Energy Deposition and Melt Deformation on the ITER First Wall due to Disruptions and Vertical Displacement Events

Jonathan Coburn

M. Lehnen, R. A. Pitts, E. Thorén, K. Ibano, L. Kos, M. Brank, G. Simic, S. Ratynskaia , R. Khayrutdinov, V. Lukash, B. Stein-Lubrano, F. J. Artola, E. Matveeva, G. Pautasso

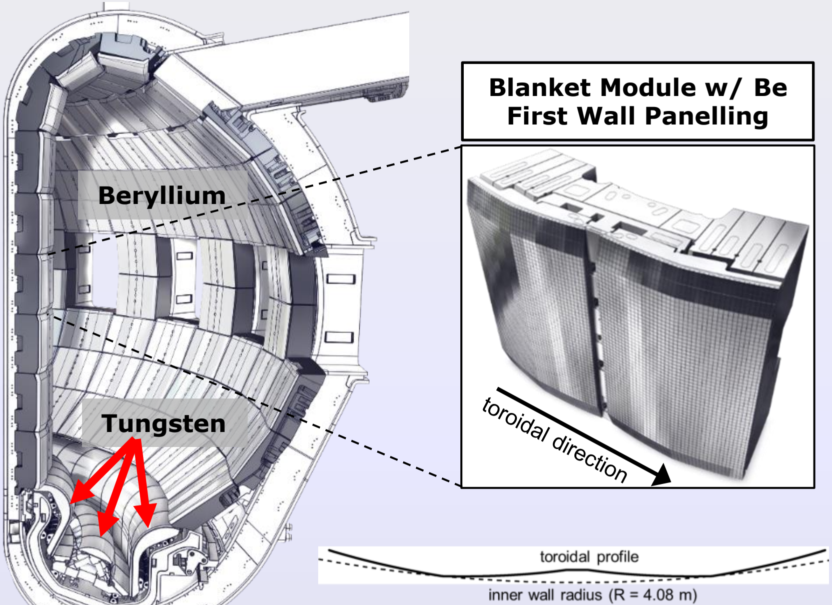
May 15th, 2021 – TH/7

Outline

- Motivation – Disruptions and VDEs on ITER
- Energy Deposition Analysis Workflow
  - DINA
  - SMITER
  - MEMOS-U
- Implications for ITER
- Final Statements

Motivation – Major Disruptions and VDEs on ITER

- The first wall (FW) is composed of 440 Blanket Modules, each with beryllium-armored panels
- Each FW panel is actively cooled
- Optimized shape for handling heat loads in specific locations
  - Inner-wall limiter startup
  - Steady-state operations
  - Ramp-down
  - **Transients/Disruptions**

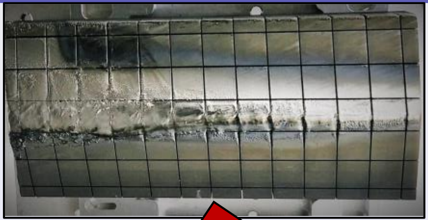


Motivation – Major Disruptions and VDEs on ITER

- Unmitigated major disruptions (MDs) and Vertical Displacement Events (VDEs) will generate large heat loads on ITER first wall (FW)
  - 100's of MJ of total energy deposition
  - 100's of ms

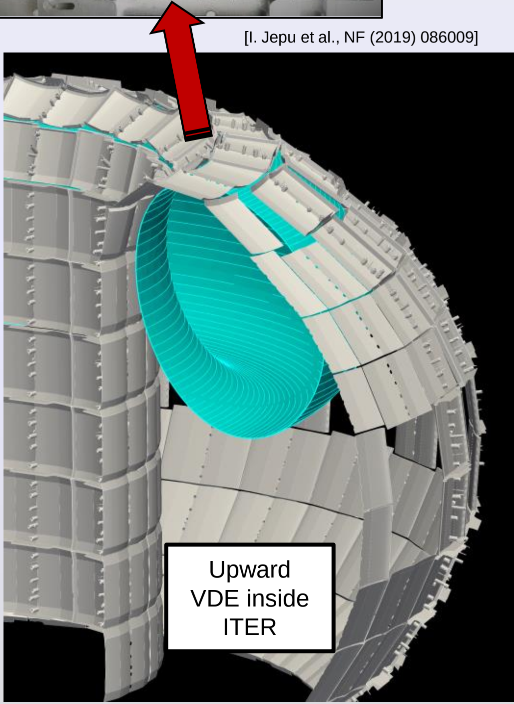
Need to avoid thermal damage to first wall components

When will MDs and VDEs pose a damage risk to ITER?



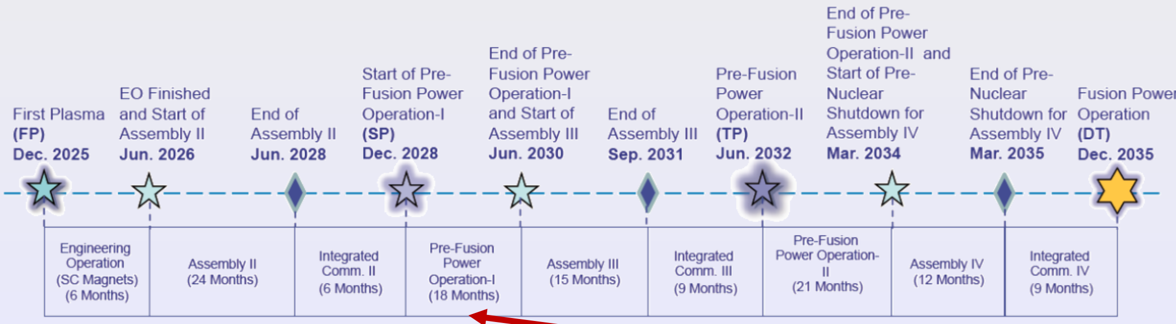
Be panel on JET after VDE

[I. Jepu et al., NF (2019) 086009]

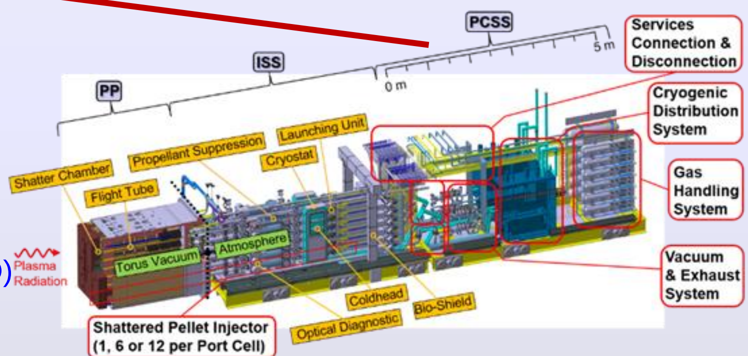


Upward VDE inside ITER

Motivation – Major Disruptions and VDEs on ITER



- The ITER staged approach will explore various q95 = 3 scenarios on the way to FPO
  - 1.8 T / 5 MA H-mode (PFPO-1)
  - 2.65 T / 7.5 MA H-mode (PFPO-1 & 2)
  - 5.3 T / 15 MA H-mode (PFPO-2 & FPO)
- Will build operation experience for both the plasma control system (PCS) and disruption mitigation system (DMS) during PFPO-1 & -2

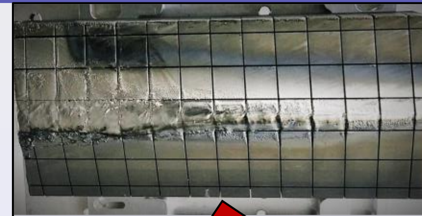


ITER DMS

See talks by T. Luce and S. Jachmich

Motivation – Major Disruptions and VDEs on ITER

- During FPO, the ITER DMS must mitigate all major disruptions and VDEs
  - VDEs are easily detected by PCS due to vertical motion
  - MDs are detected by I_p spike during thermal quench
    - Avoid melt damage during current quench



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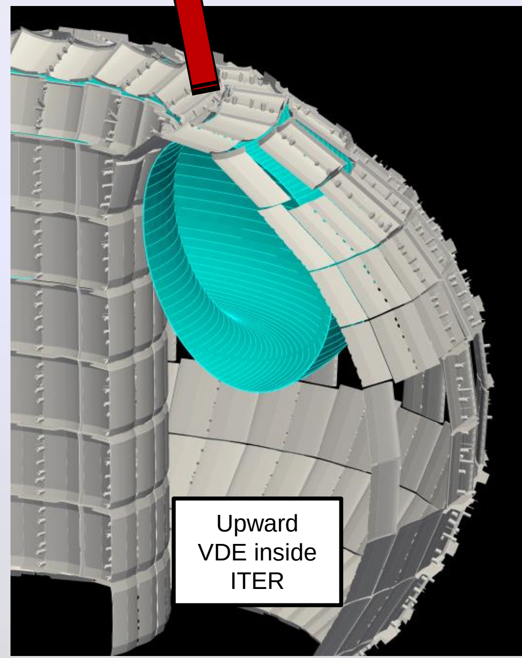


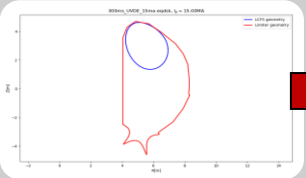
<u>Questions</u>

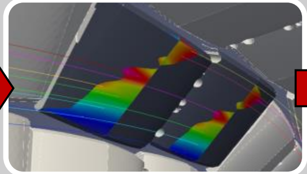
- What will be the operational limits and DMS allowance for PFPO-1 & 2?
  - How early must ITER avoid VDE/MD damage?
- What are the consequences of worst-case scenario?

