Overview of the Center for Plasma Material Interactions (CPMI)

Daniel Andruczyk

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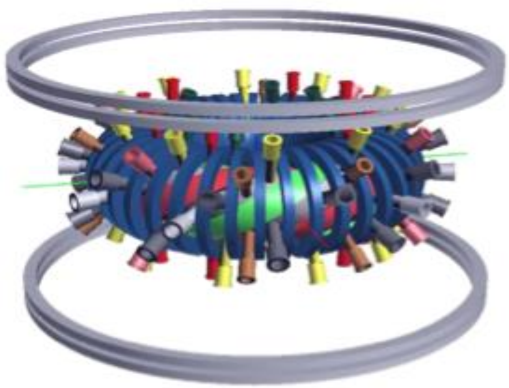
Oak Ridge National Laboratory (ORNL)

Los Alamos National Laboratory (LANL)

University of Tennessee, Knoxville (UTK)

Stony Brook University, New York (SUNYSB)



ILLINOIS

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Nuclear, Plasma, and Radiological Engineering

Center for Plasma-Material Interactions

Max Planck Institute for Plasma Physics, Greifswald (IPP)

Institute for Plasma Physics Chinese Academy of Science (ASIPP)

Dutch Institute for Fundamental Energy Research (DIFFER)

Outline

- Overall structure of CPMI
  - Overview
- PMI research and PFC development
  - SLiDE
  - LiMIT
  - DEVeX
  - TUFCON
  - Seebeck
  - MCATS
  - Sn – Li Eutectic PFC
  - Retention and Hydrogen Degassing
  - Surface texturing
- Plasma nano surface and structure
  - Lithiated Tungsten Experiments (IGNIS)
  - MAPP
  - Adaptive materials
- Plasma Theory and Modeling
  - RF modeling on Proto-MPEX
  - Fractal TRIDYNE
  - Numerical simulations for HIDRA
- Magnetic Fusion Facility
  - HIDRA
  - EAST Collaboration
- Summary

Center for Plasma Material Interactions (CPMI)

- The group consists of
  - 4 Professors
  - 1 Research Engineer
  - 3 Post-docs
  - 20 Graduate students
  - 20 – 30 undergraduate students

- 18 experiments that cover a range of PMI studies and PFC development

- The group performs research not only in fusion but also in processing and industrial plasmas

- Here I will be only concentrating on the fusion relevant experiments

Overall Structure of CPMI

Plasma Research at the Center for Plasma Material Interactions (CPMI)

Plasma and Laser nano-manufacturing

Plasma Facing Components

Liquid Fusion Walls

D. N. Ruzic

Plasma Materials Computational Modeling

Near-Wall Kinetics

3-D Edge Models

Fusion Material Wall

D. Curreli

Plasma Nano-synthesis

Plasma Science and Engineering Research

Plasma Edge Modeling Validation in HIDRA

J. P. Allain

Advanced Fusion Materials

In-situ and in-vivo surface Characterization

In-situ Plasma Diagnostics, HIDRA-MAT

D. Andruczyk

HIDRA System and Testing

Advanced PMI Diagnostics

Fusion technology Education

Overall Structure of CPMI

Plasma Research at the Center for Plasma Material Interactions (CPMI)

Plasma and Laser nano-manufacturing

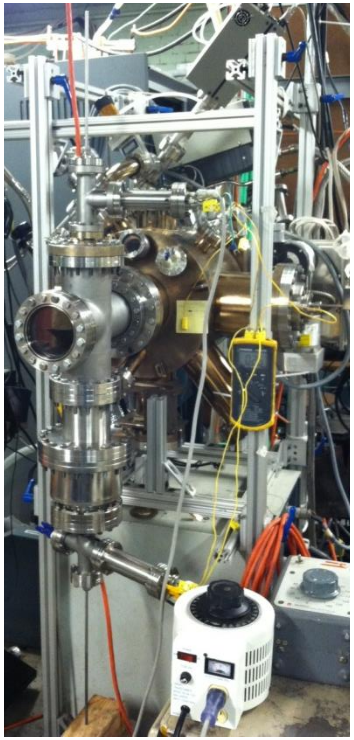
Plasma Facing Components

Liquid Fusion Walls

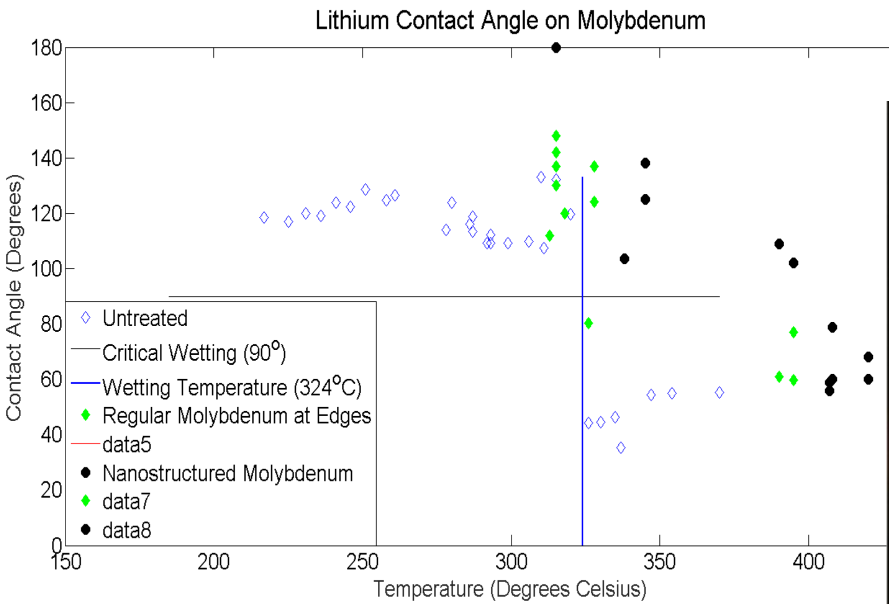
D. N. Ruzic

Plasma Science and Engineering Research

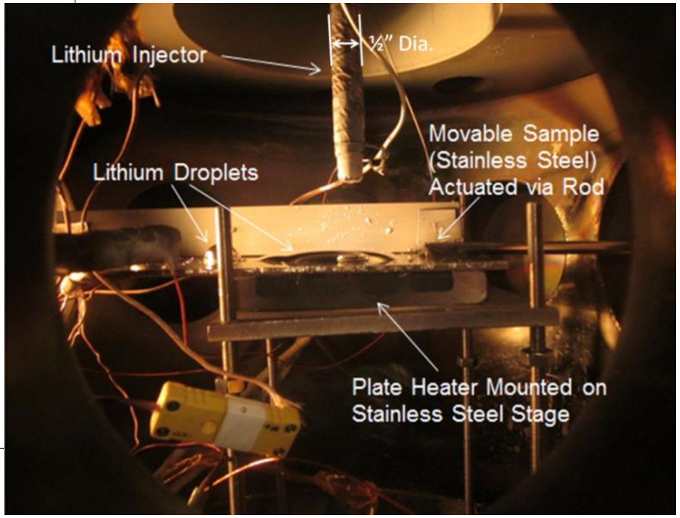
Materials Characterization Test Stand (MCATS)



Testing Liquid Lithium Wetting of PFC Materials



liquid dropper setup



Place Drop, and Take Still Frame

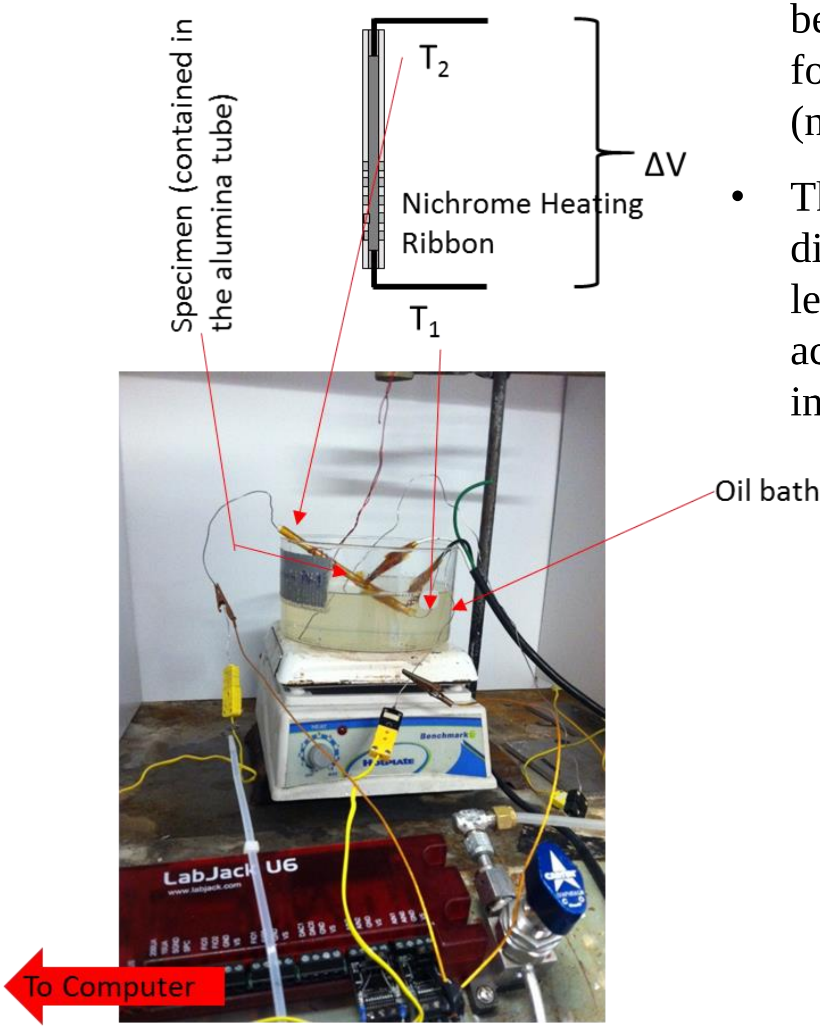
Heat Plate while Taking Still Frames at Different Temps

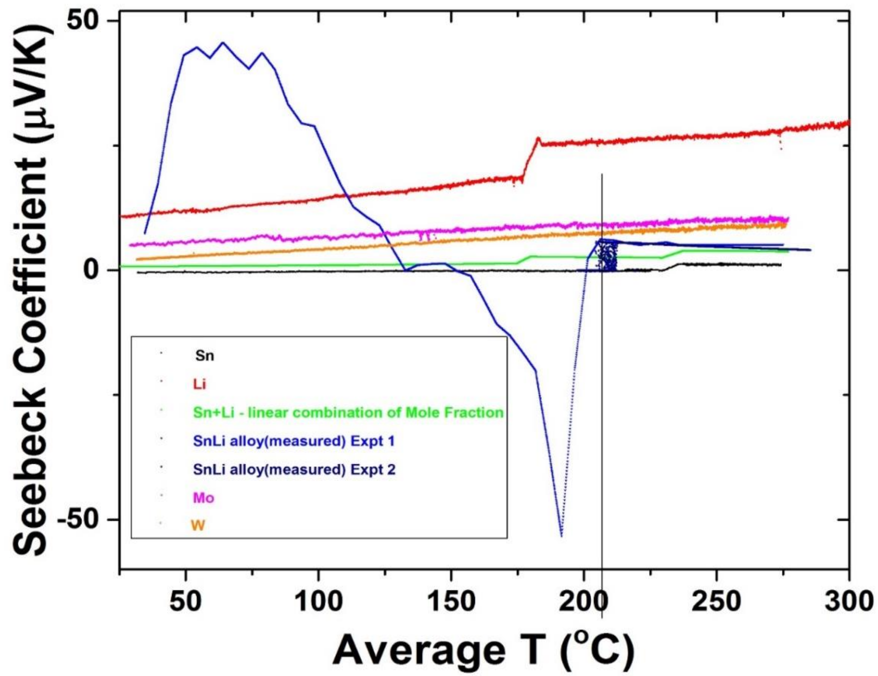
At set intervals, move plate, place new droplet

Continue to heat while taking still frames, record wetting temperature

Seebeck Coefficient Measurements

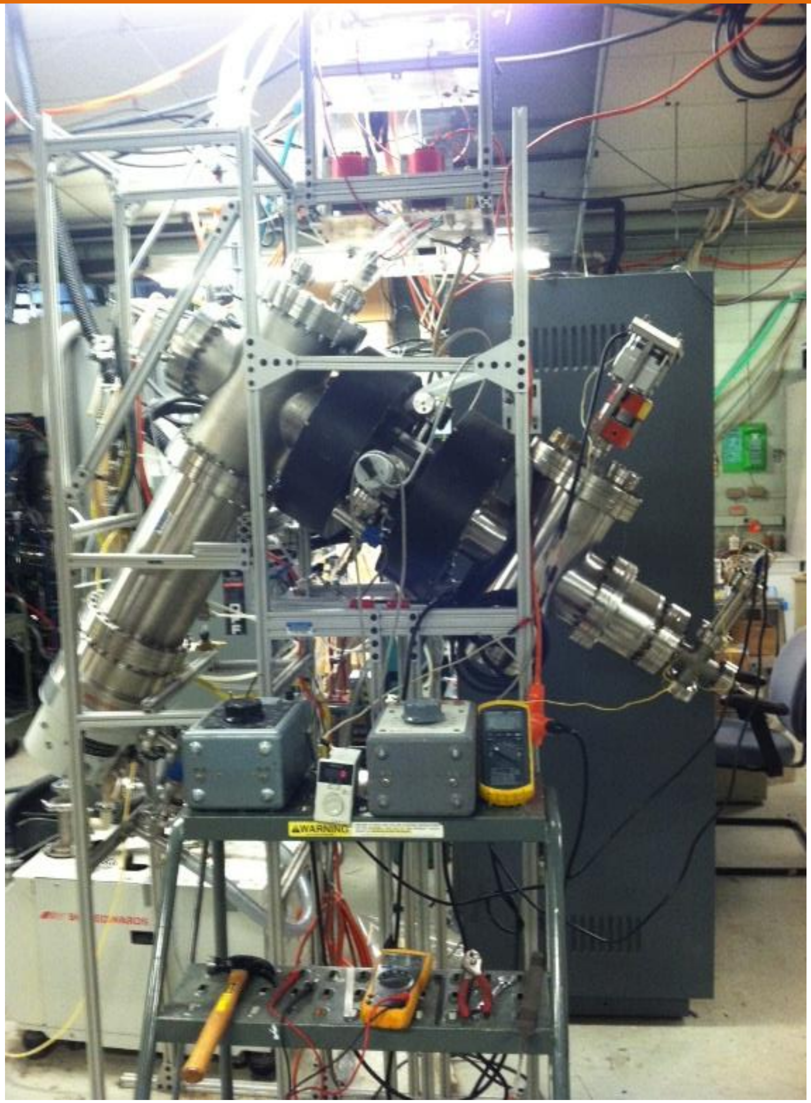
- The Seebeck coefficients for fusion relevant materials have been measured at the University of Illinois. Current efforts are focused on investigating the thermopower of a Sn-Li eutectic (nominally 80% Sn and 20% Li by mole fraction).
- The Seebeck coefficients can be seen to the right, while a diagram and image of the measurement setup can be seen to the left. It was critical to maintain a constant temperature gradient across the metallic sample, so the entire system was submerged in oil.





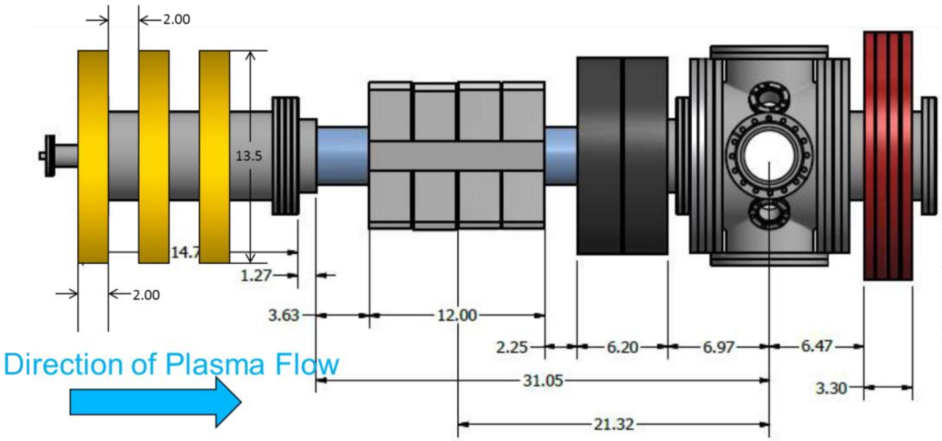
Solid/liquid Lithium Divertor Experiment (SLiDE)

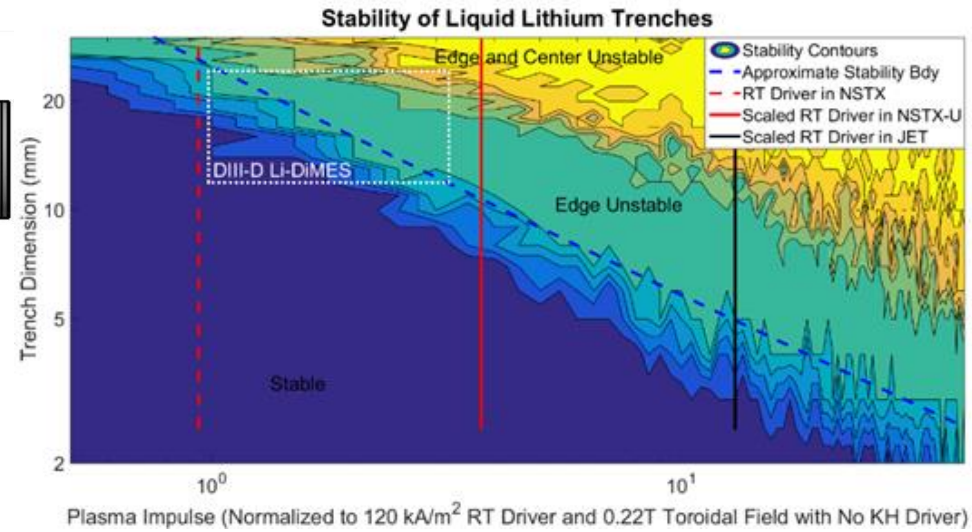
- Originally designed to provide a heat source for surface tension driven flows in a magnetic field experiments.
  - Follow on from CDX-U experiments
  - 60 MWm-2 of lithium with no noticeable evaporation
- Swirling of the liquid lithium and strong heat flux mitigation was eventually found to be driven by thermoelectric magneto-hydrodynamic (TEMHD) flows.
- SLiDE consists of an array of tungsten filaments that produce a sheet of electrons that are focused on to the surface of the target.
  - Lithium/Metal Infused Trenches (LiMIT)
  - Simulates a constant heat flux that would be seen at the divertor surface
  - $\Omega = 3$ MWm^{-2} @ $B = 0.05$ T

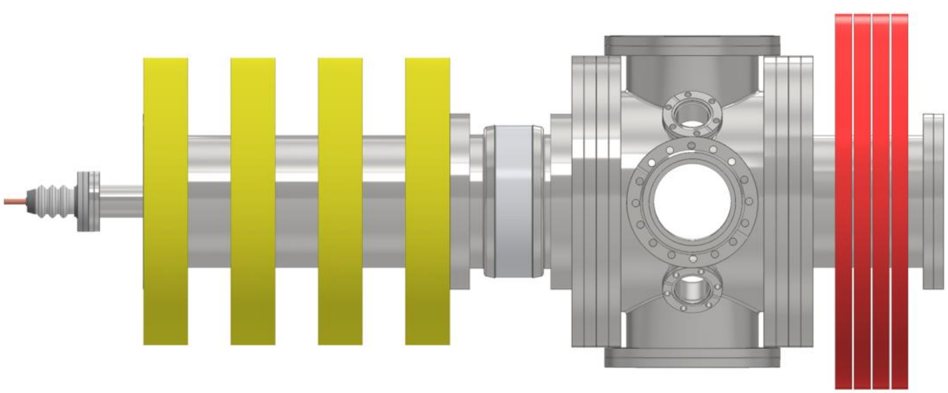


Center heat flux: 3 MW m^{-2}
Magnetic field: 0.05 T

Divertor Edge and Vapor shielding Experiment (DEVeX)





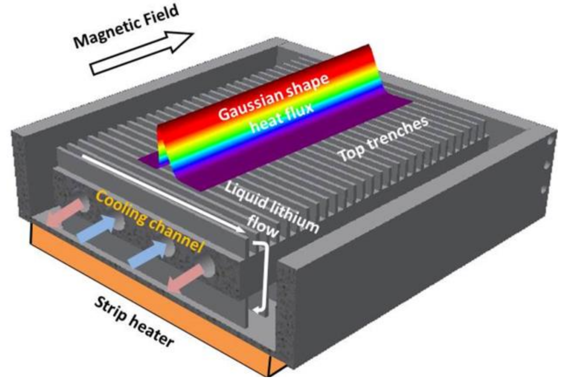


(Top Left) An Inventor diagram of the previous version of DEVeX/TELS, which utilized a coaxial plasma gun, a 1° conical theta pinch, and guiding fields to bombard fusion relevant wall materials with energies on the order of Type 1 ELMs in many larger devices (0.2 MJ m^{-2} over a pulse of 200 μs). **(Top Right)** A diagram of the lithium surface stability obtained from a combination of impulse experiments in the original iteration of DEVeX and computational solutions of the Shallow Water Equations. **(Bottom Left)** The current version of DEVeX-U/TELS-CT, which will use reconnection and compact toroid injection to increase heat flux, density and temperature.

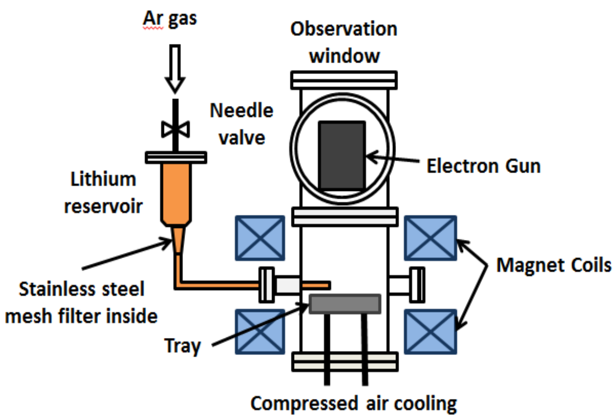
Liquid Metal Infused Trenches (LiMIT)

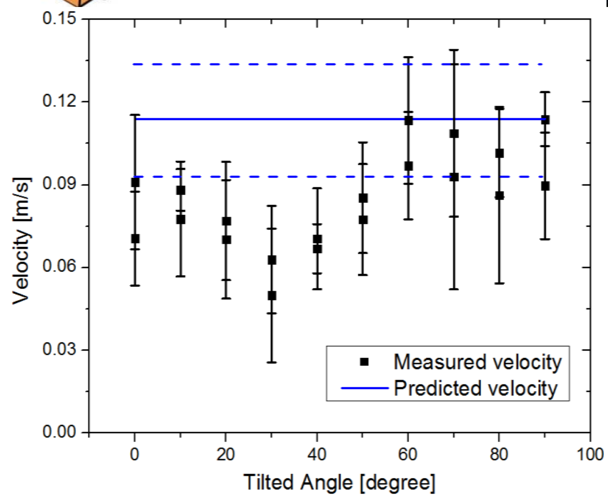
A versatile system for testing liquid metal flows for PFC applications

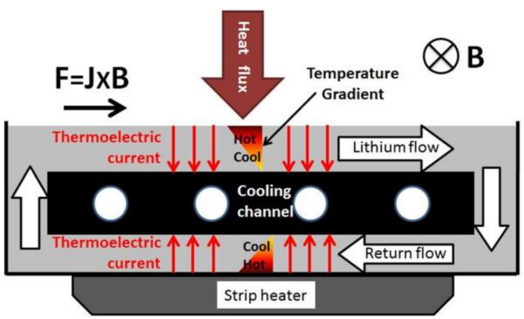
- Horizontal Flow
- Utilizes TEMHD drive for propulsion of liquid lithium through a series of trenches

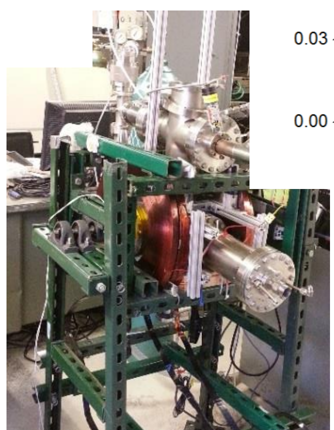


- Vertical Flow (and arbitrary angle)
- Sustained flow demonstrated at arbitrary angle from horizontal (0^o to 180^o)

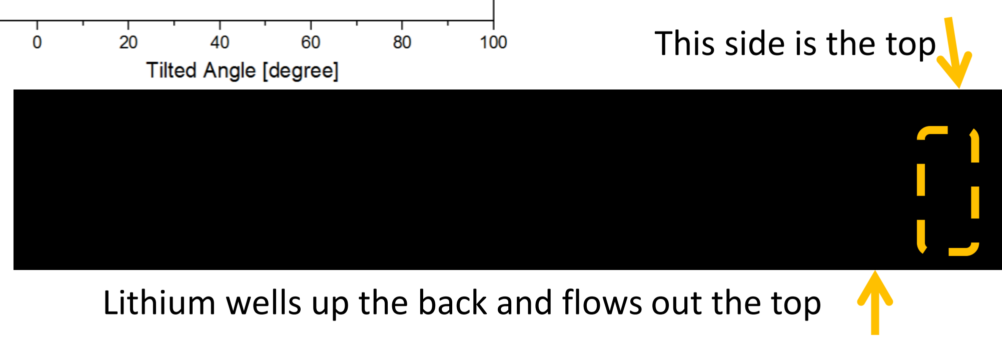








This side is the top



Lithium wells up the back and flows out the top

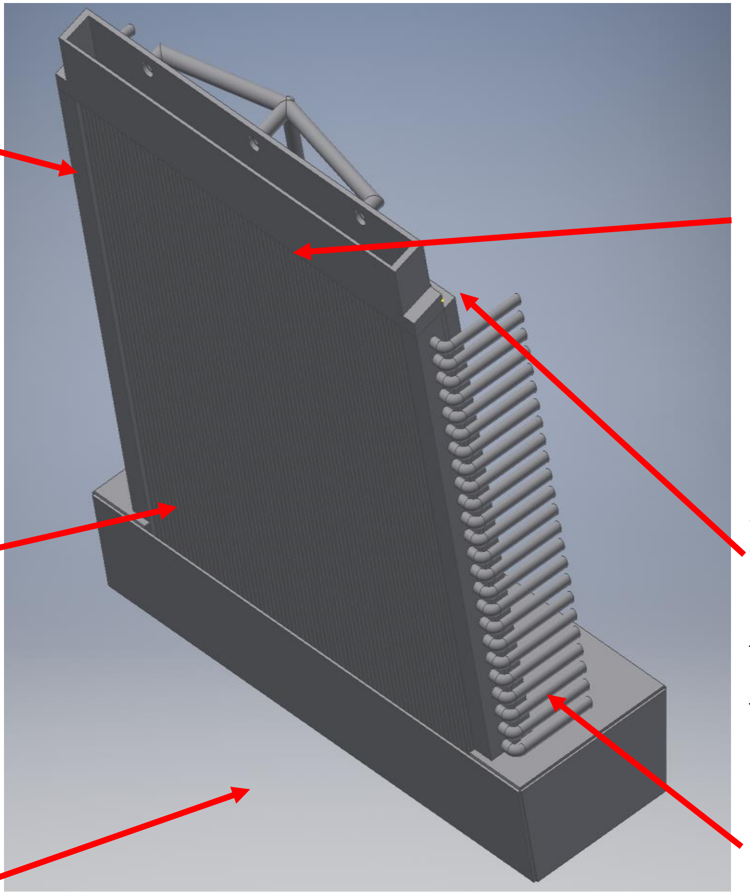
LiMIT in EAST

Large-scale testing of liquid metal PFC

Top reservoir (will be closed) allows for clean pooling and even filling of trenches

Front trenches constrain lithium flow and maintain a constant sheet, while TEMHD quickly drives lithium through high heat flux

Bottom reservoir provides lithium refill for continuous long-term operation



DC electromagnetic pump fills trenches at beginning of operation, and provides controllable lithium replenishing, while continuous LiMIT trenches allow for flow from back side

Even backside heating from cartridge heater array linked to thermocouples and temperature controllers

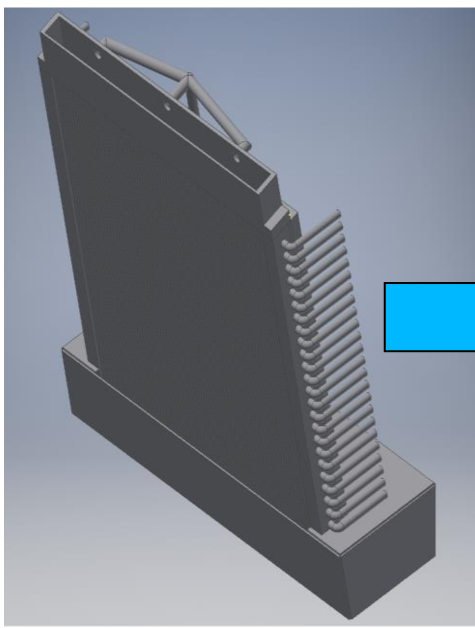
Cooling tube system allows for customizable cooling profiles, fine tuning flow over the face of the device

System Installation

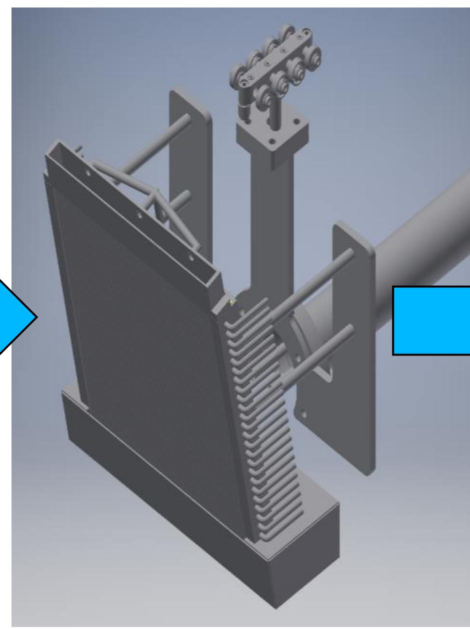
The full system offers a testable, large-scale device that exploits TEMHD-driven liquid lithium flow as an enhancement over typical PFC's and provides a constantly refreshing liquid lithium surface replenished by a reservoir during extended operation.

