W production during ICRF operations:

experiments & modelling

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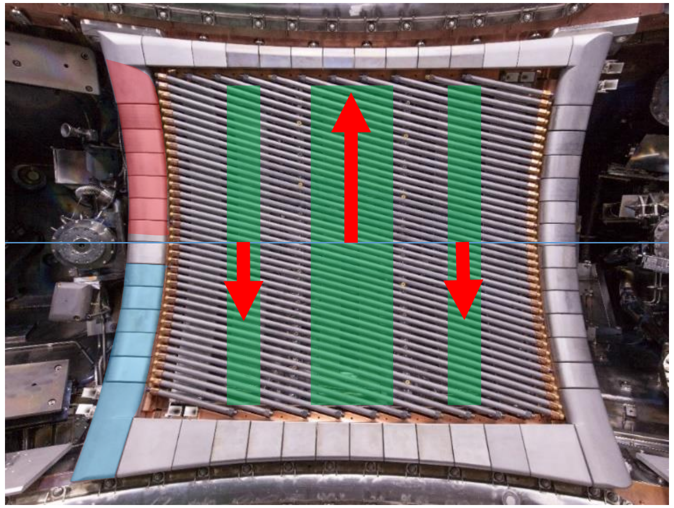

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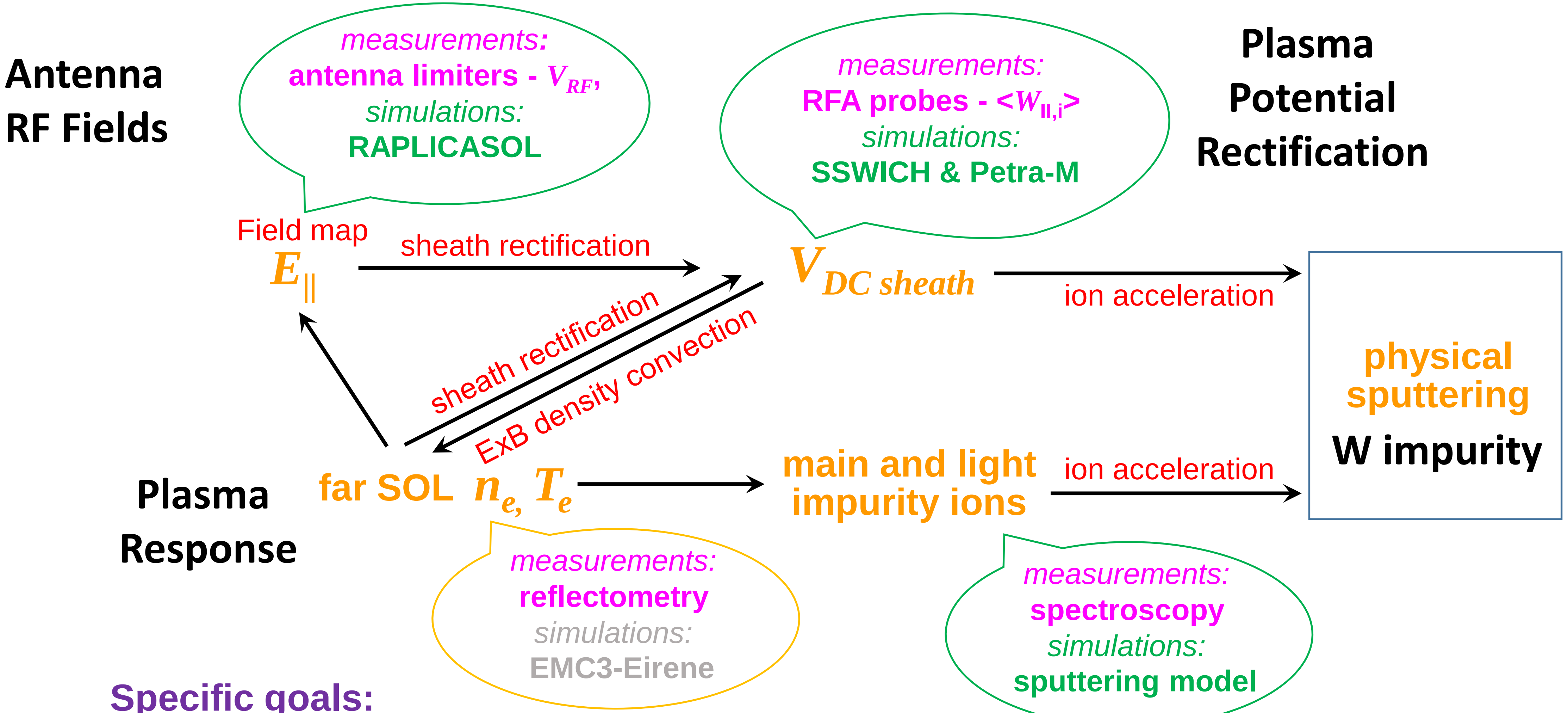
[i] U. Stroth et al. 2022 Nucl. Fusion 62 042006
[j] E. Joffrin (See the author list of "Progress on an exhaust solution for a reactor using EUROfusion multi-machines capabilities" by E. Joffrin et al. to be published in Nuclear Fusion Special Issue: Overview and Summary Papers from the 29th Fusion Energy Conference (London, UK, 16-21 October 2023)).

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Main goal: improve understanding of ICRF-induced impurities

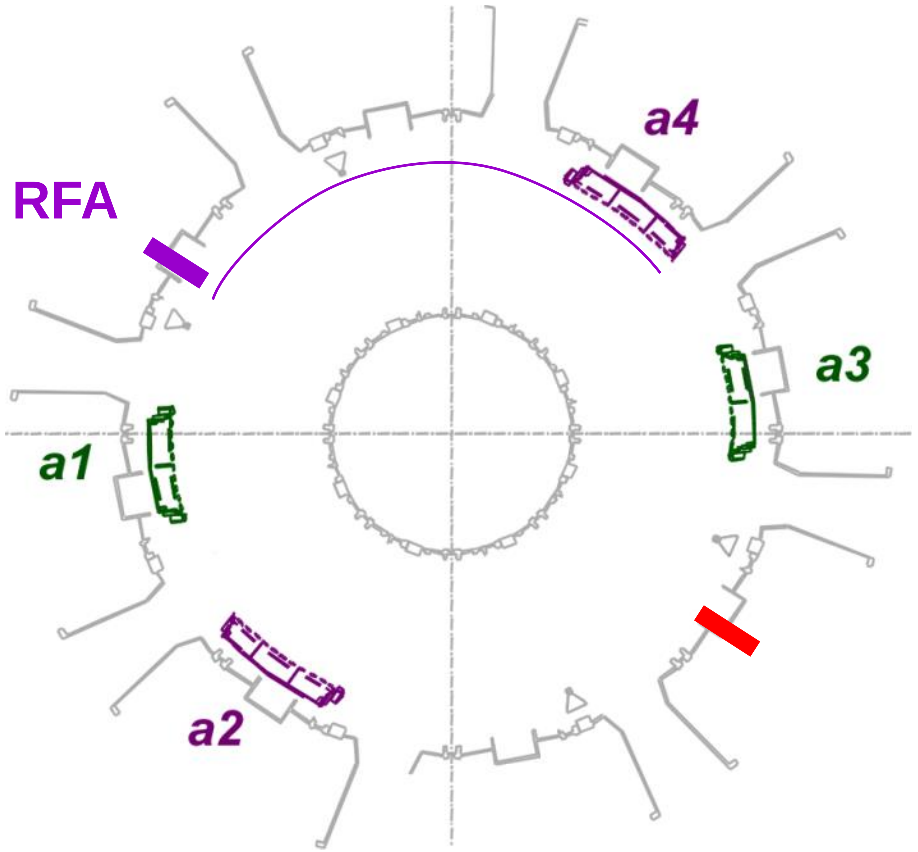


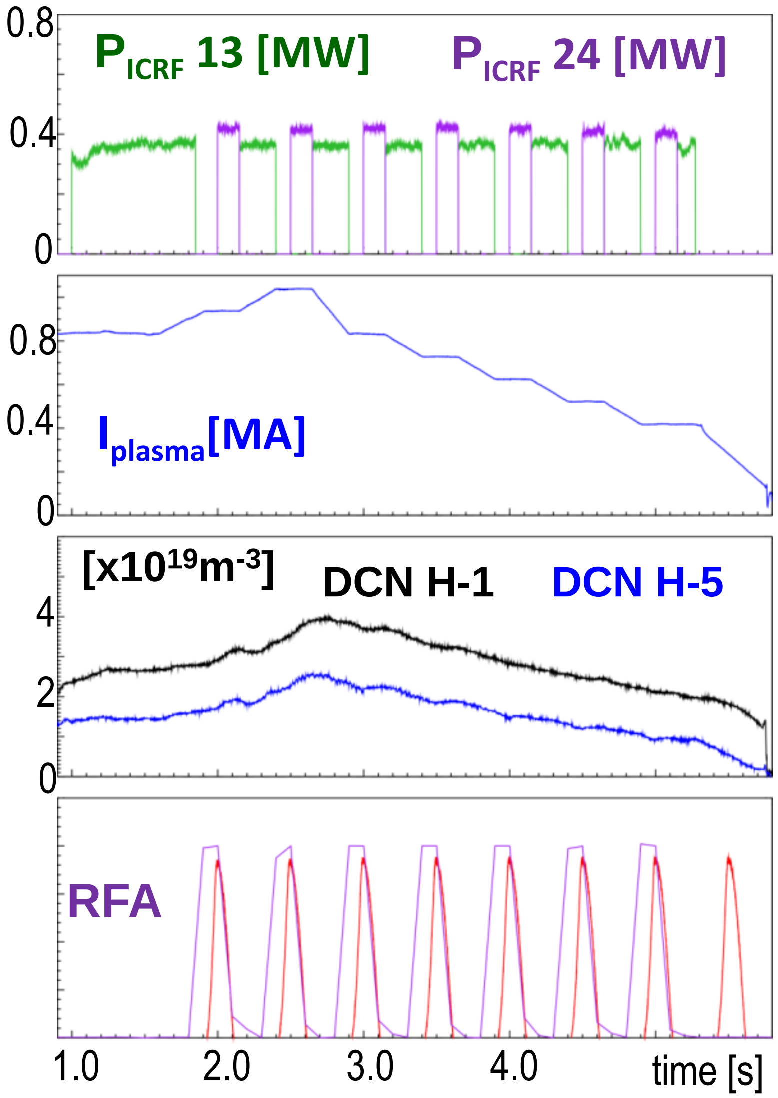
Specific goals:

- RF codes validation against RFA measurements
- SSWICH benchmark with Petra-M
- Deduce W outfluxes

Experiment overview

ASDEX Upgrade top cross-sectional view

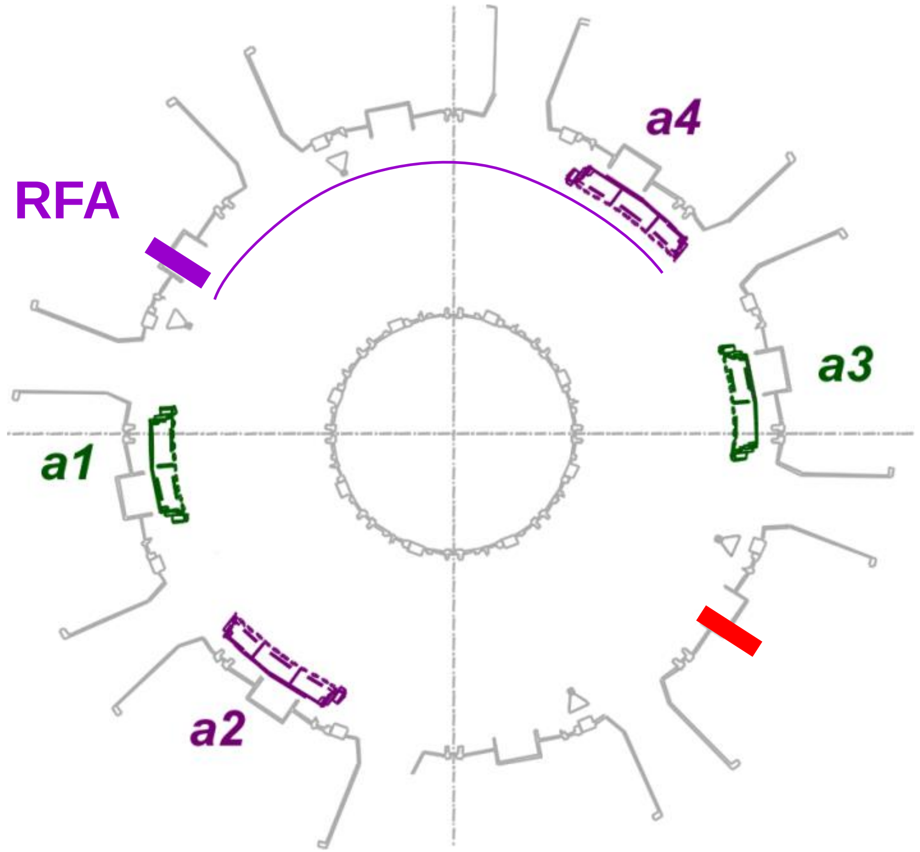




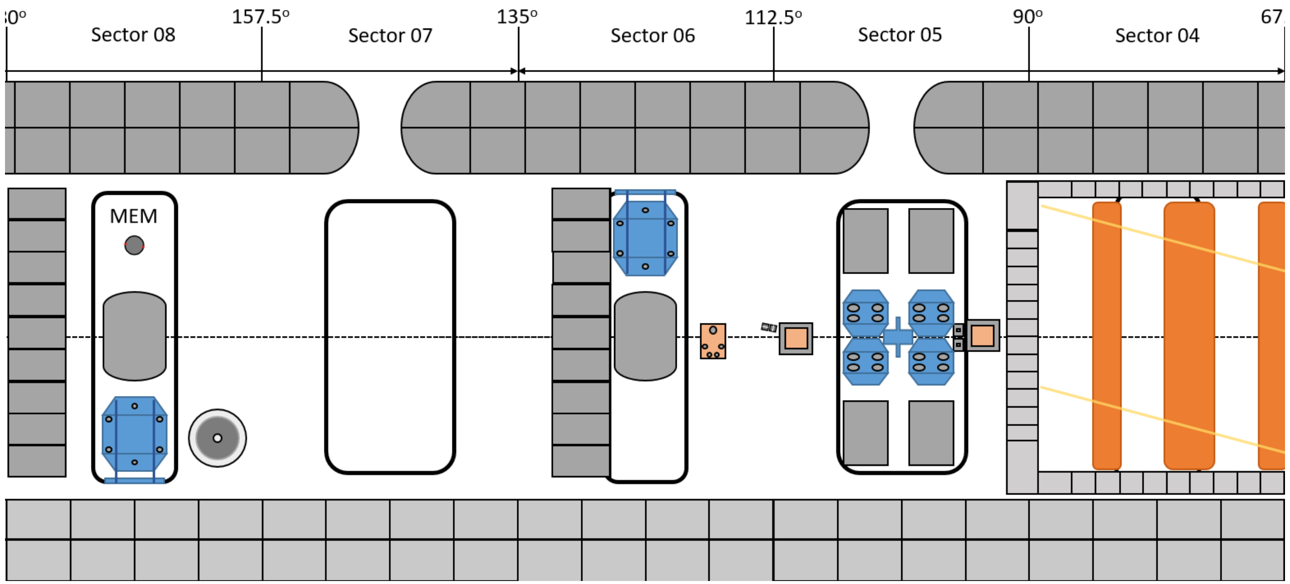
- Mean parallel ion energy $\langle W_{\parallel,i} \rangle$ on field lines connected to active antennas – quantity close to $V_{DC\ sheath}$

Ion energy measurements via RFA technique

ASDEX Upgrade top cross sectional view



ASDEX Upgrade outer wall view



- Mean parallel ion energy $\langle W_{\parallel,i} \rangle$ on field lines connected to active antennas – quantity close to $V_{DC\ sheath}$

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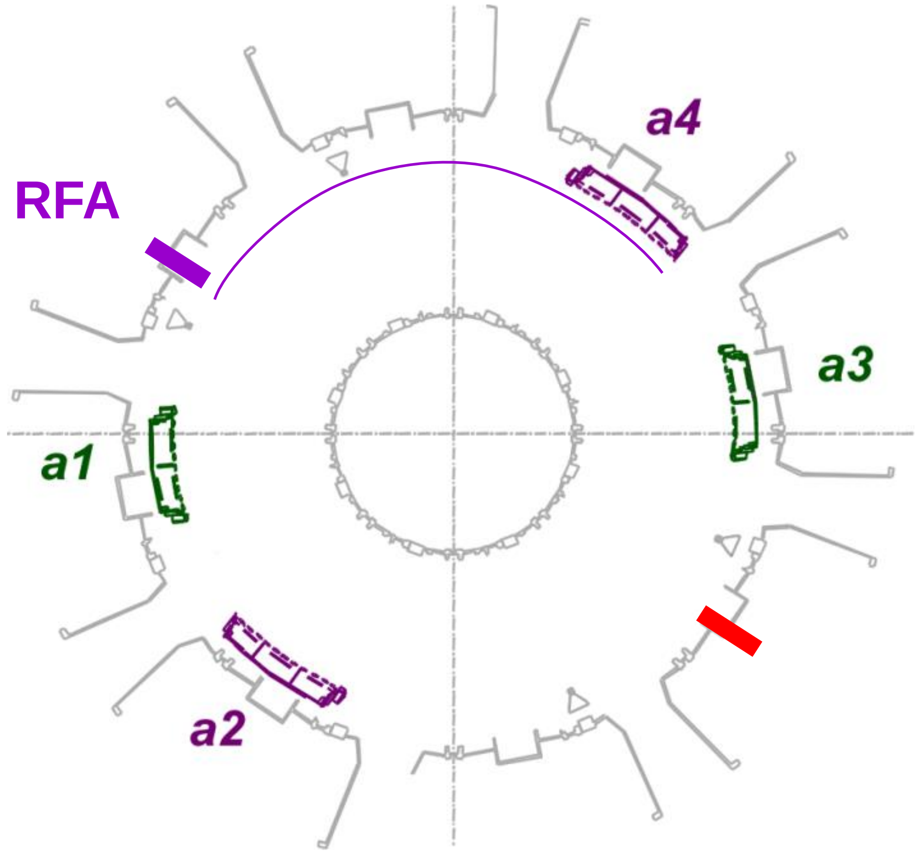
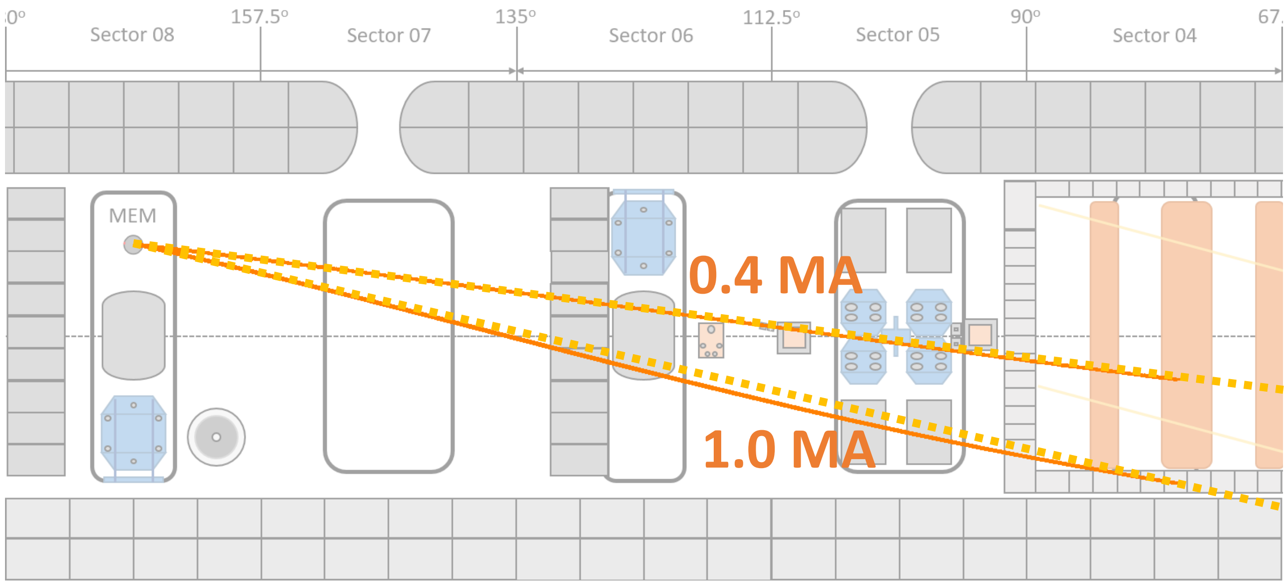