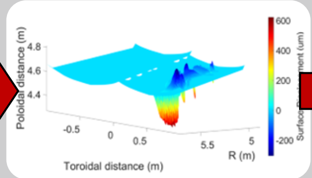
Goal: Estimate energy deposition and material damage for ITER disruption and VDE database

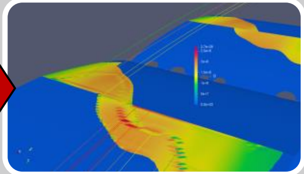
ENERGY DEPOSITION ANALYSIS WORKFLOW

Energy Deposition Analysis Workflow









DINA

- Time- dependent Plasma Equilibrium
- Various Disruption Scenarios

SMITER

- 3D Heat Flux Distribution on PFC Surfaces
  - B-field
  - Impact Angle
  - Surface Normal
- Single time-step

MEMOS-U

- Time-dependent melt formation and motion
  - Temperature
  - Melt thickness
  - Vapor Shielding
  - Surface Displacement

SMITER

- 3D Heat Flux Distribution on DAMAGED PFC Surfaces

MATLAB
Construct EQDSK input files for SMITER

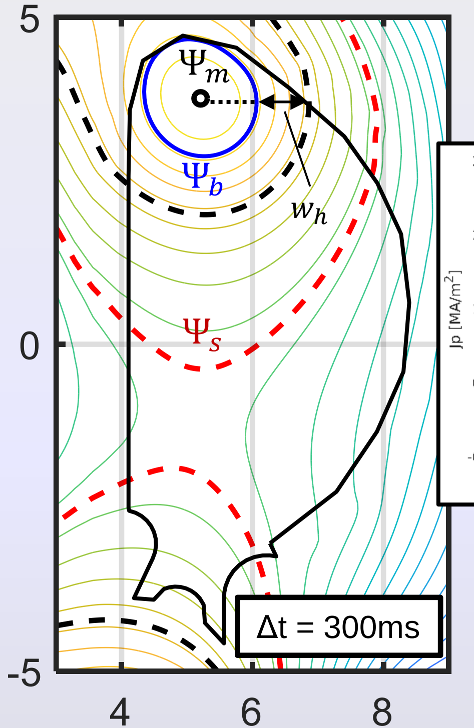
MATLAB/Python
Build single MEMOS-U input file from multiple SMITER output files

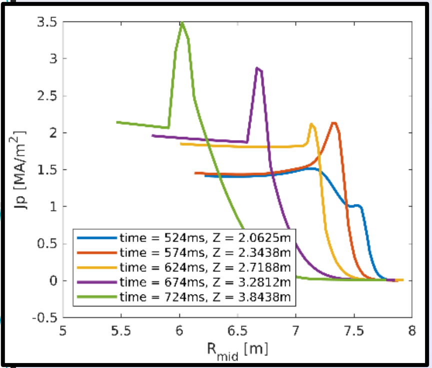
MATLAB/Python
Map MEMOS-U data back to SMITER geometry & build deformed mesh

Plasma Evolution: DINA

- The DINA code solves the time-dependent plasma transport and equilibrium for a given operation scenario
  - Conservation of toroidal magnetic flux
- Disruption/VDE modeling includes:
  - Thermal quench
  - **Current quench (CQ)**
    - **Halo current evolution**

Focus on energy deposition during CQ phase





Plasma Boundary - LCFS
Halo Current Boundary (95% Threshold)
Halo Computational Domain

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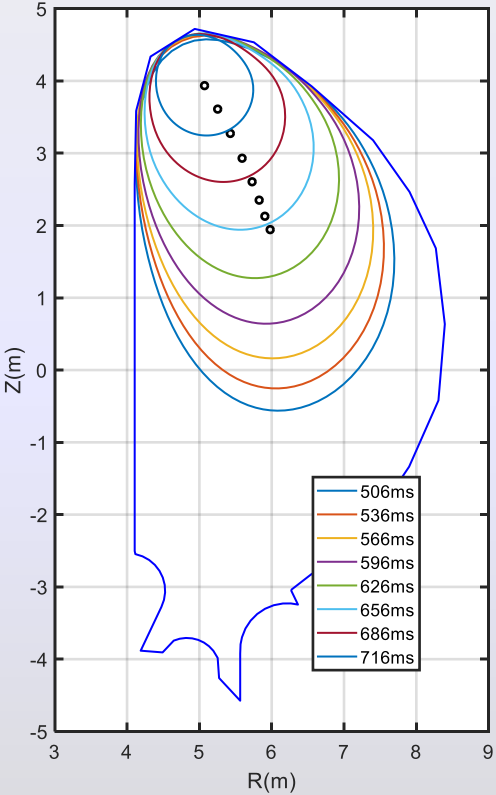
The ITER Disruption Database

Example 15MA Upward VDE



84 Total Cases

- Disruption Type
  - Major Disruption (w/ cold VDE) and Unmitigated VDE (hot)
- Variation in I_p
  - 5, 7.5, and 15 MA
- Disruption direction
- Be impurity density (constant)
  - 0, $1 \cdot 10^{19}$, and $3 \cdot 10^{19}\ m^{-3}$
- Variation in perpendicular diffusion coefficient χ
  - 1 and 4 m^2/s

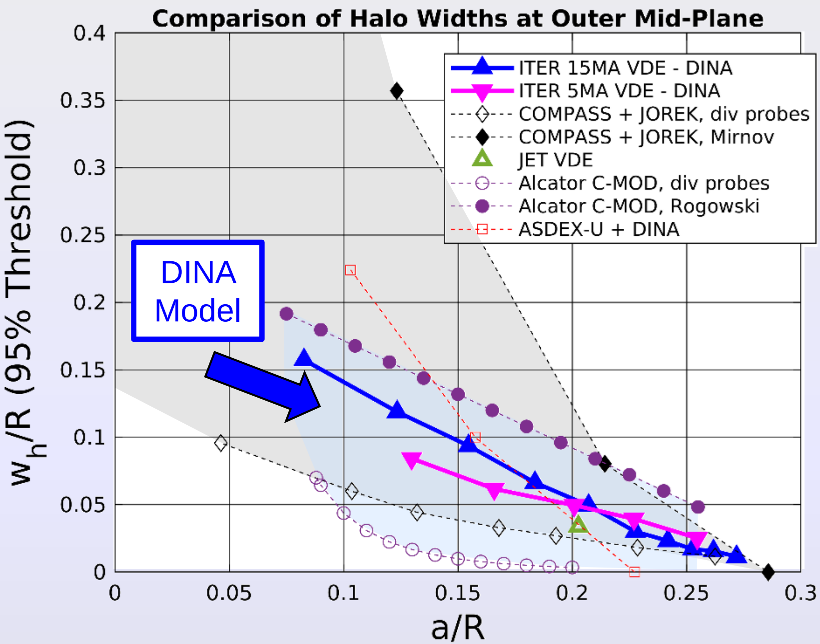
No Disruption Avoidance or Mitigation Methods are Simulated

