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Deposition of tungsten and carbon at local plasma-shadowed areas in TEXTOR test limiter experiments

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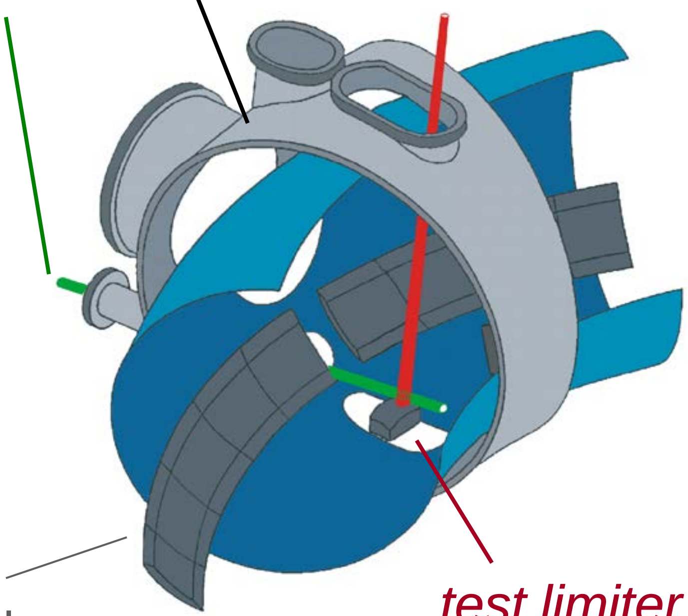
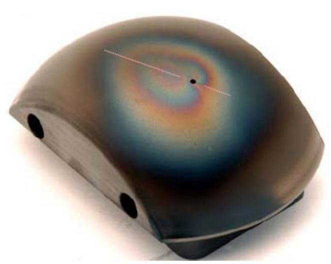
O-8 / PSI–21 / Kanazawa, Japan (27.05.2014)

Impurity injection experiments in TEXTOR





General experimental set-up

- Known amounts of gaseous impurities are injected through a hole in the test limiter surface

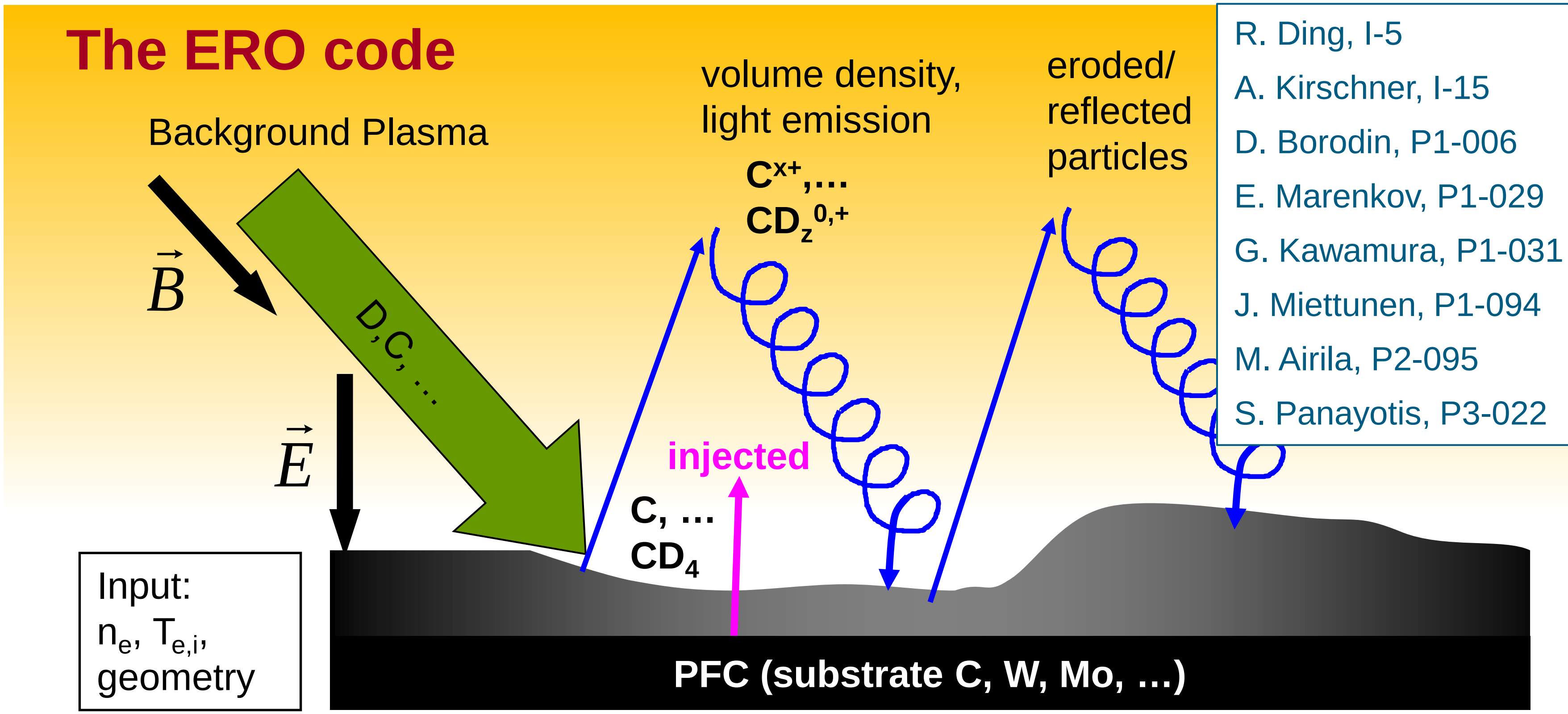
  ($^{13}CH_4$, WF_6, …)

- In-situ spectroscopy
- Post-mortem surface analysis

Local deposition efficiency

$$\frac{\text{\# injected atoms deposited on the test limiter surface}}{\text{total number of injected atoms}}$$

Modelling of injection experiments



R. Ding, I-5
A. Kirschner, I-15
D. Borodin, P1-006
E. Marenkov, P1-029
G. Kawamura, P1-031
J. Miettunen, P1-094
M. Airila, P2-095
S. Panayotis, P3-022

Local impurity transport in plasma:

- ionisation, dissociation, light emission
- friction (Fokker-Planck), thermal force
- Lorentz force
- cross-field diffusion

Plasma-surface interactions:

- physical sputtering/reflection
- chemical erosion (CD_4, BeD)
- (re-)erosion and (re-)deposition
- coupling with SDTrimSP

Impurity injection experiments in TEXTOR

A. Kirschner, PSI-2010
A. Kreter, P1-024

- **Tracer impurity experiments in TEXTOR**

  - low local deposition efficiency of injected species (0.3 - 1.7%)
  - enhanced re-erosion in ERO and EDDY (also for AUG, JET, PISCES-B);
    → low energy species deposited at plasma-wetted areas
    → no enhancement at remote locations
    → deposition efficiency increases for limiter biasing, low injection rates and high surface temperatures

