Plasma-material interactions under high-heat flux conditions and synergistic D/He effects on low Z covered tungsten surfaces

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Presented by D. Curreli[1]

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J. Hinks and S. Donnelly, Univ. of Huddersfield, UK

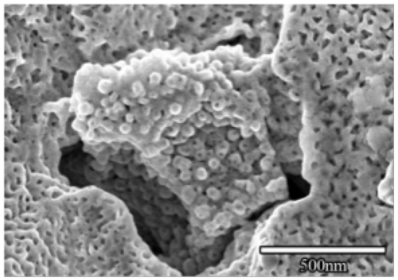
2nd IAEA Research Coordination Meeting on Plasma-wall Interactions with Irradiated Tungsten and Tungsten Alloys in Fusion Devices
Seoul, South Korea, 8-10 September, 2015

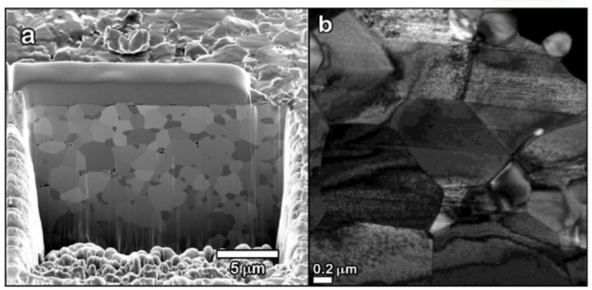
Outline

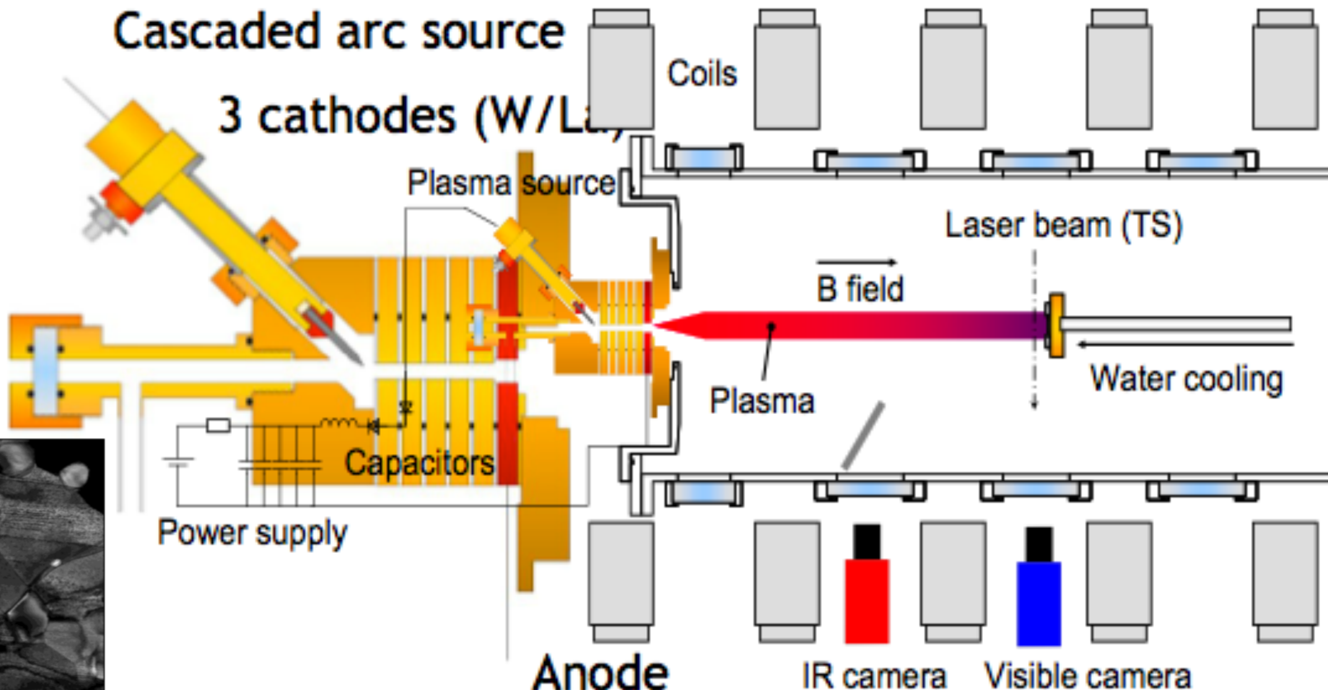
- Overview of panned activities with DIFFER
- He damage on SPD W samples
- Low-Z coating (Li) effects on retention of D/T

Collaboration with FOM-DIFFER (Dutch Institute for Fundamental Energy Research)

DIFFER
Dutch Institute for Fundamental Energy Research



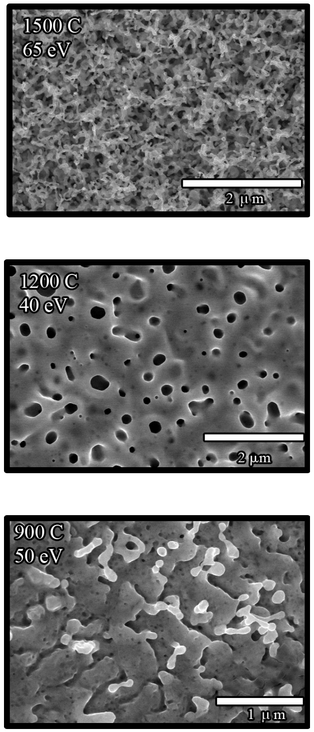




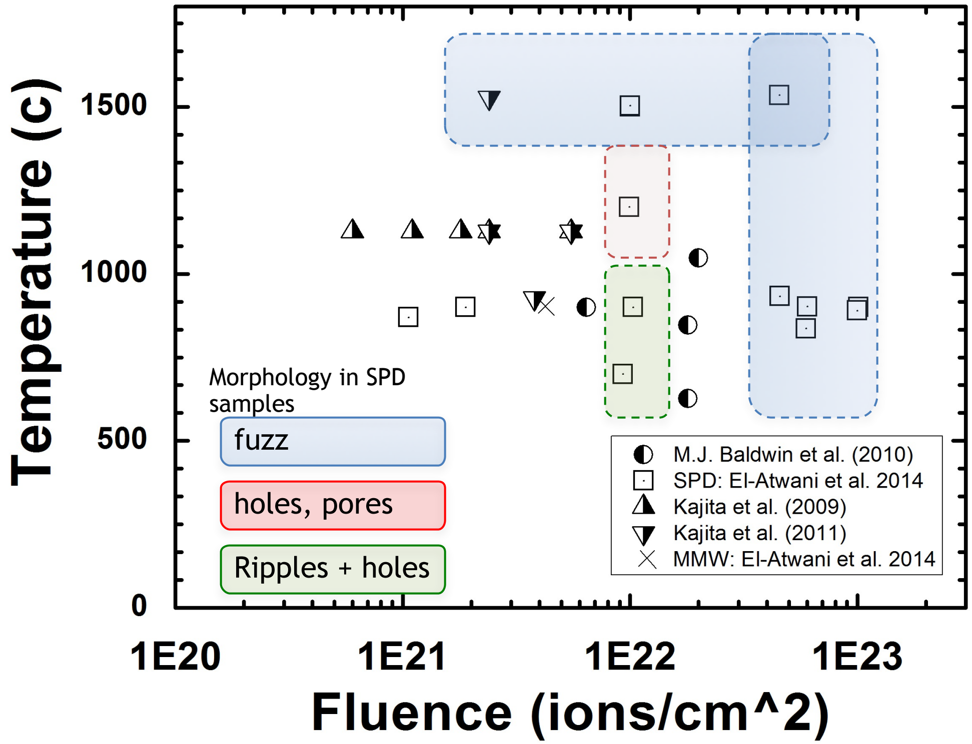
- **<u>Three lines of research</u>: 1) high-flux irradiation (quiescent + transient) of nano-structured W and Mo, 2) Surface morphology and chemistry of nano-structured Low Z coatings on W and Mo, 3) temperature-dependent erosion studies of nanostructured W and Mo irradiated w/ D plasma**

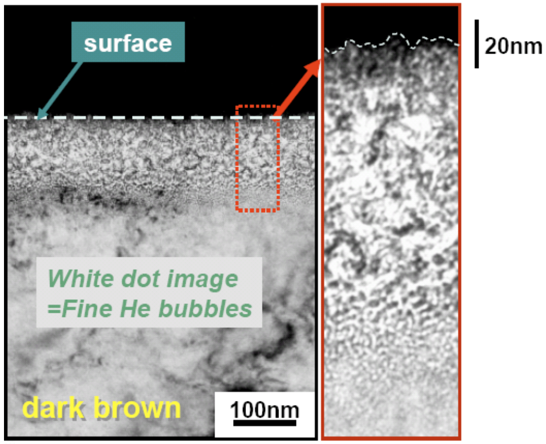
Collaboration with G. De Temmerman, DIFFER

Rich surface morphology driven by irradiation-induced instabilities at the plasma-material interface



