Overview & Initial Results from DIII-D Metal Tile Campaign

by

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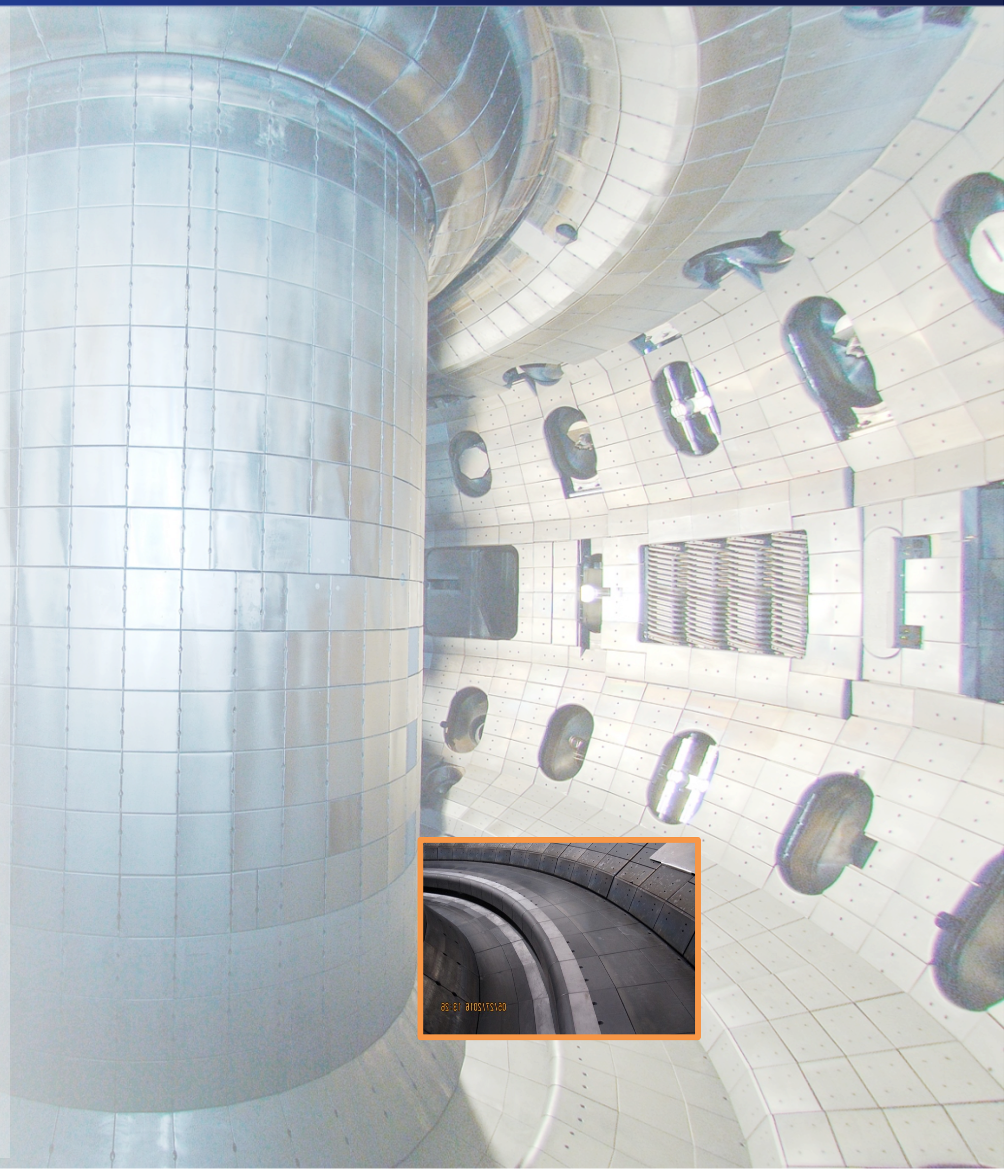

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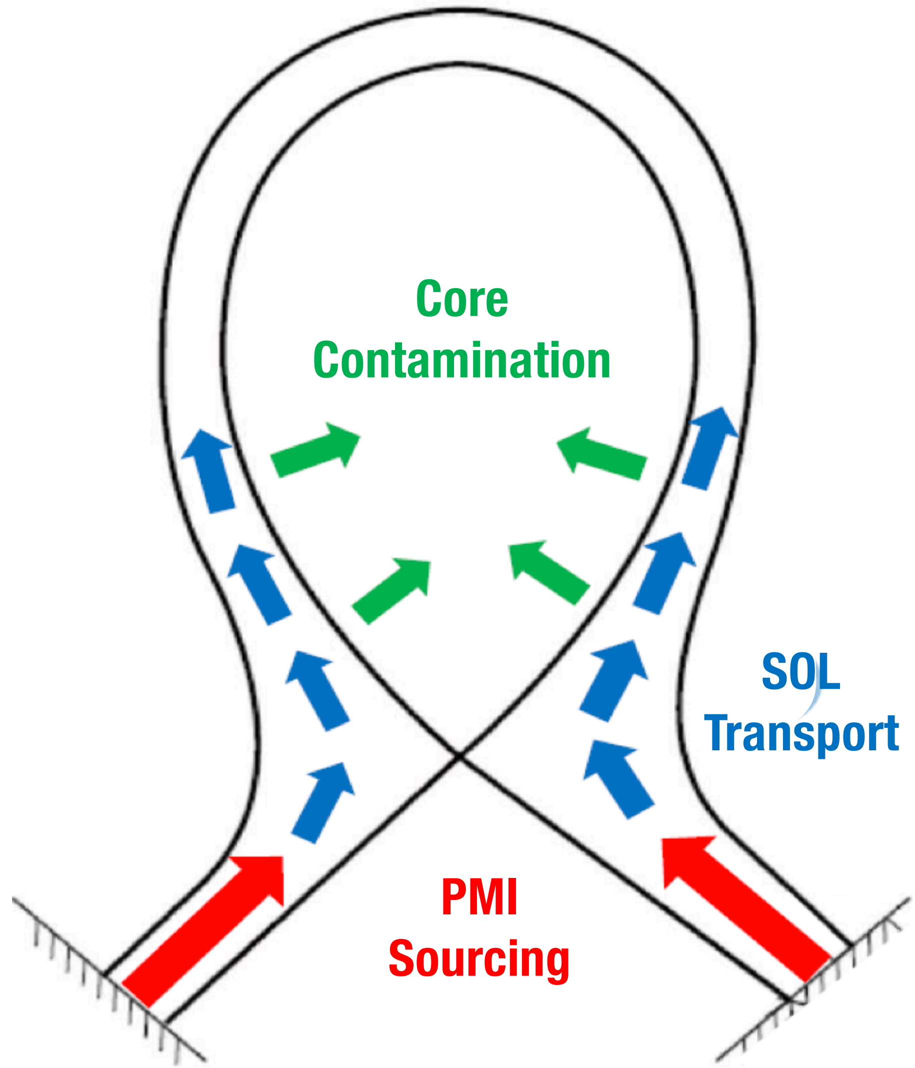
November 28, 2016

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

OAK RIDGE National Laboratory

Motivation: Understand Divertor High-Z Sourcing and Transport in H-mode Through Trace PMI Studies with Low-Z Wall

- **Experimental setup allows probing of 3 main links in divertor W transport to core**
- **Predominant C wall allows localization of W source unlike in full metal divertors**
  - Further localization of W source (i.e. SP vs divertor entrance) → use of 182W coating



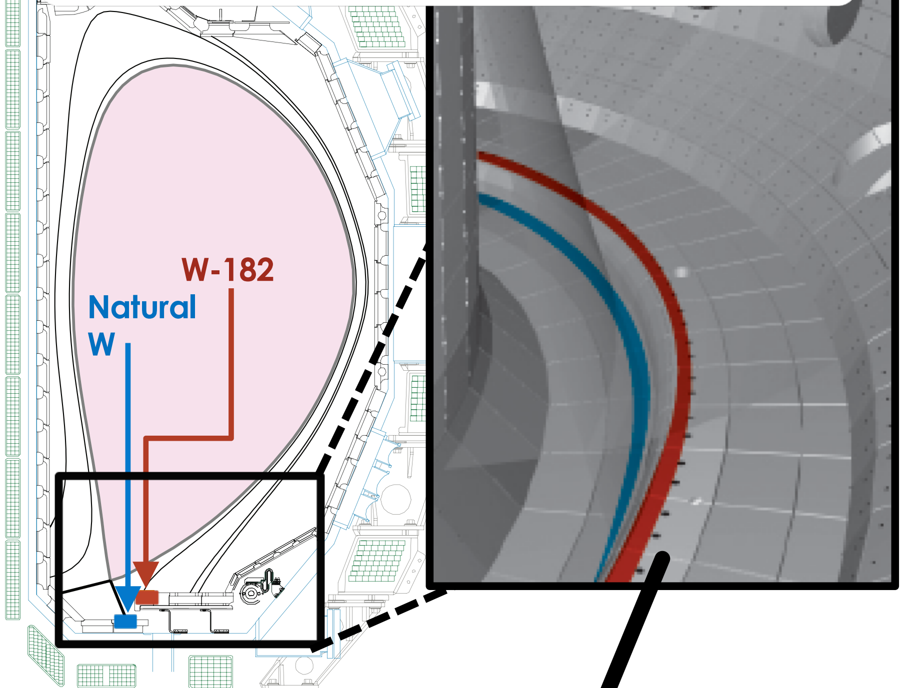
Outline: Highlighting Use of Different Divertor Tungsten Sources on SOL Migration & Impact on Core in H-mode Conditions

- **Experimental setup using metal inserts with W coatings**
  - Summary of metal inserts highlighting coating methods
  - Initial post-campaign analysis: Local migration measurements & modeling

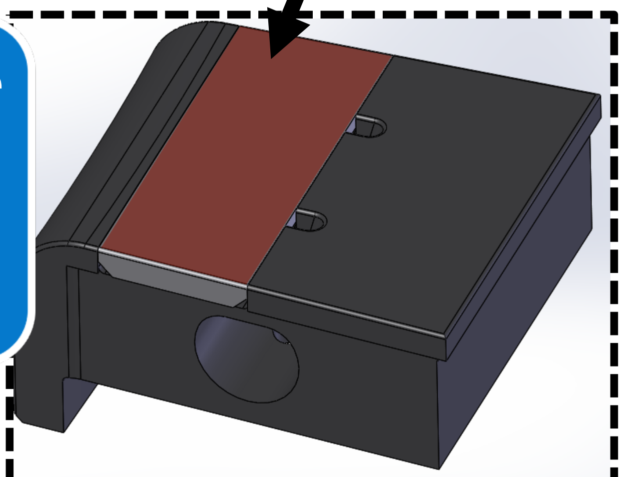
- **Highlights from campaign on W PMI sourcing & transport**
  - Recovery of high performance AT discharges with on-axis ECH
  - ELMs had major impact on measure source profiles
  - Measured upstream W profiles showed f_{ELM} dependence

W Sources were Localized to 2 Locations in Outer Lower Divertor Region; Used Novel W-182 Coating Method at 1 Location

Conceptual Layout



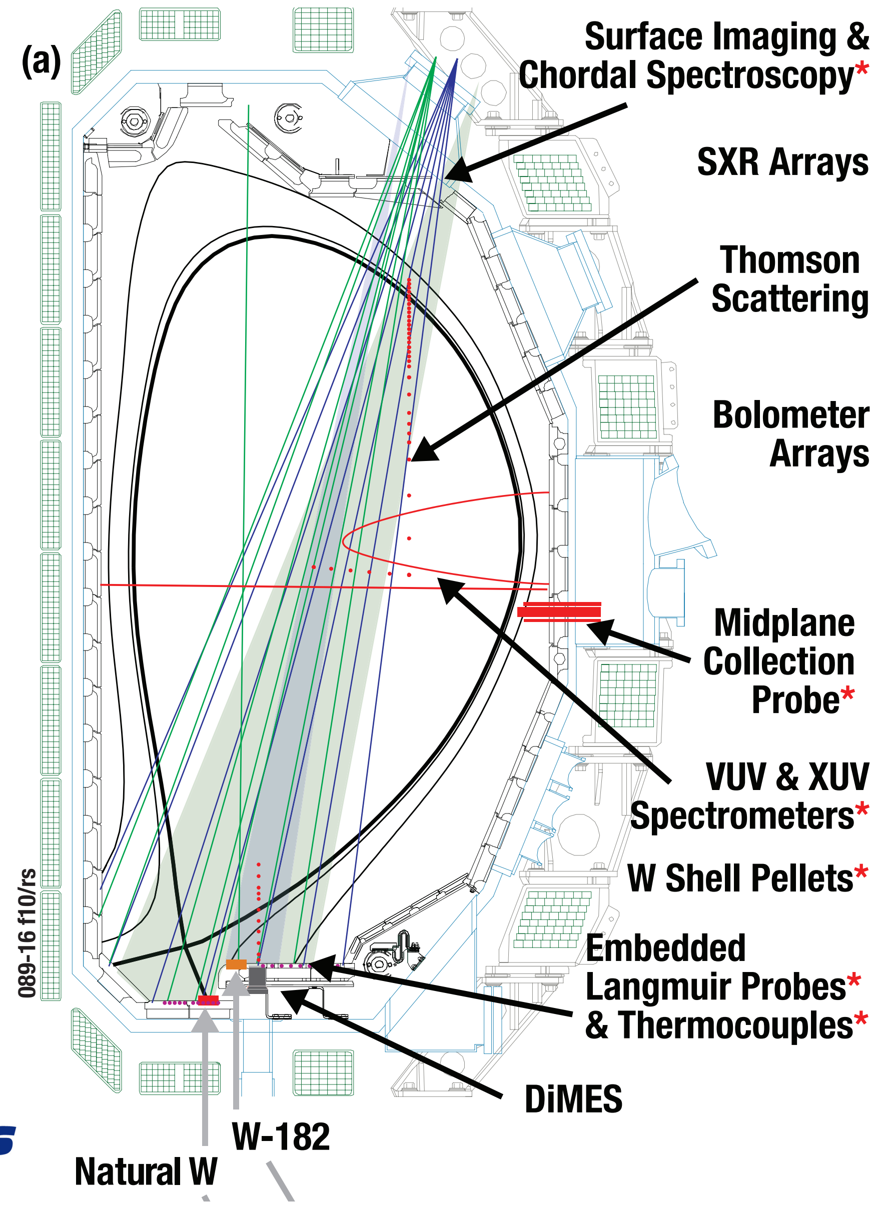
Graphite Tile + Metal Insert



DIII-D W Tile Arrays

Metal Tile Mini-campaign was a Large Multi-institutional Effort & Leveraged Wide Collection of New Diagnostics

- **Experiments & hardware from a number of collaborators**
- **Campaign specific capabilities**
  - New: XUV & visible spectroscopy, Shell pellets, Collector probes, Langmuir probes, Thermocouples
  - Surface analysis: ICP-MS, RBS, microXRF, NRA



* New for this campaign

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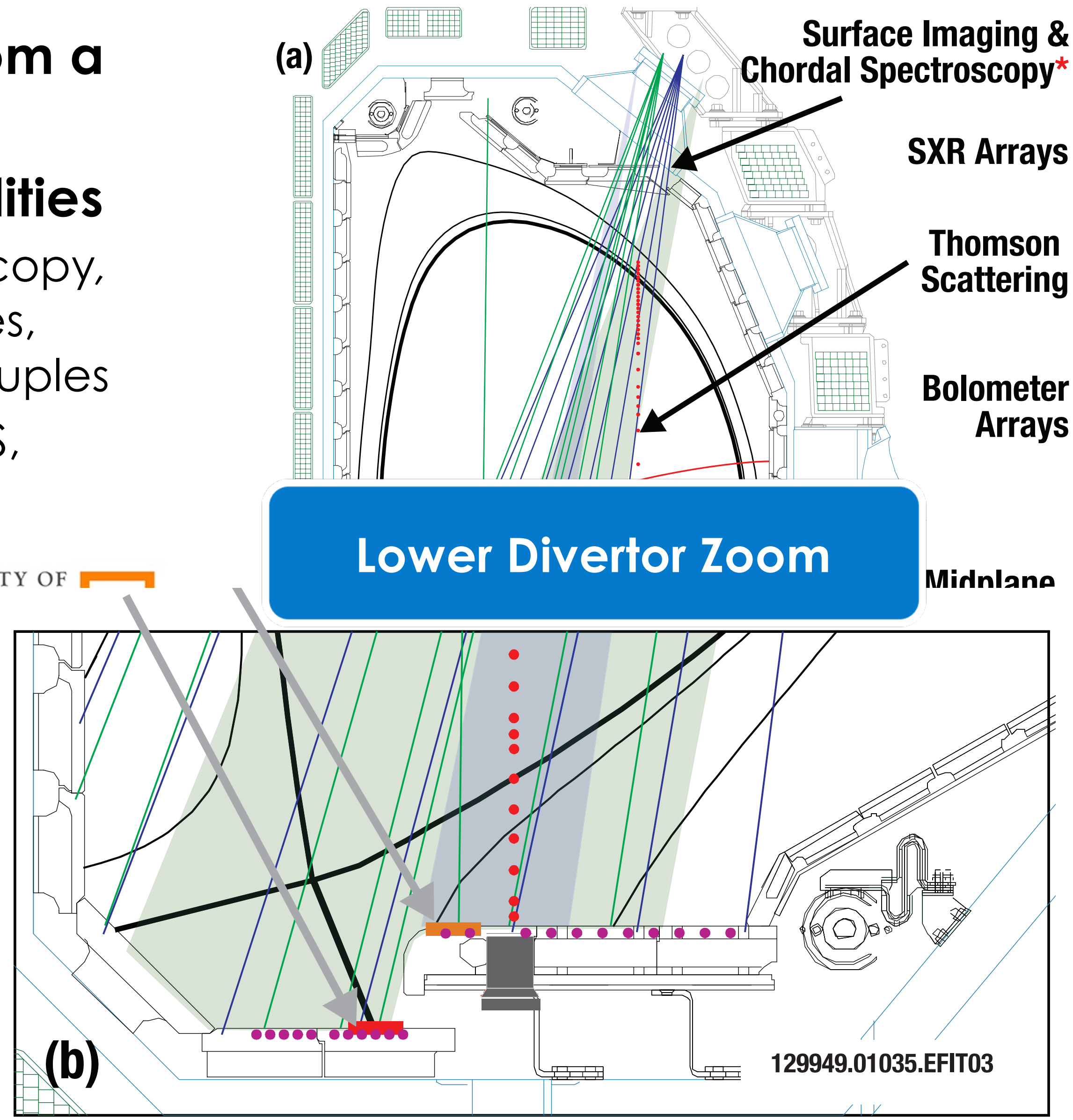
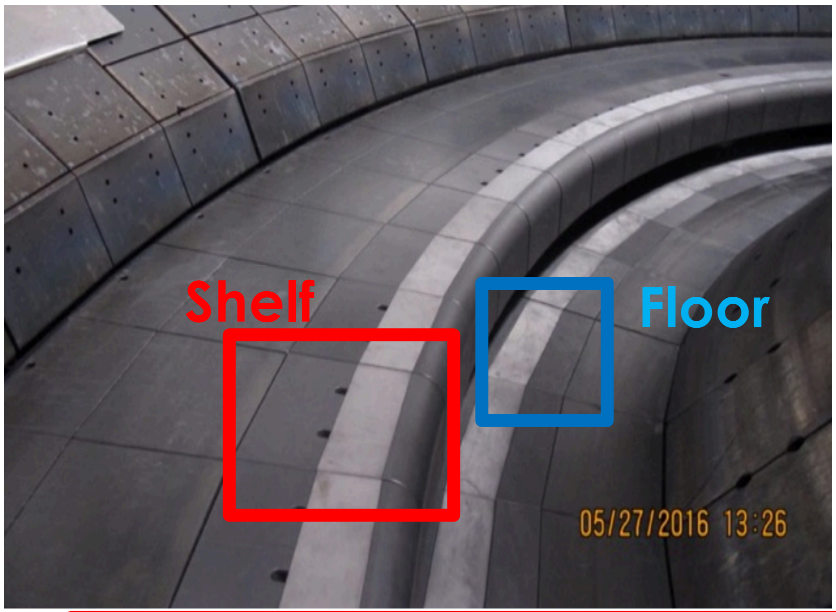
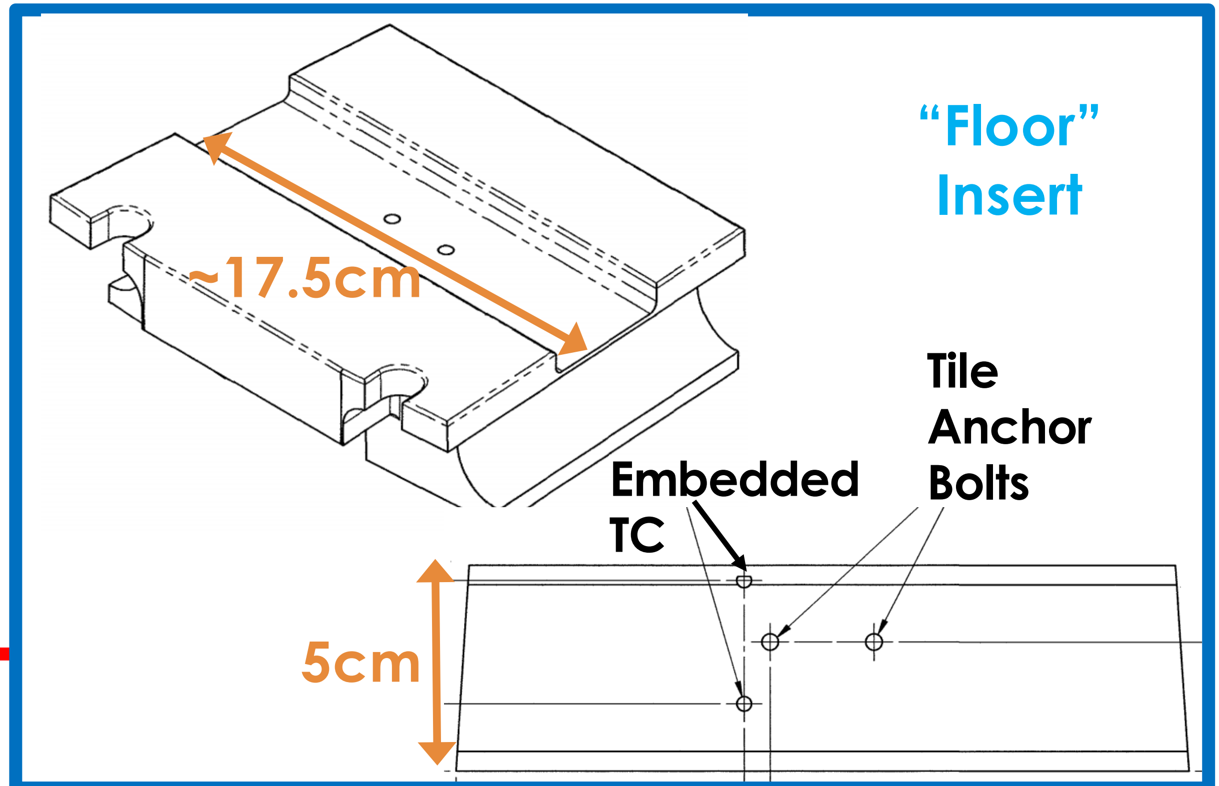
UNIVERSITY OF TORONTO
Sandia National Laboratories
Lawrence Livermore National Laboratory
OAK RIDGE National Laboratory