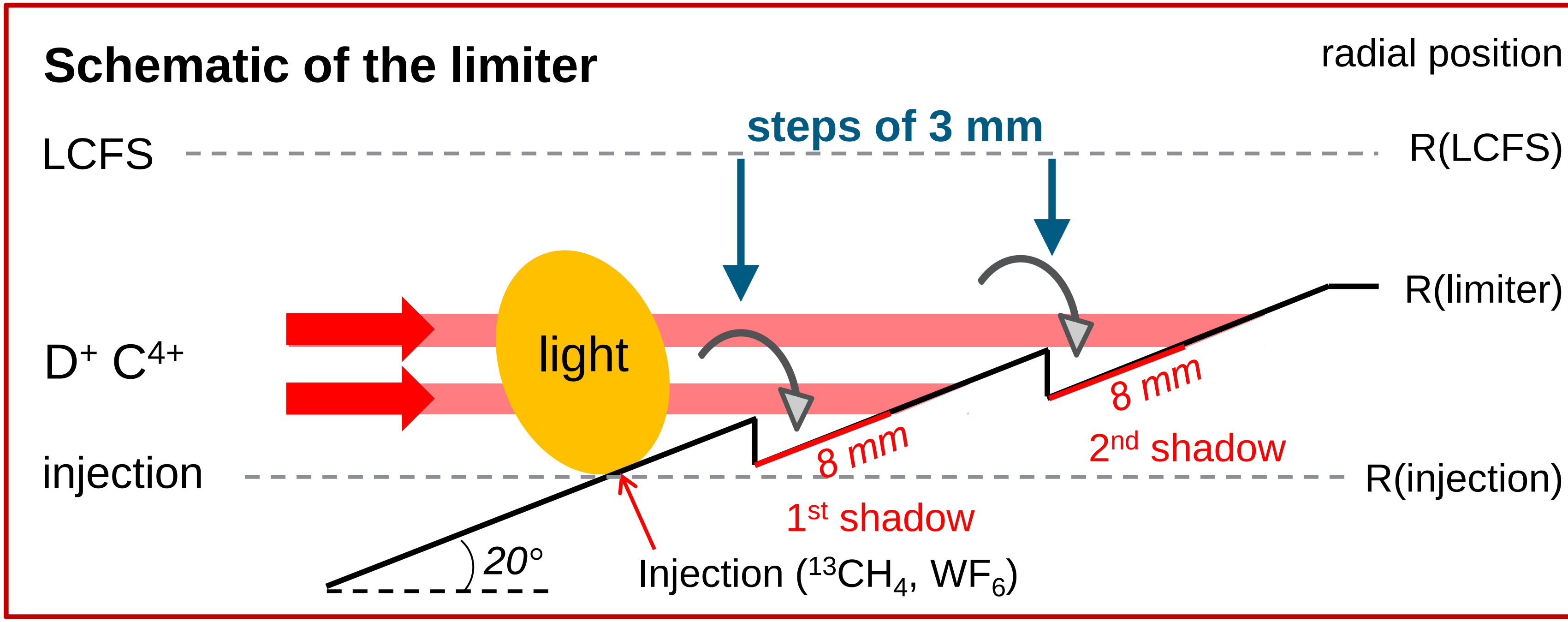
R. Doerner, P1-026

H.G. Esser, PSI-2010
A. Kirschner, PFMC-13

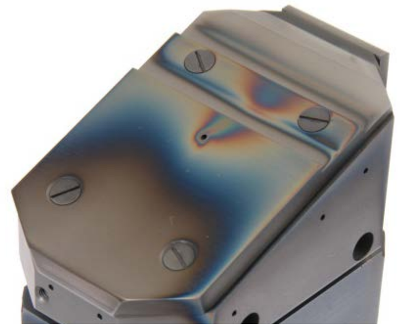
- **Further benchmarking of the ERO code is needed**

  - enhanced erosion ? reduced sticking ? underestimated particle losses ?
  - searching for experimental conditions contradicting the hypothesis
  - deposition at plasma-shadowed locations (no eroding flux from plasma) is expected to be larger and can help to validate modelled particle sources

Stepped limiter experiments



New injection experiments in TEXTOR



"stepped" limiter

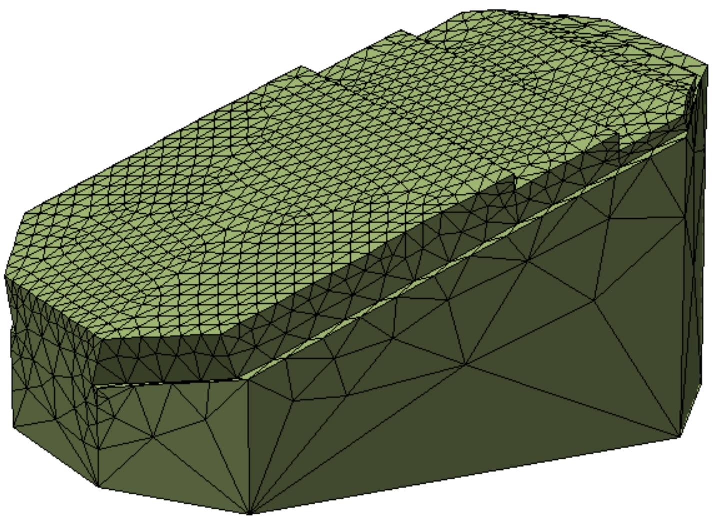
IDEA: plasma exposed and plasma shadowed surfaces in one experiment, benchmarking the ERO code

Separation of deposition and erosion in shadows due to different Larmor radii of injected ($^{13}CH_4$, WF_6) and background impurity species

New flexible geometry in ERO

MeshLib library, © S. Bozhenkov, IPP Greifswald

- Representation of surfaces with polygonal meshes
- **PROS:** flexibility with surface geometry and related calculations: particle transport, plasma parameters, connection lengths, shadowing, etc.
- **CONS:** significant increase of the computational time



Stepped limiter experiments

Ion penetration into shadowed regions (Larmor radii estimation)

