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The Particle Beam Physics Lab (PBPL): Research at the Intersection of Relativistic Beam and Plasma Physics

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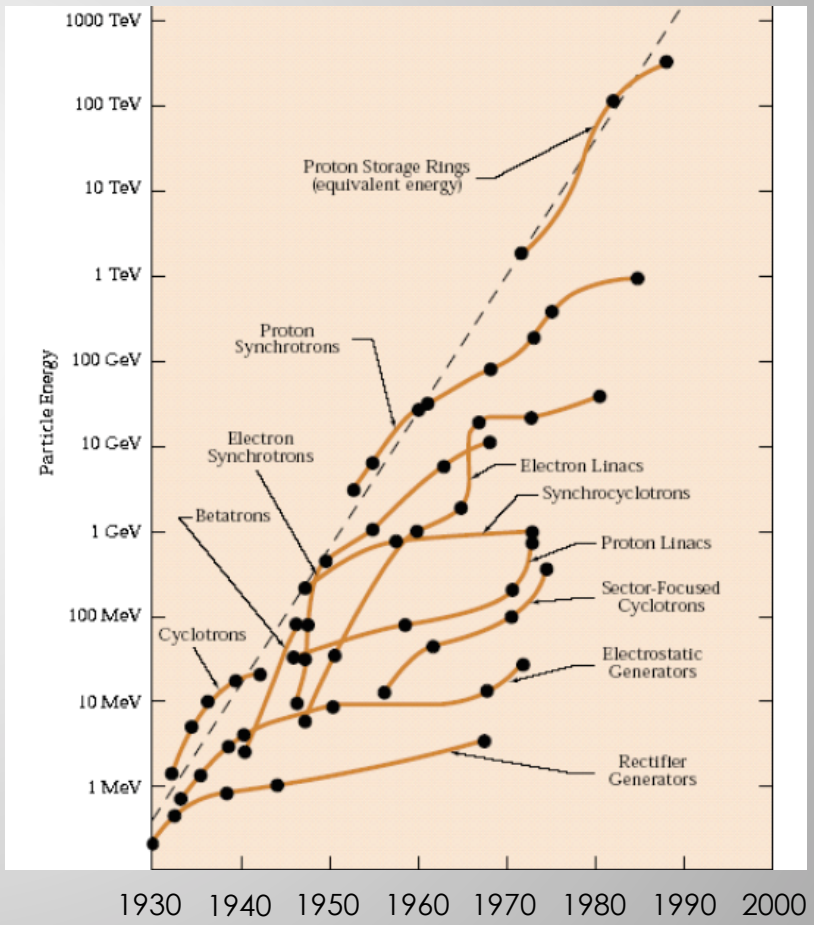
PlasmaFest 2015 -- 9/22/15

PBPL

Particle beam-based discovery of the very small demands *high energy* (TeV scale)

- Enabled by ***accelerators***

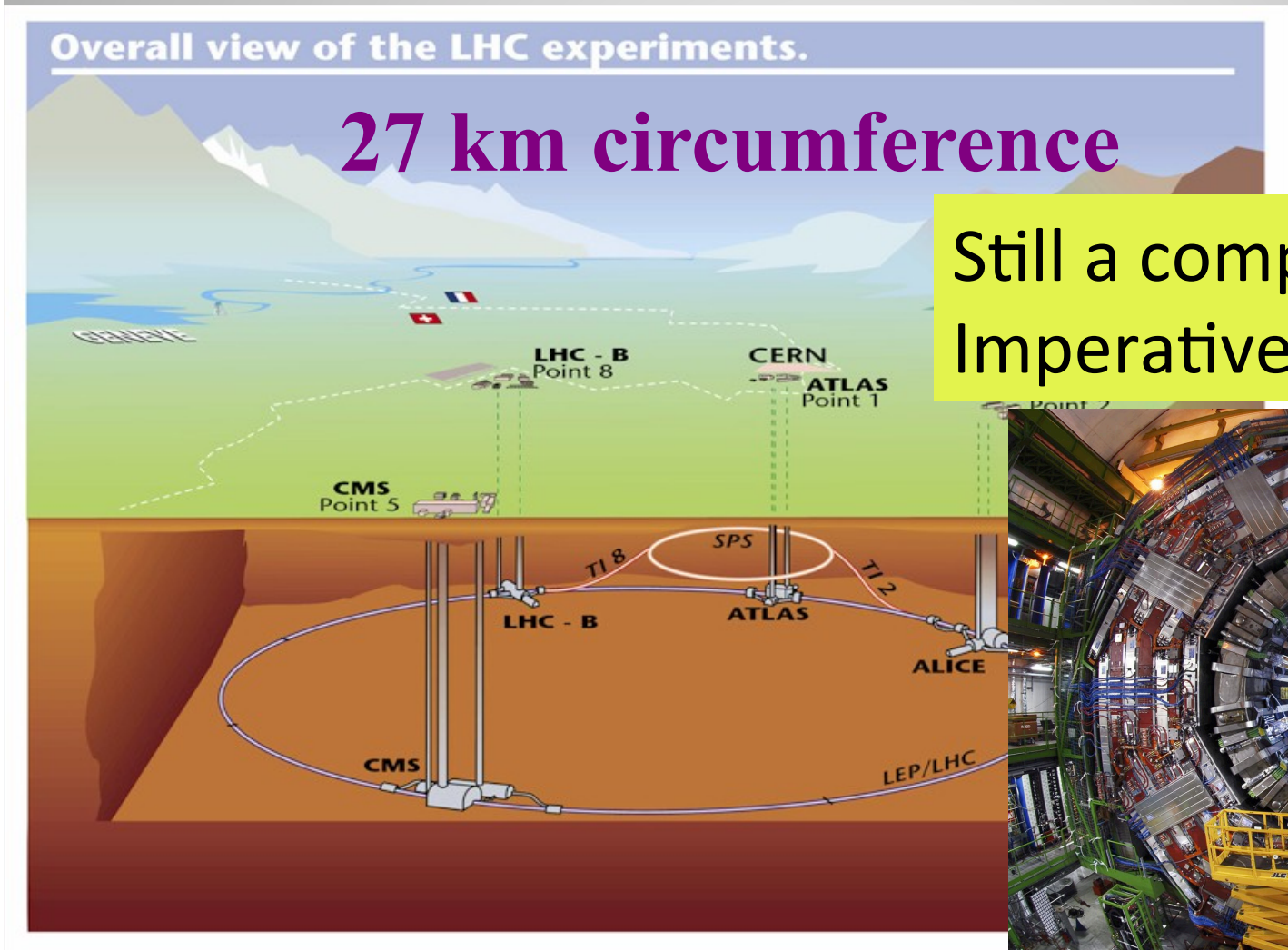
  Resolve at scale $\lambda \sim hc/U$
- Exponential growth in *t* in *available energy U*
  - Livingston plot: "Moore's Law" for accelerators
  - Now beams are at *TeV*
- Expensive success story…
  - LHC (Higgs discovery) ~ $10B
  - To go to 100 TeV (FCC), cost **greater**