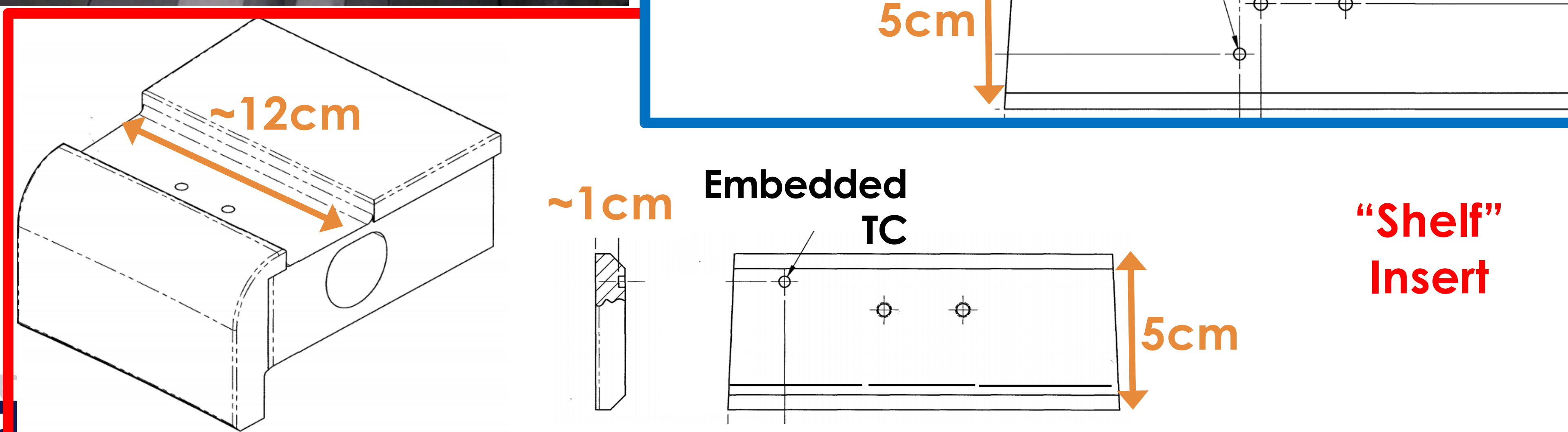


Metal Inserts were Retrofit into the Standard DIII-D Graphite Tile Structures

- Tile arrays → Mo alloy (TZM) inserts with thin W coatings



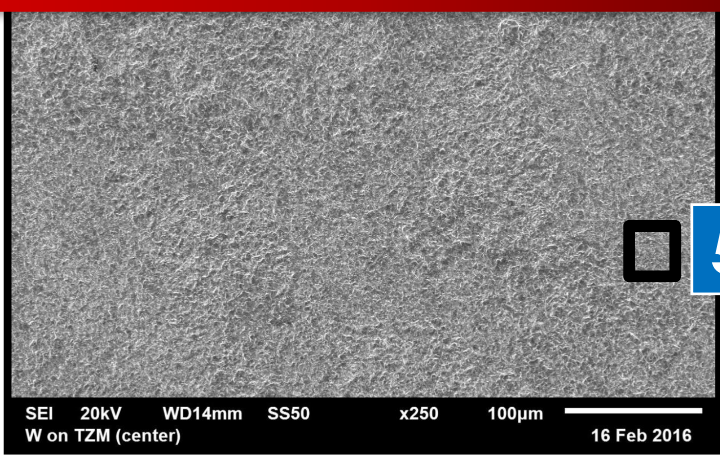




Coatings ORNL & Ultramet (Los Angeles, CA) Coated ~1/2 Each of Total (120) Inserts Needed

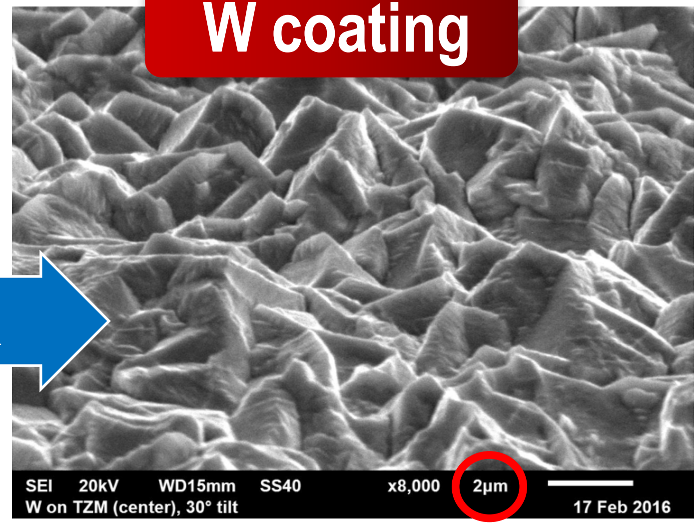
- **Both methods produced sample coatings which were tested at GA & PIECES in early Spring 2016**

CVD Coating (Ultramet)



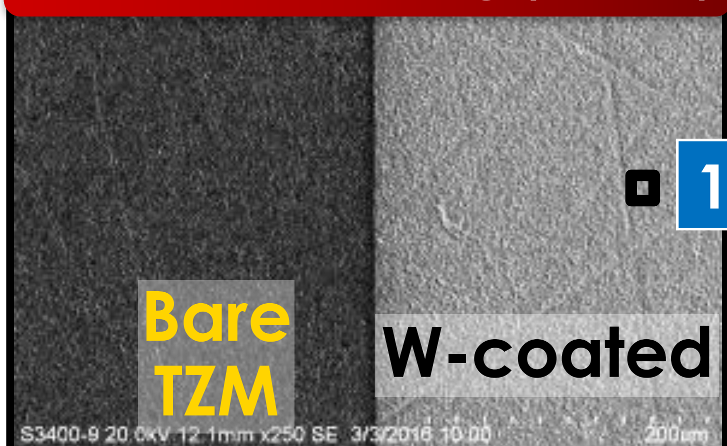
50x

W coating



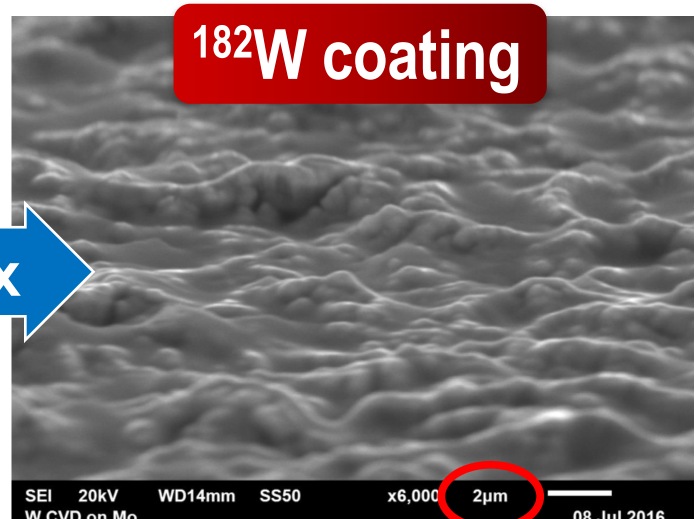
Industry "standard," but large variability in thickness (5-40um)

"E-beam" Coating (ORNL)



100x

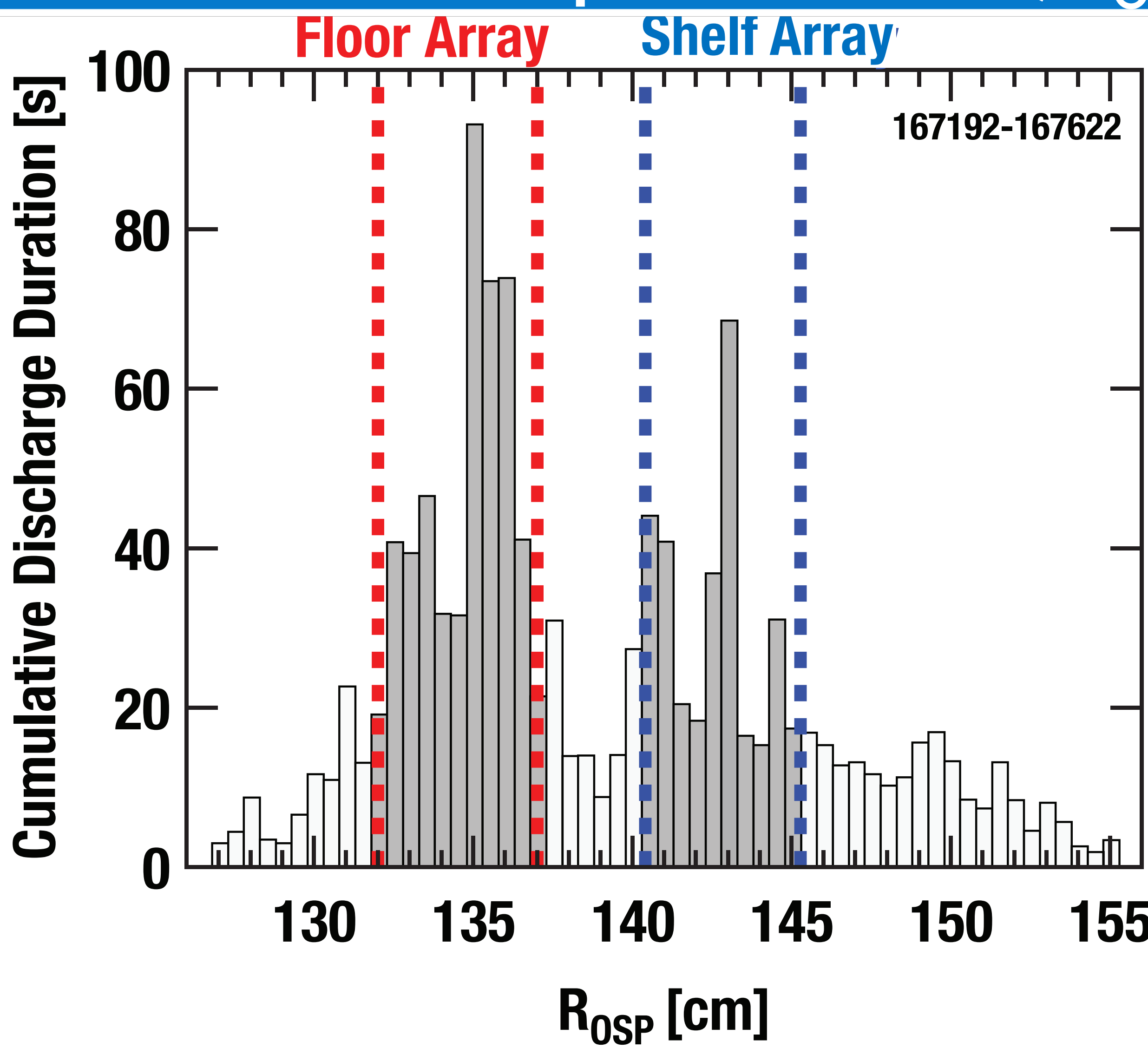
^{182}W coating



e-beam method: High recovery (95+%) of feedstock + coating well reproduced (2um +/-1um)

Majority of Discharge Time was On or Near Insert Locations

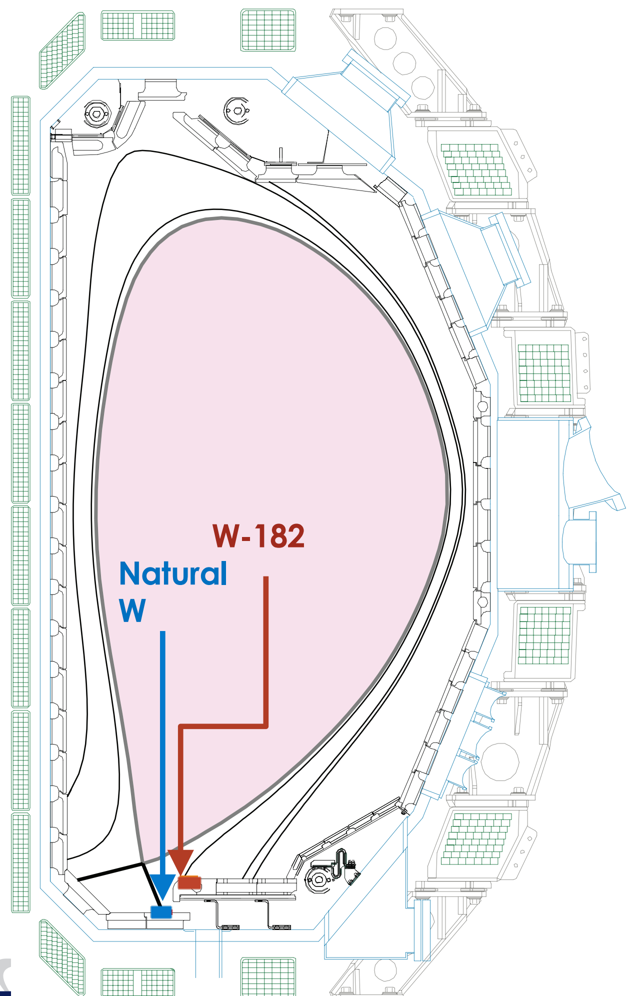
Histogram of Plasma Discharge Duration versus Outer Strikepoint Location, R_{OSP}



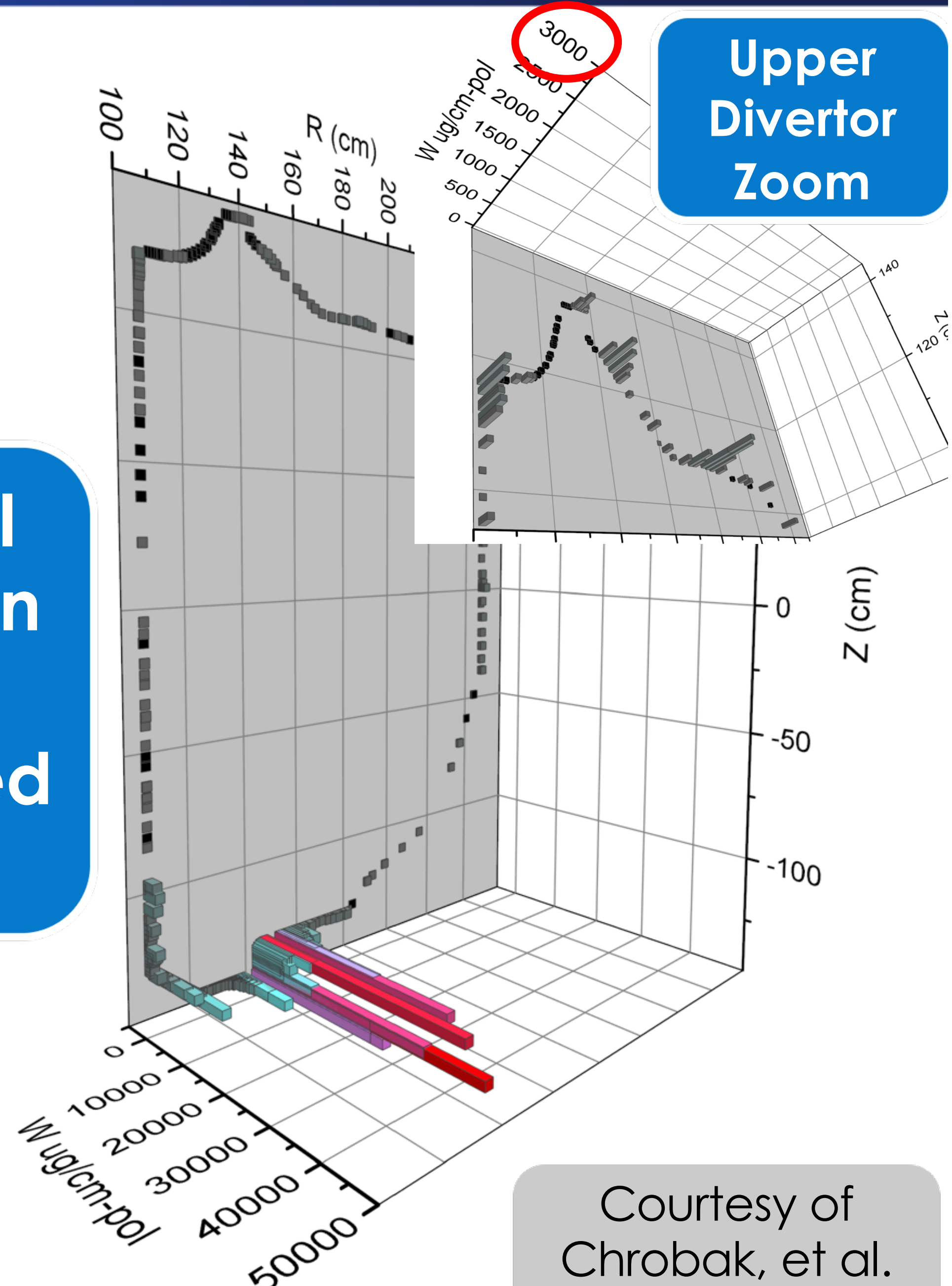
Highest P_{INJ} (~19MW) discharges had strikepoint on Floor Array

