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Lepton Colliders for the Next Generation of High Energy Physics Experiments

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Cornell LEPP Journal Club

March 7, 2014

Outline

- Introduction
- Lepton and Photon Collider Options
  from the CSS2013 Frontier Capabilities:
  Energy Frontier Lepton & Gamma Colliders Sub-Group
  - Circular e^+e^-
  - ILC
  - Other LC Concepts
  - $\gamma\text{–}\gamma$ Colliders
  - $\mu^+\mu^-$ Collider
  - And some comparisons
- A Few Words About the Muon Accelerator Program (MAP)
- Closing Comments

The Working Group and Inputs

The Working Group Assessments

Comments on Making Comparisons

INTRODUCTION

Frontier Capabilities: Lepton Colliders

- Accelerator Capabilities Convener: Bill Barletta (MIT)

  http://www-public.slac.stanford.edu/snowmass2013/SnowmassWorkingGroupReports.html

- Lepton Colliders Sub-Group:
  - Sub-conveners: Marco Battaglia (UCSC), Markus Klute (MIT), Kaoru Yokoya (KEK), & myself
  - EF Liaison: Tor Raubenheimer (SLAC)
  - Sub-Group Meeting at MIT: https://indico.cern.ch/conferenceDisplay.py?ovw=True&confId=233944

- Submissions covered a broad range of capabilities and possibilities ⇨ *many contributors to what follows*

Working Group Assessment

- The goal of the working group was to:
  - Summarize the capabilities that can support the physics needs of Energy Frontier
  - Evaluate the major technical challenges and cost drivers
  - Identify the R&D path required to develop the necessary capabilities

- It should be noted that:
  - All of the options have some technical challenges
  - None of the options under consideration is cheap
  - But, there are real options with contrasting strengths and weaknesses (as well as varying states of readiness)
    ➩ which makes the process of charting an optimal route forward challenging when we are discussing timescales of decades

Comment on Concept Maturity

- It should also be noted that the concepts described here span a broad range of maturity
  - R&D concepts requiring significant validation
  - Full technical designs where performance has been explicitly sacrificed in order to achieve something that can be built
    - And to fit within a specific budget profile
  - Design extrapolations
    - Based on well-understood individual technologies in many cases
    - Where the detailed design studies are just ramping up
      ⇨ *hence, not yet validated in full detail*

- Thus capabilities comparisons are non-trivial at this level
  - Attention should be paid to “strategic” (ie, physics) benefits
  - Audience should ask pointed questions about how realistic any individual plan is

e^+e^- Circular Colliders:

>100 GeV Scale

Linear Colliders:

- e^+e^- Colliders with E < 1 TeV & E1> 1 TeV
- γ-γ Colliders

$\mu^+\mu^-$ Colliders: Up to 10 TeV

LEPTON & PHOTON COLLIDERS

e^+e^- Circular Colliders

Comments

- LEP2 nearly reached the Higgs
- Rings are robust and well-understood technology

Technical Issues

- Synchrotron Radiation:
- RF Efficiency
- Beam Lifetime (~10^3 sec) and Top-Up Injection
- Collective Effects
- Energy Bandwidth

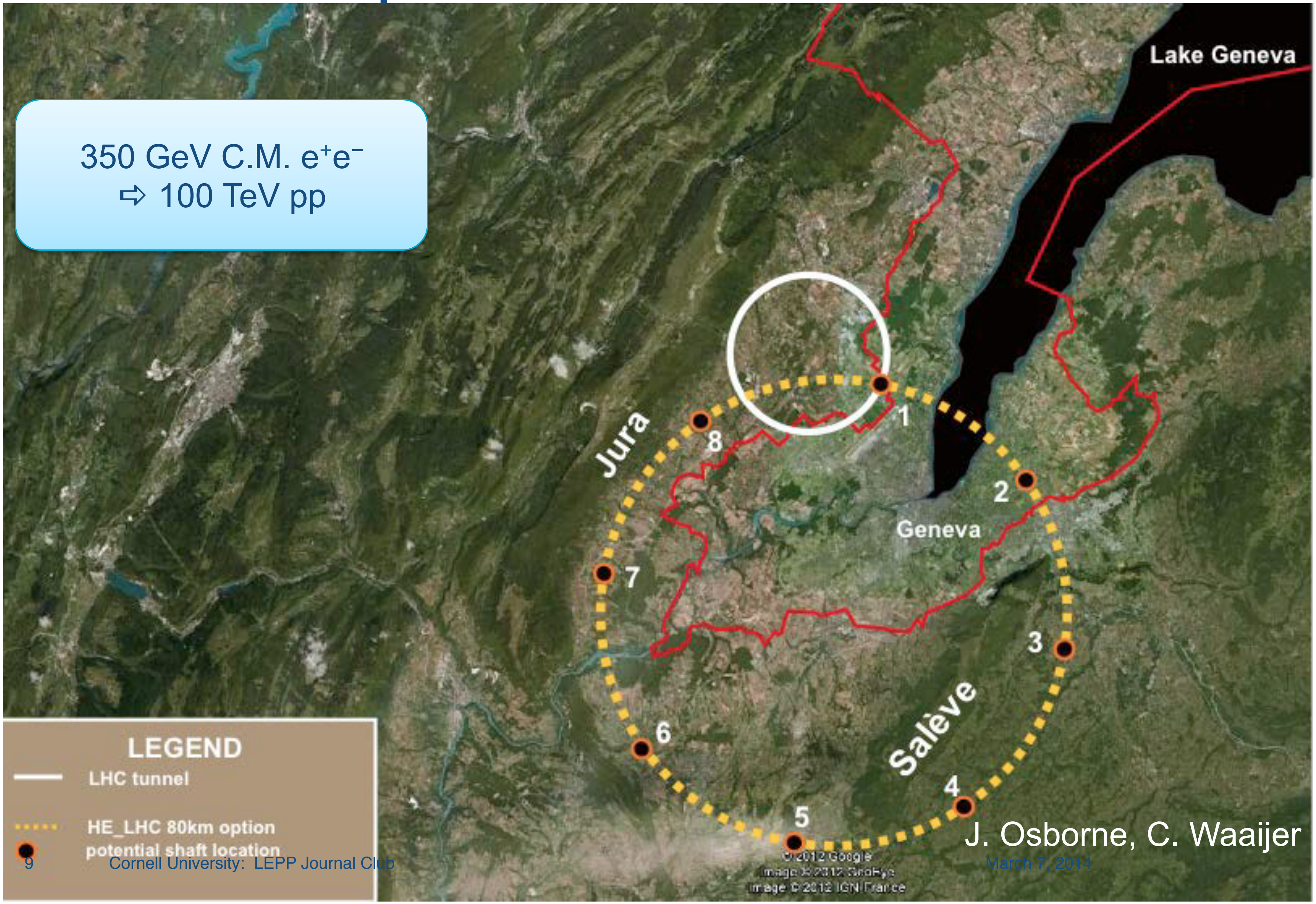
$$\Delta E\left[GeV\right] = 8.85\times10^{-5}\,\frac{E^4\left[GeV^4\right]}{\rho\left[m\right]}$$

Trends in the Discussion

- Re-use of the LEP tunnel (conflict w/LHC) as well as various site-filler options initially discussed
- Current focus: 80-100km ring leading to a 100 TeV scale hadron collider (VHE-LHC/VLHC)
  - Takes a longer term view
  - Limits SR issues
  - CERN and Chinese Inititatives

The TLEP Concept

350 GeV C.M. e^+e^-
⇨ 100 TeV pp



J. Osborne, C. Waaijer

Electron-Positron Storage Rings: Parameters for Selected Options

	LEP2	TLEP* – HZ	TLEP* - t	FNAL** - HZ
Beam Energy [GeV]	104.5	120	175	120
Circumference [km]	26.7	80	80	100
Beam current [mA]	4	24.3	5.4	12.9
Number of bunches	4	80	12	34
Bunch population [10^{12}]	0.575	40.8	9.0	0.79
Horizontal emittance [nm]	48	9.4	10	16
Vertical emittance [nm]	0.25	0.02	0.01	0.08
β_x^* [mm]	1500	500	1000	200
β_y^* [mm]	50	1	1	2
Hourglass factor	0.98	0.75	0.65	0.81
SR power/beam [MW]	11	50	50	20
Bunch length [mm]	16	1.7	2.5	3.2
Momentum acceptance [%]	1.25	2.5	2.5	3.0
Beam-beam parameter / IP	0.07	0.1	0.1	0.1
Luminosity / IP [10^{34} cm^{-2}s^{-1}]	0.0125	4.8	1.3	1.8

* Assumes 4 IPs ** Assumes 1 or 2 IPs

e^+e^- Circular Colliders

Status

- FCC Design Study now underway
- Includes 100 TeV pp goal and TLEP as an intermediate step

R&D

- Focus on detailed technical assessments
- Challenges, but no obvious showstoppers

Time

- TLEP: Conceptual Design Report by 2015
- TLEP: Technical Design Report by 2018
- TLEP: Aiming for construction readiness in 2020’s

Technical Statement

Linear Colliders

- Luminosity

$$\mathcal{L} = \frac{N^2 f_{coll}}{4\pi\sigma_x\sigma_y}\mathcal{H}_D$$

$$\mathcal{L} = \frac{P_b}{E_b}\left(\frac{N}{4\pi\sigma_x\sigma_y}\right)\mathcal{H}_D$$

- The strong fields at the interaction point result in
  - A luminosity enhancement characterized by the disruption parameter
  - Beamstrahlung emission gives rise to energy spread and backgrounds at the interaction point

Linear Collider Options

- A range of options have been explored
  - ILC: Based on SRF technology
    Most mature concept for E_{CM}<1 TeV

Yield '10 ~ '12:
> 90% @ 25 MV/m
~ 80% @ 28 MV/m
~ 70% @ 35 MV/m

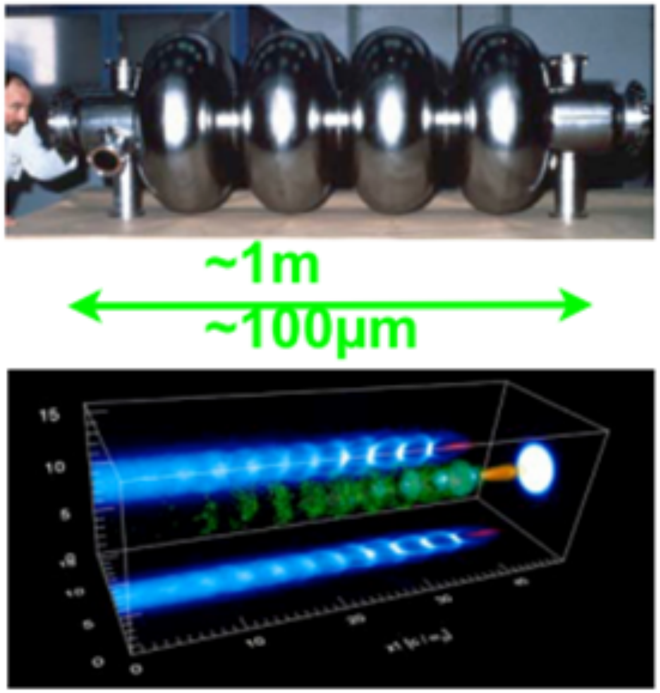
  - CLIC: Based on drive-beam and NCRF technology
    RF Gradients: 100 MV/m
    Could be applied for E_{CM}<1 TeV
    Designs up to 3 TeV are documented

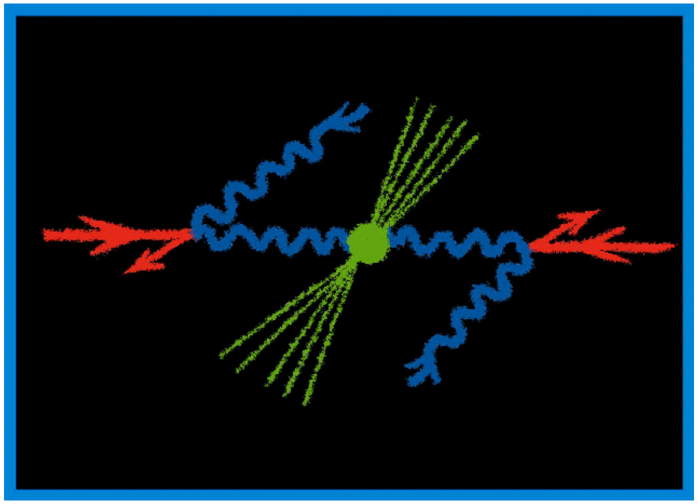
Linear Collider Options

- Options (cont’d)
  - Wakefield Accelerators:
    Potential for very high energies
    Possibly could be used for LC afterburner
    Significant R&D remains
  - $\gamma - \gamma$: High power laser beams
    Compton backscattered from e^- or e^+ beams

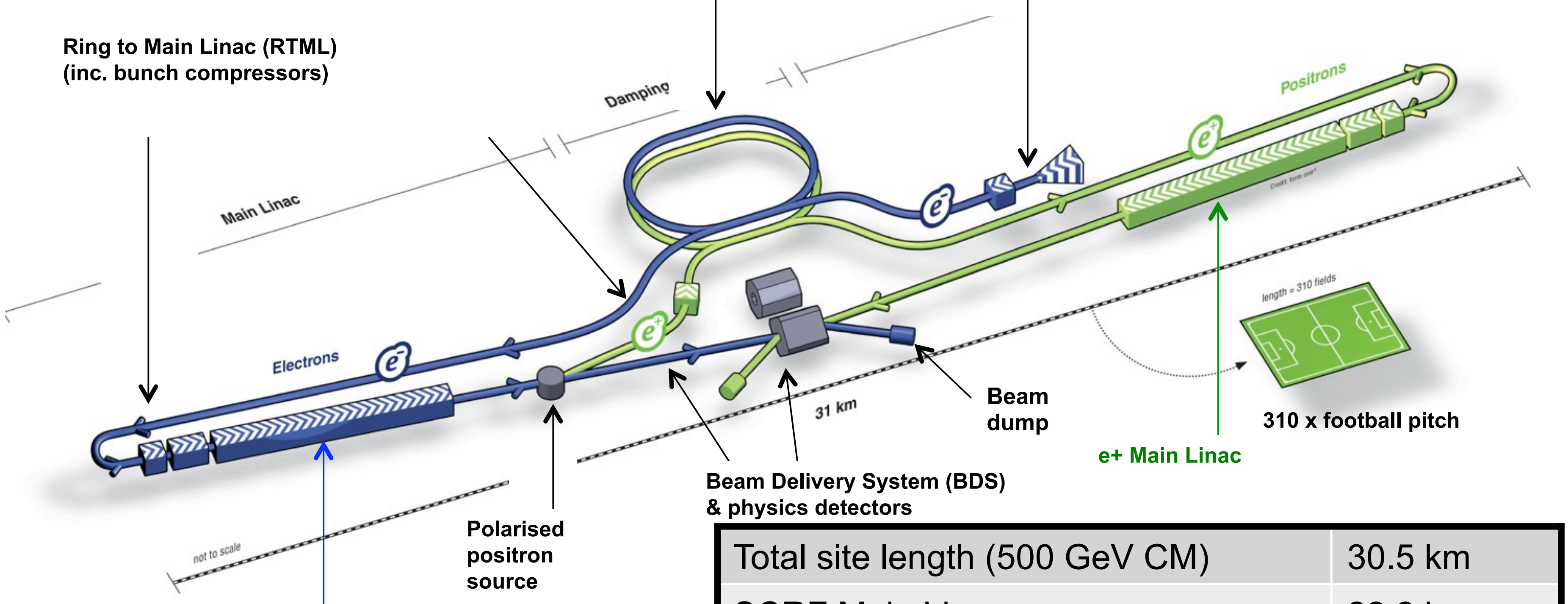
    $\gamma\gamma \Rightarrow H$ cross section ~200fb

    Concept could be applied at an ILC or CLIC





ILC in a Nutshell



Damping Rings

Polarised electron source

Ring to Main Linac (RTML)
(inc. bunch compressors)

Beam dump

310 x football pitch

e+ Main Linac

Beam Delivery System (BDS)
& physics detectors

Polarised positron source

e- Main Linac

not to scale

ILC Scheme | © www.form-one.de

Total site length (500 GeV CM)	30.5 km
SCRF Main Linacs	22.2 km
RTML (bunch compressors)	2.8 km
Positron source	1.1 km
BDS / IR	4.5 km
Damping Rings (circumference)	3.2 km

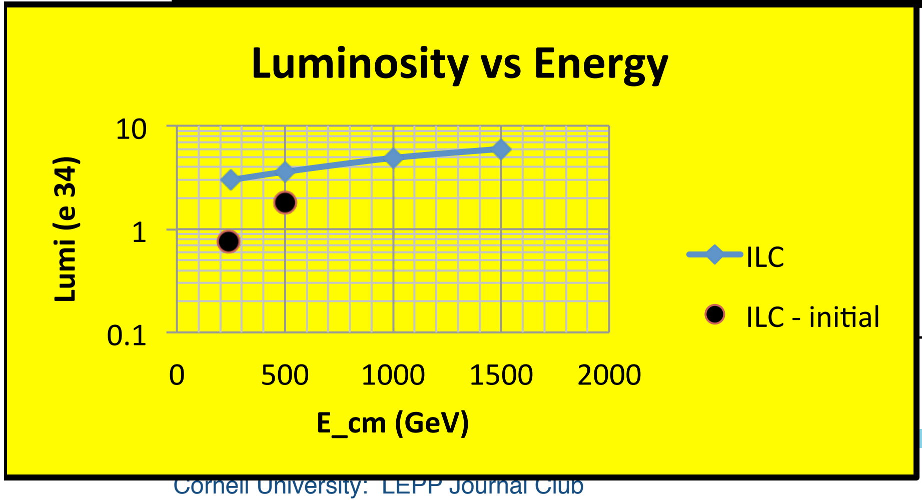
M. Ross

Luminosity

			E_cm (GeV) -->
1 TeV **150%** ***2.4*** **263 14.6**	**1 TeV Baseline** **166%** ***4.9*** **298 27.3**		**1000**
Baseline **100%** ***1.8*** **163 10.5**	**High L** **106%** ***3.6*** **204 21.0**		**500**
LHF **69%** ***0.75*** **129 9.4**	**LHF high L** **74%** ***1.5*** **161 11.8**	**LHF High L/High P** **106%** ***3*** **204 21**	**250**
1312	**2625 / (2450 4Hz)**	**2625 10 Hz**	

Number of bunches and repetition rate ->

A factor of 2.5 in L/P_{wall}



Legend	
Title	
Rel Cost	***L (e34)***
P_AC (MW)	**P_2 beam**

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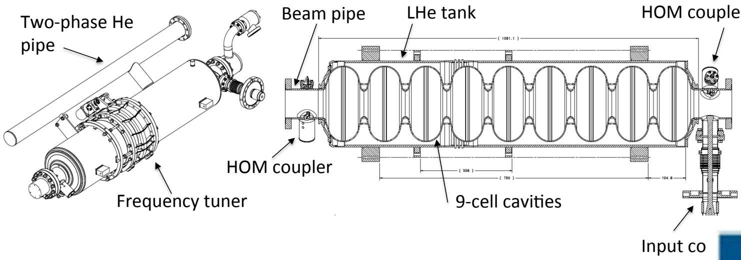
ILC SCRF Technology



