H-Sensors and Fusion Work at SNL-CA

Dean Buchenauer (SNL-CA)

Thomas Lemp and Thomas Friedman (SNL-NM)

Useful discussions with Peter Stangeby (Univ. of Toronto)
And Bob Bastasz (SNL-CA retired)

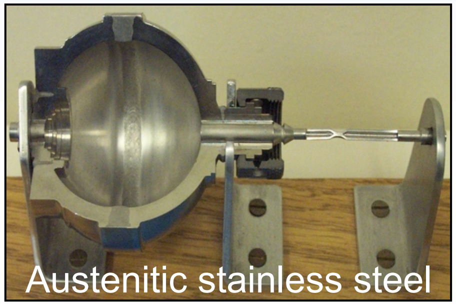
Outline

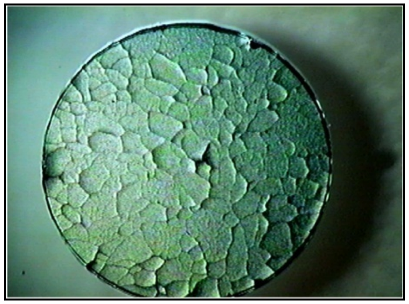
Overview of Hydrogen Work
Details of Fusion Program on PSI
Motivation for Atomic Hydrogen Measurements
Pd-MOS Hydrogen Sensors

Tritium Focus Group Meeting, INL, September 23-25, 2014

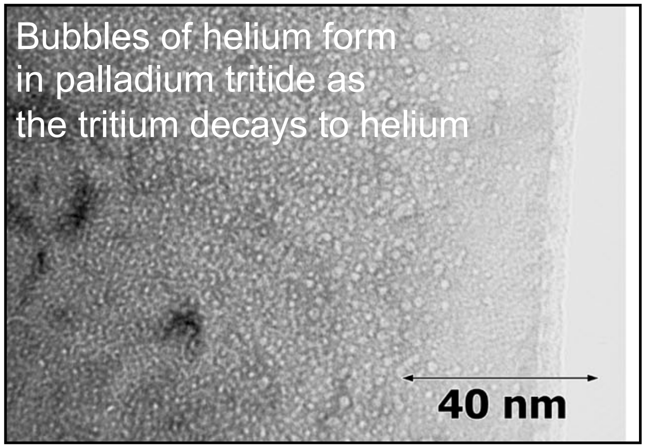
Building a science-based understanding of hydrogen (and helium) behavior in materials

- **High pressure hydrogen storage for Gas Transfer Systems and hydrogen / fuel cell industry**
  - Embrittlement, permeation, trapping, microstructural effects, corrosion, Codes and Standards (H^2 safety)
- **Metal hydride studies for hydrogen storage**
  - He trapping from T decay, film adhesion, aging, new materials
- **Tritium production (TPBAR)**
  - T migration in a complex materials environment
- **Plasma-surface interactions (PSI) studies needed for magnetic fusion energy**

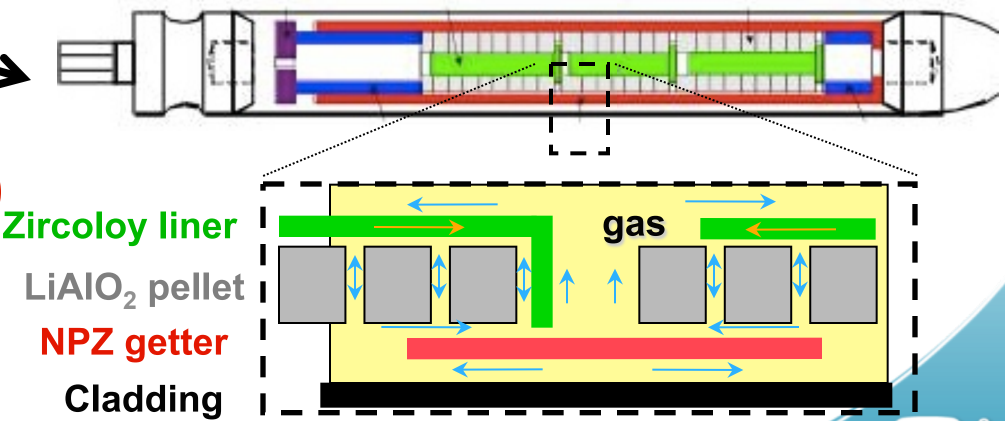




Bonding in n-tube films



Tritium Producing Burnable Absorber Rods



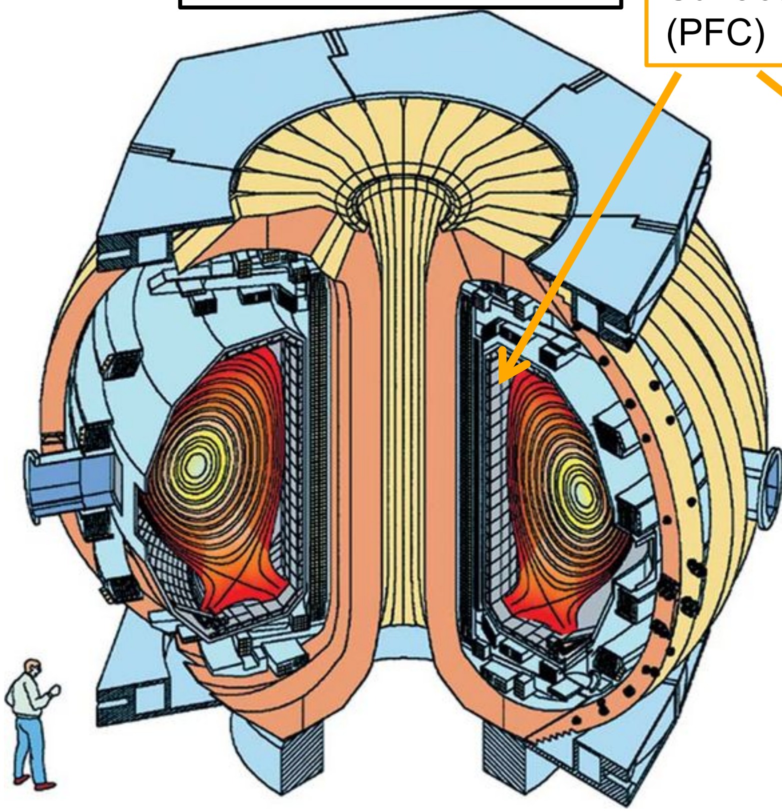
R&D efforts span a number of applied programs at SNL-CA