Fluence = 10^{22} cm^{-2}





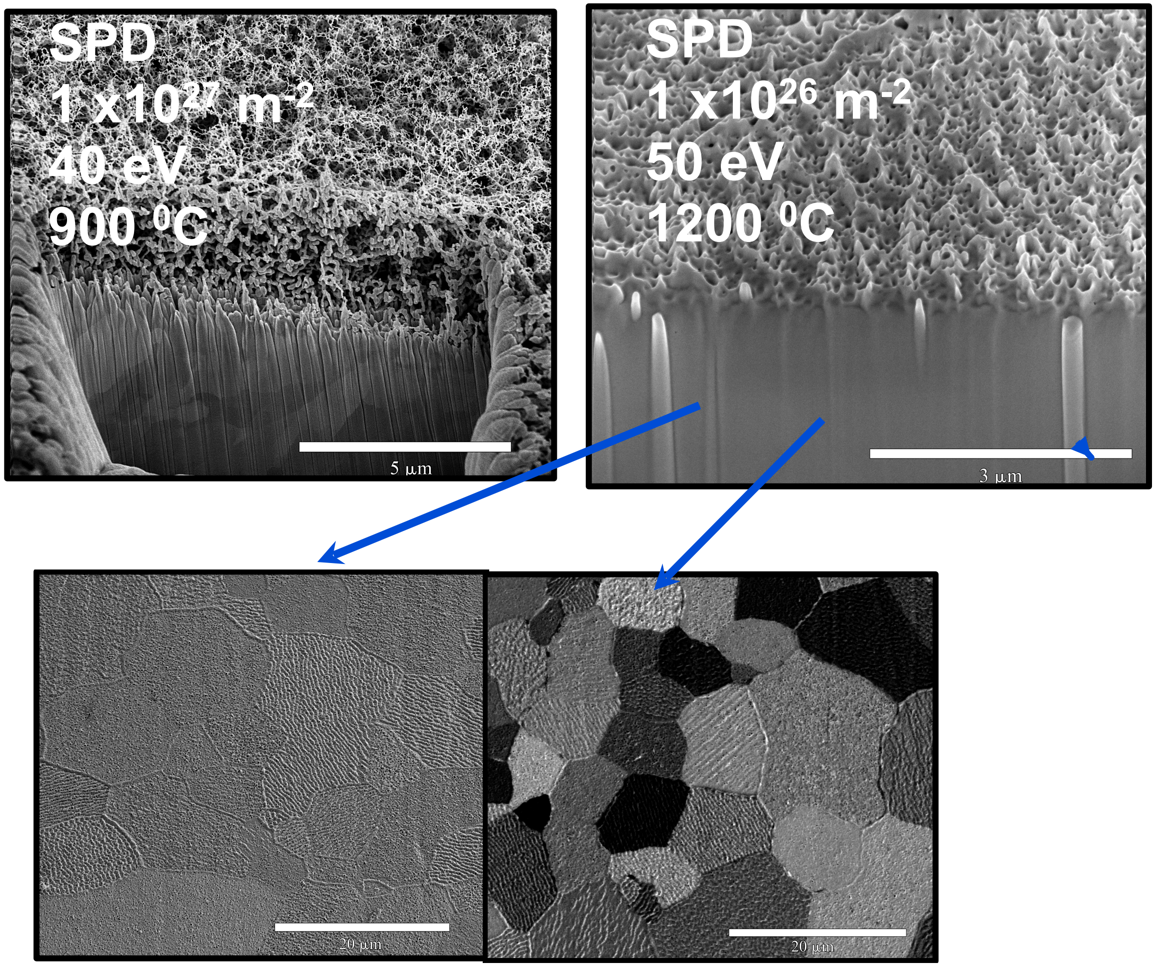
Yoshida et al. 2005

O. El-Atwani et al, Nucl. Fusion 2015

- Both system temperature of W and irradiation fluence of He particles can generate a complex morphology on the surface that is limited to penetrating depth of about 100-nm. This interface in the plasma can influence H retention and erosion

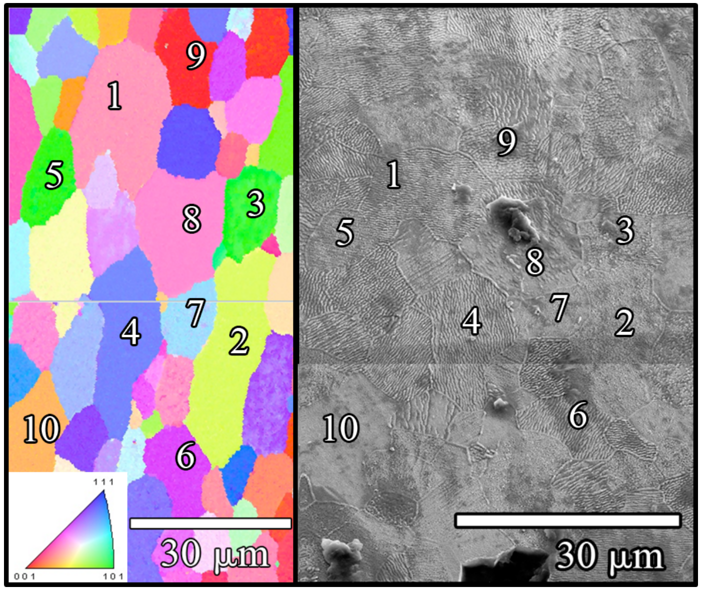
Nanostructure and morphology evolution on SPD-W

- Surface nanostructuring in multiple scales; evidence of He bubble emission at surface
- Crystallographic dependence of irradiation-driven surface patterning: *implications for hydrogen isotope interactions*



SEM SEM e-Backscattering

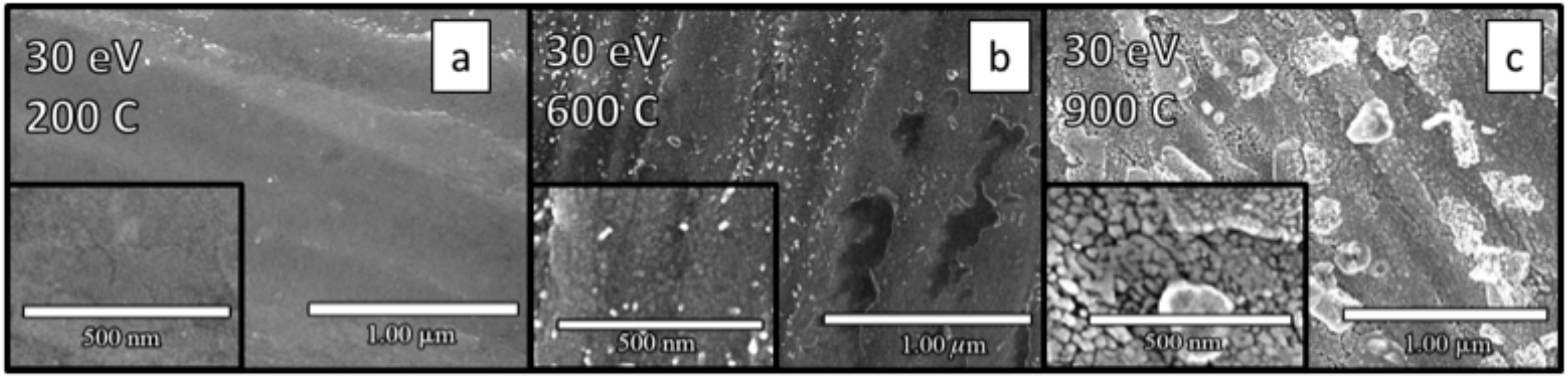
Collaboration with G. deTemmerman (DIFFER)



Colormapped on the crystallographyc orientation

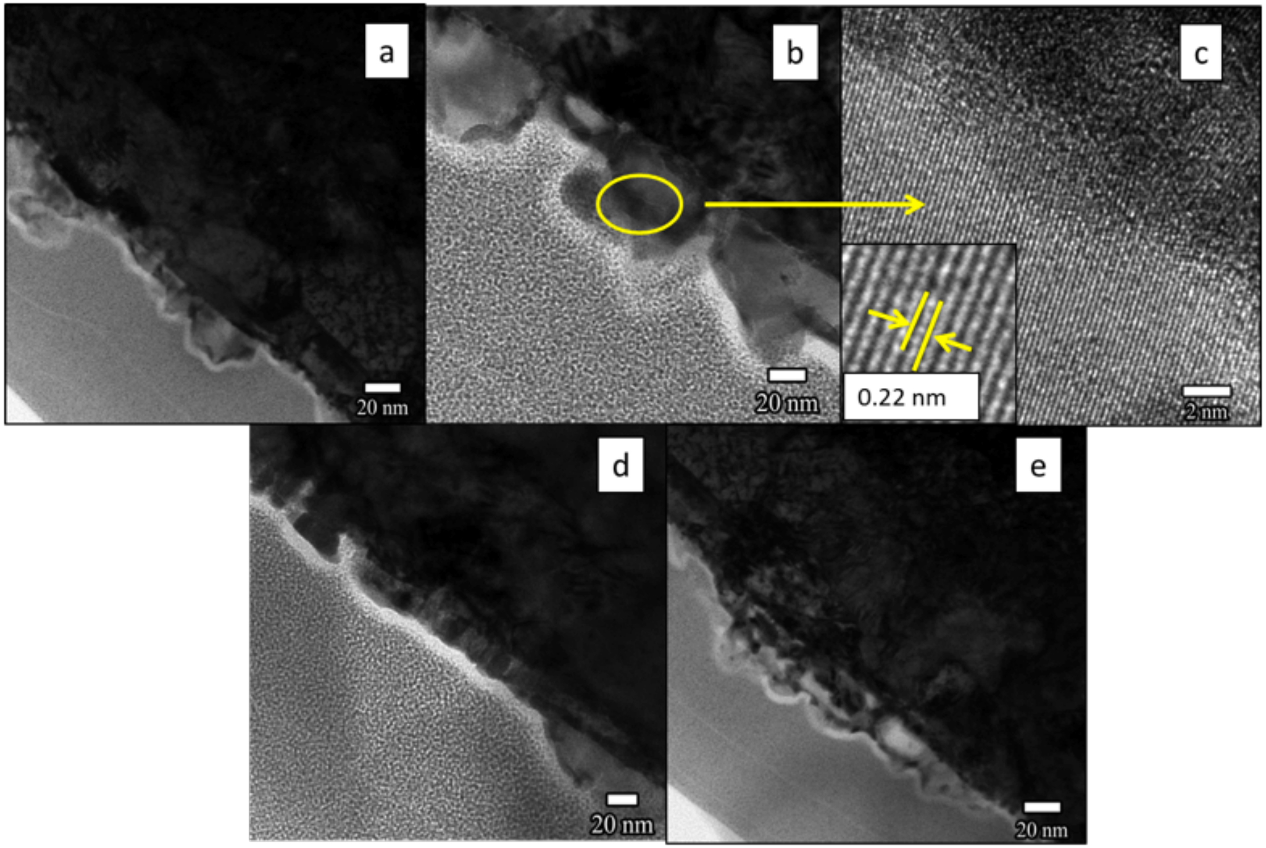
SEM and TEM micrographs of the ultrafine grained tungsten sample irradiated with 30 eV He particles to a fluence of 1×10^{19} cm^{-2} at 900 °C

