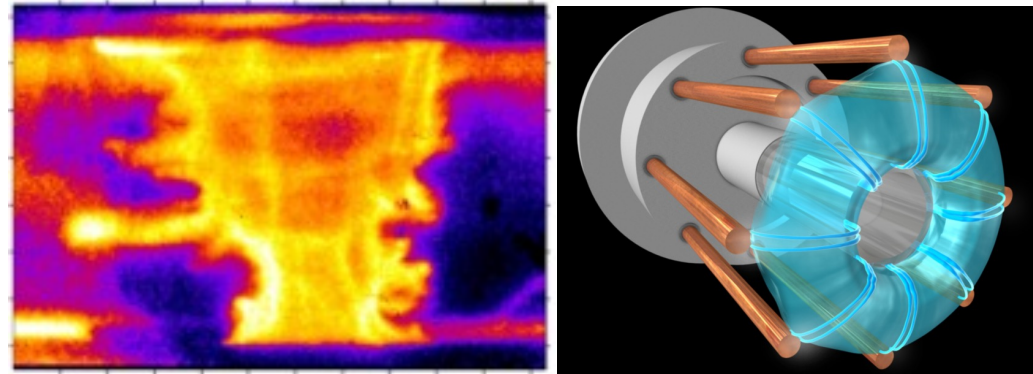


Z-pinch Research at UC San Diego



Farhat Beg

Center for Energy Research

Department of Mechanical and Aerospace Engineering

University of California San Diego

This material is based upon work supported by the Department of Energy, National Nuclear Security Administration under Award Number DE-NA0003842.

High Energy Density Physics Group

■ Research Scientists and Post docs

- Dr. Fabio Conti
- Dr. Joohwan Kim
- Dr. Mathieu Bailly-Grandvaux
- Dr. Pia Valdivia
- Dr. Simon Bolonas
- Dr. Eric Hahn

■ Graduate Students

- Joe Strehlow
- Krish Bhutwala
- Nickolas Aybar
- Tanner Cordova
- Dana Zimmer
- Alem Bogale
- Apsara Williams
- Jackie Vaughan
- Swarvanu Ghosh
- Sophie Parsons



Research Topics

- **High intensity laser matter interactions**
 - Laser plasma interaction and instabilities
 - Relativistic electron transport in solid and warm dense matter
 - Proton production, conversion efficiency and focusing
 - Modeling with EPOCH, LSP, PICLS, and ZUMA codes
- **Mono-energetic ion beams with ultra-intense las**
- **Shock Ignition**
- **Z-pinch**es
 - Staged Z-pinch for fusion
 - Supersonic jets and collisionless shocks
 - Liner physics
- **X-pinch**es
 - Point projection radiography
 - Laser cut x-pinch as rep. rate source
 - Intense source for x-ray diffraction
- **Dense Plasma Focus**



PRL 115, 054801 (2015)

PHYSICAL REVIEW LETTERS

week ending
31 JULY 2015

Self-Consistent Simulation of Transport and Energy Deposition of Intense Laser-Accelerated Proton Beams in Solid-Density Matter

J. Kim,¹ B. Qiao,^{1,*} C. McGuffey,¹ M. S. Wei,² P. E. Grabowski,³ and F. N. Beg^{1,†}

¹Center for Energy Research, University of California, San Diego, California 92093, USA

nature
physics

ARTICLES

PUBLISHED ONLINE: 11 JANUARY 2016 | DOI: 10.1038/NPHYS3614

Visualizing fast electron energy transport into laser-compressed high-density fast-ignition targets

L. C. Jarrott^{1†}, M. S. Wei^{2*}, C. McGuffey¹, A. A. Solodov^{3,4}, W. Theobald³, B. Qiao¹, C. Stoeckl³, D. Ratt^{3,4}, H. Chen⁵, I. Dallett³, T. Dönnner⁵, F. M. Giraldez², V. V. Glabau³, H. Hahara⁶, T. Iwawaki⁶

PRL 116, 155001 (2016)

PHYSICAL REVIEW LETTERS

week ending
15 APRIL 2016

Generation of Superponderomotive Electrons in Multipicosecond Interactions of Kilojoule Laser Beams with Solid-Density Plasmas

A. Sorokovikova,¹ A. V. Arefiev,² C. McGuffey,^{1,*} B. Qiao,¹ A. P. L. Robinson,³ M. S. Wei,⁴ H. S. McLean,⁵ and F. N. Beg^{1,†}

¹Center for Energy Research, University of California, San Diego, California 92093, USA

PHYSICAL REVIEW LETTERS **123**, 215001 (2019)

Self-Generated Magnetic and Electric Fields at a Mach-6 Shock Front in a Low Density Helium Gas by Dual-Angle Proton Radiography

R. Hua,¹ J. Kim,¹ M. Sherlock,² M. Bailly-Grandvaux,¹ F. N. Beg,^{1,*} C. McGuffey,¹ S. Wilks,² H. Wen,³ A. Joglekar,³ W. Mori,³ and Y. Ping^{2,†}

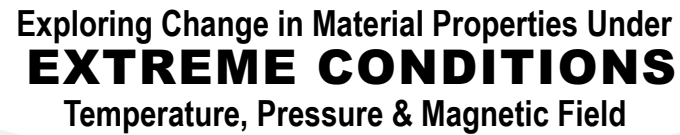
¹Center for Energy Research, University of California, San Diego, La Jolla, California 92093, USA

²Lawrence Livermore National Laboratory, Livermore, California 94550, USA

³University of California, Los Angeles, Los Angeles, California 90095, USA

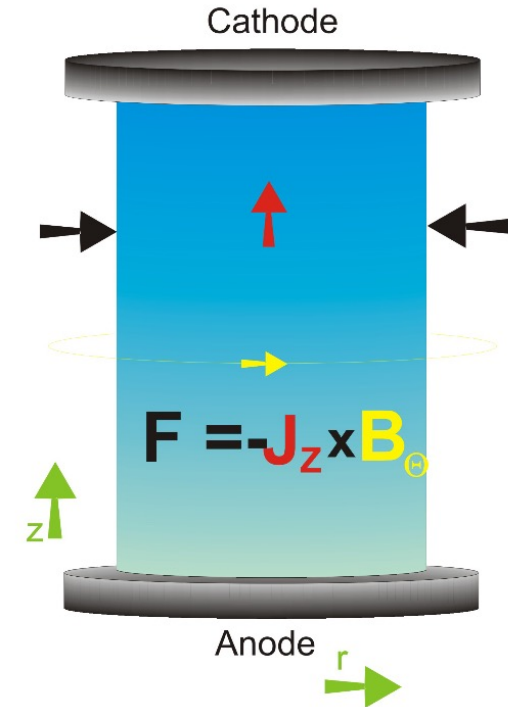
(Received 18 September 2018; revised manuscript received 17 May 2019; published 21 November 2019)

Shocks are abundant both in astrophysical and laboratory systems. While the electric fields generated at shock fronts have recently attracted great attention, the associated self-generated magnetic field is rarely studied, despite its ability to significantly affect the shock profile in the nonideal geometry where density



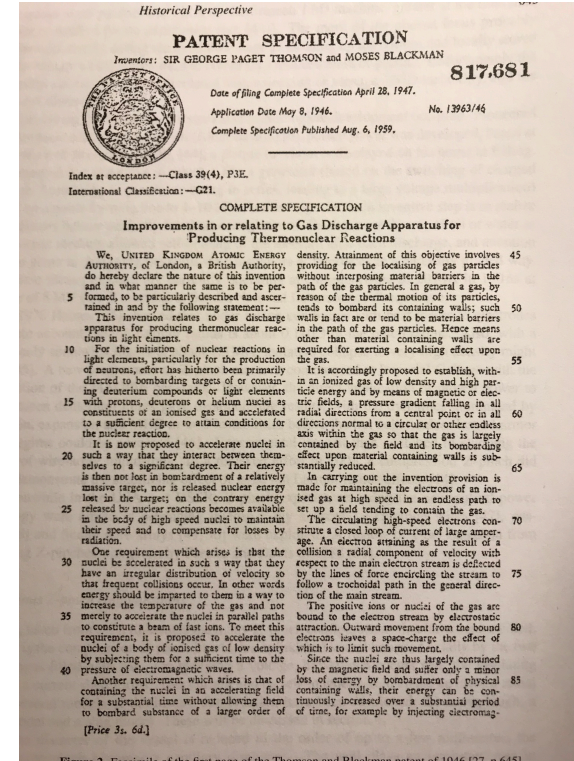
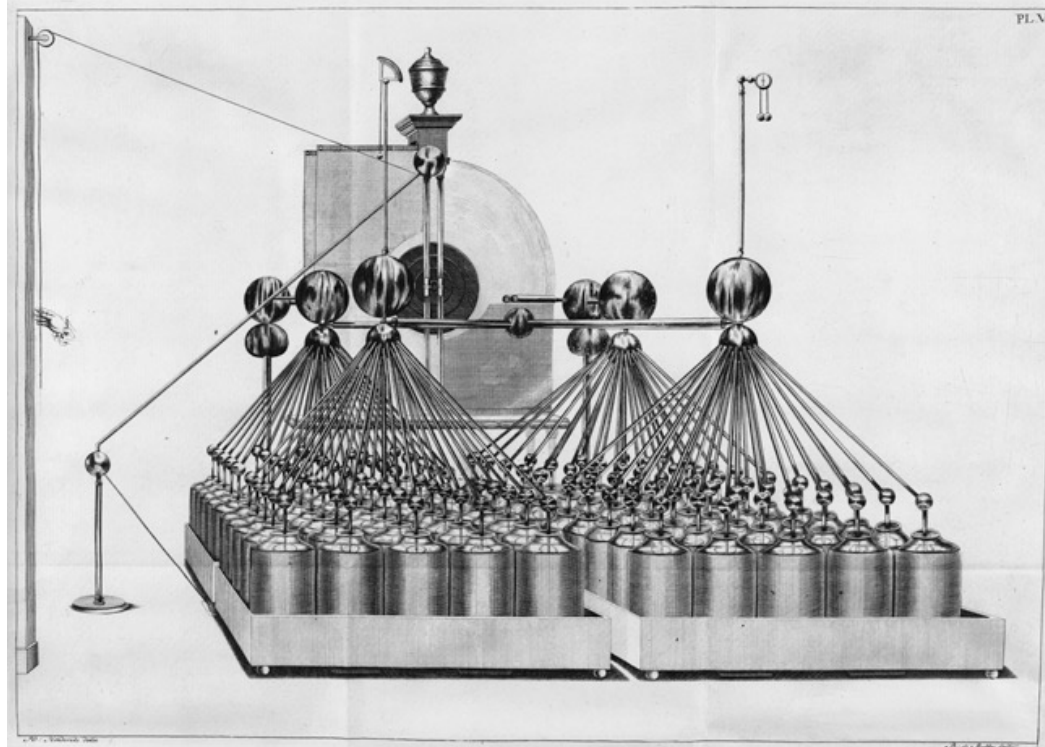
What is Z-pinch

- Z-pinch is the simplest magnetic confinement device
- We want to know detailed plasma properties
 - pinch radius
 - peak density
 - **current distribution**
- Why are these properties important?
 - can influence the potential applications
 - can determine the stability of the device
- There are certain parameters that we can control experimentally
 - current flowing in plasma
 - line density, $N = 2\pi \int_0^r n_i r dr$



Historical Perspective

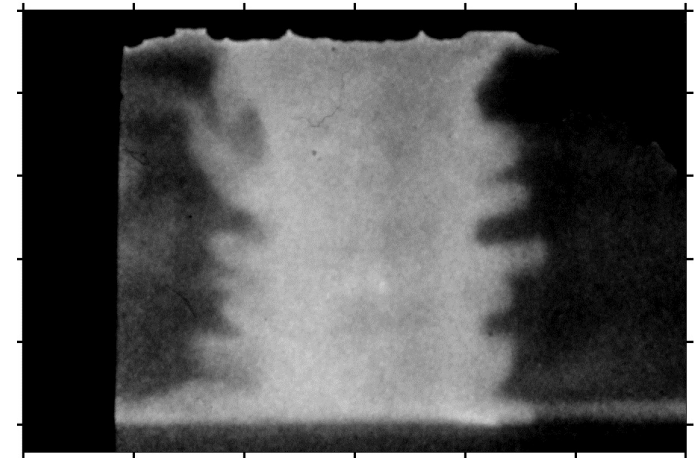
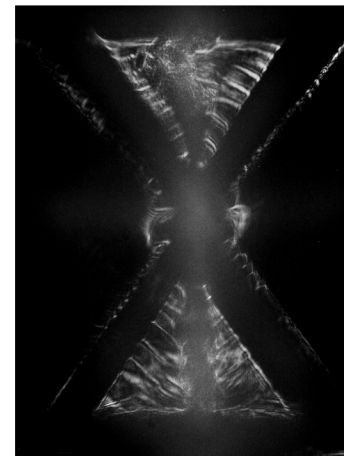
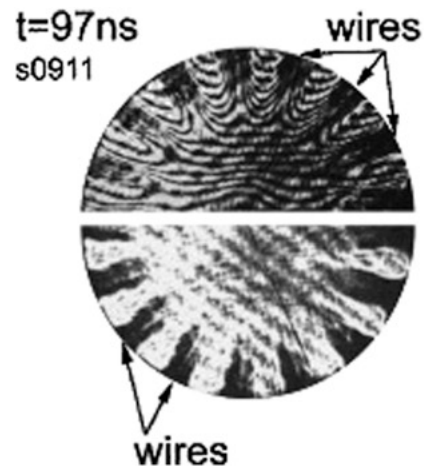
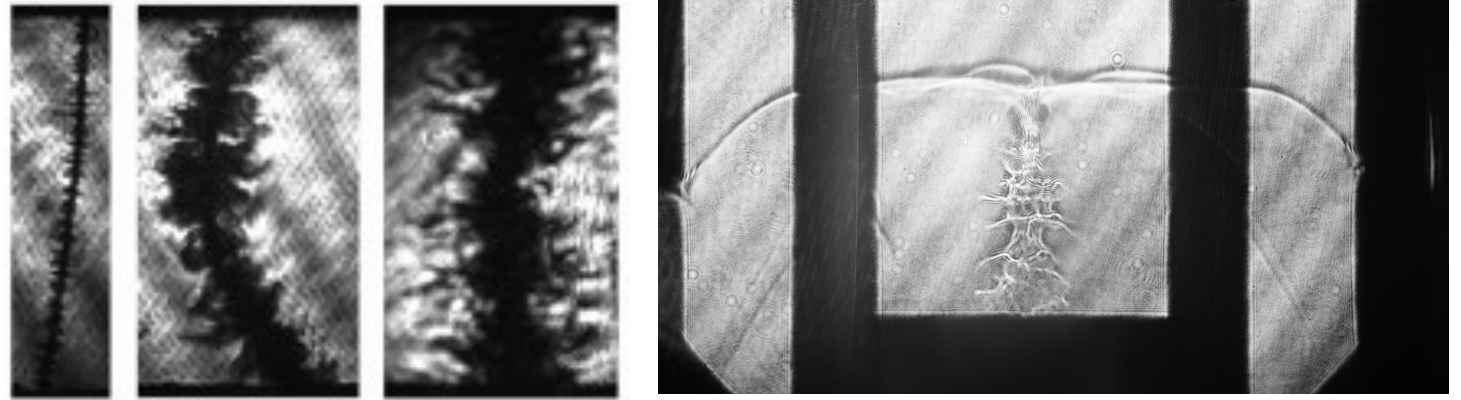
M.G. Haines, Plasma Physics and Controlled Fusion **53. 093001** (2012)



- Earliest demonstration of the Z-pinch by Martinus van Marum in Amsterdam in 1790 related to the defense industry
 - 1 kJ capacitive energy store composed of 100 Leyden jars discharged into a 1m long wire.
- In late 1940's, experiments by Thomson and Blackman at Imperial College

Types of Z-pinches

- Compressional pinch
- Gas puff pinch
- Dense Plasma Focus
- Gas embedded pinch
- Frozen deuterium fiber pinch
- X-pinch
- Sheared axial flow pinch
- Liner driven pinch
- Laser driven pinch
- Wire array pinch



Equilibria

- are states in force balance

- MHD equation of motion

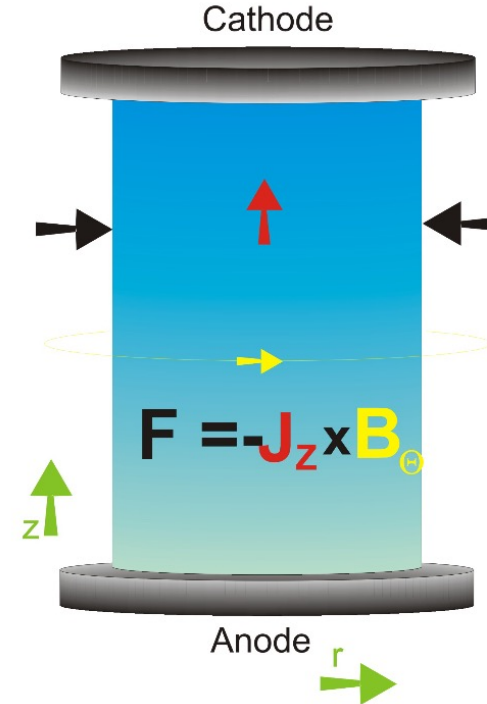
$$\rho \frac{dU}{dt} = -\nabla \cdot P + J \times B$$

- As we define equilibria in force balance,

$$\frac{\partial P}{\partial r} = -JB$$

- What are our assumptions

- quantities only vary with r
- theoretical Z-pinch is infinitely long so that end effects can be neglected



The Bennett Relation

- MHD assumes phenomena slower than c
- Ampere law has form
- In terms of line density N and average temperature

$$J = (\nabla \times B) / \mu_0$$

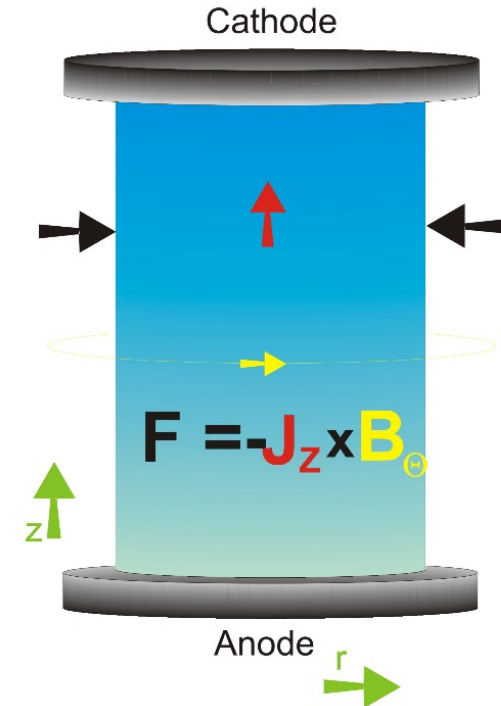
$$\mu_o I_P^2 = 8\pi N(1 + Z)k \langle T \rangle$$

- Note this relation is independent of radius
- If we assume that we have 1 MA current generator with hydrogen plasma with a line density of $N=4 \times 10^{18} \text{ m}^{-1}$, we get

$$\langle T \rangle = 10 \text{ keV}??$$

W.H. Bennett, Phy. Rev. **45**, 890 (1934)

Exciting for limitless energy



Haines showed that Z-pinches can satisfy the Lawson Criteria

- Haines showed that Z-pinch can satisfy Lawson criteria ($nt_E \sim 5.0 \times 10^{20} \text{ s/m}^3$) by ohmic heating plasma to fusion temperatures (25 keV)
- Assumptions
 - confinement time is determined by losses to electrodes
 - pinch is in radial equilibrium
- Calculated
 - time scale $t_E = 100 \text{ ns}$ leads to
 - $n = 5 \times 10^{27} \text{ m}^{-3}$, $a = 19 \text{ }\mu\text{m}$, $z_0 = 9 \text{ cm}$ and $I = 10^6 \text{ A}$
- Condition
 - stable for $1000\gamma_{\text{MHD}}$ ($\gamma_{\text{MHD}} = v_A/a$)



M. G. Haines, Laser and Particle Beams **14**, 261 (1996)

Radiative Collapse – Pease Braginskii Current

R. S. Pease, Proc. Phys. Soc. Lond. **B70**, 11 (1957)

S. I. Braginskii, Plasma Physics and the Problem of Controlled Thermonuclear Reactions (Editor: M. A. Leontovich), vol.1, 135 (1961)

J. W. Shearer, Phys. Fluids **19**, 1427 (1976)

- The current at which radiation loss is balanced by ohmic heating

$$\eta_{\perp} J^2 \cong \beta_b Z n_e^2 T^{1/2}$$

$$I_{PB} = \frac{8\sqrt{3}k_B}{\mu_0\sqrt{\alpha\beta_b}} \frac{1+Z}{2Z} = 0.433(\ln \Lambda)^{1/2} \left(\frac{1+\langle Z \rangle}{2\langle Z^2 \rangle^{1/2}} \right) \text{MA.}$$

- Neglecting conduction losses

$$\frac{\dot{a}}{a} = \frac{3}{4\tau_r} \left[\left(\frac{I_{PB}}{I} \right)^2 - 1 \right]$$

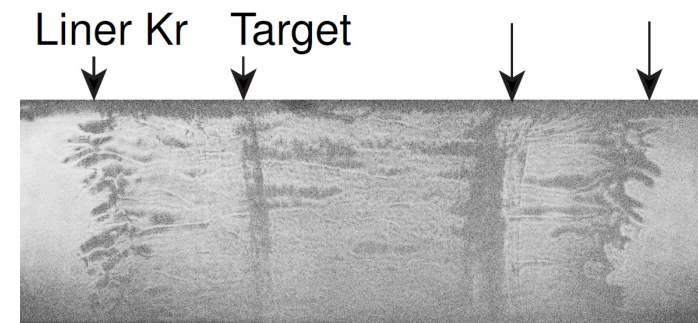
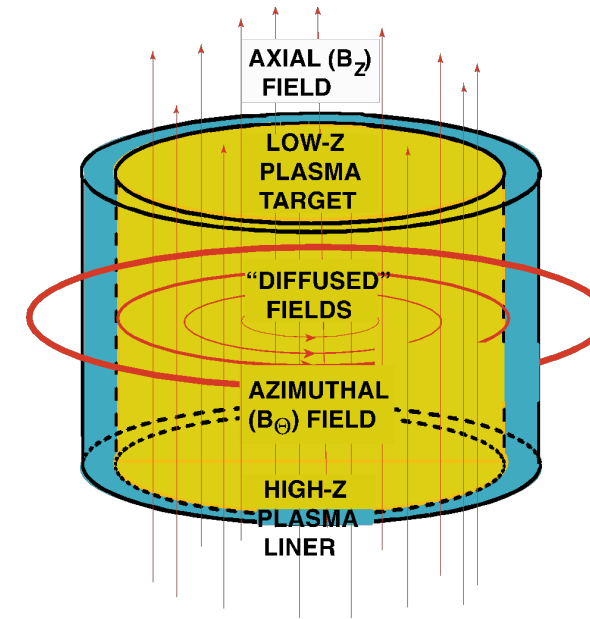
If $I < I_{PB}$, the pinch expands and for $I > I_{PB}$ pinch contracts

