EX-Fusion

Development of a Mod-Sim Workflow for Multiphysics Assessment in EX-Fusion’s Laser Fusion Test Chamber

IAEA Digital Engineering for Fusion Energy Research workshop
MIT Plasma Science and Fusion Center
December 9th, 2025

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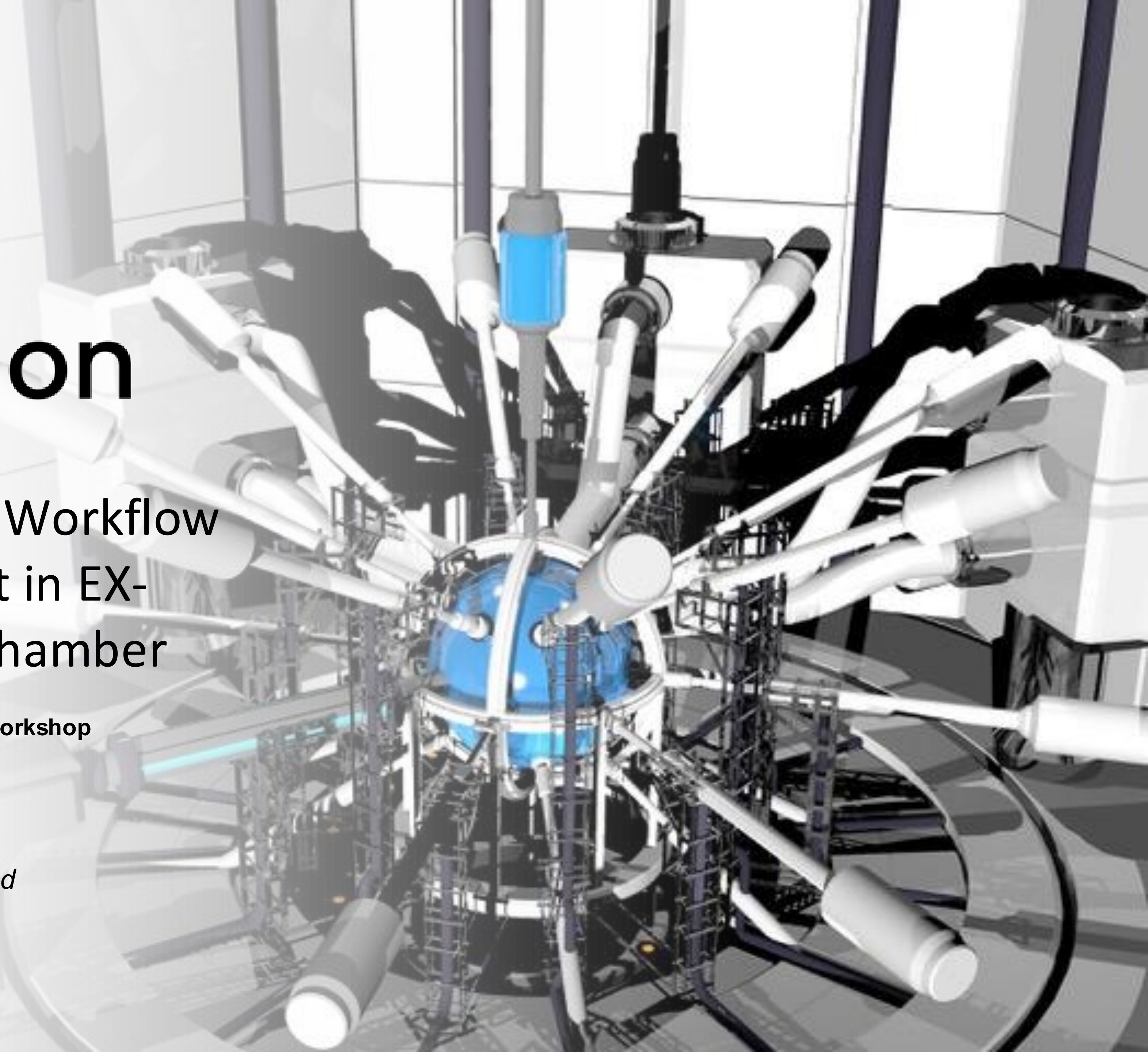
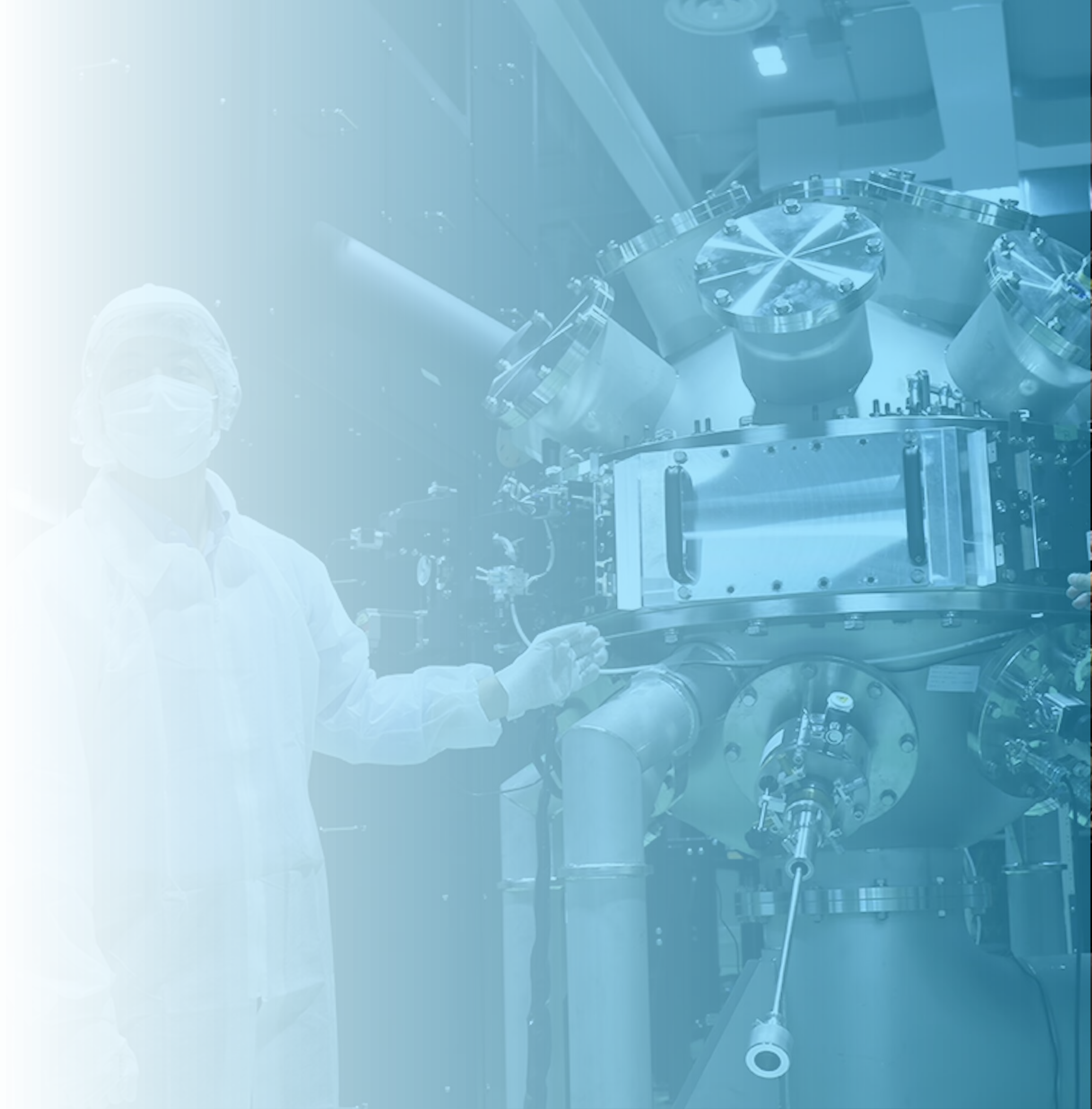


(I) INTRODUCTION



1.1. About EX-Fusion

~50 people

Osaka, Headquarters

Kyoto, Laser Processing

United States,
Reactor systems

Tokyo, lead-lithium
synthesis

Hamamatsu, R&D

Australia

R&D Partners Japan

- 大阪大学 OSAKA UNIVERSITY
- 京都大学 KYOTO UNIVERSITY
- NIFS
- Institute of SCIENCE TOKYO
- 名古屋大学 NAGOYA UNIVERSITY
- 光産業創成大学院大学 GPI
- QST
- NIMS

R&D Partners U.S.A

- OAK RIDGE National Laboratory
- INL Idaho National Laboratory
- SRNL SAVANNAH RIVER NATIONAL LABORATORY
- Lawrence Livermore National Laboratory
- SLAC NATIONAL ACCELERATOR LABORATORY
- GENERAL ATOMICS
- Berkeley UNIVERSITY OF CALIFORNIA

1.2. Direct Drive Fast ignition

Fast ignition is **10x more efficient** in energy transfer compared to central ignition (NIF)
… or requires **one tenth** the laser power

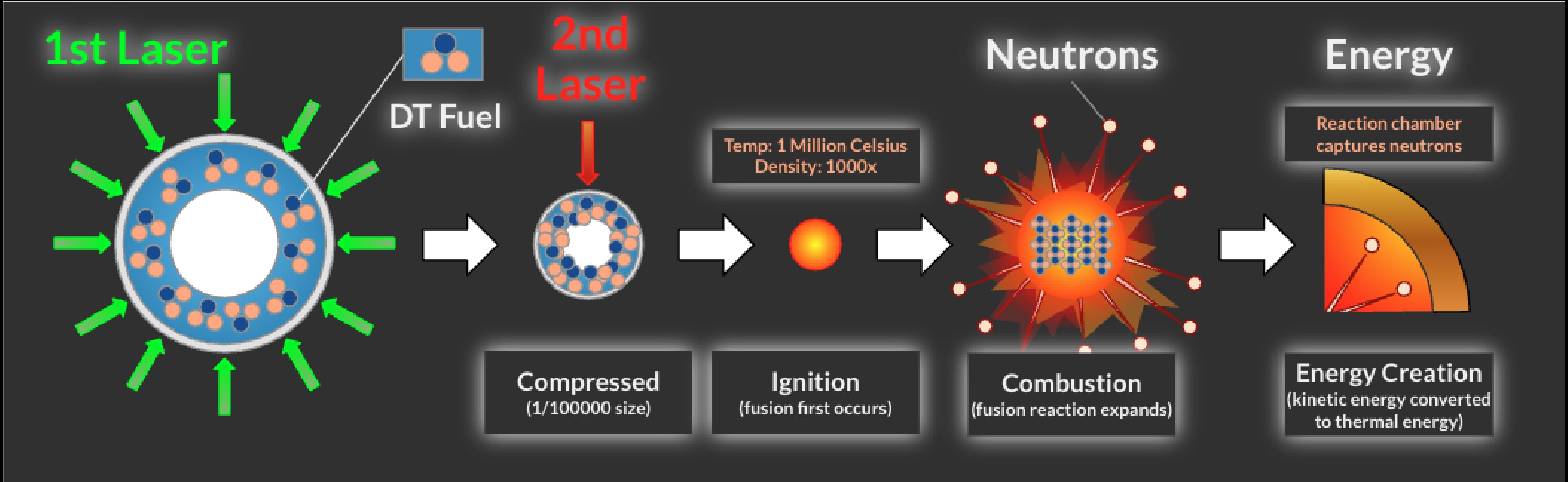
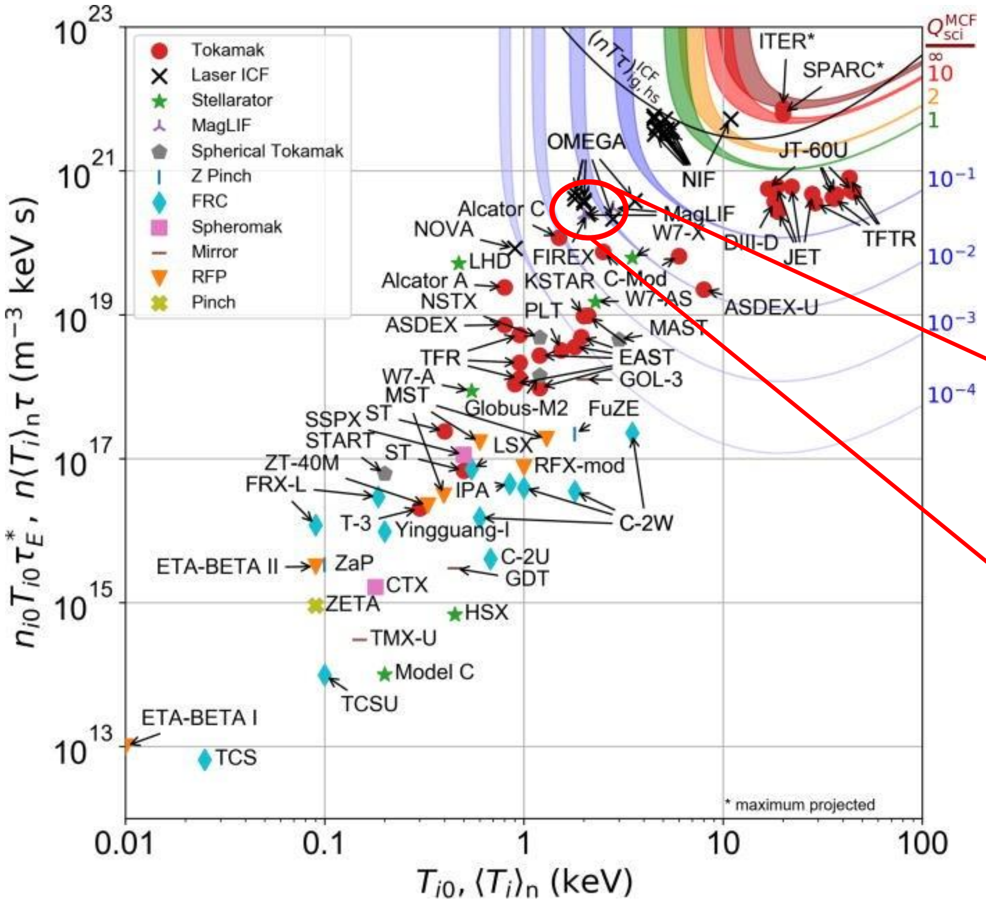
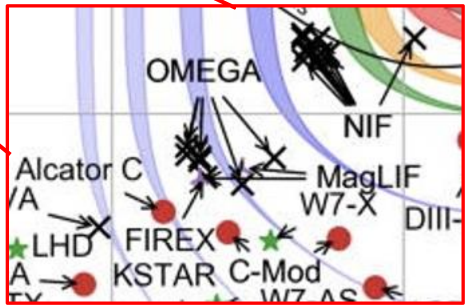


Illustration of Fast Ignition Laser Fusion

Author: Max Monange

1.2. Direct Drive Fast Ignition





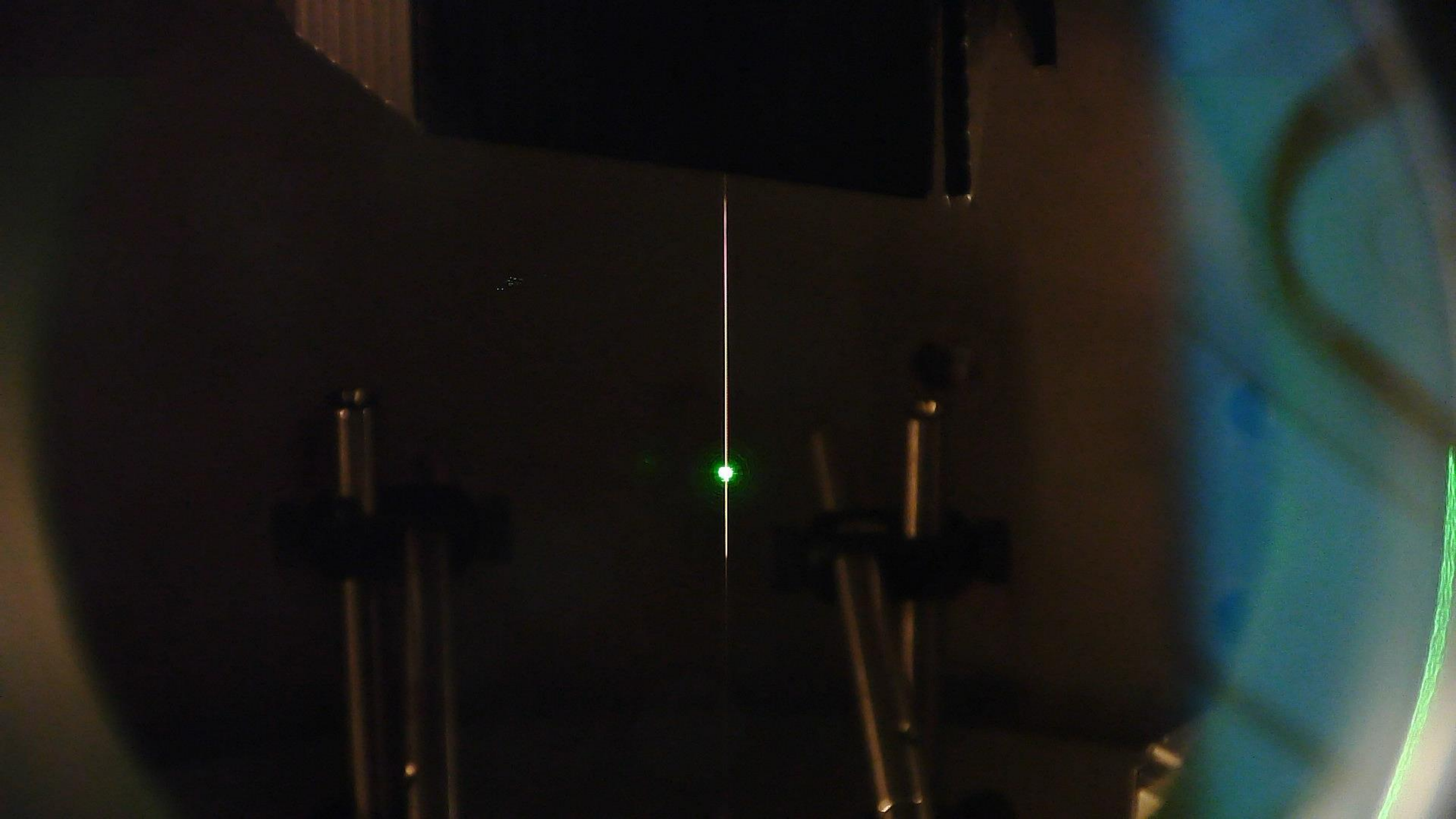
Physics of Plasmas. 2022;29(6). doi:10.1063/5.0083990

Central Ignition, NIF (Indirect Drive):
H. Abu-Shawareb *et al., Phys. Rev. Lett.* 129, 075001 (2022)

OMEGA (Direct Drive):
V. N. Goncharov *et al, Phys. Plasmas* 21, 056315 (2014)

Fast Ignition, FIREX (Direct Drive + External Heating):
K. Matsuo *et al., Phys. Rev. Lett.* 124, 35001(2020)

Author: Max Monange



1.3. Development Roadmap: Towards a Commercial Plant

Repetition rate is one of the most important parameters to prove that laser fusion is a commercial endeavour, not just a demonstration

	Grid Power Input	Electricity to laser diode efficiency	Laser Power Output	**High frequency laser operation**	Steady State Output	Estimated Energy Gain	Thermal Output	Power cycle efficiency	Electric Output	
2022 NIF	400 MJ	<1% efficient	2.05 MJ (≈10kJx 192)	Q_s = 4	8.4 MJ	8 hours per shot	–	–	–	
2040 Commercial XF-1400	15 MJ	>10% efficient	1.5 MJ	Q_s = 200	300 MJ	**10 Hz**	3,000 MW_t	~33% efficient	1,000 MW_e	Q_{grid}= 7

Price of elec.
$/kwh

$0.05/kWh

Author: Max Monange

1.4. Reactor Roadmap

2024

Phase 0
Target engagement

2027

Phase I.I
Low flux neutron demo
0.1 - 1 kJ laser
10^4-10^5 n/source
5 - 10 Hz

2030

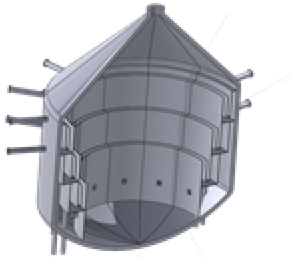
Phase I.II
High flux neutron demo
8-12 kJ laser
10^{11}-10^{13} n/source
10 Hz

2029 - 2032

Phase II
Scientific breakeven

Q = 0.1 -1
1-shot chamber
Osaka Institute of Laser Engineering (ILE) contract

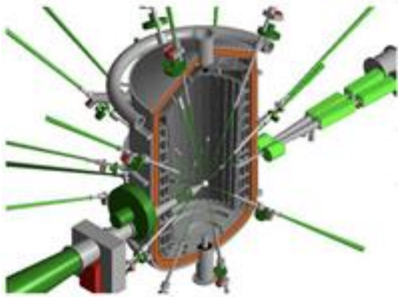
2035



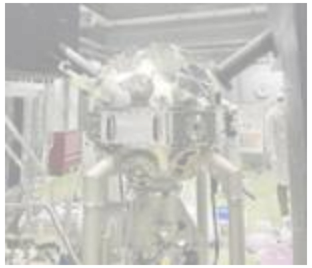
IGNIS

2040+

SOLLIS
Commercial FOAK



1.4. Reactor Roadmap



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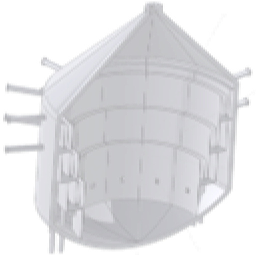

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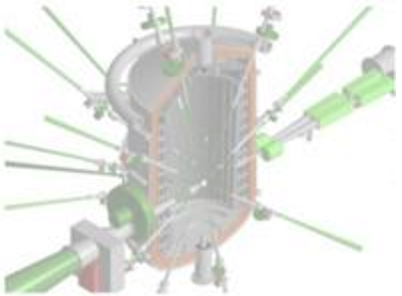

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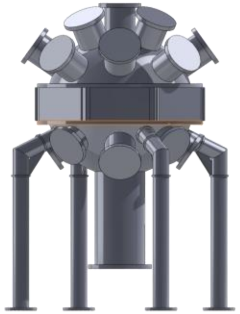
1.5. Considerations: Key Parameters for Phase I

<u>Conditions for Phase I.I (2027)</u>

- **Chamber shape**: Spherical test chamber
- **Chamber radius**: 0.5 m
- **Surface area**: 1.74 m^2
- **Laser energy**: 1kJ
- **Neutron yield**: 10^4-10^5 n/shot
- **Repetition rate**: 10Hz
- **Input power**: 10 kW
- **Energy reflection**: 80% reflectivity from the pellet
- **Output power**: 8 kW
- **Intensity**: 8,000 W / 1.74 m^2 = 4,597 W/m^2
- **Operational time**: 1 hour
- **Fuel type**: DD



<u>Conditions for Phase I.II (2030)</u>

- **Chamber shape**: Cylindrical test chamber
- **Chamber axial radius**: 0.6 m (Height = 2m)
- **Surface are**: 8.3 m^2
- **Laser energy**: 8-12 kJ (~10 kJ)
- **Neutron yield**: 10^{11}-10^{13} n/shot
- **Repetition rate**: 10Hz
- **Input power**: 100 kW
- **Energy reflection**: 80% reflectivity from the pellet
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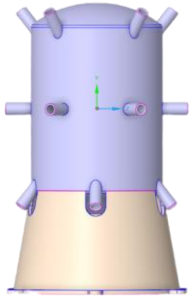

