Helical Fusion

A Liquid Metal Blanket Concept with the First Wall Covered by the Liquid Metal Surface Flow for the Helical Fusion Reactor HESTIA

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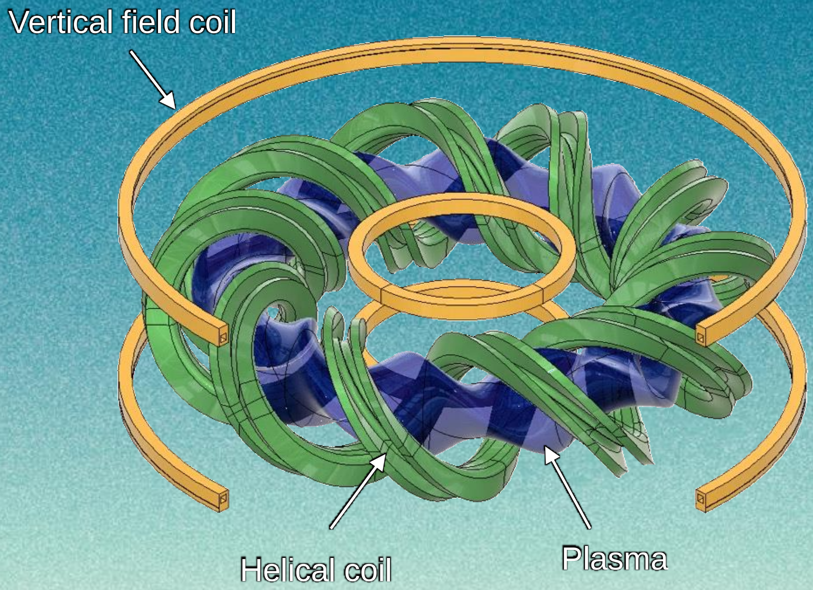
M. Sakama (Tokushima University)
D. Geng, R. Kasada (Tohoku University)
Y. Sugawara (Aoyama Gakuin University)

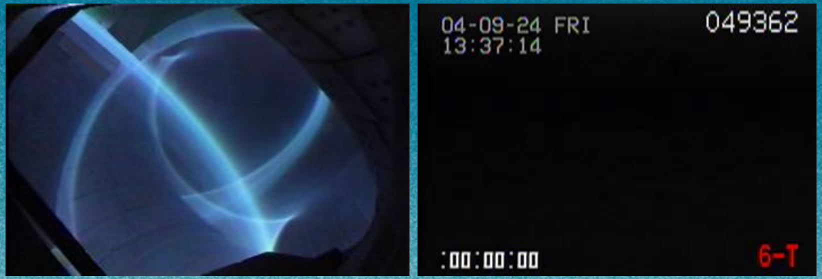
Introduction

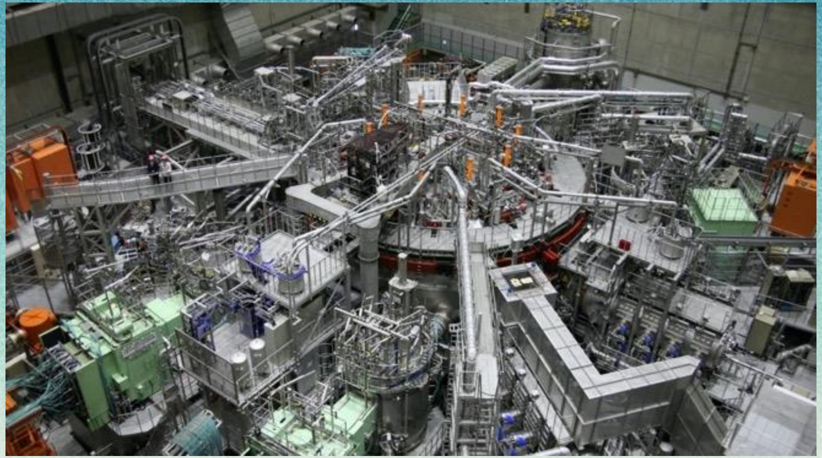


Helical

- **Helical is complex in structure, but easy to operate.**

→ We employ Helical, because we want a long-lived plasma as the Sun on Earth





LHD (Large Helical Device)
National Institute for Fusion Science (Toki, Gifu)

https://www-lhd.nifs.ac.jp/pub/LHD_Project.html

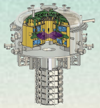
Phased Development Plan

	2020	2025	2030	2035	2040	2045	2050
Individual Technologies	Small-scale Demonstration	Large-scale Demonstration					
Prototype (HESTIA-mini)	Construction	Non-nuclear Operation	DT Operation				
FPP (HESTIA)		Construction	DT Operation				
FOAK Power Plant			2034	Construction		DT Operation	

