Quasi-Monoenergetic Plasma Wakefield Acceleration at FACET

and plans for FACET-II...

Vitaly Yakimenko, Mark Hogan, September 17, 2013

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

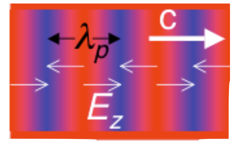
Why Plasmas?

Relativistic plasma wave (electrostatic):

$$\vec{\nabla}\cdot\vec{E} = \frac{\rho}{\varepsilon_0} \qquad k_p E_z = \frac{\omega_{pe}}{c} E_z = \frac{n_e e}{\varepsilon_0}$$

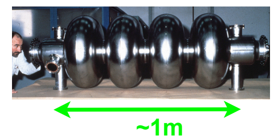
$$E_z = \left(\frac{m_e c^2}{\varepsilon_0}\right)^{1/2} n_e^{1/2} \cong 100\sqrt{n_e(cm^{-3})} = \underline{1GV/m}$$

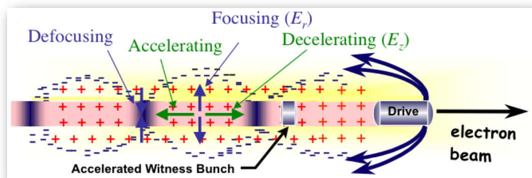
$n_e = 10^{14}$ cm^{-3}

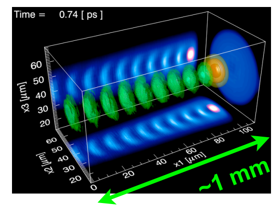


Large
Collective Response!

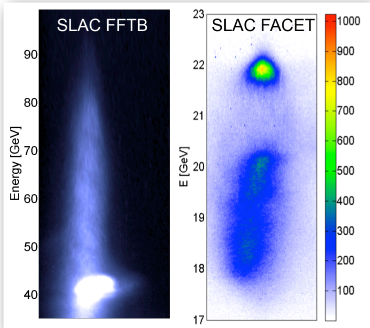
- Plasmas are already ionized, no break down
- Plasma wave can be driven by:
  - Intense laser pulse (LWFA)
  - Short particle bunch (PWFA)







Electron Acceleration in Plasmas

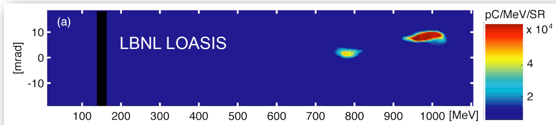


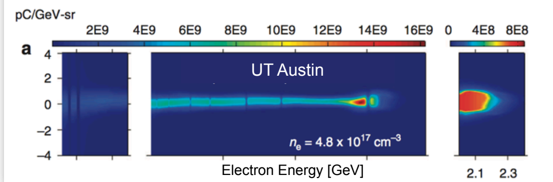
Nature ***445*** *741 (2007)*

Beam Driven Plasmas:

- 50 GeV/m fields, stable over meter scale for electrons
- Drive/witness bunches injected for stable acceleration over 30cm with narrow dE/E

Nature Physics **2**, 696 - 699 (2006)





Nat Commun. ***4****:1988 doi: 10.1038/ncomms2988 (2013)*

Laser Driven Plasmas:

- 50 GeV/m fields, stable over cm
- High quality <μm emittance beams created and accelerated in the plasma

FACET Has a Multi-year Program to Study PWFA

Primary Goal:
Demonstrate a single-stage high-energy plasma accelerator for electrons.

- Meter scale
- High gradient
- Preserved emittance
- Low energy spread
- High efficiency

Timeline:

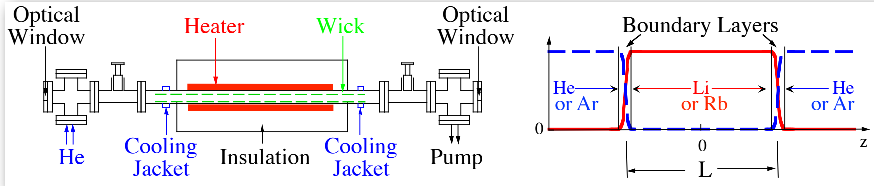
- Commissioning (2012)
- Drive & witness e^- bunch (2012-2013)
- Optimization of e^- acceleration (2013-2015)
- First high-gradient e^+ PWFA (2014-2016)

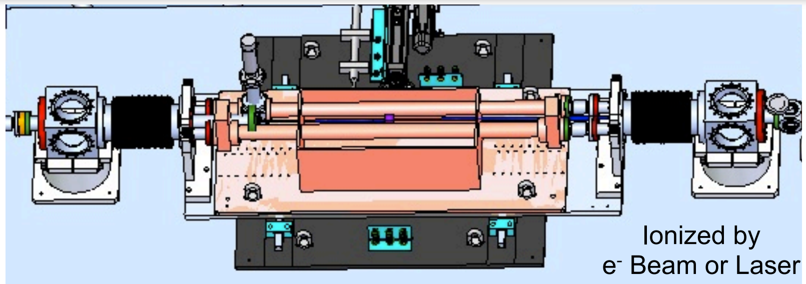
Built by DOE, operates as a user facility but with primary purpose to study beam driven PWFA

Heat Pipe Oven Has Been Heart of Plasma Source Since 1998

UCLA SLAC

Plasma source starts with a heat pipe oven: Scalable, $n_0 = 10^{14}$-10^{17} e^-/cm^3, L = 20-200 cm