Magnetic fusion energy research

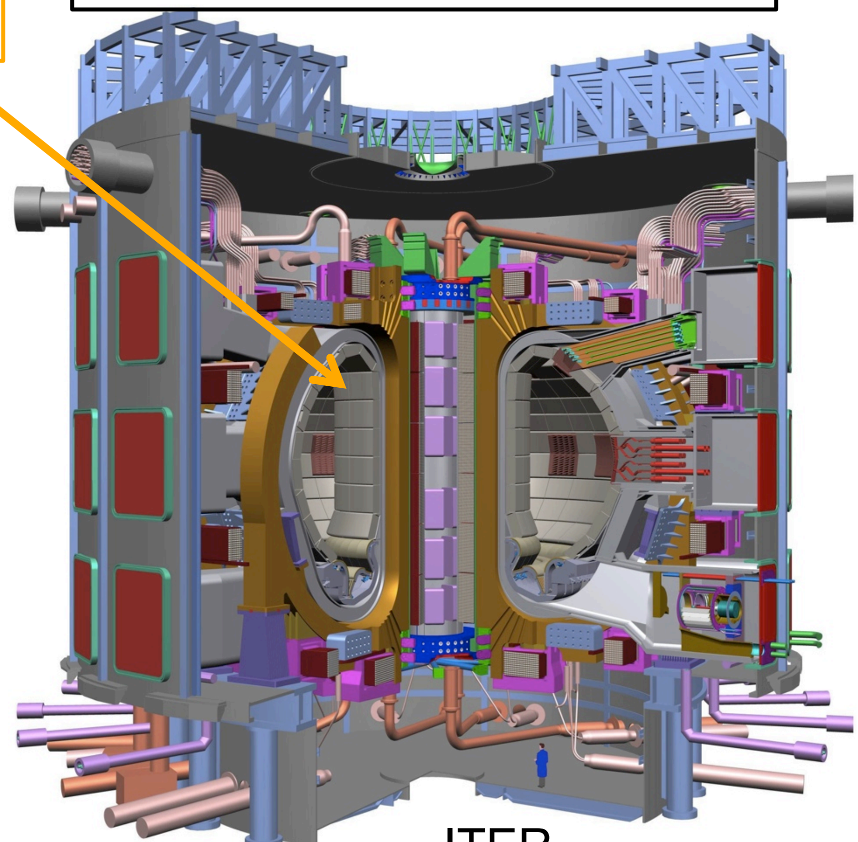
US research focused on the tokamak confinement scheme

Plasma Facing Surface (PFC)

Power and particle loading of the plasma facing components will limit fusion performance



DIII-D Tokamak at General Atomics

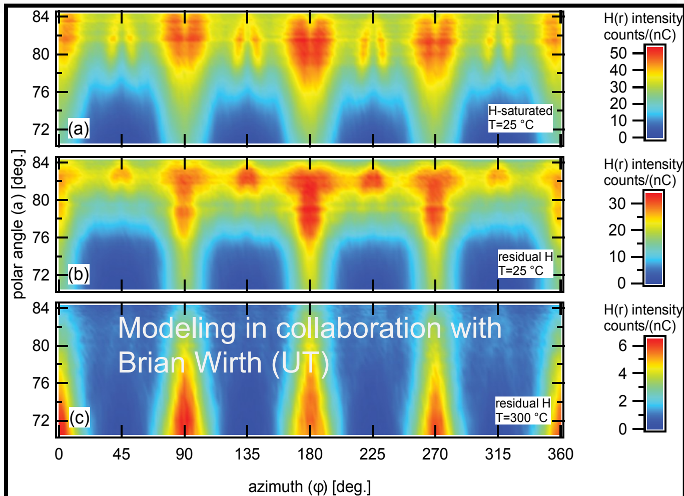


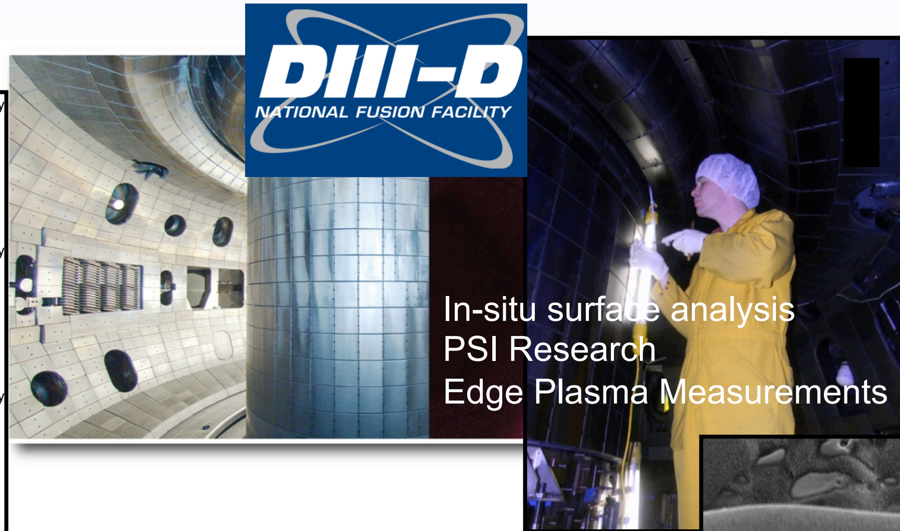
ITER

Greenwald report, ReNeW study, and OFES all agree on importance of PSI/PFC

SNL-CA PSI Science Center Research (FY10-14)

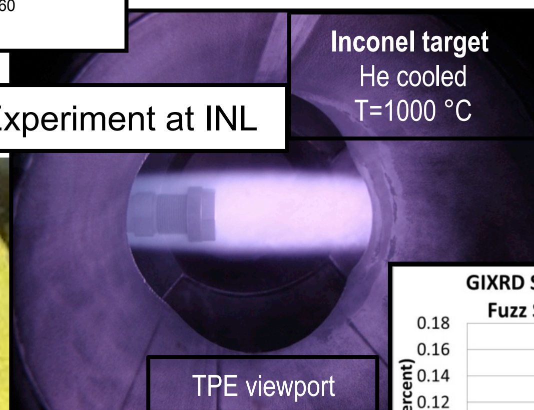
Fundamental surface science of
H effects in ARIES