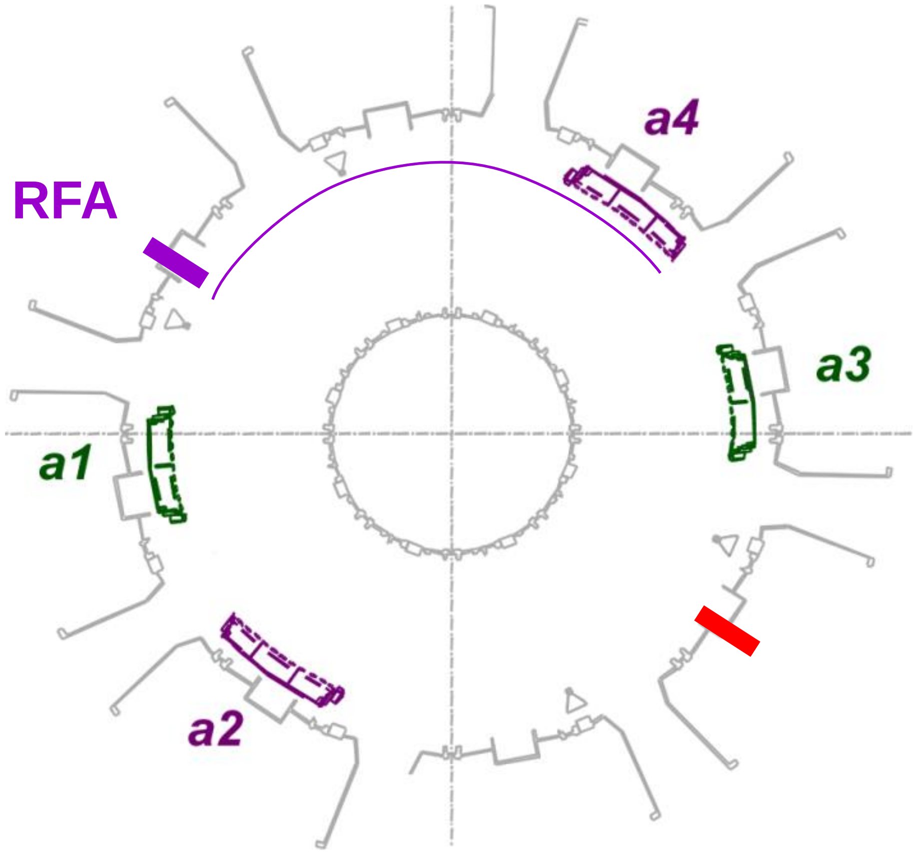
ASDEX Upgrade outer wall view



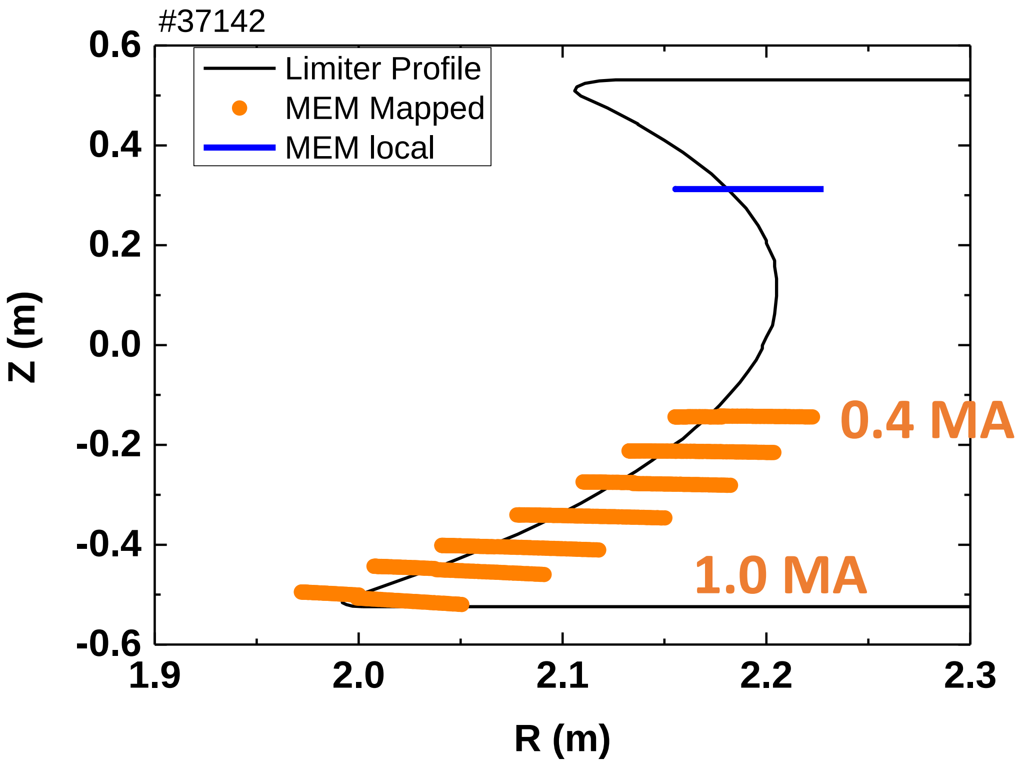
- Mean parallel ion energy $\langle W_{||,i} \rangle$ on field lines connected to active antennas – quantity close to $V_{DC\ sheath}$

Ion energy measurements via RFA technique

ASDEX Upgrade top cross sectional view



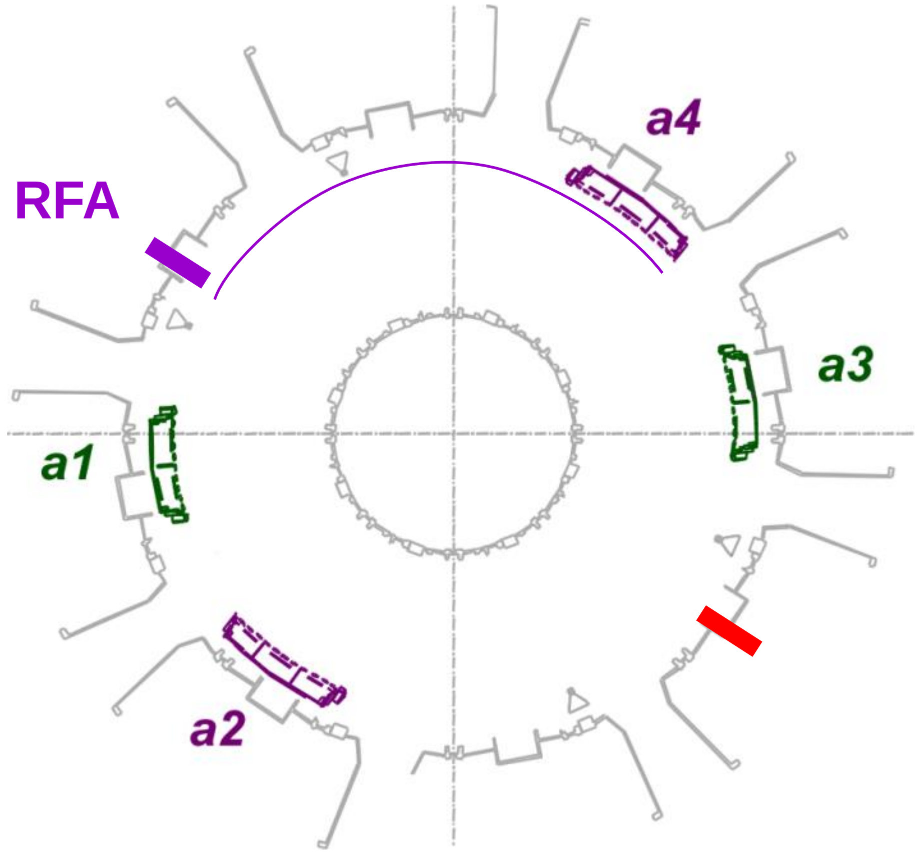
ASDEX Upgrade poloidal view



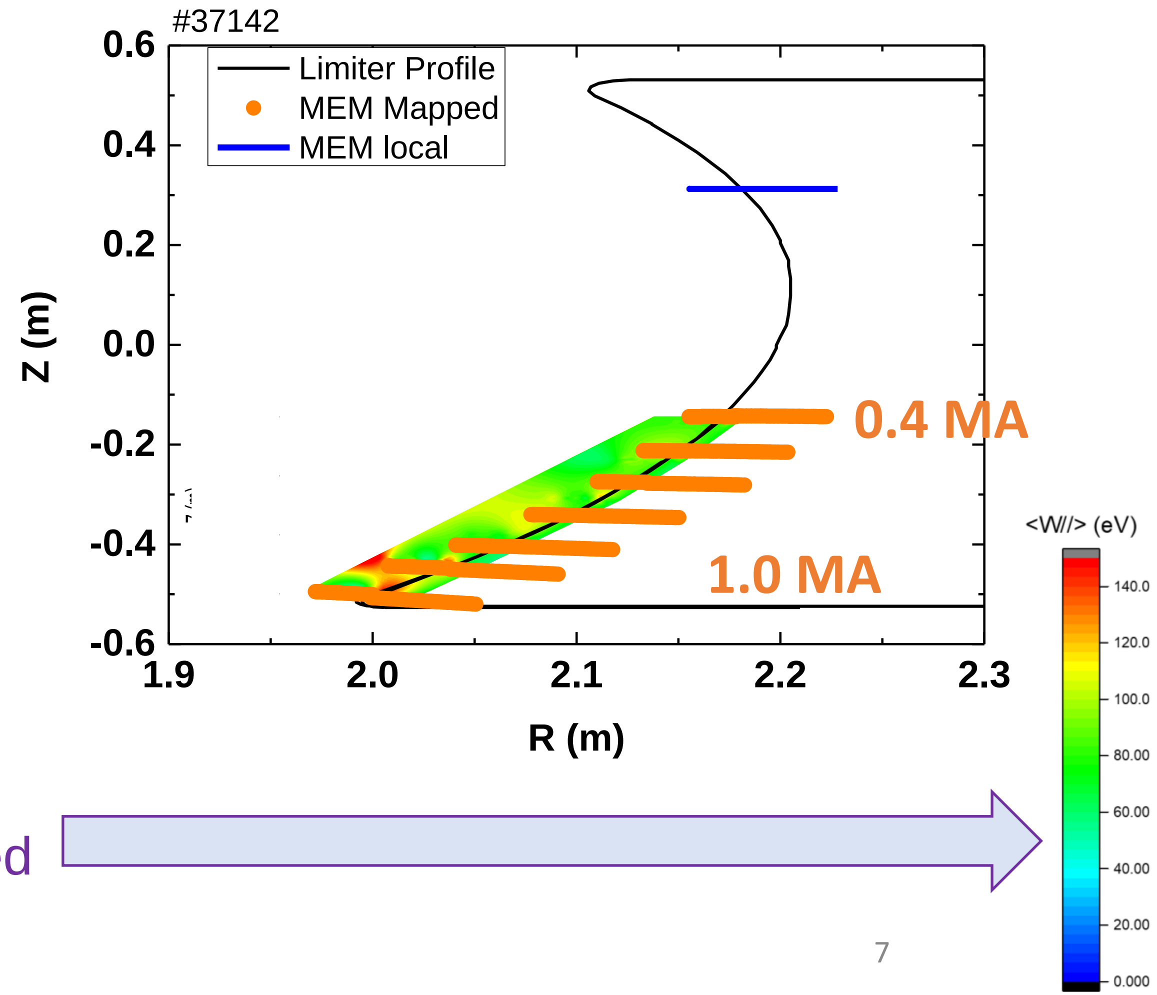
- Mean parallel ion energy $\langle W_{ll,i} \rangle$ on field lines connected to active antennas – quantity close to $V_{DC\ sheath}$

Ion energy measurements via RFA technique

ASDEX Upgrade top cross sectional view



ASDEX Upgrade poloidal view



- Mean parallel ion energy $\langle W_{\parallel,i} \rangle$ on field lines connected to active antennas – quantity close to $V_{DC\ sheath}$

3 discharges selected
same total power & different antenna excitation

a) 180^0 (dipole) phasing and $P_{cent}/P_{out} = 3/2$ (#37147)

b) 180^0 (dipole) phasing and $P_{cent}/P_{out} = 1/8$ (#37150)

c) -90^0 phasing and $P_{cent}/P_{out} = 3/2$ (#37160)

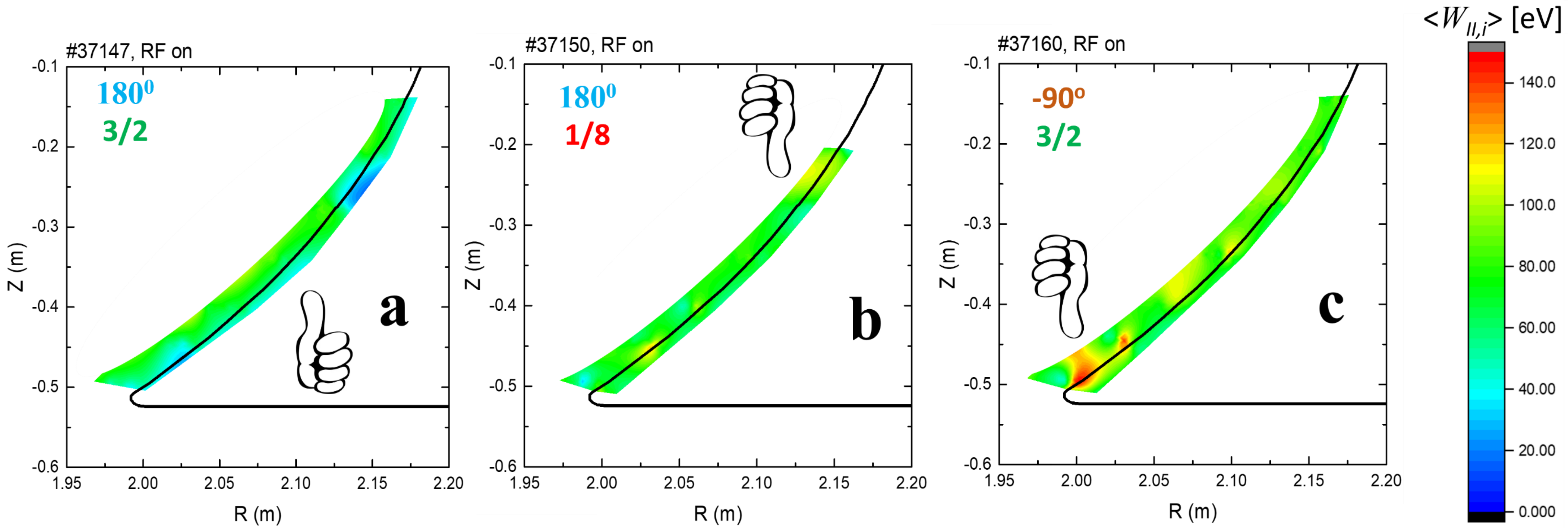
------------ **KEY QUESTION** ------------