Pulsed power made it possible to test theories

Gas Puff Z-pinch experiments

Staged Z-pinch is efficient way to couple energy to the load

- Liner-on-target (double) gas-puff
- Target is compressed inertially by the liner
- Relies on snowplow shock compression for target pre-heating
- Pre-heating from $T \leq 1\text{eV}$ to $T \sim 100\text{eV}$
- Externally-applied axial magnetic field can inhibit thermal conduction and can mitigate MRT growth
- Target can remain stable even if the liner is not

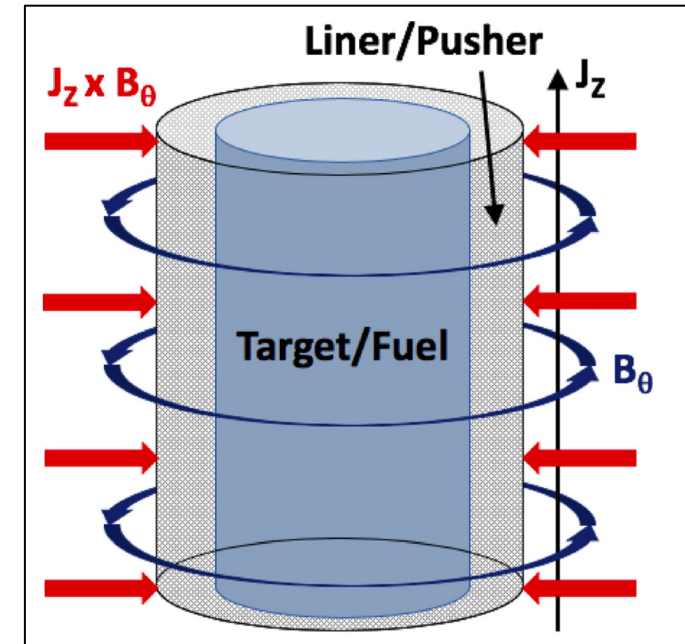


H. U. Rahman et al. Phys. Rev. Lett. **74**, 714 (1995)

A. Van Drie, Thermonuclear Fusion In A Staged Z-Pinch.
Ph.D. Dissertation, UC Irvine (2001)

Experiments have been carried out on 1 MA current generator

- **Control of plasma instabilities like Magneto-Rayleigh-Taylor**
- **Combine MRTI mitigation techniques**
 - externally-applied axial magnetic field (B_z)
 - tailored density profiles (e.g. multi-shell)
- **First experiments conducted on Zebra (UNR)**
1 MA, 100 ns, 2 Ω generator (Marx-PFL)
- **Double gas puff:**
 - krypton hollow liner:
 - $R=1.25\text{cm}$, $\text{FWHM}=0.6\text{cm}$, $\rho=2.5\mu\text{g}/\text{cm}^3$
 - deuterium target: on axis
 $\text{FWHM}=0.6\text{cm}$, $\rho=7\mu\text{g}/\text{cm}^3$
- **Externally-applied $B_{z0} = 0-3\text{ kG}$**



"Spikes and
bubbles"

F. Conti et al., Physics of Plasmas 27, 012702 (2020)

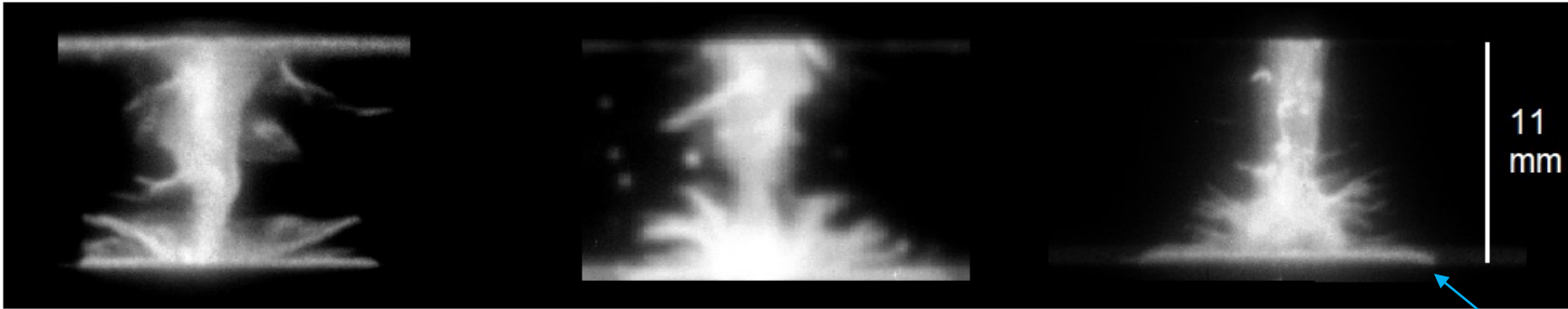
Even a modest external B_{z0} can reduce instability

$B_{z0} = 0.00$ T
 $t = 90$ ns
(shot 5331)

$B_{z0} = 0.05$ T
 $t = 91$ ns
(shot 5299)

$B_{z0} = 0.10$ T
 $t = 92$ ns
(shot 5306)

F. Conti et al., Physics of Plasmas 27, 012702 (2020).



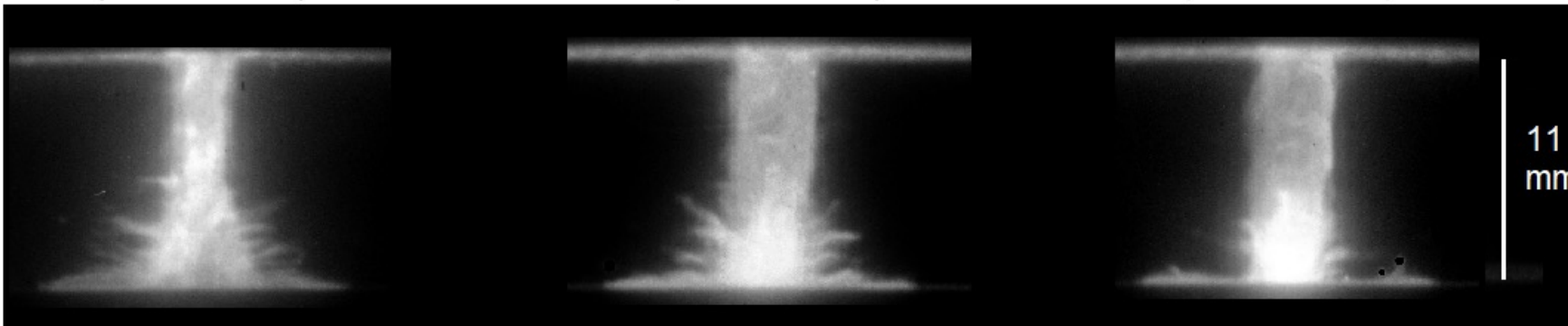
Theory predicts
 $B_{st} = I_{[MA]} / R_{0[cm]}$
 ~ 0.8 T

$B_{z0} = 0.15$ T
 $t = 89$ ns
(shot 5307)

$B_{z0} = 0.20$ T
 $t = 91$ ns
(shot 5313)

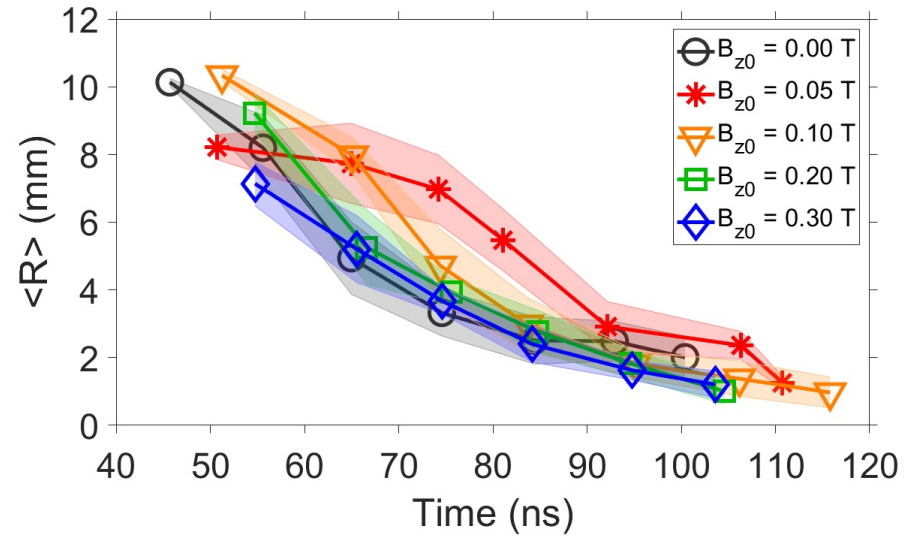
$B_{z0} = 0.30$ T
 $t = 91$ ns
(shot 5316)

Observed MRTI
mitigation

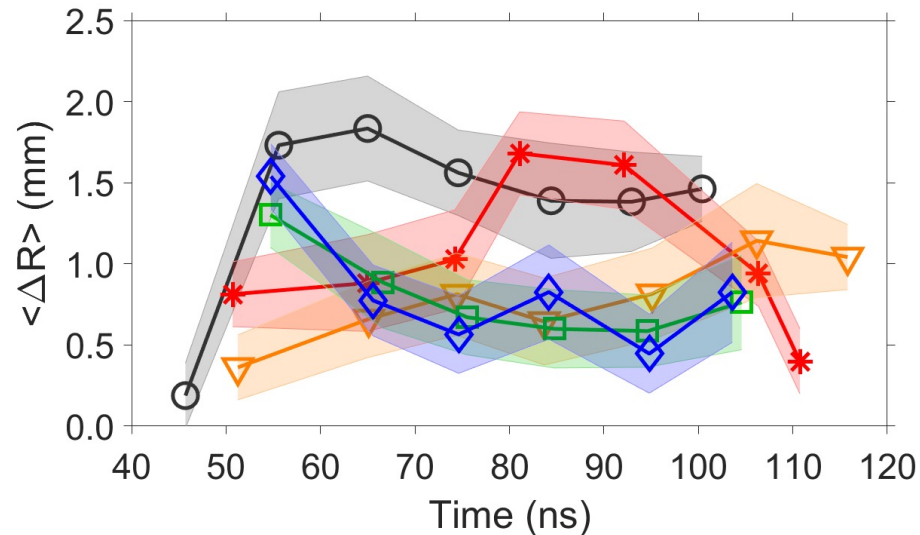


Stability threshold at small B_z pressure

Plasma
outer
radius



Instability
amplitude



- No measurable implosion slowdown
- $(B_z/B_0)^2 \leq 4\%$ at stagnation
- MRTI amplitude < 1 mm when mitigated
- Increase in stagnation radius with $B_{z0} = 0.3$ T

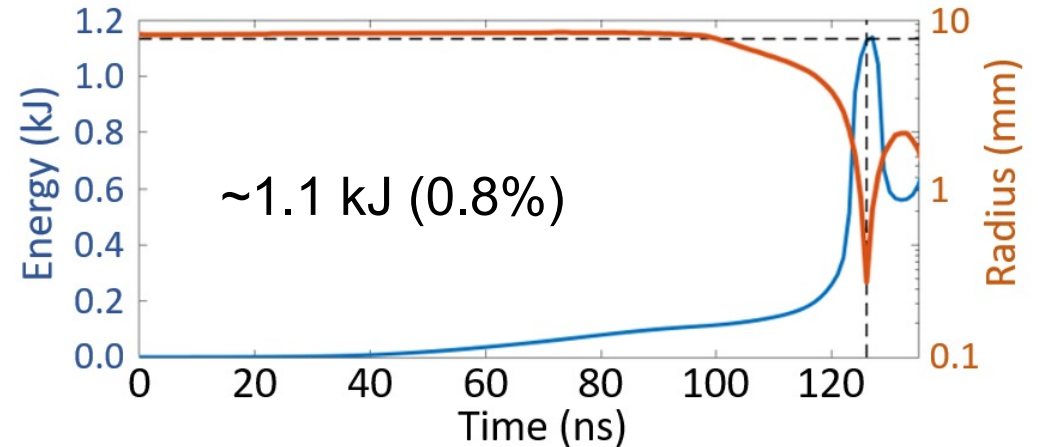
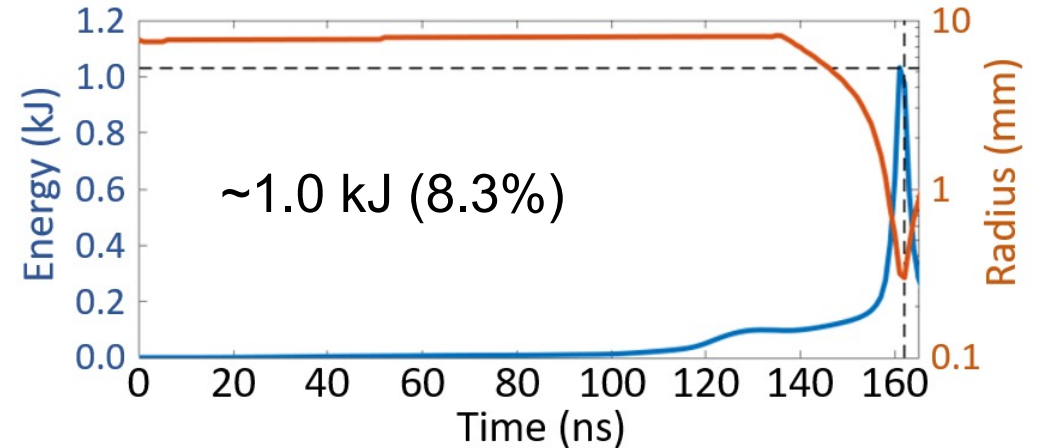
LTDs are a promising driver technology

- Linear Transformer Drivers are a new pulsed power generator architecture
- Short rise time (≤ 200 ns):
- High energy efficiency into gas puff loads
- Compact: high shot rate, parameter scans and model validation, develop diagnostics and loads
- How well can fast LTDs drive Z-pinches? Compression, energy coupling, yield...

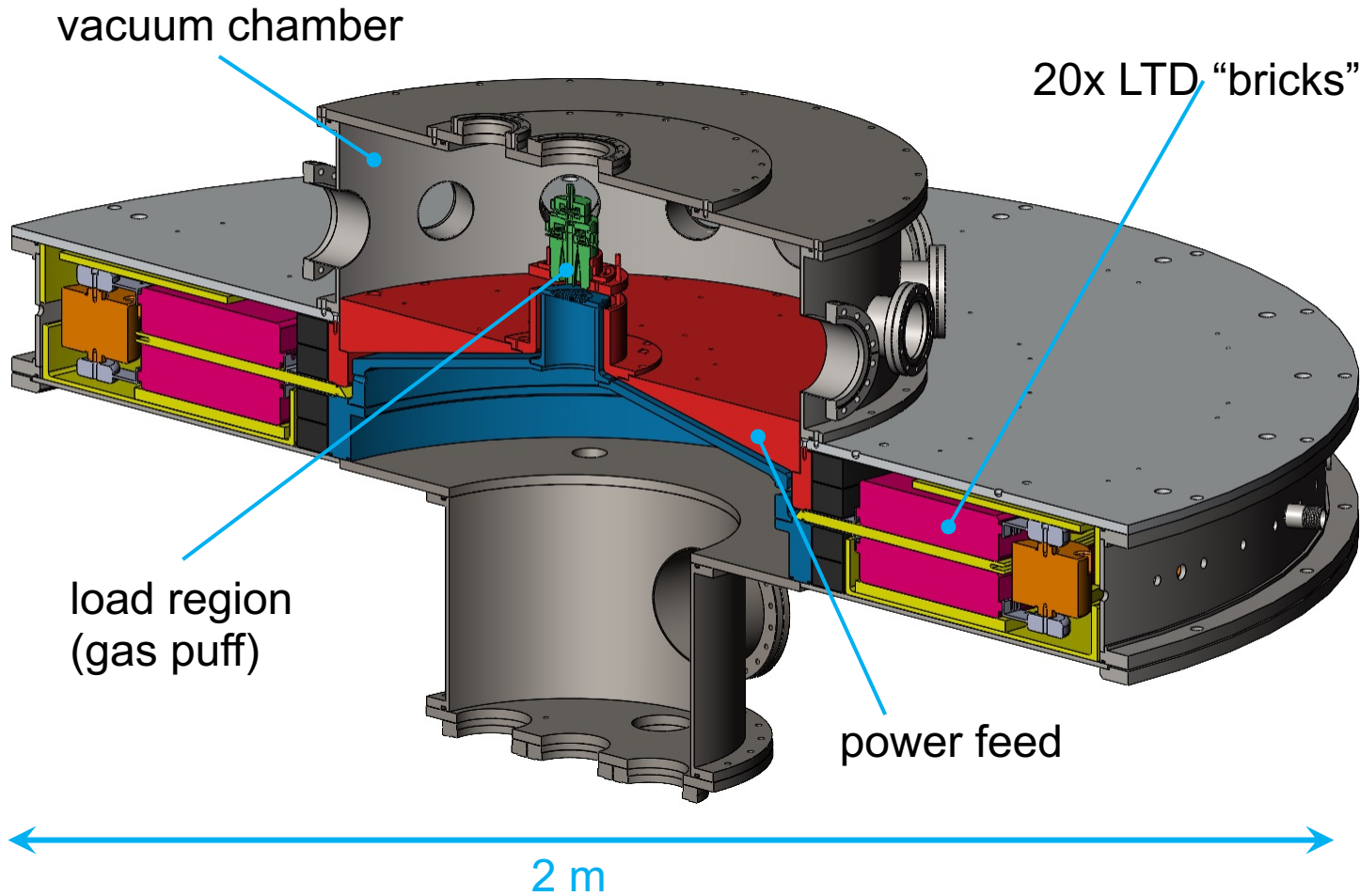
LTD
12 kJ
0.8 MA
150 ns

Marx
~130 kJ
1.0 MA
100 ns

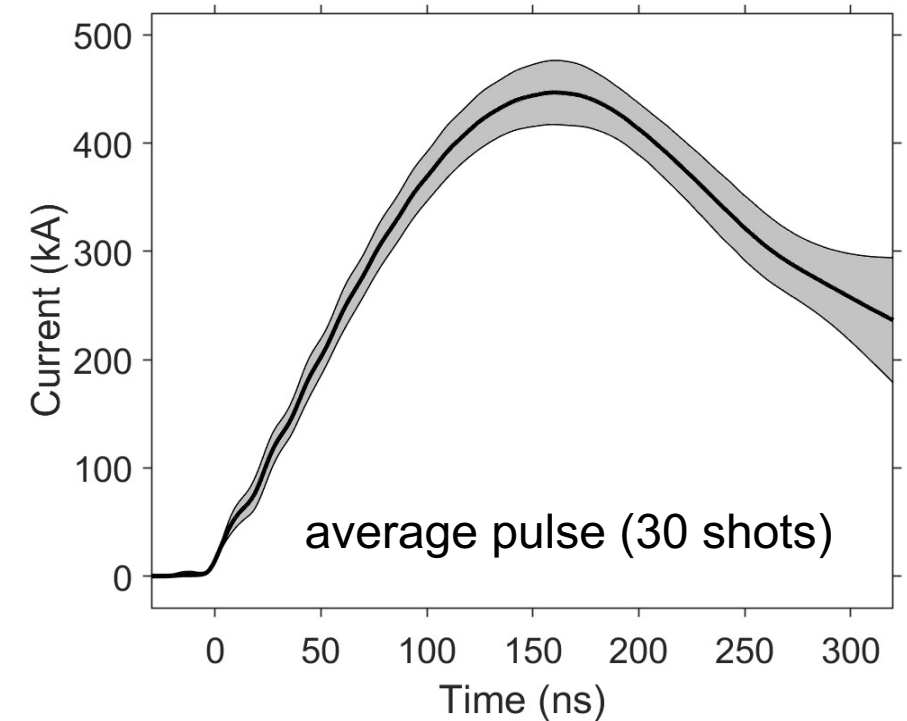
Target internal energy for shell-on-target gas puff Z-pinch (MACH2 simulations)



CESZAR is a compact 500 kA, 160 ns LTD

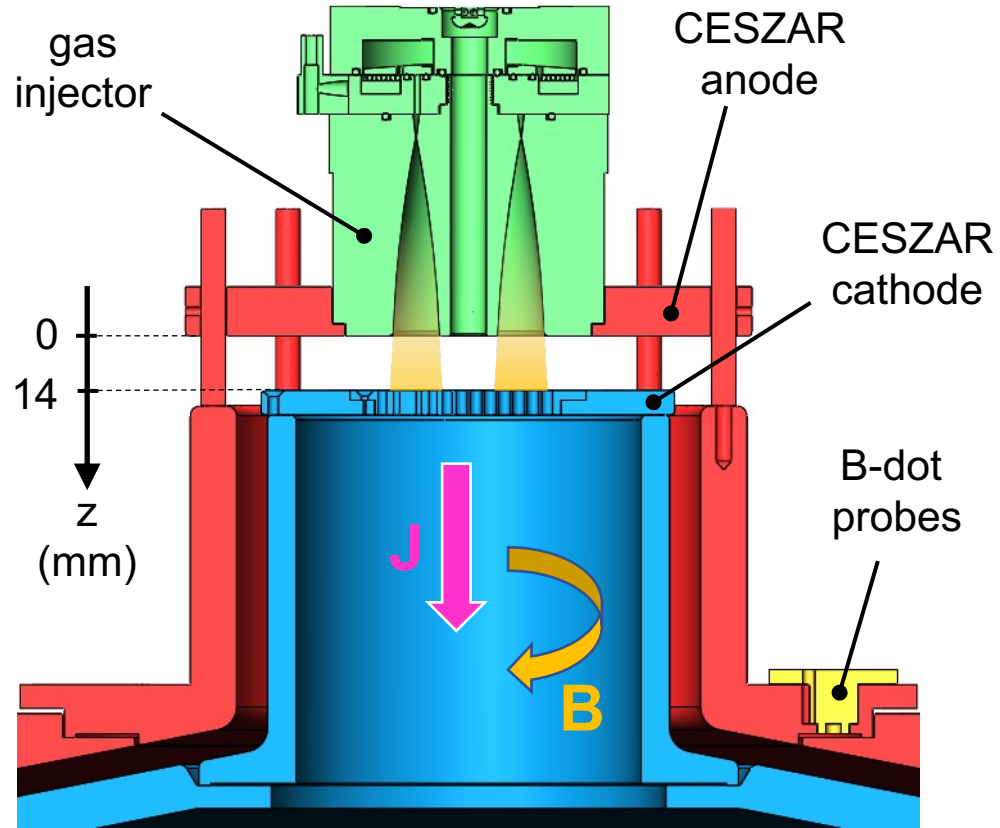


Max ~800 kA at ± 100 kV
now operating at 500 kA
4.2 kJ stored at ± 60 kV



Conti et al., *Phys. Rev. Accel. Beams* **23**, 090401 (2020)

