Staged Z-pinch

(The road ahead for Fusion Energy)

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← Experiments →

HYDRA simulation

Flash simulation

Challenges of Controlled Thermonuclear Fusion

Heating	RF heating, Neutral beam, direct current, (>50 million degree C^0) shock heating, <u>adiabatic compression</u>
Stability	MRT, Sausage, kink and other host of instabilities stabilization, <u>mitigation, or control</u>
Confinement	Lawson criteria requires for 10 keV DT plasma Confinement time ~ Several seconds for low density (10^{14} cm^{-3}) ~ 10^{-9} sec for high density (>10^{23} cm^{-3})

Our approach meets all these challenges

- Ignition requires trapping of α-particles
- Which requires large enough ρV or <u>High value of magnetic field</u>

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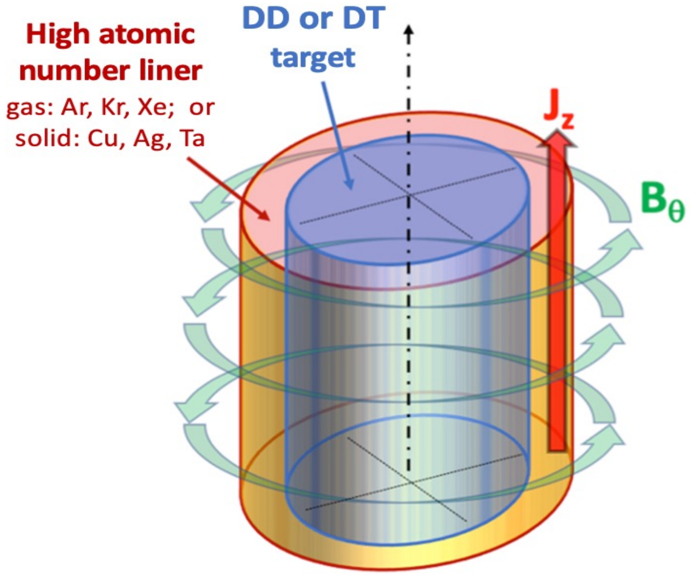
The Staged Z-Pinch (SZP) concept



- High atomic number liner compresses fusible target.
- Shock preheating of target plasma to ~ 100 eV.
- Compression of B_θ at the liner/target interface near stagnation time creates very high (10^3 - 10^4 T) magnetic field which "freezes" electrons along the B_θ lines. Mass accumulation at the interface creates large P_{RAM} and very strong adiabatic compression.

1. Rahman, et. al., Phys. Rev. Lett. 74, 714(1995)
2. Rahman, et. al., Physics of Plasmas, 58, 367 (1997)
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5. Rahman, et. al., J. Plasma Physics, 75, 749 (2009)
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7. Rahman, et. al., Physics of plasma, 19, 122701 (2012)
8. Rahman, et. al., Physics of Plasmas, 26, 052706 (2019)
9. Conti, et. al., Physics of Plasmas, 27, 012702 (2020)
10. Ruskov, et. al., Physics of Plasmas, 27, 042709 (2020)
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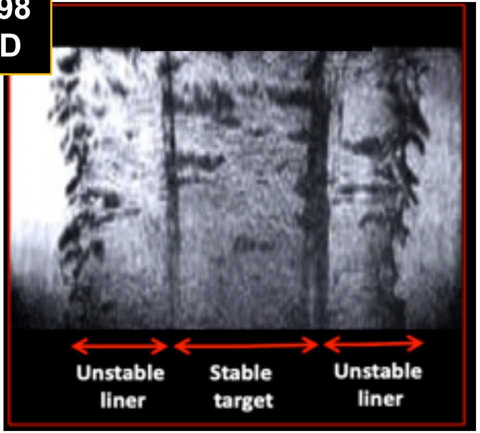
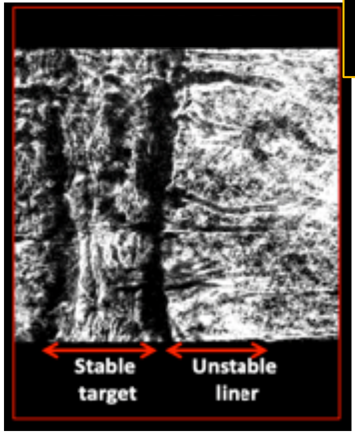
SZP shadowgraphs & XUV images on four different machines

UCI 1998
Kr on D



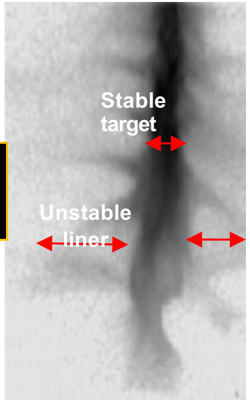


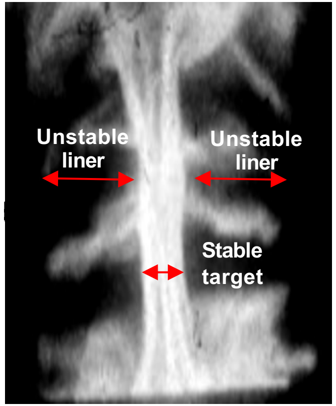
Zebra 2017
Kr on D

- 1.0 MA Marx generator
- Measured neutron yield: ~ 2×10^{10}, as predicted

Target plasma remains stable although the MRT instability grows on the outer liner surface.