Installing LiMIT as a limiter in EAST utilizes existing infrastructure, like the LIPES lithium injection system, to minimize unnecessary development

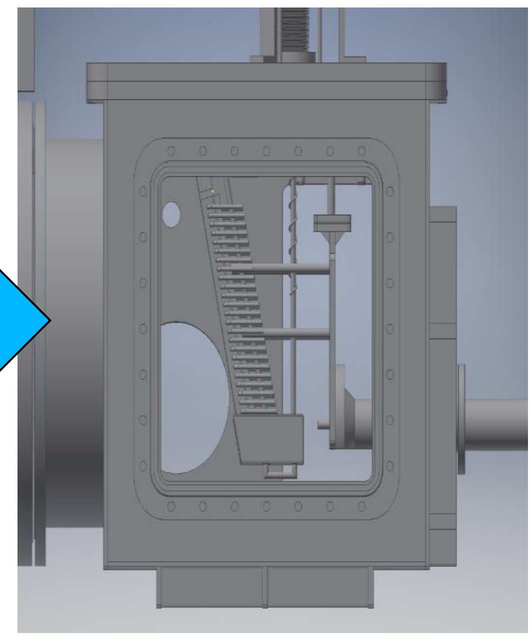
Full LiMIT Limiter System



Installed on Transfer Arm



In Exchange Box (w/ LIPES System)



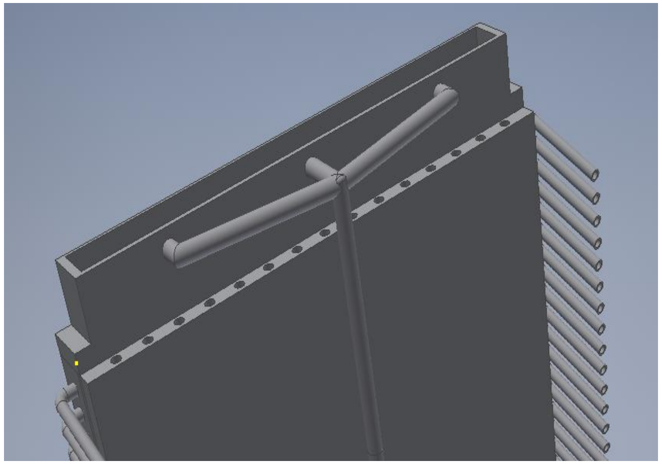
Injection and Filling

Capillary action not strong enough to fill trenches while vertical (or near vertical)

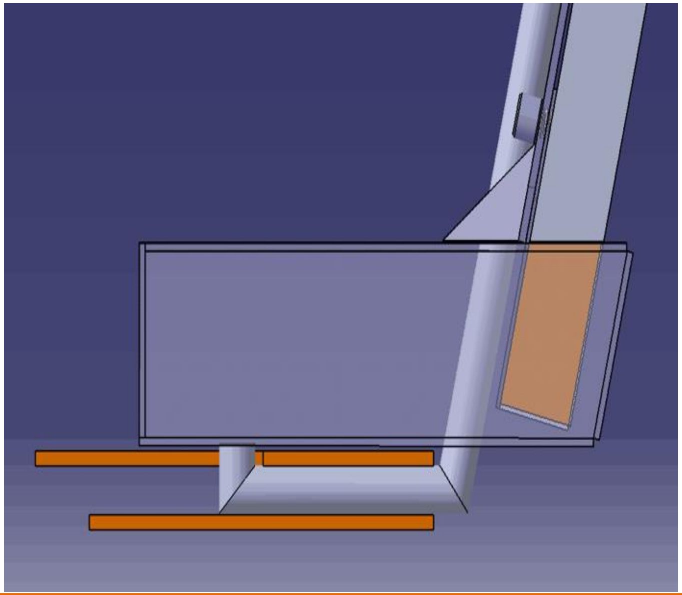
Precision needed for needle-type injection would be unnecessarily difficult

EM pump aids in filling trenches before TEMHD circulation begins

Ample flow rate allows for flow control during operation



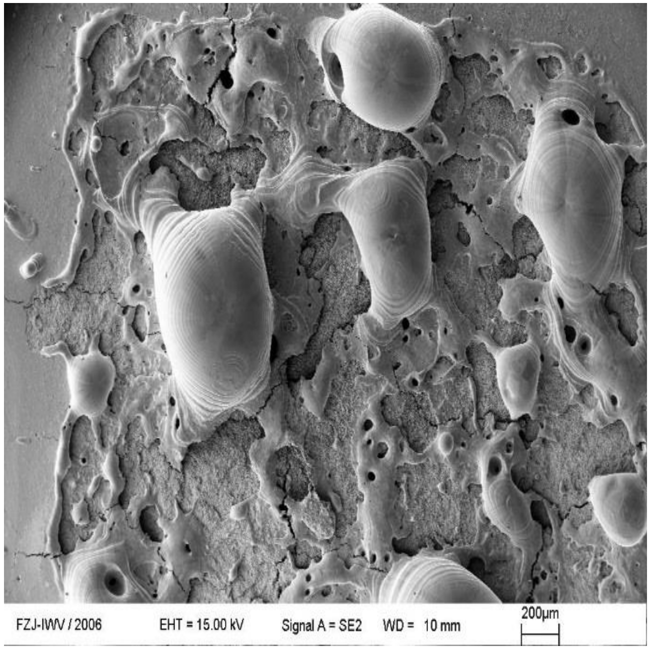
Three-fold distributor spreads filling flow and closed reservoir allows for safe pooling and slight backpressure to aid in distribution



DC electrodes (orange) provide thermoelectric driving current for lithium flow from the reservoir to the distributor

Investigation of Tin–Lithium Eutectic as a Liquid Plasma Facing Material

- High power loads on the fusion reactor walls results in materials degradation and restricts options for PFC materials
- Free flowing liquid metal PFCs
  - Better handling of the high heat flux ("self-cooling")
  - Option for fuel recycling, breeding
  - Regenerative properties - hence 'erosion' not a problem (thin-walled PFCs possibe)
  - Thermo electric effects can generate the necessary self-flow (LiMIT system at CPMI successfully demonstrated flowing lithium systems)
- Lithium is an attractive candidate
  - Has issues related to compatibility, reactivity and vapor pressure (limits the upper operating temperature)
- Tin-Lithium eutectic has a number of advantages over pure Li (or pure Sn)
  - Lower Li vapor pressure[1] in the eutectic system as compared with pure Li by a factor of ~ 1000[2].



Damage on tungsten PFCs

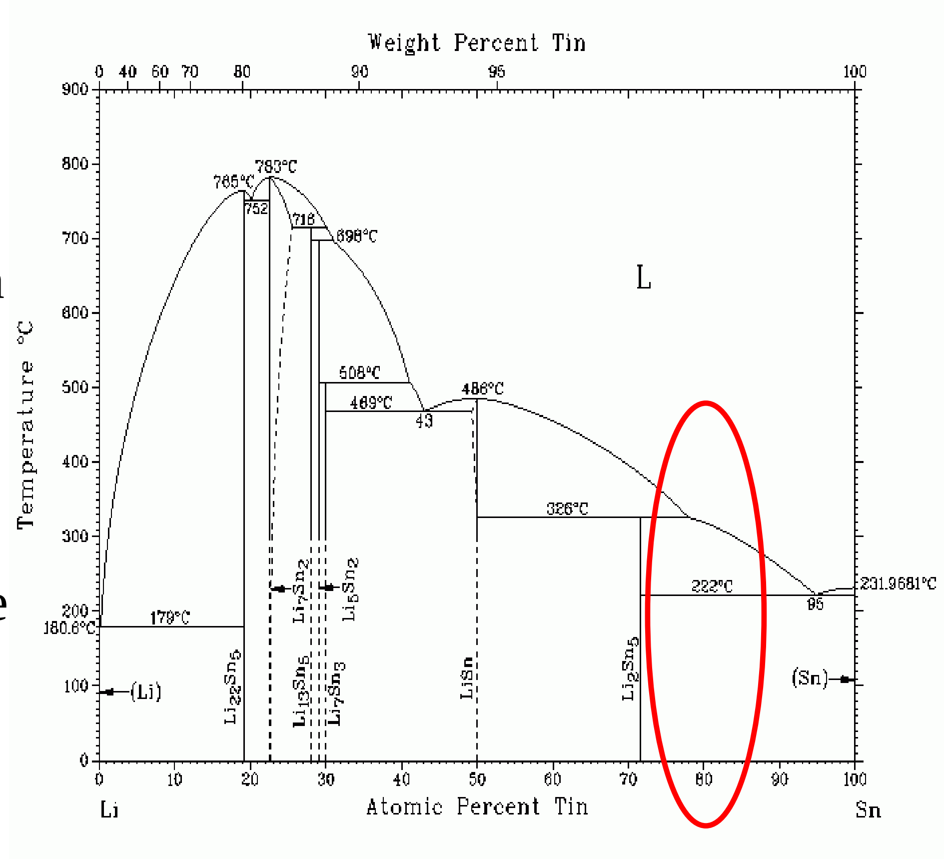
(Photo: Egbert Wessel, Julich Research Centre)

[1] D.-K. Sze, Status of Sn-Li, presented at ALPS meeting, Argonne National Laboratory, 10-11 March 1999.

[2] S. Sharafat, et al., *JNM* **329-333** (2004) 1429-1433.

Advantages of the Sn-Li system

- Low melting eutectic can handle the projected heat load
- Bulk segregation of lithium (especially during melting) has been proven in the eutectic [3,4] through Gibbsian segregation [5], which prevents the high-Z Sn from entering the plasma
  - also can make use of Li vapor shielding effects to protect the wall structure
- Sn prevents mass erosion of the segregate Li surface.
- Upon segregation, the Li surface will act as a low-recycling wall, with improved retention characteristics[3].
- Sn-Li has fewer chemical reactivity issues and improved material compatibility.

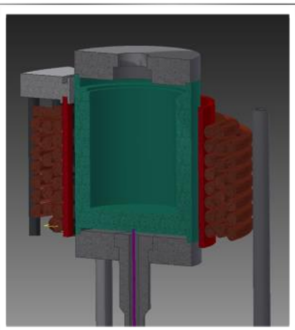


SnLi Phase Diagram – Target Composition of 80 atomic percent tin

[3] R. Bastasz, J.A. Whaley, *FED* **72** (2004) 111-119.
[4] E. Lang, A. Kapat, J.P. Allain, presented at 22nd PSI (2016).
[5] J. W. Gibbs, The Scientific Papers of J. Willard Gibbs, vol. 1, Longmans, New York, 1906, p. 219.

Ongoing Efforts: Successful Synthesis of SnLi Eutectic

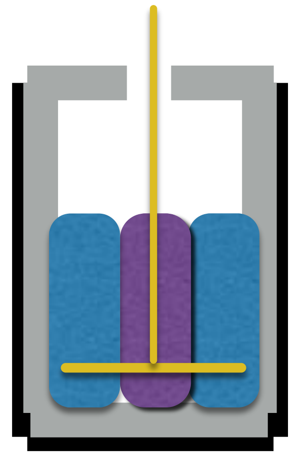
A small volume induction cast furnace was used to synthesize the samples



Casting Capabilities

- Pressure from 10^{-6} - 100 Torr
- Gas composition: Argon, Nitrogen, Helium
- Max temperature 1400C°
- Max load size (cylindrical sample): Dia 2 in, Height 2 in.
- Heat up time fastest from 0 to 1400C°: 30 min
- Cool-down time (fastest) from 1400C° to room temperature: 1 hours
- Heating method: Induction heating of the crucible

Loading Scheme



Color map:
- Carbon Crucible
- Steel Crucible
- Tin
- Lithium
- Steel mixer (with thermocouple)

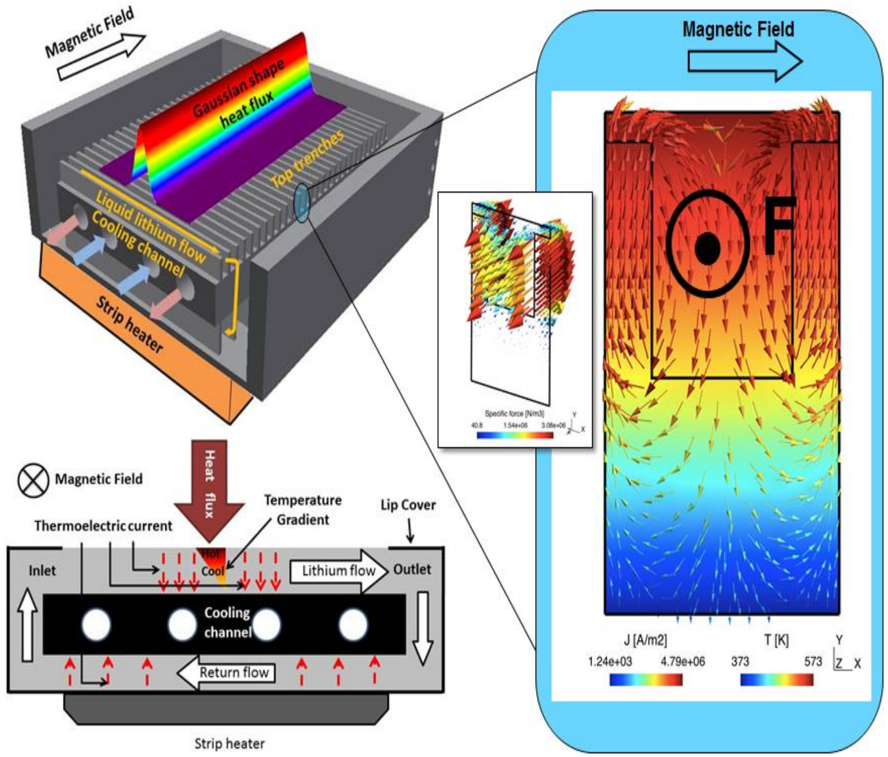
Alloy: Sn-Li , 80%+20% atomic percentage (weight ratio: 145g (Sn) + 2.16g(Li))

Before cast: Tin, lithium is about to be added

Final alloy

Ongoing Efforts: Surface Characterization and Flowing SnLi Demonstrations

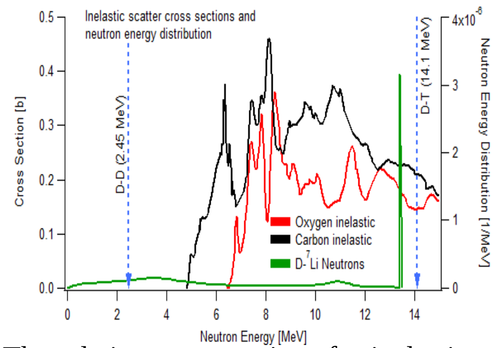
- Ongoing research efforts investigating performance of Sn-Li eutectic alloys:
  - TEMHD investigations for Sn-Li (SLiDE, CPMI)
  - Further analysis of surface characteristics and segregation behavior with Auger and XPS (ARIES, Sandia)
  - Demonstration of a flowing Sn-Li loop in a PFC module to be installed in the HIDRA fusion device (CPMI)



Concept for TEMHD based flowing systems

Lithium target development for neutron source

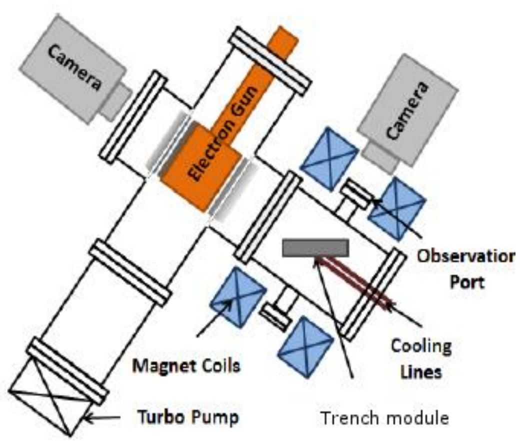
OBJECTIVE: → **Development of TEMHD module for flowing lithium to be used as neutron source**
→Testing the flowing lithium module with existing/modified high power electron beam
→Design, fabricate and test the scaled up and scaled versions of the trench module as neutron source for PFC and material testing applications



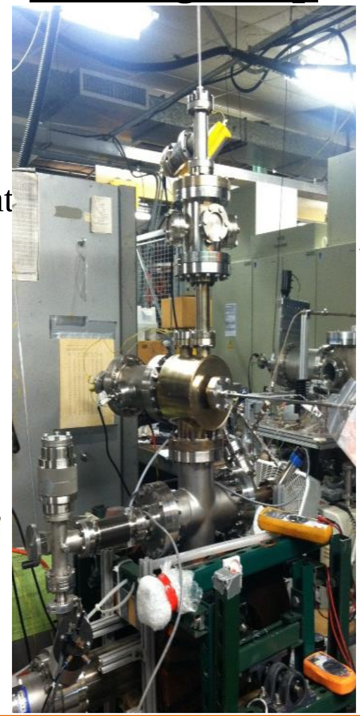
	C <$\sigma_{inelastic}$> [mb] (C-12(n,n_1)	O <$\sigma_{inelastic}$> [mb] (6113 keV)	C / C_{DT}	O / O_{DT}
Cf-252	13.4	4.17	0.064	0.029
D-T	211	145	1	1
T-T	88.1	47.3	0.42	0.33
D-Li7	127	74.5	0.60	0.51
AmBe	84.7	37.3	0.40	0.26

The SLiDE setup

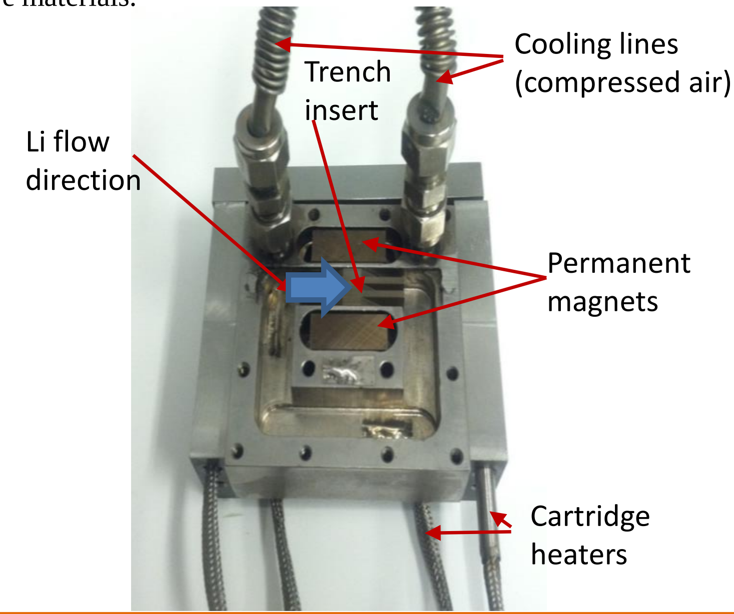
- To be reconfigured/re assembled to accommodate the new trench module
- Will serve as the test station for high heat flux impact on the designed trench modules and for verifying the flow properties at heat load



Existing setup



The relative cross sections for inelastic carbon and oxygen are shown with the D-Li neutron energies and average energies for the D-D and D-T neutron energies. Integrating over the relative cross-sections for each of the possible neutron-gamma inelastic reactions for carbon and oxygen, the D-Li7 neutron spectrum can stimulate about 50-60% of the C and O gammas than D-T on a per neutron basis. The D-Li reaction enables this measurement without any radioactive materials.



Liquid Metals Wettability on Laser Surface texturing

Roughening

Multilayer films

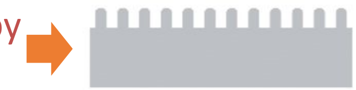
Gradient coating

Coating

Grafting

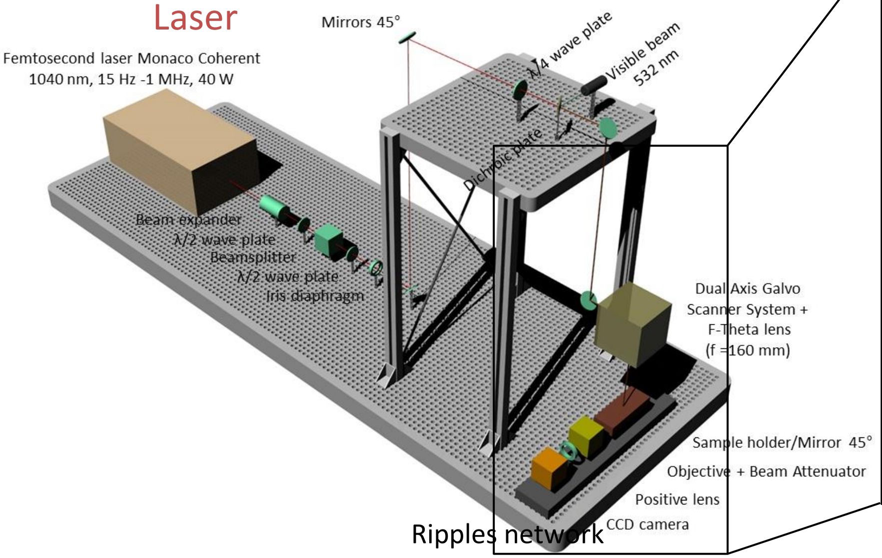
Untreated substrate

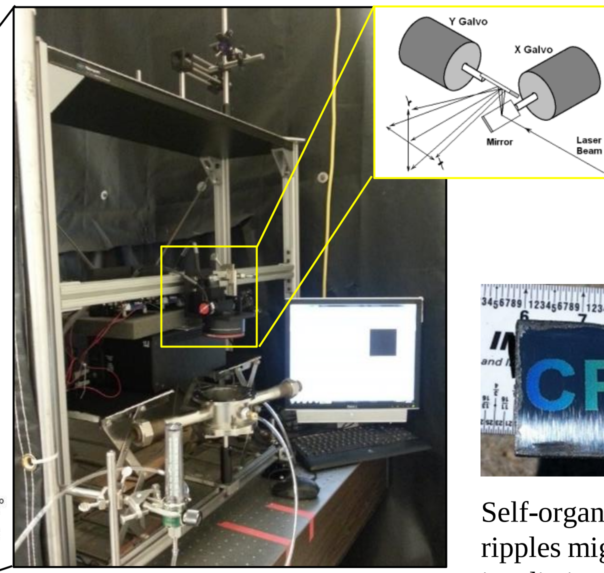
Texturing
Lithography
Direct-writing by laser
Self-assembly
3D patterning



Surface functionalization by laser texturing

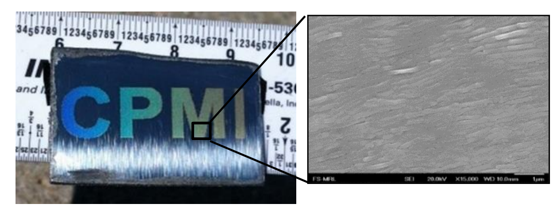
Coherent Femtosecond Laser





Galvo Scan Head

A software was developed which synchronizes the action of the laser pulses and the dual axis galvo scanner and allows to program the desired laser surface texturing.



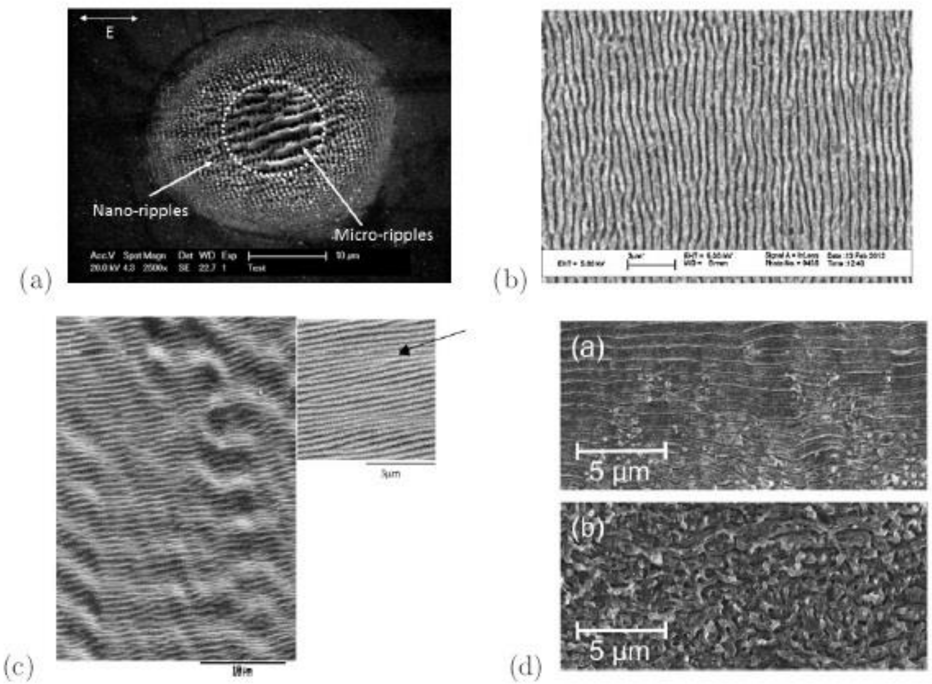
Self-organized periodic nanostructures called ripples might be generated after ultrashort laser irradiation.

