FIP/3-4Ra

Two Conceptual Designs of Helical Fusion Reactor FFHR-d1A Based on ITER Technologies and Challenging Ideas

A. Sagara, J. Miyazawa, H. Tamura, T. Tanaka, T. Goto, N. Yanagi, R. Sakamoto, S. Masuzaki, H. Ohtani, and the FFHR Design Group (NIFS, JAPAN)

FIP/3-4Rb

Development of Remountable Joints and Heat Removable Techniques for High-temperature Superconducting Magnets

H. Hashizume[1], S. Ito[1], N. Yanagi[2], H. Tamura[2], A. Sagara[2] ([1]Tohoku Univ., [2]NIFS)

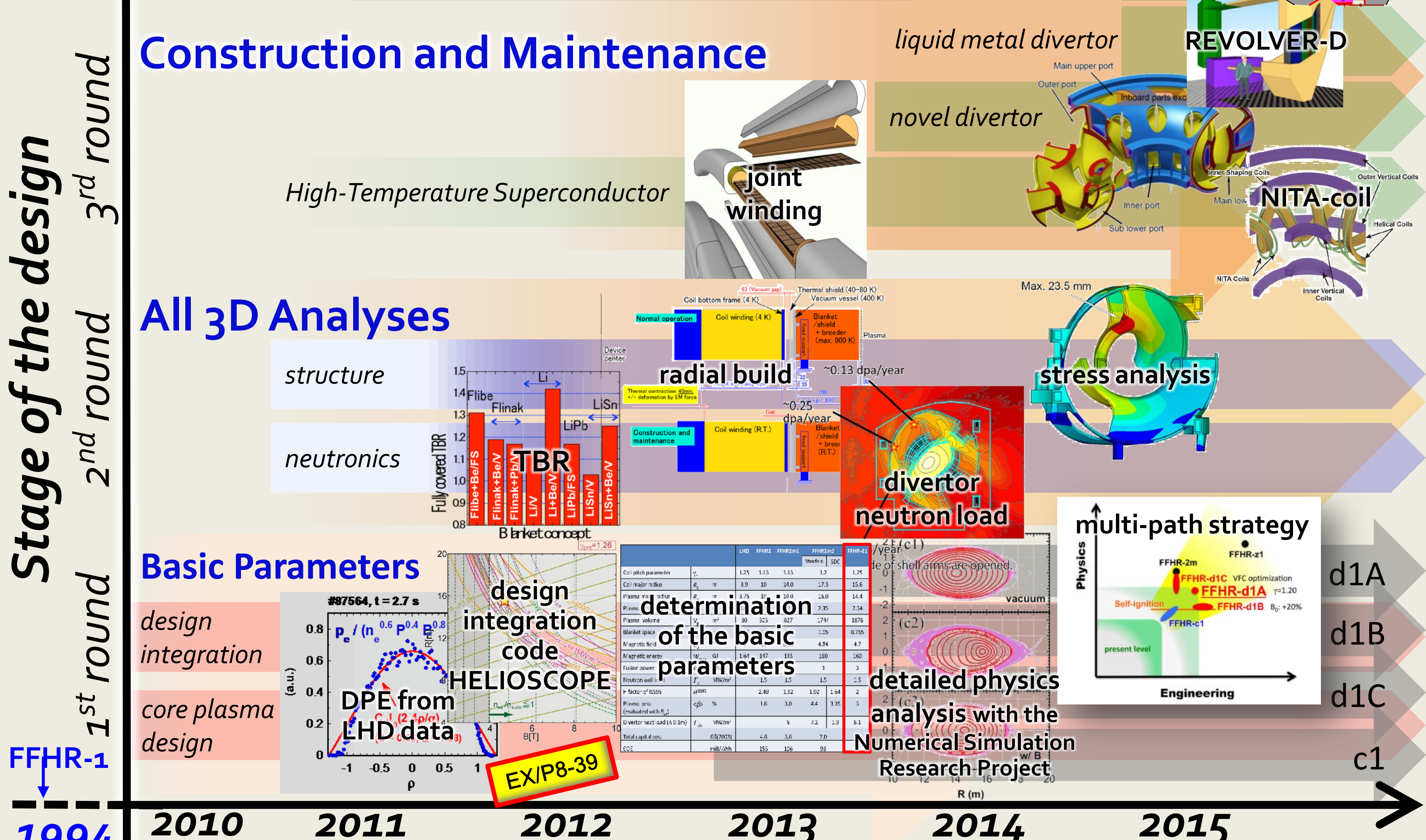
FIP/3-4Rc

Lessons Learned from the Eighteen-Year Operation of the LHD Poloidal Coils Made from CIC Conductors

K. Takahata, S. Moriuchi, K. Ooba, S. Takami, A. Iwamoto, T. Mito, and S. Imagawa （NIFS, JAPAN）

Staged progress in designing FFHR-d1

of FERP in NIFS corroborative activities



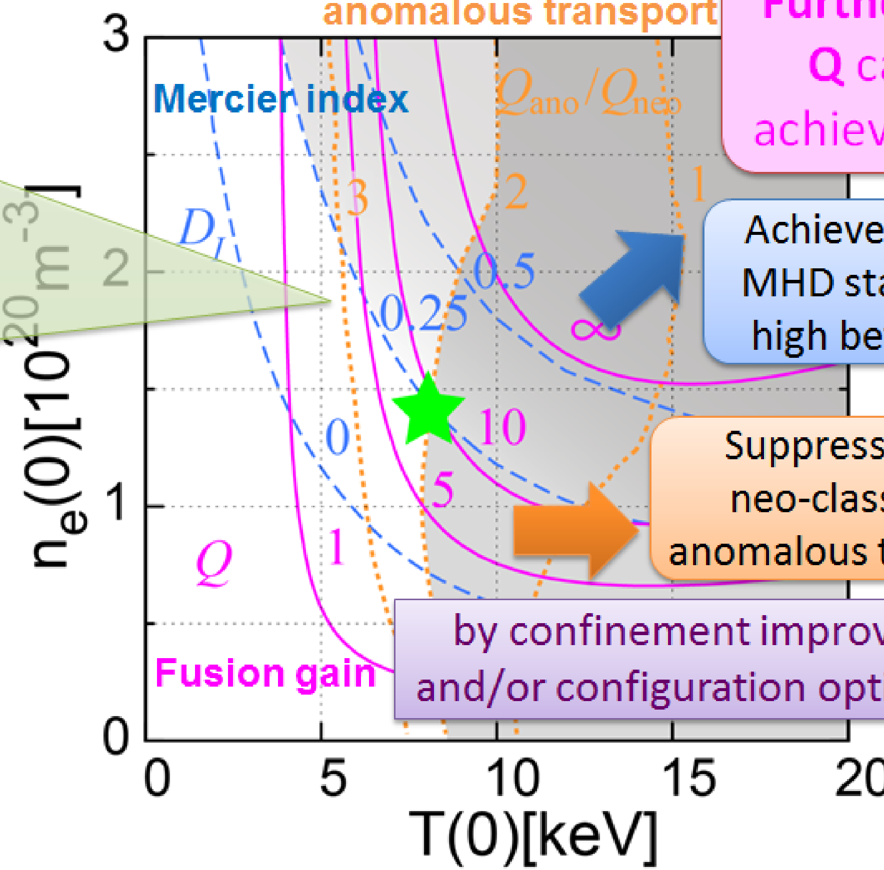
EX/P8-39

EX/P8-39
Development of a Real-time Simulation Tool towards Self-consistent Scenario of Plasma Start-up and Sustainment on Helical Fusion Reactor FFHR-d1

by Takuya GOTO *et al.*, (NIFS, Japan)

Self-consistent operation point

- Sufficiently low **neo-classical energy loss** considering anomalous transport
- **MHD equilibrium/ stability** confirmed in LHD exp.
- Sufficiently low **boot-strap current**



Further large Q can be achieved with

Achievement of MHD stability at high beta state

Suppression of neo-classical / anomalous transport

by confinement improvement and/or configuration optimization

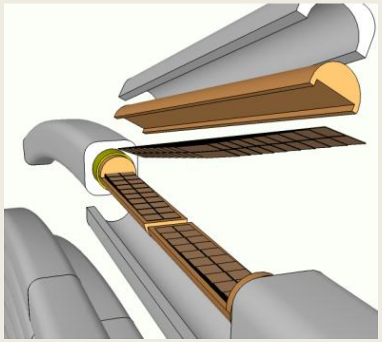
◆ Advantage of the Helical Reactor

Easy and stable plasma sustainment **without plasma current**

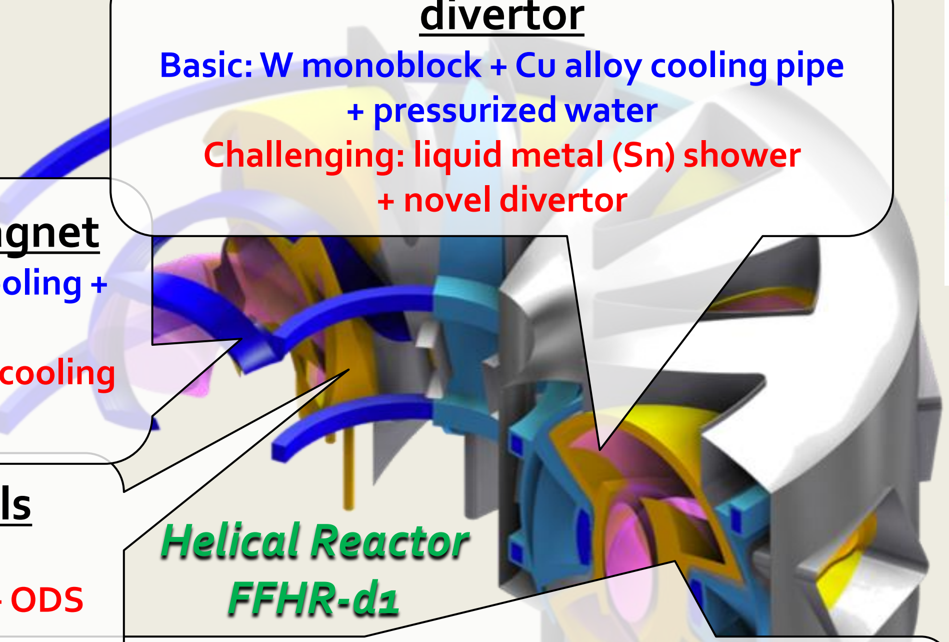
◆ Difficulty of the Helical Reactor

Need to construct a large and complicated device

➔ **2 options** of **Basic** (based on the ITER technology) and **Challenging** (easier construction & maintenance) are defined



