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Experimental results from the SPECTOR device at General Fusion

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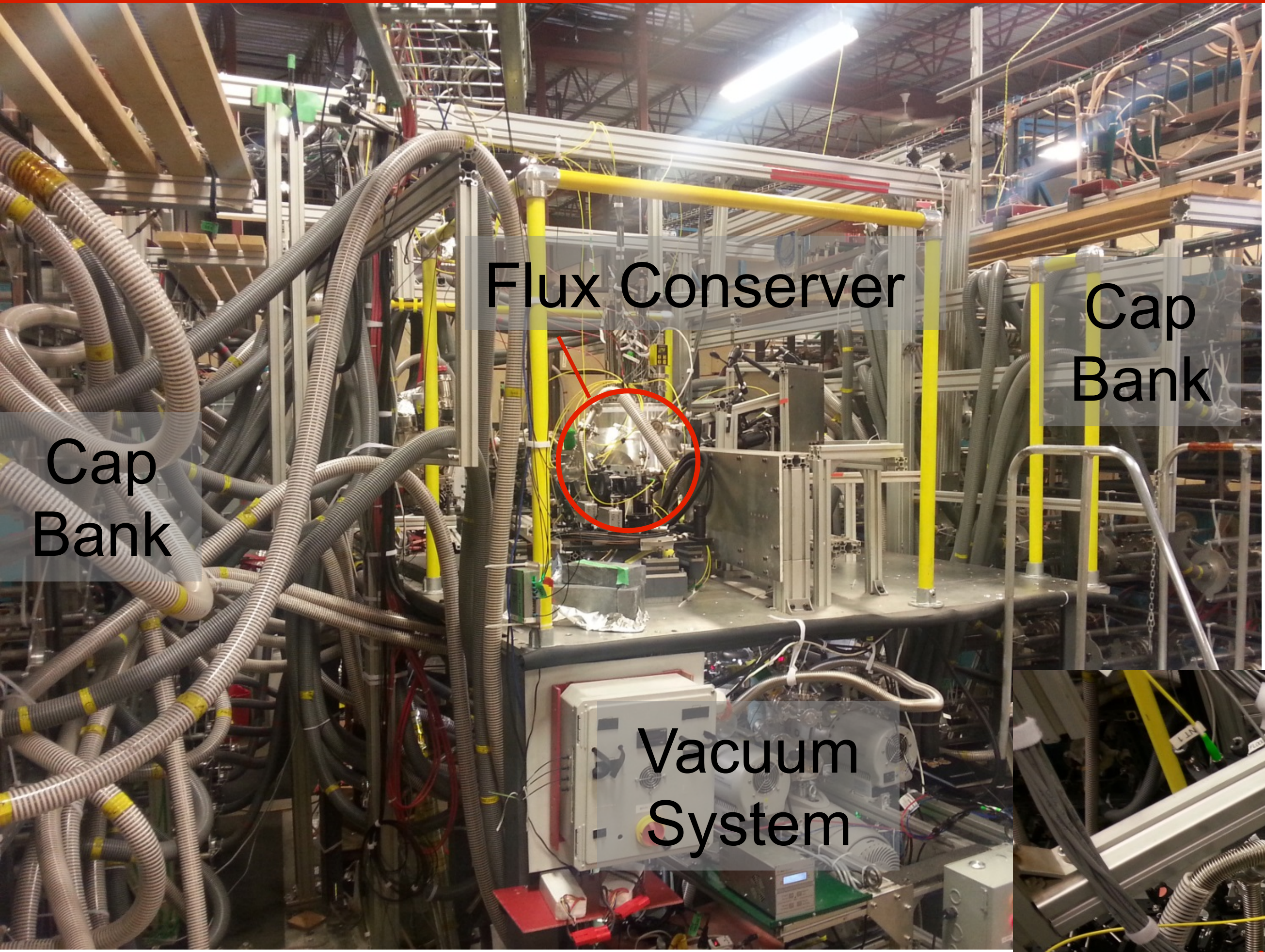
General Fusion Inc, Burnaby, British Columbia, Canada

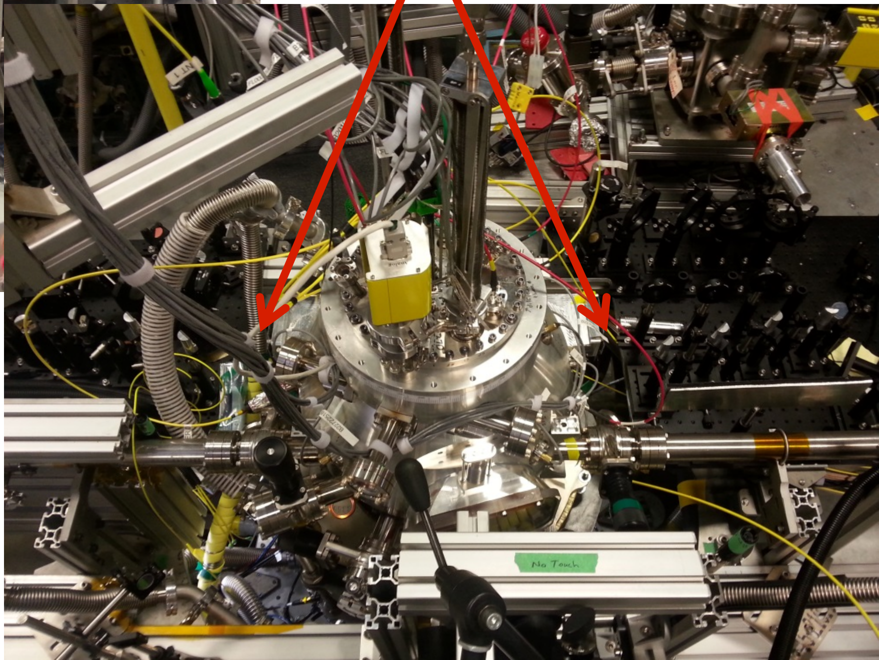
General Fusion (GF) is operating a new sequence of plasma devices called: SPECTOR (**Sp**herical **C**ompact **Tor**oid)

- Standard operation as a spherical tokamak.
- Similar to smaller scale version of HIST (1/2.5), Pegasus (1/3.75), or NSTX (1/7 scale by major radius) etc.
- Plasma start-up only uses fast coaxial helicity injection (CHI) from long Marshall gun.
- Convex outer wall design (D-shaped) expected to have good plasma stability during compression.
- Operating 1 lab-only device (Spector 1), and 2 mobile systems for out-of-lab compression tests (Spector 2, 3)
    - ➢ Here is a brief tour

Lab-only version (Spector 1)



Spector 1 vessel has good diagnostic access on flux conserver.



Mobile versions (Spector 2, 3)

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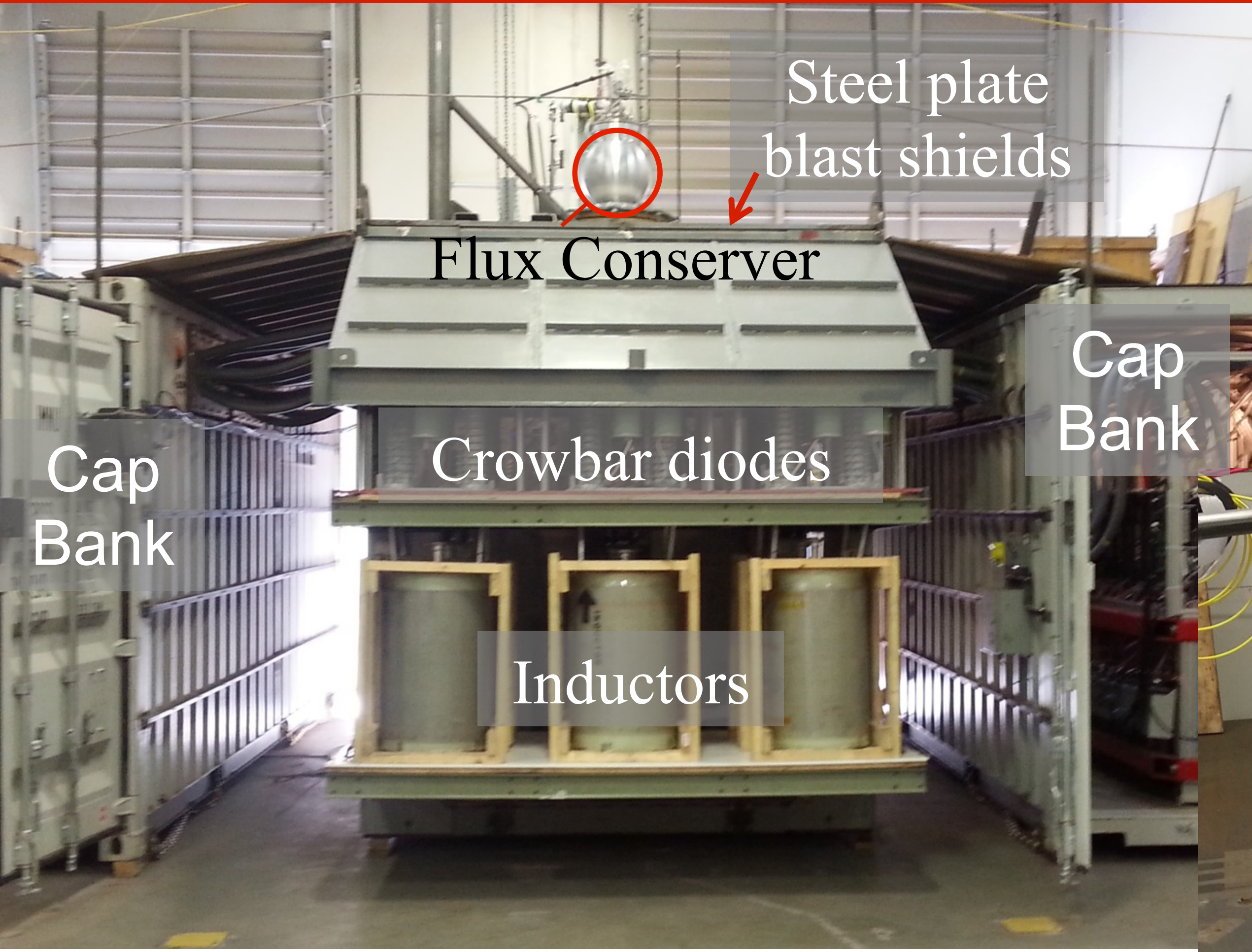
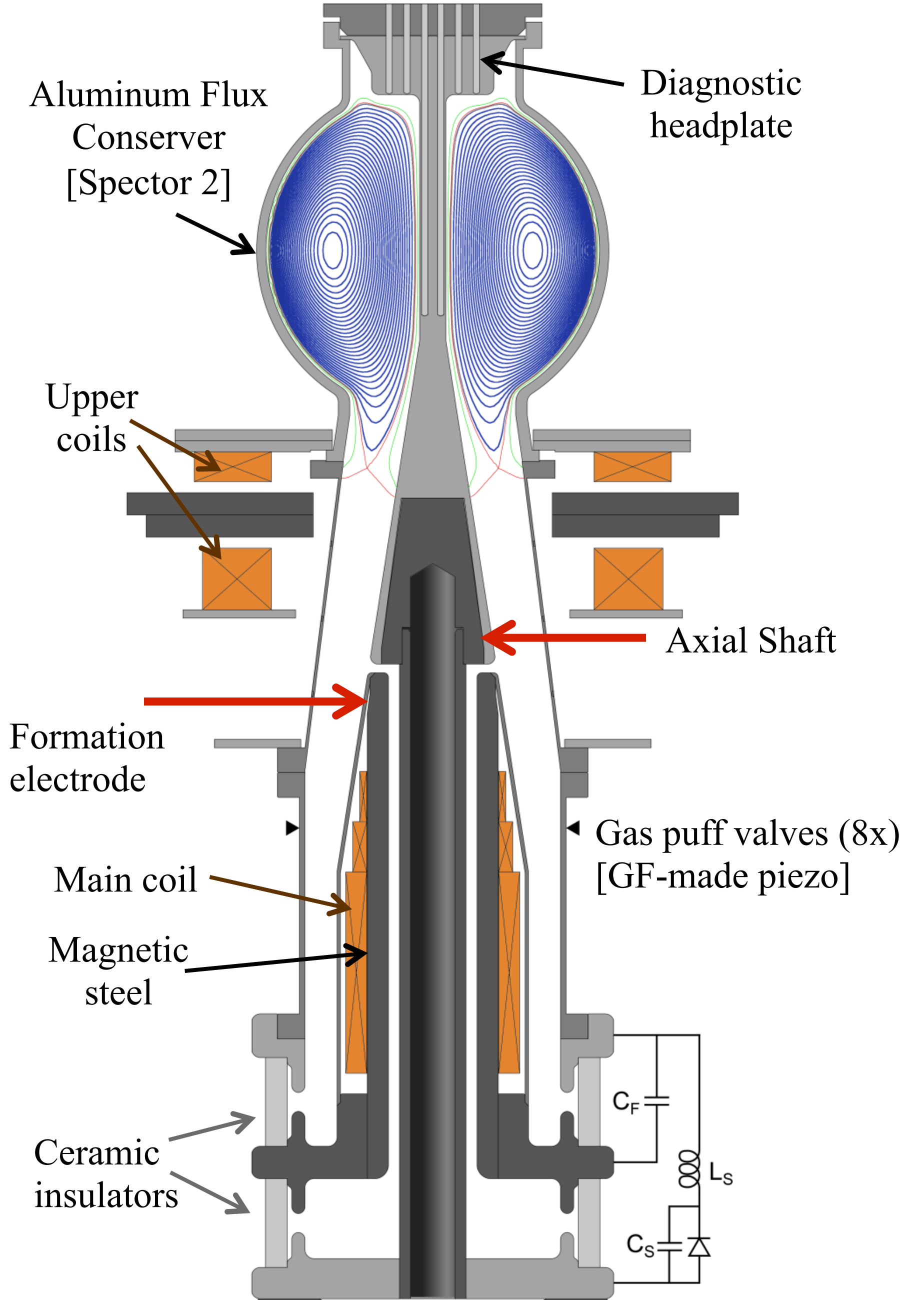


Flux Conserver only has diagnostic access on top plate to allow for uniform implosion of spherical vessel.

Vacuum system, DAQ/computer control system, and other reusable components are protected by reinforced shipping containers and steel blast shields on roof.

Spector 2, 3 will be the 13th , 14th MTF compression tests completed by General Fusion.

