Liquid Metal Modeling for Plasma Facing Components

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ABSTRACT

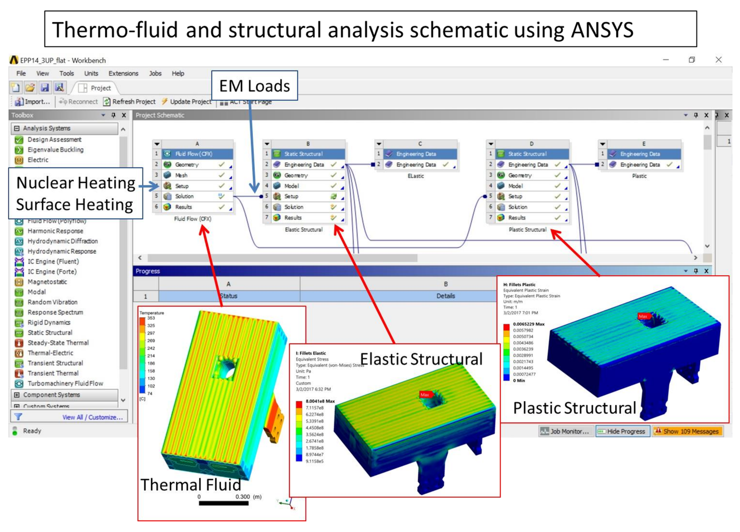
Liquid metal (LM) plasma facing components (PFC) are considered an attractive design choice for fusion devices including pilot plants. Several liquid metal concepts for the divertor region are currently under development. Solid metallic PFCs can also undergo transient melting in response to high heat flux events such as large edge-localized modes (ELM), unipolar arcs and disruptions. Changes in surface morphology caused by the motion and possible destabilization of the resulting melt layer can lead to a considerable degradation of the PFC longevity and heat-handling properties.

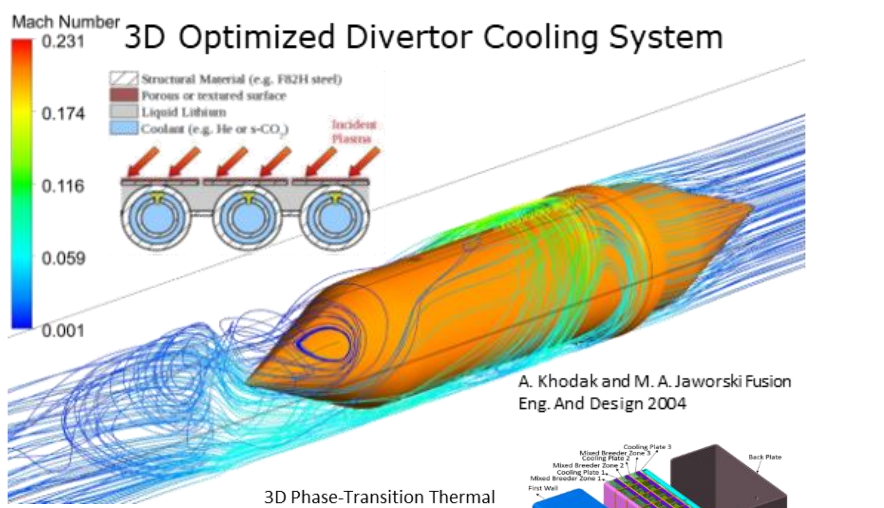
Virtual prototyping has proved useful to address some of the issues outlined above. Modeling of free-surface flows of electrically conductive liquids is facilitated by computational fluid dynamics (CFD) and MHD simulations. Moreover, phase transitions can alter the heat balance and, depending on the time scales involved, re-solidification and evaporation can also significantly affect the dynamics of the liquid. Coupling fluid dynamics and MHD solvers to heat transfer enables one to address such problem fully self-consistently. The same set of numerical tools was successfully adopted at PPPL for modeling atmospheric pressure arcs and was thoroughly validated by comparison with experimental data. Recently we adapted the model to simulate transient metal melting and splashing under conditions corresponding to unipolar arcs on tokamak PFCs. The numerical solutions accounting for phase transitions, are benchmarked against available simulation results and experimental data.