joint winding



divertor

Basic: W monoblock + Cu alloy cooling pipe + pressurized water

Challenging: liquid metal (Sn) shower + novel divertor

superconducting magnet

Basic: Nb_3Sn + liquid He cooling + continuous winding

Challenging: HTS + He gas cooling + joint winding

structural materials

Basic: ferritic steel

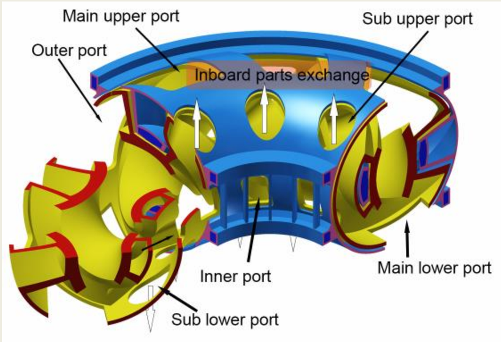
Challenging: ferritic steel + ODS + V alloy

Helical Reactor FFHR-d1

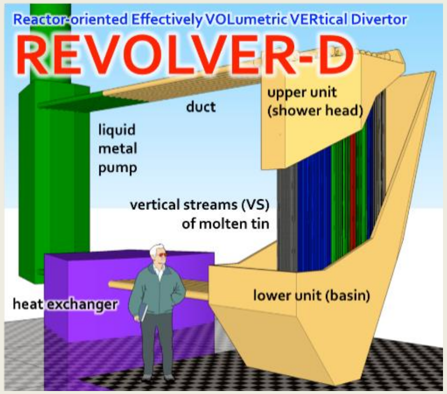
blanket

Basic: solid breeder + pressurized water + helical segmentation

Challenging: molten salt + Ti powder + horizontal / toroidal segmentation



novel divertor



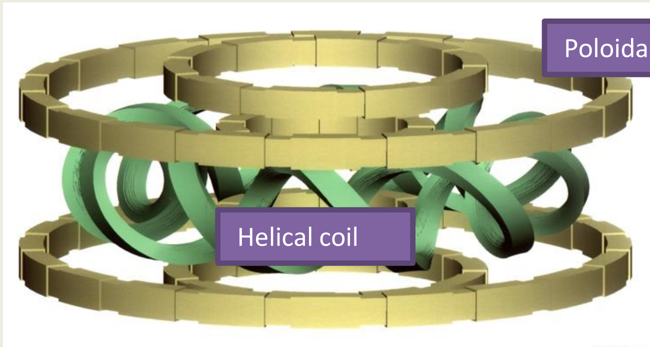
liquid metal divertor

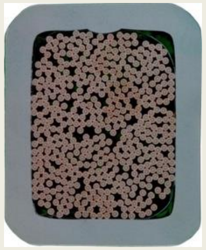
FIP/3-4Rc

Lessons Learned from Eighteen Year Operation for the LHD Poloidal Coils Made from CIC Conductors

K. Takahata, S. Moriuchi, K. Ooba, S. Takami, A. Iwamoto, T. Mito, and S. Imagawa

National Institute for Fusion Science





CIC conductor

Steady Cooling 50,000 h
Excitation 10,000 h

Stable operation
No superconducting-to-normal transition

The experience gained from eighteen years of operation has provided further useful information
– Preventive design and maintenance – Long-term changes in characteristics

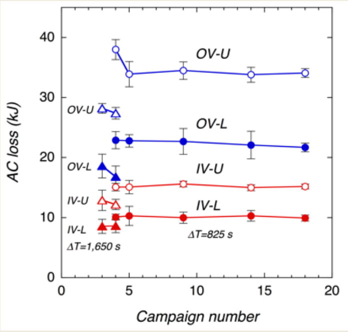
Malfunction of Quench Detection System

- 9 malfunction events
- Noise from NBI
- Out-of-balance voltage due to coupling currents
- No malfunction since 2010 thanks to various measures

Helium Leak from Insulation Break

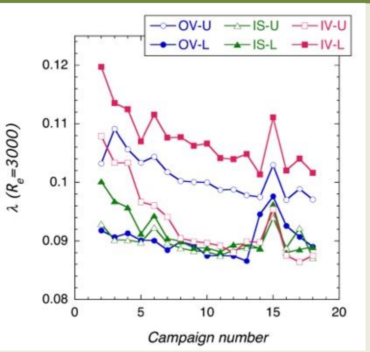
- Sudden helium leak during the 16th cool-down
- Replaced all breaks

Long-Term Changes in AC Loss



Almost unchanged

Long-Term Changes in Hydraulic Characteristics



Decreasing tendency

in good condition

Malfunction of Peripheral Equipment

FIP/3-4Rc

1. Quench Detection System

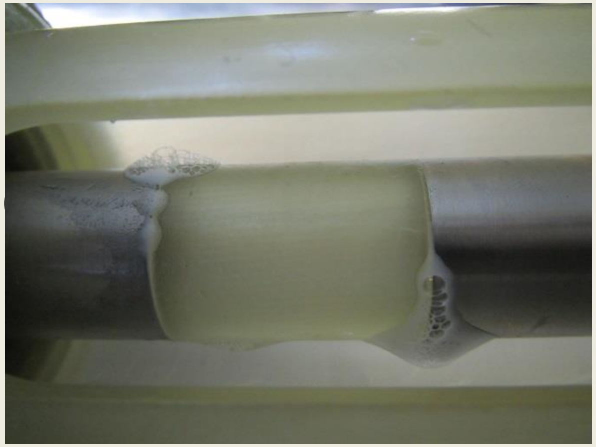
– 9 malfunction events 2002~2009
  - Surge from plasma heating devices
  - Voltage due to coupling current

