JT-60Uトカマクにおける
• 主プラズマでのタングステンの蓄積
• ダイバータプラズマでの炭素の放射過程

日本原子力研究開発機構
那珂核融合研究所
仲野友英

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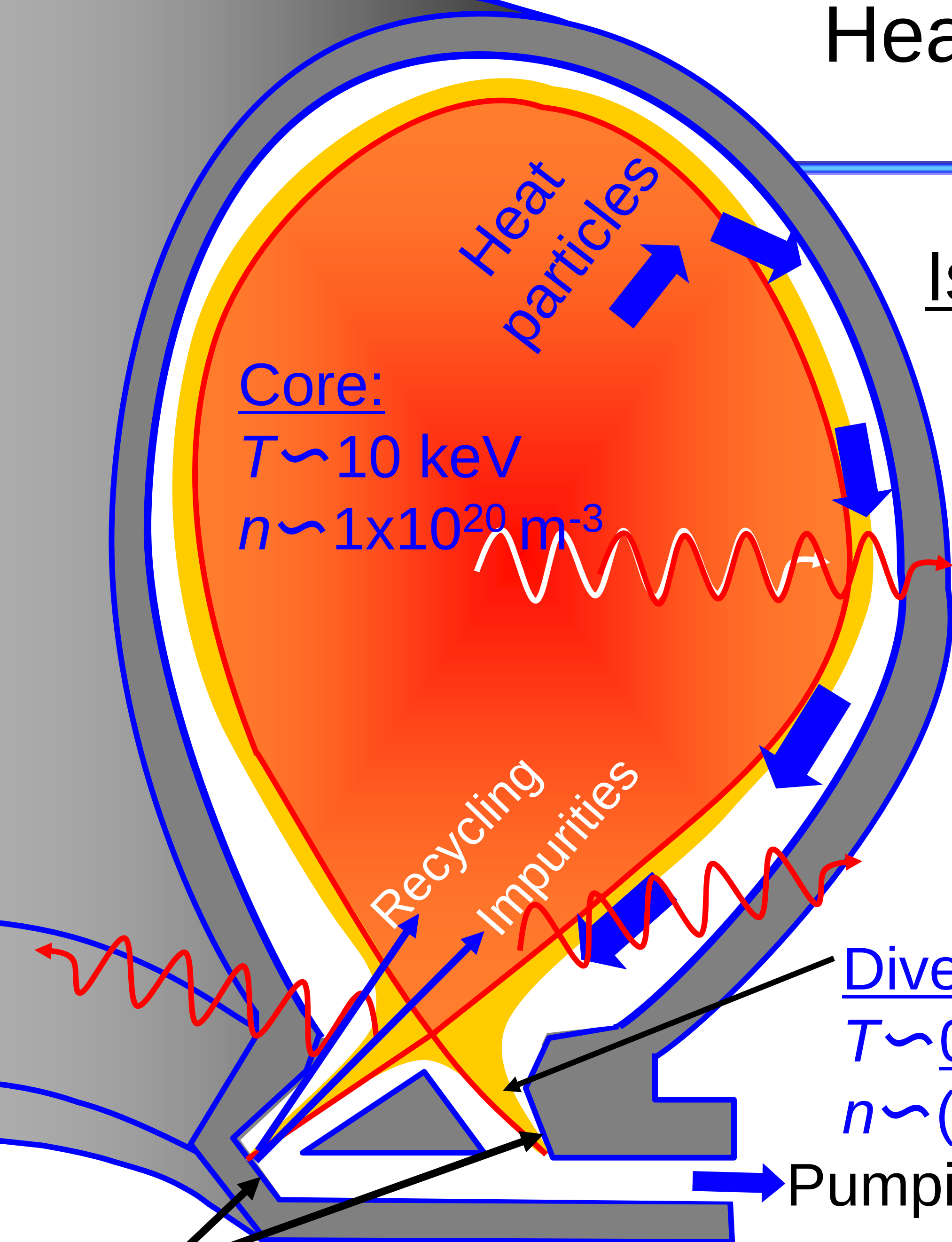
Heat and particle flow in a tokamak

JT-60U

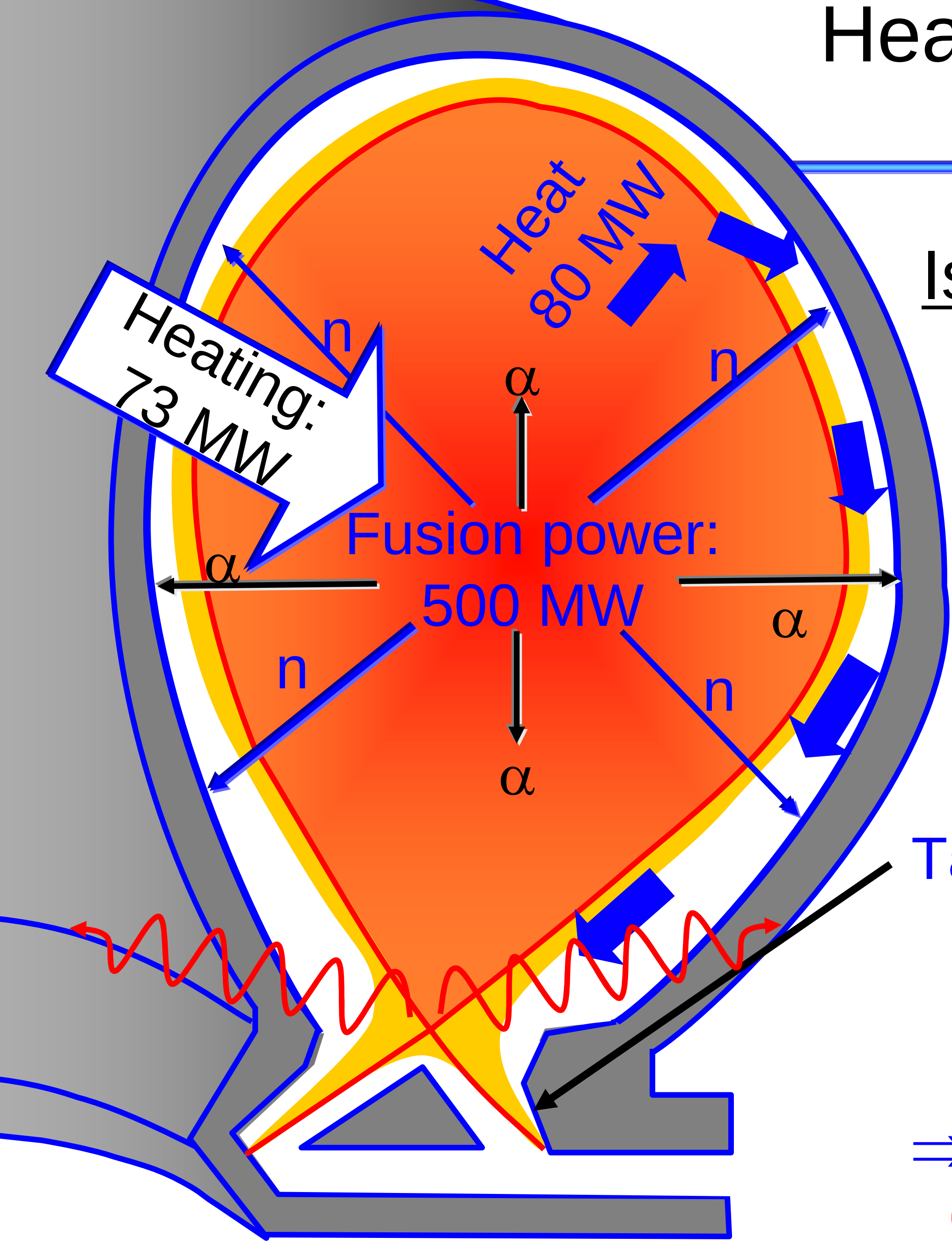


Issues:

- Control of fuel particles
- Control of impurities
- Mitigation of heat load onto target plates

⇒ Radiative cooling

Heat and particle flow in a tokamak



Heat flow in ITER

Issues:

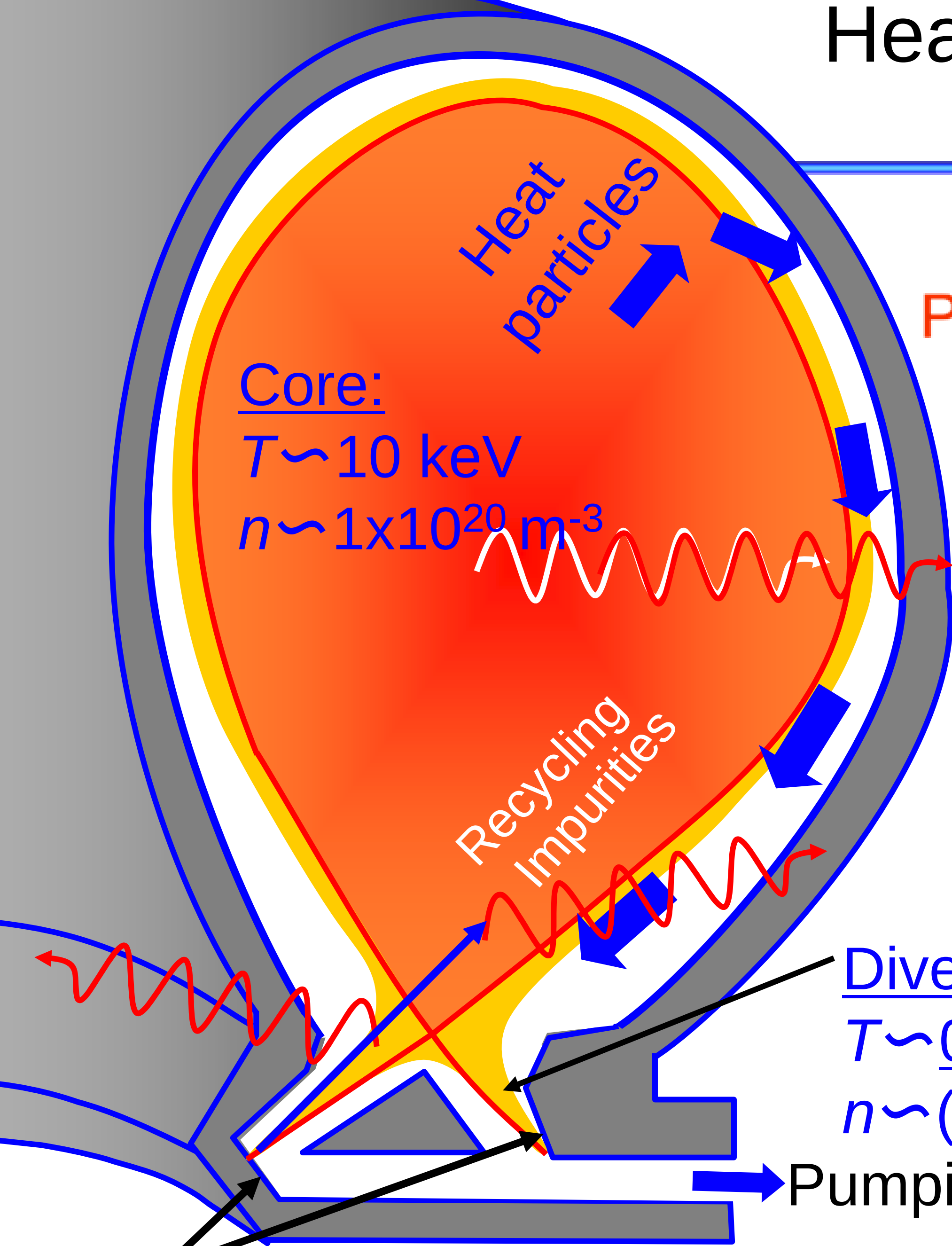
- Control of fuel particles
- Control of impurities
- Mitigation of heat load onto target plates

⇒ Radiative cooling

Target plate
(Limit 10 MW/m^2 ,
Plasma wet area 1.7 m^2):
No radiation 40 MW / 1.7 m^2
⇒ 24 MW/m^2
60% radiation 16 MW / 1.7 m^2
⇒10 MW/m^2

Heat and particle flow in a tokamak

JT-60U



Present work

- Radiator? D, C^0, C^+ ,,,,,?
- Process
  - Ionization(excitation)
  - Recombination
  - Charge eXchange ?
- Ionization/recombination balance

Divertor:

$T \sim$ 0.2*- 100 eV

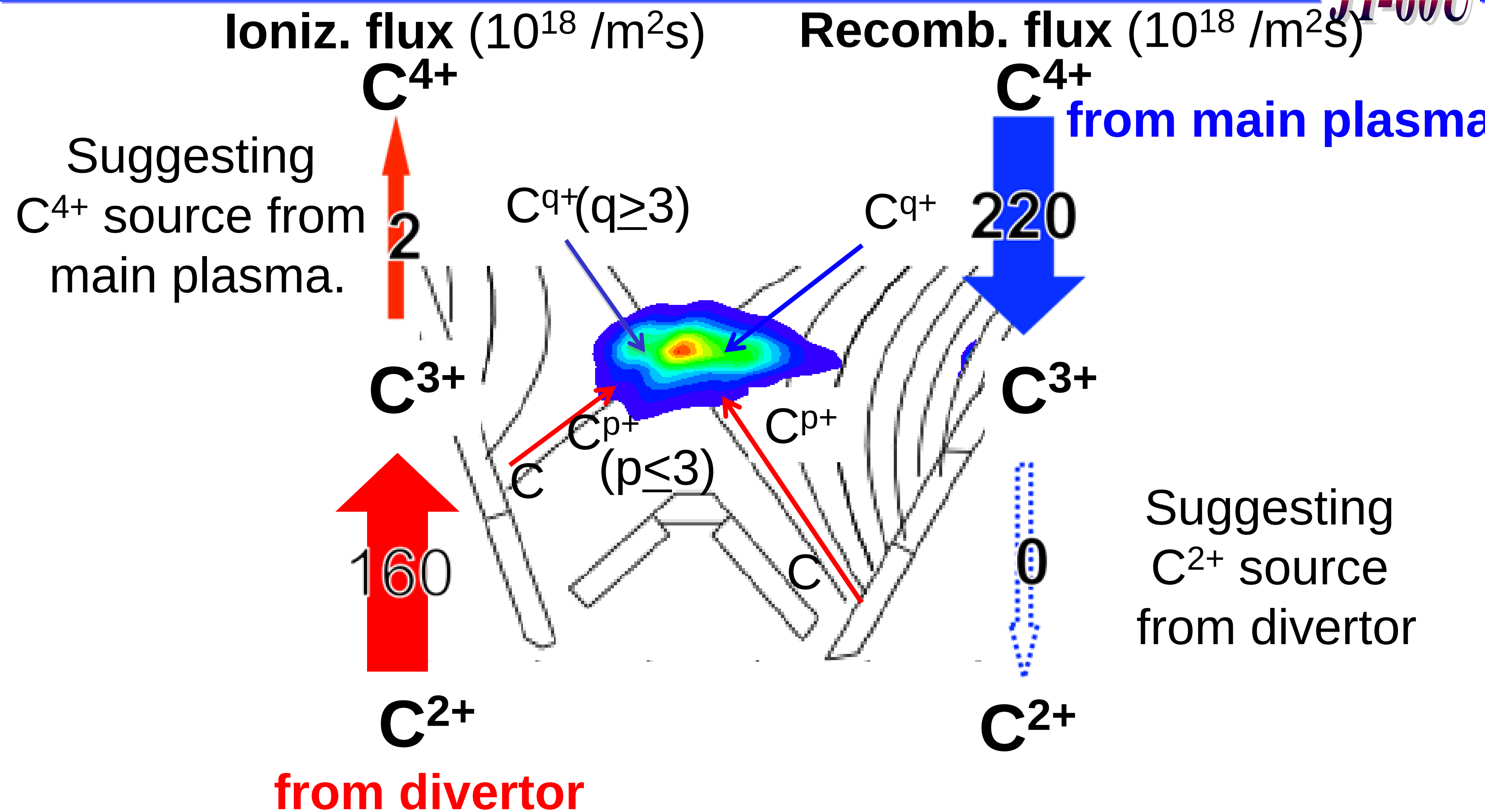
$n \sim$ (0.1- 50*)x10^{19} m^{-3}

*Recombining plasma

Divertor plates: Heat load => Erosion, impurities

Source of C^{3+}:main plasma and divertor comparable

JT-60U



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  Heat and particle flow in a tokamak

  JT-60U tokamak

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  2D visible & VUV spectrometer

- Experiment

  Discharge

- Analysis

  Collisional-Radiative model (& Atomic data)

- Results

  Ionization/Recombination balance (C^{2+}<=>C^{3+}<=>C^{4+})

  Radiation power (C^{2+} and C^{3+})