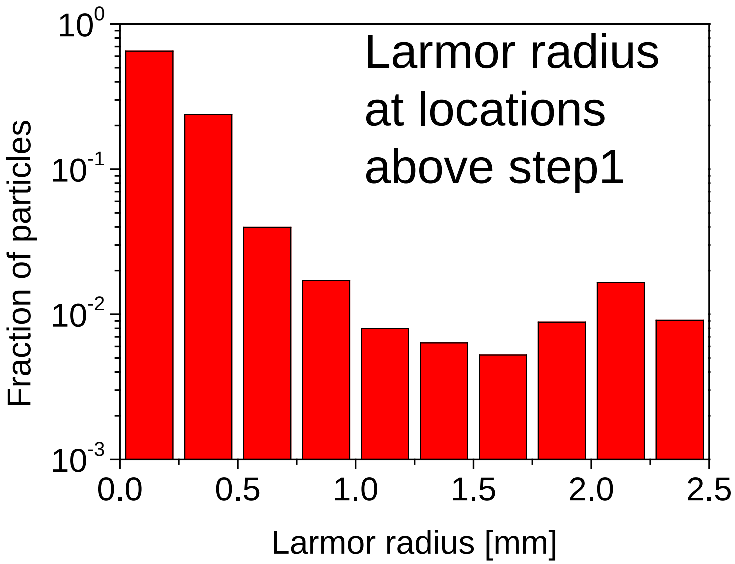
$^{13}CH_4$		WF_6	
Background plasma T_i (@step1) ≈ 77 eV		**Background plasma** T_i (@step1) ≈ 30 eV	
D^+	ρ_L = 0.8 mm	D^+	ρ_L = 0.5 mm
C^{3+}	ρ_L = 0.65 mm	C^{3+}	ρ_L = 0.4 mm
C^{4+}	ρ_L = 0.5 mm	C^{4+}	ρ_L = 0.3 mm
Injected C, CH_x (if thermalized to T_i !)		**Injected W** (if thermalized to T_i !)	
C^+	ρ_L = 1.9 mm	W^+	ρ_L = 4.8 mm
C^{2+}	ρ_L = 0.95 mm	W^{2+}	ρ_L = 2.4 mm
Real energies <~ T_i … C^+, C^{2+}, CH_x^+ not thermal !		Real energies <~ T_i … + prompt re-deposition !	

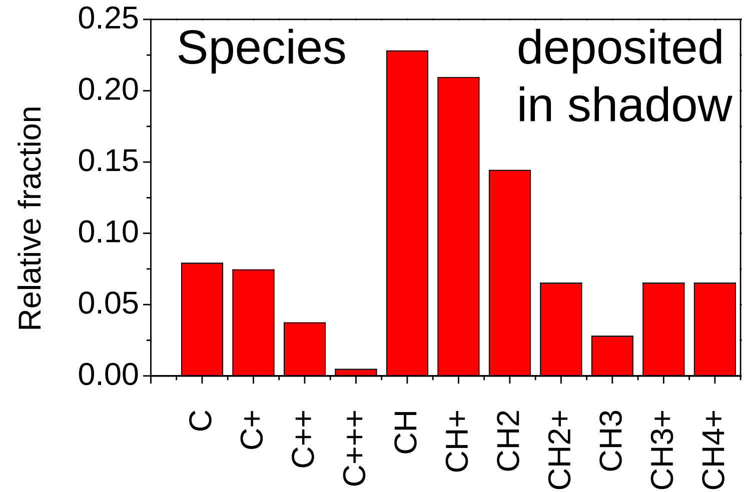
do not penetrate deep into shadow ↔ (background plasma ions)

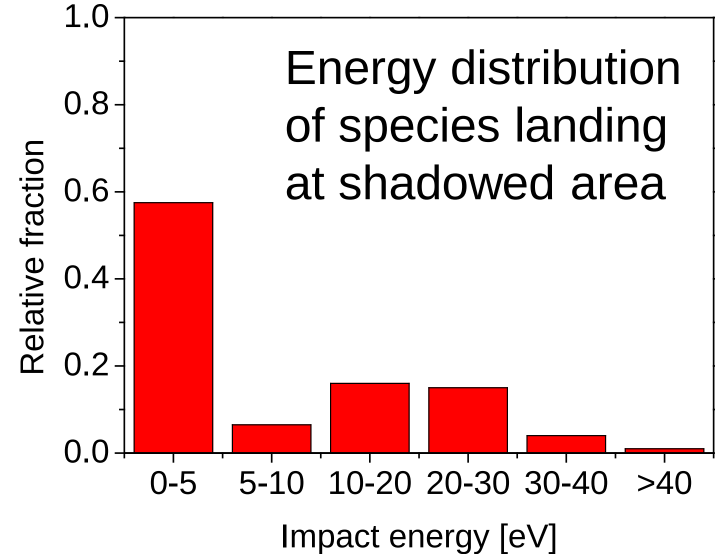
Small penetration of C comp. to W ↔ (injected ions)

$^{13}CH_4$ injection: modelling

Ion penetration into shadowed regions (ERO modelling)







Larmor radii predominantly ≤ 0.5 mm
→ ions hardly penetrate into shadow

Average penetration into shadow
→ 0.5 mm (ions), 3.7 mm (neutrals)

Total contribution of neutrals: 48%

Self-sputtering by ions possible (< 1%)

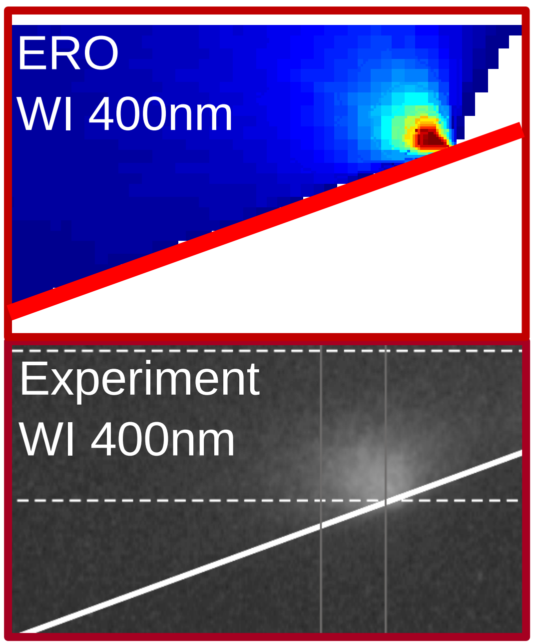
WF_6 injection: modelling

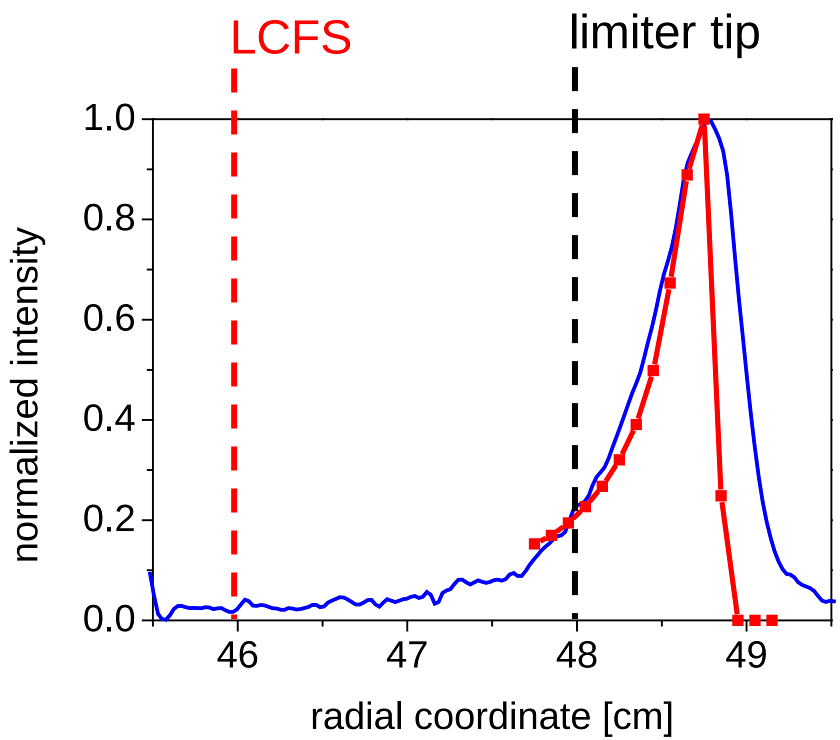
Adjustment of W effective ionization rate based on spectroscopy

