Staged Z-pinch Target for Fusion

Frank J. Wessel, Chief Scientist
Magneto-Inertial Fusion Technologies, Inc.
Tustin, CA 92780

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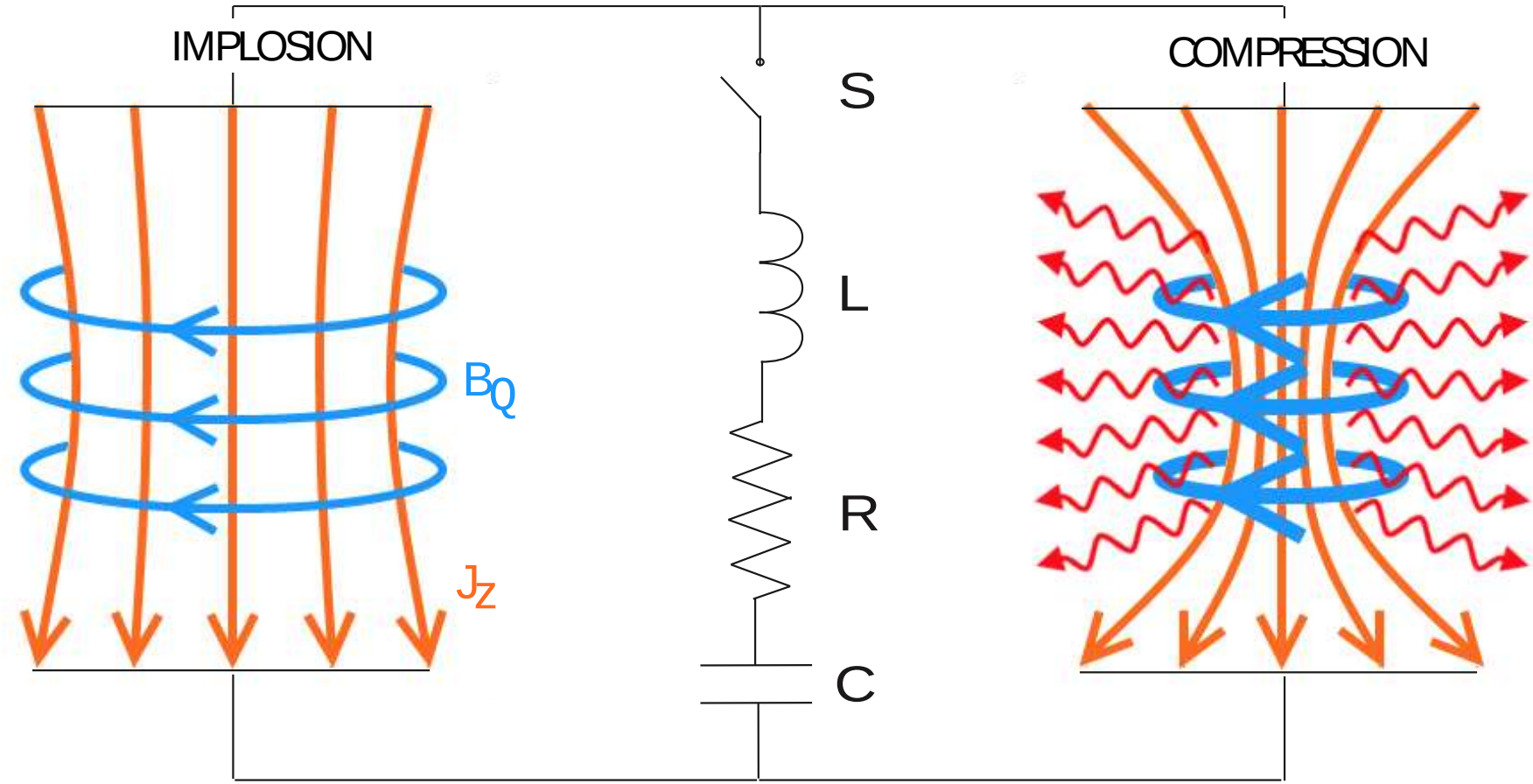
ARPA-E, DE-AR0000569

University of California, San Diego

University of Nevada, Reno

Z-pinch

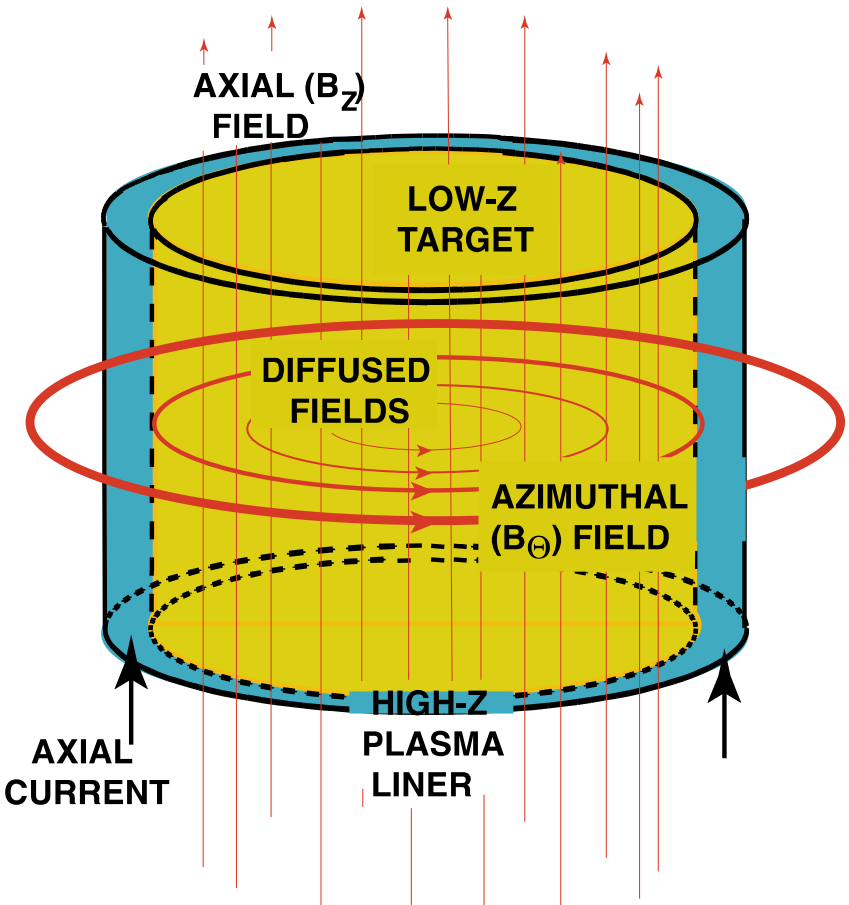


Driver Parameters:

I = 0.1 – 10's MA, V = 0.05 – 5 MV

$t_{1/4}$ = 0.1 – 10's μs, P = 10^{-3} – 100's TW

Staged Z-pinch (SZP)



