Outline

1. Introduction to the Center
2. Introduction to Pulsed Power and Diagnostic Systems
   - Marx Generators
   - Linear transformer drivers
   - Diagnostics
3. Research highlights
   - Coordinated
   - Collaborative
   - Center Partner Exploratory Accomplishments
Mission of the Multi-University Center

➢ Advance the understanding of current-driven High Energy Density (HED) plasmas through experiments supported by computer simulations and theoretical modeling.

➢ Investigate the application of current driven HED plasmas to inertial fusion energy, intense radiation generation, laboratory plasma astrophysics, etc.

➢ Develop new diagnostics for HED research; bring capabilities from international partners to the US community.

➢ Develop advanced numerical algorithms for HED plasma simulation using the extended MHD (XMHD) models (PERSEUS and GORGON)

➢ Train a new generation of HED research scientists
Center Partners

➢ Cornell University, Ithaca, NY; Awarded Cooperative Agreement – Drs David Hammer and Bruce Kusse, Co-PIs
➢ University of California, San Diego - Dr. Simon Bott-Suzuki, PI
➢ University of Michigan – Dr. Ryan McBride, PI
➢ Princeton University – Dr. Nathanial Fisch, PI
➢ Imperial College, London, UK – Dr. Simon Bland, PI
➢ Weizmann Institute of Science, Rehovot, Israel – Dr. Yitzhak Maron, PI
➢ P.N. Lebedev Institute, Moscow, Russia – Dr. Sergei Pikuz, PI
Most Important Center
Resource is People

Cornell

Faculty: David Hammer
        Bruce Kusse
        Charles Seyler
Senior Research Associates:
        John Greenly
        Steven Lantz (part time)
Research Associates:    
        E. Sander Lavine
Visiting Senior Scientists (part time)
        Niansheng Qi
        Sergei Pikuz
        Tania Shelkovenko
Technical Staff:
        Todd Blanchard
        Daniel Hawkes
        William Potter
        Harry Wilhelm
Administrative Aide: Cindy Vanostrand

Graduate Students (2019-’20):
        Jay Angel
        Jacob Banasek (now at UCSD)
        Owen Chen
        Ahmed Elshafiey
        Jason Hamilton
        Thomas Hentschel
        Jeffrey Musk, Jr.
        Sophia Rocco

4 Undergraduate this semester:
        Paul Beck
        Jake Lawson
        Hodaya Propp
        Paco Rilloraza
        Alejandro Mesa Dame
Most Important Center Resource is People

Imperial College London

Faculty: Ryan McBride
Graduate Students (2019-'20):
  - Paul Campbell*
  - Stephanie Miller*
  - Akash Shah
  - Jeff Woolstrum
Undergraduate Students (2019-'20):
  - Thomas Mundy
*partial funding through center grant or collaboration with center partners

Faculty: Simon Bland
  - Sergey Lebedev
  - Jeremy Chittenden
Postdocs/fellows:
  - Lee Suttle
  - Chris Walsh
  - Ellie Tubman (Livermore)
  - F. Suzuki-Vidal
  - D. Yanuka

Graduate Students:
  - A. Boxall
  - J.W.D. Halliday
  - J. MacDonald
  - D. Russell

Faculty:
  - Simon Bott-Suzuki
Graduate Students (2019-'20):
  - Sam Cordaro

Lebedev Physical Institute

Faculty: Sergey Pikuz
  - Tatiana Shelkovenko
Senior Research Scientists:
  - Aleksey Agafonov
  - Ivan Tillikin
Technical Staff:
  - Sergey Mishin

Faculty: Yitzhak Maron
  - Yuri Zarnitsky
Senior staff scientists:
  - Eyal Kroupp
Postdoctoral Fellows:
  - Dimitry Mikitchuk
  - Marko Cvejic
  - Tal Queller
Technical staff:
  - Shimon Shargorodsky

WIS

Faculty: Nathaniel Fisch
Senior Researchers:
  - Vladimir Malkin
Postdoc: Seth Davidovits*
Graduate Students (2019-'20):
  - Alec Griffith
  - Elijah Kolms
  - Mikhail Mlodik
  - Ian Ochs*
*supported by outside fellowship

PPPL

Faculty: Nathaniel Fisch
Senior Researchers:
  - Vladimir Malkin
Postdoc: Seth Davidovits*
Graduate Students (2019-'20):
  - Alec Griffith
  - Elijah Kolms
  - Mikhail Mlodik
  - Ian Ochs*
*supported by outside fellowship

Princeton Plasma Physics Laboratory

Faculty: Nathaniel Fisch
Senior Researchers:
  - Vladimir Malkin
Postdoc: Seth Davidovits*
Graduate Students (2019-'20):
  - Alec Griffith
  - Elijah Kolms
  - Mikhail Mlodik
  - Ian Ochs*
*supported by outside fellowship