- Irradiation ultra fined grained W sample



- SEM micrographs suggest that surface nano-structuring appears at elevated temperatures under low-energy He irradiation on ultra fined grained W sample

SEM and TEM micrographs of the ultrafine grained tungsten sample irradiated with 30 eV He particles to a fluence of $1x10^{19}$ cm^{-2} at 900 °C



- TEM micrographs showing (a),(b) eroded grain leaving stone-shape nanostructures; (c) high resolution of one stone-shape nanostructure; (d) region of a nanostructures grain (pinholes) and (d) eroded grain leaving fiber-form nanostructures

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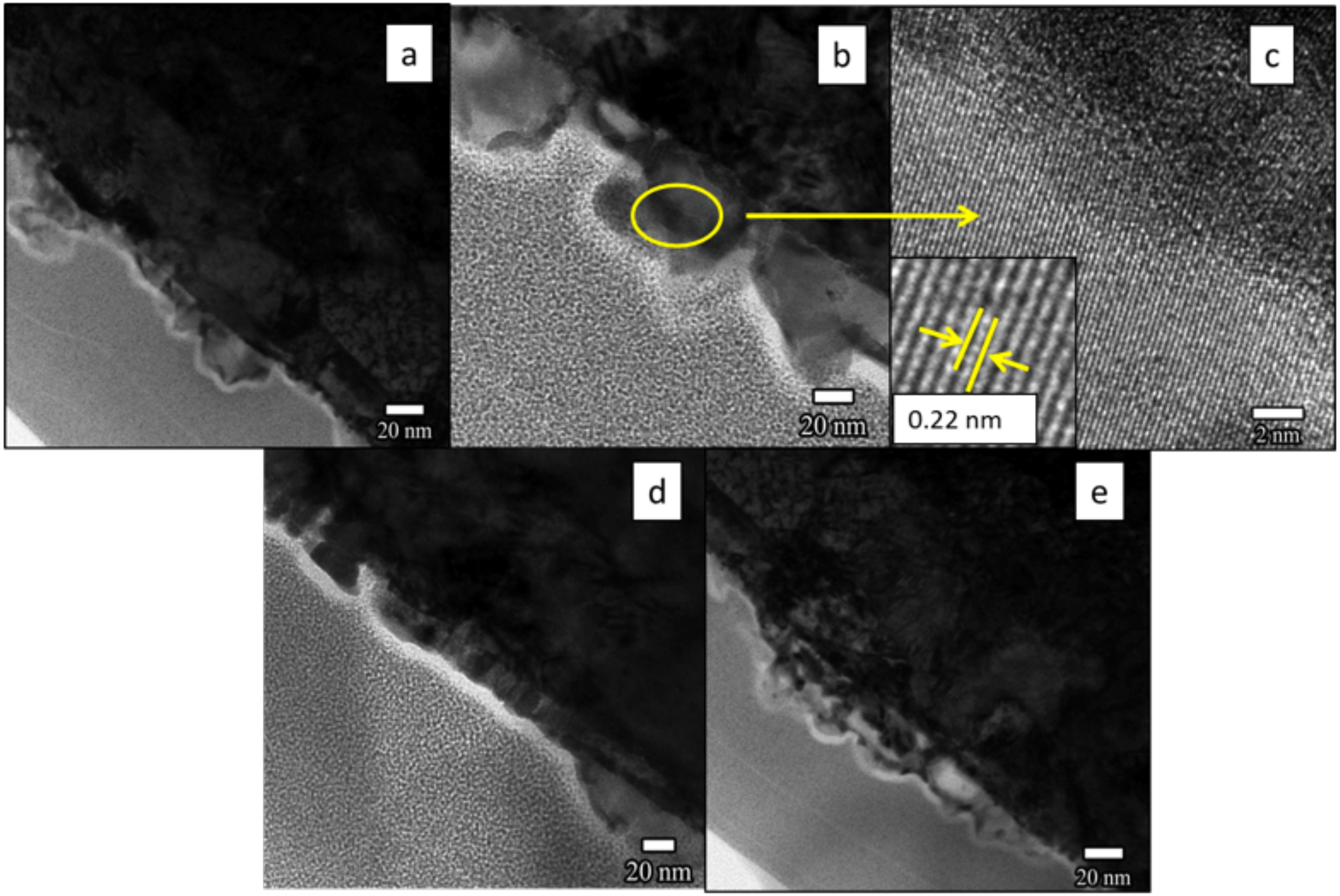
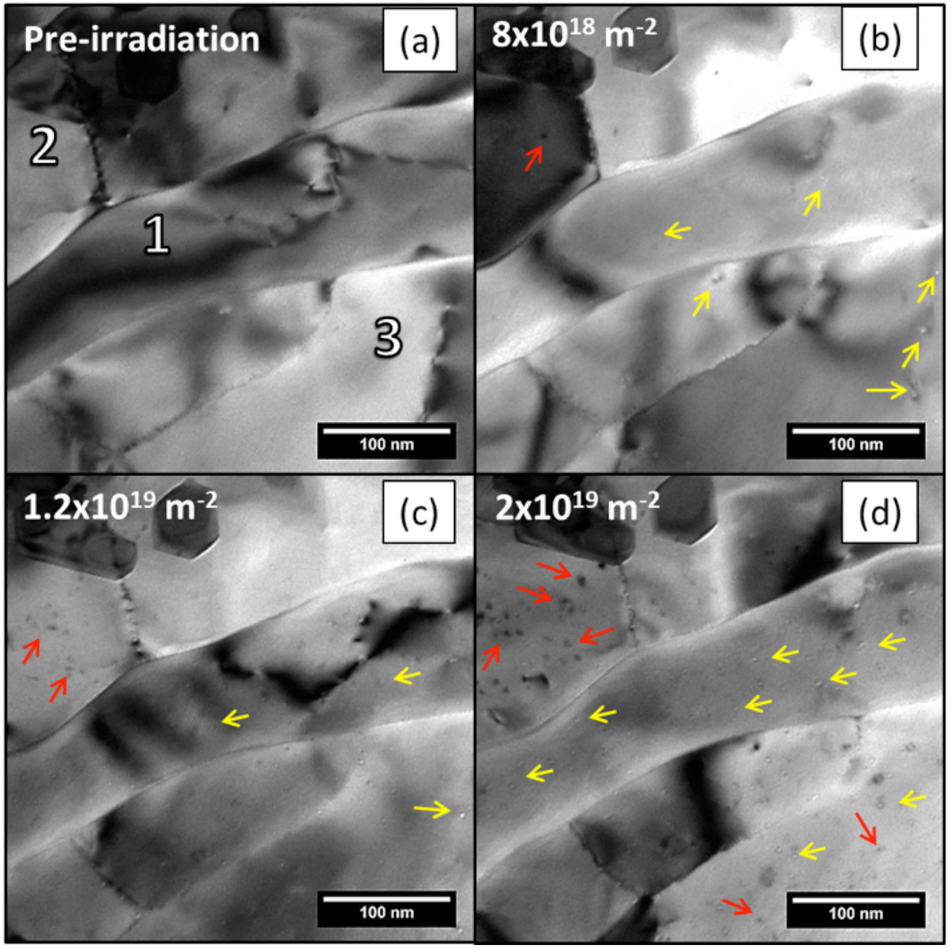


