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Multiphysics analysis of LBE windowless target design under high-power electron beam

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8th High Power Targetry Workshop (HPTW2023)
November 7th, 2023

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U.S. DOE NNSA Mo-99 Program

Overview

LANL

Accelerator Operational Technology
(AOT) Division

Mechanical Design Engineering
(MDE) group

Mo-99 project team


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SUPPORT

SUPPORT

NNSA Mo-99 Program

- Establish a reliable <u>domestic supply of Mo-99</u> using non-HEU targets.
- Provide funds to <u>National labs</u> to support <u>commercial entities</u>.
- Diverse <u>Mo-99 production technologies</u> involved:
  Accelerator, Fission, Neutron capture..

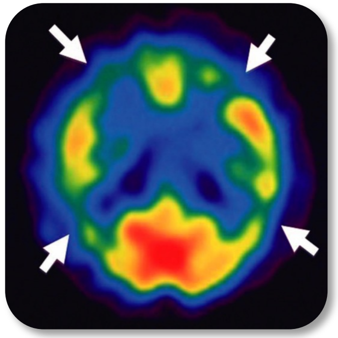
NIOWAVE
Accelerating the Fight Against Cancer

NorthStar
MEDICAL RADIOISOTOPES, LLC

SHINE

EDEN RADIOISOTOPES

Mo-99 → Decay → Tc-99m



Medical Isotope Production without Highly Enriched Uranium. National Academies Press (US), 2009.

Used in >40K <u>nuclear medical procedures</u> in U.S. each day.

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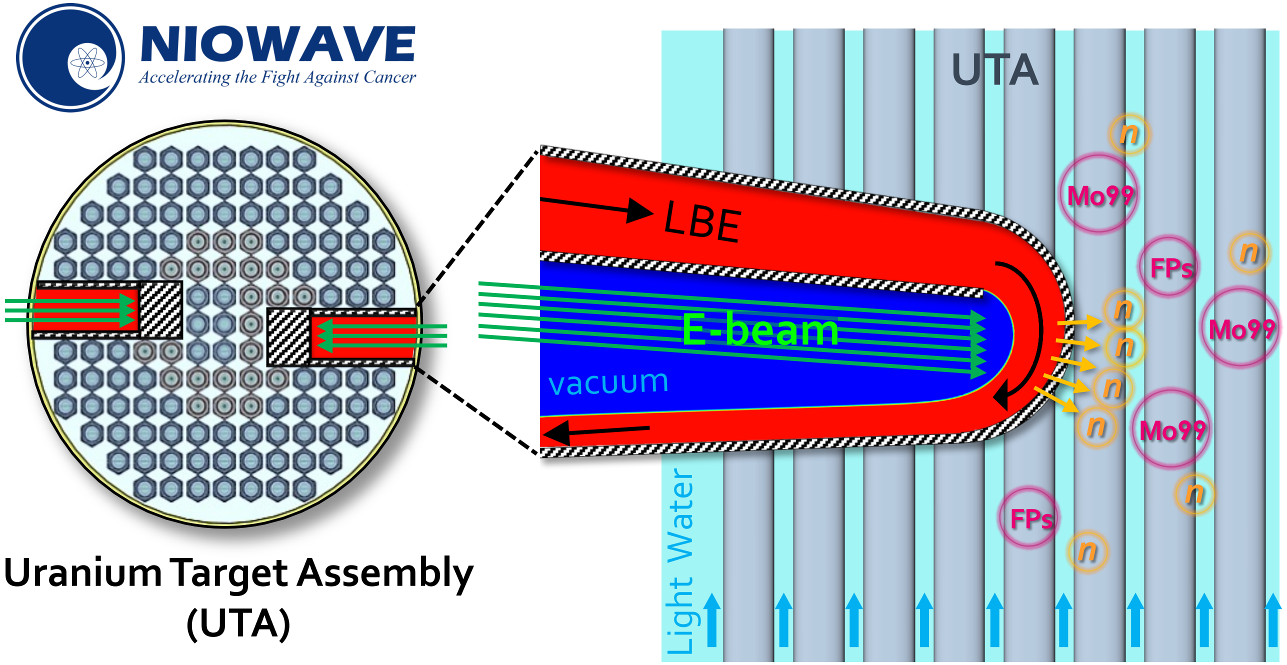
Niowave Inc. Mo-99 Production System

Objective



Uranium Target Assembly (UTA)