▶ **How much more tungsten locally eroded when powering an ICRF antenna ?**

Increase factor

$$\Lambda = \Gamma_{Wtot}^{ICRH \to ON} / \Gamma_{Wtot}^{ICRH \to OFF}$$

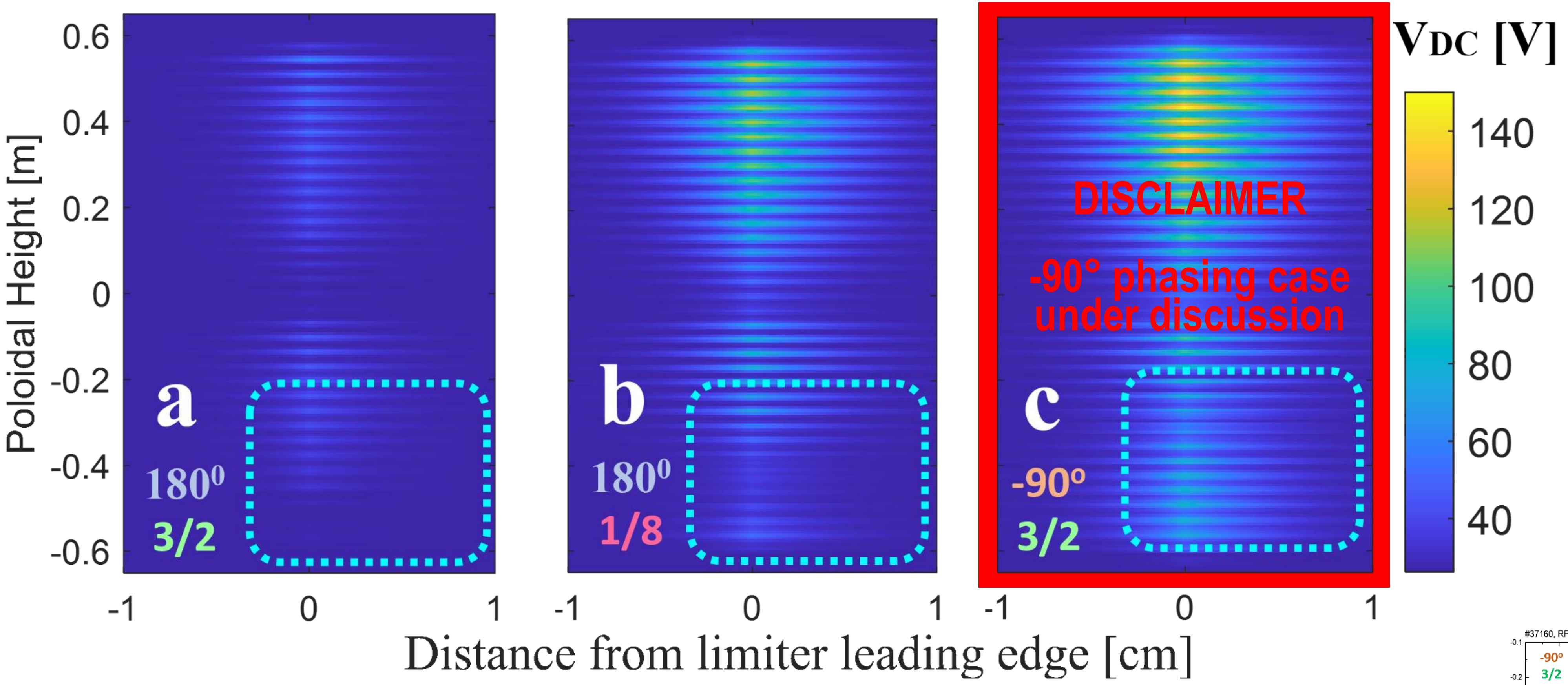
RFA → Mean parallel ion energy $\langle W_{\parallel,i} \rangle$

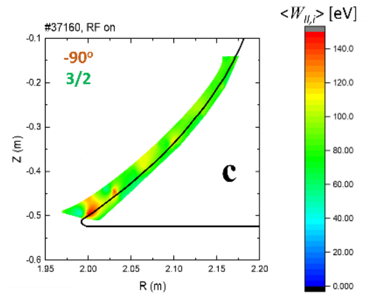


- Ions energy on average smallest for the optimal excitation (a) & worst for the -90º phasing (c) with peaks at the corners
- **SSWICH** & **Petra-M** simulations in good quantitative and qualitative agreement with **RFA** measurements ($\langle W_{\parallel,i} \rangle \sim V_{DC}$)

R. Ochoukov, RSI. 91, 063506 (2020)

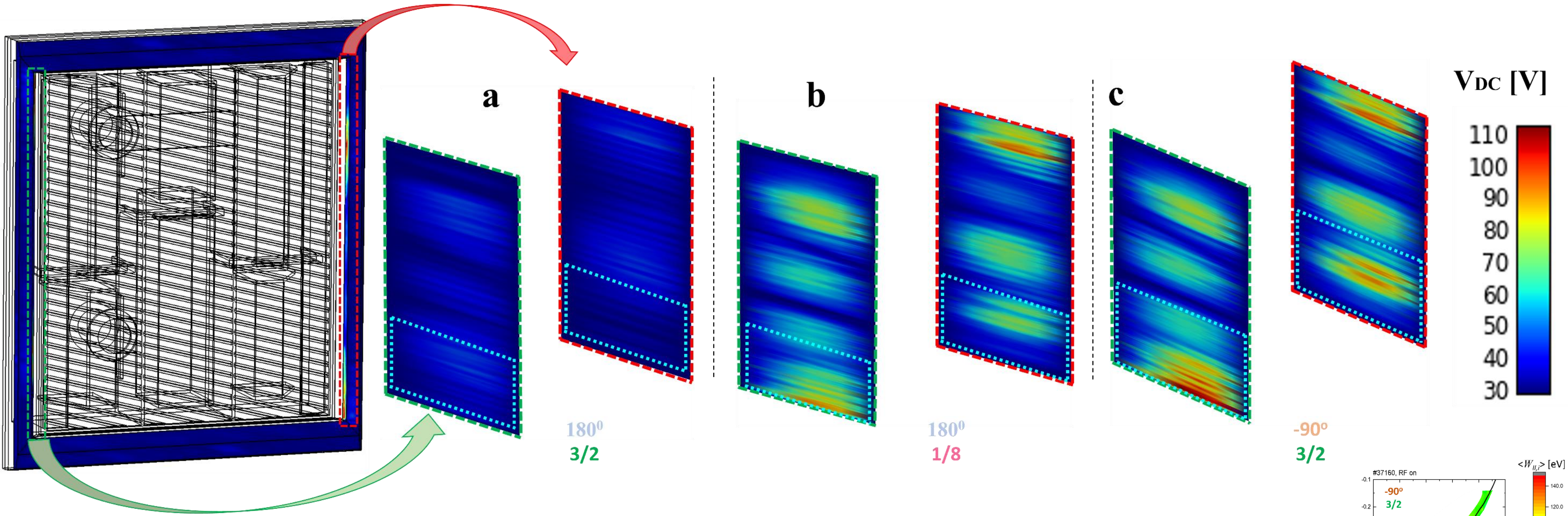
SSWICH → Rectified potentials along limiters

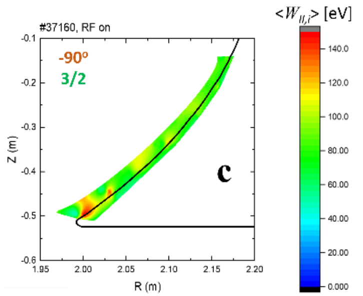




- **SSWICH** simulations in good quantitative and qualitative agreement with **RFA** measurements ($\langle W_{II,i} \rangle \sim V_{DC}$) for dipole phasing (-90° phasing still under discussion)

Petra-M → Rectified potentials along limiters



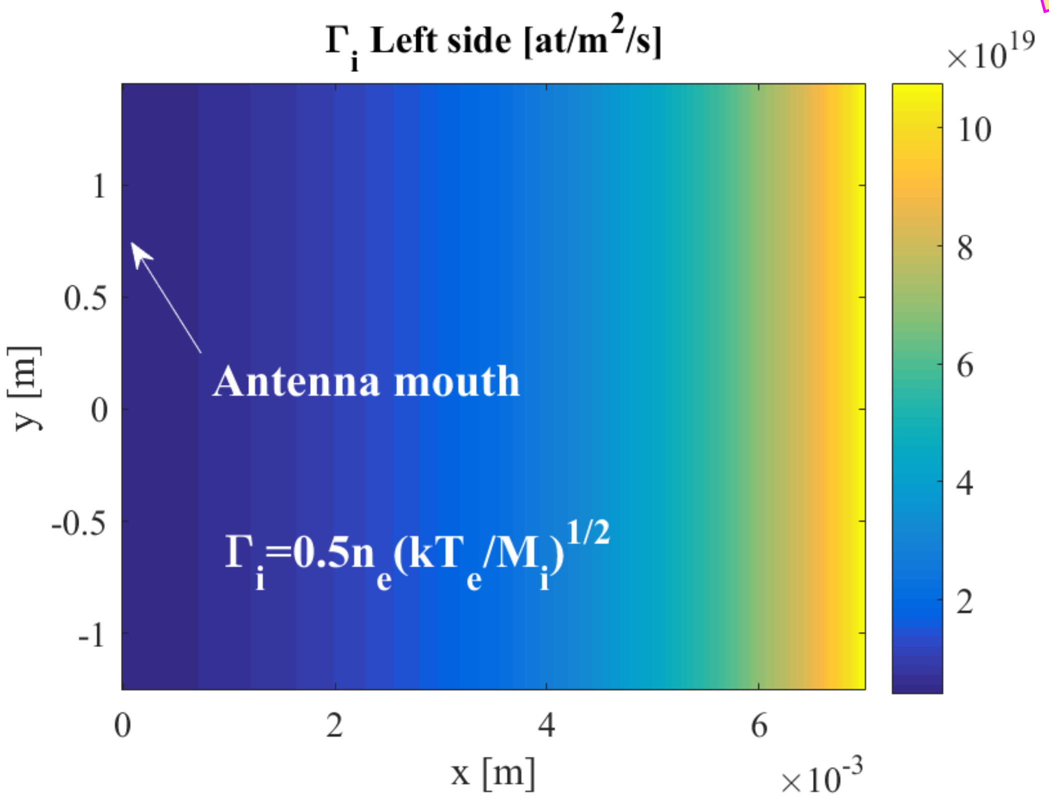


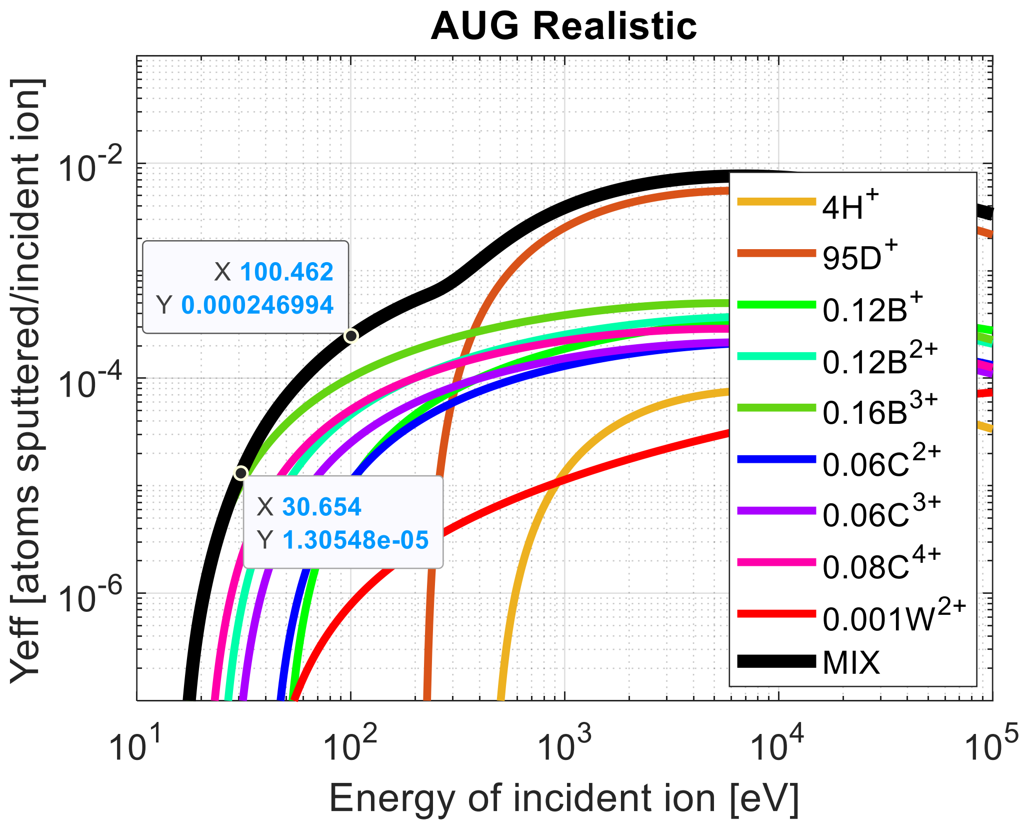
- **Petra-M** simulations in good quantitative and qualitative agreement with **RFA** measurements ($\langle W_{II,i} \rangle \sim V_{DC}$) (-90° case a bit smaller than RFA)

N. Bertelli, 2022 Nucl. Fusion 62 126046
S. Shiraiwa, 2023 Nucl. Fusion 63 026024

From potential rectification to W erosion

$$\Gamma_{\text{W atoms out}} = \Gamma_{\text{ion in}} * Y_{\text{Eff}}(E_{in})$$

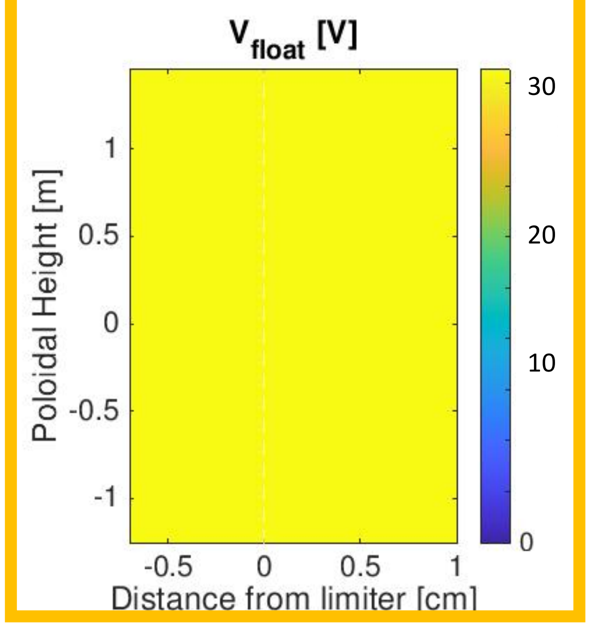


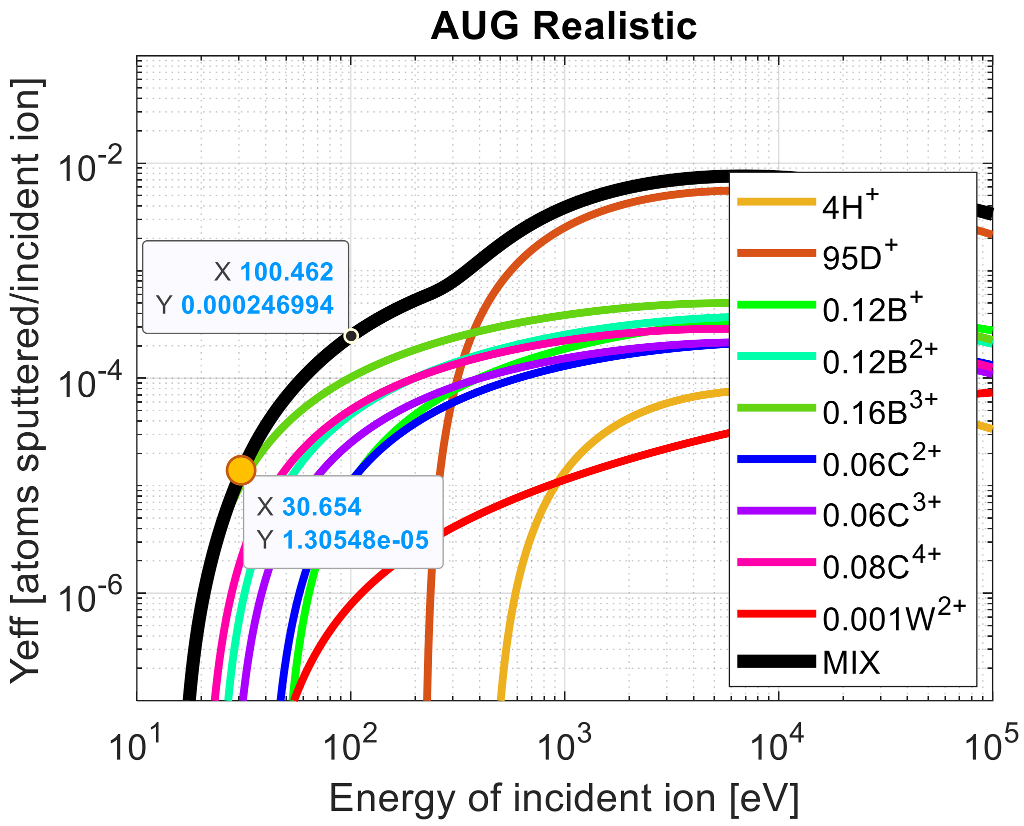


From potential rectification to W erosion

$$\Gamma_{\text{W atoms out}} = \Gamma_{\text{ion in}} * Y_{\text{Eff}}(E_{in})$$