O. El-Atwani et al, To be submitted 2013, J. Nucl. Mater.

Early and latter stages of damage observed with in-situ TEM

2 keV He+ ion irradiation of W at 950°C

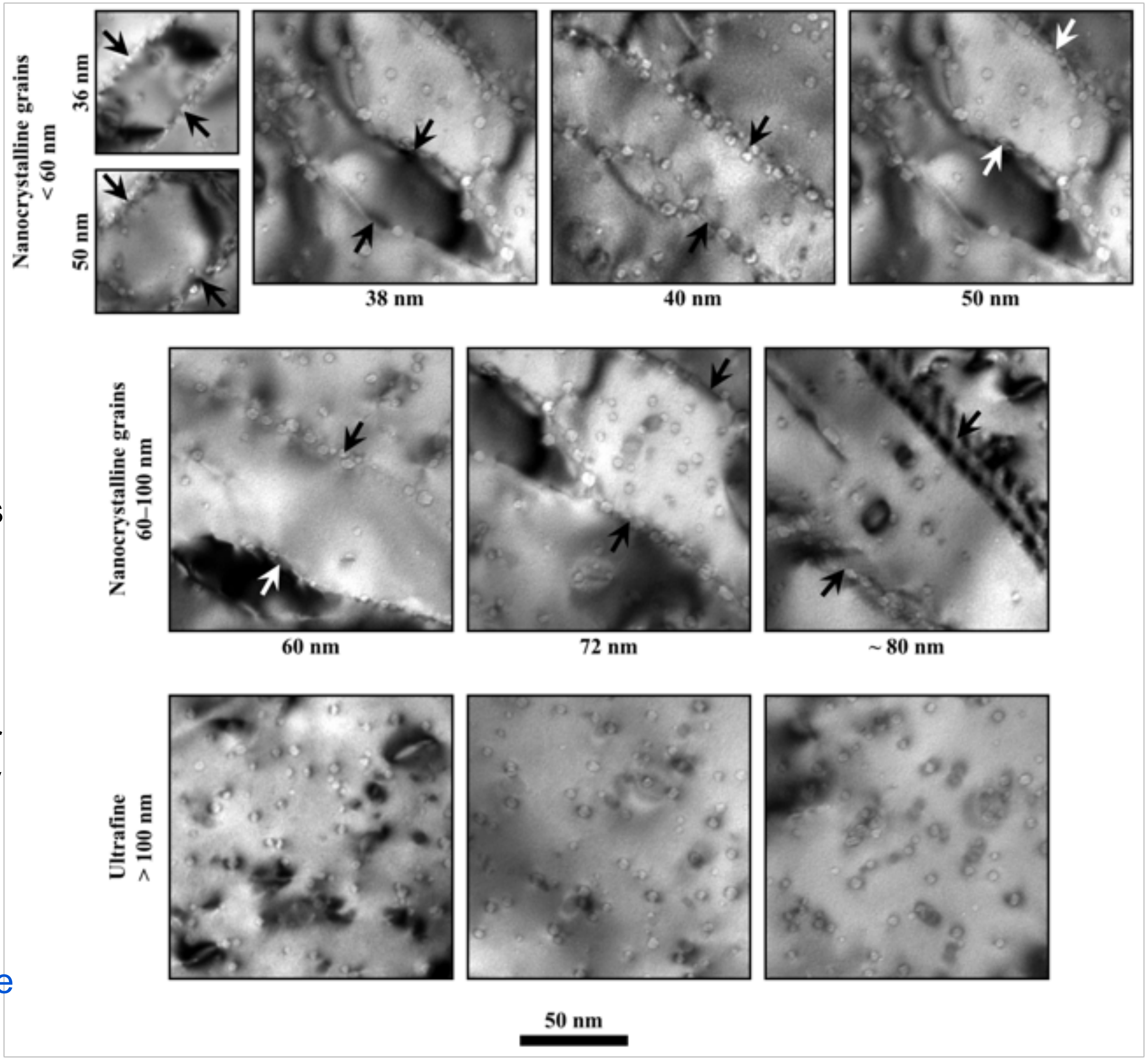
- **(a)** nanocrystalline (1) and ultrafine (2 and 3) grains before irradiation
- **(b)** at a fluence of 8×10^{18} ions.m^{-2} and greater He bubble nucleation (bubbles indicated by yellow arrows)
- **(c)** after irradiation to a fluence of 1.2×10^{19} ions.m^{-2} showing point defect cluster formation (indicated by red arrows) occurred preferentially in grains 2 and 3
- **(d)** after irradiation to a fluence of 2.0×10^{19} ions m^{-2}, a higher areal density of point defect clusters and small dislocation loops evident in grains 2 and 3 while grain 1 demonstrates a uniform distribution of bubbles and a significantly lower areal density of defect clusters and dislocation loops.



O. El-Atwani et al, *In-situ TEM observation of the response of ultrafine- and nanocrystalline-grained tungsten to extreme irradiation environments*, Sci. Rep., Nature Publishing group 4, 4716 (2014)

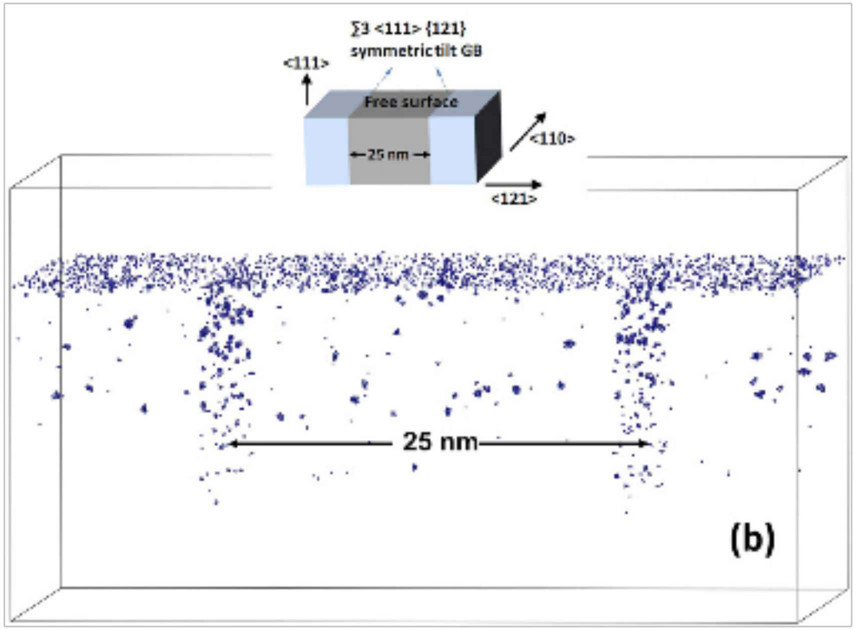
He clusters at grain boundaries of SPD tungsten

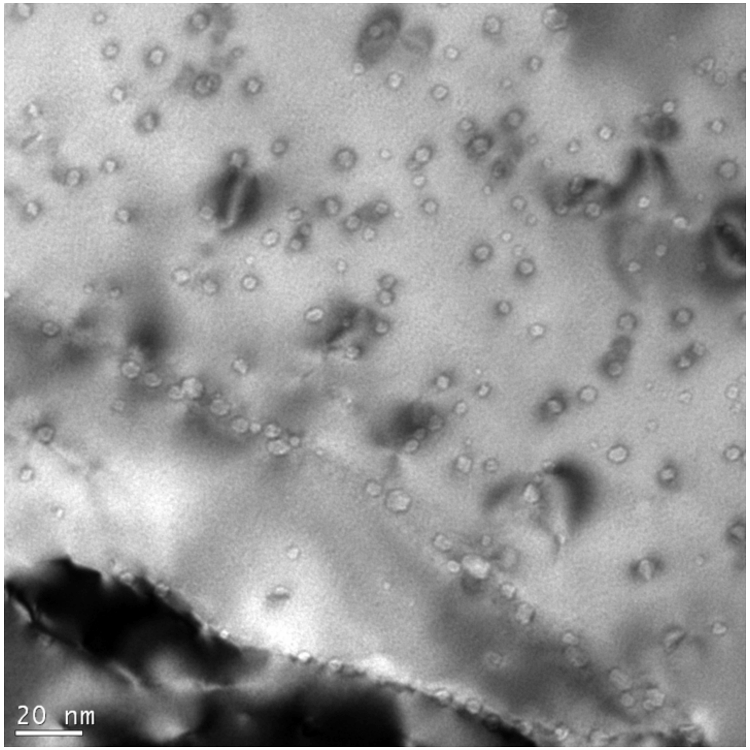
- Observation of defect formation and bubble accumulation on nano crystalline grains of different size
- Nano-crystalline grains of size <60 nm evidence less damage and defect formation; no dislocation loops observed
- Nano-crystalline grains of size between 60-100 nm evidence more defect density and appearance of dislocation loops
- Ultrafine grains (>100 nm) has the larger density of defect formation, dislocation loops, clusters, etc.
- >> Less damage on the smaller grains >> grain boundaries play a big role in the dynamics of interstitial defects and vacancies



O. El-Atwani et al, Sci. Rep., Nature Publishing group 4, 4716 (2014)

He clusters at grain boundaries of SPD tungsten: comparisons to atomistic modeling

