Divertor/SOL Breakout Outbrief

Adam McLean, LLNL
and
Jonathan Yu, GA

Attendees: McLean, Yu, Losada, Kapat, Lasnier, Marini, Rudakov, Scotti, Ronchi, Nichols, Davda, Yadava, Perillo, Hong, Allen, Soukhanovskii, Ma, Holm, Wauters, Truong, Lanctot, Groth

Presented to
DIII-D Community Wall-Changeout Forum

June 13, 2024

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Divertor/SOL Breakout Outbrief

https://fusion.gat.com/conference/e/WallChangeForum
Sharepoint link

Wednesday - Overviews, Breakout Sessions			
Time (PDT)	ID#	Name	Title
08:15 AM			Coffee, Refreshments
08:30 AM	01	J.P. Allain	Opening Remarks from DOE-FES
08:35 AM	02	R. Buttery	Opening Remarks from DIII-D Directorate
08:40 AM	03	T. Abrams	Overview of Wall Change Process & Forum Goals
09:00 AM	04	B. Wirth	FMCC Plasma/Debris Interactions Draft Roadmap
09:30 AM	05	K. Schultz	DIII-D Wall Change Engineering Scope Considerations
10:00 AM	06	T. Abrams	Break-out Session Guidance
10:15 AM			Coffee Break
10:30 AM	07	A. Garofalo C. Holcomb	Core Physics/AT Scenarios Breakout (Room 15-019, Zoom Link)
		A. McLean J. Yu	Divertor/SOL Breakout (Room 15-018, Zoom Link)
		B. Wirth G. Sinclair	Fusion Materials & Technology Breakout (Room 13-301, Zoom Link)
		H. Wang S. Zamperini	Pedestal/Core-Edge Breakout (G34 CR Conf. Room, Zoom Link)
		F. Effenberg A. De	Plasma-Materials Interactions Breakout (Room 13-530, Zoom Link)
12:30 PM			Breakout Groups Adjourn

Breakout Group Talks

Divertor/SOL Breakout (Room 15-018, Zoom Link)		
Name	Institution	Title
Adam McLean	LLNL	Operational and diagnostic considerations for a wall changeout
Charlie Lasnier	LLNL	Effect of Metallic Wall on Optical Diagnostics
Filippo Scotti	LLNL	How radiative divertor studies will be affected by the wall change out
Jake Nichols	ORNL	Decoupling functional requirements and materials for different regions of the main wall

- https://fusionga.sharepoint.com/sites/DIII-DTechnology/_layouts/15/doc.aspx?sourcedoc={ad4a9b9f-329a-45e7-a447-4205369f4014}&action=edit
- Folder

- **Thanks to our scribe, Jonathan Yu!**

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McLean: Changing the wall will have massive implications for how we run DIII-D, and may have massive implications for diagnostics

- **We have been spoiled. For 30 years, the DIII-D carbon wall has given us the gift of 'radiation'**
  - Carbon provides a benign wall, and an intrinsic source of radiation, which radiates primarily in the edge and not in the hot core
  - **Typically >2/3 of input power is radiated by C (the rest by D), reducing heat flux from ions to the wall**
- **And we have taken full advantage; many DIII-D scenarios include very low densities, and very hot divertors**
  - Without a graphite wall, intrinsic C radiation will need to be replaced: **As important as the wall choice**
  - ***C radiation can't be replaced with W (or other high-Z) because high-Z radiates in the core, and a high self-sputtering yield for W → W***
  - ***Re-learning how to run every discharge, every scenario, conditioning, etc. will take time***
- **The current DIII-D diagnostic set is optimized for low-Z and low reflectivity; medium/high-Z and/or higher reflectivity will require new diagnostics and re-interpretation**
  - TanTV, Thomson, CER, IRTV, FIDA, MDS, FSs, CIS, WiSE, BES, MSE, Vbrem, FASTCAM, and more **all may need reinterpretation**
  - ***Major effort essential to maintain DIII-D as having the best diagnostic set in the world***
- **Engineering places extreme restrictions on high-Z tiles compared to graphite**
  - Sub mm accuracy essential; ~0.3 mm W droplet/dust (0.3 mg) can radiate 10 MW of power in DIII-D

Lasnier: Effect of metallic wall on optical diagnostics

- **Quality and extent of the DIII-D optical diagnostic set has been key to research**
  - Over a dozen intensity and spatially calibrated diagnostics on the machine
  - **Critical for interpretation and code validation efforts**
  - **Benefited from low reflectivity, and ~constant emissivity of graphite**
- **Diffuse background reflection/scattering of light from other parts of the tokamak**
  - **Increased use of viewing dumps will be required to reduce signal from other locations**
- **Ghost images of other light sources reflected in the wall**
  - Much harder to identify in signals from discrete detectors, viewing individual chords
- **High reflectivity means low emissivity for infrared wall temperature and heat flux**
  - Emissivity of a metallic wall can vary widely depending on surface condition; e.g. tungsten
  - **Severe changes in time due to deposits/surface polish, structure: Need for in-vessel light source for more regular calibration**
- **Emissivity changes can be accounted for with two-color/dual band approach**
  - But cost/resources for extra cameras or optics is high
  - **But only modeling can attempt to account for reflections**

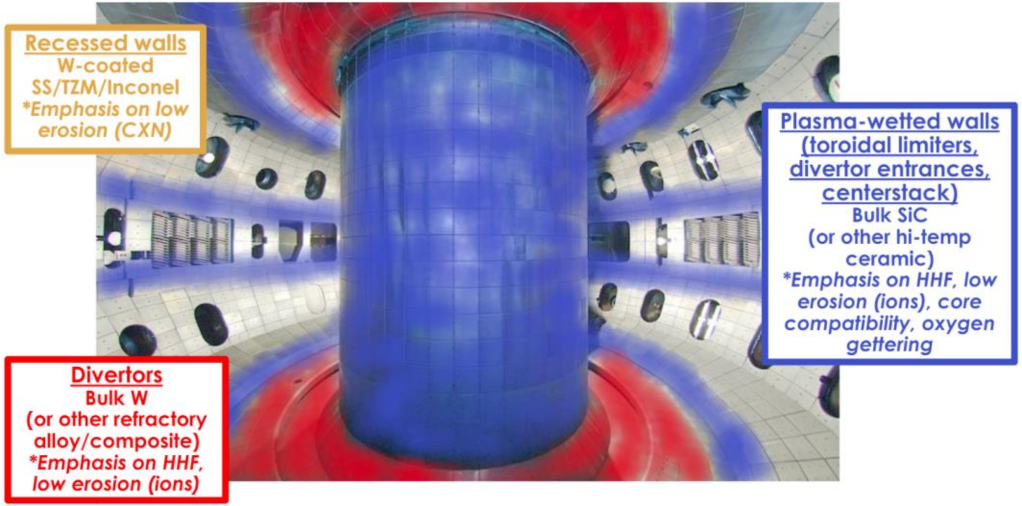
Scotti: Effect of wall changeout on radiative divertor studies

- **Reduction in low Z intrinsic impurity source with wall changeout brings the necessity of impurity seeding for divertor dissipation studies**
  - Impurity concentration ~ sputtering yield $Y_{phys}(Te, Ti) + Y_{chem}$ (no threshold on Ychem)
- **Non-forgiving nature of metallic wall → high collisionality or seeding could be the default way of operation in some regimes**
  - Full wall changeout aims to reduce intrinsic impurity levels
  - **Metallic divertor PFCs not forgiving (melting, sputtering, high core P_{rad}), operation at high collisionality or with impurity seeding might be necessary for some scenarios**
- **N provides most seamless transition (similar radiation/compression to C) with added controllability, different scenarios to rely on different mixes (B, N, Ne, Ar)**
  - **We already achieve conditions where extrinsic impurity is the dominant divertor radiator**
- **Move to higher Z radiators needs a re-optimization of diagnostics for radiative divertor studies**
  - **Move to higher Z seeded radiators shifts useful spectral range towards UV**

Nichols: Decoupling functional requirements and materials for different regions of the main wall