COBRA 2017
Kr on H



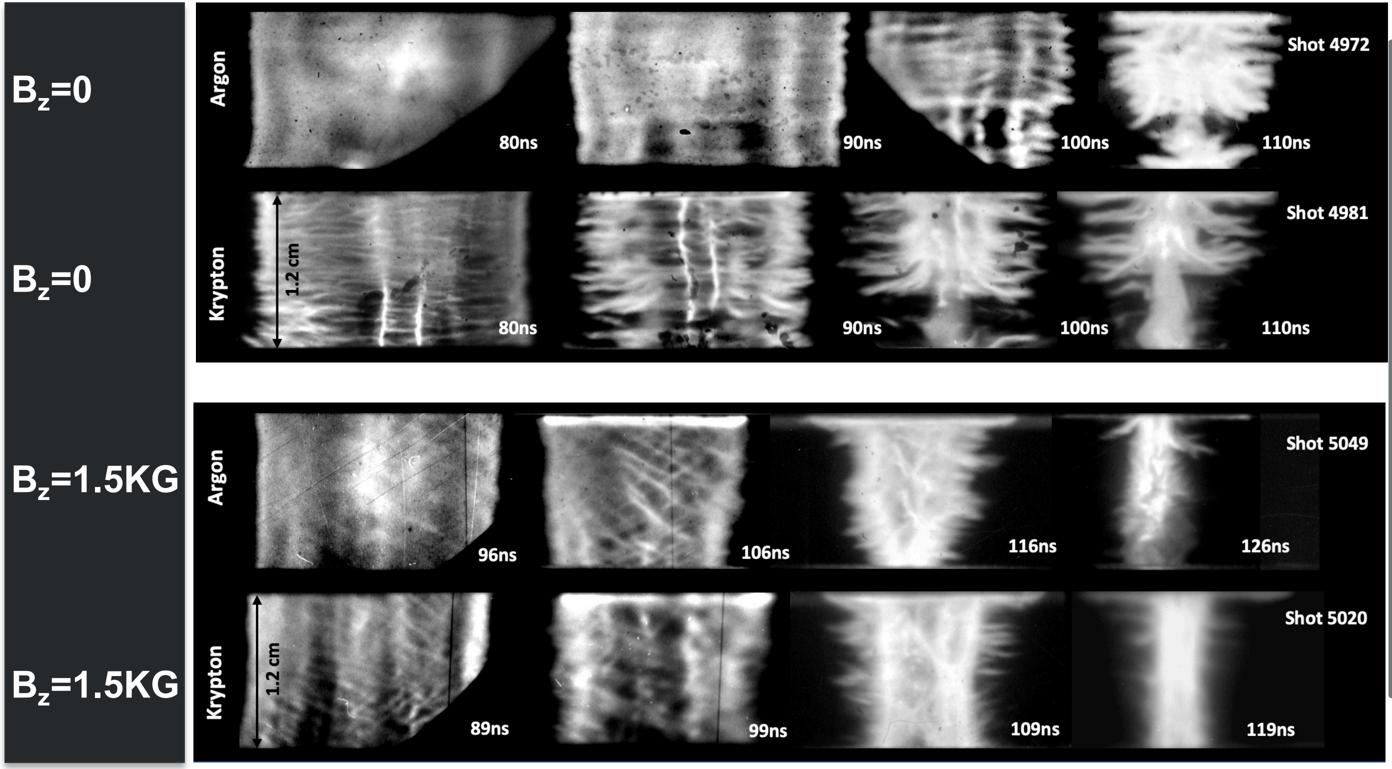


CESZAR 2022
Kr on D

- 0.5 MA LTD generator
- Measured neutron yield: ~ 10^8 , as predicted

Stability of Staged Z-pinch (Kr vs. Ar liners)

4-frame XUV pinhole camera images



- Initial axial magnetic field B_z from to 1 to 2 kG grows to mega-gauss level during implosion.
- Suppresses the MRT instability.
- Produces a uniform target plasma
- This produces thermonuclear fusion

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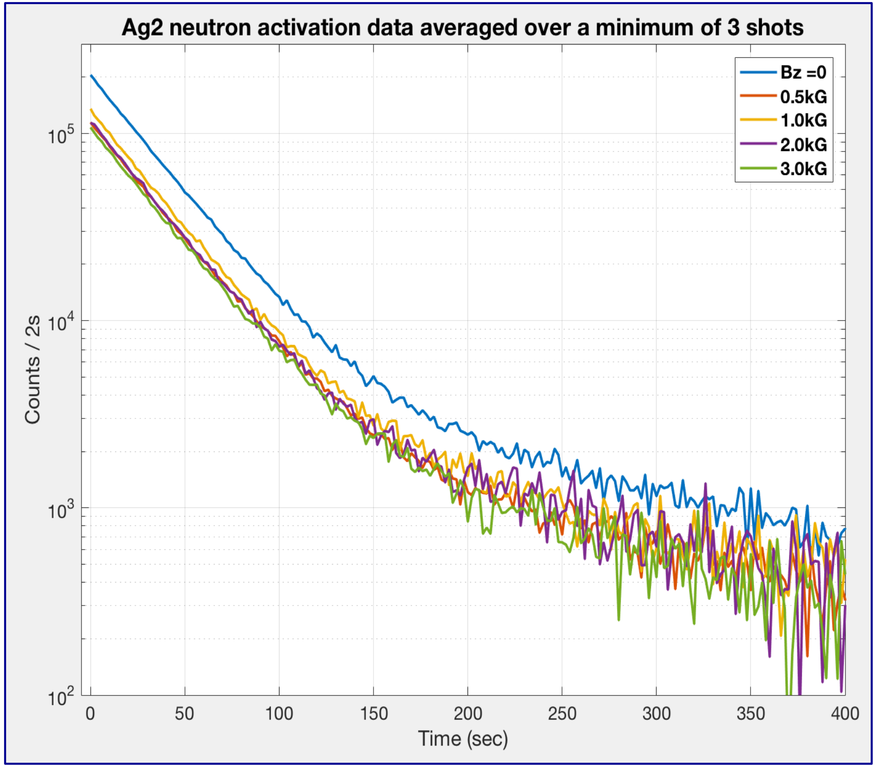
Neutron Yield for Kr on D (1MA ZEBRA machine)

Signal from Ag activation detector



Bz (Gs)	Avrg.yield (x1e10)
0	1.7
500	0.9
1000	1.0
2000	0.9
3000	0.8

- Consistent yield measured when axial magnetic field B_z=0.5-3kG is applied.
- Highest yield measured when the magnetic field is zero: **2.3×10^{10}**