Dissociation data for WF_6 not available in ERO

→ *inject W^0 atoms* & *reduce ionisation rate for injected W^0*

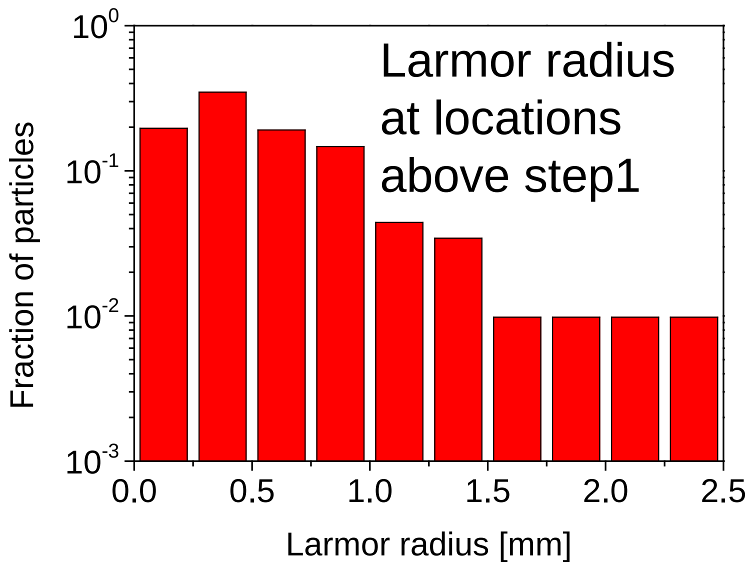
→ match observed W^0 light ← effective "dissociation + ionization" rate

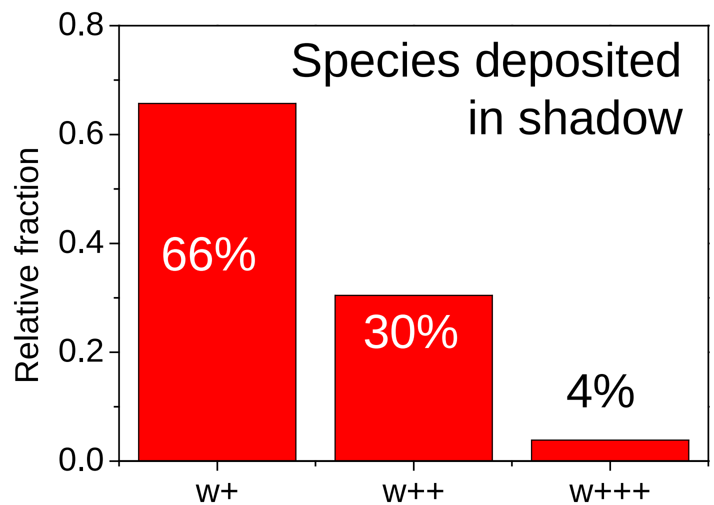


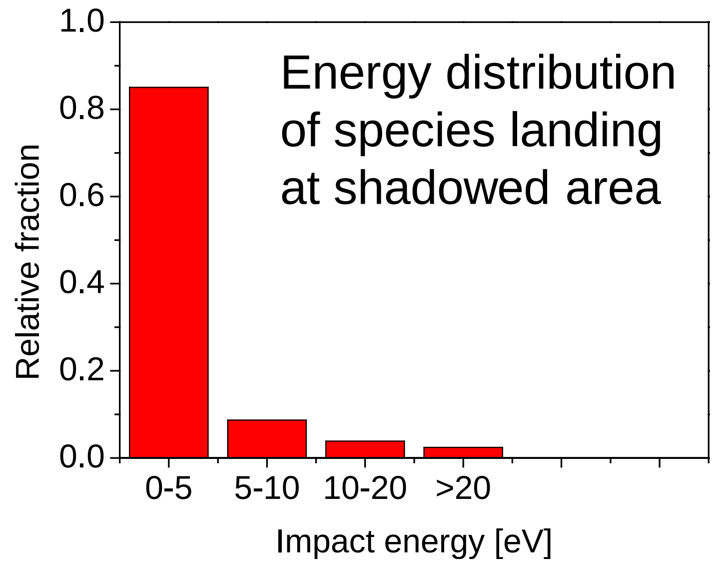


WF_6 injection: modelling

Ion penetration into shadowed regions (Larmor radii estimation)







Larmor radii predominantly ≤ 1.0 mm
→ deeper penetration vs C ions

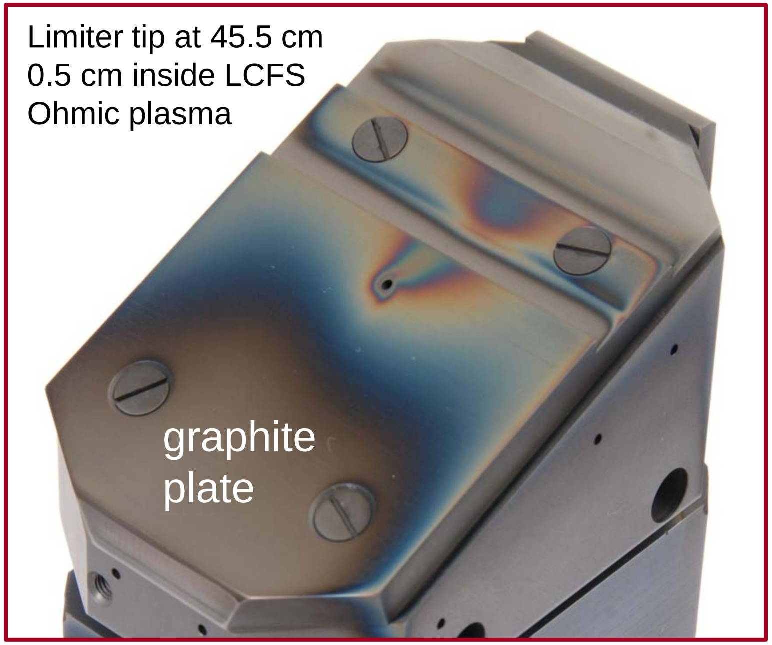
Average penetration into shadow
→ 2.7 mm (W^+), 2.6 mm (W^{2+})