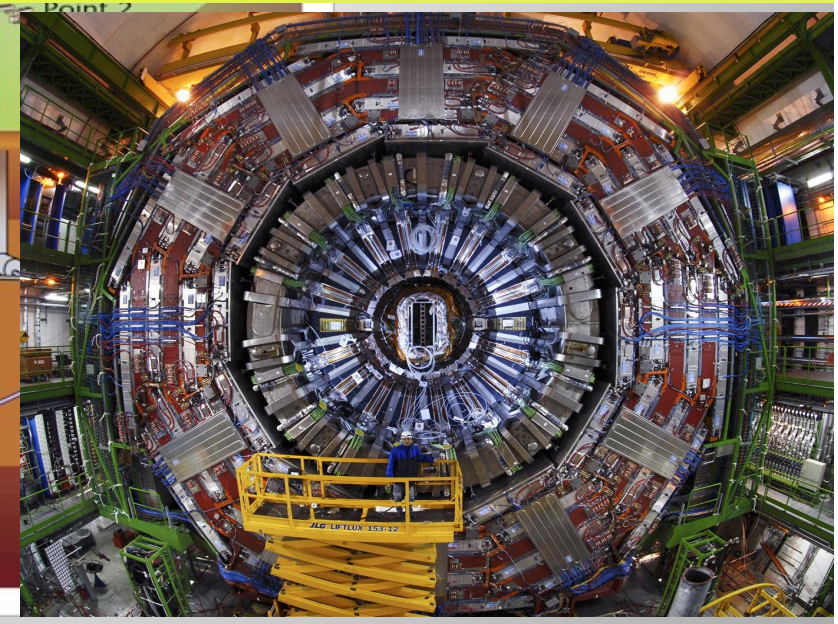
Moore's law for HEP discovery

Accelerators started small now dominate science, industry, medicine…

Unitary limits in R/$ reached



Still a compelling field!
Imperative: miniaturize

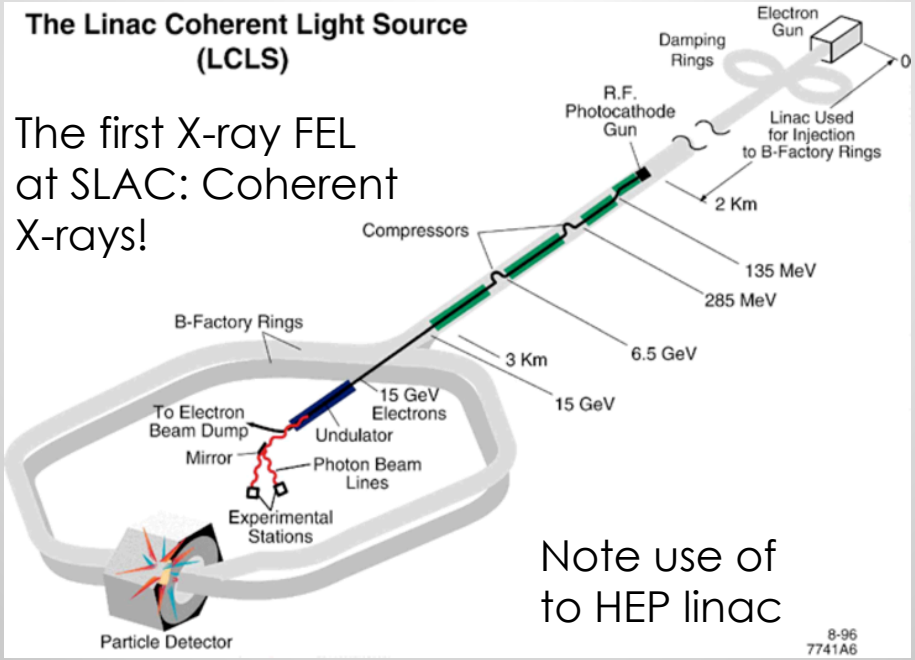


Costly, *and* complex as a moon shot

Modern light source: X-ray Free-Electron Laser (FEL)

- Large linear accelerator (km-scale, E=15 GeV)
- Introduces X-ray coherence, and *fs resolution*
- UCLA played essential role in development

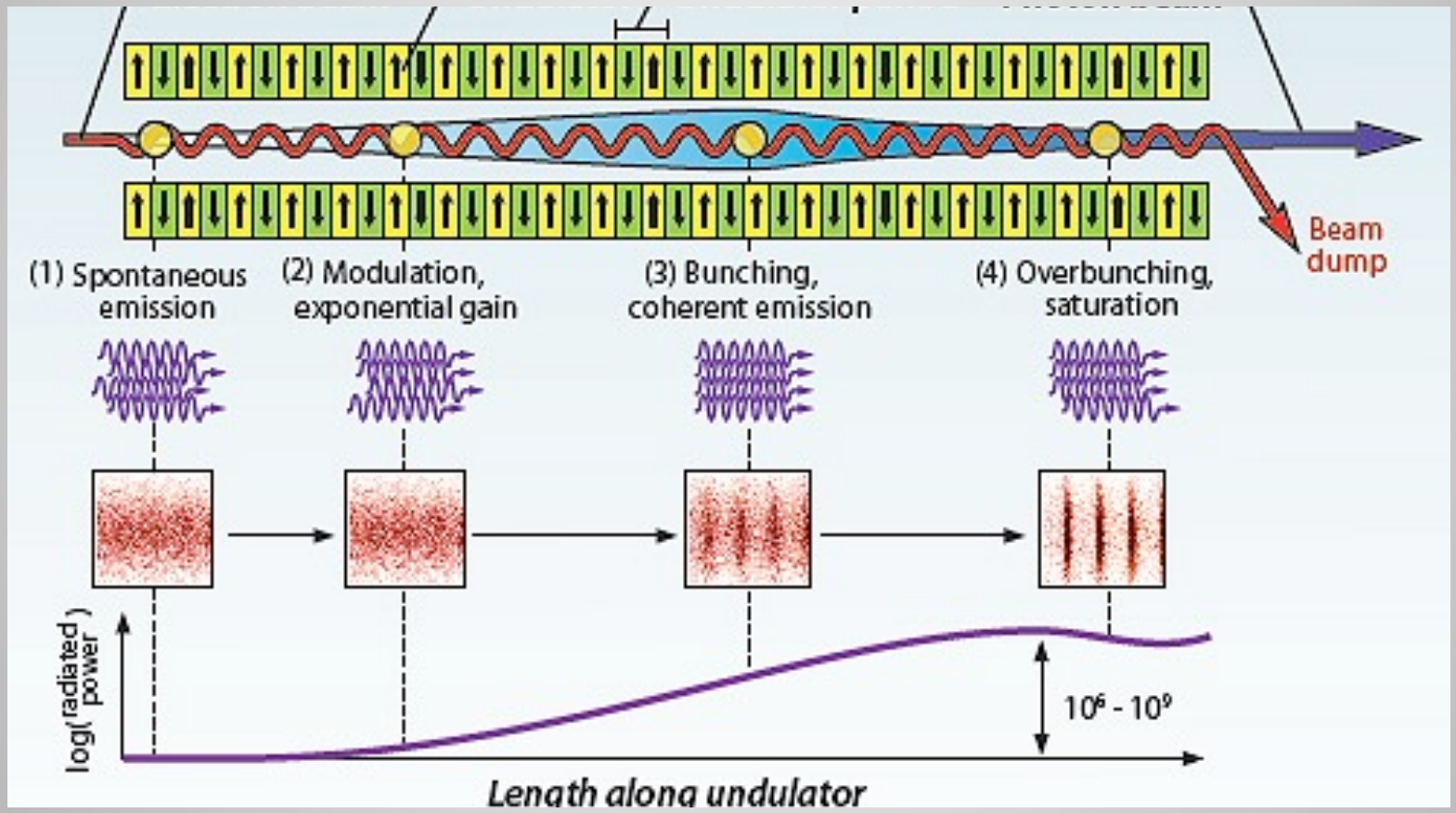
SLAC <2000: Dedicated to HEP



SLAC >2010: Dedicated to FEL

Light sources — before: HEP spin-off, now big science (>$1B).
XFEL provides much motivation for accelerator research

X-ray FEL schematically



Undulator period ~ few cm, through **3-wave instability** gives Doppler shifted **coherent** light, **hard X-rays and beyond**