Extensive Survey of Post-Campaign PFMs showed Most W was Near Insert Locations

- **Hand-held X-ray Flourescence Spectrometer (XRF) used in survey**



Poloidal X-section of Deposited W



Upper Divertor Zoom

Courtesy of Chrobak, et al. APS 2016

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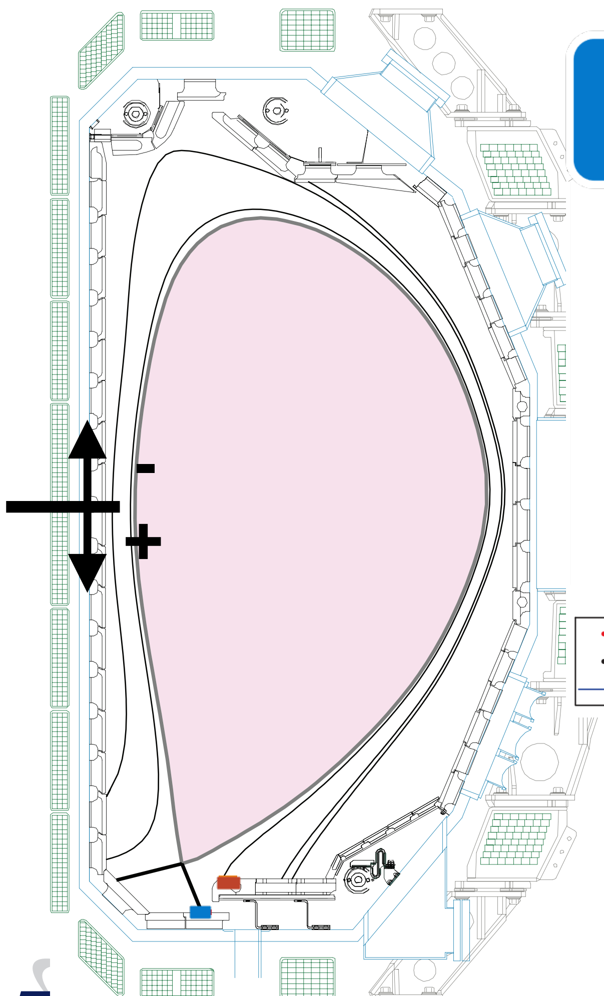
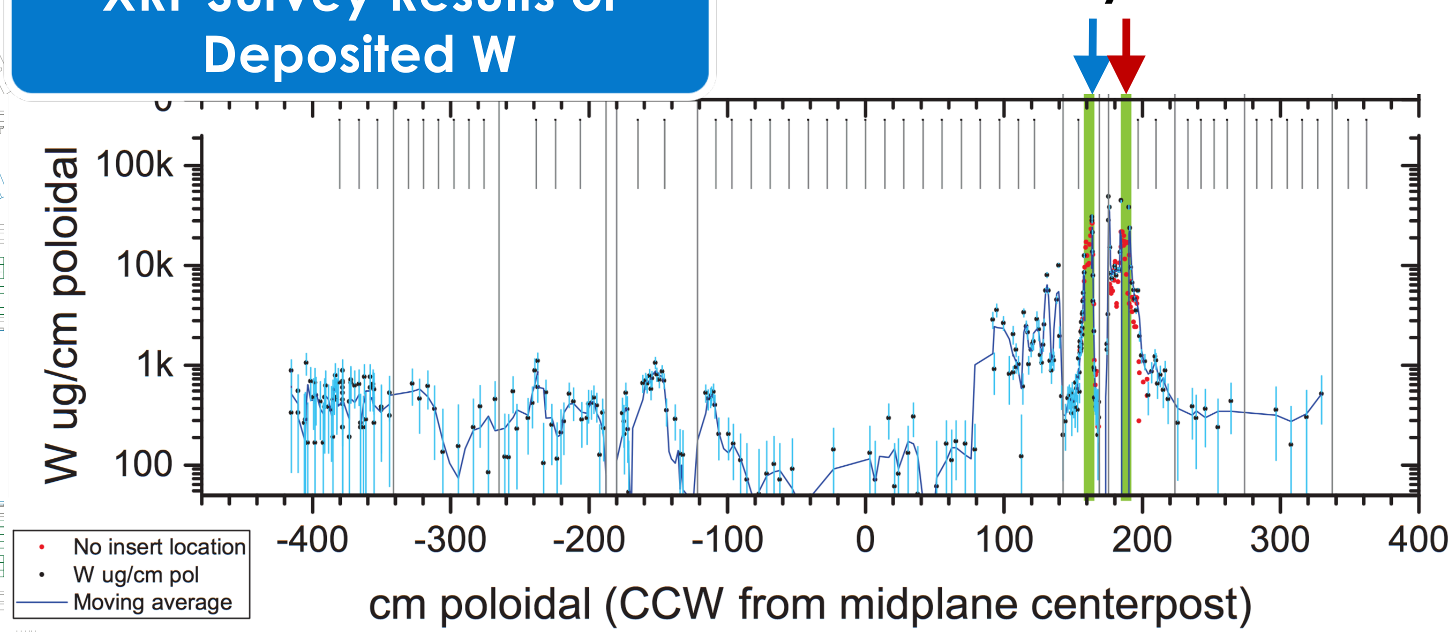


XRF Survey Results of Deposited W

W Array locations



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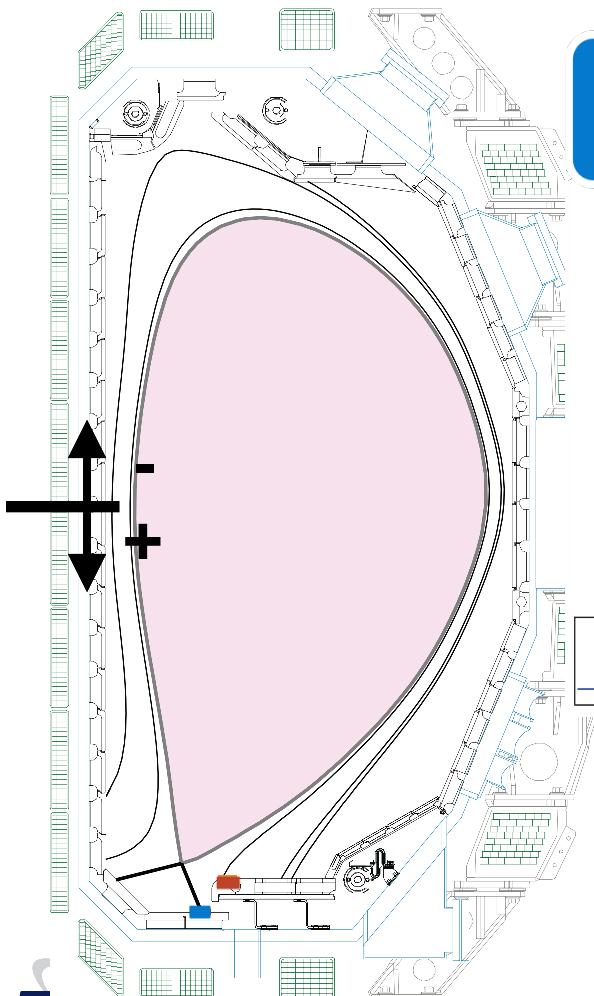
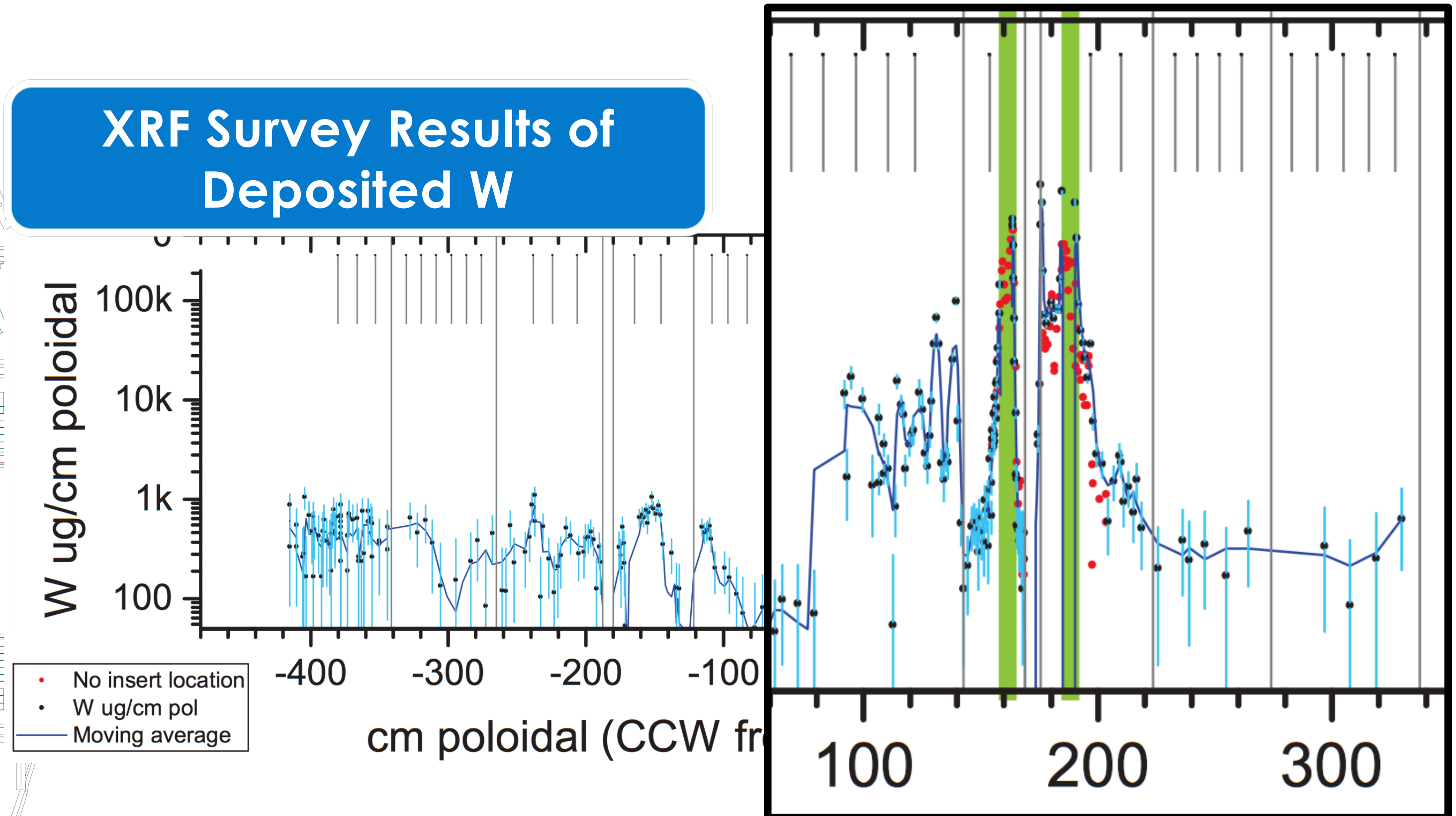


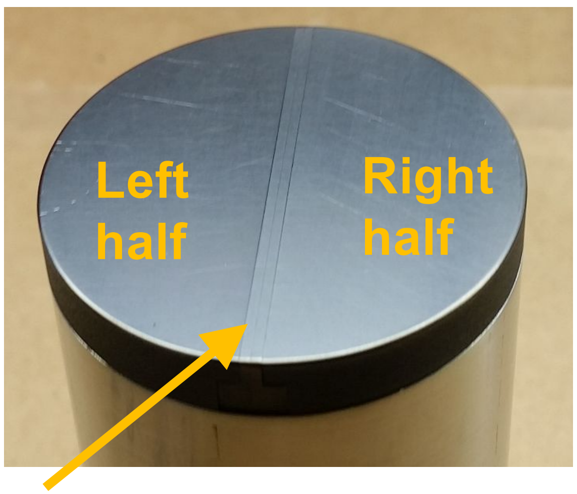


Courtesy of Chrobak, et al. APS 2016

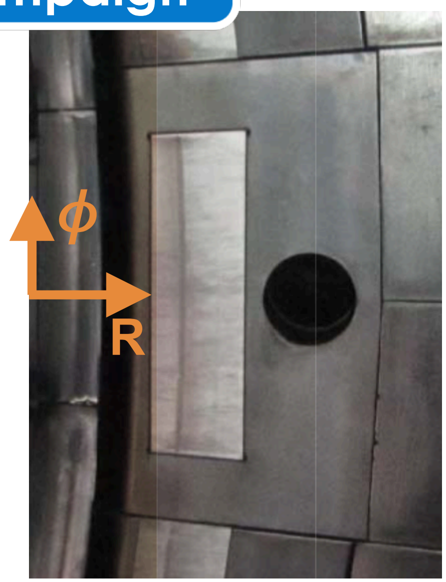
DiMES Used as Local Deposition Probe During Initial Dedicated W Migration Experiments

- Clamshell-like design allowed for local migration measurements in time
- Seems carbon redeposition dominating far-SOL pattern

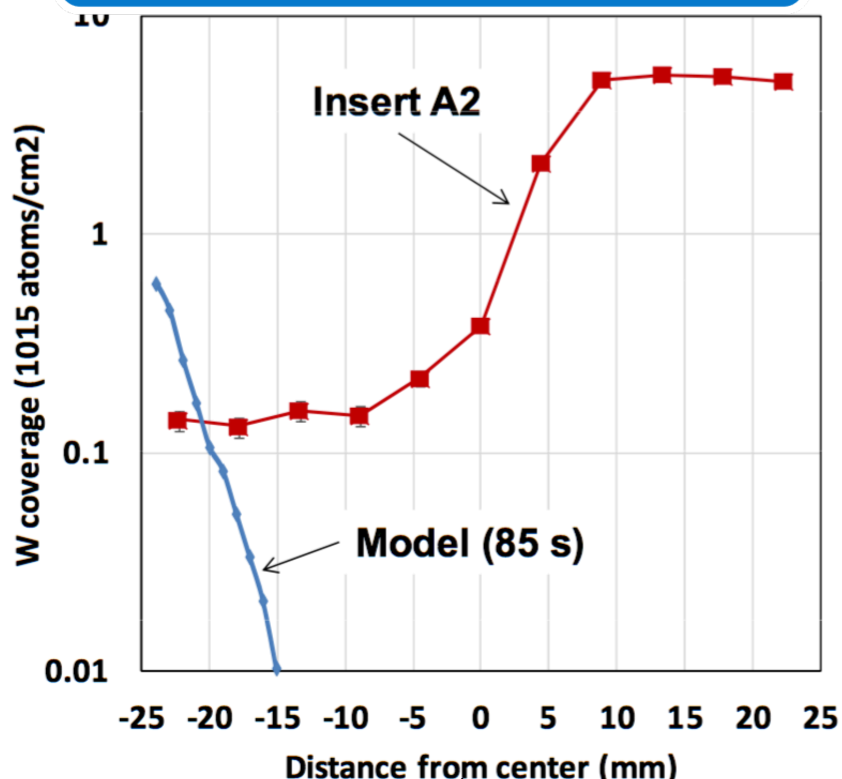
Geomtery & Head Design for Metal Ring Campaign

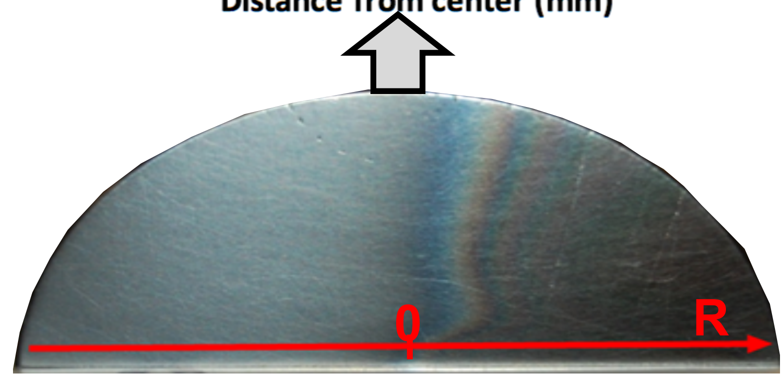


Radial inserts



RBS W measurement compared to ERO estimates





Courtesy of Rudakov, et al. APS 2016

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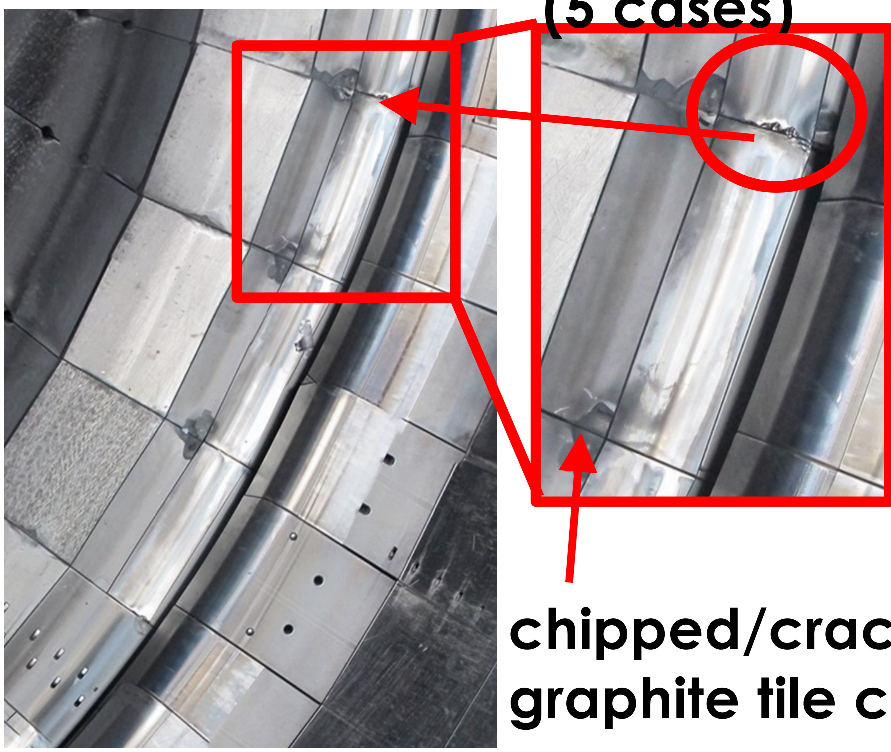
Summary of Metal Insert: Modeling W Migration via ERO & Leading Edge Melting On-going

- **Floor array showed damage due to leading edges & stress beyond design**

Top-down View of Lower Divertor



- **Accurate accounting of C distribution is main focus of migration modeling**

W migration Workflow Schematic

LP & TS exp. data

↓

OSM (OEDGE)

↓

Plasma conditions ⟷ Hα & β spectro data

↓

DIVIMP (OEDGE)