- ***Challenges are looming for the first wall of a reactor scale tokamak***
- **Divertor-relevant high-density regimes → high heat/particle transport to main wall**
  - Density shoulders, grassy ELMs/QCE
- **Thin main walls are needed for adequate T breeding**
  - Tritium Breeding Ratio (TBR) > 1 requires armor < 5 mm
  - Limited to low heat flux components, < 1 MW/m^2
- **Possible integration options:**
  - Shaped HHF walls (ITER) → Poor TBR
  - Large plasma-wall gaps (EU DEMO) → Poor economics
  - **Decouple plasma contact regions from breeding regions**

Proposal for a decoupled main wall in DIII-D



Discussion Topic #1: Capability Gaps

- Gaps in diagnostics: Major effort needed in coordination with any wall changeout
- Extrinsic impurity injection: Ensure sufficient radiation to reduce heat flux, maintain integrity of divertor
- Need for flexibility in future compatibility of wall change with staged divertor goals
  - Hold off on deciding what divertor design is used until Stage 1 and 2 research progresses
- What if we put in W and it gets damaged? Can we just replace the tile(s) and clean up the melted W? How much flexibility will we have to do that?
  - Key need to monitor ALL of the divertor to find hot spots / damage, make fast decisions
- Tritium retention – the key perceived downside to C – is a future issue; do we say "you can't run scenario X due to this future issue?"
  - Much of Europe/Asia facilities already made this decision, removed C
- Is the highest priority to reproduce DIII-D scenarios without a C intrinsic radiator?

Discussion Topic #1: Capability Gaps, con't

- **$T_{e,surface}$ and heat/particle fluxes are the key parameters of interest for the divertor/wall**
- **Need to make high quality measurements key; cannot assume toroidal symmetry**
  - More cameras would save time and effort in long term to identify local hot spots or damage
  - ITER's approach is along these lines, many cameras. Also need for in-vessel light source
- **Impact of not resolving the physics gaps: DIII-D the only working tokamak in U.S. NSTX could start earliest 2026. SPARC will be starting with all W in 2026, quite soon, and projected 150 MW with D-T by ~2028**
- **Divertor survival while attempting to continue to operate**
- **Key outcome to judge success to evaluate any damage to divertor and whether the divertor survives**
- **Heat flux below acceptable levels**
- **Sputtering issues**

Discussion Topic #2: Alignment

- **Care extrapolating behavior of coatings with monolithic material, since coatings can act unexpectedly (delamination, etc.)**
  - Considerable experience now with coatings of Mo/W on DIII-D metal rings tiles and SAS-VW tiles; a lot learned
- **Will community question results if some C remains in the plasma; some may be unforgiving about any C content**
  - C 'boogyman'… (now O similarly undesirable)
  - LPs are all graphite-tip, replacing would be huge effort for all metal; ok to leave as graphite?
  - Similarly for RCPs, SETCs, DiMES, MiMES, IR calibration heated tile
- **Private companies current focus is on W or LMs; SiC not at the forefront**
- **Compatibility of new material – particularly W – with high performance**
  - Some experience with W in SAS-VW and lower tile rings
  - Neutral reflections for fueling; high recycling environment with C and W
  - **Essential to integrate detachment with other scenarios: T_e < 10 eV, heat flux < 10 MW/m^2**
  - Tailor high-Z transport, screening with weak pedestal gradient

Discussion Topic #3: Approaches and Resources

- **'Hot' walls – at 300-600 – considerable advantage for recycling, lowering retention**
  - FPP will need to operate with hot walls for thermal efficiency
  - Neil Brooks performed conceptual study on hot walls on DIII-D ~15 years ago; doable to some temperature

- **Gyrotrons need low density, but W wall requires high density**

- **Prepare for risk of damage to wall/divertor, and also diagnostics**

- **Some scenarios may not be successful at integrating a detached/low heat flux divertor; decision must be made to risk damage, or not run during wall change**
  - **Consideration to 'go back' to graphite after changeout period**
  - **Encourage close cooperation/integration with div/sol**

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Key Advantages of DIII-D Over Other Metal Wall/Divertor Machines i.e., how does DIII-D stand out from ASDEX-U, EAST, and WEST

1. **Plasma shaping flexibility**
   - High to negative triangularity, strike point sweeping, long leg shaping
2. **Tile changeout with fast turnover**
   - Divertor/wall configuration and material changes, fast recovery from personnel vent
3. **Flipping toroidal field direction**
   - Enables studies and code validation of impact from E×B drifts to the divertor/edge
   - *Possibly compromised with tiles that include facets for heat flux control*
4. **Diagnostic set**
   - Strength in integrated/comprehensive diagnostic set and close coupling to model validation
   - *Possibly compromised with reflections/emissivity changes with metal walls; new diagnostics needed for full wall coverage, extend diagnostics to high-Z*
5. **High temperature baking (350°C) and cleaning/conditioning**
   - Enables low-O content, typically minimizes other impurities
   - *Possibly compromised with non-C wall choices, particularly conditioning with swept plasmas*
6. **Neutral beam flexibility: Balanced injection, off axis injection**
   - Not possible at ASDEX-U, EAST, WEST
7. **Mix of heating sources: NBI, ECH, LHCD, Helicon**

DIII-D Community Agreements

DIII-D New Wall Community Workshop Breakout Group Guidance

Topic #1

Capability Gaps (30 minutes)

Develop technical consensus regarding the capability gaps. Clearly describe the research gap(s) or shortcoming(s) within your topical area that the DIII-D Wall Change Out should address. This can include gaps in physics understanding, operational performance, and technological capability.

- *In the context of the DIII-D Wall Change Out Project, what should be the highest priority research goals and activities within the DIII-D program?*
- *What are the key physical parameters of interest and their relevance to the present project? If possible, provide a table that compares the current state to the desired state.*
- *What is the impact of not resolving the physics gaps implied by the research goals above?*
  - *How detrimental would lack of resolution be in terms of overall DOE-FES strategy?*
- *What are the targeted outcomes and quantitative metric that would confirm the activity was successful?*

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Topic #2

<u>**Alignment (30 minutes)**</u>

Evaluate the level of alignment between the DIII-D/DOE-FES missions and the research gap closures that could be achieved by different wall/divertor material change-out options.

- *How well do different material options align with the overall DIII-D research mission? (DIII-D Mission: "Identify and develop solutions to key remaining fusion science and technology challenges.")*
- *How well do different material options enable the DIII-D program to address science and technology gaps in the FES Long Range Plan and other recent community reports?*
  - *How can the wall change out best align with the overall DOE-FES strategy ("The Bold Decadal Vision") of building bridges between the public program and FPP developers?*
- *What is the priority of addressing these research gaps relative to other facility activities within DIII-D? Within the fusion ecosystem more broadly?*
  - *Discuss the ability of the DIII-D wall material change-outs to research gaps in the context of the capabilities of other domestic and international facilities.*

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Topic #3

<u>Approaches and Resources (30 minutes)</u>

Identify and describe the various alternatives/approaches to resolving capability gaps and the risk/reward spectrum. Include a “Do Nothing” alternative that would retain the existing C wall. Feel free to make assumptions regarding cost and scope using information available to you.

