Quasi-Monoenergetic Plasma Wakefield Acceleration at FACET

and plans for FACET-II...

Mark Hogan, September 19, 2013

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Great Desire for Compact Access to High Energy Beams

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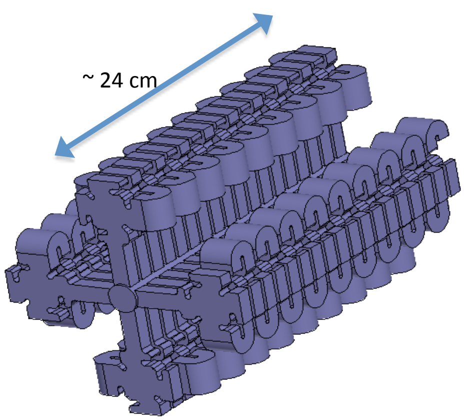
High energy particle accelerators are the ultimate microscopes

- Reveal fundamental particles and forces in the universe at the energy frontier
- Enable x-ray lasers to look at the smallest elements of life on the molecular level

Looking to advanced concepts to shrink the size and cost of these accelerators by factors of 10-1000

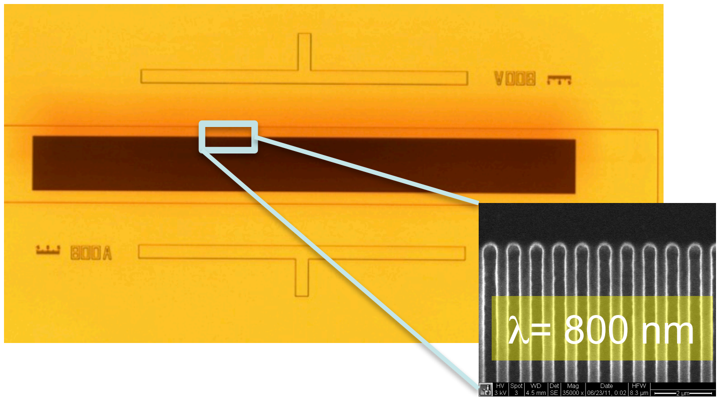
Combine efficient accelerator drivers with high-field dielectric and plasma structures to develop new generation of particle accelerators

~100MeV/m



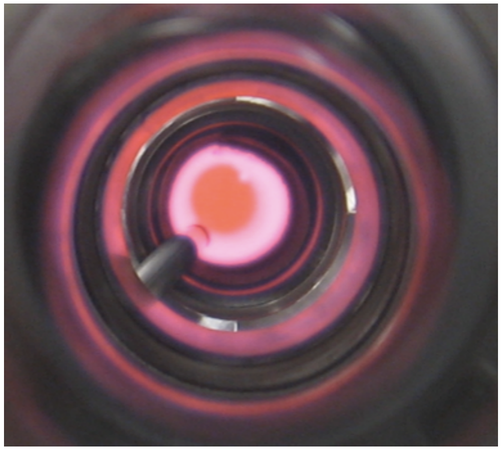
New designs and materials push metal structures to the limit

~1GeV/m



Telecom and Semiconductor tools used to make an 'accelerator on a chip'

~10GeV/m



Extremely high fields in 1,000°C lithium plasmas have doubled the energy of the 3km SLAC linac in just 1 meter

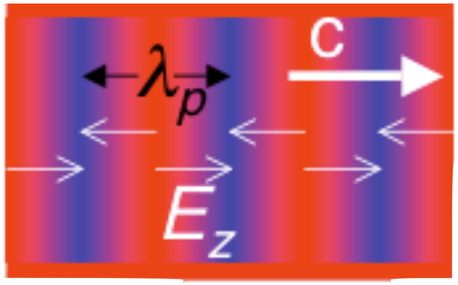
Why Plasmas?

Relativistic plasma wave (electrostatic):

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

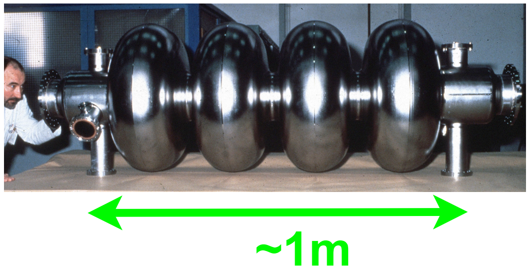
$$E_z = \left(\frac{m_e c^2}{\varepsilon_0}\right)^{1/2} n_e^{1/2} \cong 100\sqrt{n_e(cm^{-3})} = \underline{1GV/m}$$

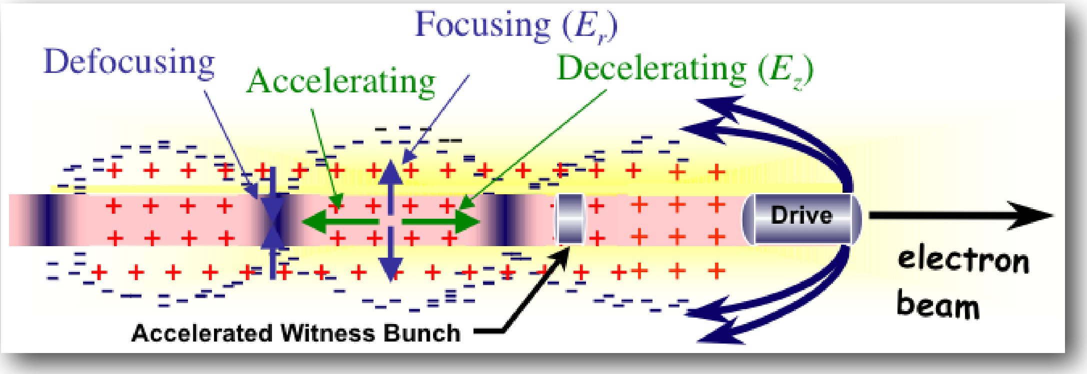
$n_e = 10^{14}\ cm^{-3}$

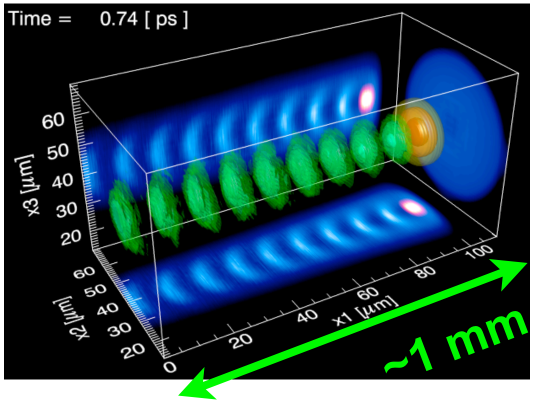


Large
Collective Response!

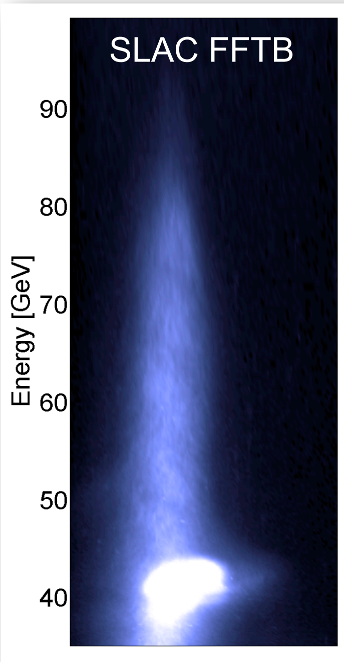
- Plasmas are already ionized, no break down
- Plasma wave can be driven by:
  - Intense laser pulse (LWFA)
  - Short particle bunch (PWFA)







Electron Acceleration in Plasmas



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

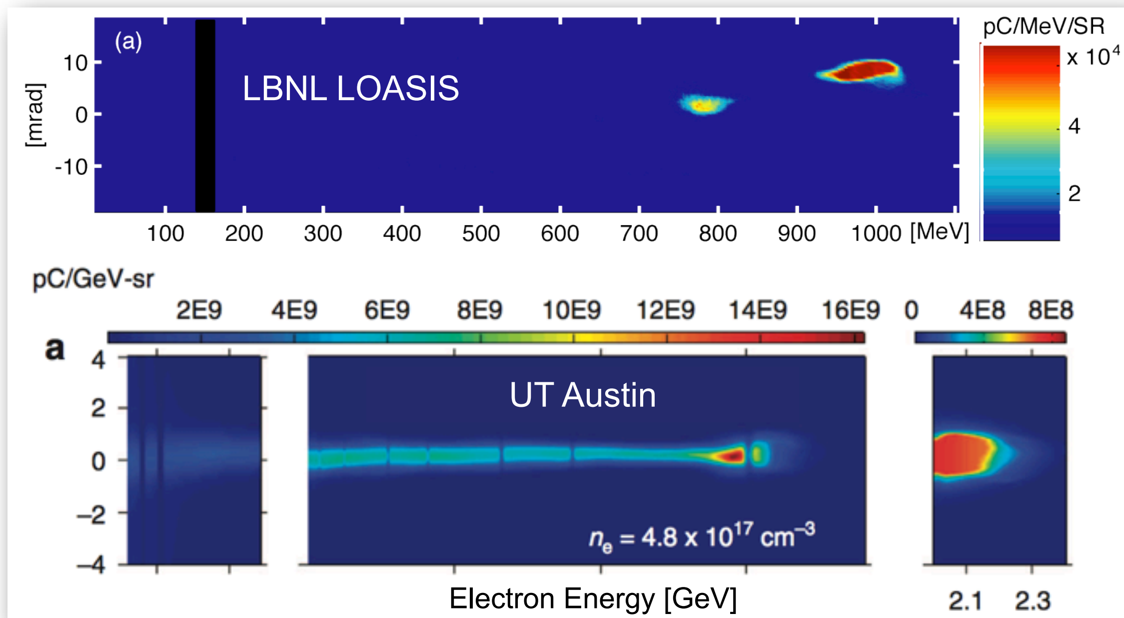
Beam Driven Plasmas:

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

Laser Driven Plasmas:

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

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



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

FACET Has a Multi-year Program to Study PWFA

Primary Goal:

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

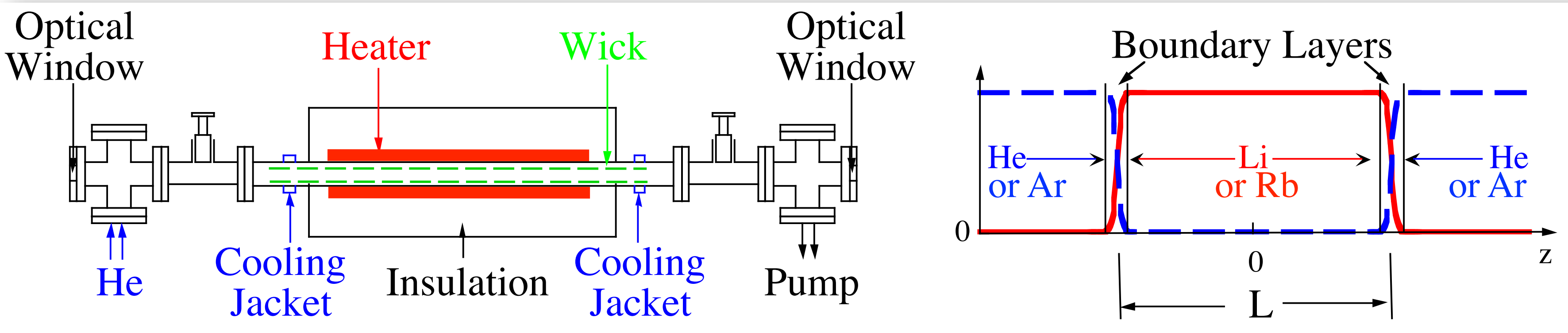
- Meter scale
- High gradient
- Preserved emittance
- Low energy spread
- High efficiency