Only ions: 66% W^+ ; 30% W^{2+}

E_{in} < 5eV, self-sputtering negligible

Experimental deposition efficiency

$^{13}CH_4$ injection



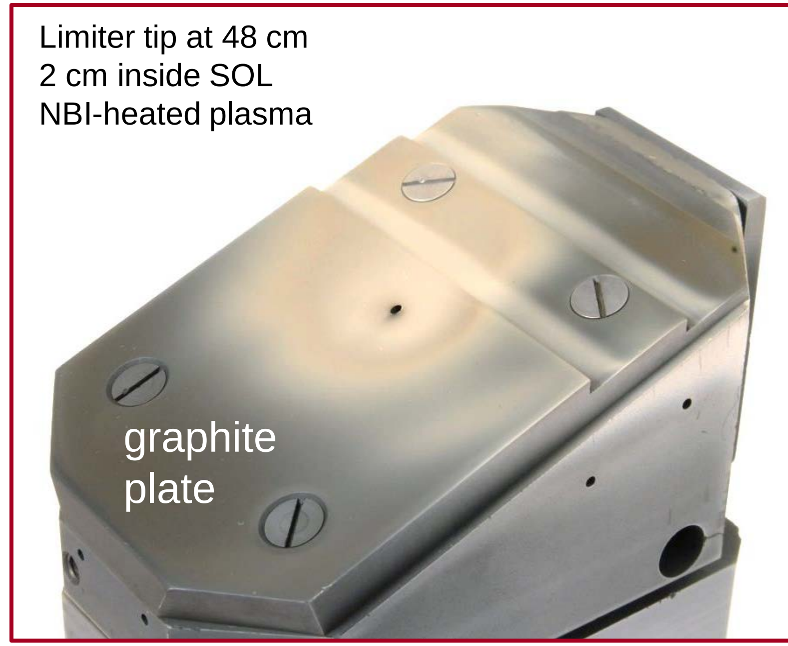
Total injection: 1.28×10^{21} $^{13}CH_4$

Local deposition efficiency

0.45 for ^{13}C

[roof limiter: **0.3-1.7%]**

WF_6 injection



Total injection: 3.26×10^{20} WF_6

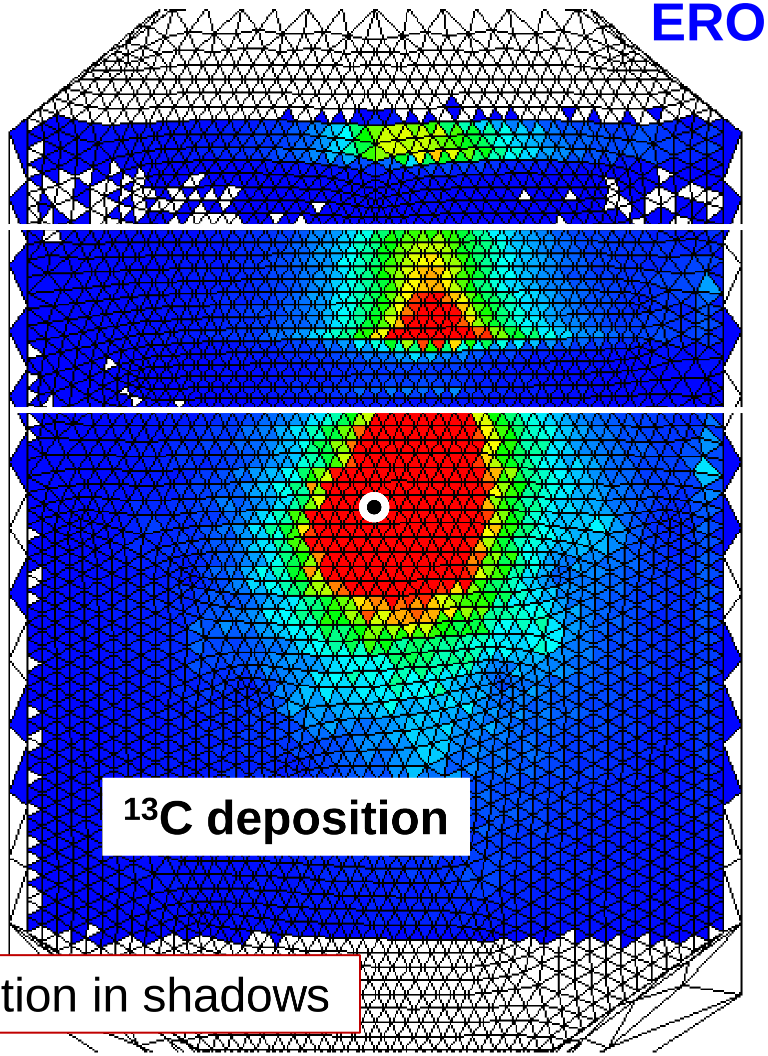
Local deposition efficiency

1.9% for W, < 0.02% for F

[roof limiter: **~1%**]

Different conditions → no clear effect on deposition efficiency → modelling !