Lessons

Noises should be estimated in advance of operation

2. Cryogenic Insulating Breaks

– One of the breaks suddenly leaked during the 16th cool-down in 2012

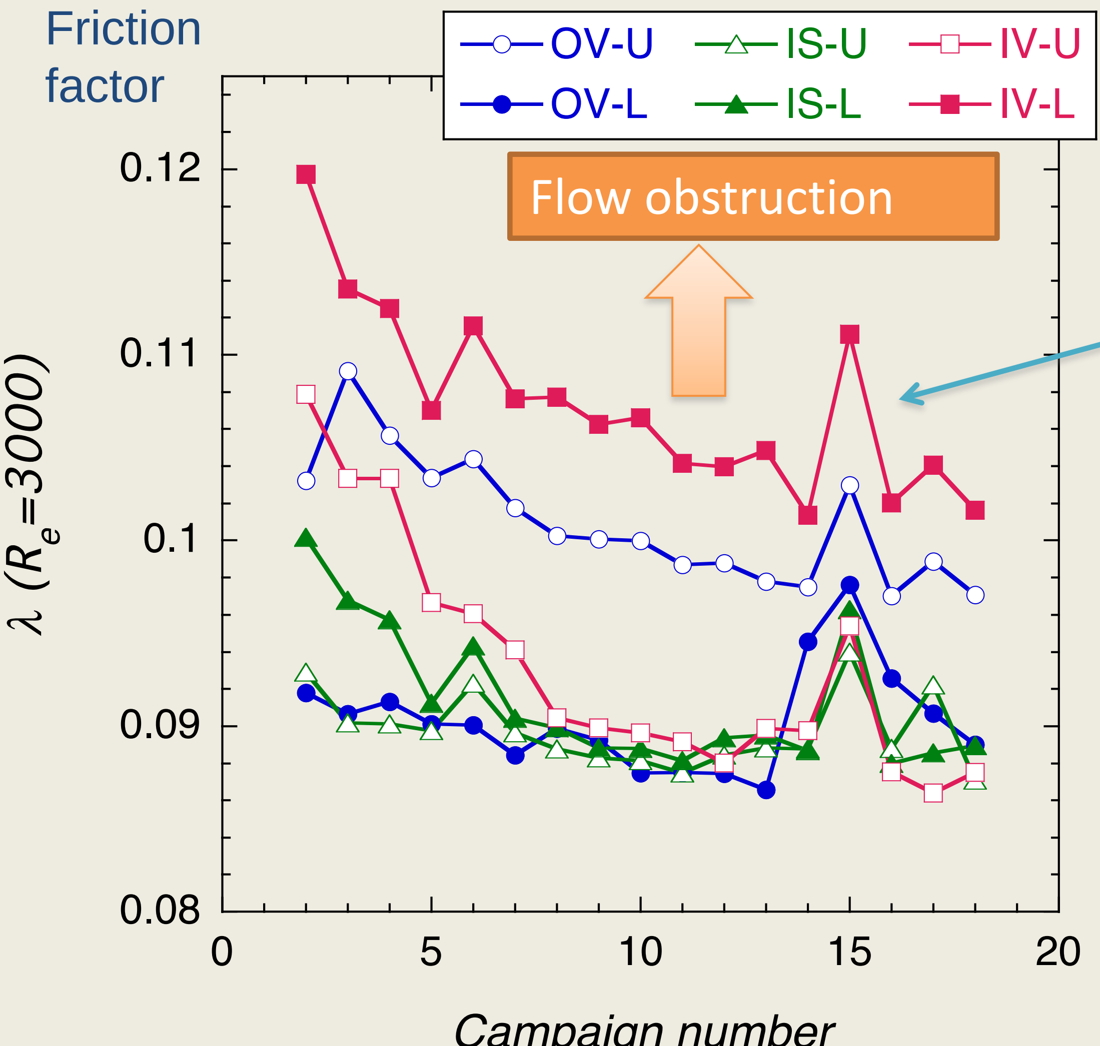


Lessons

Breaks should be designed conservatively

FIP/3-4Rc

Trends in Hydraulic Characteristics



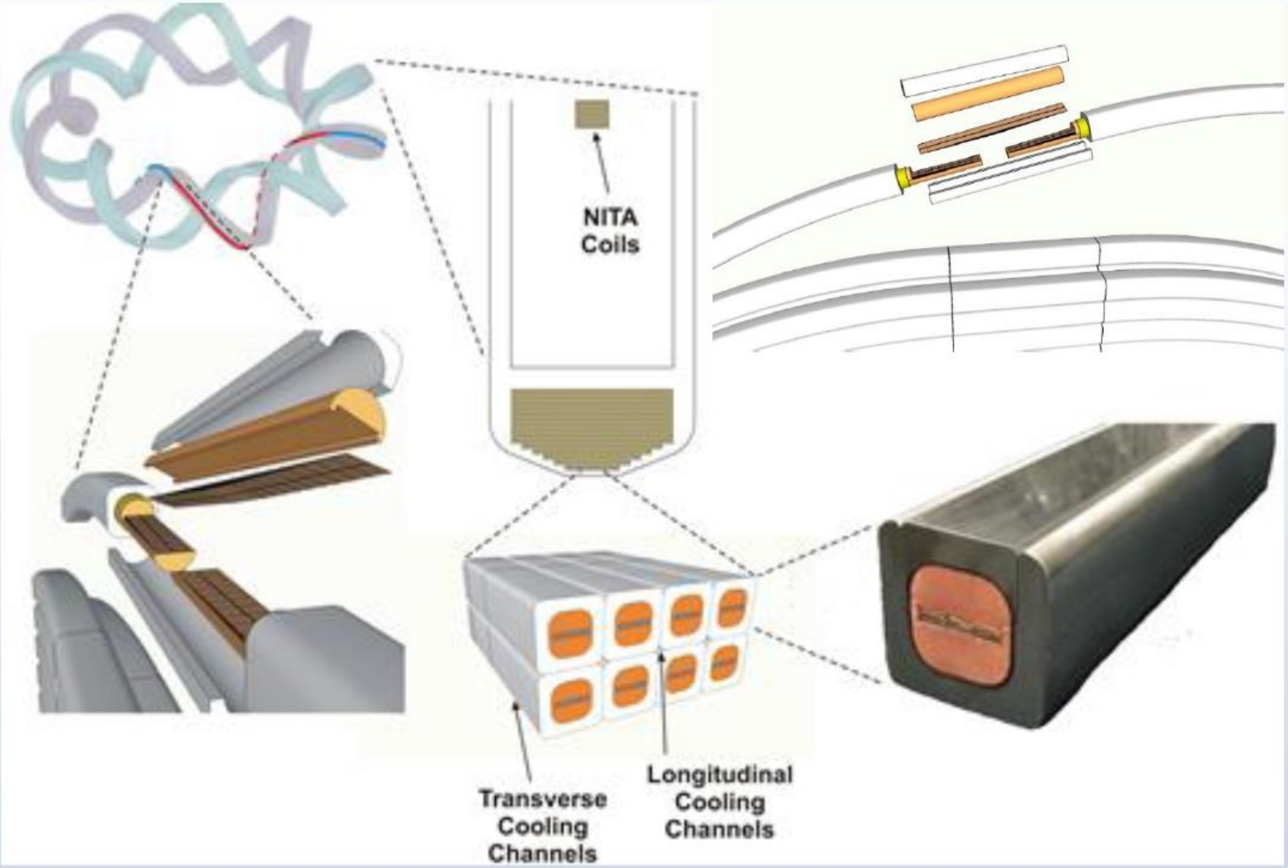
- The friction factor showed a tendency to decrease
- The sudden increase in the 15th campaign was probably caused by tiny particle of solidified gasses from new compressor oil

Lessons

- Compressor oil is a potential source of impurity gasses
- Mesh filter is effective

FIP/P7-11: N. Yanagi *et al.*, NIFS

"Helical Coil Design and Development with 100-kA HTS STARS Conductor for FFHR-d1"



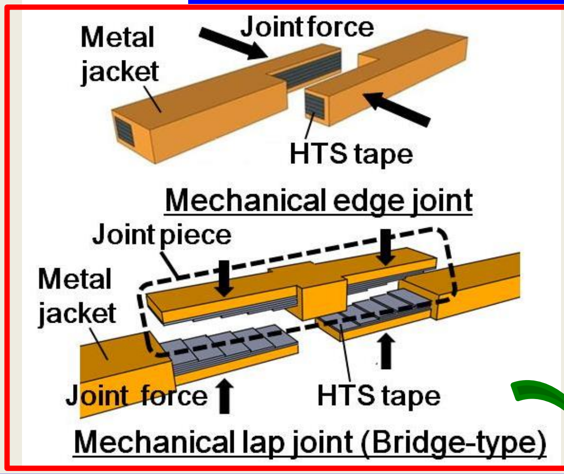
- Magnet design with High-Temperature Superconducting (HTS) option is progressing for the helical fusion reactor
- Prototype conductor sample achieved 100 kA at 5.3 T, 20 K with high stability
- Analysis on quench protection, feasibility study of helium gas cooling

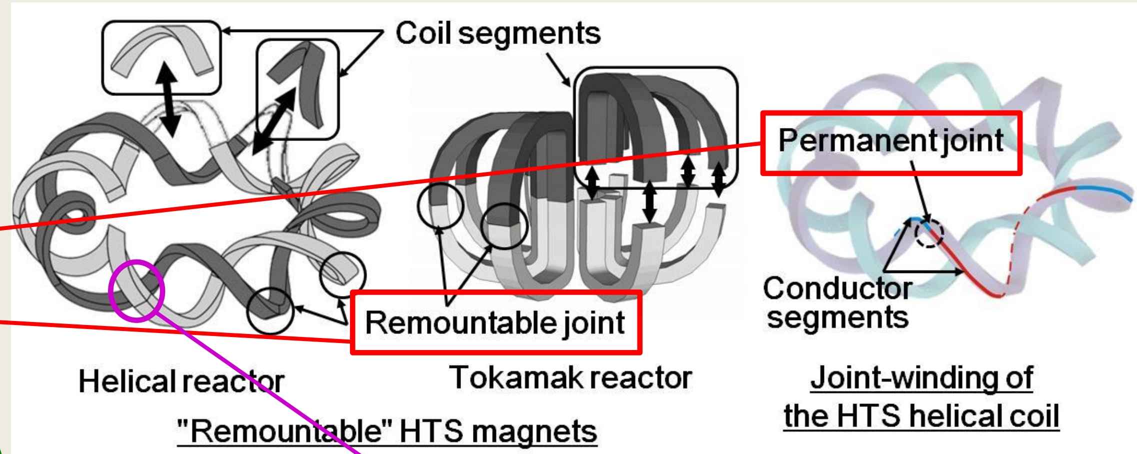
FIP/3-4Rb

Development of Remountable Joints and Heat Removable Techniques for High-temperature Superconducting Magnets

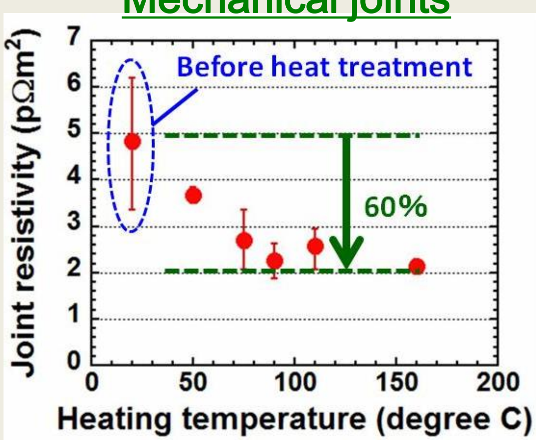
H. Hashizume[1], S. Ito[1], N. Yanagi[2], H. Tamura[2], A. Sagara[2] ([1]Tohoku Univ., [2]NIFS)