R&D on Individual Technologies

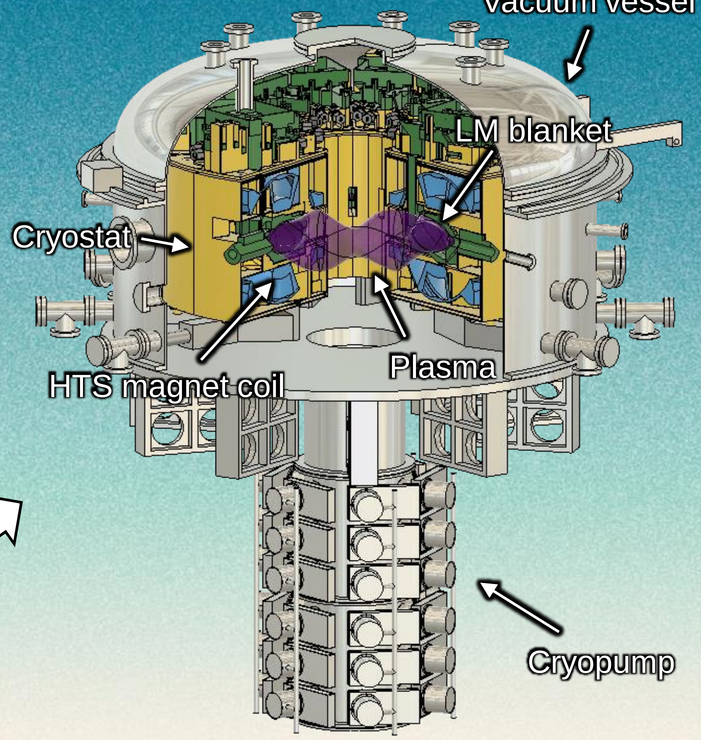
- Configuration optimization
- HTS magnet
- **Liquid Metal Blanket**
- ECH (Electron Cyclotron Heating)
- Pipe-gun pellet injector
- DIR (Direct Internal Recycling)
- SCO_2 gas turbine generator
- H_2 liquefaction and storage system

HESTIA-mini
as Prototype



4 m

HESTIA
as FPP (Fusion Pilot Plant)



30 m

Fusion Pilot Plant: HESTIA

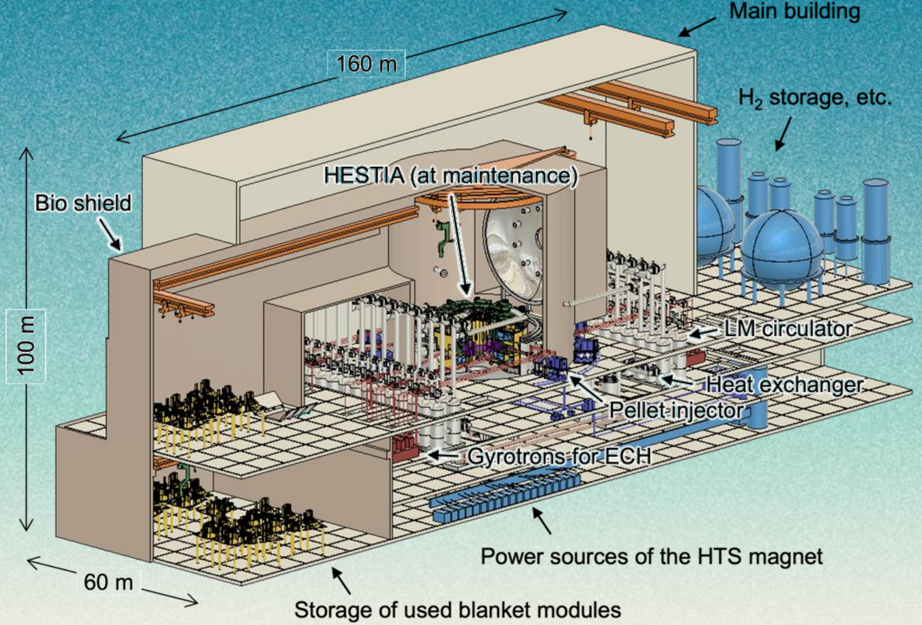
Helical Fusion

Helical Fusion is developing a 50 MWe-class FPP named HESTIA.

The FOAK power plant following HESTIA will be a 100 MWe-class steady-state helical fusion reactor.

Specifications of HESTIA

- Helical coil major radius, R_c: 7.8 m
- Magnetic field strength, B_c (at R_c): 8.0 T
- ECH heating power, P_{ECH}: 20 MW
- Fusion power, P_{fusion}: 260 MW
- Net electricity: 70 MWe
- Continuous operation time: 1 year
- Availability: > 80 %



Overall view of HESTIA

J. Miyazawa et al., PoP **30** (2023) 050601.

Prototype: HESTIA-mini

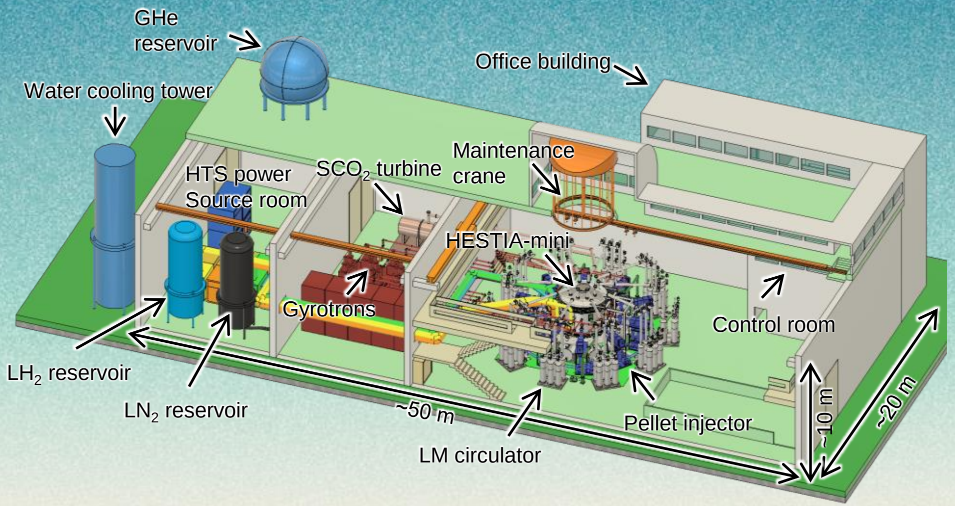
Helical Fusion

Before proceeding to HESTIA, an integrated demonstration of plasma, HTS magnet, and **Liquid Metal (LM) blanket** is needed.

