Developments in Accelerators for Future High Energy Machines

Mark Palmer

Brookhaven National Laboratory

DPF Meeting 2017

APS DIVISION OF PARTICLES & FIELDS

July 31 – August 4

dpf2017.fnal.gov

Fermilab

70 YEARS OF DISCOVERY

A CENTURY OF SERVICE

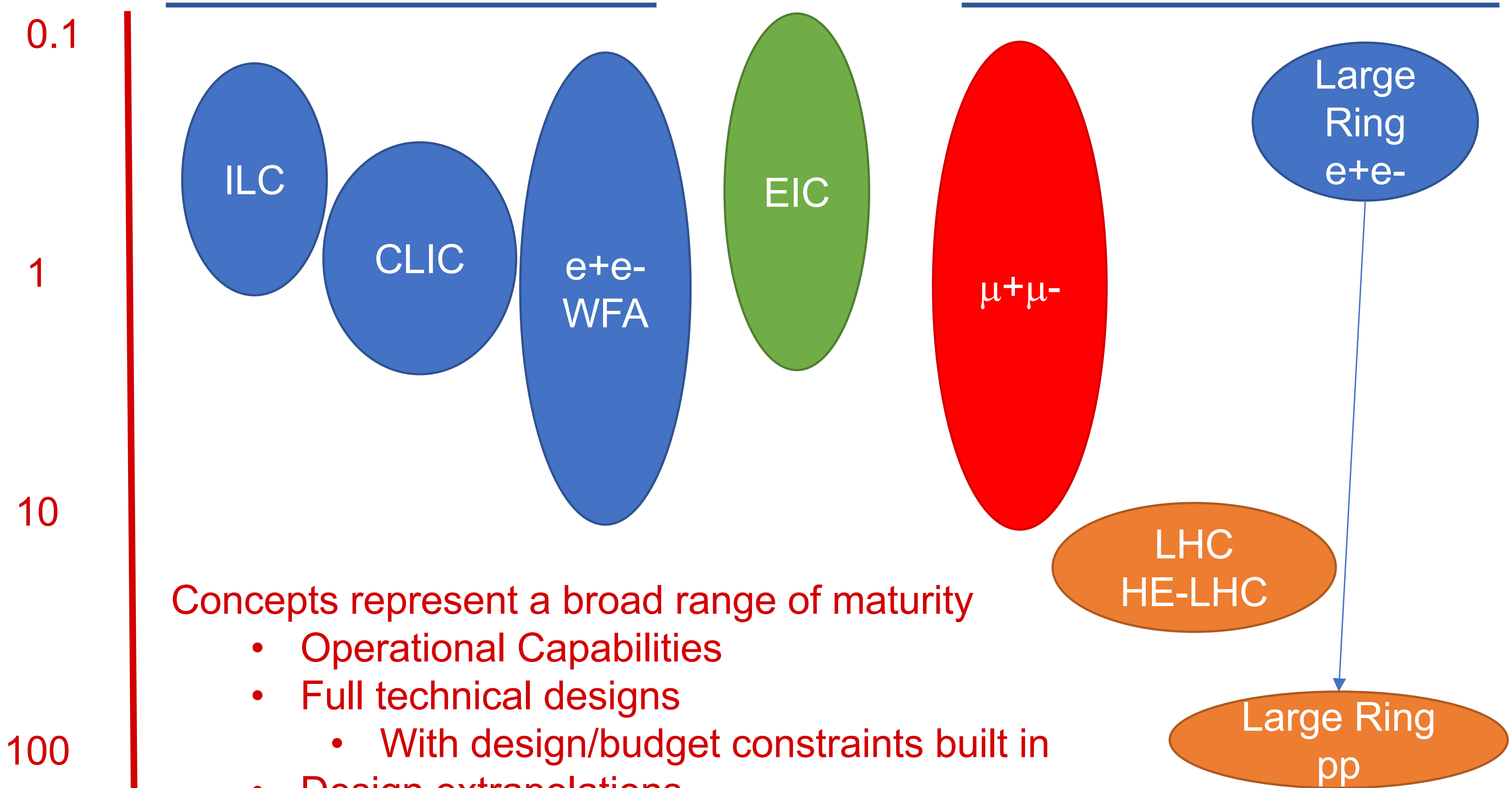
U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

What are the possible paths forward for future high energy capabilities?

- Will focus on paths to next generation colliders

Linear Colliders — Circular Colliders



E_{CM} (TeV)

Concepts represent a broad range of maturity

- Operational Capabilities
- Full technical designs
  - With design/budget constraints built in
- Design extrapolations
  - With some focused R&D required
- R&D concepts requiring significant validation

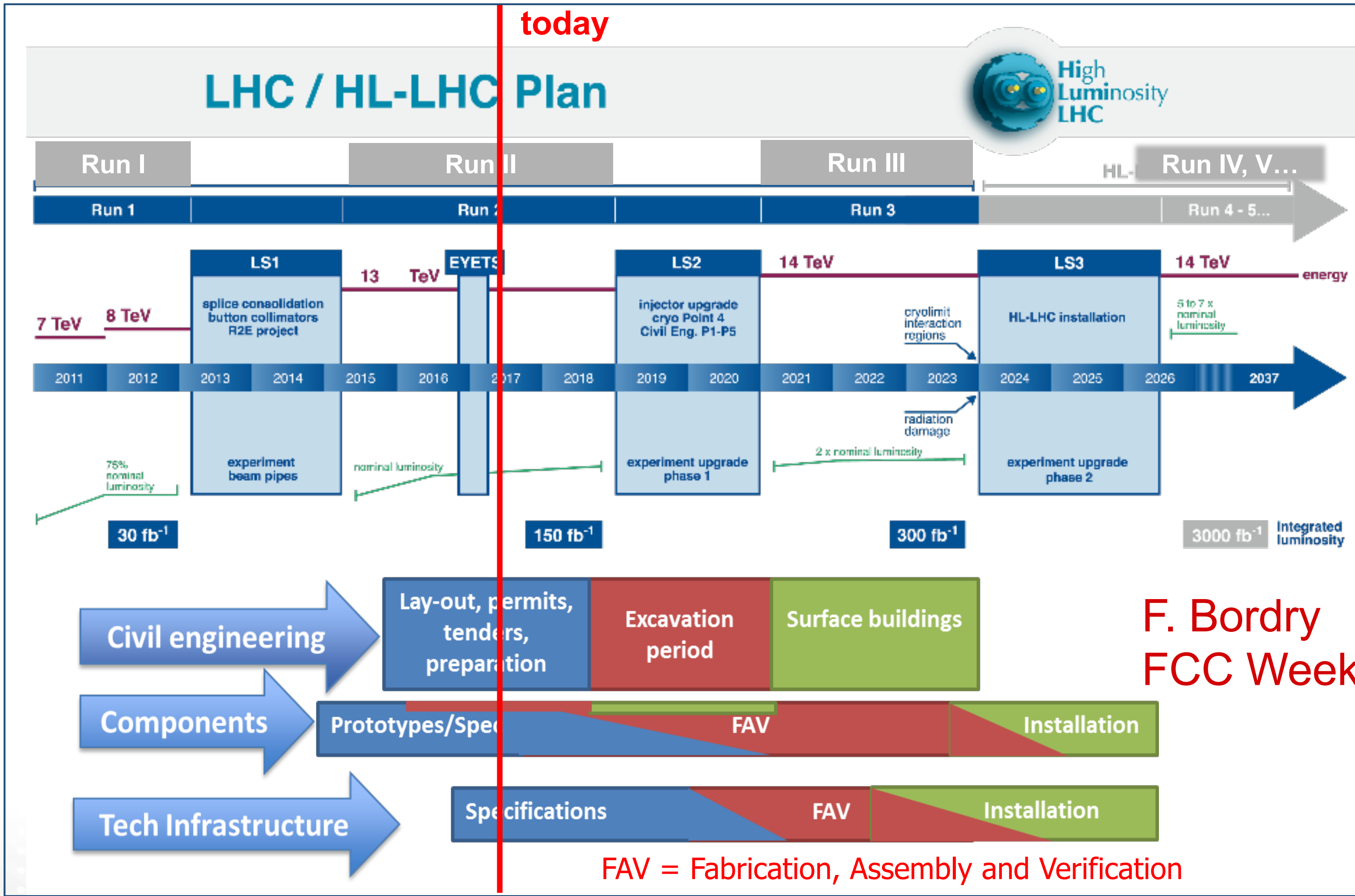
Hadron Capabilities

A Short Status Overview

LHC ⇨ HL-LHC Program

Upgrades:

- IR Quads
- Nb_3Sn short dipoles
- Collimation
- Crab Cavities
- Cryogenics
- Machine Protection
- Detectors