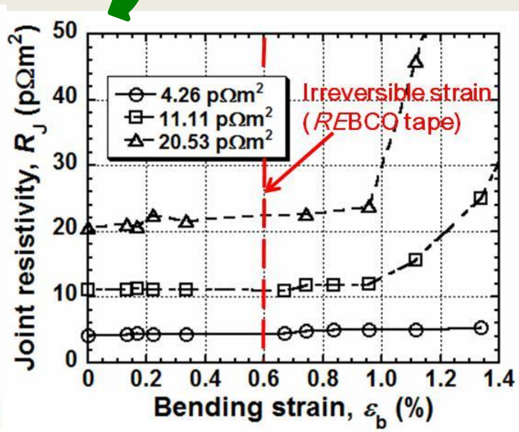
Innovative design for superconducting magnet, "Segment-fabrication"





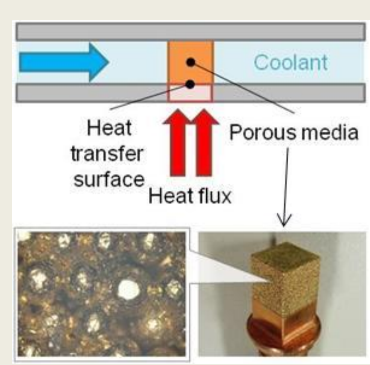
Mechanical joints

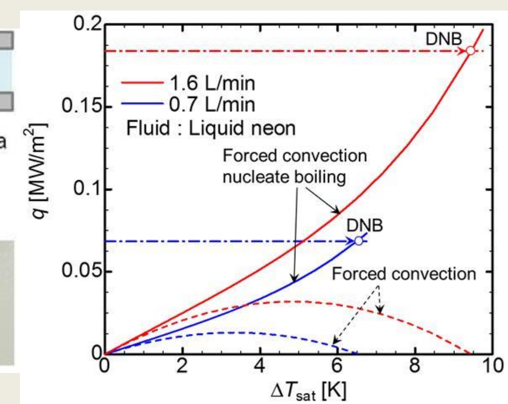




- Heat treatment → reduce joint resistance and its dispersion
- Bending strength (Joint) > Irreversible strain (*RE*BCO tapes)
  → can fabricate curved joint by "joining-then-bending"

Local heat removal with porous media





- New heat transfer correlation was established
  → can predict heat transfer performance
  (needed for thermal stability analysis)

FIP/3-4Rb

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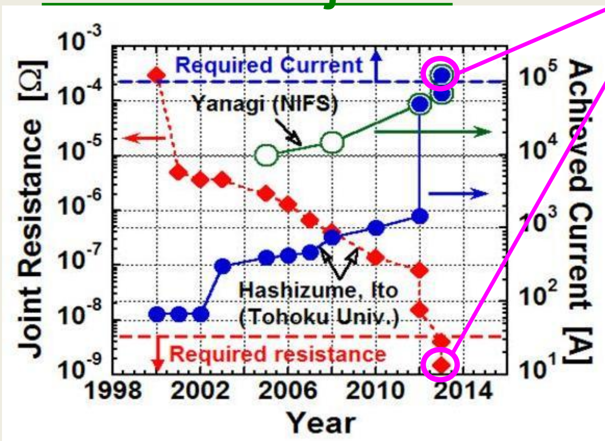
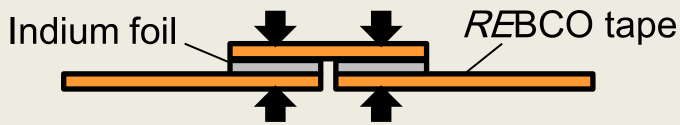
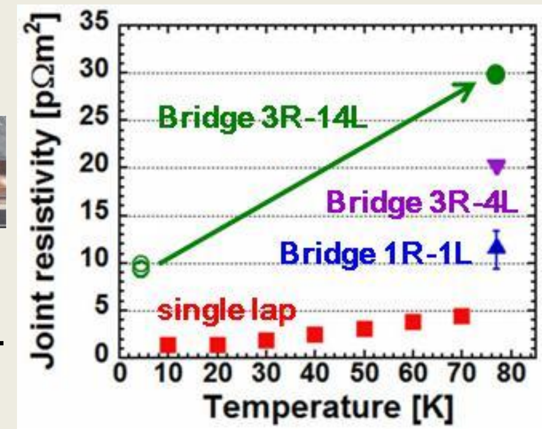
Mechanical joints



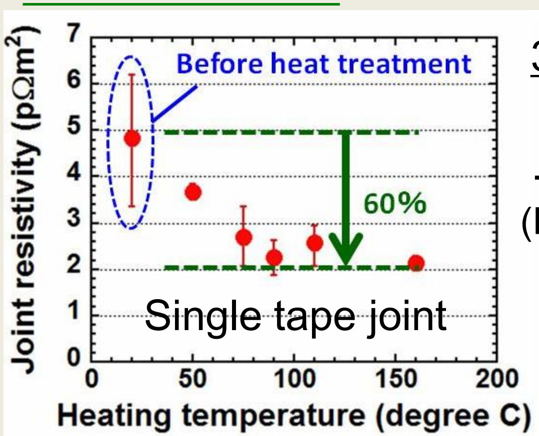
Bridge-type mechanical lap joint (100-kA-class HTS conductor)





- Joint resistivity > expected value
- The joint has a straight geometry…
  → Ideally bent and twisted

Heat treatment

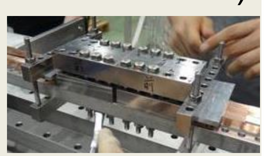


3-row, 1-layer

25 pΩm²

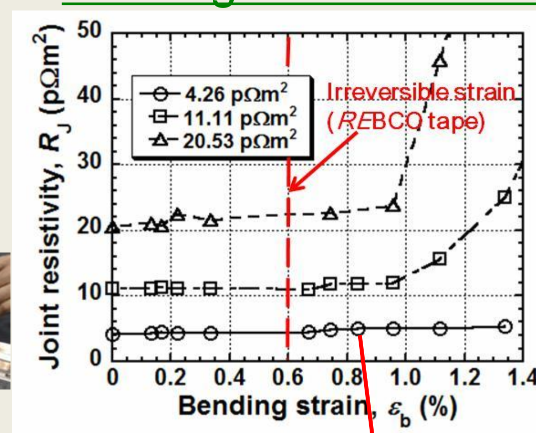
→ 8 pΩm²

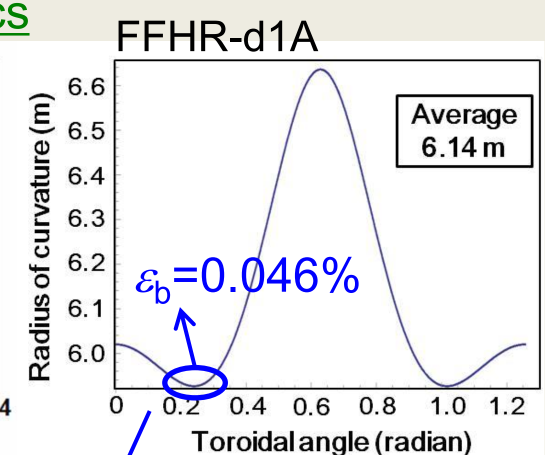
(Heat treatment)



- Baking + Heat treatment (~100 °C)
  → promising to be applied to large-scale conductor joints

Bending characteristics





- Strength (Joint) > Irreversible strain (*RE*BCO tapes)
- Bending strain: 0.046%
  Tensile strain (EM forces): 0.145% < Irreversible strain (0.6%)

→ can fabricate curved joint by "joining-then-bending"

FIP/3-4Rb

Development of Remountable Joints and Heat Removable Techniques for High-temperature Superconducting Magnets

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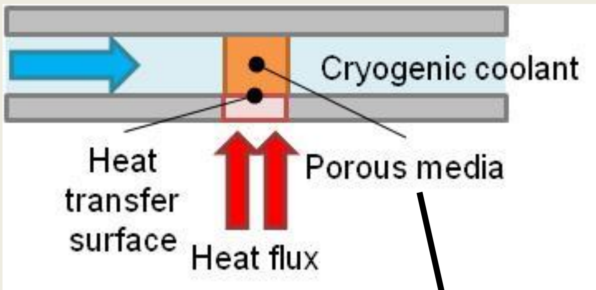
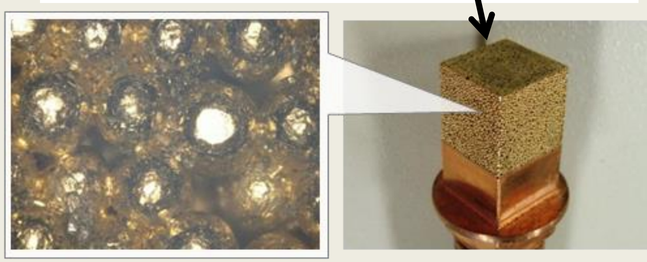
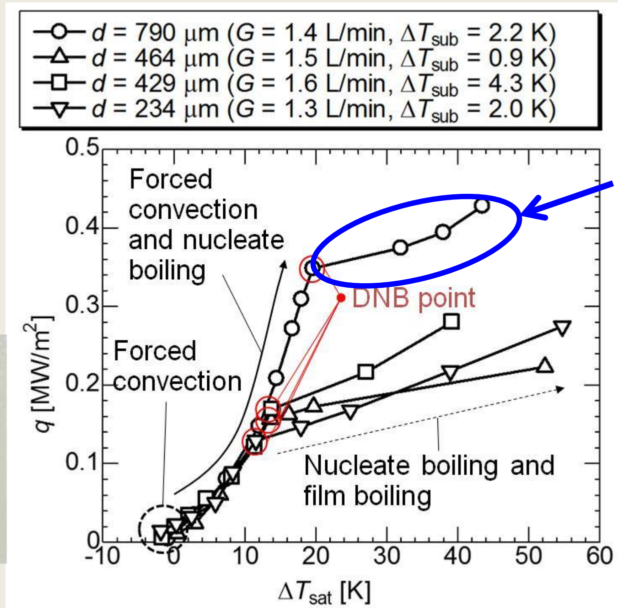
Local heat removal with porous media