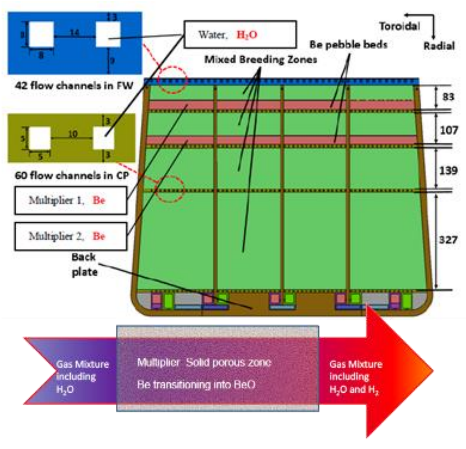
THERMAL CFD ANALYSIS FOR FUSION APPLICATIONS

- The analysis of many fusion applications such as first wall blankets requires application of Computational Fluid Dynamics (CFD) methods.
- Highly customized version of ANSYS CFX is used for thermal analysis of complex systems involving fluid flow and heat transfer in liquids and solids
- Thermal and CFD analysis is a part of virtual prototyping system which includes also structural and EM

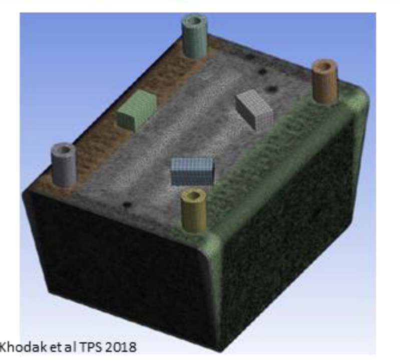
Thermo-fluid and structural analysis schematic using ANSYS



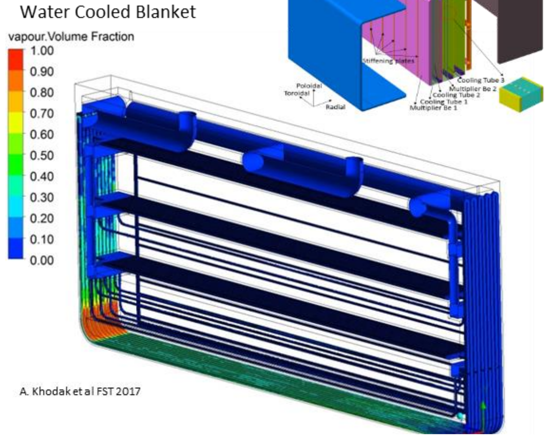




3D Unsteady Model for Be-steam Reaction in Water Cooled Ceramic Breeder Blanket



3D Phase-Transition Thermal and Flow Analysis for CFETR Water Cooled Blanket



UNIVERSAL SELF CONSISTENT MODEL

Magnetic Vector Potential Formulation for Free Surface MHD

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}\cdot(\rho\vec{V}) = 0$$

$$\frac{\partial \rho\vec{V}}{\partial t} + \vec{\nabla}\cdot(\rho\vec{V}\vec{V}) = -\vec{\nabla}p + \vec{\nabla}\cdot(\boldsymbol{\tau}) + \rho\vec{g} + \vec{j}\times\vec{B} - \gamma k\delta\vec{n} + \vec{\nabla}_S\gamma$$

Lorentz Force; Surface Tension; Curvature $\gamma\,\vec{\nabla}\cdot\left(\frac{\vec{\nabla}\varphi_m}{|\vec{\nabla}\varphi_m|}\right)\frac{\vec{\nabla}\varphi_m}{|\vec{\nabla}\varphi_m|}$; Marangoni Term

$$\frac{\partial \rho c_p T}{\partial t} + \vec{\nabla}\cdot(\rho\vec{V}c_pT) = \vec{\nabla}(\lambda\vec{\nabla}T) + \boldsymbol{\tau}:\vec{\nabla}\vec{V} + \vec{j}\cdot\vec{E} + \dot{h}$$