F. Bordry
FCC Week

Options for Next Generation pp Machines

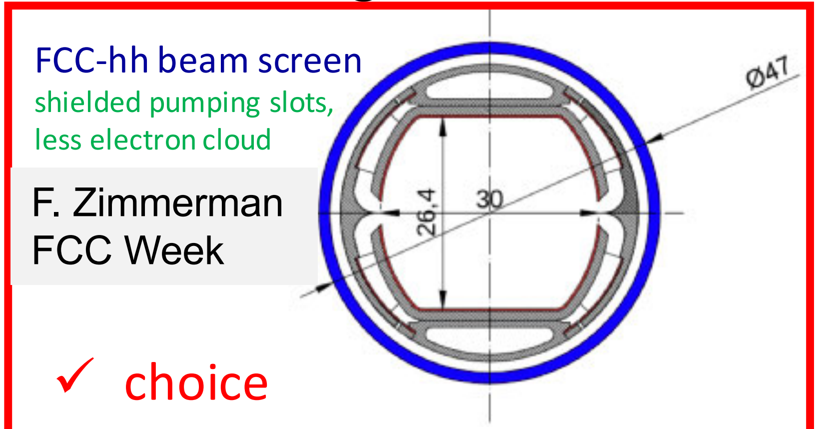
F. Zimmerman – FCC Week

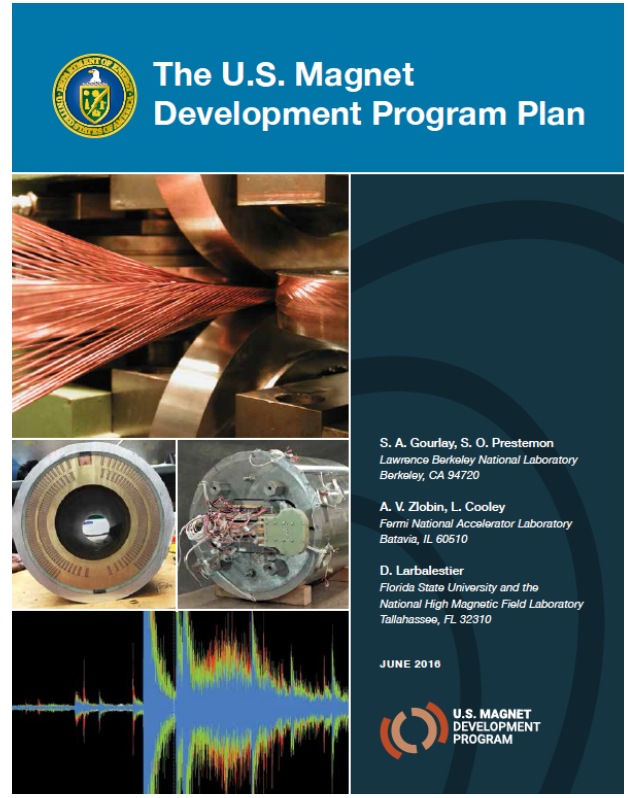
parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.33
circumference [km]	100		27	27
straight section length [m]	1400		528	528
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25 (5)	25
rms bunch length [cm]	7.55		7.55	(8.1) 7.55
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	25	(5) 1
events/bunch crossing	170	1k (200)	~800 (160)	(135) 27
stored energy/beam [GJ]	8.4		1.3	(0.7) 0.36
beta* [m]	1.1-0.3		0.25	(0.20) 0.55
norm. emittance [μm]	2.2 (0.4)		2.5 (0.5)	(2.5) 3.75

Also Chinese SPPC option as follow-on to CEPC

Key Issues

- Focus on 16T dipole
  - Includes US Magnet Development Program Efforts
  - Compact design required for HE-LHC
- Vacuum System Design





- Crab Cavities and Electron Lenses based on HL-LHC
- Other issues: Beam Parameters, Electron Cloud, Pileup
- Cost Evaluation

Lepton Collider Options

A Short Status Overview

e^+e^- Circular Colliders

Comments

- LEP2 nearly reached the Higgs
- Rings are robust and well-understood technology
- Current focus: 80-100km ring leading to a 100 TeV scale hadron collider

Technical Issues

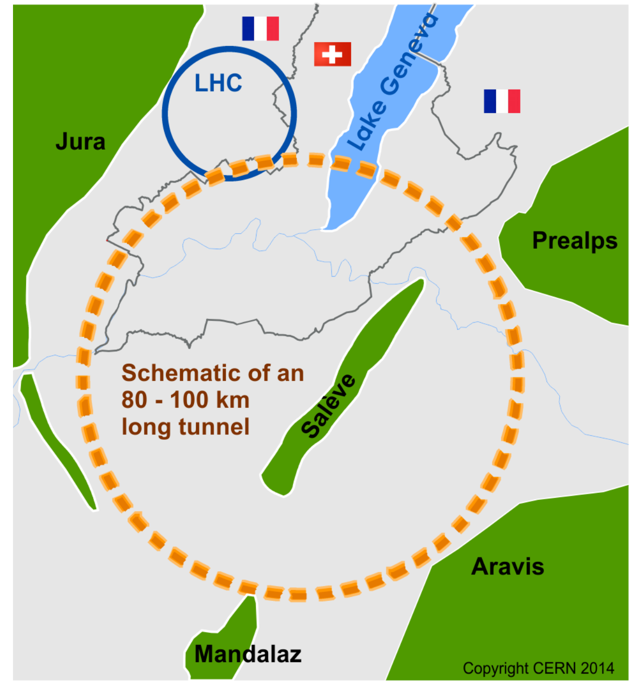
$$\Delta E[GeV] = 8.85 \times 10^{-5} \frac{E^4[GeV^4]}{\rho[m]}$$

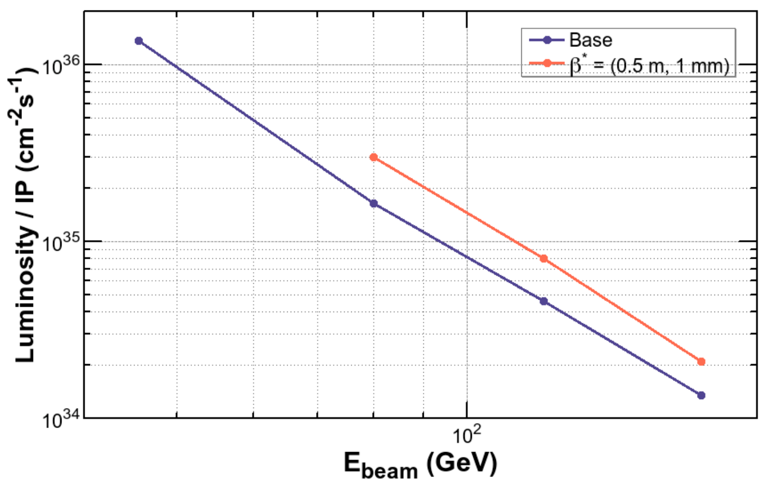
- SR energy:
- RF Efficiency
- Beam Lifetime (~10^3 sec) and Top-Up Injection
- Collective Effects
- Energy Bandwidth

FCC-ee in 2017

K. Oide – FCC Week

Design		2017			
Circumference	[km]	97.750			
Arc quadrupole scheme		**twin aperture**			
Bend. rad. of arc dipoles	[km]	10.747			
Number of IPs / ring		2			
Crossing angle at IP	[mrad]	30			
Solenoid field at IP	[T]	±2			
ℓ^*	[m]	2.2			
Local chrom. correction		y-plane with crab-sext. effect			
RF frequency	[MHz]	400			
Total SR power	[MW]	100			
Beam energy	[GeV]	45.6	80	120	175
SR energy loss/turn	[GeV]	0.036	0.34	1.72	7.80
Long. damping time	[ms]	414	76.8	22.9	7.49
Current/beam	[mA]	1390	147	29.0	6.4
Bunches/ring		70760	7280 (4540)	826 (614)	64 (50)
Particles/bunch	$[10^{10}]$	4.0	4.1 (6.6)	7.1 (9.6)	20.4 (26.0)
Arc cell		60°/60°	90°/90°		
Mom. compaction α_p	$[10^{-6}]$	**14.79**	7.31		
β-tron tunes ν_x / ν_y		269.14 /267.22	389.08 / 389.18		
Arc sext. families		208	292		
Horizontal emittance ε_x	[nm]	**0.267**	0.28	0.63	1.34
$\varepsilon_y/\varepsilon_x$ at collision	[%]	0.38	0.36	0.2	0.2
β^*_x / β^*_y	[m / mm]	**0.15 / 1**	1 / 2 (0.5 / 1)		
Energy spread by SR	[%]	0.038	0.066	0.099	0.147
Energy spread SR+BS	[%]	0.073	0.072 (0.091)	0.106 (0.122)	0.193 (0.212)
Hor. beam-beam ξ_x		0.008	0.080 (0.046)	0.081 (0.053)	0.082 (0.049)
Ver. beam-beam ξ_y		0.106	0.141 (0.141)	0.140 (0.140)	0.140 (0.138)
RF Voltage	[MV]	**255**	696	2620	9500
Bunch length by SR	[mm]	2.1	2.1	2.0	2.4
Bunch length SR+BS	[mm]	4.1	2.3 (2.9)	2.2 (2.5)	2.9 (3.5)
Synchrotron tune ν_z		−0.0413	−0.0340	−0.0499	−0.0684
RF bucket height	[%]	3.8	3.7	2.2	10.3
Luminosity/IP	$[10^{34}/\mathrm{cm}^2\mathrm{s}]$	**137**	16.4 (30.0)	4.6 (8.0)	1.35 (2.09)