No Peaking Factors to account for asymmetric VDEs/MDs

ITER Disruption Database – Experiment Comparison

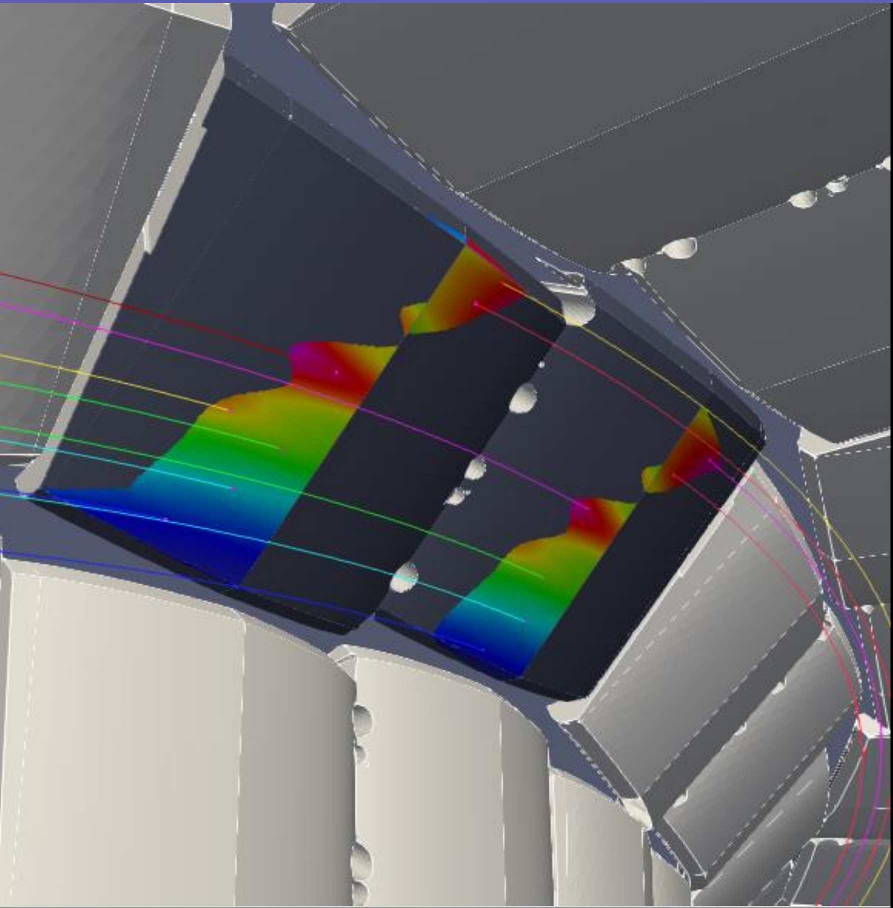
The halo width (w_h) in DINA falls within the wide range of experimental values

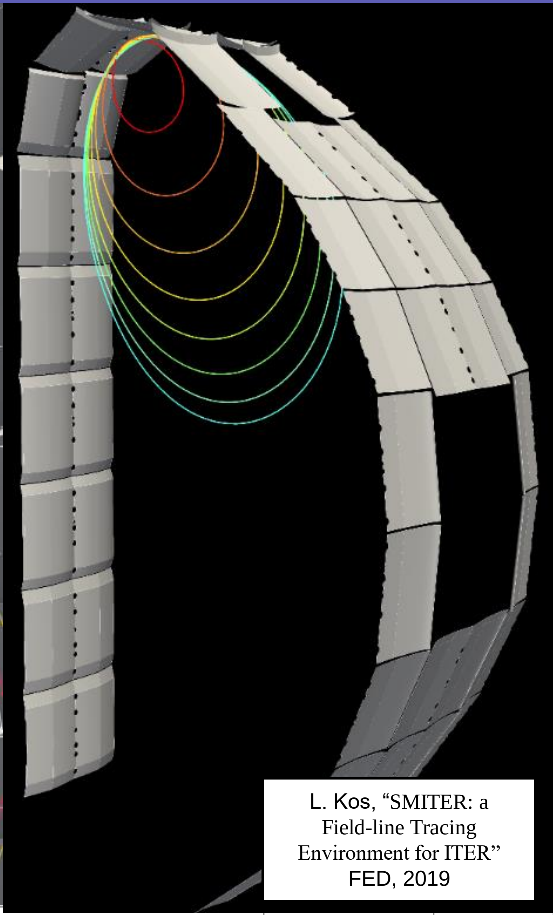
- Define w_h as a radial width (in meters) mapped to the outer mid-plane
- Comparison with **COMPASS**, **JET**, **Alcator C-Mod**, and **ASDEX-U**
- See NF manuscript for details



We encourage continued effort by the fusion community to cross-compare halo current data across tokamak devices using a common scaling and a fixed definition of halo width

Heat Flux Analysis: SMITER Field Line Tracing





L. Kos, "SMITER: a Field-line Tracing Environment for ITER" FED, 2019

Heat Flux Analysis: SMITER Field Line Tracing

- $q_{||}$ profile is specified at the mid-plane (usually the OMP) and mapped to limiter surface
- Field lines then traced back from the limiting FWP to compute magnetic wetted areas

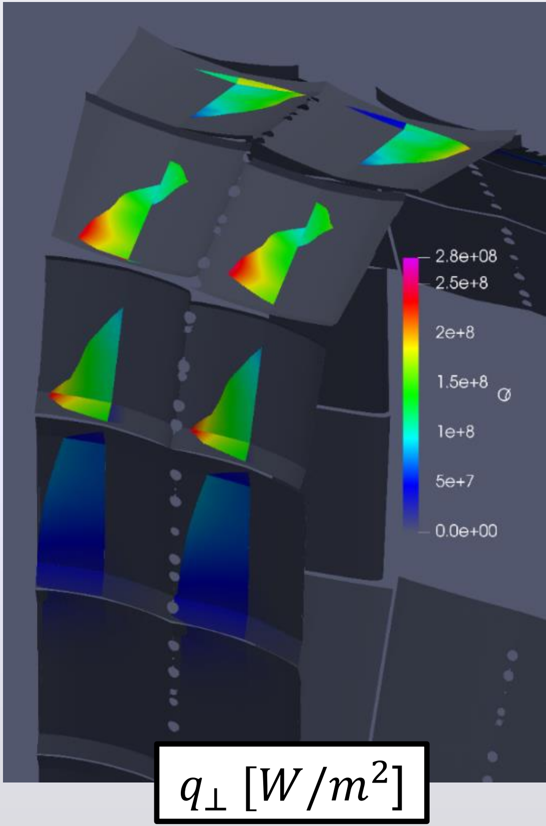
SOL heat flux profile is often assumed as an exponential profile:

Single Exponential Model

$$q_{\|}(r) = q_{\|omp} \exp\left(-\frac{r - r_{sep}}{\lambda_q}\right)$$

where $q_{\|omp}$ is the parallel heat flux at the OMP

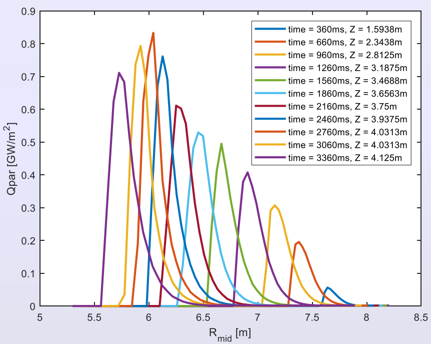
$$q_{\|omp} = \frac{P_{SOL}}{4\pi R_{omp}\lambda_q \left(\frac{B_\theta}{B_\phi}\right)_{omp}}$$



Heat Flux Analysis: SMITER Field Line Tracing

- $q_{||}$ profile is specified at the mid-plane (usually the OMP) and mapped to limiter surface

For this work, we extract the $q_{||}$ profiles from DINA output:



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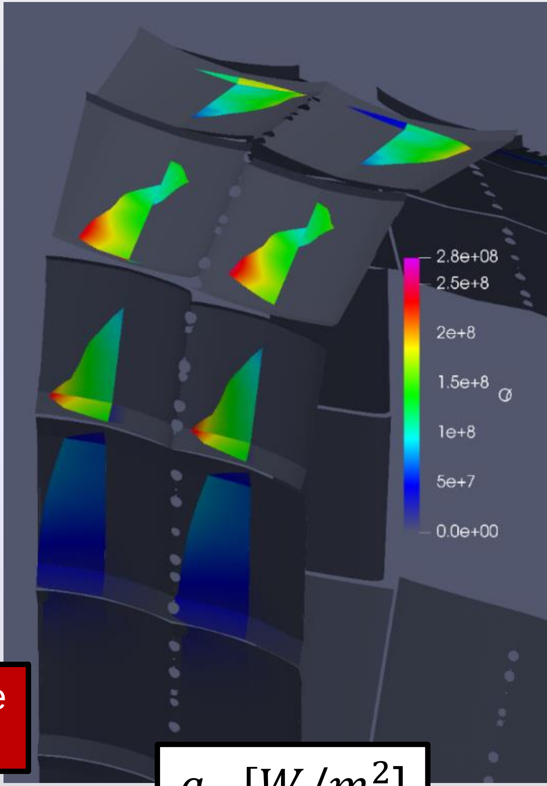
Scaling Factor