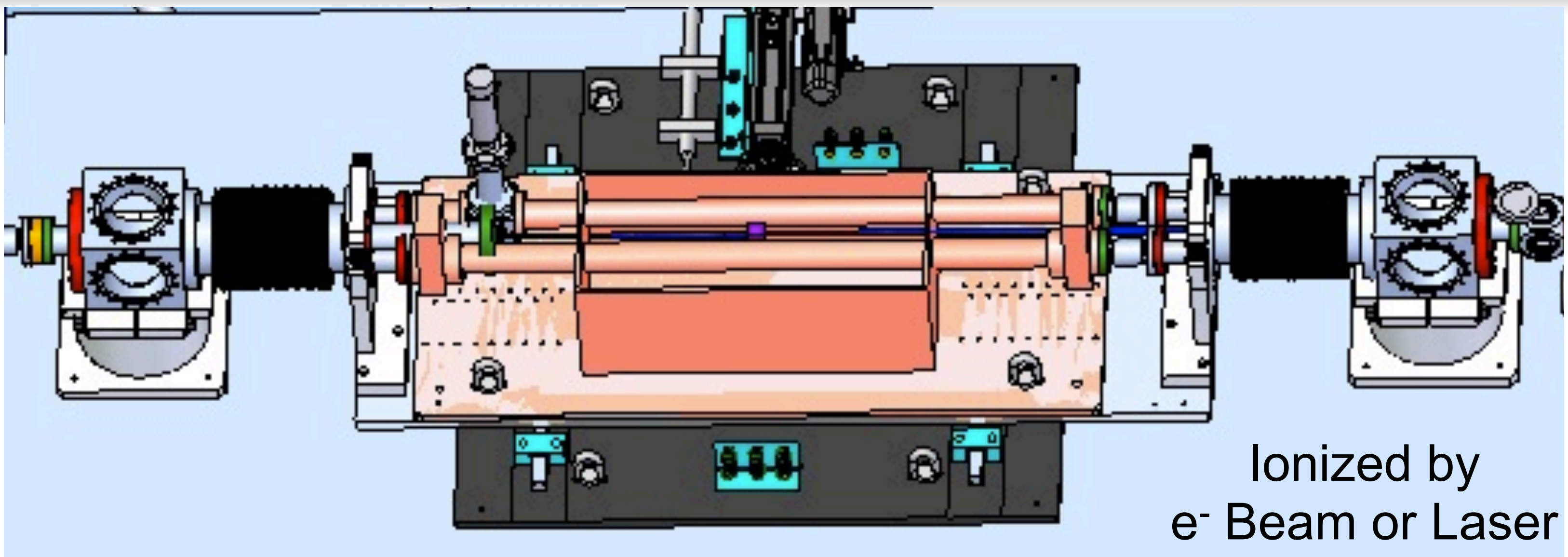
Timeline:

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

Heat Pipe Oven Has Been Heart of Plasma Source Since 1998

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



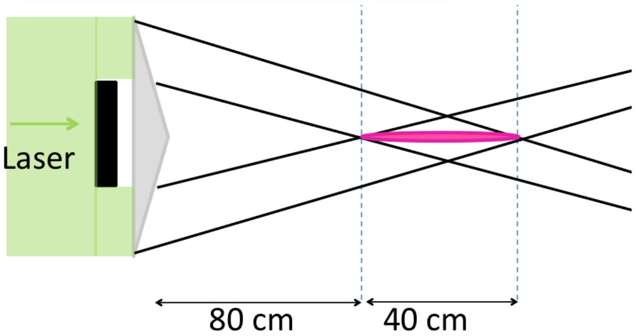


High-energy accelerator requires meter scale uniform high-density plasma

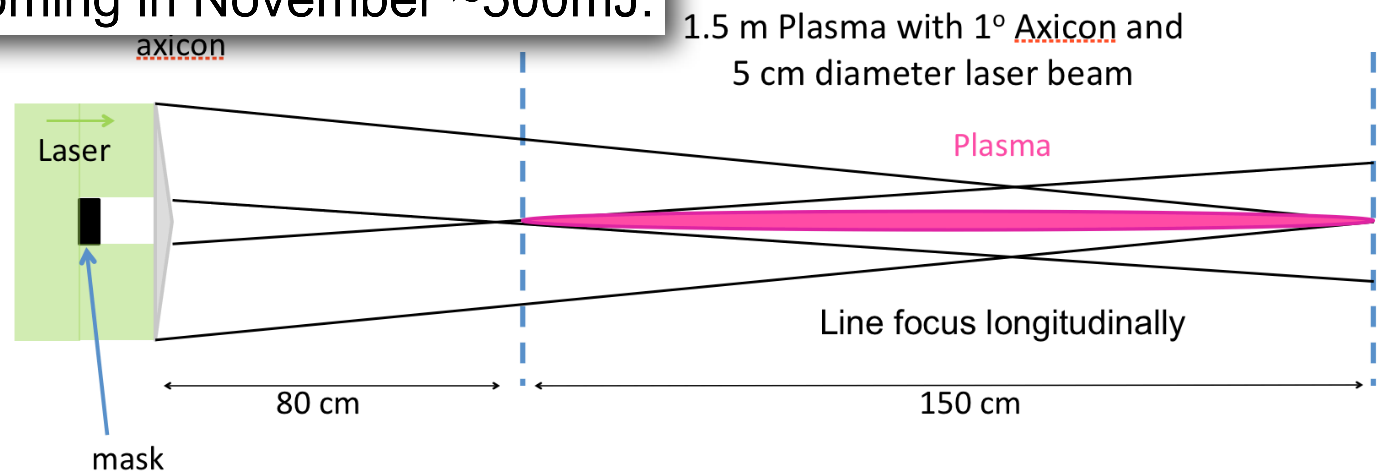
Use a Laser to Turn Lithium Vapor into a Plasma – Axicon Geometry Determines the Plasma Length

UCLA SLAC

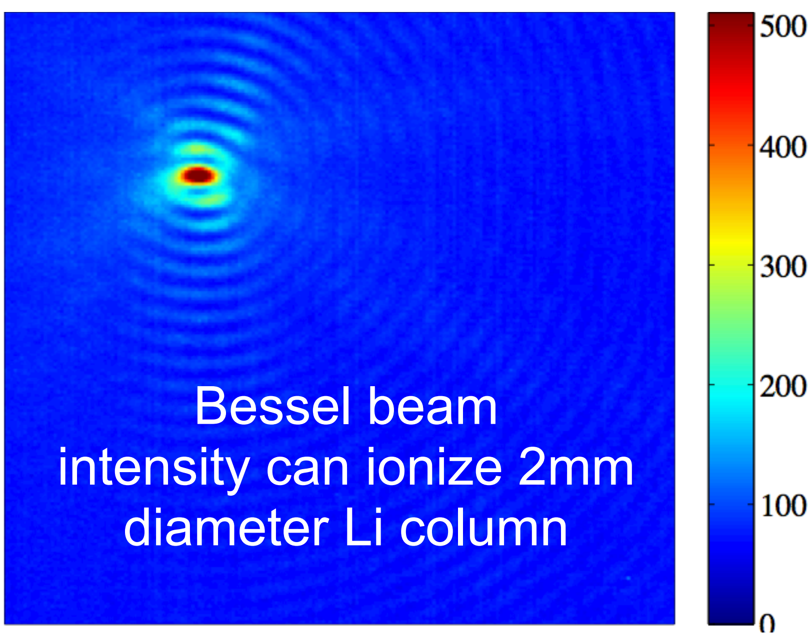
July '13 ~250mJ:



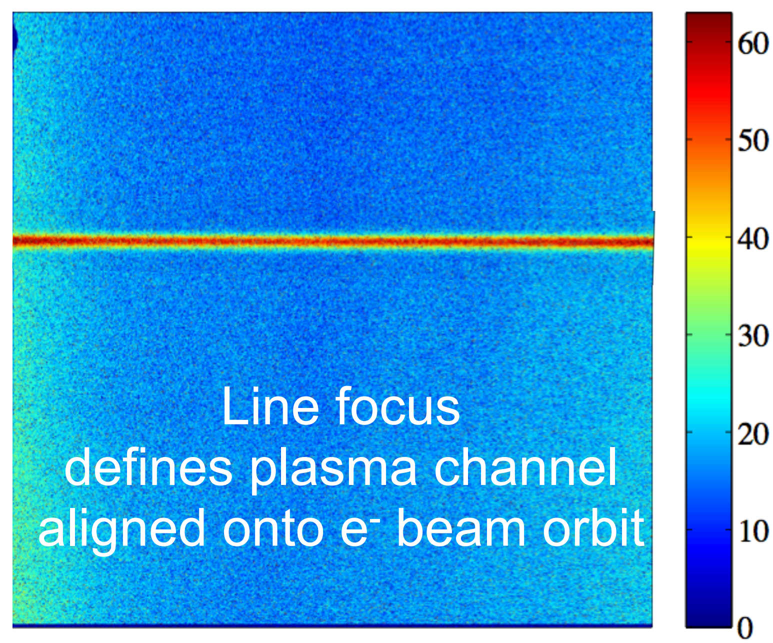
Coming in November ~500mJ:



Measured Transverse Profile



Side View of Plasma Column



Collimation System Shapes Longitudinal Phase Space (Better?)

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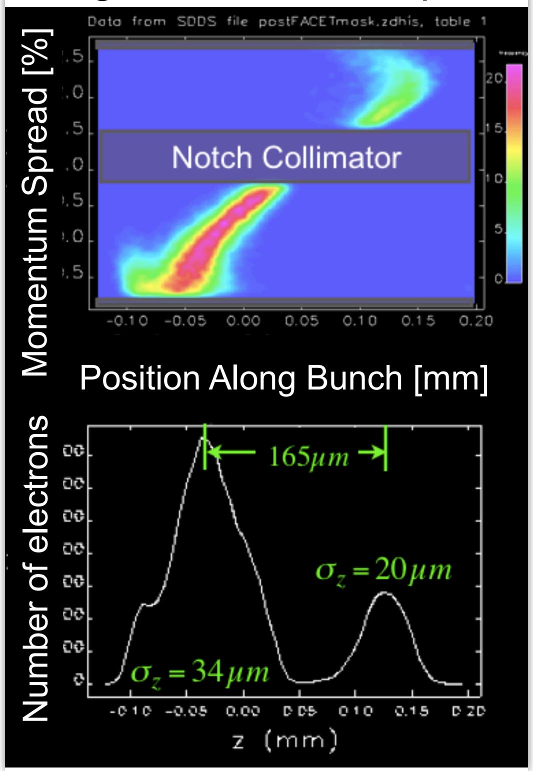
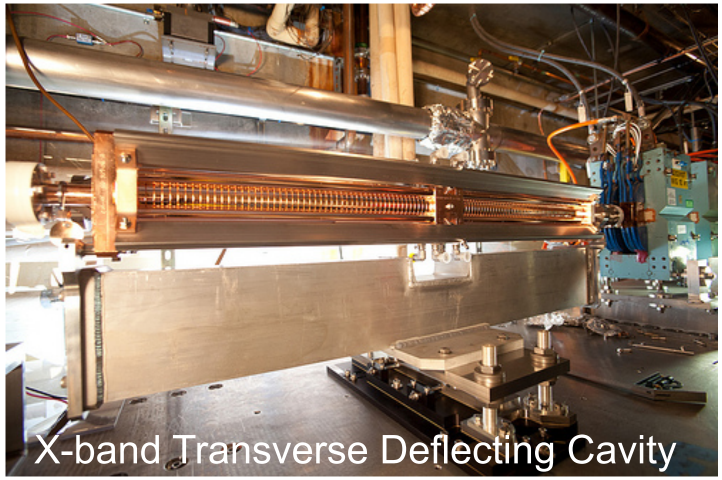
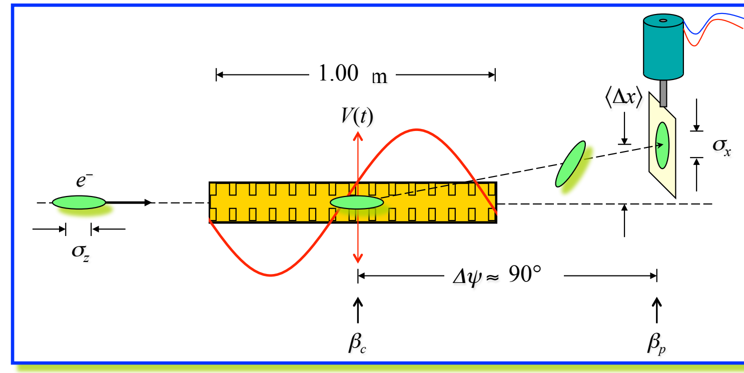
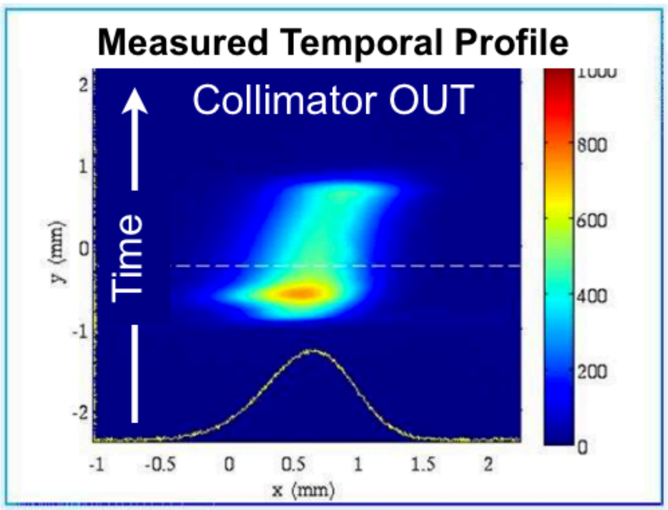
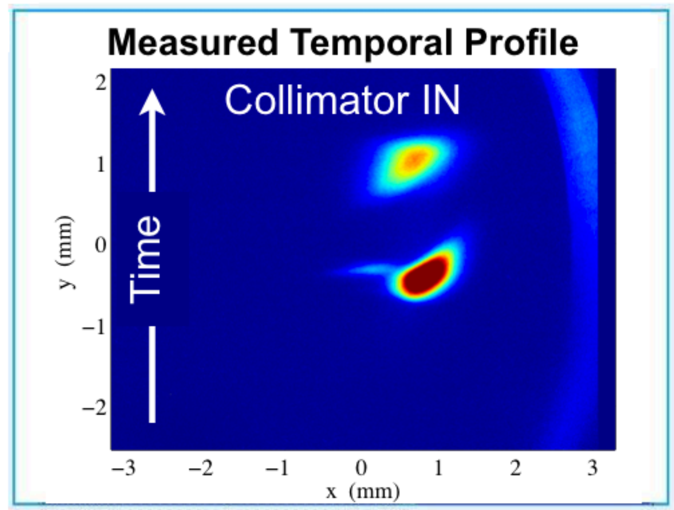
Simulation of Collimated Longitudinal Phase Space











Have developed techniques to create and measure drive-witness bunch pairs spaced a fraction of a plasma wavelength apart

Multi-GeV Energy Gain in <30cm plasma!