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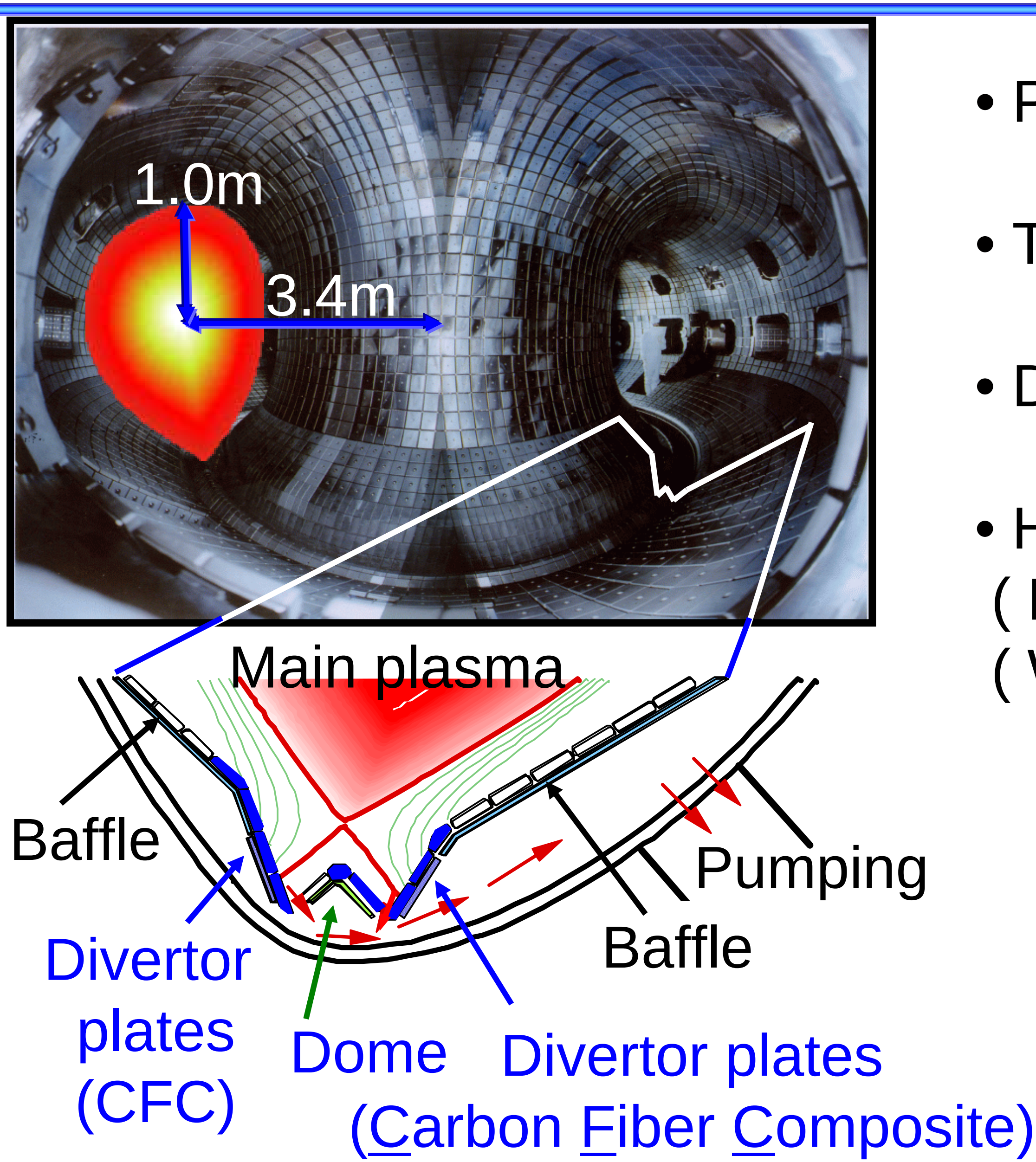
JT-60U tokamak



- Plasma current:
  < 2.5 MA
- Toroidal Magnetic field:
  < 4.1 T
- Discharge duration:
  < 65 s
- Heating
  (Neutral Beam)< 25 MW
  (Waves) < 8 MW

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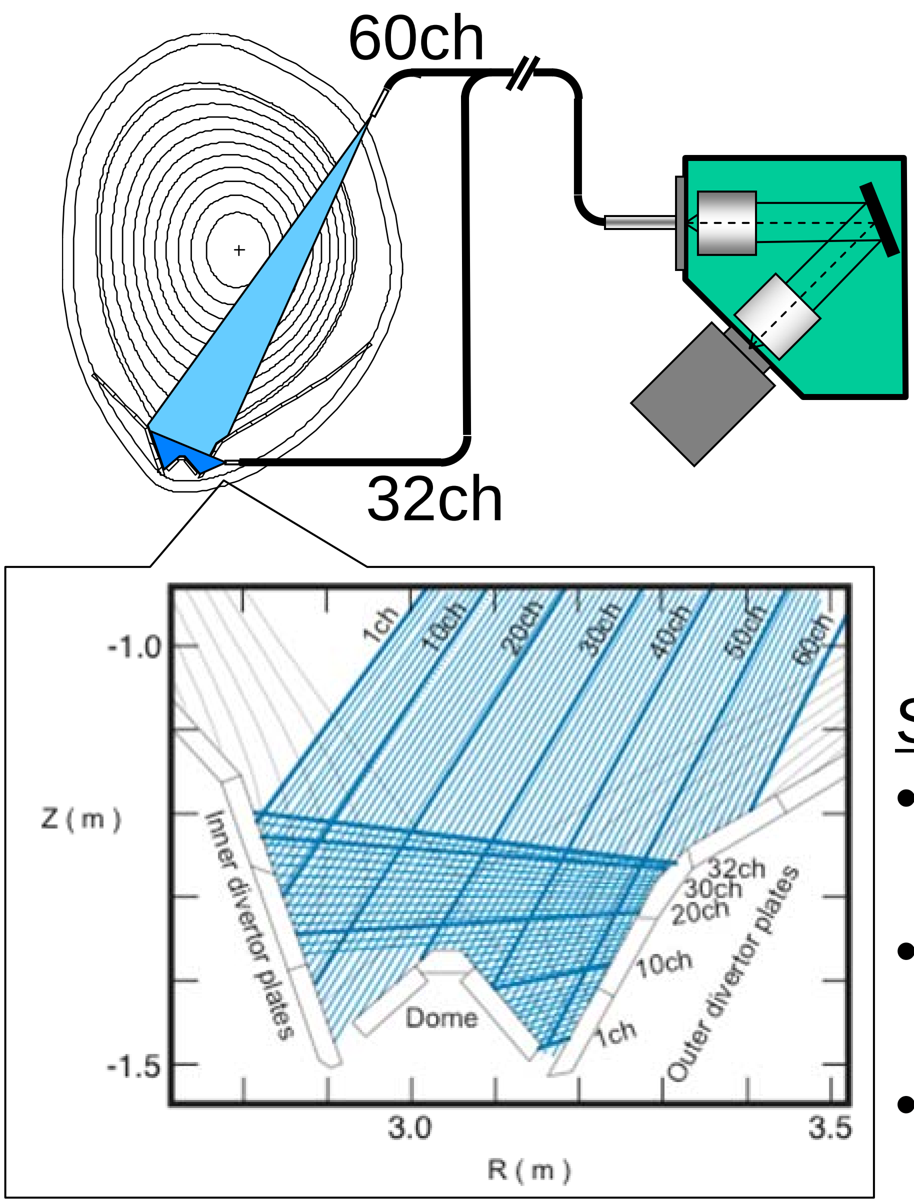
2D visible wide-spectral-band spectrometer



<u>Spectrometer</u>

- Grating : 300 g/mm
- Focal length : 0.2 m
- F number : 2

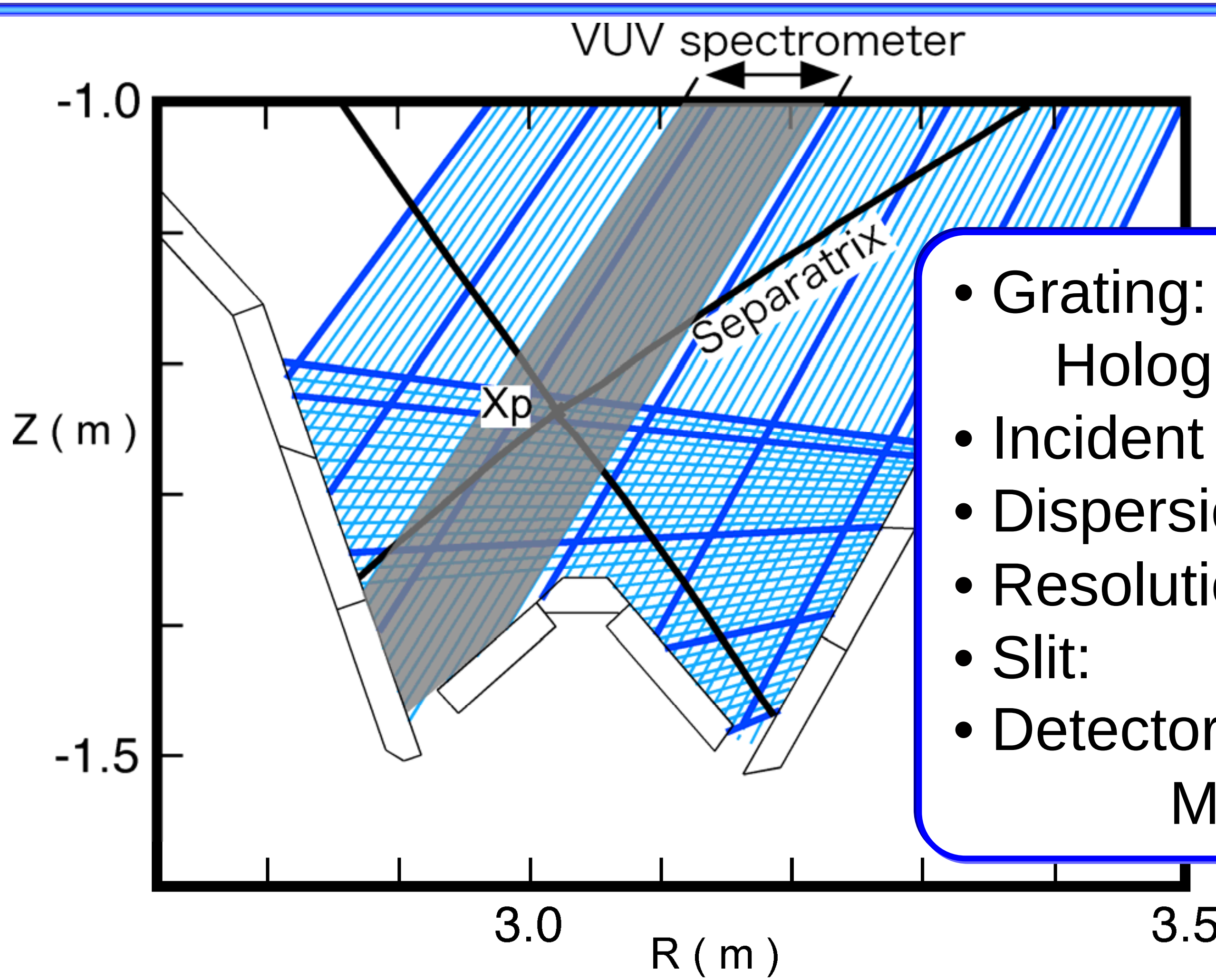
<u>CCD (Back-illuminated)</u>

- Pixel : 20 x 20 μm
- Format : 1340 x1300 p
- Time resolution : 300ms

<u>Specifications</u>

- Instrumental width (FWHM): ~ 0.74 nm (2.3 pixels)
- Spectral Band: ~ 430 nm (350 - 780 nm)
- Spatial resolution: ~ 1 cm

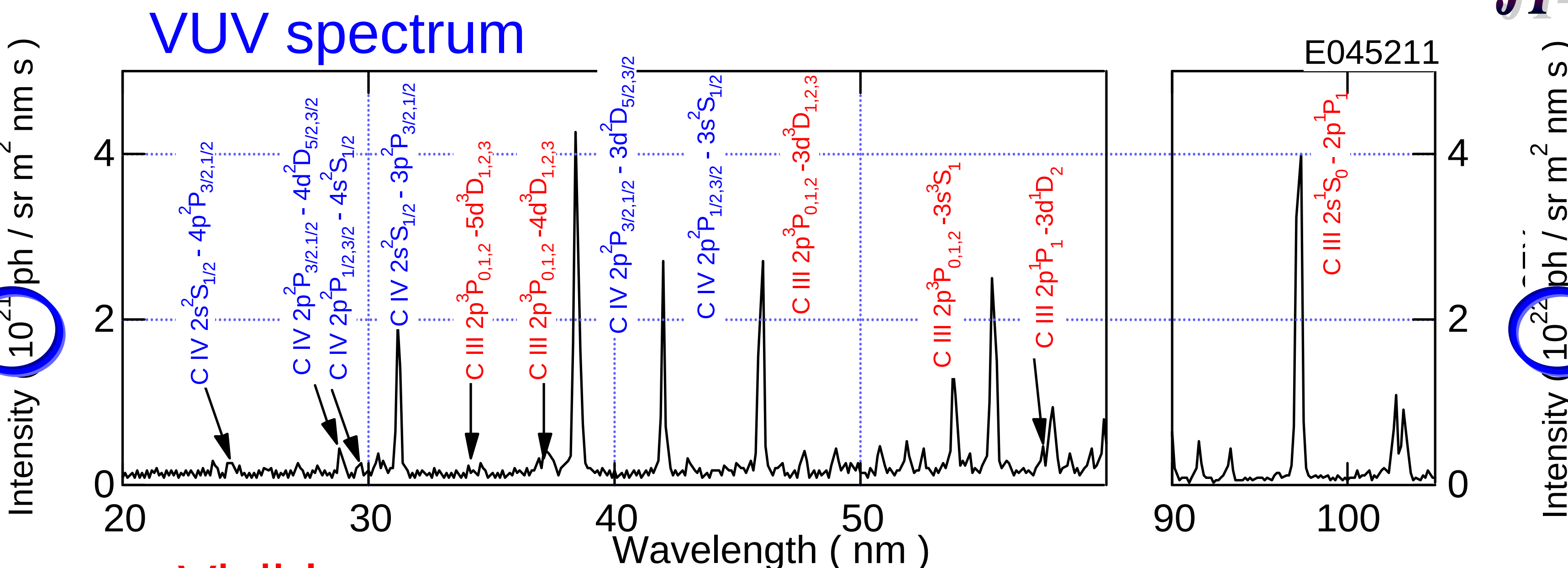
Vacuum Ultra Violet spectrometer

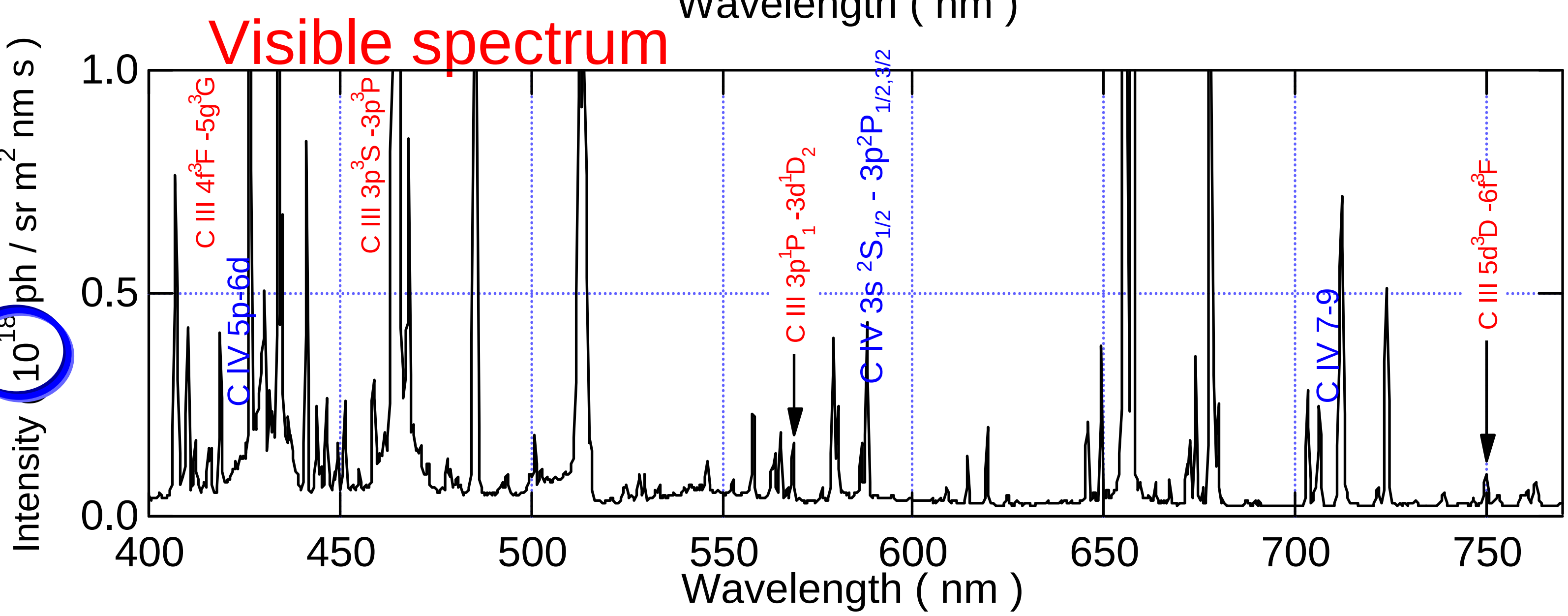


- Grating:
  Holographic (300 g / mm)
- Incident angle: 85^o
- Dispersion: 2 nm / mm
- Resolution: $(\lambda / \Delta\lambda) \sim 150$
- Slit: 10 μm x 5 mm
- Detector:
  MCP 50 μm x 1024 ch

- Similar viewing chord to the visible spectrometer
- Absolute calibration of sensitivity by a branching ratio method