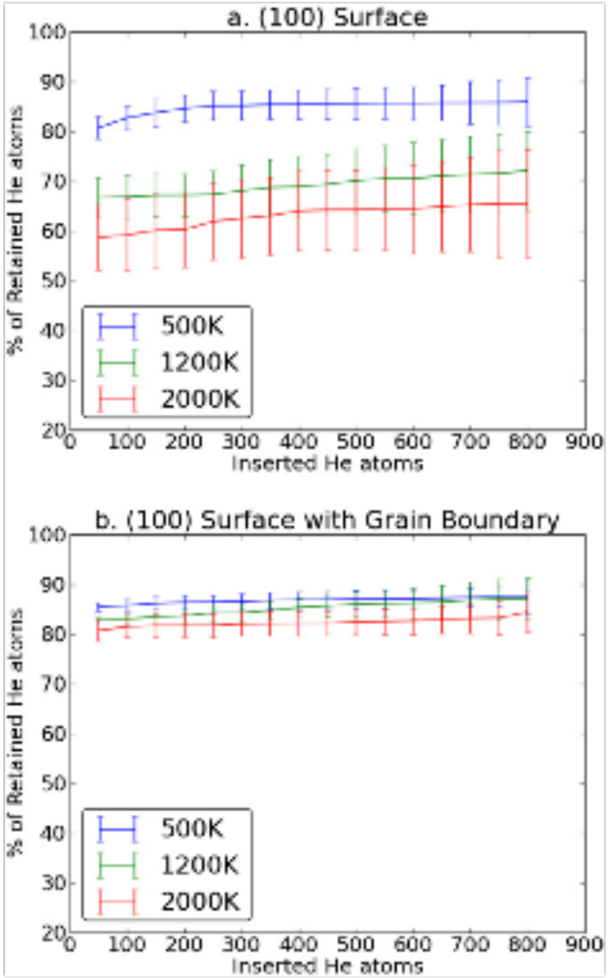


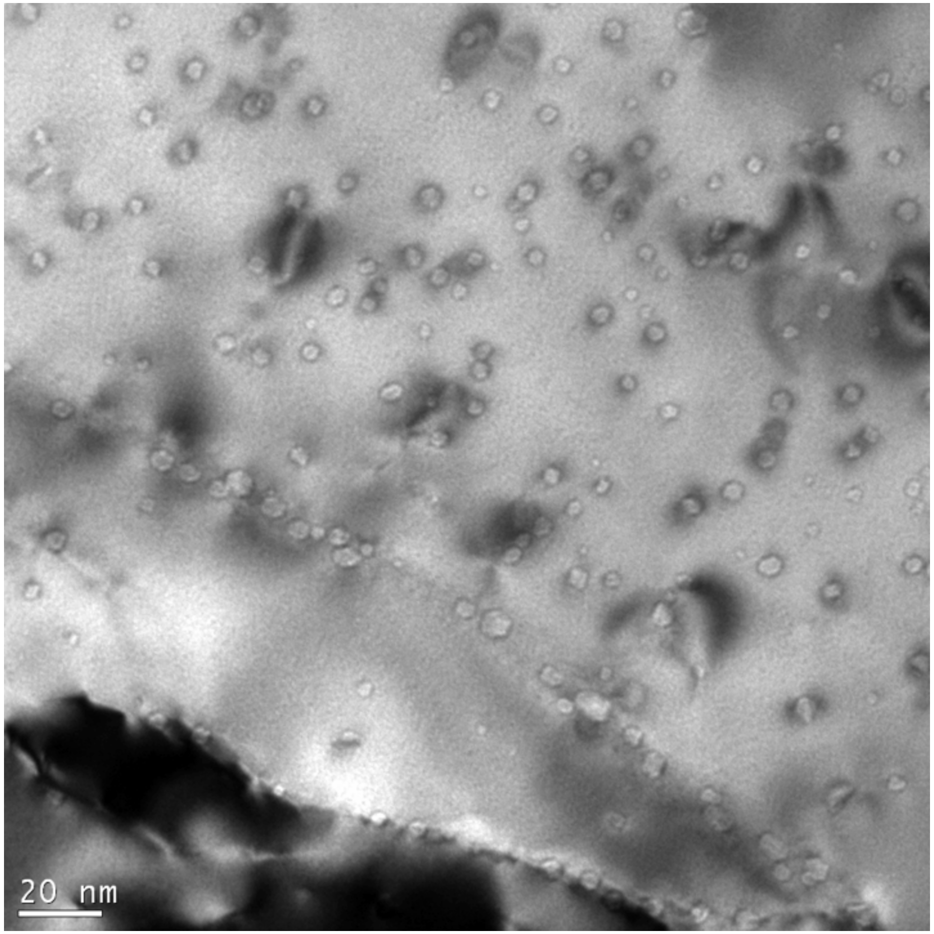


- Work by F. Sefta, Lin Hu and B. Wirth et al. open up understanding of self-driven mechanisms for He cluster formation and role of grain boundaries
- How do we couple impurity-driven surface structuring and defect evolution in irradiated materials? How do we close the gap in space and time between models and diagnosis?

F. Sefta et al., Nuclear Fusion 53 (2013) 073015
Lin Hu et al., J. Appl. Phys, 115 (2014) 173512

He clusters at grain boundaries of SPD tungsten: comparisons to atomistic modeling



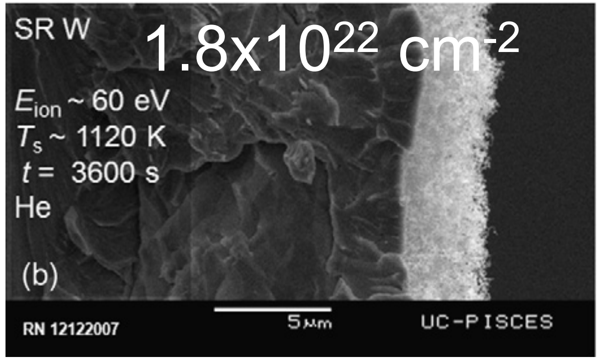


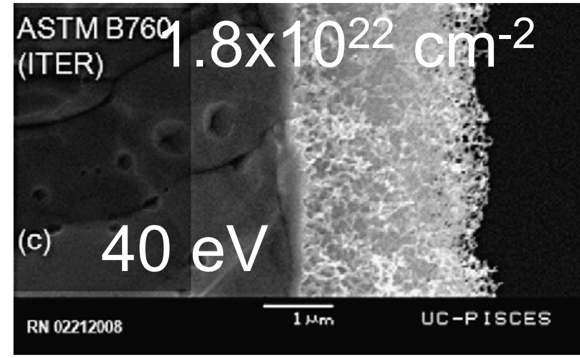
F. Sefta et al., Nuclear Fusion 53 (2013) 073015
Lin Hu et al., J. Appl. Phys, 115 (2014) 173512

Comparison with literature (fuzz formation)

PISCES

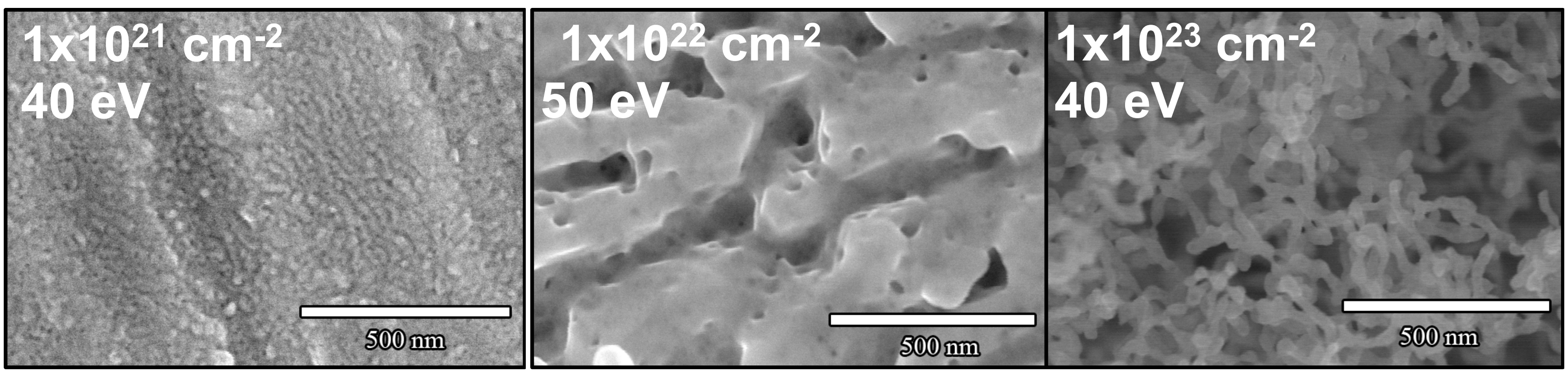
Smaller grains on PISCES lead to a lower threshold for the fuzz formation





Baldwin et al, JNM, 2010

DIFFER



SPD samples (UFG) have higher fuzz formation fluence thresholds, however fuzz thickness growth rate is faster

O. El-Atwani et al, Nucl. Fusion 2015

Summary of studies of low-Z coatings on irradiated tungsten with D/He plasmas

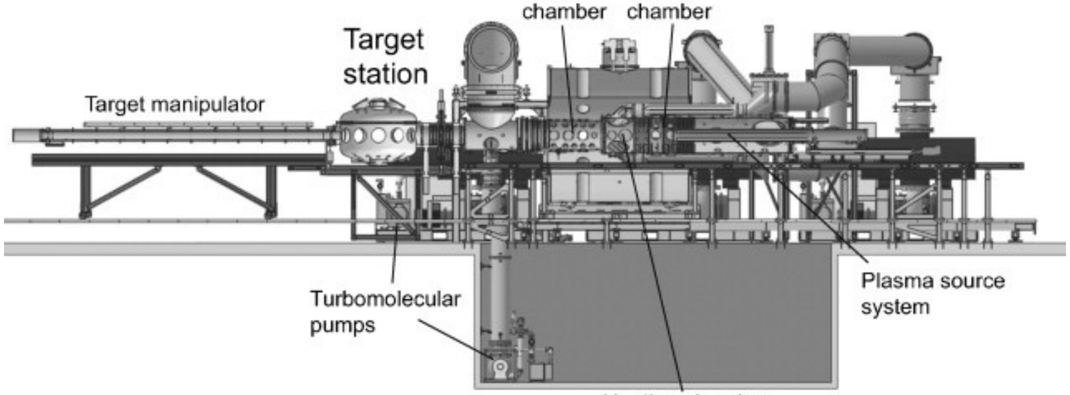
- Re-deposited coatings on irradiated tungsten can have significant consequences on both surface damage and fuel retention
- Li and Be has similar oxygen surface reactivities and hydrogen retention, up to <50% of retention of H in Li [Allain *et al*. Nuc Fusion 2002]
- Synergistic effects between D and He have been demonstrated to enhance fuel retention at the surface
- High heat-flux D plasmas seeded with He can help elucidate mechanisms that drive D retention in region of He-induced damage
- Low-Z coatings can help “mimic” re-deposited particles that may impact fuel retention

A. Neff et al, J. Nucl. Mater. 2015

W-Li Experiments

- Tungsten discs were made of polycrystalline tungsten: Diameter ≈ 10 mm and Thickness ≈ 3 mm
- Surface temperature varied from room temperature up to 1100 C
- Li layer thickness was 500 nm (measured
- Sample biased to -35 V and exposed to D, He, and He seeded D plasmas.
- Flux: 1.4-5.3 x 10^{23} $m^{-2}s^{-1}$
- Fluence: 1 x 10^{25} m^{-2}
- XPS was used to characterize the surface chemistry
- Surface morphology was characterized with SEM*