MACH2 code calculates plasma parameters close to experimental values

Liner	B_{0z} (kG)	$B_{z\ max}$ (MG)	$B_{\theta\ max}$ (MG)	τ_{imp} (ns)	N_i (cm^{-3})	T_i (KeV)	$V_{r\ peak}$ (cm/μs)	Rl_{min} (mm)	τ_{dwell} (ns)	Neutron Yield Y_{DD}
Ar (XP)	1.0	15.0	1.4	127.85 (129±11)	9.2×10^{20}	6.1	59 (50)	1.3 (1.4)	1.7	2.3×10^{9} (2.2×10^{9})
Ar (XP)	1.5	11.0	1.25	127.95 (133±3)	4.8×10^{20}	8.2	58 (65)	1.6 (1.7)	2.2	1.6×10^{9} (2.1×10^{9})
Kr (XP)	1.0	11.0	1.6	127.6 (123±11)	6.0×10^{20}	12.1 (8.0)	63 (37)	1.2 (1.3)	2.0	1.7×10^{10} (1.0×10^{10})
Kr (XP)	1.5	8.3	1.34	127.75 (117±8)	3.9×10^{20}	12.8 (8.0)	55 (50)	1.5 (1.4)	2.5	8.3×10^{9} (1.0×10^{10})

Measured parameters are close to values from 2D MACH2 simulations:

- Implosion time from B-dot probe
- Implosion velocity from Streak image
- Plasma Temperature from NTOF detector.
- minimum radius from XUV images
- Lawson's Triple product $n.T.\tau \sim 10^{19}$ (Kev.s.m^3)

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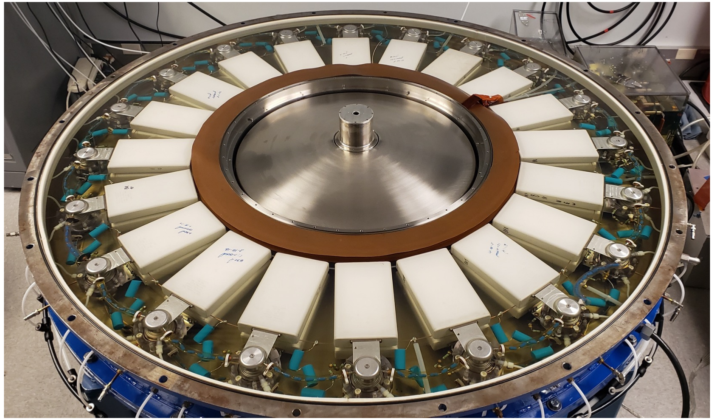
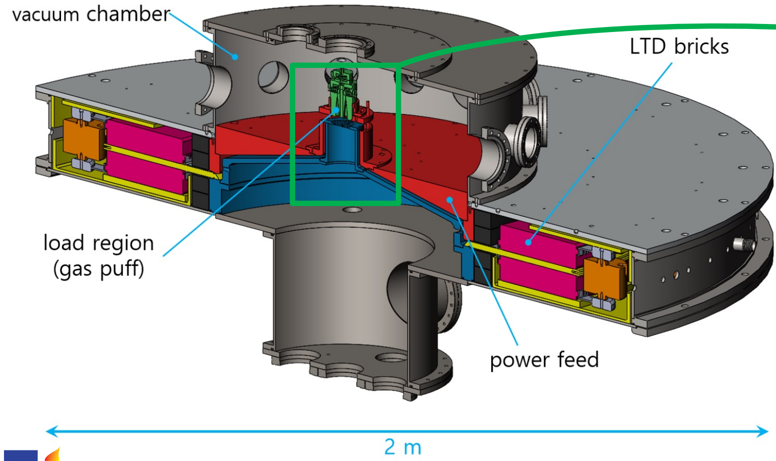
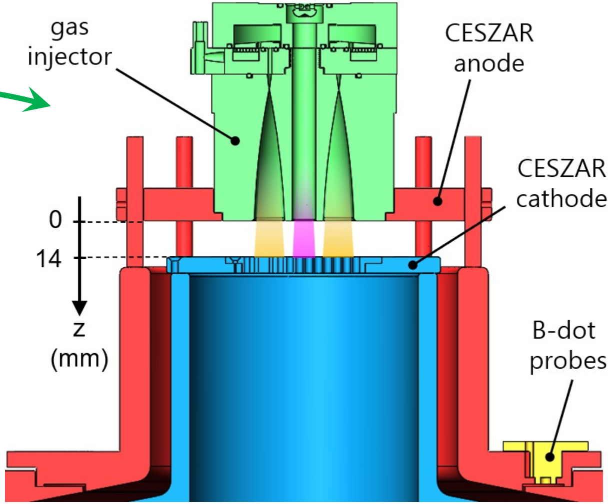
Staged Z-pinch Experiments with CESZAR LTD Generator