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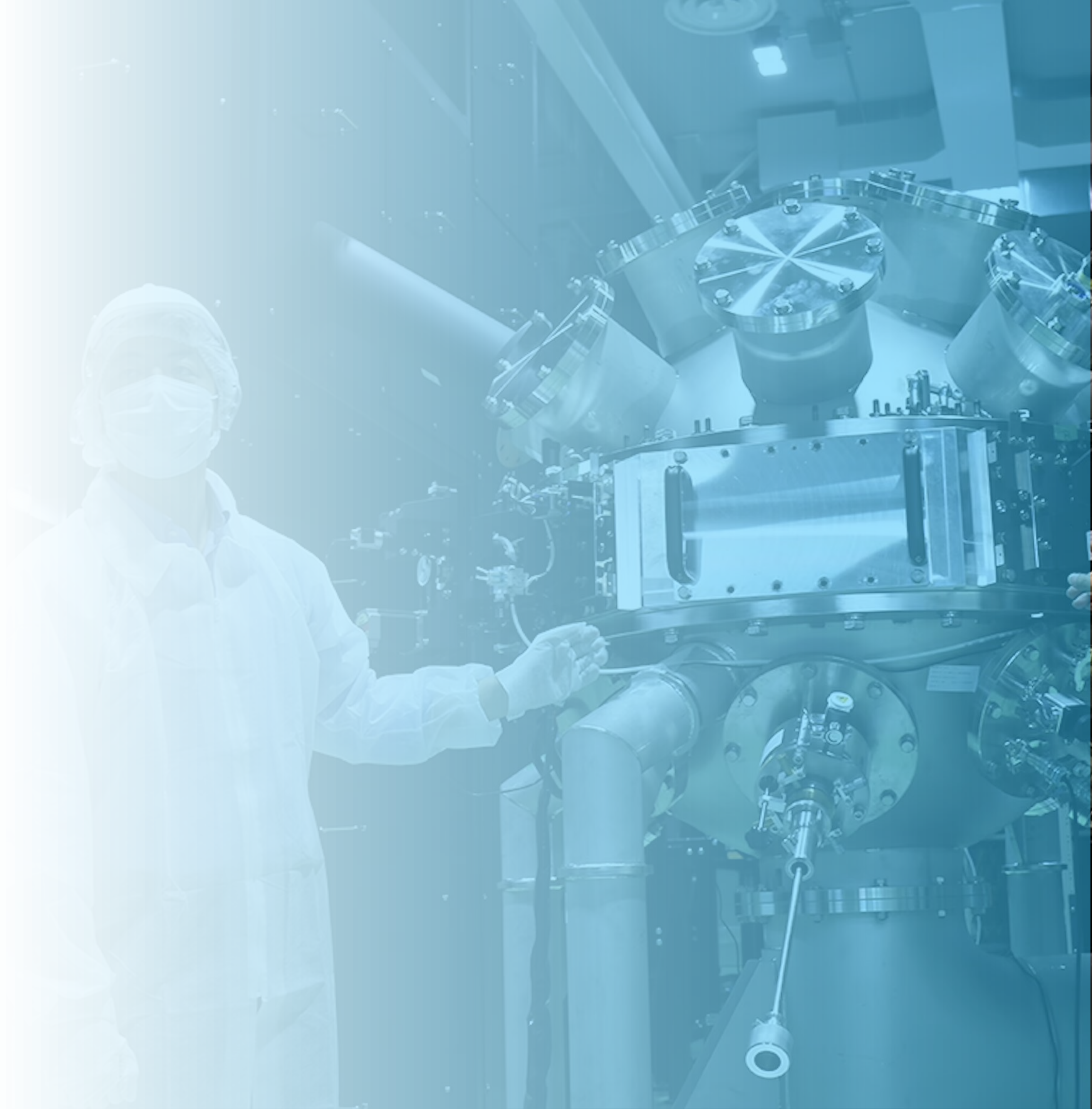
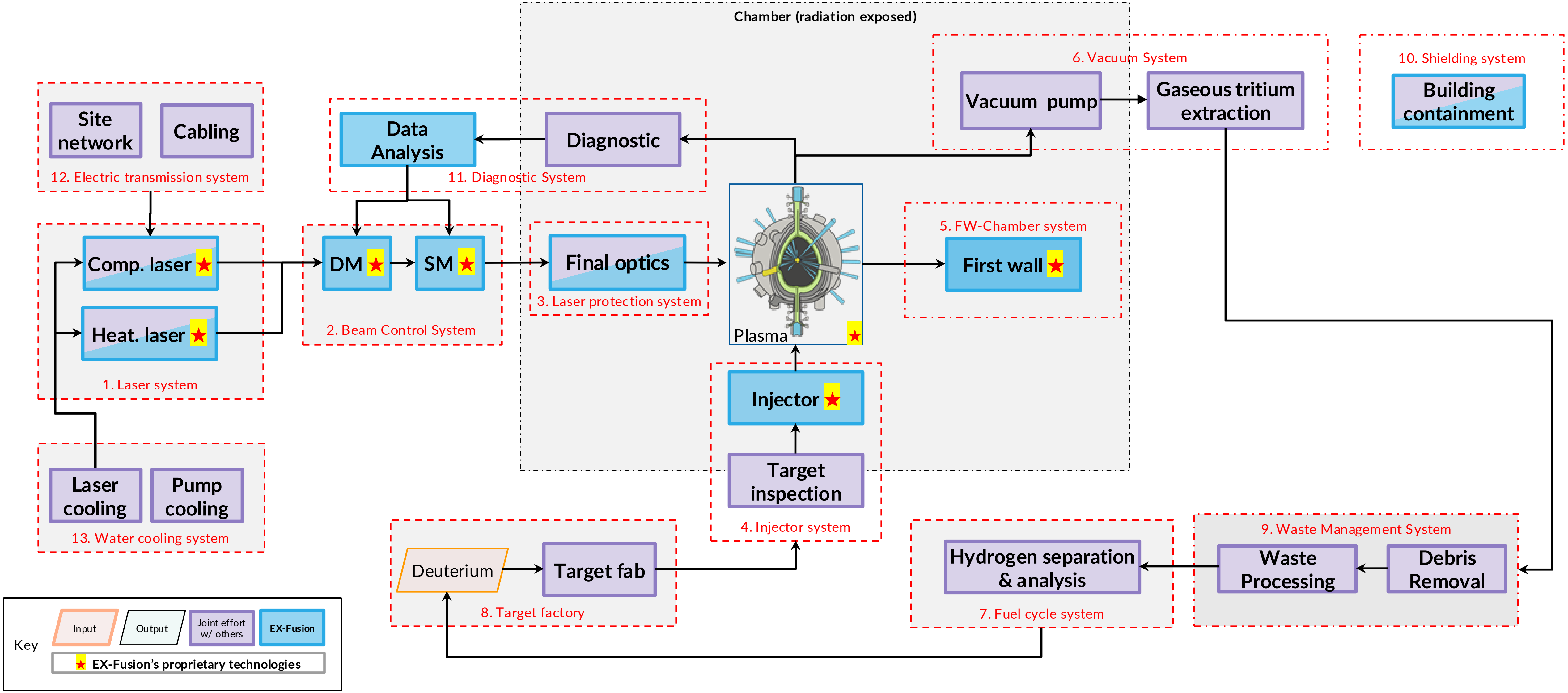
(II) SYSTEMS ENGINEERING PERSPECTIVE



2.1. Continuous Neutron Demonstrator (Phase I)

Systems Map



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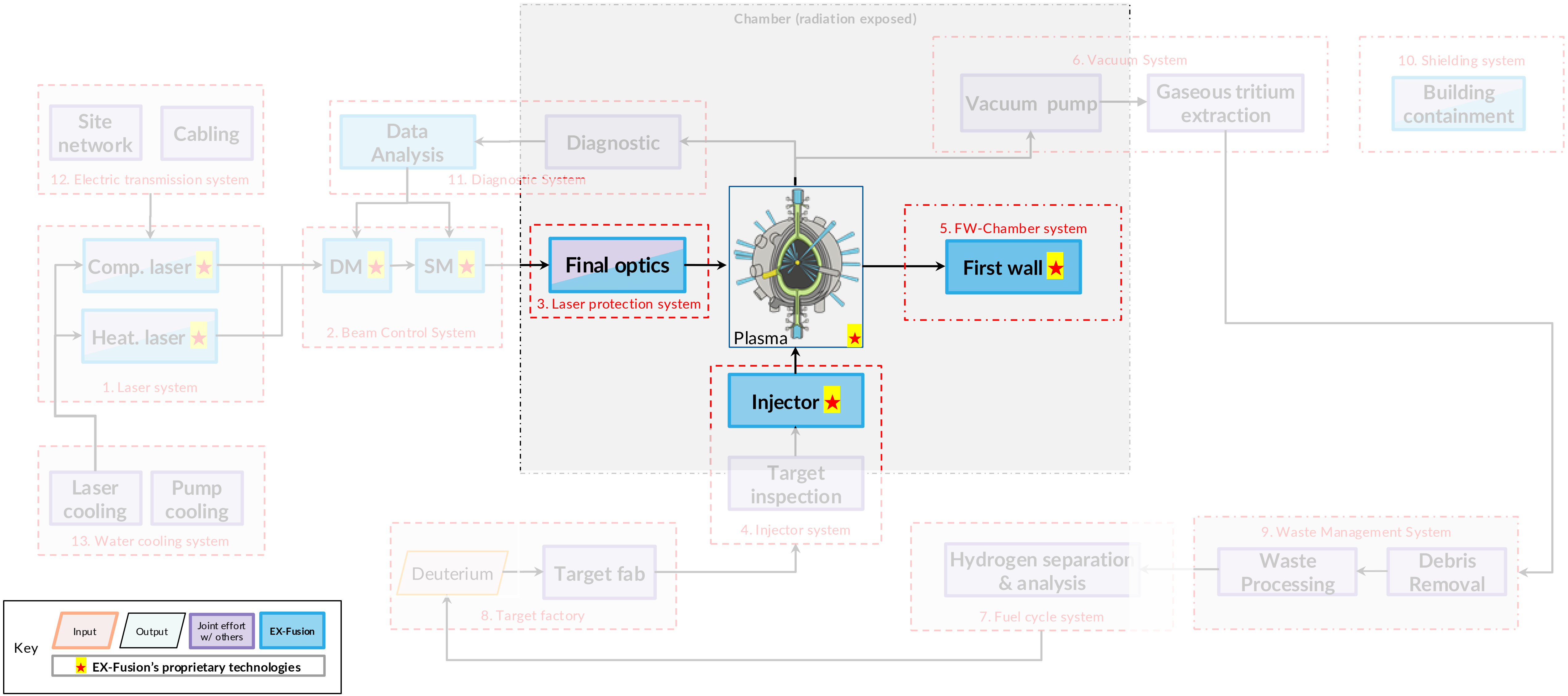
2.1. Continuous Neutron Demonstrator (Phase I)

Reactor Team's scope



Author: Max Monange

2.2. Continuous Neutron Demonstrator (Phase I)

Multiphysics requirements

Experimental Facility

- Radiation Safety
  - Tritium transport studies
    - T accountancy
    - In vessel tritium retention
    - Losses in gaseous extraction system
    - Circulation in the room
  - particle transport studies
    - Component vs. system vs. facility level
    - Shielding Analysis
    - Dose rate (during operations / after shutdown)
    - Activation analysis (+ rad waste management)
    - Variance reduction for Monte Carlo simulation
- Economical considerations
  - Chamber integrity ↔ Final optics design
  - Chamber integrity
    - particle transport studies
    - mechanical studies
    - CFD studies
      - Chamber material selection
      - Chamber shape
      - Temperature profile
      - Von Mises stress profile
      - Cooling
      - Cracking
      - Failure point studies
  - Final optics design
    - particle transport studies
      - Maximum allowable load
      - Distance requirements
      - Material selection

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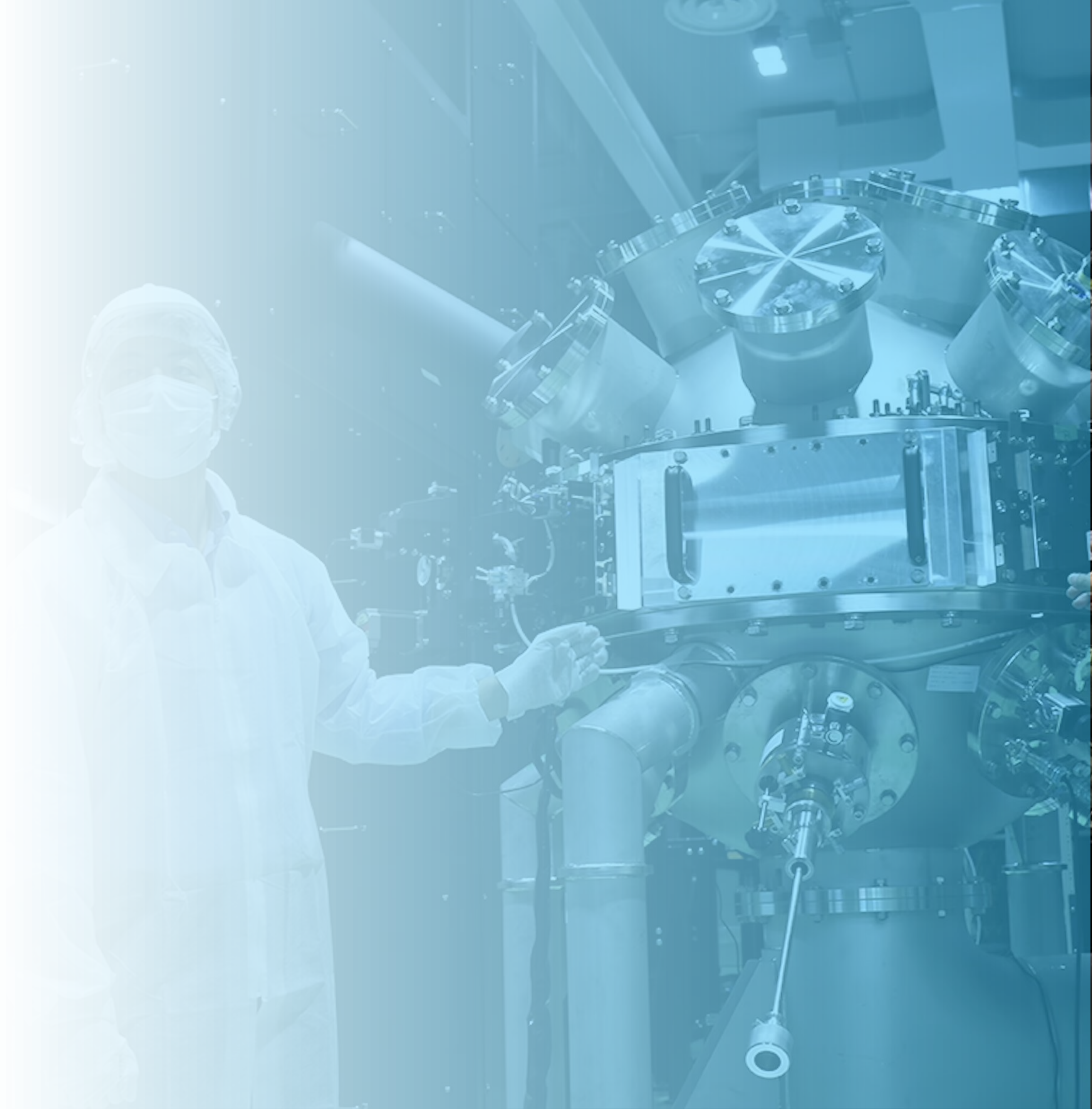
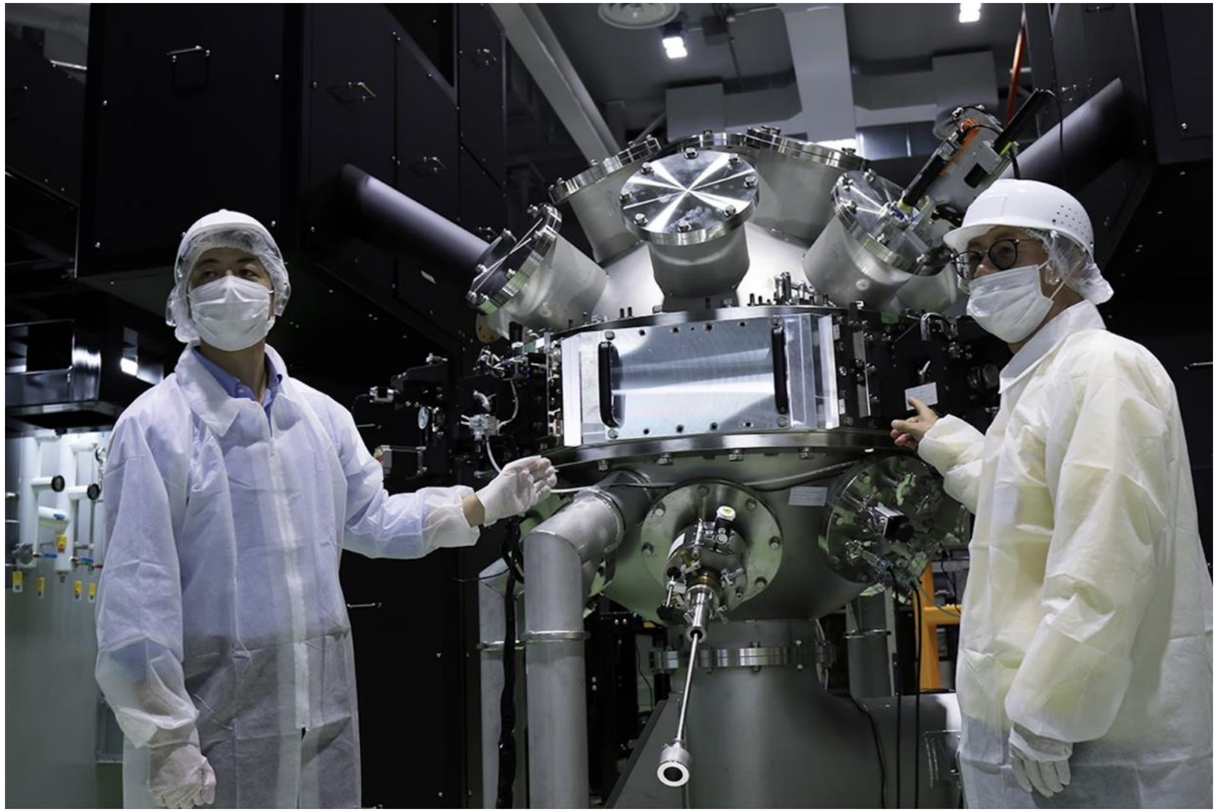
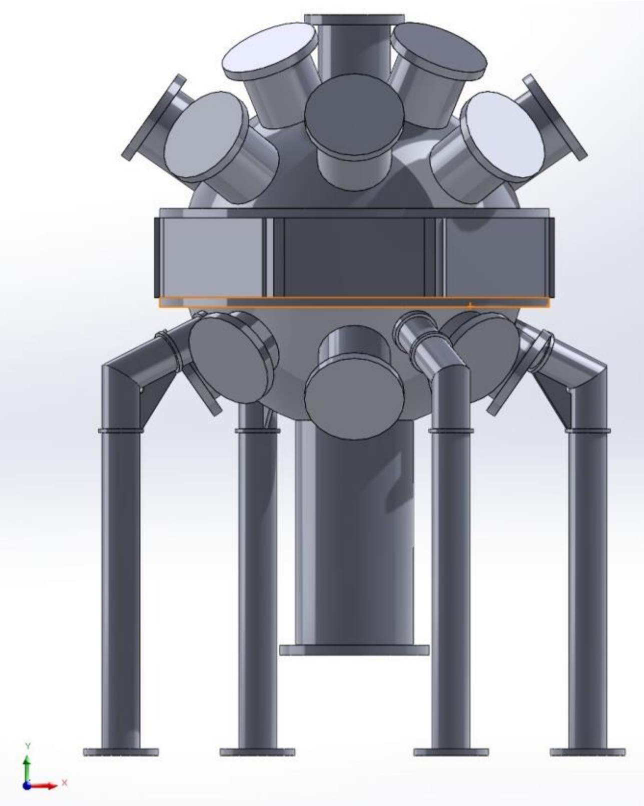
(III) CHAMBER MECHANICAL STUDIES



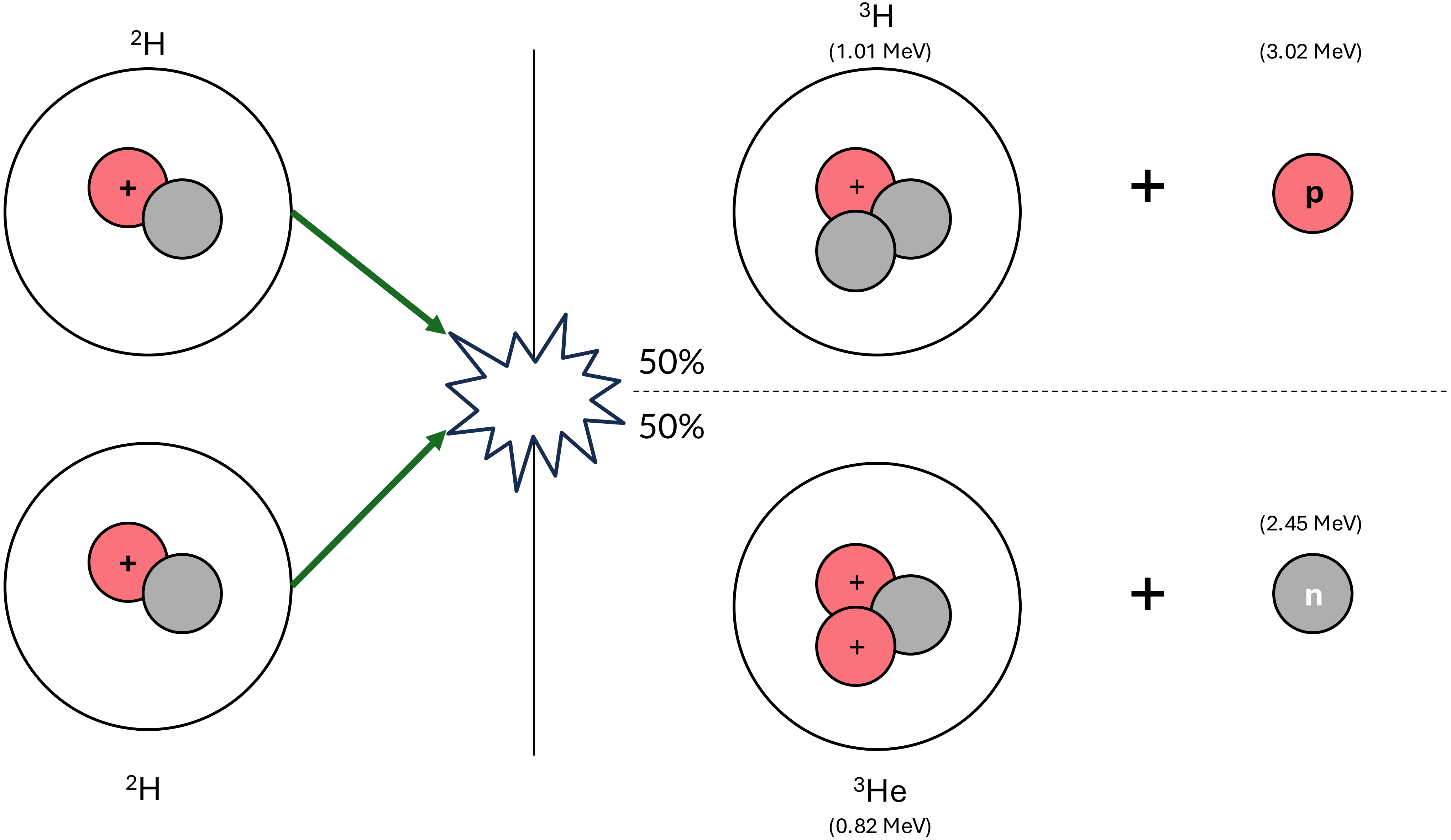
3.1. Considerations: CAD Model





Author: Max Monange

3.1. Considerations: DD Fusion



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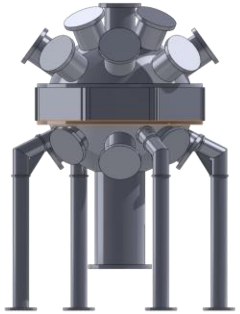

Conditions for Phase I.II (2030)

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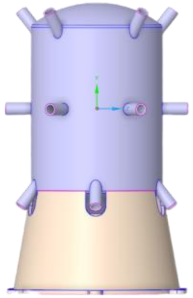


Author: Max Monange

3.1. Considerations: Neutron number depends on laser input energy

1. **Implosion-Mimic Laser**:
- Four-beam
- 0.53 µm wavelength
- 4 J per 10 ns pulse
- 10 Hz

2. **Heating-Mimic Laser**:
- Two-beam
- 0.8 µm wavelength
- 0.2J per 100 fs pulse (2TW)
- 10 Hz

➢ Upgrades are planned to achieve 10 TW (0.6 J/60 fs).

Author: Max Monange

3.1. Considerations: Energy deposition

Laser energy

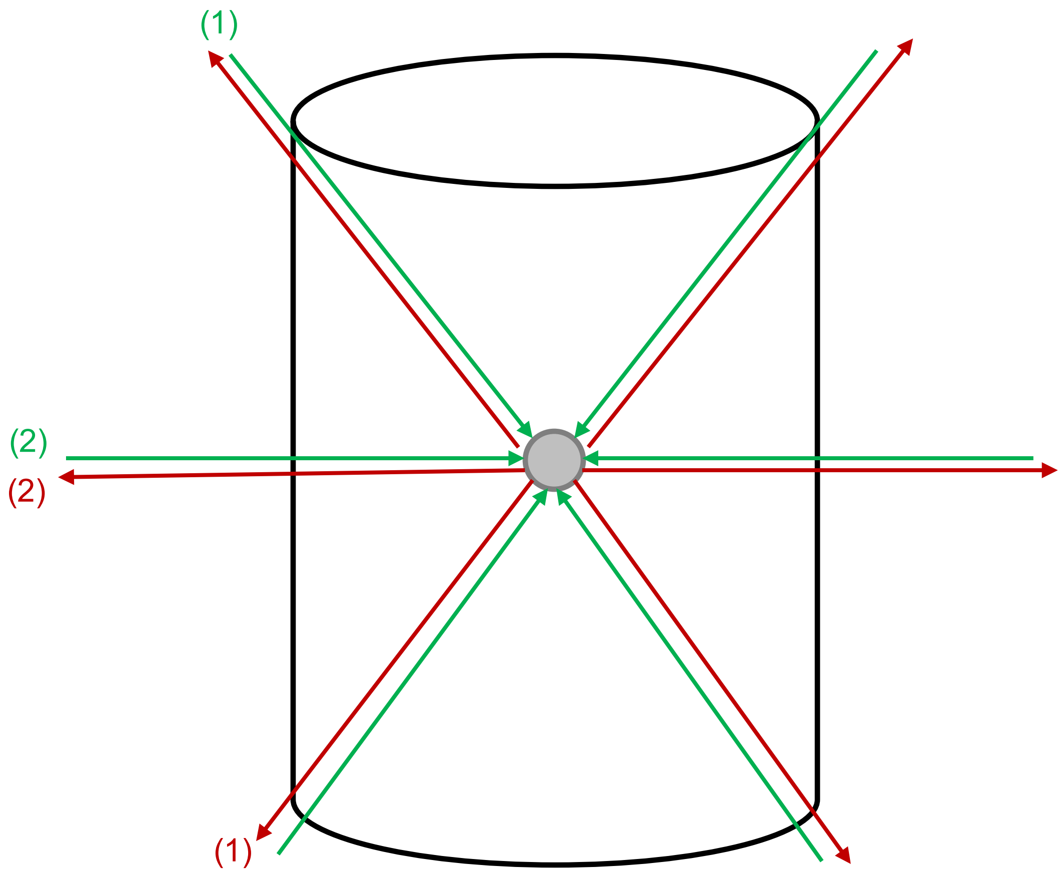
- Key phenomenon: **laser reflection**
- At low laser input energies, **~20%** of the laser energy is **coupled** to the pellet
- The rest (80%) is reflected off the target

Particles

- At low fluences (10^4–10^{13}/n/shot/area), the energy deposition from neutrons (2.45 MeV in DD fusion), protons (3.02 MeV), and other particles in **negligible** on nuclear heating **if** the particle distribution is uniform across the chamber

➢ 10^{-9}J/shot for for Phase I.I

➢ 5.2 – 6.5 J/shot/area for Phase I.II

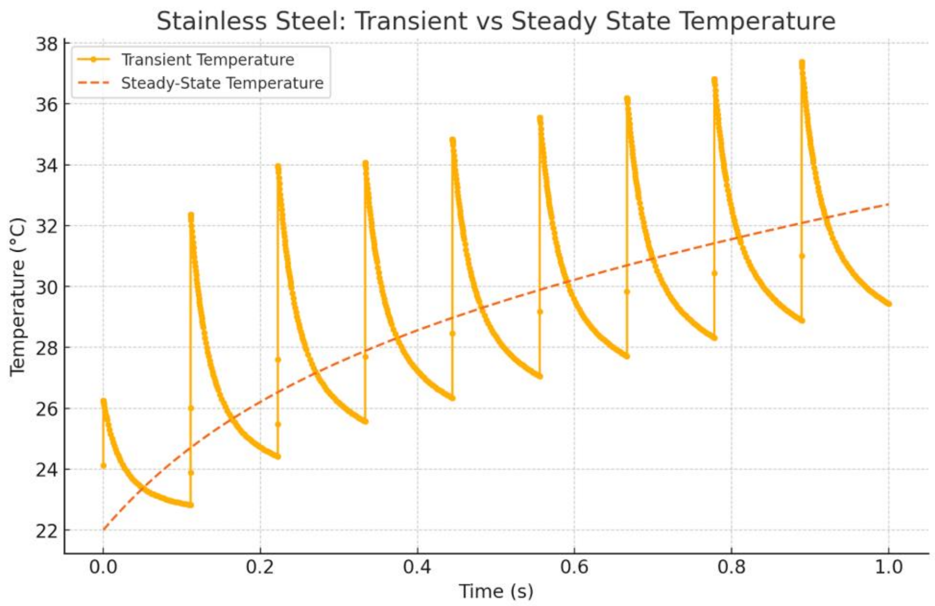


Author: Max Monange

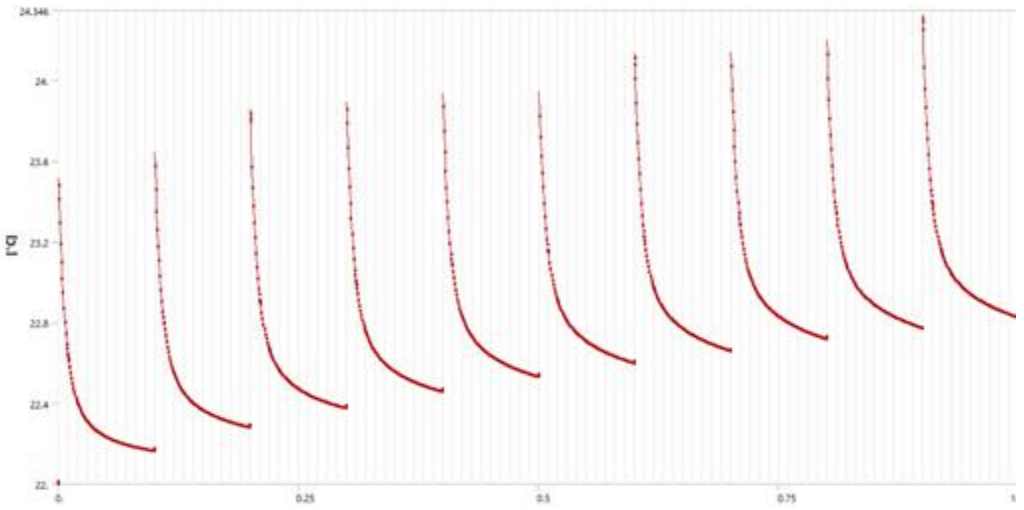
3.1. Considerations: Note on the heat source (Transient vs. Steady State)

- Pulsed transient thermal simulation operating at 10 Hz for extended time periods is too **computationally expensive**
- Both the transient and steady-state sources produced similar results in terms of temperature increase.

