Compact Approach to Fusion Energy with the Sheared Flow Stabilized Z-Pinch

Uri Shumlak

Aerospace & Energetics Research Program
University of Washington, Seattle

Michigan Institute for Plasma Science and Engineering (MIPSE)
University of Michigan

16 September 2015

ZaP Personnel

Graduate Students

Elliot Claveau

Michal Hughes

Lorcan McGonigle

Michael Ross

Jonathan Weed

Undergraduate Students

Shawn Doty

Eleanor Forbes

Bonghan Kim

Leanne Su

Ryan Townsend

Faculty

Brian A. Nelson (Co-PI)

Uri Shumlak (PI)

Staff

Raymond Golingo

Dzung Tran

Collaborators

Daniel Den Hartog (U Wisc)

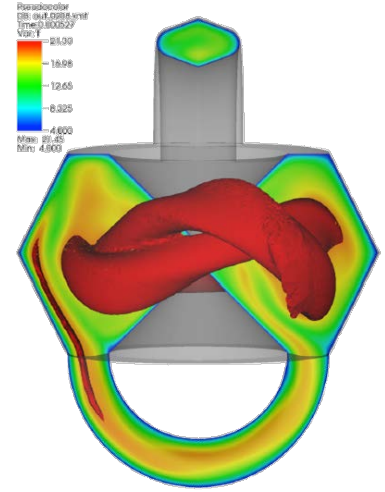
Charles Hartman (LLNL)

Harry McLean (LLNL)

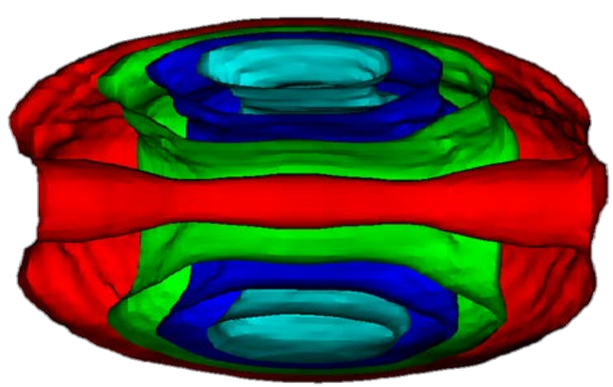
Andrea Schmidt (LLNL)

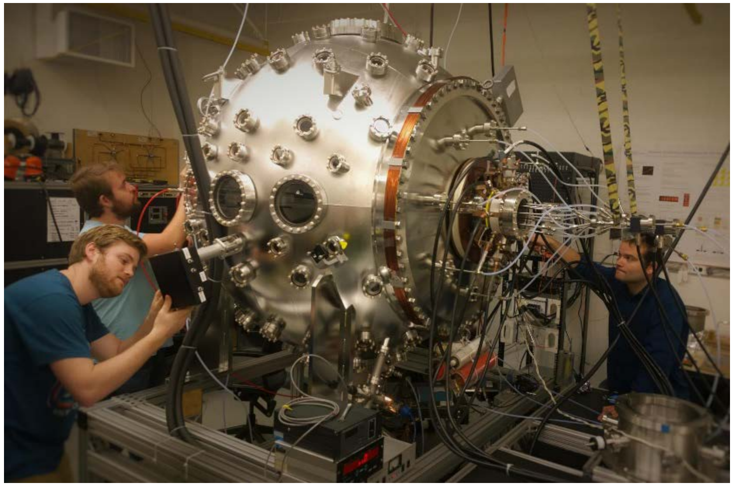
University of Washington Plasma Group

- 7 faculty, 6 staff, approx. 20 graduate students
- experimental & computational research in plasma dynamics, fusion energy, and advanced space propulsion
- Computational Plasma Dynamics – develop high-fidelity physics models and novel numerical solution algorithms



- Helicity Injection Current Drive – self-organized spheromak configurations
- Laboratory Astrophysics – form helical plasma jets to study interaction between plasma flows and helical magnetic fields





Uri Shumlak, shumlak@uw.edu

Presentation Outline

- Promise and challenge of nuclear fusion energy: why is it so difficult, so expensive, and so far away?
- Rethinking plasma stability by replacing magnetic shear with flow shear
- Sheared flow stabilization applied to the Z-pinch – theoretical findings and experimental investigation
- Experimental data showing low MHD mode activity coincident with sheared plasma flow in ZaP device
- Improved performance on next generation ZaP-HD device showing higher energy density and consistent stability behavior.
- Sheared flow stabilized Z-pinch scaling relations show a path to HEDP and fusion conditions. Motivates new project, FuZE.
- Other applications include EUV lithography

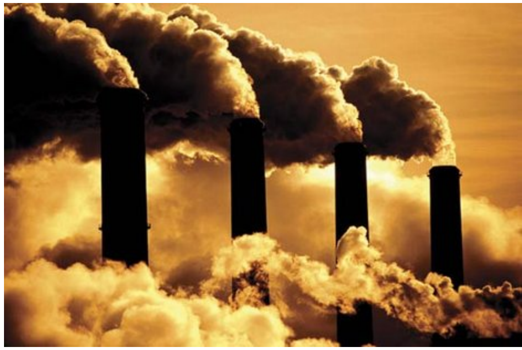
Uri Shumlak, shumlak@uw.edu

Fusion is the ultimate energy source, but control is hard

Energy availability elevates developing countries. As standards of living improve, energy production and consumption will increase. Existing energy sources have drawbacks:

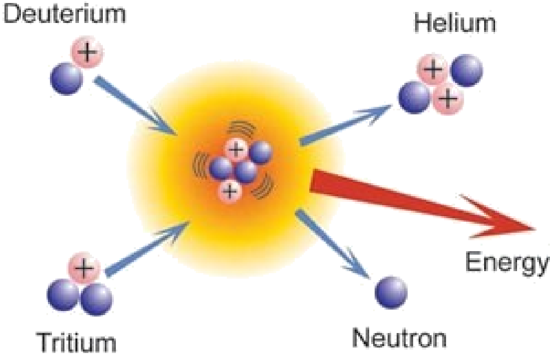
- Fossil fuels are being depleted; greenhouse gases
- Nuclear fission has disposal concerns; public anxiety
- Hydro & solar power can have negative environmental impacts and are limited by power output and location possibilities

None are applicable for human exploration of deep space.



Nuclear fusion reactions release a tremendous amount of energy with a fuel supply that could last 5 million years.

$$^{2}_{1}D + ^{3}_{1}T \rightarrow ^{4}_{2}He + ^{1}_{0}n + 17.6\text{ MeV}$$



Developing controlled fusion energy has proven to be much harder than originally imagined.

Fusion is the ultimate energy source, but control is hard

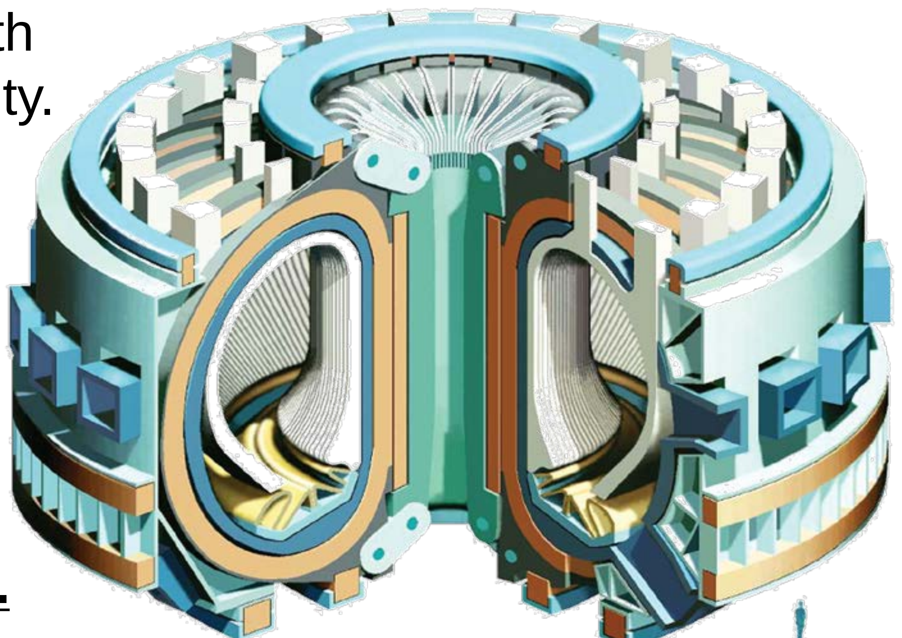
Developing controlled thermonuclear fusion energy is difficult.

- Positively-charged nuclei must approach close distances overcoming electrostatic repulsion until the **nuclear strong force** engages
- Nuclei must be heated to high energies, insulated from cold structural materials, and confined while fusing collisions occur

$$n\tau > 3\times 10^{20}\ \mathrm{s/m^3}\ \text{at}\ T = 15\ \mathrm{keV}\ (\approx 150{,}000{,}000\ ^{\circ}\mathrm{C})$$

Some of the best results have been achieved in tokamaks – massive devices with relatively low plasma energy density.

- Efficiency drives to smaller, compact designs.
- Plasma stability requires large magnetic fields. (static plasmas)



<u>Rethink plasma stability with a search for compact configurations.</u>

ZaP Flow Z-Pinch

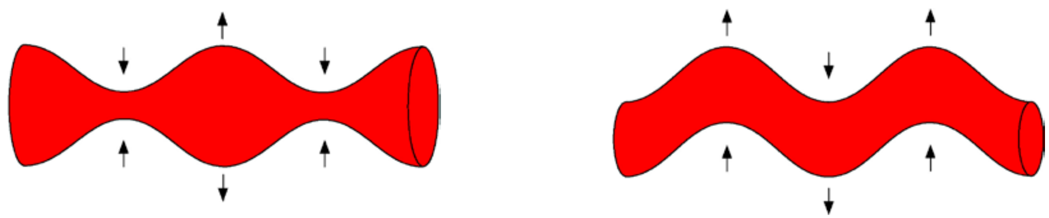
Uri Shumlak, shumlak@uw.edu

Z-pinch offers a simple configuration for fusion energy

The Z-pinch equilibrium (no applied axial fields) is described by

$$\frac{B_\theta}{\mu_o r}\frac{d\left(rB_\theta\right)}{dr}+\frac{dp}{dr}=0.$$

Increasing the current and the resulting azimuthal magnetic field compresses the plasma to fusion conditions in a compact device – no magnetic field coils. However, the equilibrium is classically unstable to m = 0 sausage and m = 1 kink modes.



Crushed lightning rod.[1]

Stability can be restored by limiting the pressure gradient[2], introducing an axial magnetic field[3], or installing a close-fitting conducting wall[4].

These approaches are incompatible with a compact fusion device.

UNIVERSITY of WASHINGTON

[1]Pollock & Barraclough, PRS (1905); [2]Kadomtsev, RPP (1966); [3]Kruskal et al., PRS (1954); Shafranov, SJAE (1956); [4]Knecht et al. IEEE TPS (2014)

The Z-pinch can be stabilized with a sheared flow.

Plasma flow destroys the convenient Hermitian quadratic form that results from the energy principle stability analysis.

$$\delta W = -\int \xi^* \cdot \mathrm{F}(\xi) + \underbrace{2i\omega \int \rho_0 \xi^* \cdot (\mathrm{v}_0 \cdot \nabla)\xi}_{\textit{Flow}} = -\omega^2 \int \rho_0 \xi^* \cdot \xi$$

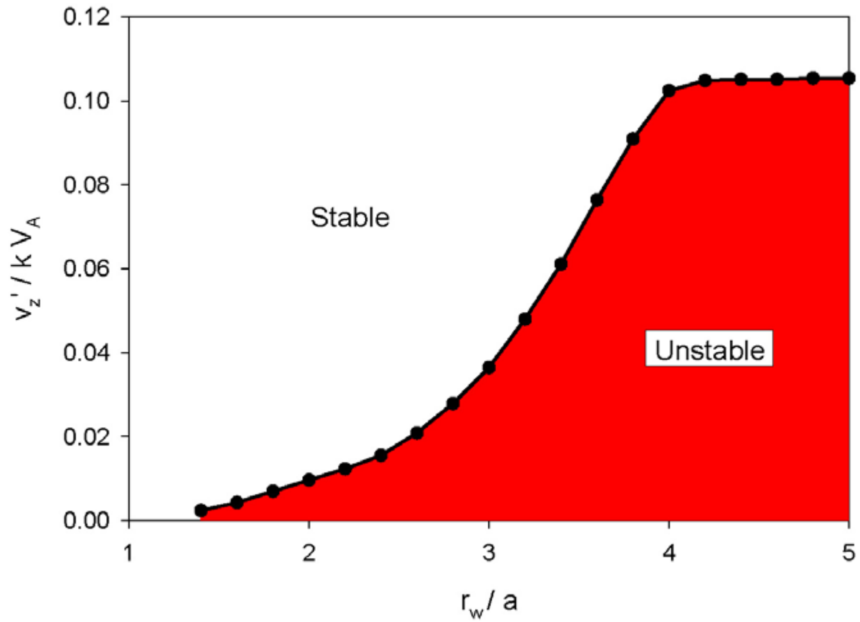
Solving a more complicated linear stability analysis for a marginally stable Kadomtsev equilibrium,[1]

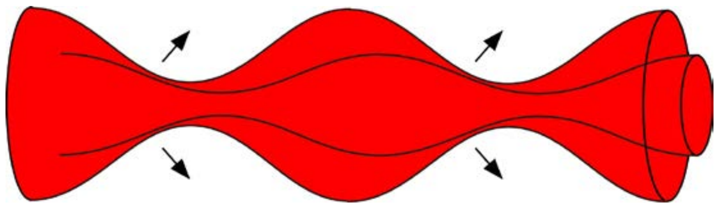
$$-\frac{d\ln p}{d\ln r} = \frac{4\gamma}{2+\gamma\beta}.$$

In the no-wall limit, the Z-pinch is stabilized with a sheared flow,[2]

$$\frac{d\mathrm{v}_z}{dr} \equiv \mathrm{v}_z' \geq 0.1 kV_A.$$

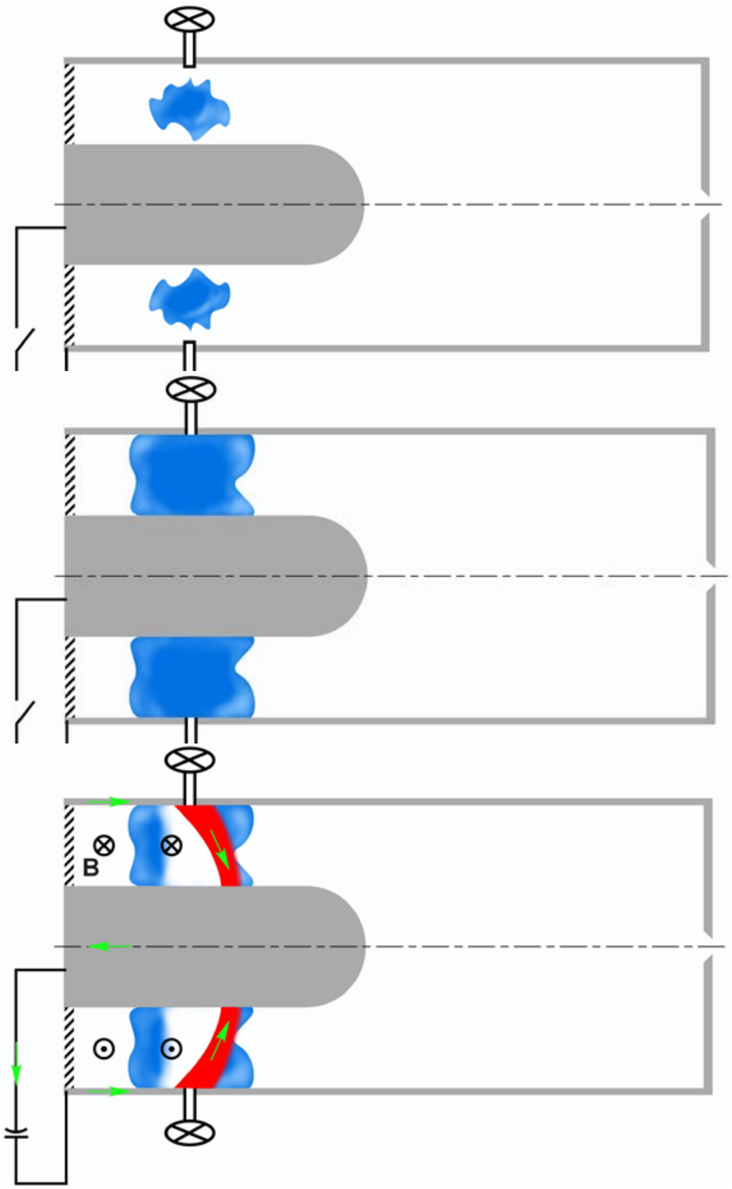
The sheared flow stabilization effect is a phase mixing at different radii in the pinch.





[1]Kadomtsev, RPP (1966); [2]Shumlak & Hartman, PRL (1995)

Schematic illustrates flow Z-pinch formation



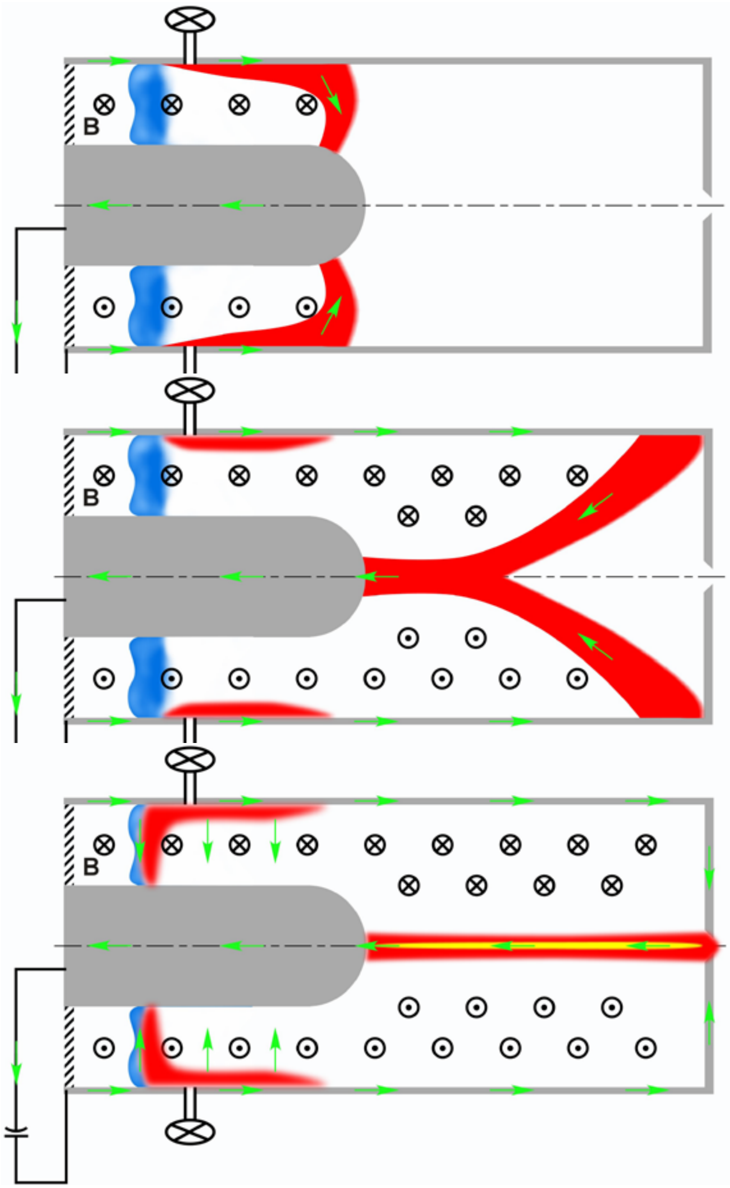
t_1 Neutral gas is injected through puff valves into the annulus of a coaxial plasma accelerator.

t_2 Neutral gas expands before a capacitor bank is discharged across the electrodes.

t_3 The plasma accelerates down the coaxial accelerator due to generated currents and magnetic fields.

Uri Shumlak, shumlak@uw.edu

Schematic illustrates flow Z-pinch formation



t_4 The plasma continues down the accelerator in a snow-plow manner.

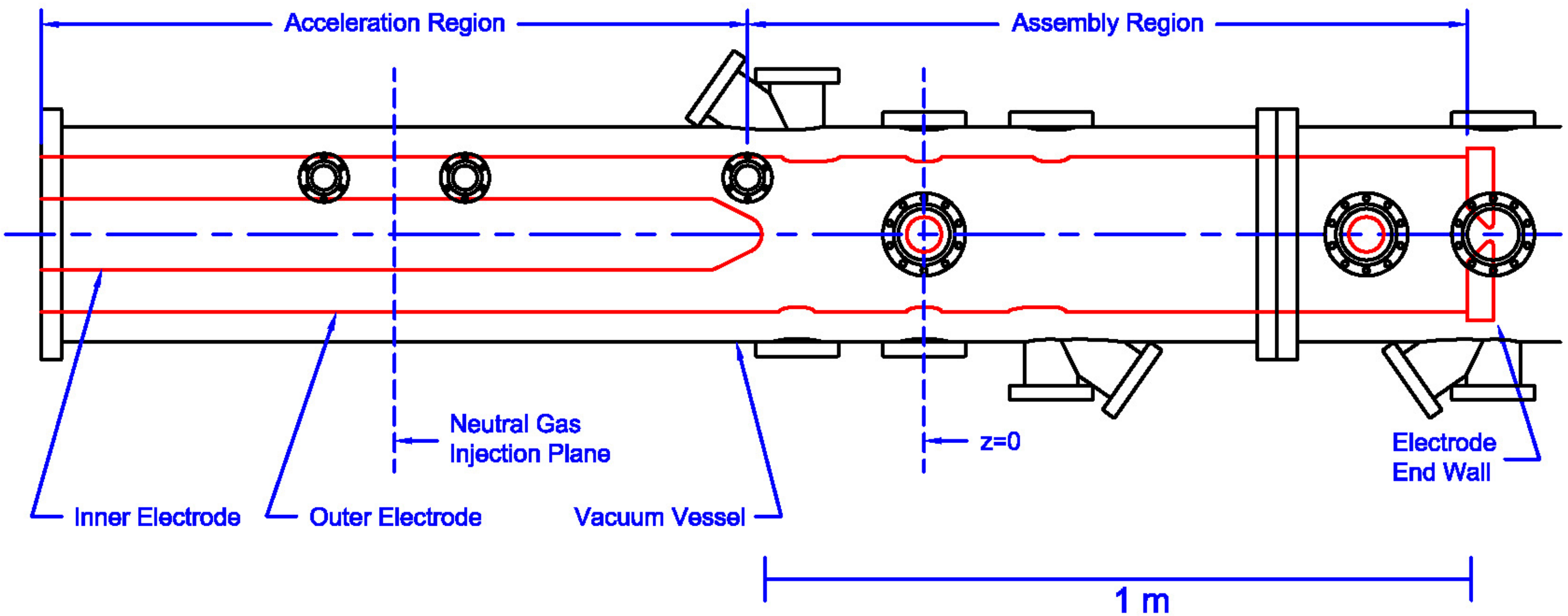
t_5 At the end of the accelerator the plasma assembles into a Z-pinch configuration.

t_6 Inertia and gun currents maintain the plasma flow and supply until the accelerator plasma empties or the capacitor current vanishes.

Uri Shumlak, shumlak@uw.edu

The ZaP Flow Z-Pinch Experiment

The ZaP Flow Z-Pinch experiment investigates the concept of using flows to stabilize an otherwise unstable plasma configuration.



Uri Shumlak, shumlak@uw.edu

Diagnostics measure plasma flow and stability

The ZaP diagnostics measure equilibrium plasma parameters, plasma flow, and magnetic mode activity (stability).

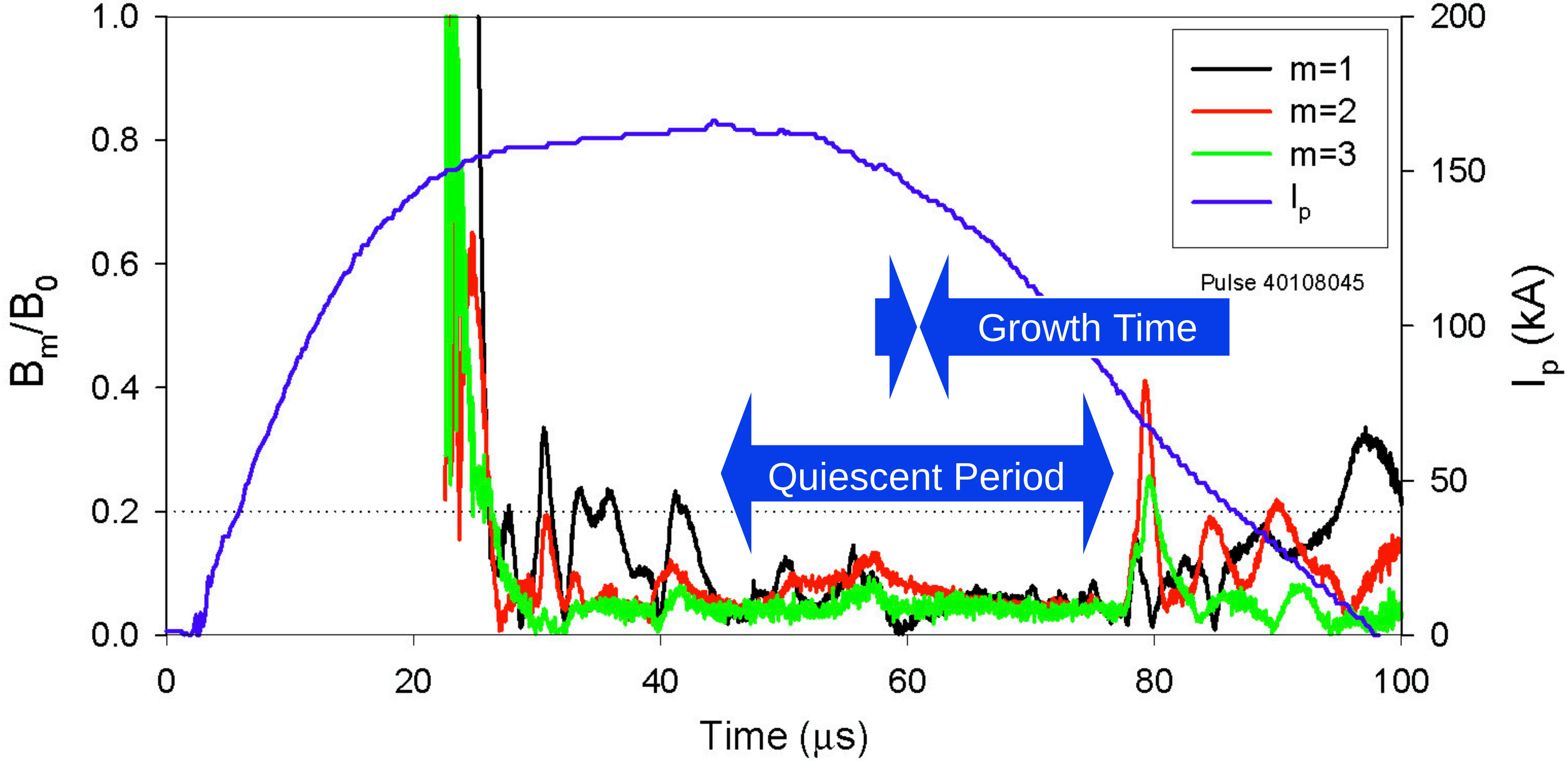
- Surface-mounted magnetic field probes → Analyze magnetic fields, magnetic fluctuations, and plasma stability[1]
- Fast framing camera with optical filters → Qualitative measure of plasma structure
- Four-chord HeNe interferometer → Measure plasma density profile[2]
- 0.5 m imaging spectrometer with 20 input chords and an intensified CCD detector → Doppler shift for plasma flow profile,[1] Doppler broadening for ion temperature, Zeeman splitting for magnetic fields,[3] Stark broadening for density[4]
- Thomson scattering system using ruby laser & Hibshman spectrometer → Measure electron temperature
- Digital holographic interferometer → Measure two-dimensional plasma density structure

UNIVERSITY of WASHINGTON

[1]Shumlak et al., PoP (2003), Golingo et al., PoP (2005); [2]Jackson & Shumlak, RSI (2006); [3]Golingo et al., RSI (2010); [4]Vogman & Shumlak, RSI (2011)

Magnetic fluctuations diminish after pinch forms

Fluctuations of the magnetic modes are significantly reduced for ≈ 37 μs after pinch forms. Mode activity increases again after this quiescent period. Experimental data suggests the quiescent length is limited by plasma supplied from the accelerator.

