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Use of In-Situ Anode Heating and Plasma Glow Discharge Cleaning and its Effects on Impedance Behavior in the Self-Magnetic Pinch (SMP) Diode on the RITS-6 Accelerator* **

Timothy J. Renk, Sean Simpson, Timothy J. Webb, Mark D. Johnston,

Josh J. Leckbee, Michael G. Mazarakis, Sonal Patel, and Mark L. Kiefer

Sandia National Laboratories, Albuquerque, NM 87185 USA

Nichelle Bennett

National Security Technologies, LLC, Las Vegas, NV 98512 USA

***** a tale of Unintended Consequences***

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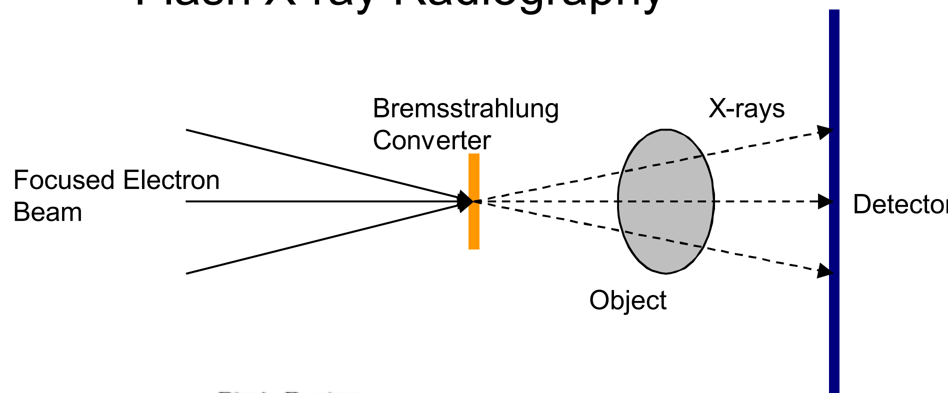
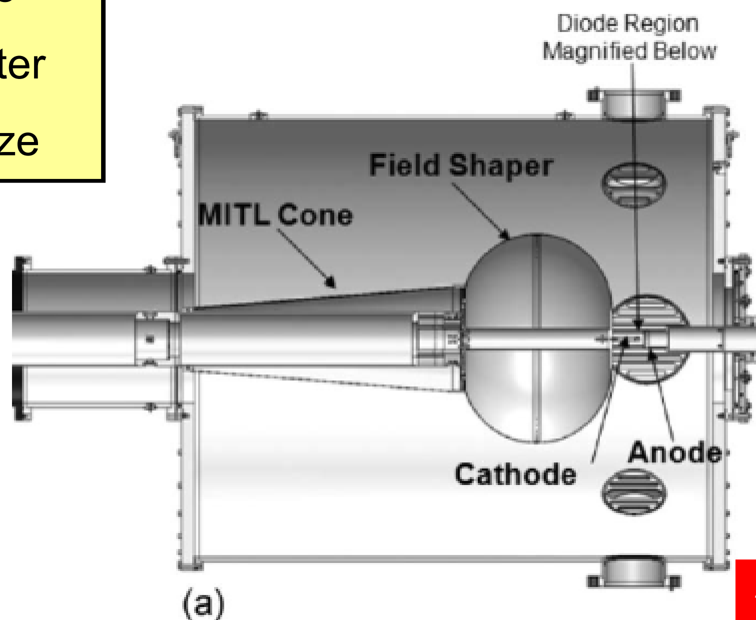
Schematic view: RITS front end

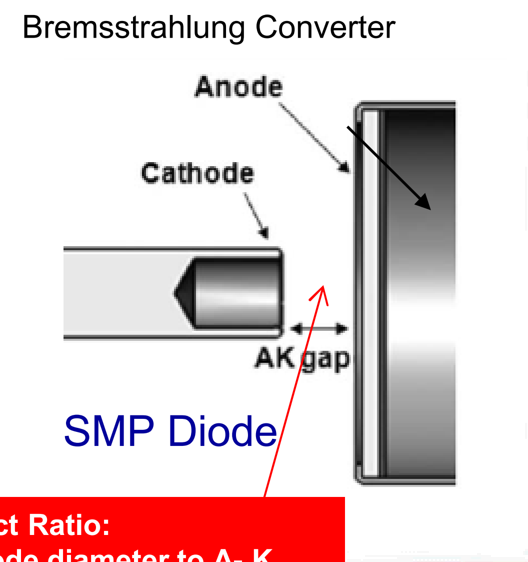
SMP Diode Parameters[2]

- 3.5-7+ MV
- 150 kA (~15% ions)
- 80-50 ohms Impedance
- 70ns Electrical Pulse
- 45ns Radiation Pulse
- > 350 Rads @ 1 meter
- < 3 mm focal spot size

Flash X-ray Radiography







Aspect Ratio:
Cathode diameter to A- K gap in mm. Example: 12.5-12

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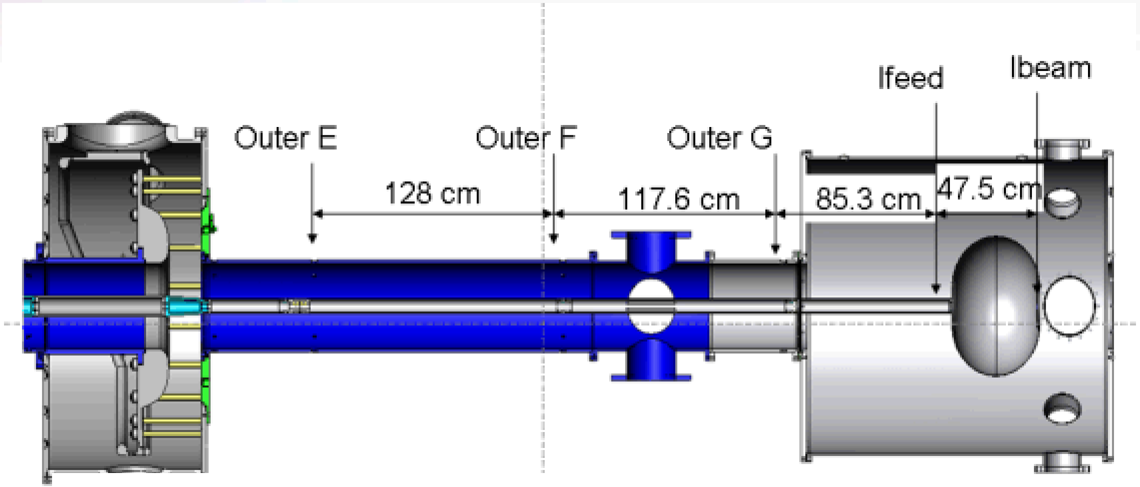
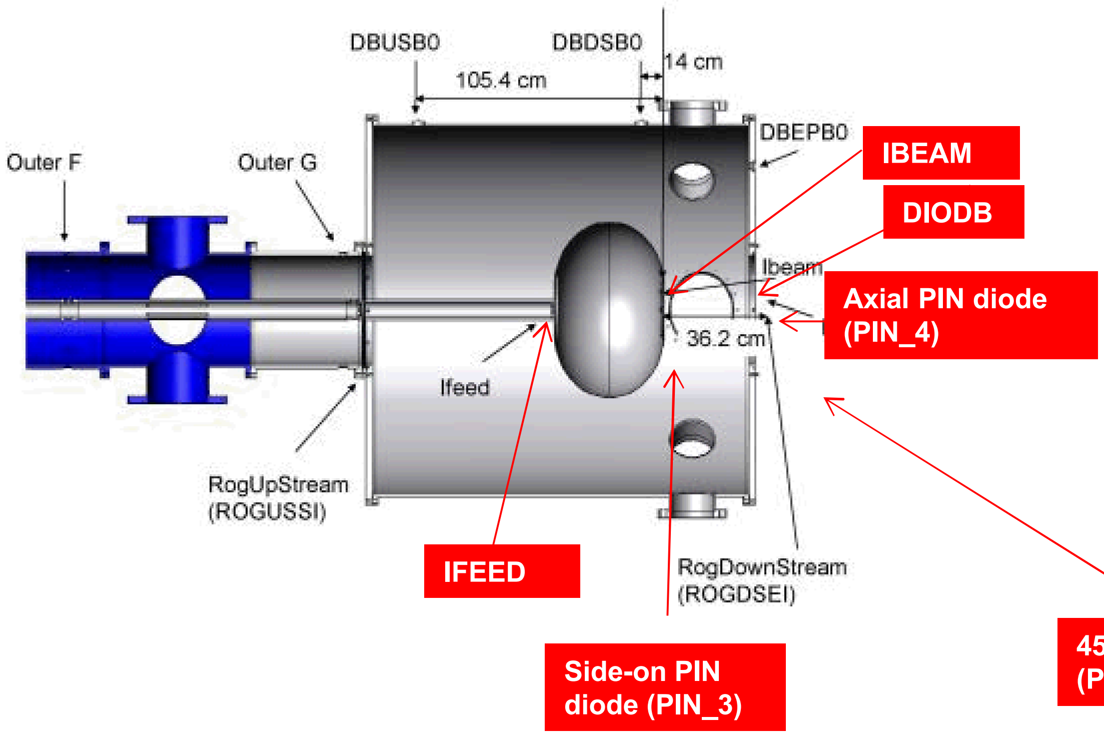
[2] K. Hahn, et. al., *IEEE TRANSACTIONS ON PLASMA SCIENCE*, VOL. 38, NO. 10, OCTOBER 2010, pp.2652-62.