Observed spectra





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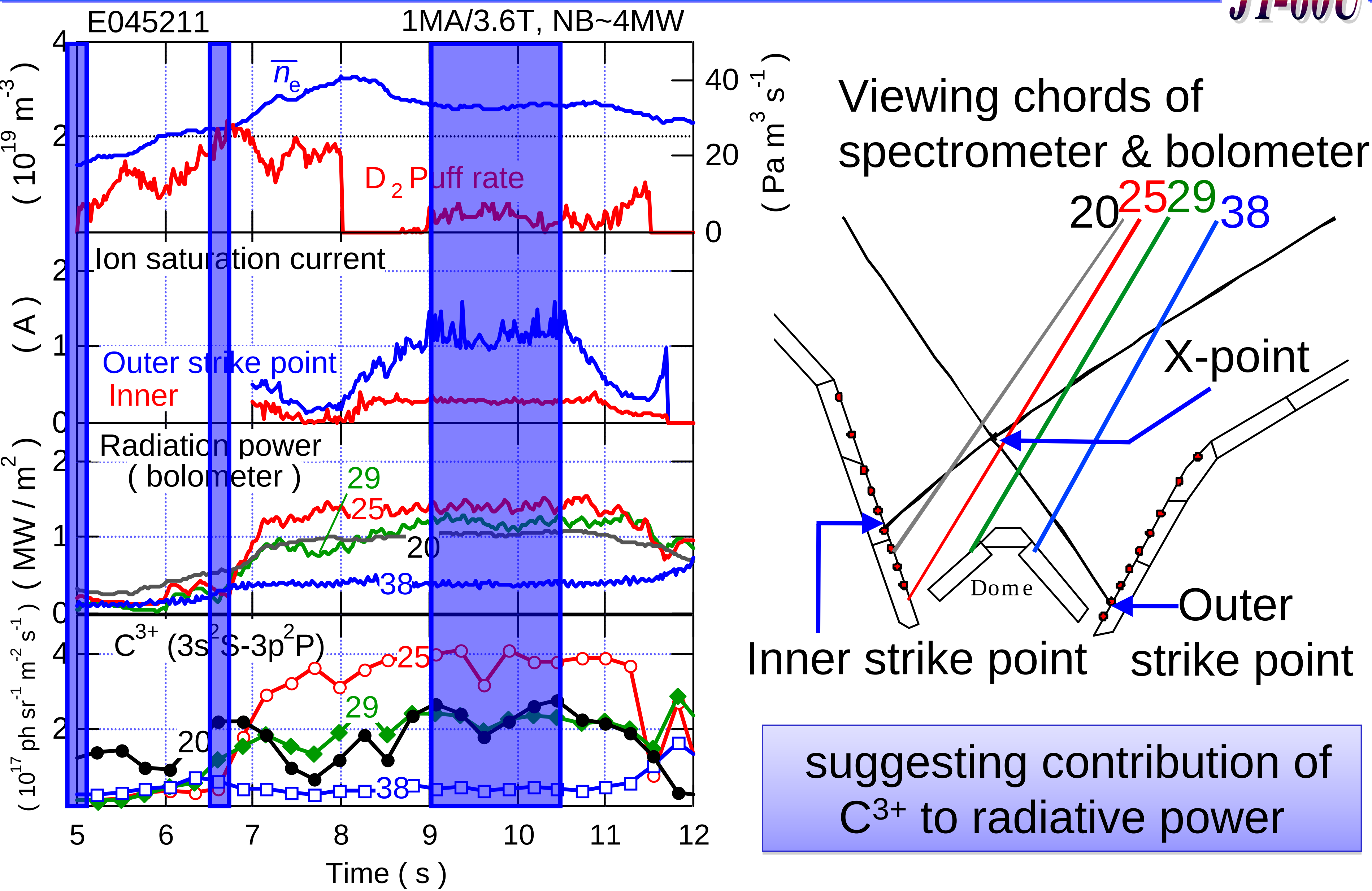
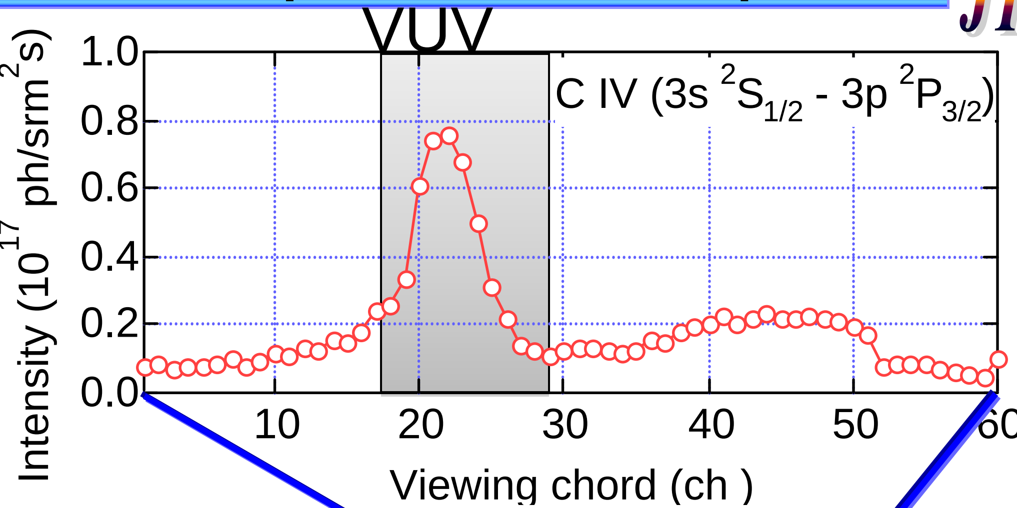
High density discharge
Radiation zone moves toward X-point

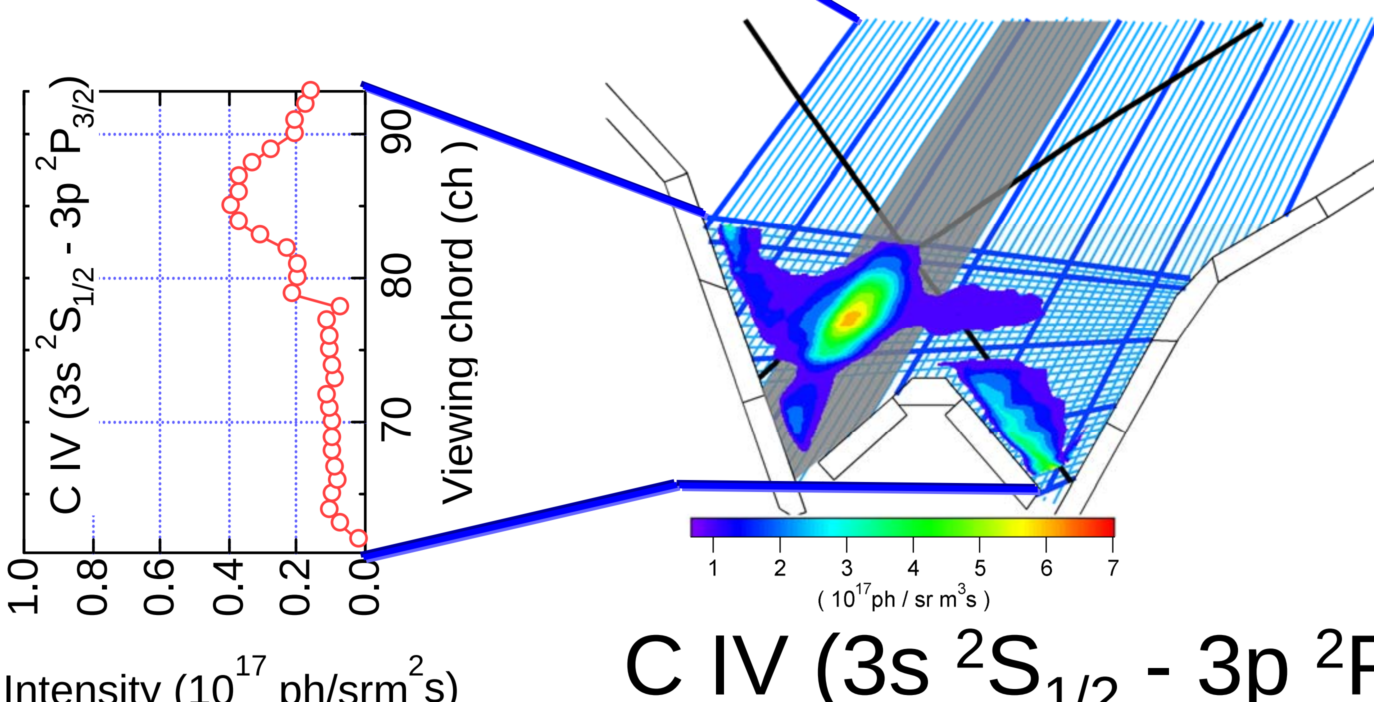


suggesting contribution of C^{3+} to radiative power

Before gas puffing:
Peak between inner strike point and X point

- Tomography by MEM.
- Peak is observed by the VUV spectrometer.



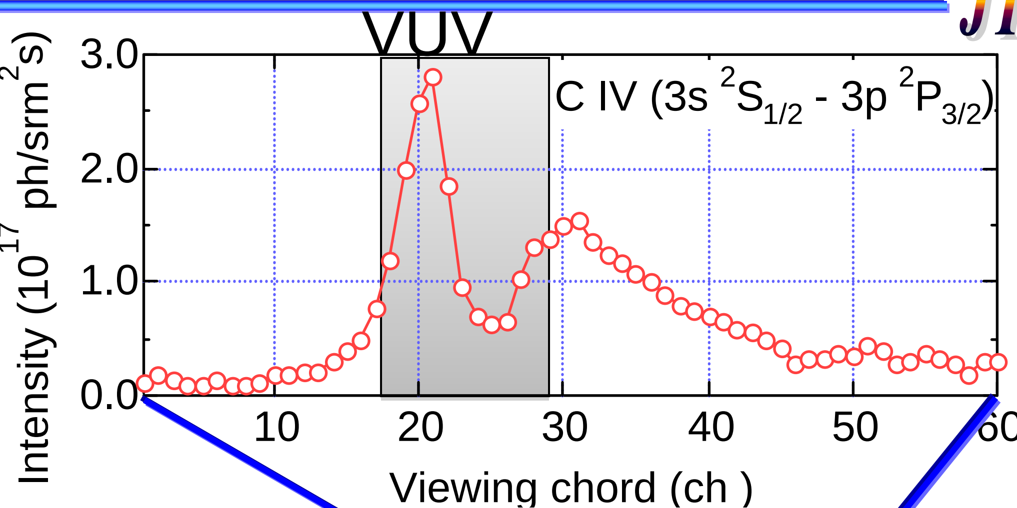


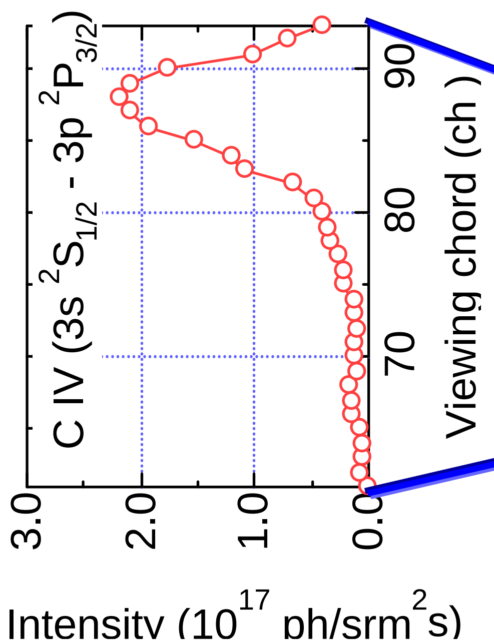
C IV (3s $^2S_{1/2}$ - 3p $^2P_{3/2}$)

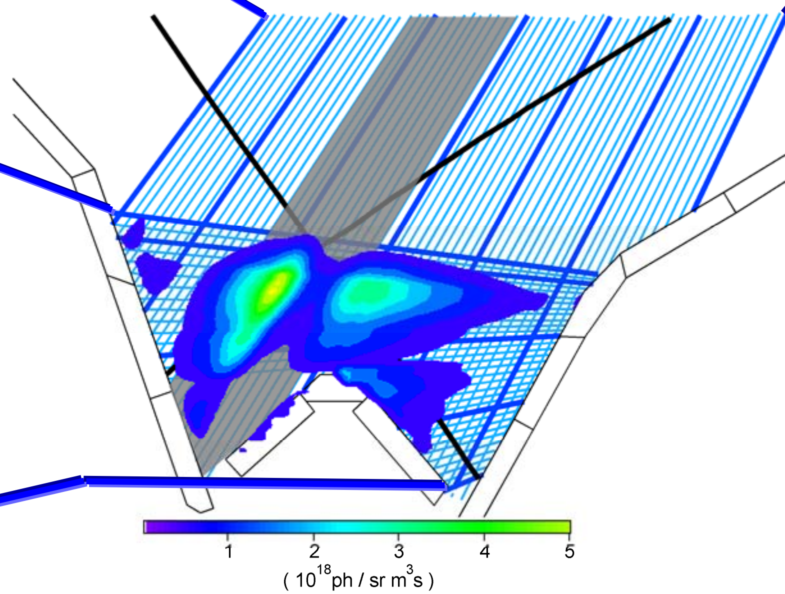
Before high radiation:
Two peaks near X point

JT-60U

The inner peak is still observed by the VUV spectrometer.





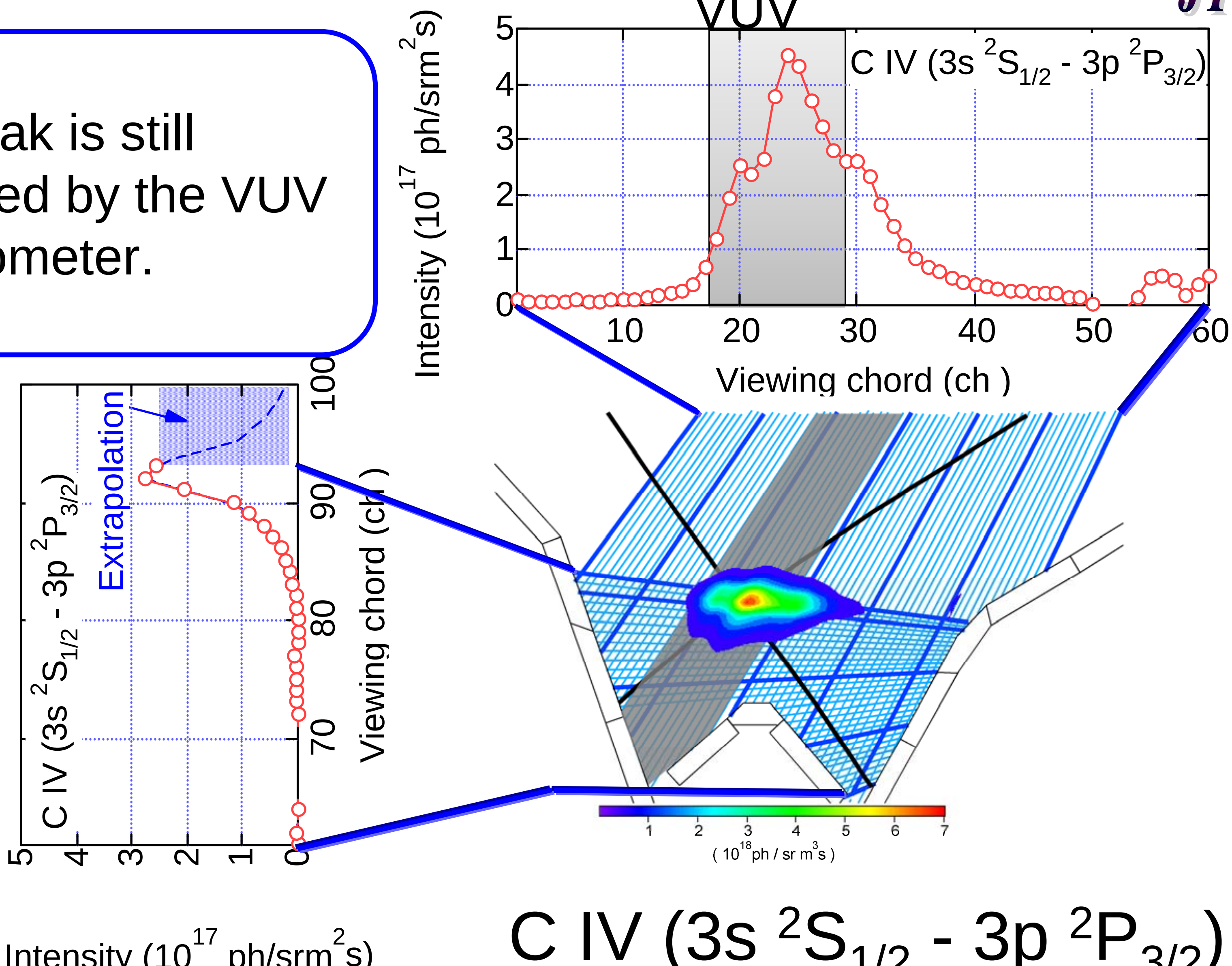


C IV (3s $^2S_{1/2}$ - 3p $^2P_{3/2}$)

