

# Accelerator Capabilities for the Energy Frontier

Mark Palmer

Frontier Capabilities:

Energy Frontier Lepton & Gamma Colliders Sub-Group

July 1, 2013

**SNOWMASS ENERGY FRONTIER WORKSHOP**

June 30 – July 3, University of Washington, Seattle



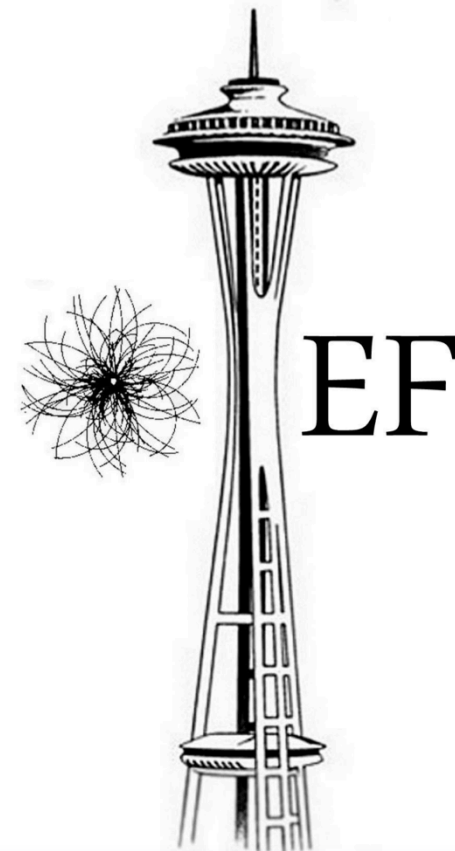
# Outline

- Introduction
- Hadron Colliders
- Lepton and  $\gamma\text{--}\gamma$  Colliders
- Closing Comments

The Working Groups and Inputs

The Working Group Assessments

The “Boundary Conditions”



# INTRODUCTION

# Frontier Capabilities Sub-Groups & Inputs

- Accelerator Capabilities Convener: Bill Barletta (MIT)
- This talk draws principally on materials submitted to 3 of the Capabilities Frontier sub-groups:
  - Hadron Colliders
    - Sub-conveners: Marco Battaglia (UCSC), Markus Klute (MIT), Soren Prestemon (LBNL), & Lucio Rossi (CERN)
    - EF Liaison: Eric Prebys (FNAL)
    - Sub-Group Meeting at CERN (Feb):  
<http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=223094>
  - Lepton Colliders
    - 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>
  - R&D Capabilities
    - Sub-conveners: Georg Hoffstaeter (Cornell), Mark Hogan (SLAC), & Vladimir Shiltsev (FNAL)
    - Sub-Group Meeting at Univ. of Chicago:  
<https://indico.fnal.gov/conferenceDisplay.py?ovw=True&confId=6326>
- Submissions covered a broad range of capabilities and possibilities  
⇒ many contributors to what follows
  - Particular thanks to E. Prebys, T. Raubenheimer, S. Henderson



# Working Group Assessments

- The goal of the aforementioned working groups has been 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, we do have 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

# 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

# Jim Siegrist's "Boundary Conditions"

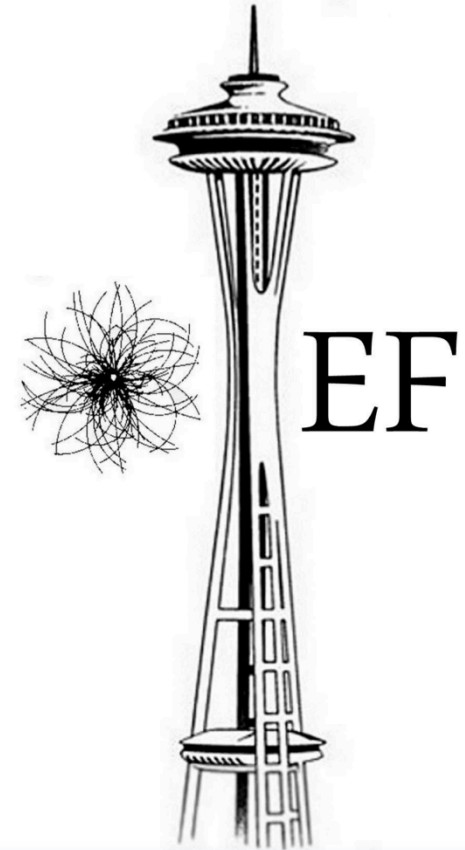
- **Note that a 'brute force' approach that seeks to spend vast sums in order to build some facility/physics capability simply will not work in today's fiscal environment. This has been empirically demonstrated.**
  - Most recently, via our discussions on LBNE, we have confirmed that single domestic 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.**

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- 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

Jim Siegrist, CPM2012

LHC and Its Upgrade Path  
Very High Energy Options:  
VHE-LHC  
VLHC



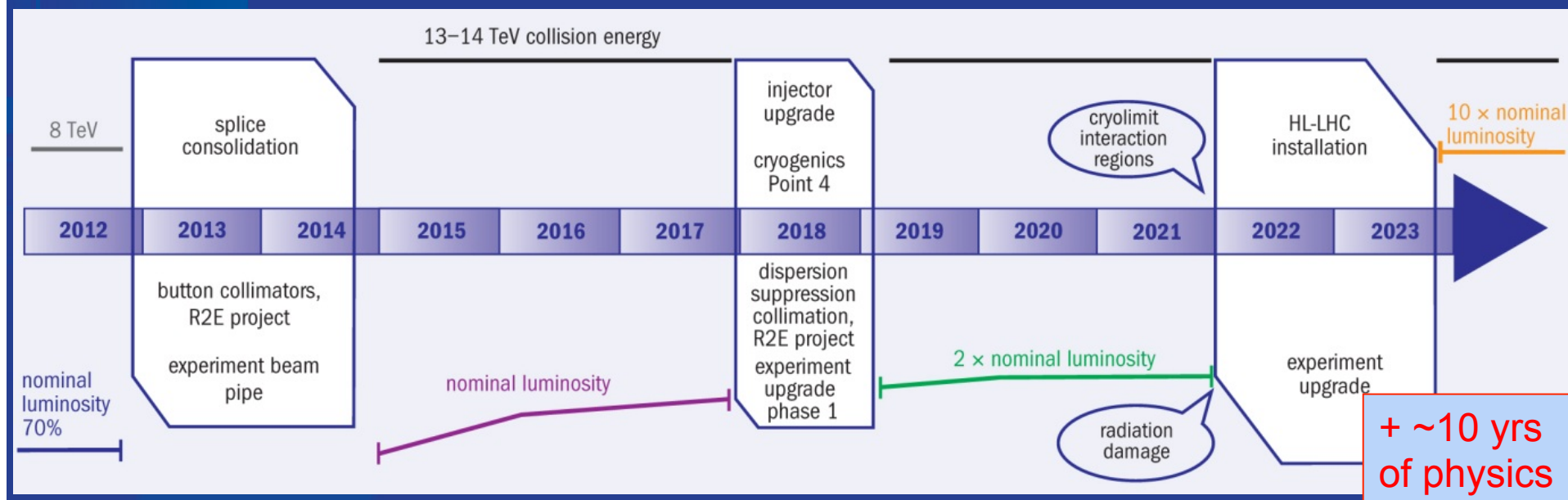
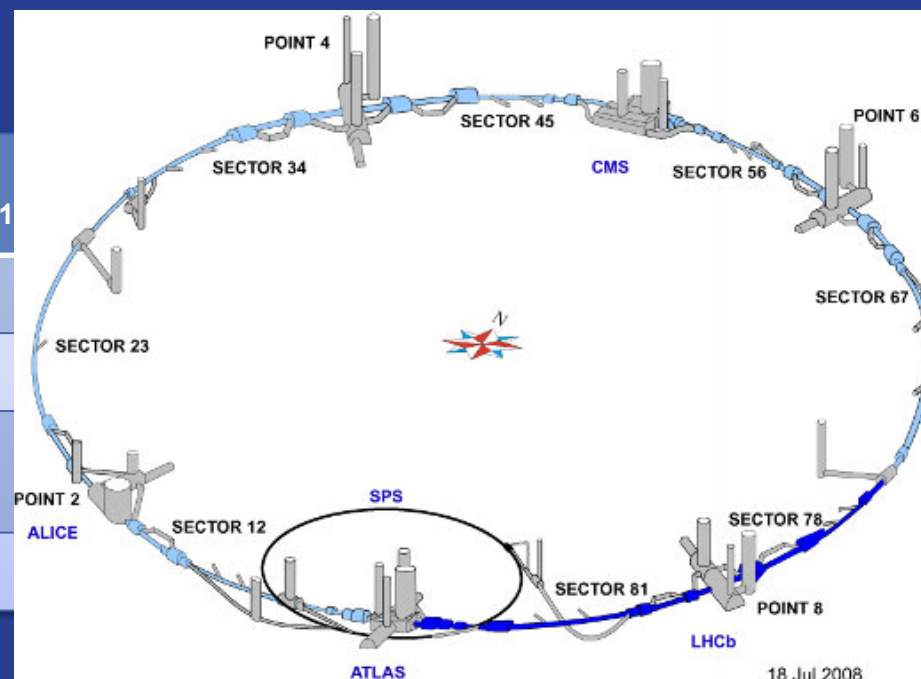
# HADRON COLLIDER CAPABILITIES



# The LHC

Start	Facility	$E_{CM}$	Lumi ( $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ )
2014	LHC	13-14 TeV pp	1 $\Rightarrow$ 2 Peak
2024	HL-LHC	14 TeV pp	5 Leveled
2024	LHeC?	7 TeV p + 60-140 GeV $e^{\pm}$	$\sim .1$ -1
$\sim$ 2035	HE-LHC?	33 TeV pp	$\geq 2$

A >3 decade hadron program



# The LHC Sequence of Parameters

Parameter	LHC		HL-LHC		HE-LHC
Bunch Spacing	25 ns	50 ns	25 ns	50 ns	50 ns
Beam Energy [TeV]	6.5-7	6.5-7	7	7	16.5
$n_b$	2808	1404	2808	1404	1404
$N_b$ ( $\times 10^{11}$ )	1.15(1.7)	1.7(2.0)	2.2	3.5	1.3
$\beta^*$ [m]	.55	.55	.15	.15	0.4-1
$\sigma_{x,y}$ [ $\mu\text{m}$ ]	16.7	16.7	7.5	7.5	$\sim 10$
$\sigma_z$ [cm]	7.6	7.6	7.6	7.6	$\sim 6$
Total Energy/beam [MJ]	362 (535)	267 (314)	692	550	482
$L$ (peak) [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ]	$\sim 1$ (2)	$\sim 1$ (2)	5	2.5	2
Events/crossing	27 (54)	54 (108)	140	140	$\sim 60$
$L$ (int) [ $\text{fb}^{-1}/\text{year}$ ]	40 (80)	40 (80)	250	250	250
$L$ (int) [ $\text{fb}^{-1}$ , goal]	$\sim 300$		$\sim 3000$		---

() = ultimate parameters

Detector  
Pile-up Issues  
of concern

Chosen to  
limit Pile-up

# Luminosity “Constraints”\*

**Total Current**, limited by

- instabilities (eg, e-cloud)
- machine protection issues!