- 3D, non-uniform power deposition
- pitch angle

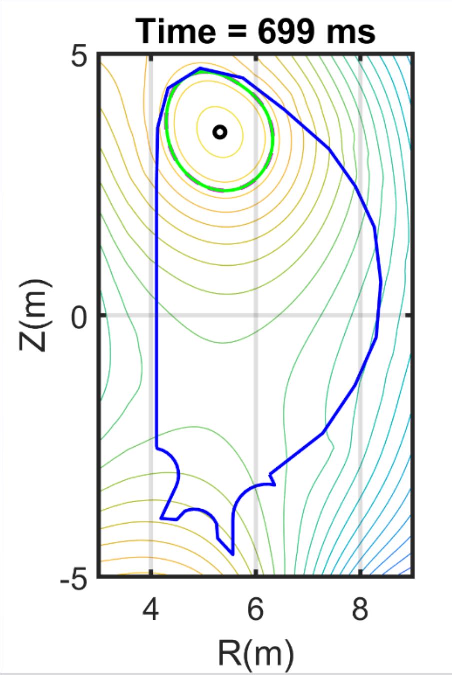
0-D Power Balance (DINA) = **3-D** Power Balance (SMITER)

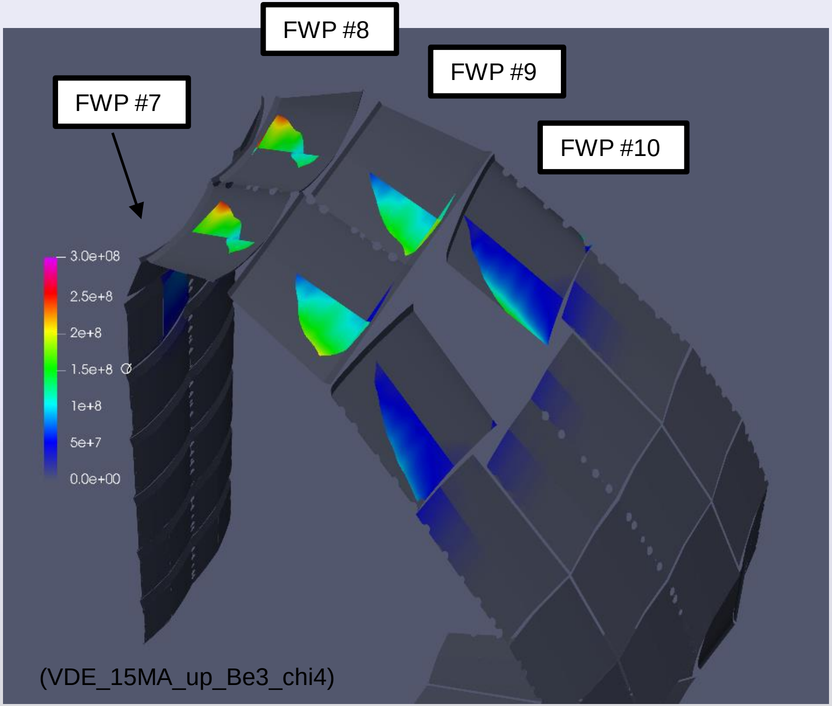


$q_{\perp}\ [W/m^2]$

Heat Flux Analysis: Upward VDEs/MDs

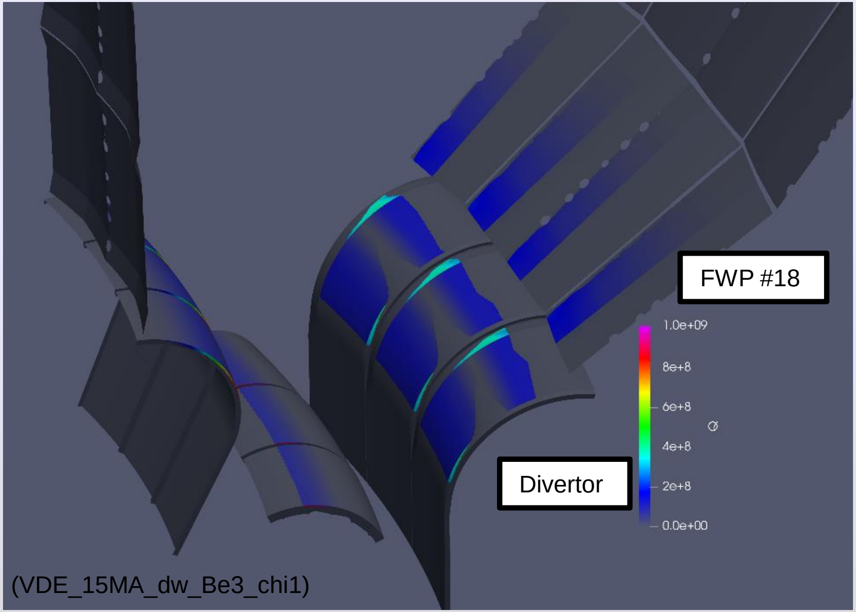
- Upward VDEs and disruptions deposit all CQ energy on the upper FW panels
- At Risk: FWP 7, FWP 8, FWP 9

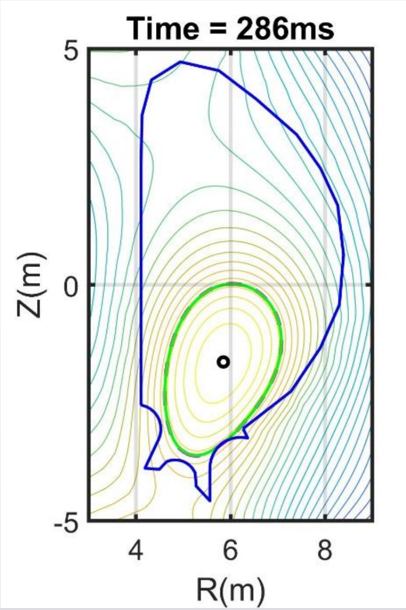




Heat Flux Analysis: Downward VDEs/MDs

- Downward VDEs and disruptions deposit energy on both the FW panels and the tungsten divertor
  - Power balance must account for energy deposition on divertor
- For Be FWPs, the downward VDEs are **<u>less extreme</u>** than corresponding upward VDE cases



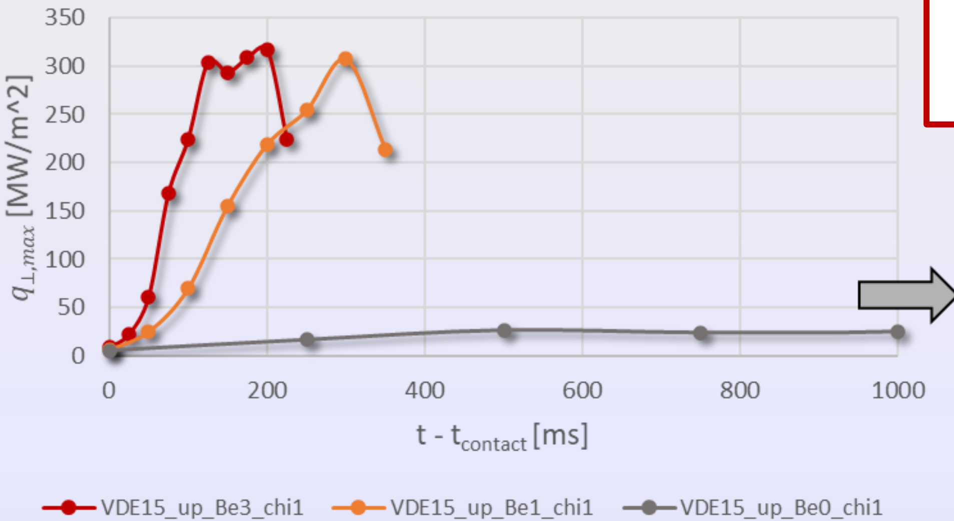


Heat Flux Analysis: Results

General Conclusions

- 37 of 84 DINA scenarios have been assessed in SMITER
- As B_t and I_p increase, so does VDE/MD duration and intensity
  - 5MA / 1.8T: **~80 MW/m²** **50 – 150 ms**
  - 7.5MA / 2.65T: **~130 MW/m²** **75 – 200 ms**
  - 15MA / 5.3T: **~320 MW/m²** **140 – 400 ms**
- MDs often show higher energy deposition area and longer duration than corresponding VDEs
- The value of chi had minimal impact on VDE dynamics & heat flux
  - Chi = 1 gives slightly higher $q_{\perp}$
- The assumed Be impurity density had a **strong effect** on the disruption dynamics
  - Time duration, $q_{\perp,max}$, and total power deposition
  - Higher Be impurity → shorter CQ → lower total E_{dep}, but higher $q_{\perp}$
    - More pronounced effect for MDs than VDEs (TQ happens before FW contact)
  - Which poses the greatest risk of melt damage? Depends on T_{surf}