↓

Carbon distribution ⟷ CII & III spectro data

↓

ERO

↓

Tungsten erosion ⟷ WI spectro data

Courtesy of Guterl, et al. & Barton et al. APS 2016

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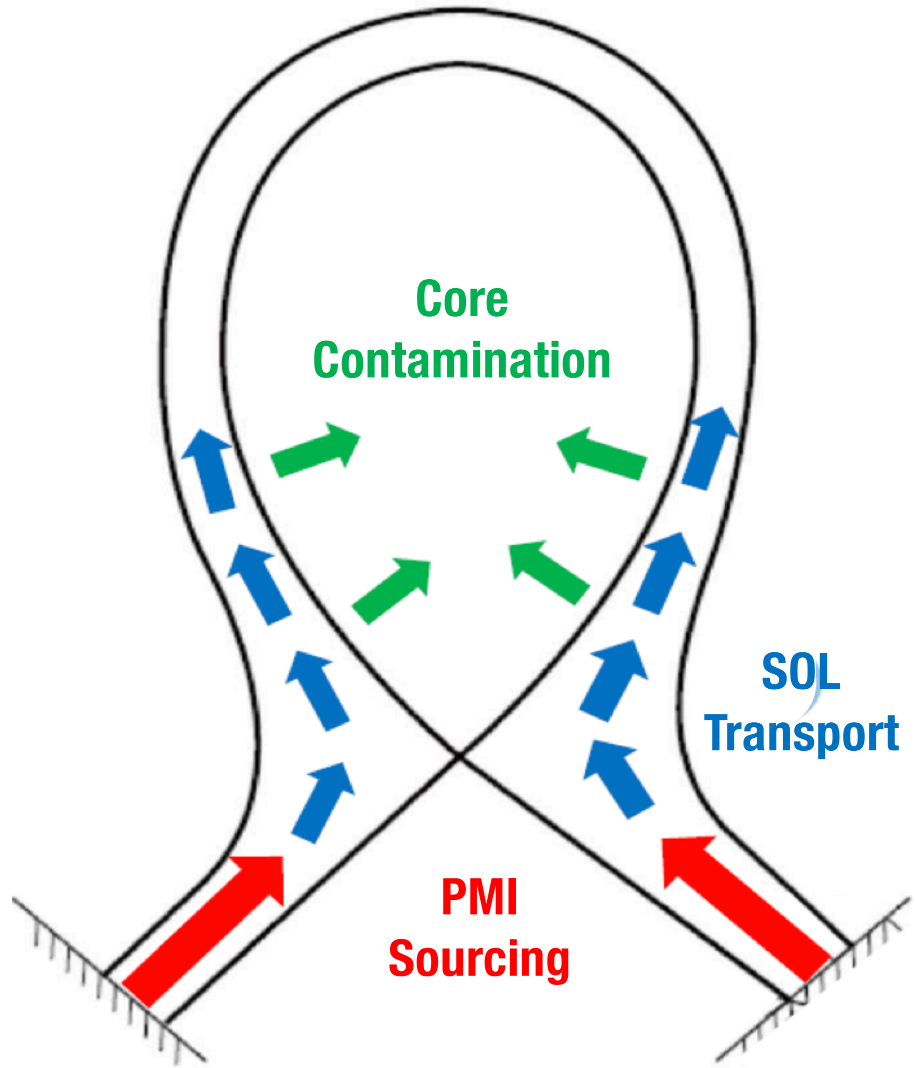
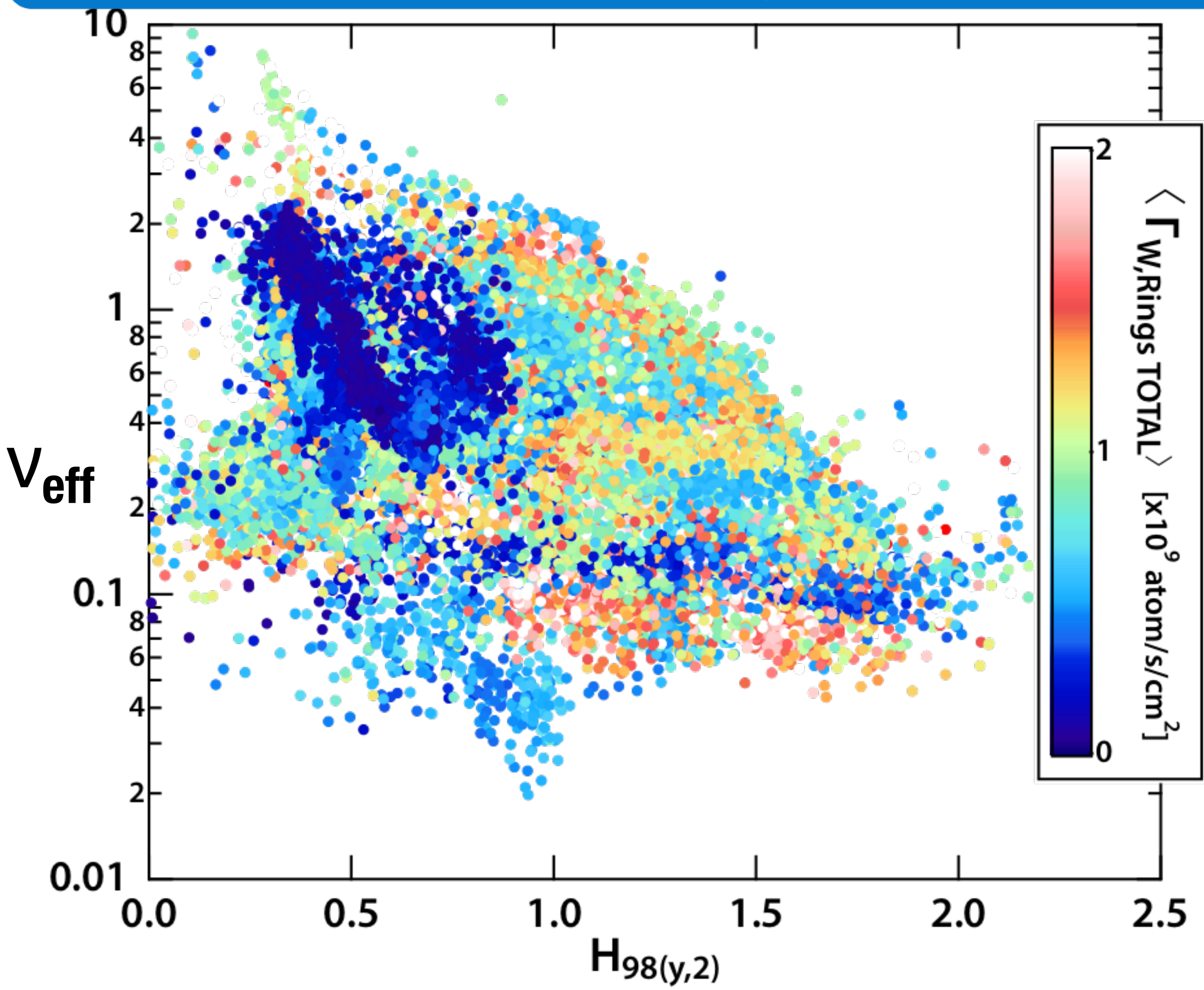


Large Set of Discharges were in Very Good Performance Regime

- **Collisionality, ν_{eff} <~1 → Favorable for density peaking**

Campaign Statistics: Scatter plots of core collisionality versus H_{98} & W erosion



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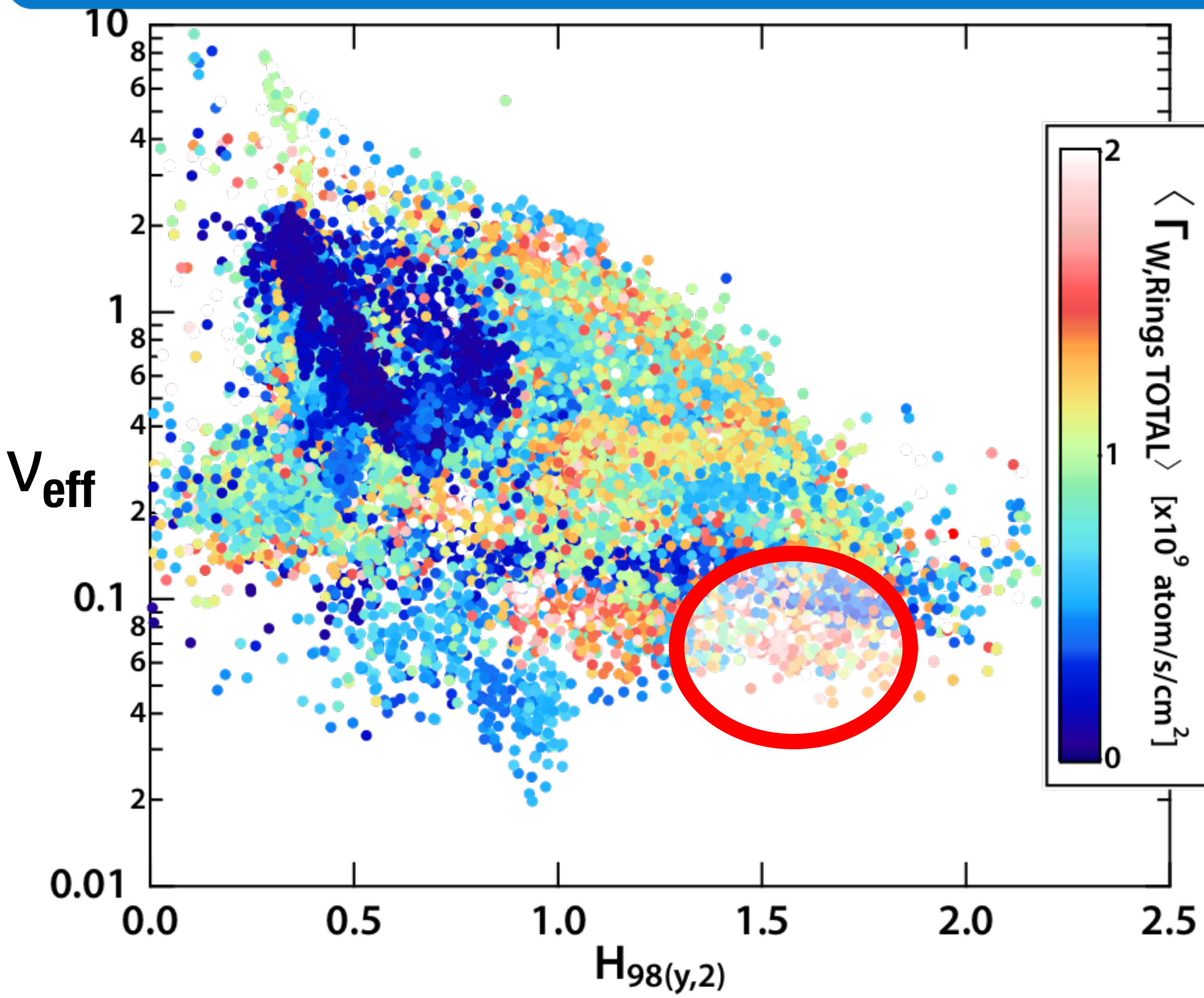
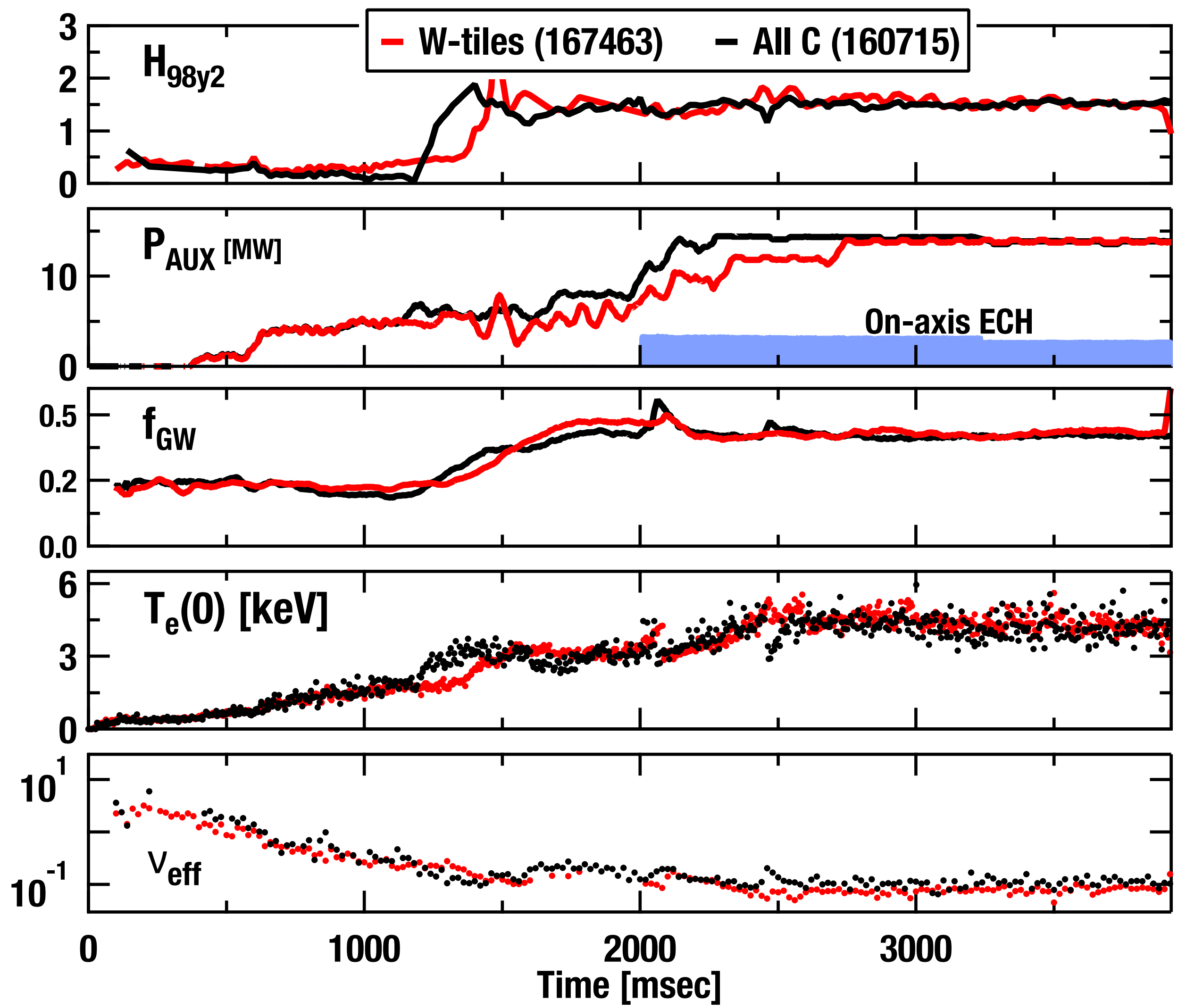


High-performance Discharges with OSP on W Target Required On-axis ECH to Keep Core Accumulation Down

- **Standard AT hybrid conditions replicated w/ & w/o W-tiles**
  - ~4 MW on-axis ECH in both
- **Accumulation was sensitive to profiles**
  - Core MHD also plays role
  - e.g. hybrids w/o on-axis ECH show strong accumulation



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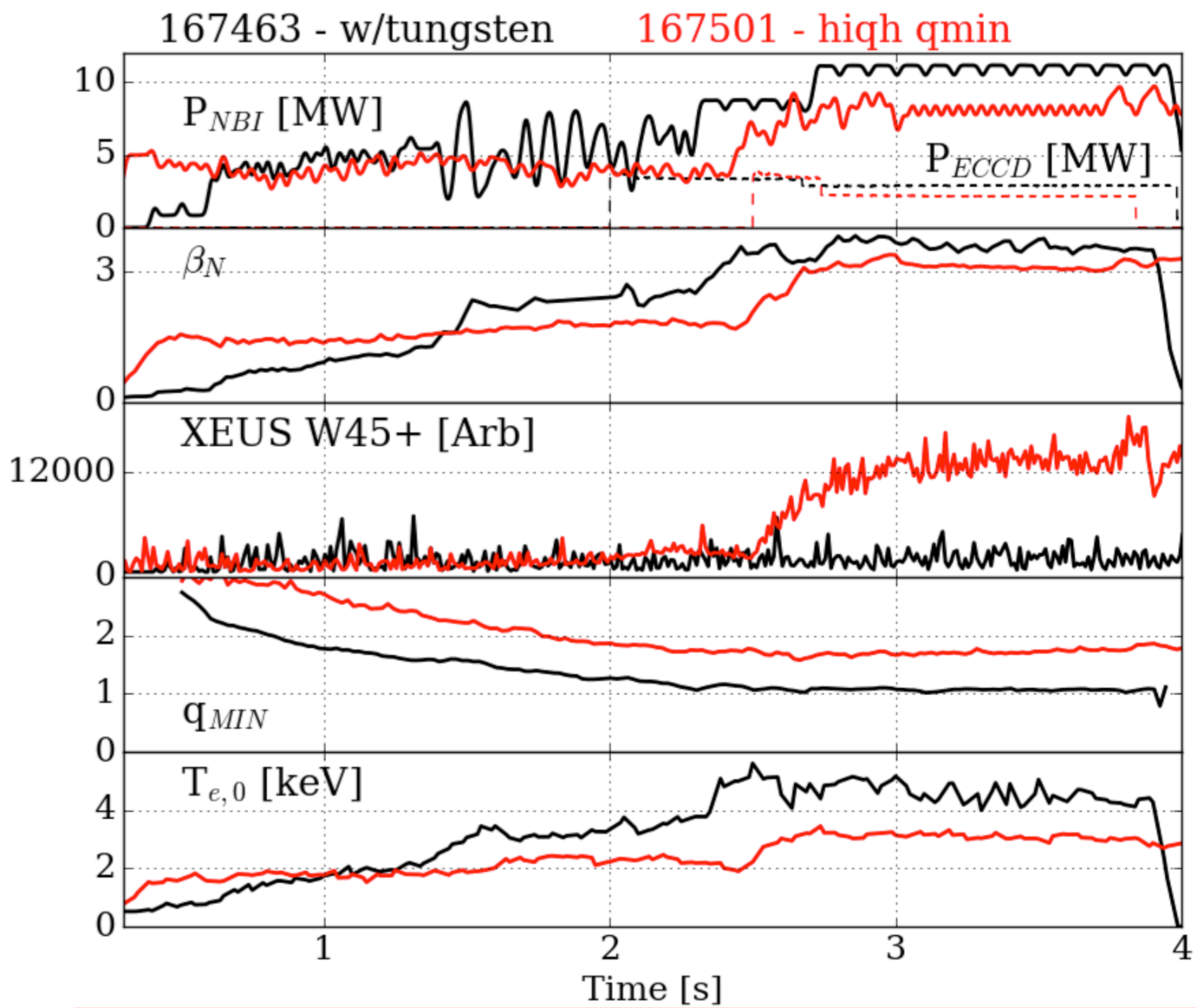
Core

Changing ECH Resonance Location Changed Core W Accumulation

- **AT scenerios with higer q_{min} require off-axis curent drive**
  - Here via ECCD (red)
- **Changed core gradient enough → W accumulation**



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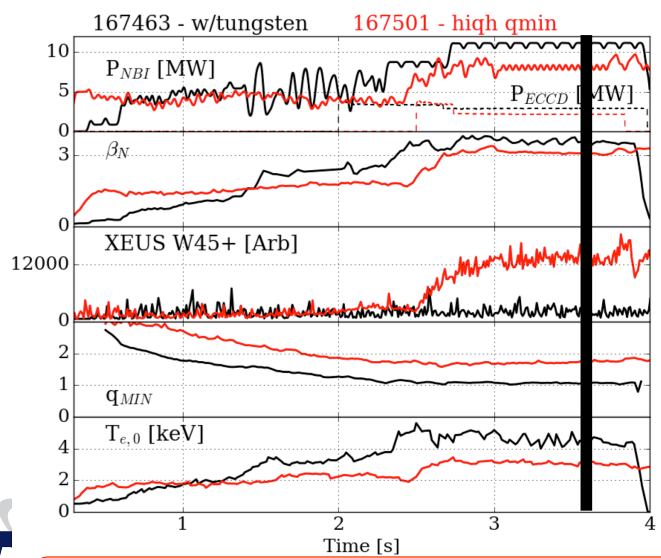