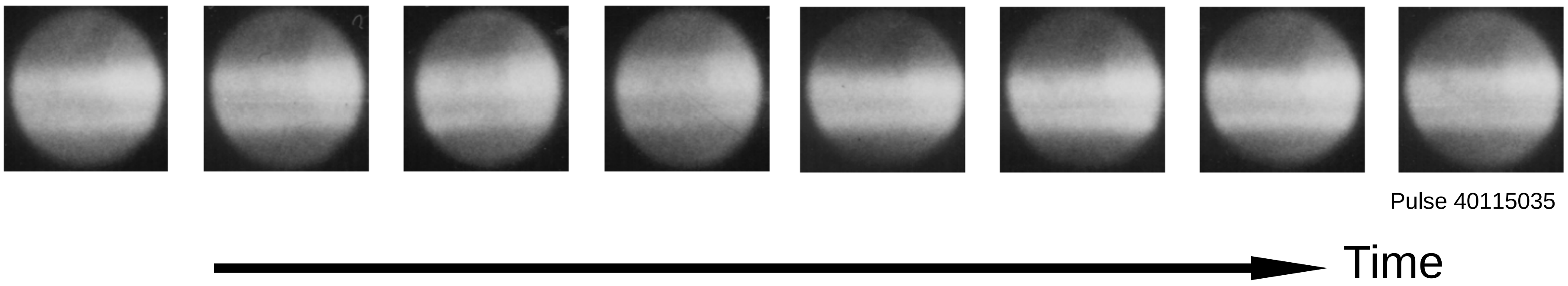


Uri Shumlak, shumlak@uw.edu

Optical images show a stationary plasma pinch

Visible emission images are obtained of the pinch, every 200 ns, through a 5 cm hole with an Imacon fast-framing camera.

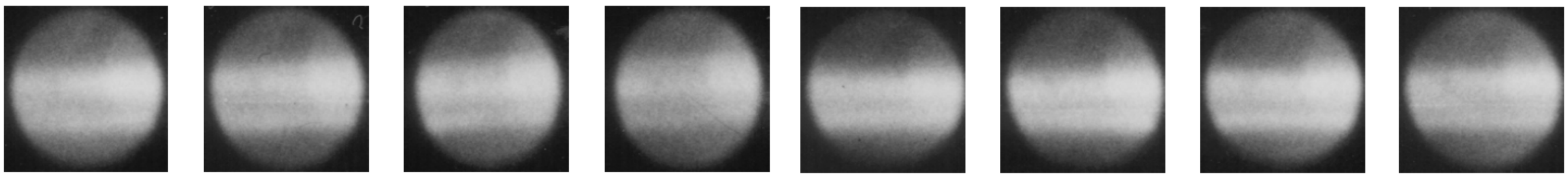
Images show a stationary plasma pinch during the quiescent period. Note hollow structure.



Optical images show a stationary plasma pinch

Visible emission images are obtained of the pinch, every 200 ns, through a 5 cm hole with an Imacon fast-framing camera.

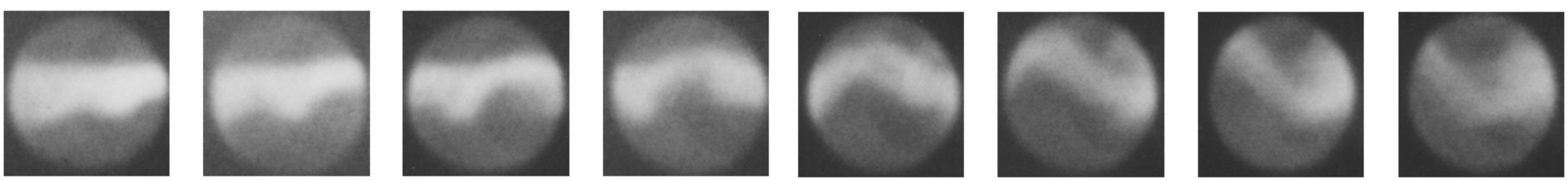
Images show a stationary plasma pinch during the quiescent period. Note hollow structure.



Pulse 40115035

Time

Gross kink & sausage instabilities appear at the end of the quiescent period.



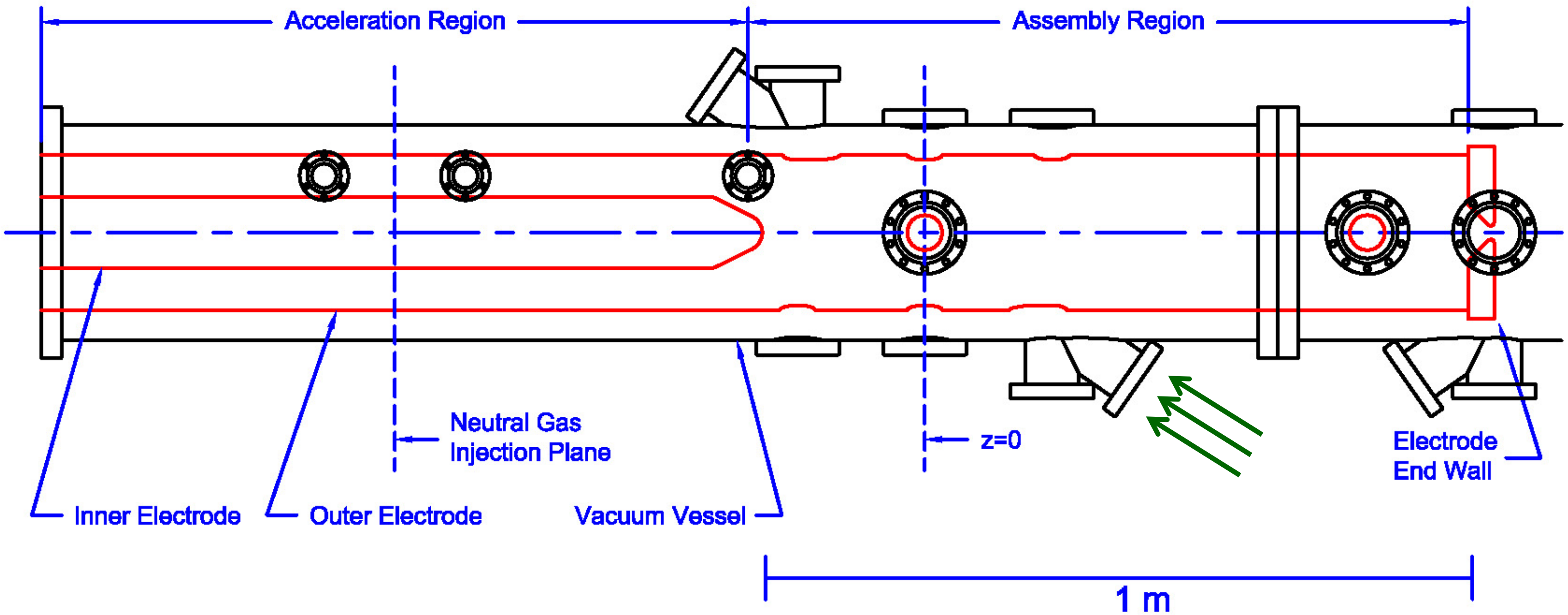
Pulse 40127041

Uri Shumlak, shumlak@uw.edu

Multichord spectrometer provides velocity profiles

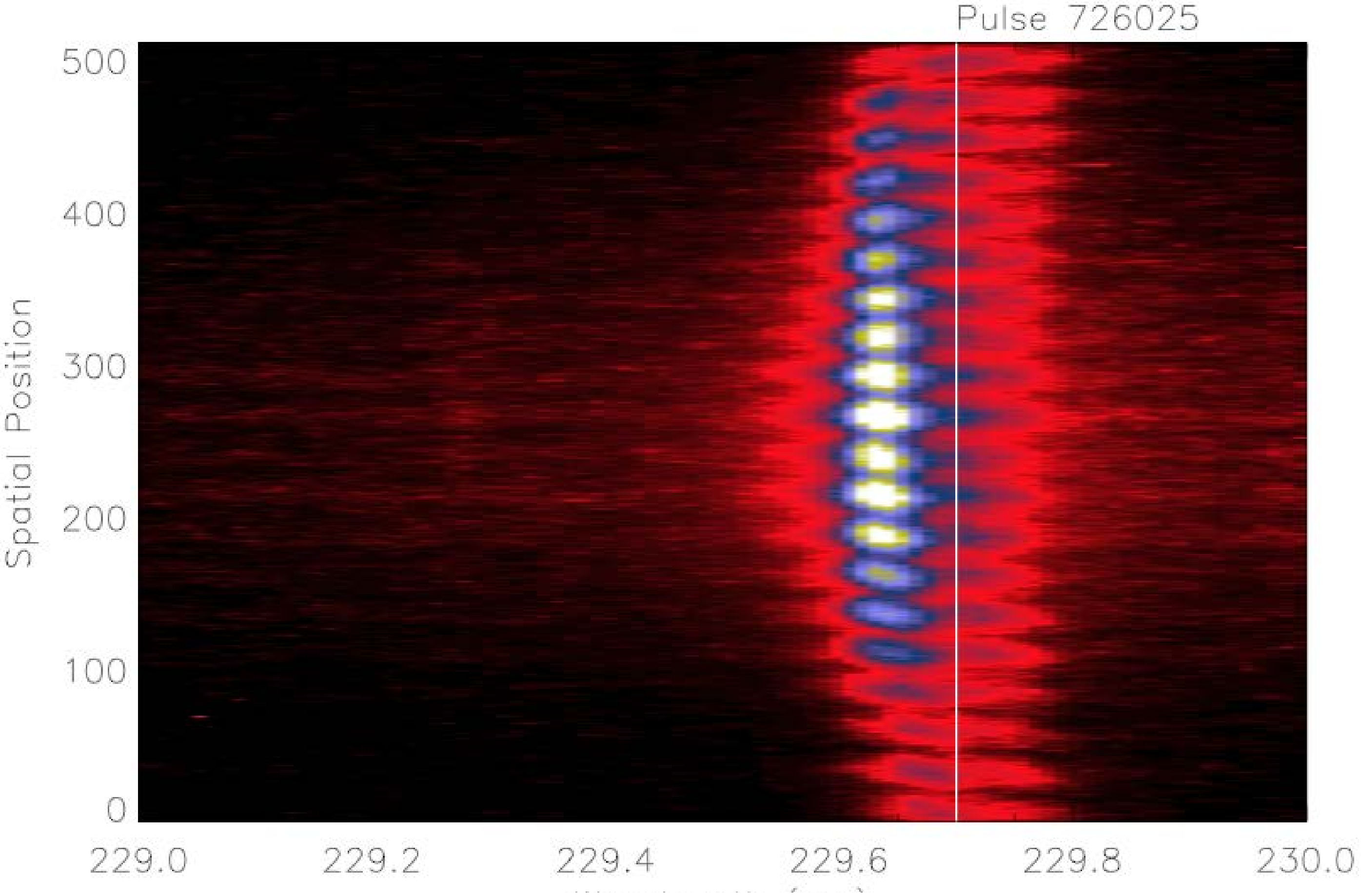
A 20-chord imaging spectrometer is connected to an intensified CCD detector to measure the Doppler shifts of impurity emission lines.

The chords are spaced out of plane in the drawing below.



Large flow velocity exists during the quiescent period[1]

Large Doppler blue-shift of the C-III impurity line (229.7 nm) during the quiescent period.

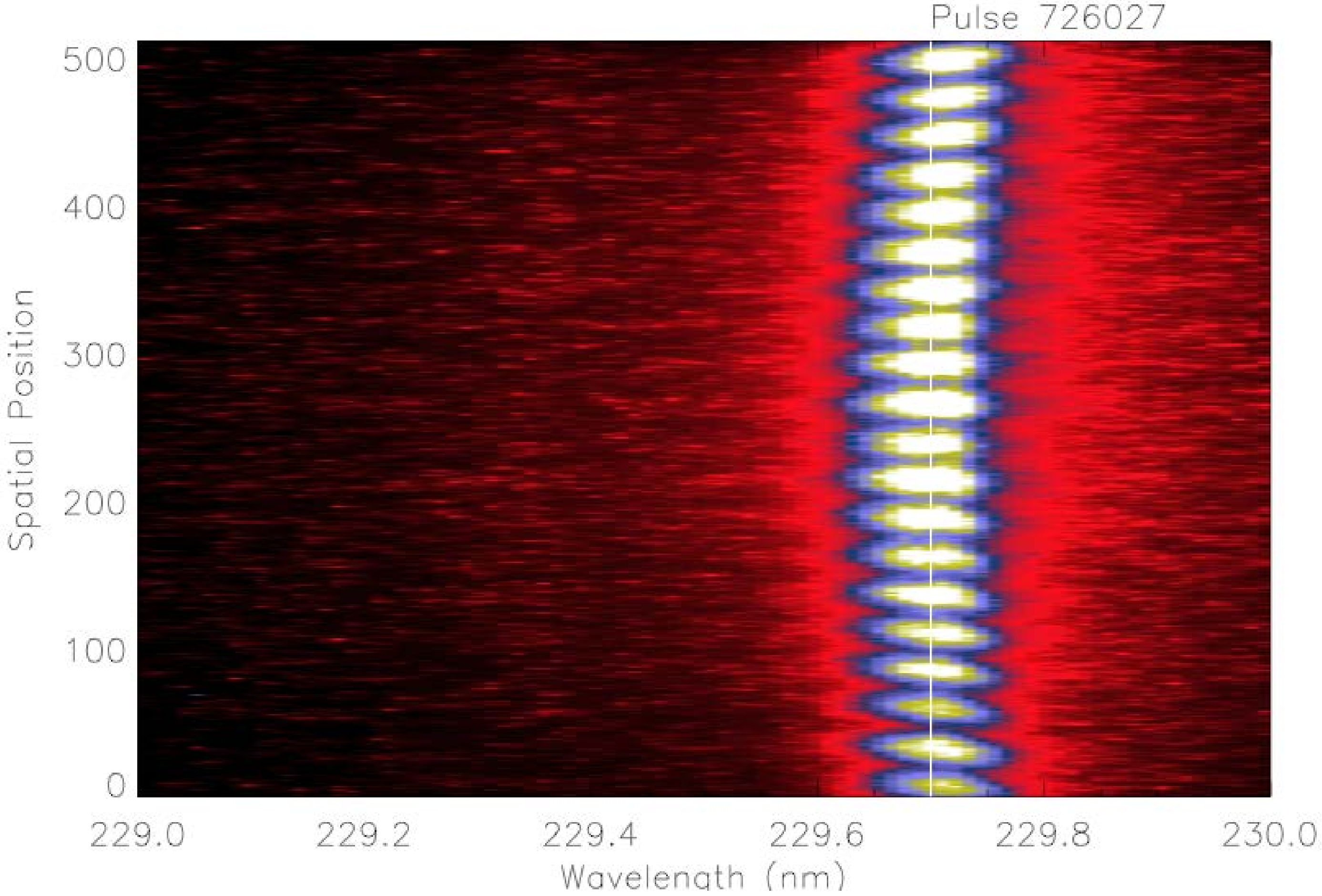


UNIVERSITY of WASHINGTON

[1]Shumlak, Golingo, Nelson, & Den Hartog, PRL (2001)

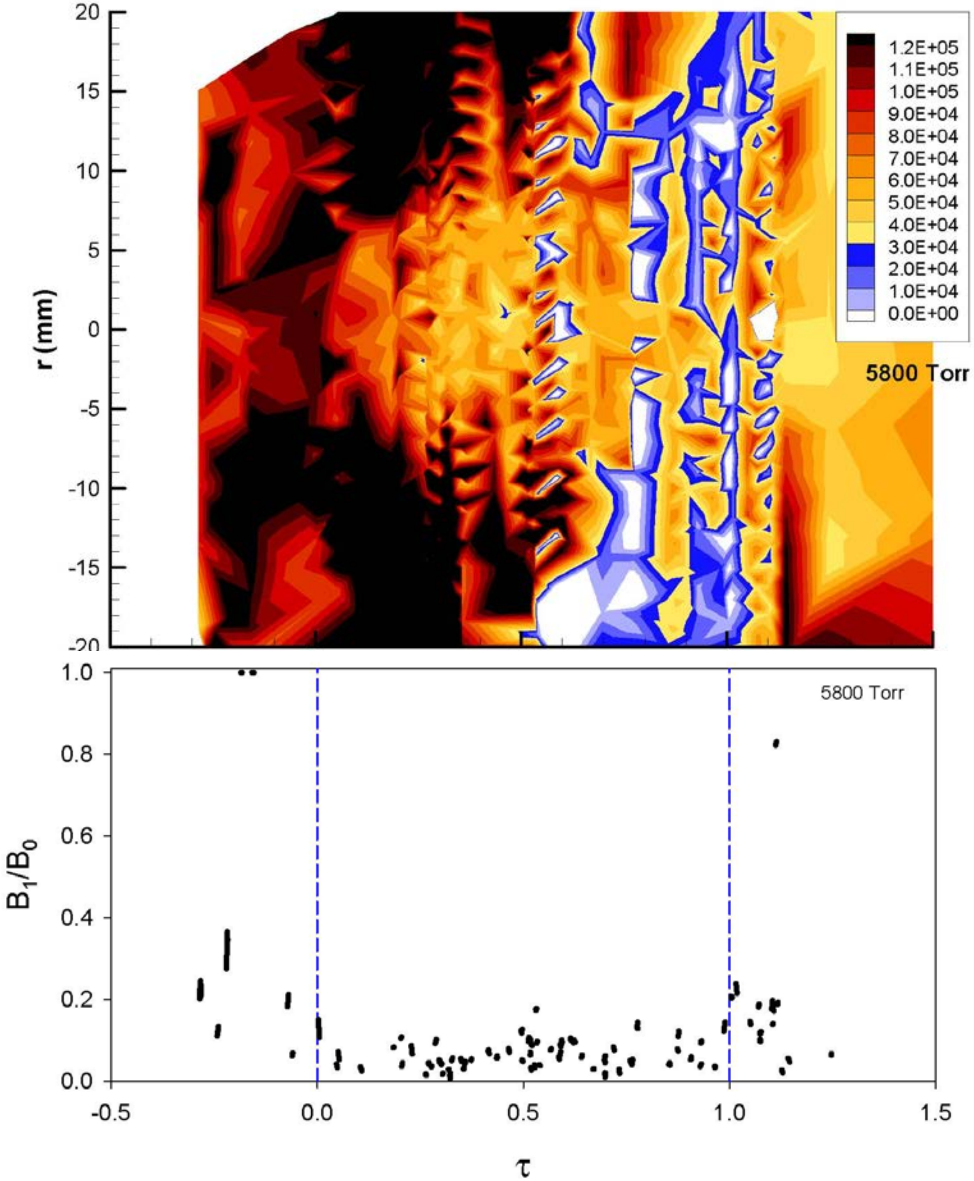
Flow velocity decreases at end of the quiescent period

Small Doppler shift of the C-III impurity line (229.7 nm) at the end of the quiescent period.



Uri Shumlak, shumlak@uw.edu

Flow profile is correlated to plasma stability

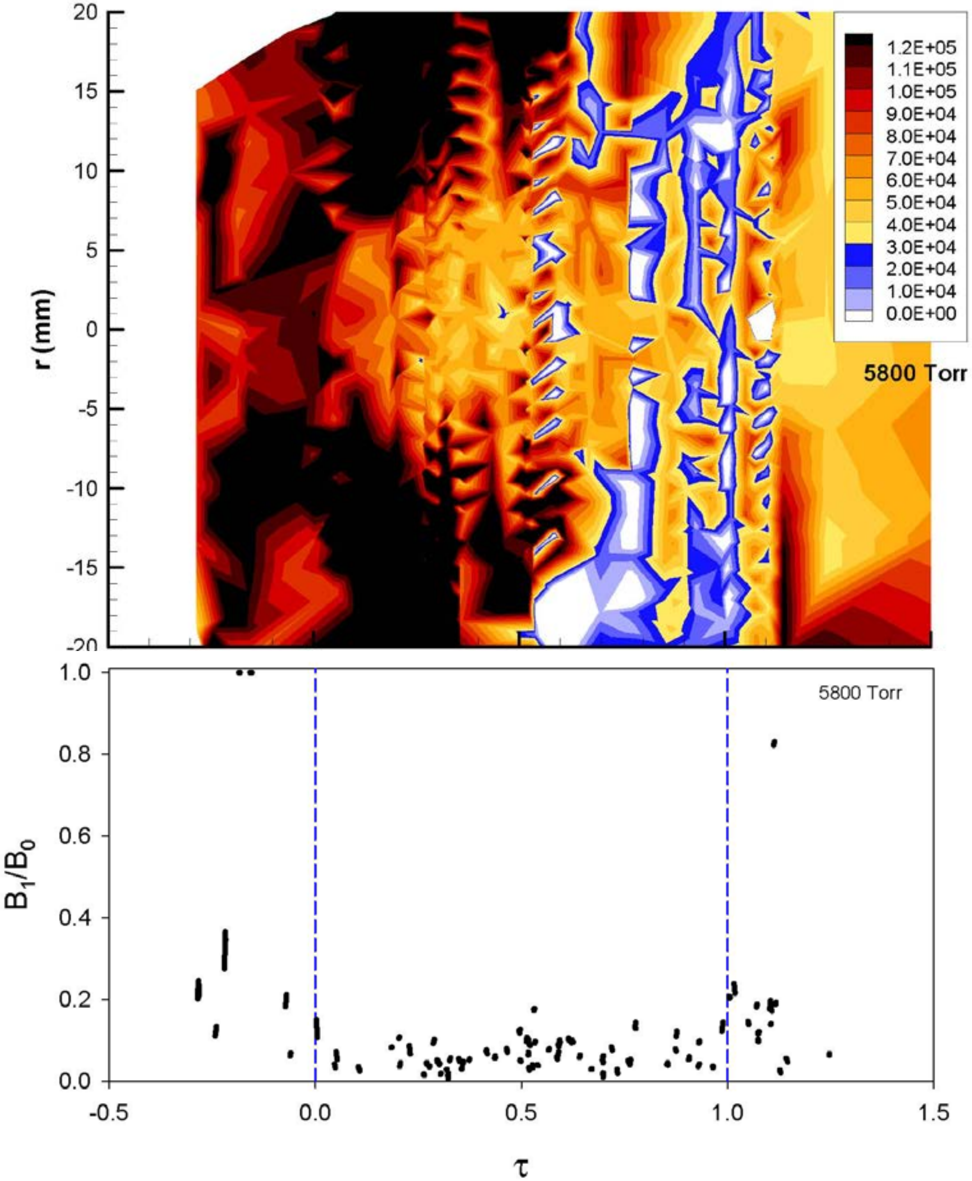


During initial plasma assembly ($\tau < 0$), the axial plasma velocity is high and uniform.

$v_z' \approx 0\text{-}4 \times 10^6\ s^{-1}$

Uri Shumlak, shumlak@uw.edu

Flow profile is correlated to plasma stability



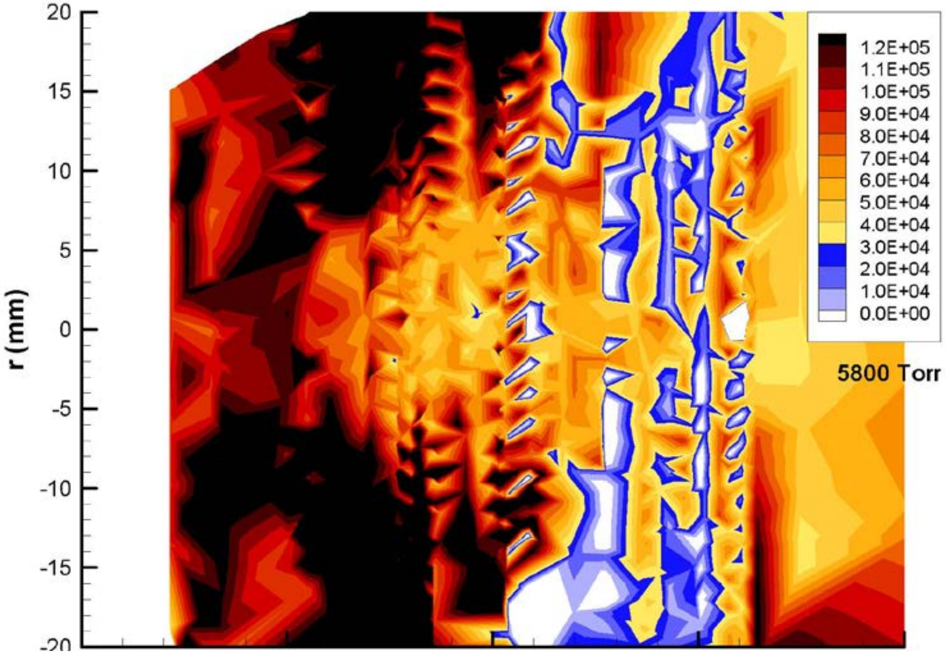
Plasma assembly ($\tau < 0$), the axial plasma velocity is high and uniform. ($v_z' \approx 0\text{-}4 \times 10^6\ s^{-1}$)

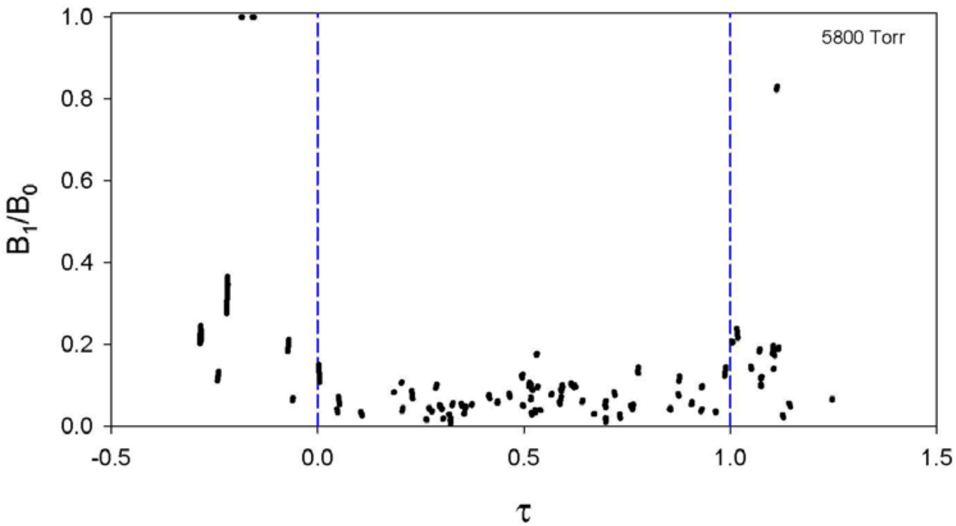
At the start of quiescent period ($\tau = 0$), the velocity slows on axis. The velocity profile is high at the plasma edge and lower at the axis.

$$v_z' \approx 7\text{-}12 \times 10^6\ s^{-1}$$

Uri Shumlak, shumlak@uw.edu

Flow profile is correlated to plasma stability





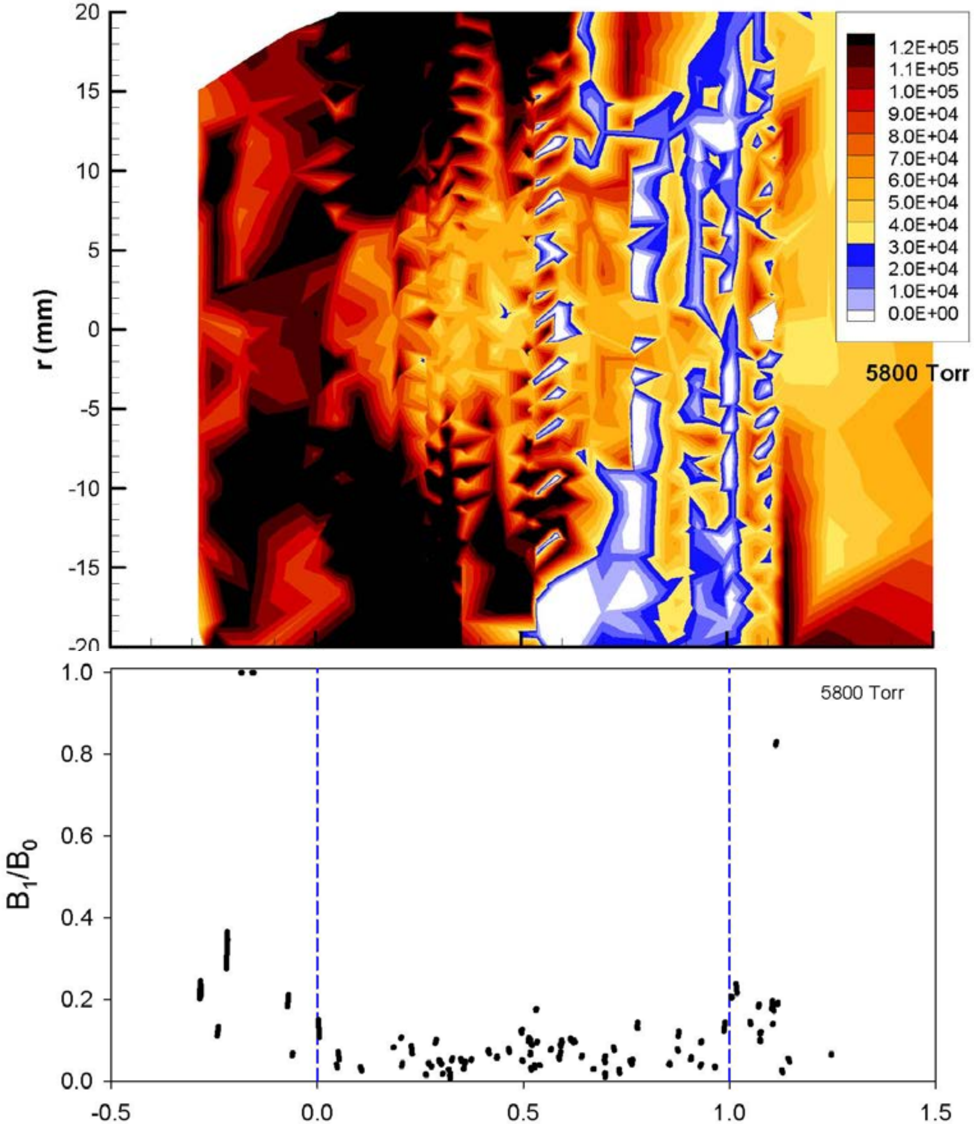
Plasma assembly ($\tau < 0$), the axial plasma velocity is high and uniform. ($v_z' \approx$ 0-4 $\times 10^6$ s^{-1})

Start of quiescent period ($\tau = 0$), the velocity profile is high at the plasma edge and lower at the axis. ($v_z' \approx$ 7-12 $\times 10^6$ s^{-1})

At the end of quiescent period ($\tau = 1$), the plasma velocity profile is low and uniform.

$$v_z' \approx 0\text{-}6 \times 10^6 \text{ s}^{-1}$$

Flow profile is correlated to plasma stability[1]



Plasma assembly ($\tau < 0$), the axial plasma velocity is high and uniform. ($v_z{}' \approx 0\text{-}4 \times 10^6\ s^{-1}$)

Start of quiescent period ($\tau = 0$), the velocity profile is high at the plasma edge and lower at the axis. ($v_z{}' \approx 7\text{-}12 \times 10^6\ s^{-1}$)

End of quiescent period ($\tau = 1$), the plasma velocity profile is low and uniform. ($v_z{}' \approx 0\text{-}6 \times 10^6\ s^{-1}$)

For these plasma parameters, the theoretical growth time $\approx$ 20 ns.