- *How do the material options compare in terms of functional, technical, operational, staffing, and financial constraints on the DIII-D facility?*
  - *Organize by first wall and divertor material options (tungsten, SiC, liquid metal, etc.)*
  - *Include a “Do Nothing” alternative that would retain the existing graphite wall.*
- *For each option, identify any notable limitations incurred on facility capabilities.*
- *What are the key technical risks incurred by each alternative?*
- *Consider trade-offs: How do additional costs and technical risks lead to the closure of research gaps, higher performance parameters, and/or access to additional parameter space?*

Operational an diagnostic considerations for a new wall

Adam McLean, LLNL

Presented to

DIII-D Community Wall-Changeout Forum

June 12, 2024

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Lawrence Livermore National Laboratory

Premise: Changing the wall will have massive implications for how we run DIII-D, and may have massive implications for diagnostics

- **We have been spoiled.**
  - Carbon provides a benign wall, and an intrinsic source of radiation, which radiates primarily in the edge and not in the hot core
- **And we have taken full advantage; many DIII-D scenarios include very low densities, and very hot divertors**
  - Without a graphite wall, the intrinsic radiation from C will need to be replaced
- **The current DIII-D diagnostic set is optimized for low-Z and low reflectivity; medium/high-Z and/or higher reflectivity will require new diagnostics and re-interpretation**
  - Major effort essential to maintain DIII-D as having the best diagnostic set in the world

Premise: Changing the wall will have massive implications for how we run DIII-D, and may have massive implications for diagnostics

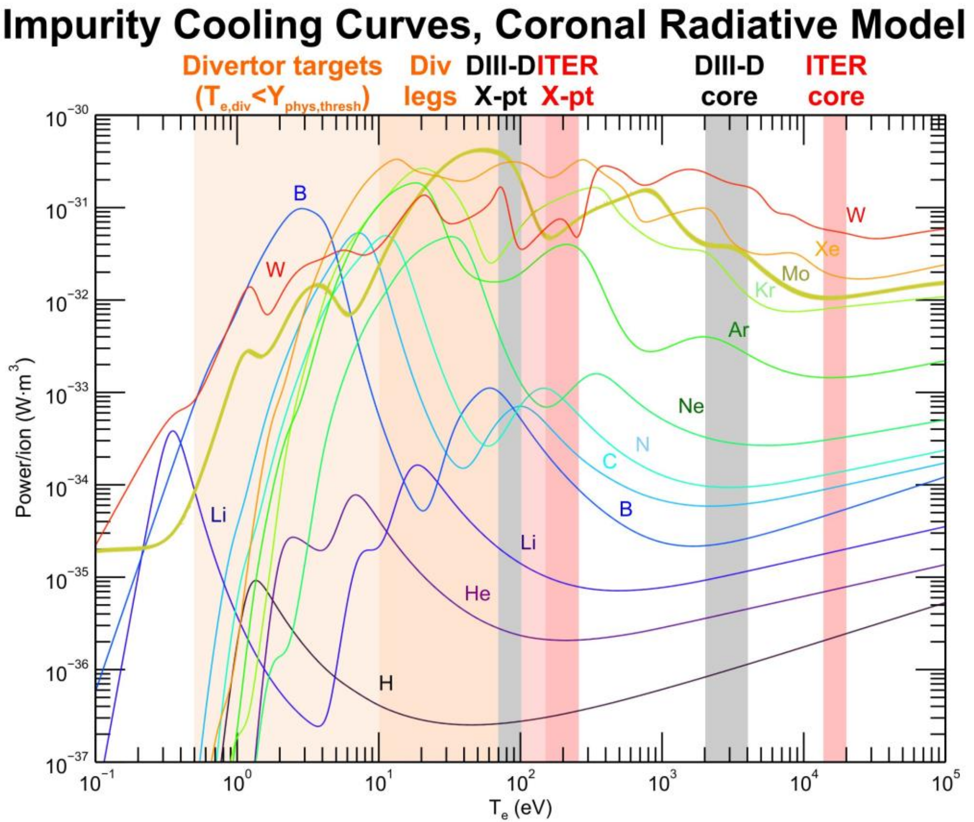
- **We have been spoiled.**
- **For 30 years, the DIII-D carbon wall has given us the gift of 'radiation'**
  - Power in (P_{NBI}+P_{ECH}+P_{RF}+P_{OH}+P_{fusion}) = power out (~1 to 20+ MW)
  - Power out → ions (heat flux, primarily divertor) and radiation (photons go all directions)
  - Graphite erodes 'intrinsically': D→C $Y_{physical}$~2%, $Y_{chemical}$~2% (↑ plasma flux, ↑ eroded flux)
  - In the divertor, C cools by radiation ~100-1000X more efficiently than D per atom
    - i.e., 1% C goes a long way…
- **Typically a DIII-D plasma will radiate 50-90% of the input power**
  - This keeps heat flux at a manageable level at the targets
    - ITER will need to be >90%, and FPP will need to be >95%
- **And typically >2/3 of the power is radiated by C (the rest by D)**
  - C primarily radiates in the plasma edge (~80% in the divertor), far from the hot plasma core
  - Increasing either D or C density in the plasma will lead to more radiation, and less heat flux
- **Reducing either D or C leads to higher heat fluxes; adding high-Z and removing C without replacing it with something else = melting**

A simple heat flux calculation shows the loss of intrinsic radiation may need to be supplemented with regular extrinsic impurity injection

- **Simplified case with graphite wall, intrinsic C:**
  - Input power = 10 MW
  - Radiated fraction = 75% (2.5 MW by D, **5.0 MW by C** → bathed uniformly over 40 m^2 → 7.5 / 40 = 0.2 MW/m^2)
  - Power to divertor surface = 2.5 MW (non-radiated fraction)
  - Target major radii = 1.1 and 1.3 m
  - Ring heat flux width = 2 cm
  - Target footprint area = 0.25 m^2
  - Average heat flux = 2.5 / 0.25 = **10 MW/m^2:** Result: Hot, but happy graphite
- ***But C radiation can't be fully replaced with W (or other high-Z) because high-Z radiates in the core, and a high self-sputtering yield for W → W***
- **Replace wall with metal, impose ~zero high-Z erosion, no extra radiator:**
  - ***10 MW * 75% * 2/3 = 5 MW radiated by C is lost***
  - Power to divertor surface = 2.5 MW + **5.0 MW** = 7.5 MW
  - Average heat flux = 7.5 / 0.25 = **30 MW/m^2**
    - Result: A lot of melted metal, no functional divertor, no chance of good plasma operation…
- **If the intrinsic radiator is removed, it needs to be replaced to control heat flux, W erosion**
  - Every shot may need to have ('extrinsic') N, Ne, Ar, Xe, Kr, or C etc. added/puffed ('seeded') to maintain P_{rad}/P_{inj} fraction or risk damaging/melting the divertor
  - ***Re-learning how to run every discharge, every scenario, conditioning, etc. will take time***

Cooling power varies widely depending on the species

- **Lightest atoms don't radiate well anywhere, however plasma can tolerate high concentration**
  - e.g., liquid Li wall requires a 'lot' of Li in the edge plasma
- **High-Z radiates power at high T_e**
  - **Reason that W conc must be <~E-4**
  - **Makes spatial measurements of concentration important**
- **Low/medium Z seemingly ideal**
  - **Radiates well in the legs, but not the core**
- **DIII-D vs. ITER conditions**
  - T_e at core and X-pt significantly different
  - **Divertor targets and legs, however, are necessarily similar**
    - **T_e<10 eV at the OSP to be <$Y_{phys,thresh,D \rightarrow imp}$**



P_{rad} [W/m³] = power/ion [Wm³] * n_e [/m³] * n_{imp} [/m³]

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The DIII-D diagnostic suite is well optimized for low-Z

- **Low-Z**
  - Dominant lines that radiate the majority of power are the EUV/VUV
    - Div SPRED and Core SPRED spectrometers
  - Low charge-state and CX lines for impurities in the visible
    - CER, TanTV, FASTCAM, CIS, FS, MDS
- **Low reflectivity**
  - Graphite reflectivity <10% allows direct interpretation
    - TanTV, Thomson, CER, IRTV, FIDA, MDS, FSs, CIS, WiSE, BES, MSE, Vbrem/Zeff
- **Ease of PFC material co-integration**
  - Graphite components ease design
    - Langmuir probes, RCPs, SETCs, DiMES, MiMES, IR calib. heated tile

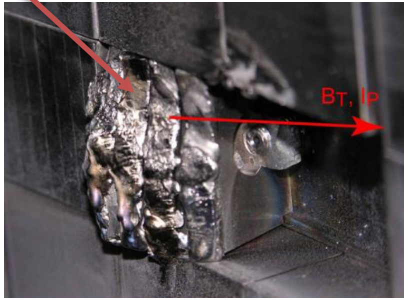
The DIII-D diagnostic suite is not as well optimized for high-Z