No ICRF





From potential rectification to W erosion

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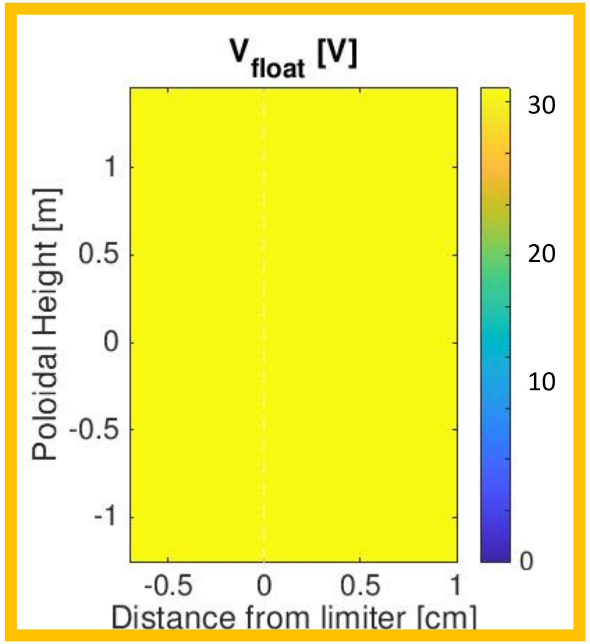
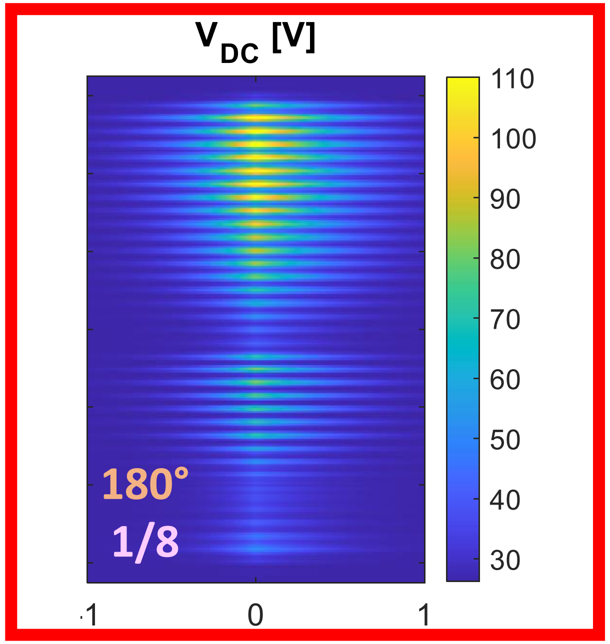
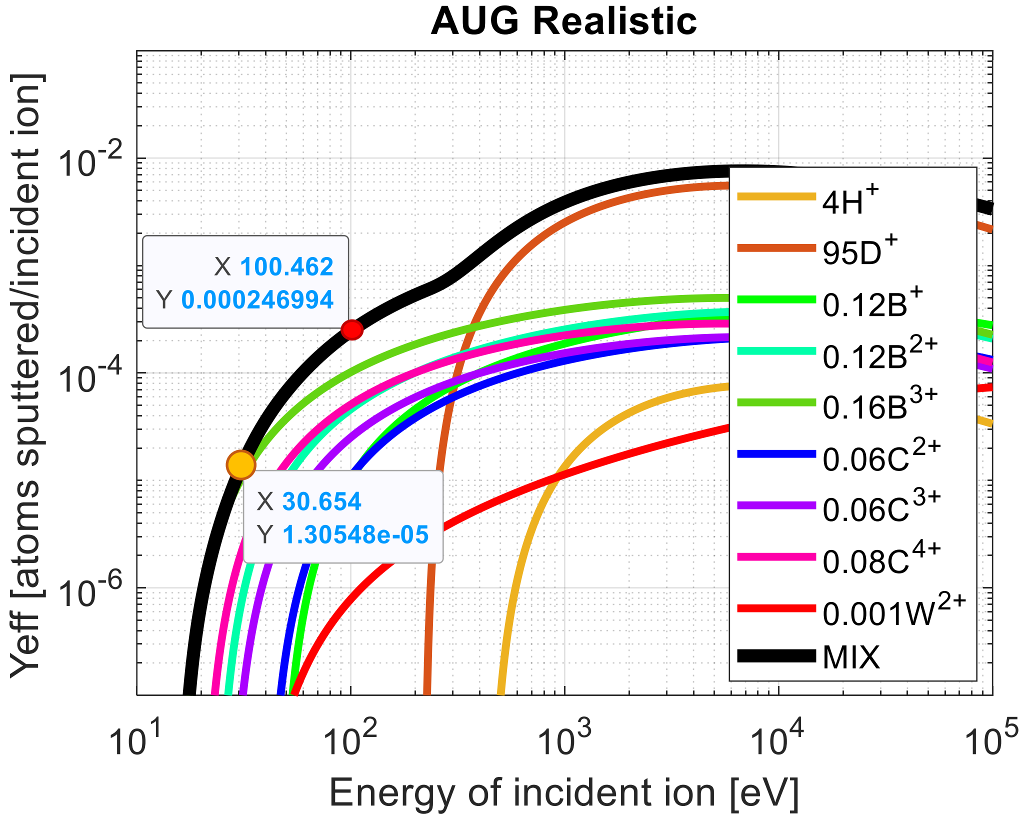
No ICRF

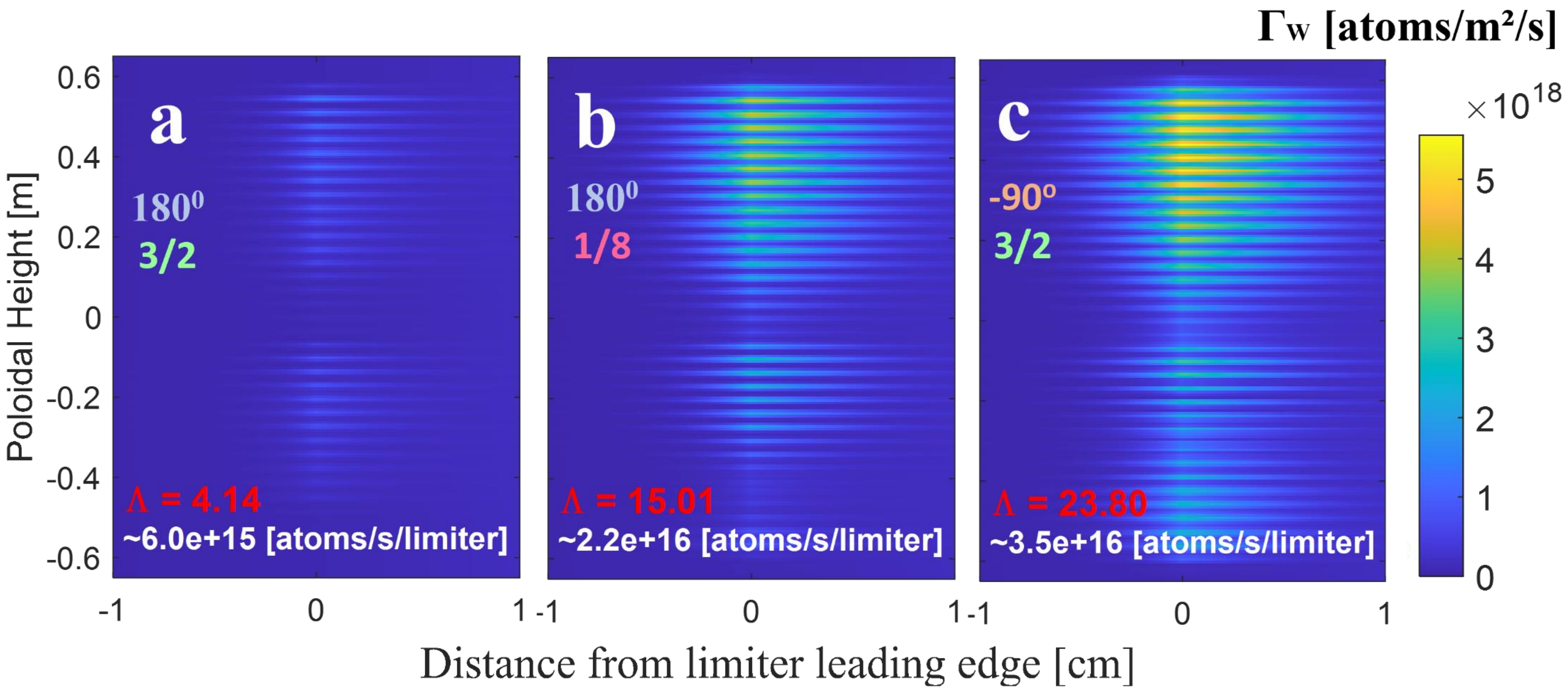


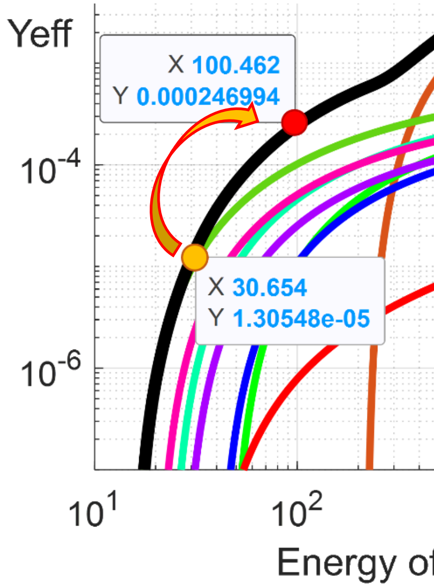
ICRF ON





W source on a limiter when powering ICRF on AUG plasma



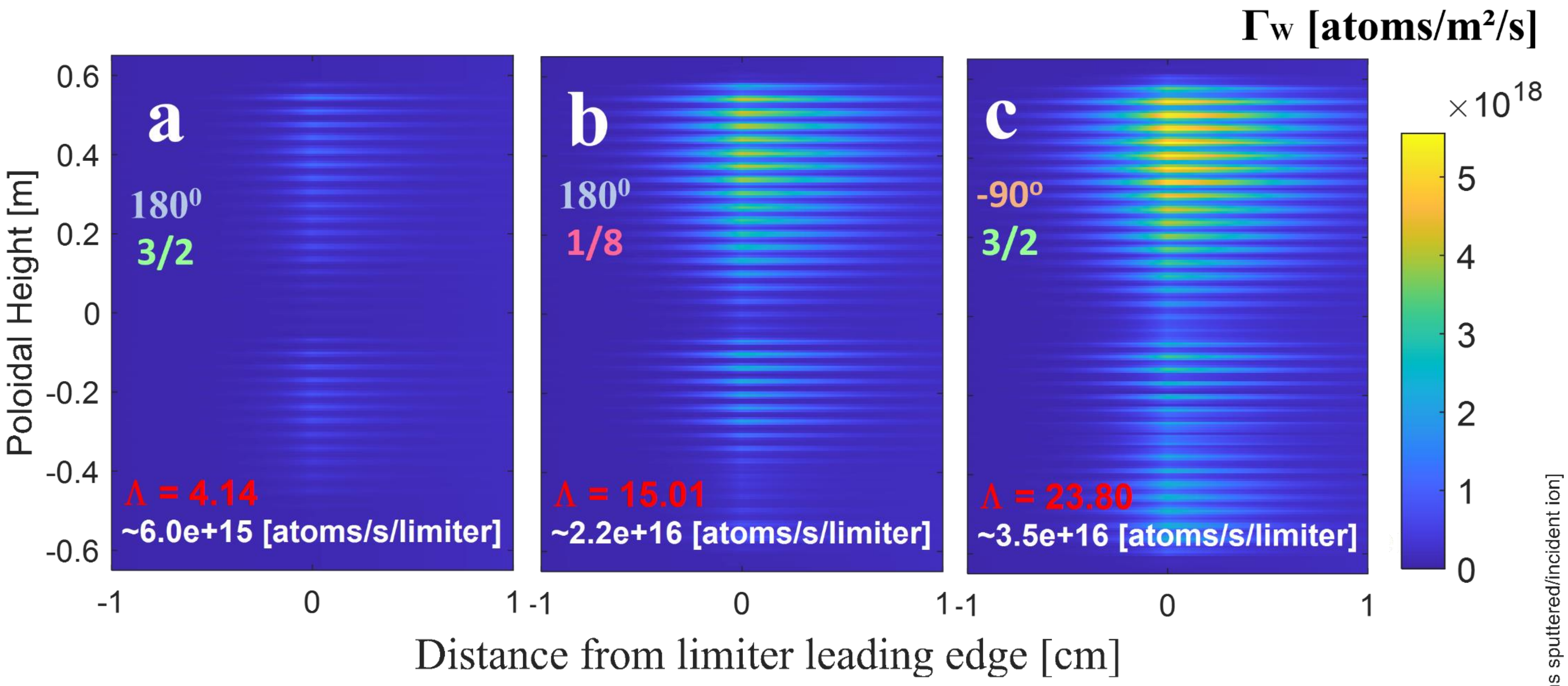


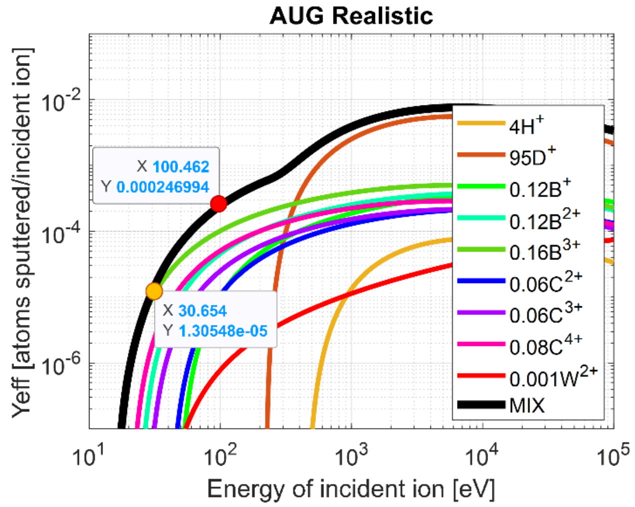
Increase factor

$$\Lambda = \Gamma_{Wtot}^{ICRH \to ON} / \Gamma_{Wtot}^{ICRH \to OFF}$$

with $\Gamma_{Wtot} = \iint_{Limiter} \Gamma_W$

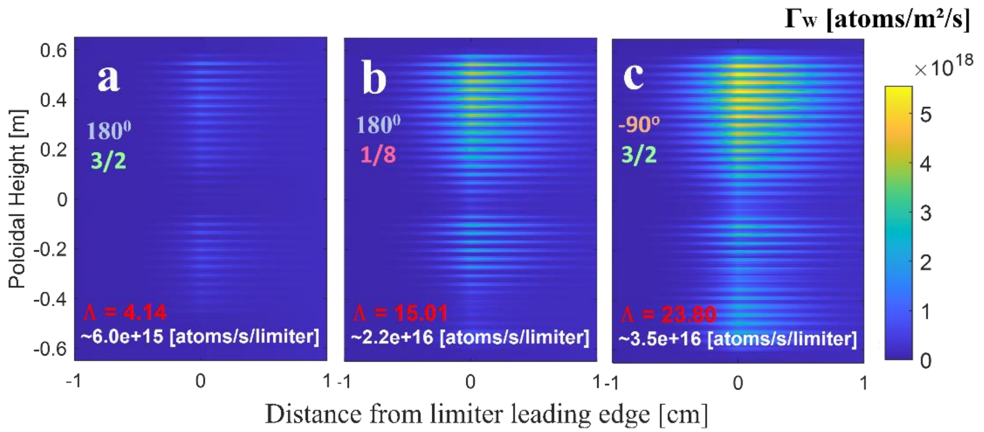
W source on a limiter when powering ICRF on AUG plasma



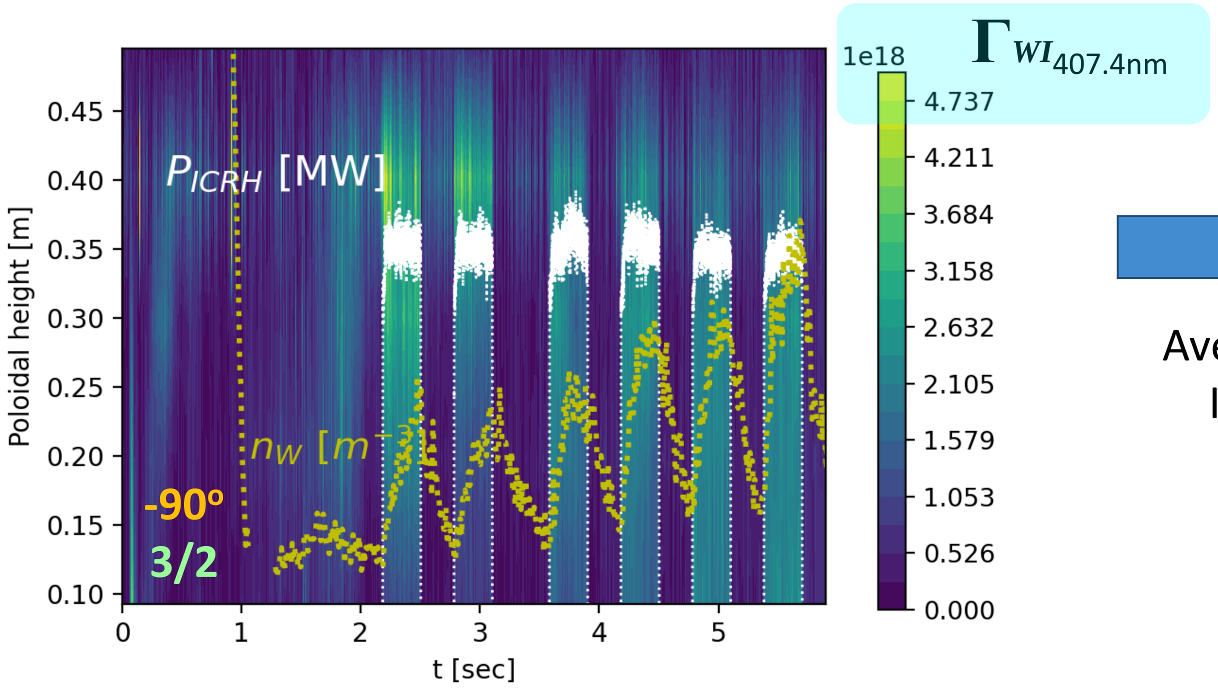


- W sources from RF codes vary
- coherently with antenna excitation
- in agreement with visible spectro measurements

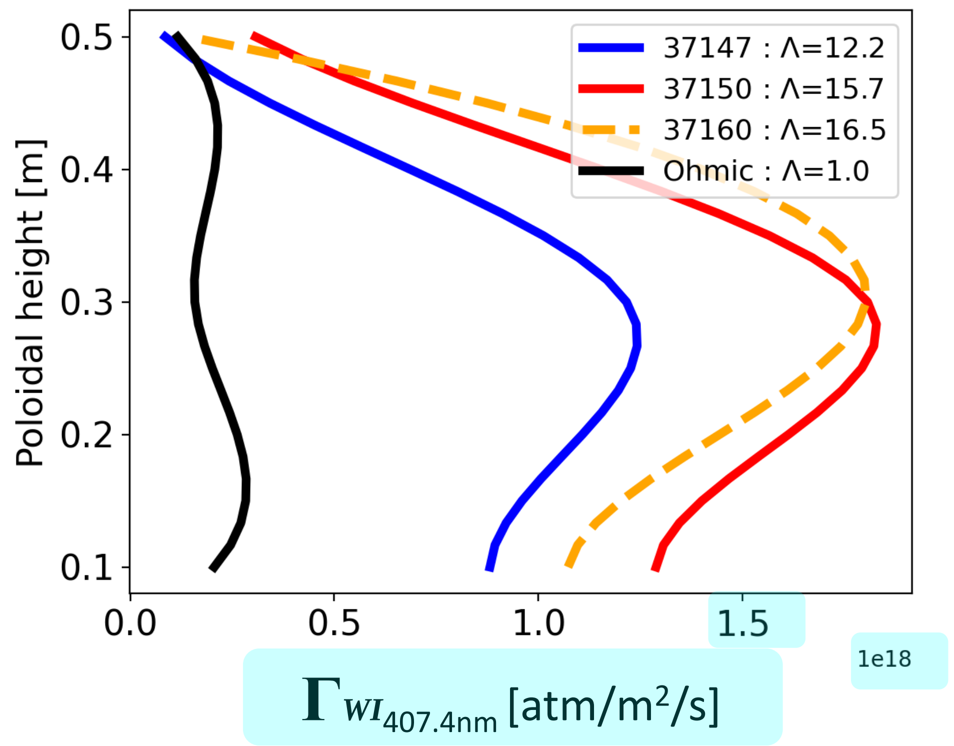
W outfluxes from AUG visible spectroscopy