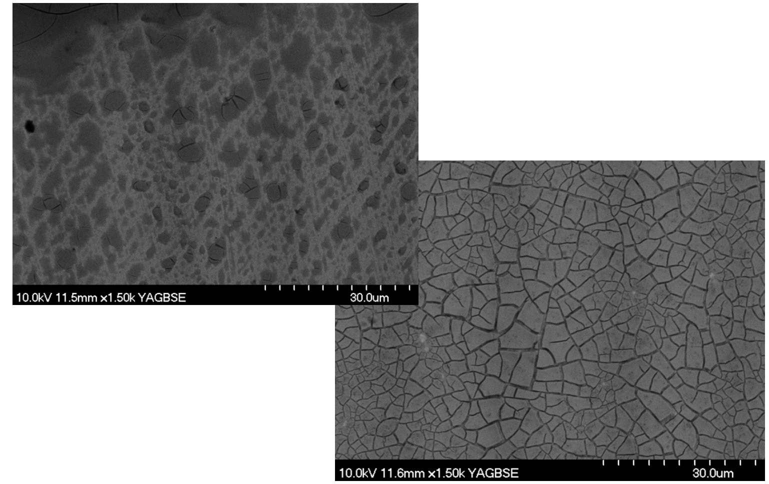
Magnum-PSI

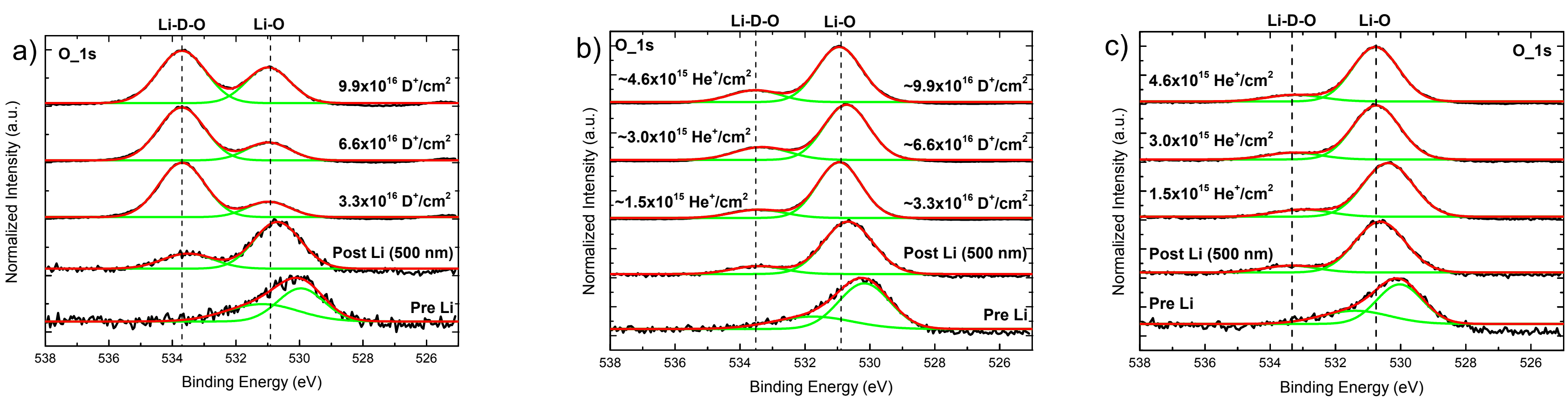


A. Neff et al, J. Nucl. Mater. 2015

Surface Morphology of Low-Z re-deposited layer on W

- SEM micrographs indicate a low-Z coating persisting after high-fluence irradiation
- Possible cracking is evidenced
- The patterns formed on the surface could also be driven by the compositional variation during exposure
- Additional high-fluence and high-temperature irradiation confirm effect on surface morphology and XPS retention of D





534 eV O1s XPS peak shows D retention complex for
(a) D plasma, (b) D-0.1 He plasma and (c) He-only plasma

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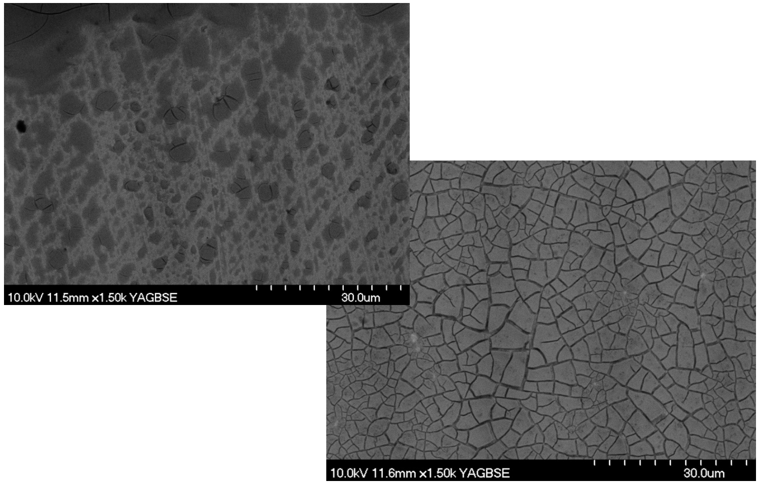

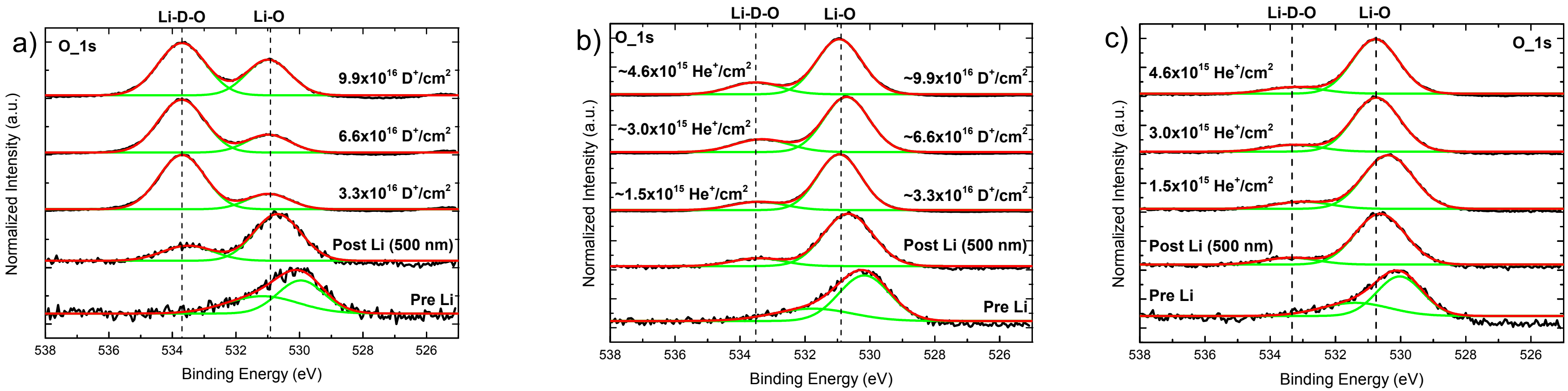

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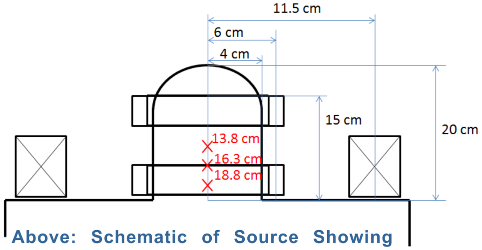
Future work on irradiated tungsten with D/He plasmas

- We received ITER-grade samples from Julich in April 2015 and began TEM sample preparation for *in-situ* TEM irradiated W work at DIFFER and Huddersfield
- Synergistic effects between D and He will be conducted in facilities there to look at effect of He-seeded D plasmas at high temperature with re-deposited low-Z materials (e.g. Li)
- Also looking at *in-situ* surface chemistry effects on D retention by oxygen impurities on surface
- *In-situ TDS* (at MRL) coupled to environmental XPS and TEM system planned for 2016

Final Remarks: two new experimental facilities at Illinois relevant to the CRP on irradiated W

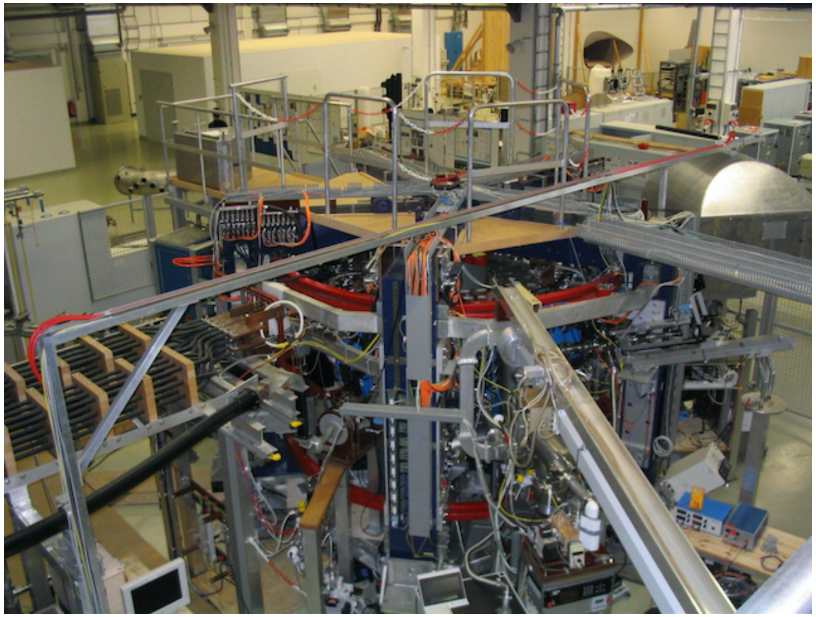
Helicon Source for ion irradiation on W

- MORI 200, HH 13.56MHz Antenna and Automatic Matching Network
- “RFPP RF 30S” RF Generator
- EMS 7.5-13-2-D-1159 Magnet Power Supply (0 - 500Gauss at center tube)
- Experiments performed at 5 mTorr