**“Brightness”**, limited by

- Space charge effects
- Instabilities
- Beam-beam tune shift (ultimate limit)

number of bunches

Bunch size

$$L = \frac{\gamma f_{rev} n_b N_b^2}{4\pi\beta^* \varepsilon_N} R_\varphi$$

**Geometric factor** related to crossing angle and hourglass effect

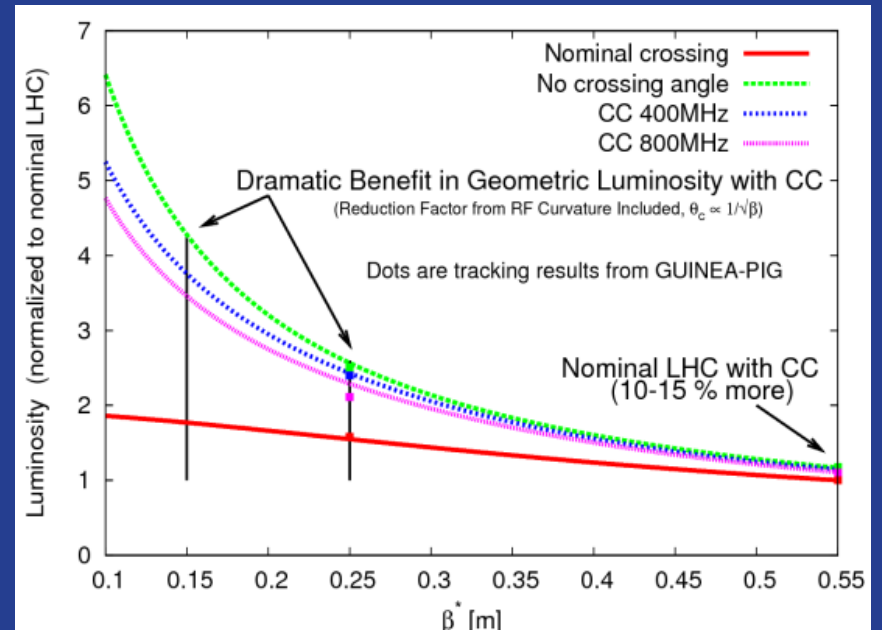
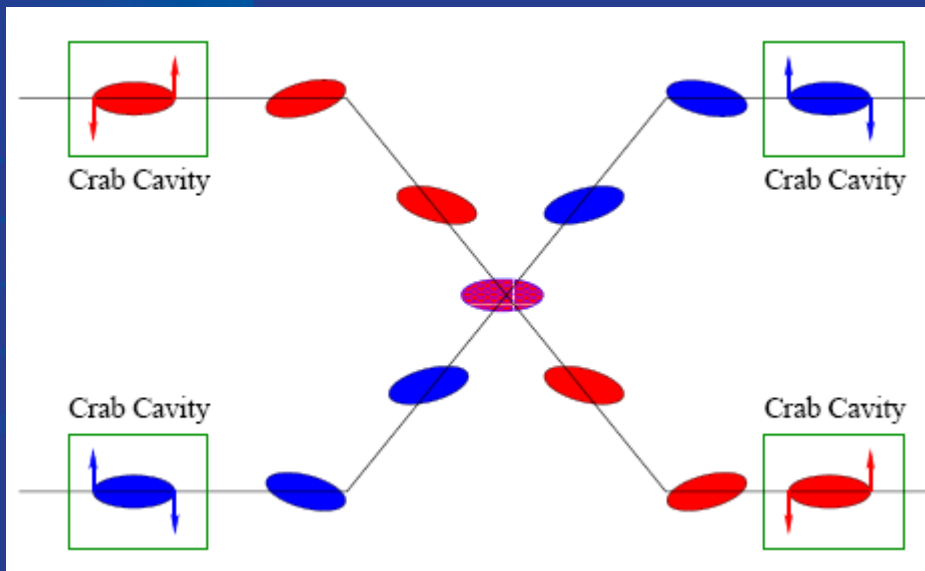
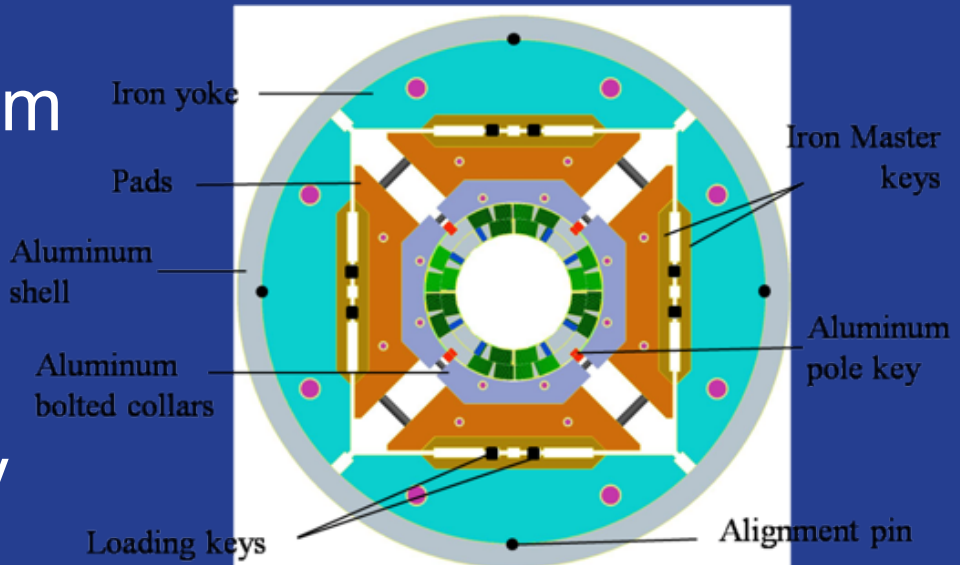
**$\beta^*$** , limited by

- magnet technology
- chromatic effects

\*a la Frank Zimmermann

# Issues for the HL-LHC

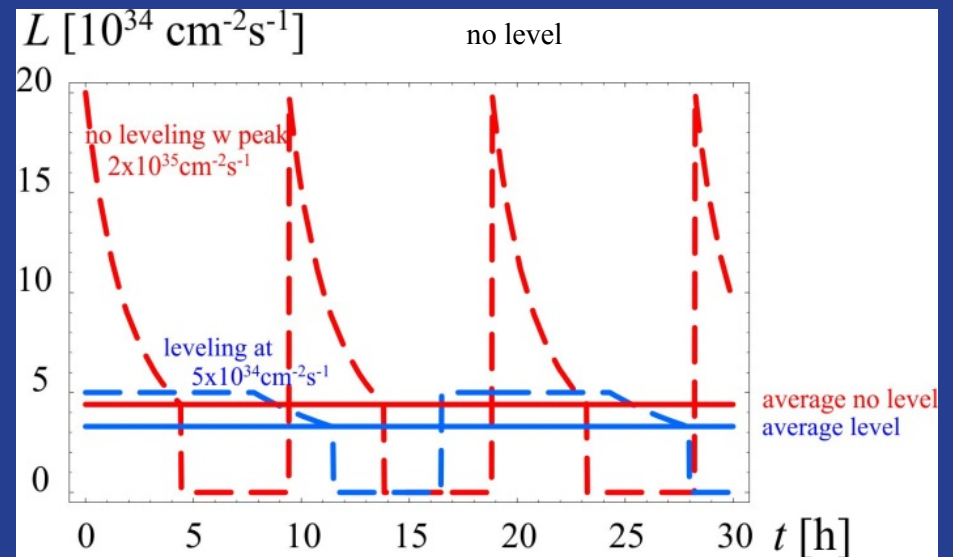
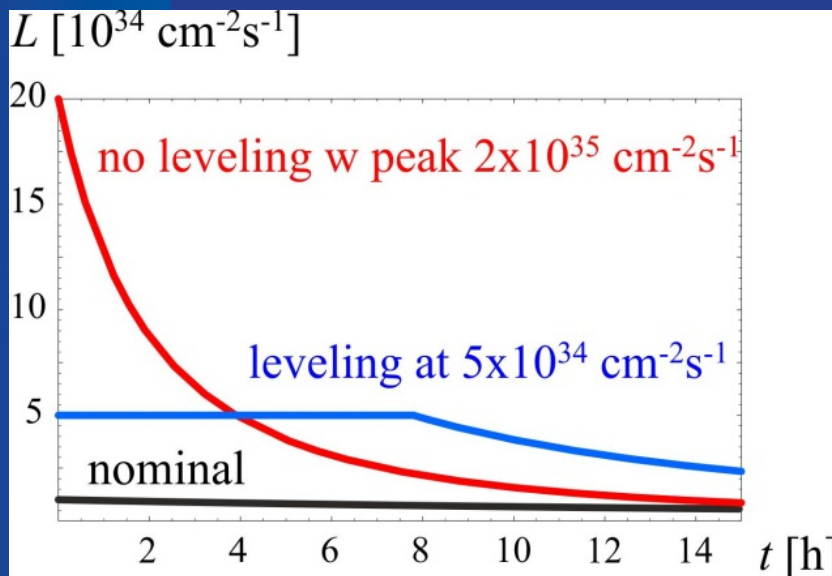
- Reduce  $\beta^*$ : 55 cm to 15 cm
  - Requires move to  $\text{Nb}_3\text{Sn}$
  - Increases effect of crossing angle
- Baseline plan is to employ crab cavities