Feedback yields instability, then coherence and *very* high power

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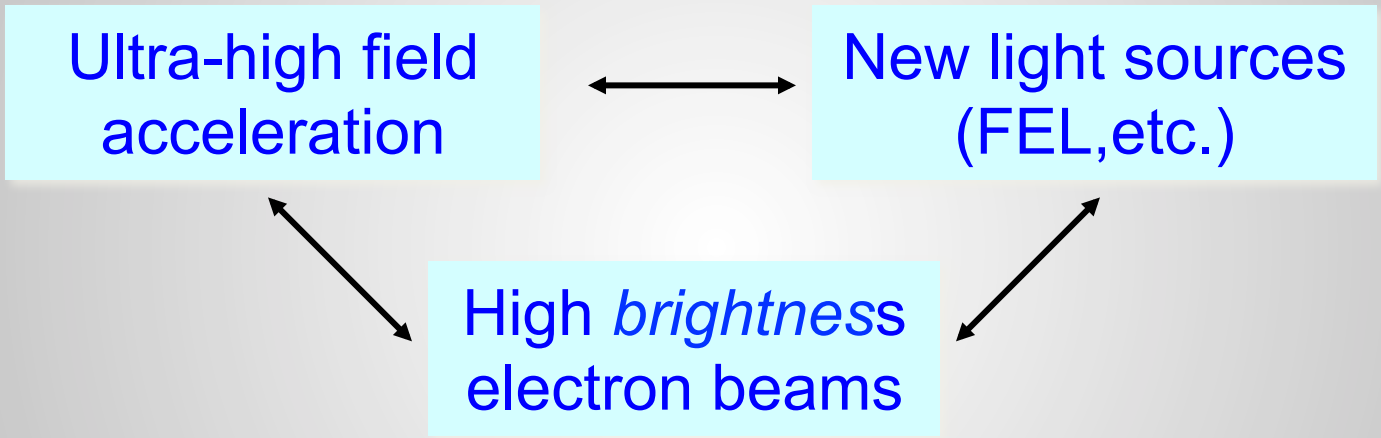
UCLA Particle Beam Physics Lab: PBPL

- Group (Musumeci+Rosenzweig) built on 3 research thrusts



- Strong connections between all areas
  - Common themes: *multi-disciplinary*, high energy density (relativistic) interactions, ultra-fast systems
- Fundamental beam (plasma) physics and advanced technology underpins other two areas
- Now moving to cutting edge *applications* (femto-second resolved imaging, THz, etc.)

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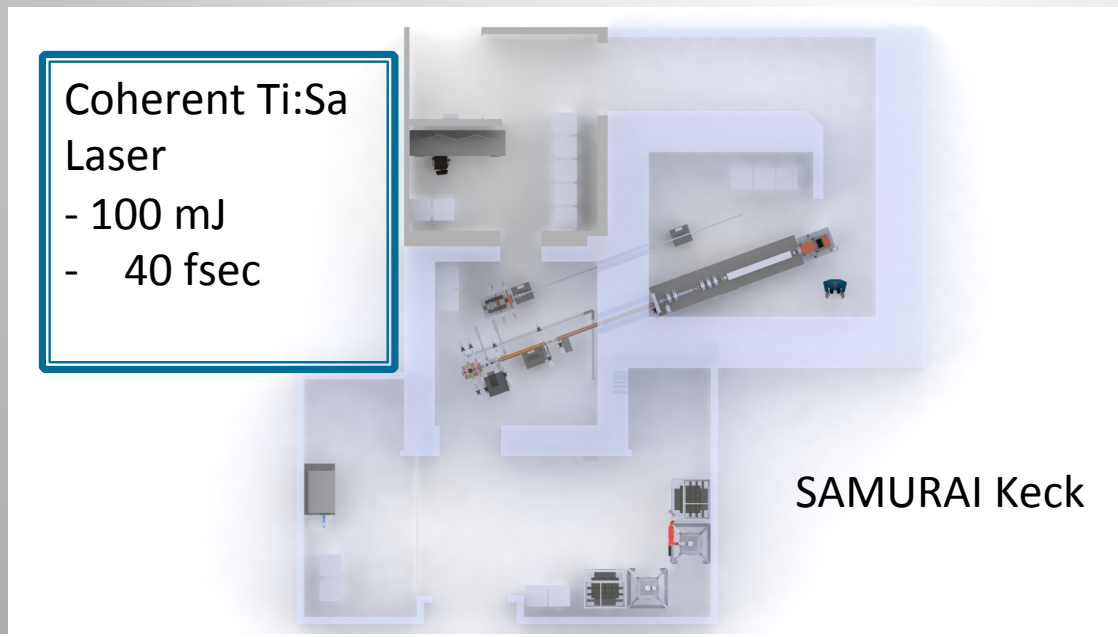
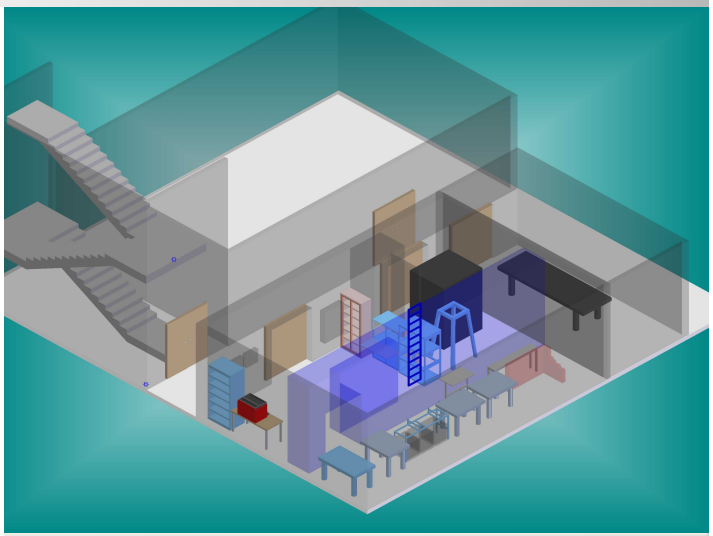
PBPL Experimental Facilities

- State-of-the-art accelerator/laser labs
- Keck-SAMURAI Lab (Rosenzweig)
  - >65 <MeV, FEL, advanced acceleration
- PEGASUS High Brightness Beam Lab (Musumeci)
- Off-campus (PBPL aided in construction)
  - BNL ATF; SLAC NLCTA, FACET; INFN/LNF SPARC



SAMURAI Keck

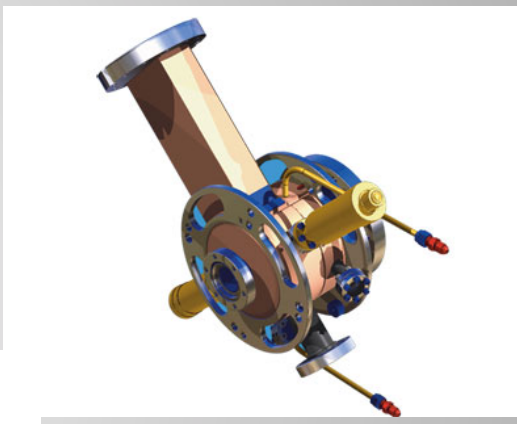


Pegasus lab (Knudseon Hall)

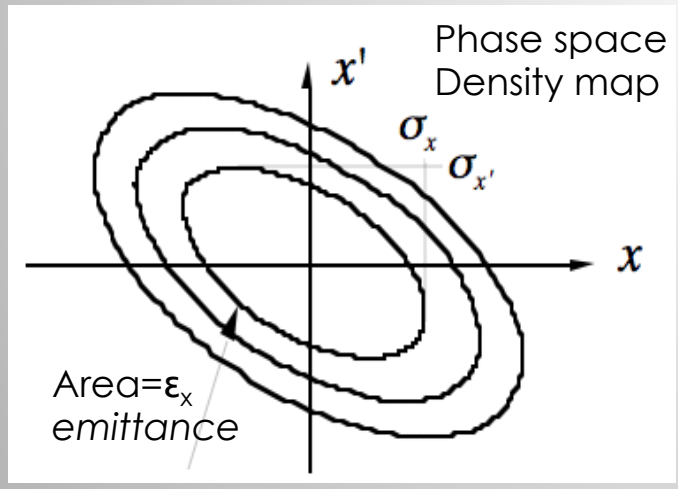
Essential ingredient in beam-based discovery: high brightness electron beam