➢ Therefore, the steady-state heat source was used for the thermal shock studies



Comparison between transient and Steady-state heat source impact on Stainless Steel in a 1 second run time.



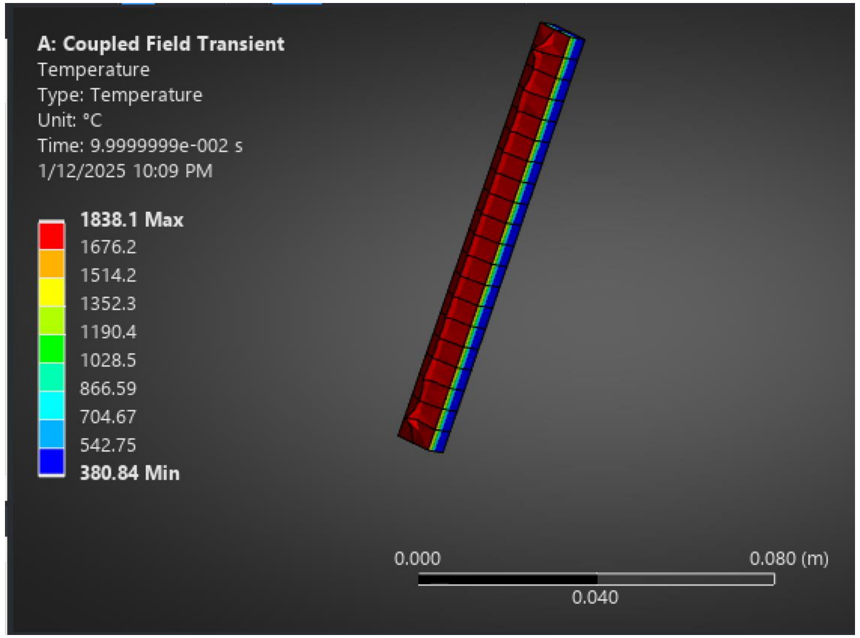
Pulsed surface temperature vs. time (10 shots) with refined timestep

3.2. Chamber material selection

- Steady-state thermal simulation with a constant surface heat flux (80 kW)

Material	Temperature Limit [°C]
Stainless Steel 316L	415
Aluminum 6064	205
Titanium Grade 1	315
Zircaloy Z4	400
Tungsten	850
RAFM Steel	550

Materials with their temperature limits [ASME BPV] and Maximum Allowable Operational Time (MAOT)



Ansys simulation showing thermal response of bare ODS FeCrAl first wall sample at commercial reactor conditions

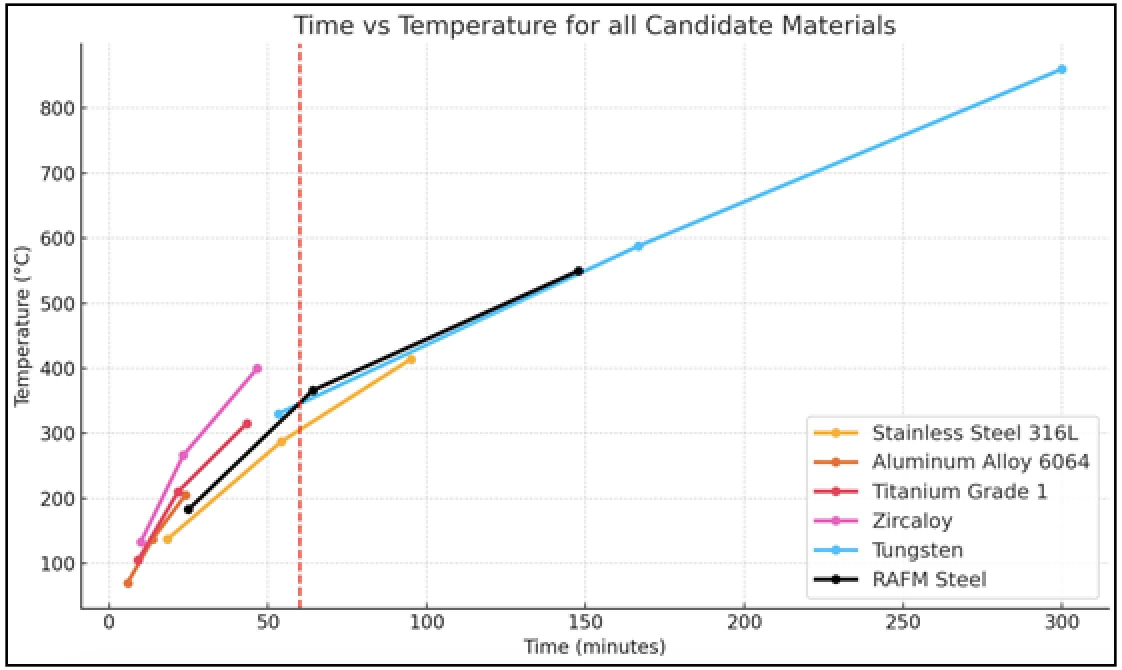
Author: Max Monange

3.2. Chamber material selection

- MAOT = time at which the material reaches its maximum allowable temperature

Material	Temperature Limit [°C]	MAOT [min]
Stainless Steel 316L	415	90
Aluminum 6064	205	25
Titanium Grade 1	315	40
Zircaloy Z4	400	45
Tungsten	850	300
RAFM Steel	550	145

Materials with maximum allowable temperature limits [ASME BPV] and Maximum Allowable Operational Time (MAOT)



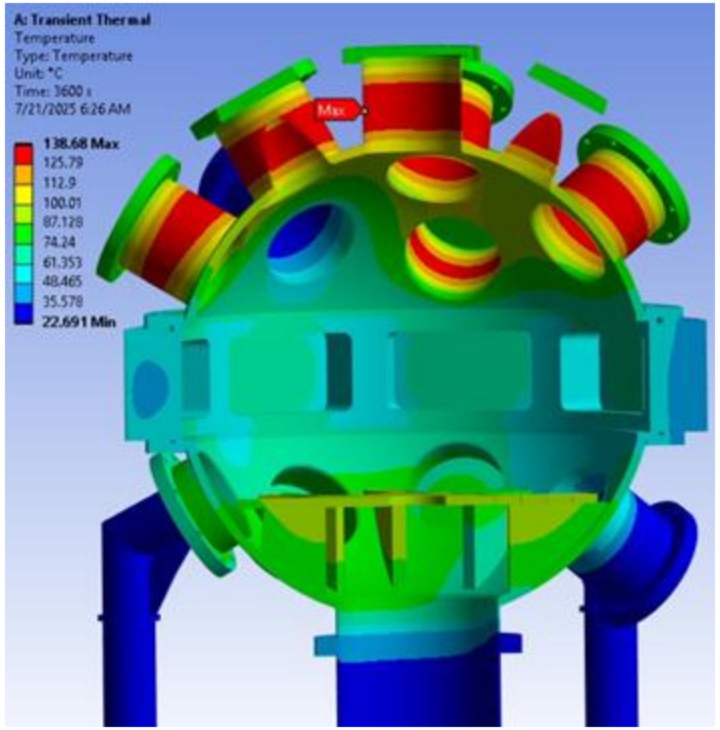
Time dependent temperature evolution of material candidates with constant 80 kW surface heat flux applied

- Only three materials passed: **Stainless Steel 316L, Titanium Grade 1, and RAFM Steel**

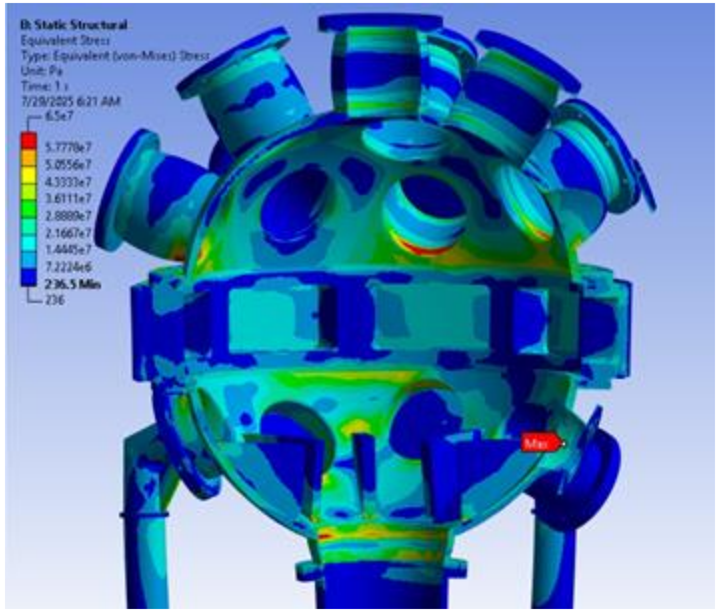
Author: Max Monange

3.3. Temperature & Stress Profile [Phase I.I]

- **Source:** surface heat flux of 4.6 kW/m^2
- **Module**: Ansys Transient Thermal



Temperature distribution profile



Static Structural Stress Analysis

Author: Max Monange

3.3. Temperature & Stress Profile

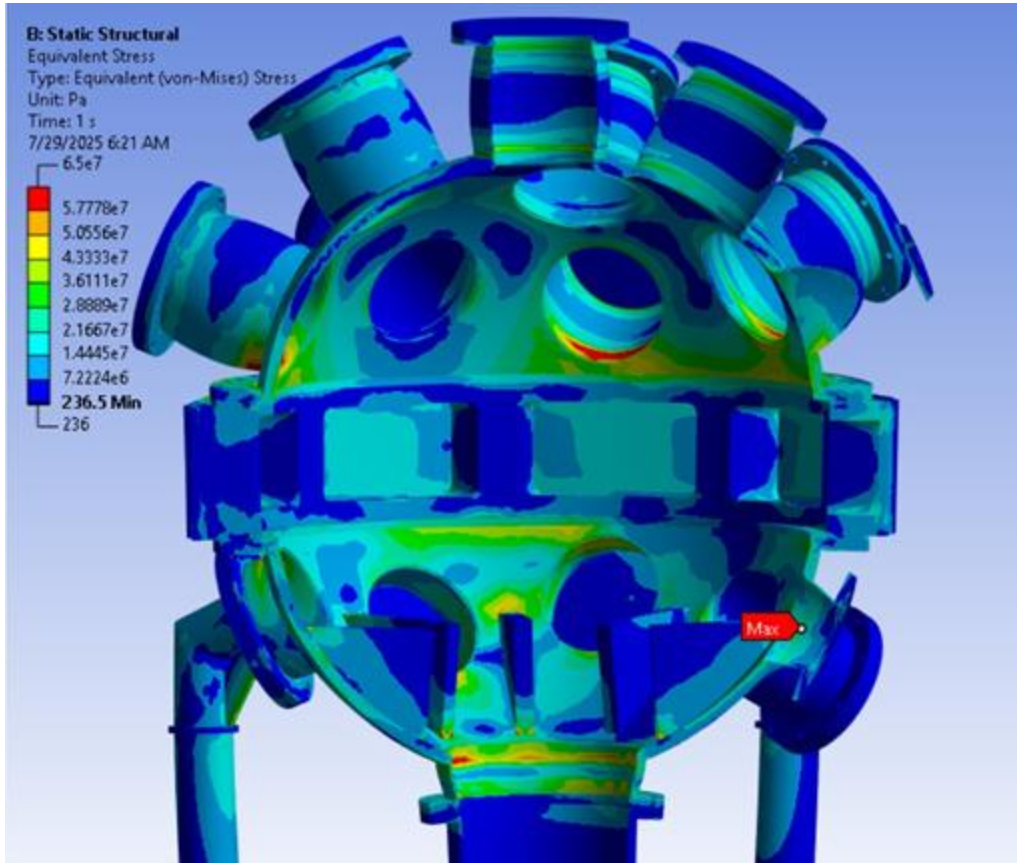
Material temperature	1 % Yield strength of Stainless steel, Rp 1.0	Tensile strength of Stainless steel, Rm
100 / 212 °C/°F	>= 199 / >= 28.9 N / mm² / ksi	430 / 62.4 N / mm² / ksi
200 / 392 °C/°F	>= 167 / >= 24.2 N / mm² / ksi	390 / 56.6 N / mm² / ksi
300 / 572 °C/°F	>= 145 / >= 21.0 N / mm² / ksi	380 / 55.1 N / mm² / ksi
400 / 752 °C/°F	>= 135 / >= 19.6 N / mm² / ksi	380 / 55.1 N / mm² / ksi
500 / 932 °C/°F	>= 128 / >= 18.6 N / mm² / ksi	360 / 52.2 N / mm² / ksi

Properties of AISI 316 / 316L stainless steel sheets and plates

[Source: mirrorinox]

Author: Max Monange

3.3. Stress Profile: Comments [Phase I.I]



Static Structural Stress Analysis

Yield Stress

- Maximum Von Mises stress of ~**60 MPa** | Maximum T of **138°C**
  - Compared to yield strength of **~180 MPa @140°C**

Assumptions

- This is a very simplified model - we will add:

(1) **Ray tracing / direct ordinate simulation** for more accurate temperature distribution, especially inside the beam ports

(2) **Appropriate cooling mechanism (no cooupling)**

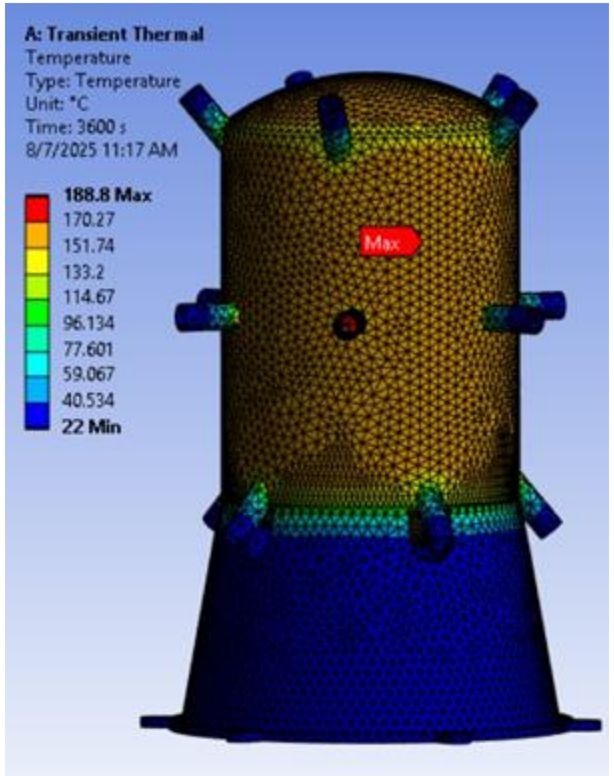
- We assumed natural convection air cooling
- But we need to take in account locational dependence of the heat transfer coefficient (varies based on T gradient, fluid velocity)

Next step

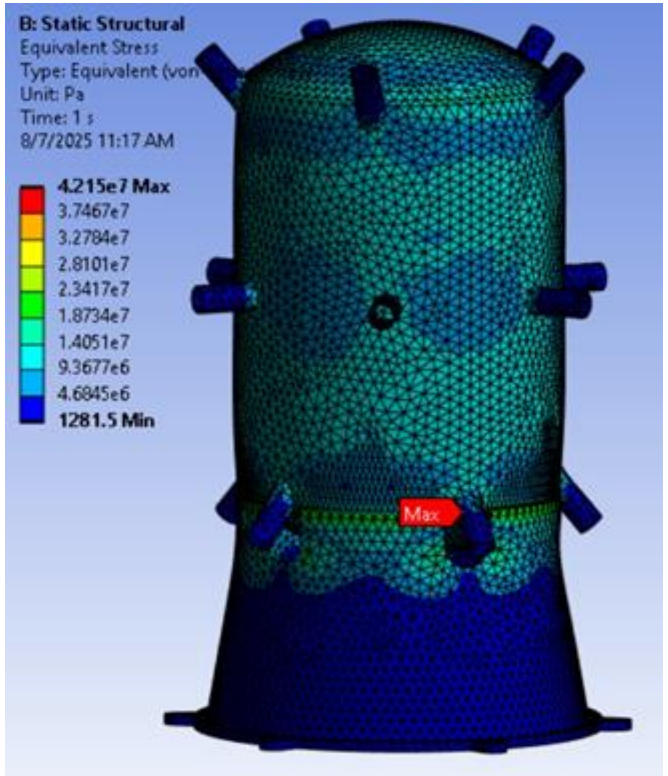
- Model validation via experiment in Osaka ILE

3.4. Temperature & Stress profile [Phase I.II]

- **Source:** surface heat flux of 9.6 kW/m^2
- **Module**: Ansys Transient Thermal



Chamber temperature profile



Static Structural Stress Analysis

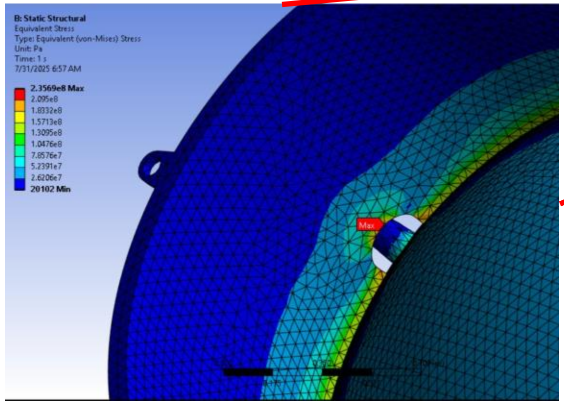
Note: No coupling i.e., no convective air cooling in the room

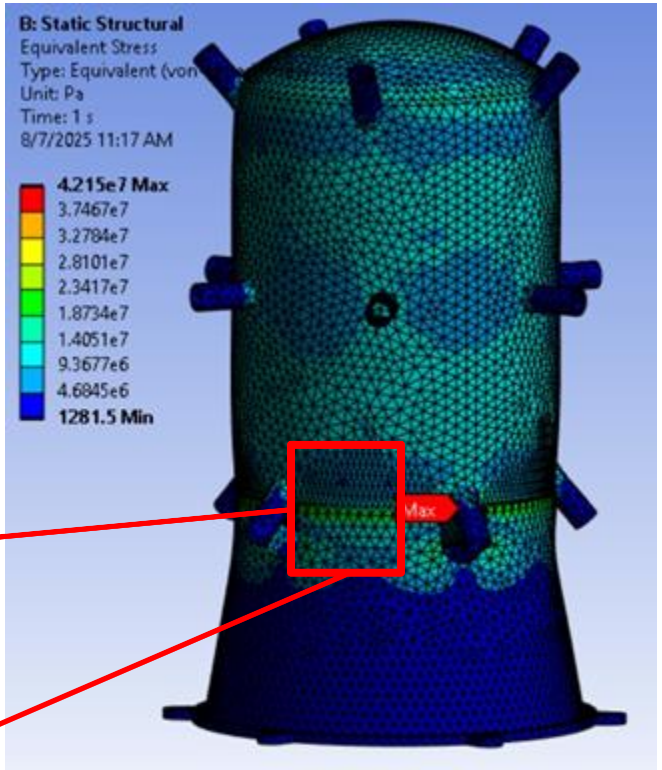
3.4. Temperature & Stress profile [Phase I.II]: Comments

Note: No coupling i.e., no convective air cooling in the room

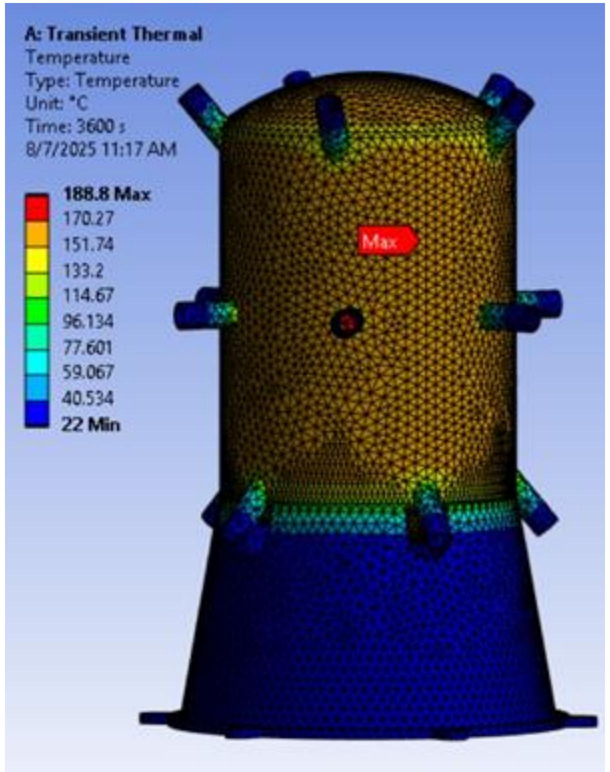
Comments

- Max temperature: 188°C
- Max stress: 42 MPa (Yield is ~180 MPa)
- Highest stress concentration where the chamber rests on the skirt





Static Structural Stress Analysis

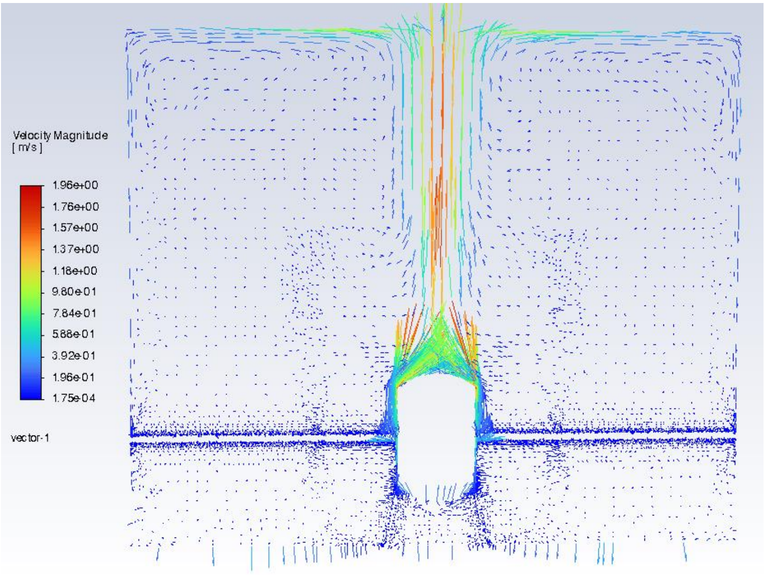


Temperature distribution profile

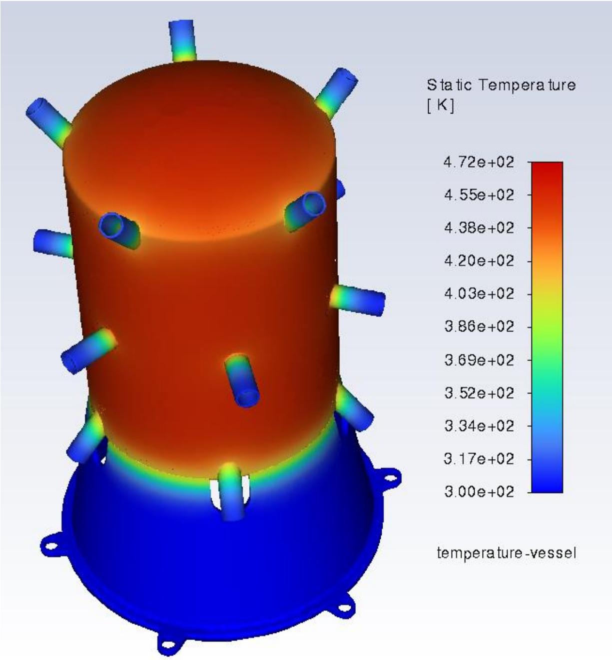
Author: Max Monange

3.5. CFD Temperature Profile [Phase I.II]

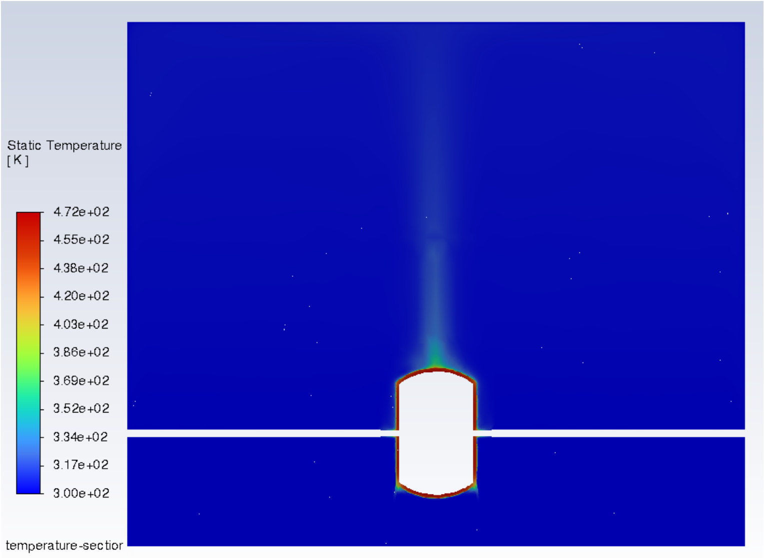
- **Module**: Ansys Fluent
- New temperature profiles with appropriate cooling



Air velocity profile after 60min of operations
(Max velocity = 2m/s)

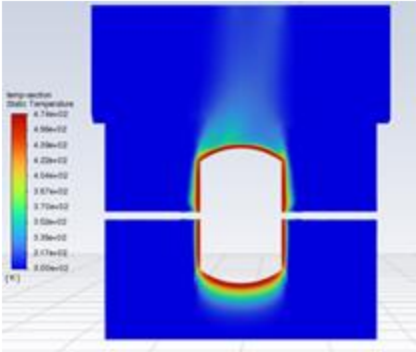


Chamber temperature profile after 60min of operations
(Max T = 198°C)