Heat Flux Analysis: Results



$n_{Be} = 3 \cdot 10^{19}$
Δt = 250 ms
E_{dep} = **418 MJ**

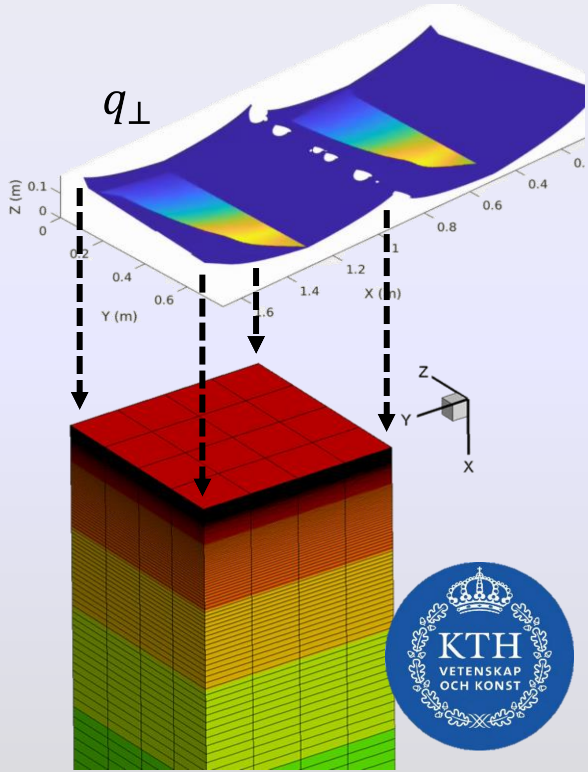
$n_{Be} = 1 \cdot 10^{19}$
Δt = 400 ms
E_{dep} = **593 MJ**

$n_{Be} = 0 \cdot 10^{19}$
Δt = 2750 ms (!)
E_{dep} = **943 MJ**

- The assumed Be impurity density had a **strong effect** on the disruption dynamics
  - Time duration, $q_{\perp,max}$, and total power deposition
  - Higher Be impurity → shorter CQ → lower total E_{dep}, but higher $q_\perp$
    - More pronounced effect for MDs than VDEs (TQ happens before FW contact)
  - Which poses the greatest risk of melt damage? Depends on T_{surf}

Melt Analysis: MEMOS-U

- 3D heat flux maps of $q_\perp$ from SMITER are used as input for the MEMOS-U
- Estimates extent, depth, and motion of any molten Be on the FWPs
  - 3-D heat equation
  - Navier Stokes equations w/ 2D shallow water approximation
    - Accounting for $\vec{J}\ x\ \vec{B}$ acceleration
- Additional input:
  - Thermophysical properties of solid and molten Be
  - Halo current density map across FWP target
  - Map of $\vec{B}$ intersecting the FWPs.

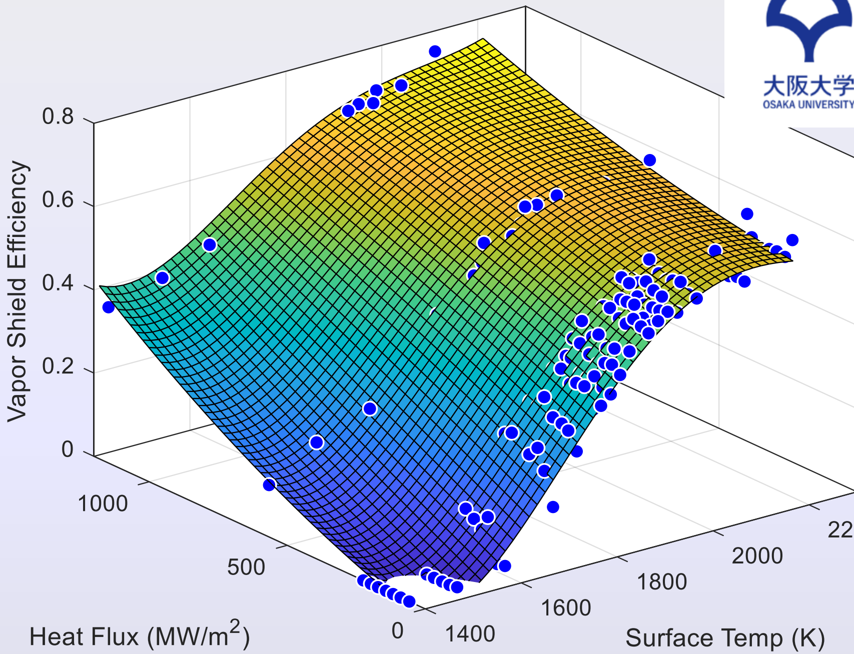


[E. Thoren et al, Plasma Phys. Control. Fus. 63 (2021) 035021]

[S. Ratynskaia et al, NF 60 (2020) 104001]

Melt Analysis: MEMOS-U with Vapor Shielding

- A vapor shielding dataset has now been supplied to MEMOS-U using PIXY PIC model
  - VS efficiency as a function of
    - Surface Temperature, T_{surf}
    - $q_\perp$
  - NOTE: depends on set values for $B_T, \rho_e/\rho_i$



$$\varepsilon_{vs}\left(T_{surf}, q_\perp\right) = \frac{q_{\perp,i} - q_{\perp,f}}{q_{\perp,i}}$$

ε_{vs} increases with increasing T_{surf}, and roughly increases with increasing $q_\perp$

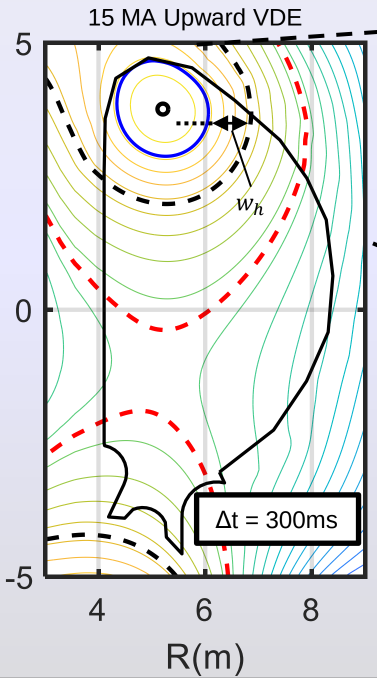
[K. Ibano et al, in preparation for Physics of Plasmas]

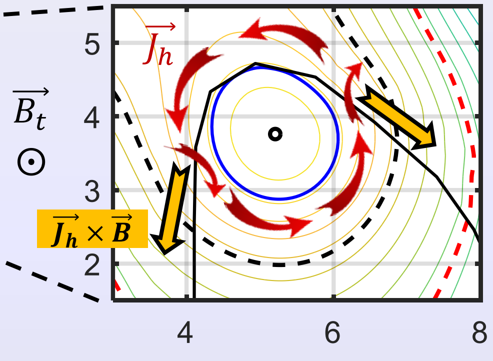
[K. Ibano et al, NF 59 (2019) 076001]

Melt Analysis: MEMOS-U Results

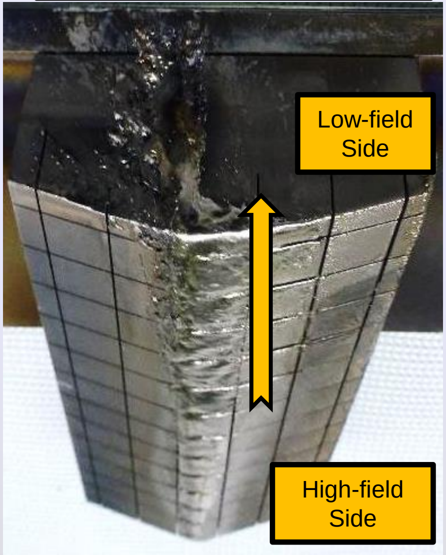
Beryllium FWP damage and melt motion are documented on JET ITER-like wall!