SPECTOR Overview



Machine Geometry & Operating parameters

SPECTOR forms spherical tokamak plasmas by coaxial helicity injection into a flux conserver

- Major, minor radius R= 12 cm, a = 8 cm
- Vessel radius = 19 cm (interior)
- $\lambda_{Taylor} = 23.9\ m^{-1}$
- Current in axial shaft $\leq$ 500 kA [crowbarred] creates pre-existing toroidal field before formation plasma
- Density range = 5×10^{19} to 5×10^{20} m^{-3}
- Poloidal Flux in CT = 30 mWb
- Toroidal Flux in CT = 300 mWb
- Toroidal plasma current = 250 kA
- Total magnetic energy in CT = 120 kJ
- Best magnetic lifetime of
  - 800 us (FWHM)
  - 1700 us until termination
- **Peak Te > 400 eV**

- Circuit parameters
  - Formation: C_F = 3.2 mF, V_F = 18 kV max
  - Shaft: C_S = 2.5 mF, V_S = 18 kV max
  - L_S = 1.27 μH, Diodes max 25 kV, 600 kA

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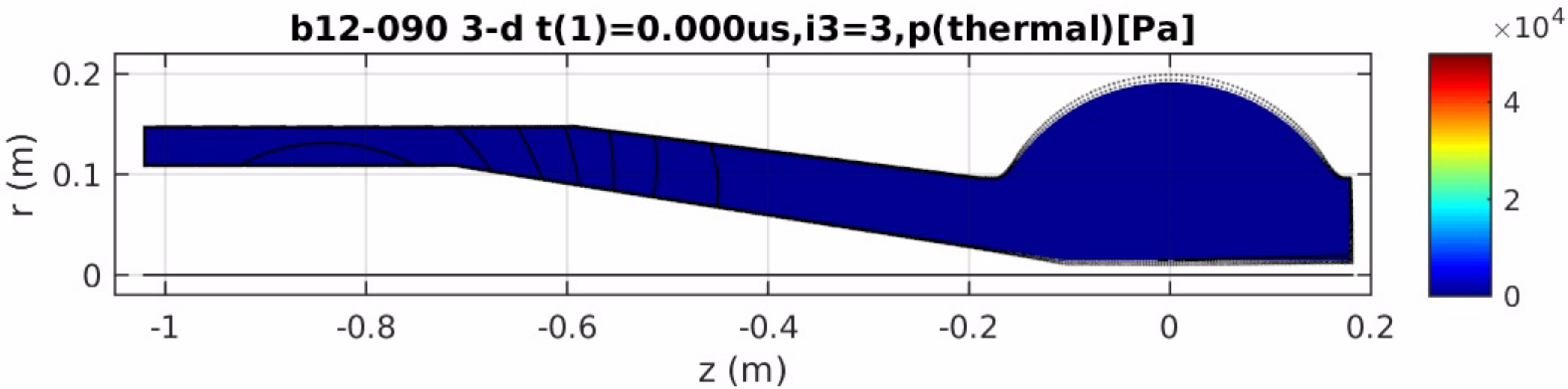
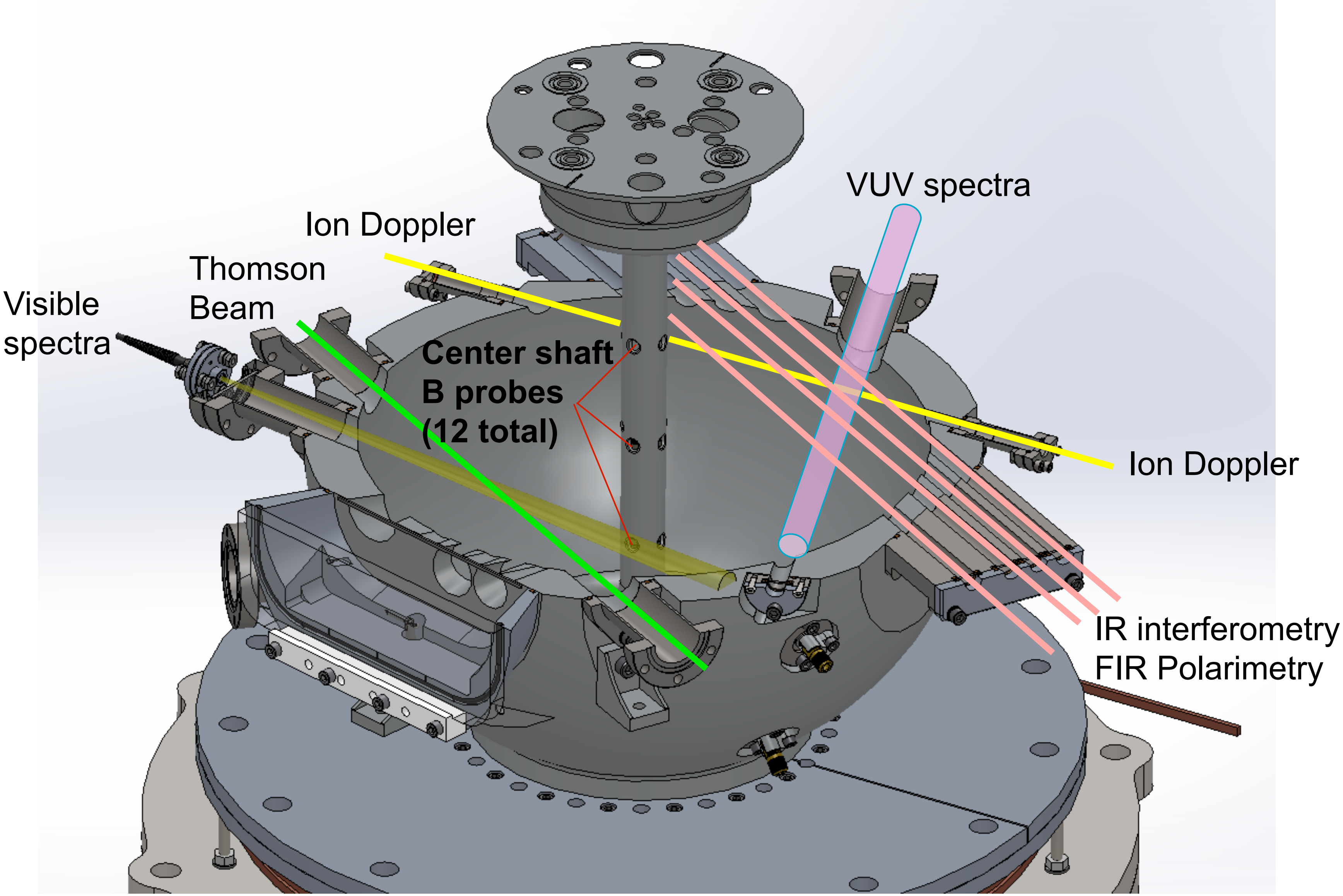
Spector uses a fast CHI formation process (Marshall gun bubble-out)



- Contours show average poloidal flux Ψ(r,z)
- Color scale show plasma pressure
- Oscillations happen just after CHI bubble-out, but calm down by 50 µs
- Key parameters of simulation:
  - Initial 30 mWb vacuum poloidal gun flux (aka bias flux),
  - Pre-existing 450 kA current on center shaft before plasma is formed
  - Final 70 mWb poloidal CT flux after dynamo (factor of 2.3x amplification)

Diagnostics (equatorial view)



Diagnostics (poloidal view)

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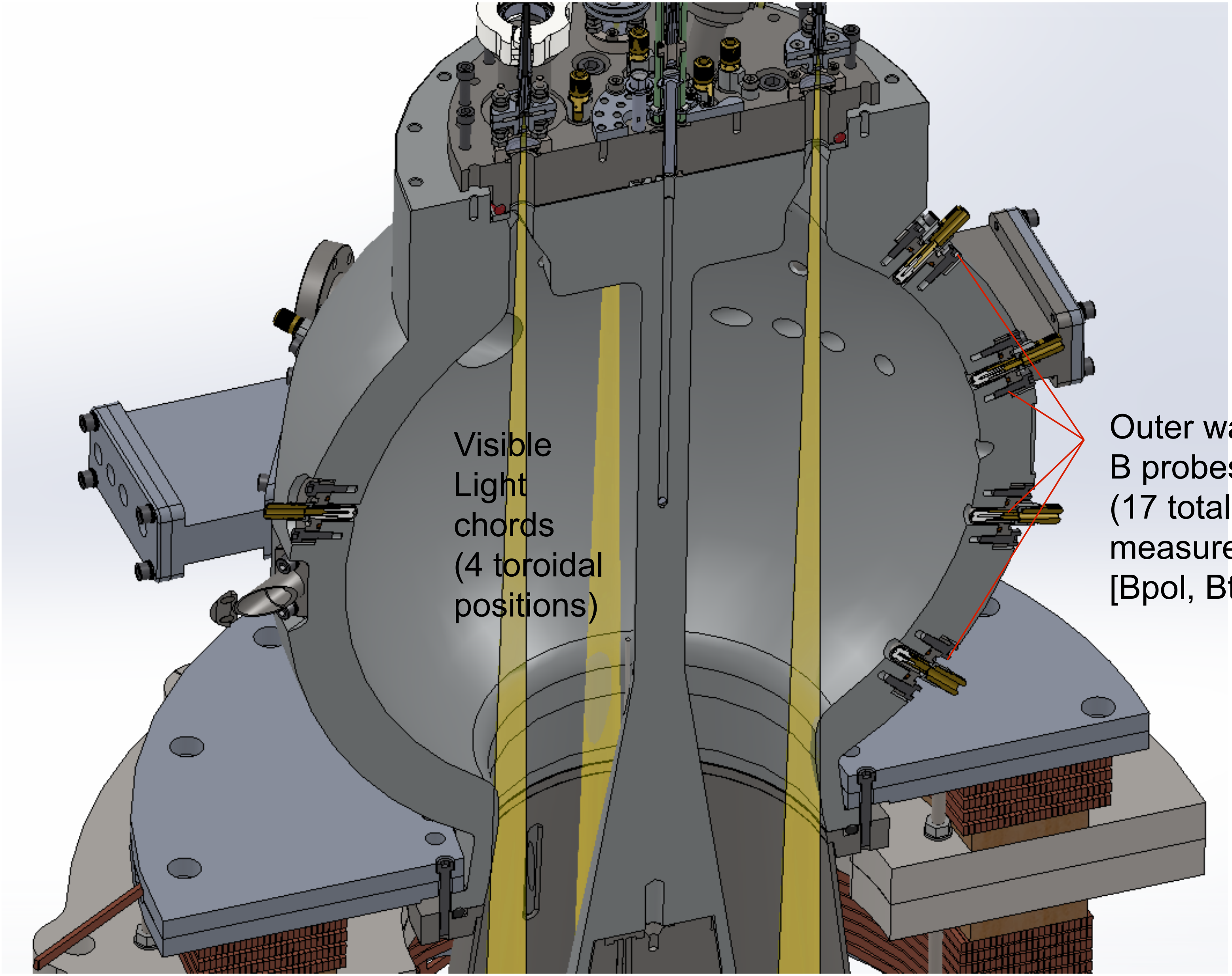

Other diagnostics beyond the scope of this talk

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- Dual wavelength IR interferometry (1330, 1550 nm, 2 chords)
- Visible survey spectrometers (3 in use on Spector 1)
- Liquid Scintillator (Gamma + Neutron detector, PSD)
- VUV spectrometer (50 nm to visible)
- X-ray pinhole camera, with Phantom high speed video

- Filtered X-ray photodiodes (in development)
- 4-chord FIR Polarimeter system (in development)

Formation occurs with a pre-existing Toroidal field

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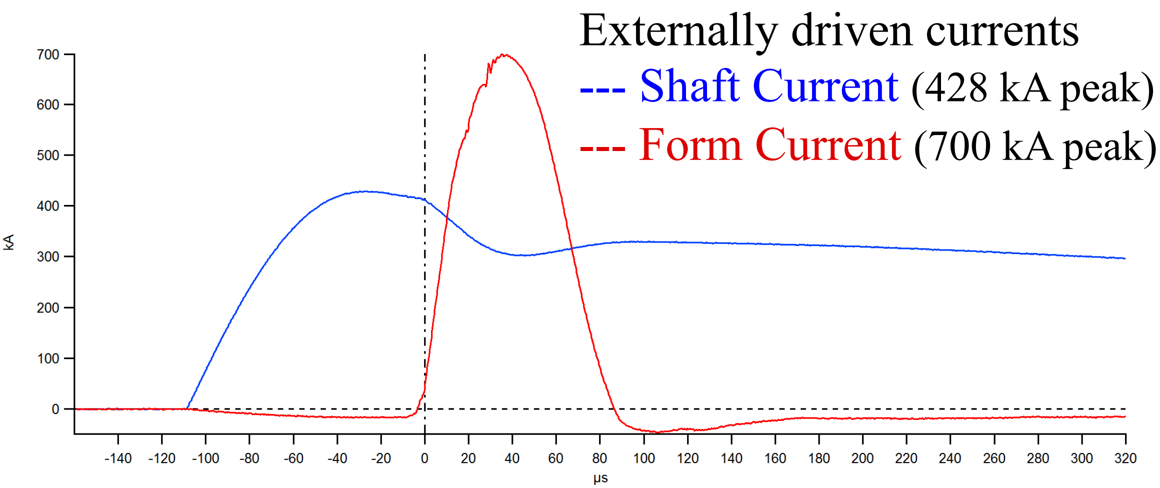
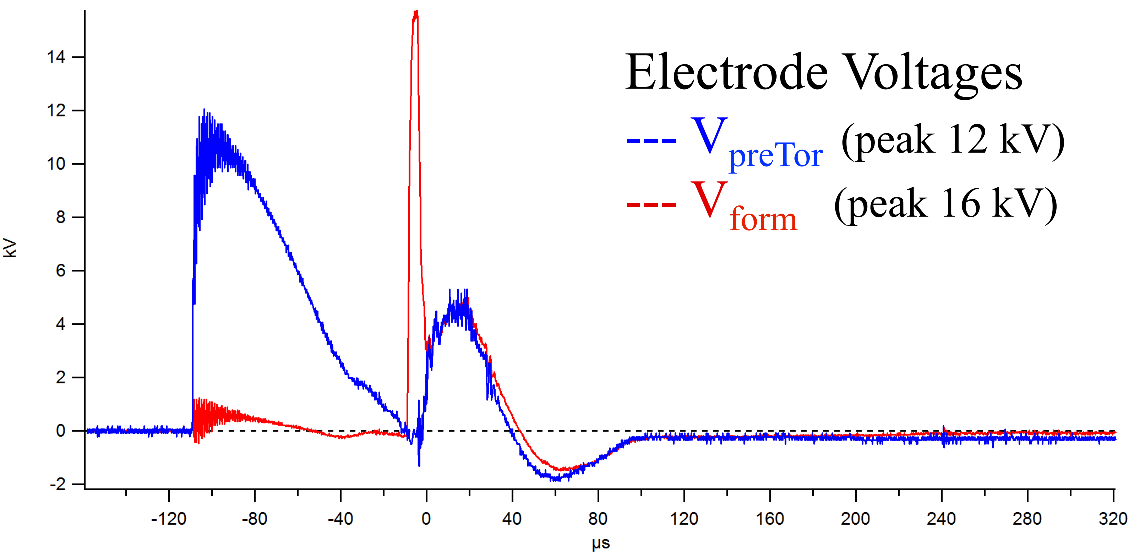