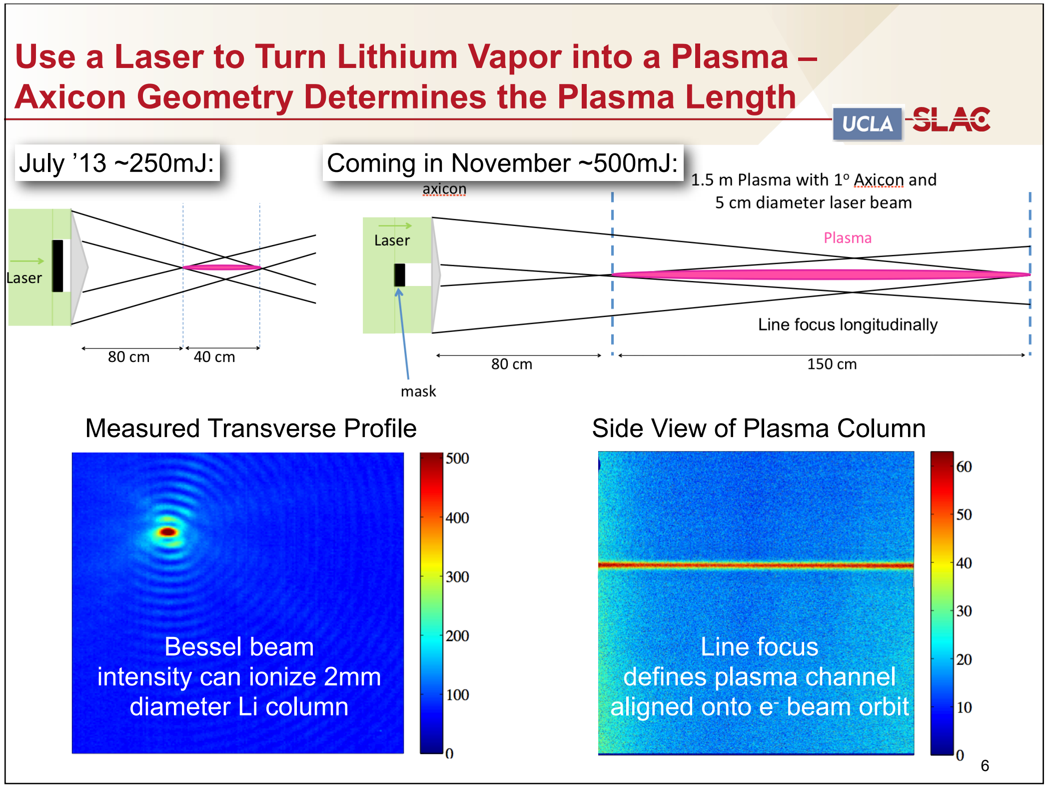




High-energy accelerator requires meter scale uniform high-density plasma

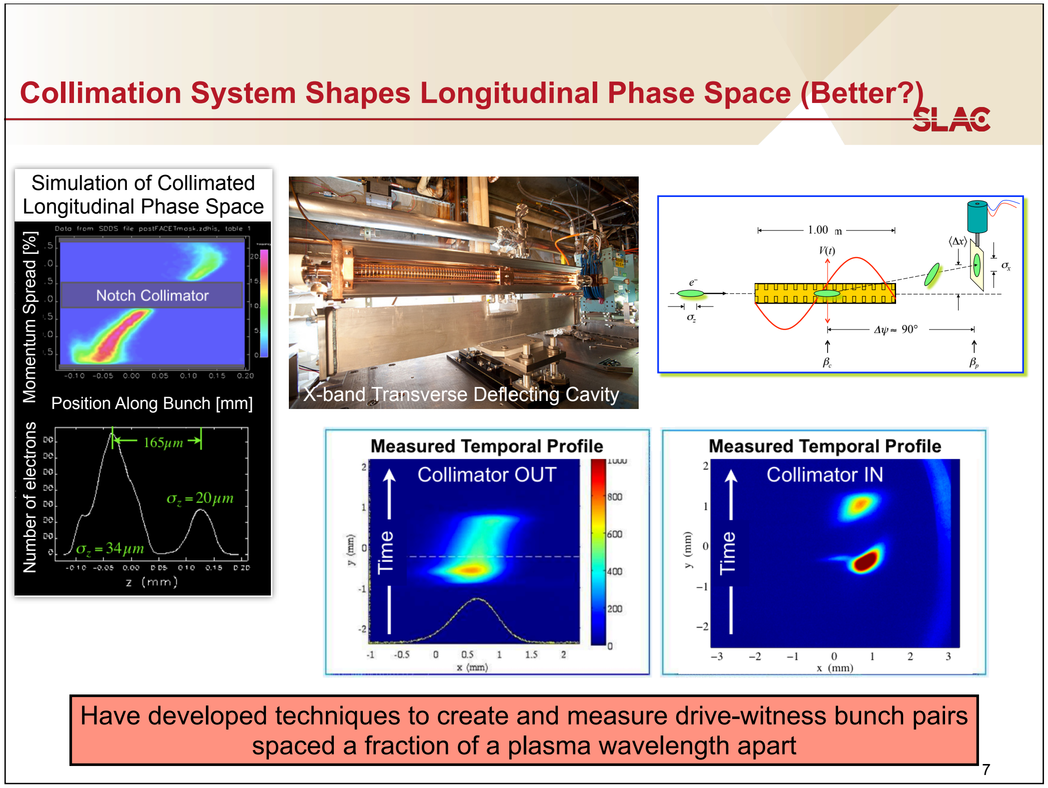
Need to introduce idea of vapor inside hot zone, buffer outside (ON/OFF condition)

Head erosion that depends on parameters like emittance and ionization energy – we will study these experimentally while complete the laser



Splitting/collimating the bunch reduces the peak fields so for maximum efficiency/interaction we want a preformed plasma.

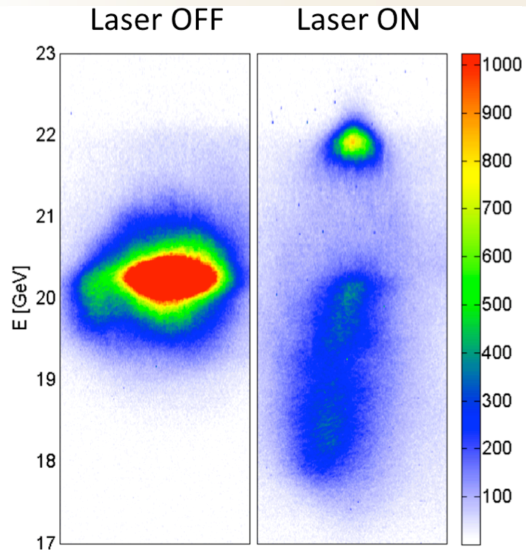
A couple years ago no one knew how to make the plasma we needed for these experiments – Developed at UCLA



Started with E200, now available to all

Multi-GeV Energy Gain in <30cm plasma!

UCLA SLAC



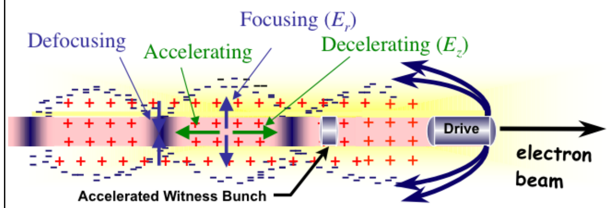
- Negligible wakefield without pre-formed plasma
- Drive bunch looses energy
- Witness gains nearly 2GeV
- Accelerating wakefield ~ 6GeV/m

FY13 FACET Run put all the tools in place: pre-ionized plasma and tailored two-bunch structure for first beam driven mono-energetic acceleration

Plasma length and width TBD so we say less than 30cm

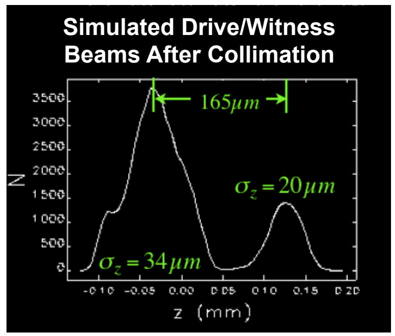
Primary Scientific Goal of FACET: Demonstrate a Single Stage Plasma Accelerator for Electrons

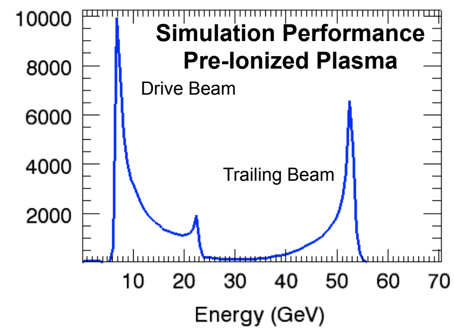
E200: Collaboration between SLAC/UCLA



After ~ 1.5 m of 5 x 10^{16} plasma

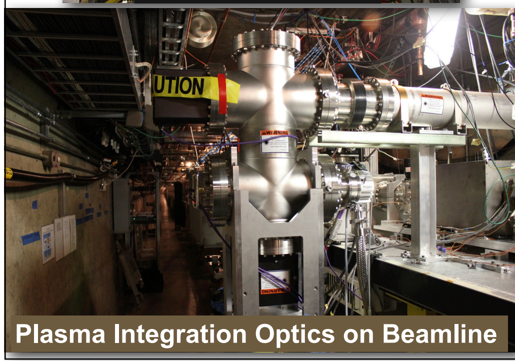
- Energy Gain 30 GeV
- Energy Spread ~ 5%
- Energy Loss 17 GeV, Beam loading efficiency 64%