- Axial magnetic field, B_z
- High atomic # liner, Kr
- Low atomic # target, DT

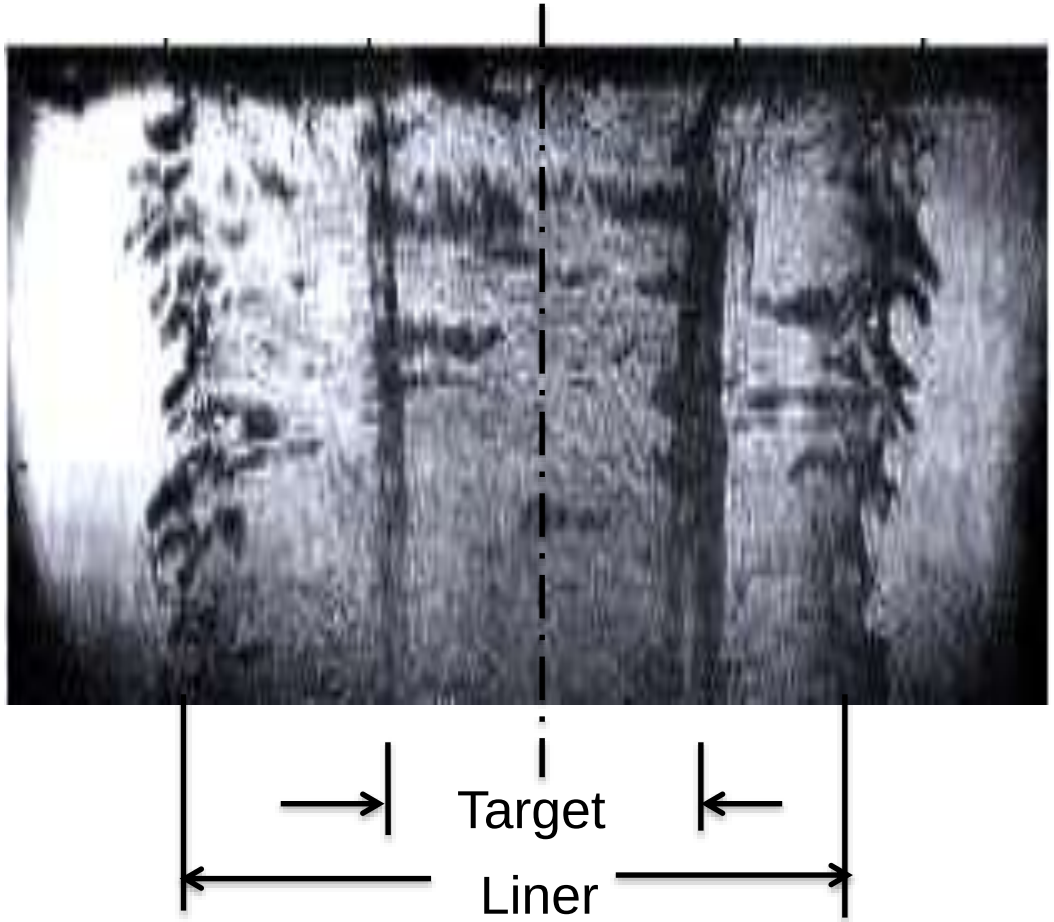
- Stable-target implosion
- Magneto-inertial compression
- Fusion-product containment
- Target ignition
- Existing driver systems

F. J. Wessel, F. Felber, et.al., Applied Physics Letters 48, 48 (1986), 1119.
H. U. Rahman, F. J. Wessel, et.al., Physical Review Letters 74 (1995), 714.
H. U. Rahman, F. J. Wessel, et. al. Phys. Plasmas 19 (2012), 122701:1–13.
F. J. Wessel, H. U. Rahman, et.al., Fusion in a Staged Z-pinch. AIP Conf.Proc., Mar. 2015.

SZP - UC Irvine (~1993-1998)

Kr -> D^+, B_z = 0.01 T

5 ns, Laser Schlieren Image



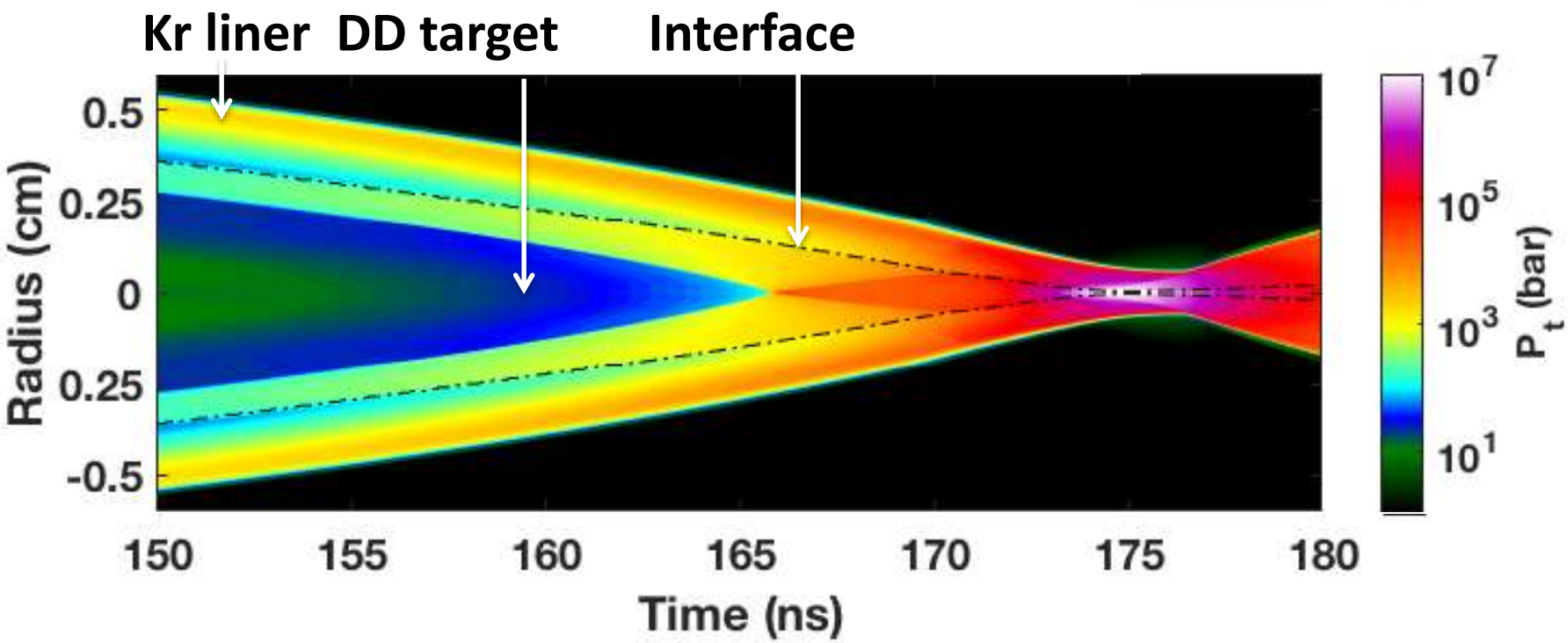
Unstable liner

Stable target

Outline

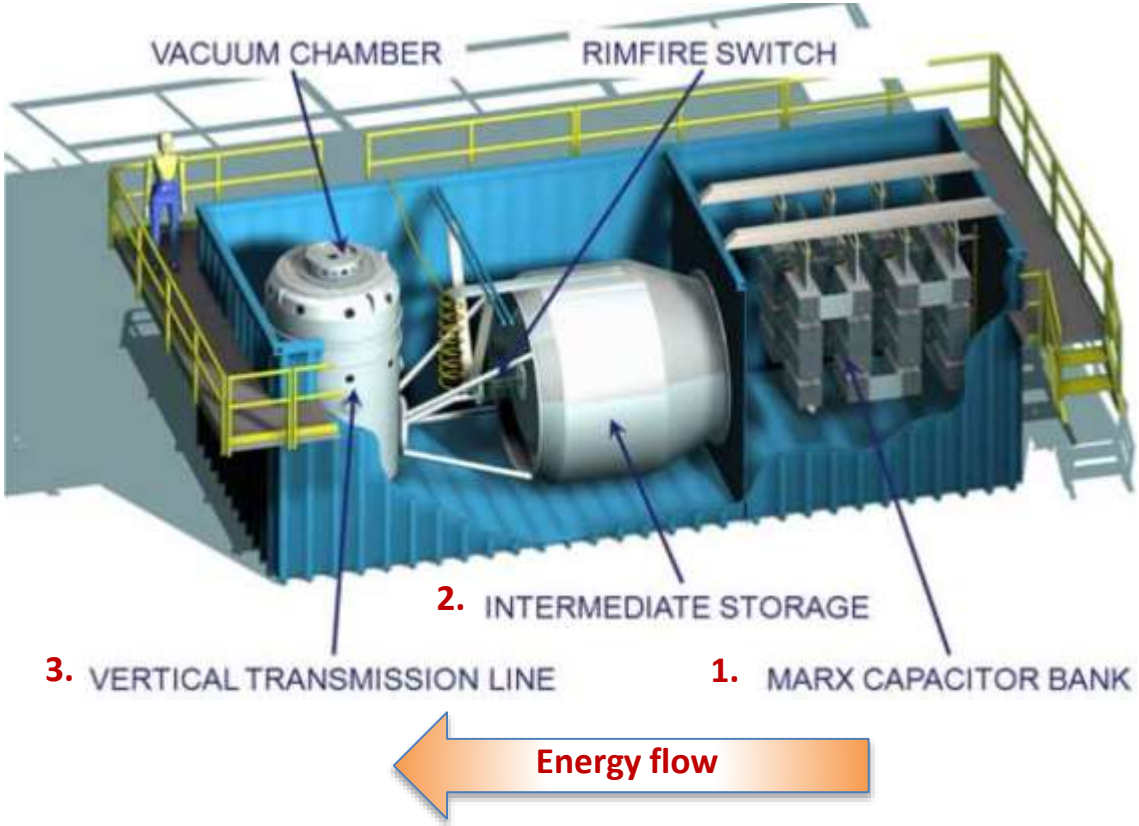
- Staged Z-pinch Overview
- Status
- Next steps

