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Energetiq Source Update [P46]

06/13/2019

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OUTLINE

- **Previous Work at Energetiq**
  - Stability Improvement by Adding Helium into Xenon Pinch
  - Gated Fast Imaging of the Pinch
  - Theoretical Explanation of the Effect of Helium

- **Fast Imaging with Additive Helium Flow**
  - Experimental Setup & Typical Images
  - Discussions

- **Summary**

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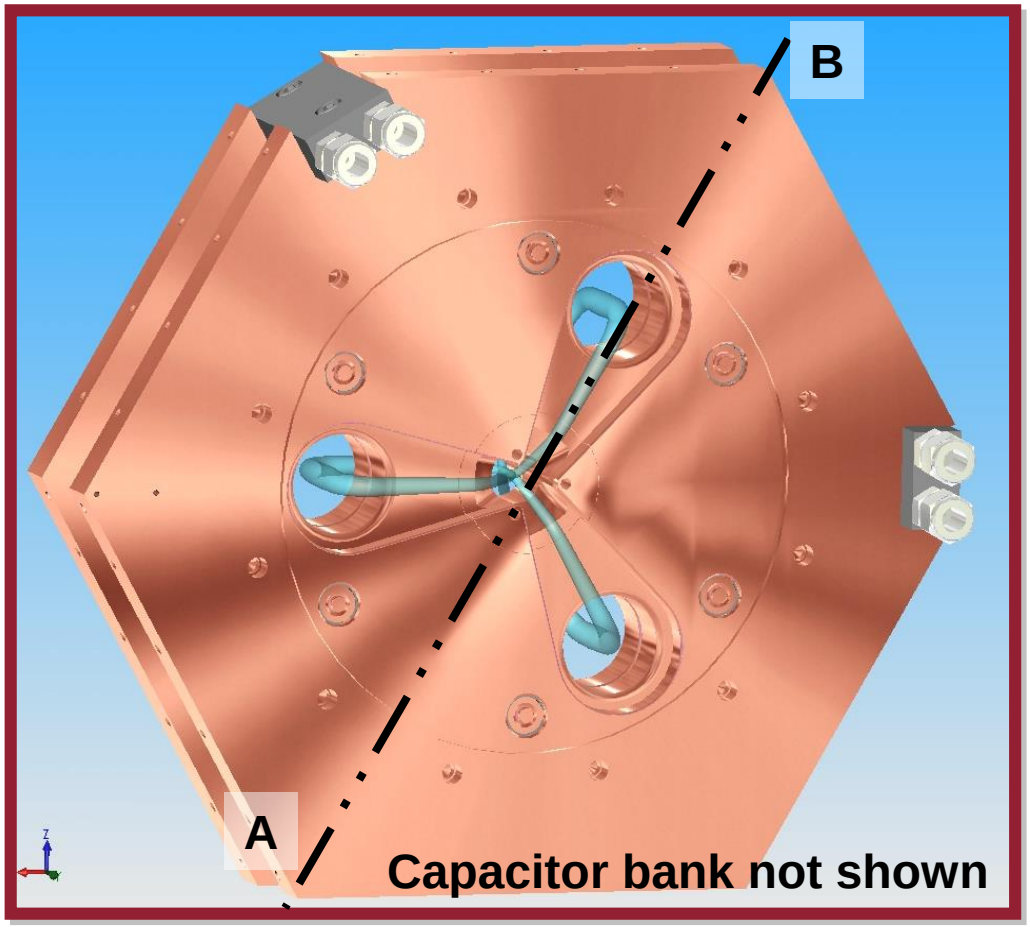
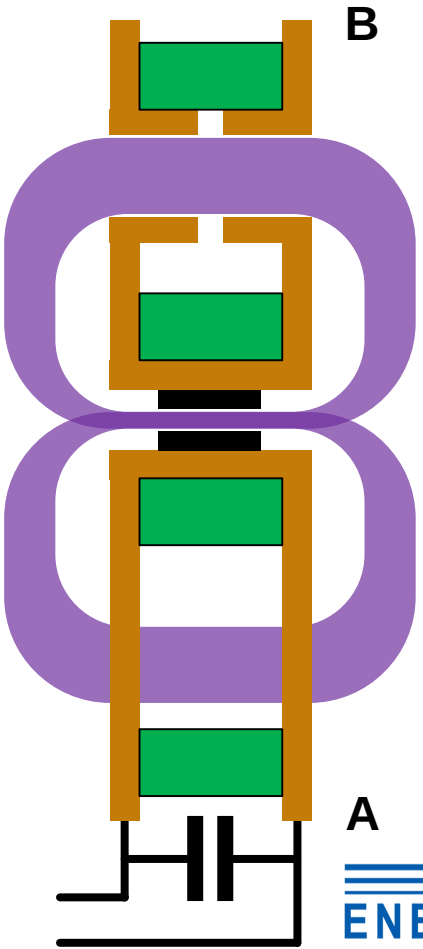
Energetiq: Electrodeless Z-pinch™ EUV/SXR Source





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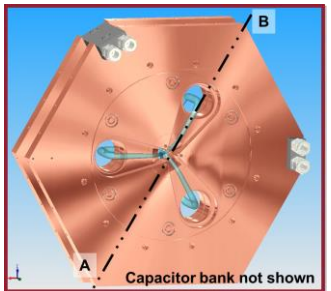
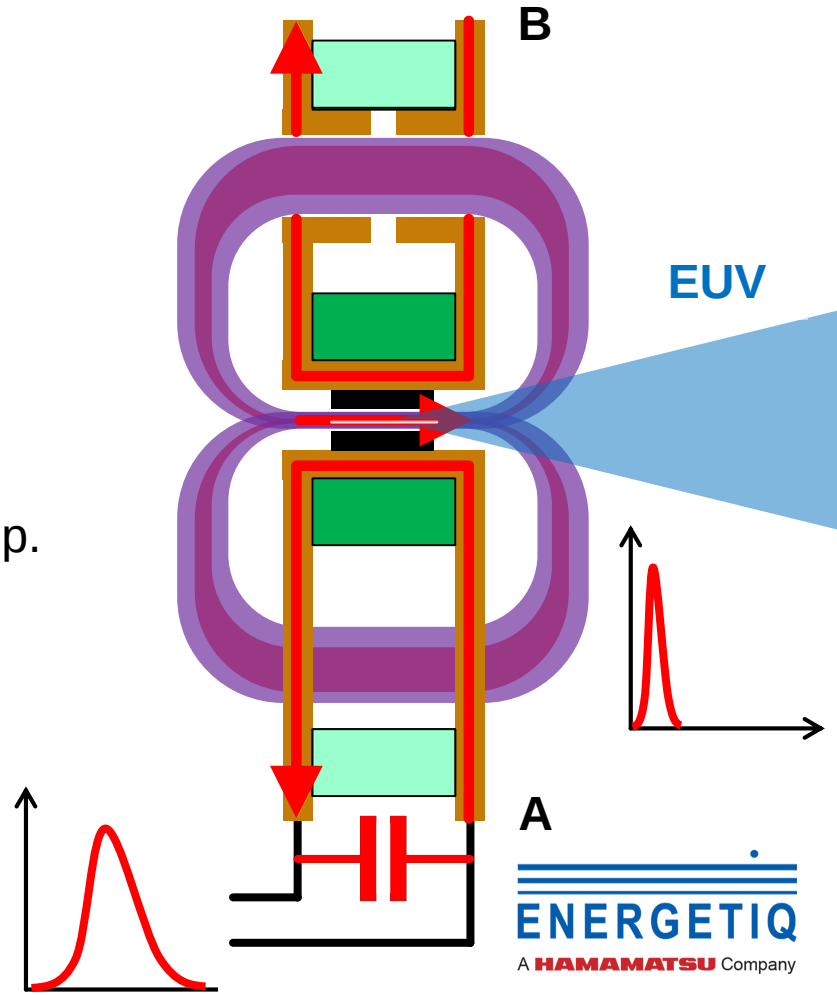
Energetiq: Electrodeless Z-pinch™ EUV/SXR Source