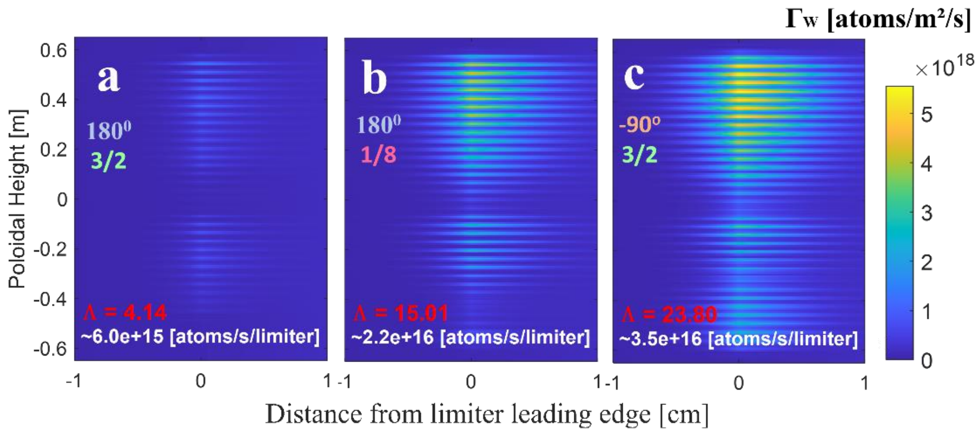
$$\Lambda = \Gamma_{Wtot}^{ICRH \rightarrow ON} / \Gamma_{Wtot}^{ICRH \rightarrow OFF}$$



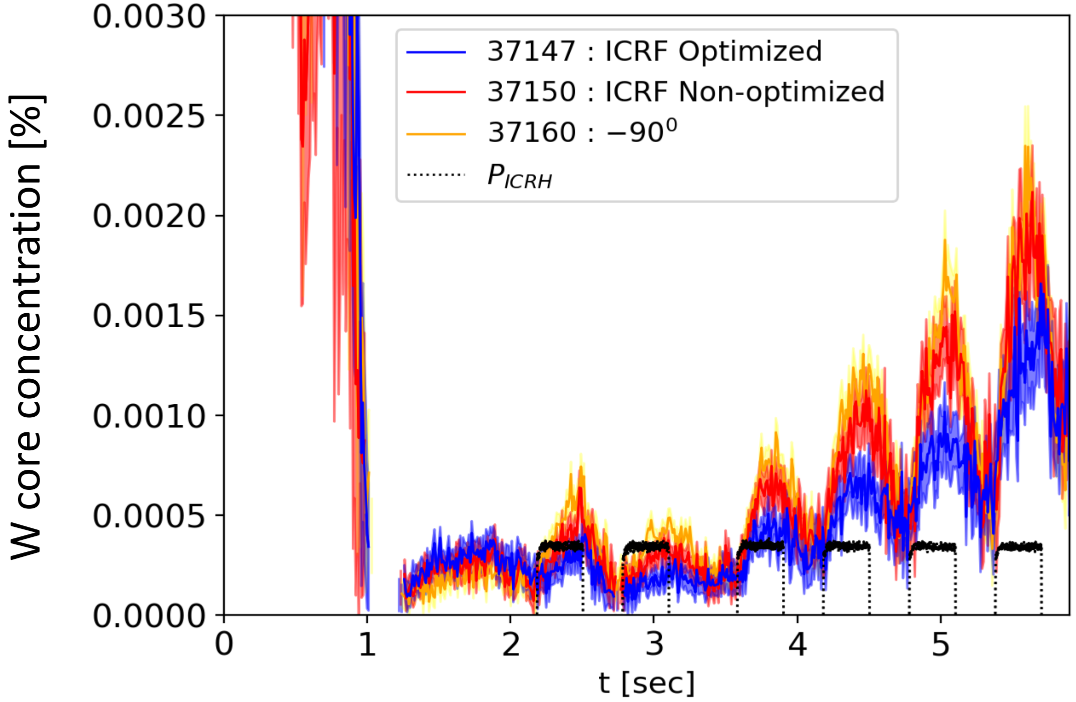
Average during ICRF pulse



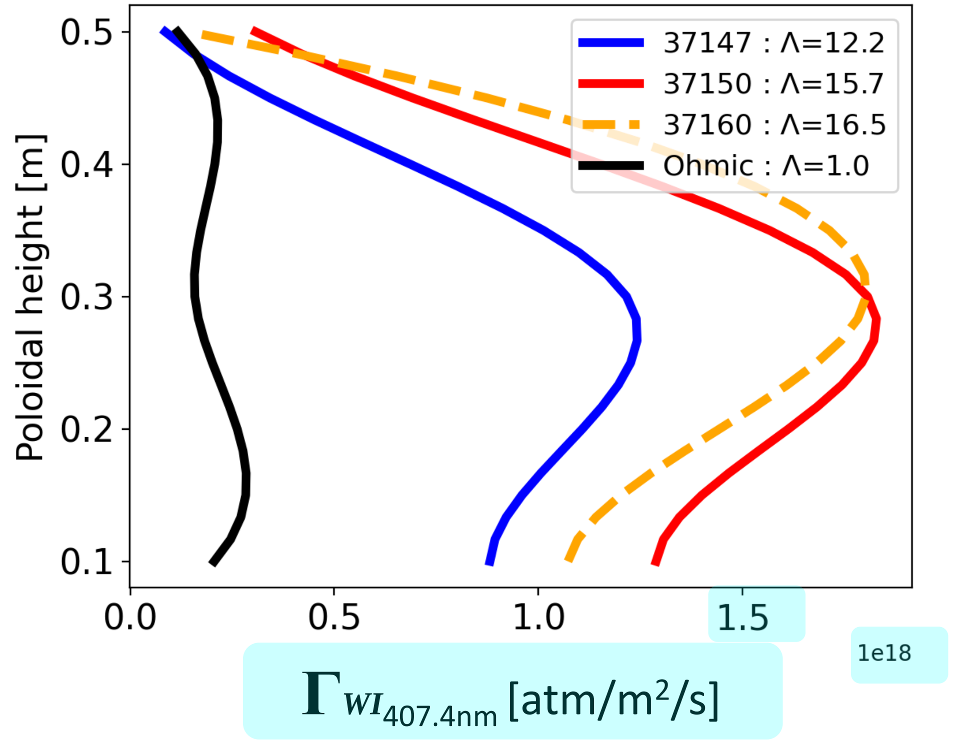
Visible & SXR Spectro → $\Gamma_{WI_{407.4nm}}$ & C_W in AUG core



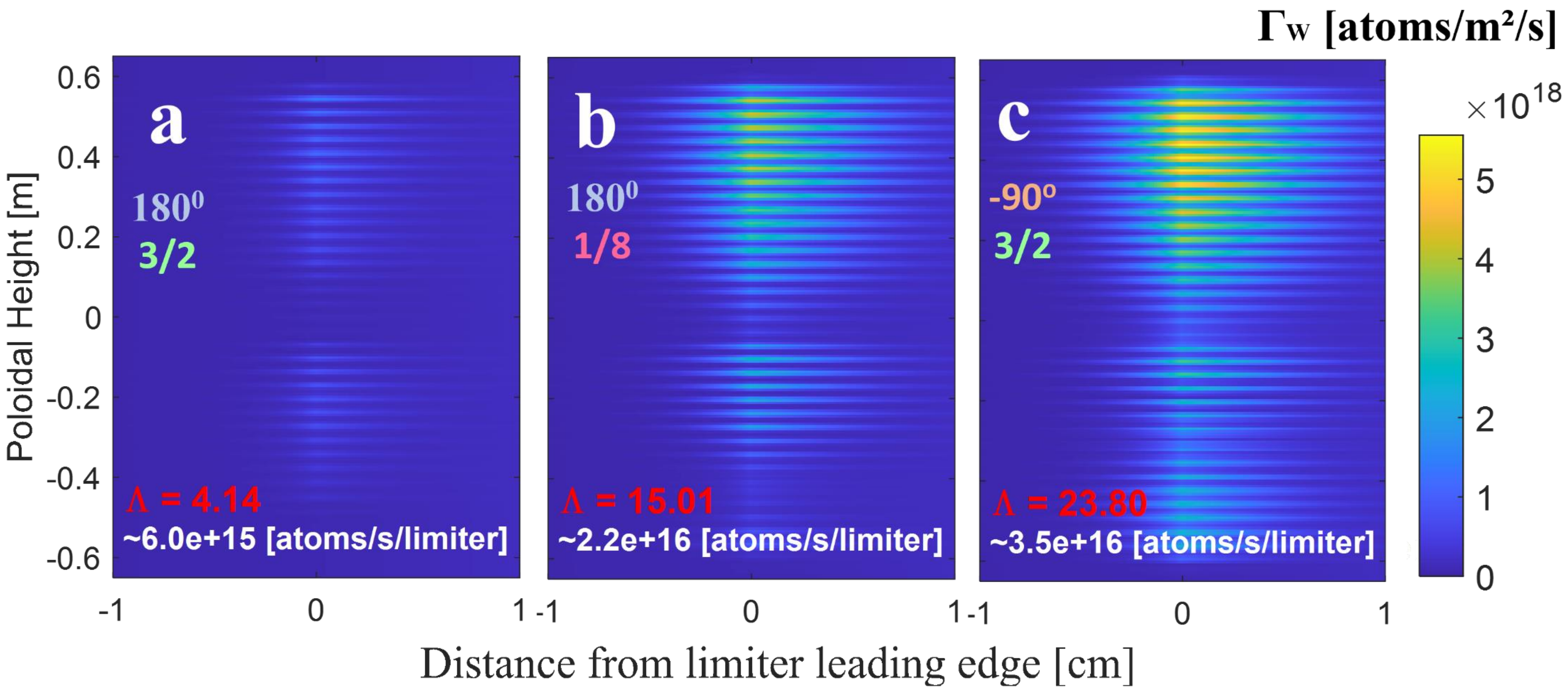
$$\Lambda = \Gamma_{Wtot}^{ICRH \rightarrow ON} / \Gamma_{Wtot}^{ICRH \rightarrow OFF}$$

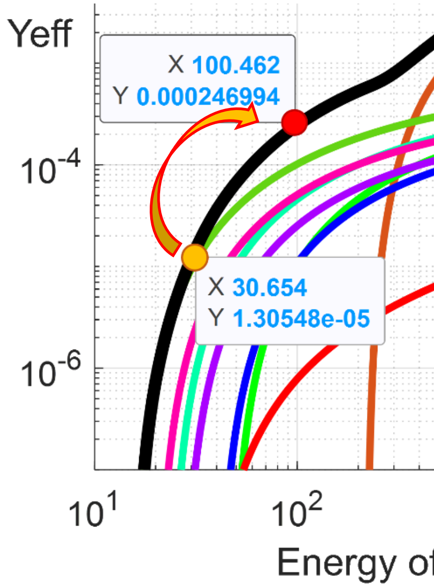


Transport to the core



W source on a limiter when powering ICRF on AUG plasma



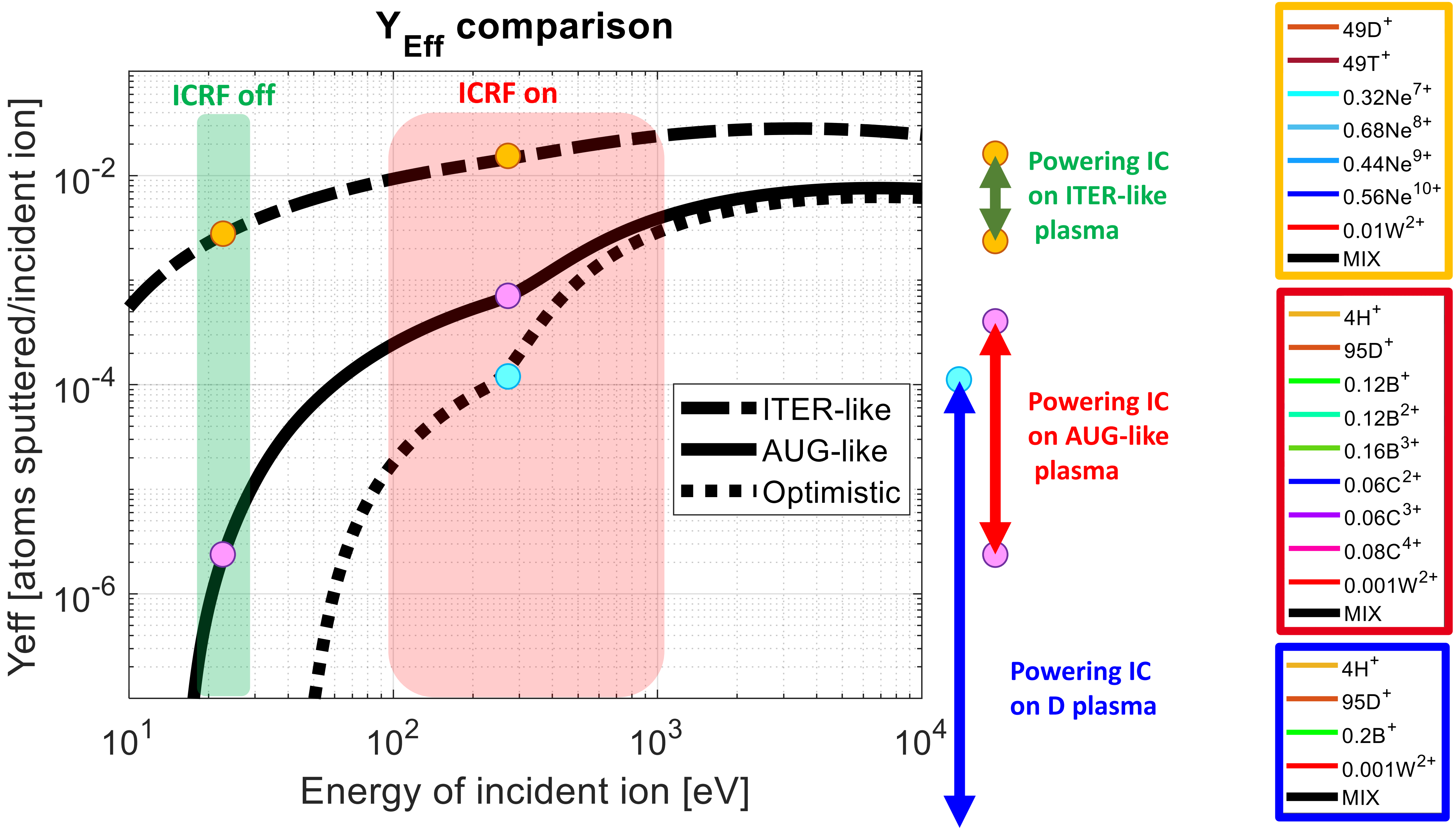


Increase factor

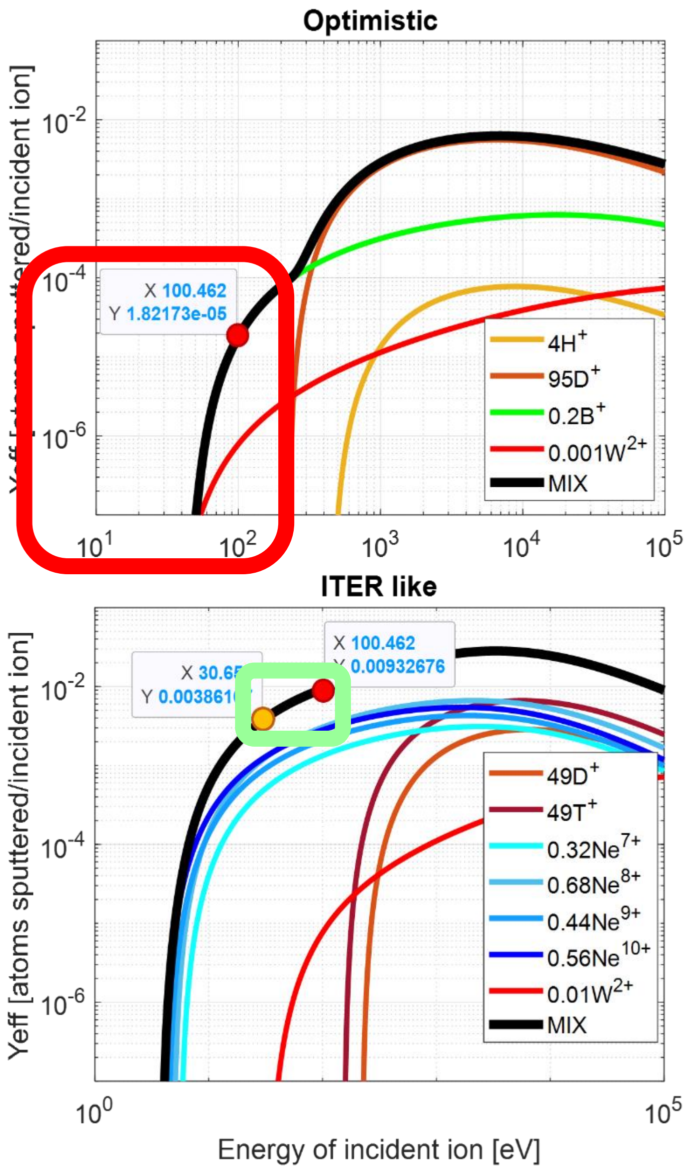
$$\Lambda = \Gamma_{Wtot}^{ICRH\rightarrow ON} / \Gamma_{Wtot}^{ICRH\rightarrow OFF}$$