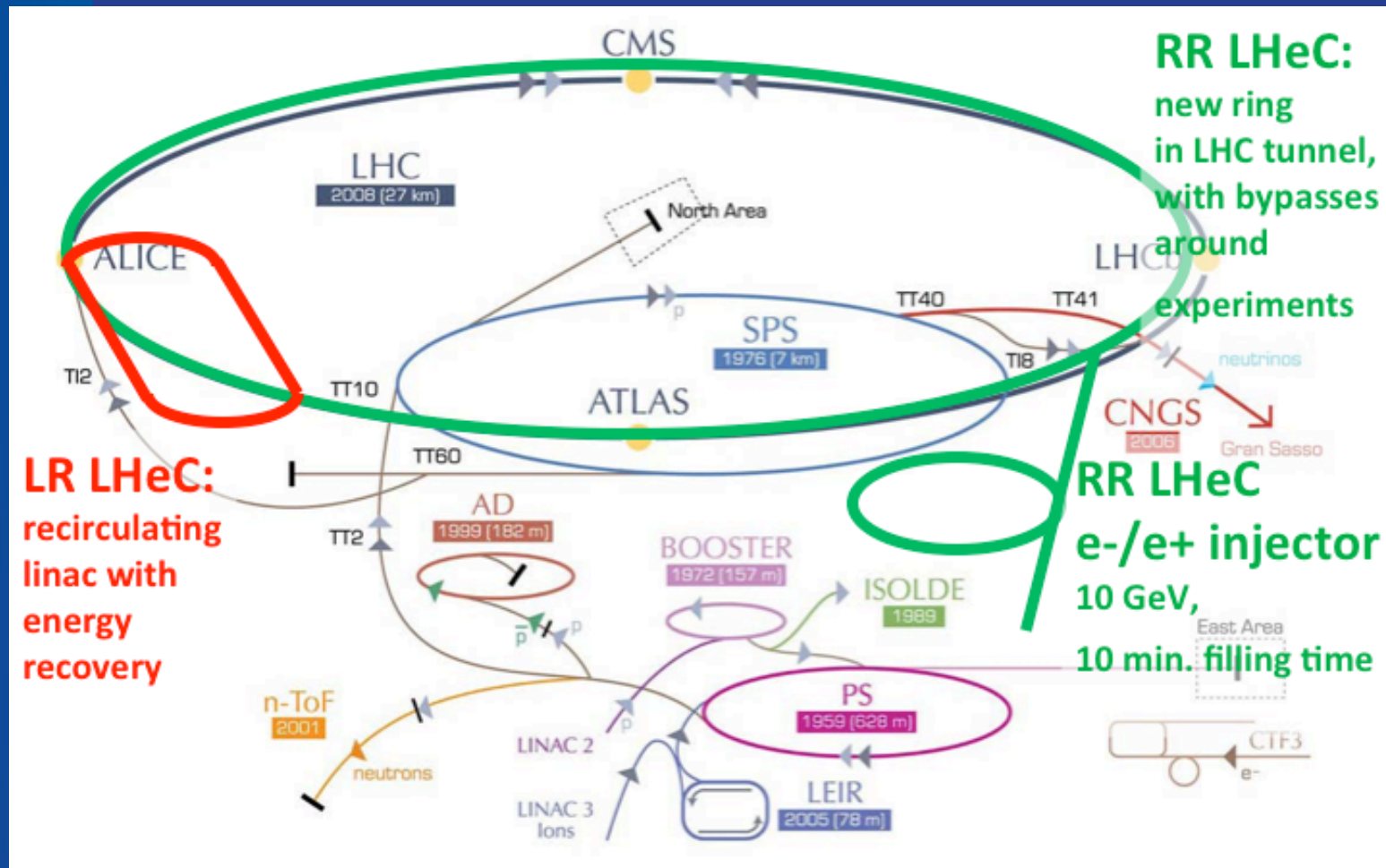
# Luminosity Leveling

- Original goal of luminosity upgrade:  $>10^{35} \text{ cm}^{-2}\text{s}^{-1}$ 
  - Leads to unacceptable pileup in detectors
- New goal:  $5 \times 10^{34}$  *leveled* luminosity



- Options
  - Crab cavities
  - $\beta^*$  modifications
  - Lateral separation

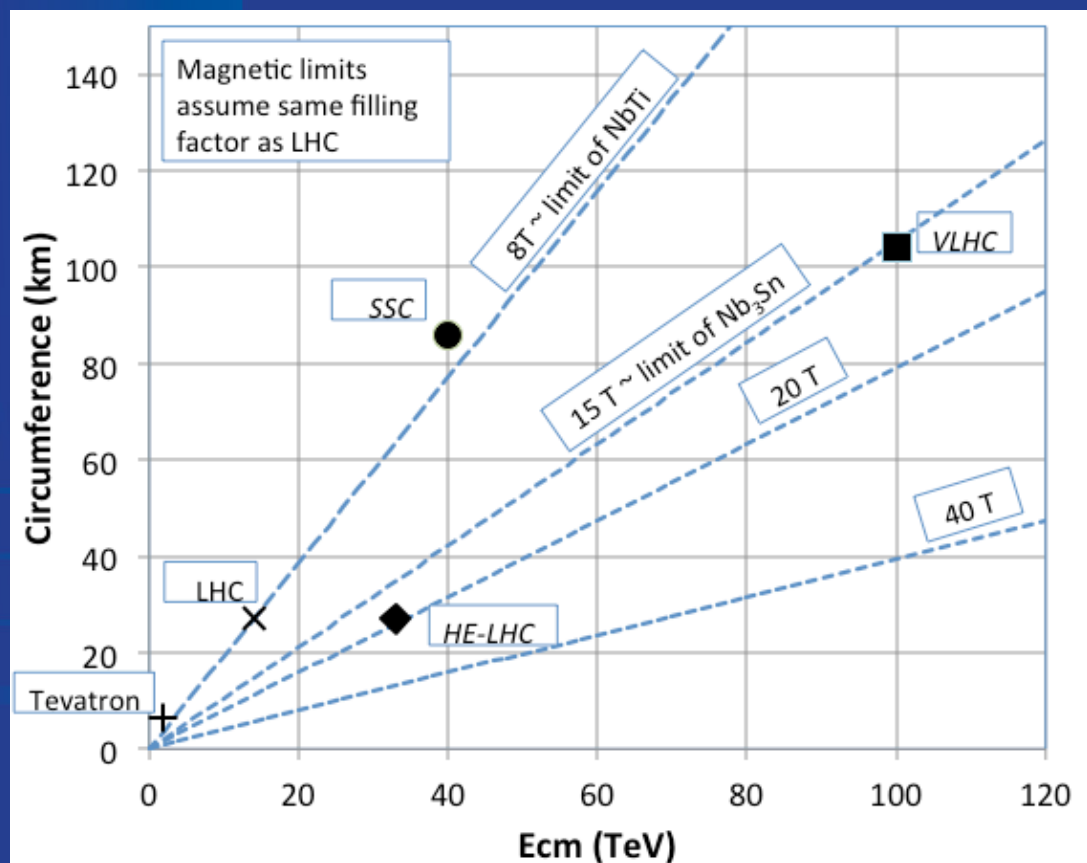
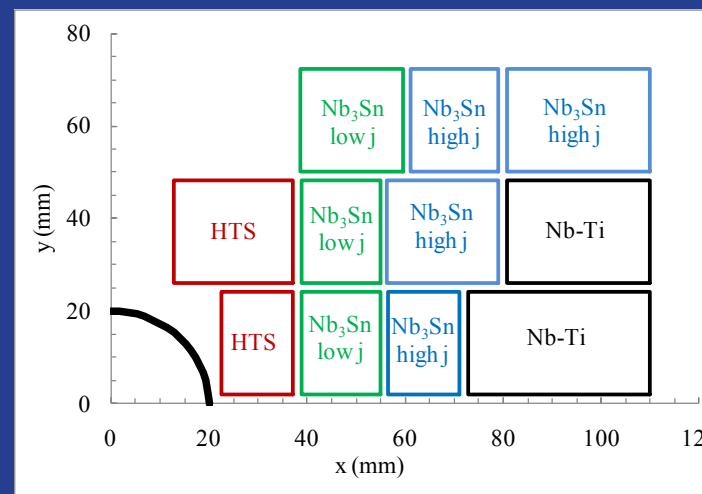
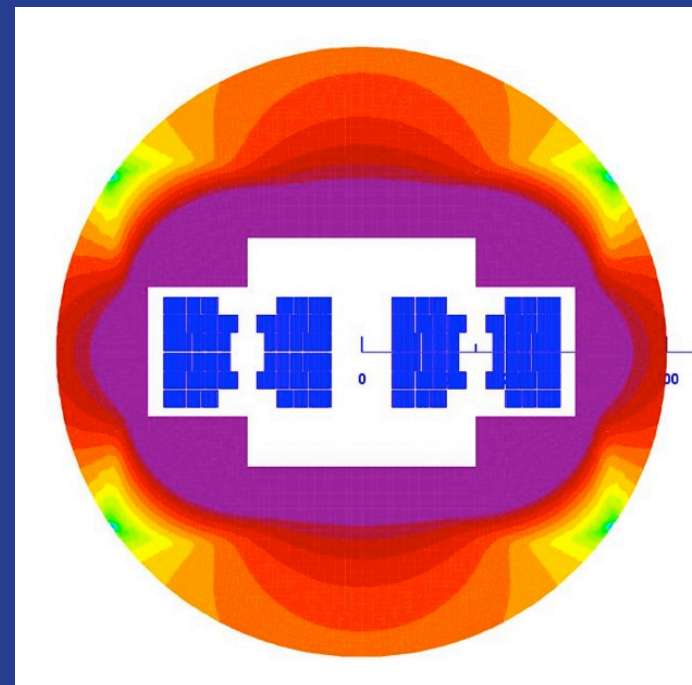
# LHeC: Options Considered