1.3 GHz Nb 9-cellCavities	16,024
Cryomodules	1,855
SC quadrupole pkg	673
10 MW MB Klystrons & modulators	436 *

* site dependent

Approximately 20 years of R&D worldwide
→ Mature technology

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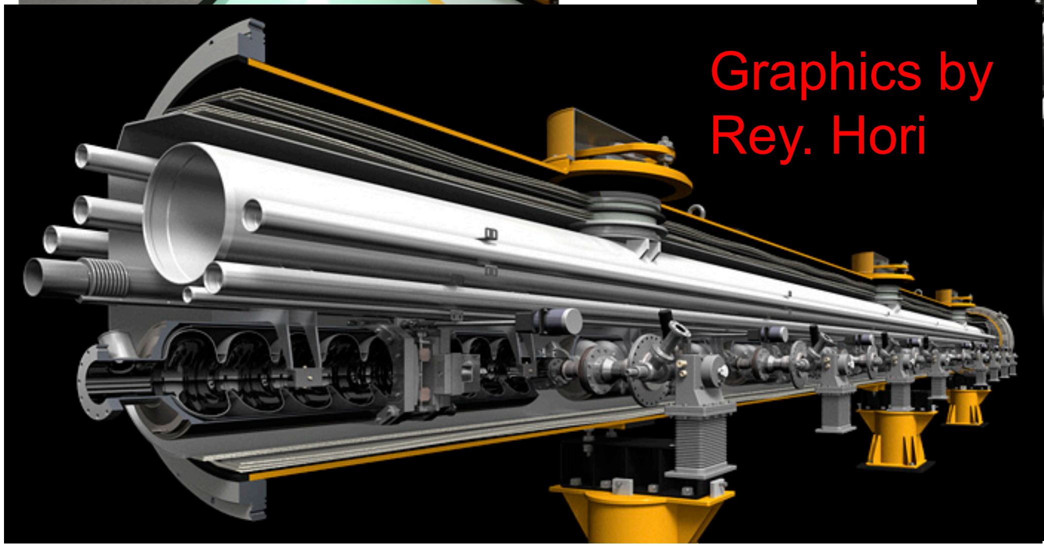
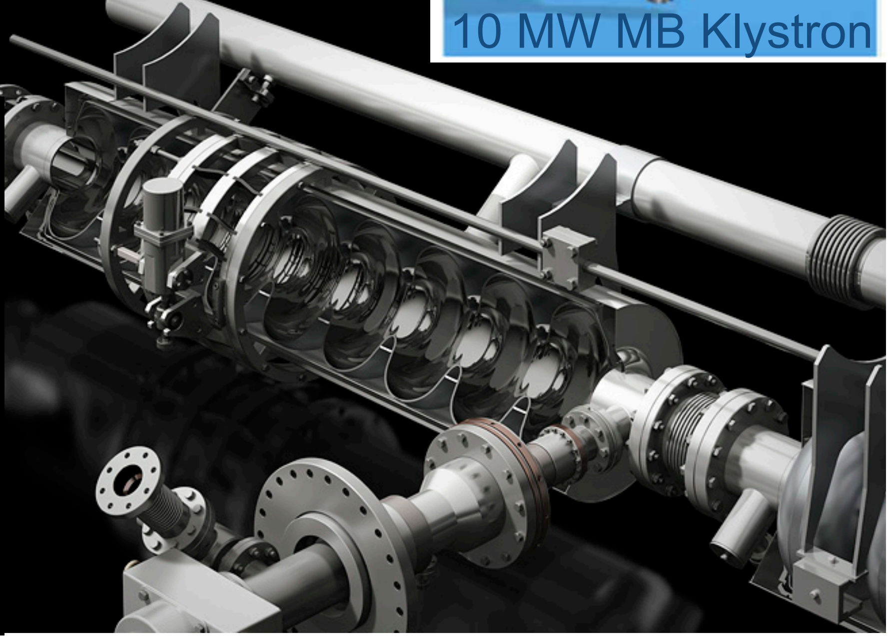
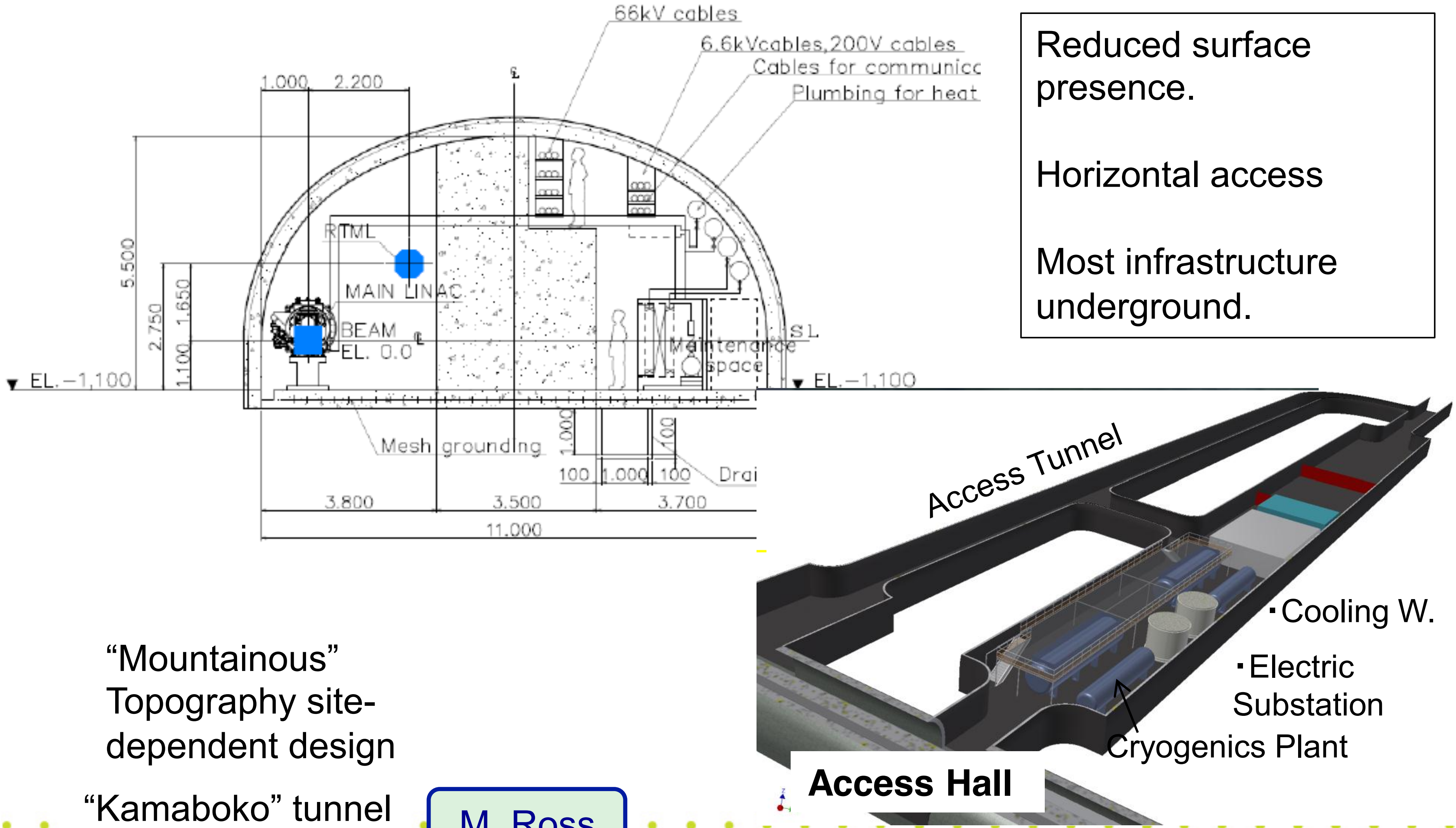
10 MW MB Klystron



Graphics by Rey. Hori



Building ILC in Japanese Mountains:



Reduced surface presence.

Horizontal access

Most infrastructure underground.

“Mountainous” Topography site-dependent design

“Kamaboko” tunnel

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Japanese Siting

Candidate site (1 of 2) in northeastern Japan

Tohoku ‘Mountain Region’

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(Photo taken100 km north of Sendai.)

The ILC alignment would be 50 to 400 meters below these hills.

ILC Parameters

Centre-of-mass energy	E_{cm}	**GeV**	**250**	**350**	**500**		**1000**
Beam energy	E_{beam}	GeV	125	175	250		500
Estimated AC power	P_{AC}	MW	128	142	162		300
Collision rate	f_{rep}	Hz	5	5	5		4
Electron linac rate	f_{linac}	Hz	10	5	5		4
Number of bunches	n_b		1312	1312	1312		2450
Bunch separation	Dt_b	ns	554	554	554		366
Pulse current	I_{beam}	mA	5.8	5.8	5.79		7.6
RMS bunch length	σ_z	mm	0.3	0.3	0.3		0.250
Electron polarisation	P_-	%	80	80	80		80
Positron polarisation	P_+	%	30	30	30		20
Luminosity (inc. waist shift)	L	**$\times 10^{34}$ cm^{-2}s^{-1}**	**0.75**	**1.0**	**1.8**		**3.6**
Fraction of luminosity in top 1%	$L_{0.01}/L$		87.1%	77.4%	58.3%		59.2%

The ILC

Status

- Technical Design Report now complete
- Decision point on moving forward has been reached
- Japanese government formally evaluating whether to launch a project

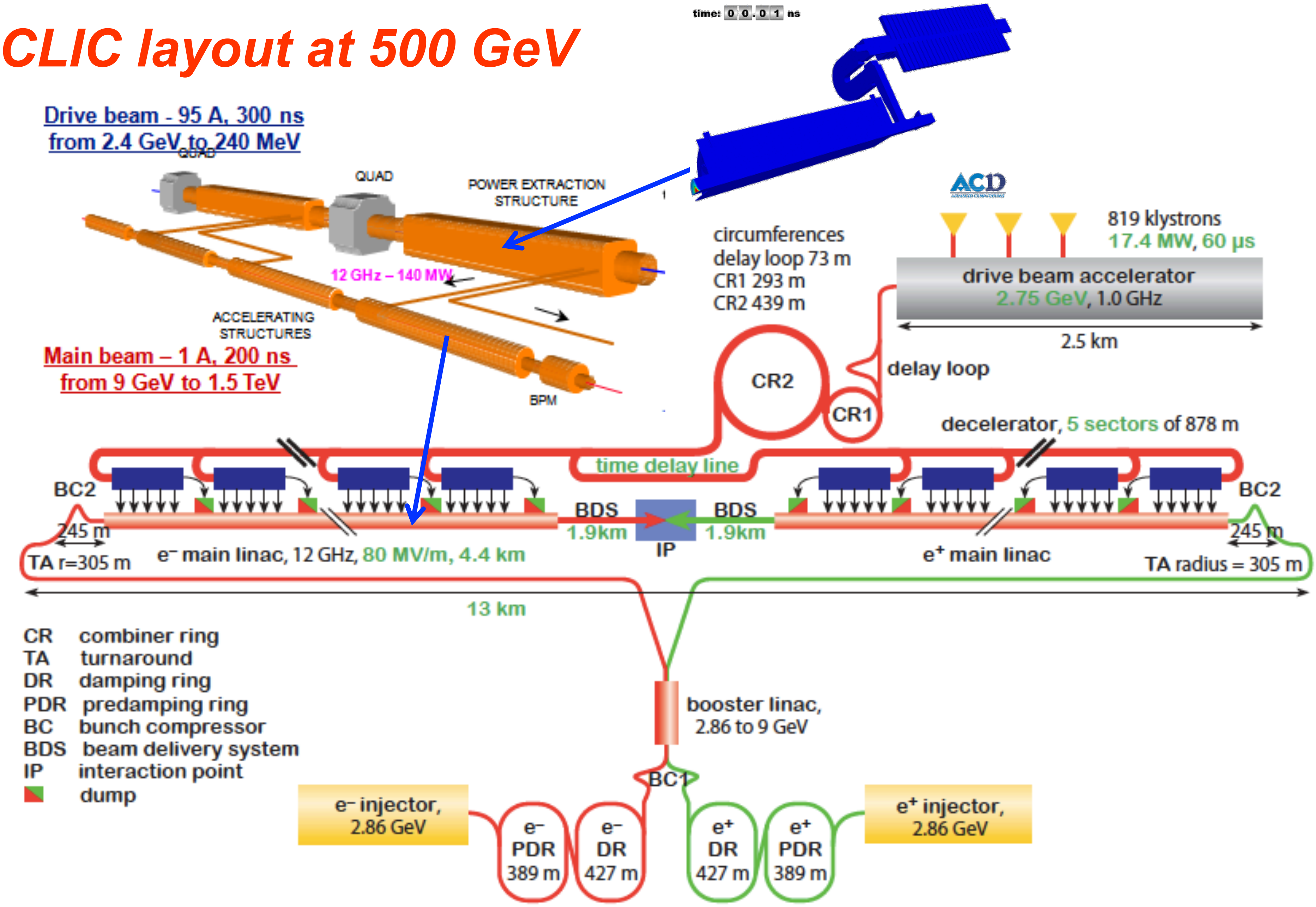
R&D

- Most significant R&D issues addressed during ILC Technical Design Phase [SRF cavity R&D, including industrialization; FLASH beam tests; damping ring studies, CESRTA; damping ring and beam delivery system studies at KEK-ATF]
- Some technical challenges remain (eg, complete ATF2 program), but no obvious showstoppers

Time

- Team ready to move forward with detailed engineering and site-specific design
- Timescale contingent on decision process and international support

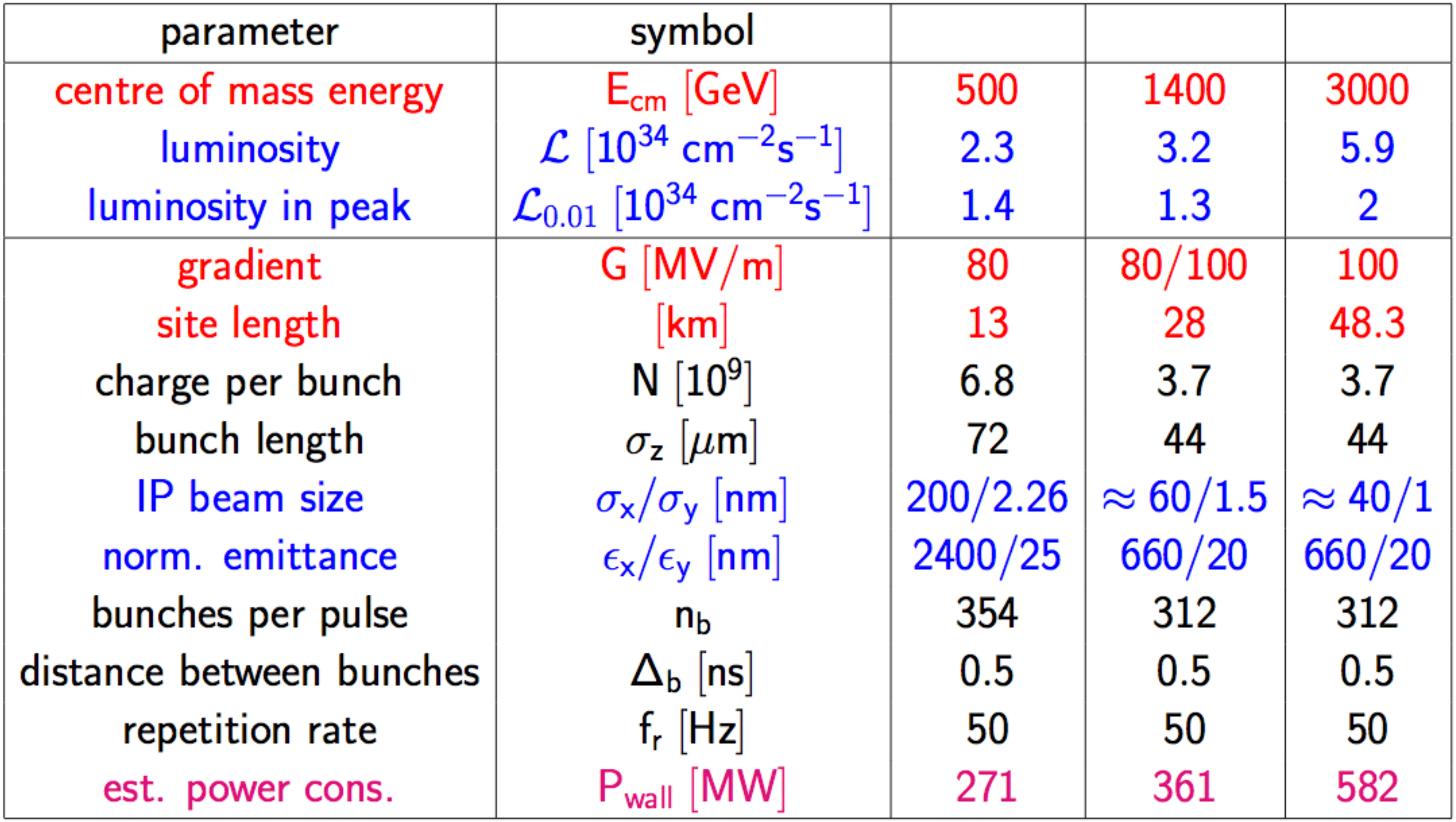
CLIC layout at 500 GeV



CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
🟥	dump

Fig. 3.2: Overview of the CLIC layout at $\sqrt{s}$ =500 GeV.

Potential Staged CLIC Parameters



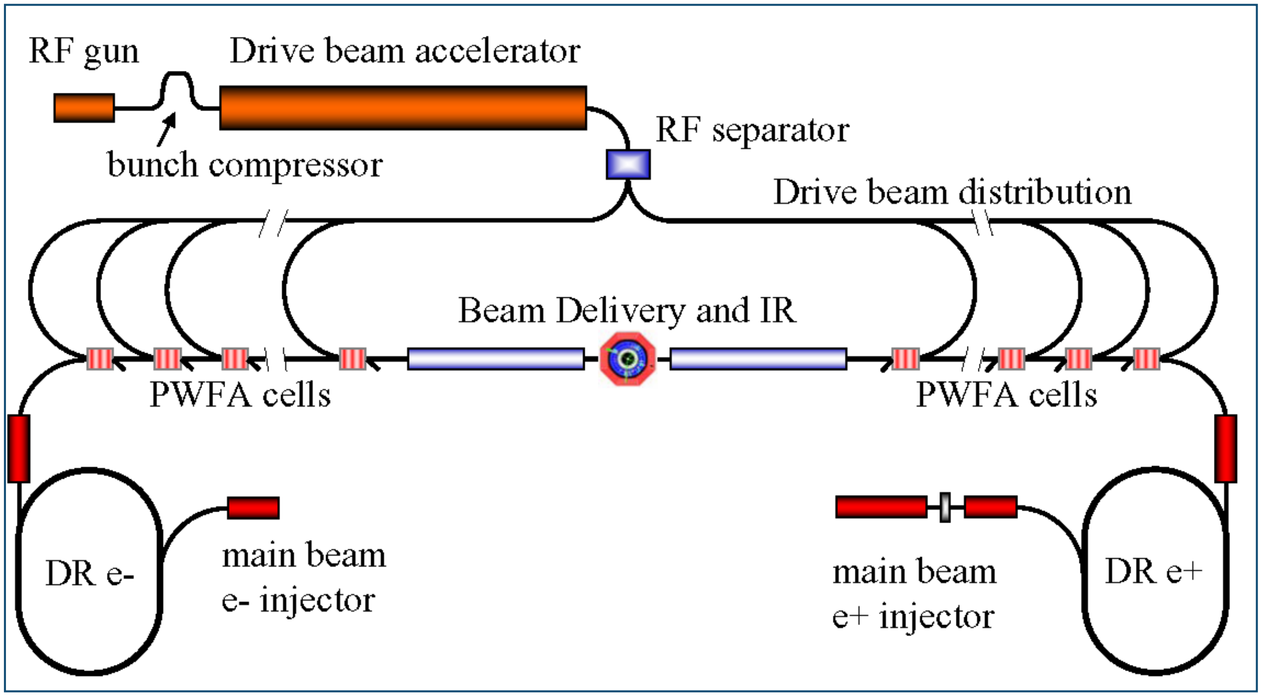
parameter	symbol			
centre of mass energy	E_{cm} [GeV]	500	1400	3000
luminosity	$\mathcal{L}$ [10^{34} cm^{-2}s^{-1}]	2.3	3.2	5.9
luminosity in peak	$\mathcal{L}_{0.01}$ [10^{34} cm^{-2}s^{-1}]	1.4	1.3	2
gradient	G [MV/m]	80	80/100	100
site length	[km]	13	28	48.3
charge per bunch	N [10^9]	6.8	3.7	3.7
bunch length	σ_z [μm]	72	44	44
IP beam size	σ_x/σ_y [nm]	200/2.26	$\approx$ 60/1.5	$\approx$ 40/1
norm. emittance	ϵ_x/ϵ_y [nm]	2400/25	660/20	660/20
bunches per pulse	n_b	354	312	312
distance between bunches	Δ_b [ns]	0.5	0.5	0.5
repetition rate	f_r [Hz]	50	50	50
est. power cons.	P_{wall} [MW]	271	361	582

Linear Colliders with E > 1 TeV

- ILC is ~ 50 km at 1 TeV
    - Possible to consider higher gradient SCRF materials or PWFA boost
- CLIC design is aimed at upgradable design → 0.5-3 TeV
    - Geographic gradient of 4x higher than ILC
- Advanced acceleration options (plasma, dielectric)
    - Plasma acceleration has made great progress however still huge challenges in beam quality and stability
    - Extremely low charge dielectric-laser accelerators may provide only reasonable parameters in multi-TeV regime
    - None of AARD options are close to being ready
- Some plasma and dielectric options act as transformers taking high power beams → high energy beams
    - Possible to develop upgrade options for ILC-like technology?

