Facilities for Beam Driven PWFA

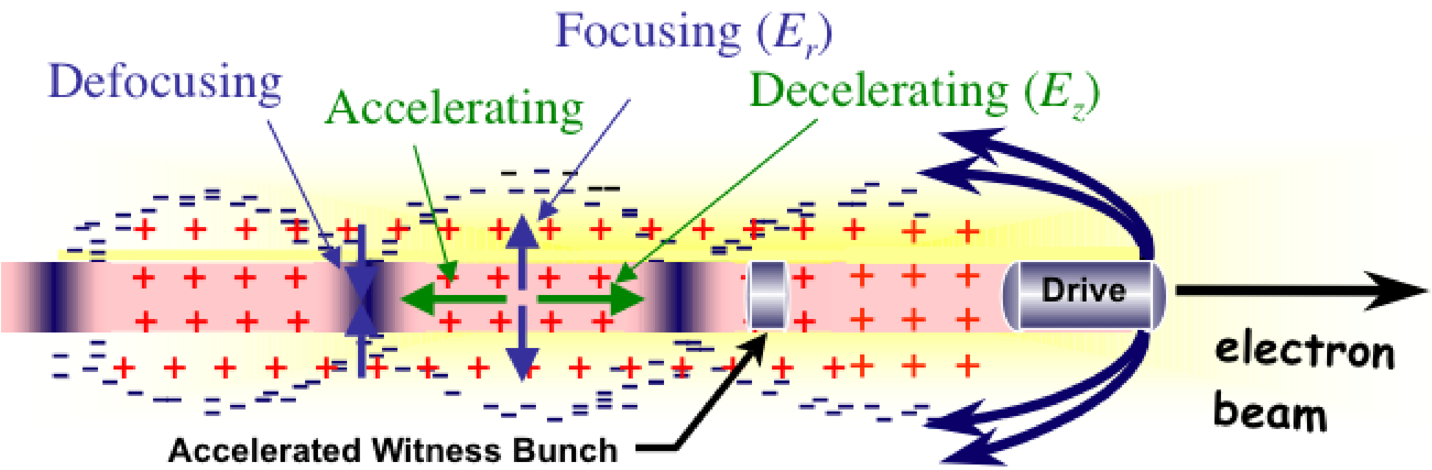
Snowmass Preparatory Workshop, U. of Chicago

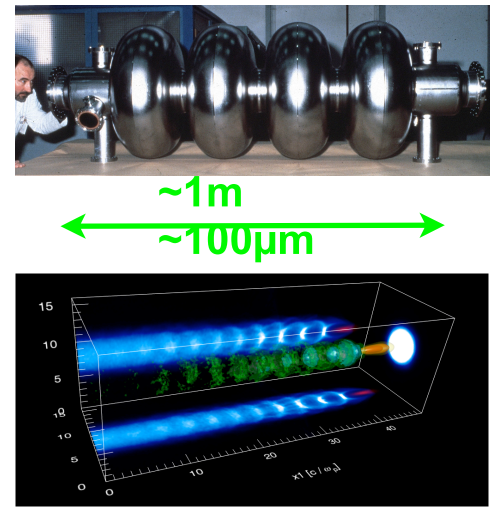
Mark Hogan February 25, 2013

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

The Beam Driven Plasma Wakefield Accelerator

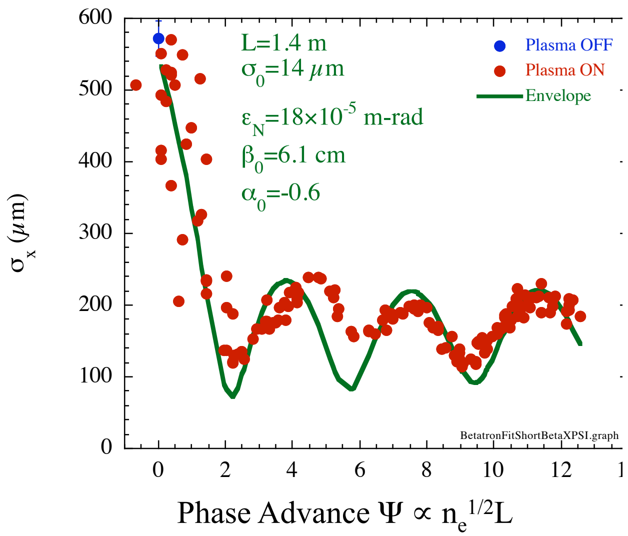




- Two-beam, co-linear, plasma-based accelerator
- Plasma wave/wake excited by relativistic particle bunch
- Deceleration, acceleration, focusing by plasma
- Accelerating field/gradient scales as ne1/2
- Typical: $n_e \approx 10^{17}$ cm^{-3}, $\lambda_p \approx 100$ µm, G>MT/m, E>10 GV/m
- High-gradient, high-efficiency energy transformer
- “Blow-out” regime when n_b/n_p >> 1

SLAC/UCLA/USC Experiments @ FFTB
Studied many aspects of beam-plasma interaction

Focusing & Matching e^-

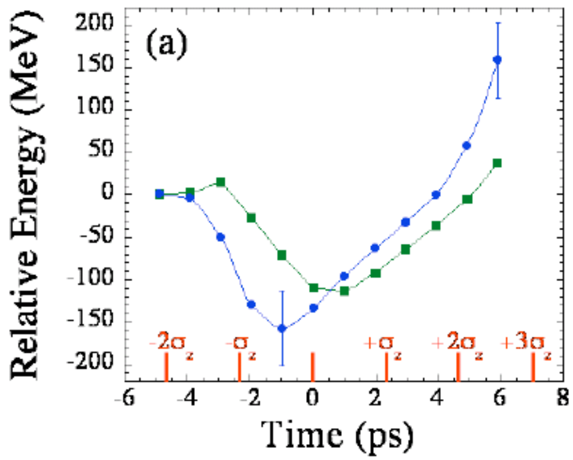


Phys. Rev. Lett. **93**, 014802 (2004)

X-ray Generation

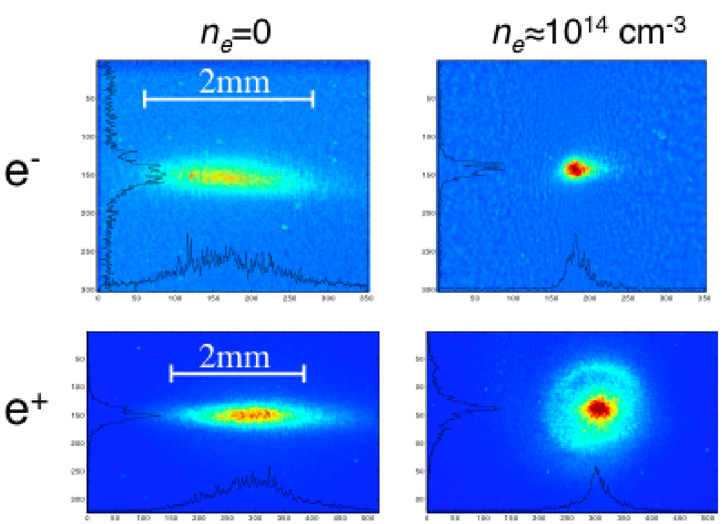
Phys. Rev. Lett. **88**, 135004 (2002)