- ~~RR:  $e^\pm$  circulate in new 60 GeV ring, which shares tunnel with LHC~~
- LR: CW Energy recovery linac collides 60  $e^\pm$  with LHC beam
- LR:\* Pulsed energy recovery linac collides 140 GeV  $e^\pm$  with LHC beam

# Going Beyond LHC: Limits to Energy

- The energy of Hadron colliders is limited by feasible size and magnet technology. Options:
  - Get very large (eg,  $C \sim 100$  km)  
VHE-LHC in TLEP Tunnel or VLHC concept
  - More powerful magnets (HTS)



# Important R&D and Questions for HE Hadron Colliders

- Magnets, magnets, magnets
  - New conductors: Nb<sub>3</sub>Sn, HTS, hybrid designs
  - Rapid cycling SC magnets
  - Rad hardness and energy deposition studies (simulation and experiment).
- Machine Protection
  - Collimation design and materials research
  - Accelerator physics and simulation
    - Halo formation and beam loss mechanisms (historically not accurate)
- Crossing angle issues
  - Crab cavity development
  - New ideas: eg, flat beams
- Key question for the HEP community:
  - Luminosity vs. pile-up as a function of energy
    - What luminosity do you need?
    - What pile-up can you live with?

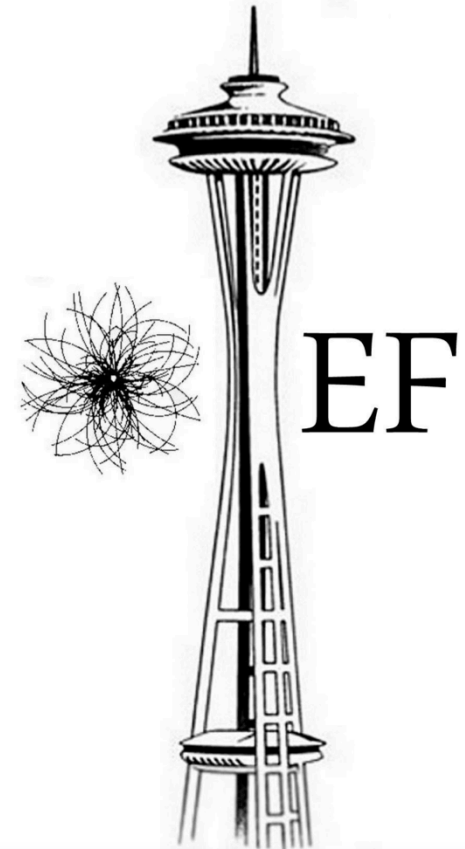
E. Prebys

$e^+e^-$  Circular Colliders:  
>100 GeV Scale

Linear Colliders:

- $e^+e^-$  Colliders with  
 $E < 1 \text{ TeV}$  &  $E > 1 \text{ TeV}$
- $\gamma\text{-}\gamma$  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 ( $\sim 10^3$  sec) and Top-Up Injection
- Collective Effects
- Energy Bandwidth

$$\Delta E [GeV] = 8.85 \times 10^{-5} \frac{E^4 [GeV^4]}{\rho [m]}$$

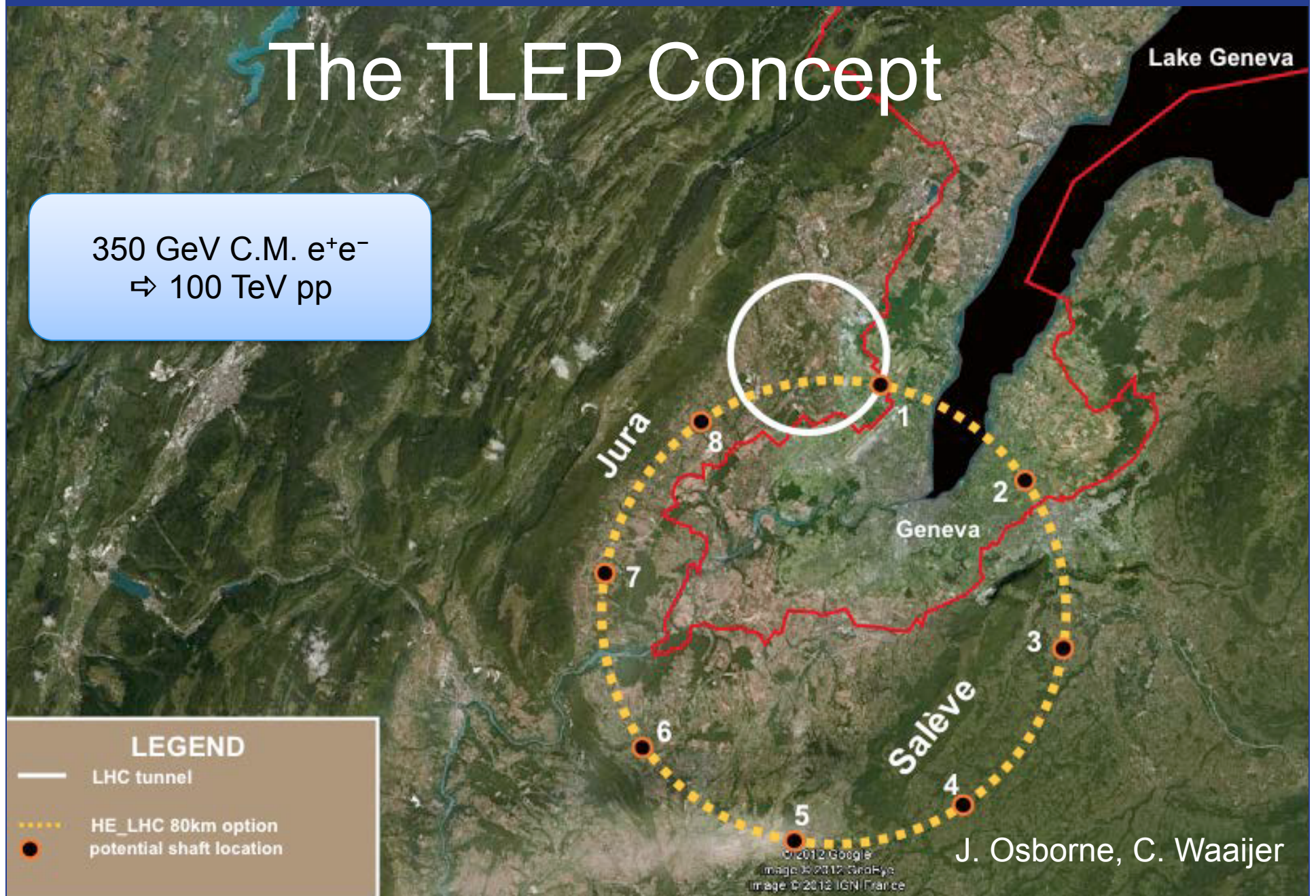
## Trends in the Discussion

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



# The TLEP Concept

350 GeV C.M.  $e^+e^-$   
 $\Rightarrow$  100 TeV pp



# 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
$\beta_x^*$ [mm]	1500	500	1000	200
$\beta_y^*$ [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	9.4	4.9	3.0
Beam-beam parameter / IP	0.07	0.1	0.1	0.1
Luminosity / IP [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ]	0.0125	4.8	1.3	1.8

\* Assumes 4 IPs

\*\* Assumes 1 or 2 IPs



# $e^+e^-$ Circular Colliders

## Status

- TLEP Design Study has been launched
- Not aware of any other significant effort underway

## 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  $\mathcal{H}_D$
  - 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  $E_{\text{CM}} < 1$  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  $E_{\text{CM}} < 1$  TeV, but 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

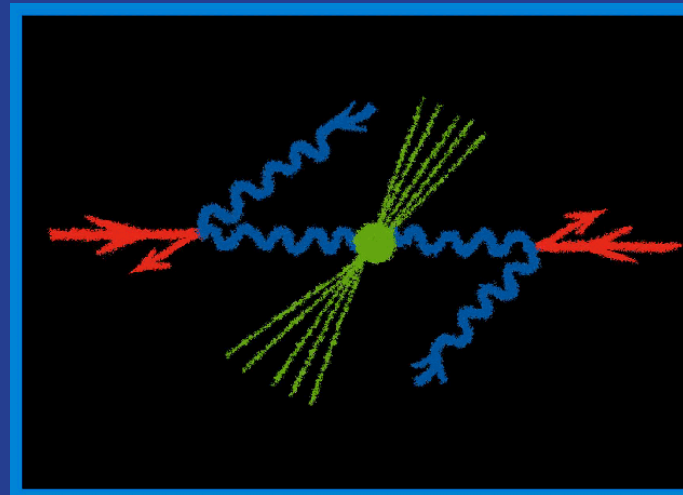
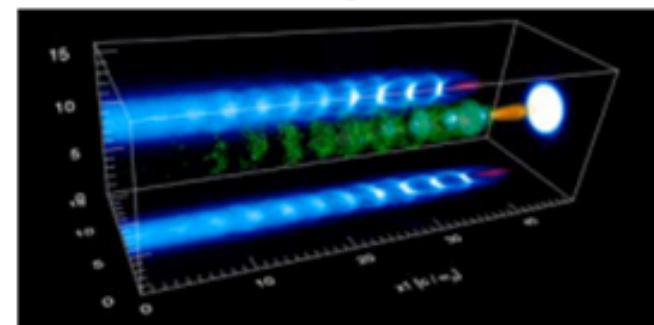
- $\gamma\text{-}\gamma$ : High power laser beams  
Compton backscattered from  
 $e^-$  or  $e^+$  beams