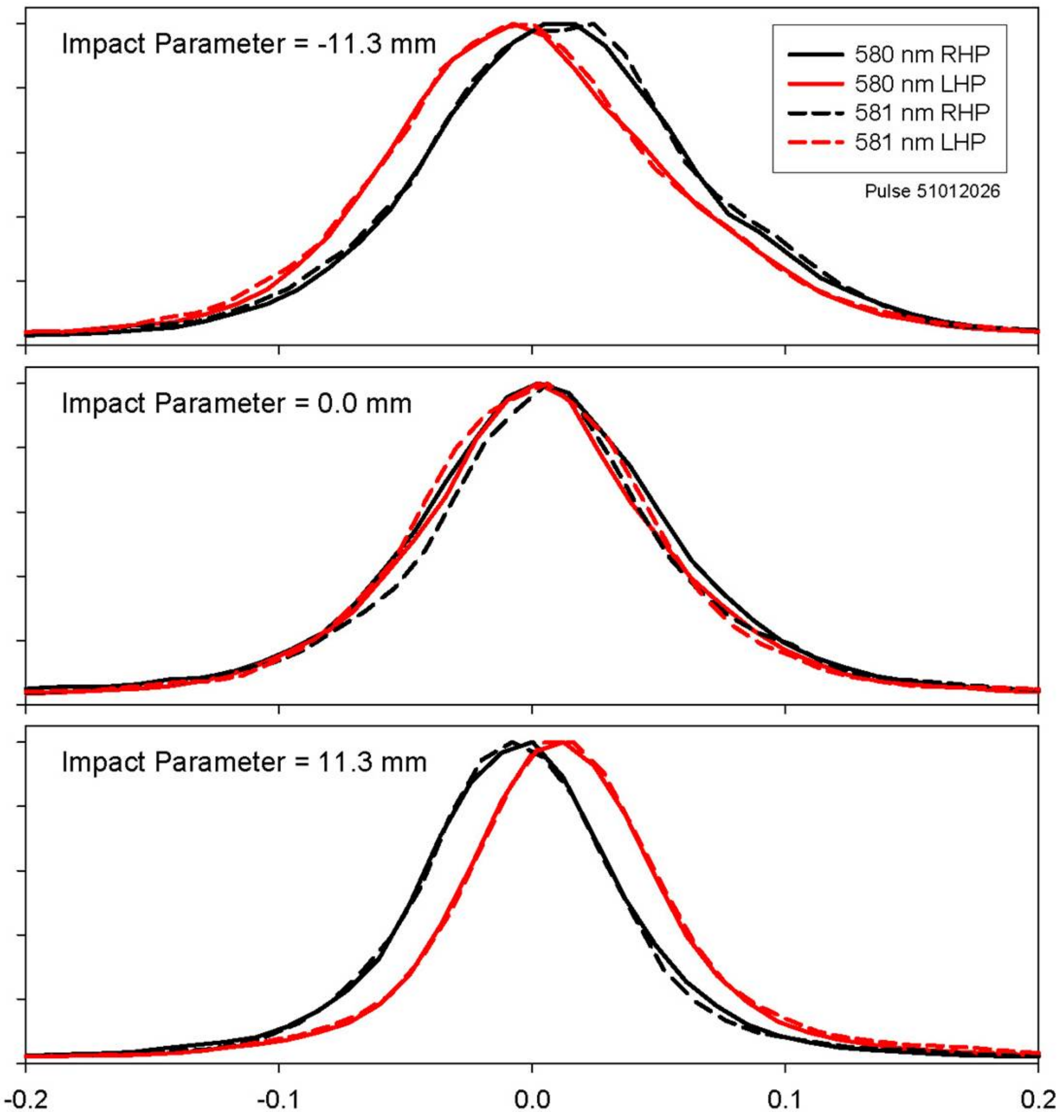
Linear theory specifies a shear threshold of $\approx 5 \times 10^6\ s^{-1}$.

UNIVERSITY of WASHINGTON

[1]Shumlak et al., PoP (2003); Golingo et al., PoP (2005); Shumlak et al., NF (2009)

Zeeman splitting measures internal magnetic field[1]

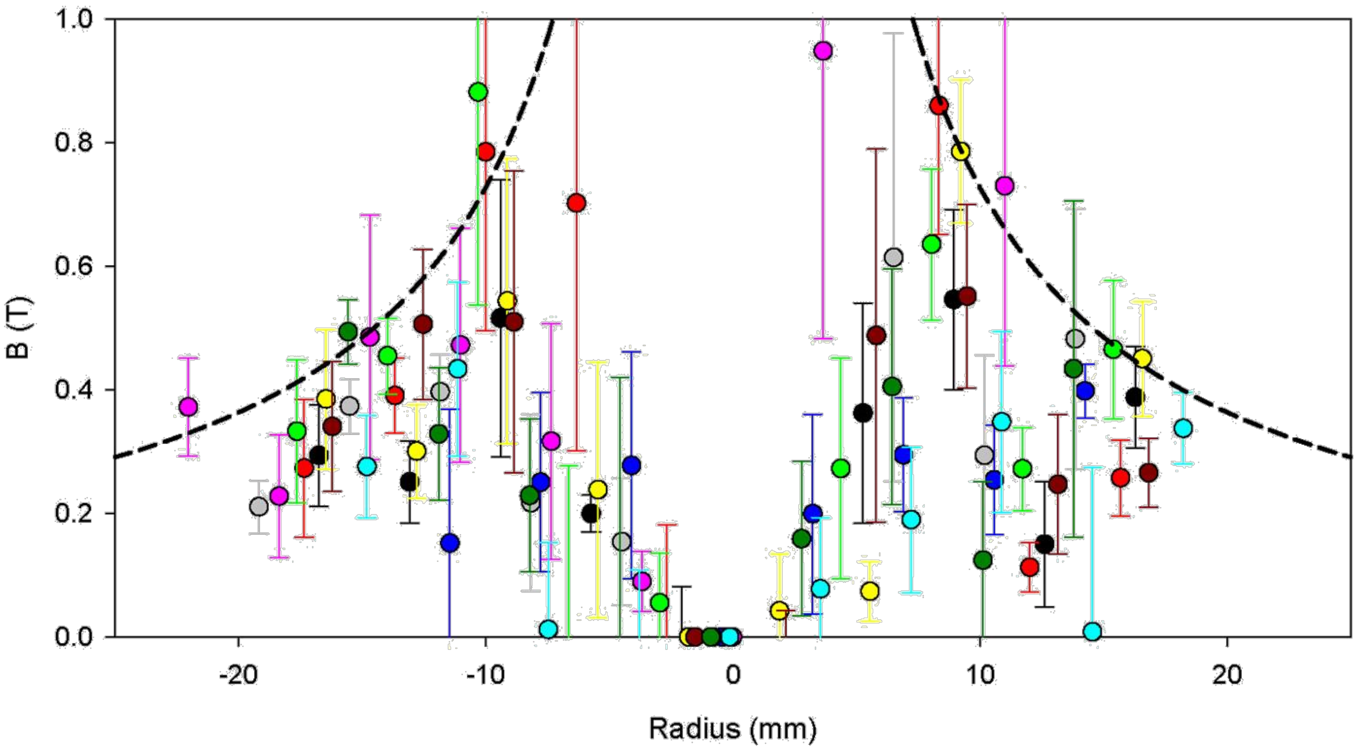
- Zeeman splitting measurements have been made to determine the internal magnetic field of the plasma pinch.
- Impurity emission of the C IV doublet at 580.1 & 581.2 nm is collected perpendicular to the plasma.
- Circularly polarized light is collected along 10 parallel chords through the pinch.
- Operated with reduced capacitor bank energy of 35 kJ.



[1]Golingo, Shumlak, & Den Hartog, RSI (2010)

Zeeman splitting measures internal magnetic field

Deconvolved magnetic field values are compiled for many pulses to provide an average magnetic field profile. The magnetic field peaks at the pinch radius and then decays as inverse radius to the value measured at the outer electrode.

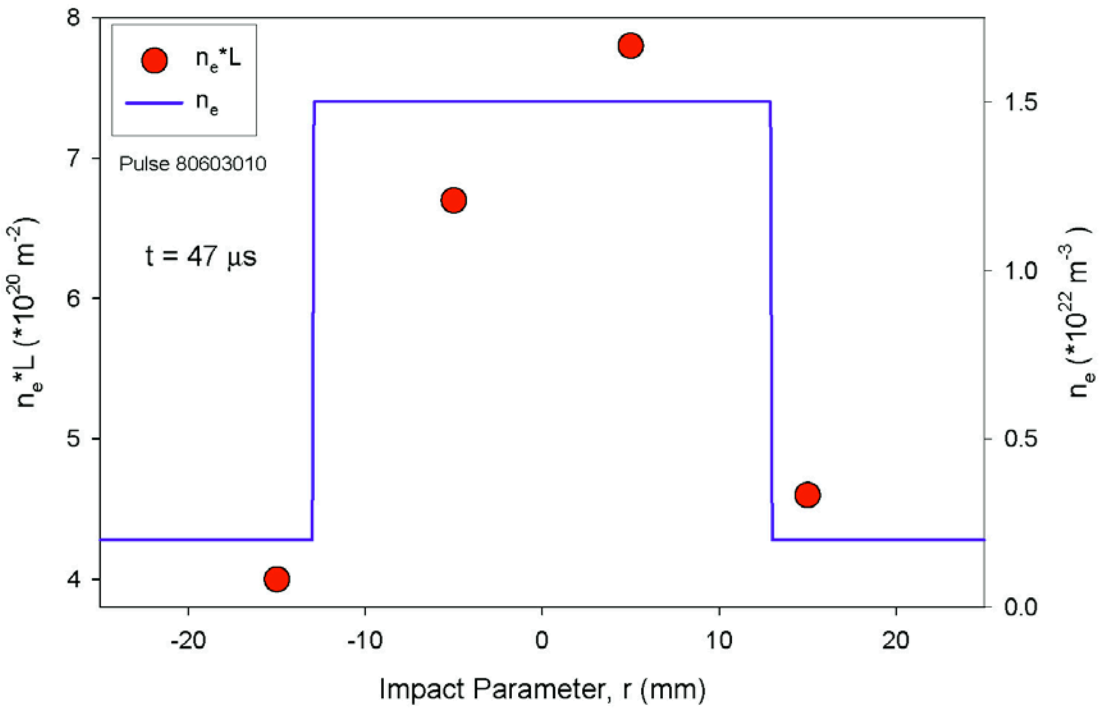


Interferometry provides plasma density and radius

The Z-pinch equilibrium has no applied magnetic fields and is described by

$$\frac{B_\theta}{\mu_o r}\frac{d}{dr}\left(rB_\theta\right)+\frac{d}{dr}\left(n\left(T_i+T_e\right)\right)=0$$

The four-chord interferometer provides chord-integrated density along parallel chords spaced 10 mm apart. Density data obtained at the same time as spectroscopy can be fit with a constant density plasma core with a surrounding background.[1]



Plasma radius, *a*, and core density, n_e, are determined.

Shown are *a* = 13 mm, $n_e = 1.5 \times 10^{22}$ m^{-3}.

[1]Knecht, Golingo, Nelson, & Shumlak, IEEE TPS (2015)

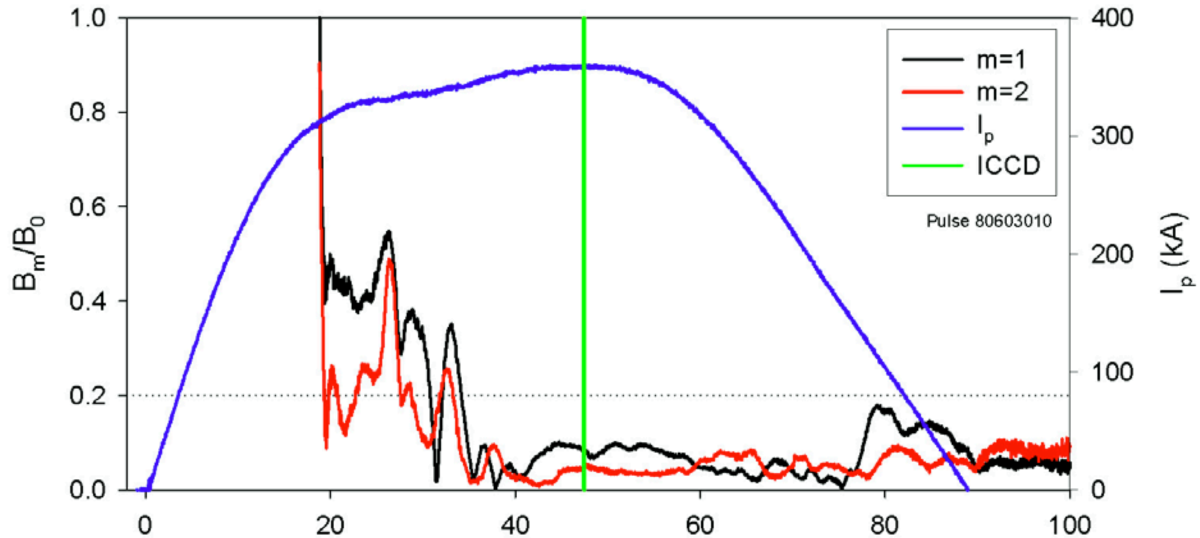
Ion temperature is measured from spectroscopy

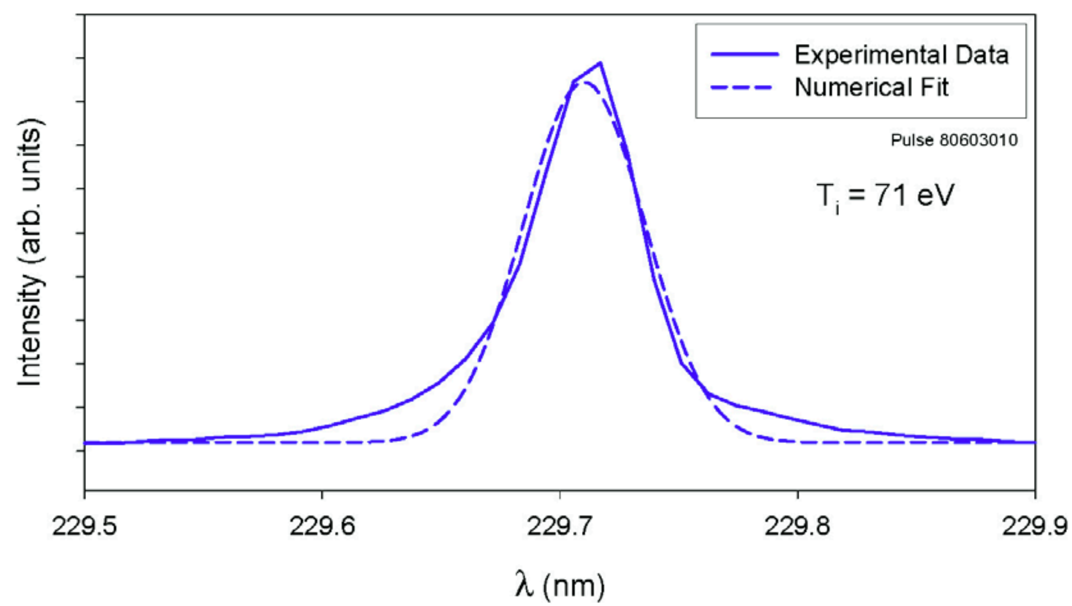
Viewing the plasma radially with the ICCD spectrometer, the Doppler broadening of impurity lines are measured.

A 100 ns gate is used and triggered at τ = 0.2 to collect C III emission (229.7 nm).

The chord-integrated data is fit to determine ion temperature.

Shown is T_i = 71 eV.



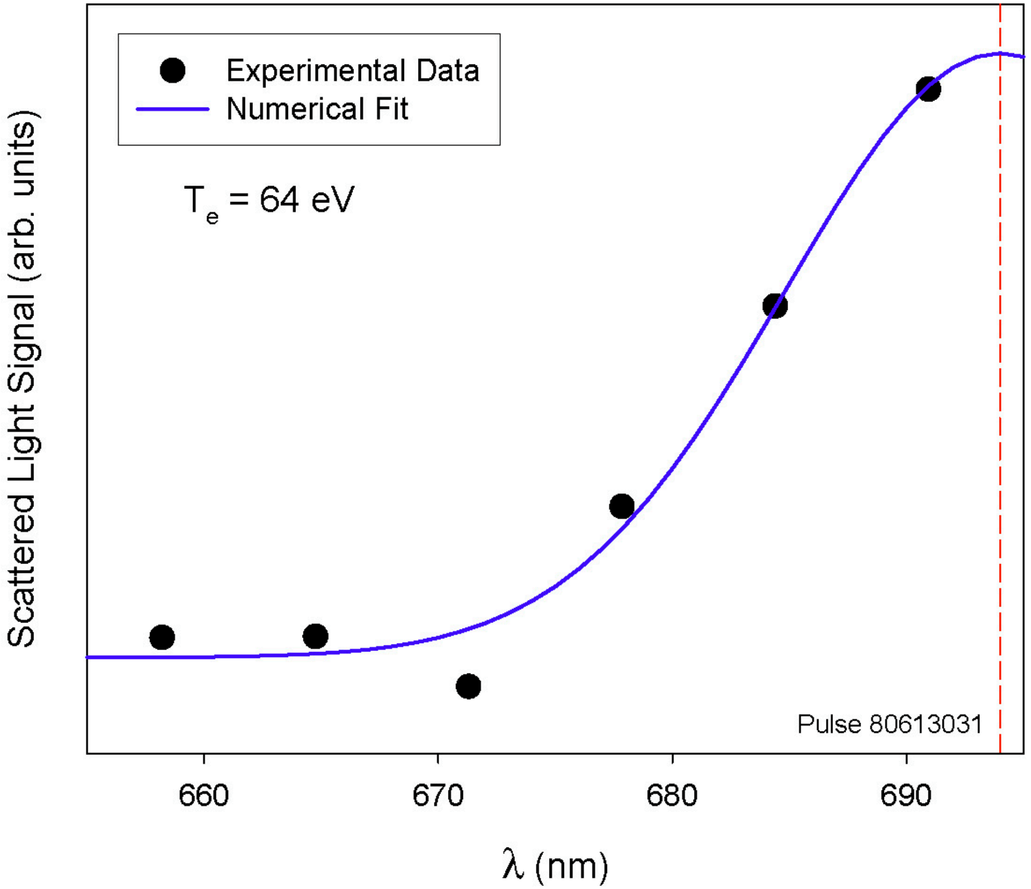


Thomson scattering measures hot plasma core

A single-point Thomson scattering system has been developed and installed on ZaP. The diagnostic uses a 10 J Korad ruby laser, a Hibshman spectrometer, and an array of PMTs for 8 wavelength bins.

The system views a cylindrical scattering volume 2.5 mm × Φ3 mm at the machine axis. The laser pulse and scatter pulse waveforms are recorded, as well as background light.

Results show an electron temperature of $T_e = 64 \pm 11$ eV.



Uri Shumlak, shumlak@uw.edu

Radial forces balance demonstrating equilibrium

The experimental values can now be used to determine consistency with equilibrium force balance. Using the data presented: a = 13 mm, $n_e = 1.5 \times 10^{22}$ m^{-3}, B_{wall} = 0.13 T, (assuming no current outside of pinch B_a = 1 T).

Assuming a uniform pressure inside the plasma core, gives a total temperature

$$T_i + T_e = 160 \text{ eV}.$$

This value can be compared with the independently measured ion and electron temperatures.

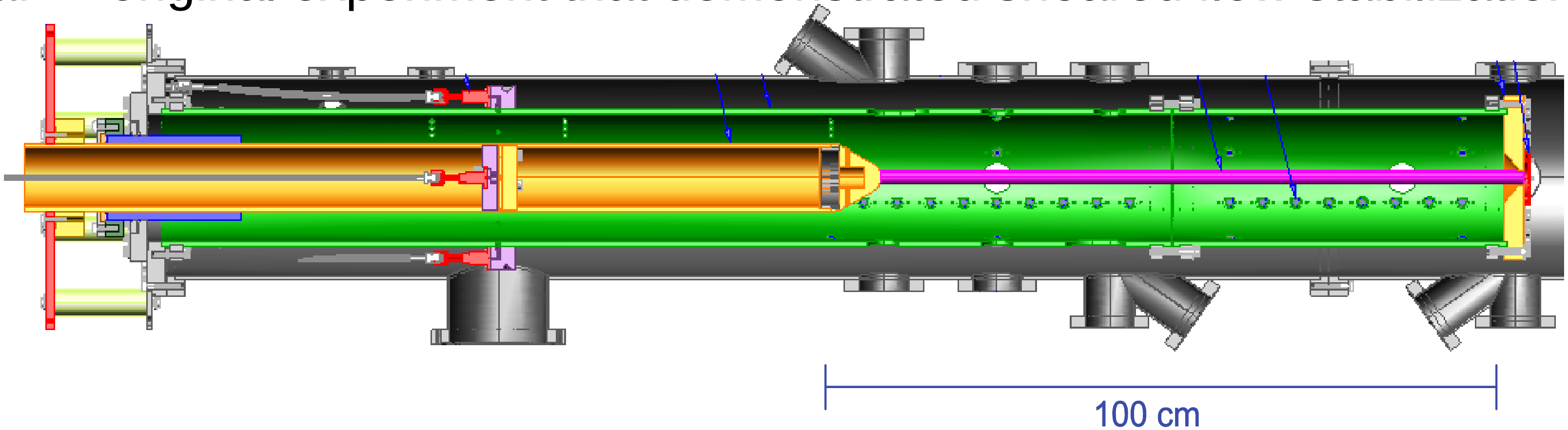
$$T_i + T_e = 71 \text{ eV} + 64 \text{ eV} = 135 \text{ eV}$$

Uri Shumlak, shumlak@uw.edu

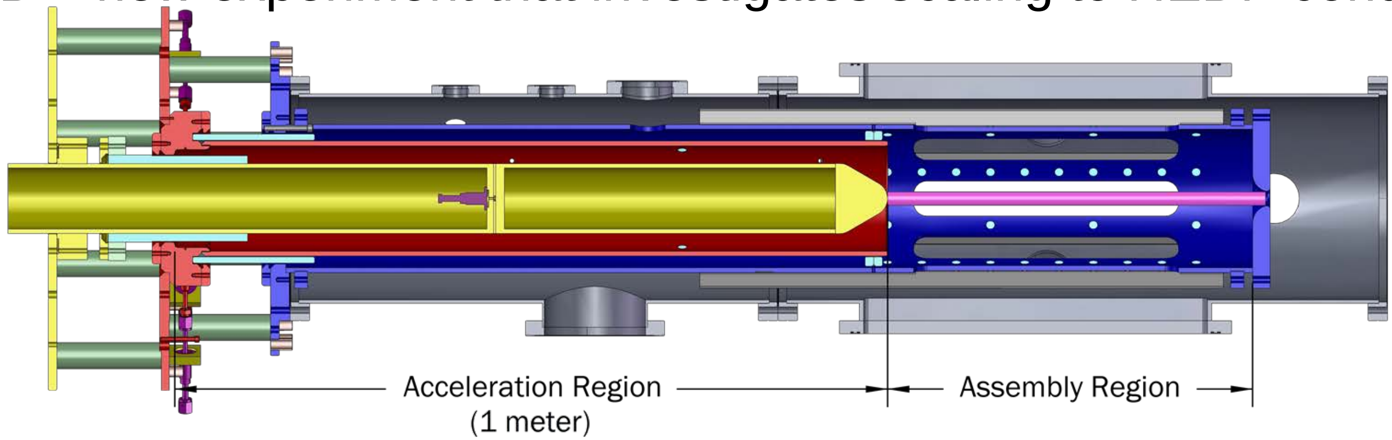
ZaP-HD expands the capabilities of ZaP

ZaP-HD Flow Z-Pinch separates the acceleration and compression functions to increase control of density, flow, and magnetic field.