Pressure (r, t)



- Shock breakout, ~ 90 ns
- Target compressed, ~166 ns
- Target recompressed, ~174 ns

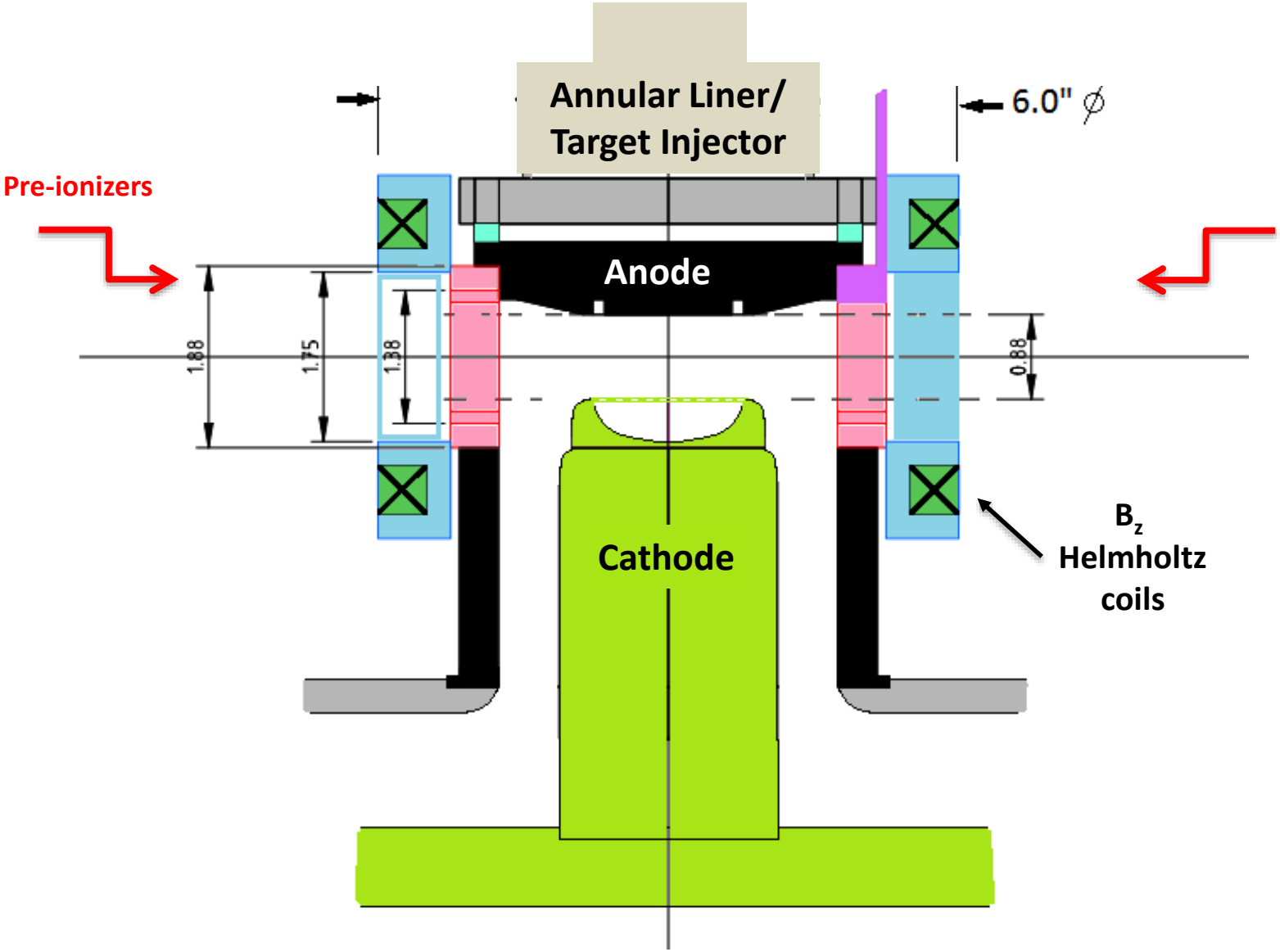
Zebra (UNR)