HESTIA-mini will be constructed as a prototype for this purpose.

Specifications of HESTIA-mini

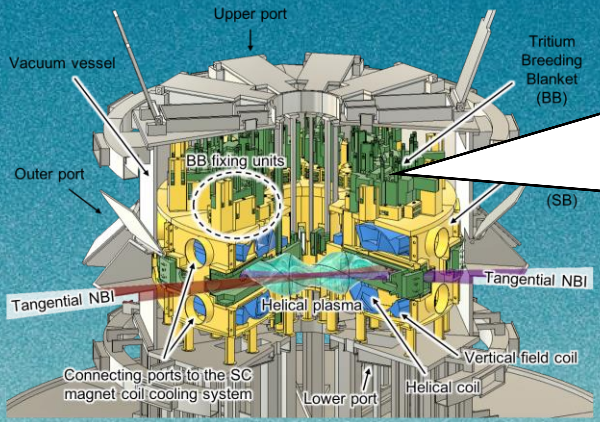
- Helical coil major radius, R_c: 1.092 m
- Magnetic field strength, B_c (at R_c): 2.0 T
- ECH heating power, P_{ECH}: 2 - 10 MW
- Continuous operation time: > 1 day
- Non-nuclear in the 1st phase exp.
- DT operation will be conducted in the 2nd phase, after relocation to the fusion reactor construction site.

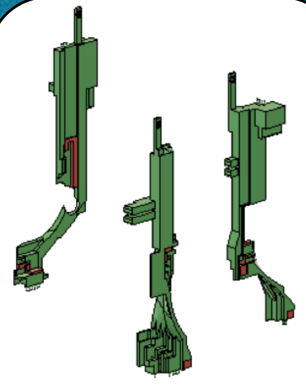


Overall view of HESTIA-mini

Cartridge-type Liquid Metal Blanket

Helical Fusion

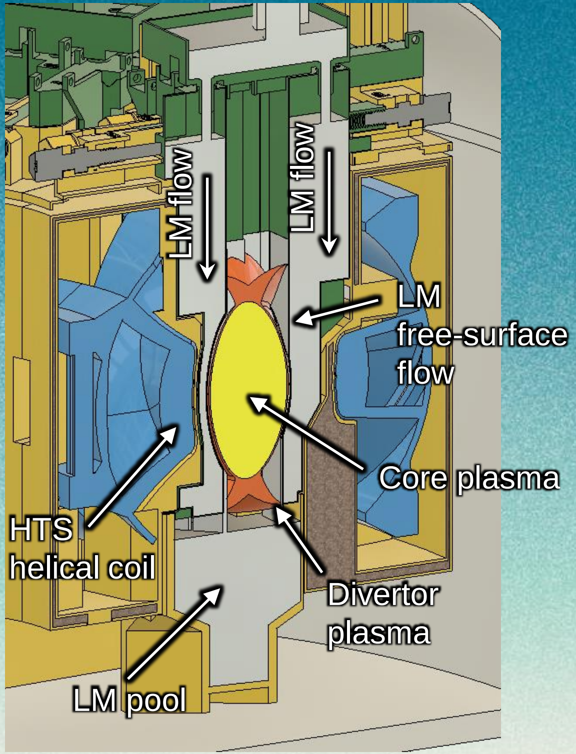




Blanket cartridges

J. Miyazawa et al., PFR **14** (2019) 1405163.

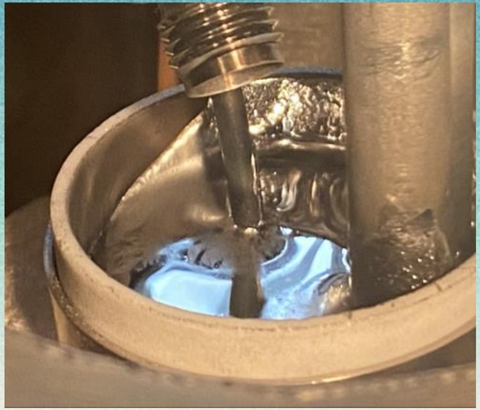
- 90 main modules and 10 TBM.
- Main modules can be easily pulled out to the device top at maintenance.
- Liquid metal: Tin-lead-lithium alloy
- Structure material: High-manganese steel
- 1^{st} wall is composed of porous structures.
- Liquid metal oozes from the porous forms LM free-surface and protects the first wall.
- No divertor.



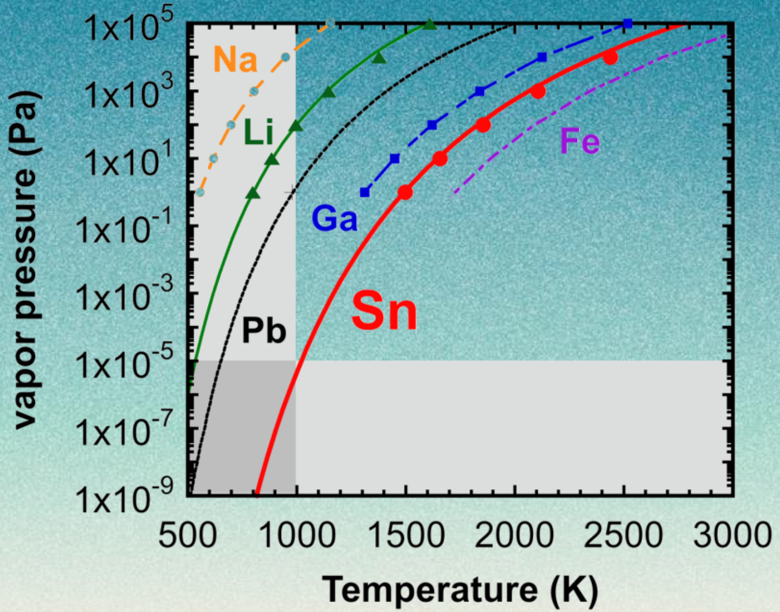
LM blanket with the 1^{st} wall covered by LM free-surface flow

Tin-Lead-Lithium Alloys

- Sn is chosen as the base material, because of the low vapor pressure (< 10^{-5} Pa at 1,000 K).
- Li is added for T production.
- Pb is added for neutron multiplication.
- The melting point will be lower than 200℃.