First gas puff Z-pinch experiments on fast LTD

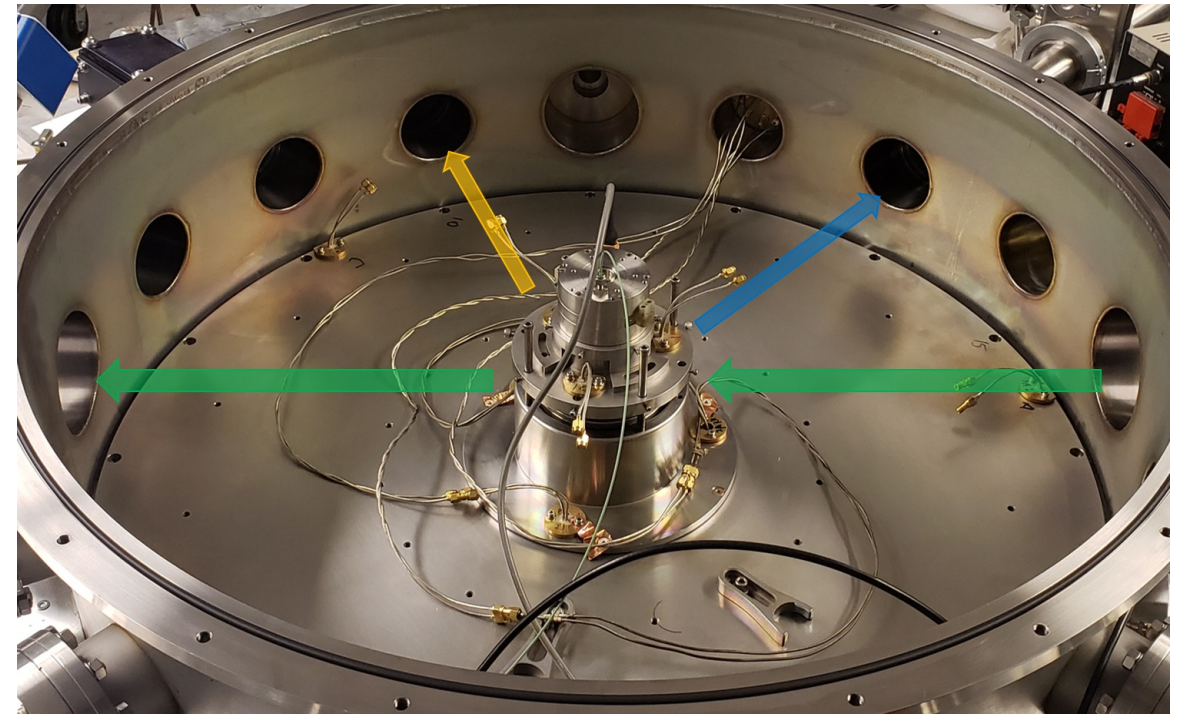


Single, hollow gas shell ($R_0 = 1.3$ cm)
Ar and Ne with similar initial mass

Laser schlieren imaging (2 frames/shot)

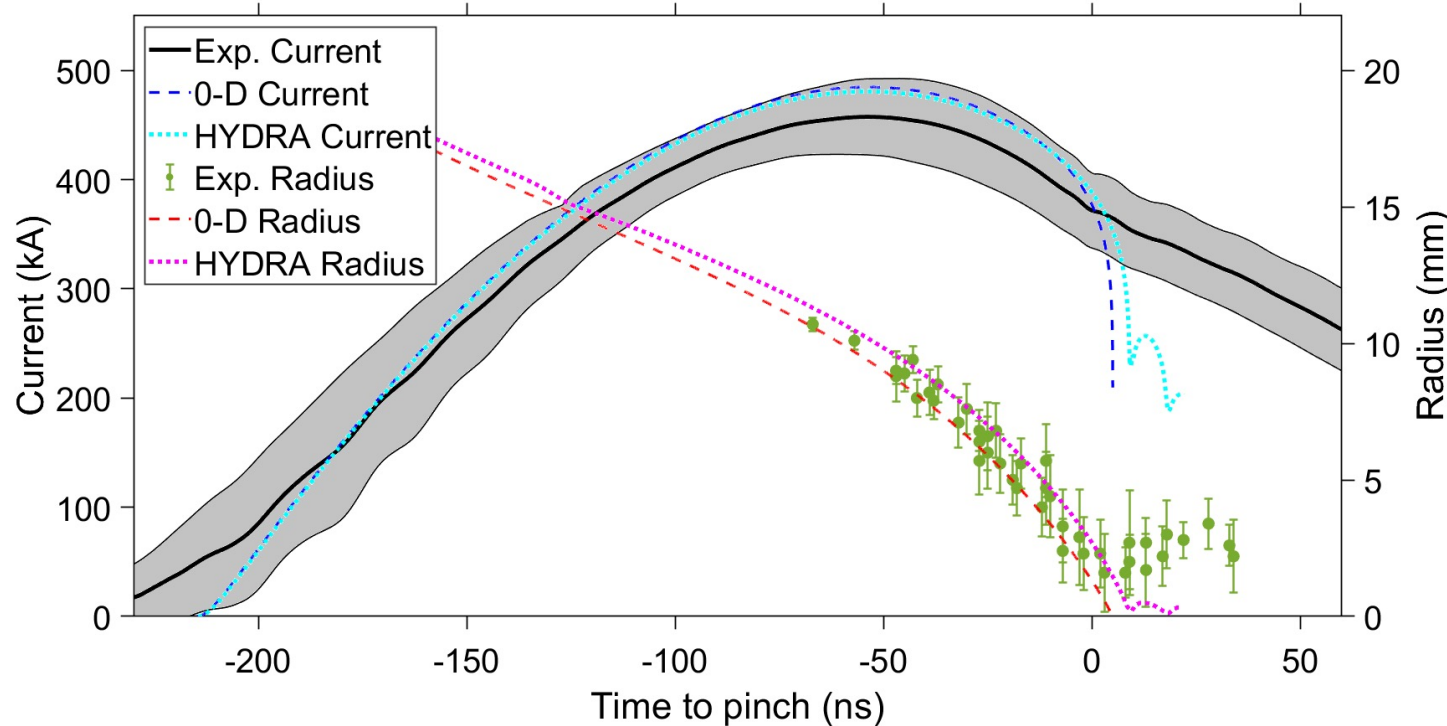
XUV framing camera (4 frames/shot)

Soft X-rays photodiodes



Implosion is consistent with models except near stagnation

Current and radius with time relative to X-ray time ($t=0$)



- Run-in phase compares well with 0-D model and 1-D HYDRA with adjusted initial radius/mass
- $V_r = 200 \pm 20$ km/s
 $E_{\text{kin}} = 300 \pm 50$ J
- $\langle R_{\text{min}} \rangle = 1.5$ mm (CR~9)
- Near stagnation, small current dip means that current flows at larger radius than pinch

- ~7% of capacitor stored energy is coupled into kinetic energy
- Compression may be improved by reducing current shunting

F. Conti et al., J. Appl. Phys. **130**, 023301 (2021)

Argon and neon gas puffs show different dynamics

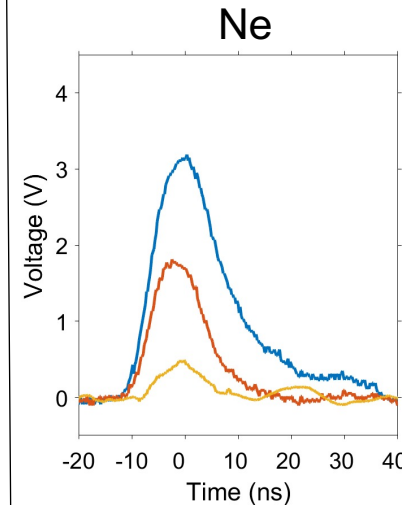
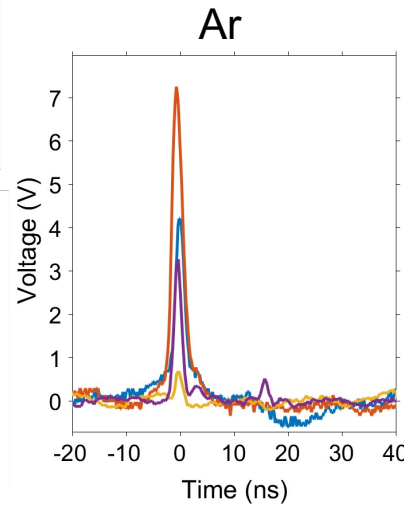
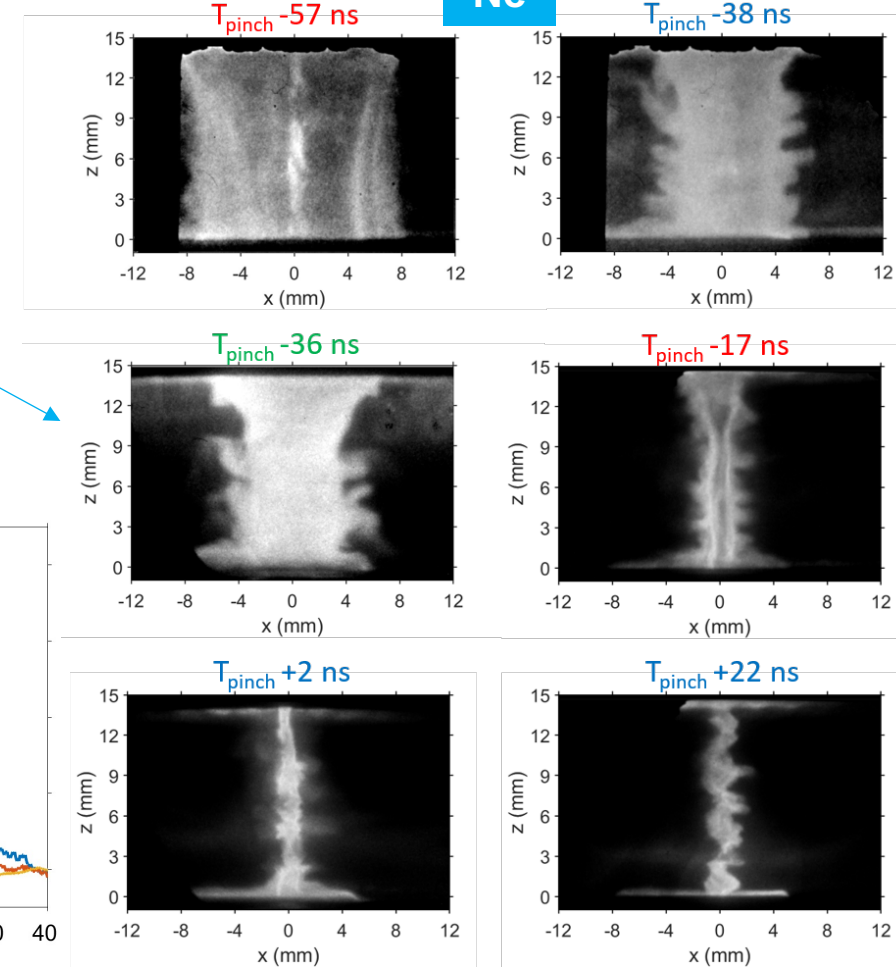
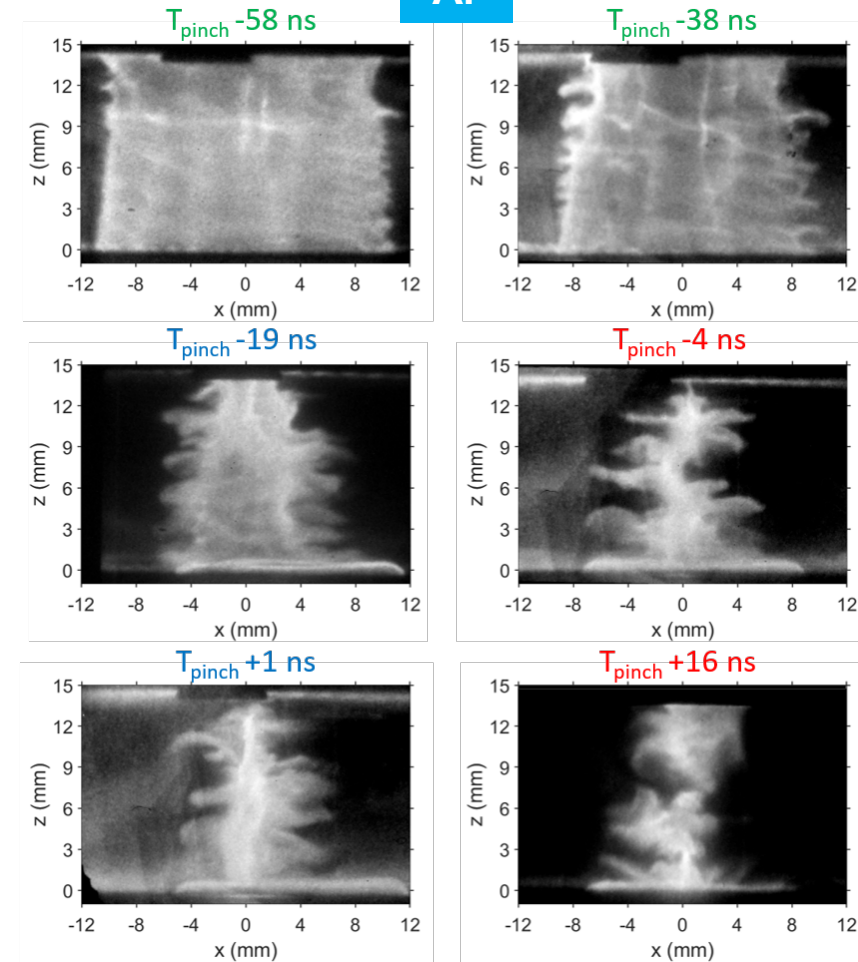
F. Conti et al., J. Appl. Phys. **130**, 023301 (2021)

Ar

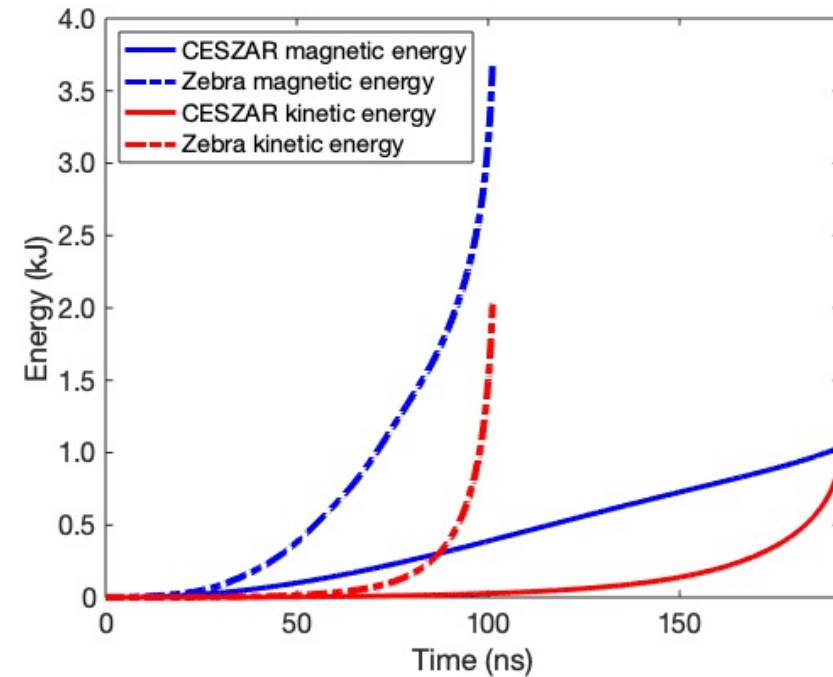
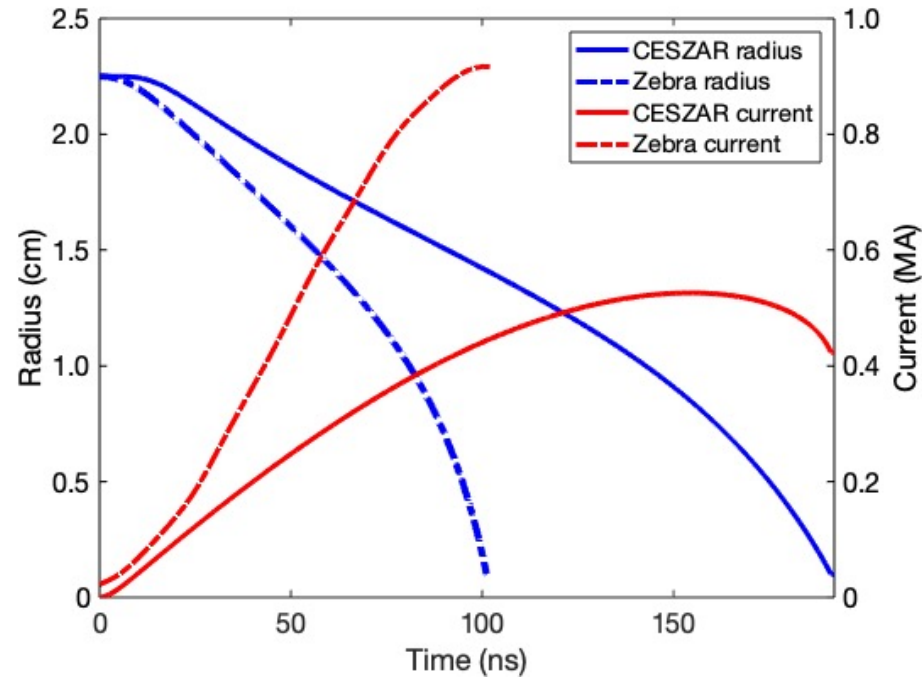
Ne

Ar has large instability
and sharp X-ray emission
 $\tau=2-5$ ns, $Y_K=0.2-0.5$ J

Ne is more stable with
longer X-ray emission
 $\tau=12-25$ ns, $Y_K=2.2-3.9$ J



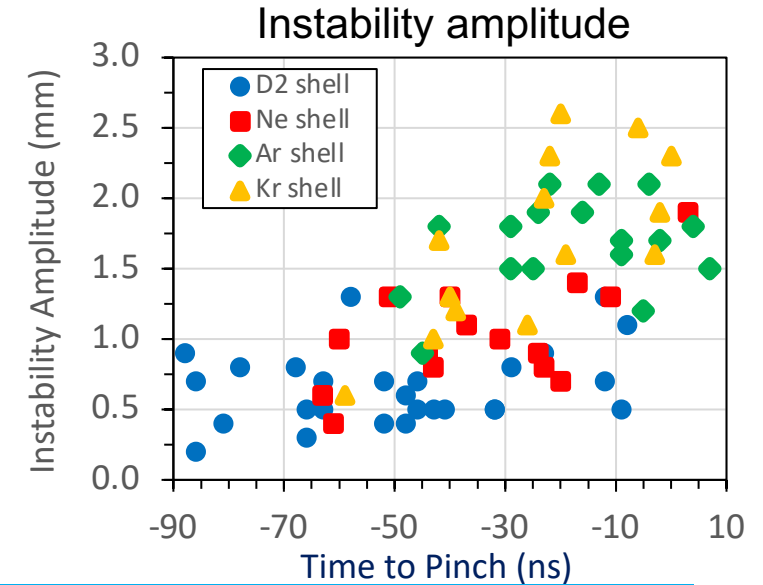
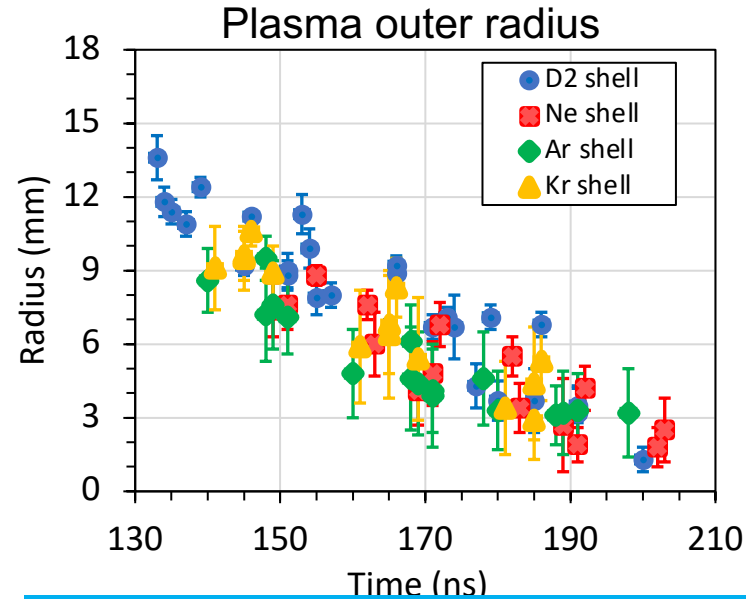
Energy coupling efficiency to load increases by an order of magnitude from traditional Marx-bank drivers to LTDs



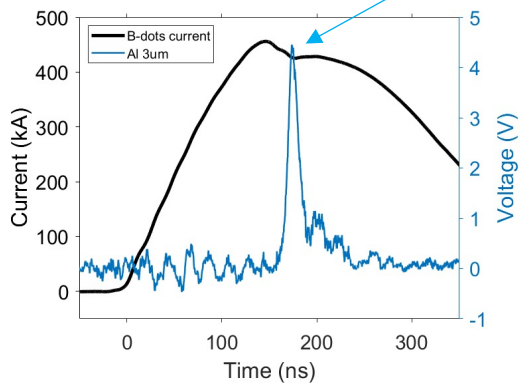
Driver	Stored Energy	Peak Current	Implosion time	JxB Energy	Kinetic Energy (EXP)	Kinetic Energy (SIM)
Zebra (Marx)	133 kJ	0.98 MA	~110 ns	3.7 kJ	1.1 kJ (0.8%)	2.8 kJ (2.1%)
CESZAR (LTD)	4.18 kJ	0.47 MA	~200 ns	1.0 kJ	0.3 kJ (7%)	0.65 kJ (15%)

Shell-on-target pinches have better machine matching and reproducibility

- Better repeatability of implosion trajectory
- Lower mass allowed in the shell due to center jet facilitating breakdown
- Improved machine coupling earlier pinch, inductive notch