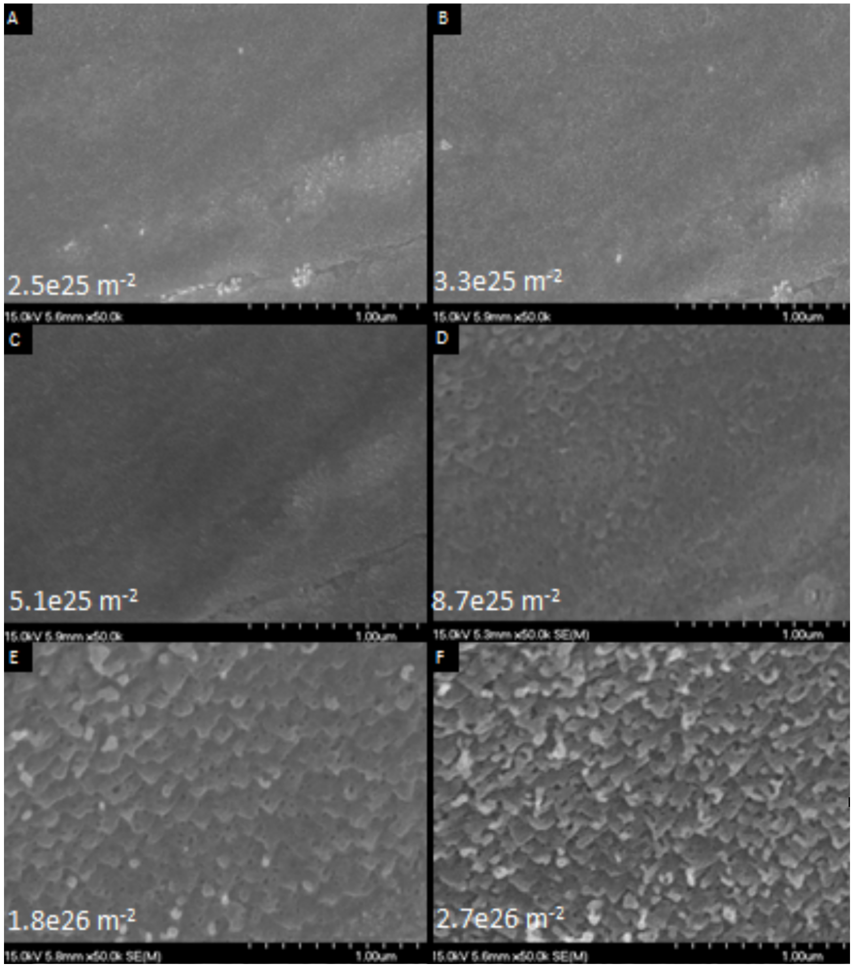


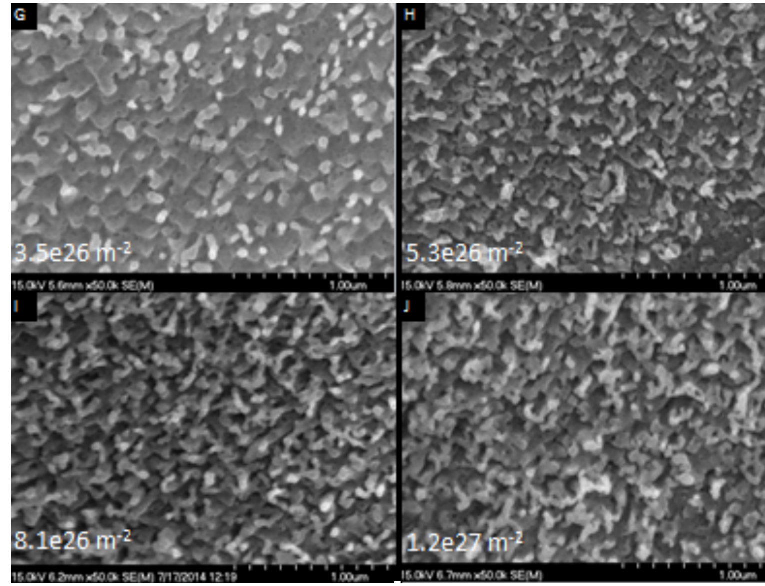
Above: Schematic of Source Showing Dimensions and Location of Axial Measurements

HIDRA : Hybrid Illinois Device for Research and Applications



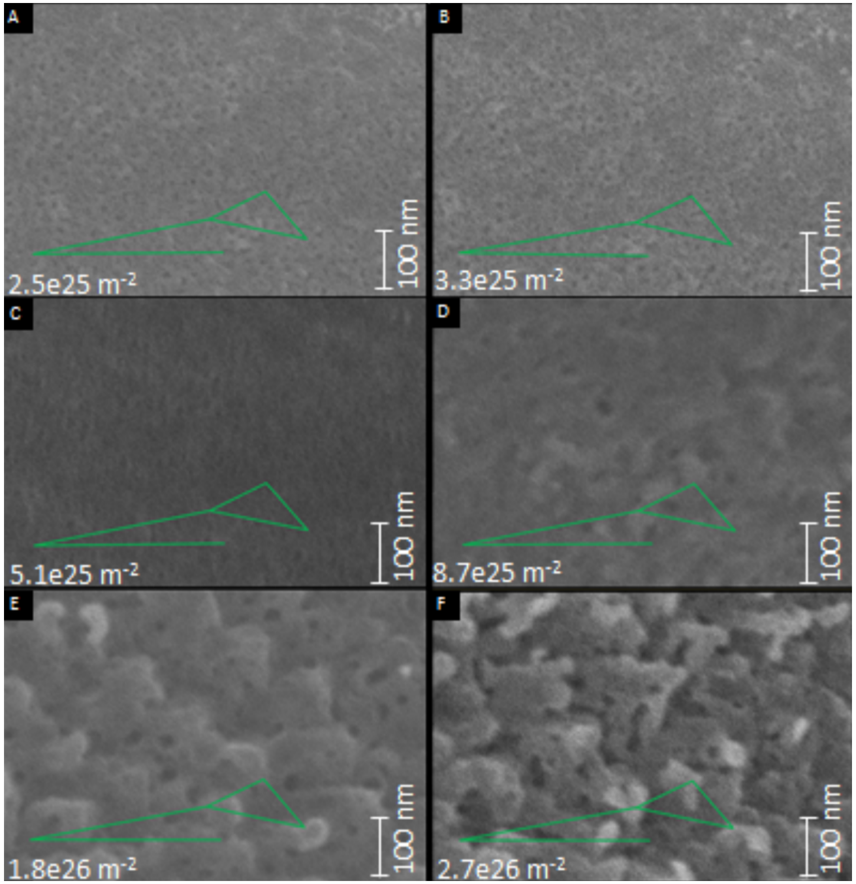
Direct time-resolved observation of tungsten nanostructured growth due to helium plasma exposure

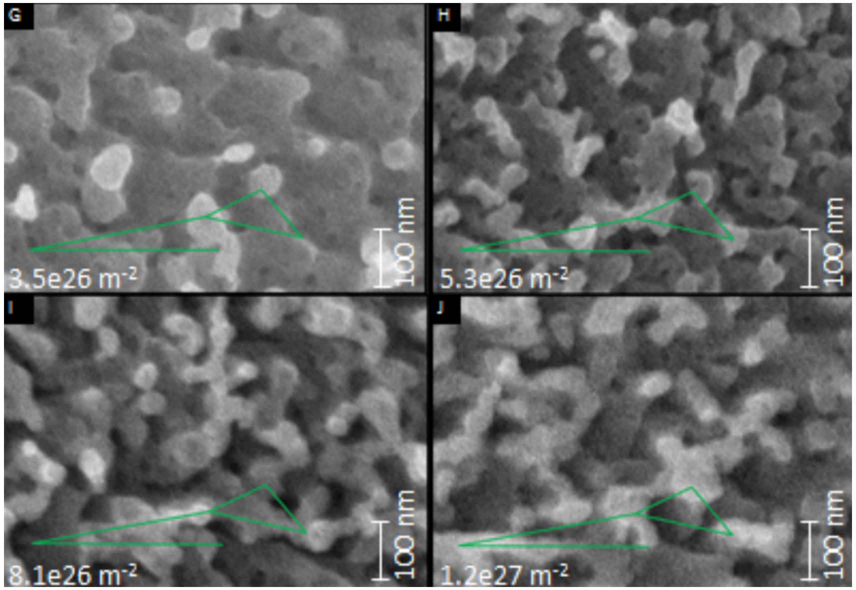




P. Fiflis, D. Curreli, D.N. Ruzic, *Direct time-resolved observation of tungsten nanostructured growth due to helium plasma exposure*, Nucl. Fusion 55 033020 (2015)

Direct time-resolved observation of tungsten nanostructured growth due to helium plasma exposure