ZaP – original experiment that demonstrated sheared flow stabilization



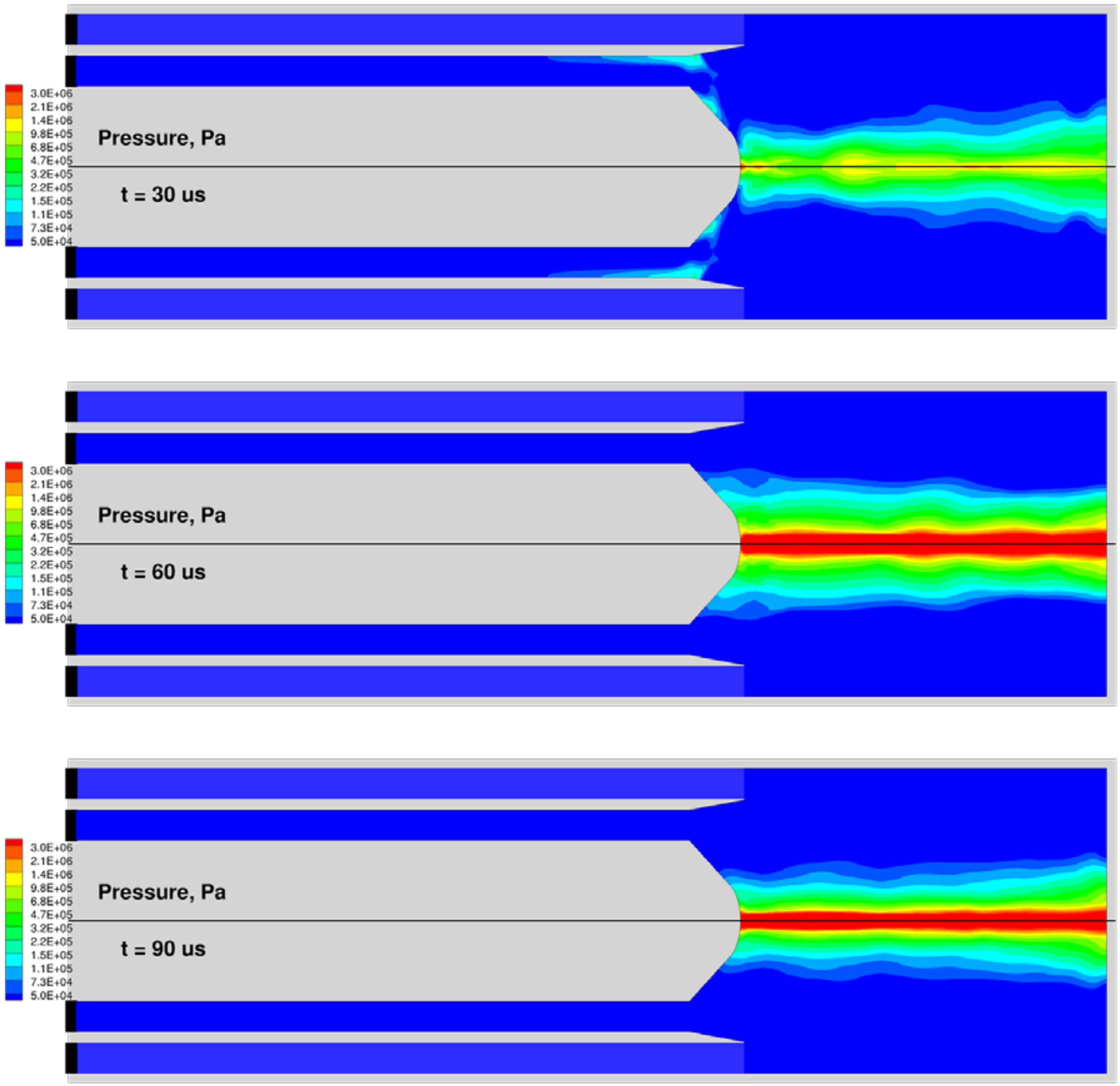
ZaP-HD – new experiment that investigates scaling to HEDP conditions



Uri Shumlak, shumlak@uw.edu

Simulations show formation of high pressure plasma

- Time-dependent simulations of ZaP-HD indicate the formation of a high pressure plasma that extends through the Z-pinch assembly region and has a high degree of axial uniformity.
- Simulations are performed with the Mach2 resistive MHD code using realistic circuit solvers from two capacitor banks.



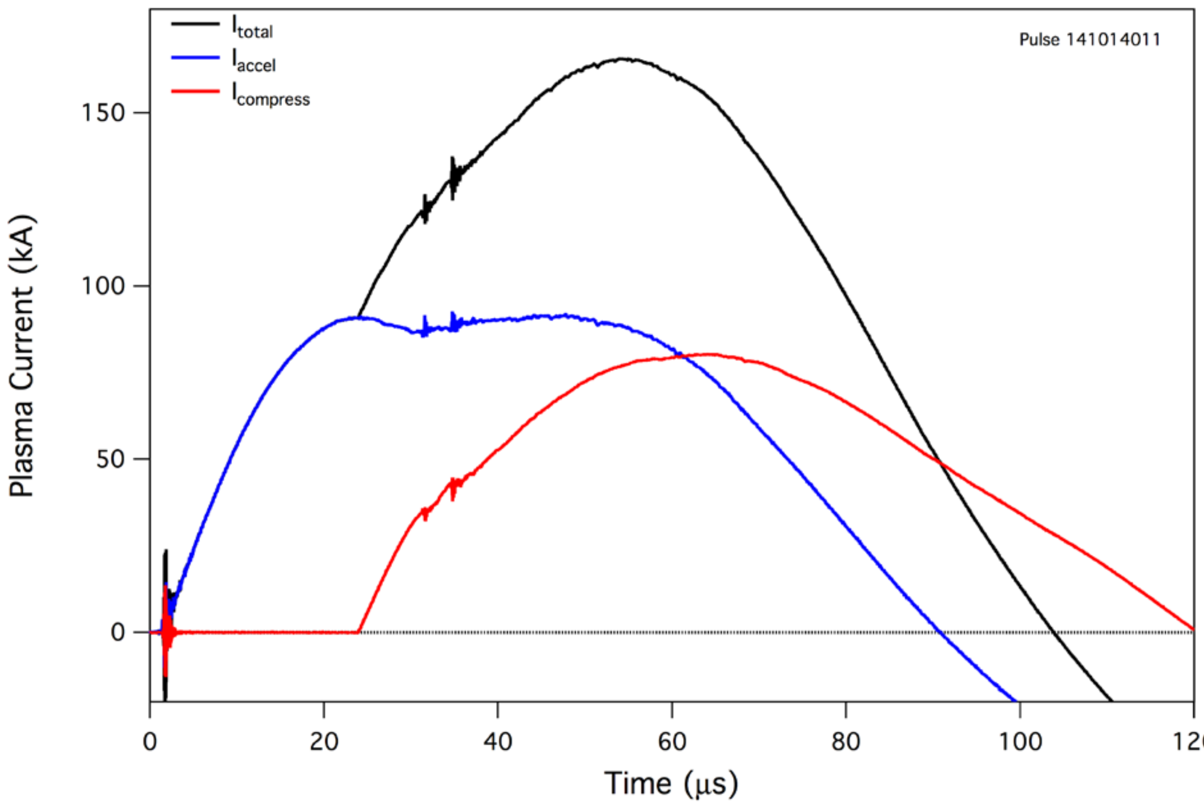
ZaP-HD is flexible platform to study sheared flow effects

ZaP-HD experiment offers independent control of plasma acceleration, which dictates the mass in the plasma column, and the pinch current, which compresses the plasma column.

The acceleration capacitor bank drives current between the inner and middle electrodes.

The compression capacitor bank drives current between the inner and outer electrodes.

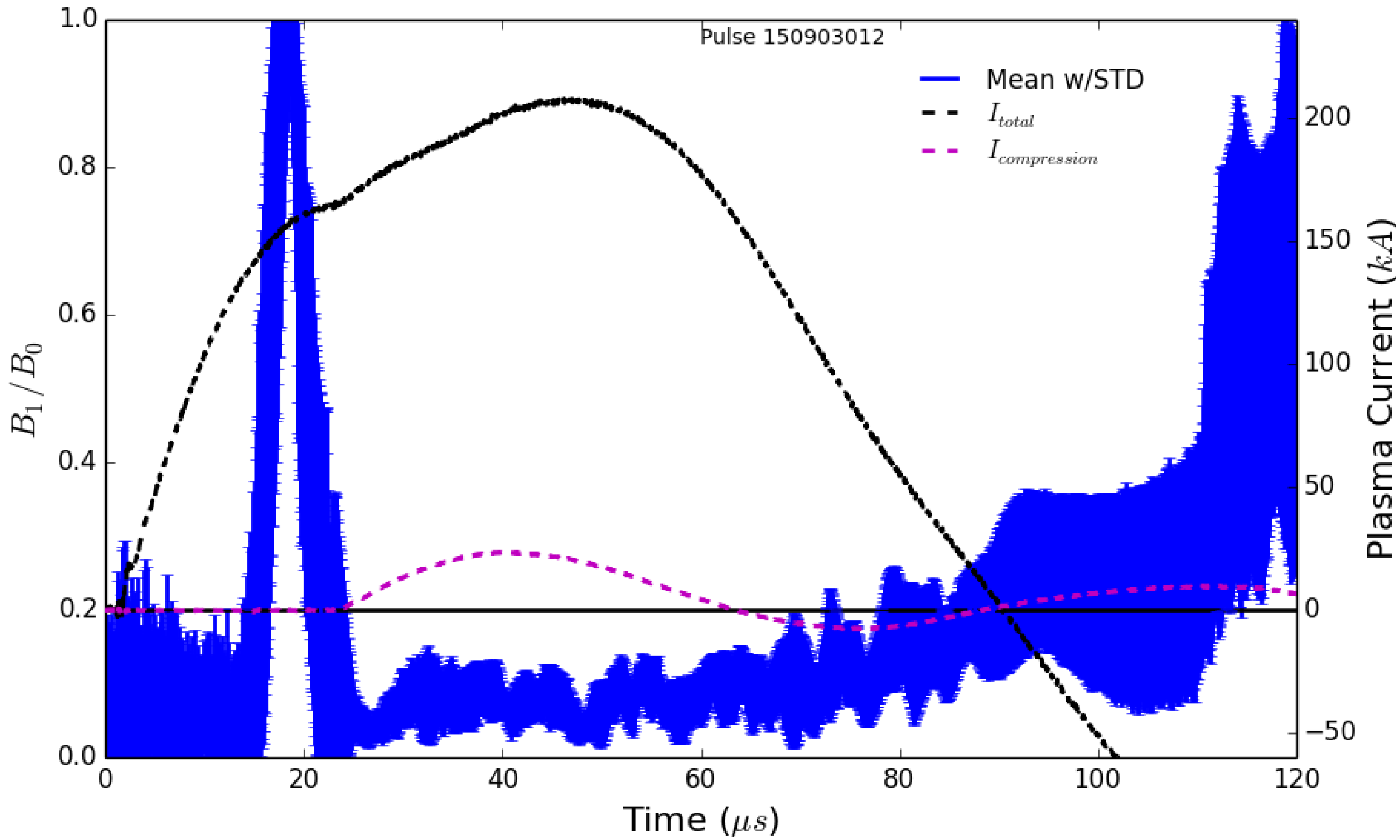
Relative trigger timing is a user-specified run parameter.



ZaP-HD design allows detailed measurements

Magnetic probes in ZaP-HD are located to allow 3D reconstruction of the magnetic topology along the entire 50 cm length of the pinch plasma.

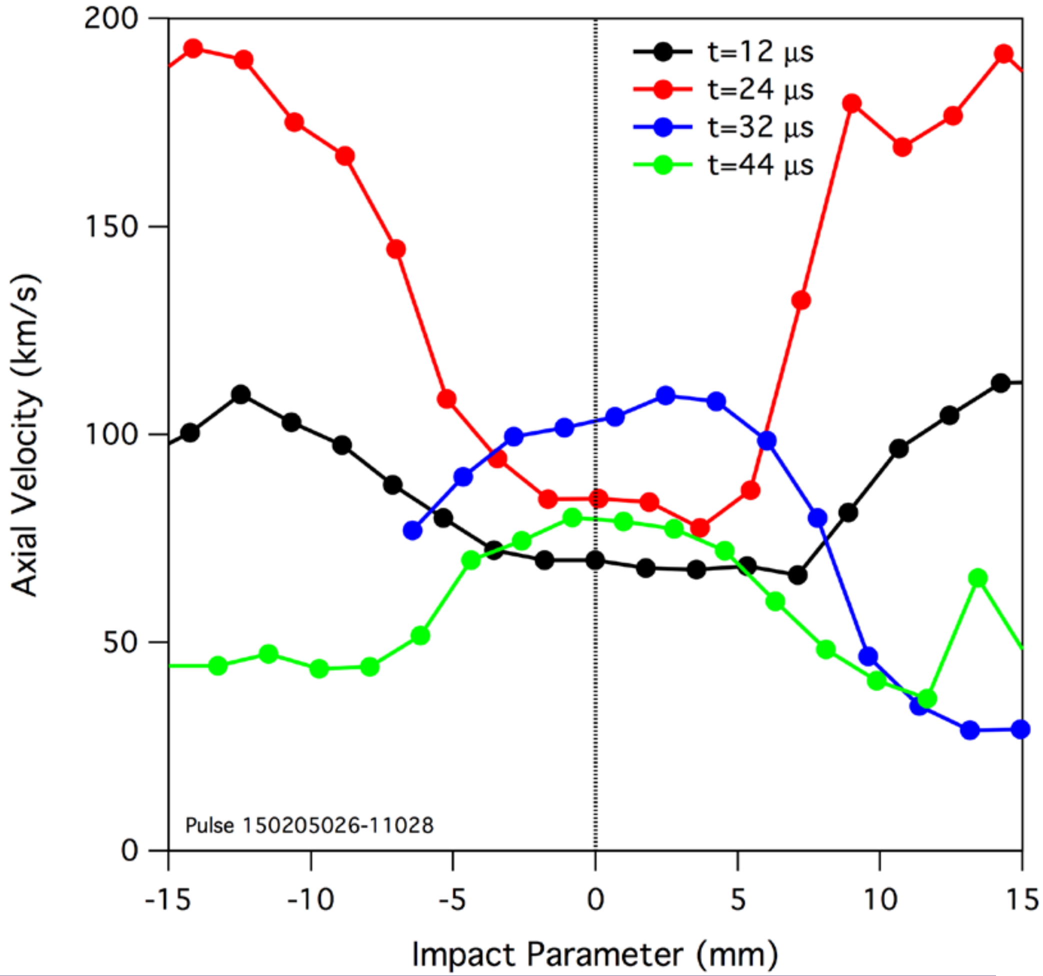
Consistent with ZaP experimental results, a quiescent period is observed in ZaP-HD. The behavior is evident at all axial locations along Z-pinch.



Uri Shumlak, shumlak@uw.edu

Velocity profiles exhibit shear during quiescent period

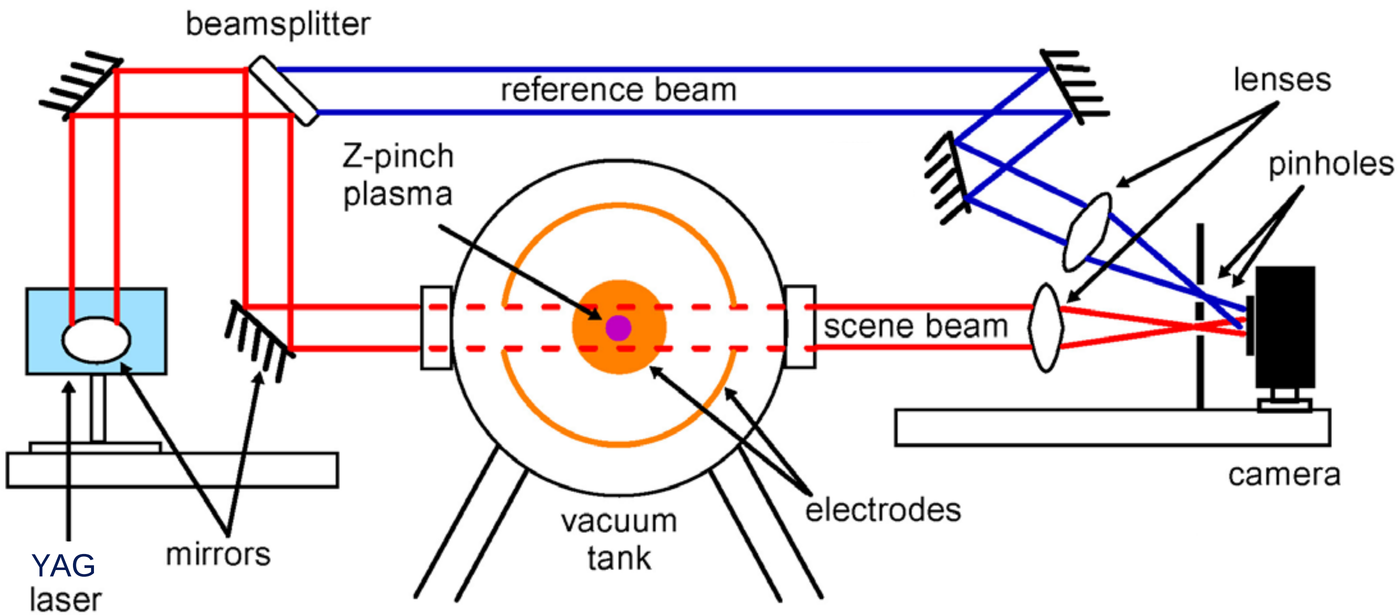
Preliminary velocity measurements show a sheared flow during the quiescent period. The shear reverses but remains large and is hypothesized to produce stability.

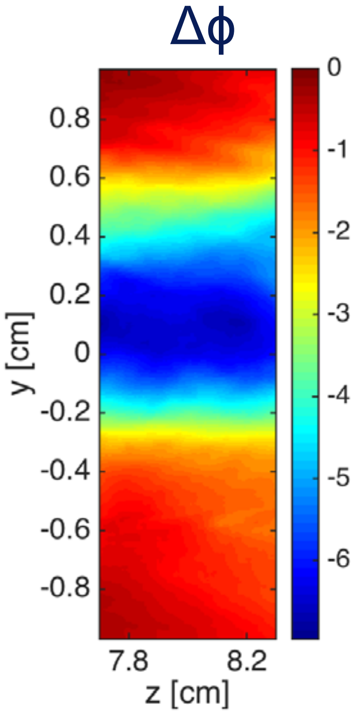


Uri Shumlak, shumlak@uw.edu

Holographic interferometry measures the density profile

Digital holographic interferometer uses a new Ekspla Nd:YAG laser* and digital SLR to provide high-resolution measurements of the plasma density structures.





The phase change gives the line-integrated density

Pulse 141209015

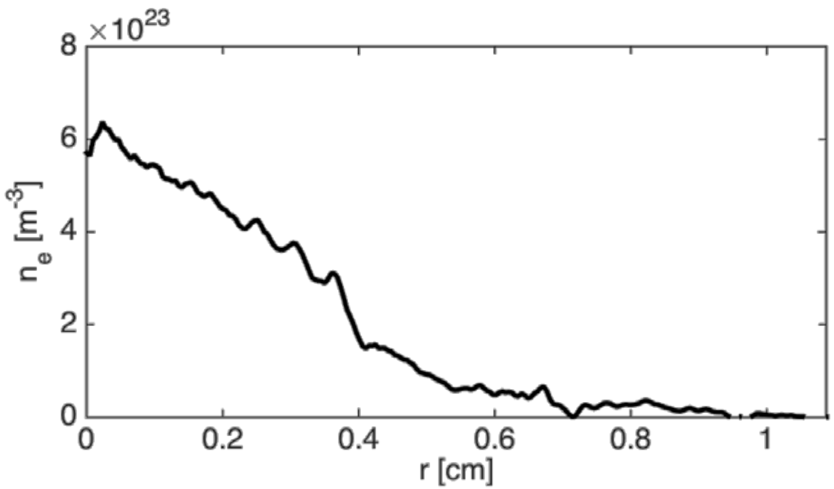
$$\Delta\phi = \frac{\lambda e^2}{4\pi c^2 \epsilon_0 m_e} \int n_e(x)\,dx.$$

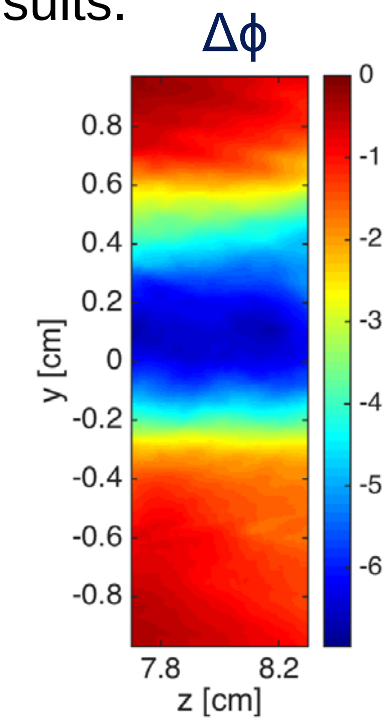
Uri Shumlak, shumlak@uw.edu

Holographic interferometry measures the density profile

The digital hologram is recorded on the camera and then numerically reconstructed to give the complex wave field, which gives the phase change. After unwrapping, a 2D map of phase change results.

The line-integrated density is Abel inverted to yield a density profile.





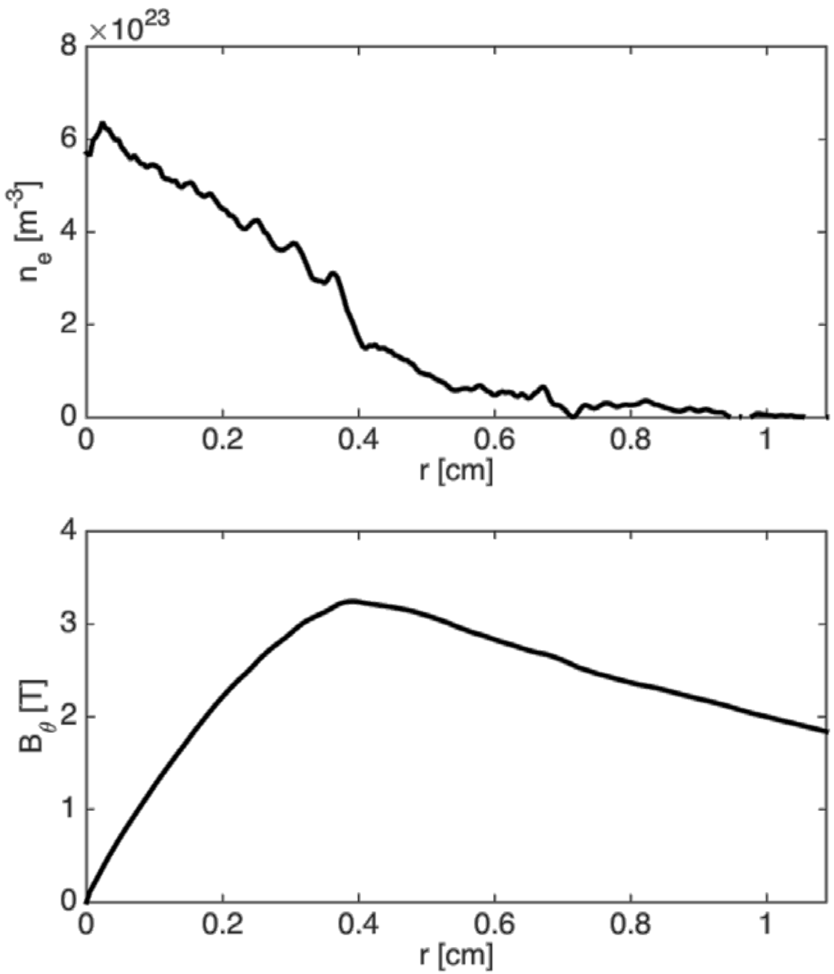
Pulse 141209015

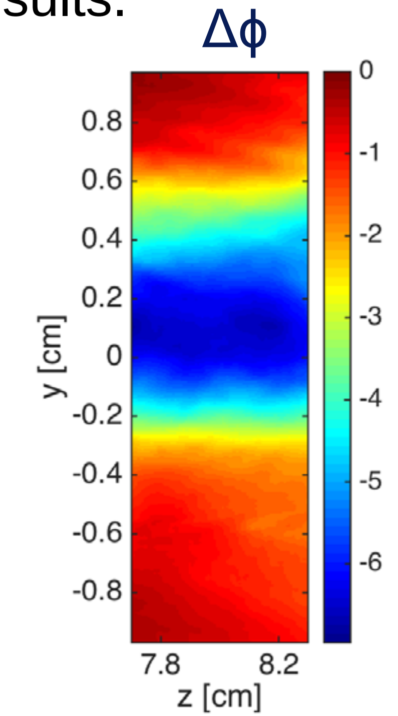
Holographic interferometry measures the density profile

The digital hologram is recorded on the camera and then numerically reconstructed to give the complex wave field, which gives the phase change. After unwrapping, a 2D map of phase change results.

The line-integrated density is Abel inverted to yield a density profile.

Assuming a constant drift speed and matching the experimentally measured plasma current, the magnetic field profile is computed.





Pulse 141209015

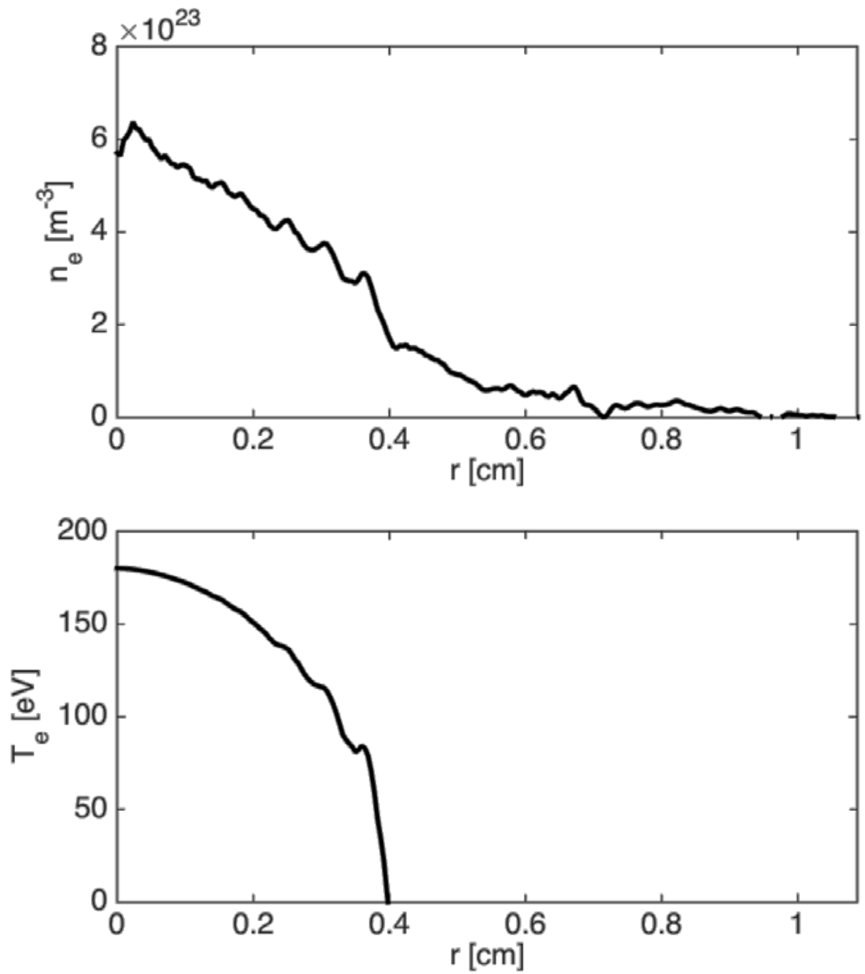
Uri Shumlak, shumlak@uw.edu

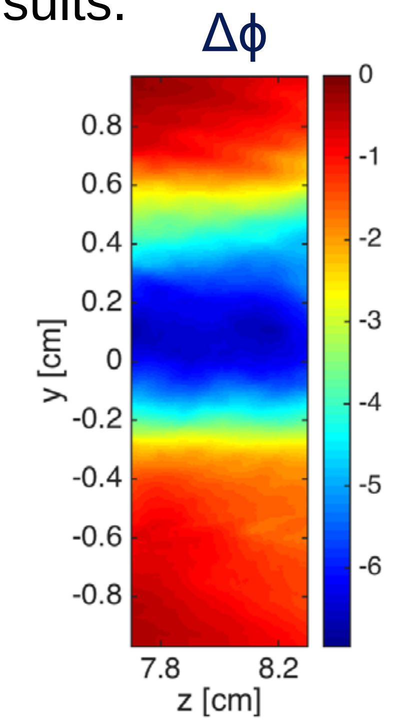
Holographic interferometry measures the density profile

The digital hologram is recorded on the camera and then numerically reconstructed to give the complex wave field, which gives the phase change. After unwrapping, a 2D map of phase change results.