Location of RITS Bdots, P-I-Ns





- Inner-outer Bdots at locations E, F, G (shown). Voltage (e.g. V at E) calculated from Mendel. On typical full-pulse shot, waveforms ~ identical.
- In Dustbin:
  - (4) IFEED (upstream of Knob)
  - (4) IBEAM, outside of cathode position
  - (4) DiodB, on downstream wall outside of anode plate
- Three P-I-N diodes, axial (PIN_4), 45° (PIN_6), 95° (PIN_3, PIN_5)
- ‘DERIVED’ SIGNALS:
  - VCORR_G: V at G is moved ~ +10ns, Lidot-corrected with IBEAMdot
  - ZDIODE: VCORR / IBEAM
  - V from Radiographer’s Eq inverts: 20mono, 30mono, etc (CYLTRAN)

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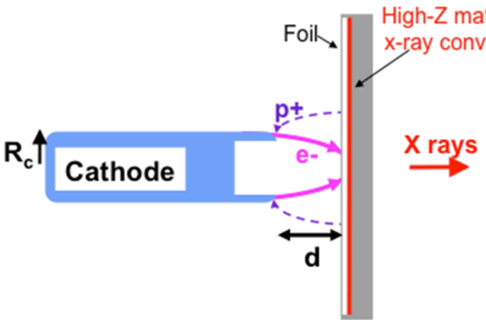
Premise: in-situ heating to extend radiation pulsewidth

- Factors affecting Spot Size in the Self-Magnetic Pinch (SMP) diode
  - Output voltage: slight downward trend with rising voltage
  - Cathode size: smaller cathode diameter → reduced spot size
- 12.5 mm Cathode diameter + 12 mm A-K gap (12.5-12) is 'standard' SMP diode (40 ohm MITL)
  - Good: Stable operation, full radiation pulse. Desire: smaller spot size
  - 8.5 – 8.3 SMP produces smaller spot size. Downside: FWHM can be reduced
  - Premature impedance (Z) collapse on 50% of 8.5 - 8.3 shots.
  - One hypothesis: cause is electrode plasma-induced gap closure
    - N. Bennett et al, Phys. Plasmas **22**, 033113 (2015)
- Proposed Mitigation: In-situ DC heating and/or glow discharge cleaning to reduce adsorbates, interstitial hydrogen (Ta anode) in as - provided parts
  - Cleaner diode should result in full-pulse operation
  - Key metric: increased diode impedance
  - For 'stable' 12.5 – 12 diode operation (at 7-8 MV): heating should have little impact
  - For 'unstable' 8.5 – 8.3 operation, greatest impact expected here



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Question:

- PREMISE relies on the assumption that Diode Impedance is an independent variable.
- What if this is not true?

- Addressing THIS question changes the Storyline of this Talk:
  - from Heating
  - to a Systems Study of IVA-Diode Interaction

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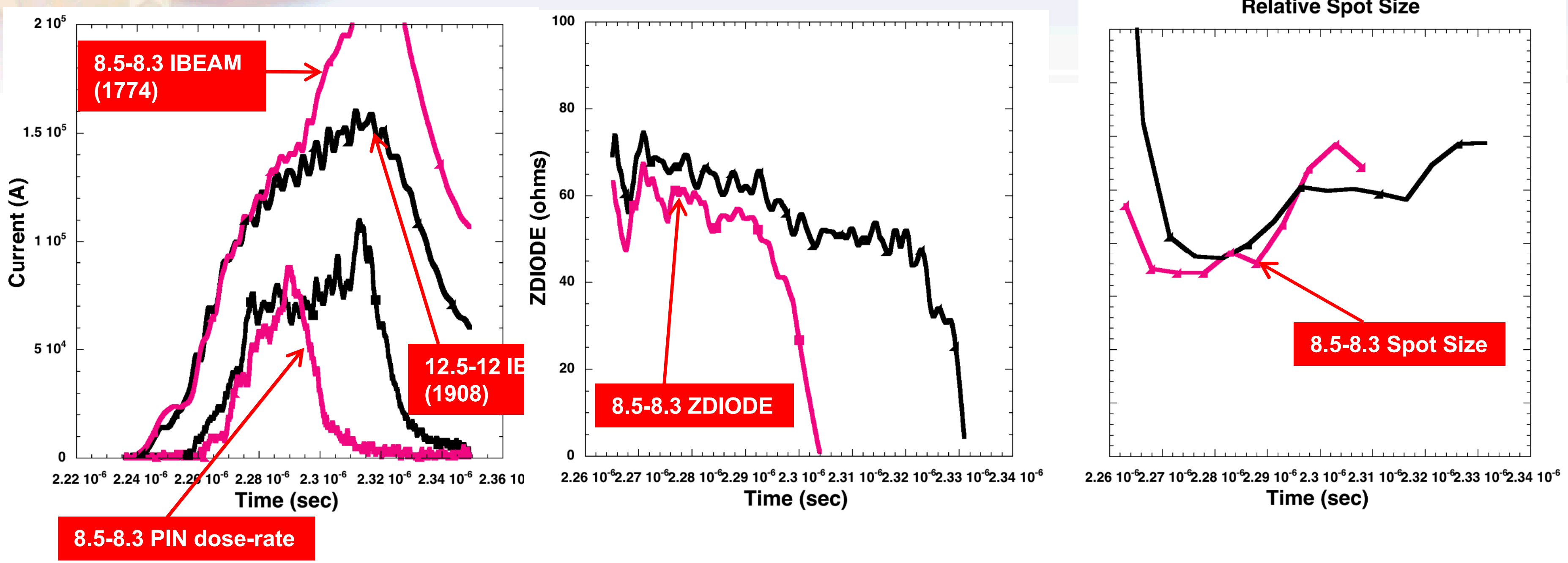
UNHEATED 12.5 vs 8.5 compare

An example of Standard Foil 12.5 – 12 vs 8.5 - 8.3 diode operation (1908 vs 1774)



- **(LEFT)** Beam current (IBEAM) for 8.5 – 8.3 (RED) increases faster then 'runs away'. 8.5 – 8.3 radiation dose-rate (RED) almost equals 12.5-12, then collapses.
- **(MIDDLE)** 8.5 – 8.3 Corrected Diode Impedance (ZDIODE) less than 12.5-12, then collapses.
- **(RIGHT)** 8.5 – 8.3 pinch Spot Size (RED) initially smaller than 12.5 – 12, then increases as voltage collapses.

- **TWO PARTS** to question of in-situ heating success:
- **1) Does the heating remove adsorbates and interstitials?**: **Light Lab** measurements (Simpson) confirm **YES**. **Activation** measurements on heated shots (Mazarakis) **confirm** protons removed.
- **2) Does the removal of contaminants improve shot performance?** Let's address this.

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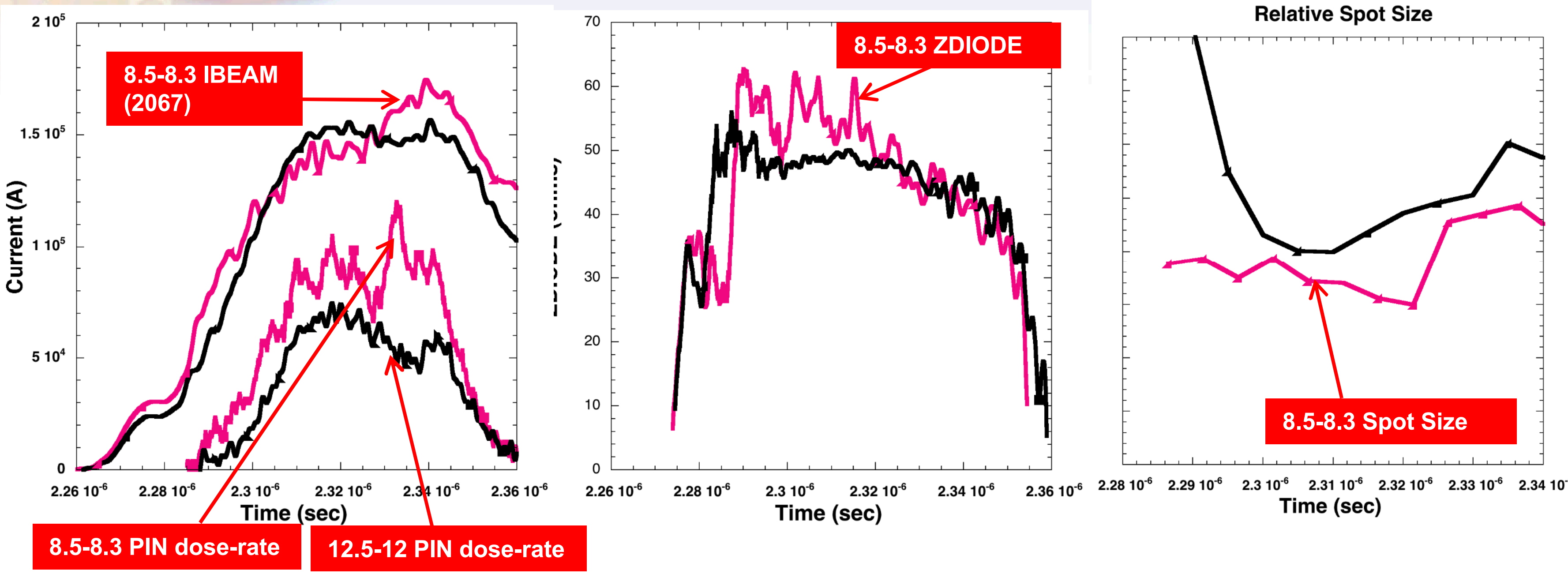
Now compare two heated Bare Ta 12.5 – 12 vs 8.5 - 8.3 (1986 vs 2067)



- **(LEFT)** Beam current (IBEAM) for 8.5 – 8.3 (**RED**) does not 'run away'. 8.5 – 8.3 radiation dose-rate (**RED**) exceeds 12.5-12 by significant amount.
- **(MIDDLE)** 8.5 – 8.3 Corrected Diode Impedance (**ZDIODE**) runs **HIGHER** than 12.5–12.
- **(RIGHT)** 8.5 – 8.3 pinch Spot Size (**RED**) stays significantly smaller than 12.5–12 for entire pulse.