Neutron source converter

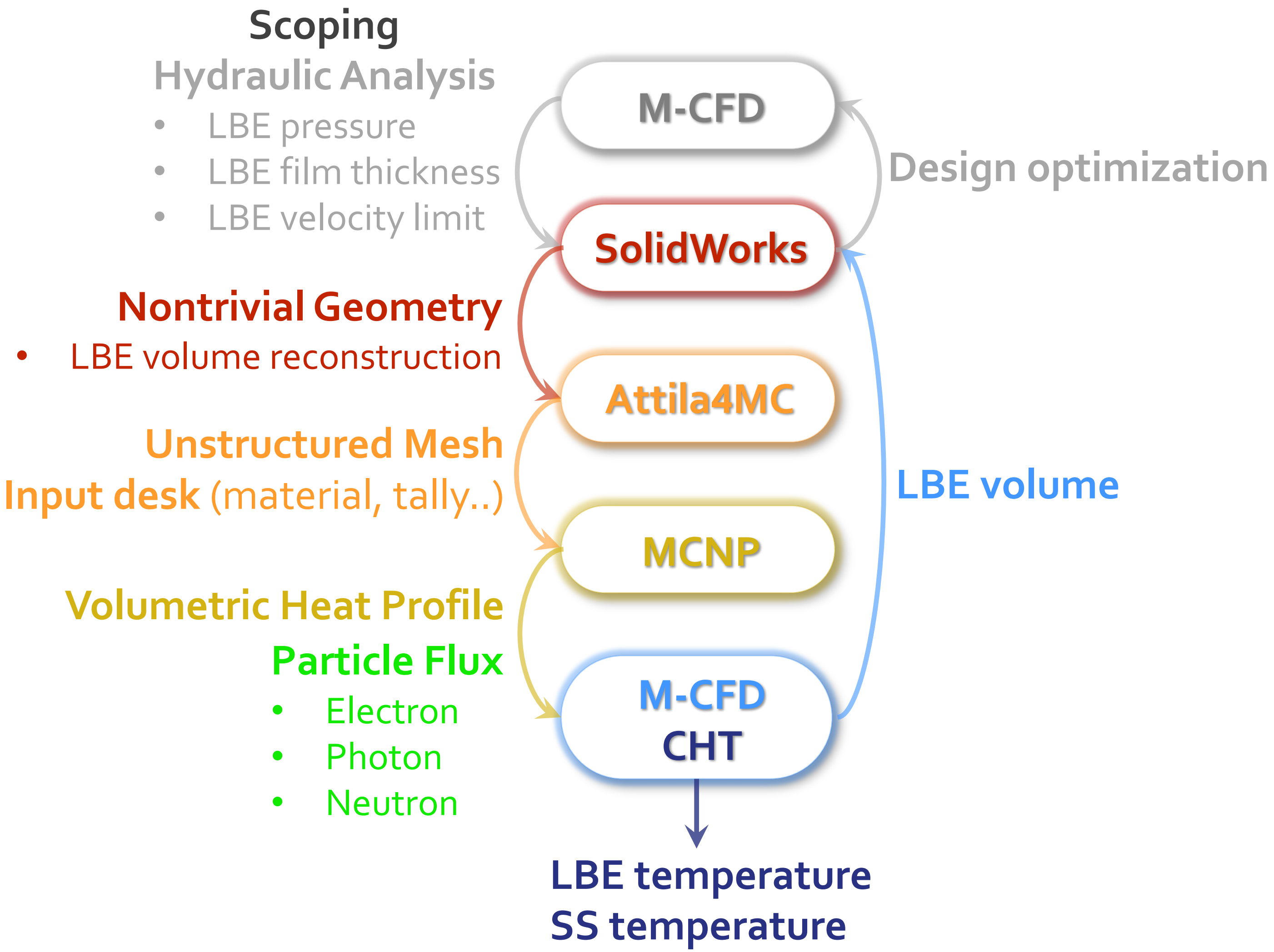
- 200 kW, 40 MeV electron linear accelerator.
- Windowless Lead-Bismuth-Eutectic (LBE) target falls driven by gravity and forms free-surface in vacuum.
- Neutron is produced by photonuclear reaction.
- Heat deposited on the irradiated LBE & SS housing.

Uranium target assembly (UTA)

- Mo-99 is produced as one of fission products (FPs) in low-enriched uranium (LEU) under subcritical conditions.

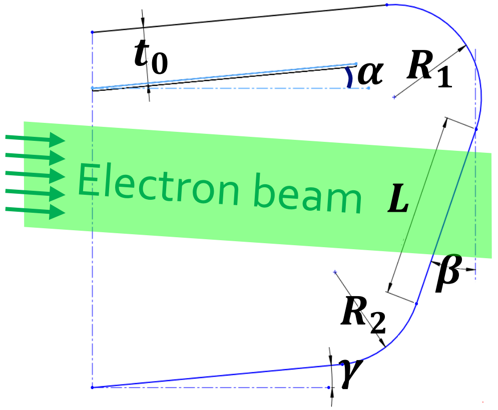
High-fidelity simulation is essential to assess the integrity of the high-power target system and ensure the target in-beam survival.