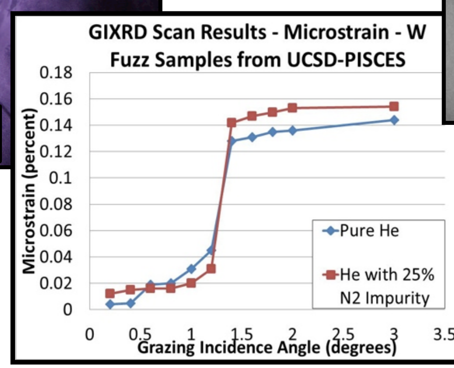


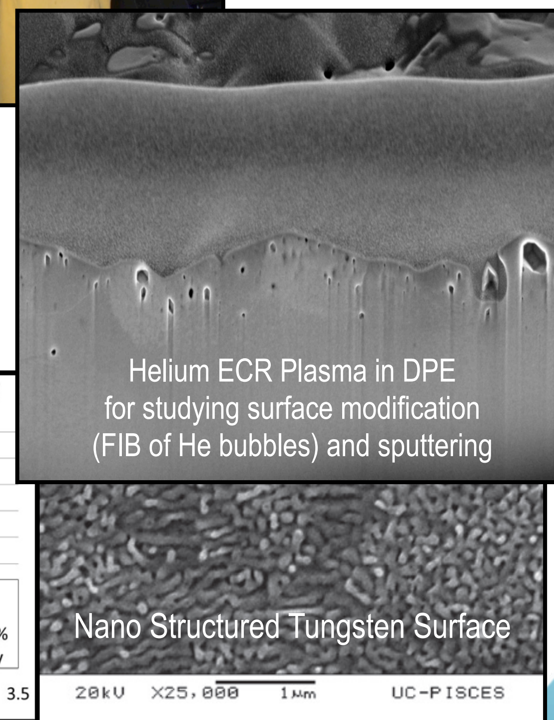
PSI Science Center

MIT UT UCSD Sandia National Laboratories



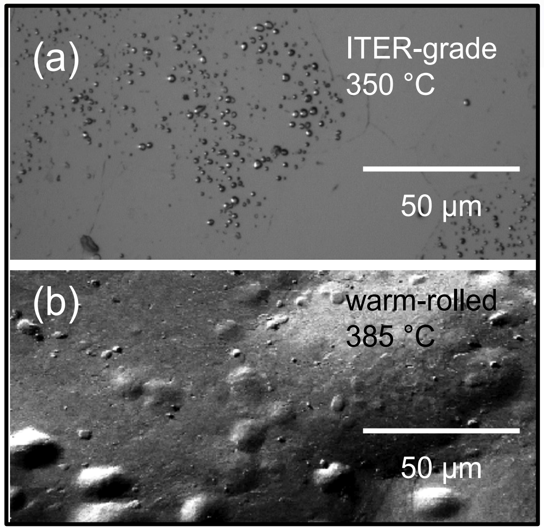
Tritium Plasma Experiment at INL



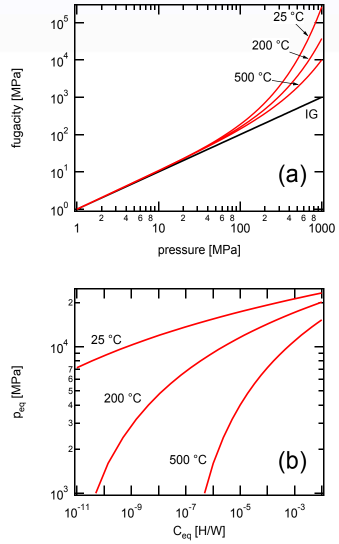


The PSI SC efforts are heavily leveraged with our base program funding

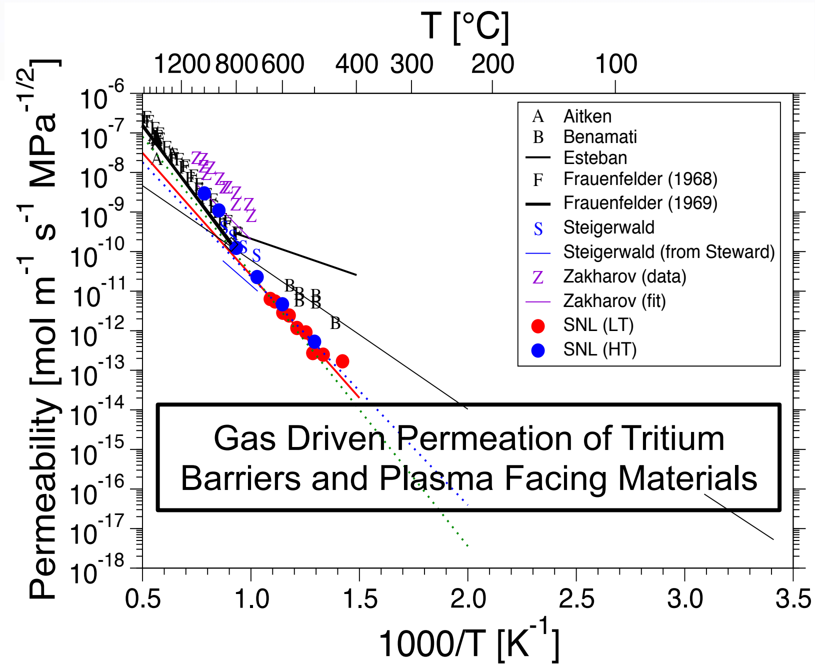
SNL-CA base program (Technology & DIII-D)

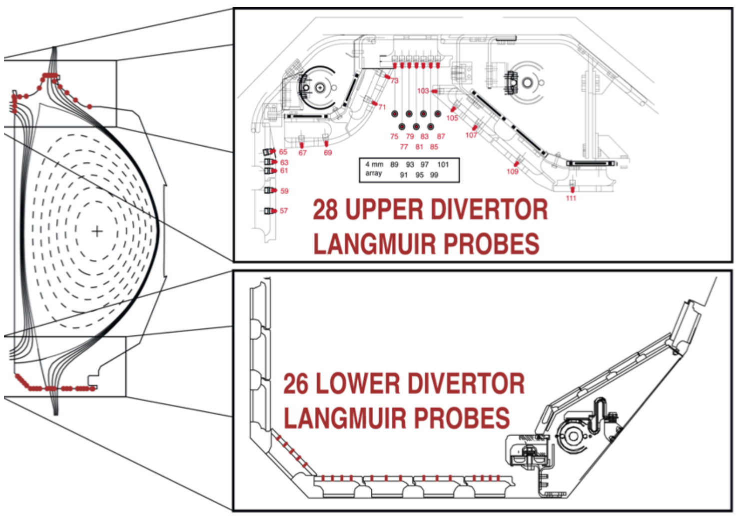


Hydrogen induced blistering of W

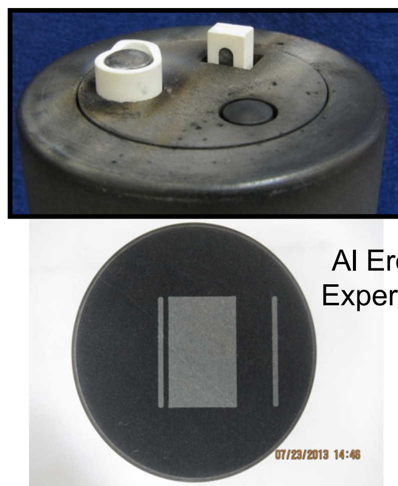


Equilibrium Pressure From Bubble Model



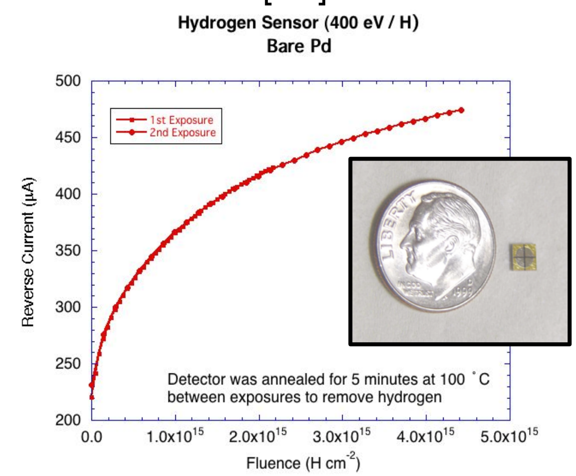


Edge Plasma Characterization in DIII-D



Al Erosion Experiment

Plasma Measurements and Erosion/Redeposition Experiments on DiMES (DIII-D)

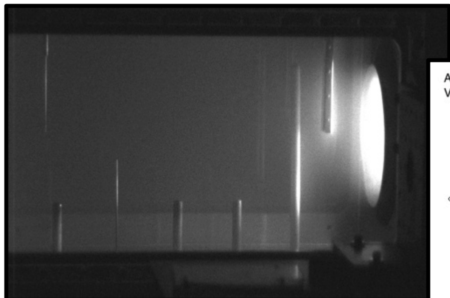


Hydrogen Microsensor Development

Other fusion research at SNL-CA

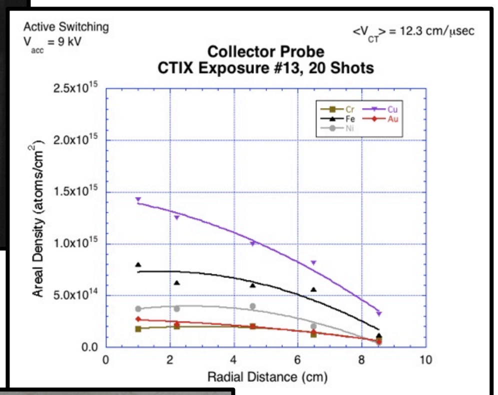
UCDAVIS
COLLEGE of ENGINEERING
Center for Advanced Laboratory Fusion Science and Engineering (CALFUSE)
COMPACT TORUS INJECTION EXPERIMENT (CTIX)