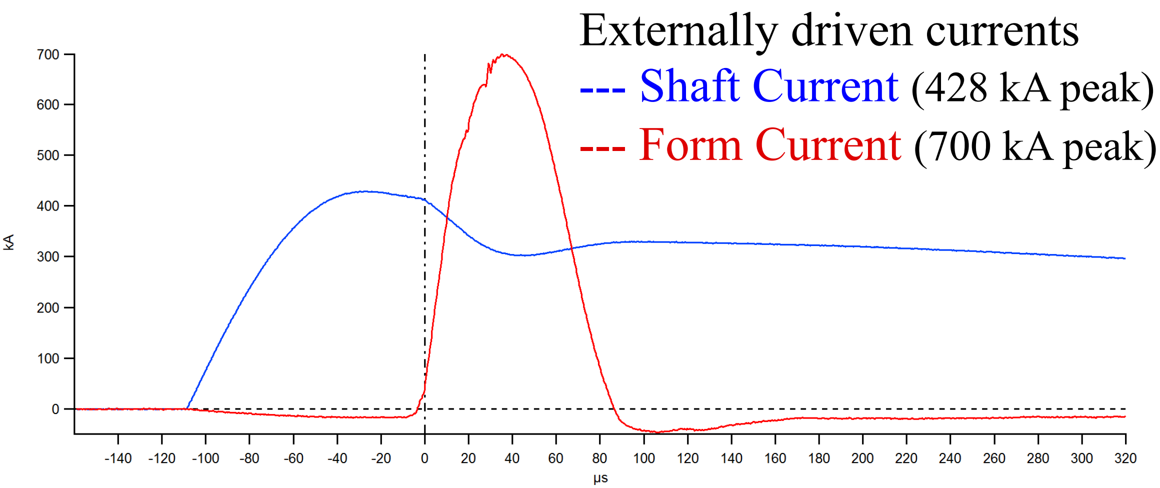


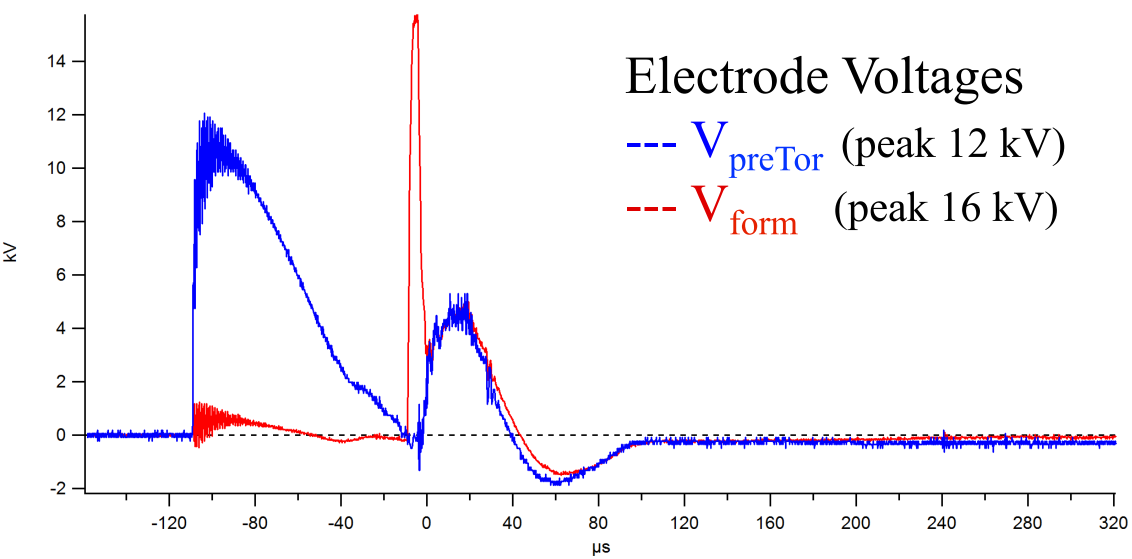
Shot 6266 chronology

time	Event

Formation occurs with a pre-existing Toroidal field

- DC magnets





Shot 6266 chronology	
time	Event
- 1 sec	DC bias magnets turn on. Ψ_{Gun} = 13.6 mWb

Formation occurs with a pre-existing Toroidal field

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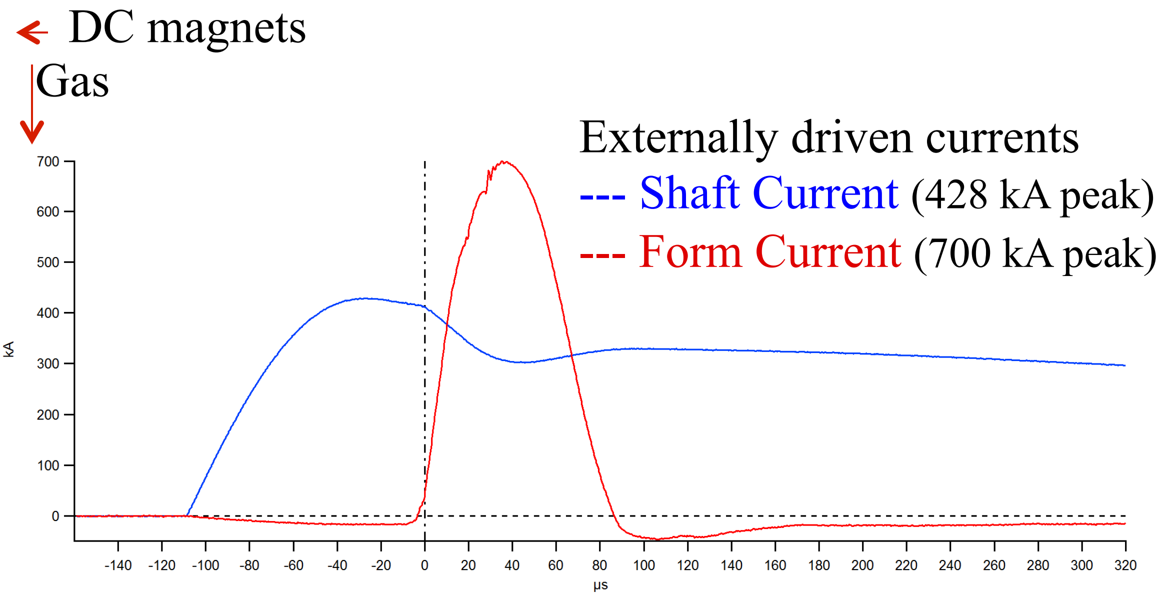

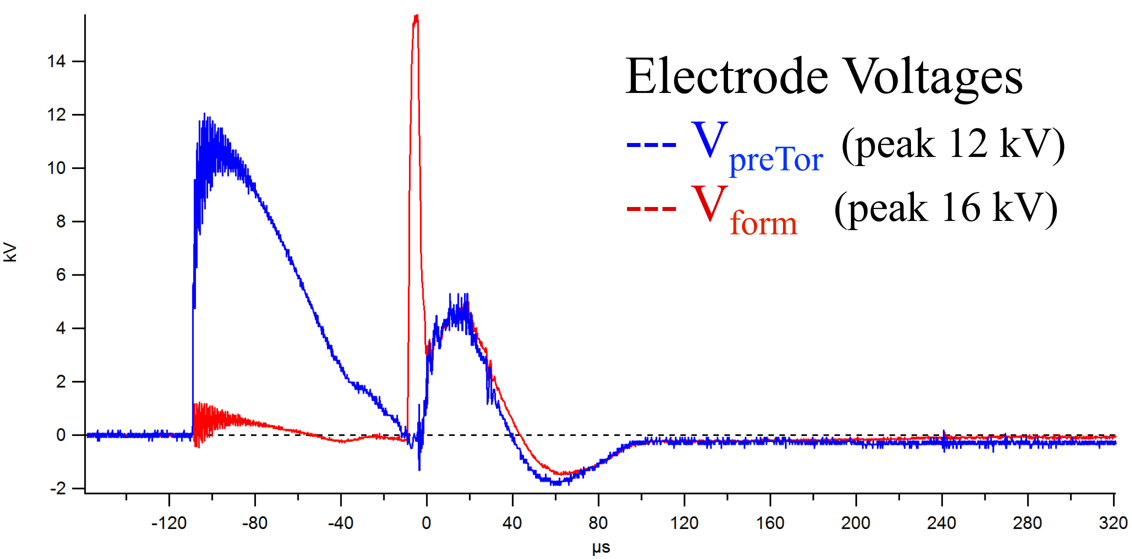

Shot 6266 chronology

time	Event
- 1 second	DC bias magnets turn on. Ψ_{Gun} = 13.6 mWb
- 234 µs	Deuterium is puffed

Formation occurs with a pre-existing Toroidal field

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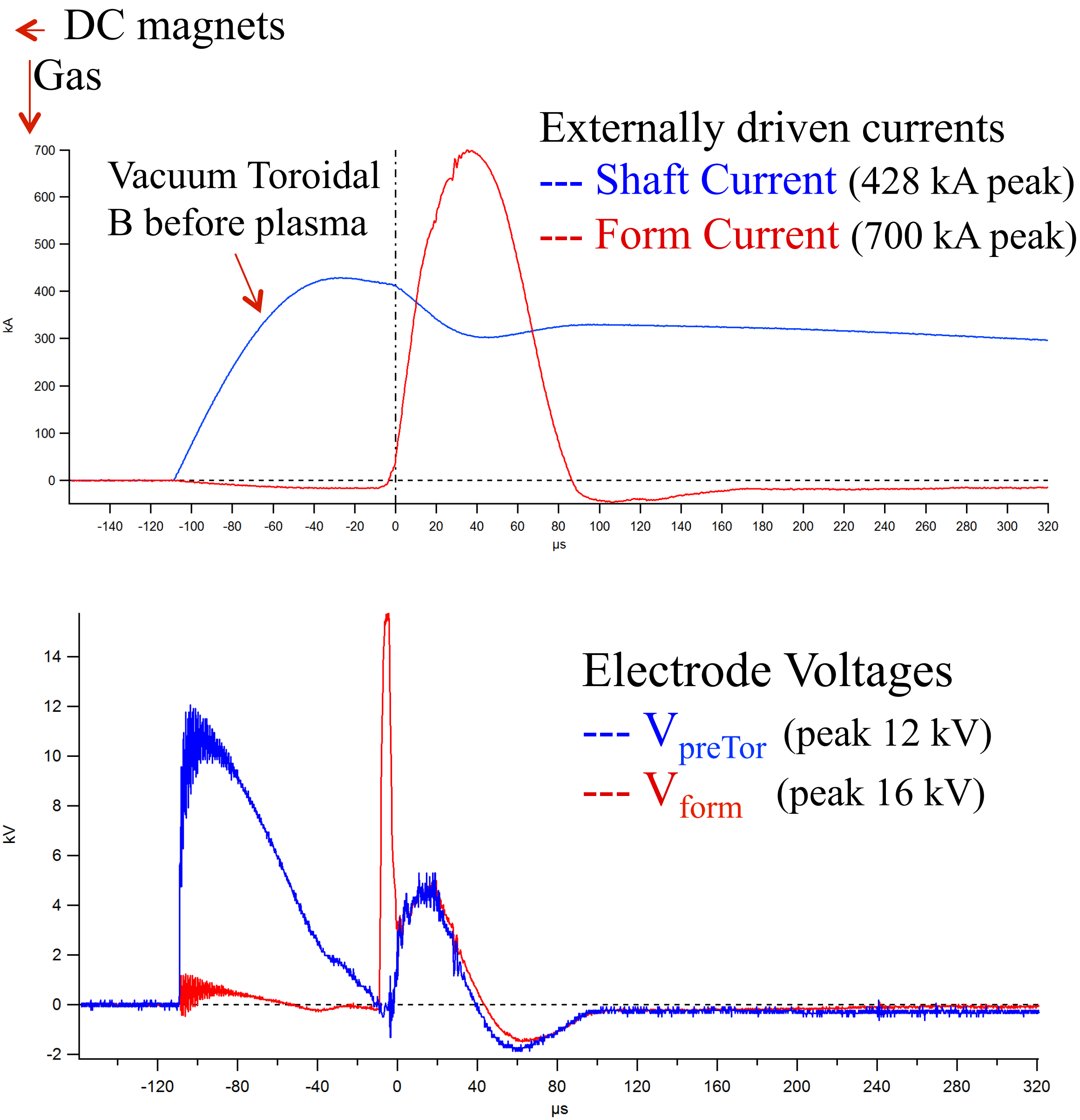

Shot 6266 chronology

time	Event
- 1 second	DC bias magnets turn on. Ψ_{Gun} = 13.6 mWb
- 234 μs	Deuterium is puffed
- 110 μs	Shaft circuit fires, creates vacuum B_{Tor}

Formation occurs with a pre-existing Toroidal field

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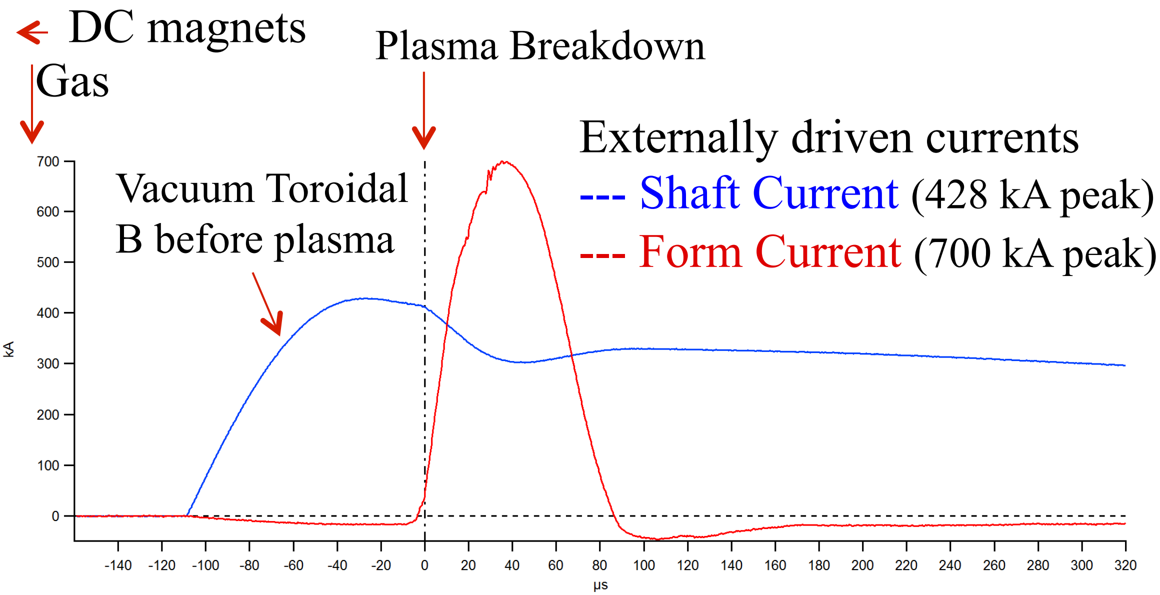

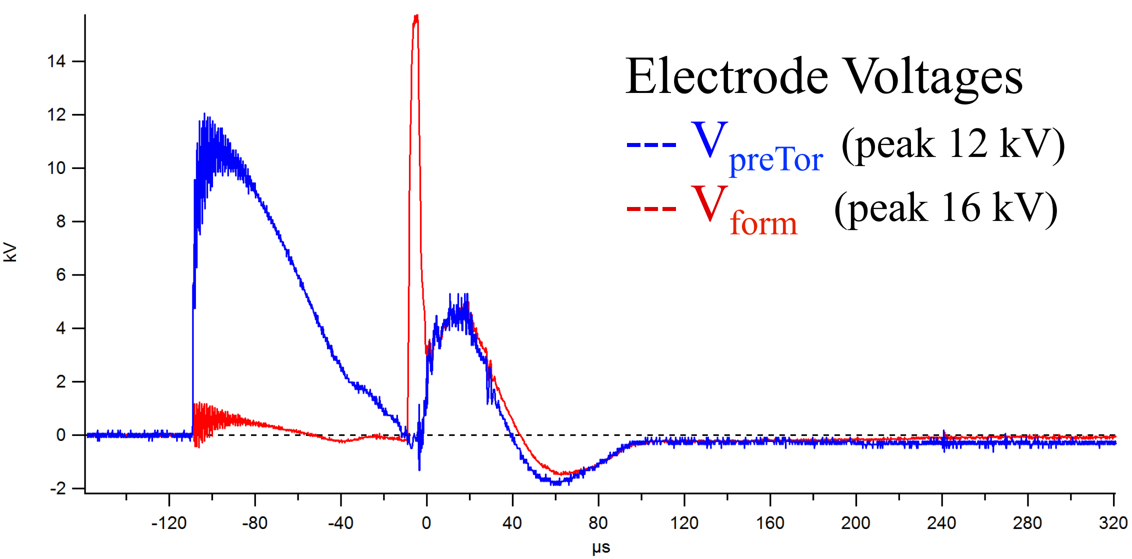

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t = 0	Formation fires, plasma breaks down. I_{shaft} crowbarred at 400 kA