PPPL

Faculty: Nathaniel Fisch
Senior Researchers:
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Postdoc: Seth Davidovits*
Graduate Students (2019-'20):
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  - Elijah Kolms
  - Mikhail Mlodik
  - Ian Ochs*
*supported by outside fellowship

PPPL
Center Contributions (FY 2019)

• 19 Peer reviewed publications
• 10 Conference proceedings
• 10 Invited Talks
• 51 Contributed talks/posters
Research Topics in the Multi-University Center

• Fundamental HED plasma physics
• MagLIF, ICF, and HED radiation source physics
• Laboratory Astrophysics
• HED diagnostic development
• Advanced computer simulation codes

• Gas-puff z-pinches
  ➢ Characterize energy flow in detail
  ➢ Instability studies and dynamics
  ➢ XMHD effects
• Shocks – collisional vs collisionless; radiative vs non-radiative
• Cylindrical liners
  ➢ Configurations driven by rotating field
  ➢ Anomalous current penetration due to azimuthal asymmetries?
  ➢ Understanding inner and outer ablation phenomena
• Radial/conical wire arrays/foils – laboratory jets
• Imploding/exploding wire arrays
• X-pinches
• Novel configurations/experiments
• Power feed plasma flow
Opportunities for Training and Professional Development

• All (experimental) graduate students and postdocs are expected to design and lead experiments on pulsed power machines operated by center partners
  • Learn about/maintain/upgrade pulsed power technologies
  • Gain experience with diagnostics and analysis techniques relevant to HED plasmas
• Collaboration and training with center partners and national labs
• Access to state-of-the-art simulation codes used by center partners
• Significant undergraduate training opportunities ranging from hands-on experimental work to simulation code development
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Pulsed Power Produced
Plasmas – Cornell’s Specialty
for >50 Years

COBRA, Cornell’s ~$10^{12}$ W, $10^6$ A, 100-220 ns rise time, 0.5Ω
pulsed power machine is used to produce high energy density plasmas.
Reached 5000 shots in summer 2018 (now about 5700)
Pulsed Power Produced
Plasmas – Cornell’s Specialty
for >50 Years

Half-machine mode – Highly reproducible 750 kA, 120 ns rise time
Pulsed Power Produced Plasmas – Cornell’s Specialty for >50 Years

XP – ‘small machine’ capable of 250 kA, 50 ns or 350 kA, 150 ns Primarily used for x-pinch studies
Marx Generator Systems at Center Partners

MAGPIE – Imperial College 1.4 MA, $\sim 10^{12}$ W, 250 ns rise time
Some Center Partners have LTDs (Linear Transformer Drivers)

Basic LTD circuit: High-$\mu$ ferromagnetic core increases inductance of undesired/parasitic surface current path

Build pulsed-power machine with “bricks” in parallel (series) for more current (voltage).

3-m-diameter MAIZE LTD (UM): (a) cutaway drawing, (b) open-top system photo; has 40 bricks in parallel in one stage. Each brick has a switch (1) between two capacitors (2); iron cores (3); high voltage insulators (4); coaxial (5) and radial (6) transmission lines delivering current to conical power feed (7) and the vacuum load region (8).
Highly Capable Diagnostic Suites Characterize Major Center Facilities

Examples shown at CU

(a) High-speed 12 frame camera (Visible/UV upgrade)
(b) 10 J, 3 ns, 527 nm Laser for Thomson Scattering
(c) Visible spectroscopy, streak photography, and PLIF system
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Working to Understand Gas-Puff Z-Pinch implosions

Neutral gas injection

Interaction of axial current and induced azimuthal field drives radial implosion

Stagnation
Thermalization
Radiation
Working to Understand Gas-Puff Z-Pinch implosions

Energy partition and turbulence

➢ WIS – Spectroscopic measurements suggest $T_i$ dominated by nonthermal hydrodynamic KE near stagnation ($T_i^{\text{eff}} > T_i$)

➢ Princeton – Sudden viscous dissipation mechanism can rapidly convert turbulent KE into thermal energy

➢ Cornell – Identify origin of the difference between $T_i$ and $T_i^{\text{eff}}$ using Thomson scattering

Variable $T_i$

$T_i = T_e$

+Gaussian Velocity dist.
Working to Understand Gas-Puff Z-Pinch implosions

Energy partition and turbulence

- **Microwave/IR Radiometry** to study radiated power at early times (compression)
- **Phase Contrast Imaging** to study turbulent density fluctuations during compression

Radiometer Channel

94 GHz
Received power from COBRA Ne gas-puff pinch

Phase Contrast Imaging

\[ \bar{k}_s = \bar{k}_i + \bar{k} \]
\[ \theta_s = 2\sin^{-1}\left(\frac{\bar{k}}{2k_i}\right) \]
Working to Understand Gas-Puff Z-Pinch implosions
Effects of axial magnetic field