1. “Slow” pulse from modulator
2. Capacitor banks charge up.
   → Small leak current maintains the loop.
3. Outer core saturates.
   → Impedance goes to zero.
4. Capacitor discharges (Pulse Compression).
5. Inner core couples current pulse to plasma loop.
6. **Z-pinch !**



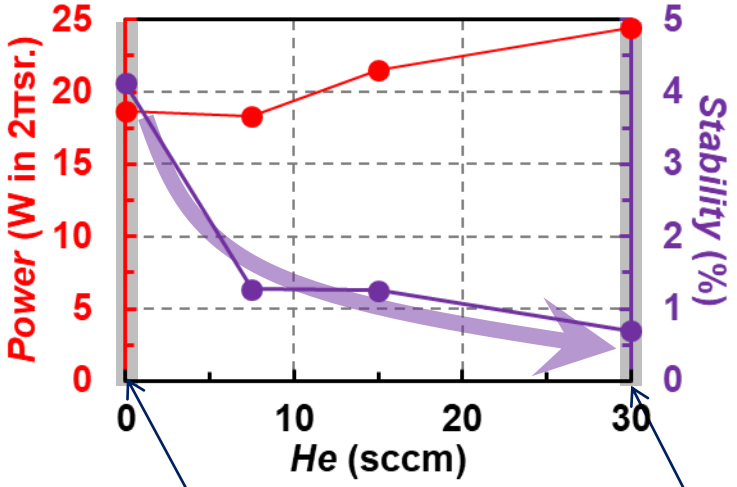


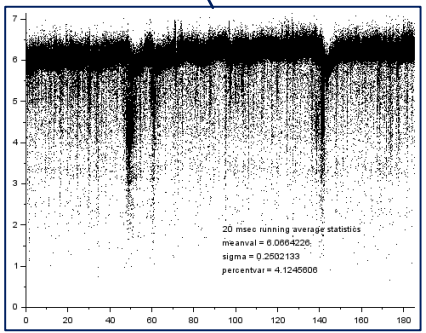
Why Helium ? … Helium does not do anything !

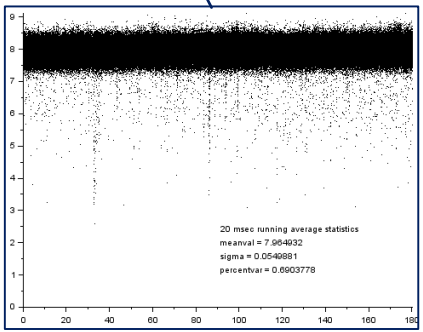
- **In the bulk plasma … the loops , pre-pinch**
  - Ionization potential … He : 24.6 eV (1^{st}) ; Xe : 12.13 eV (1^{st}) , 21.2 eV(2^{nd})
    - He is not completely ionized and will mostly remain as neutral.
    - He will not participate in the plasma physics.

- **In the pinch plasma … EUV plasma**
  - Electron temperature : T_e ~ 25 eV
    - He will ionize and participate in the plasma physics.
  - Atomic mass … He : 4 g/mol ; Xe : 131 g/mol
    - He will not affect the pinch dynamics because of its lighter mass.

Stability Improvement by Helium







Operating Condition

300 V , 2.5 kHz , Xe: 35 sccm , 70 mT

Helium improves stability.

20 ms running average

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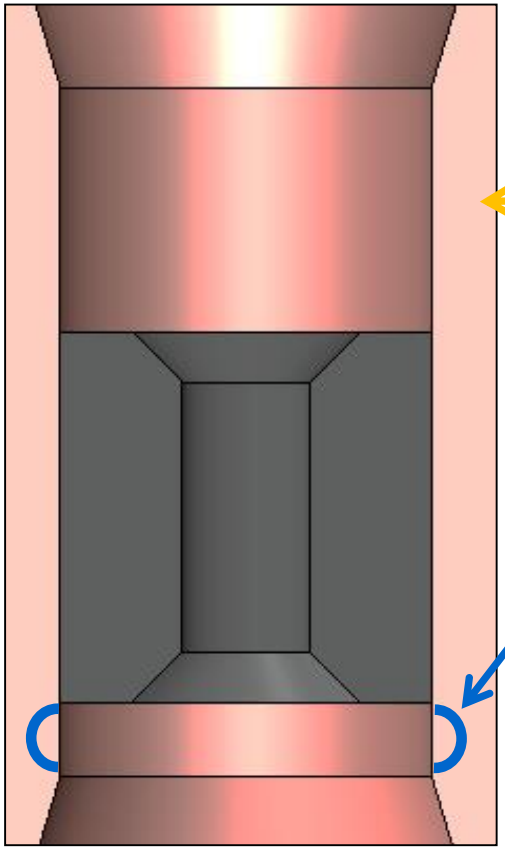
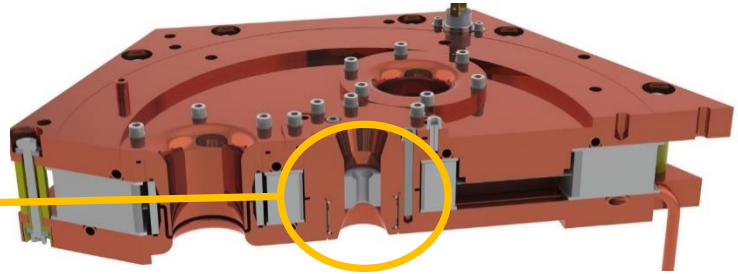
What is pulse-to-pulse stability all about?

- Each EUV pulse should be the same as the last.
- Differences might be due to
  - Different initial conditions -- variation in electrical joules delivered
  - Different final conditions – EUV pulse terminates prematurely
- Since the power delivery system is made up of components that have memory (capacitors, magnetics) initial conditions for n'th pulse may depend on details of the (n-1)'th pulse.
  - Presumably, if the (n-1'th) pulse was like all the previous pulses, then initial conditions for the n'th pulse will also match the earlier ones.
- Try to understand pulses that end prematurely.