Formation occurs with a pre-existing Toroidal field

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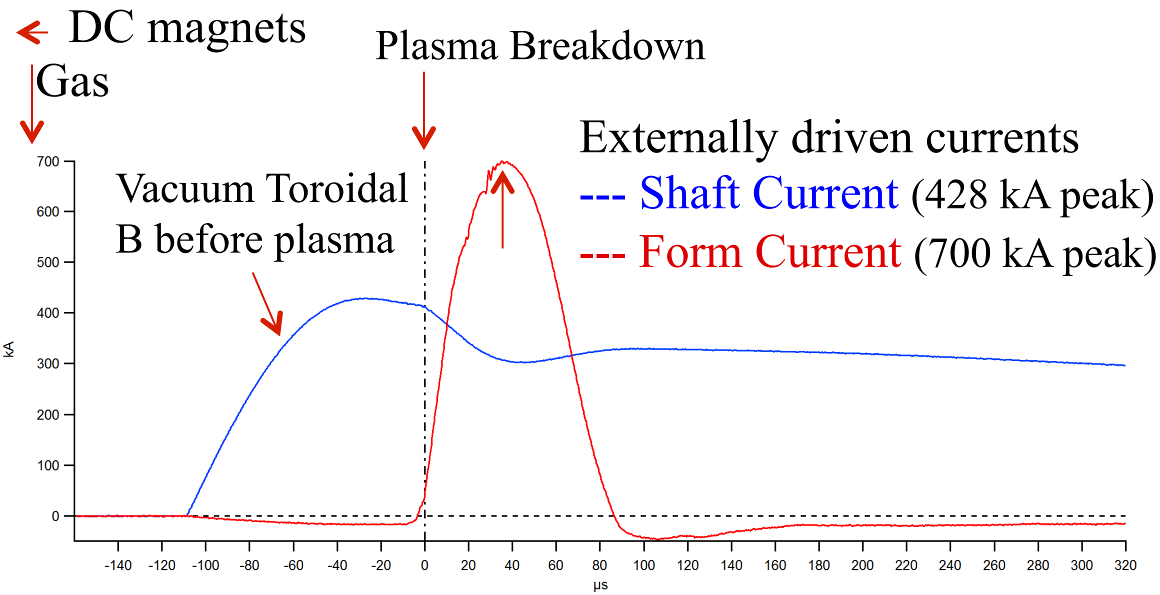

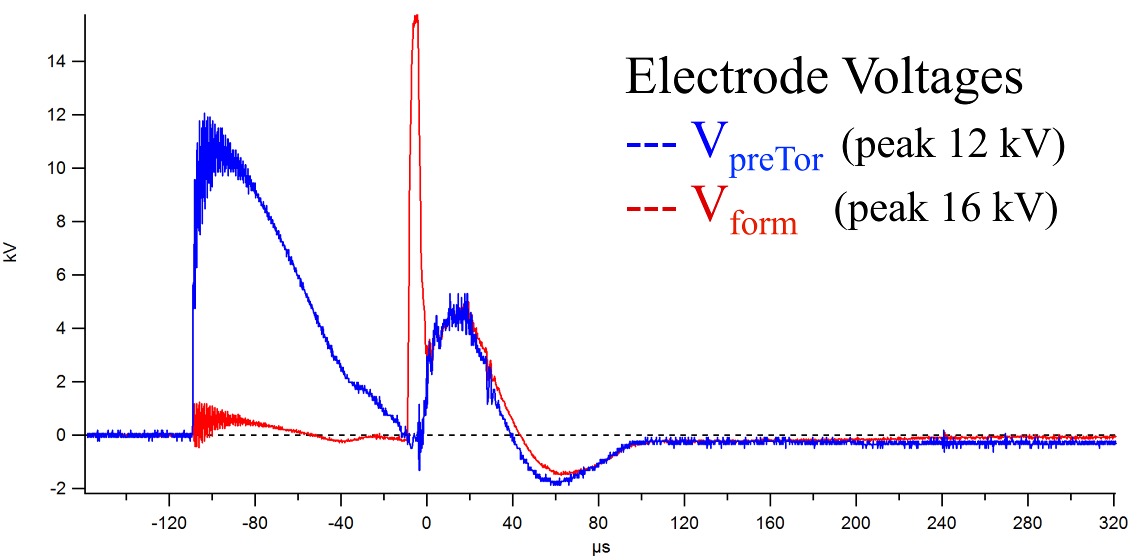

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+ 35 μs	Form current peaks 700kA Fast Marshall gun bubble-out (CHI) has pushed flux into upper chamber

Formation occurs with a pre-existing Toroidal field

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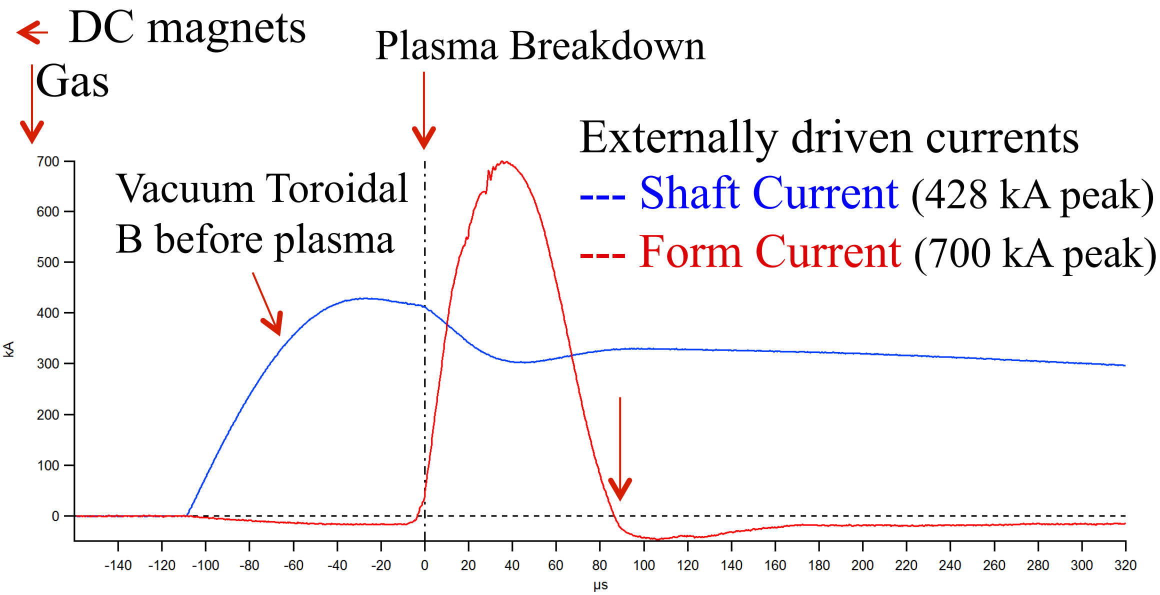

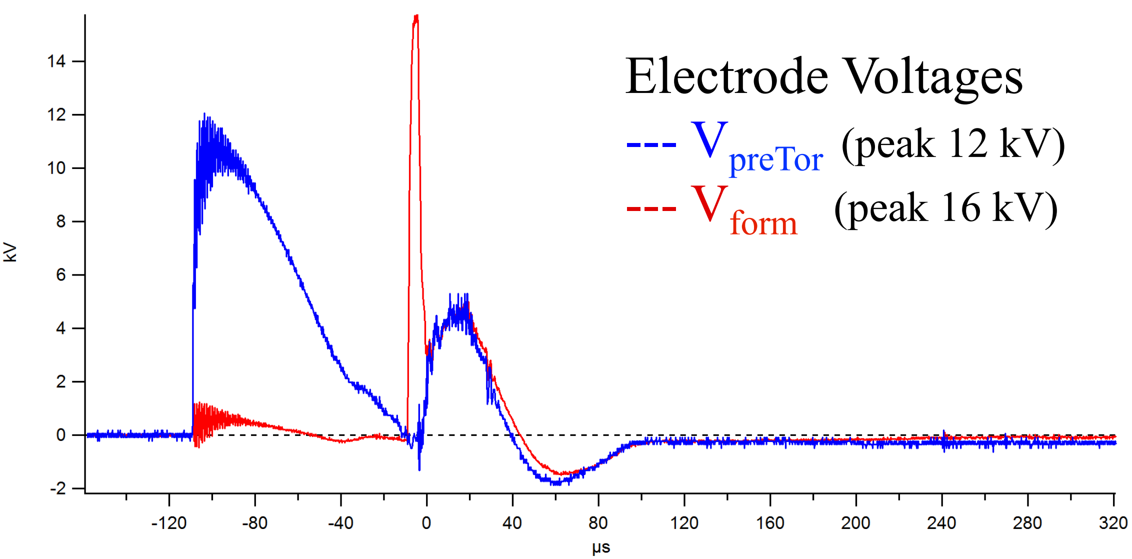

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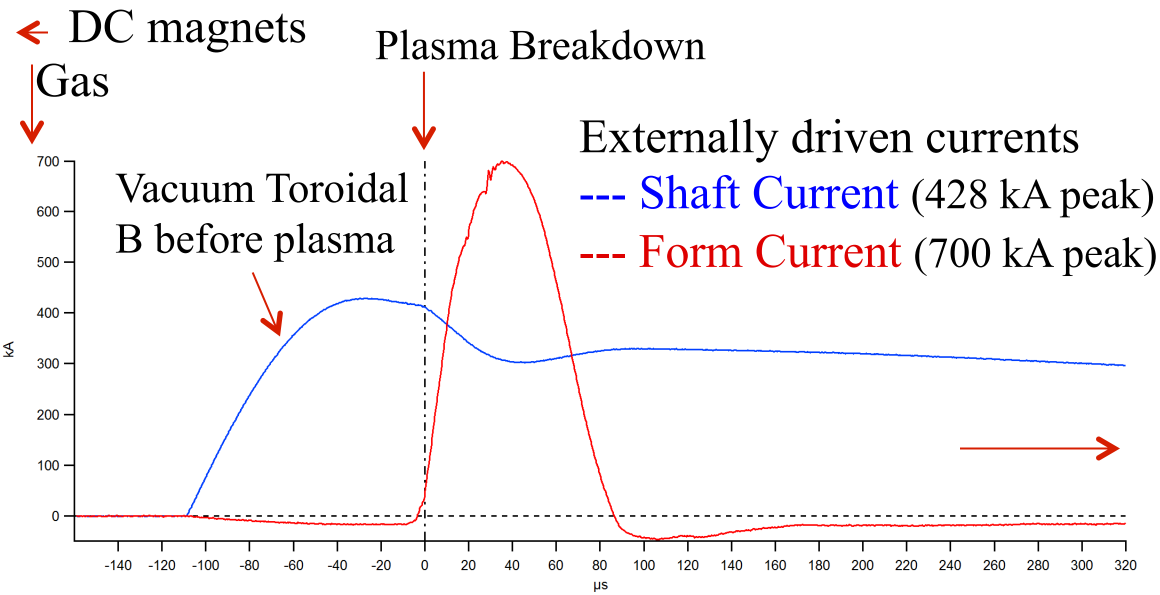
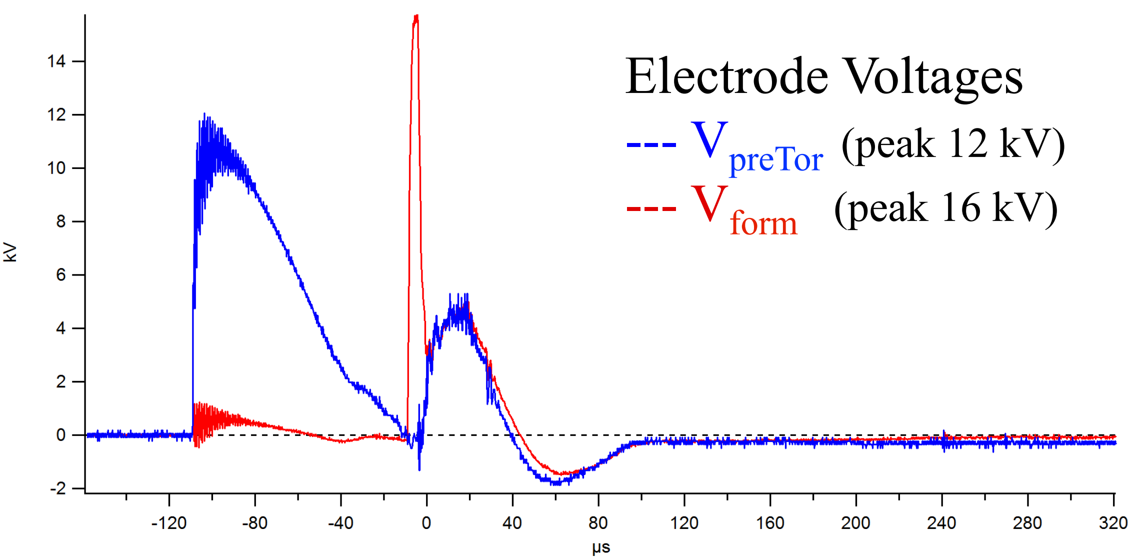
+ 35 µs	Form current peaks 700kA Fast Marshall gun bubble-out (CHI) has pushed flux into upper chamber
+ 90 µs	Form current ends.

Formation occurs with a pre-existing Toroidal field





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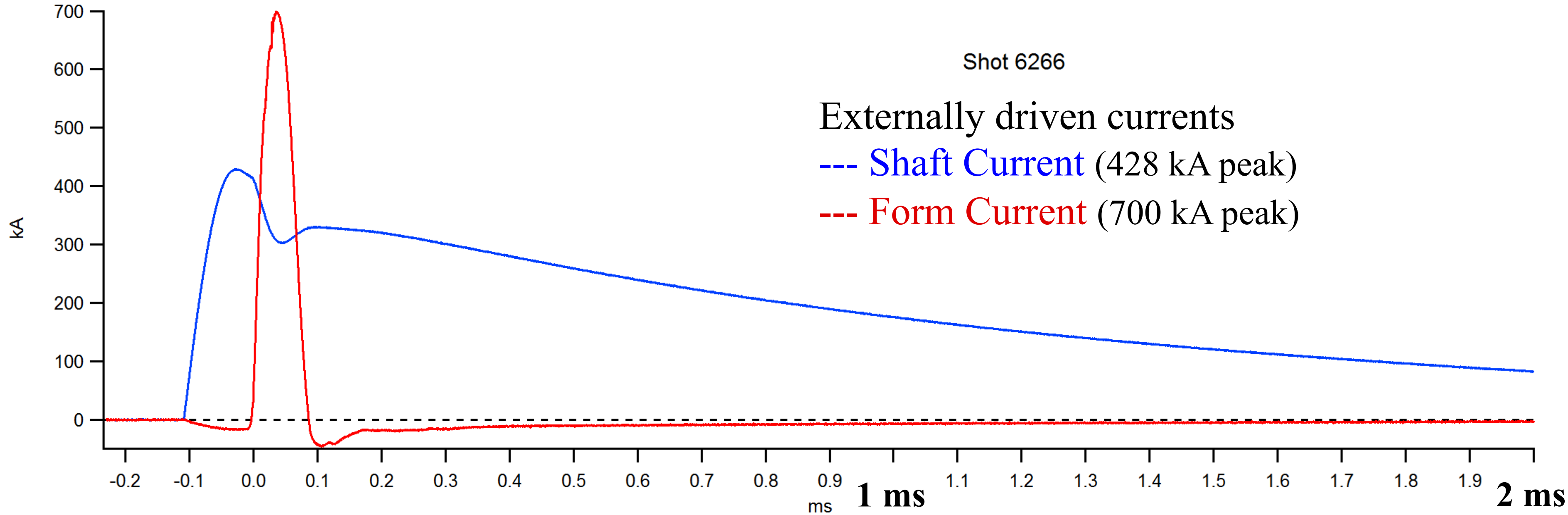
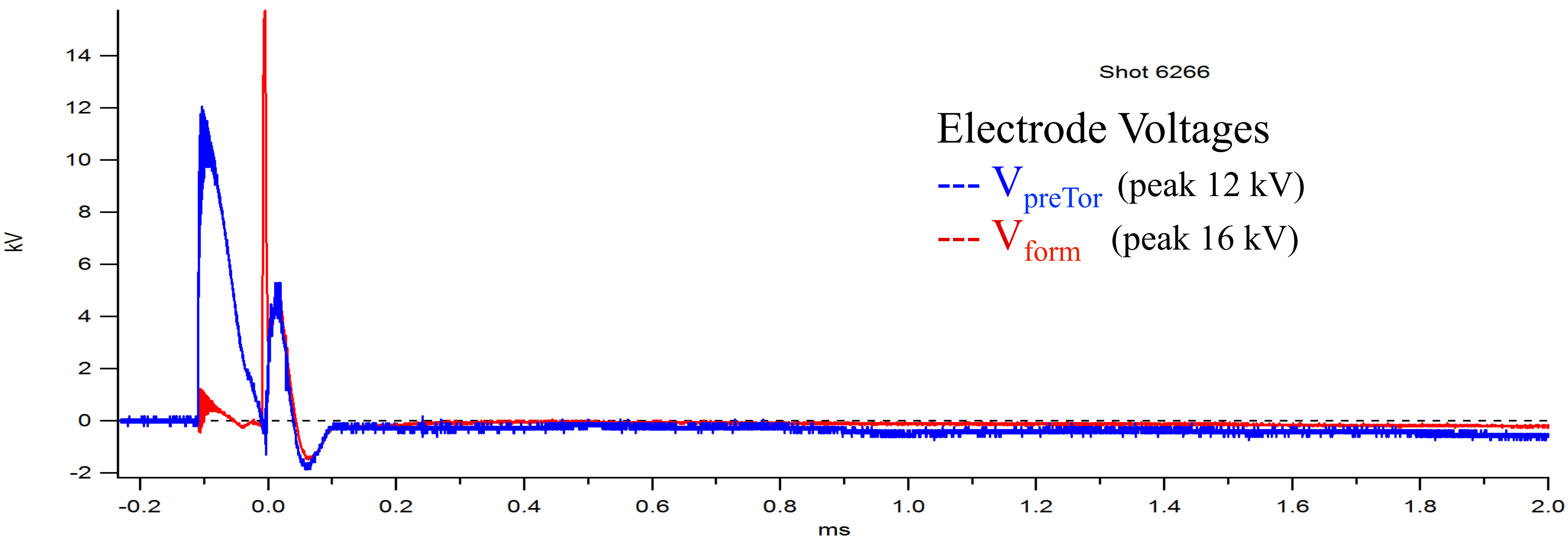
+ 35 µs	Form current peaks 700kA Fast Marshall gun bubble-out (CHI) has pushed flux into upper chamber
+ 90 µs	Form current ends.
t =1.7 ms 1700 µs	**End of CT toroidal plasma current.**