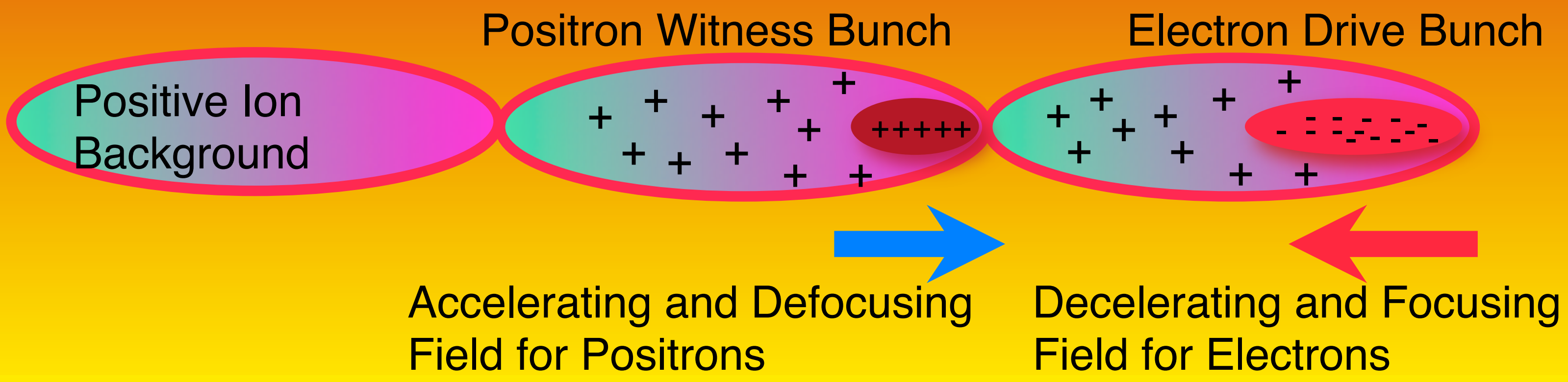
Concept of Beam-Driven Plasma Linac

- Concept for a 1 TeV plasma wakefield-based linear collider
  - Use conventional Linear Collider concepts for main beam and drive beam generation and focusing and PWFA for acceleration
    - Makes good use of PWFA R&D and 30 years of conventional rf R&D
  - Concept illustrates focus of PWFA R&D program
    - High efficiency
    - Emittance preservation
    - Positrons
  - Allows study of cost-scales for further optimization of R&D



Challenges for Positron Plasma Wakefield Acceleration

M. Hogan



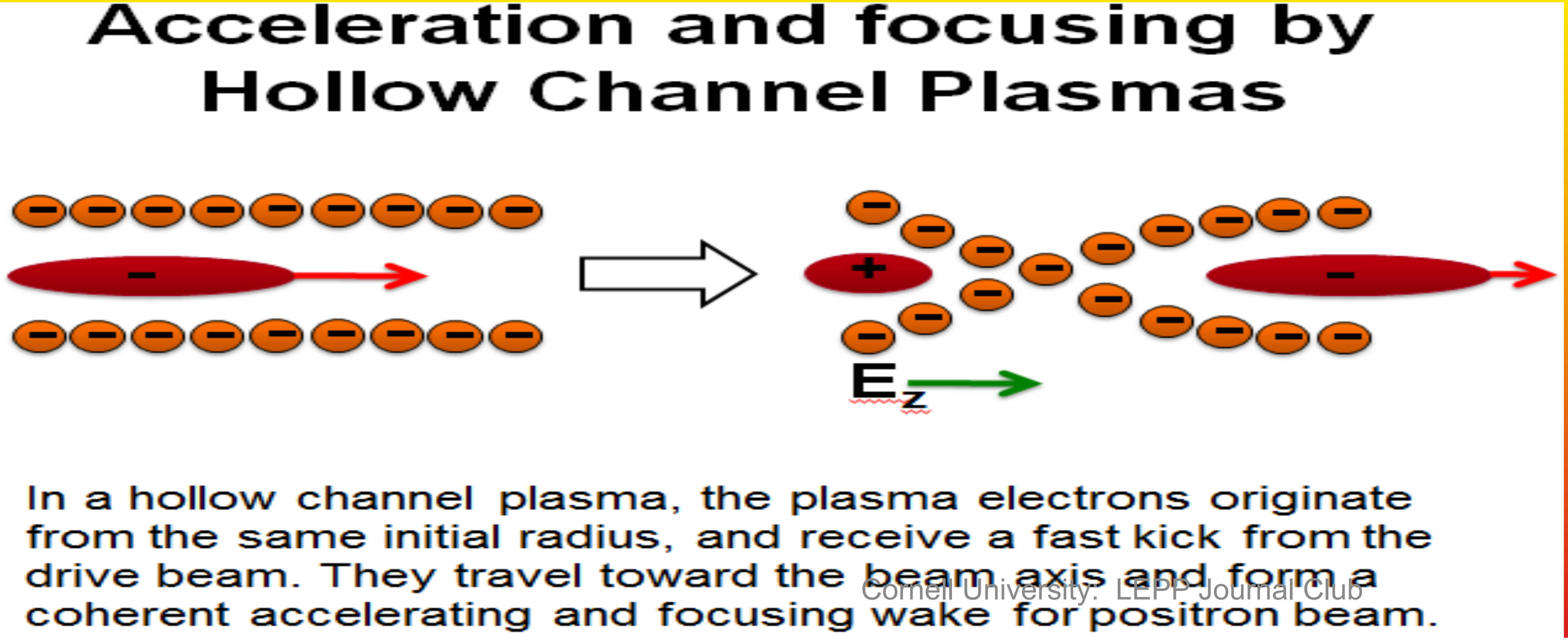
Positron Witness Bunch

Electron Drive Bunch

Positive Ion Background

Accelerating and Defocusing Field for Positrons

Decelerating and Focusing Field for Electrons



Acceleration and focusing by Hollow Channel Plasmas

In a hollow channel plasma, the plasma electrons originate from the same initial radius, and receive a fast kick from the drive beam. They travel toward the beam axis and form a coherent accelerating and focusing wake for positron beam.

Possible Linear Collider Parameters

Case	**0.5 TeV ILC**	**3 TeV CLIC**	**10 TeV Dielectric Beam Acc.**	**10 TeV Plasma Accelerator**	**10 TeV Dielectric Laser Acc.**
Energy per beam (TeV)	0.25	1.5	5	5	5
Luminosity (10^{34} cm^{-2}s^{-1})	2	6.4	49	71.4	105
Electrons per bunch ($\times 10^9$)	20	3.7	4	4	0.002
Rep. rate (Hz) / number / train	5 / 1312	50 / 312	50 / 416	17,000 / 1	25,000,000 / 1
Horizontal emittance $\gamma\varepsilon_x$ (nm-rad)	10,000	660	1000	200	0.1
Vertical emittance $\gamma\varepsilon_y$ (nm-rad)	30	20	10	200	0.1
β* x/y (mm)	11 / 0.2	4 / 0.1	10 / 0.1	0.2	0.4
Horizontal beam size at IP σ^*_x (nm)	474	49	32	2	0.06
Vertical beam size at IP σ^*_y (nm)	3.8	1.0	0.3	2	0.06
Luminosity enhancement factor	1.6	1.9	1.9	1.35	6.05
Bunch length σ_z (μm)	300	50	20	1	335
Beamstrahlung parameter Υ	0.07	6.7	56	8980	0.4
Beamstrahlung photons per electron n_γ	1.7	1.5	1.4	3.67	0.5
Beamstrahlung energy loss δ_E (%)	4.3	33	37	48	4.3
Accelerating gradient (GV/m)	0.031	0.1	0.5	10	0.5
Average beam power (MW)	5.3	13.9	55	54	38
Wall plug power (MW)	200	568	~1200	~1200	~550
One linac length (km)	15.5	23.5	10	1.0	10.5

ILC and CLIC parameters from design reports; 10 TeV DBA scaled from Wei Gai communication; 10 TeV DLA and Plasma Accelerator from 2010 ICUIL/ICFA Workshop

CLIC and Wakefield LCs

Status

- CLIC Conceptual Design Report complete
- Wakefield Accelerator Concepts – Feasibility being assessed

R&D

- CLIC: Focus on technology and advanced systems R&D
- Wakefield Accelerators:
  - Ability to accelerate positrons
  - Demonstration of multi-stage acceleration
  - Understanding the extrapolation of all parameters to the regimes required for HEP accelerator use (emittance preservation, achievable energy spread, beam loading, repetition rate)

Time

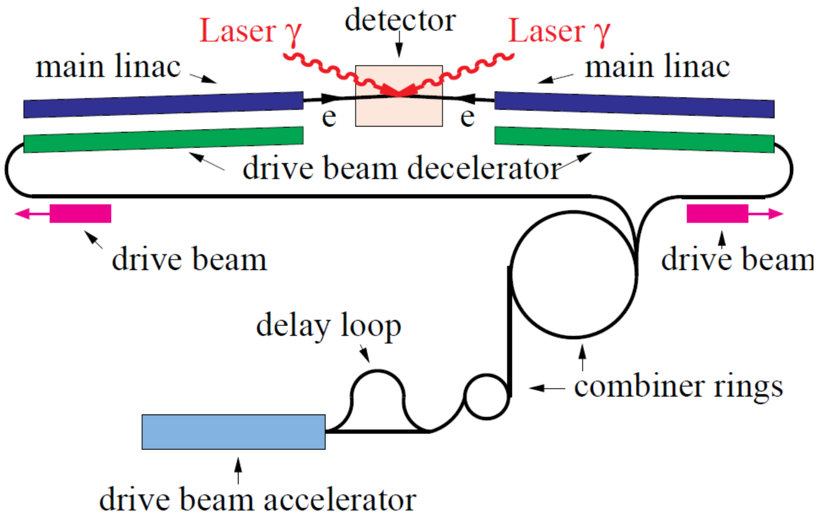
- CLIC: Timescale dependent on finalized technical design and physics needs
- Wakefield LCs:
  - Expect non-HEP applications on the ~decade timescale
  - Collider R&D phase to fully assess feasibility is likely decades scale
  - First application might be an ILC “afterburner”

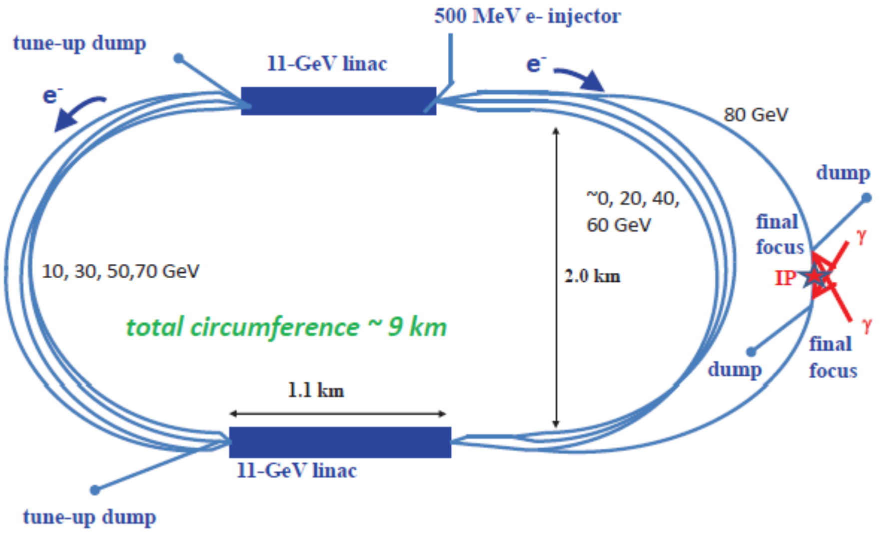
γ–γ Collider Concepts

- γ–γ Higgs Factory (E_{CM}~160 GeV, photons carry ~80% of CM E) might represent a `low cost’ option to demonstrate the technology
- Relative to LC: No positrons, damping rings, bunch compressors,…
- Laser parameters are challenging; requires optical cavity schemes

	SAPPHiRE
Beam Energy	80 GeV
Power Consumption	100 MW
Polarization	80%
Ave Beam Current	0.32 mA
E-e- geometric luminosity	2.2x10^34
Laser wavelength	351 nm
Repetition rate	200 kHz
Laser pulse energy	~5 J

CLICHÉ: CLIC Higgs Experiment





γ–γ Colliders

Status

- Principal technical challenge is laser system
- Question: Would the community be interested in a standalone facility versus eventual companion capability with an e^+e^- LC? Can this provide the required physics?

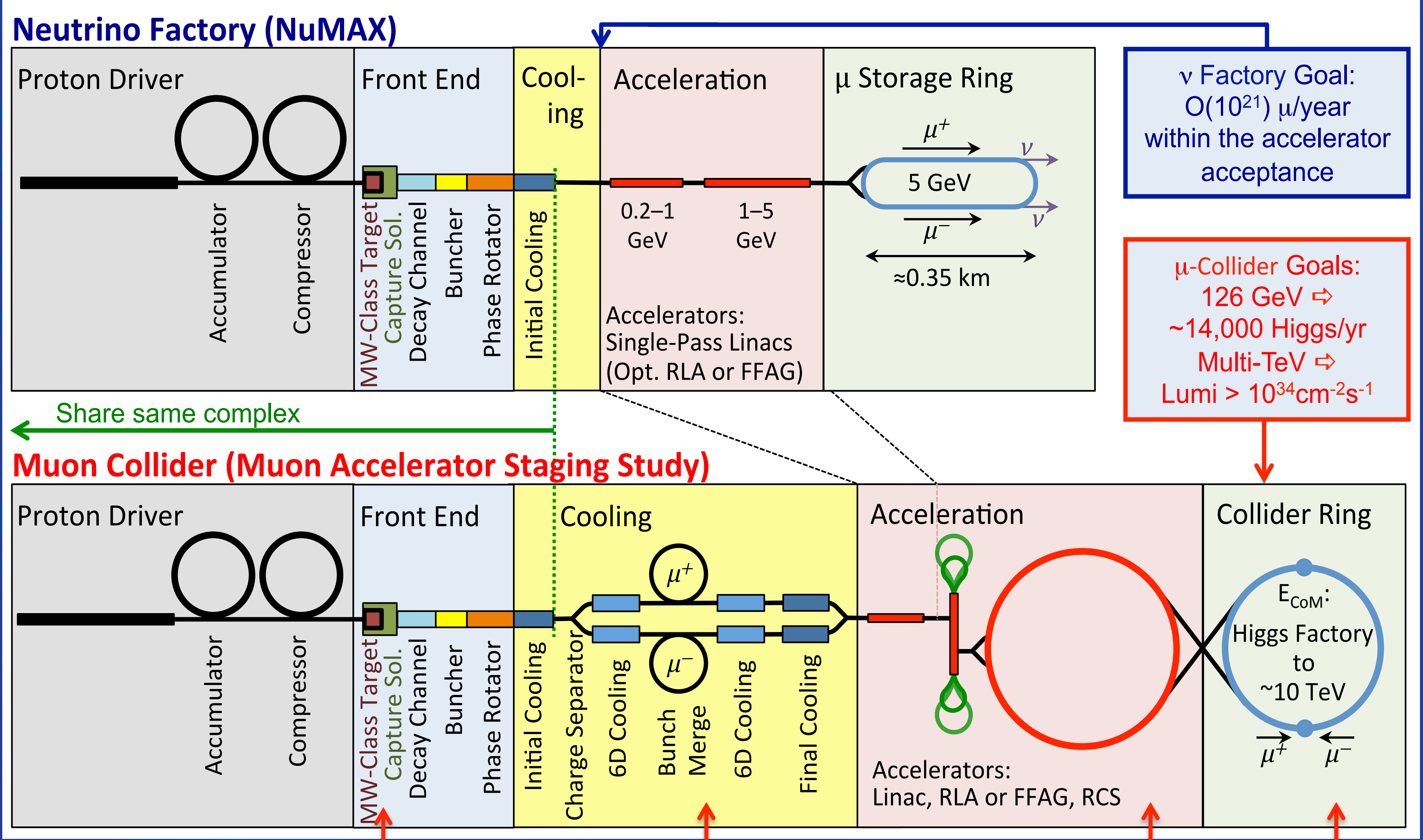
R&D

- Validate feasibility of required laser – significant recent progress
- Would need to establish a full Technical Design

Time

- In principle, a decision point could be reached in a few years

Muon Accelerator Concepts



Neutrino Factory (NuMAX)

ν Factory Goal:
O(10^{21}) μ/year
within the accelerator acceptance

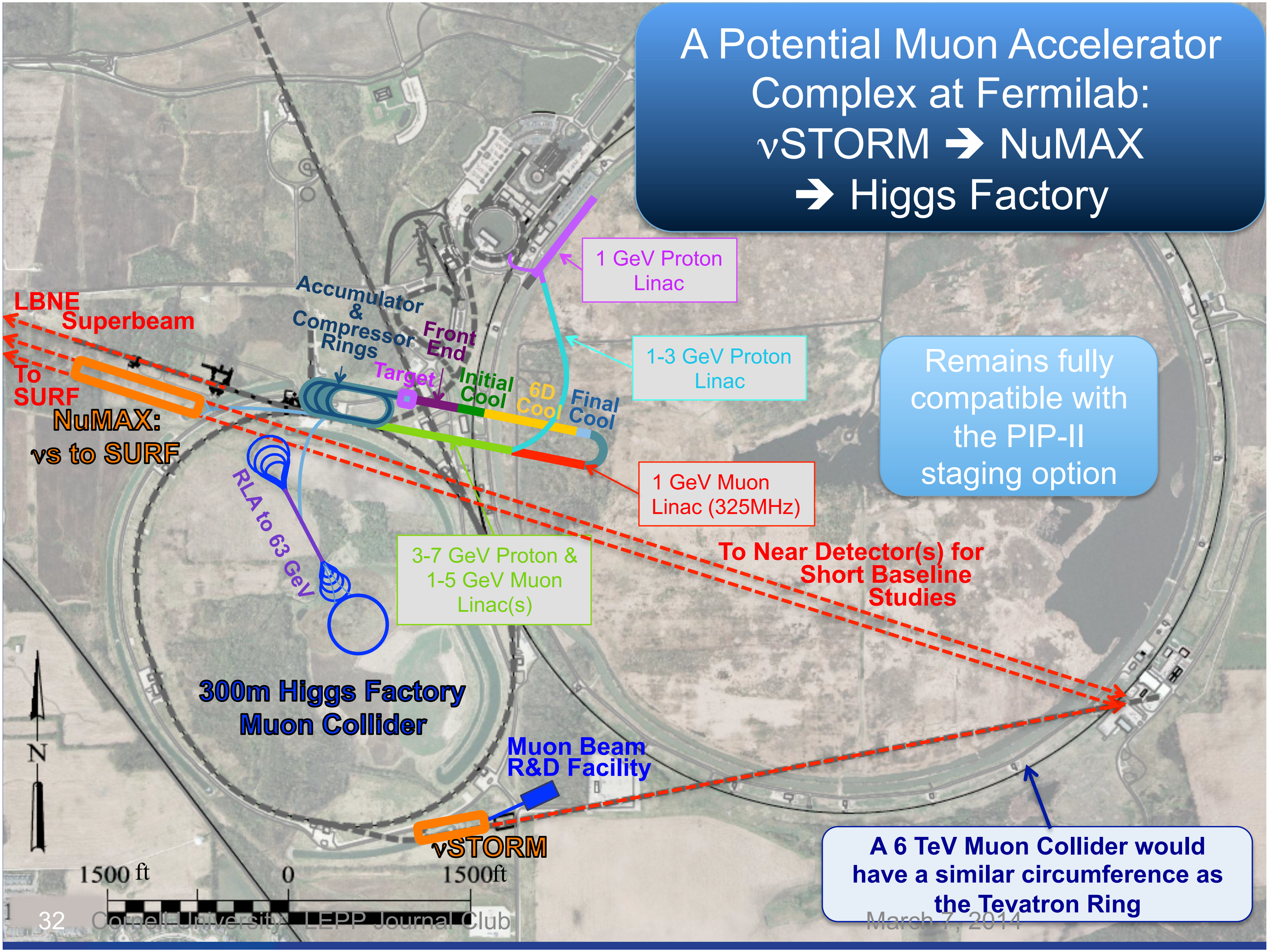
μ-Collider Goals:
126 GeV ⇨
~14,000 Higgs/yr
Multi-TeV ⇨
Lumi > 10^{34}cm^{-2}s^{-1}

Share same complex

Muon Collider (Muon Accelerator Staging Study)

Major Challenges

A Potential Muon Accelerator Complex at Fermilab: νSTORM ➔ NuMAX ➔ Higgs Factory

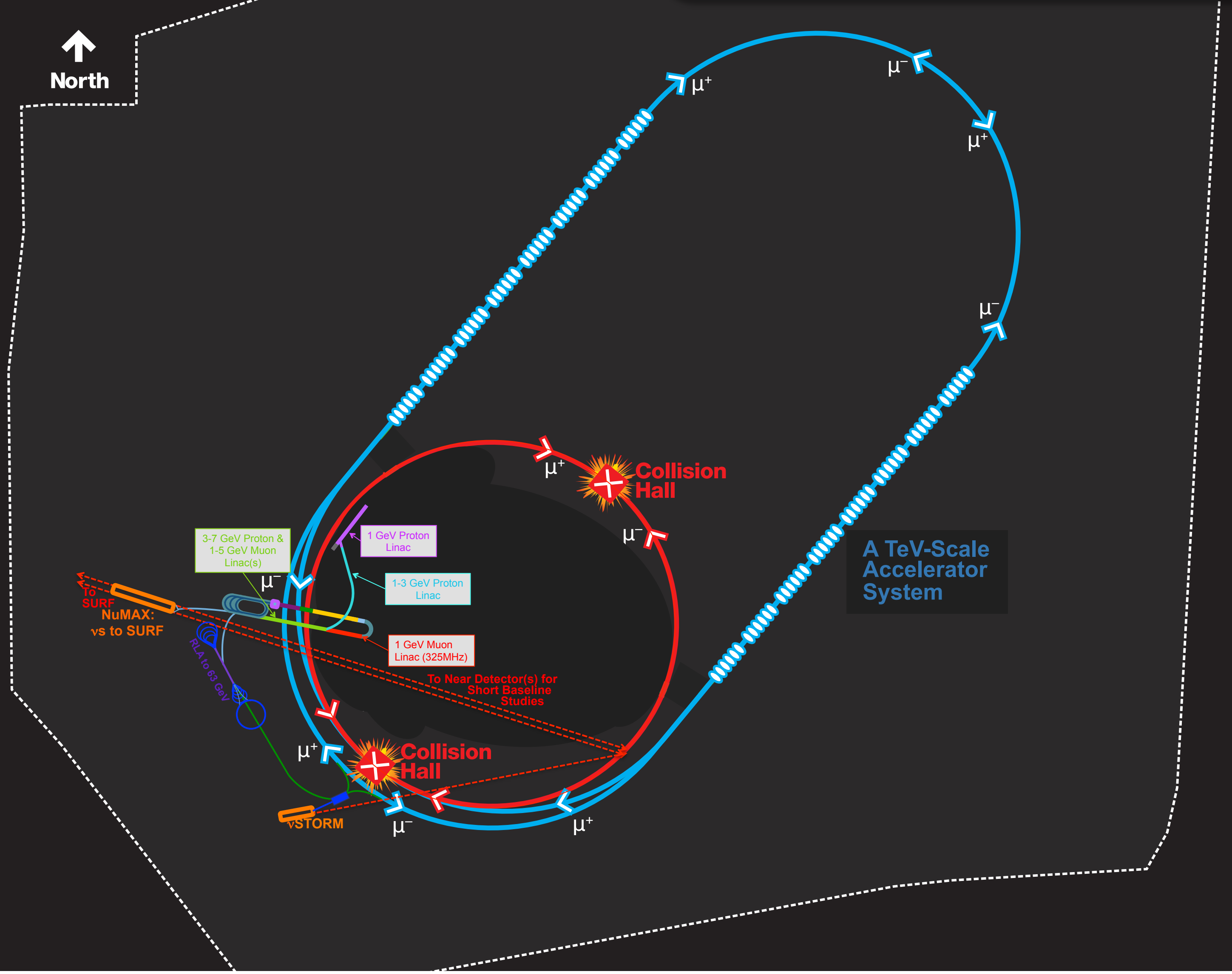


Remains fully compatible with the PIP-II staging option

A 6 TeV Muon Collider would have a similar circumference as the Tevatron Ring

A Potential Muon Accelerator Complex at Fermilab:

➔ Multi-TeV Collider



MAP Designs for a Muon-Based Higgs Factory and Energy Frontier Colliders

Range of Top Params:
$\delta E/E \sim 0.01 - 0.1\%$
$L_{avg} \sim 0.7 - 6 \times 10^{33}$

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

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

Muon Collider Baseline Parameters

		Higgs Factory		**Multi-TeV Baselines**	
Parameter	***Units***	Startup Operation	Production Operation		
CoM Energy	TeV	0.126	0.126	1.5	3.0
Avg. Luminosity	10^{34}cm^{-2}s^{-1}	0.0017	0.008	1.25	4.4
eam Energy Spread	%	0.003	0.004	0.1	0.1
Higgs/10^7sec		3,500	13,500	37,500	200,000
Circumference	km	0.3	0.3	2.5	4.5
No. of IPs		1	1	2	2
Repetition Rate	Hz	30	15	15	12
β^*	cm	3.3	1.7	1 (0.5-2)	0.5 (0.3-3)
No. muons/bunch	10^{12}	2	4	2	2
No. bunches/beam		1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	70	70
Bunch Length, σ_s	cm	5.6	6.3	1	0.5
Beam Size @ IP	μm	150	75	6	3
Beam-beam Parameter / IP		0.005	0.02	0.09	0.09
Proton Driver Power	MW	$4^{\#}$	4	4	4

[#] Could begin operation with Project X Stage 2 beam

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

Muon Colliders

Status

- MAP Feasibility Assessment underway

R&D

- Establishing Initial Baseline Design
- Technology R&D: Cooling channel hardware, RF in B-fields, high field magnets (synergistic with high energy pp collider needs)
- Staging Study: Physics + R&D + Demos required for next stage
- Muon Ionization Cooling Experiment (MICE) at RAL

Time

- Feasibility Assessment by end of decade
- Completion of MICE by end of decade
- nuSTORM short baseline NF could begin CD process immediately (Sterile neutrino program)
- NuMAX (initial long baseline NF): Informed Decision by ~2020
- Collider Program: Informed Decision by mid-2020s

Long-Term Perspective

Conclusions

CONNECTIONS

Some Connections…

- A theme in the capabilities discussions was that of upgrade paths
    - Note that a number of “constrained” options didn’t even get mentioned in this presentation
- There are many special synergies that also come into play:
    - TLEP and a ~100 TeV hadron collider
    - Muon Collider and the Neutrino Program
    - Technology linkages (eg, MAP and high energy pp collider magnet development)
    - $\gamma-\gamma$ as a companion capability to an LC
    - A wakefield accelerator upgrade to a conventional LC
    - And this is not an exhaustive list…

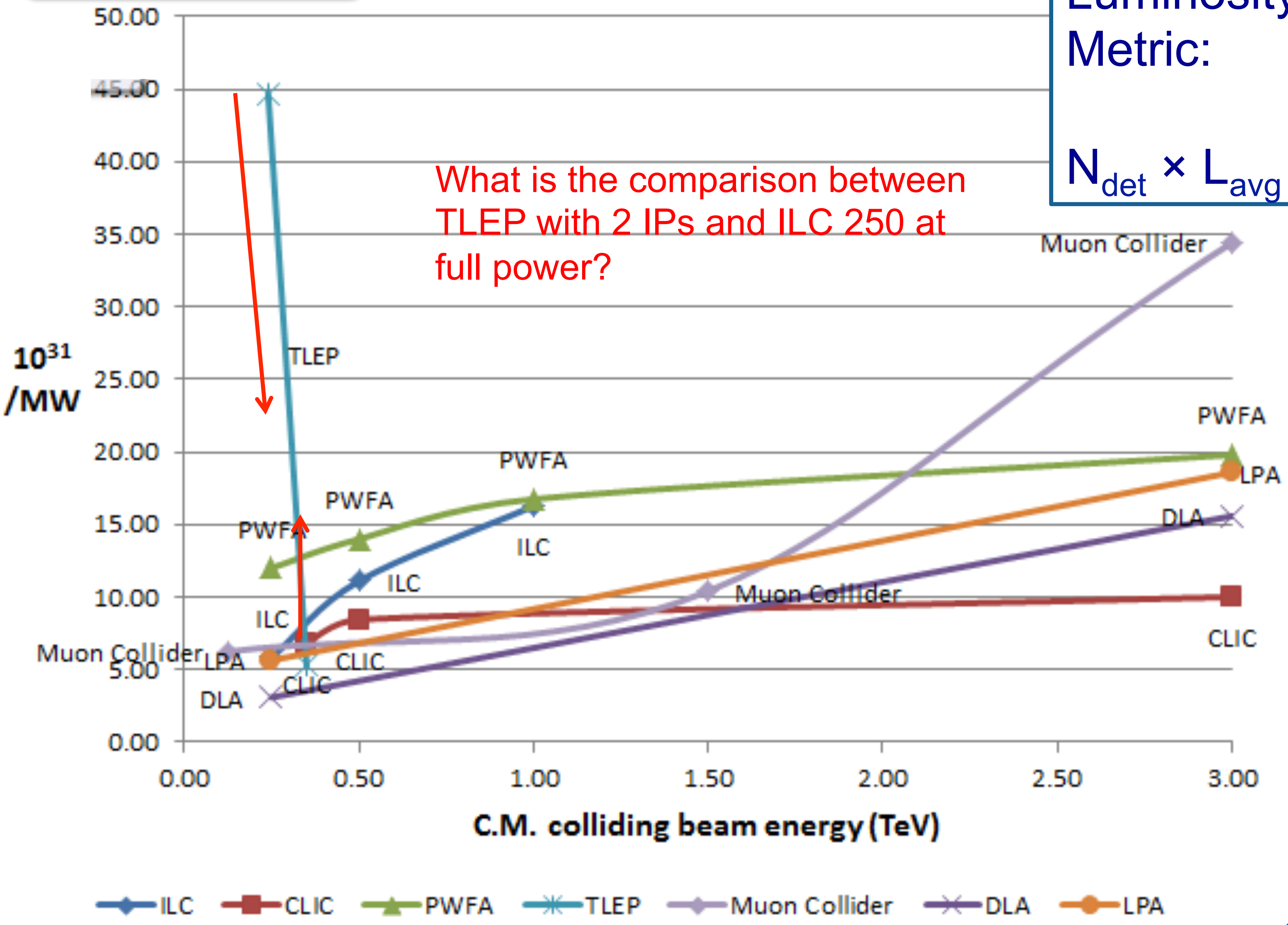
Some Thoughts and Comparisons…

- The LHC program for the next 20 years is well-defined
  - Questions arise as to what comes next
    - For example: Is an investment in a facility such as TLEP desirable on the 10 year timescale because it can lead to a VHE-LHC/VLHC capability in ~30 years?
- There is little question that the ILC design is, at present, the most complete and well-studied design for a machine targeted at the Higgs
  - But, what will we do if the next round of LHC data finally shows something at > 1 TeV?
  - On the relevant timescale (assuming advances in the R&D program), we may want to consider comparisons such as the plot on the next page…

J-P. Delahaye

Luminosity Metric:

$N_{det} \times L_{avg} / P_{tot}$



What is the comparison between TLEP with 2 IPs and ILC 250 at full power?

A FEW WORDS ON THE MUON ACCELERATOR PROGRAM (MAP)

Program Mission

The mission of the Muon Accelerator Program (MAP) is to develop and demonstrate the concepts and critical technologies required to produce, capture, condition, 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. Coordination with the parallel Muon Collider Physics and Detector Study and with the International Design Study of a Neutrino Factory will ensure MAP responsiveness to physics requirements.

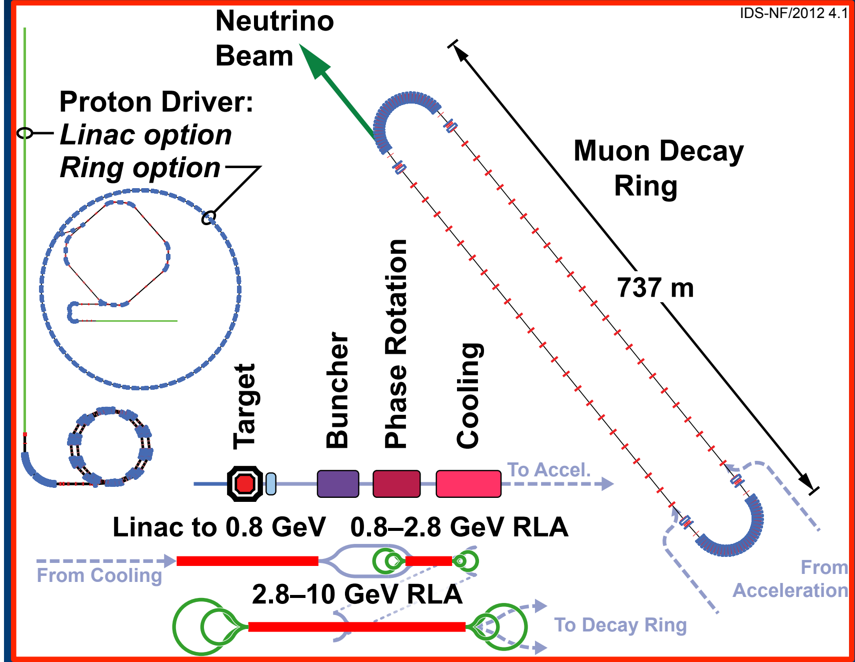
How we are executing this mission?

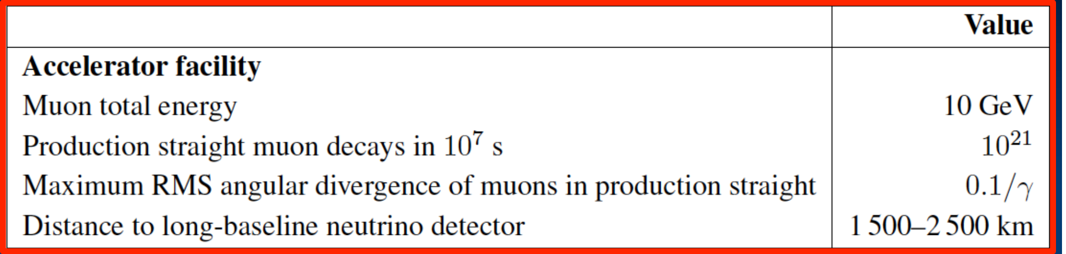
By supporting the development of muon accelerator technologies for the full range of capabilities described:

- Short baseline neutrino factory:
  - nuSTORM design, costing and proposal –
    a design for which *no new technology requirements exist*
- Long baseline neutrino factory:
  - IDS-NF design – *aimed at optimal physics reach*
  - Staged complex at Fermilab –
    aimed at a ***realistic*** *(ie, staged) deployment of NF capabilities ⇨* ***NuMAX*** *concept*
    - *Starting with a 1 MW proton driver and no ionization cooling…*
- Collider options:
  - From a *Higgs Factory* to…
  - A *multi-TeV Collider* (extending up to energy ranges that may be required by LHC results)
  - Again utilizing a staged complex at Fermilab…

Long Baseline Neutrino Factory

- IDS-NF



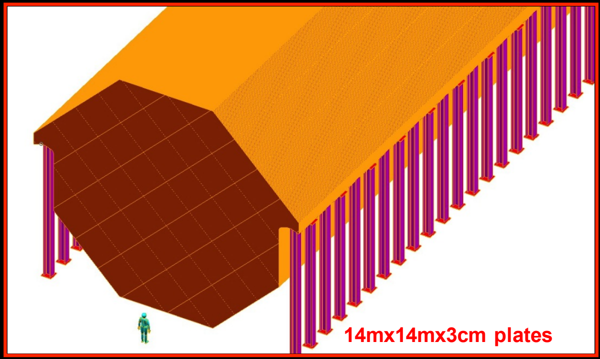


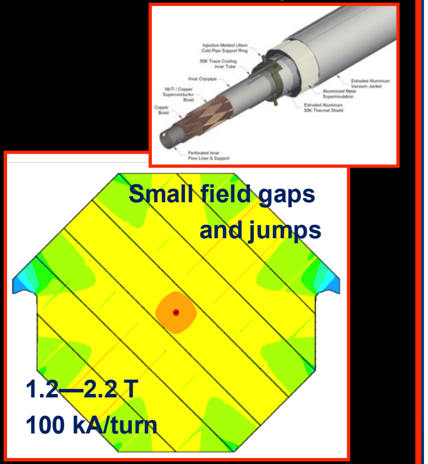
	Value
Accelerator facility	
Muon total energy	10 GeV
Production straight muon decays in 10^7 s	10^{21}
Maximum RMS angular divergence of muons in production straight	$0.1/\gamma$
Distance to long-baseline neutrino detector	1 500–2 500 km

- NuMAX aims for a staged facility at Fermilab with different technical and cost optimization

Magnetized Iron Neutrino Detector (MIND):

- **IDS-NF baseline:**
  - Intermediate baseline detector:
    - 100 kton at 2500—5000 km
  - Magic baseline detector:
    - 50 kton at 7000—8000 km
  - Appearance of “wrong-sign” muons
  - Toroidal magnetic field > 1 T
    - Excited with “superconducting transmission line”
  - Segmentation: 3 cm Fe + 2 cm scintillator
  - 50-100 m long
  - Octagonal shape
  - Welded double-sheet
    - Width 2m; 3mm slots between plates



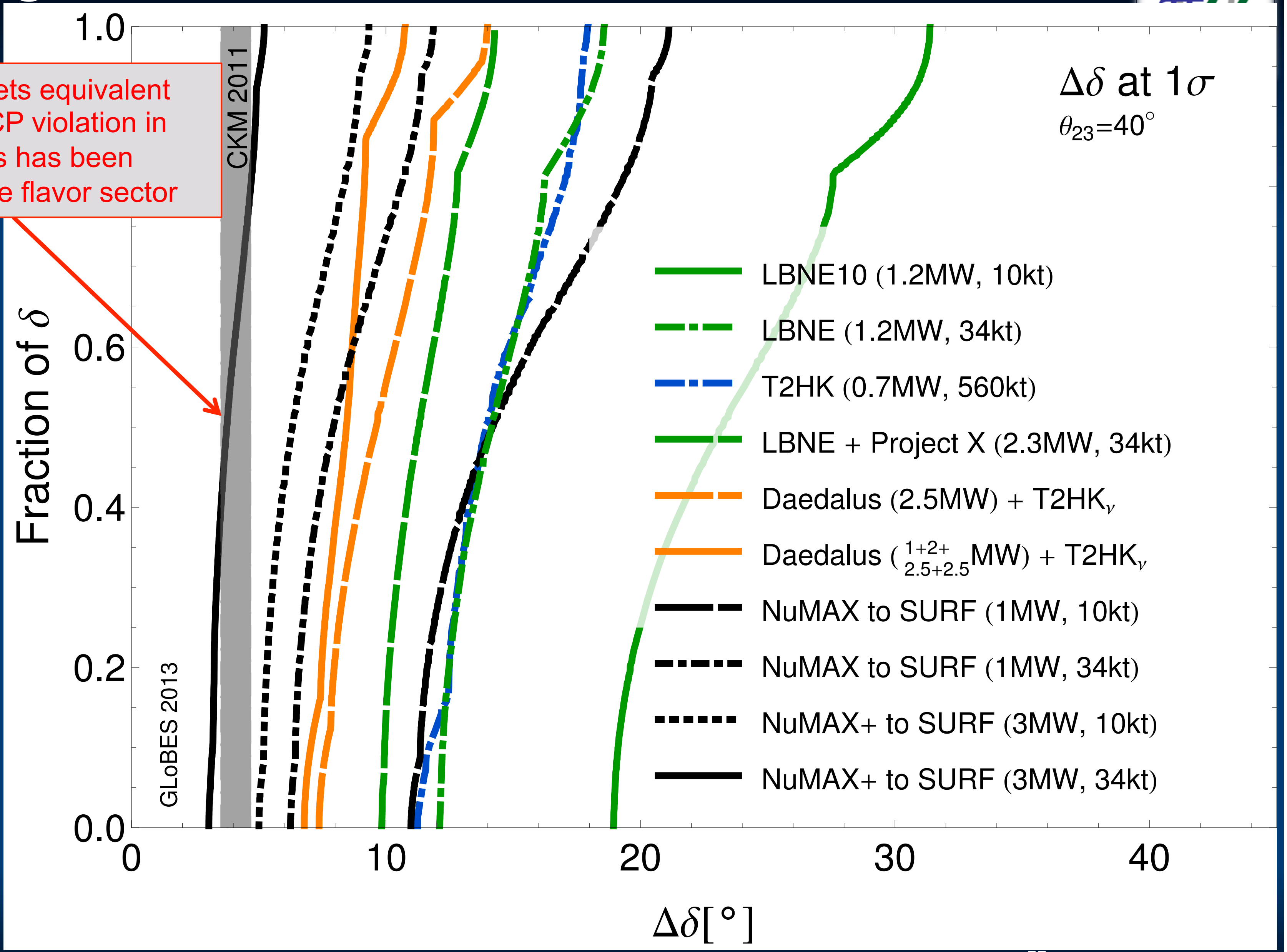


Bross, Soler

A Staged Plan with NuMAX at Fermilab

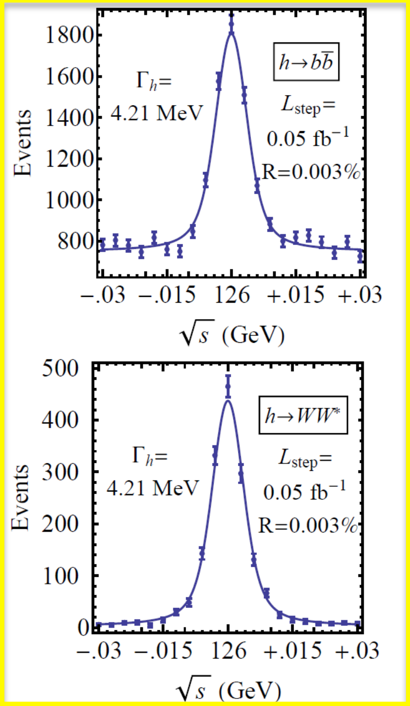
NuMAX+ targets equivalent sensitivity to CP violation in the ν sector as has been achieved in the flavor sector

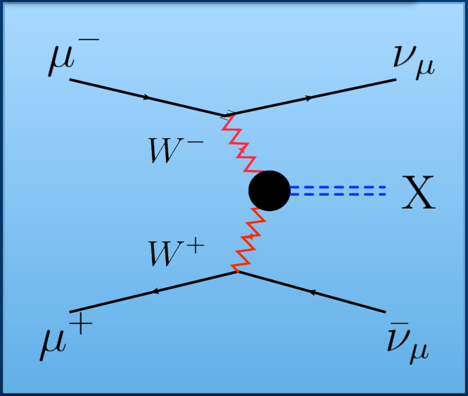
GLoBES Comparison of Potential Performance of the Various Advanced Concepts *(courtesy P. Huber)*