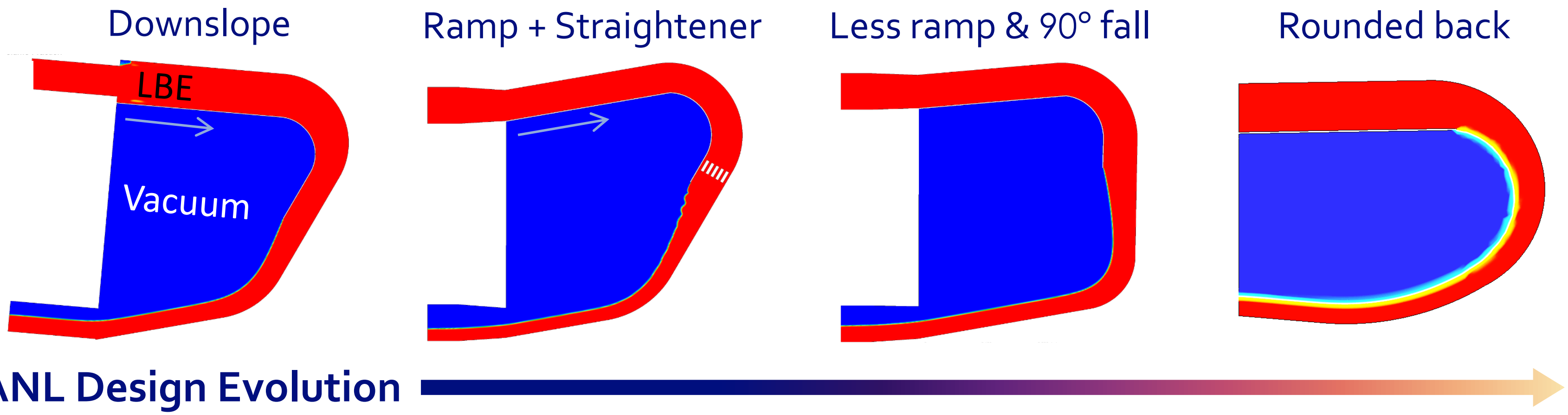
Multiphysics Computation Scheme



2D Hydraulic Analysis

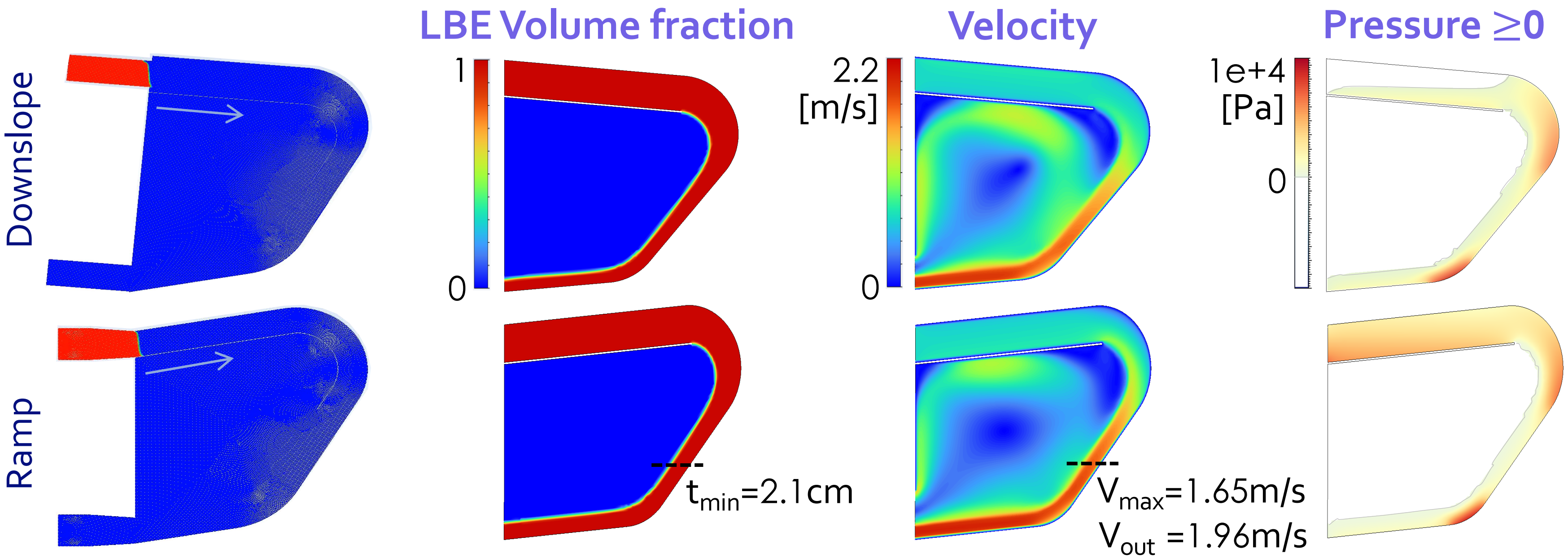
LBE Film thickness, Velocity limit, Pressure





Design requirements

- Thicker LBE film is better for neutron population.
- Velocity limit of 2 m/s to avoid corrosion & erosion.
- Positive pressure desired to avoid cavitation on LBE.



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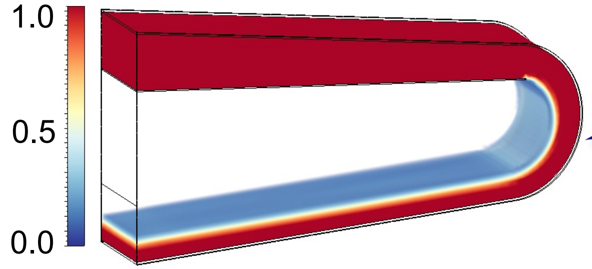
3D Hydraulic Analysis

LBE volume reconstruction

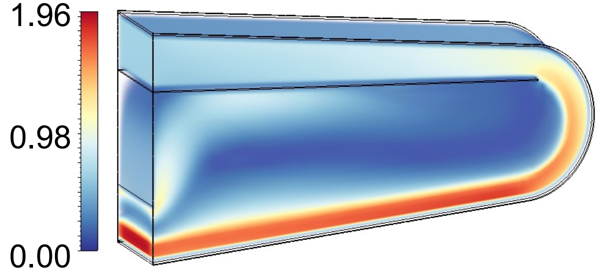
M-CFD

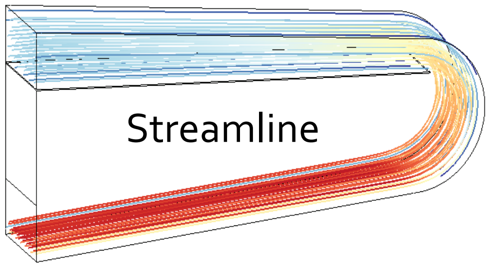
LBE
Volume fraction [-]



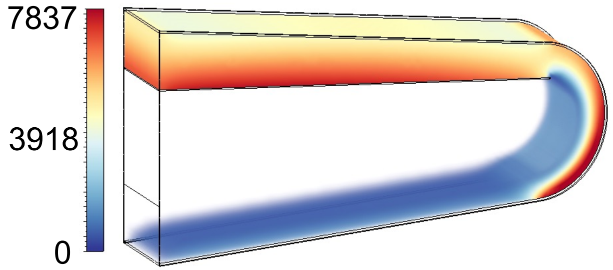
Mid-plane LBE profile
(volume fraction>0.9)

Velocity [m/s]



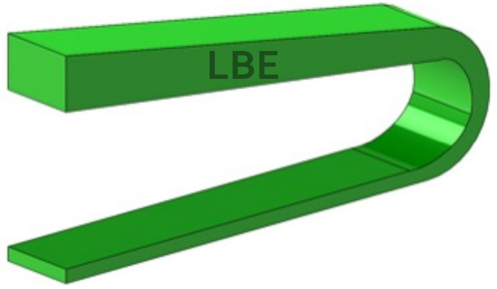


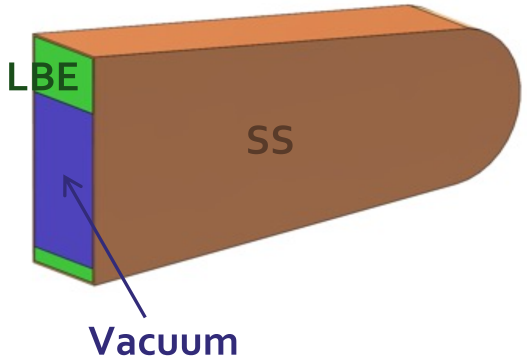
Pressure [Pa]



- Stable symmetric 3D LBE layer
- Maximum velocity of 1.96 m/s
- Favorable pressure gradient