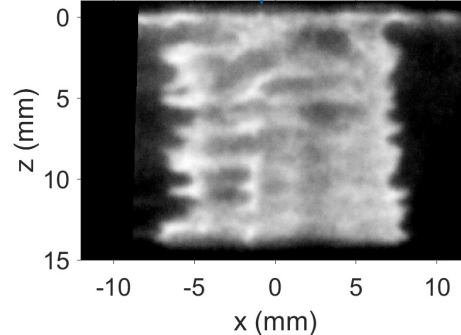


Instability amplitude increases with liner atomic number

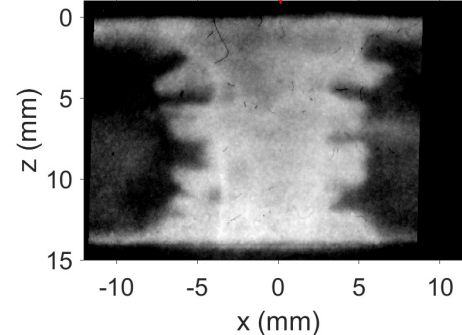


No B_z

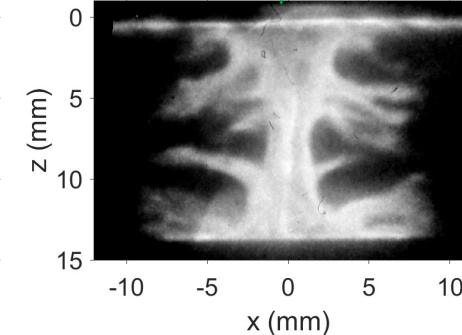
D_2/D_2 T_{pinch} -32ns



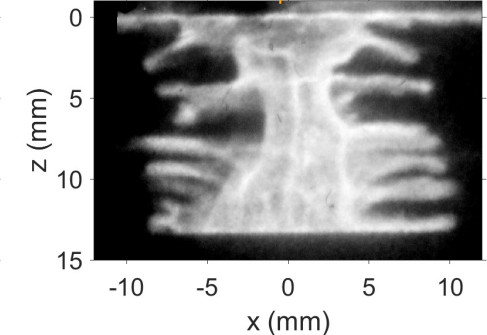
Ne/D_2 T_{pinch} -33ns



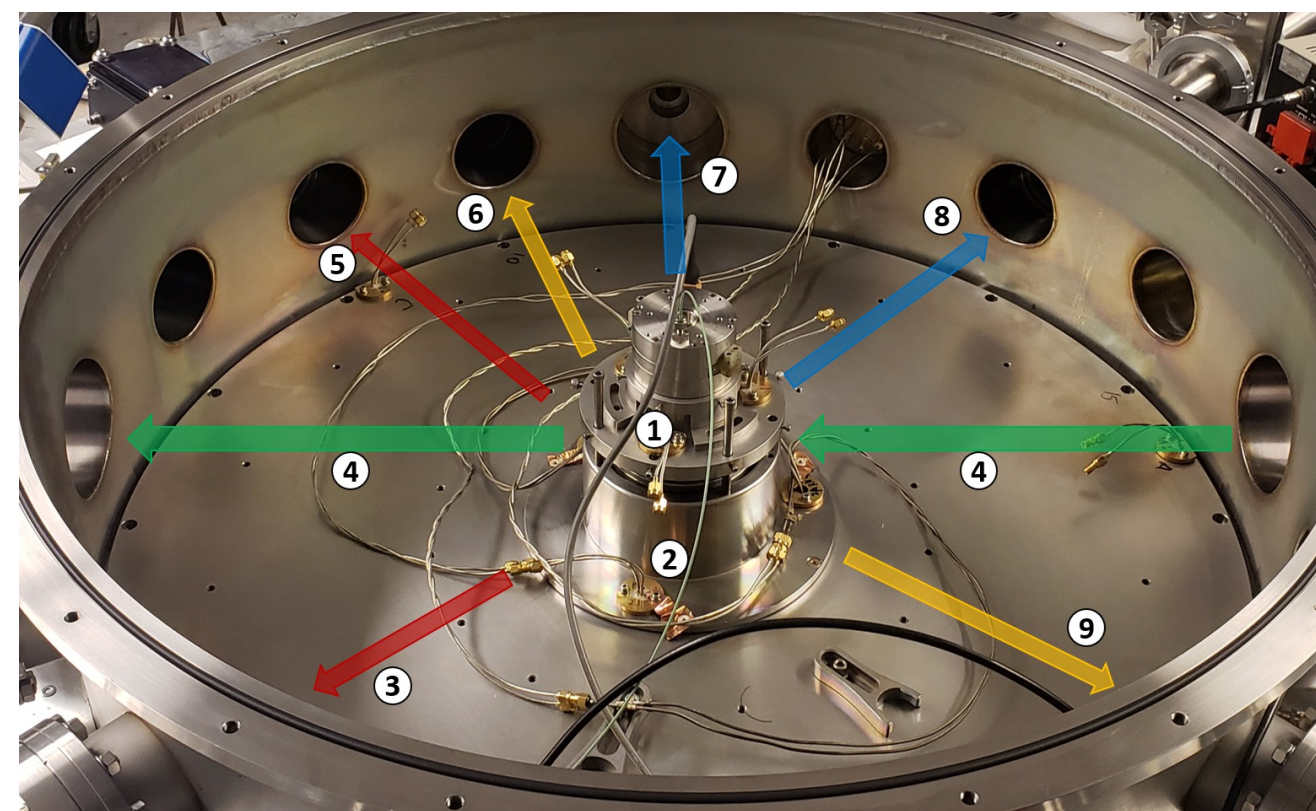
Ar/D_2 T_{pinch} -29ns



Kr/D_2 T_{pinch} -29ns

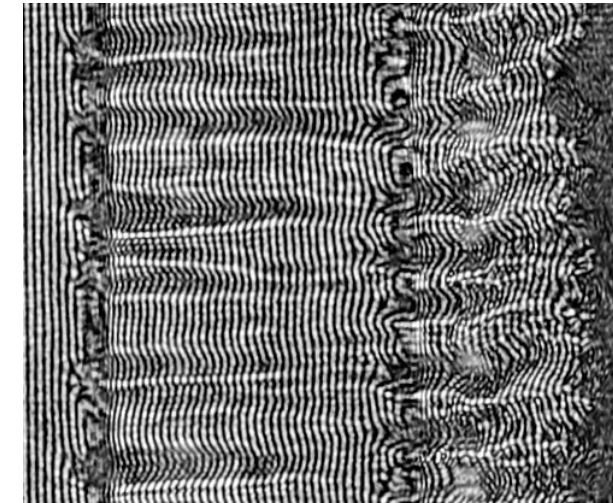


Implementing a variety of diagnostics



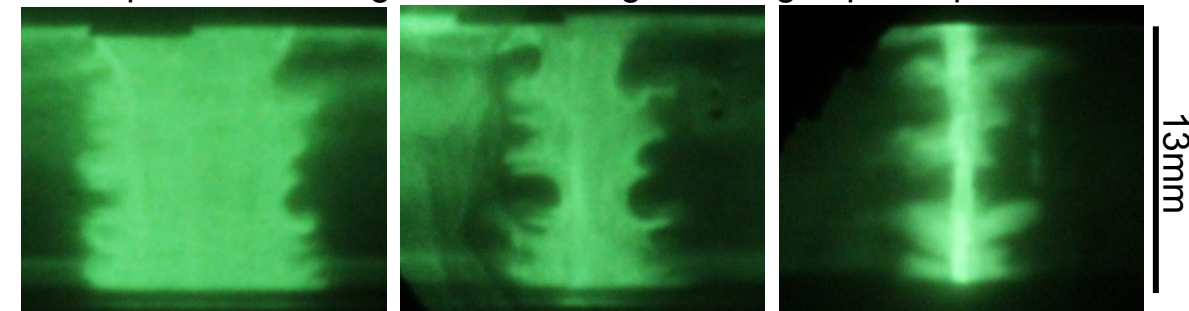
- | | | |
|------------------------------------|---|----------------------------------|
| 1) Load | 5) Mica spectrometer | 8) Time-gated XUV pinhole camera |
| 2) B-dot probes | 6) Soft X-rays photodiodes | 9) Hard X-rays photodiodes |
| 3) Time-gated visible spectrometer | 7) Time-integrated X-ray pinhole camera | |
| 4) Probing laser | | |

laser interferogram of wire array Z-pinch



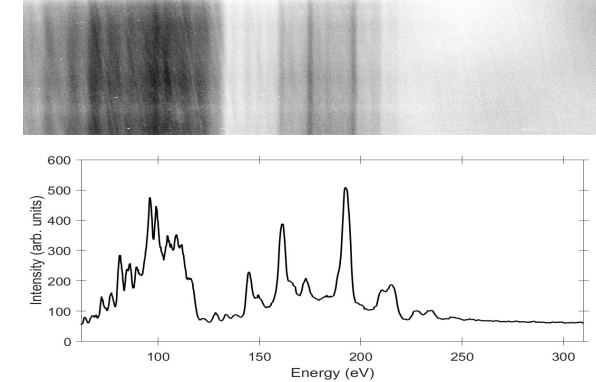
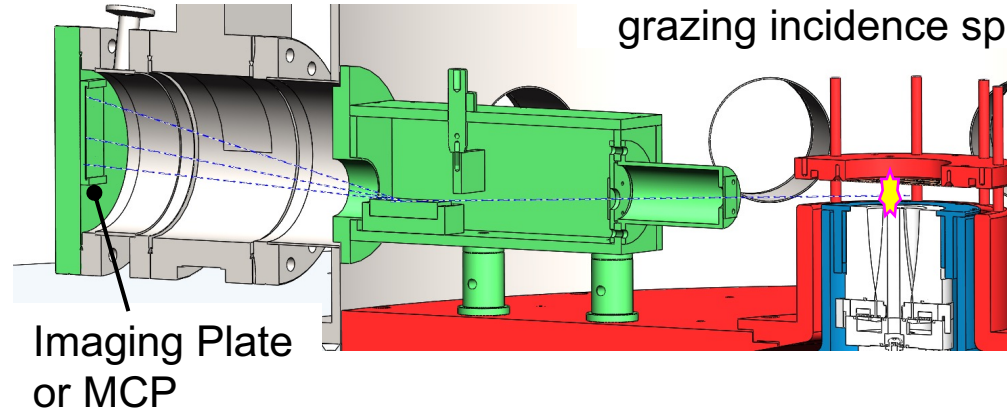
5mm

sequence of time-gated XUV images from gas puff Z-pinch



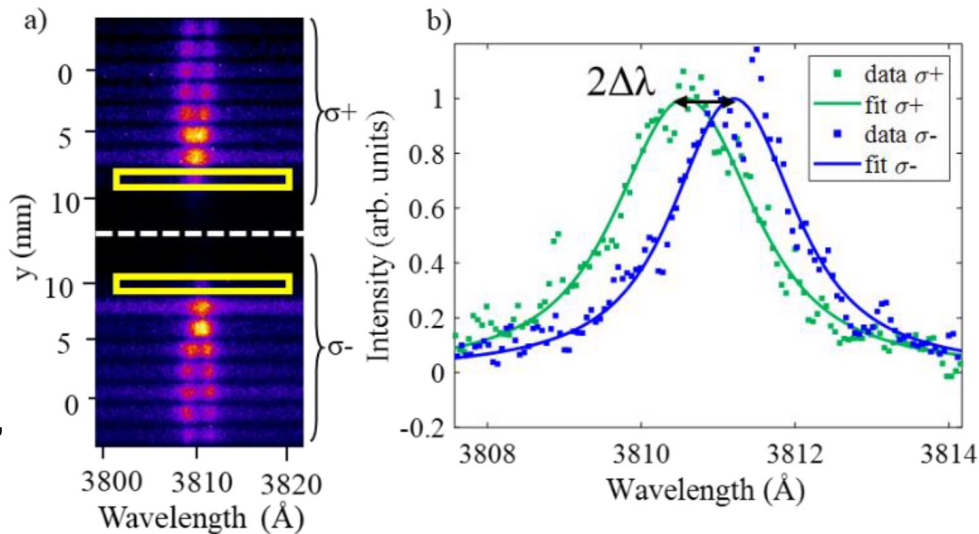
Expanding available diagnostics

XUV / Soft X-ray spectroscopy

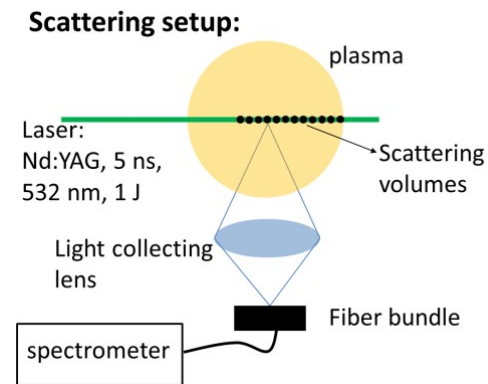


Zeeman polarization spectroscopy

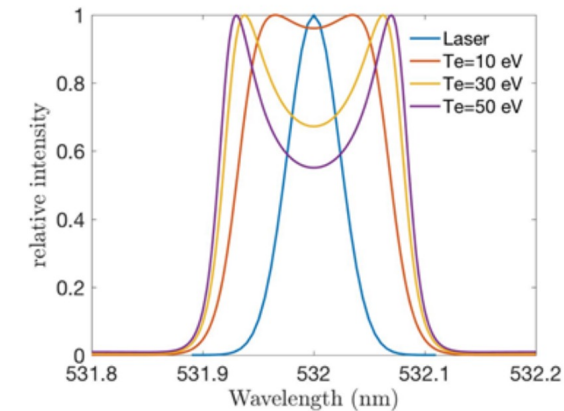
N. Aybar et al,
submitted to
IEEE TPS
(2022)



Thomson scattering



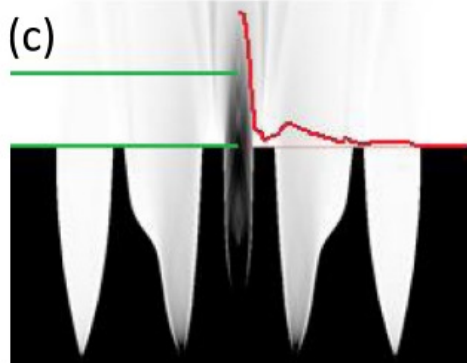
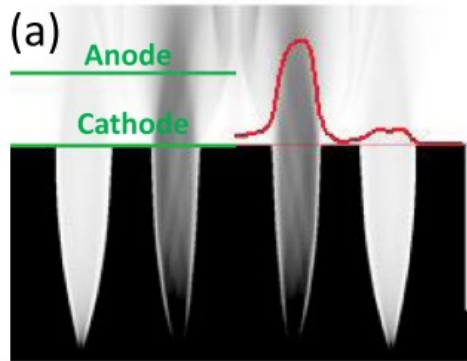
Synthetic IAW spectra ($T_i=50$ eV, $N_i=10^{18}$ cm $^{-3}$,



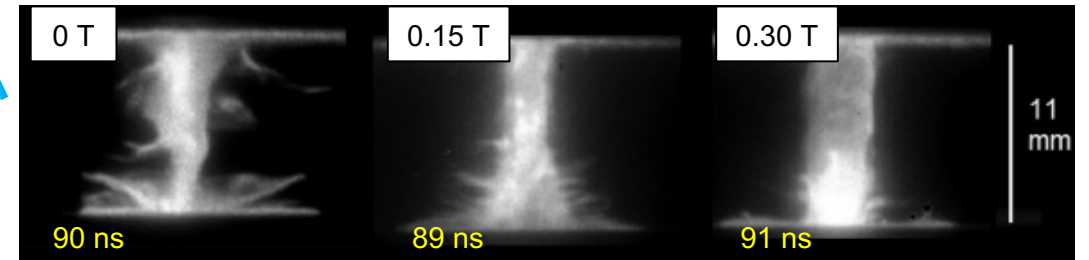
Combining MRTI mitigation techniques can improve compression in MHD simulations

- The magneto-Rayleigh-Taylor instability (MRTI) is ubiquitous in gas-puff Z-pinches
- Two successful approaches to MRTI mitigation are B_{z0} and density tailoring

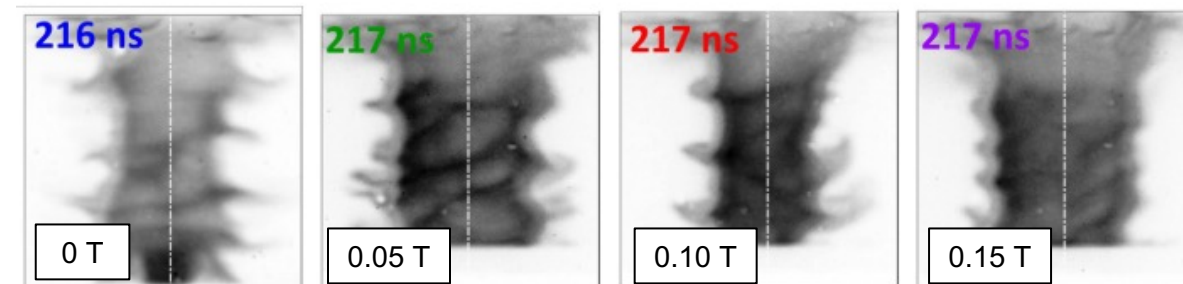
$$\gamma_{MRT}^2 = gk - \frac{(\mathbf{k} \cdot \mathbf{B})^2}{\mu_0 \rho} + C(kR)$$



Adapted from C. Jennings et al.,
Phys. Plasmas **22**, 056316 (2015)

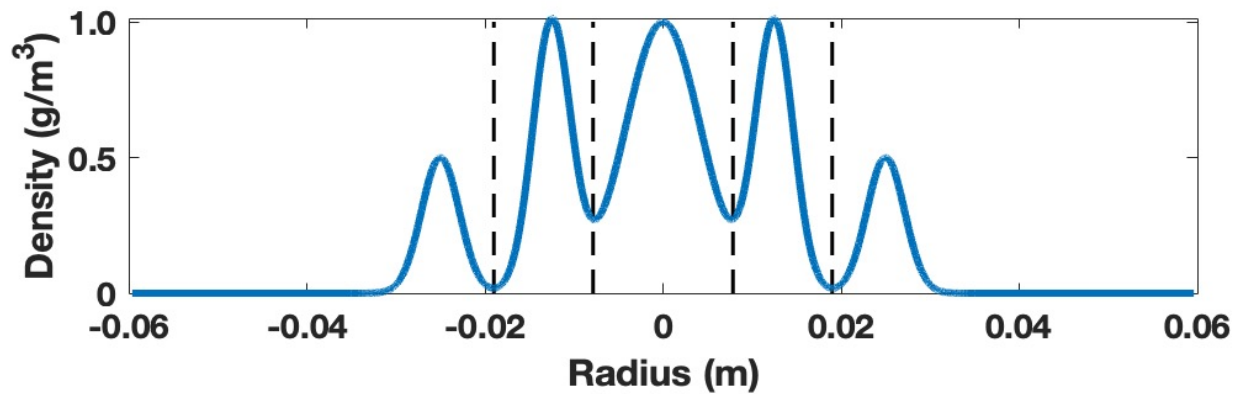
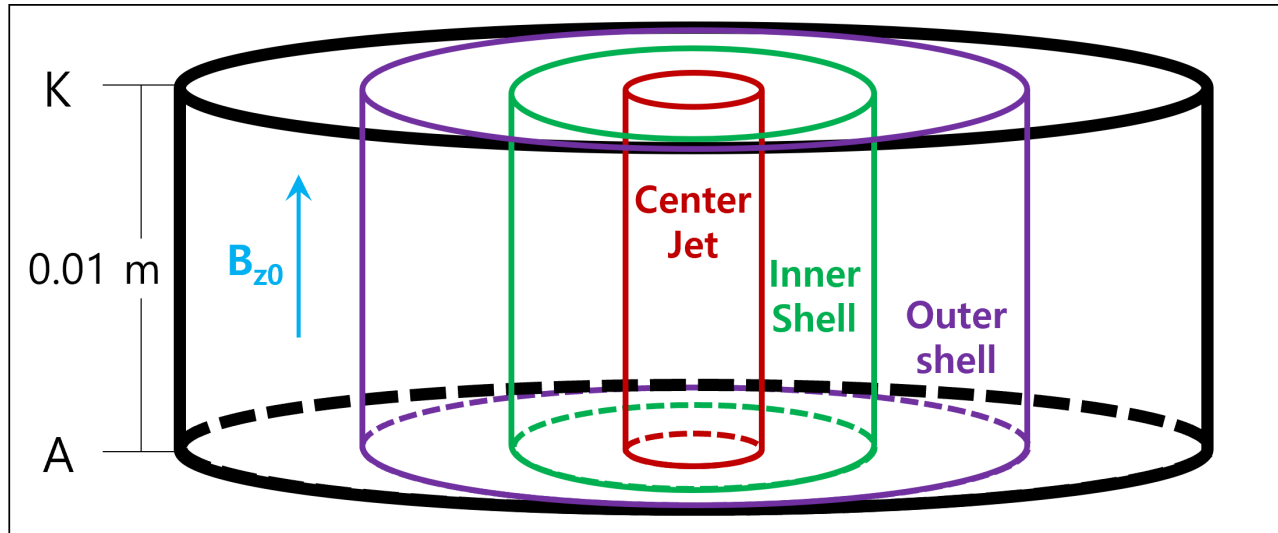


Adapted from F. Conti et al., Phys. Plasmas **27**, 012702 (2020)



Adapted from E. Lavine et al., Phys. Plasmas **28**, 022703 (2021)

Combining MRTI mitigation techniques improves compression



What B_{z0} is needed to stabilize:

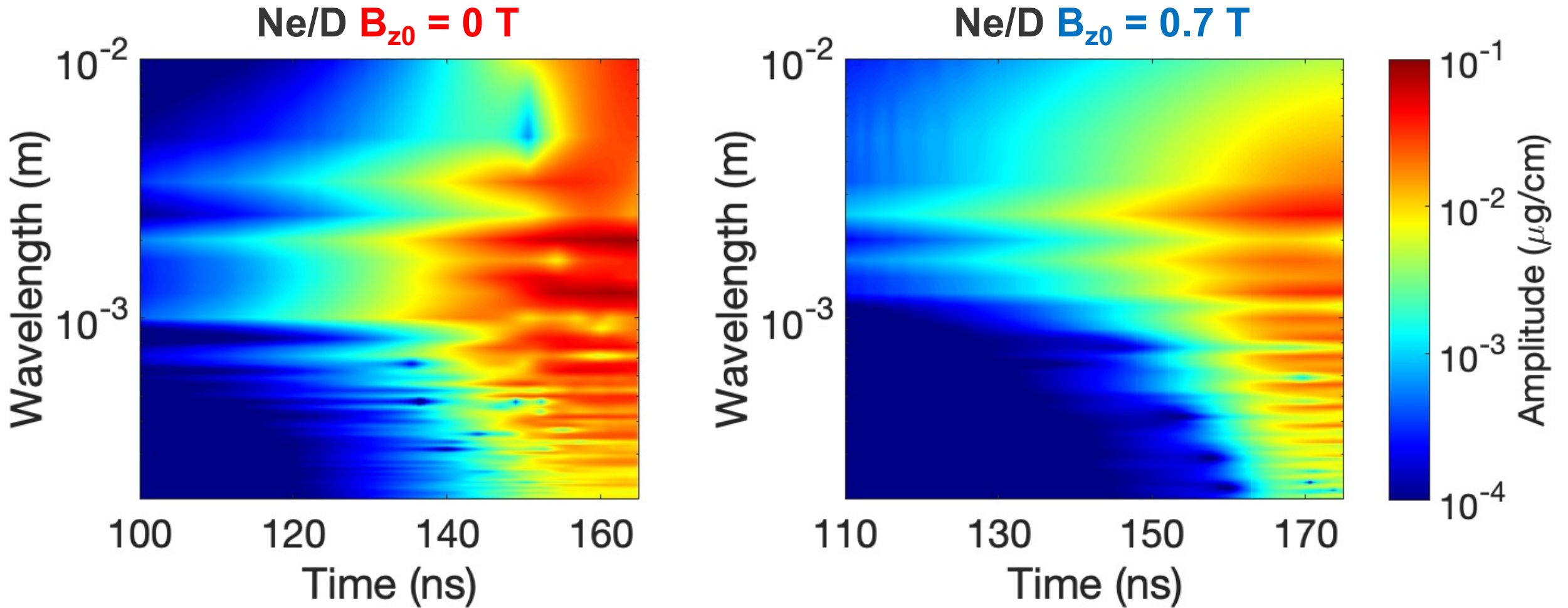
- Outer Shell + Center Jet
- Outer Shell + Inner shell + Center Jet