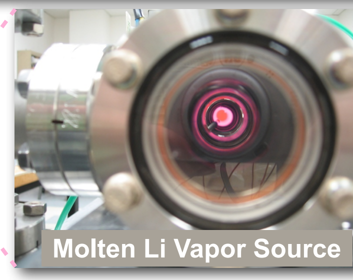




This is where we hope to be in a couple years

10TW FACET Ionization Laser:
Enabling technology for many new experiments

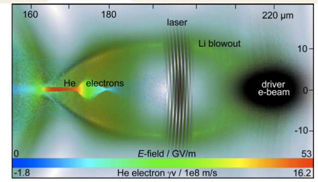


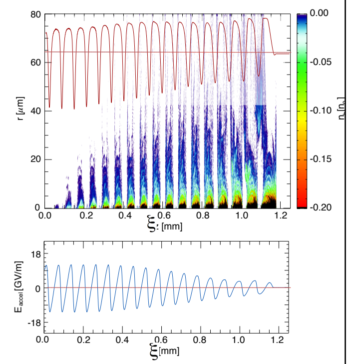


No commercial company could deliver this in this kind of time

The Future: The next Few Years
Expanding Plasma Collaborations and Directions

SLAC





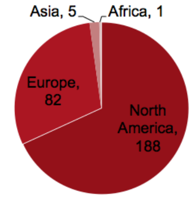
- Trojan Horse Plasma Wakefield Acceleration
  - (UCLA/SLAC/Tech-X/MPI/HHU)
- Study of the Self-Modulation of Long Lepton Bunches in Dense Plasmas and its Application to Advanced Acceleration Techniques
  - (IST/MPI/SLAC)
- Investigation of Hot Plasmas and Fourier Domain Holography of Plasma Wakes
  - (Duke/SLAC/U.T. Austin/UCLA)
- Density Downramp Injection
  - (DESY/SLAC)
- Helmholtz VI for Plasma Acceleration

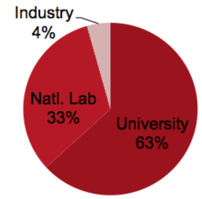
Facility upgrades like the laser are enabling additional programs that will accelerate progress and increase FACET science output

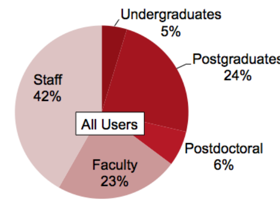
FACET Operates as a National User Facility

SLAC

- Diverse and growing user community
- 1/3 from outside U.S.
- Majority from Universities
- Strong educational component
- Delivered to 6 experiments in 2013
- 8 experiments scheduled this Fall
- 13 experiments scheduled for 2014



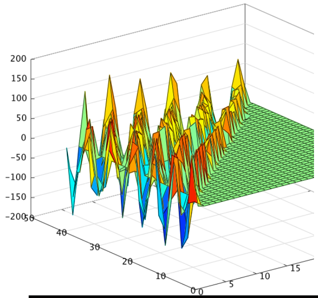


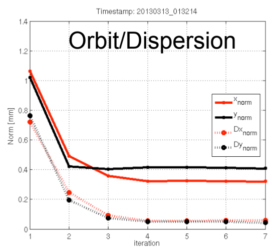


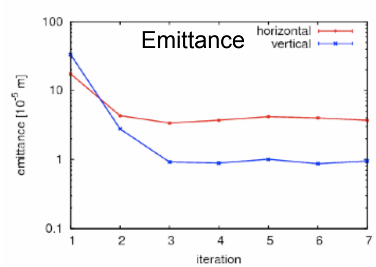
8 new experiments proposed at July'13 User meeting

E211: Beam-Based Alignment tests at FACET
Dispersion-free Steering (DFS) proof of principle (500m)

- Algorithms predict can correct dispersion and as a result preserve emittance in ILC type linac
- Has never been demonstrated in long linac without e^- & e^+ together
- Need a long linac to test
- Experiments at FACET will understand limitations of this technique with single charge particles – critical item for ILC





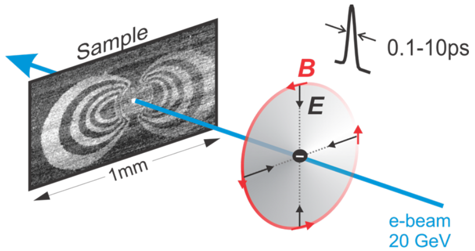


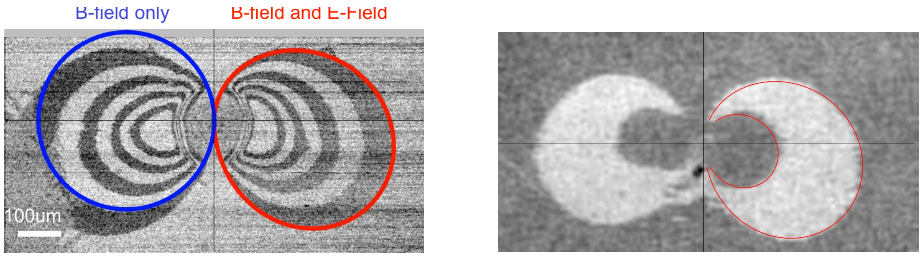
Will iterate these techniques when positrons available

E202: E-field, Spin Dynamics and Switching Mechanisms in Ultrafast Electromagnetic Pulses

Intense E-, B-fields from compressed FACET bunch access unique physics

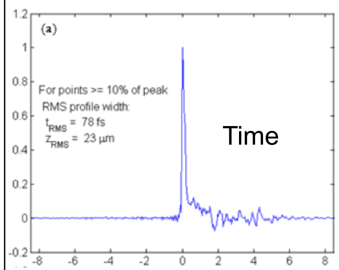
- Studying different materials and geometries
- Quantify torque ratio, damping times and penetration depth

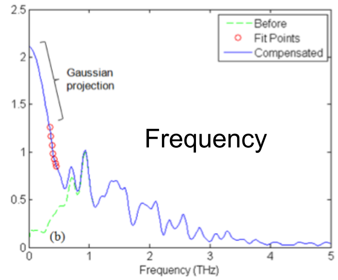




Surprising results from thick films – switching penetration beyond a skin depth points to new physics

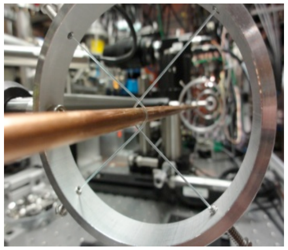
E206: Intense THz for Diagnostic & Pump-probe Applications