Current and Voltage over duration of shot





B Poloidal near center shaft (0.9 Tesla peak)

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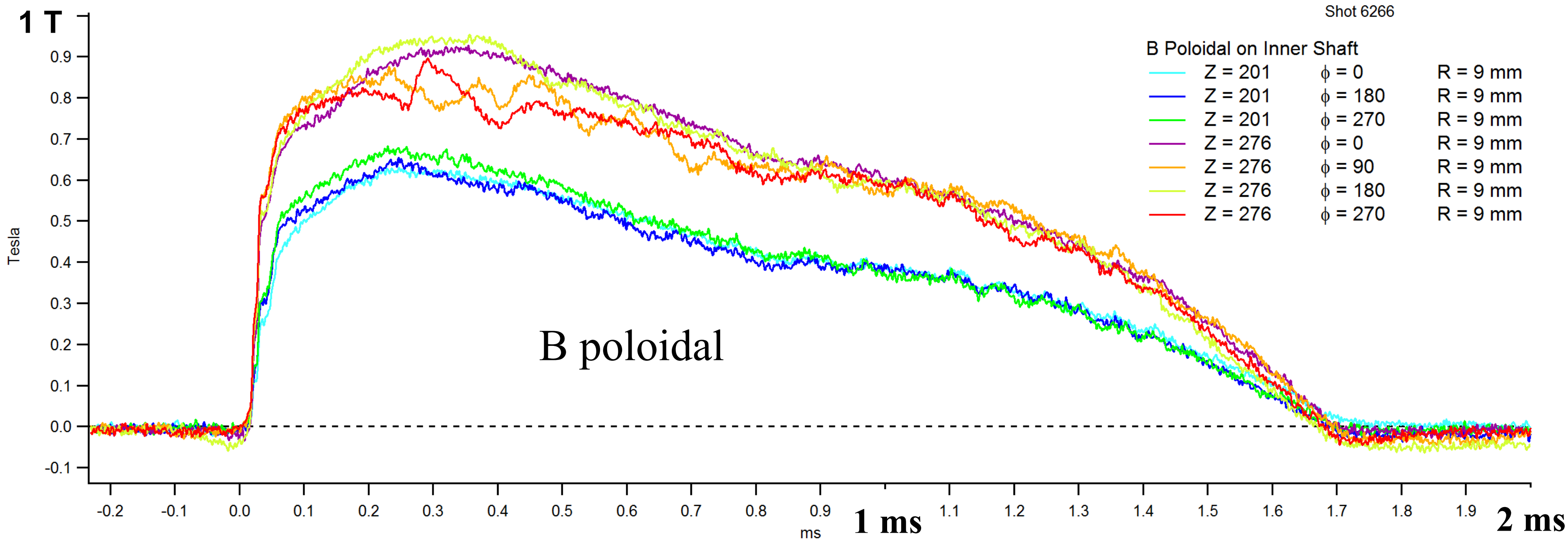

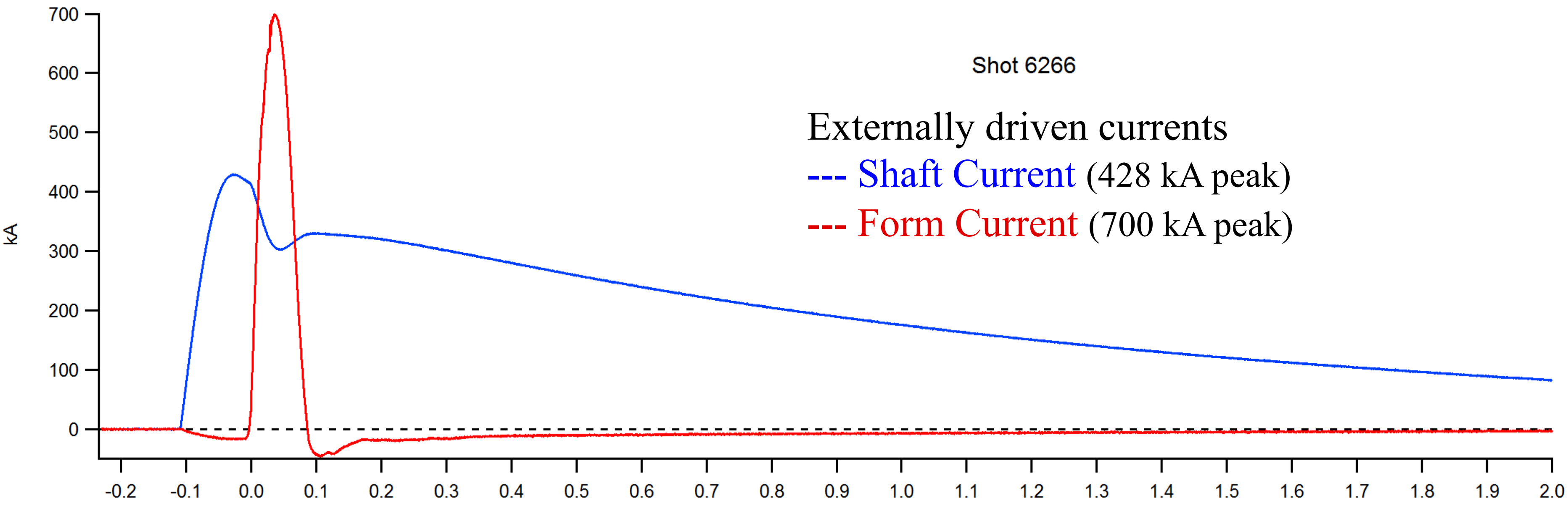

Toroidal B field shows internal plasma crowbar

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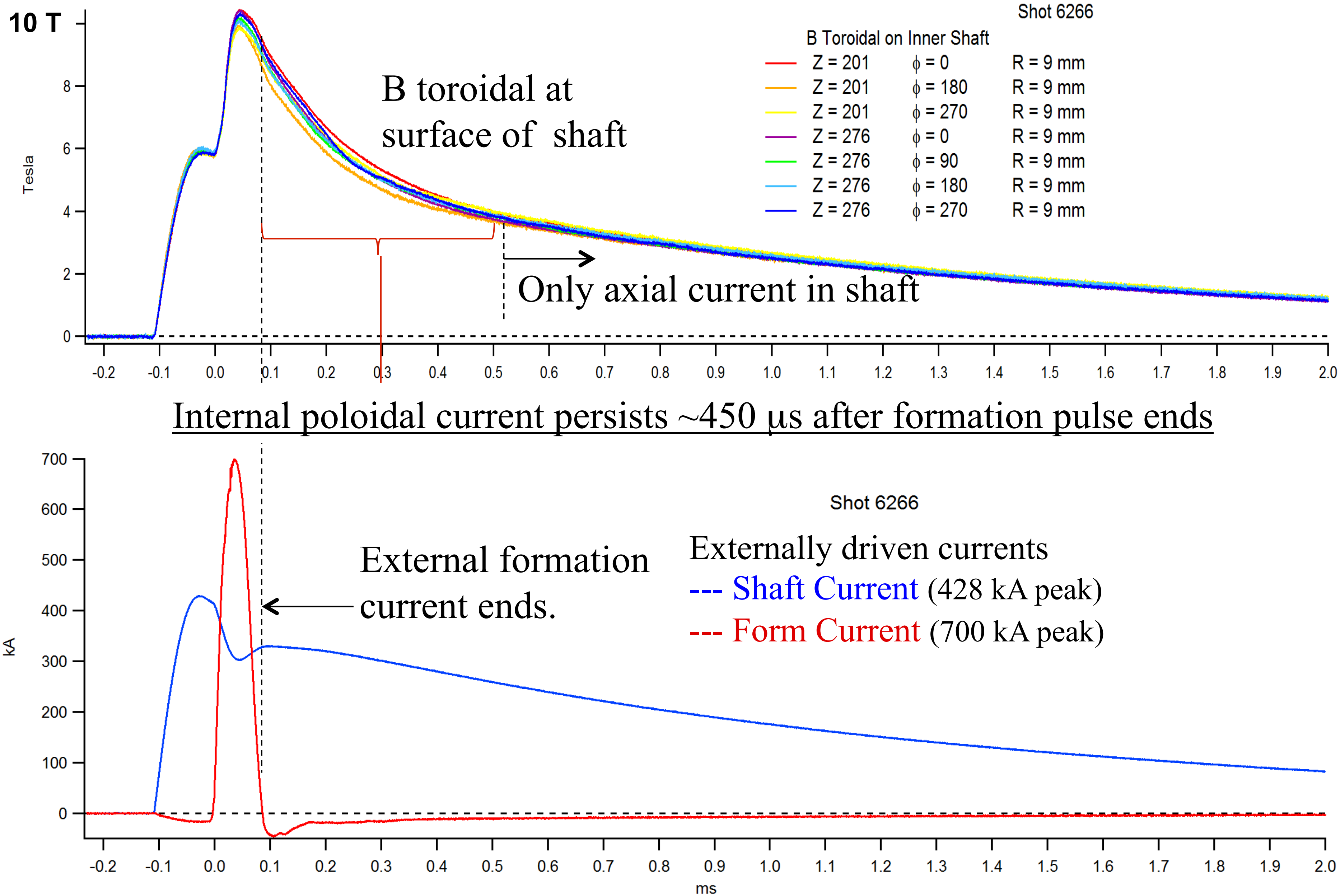

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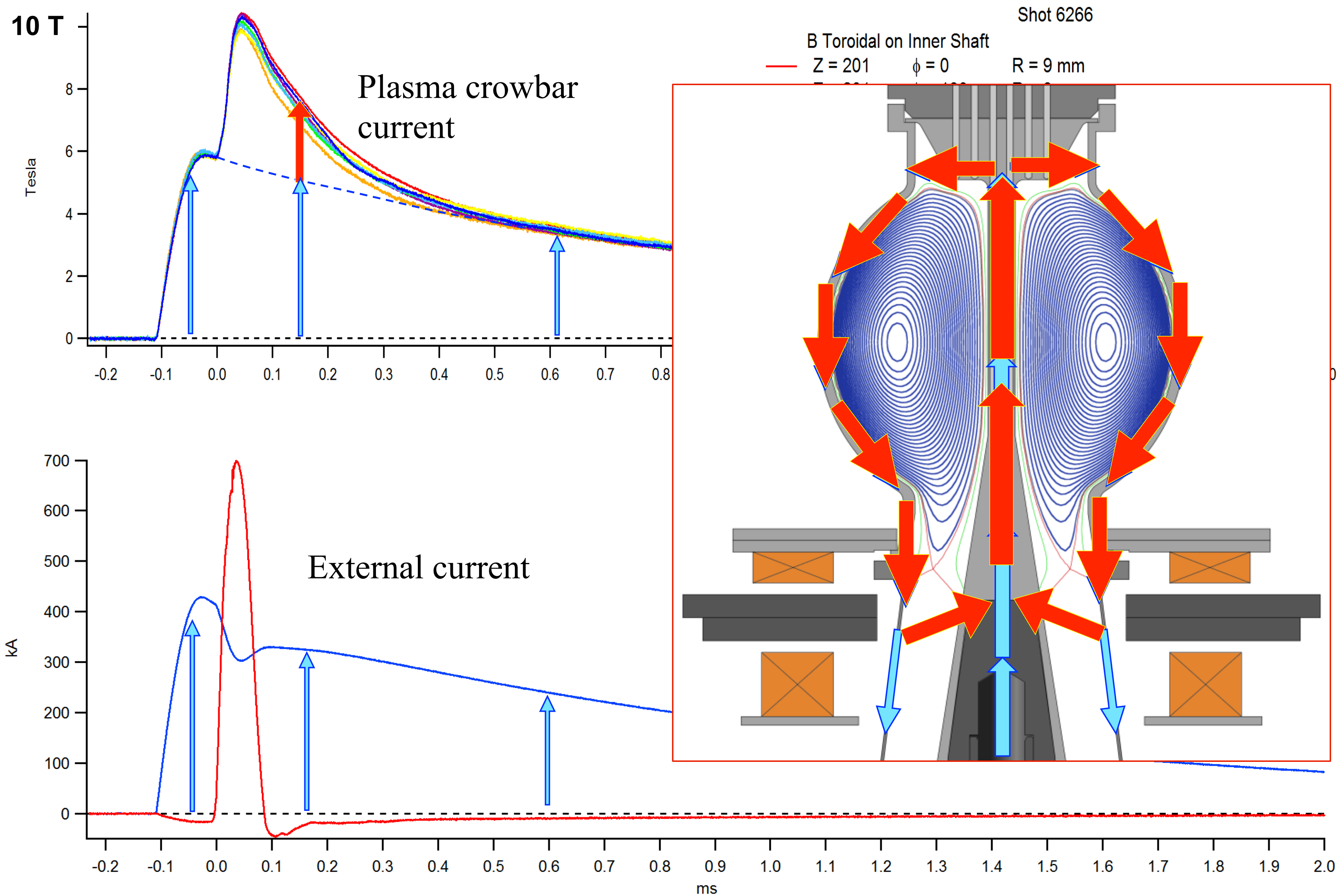