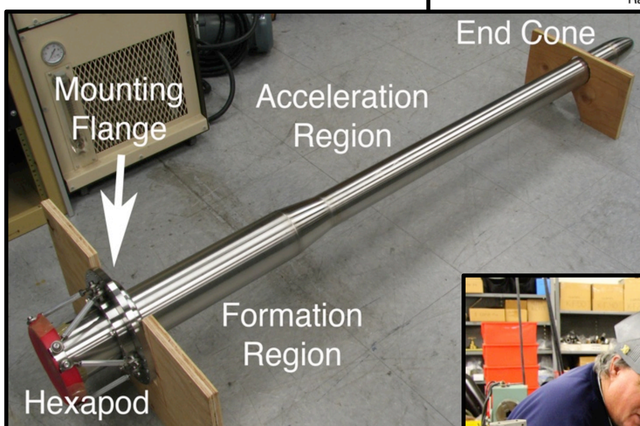
Plasma Surface Interactions in the Compact Toroid Injection Experiment (started in FY10)



Collector Probes in CTIX

Impurities Exiting the Plasma Accelerator

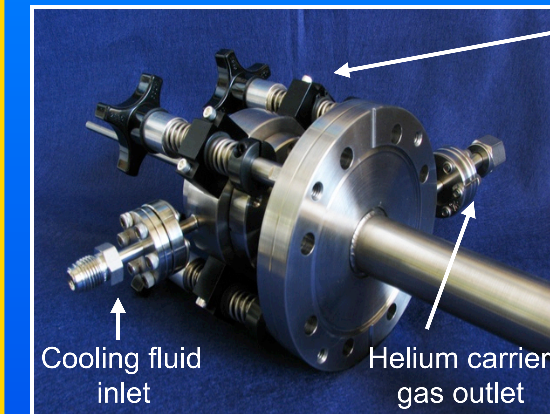




Improved Electrode Design

Final weld alignment

Membrane Holder Photos



Development of Plasma driven Permeation holder for TPE

2013-2018 HENIX
JAPAN-US JOINT PROJECT

US-Japan Collaboration on PFC evaluation by Tritium Plasma, Heat, and Neutron Irradiation eXperiments

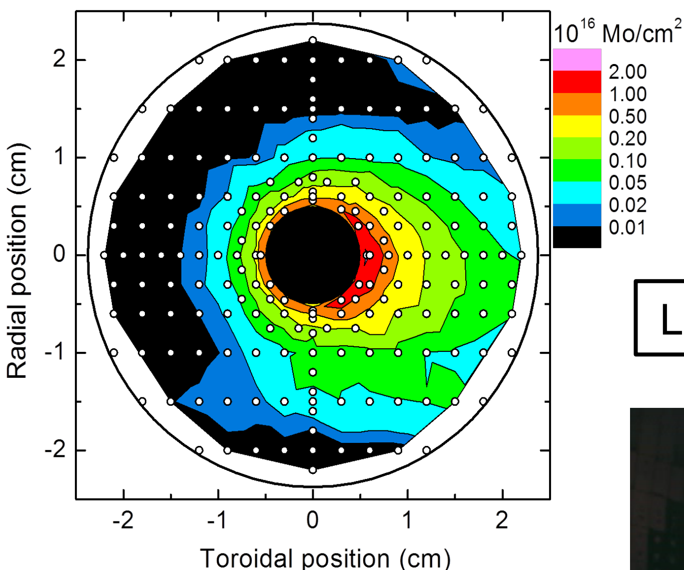
Sandia National Laboratories

Sandia Ion Beam Laboratory (NM)

DiMES experiments on DIII-D

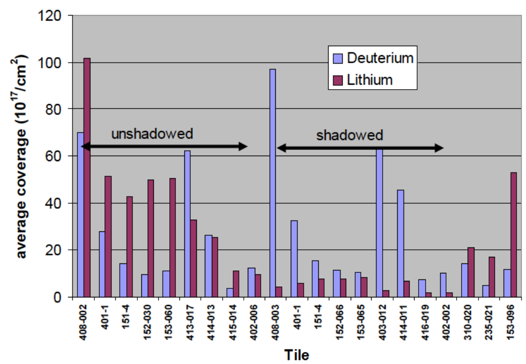
Molybdenum

erosion 0.5 nm/s



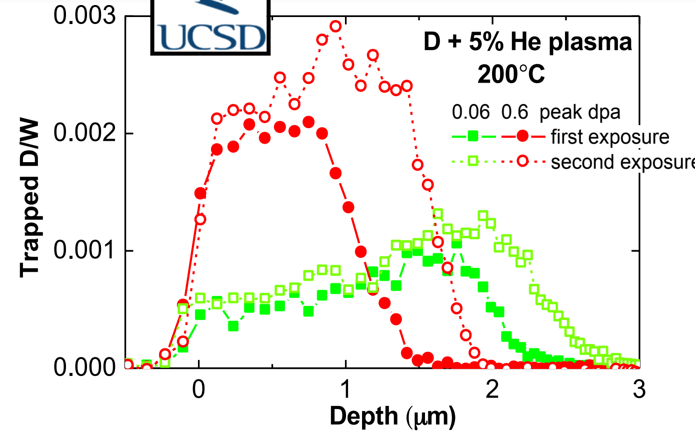
19% redeposited locally with λ=2.3 mm

PRINCETON PLASMA PHYSICS LABORATORY



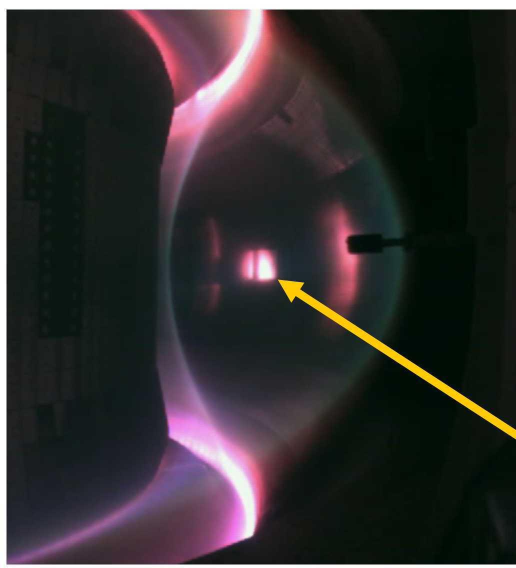
Tiles in Li shadow have ~ 10x less Li than unshadowed tiles, whereas D coverage is similar.

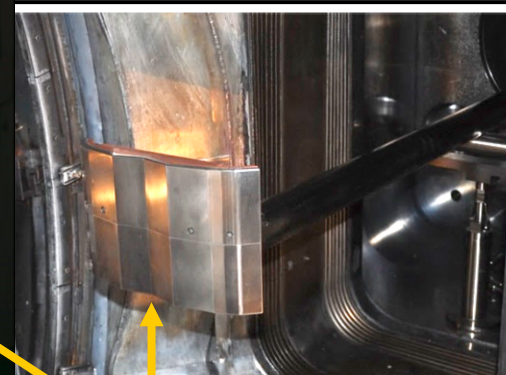
Li and D coverage on NSTX tiles



Deuterium trapping studies on damaged tungsten in PISCES

EAST/MAPES Material Erosion Experiment



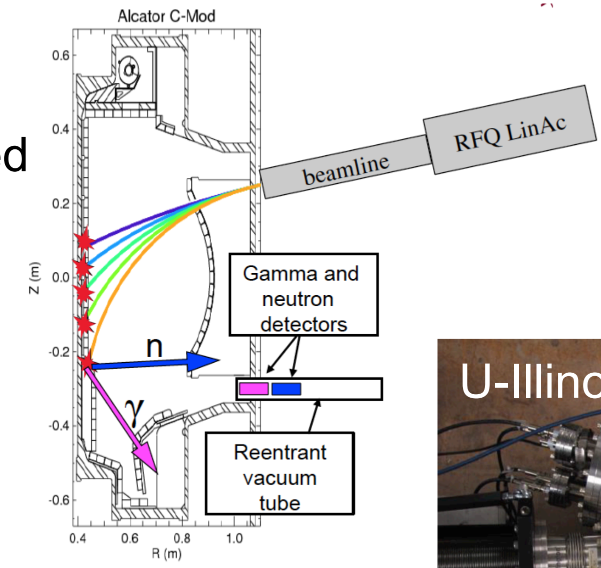


MAPES

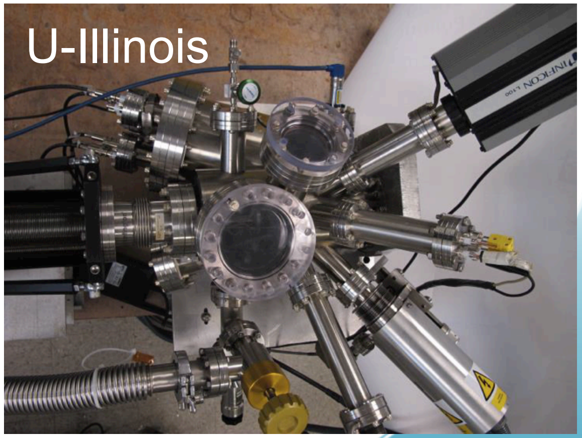
US fusion program has a major focus studying plasma-material interactions (including erosion)