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

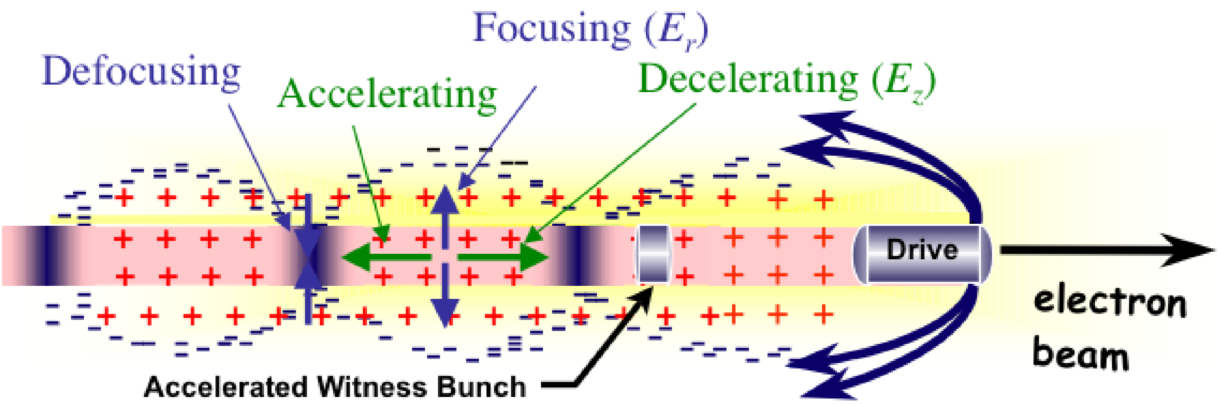
FY13 FACET Run put all the tools in place: pre-ionized plasma and tailored two-bunch structure for first beam driven mono-energetic acceleration

I’m sorry, this has been removed pending publication...

Some plots removed from previous viewgraph to satisfy embargo policies of some journals. Can release pending publication.

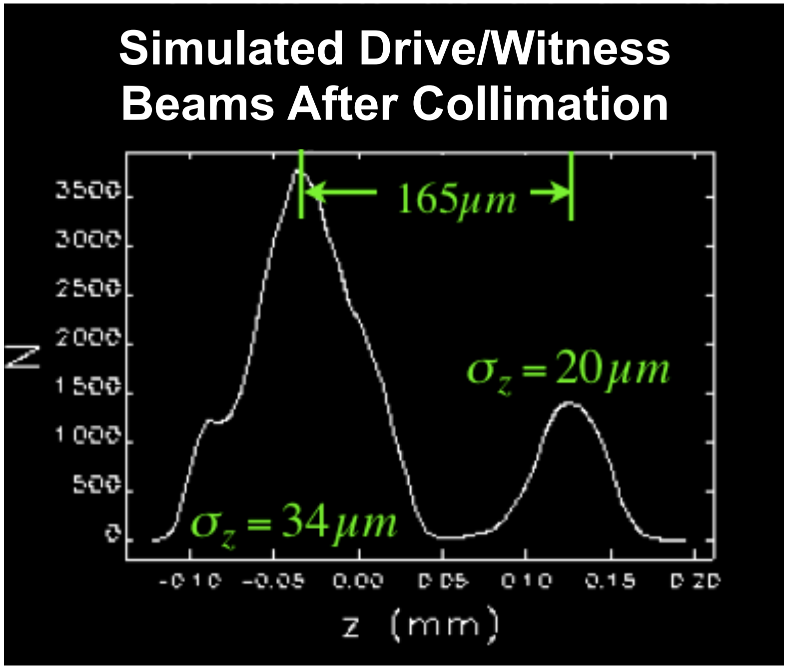
Primary Scientific Goal of FACET: Demonstrate a Single Stage Plasma Accelerator for Electrons

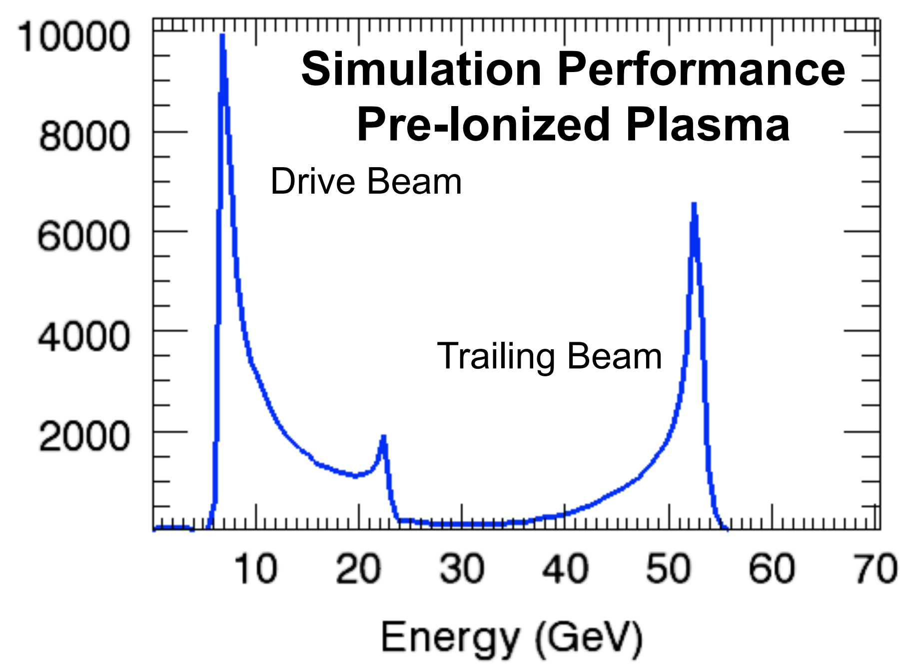
E200: Collaboration between SLAC/UCLA



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%

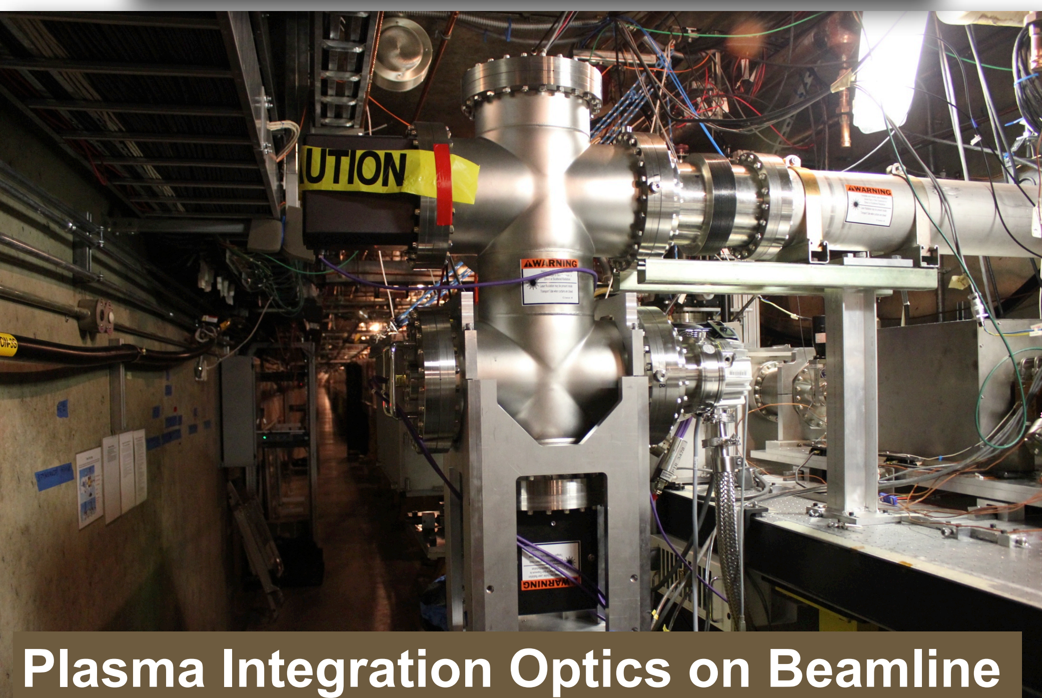




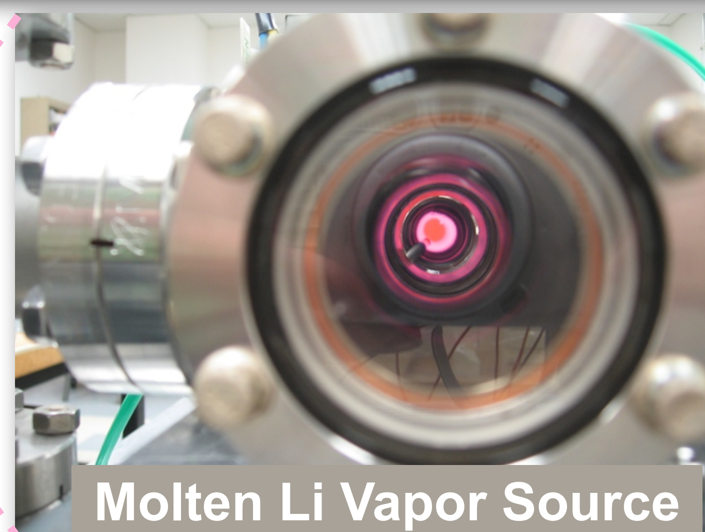
10TW FACET Ionization Laser:
Enabling technology for many new experiments

Laser Transport in Klystron Gallery

Laser System in new S20 Laser Room



Plasma Integration Optics on Beamline



Molten Li Vapor Source

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

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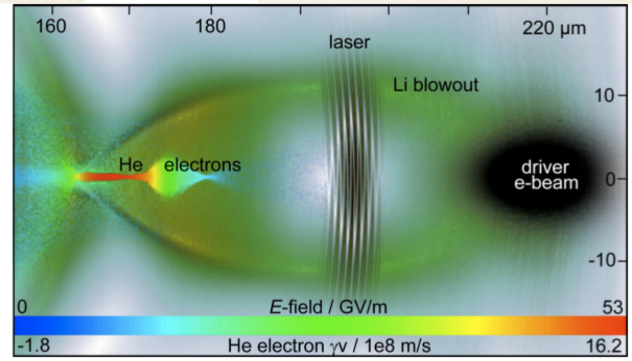

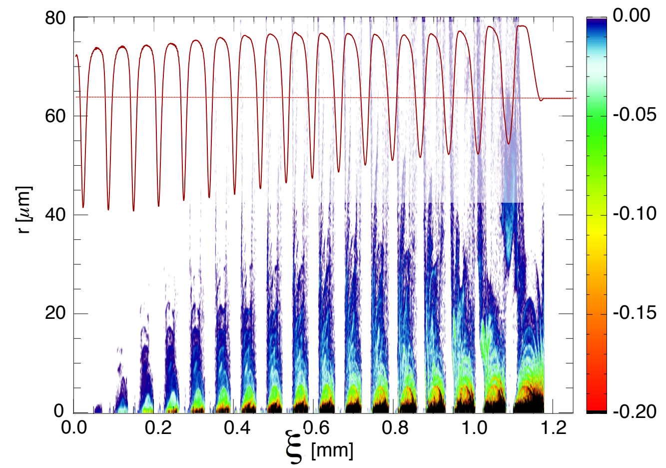

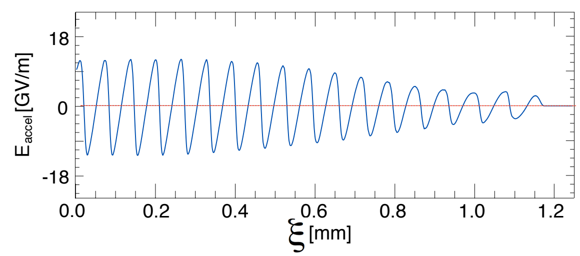

- Trojan Horse Plasma Wakefield Acceleration
  - (UCLA/SLAC/Tech-X/MPI/HHU)
- Study of the Self-Modulation of Long Lepton Bunches in Dense Plasmas and its Application to Advanced Acceleration Techniques
  - (IST/MPI/SLAC)
- Investigation of Hot Plasmas and Fourier Domain Holography of Plasma Wakes
  - (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