Behavior of B poloidal varies across radius

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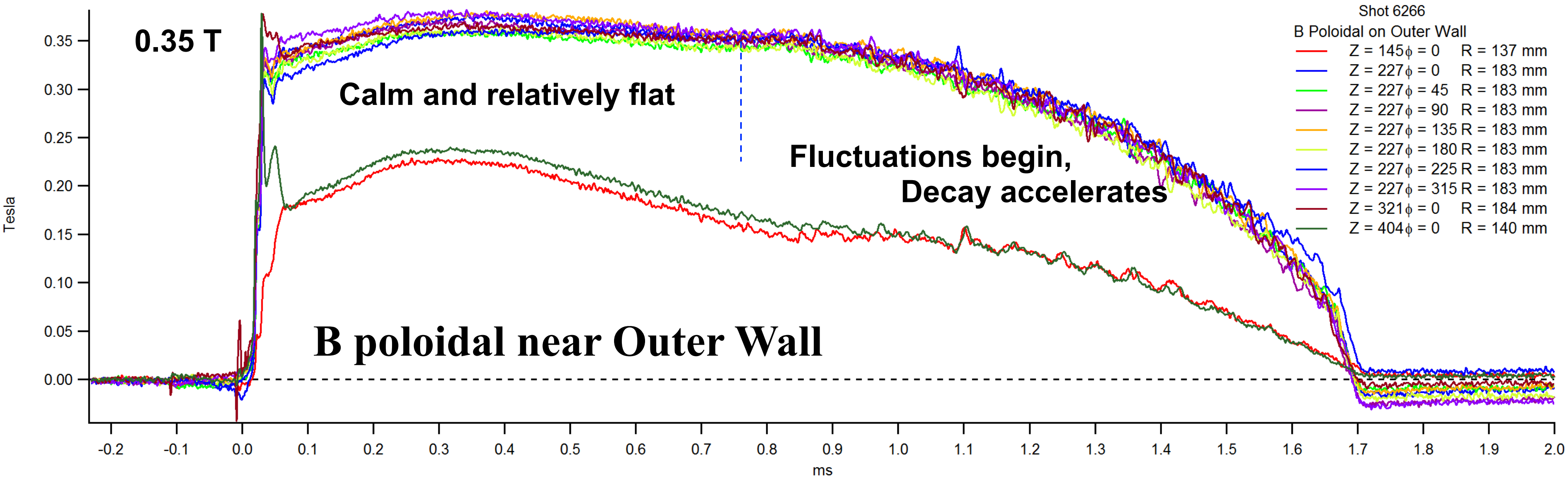

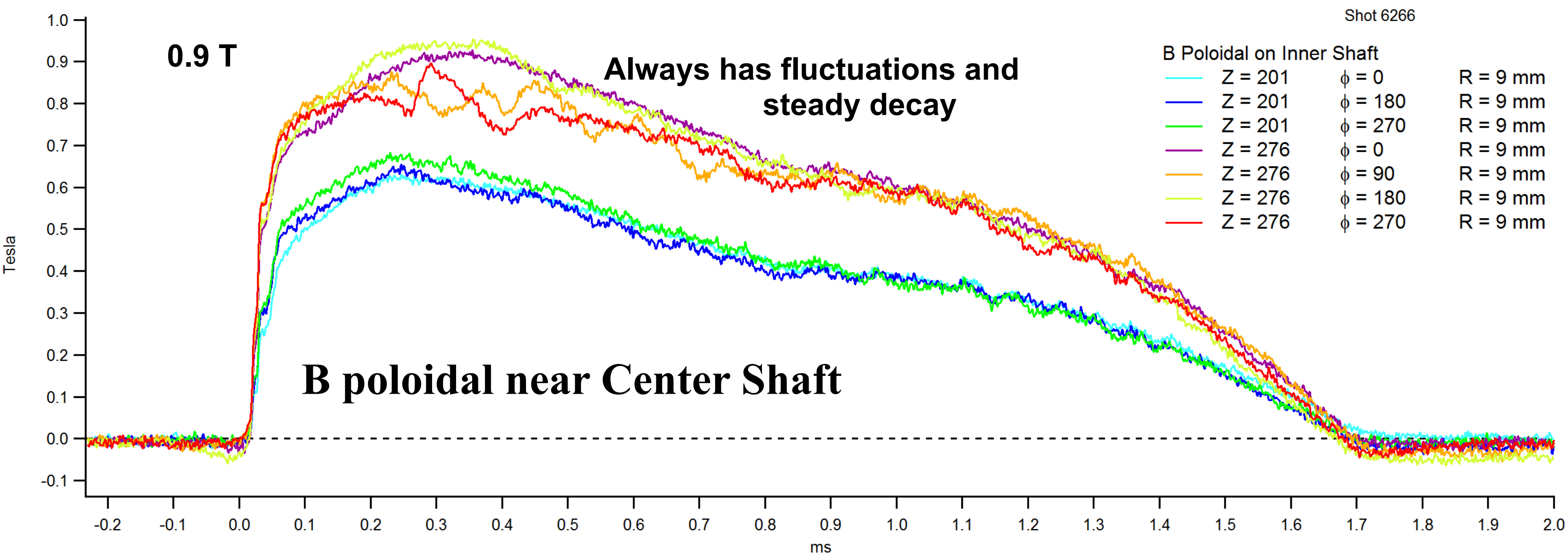

Spector geometry allows equilibrium reconstruction

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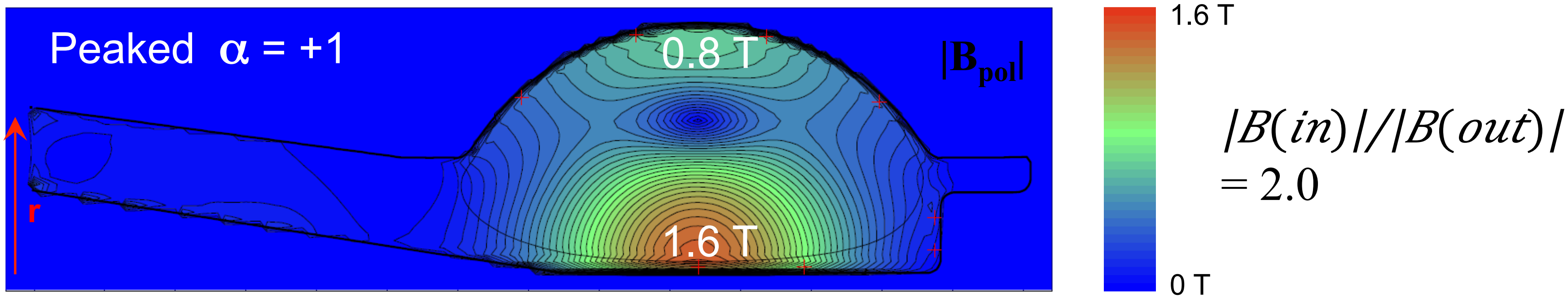
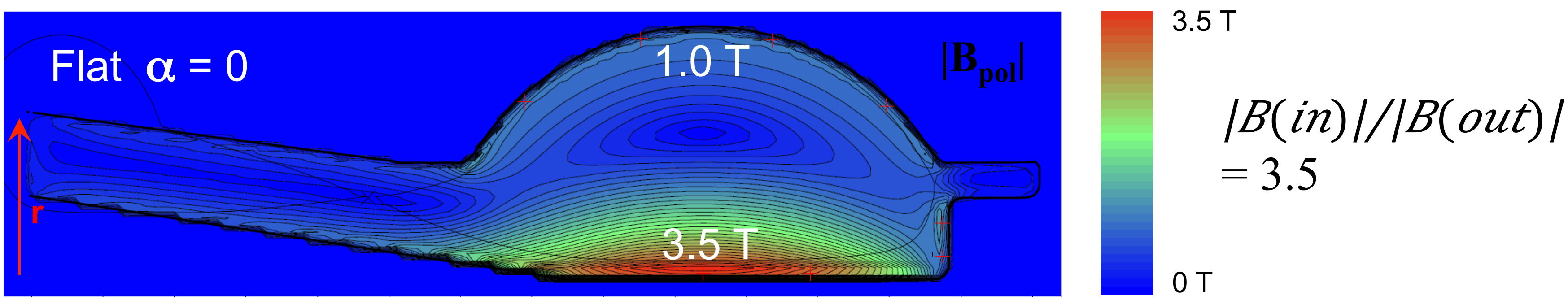
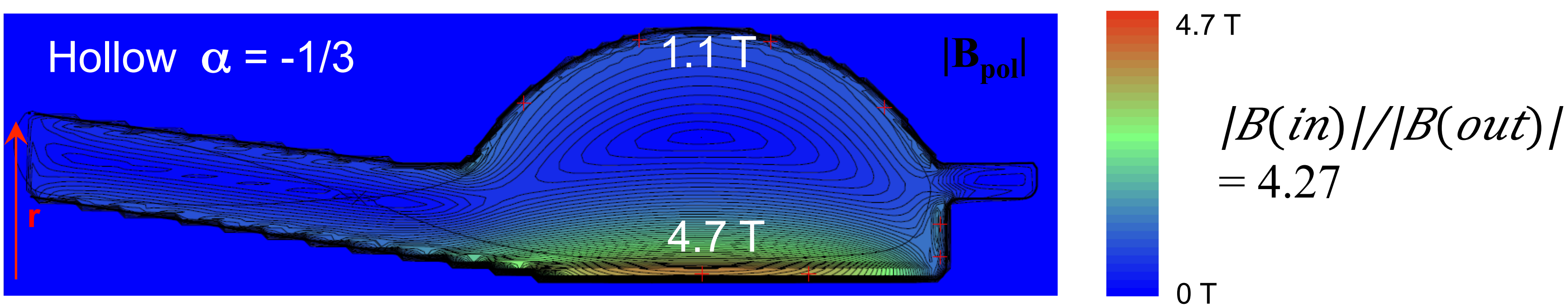
The primary variation in magnetic structure is due to the overall slope of $\lambda(\psi)$, given by $\boldsymbol{\alpha}$. Here are 3 example cases of GS equilibria (calculated by Corsica) that span the set of possibilities for this linear λ profile model. Contours of $|\mathbf{B}_{pol}|$ from are plotted. [Ψ_{CT} = 30 mWb, I_{shaft} = 450 kA]

<u>Wall values for $|\mathbf{B}_{pol}|$ uniquely determine $\lambda(\psi)$ to first order.</u>







Corsica Shows Extended Poloidal Flux Amplification

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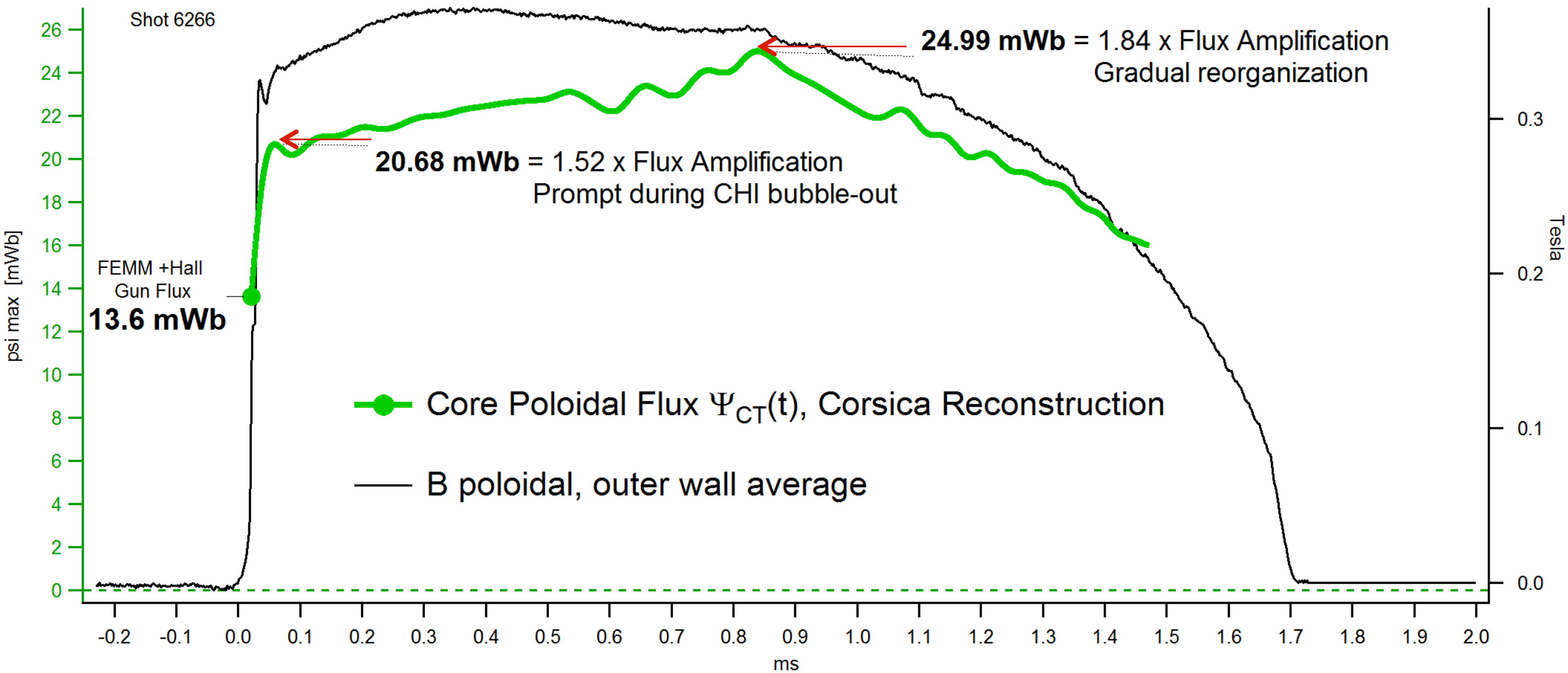

- Flux amp of 1.84x is similar but less than 2.3x from 3D VAC
- Corsica fits to experimental data also show $\lambda(\psi)$ profile as being always peaked $\alpha > +0.5$, increasing with time