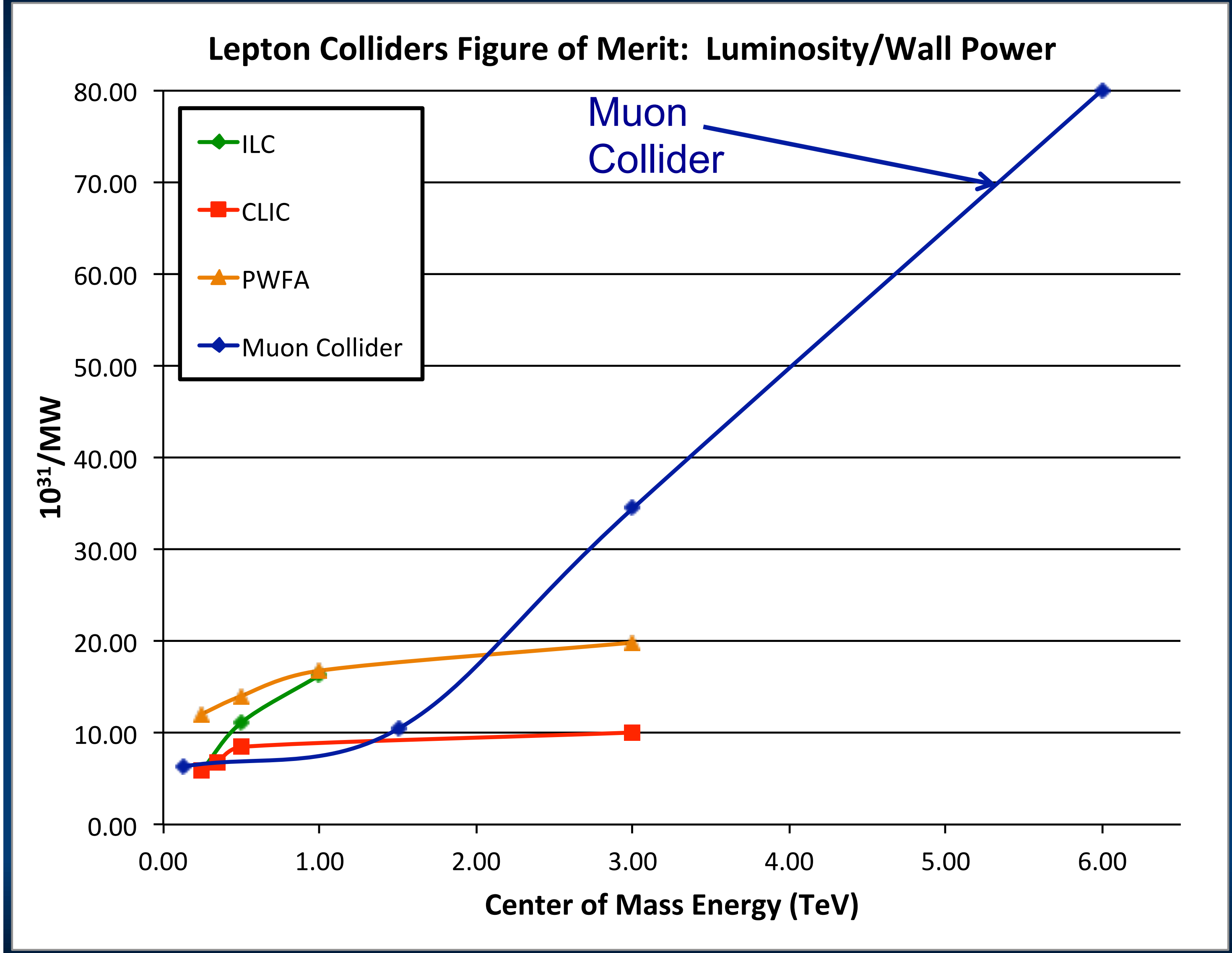
Physics Case for a Muon Collider

- Superb Energy Resolution
  - SM Thresholds and Higgs Factory operation
- At multi-TeV
  - Compact & energy efficient machine
  - Luminosity > 10^{34} cm^{-2} s^{-1}
  - Option for 2 detectors in the ring
- For $\sqrt{s}$ > 1 TeV: Fusion processes dominate
  ⇨ an Electroweak Boson Collider
  ⇨ a discovery machine complementary to a pp collider with $E_{pp} \approx 7E_{MC}$
- At > 5 TeV CoM, could provide Higgs self-coupling resolutions of <10%
- What if upcoming runs with the LHC shows evidence for a multi-TeV particle spectrum?





Luminosity Production Metric

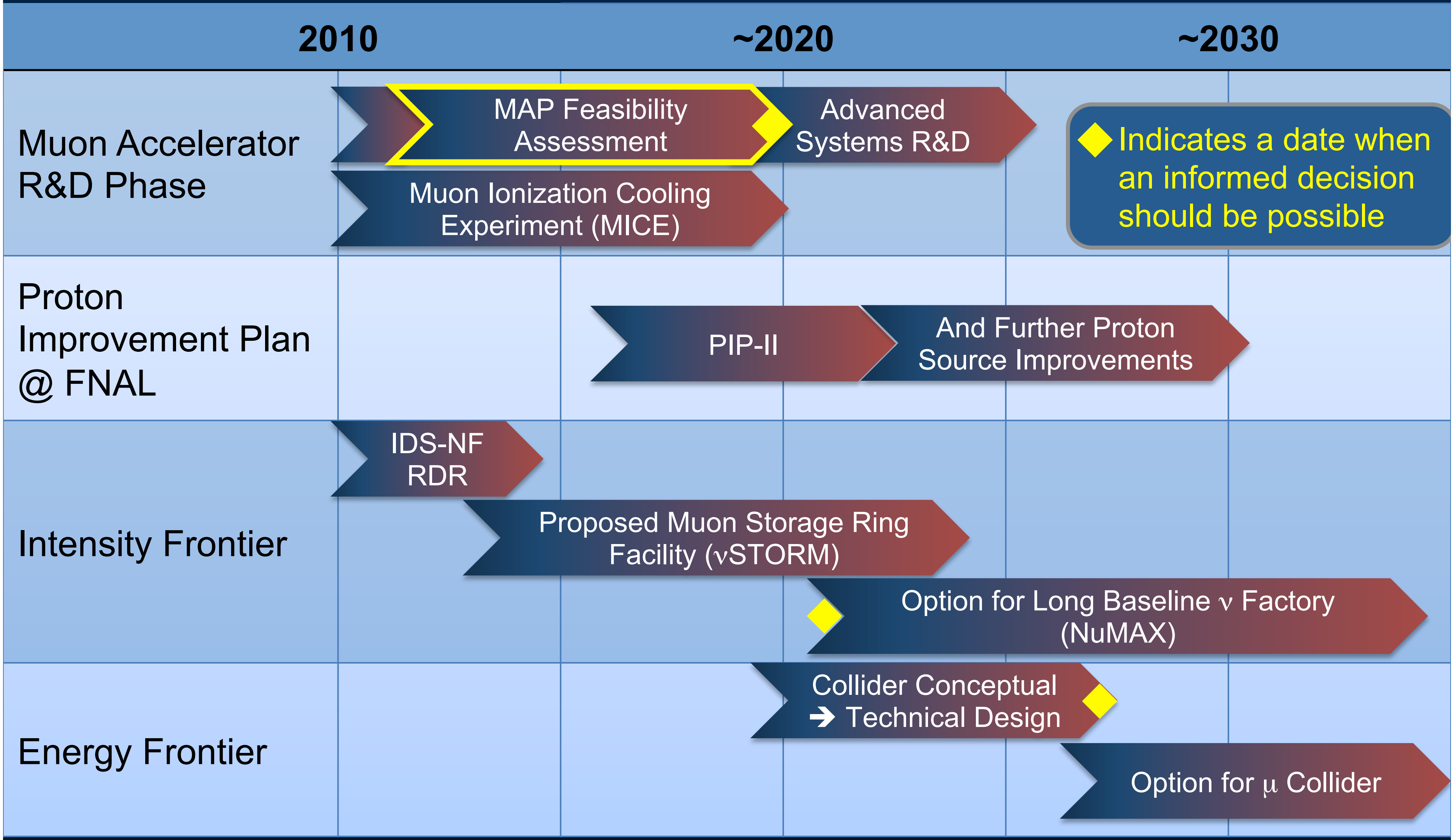


Muon Collider

Luminosity Metric:

$N_{det} \times L_{avg} / P_{tot}$

MAP Timeline ⇨ Provide Informed Decision Points



2010

~2020

~2030

Muon Accelerator R&D Phase

◆ MAP Feasibility Assessment

Advanced Systems R&D

Muon Ionization Cooling Experiment (MICE)

◆ Indicates a date when an informed decision should be possible

Proton Improvement Plan @ FNAL

PIP-II

And Further Proton Source Improvements

Intensity Frontier

IDS-NF RDR

Proposed Muon Storage Ring Facility (νSTORM)

◆ Option for Long Baseline ν Factory (NuMAX)

Energy Frontier

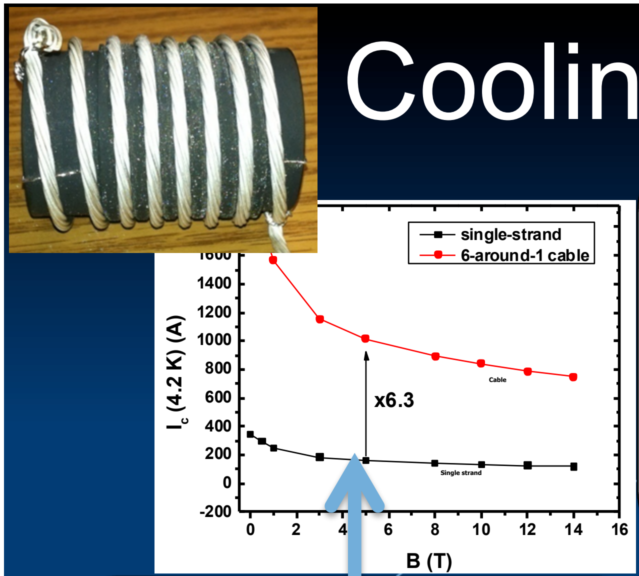
Collider Conceptual ➔ Technical Design ◆

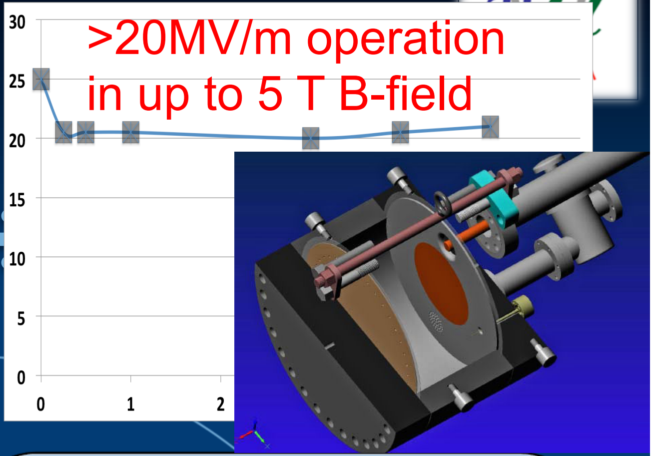
Option for μ Collider

R&D Effort

- Scope – ***Note that MAP is constituted as a directed Accelerator Technology R&D Effort to demonstrate feasibility***
  - Provide:
    - Specifications for all required technologies
    - Baseline design concepts for each accelerator system (see block diagram to follow)
  - For novel technologies:
    - Carry out the necessary design effort and R&D to assess feasibility
    - Note: a program of advanced systems R&D is anticipated ***after*** completion of the feasibility assessment
  - Ongoing Technology R&D and feasibility demonstrations include:
    - MuCool Test Area experimental program (FNAL): RF in high magnetic fields
    - The Muon Ionization Cooling Experiment (MICE@RAL):
      - Demonstration of emittance reduction
      - Validation of cooling channel codes
    - Advanced magnet R&D
      - Very high field magnets (cooling channel and storage rings)
      - Rapid cycling magnets for acceleration of short-lived beams

Cooling Channel R&D Effort




>20MV/m operation in up to 5 T B-field

Successful Operation of 805 MHz “All Seasons” Cavity in 5T Magnetic Field under Vacuum

MuCool Test Area/Muons Inc

Breakthrough in HTS Cable Performance with Cables Matching Strand Performance

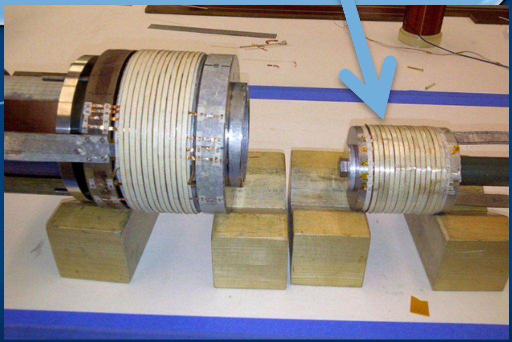
FNAL-Tech Div
T. Shen-Early Career Award

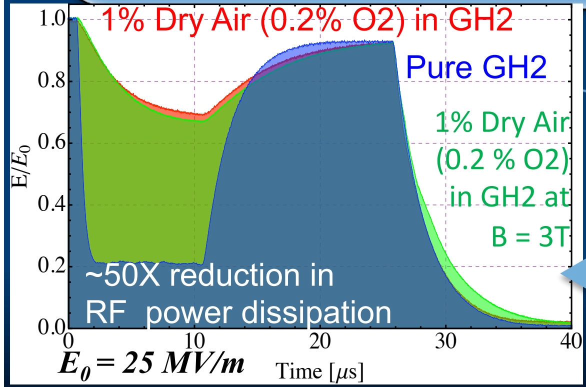
The Path to a Viable Muon Ionization Cooling Channel

World Record HTS-only Coil

15T on-axis field
16T on coil

PBL/BNL




~50X reduction in RF power dissipation

$E_0 = 25$ MV/m

Demonstration of High Pressure RF Cavity <u>in 3T Magnetic Field with Beam</u>

Extrapolates to
μ-Collider Parameters

MuCool Test Area

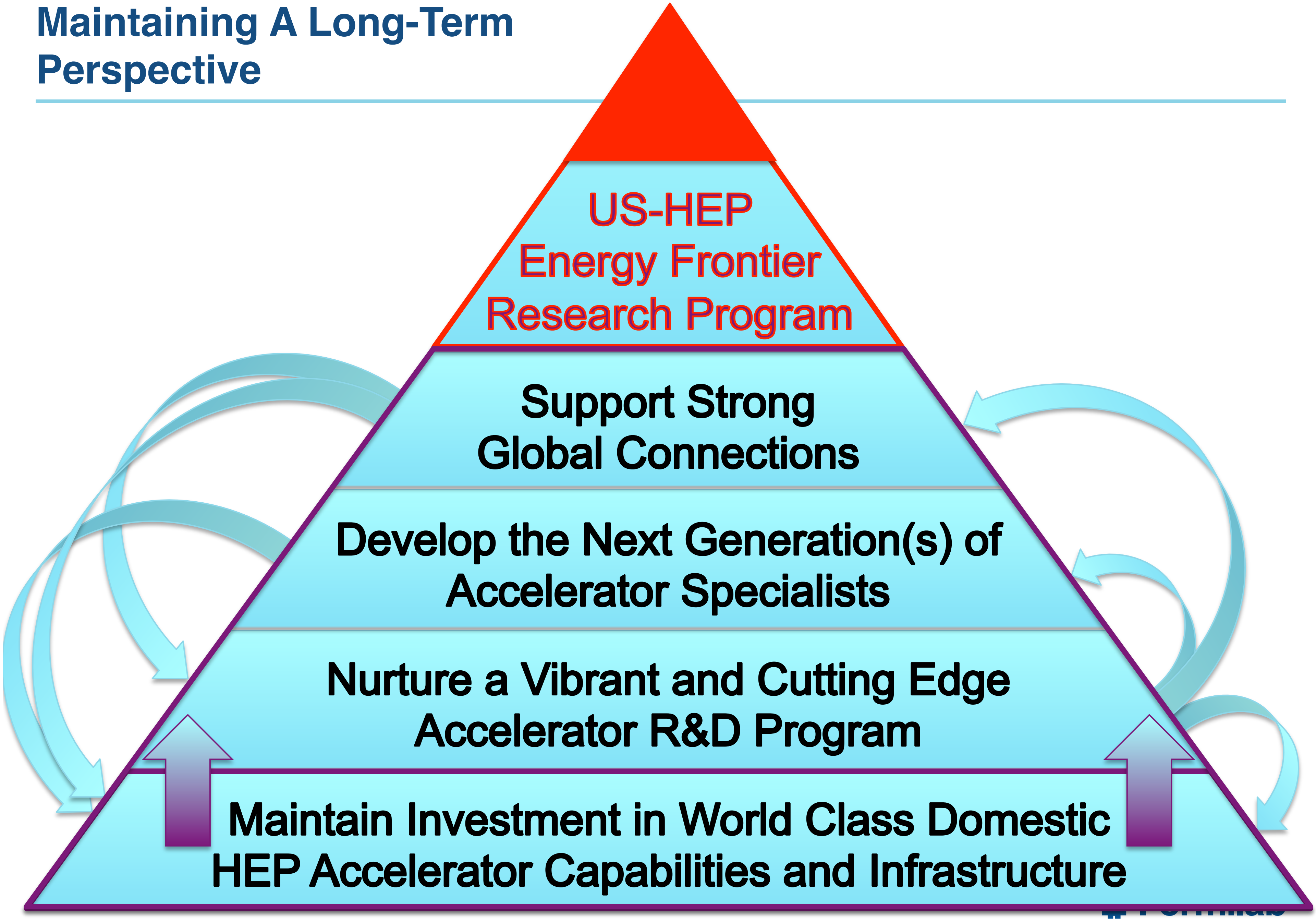
The Key Choices

- The breadth of science that can be supported by a muon accelerator capability argues for continued support of the directed national accelerator R&D program (integrated with a global R&D effort) which is now in its 3rd year
  - Feasibility Assessment available by the end of the decade – in time for the next P5 round
- NF:
  The R&D would support future high precision capabilities with well-understood systematics
- MC:
  The R&D would prepare for the possibility that LHC running reveals the lowest states of a new particle spectrum

  Note that the MC may be the only viable route to a several TeV lepton collider capability in the next 20 years

CLOSING COMMENTS

Maintaining A Long-Term Perspective



US-HEP
Energy Frontier
Research Program

Support Strong
Global Connections

Develop the Next Generation(s) of
Accelerator Specialists

Nurture a Vibrant and Cutting Edge
Accelerator R&D Program

Maintain Investment in World Class Domestic
HEP Accelerator Capabilities and Infrastructure

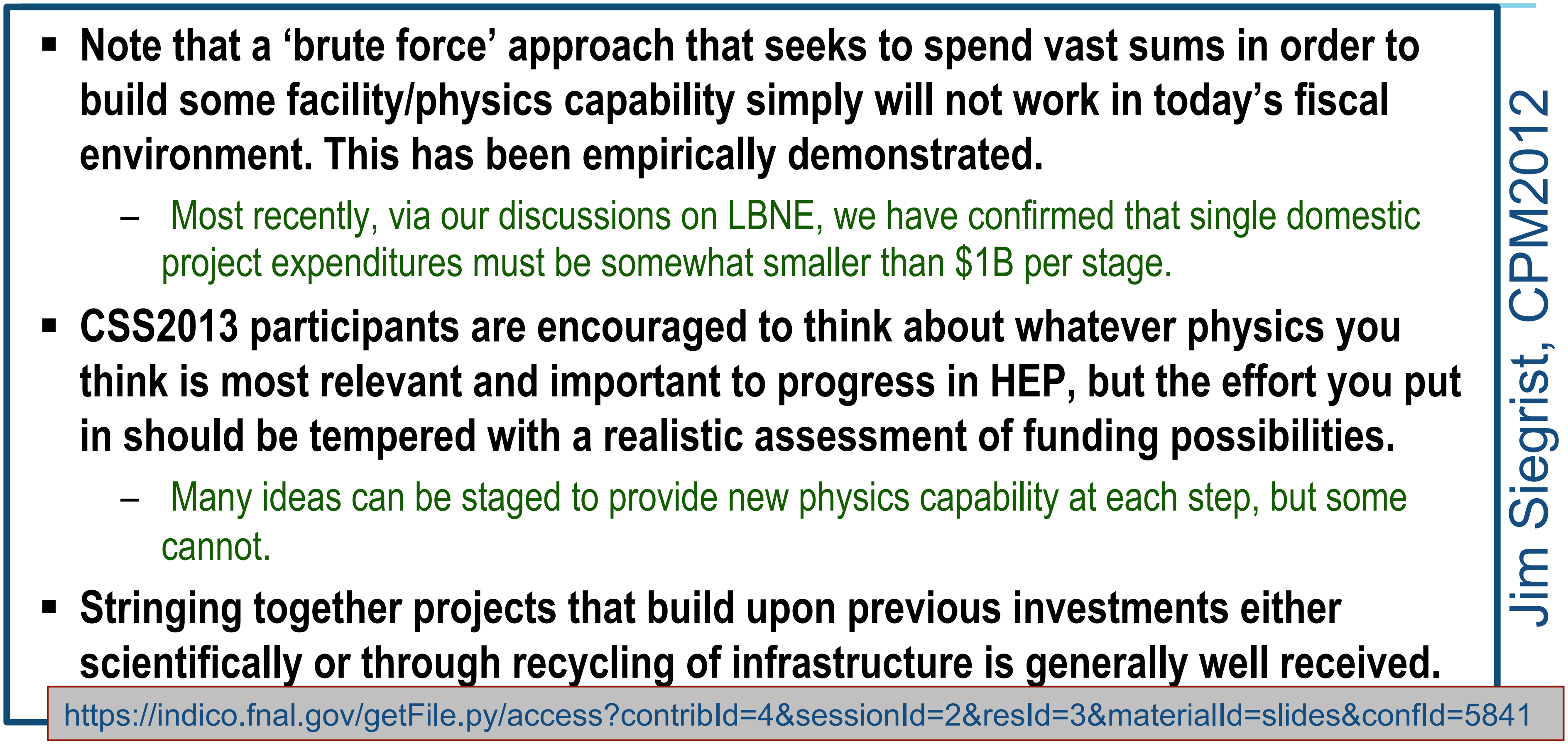
What do you get for a Billion Dollars?