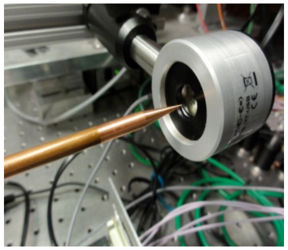




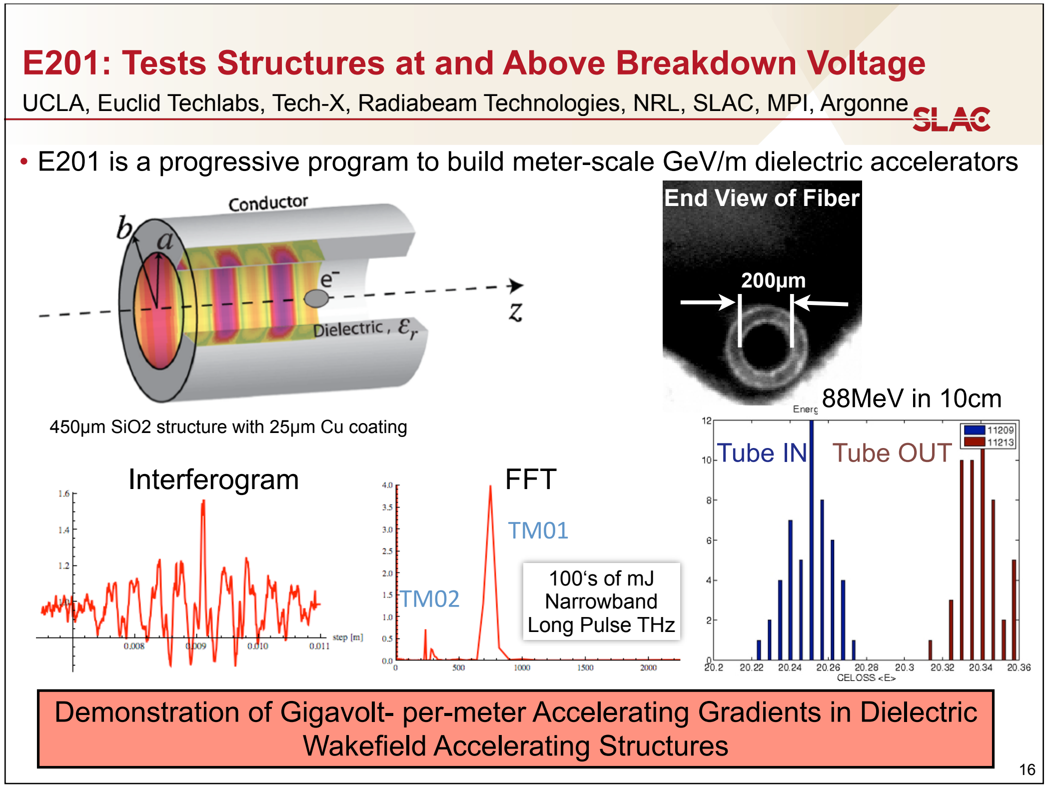
- THz interferometer can passively monitor longitudinal profile
- Developed and operates parasitically to main programs

- Single FACET bunch produces ~ mJ broadband short pulse THz from CTR
- Focused THz creates fields approaching V/Å



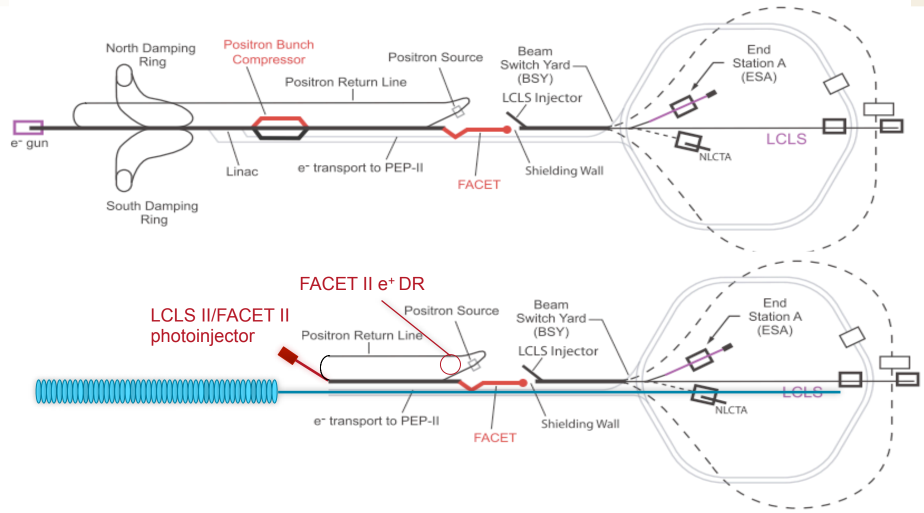


Developing techniques to transport and focus intense THz pulses for users



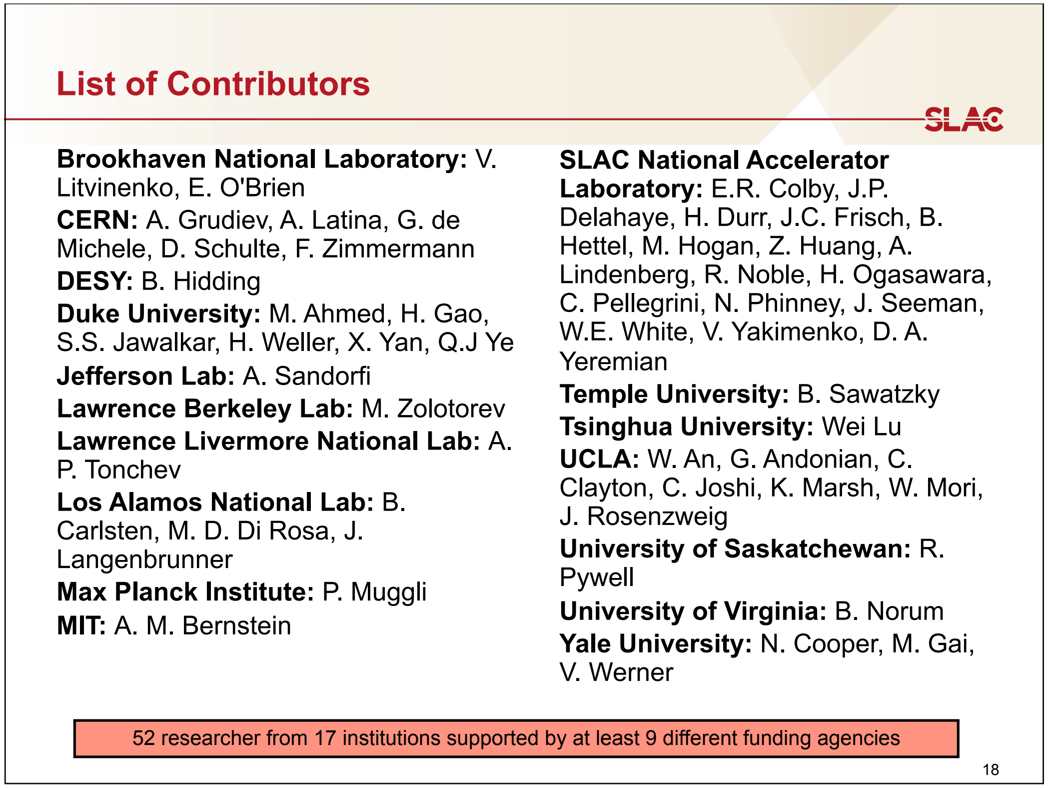
- Multimode excitation with single bunch, 70J (100's of mJ THz!)
- High-power (~10MW), narrowband THz source
- Preservation of structural integrity and cladding at high gradient (>200MV/m)

FACET-II in Sectors 10-20



Latest LCLS-II plan is to use 1st 1/3 of the tunnel. It allows for ~10GeV e-beam facility in Sectors 10-20

SLAC is now considering an alternate approach to LCLS-II to meet highest priorities for the future as discussed in BESAC report. This represents a great opportunity for FACET-II



breadth of the potential research program makes FACET II truly unique. It will synergistically pursue accelerator science that is vital to the future of both advanced acceleration techniques for High Energy Physics, ultra-high brightness beams for Basic Energy Science, and novel radiation sources for a wide variety of applications. No other test facility has attracted such broad interest across so many branches of the Office of Science.

An international group of high energy physicists are interested in using it as a foundation for the world's the first photon collider.

Nuclear physicists have proposed using the unprecedentedly high intensity gamma beams to study the structure of nuclei and as a novel particle source for future colliders.