Steady progress addressing design challenges

CEPC – 100km baseline

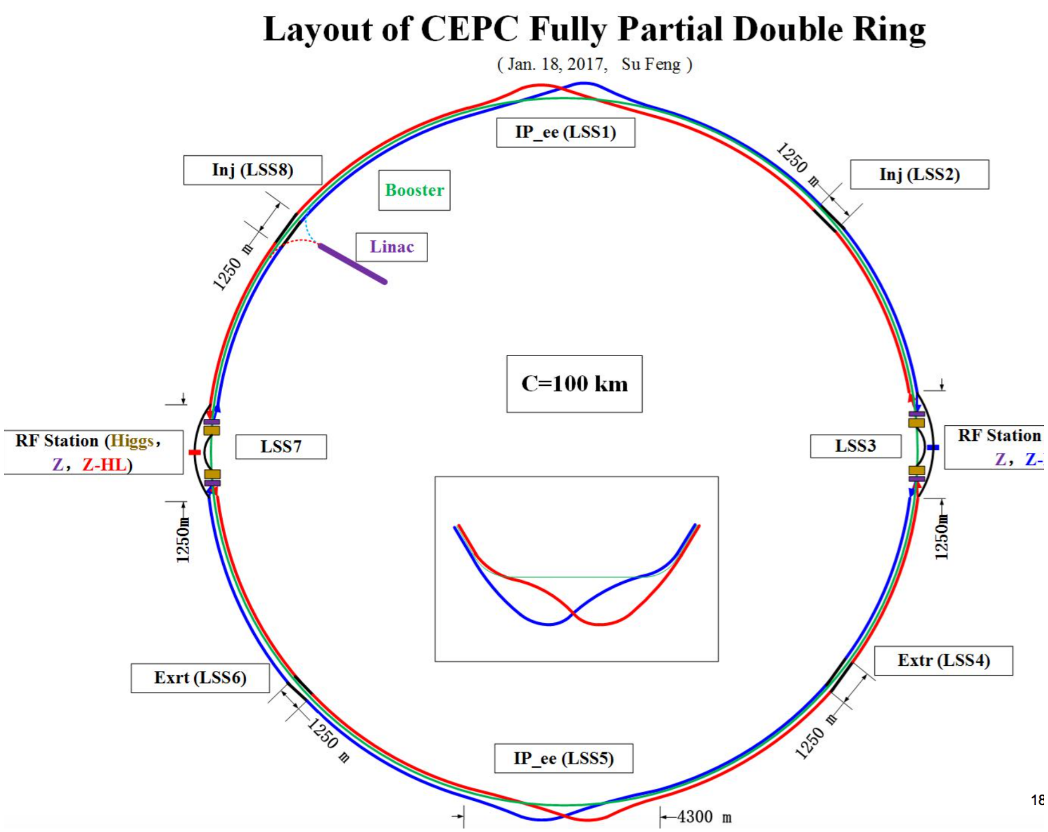


Table 1. Parameters for 100 km CEPC double ring with 2 mm vertical β*.

	Pre-CDR	Higgs	W	Z
Number of IPs	2	2	2	2
Energy (Gev)	120	120	80	45.5
Circumference (km)	54	100	100	100
SR loss/turn (Gev)	3.1	1.67	0.33	0.034
Half crossing angle (mrad)	0	16.5	16.5	16.5
Piwinski angle Φ	0	3.19	5.69	4.29
N_e/bunch (10^{11})	3.79	0.968	0.365	0.455
Bunch number	50	412	5534	21300
Beam current (mA)	16.6	19.2	97.1	465.8
SR power /beam (MW)	51.7	32	32	16.1
Bending radius (km)	6.1	11	11	11
Momentum compaction (10^{-5})	3.4	1.14	1.14	4.49
$\beta_{IP\ x/y}$ (m)	0.8/0.0012	0.171/0.002	0.171 /0.002	0.16/0.002
Emittance x/y (nm)	6.12/0.018	1.31/0.004	0.57/0.0017	1.48/0.0078
Transverse σ_{IP} (um)	69.97/0.15	15.0/0.089	9.9/0.059	15.4/0.125
ξ_x/ξ_y/IP	0.118/0.083	0.013/0.083	0.0055/0.062	0.008/0.054
V_{RF} (GV)	6.87	2.1	0.41	0.14
f_{RF} (MHz)	650	650	650	650
Nature σ_z /Total σ_z (mm)	2.14/2.65	2.72/2.9	3.37/3.4	3.97/4.0
HOM power/cavity (kw)	3.6 (5cell)	0.41(2cell)	0.36(2cell)	1.99(2cell)
Energy spread (%)	0.13	0.098	0.065	0.037
Energy acceptance requirement (%)	2	1.5		
Energy acceptance by RF (%)	6	2.1	1.1	1.1
n_γ	0.23	0.26	0.15	0.12
Life time due to beamstrahlung_cal (minute)	47	52		
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	2.04	2.0	5.15	11.9

Wang – J. Phys, Conf. Series **874** (2017) 012009

Robust design and component R&D program underway

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

70 YEARS OF DISCOVERY
A CENTURY OF SERVICE

Linear Colliders

- Luminosity

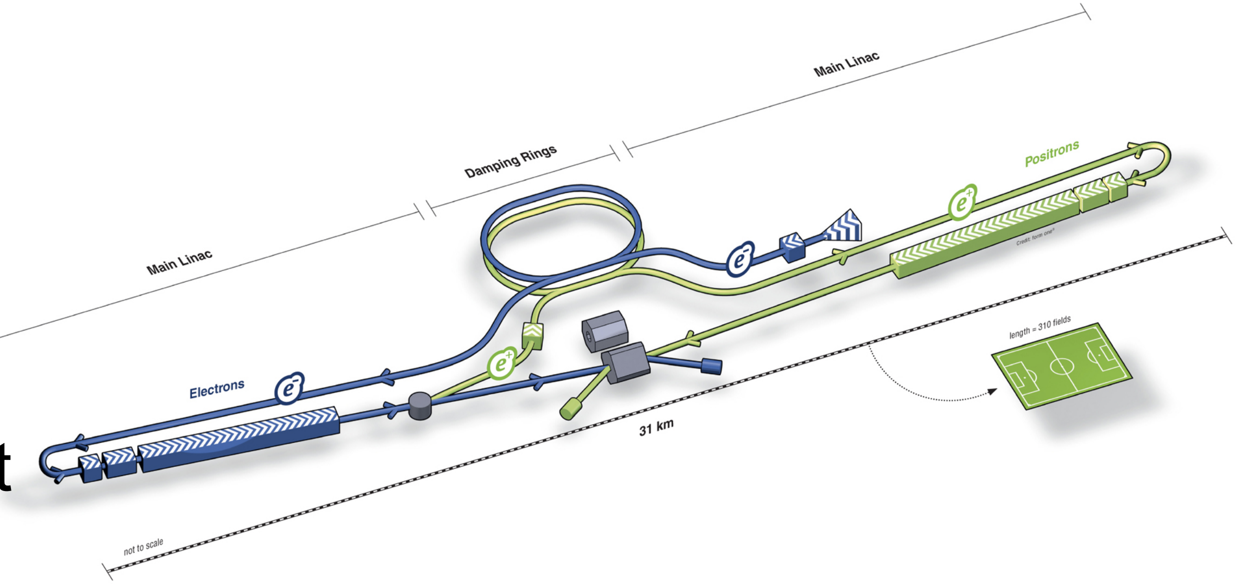
$$\mathcal{L} = \frac{N^2 f_{coll}}{4\pi\sigma_x\sigma_y}\mathcal{H}_D$$

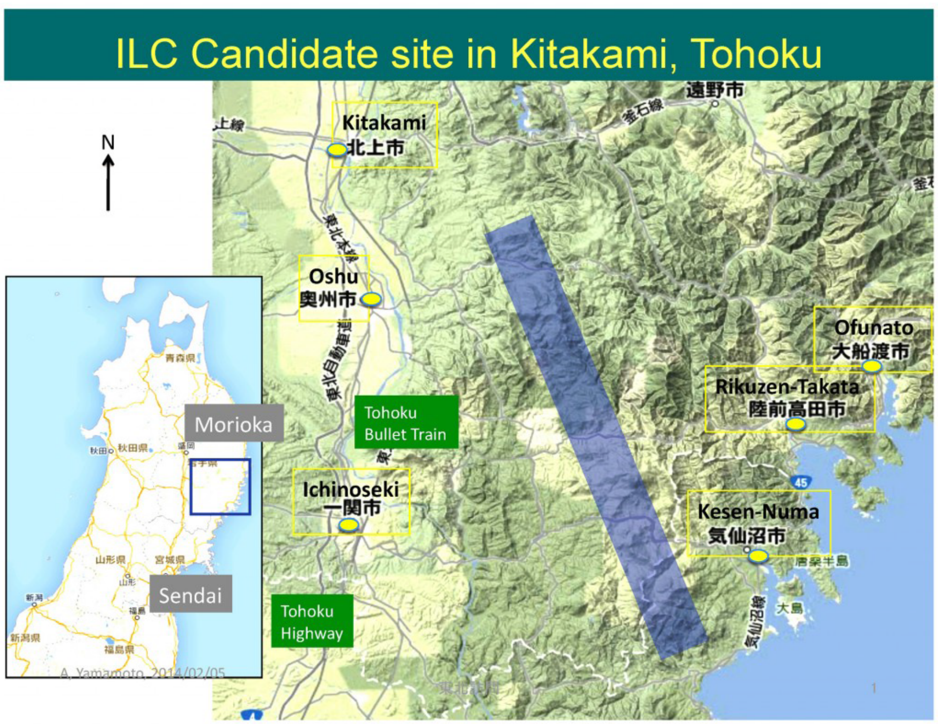
$$\mathcal{L} = \frac{P_b}{E_b}\left(\frac{N}{4\pi\sigma_x\sigma_y}\right)\mathcal{H}_D$$