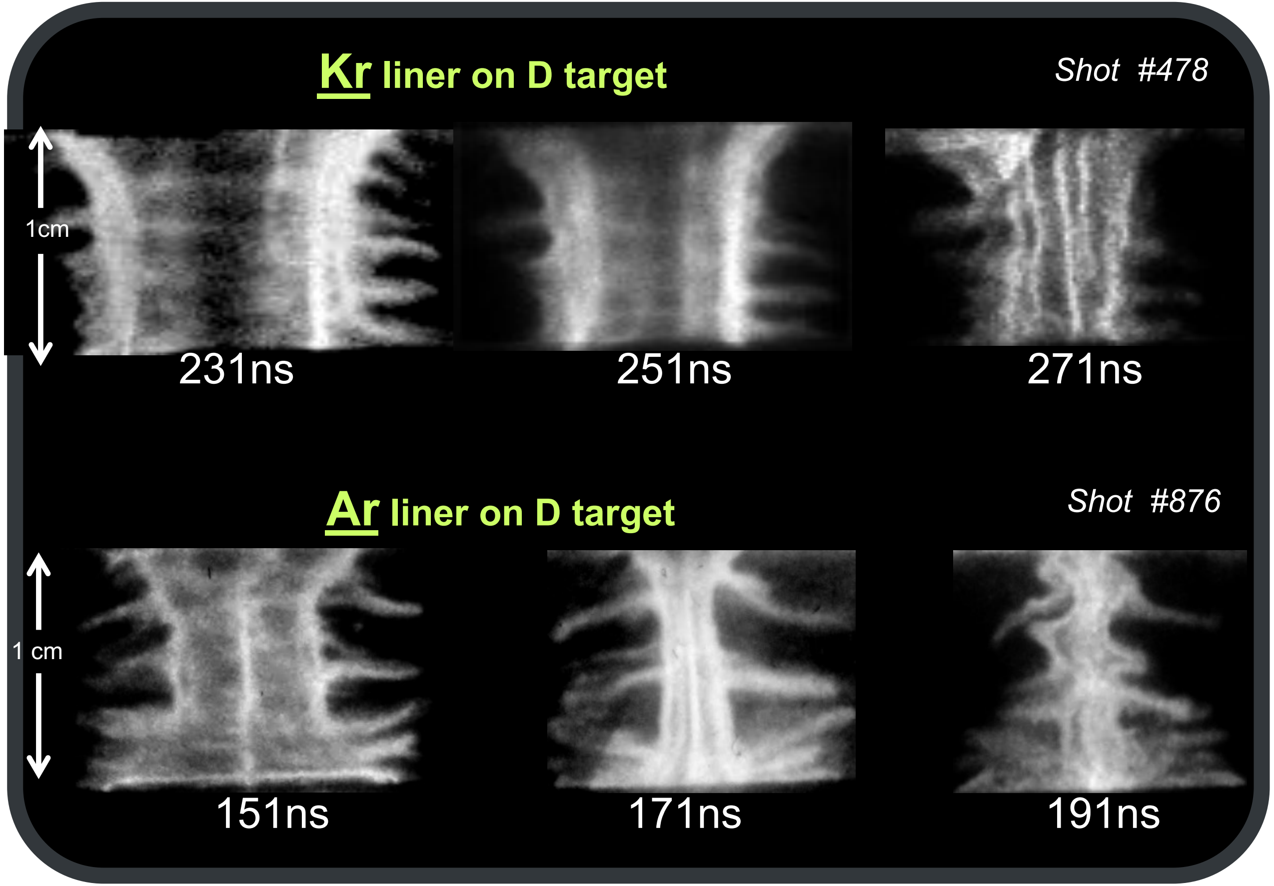


- **CESZAR is a compact machine at UC San Diego, based on new Linear Transformer Driver (LTD) generator technology.**
- **4 kJ stored energy, 0.5 mega-ampere current, 200 ns rise time**
- **Experiments using various liner gases (Ne, Ar, Kr) on deuterium target**





XUV images of Kr & Ar liner on D target at CESZAR



- **MRT instability develops on the pinch surface**
- **Target remains stable during the implosion**
- **Shot to shot reproducibility remains quite good**
- **A dense plasma layer develops at the liner-target interface**
- **High ram pressure compresses the target to high energy density plasma**

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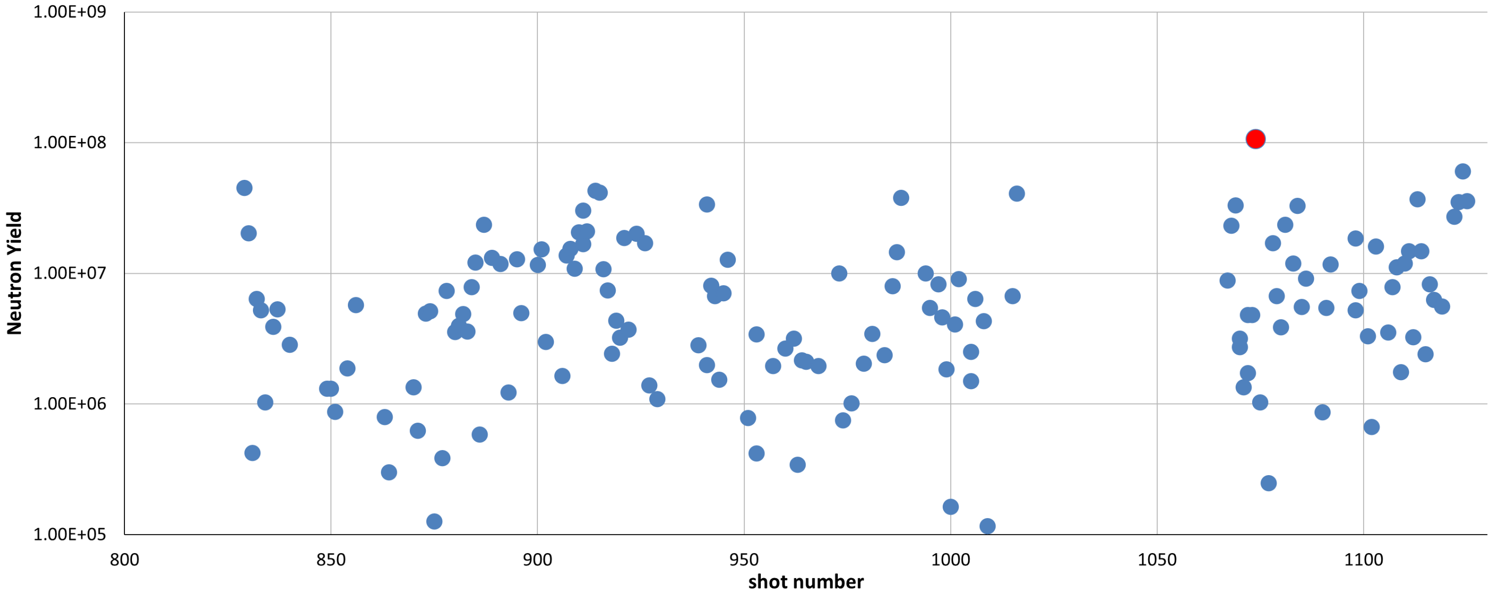
Neutron yield measured with a calibrated $LaBr_3$ detector



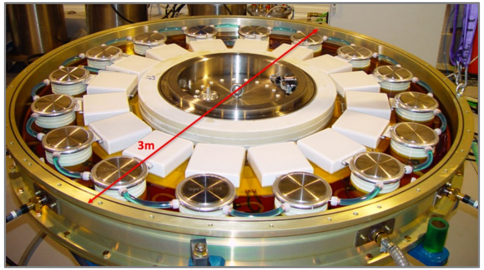
Maximum Neutron Yield: 10^8

- The $LaBr_3$ diagnostic was absolutely calibrated at LLNL.
- It provides automated yields in <3 minutes to allow parameters such as gas pressure to be optimized.