A clue.. Used bores often show a feature…





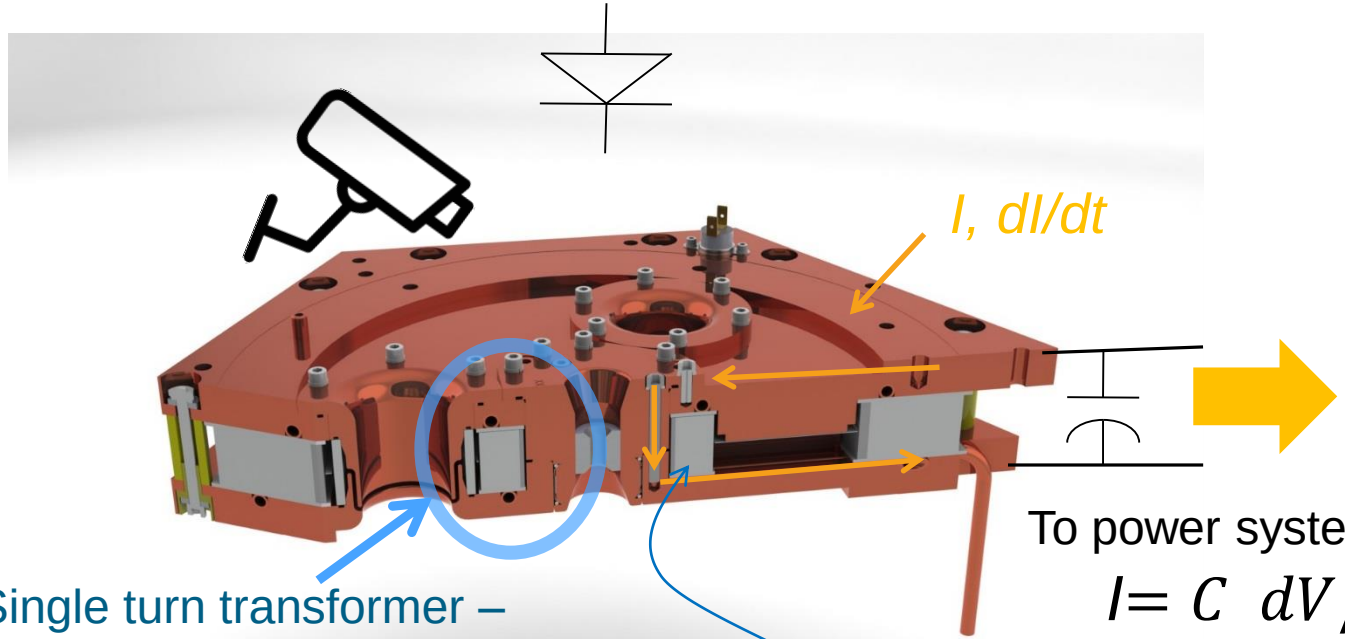
We often see an area of erosion just behind the bore insert. This erosion process requires energy, presumably stolen from the pinch. Likely related to pulse variability.

Operating assumption- some sort of arc forms in this region.

-- We should be able to verify an arc from electrical measurements..

Compare “normal” and “abnormal” electrical measurements.

Diagnostics – Diode, fast camera, capacitor voltage



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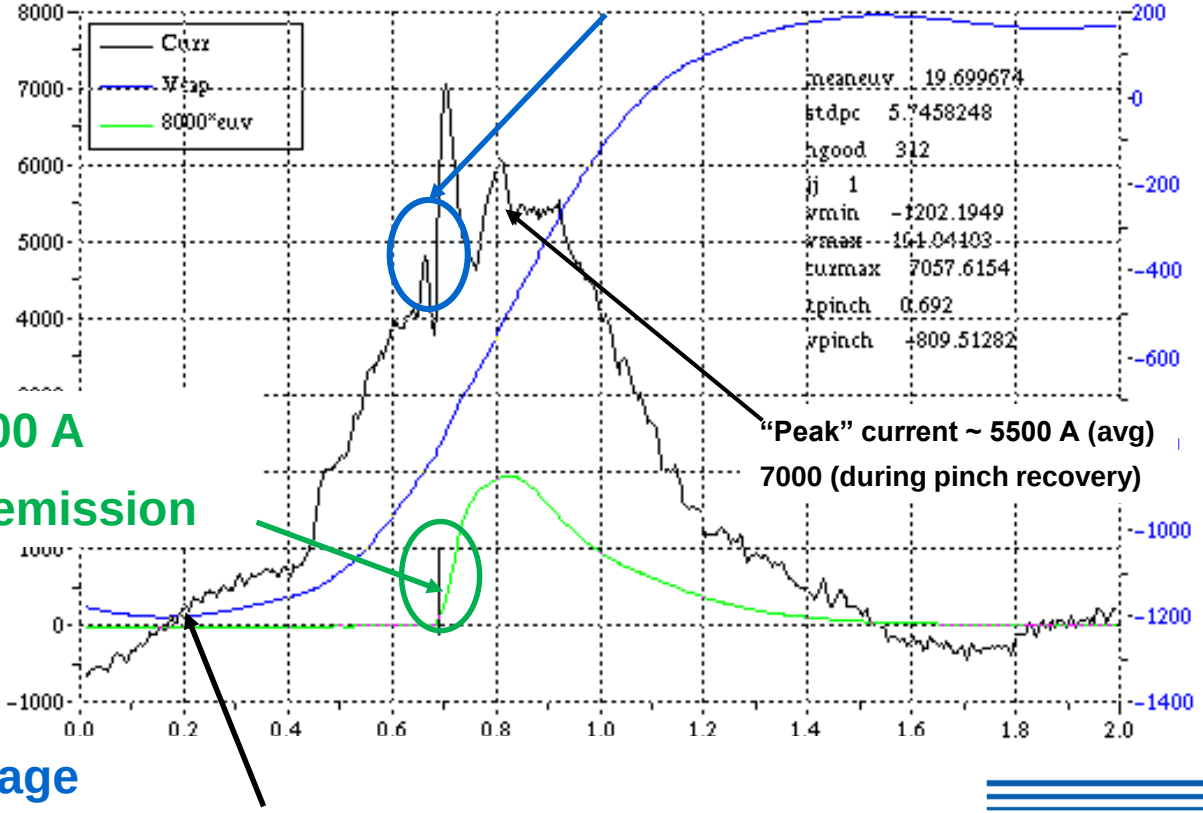
A “normal” pulse

Current glitch due to pinch –d/dt(LI)



EUV pulse – starts ~ 4000 A

Slow diode; risetime is emission

“Peak” current ~ 5500 A (avg)

7000 (during pinch recovery)