- High phase space density (**cold, focusable, intense**)
- Measure: **beam brightness**

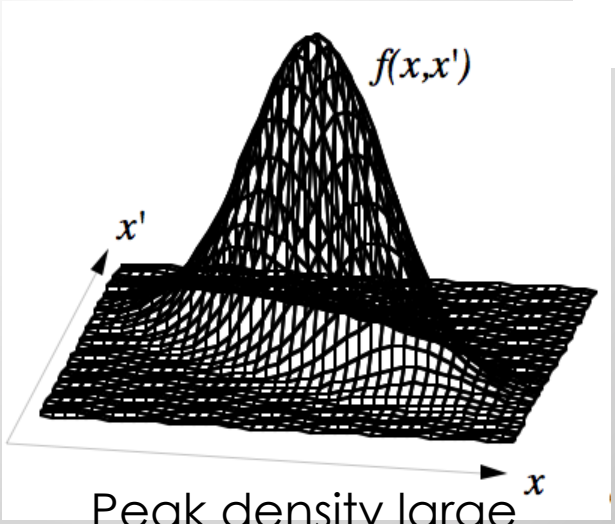
$$B_e = \frac{2I}{\varepsilon_x^2}$$



- Space-charge (dense, cold ***plasma***) effects strong in high brightness beams, challenging physics



Area (temperature) small



Peak density large

The secret:
RF photoinjector
(UCLA expertise)

Neede for FELs and HEP linear collider (very high high B_e)

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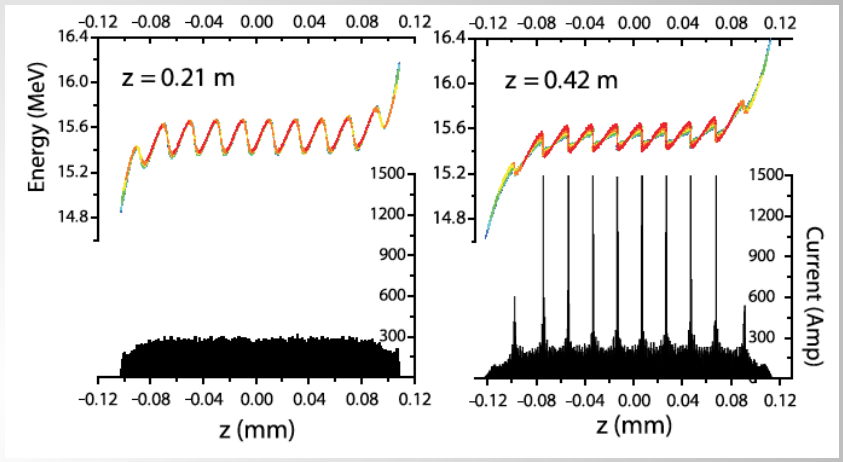
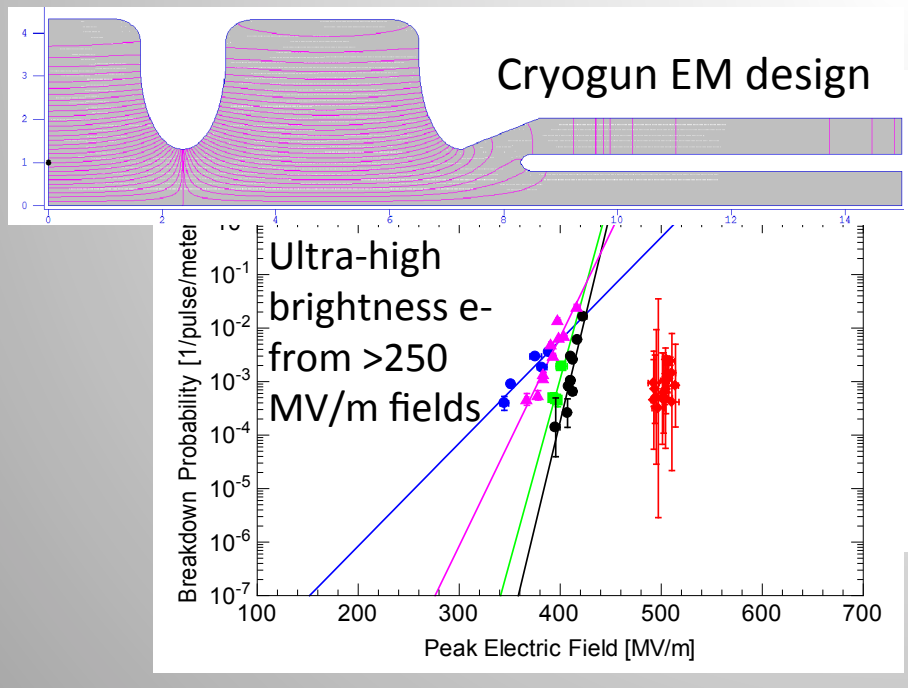
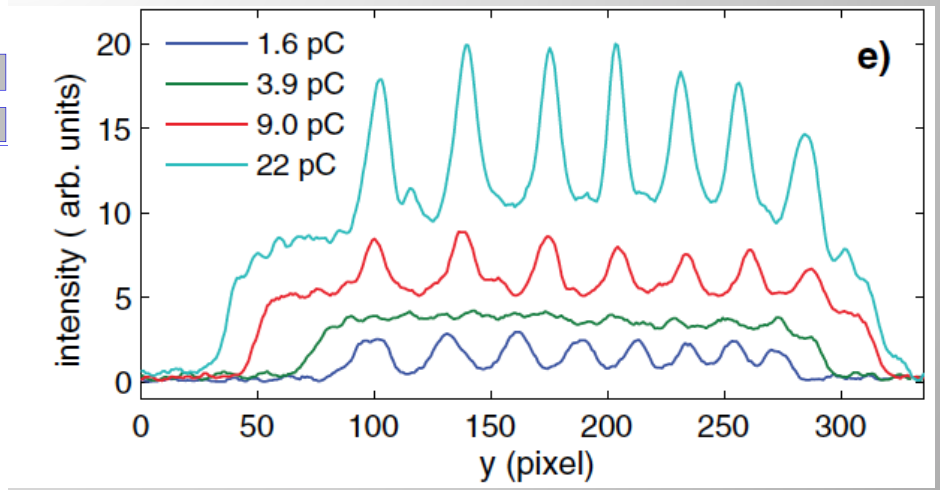
Electron Source Physics and Technology

- Advanced approaches
  - Cryogenics, plasmonics
- Physics of relativistic plasmas under violent acceleration



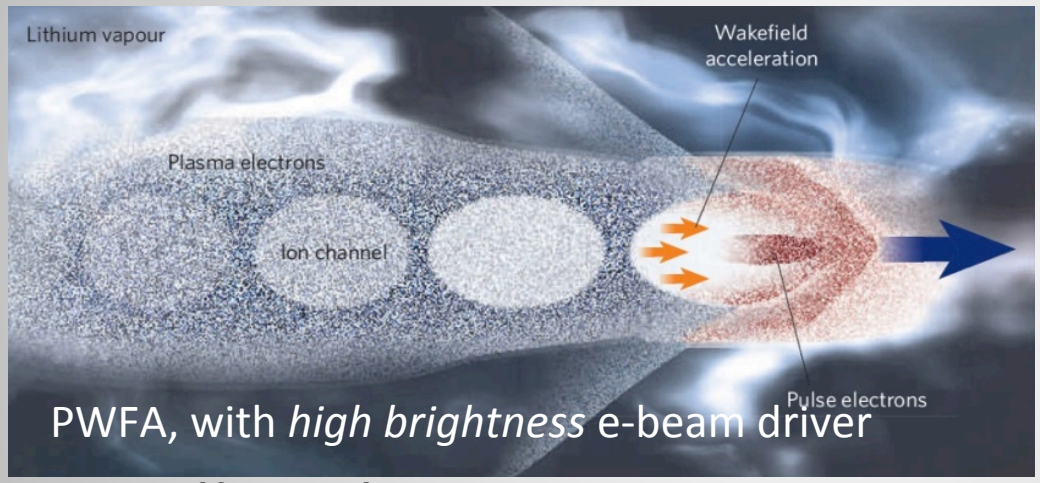




Nonlinear plasma oscillations observed in accelerating e-beam I(Musumeci)