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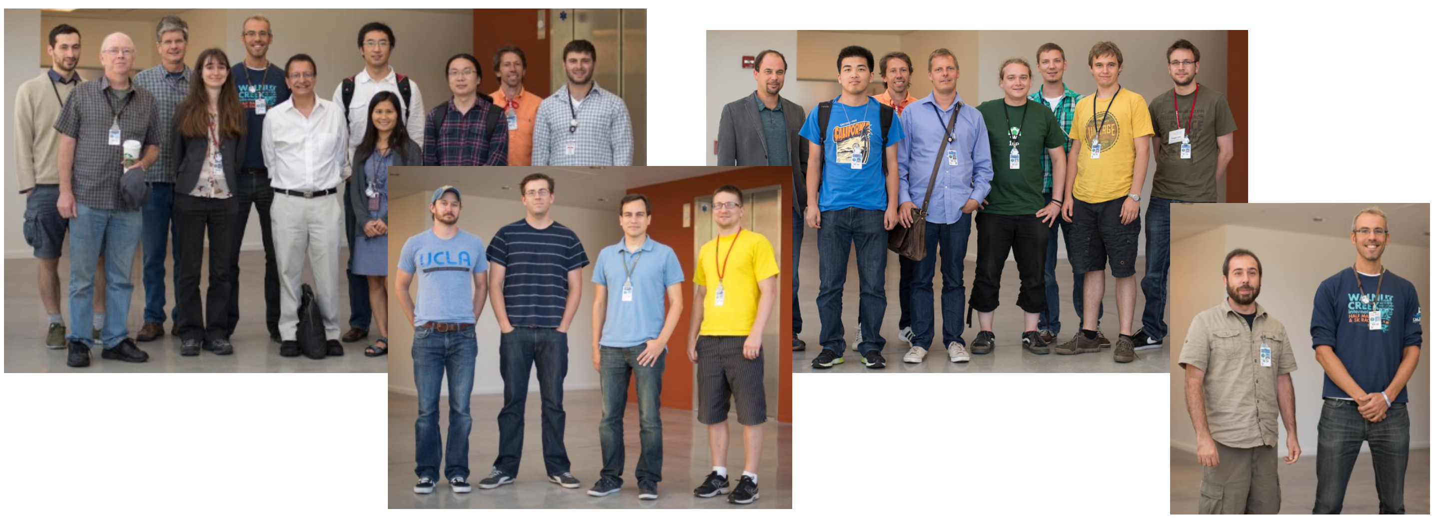
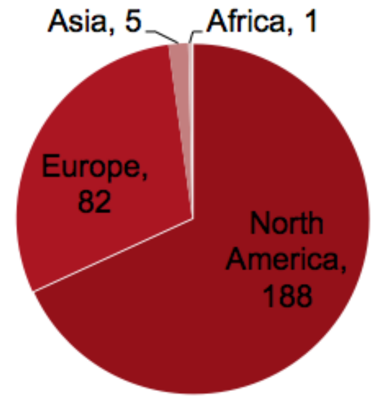
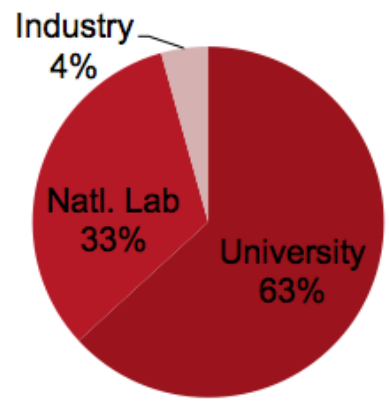
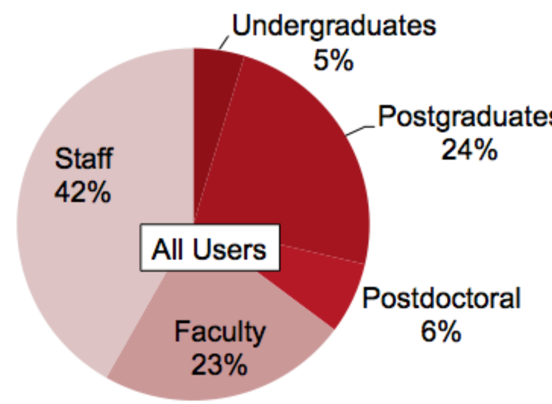
- Diverse and growing user community
- 1/3 from outside U.S.
- Majority from Universities
- Strong educational component
- Delivered to 6 experiments in 2013
- 8 experiments scheduled this Fall
- 13 experiments scheduled for 2014





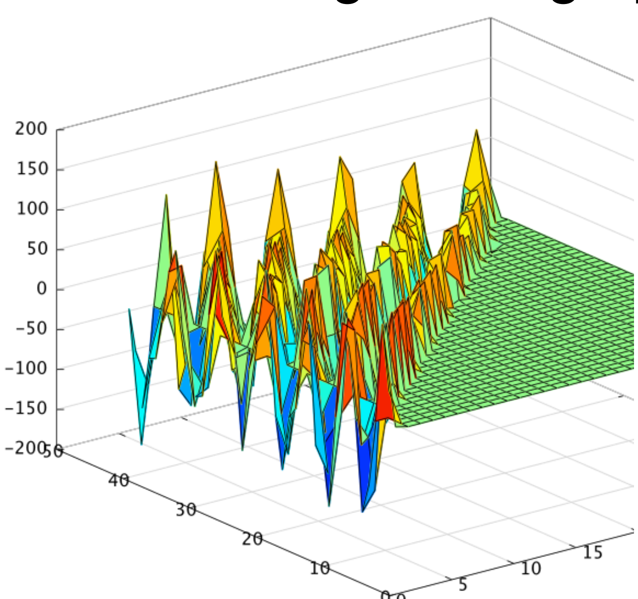


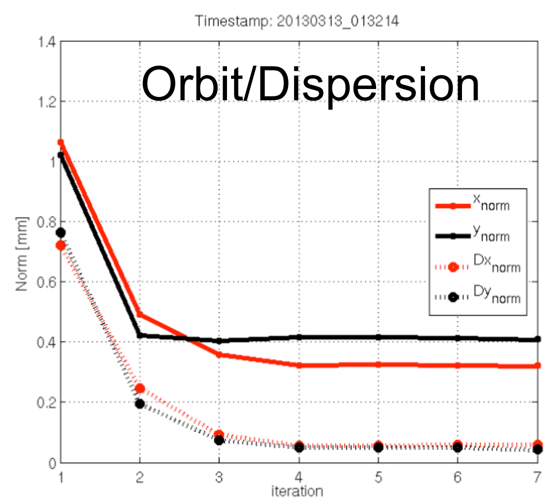


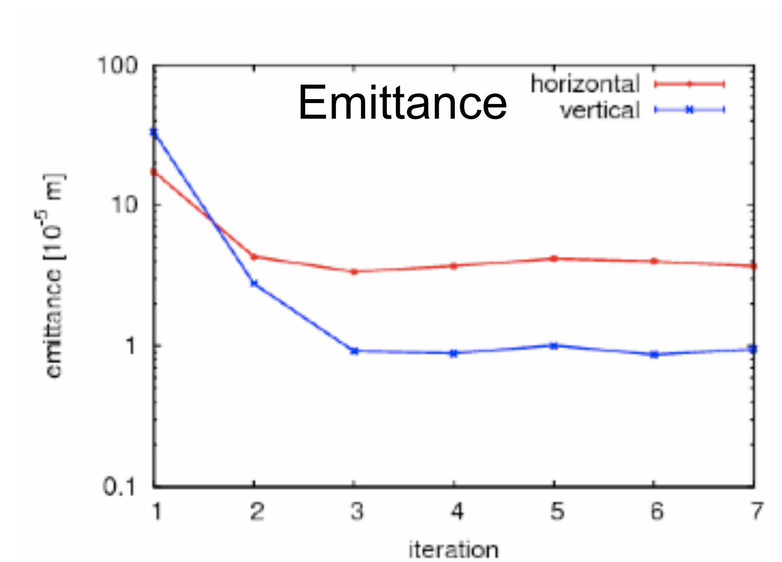
8 new experiments proposed at July'13 User meeting

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





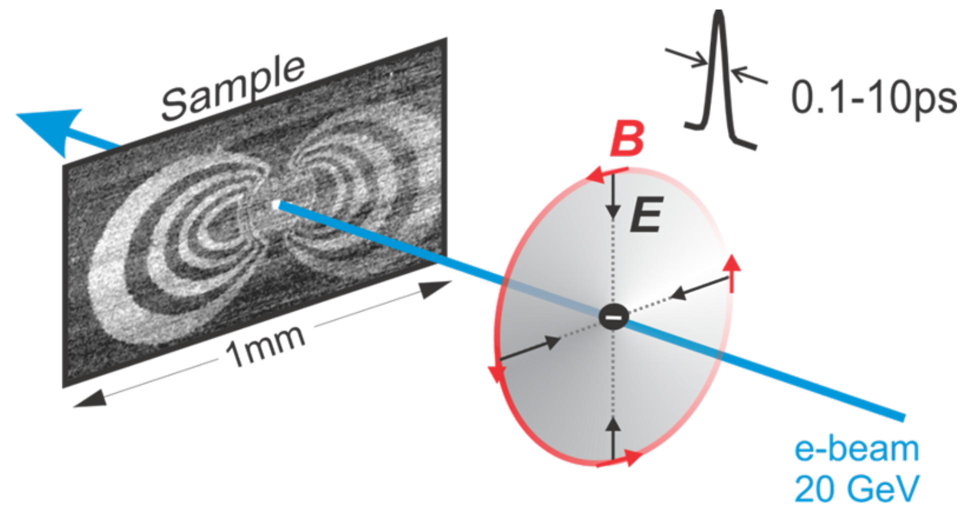


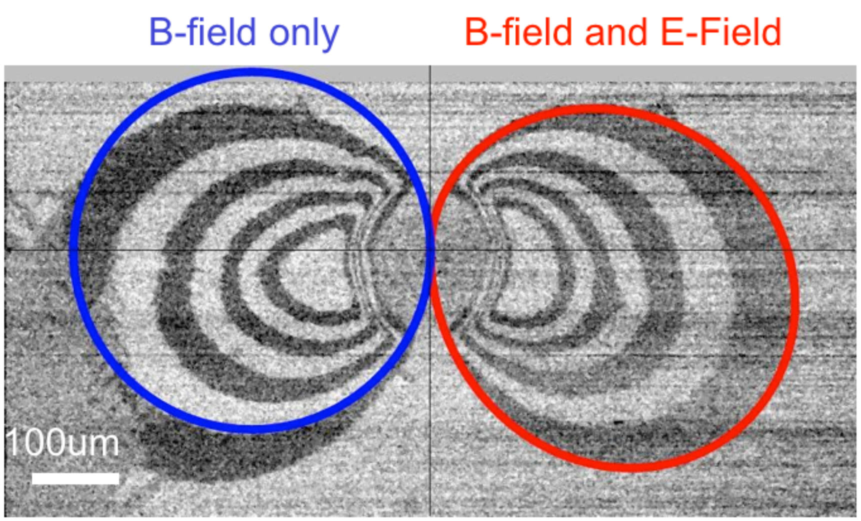
Will iterate these techniques when positrons available

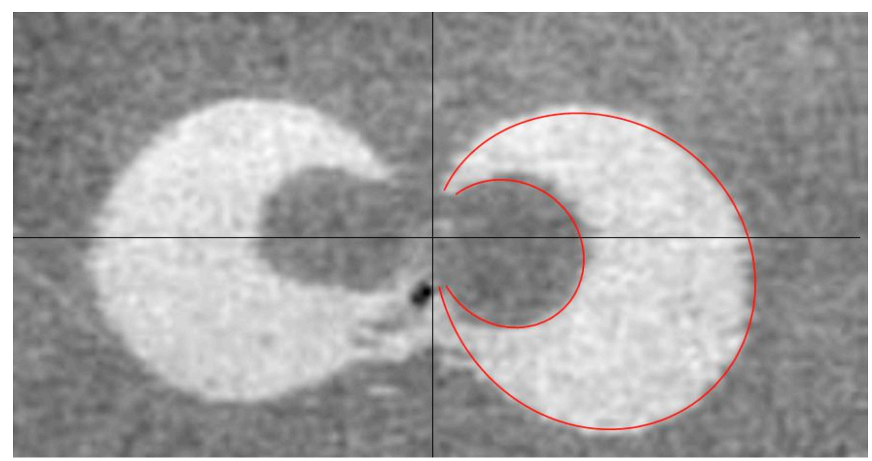
E202: E-field, Spin Dynamics and Switching Mechanisms in Ultrafast Electromagnetic Pulses