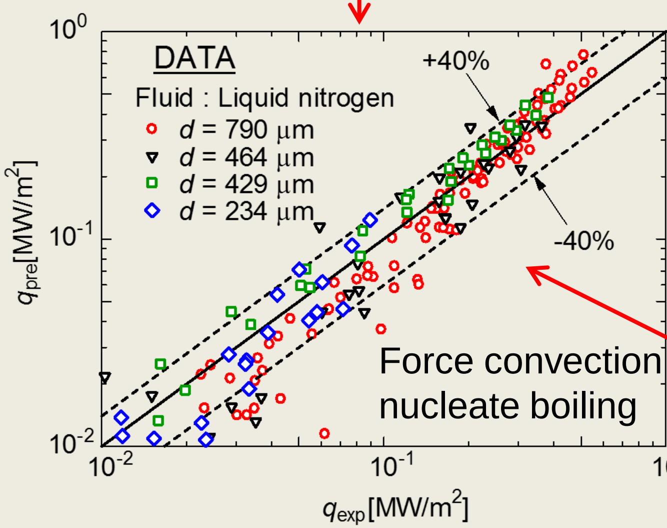




Large heat-transfer surface area

Prevention of transition to film boiling by capillary action

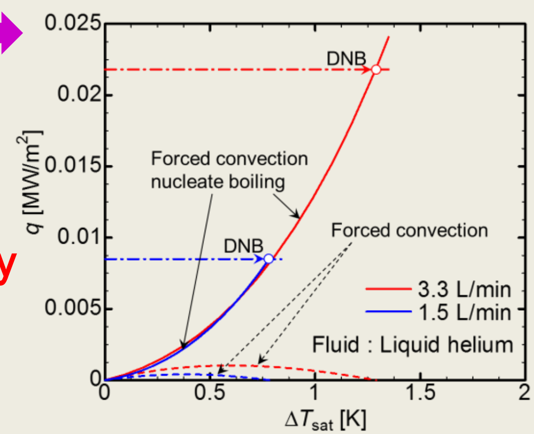
This study established new **heat transfer correlation**

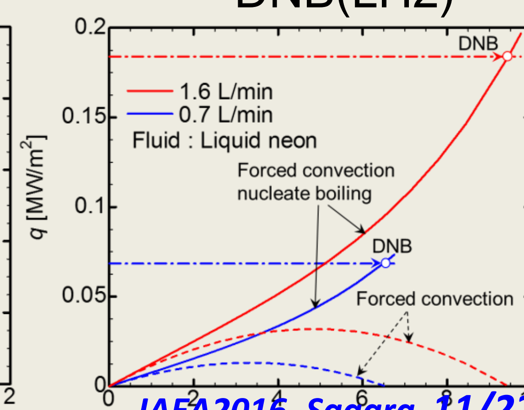


Accuracy ±40%

Prediction

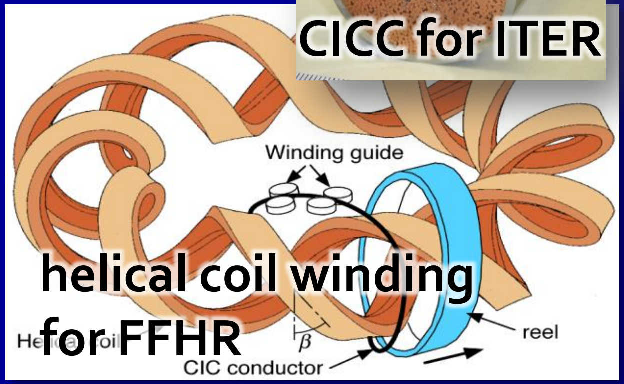
DNB(LHe) — 10 times → DNB(LNe) DNB(LH2)





Superconducting Magnet

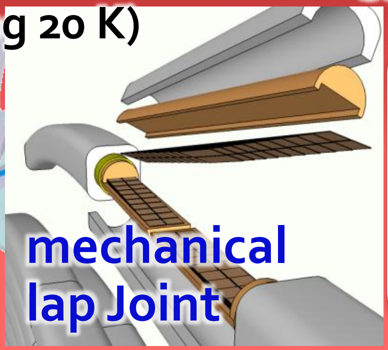
Basic



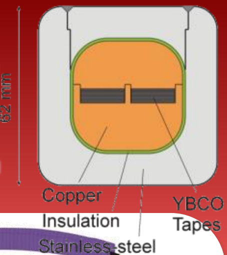
- Cable in Conduit Conductor (CICC) of Nb_3Sn as ITER (or NB_3Al)
- Continuous winding of helical coil using a winding machine as LHD FIP/3-4Rc
- Cooled by liquid He

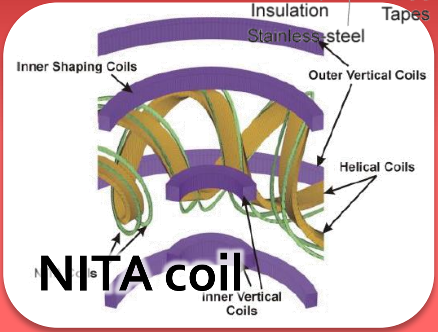
Challenging

helical coil for FFHR-d1
(helium gas cooling 20 K)



100 kA-class
HTS
conductor





- High Temperature Superconductor (HTS) of ReBCO (YBCO, GdBCO…) FIP/P7-11
- Joint winding of helical coil based on the lap joint technique FIP/3-4Rb
- Indirectly cooled by He gas

Optimal welding conditions were obtained for joints between 9Cr-ODS and JLF-1 steels

Nagasaka et al., MPT/P5-21

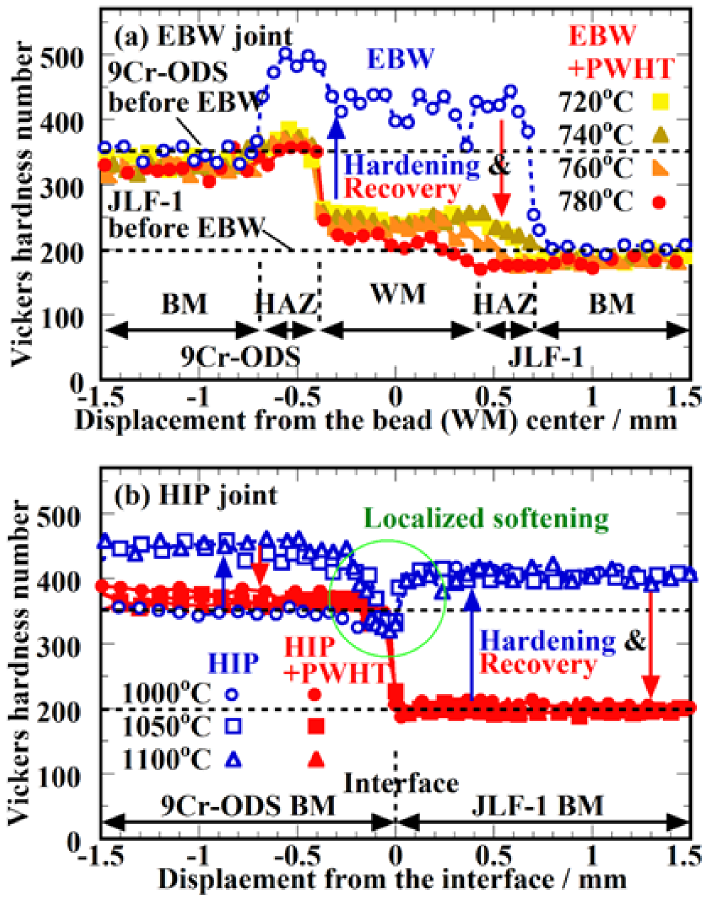


Fig. Hardness around the bonding interface in the dissimilar-metals joints

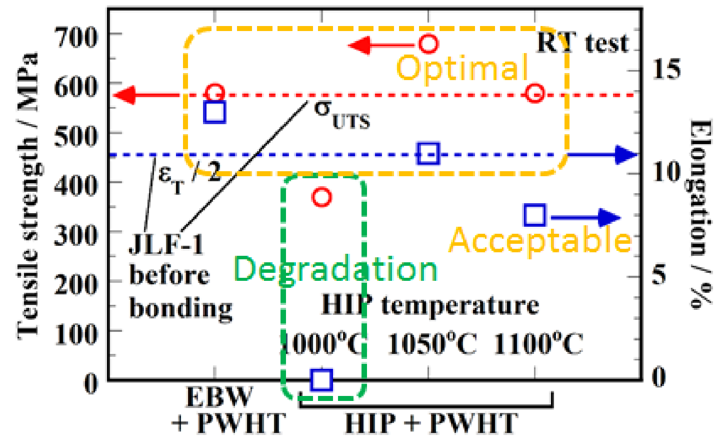


Fig. Tensile properties of dissimilar-metals joint with various welding conditions