Room temperature profile (8m x 10m)

3.5. CFD to Static Structural Stress Coupling



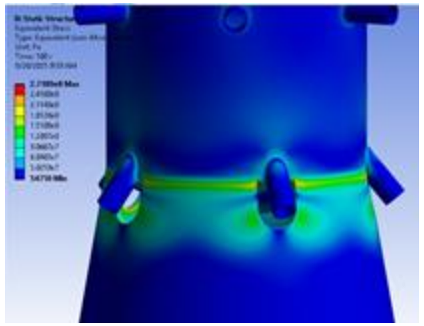
CFD
(heat transfer)

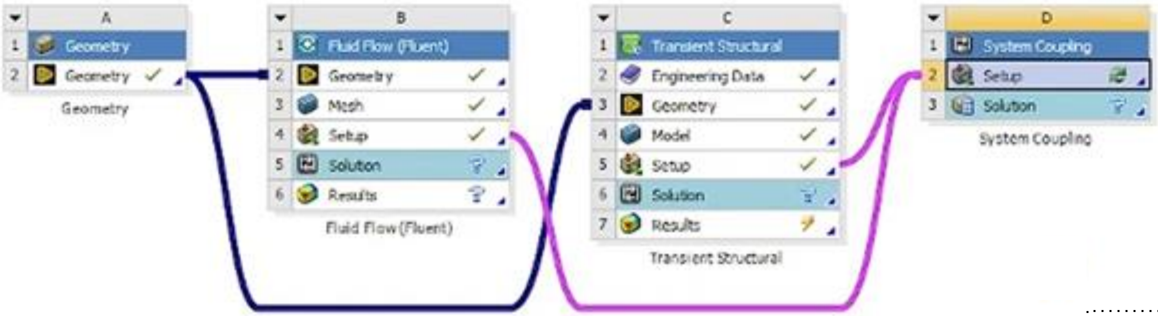
Ansys FLUENT

Temperature →

Structural

Ansys



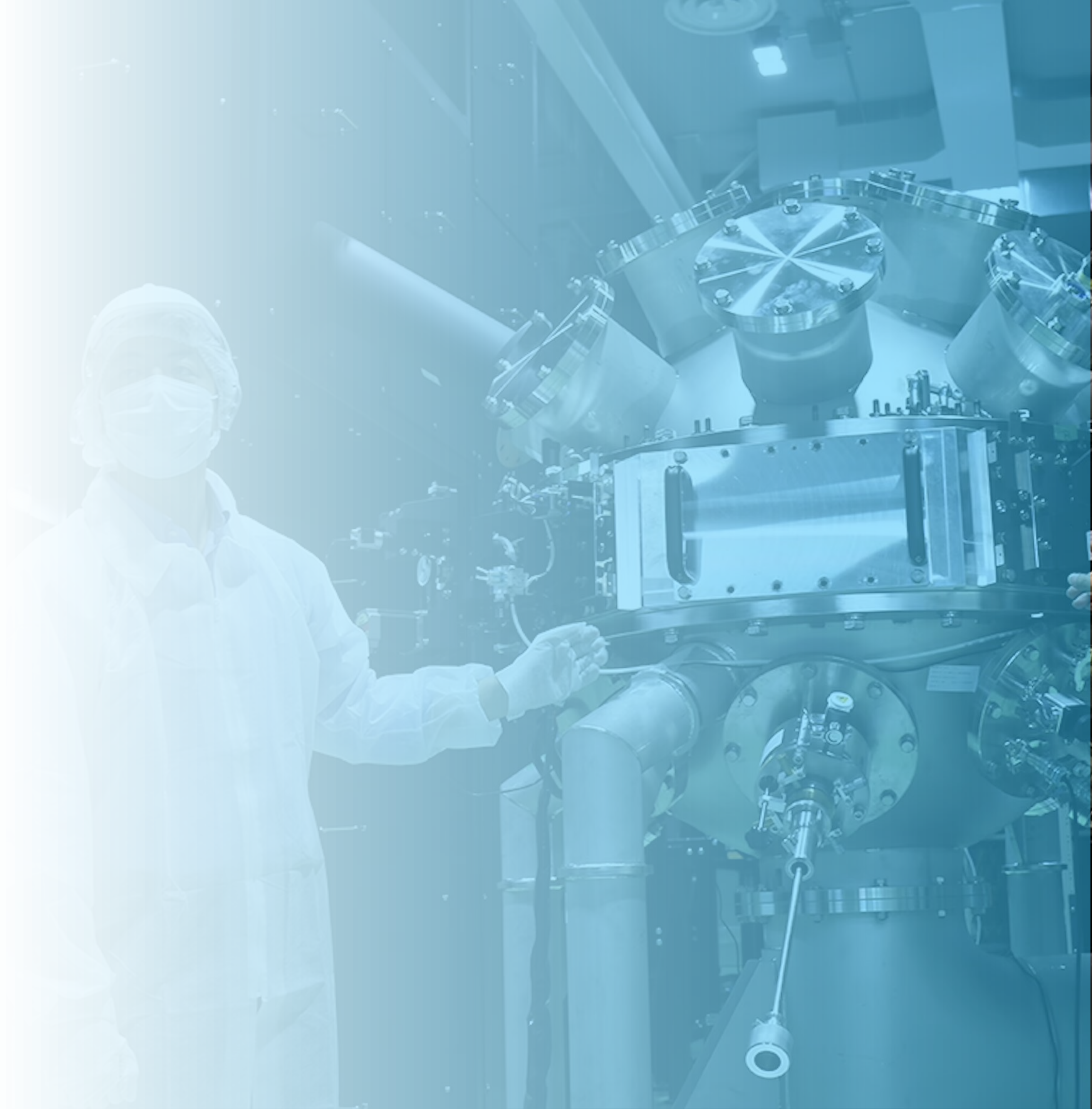


Fields passed between codes

Software

Author: Max Monange

(IV) CHAMBER NEUTRONICS



For considerations in our particle transport studies…

1. Component vs. system vs. facility level
2. Shielding Analysis
3. Laser and final optics protection
4. Dose rate
    a. Dose rate during operations
    b. Dose rate after shutdown
5. Activation analysis (+ rad waste management)
6. CAD to neutronics conversion (meshing)
7. Variance reduction for Monte Carlo simulation
8. In vessel tritium retention

Author: Max Monange

Experimental facilities

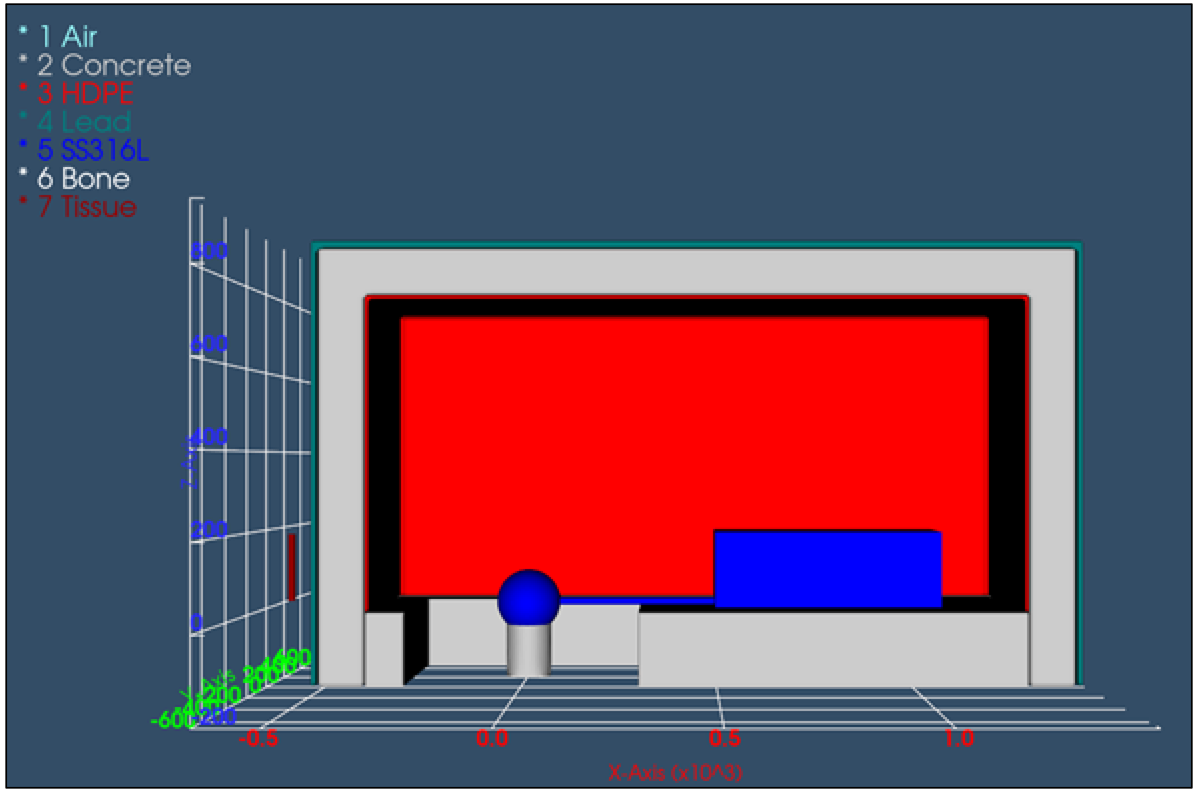
Osaka University | Institute of Laser Engineering (ILE)

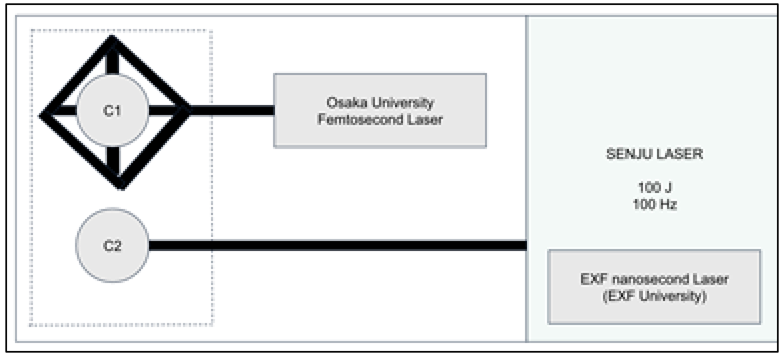
Particle transport conditions

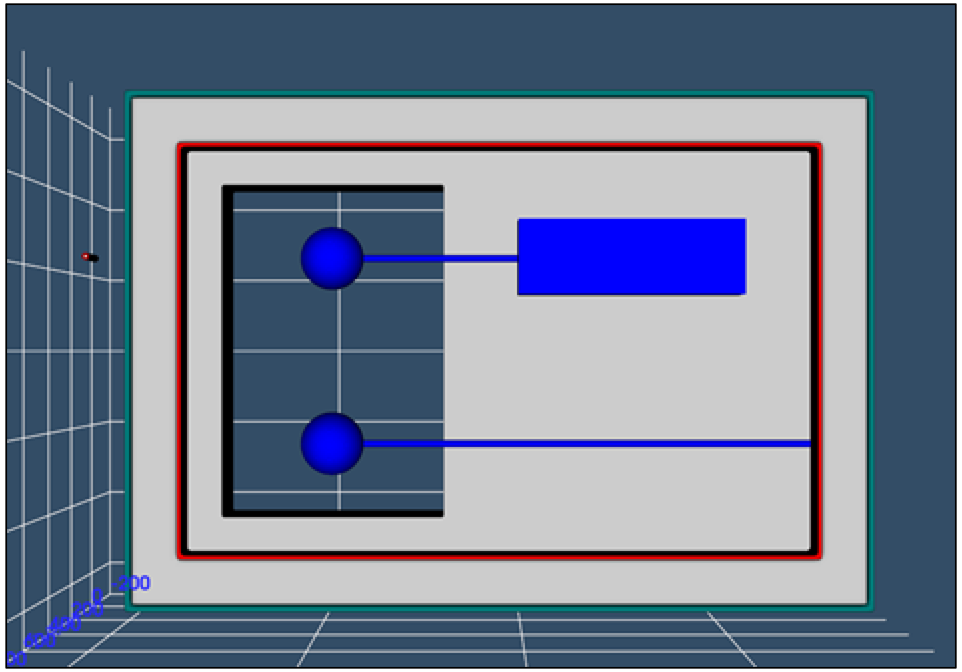
- **Fuel type**: DD
- **Neutron number**: 10^{4-5}/shot (Phase I.I) and 10^{11-13}/shot (Phase I.II)
- **Nuclear energy**: 10^{-9}J/shot (Phase I.I) and 5.2–6.5 J/shot (Phase I.II)
- **Repetition rate**: 10Hz
- **Operation time**: 1 hour

Author: Max Monange

4.1. CSG Model [Phase I.I]

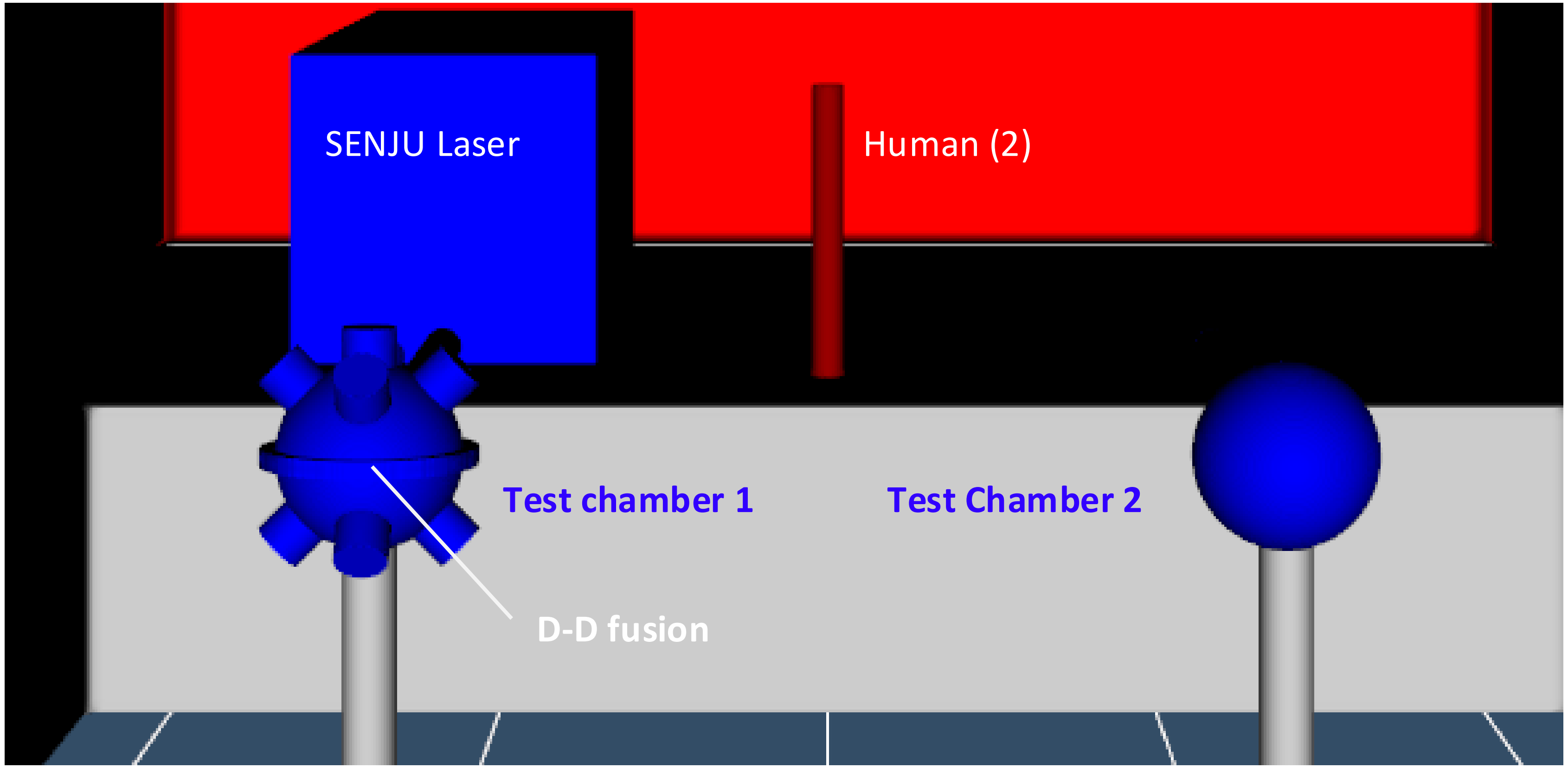




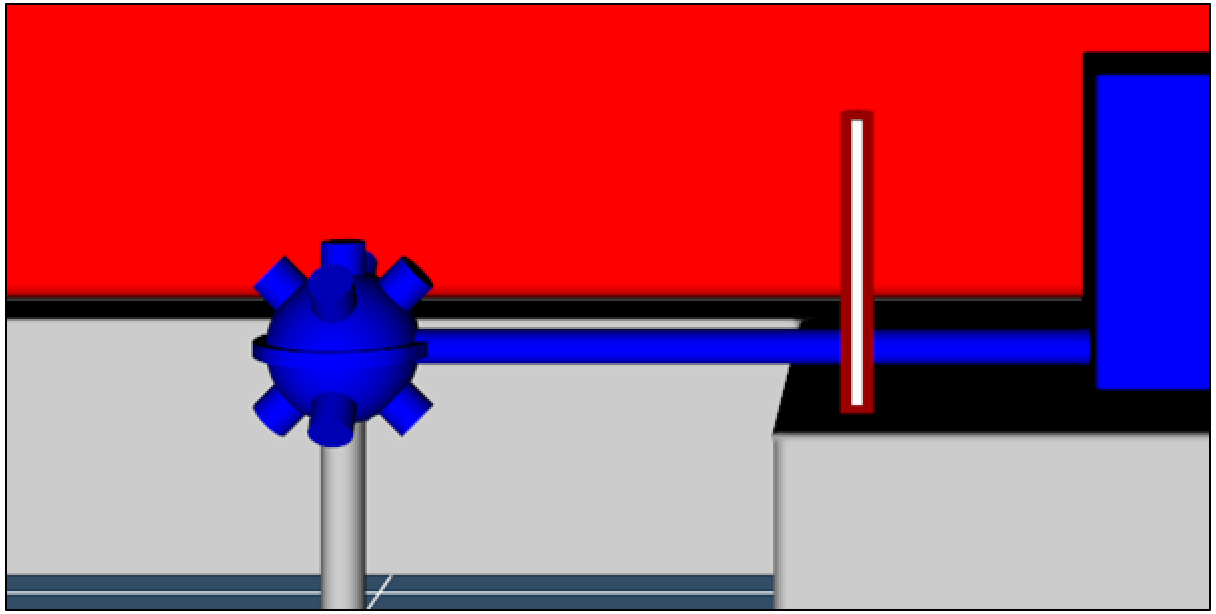


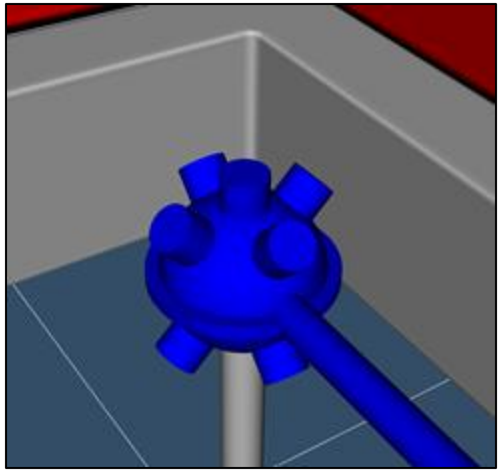
Mainly using CSG geometries in particles transport simulations, making fast iteration hard (haven't achieved clean workflow for tetrahedral meshing with PHITS independently yet)

4.1. CSG Model [Phase I.I]



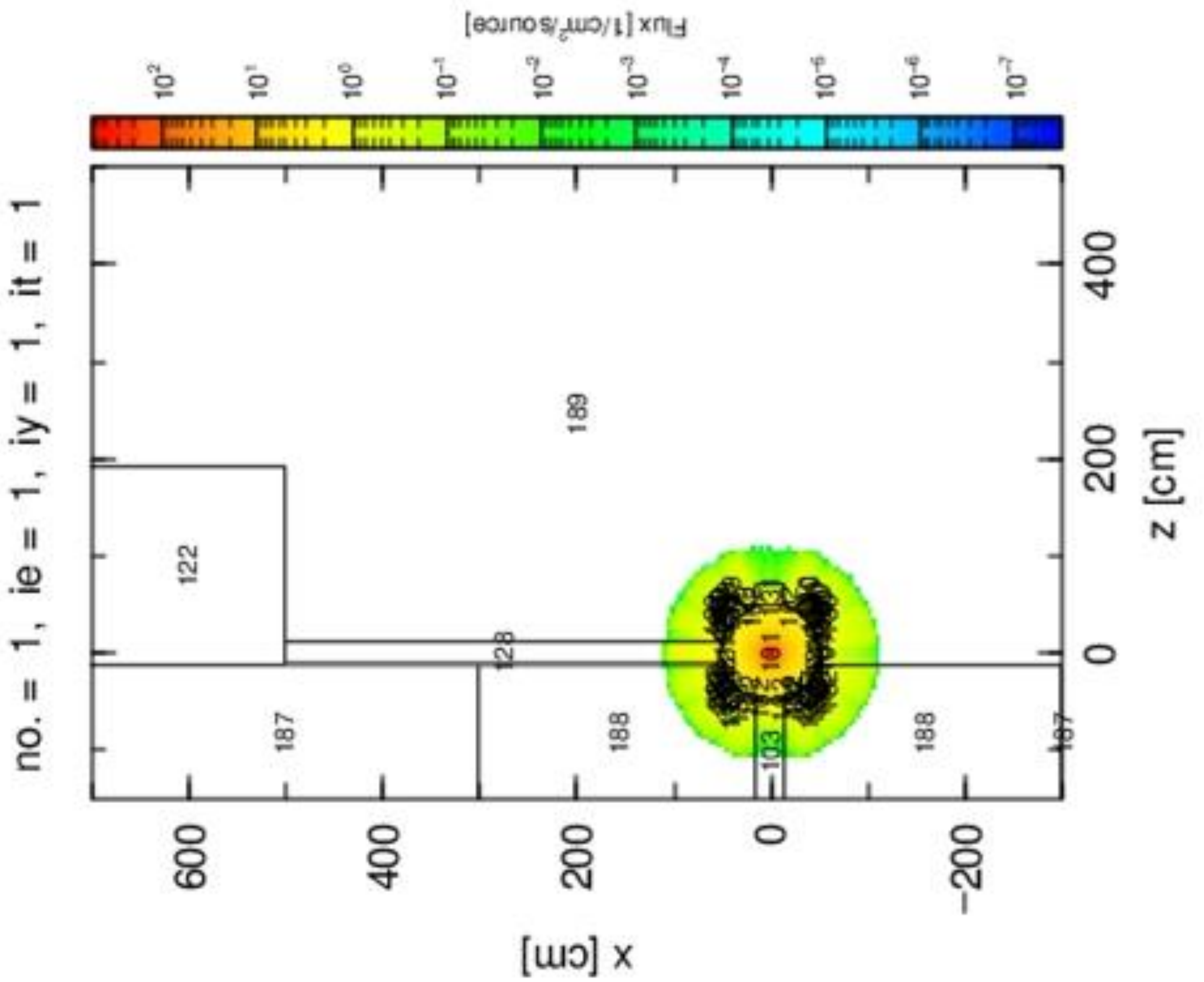
4.1. CSG Model [Phase I.I]

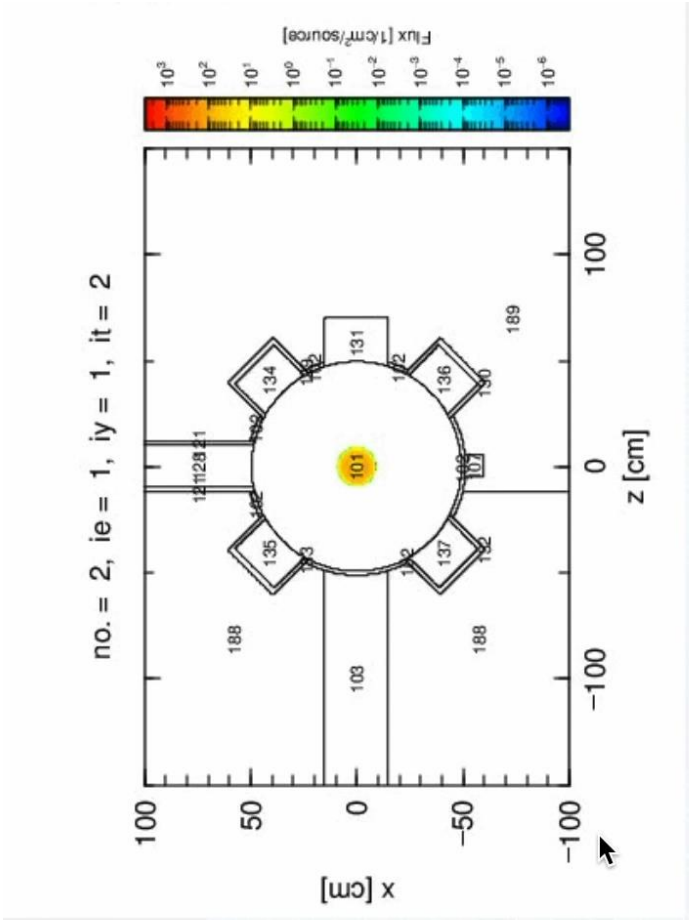




Author: Max Monange

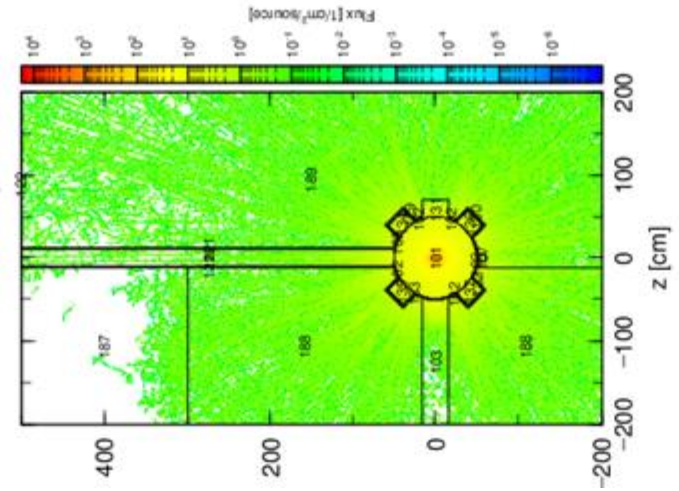
4.2. Neutron track after implosion [Phase I.I]