During high radiation: Peak at X point

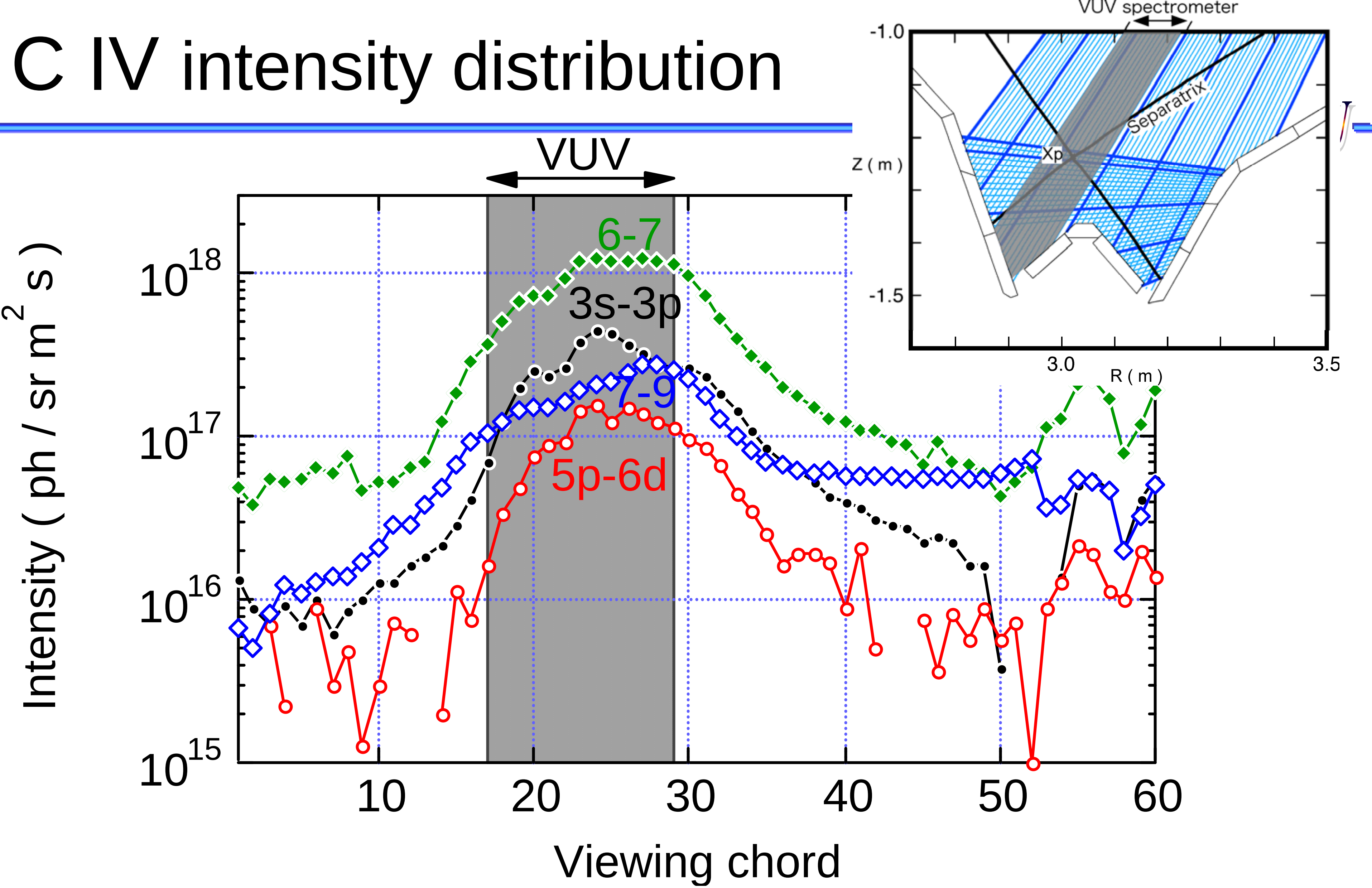
JT-60U

The peak is still observed by the VUV spectrometer.

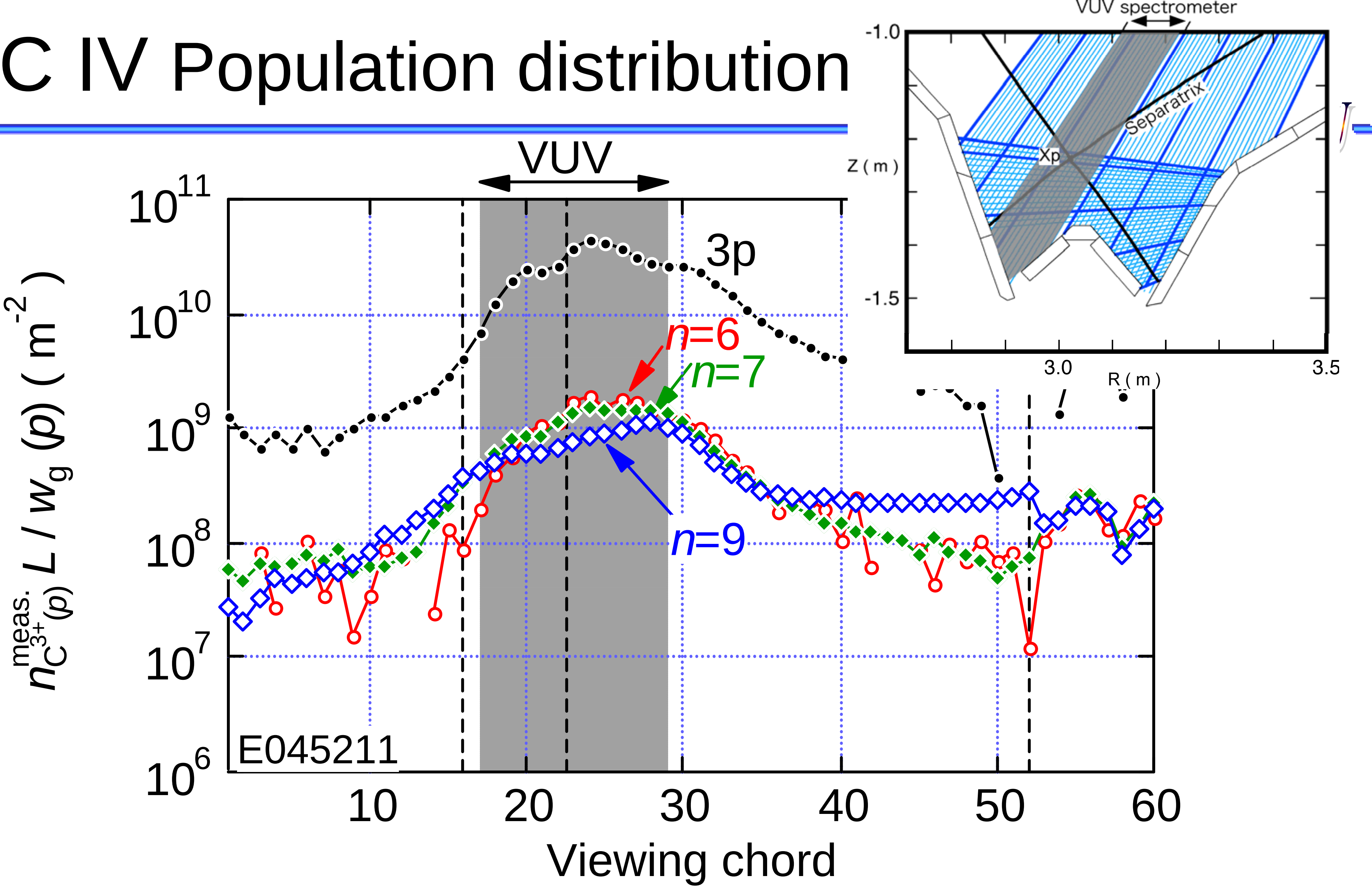


C IV (3s $^2S_{1/2}$ - 3p $^2P_{3/2}$)

C IV intensity distribution



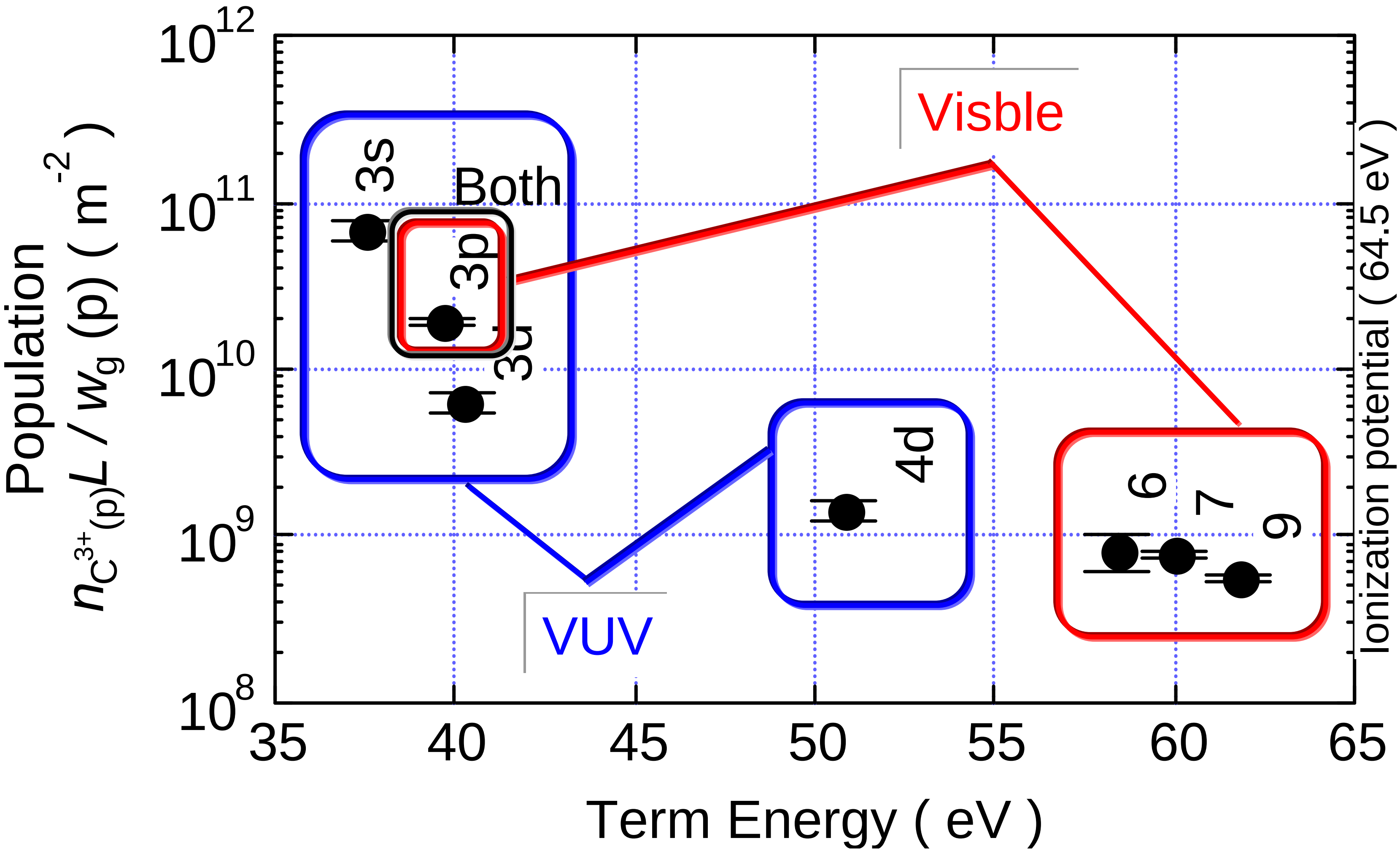
C IV Population distribution



Visible: 3p, n=6,7 and 9
VUV : 3s, 3p, 3d and 4d => Simultaneous analysis

Volume-averaged population density of C^{3+}

JT-60U



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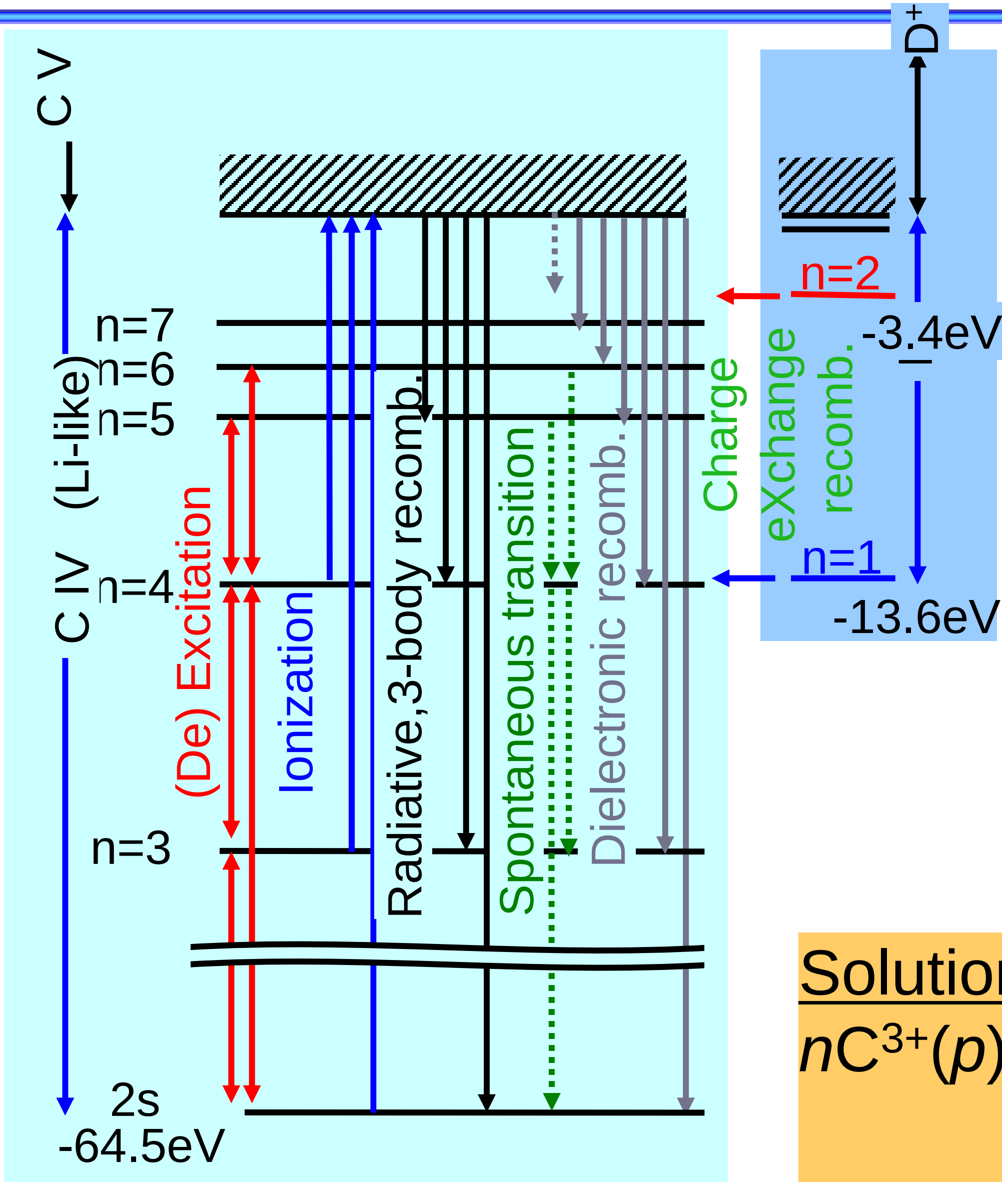
Collisional-Radiative model for C IV

JT-60U



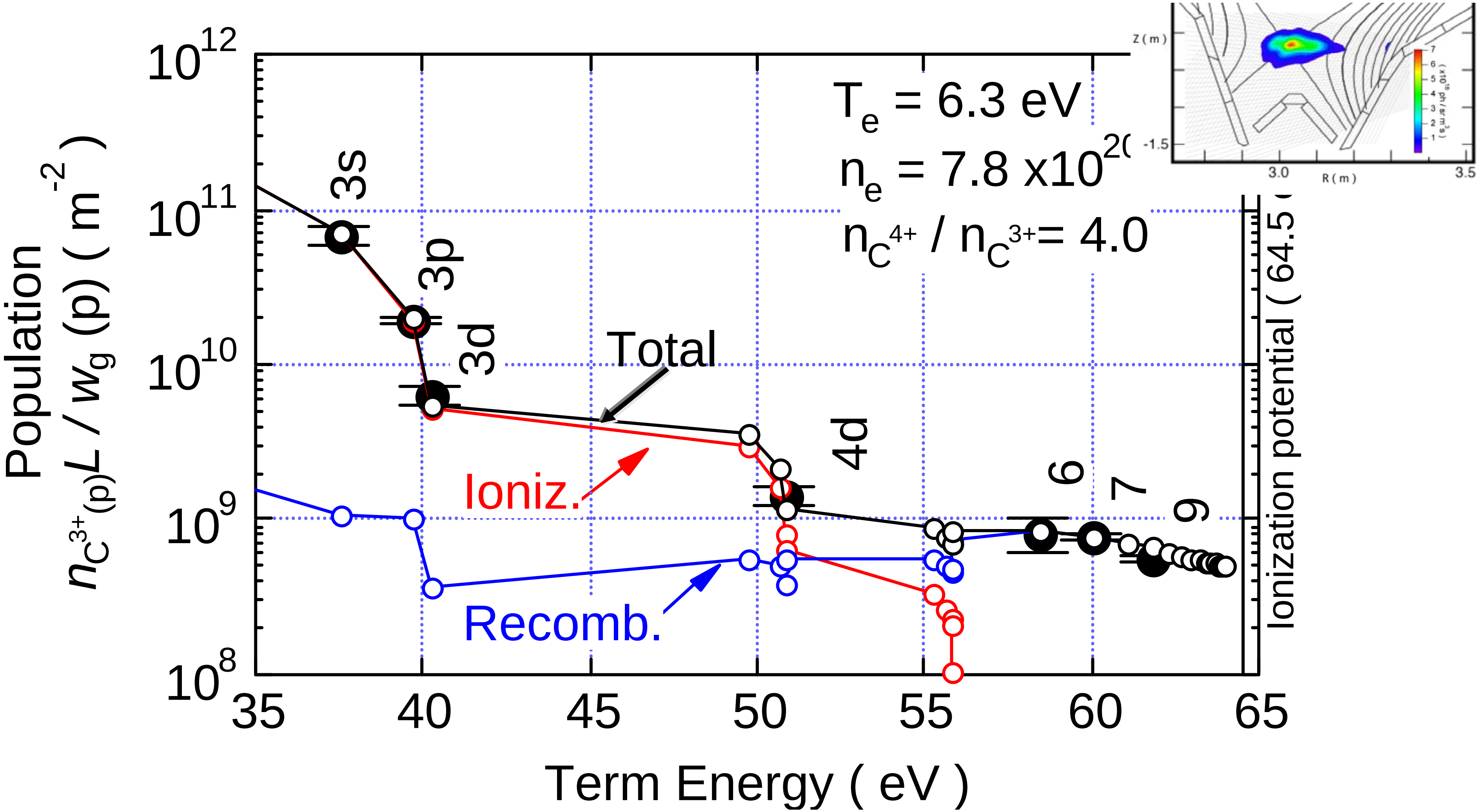
- A coef. & (De) excitation:
  n≤5 ADAS
  n≥6 Hydrogenic approx.
- Ionization, 3-body recomb.:
  ECIP approx.
- Radiative & Dielectronic recomb.:
  n ≤ 10 Nahar
- Charge exchange recomb.:
  D(n=1): ADAS
  D(n=2):Shimakura

<u>Solution of Rate Equation</u>

$nC^{3+}(p) = R_0 n_e n_{CV}$ (Recombining)
$+ \ R_0' n_D n_{CV}$ (CX-Recomb.)
$+ \ R_1 n_e n_{CIV}$ (Ionizing)

C^{3+} :n ≤ 4 : Ionizing component (Term Energy < ~50eV)
n ≥ 5 : Recombining component

JT-60U



low excited levels (2p, 3s) are dominated by ionizing component in the three cases.