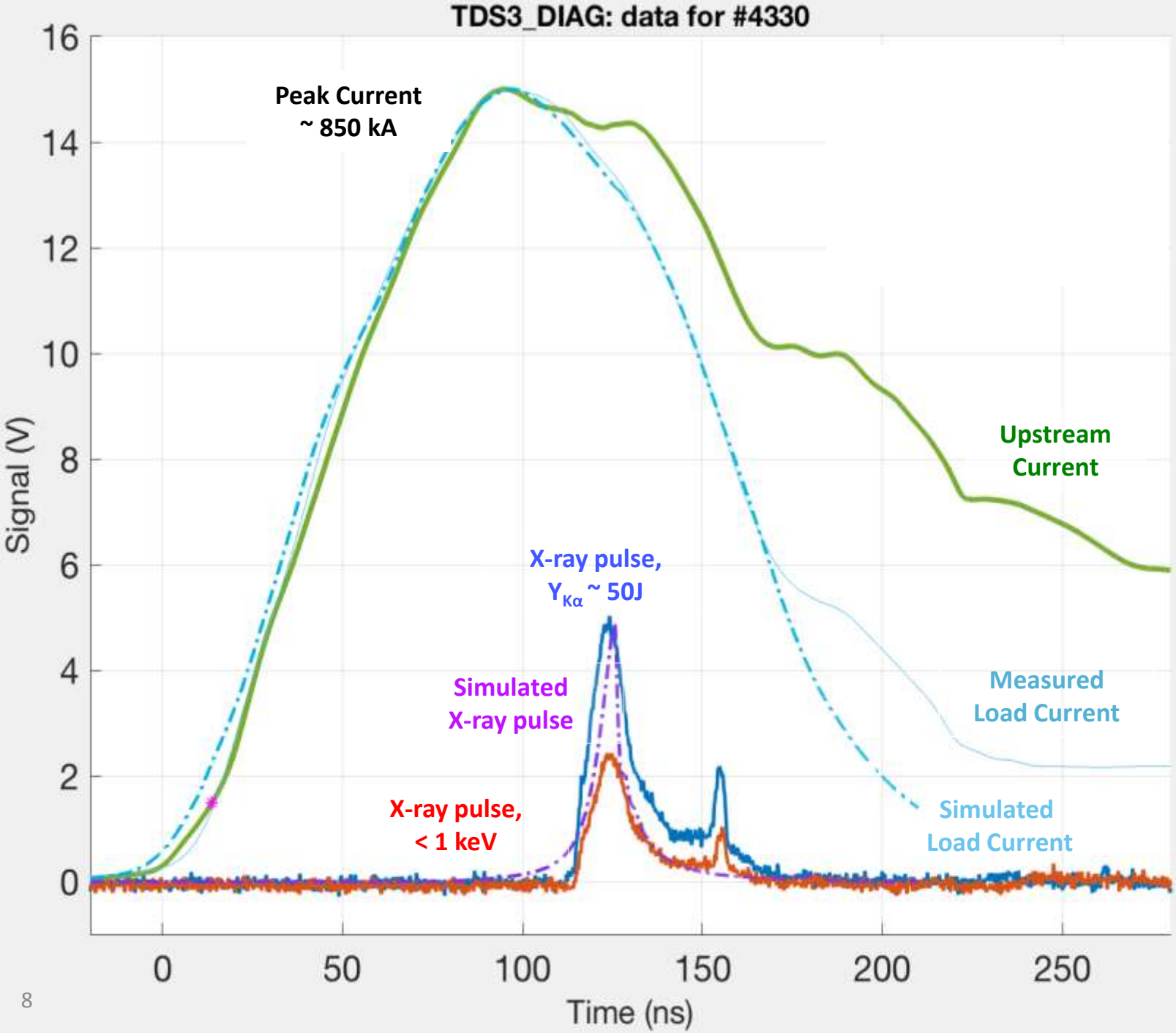


Installing the injectors

2 TW, 1 MA, 100 ns, 1.9 Ω

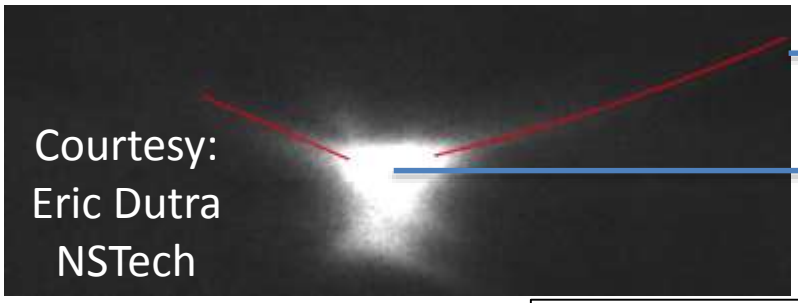
SZP Layout


Annular Liner/
Target Injector
6.0" ∅
Pre-ionizers
Anode
1.88
1.75
1.38
0.88
Cathode
B_z
Helmholtz
coils


TDS3_DIAG: data for #4330
Peak Current
~ 850 kA
Upstream
Current
X-ray pulse,
$Y_{K\alpha}$ ~ 50J
Simulated
X-ray pulse
Measured
Load Current
X-ray pulse,
< 1 keV
Simulated
Load Current
Signal (V)
Time (ns)
16
14
12
10
8
6
4
2
0
0
50
100
150
200
250

Shot 4328: v_r , n_i , T_e

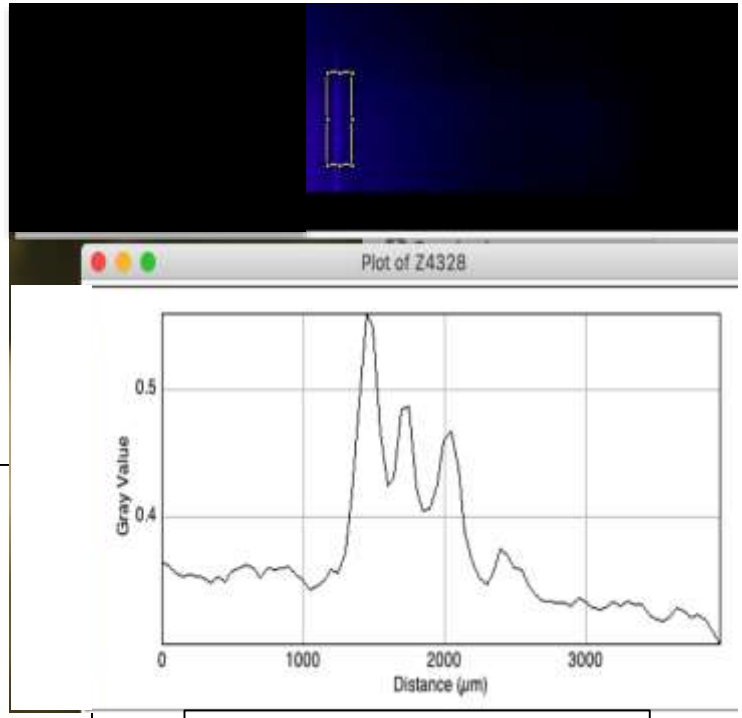
Optical Streak



50 ns

V_r ~ 35 - 40 cm/μs

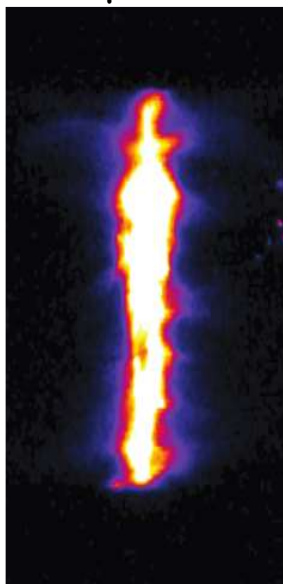
Filtered X-ray spectra - 1 μm Ni



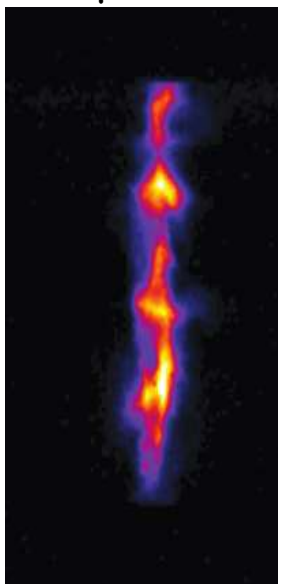
n_{f_Ar} ~ 5 x 10^{18} cm^{-3}
T_{fe} ~ 500 eV
$Y_{K\alpha}$ ~ 50J

Filtered X-ray pinholes

1 μm Ni



6 μm Ti



r_0 = 12 mm
Δr_0 = 5 mm
r_f ~ 0.6 mm
$C = r_0/r_f = 20$
$B_{z0} = 10^{-2}$ T
B_{zf} = 50 T
$n_{0\_Ar} = 5 \times 10^{17}$ cm^{-3}
$n_{f\_Ar} < 2 \times 10^{20}$ cm^{-3}

Next Steps

- Fall campaign - 12-30 September 2016
  - Improved liner/target injectors
    - nozzle refinements
    - target-plasma density
  - Laser diagnostics
  - Gated-optical imaging

- Optimal target density (from simulations):
  - $n_{0\_target} \sim 5 \times 10^{17}/cm^3$, $Y_{Neutron} \sim 10^{12}$
  - $n_{target} \sim 50 \times$ Spring campaign

?'s

Zebra Experiments

- 17 shots: 28 April 2016 – 6 May 2016
  - ½ time hardware/diagnostics, ½ time shots
  - 9 shots, liner only, w/ & w/o B_z field
  - 4 shots, liner + gas-jet target, w/ B_z field
  - 4 shots, liner + plasma-jet target, w/ B_z field

Zebra Diagnostics

Standard electrical probes: V-dot, B-dot, etc.