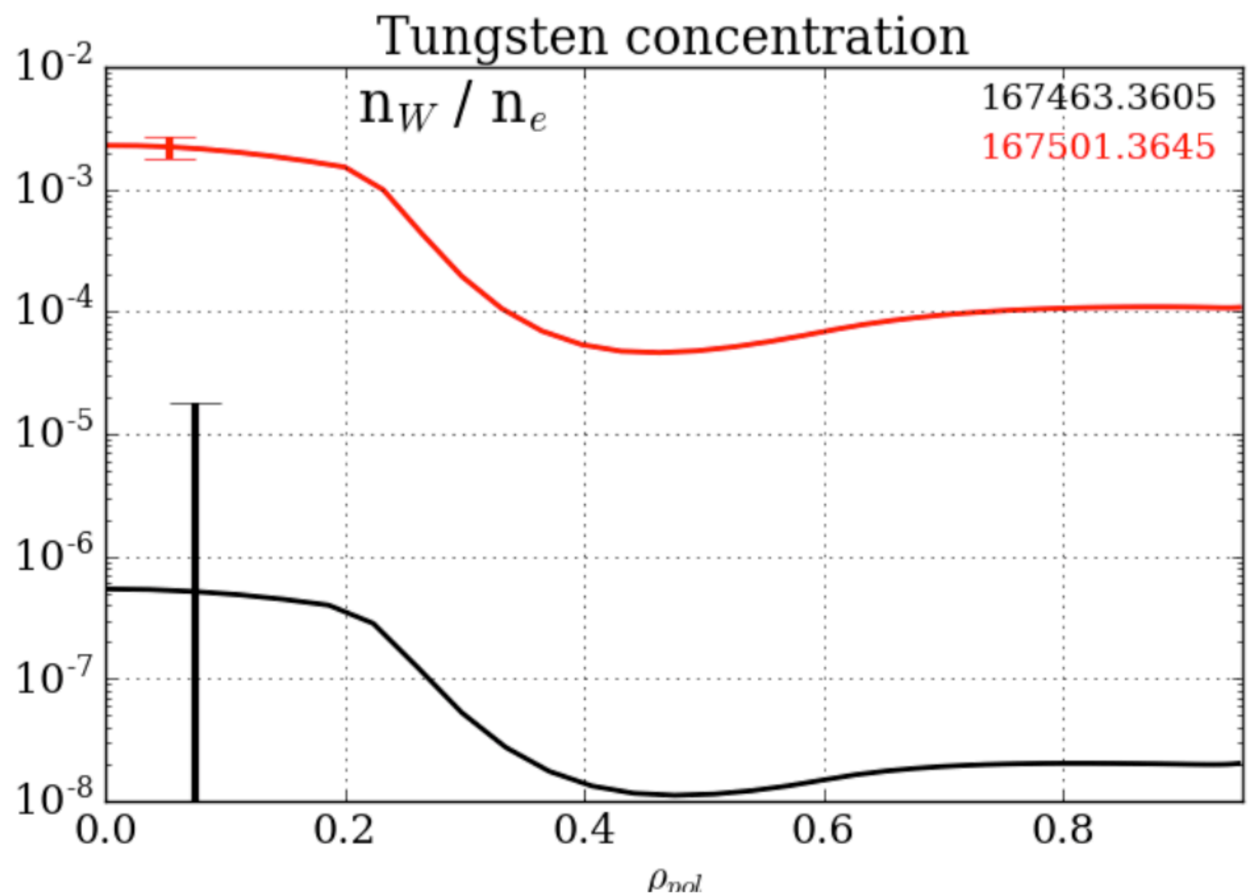

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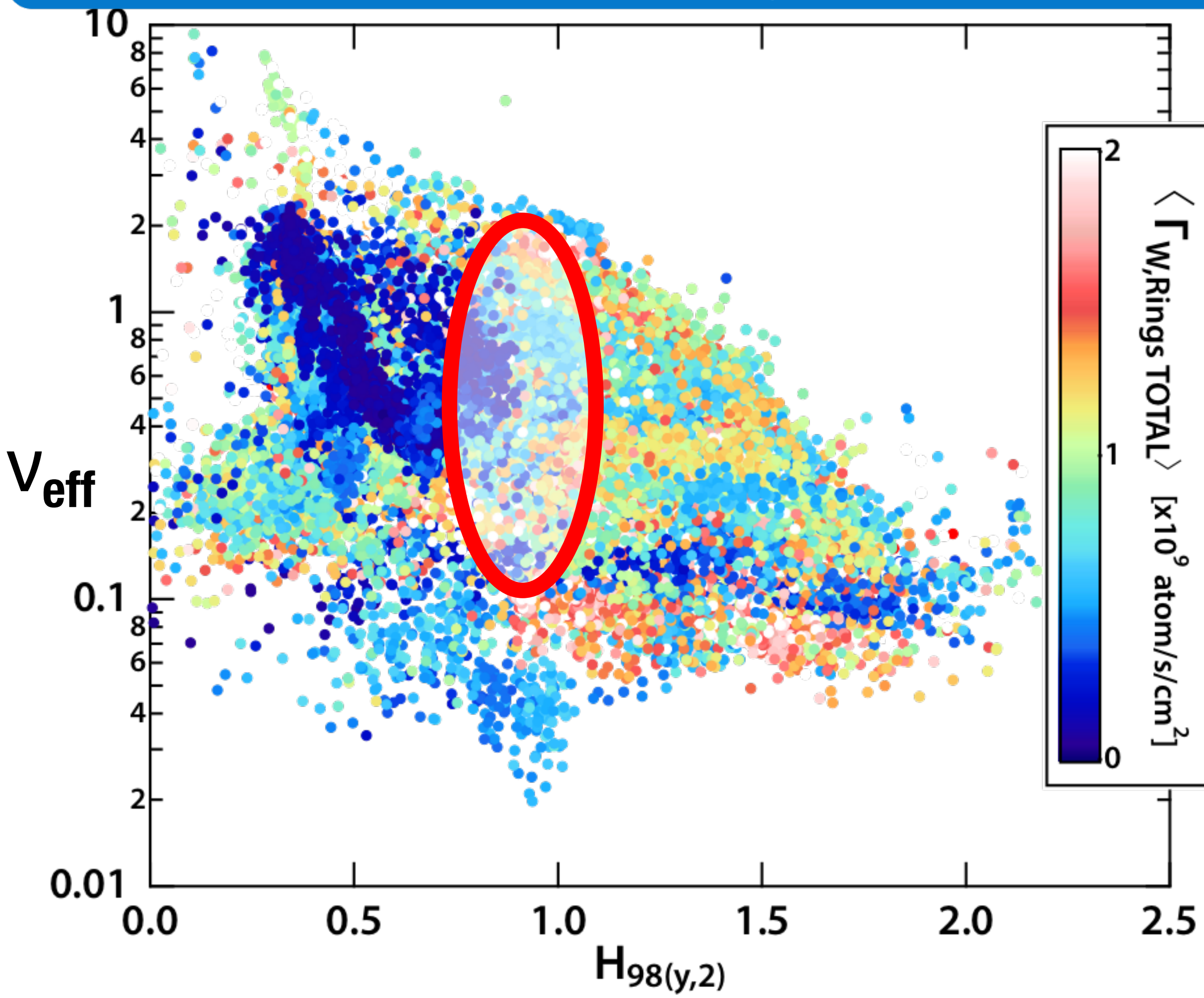
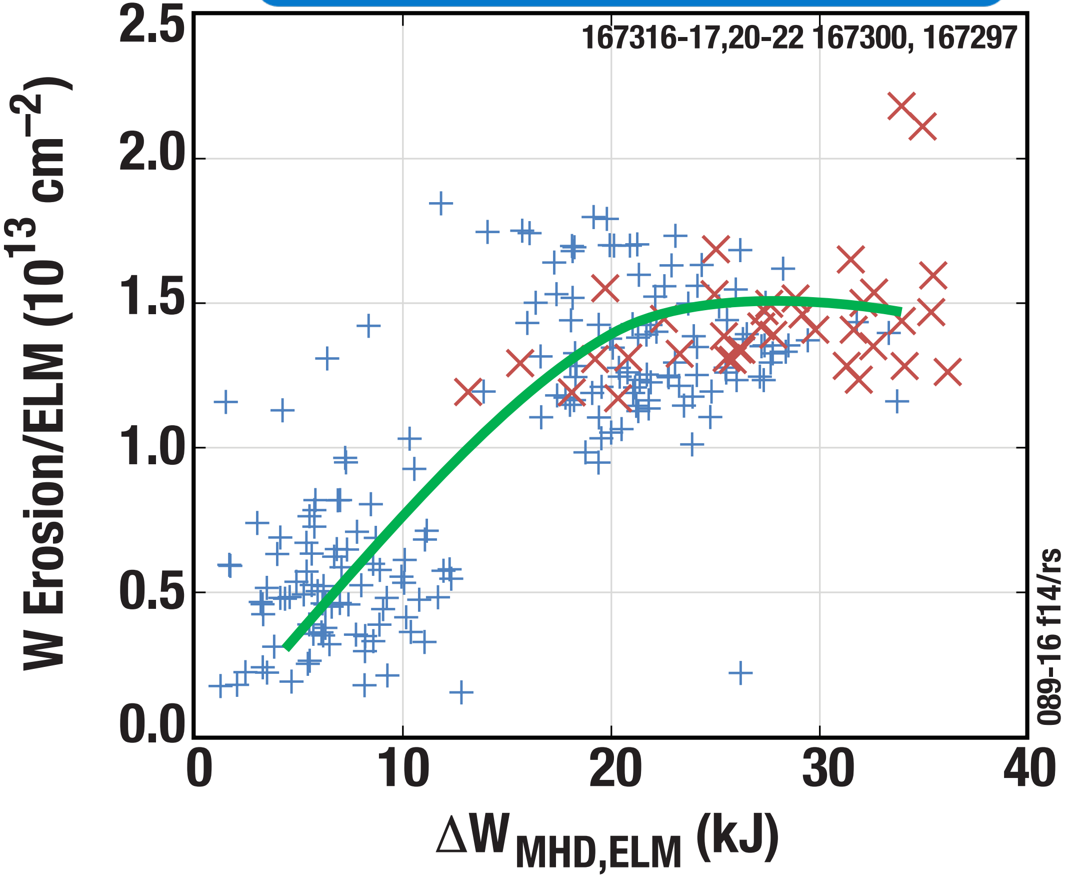


Erosion per ELM Saturates due to Spreading of Fluxes of W Target Inserts

- **Expect a linear increase source strength with ELM size***
  - Holds ~ up to a given ELM size
- **Roll-over at highest ELM size could be due to departure of peak flux profile away from OSP**

W gross erosion/ELM versus ELM size

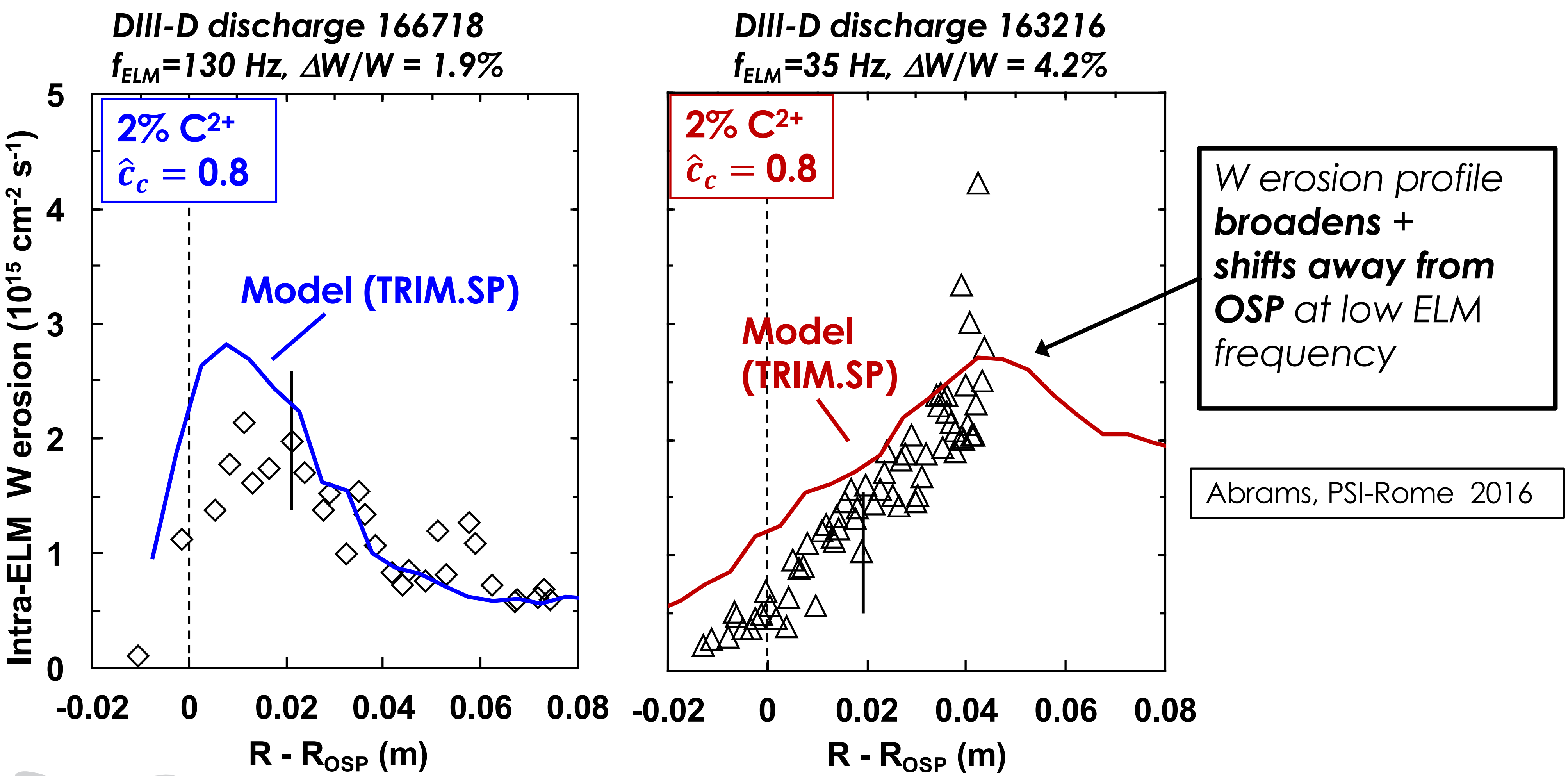


* denHarder et al., Nuc. Fusion (2016)

Sourcing

Intra-ELM W Erosion Profiles Depend on ELM Size but are Consistent with Sputtering Models

- **Similar to heat flux broadening seen during large ELMs***
- **Model uses C flux fraction & C/W surface ratio as free parameters**



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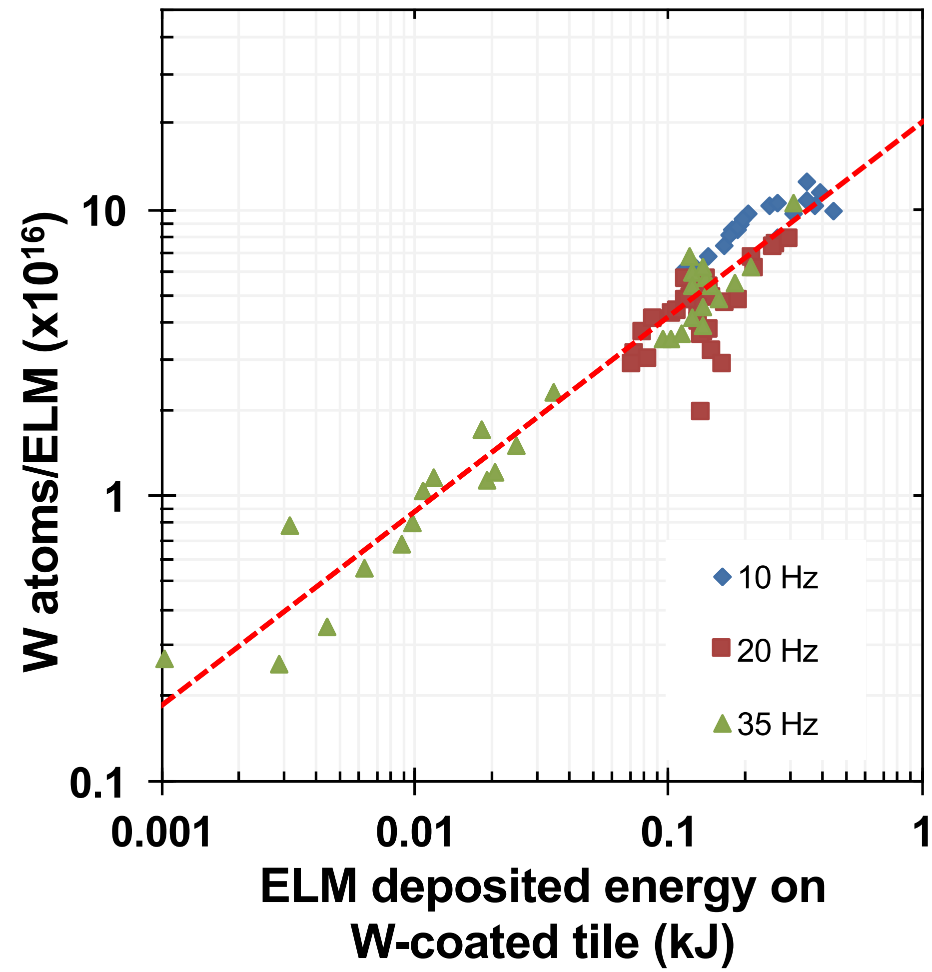
*Jakubowski NF 2009, Eich JNM 2011

Sourcing

W Sourcing During ELMs shows a Strong Correlation with Deposited Energy

- **Comparison with heat flux measurements confirm broadening of peak flux away from OSP**
- **OSP placed on inboard edge of W-coated tile**
  - ELM freq./energy varied via P_{INJ},δ_{upper}
- **W source scaling is independent of ELM frequency**

ELM W gross erosion compared to ELM heat flux on source



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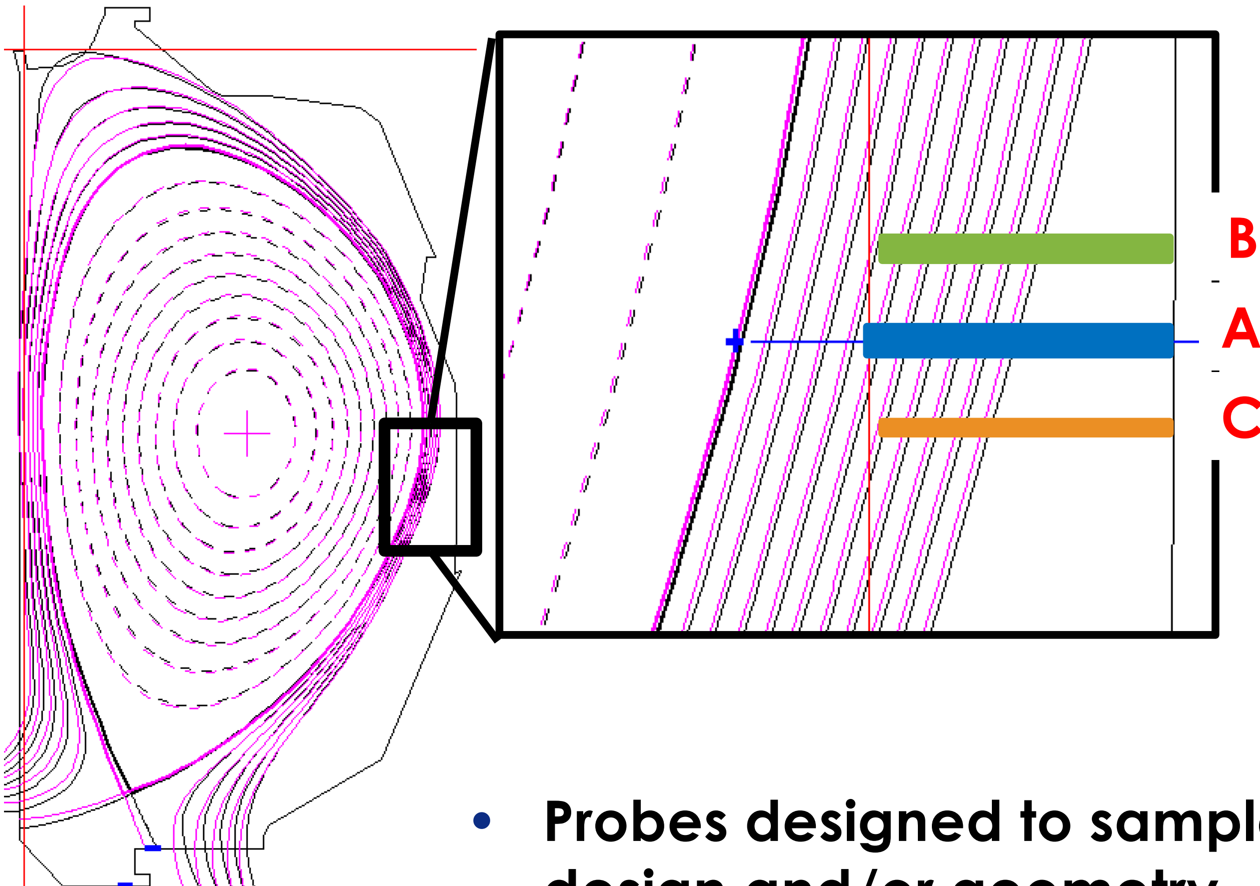
Sourcing