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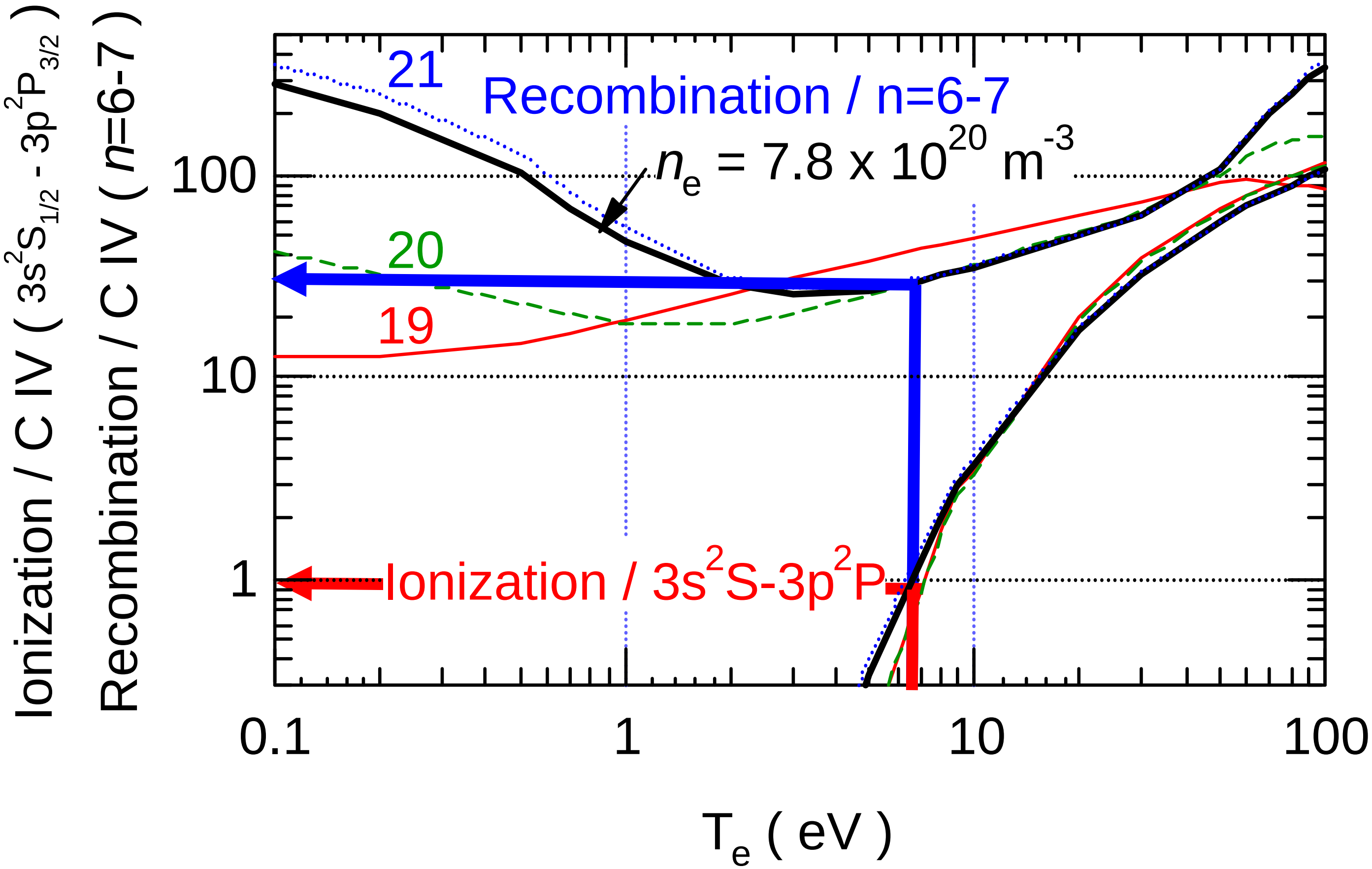
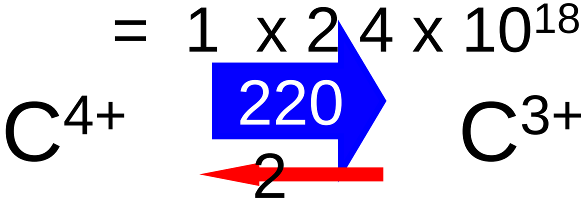
Ionization/ Recombination balance between C^{3+} and C^{4+}

JT-60U

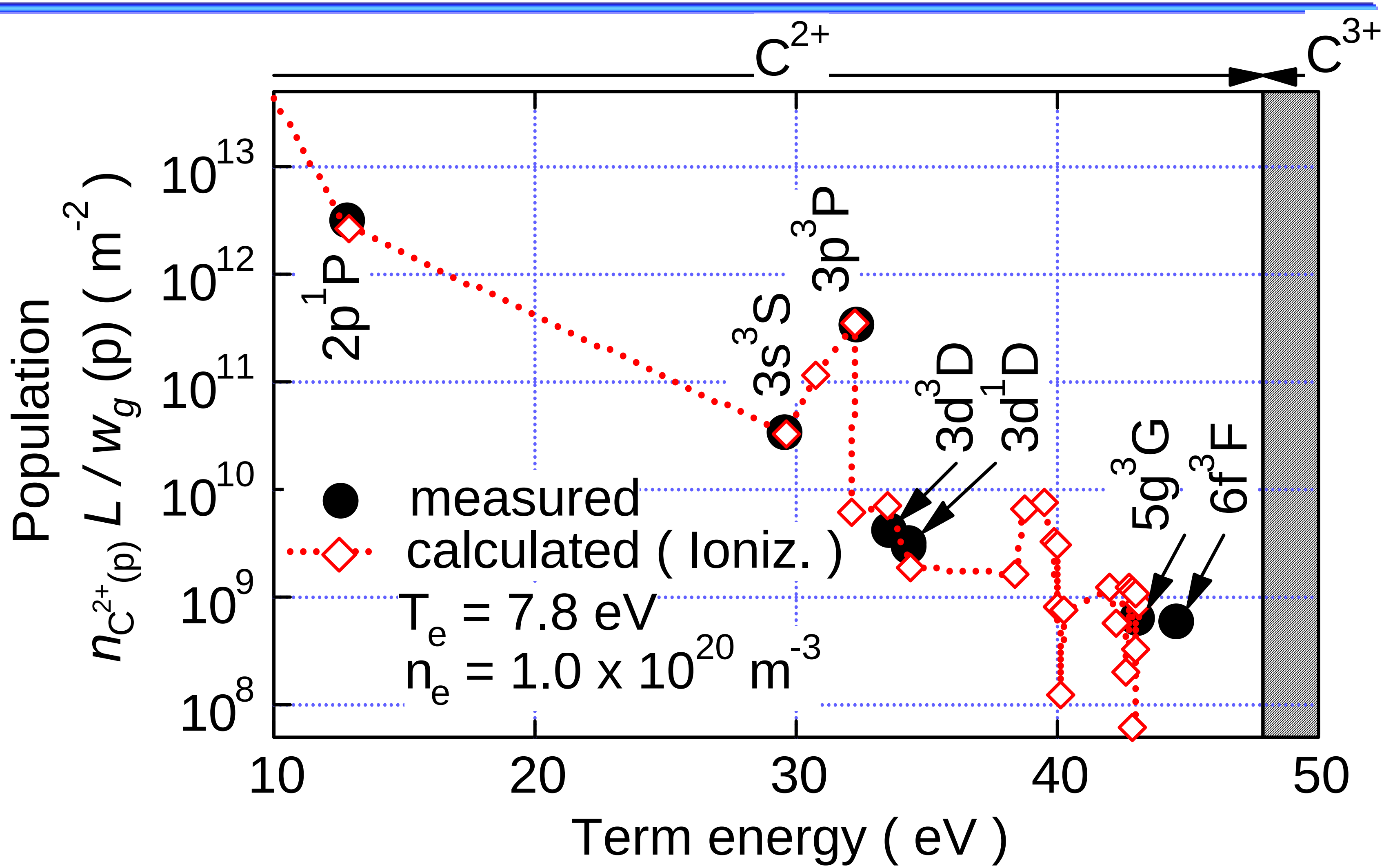


- C^{4+} recombination flux = 29 x 7.5 x 10^{18} = 2.2 x 10^{20} /m^2s
- C^{3+} ionization flux = 1 x 2.4 x 10^{18} = 2.4 x 10^{18} /m^2s



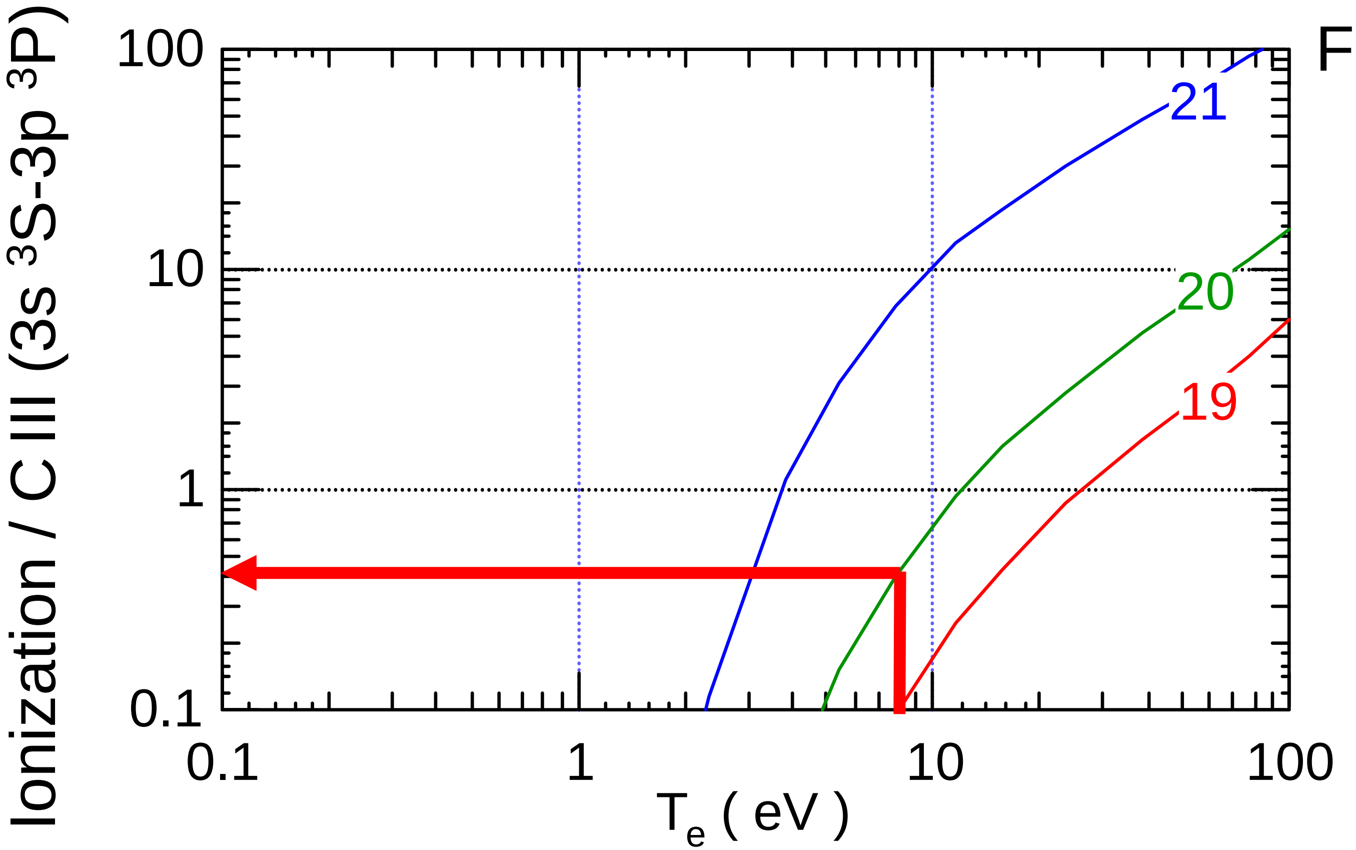
C III (C^{2+}):Ionization components dominates

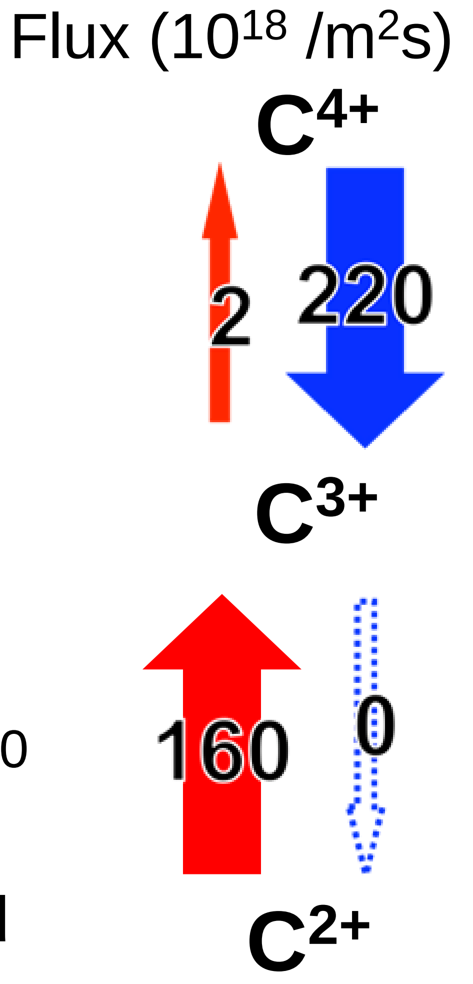
JT-60U



No recombining component.

Flux balance : C^{2+} ioniz. >> C^{3+} recomb.