Capacitor voltage

Magnetic switch saturates; high-current pulse begins

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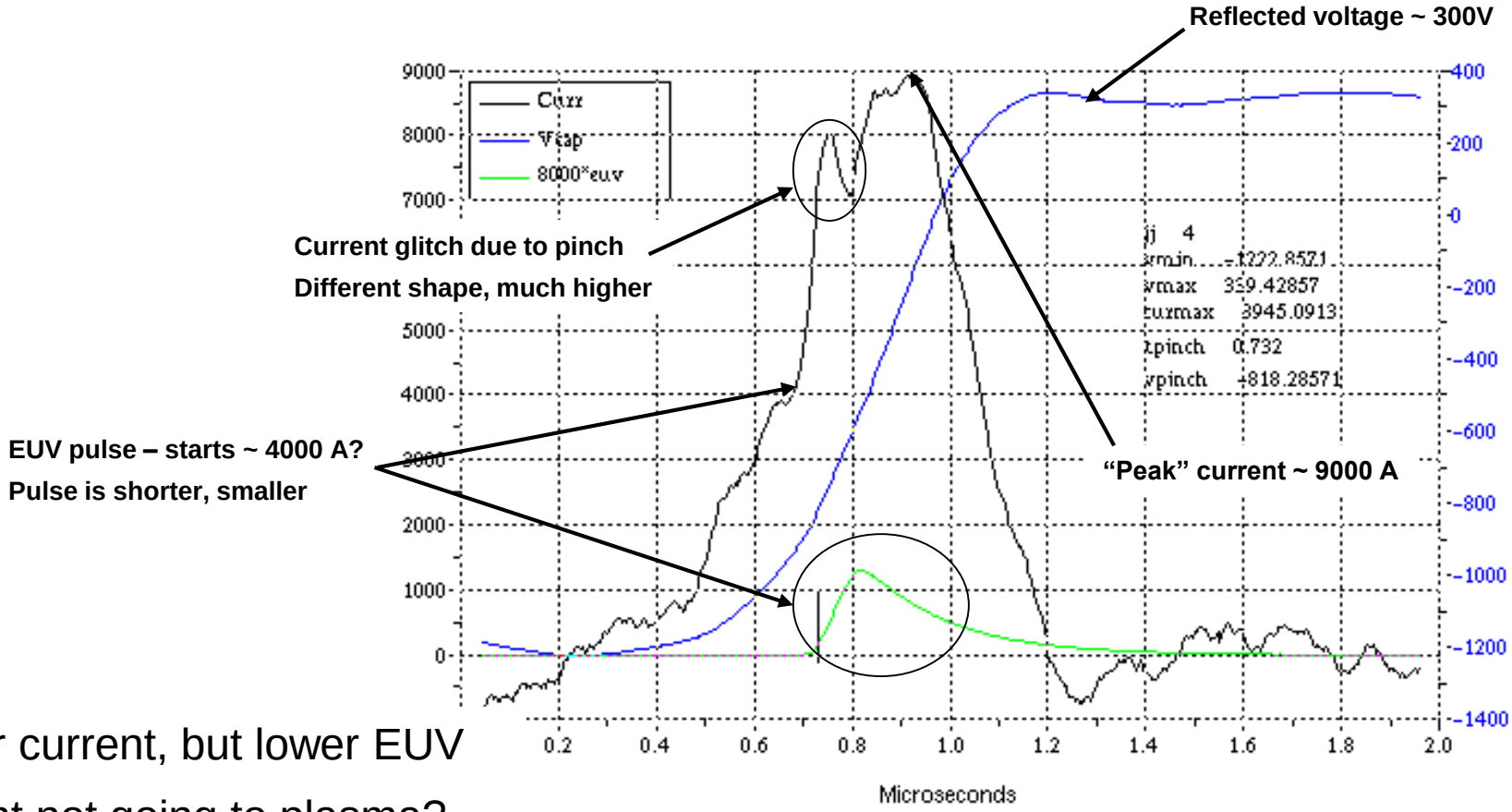
A “abnormal” pulse – higher current, lower EUV…



Higher current, but lower EUV

Current not going to plasma?

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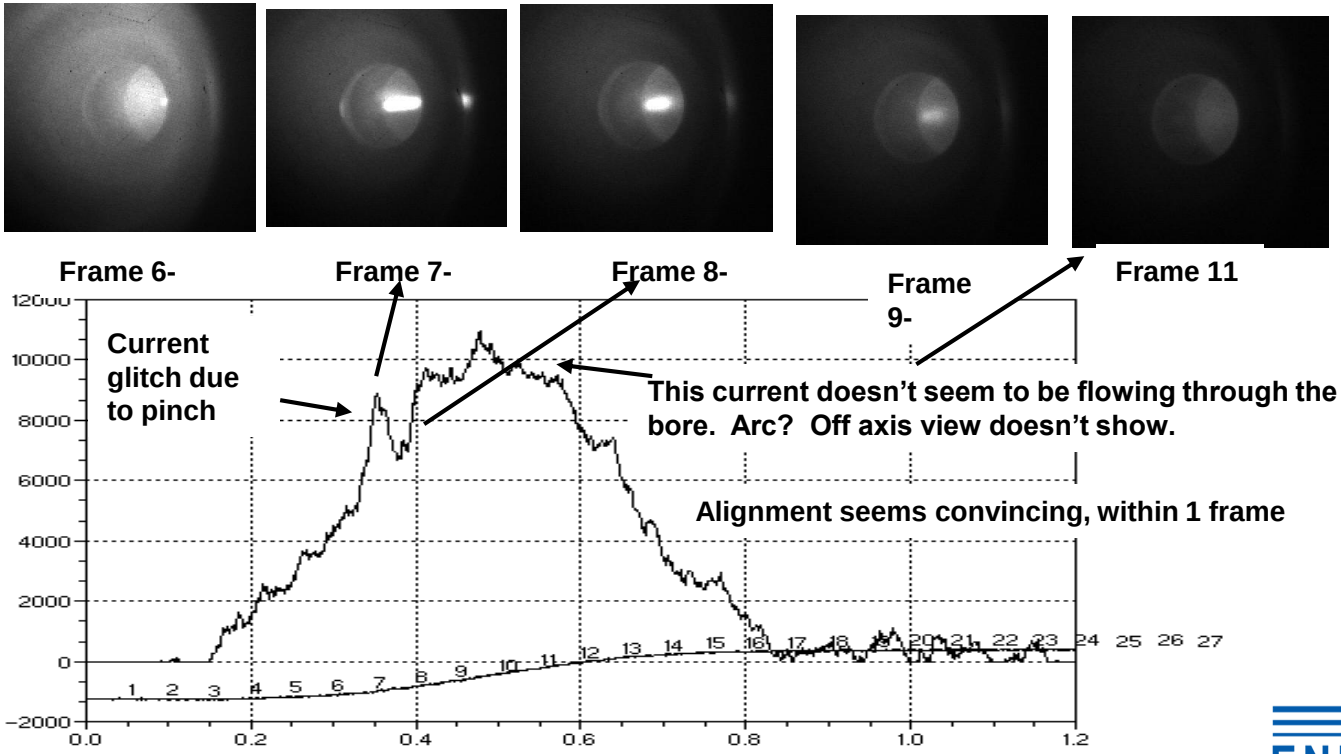
High-speed camera captures visible images of plasma … 10 deg. Off-axis view



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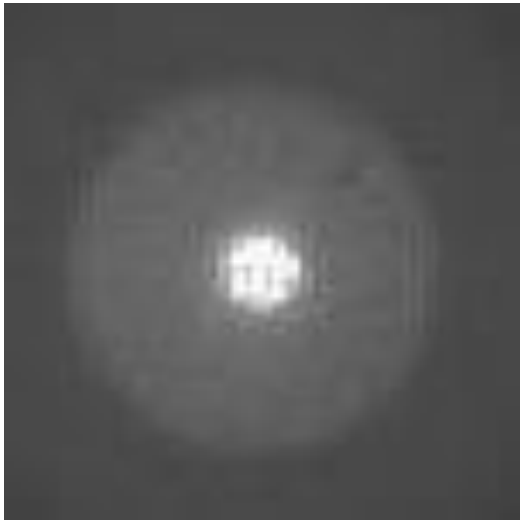
On-axis image of “abnormal” pulse shows radial plasma jet

normal



abnormal

First frame shows pinch. From previous slide, plasma current is still high for several frames after the pinch. Here, the frame just after the pinch shows a radial jet of plasma from axis to wall- at the location where we see erosion

Comparison of normal and abnormal pulses → "abnormal" pulse terminates early due to a "unipolar" arc.