Three Parts of FACET-II Science Case:

High gradient acceleration (Plasma Wakefield acceleration)

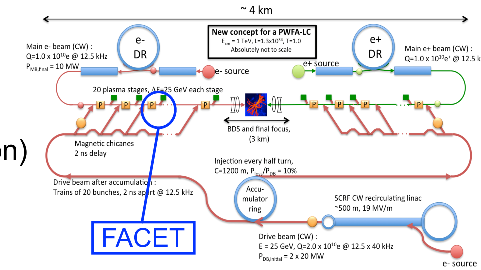
- Up to **1000x** improvement in gradient

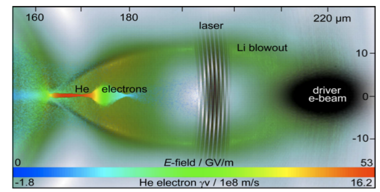
Extreme **brightness** beam generation (Trapping in Plasma Wakefield acceleration)

- Up to **1000x** improvement in emittance

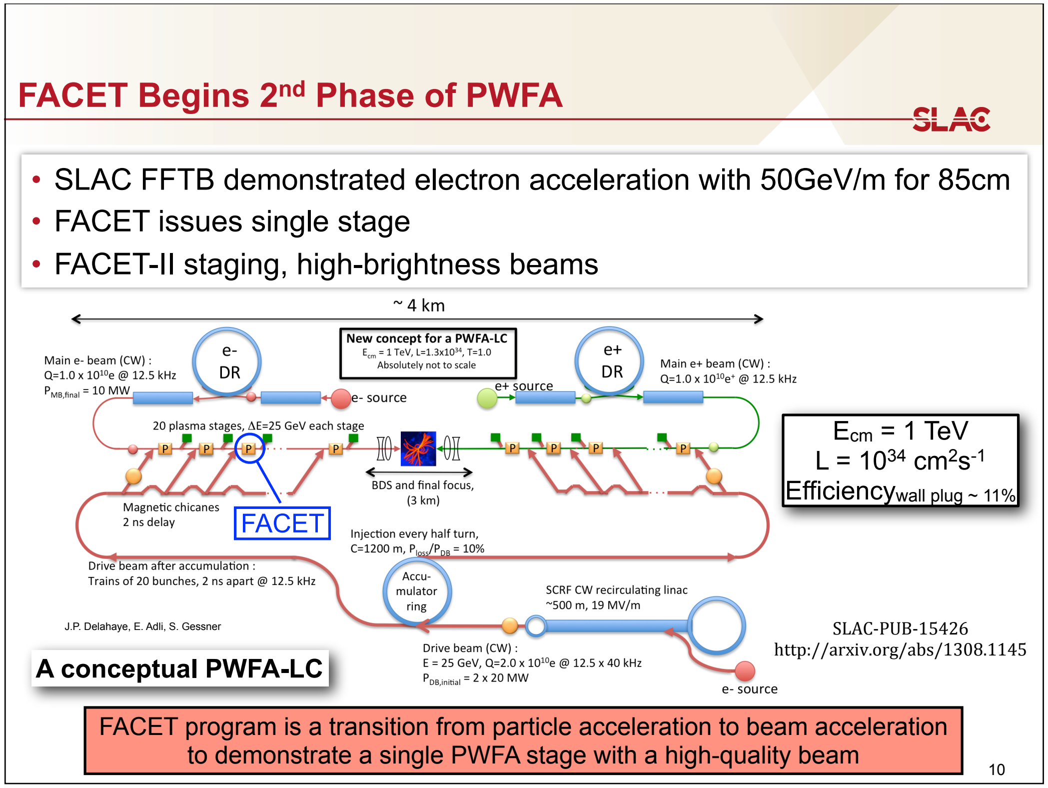
High flux of **gamma beam** generation (Compton Backscattering)

- Up to **100x-1000x** improvement in monoenergetic gamma flux at 10MeV-5GeV
- Up to **10,000x** improvement in total gamma flux at up to 5GeV





FACET-II is a user facility based on high energy high brightness beams and their interaction with plasma and lasers



'Compact' TeV collider using mostly conventional technology

Heart is the high gradient, high efficiency plasma accelerator module – study the physics of these at FACET, FACET-II

Remaining Challenges for a PWFA-LC

SLAC

The concept for the PWFA-LC highlights the key beam and plasma physics challenges must be addressed by experimental facilities such as FACET. A reasonable set of design choices for a plasma-based linear collider can benefit from the years of extensive R&D performed for the beam generation and focusing subsystems of a conventional rf linear collider. The remaining experimental R&D is directly related to the beam acceleration mechanism. In particular, the primary issues are:

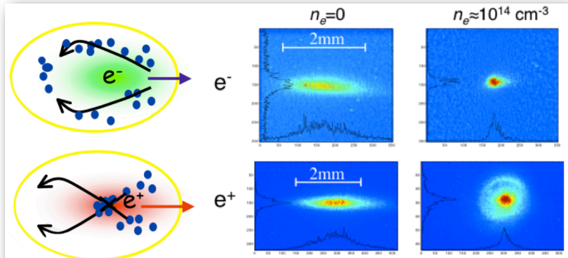
Positrons, beam quality, efficiency, and staging

- Preservation of small positron beam emittances (required to achieve luminosity) and mitigation of effects resulting from plasma electron collapse
- Average bunch repetition rates in the 10's of kHz (required to achieve luminosity)
- Synchronization of multiple plasma stages to achieve the desired energy, and
- Optical beam matching between plasma acceleration stages and from plasma to beam delivery systems.

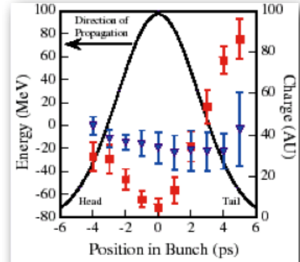
Answering these questions requires dedicated test facilities like FACET & FACET-II

Positron Focussing and Acceleration

Focusing and acceleration of positrons has been characterized at low densities

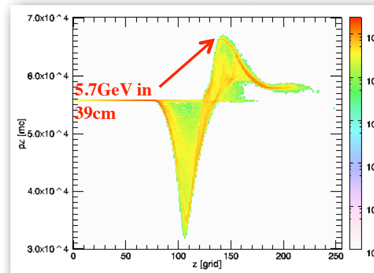


Phys. Rev. Lett. **90**, 205002 (2003) *Phys. Rev. Lett.* **101**, 055001 (2008)



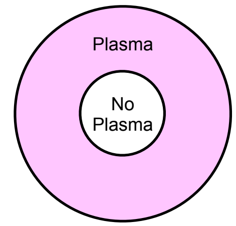
Phys. Rev. Lett. **90**, 214801 (2003)

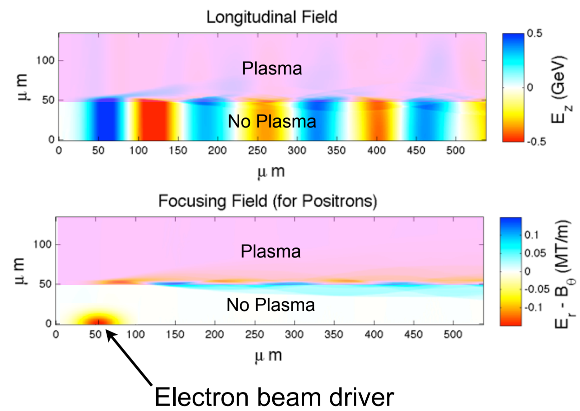
- High-gradient positron acceleration is possible
  - Can use wake of an electron or positron beam
- Need to iterate plasma source to minimize emittance growth but preserve high-gradients (hollow channels)
- FACET will make first tests of high-gradient positron acceleration in the next couple years