- **DIII-D**
  - DiMES (divertor) and MiMES (first wall) experiments provide erosion / redeposition data for plasma-material interaction model validation (REDEP/ WBC-ITMC code)

- **Alcator C-Mod**
  - High Z erosion and redeposition studied using a dedicated ion beam facility
  - AIMS: Accelerator-based In-situ Materials Surveillance (compact RFQ LinAc injects 0.9 MeV D+)

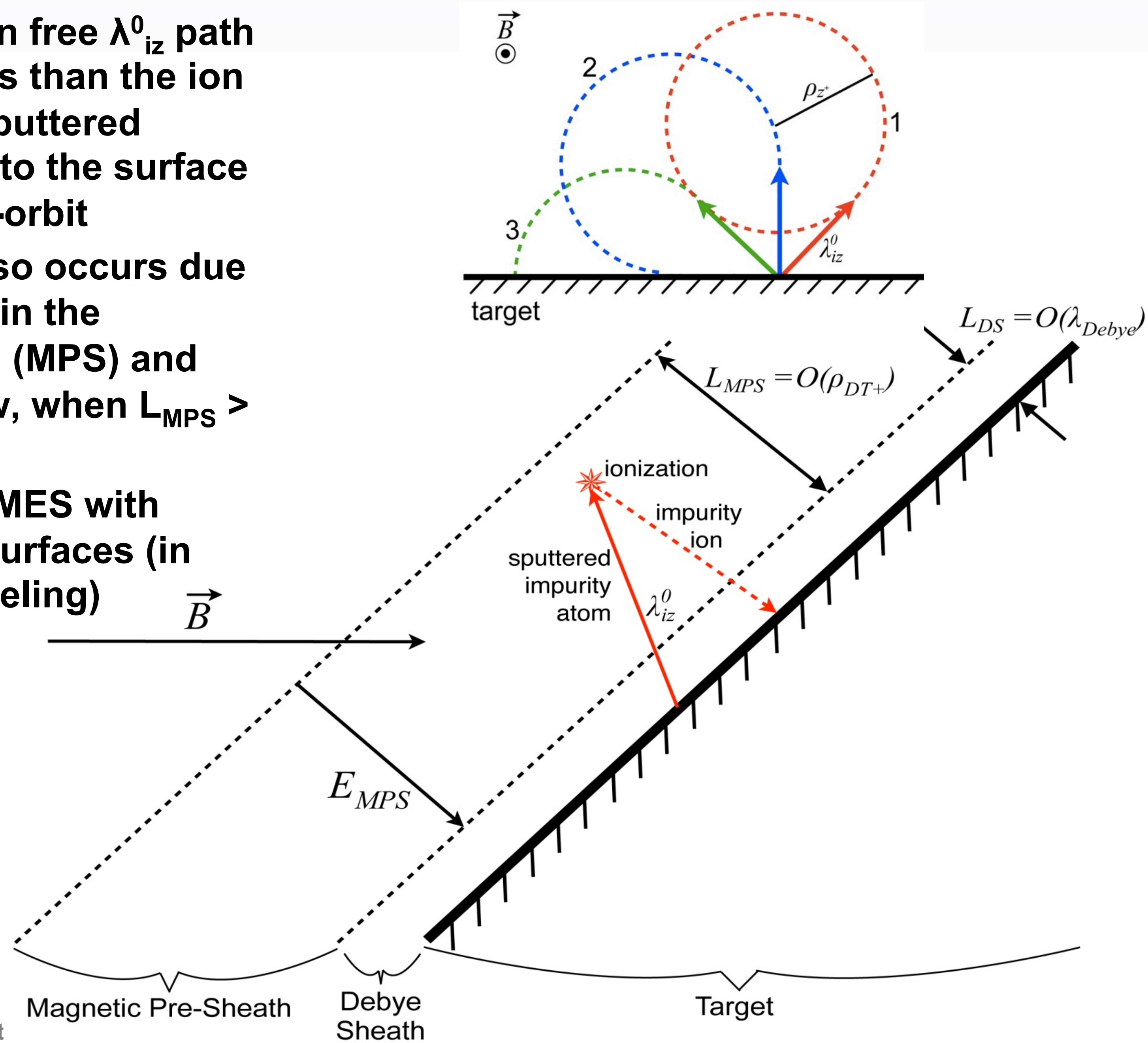


- **NSTX-U**
  - MAPP: Material Analysis and Particle Probe (sample exposure with in-situ TDS, XPS, LEISS, DRS)