Objective: Control the wetting and non-wetting properties of liquid metals on specific surfaces

Liquid Metals Wettability on Laser Surface texturing

Femtosecond laser induced multi-scale self-organized structures :

A variety of micro/nano structures may emerge after an ultrashort laser irradiation in a suitable energetic regime and is observable on a wide range of materials: the most remarkable one is called **Ripples** or **Laser Induced Periodical Surface Structure**.

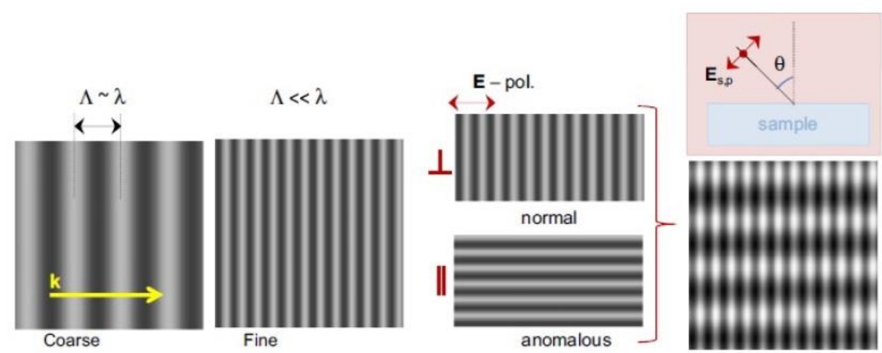


(a) Stainless steel, (b) silicone, (c) CaF_2 and (d) polyimide

Classification of LIPSS or ripples according their spatial periodicity Λ:

- LSF-LIPSS : Low Spatial Frequency LIPPS
  Δ_{laser}
- HSF-LIPSS : High Spatial Frequency LIPP
  Δ_{laser}

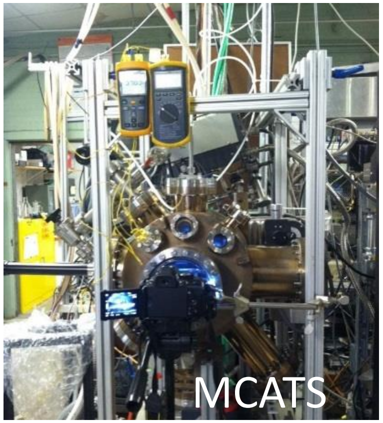
An other critical geometric parameter is the ripples orientation depending on the electric filed direction of the electromagnetic wave :



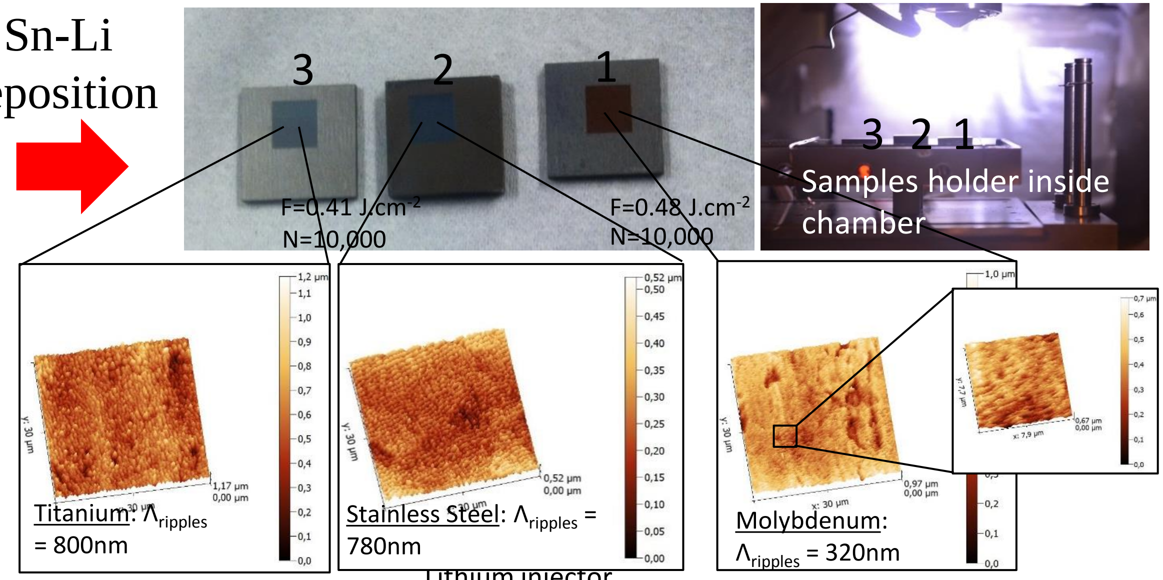
Buvidas *et al.*, 2012

Liquid Metals Wettability on Laser Surface texturing

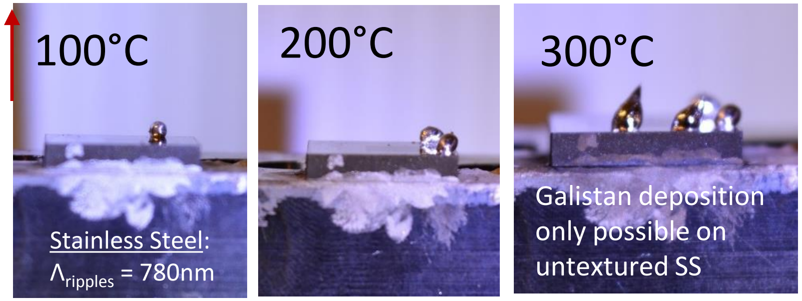
Investigation of the influence of the nanostructures induced by laser on liquid metal wettability:



Sn-Li deposition



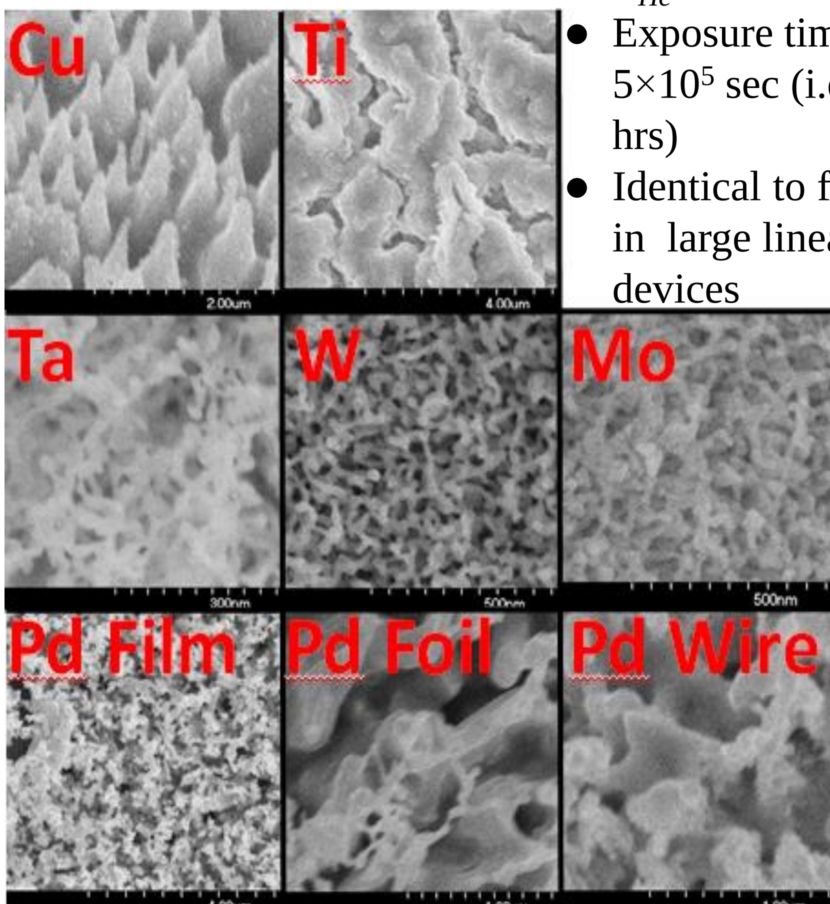
Gallinstan deposition



For both experiments, all surface texturing tested were totally liquid metal phobic and no contact angles have been measured.

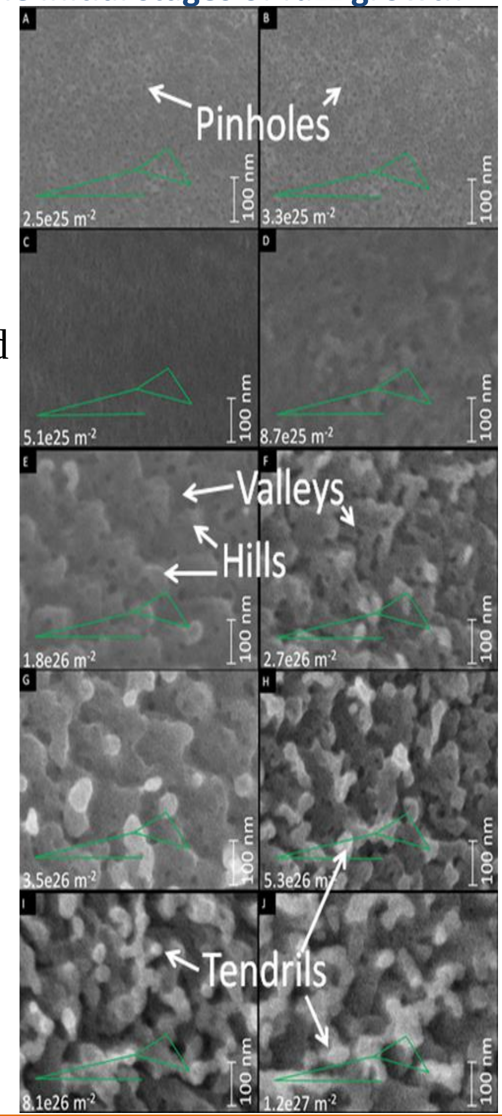
Nano Structure Formation by Low Energy Helium Ion Bombardment

- Commercial helicon plasma source, MORI, (700 W, 100 mTorr of helium) N_e=1e18 m^{-3} T_e=4 eV
- Substrates are ohmically heated, negatively biased
  - $\Phi_{He} = 2.5\times10^{21}\ m^{-2}s^{-1}$, E_{He} = 40 eV
  - Exposure time: 1×10^4 – 5×10^5 sec (i.e. 3 hrs to 40 hrs)
  - Identical to fuzz produced in large linear plasma devices



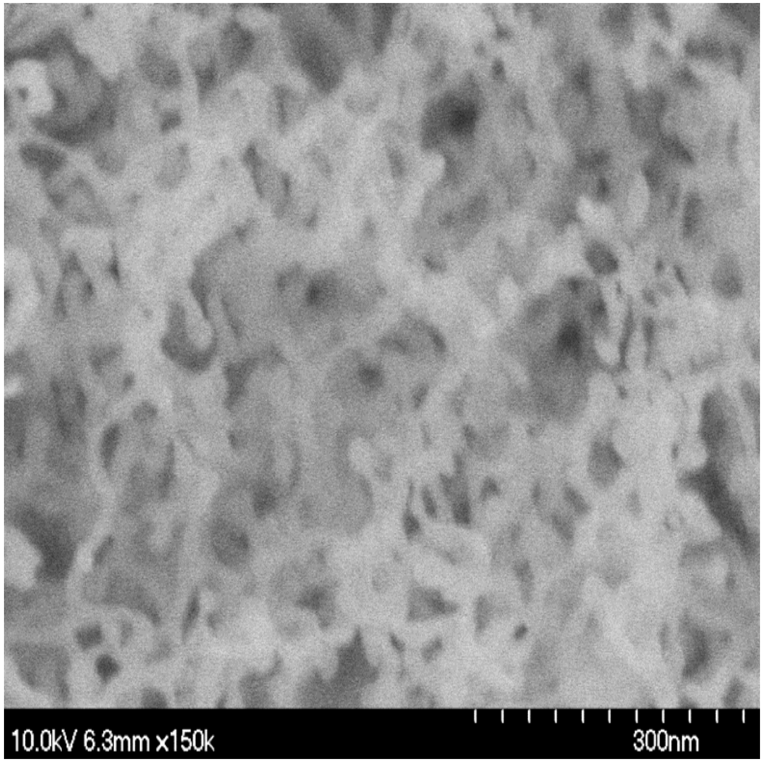
Types of fuzz structures observed on different substrates

P. Fiflis, et. al. Experimental demonstration of the initial stages of fuzz growth



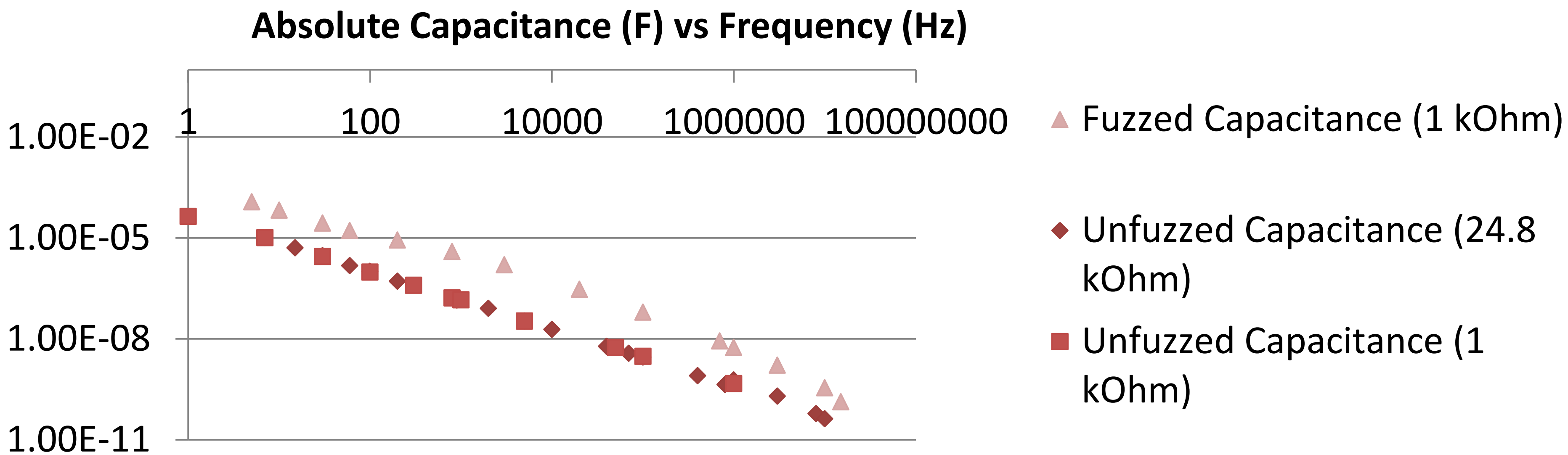
Tantalum Oxide Supercapacitor

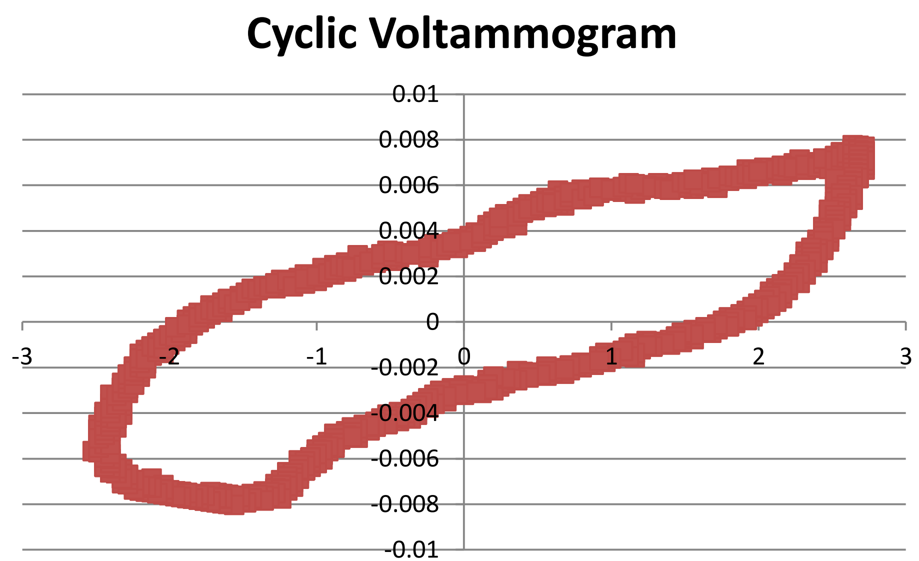
- Tantalum plates nanostructured and oxidized to produce supercapacitors
- Two tests performed to determine the efficacy of nanostructuring for tantalum supercapacitors
- Nanostructured tantalum under cyclic voltagmmogram and capacitance vs frequency testing performed 10x better than non-fuzzed samples



- Much like molybdenum and tungsten nanostructures formed are fuzz-like in nature
- Lower temperature limit observed for fuzz formation to be similar to that of Mo and W

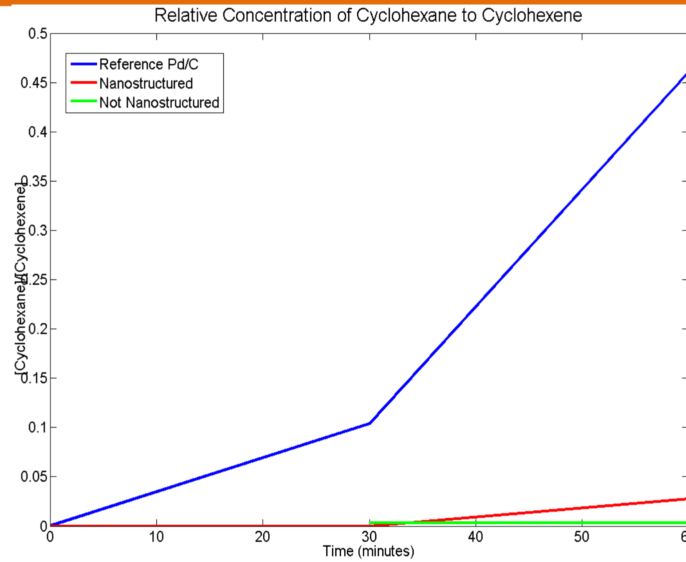
Tantalum Oxide Supercapacitor

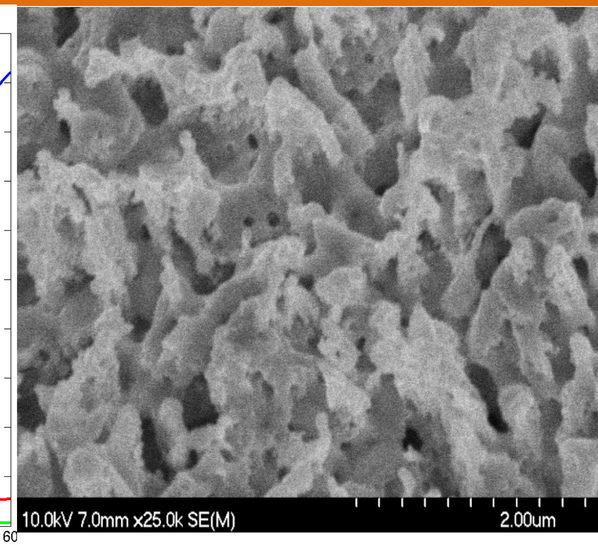


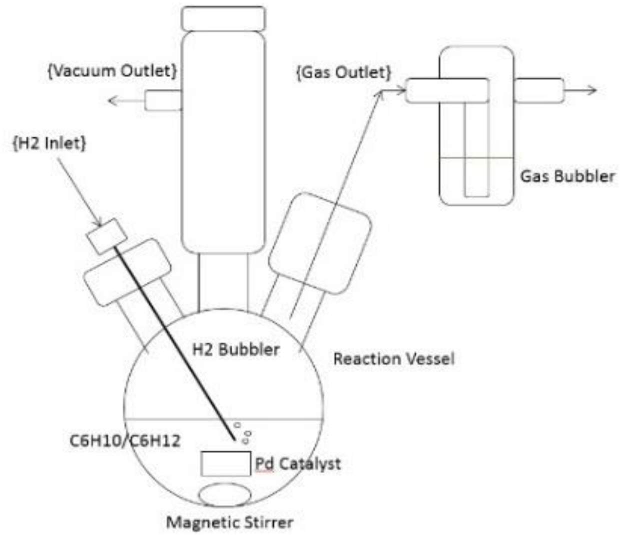


Nanostructured Palladium for Catalysis

- Catalytic reduction of cyclohexene to cyclohexane performed with palladium catalyst
- Nanostructured catalyst showed >10x increase in catalytic activity over non – nanostructured catalyst (0.5 mm thick Pd plate)

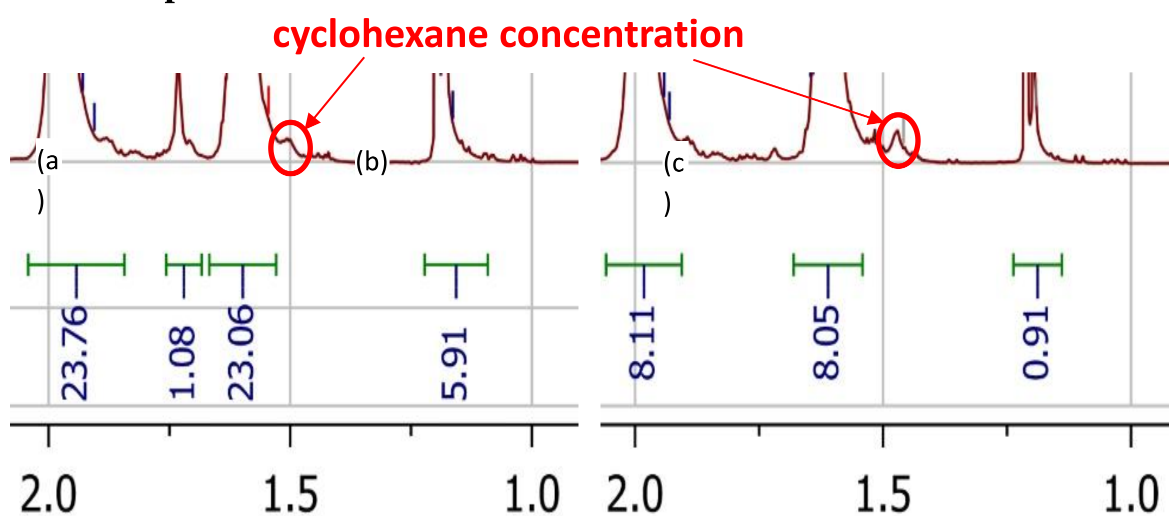






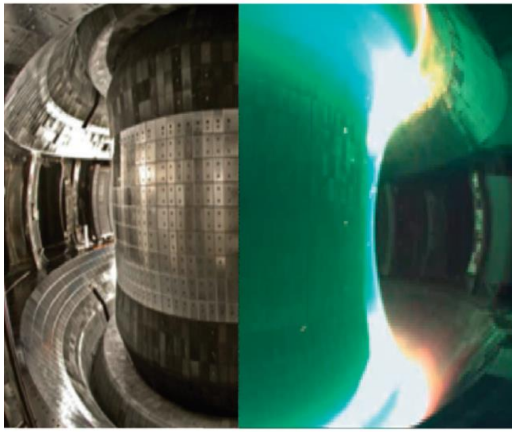
Experimental scheme for evaluating the catalytic activity

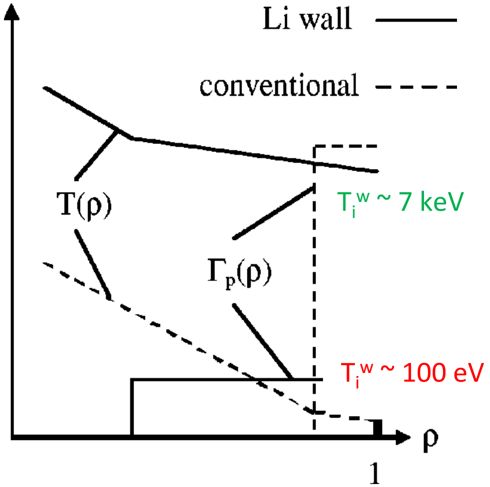
the NMR spectra of the reactants for the process using the normal palladium and fuzzed palladium

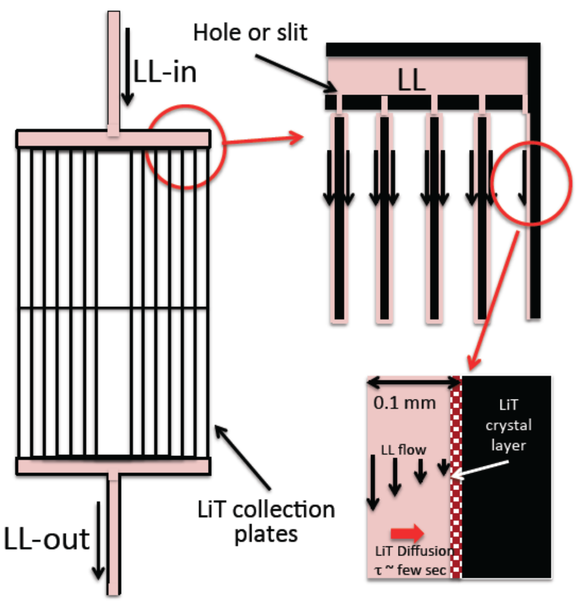


Lithium Hydride Degassing Experiment – LiHDE

- The overall goal for fusion is to create a nuclear utility from a sustainable reaction to meet the world's growing power demands.
- While scientific advancements are the current driving force for fusion research, economics will decide if utilities are feasible.
  - ITER capital costs have been evaluated above 13 billion euros[1]
  - DEMO will require even more manufacturing and upfront capital costs – not viable for a power plant







- These machines rely on high-Z, solid wall materials
  - T_i^w is ~ 10-100 eV due to the pedestal and high wall recycling
- What if we could access the "burning zone" across the entire plasma radius?
  - Smaller reactor size needed
  - Low-R Li walls can provide this
- Li can allow access to a new confinement regime
- Low recycling is both a blessing and a curse
  - Need for removal of now trapped fuel species
- Important step for extraction loop systems is to determine how to recover D and T from a Li-LiD-LiT system

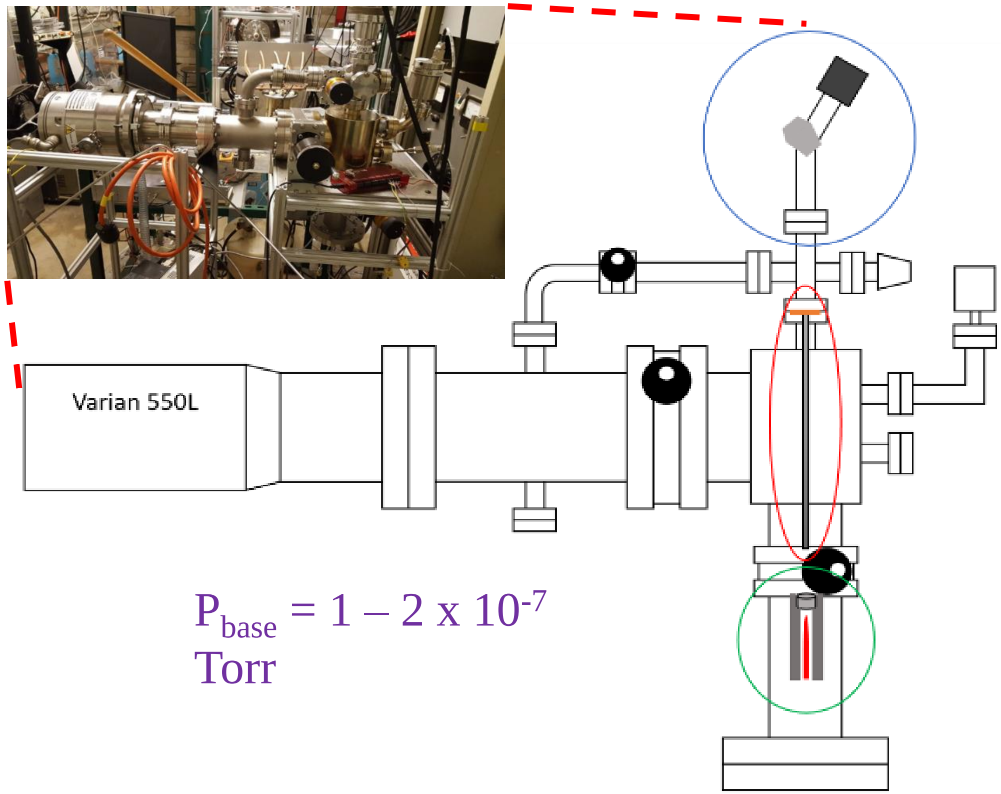
[1] http://www.iter.org/faq#Do_we_really_know_how_much_ITER_will_cost [accessed: 01-18-2017]

[2] J. Li, et al., *Nat. Phys.* 9 (2013) 817.