Hollow Channel Plasmas

- Beam propagates down the axis in no plasma
- Plasma wake from inner sheath of channel
  - Acceleration
  - No focusing (no emittance growth)





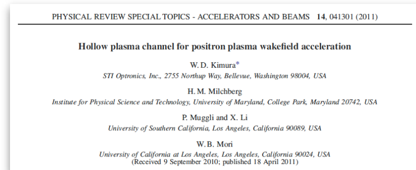
Uniform longitudinal fields

No focusing fields on axis

Hollow Channel Plasma Experiments at FACET

Kimura et. al. propose using a high-order bessel beam to create an annular ionization region in the gas. See also:

- J. Fan et. al. J. Fan, E. Parra, I. Alexeev, K.Y. Kim, H. M. Milchberg,L.Ya. Margolin, and L. N. Pyatnitskii, Phys. Rev. E 62, R7603 (2000).
- N. E. Andreev, S. S. Bychkov, V.V. Kotlyar, L.Ya. Margolin, L. N. Pyatnitskii, and P. G. Serafimovich, Quantum Electron. 26, 126 (1996).


PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **14**, 041301 (2011)

Hollow plasma channel for positron plasma wakefield acceleration

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STI Optronics, Inc., 2755 Northup Way, Bellevue, Washington 98004, USA
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University of Southern California, Los Angeles, California 90089, USA
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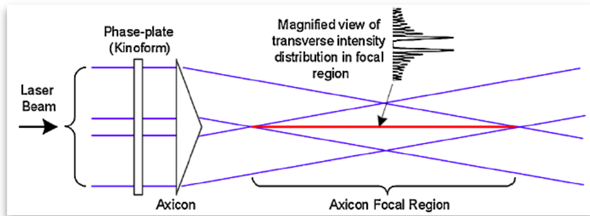
University of California at Los Angeles, Los Angeles, California 90024, USA
(Received 9 September 2010; published 18 April 2011)

Laser/Kinoform Parameters

Power	1 TW (300 mJ/ 300 fs)
$r_{kinoform}$	1.6 cm
Bessel Mode	5
“Axicon Angle”	1˚

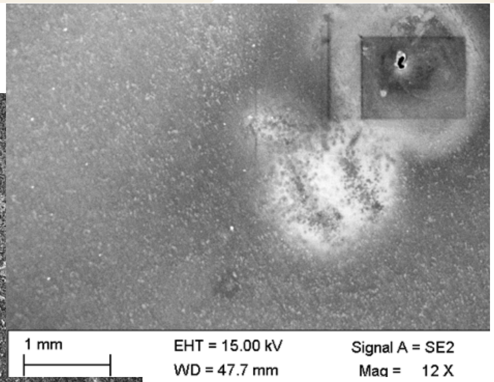


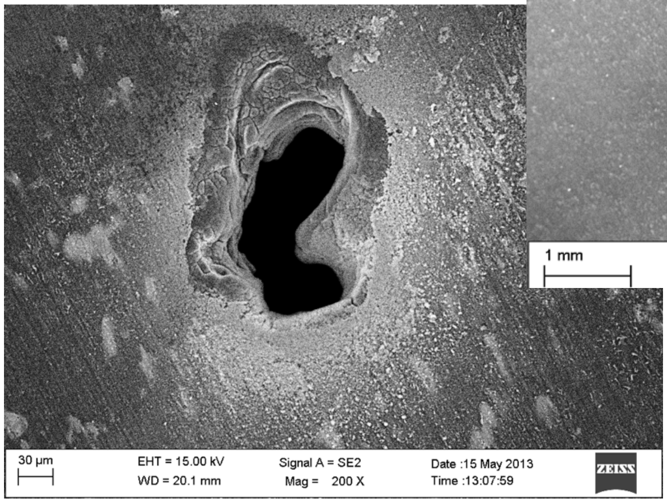
Plasma Parameters

Density	1×10^{17}
J_5 Peak	46 µm
Plasma Start	40 cm
Plasma End	91 cm

Positron Systems will re-commission this Fall with first experiments in 2014

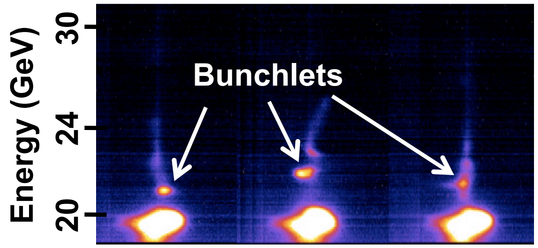
Unprecedented beam density



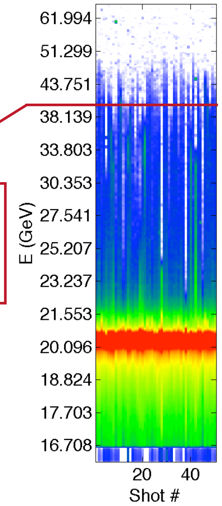


High Brightness Beam Development

- Quest for better beam quality in LWFA has led to investigation of many ways to control injection into the plasma bubble/wake
- Large fields generated by focused FACET beam have given rise to additional methods of injection
  - Beam fields large enough to melt Be, Ti
  - Ionization of Li, Rb, Rb++, Ar, He...



Energy doubling
100GeV/m
in 10^{18} Ar gas

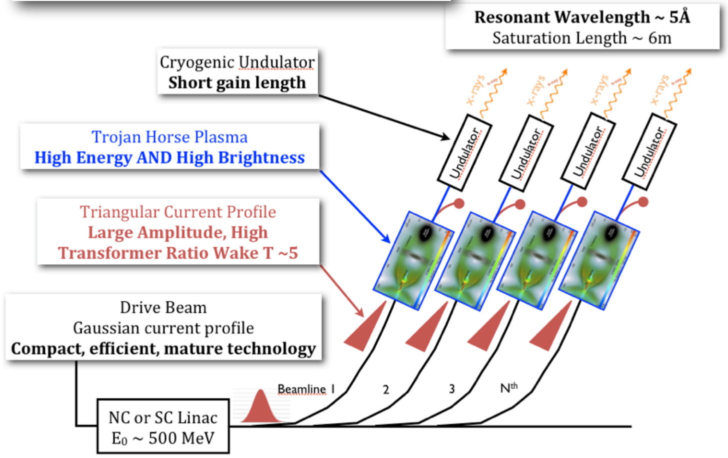


Tailored plasma can act as high-brightness injector AND high-gradient accelerator

Applications Go Beyond HEP

SLAC

Plasma Based FEL Concept



Drive Beam	
Charge	3nC
Energy	500 MeV
Rep Rate	1MHz
Bunch length	210μm, ramped
Peak Current	8.5kA
Normalized Emittance	2.25 mm-mrad
Trojan Horse (plasma)	
Plasma Density	10^{17} e^-/cc
Plasma Length	20 cm
Transformer Ratio	5
Trojan Horse (beam)	
Charge	3 pC
Energy	2.5 GeV
Energy Spread	2×10^{-4}
Normalized Emittance	3×10^{-8} m-rad
Peak Current	300A
Bunch length	12 fs
Brightness	7×10^{17} A/m^{2}rad
Undulator Parameters	
Period	9 mm
K	2
Number of periods (N)	660
Radiation Parameters	
Wavelength	5.4 Å
Single pulse energy	50 μJ
Number of Photons	$>10^{11}$
Peak Power	1.6 GW

FACET-II has the opportunity to develop next-generation light sources using plasma accelerators as drivers, and to test novel concepts.