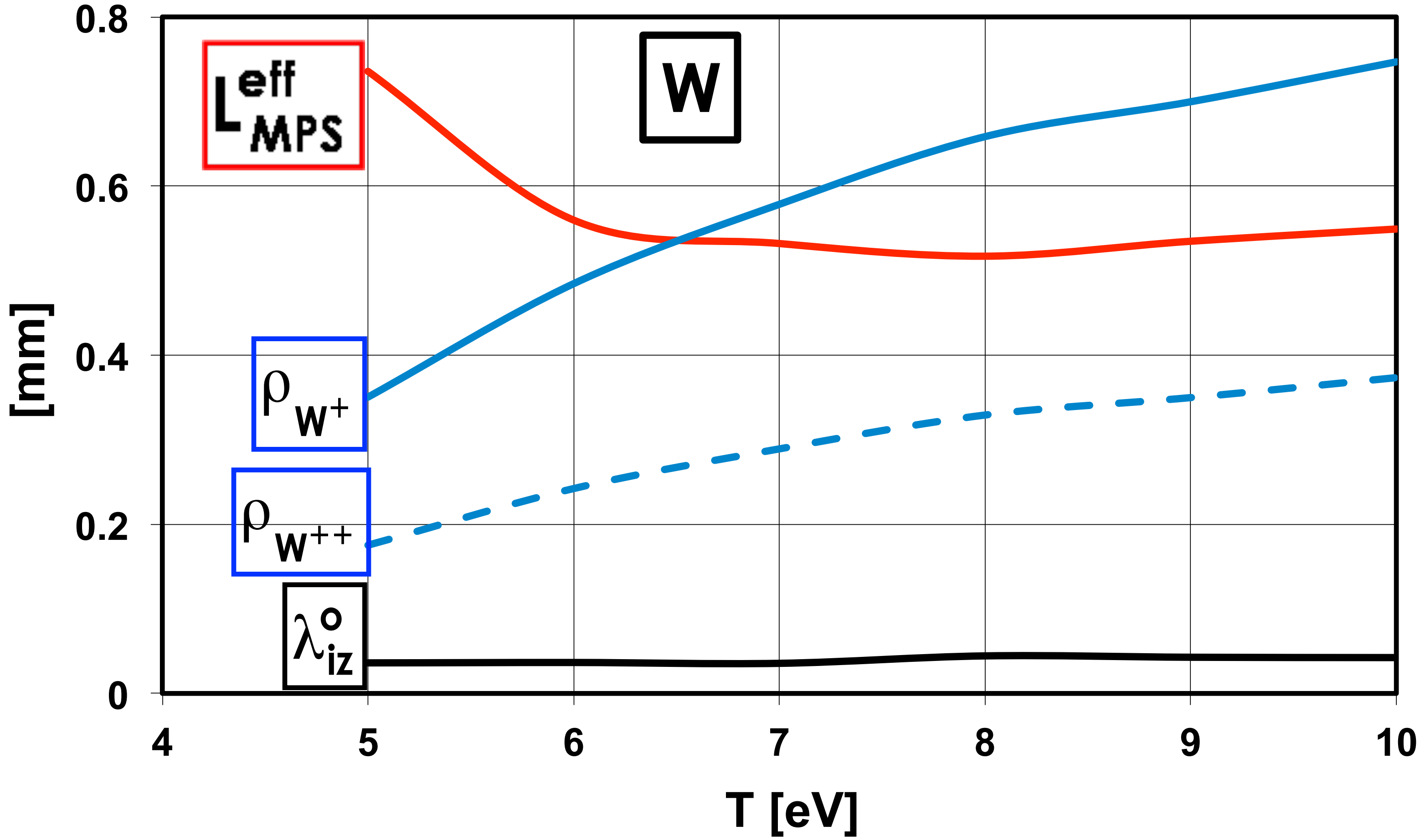


Prompt redeposition by ρ_{z+} / magnetic sheath of the divertor is expected to reduce net erosion

- If the ionization mean free λ^0_{iz} path is comparable or less than the ion Larmor radius ρ_{z+}, sputtered impurity ions return to the surface during the first gyro-orbit
- Fast redeposition also occurs due to the strong E-field in the magnetic pre-sheath (MPS) and friction with fast flow, when $L_{MPS} > \lambda^0_{iz}$
- Demonstrated on DiMES with tungsten and moly surfaces (in agreement with modeling)



For tungsten, prompt deposition should be effective in DT devices via both strong MPS forces and large ρ_W



ITER case with $n_e = 10^{21}\ m^{-3}$, B = 5 T

Courtesy of P. Stangeby

Prompt deposition *is not* expected at the first wall

- **Much lower far scrape off layer (SOL) plasma density (~ x10^{-3}) will result in longer ionization mean free path λ^0_i**
  - Sputtered wall neutrals will penetrate into the far SOL and experience migration towards the divertor
- **The sputtering can be due to either plasma ions or charge exchange (c-x) neutrals**
- **While several efforts to characterize the first wall c-x flux occurred during the 80's / 90's, no current investigations exist on US tokamaks**
  - LENA (Low Energy Neutral Analyzer): PLT, ASDEX, Alcator C-Mod (installed only)
  - CRP (Carbon Resistance Probe): TMX-U, PLT, ASDEX, TFTR
  - Pd-MOS H-sensors (Palladium Metal-Oxide-Semiconductor)
    - Diode type: ZT-40M and TFTR
    - Capacitance type: DIII-D, NSTX
- **Is the flux of c-x neutrals important in FW erosion? What is the poloidal and toroidal distribution of the c-x flux? How will c-x induced erosion scale in future devices?**
- **Simple estimate on next viewgraph: physical sputtering of T using E=300 eV (Eckstein 2002), normal incidence yield doubled to account for surface roughness, no sputtering by other plasma or wall species, P_{cx} = 0.05 P_{heat} (~Kukushkin for ITER)**

Rough estimate of c-x induced FW erosion

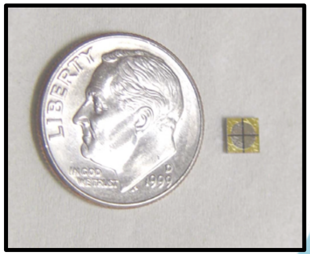
For 300 eV T° c-x sputtering of walls	P_{heat} [MW]	annual run time [s/year]	beryllium net wall erosion rate [kg/yr]	boron net wall erosion rate [kg/yr]	carbon net wall erosion rate [kg/yr]	tungsten net wall erosion rate [kg/yr]
DIII-D	20	10^4	0.13	0.11	0.08	0.16
JT-60SA	34	10^4	0.22	0.19	0.15	0.27
EAST	24	10^5	1.6	1.2	0.82	1.8
ITER	100	10^6	77 [29*] {60***}	64	44 [53*] {54***}	92 [41*] {46***}
Vulcan	20	10^7	120	100	70	150
FDF	100	10^7	610	500	340	740
Reactor	400	$2.5x10^7$	6500	5300	3700	7900 [5000**]

* Kukushkin B2-EIRENE calculation
**Lackner
***Behrisch

Courtesy of P. Stangeby

Techniques for measuring c-x flux

- **LENA (Low Energy Neutral Analyzer)**
  - Pros: provides good time and energy resolution
  - Cons: Available at only a few locations (usually one) due to size and complexity
- **CRP (Carbon Resistance Probe)**
  - Pros: compact and low power device, energy discrimination by array with varying overlayers, good time resolution
  - Cons: device saturates permanently at 2 x 10^{15} H/cm^2
- **Pd-MOS H-sensors (Palladium Metal-Oxide-Semiconductor)**
  - Pros: compact and low power device, energy discrimination by array with varying overlayers, in-situ reset through heating of device
  - Cons: dosimetric (shot by shot), lifetime limited by charge trapping



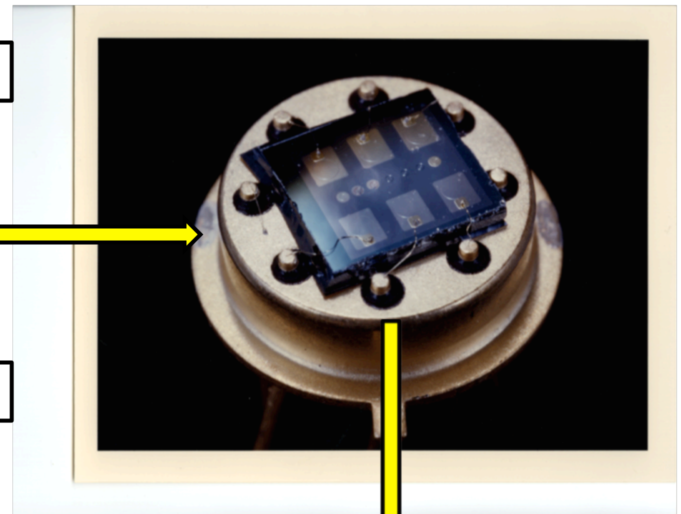
Each device can play a role towards quantifying c-x flux in existing experiments

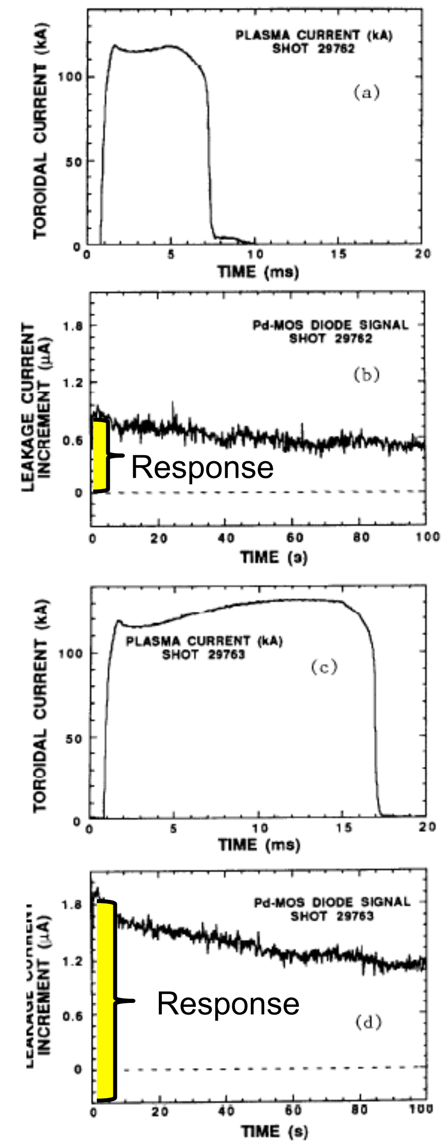
Pd-MOS sensor use in confinement experiments