The line-integrated density is Abel inverted to yield a density profile.

Assuming a constant drift speed and matching the experimentally measured plasma current, the magnetic field profile is computed.





Pulse 141209015

ZaP plasma features extend to ZaP-HD

ZaP demonstrated sheared flow stabilization and produced high-temperature, high-density, long-lived pinch plasma.

Entity	
asma Lifetime	20 – 50 μs

ZaP-HD provides flexibility to separately control plasma acceleration and compression, and produces plasmas with higher temperatures and higher densities with similar long lifetimes.

Uri Shumlak, shumlak@uw.edu

Z-pinch scales to HEDP and to fusion reactor plasmas

Flow-stabilization theory of a Z-pinch shows no additional limitations as the plasma is scaled to different parameters. If the experimental results also hold, then the Z-pinch can be scaled from ZaP conditions to higher performance conditions by assuming adiabatic compression

$$\frac{d}{dt}\left(\frac{p}{n^{\gamma}}\right) = \frac{d}{dt}\left(\frac{(1+Z)kT}{n^{\gamma-1}}\right) = 0$$

and using the linear density is given by the Bennett relation:

$$(1+Z)NkT = \frac{\mu_0 I^2}{8\pi}, \text{ where } N = \int_0^a n_i(r)2\pi r dr.$$

The resulting scaling relations are[1]

$$\frac{p_2}{p_1} = \frac{n_2}{n_1}\frac{T_2}{T_1} = \left(\frac{I_2}{I_1}\right)^{\frac{2\gamma}{\gamma-1}}\left(\frac{N_1}{N_2}\right)^{\frac{\gamma}{\gamma-1}}$$

$$\frac{a_2}{a_1} = \sqrt{\frac{n_1}{n_2}\frac{N_2}{N_1}} = \left(\frac{I_1}{I_2}\right)^{\frac{1}{\gamma-1}}\left(\frac{N_2}{N_1}\right)^{\frac{\gamma}{2(\gamma-1)}}$$

$$\frac{n_2}{n_1} = \left(\frac{T_2}{T_1}\right)^{\frac{1}{\gamma-1}} = \left(\frac{I_2}{I_1}\right)^{\frac{2}{\gamma-1}}\left(\frac{N_1}{N_2}\right)^{\frac{1}{\gamma-1}}$$

UNIVERSITY of WASHINGTON

[1]Shumlak et al., FST (2012)

Z-Pinch scales to HEDP and to fusion conditions[1]

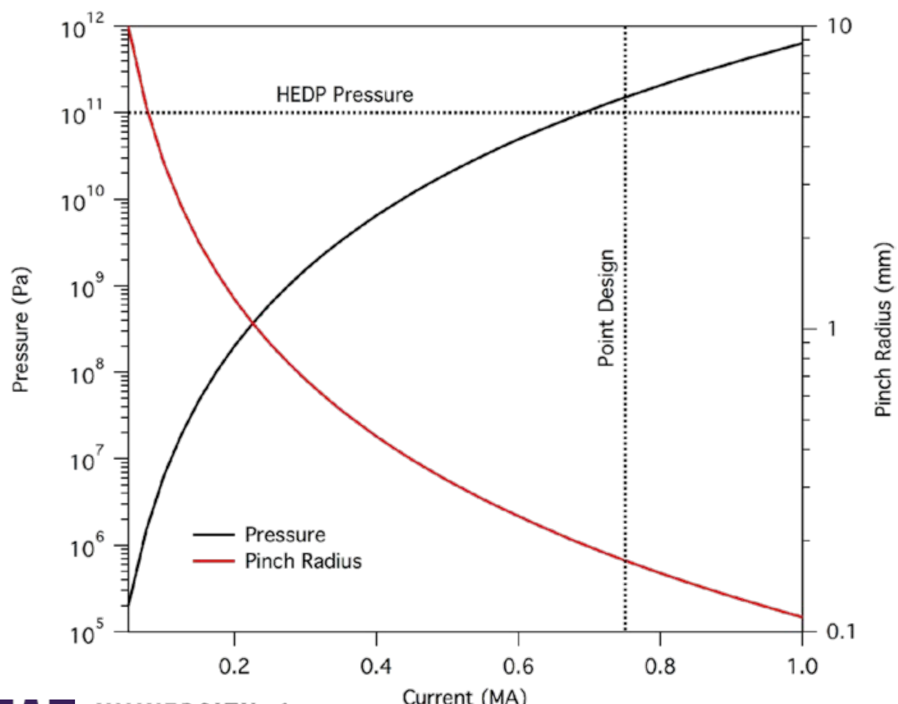
Starting with ZaP plasma parameters, the plasma can be scaled by increasing the current with a fixed linear density. Fusion gain *Q* now includes flow power.

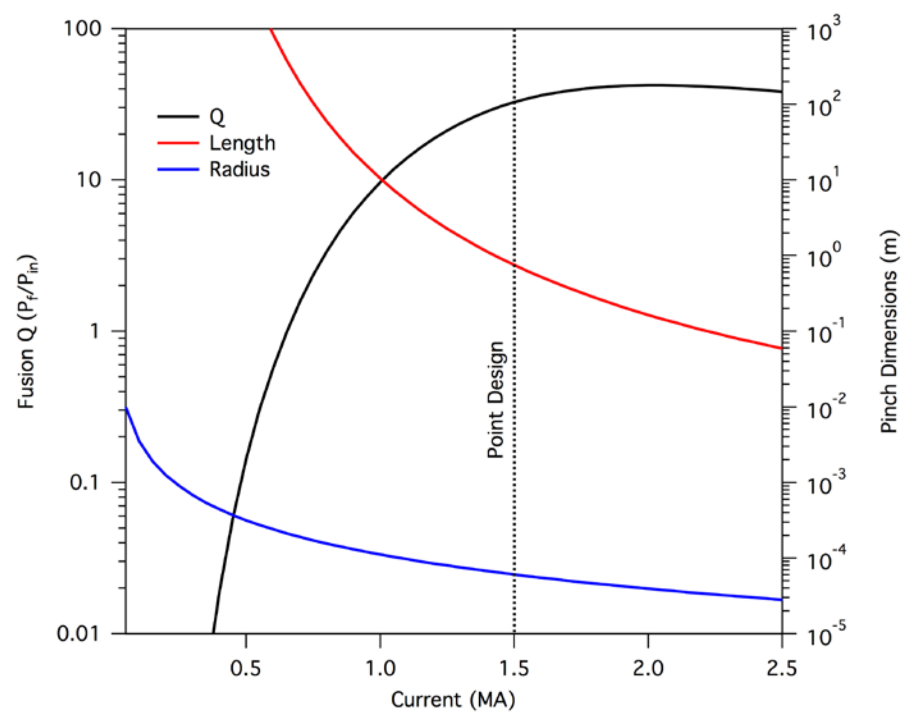
$$Q \equiv \frac{P_f}{P_{th} + P_{flow} + P_{rad}}$$

I_p = 750 kA	T = 4.5 keV
p = 0.3 TPa	a = 170 μm

Assuming steady state:

I_p = 1.5 MA	T = 22.5 keV
L = 75 cm	a = 61 μm
Q = 33	P_f = 4.6 TW





[1]Shumlak et al., FST (2012)

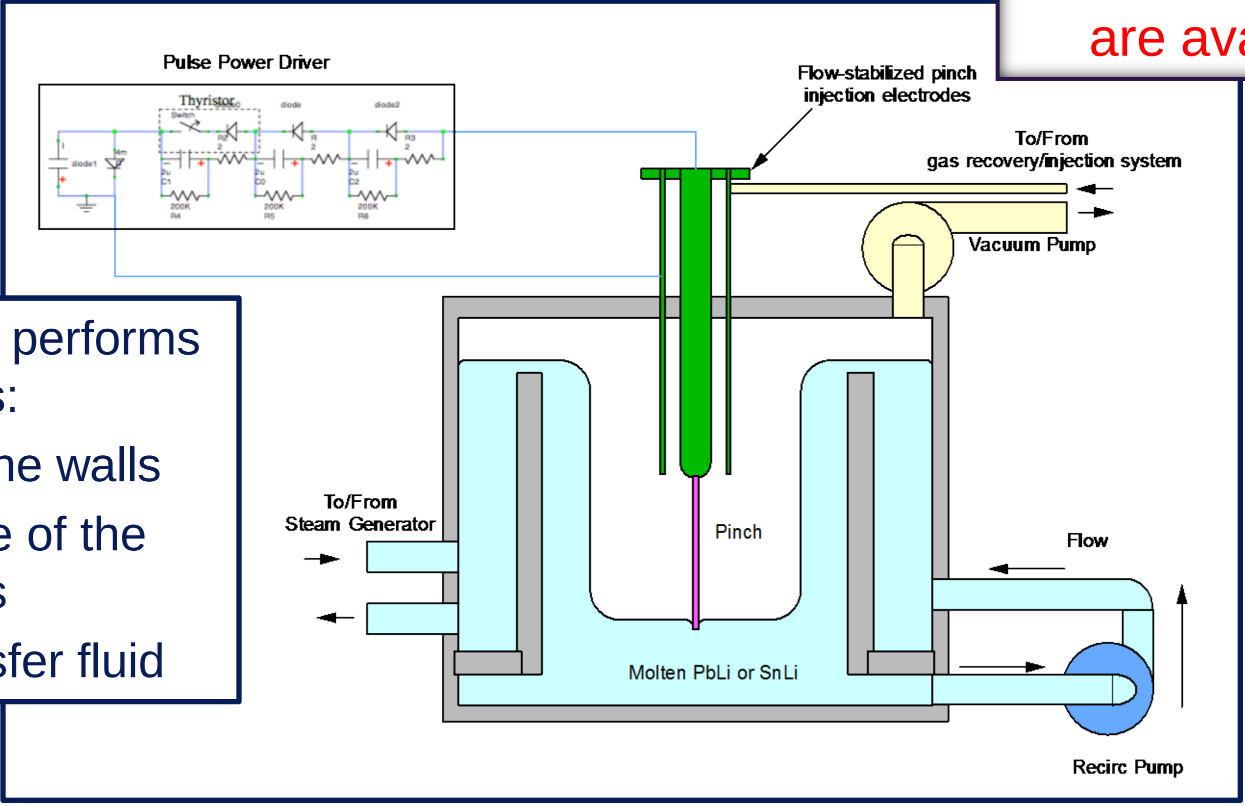
Results motivate the Fusion Z-pinch Experiment (FuZE)

UW and LLNL are partnering on a new ARPA-E project, FuZE, to investigate the viability of a compact fusion device based on the sheared flow stabilized Z-pinch.*

– How do drift and kinetic effects alter plasma stability?

– Are there limitations to sheared flow stabilization?

*Postdoctoral positions are available.



Liquid metal performs multiple jobs:

- Protects the walls
- Act as one of the electrodes
- Heat transfer fluid

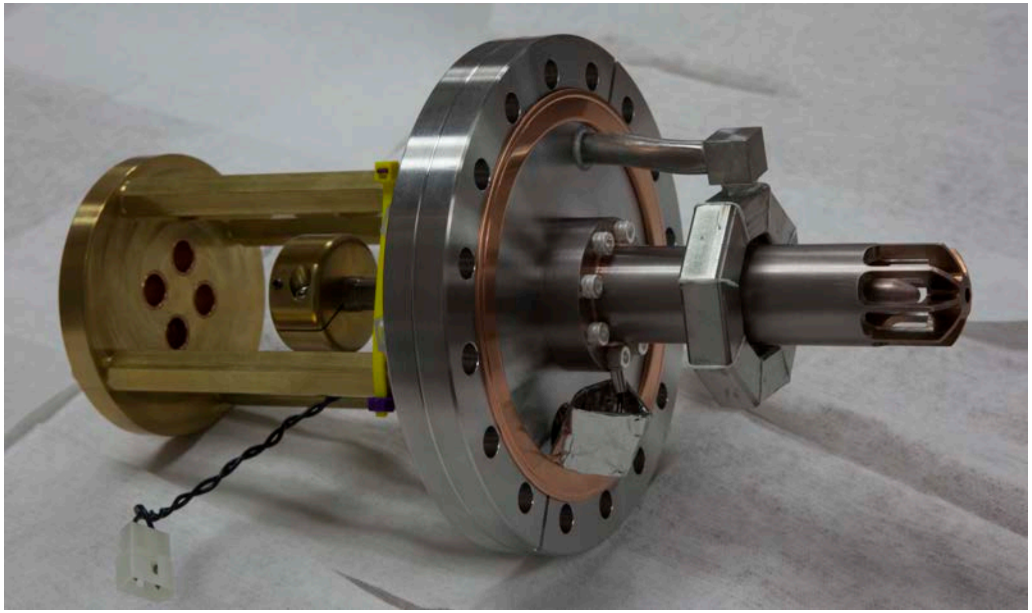
EUV light source based on the SFS Z-pinch

If Moore's Law will end, unless EUV lithography is successful.

For over ten years, the semiconductor industry has searched for an EUV (13.5 nm) light source with sufficient power. None has been found.

The leading approach hits tin droplets with a high power laser to produce short bursts (100 ns) of EUV light.

Our approach[1] forms an SFS Z-pinch from xenon to emit 4 μs pulses of EUV light from a plasma volume less than 1 mm^3.



[1]Shumlak, Golingo, & Nelson, US 7,372,059 B2; US 7,825,391 B2;

Summary & Conclusions

- Nuclear fusion has an energy rich and abundant fuel that alleviates many of the problems of current energy sources.
- Mainline approach to fusion energy leads to a large, expensive reactor.
- Innovative approach using sheared flows instead of magnetic shear for stability could provide more compact and affordable reactors.
- The ZaP experiment produces Z-pinch plasmas that exhibit gross stability during an extended quiescent period.
- The quiescent period is coincident with a sheared plasma flow that is consistent with sheared flow stabilization theory.
- ZaP-HD extends the positive results to investigate scaling of the flow Z-pinch to higher energy densities.
- Scaling relations demonstrate that the sheared flow stabilized Z-pinch can be scaled to fusion conditions with reasonable parameters, which will be pursued with the new FuZE project.
- Sheared flow stabilized Z-pinch also makes a viable EUV light source.

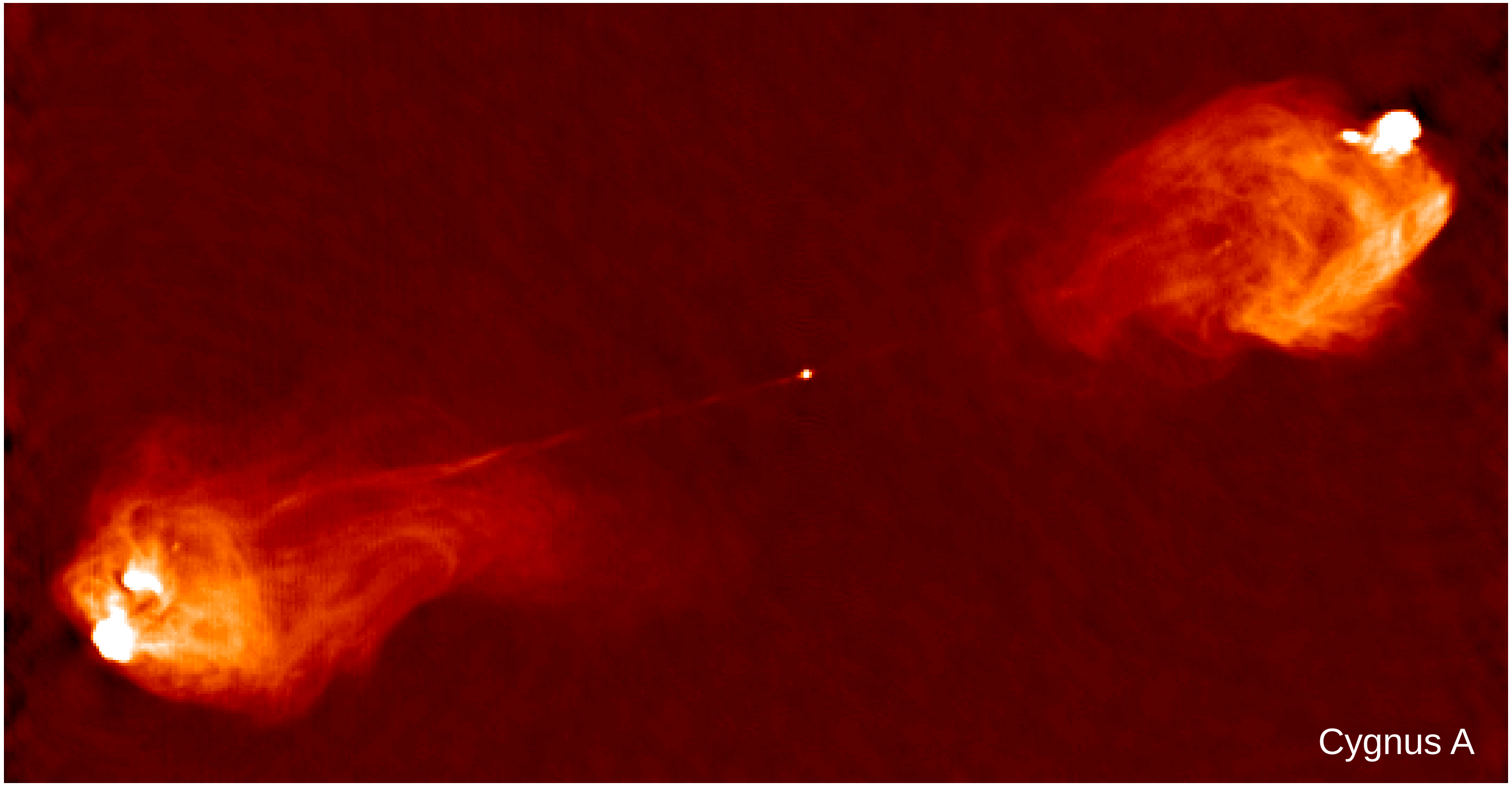
Uri Shumlak, shumlak@uw.edu

Backup Slides

Astrophysicists observe extended plasma jets.

Long-lived astrophysical plasma jet structures have been observed to have remarkable stability.

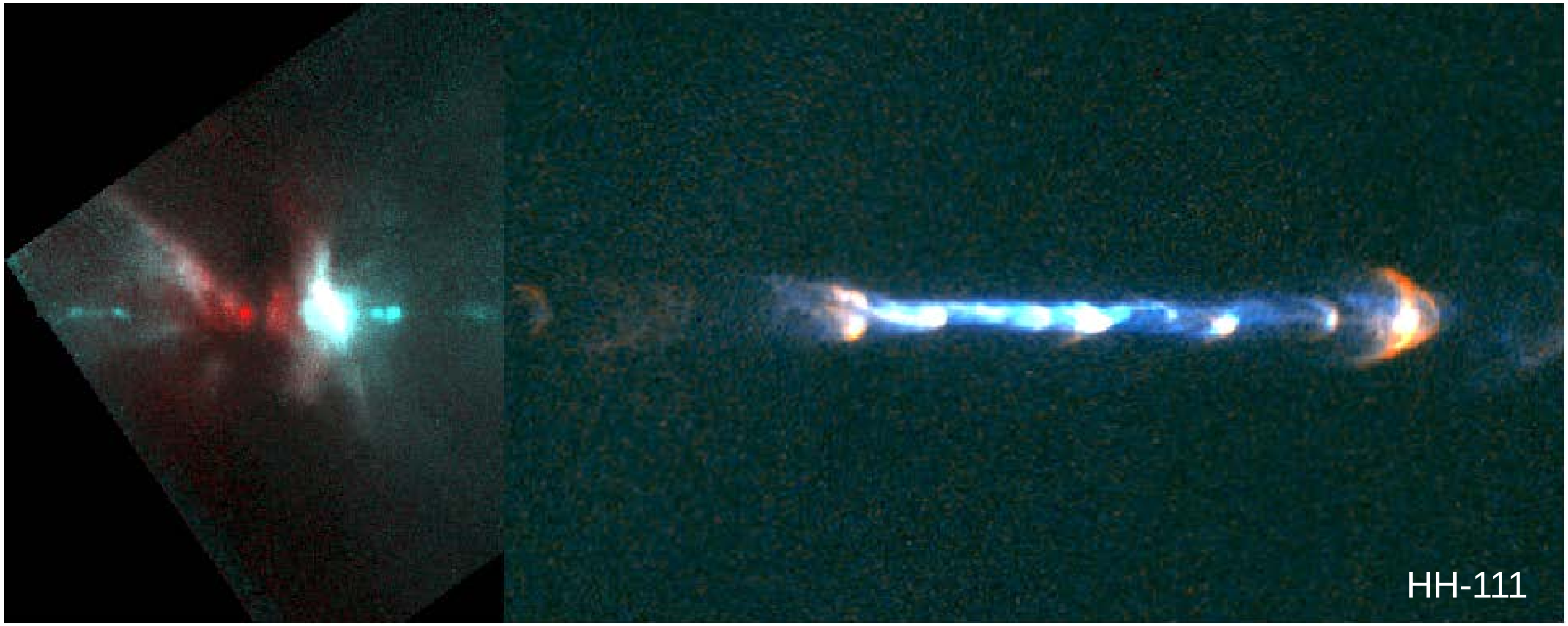
The jets arise from many diverse sources such as active galactic nuclei (AGN), massive black holes. Length is 300,000 lightyears.



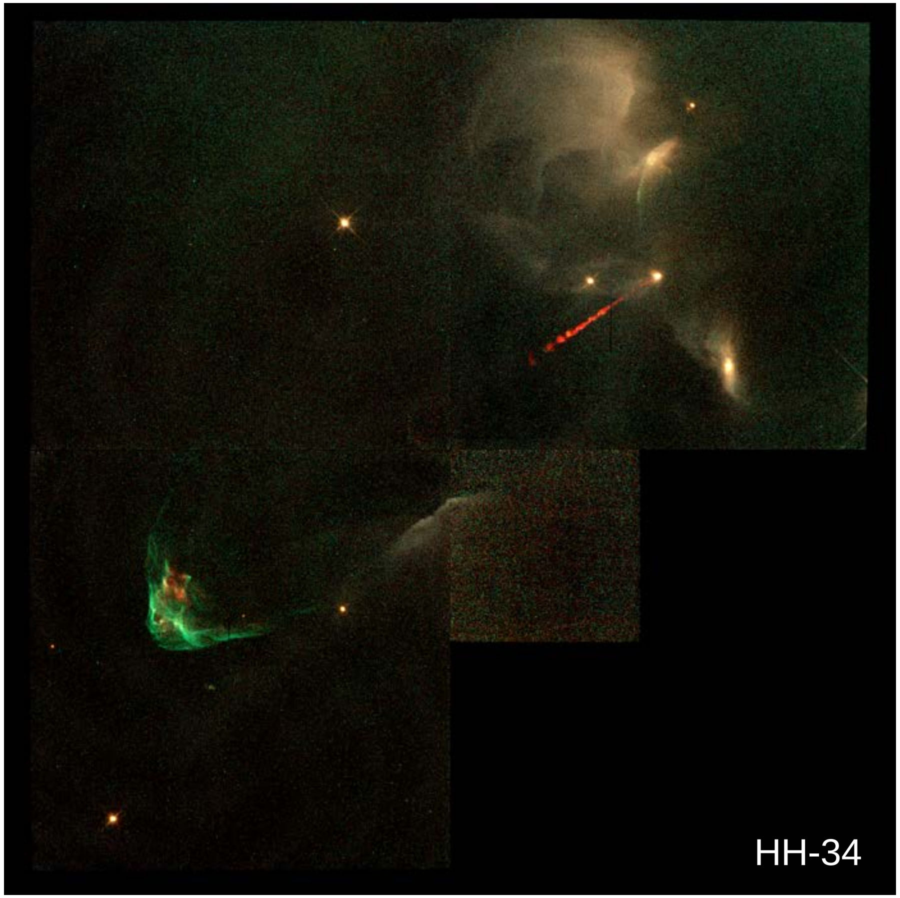
Astrophysicists observe extended plasma jets.

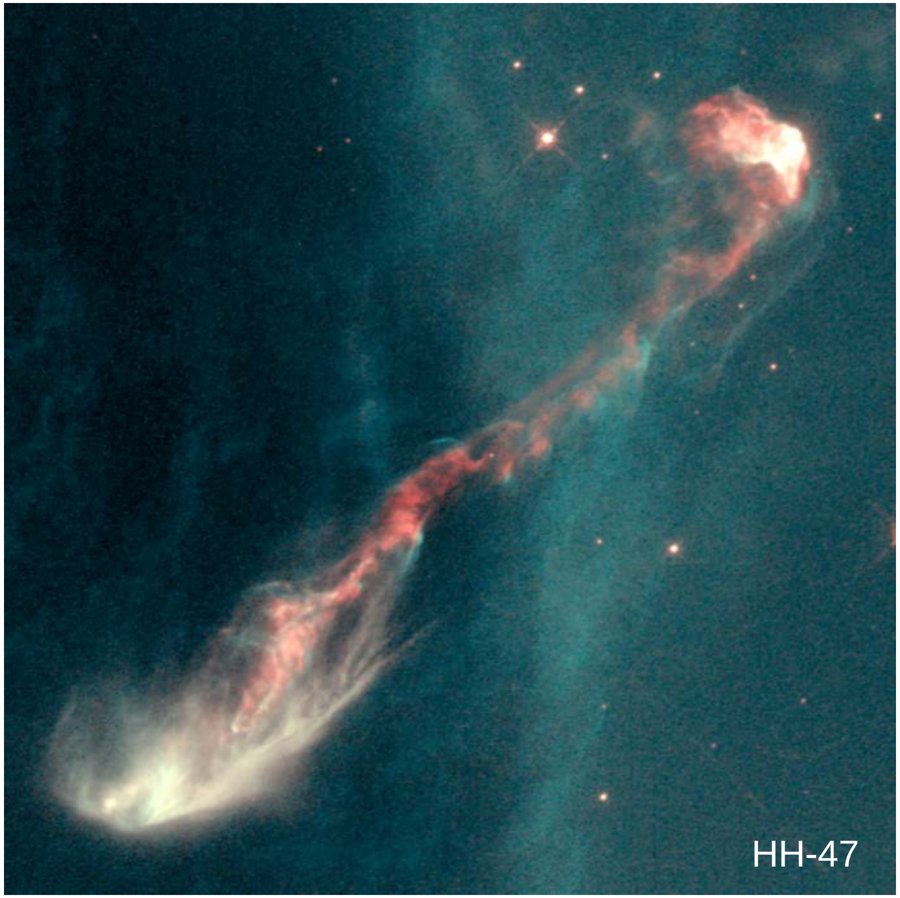
Long-lived astrophysical plasma jet structures have been observed to have remarkable stability.

The jets also arise from newly born stars, young stellar objects, such as Herbig-Haro objects. Length is 12 lightyears.



Other examples of HH objects exist.