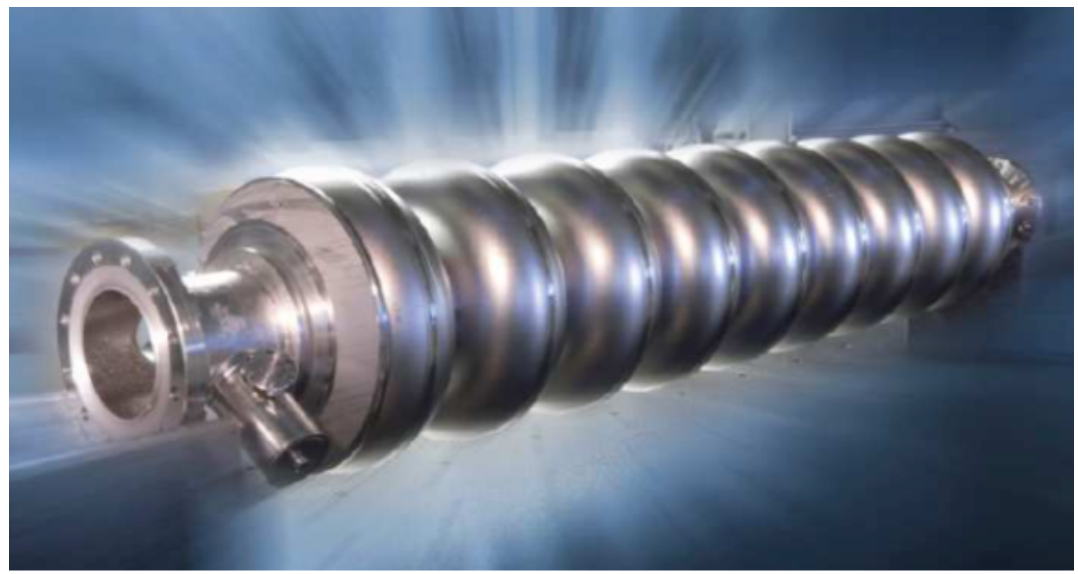
- The strong fields at the interaction point result in
  - A luminosity enhancement characterized by the disruption parameter $\mathcal{H}_D$
  - Beamstrahlung emission gives rise to energy spread and backgrounds at the interaction point

ILC in Japan

- Start with 250 GeV implementation
- Upgradeable to 1 TeV
- Government statement expected in 2018







Technology is ready
Costs well-understood

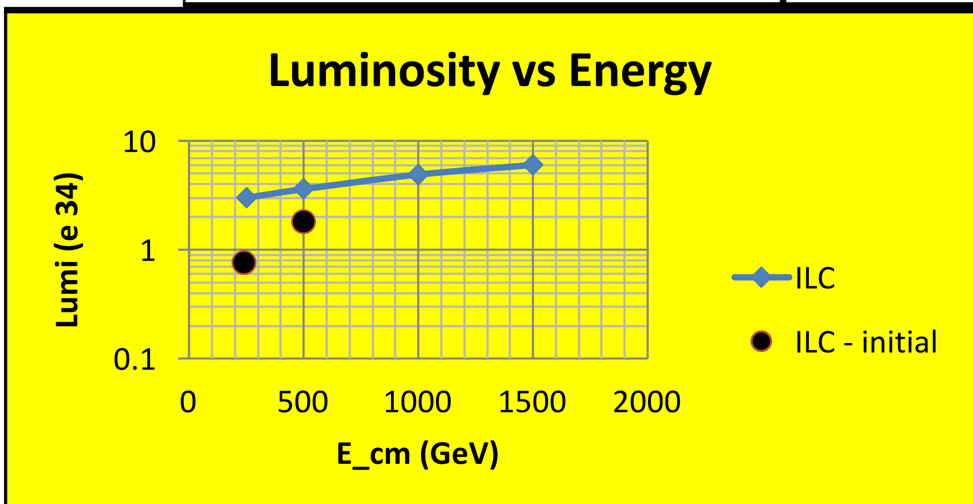
Luminosity

1 TeV	1 TeV Baseline		E_cm (GeV)
150% *2.4* 263 14.6	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 ->

E_cm (GeV) -->

A factor of 2.5 in L/P_{wall}



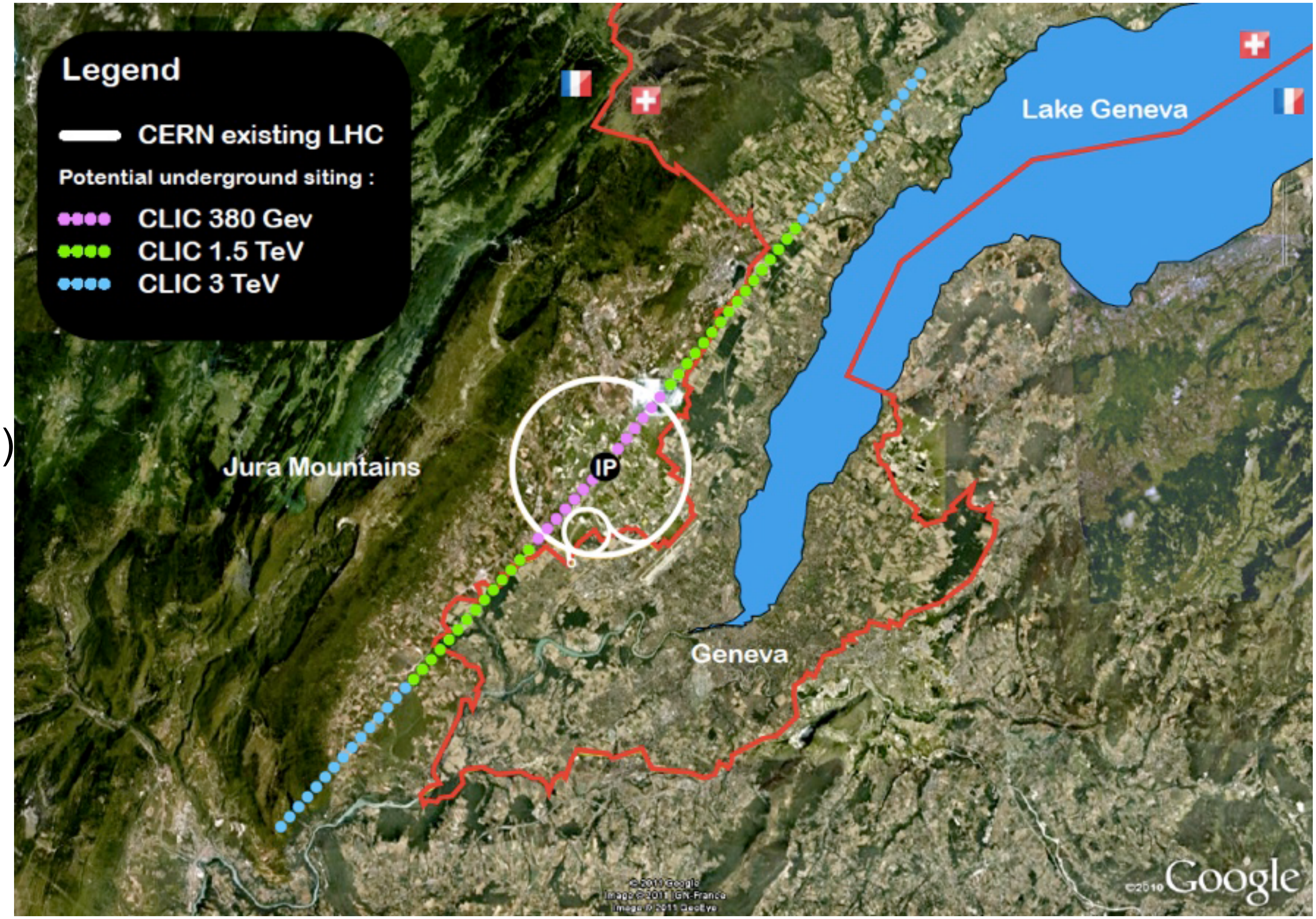
Legend	
Title	
Rel Cost	*L (e34)*
P_AC	P_2
(MW)	beam

M. Ross

CLIC

Updated Baseline Document (CERN-2016-004)