Molten tin-lead-lithium alloy



Vapor pressure of various metals

J. Miyazawa et al., NF **61** (2021) 126062.

Major 6 R&D Items for LM Blanket in HESTIA

(1) ANSYS simulation of LM flow:
- In collaboration with NIFS.

(2) PoP experiment on LM surface flow generation:
- In collaboration with NIFS.

(3) Development of pressurized-gas-driven LM pump:
- In collaboration with NIFS and a private company.

(4) 3D neutron transport simulation:
- In collaboration with Tokushima Univ.

(5) Development of new non-magnetic structural material:
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(6) Examination of maintenance method using a three-point suspension crane:
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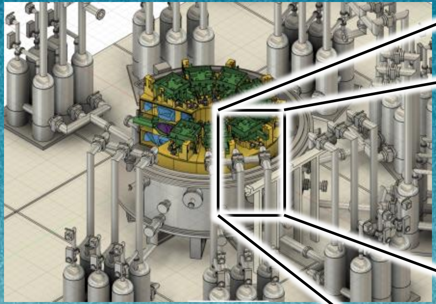
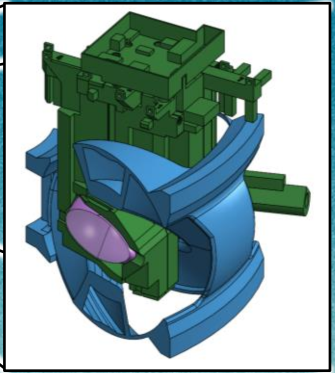
ANSYS Simulation of LM Flow

