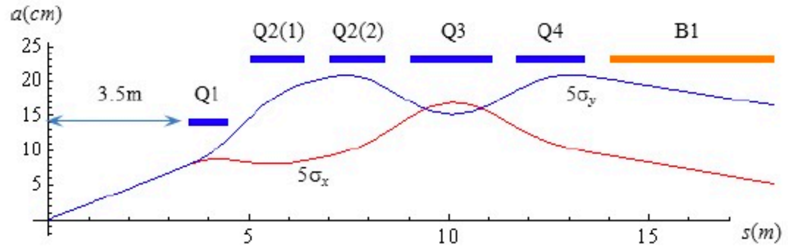


Figure 12. Higgs factory IR quadrupoles aperture and 5σ beam envelopes for $\beta^* = 2.5$ cm. Beam parameters are given in table 3.

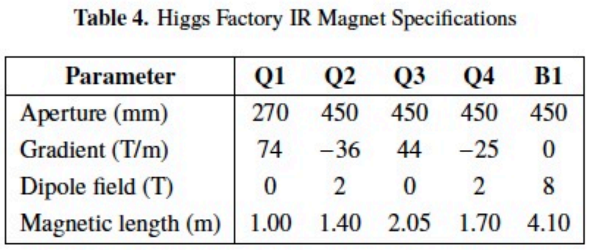


Table 4. Higgs Factory IR Magnet Specifications

Parameter	Q1	Q2	Q3	Q4	B1
Aperture (mm)	270	450	450	450	450
Gradient (T/m)	74	−36	44	−25	0
Dipole field (T)	0	2	0	2	8
Magnetic length (m)	1.00	1.40	2.05	1.70	4.10

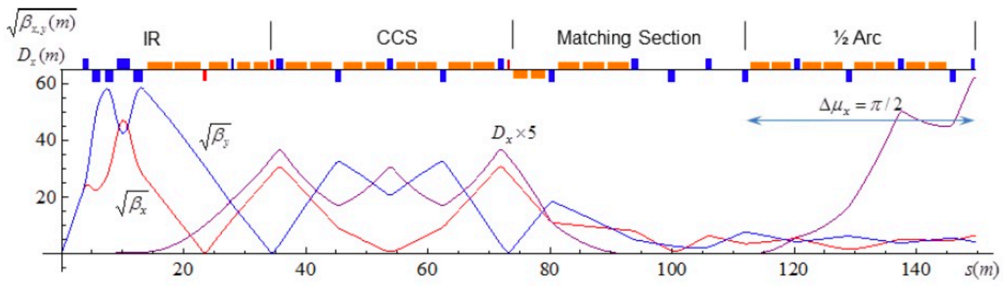
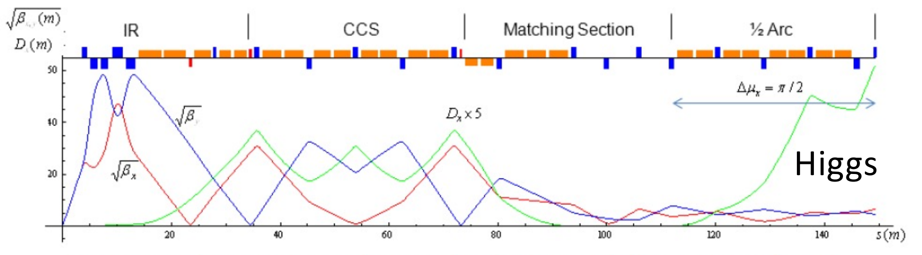


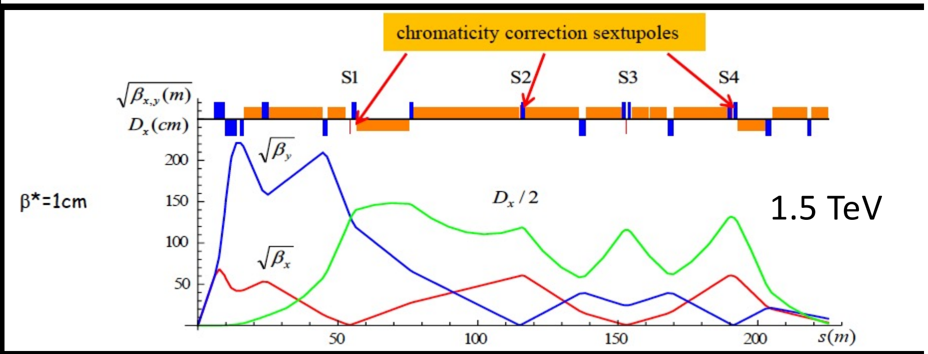
Figure 13. Layout and optics functions in half ring of the Higgs factory.