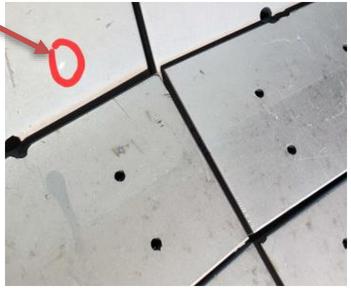
- **~~Low-Z~~ High-Z**
  - Dominant lines that radiate the majority of power are the ~~EUV/VUV~~ **SXR**
    - Div SPRED and Core SPRED spectrometers, **XEUS and more**
  - Low charge-state and CX lines for impurities in the ~~visible~~ **UV**
    - CER, TanTV, FASTCAM, CIS, FS, MDS **UV spectroscopy/imaging**
- **~~Low reflectivity~~ High reflectivity**
  - ~~Graphite reflectivity <10%~~ **Metal reflectivity can be >80%, vary widely**
    - TanTV, Thomson, CER, IRTV, FIDA, MDS, FSs, CIS, WiSE, BES, MSE, Vbrem/Zeff **all may need reinterpretation**
- **~~Ease of PFC material co-integration~~ Re-integration necessary**
  - Graphite components **may need to be remade with metals**
    - Langmuir probes, RCPs, SETCs, DiMES, MiMES, IR calib. heated tile

Engineering places extreme restrictions on high-Z tiles compared to graphite

- **Graphite is forgiving to imperfections in design, fabrication, and installation:**
  - 'Proud' edges in the shallow magnetic field erode to a smooth surface/transition
- **Not the case with metal:**
- **B. Lipschultz, et al., "Divertor tungsten tile melting and its effect on core plasma performance" NF 52 (2012) 123002** https://iopscience.iop.org/article/10.1088/0029-5515/52/12/123002/meta
  - "There is no evidence of healing of the surface with repeated melting. Forces on the melted tungsten tend to lead to prominences that extend further into the plasma."
- **~0.3 mm diameter W droplet/dust (0.3 mg) can radiate 10 MW of power in DIII-D**
  - ~0.16 mm diameter in C-Mod radiates 5 MW, 0.9 mm diameter in ITER radiates 150 MW
- **Last year we lost 400+ discharges due to small bits of cracked BaF_2 window**
- **This year, lost 100+ discharges due to small bits of stainless steel wire**

- **Physics reality: Factors of 2X, 10X often present**
  - E.g., Model grid density leads to 2X change in q||, 50% change in SXB applied, spectroscopy 'matches' within a factor of 2-5X, etc.
- **Engineering reality: Factors of 10-20% can be critical…**
  - E.g., 10 MW/m^2: surface survives. 12 MW/m^2: surface melts.





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Bonus slides

But switching to high-Z PFCs does not mean low-Z isn't required

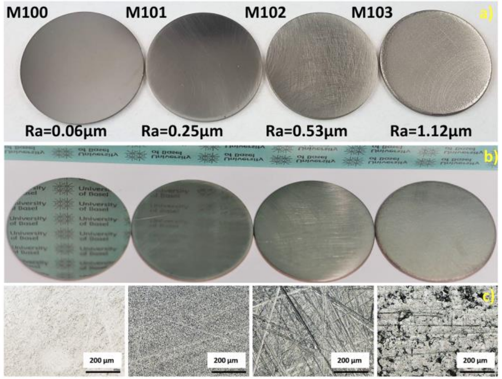
- **High-Z wall needs a low/medium Z radiator, and O-gettering**
  - ITER: W + Ne (or Ar/Ne), plus B as a O getter+for 'wall protection' from fast ions, hot spots
- **Extrinsic injection not just sometimes, but essential EVERY shot…**
  - C currently accounts for 50-75% of total radiated power in DIII-D
    - Primarily CIII and CIV resonance lines, majority of remainder is D^0 Lyman-a
  - Removing C means power transports unmitigated to the targets
  - W is not forgiving to high heat flux like: C erodes. **W melts.**
  - Eroded C smooths out, self correcting. **Melted W exposed to more heat flux will melt more**, only getting worse.
  - Tiny melted area can surpass allowable core contamination for high performance
  - Melted W will necessitate tile replacement, requiring a dirty vent
- ***Every reference shot will be different; necessitate relearning how to run with an extrinsic radiator***
  - *N radiatively similar to C, but gas puffing may not be the same as intrinsic erosion*
  - *Medium Z radiators – Kr, Ar – radiate near/in the pedestal, leading to stability challenges*

Tokamaks with high-Z

- C-Mod: All TZM-Moly (1993-2016)
- FTU: TZM-Moly inner limiter/SS outer wall (since 1996)
- ASDEX-U: All Tungsten (since 2007)
- JET: Tungsten divertor (2011-2023)
- WEST: All Tungsten (since 2016)
- T-10: All Tungsten (since 2017)
- LHD: Tungsten divertor (since 2017)
- EAST: All Tungsten (starting 2024)
- *SPARC: All Tungsten (starting 2025)*
- *ITER: All Tungsten (starting 2027-ish)*

Reflections make interpretation of any observed light a challenge

- **Pure/polished metals are shiny**
- **Reflectivity varies widely with surface condition**
  - Erosion, conditioning, deposition, co-deposits
  - Potentially extremely complicated both spatially and temporally…
- ***Potential impact to all UV/visible/IR diagnostics***
- **Dual-band/dual-color ratio-based measurements (e.g., for the IR) make result independent of emissivity, but not reflections**
- **Solution largely based on full vessel modeling of light sources, materials**
  - Ray tracing plus bidirectional reflectance distribution function (BRDF)
- WEST measurements, impact to imaging: M.B. Yaala, et al., RSI 92 (2021) 093501



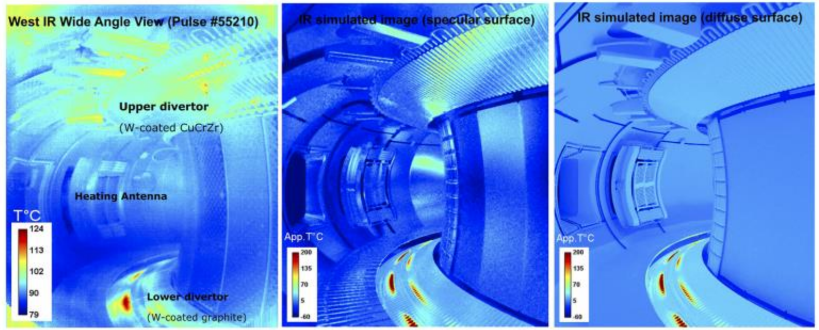


FIG. 11. (Left) Infrared experimental image of WEST wide angle tangential view [3300–3400 nm filter band], (middle) the simulated image assuming a high specular surface further to W sample measurement in the laboratory, and (right) the simulated image assuming all diffuse surfaces.

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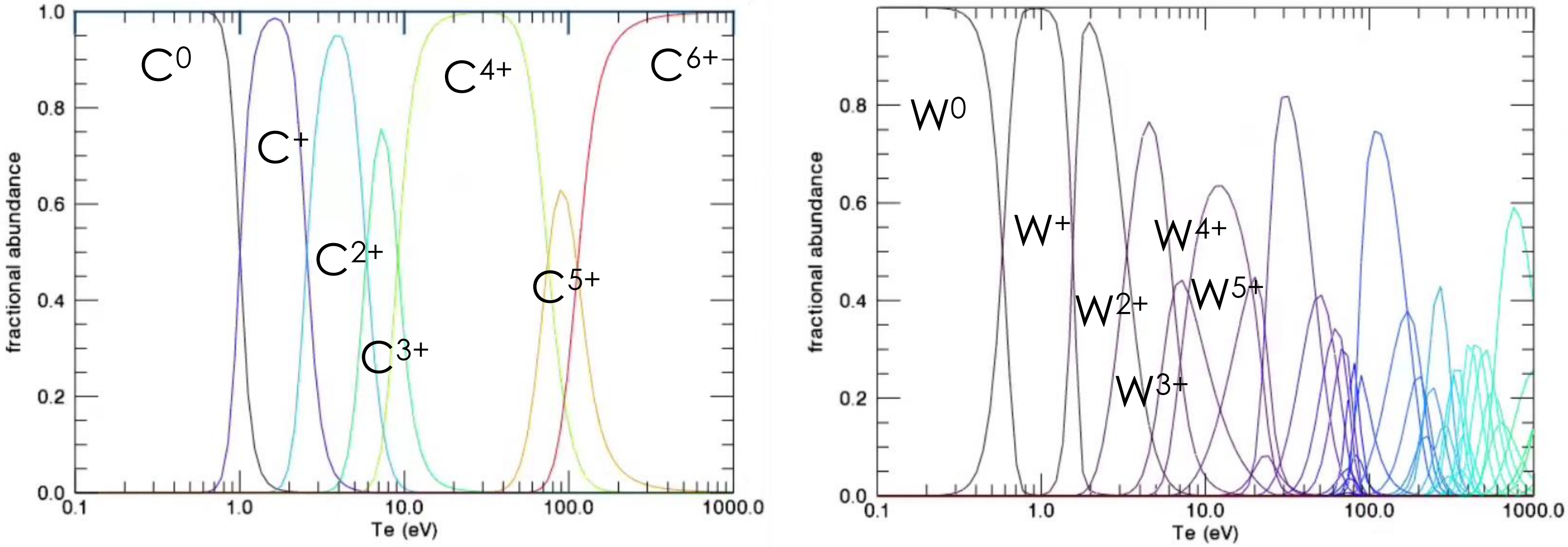
Higher Z means more charge states to track
Potentially good, but available spectroscopic data is limited