Setup:

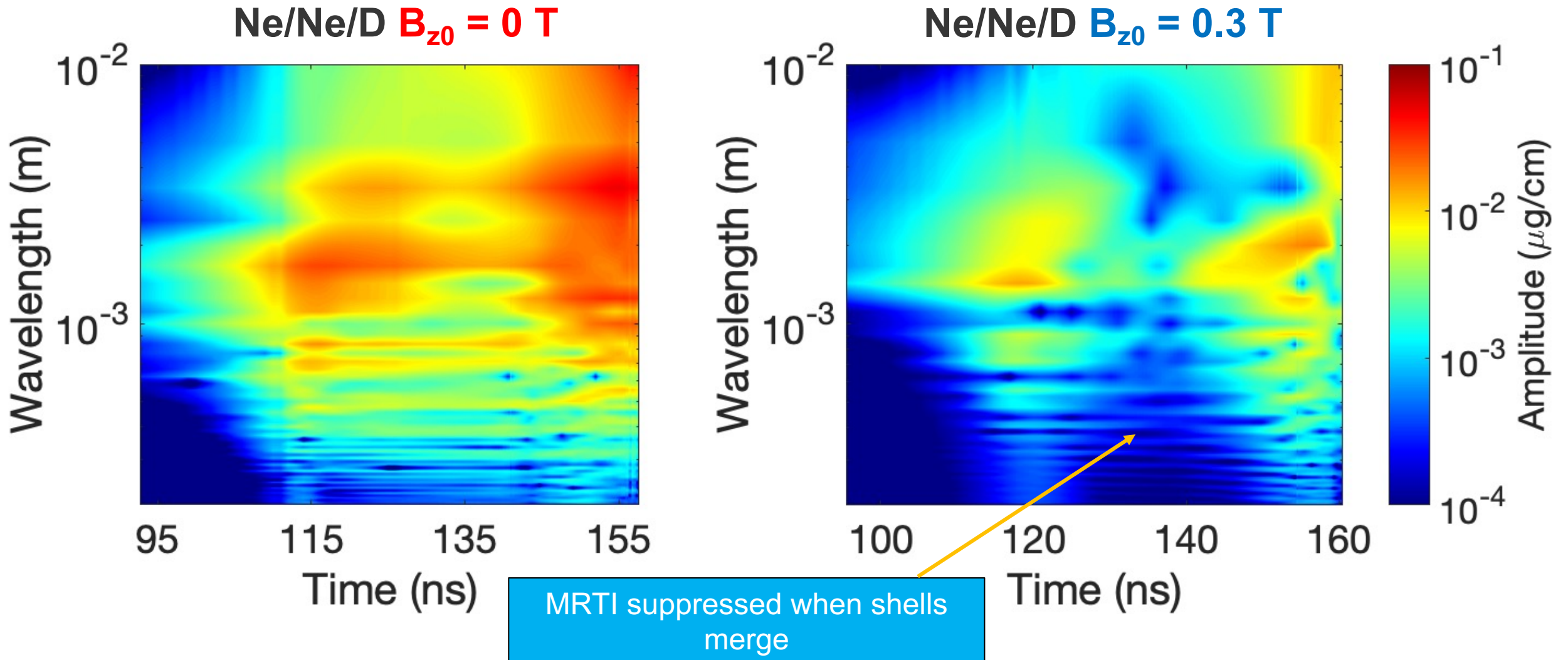
- $I_{pk}=850$ kA, $T_{1/4}=160$ ns (CESZAR @ UCSD)
- Outer: Ne, $R_0=2.5$ cm, $\rho_0=0.5$ or 1.0 $\mu\text{g/cc}$
- Inner: Ne, $R_0=1.25$ cm, $\rho_0=0.5$ $\mu\text{g/cc}$
- Center: D, $R_0=0$ cm, $\rho_0=1.0$ $\mu\text{g/cc}$

J. Narkis et al, Phys. Rev. E **104**, L023201 (2021)

2-D HYDRA shows growth of single-shell on jet gas puff is reduced with $B_{z0}=0.7$ T

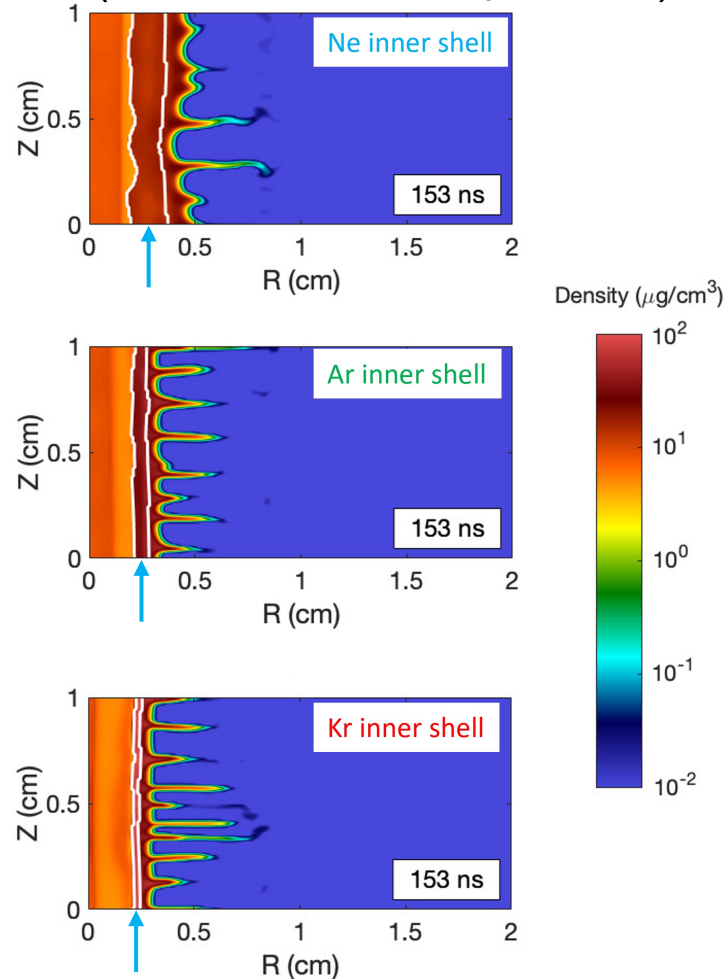


For double-shell on jet, required field is just 0.3 T

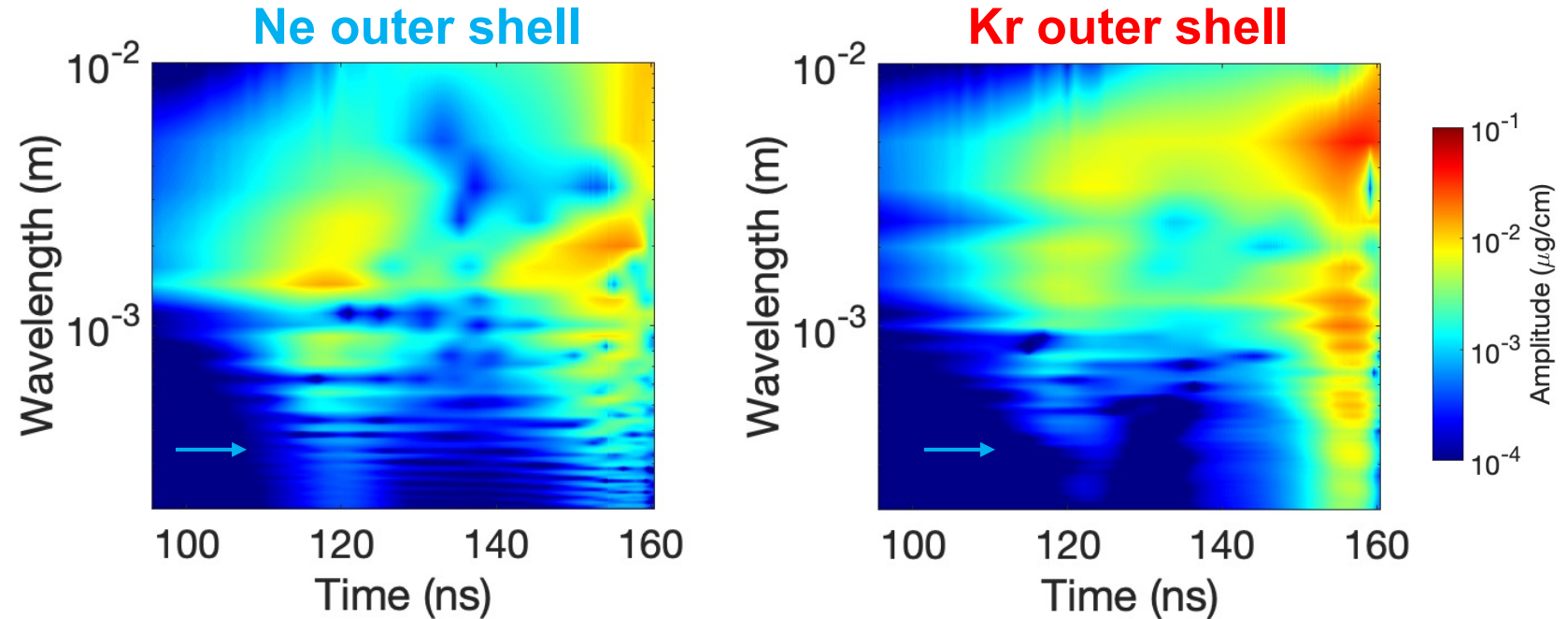


Increasing the gas Z can reduce instability growth when B_z is used

Varying inner shell
(Ne outer shell, $B_{z0} = 0.3$ T)



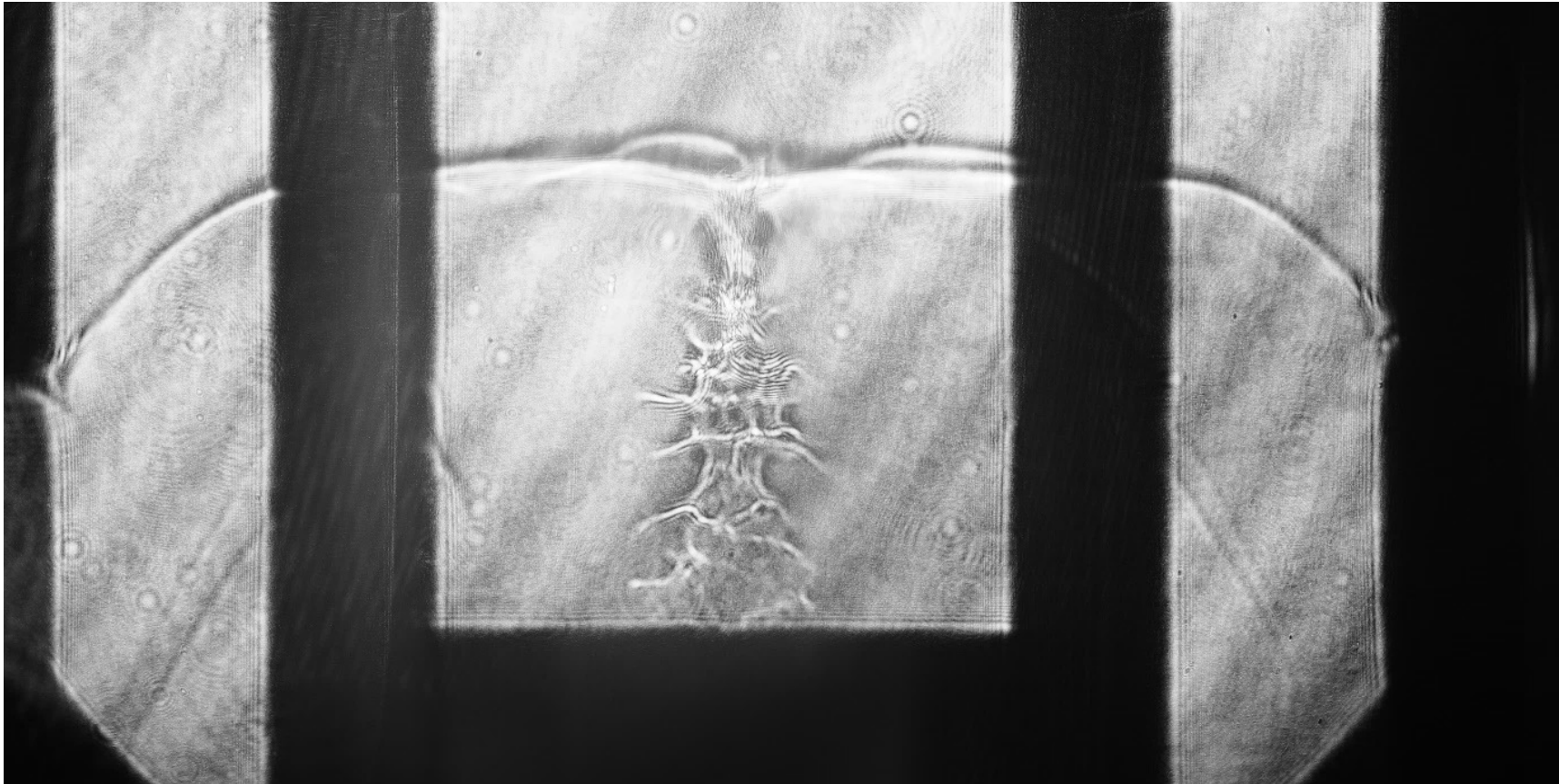
Varying outer shell
(Ne inner shell, $B_{z0} = 0.3$ T)



Increased compression from higher Z material (Kr)
→ increased B_z field-line tension, reduced MRTI growth

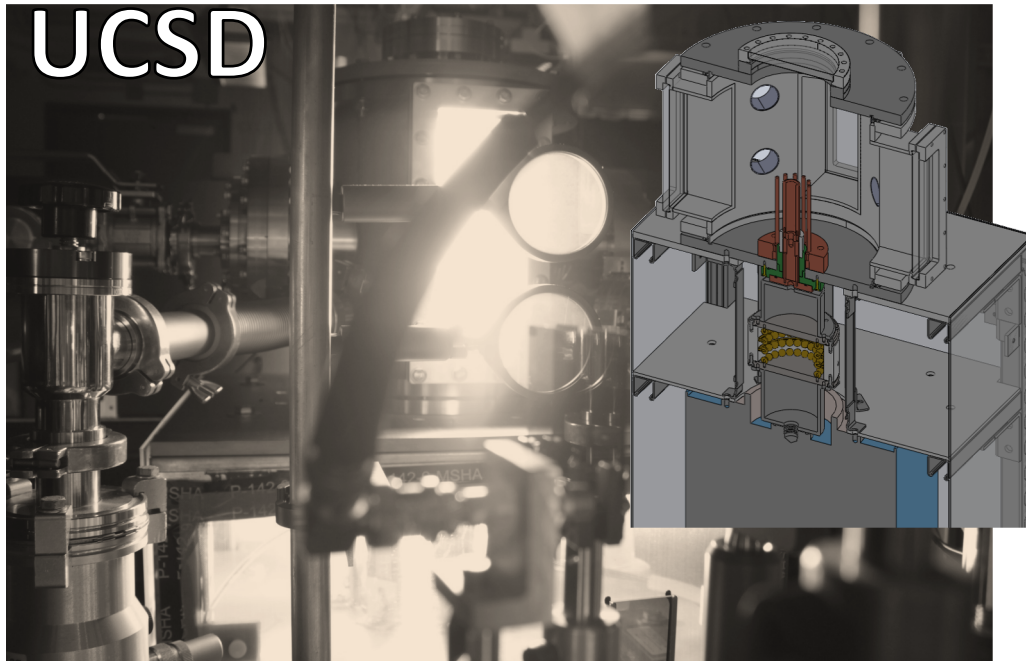
J. Narkis et al., PRE (under review)

Dense Plasma Focus

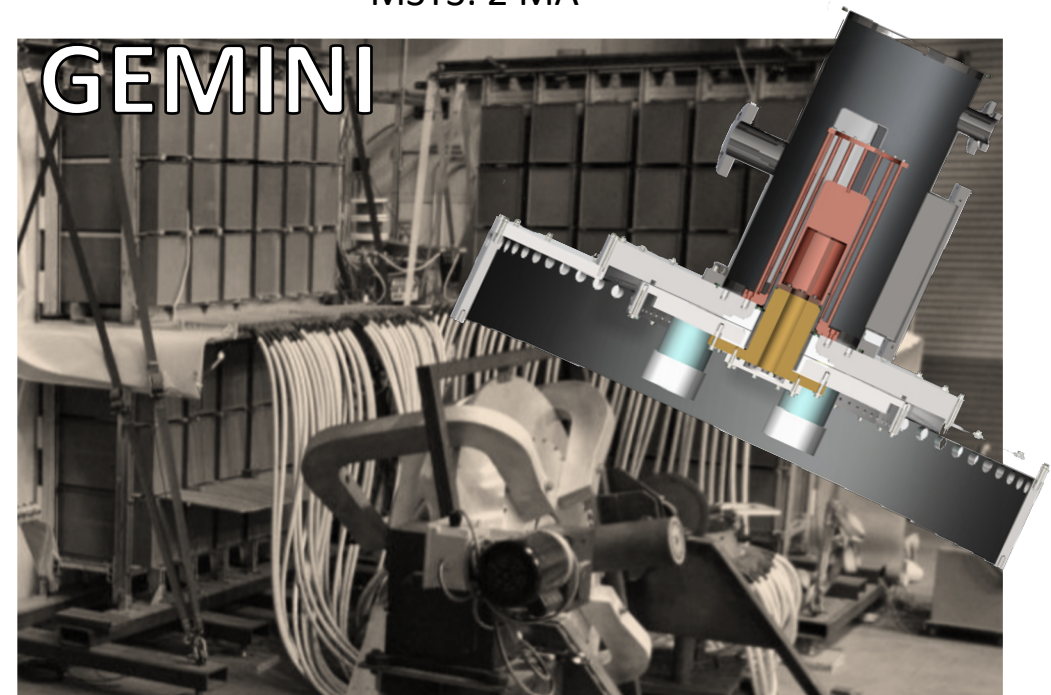


Dense Plasma Focus

UCSD: 300 kA



MSTS: 2 MA

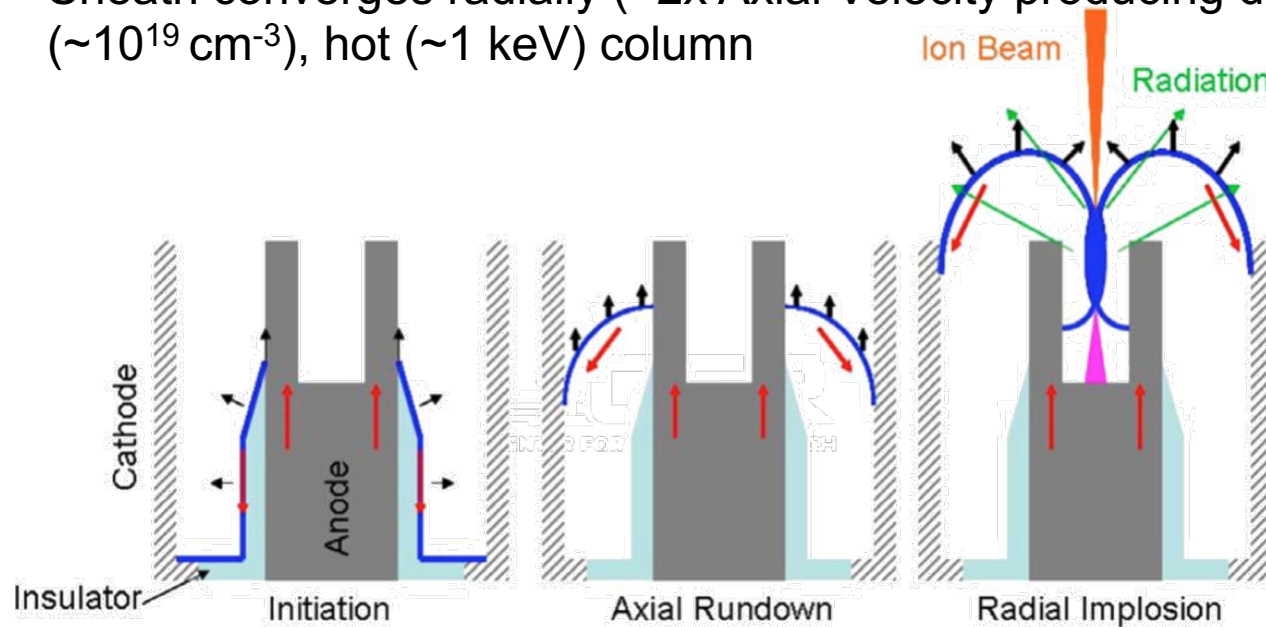


This work was performed with the support of the Air Force Office of Scientific Research

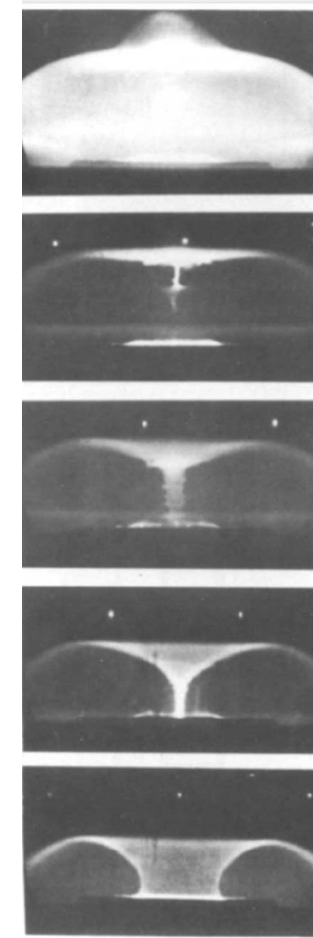
AFOSR FA9550-18-S-0003

Dynamics of the DPF

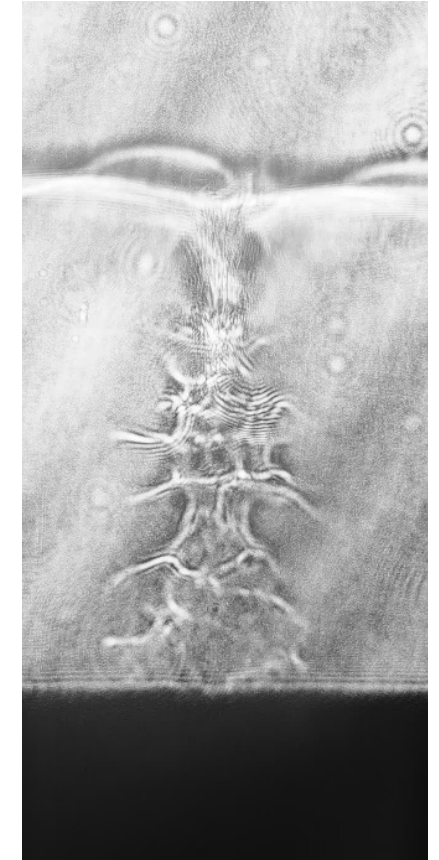
- Two coaxial electrodes with a capacitive driver to induce a voltage
- Insulator flashes over (breakdown) and forms a current sheath due to Lorentz ($\mathbf{J} \times \mathbf{B}$) force
- Plasma sheath snowplows background gas ($\sim 20\text{-}100\text{ km/s}$)
- Sheath converges radially ($\sim 2 \times$ Axial Velocity) producing dense ($\sim 10^{19}\text{ cm}^{-3}$), hot ($\sim 1\text{ keV}$) column



