Developments in Accelerators for Future High Energy Machines

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Brookhaven National Laboratory

DPF Meeting 2017 70 YEARS OF **DISCOVERY July 31 – August 4** dpf2017.fnal.gov Fermilab

APS PARTICLES & FIELDS

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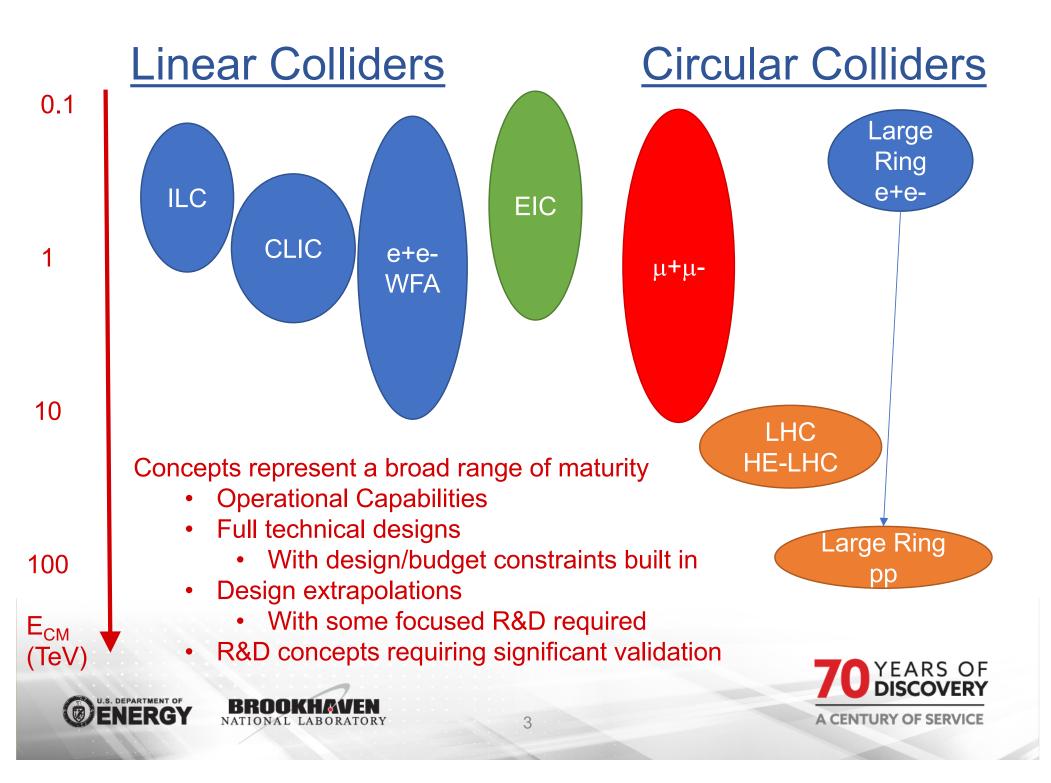
What are the possible paths forward for future high energy capabilities?

• Will focus on paths to next generation colliders









Hadron Capabilities

A Short Status Overview







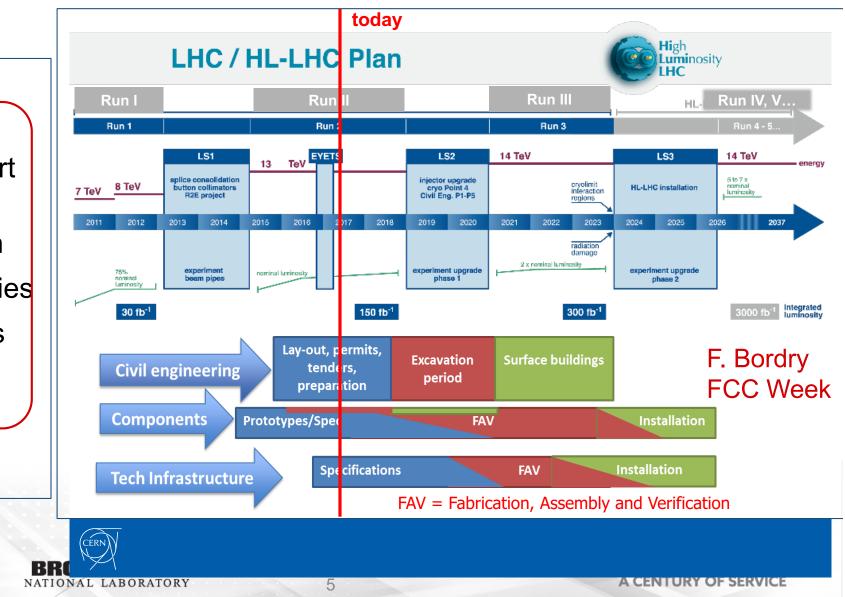
LHC ⇒ HL-LHC Program

Upgrades:

- IR Quads
- Nb₃Sn short dipoles
- Collimation
- Crab Cavities
- Cryogenics
- Machine Protection
- Detectors

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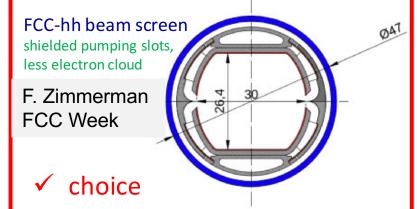
Options for Next Generation pp Machines

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]	1	00	27	27
straight section length [m]	1	400	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	3.4	1.3	(0.7) 0.36
beta* [m]	1.1	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 SF	PC option as foll	ow-on to CEPC

Key Issues

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







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JUNE 2016



- 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

- 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	l
Issues	

Comments

- SR energy:
- $\Delta E[GeV] = 8.85 \times 10^{-5} \frac{E^4 [GeV^4]}{\rho [m]}$ • RF Efficiency
- Beam Lifetime (~10³ sec) and Top-Up Injection
- Collective Effects
- Energy Bandwidth







FCC-ee in 2017 K. Oide – FCC Week

Design			201	17		
Circumference	[km]		97.7	750		
Arc quadrupole scheme			twin ap	oerture		Jura Jura
Bend. rad. of arc dipoles	[km]		10.7	747		
Number of IPs / ring			2	1		
Crossing angle at IP	[mrad]		30	C		
Solenoid field at IP	[T]		±	2		
ℓ^*	[m]		2.	2		
Local chrom. correction			y-plane with cr	ab-sext. effect		
RF frequency	[MHz]		40	0		Schematic of an 80 - 100 km
Total SR power	[MW]		10	0		
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	Arav
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		$60^{\circ}/60^{\circ}$		90°/90°		Mandalaz Copyright
Mom. compaction α_p	$[10^{-6}]$	14.79		7.31		Copyright
β -tron tunes ν_x / ν_y		269.14 /267.22		389.08 / 389.18	3	
Arc sext. families		208		292		► Base
Horizontal emittance ε_x	[nm]	0.267	0.28	0.63	1.34	$\mathbf{F}_{\mathbf{S}}^{\mathbf{S}} = (0.5)$
$\varepsilon_y/\varepsilon_x$ 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	<u> </u>
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)	≥ 1035
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	Ĕ
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	24
RF bucket height	[%]	3.8	3.7	2.2	10.3	10 ³⁴ 10 ²
Luminosity/IP	$[10^{34}/cm^2s]$	137	16.4(30.0)	4.6 (8.0)	1.35(2.09)	E _{beam} (GeV)

design challenges

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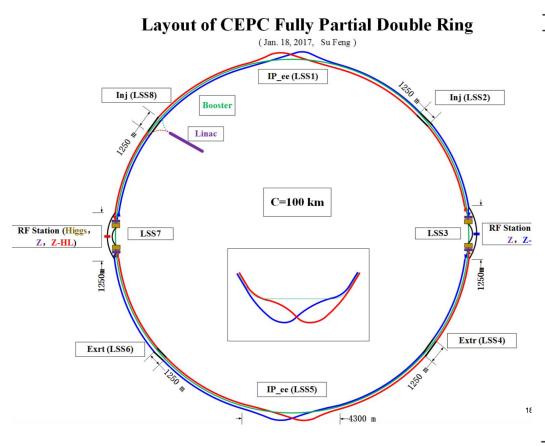
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CEPC – 100km baseline



	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 👁	0	3.19	5.69	4.29
N _s /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*)	3.4	1.14	1.14	4.49
$\beta_{\Pi' x' y}(\mathbf{m})$	0.8/0.0012	0.171/0.002	0.171 /0.002	0.16/0.002
Emittance 1/y (nm)	6.12/0.018	1.31/0.004	0.57/0.0017	1.48/0.0078
Transverse on (um)	69.97/0.15	15.0/0.089	9.9/0.059	15.4/0.125
ζ,/ζ,/IP	0.118/0.083	0.013/0.083	0.0055/0.062	0.008/0.054
$V_{\rm RF}$ (GV)	6.87	2.1	0.41	0.14
f _{RF} (MHz)	650	650	650	650
Nature oz /Total oz (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 _y	0.23	0.26	0.15	0.12
Life time due to beamstrahlung_cal	47	52		
(minute) L _{mav} /IP (10 ³⁴ cm ⁻² s ⁻¹)	2.04	2.0	6.16	11.0
Lunion (In cm 2)	2.04	2.0	5.15	11.9