- **Shot 2067 (and one repeat)** show success of heating/discharge cleaning with Bare Ta anode – full pulse. **But Wait.** 2067 (8.5 – 8.3) performance doesn't just match 12.5 – 12, but *really* exceeds it.
- **So what happened, did 8.5–8.3 improve that much, or did 12.5-12 degrade, or both?**

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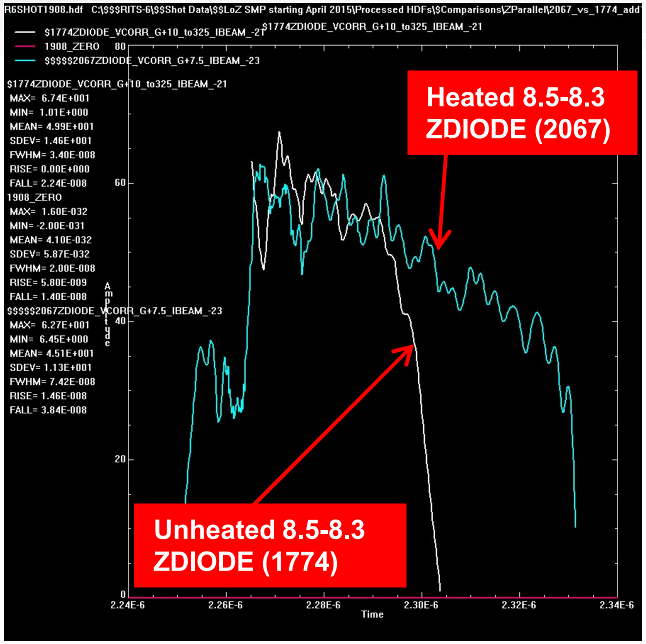
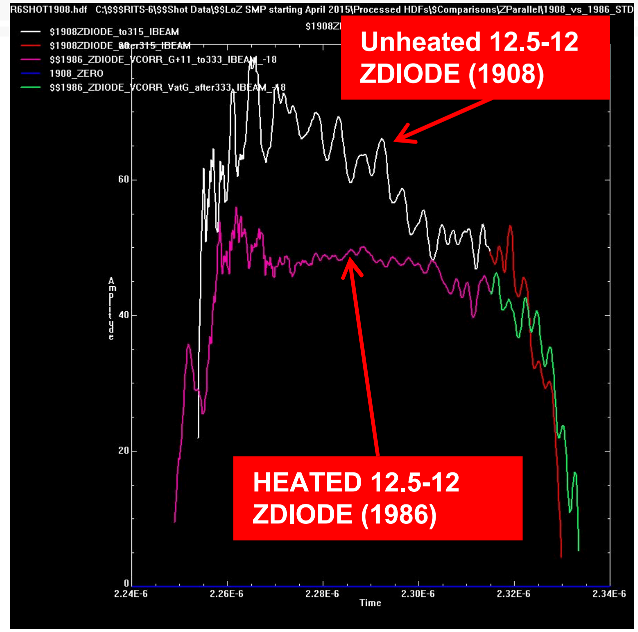
Heated 8.5-8.3 improves FWHM, maintains ZDIODE. Heated 12.5-12 does NOT

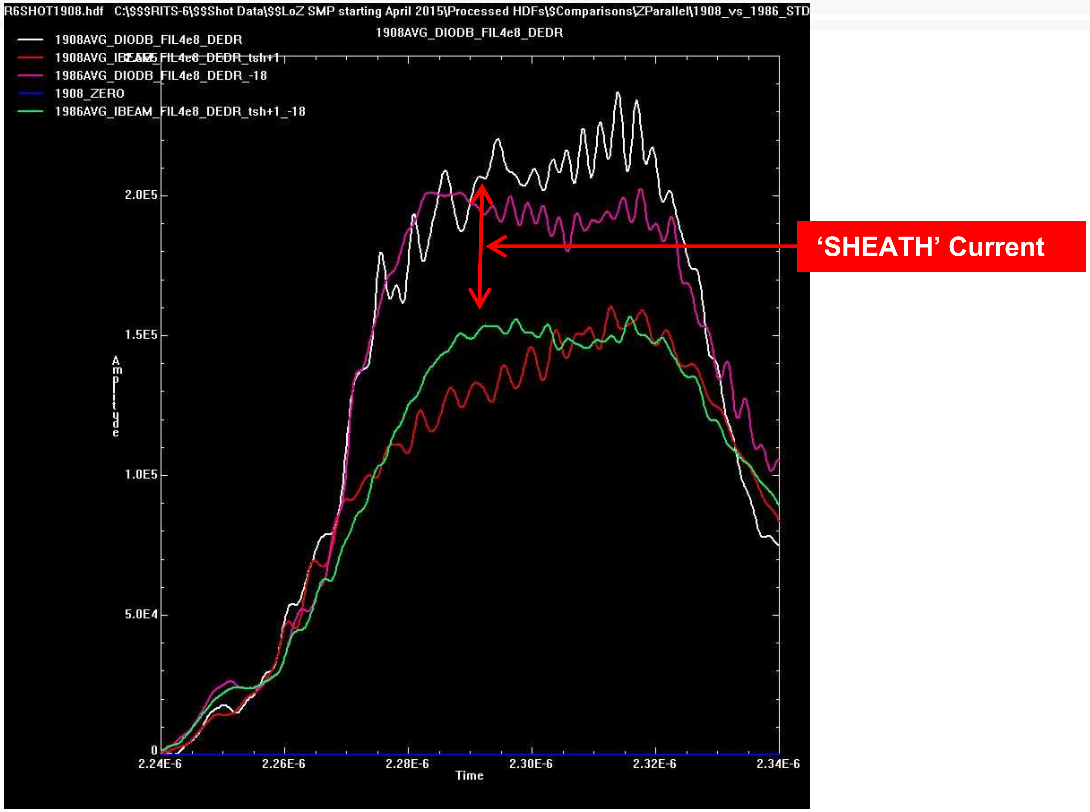




- **(LEFT) 2067 heated 8.5-8.3 ZDIODE (BLUE) equals 1774 DIODE (unheated) before 1774ZDIODE collapses.**
- **(MIDDLE) 1986 heated 12.5-12 ZDIODE runs WAY below 1908 unheated ZDIODE. Not only that, 1986 ZDIODE stays ~ constant with time, e.g. appears to suffer no ZDIODE decline due to gap closure (heated 2067 ZDIODE DOES decline with time)**
- **(RIGHT) Heated 12.5 – 12 Spot Size (LT BLUE) runs slightly HIGHER than unheated Spot Size.**
- **How can One explain a flat ZDIODE with time, and reduced in magnitude compared with unheated?**

SHEATH current defined

Wait. That's not all. DIODB *decreases* while IBEAM *increases* on the heated 12.5-12 shot.



- 1908 unheated DIODB (WHITE) and IBEAM (RED) increase continuously during the power pulse.
- 1986 heated DIODB (MAGENTA) and IBEAM (GREEN) rise but then plateau and actually DROP slightly before the end of the power pulse.
- So for a time in the middle of the power pulse, heated DIODB runs BELOW unheated DIODB, while heated beam current (IBEAM) runs ABOVE unheated IBEAM. How can this be?
- Answer: IBEAM is NOT the entire current in the diode region. There is a 'Sheath' current (shown) that's the DIFFERENCE between DIODB and IBEAM. That current behaved differently.