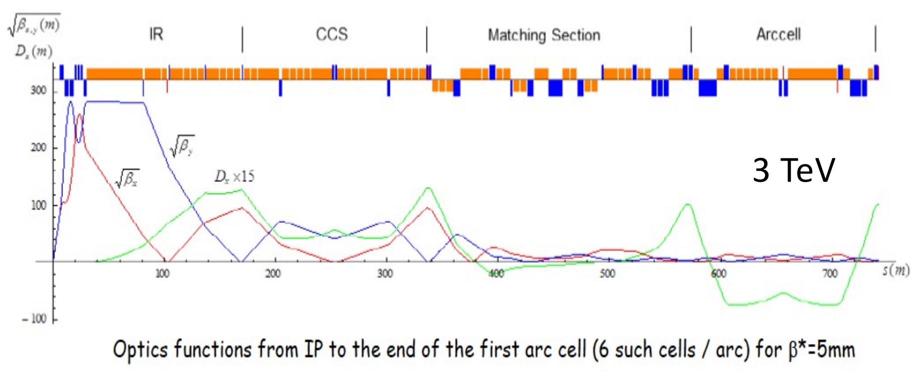
Multi-TeV Colliders

- MAP Optics Designs for
  - Higgs Factory (125 GeV)
  - 1.5 TeV CoM
  - 3.0 TeV CoM
  - 6.0 TeV CoM
- Magnet Characteristics
  - MAP designs assumed B_{dipole}~10 T
    - Higher is better ⇨ strong coupling to HFM R&D Program
    - MC luminosity ∝ B_{dipole}
  - Large apertures required to accommodate shielding around beam
    - Muon decays ⇨ radiation loads O(kW/m)
    - Particularly an issue for the Interaction Region magnets
  - IR combined function magnets to mitigate ν radiation



Higgs Factory lattice and optics functions for β*=2.5cm in a half-ring starting from IP

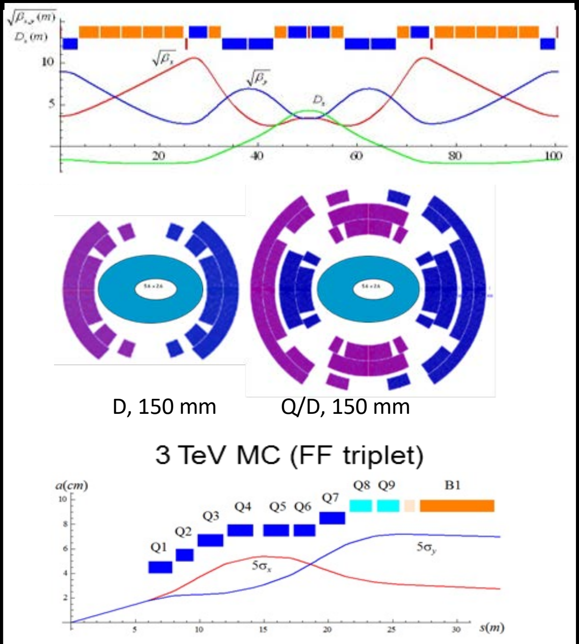




Optics functions from IP to the end of the first arc cell (6 such cells / arc) for β*=5mm