Collector Probe was Retrofit to DIII-D MiMES/RCP Allowing a Large Variety in Probe Geometry



UCSD/ORNL Collector Probe

- **Probes designed to sample different SOL surfaces; by design and/or geometry**
  - Design: Different diameters have different connection lengths
  - Geometry: Location of MiMEs below midplane + shaping leads to a radial spread in location

Stable Isotope Mixing Models (SIMMs)* are Commonly used to Determine Unique Isotopic Source Contributions

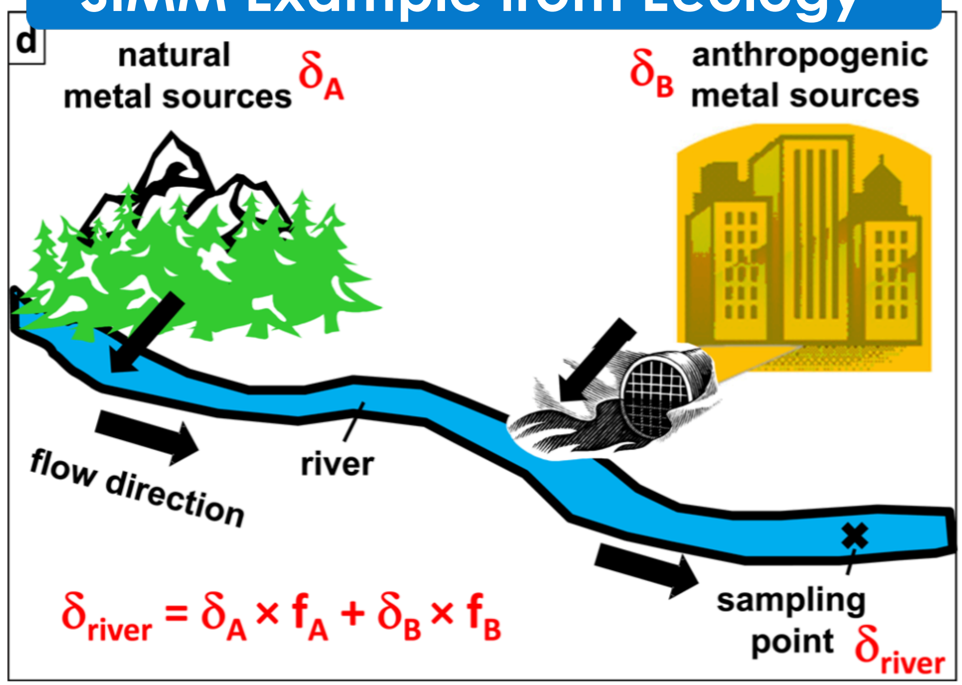
- **Define a standard, $\delta^x E$, & an isotope ratio, R^x_y, of element E;**

$$\delta^x E = \frac{R_{samp}}{R_{std}} - 1 \qquad R^x_y = \frac{E^x}{E^y}$$

- **A 2 W source mixing model using, R^{182}_{184}, is straightforward to interpret;** $$\delta W_{mix} = \delta^{182} W \cdot f_{182} + \delta^{nat} W \cdot f_{nat}$$
  - where $f_{182} + f_{nat} = 1$
  - f = fractional far-SOL flux of each source

- **δW_{mix}, δW_{182}, δW_{nat} measured by ICP-MS**
  - δW_{mix} is from DP
  - δW_{182} & δW_{nat} are pre-determined standards

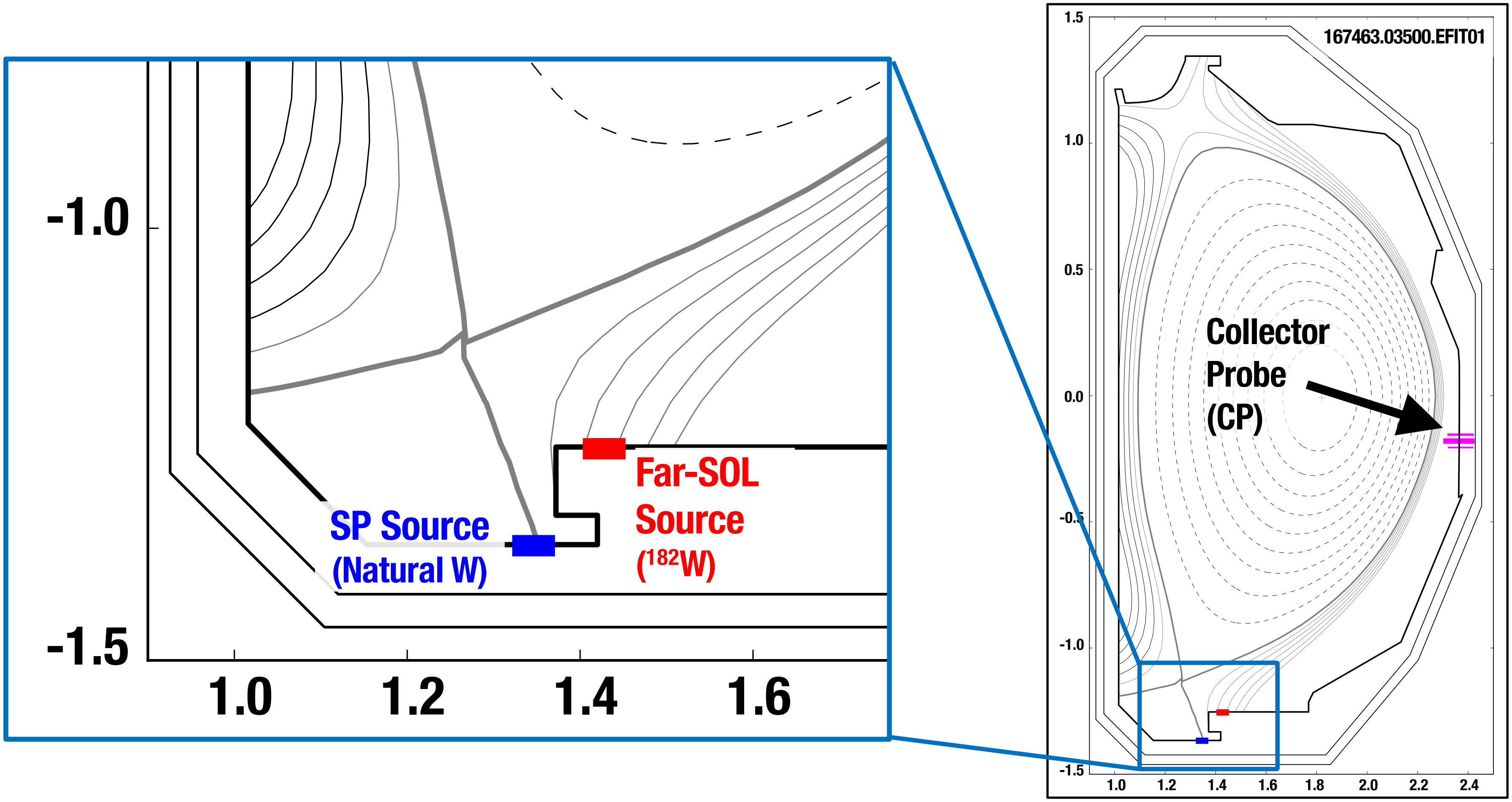
SIMM Example from Ecology*



*See: J.G. Wiederhold, Environ. Sci. Tech. 49 (2015); M. Ben-David et al., J. Mammalogy 93(2) (2012)

Localization of Divertor W Sources Made Possible By Novel Isotopic Coating and Detection Methods

- **Upstream divertor W sources → CP + ex-situ mass spectroscopy, ICP-MS (UT-Knoxville)**
  - Coupled with localized in-situ source W-I spectroscopy



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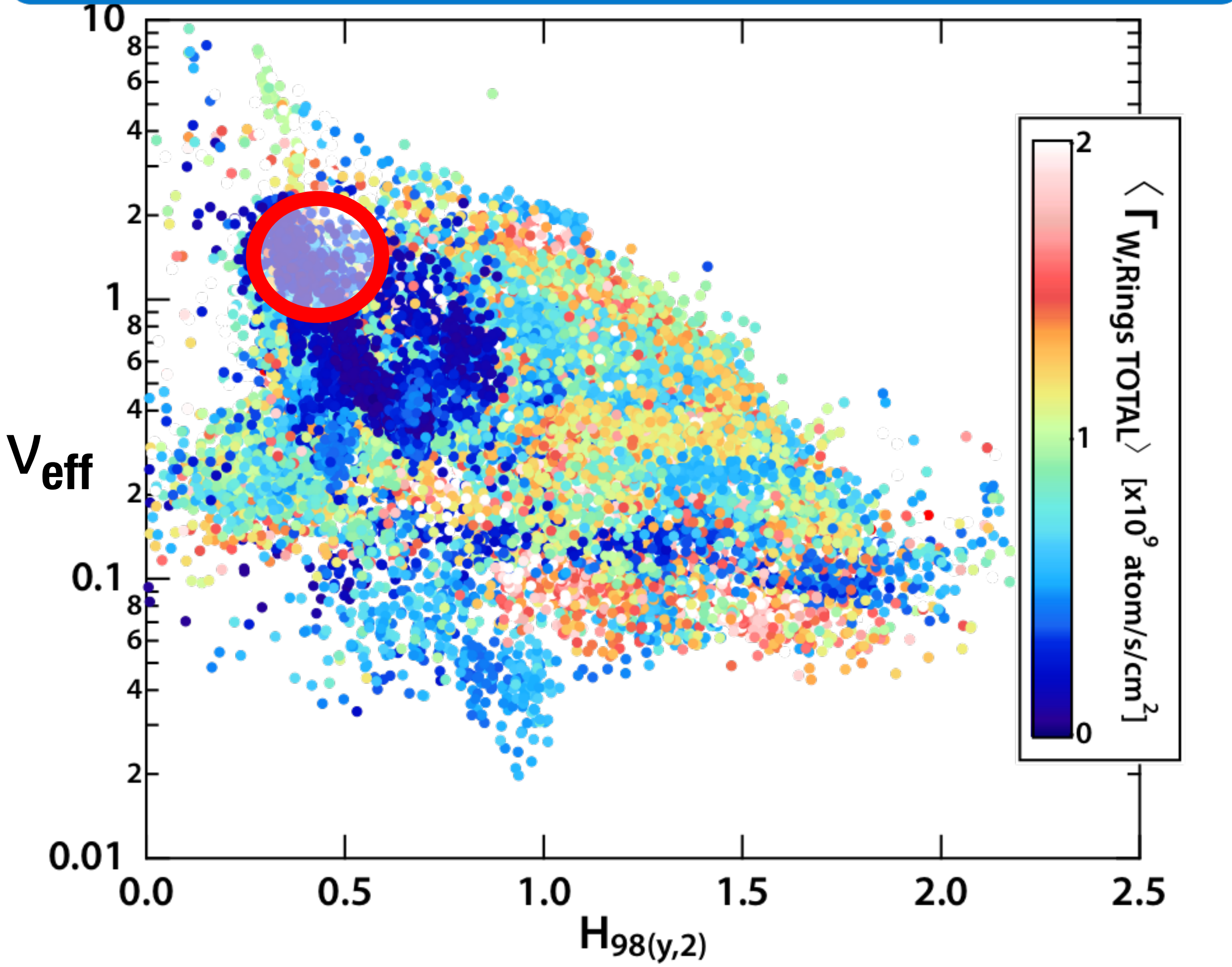

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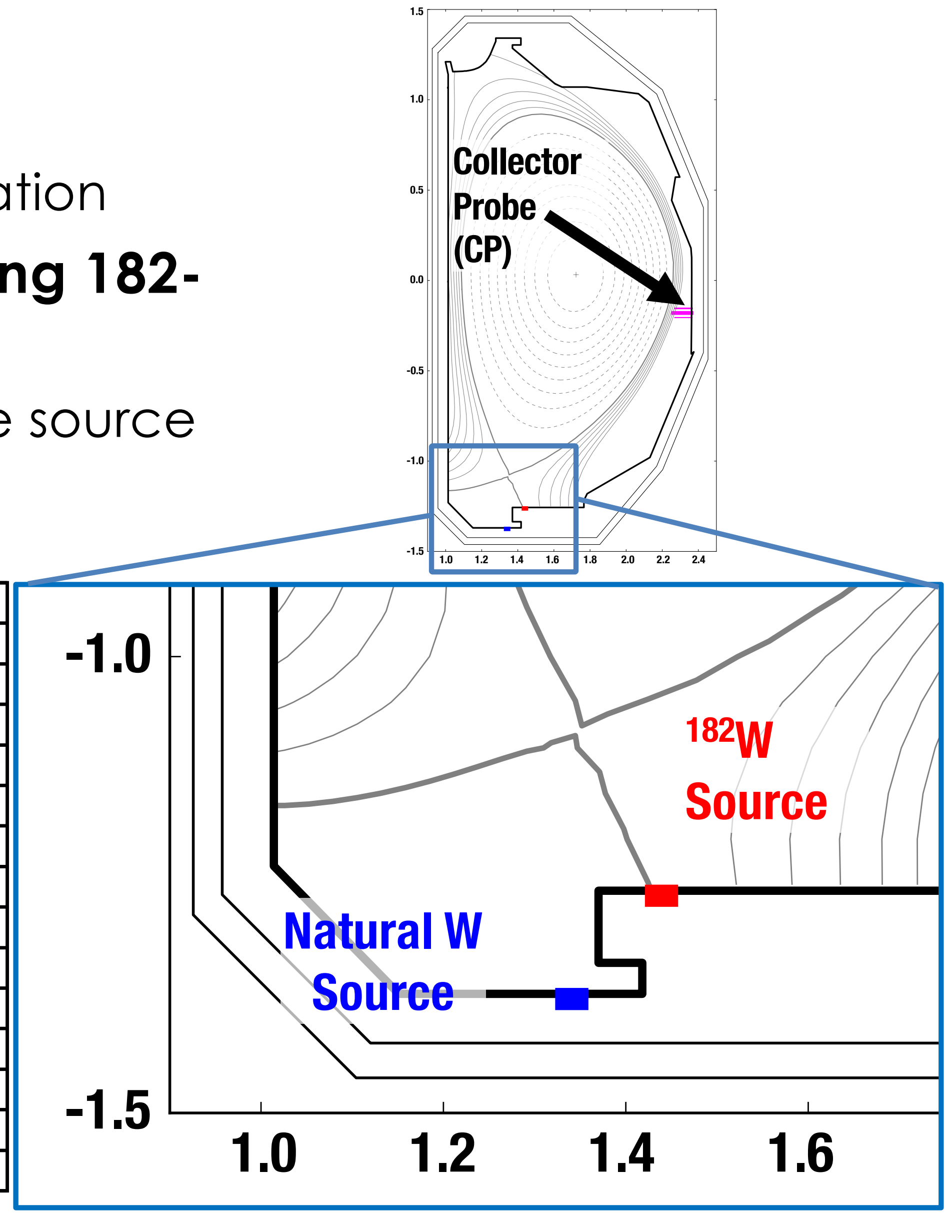
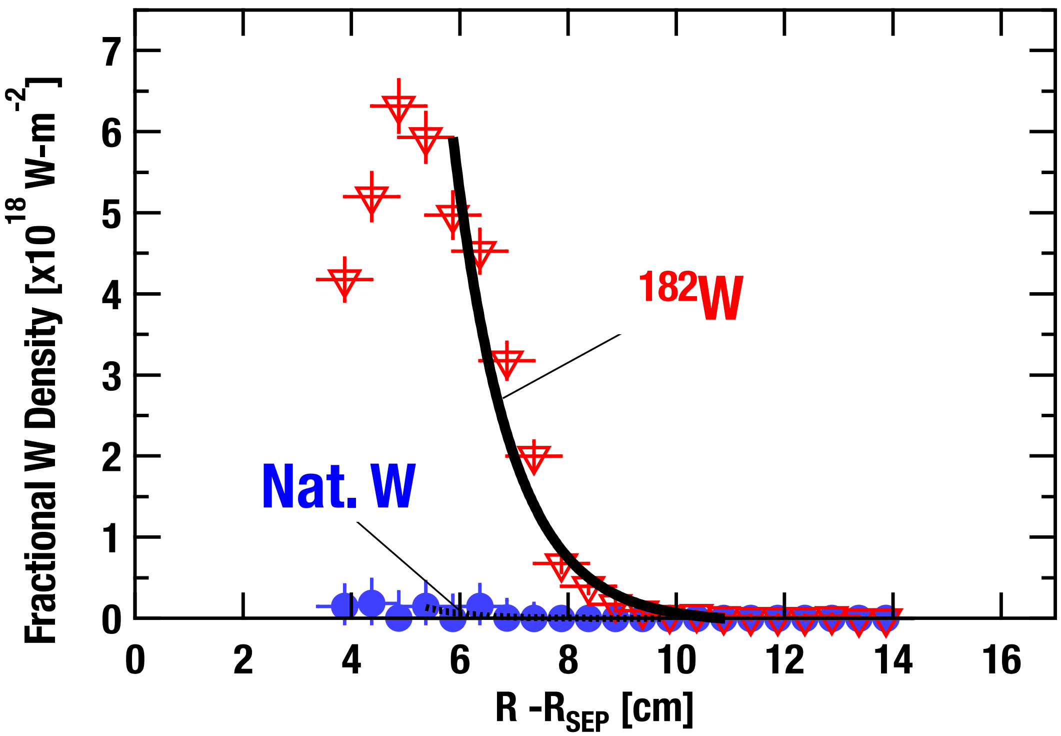
Cross-check of Source Determination (SIMMs) Model Performed in L-mode with SP on Shelf; Showed Dominate ^{182}W Upstream

- **High power (P_{INJ} ~3MW) L-mode at begining of campaign**
  - Very likely no migration contamination
- **“Classic” CP profiles seen with strong 182-W signature**
  - Sanity check probe ‘saw’ only one source