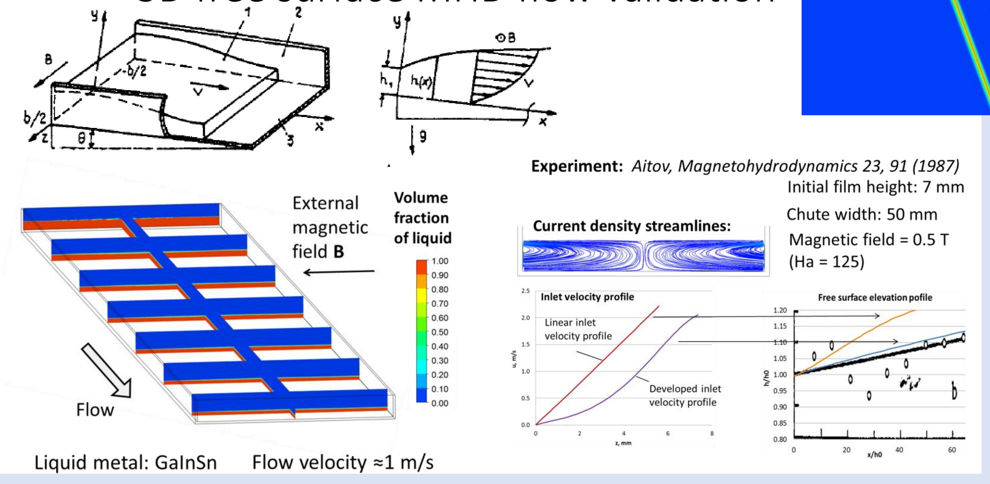
Volumetric Heat Source $\dot{h} = \dot{q_{fs}}\cdot\vec{\nabla}\varphi_m$; Joule Heat

$$\frac{\partial \varphi_m\rho_m}{\partial t} + \vec{\nabla}\cdot(\varphi_m\rho_m\vec{V}) = 0$$

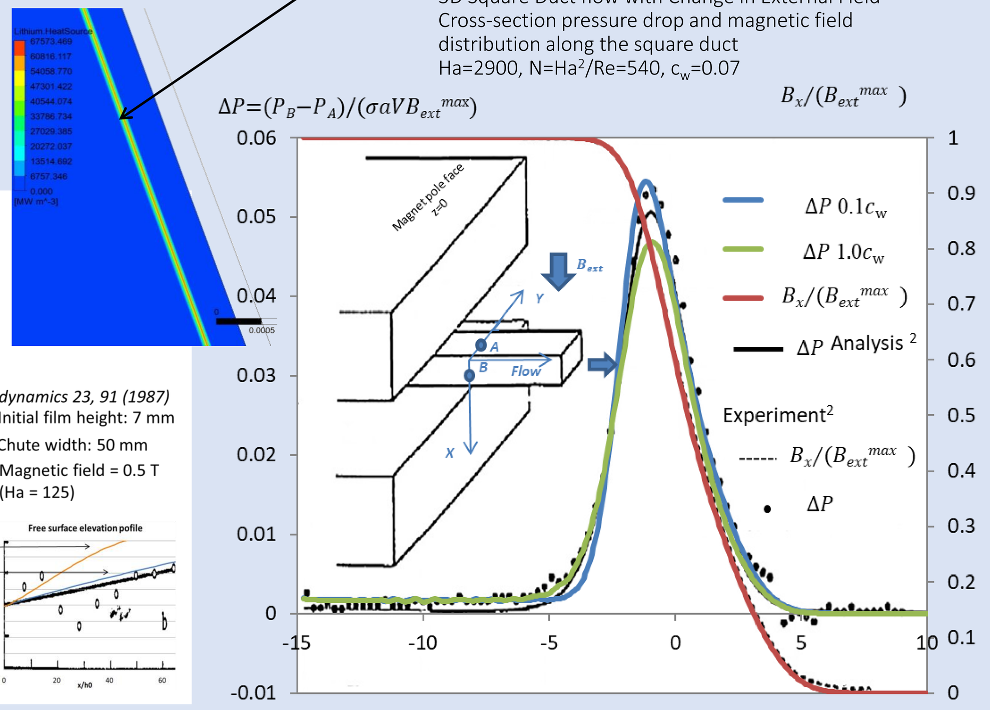
$$\vec{\nabla}\times(\vec{\nabla}\times\vec{A}) = \mu\vec{j} \qquad \vec{B} = \vec{B}_{ext} + \vec{\nabla}\times\vec{A}$$