Scaling for the Higher Current Machine, Breakeven and Beyond

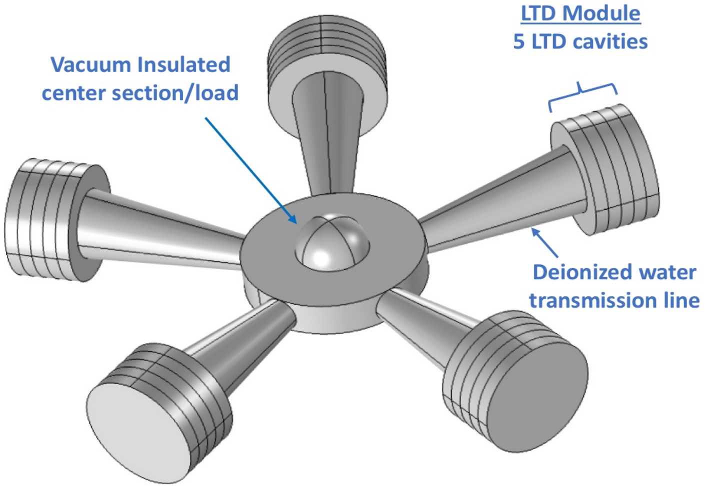
Conceptual design for 10MA machine to study the scaling

1MA Single Cavity



LTD brick

10MA LTDX

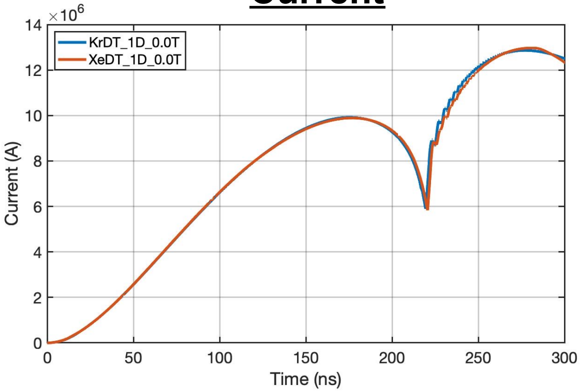


Configuration:

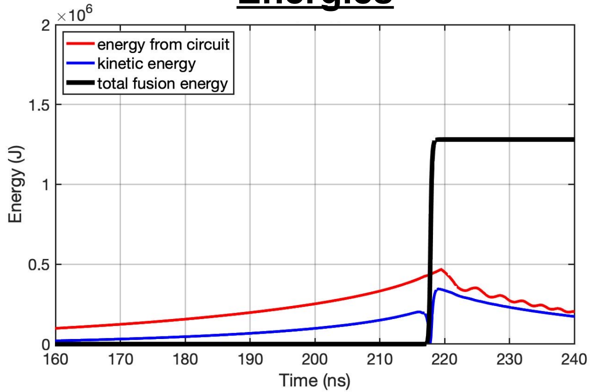
- 5 Linear Transformer Driver (LTD) modules with 5 LTD cavities each
- Each cavity contains 20 capacitor-switch units called “bricks”
- Current is transmitted from the LTD modules to a central vacuum section and load
- Generator is impedance matched to maximize energy delivery
- Total stored energy is 800 kJ
- Diameter is ~10 meters

10 MA LTDX machine current yield with Kr vs. Xe liner on DT (MACH2)

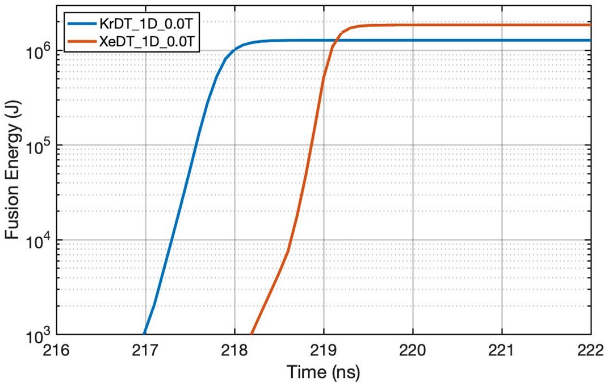
Current

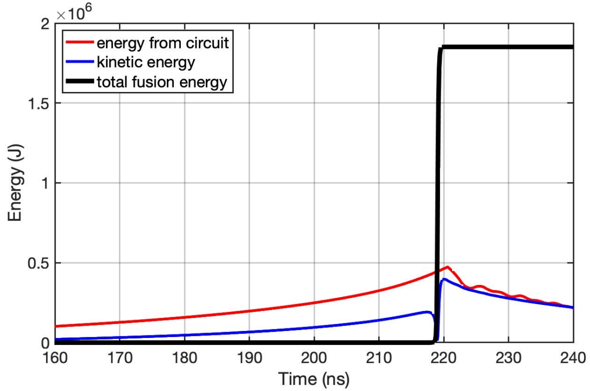


Energies



Fusion Energy





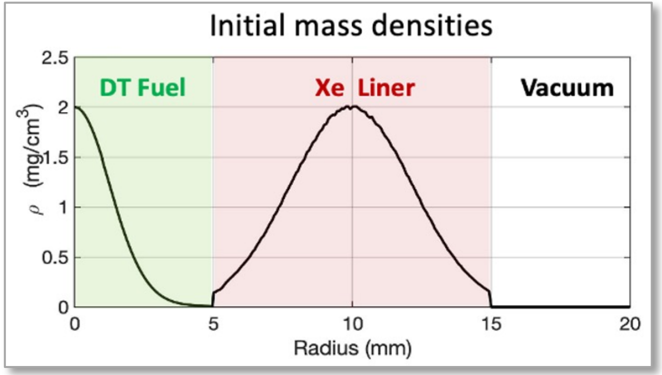
Stored energy: 0.8 MJ
Energy from circuit: 0.48 MJ