- **C neutral to +6 spans divertor conditions nicely**
  - Provides no separation at T_e>~200 eV
- **ASDEX/DIII-D (~5 keV) conditions span up to W^{+48}, ITER (15 keV) will span to W^{+72}**

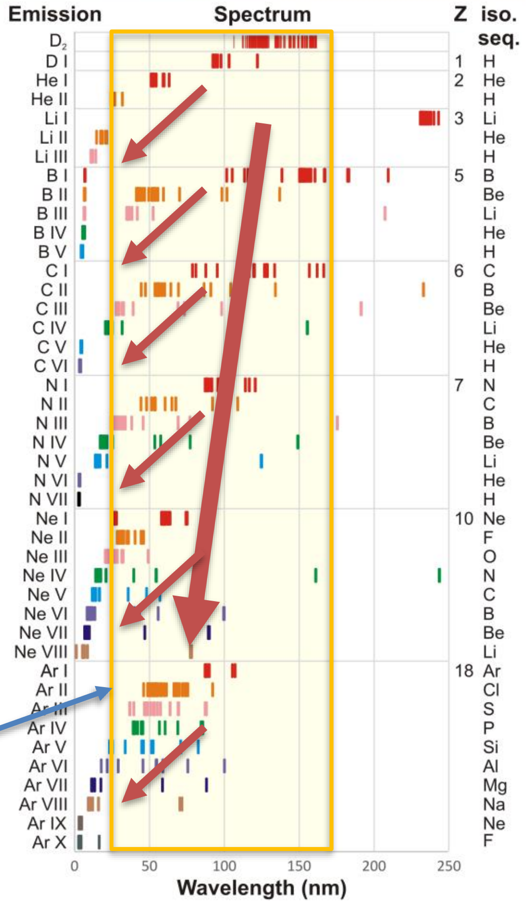
Fractional abundance plots



Heavier atoms, and their higher charge states generally radiate at shorter wavelengths – primarily vacuum

- **More energy between electron states → shorter wavelengths**
  - Wavelengths <~200 nm absorbed by air molecules
- **Observable emissions for each charge state give a valuable piece of validation information in the chain of ionization**
  - More data points give more comparables to codes
  - Less data points leave gaps in the chain…
- **DivSPRED: Monitors +1, +2, +3, +4 for C and N simultaneously**
- **For W, however, charge states span EUV, SXR, HXR requiring multiple spectrometers**

Resonance emission lines



Observable with DivSPRED (yellow)

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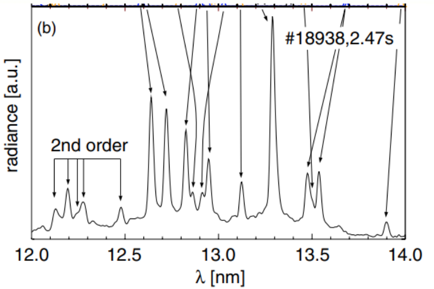
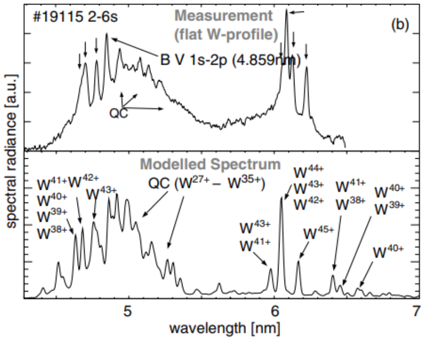
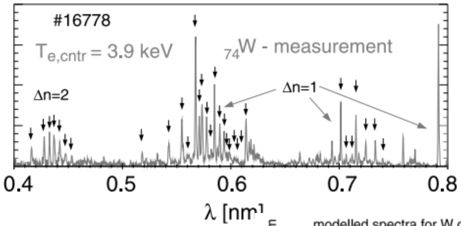
Tungsten spectroscopy: Observed emissions

- 10-30 nm: Quasi-continuum
- 12-14 nm: W^{40+} to W^{45+}
- ~8 nm: W^{57+} to W^{70+}
- ~5 nm: W^{21+} to W^{38+}, quasi-continuum
- 1.8-3.5 nm: W^{24+} to W^{30+}
- 0.4-0.8 nm: W^{39+} to W^{49+}
- 0.1-0.15: W^{50+} to W^{68+}







- *Interpretation heavily dependent on fractional abundance of each ionization stage, plasma conditions and gradients*
- Pütterich, et al., PPCF 50 (2008) 085016

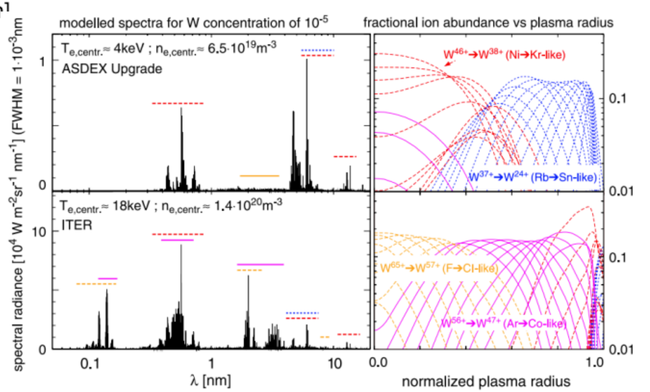


Figure 15. Modelling results and predictions for a typical ASDEX Upgrade plasma and the standard

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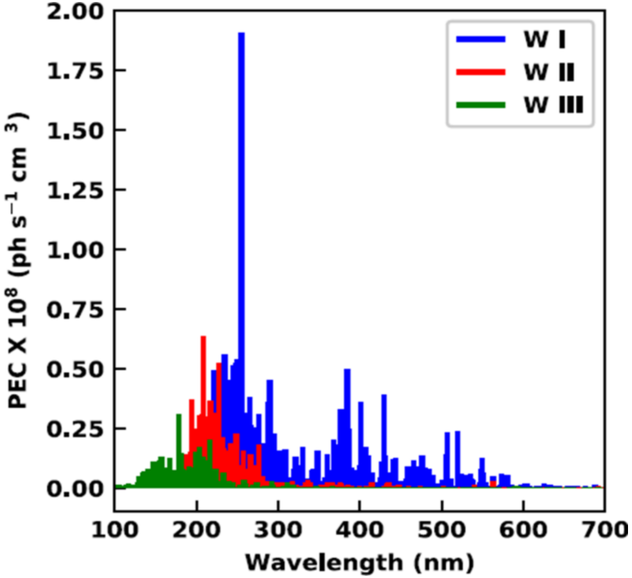
DSI

Lower-charge state W emissions also exist, but some are short lived and (relatively) dim