SolidWorks





- Discrete geometries of LBE, vacuum, and SS housing

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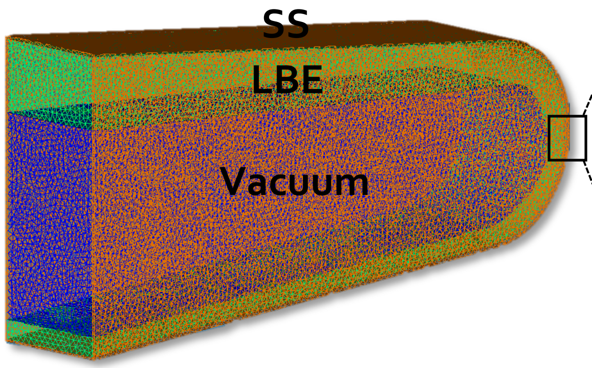
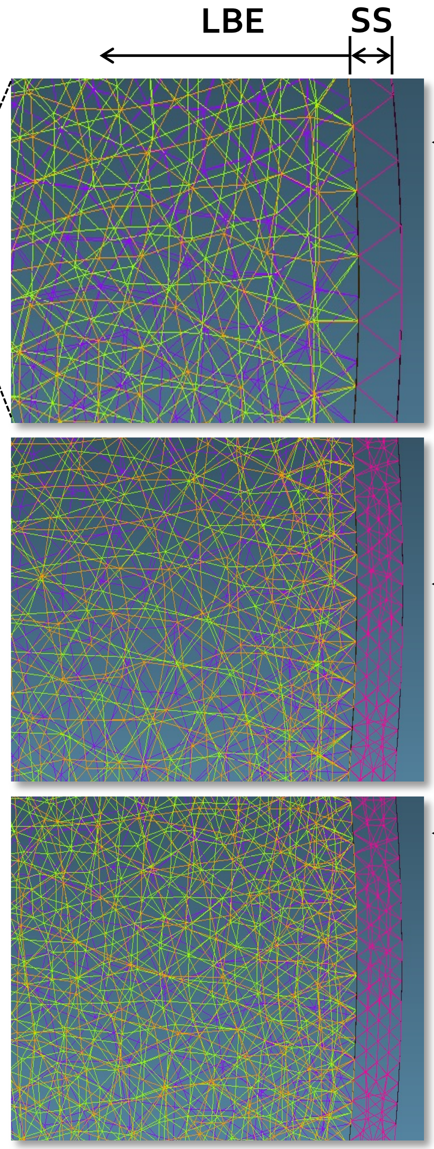
Unstructured Meshing for MCNP

Mesh sensitivity





	LBE	SS	TOTAL
Max. edge length	2 mm	2 mm	
Heat deposition	195561 W	2942 W	198503 W
Max. temperature*	363.7 °C	386.5 °C	
Max. edge length	2 mm	1 mm	
Heat deposition	194005 W	3637 W	197643 W
Max. temperature	363.7 °C	420.8 °C	
Max. edge length	2 mm	0.6 mm	
Heat deposition	193097 W	3760 W	196858 W
Max. temperature	363.2 °C	421.4 °C	
Max. edge length	1 mm	0.6 mm	
Heat deposition	199515 W	3650 W	203165 W
Max. temperature	367.6 °C	418.6 °C	
Max. edge length	1 mm	2 mm	
Heat deposition	199268 W	2718 W	201986 W
Max. temperature	367.6 °C	383.1 °C	

*** CFD mesh**
LBE: 2 mm hexa
SS: 2 mm tetra

- LBE max. temperature is less sensitive to mesh size.
- Fine mesh is required for thin SS wall (~1.5 mm thick) to capture peak value and avoid mesh overlap.

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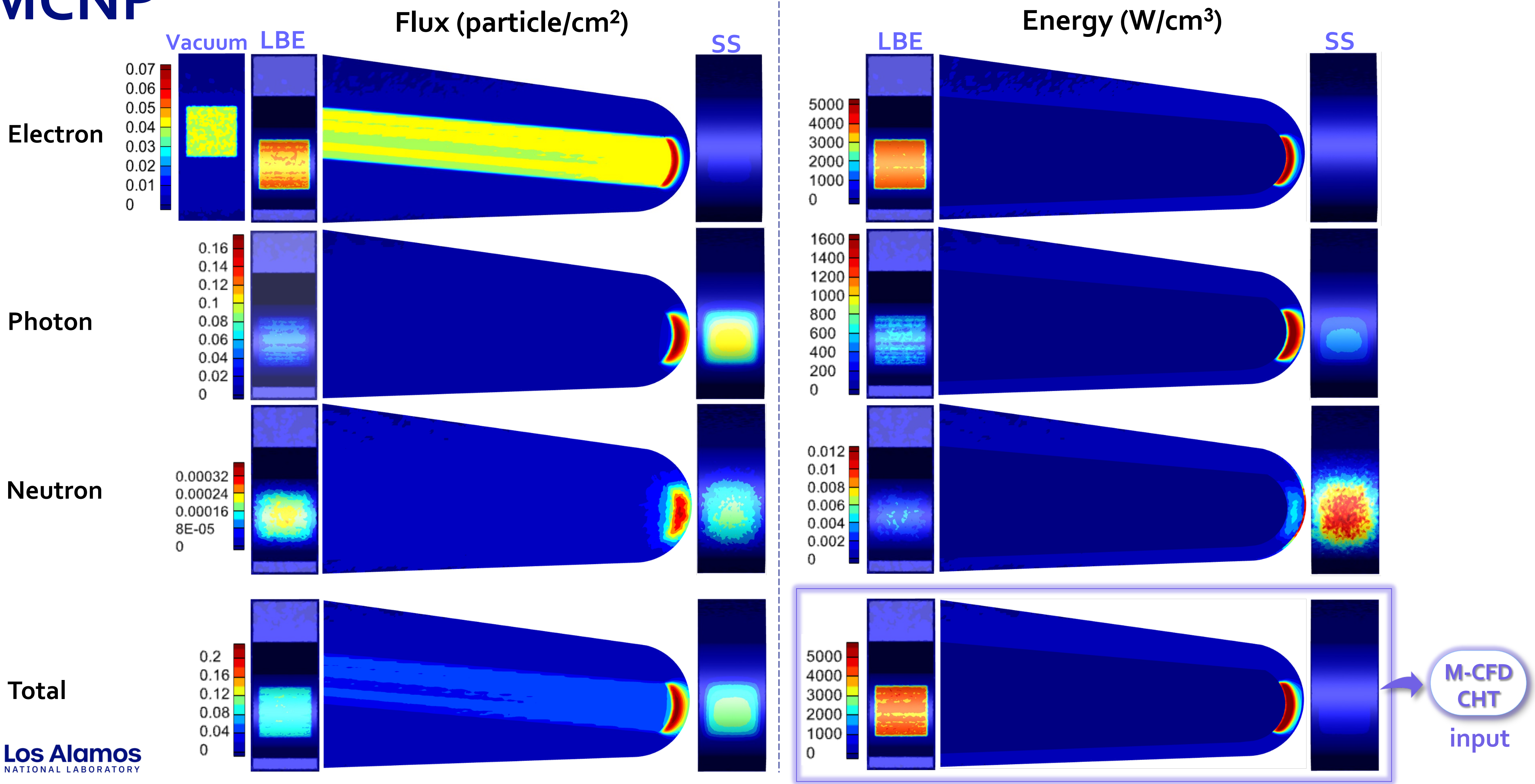
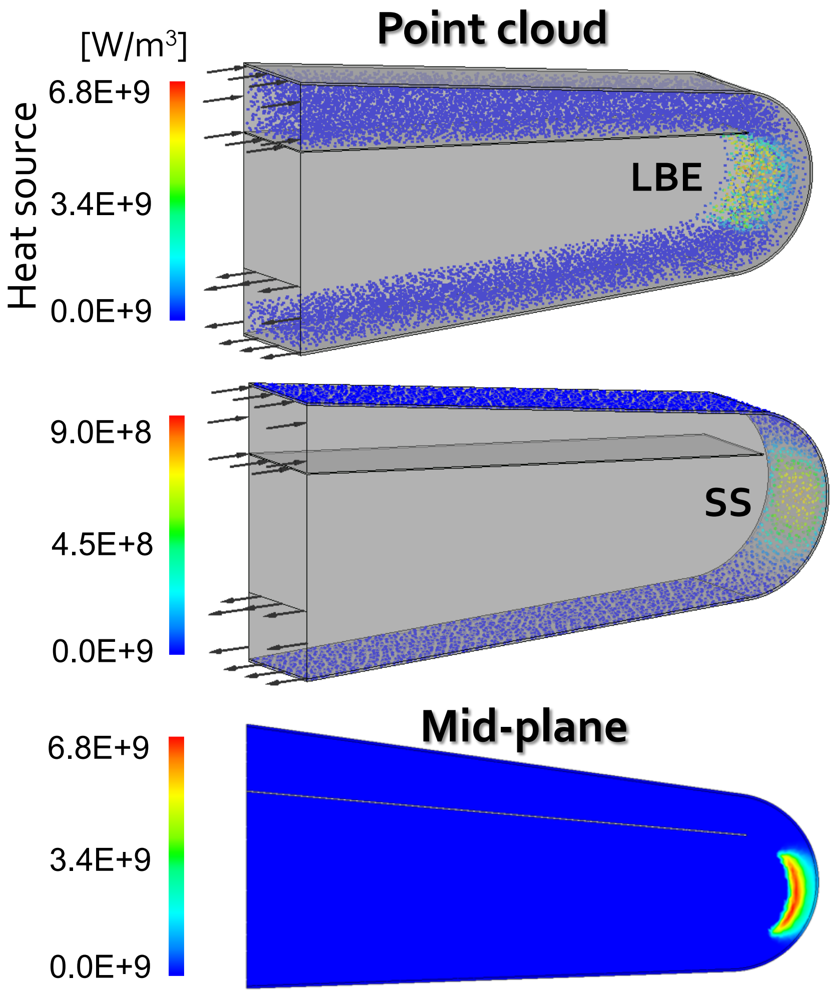
MCNP