Wakefield Acceleration e^-



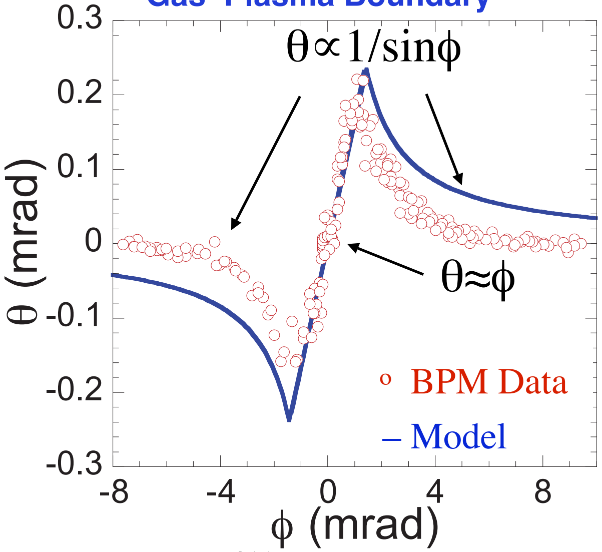
Phys. Rev. Lett. **93**, 014802 (2004)

Focusing & Halo Formation e^+



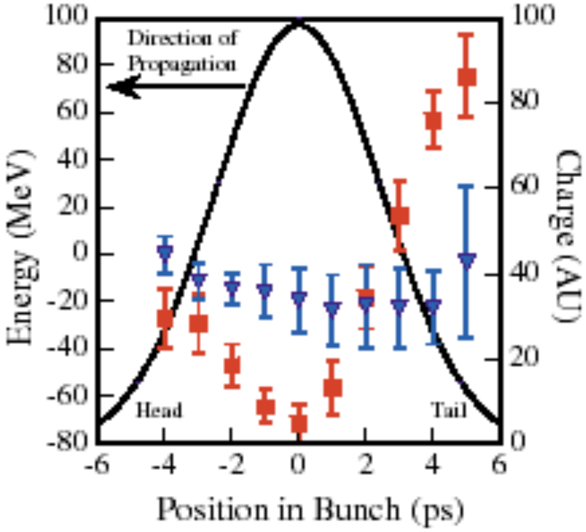
Phys. Rev. Lett. **101**, 055001 (2008)

Electron Beam Refraction at the Gas–Plasma Boundary



Nature **411**, 43 (3 May 2001)

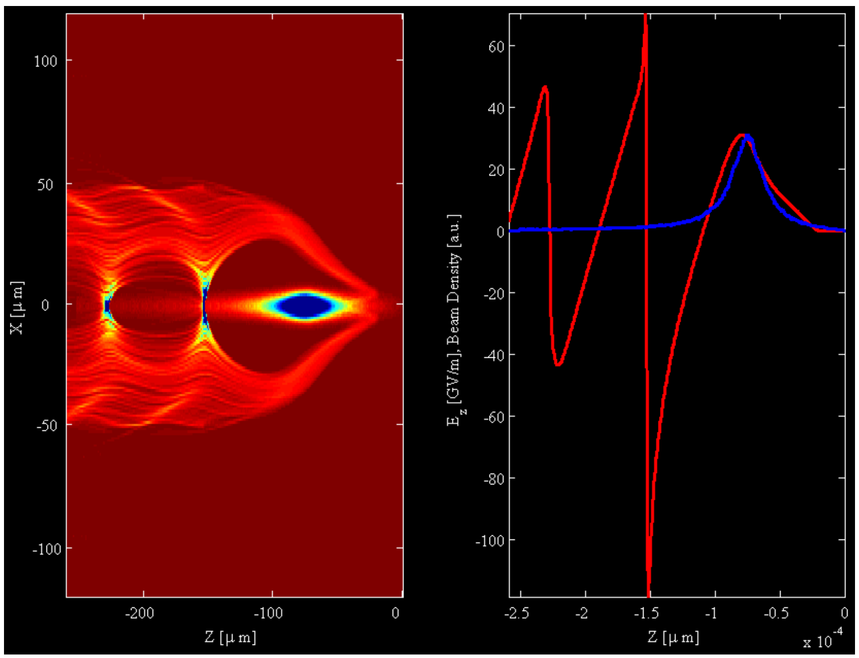
Wakefield Acceleration e^+

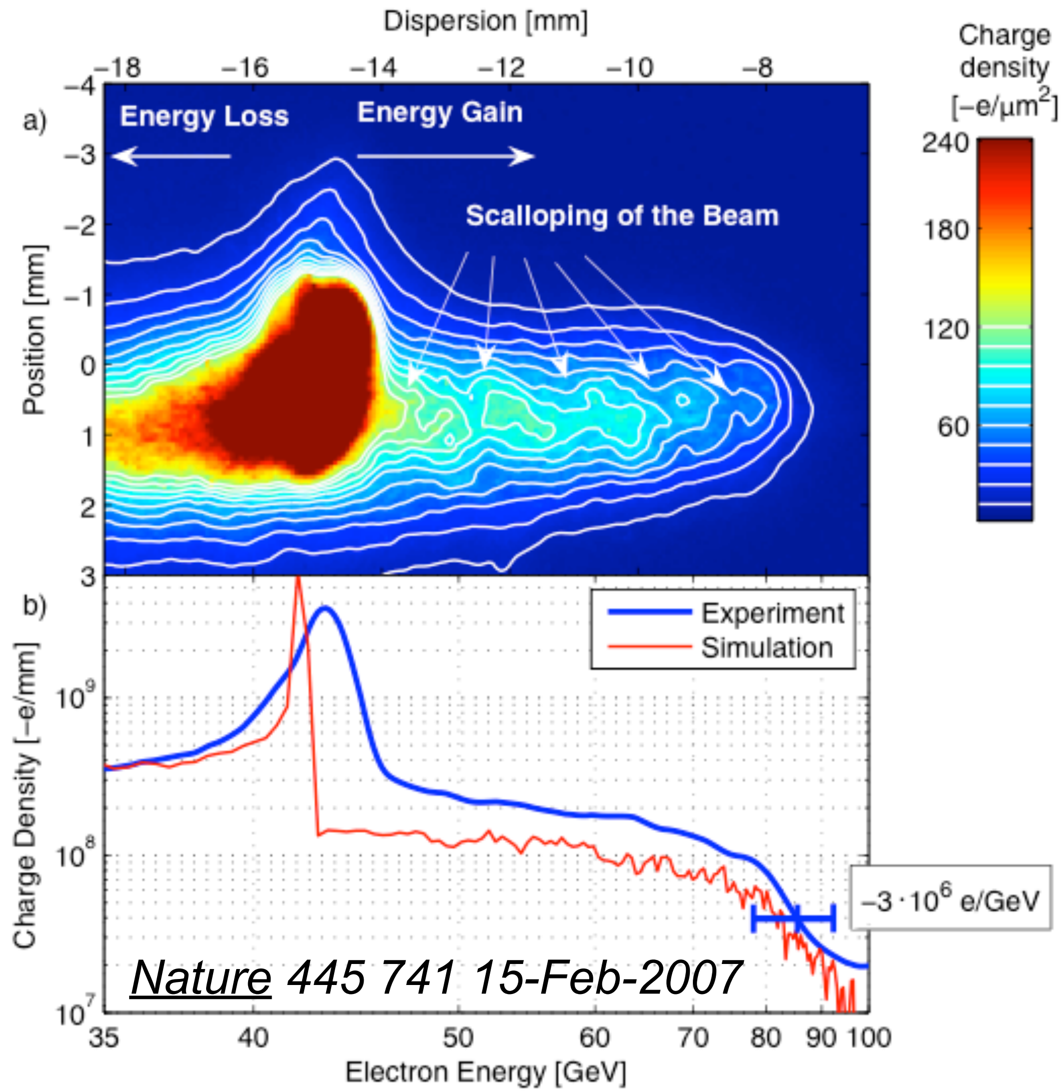


Phys. Rev. Lett. **90**, 214801 (2003)