- **W I,II,III theoretical spectrum from Ennis, Lock, Losada**



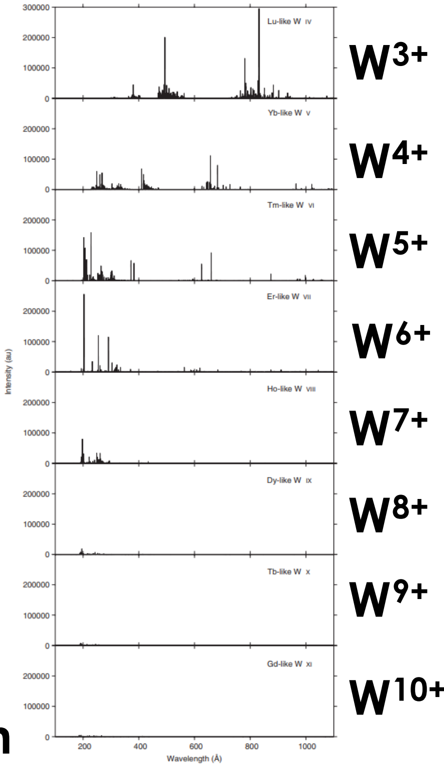
IOP Publishing
Journal of Physics B: Atomic, Molecular and
J. Phys. B: At. Mol. Opt. Phys. 43 (2010) 144009 (8pp)
doi:10.1088/0953-4075

Tungsten spectroscopy relevant to the diagnostics of ITER divertor plasmas

J Clementson[1], P Beiersdorfer, E W Magee, H S McLean and R D Wood

Challenges with resolution + integration time, plus other impurities in the background

J. Phys. B: At. Mol. Opt. Phys. 43 (2010) 144009

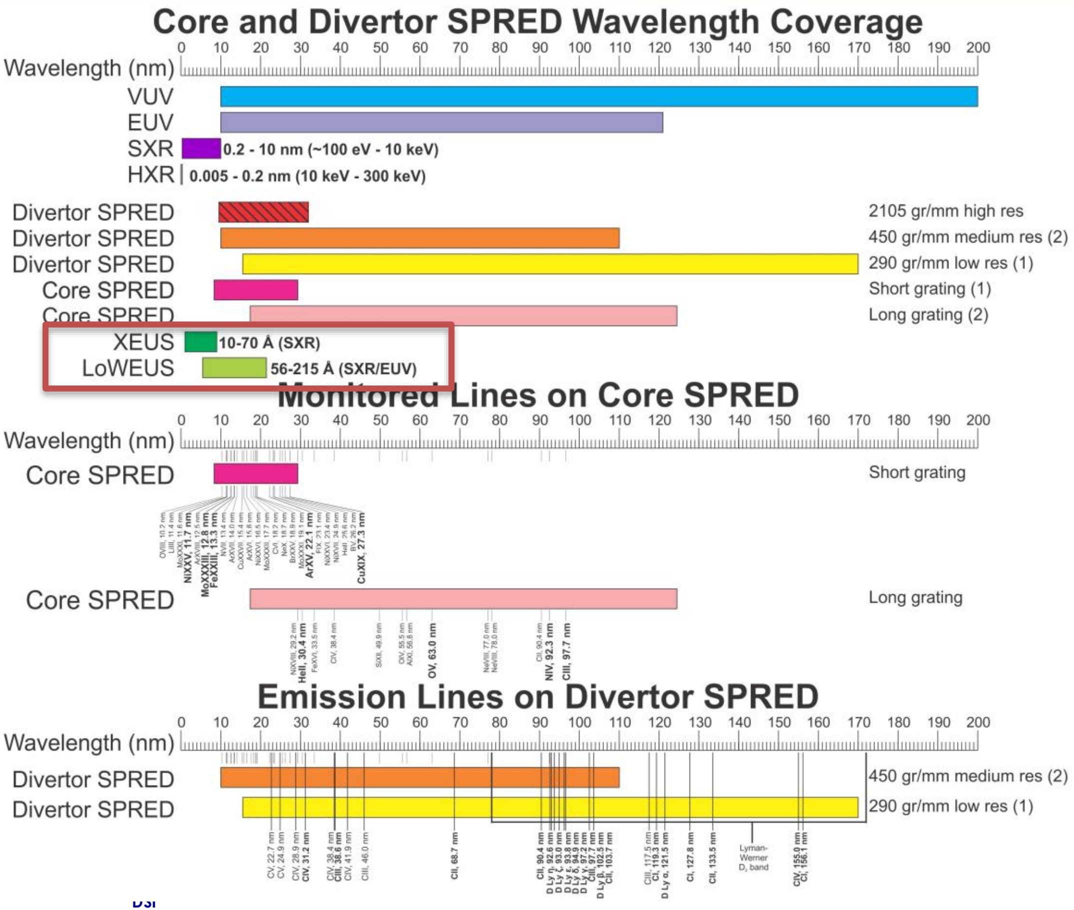


Range of 20-100 nm

Figure 1. Calculated tungsten spectra at $T_e = 100$ eV and $n_e = 10^{14}$ cm^{-3}. The intensity scale is set to the same value for each charge state in order to provide a direct comparison of the expected line intensities.

Current EUV coverage by SPRED spectrometers Prior installation of SXR coverage for W rings expt. in 2017

- **EUV coverage optimized for medium-Z metals**
  - Ni, Cr, Fe (Inconel, stainless)
- **XEUS and LoWEUS SXR spectrometers installed temporarily (on loan from LLNL)**
- **Require shield boxes for use with high NBI**
  - Weight and volume
- **Midplane port is ideal for interpretation and installation**
  - Very limited availability



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Question of how much C is okay?

- Langmuir probes, RCPs, SETCs, DiMES, MiMES, IR calib. heated tile all currently have some exposed graphite
- **How much C in the plasma is 'too' much…**

- **Early expts with W targets/divertor in ASDEX had 90% of the strike zone surface**
- Tungsten coated tiles, manufactured by plasma spray on graphite, were mounted in the divertor of the ASDEX Upgrade tokamak and cover almost 90% of the surface facing the plasma in the strike zone. Over 500 plasma discharges, among which around 300 were heated with heating powers up to 10 MW, were performed Under normal discharge conditions W-concentrations of around 10^{-5} or even lower were found. The influence on the main plasma parameters was negligible. In a few low power discharges accumulation of tungsten occurred and the temperature profile was flattened. **The concentrations of the intrinsic impurities carbon and oxygen are comparable to the discharges with graphite divertor**. Furthermore, the density-limits and the β-limits remained unchanged and no negative influence on the energy confinement as well as on the H-mode threshold was found.

R. Neu, et al., JNM 241-243 (1997) 678

Scientific output in the duration while we 'catch up' to ASDEX and other machines

- Diagnostics critical to inform interpretation
- Match and go beyond what has been done elsewhere

Notes: After Tyler's talk

- Charge to move fully away from graphite; is some accepted; proxy material could make sense – input from DOE, PMI R&D program
- Few tiles worth of C; okay?
- Proxy for W radiation addresses core confinement issues
- Wall geometry that looks reactor relevant; conformal wall not relevant; need toroidal limiter, open/closed divertor for more reactor-like geometry
- Idea of proxy not black and white; needs considered by each subfield, compromise
- TRL demonstration; requirement
- Upper/lower divertors to be abandoned? No, maintain both is the hope/plan
- We are known for physics knowledge; how much gets lost with wall change
- W has issues; blistering, neutron damage
- FPP in 10-20 years; existing technology. LM not ready, but maybe 2-3rd generation of FPP
- SiC interesting but not serious for FPP

Notes: After Shawn's talk

- Retention in SiC; support for use in main wall. SiC retention actually higher in the bulk, but codeposition is the main worry.
- Hot walls: Clement Wong; reactor thermodynamics requires reactor to operate at 700degC or thereabouts
- SiC is semiconductor – not a conductor; could affect electric fields, edge transport
- C or SiC still has retention problem; so what point. Hot walls should solve.
- Why was SiC not pursued back in the 1990s? Asdex decided on B as it made more sense at the time. Silane poisonous and explosive
- SiC on wetted areas vs. recessed areas where thermal/CX neutrals dominant – does it make sense, or have metal there?
- Why SiC vs C – surface chemistry, hydrocarbon physics different
- O baking, ammonia scavenging techniques
- Low-Z is essential for any vacuum – surface chemistry doesn't go away
- Hot walls – can DIII-D do that? Neil Brooks report
- SiC form an amorphous layer, or mostly Si or C? Impact on sputtering yields. Walls mostly covered in C, but leave Si-rich areas. Does that impact sputtering yield?
- Upgrades to allow retention measurements at higher temps – doe not receptive?
- Tritium removal – may not need to remove thermally or chemically. In JET, T codeposits self segregated; migrated to water-cooled louvers, then exfoliated; contained all of the T – could have used catcher troughs. Migration of codeposits – thermomechanical instability with ceramics (may be the key), may not be the same with metals. Exfoliation leads to dusts – but didn't in JET DT1. Not known if SiC or B would act the same.
- Temps to release Tritium might not be so high. Temps quoted are lower than most relevant – the near surface layer is the hotest