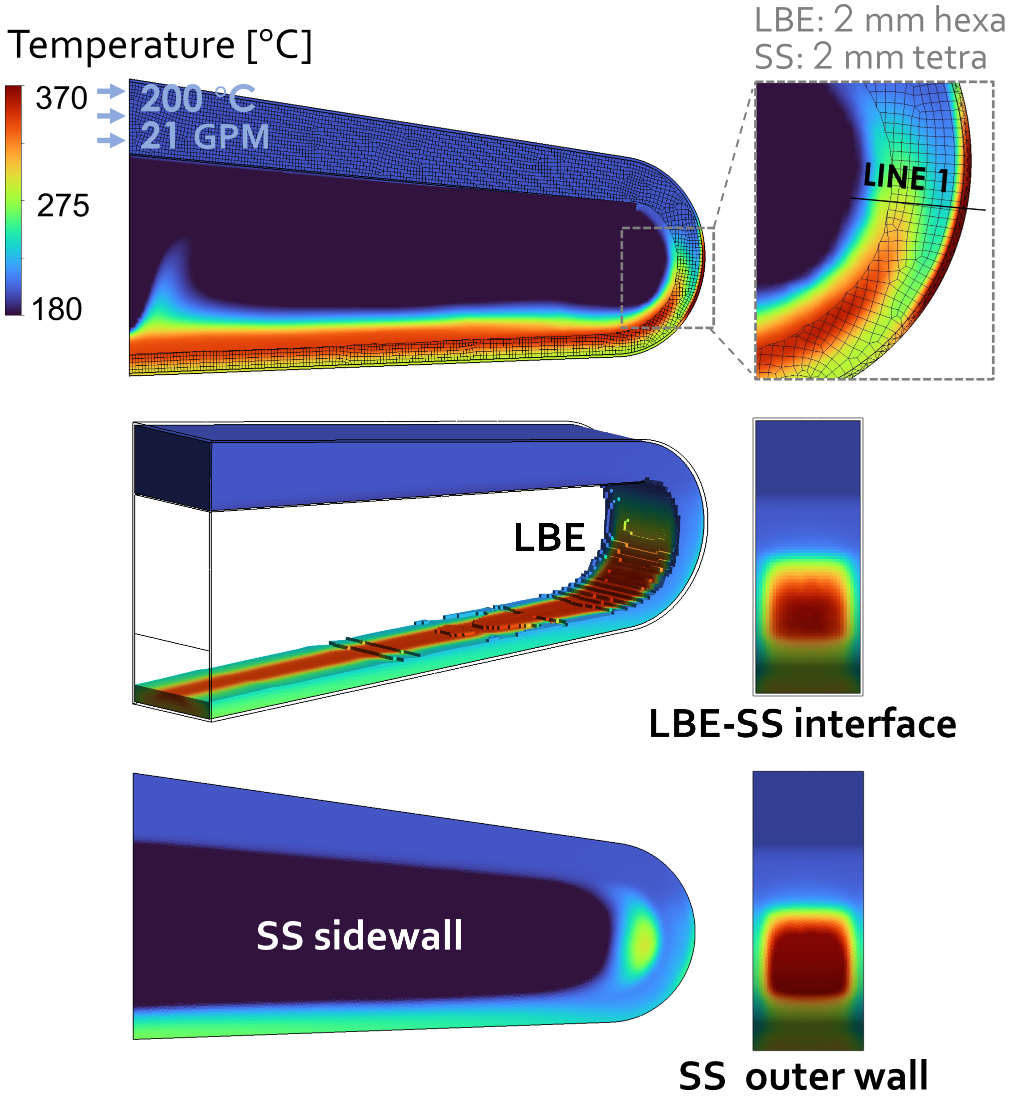

Flux (particle/cm²)
Energy (W/cm³)
Vacuum
LBE
SS
LBE
SS
Electron
Photon
Neutron
Total
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
5000
4000
3000
2000
1000
0
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
1600
1400
1200
1000
800
600
400
200
0
0.00032
0.00024
0.00016
8E-05
0
0.012
0.01
0.008
0.006
0.004
0.002
0
0.2
0.16
0.12
0.08
0.04
0
5000
4000
3000
2000
1000
0
M-CFD CHT
input