- MEMOS-U has been used to successfully model melt damage on JET upper-dump plate: [S. Ratynskaia et al, NF 60 (2020) 104001]





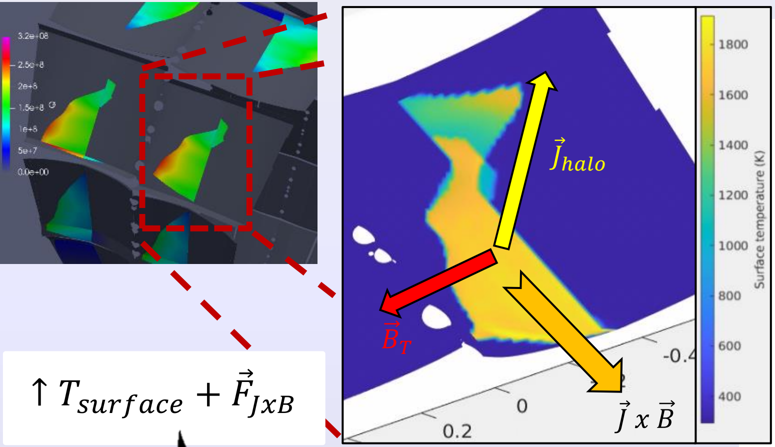
Melt dynamics for ITER match JET observations



[I. Jepu, 17th PFMC Conference]

Melt Analysis: MEMOS-U Results

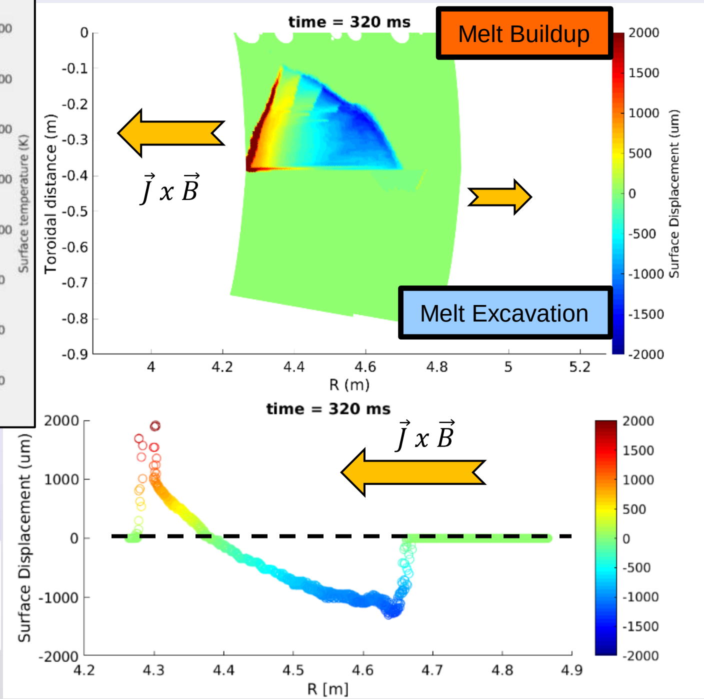
Variation in time duration and total deposited energy strongly influence melt occurrence and dynamics



$\uparrow T_{surface} + \vec{F}_{JxB}$

Melt Motion

Surface Excavation



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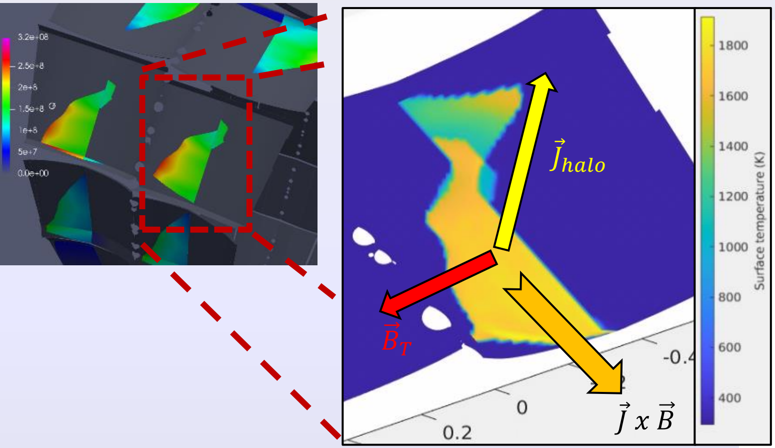
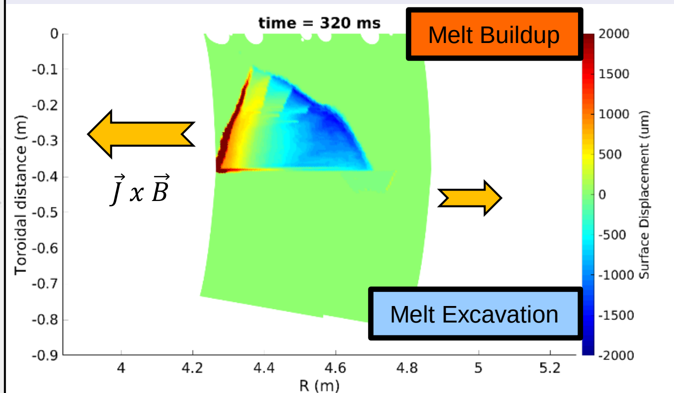
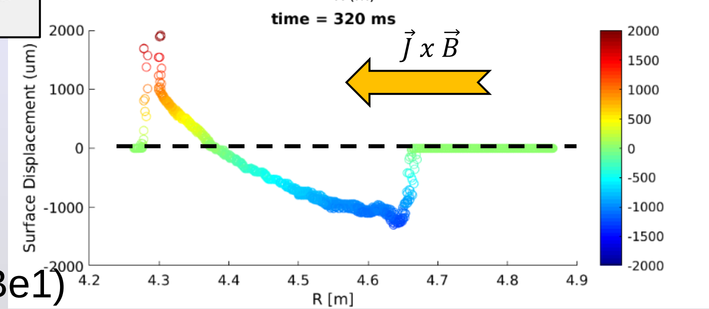
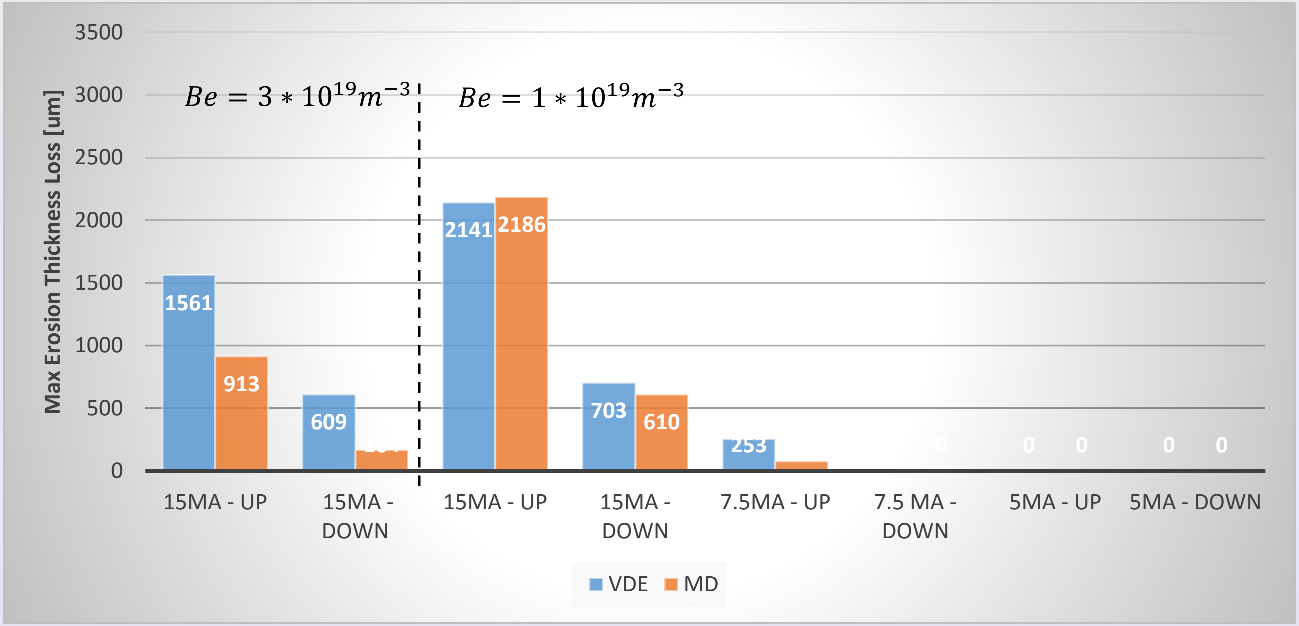