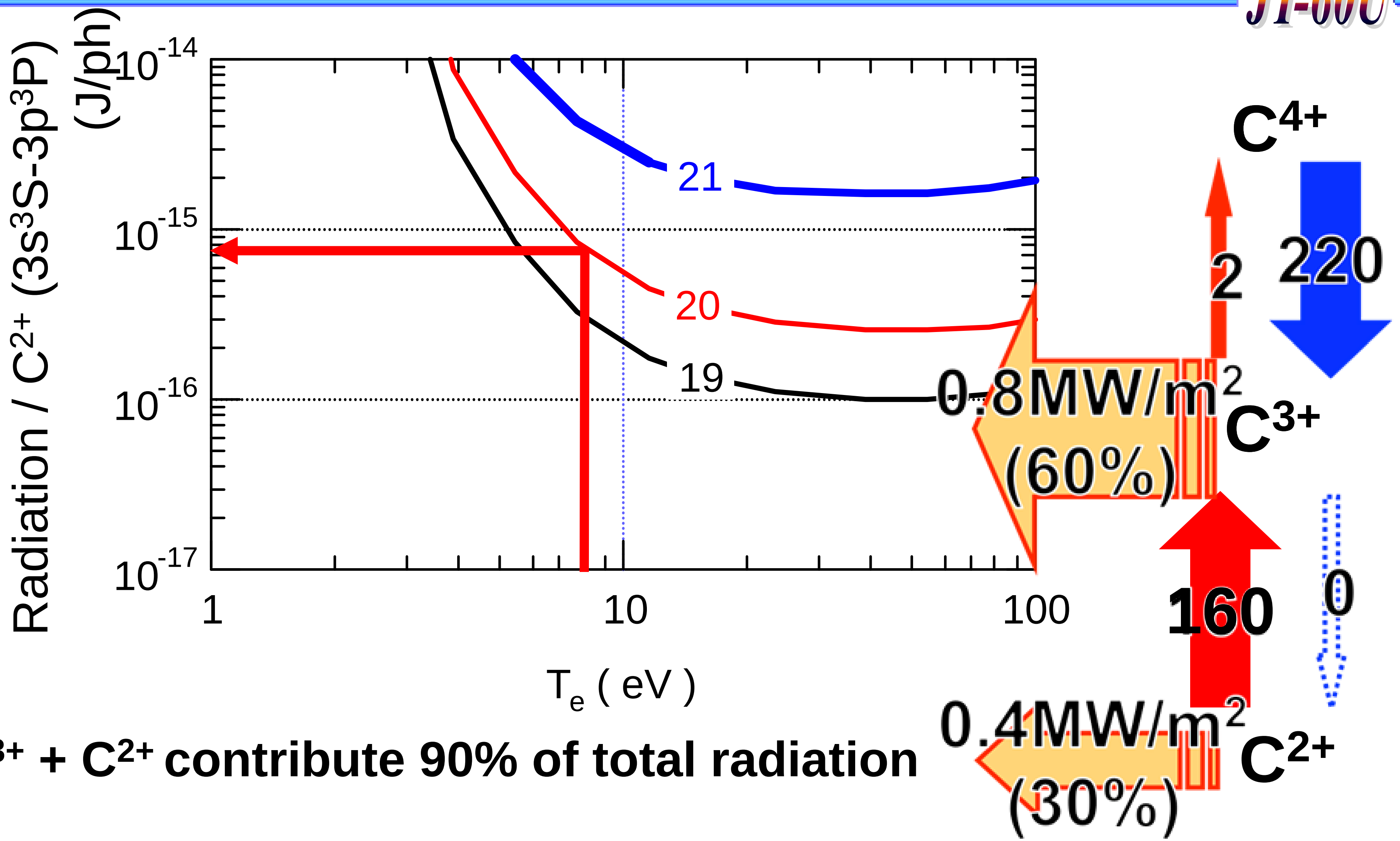




Transport loss of C^{3+} is suggested

Radiation power : C^{2+} contributes 30%

JT-60U



C^{3+} + C^{2+} contribute 90% of total radiation

Summary

JT-60U

In a cold and dense peripheral plasma (divertor plasma) of the JT-60U tokamak,

- C^{3+} is produced by C^{2+} ionization and C^{4+} recombination
- C^{3+} is lost little by C^{3+} ionization and not by C^{3+} recombination

$\Rightarrow$ Significant transport loss of C^{3+} from the X-point

- C^{3+} and C^{2+} radiate 60% and 30%, respectively, of total radiation power

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Tungsten as a PFM

<u>Merit :</u>

high melting point

low T retention => Significant merit for DT devices

low sputtering yeild

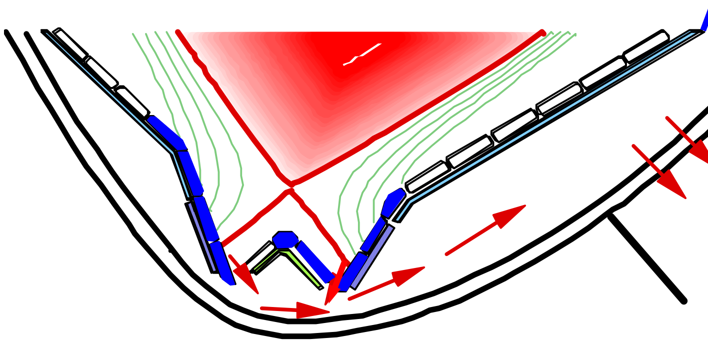
large larmor radius => Prompt redeposition

<u>Demerit :</u>

high Z => High radiation efficiency

accumulation

=> degrades of core confinement



Experiments in Large tokamaks:

simulation or test of W PFM for future devices.

• High heat and particle load onto the W-tile by Type I ELMs,

leading to high W

sputtering.

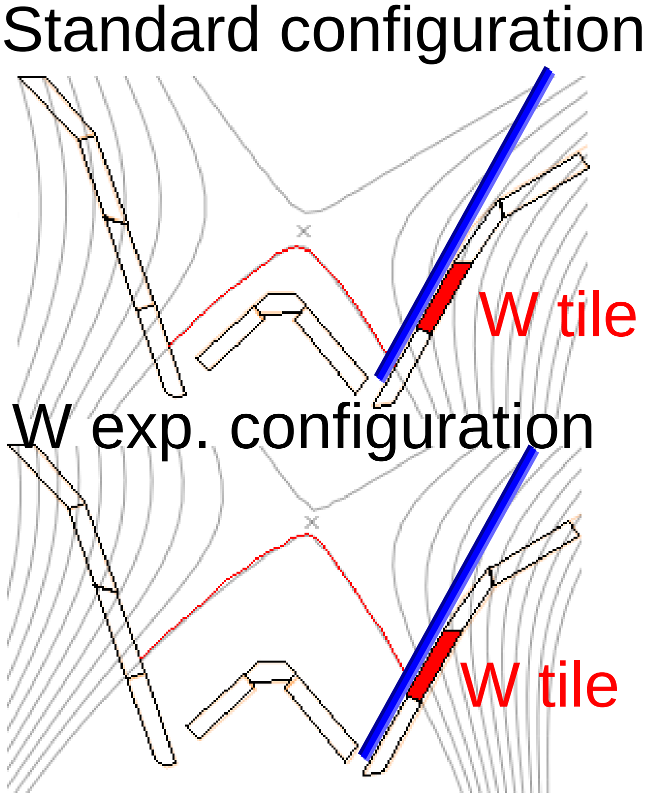
• Highly ionized tungsten (> W^{50+}) in high temperature plasmas,

W divertor plates in JT-60U

W coated CFC tiles:

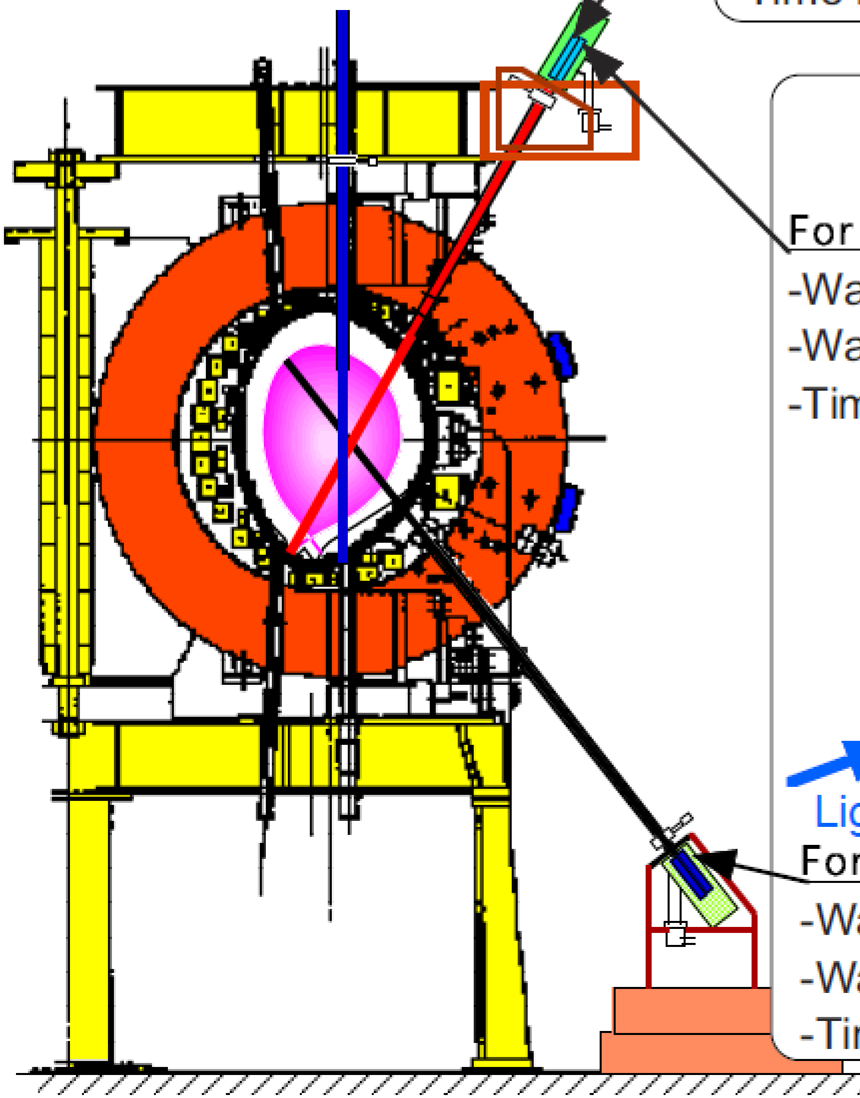
50 μm with Re multi-layer
12 tiles (1/21 toroidal length)

Visible spectroscopy:
for W I (W source)



VUV spectrometer

JT-60U



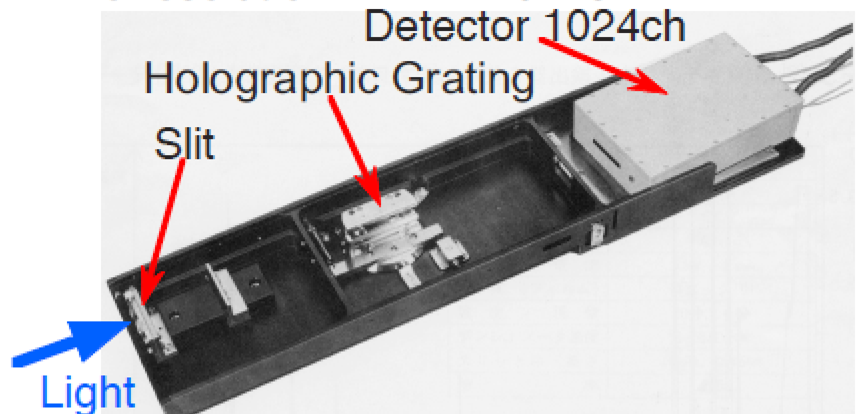
Normal incidence spectrometer[1]

- -Wavelength range: 97 nm - 155 nm
- -Wavelength resolution: $\lambda/\Delta\lambda$ ~ 1000 (@150nm)
- -Time resolution: 20 ms

Flat-field grazing incidence spectrometer

For divertor[1]

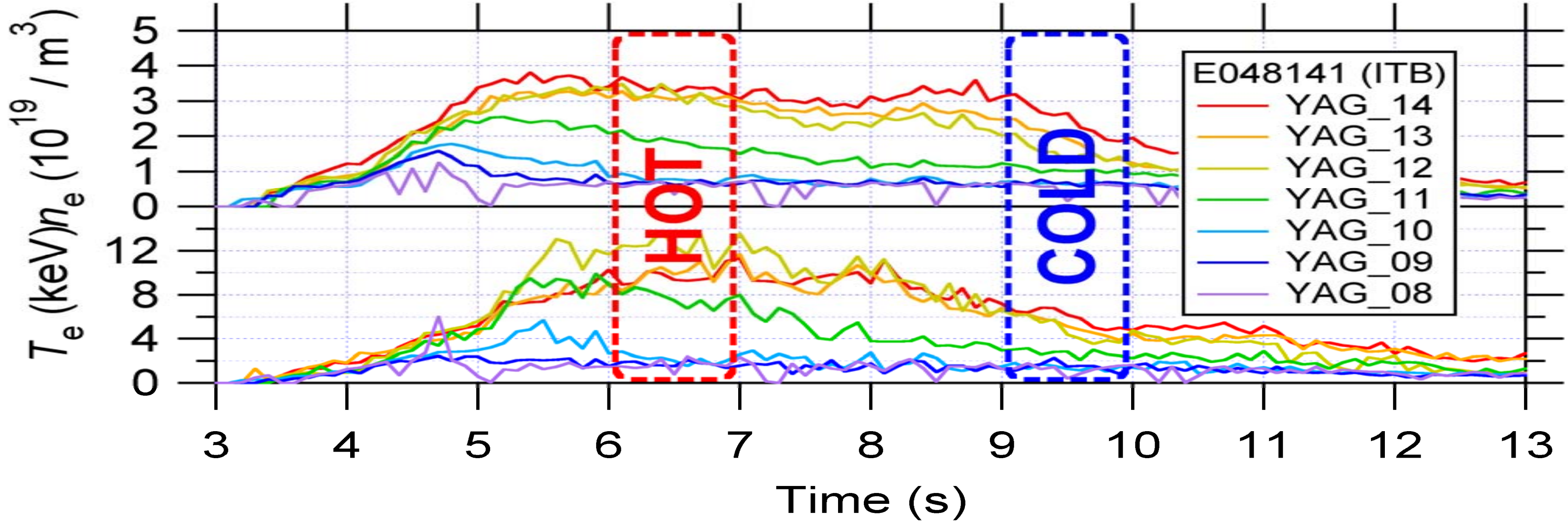
- -Wavelength range: 2.5 nm - 130 nm
- -Wavelength resolution: $\lambda/\Delta\lambda \geq$ 400 (@100nm)
- -Time resolution: 20 ms

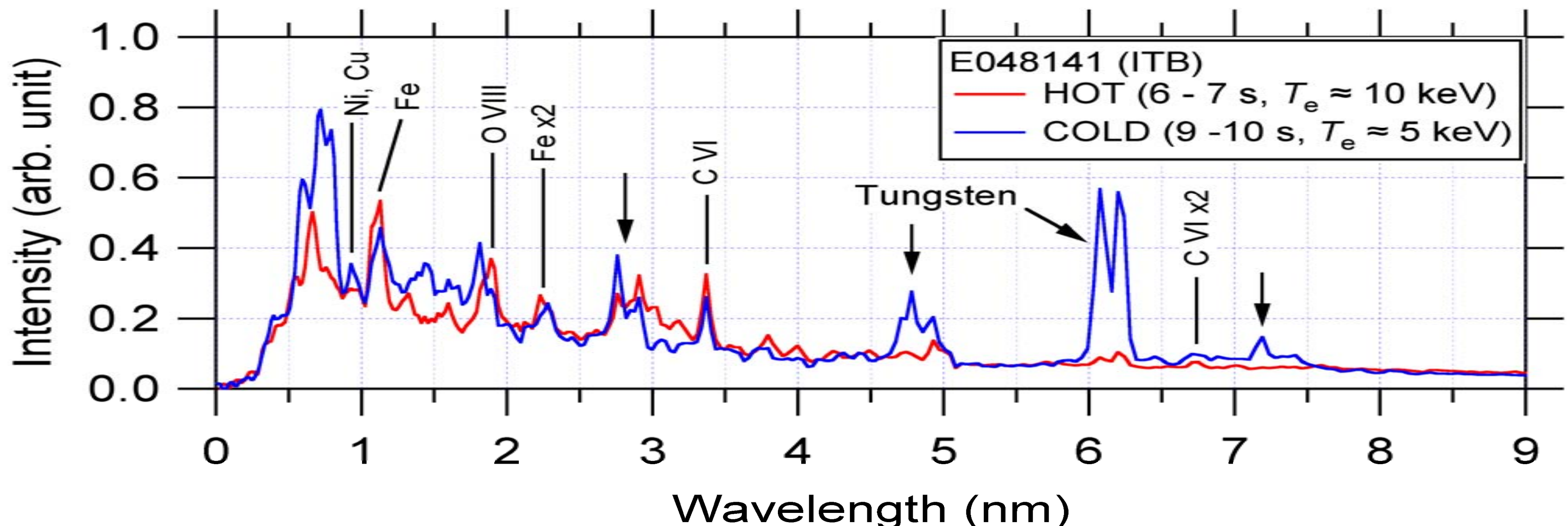


For main plasma[2]