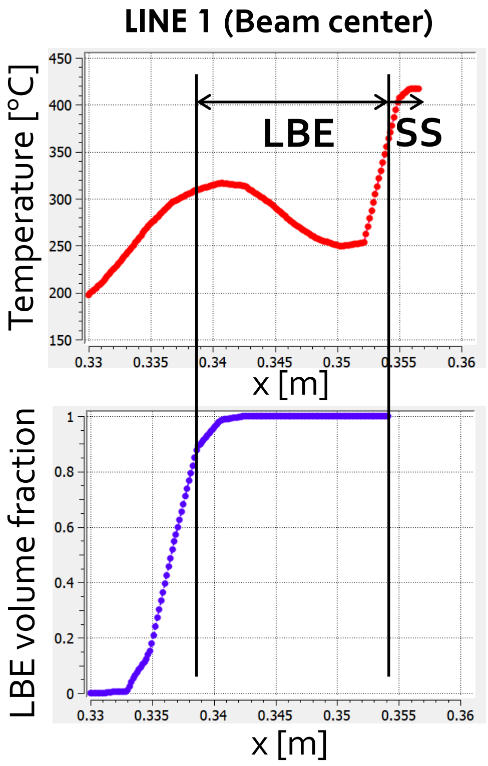
Conjugate Heat Transfer (CHT) Analysis

Volumetric heat input



Temperature

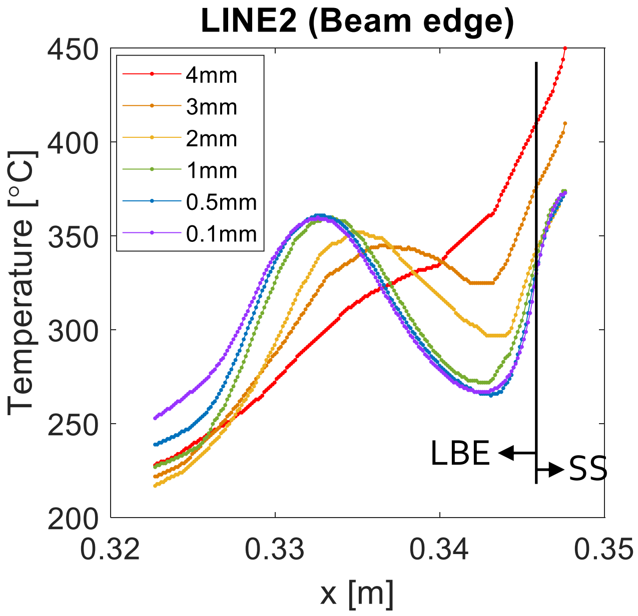


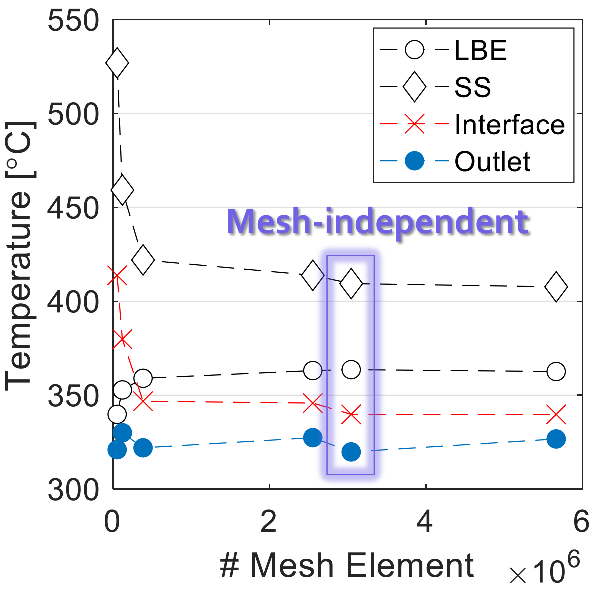


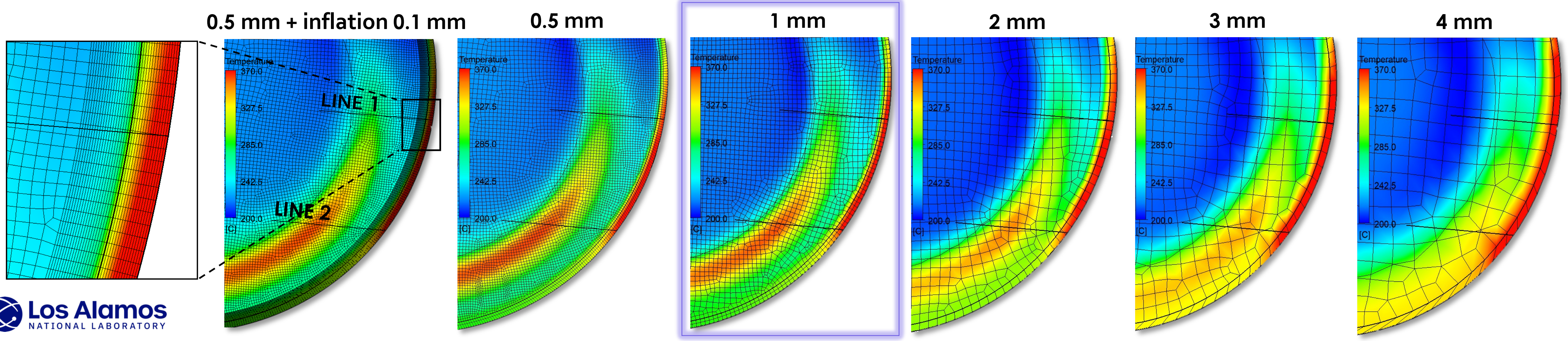
M-CFD/CHT Mesh Sensitivity

CFD Mesh	0.1 mm*	0.5 mm*	1 mm	2 mm	3 mm	4 mm
# cells	5,663,800	2,554,462	3,044,748	385,307	121,266	54,572
LBE thickness	1.65 cm	1.63 cm	**1.6 cm**	1.51 cm	1.41 cm	1.32 cm
LBE max.	362.6 °C	363.6 °C	**363.1 °C**	359 °C	352.8 °C	339.8 °C
SS max.	407.7 °C	409.4 °C	**413.8 °C**	422 °C	459.2 °C	526.9 °C
Interface @ LINE 1	307.8 °C	304.8 °C	**330.8 °C**	363.8 °C	397.8 °C	443.8 °C
Interface @ LINE 2	339.8 °C	339.8 °C	**345.8 °C**	346.8 °C	379.8 °C	413.8 °C
Outlet	326.7 °C	319.8 °C	**327.4 °C**	322 °C	330 °C	321 °C