- EUV starts at similar current in both cases
- Abnormal pulse has smaller amplitude euv pulse that lasts for shorter time
- Current trajectory at pinch time is different –
  - Peak current much higher in abnormal pulse (9000 A vs 5500 A)
- Current is finding a different path – lower impedance, not through plasma.
- Camera data identifies a radial plasma jet behind the bore

It's a unipolar arc, from plasma to wall

(We're not supposed to have electrodes in this device – when one develops spontaneously it's a problem!)

The story so far..

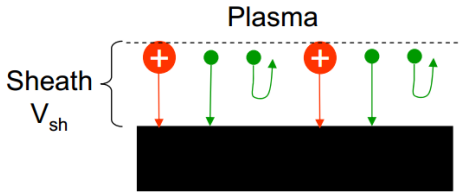
- Good evidence that pulse-pulse variability is caused by an arc, immediately behind the bore.
  - Electrical measurements consistent with an arc
  - Camera observations capture a plasma plume in that location.
  - Erosion is observed in that location.
- Data – we have an arc that is suppressed by Helium.

How interpret the data? What's the physics?

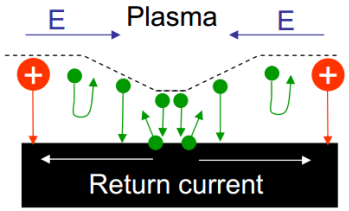
- **What drives arc formation and location?**
- **Why does Helium reduce the effect?**

First component … plasma floating (ambiplolar) potential

- A positive potential develops between the bulk plasma and the wall – the “ambipolar” potential.
  - Electrons are much more mobile than ions; higher energy electrons exit the plasma
  - A positive potential develops - reduces electron losses, enhances ion losses so ion and electron fluxes are equal – no net current.
  - The potential is typically a few times *Te*, the electron temperature.
  - If this voltage exceeds breakdown voltage, an arc can develop…
  - Investigating ambipolar arcs is an industry in Tokamak research



Dielectric wall:
$J_i = J_e$, everywhere
$V_{sh} = T_e \mathrm{Ln}(M/2\pi m)^{0.5}$



Conductive wall with electron emitting (δ) spot

Global floating condition:
$\int_s [J_e(1-\delta)-J_i]\cdot dS = 0$,

Summary of the ANL Workshop on Unipolar Arcs

Yevgeny Raitses
Princeton Plasma Physics Laboratory

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There's more to the story…
What are electrical conditions at the Z-pinch?

Electric field is induced by coupling core transformer action

$$\oint E \cdot dl = -d\Phi/dt = V$$

This tells us total voltage around the plasma loop, but doesn't tell us about the distribution of the electric field. We also have, locally

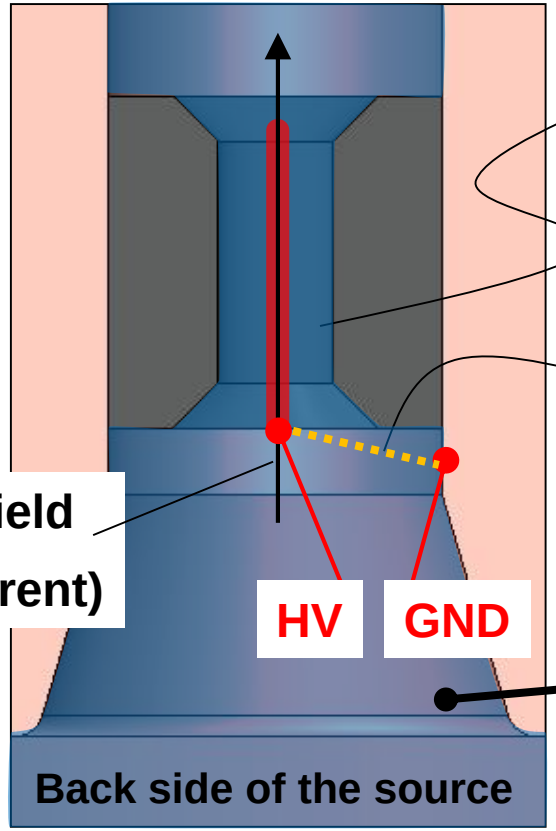
$$V(s) = d/dt\,(L(s)I) = L(s)\dot{I} + \dot{L(s)}I$$

where *s* is some section of the path, L the inductance of that section, I the current, and V the voltage across that section of path.

The local inductance *L(s)* goes as *1/r* of the current path, so at the pinch *L* increases enormously. Nearly the full loop voltage will appear across the length of the Z-pinch.

Analysis of the *E*-field direction → *E* points from the back of the bore to the front – that in the region where we see erosion, the induced voltage is positive relative to the wall.

So highest wall-plasma potential is where we see the arc. Plausible. Why does Helium reduce or eliminate the arc?



- **Helium blanket**. Bore acts like a plasma limiter, so this region is mostly empty of plasma → largely neutral gas. When pinch occurs, any ions are swept up, leaving neutral gas behind. Mostly Helium, which has high ionization voltage.
- **Neutral Helium forms a blanket around the pinch, increasing the breakdown voltage to the wall**

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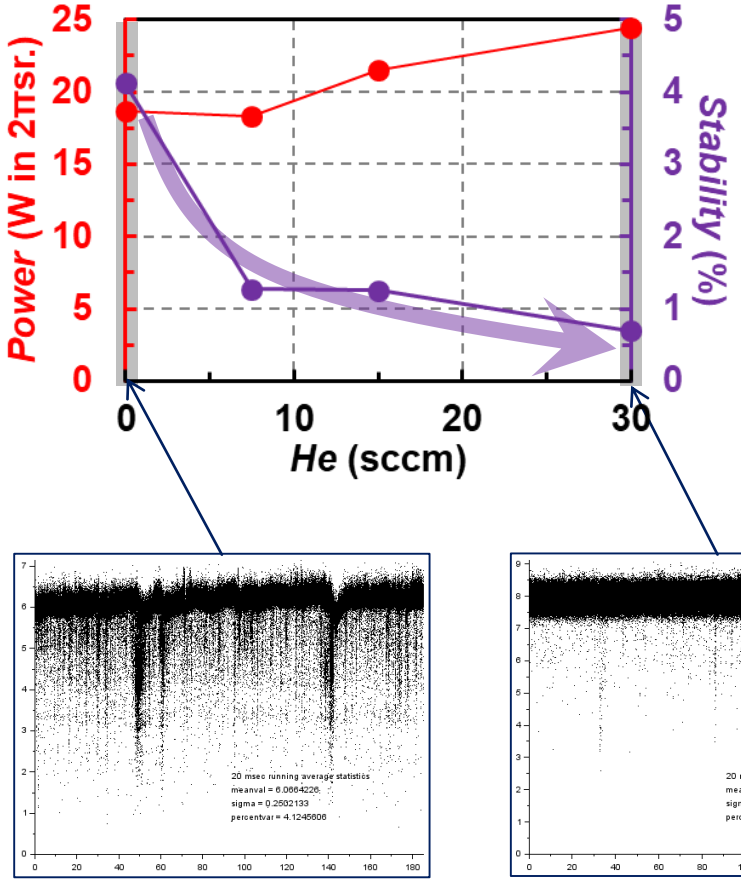
Stability Improvement by Helium