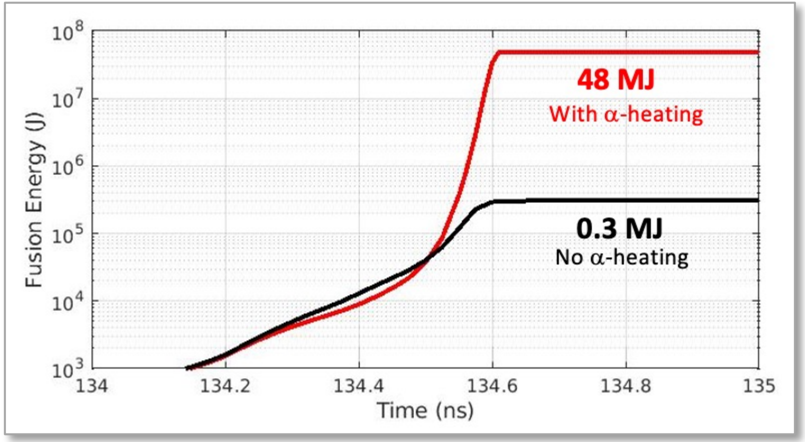
Fusion Energy

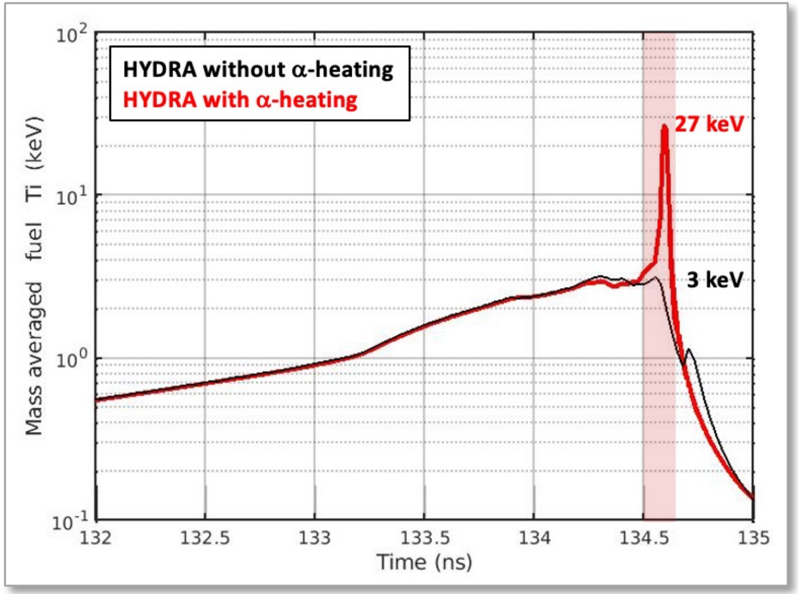
Kr on DT: 1.28. MJ
Xe on DT: 1.85 MJ (~50% higher)

Breakeven is possible

HYDRA code modeling of Xe gas-puff Staged Z-pinch (Z-machine, ~20 MA)



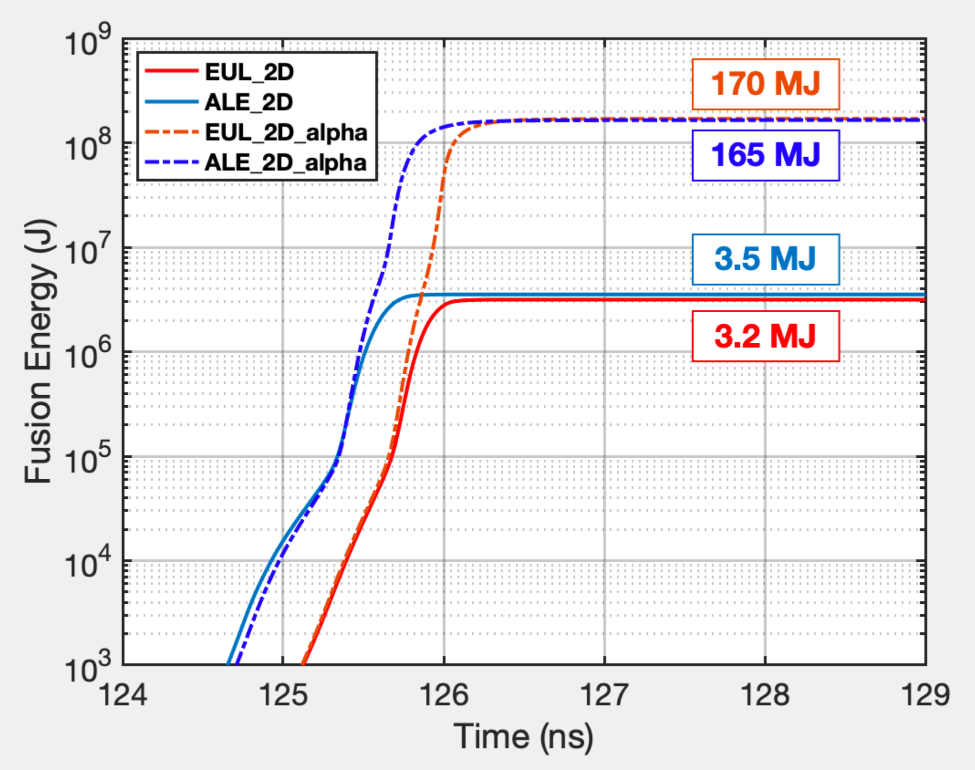




- **Xe SZPs modeled with HYDRA and MACH2 calculate 50-100 MJ of fusion energy when α–heating is included.**
- **The liner temperature was limited to 500 eV for the model shown on this slide.**

MACH2: Silver liner on DT target (Z-machine, ~20 MA)

Fusion Energy with and without α–heating



- **Proper Eulerian and Adaptive Lagrangian-Eulerian (ALE) MACH2 simulations suggest that:**
- **Solid silver liner imploding on a 50% - 50% DT mix may create breakeven conditions even without alpha α–heating taken into account!**
- ***Note:* The MACH2 α–heating model assumes that all alphas are confined.**
- **Ignition may be possible in this machine**