X-ray:

Fast XRD/PCD, < 10keV detectors
Curved KAP crystal spectrometer (film, time-integrated)
X-ray pinhole camera imaging (film, time-integrated)
Hard x-ray (> 50keV) scintillator detectors (n-TOF)

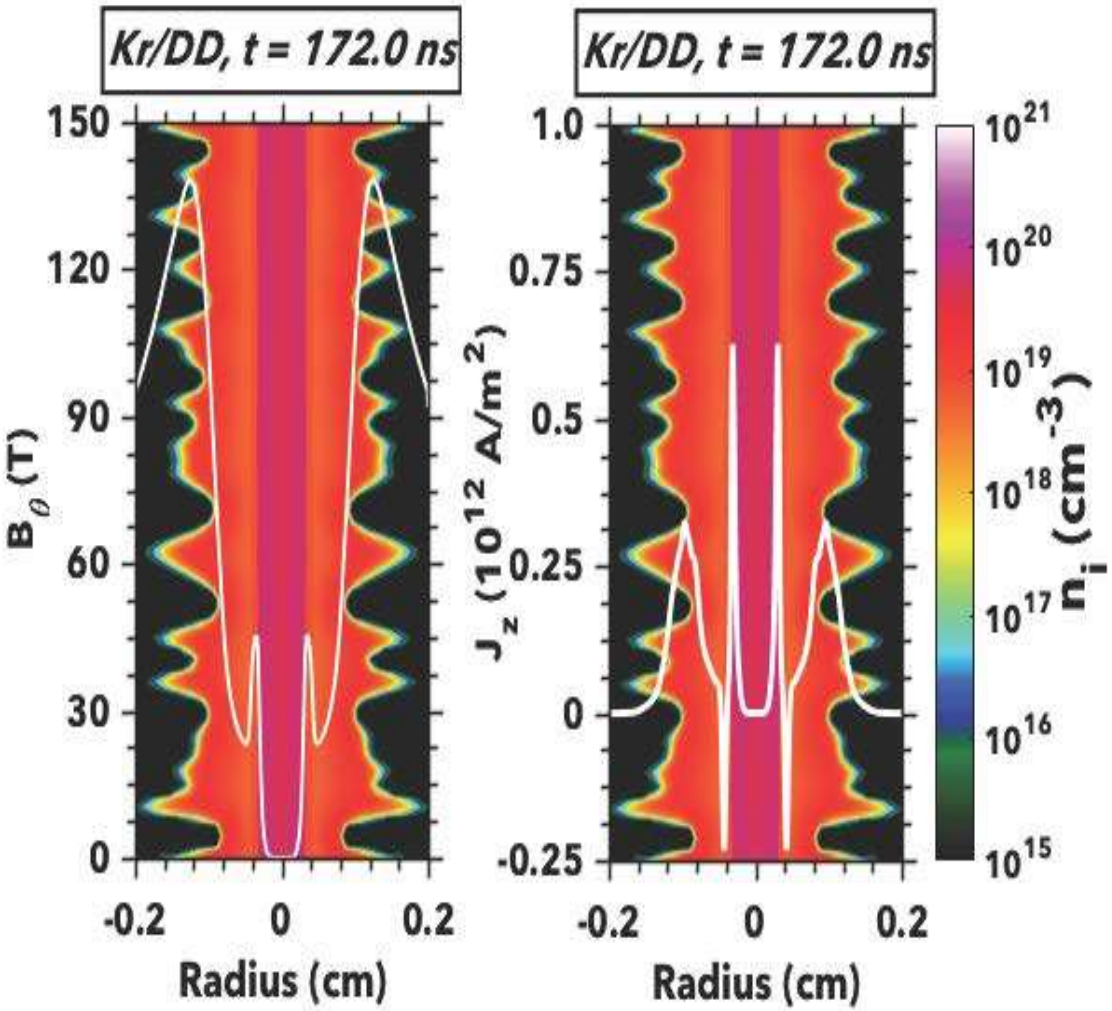
Optical:

Visible emission streak imaging
Fast 2-image transmission imaging (Ekspla 1064/532/266nm)

Neutron:

Ag, Y – activation yield detectors, calibrated
4 fast neutron time-of-flight (TOF) scintillation detectors

n_i , J_z , and B_θ



Peak Compression

Unstable liner

Flux compression

Current reversal

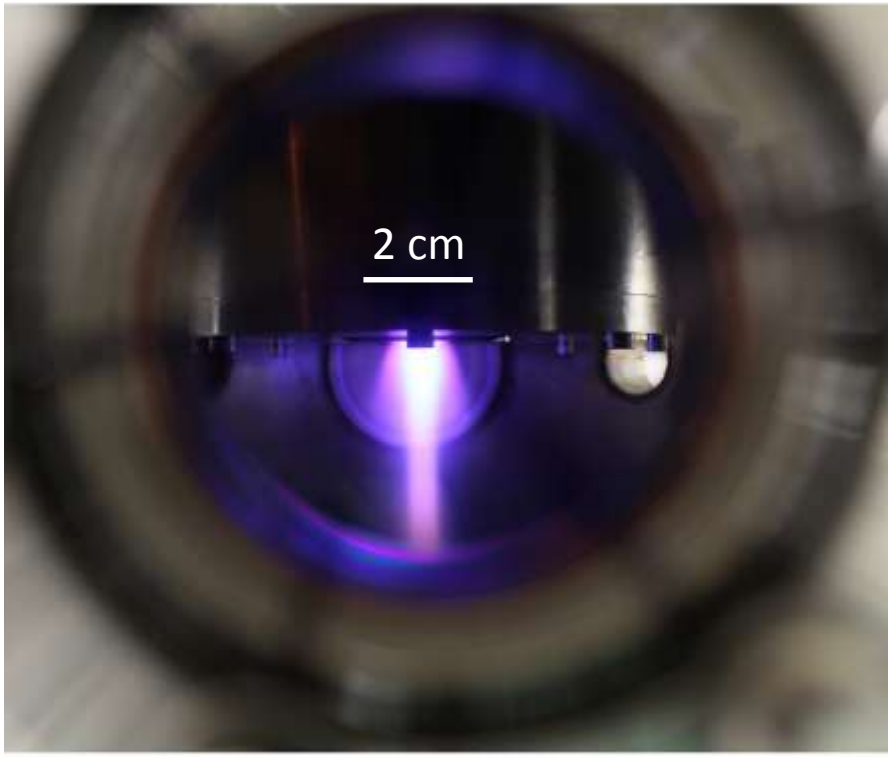
Shock front

Stable target

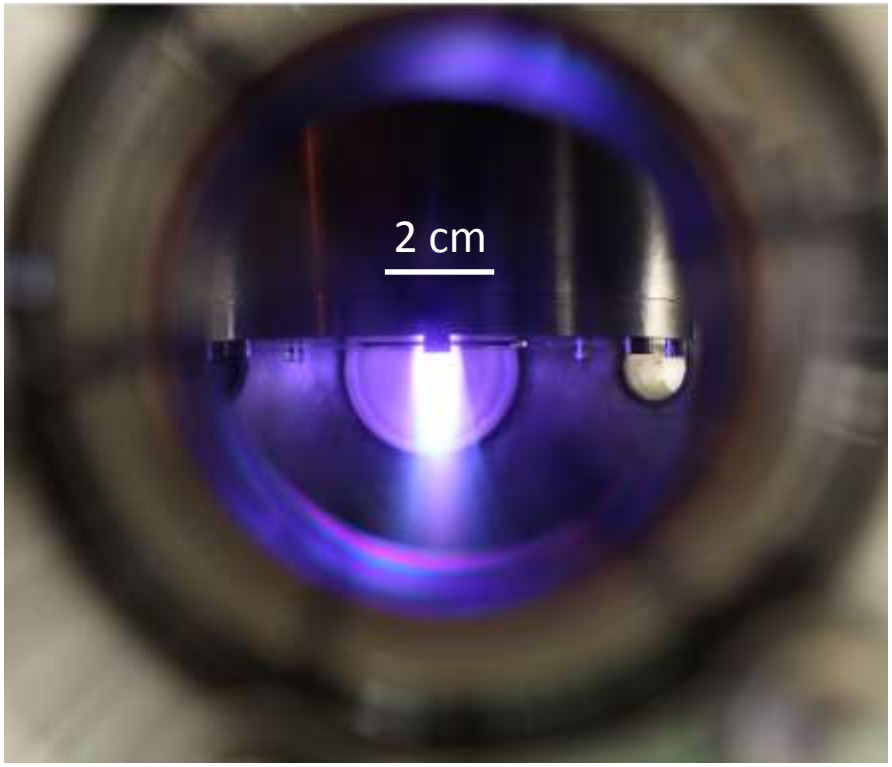
Characterization of the Liner - Target Injector (Test-Stand Results)

