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

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Particle beam-based discovery of the very small demands \textit{high energy} (TeV scale)

- Enabled by \textit{accelerators}
  Resolve at scale $\lambda \sim \hbar c/U$
- Exponential growth in $t$ in \textit{available energy} $U$
  - Livingston plot: “Moore’s Law” for accelerators
  - Now beams are at $TeV$
- Expensive success story...
  - LHC (Higgs discovery) $\sim$ $10B$
  - To go to $100$ TeV (FCC), cost \textit{greater}
Accelerators started small now dominate science, industry, medicine...

An adventure in innovation for nearly a century, from betatron... To the largest machines ever built.

The $U=1$ MeV betatron (1940)
Unitary limits in R/$ reached

Costly, and complex as a moon shot

Overall view of the LHC experiments.

27 km circumference

Still a compelling field!
Imperative: miniaturize
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

The first X-ray FEL at SLAC: Coherent X-rays!

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.
Feedback yields instability, then coherence and very high power

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

X-ray FEL schematically
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.)

- Ultra-high field acceleration
- New light sources (FEL, etc.)
- High *brightness* electron beams
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

Coherent Ti:Sa Laser
- 100 mJ
- 40 fsec
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)

Need for FELs and HEP linear collider (very high high \( B_e \))
Electron Source Physics and Technology

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

Ultra-high brightness e- from >250 MV/m fields

Breakdown Probability [1/pulse/meter]

Peak Electric Field [MV/m]

Nonlinear plasma oscillations observed in accelerating e-beam (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

- 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
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.
Advanced plasma source work: Micro-Dense Plasma Focus

- DARPA ICONS (Intense COrpact Neutron Source)
- Miniaturization of dense plasma focus, enable array MEMS of gated neutron emitters for imaging
GeV/m Dielectric Wakefield Acceleration

- GeV/m accelerator without plasma; THz dielectric wakes
- Recently observed
  - 2 GeV/m deceleration (metallic coating)
  - Witness beam acceleration, \( \sim 80\% \) 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 helically-bunched beam
- Analyze with phase retrieval (coherent imaging, J. Miao: *helical phase* (OAM))

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

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

\[ a_0 < 0.25 \]
\[ a_0 \sim 0.6 \]

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

Calculated harmonic angular patterns

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, $\lambda_r$ 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