* Biased





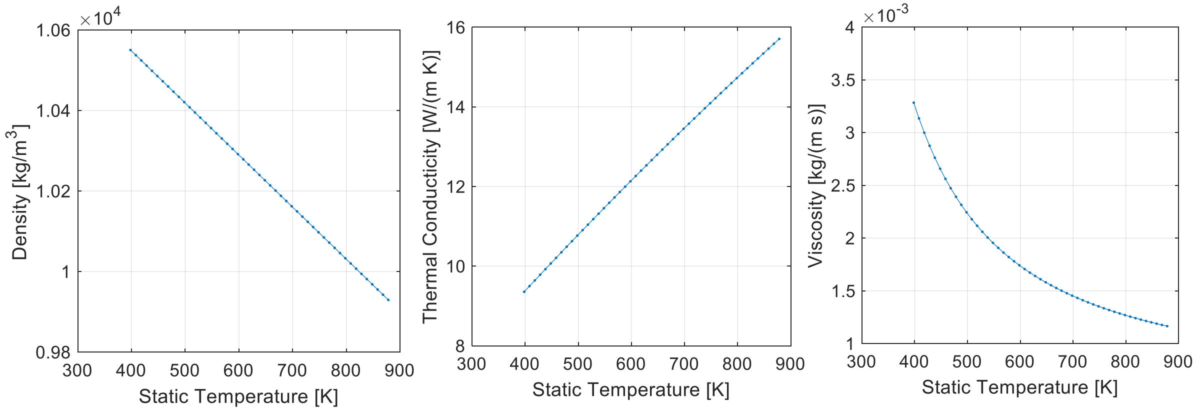


Final Results

MCNP LBE 2 mm, SS 0.6 mm / CFD 1 mm Hexa

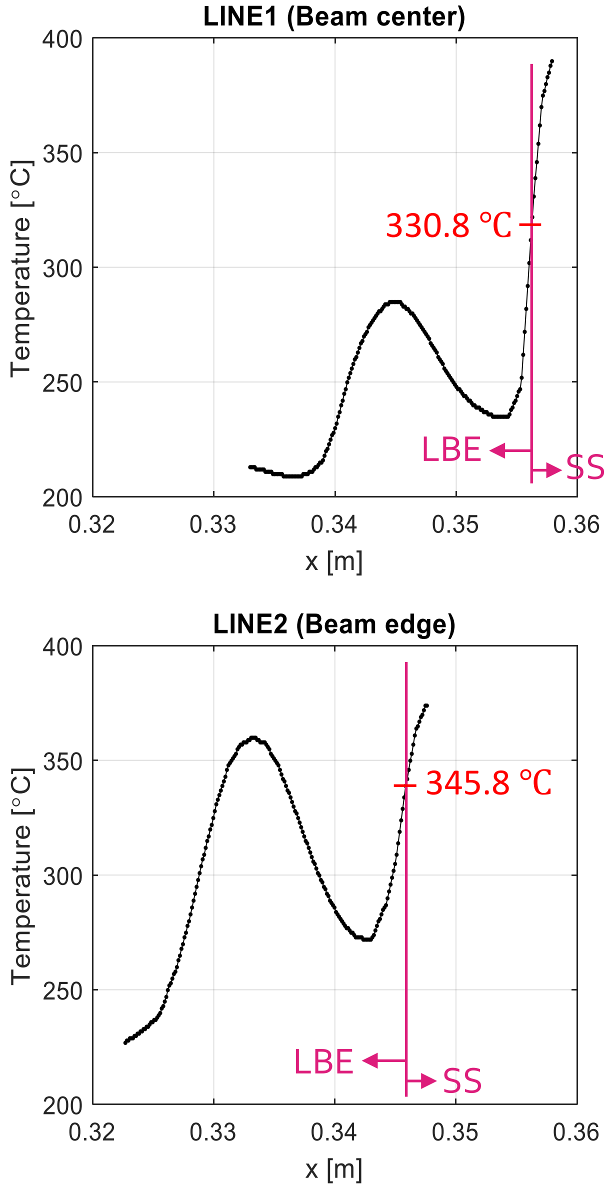
ANSYS FLUENT

- RANS, Standard k-epsilon with enhanced wall function
- Homogeneous Volume of Fluid (VOF), LBE-Nitrogen
- Operating pressure at 1 Pa
- Temperature dependent LBE, SS properties



	Max.
LBE layer thickness	1.6 cm
Velocity	1.84 m/s
Pressure	8220 Pa
LBE heat deposition	172134 W
SS heat deposition	3983 W
LBE	363.1 ℃
SS Front	413.8 ℃
Interface @ LINE 1	331 ℃
Interface @ LINE 2	346 ℃
Outlet	327.4 ℃

- LBE max. temperature is below LBE evaporation initiative temperature
- LBE-SS interface temperature has low risk of severe SS corrosion problem.



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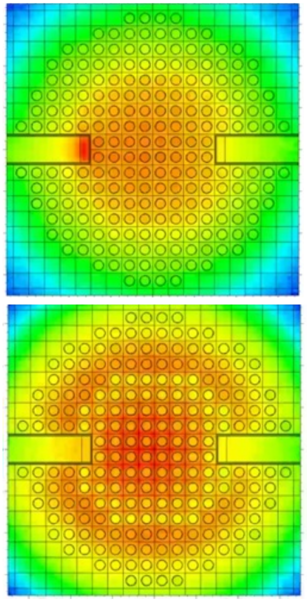

Nuclear physics Analysis

Scoping

Hydraulic Analysis

- LBE pressure
- LBE film thickness
- LBE velocity limit

Nontrivial Geometry

- LBE volume reconstruction

Unstructured Mesh

Input desk (material, tally..)