SLAC Plasma Research Motivated by Access to the Energy Frontier and Compact XFELs

- Acceleration Gradients of ~50GeV/m (3,000 x SLAC)
  - Doubled energy of 45 GeV electrons in 1 meter plasma
- Single Bunch





SLAC NATIONAL ACCELERATOR LABORATORY UCLA USC

Next Step: Particle acceleration to beam acceleration @ FACET

MULTIBUNCH PWFA

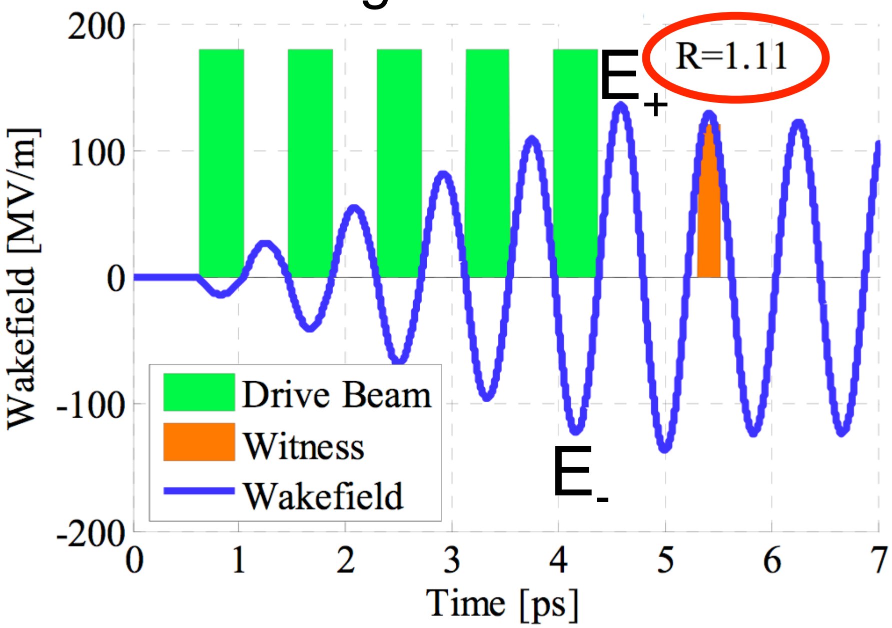
Transformer Ratio: $R = E_+ / E_-$ Energy Gain: $\leq RE_0$