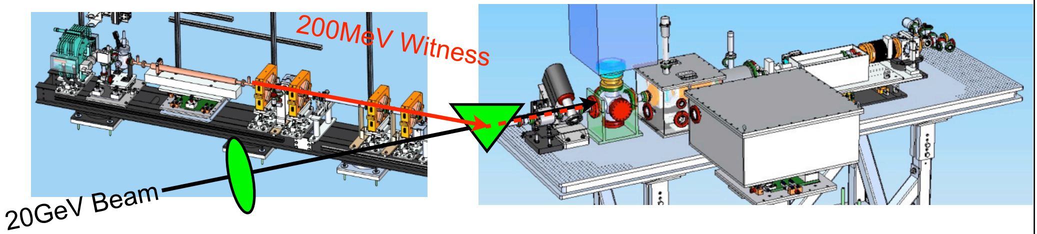
Staging Will Be Required to Reach Very High Energies

Upstream of stage:

- Inject high-brightness witness bunch from independent source
- Investigate tolerances on timing, alignment

Downstream of stage:

- Extract/Dump spent drive beam
- Preserve emittance of accelerated beam

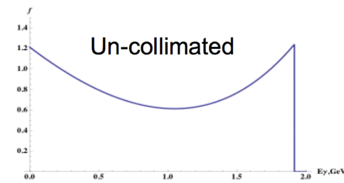


FACET-II has all the tools to investigate staging multiple plasma cells together as desired for very high energy applications

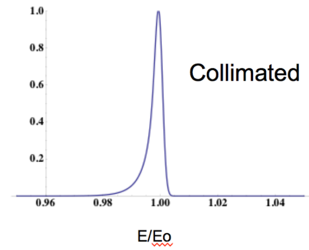
BIG: Beams of Intense Gamma-rays at FACET-II

- Generate Intense gamma beams by backscattering high-power lasers off high-energy electron beam
  - Energy range: 2 MeV - 4 GeV
  - Flux 10^{9}-10^{11} /sec;
  - Nearly 100% polarization

- Modes of operations:
  - High peak flux – single burst per pulse
  - White (un-collimated) and mono-energetic (collimated) gamma-rays
  - Linear, circular, elliptical polarization



$$E_\gamma = \frac{4\gamma^2 E_{ph}}{\left(1 + r + \gamma^2\theta^2\right)}; \quad r = \frac{4\gamma E_{ph}}{mc^2};$$



High-energy beam combined with state of the art laser systems deliver unprecedented combination of gamma-ray energy and flux

Energy resolution due to high brightness of the beam

Source brightness proportional to geometric emittance and with 10µm. For given photon energy need combination of beam energy and photon energy, with longer wavelength light, use higher E beam and thus lower geometric emittance and higher brightness

10µm with 100mJ same # photons as 1µm and 1mJ

Comparing BIG with other Compton Sources

SLAC

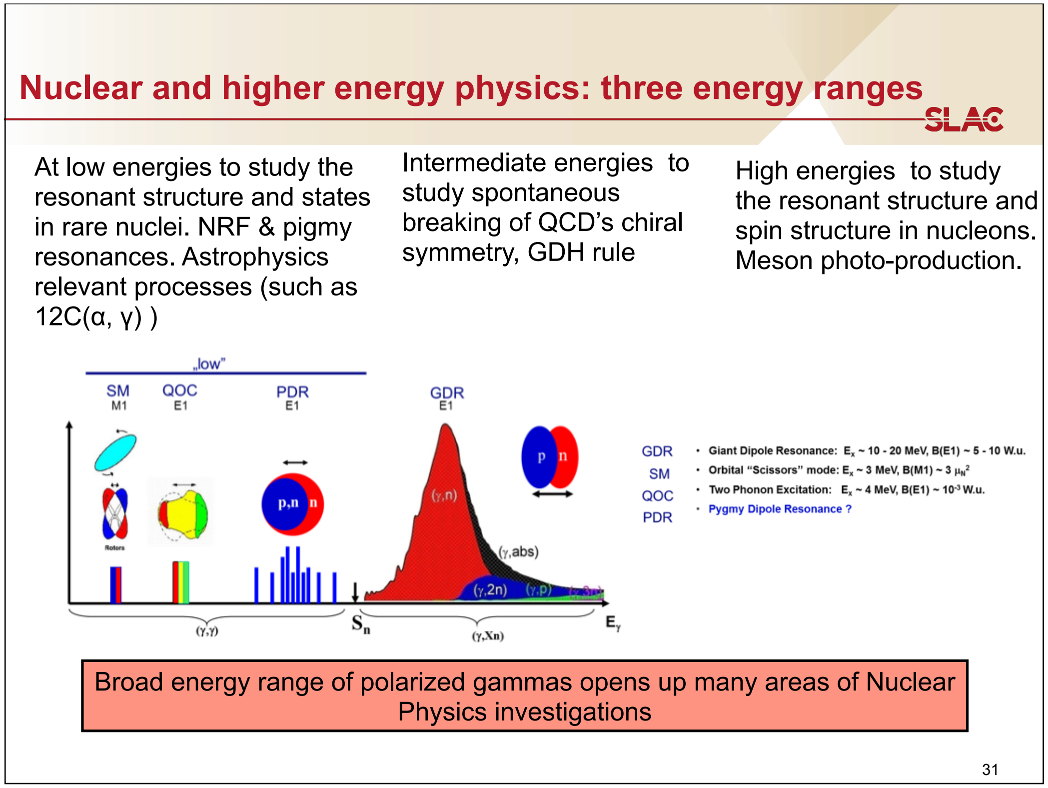
Name	ROKK	GRAAL	LEPS	HIγS	**BIG**
Location	Novosibirsk, Russia	Grenoble, France	Harima, Japan	Durham, US	**Menlo Park, US**
Accelerator	VEPP-4M	ESRF	SPRING-8	Duke SR	**SLAC**
e-beam, GeV	1.4 - 6	6	8	0.24 – 1.2	**1-10**
γ-beam, GeV	0.1-1.6	0.55-1.5	1.5-2.4	0.001-0.095	**0.001-2 (5)**
best γ–energy resolution, %	1-3	1.1	1.25	0.8-10	**0.1**
Maximum total flux, γ/sec	10^6	3×10^6	5×10^6	3 $\times10^9$, E<20 MeV 2 $\times10^8$, E>20 MeV	**10^{11} (10^{10})**

BIG is a superior source:

- Few thousand-fold γ–ray energy span from MeV to GeV
- About 10-fold better energy resolution
- Orders of magnitude larger flux

Unprecedented intensities and unique time structure open new opportunities in fundamental and applied research

Linac is advantageous since can interact with large percentage of the beam electrons (10%) unlike rings that have to limit beam disruption = lifetime issue



NP passionate about access to high energy gammas at Higgs (sp?) at Duke but cannot reach required energy and flux (decades long program)

From FACET Proposal:

The nuclear dipole response covers a range of structural phenomena, as shown in Figure 2-24. Physics themes involving electric and magnetic dipole distributions, which can easily be separated making use of the polarization of the photon beams, range from the study of isospin purity of states, to the emergence and evolution of nuclear quadrupole and octupole collectivity, and the build-up of nucleon skins. The best-known dipole excitation is the giant dipole resonance (GDR), which is typically found at energies around 15 MeV, well above the neutron-separation threshold. On the low-energy tail of the GDR another structure has been identified in a small set of nuclei, as mentioned above. This enhancement of strength around or below the neutron-separation threshold, referred to as Pygmy dipole resonance (PDR), is typically interpreted as the effect of a neutron skin building up around a proton-neutron symmetric core. The lowest part of the electric dipole response, at few MeV excitation energy, is dominated by multi-phonon excitations involving the octupole degree of freedom. The latter requires a short bursts of γ-rays natural for BIG's time structure. In either case, the enhanced, collective electric dipole strengths at low energies are a challenge to nuclear theory, since they can usually only occur due to particle-hole excitations across a major shell.