Helical Fusion

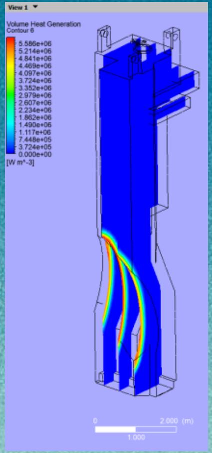


CAD data of HESTIA

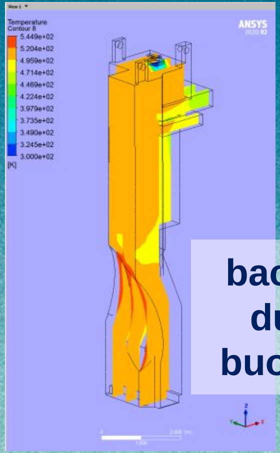


CAD data of blanket cartridges

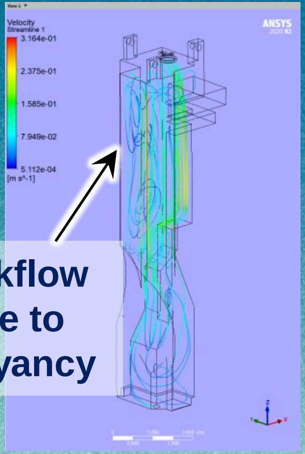
ANSYS



Nuclear heating distribution



Temperature distribution

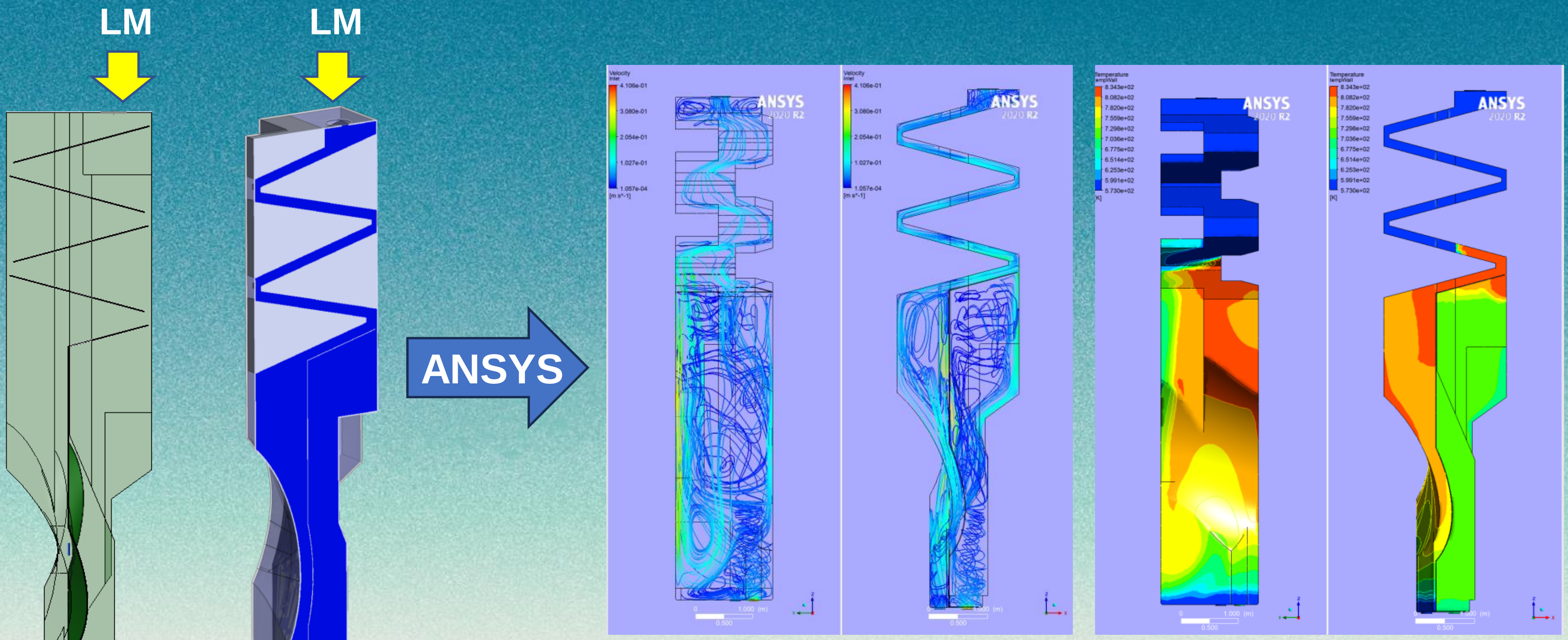


Streamlines and velocities

- LM flow analysis using ANSYS is being carried out.
- The LM flows down inside the blanket cartridge under the force of gravity.
- Nuclear heating proportional to the distance from the first wall surface is assumed.
- Backflow due to buoyancy is observed → Devise flow paths.

By S. Nakagawa, Y. Hamaji, and T. Murase (NIFS)

Example: Wedge-Shaped Channels



Streamlines and velocities

Temperature distribution

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Development of “GaLF”

LM surface flow formation experiment is being carried out in collaboration with NIFS.

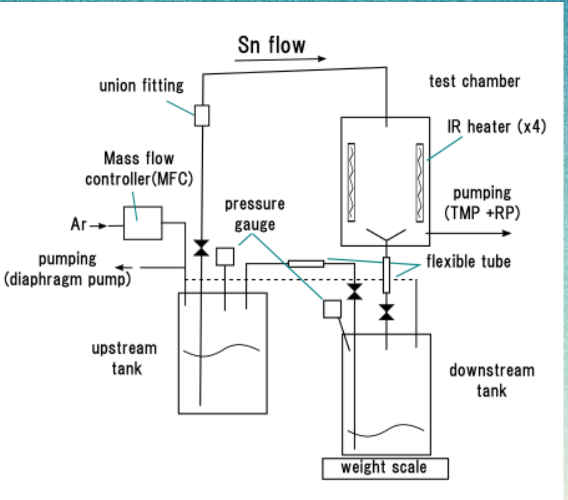
GaLF (Gas-driven Liquid metal Free-surface flow test device) has been developed.

LM is driven by pressurized Ar gas in vacuum in GaLF.

Specifications of GaLF

- LM material: Sn
- LM temperature: 350 ℃
- Ar gas pressure: < 1 atm
- LM flow rate: 100 – 2,000 cc/min
- LM flow duration: 1 – 20 min
- The flow rate is estimated from the weight change of the downstream LM tank.
- An IR heater heats the test piece simulating the LM blanket.

GaLF (and Hamaji)



Flow circuit of GaLF

By Y. Hamaji (NIFS)

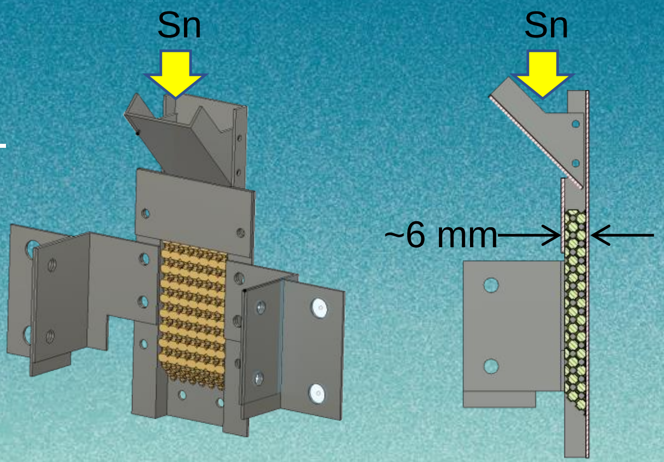
LM Surface Flow Formation using Porous

LM surface flow has been successfully formed in GaLF!!

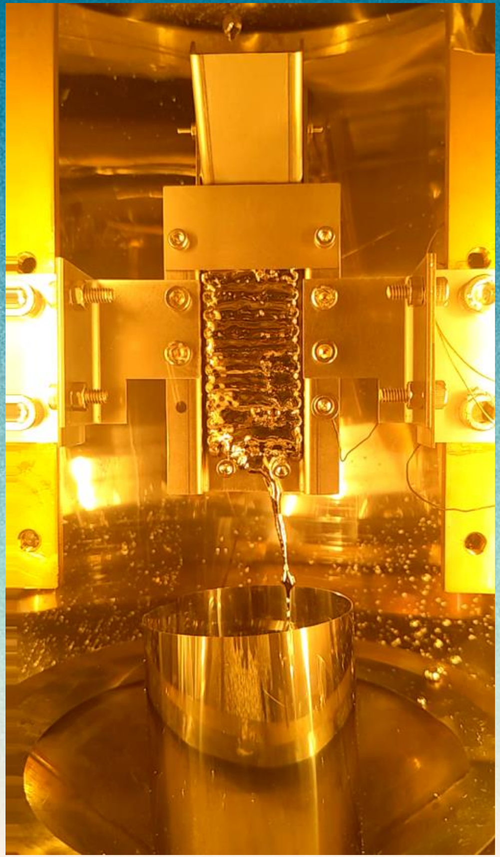
But unfortunately, it was short-lived...