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Scaling of fusion energy gain with current (DT fuel)

Facility	Max current (MA)	Capacitor energy (J)	Circuit energy (J)	Fusion energy (J)	Scientific gain	Gain
CESZAR	0.5	4.9 e3	8 e2	2 e-2	2.5 e-5	-
ZEBRA	1.0	200 e3	4.5 e3	10	2.2 e-3	-
Double Eagle	5.0	800 e3	200 e3	500 e3	2.5	-
LTDX	10.0	800 e3	480 e3	1.85 e6	3.8	2.3
Z-machine	20.0	20 e6	8 e6	100 e6	12.5	5.0

Scientific gain = Fusion Energy / Circuit Energy

Gain = Fusion Energy / Capacitor Energy

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Summary

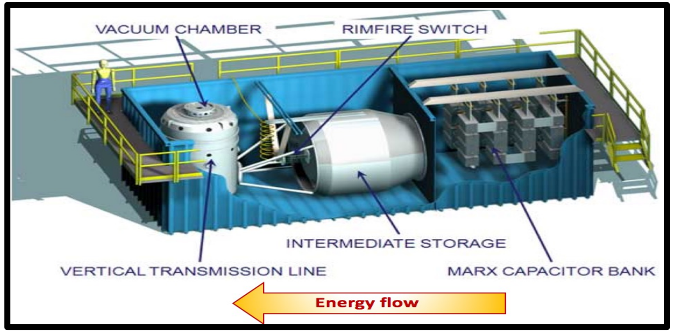
- Staged Z-pinch is based on flux-compression experiments started 30 years ago at UCI
- Liner-on-target (Ar, Kr → H2, D2 or DT) produces stable Z-pinch
- Higher atomic number liner provides better compression and stability
- A modest axial magnetic field improves the pinch uniformity and further insulates the hot target plasma from the cold liner plasma
- Implosion velocity is V_r ~ 30 – 50 cm/μs and the ion temperature is T_i ~ 5 – 10 KeV
- Maximum yield of 2.3×10^{10} measured at ZEBRA
- Code verification is done using four different codes (MACH2,HYDRA,FLASH & TRAC2)
- Our plan is to extensively study SZPs on a 500 kA LTD machine at UCSD, and upgrade it to 1MA to obtain results similar to ZEBRA
- Next year we'll conduct experiments on a 4 MA machine (Double Eagle)
- Modeling of a 10 MA LTDX machine suggests possibilities of breakeven and beyond

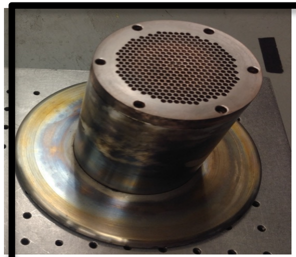
Thanks
Any Question?

Back-up slides

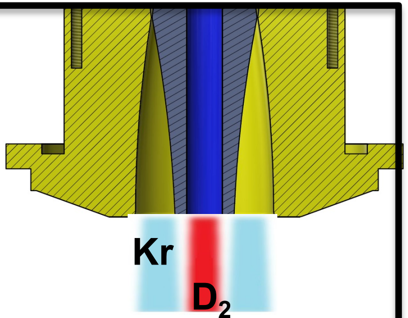
Experiments at Nevada National Terawatt Facility

Zebra: 2 TW, 1 MA, 100 ns





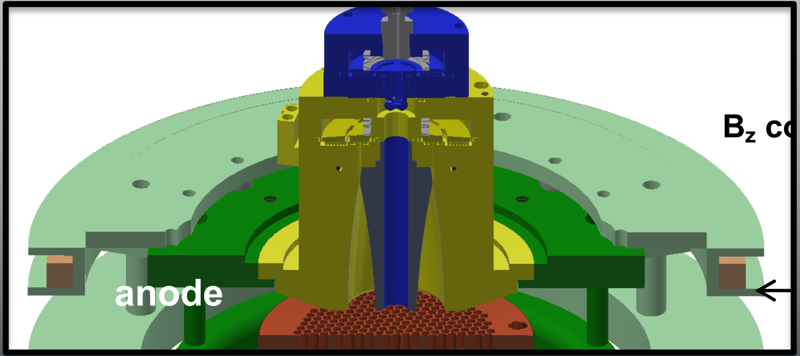
Cathode



Double gas shell injector

Mega-ampere currents.

Multiple experiments using Ar and Kr liners.