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

Robust design and component R&D program underway

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

Linear Colliders

- $\mathcal{L} = \frac{N^2 f_{coll}}{4\pi\sigma_x \sigma_y} \mathcal{H}_D$ $\mathcal{L} = \frac{P_b}{E_b} \left(\frac{N}{4\pi\sigma_x \sigma_y} \right) \mathcal{H}_D$
- The strong fields at the interaction point result in
 - A luminosity enhancement characterized by the disruption parameter $\mathcal{H}_{\scriptscriptstyle D}$
 - Beamstrahlung emission gives rise to energy spread and backgrounds at the interaction point



Luminosity



ILC in Japan

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



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Main Linac

Technology is ready Costs well-understood

Damping Rings

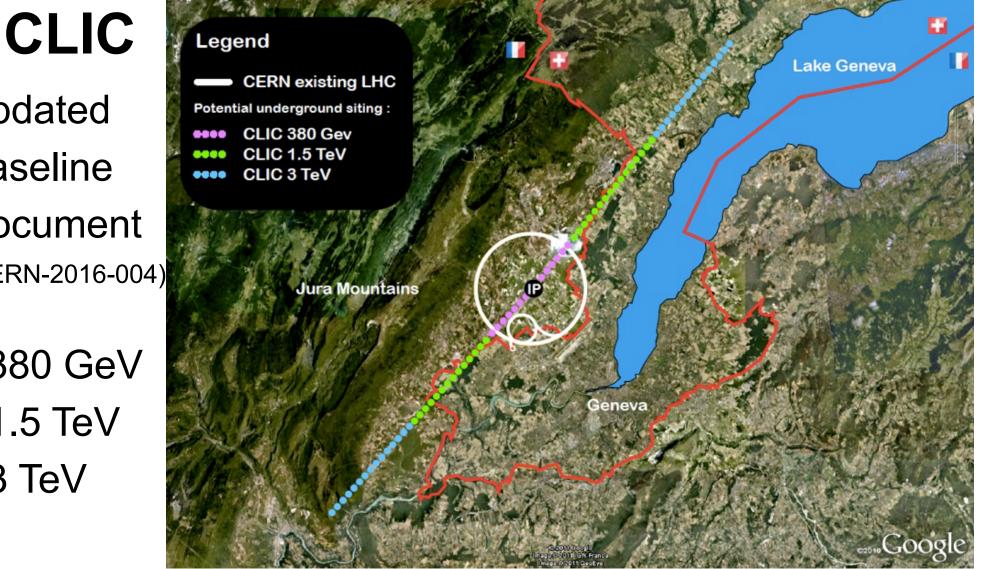




Lumi (e 34)

Luminosity

1								
	1 T	eV	1 TeV Ba	seline				
	150%	2.4	166%	4.9			1000	
	263	14.6	298	27.3				_
	Base	line	High	L				
	100%	1.8	106%	3.6			500	
	163	10.5	204	21.0				
	LH	IF	LHF hi	gh L	LHF High	L/High P		E_cm (GeV)
	69%	0.75	74%	1.5	106%	3	250	.
	129	9.4	161	11.8	204	21		_ ш'
	13:	12	2625 / (24	150 4Hz)	2625	10 Hz	A fact	
	Number of	f bunches a	and repetitio	on rate ->			2.5 in	L/P _{wall}
	Lumino	sity vs Ene	rgv			Leg	end	
10 -			01			Ti	tle	
						Rel Cost	L (e34)	
1 -	•		→ -ILC			P_AC	P_2	
0.1 -			• ILC - initi	al • • •	• • • • •	(MW)	beam	· • • •
) 500 100 -		00			M. Ros		RS OF
	E_cm ((GeV)					A CENTURY OF	
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Updated **Baseline** Document (CERN-2016-004)