SOL Transport

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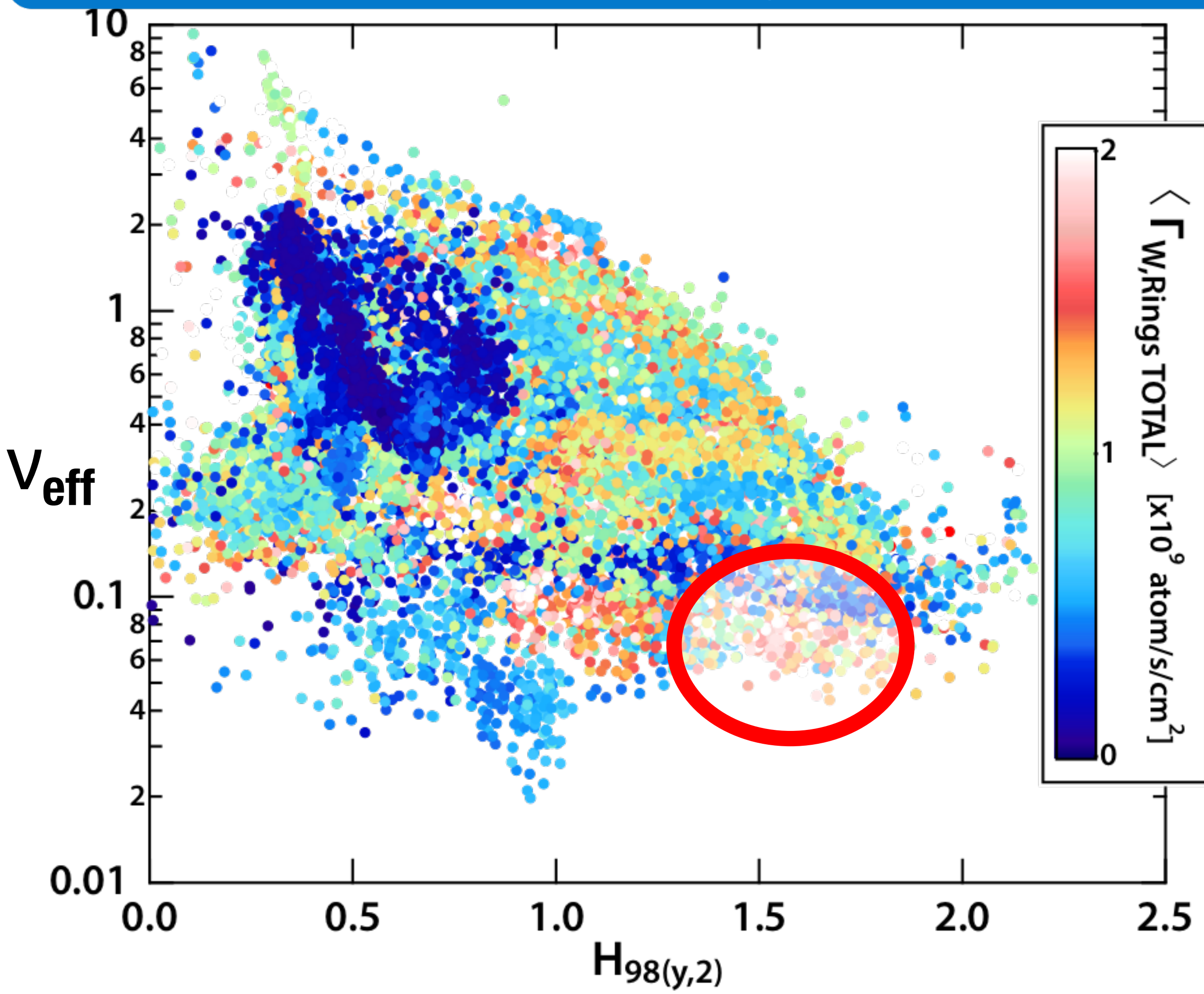
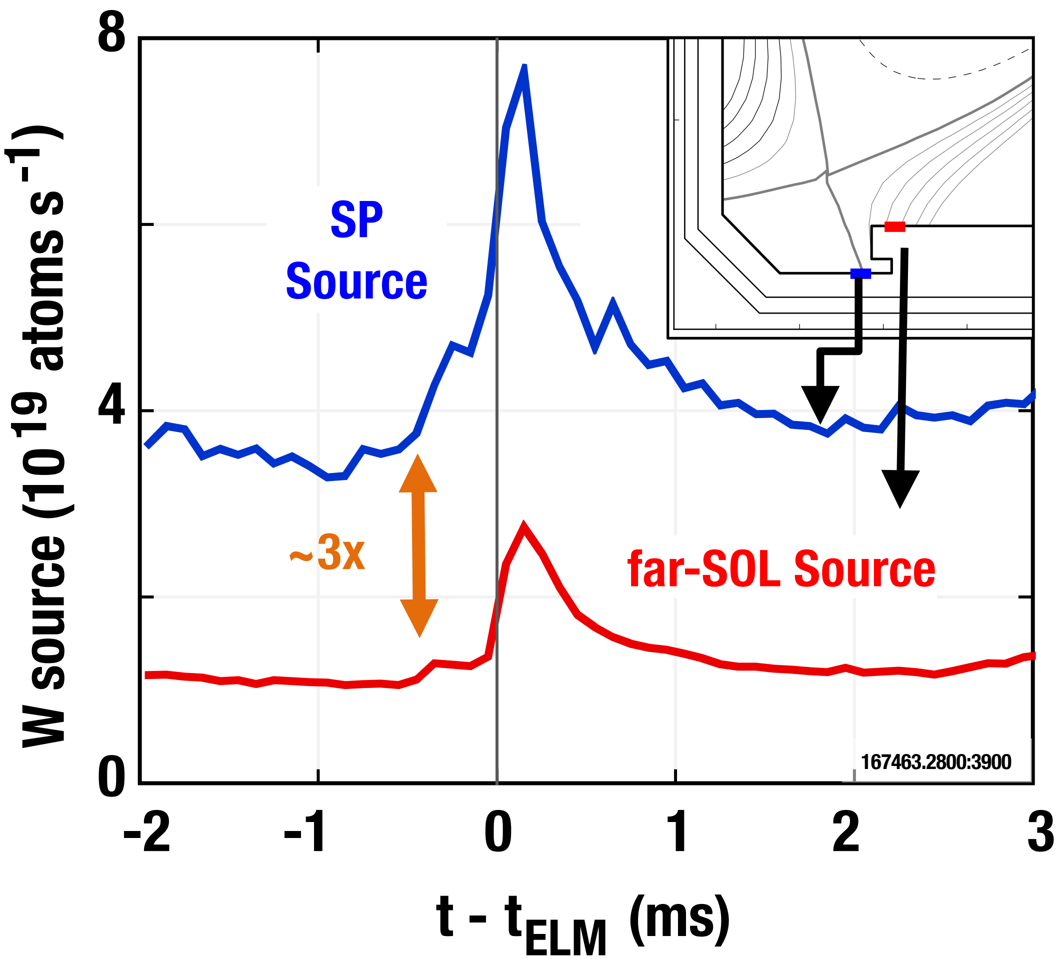


ELM Resolved W Sputtering Fluxes Show a Dominate SP W Source in High-f_{ELM}, High-power H-modes

W gross erosion via W-I spectrscopy

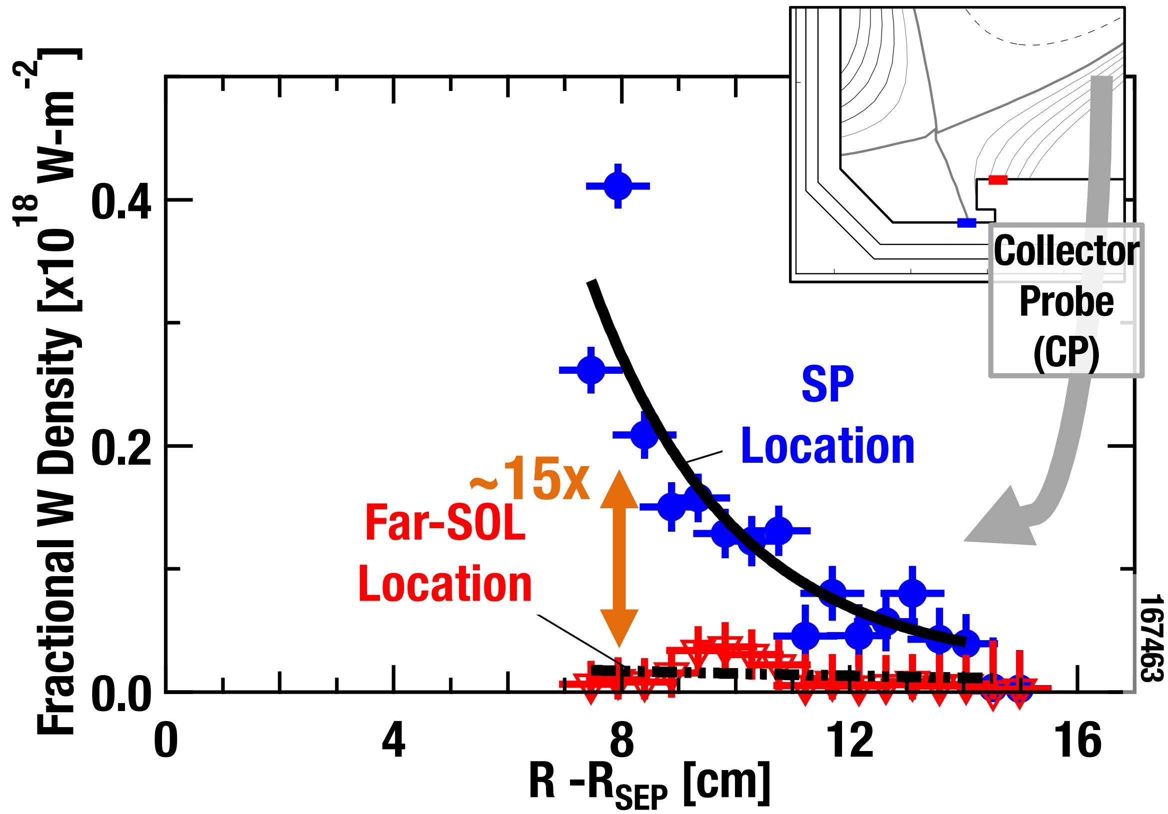
- Data is ensemble average over ~ 1sec (2800-3900) period
- Strongest W source is from floor during ELM (inter-ELM)
- Floor source is ~3x that of shelf for this condition; small deviation during ELM seen



Measured Upstream W Density Dominated by SP W Sources in High-f_{ELM}, High-power H-modes

- **Ratio of floor to shelf density is significantly higher than source ratio**
  - Source floor/shelf ratio ~3
- **CP analysis: Floor (SP) contributes ~15x that of divertor shelf source**
- **Suggests SP is more efficient at SOL contamination than far-SOL**

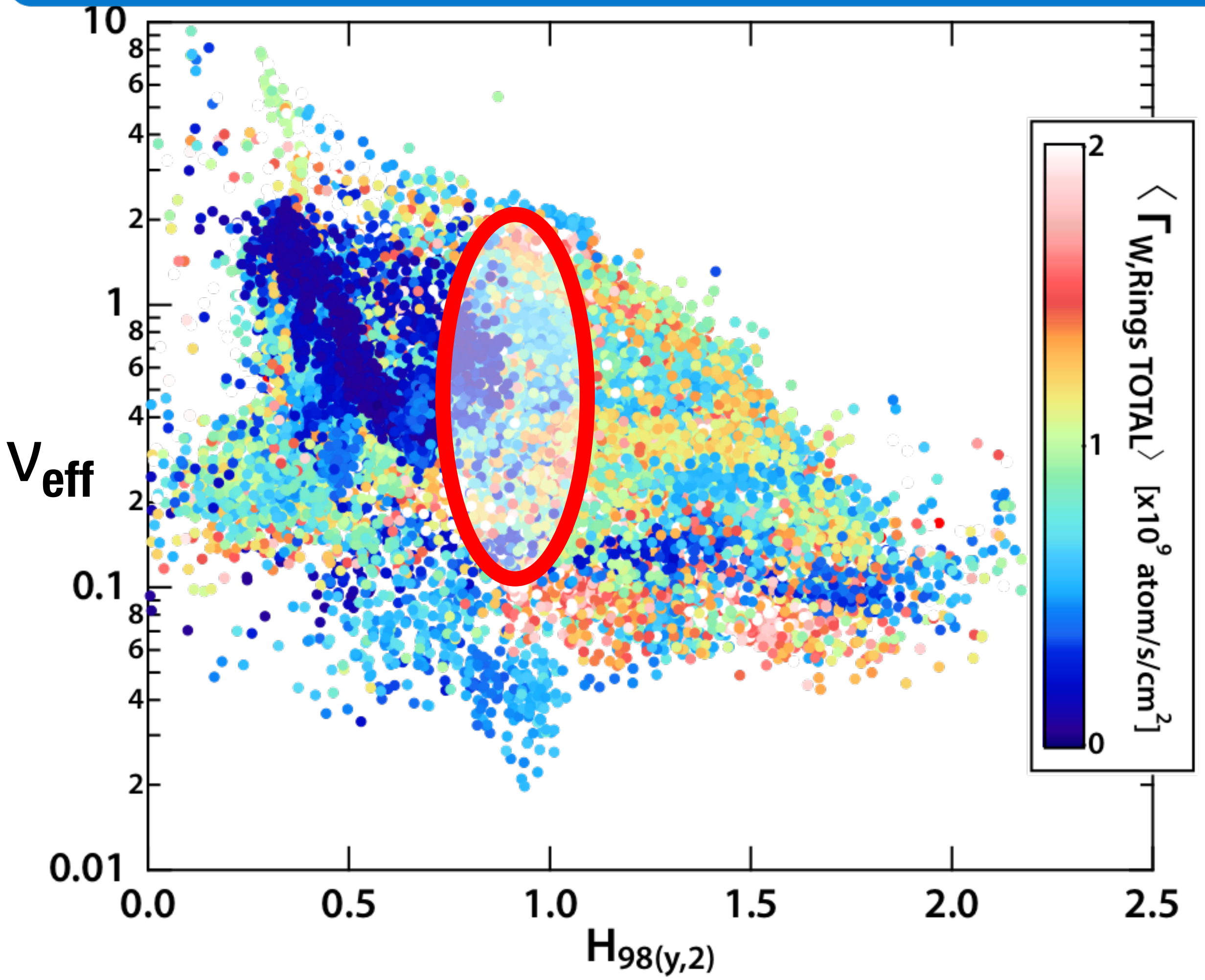
Radial upstream W profile from each source via ICP-MS + RBS



Large Set of Discharges were in Very Good Performance Regime

- **Collisionality, ν_{eff} <~1 → Favorable for density peaking**

Campaign Statistics: Scatter plots of core collisionality versus H_{98} & W erosion



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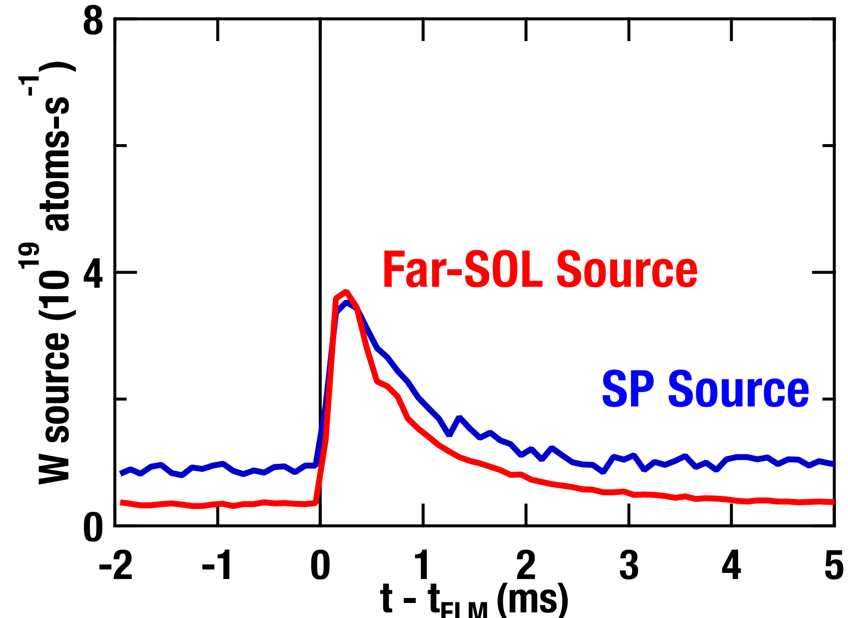
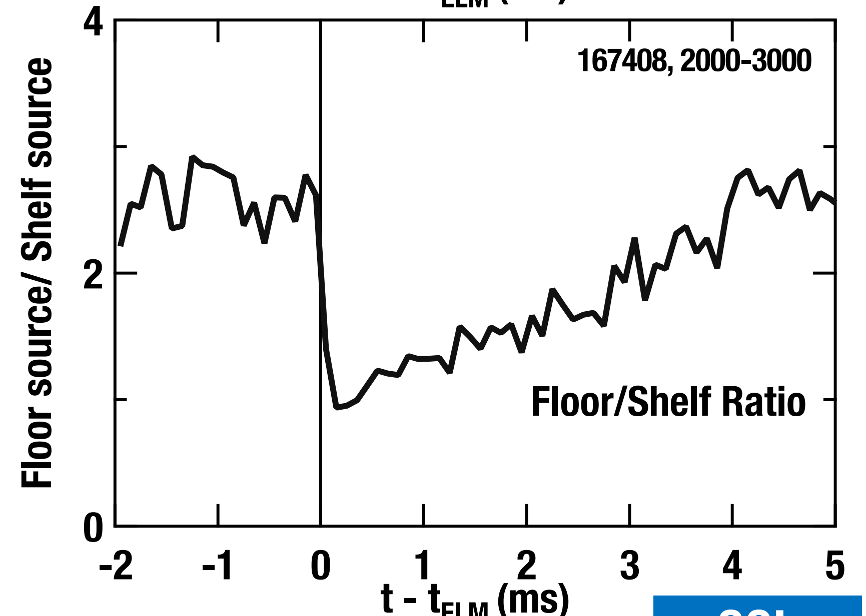
In Discharges with Lower f_{ELM} (& Lower P_{AUX}), W Source Location become Comparable; ~ Same for inter-ELM Sourcing

- **ELM source evolution is also very different from higher P_{AUX} case**
  - Much bigger Type-I in these cases
- **Inter-ELM source ratio is similar to that in high P_{AUX} case; ~3x**
- **This W sourcing signature dramatically changes upstream W content**





SOL Transport

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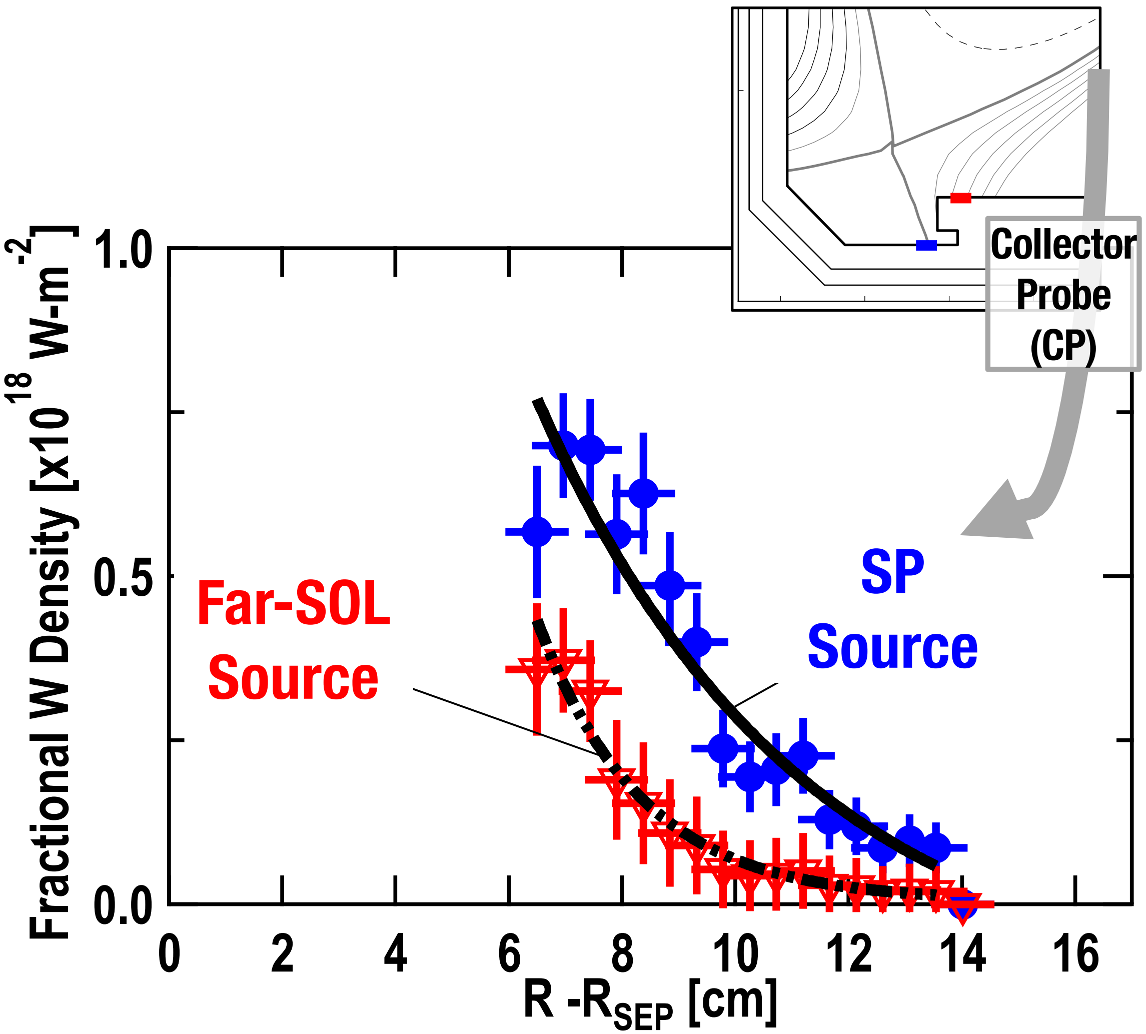
Case with Lower ELM Frequency Shows Upstream Isotope Distribution Coming More from far-SOL Source