σ_r=125 μm, n_e=1.8x10^{16} cm^{-3}, λ_p=250 μm

E_0: incoming energy

Q=30 pC/bunch, Δz=250 μm≈λ_p

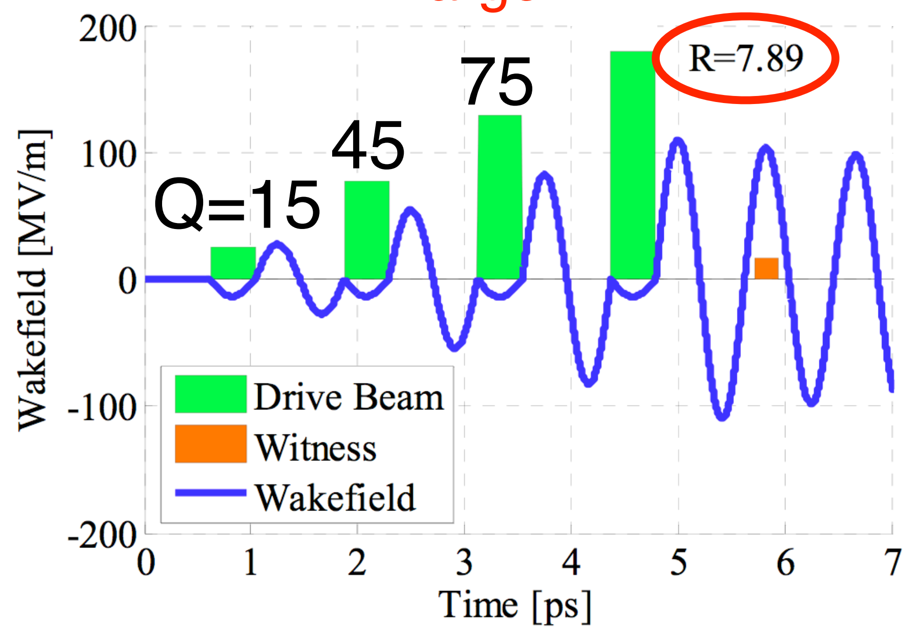
Bunch Train
Large wakefield



Kallos, PAC'07 Proceedings

Δz=375 μm≈1.5λ_p

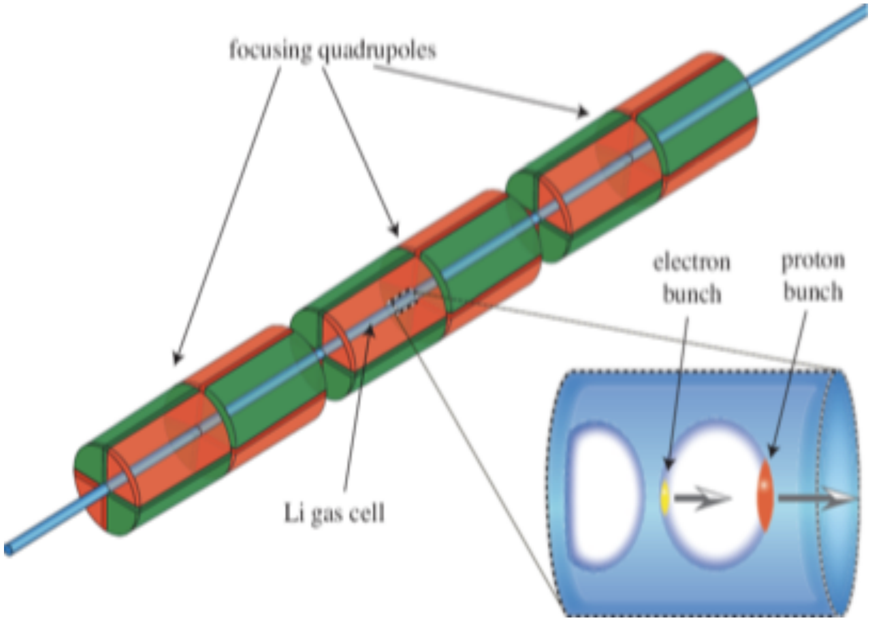
Ramped Bunch Train*
Large R

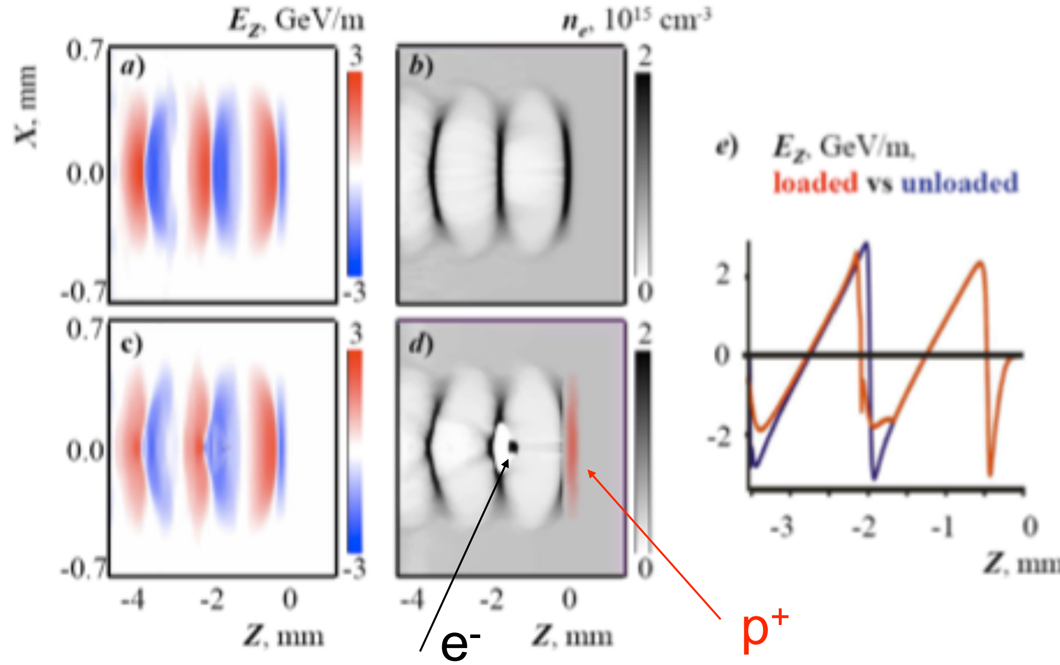


*Tsakanov, NIMA, 1999

- R=7.9 => multiply energy by ≈8 in a single PWFA stage!
- Large energy transfer efficiency

Proton-driven plasma wakefield acceleration (PDPWA)





Drive beam: p^+

$E=1$ TeV, $N_p=10^{11}$

$\sigma_z=100$ μm, $\sigma_r=0.43$ mm

$\sigma_\theta=0.03$ mrad, $\Delta E/E=10\%$

Witness beam: e^-

$E_0=10$ GeV, $N_e=1.5\times10^{10}$

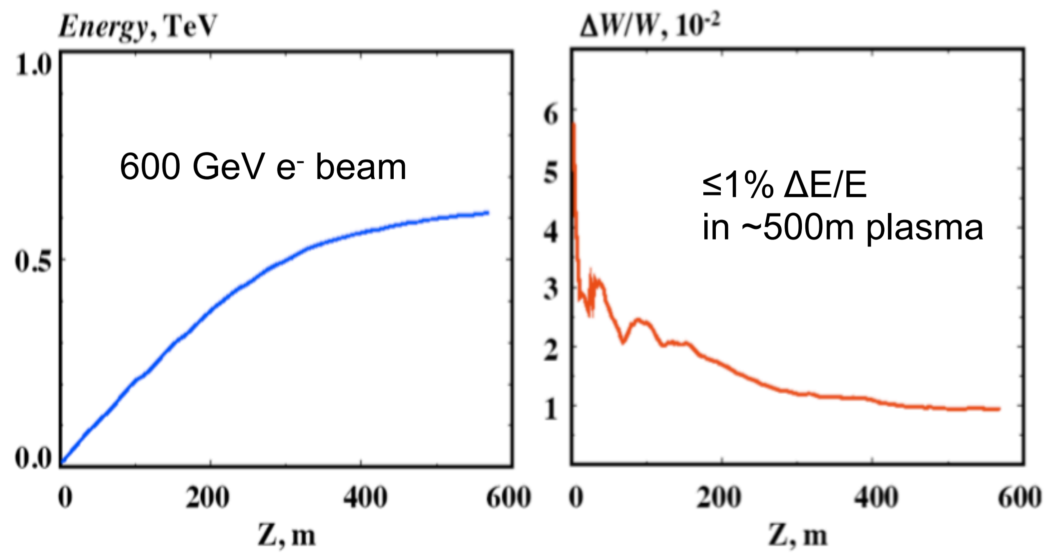
Plasma: Li^+

$n_p=6\times10^{14}$ cm^{-3}

External magnetic field:

Field gradient: 1000 T/m

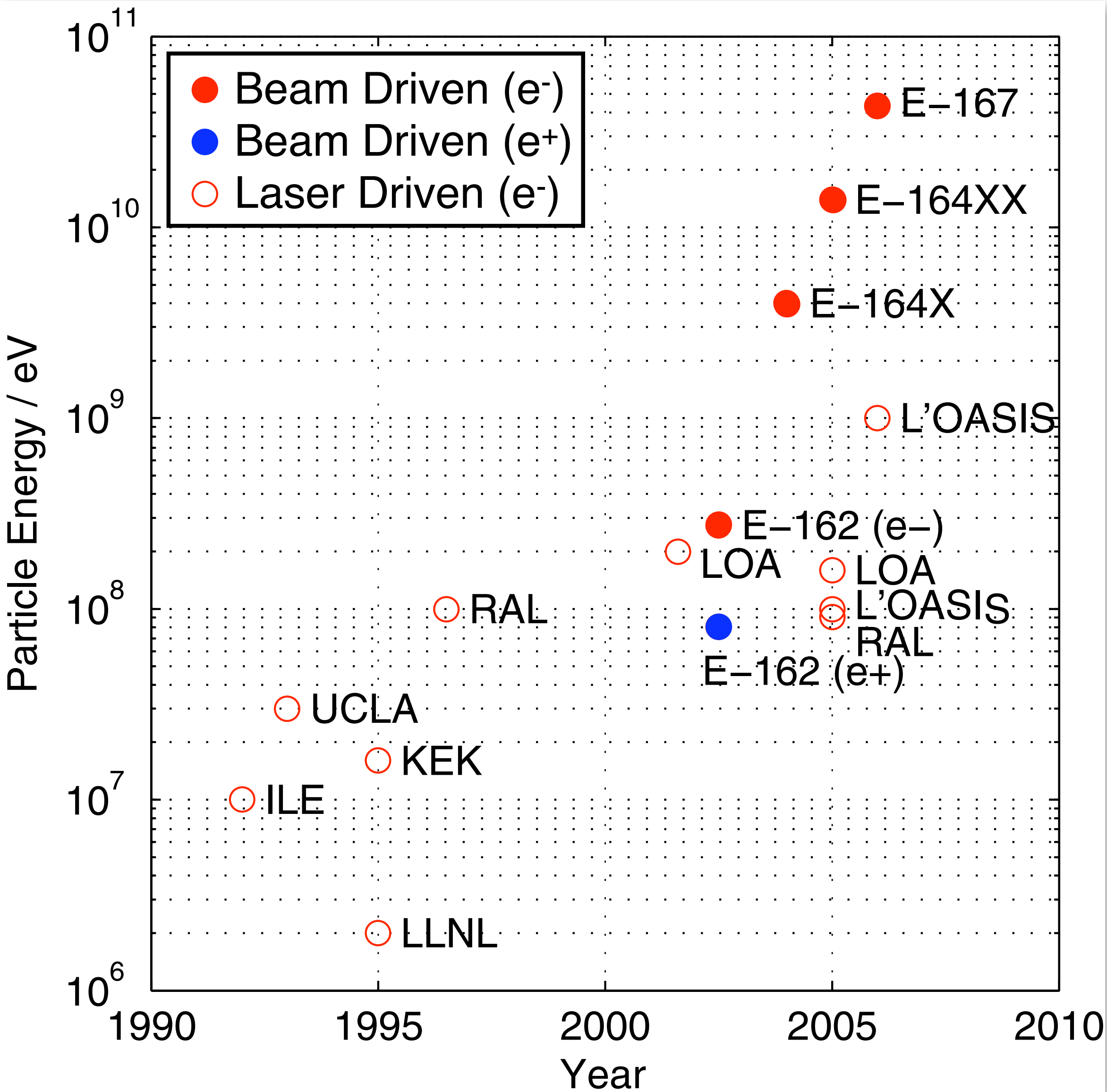
Magnet length: 0.7 m



A. Caldwell, K. Lotov, A. Pukhov, F. Simon, Nature Physics 5, 363 (2009).

DOE HEP Investments Have Realized Beam & Laser Driven Plasma Accelerators > GeV

SLAC



Laser Driven Plasma Accelerators:

Large Gradients:
- Accelerating Gradients > 100GeV/m (measured)
- Narrow Energy Spread Bunches
- Interaction Length limited to cm's

Specialized Facilities:
- Multi-TW-PW lasers
- Plasma Channels/Capillaries

Beam Driven Plasma Accelerators:

Large Gradients:
- Accelerating Gradients > 50 GeV/m (measured!)
- Focusing Gradients > MT/m
- Interaction Length ~ meters

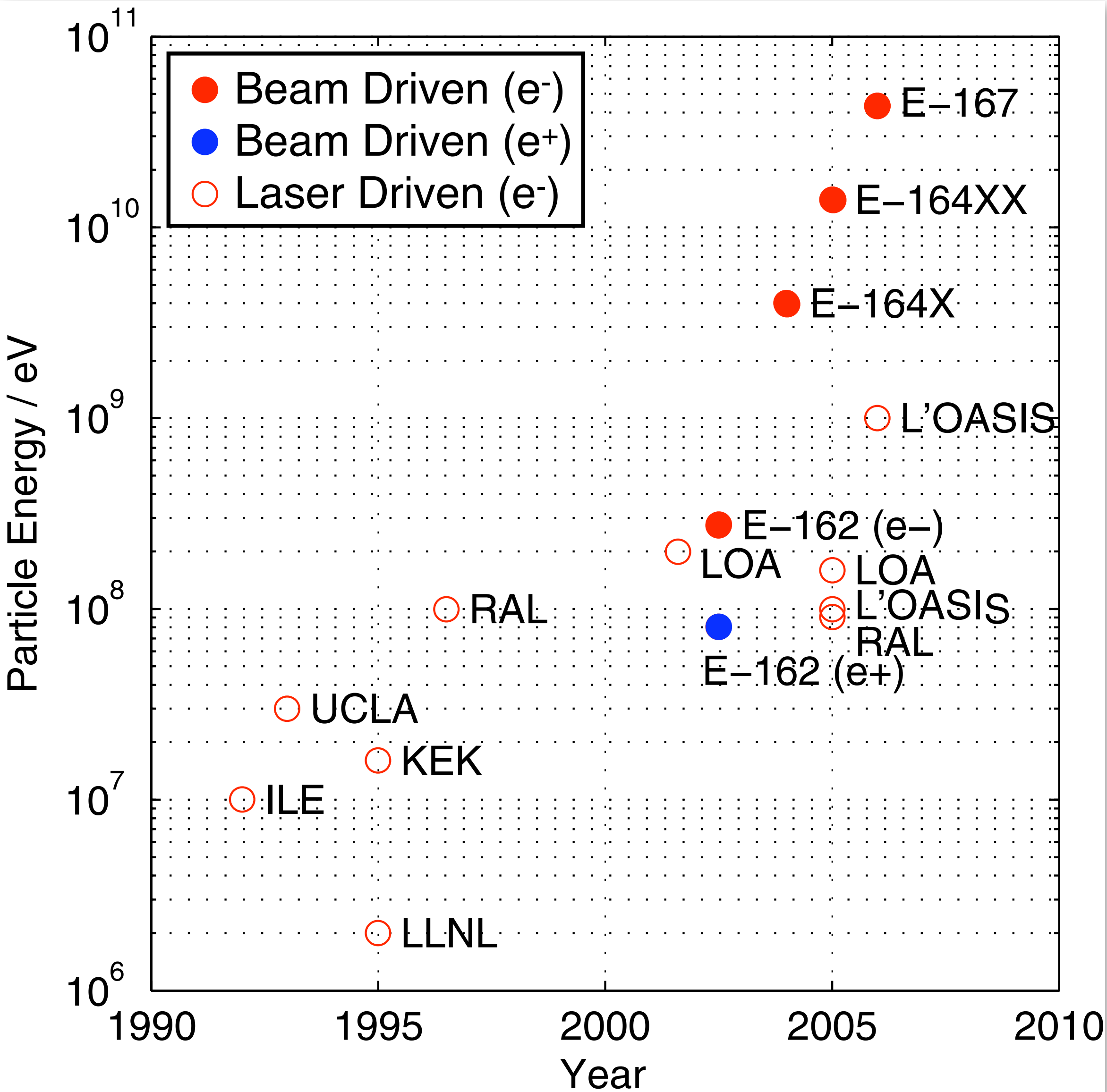
Unique SLAC Facilities:
- FFTB < 2006, FACET > 2011
- High Beam Energy
- Short Bunch Length
- High Peak Current
- Power Density
- e- & e+

LWFA: T. Tajima and J. M. Dawson
Phys. Rev. Lett. 43, 267 - 270 (1979)

PWFA: P. Chen et al
Phys. Rev. Lett. 54, 693 - 696 (1985)

DOE HEP Investments Have Realized Beam & Laser Driven Plasma Accelerators > GeV

SLAC



DOE HEP Office Of Science Issued CD-0 for Advanced Plasma Acceleration Facility February 2008

Answered by Two Facilities:
BELLA (LWFA) @ LBNL
FACET (PWFA) @ SLAC

LWFA: T. Tajima and J. M. Dawson
Phys. Rev. Lett. 43, 267 - 270 (1979)

PWFA: P. Chen et al
Phys. Rev. Lett. 54, 693 - 696 (1985)

FACET:
Facility for Advanced Accelerator Experimental Tests

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New Installation @ 2km point of SLAC linac:
Chicane, FF, Experimental Area

Multi-GeV meter-scale plasma cells require:

- High-density plasmas – gradient
- High-energy beams – stored energy
- Tightly focussed – match to plasma focusing channel
- High peak-current – large wake amplitude

FACET Beam Parameters	
Energy	23 GeV
Charge	3 nC
s_r	20 µm
s_z	20 µm
Peak Current	20 kA
Species	e^- & e^+

Beam Requirements for Next Generation PWFA Experiments

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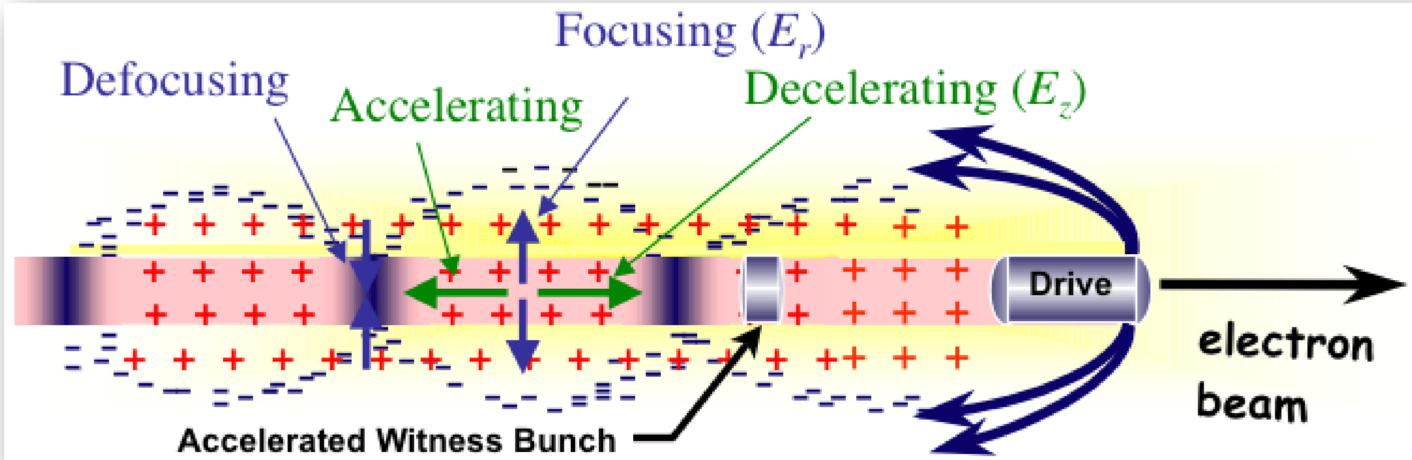
High gradients need high density plasmas