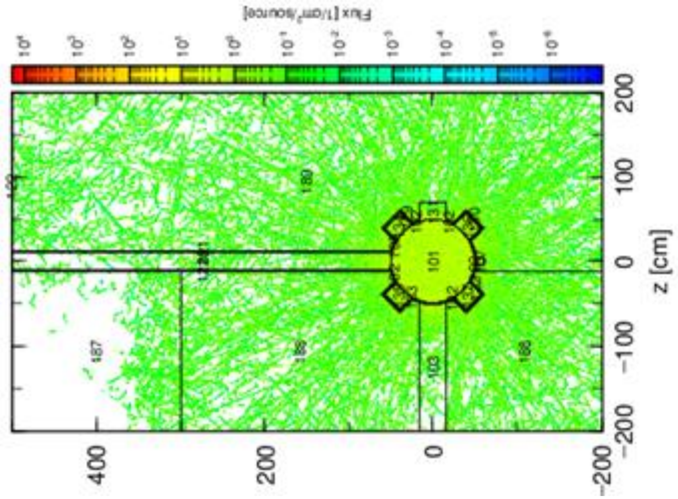


Author: Max Monange

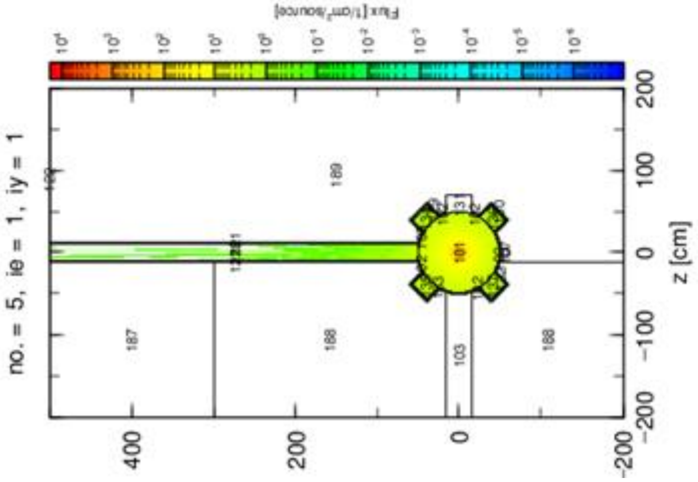
4.3. Particle flux (T-Track Tally) [Phase I.I]



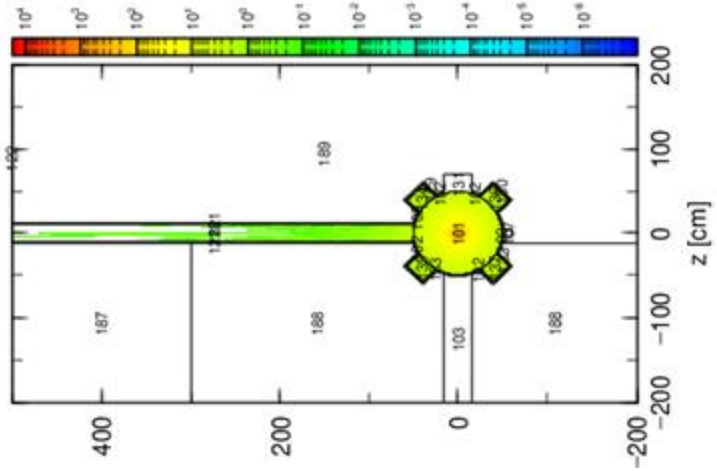
Neutron



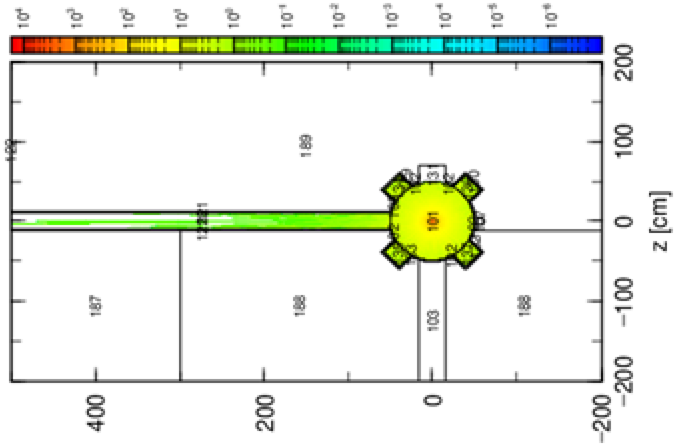
Photons (Gammas)



Proton



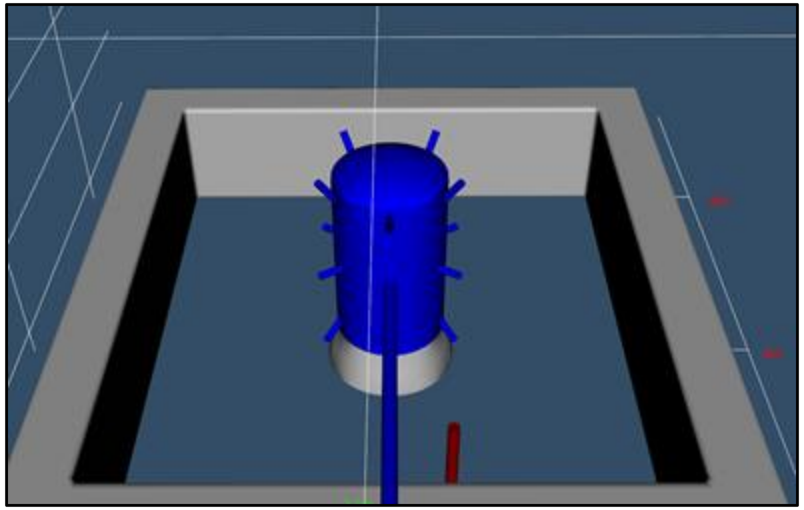
Tritium

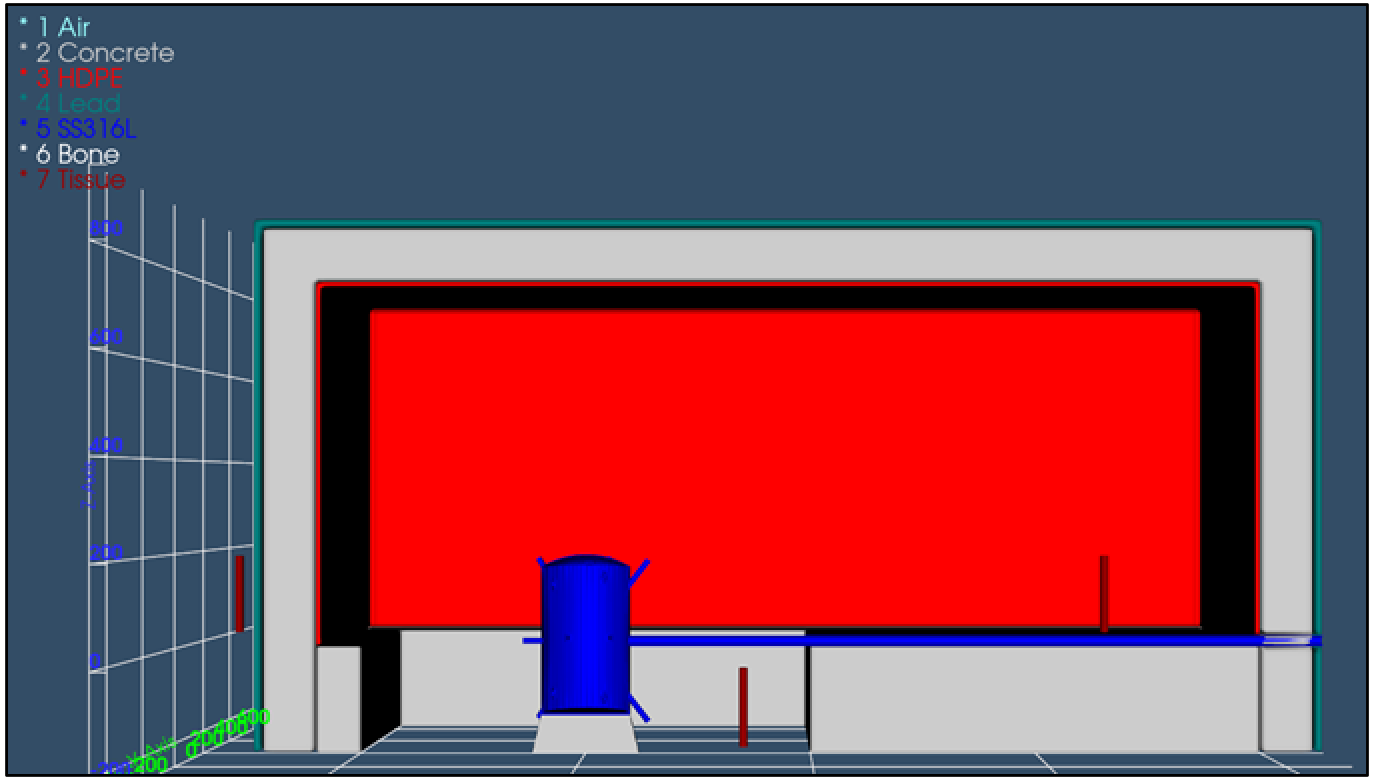


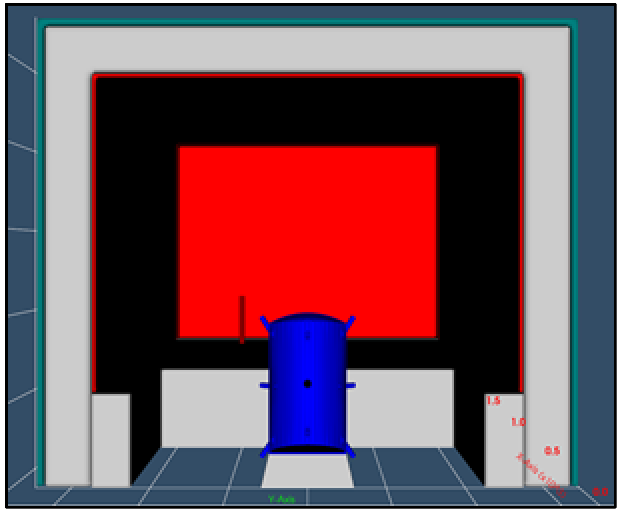
Helium-3

Author: Max Monange

4.4. CSG Model [Phase I.II]

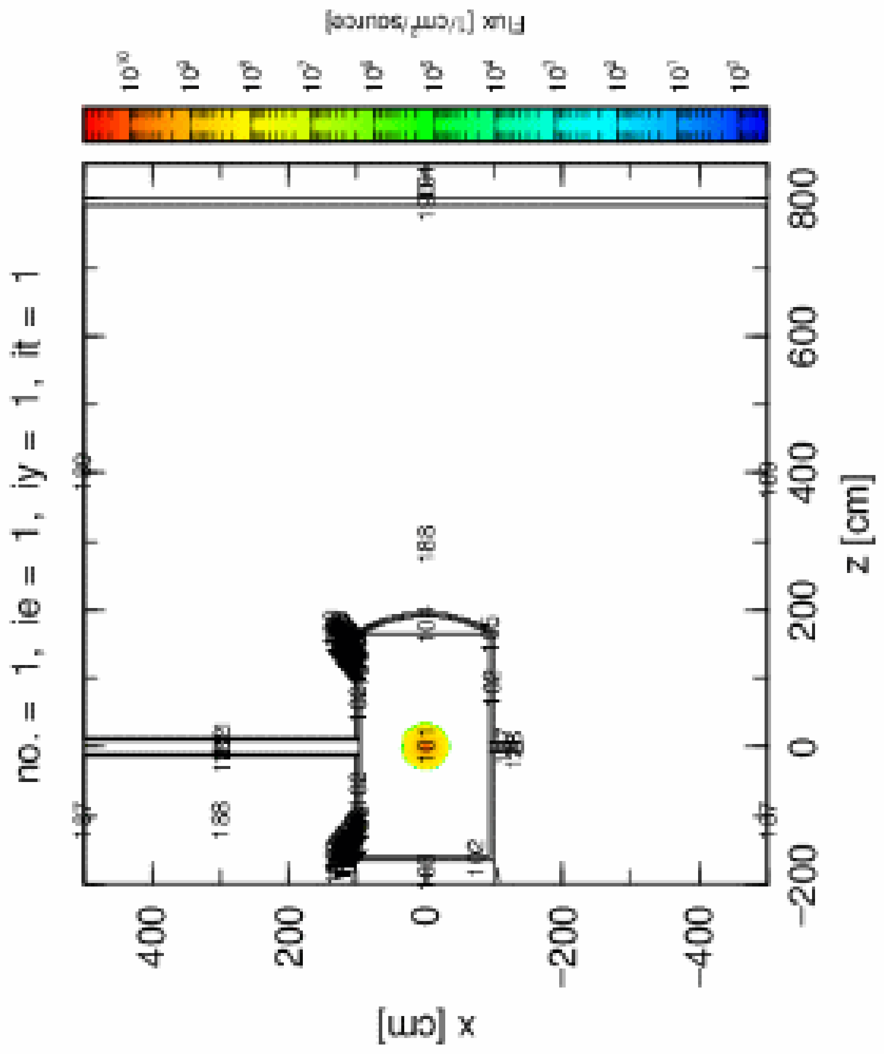






Author: Max Monange

4.5. Neutron track after implosion [Phase I.II]



Neutron

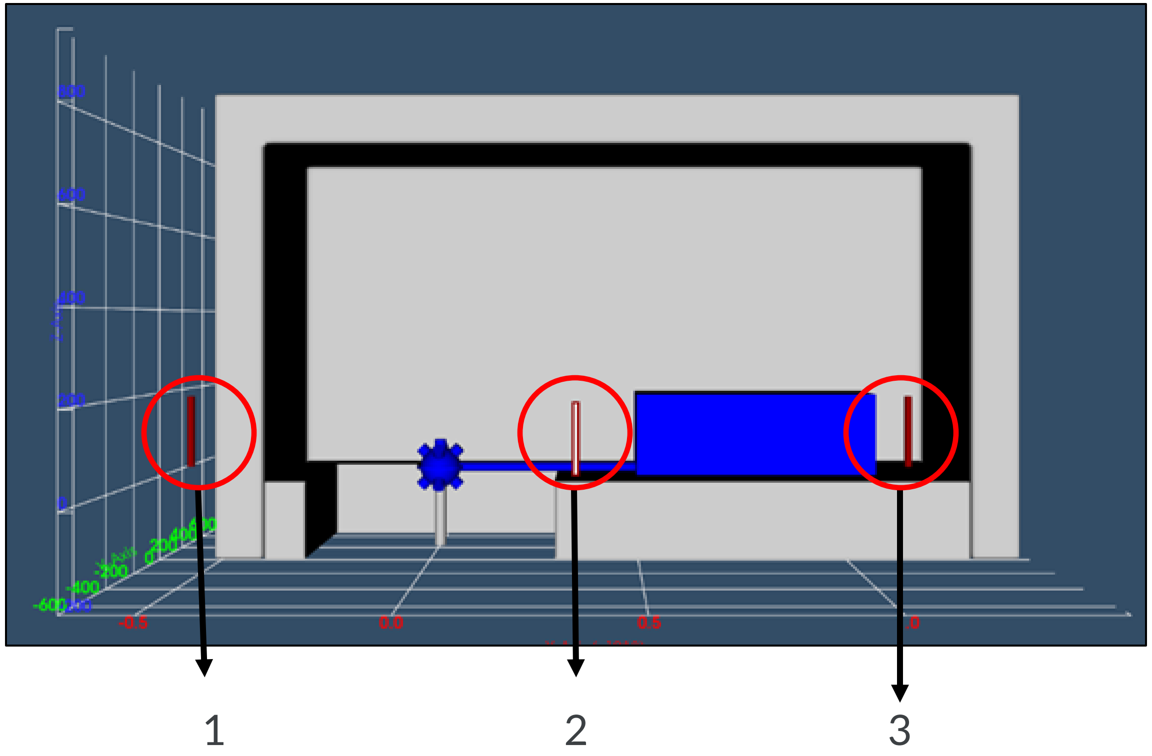
Author: Max Monange

(V) DOSE CALCULATIONS

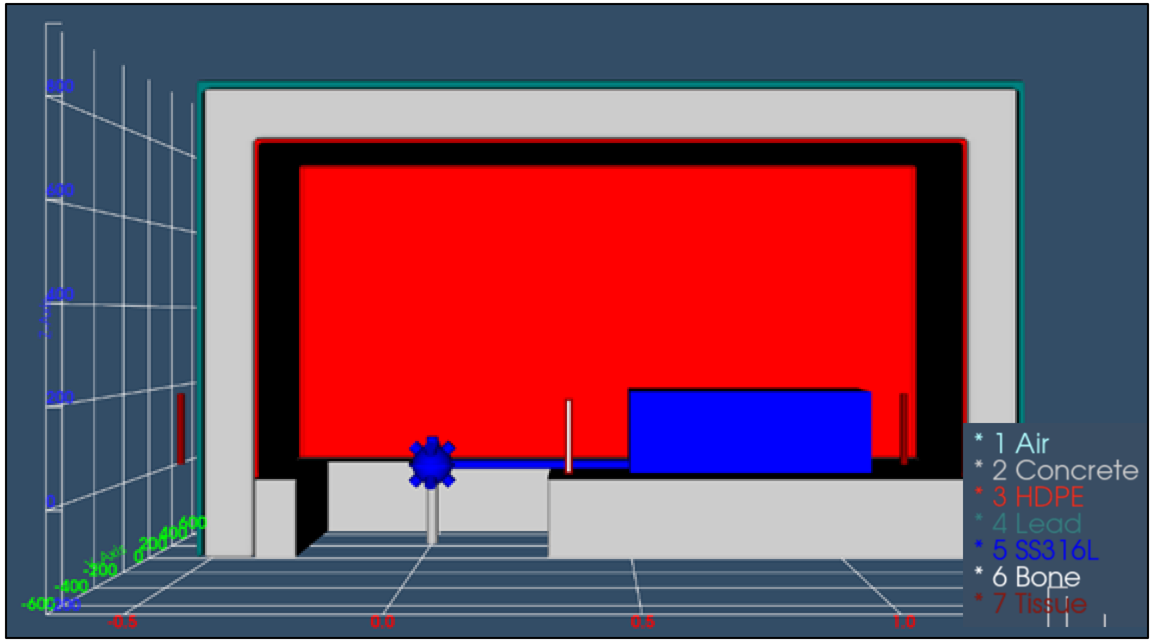
5.1. Dose analysis: Simulation Set-up

- Bodies (cylinder with mix of 8% bone and 92% tissue) were located at different locations in the room
- Used the ICRU “compact bone” definition (density ≈1.85 g/cm^3) is the standard reference for average adult human bone in dosimetry and treatment-planning.

Unshielded



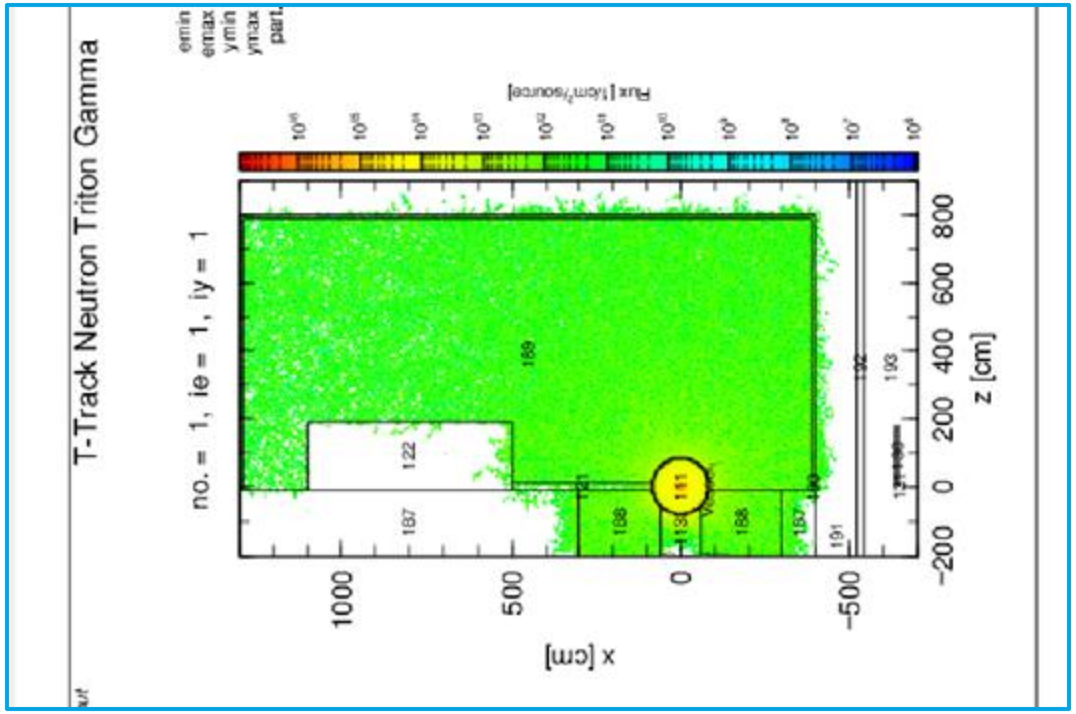
Shielded

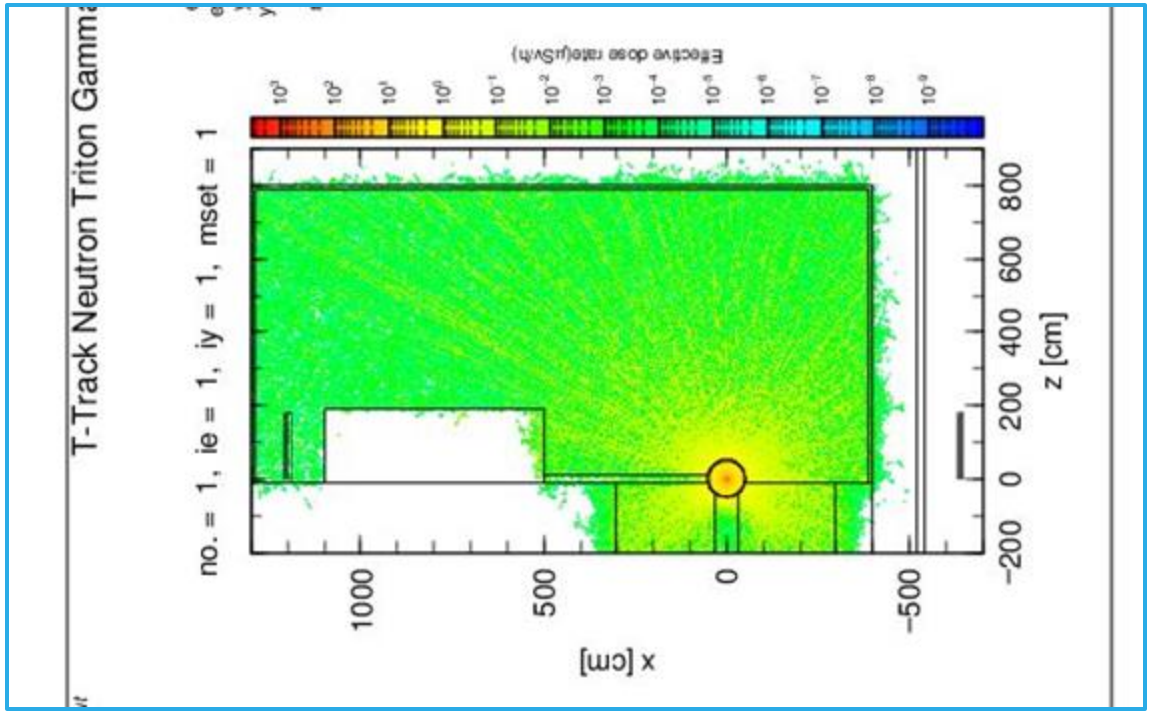


 Author: Max Monange

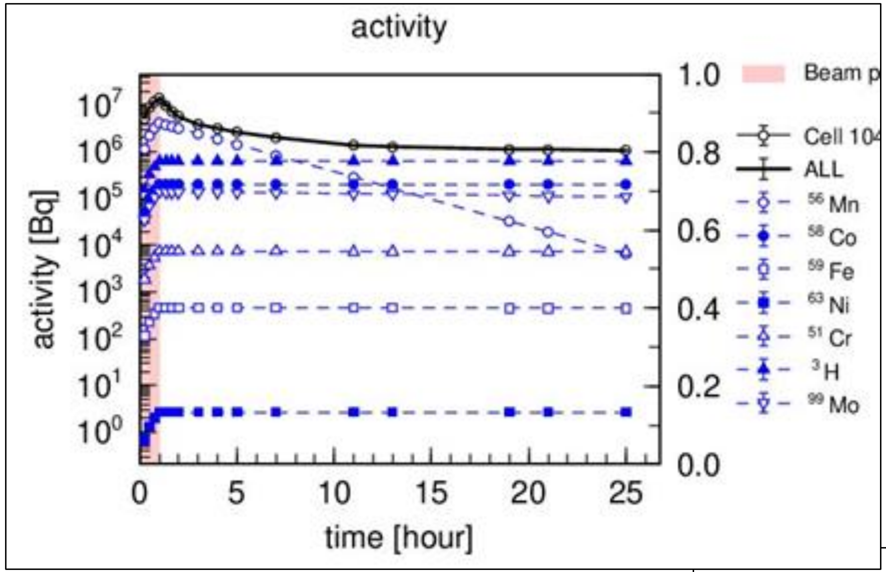
5.2. Dose Analysis: Results during operations (Dchain Tally)

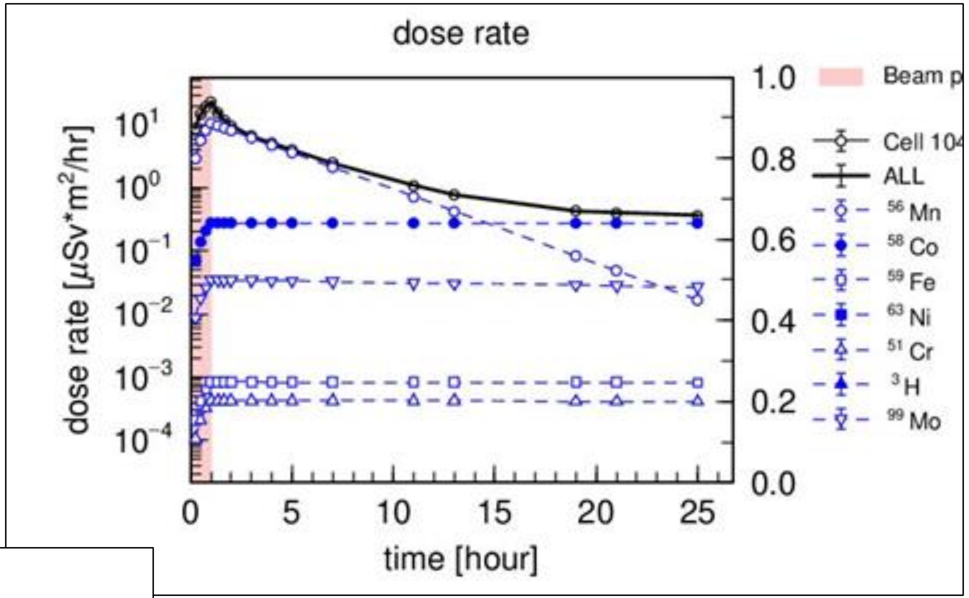
Fluence [1/cm²] ⟶ Effective Dose rate [μSv/hr]