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

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

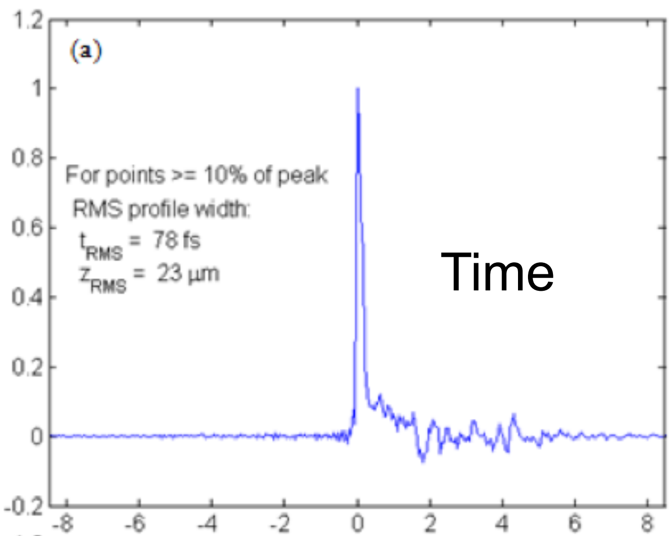


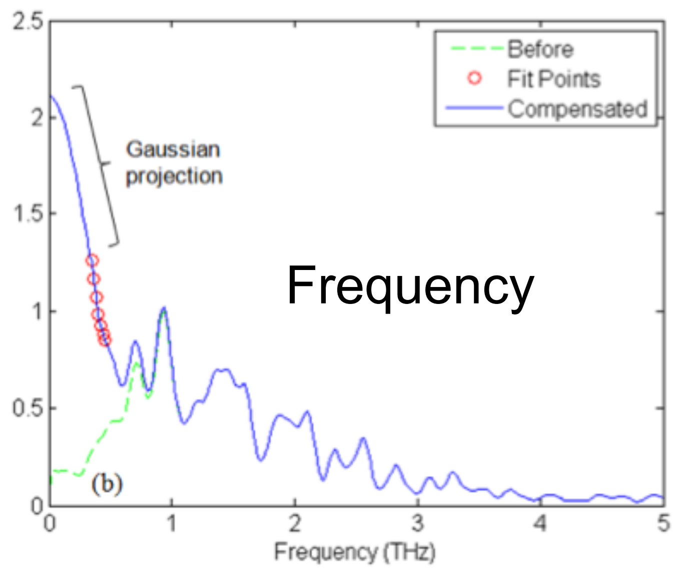




Surprising results from thick films – switching penetration beyond a skin depth points to new physics

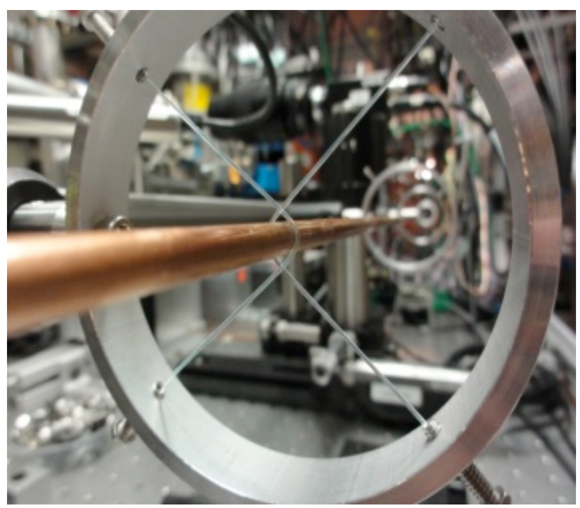
E206: Intense THz for Diagnostic & Pump-probe Applications

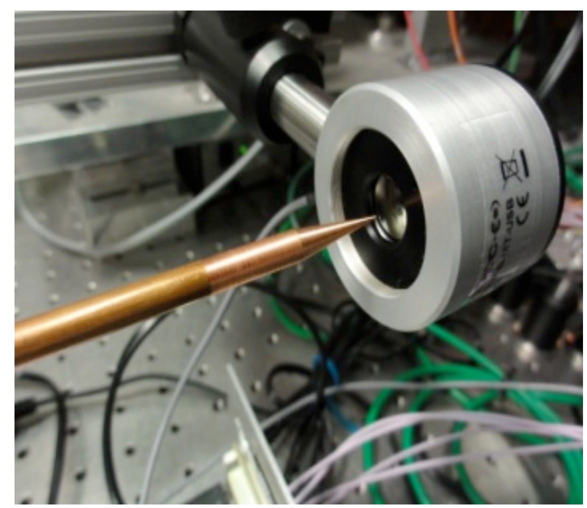




- THz interferometer can passively monitor longitudinal profile
- Developed and operates parasitically to main programs

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



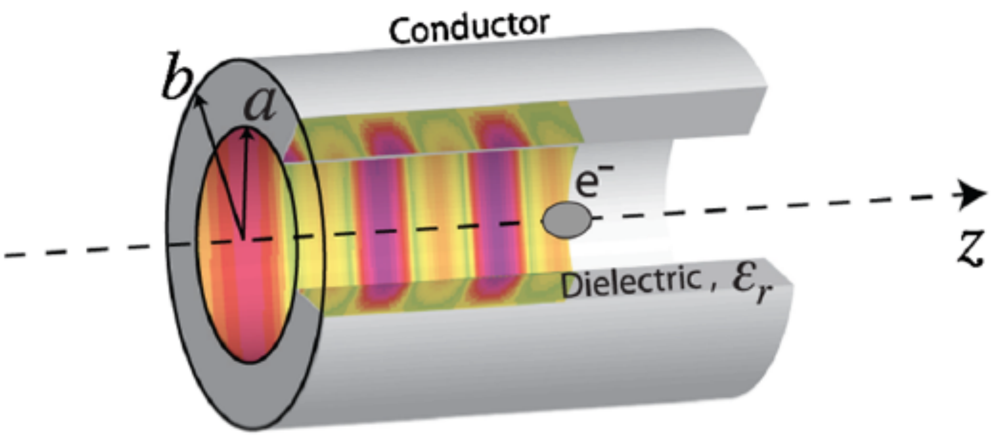


Developing techniques to transport and focus intense THz pulses for users

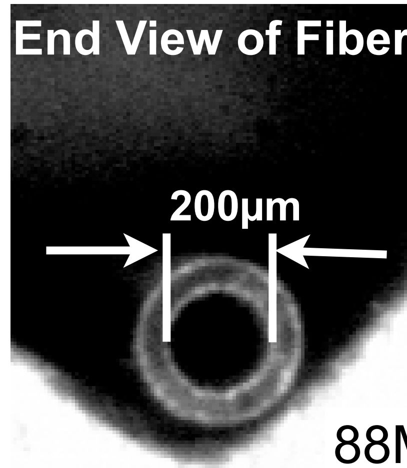
E201: Tests Structures at and Above Breakdown Voltage

UCLA, Euclid Techlabs, Tech-X, Radiabeam Technologies, NRL, SLAC, MPI, Argonne

- E201 is a progressive program to build meter-scale GeV/m dielectric accelerators



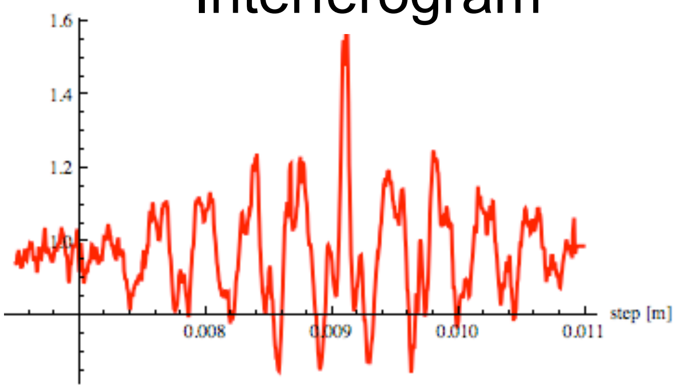
450µm SiO2 structure with 25µm Cu coating



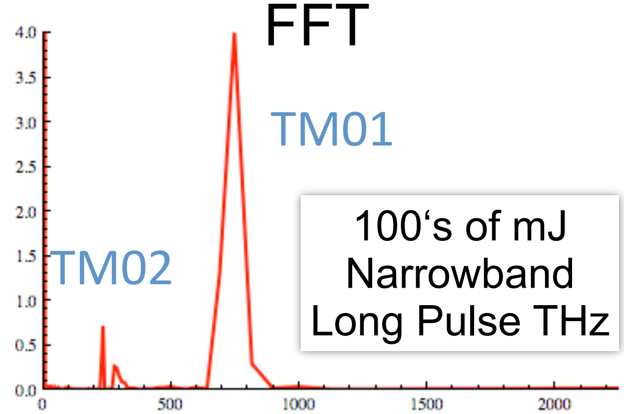
88MeV in 10cm

Tube IN Tube OUT

Interferogram



FFT



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

I’m sorry, this has been removed pending publication...

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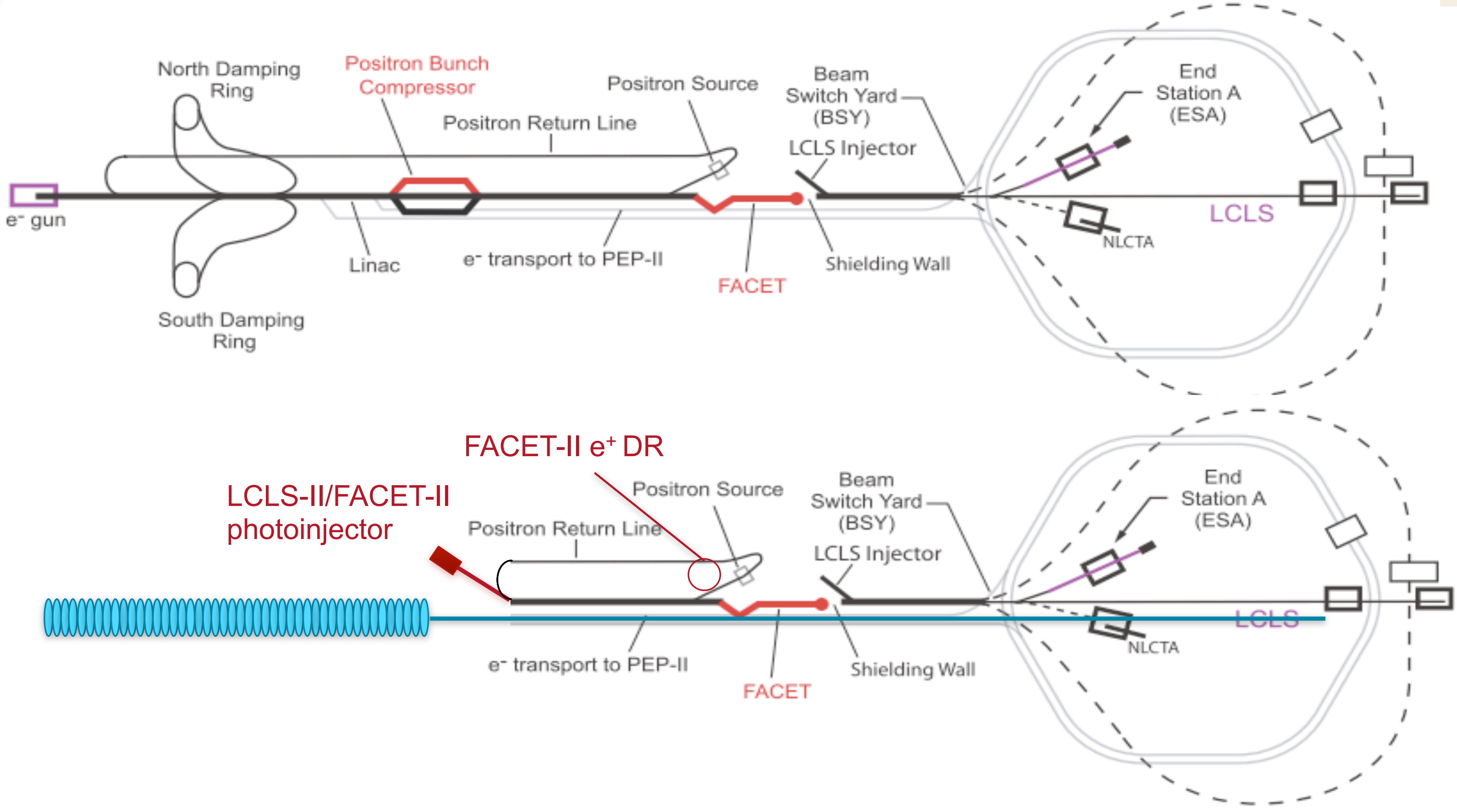
FACET-II in Sectors 10-20



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

List of Contributors

Brookhaven National Laboratory: V. Litvinenko, E. O'Brien

CERN: A. Grudiev, A. Latina, G. de Michele, D. Schulte, F. Zimmermann

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Max Planck Institute: P. Muggli

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University of Saskatchewan: R. Pywell

University of Virginia: B. Norum

Yale University: N. Cooper, M. Gai, V. Werner

52 researcher from 17 institutions supported by at least 9 different funding agencies

Three Parts of FACET-II Science Case:

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High gradient acceleration (Plasma Wakefield acceleration)