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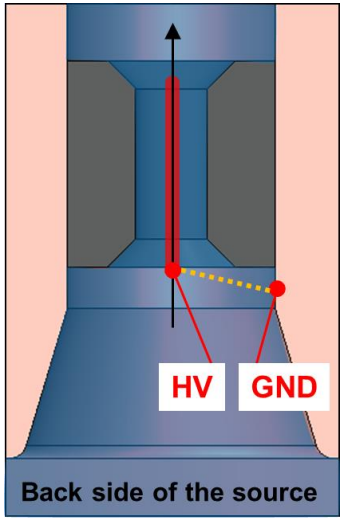

20 ms running average

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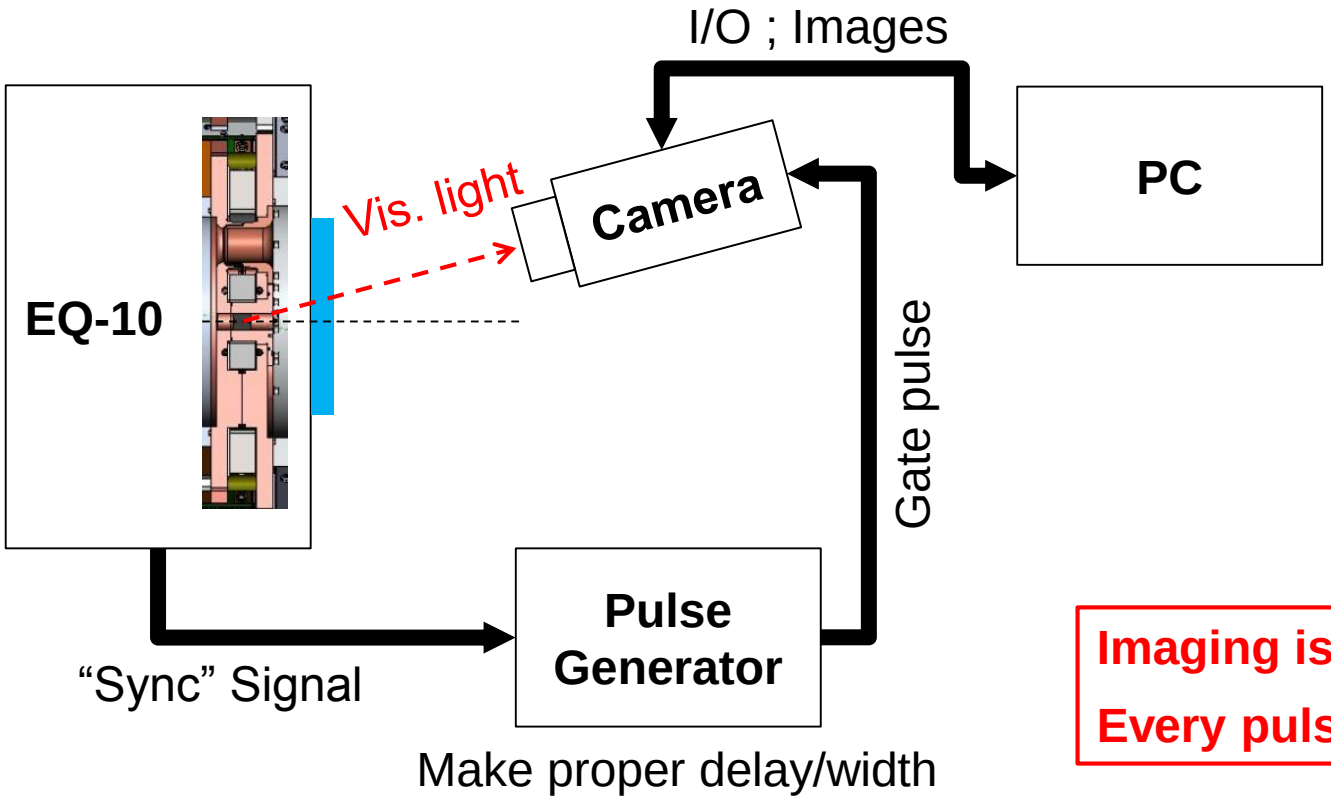
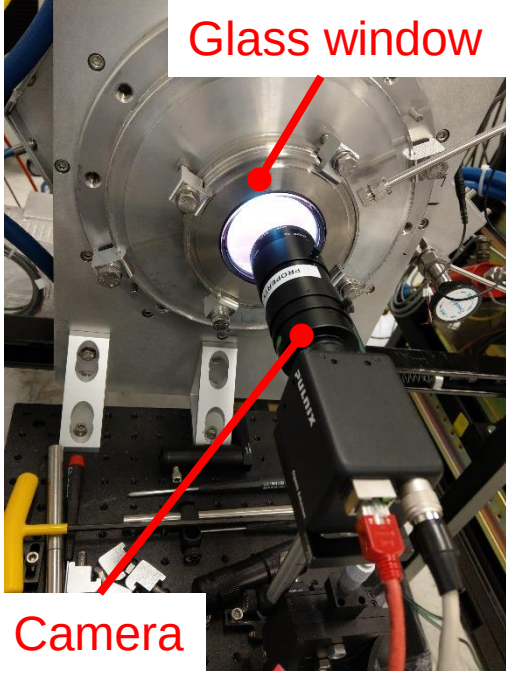
Experimental Setup





Imaging is gated to the Pinch.

Every pulse image captured.

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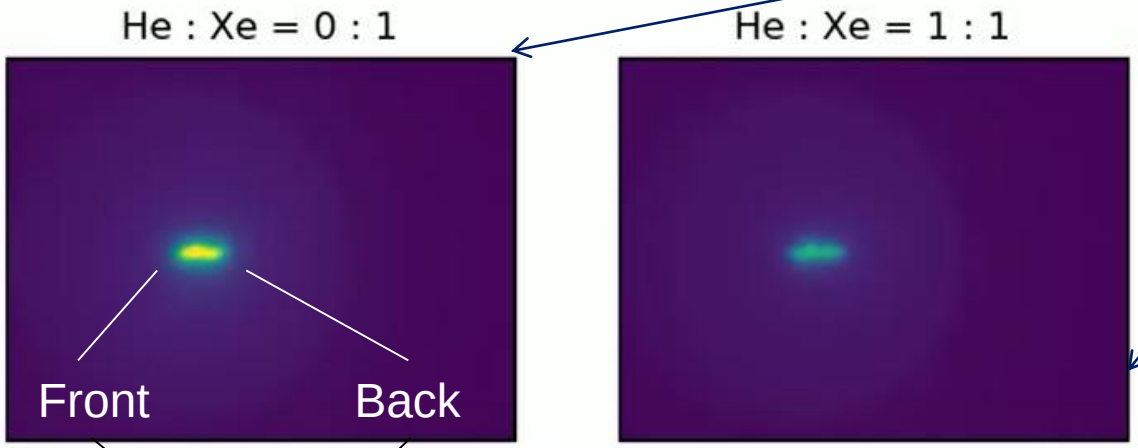
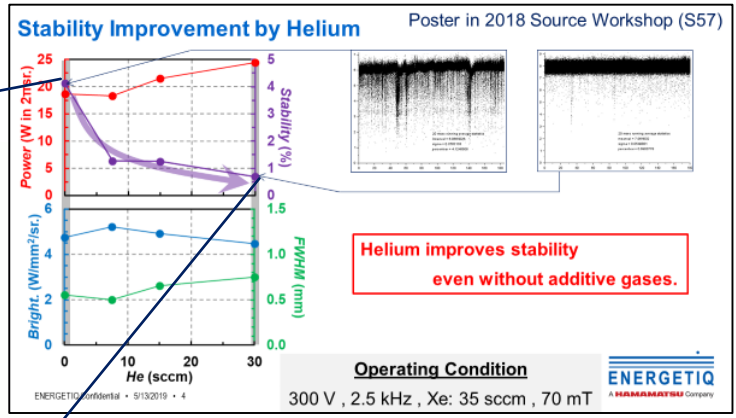
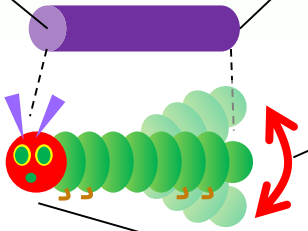
Movie