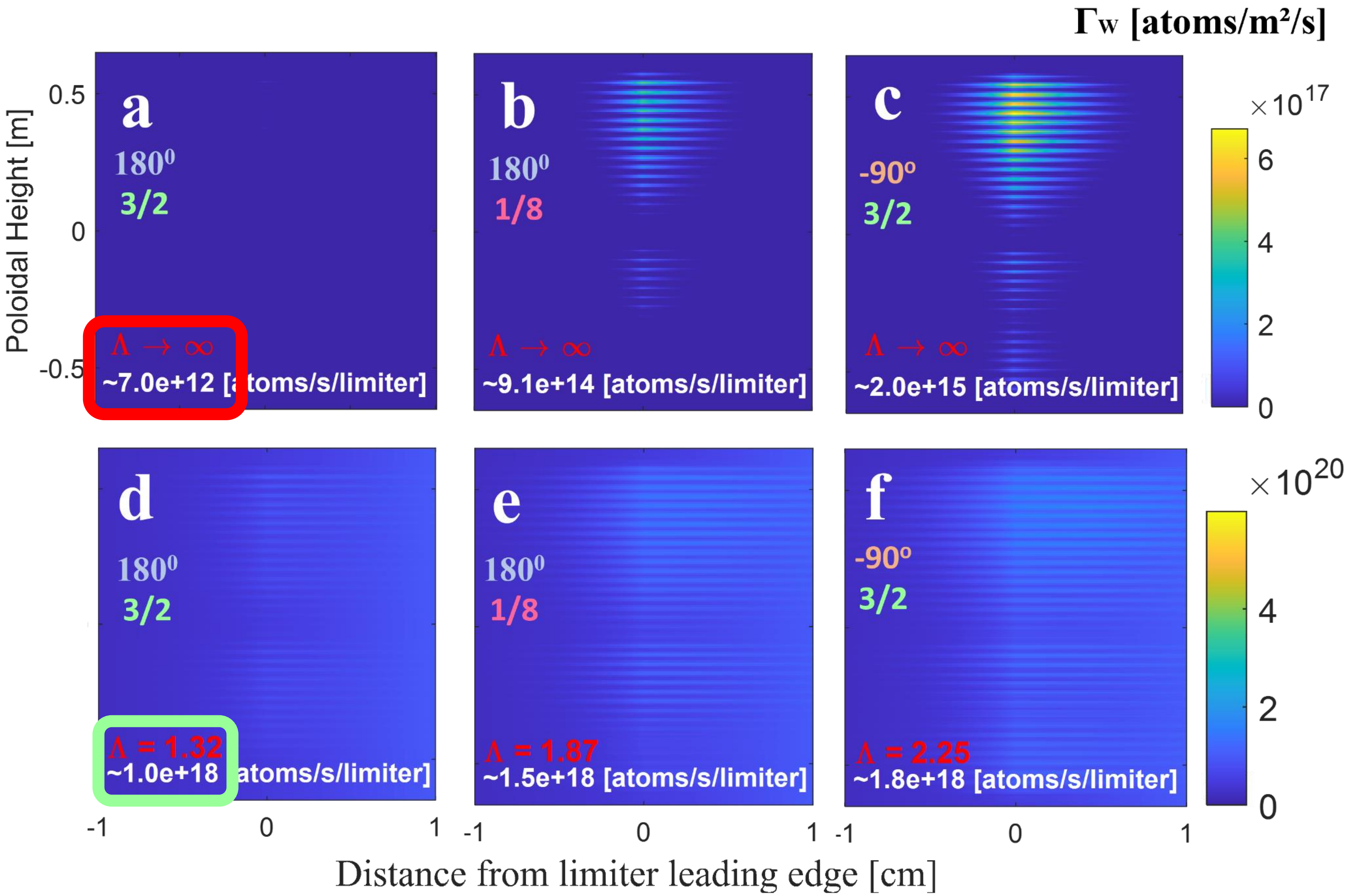
with $\Gamma_{Wtot} = \iint_{Limiter} \Gamma_W$

ICRF induced W source for different plasma mixtures

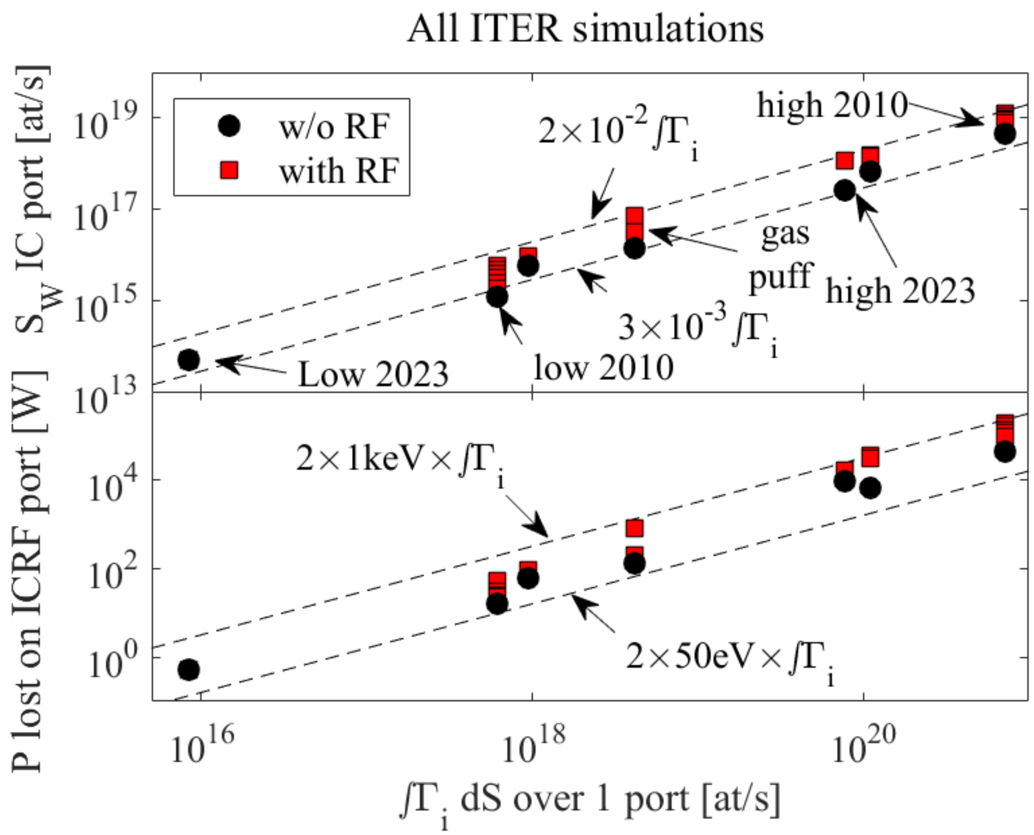


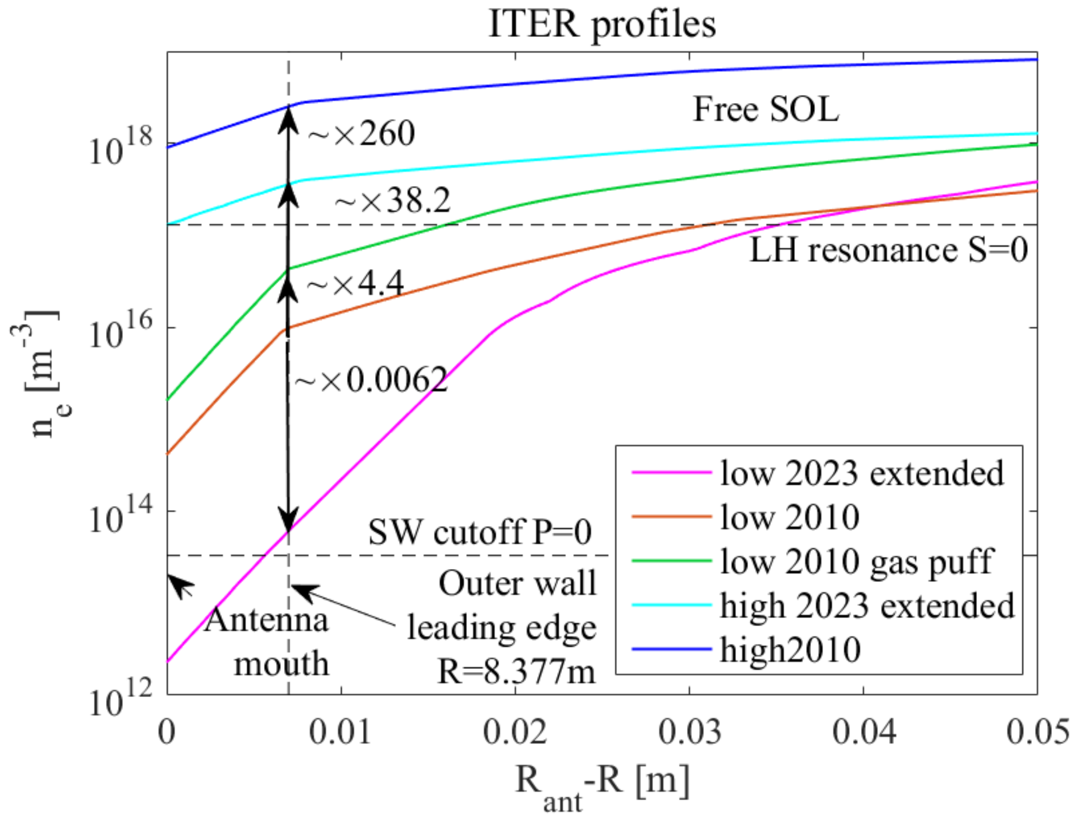
ICRF induced W source for optimistic and ITER plasma mixtures





ICRF induced W source for different ne profiles from ITER





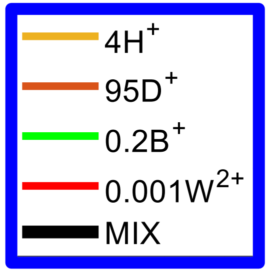
- L. Colas et al. NME 2024 – PSI Proceeding « Numerical assessment of ICRF-specific Plasma-Wall Interaction in the new ITER baseline using the SSWICH-SW code »
- V. Bobkov et al. NME 2024 – PSI Proceeding «ICRF-specific W sources: advances in minimization in ASDEX Upgrade and near-field based extrapolations to ITER with W-wall »

Conclusions

------------ KEY QUESTION ------------

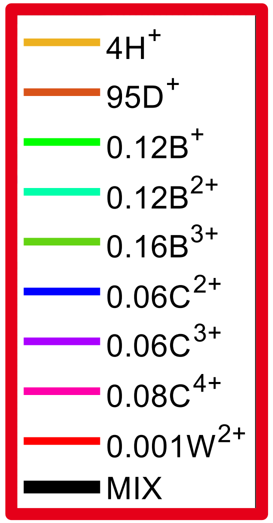
- **How much more tungsten locally eroded when powering an ICRF antenna ?**

“Over” optimistic

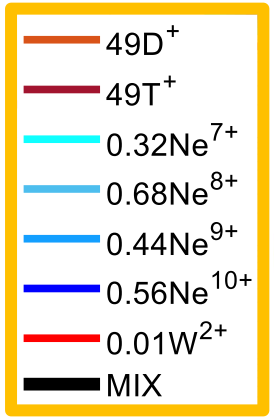


$\Lambda \rightarrow \infty$

AUG like



$\Lambda \rightarrow 15$



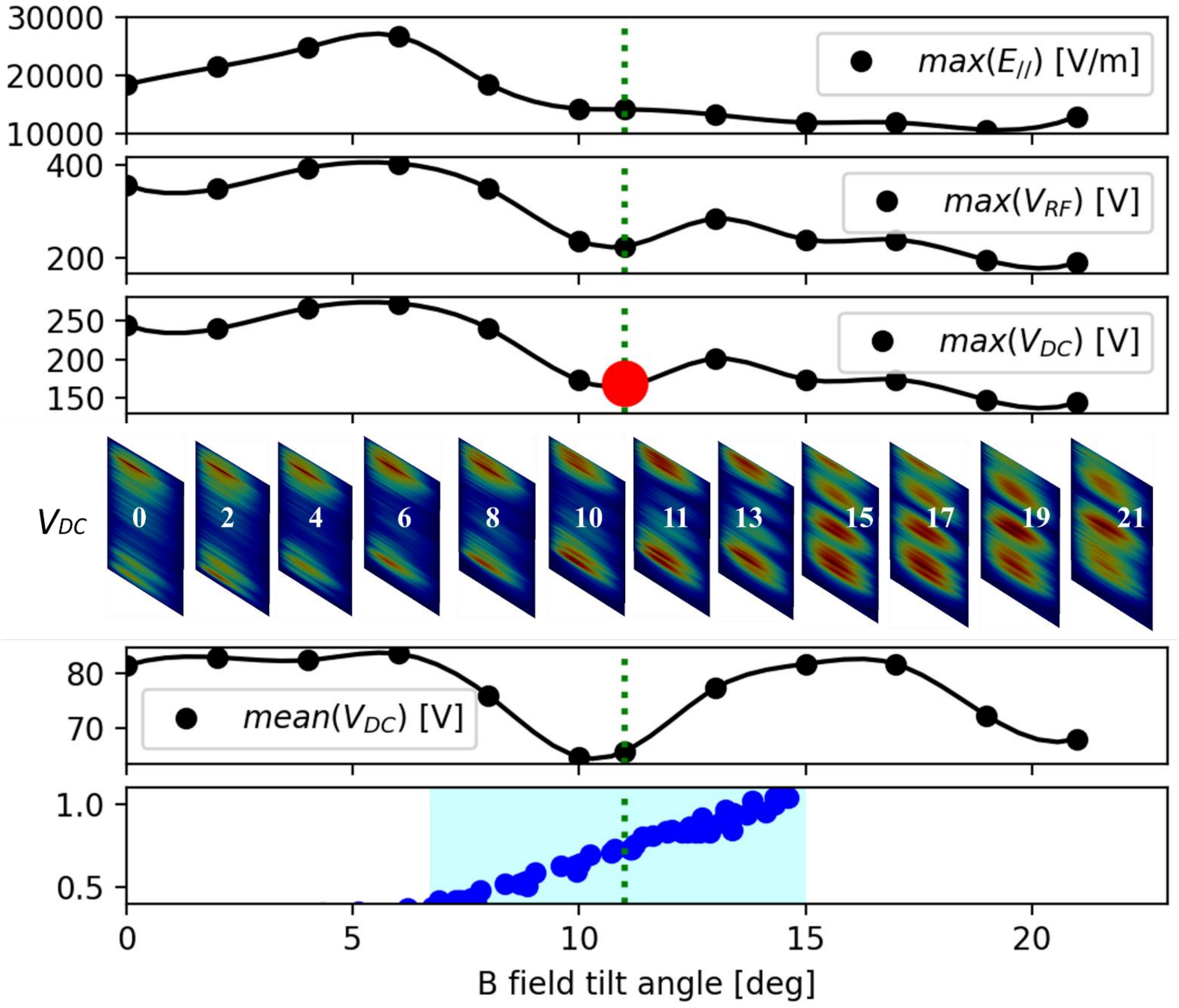
iter like

$\Lambda \rightarrow 2$

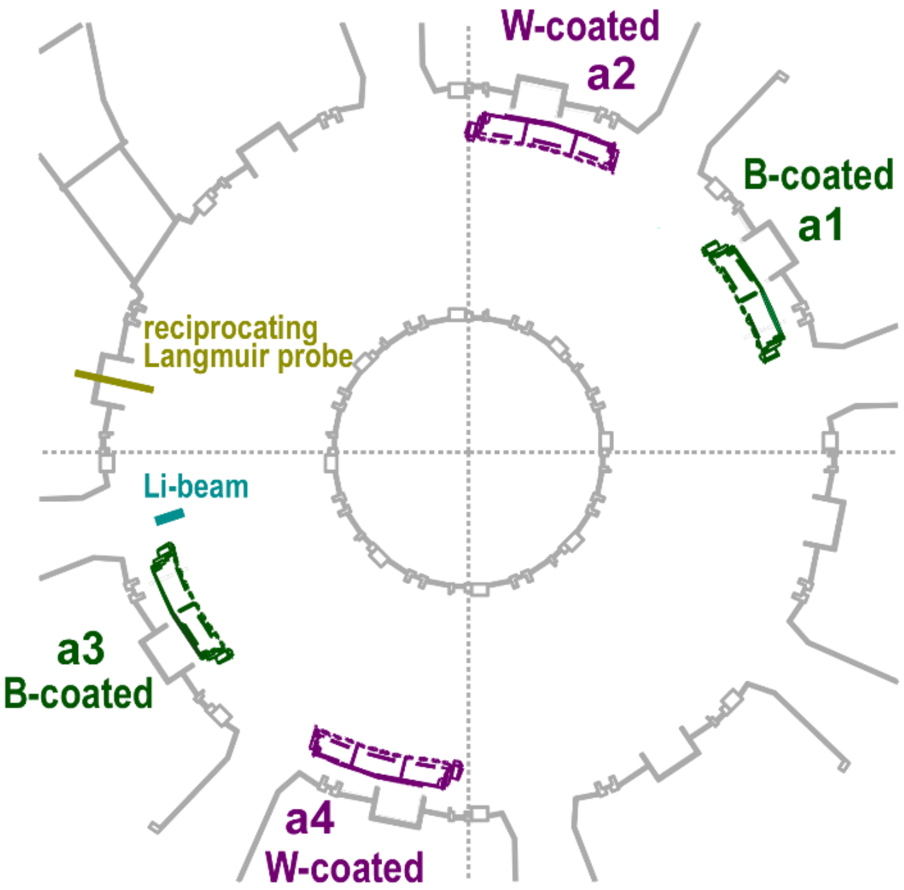
------------ OPEN QUESTIONS ------------