$$\vec{\nabla}\cdot\vec{j} \equiv \vec{\nabla}\cdot\left(\sigma\left(-\vec{\nabla}\varphi + \vec{V}\times\vec{B}\right)\right) = 0$$

3D free surface MHD flow validation



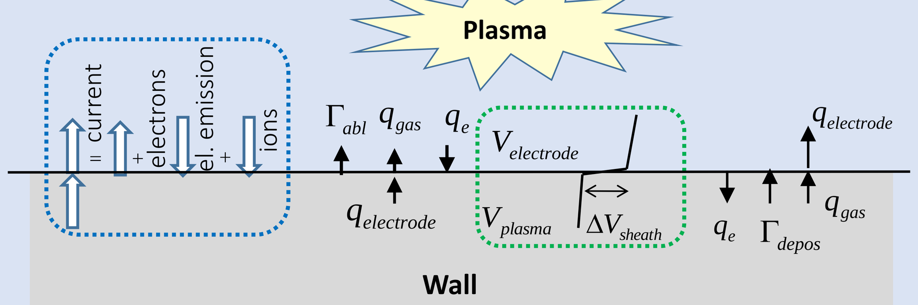
3D MHD flow validation
3D Square Duct flow with Change in External Field
Cross-section pressure drop and magnetic field distribution along the square duct
Ha=2900, N=Ha²/Re=540, c_w=0.07

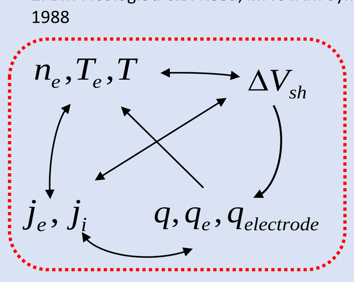


1. A. Khodak "Numerical Analysis of 2D and 3D MHD Flows Relevant to Fusion Applications" accepted Fusion Eng. and Des.

2. B.F. Picologlou C.B. Reed, in: IUTAM Symposium on liquid metal MHD, Riga, USSR, May 16, 1988

Plasma-interface coupling:





Heat balance accounting for:

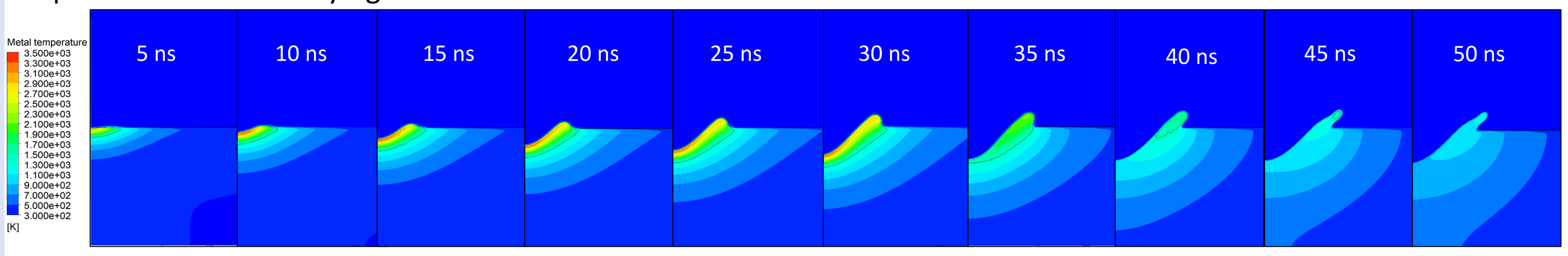
- ✓ sheath contribution;
- ✓ work function;
- ✓ ablation/deposition;
- ✓ ionization energy;
- ✓ emission;
- ✓ radiation;