CU

Average Instability Amplitude

- $B_z = 0$
- $B_z = 660 G$
- $B_z = 1 kG$
- $B_z = 1.5 kG$

Effects of axial magnetic field

- MRTI stabilized with weak $B_z$
- Observation of helical instability modes
- Flux compression in sheath
- Observations suggest full current flows in pinch

WIS

Magnetic field (T)

- $I = 200 kA$
- $I = 50 kA$

Azimuthal rotation profile

- <25% of current in imploding plasma
- Rotation with shear ($v_\theta \approx v_r$ near stagnation)
- Large fraction of energy and pressure in rotation
Working to Understand Gas-Puff Z-Pinch implosions

Effects of axial magnetic field

Flux amplification by force-free currents – an under investigated effect of the Hall term

- Strong enhancement of $B_z$ in Hall MHD case due to force-free currents in low density region near outer boundary
Experiments show current channel moves outward near stagnation

C. Stollberg, PhD thesis

Evolution of the current distribution depends strongly on the specifics of the implosion profile

Working to Understand Gas-Puff

Z-Pinch implosions

Effect of gas species and fill density

Species/density dependent piston profile and instability growth

$m^+ \sim 15 \mu g/cm$

$m^+ \sim 30 \mu g/cm$

Species dependent ionization of center gas puff

Neon 1.4/4.2/15
145 ns

Argon 0.7/2.1/15
125 ns

Krypton 0.7/2.1/15
157 ns

Ne 1.4:4.2:15 psia
163 ns

Ar 0.6:1.8:15 psia
176 ns

188 ns

192 ns
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Zeeman Polarization Spectroscopy
Diagnostic Development

C IV lines with no evident shift, suggesting both polarized components got through (not viewing || to B)

$r = 11$ mm (fiber 8)
edge of pinch

C IV shift indicates $B_\theta \approx 1.7$ T, consistent with prediction based on machine current

Advanced Thomson Scattering Diagnostic Development

Example TS setup for gas puff z-pinch experiments on COBRA

Laser update: 2.3 ns to ~12 ns pulse length

First EPW features measured in gas-puff z-pinch

Prism-based beam-splitting technique 4 x 2.5 J laser pulses delivered colinearly with arbitrary delays

12 ns streaked IAW feature
PERSEUS code in use at CU, SNL, LLNL, and UM is being upgraded to include thermoelectric transport with higher moment plasma models

- Solve up to 13-Moment equations to include non-equilibrium physics such as Nernst effect
- Keeps all equations hyperbolic with completely local implicit source terms
- Allows accurate modeling of lower collisionality regimes, bridging gap between fluid and kinetic models
- Passes 1D validation and verification tests
Dynamic Screw Pinch*

- Testing the effects of rotating the driving magnetic field during a thin-foil implosion
- Cornell’s COBRA facility used via center collaboration

Axial magnetic field ($B_z$) of 14 T generated by helical return current and measured with John Greenly’s micro B-dot probes

Helical return current (dynamic screw-pinchn)

Straight return current (standard z-pinchn)

CAD Model of return-current structure

Visible self-emission images

Helical instability structures

XUV images

Paul Campbell (UM – HEDP #8)

No helical instabilities; large trailing finger-like structures

Perseus 3D XMHD simulations now running on FLUX cluster to model cylindrical liner implosions and validate experimental observations

Effects of on-axis support rod on helical modes post-stagnation:

With Rod

No Rod

Pre-Imposed Bz Sims: Helical mode validation with MAIZE LTD data

m = 2 modes found in sims & experiments

Wire array PERSEUS validation

Dynamic Screw Pinch Sims: Validation with COBRA data

Laser Gate*

- Laser entrance hole (LEH) window is believed to be a source of contaminant mix in the MagLIF fuel
- Laser Gate will “pop” the window open well before the Z machine fires
- First targets built, pressurized, and tested by LRGF Fellow Stephanie Miller

Target-Fab with S. Klein (UM) & C. C. Kuranz (UM)

Stephanie Miller
(UM – HEDP #7)
(Last summer at SNL)

Demonstrate bow-shock formation on COBRA at high in-flow density: \( n_e = 1 \times 10^{17} \) to \( 1 \times 10^{19} \) cm\(^{-3}\) \( T_e = 5\) - \( 60 \) eV

Examine plasma velocity and temperature using multi-point Thomson scattering diagnostic; \( \alpha = 1/k\lambda_D = 1 - 5 \) (collective)

Recent results show plasma heating ahead of shock position, while in-flow velocity is still high – indicative of a radiative precursor ahead of the shock
Coaxial Vacuum Gap Breakdown for Pulsed Power Liners