[3] S.I. Krasheninnikov, et al., *Phys. Plas.* 10(2003) 1678.

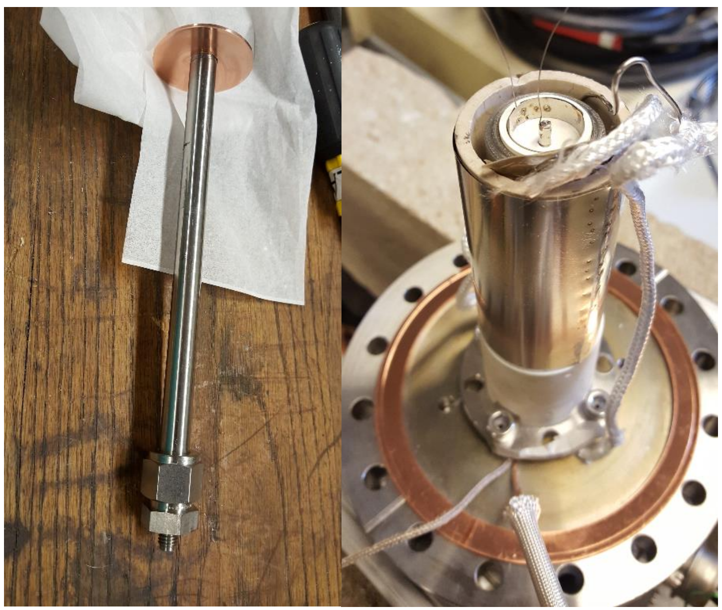
[4] M. Ono, et al., *Fus. Eng. Des.* (2016) in press.

LiHDE Chamber



P_{base} = 1 – 2 x 10^{-7} Torr

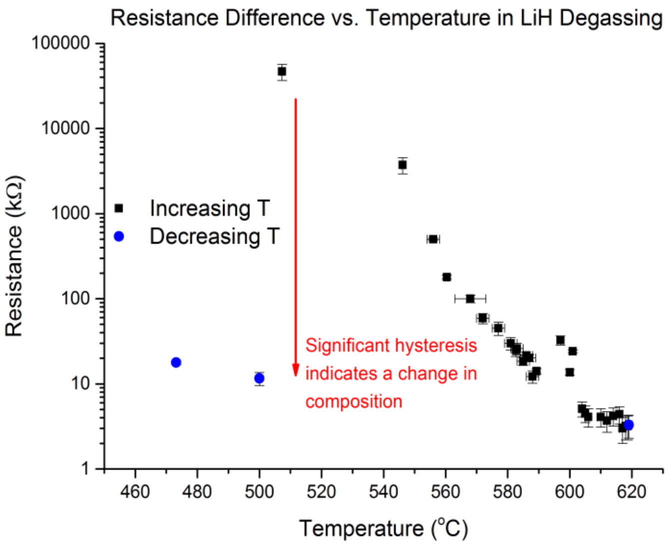
- Vacuum Technologies, Inc. Magnetic Sector Residual Gas Analyzer used to monitor partial pressures.
- “Sniffer tube” constructed and used to extend capabilities of RGA down to the level of the sample holder.
- Heater stage constructed using a TZM body, a boron nitride crucible (new) to hold the sample and measure resistivity, a nitride ignitor, and a SS316 radiation shield.

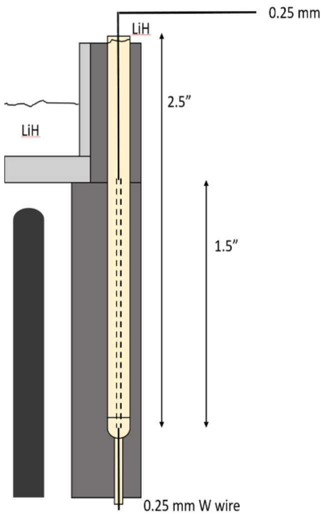


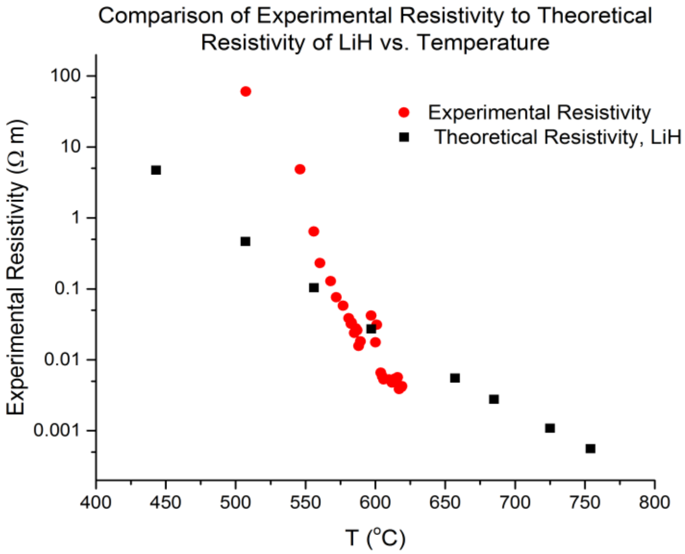
New setup as of 02/2017

- The **new** crucible setup has the capacity to hold nearly 1 cm^3 of sample
  - ➢ Experiments used 0.2 cm^3 of sample (0.16 ± 0.05 g)
  - ➢ Initial setup could hold 3 cm^3 of sample between 2 crucibles
- Machined TZM rod used for heater body
- “Sniffer tube” narrowed to 1.6 mm orifice

Resistivity Measurements – Initial Setup





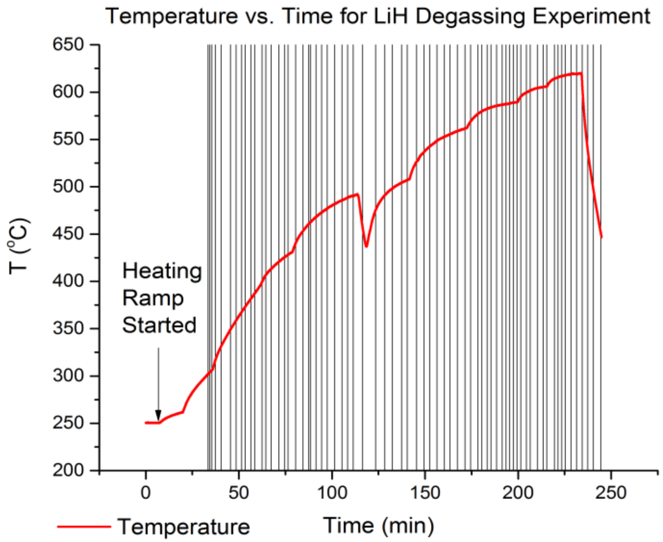


- Significant hysteresis seen in resistance curves between heating and cooling
  - Indicative of permanent composition change
- Sample in both crucibles also changed physical appearance – metallic luster noticeable
- Resistivity measurement in this setup somewhat ambiguous
  - Multiple resistance paths considering top electrode is buried in LiH
- Path of least resistance considered for resistivity calculation

$$\sum_{i,parallel}^{n} R_i < R_{least}$$

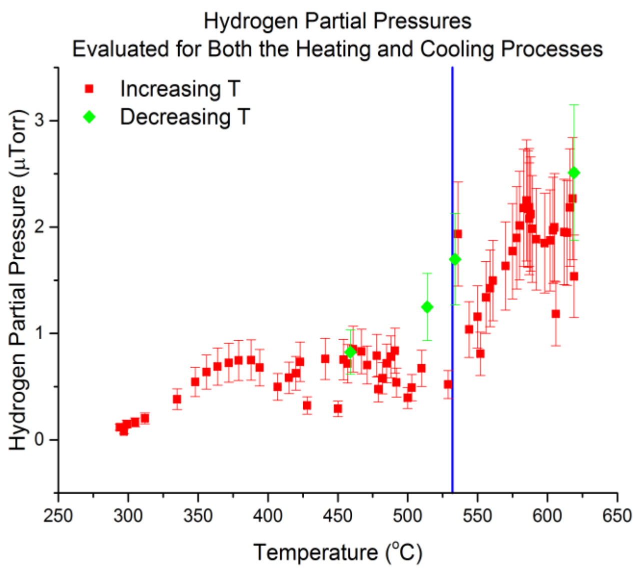
$$\rho = R\,\frac{A}{l}$$

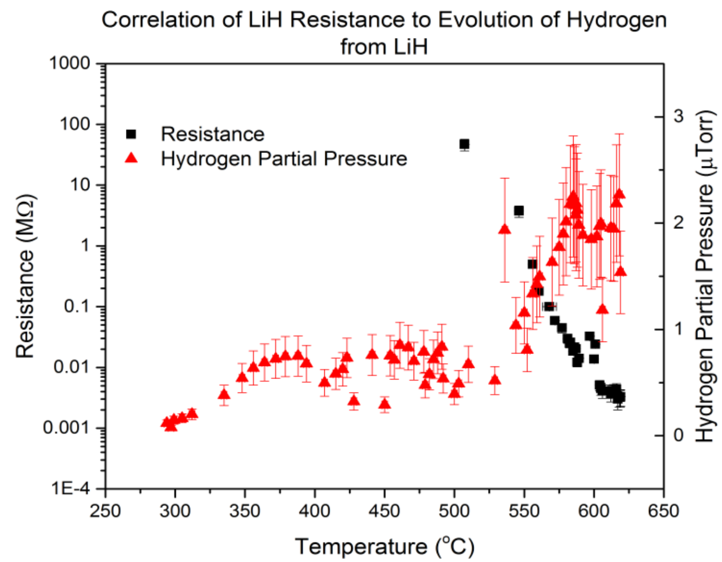
LiHDE Measurements – Initial Setup



- System baked at 250 °C for ~ 36 hrs before experiments
  - ➢ Purpose – eliminate impurity layers, as described in Dinh, et al. [5]
- Temperature slowly ramped over the course of 4 hrs
- Significant change in degassing rate seen at 535 °C
  - ➢ Also beginning of orders-of-magnitude resistance drop
  - ➢ Minimal hysteresis during temperature decrease

(Above) Plot of experimental temperature ramp. Sample baked at 250 °C for 36 hours before testing. P vs. t unavailable, so multiple analog scans taken at various times (vertical lines). Heater failure at 620 °C.



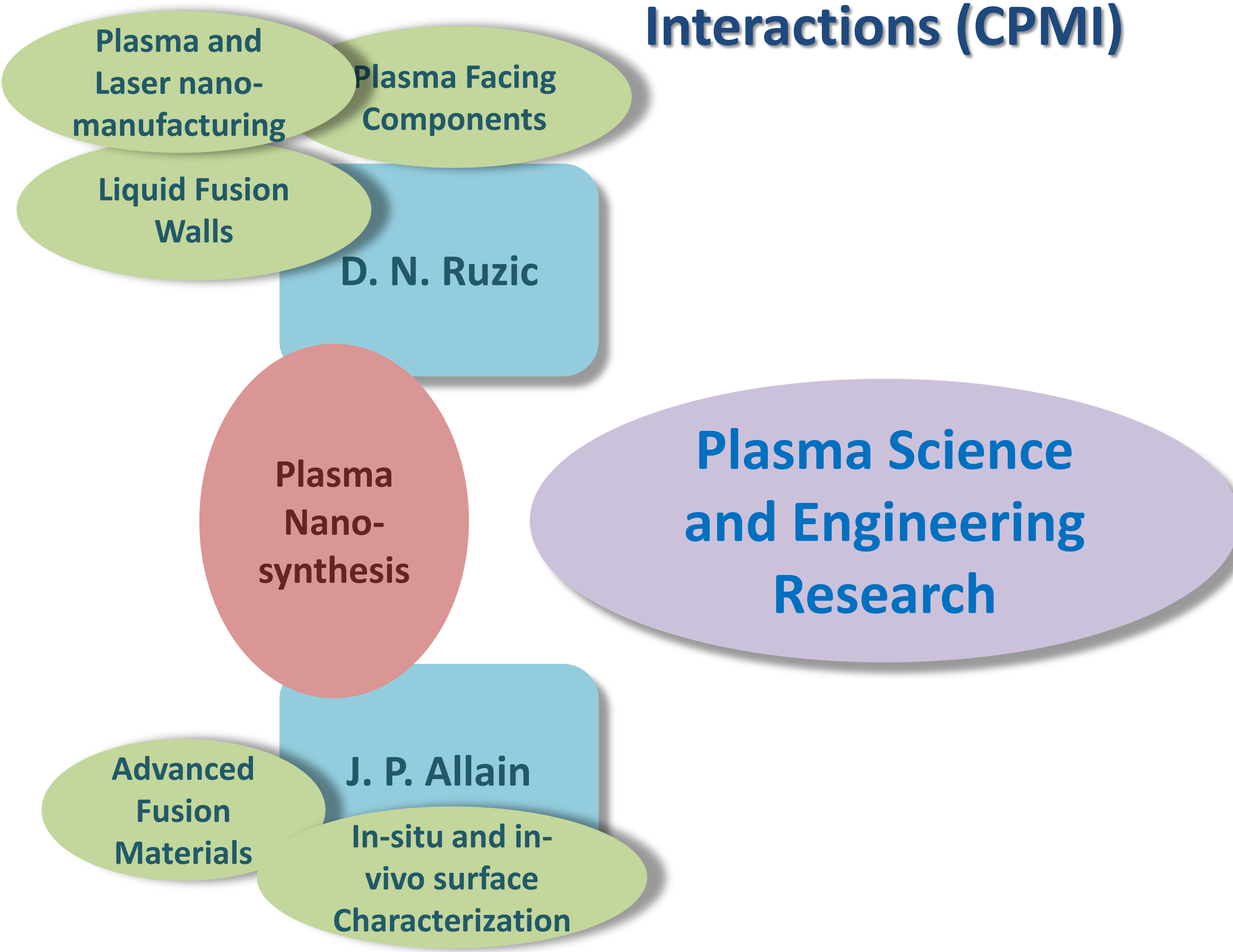


(Right) Hydrogen partial pressure and resistance results from the experiment. Significant change seen in degassing rate at 535 °C.

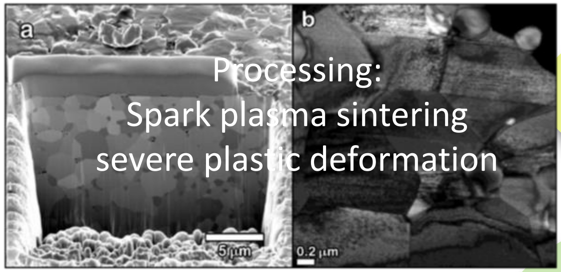
[5] L.N. Dinh, et al., *Report for LLNL*, 2006.

Overall Structure of CPMI

Plasma Research at the Center for Plasma Material Interactions (CPMI)



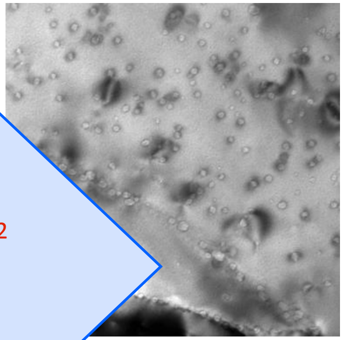
Process-property-performance relationships studied in well-diagnosed *in-situ* experiments at Illinois and collaborators worldwide. Emphasis on nanoscale materials design and *in-situ* testing coupled to computational models

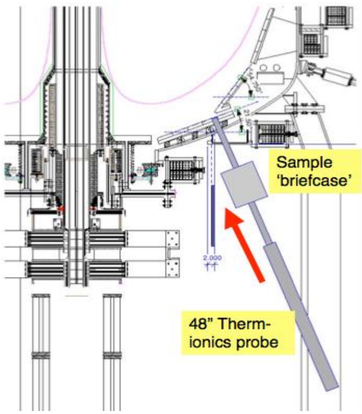


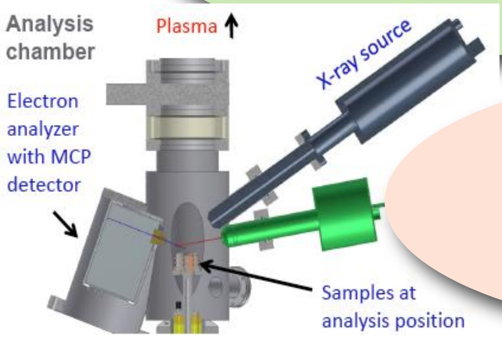
Multi-scale irradiation on extreme-refined grained and porous W

Irradiation behavior of hot lithium-based coatings on nanocomposite refractory and graphitic substrates

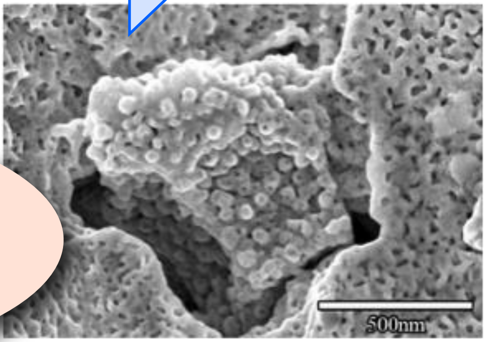
Fluxes: 10^{18}-10^{24} $m^{-2}s^{-1}$
Fluence ~ 10^{18}-10^{26} m^{-2}
T ~ RT up to 1200K
E ~ 10 eV to 2-keV







In-situ PMI diagnostics:
MAPP in LTX and NSTX-U



2016-2017 Publications

[1] C.H. Skinner, F. Bedoya, F. Scotti, et al. J. Nucl. Mater. and Energy (2017)
[2] F. Bedoya, J. P. Allain, R. Kaita, et al. Review of Scientific Instruments 87, (2016)
[3] E. Lang, A. Kapat, J.P. Allain, Submitted to Nucl. Mater. And Energy (2016)
[4] F.J. Dominguez-Gutierrez, F. Bedoya, P. Krstic, J.P. Allain, et al. Nucl. Fusion 2017
[5] P. Krstic, F. Domínguez-Gutiérrez, F. Bedoya, J.P. Allain, et al. Submitted to Nuclear Fusion (2017)

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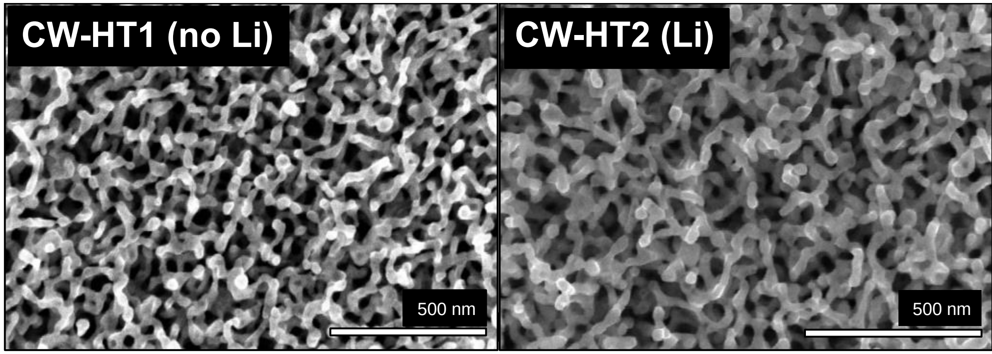
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

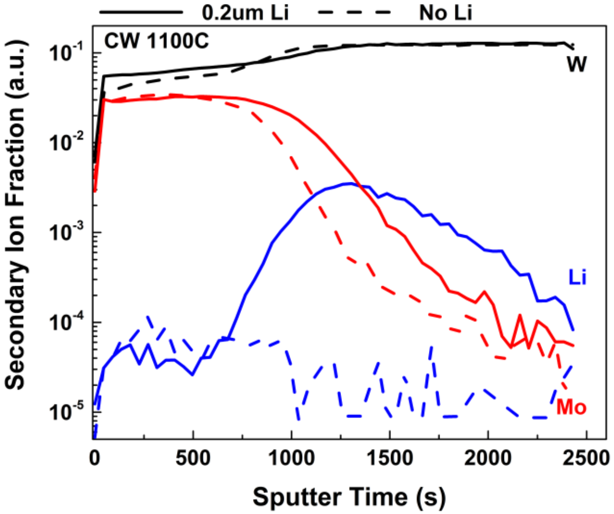
PhD students: F. Bedoya, A. Neff, E. Lang, A. Kapat, N. Ried and H. Schamis

Elucidating low-Z thin film dynamics under high-fluence plasma exposure on nanostructured W

- Prof. Allain's group is determining the role of low-Z coatings (or other ductile phase systems) on W surface PMI properties
- Under reactor relevant conditions W PMI can include damage:
  - Surface blisters
  - Nano-structure "Fuzz" and porous structures
- We are conducting He/D exposures at early-stage fluence (e.g. < 10^{19} cm^{-2}) and reactor-relevant fluences (e.g. > 10^{20} cm^{-2}) on mixtures of low Z/W interactions
- Li is found to persist in the surface nanotendrils after high flux exposure in Magnum PSI at DIFFER.
- This persistent Li layer may protect the fuzz from erosion.
- Now conducting *in-situ* IGNIS studies of He/W interactions to determine effect on erosion and D retention

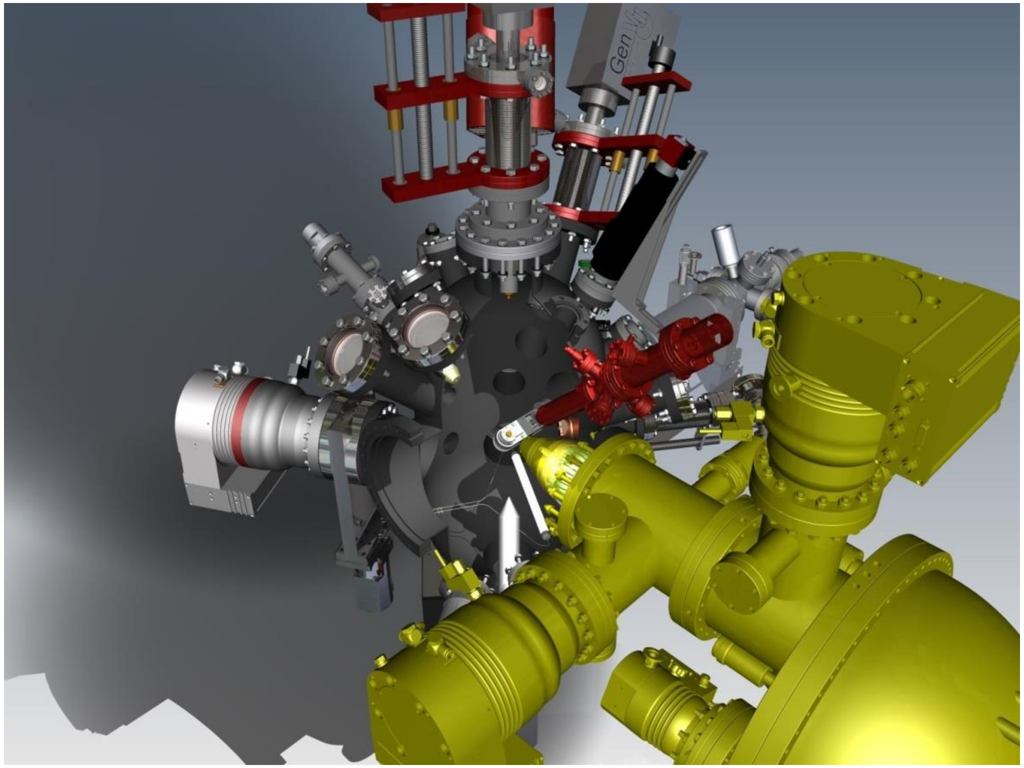
Coarse Grained W @ ~1373 K, Fluence ~4.0E26 m^{-2}