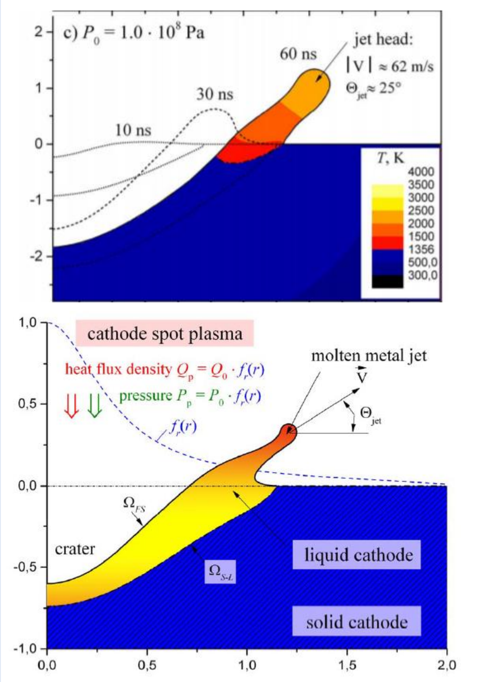
arXiv:1902.09991 (2019)
Validated Modeling of Atmospheric-Pressure Anodic Arc
A. Khrabry, I. Kaganovich, A. Khodak, V. Vekselman, Y. Raitses

ANALYSIS RESULTS

Transient melting and splashing of metallic surfaces exposed to "harsh" plasmas in fusion conditions

Coupled fluid dynamics, heat transport and electro-magnetic models
3 phases with time-varying interfaces





Cathode spot on a copper cathode
[Mesyats and Uimanov, IEEE T. Plasma Sci. 43 (2015) 2241]

Time History of Cathod Melting Simulated Using Modified Ansys CFX

Homogeneous VoF → single fluid solved over the whole domain + metal volume fraction α

Liquid fraction $\beta := \frac{1}{2} + \frac{T - T_m}{\Delta T_m}$ for T between $T_m \pm \frac{\Delta T_m}{2}$ with ΔT_m= 100 K