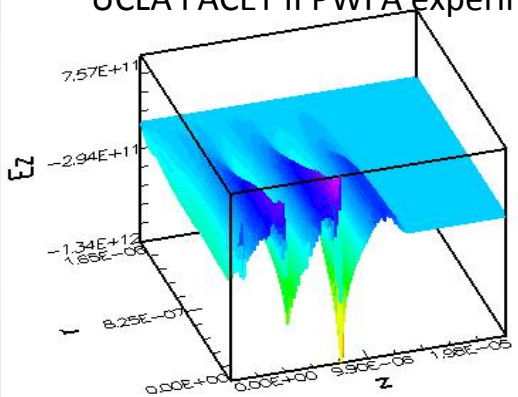
Beams-as-plasmas to *beams in plasmas*

- Plasma wakefield acceleration (PWFA) in extreme nonlinear blowout regime, $n_b >> n_p$

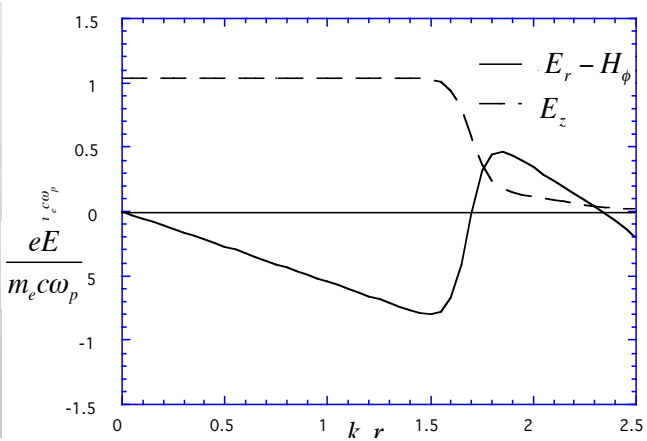


PWFA, with *high brightness* e-beam driver

>1 TVm accelerating fields in UCLA FACET II PWFA experiment

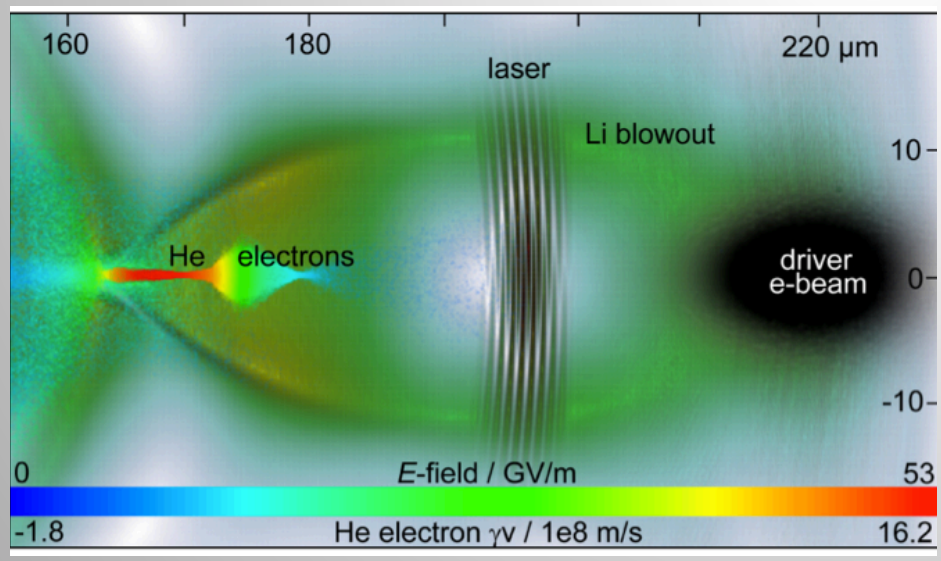


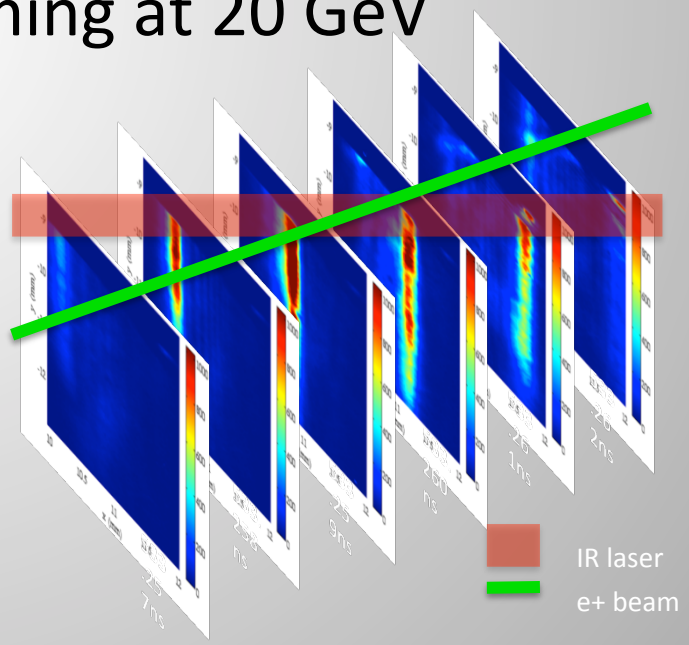
- Excellent beam properties
  - Like linac structure moving at *c*
  - Ultra-strong (MT/m) ion focusing
  - Up to TV/m foreseen



"Trojan Horse" PWFA-based e- Source

- Extreme high brightness beam from "plasma photo-injector"; 300 MV/m->30 G/m
- Experiments underway at SLAC FACET
  - Laser-electron femtosec timing at 20 GeV