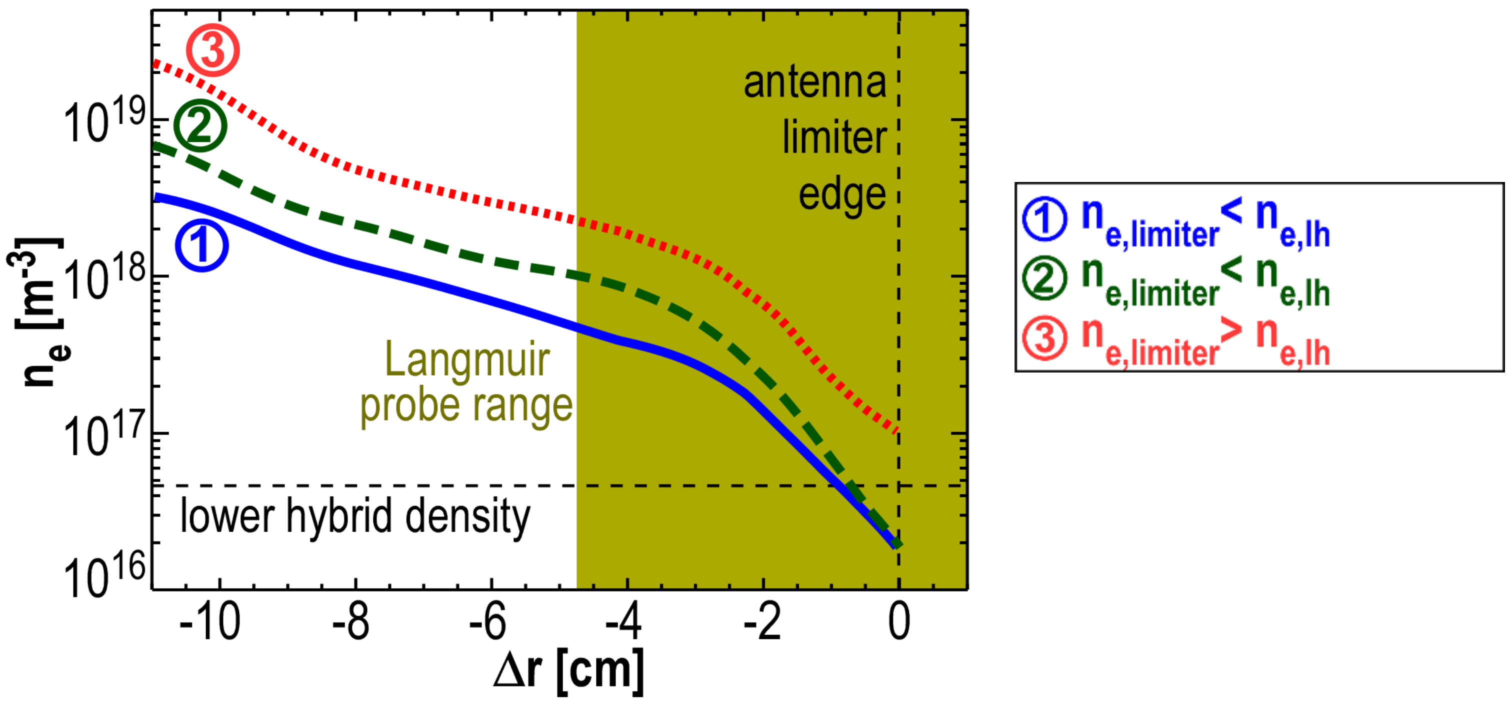
- Can ICRF trigger a W self sputtering avalanche in ITER ?
- When W is sputtered, where does it migrates & how much promptly redeposits ?
- Role of propagative slow wave on plasma surface interactions

Potential rectification dependance on B field tilt angle modeled with Petra-M code



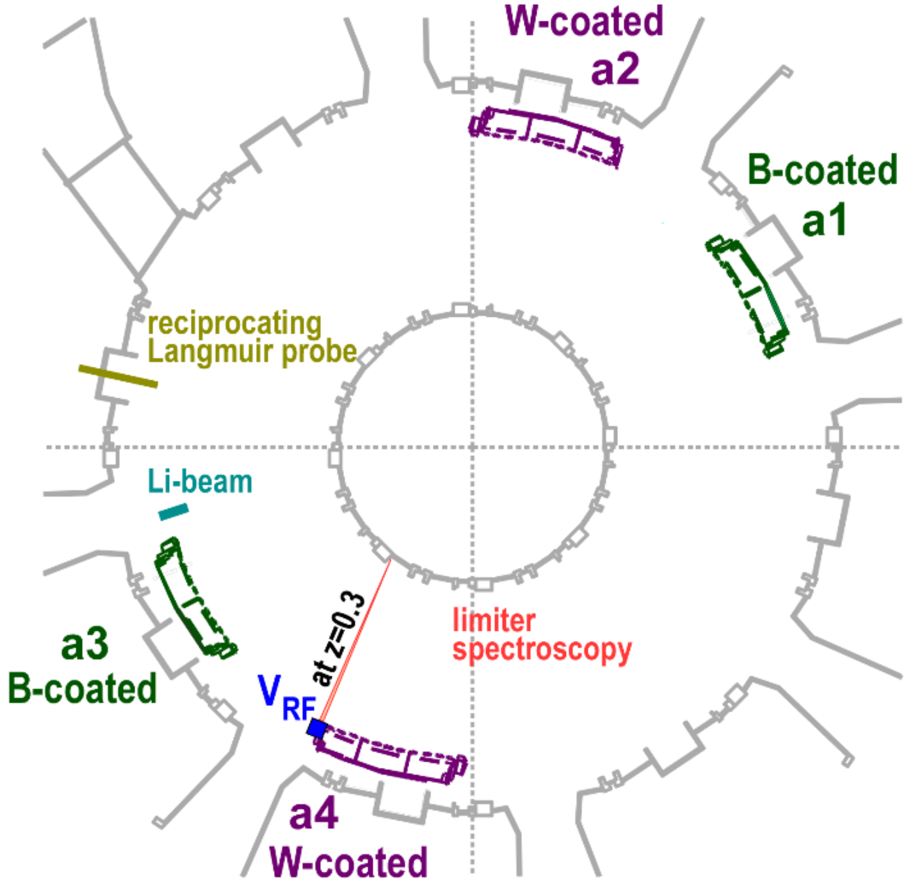
AUG conditions with propagative slow wave



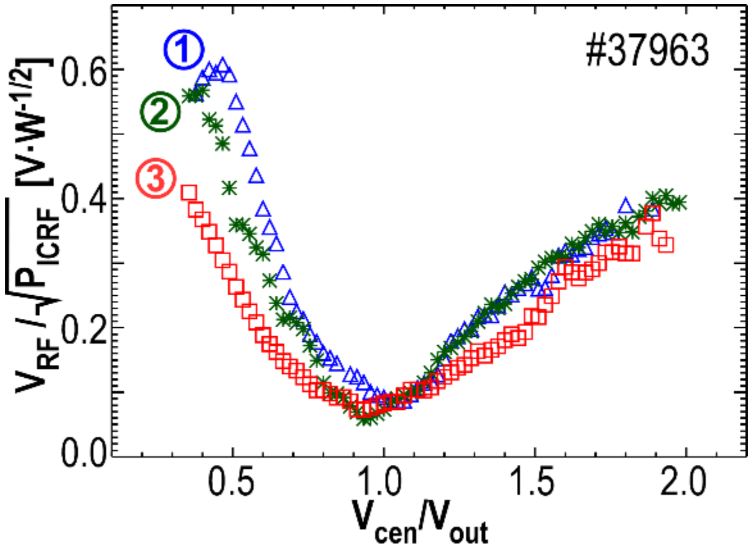


- Very special configuration for ASDEX Upgrade with very low density and large antenna-wall clearance
- Profiles ① and ② correspond to $n_e < n_{e,lh}$ and propagative slow wave at limiters
- Using voltage balance at low n_e instead of power balance (AUG measurements tricky at low coupling)

No indication of propagative slow wave impacting near-fields and sputtering



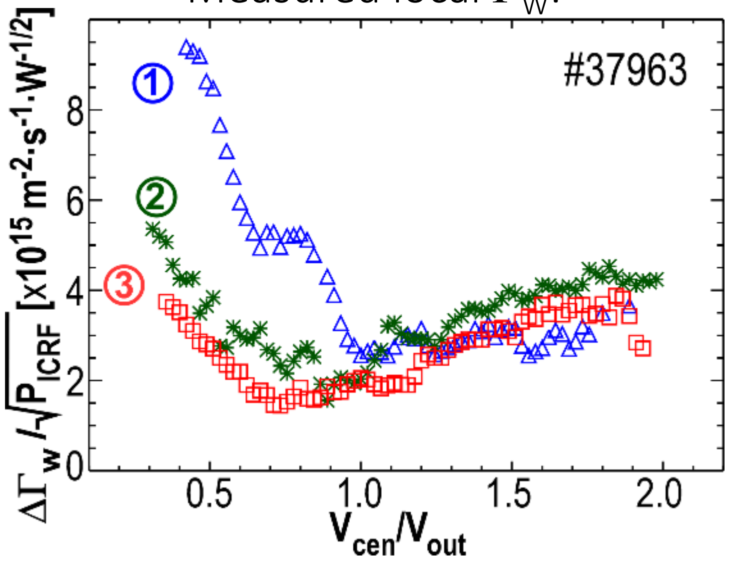
Measured local RF amplitude:



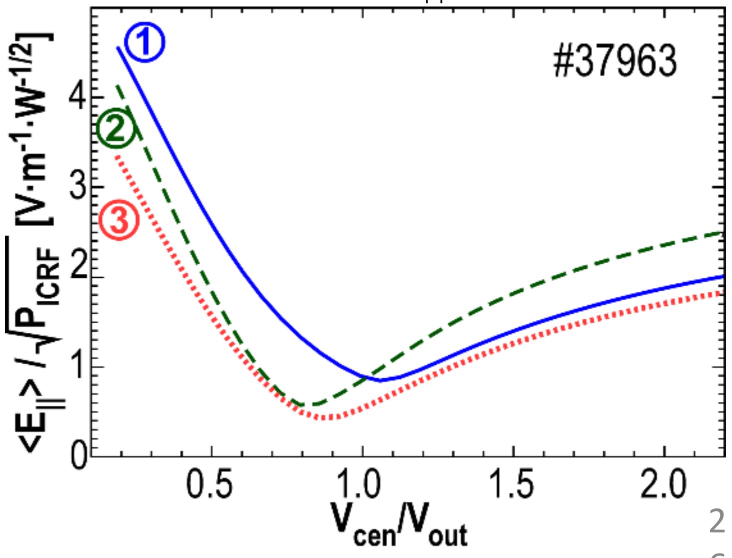
strap voltage balance

① $n_{e,limiter} < n_{e,lh}$
② $n_{e,limiter} < n_{e,lh}$
③ $n_{e,limiter} > n_{e,lh}$

Measured local Γ_W:



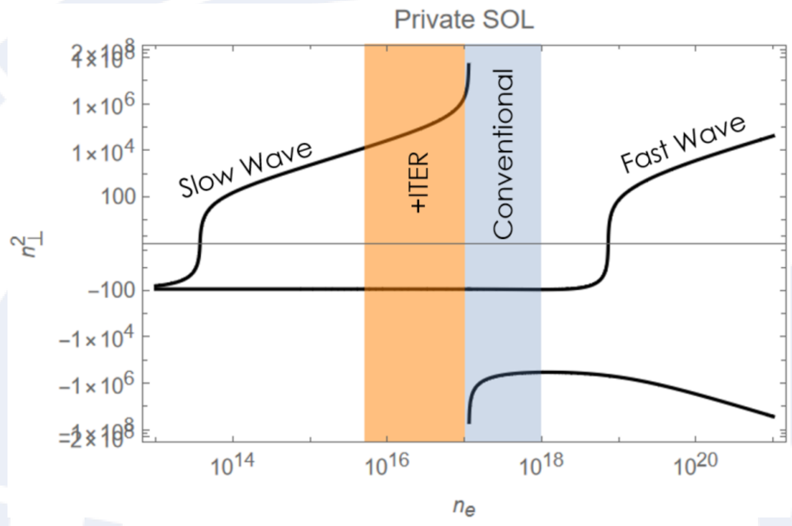
Calculated local $E_{||}$ (TOPICA):



- No change of behavior with extended slow wave propagation ($n_e<n_{e,lh}$)
- Minimum only weakly dependent on n_e
- Consistent with $E_{||}$-calculations w/o slow wave propagation

Coupling 1MW ICRF with a propagative Slow Wave (low density)

- **Proponents and contact person:**
  - Guillaume URBANCZYK (guillaume.urbanczyk@ipp.mpg.de), Wouter TIERENS, Raymond DIAB, Ralph DUX, Roberto BILATO, Roman OCHOUKOV
- **Scientific Background & Objectives**
  - **ITER will have to operate its ICRF system with a propagative slow wave, which is unusual**
  - **Can we couple 1MW ICRF on a low density plasma where the slow wave is propagative ?**
  - **If yes, what is the impact of the slow wave on impurity production and heating efficiency ?**
  - **Can we move the LH resonance behind the antenna using local gas injection ?**



- **Experimental Strategy/Machine Constraints and essential diagnostic**

1) Repeat #**37963** (~100kW ICRF power coupled for ~160kW injected à ~40% reflected)
2) Repeat #**1** by achieving 1MW power coupled per antenna. To do so, we wish to feedback control the coupled power, but if this controller is too difficult to implement, we will otherwise assume for ~40% power reflected, and require ~1.6MW ICRF to each generator to get 1MW coupled in per antenna pure deuterium plasma (without injecting low-Z impurities) with updated waveforms (cf. below)
3) Repeat discharge #2 by moving the plasma closer to the antenna (Raus scan), to start with the LH resonance in front of the antenna and push it slowly behind
4) Repeat discharge #2 by feedback controlling the core density with main valves, and feedforward injecting gas locally at the surrounding of the active antenna (to assess local gas injection in moving the LH resonance behing the antenna and improve its coupling)
5) Repeat #3 by adding 2 Hz ICRF power modulation to track with Break In Slope analysis how the heating efficiency evolves (this will help checking rather if the different waves generated from mode conversion occuring at different densities are still well absorbed in the core, in particular IBWs)
6) Repeat #5 at Ip = 700kA to change the magnetic connections and increase the changes to register meaningful signal

- Visible + UV spectroscopy, RFA probe, antenna reflectometry, B-dot probes

Proposed pulses

Device	# Pulses/Session	# Development
AUG	6	12
MAST-U	-	-
TCV	-	-
WEST	-	-

Ne and Ar seeding influence on ICRF-induced W release

- **Proponents and contact person:**
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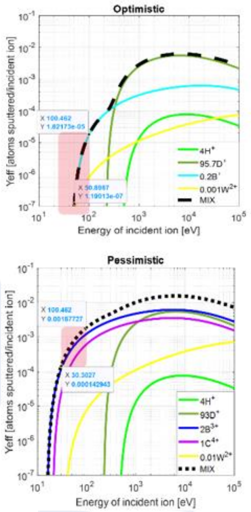
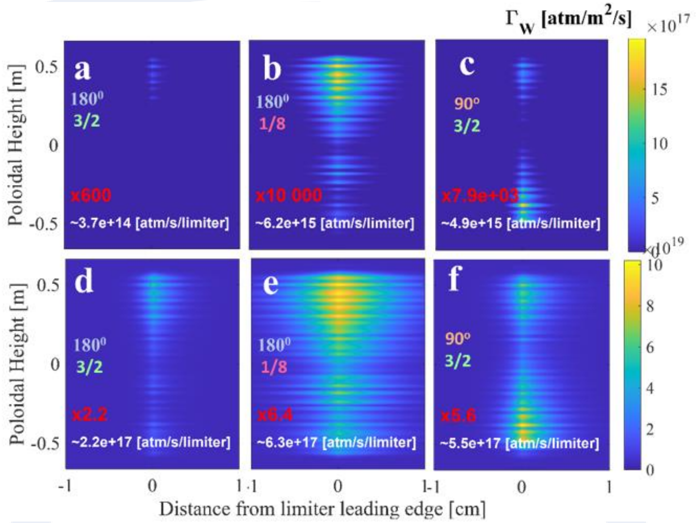
- **Scientific Background & Objectives**
  - **How much more tungsten will ICRF produce in ITER when powered, i.e., in presence of seeded Neon?**
  - Assess the increase of W production when powering ICRF in seeded discharges with Ne (and Ar). The discharge will be divided in several plateaus with constant P_{TOT} but with different auxiliary heating mix. The question will be answered by assessing the increase of W impurity using visible spectroscopy lines of sight looking at the 3-strap ICRF antenna limiter

- **Experimental Strategy/Machine Constraints and essential diagnostic**

1) Repeat #41031 but with pure deuterium plasma (without injecting low-Z impurities) with updated waveforms (cf. below) → *non-seeded reference used as a reference point for all measurements*
2) Repeat discharge #1 with moderate injection of Ne
3) Repeat #2 by increasing the amount of Ne injected as much as possible (2 shots suited)
4) Repeat #3 with 90° phasing on the ICRF antenna
5) Repeat #2 with Ar (cf. # 41033)
6) Repeat #3 with Ar

- Visible + UV spectroscopy, RFA probe, antenna reflectometry





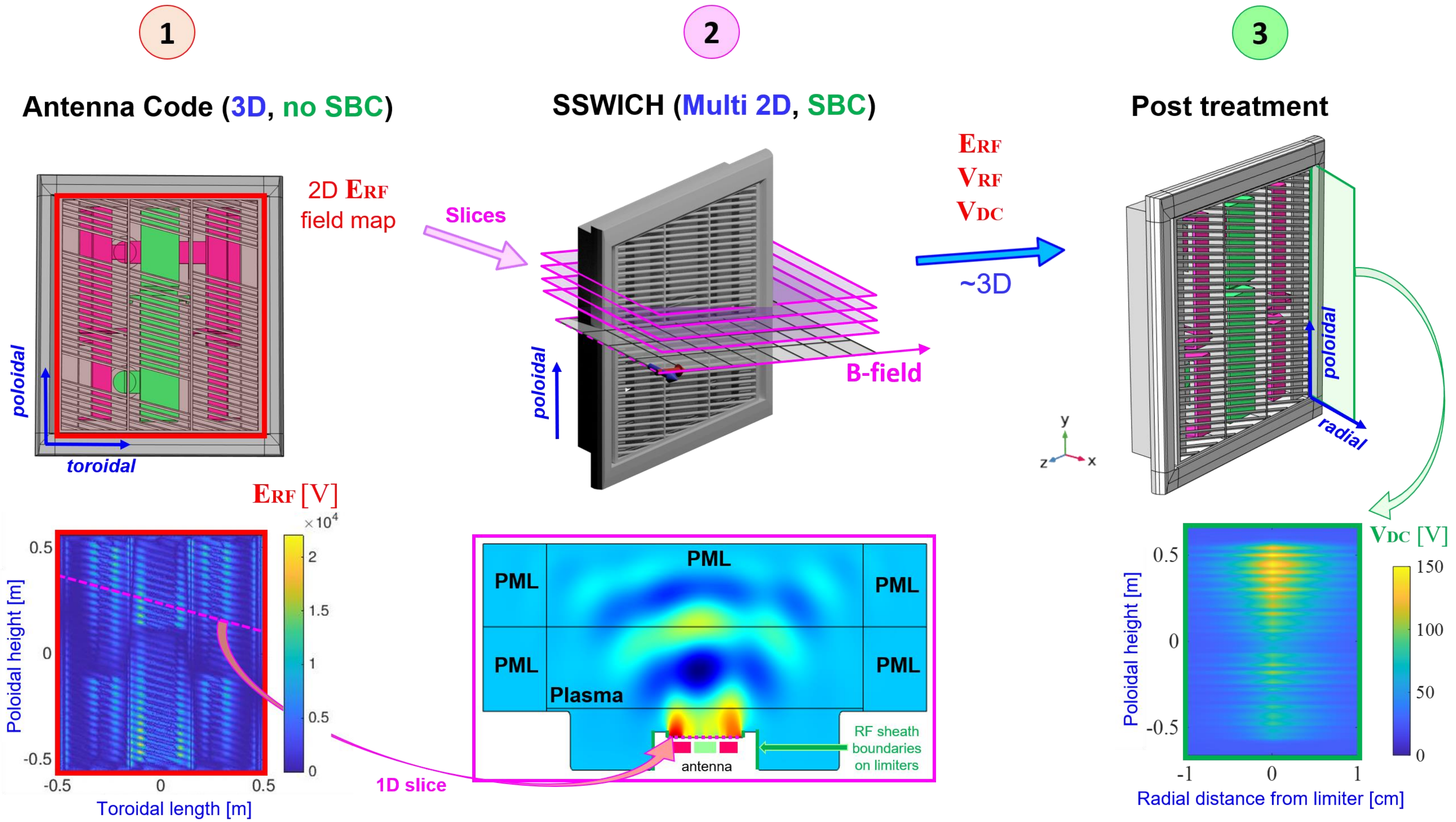
$$\Lambda = \Gamma_{Wtot}^{ICRH \to ON} / \Gamma_{Wtot}^{ICRH \to OFF} \quad \text{with } \Gamma_{Wtot} = \iint_{Limiter} \Gamma_W$$