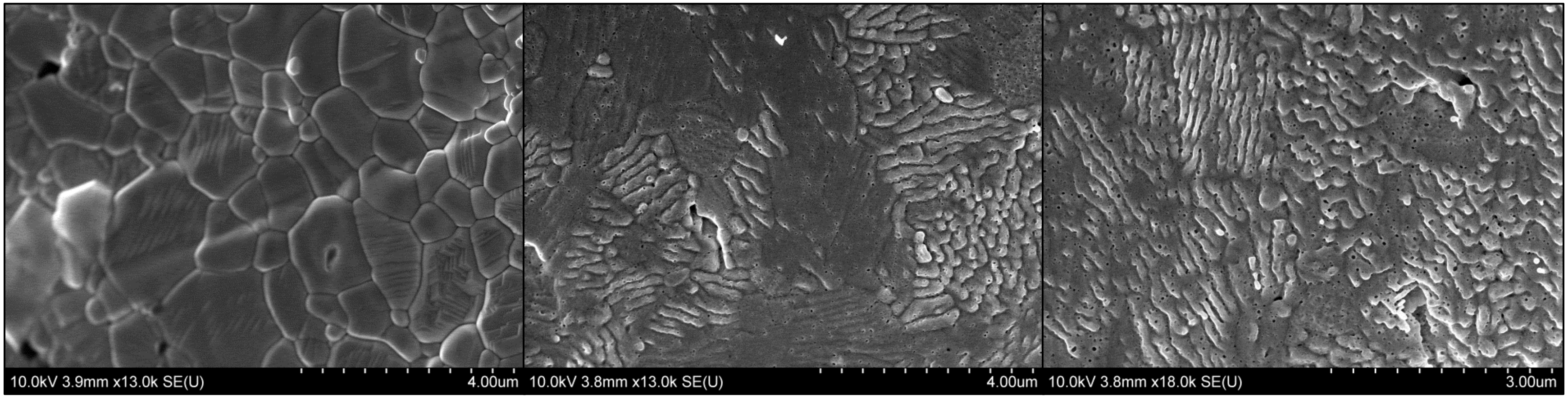
SIMS depth profile of the samples above

Multiple-beams and plasma-induced nanostructuring of a variety of materials

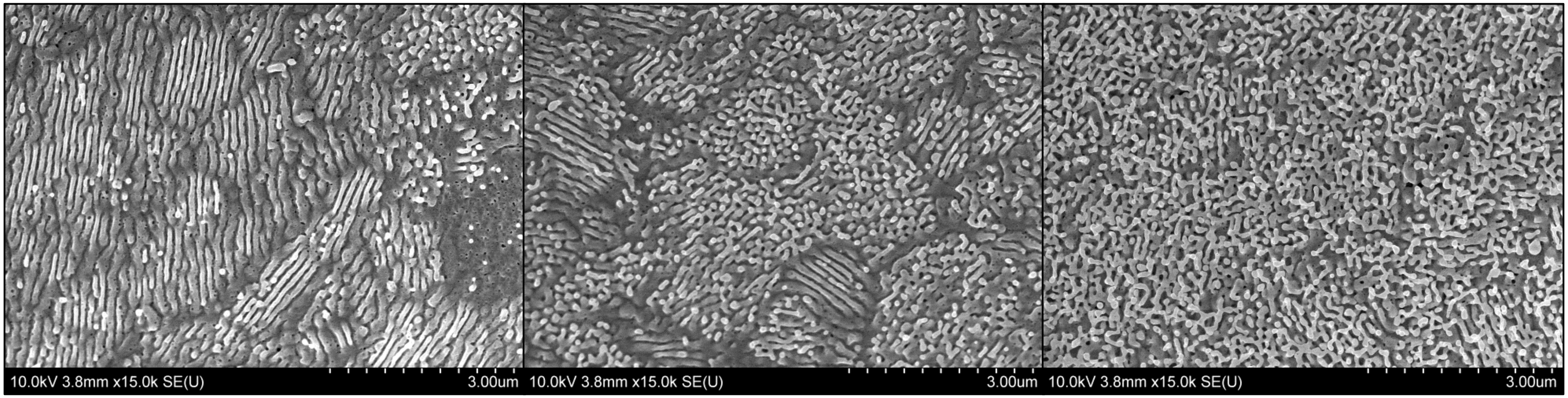


- IGNIS is a state-of-the art facility enabling the diagnosis of surfaces *during* plasma irradiation at high pressures (from UHV to mTorr and up to 10 Torr)
- Correlating plasma-induced nanostructuring and surface composition on gas-covered surfaces probed *during* plasma exposure and connecting parameters of the modifier source (e.g. plasma, ions, etc..) to the surface nanostructures synthesized and erosion properties

Effect of crystalline orientation and grain boundary effects on self-organization are evident as a function of fluence



Increasing Fluence



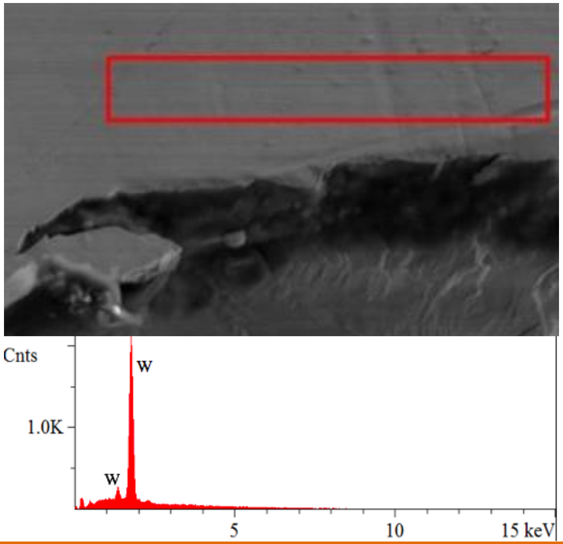
Increasing Fluence

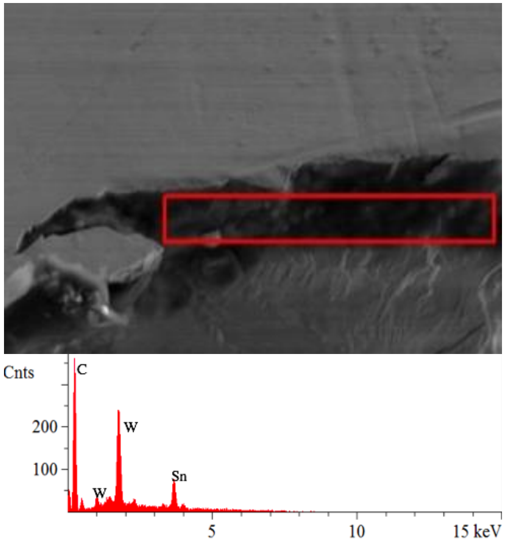
Innovating adaptive PMI with porous refractory metals combined with liquid-metal-solid hybrid nanocomposites

Adaptive PMI: Porous Tungsten

- Previous work on refined grain tungsten demonstrates suppressed fuzz formation[1]
  - Grain boundaries act as vacancy sinks for He-vacancy complex, prevents He bubble nucleation intra-grain
- Surface also acts a 2D defect that is a vacancy sink
  - Increased surface-area-to-volume ratio maximizes the surface's capacity as vacancy sink
- Porous structure can also act as scaffold for liquid metal systems
  - Low-Z, high-Z hybrid materials
- Currently manufacturing samples via spark plasma sintering, in collaboration with Dr. Jessica Krogstad (MSE UIUC)

Currently examining adaptive PMI properties: self-healing during high-heat flux exposure and understanding of retention properties



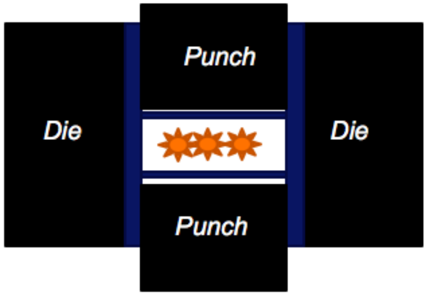


Dispersion-Strengthened Tungsten

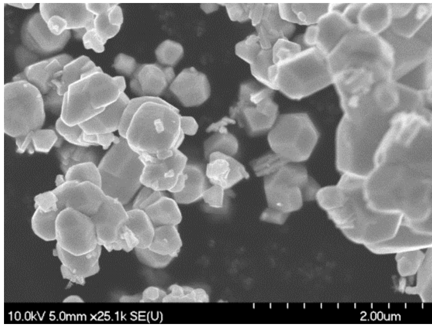
- Tungsten has limited range of temperature operation
  - Radiation-induced and recrystallization-induced embrittlement
  - Brittle fracture occurs at grain boundaries

- Micro-alloyed tungsten alloys created via Spark Plasma Sintering
  - Apply high current and pressure to compact powders
  - Micro-alloying with carbides may capture impurities and purify grain boundaries
  - Dispersed particles limit grain growth and stabilize GBs
  - High grain boundary density => enhanced radiation resistance

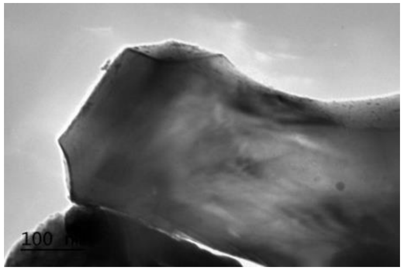
- Samples created with 500 nm W and 40 nm ZrC powders
  - Initial characterization shows development of micron-sized grains
  - Alloyed with 0.5 wt. % and 1.0 wt. %
  - Further testing of mechanical properties (hardness, strength)
  - Exposure of samples to various high and low energy plasma sources to investigate response of microstructure to energetic ions



Spark Plasma Sintering Setup

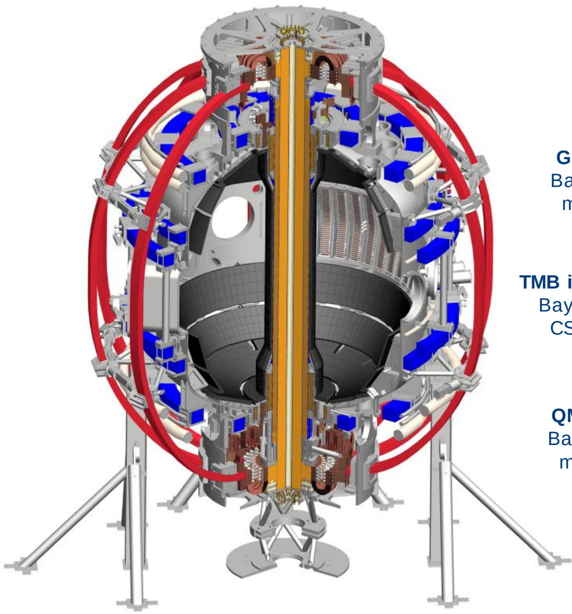


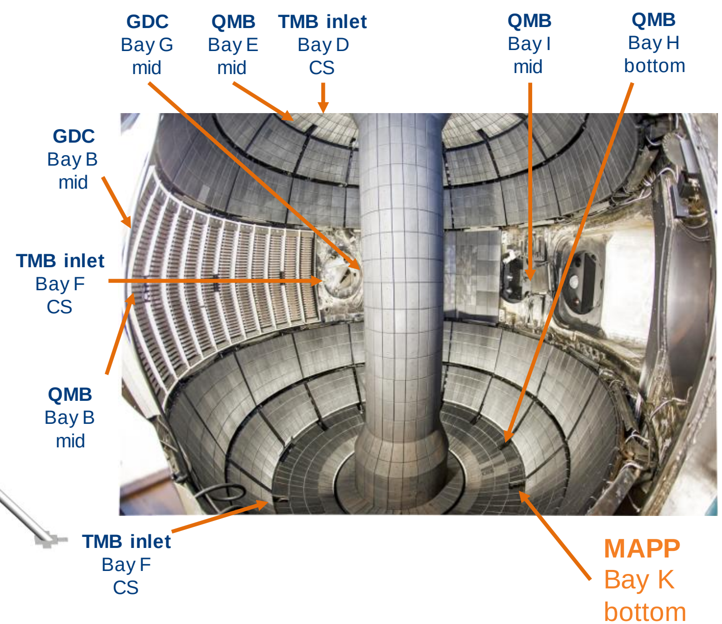
500 nm W Powder

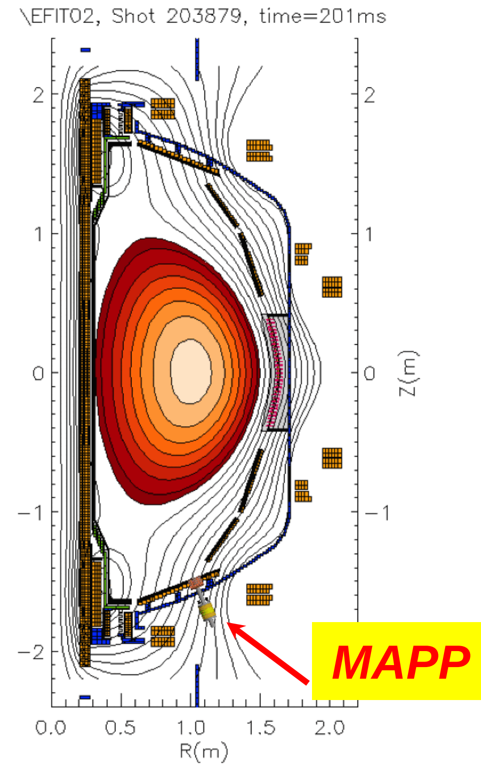


TEM Micrograph of sintered sample

The Materials Analysis Particle Probe (MAPP) diagnostic facility at PPPL in NSTX-U

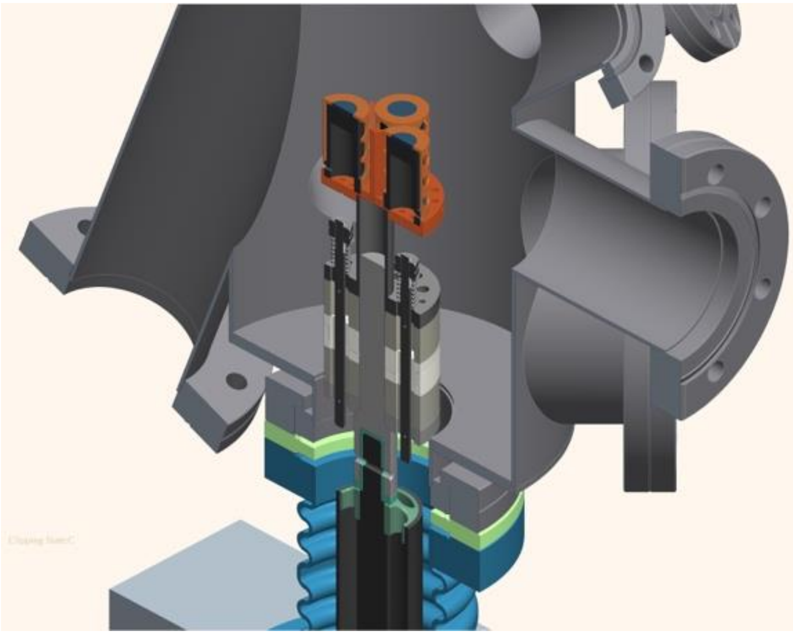


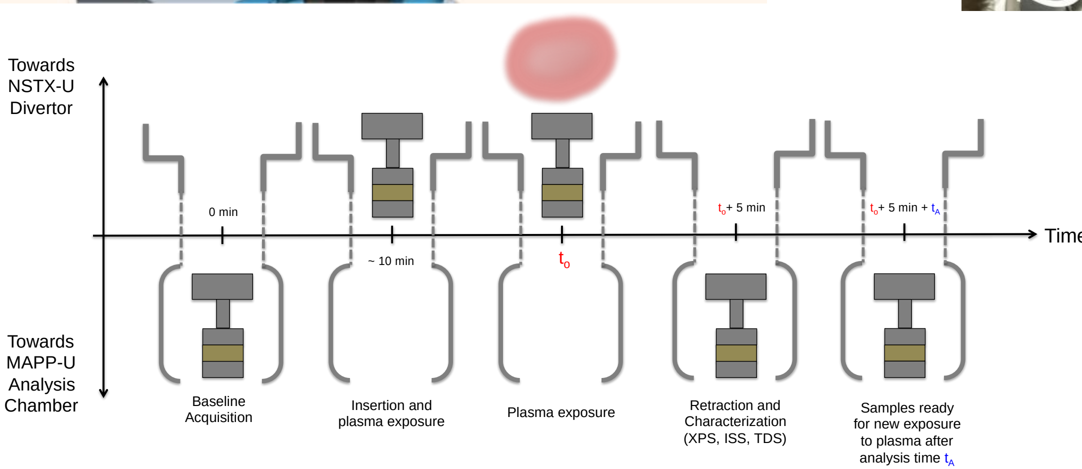


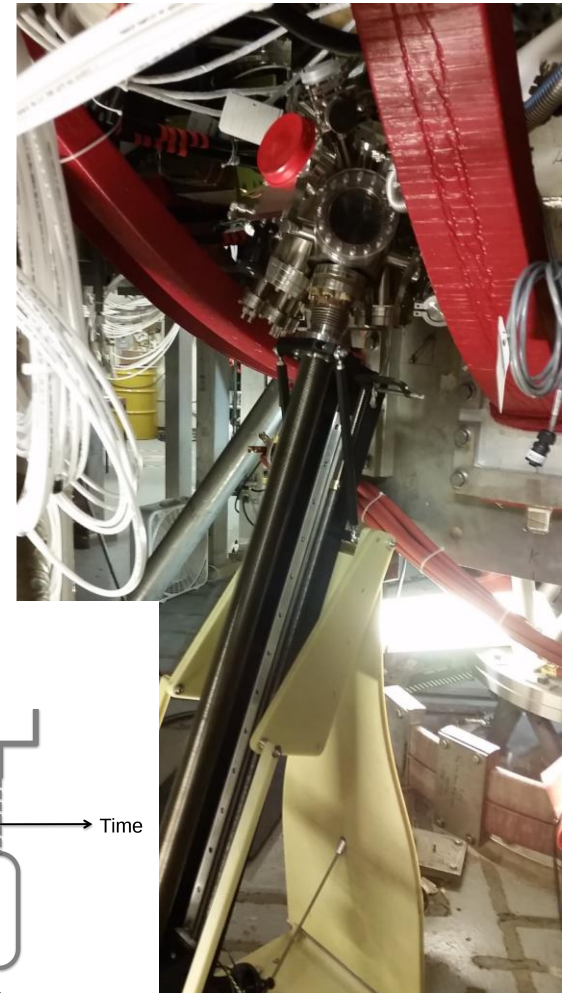


- The MAPP facility is an *in-situ ex-tempore* PMI diagnostic system consisting of surface-sensitive tools that probe between 1-8 nm and provide “real-time” dynamic evolution of surface chemistry as a function of various complex scenarios in NSTX-U
- MAPP is the first surface analysis station that probes the extreme regions of high-heat flux scenarios provided by a diverted plasma exploring far-SOL, OSP, PFR conditions

The Materials Analysis Particle Probe (MAPP) major systems and integration in NSTX-U







Boronized-ATJ XPS Chemistry results and surface evolution

High oxygen % Low % of B in metallic state

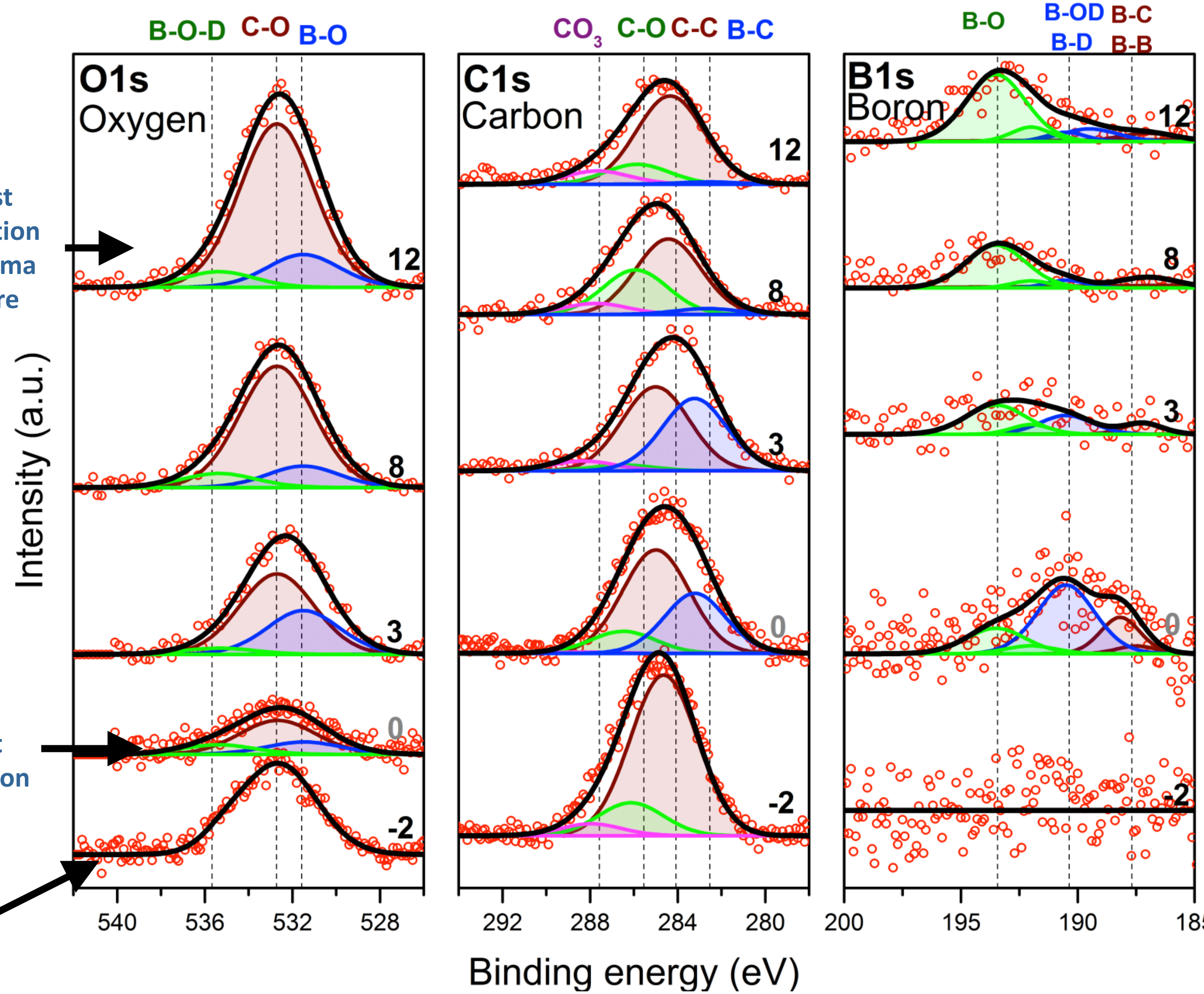
ATJ post boronization post plasma exposure

Days after boronization **D⁺ fluence increasing**

Low oxygen % High % of B in metallic state

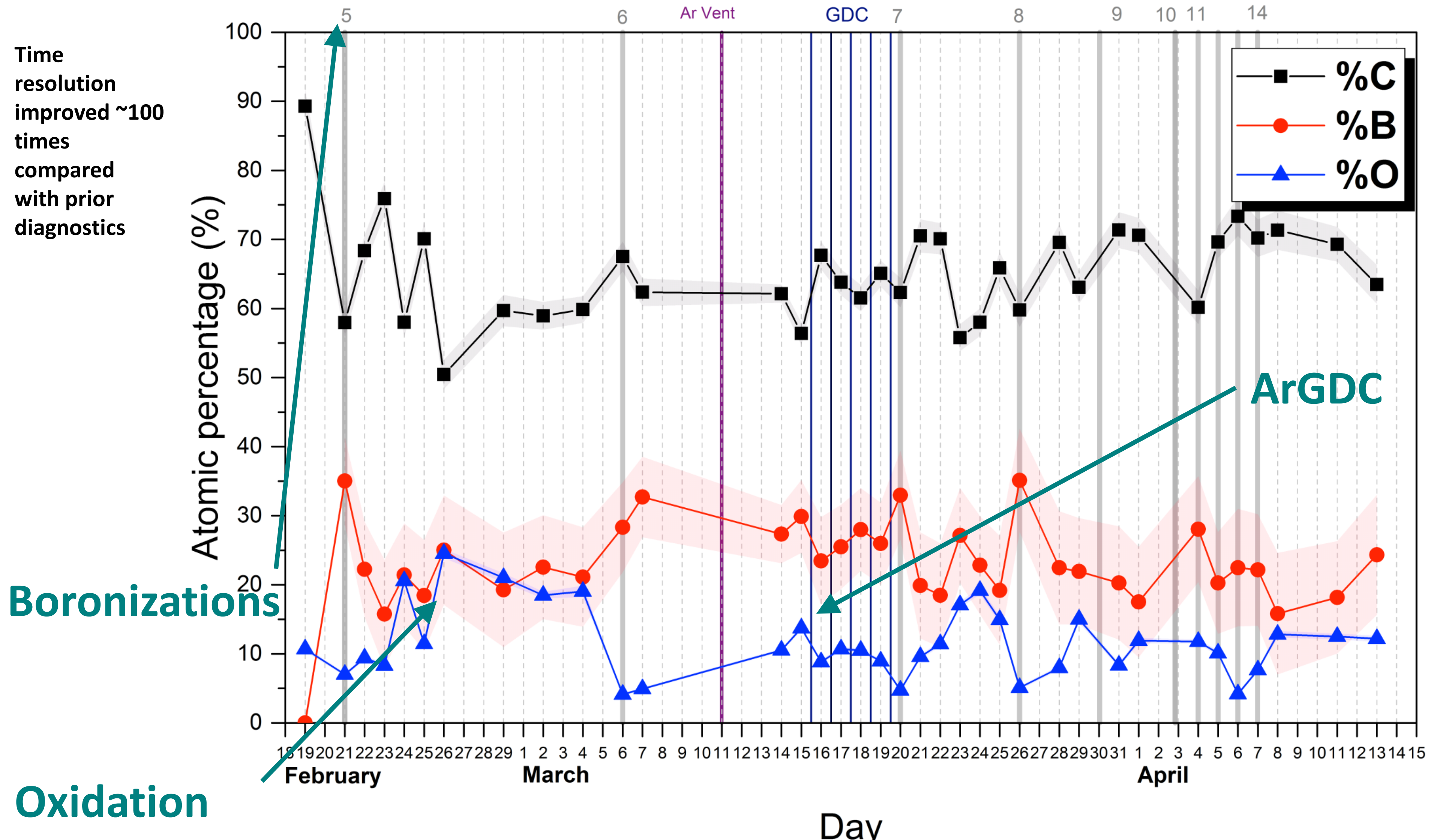
ATJ post boronization

ATJ graphite



Evolution of atomic concentrations of b-ATJ in vacuo

Time resolution improved ~100 times compared with prior diagnostics

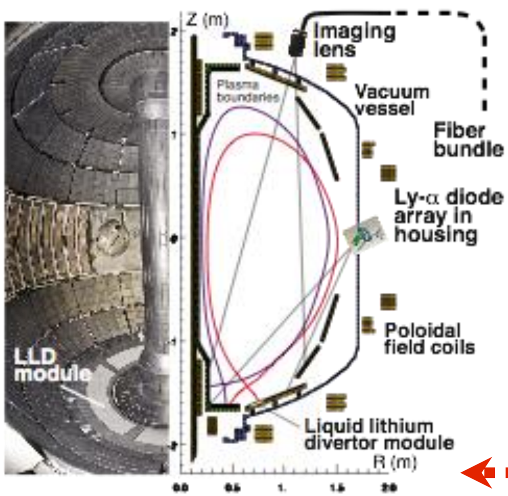


Probing extreme environments with in-situ diagnostics: testing low Z/high Z systems

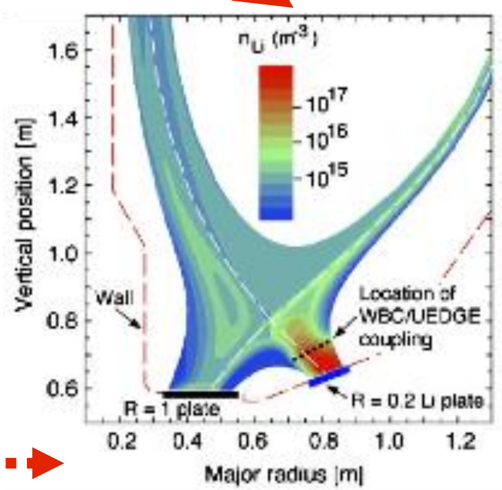
IGNIS: in-situ surface chemistry, sputtering, morphology and MAPP: NSTX-U PMI probe
Prof. J.P. Allain (Illinois)