NSLS-II: $0.9B, 0.8 km storage ring

SNS: $1.4B, 1 GeV Linac, Ring, high-power target, 1km

S. Henderson
HF2012

P5 Is Underway: But it's still worth remembering the boundary conditions that were stated at the start of the process…



- **Note that a 'brute force' approach that seeks to spend vast sums in order to build some facility/physics capability simply will not work in today's fiscal environment. This has been empirically demonstrated.**
  - Most recently, via our discussions on LBNE, we have confirmed that single domestic project expenditures must be somewhat smaller than $1B per stage.
- **CSS2013 participants are encouraged to think about whatever physics you think is most relevant and important to progress in HEP, but the effort you put in should be tempered with a realistic assessment of funding possibilities.**
  - Many ideas can be staged to provide new physics capability at each step, but some cannot.
- **Stringing together projects that build upon previous investments either scientifically or through recycling of infrastructure is generally well received.**

Jim Siegrist, CPM2012

https://indico.fnal.gov/getFile.py/access?contribId=4&sessionId=2&resId=3&materialId=slides&confId=5841

- It's imperative to make the case for the physics we need,
- But we must also develop a coherent plan that is realistic if we want to preserve the health and vitality of the U.S. HEP program
- The challenges for **all** of the options presented here go beyond the technical

Conclusions

- The necessity of US engagement in the ongoing LHC program is clear
- As is maintaining global connections if the next collider facility is off-shore
- At the same time we cannot ignore other elements of the US HEP program
  - Investing in our domestic facilities which support non-collider portions of HEP
  - Maintaining a robust R&D program which benefits both our global connections and can open the door to additional world class capabilities in the US
  - And continue to train the experts to support the next generation of facilities

Backup Slides Follow

There is only one real challenge …
the parameter list

Optics Challenges for TLEP

Bernhard Holzer

at the recent FCC Kick-Off Meeting

	Z	W	H	tt
Beam energy [GeV]	45.5	80	120	175
Beam current [mA]	1450	152	30	6.6
Bunches / beam	16700	4490	1360	98
Bunch population [10^{11}]	1.8	0.7	0.46	1.4
Transverse emittance e				
- **Horizontal [nm]**	29.2	3.3	0.94	2
- **Vertical [pm]**	60	7	1.9	2
Momentum comp. [10^{-5}]	18	2	0.5	0.5
Betatron function at IP b*				
- **Horizontal [m]**	0.5	0.5	0.5	1
- **Vertical [mm]**	1	1	1	1
Beam size at IP s* [mm]				
- **Horizontal**	121	26	22	45
- **Vertical**	0.25	0.13	0.044	0.045
Bunch length [mm]				
- **Synchrotron radiation**	1.64	1.01	0.81	1.16
- **Total**	2.56	1.49	1.17	1.49
Energy loss / turn [GeV]	0.03	0.33	1.67	7.55
Total RF voltage [GV]	2.5	4	5.5	11

design & optimise a lattice
for 4 different energies

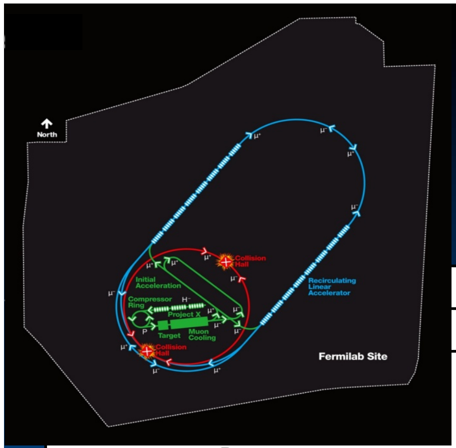
Interaction Region layout
for a large number of bunches
$\Delta s = 6m$ (LHC = 7.5m)

small hor. emittance
increasing with reduced energy
$\varepsilon_y / \varepsilon_x = 10^{-3}$

extremely small vert. beta
$\beta_y = 1mm$
→ *high chromaticity*
→ *challenging dynamic aperture*

high synchrotron radiation losses
include sophisticated
absorber design in the lattice

Muon Collider Parameters



Muon Collider Parameters

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

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

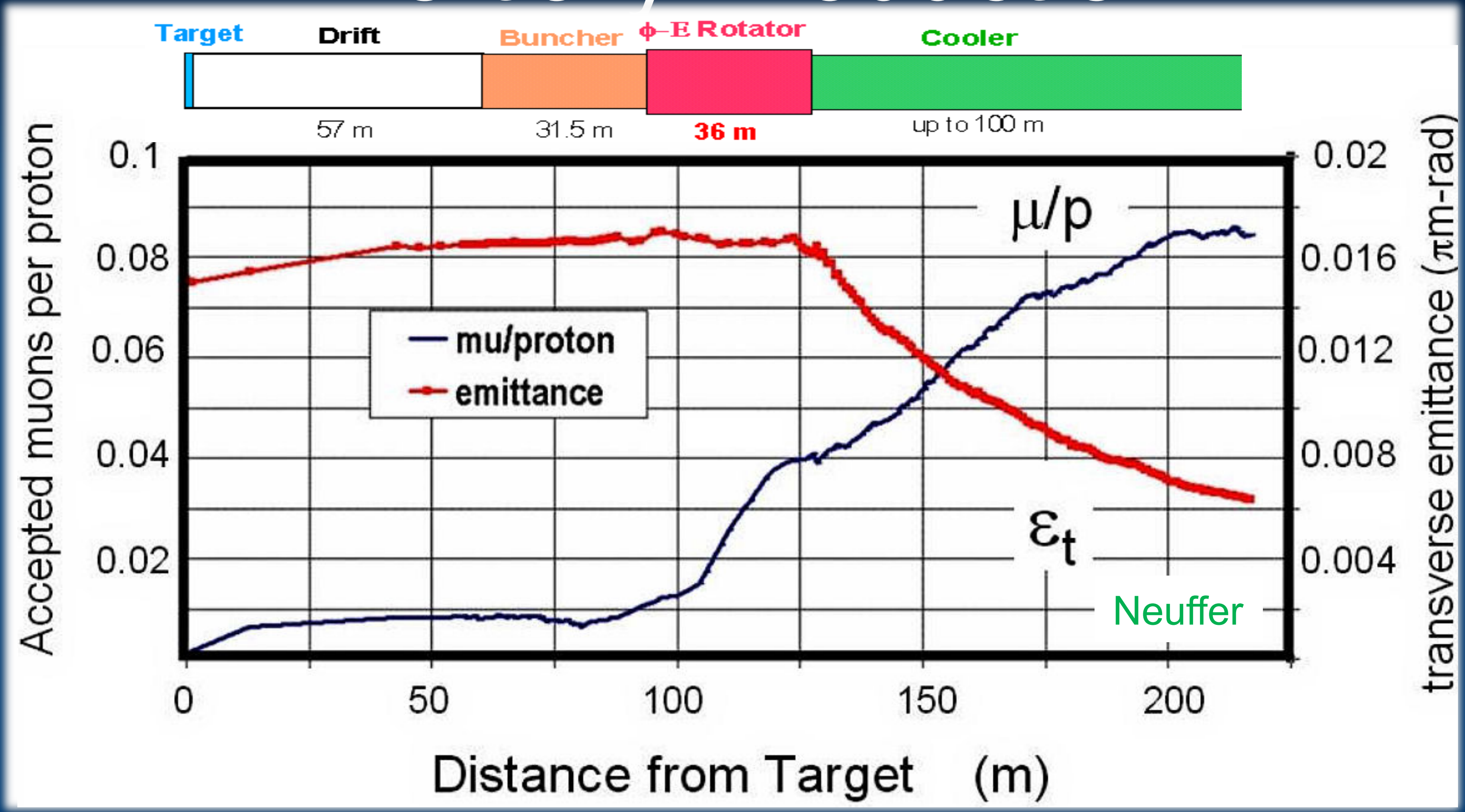
Success of advanced cooling concepts ⇨ several × 10^{32}

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

MAP Initial Baseline Selection Process

- Now to 2016:
  - Explore, develop, and select the **Initial Baseline Design (IBS)** of all accelerator subsystems
    - Clear specifications are absolutely critical to the technology demonstrations that are being undertaken to establish the feasibility of high intensity muon accelerators
    - The coupling between design and technology is clearly iterative
    - However, given the knowledge that we presently have, it is crucial to clearly define the design concepts for individual systems
  - To enhance the quality of the designs, the IBS process will focus primarily on a site-specific implementation at Fermilab which would build on the superconducting linac upgrade presently being planned
    - It will also focus on specifications that are compatible with the conclusions of the Muon Accelerator Staging Study (MASS)
- In the 2016-2020 timeframe, will launch the next set of feasibility R&D activities (on the basis of the IBS-specified designs)

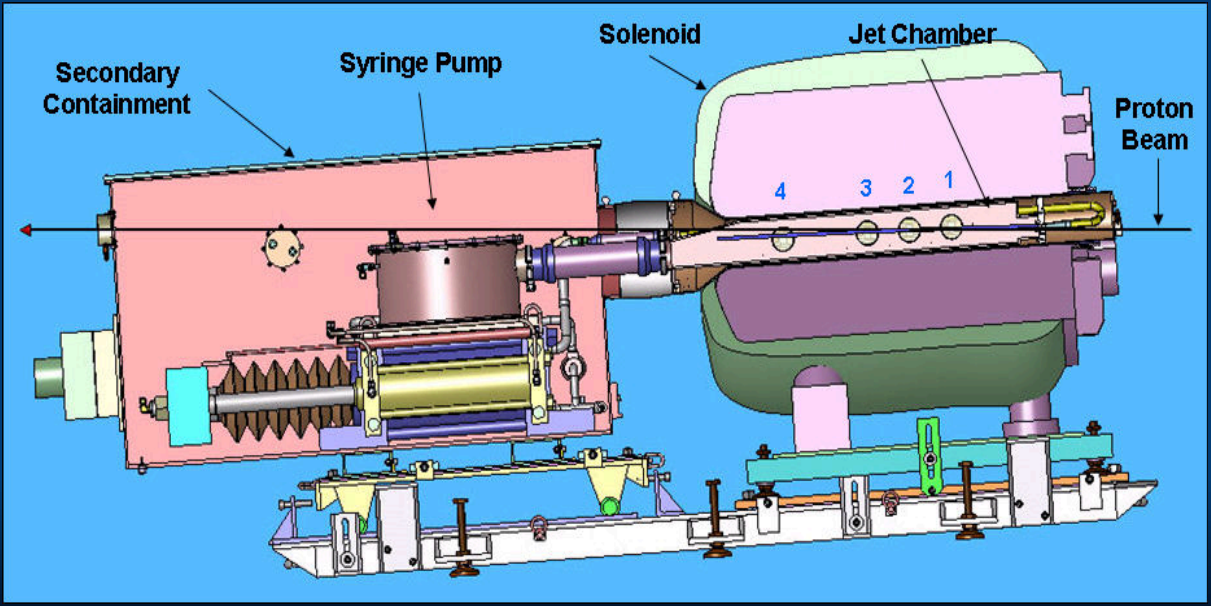
Technology Challenges – Tertiary Production

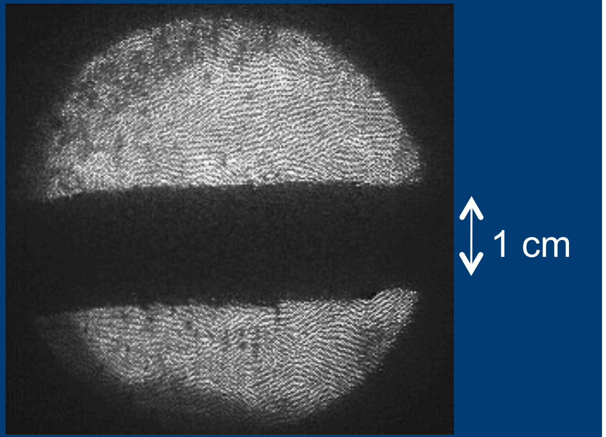


- A multi-MW proton source, *i.e.*, the extension of PIP-II, will enable O(10^{21}) muons/year to be produced, bunched and cooled to fit within the acceptance of an accelerator.

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

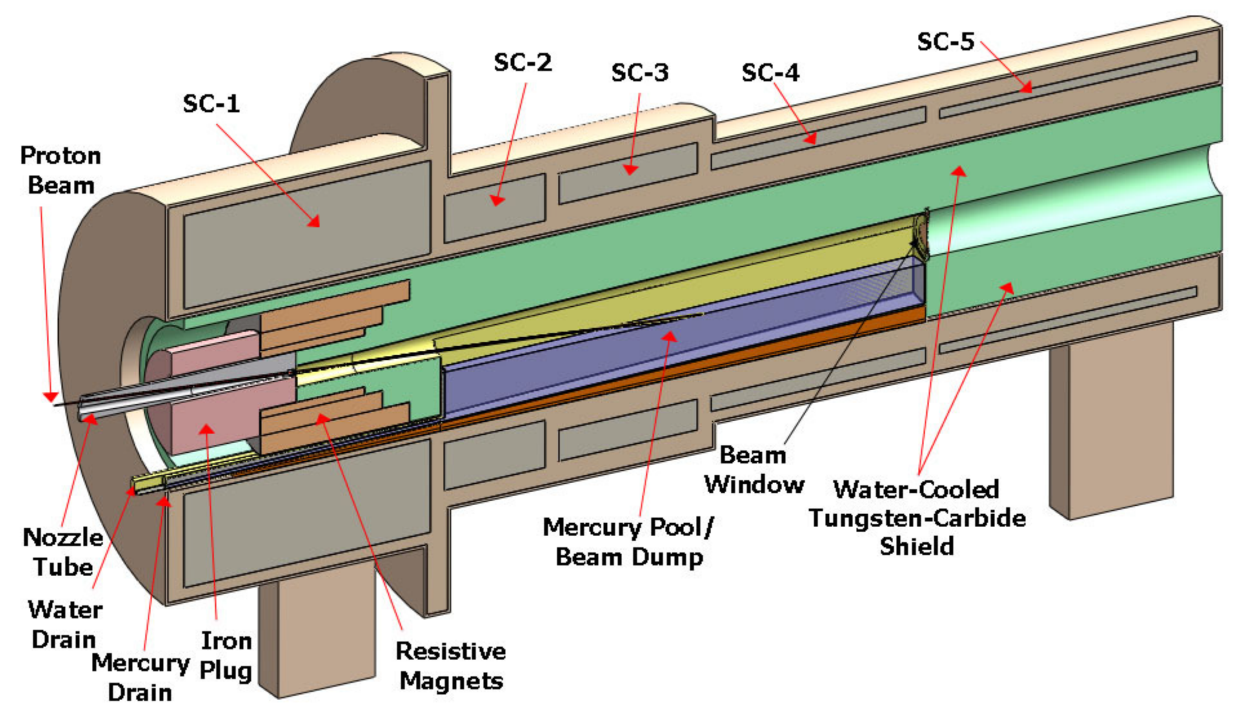
Technology Challenges – Capture Solenoid

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

$E_{stored} \sim 3$ GJ

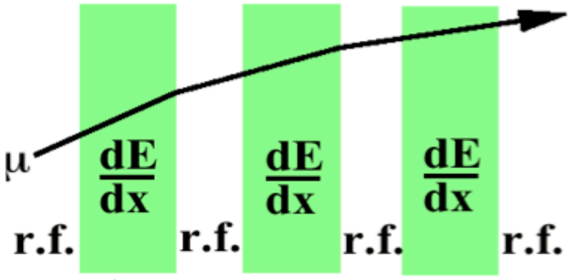
O(10MW) resistive coil in high radiation environment

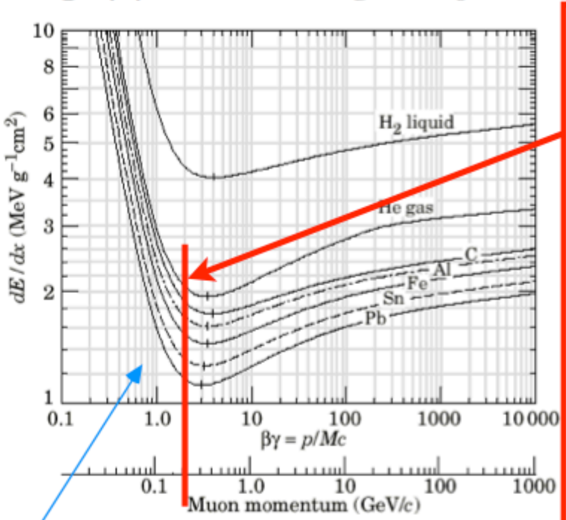
Possible application for High Temperature Superconducting magnet technology



Ionization Cooling

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





- Absorbers:

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

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

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

(emittance change per unit length)

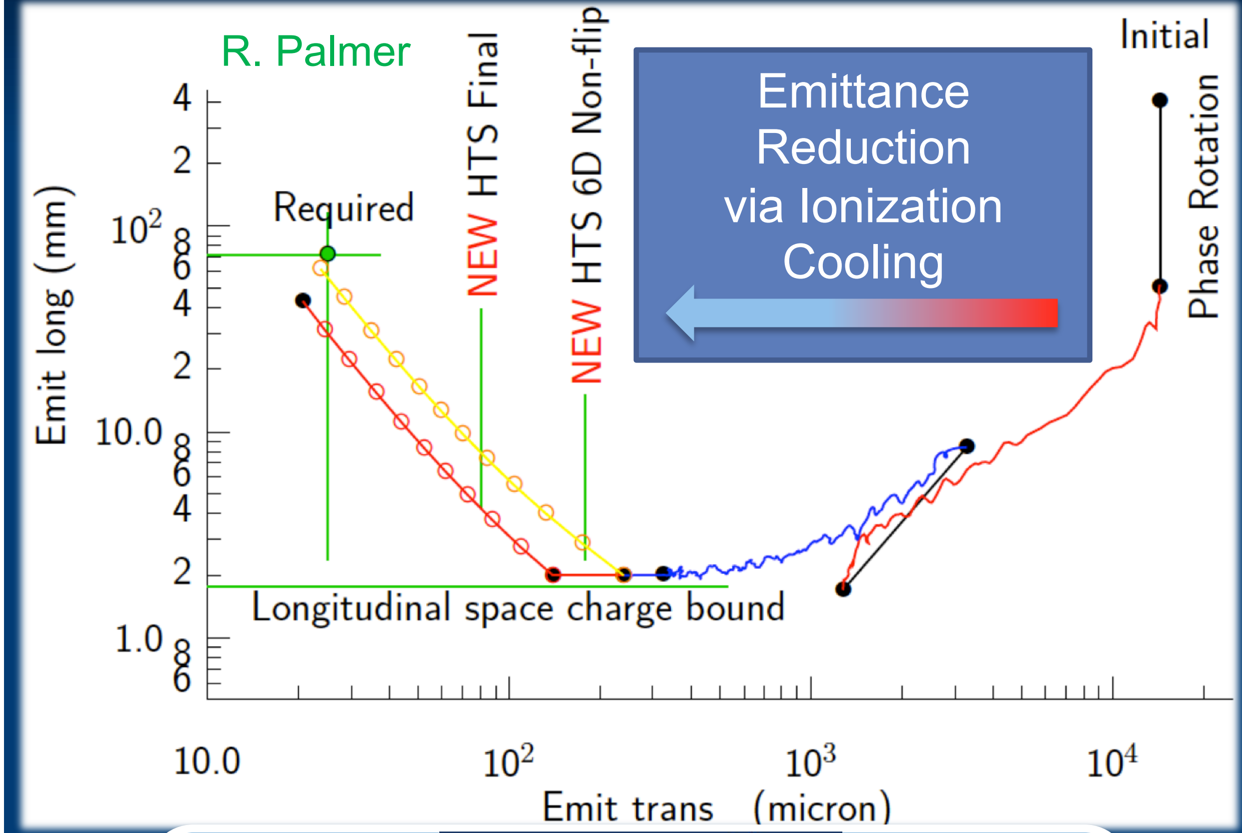
- ionization minimum is ≈ optimal working point:
  - longitudinal +ive feedback at lower *p*
  - straggling & expense of reacceleration at higher *p*

- 2 competing effects ⇒ ∃ equilibrium emittance

D. Kaplan

Technology Challenges - Cooling

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

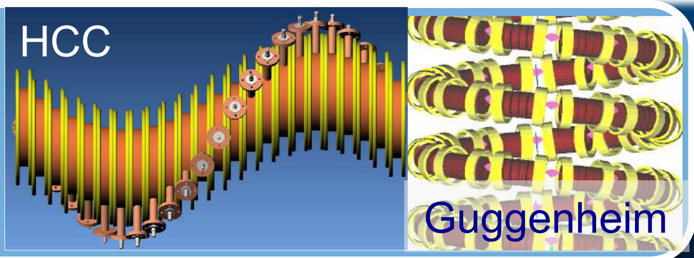


Emittance Reduction via Ionization Cooling

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

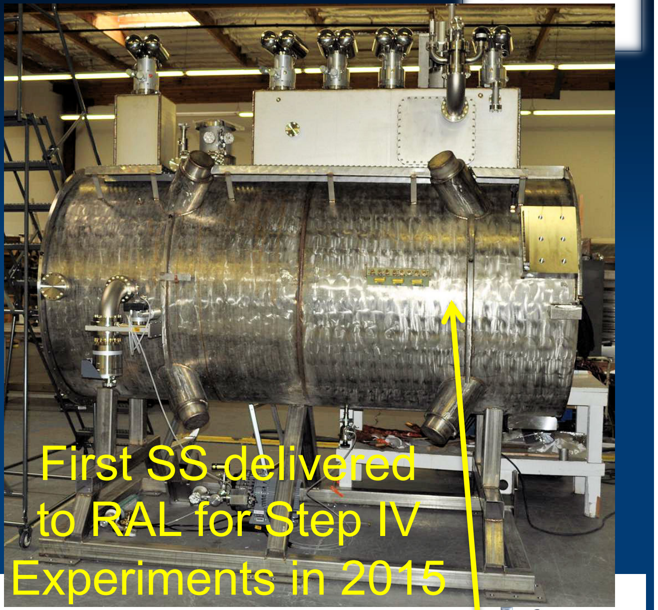
The program targets critical magnet and cooling cell technology demonstrations within its feasibility phase.