Corsica Shows Extended Poloidal Flux Amplification

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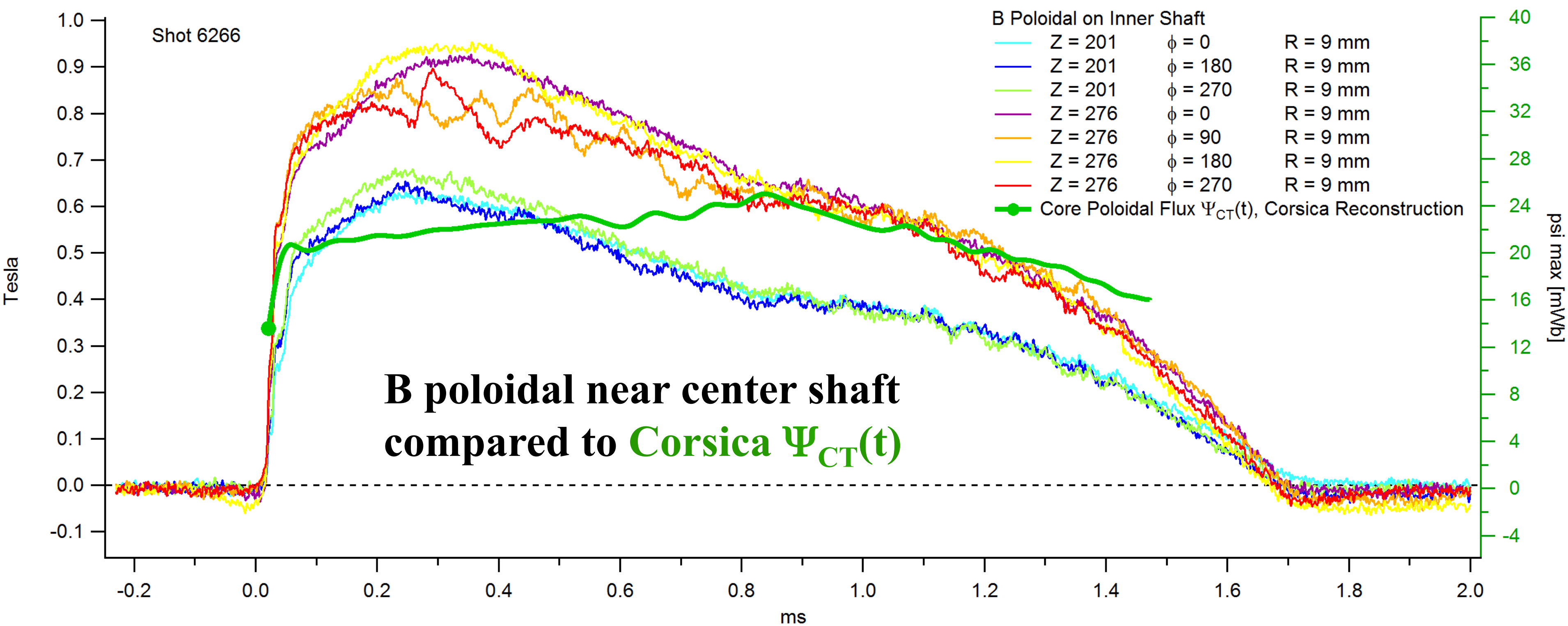
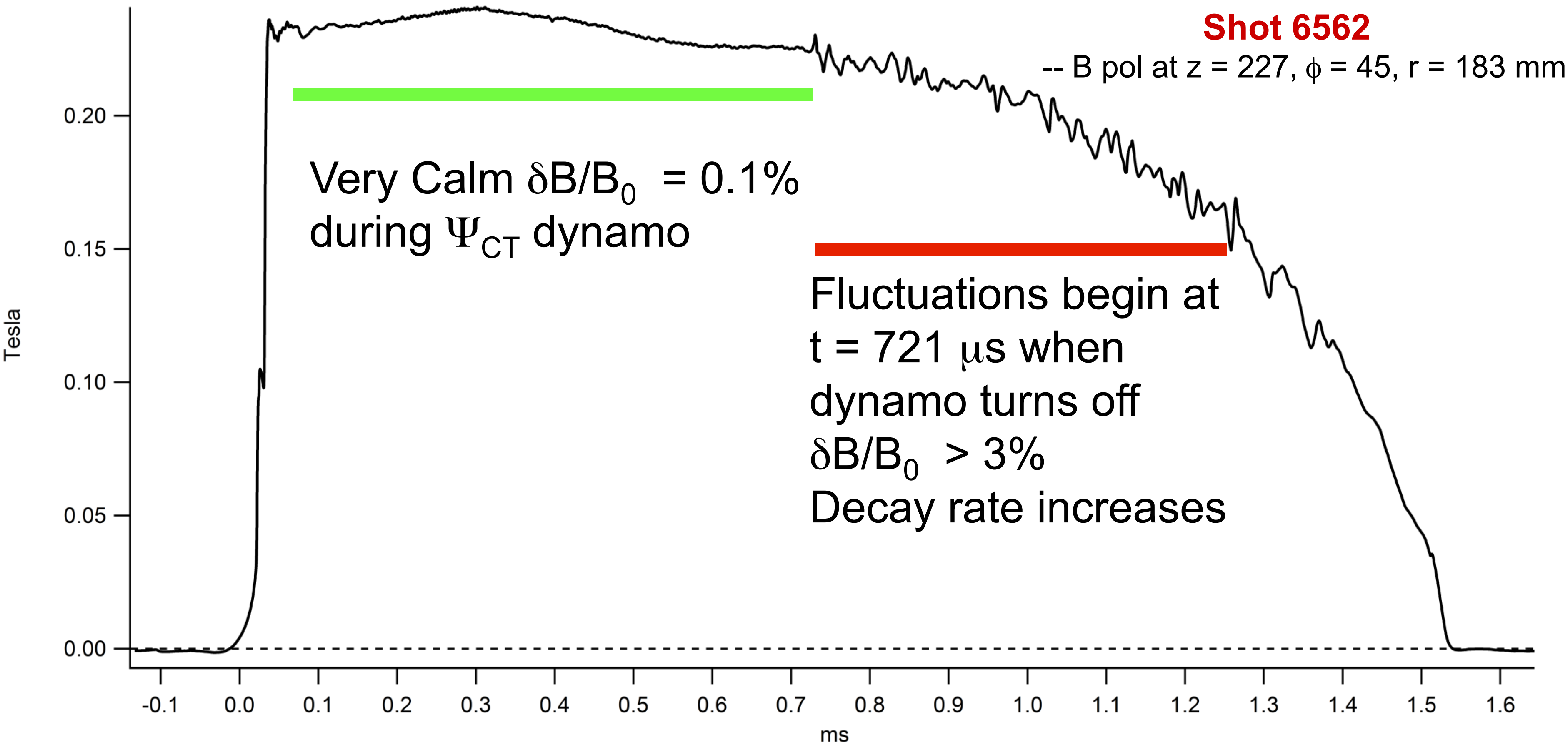


Fluctuations near shaft could be signature of dynamo process.

- $n = 1$ and $n = 2$ spatial modes as large as 5% , 9 % of $n = 0$
- $n = 0$ has temporal fluctuations.
- $n = 2$ becomes low amplitude ~ 1% in final decay phase.

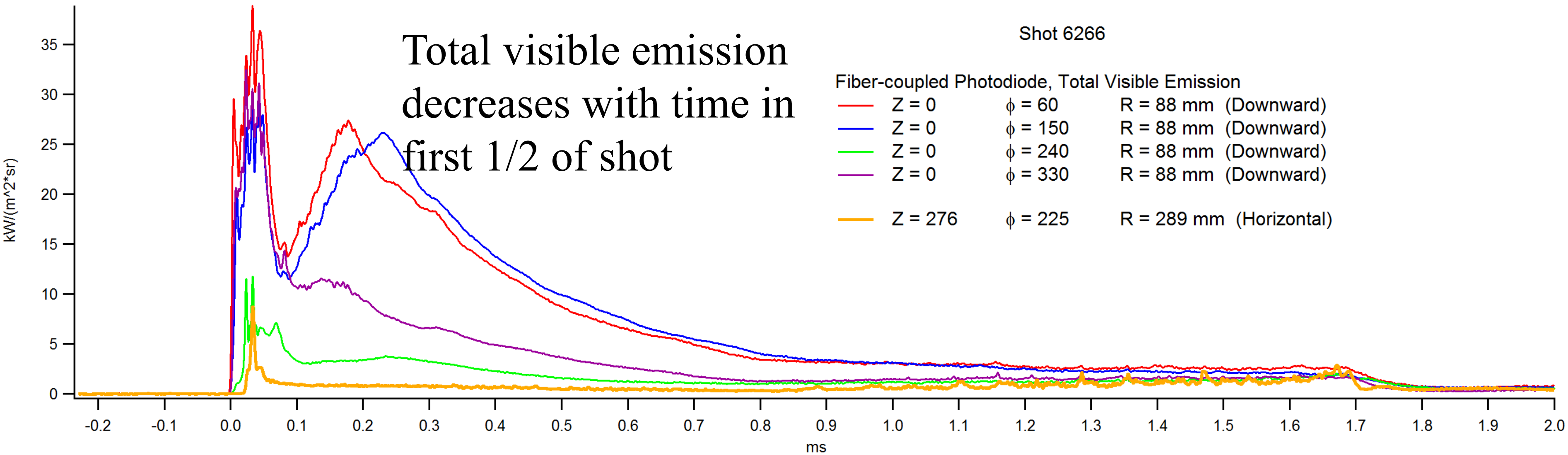
Outer fluctuations begin after half-way point

Here is a different shot where the transition is very clear and abrupt

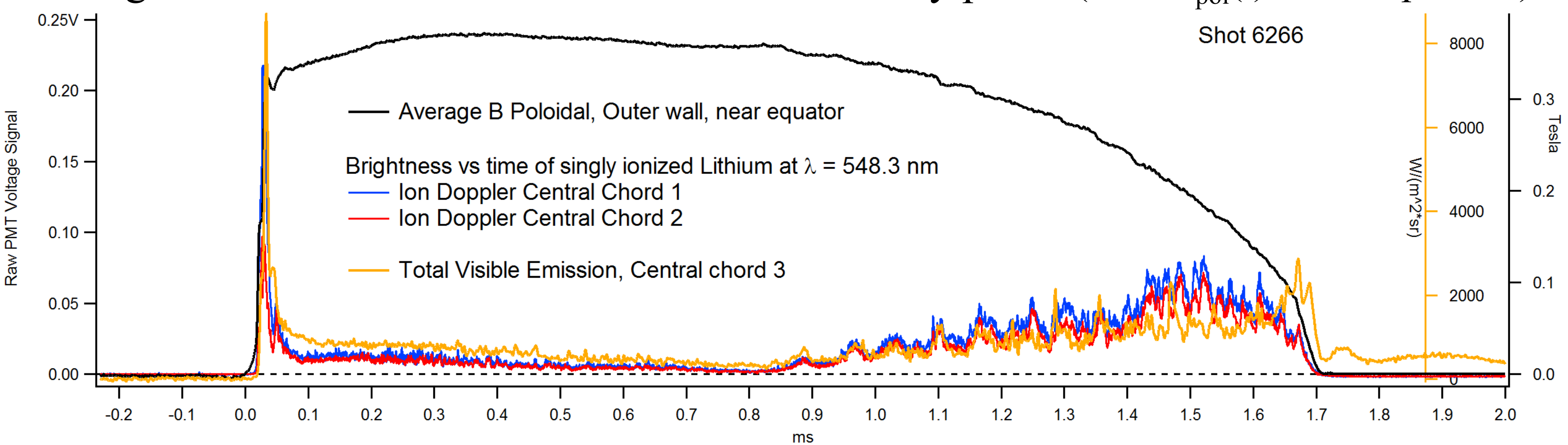


Visible light emissions may imply change in Transport

Total visible emission decreases with time in first 1/2 of shot



Brightness of Li II at 548.3 nm increases in decay phase (with $B_{pol}(t)$ for comparison)



Edge fluctuations in second phase seem to be increasing transport of Li from wall deeper into CT plasma.

Easy-to-use Lithium gettering system

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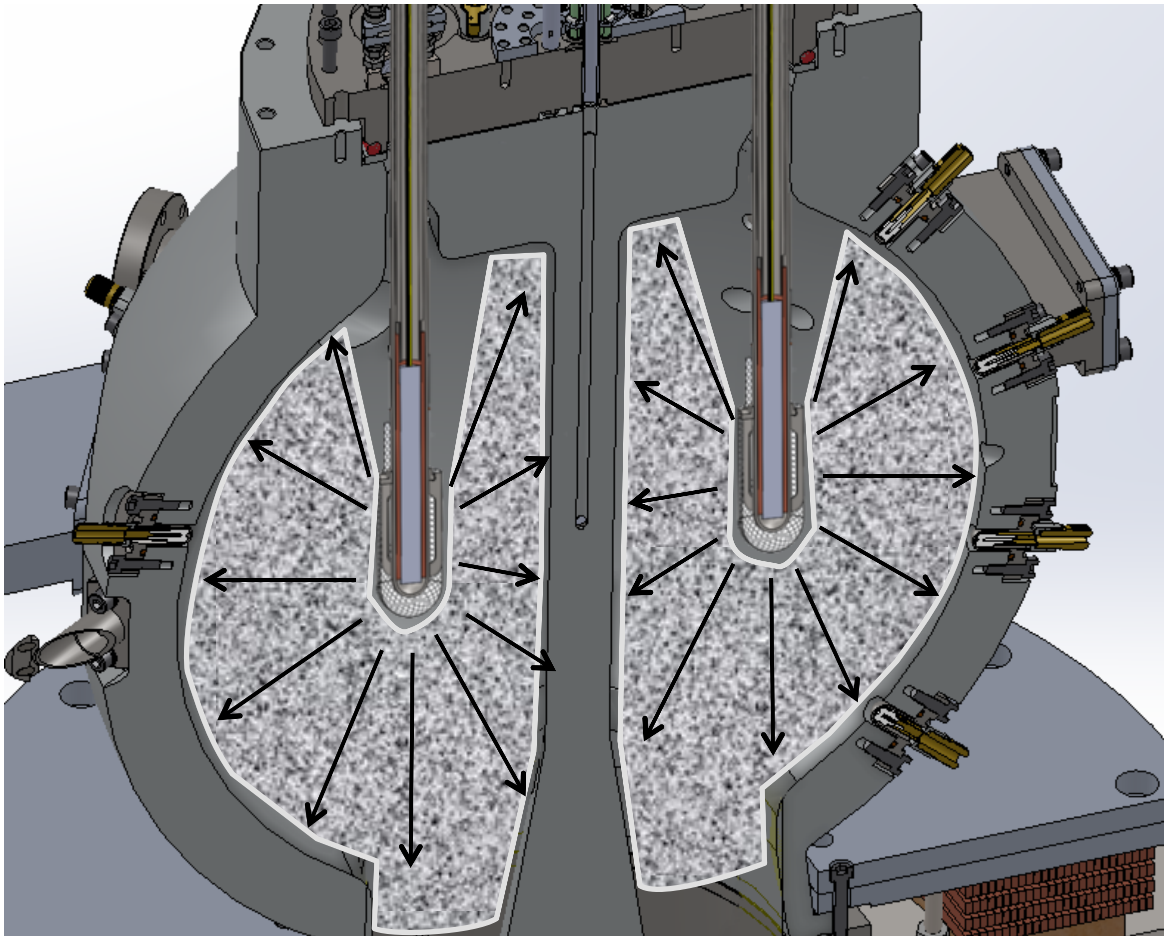
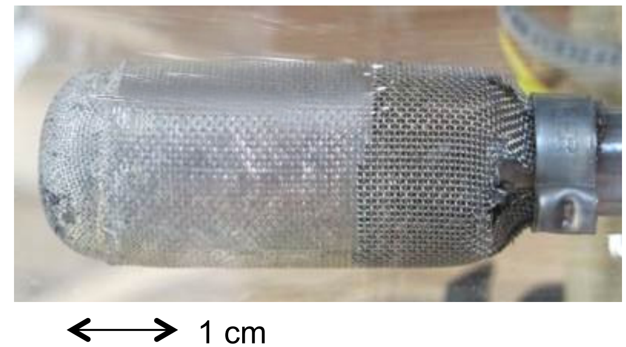
Retractable Lithium evaporation sticks (GF patent pending) deposit a fresh coat of ~2 μm of Li over 20 min. Stainless mesh basket holds liquid Li in place by surface tension, evaporates when above 400 C. Stick depletes after ~10 coatings. Cools back to room temperature (Li solidifies) and retracts upward before shots begin.





Lithium coating:

- Reduces ion and electron recycling coefficient
- Bigger improvement with D plasmas, still helps He.
- Minimizes other wall-sourced impurities.