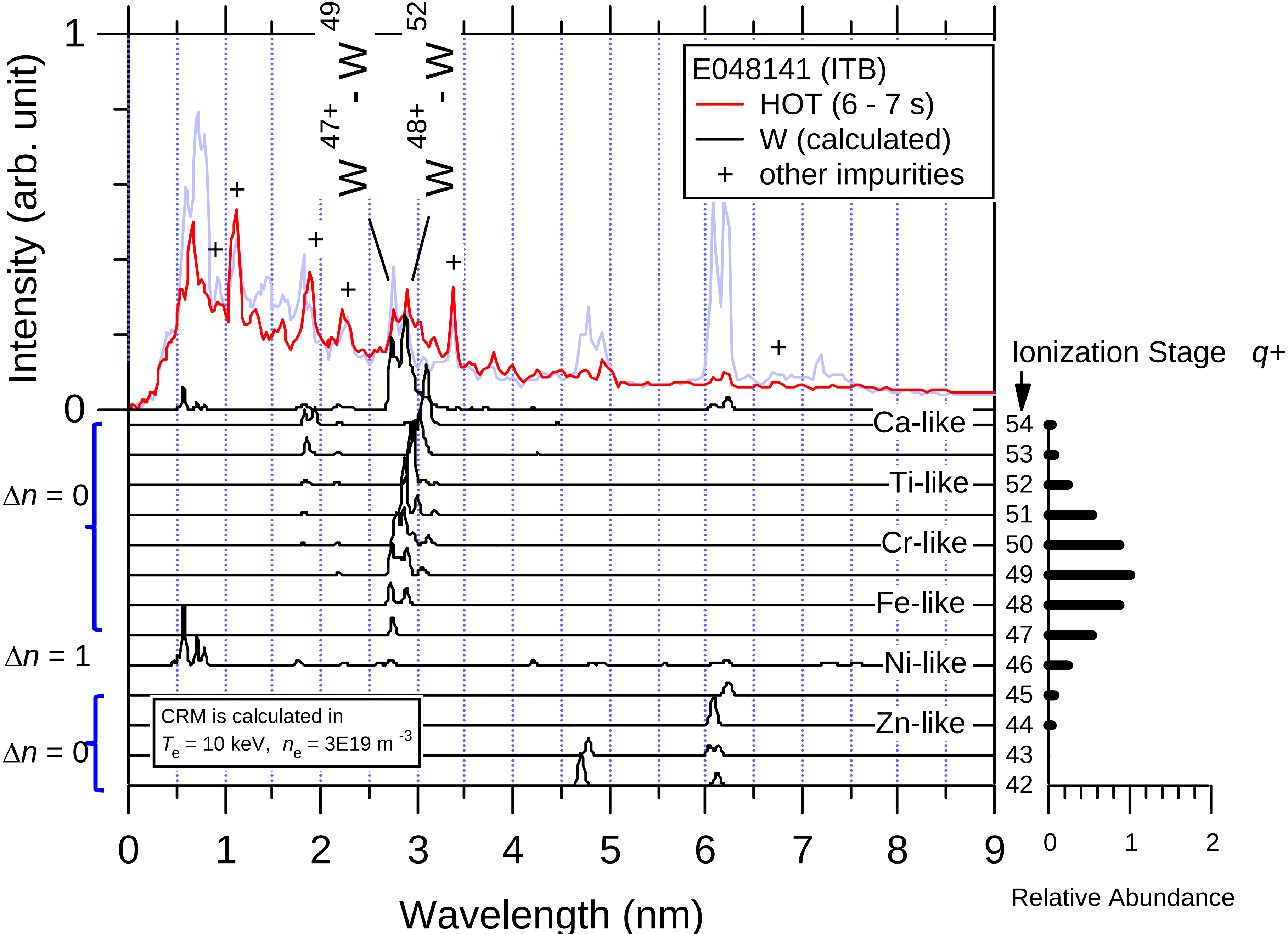
- -Wavelength range: 0.5 nm - 40 nm
- -Wavelength resolution: $\lambda/\Delta\lambda \geq$ 50 (at 5nm)
- -Time resolution: 20 ms

Highly Charged W Spectrum





Calculated W spectrum (FAC code)



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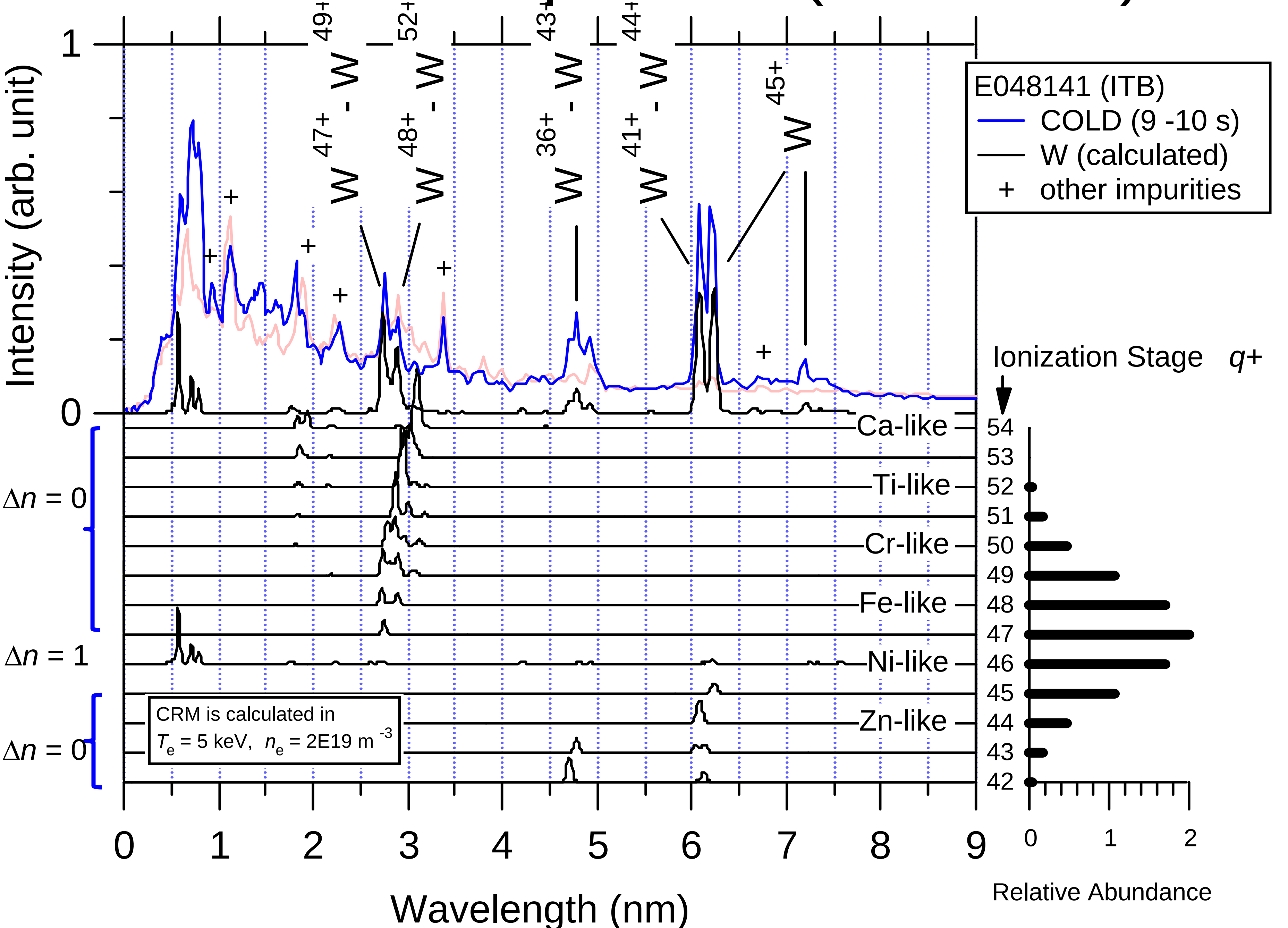
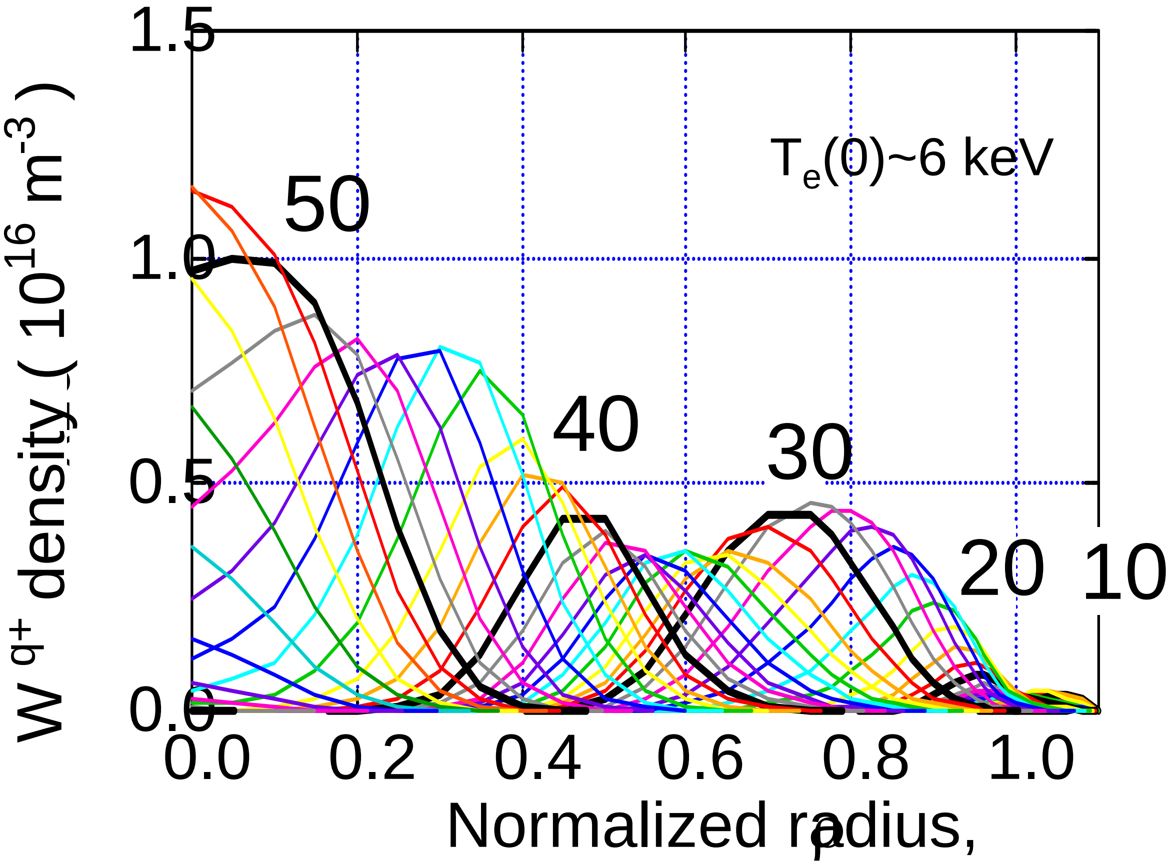


Calculated W distribution



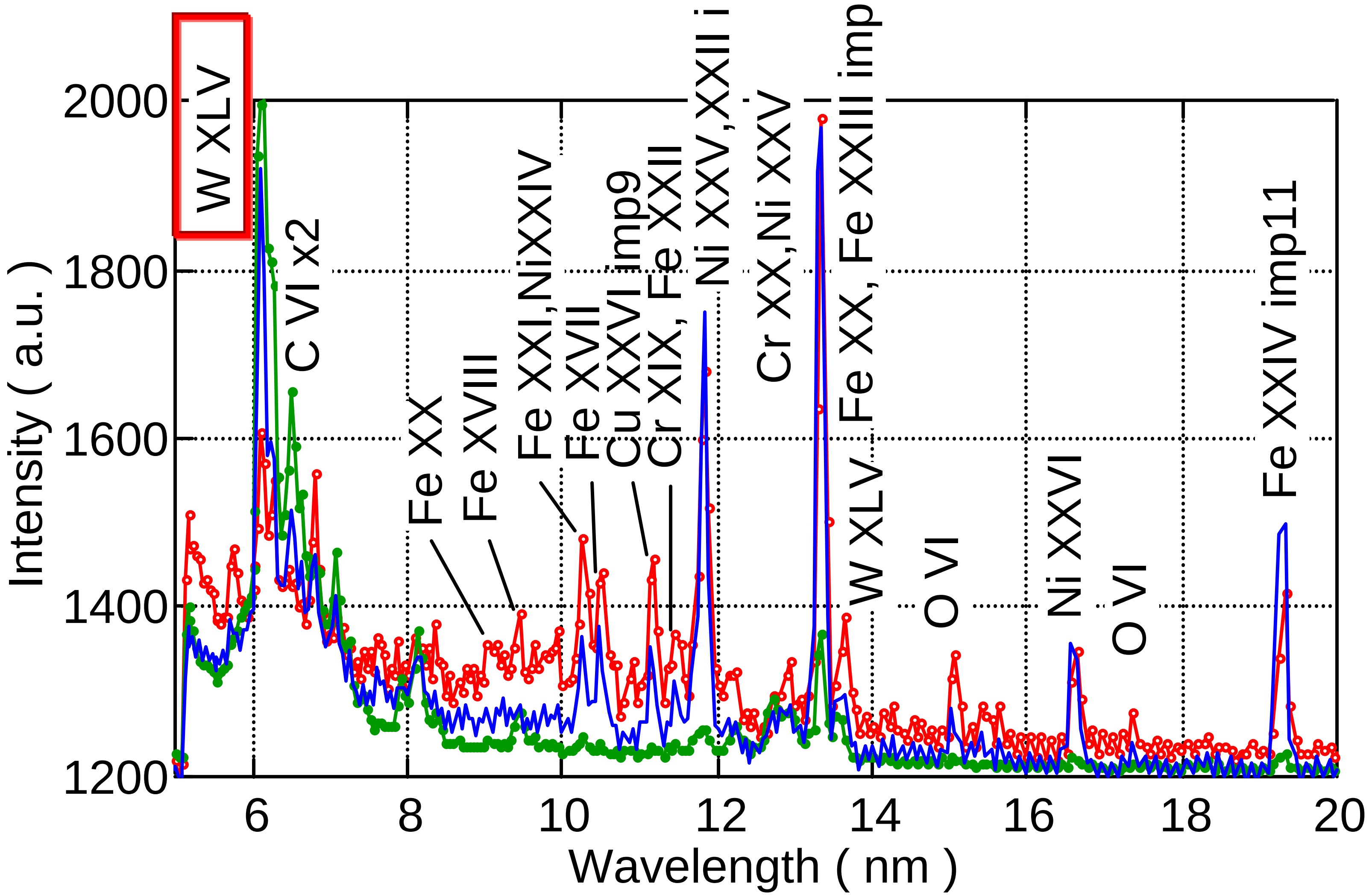
W^{44+} (W XLV) is peaked around ρ = 0.35

Intense brems. Emission from the core

VUV spectrum (5 - 20 nm)

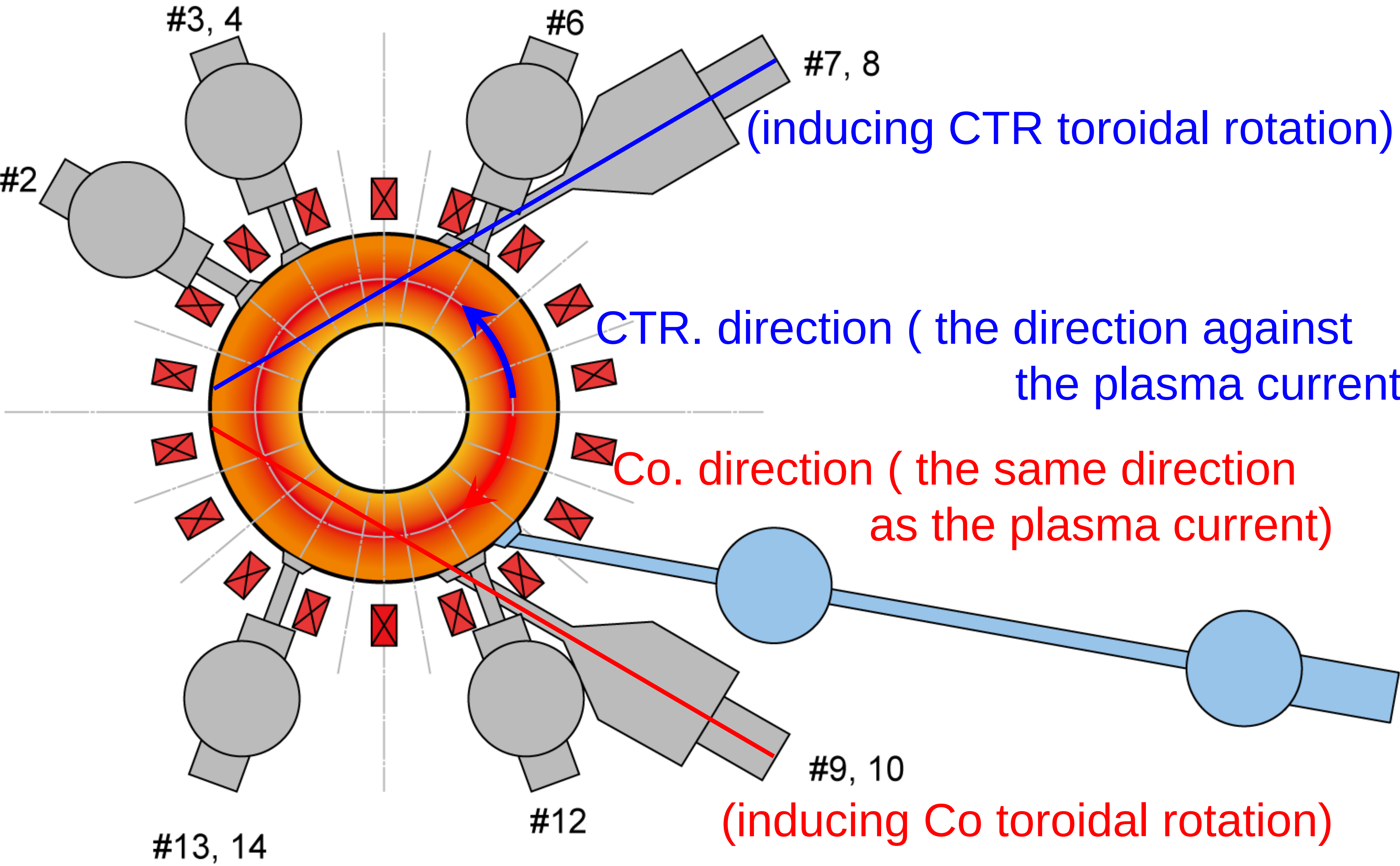
JT-60U

W XLV is used as a measure of the core accumulation.