Latent heat Δh added to heat capacity

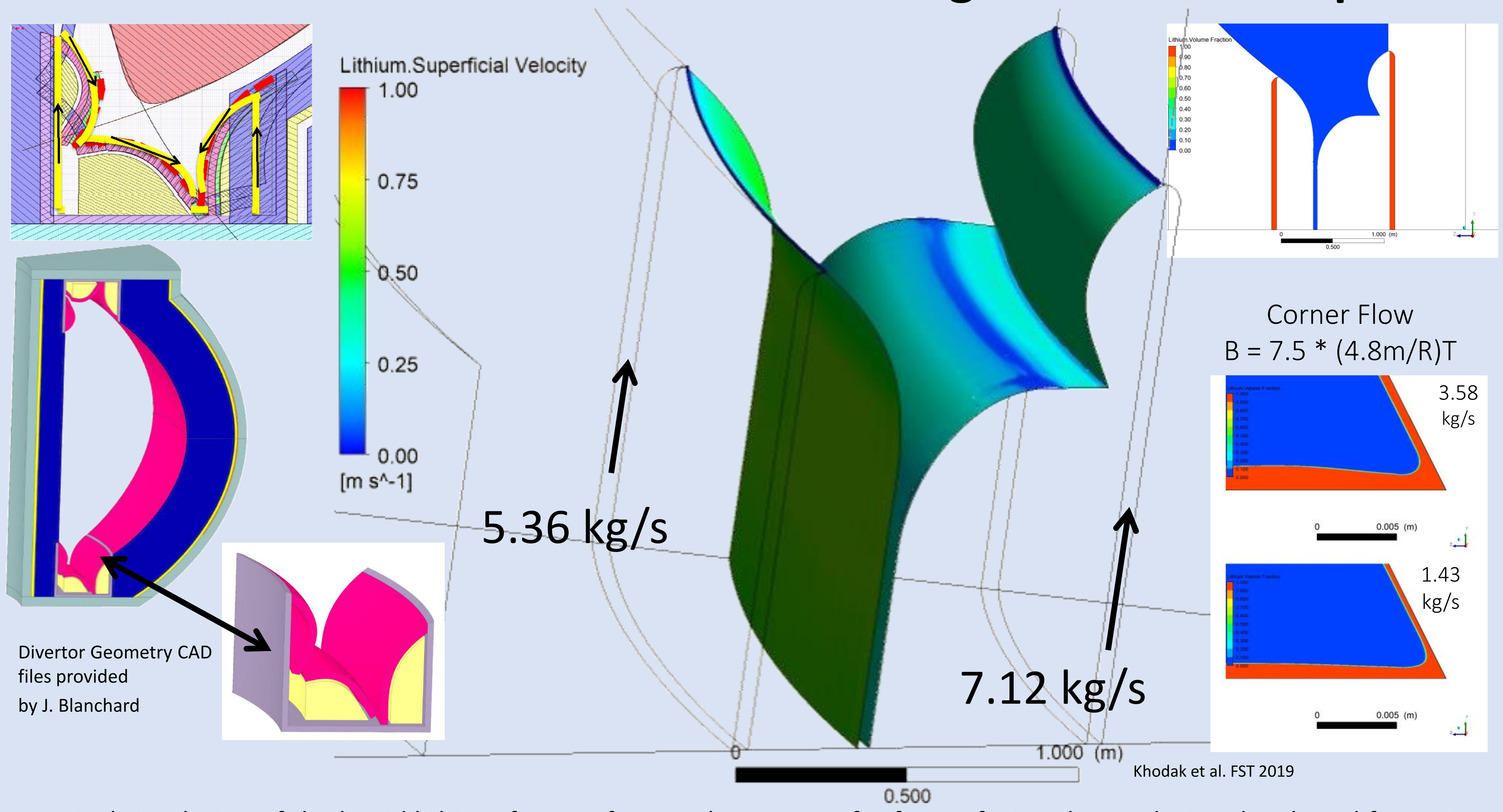
$$c_p^{sim} = (1-\beta)c_p^{sol} + \beta c_p^{liq} + 6\beta(1-\beta)\frac{\Delta h}{\Delta T_m}$$

Extra source terms in Navier-Stokes and heat equation

- Surface tension (automatic): $\boldsymbol{F}_{surf} = \sigma\kappa\boldsymbol{\nabla}\alpha$
- External heating: $Q_{ext} = q_{ext}(r,t)|\boldsymbol{\nabla}\alpha|$
- External pressure: $\boldsymbol{F}_{ext} = (1-\alpha)\boldsymbol{\nabla}p_{ext}(r,t)$
- Solid behavior: $\boldsymbol{F}_{solid} = -\alpha\frac{(1-\beta)^2}{\max(\beta^3, 0.001)}K\boldsymbol{v}$ with $K = 10^{14}$ N-s/m⁴

Future Plans:
Plasma response to the evolving metal surface (sheath geometry, vaporized neutrals, strong local emission currents)
3D effects (current closure patterns, 3D free-surface breaking, asymmetries due to the arc self-field)