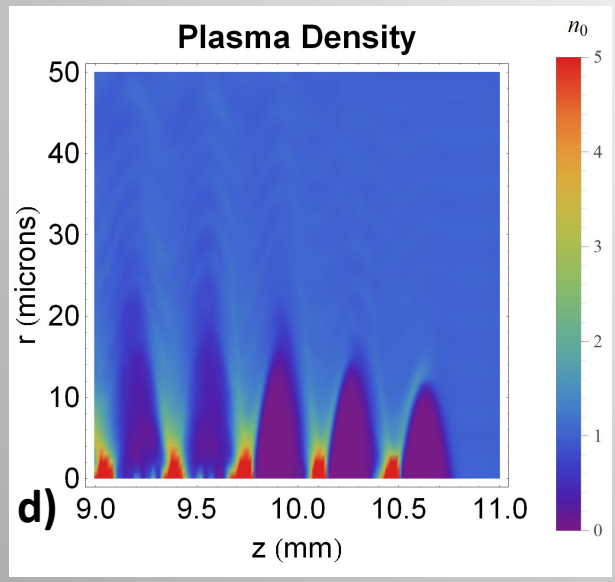


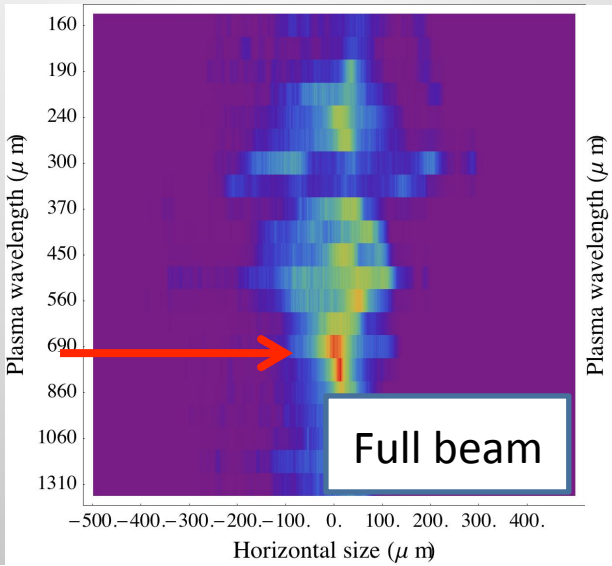


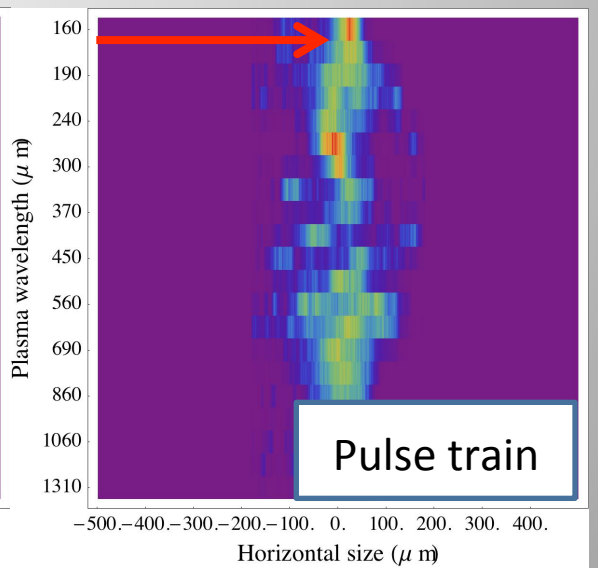
Electro-optic signal for 100 fs timing

Exploring Nonlinear Plasma Response

- Resonant excitation needed, but relativistic plasma response is anharmonic
- High brightness beam permits $n_b >> n_p$ without nonlinearity – *quasi-nonlinear regime*
- 1st experiments at BNL ATF (national user fac.)

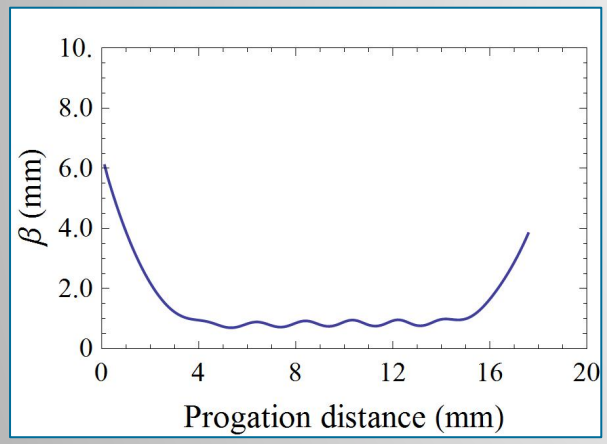


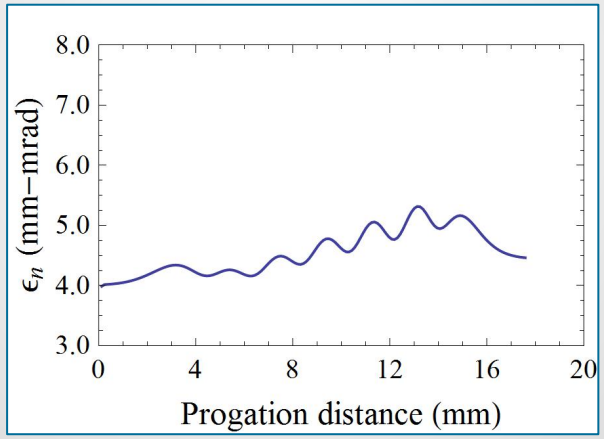


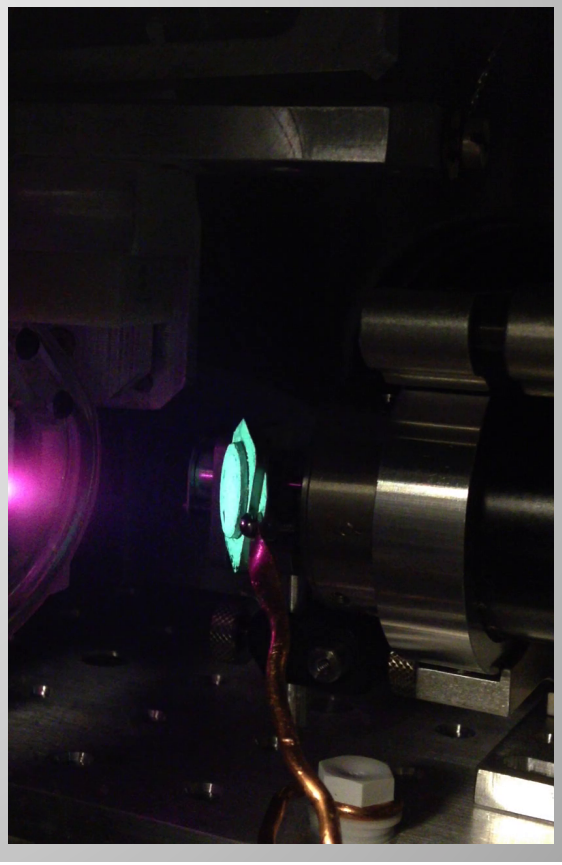


Next generation experiments at Frascati

- "Matching" to GV/m PWFA; adiabatic lens for HEP
- Emittance preservation for... free-electron laser







Simulation of beam focusing and emittance evolution in INFN-LNF (Frascati) experiments. (Right) plasma discharge source.

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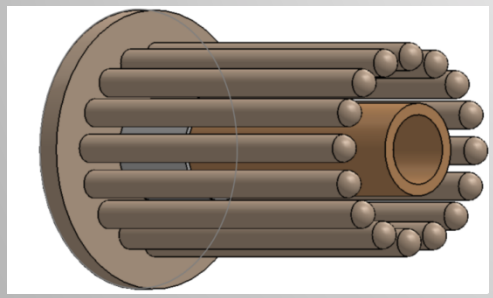
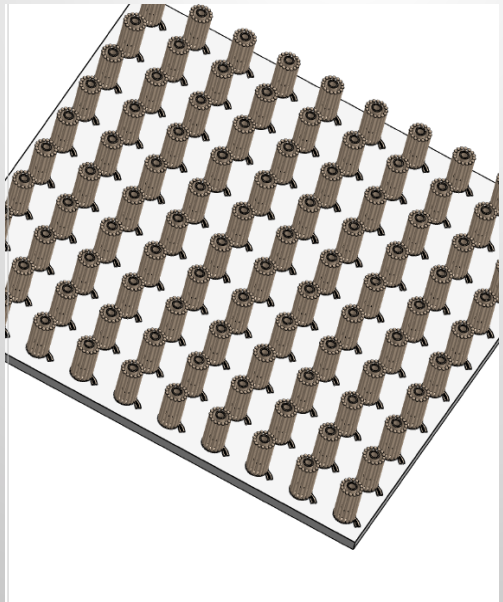
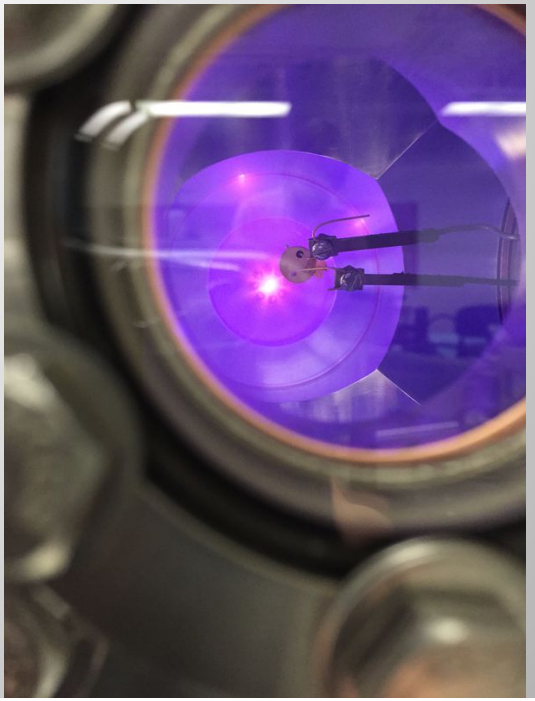
Advanced plasma source work: Micro-Dense Plasma Focus