$\gamma\gamma \Rightarrow H$  cross section  $\sim 200\text{fb}$

Concept could be applied at an  
ILC or CLIC



$\sim 1\text{m}$   
 $\sim 100\mu\text{m}$



# 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	$\sigma_z$	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)	$L$	$\times 10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$	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

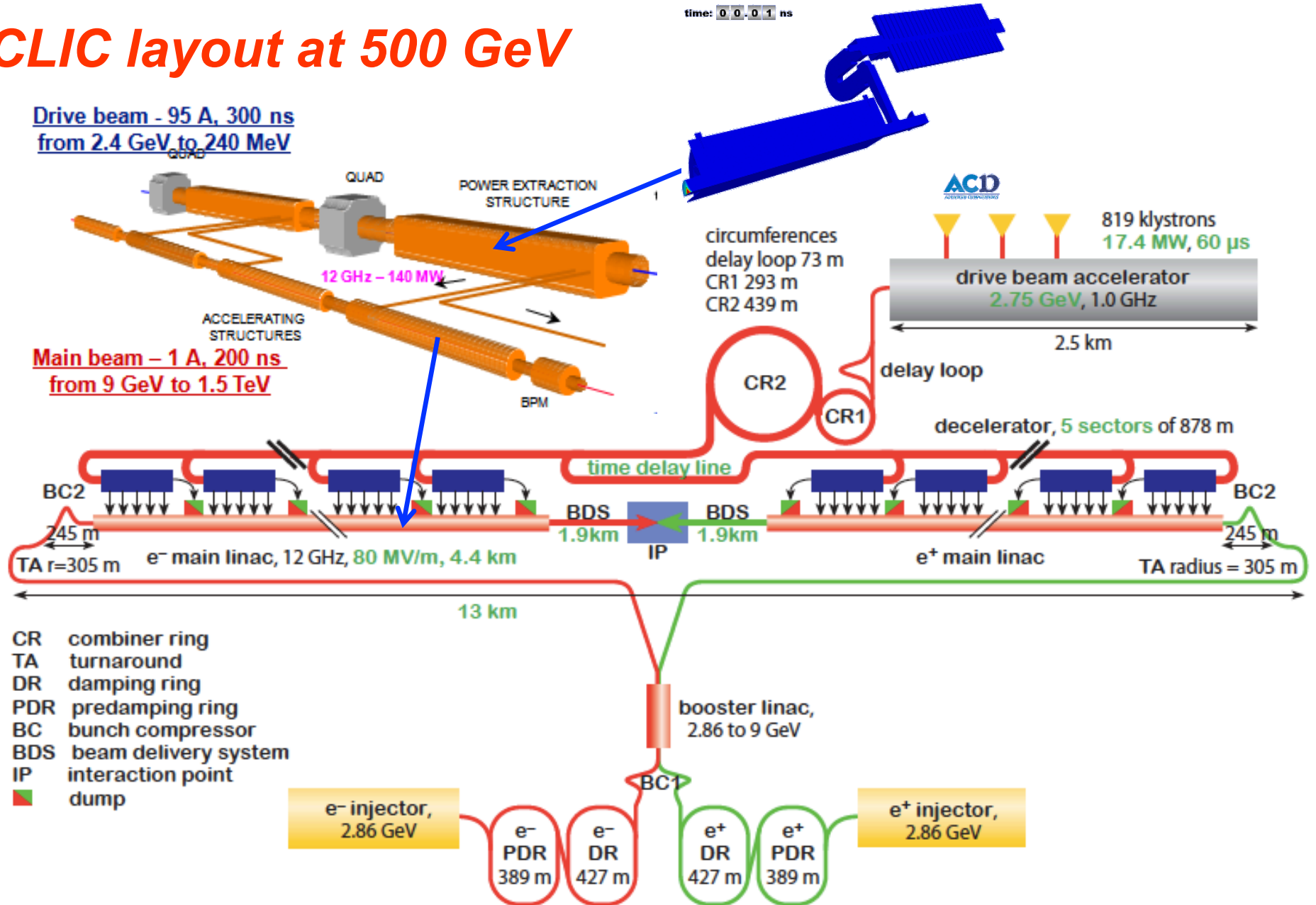
## R&D

- 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



# Potential Staged CLIC Parameters

parameter	symbol			
centre of mass energy	$E_{\text{cm}}$ [GeV]	500	1400	3000
luminosity	$\mathcal{L}$ [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ]	2.3	3.2	5.9
luminosity in peak	$\mathcal{L}_{0.01}$ [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ]	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	$\sigma_z$ [ $\mu\text{m}$ ]	72	44	44
IP beam size	$\sigma_x/\sigma_y$ [nm]	200/2.26	$\approx 60/1.5$	$\approx 40/1$
norm. emittance	$\epsilon_x/\epsilon_y$ [nm]	2400/25	660/20	660/20
bunches per pulse	$n_b$	354	312	312
distance between bunches	$\Delta_b$ [ns]	0.5	0.5	0.5
repetition rate	$f_r$ [Hz]	50	50	50
est. power cons.	$P_{\text{wall}}$ [MW]	271	361	582

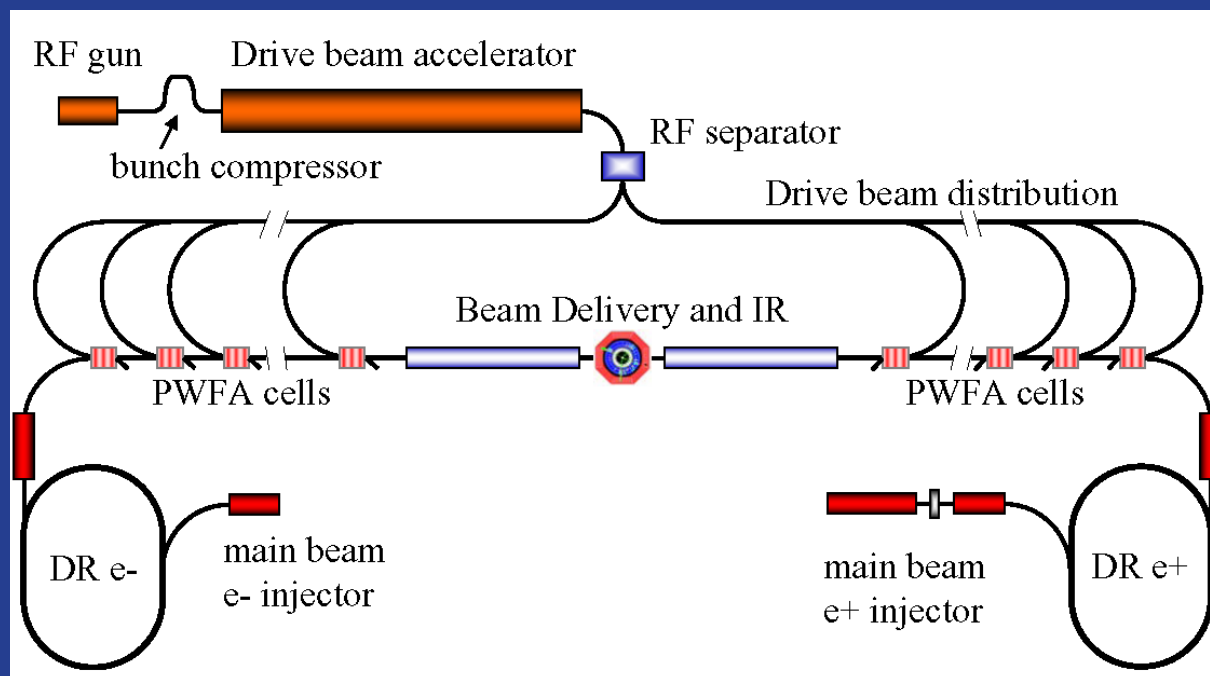


# Linear Colliders with $E > 1$ TeV

- ILC is  $\sim 50$  km at 1 TeV
  - Possible to consider higher gradient SCRF materials or PWFA boost
- CLIC design is aimed at upgradable design  $\rightarrow 0.5$ -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  $\rightarrow$  high energy beams
  - Possible to develop upgrade options for ILC-like technology?