Load region

Electrodes made from Cu/W survive multiple shots >50 tested

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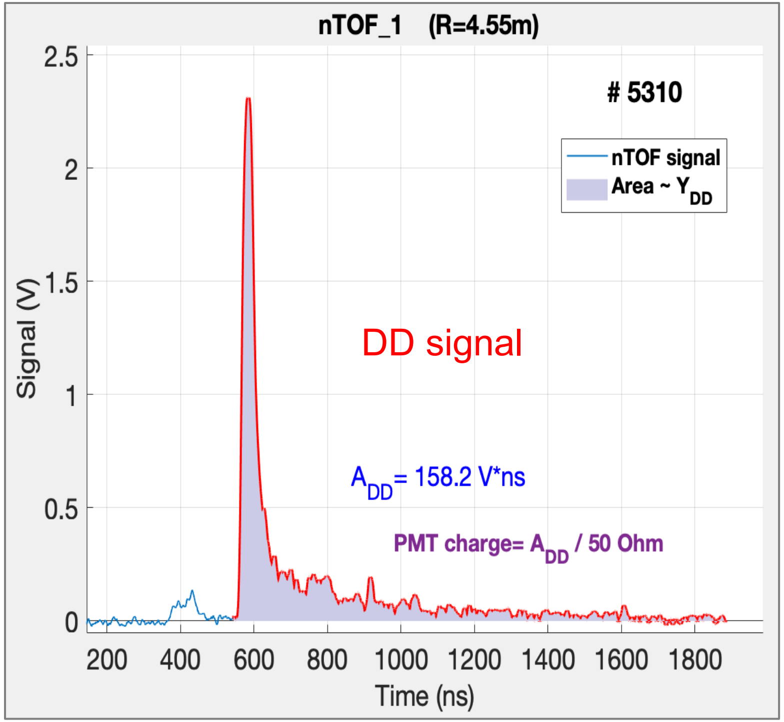
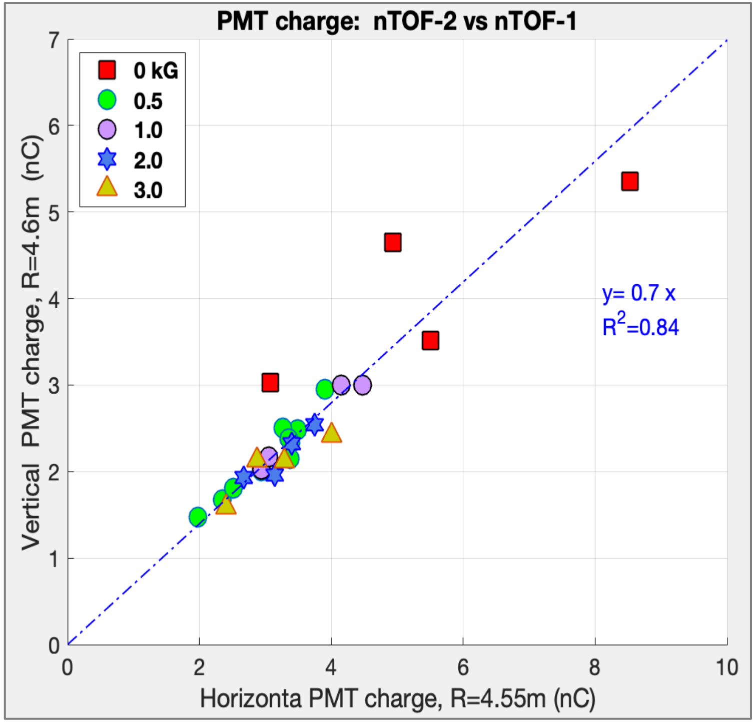
Neutron emission is isotropic for B_z > 500Gs



Area under the DD signal is proportional to the neutron flux captured by the nTOF.



Linear correlation between the neutron flux captured by the vertical and horizontal nTOF detectors suggests isotropic, thermonuclear neutron emission.

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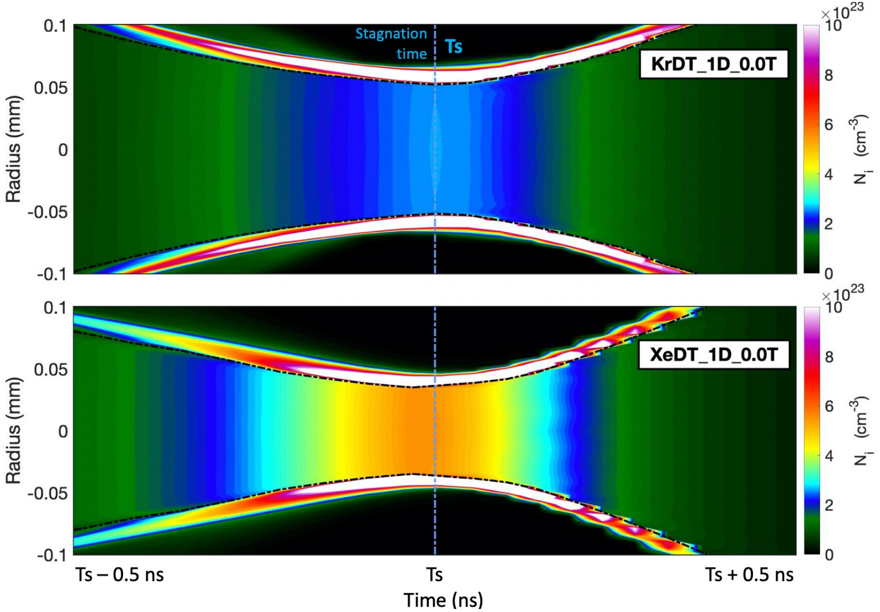
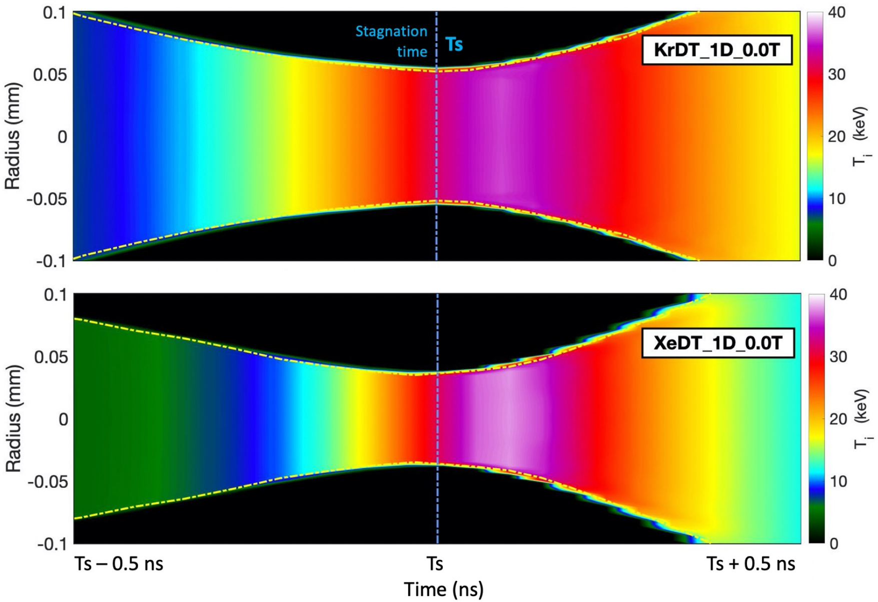
Comparison plasma parameters for 10MA LTDX machine near peak

Plasma Density



Ion Temperature



- A thin magnetized high density layer of liner plasma develops at the interface.
- The ram pressure is almost twice for Xe liner as compared to Kr liner.
- This thin layer compresses the preheated target adiabatically.
- The ion temperature at stagnation is around 25KeV for both Kr & Xe liner.
- Plasma density of target plasma reaches twice for Xe Liner than Kr liner.

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