Cooling Channel Concepts

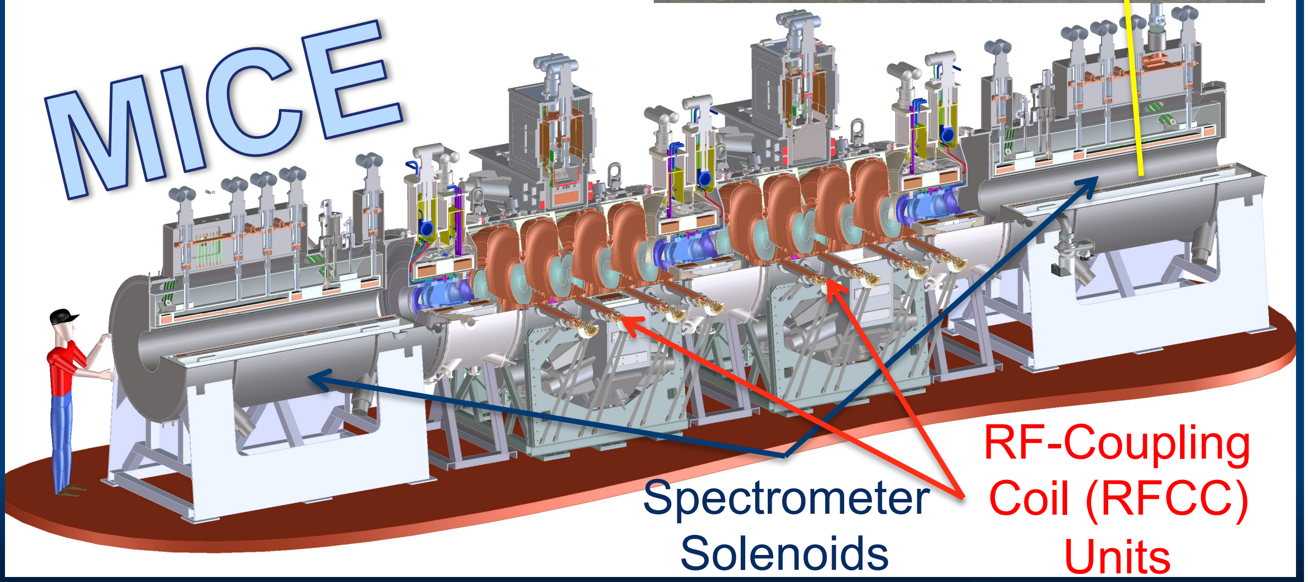


Technology Challenges - Coolin

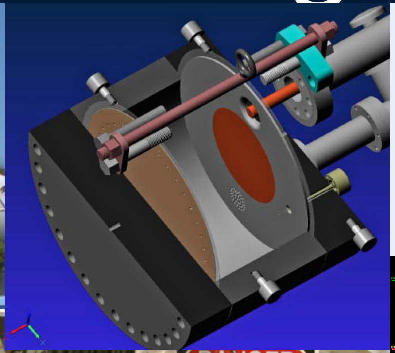
- Tertiary production of muon beams
  - – Initial beam emittance intrinsically large
  - – Cooling mechanism required, but no radiation damping
- Muon Cooling ⇨ Ionization Cooling
  - dE/dx energy loss in materials
  - RF to replace p_{long}


First SS delivered to RAL for Step IV Experiments in 2015

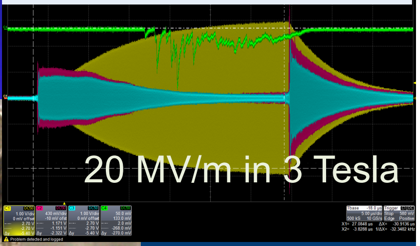
The Muon Ionization Cooling Experiment: Demonstrate the method and validate our simulations

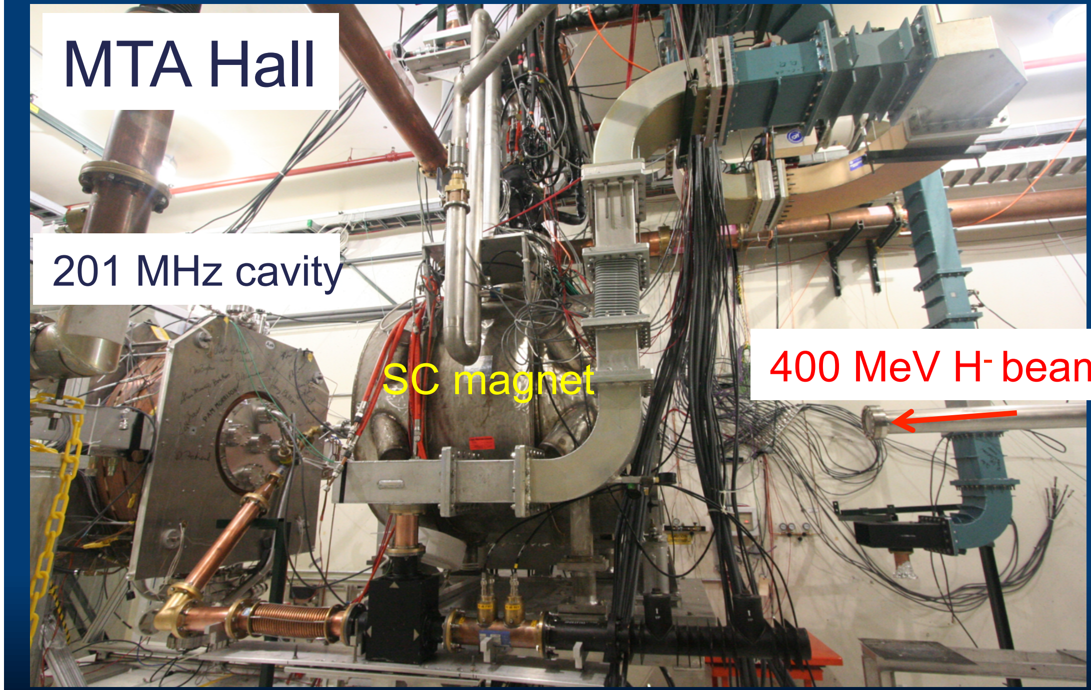


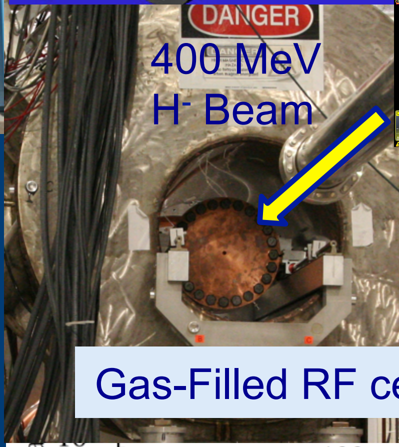
Elements of the R&D Program



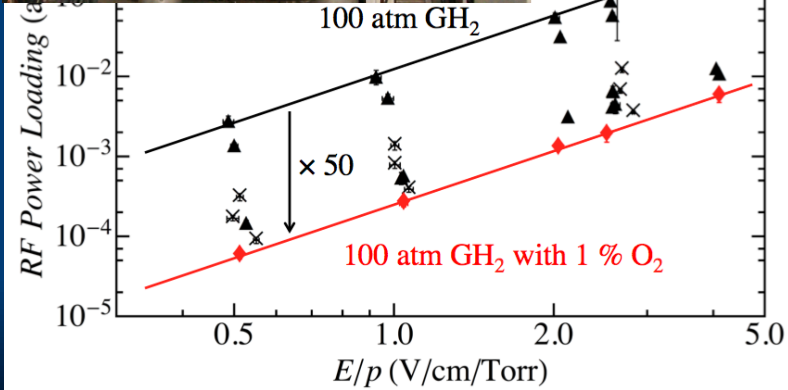
Vacuum RF Cavity – now operational in 5T B-field



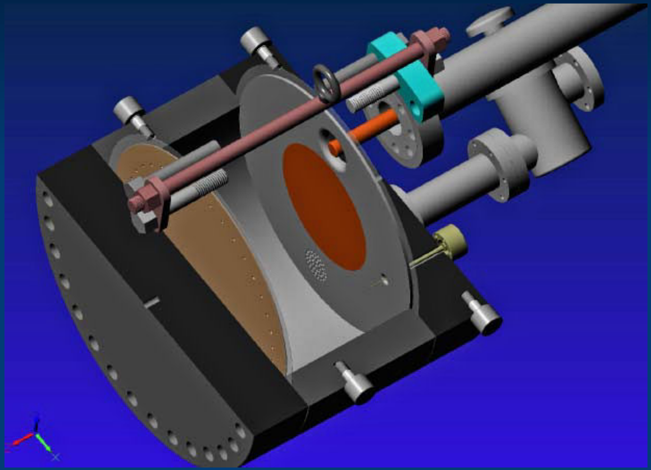




Gas-Filled RF cell

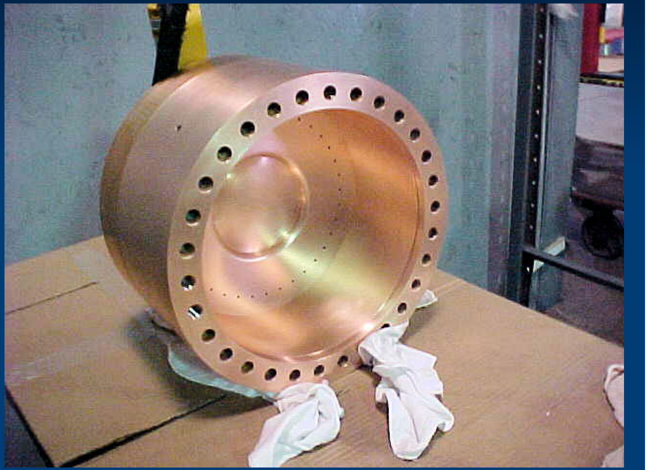


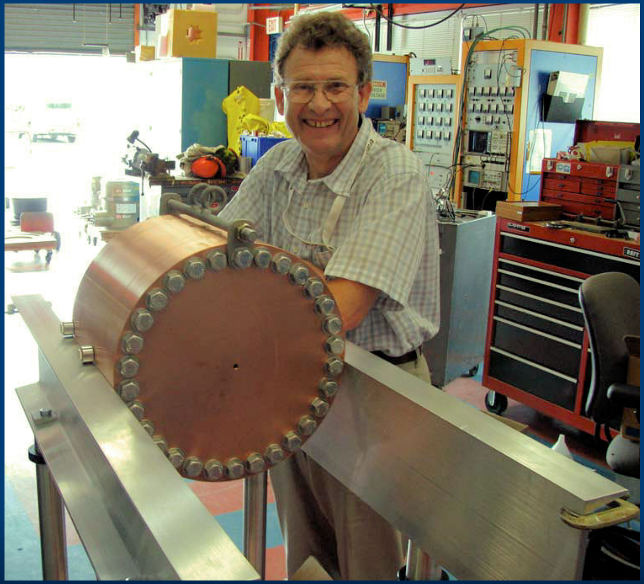
Recent Progress – Vacuum RF



All-Seasons Cavity

(designed for both vacuum and high pressure operation)

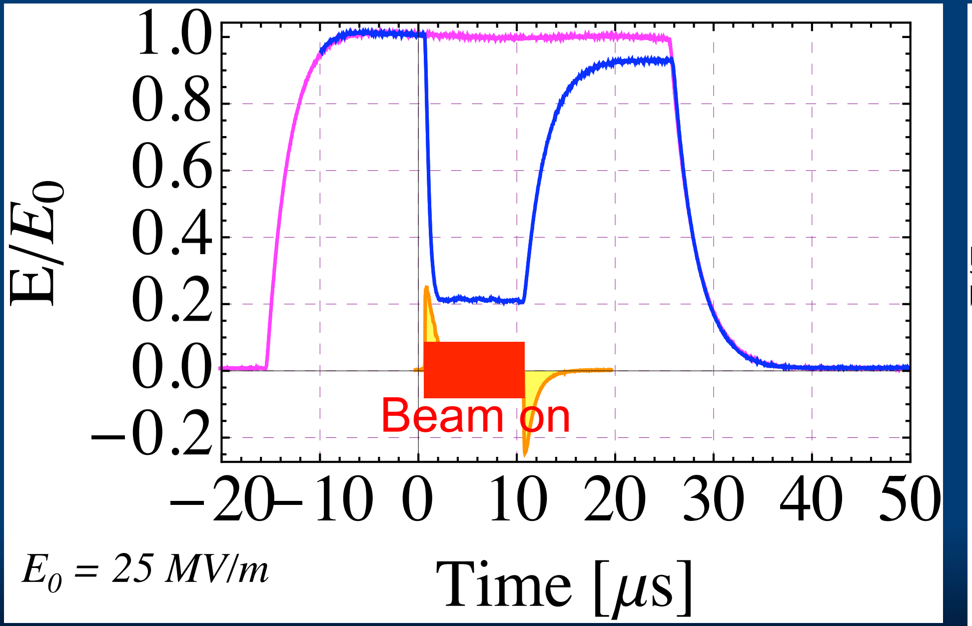




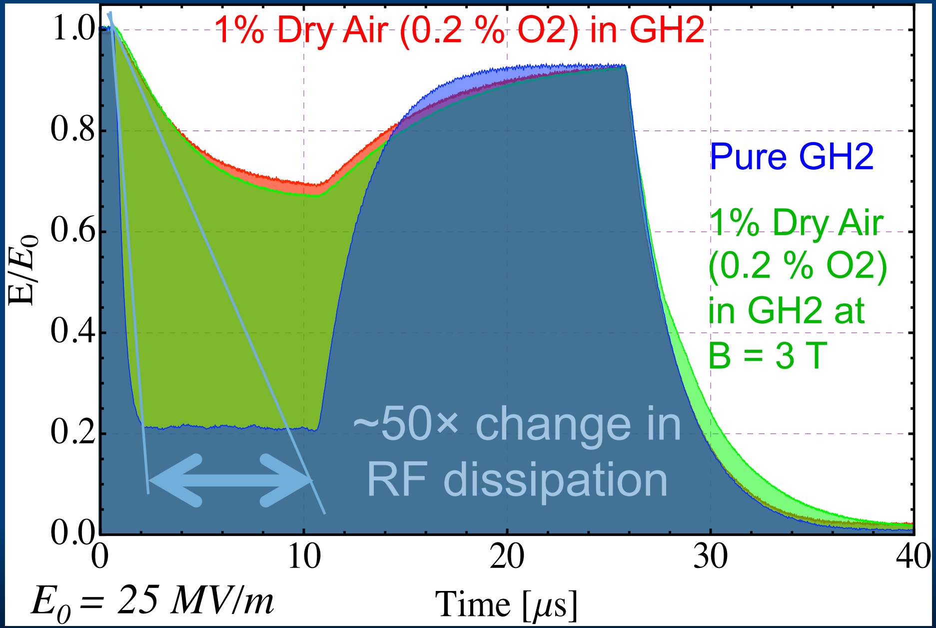
- Now operated in magnetic fields up to 5T:
  - Gradients > 20 MV/m
- Demonstrates possibility of successful operation of vacuum cavities in magnetic fields with careful design
- Successor design (the *805 MHz Modular Cavity*) will be ready for testing during FY14
- *Also progress on alternative cavity materials*

Recent Progress - High Pressure RF

- Gas-filled cavity
  - Can moderate dark current and breakdown currents in magnetic fields
  - Can contribute to cooling
  - Is loaded, however, by beam-induced plasma
- Electronegative Species
  - Dope primary gas
  - Can moderate the loading effects of beam-induced plasma by scavenging the relatively mobile electrons



$E_0 = 25\ MV/m$



$E_0 = 25\ MV/m$

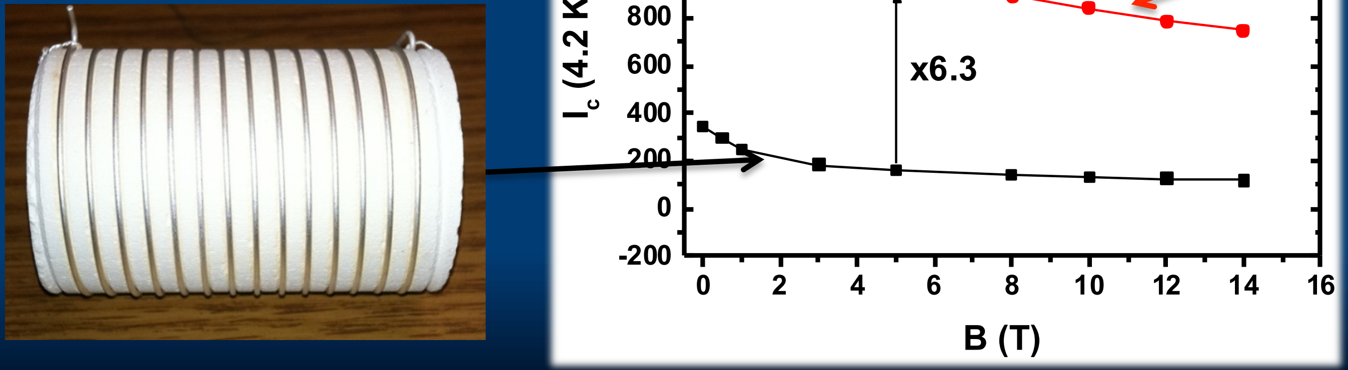
Recent Progress - High Field Magnets

Progress towards a demonstration of a final stage cooling solenoid:

- Demonstrated 15+ T (16+ T on coil)
  - ~25 mm insert HTS solenoid
  - BNL/PBL YBCO Design
  - Highest field ever in HTS-only solenoid (by a factor of ~1.5)
- Developing a test program for operating HTS insert + mid-sert in an external solenoid ➩ >30 T

BSCCO-2212 -

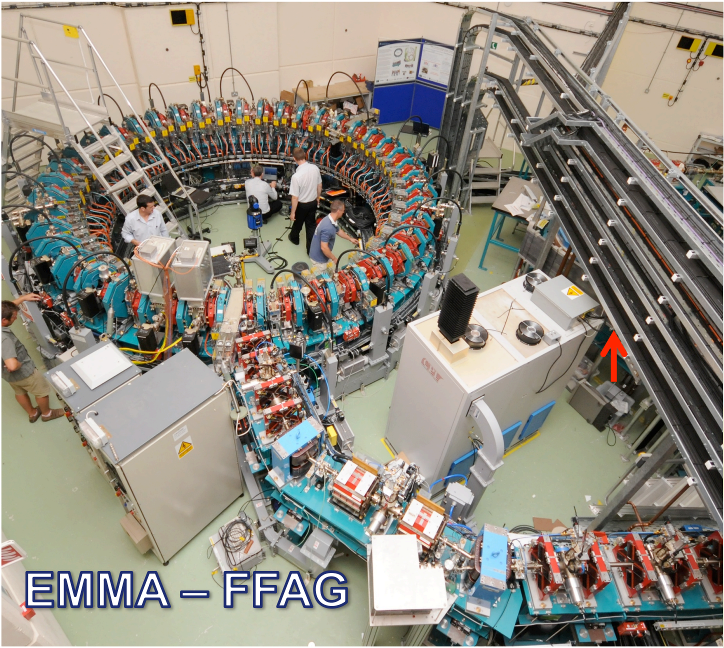
- New cable fabrication methods with demonstrated J_E
- Hyperbaric processing to avoid strand damage