Notes: After Adam’s talk

- Impact of reflections is less for visible/UV compared to IR
- Increased coverage of cameras needed to ensure we can identify hot spots

Chat comments during the talks:

- 13:07:21 From Adam McLean to Everyone:
- https://fusionga.sharepoint.com/:x:/r/sites/FPPResearch/_layouts/15/Doc.aspx?sourcedoc=%7B0B085558-4685-4870-911F-D822E9A33032%7D&file=List%20of%20mailing%20lists.xlsx&fromShare=true&action=default&mobileredirect=true
- 13:25:33 From Steve Allen to Everyone:
- My one string fiddle. These curves are all coronal and don't include and transport effects which will flatten them at higher temperatures
- 13:30:33 From jboedo to Everyone:
- Is the weight of a full W or Mo armor sustainable with existing structure?
- 13:35:32 From Max Fenstermacher to Everyone:
- Weight all depends on the thickness we're talking about?
- 13:43:28 From Zeke Unterberg to Everyone:
- Not according to the plot Tyler showed from J. Brooks. Mo vs W had different properties vs background plasma conditions
- 13:43:53 From Ane Lasa to Everyone:
- But the conditions won't be the same at DIII-D and a reactor
- 13:44:57 From Zeke Unterberg to Everyone:
- This is always the case for anything on PWI w/r/t DIII-D vs FPPs
- 13:45:00 From Adam McLean to Everyone:
- I would clarify that the conditions at the targets/legs will be necessarily similar (i.e., Te<~10 eV for Yphys), but not the core
- 13:55:53 From Huiqian Wang to Everyone:
- Thanks Tyler! We will continue the discussion in tomorrow's core-edge meeting.
- 13:57:33 From Tyler Abrams to Everyone:
- Replying to "Is the weight of a f..." From what I hear, probably not with the existing tile design, but it might work if we go to thinner tiles + copper pedestals. Or some bulk tiles and some coated graphite tiles
- 14:00:08 From Tyler Abrams to Everyone:
- Replying to "I would clarify that..." Yes this is the major tension of a "reactor-relevant wall" from a core-edge integration perspective
- 14:08:21 From Adam McLean to Everyone:
- Don't tell Dan that we don't have a Li Beam system... 😐

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Chat comments during the talks:

- 14:17:24 From Jonathan Yu to Everyone:
- Maybe a brittle basket?
- 14:18:17 From Zeke Unterberg to Everyone:
- Or a melting basket. ;)
- 14:29:44 From Adam McLean to Everyone:
- Neil Brooks led a study on DIII-D with hot walls back about 10ish years ago - I think he concluded it was doable to some level - perhaps 300 degC?
- 14:31:28 From Zeke Unterberg to Everyone:
- 300degC was a non-starter for graphite b/c retention goes up (e.g. JET runs/ran walls at 200-250degC and showed more retention). It's not clear if that's the same story with SiC?
- 14:33:01 From Adam McLean to Everyone:
- Reacted to "300degC was a non-st..." with 👍
- 14:34:17 From Matthew Parsons to Everyone:
- Perhaps the new management at DOE would be more open to PMI studies like this
- 14:35:17 From Zeke Unterberg to Everyone:
- Very nice talk Shawn! Got to go.
- 14:38:51 From Greg Sinclair to Everyone:
- Reacted to "Perhaps the new mana..." with 🙌

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ITER first wall to all-W

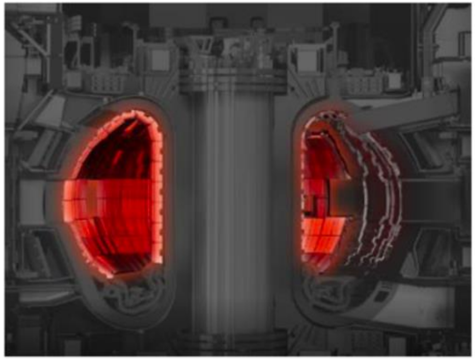
Reconsideration of Armour Material: Rationale

1. The choice of Be as Blanket First Wall (FW) plasma facing material for ITER is reconsidered in view of the updated understanding of its implications on the armour bridging during plasma off normal conditions, T retention, dust production, health and safety, assembly, manufacturing issues, radwaste, remote handling, gas baking, etc.

2. The recent push of the First Plasma date, associated with the fixed end date of the ITER Agreement, reduces the operation time. This new fact limits the possibility of a later full replacement of the Blanket FW with a high-Z wall to allow ITER to perform DEMO-like high-Q operation, which would require a machine shutdown of at least 2-3 years, but realistically, much longer. This implies building a DEMO reactor without having ever tried a high-Z wall in a tokamak with reactor-scale/self-heated DT plasmas before.

3. On the other hand, the recent push of the First Plasma date and the later installation date of the FW panels opens the new possibility to develop, qualify and procure a FW with non-Be armour (*this was precluded in the present baseline Schedule*).

4. Finally, the recently proposed introduction of an "Augmented First Plasma" campaign (as envisaged in Scenario B) would allow a learning phase on how to operate the ITER machine, thus better preparing the ground for a later installation of the FW panels with a non-Be armour.



M. Merola, all staff meeting, 31May 2023

Boronization

- Boronization (by Glow Discharge, with B_t off) of the plasma chamber has the main objective of gettering impurities (typically oxygen). In fact, W is not an oxygen getter, while boron is. It also limits W material from entering the plasma from wetted plasma facing areas, which is a secondary benefit.
- Oxygen getter effect decays in time due to boron erosion → boronization to be repeated (up to each 2 weeks)
- Starting operation without boronization in a W machine is possible but challenging (WEST, AUG, C-Mod, etc.). Hence, the use of boronization is the reference choice.
- Boronization is routinely used on fusion machines; however, it has not been done:
    - On such a scale as at ITER
    - In a tritium machine
- This also implies the introduction of a new system in a machine already largely designed and under construction.
- Based on ASDEX Upgrade experience there is now the expectation that the ITER cryopumps can be used for boronization.
- Boron retains hydrogen isotopes and can potentially (if applied frequently) lead to large T retention in DT-1 (100's g) → fuel removal scheme is required.
- Most effective way to remove trapped fuel is Ion Cyclotron Wall Conditioning (ICWC) → demonstration in A-FP

M. Merola, all staff meeting, 31May 2023

DIII-D wall material discussion, thinking about the future…

- **From Richard on 11/30, indication from DOE that a wall change is desirable**
- **SiC, W, other options (and combinations) on the table**
  - Also W alloys, Mo, V, liquid metals (Li, Sn, Ga)
  - By 'wall', assuming that means all PFCs; wall and divertors, though not necessarily the same material in the wall and divertor
- ***Change not (necessarily) permanent; option to return to C afterwards***
- **Deployable within ~2 years for the full wall (~3200 tiles)**
- ***Potentially enormous implications for both the experimental program and diagnostics***

- ***'Learning' how to run with (cope with…), diagnose, and interpret a new wall highlights DSI capabilities and strengths***

Adam's thoughts follow… a 'work in progress' only, very open to more ideas/suggestions/data

For the DIII-D mission to date, graphite is the perfect PFC material

- **Pros**
  - Erosion of C under attached conditions lessens power load to the wall; negative feedback
  - Carbon radiates extremely well at divertor conditions; controls power loading
  - Low Z impurity; high plasma tolerance
  - Low reflectivity / high emissivity; interpretability
  - Spectral emissions common in the VUV/UV/visible regions; diagnostic characterization
  - 'Self corrects' misalignments/proud regions to the plasma; forgiving to installation/design
  - High thermal conductivity
  - Ease of machinability
  - Commonly available in large quantities, low cost