M. Krishnan, "The dense plasma focus: A versatile dense pinch for diverse applications," 2012.

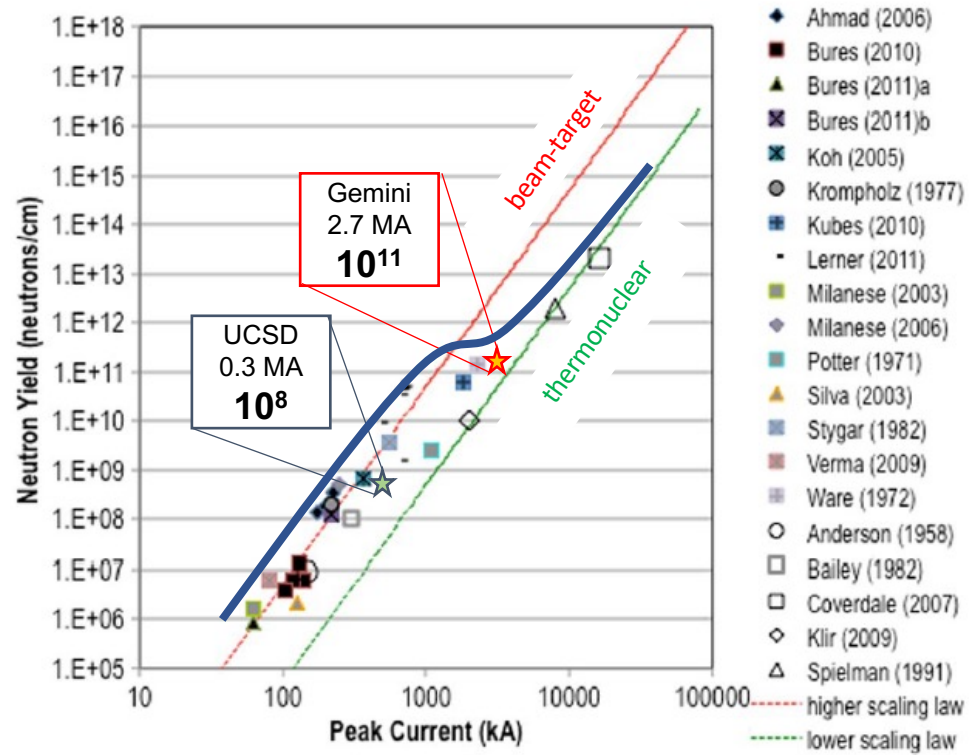


A. Bernard et al "The dense plasma focus - a high intensity neutron source," 1977.

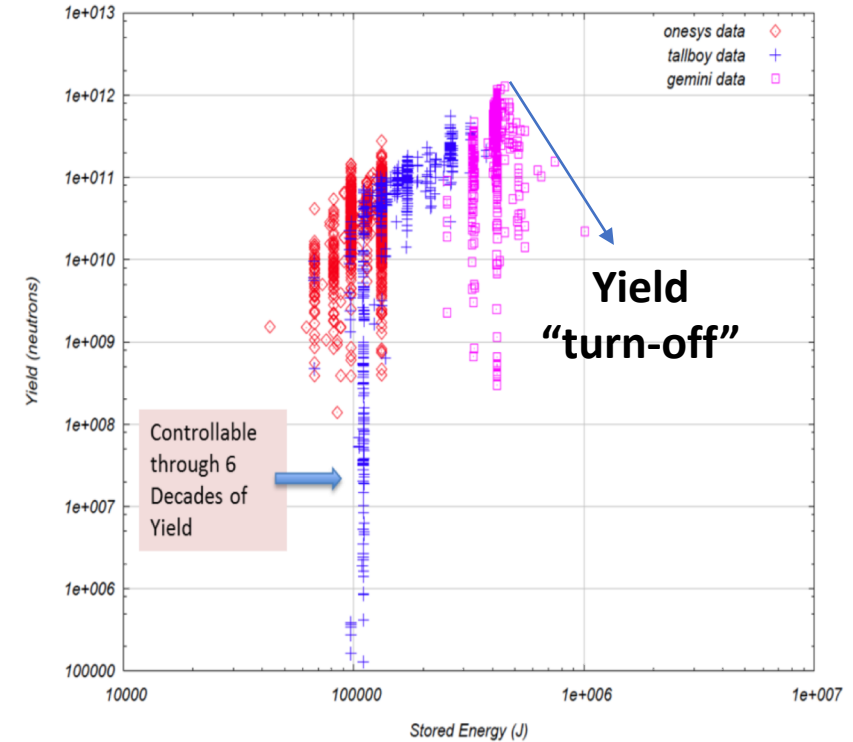


UCSD DPF
0.6 torr Ne

Scalability of DPF related to active neutron mechanism

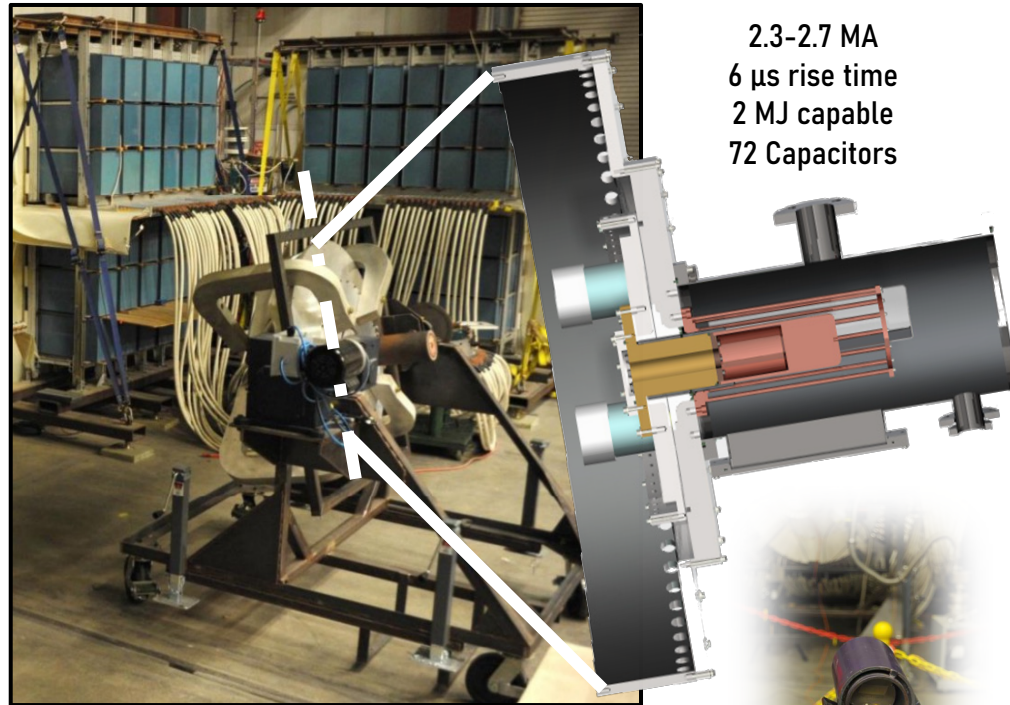


M. Krishnan, *IEEE Trans. Plasma Sci.* **40**, 3189 (2012)



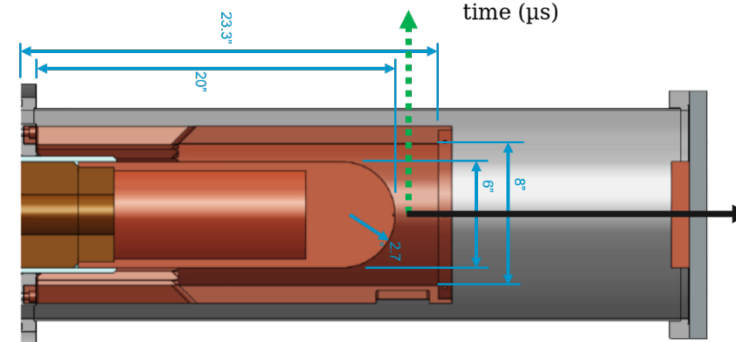
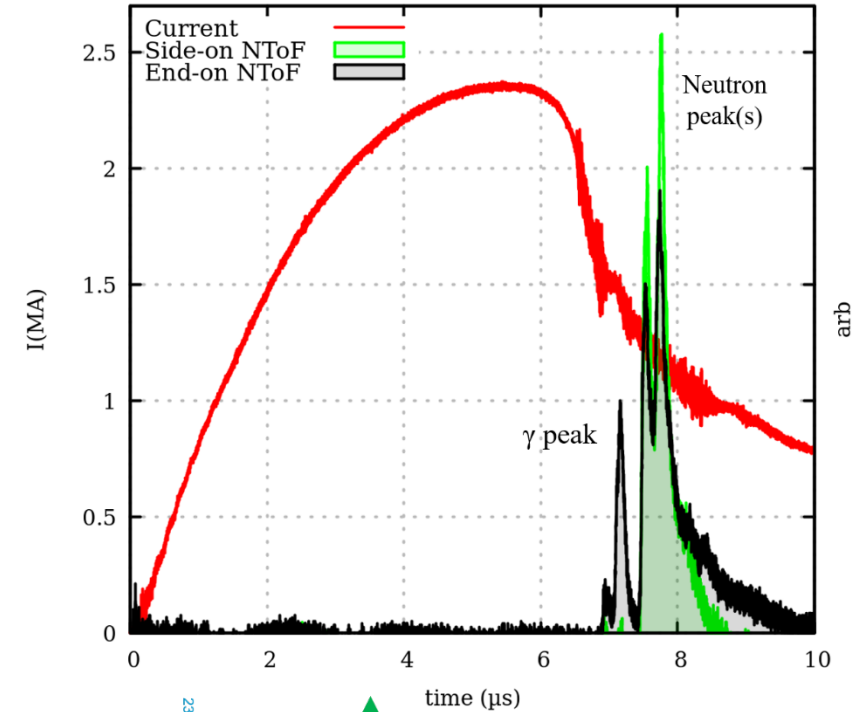
D. Lowe, DOE/NV/25946--2147

Experiments conducted on the GEMINI 2 MJ DPF to study admixtures effect on neutron yield



C. Hagen et al., Stockpile Stewardship Quarterly 4, 10 (2014)

NTOF array
Activation counter suite

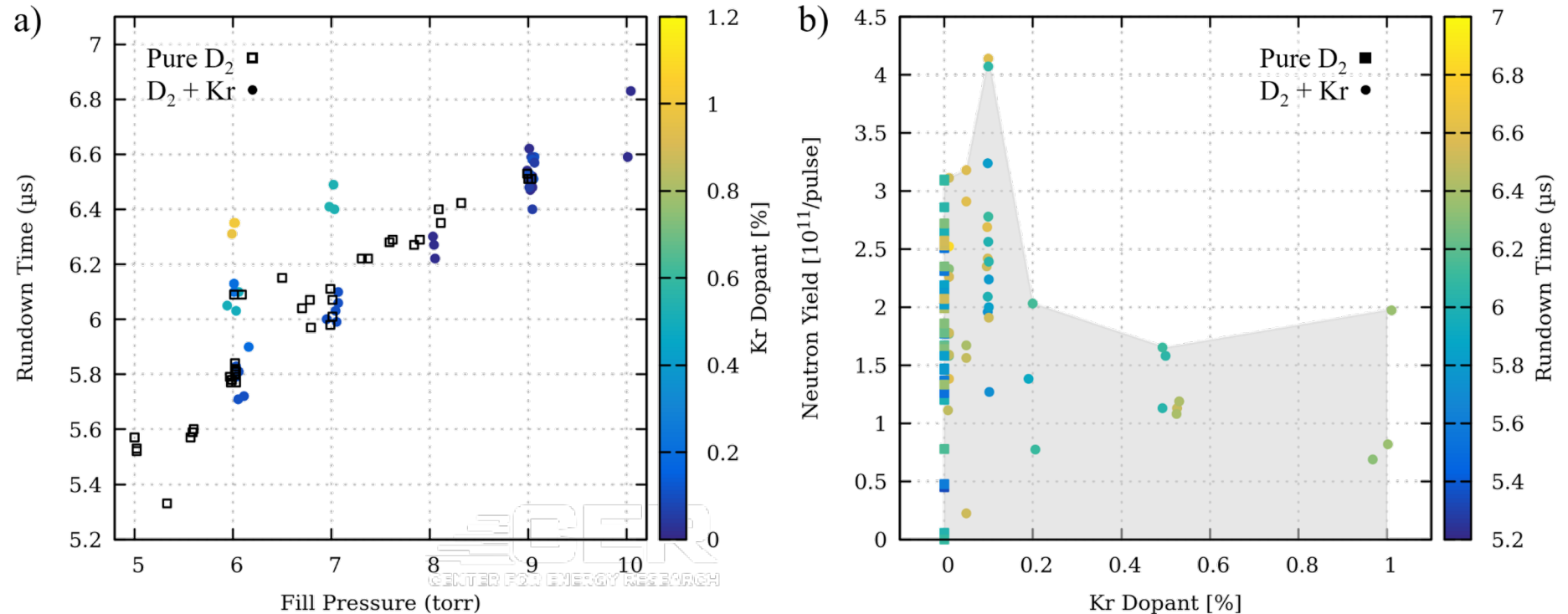


E. Hahn et al., J. Appl. Phys. **128**, 143302 (2020)

Effect of Kr dopant was studied on neutron yield

- Scanned different rundown times and fill pressures to empower statistical analysis.

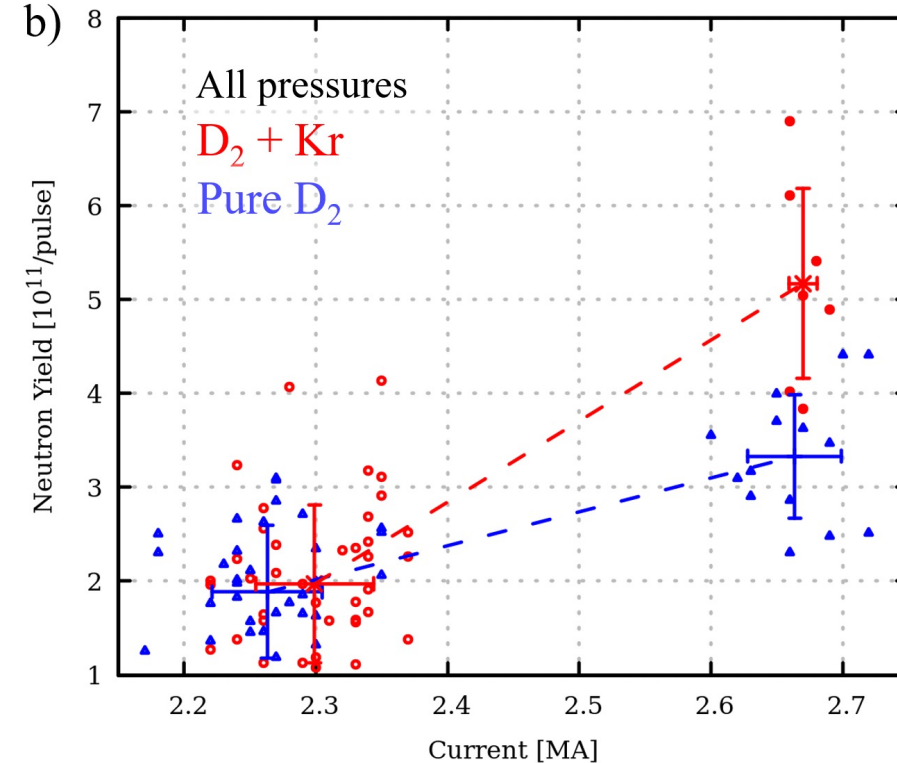
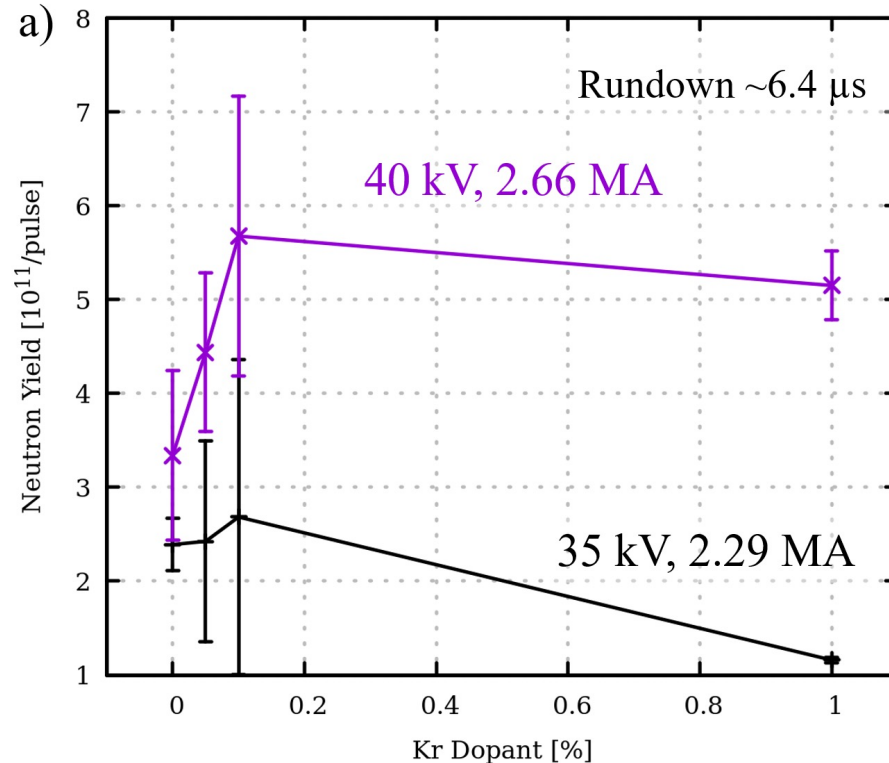
35 kV, 2.29 MA



- Local maximum in neutron yield at 0.1% Kr doping for 35 kV, and 2.29 MA.
- Rundown time (between 5.5 and 7 μs) has negligible impact on yield

E. Hahn *et al.*, J. Appl. Phys. **128**, 143302 (2020)

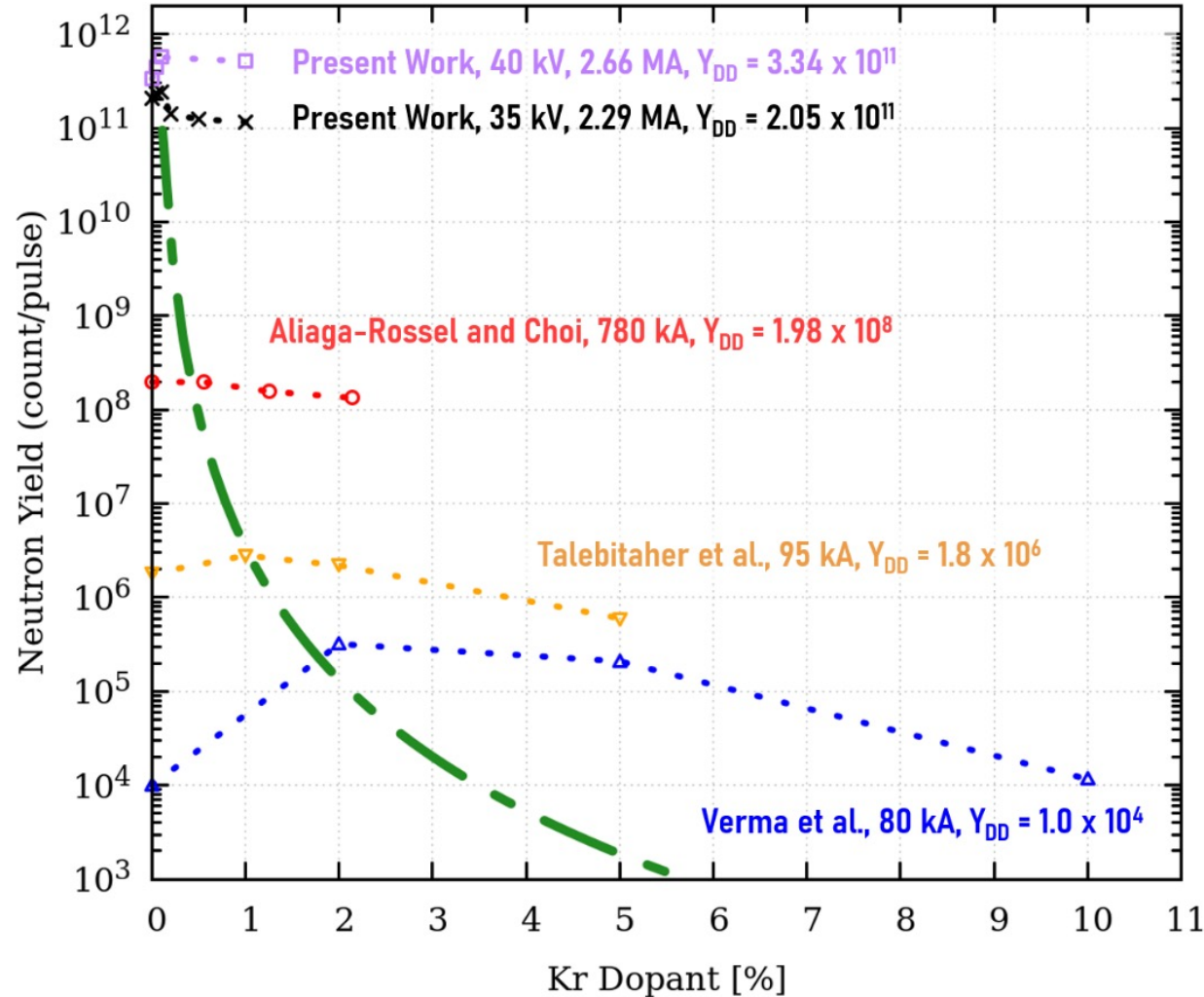
Significant enhancement of yield with Kr dopant at 40 kV is observed.