Ar liner @ 3 Bar, D_2 target @ 20 Bar
Plasma Gun - 3 kV, 3 kA, 15 μs

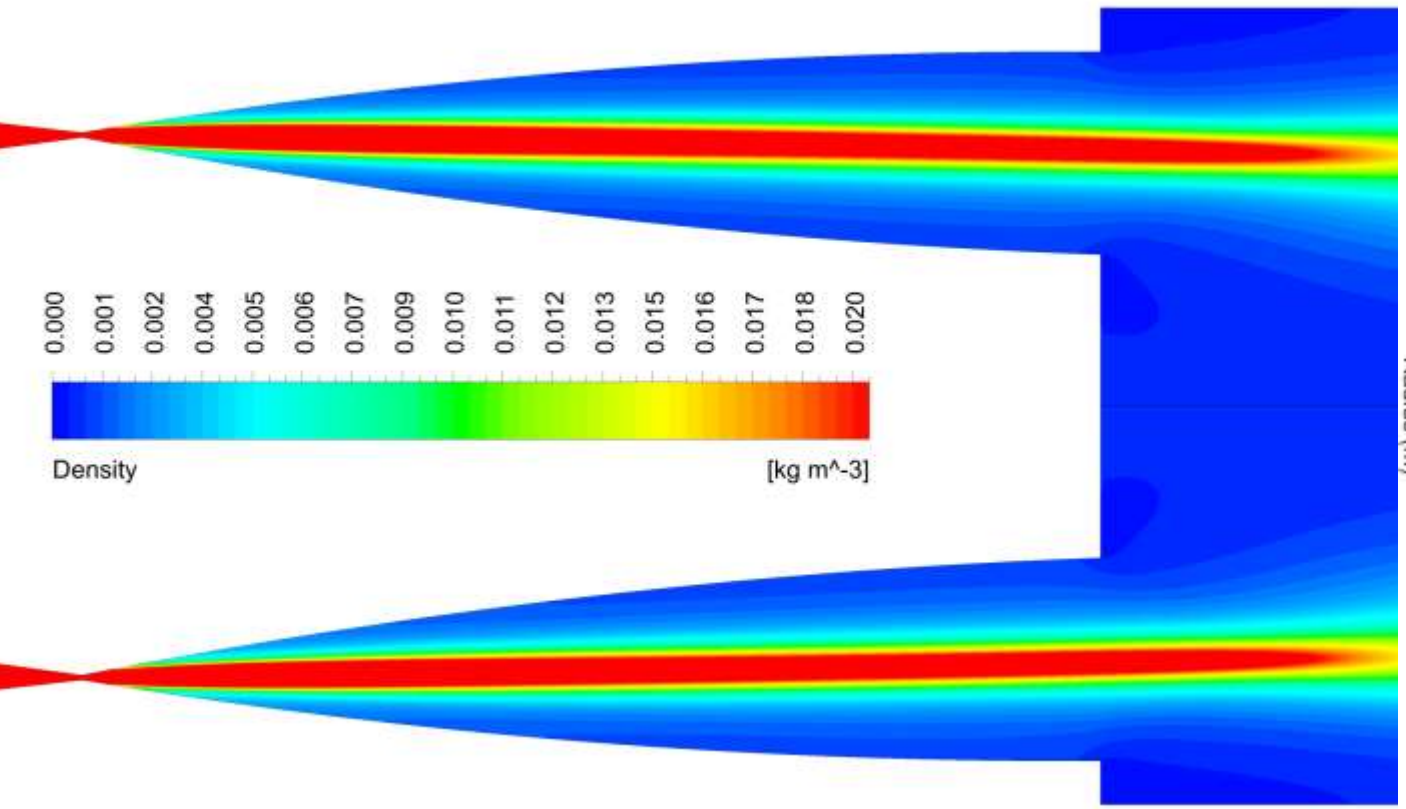
Target delay - 180 us

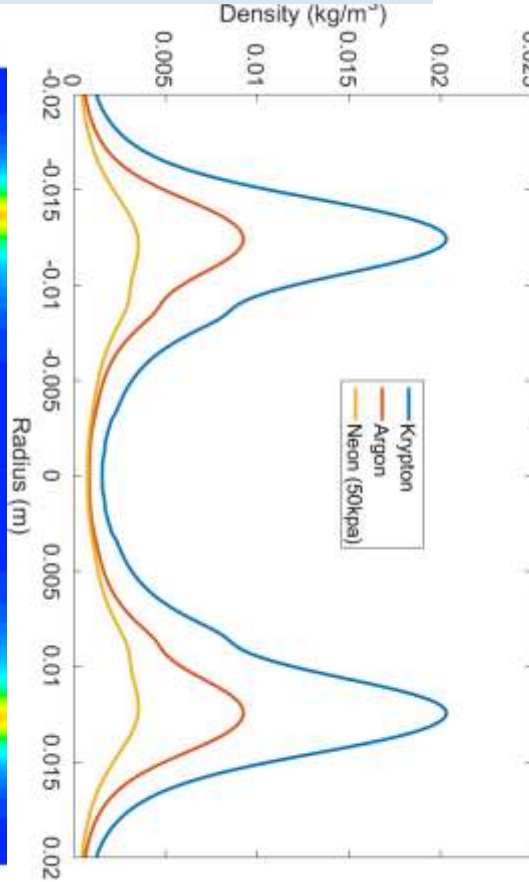


Target delay - 300 us



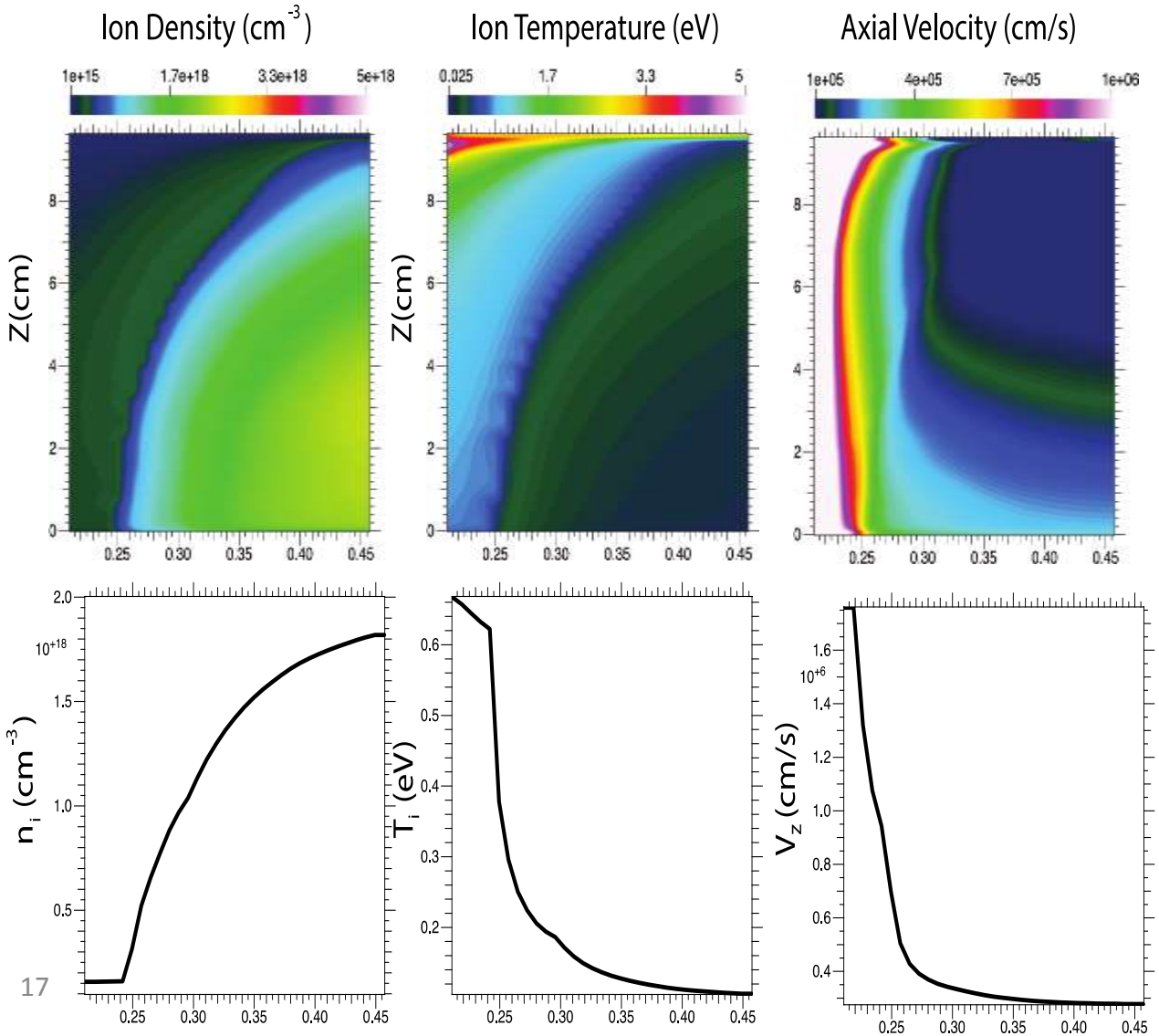
Liner Injector - CFD Simulation





- R = 1 cm, n ~ 10^{17}cm^{-3}, ρ ~ 0.01kg/m^3, 50 kPa Ar
- MACH Number ~ 7, for Ne, Ar, Kr