- **First use on ZT-40M demonstrated dosemetric effect of sensors**

R. Bastasz, J. Nucl. Mater. 162-164 (1989) 587.

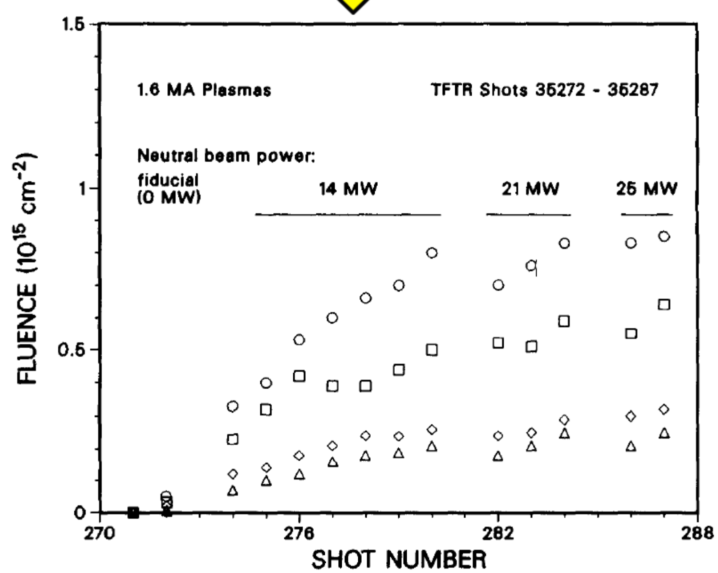
Work by Bob Bastasz and Bob Hughes





- **An array sensor was used on TFTR to demonstrate energy resolving c-x measurement**

R. Bastasz, J. Nucl. Mater. 176-177 (1990) 1038.



- **Switched to capacitance type detectors for easy of fabrication**

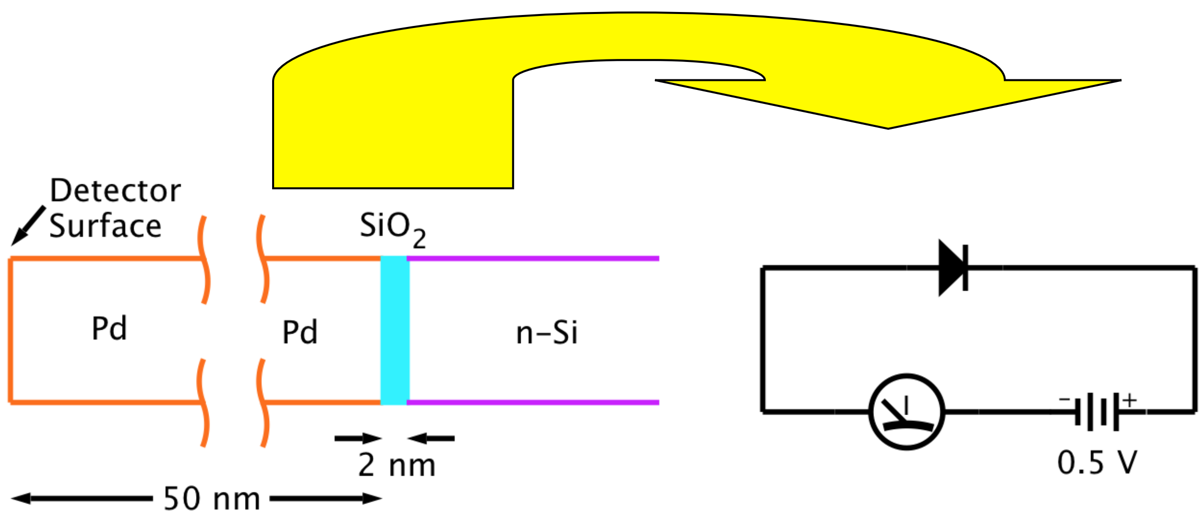
- **Tests on DIII-D and NSTX were not successful**
  - Likely cause: charge production in thick oxide layer due to x-rays or high energy charged particles

Pd-MOS Schottky diode type H-sensors

- **Diode type detectors will limit charge production due to thin tunnel oxide while a thicker Pd coating can protect from high energy particles**
- **Hydrogen entering the palladium metal diffuses rapidly, filling surface sites at the Pd-tunnel oxide interface, and changing the barrier height of the diode**
  - Simple model of current under reverse bias

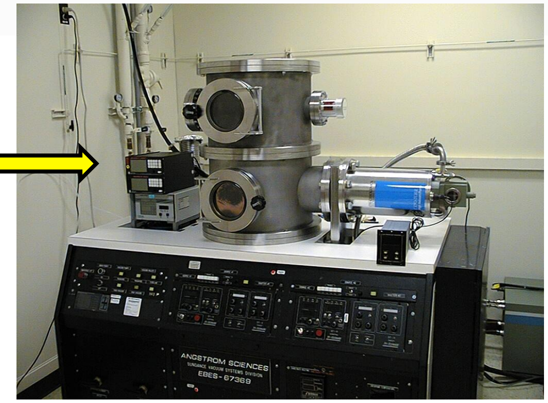
$$I_r = AT^2 \exp\left[-\phi_b / kT\right] \qquad \phi_b = \phi_m - \chi$$

  - A is a factor depending on the device size and applied voltage, T is the temperature, and ϕ_b is the barrier height. ϕ_m is the metal work function and χ is the electron affinity of the silicon. Hydrogen at the interface changes ϕ_m giving a large change in reversed current.

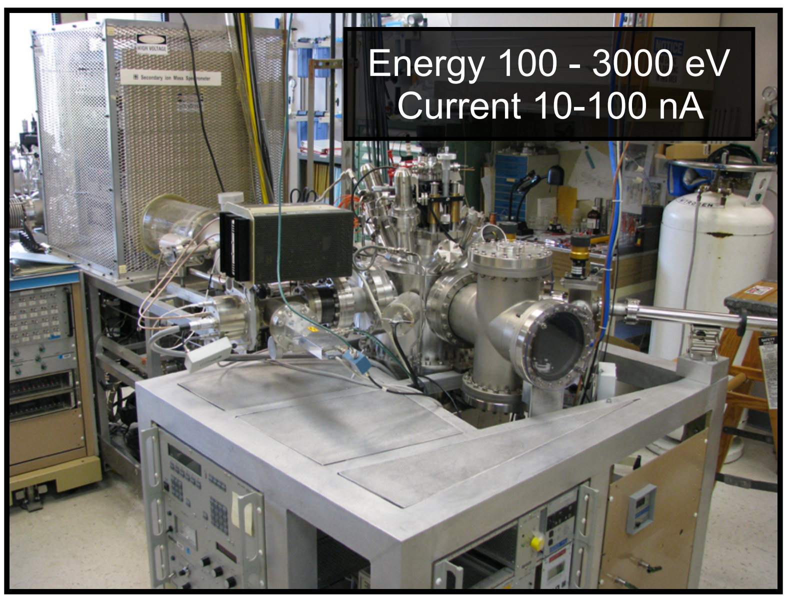


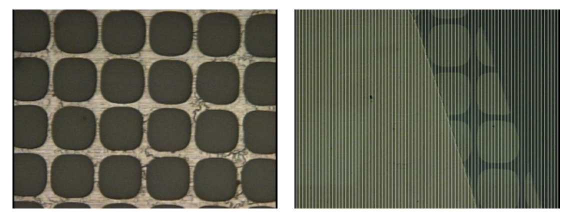
Initial attempts to fabricate rugged Pd-MOS H-sensors