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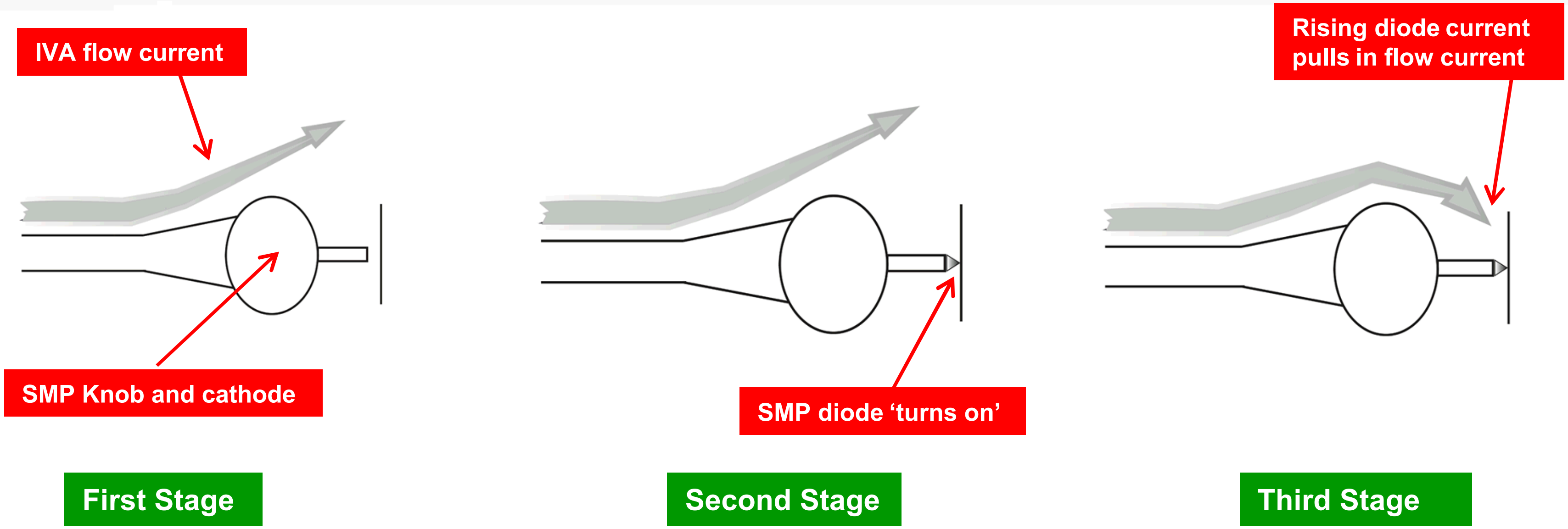
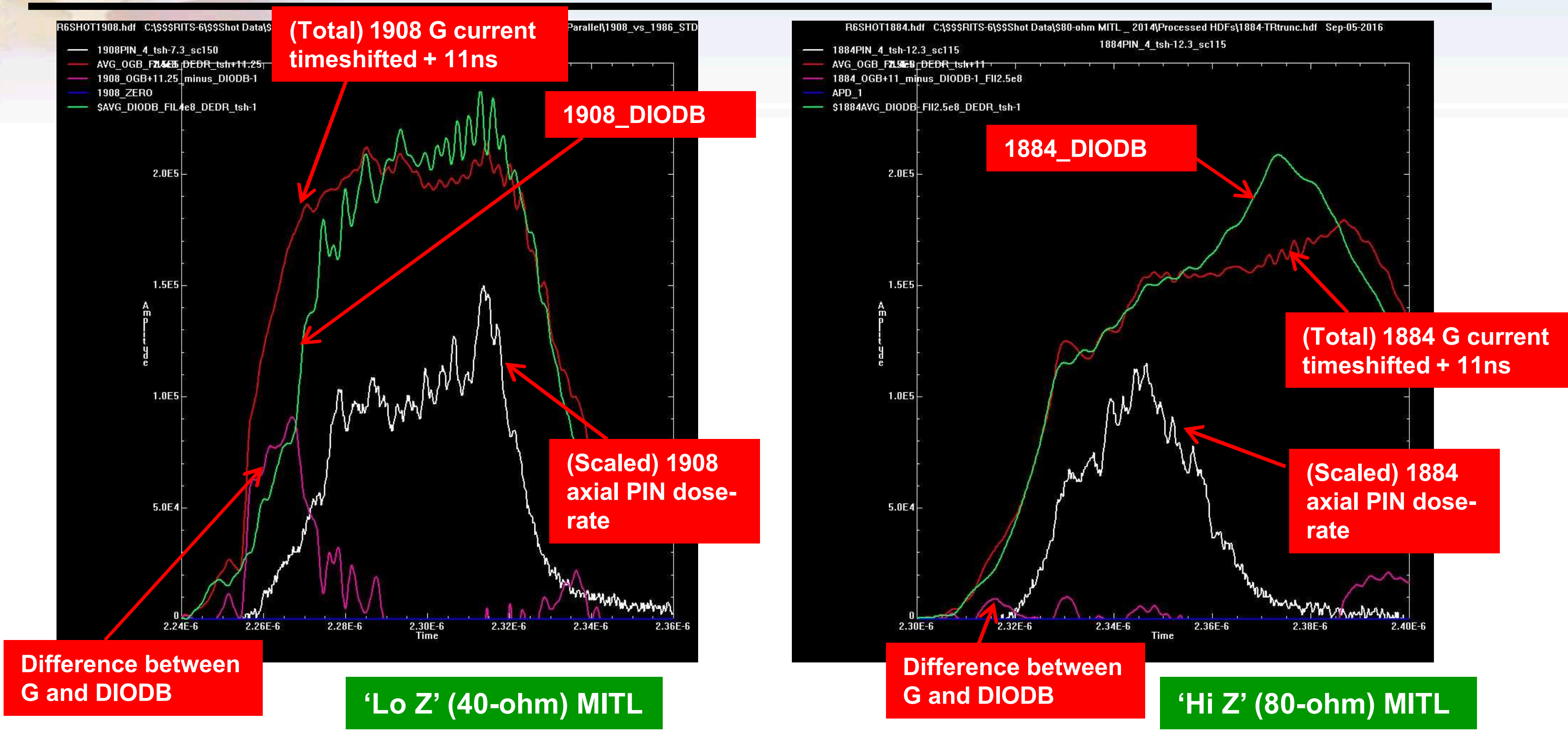
Where does the 'Sheath' Current come from? It happens when IVA Flow interacts with a diode load



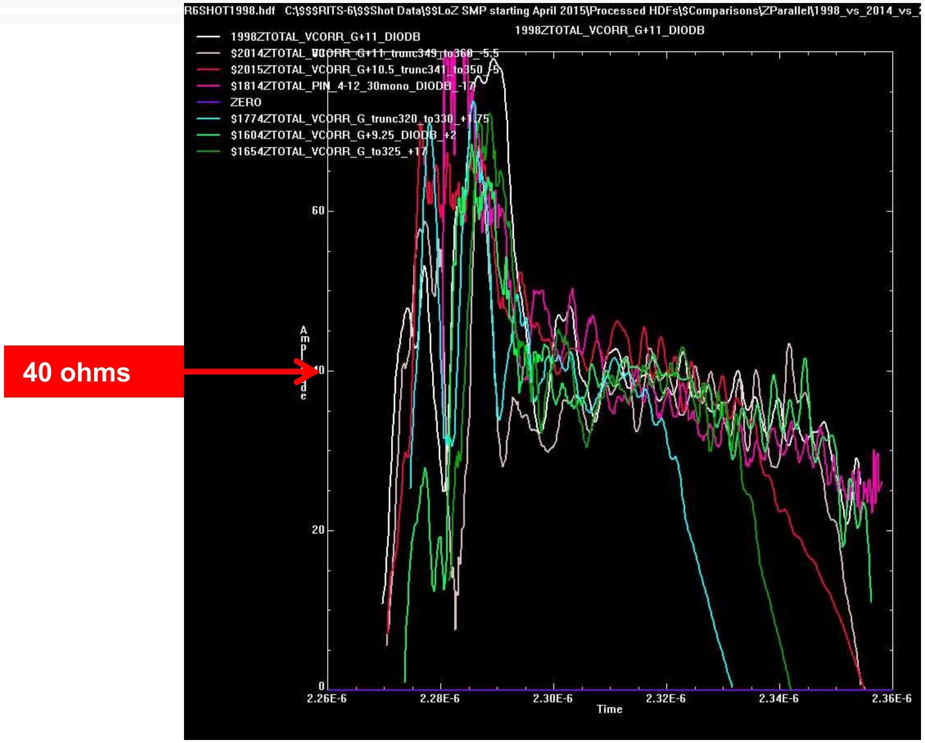
- **(LEFT) First Stage: Flow current enters diode region and is diverted from load.**
- **(MIDDLE) Second Stage: SMP diode (or any diode load) 'turns on' in response to applied voltage. Diode Physics governs load (IBEAM) current generated.**
- **(RIGHT) Third Stage: Rising current B-field can re-direct flow current into load region if knob does not successfully divert flow current. This current (mostly) constitutes 'Sheath Current', which can adversely affect diode (and spot) behavior.**

The DIODB waveform is (almost) same as upstream *total* current.