- 380 GeV
- 1.5 TeV
- 3 TeV



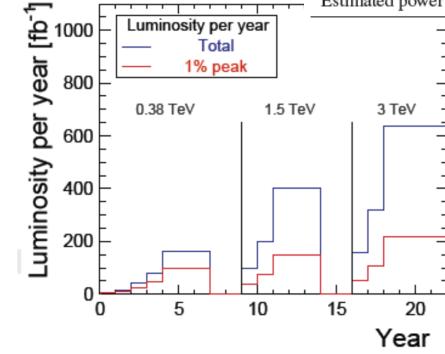


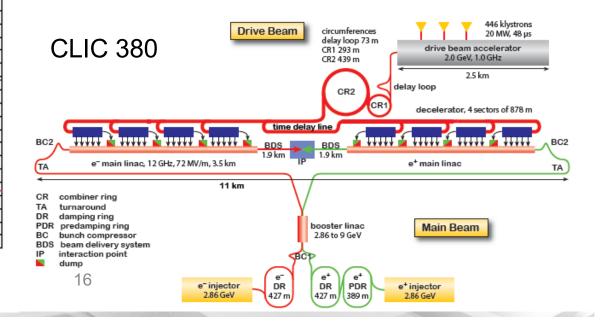


CLIC Stages

- 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	$f_{\rm rep}$	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	$ au_{ m RF}$	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	L	$10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$	1.5	3.7	5.9
Luminosity above 99% of \sqrt{s}	$\mathscr{L}_{0.01}$	$10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$	0.9	1.4	2
Main tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	Ν	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





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.

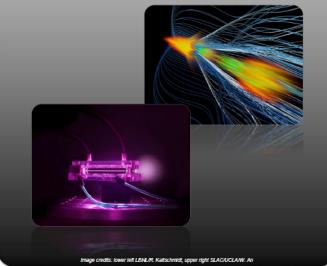
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Advanced Accelerator Development Strategy Report

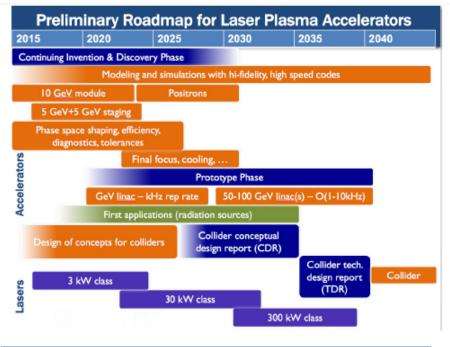
DOE Advanced Accelerator Concepts Research Roadmap Workshop February 2–3, 2016





Development Roadmaps (US & EU)

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	DW	FA LC 10	YEAR ROA	ADMAP	
2016	2018	2020	2022	2024	2026
DWI	A LC Baselin	e Technology	(potential mu	lti-fold cost redu	iction)
Technol		tion Phase			
			Technology	Integration Ph	ase
Single Stage					
I	ligh Fidelity Sta	ging			
		Main I	Beam Source		
				3GeV Acc	eleration Facility
	Bunch Sha	ping for Doubli	ng RF-Beam Ef	ficiency	
	High Efficiency	y Klystron (Syn	ergy efforts from	n CLIC/SLAC)	
					CDR for L
DWFA	Exploratory 8	tudies (potent	ially order of n	nagnitude cost r	eduction)
	Science Di	scovery and T	echnology Inv		
			Ultralow Emi	ttance e-	
		Ultralow Er	nittance e+ (Sy	nergy efforts fron	n LPWA)

	2016	2020	2025		2030	2035	2040
	LHC Physics Pro	gram				★ End LHC Phy	rsics Program
	Plasma Accelera other National &						
	PWFA-LC Conce	epts & Parame	ter Studies P	WFA-LC CDR	1	PWFA-LC TDR	PWFA-LC Construction
	Beam Dynamics	& Tolerance S	tudies				
Ĕ	Plasma Source D	Development					
Development	FACET-II Constru	uction				Leg	end
	FA	CET-II Operati	on				mulation/Design
Š,	Experimental Design & Protoyping					-	ng/Construction
ŏ	En	nittance Preser	vation			Experimen	ts/Operations
ē		Transfor	rmer Ratio > 1				
Hesearch			Staging Studies		Multiple Stages		
PWFA	PWFA App Dev. & CDR	PWFA-App TDR	PWFA-App Construction	PWFA-App	Operation		
L			ure Facility Desig TBD)	n FFTBD Constructio		Operation & Collider Prototy est'	pe
	Positron PWFA Concept Dev.		PWFA in C Regime				
lech.	Euro XFEL Construction	Euro XFEL C	Operation				
Driver	LCLS-II Construction	LCLS-II Ope	ration				