- ~10^{17} e^-/cm^3
- >10GeV/m acceleration
- >MT/m focusing



FACET Needs:

- Need two bunches, 100’s fs apart
- Individual bunches small in all three dimensions
- High bunch charge for blow-out with large wake amplitude & good transport
- Need long, uniform high-density plasmas
- High-energy for extended meter-scale interaction

FACET is the only facility in the world where we can do meter-scale high-gradient plasma acceleration

FACET E200 PWFA Program Goals – Next Four Years

Collaboration between SLAC/UCLA/MPI

- Demonstrate a single-stage high-energy plasma accelerator for electrons
  - This is THE highest scientific priority for FACET
- Meter scale, high gradient, preserved emittance, low energy spread, and high efficiency
  - Commission beam, diagnostics and plasma source (2012)
  - Produce independent drive & witness bunch (2012-2013)
  - Pre-ionized plasmas and tailored profiles to maximize single stage performance: total energy gain, emittance, efficiency (2013-2015)
- First experiments with compressed positrons
  - Identify optimum technique/regime for positron PWFA (2014-2016)

Want to demonstrate a plasma module with beam parameters and energy gain at the level required for novel radiation sources and Higgs Factory upgrade

FACET is Beginning the 2nd Phase of Beam Driven Plasma Wakefield Accelerators

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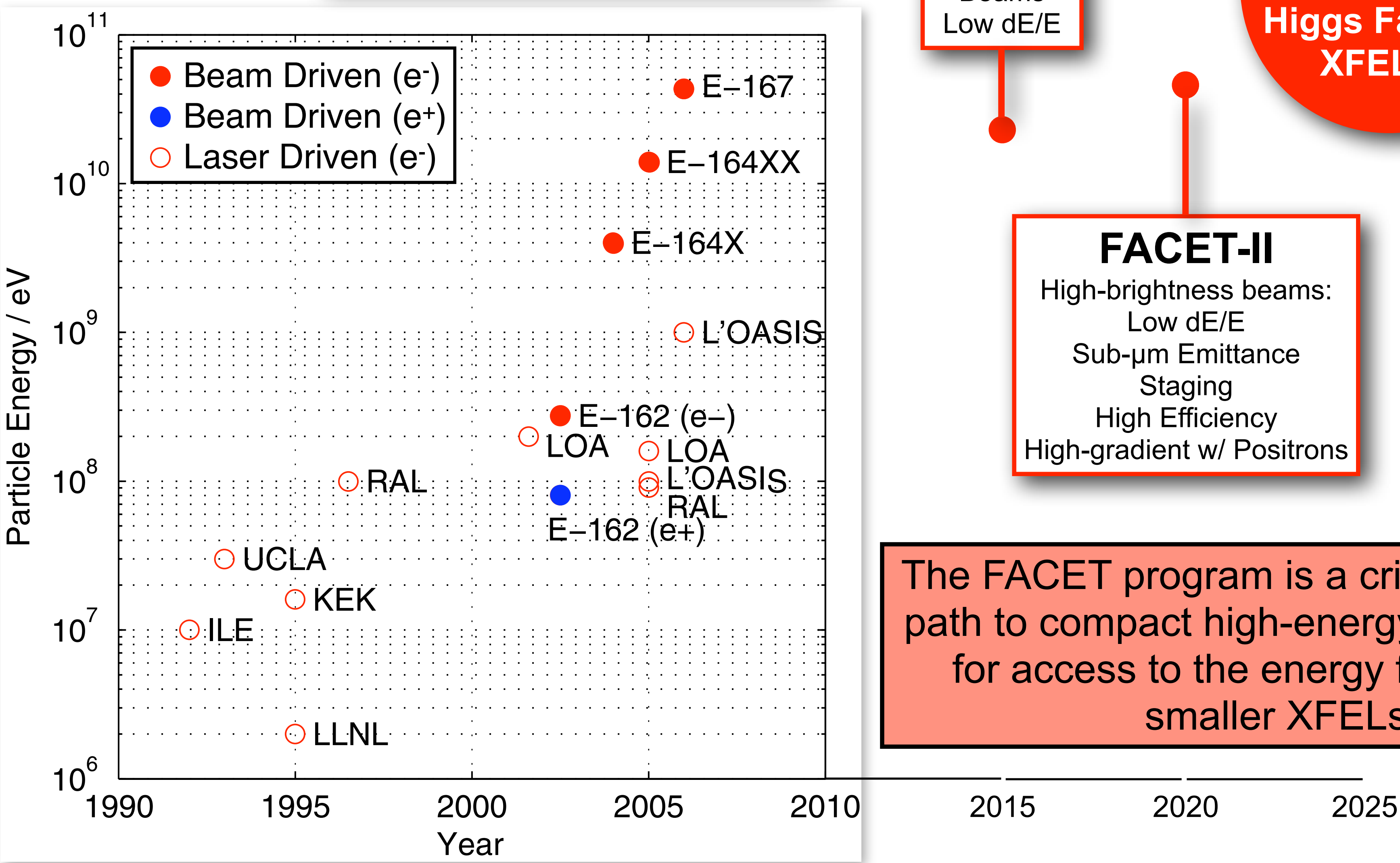
FFTB
Ultra-high-gradient particle acceleration
Meter scale

FACET
Beams
Low dE/E

Demonstration Machine: Higgs Factory, XFEL, ?



FACET-II
High-brightness beams:
Low dE/E
Sub-μm Emittance
Staging
High Efficiency
High-gradient w/ Positrons

The FACET program is a critical step on a path to compact high-energy accelerators for access to the energy frontier and smaller XFELs