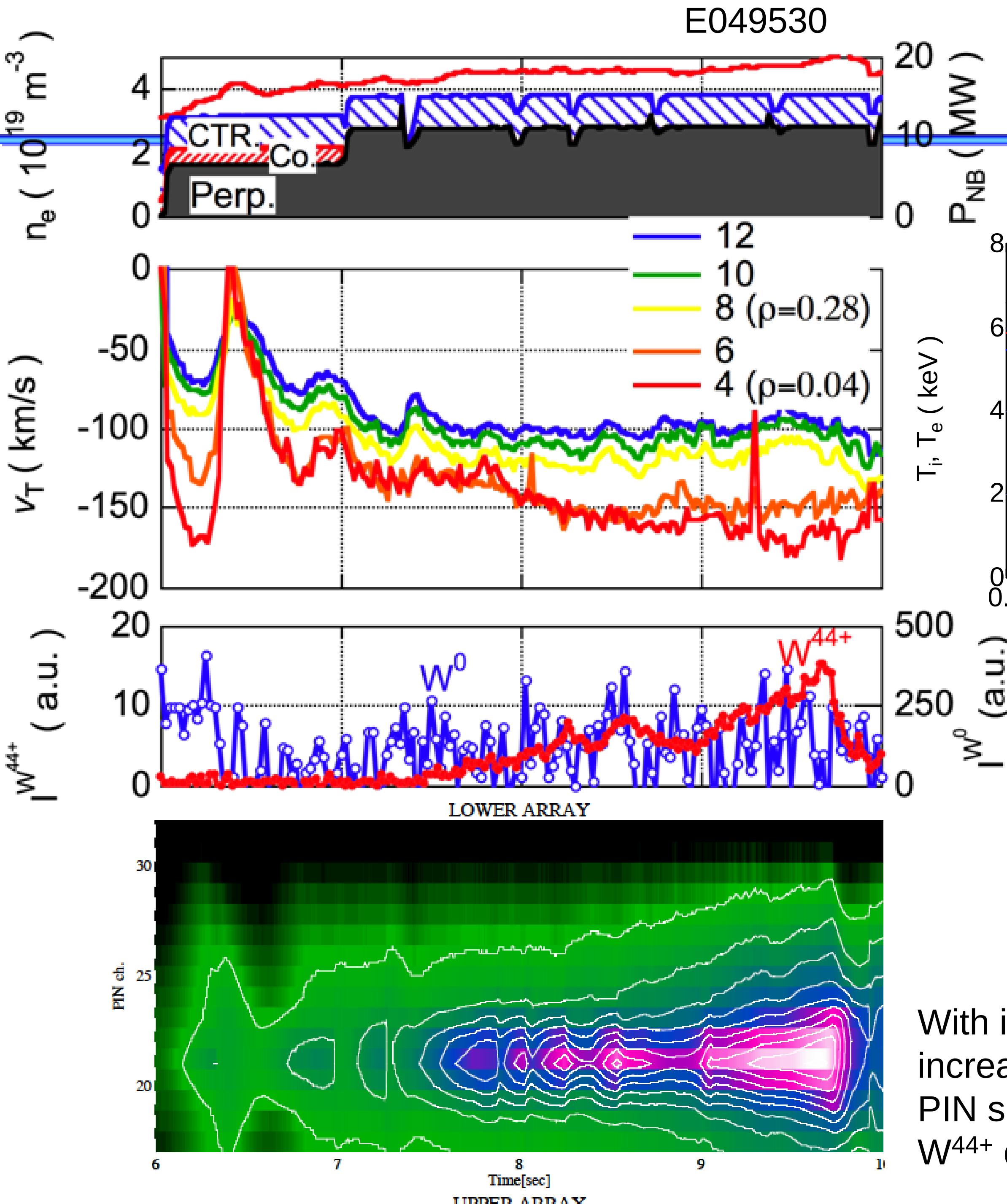
Neutral Beam Injection (NBI) system

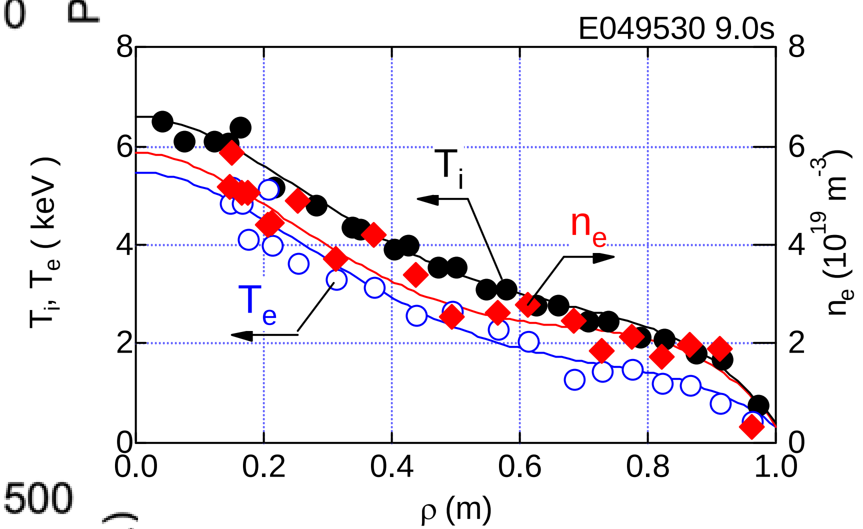
JT-60U



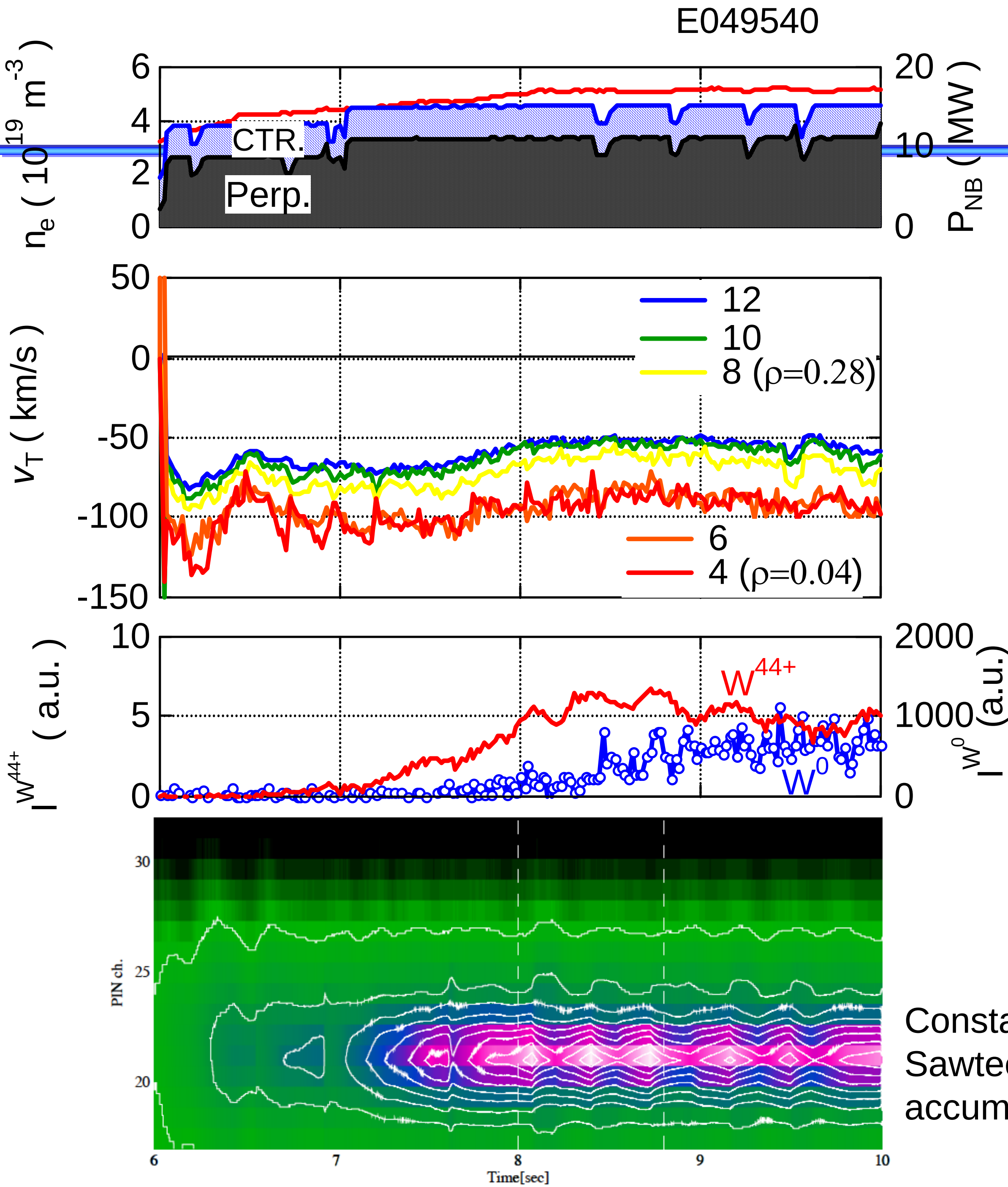
H-mode 1.6MA/3.6T (q_{eff}=4.8)
CTR rotation => W accumulation

JT-60U





With increasing $|V_t(8)-V_t(4)|$, W^{44+} increases.
PIN signal inverses at ~ 14 & 24 ch when W^{44+} decreases.



H-mode 1.6MA/3.6T (q_{eff}=4.8)

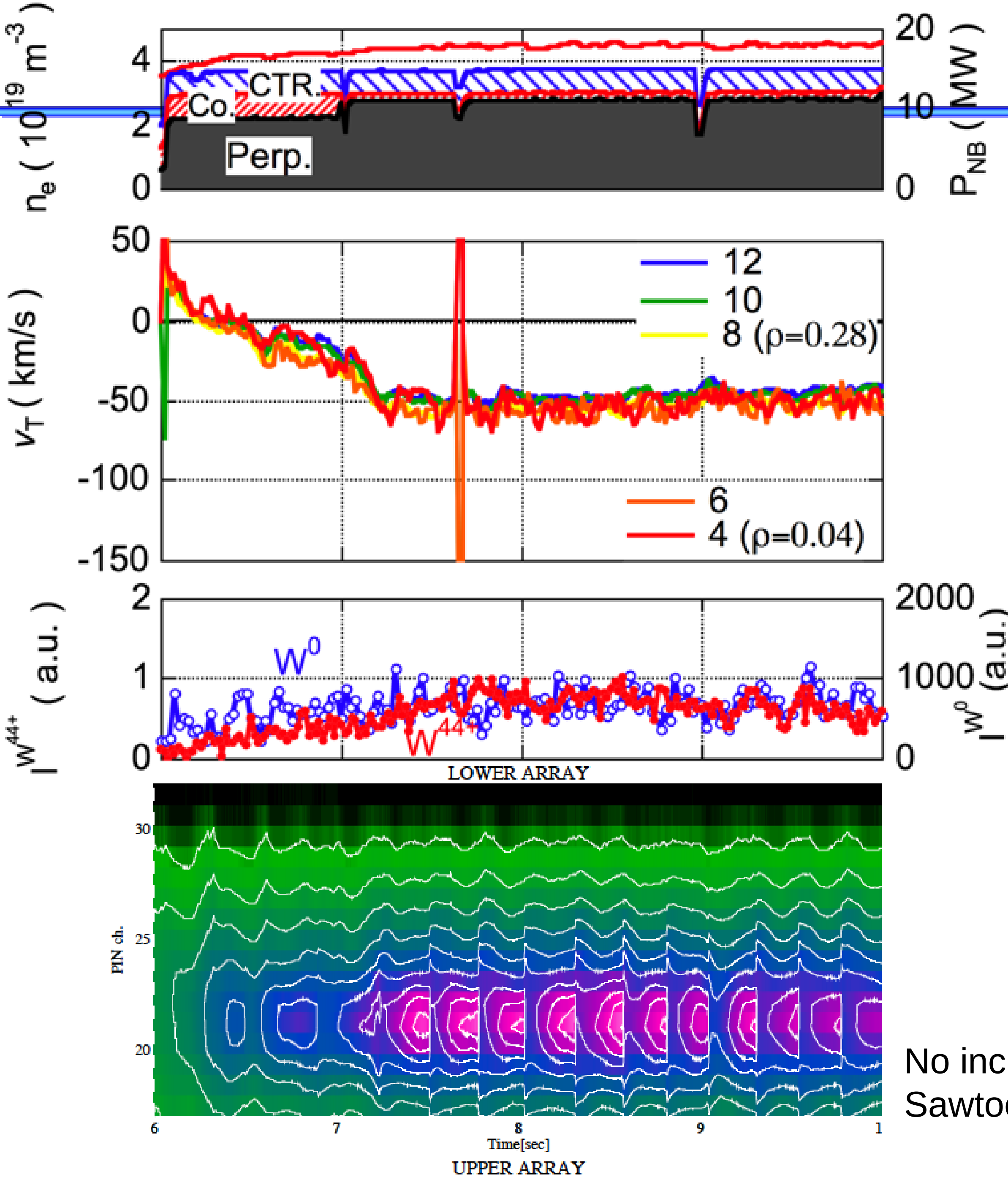
weak CTR rotation

=> moderate W accumulation

Constant $|V_t(8)-V_t(4)|$ and W^{44+}.

Sawteeth-like activity seems to expel the accumulated W

E049538



H-mode 1.6MA/3.6T (q_{eff}=4.8)

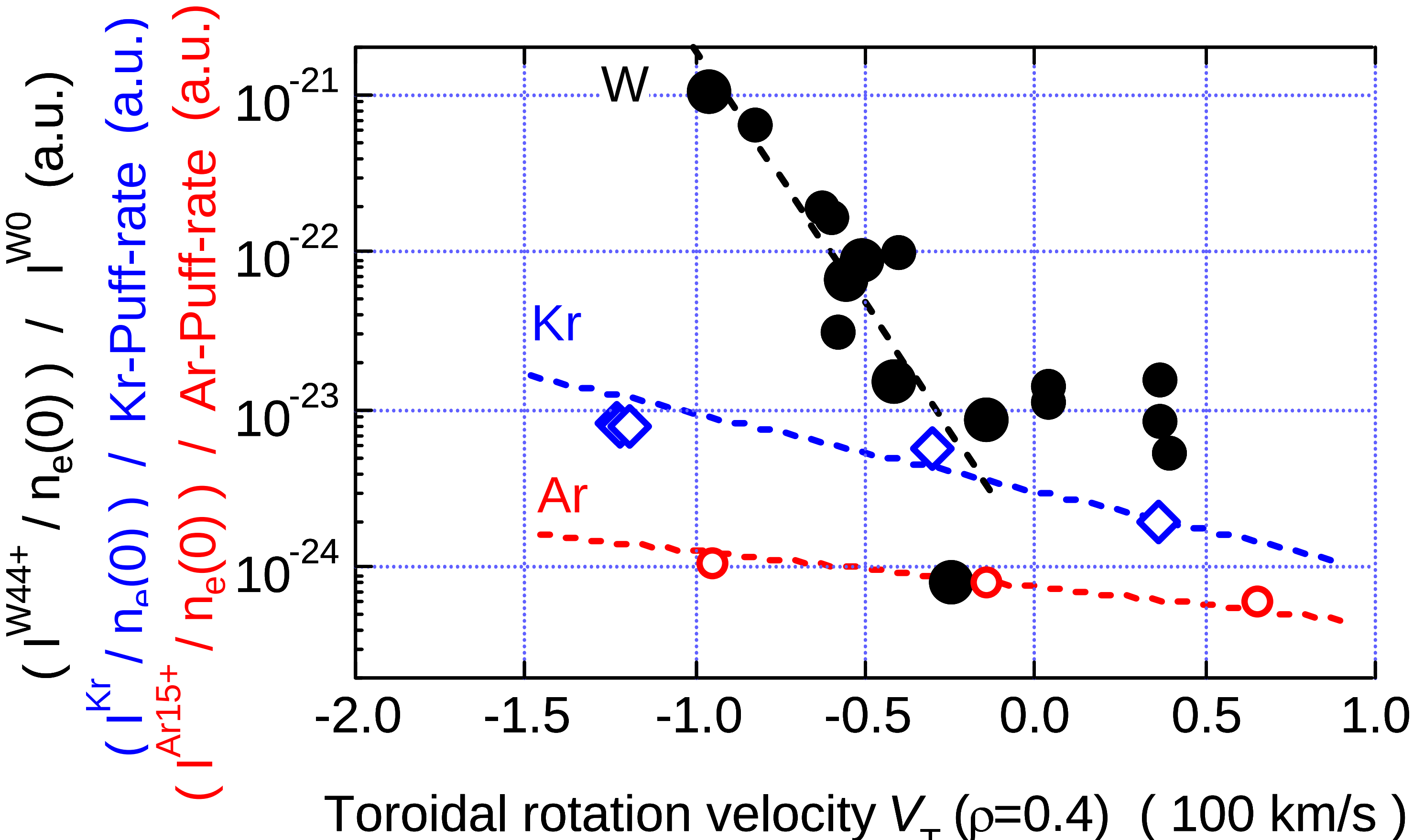
weak CTR rotation

=> moderate W accumulation

No increase in $|V_t(8)-V_t(4)|$ and W^{44+}.

Sawtooth inversion layer is at ~ 15 & 23 ch.

More significant W accumulation trend than Ar and Kr



With decreasing Vt,
W accumulation becomes more significant than Ar & Kr.
=> Significant Z dependence of accumulation

Summary

- With increasing toroidal plasma rotation velocity against the plasma current, W accumulation tends to be more significant.
- From the comparison of Ar and Kr reference discharges, Z dependence of impurity accumulation is observed.
- W spectrum analysis by FAC code is in progress.