- **(LEFT) RED curve is upstream outer G (total) current coming forward for Shot 1908, timeshifted to DIODB position. Difference between OG+11 and DIODB is MITL Flow Loss (~ 80 kA peak). After ~ 15-20 ns (and before Axial rises substantially), Flow Loss drops to ~ zero. This is typical for a 'Lo Z MITL' shot.**
- **(RIGHT) same color scheme for Shot 1884, a 'Hi Z MITL' shot. But NOW the Flow Loss is almost = Zero. In other words, for Hi Z MITL operation on RITS, the Knob does not divert MITL flow.**
- **So in either case, DIODB functions as a Total Current for the diode region. In the Lo Z MITL case, this occurs after a time delay of ~ 15 – 20 ns.**
- **In that case, we can define ZTOTAL = Corrected Diode Voltage /DIODB.**

It turns out that after an initial period, all ZTOTALs end up about the same



- The WHITISH and REDDISH shots are 12.5 – 12, the GREENISH shots are 8.5.
- After an initial fluctuation phase, all shots settle in around ~ 40 ohms for ZTOTAL.
- Now 40 ohms is the RITS MITL impedance WITH VACUUM FLOW, so this might be expected. A plot of 80 ohm MITL shots would show the same trend, but around 80 ohms flow impedance.
- Then suppose we take this as an Operating Principle for IVA-load behavior. What implications are there for Total, Beam, and Sheath current?

ZParallel defined

Sheath current can be characterized by a Sheath impedance. We define then a 'Zsheath' or 'ZParallel', derived from ZTOTAL and ZDIODE

- **Assume there is an effective 'ZParallel' in the diode region. The relationship to ZTOTAL and ZDIODE is then**

  - **1/ ZParallel = 1/ZTOTAL – 1/ZDIODE**

Let's calculate ZParallel for selected 8.5 and 12.5 shots.

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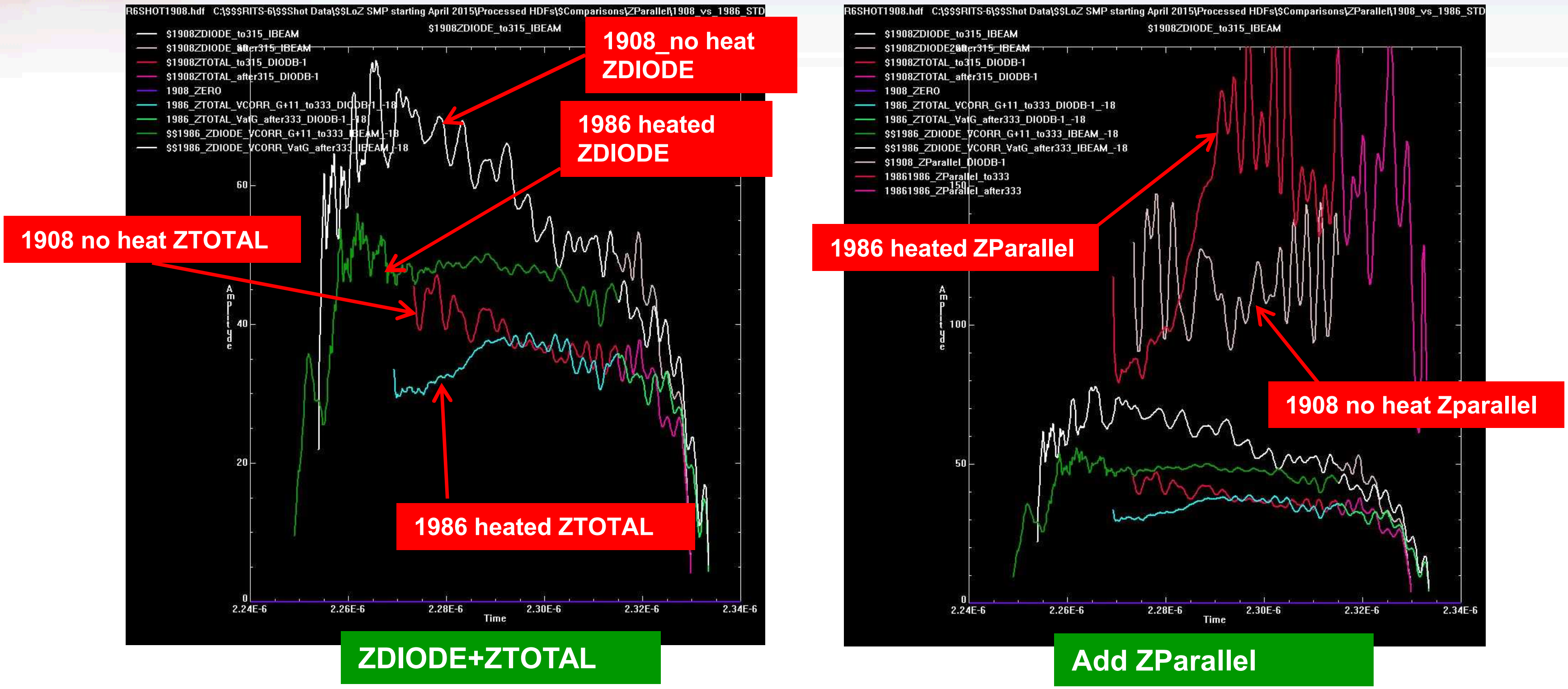
Return to unheated vs heated12.5 – 12 (1908 vs 1986), add ZTOTAL and ZParallel



- **(LEFT)** To **1908 and 1986 ZDIODE** (WHITE and GREEN, from Slide 8) add **1908_ZTOTAL** (no heat) and **1986_ZTOTAL** (heat). NOTE: **unheated ZTOTAL** declines from ~ 40 ohms, but **heated ZTOTAL** *increases* from ~ 30 ohms to join up with unheated ZTOTAL. Only after the join-up does heated ZTOTAL begin to decline.
- **(RIGHT)** lower part of Plot same as at Left. **No Heat ZParallel** ~ constant at ~ 120 ohms. But **heated ZParallel** starts at ~ 80 ohms, then rises to ~ 175 ohms during the time that **ZTOTAL** is rising.
- Since the ZTOTALs become the same, and ZParallel (heated) becomes much greater than unheated, **this means heated ZDIODE must be lower than unheated**.
- Since ZDIODE depends upon ZTOTAL and ZParallel, **it does not behave as an independent variable.**

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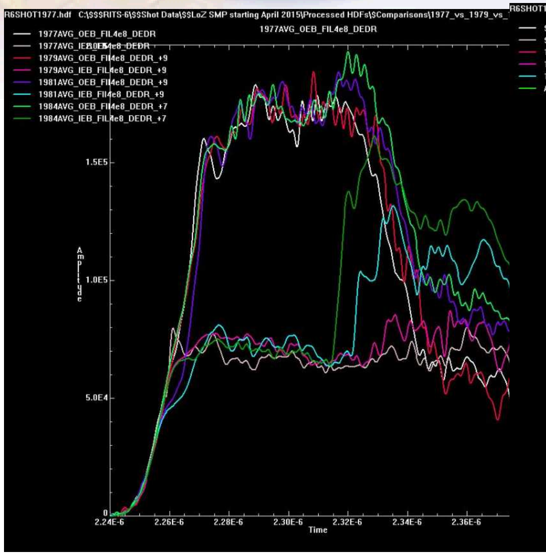
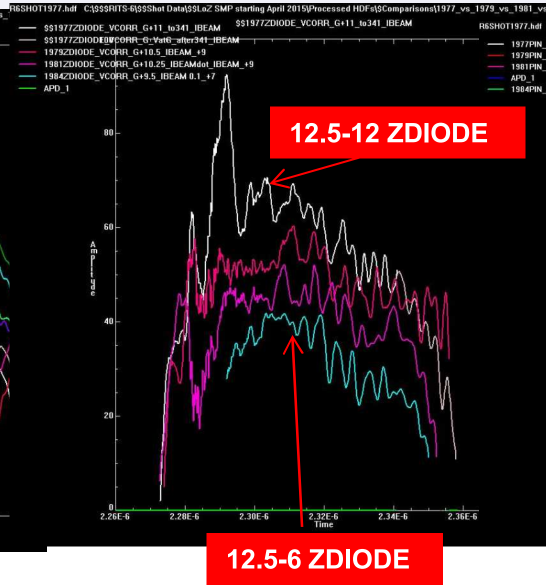
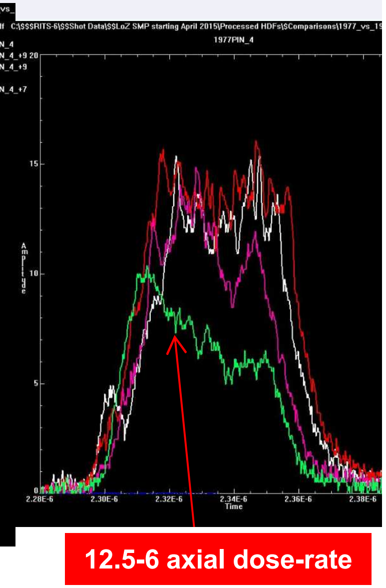
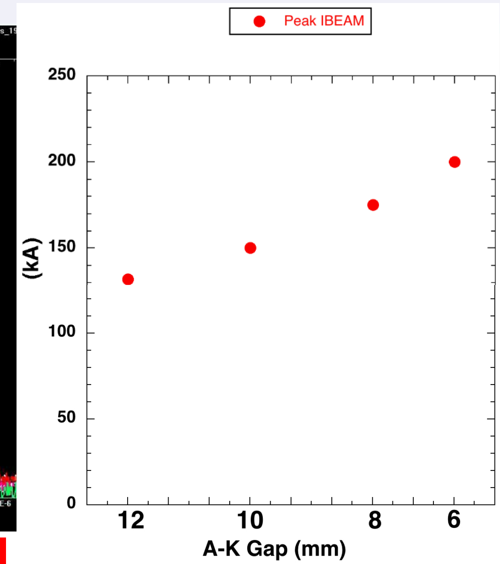
Generally, ZDIODE follows expected trends for Lo Z MITL, as in this A-K gap scan