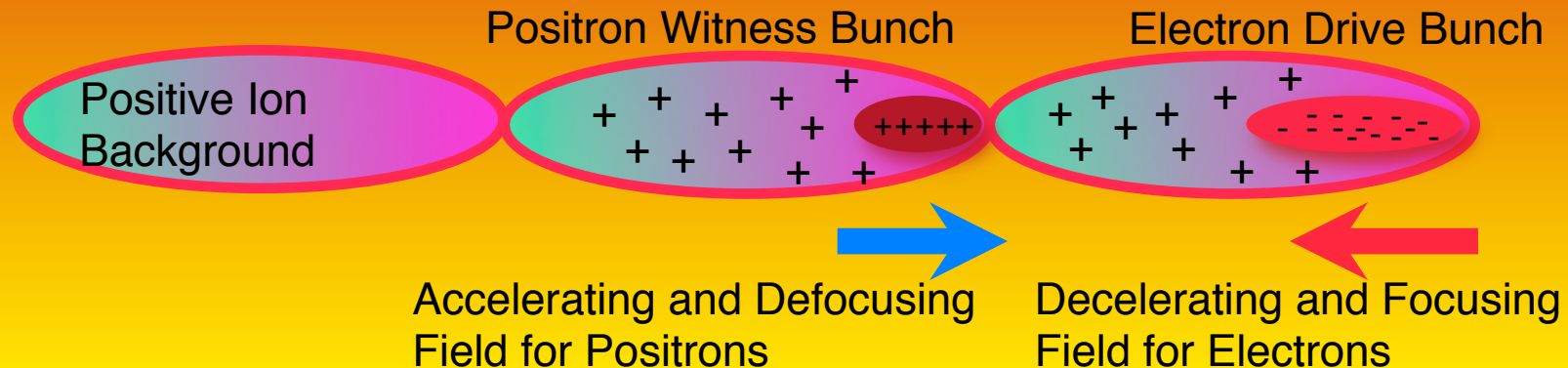
# Concept of Beam-Driven Plasma Linac

- 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

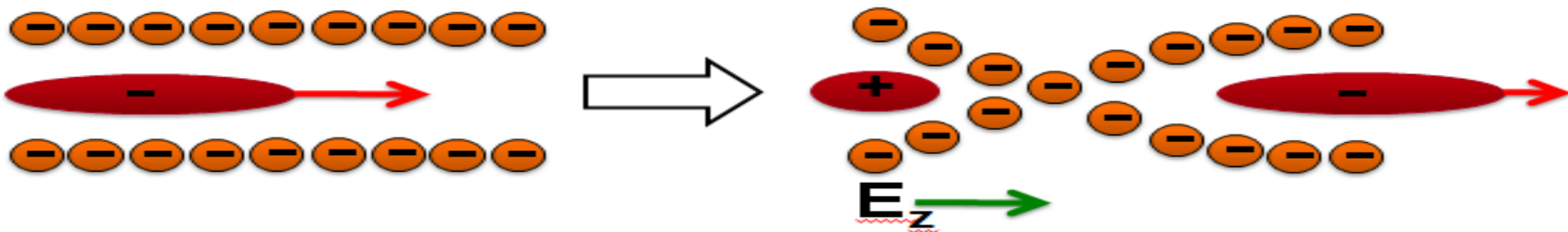


# Challenges for Positron Plasma Wakefield Acceleration

M. Hogan



## 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 ( $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ )	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 $\gamma\epsilon_x$ (nm-rad)	10,000	660	1000	200	0.1
Vertical emittance $\gamma\epsilon_y$ (nm-rad)	30	20	10	200	0.1
$\beta^*$ x/y (mm)	11 / 0.2	4 / 0.1	10 / 0.1	0.2	0.4
Horizontal beam size at IP $\sigma_x^*$ (nm)	474	49	32	2	0.06
Vertical beam size at IP $\sigma_y^*$ (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 $\sigma_z$ ( $\mu\text{m}$ )	300	50	20	1	335
Beamstrahlung parameter $\Upsilon$	0.07	6.7	56	8980	0.4
Beamstrahlung photons per electron $n_\gamma$	1.7	1.5	1.4	3.67	0.5
Beamstrahlung energy loss $\delta_E$ (%)	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

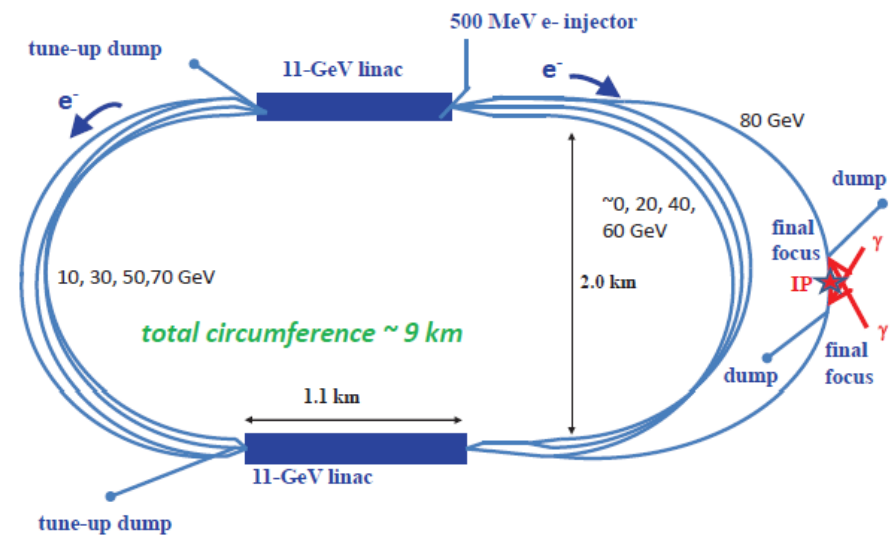
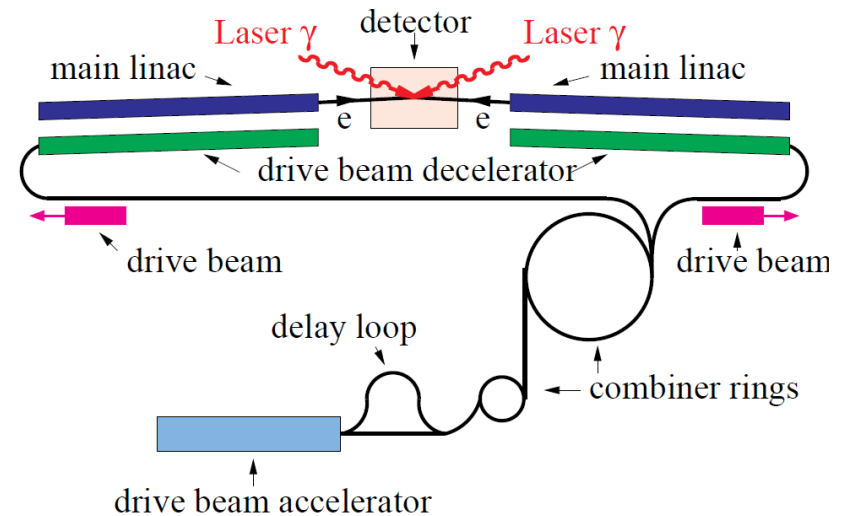
- CLIC: Timescale dependent on finalized technical design and physics needs
- Wakefield LCs:
  - Expect non-HEP applications on the ~decade timescale
  - Collider R&D phase to fully assess feasibility is likely decades scale
  - First application might be an ILC “afterburner”

# $\gamma\text{-}\gamma$ Collider Concepts

- $\gamma\text{-}\gamma$  Higgs Factory ( $E_{\text{CM}} \sim 160$  GeV, photons carry  $\sim 80\%$  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	$2.2 \times 10^{34}$
Laser wavelength	351 nm
Repetition rate	200 kHz
Laser pulse energy	$\sim 5$ J

## CLICHÉ: CLIC Higgs Experiment



# $\gamma\text{-}\gamma$ 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?

R&D

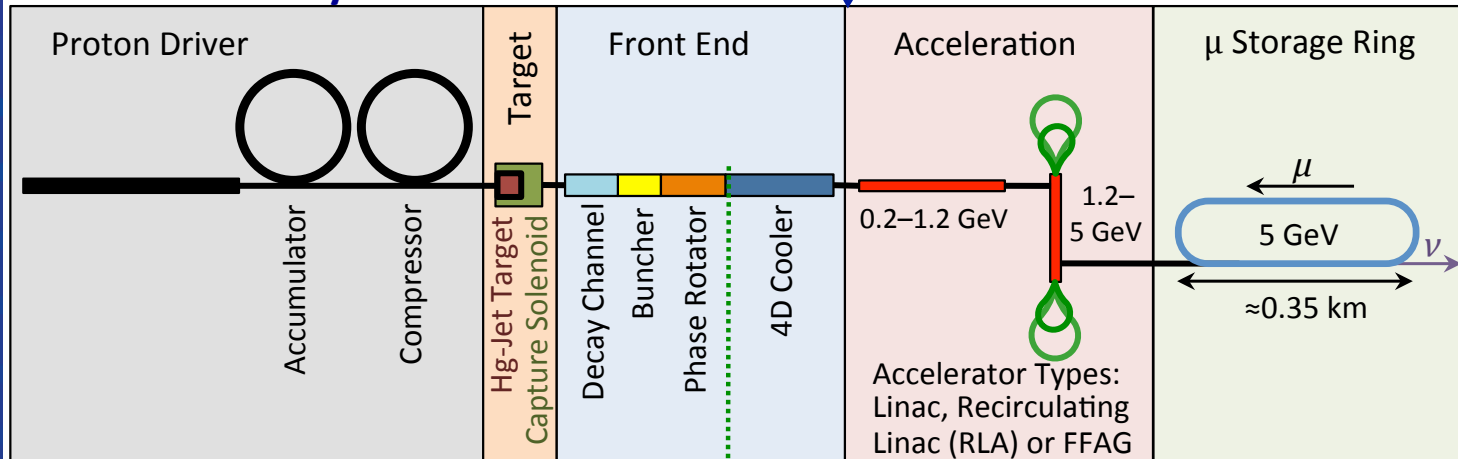
- Validate feasibility of required laser
- Would need to establish Technical Design