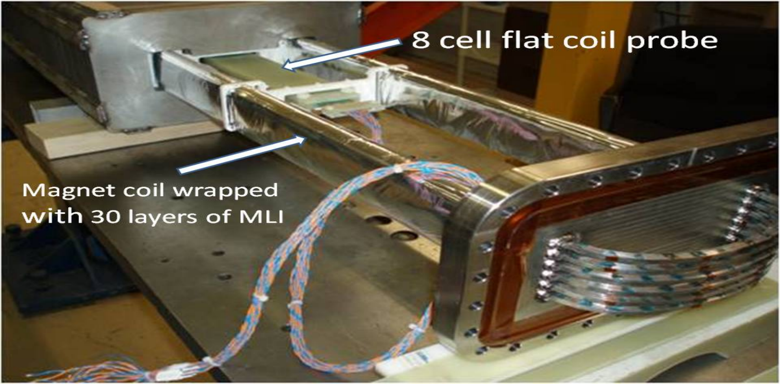


Multi-strand cable utilizing chemically compatible alloy and oxide layer to minimize cracks

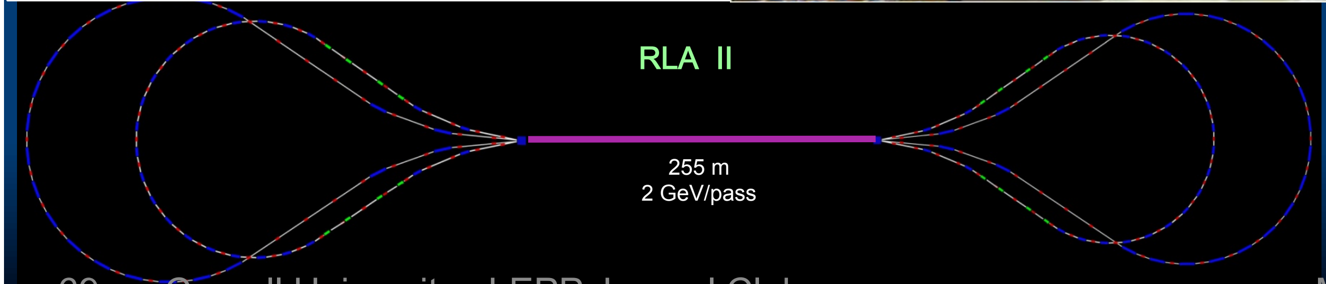
Technology Challenges - Accelerati

- 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)



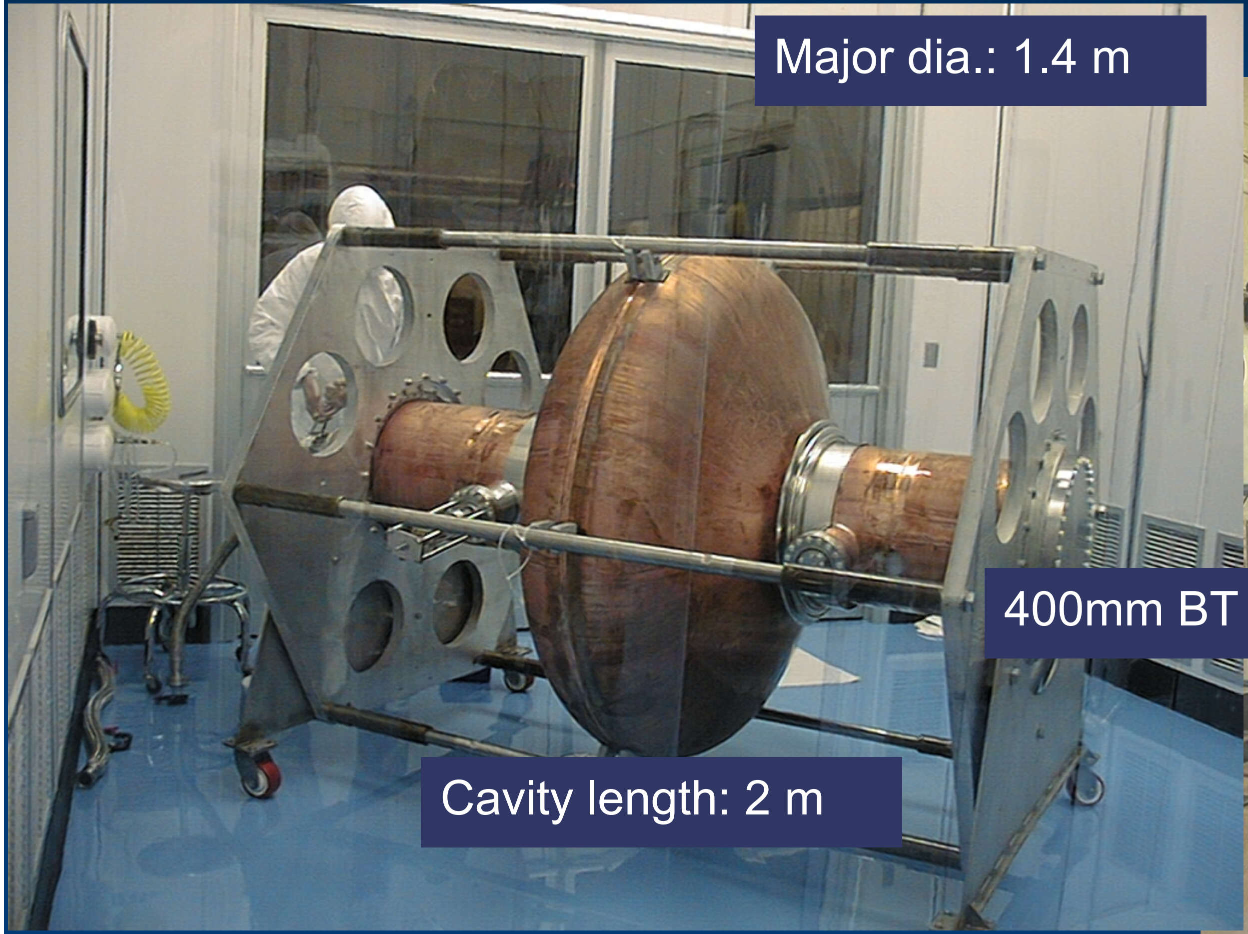


RCS requires
2 T p-p magnets
at f = 400 Hz
(U Miss & FNAL)



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

Superconducting RF Development

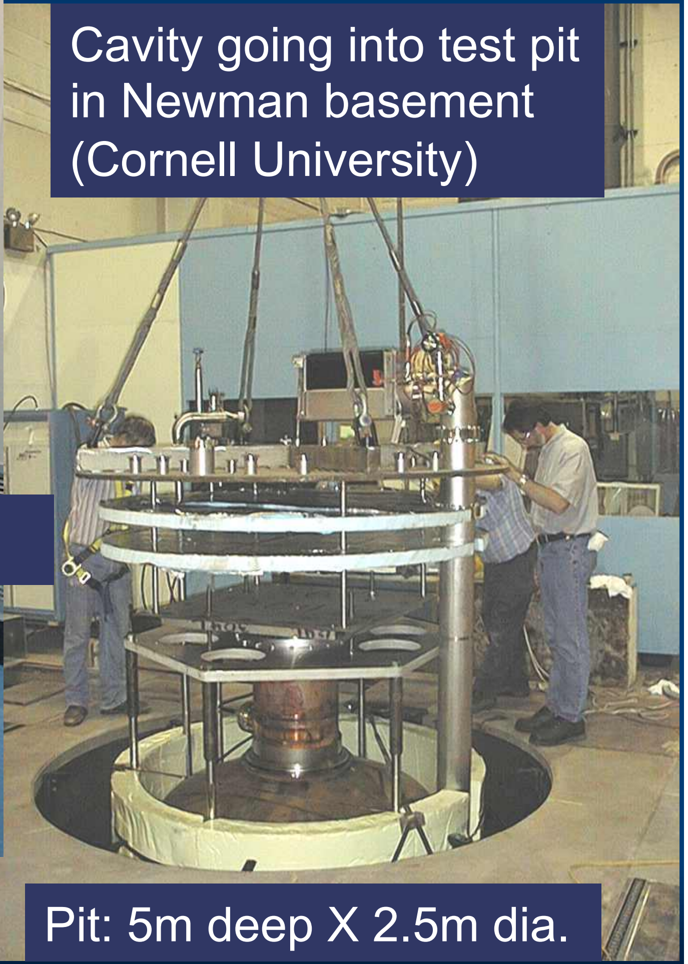


Major dia.: 1.4 m

400mm BT

Cavity length: 2 m

201 MHz SCRF R&D

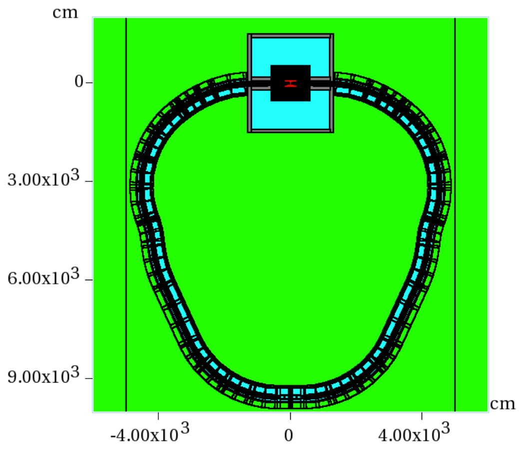


Cavity going into test pit in Newman basement (Cornell University)

Pit: 5m deep X 2.5m dia.

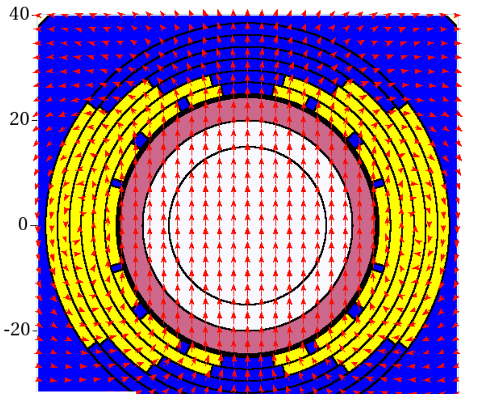
Technology & Design Challenges – Ring, Magnets, Detector

- Emittances are relatively large, but muons circulate for ~1000 turns before decaying
  - – Lattice studies for 126 GeV, 1.5 & 3 TeV CoM

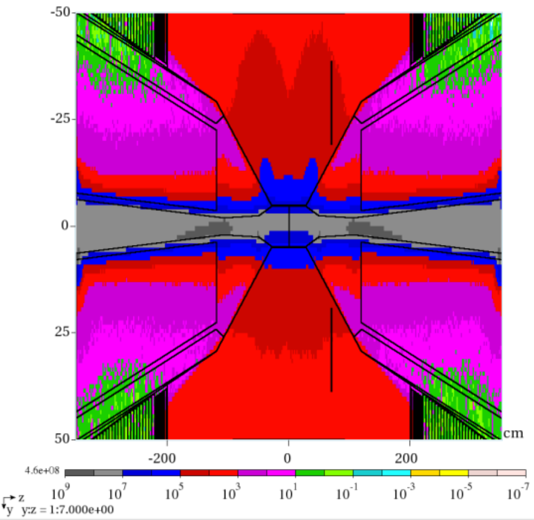


- High field dipoles and quadrupoles must operate in high-rate muon decay backgrounds
  - – Magnet designs under study

MARS energy deposition studies for Higgs Factory magnets and IR



- Detector shielding & performance
  - – Initial studies for 1.5 TeV, then 3 TeV and now 126 GeV
  - – Shielding configuration
  - – MARS background simulations

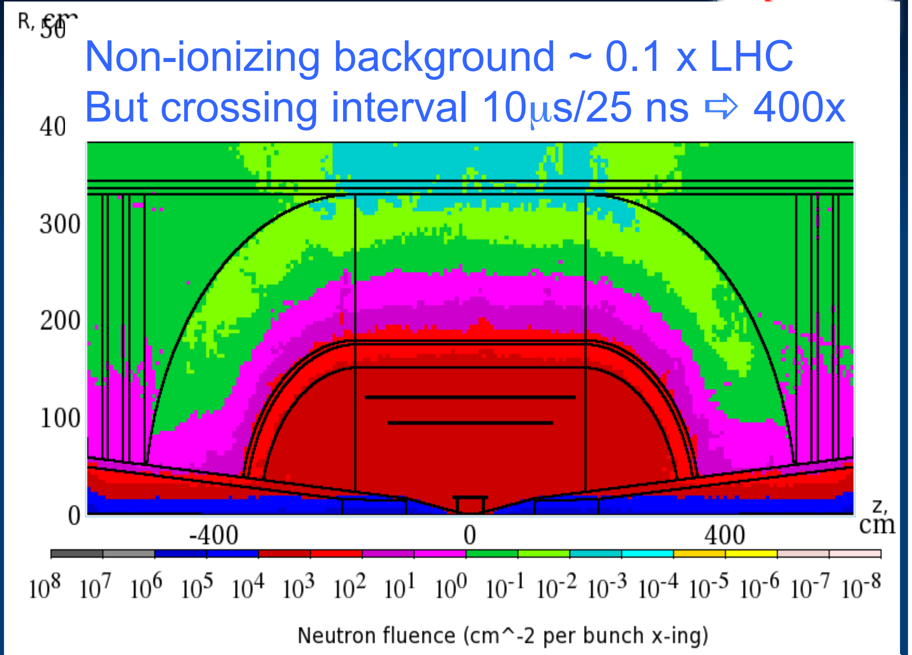


Backgrounds and Detector

Much of the background is soft and out of time

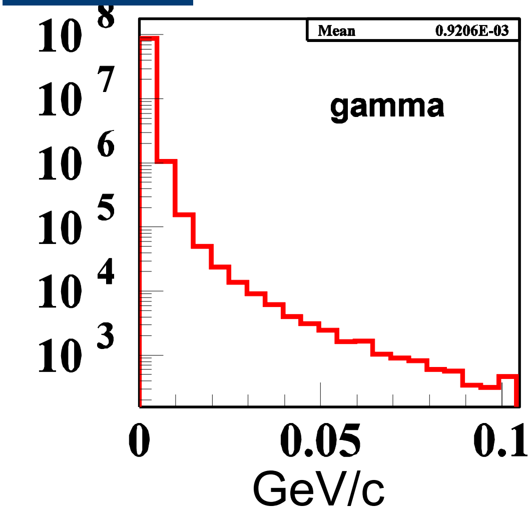
- Nanosecond time resolution can reduce backgrounds by three orders of magnitude

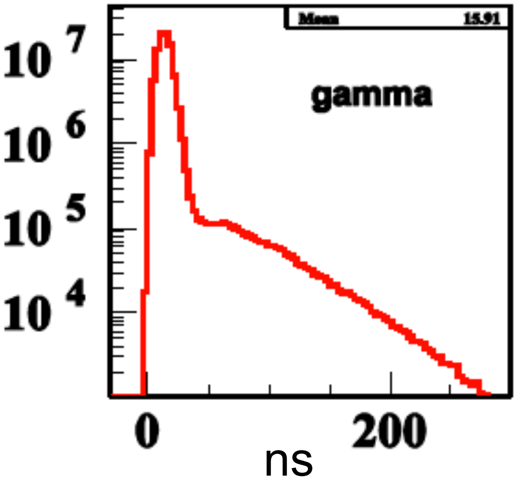
Requires a fast, pixelated tracker and calorimeter.


Non-ionizing background ~ 0.1 x LHC

But crossing interval 10μs/25 ns ⇨ 400x

	Cut	Rejection
Tracker hits	1 ns, dedx	$9\text{x}10^{-4}$
Calorimeter neutrons	2 ns	$2.4\text{x}10^{-3}$
Calorimeter photons	2 ns	$2.2\text{x}10^{-3}$

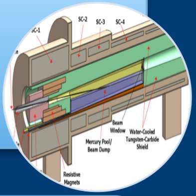




Overview of MAP Magnet Pull

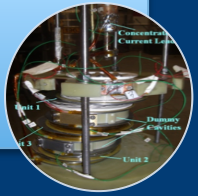
- Characteristics:
  - High field (15-20T)
  - Large bore (meter-scale)
  - Intense radiation environment – NC or HTS insert coil

Capture Solenoid for Simultaneous mu+ & mu- Beams



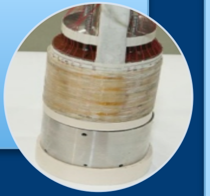
- Characteristics:
  - Solenoid-based cooling channel (LH_2/LiH absorbers)
  - RF cavities integral to focusing channel
  - Fields ranging from LTS to HTS conductor regime

Muon Ionization 6-Dimensional Cooling Channel



- Characteristics:
  - Emittance exchange channel for TeV-scale colliders (trade increased longitudinal beam emittance for smaller transverse emittance
  - Baseline: 30T class HTS solenoids with a>25mm

Muon Ionization Final Cooling Channel

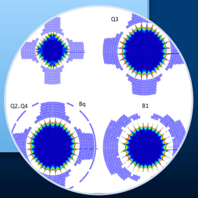


- Characteristics:
  - Present baseline based on the use of Rapid Cycling Synchrotrons
  - Requires magnets capable of ~400Hz operation with >1.5T peak fields

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



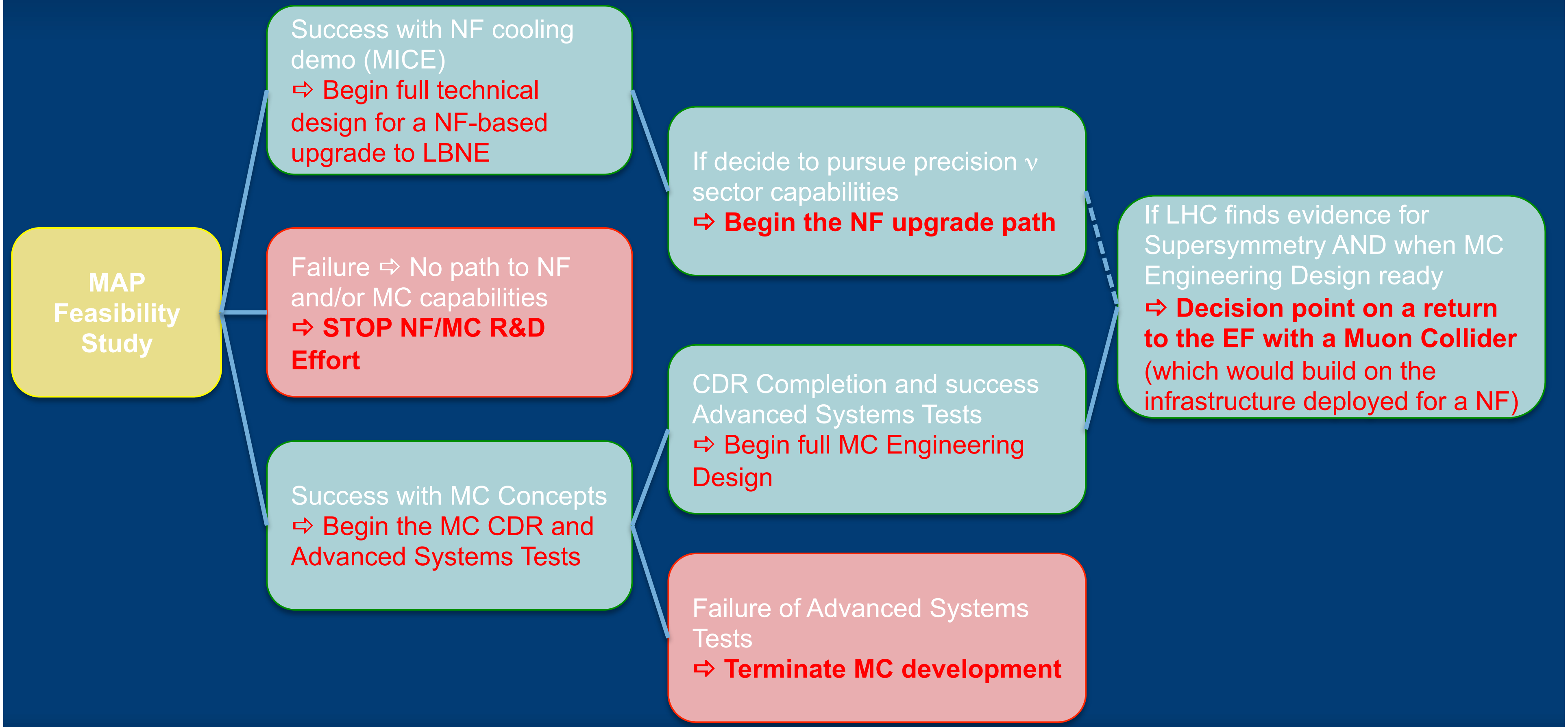
- Characteristics:
  - A MC (w/decaying beams) obtains the greatest performance enhancement of any HEP collider from HTS magnet technology
  - High quality HTS cables and magnets must be a priority

HTS Magnet Development

Feasibility R&D through End of Decade

A Muon Accelerator Capabilities Technical Decision Tree

| Thru ~2020 | ~2020 | ~2025 | Late 2020s |



MAP Feasibility Study

Success with NF cooling demo (MICE)
⇨ Begin full technical design for a NF-based upgrade to LBNE

Failure ⇨ No path to NF and/or MC capabilities
⇨ STOP NF/MC R&D Effort

Success with MC Concepts
⇨ Begin the MC CDR and Advanced Systems Tests

If decide to pursue precision ν sector capabilities
⇨ Begin the NF upgrade path

CDR Completion and success Advanced Systems Tests
⇨ Begin full MC Engineering Design

Failure of Advanced Systems Tests
⇨ Terminate MC development

If LHC finds evidence for Supersymmetry AND when MC Engineering Design ready
⇨ Decision point on a return to the EF with a Muon Collider
(which would build on the infrastructure deployed for a NF)