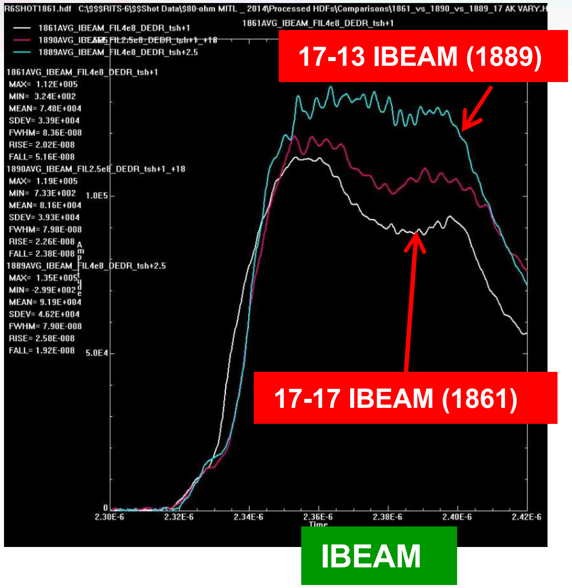


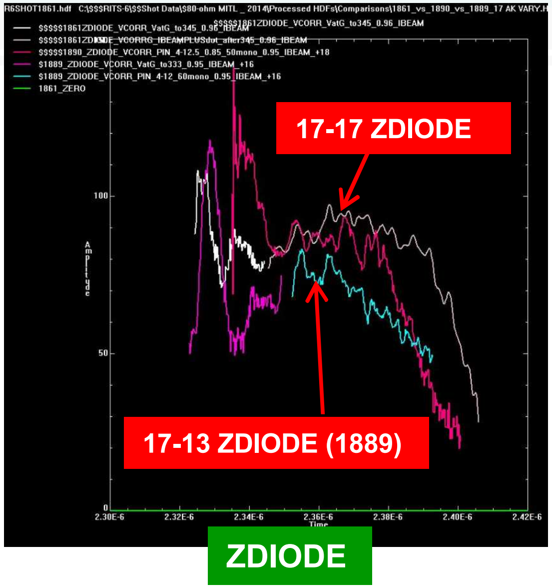


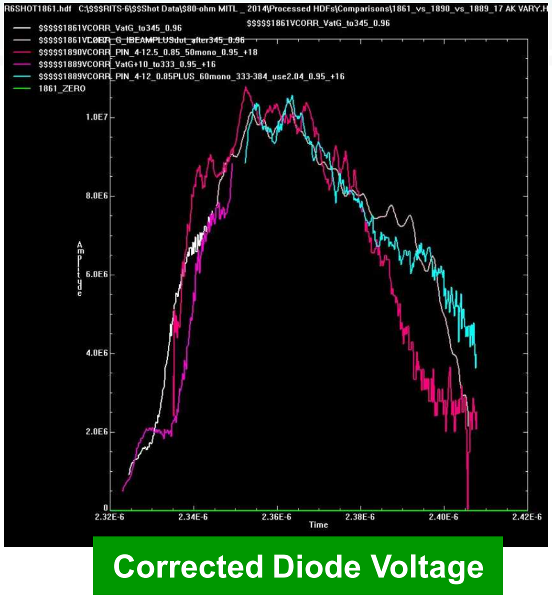
- **(LEFT) E currents, 12.5 with AK gaps of 12, 10, 8, and 6mm. Outer (total) at top. At 12 mm A-K gap, retrapping wave (offwhite) is almost non-existent. It then grows to maximum with 6 mm (OLIVE).**
- **(LEFT MIDDLE) ZDIODE. WHITE is 12 mm, LT BLUE is 6 mm. As gap drops, so does ZDIODE.**
- **(RIGHT MIDDLE) axial PIN dose-rate. As gap decreases, dose-rate drops.**
- **(RIGHT) Plot of peak IBEAM current. This rises steadily as A-K gap decreases.**

Hi Z MITL 17mm A-K gap scan (unheated)

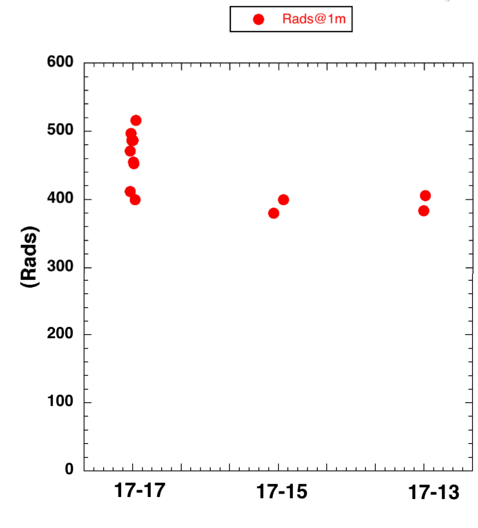
Hi Z MITL operation is totally different, as seen in this 17mm A-K gap scan







- **(LEFT) IBEAM currents**, 3 shots with 17-17 (WHITE), 17-15 (RED), and 17-13 (BLUE). Peak values are not that different, but why the DIPS in two of the shots? (It's not bad power flow.) More later.
- **(MIDDLE) ZDIODE**. 17-17 are almost identical. 17-13 (Lt Blue) drops lower.
- **(RIGHT) Corrected Diode Voltage**. Virtually identical shape.
- **(Near RIGHT) Rads @ 1m vs A-K gap**. As with ZDIODE, dose falls, but not as much as with the LoZ MITL scaling.
- Diode voltage is virtually unchanged as the gap is lowered. **Thus, 'undermatching' the load by lowering the A_K gap is ineffective.** Why?



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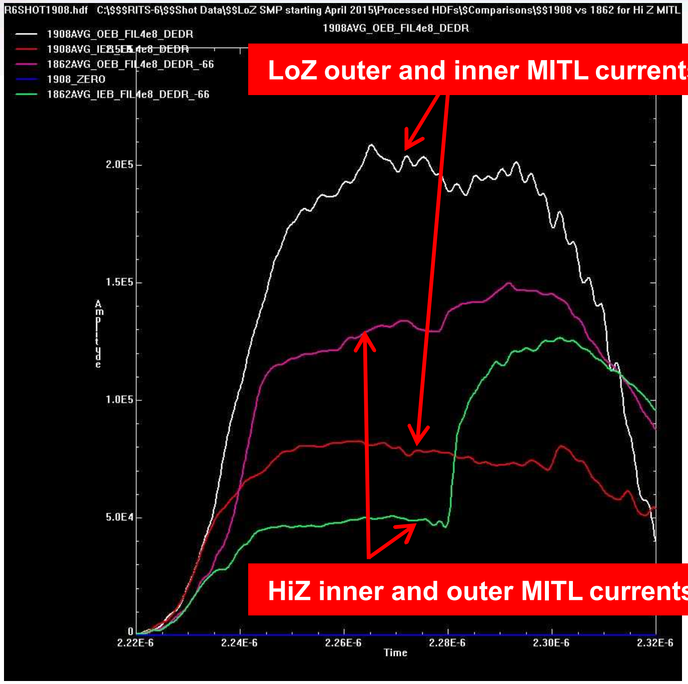
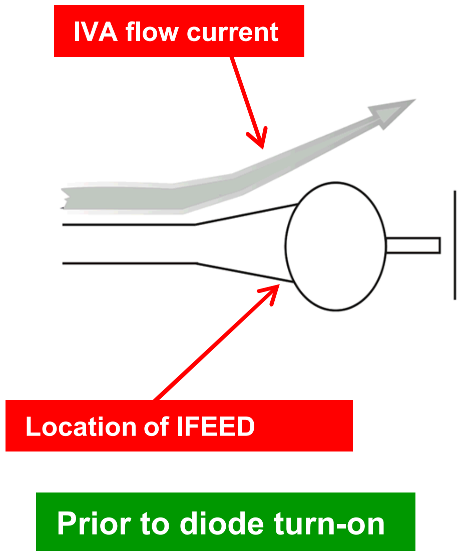
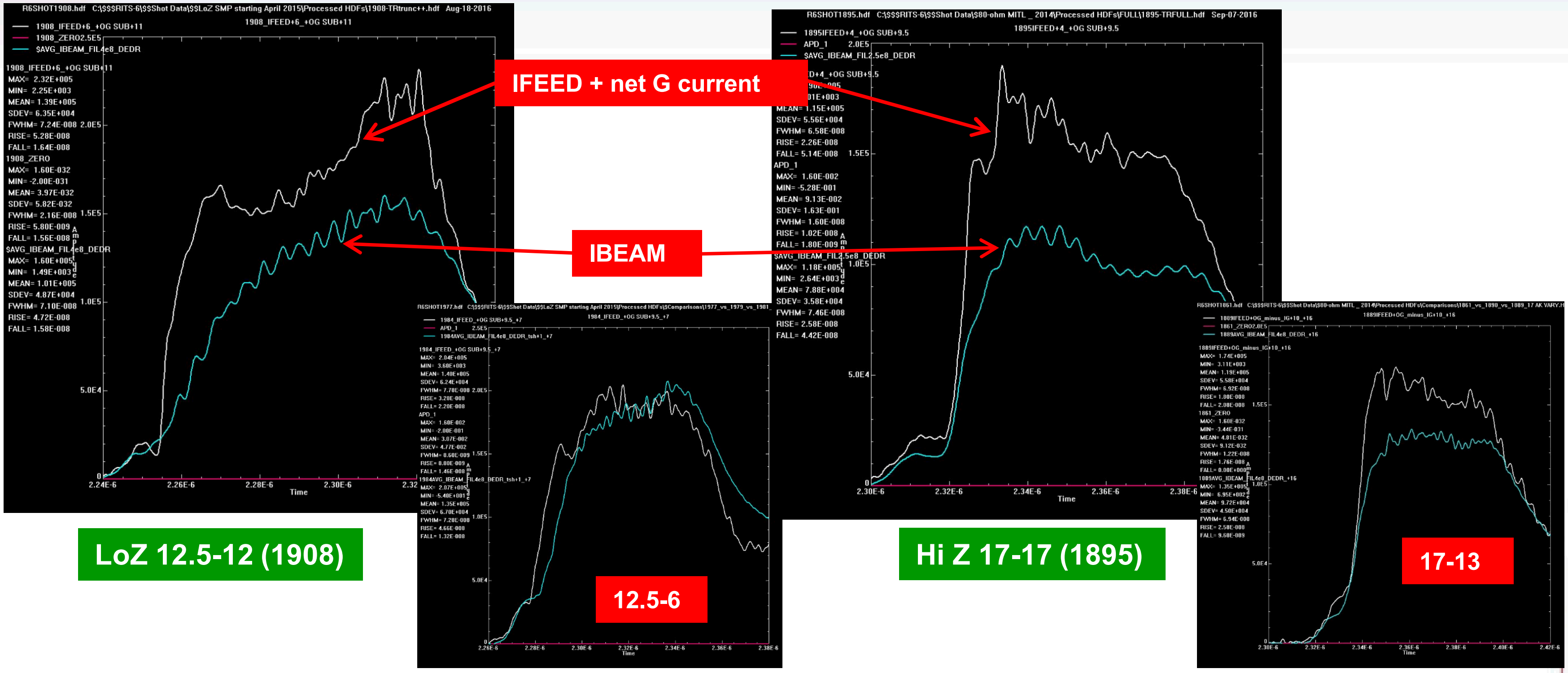
I propose the Concept of ‘Total Current Inventory’. As calculated, Inventory is LESS for a Hi Z MITL shot. This limits the behavior of IBEAM.