Proposed pulses

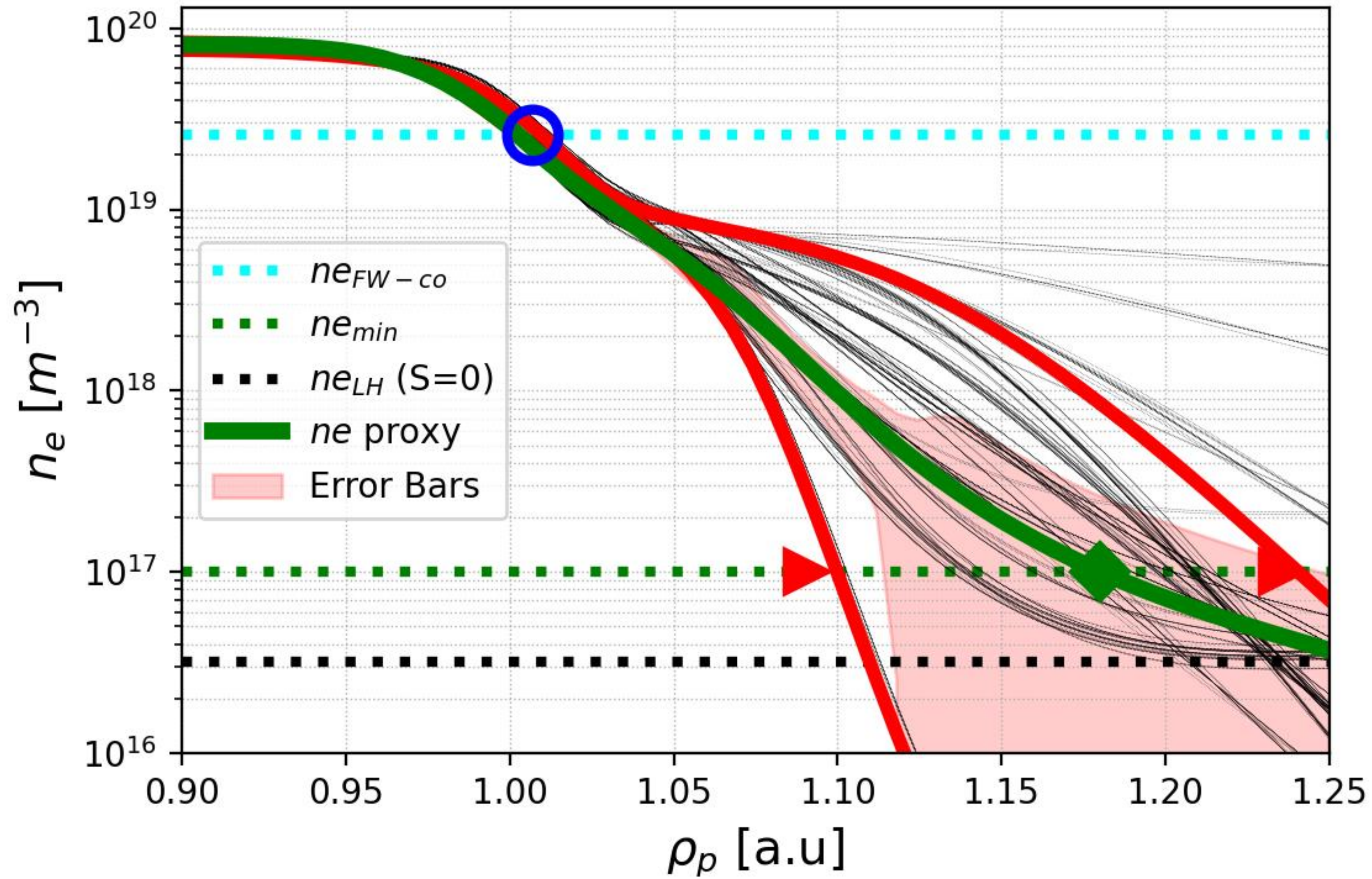
Device	# Pulses/Session	# Development
AUG	6	6
MAST-U	-	-
TCV	-	-
WEST	6	14

SSWICH code

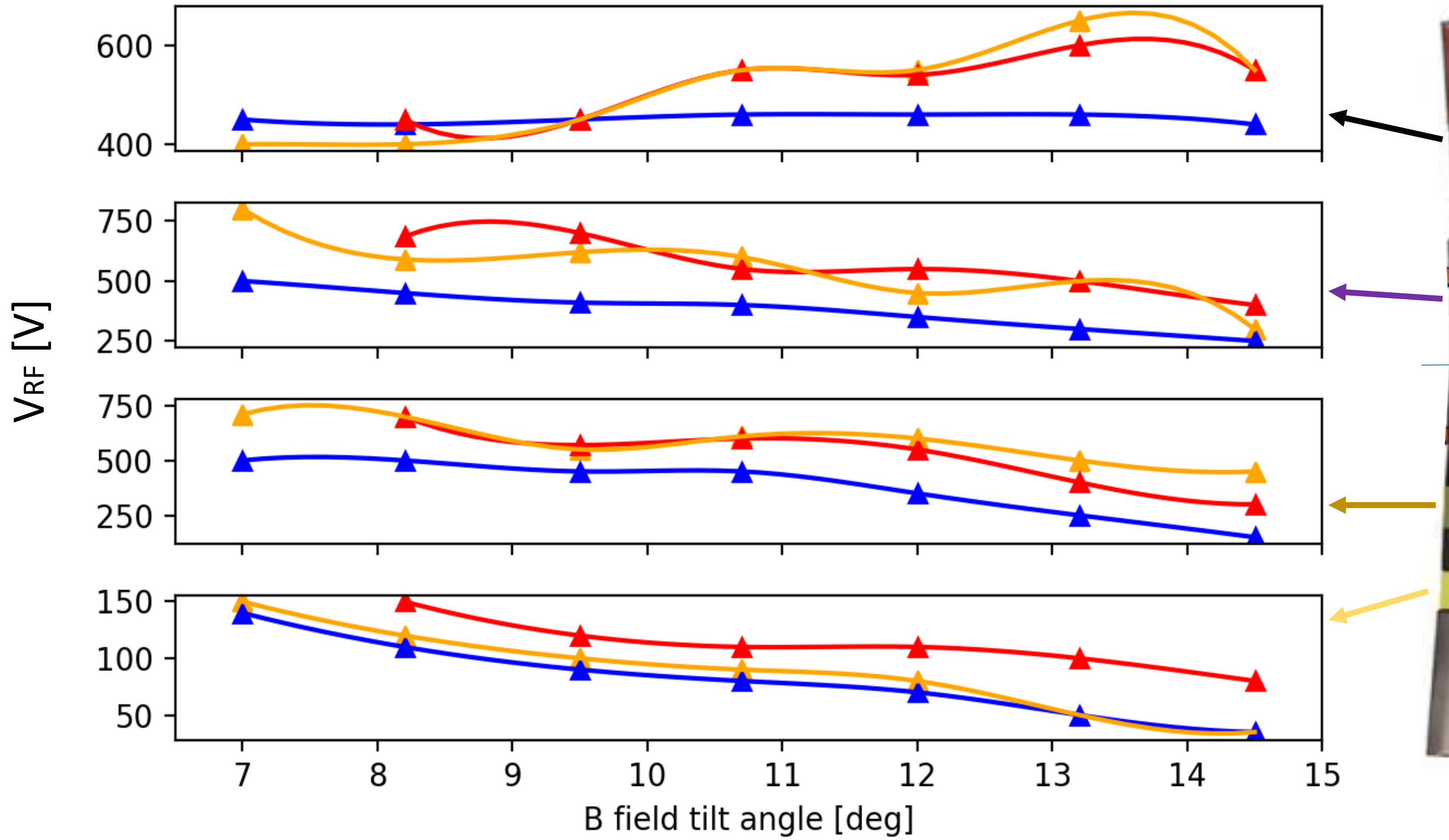
J. Jacquot, Phys. Plasmas 21 061509 (2014)
L. F. Lu, 2018 PPCF 60 035003

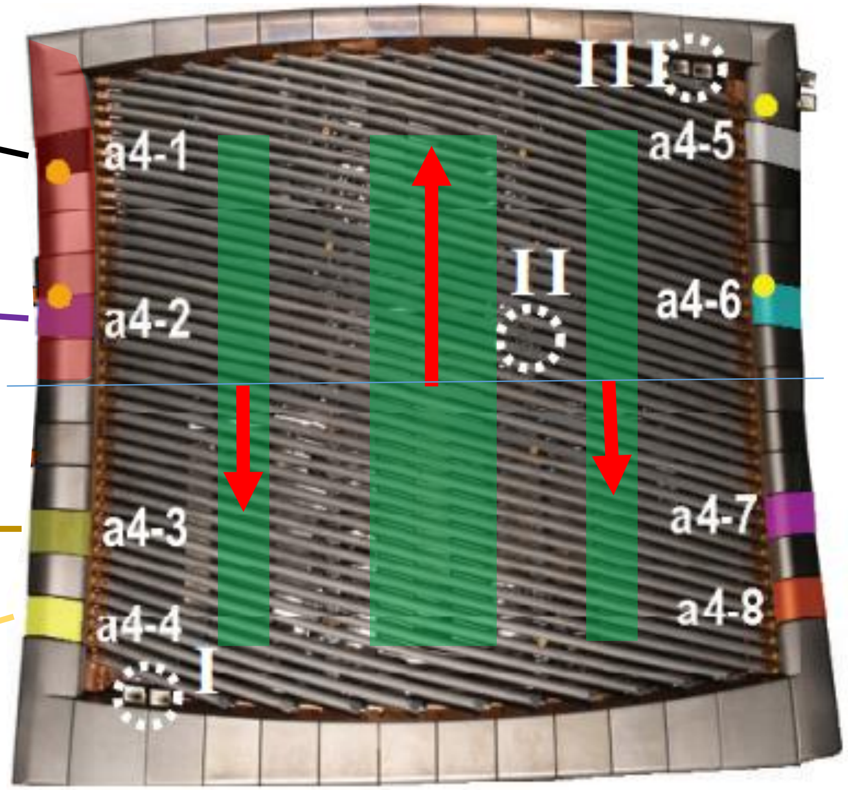


Density profiles



RF shunts data variation over B field tilt-angle scan

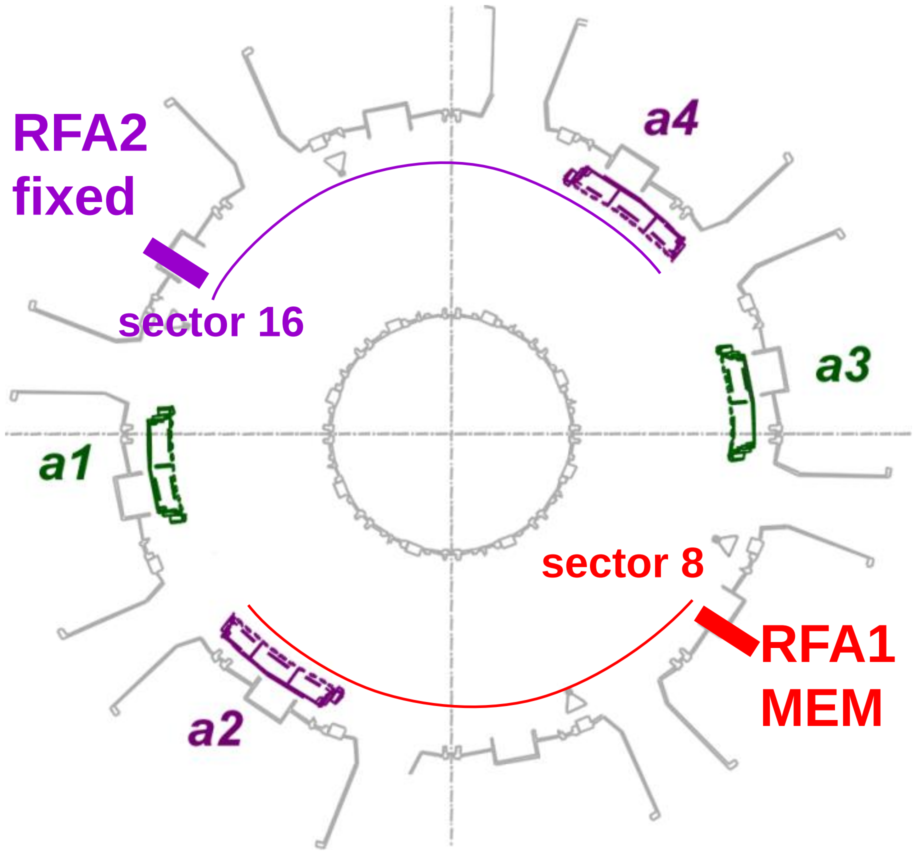


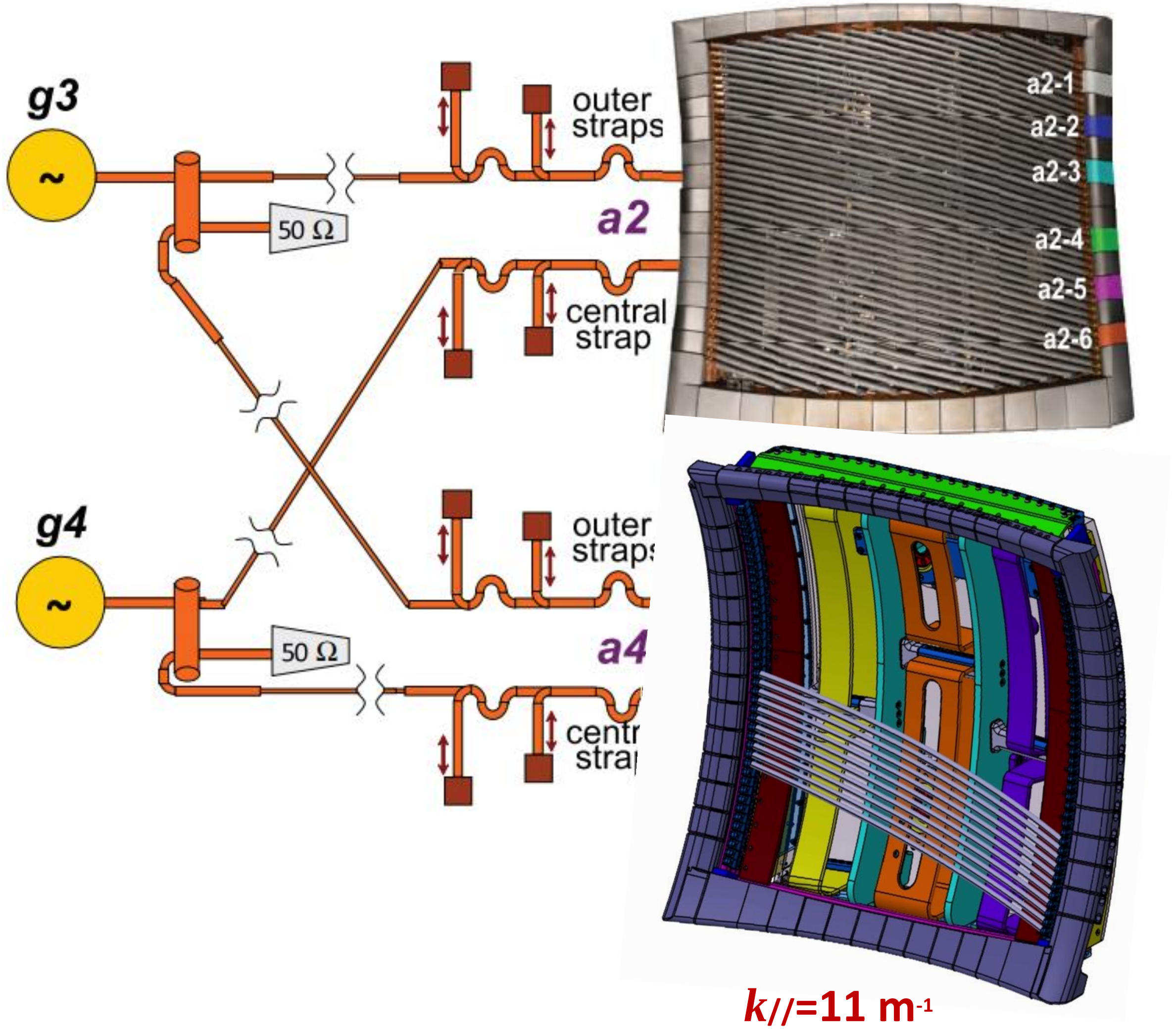


▶ However the tilt-angle (Ip scan) seems to play a role on the impurity source (historically assumed negligible in similar experiments, cf. dedicated investigation)

ASDEX-Upgrade ICRF system

ASDEX Upgrade top cross-sectional view





$k_{//}$=11 m^{-1}

Ne injection influence on ICRF JET