- **Mix of SP → far-SOL becomes comparable**
  - Closer to separatrix (small $R\text{-}R_{sep}$) ratio → 1
- **In this scenerio, far-SOL source becomes more important**
  - ELM wetted area increased



Overall Summary: Divertor W Sources at OSP Became Dominant SOL Contamination Location at High Power, High f_{ELM}

- **Unique experimental setup allowed distinguishable W sources at OSP versus divertor shelf/entrance**
  - ELM-y H-mode conditions coupled with upstream CP
- **ELMs had major impact on source strength & upstream density characteristics**
  - Depended on ELM size & flux profile
- **Measurements of upstream W densities show SP/far-SOL shows are dependent on operating scenario**
  - CP measurements show ~15x W from SP/far-SOL compared to ~3:1 source ratio
  - Lower f_{ELM} shows a drop ~5x SP/far-SOL distribution

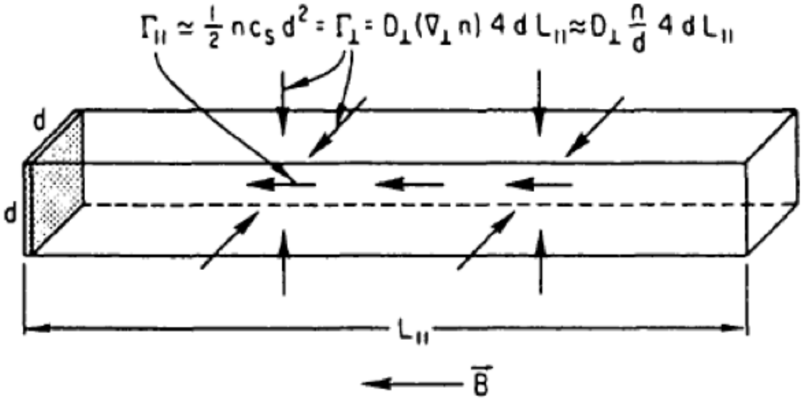
Backups Break

- **End**
  - ..
    - ..
- **Fin**

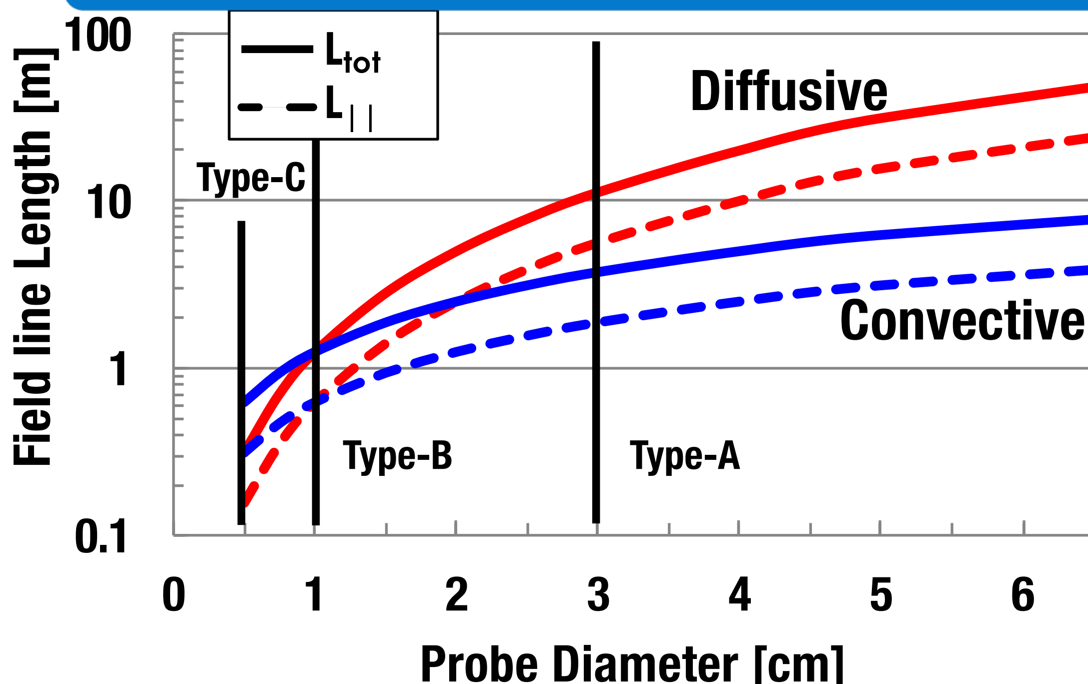
Concept of Collector Probes (CP) are Used Frequently in Tokamak PMI/Surface Analysis Studies

- **70s & 80s saw many in use* (T10, TEXTOR, JET, ASDEX, PLT)**
- **Perturbation length, $L_{||}$, is a balance in ambipolar transport**
  - In far-SOL can be set by diffusive or convective transport
  - Related to Collection Length, $L_{tot} = 2 \times L_{||}$

Diagram of perturbation length



Sampling Length for DIII-D probe-set



*see e.g., Cohen JNM (1978); Goodall et al., JNM (1980); Stangeby, J.Phys.D (1985); Stangeby, Phys. Fluids (1987); Staudenmaier et al., JNM (1987); Hildebrandt et al., Cont. Plasma Phys. (1988); Grote et al., JNM (1989)

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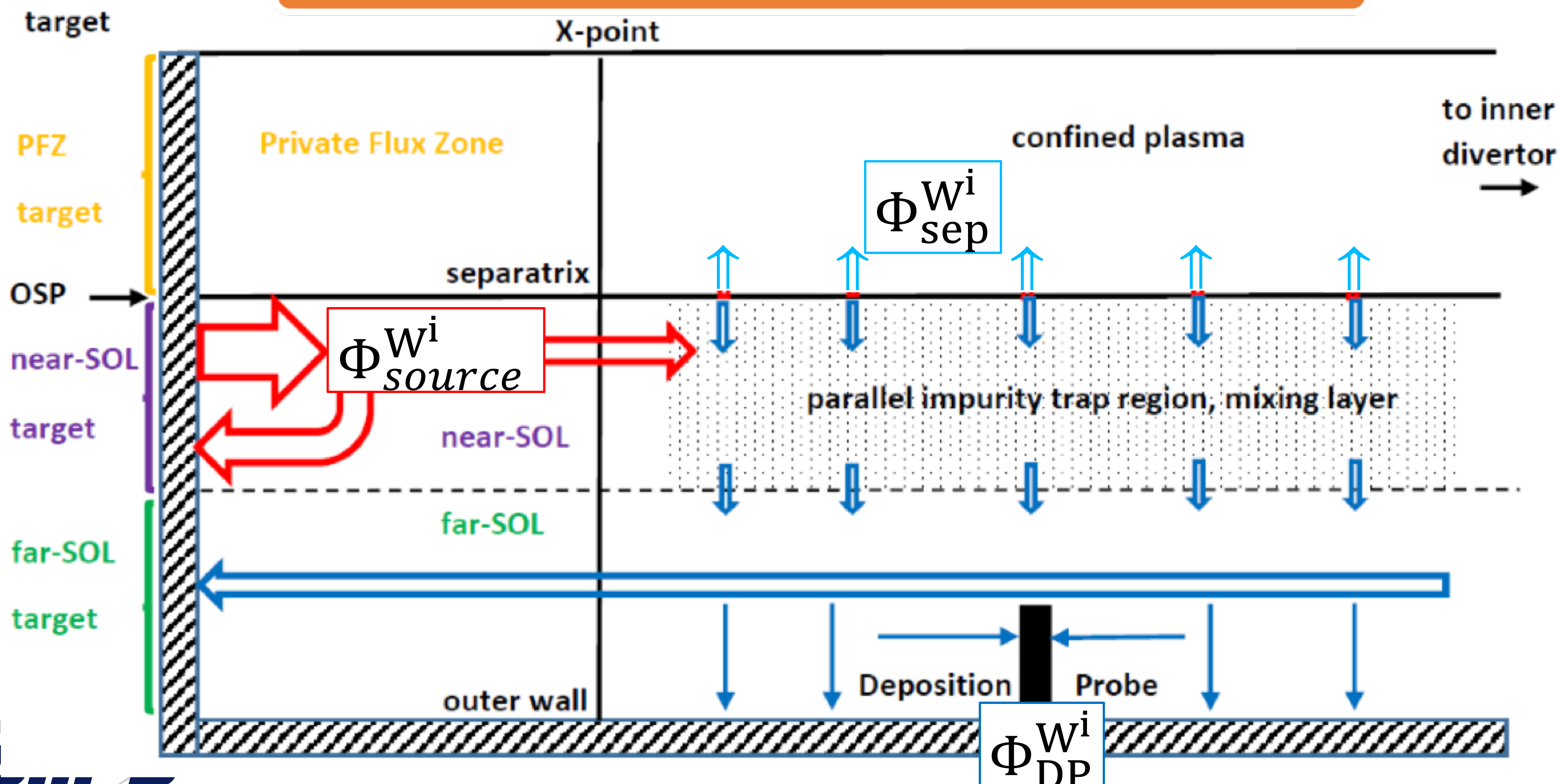
SOL Transport

Midplane Collector Probe Hypothesis Provides a Connection Between Φ^{W}_{sep} & Φ^{W}_{DP} – But Needs to be Verified

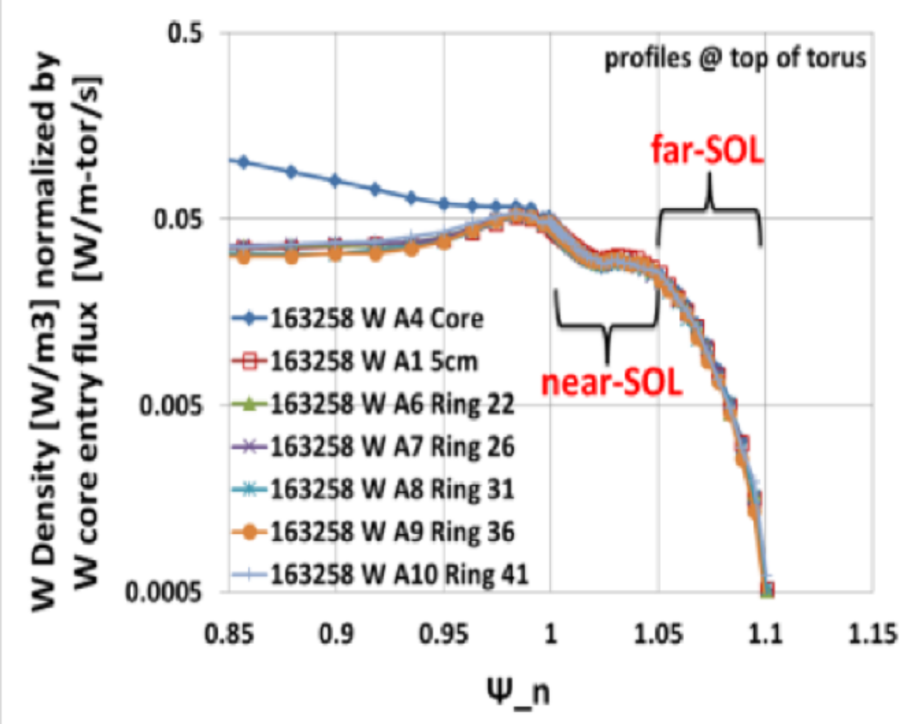
Testing: $c_W \propto \Phi^{W^i}_{DP} \propto \Phi^{W^i}_{source}$; **also check if:** $\dfrac{\Phi^{W^i}_{DP}}{\Phi^{W^i}_{sep}} \approx \dfrac{\Phi^{W^{pellet}}_{DP}}{\Phi^{W^{pellet}}_{pellet}}$

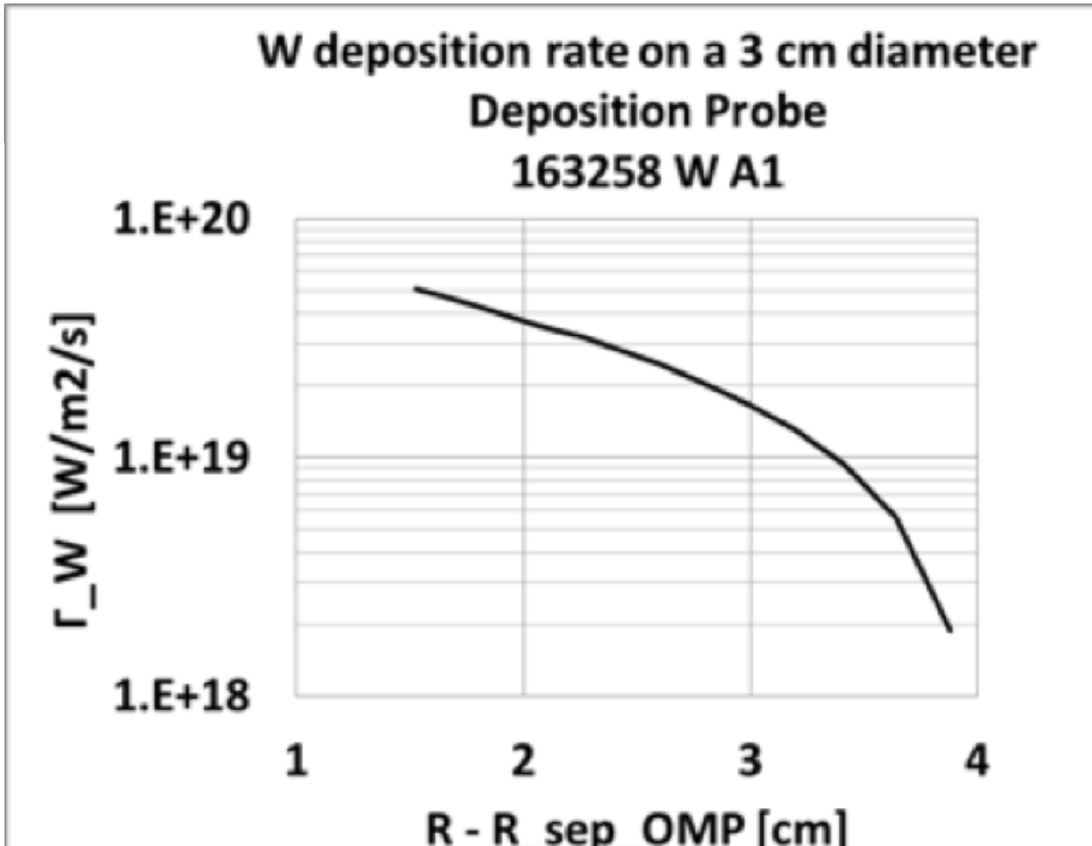
Schematic of DIV SOL Fluxes



Peter/DIVIMP predicted this: modeling with DIII-D metal tile geometry has given some predictions/trends

n_W profiles
of various ring geometries
(D. Elder PSI 2016)

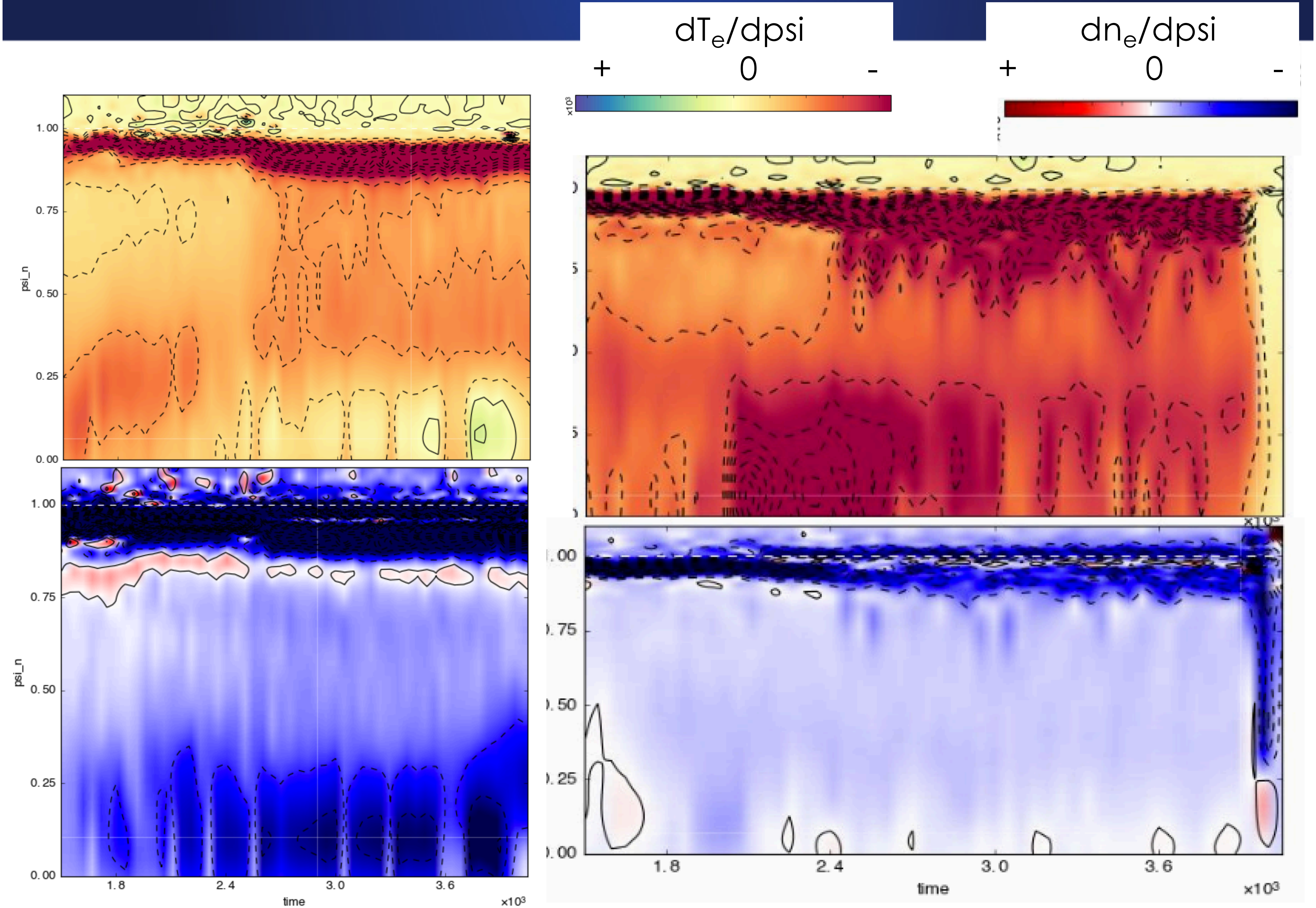




From Stangeby BPMIC talk a couple months ago

- **Expected deposition rate on DP more than adequate for ICPMS & RBS analysis**
  - Corroborated by past results from AUG DP, e.g. see

Core T_e and n_e gradient changes



Preliminary Planning for Extended/More High-Z Divertor Experiments

- **Considering Metal Tiles in FY19 & Beyond:**
  - Concept #1: Locations Give Wider Range of Conditions/Configurations
  - Concept #2: Metal Target Impact on Detachment Onset
- **Also: Div: W + Main Chamber: SiC**