Challenges in LM surface flow formation

- Good wettability that does not change over time.
- Optimization of porous material.
- Optimization of porous design.
- Fabrication of large porous structures.
- Demonstration in actual equipment size.



A test piece simulating the LM blanket



LM surface flow formed in GaLF

By Y. Hamaji (NIFS)

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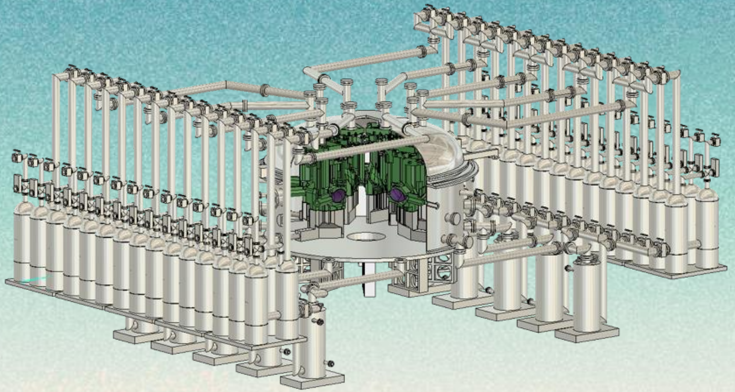
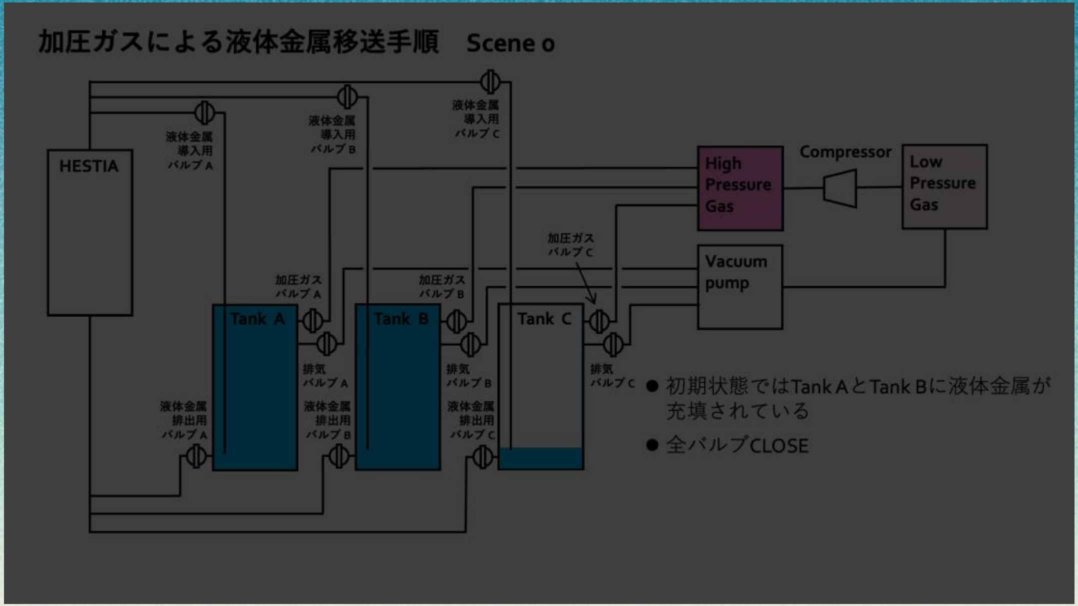
Liquid Metal is Circulated by Pressurized Gas

HESTIA adopts an LM circulation system driven by pressurized gas aiming at a high reliability.

- Based on GaLF
- No mechanical pump or EM pump



LM circulation system



Sequence of LM circulation by pressurized gas

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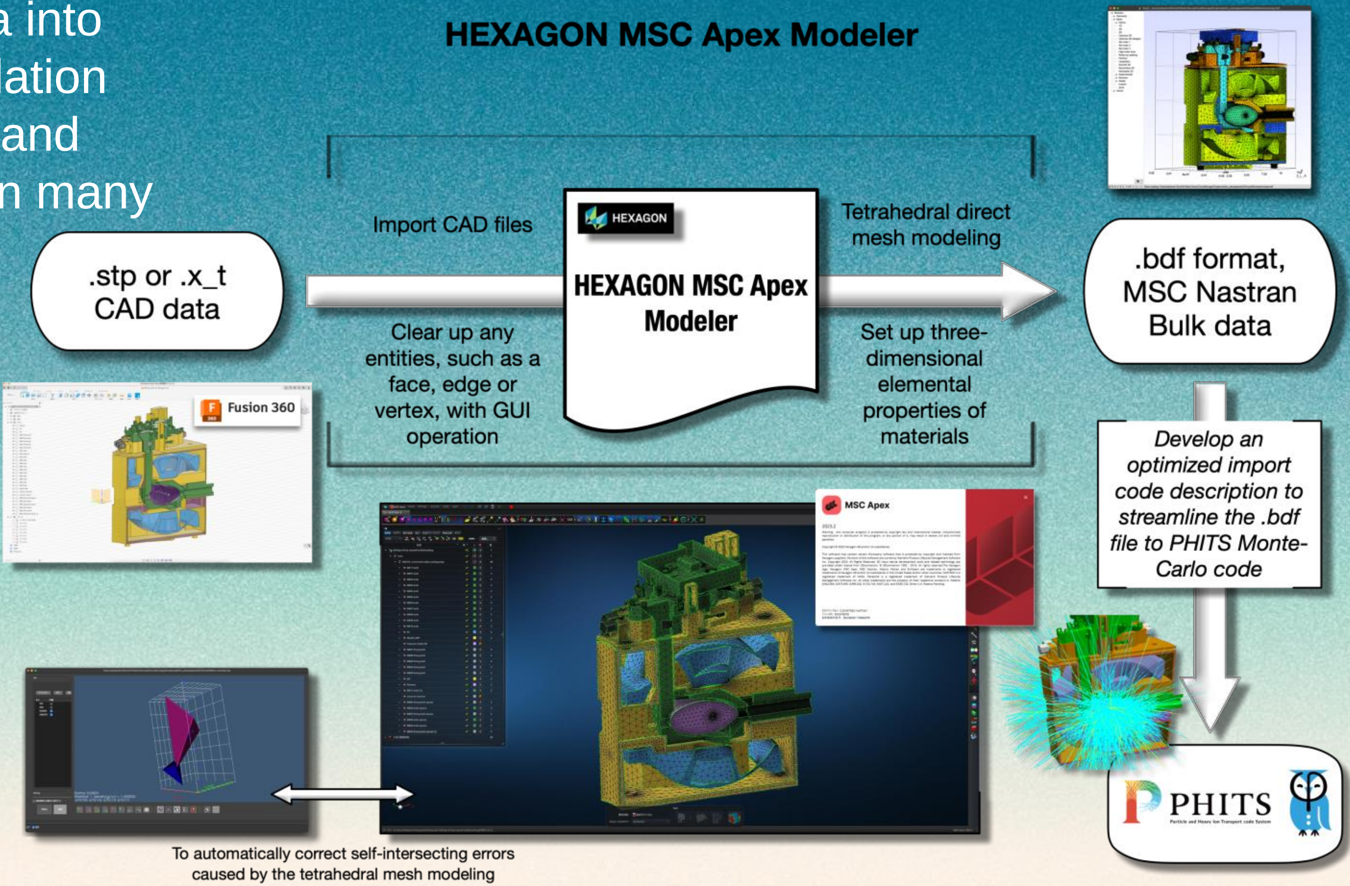
Ready to Import 3D-CAD Data into PHITS