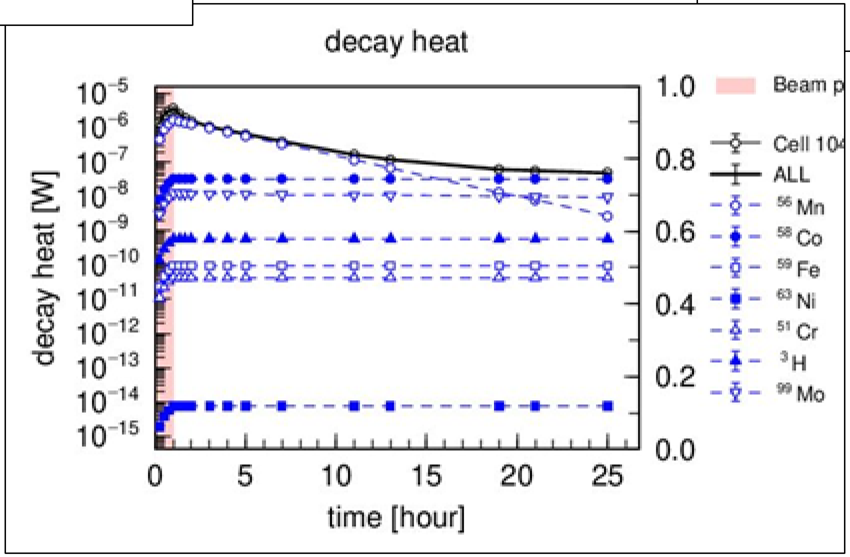




5.3. Dose Analysis: Results after shutdown (Dchain Tally)







All plots taken at the vacuum vessel

Highest activity:

- ^{56}Mn > ^{3}H > ^{58}Co > ^{99}Mo > ^{51}Cr > ^{59}Fe > ^{63}Ni

Highest dose rate:

- ^{56}Mn > ^{58}Co > ^{99}Mo > ^{59}Fe > ^{51}Cr

Highest decay heat:

- ^{56}Mn > ^{58}Co > ^{99}Mo > ^{3}H > ^{59}Fe > ^{51}Cr > ^{63}Ni

 Author: Max Monange

5.4. Conclusion: Dose delivered

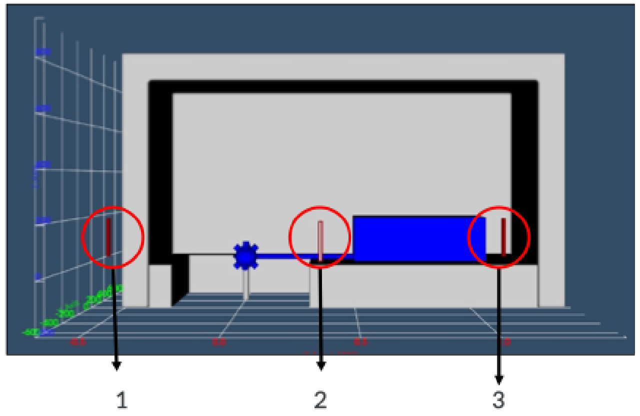
×10^6 greater

Spherical vessel
1×10^5 neutrons/source

Cylindrical vessel
1×10^{11} neutrons

DOSE RESULTS		
Body	Phase I.I - Effective dose [µSv/shot]	
	Unshielded room (actual ILE)	Shielded room
1	$9.02\cdot10^{-8}$	**0.00**
2	$1.23\cdot10^{-2}$	$1.13\cdot10^{-2}$
3	$6.88\cdot10^{-4}$	$3.83\cdot10^{-4}$

DOSE RESULTS		
Body	Phase I.II - Effective dose [µSv/shot]	
	Unshielded room (actual ILE)	Shielded room
1	0.00	**0.00**
2	$1.22\cdot10^{4}$	$1.18\cdot10^{4}$
3	$1.97\cdot10^{3}$	$1.40\cdot10^{3}$



1 = outside
2 = next to vessel
3 = other side of the room

Author: Max Monange

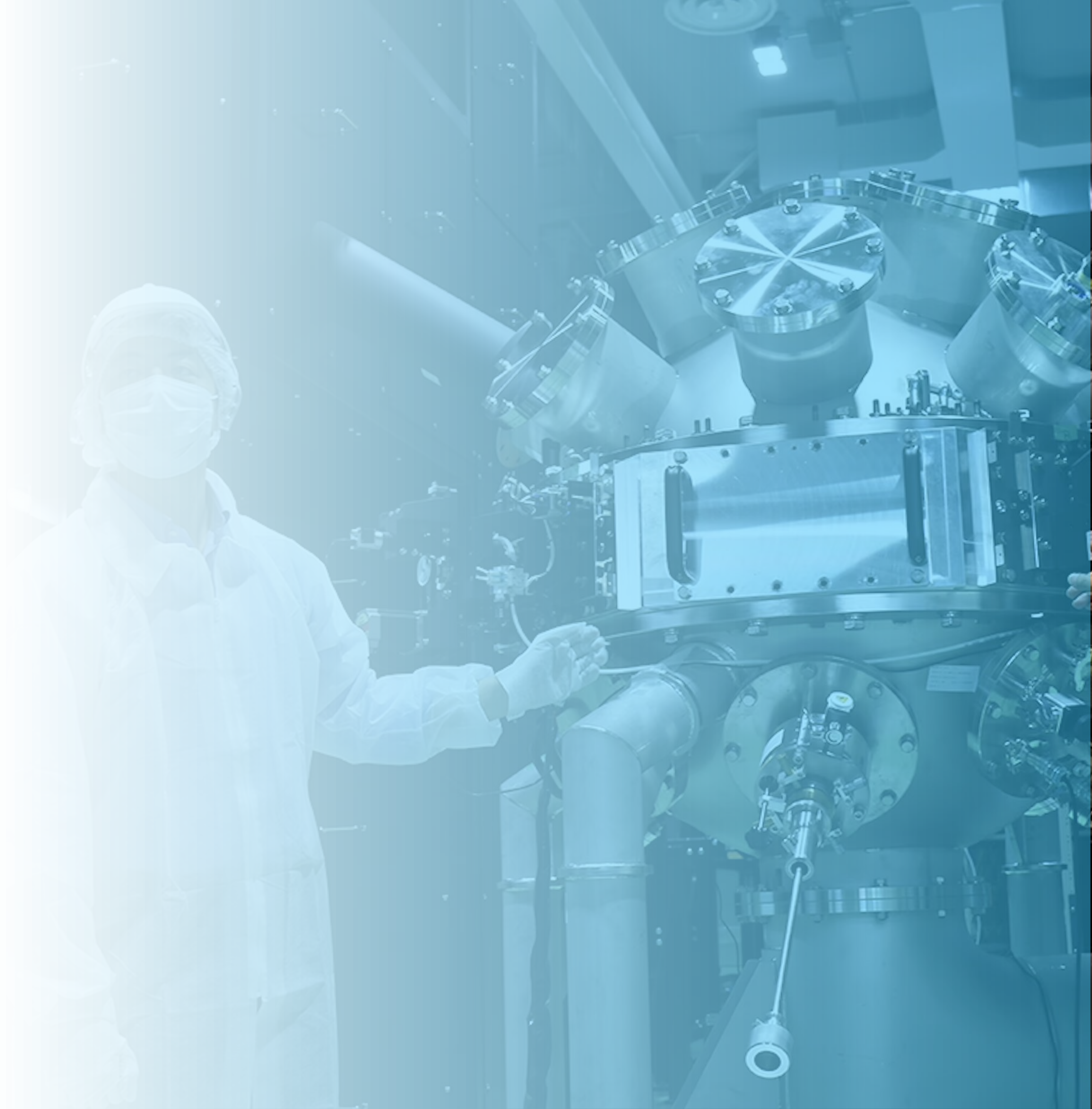
5.4. Conclusion: Dose delivered

DOSE RESULTS		
Body	Phase I.II - Effective dose [μSv/shot]	
	Unshielded room (actual ILE)	Shielded room
1	0.00	**0.00**
2	$1.22 \cdot 10^4$	$1.18 \cdot 10^4$
3	$1.97 \cdot 10^3$	$1.40 \cdot 10^3$

Category	Limit Type	Limit Value	Converted / Context
Radiation Worker Trained personnel	**Annual effective dose (whole body)**	**50 mSv/year**	≈ 0.96 μSv/hr (if exposed 24/7)
	Lens of eye dose	150 mSv/year	≈ 2.9 μSv/hr (if continuous)
	Shallow dose (skin/extremities)	500 mSv/year	≈ 9.6 μSv/hr (if continuous)
General Public In unrestricted area	Annual effective dose	1 mSv/year	≈ 0.114 μSv/hr (if exposed 24/7)
	Instantaneous dose rate limit	**25 μSv/hr**	Short-term rate limit
	Weekly dose (NRC guidance)	—	≤ 500 μSv/week (to stay ALARA)

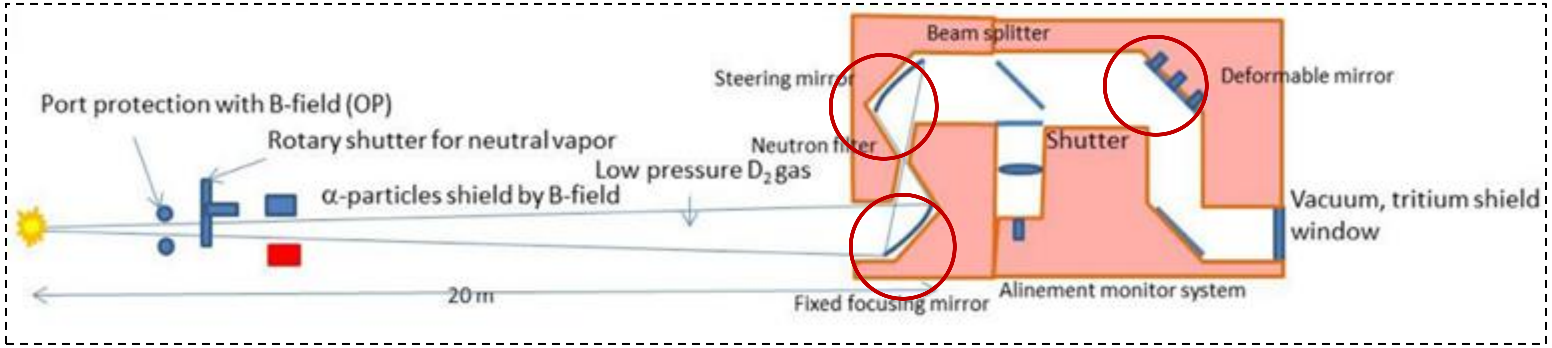
Dose limits guidelines [NRC]

(VI) FINAL OPTICS DAMAGE



6.1. Beam Control in IFE

Key components of the laser control system



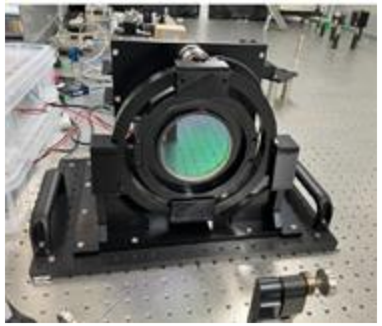
T. Norimatsu et.al., Nucl. Fusion 57 (2017) 116040

Consists of three mirrors

1. Steering mirror
2. Deformable mirror
3. Final mirror

Steering mirror

Adjusts the laser beam direction to track the flying target's position.

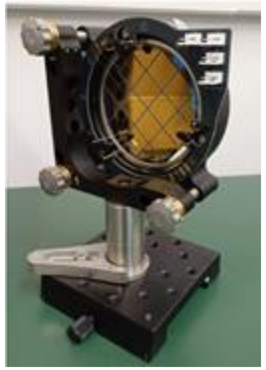


- 10Hz track:
  Settling time < 80 ms
- High precision:
  Accuracy ≤ 10 μm
  @30m = ± 0.167 μrad

This steering mirror incorporates optical sensing technology developed for gravitational-wave detection

Deformable mirror

Mirror shape is actively controlled to compensate for wavefront

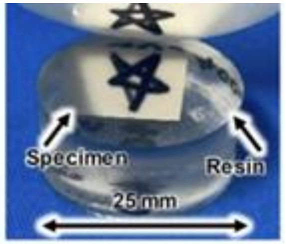


- High heat resistance
  ≥ 100°C (piezoelectric types are ~60°C)
- Correction for Zernike terms ≥ 7th order

Utilizes a novel-material deformable mirror

Final mirror

Final-stage focusing mirror for precise laser delivery to the target

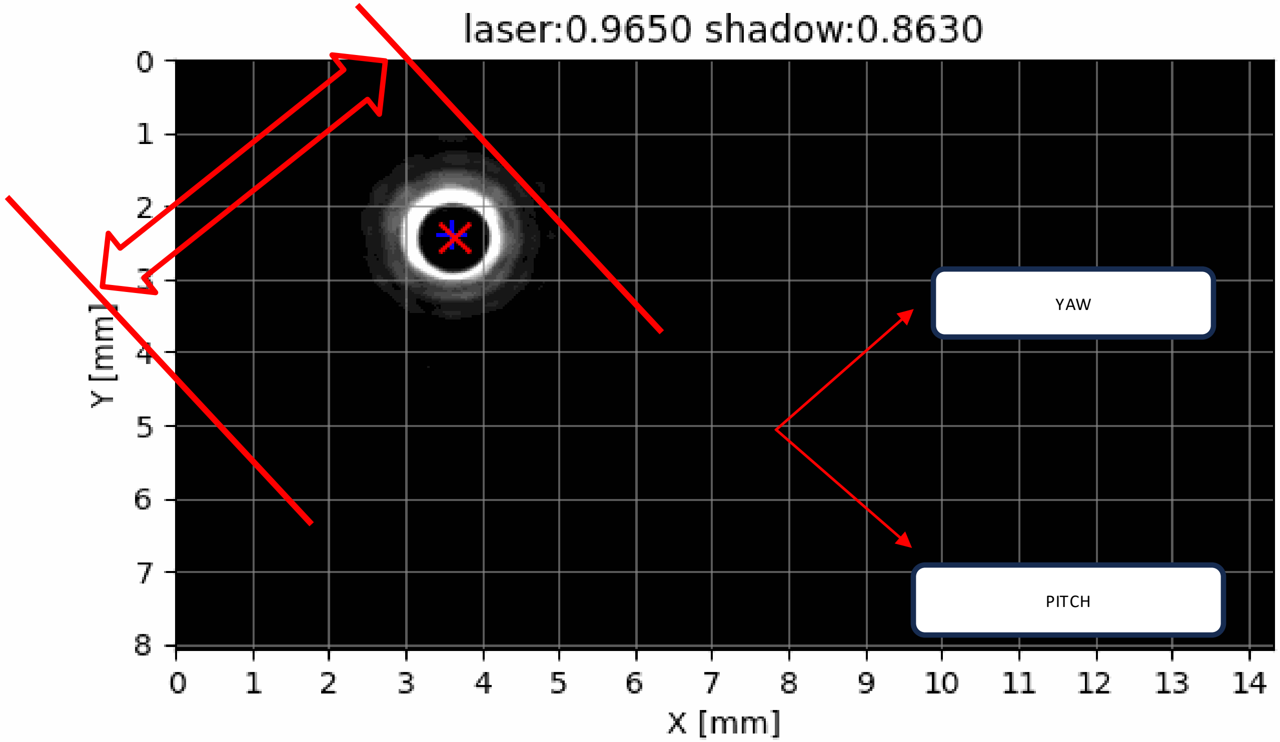


Requires high heat resistance, low-activation materials, and regular replacement.

Low-melting-point metal mirrors

Author: Max Monange

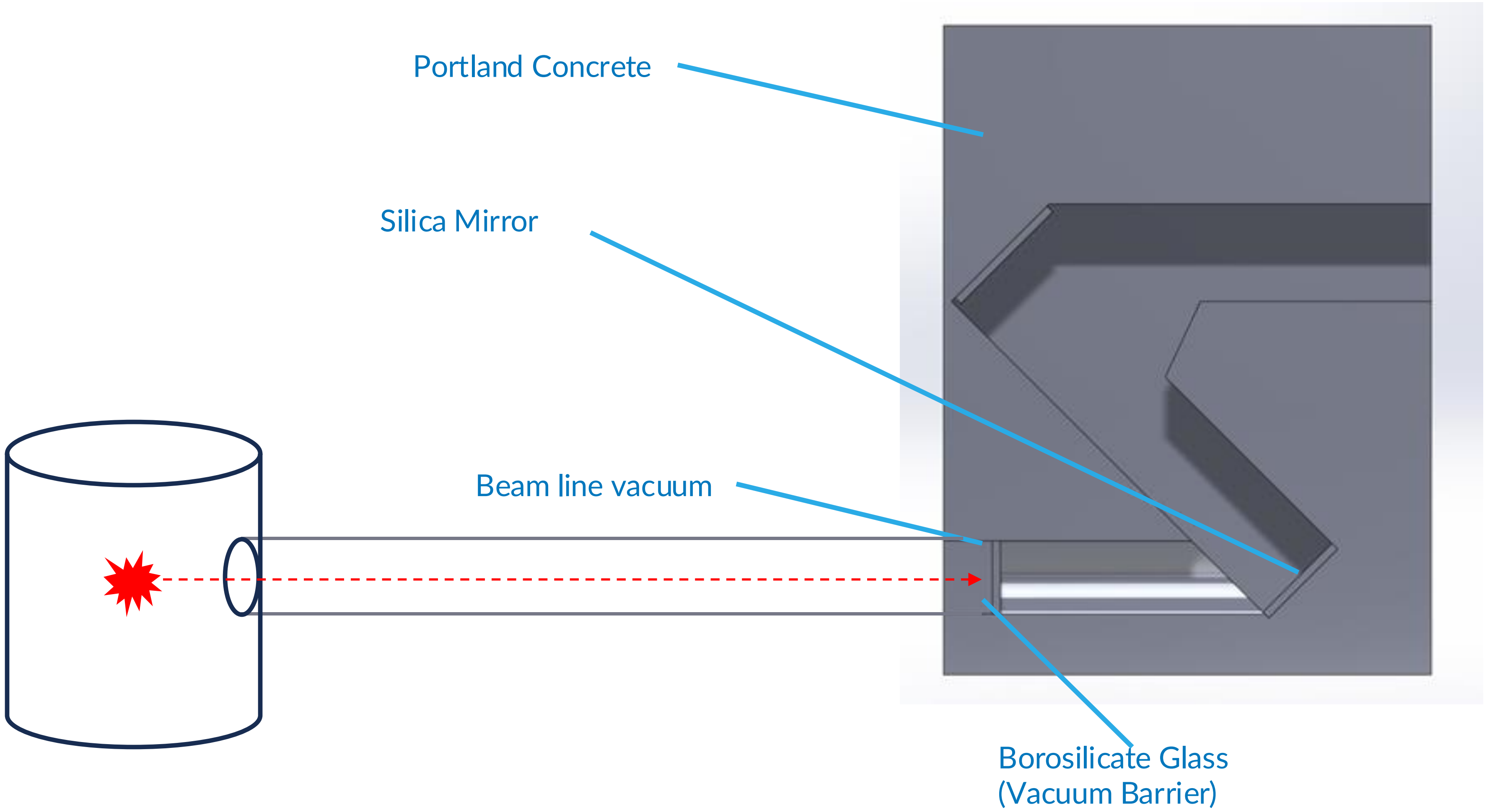
6.1. 6-inch Steering Mirror Achieves Commercial Standards



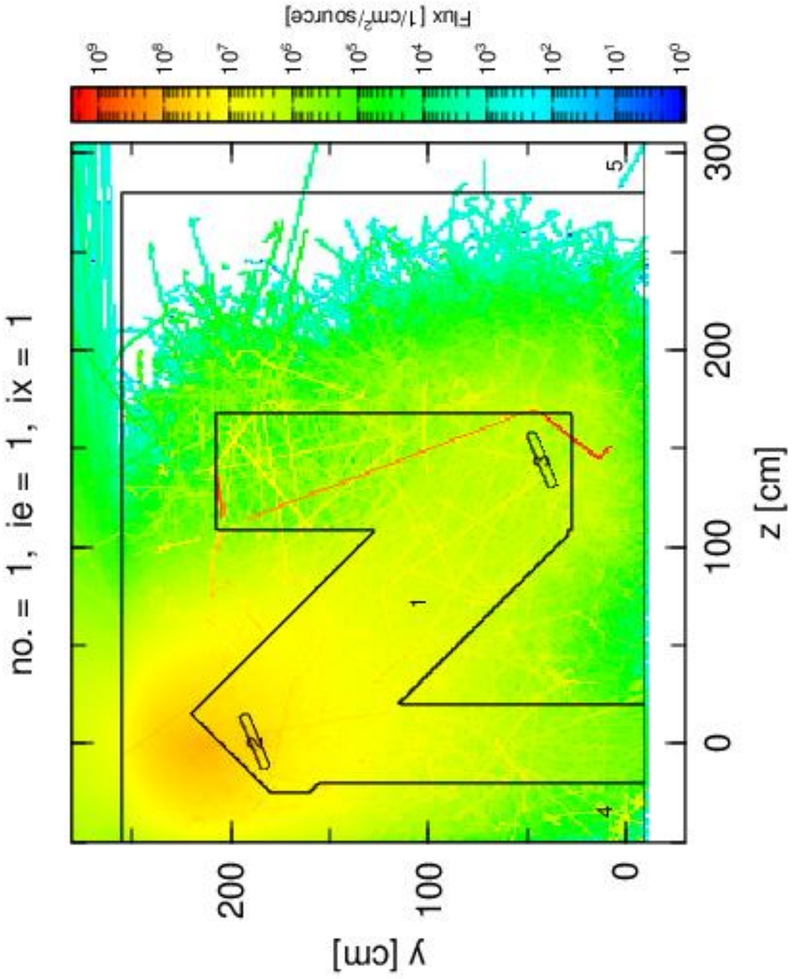
Target tracking

Author: Max Monange

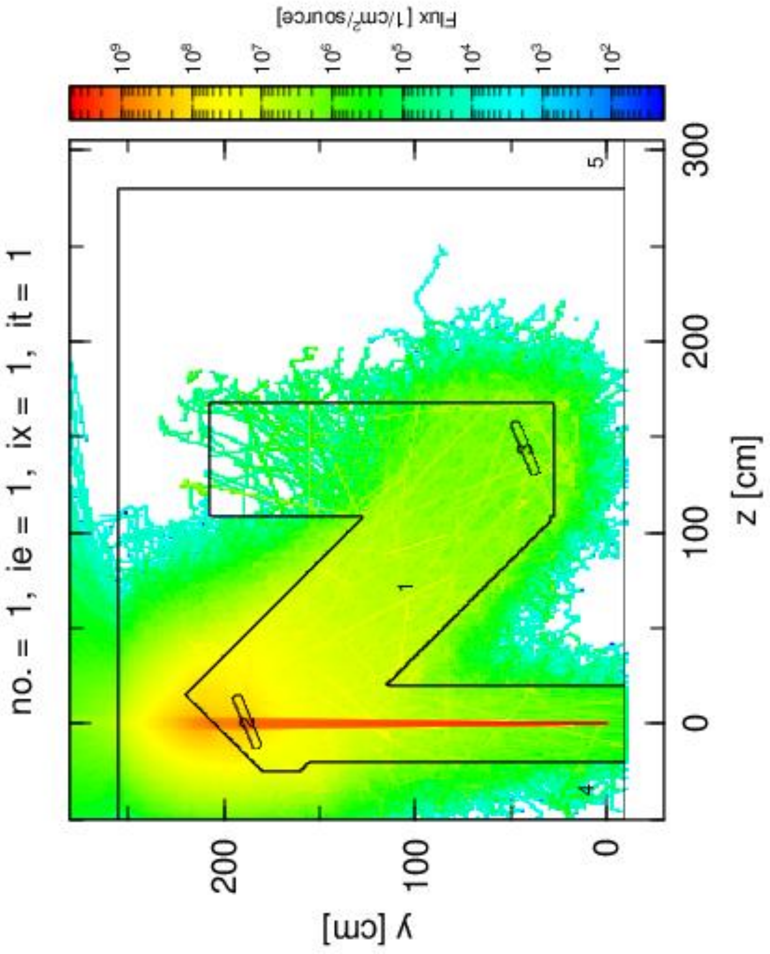
6.2. CAD Geometry



6.3. Particle flux @system level (T-Track Tally)



Photons (Gammas)

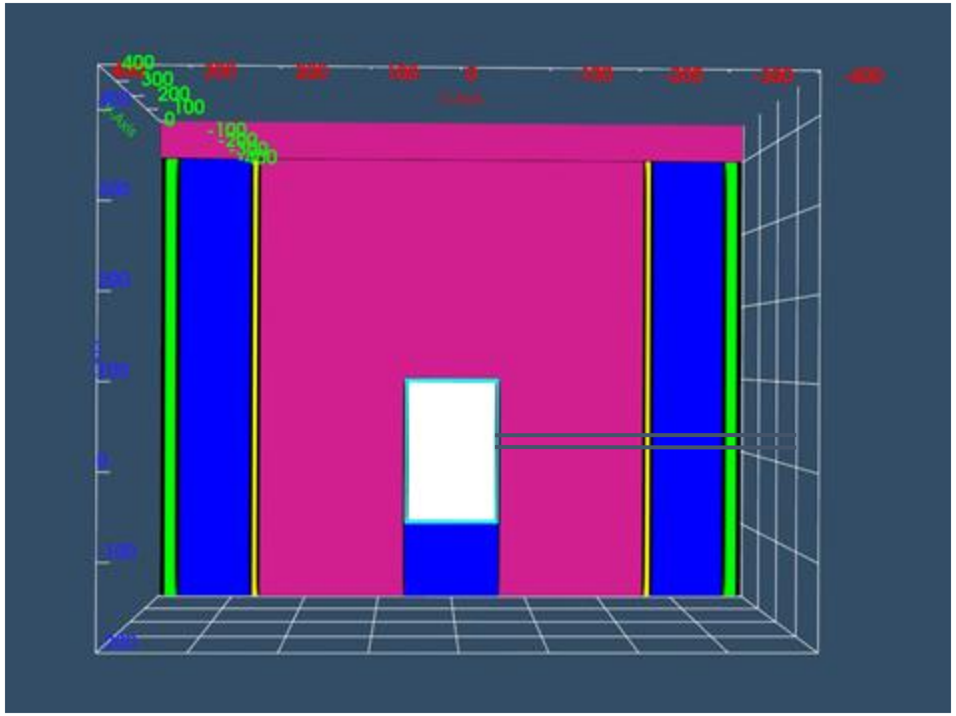


Neutron

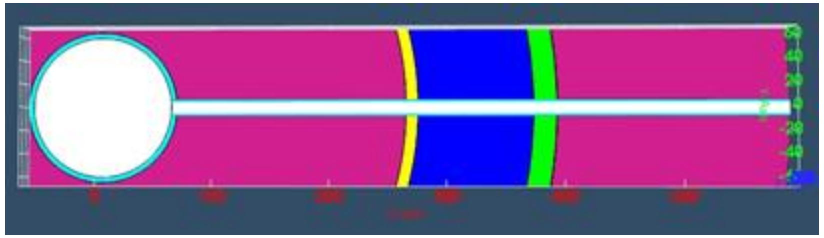
Author: Max Monange

6.3. Particle flux @facility level (T-Track Tally)

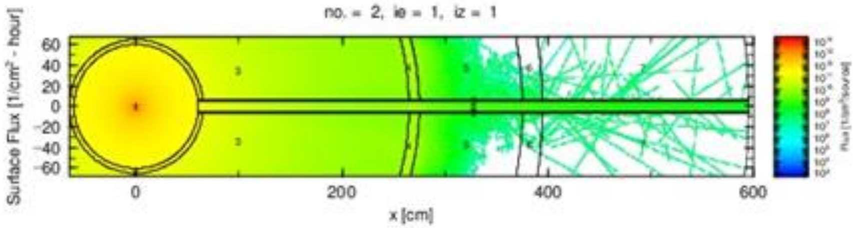
- Distance to of the mirrors to the chamber is a fully controllable parameter