Facet-II beams

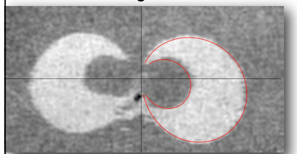
Injectors	Beam	Energy [GeV]	ε_{NX} x ε_{NY} [μm x μm]	σ_X x σ_Y [μm x μm]	σ_Z x ΔE/E [μm x %]
Thermionic	3nC e^-	10	30 x 3	20 x 20	20 x 1
	1.5nC e^+	10	30 x 3	20 x 20	20 x 1
Photoinjector	20pC e^-	10	0.1 x 0.1	1 x 1	2 x 1
	1nC e^-	10	1 x 1	3 x 3	5 x 1
	6nC e^-	10	5 x 5	10 x 10	20 x 1
	3nC e^+	10	30 x 3	20 x 20	40 x 1
Witness photoinjector	0.1nC e^-	0.1	1 x 1	50 x 50	20 x 0.1

Lasers	Energy / Power [Joule / TW]	Rep rate [Hz]	τ [fs]	λ [μm]
TI: Sapphire	1 / 30	120	30	0.8
CO_2 laser	0.1 / 0.1	120	1000	10.2

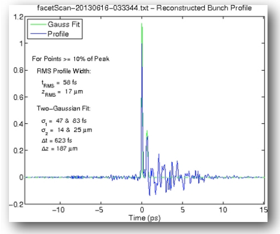
Gamma beams (Inverse Compton)	Energy [GeV]	Intensity	Rep rate [Hz]	σ_X x σ_Y [μm x μm]	σ_Z [μm]
TI: Sapphire	1.8 GeV	10^{10}	120	5 x 5	10
CO_2 laser	150 MeV	10^{10}	120	5 x 5	10

Very Productive User Run
Every Program Expecting Publishable Results

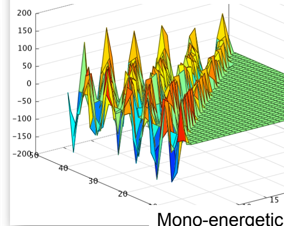
Switching Mechanisms in Ultrafast Electromagnetic Pulses



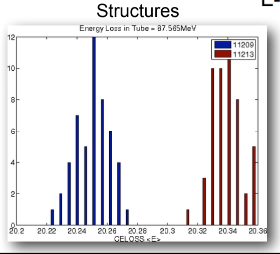
THz Reconstruction of Two-Bunch Profile

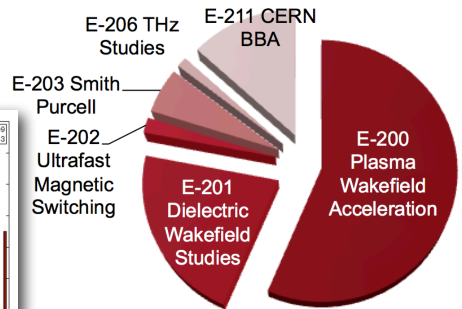


An Automated Method for Dispersion Free Steering

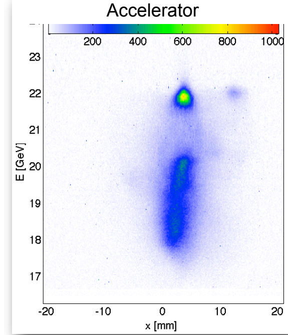


Demonstration of Gigavolt-per-meter Accelerating Gradients in Dielectric Wakefield Accelerating Structures





Mono-energetic Acceleration in a Beam-driven Plasma Wakefield Accelerator



Science/User Perspective

FACET is living up to its' potential and performance and machine performance is exceeding expectations

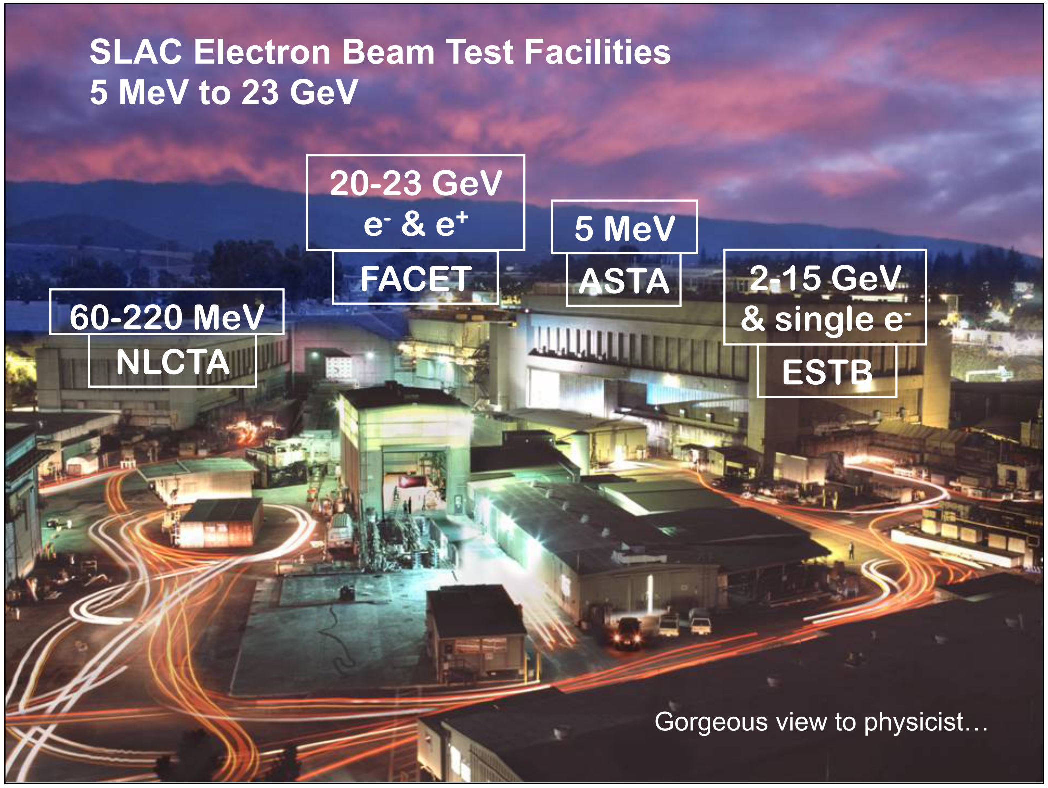
FY13 Run demonstrates the importance of doing experiments:

- Ionization of Ar, He not expected and would have missed opportunity to investigate ionization injection
- Cannot properly simulate ionization injection even on most powerful computers
- FACET offers unique opportunity to demonstrate emittance preservation in long linac

Word is getting out and new proposals coming in – anticipating great user meeting next week

It is a very exciting time for beam driven wakefield accelerators!

- Dielectric structures finally breaking the GeV/m barrier
- Optimistic we will see demonstration of high-gradient meter scale plasma stage within the next year with good beam quality and efficiency
- Coming years will build on this with injection and higher brightness beams paving the way for the first applications


SLAC Electron Beam Test Facilities
5 MeV to 23 GeV
20-23 GeV
e- & e+
FACET
5 MeV
ASTA
60-220 MeV
NLCTA
2-15 GeV
& single e-
ESTB
Gorgeous view to physicist…