Optimal conditions:

(1) Electron-beam welding (EBW) process

Post-weld heat treatment (PWHT): 780ºC x 1 h

→ To form tempered martensite by recovery

(2) Hot iso-static pressing (HIP) process

HIP temperature: 1050ºC or 1100ºC

→ To enhance matrix Fe diffusion

PWHT: 1050ºC x 1 h + 36ºC /min cooling + 780ºC x 1 h

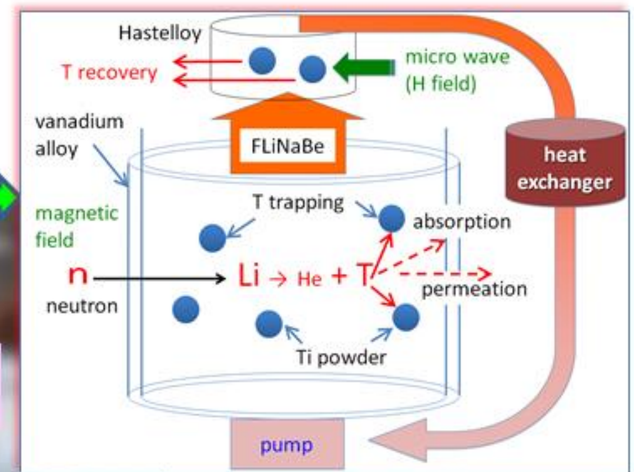
→ To eliminate the locarized soften and to form refined carbide and tempered martensite by recovery

TOFE2016

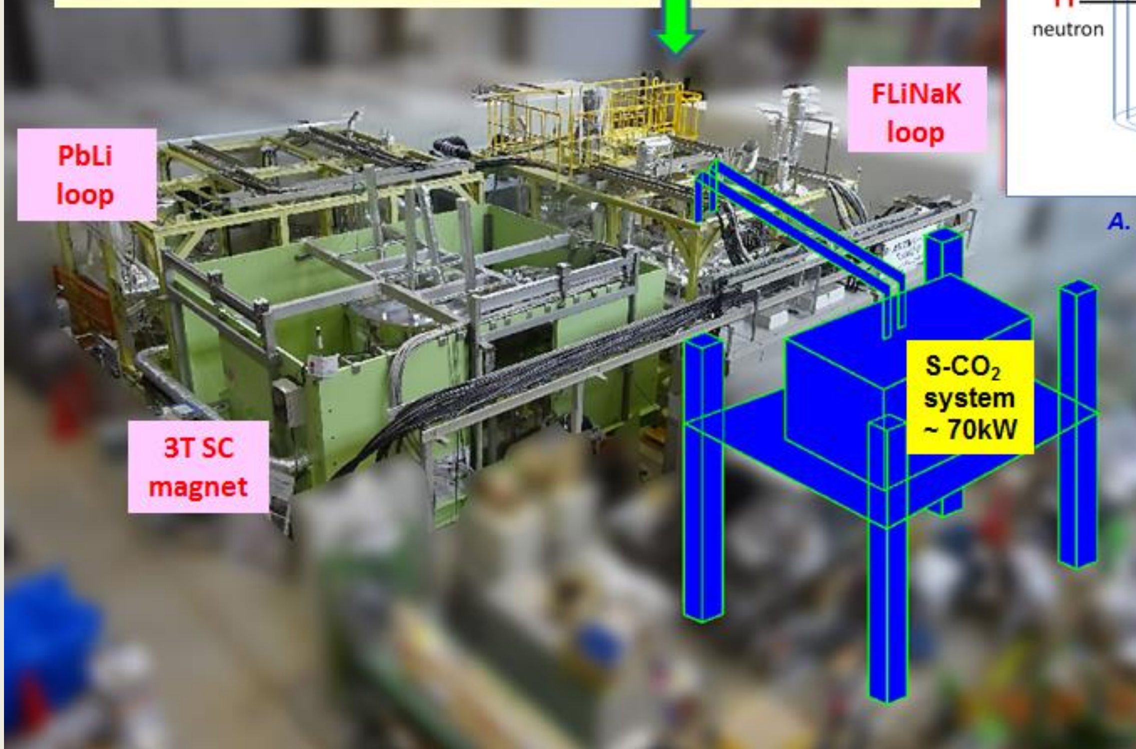
Oroshhi-2 in NIFS (2016--)

TOFE-2016 by Sagara

- MHD effects on LiPb
- Corrosion and mass transfer under non-equilibrium and ΔT
  - Heat transfer on FLiNaK under high B
  - Hydrogen charging and recovery
    - Metal powder mixed system
    - Operation of S-CO_2 system for Flinak

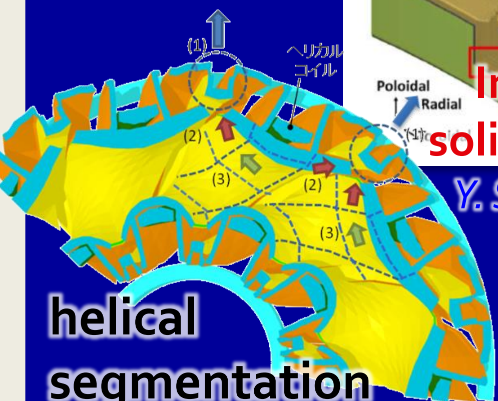


A. Sagara et al., FED 89 (2014) 2114–2120

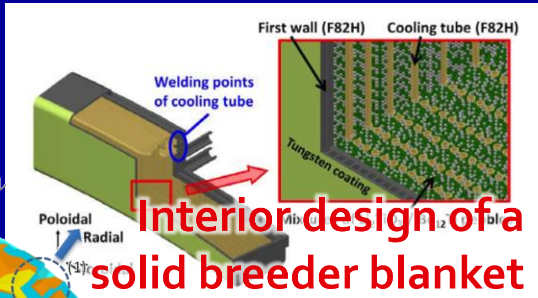


Breeding and Shielding Blankets

Basic

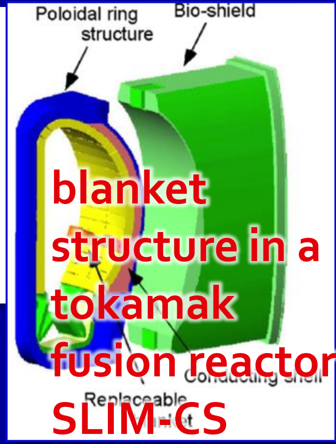


helical segmentation



Interior design of a solid breeder blanket

Y. Someya, IAEA FEC 24 (2012) FTP/P7-33



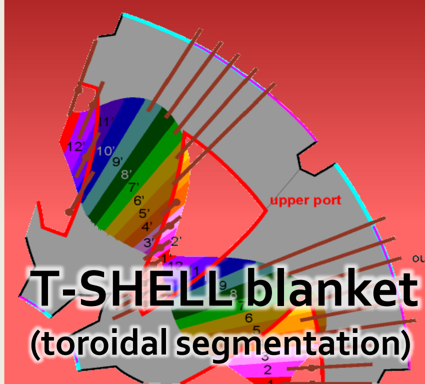
blanket structure in a tokamak fusion reactor SLIM-CS

K. Tobita, FED 85 (2010) 1342

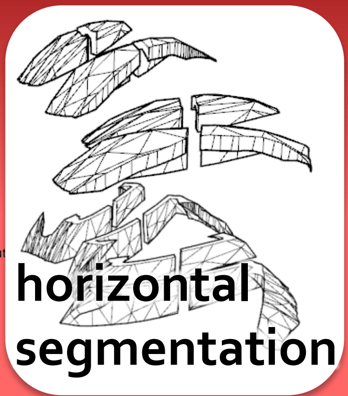
MPT/P5-21

- The 1st option of the Japanese tokamak DEMO and Japanese ITER TBM
- Cooling by highly pressurized hot water of > 200 atm and > 600 K