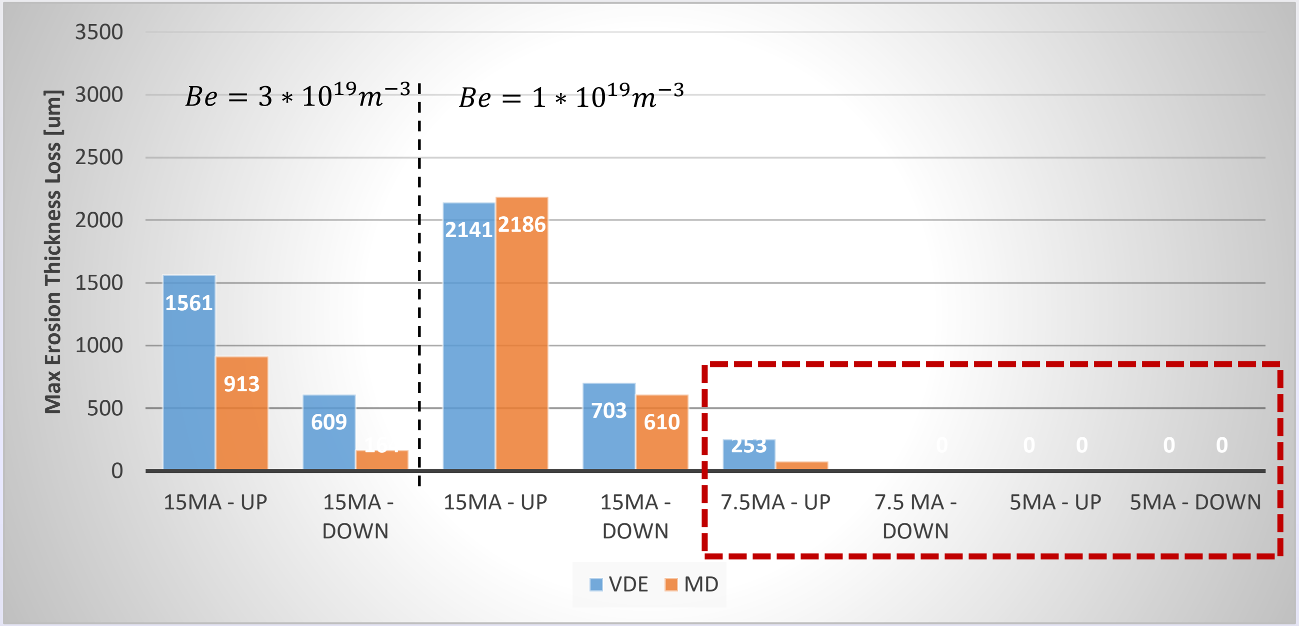
- 16 Scenarios Analyzed
  - Multiple FWPs
  - With/without Vapor shielding
- Focused on worst-case scenarios (Be1)

Melt Analysis: MEMOS-U Results w/ Vapor Shielding



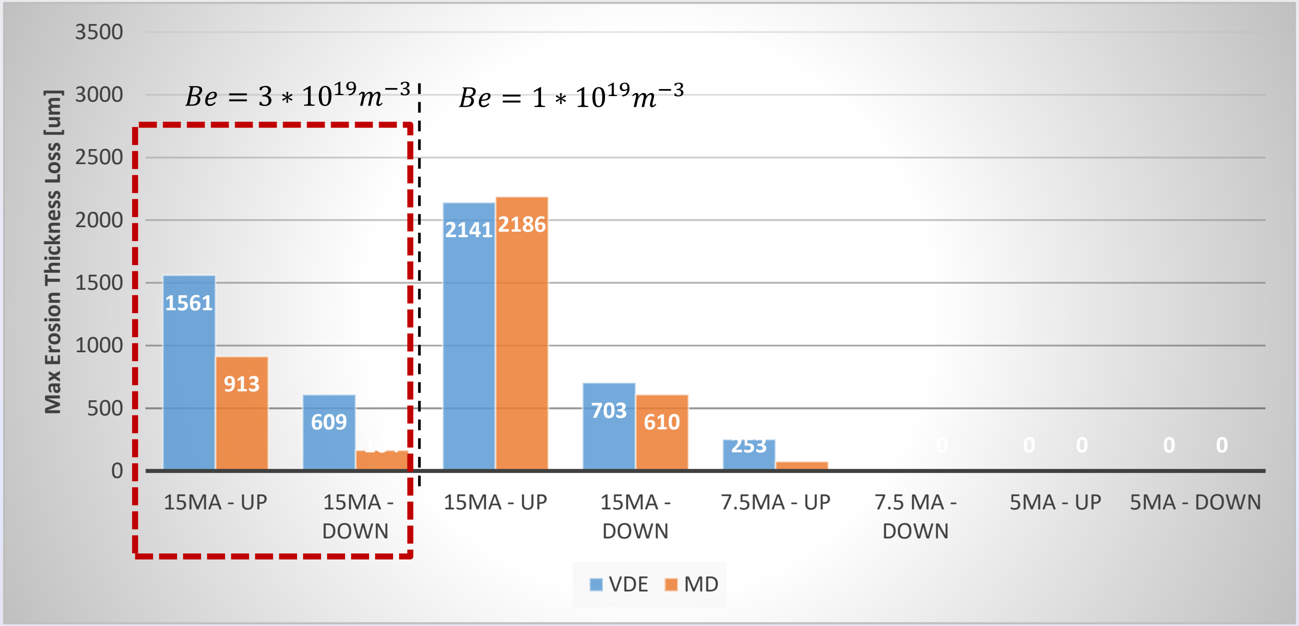
Metric for FWP damage → maximum depth of material loss

Melt Analysis: MEMOS-U Results w/ Vapor Shielding



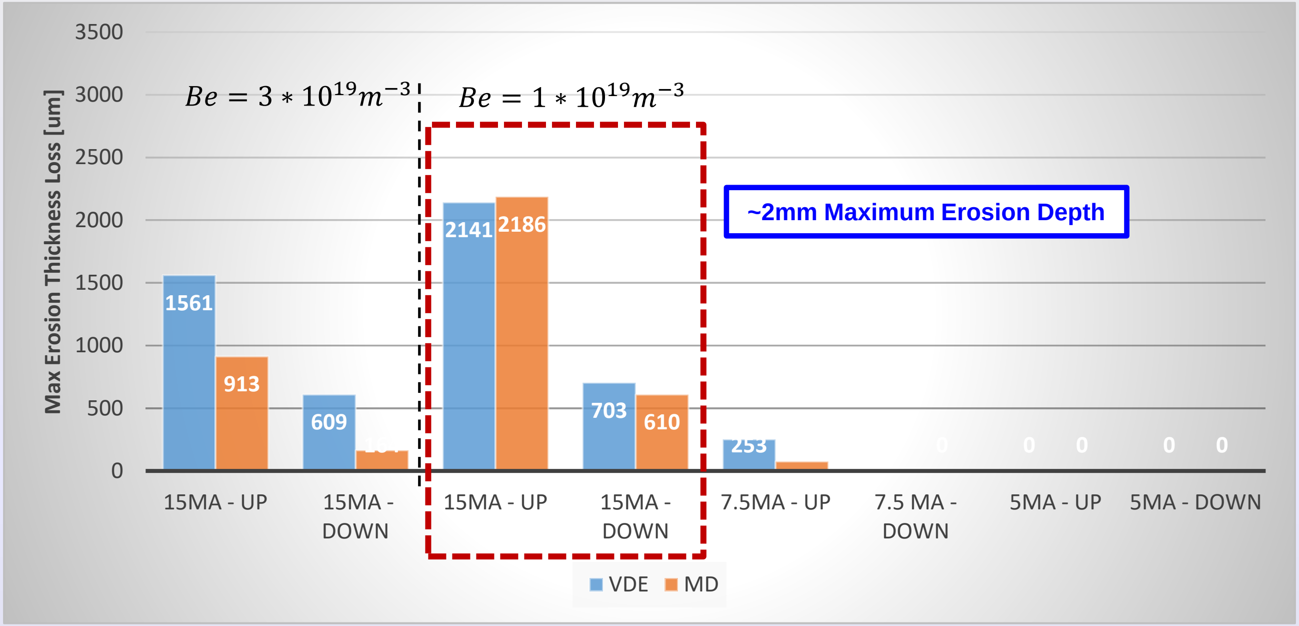
- For 7.5MA and lower, only the upward cases with impurity $1 * 10^{19} m^{-3}$ cause melt damage
  - All other cases remain below melt threshold for beryllium