Sam Cordaro (UCSD - HEDP #9)

- Coaxial vacuum gap on a liner to mimic Sandia z-machine MagLIF experiment
- Monitor current density distribution and evolution in time and space of liner and across gap with magnetic field probes, and image with gated optical framing camera
- Clear non-uniformity observed in azimuthal current distribution for most experiments up to 1MA
- Coating electrodes with various metals can improve current density uniformity
Time-resolved Spectra of Hybrid X-Pinches on XP
New ultra portable X-pinch ‘Dry pinch 1’ – 50 kg, 30x30x80 cm
- Easy to use – 3hrs training! No oil, water or SF6
- Current up to 140 kA in 200 ns
- Spot size <25 μm, ns duration, 10 mJ in <10keV; used for radiography and EXAFS
- New system with inbuilt charging, triggering, and higher dI/dt in production (will just need a laptop and 24 V power supply – designs distributed by CC)
Effects of collisions in warm dense matter

- Calculating dielectric functions, $\varepsilon$, for arbitrary temperatures & densities
  - First ignoring individual interactions/collision in a material
  - Then incorporating ionic structure via an electron-ion collision frequency
- examples: dynamic structure factor for x-ray TS, dielectric functions to calculate conductivities

X-ray Scattering spectra for aluminum

$E_0 = 7980$ eV, $\theta = 24^\circ$, $T = 6$ eV, $n_e = 1.8e+23$ e/\(\text{cc}\)
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Bow Shocks in Magnetized Flows

- Spherical Obstacle placed in the flow from a radial foil (right) or exploding wire array (top)
- Supersonic flow with $M_s \sim 3$, $M_A \sim 2$ (right)
- Flow carries poloidal magnetic field $B \sim 3$ T (right)
- Thomson scattering in downstream region to investigate bow shock structure
Radiography of Convergent Shockwaves at ESRF

- Pulsed power experiments at ESRF used to explore imploding shockwaves generated by wire arrays in water
  - Absolute density measurements via radiography
  - Enables first quantitative comparisons to MHD codes, can now predict high pressure conditions on axis
Hybrid X-pinche Study

Twisted Wires

Demonstrates the ability to perform dynamic radiography using two small sized hotspots, the amplitude of each can be controlled by the number of twists.
Magnetic Mirror for Wire Plasma Confinement

- Magnetic mirror liner inspired by automag concept
  - Preheat plasma simulated by wire on axis
- Demonstrated B field agreement between ANSYS sims and experiments on COBRA
  - 11.4% difference
- Simplified wire ‘liners’ used for proof of principle
TS and XMHD Effects in Laboratory Plasma Jets

First identification of EPW feature on COBRA

Heating differences suggest differences in \( n_e \)

Experimental agreement with PERSEUS Sims

Jacob Banasek
(CU \( \rightarrow \) UCSD)
Thank you for your attention

please check out our student posters!
Extra slides


Peer Reviewed Journal Publications (FY 2019)

19 Peer reviewed publications


3. Magnetized shock experiments using exploding wire arrays, L. Suttle, 11th Int. Conf. on Dense Z-pinches, Beijing, China, August 2019.

4. Study of flat foil explosion at (0.1 -- 5)·10^9 A/cm^2 current density, T. A. Shelkovenko, S. A. Pikuz, I. N. Tilikin, A. R. Mingaleev, W. Potter, D. A. Hammer, 11th Int. Conf. on Dense Z-pinches, Beijing, China, Book of Abstracts, p.71. (2019).

5. Z-pinch driven laboratory astrophysics experiments at Imperial College, S.V. Lebedev, 11th Int. Conf. on Dense Z-pinches, Beijing, China, August 2019.

6. Z-pinch Simulations at Imperial College, J. Chittenden, 11th Int. Conf. on Dense Z-pinches, Beijing, China, August 2019.

7. New insights into the pulsed power-driven explosion of underwater wires and wire arrays, S. N. Bland, 11th Int. Conf. on Dense Z-pinches, Beijing, China, August 2019.


Invited Talks
(FY 2019)


4. **Interacting magnetized plasma flows in pulsed-power driven experiments**, L. Suttle, 46th EPS Conference on Plasma Physics, Milan, Italy, July 2019

5. **Interactions of magnetized plasma flows in pulsed-power driven experiments**, L. Suttle, 6th Workshop on Magnetic fields in Laboratory High Energy Density Plasmas, Pingtang, China, June 2019

6. **Interacting magnetized plasma flows in pulsed-power driven experiments**, L. Suttle, Xian Jiaotong University, August 2019


8. **Upgrades to the 1-MA, 100-ns MAIZE Pulsed Power Facility** A. P. Shah at the High-Energy-Density Summer School, University of California, San Diego (La Jolla, July 28 – August 10, 2019)


10 Invited Talks