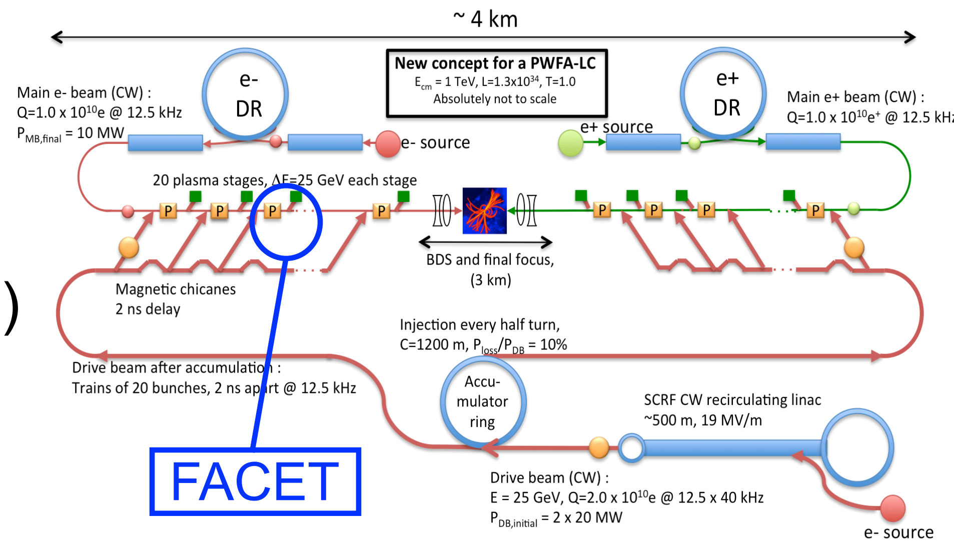
- Up to **1000x** improvement in gradient

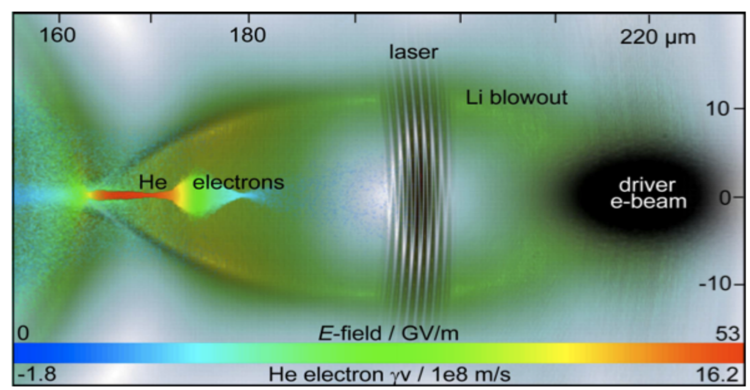
Extreme **brightness** beam generation (Trapping in Plasma Wakefield acceleration)

- 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

FACET Begins 2nd Phase of PWFA

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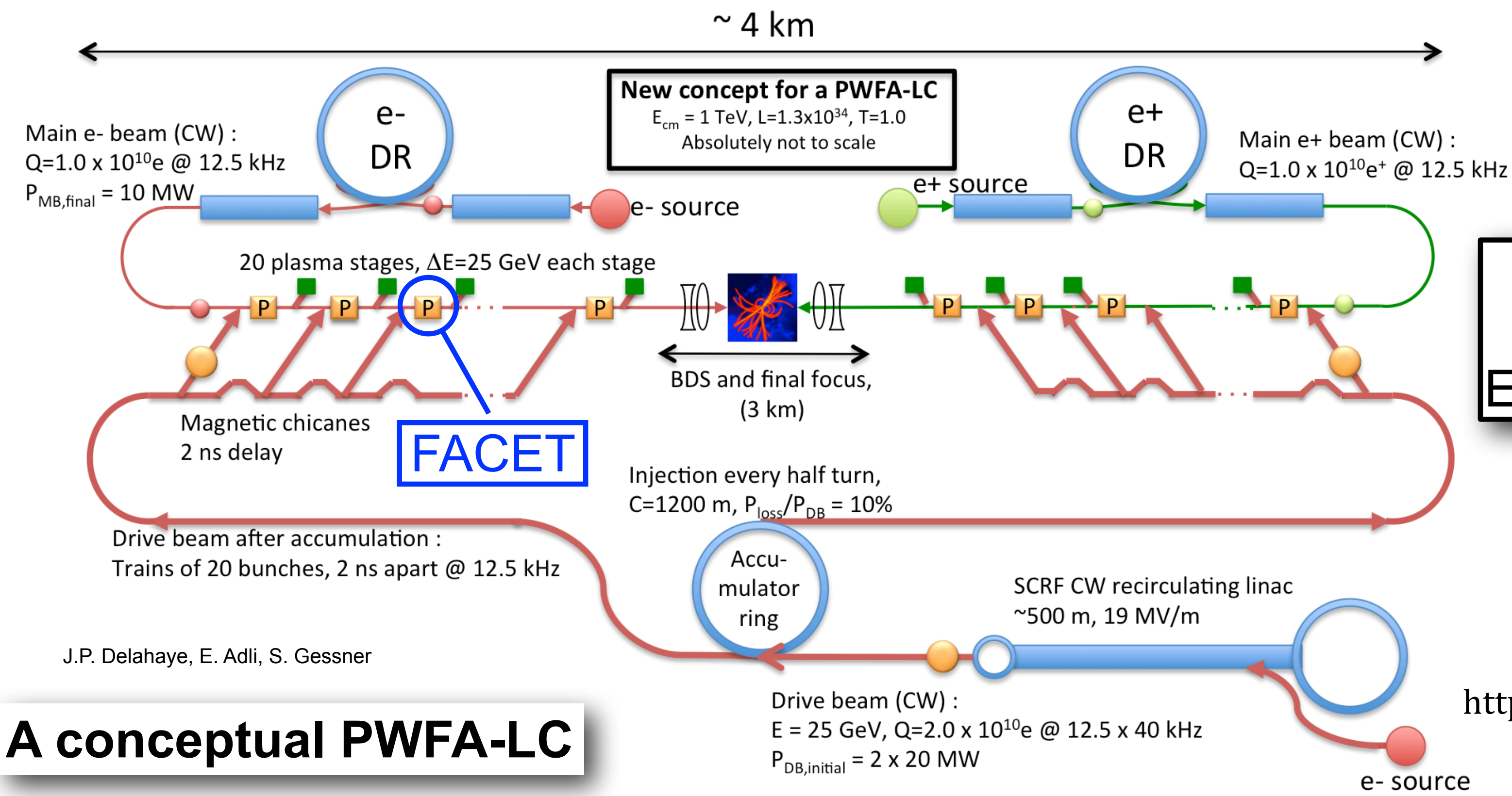
- SLAC FFTB demonstrated electron acceleration with 50GeV/m for 85cm
- FACET issues single stage
- FACET-II staging, high-brightness beams



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

J.P. Delahaye, E. Adli, S. Gessner

SLAC-PUB-15426
http://arxiv.org/abs/1308.1145

A conceptual PWFA-LC

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

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:

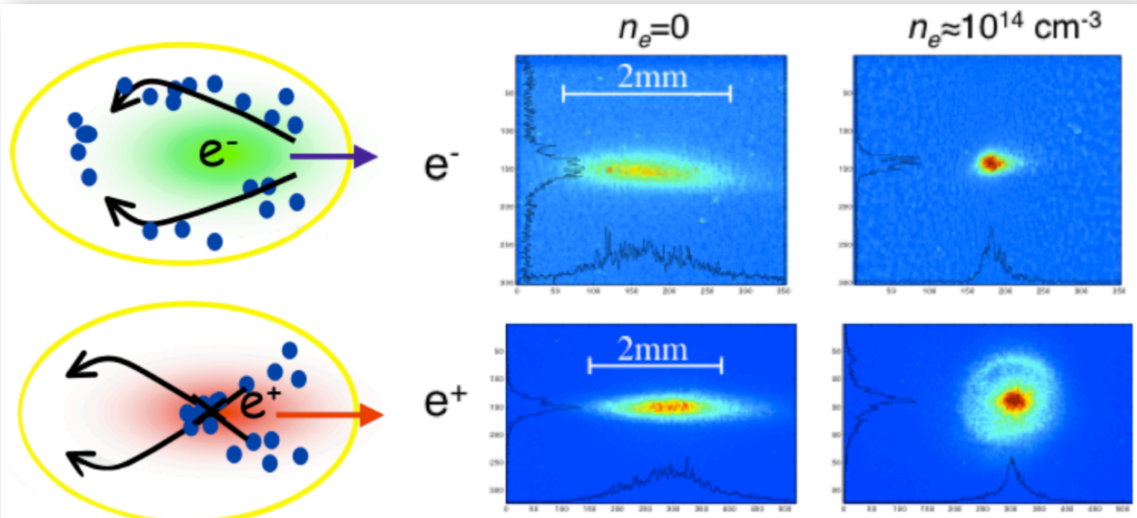
Positrons, beam quality, efficiency, and staging

- 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.

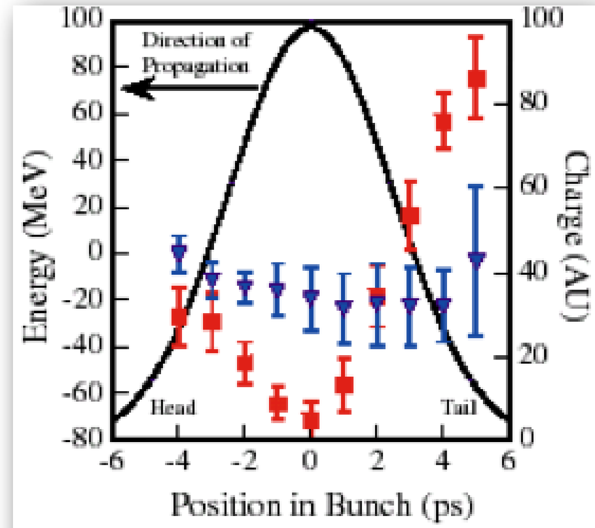
Answering these questions requires dedicated test facilities like FACET & FACET-II

Positron Focussing and Acceleration

Focusing and acceleration of positrons has been characterized at low densities

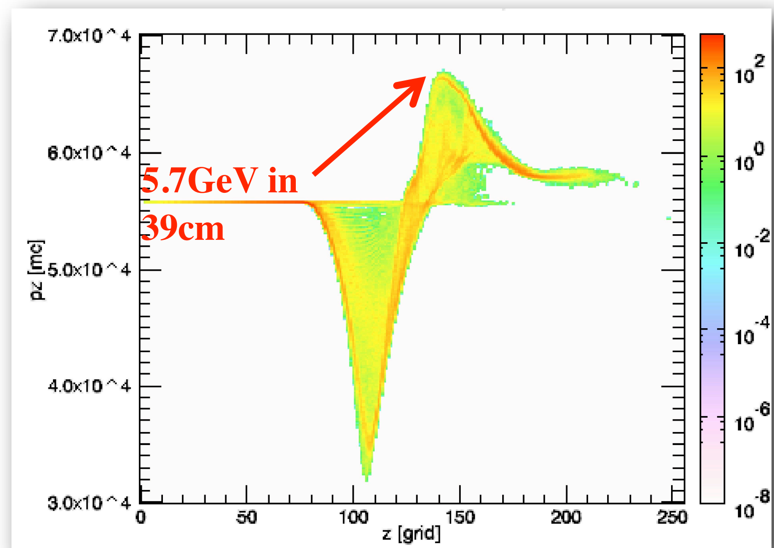


Phys. Rev. Lett. **90**, 205002 (2003) *Phys. Rev. Lett.* **101**, 055001 (2008)



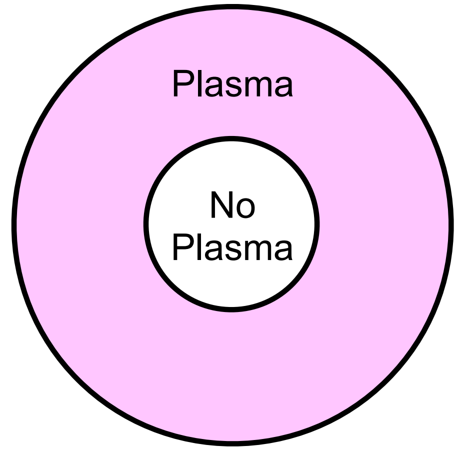
Phys. Rev. Lett. **90**, 214801 (2003)