- (LEFT) Comparison, Inner and Outer Currents, LoZ vs HiZ MITL.
  - Outer (total) LoZ current (1908) peaks at ~ 200 kA, inner at ~ 80 kA.
  - Outer HiZ current ~ 130-150 kA peak, inner at ~ 45 kA.
- (RIGHT) (previous image): We can QUALITATIVELY* define ‘Total Current Inventory’ as the combination of Flow plus Electrode current coming forward.
  - Flow current estimate*: Outer_minus_Inner G current, timeshifted to diode location (+10ns).
  - Electrode current estimate: IFEED current shifted to diode location (+2ns).
- * Both outer and inner G currents consist of a forward- and backward-wave (Retrapping), so moving BOTH +10 ns is not mathematically correct. But if anything, this OVERESTIMATES net flow current.

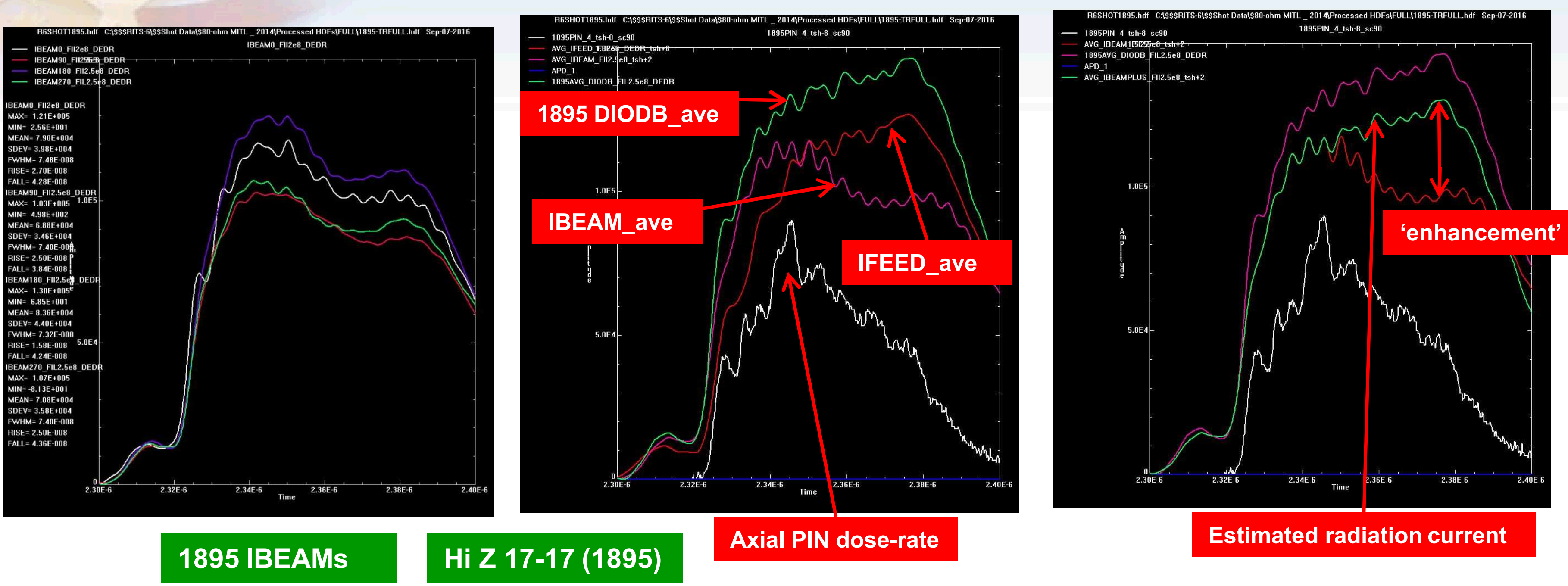
IBEAM current qualitatively follows the shape of the 'Total Current Inventory' for both LoZ and HiZ MITL shots



- (LEFT and inset) IFEED+Net G (IF-G) compared to IBEAM, 1908 LoZ 12.5-12. IF-G rises through the power pulse, as does IBEAM. Load impedance ~ 60-70 ohms is compared to 40 ohms ZFLow of MITL.
  - This implies ratio ZDIODE/Zflow ~ 1.5, to minimize retrapping wave. This is higher than one expects from Transmission Line Theory. I believe that this allows for flexibility for adjustment of sheath vs IBEAM current, e.g. so that ZDIODE can operate closer to its 'natural' level.

- (RIGHT and inset) IF-G compared to IBEAM, 1895 Hi-Z 17-17. Now IF-G does NOT rise throughout the pulse, but peaks early and then falls. IBEAM peaks and falls at the same time as IF-G. This is because:
  - 1) There is less net G current coming forward at HiZ.
  - 2) The Very Large Retrapping wave reduces net G current further.

This explains the ‘dip’ in the 17-17 IBEAM current (Example: Shot 1895 HiZ)



- (LEFT) 4 individual IBEAM currents before averaging. **All show same general waveshape, variation ~ 25%, no evidence of localized spikes. Averaged IBEAM clearly shows dip.**
- (MIDDLE) DIODB, IBEAM, IFEED, all averaged signals, plus (Scaled) axial PIN dose-rate. **Note that IFEED ‘overtakes’ IBEAM, suggesting knob emission. Axial PIN drops after this time, reinforcing this idea.**
- (RIGHT) **IV2.1 scaling of axial PIN signal is NOT consistent with IBEAM as the radiation current. The GREEN curve (with enhanced value over IBEAM) is estimate for rad current, consistent with scaling from both axial and side-on PINs. Source of extra current: either knob emission, or MITL flow adding to current in pinch.**
- **Extra current is consistent with larger-than expected Spot Size.**
- **Axial PIN dose-rate peaks early because Voltage falls early. Explains why, even with voltage substantially higher than LoZ, Rad output here is DOWN from best LoZ 12.5-12 shots.**
- **Next Slide shows IMPEDANCE calculations for this shot.**