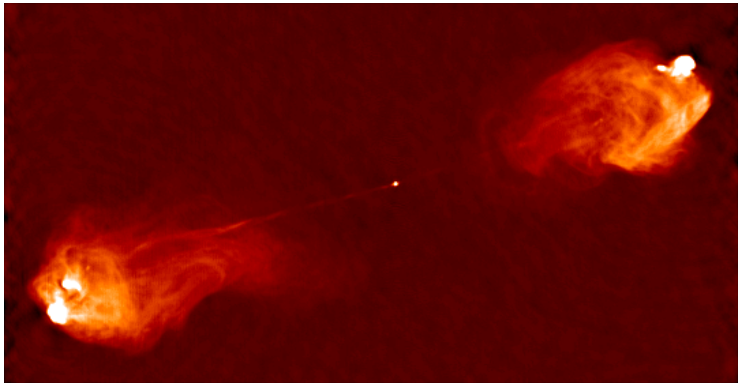


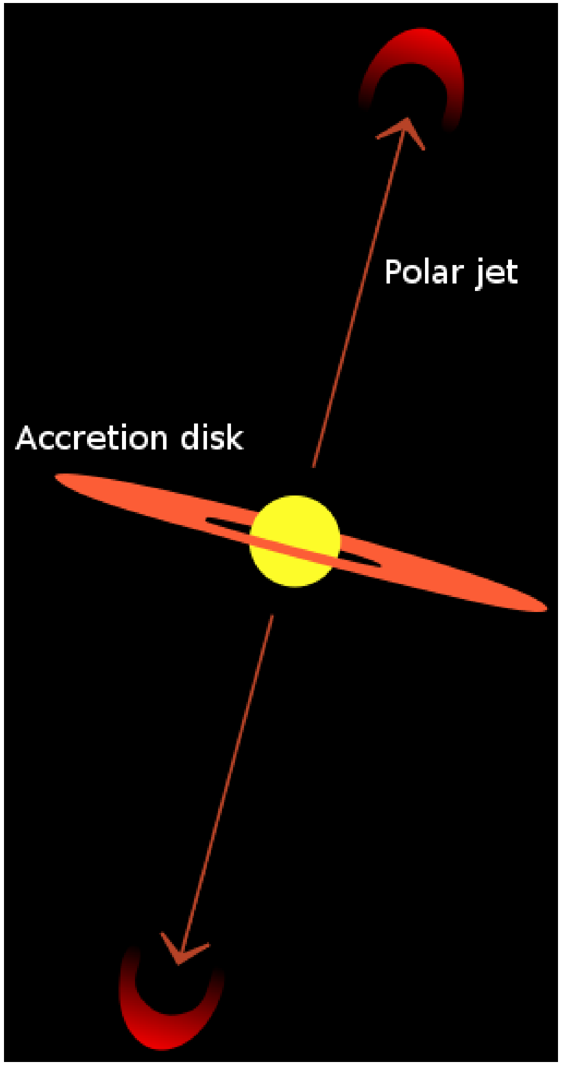


Length is 60 lightyears.

Length is 1 lightyear.

Observed behavior is unexplained.

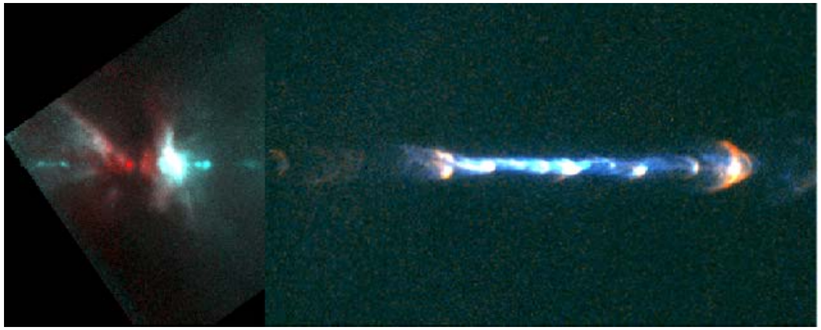




Jet formation mechanism is believed to involve inward mass flow in an accretion disk.

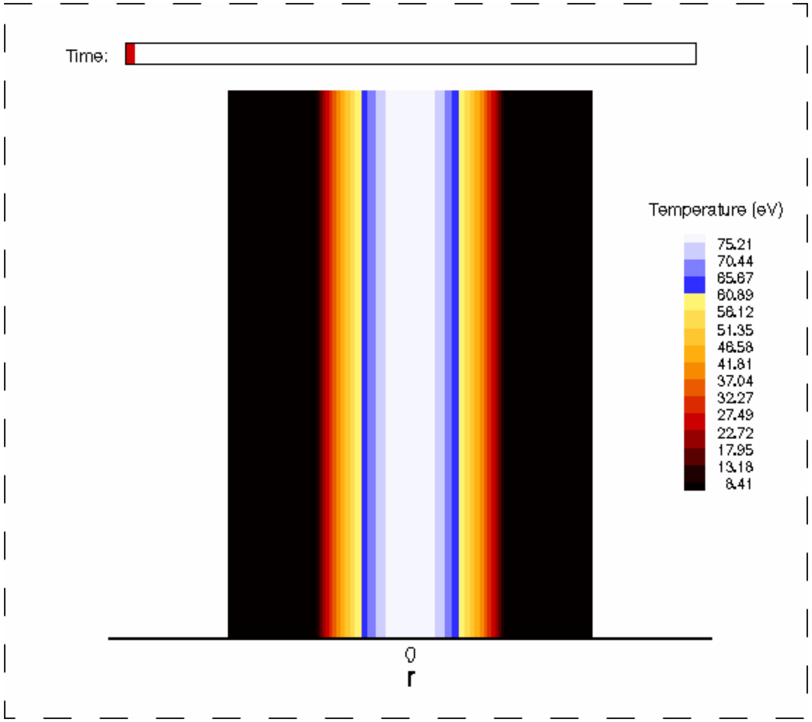
Mass carries an axial magnetic field that twists at the poles and produces bipolar jets.

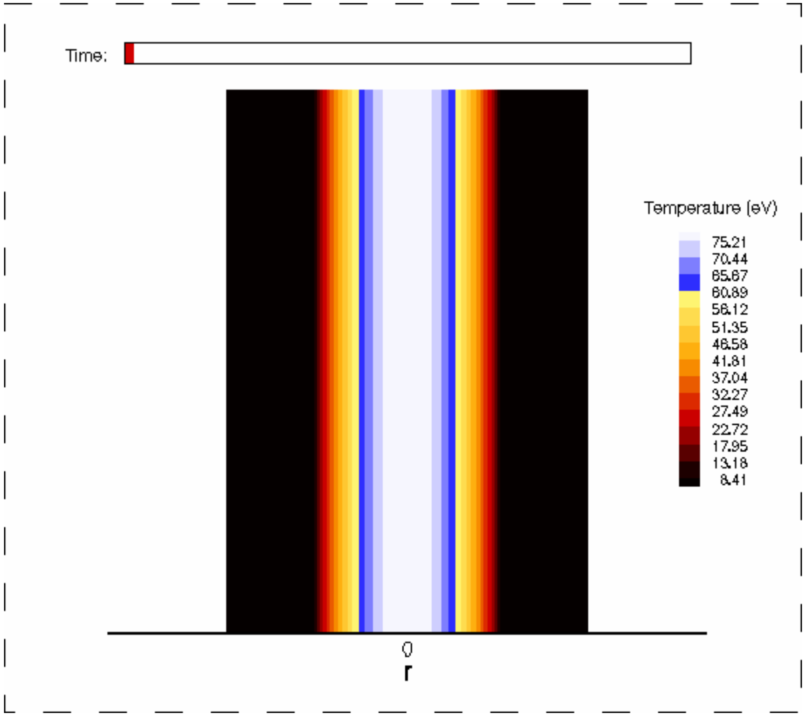
- ➔ Why are plasma jets so stable?
- ➔ How are such large aspect ratios produced?



Uri Shumlak, shumlak@uw.edu

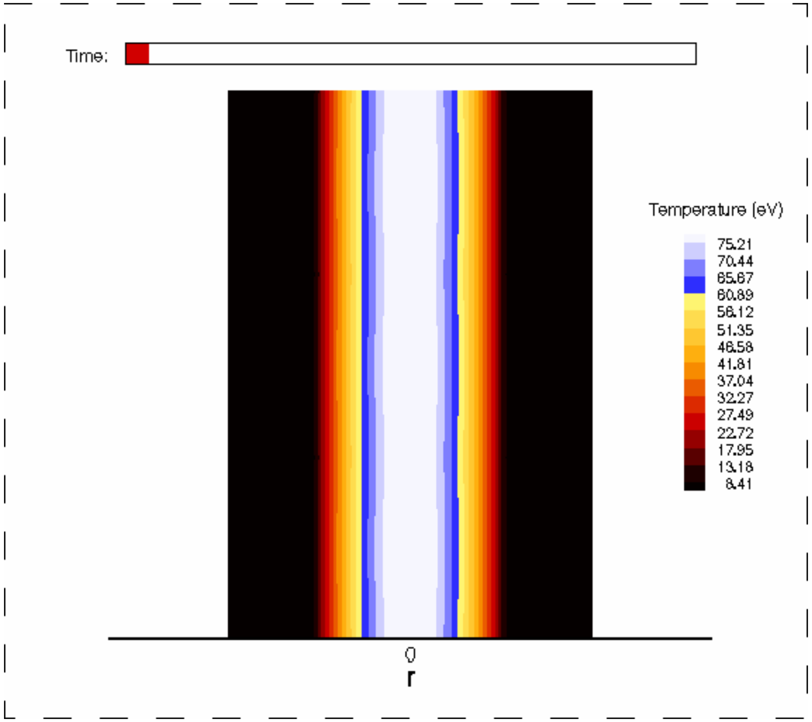
Nonlinear simulations support the linear result.

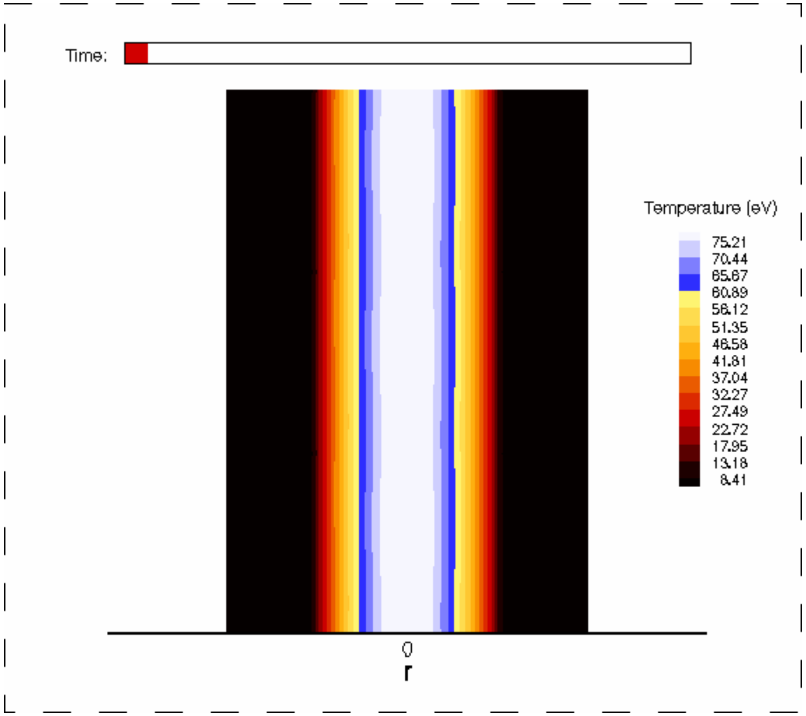




Uri Shumlak, shumlak@uw.edu

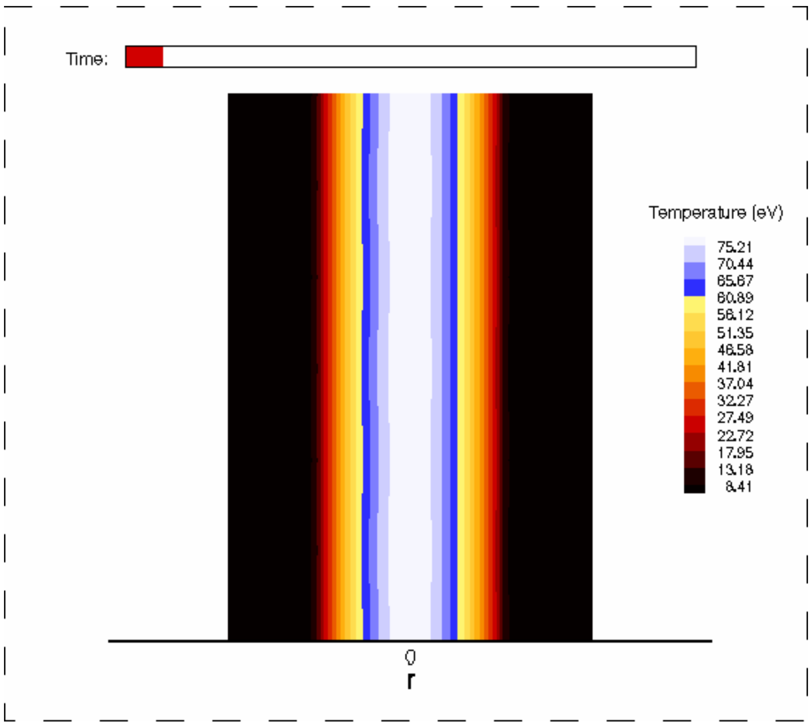
Nonlinear simulations support the linear result.

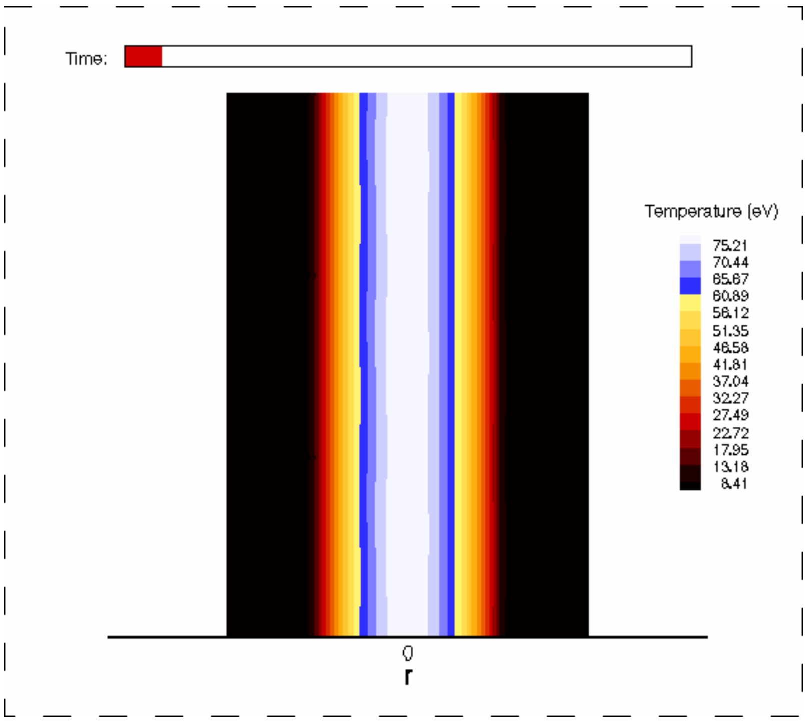




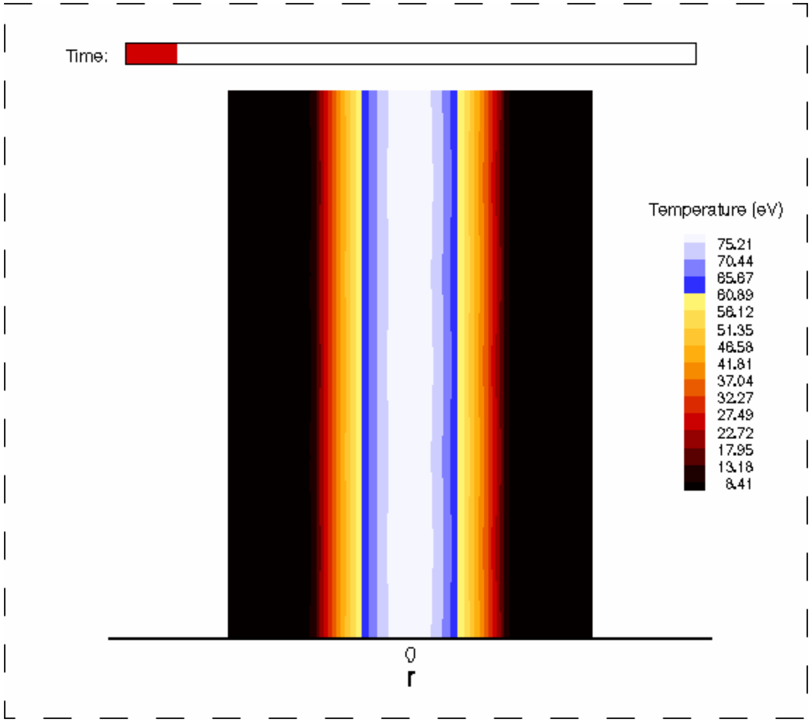
Uri Shumlak, shumlak@uw.edu

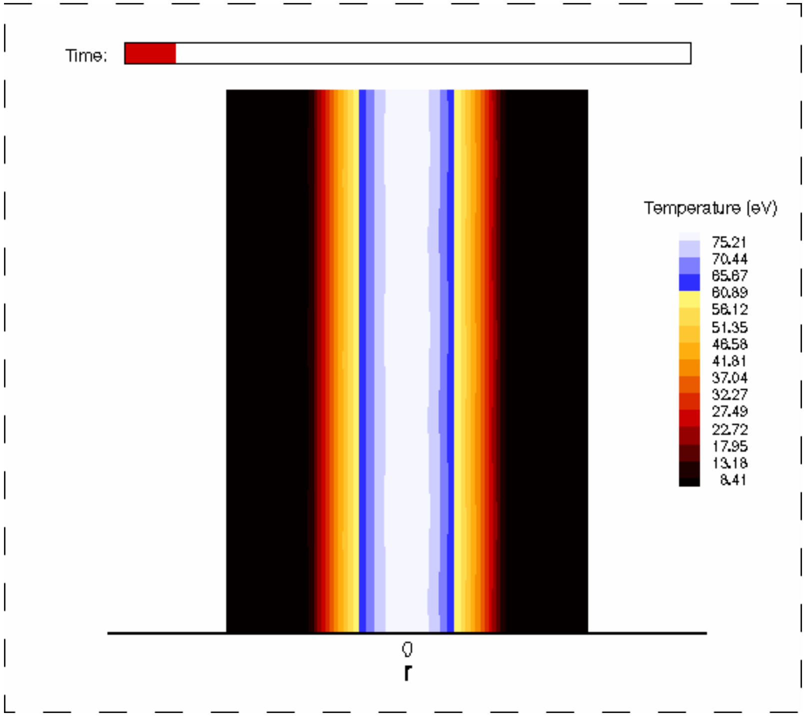
Nonlinear simulations support the linear result.



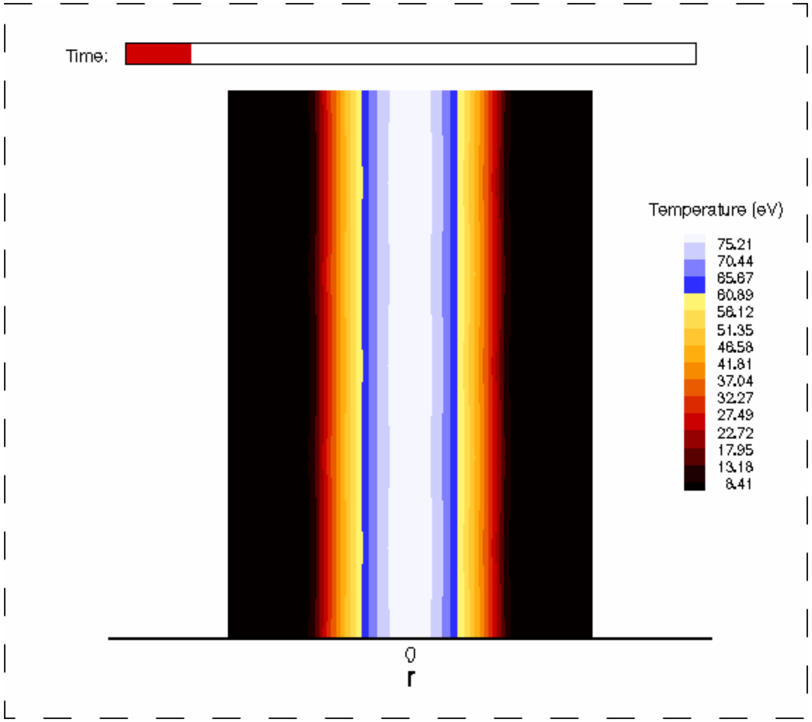


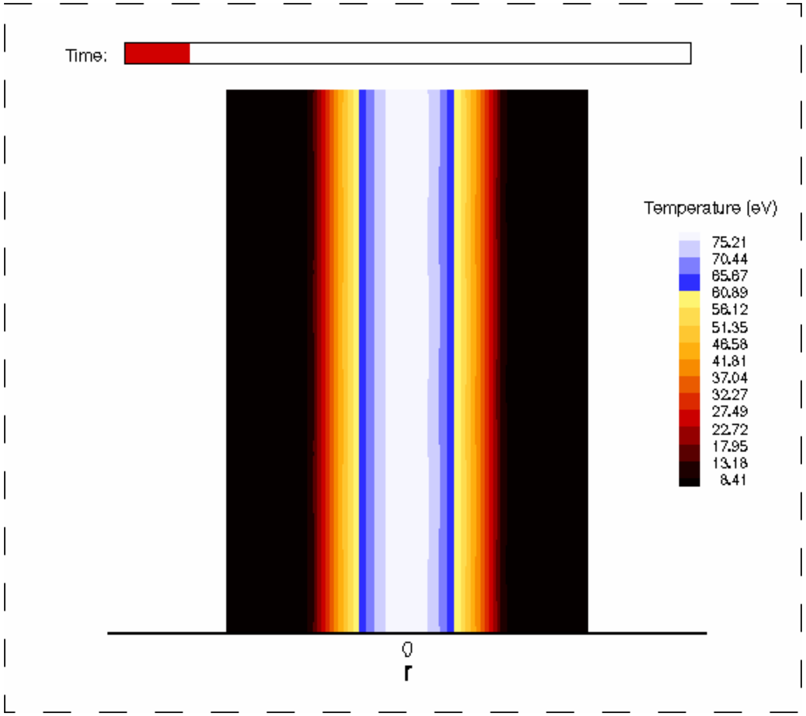
Nonlinear simulations support the linear result.



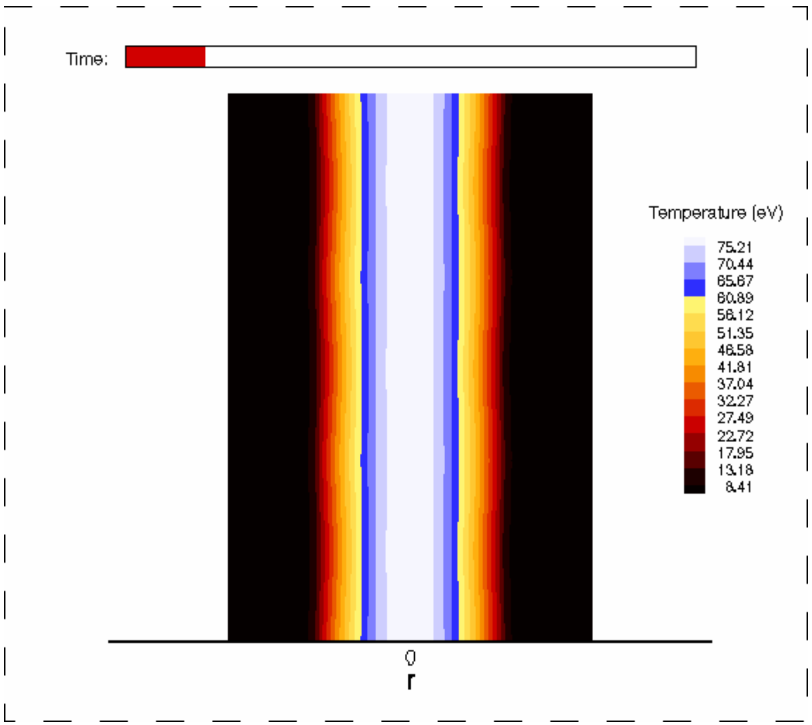


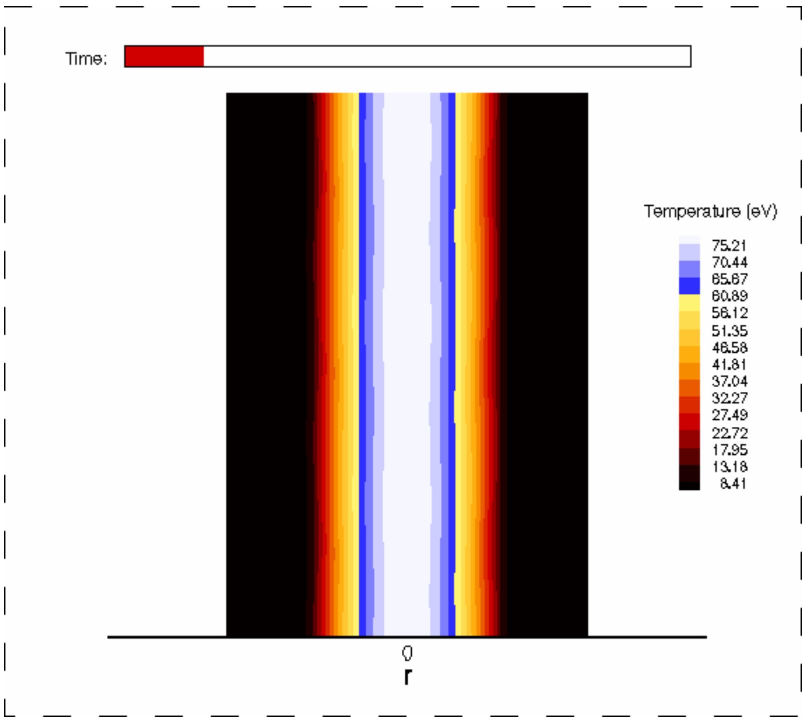
Nonlinear simulations support the linear result.



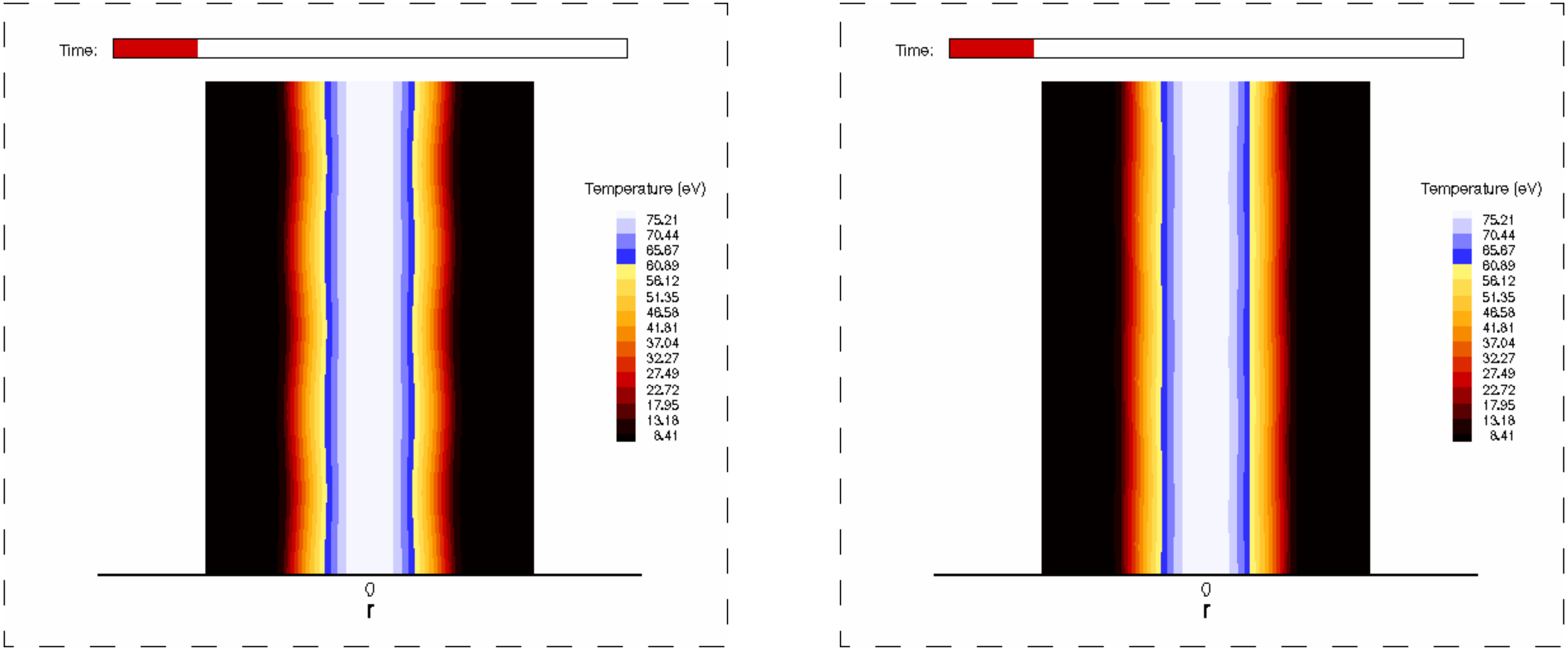


Nonlinear simulations support the linear result.