Beam Driven Plasma Accelerator Roadmap for HEP



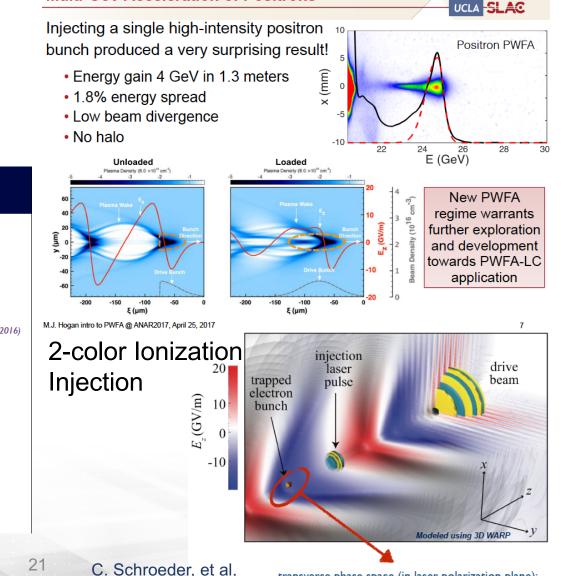
	2020	2025	2030	2035	2040
LHC Physics Pro	gram 🌞 uronit langar				END LIK: Physica Program
High efficiency l	aser #80 (ICAN) Popula	_	100 stigh efficiency laser #3 W	•	
Masma acceleration and beam	tion 880 in independent national t n triven	wropean facilities			
EuPRAXIA Desig		tion EuPRAXIA Comm. 3 GeV HD +. Ine EPP	EuPRAXIA - HEP test beam and ot	her applications	
opproval and July June			EUPRAXIA - Pilot plasma XFEL (low	rate towards operational P-XFI	IL (high rate)
5-DeV: loser er					
dites - blow	or external	Construction	UPGRADE EuPRAXIA - Plasma Acc e+, pp. effciency	elerator R&D	
injaction-plan	ins solvidage	Plasma eve- or TV U		LC Technical Design & leve- or o	or 17 PLC Construction
	ere or m. pols srarge h	Design	Prototyping		
approval and funded of AIWARE	protiven places accession	performance potential and collider concept for p-driven	PROJECT DECISION & FUNDERIE - Ix leaser driver, anging, been quelity, efficiency, leaser technology (If lease	uni.cost.	
	AWARE Collider Conceptual Design (or exemple op satisfer)				
BELLA, BELLA-İ, İ LWAA, KW power, eti	BELLA-k Idency, intermediate applications, staging		Cine collaboration between fumpear on glora la endesgen end apported in 82	I UT or Adle	
PACET, PACET-B PARA, efficiency, exe					

AC EUPRAXIA

Some Recent Highlights

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

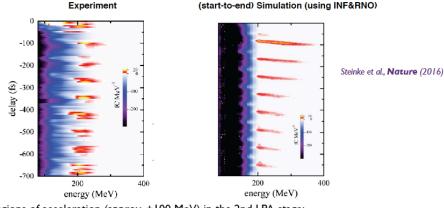
Multi-GeV Acceleration of Positrons



Corde et al., Nature August 2015

Staged LPA: electron spectra vs laser delay

Electron spectra as a function of delay between Laser/I (electron beam) and Laser/2



Periodic regions of acceleration (approx. +100 MeV) in the 2nd LPA stage:

- multiple accelerating buckets
- 80 fs modulation period (24 micron plasma wavelength; consistent with 1.9x10¹⁸/cc)
- quasi-linear wakefield regime (consistent with laser-plasma parameters, $l_2=1.4 \times 10^{18}$ W/cm2)
- bunch length $< \lambda_p/4$





transverse phase space (in laser polarization plane): PRSTAB 2014 and SPIE 2014, normalized emittance = 20 nm

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!