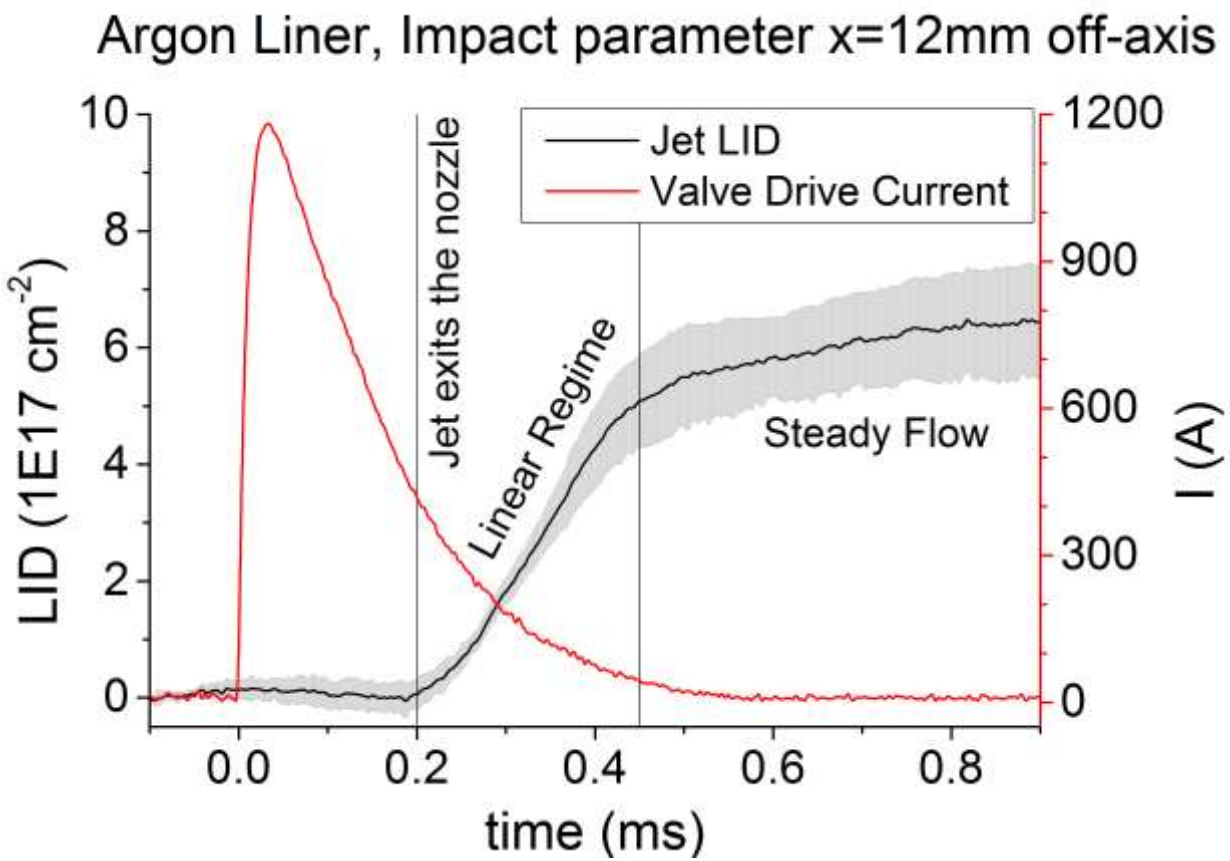
Target Injector - MHD Simulation



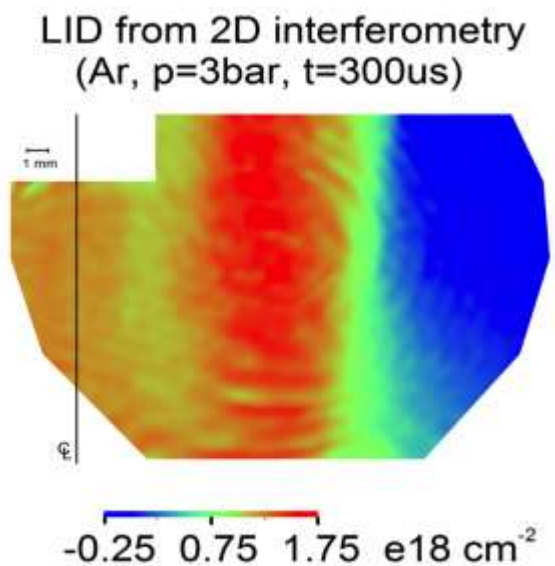
- On-axis valve injects D_2
- HV pulse accelerates plasma into the AK gap
- Plasma enhances ionization and defines the initial target
- Results shown at left: 4 μs & z = 0 cm

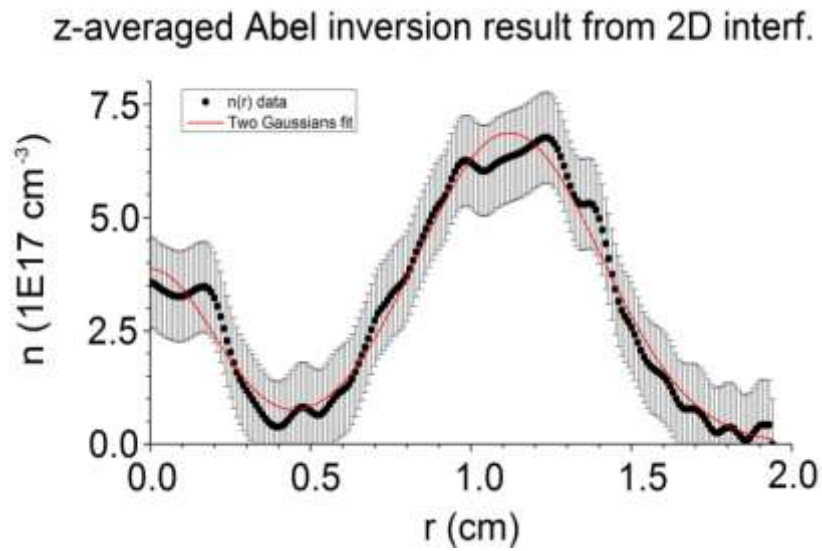
Annular-Liner Injector – n(t, z = 6mm)