Tail : Back side of the pinch … **moving around w/ Non Helium**

Head : Front side of the pinch

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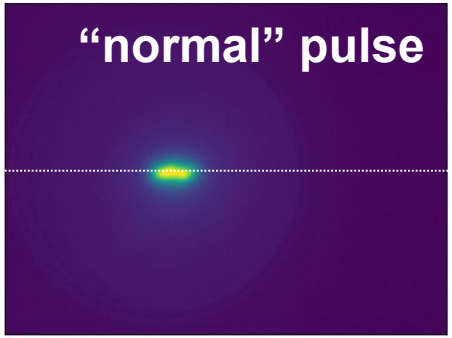
Typical Images (Off-Axis Images of Pinch)

He:Xe = 0:1



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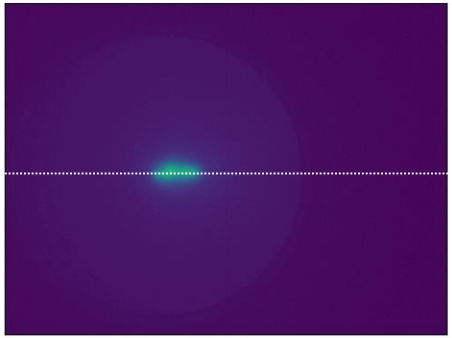

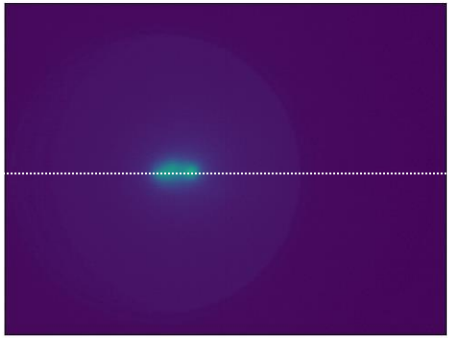

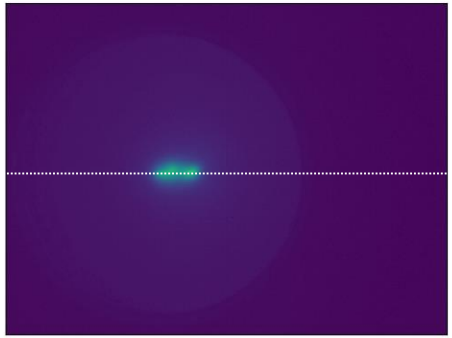

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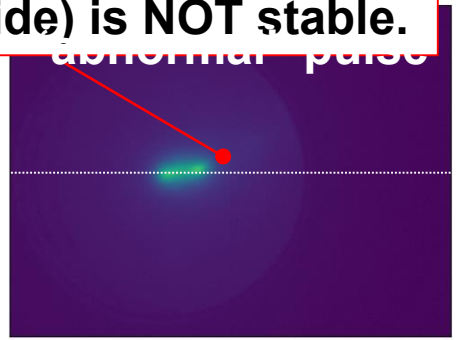
Typical Images (Off-Axis Images of Pinch)

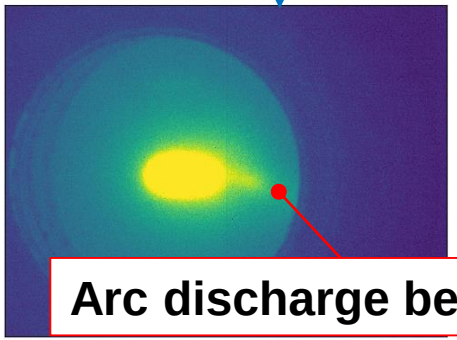
He:Xe
= 0:1

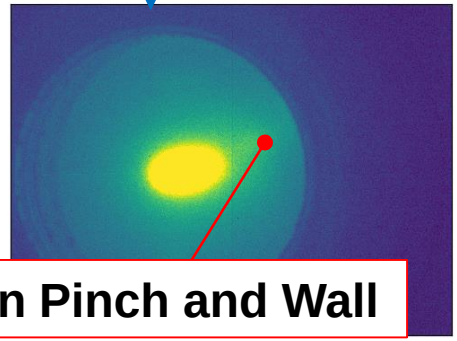
Position of “tail” (back side) is NOT stable.



Sometimes brighter , sometimes darker.

Down scaled





Arc discharge between Pinch and Wall

- Energy into pinch get lower
  when unipolar arc occurs.
- Unipolar arc
  from plasma to wall.

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Typical Images (Off-Axis Images of Pinch)