- DARPA ICONS (Intense COmpact Neutron Source)
- Miniaturization of dense plasma focus, enable array MEMS of gated neutron emitters for imaging







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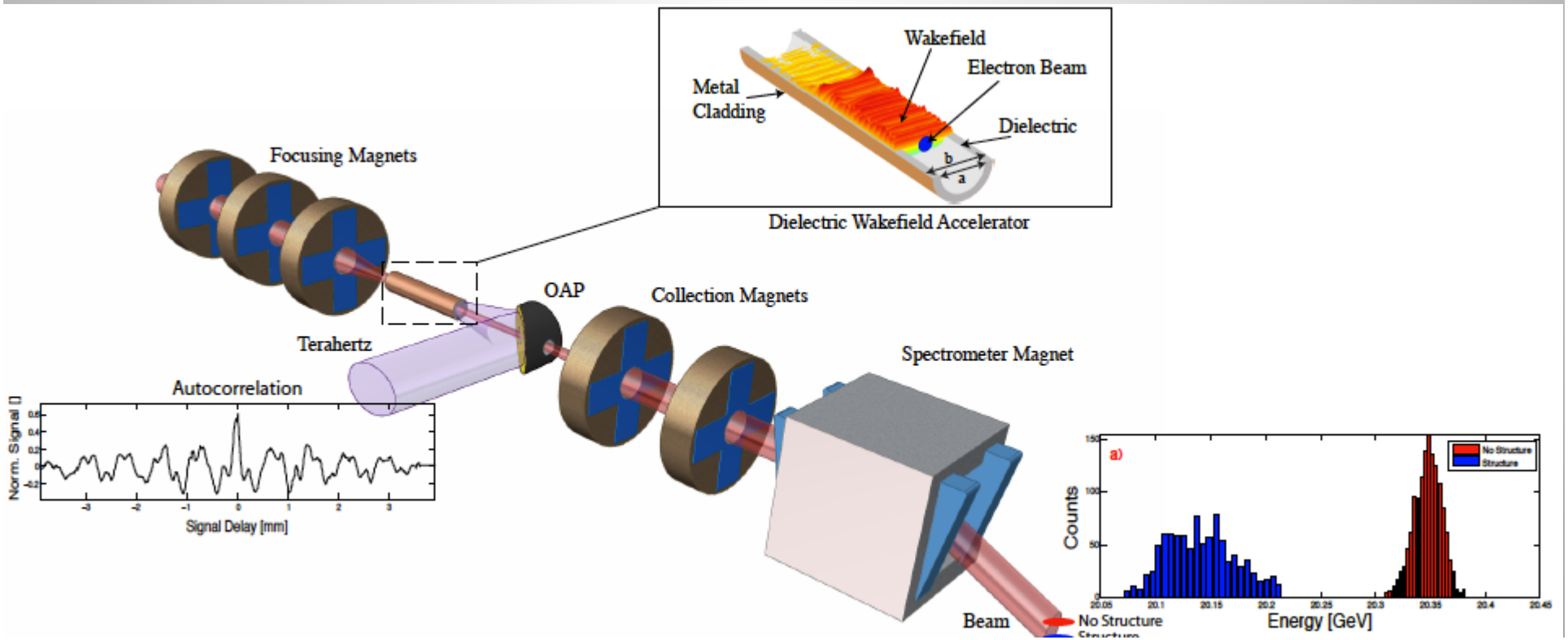
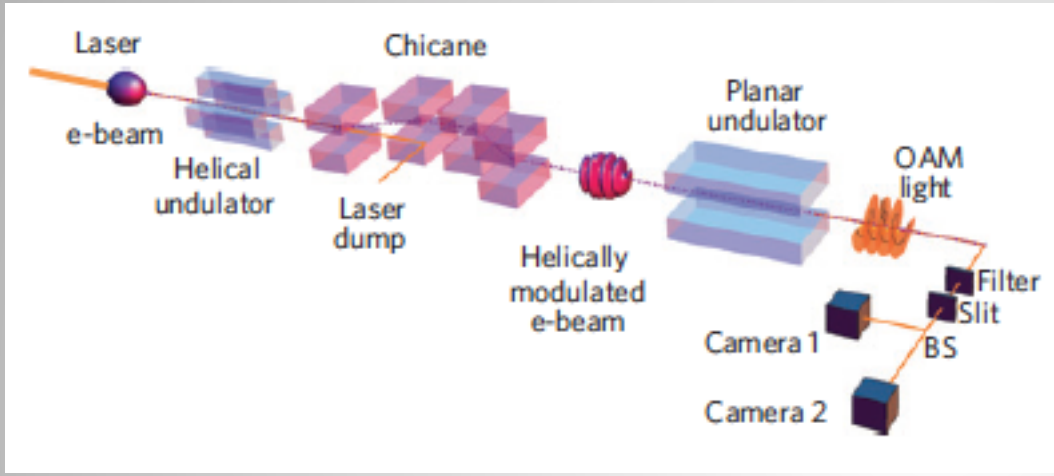
GeV/m Dielectric Wakefield Acceleration

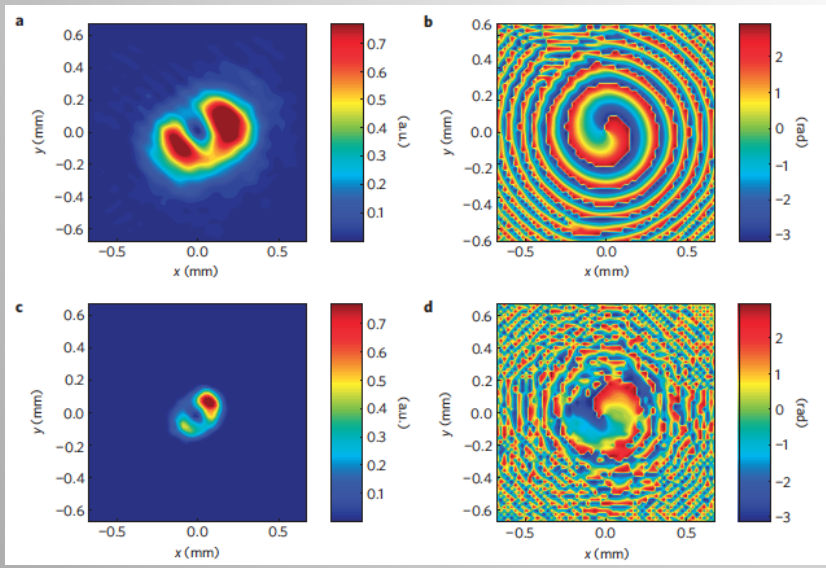
- GeV/m accelerator without plasma; THz *dielectric wakes*
- Recently observed
  - **2 GeV/m deceleration** (metallic coating)
  - Witness beam acceleration, **~80% efficiency**
  - Wakefield mapping, high-field-induced damping



Advances in FEL: Demonstration of Orbital Angular Momentum FEL



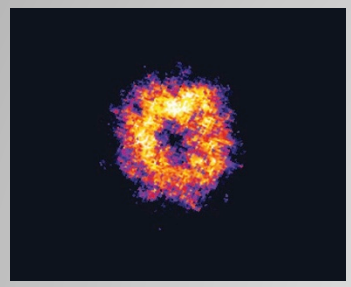
- SLAC NLCTA facility
- Follow-on to UCLA experiments (Neptune)