$^{13}CH_4$ injection: deposition patterns



No significant ^{13}C deposition in shadows

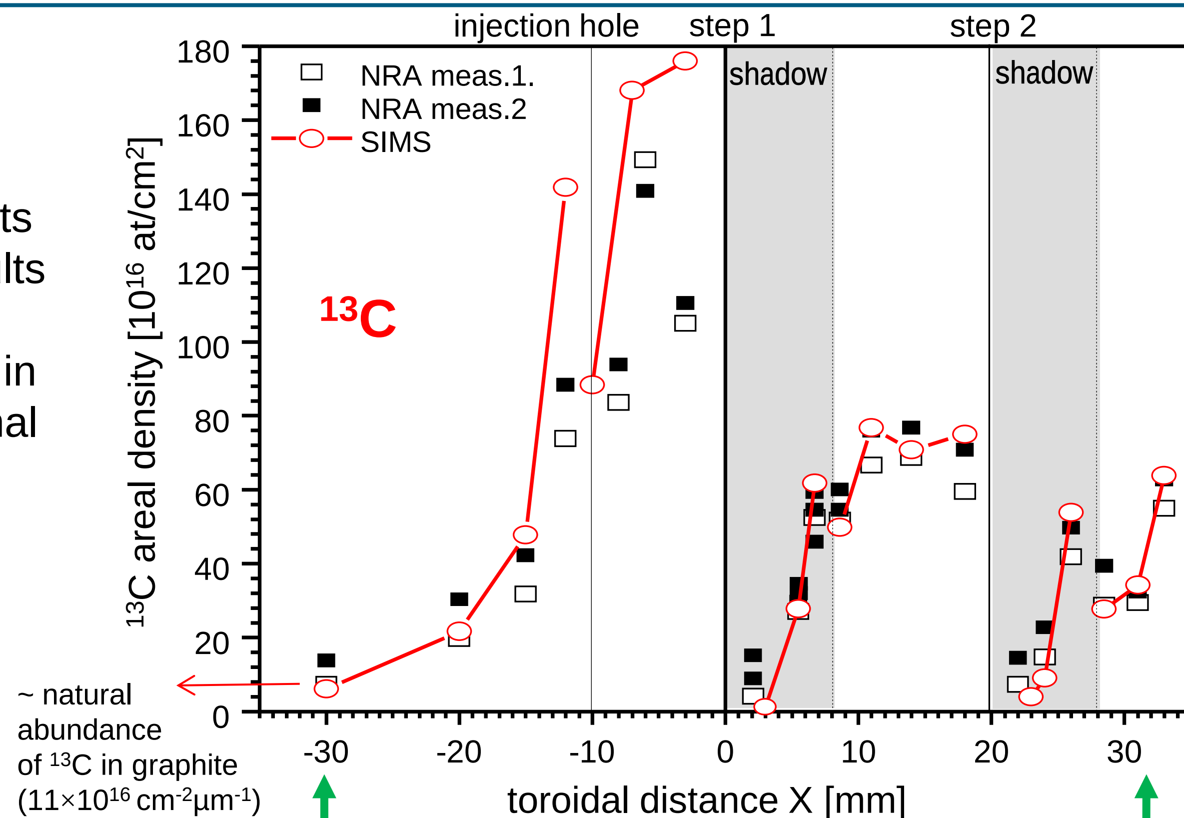
$^{13}CH_4$ injection: surface analyses

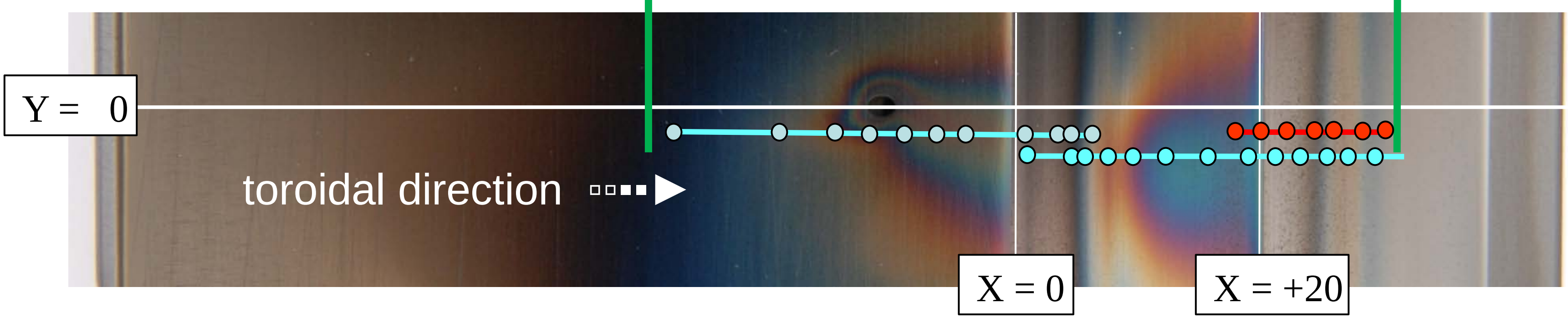
NRA