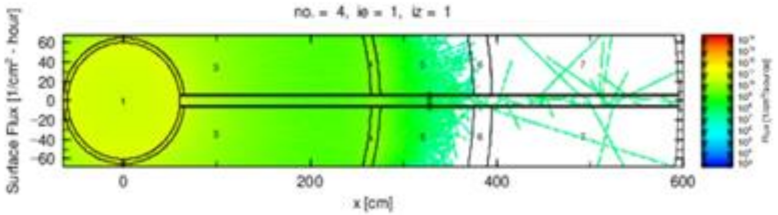
Section view
Magenta = **air**
Yellow = **HDPE**
Blue = **concrete**
Green = **lead**



SimpleGeo Model - top view



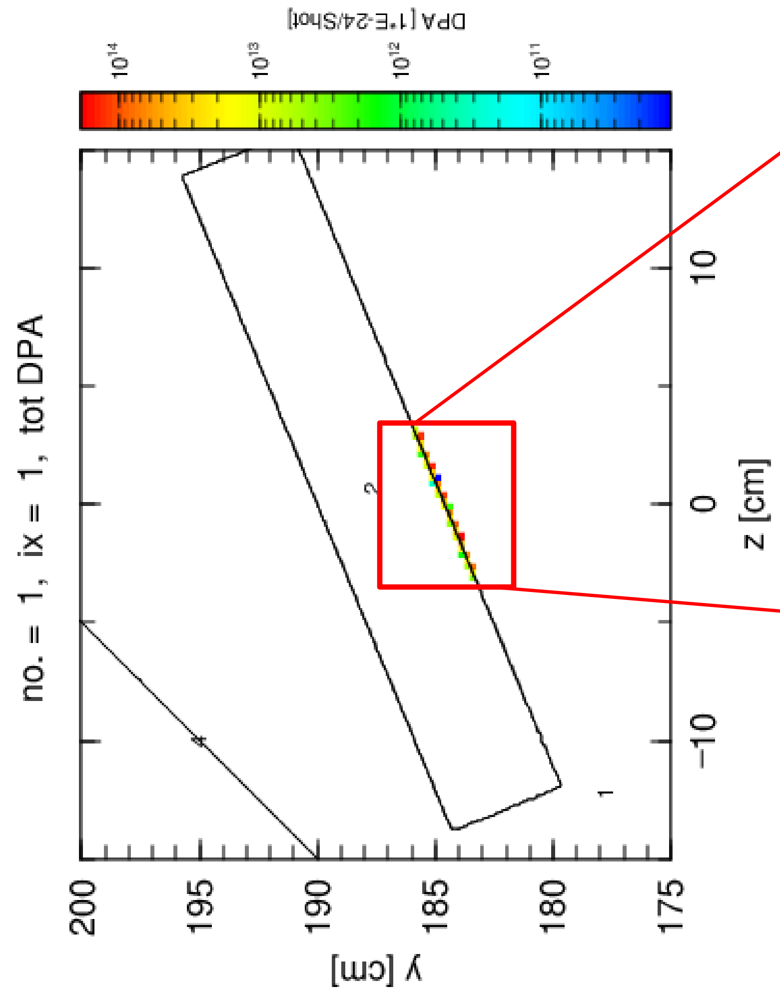
Neutron track distribution in the beam port
(Units are 1/cm2×hour)

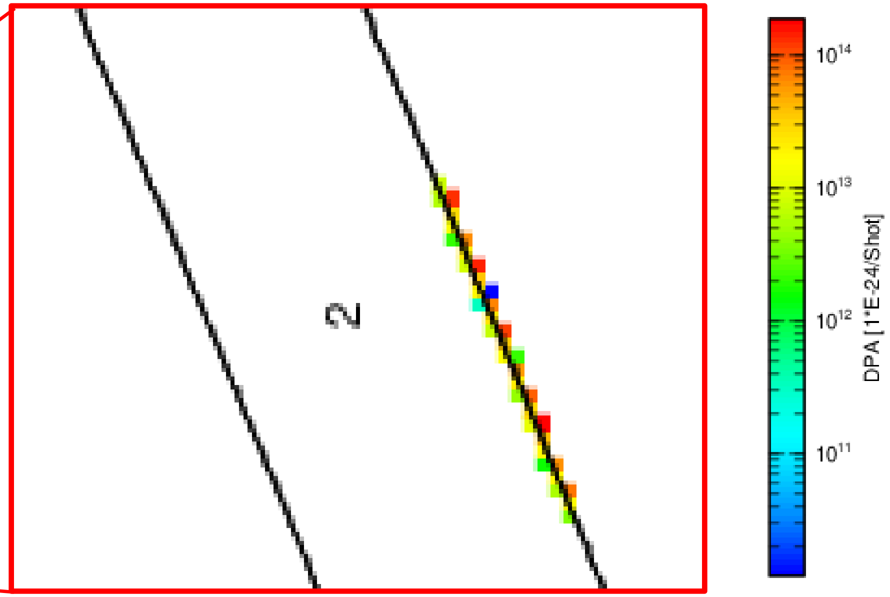


Gamma track distribution in the beam port
(Units are $1/cm^2 \times hour$)

Author: Max Monange

6.4. DPA distribution on the final mirror





Dpa distribution (material: SiO_2)

- $2 \cdot 10^{-10}$ DPA per shot
- $7.2 \cdot 10^{-7}$ to DPA per hour
- 0.0063 DPA per year

Heat deposition

- ?

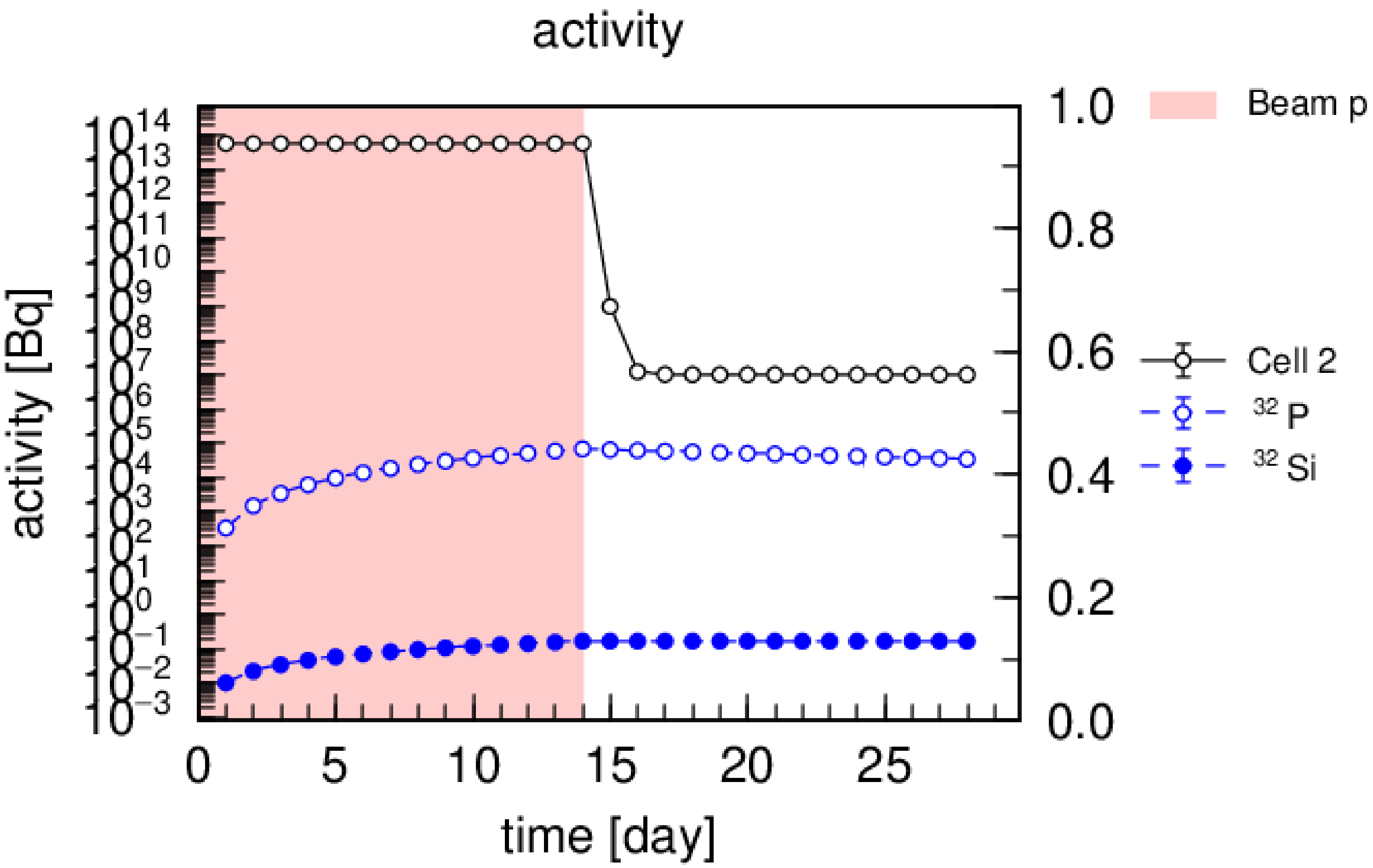
Author: Max Monange

6.5. Activation of the final mirror

- P-32 and Si-32

Inventory of isotopes

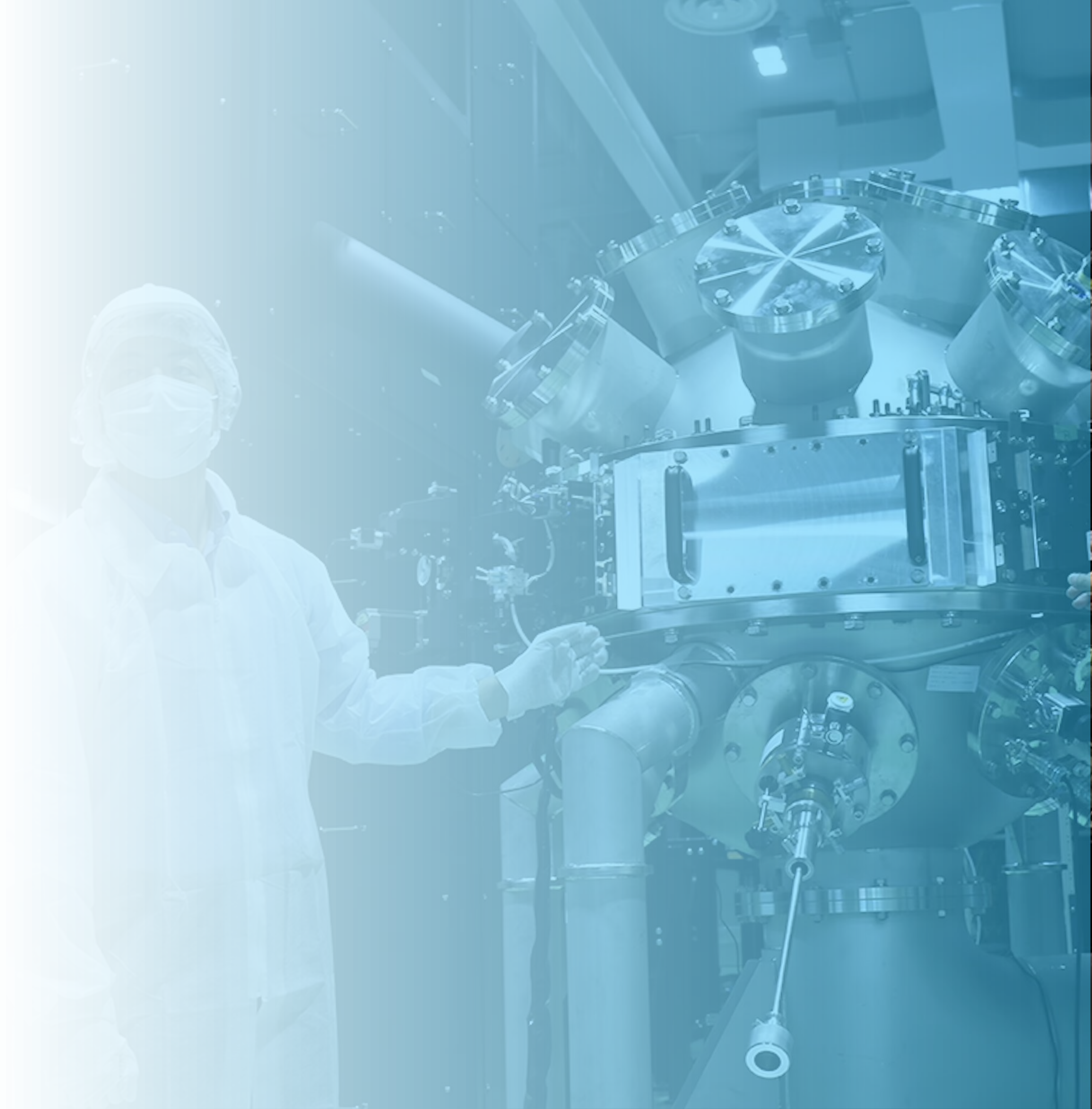
- Si-32: $3.37 \cdot 10^{-5}$ atoms
- P-32: $3.34 \cdot 10^{7}$ atoms
- After 1 day of DT irradiation for a 40 MW reactor



Plot of the total activity of a SiO_2 mirror after irradiation

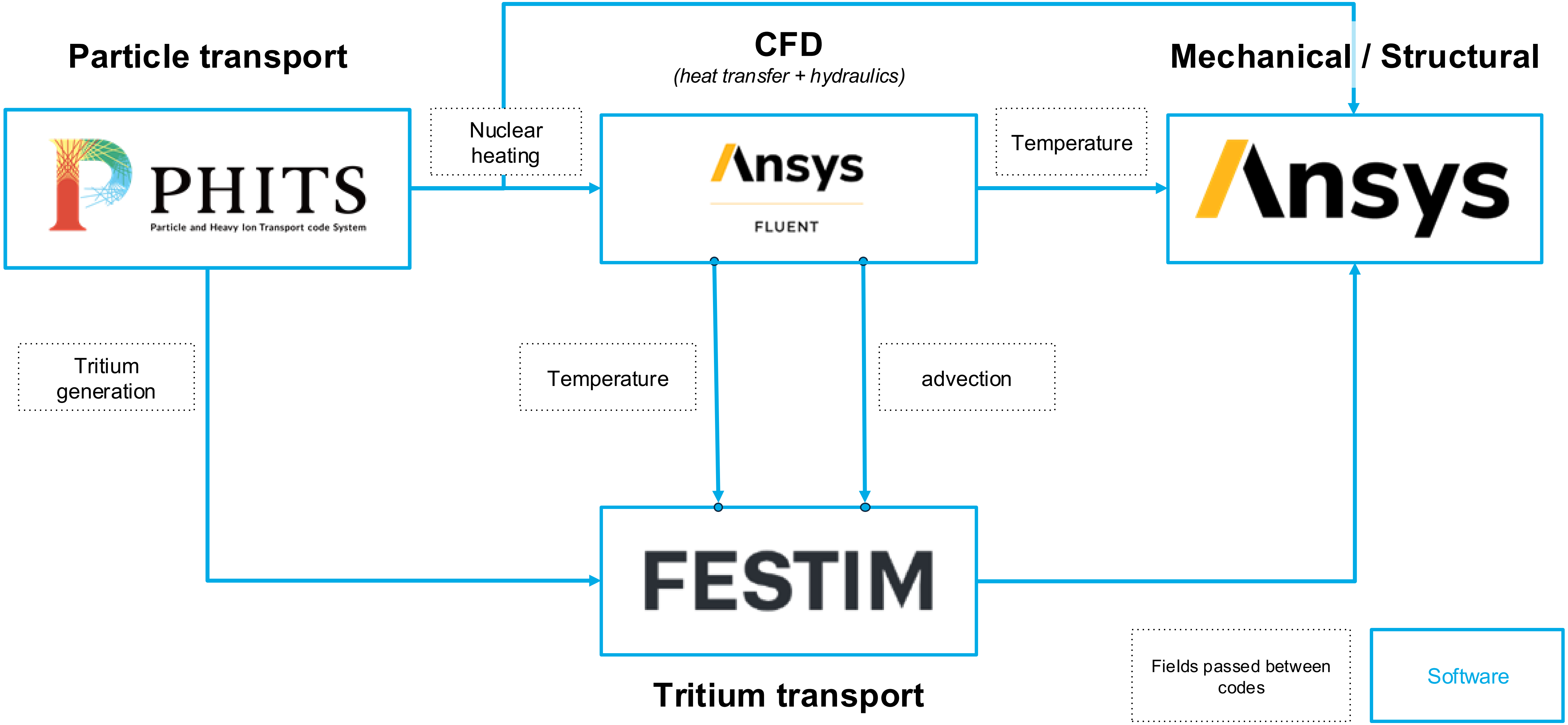
Author: Max Monange

(VI) EVOLUTION OF OUR MOD-SIM STRATEGY



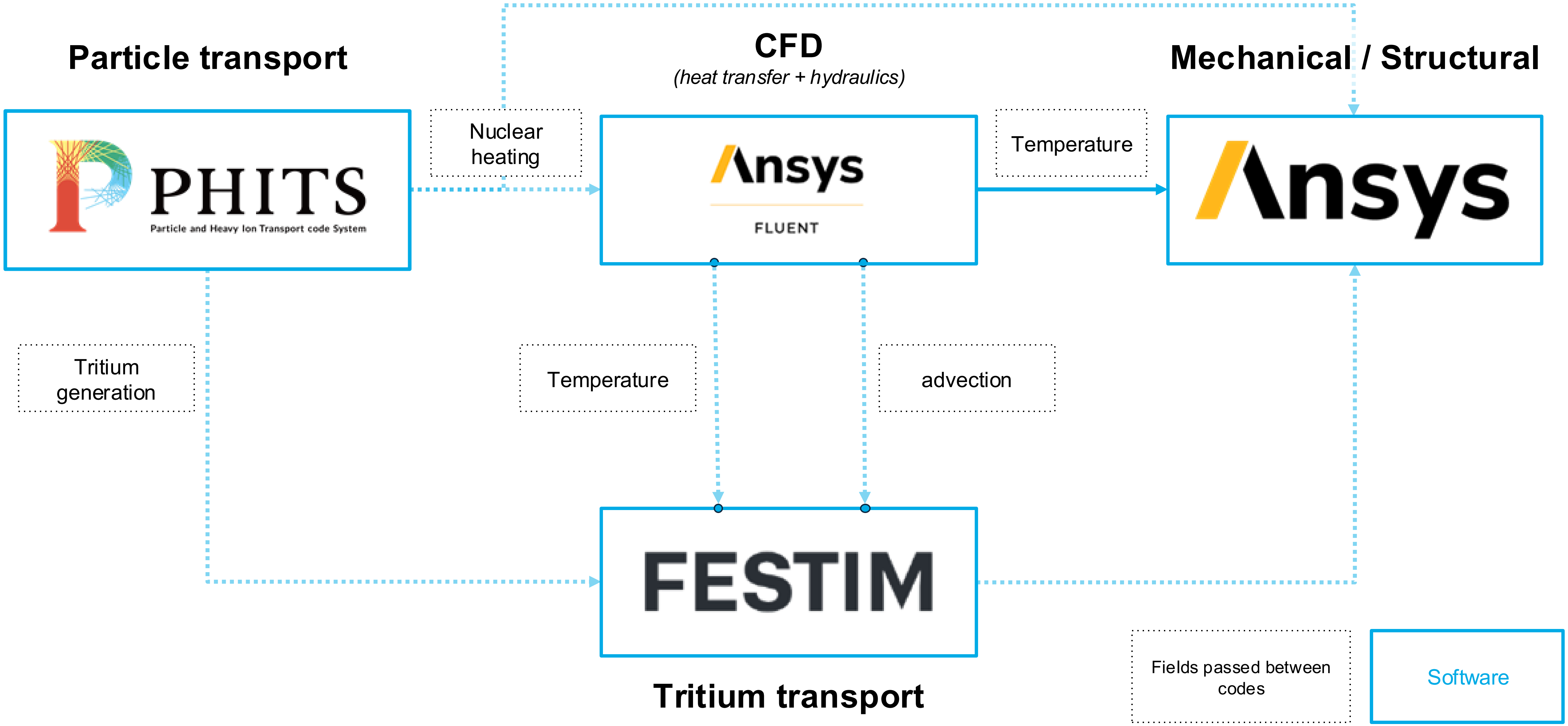
Mod-sim Workflow to Facilitate Multiphysics Coupling

Our Current Approach at the Systems Level



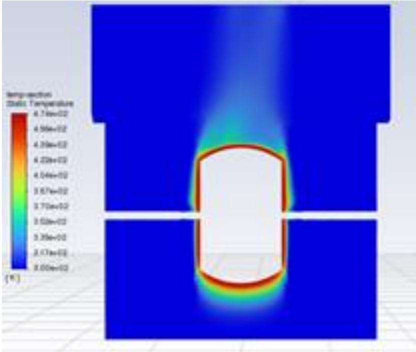
Mod-sim Workflow to Facilitate Multiphysics Coupling

Our Current Approach at the Systems Level



Coupling so far

For Test Chamber



CFD

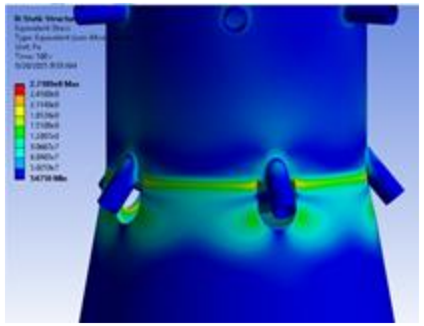
(heat transfer + hydraulics)

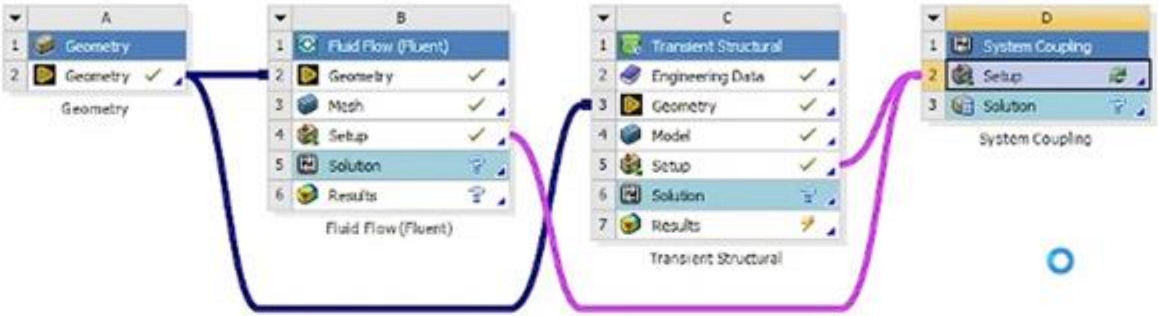
Ansys FLUENT

Temperature

Structural

Ansys



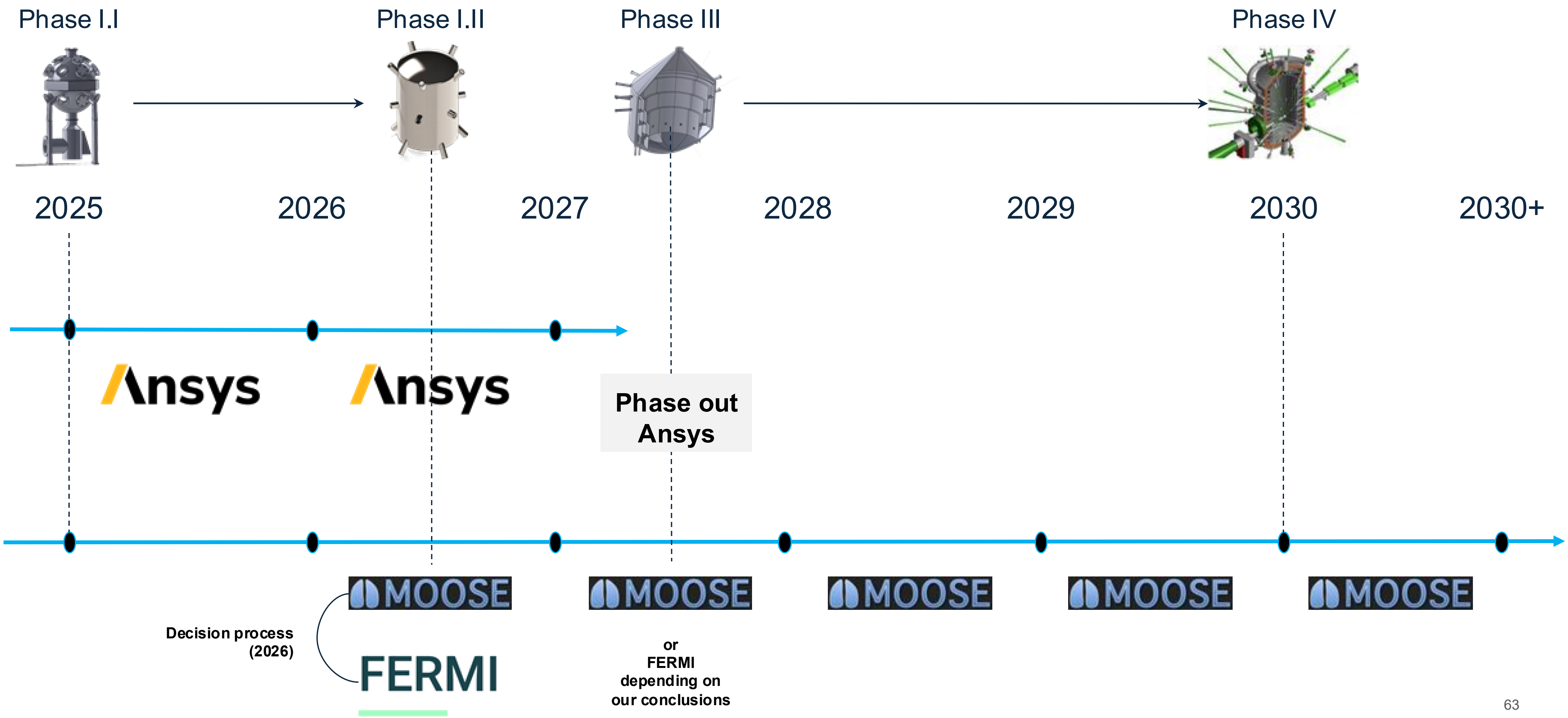


Fields passed between codes

Software

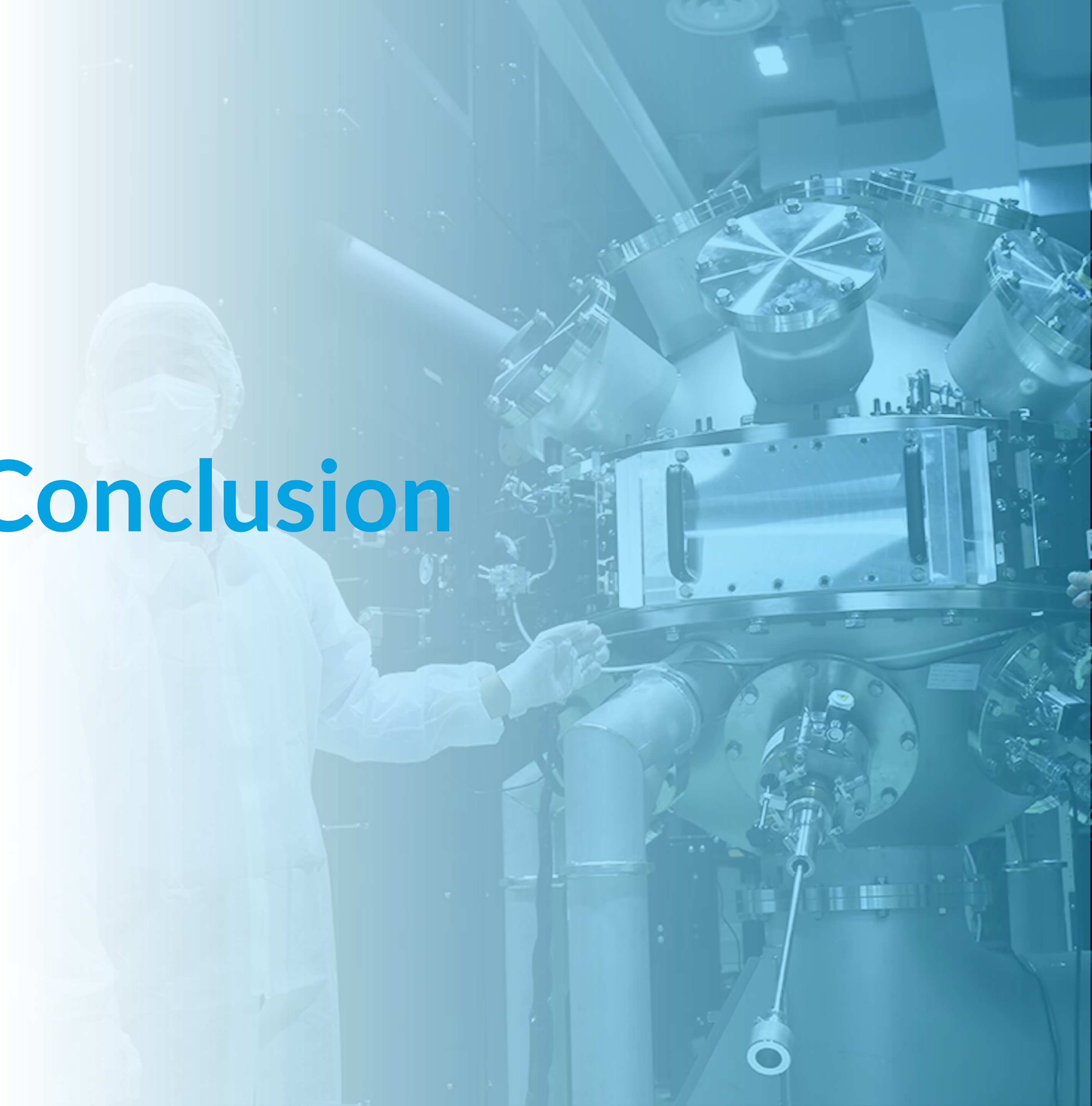
Choice of Multiphysics Framework: Short- & Long-Term Strategy