A Concept for a Beam Driven Plasma Wakefield Accelerator Linear Collider

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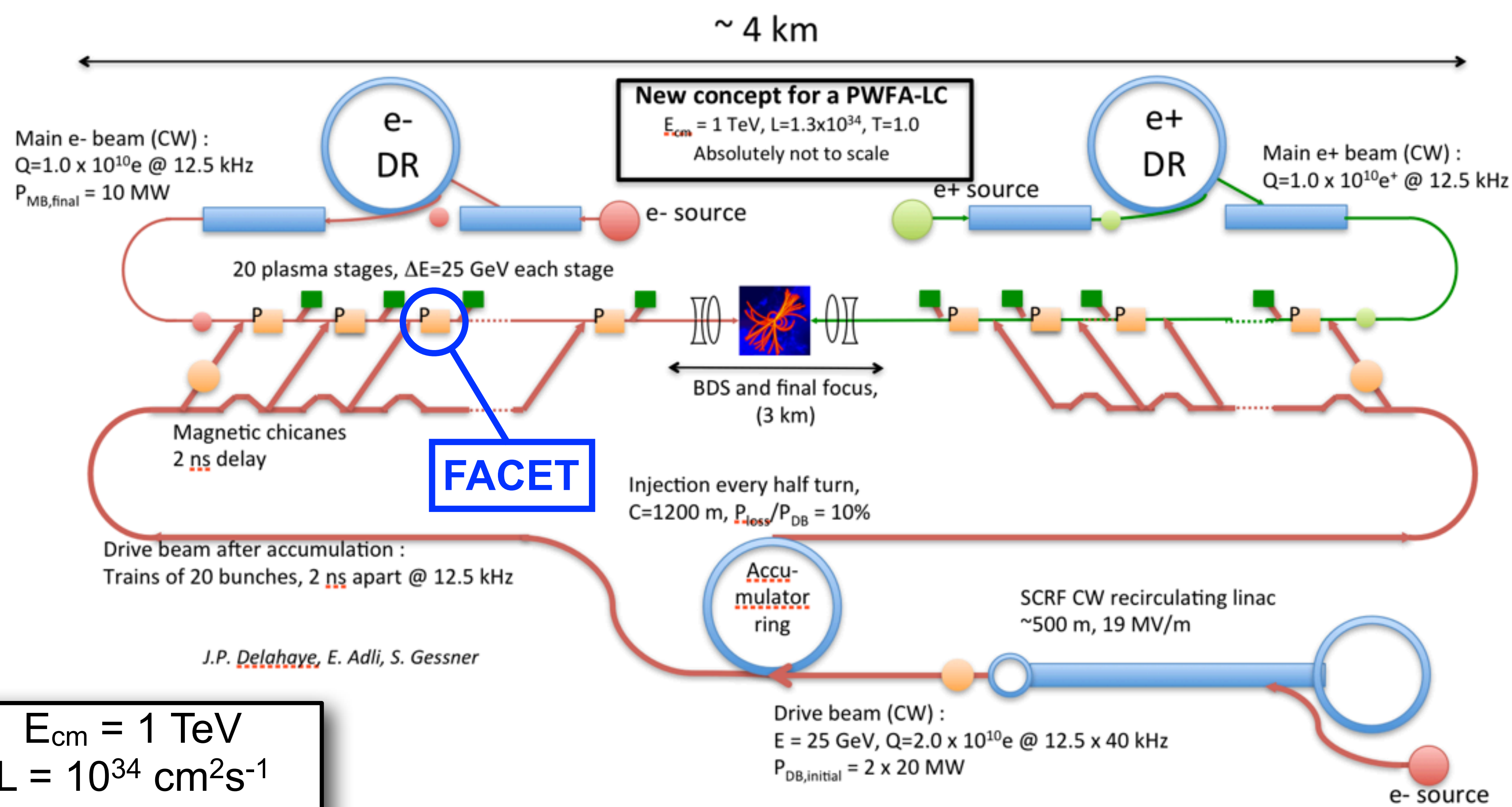
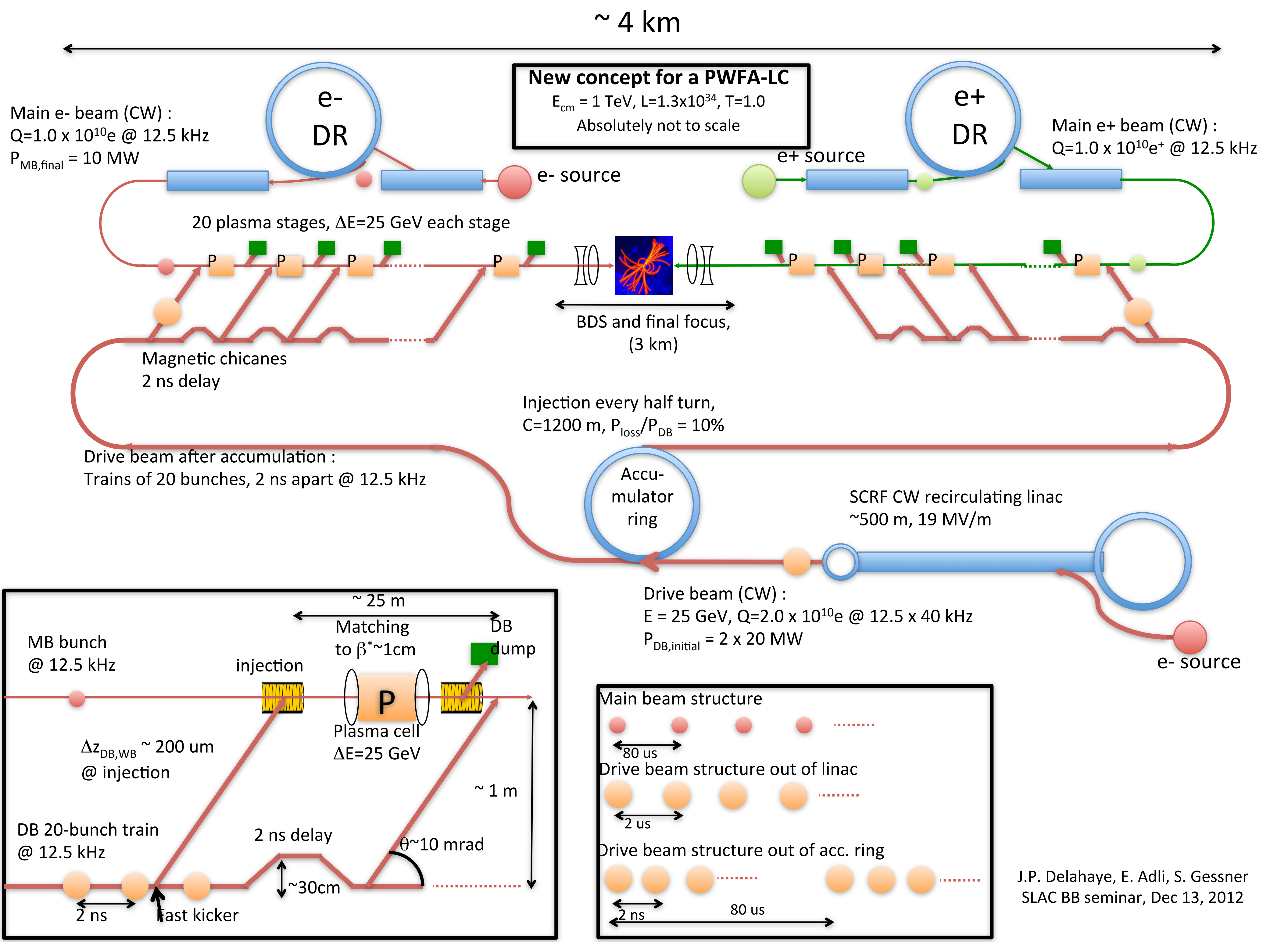


E_{cm} = 1 TeV
L = 10^{34} $cm^2 s^{-1}$
$Efficiency_{wall\ plug}$ ~ 11%

FACET program will transition from particle acceleration to beam acceleration and demonstrate a single PWFA stage with a high-quality beam


~ 4 km
New concept for a PWFA-LC
E_{cm} = 1 TeV, L=1.3x10^{34}, T=1.0
Absolutely not to scale
e- DR
e+ DR
Main e- beam (CW) :
Q=1.0 x 10^{10}e @ 12.5 kHz
$P_{MB,final}$ = 10 MW
e- source
e+ source
Main e+ beam (CW) :
Q=1.0 x 10^{10}e^{+} @ 12.5 kHz
20 plasma stages, ΔE=25 GeV each stage
P
BDS and final focus,
(3 km)
Magnetic chicanes
2 ns delay
Injection every half turn,
C=1200 m, P_{loss}/P_{DB} = 10%
Drive beam after accumulation :
Trains of 20 bunches, 2 ns apart @ 12.5 kHz
Accu-
mulator
ring
SCRF CW recirculating linac
~500 m, 19 MV/m
Drive beam (CW) :
E = 25 GeV, Q=2.0 x 10^{10}e @ 12.5 x 40 kHz
$P_{DB,initial}$ = 2 x 20 MW
e- source
~ 25 m
Matching
to β*~1cm
DB
dump
MB bunch
@ 12.5 kHz
injection
P
Plasma cell
ΔE=25 GeV
$\Delta z_{DB,WB}$ ~ 200 um
@ injection
~ 1 m
DB 20-bunch train
@ 12.5 kHz
2 ns delay
θ~10 mrad
~30cm
2 ns
Fast kicker
Main beam structure
80 us
Drive beam structure out of linac
2 us
Drive beam structure out of acc. ring
2 ns
80 us
J.P. Delahaye, E. Adli, S. Gessner
SLAC BB seminar, Dec 13, 2012