DIFFER high-flux plasma linear device facilities
Dr. Thomas Morgan

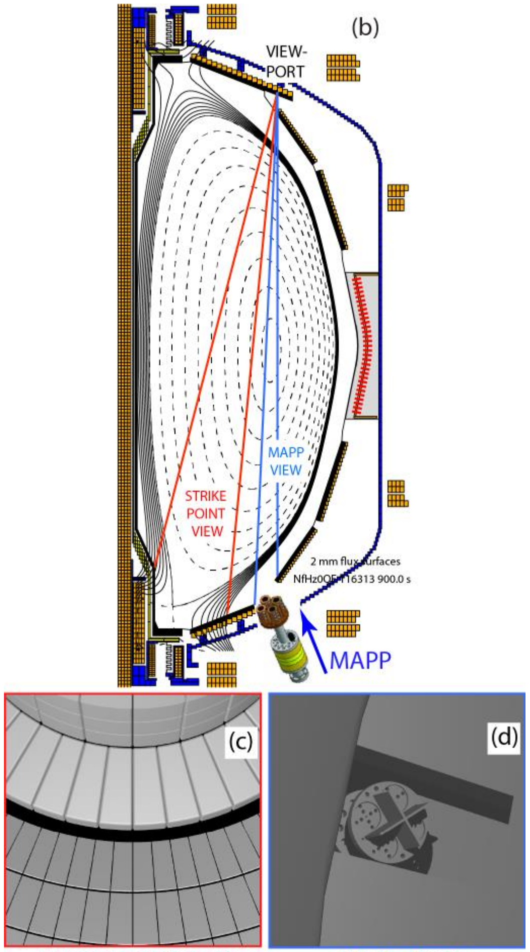
Computational modeling: atomistic irradiation and multi-scale surface evolution under hydrogenous plasma irradiation
Prof. Brian Wirth (UTK)
Predrag Krstic (Stony Brook)



NSTX-U edge diagnostics

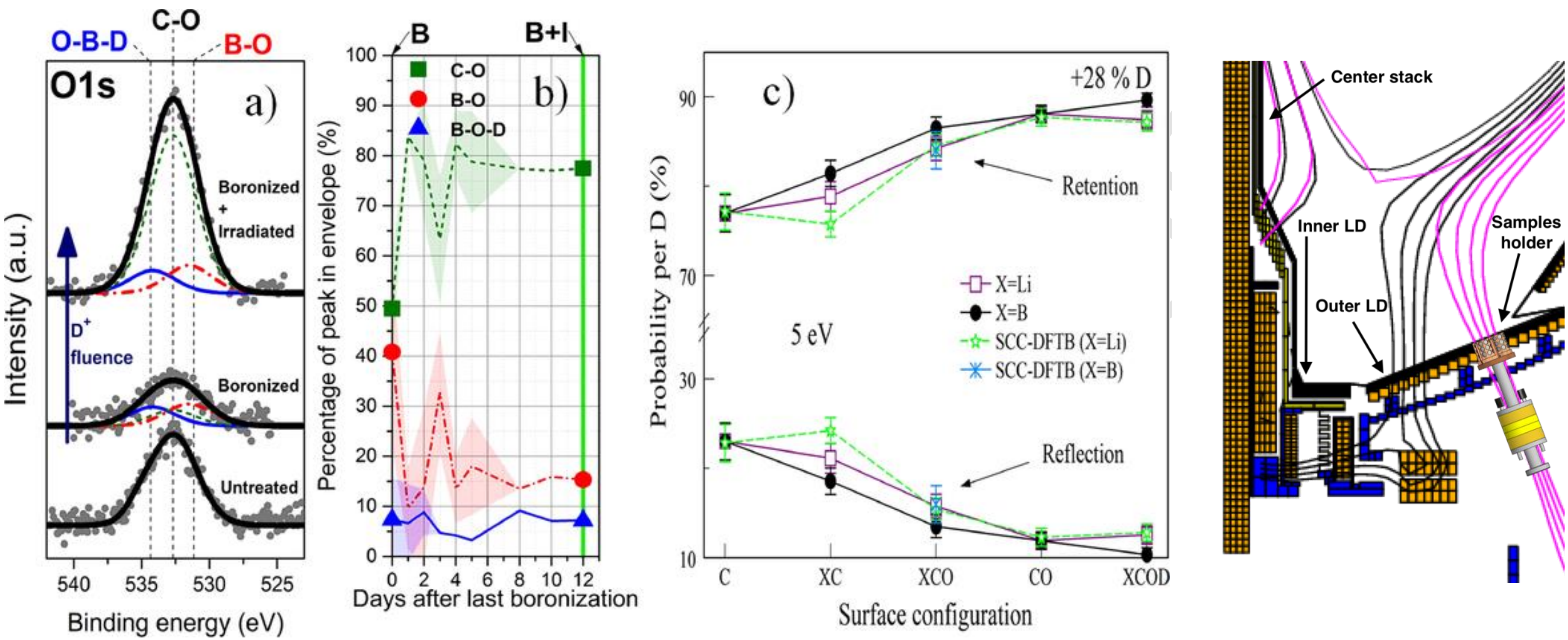


Plasma edge codes



STRIKE POINT VIEW
MAPP VIEW

In-situ PMI measurements and modeling of complex boronized surfaces with MAPP in NSTX-U



- In collaboration with Predrag Krstic at Stony Brook, we are exploring the details of atomistic-level chemical interactions and their evolution under plasma-induced irradiation
- Combining ex-vessel *in-situ* measurements in facilities pioneered by Allain et al. such as: PRIHSM (Purdue), IMPACT (formerly at Argonne) and IGNIS (UIUC), we are unraveling both the surface physics and chemistry in far-from equilibrium conditions in the PMI

Overall Structure of CPMI

Plasma Research at the Center for Plasma Material Interactions (CPMI)

Plasma and Laser nano-manufacturing

Plasma Facing Components

Liquid Fusion Walls

D. N. Ruzic

Plasma Materials Computational Modeling

Near-Wall Kinetics

3-D Edge Models

Fusion Material Wall

D. Curreli

Plasma Nano-synthesis

Plasma Science and Engineering Research

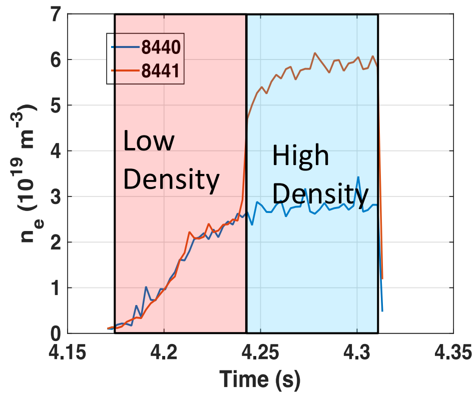
J. P. Allain

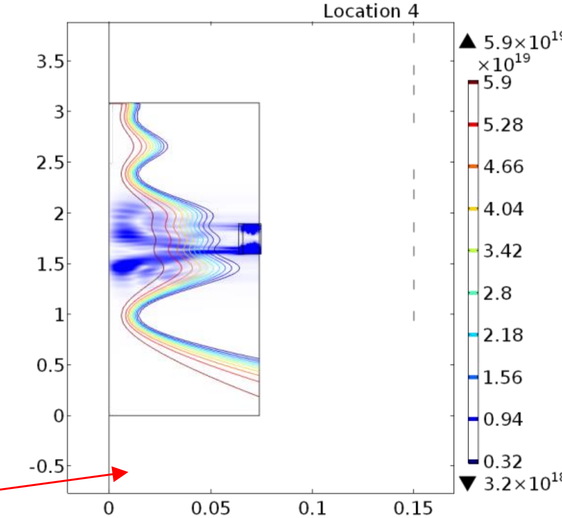
Advanced Fusion Materials

In-situ and in-vivo surface Characterization

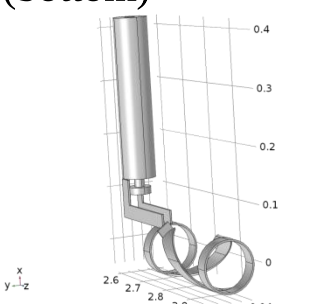
Modeling of RF systems on Proto-MPEX

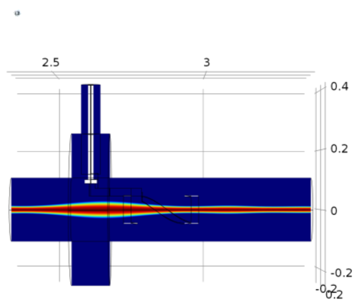
- Full-wave modeling of the ICH and helicon antennas using COMSOL RF package
- Current progress is using helicon RF model to understand which helicon eigen-mode is responsible for high-density operation on proto-MPEX

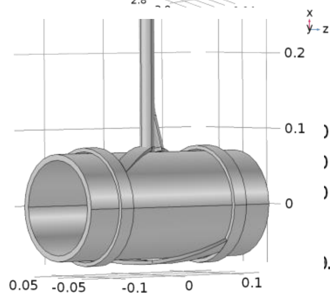


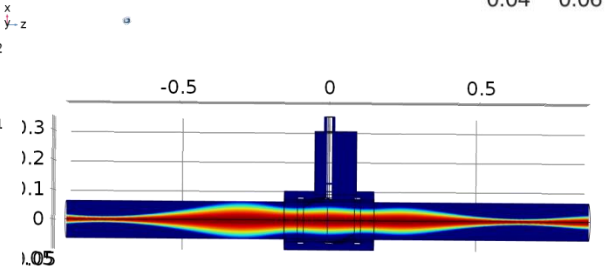


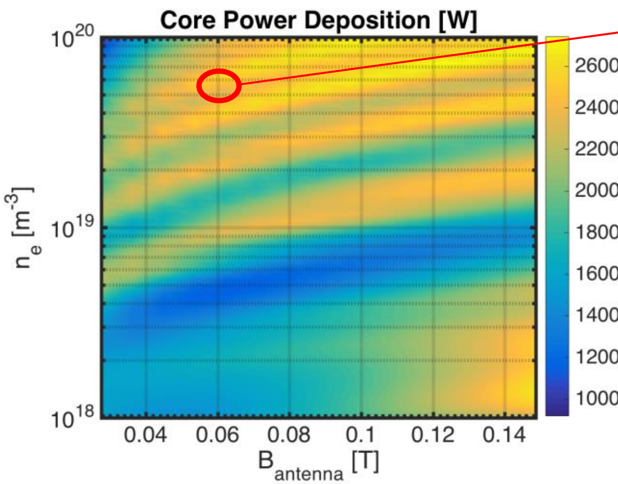
COMSOL model of Helicon antenna (left) and ICH antenna (right) with plasma density profiles (bottom)



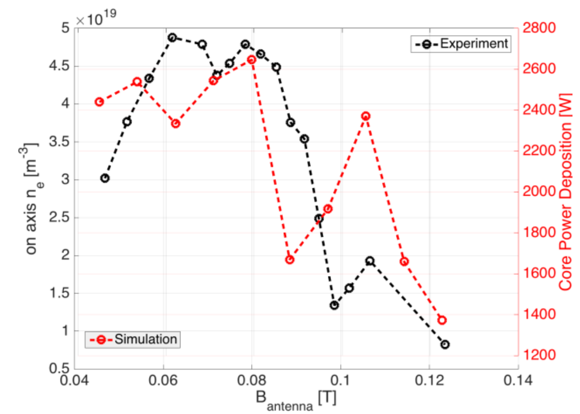




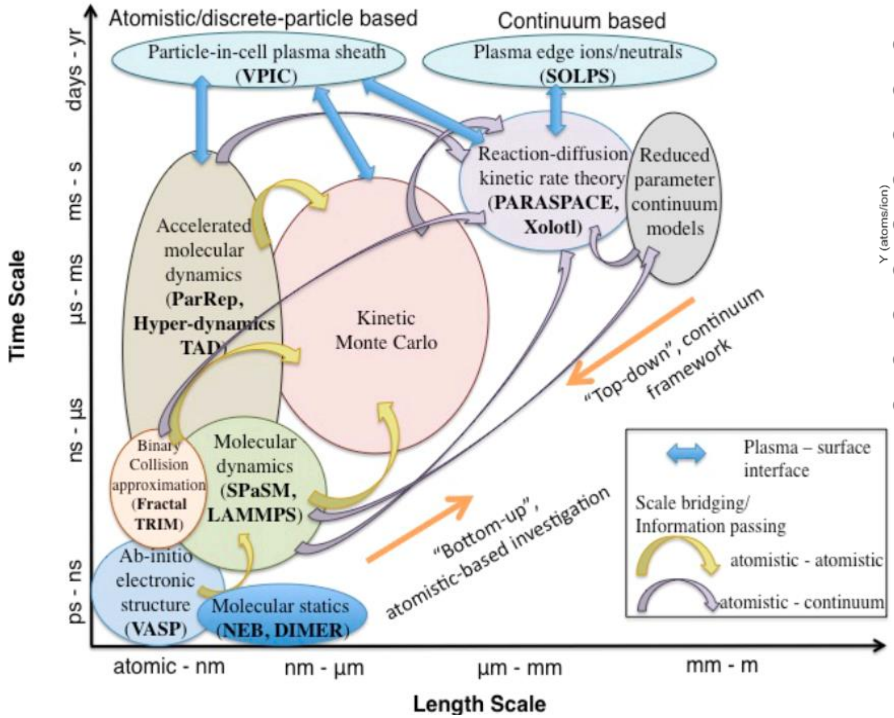


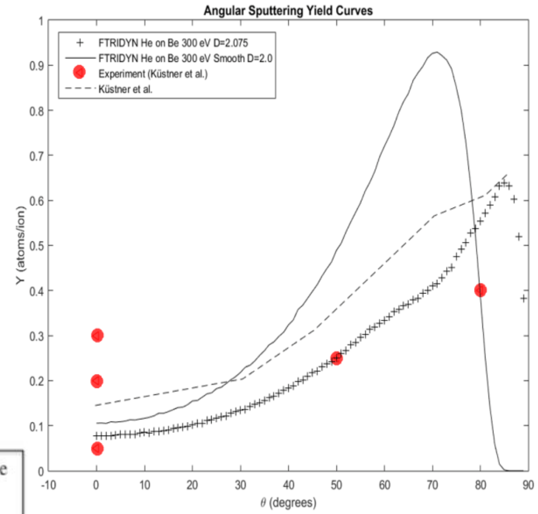


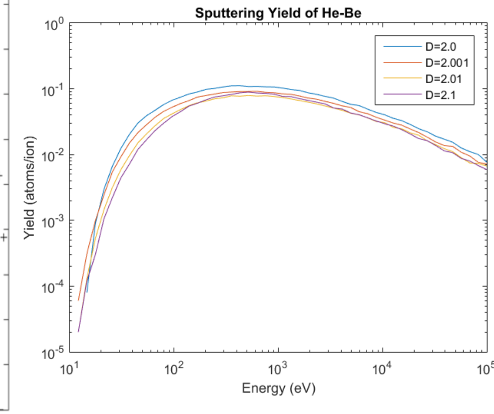
Combination of 1st and 2nd radial eigen-mode in high density regime



Fractal TRIDYN Ion-Surface Interaction Code



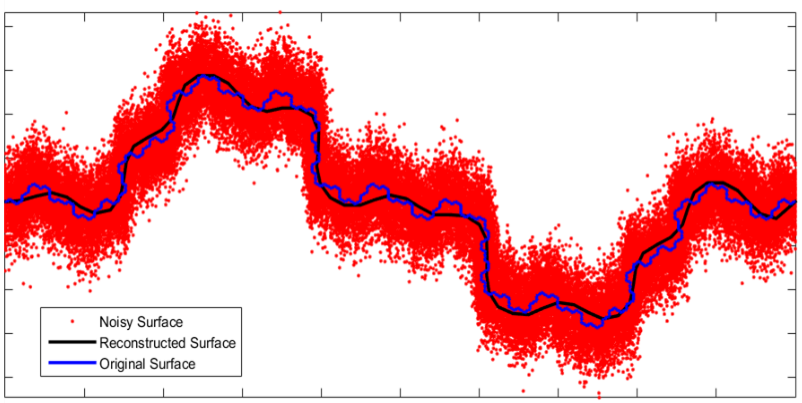




Goal: Understand the complex interactions of energetic ions with a dynamic surface

Fractal TRIDYN is a Monte Carlo code that use the Binary Collision Approximation to simulate ion trajectories in materials

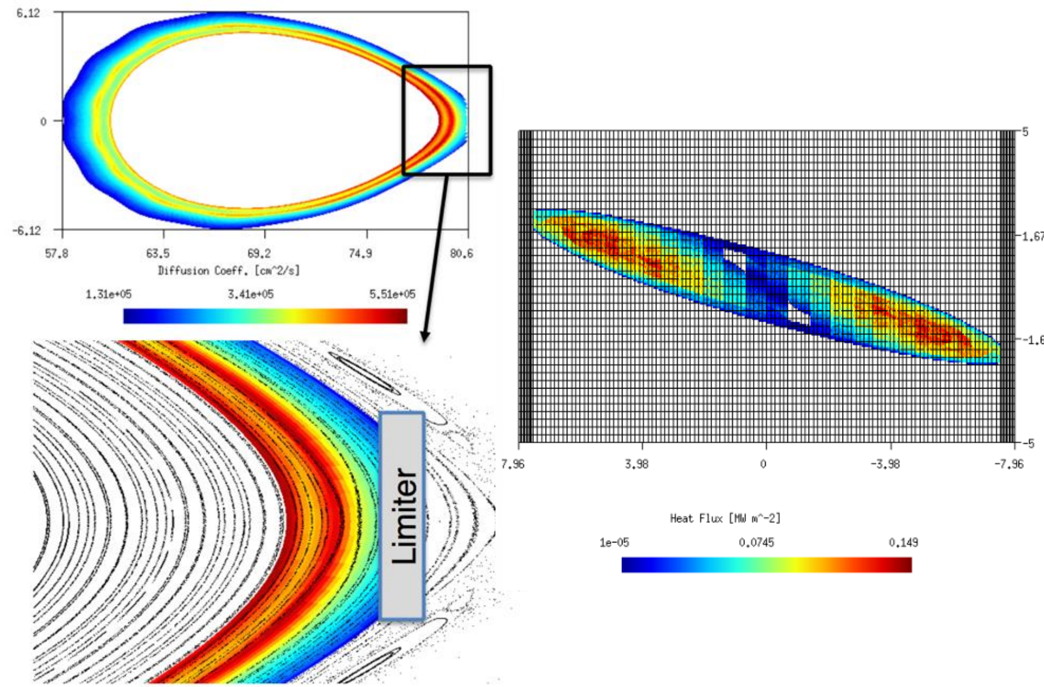
FTRIDYN includes routines for the simulation of dynamic surface morphology and composition

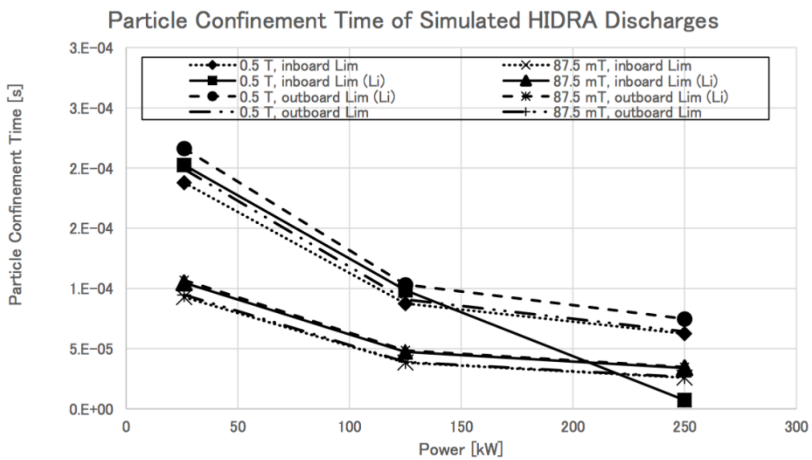


Monte Carlo codes fill an important time- and length-scale gap in multiscale code suites such as the PSI-SciDAC code for simulation of multiscale plasma-surface interactions for fusion relevant conditions

Numerical Characterization of Expected Operating Conditions with EMC3-EIRENE

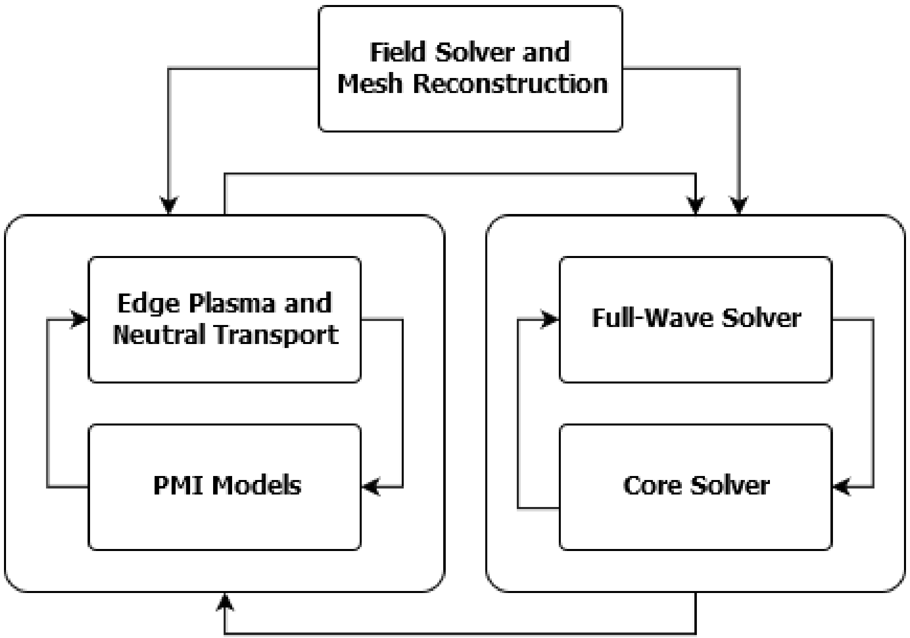
- A numerical characterization of the particle and heat fluxes at several limiter locations in HIDRA has been performed with EMC3-EIRENE code
- A local Bohm diffusivity has been added to EMC3; despite the increased non-linearity of the transport equations compared to constant diffusivities, numerical stability has been reached with sufficient relaxation
- Results
  - With the current HIDRA setup, heat fluxes on HIDRA can approach ~ 1 MWm^{-2} in small areas at the inboard surface; heat fluxes can be increased to 3 MWm^{-2} with 250 kW of klystron input power
  - Particle fluxes combined with steady – state (87.5 mT) or long pulse (0.5 T) operation can provide fluences on the order of 9×10^{22} cm^{-2}

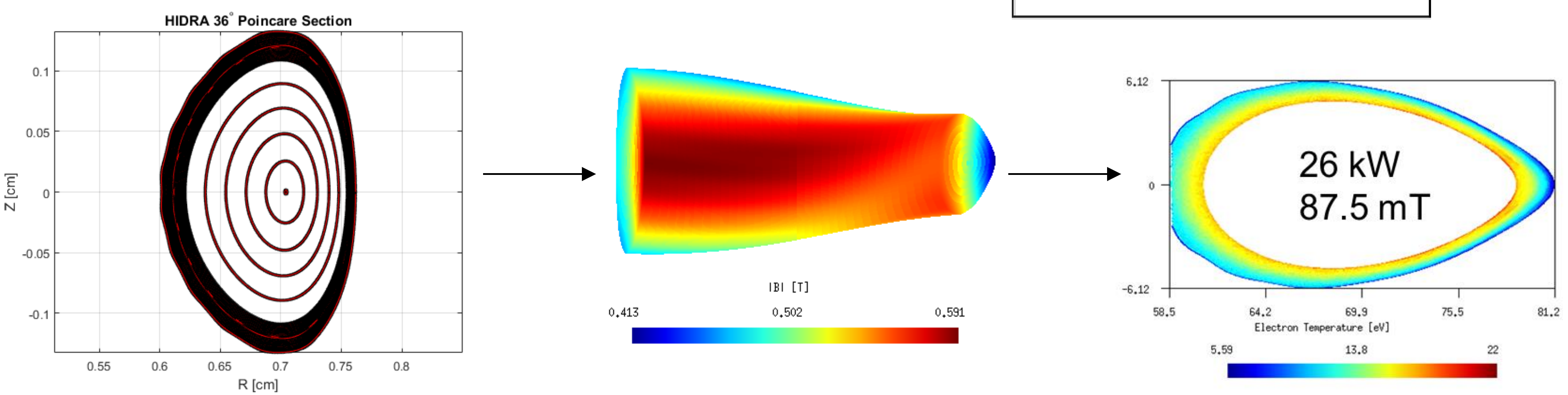




HIDRAmod

- Software Suite for Full-Device Modeling
- Currently, FIELDLINES and EMC3-EIRENE implemented for magnetic mesh reconstruction and edge transport
- How much insight into surface conditions can be gathered for PMI experiments?
- Can HIDRAmod be used as a testbed for PMI models in the context of a full device?

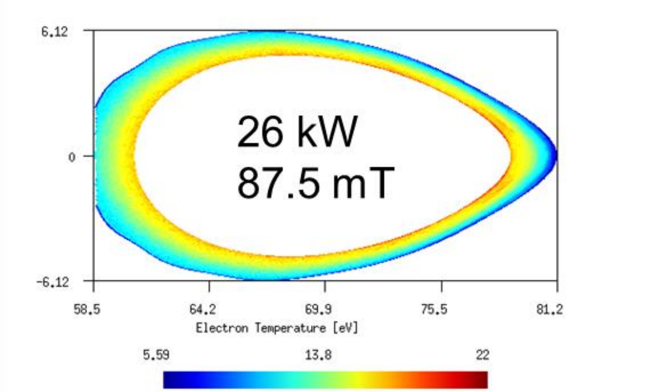


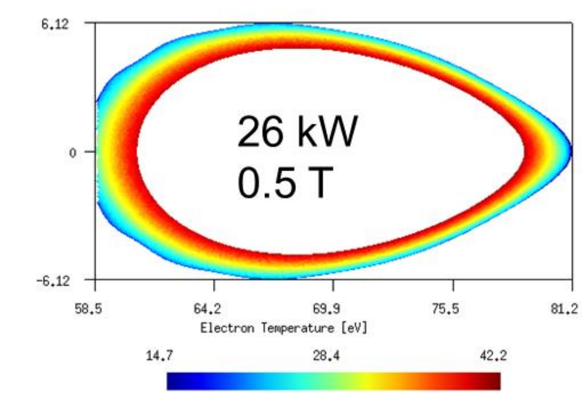


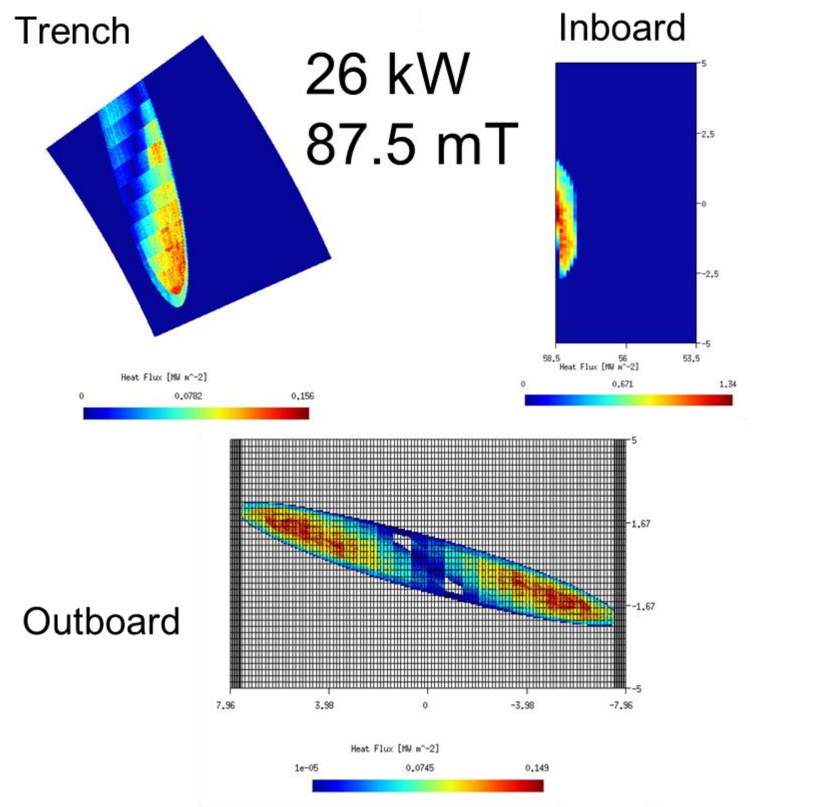
HIDRAmod

HIDRAmod enables analysis of expected edge conditions over a range of HIDRA operating conditions and their affects on near-surface properties of the plasma.