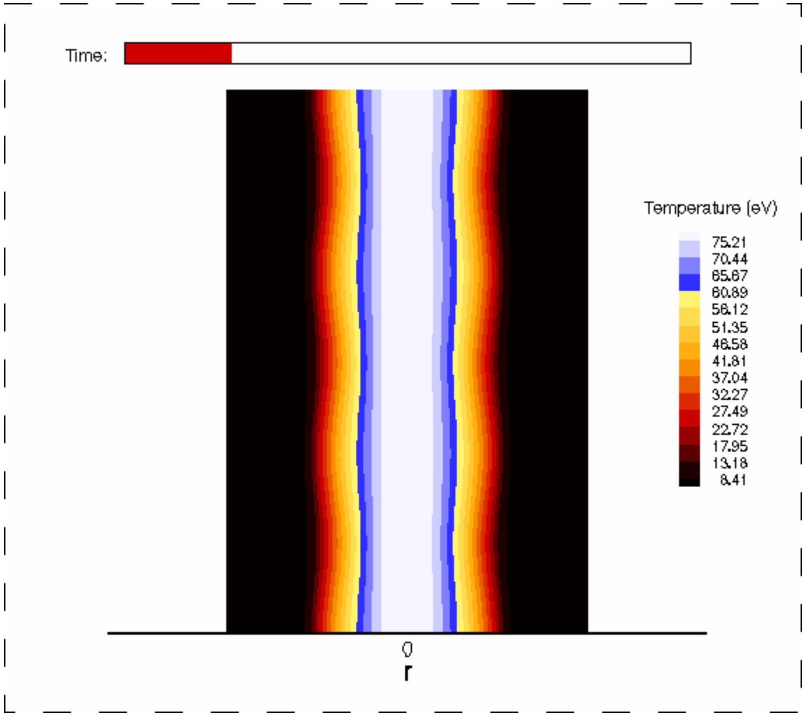


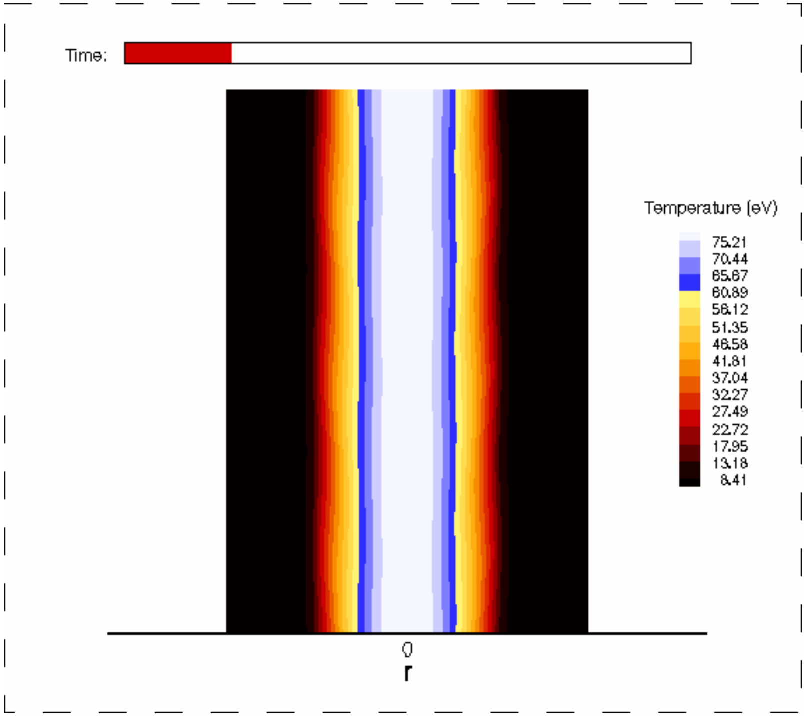


Nonlinear simulations support the linear result.



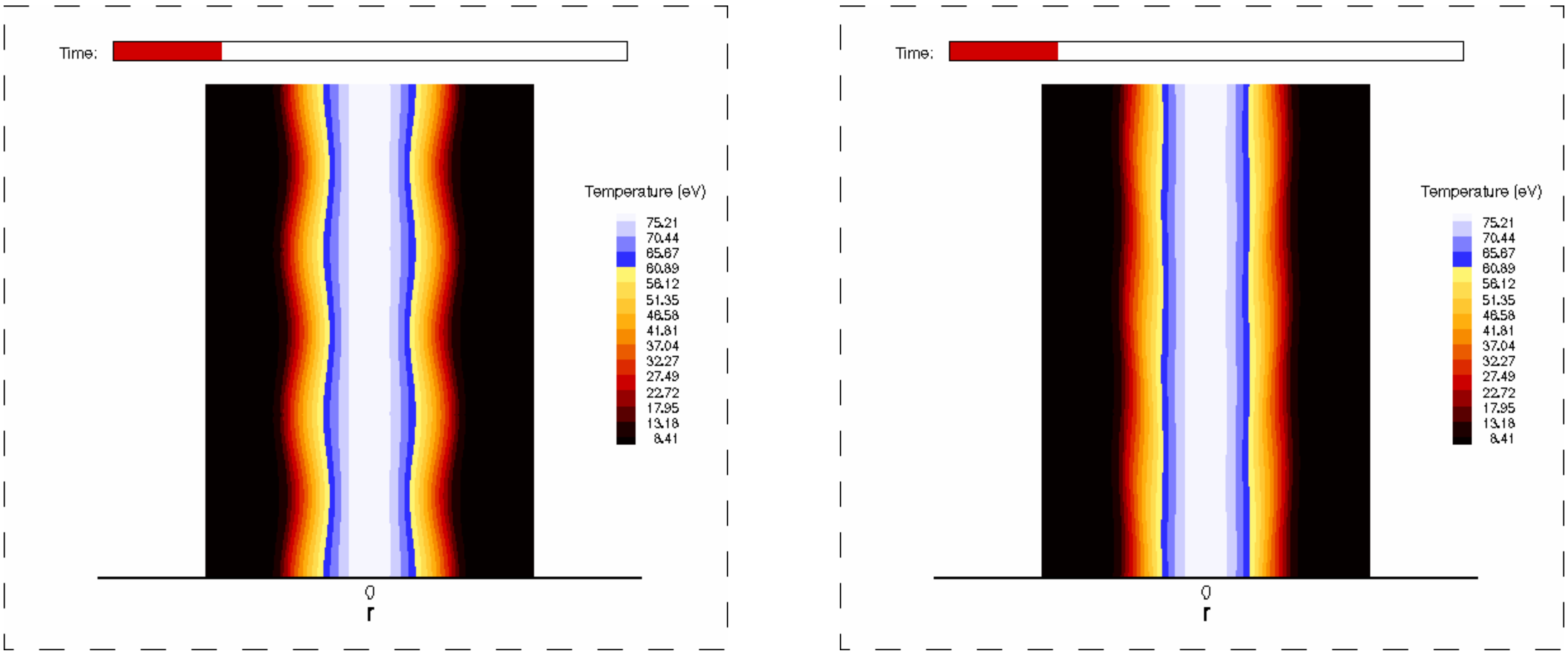
Nonlinear simulations support the linear result.



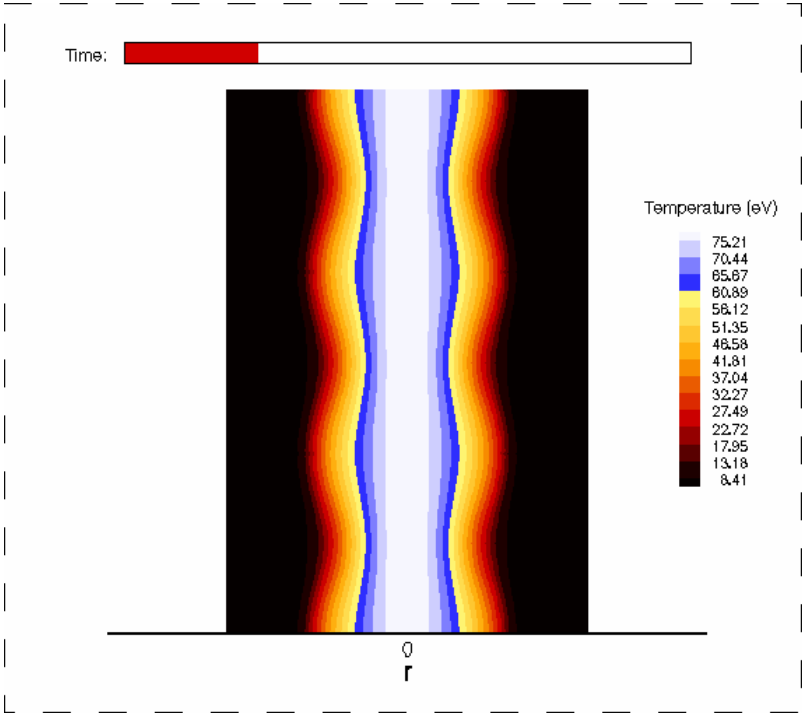


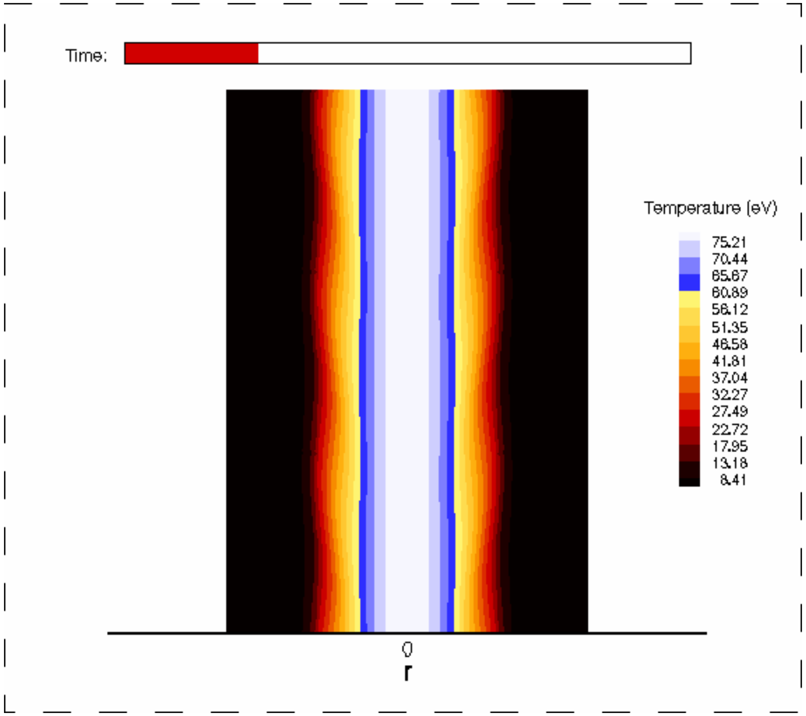
Uri Shumlak, shumlak@uw.edu

Nonlinear simulations support the linear result.

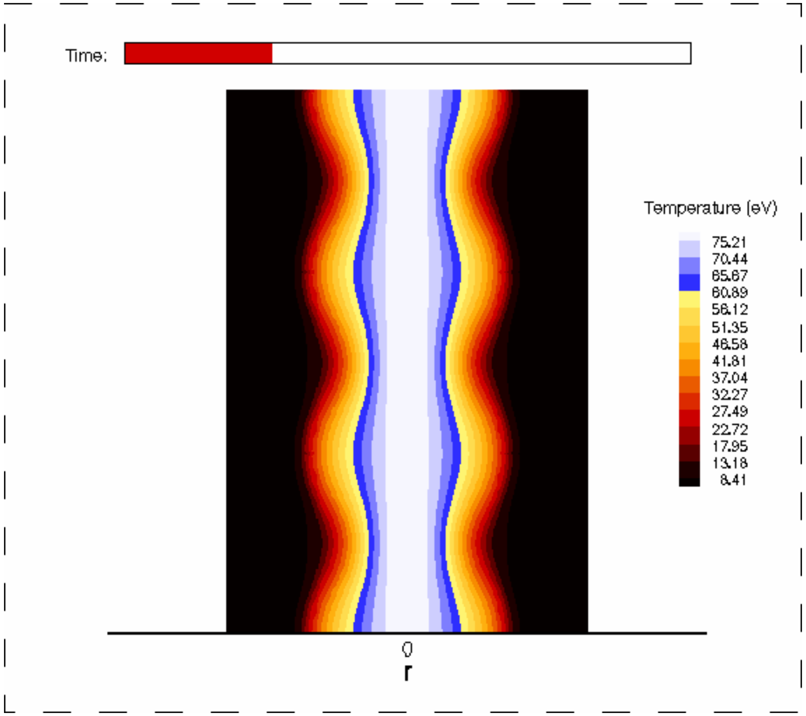


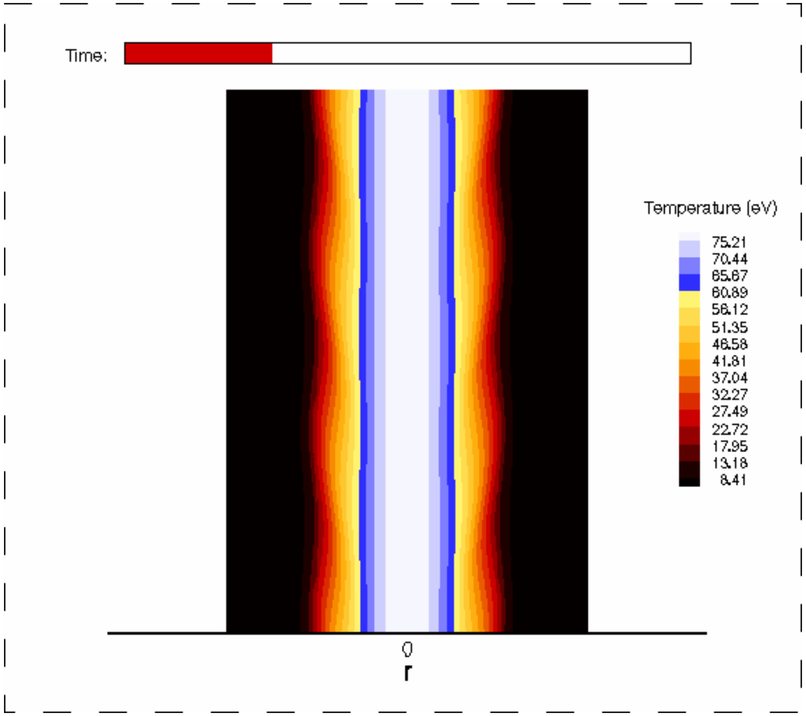
Nonlinear simulations support the linear result.



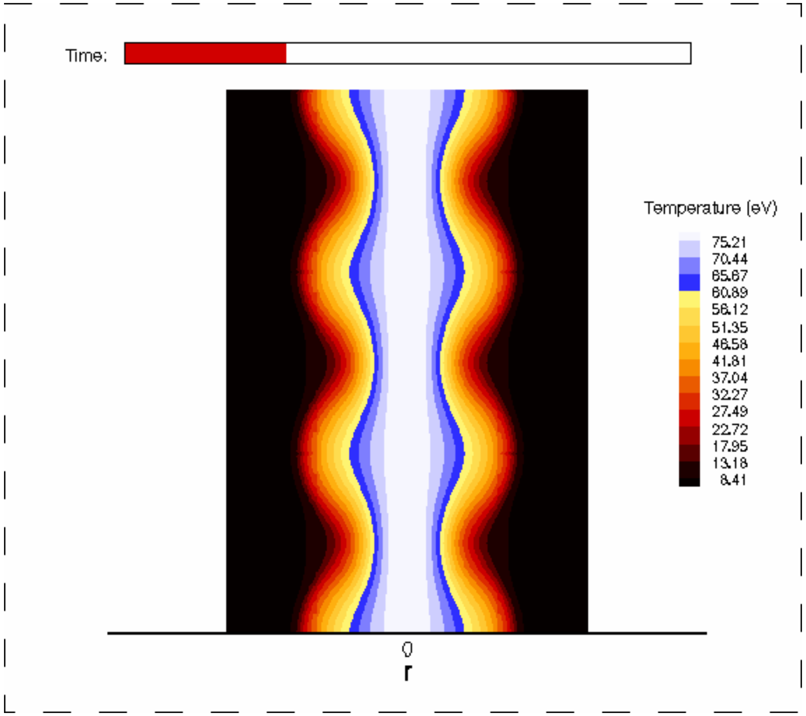


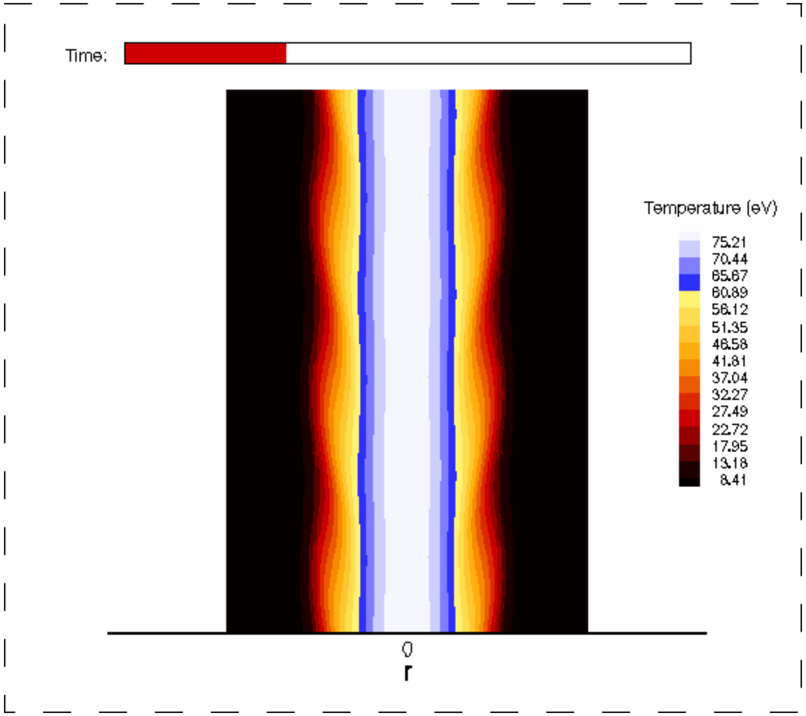
Nonlinear simulations support the linear result.





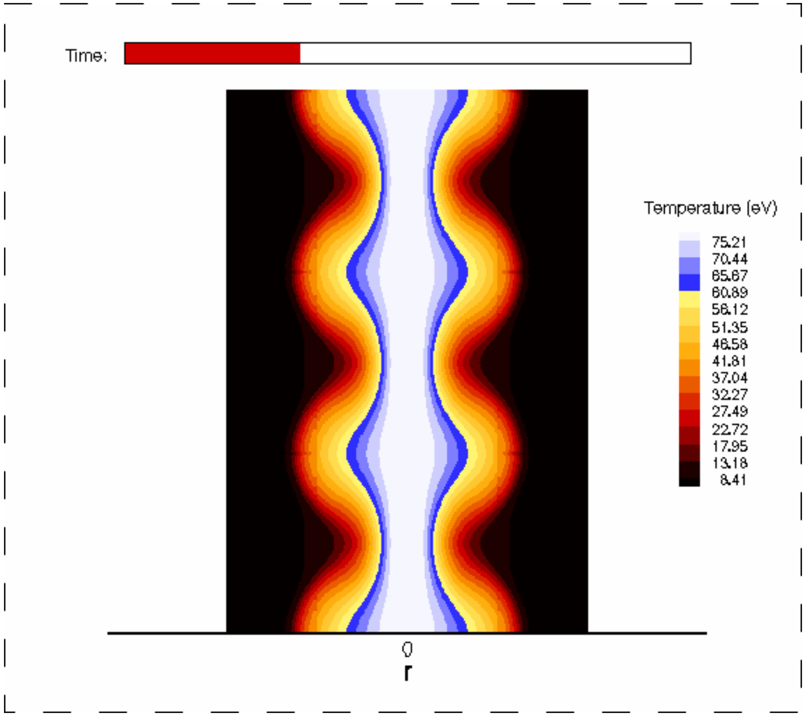
Nonlinear simulations support the linear result.

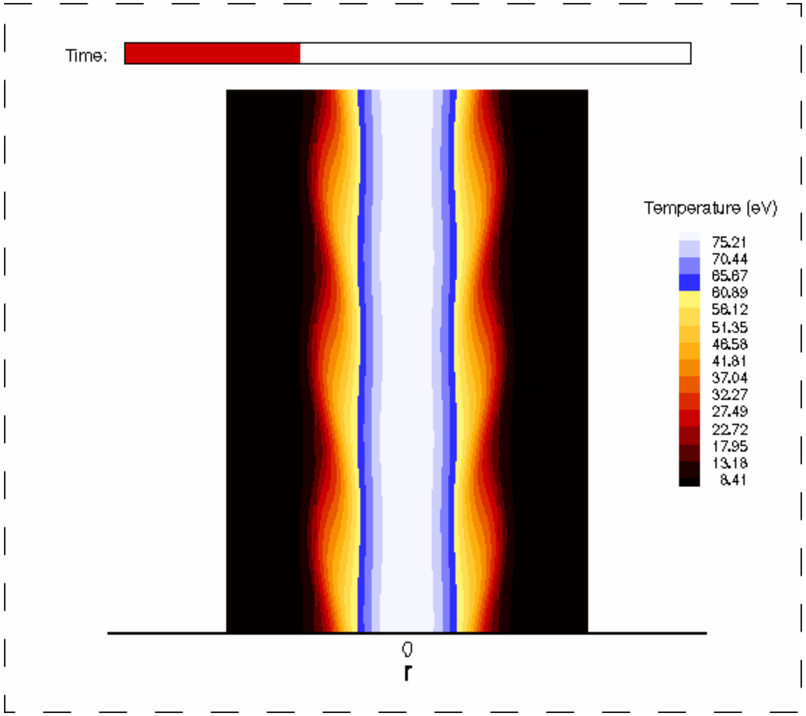




Uri Shumlak, shumlak@uw.edu

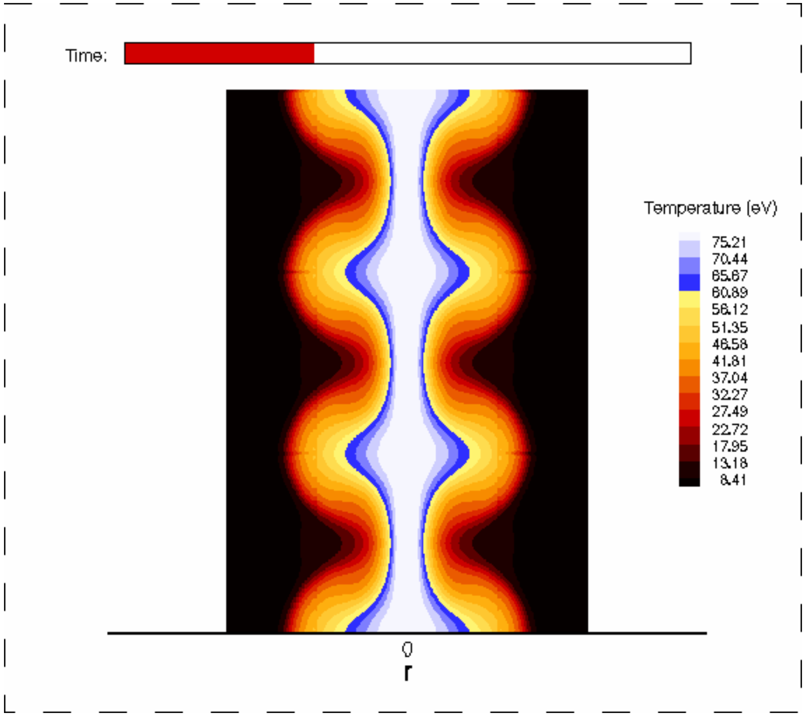
Nonlinear simulations support the linear result.

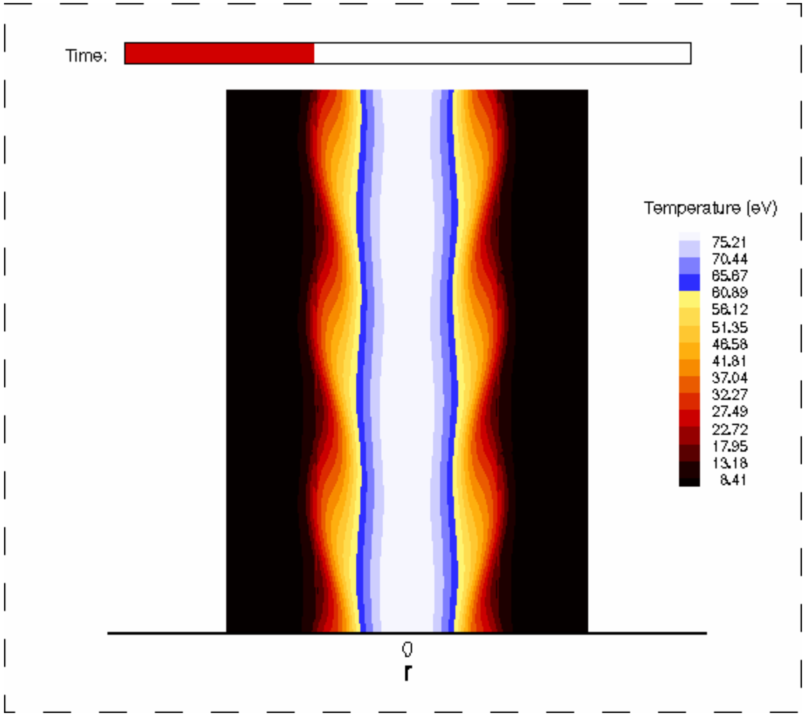




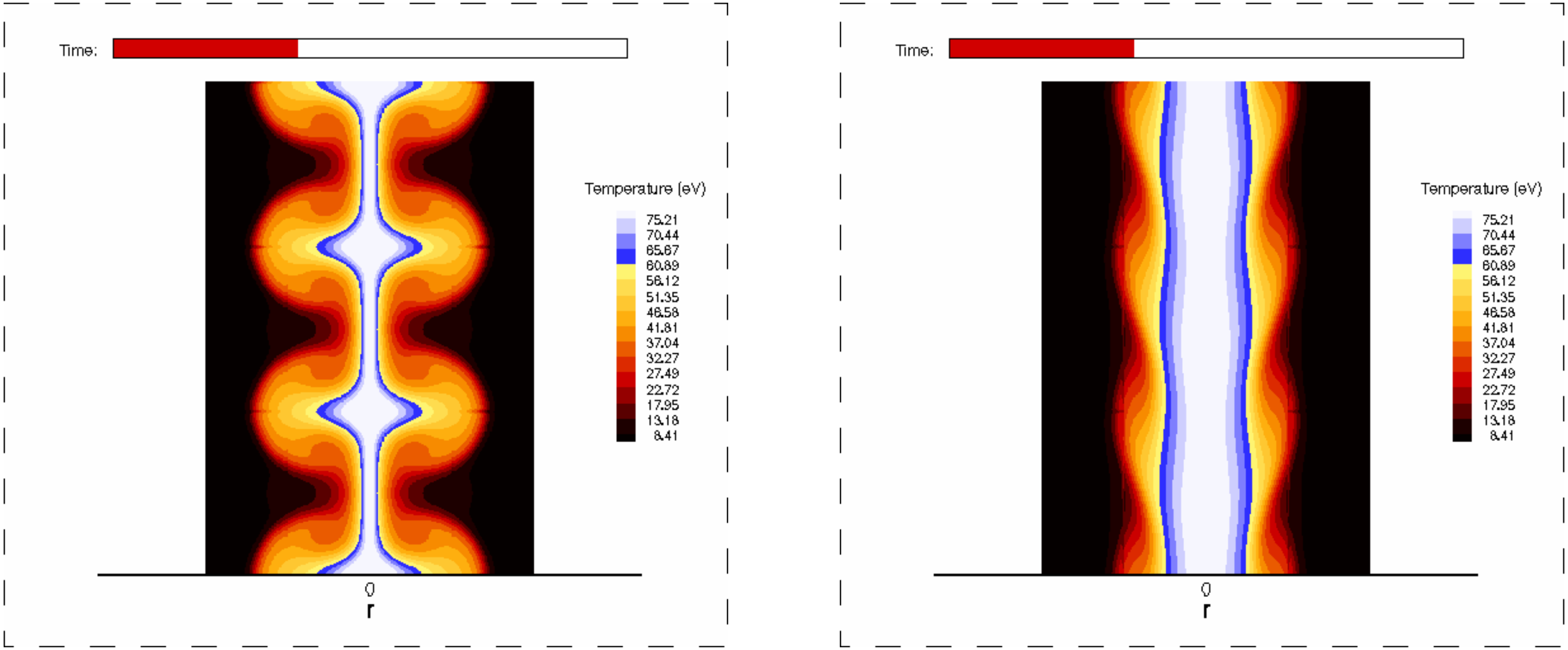
Uri Shumlak, shumlak@uw.edu

Nonlinear simulations support the linear result.