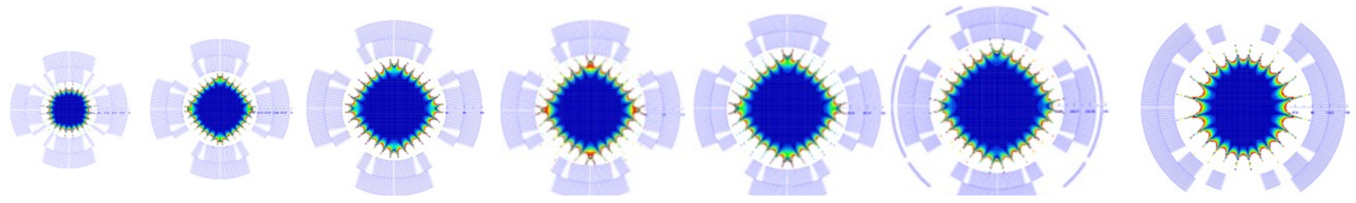
A look at the 3 TeV Collider Magnets

- Arc magnets
  - B_{op}=10.4 T, G_{op}=31-85 T/m, B_{op}=8-9T, 56 mm×26 mm
  - 15 cm aperture cosθ D and combined Q/D
  - Elliptical liner with shifted bore
  - Results
    - B_{op}=10.4 T with ~30% margin at 4.5 K => 2-layer coils
    - B_{op}~8-9T and G_{op}~80T/m with ~20% margin (B_{coil}~18 T) at 4.5 K => nested Q/D with 4-layer coils
- IR magnets
  - B_{op}=8 T (D), B_{op}~11 T (Q)
  - Aperture 80-180 mm
  - Results
    - B_{des}=14-15 T with 2-layer coils
    - 20-30% (Q) and 45% (D) operation margin
- Tungsten masks and inner absorbers



D, 150 mm Q/D, 150 mm

3 TeV MC (FF triplet)

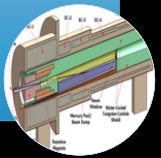


Q1, 80 mm Q2, 100 mm Q3, 125 mm Q4-6,140 mm Q7, 160 mm Q8-9, 180 mm B1, 180 mm

Summary of the Muon Collider Magnet Pull

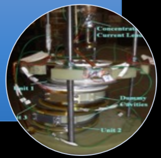
- Characteristics:
  - High field (15-20T)
  - Large bore (meter-scale)
  - Intense radiation environment – NC or HTS insert coil

Capture Solenoid for Simultaneous mu+ & mu- Beams



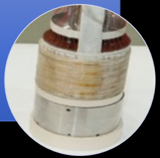
- Characteristics:
  - Solenoid-based cooling channel (LH_2/LiH absorbers)
  - RF cavities integral to focusing channel
  - Fields ranging from LTS to HTS conductor regime

Muon Ionization 6-Dimensional Cooling Channel



- Characteristics:
  - Emittance exchange channel for TeV-scale colliders – trade increased longitudinal beam emittance for smaller transverse emittance
  - Goal: 40-60 T HTS solenoids with d ~ 50mm

Muon Ionization Final Cooling Channel

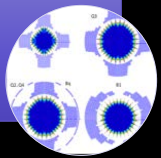


- Characteristics:
  - Present baseline based on the use of Rapid Cycling Synchrotrons
  - Requires magnets capable of ~400Hz operation with B>1.5T
  - Novel magnets, suitable modeling, efficient power system

Acceleration to the TeV Energy Scale for Muon Colliders

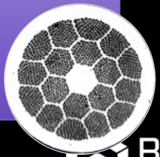
- Characteristics:
  - Decaying muon beams mean that luminosity is inversely proportional to circumference
  - 10T dipole ⇨ 15-20T dipoles improves luminosity
  - Radiation environment
  - Challenging IR magnets

Muon Collider Magnet Needs



- Characteristics:
  - A MC (w/decaying beams) obtains the greatest performance enhancement of any HEP collider from HTS magnet technology
  - High quality HTS cables and magnets must be a priority

HTS Magnet Development



Looking Forward...

- Muon Colliders offer an energy-efficient path to multi-TeV CoM energies
- Recent physics studies indicate that important collider physics is accessible
- The MAP R&D Program and the MICE Experiment have demonstrated the feasibility of key accelerator physics concepts
- A new International Muon Collider Collaboration is now leading the design effort with the goal of being able to deliver a multi-TeV muon collider sometime in the 2040s
- ***This effort needs the strong engagement of the magnet community in order to succeed!***

Some Useful References and Links

- Muon colliders to expand frontiers of particle physics, K.R. Long et al., Nature Physics **17**, pp 289–292 (2021)
- The Future Prospects of Muon Colliders and Neutrino Factories, Boscolo, Delahaye, Palmer, RAST, Vol 10, No. 01, pp. 189-214 (2019)
- The JINST dedicated volume on Muon Collider Research and Technology: Muon Accelerators for Particle Physics https://iopscience.iop.org/journal/1748-0221/page/extraproc46
- Demonstration of cooling by the Muon Ionization Cooling Experiment, MICE Collaboration, Nature 578, 53-59(2020)

- The International Muon Collider Collaboration

Thank you for your attention!