- **Wafers were stripped and 2 nm tunnel oxide grown in the MESAfab (silicon fab at SNL-NM)**
- **Pd films and titanium adhesion grids were deposited at SNL-CA (summer of 2010)**
  - Ti used to improve adhesion in the semiconductor industry
- **Each wafer produced many sensors (3.6 mm square)**
- **Sensors were evaluated using a mass and energy filtered ion beam (SNL-CA)**

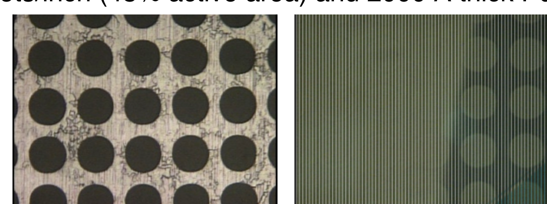


10 keV dual e-beam evaporator used to deposit Pd, Ti, and Au under high vacuum (10^{-6} Torr). Typical deposition rates are 50 Å/s.





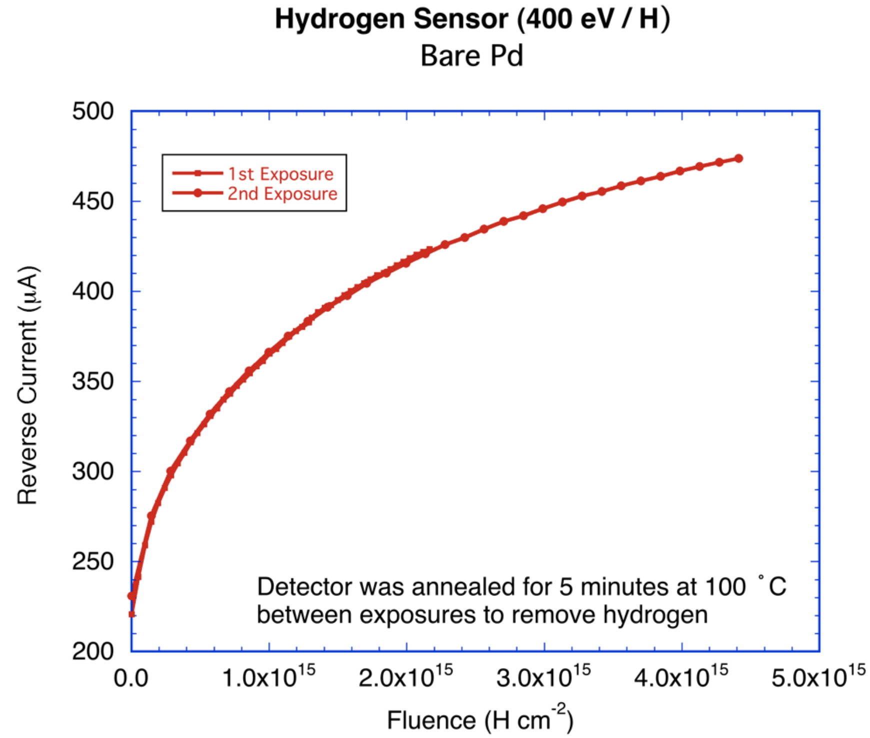
200 Å thick Ti posts at 200 dots/inch (48% active area) and 2000 Å thick Pd



200 Å thick posts at 200 dots/inch (76% active area) and 2000 Å thick Pd

Ti posts unsuccessful, but diode-type H-sensors did exhibit similar behavior to previous detectors

- 20 nm Ti post array was too reactive and shorted the Pd metal-oxide interface
- Bare Pd sensors exhibited good response and reproducibility. Energy sensitivity needs further study.
- Exploring other options which will exploit extensive processing capabilities at the MESAfab
- Development of rugged detectors will require more than the 2010 several-month effort described here
- Leveraging of the MESAfab facility and expertise would require only a modest investment



MESAfab Key Fabrication Capabilities

• Photolithography Processes (Coat/Expose/Develop) • Electron Beam (E-Beam) Lithography • Reactive Ion Etch • Wet Etch/Clean • Oxidation and Diffusion • Thin Films • Chemical Mechanical Polishing (CMP) for planarization • Ion Implantation • Metrology • Deep Reactive Ion Etch (DRIE)	• Electroplating • Packaging • MEMS Release • Yield Learning • Statistical Process Control • III-V Compound Semiconductor Epitaxial Growth • Mixed-Technology Integration and Processing • 3D Integration • Materials Characterization • Failure Analysis • Wafer Bonding and Thinning

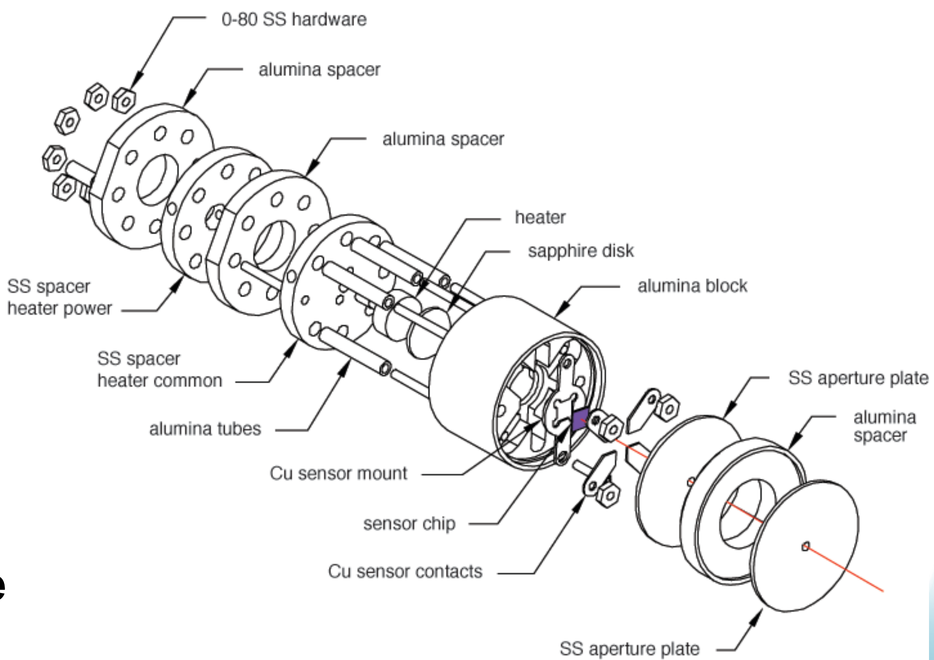
Summary

- Unlike the divertor, the first wall of tokamaks will not experience prompt redeposition of sputtered material. Thus net erosion will be ~ gross erosion.

- Simple estimates and more complete simulations indicate that charge-exchange sputtering will result in large migration of first wall material in future devices.

- The development of Pd-MOS diode H-sensors would provide a tool that could quantify the poloidal and toroidal charge-exchange flux.

- Combined with the high energy and time resolution of a LENA, arrays of Pd-MOS devices could provide critical data for edge plasma – neutral model validation.



Pd-MOS H-sensor DiMES head

Continued interest at DIII-D and NSTX to evaluate Pd-MOS H-sensors