Bohm-like diffusion provides a spatially-varying self-consistent diffusivity for the transport solver. A coupled full-wave and core solver would allow for a self-consistent device efficiency.







Overall Structure of CPMI

Plasma Research at the Center for Plasma Material Interactions (CPMI)

Plasma and Laser nano-manufacturing

Plasma Facing Components

Liquid Fusion Walls

D. N. Ruzic

Plasma Materials Computational Modeling

Near-Wall Kinetics

3-D Edge Models

Fusion Material Wall

D. Curreli

Plasma Nano-synthesis

Plasma Science and Engineering Research

Plasma Edge Modeling Validation in HIDRA

J. P. Allain

Advanced Fusion Materials

In-situ and in-vivo surface Characterization

In-situ Plasma Diagnostics, HIDRA-MAT

D. Andruczyk

HIDRA System and Testing

Advanced PMI Diagnostics

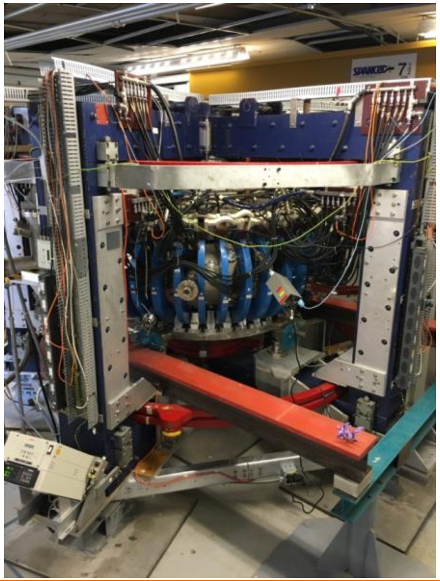
Fusion technology Education

HIDRA Parameters

- Stellarator as well as tokamak capabilities.
  - Vessel splits in half, easier access to install larger components
- Magnet configuration
  - 40 toroidal coils
  - 4 helical coils
  - 2 vertical field coils
  - 84 ports, 6 sizes accessible
- Stellarator operations in Greifswald
  - **$R_0 = 0.72$ m**
  - **$r = 0.19$ m**
  - **$B_0 = 0.087 – 0.5$ T**
  - **$f_{mag} = 2.54$ GHz, $P_{mag} = 6$ kW + 20 kW**
  - **$n_e < 1\times10^{18}$ m^{-3}**
  - **$T_e = 5 – 25$ eV**
  - **$t_{pulse} < 60$ min**
  - $f_{gyr} = 28$ GHz, $P_{gyr} = 10$ kW cw, 40 kW pulsed
  - **$\Gamma = 1\times10^{22}$ m^{-2}s^{-1}**

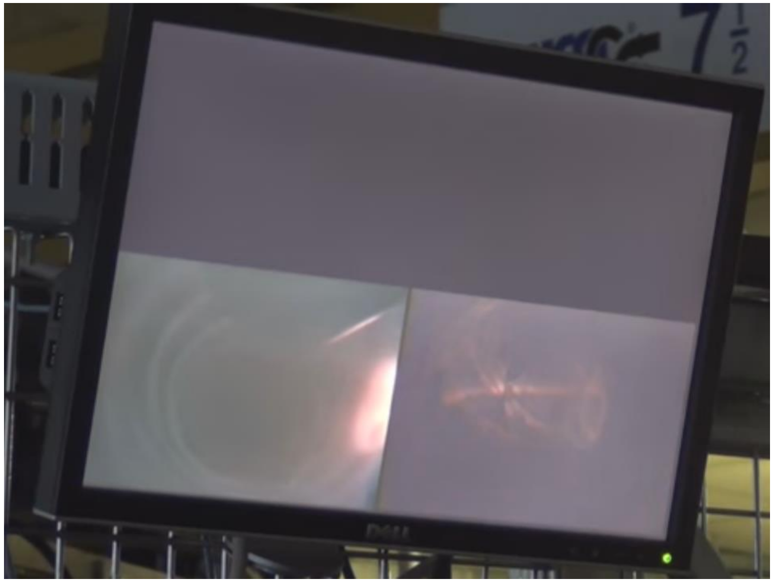
Tokamak Operation in France

Plasma current	$I_P = 45 – 60$ kA
Ohmic heating power	$P_{ohm} = 100 – 130$ kW
Peak electron density	$n_e = 1.6\times10^{19}$ m^{-3}
Peak electron temperature	$T_e = 600 – 900$ eV
Peak ion temperature	$T_i = 150 – 250$ eV
Energy confinement time	$\tau_E = 3 – 5$ ms
RF frequency	f = 500 MHz
Maximum RF power	$P_{RF} = 100$ kW
Maximum pulse duration	$\Delta t_{RF} = 5 – 15$ ms

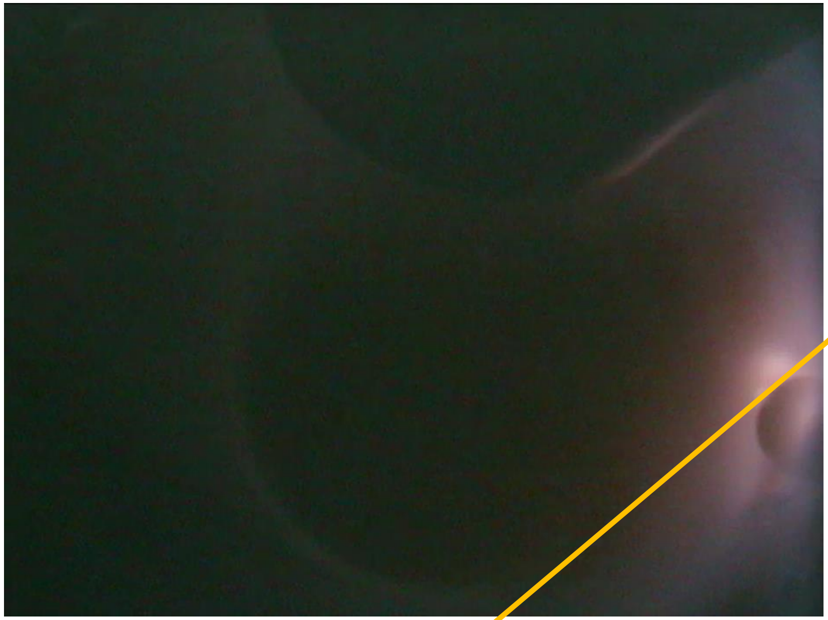


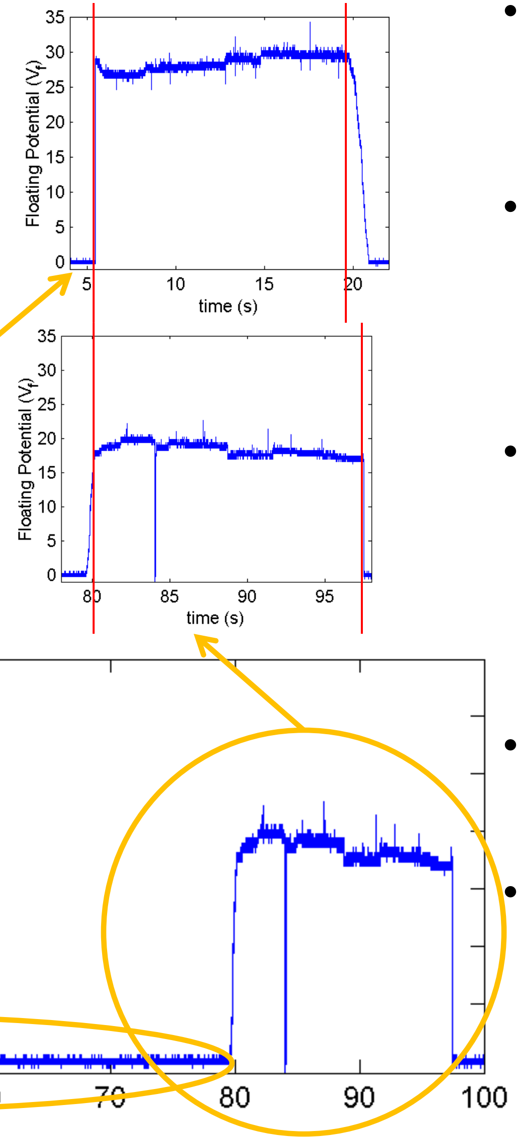
First Plasma, 22 April 2016

- First plasma achieved on Friday 22 April 2016 at 4:15pm
  - Base pressure down to 104 μPa (8×10^{-7} torr)
  - Operational pressure 13 mPa (10^{-4} torr)
- Part of the NPRE open house celebrations.
- Public was there to see the HIDRA, first plasma and CPMI lab



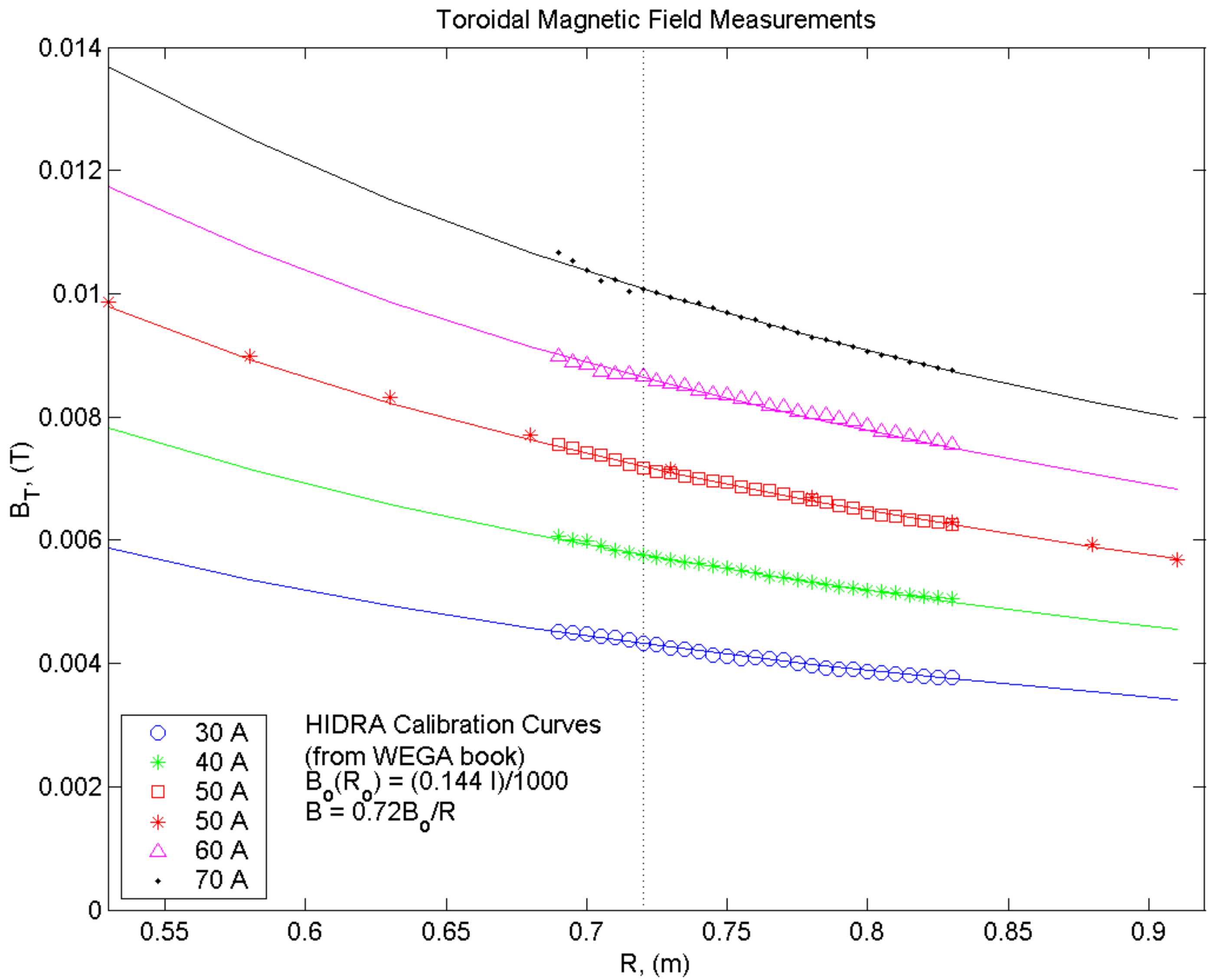
Plasma Glow Discharge With B-Fields



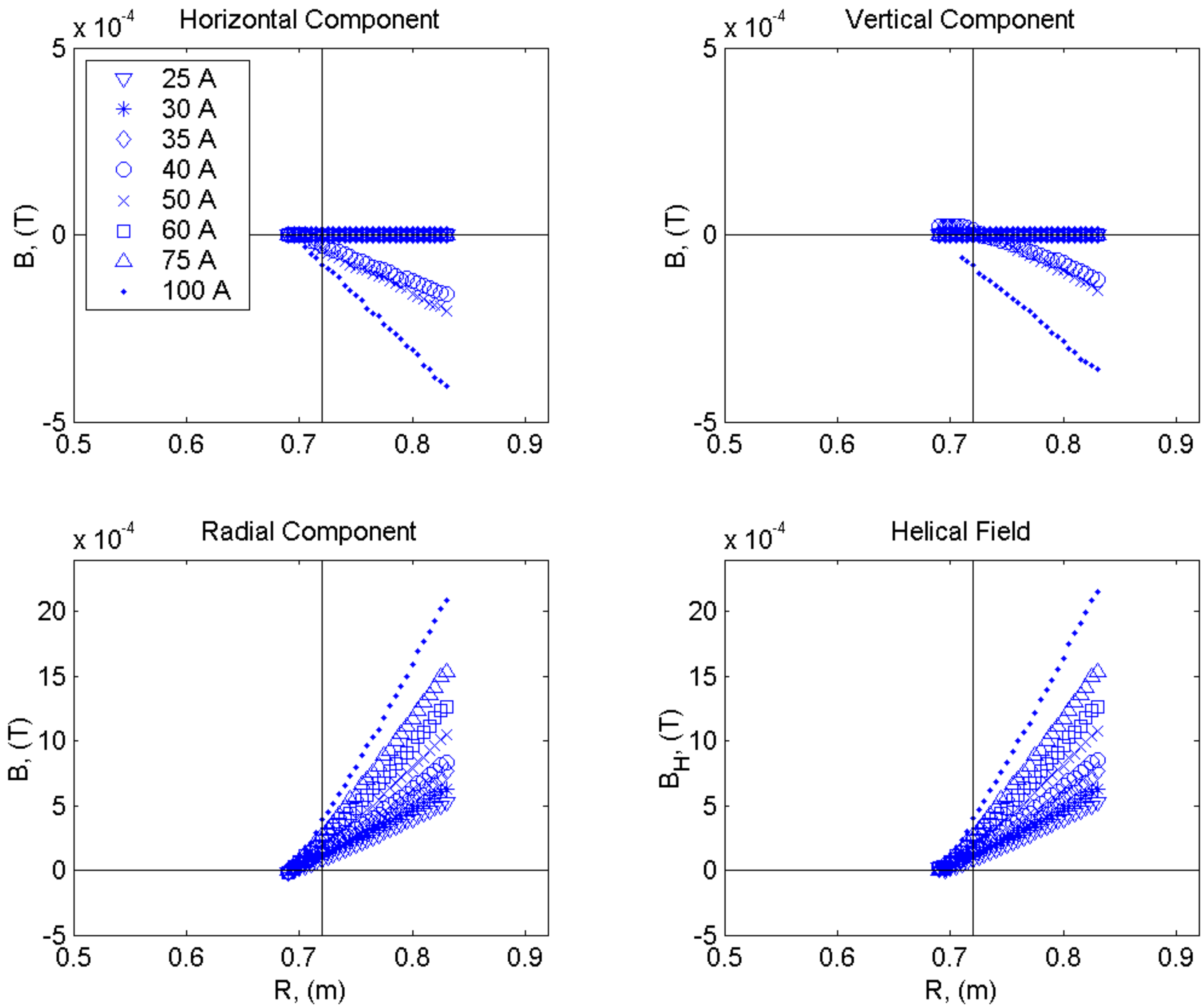


- Plasma generated via glow discharge GDC electrodes
- Langmuir probe inserted 2 cm from the outer wall of plasma measured floating potential
- As the B-field is ramped up the plasma is confined more towards the center of vessel and away from probe.
- V_f drops since no plasma present.
- When B-field is ramped down then the plasma comes back and V_f is measured.