Time

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

# Muon Accelerator Concepts

## Neutrino Factory

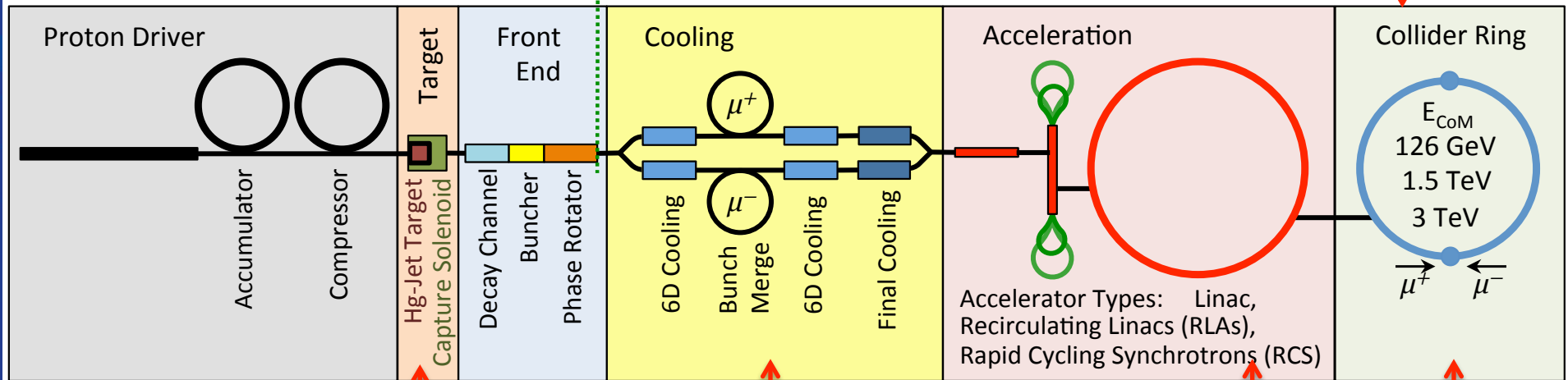


ν Factory Goal:  
 $O(10^{21})$  μ/year  
 within the accelerator  
 acceptance

μ-Collider Goals:  
 126 GeV ⇒  
 ~40,000 Higgs/yr  
 Multi-TeV ⇒  
 $Lumi > 10^{34} \text{cm}^{-2}\text{s}^{-1}$

Share same complex

## Muon Collider



## Major Challenges



# Muon Accelerators

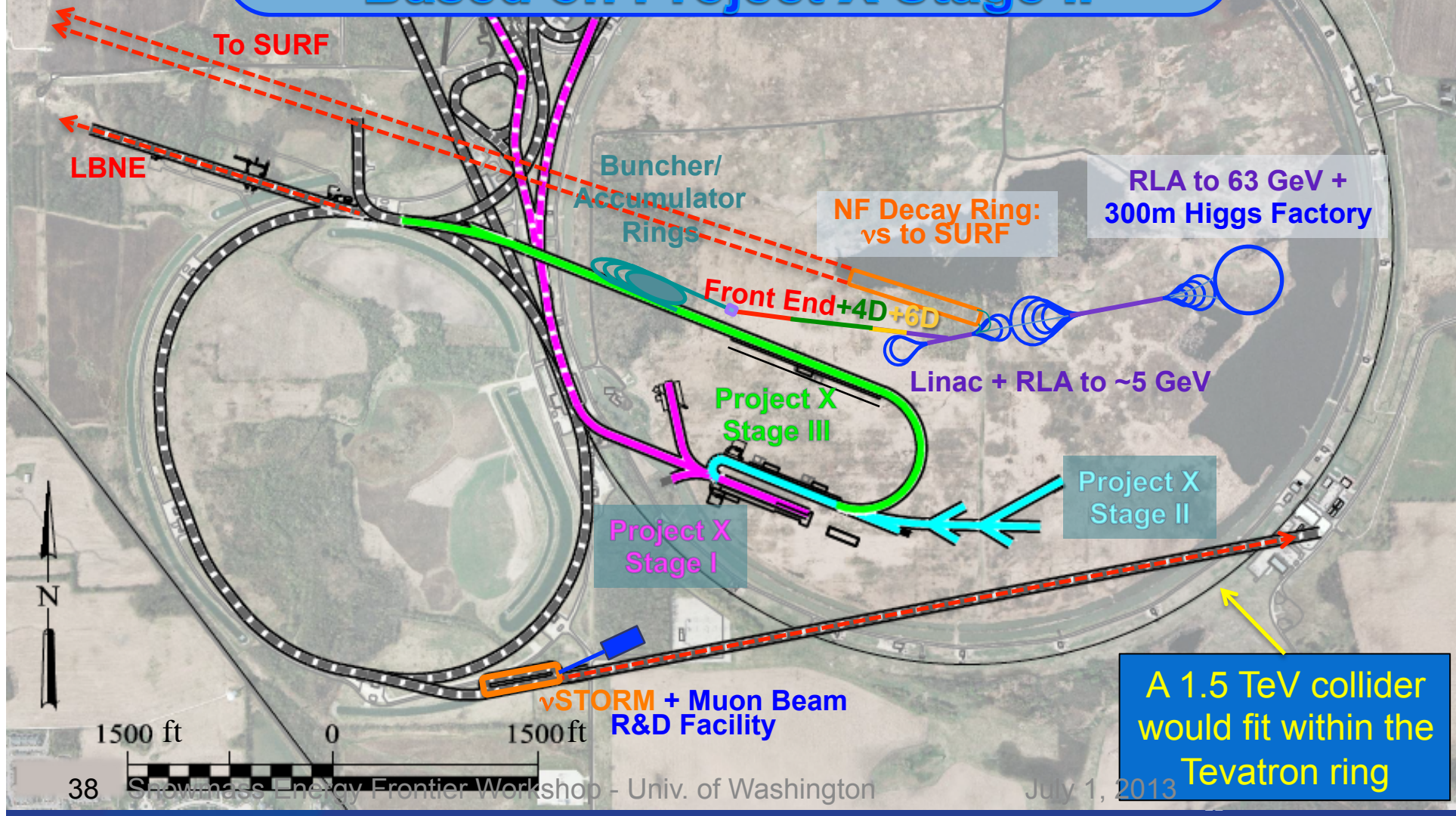
Accelerator	Energy Scale	Performance
<b>Cooling Channel</b>	<b>~200 MeV</b>	<b>Emittance Reduction</b>
<i>MICE</i>	<i>160-240 MeV</i>	<i>10%</i>
<b>Muon Storage Ring</b>	<b>3-4 GeV</b>	<b>Useable <math>\mu</math> decays/yr*</b>
<i><math>\nu</math>STORM</i>	<i>3.8 GeV</i>	<i><math>3 \times 10^{17}</math></i>
<b>Intensity Frontier <math>\nu</math> Factory</b>	<b>4-10 GeV</b>	<b>Useable <math>\mu</math> decays/yr*</b>
<i>FNAL NF Phase I (PX Ph 2)</i>	<i>4-6 GeV</i>	<i><math>8 \times 10^{19}</math></i>
<i>FNAL NF Phase II (PX Ph 2)</i>	<i>4-6 GeV</i>	<i><math>5 \times 10^{20}</math></i>
<i>IDS-NF Design</i>	<i>10 GeV</i>	<i><math>5 \times 10^{20}</math></i>
<b>Higgs Factory</b>	<b>~126 GeV CoM</b>	<b>Higgs/yr</b>
<i>s-Channel <math>\mu</math> Collider</i>	<i>~126 GeV CoM</i>	<i>5,000-40,000</i>
<b>Energy Frontier <math>\mu</math> Collider</b>	<b>&gt; 1 TeV CoM</b>	<b>Avg. Luminosity</b>
<i>Opt. 1</i>	<i>1.5 TeV CoM</i>	<i><math>1.2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}</math></i>
<i>Opt. 2</i>	<i>3 TeV CoM</i>	<i><math>4.4 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}</math></i>
<i>Opt. 3</i>	<i>6 TeV CoM</i>	<i><math>12 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}</math></i>

\* Decays of an individual species (ie,  $\mu^+$  or  $\mu^-$ )



Program Baselines  
And Potential Staging Steps

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



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

## Muon Collider Baseline Parameters

### Higgs Factory

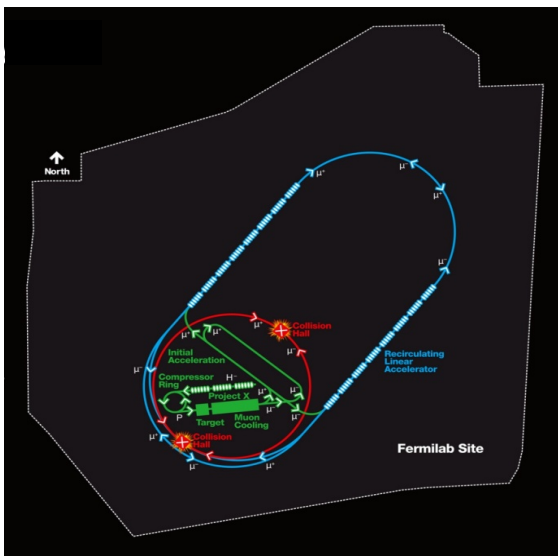
### Multi-TeV Baselines

Parameter	Units	Initial Cooling	Upgraded Cooling / Combiner		
CoM Energy	TeV	0.126	0.126	1.5	3.0
Avg. Luminosity	$10^{34} \text{cm}^{-2} \text{s}^{-1}$	0.0017	0.008	1.25	4.4
Beam Energy Spread	%	0.003	0.004	0.1	0.1
Circumference	km	0.3	0.3	2.5	4.5
No. of IPs		1	1	2	2
Repetition Rate	Hz	30	15	15	12
$\beta^*$	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, $\epsilon_{\text{TN}}$	$\pi \text{ mm-rad}$	0.4	0.2	0.025	0.025
Norm. Long. Emittance, $\epsilon_{\text{LN}}$	$\pi \text{ mm-rad}$	1	1.5	70	70
Bunch Length, $\sigma_s$	cm	5.6	6.3	1	0.5
Beam Size @ IP	$\mu\text{m}$	150	75	6	3
Beam-beam Parameter / IP		0.005	0.02	0.09	0.09
Proton Driver Power	MW	4 <sup>#</sup>	4	4	4