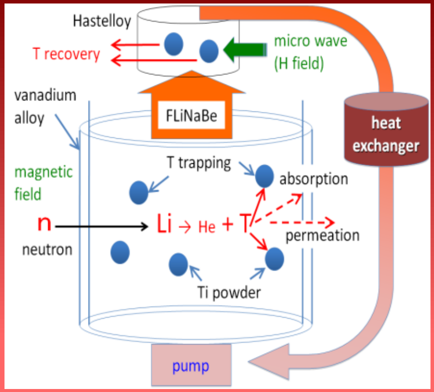
Challenging



T-SHELL blanket (toroidal segmentation)



horizontal segmentation



FLiNaBe mixed with Ti powder

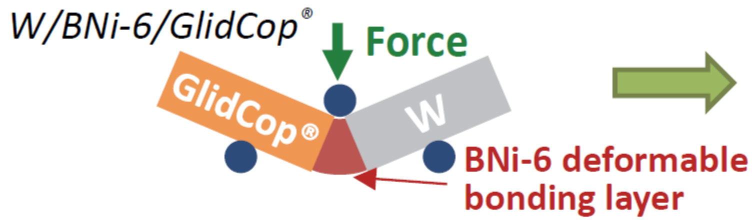
- Use FLiNaBe (T_m ~ 600 K)
- Mixed with metal powders (~μm) (e.g., Ti) to enhance hydrogen solubility
- S-CO2 secondary system
- Toroidal / horizontal segmentation of the blanket module

TOFE2016

FIP/P4-37

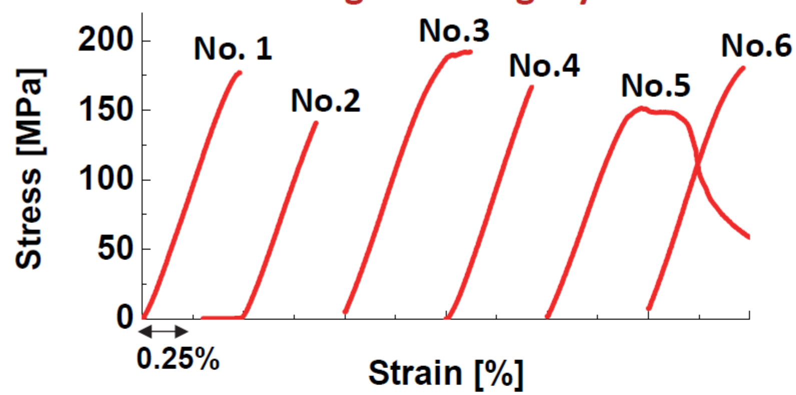
The small-scale divertor mock-up by improved brazing technique showed an excellent potential for using in the reactor divertor

Improved brazing technique between W armour and ODS-Cu (GlidCop®) heat sink was found by using BNi-6 (Ni-11%P) filler material



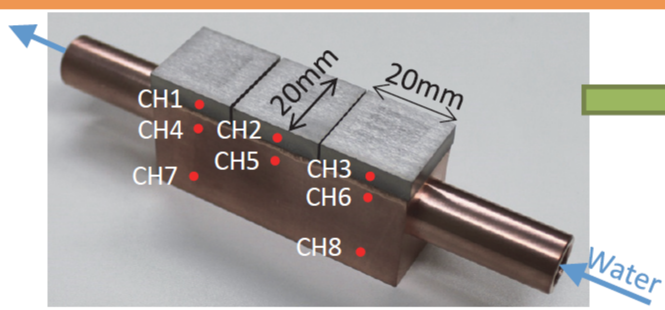
Schematic view of the three-point bending test of the W/BNi-6/GlidCop® specimen after deformation.

Tough bonding layer !!

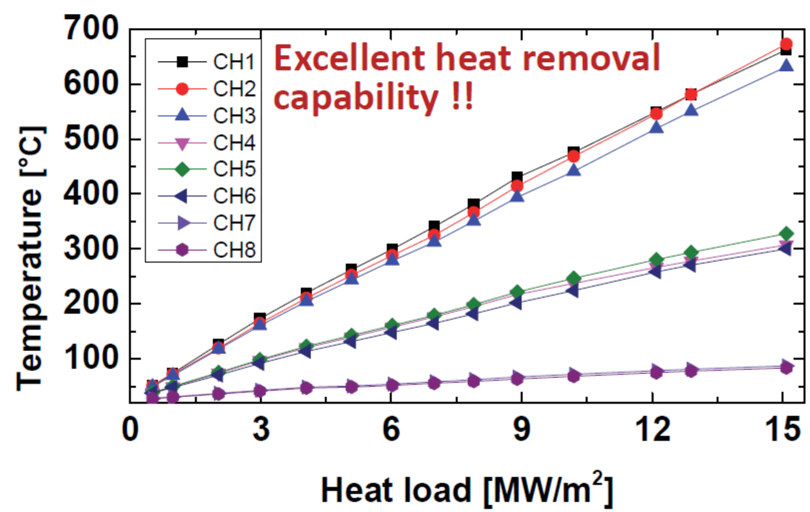


Stress-strain curves of W/BNi-6/GlidCop® specimens.

W/BNi-6/GlidCop® small-scale divertor mock-up showed an excellent heat removal capability



W/BNi-6/GlidCop® small-scale divertor mock-up.



Temperature profile of the W/BNi-6/GlidCop® mock-up during a steady state heat loading.

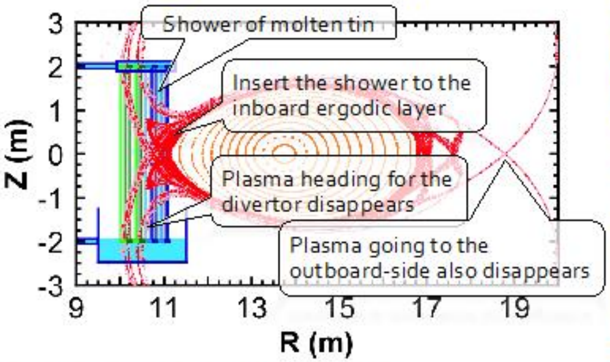
M. Tokitani et al., FIP/P4-37

FIP/P7-2

REVOLVER-D: The Ergodic Limiter/Divertor Consisting of Molten Tin Shower Jets Stabilized by Chains

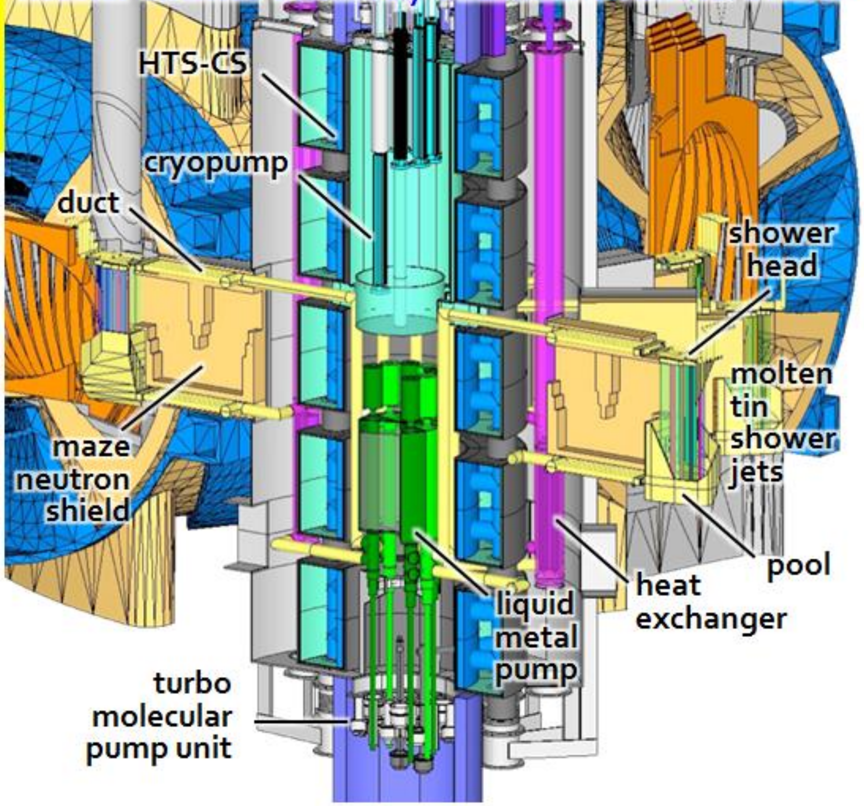
J. Miyazawa, et al.
National Institute for Fusion Science, Japan

The Ergodic Limiter/Divertor



REVOLVER-D

Reactor-oriented Effectively VOLumetric VERtical Divertor



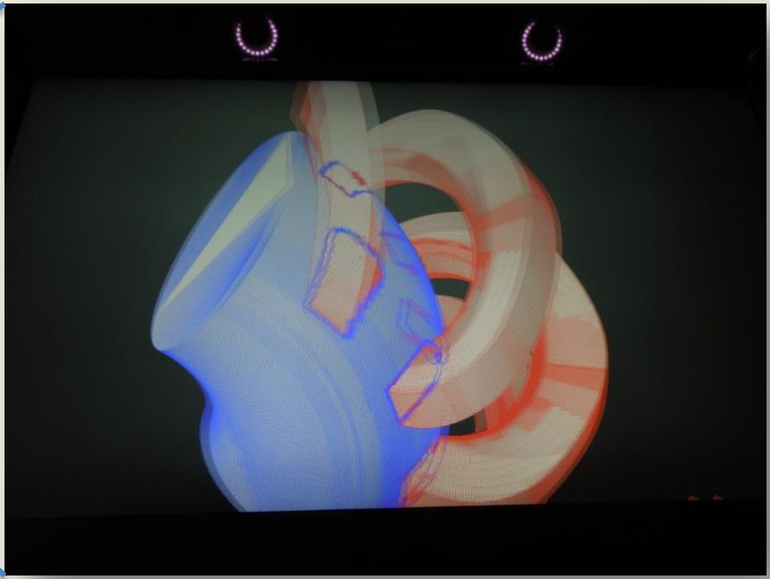
New ergodic limiter/divertor concept with **showers of molten tin sheath jets** is proposed for the LHD-type helical reactor FFHR-d1