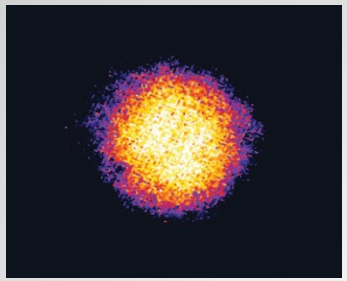
- Undulator radiation from <u>helically-bunched</u> beam
- Analyze with phase retrieval (coherent imaging, J. Miao: *helical phase* (OAM)

E. Hemsing, et al., *Nature Physics* 9, 549 (2013).

Using the laser as undulator: Inverse Compton Scattering (ICS)

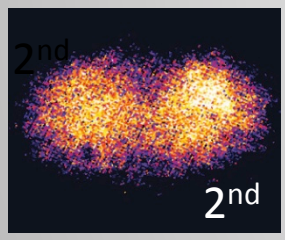


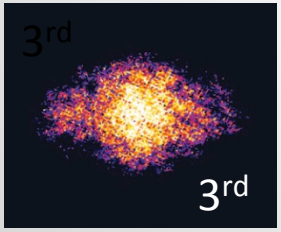
a_0<0.25



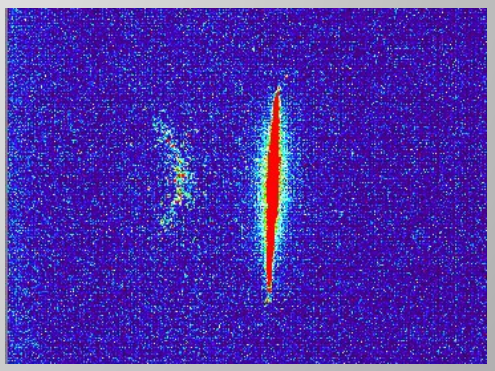
a_0~0.6

K-edge filtered X-rays, redshifted by large a_0. Harmonics revealed at a_0=0.6

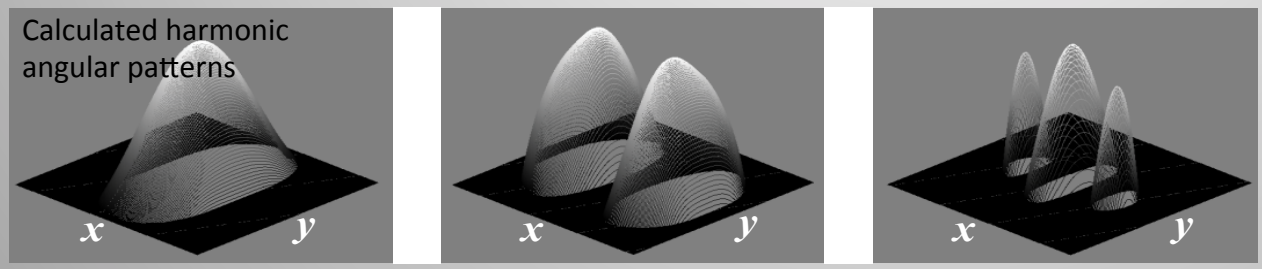




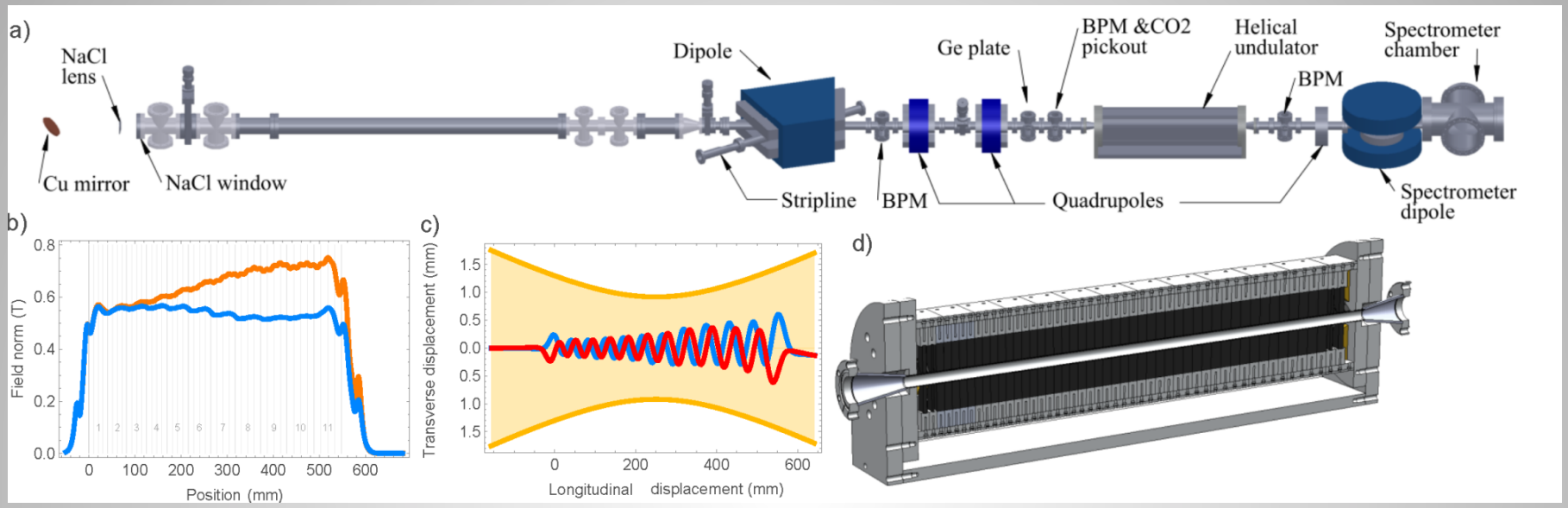
- BNL ATF experiments
- First demonstration of nonlinear redshift
- First demonstration of 3rd harmonic radiation
- Single shot Bragg diffraction
- Single shot double-differential spectrum



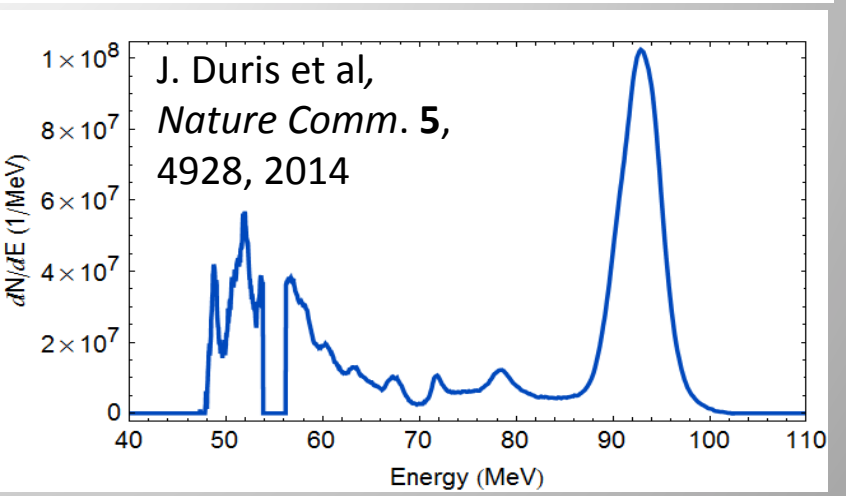
Curve indicates off-axis redshift



IFEL: the FEL in reverse



- High quality beam accelerated (double *U*)
- Next: ICS based on IFEL —all optical light source
- Inspires ultra-efficient FEL based on tapering...



Future directions

- **SAMURAI** (Spontaneous Amplified Micro-Undulator Radiation And Interactions). FEL *and* advanced accelerators
- Soft-X-ray Raman **(*plasma dominated*)** FEL with MEMS undulator
  - 800 um period, 2 m long SASE FEL, λ_r 26 nm with 63 MeV beam
  - Collaboration with P. Musumeci, R. Candler
- Low energy PWFA for *space radiation simulation* (exponential energy spectrum, killer electrons)
  - Uniquely enabled by advanced photoinjector giving 100 fs, kA e-beams