Gas exits ~200 us, linear increase ~220 us, asymptotic flow ~ 450 us



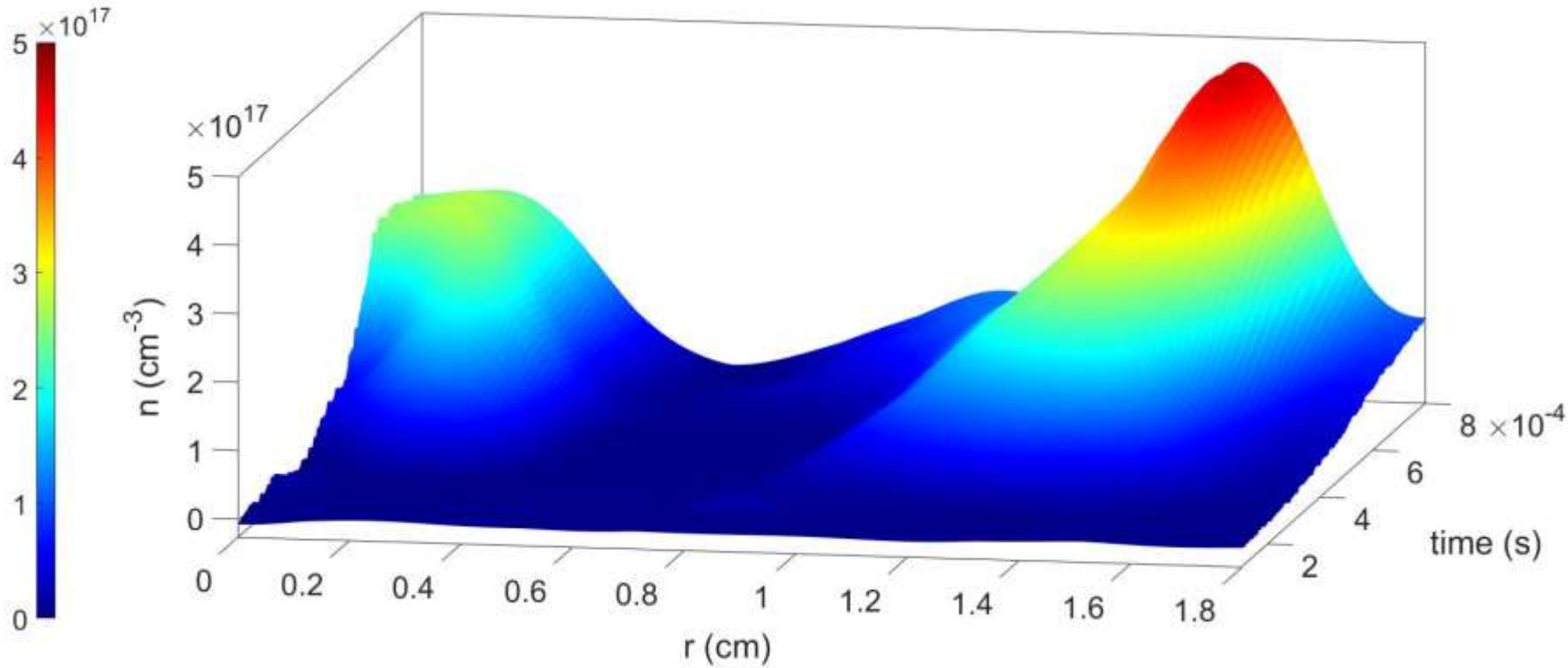
Annular-Liner Injector – n(r, z = 6mm)





- The gas jet is imaged 300 us after valve firing (linear regime)
- Flow is well-collimated axially with a radius, R = 1 cm
- The density is suitable for the experiments
- Gas density present on axis

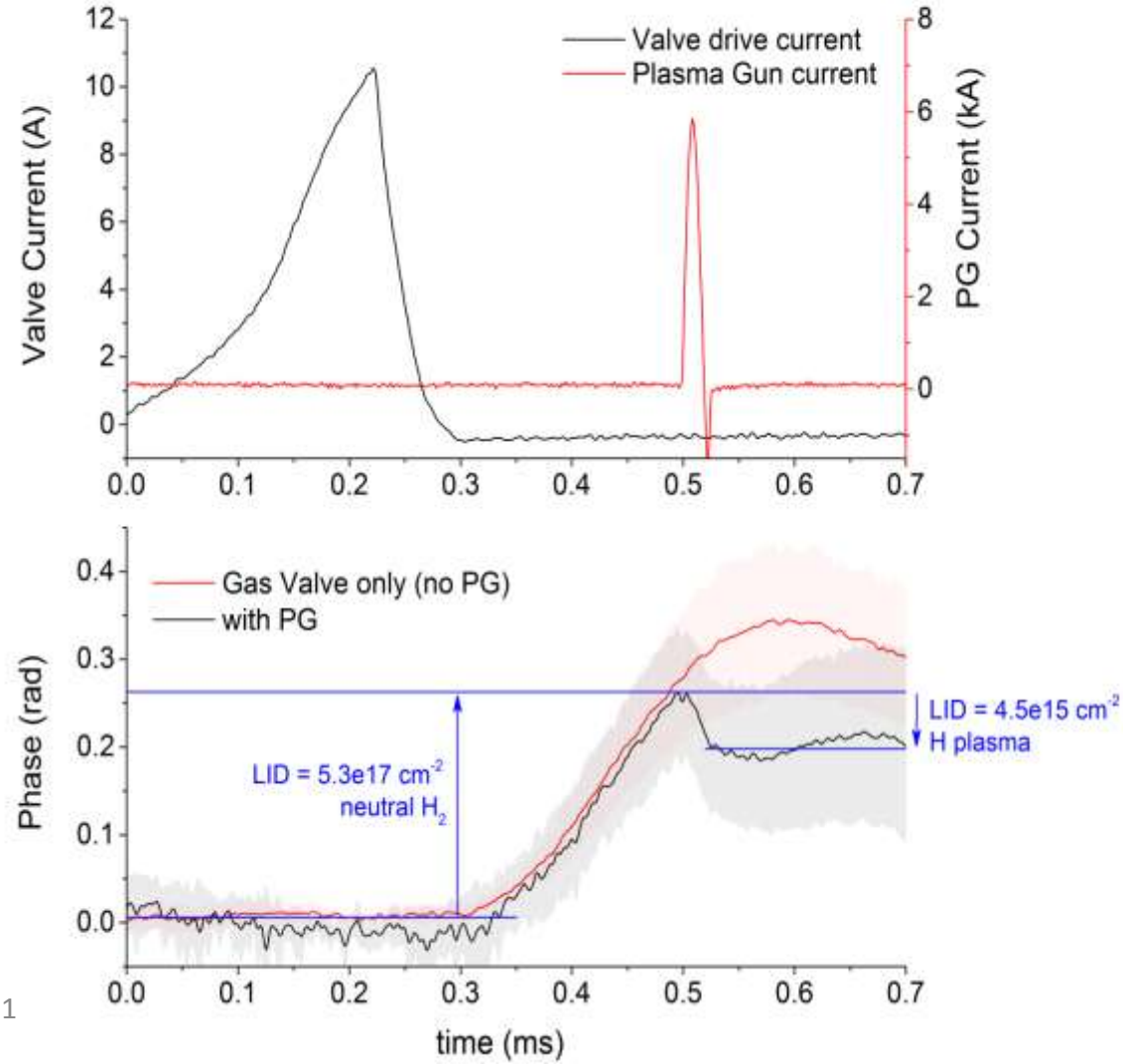
Annular-Liner Injector, n(r, t, z = 6mm)



- Gas evolves on-axis during the linear-flow regime
- Due to gas flow interaction with boundaries, late in time
- Appropriate timing will reduce its effect

Target Jet Injector LID

Plasma Gun operation p = 300 psig, x = 0mm



Jet with known dynamics

HV pulse ionizes/accelerates

Plasma is highly reproducible

Pre-ionization level <10%

Δt_{jitter} ~ 1 μs,

V_z ~1-2 cm/μs,

$\tau_{lifetime}$ ~20 μs

Refractive indices opposite sign for the gas & plasma

Target Jet Injector – Visible Light

- Plasma exits in ~ 5us
- Lifetime is ~20 us