Technical risks and maturity of some of the pieces

SLAC

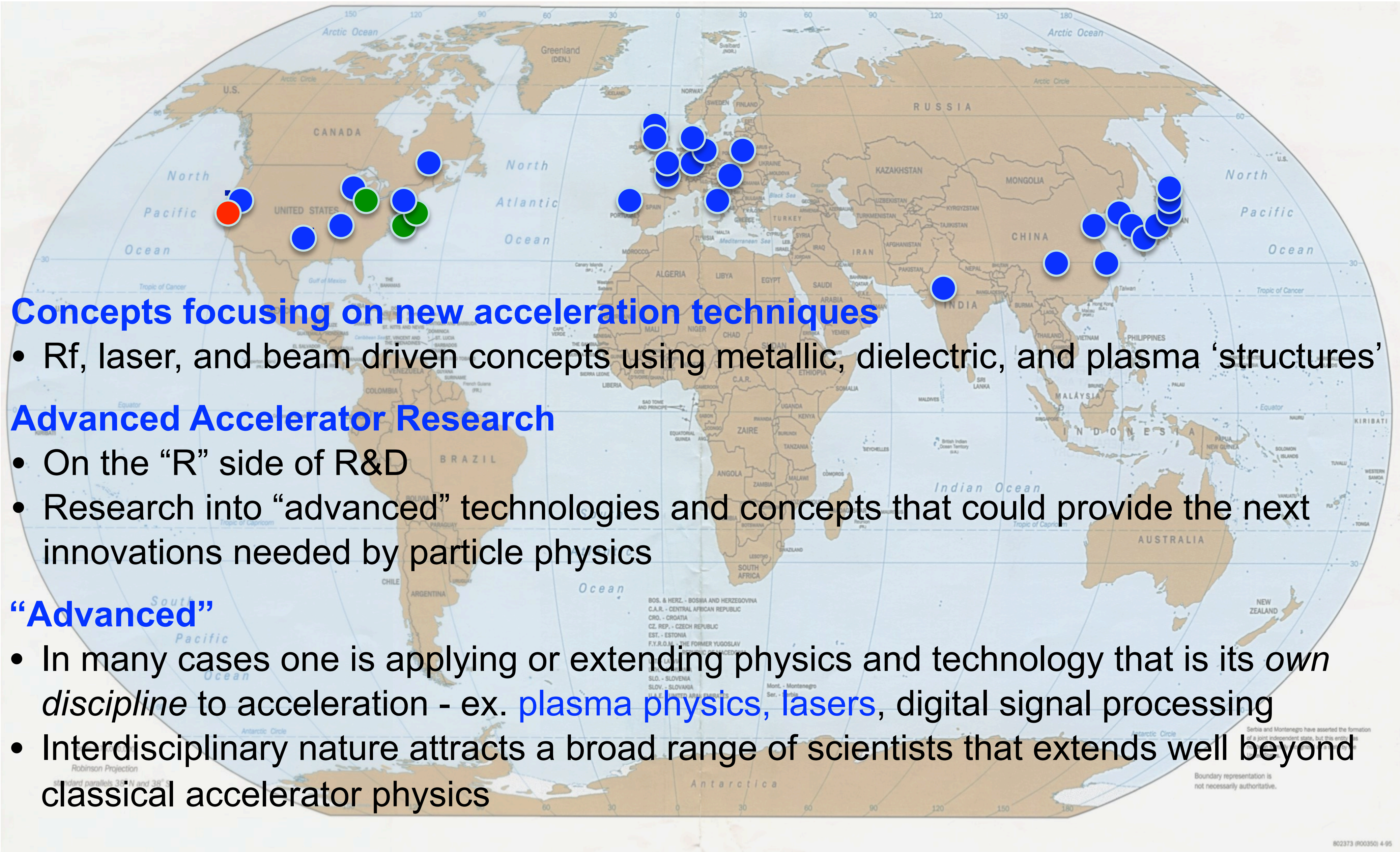
System	Risk to Design	Risk Can Do It	Timeframe
Gradient	Medium	Low	Now
Energy Gain	Medium	Low	Now
Emittance Preservation	Medium	Medium/High	5-10 years
Energy Spread	Medium	Medium	5-10 years
Staging	High	Medium	10 years
Polarization	High	Medium	>10 years
Efficiency	High	Medium	5-10 years
Positrons	High (e+/e-)	High	5-10 years
Hot Plasma Effects	High	High	10 years
Plasma Sources	High	Medium	5-10 years

Note: Timeframe assumes successful FACET program and timely funding of FACET-II

Facilities

Facility	Years	Energy	Particles/s	Macropulse duration	Rep rate/ max # of bunches	Bunch-length	Emittance	?	Comments
ATF		25-70 MeV e-	$(3\text{-}10)\times10^{11}$	up to 3 µs	1-3 Hz /200				
A0	1995-2010	16 MeV e-	$(0.5\text{-}2)\times10^{11}$	up to 100 µs	~1 Hz / up to 100				
AWA		70 MeV e-	up to 2×10^{13}	2 µs	~1Hz /32				
BELLA		1-5 GeV e-	~0.1×10^{11}	<0.3 ps	<1 Hz / 1				
FACET		21 GeV e-, e+	0.6×10^{11}	0.1 ps	30 Hz / 1				
CESR-TA		1.8-5.3 GeV e-,e+	1.6×10^{11}/bunch	ring	Ring / 45				
UMER		10 keV e-	$(0.02\text{-}3)\times10^{10}$	100's turns	Ring/ 1				
ASTA	2014 (?) -	800 MeV e-	3×10^{14}	1 ms	5 Hz / 3000				proposal
SLAC ASTA	1993-Present	6-60 MeV	6×10^{9}/bunch	0.5-1.0 ps	120 Hz/2		0.5 µm		Mainly RF testing and Gun development, but could provide a 60MeV beam
NLCTA	1997-Present	60-120 MeV	(2-60)x10^7/bunch	1 ps	10 Hz	1 ps	>1.4 mm-mrad		
ESTB	2013-	2-15GeV	1x10^9/bunch or single electrons		5-120Hz	250um			ESTB uses LCLS beams
MIT									
NRL Mgnkon									

Advanced Accelerators are a Worldwide Effort



Concepts focusing on new acceleration techniques

- Rf, laser, and beam driven concepts using metallic, dielectric, and plasma ‘structures’

Advanced Accelerator Research

- On the “R” side of R&D
- Research into “advanced” technologies and concepts that could provide the next innovations needed by particle physics

“Advanced”

- In many cases one is applying or extending physics and technology that is its *own discipline* to acceleration - ex. plasma physics, lasers, digital signal processing
- Interdisciplinary nature attracts a broad range of scientists that extends well beyond classical accelerator physics

● Laser Wake Expts ● Electron Wake Expts ● e-/e+ hi γ Wake Expts