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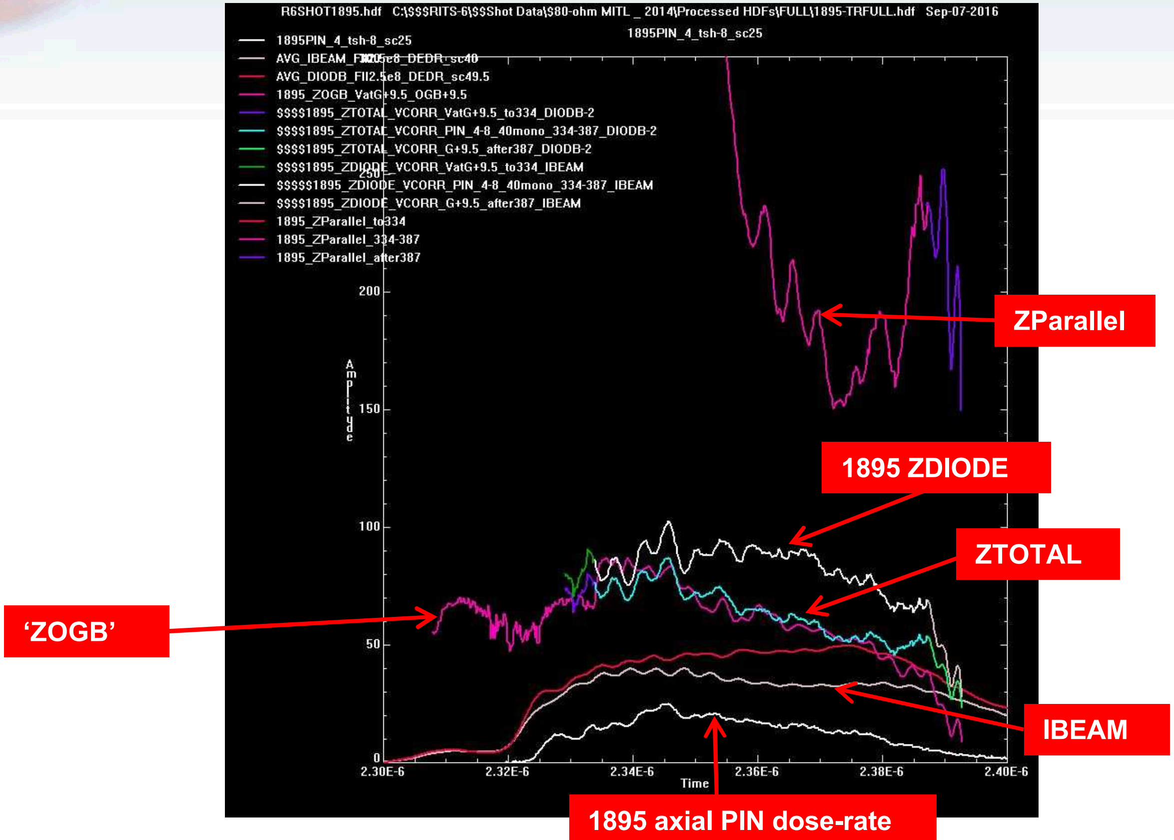
IBEAM dip results in ZDIODE INCREASING above 80 ohm ZFLOW



- Sequence of Events:
  - Diode currents rise, dose-rate increases. ZOGB – Voltage at G divided by outer G, rises to 80 ohms, then gradually falls.
  - Initially, ZDIODE ~ ZTOTAL (ZParallel > 500 ohms). Then IBEAM peaks and falls, ZParallel drops quickly as ZDIODE *rises* to ~ 90 ohms. As ZParallel stabilizes at ~ 160 ohms, ZDIODE begins to fall. ZTOTAL has already begun to track along with ZOGB, declining from 90 ohms.

- Interpretation: initial IBEAM value is TOO HIGH for a 90 ohm SMP load. As IBEAM decreases, ZDIODE increases to its 'natural' value as an SMP load. Parallel (sheath) current is created out of MITL flow.

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Summary

- Heating/glow discharging cleaning of a 8.5-8.3 bare Ta anode is successful (2 shots), NOT because reduction of contaminants increased ZDIODE, but because the pinch appears to be stabilized.
- From a Systems Viewpoint, Diode Impedance is dependent upon interactions between the BEAM, Total, and Sheath Currents. It is therefore not a completely independent variable.
- If ZDIODE is not an independent variable, then looking towards changing it by some procedure does not tell the whole picture. A Systems Approach is needed.
- Unlike a Bremsstrahlung diode (basically a terminated MITL), adding a knob structure to an IVA results in separate Diode Physics to initiate the Beam. If the subsequent beam current is ‘incompatible’ with the Flow+Beam system, then unexpected results will occur.
- HiZ MITL operation (increase from 40 to 80 ohms Zflow here), at least as reported here, leads to more restrictive range of operation into a diode load. This occurs because the level of flow current is reduced, and unless the diode load is raised higher (to an estimated 130-150 ohms), the huge retrapping wave removes flow current from the front end region. This can restrict the level of IBEAM and Clamp the load voltage.
  - For SMP diode loads, there has not yet been a successful 130-150 ohm SMP diode demonstrated.
- Recommendations for HiZ MITL operation into an SMP load:
  - Possible Good News: If the IBEAM dip is NOT caused by knob emission, then Variations in cathode size/A-K gap can be explored to produce a possible Undermatched load operating point. Ex: small diameter cathode (e.g. 9-9, 7-7, etc). Reducing A-K gap on a bigger cathode will increase electron angle on converter, decreasing dose.
  - Possible Bad News: If Knob Emission DOES occur, then undermatching the load will NOT drop the voltage stress.
  - Maybe the BEST PLAN: drop from 80 to 60 ohms Zflow by installing a fatter center conductor.

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Questions?

Extra Slides

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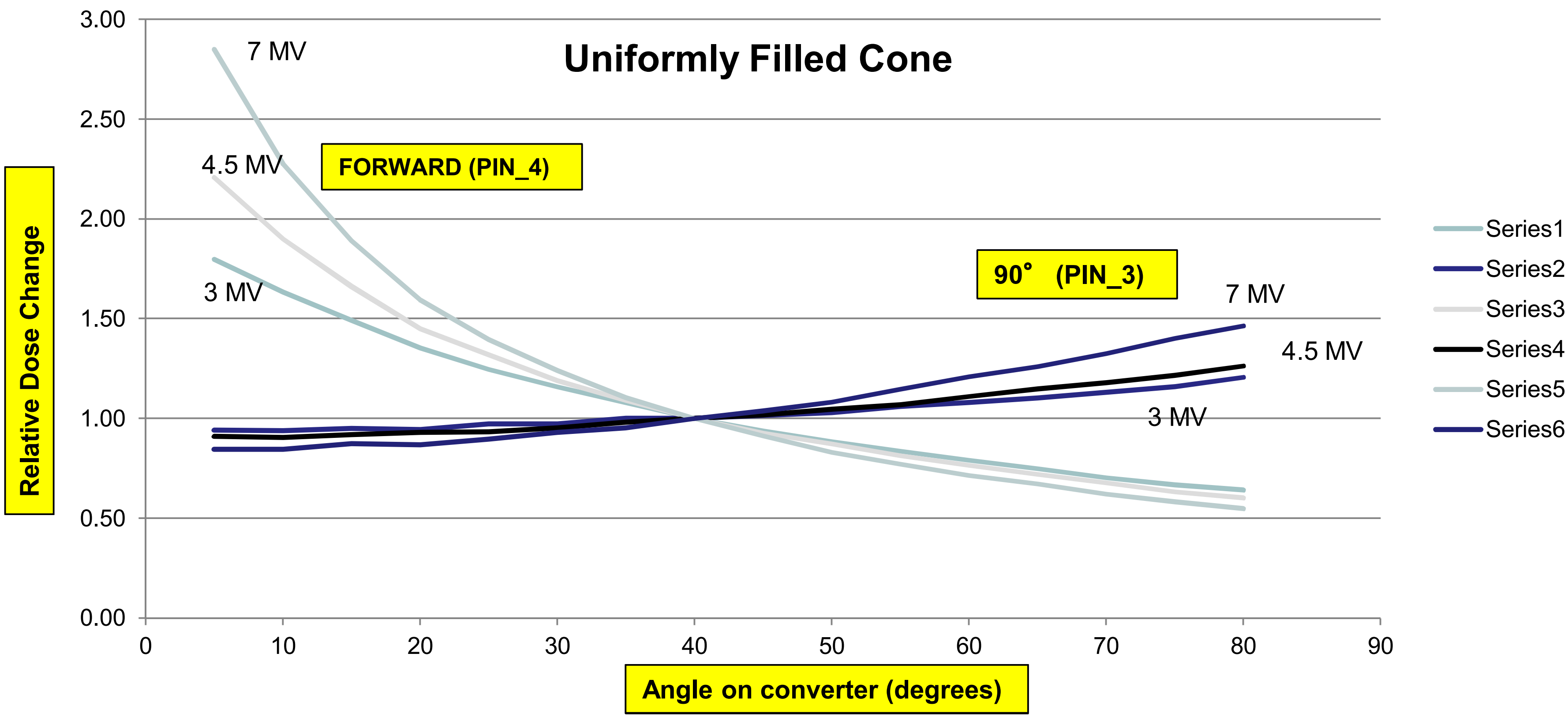
MCNP: Side-on and Head-on P-I-N diode to X-rays scales oppositely as e-beam angle on converter increases



- Relative dose change using mono-angular electrons with angle is even larger
- Both Coefficient and Raise-to-Power (RTP) factor change. We consider only RTP factor changes here.
- As e-beam pinch angle changes, 90° PIN goes UP while Forward PIN goes DOWN.
- Therefore, comparing PIN_3 to PIN_4 gives insight on Pinch angle change with time