Helical Fusion

Importing 3D-CAD data into neutron transport simulation codes such as MCNP and PHITS usually results in many error messages…

Our solution is:

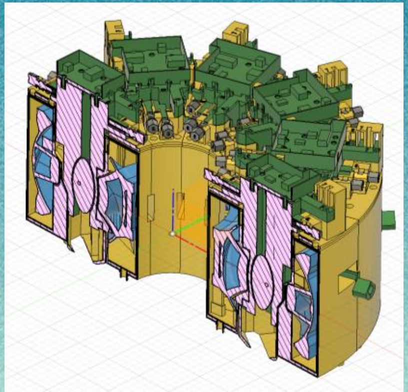
- To convert CAD data to bdf format data using **HEXAGON MSC Apex Modeler**.
- Then, import it to PHITS using an import script.

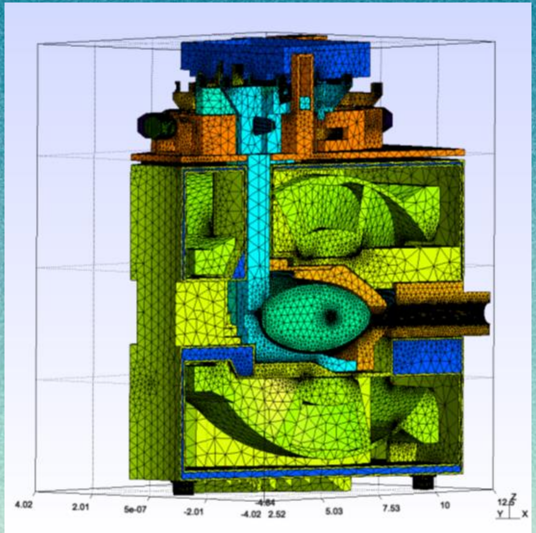


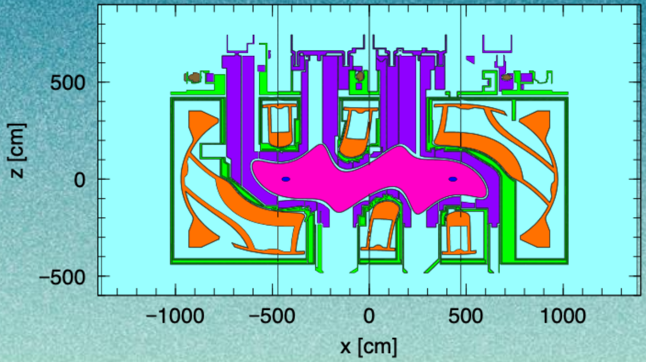
https://hexagon.com

By M. Sakama (Tokushima Univ.)

Example of 3D-CAD data Imported into PHITS







Fusion 360
(3D-CAD)

MSC APEX Modeler
(data type converter)

PHITS
(neutron simulation code)

By M. Sakama (Tokushima Univ.)