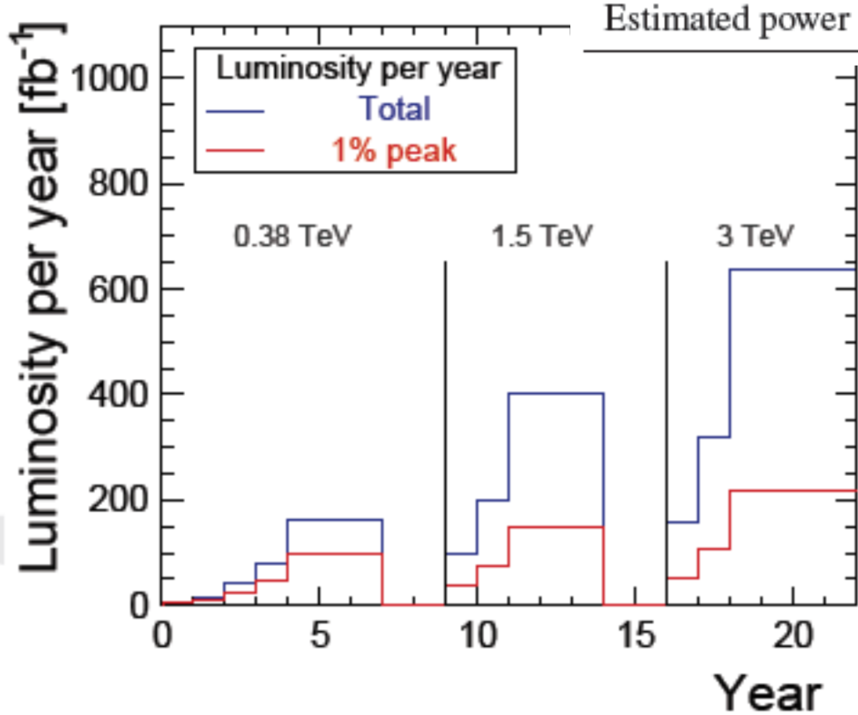
- 380 GeV
- 1.5 TeV
- 3 TeV



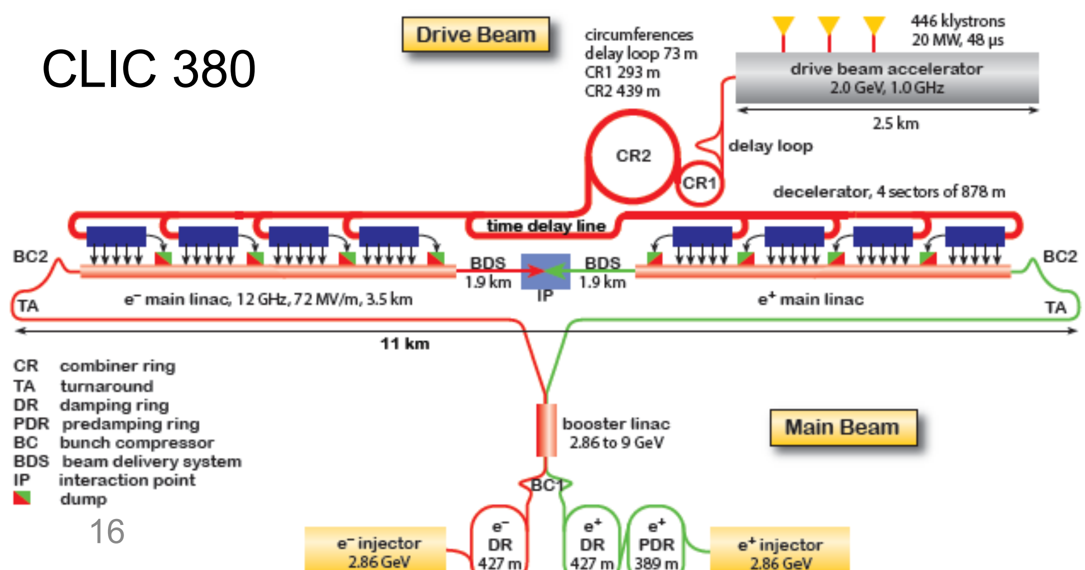
CLIC Stages

- Successful CTF3 demonstrator program recently completed
- Technology is ready for full demonstrator
- Costs and staging plan well-understood

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	0.9	1.4	2
Main tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	μm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	920/20	660/20	660/20
Normalised emittance (at IP)	$\varepsilon_x/\varepsilon_y$	nm	950/30	—	—
Estimated power consumption	P_{wall}	MW	252	364	589



CLIC 380



Novel Longer-Term Concepts

Wakefield Acceleration Schemes

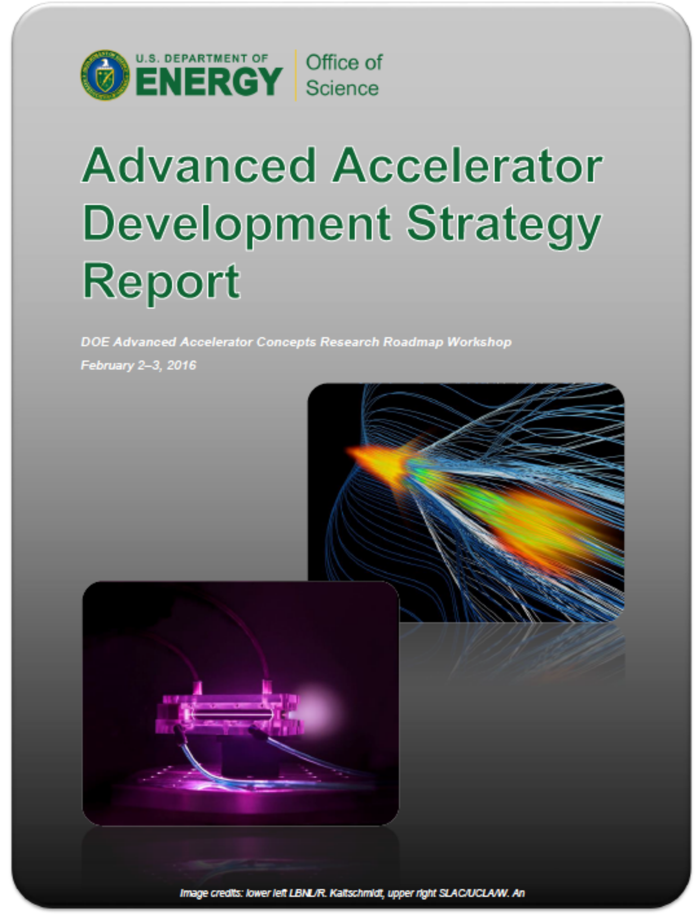
- Leverage the potential for accelerating gradients in the GV/m range
  - Beam-Driven Wakefield Accelerators (PWFA)
    - In US: FACET/FACET-II
  - Laser-driven Wakefield Accelerators (LWFA)
    - In US: BELLA (at 1 micron), early studies of 10 micron options planned for ATF/ATF-II
  - Dielectric Wakefield Acceleration (DWFA)
    - In US: AWA, ATF
  - Major research efforts are also underway in Europe and Asia
    - Some are: AWAKE (CERN), Eupraxia, FLASH_Forward (DESY), SPARC_Lab (INFN)

Advanced Accelerator Development Strategy Report

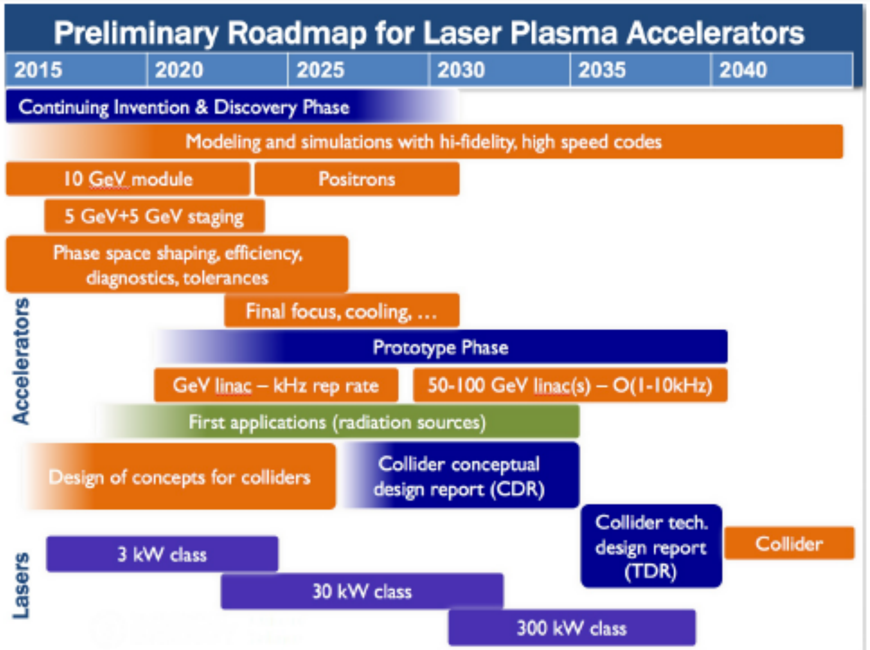
DOE Advanced Accelerator Concepts Research Roadmap Workshop, Feb 2-3, 2016

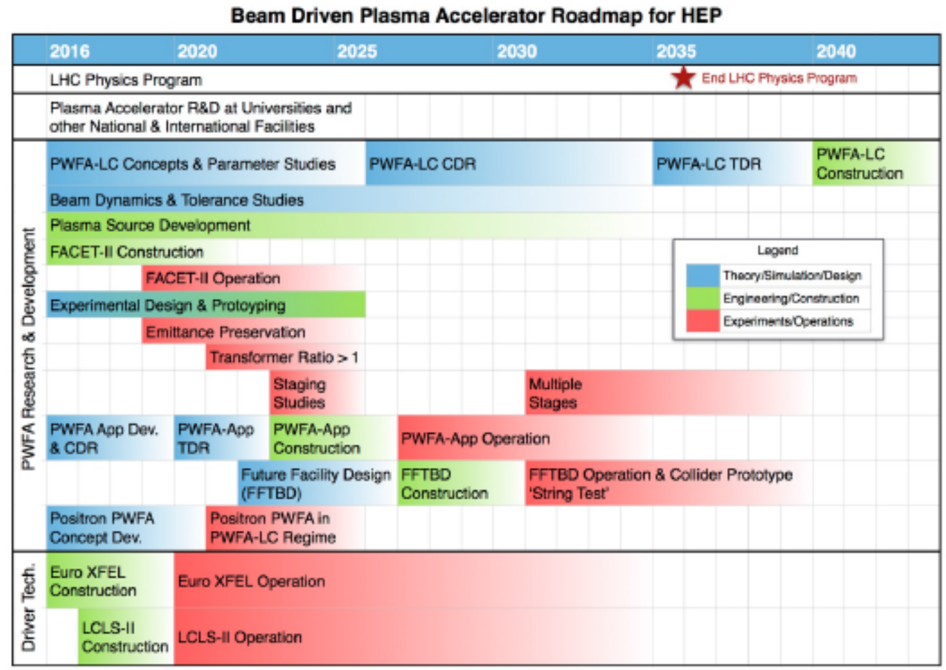
The next ten years of AAC research should focus on addressing common challenges identified during the workshop:

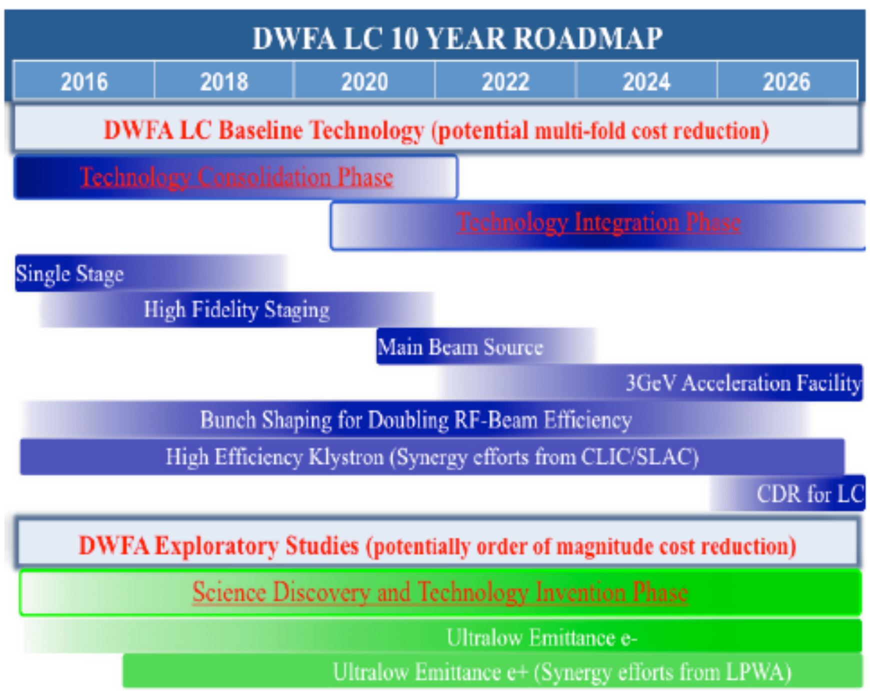
1. Higher energy staging of electron acceleration with independent drive beams, equal energy, and 90% beam capture;
2. Understanding mechanisms for emittance growth and developing methods for achieving emittances compatible with colliders;
3. Completion of a single electron acceleration stage at higher energy;
4. Demonstration and understanding of positron acceleration; and
5. Continuous, joint development of a comprehensive and realistic operational parameter set for a multi-TeV collider, to guide operating specifications for AAC.

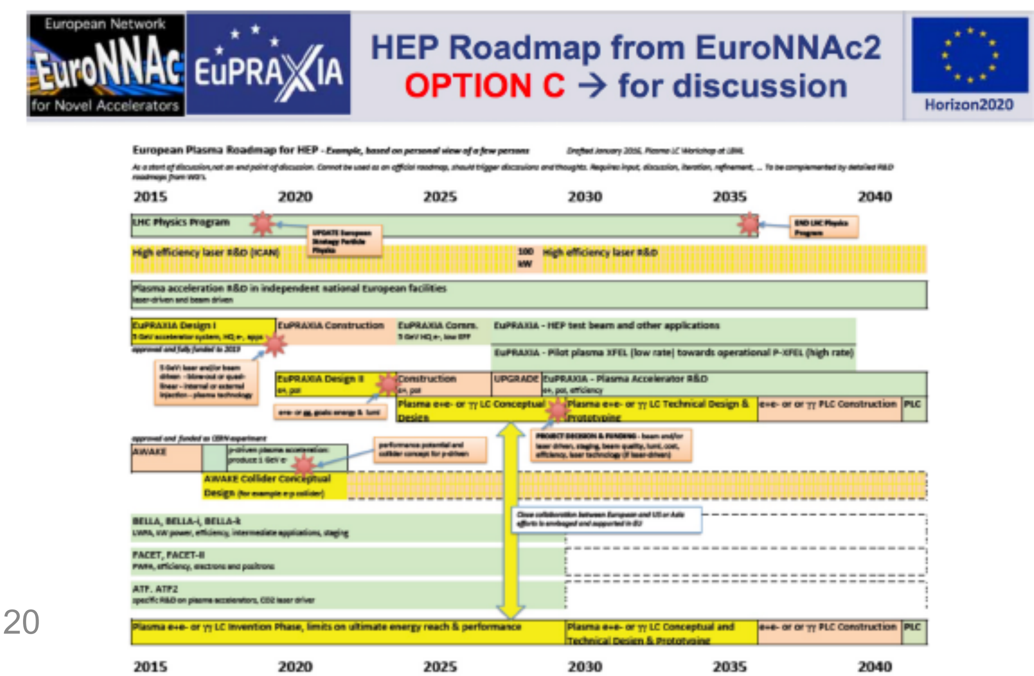


Development Roadmaps (US & EU)



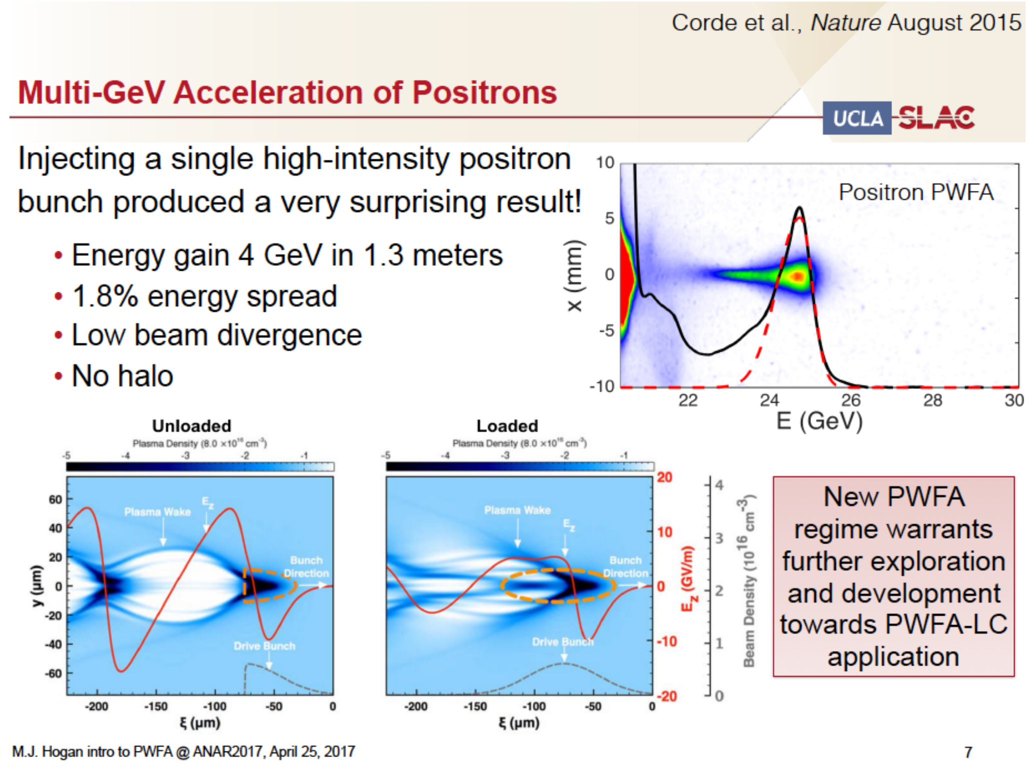


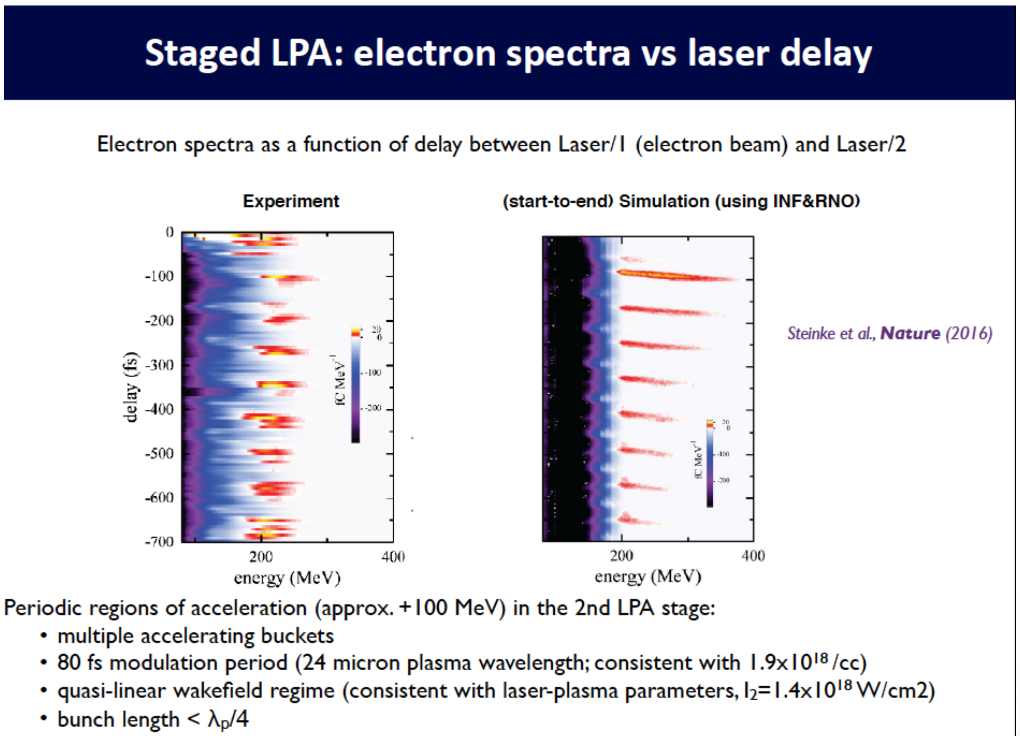




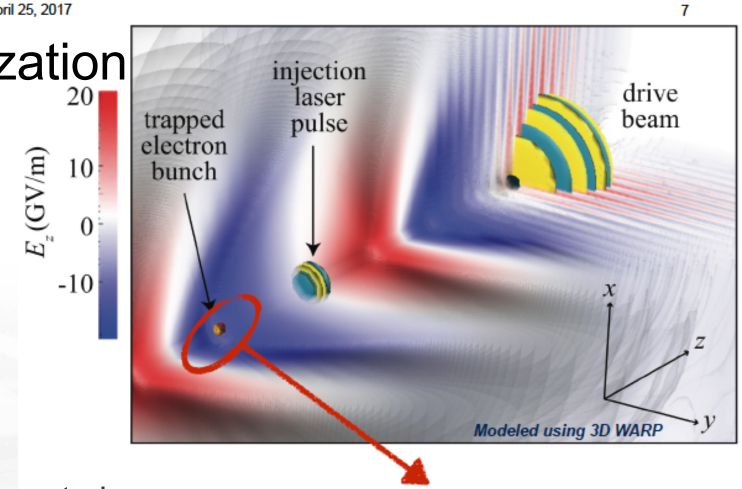
Some Recent Highlights

- Progress on positron acceleration
- Multi-stage acceleration
- Studies of injection schemes