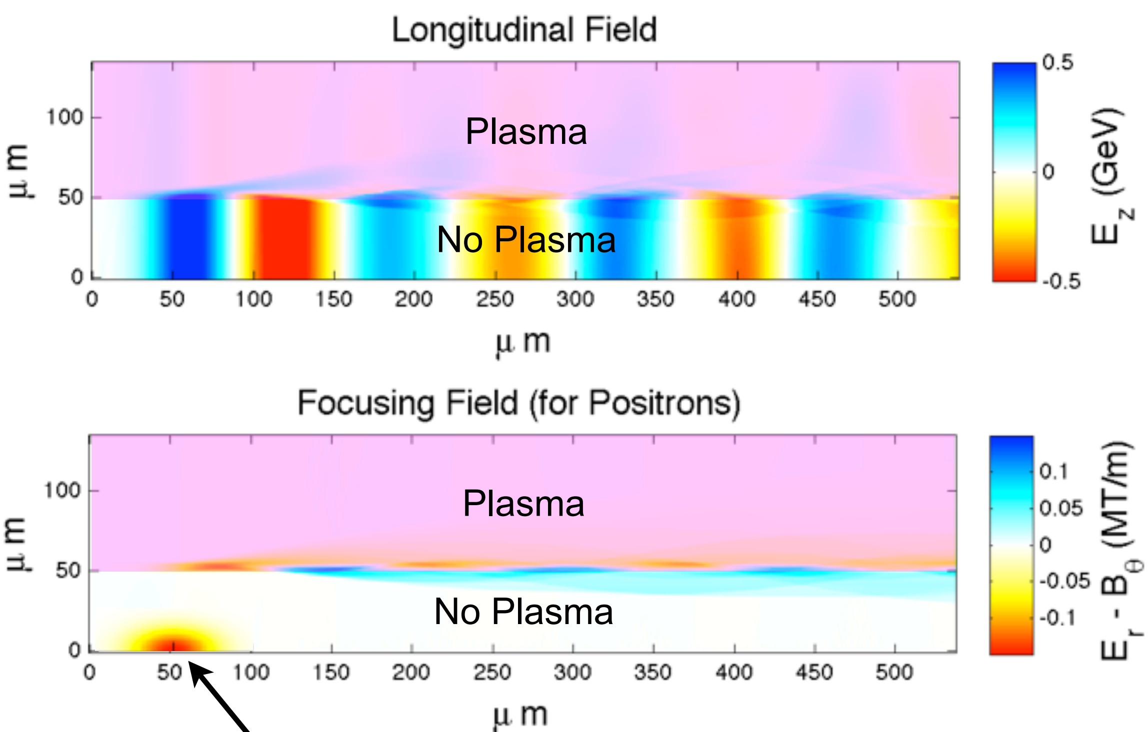
- High-gradient positron acceleration is possible
  - Can use wake of an electron or positron beam
- Need to iterate plasma source to minimize emittance growth but preserve high-gradients (hollow channels)
- FACET will make first tests of high-gradient positron acceleration in the next couple years



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

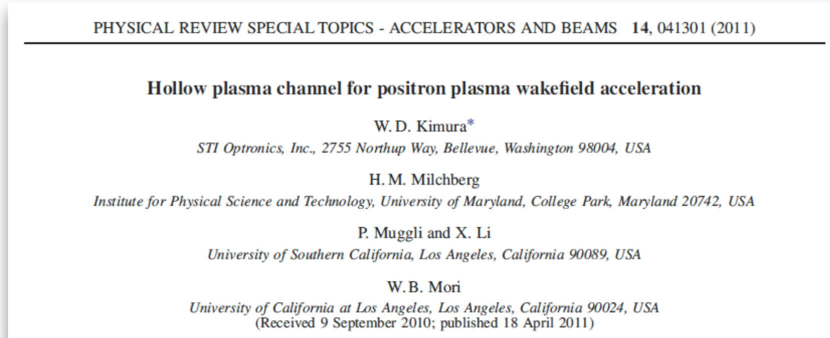
Electron beam driver

2D Osiris Simulations
Run on Hoffman2 Cluster at UCLA

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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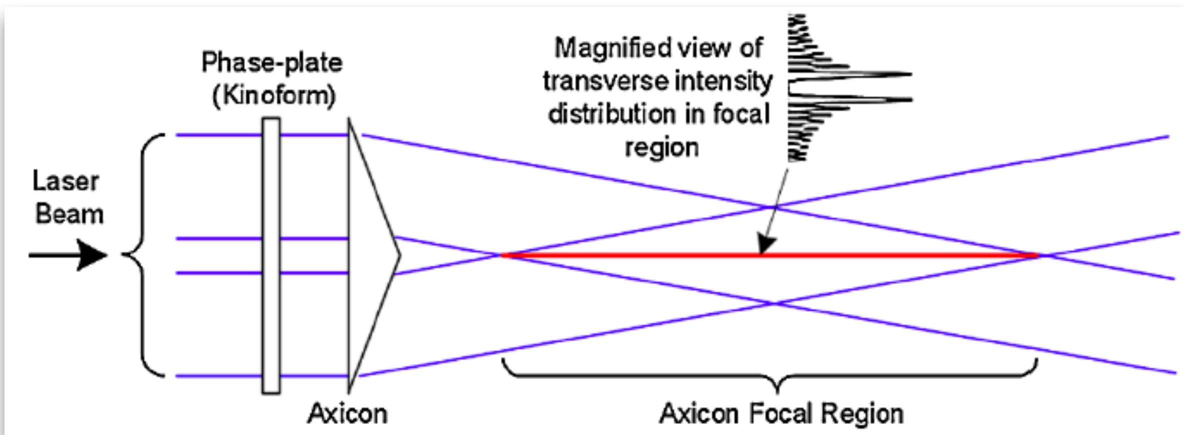
Laser/Kinoform Parameters

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



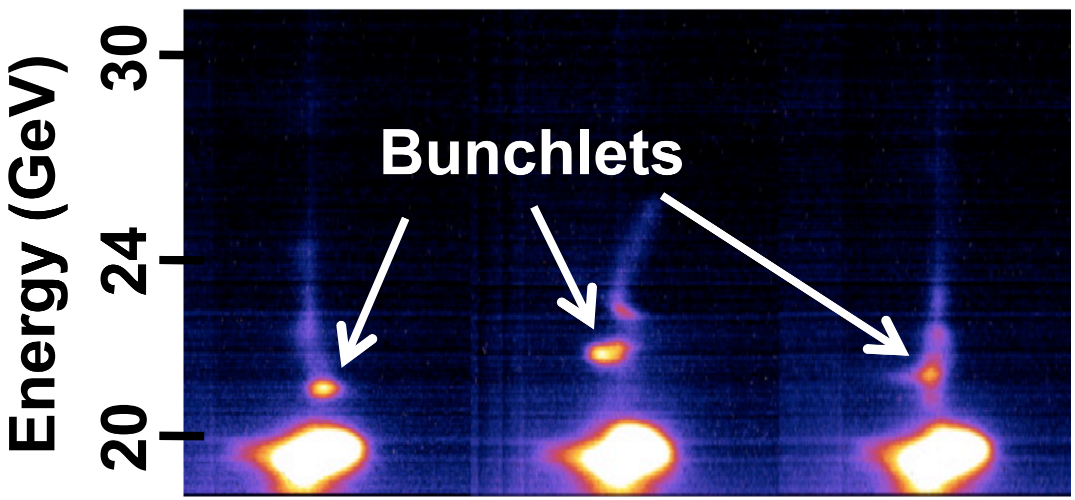
Plasma Parameters

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

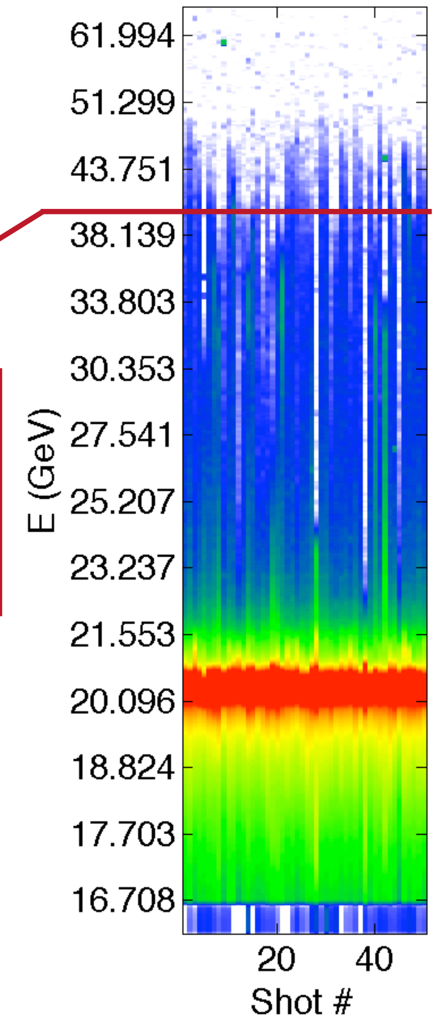
Positron Systems will re-commission this Fall with first experiments in 2014

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

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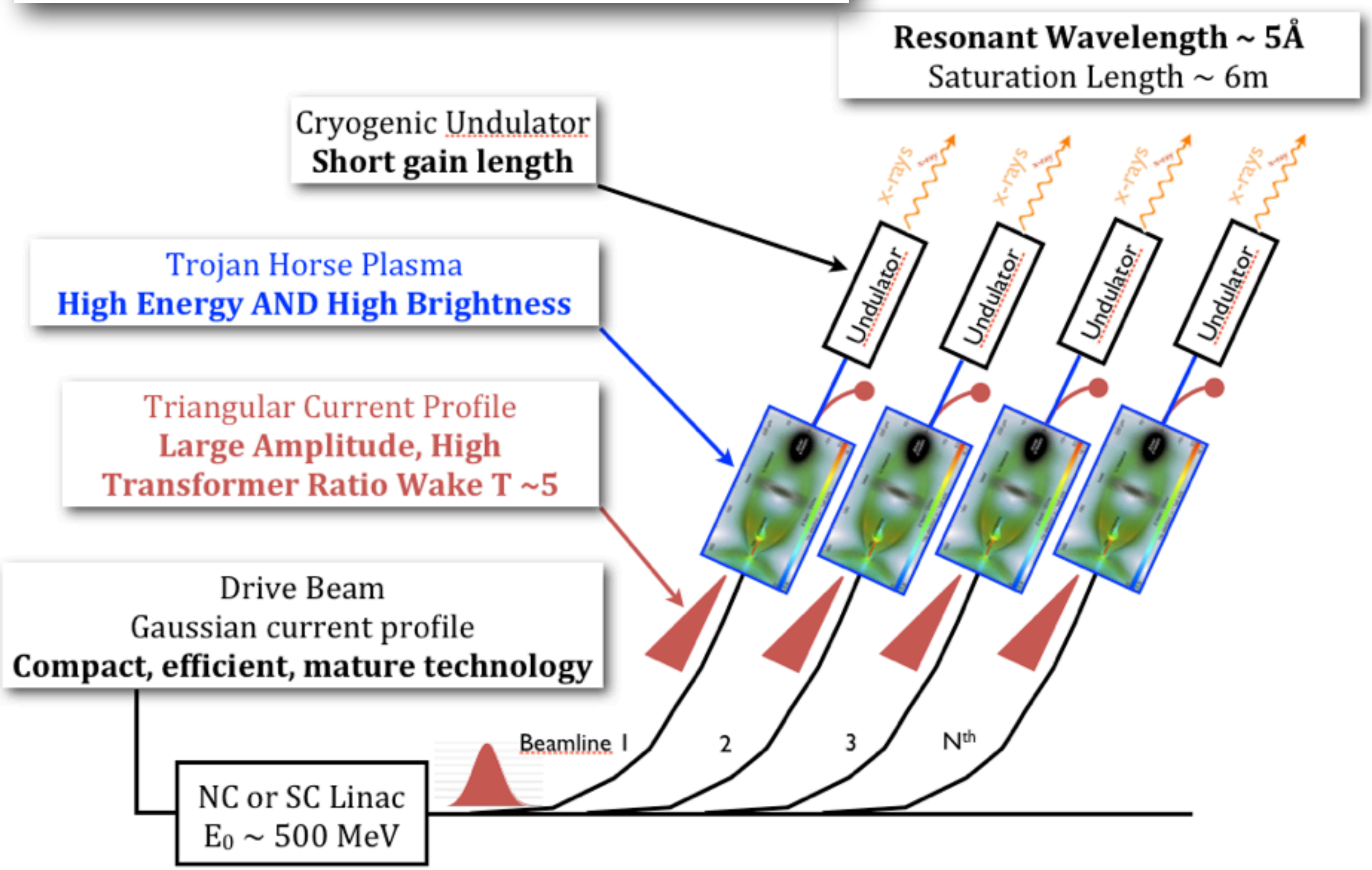
Plasma Based FEL Concept



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/m²rad
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.