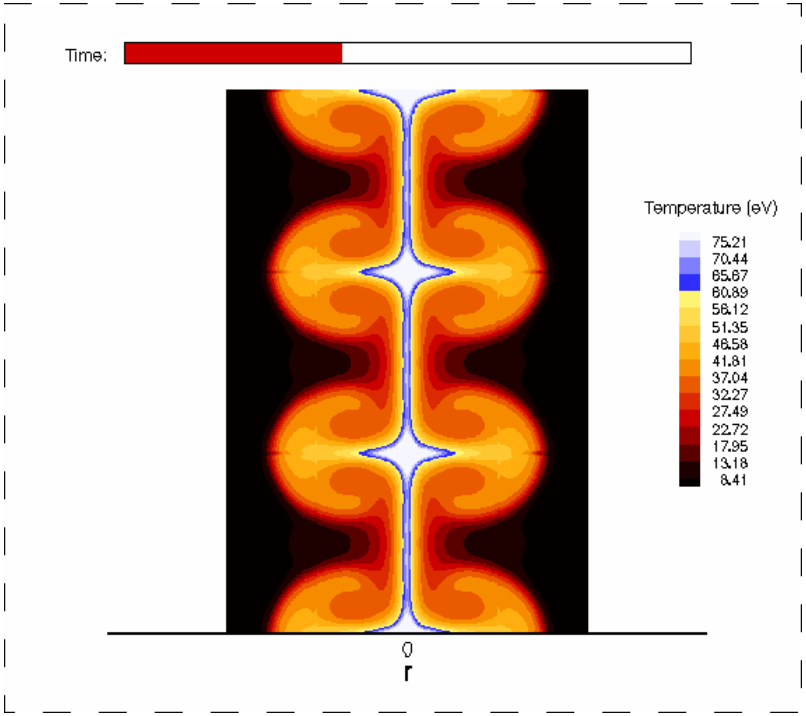


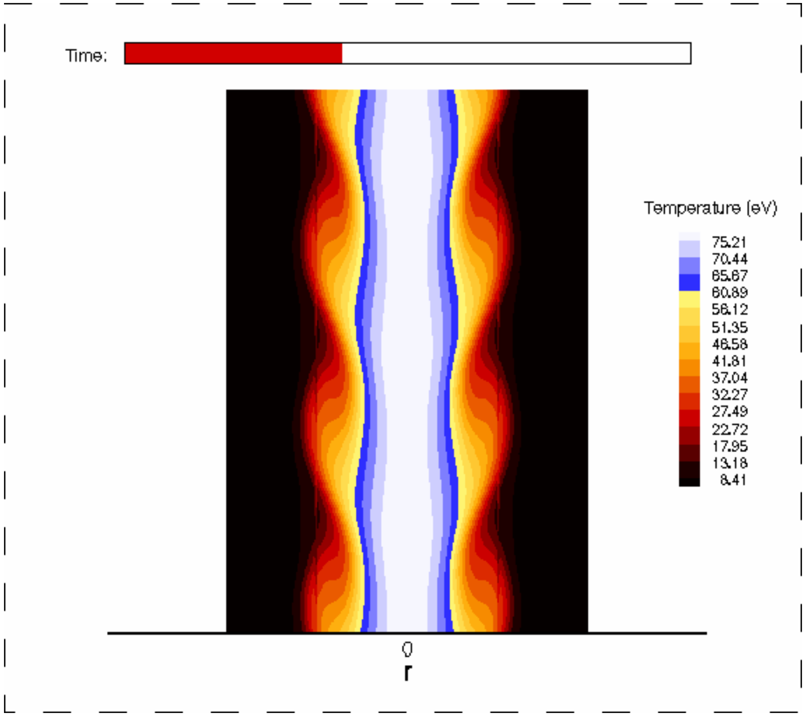


Nonlinear simulations support the linear result.

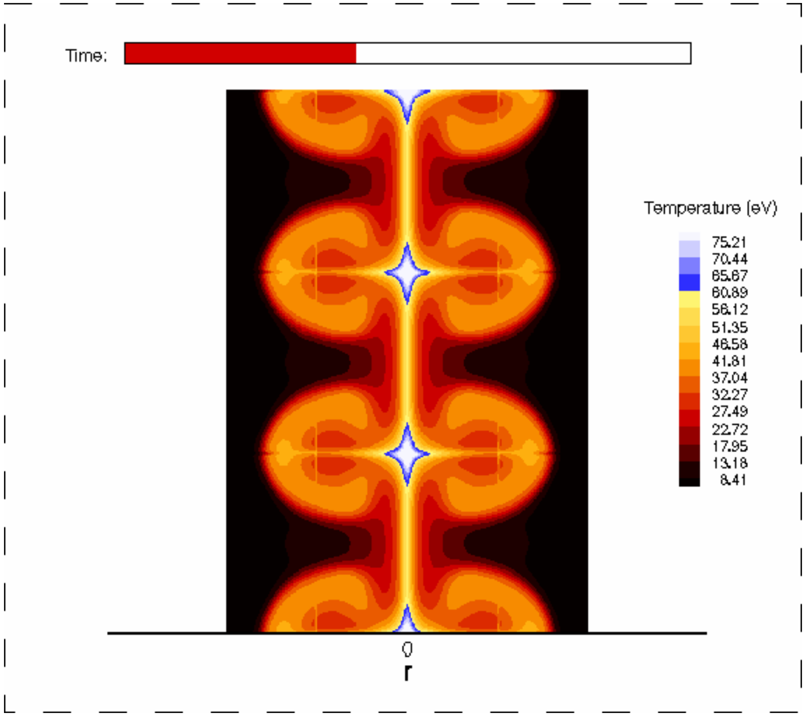


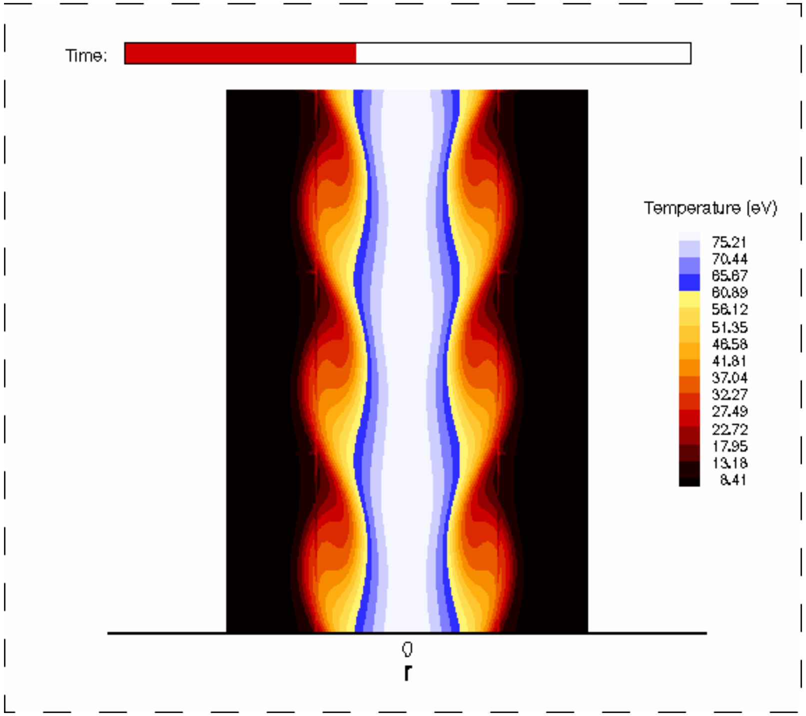
Nonlinear simulations support the linear result.





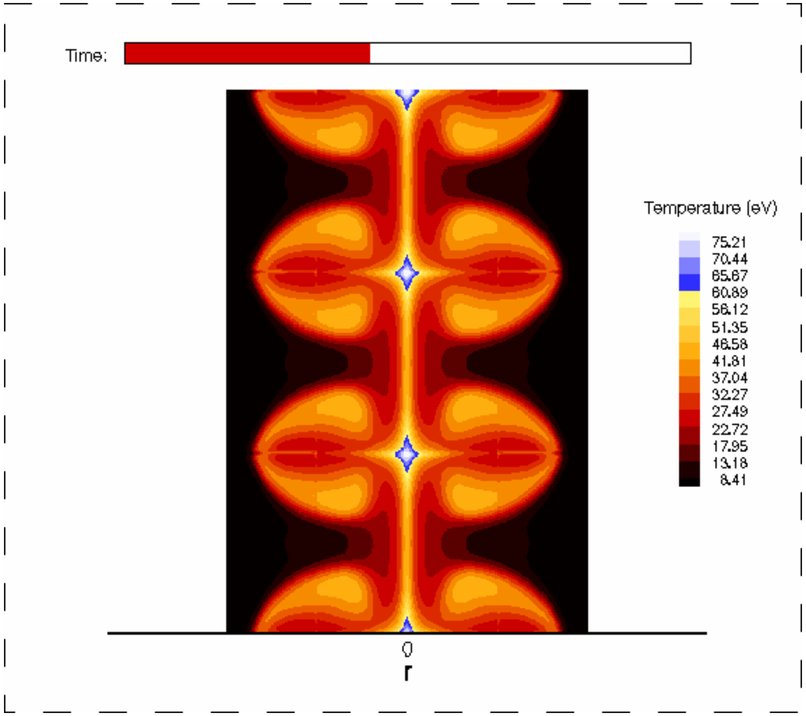
Nonlinear simulations support the linear result.

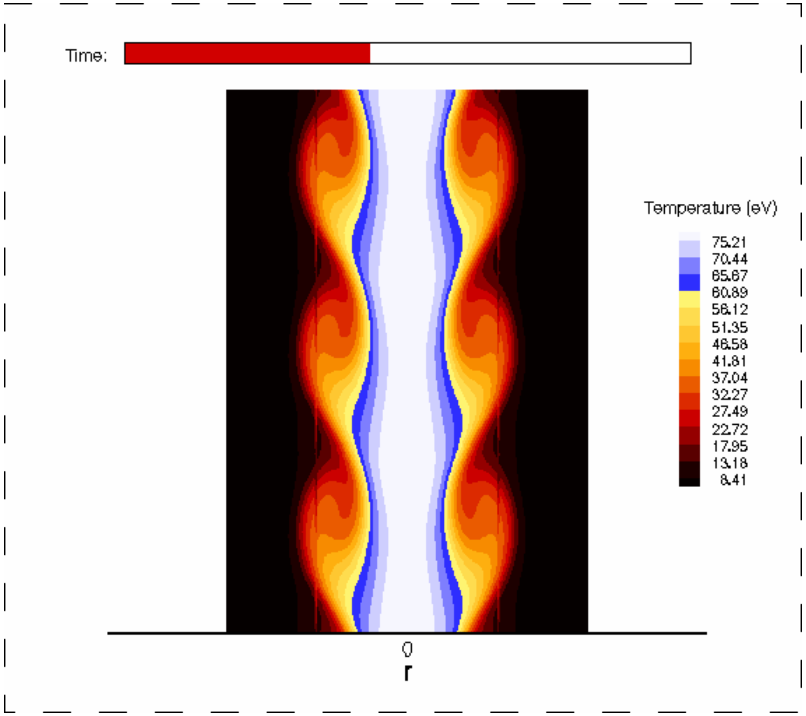




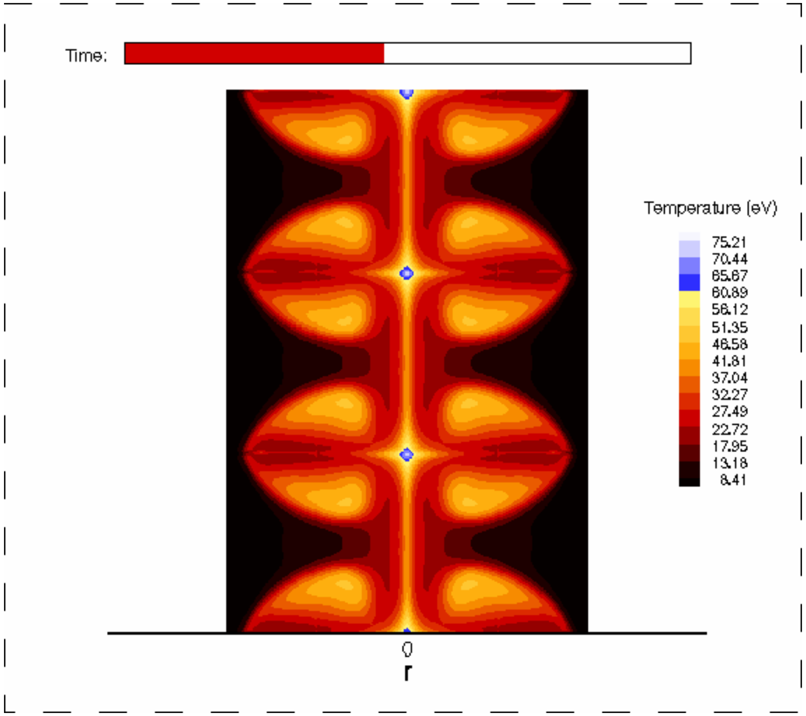
Uri Shumlak, shumlak@uw.edu

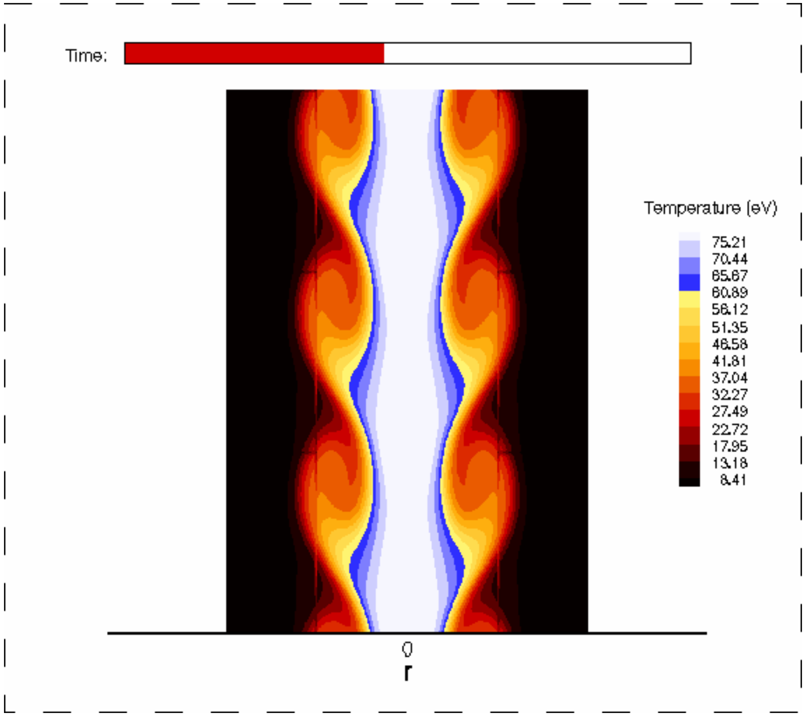
Nonlinear simulations support the linear result.





Nonlinear simulations support the linear result.



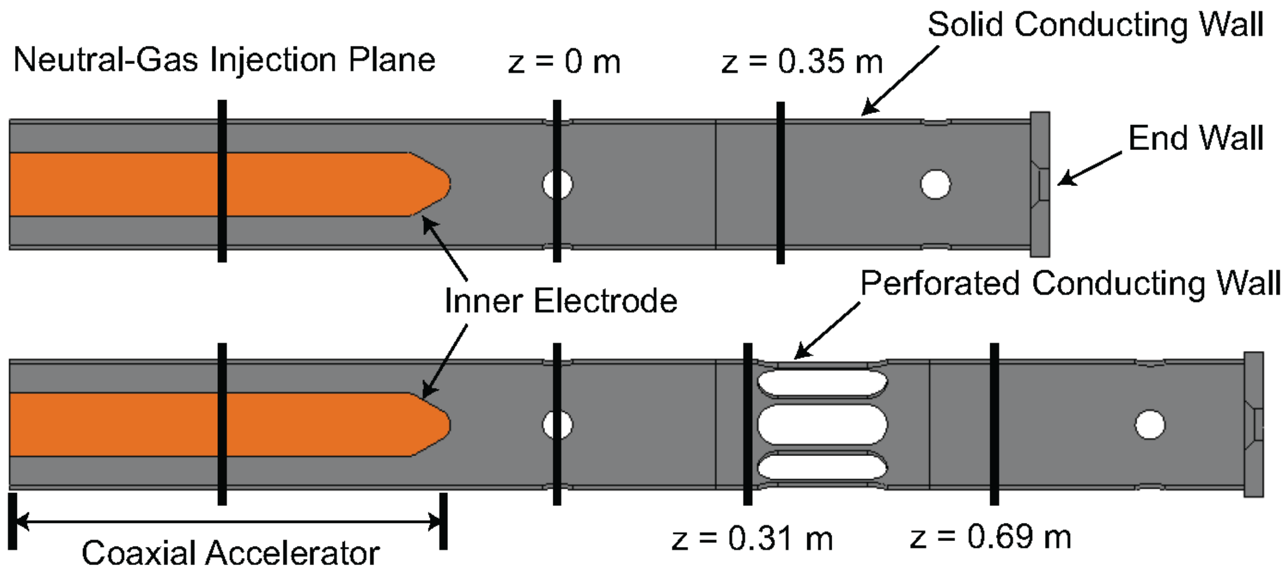


Uri Shumlak, shumlak@uw.edu

Perforated conducting wall isolated stabilization effect[1]

Close-fitting conducting walls are known to stabilize gross plasma motion. Sheared-flow stabilizing effect was isolated by perforating conducting wall, ≈70% removed.

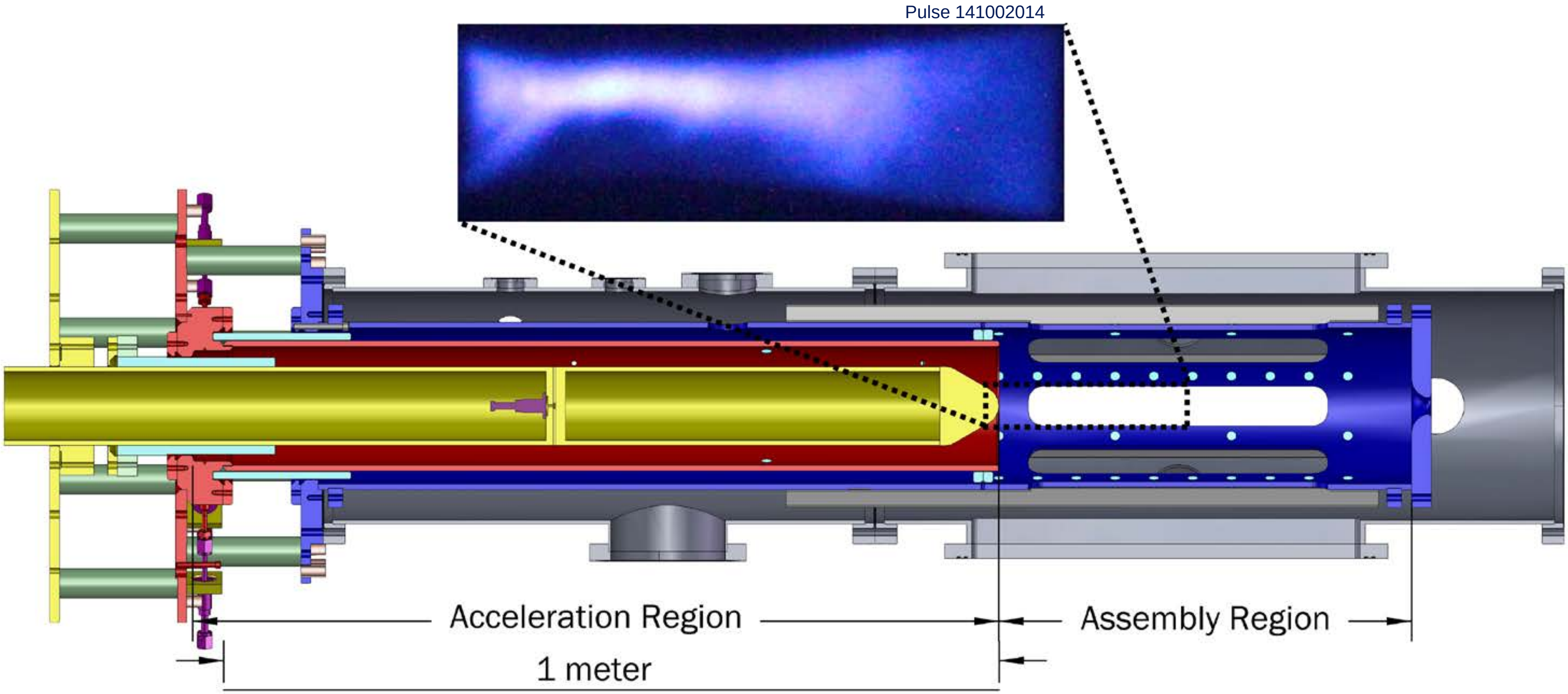
Overall plasma behavior was indistinguishable.



[1]Knecht, Lowrie, & Shumlak, IEEE TPS (2014)

ZaP-HD design allows detailed measurements

Large rectangular openings in the outer electrode and corresponding viewports provides extensive optical access to the plasma for fast framing photography, interferometry, and spectroscopy.

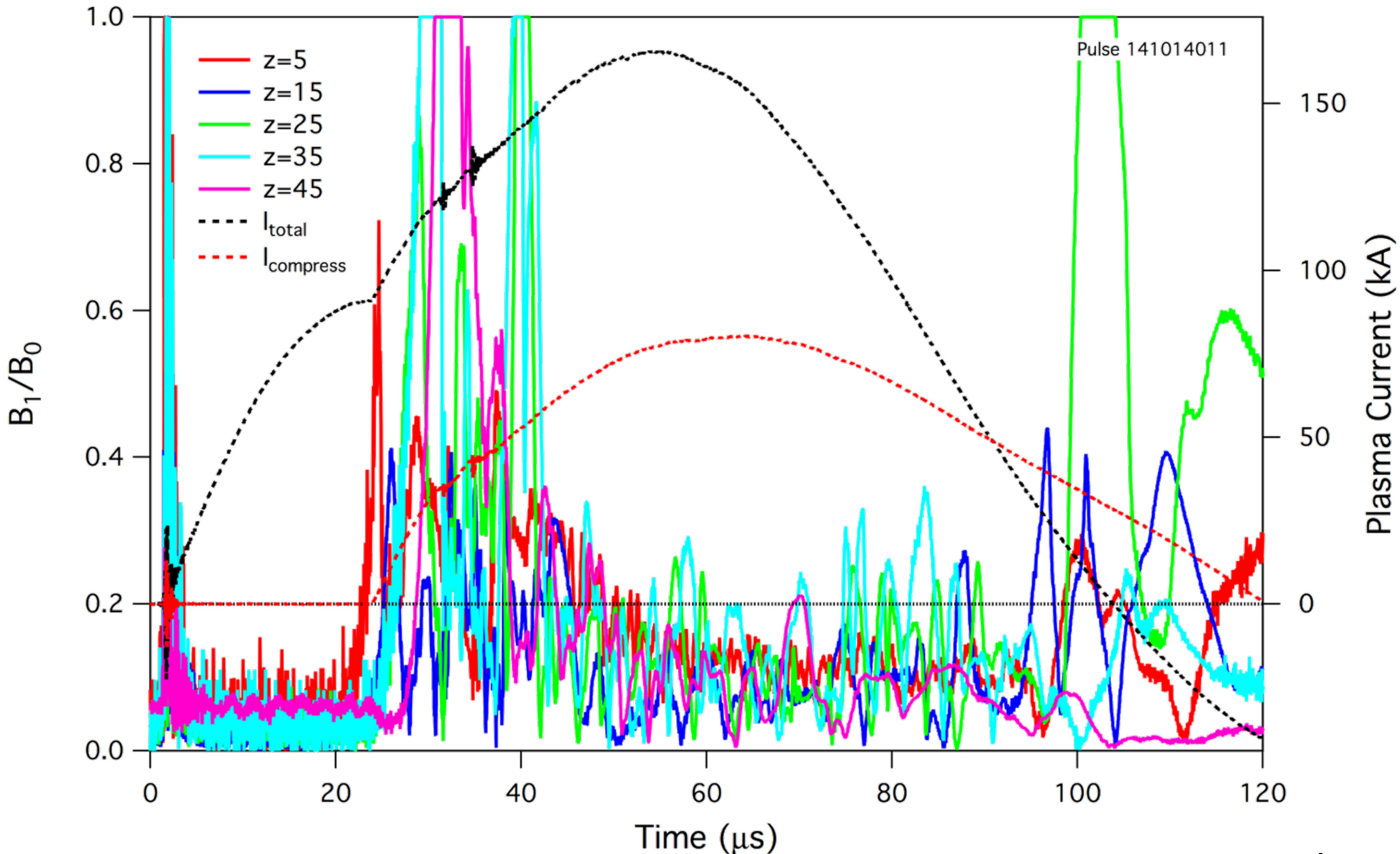


Uri Shumlak, shumlak@uw.edu

ZaP-HD design allows detailed measurements

Magnetic probes in ZaP-HD are located to allow 3D reconstruction of the magnetic topology along the entire 50 cm length of the pinch plasma.

Consistent with ZaP experimental results, a quiescent period is observed in ZaP-HD. The behavior is evident at all axial locations along Z-pinch.



Flow Z-pinch can generate fusion reactor plasmas

Analysis of the flow Z-pinch using the scaling laws leads to a solution with reasonable size (length L and radius a) and high power.

Fusion power is given as

$$P_f = n_D n_T \langle \sigma v \rangle_{DT} E_{DT} \pi a^2 L = \frac{n^2}{4} \langle \sigma v \rangle_{DT} E_{DT} \pi a^2 L$$

Input power must be supplied to heat and compress the plasma, to drive the flow, and to replace radiative losses.

$$P_{th} = \frac{3}{2} \sum_\alpha \dot{n}_\alpha k T_\alpha \pi a^2 L \quad \text{for } \alpha = D, T, e, e$$

$$= 3 \dot{n} k T \pi a^2 L = 3 n k T v_z \pi a^2$$

$$P_{flow} = \frac{1}{2} \dot{m} v_z^2 = \frac{M_D + M_T}{4} \dot{n} v_z^2 \pi a^2 L = \frac{M_D + M_T}{4} n v_z^3 \pi a^2$$

$$P_{rad} = C n_e \sqrt{T_e} \sum_i Z_i^2 n_i = 3.4 \times 10^{-38} n_{\mathrm{m}^{-3}}^2 \sqrt{T_{\mathrm{eV}}}$$