- Yield increase can not be completely attributed to yield scaling as $\sim I^4$
- Kr additions at 40 kV increase the neutron yield at all volume fractions, with maximum at 0.1%.
- This contrasts with the reduced effect of 1% Kr during 35 kV operation. Agrees with a peak production at 0.1% Kr admixtures.

E. Hahn *et al.*, J. Appl. Phys. **128**, 143302 (2020)

Together with previous results from literature an emergent trend of optimal Kr doping emerges



The relationship between peak neutron yield (Y_N) and percent Kr volume fraction (ϕ_{Kr})

$$Y_N = 3.37 \times 10^6 \phi_{Kr}^{-4.66}.$$

E. Hahn *et al.*, J. Appl. Phys. **128**, 143302 (2020)

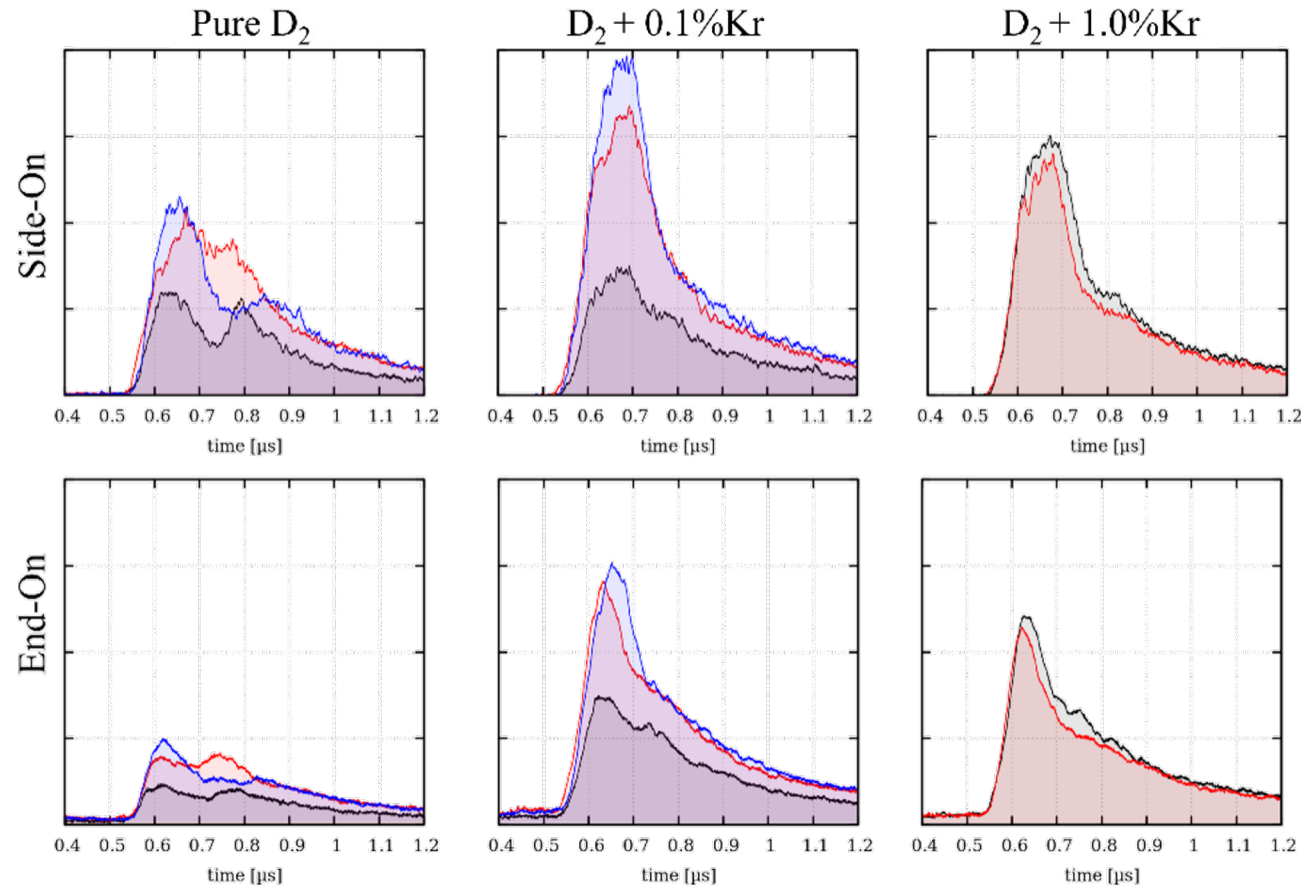
NToF data taken End-on and Side-on show flux and energy asymmetry.

- NToF peaks shifted down in magnitude (flux asymmetry ratio < 1) and earlier in time (energy asymmetry > 1) for end/side.
- Pulse shape changes from double peak to a predominately single peak with Kr doping.

40 kV
2.66 MA

10, 11 and 12 torr fill
pressure for DD, 0.1% Kr and
1% Kr respectively.

Rundown time $\sim 6.4 \mu\text{s}$



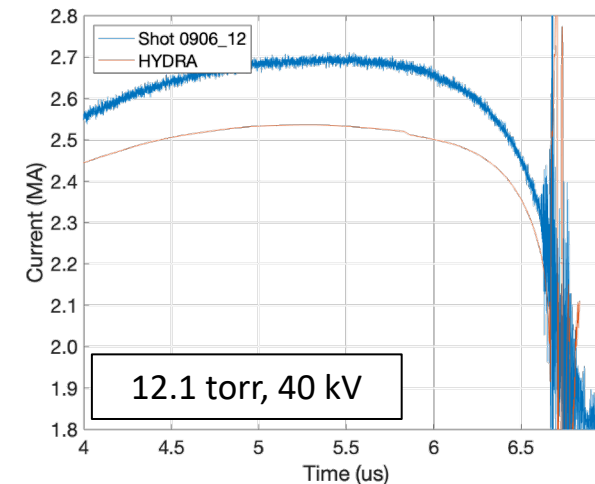
MHD simulations of DPFs can provide insight when fully kinetic or hybrid simulations are infeasible

- Standard approach for DPF modeling:
 - Kinetic simulation to model breakdown (~1-several μs)
 - Fluid simulation to model rundown (~several μs)
 - Kinetic simulation to model pinch (~10s of ns)
- Kinetic simulations are more accurate, but computationally infeasible for μs timescales
- MHD simulations are less accurate when kinetic effects become important
- Addition of dopant in MHD simulations is simpler, but much more straightforward than in kinetic simulations

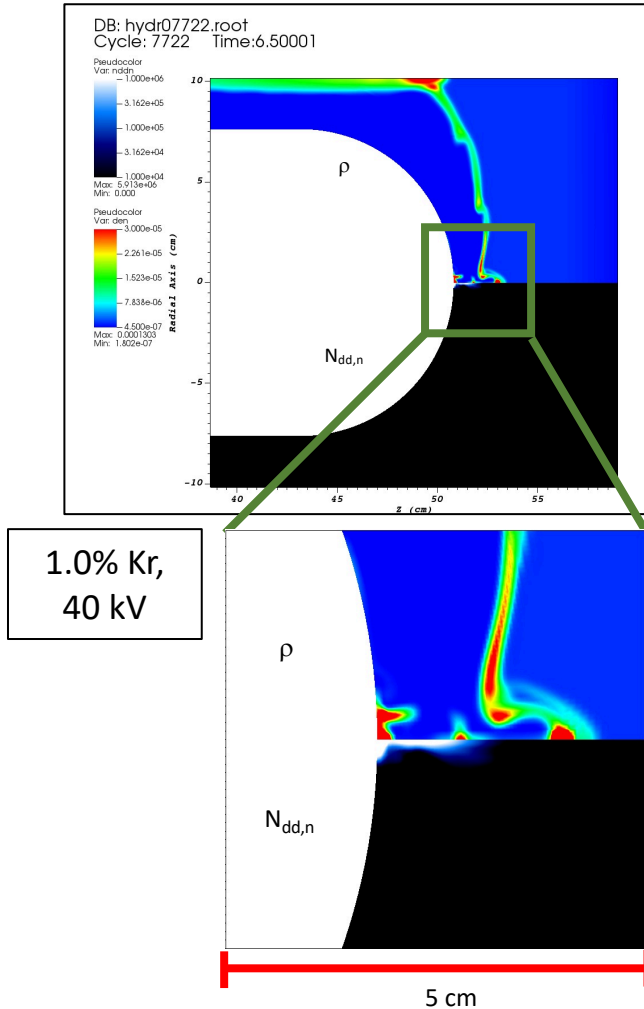
Collaboration with M. Marinak, LLNL using Hydra MHD code

Implosion times on **2 MJ GEMINI** were approximately matched via current trace using:

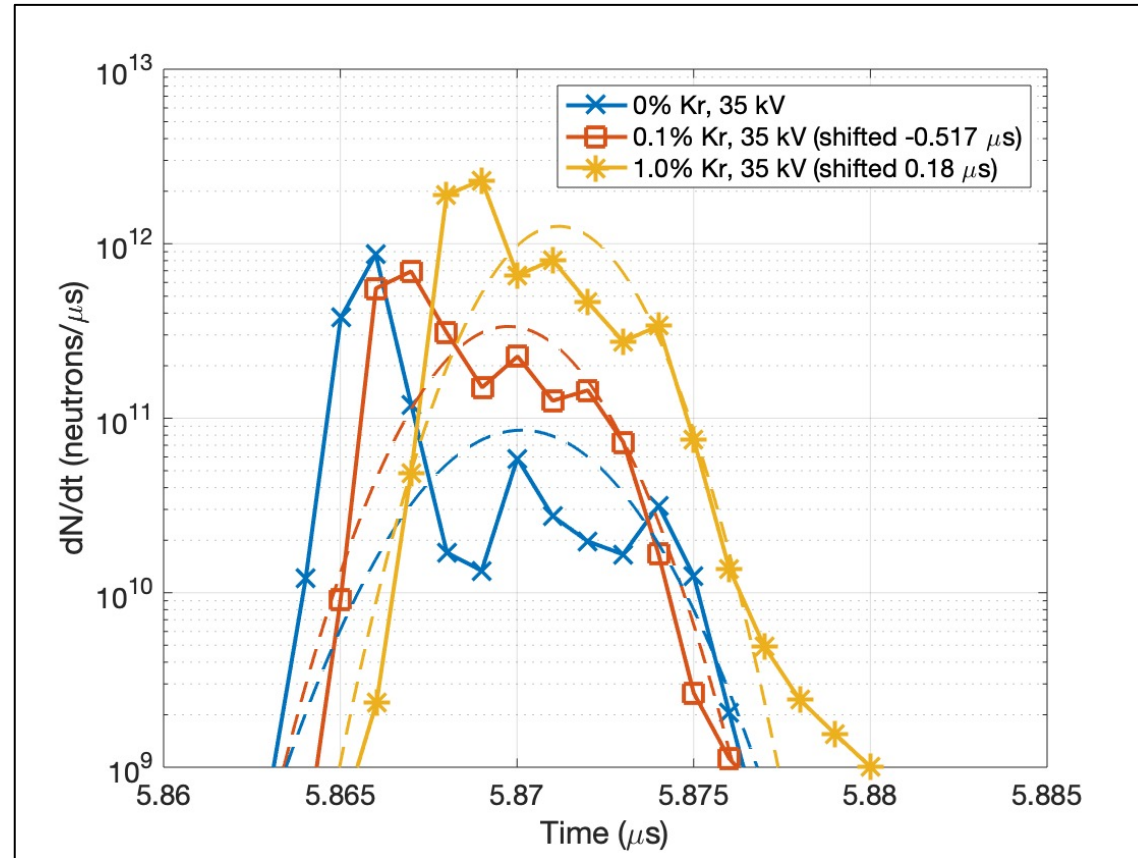
$R = 1.4 \text{ m}\Omega$, $L = 40 \text{ nH}$, $C = 432 \text{ }\mu\text{F}$ and 0.75x mass multiplier



Neutron 'pulse shape' narrows and steepens with increasing dopant percentage

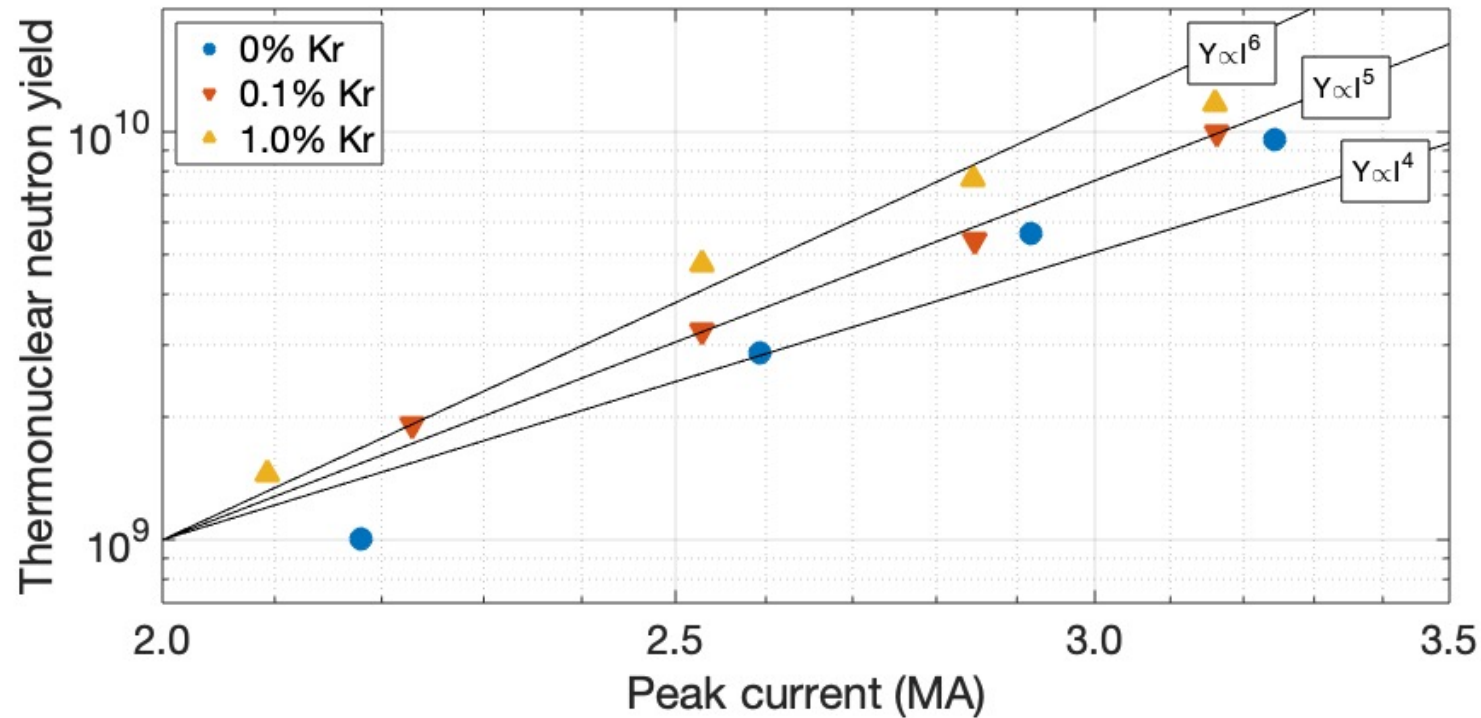


Dashed lines are ad-hoc fits: $\log(dN/dt) \propto t^2$



J. Narkis *et al.*, *Physics of Plasmas* **28**, 022707 (2021)

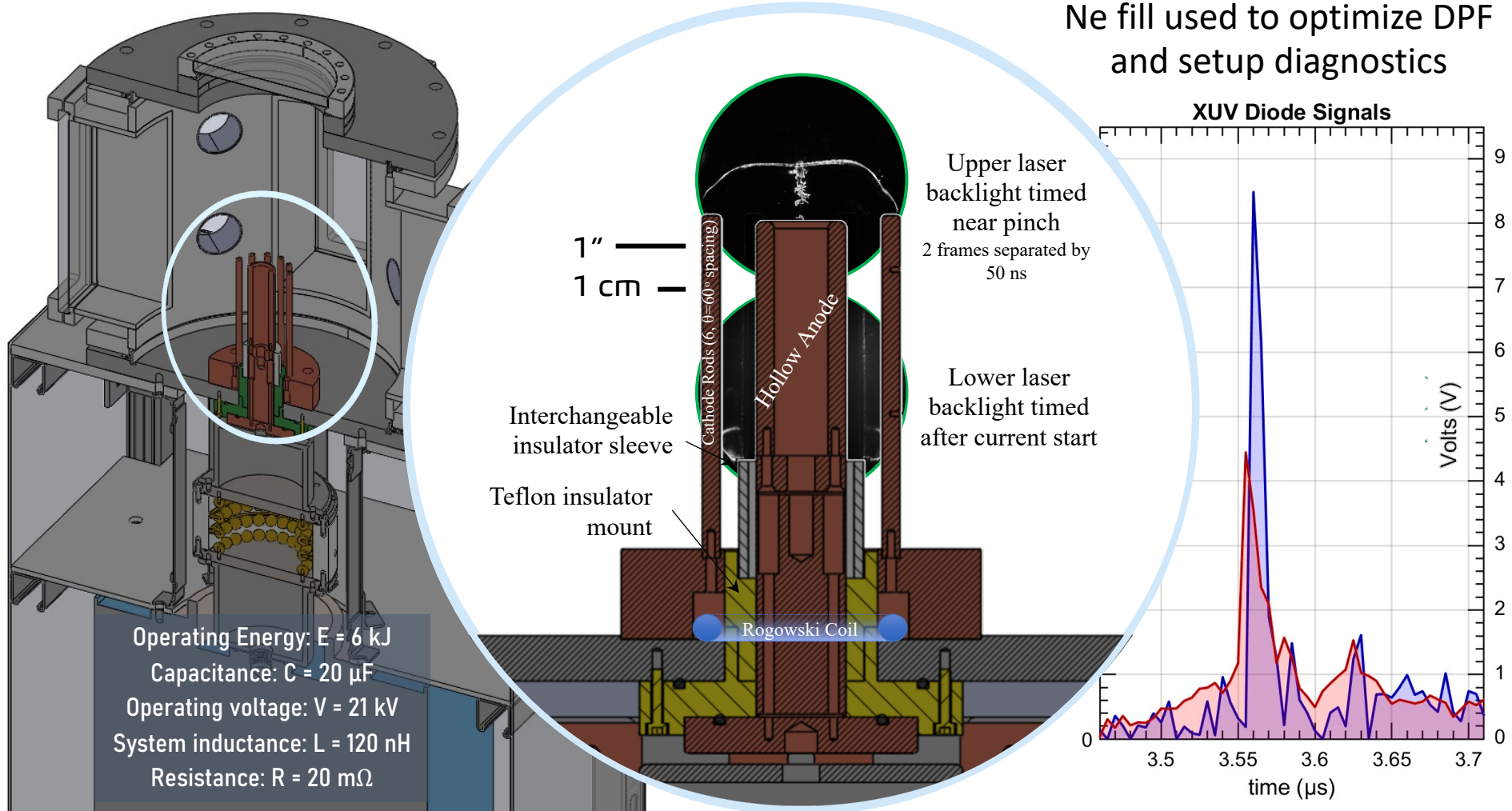
Predicted thermonuclear neutron yields scale in excess of I^4 in 2D MHD



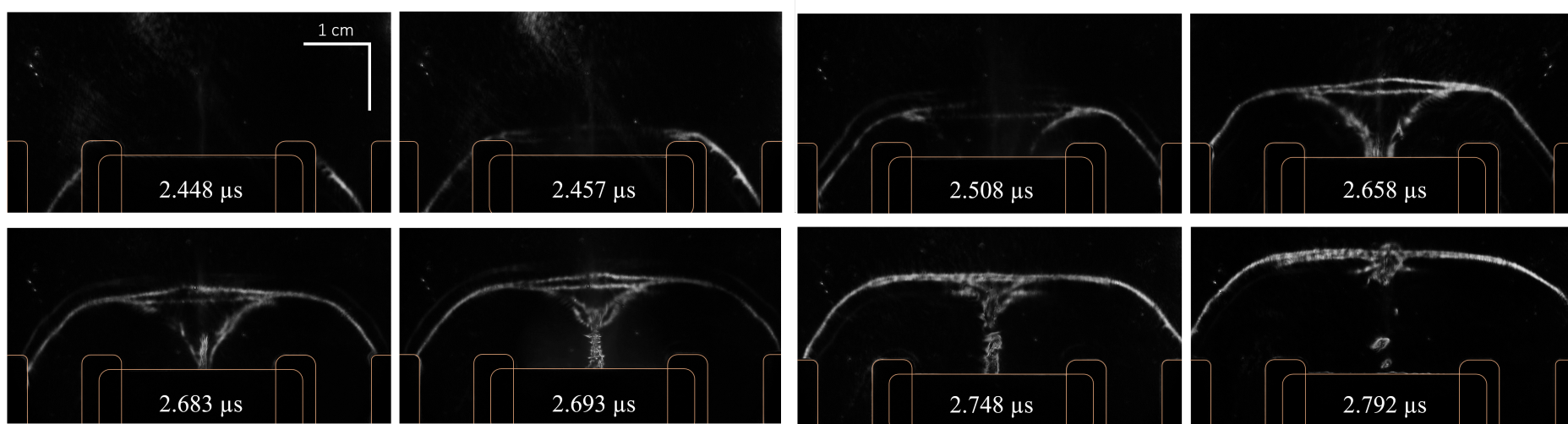
- Yield drop-off above 3 MA observed empirically and in kinetic simulations is not observed