Lithium Gettering increases T_e and plasma lifetime

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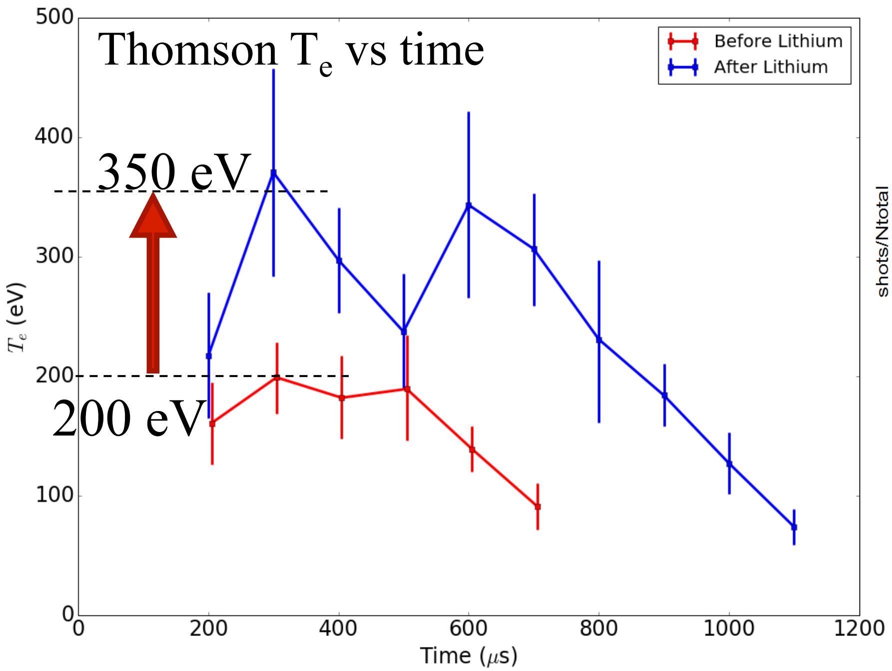
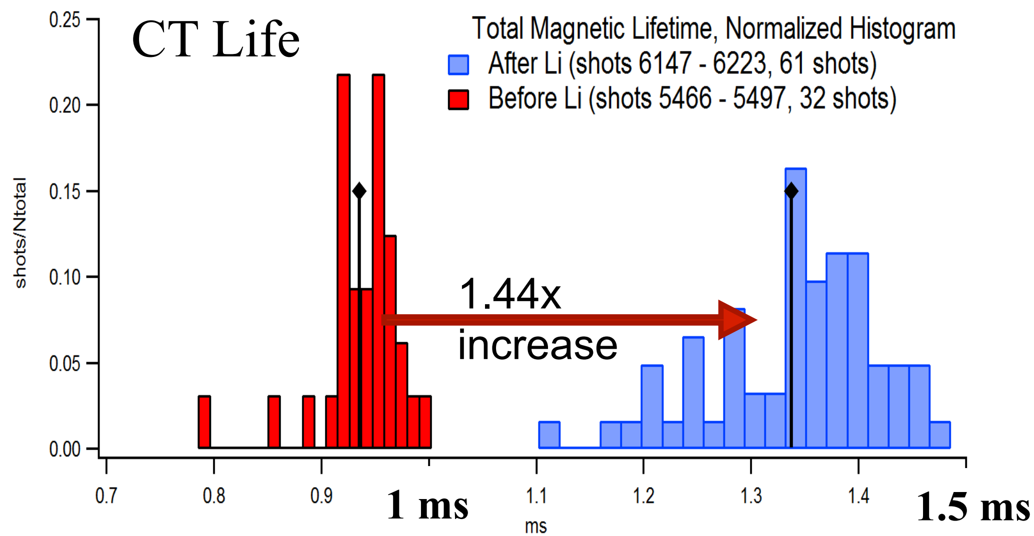
After first 80 min total of Li gettering with 2 sticks
~320 mg, ~8 micron layer deposited on walls.
This show prompt effect on Deuterium plasmas repeated under similar conditions





Before Li (shots 5466 – 5497)

After Li (shots 6147 – 6223)

Effect due directly to Li coating:

- Core T_e increased by from **200 eV** to **350 eV** (1.73x)
- CT Total Life increased by 1.44x.

Further improvements occurred with continued shooting, optimization

Detail of Thomson Collection Optics

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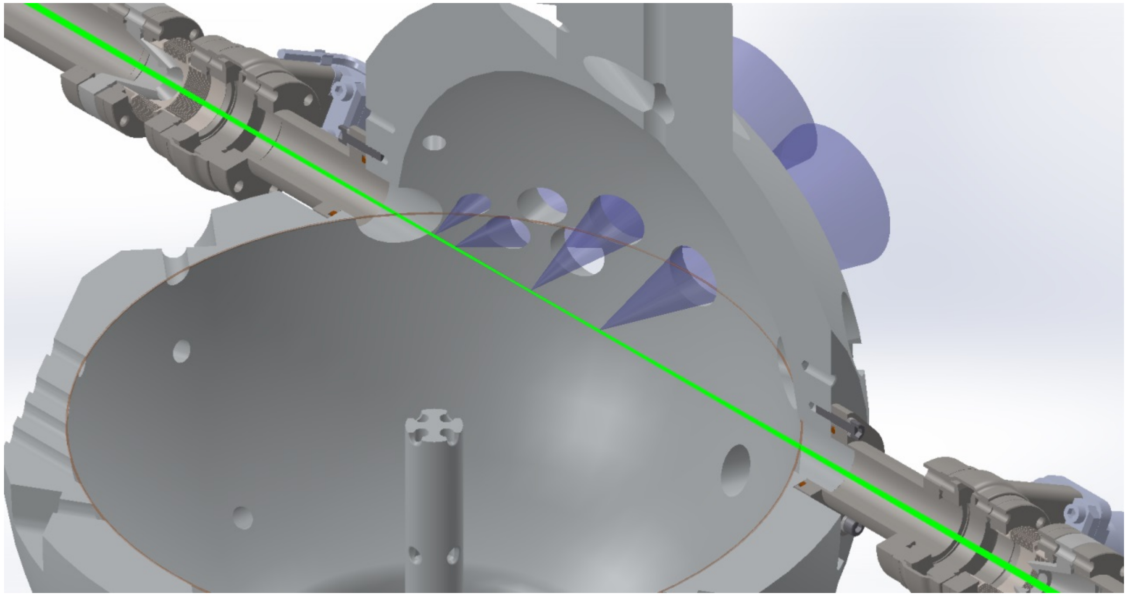

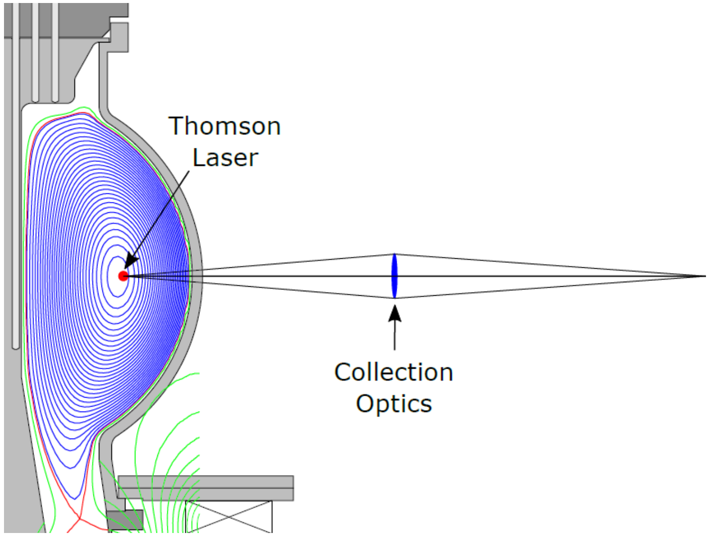

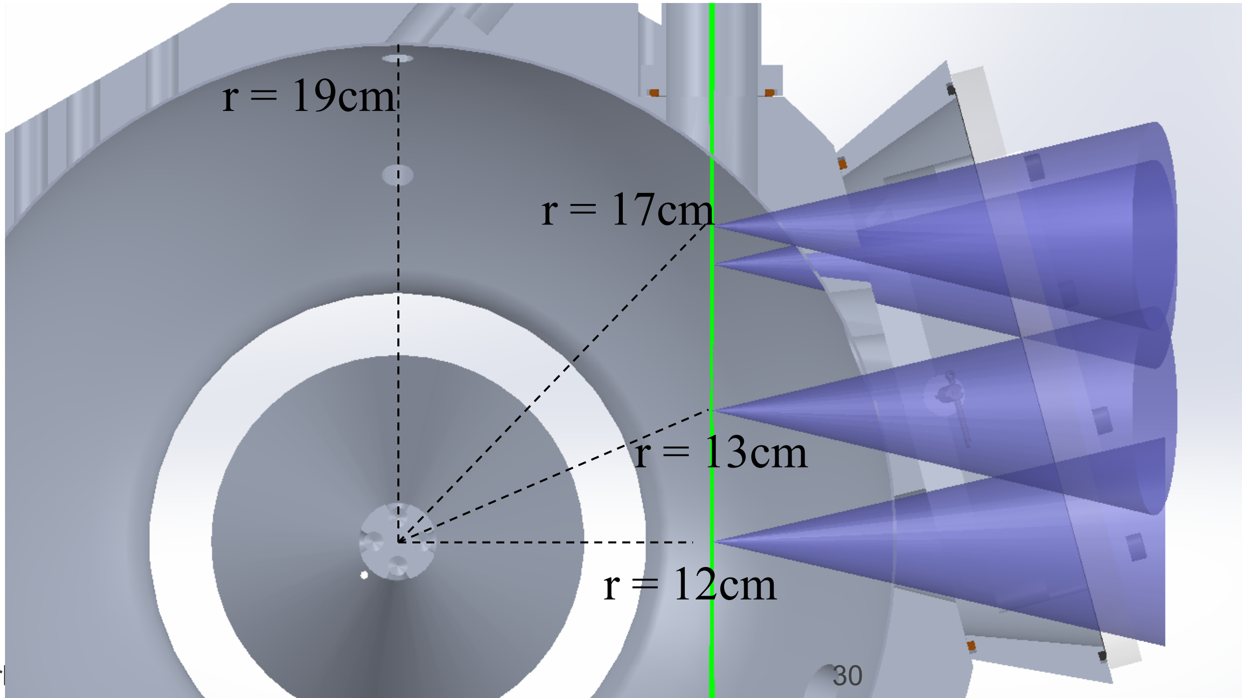

<u>TS laser system</u>

532 nm

10 ns pulse

1.5 J per pulse

1 pulse per plasma shot

3 collection points

Upgrade to 6 collection points soon.

Core T_e > 400 eV has been measured

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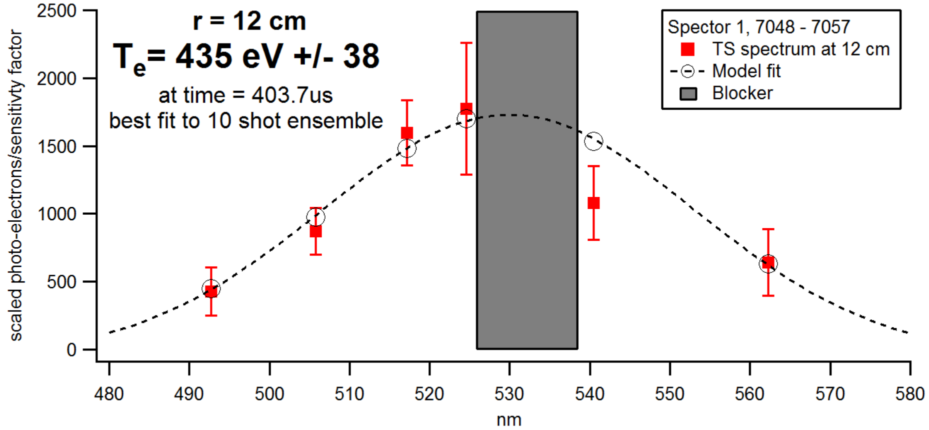
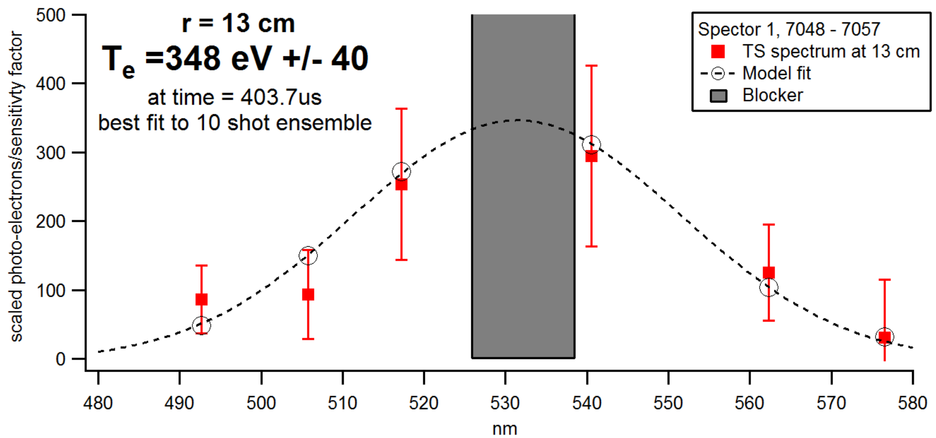
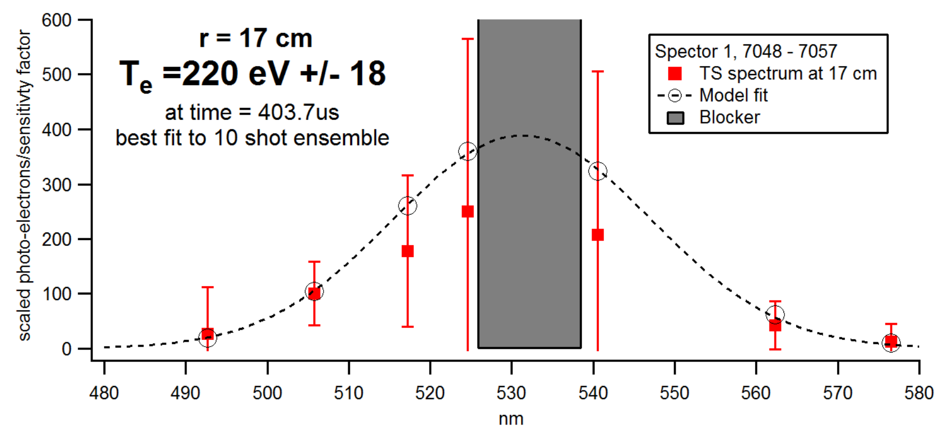
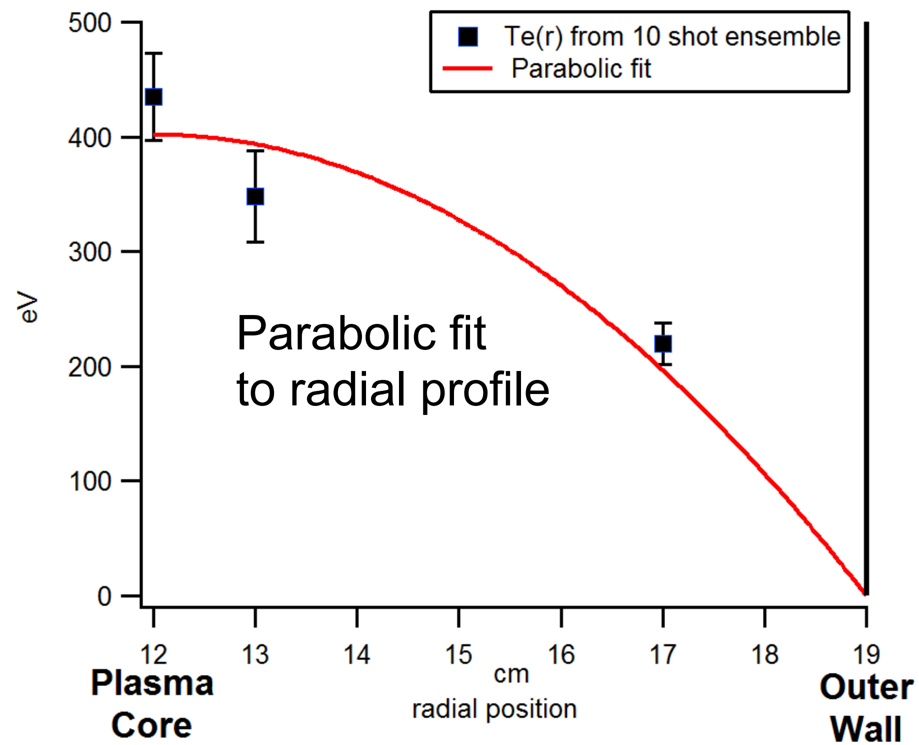






TS ensemble of 10 recent (consecutive) Deuterium shots [error bars show st.dev. of scatter within measurement set]



Data is consistent with parabolic-like $T_e(r)$ profile during calm period at t = 403 μs.

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- MTF compression test of Spector plasma looks promising.
- Adiabatic spherical compression $T \sim 1/R^2$
  - $R_0/R_{min} = 4$ ➔ T_e increases from 400 eV to 6.4 keV
  - $R_0/R_{min} = 5$ ➔ T_e increases from 400 eV to 10 keV
- Still subscale on density, magnetic energy, won't get Q >1 yet…
- **Starting to explore fusion relevant physics**.