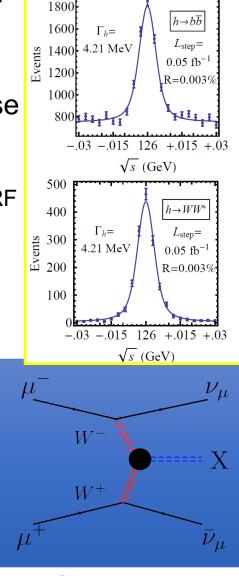


Other options

- 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 > 10³⁴ 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%



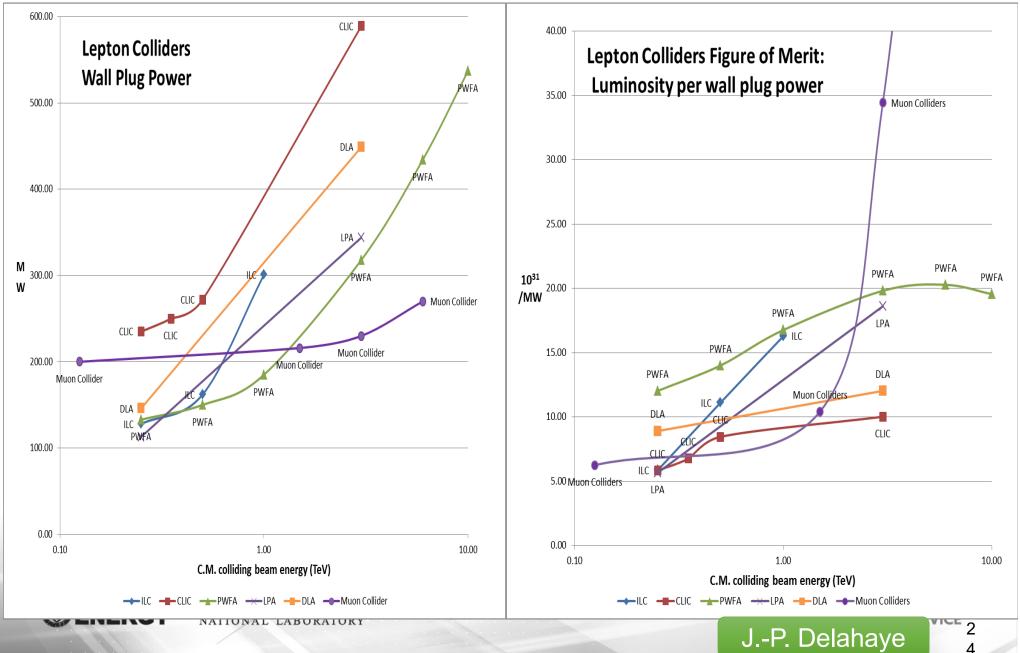




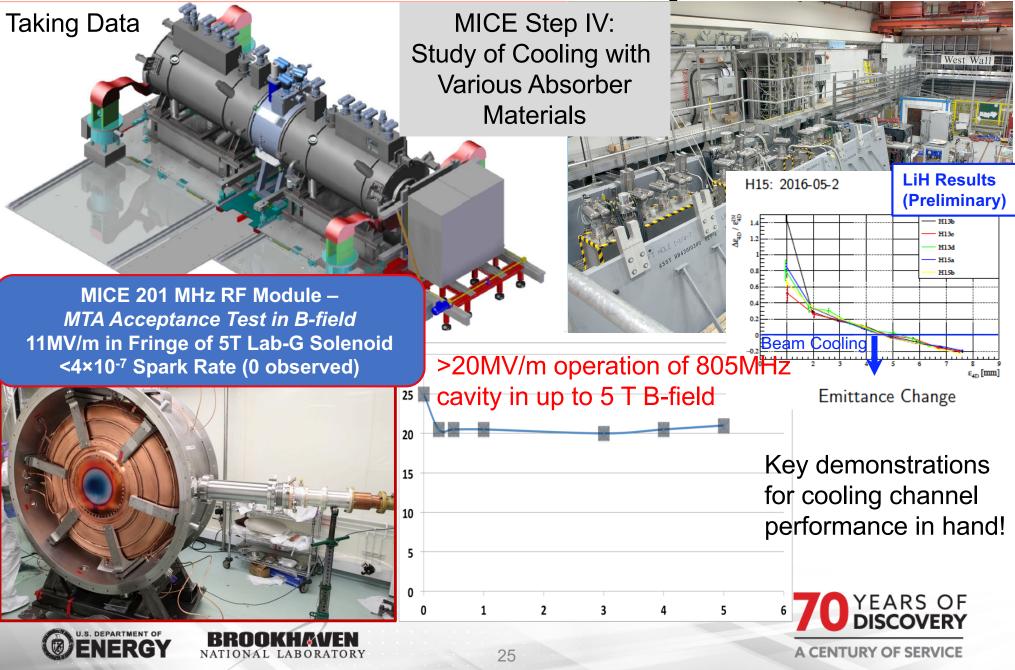
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Muon Colliders extending high energy frontier with potential of considerable power savings



R&D Towards Muon Capabilities



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