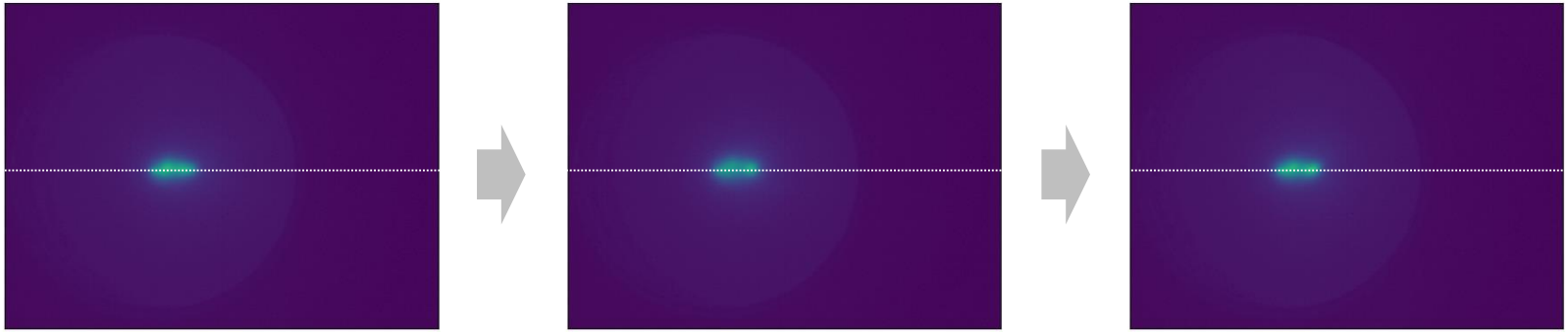
Additional Helium Improves both of

- Brightness stability between pulse to pulse

- Position stability

He:Xe

= 1:1



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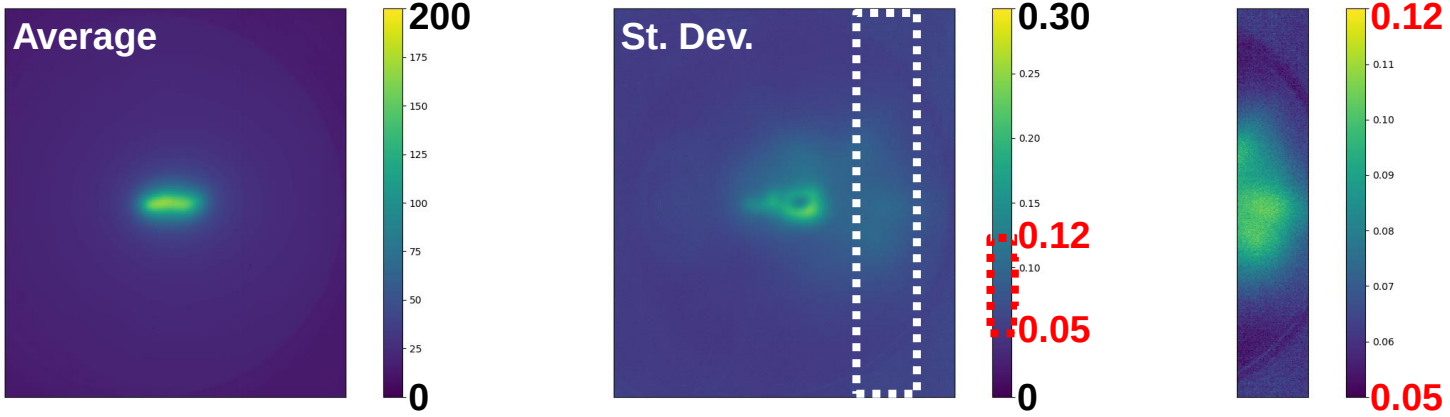
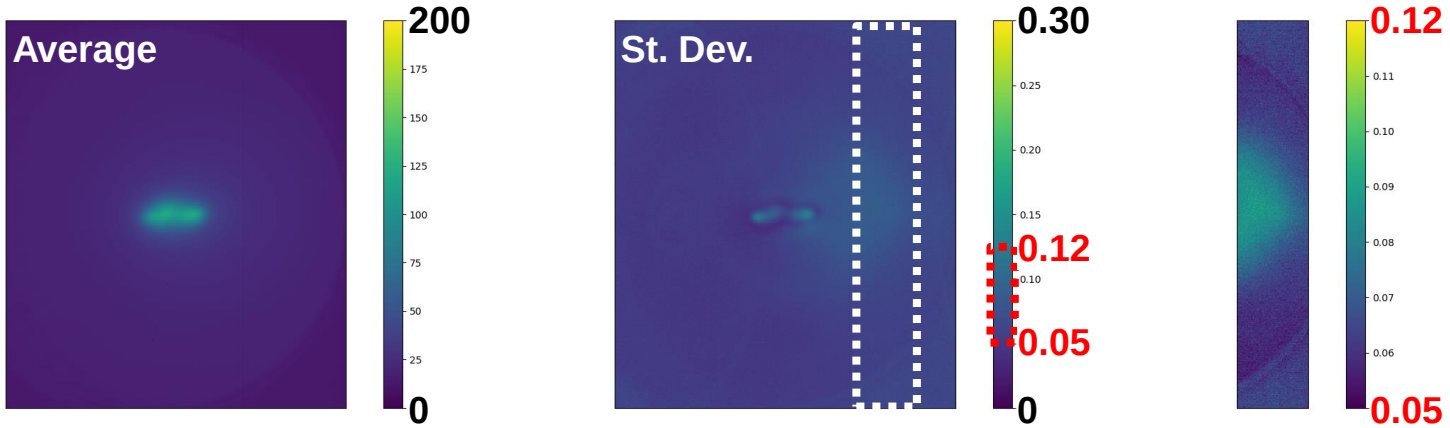
Average / Standard Deviation of Pixel Counts

Statistics over 300 images



He:Xe = 0:1



He:Xe = 1:1

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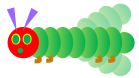
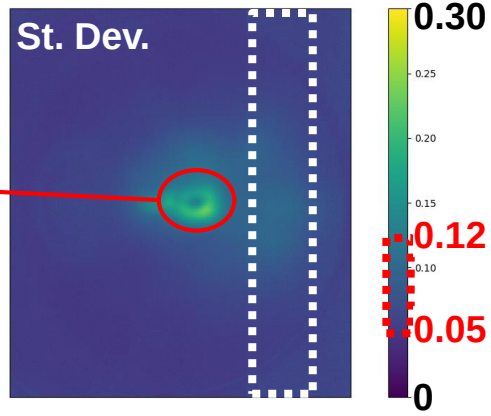
Average / Standard Deviation of Pixel Counts

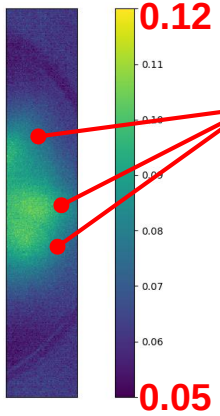
Statistics over 300 images

He:Xe = 0:1

Large deviation due to moving tail





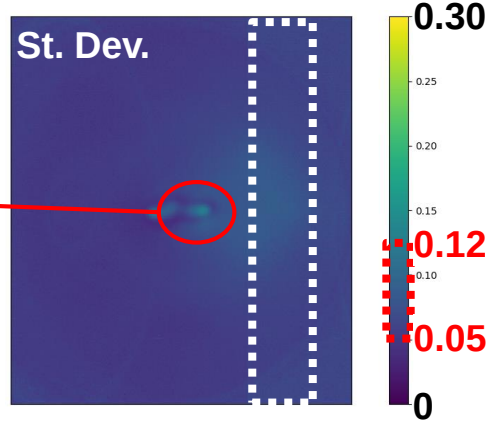


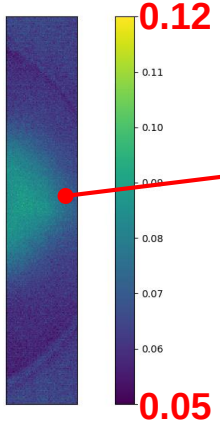
Deviation due to arc

Arc is likely to occur along some specific paths.

He:Xe = 1:1

Helium suppress the moving.





Helium suppress the arc.

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Summary and Conclusions

- The cause of the **instability** for pure Xenon is plausibly identified as a "**unipolar arc**".
  - Due to the voltage between back side of the pinch and wall

- The instability has two characteristics
  - **Position : immediately behind the bore**
    - Voltage from plasma to wall is highest
  - **Power**
    - The arc steals power from the pinch , which makes lower energy pulse.

- **Helium suppresses the instability described above.**

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