2-color Ionization Injection



transverse phase space (in laser polarization plane): normalized emittance = 20 nm

C. Schroeder, et al, PRSTAB 2014 and SPIE 2014.

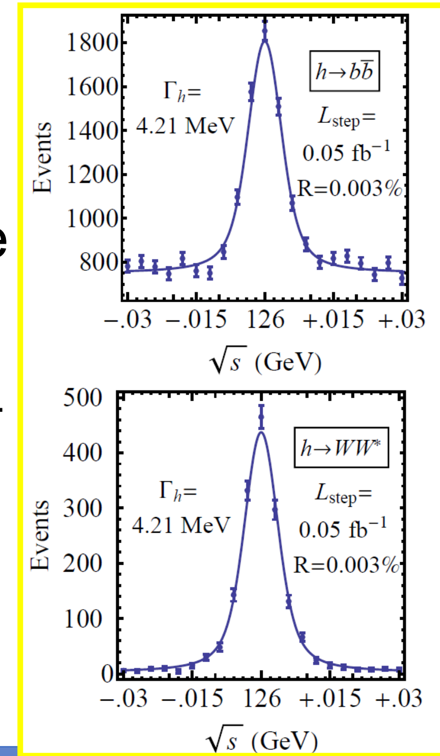
Some Comments

- Research remains focused on studying the physics and executing laboratory demonstrations of basic concepts (i.e., we're at low Technology Readiness Levels)
- In addition to the acceleration techniques research, will need to explore full capability issues to understand the constraints and reach for HEP applications:
  - Beam delivery system
  - Machine detector interface
  - Bunch pattern issues
  - Full systems engineering
  - Multi-system integration
  - Realistic performance with achievable engineering designs
  - Etc.

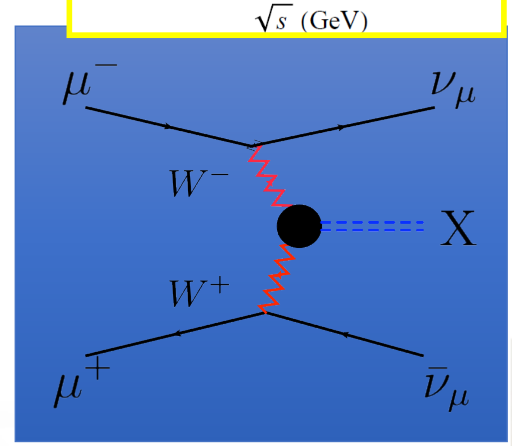
⇨ Much to do before we understand how to build an HEP machine!

Other options

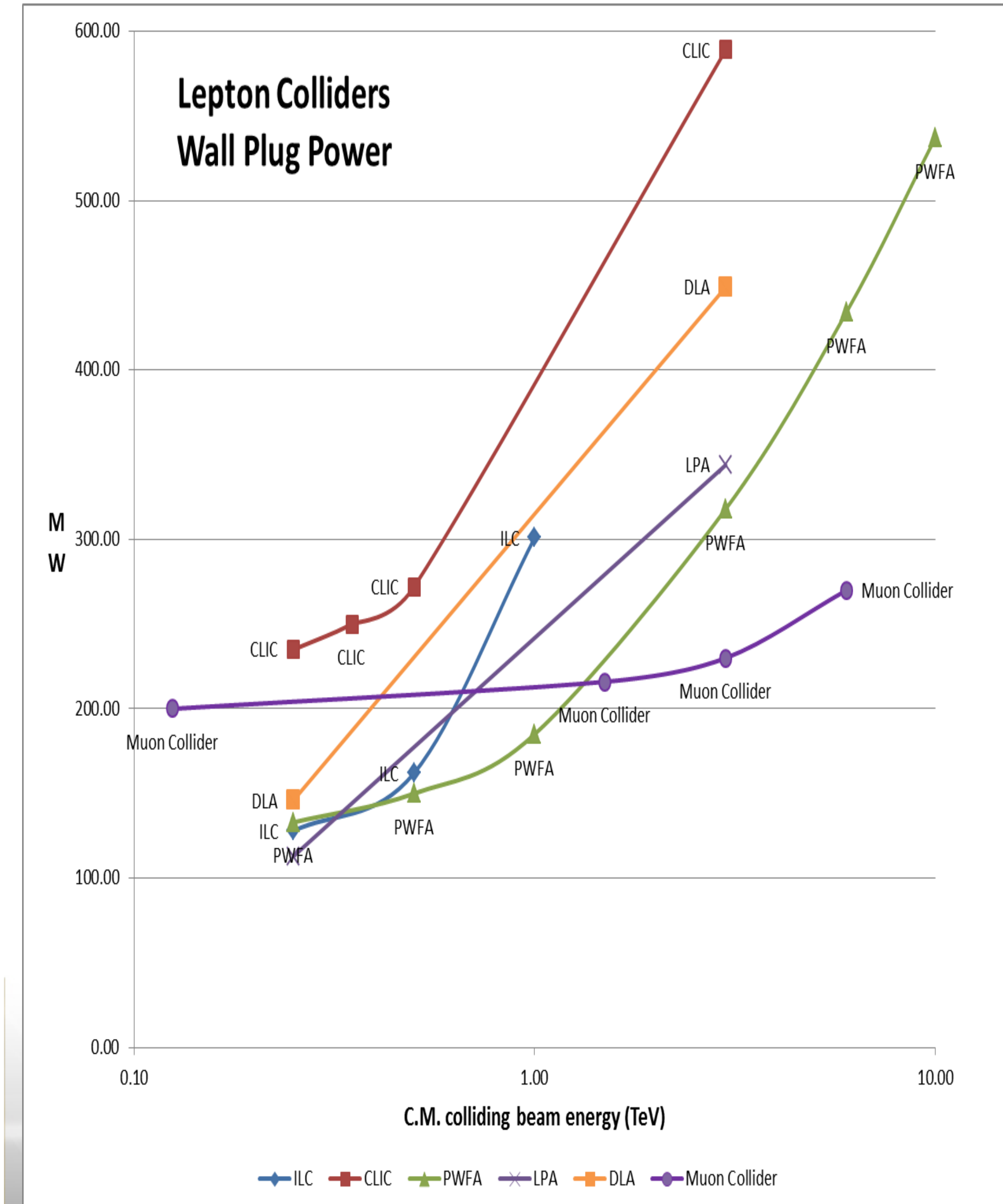
- While the US MAP program will complete its ramp-down this year, muon options offer an alternative path depending on the physics needs
  - European study will contribute to the 2018 European Strategy
- Recent design and R&D efforts continue to show promise
  - The International Muon Ionization Cooling Experiment at Rutherford Appleton Laboratory is currently characterizing the cooling effects of potential absorbers for muon cooling
  - Multiple solutions have now been identified for the challenge of RF in magnetic fields