J. Narkis *et al.*, *Physics of Plasmas* **28**, 022707 (2021)

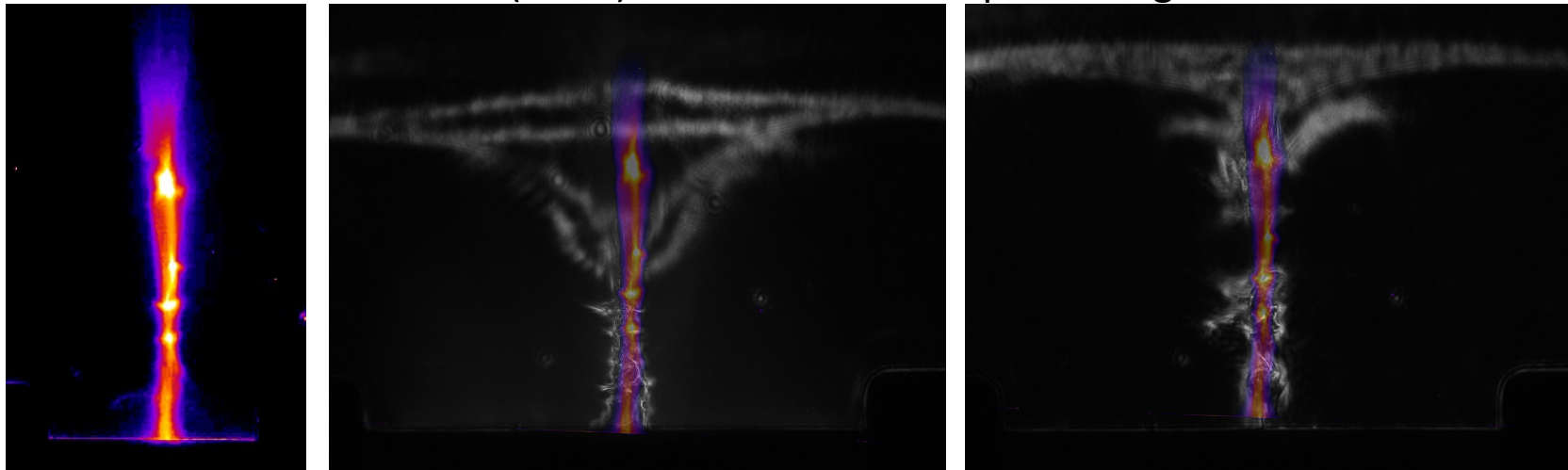
10 kJ UCSD Dense Plasma Focus



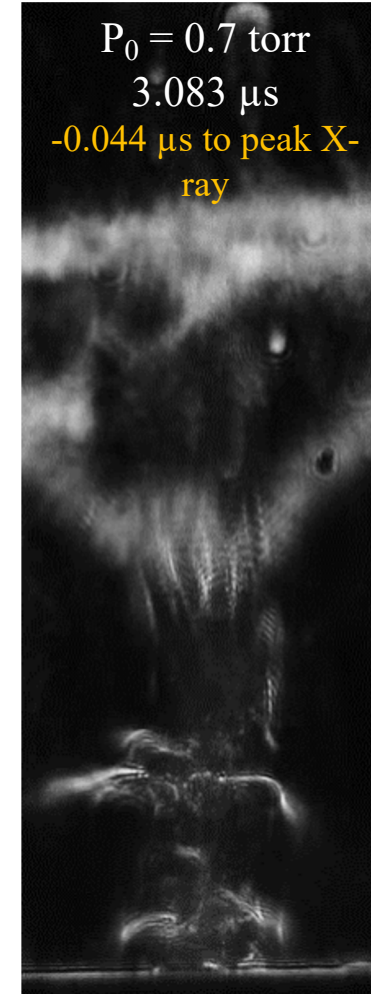
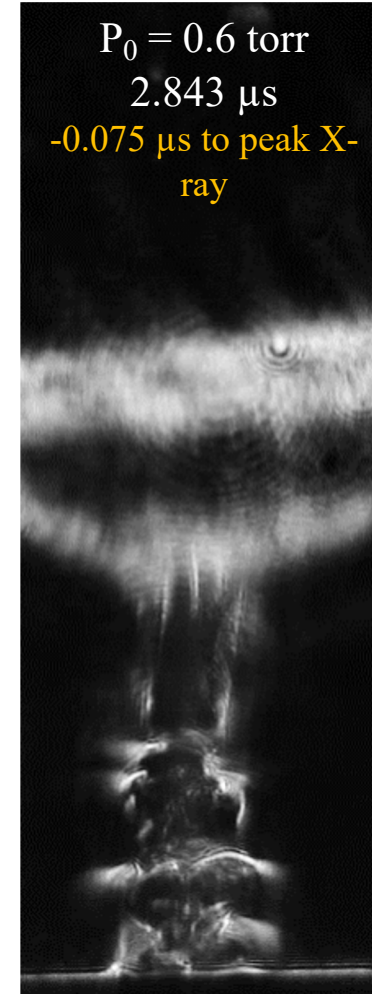
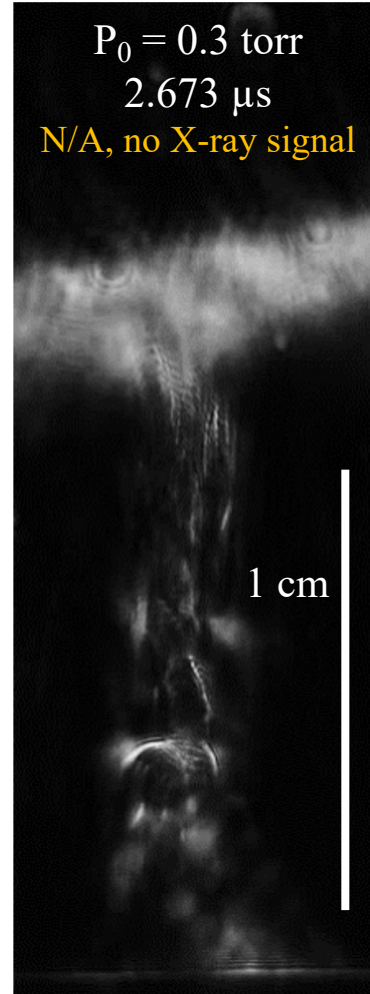
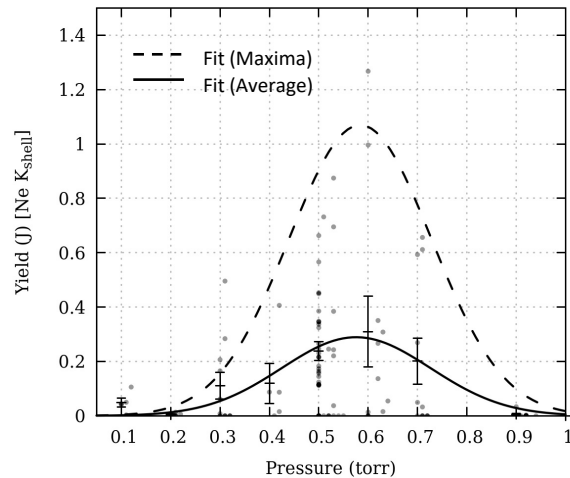
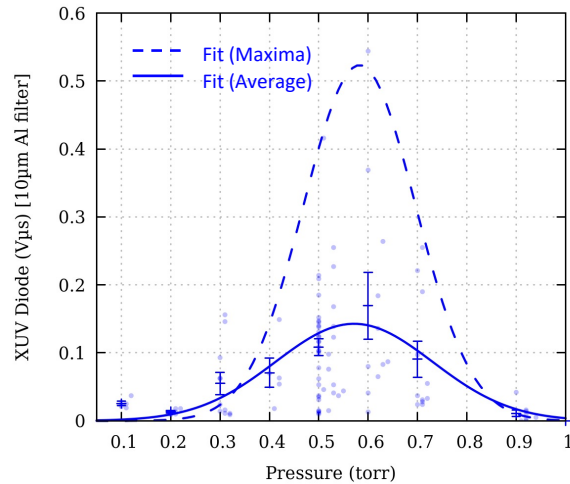
Detailed sheath evolution of the radial collapse phase through pinch and expansion



Self-emission of Ne-I lines ($\sim 2\text{eV}$) reveal several hotspots along the column

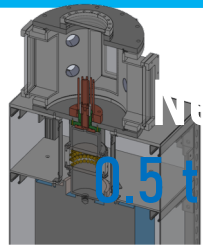


Optimal fill pressure for K_{shell} Radiation is ~ 0.6 torr Ne

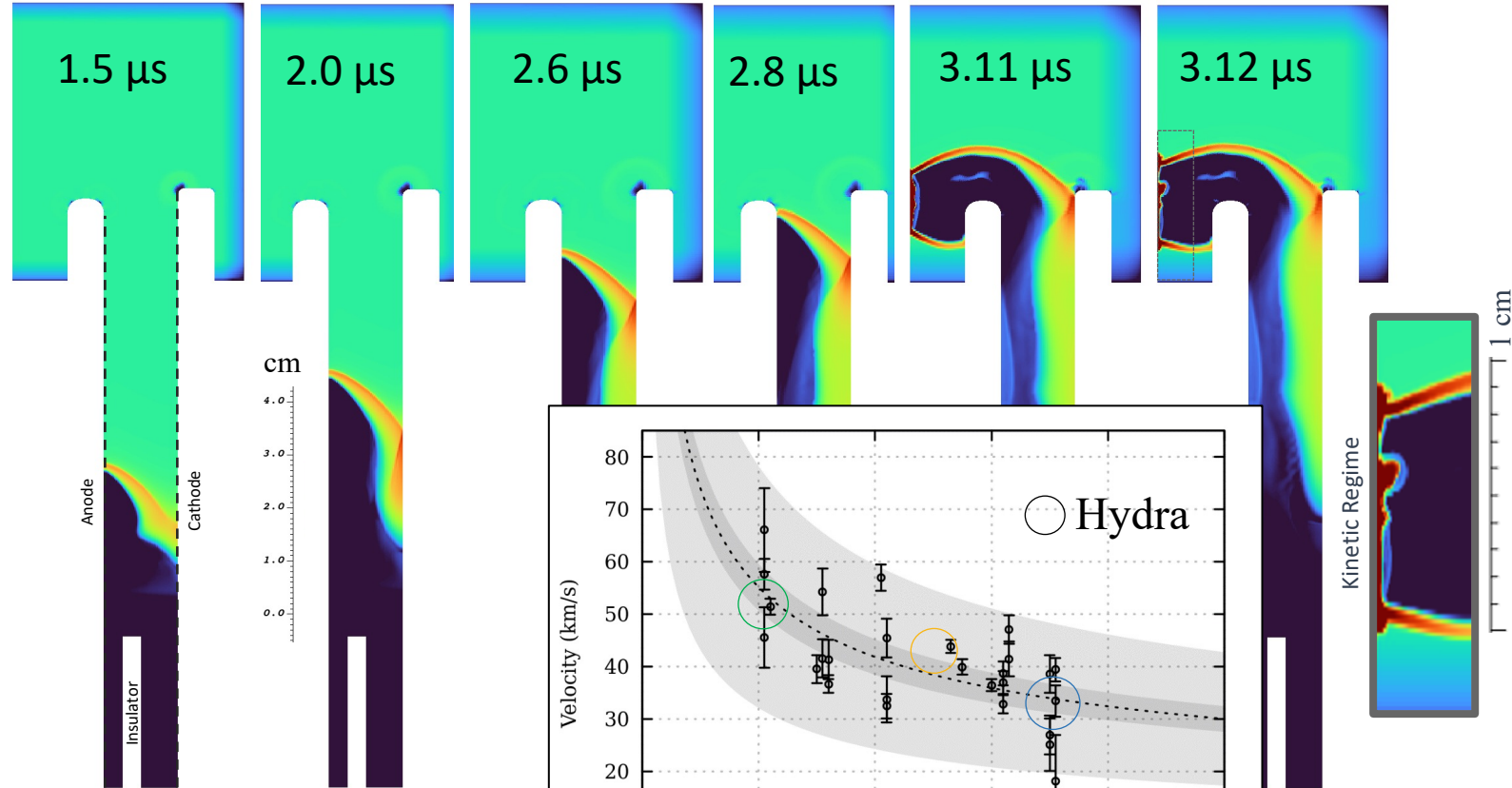
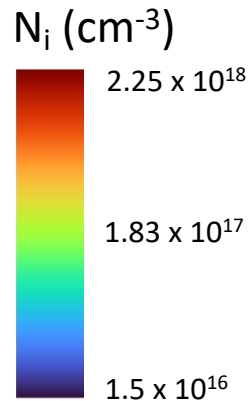


D. Housley et al., Journal of Applied Physics **129**, 223303 (2021)

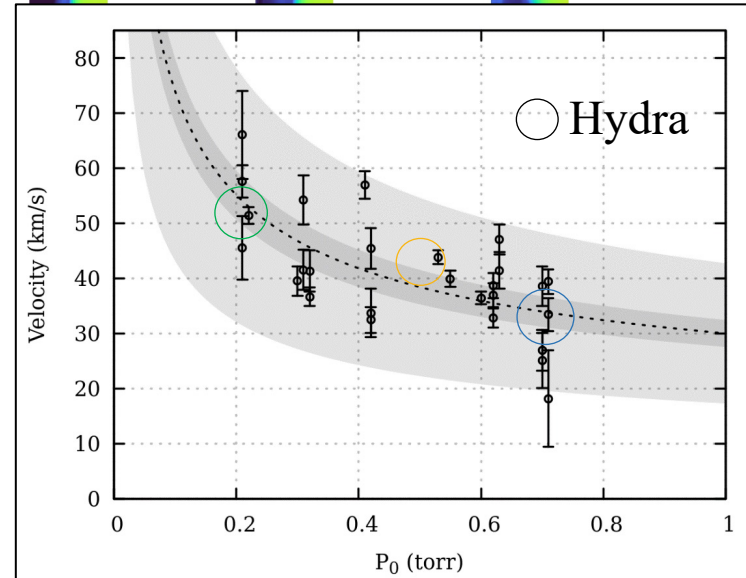
Hydra MHD Simulation shows dynamics similar to experiments



0.5 torr

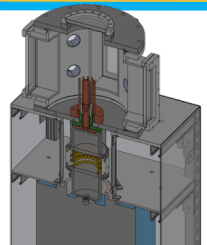


$V_{a,max} = 45$ km/s at 2.6 μ s (current max).
 $V_a = 35$ km/s as the sheath transitions from axial to radial

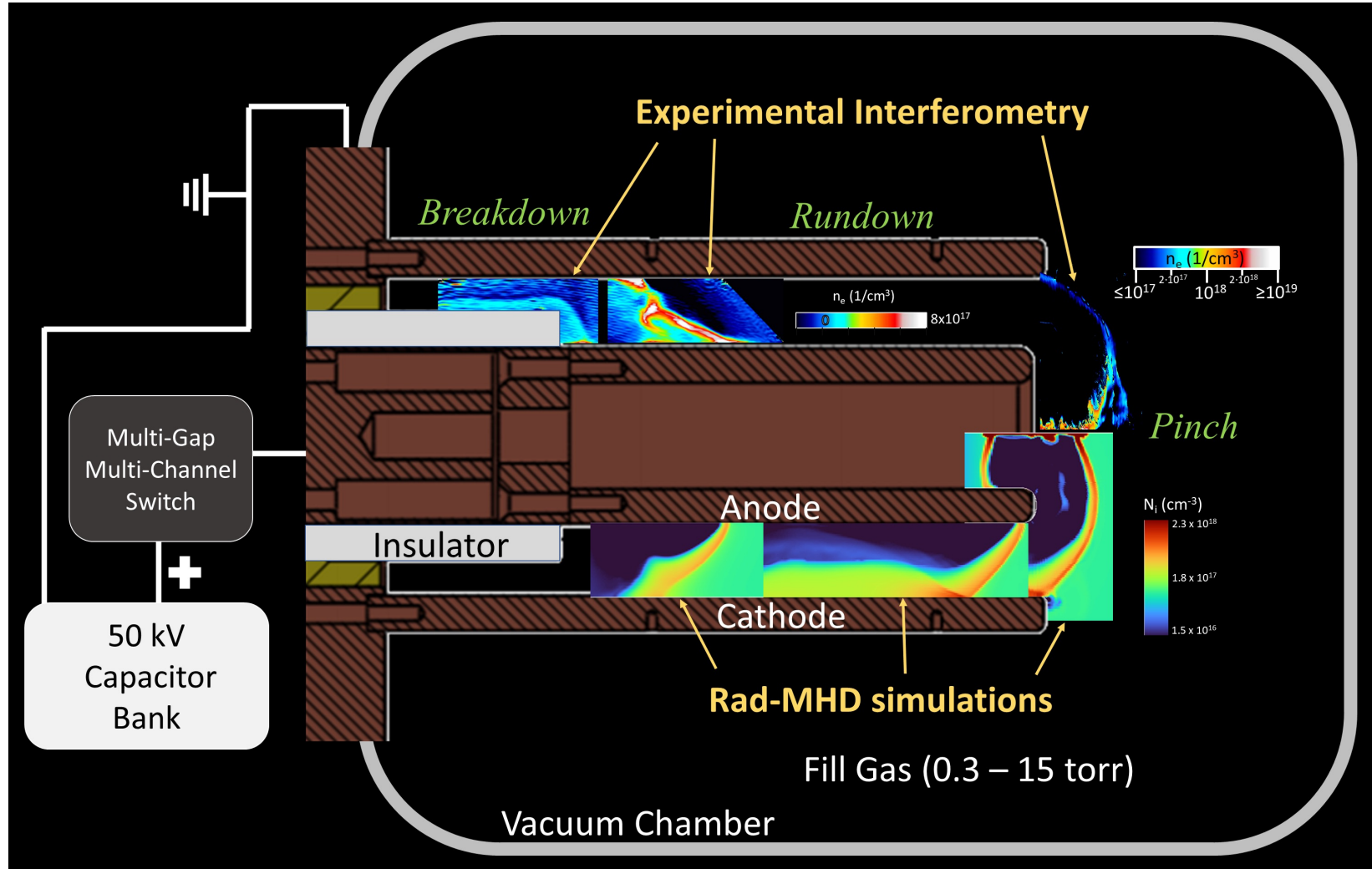


D. Housley et al., Journal of Applied Physics **129**, 223303 (2021)

Starting to make 1-1 comparisons between Hydra simulations and experiments

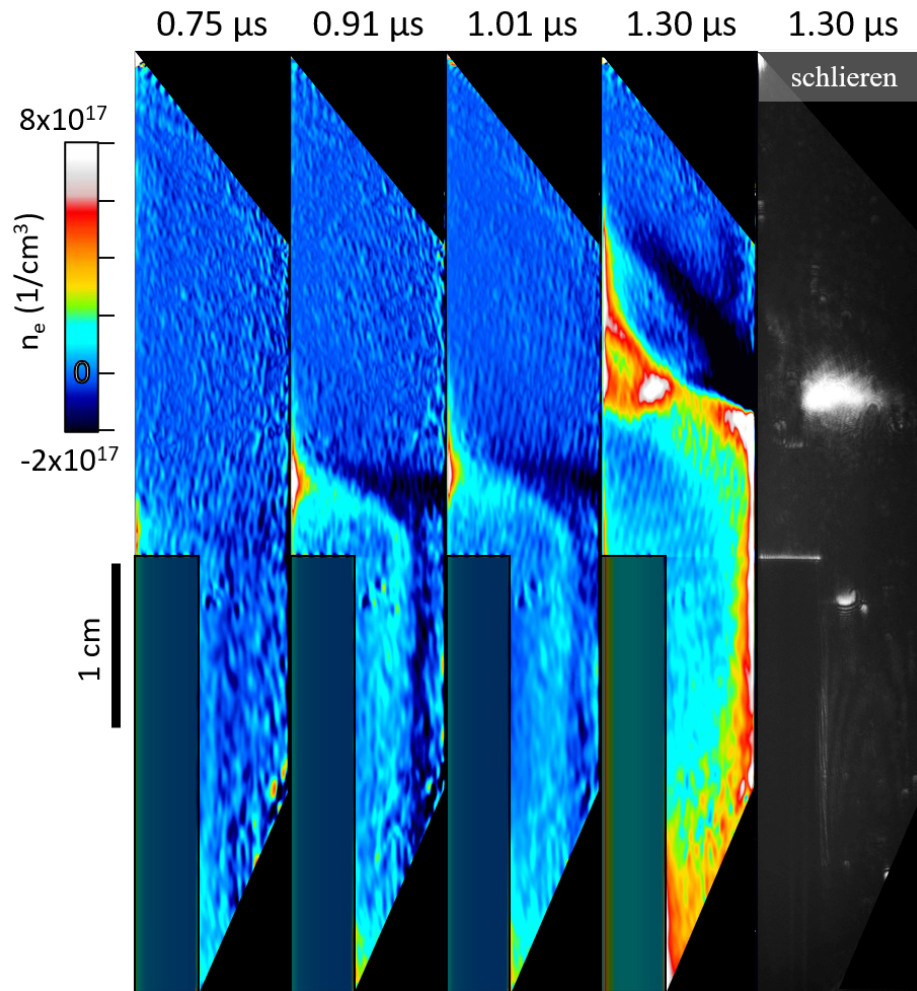


Ne
0.5 torr

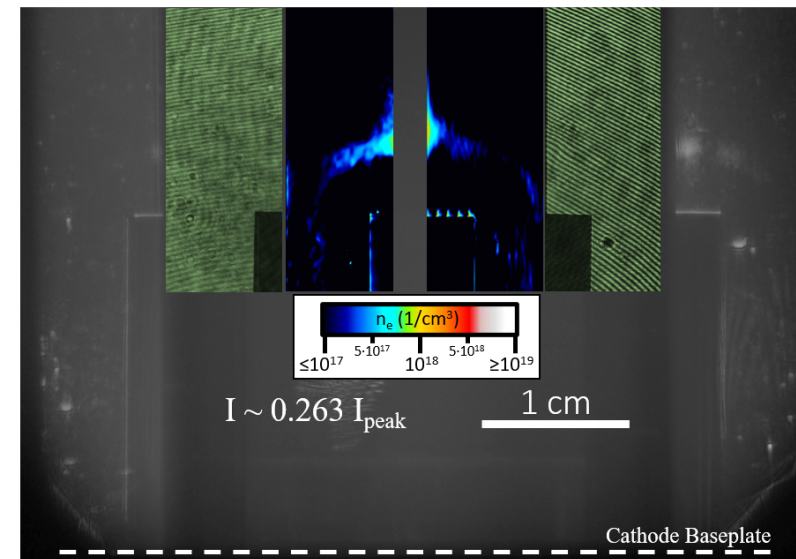
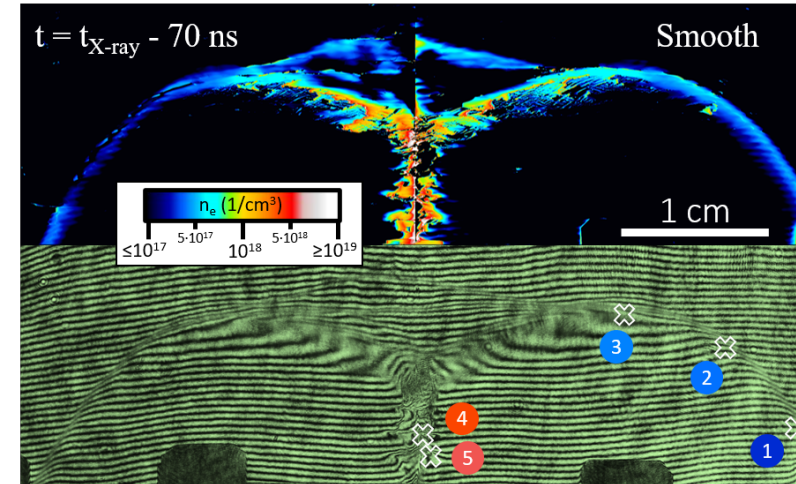


Observations of sheath formation and same shot diagnostics illustration

Ne
0.7 torr



*times relative to current start, one image per shot



Summary

- Z-pinch is the simple device that can be used to produce matter under extreme conditions.
- Gas puff Z-pinches are attractive for thermonuclear fusion and as an intense x-ray source
- One of the requirements for applications is to produce stable pinch
 - moderate external magnetic field can mitigate MRTI
 - combination of density tailoring and external magnetic field can further mitigate MRTI
- Linear Transformer drivers offer better energy coupling into matched loads.
- Neutron yield in Dense Plasma Focus is enhanced with an addition of dopant gas
- Enhancement is due to radiation cooling