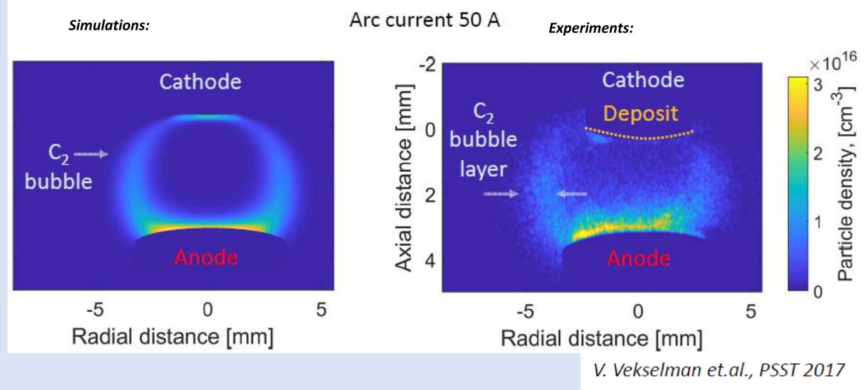
Numerical Simulation of Modified Flowing Surfaces Concept

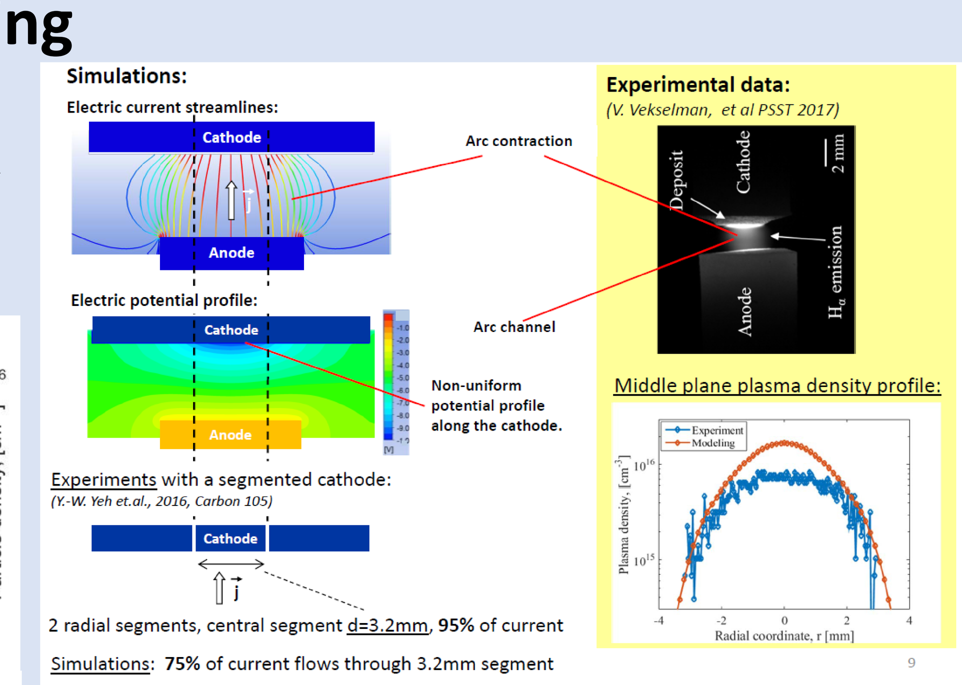


Numerical simulation of the liquid lithium free-surface cooling system for future fusion device design developed for FNSF program. Design includes LM PFC covering convex diverter surfaces, as well as lithium supply and removal lines.

High Collisional Plasma Modelling

Self-Consistent model of carbon arc discharge in helium atmosphere was developed and implemented into a general purpose CFD code
Multiphysics platform was developed, non-equilibrium effects were introduced via additional transport equations, and user-defined boundary conditions
Numerical Simulation of Atmospheric Arc showed good agreement with experimental data for the Discharge Investigated by PPPL Nano Lab





CONCLUSION

- A universal computational platform for simulation of interacting solids, fluids, gases, and highly collisional plasma is under development.
- The platform is implemented into 3D CFD code ANSYS CFX which was highly customized for this purpose.
- Magneto hydrodynamics (MHD) flows are simulated for high Hartman numbers.
- Free Surface MHD flow analysis was performed on the Liquid Metal PFC divertor geometry

ACKNOWLEDGEMENT

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