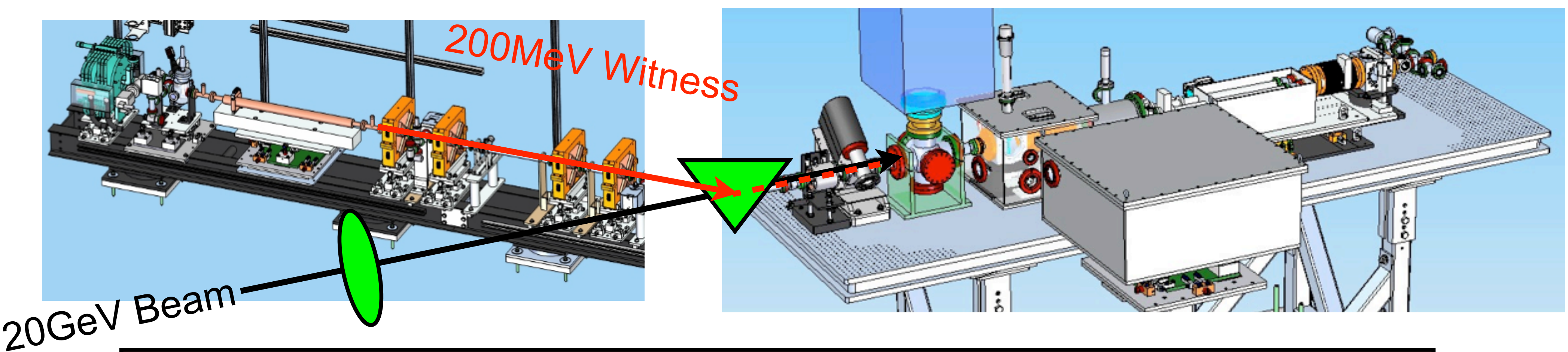
Staging Will Be Required to Reach Very High Energies

Upstream of stage:

- Inject high-brightness witness bunch from independent source
- Tailored current profiles for maximum efficiency
- Investigate tolerances on timing, alignment

Downstream of stage:

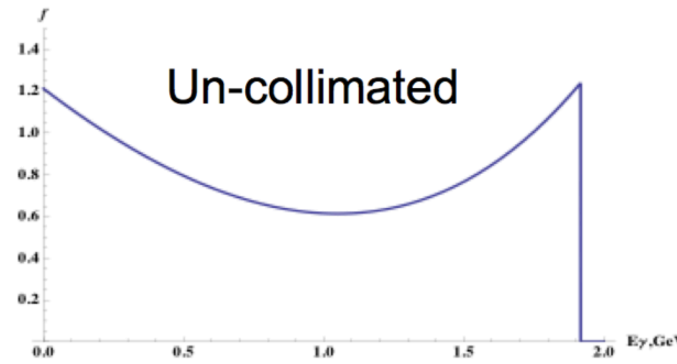
- Extract/Dump spent drive beam
- Preserve emittance of accelerated beam



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

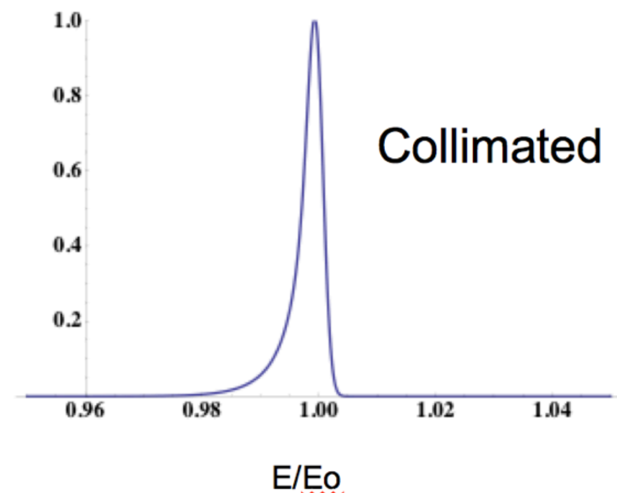
BIG: Beams of Intense Gamma-rays at FACET-II

- 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



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

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



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

Comparing BIG with other Compton Sources

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	$3x10^6$	$5x10^6$	3 $x10^9$, E<20 MeV 2 $x10^8$, 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

Nuclear and higher energy physics: three energy ranges

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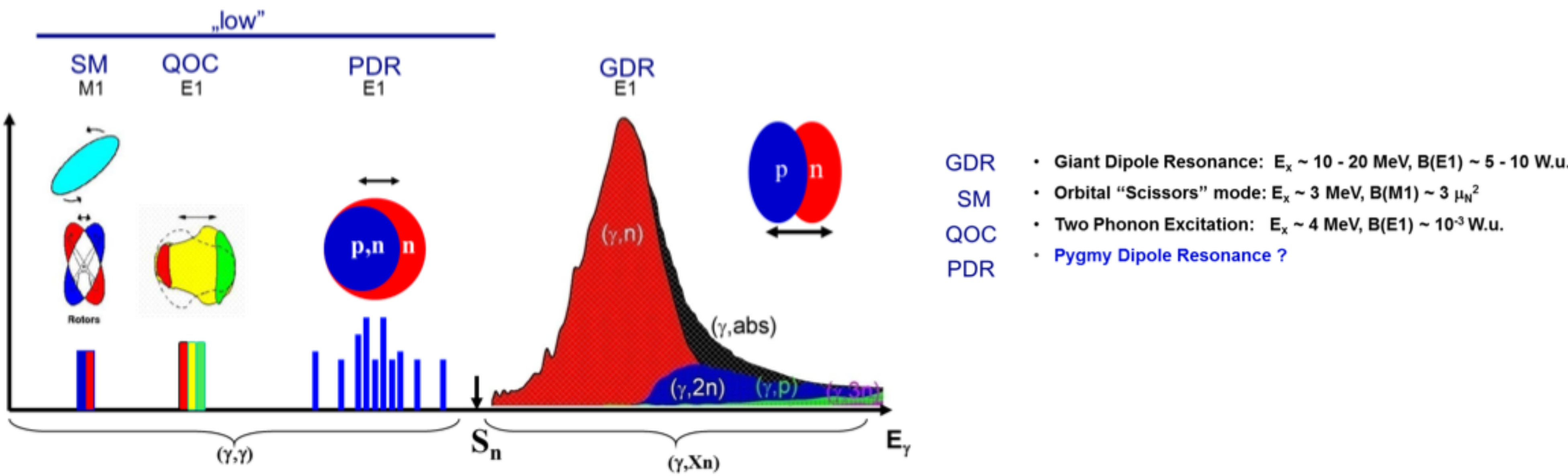
At low energies to study the resonant structure and states in rare nuclei. NRF & pigmy resonances. Astrophysics relevant processes (such as 12C(α, γ))

Intermediate energies to study spontaneous breaking of QCD's chiral symmetry, GDH rule

High energies to study the resonant structure and spin structure in nucleons. Meson photo-production.



Broad energy range of polarized gammas opens up many areas of Nuclear Physics investigations

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 $\Delta E/E$ [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

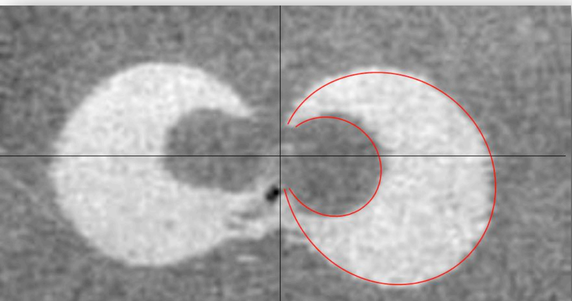
Lasers	Energy / Power [Joule / TW]	Rep rate [Hz]	τ [fs]	λ [μm]
TI: Sapphire	1 / 30	120	30	0.8
CO_2 laser	0.1 / 0.1	120	1000	10.2

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

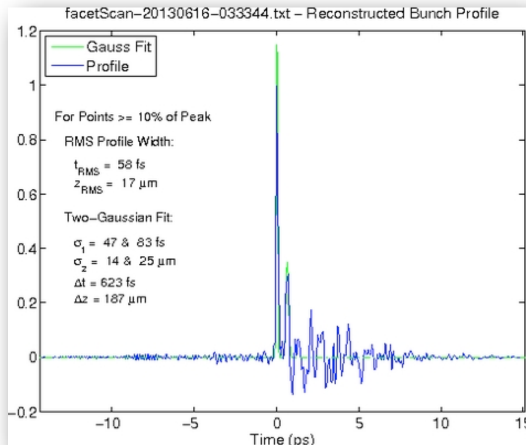
Very Productive User Run
Every Program Expecting Publishable Results

SLAC

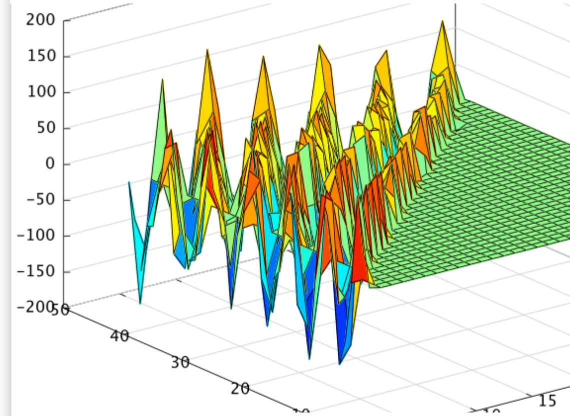
Switching Mechanisms in Ultrafast Electromagnetic Pulses



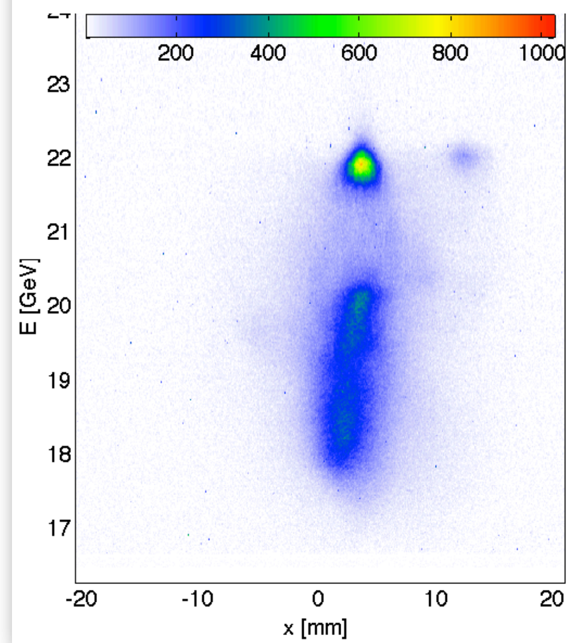
THz Reconstruction of Two-Bunch Profile



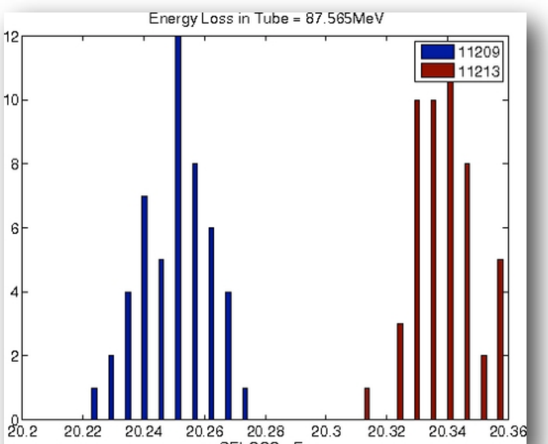
An Automated Method for Dispersion Free Steering

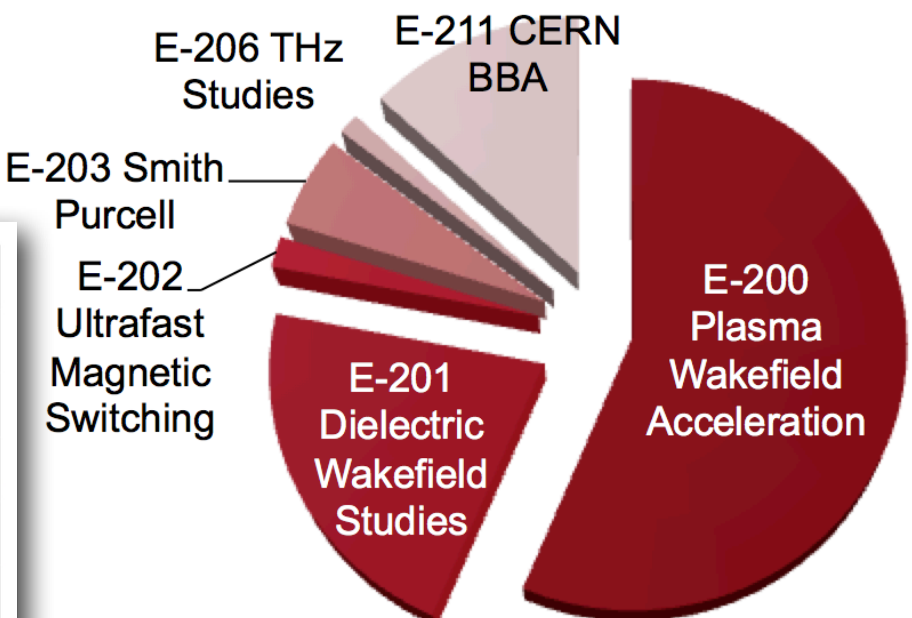


Mono-energetic Acceleration in a Beam-driven Plasma Wakefield Accelerator



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





I’m sorry, this has been removed pending publication...

Some plots removed from previous viewgraph to satisfy embargo policies of some journals. Can release pending publication.

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