From Test Chamber to FPP

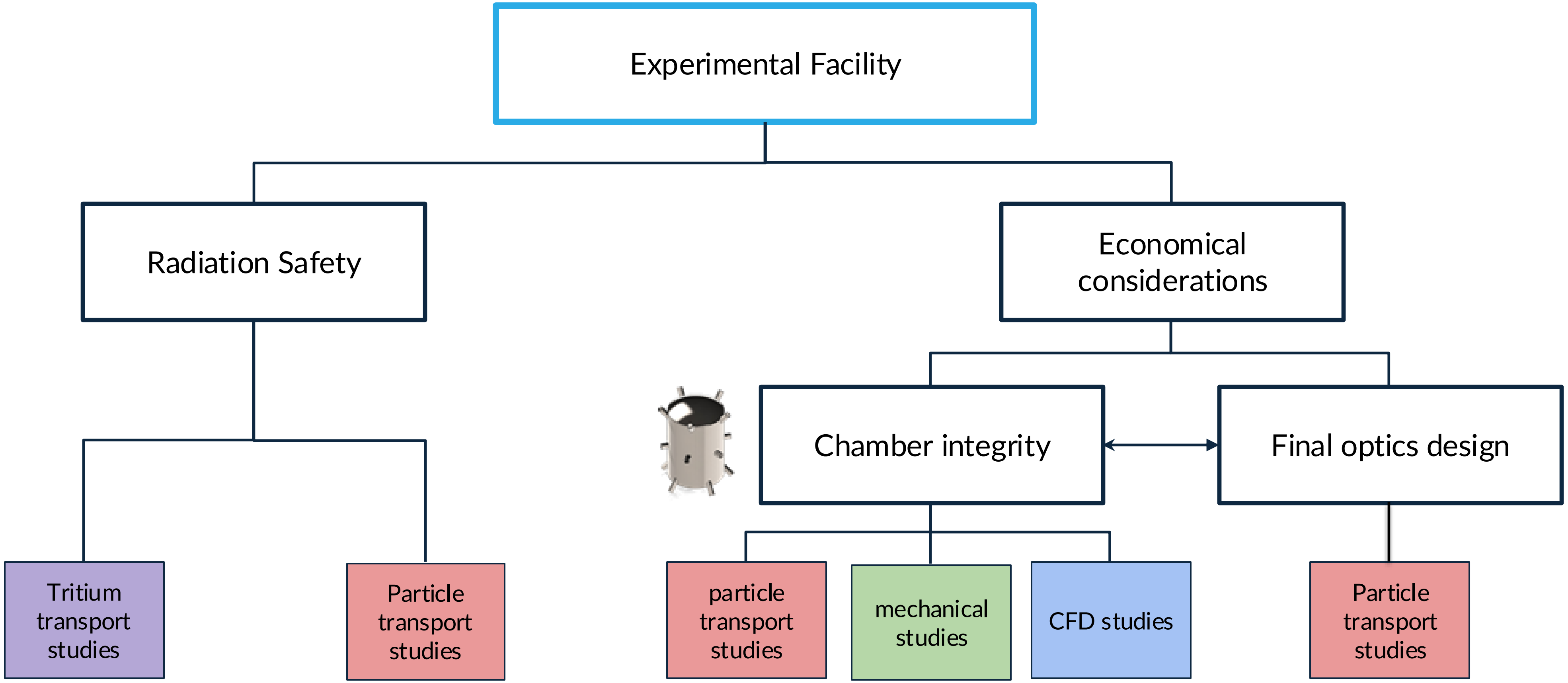


Author: Max Monange

(VII) Conclusion

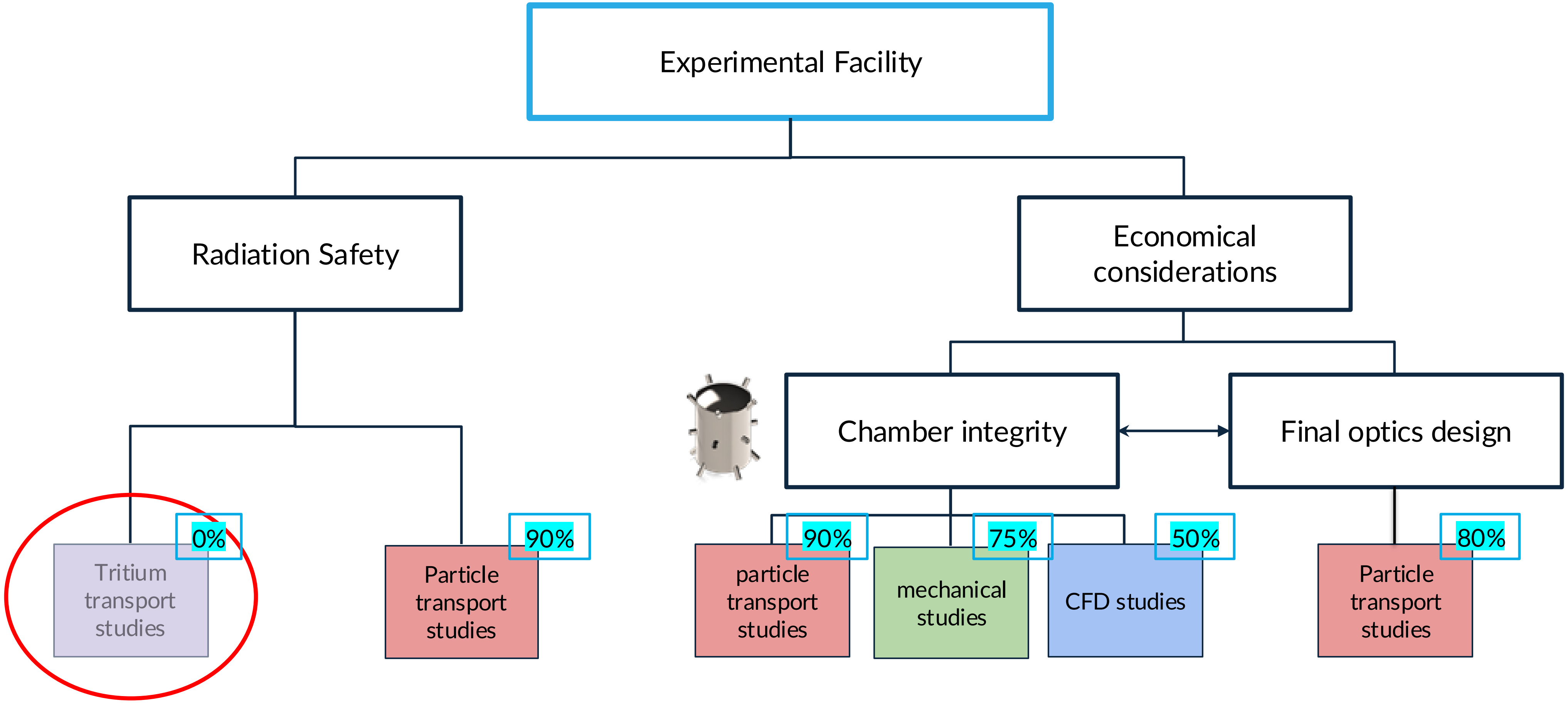


Progress: Key points



Author: Max Monange

Future work

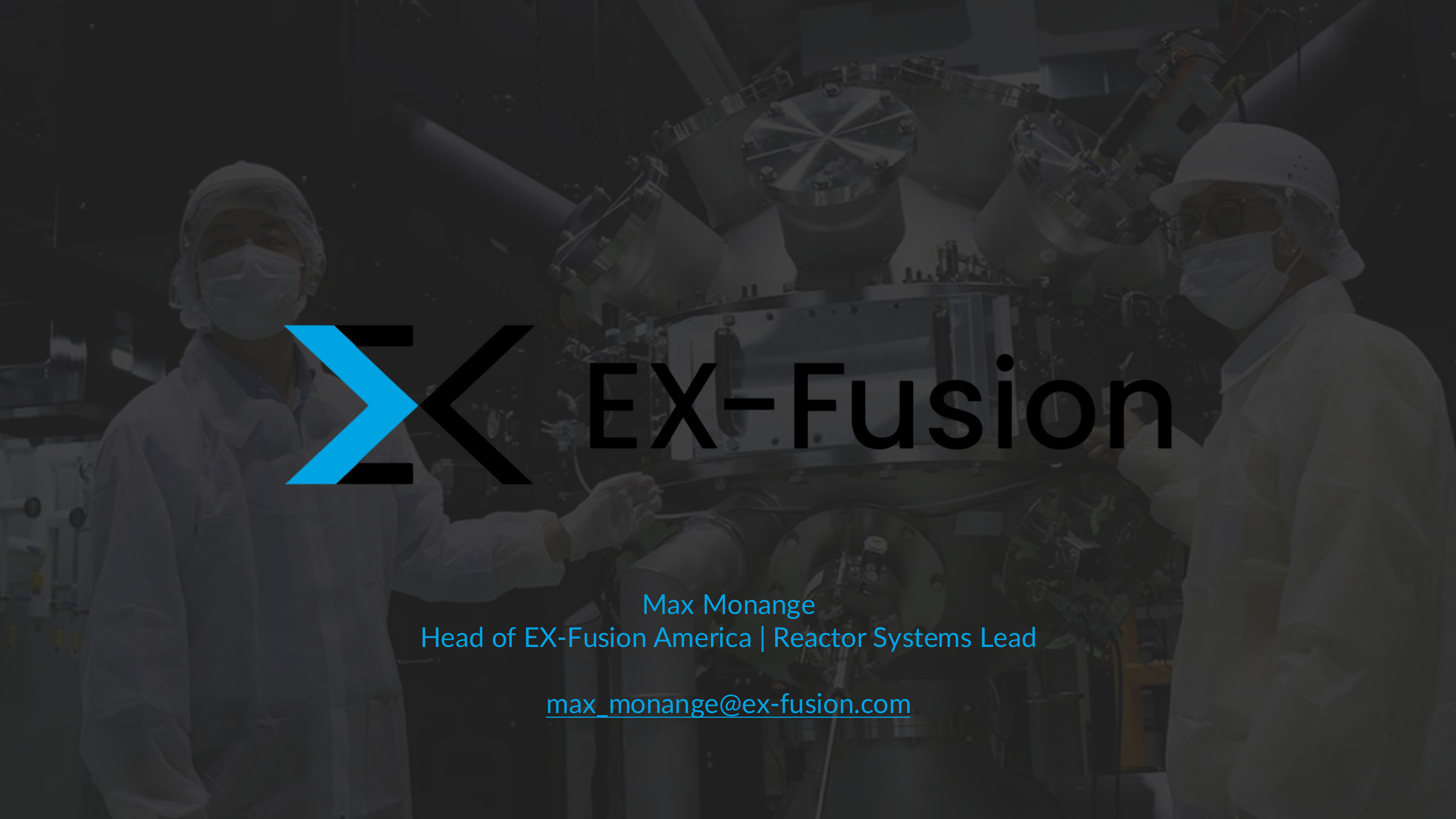


2-way coupling in progress (CFD + structural mechanical) using Ansys

3-way coupling on the roadmap (neutronics + CFD + mechanical)

4-way coupling will be outsourced / completed using an existing Multiphysics framework

 Author: Max Monange



EX-Fusion

Max Monange
Head of EX-Fusion America | Reactor Systems Lead

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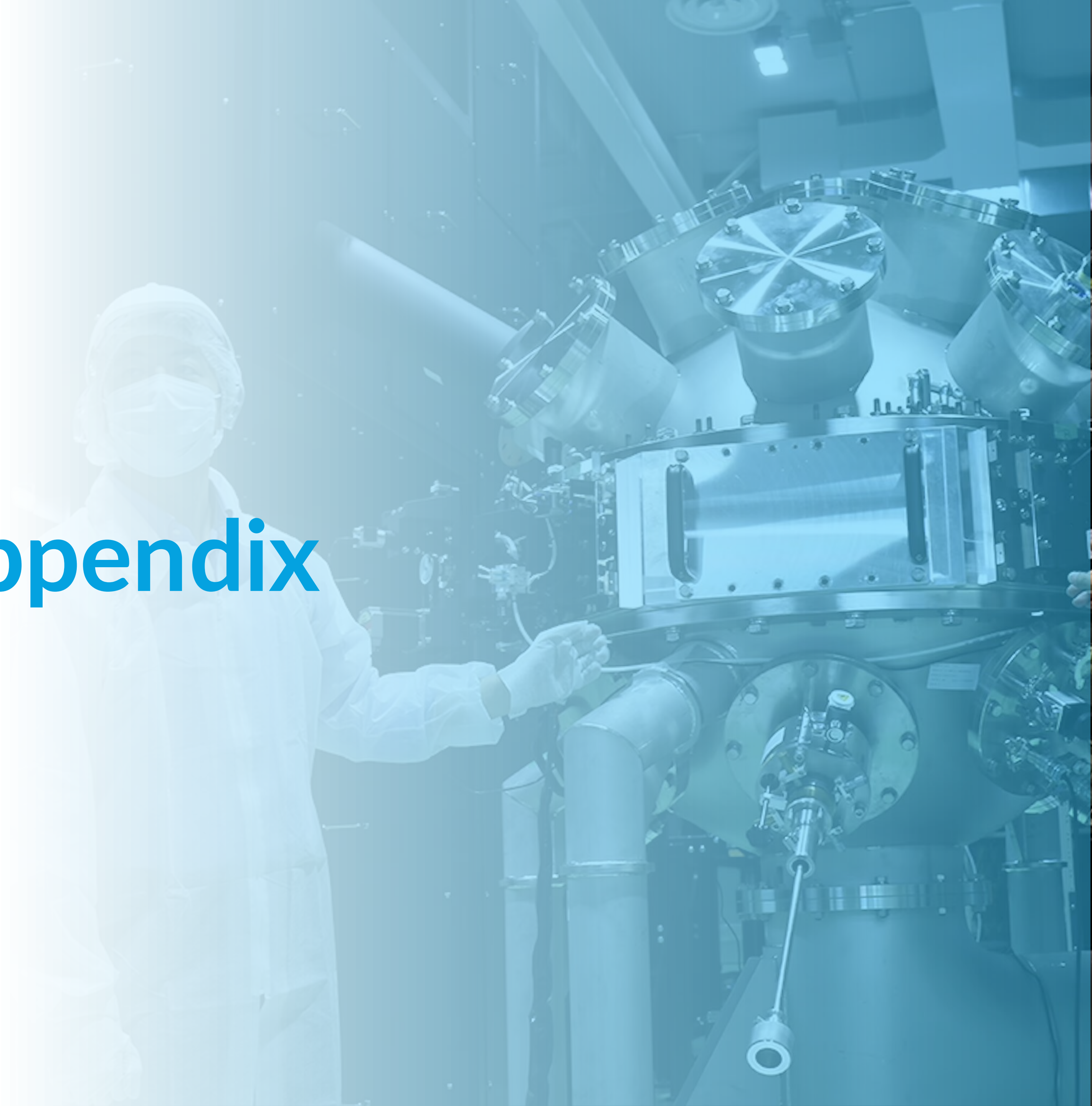
Appendix

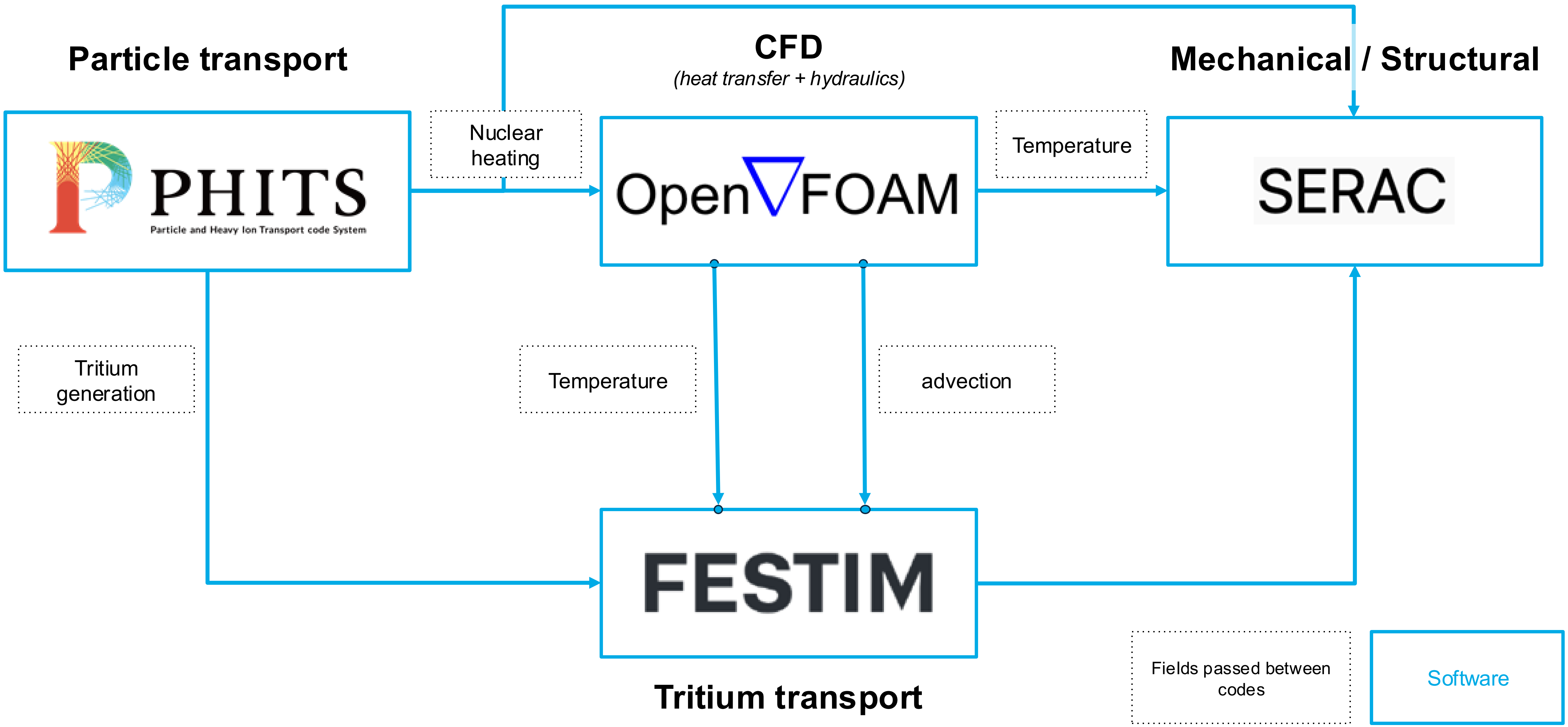


Leveraging Already Existing Multiphysics Frameworks

For System-level Modeling

	FERMI	MOOSE	Feature importance (1-5)
Has PHITS	Yes (can be integrated, will take time)	No	5
User interface / friendliness	?	?	5
User support	Needs funding, documentation not released yet	Workshops, referred to documentation, large active team	5
Open Source	In progress, may take time	Yes	4
Individual apps	Relies on existing apps / softwares with larger user base	INL created their own CFD / mechanical codes	4
Performance	?	Heard it can be slow to run	4
Support pricing/h	?	?	4
Existing users	CFS, ITER	UKAEA, UCLA, IDIOM (no private fusion company)	3
V&V	No existing validation against experiments?	Extensive V&V and documentation for individual apps	3
Physics coupling	Proprietary to ORNL	Each software has the same source code making it easier for apps to "talk to one another", push framework-wide updates	2
Meshing	Very strong meshing alignment between softwares through Cubit	?	2

FERMI



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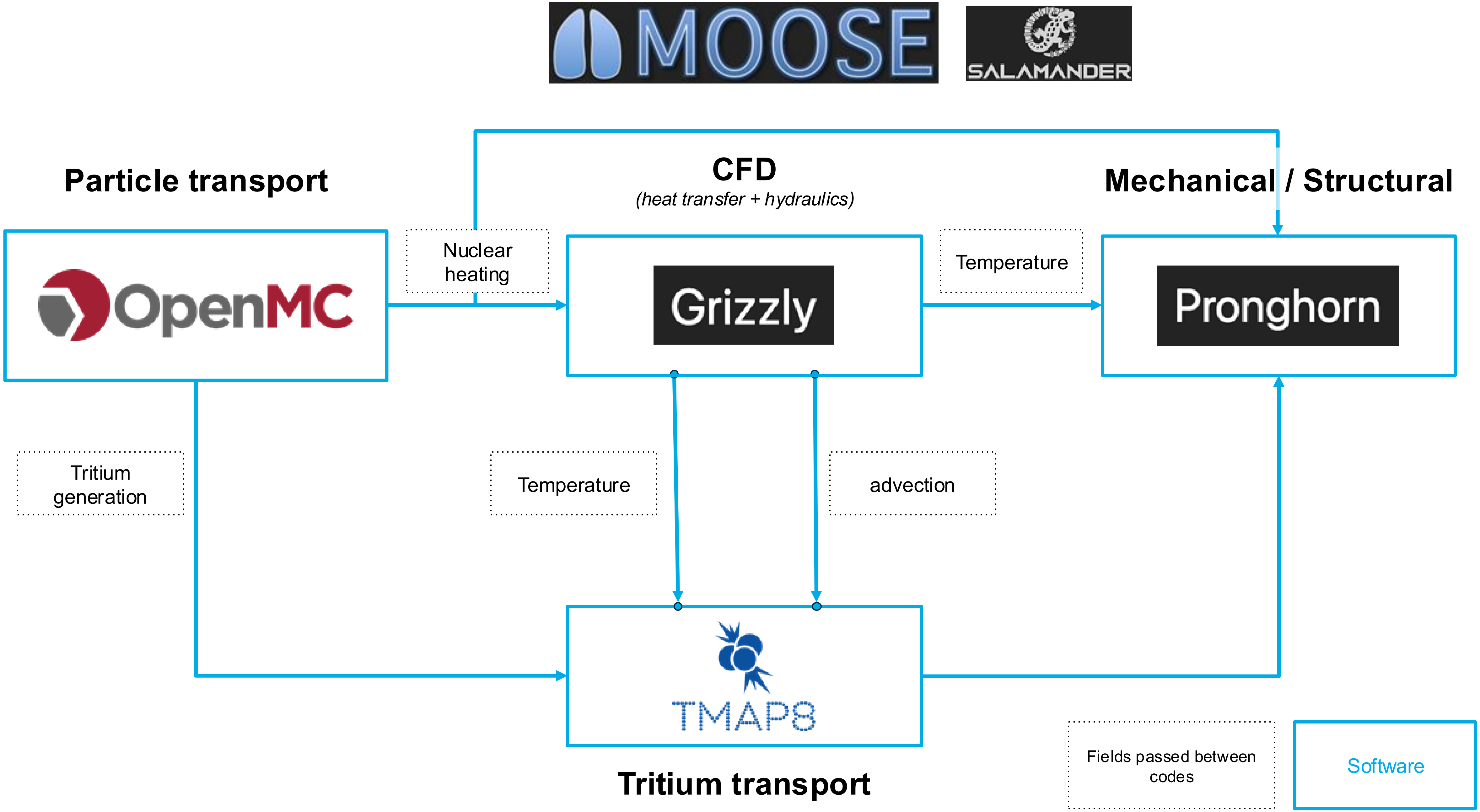
MOOSE
SALAMANDER
Particle transport
CFD
(heat transfer + hydraulics)
Mechanical / Structural
OpenMC
Nuclear heating
Grizzly
Temperature
Pronghorn
Tritium generation
Temperature
advection
TMAP8
Tritium transport
Fields passed between codes
Software