Volumetric Heat Profile

Particle Flux

- Electron
- Photon
- Neutron

M-CFD

SolidWorks

Attila4MC

MCNP

M-CFD CHT

Design optimization

LBE volume/density ----> **Multiphase Analysis**

- LBE evaporation
- Outgassing
- Emanations of volatile spallation products

LBE temperature

SS temperature ----> **Mechanical Analysis**

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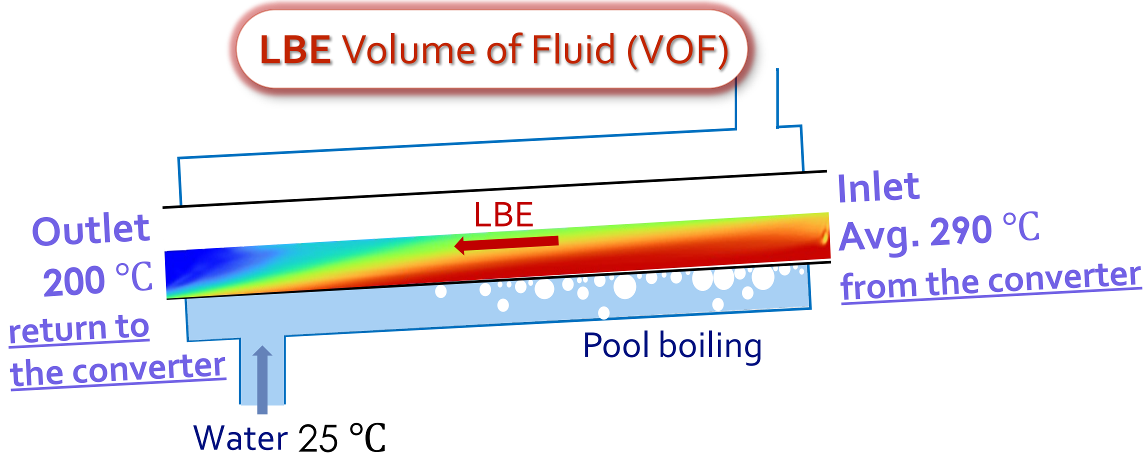
Continuation of Work

LBE loop heat exchanger (HX) design/evaluation



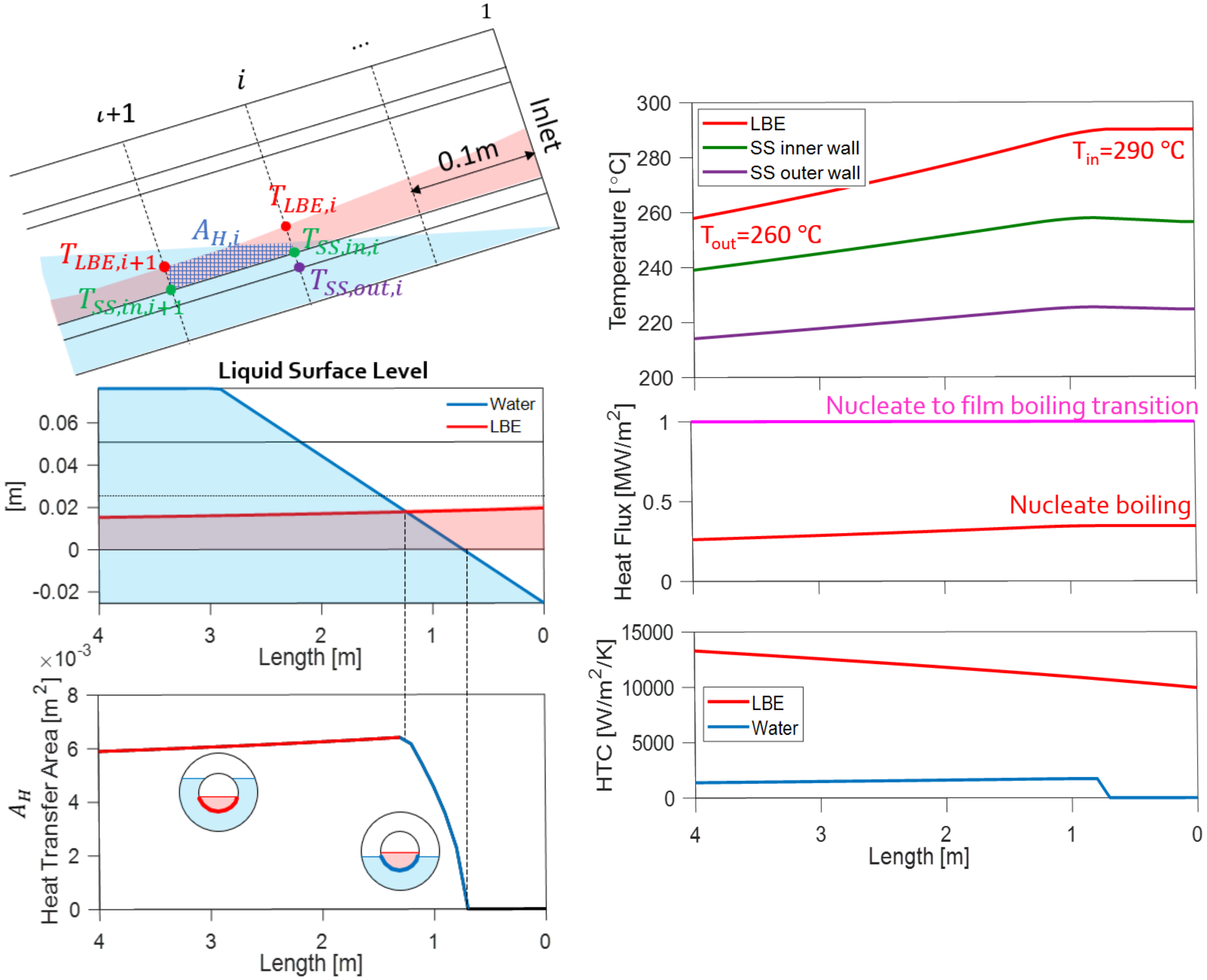
Water RPI Wall Boiling

LBE – SS – Water CHT

- HX length and angle (e.g., 4 m 2° downward tilt)
- HX location (e.g., supply line with a complete full pipe)
- HX shape (e.g., multiple tube configuration)

…

Preliminary analytical studies using empirical correlations



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Acknowledgement

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