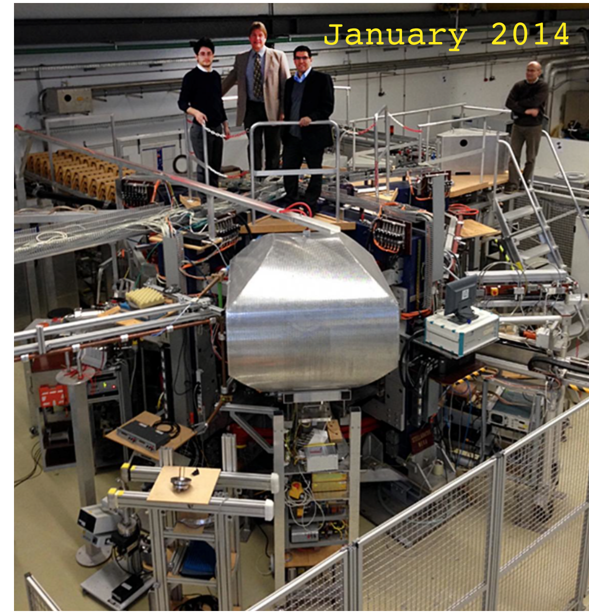


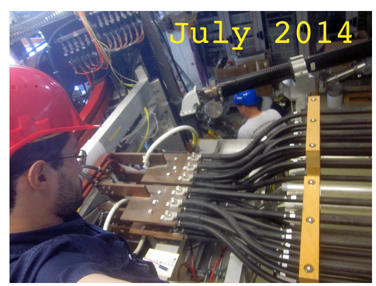


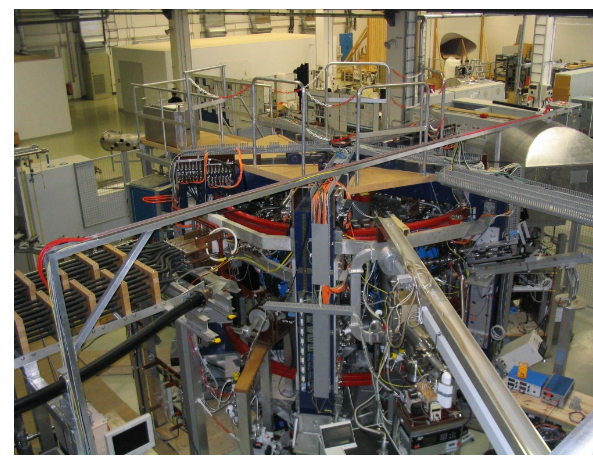
Zoomed, rotated, and aligned SEM micrographs of *the same* area over time

*P.Fiflis, D. Curreli, D.Ruzic, *Nucl. Fusion*, (accepted), 2015

HIDRA: Hybrid Illinois Device for Research and Applications



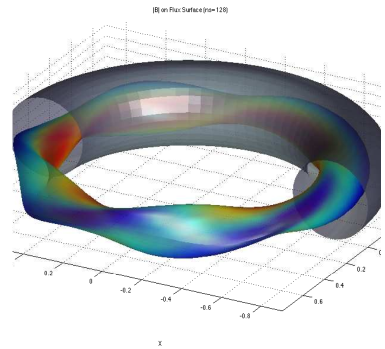


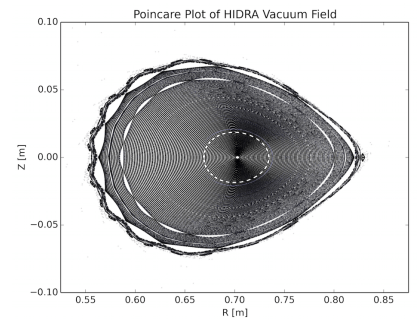


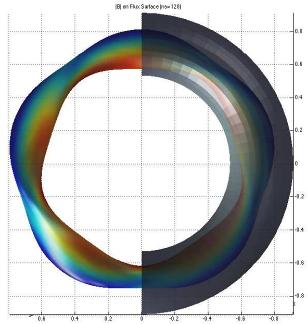
http://npre.illinois.edu/news/npre-gains-major-plasmafusion-facility-german-institute

HIDRA: Hybrid Illinois Device for Research and Applications

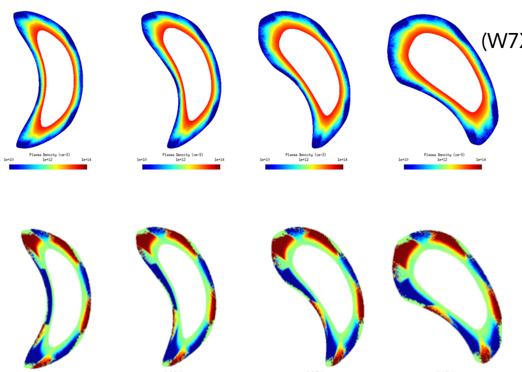
MAGNETIC FIELD AND IDEAL MHD STRUCTURE
(STELLOPT)

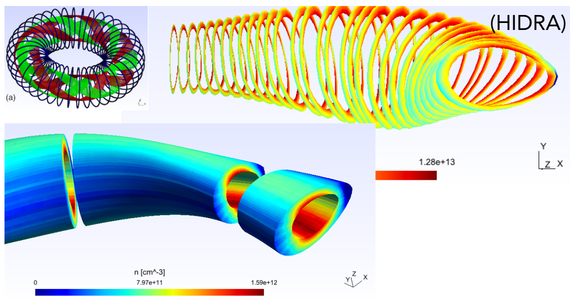




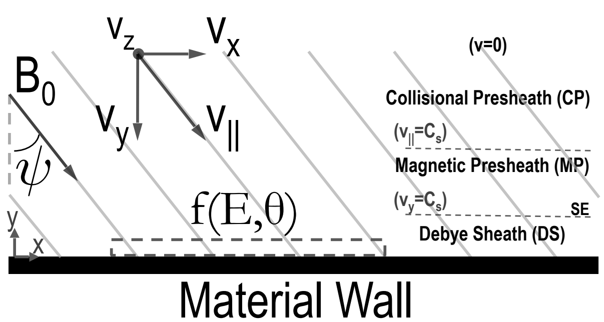


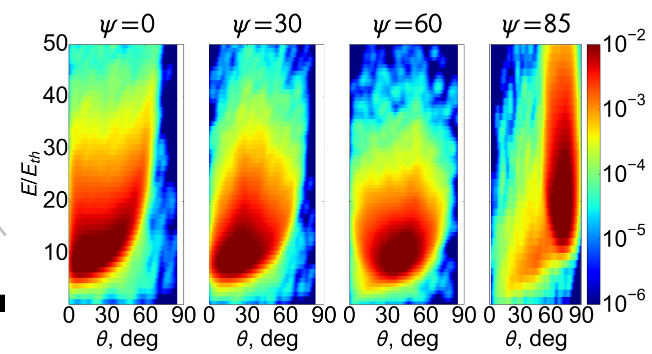
EDGE TRANSPORT AND NEUTRAL KINETICS
(EMC3-EIRENE)





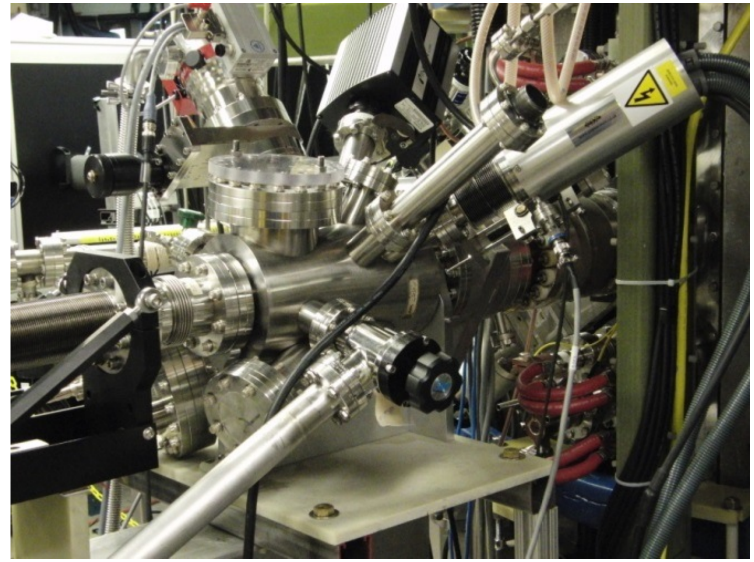
BOUNDARY LAYER AND SHEATH PHYSICS
(PIC CODE DEVELOPMENT)

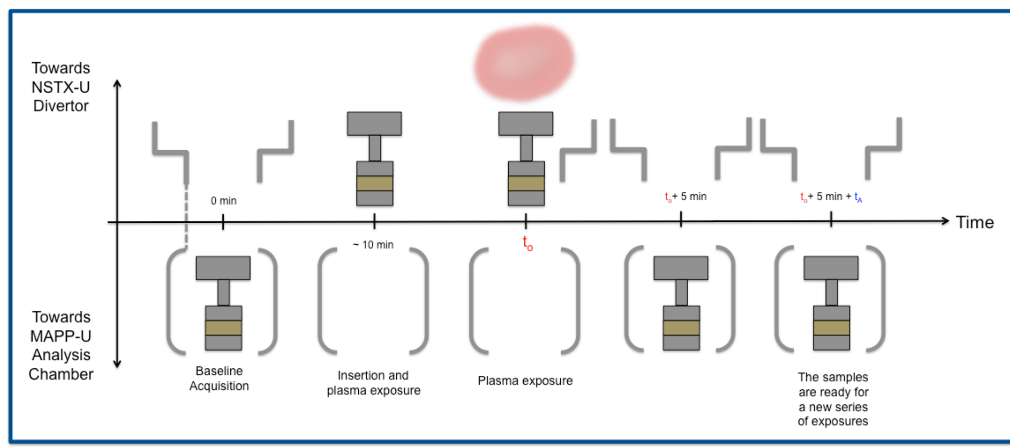




Development of In-situ Material Diagnostics, HIDRA-MAT

- MAPP consists of 3 mian analysis techniques:
    1. X-ray photoelectron spectroscopy (XPS)
    2. Ion-scattering and Direct Recoil Spectroscopy (DRS)
    3. Thermal Desorption Spectroscopy (TDS)
- Furthermore, MAPP also includes *local Langmuir probes* and has the capability of *quartz-crystal microbalance* technology for dust transport and erosion-redeposition studies
- Originally developed by Prof. JP Allain and tested on LTX & NSTX





HIDRA: Assembly at University of Illinois (Nov/Dec 2014)