<sup>#</sup> Could begin operation with Project X Phase 2 beam

Exquisite Energy Resolution  
Allows Direct Measurement of Higgs Width

Site Radiation mitigation with depth and lattice design:  $\leq 10 \text{ TeV}$





# Muon Colliders

## Status

- MAP Feasibility Assessment underway

## R&D

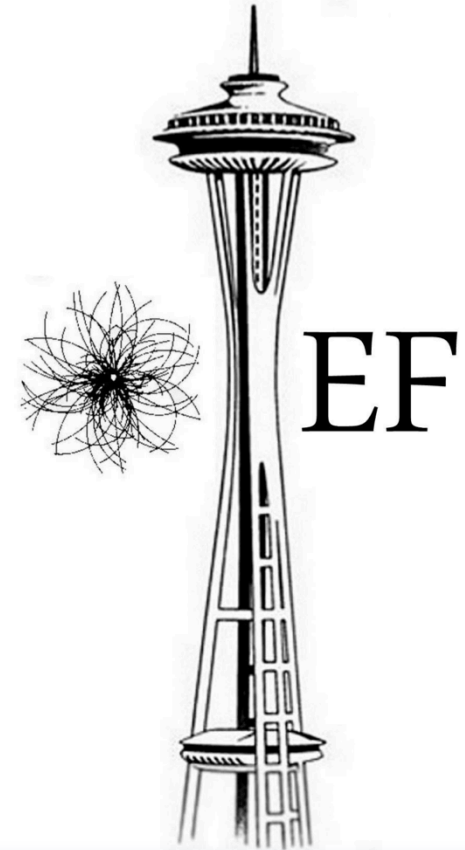
- Establishing Initial Baseline Design
- Technology R&D: Cooling channel hardware, RF in B-fields, high field magnets (synergistic with HE-LHC needs)
- Staging Study: Physics + R&D + Demos required for next stage
- Muon Ionization Cooling Experiment

## Time

- Feasibility Report by end of decade
- Completion of MICE by end of decade
- NuMAX (initial long baseline NF): Informed Decision by ~2020
- Collider Options: Informed Decision point by mid-2020s

Long-Term Perspective

Conclusions



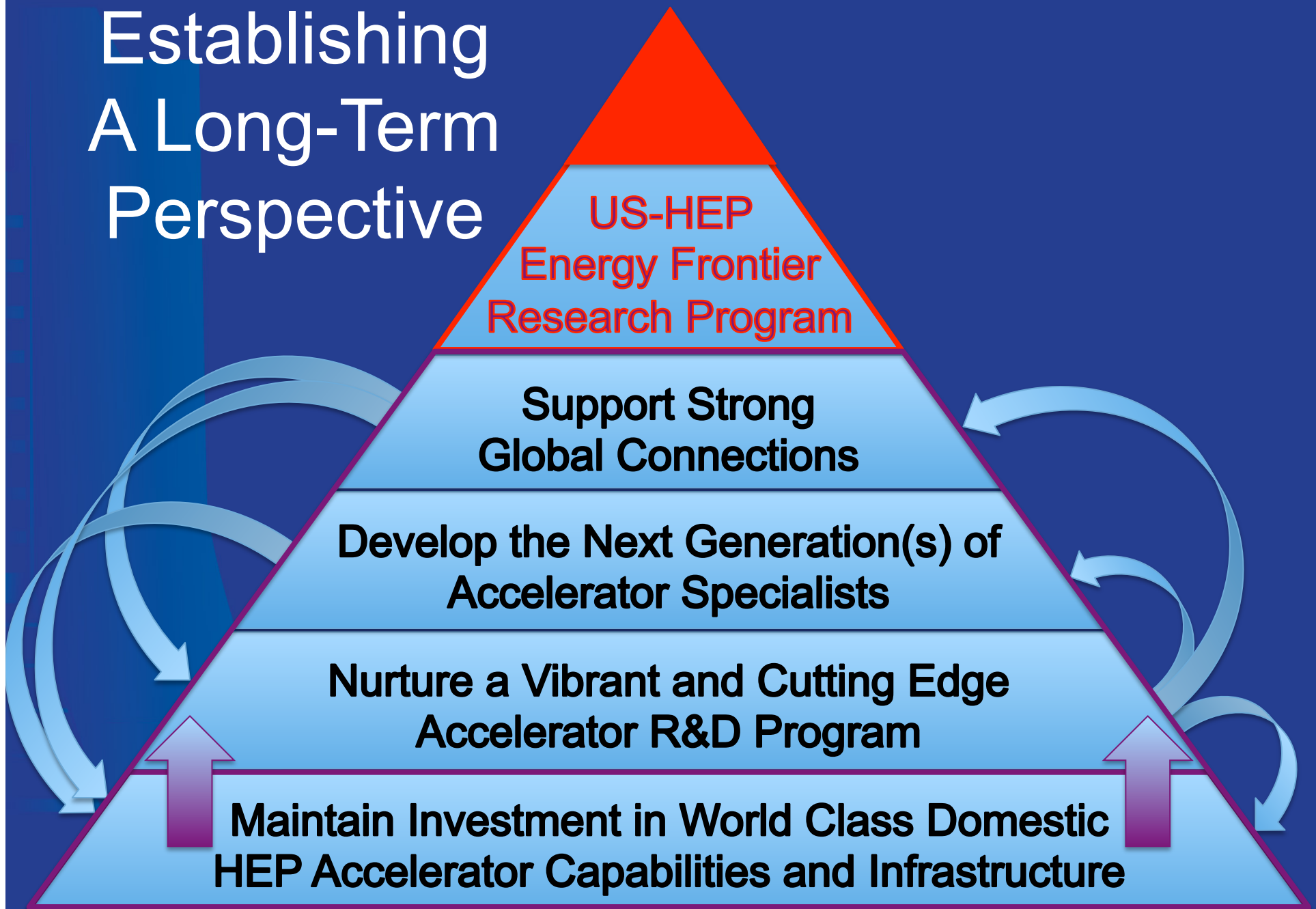
# CLOSING REMARKS

# Some Connections...

- A theme that has arisen in the capabilities discussions has been that of upgrade paths
  - Note that a number of “constrained” options didn’t even get mention in this presentation
- There are many special synergies that also come into play:
  - TLEP & VHE-LHC
  - MC and the Neutrino Program
  - Technology linkages (eg, MAP and HE LHC magnet development)
  - $\gamma\text{-}\gamma$  as a companion capability to an LC
  - A wakefield accelerator upgrade to a conventional LC
  - And this is not an exhaustive list...



# Establishing A Long-Term Perspective

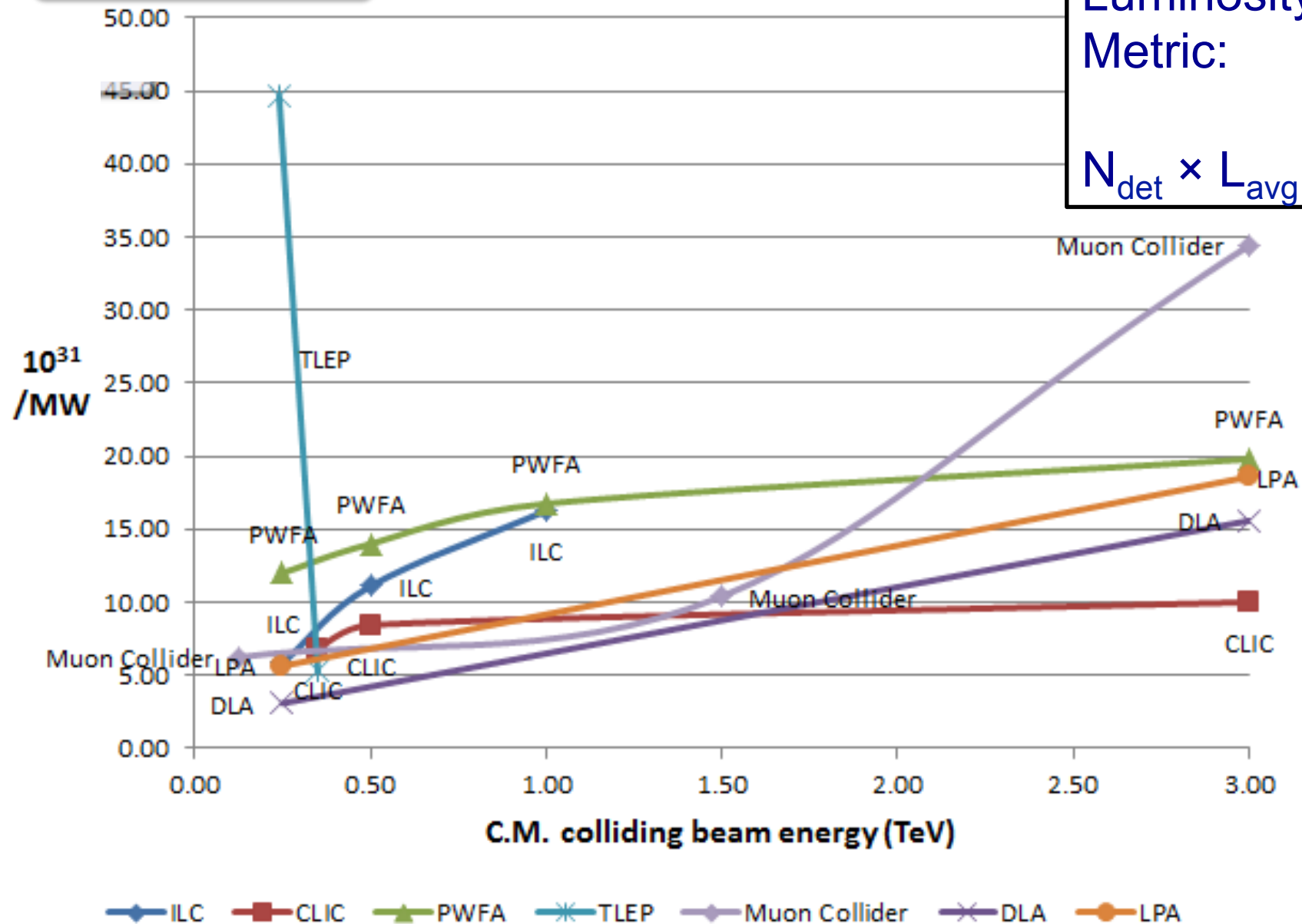


# Conclusions I

- 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...

Luminosity  
Metric:

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



# Conclusions II

- 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