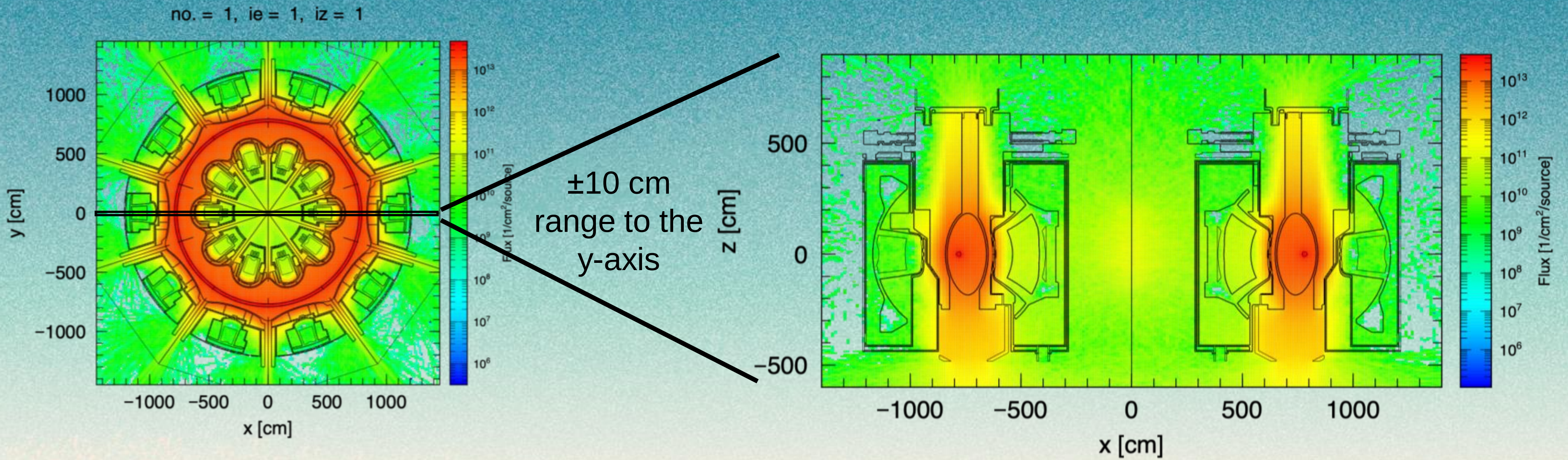
Example of PHITS Results

Helical Fusion

It is working very well.

The next problem is computing time.

- 3 days for 10 million histories, 30 days for 100 million histories.
- A faster computing environment is being prepared using AWS.



2D distribution map for neutron flux on ±10cm z-axis

2D distribution map for neutron flux on ±10cm y-axis

By M. Sakama (Tokushima Univ.)

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New Non-Magnetic Structural Material

Helical Fusion

We will adopt low-activation steels for structural materials to reduce radioactive waste.

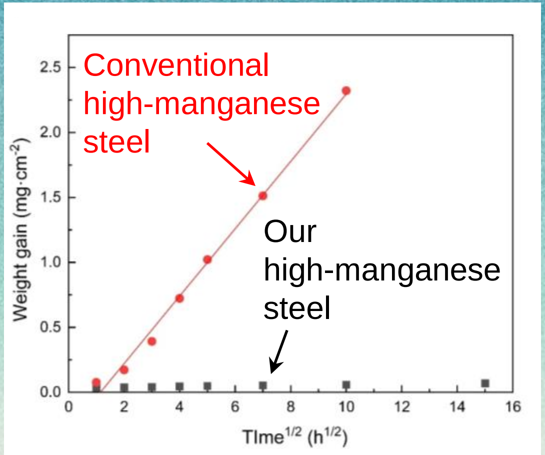
RAFM, however, is undesirable for helicals and/or stellarators where error magnetic fields have a significant influence.

We are developing low activation high manganese steels in collaboration with Tohoku Univ.

Recent status:

- We have created a high manganese steel with excellent anti-oxidation properties at high temperatures (patent pending).
- Strength and corrosion resistance tests are planned in the future.

Newly developed high manganese steel ingot



Weight gain curves of conventional steel and our steel at 600°C in air for 225 hours

By D. Geng and R. Kasada (Tohoku Univ.)

Helical Fusion

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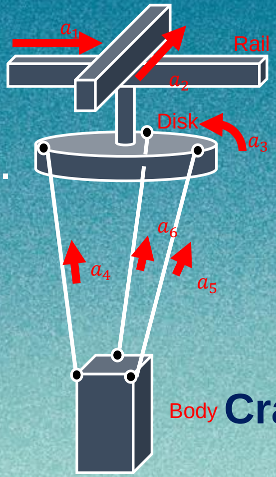
Maintenance using a 3-Point Suspension Crane

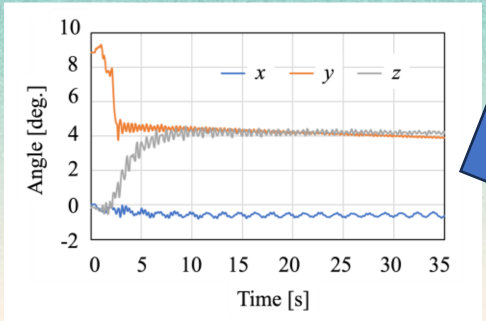
Helical Fusion

Maintenance is one of our key issues.

Research is underway with Aoyama Gakuin University on maintenance using a three-point suspension crane.



Crane Maintenance Simulator



Real-time motion analysis

Recent status:

- Research on feed-forward control methods for suppressing swing of suspended loads.
- Development of a crane maintenance simulator.
- Development of real-time motion analysis system.

Next Issues:

- Numerical data generation of trajectory during maintenance of blanket cartridges.
- Demonstration of remote maintenance.

By Y. Sugawara (Aoyama Gakuin Univ.)

Summary

Helical Fusion Co., Ltd. is working on LM blanket R&D, in the topics of:

- **ANSYS simulation of LM flow,**
- **PoP experiment on LM surface flow generation.**
- **Development of pressurized-gas-driven LM pump,**
- **3D neutron transport simulation,**
- **Development of new non-magnetic structural material, and**
- **Examination of maintenance method using a three-point suspension crane.**

These are progressing successfully through joint research with NIFS, Tokushima University, Tohoku University, Aoyama Gakuin University, and private companies…

toward the realization of a steady-state helical fusion reactor in 2034.

Humanity evolves with nuclear fusion

Helical Fusion