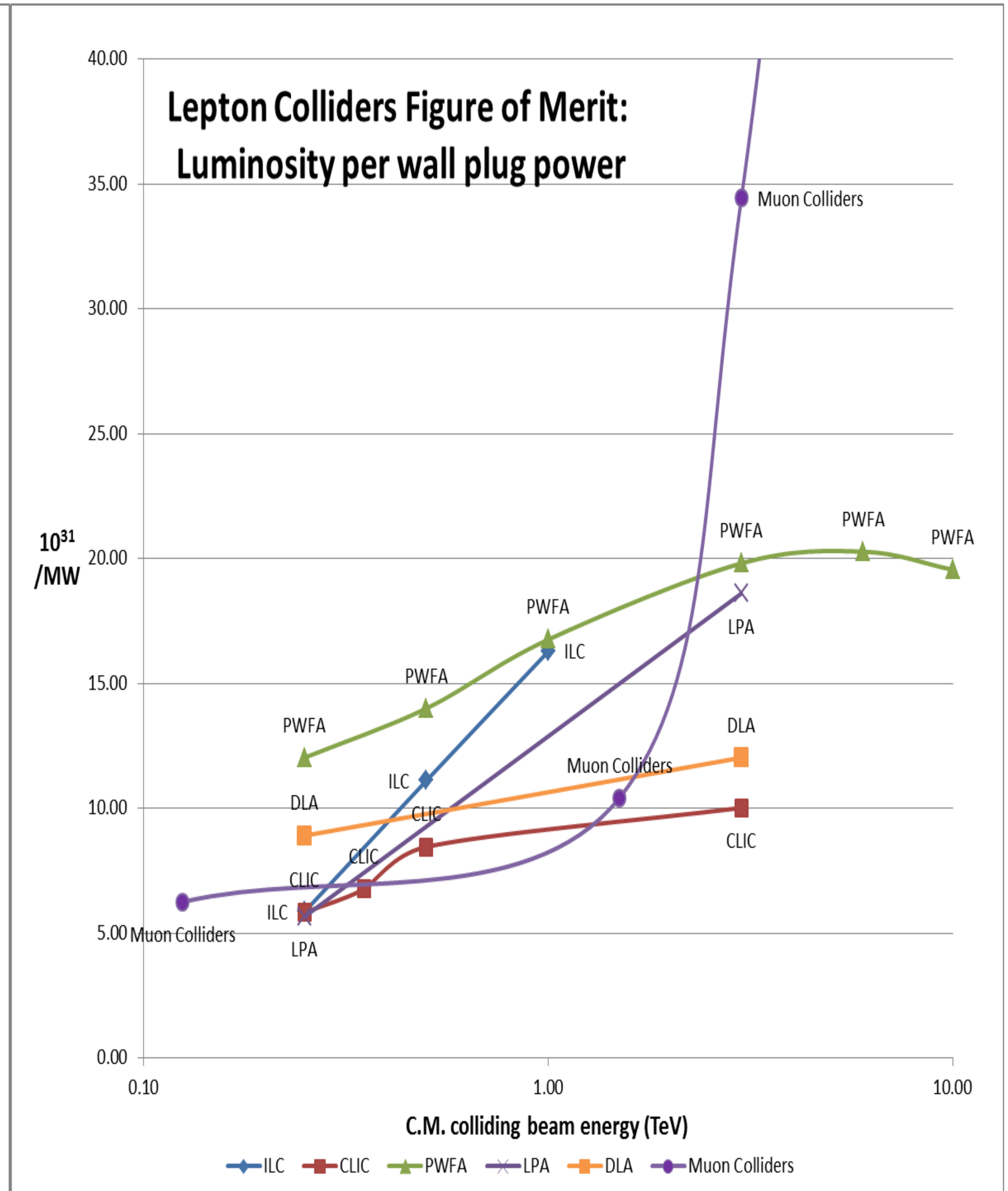


- A Muon Collider offers:
  - Superb Energy Resolution
    - SM Thresholds and s-channel Higgs Factory operation
  - Multi-TeV Capability (≤ 10TeV):
    - Compact & energy efficient machine (multi-pass RF)
    - Luminosity > 10^{34} cm^{-2} s^{-1}
    - Option for 2 detectors in the ring
  - For √s > 1 TeV: Fusion processes dominate
    ⇨ an Electroweak Boson Collider
    ⇨ a discovery machine complementary to a very high energy pp collider
    - At >5TeV: Higgs self-coupling resolutions of <10%



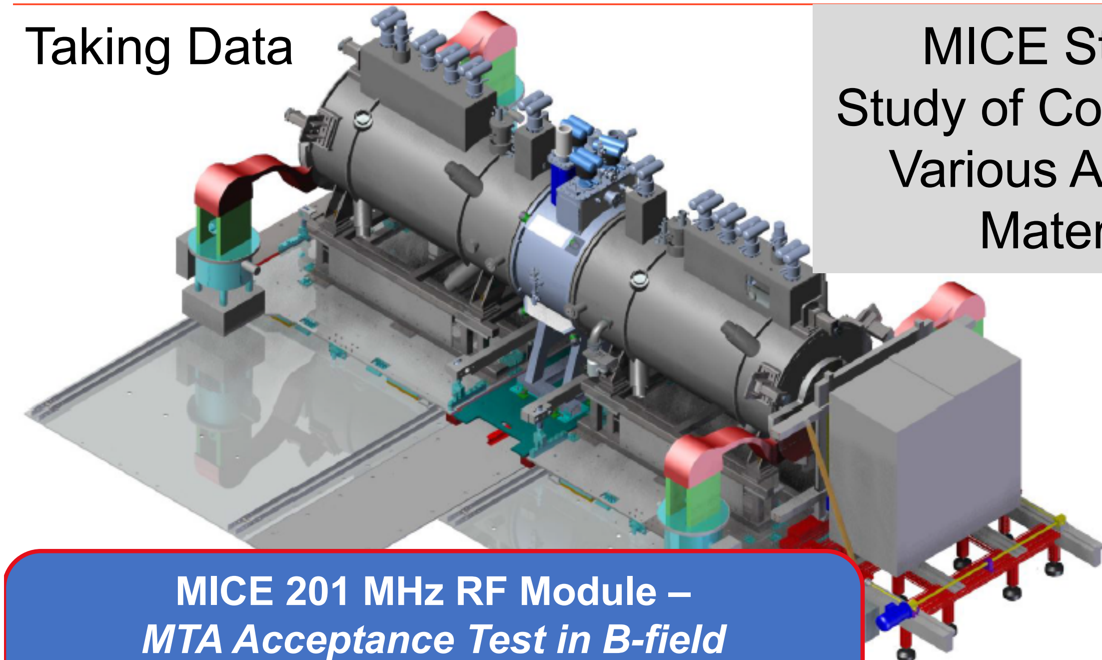
Muon Colliders extending high energy frontier with potential of considerable power savings



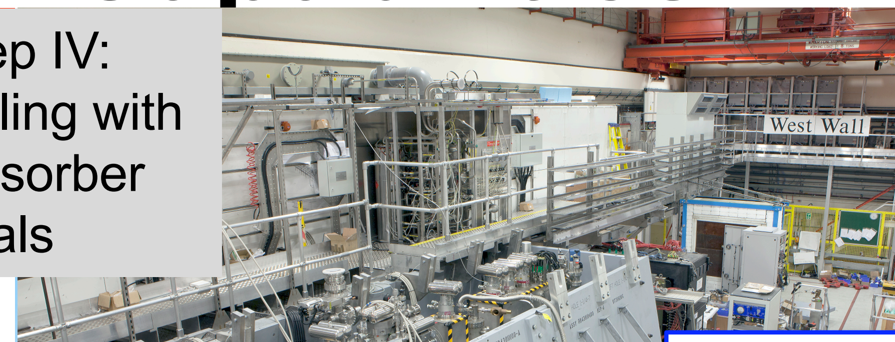


R&D Towards Muon Capabilities

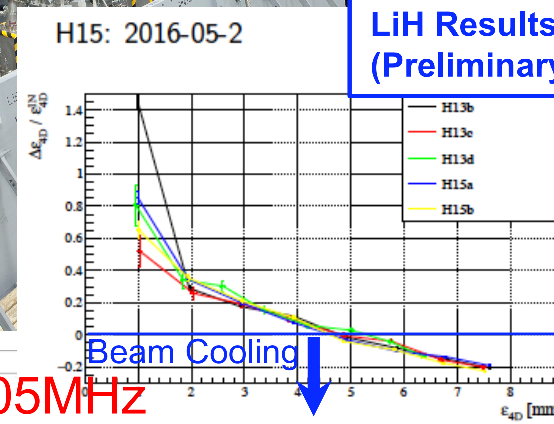
Taking Data



MICE Step IV:
Study of Cooling with
Various Absorber
Materials

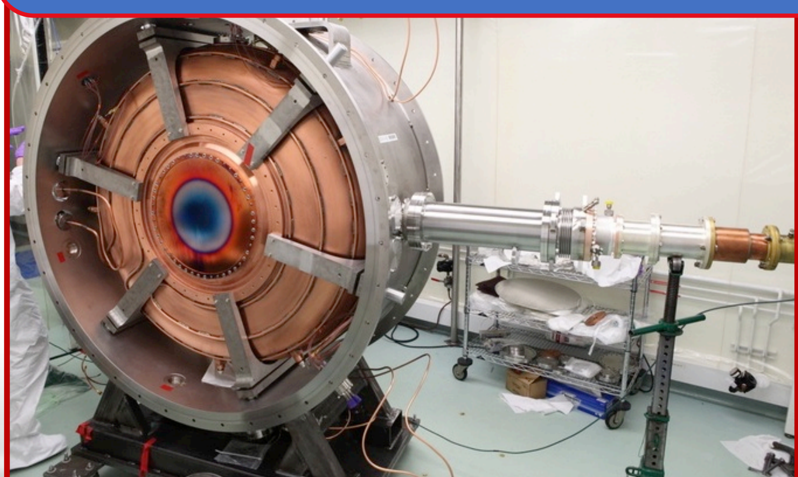


LiH Results (Preliminary)

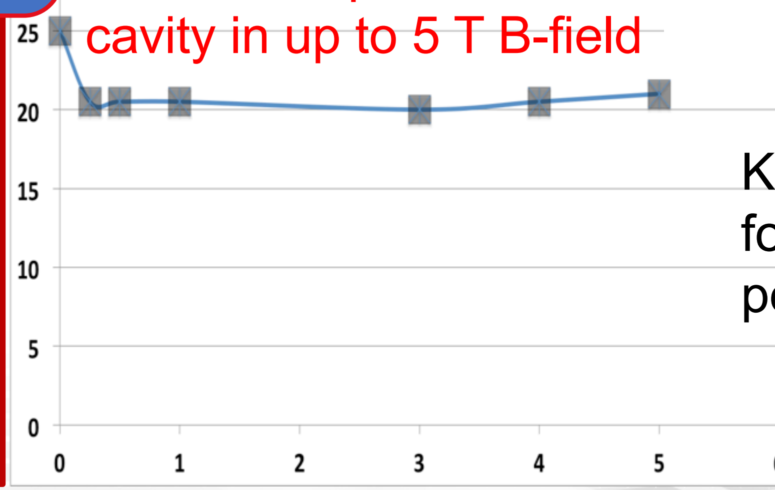


Emittance Change

MICE 201 MHz RF Module –
MTA Acceptance Test in B-field
11MV/m in Fringe of 5T Lab-G Solenoid
<4×10^{-7} Spark Rate (0 observed)



>20MV/m operation of 805MHz cavity in up to 5 T B-field



Key demonstrations for cooling channel performance in hand!

Accelerator Capabilities Summary and Conclusions

- Near-Term Collider Capabilities:
  - LHC is running
  - SuperKEKB is commissioning
  - HL-LHC project moving forward
- Mid-Term Capabilities
  - Looming decisions for an electron-positron option
  - Design reports and cost estimates are needed to clarify our hadron machine options
- Long-Term Capabilities
  - Challenges
    - Maintaining funding to conduct the R&D for our future options
    - Moving to TRLs compatible with knowing whether we can actually achieve our desired collider capabilities