NRA measurements confirm SIMS results

Penetration of ^{13}C in shadows is marginal

Larger D content in shadows





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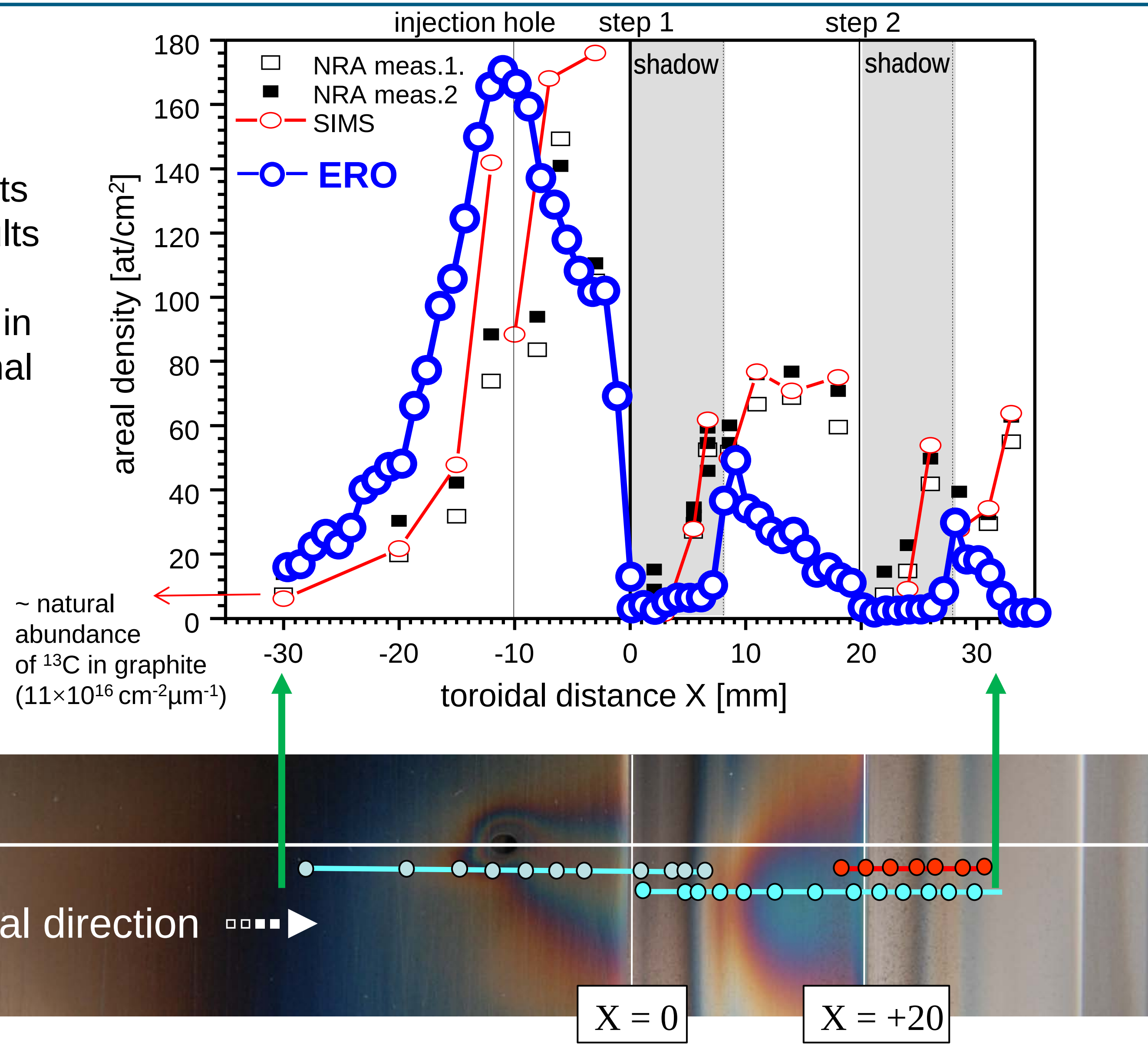
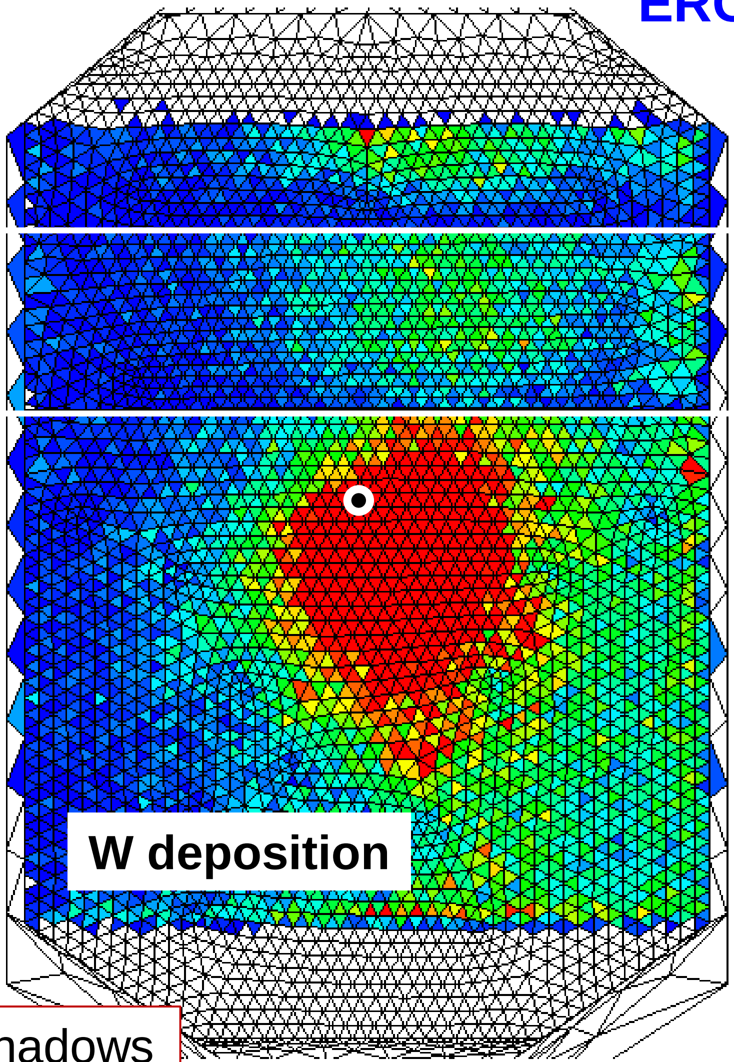