Melt Analysis: MEMOS-U Results w/ Vapor Shielding



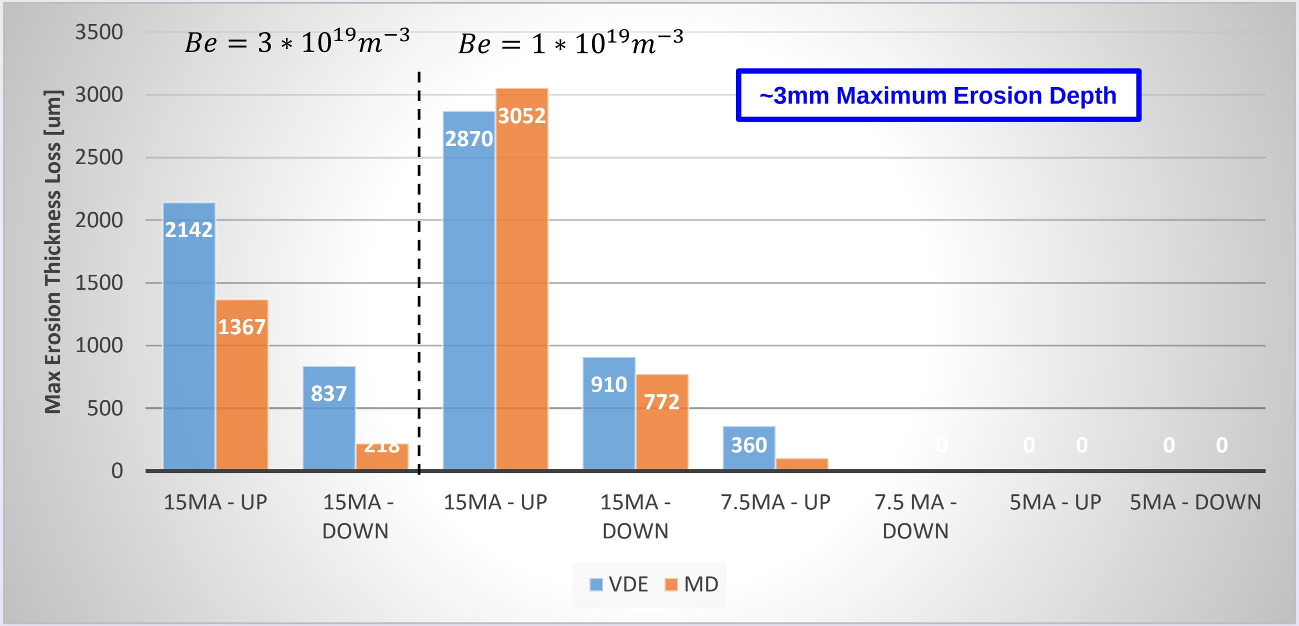
- For cases of higher Be impurity density ($3 * 10^{19} m^{-3}$), the VDE scenarios are more damaging than the MDs (Up & Down).
  - Higher impurity concentration allows for more plasma energy to radiate away before MD plasma contacts the first wall and starts depositing energy

Melt Analysis: MEMOS-U Results w/ Vapor Shielding



- For cases of lower impurity ($1 * 10^{19} m^{-3}$), MD damage is on-par with VDE damage for 15 MA cases (Up & Down)
  - MD deposits more energy to the first wall than VDE, but over a longer time duration and at slightly lower peak heat fluxes. Balances out to give similar erosion depth and ~25% more volume displacement than the VDE.

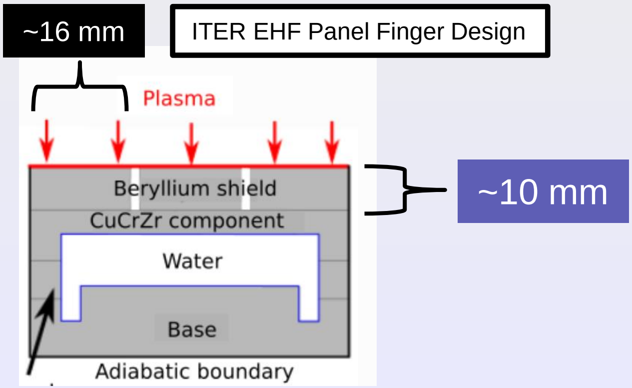
Melt Analysis: MEMOS-U Results without Shielding



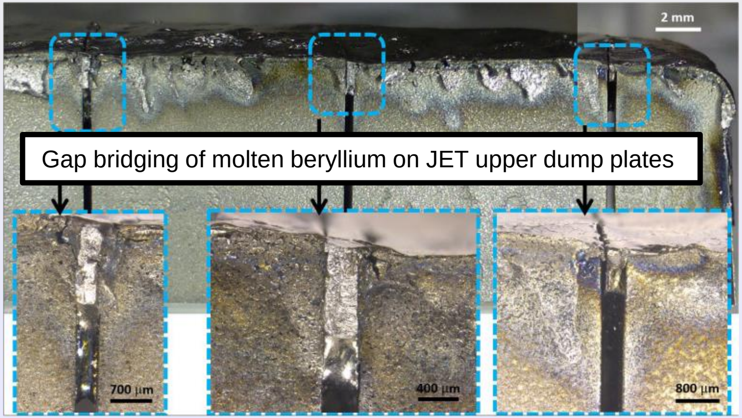
- Accounting for vapor shielding does significantly reduce damage depth
  - **50%** reduction for worst-cases: 2mm vs 3mm

IMPLICATIONS FOR ITER

Implications for ITER: Why must we avoid melt damage?



[static.iter.org/imas/assets/smiter]



[I. Jepu et al., NF (2019) 086009]

Loss of material integrity

- Thickness loss of ~mm will severely reduce component lifetime

Increased local $q_\perp$ during operations

- How does melt damage overlap with steady state heat loads?
  - See Nuclear Fusion manuscript for details

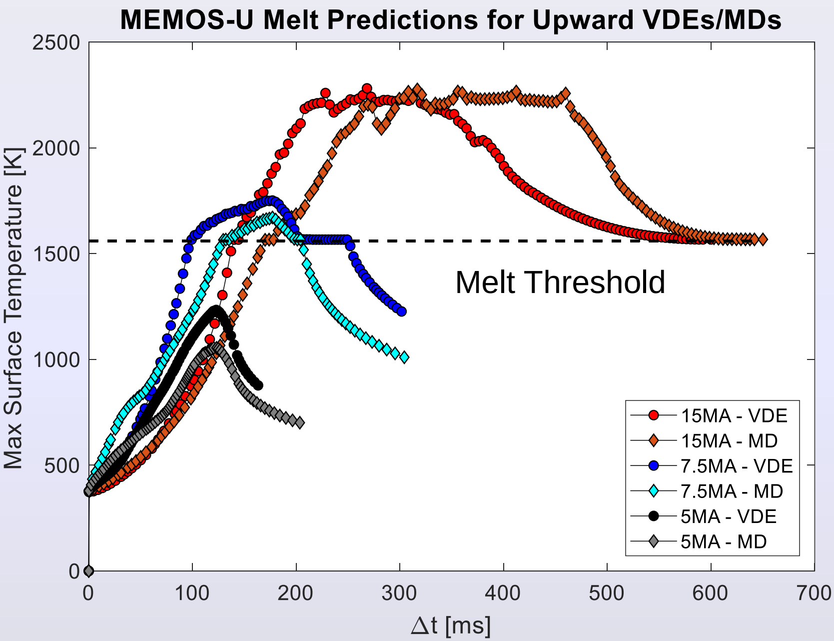
Gap-bridging across panels

- Poloidal melt-motion of ~10s of mm will lead to Be accumulation between fingers
- Will complicate thermal stress / fatigue response of FWPs
  - material ejection?
- Increased eddy current forces

Implications for ITER: Operating Space

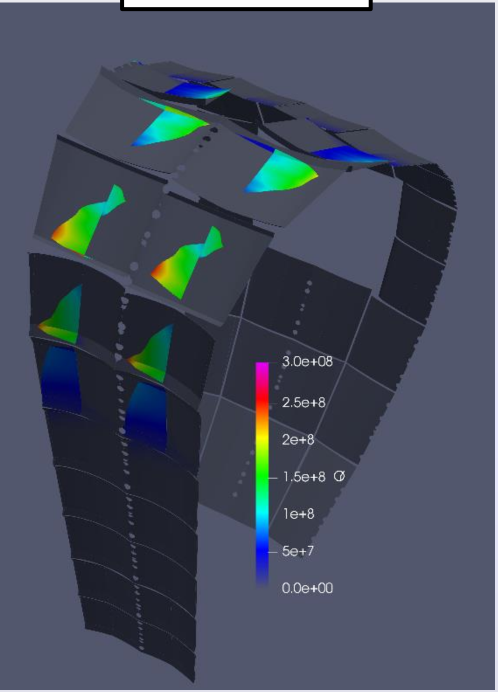
- **<u>Deliberate 5 MA VDEs & MDs will be acceptable</u>** during PFPO-1 & -2
  - Less energy deposited during current quench
  - Shorter time duration
- **<u>Some 7.5 MA events will also be acceptable</u>**
- Will allow time for operational experience for ITER's PCS & DMS

- During FPO, 15MA VDEs and MDs must be kept to **<u>once-in-a-lifetime</u>** events



Final Statements

15MA Upward VDE



The tools are in place at ITER for further modeling of VDE & disruption scenarios

- The power-handling capabilities of the ITER FW will be maintained through PFPO-1 & -2
- Results from this study, along with early ITER operations, will finalize "ITER Disruption Budget" for FPO

A self-consistent, multi-physics workflow is important in estimating a realistic lifetime for the ITER first wall

- Multiple physics characteristics of plasma disruptions influence melt damage
  - More Be impurities → shorter CQ → less melt damage
  - Larger energy deposition area → Lower $q_{\perp}$, but + longer CQ → more melt damage
- Accurate models of VDEs/MDs is essential
  - Factor ~2 accuracy not good enough for melt calculations

THANK YOU FOR YOUR ATTENTION