Graphite makes a wall whose response to challenging target/wall conditions is largely benign and self-limiting, allowing for exploration of a broad range of core scenarios in the DIII-D program

For the DIII-D mission to date, graphite is the perfect PFC material
But in a FPP, graphite may be a challenge

- **Pros**
  - Erosion of C under attached conditions lessens power load to the wall; negative feedback
  - Carbon radiates extremely well at divertor conditions; controls power loading
  - Low Z impurity; high plasma tolerance
  - Low reflectivity / high emissivity; interpretability
  - Spectral emissions common in the VUV/UV/visible regions; diagnostic characterization
  - 'Self corrects' misalignments/proud regions to the plasma; forgiving to installation/design
  - High thermal conductivity
  - Ease of machinability
  - Commonly available in large quantities, low cost

- **Cons**
  - Tritium codeposition (Oxygen baking may be a solution…)
  - Neutron damage leads to loss in thermal conductivity (annealing at high temp may be a solution…)

Approach taken by ITER and many of the European/Asian machines is to solve the 'cons' with W

- **Pros**
  - Erosion of C under attached conditions lessens power load to the wall; negative feedback
  - Carbon radiates extremely well at divertor conditions; controls power loading
  - Low Z impurity; high plasma tolerance
  - Low reflectivity / high emissivity; interpretability
  - Spectral emissions common in the VUV/UV/visible regions; diagnostic characterization
  - 'Self corrects' misalignments/proud regions to the plasma; forgiving to installation/design
  - High thermal conductivity
  - Ease of machinability
  - Commonly available in large quantities, low cost

- **Cons**
  - ✓ ~~Tritium codeposition (Oxygen baking may be a solution…)~~ Though still some T trapping…
  - ✓ ~~Neutron damage leads to loss in thermal conductivity (annealing at high temp may be a solution…)~~ Even W may not survive FPP conditions…

Approach taken by ITER and many of the European/Asian machines is to solve the 'cons' with W, but it also brings other challenges to solve...

- **Pros**
  - X ~~Erosion of C under attached conditions lessens power load to the wall; negative feedback~~
  - X ~~Carbon radiates extremely well at divertor conditions; controls power loading~~
  - X ~~Low Z impurity; high plasma tolerance~~
  - X ~~Low reflectivity / high emissivity; interpretability~~
  - X ~~Spectral emissions common in the VUV/UV/visible regions; diagnostic characterization~~
  - X ~~'Self corrects' misalignments/proud regions to the plasma; forgiving to installation/design~~
  - High thermal conductivity
  - Ease of machinability
  - Commonly available in large quantities, low cost

- **Cons**
  - ✓ ~~Tritium codeposition (Oxygen baking may be a solution…)~~ Though still some T trapping…
  - ✓ ~~Neutron damage leads to loss in thermal conductivity (annealing at high temp may be a solution…)~~ Even W may not survive FPP conditions…

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Approach taken by ITER and many of the European/Asian machines is to solve the 'cons' with W, but it also brings other challenges…

- **Challenges to re-solve with W…**
  - ~~Erosion of C under attached conditions lessens power load to the wall; negative feedback~~
    - W requires constant control of target conditions to limit erosion, transport, re-erosion
  - ~~Carbon radiates extremely well at divertor conditions; controls power loading~~
    - W requires extrinsic impurity injection to radiate power in the divertor
  - ~~Low Z impurity; high plasma tolerance~~
    - Severe limits on core contamination before confinement is affected
  - ~~Low reflectivity / high emissivity; interpretability~~
    - Accounting for reflections will be critical for all optical diagnostics
  - ~~Spectral emissions common in the VUV/UV/visible regions; diagnostic characterization~~
    - Expansion of spectroscopic capabilities critical
  - ~~'Self corrects' misalignments/proud regions to the plasma; forgiving to installation/design~~
    - Installation tolerances are critical, need for expanded spatial coverage to find hot-spots

These all have solutions, but they require
a) new/expanded diagnostics, b) great care with design/installation
c) learning to run plasmas by experience/trial-and-error
d) and may potentially limit experimental scenarios that can run

Silicon Carbide offers a low/medium-Z option, likely less impact

- **Previously tested in localized areas, but not in a full machine**
- **Indications of reduce sputtering, both chemical and physical**
  - Less C in the plasma (however, that means less radiation with extrinsic injection)
- **Benefit of low/medium-Z; more tolerable to the plasma**
- **Relatively less impactful to existing diagnostics**
  - Emissivity / reflectivity comparable to graphite
  - Existing coverage of C and potentially Si spectroscopically
- **But sputtering, and thus T codeposition in a DT device is not ~nil (as it could be with all W + Ar/Ne/Xe Nobel gas radiators)**
  - Question of 'relevance' to future devices from community perspective

Notes from discussion on PFC changeout in DIII-D, 1/2

- **C vs SiC; customer for material choice**
  - Deployed as full wall material
  - Some Si erosion; Si as O getter
- **DOE request – move away from graphite; broad latitude otherwise**
- **Working group, public discussions**
- **All-W will duplicate effort from ASDEX, EAST, WEST**
- **Main wall as SiC; minimal Ychem**
- **SiC not a good electrical conductor? Impact to currents, drifts**
- **Tolerance for T inventory with codeposition**
- **C to W transition in European machines, W decision on SPARC**
- **Types of SiC; poly types/crystal structures to explore**
- **Purpose of wall changeout also to look at impact to plasma; match radiation in an FPP**

Notes from discussion on PFC changeout in DIII-D, 2/2

- Murphy – main wall, is Inconel sufficient?
- High-Z in the target; lower Z elsewhere
- DIII-D with Inconel walls – impurity influx, C helped
- What is the goal? Move away from C – why? FPP relevance or something else? For scenario development – disruptions, etc.
- What physics can we do without a lot more W spectroscopy? Diagnostic cost is major for W
- Outer wall not conforming
- PAC and 5YP reviews; continuous feedback of not having C
- How much of program will need to be cut with W?
- Scenarios might scale differently; QH mode pedestal conditions/collisionality with low Te targets

Zoom chats ‘To everyone’ during the discussion

- 14:12:52 From Christopher Holcomb To Everyone:
- Adam, thanks for the really nice review & summary of issues.
- 14:21:33 From Mathias Groth To Everyone:
- Rudi Neu would also be a suitable person. And/or Guy Matthews.
- 14:21:58 From Tyler Abrams To Everyone:
- I also disagree that the Europeans hold back their opinions on low-Z 😅
- 14:22:20 From Aveek Kapat To Everyone:
- Reacted to "I also disagree that..." with 👍
- 14:23:17 From Tyler Abrams To Everyone:
- Replying to "I also disagree that..." Reminder that Thomas Putterich gave a seminar on the AUG experience with W several years ago- a good talk to review https://diii-d.gat.com/diii-d/EBP/Meetings
- 14:26:59 From Galen Burke To Everyone:
- Are there any discussions with regulators about tritium inventory in a FPP? DOE is not specifying some amount, that would come from NRC? Maybe this has already been settled and I am not aware of it.
- 14:28:50 From Mathias Groth To Everyone:
- With an Inconel main chamber wall, we likely have to deal with Ni in the core. Even an issue in JET with the recessed main chamber wall (and the Be limiters).
- 14:31:44 From Bob Wilcox To Everyone:
- There are also some people at ORNL looking into ultra-high temperature ceramics, that are lower-Z but have good thermal, sputtering and T retention properties. It’s a whole class of materials, and the PMI is not as well understood yet as W or SiC, but might be worth including some of those in the brainstorming discussion
- 14:32:43 From Dmitry Rudakov To Everyone:
- I don't think these ceramics are at a sufficient TRL to coat the whole wall
- 14:33:31 From Mathias Groth To Everyone:
- ASDEX Upgrade, I’d say. DTT in 2030s?
- 14:33:50 From Tyler Abrams To Everyone:
- Solid W in divertor, W-coated graphite on main wall
- 14:34:08 From Tyler Abrams To Everyone:
- Replying to "Solid W in divertor,..." For WEST and AUG I believe
- 14:34:40 From Anthony leonard To Everyone:
- Replying to "Solid W in divertor,..." Also including their wall conditioning with boronization