WF_6 injection: deposition patterns



W deposition in shadows

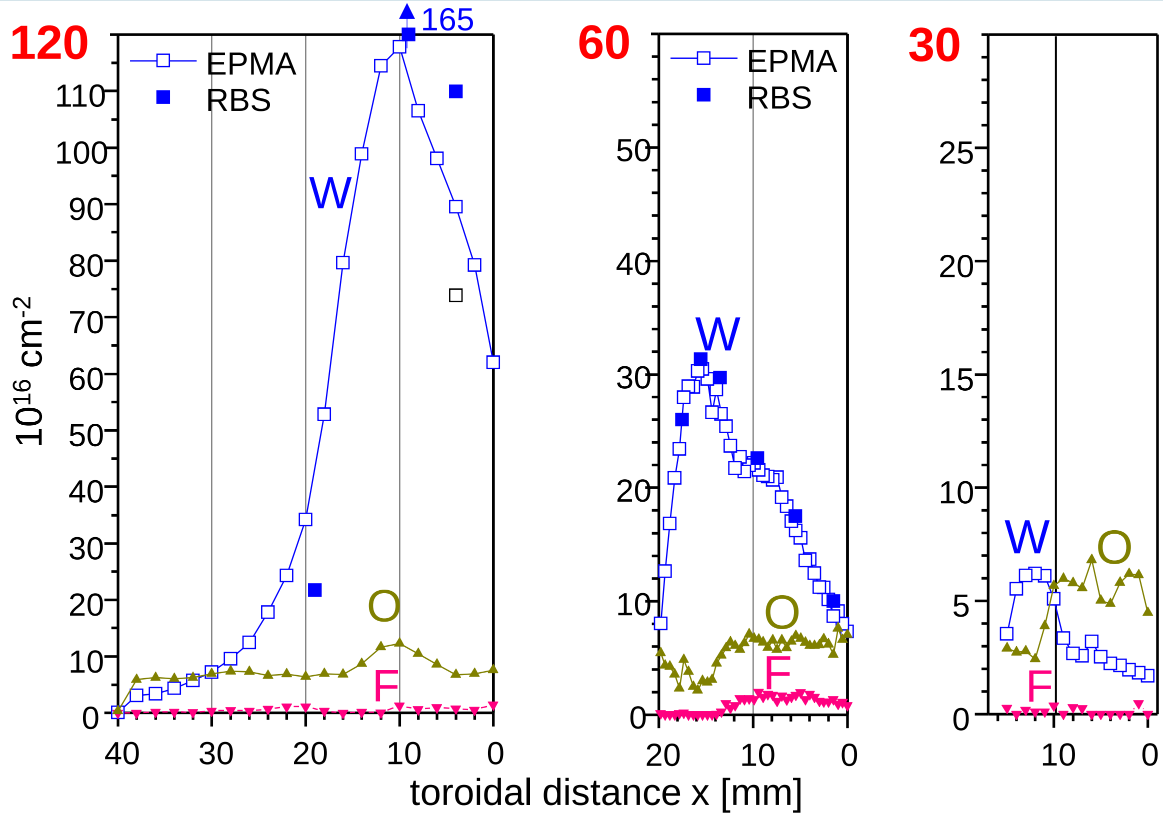
WF_6 injection: surface analysis

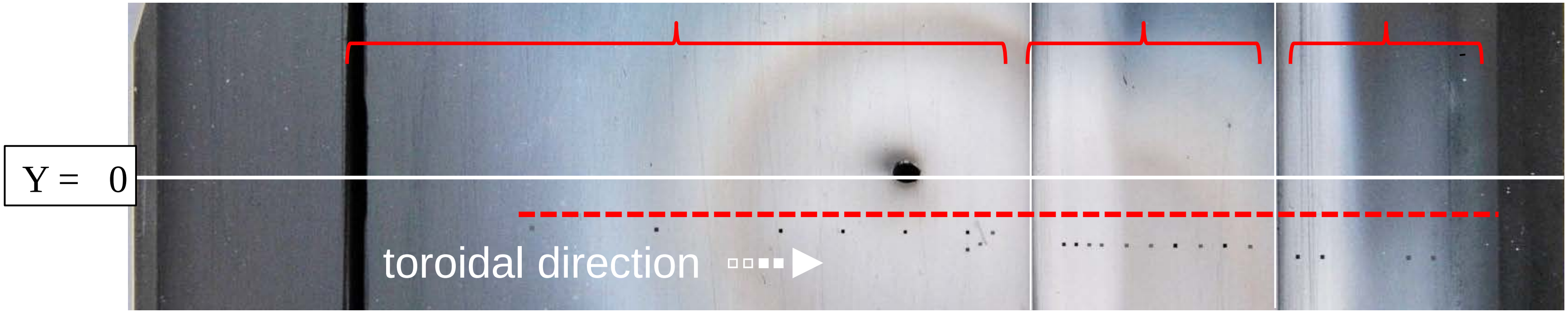
EMPA

RBS confirms EPMA within 30%

12×10^{17} W/cm^2 near injection hole, 400nm → 3×10^{22} cm^{-3} = x2 less than C in TEXTOR a-C:H (~6.5×10^{22}, H/C ~ 0.4)

3×10^{17} & 0.6×10^{17} W/cm^2 in shadows = factor 2-3 more than outside





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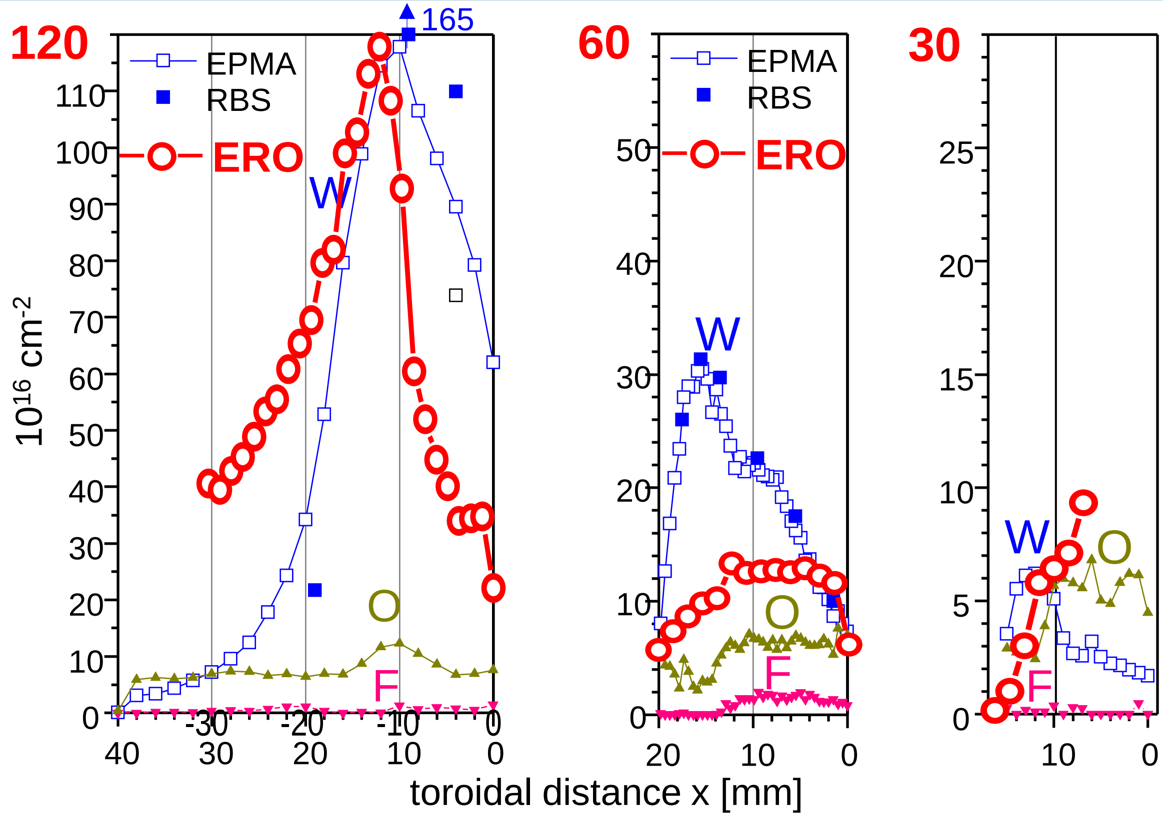

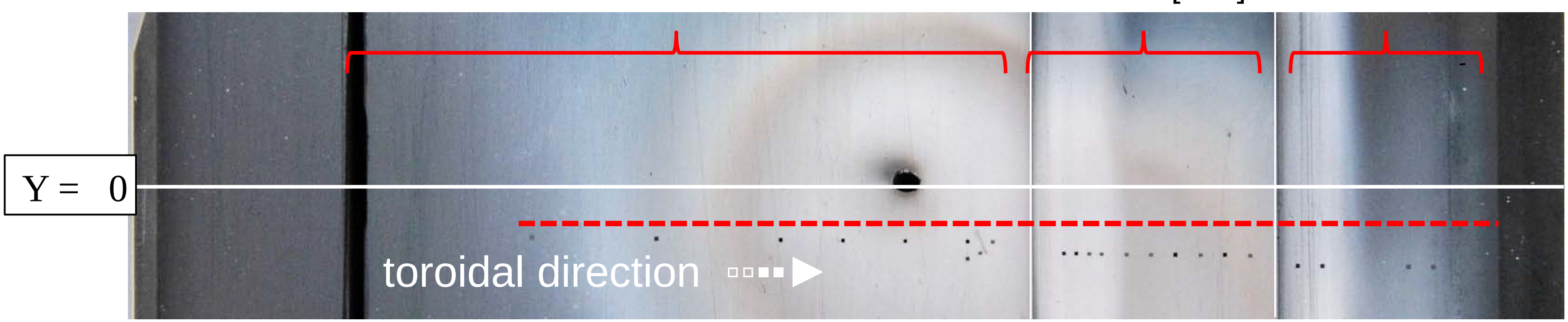

Summary and conclusions

- The effect of *low deposition efficiency* is observed in TEXTOR for carbon as well as for metallic species (W, Mo)
- Assumption of *enhanced (re-)erosion* is applied in ERO to reproduce experimental findings
- Impurity injection experiments through stepped limiters in TEXTOR
  - Valuable benchmark for quantification of particle sources in ERO
  - ERO code significantly upgraded to allow flexible surface geometry
  - General trends of impurity deposition on the limiter surface and in local shadows are reproduced
  - From the current status, the experiments and modelling performed do not contradict the hypothesis of enhanced (re-)erosion
  - Quantitative comparison with experimental data requires accounting for multi-step re-erosion and re-deposition, simulations are ongoing
- The physical nature of enhanced (re-)erosion is still to be clarified, thus dedicated laboratory experiments in combination with modelling needed

Thank you for your attention !