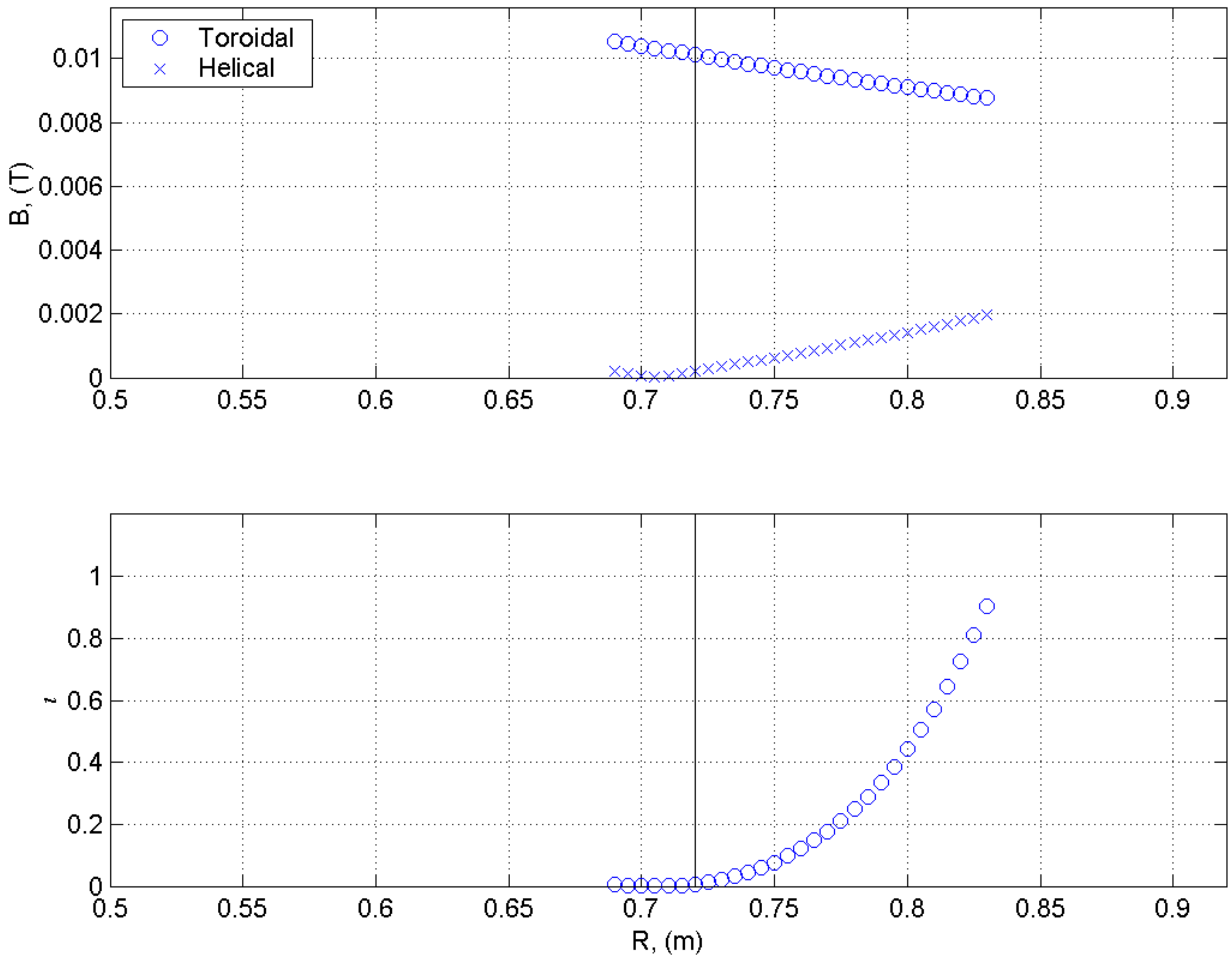
Magnetic Field Mapping – Toroidal



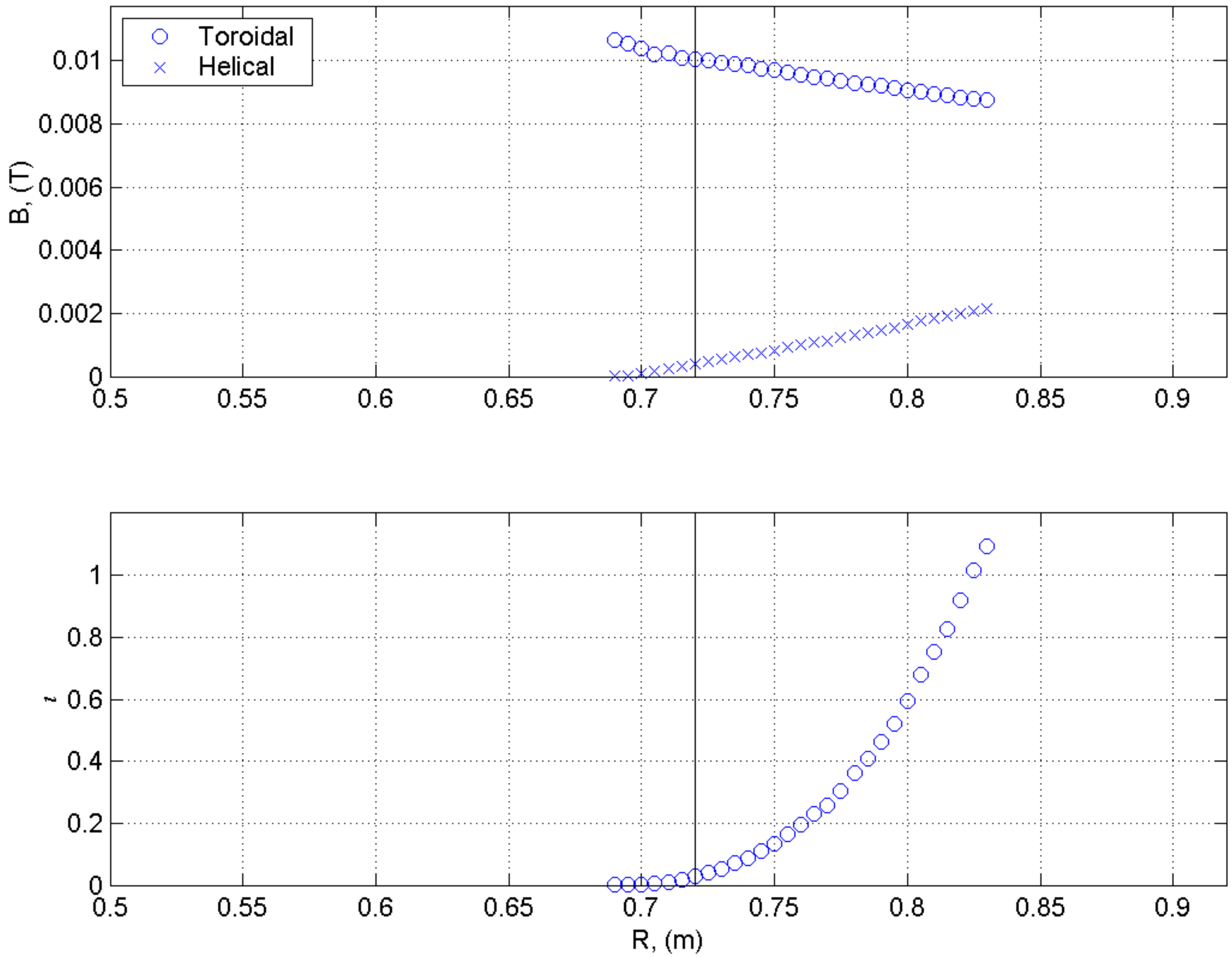
Magnetic Field Mapping – Helical



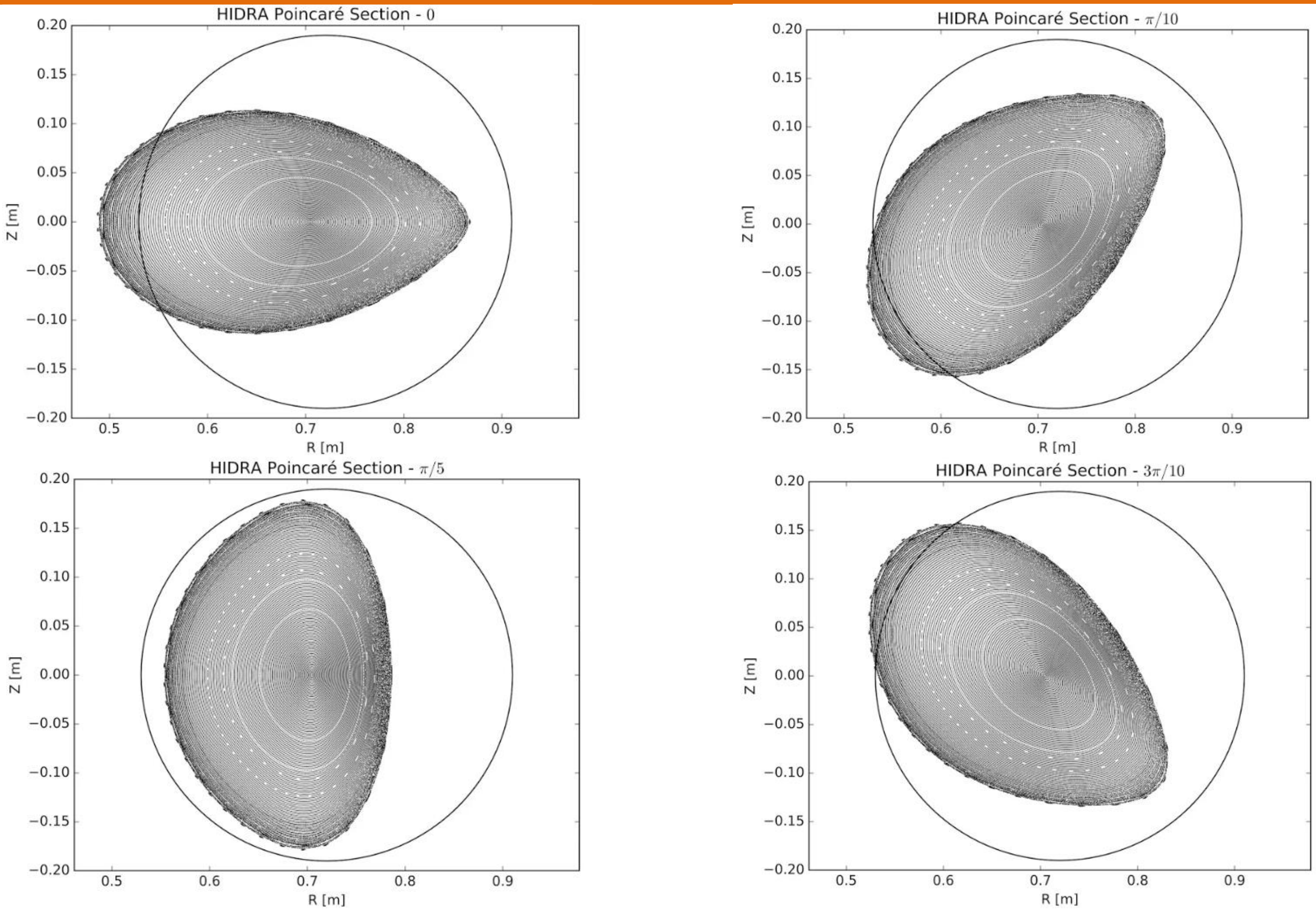
Theoretical, iota measurements



Experimental, iota measurements

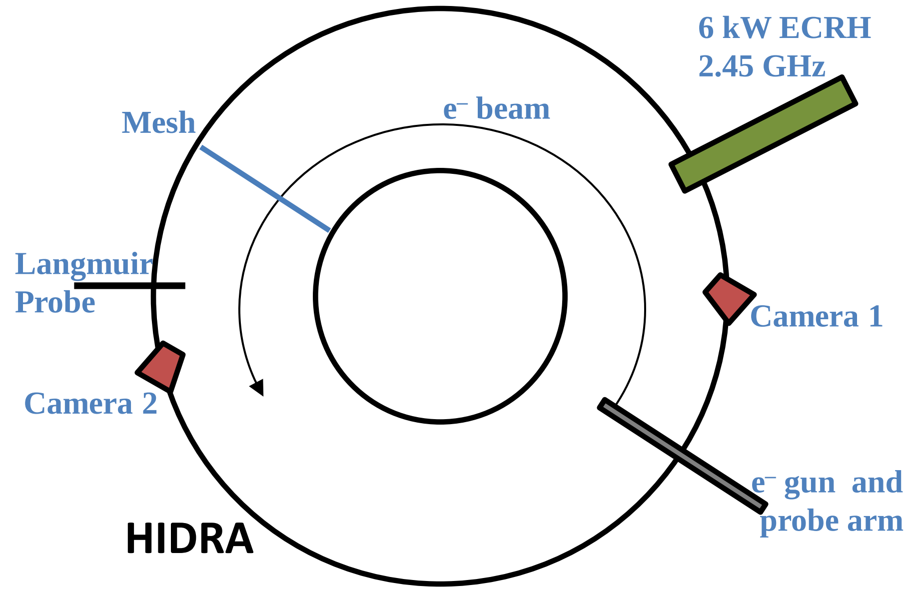


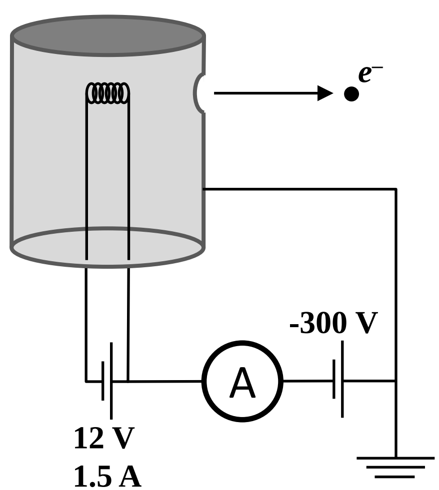
Calculated Flux Surface Profiles



e^- beam and Mesh for Field Mapping

- A simple electron gun has been designed to do magnetic field and flux line mapping
- Based on the filament from a halogen lamp
  - 12 V – 15 V and up to 2 A for emission voltage and current
  - Up to –300 V for the bias to extract the electrons
- Electron will follow a magnetic field line from a set position.
  - Visualize with cameras
  - Flux lines eventually will be visualized via a mesh with fluorescing powder and cameras.





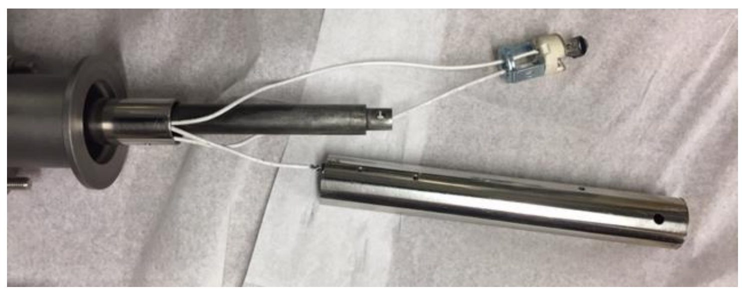
- Electron gun is mounted on a reciprocating probe arm
  - Extended all the way to the high field side wall to the low field side wall
  - Scans from the center to the 10 cm from the center of vessel (R0 = 0.72 ⟶ 0.82 m
- Two cameras are used to visualize the electron beam.
- Currently the parameters of beam, pressure, gas type and B field used

e^- gun

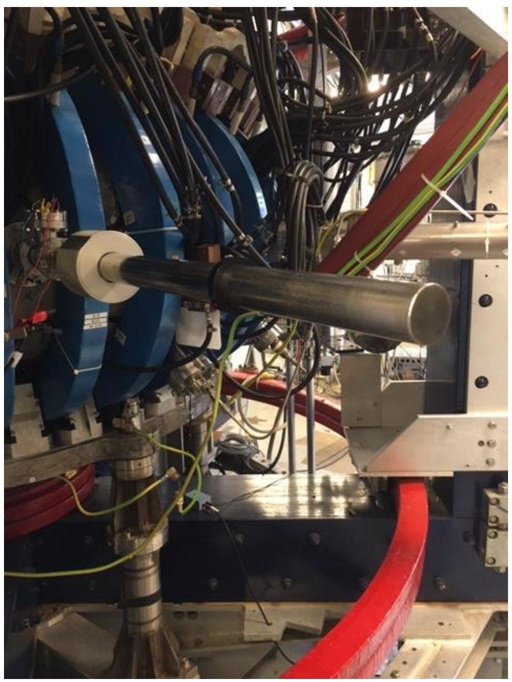
Above: Installed edge Langmuir probe and camera 2.

Right: Video of e^- beam following a field line, visualized with cameras.

Above: The mesh that will be used to visualize the magnetic flux lines



Left: e – gun showing the filament and biased cover to extract electrons.



Right: assembled e^- gun .

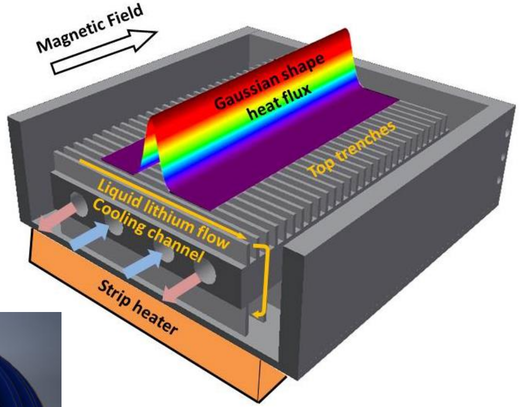
Left: e^- gun installed on HIDRA

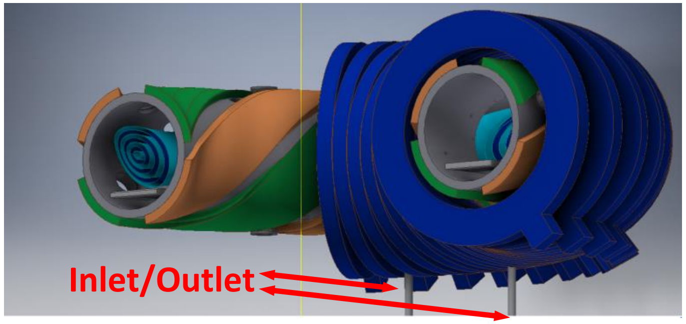
Future Work and Research

Testbed for LM concepts such as Self-Driven Thermoelectric Flows

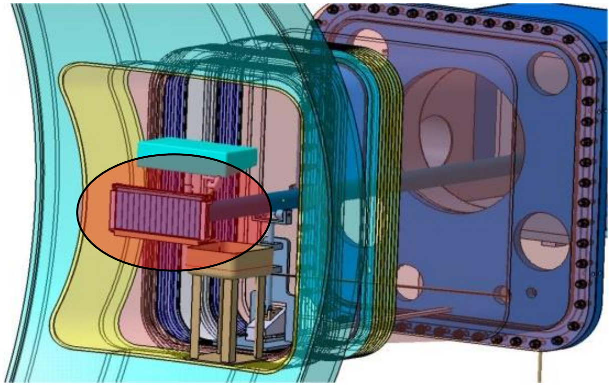
- Important question in fusion:
  - Can a **self driven flow** work in the divertor and the first wall?
  - Will it withstand the **heat flux**?
- Answer can be provided Using HIDRA
  - $n_e = 1\times10^{18}$ m^{-3}
  - $T_e = 5 - 25$ eV
  - Flux outside LCFS $\Gamma = 1\times10^{22}$ m^{-2}s^{-1}
  - At $B_0 = 0.087$ T can get up to **60 minutes**
  - $B_0 = 0.5$ T tens of seconds.
- TEMHD concepts like LiMIT, FLiLi can be tested
  - Fully toroidal
  - Island limiter/divertor concept
- Solutions for machines like NSTX-U, EAST, W7-X and future machines.

The LiMIT concept whereby a thermoelectric current is driven due to the temperature gradient induced by the plasma heat flux and toroidal magnetic field.

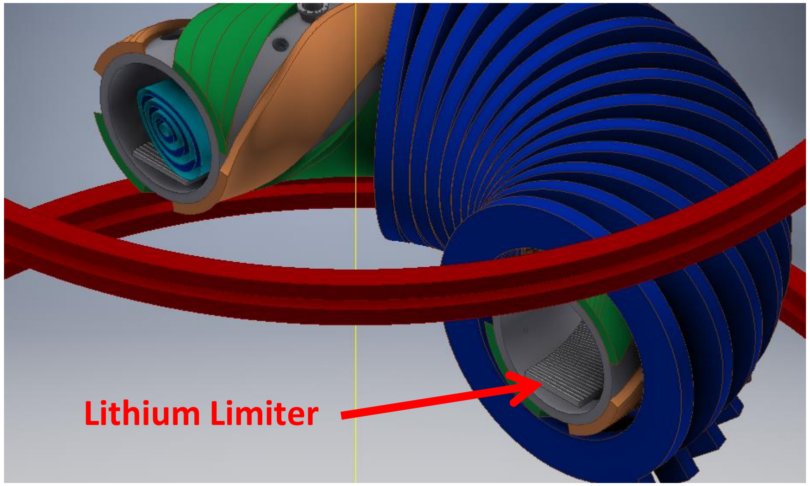




First conceptual design for a LiMIT limiter to be installed in HIDRA. The Liumit trenches can be seen on the bottom of the plasma vessel (below) with the inlet and outlet lines for lithium and cooling (left).



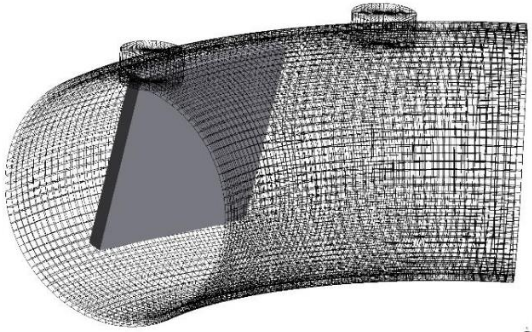
Concept of LiMIT to be installed on EAST. This will be tested either at the end of 2017 or early 2018.

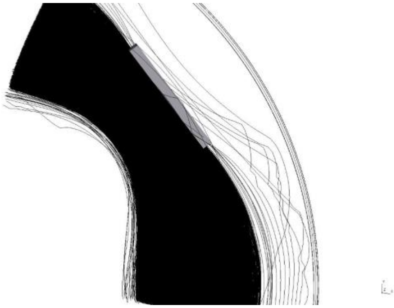


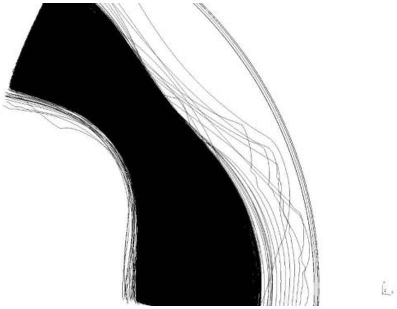
EAST Collaboration

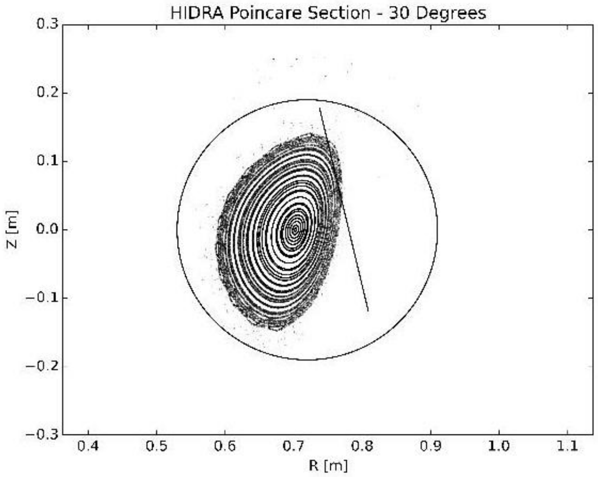
- CPMI will help test liquid lithium/metal solutions for EAST.
  - HIDRA will be the test–bed for developing and perfecting the technology before installation on EAST.
  - Part of a large collaboration lead by PPPL.

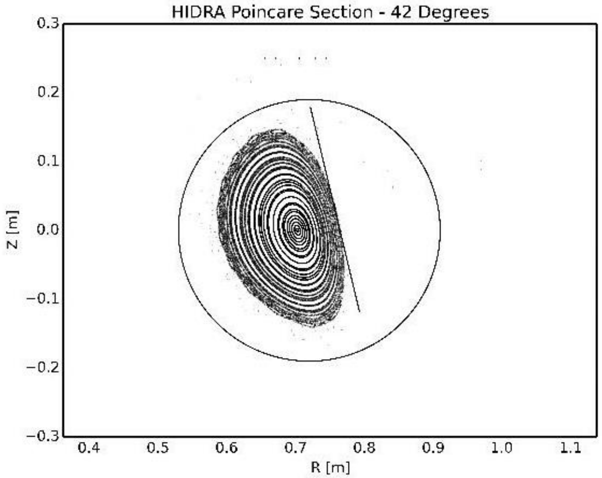
- Initial modeling to see the best position in HIDRA to test LiMIT
  - LiMIT plate needs to be inclined at 13.5º as in EAST
  - Can the plasma still impact a plate

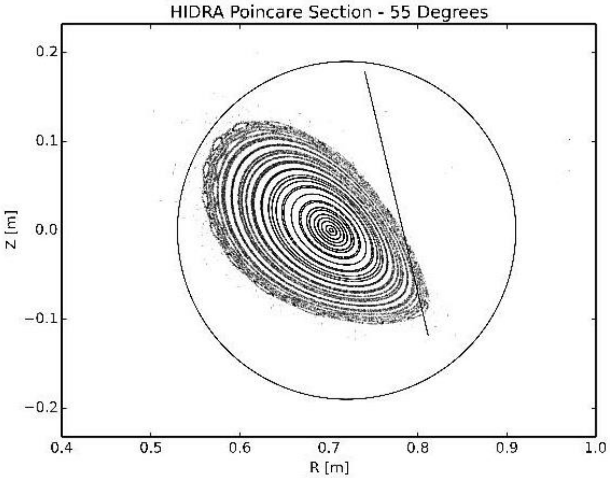






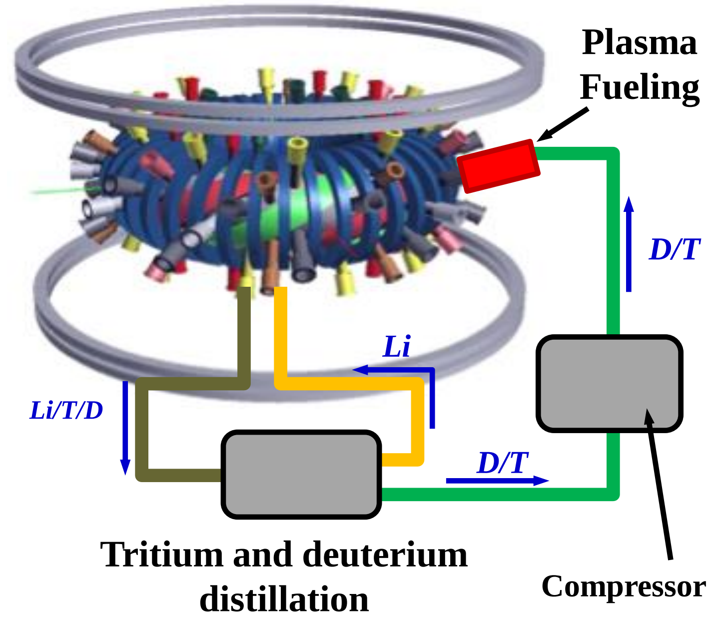


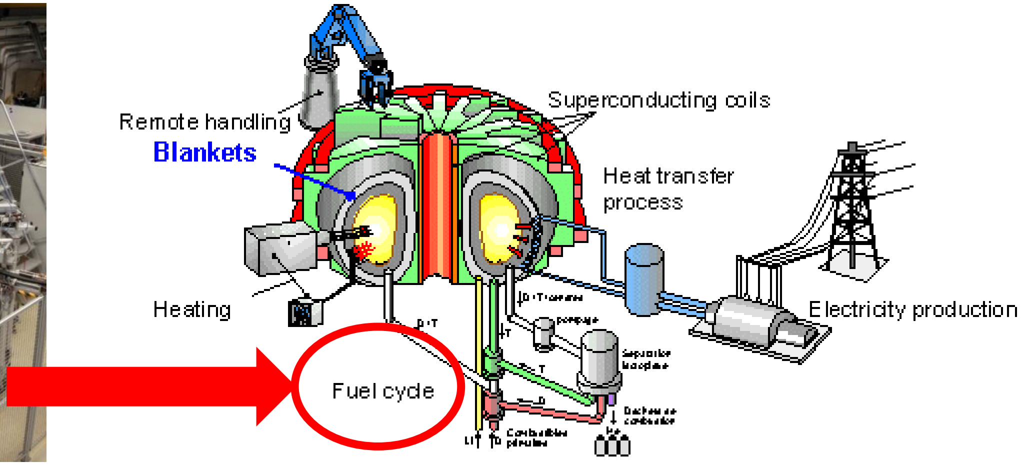




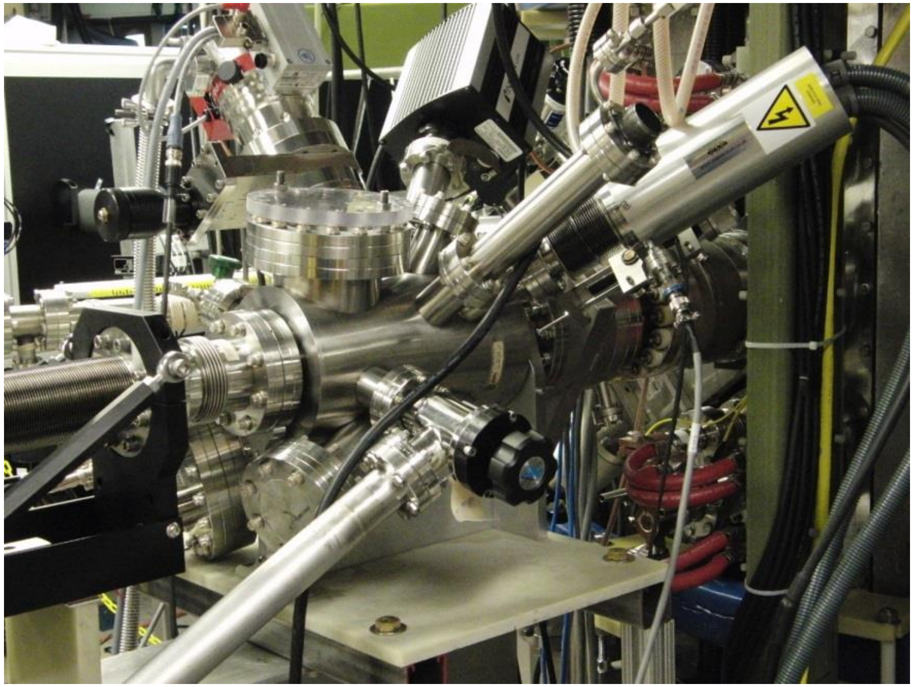
Liquid Metal Toroidal Test Bench and Li Loop – D Recycling

- Can a **toroidal liquid metal** loop function in a fusion environments
  - MHD Effects
  - Transient Fields
  - High heat flux
- HIDRA can answer these questions.
  - Test transient behaviour during start up
  - Plasma induces eddy currents
  - Runaway Electrons
- Liquid Lithium Loop
  - Does liquid lithium really **provide low recycling**?
  - Can **D be removed and recycled** easily?
- **HIDRA can run "Steady State" on molten lithium**





HIDRA: Materials Analysis Tool (HIDRA-MAT)



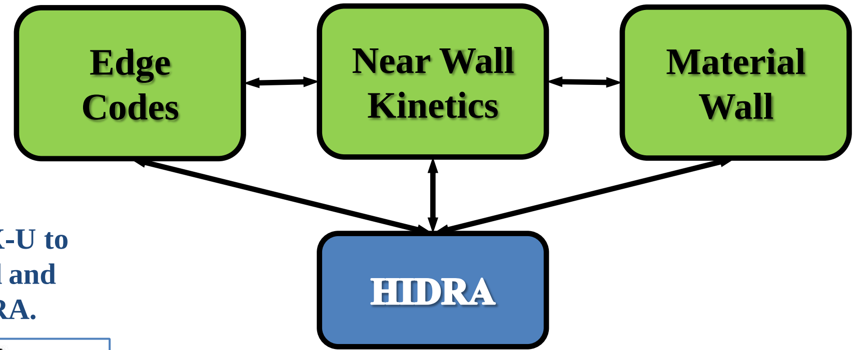
The MAPP facility installed on LTX at PPPL and will be put on NSTX-U. The HIDRA-MAT facility will be similar to this for material studies on HIDRA. This is an in-situ facility with XPS, TDS and DRS diagnostics to do surface analysis.

- HIDRA-MAT *in-situ* PMI facility
  - Conduct material testing experiments
  - Based on MAPP facility at PPPL
- Materials development
  - Test various approaches
  - Issues with operational temperature
  - Hydrogen retention
- Plasma edge diagnostics
  - liquid metals as the plasma material interface
  - Extensive experience with plasma diagnostics in extreme environments.
- **Establish empirical scaling to future plasma-burning devices at the plasma edge.**

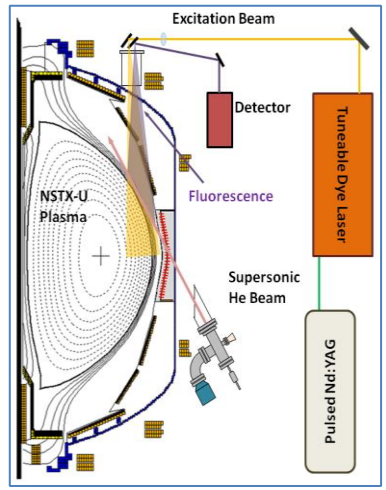
Validation of PMI, Edge and Materials Models

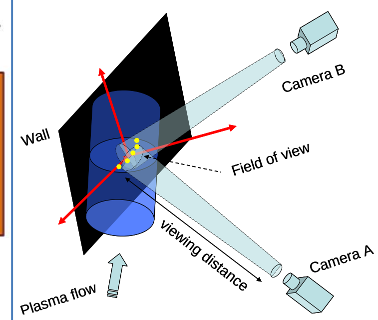
Computational Modelling, PSI & Edge Plasmas

- Development of Near Wall Kinetic models
  - Interface with edge and material codes
  - Extreme conditions of plasma material interactions
- Reconcile 2D/3D models
  - Fluid modeling with plasma kinetic behaviour
  - Coupling kinetic solver with fluid solver
- UIUC computational resources
  - Illinois Campus Cluster – Taub and Golub
  - Petascale Computing Facility – Blue Waters
- HIDRA
  - Benchmark near wall/materials
  - Plasma edge physics

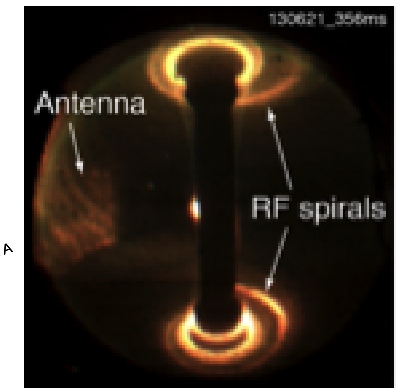


E_r, measurement proposed for NSTX-U to be developed tested and calibrated on HIDRA.





Schematic of the proposed dust diagnostic using two cameras to image the dust and determine the dust parameters.



Antenna and divertor heat deposition in NSTX from B-field lines passing near the antenna.

Development of New Diagnostics

- Diagnostics and facilities already describes
  - LiMIT
  - Liquid lithium look/recycling
  - HIDRA-MAT
- Other Diagnostics
  - Radial Electric Field measurements in the edge
    - Edge Turbulence, Transport, H-Mode and Enhanced Pedestal H-mode
    - Related to materials and recycling
    - Testing and development for other machines e.g. NSTX-U

– Dust Plasmas
- Generated from plasma facing components
- Core Contamination
- Instabilities
- Tritium retention
- *In-situ* studies of dust
- ELM Control

– Interaction of plasmas with RF antennas
- Fundamental important process
- Plasma heating
- RF plasma sheath leads to focused particle and energy fluxes on antenna surface
- Influence on T retention, dust formation and impurity transport

Summary

- Center for Plasma Material Interactions offers a comprehensive facility and set of tools for materials studies
  - Understanding PMI
  - PFC development
- Fusion and processing/industrial plasma experiments
- The overall group consists of
  - 4 Professors, 1 Research Engineer, 3 Post-docs
  - 20 Grad students, 20 undergrads
- There are 4 main areas of research that are all tied in together
- Ability to test out the basic parameters of materials, LiLi, LiSn, W as well as then studying their interaction with plasmas
  - Fuzz
  - Texturing
  - LiMIT
- PMI diagnostics to understand the changing face of materials as they are exposed to a plasma.
  - MAPP
  - Adaptive materials
- Plasma modeling
  - Fractal TRIDYNE
  - Plasma modeling
- HIDRA operation scenarios, dedicated toroidal PMI facility
  - International collaboration with EAST to develop, test and install flowing liquid lithium PFCs

Video of HIDRA being assembled at the University of Illinois after arriving from Greifswald.