Desktop Virtual-Reality (VR) System is Ready to Support the Design Activity

A desktop-type VR system

- immersive monitor
- sensors

The viewer can watch, lift, and rotate the reactor components by the stylus-type 3D mouse with **collision detection**

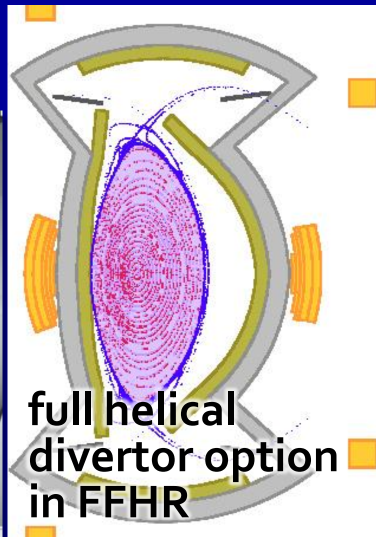


These pictures are composite photographs and only the viewer can watch the CAD data in the VR world

Divertor

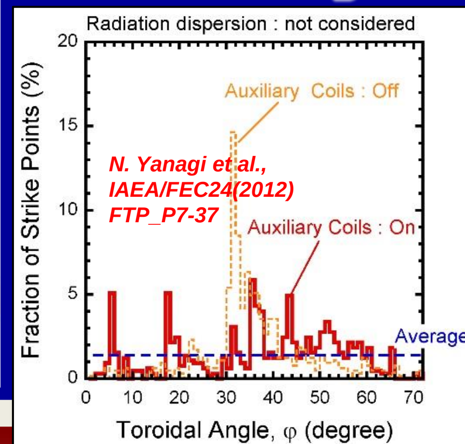
Basic

closed divertor in LHD



full helical divertor option in FFHR

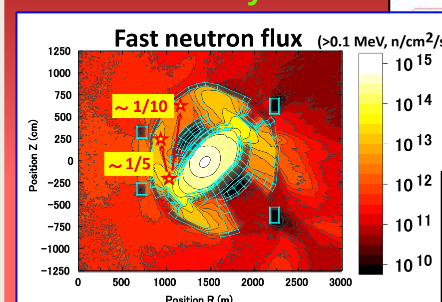
Toroidal asymmetry of heat flux is a big issue

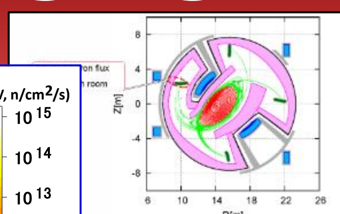


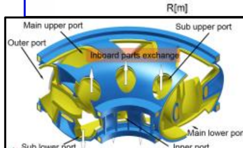
- Developed for ITER and the 1st option of Japanese tokamak DEMO
- Use of pressurized water
- Permissible heat load below 10 MW/m²
- Issues on maintainability and radwastes

Challenging

First proposal of Cu use and lifetime ~ 6 years



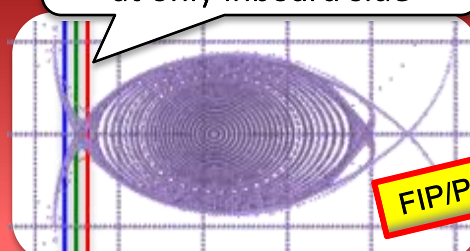




novel divertor

H. Tamura, T. Tanaka, FED98-99(2015)1629.

Shower of molten tin Sn stabilized by chains at only inboard side



liquid metal ergodic limiter/divertor

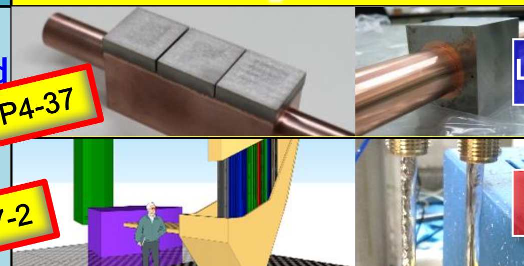
J. Miyazawa, submitted to FED

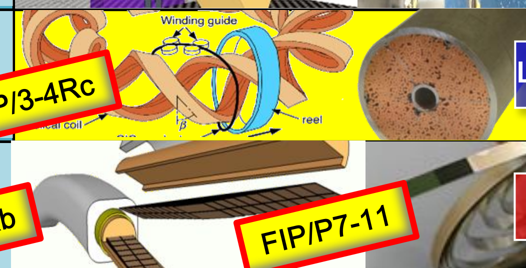
- Proposed recently for FFHR-d1 (FIP/P4-37)
- Good maintainability
- Shower of molten Sn (Tm ~ 500 K) in a few m/s as an "ergodic limiter/divertor"
- Issues on temp.window for Cu and MHD for shower

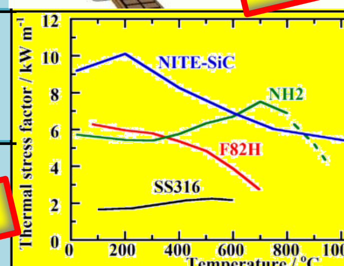
R&D Strategy Toward TRL 6

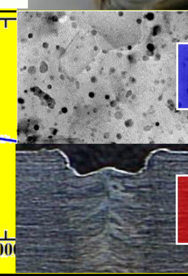
TRL		1	2	3	4	5	6	7	8	9
Technology Readiness Levels		Basic Technology Research		Technology Development / Research to Prove Feasibility		Technology Demonstration	System/Subsystem Development		System Test, Launch & Operations	

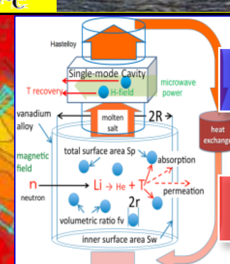
Component	Option	Concept (TRL 1–4)	Paper	TRL 5	TRL 6
Divertor	Basic	W monoblock + Cu alloy cooling pipe + pressurized water	FIP/P4-37	LHD / JT-60SA	ITER
Divertor	Challenging	liquid metal (Sn) shower + novel divertor	FIP/P7-2	R&D in NIFS, Univs. QST	LHD
Super-conducting magnet	Basic	Nb_3Sn + liquid He cooling + continuous winding	FIP/3-4Rc	LHD / JT-60SA	ITER
Super-conducting magnet	Challenging	HTS + He gas cooling + joint winding	FIP/3-4Rb, FIP/P7-11	R&D in NIFS, Univs., QST	LHD
Structure materials	Basic	ferritic steel		R&D in QST, NIFS, Univs.	ITER
Structure materials	Challenging	ferritic steel + ODS + V alloy	MPT/P5-21	R&D in NIFS, Univs., QST	LHD
Blanket	Basic	solid breeder + pressurized water + helical segmentation		R&D in QST, NIFS, Univs	ITER
Blanket	Challenging	molten salt + Ti powder + horizontal / toroidal segmentation	TOFE2016	R&D in NIFS, Univs., QST	LHD











TRL 6 should be achieved before starting construction of DEMO

Basic option will be achieved in ITER

Challenging option will be achieve in LHD

Summary

- Conceptual design of the helical fusion reactor **FFHR-d1A** is ongoing with **2 options** based on broad & joint R&D activities
- The "**basic option**" is based on the **ITER technology**
- The "**challenging option**" boldly includes the **new ideas** that would possibly be beneficial for making the reactor design more attractive
  - ✧ **SC magnet**: gas He cooled **HTS** with joint winding
  - ✧ **Blanket**: self-cooling of molten salt **FLiNaBe** mixed with metal powder, with toroidally / horizontally segmented units
  - ✧ **Divertor**: **REVOLVER-D** (shower of molten tin inserted to the inboard ergodic layer)

Thank you for your attention

Wed. FIP/P4-37 Tokitani
"Fabrication of Divertor Mock-up with ODS-Cu and W by Improved Brazing Technique"

Thu. MPT/P5-21 Nagasaka
"Development of dissimilar-metals joint of oxide-dispersion-strengthened (ODS) and non-ODS reduced-activation ferritic steels"

Fri. EX/P8-39 Goto
"Development of a Real-time Simulation Tool towards Self-consistent Scenario of Plasma Start-up and Sustainment on Helical Fusion Reactor FFHR-d1"

Fri. FIP/P7-2 Miyazawa
"REVOLVER-D: The Ergodic Limiter/Divertor Consisting of Molten Tin Shower Jets Stabilized by Chains"

Fri. FIP/P7-11 Yanagi
"Helical Coil Design and Development with 100-kA HTS STARS Conductor for FFHRd1"

Sat. FIP/3-4Ra Sagara
"Two Conceptual Designs of Helical Fusion Reactor FFHR-d1A Based on ITERTechnologies and Challenging Ideas"

Sat. FIP/3-4Rb Hashizume
"Development of Remountable Joints and Heat Removable Techniques for Hightemperature Superconducting Magnets"

Sat. FIP/3-4Rc Takahata
"Lessons Learned from the Eighteen-Year Operation of the LHD Poloidal Coils Made from CIC Conductors"