

Progress of conceptual and engineering design studies on the LHD-type heliotron fusion reactor

Nagato Yanagi, Fusion Engineering Research Project

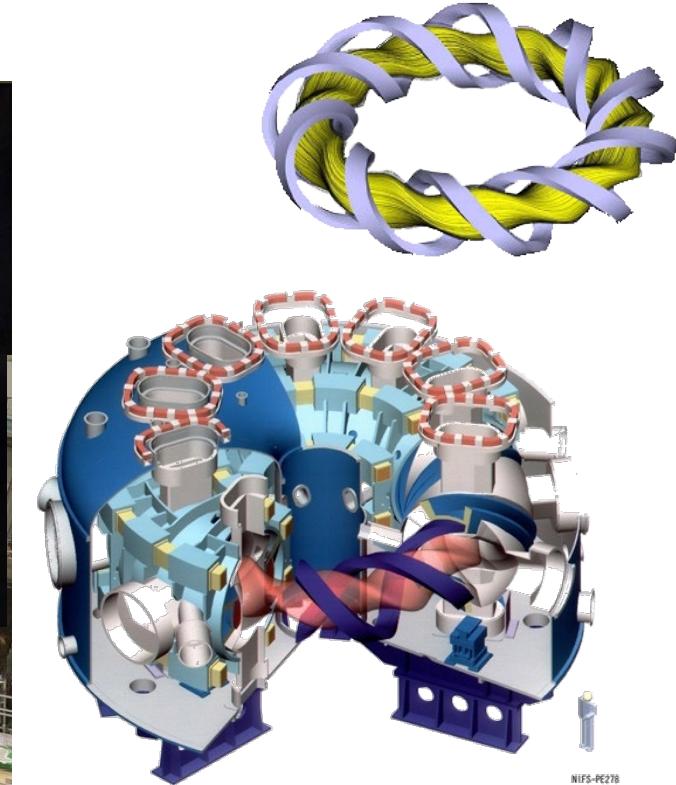
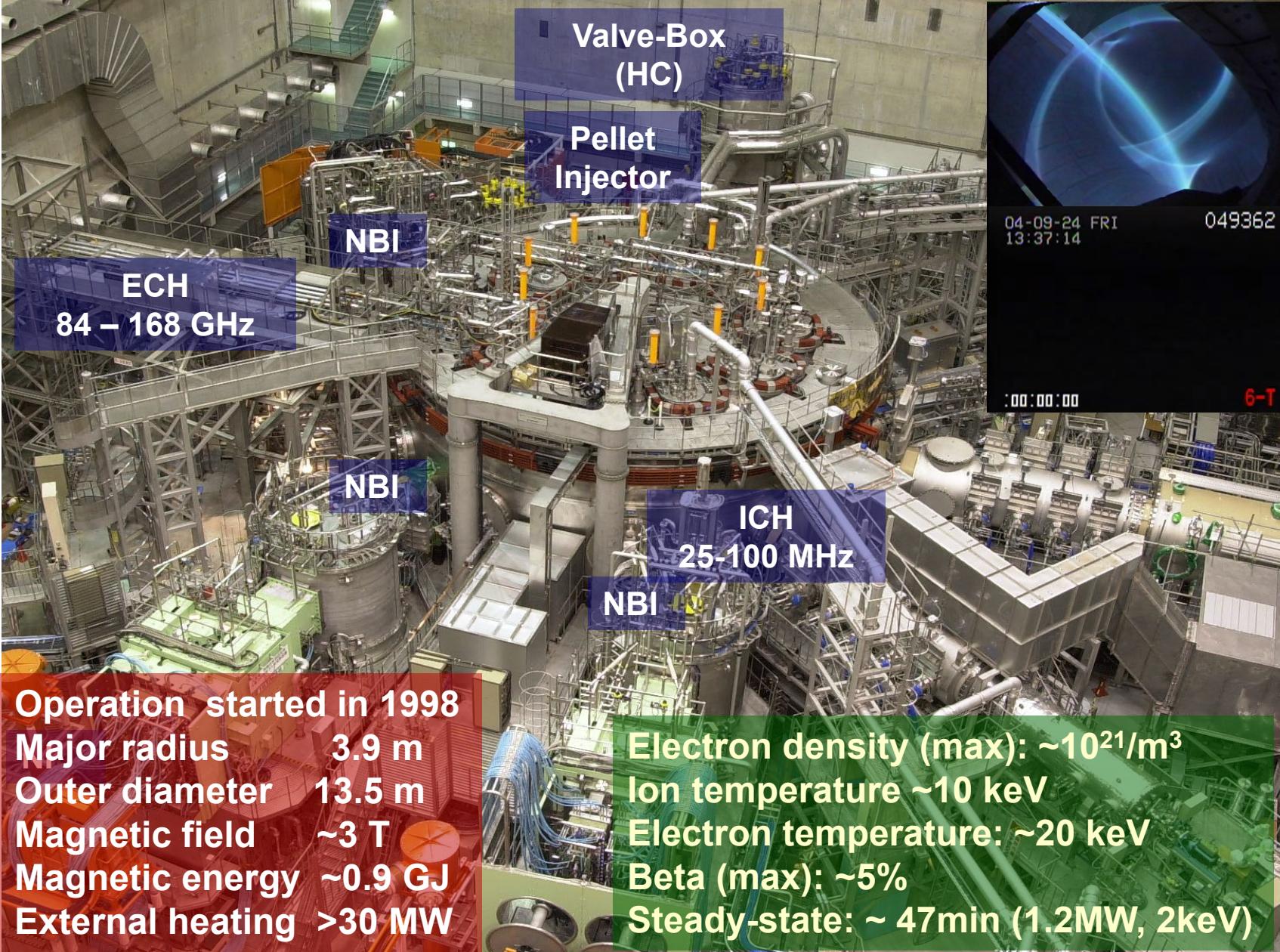
National Institute for Fusion Science



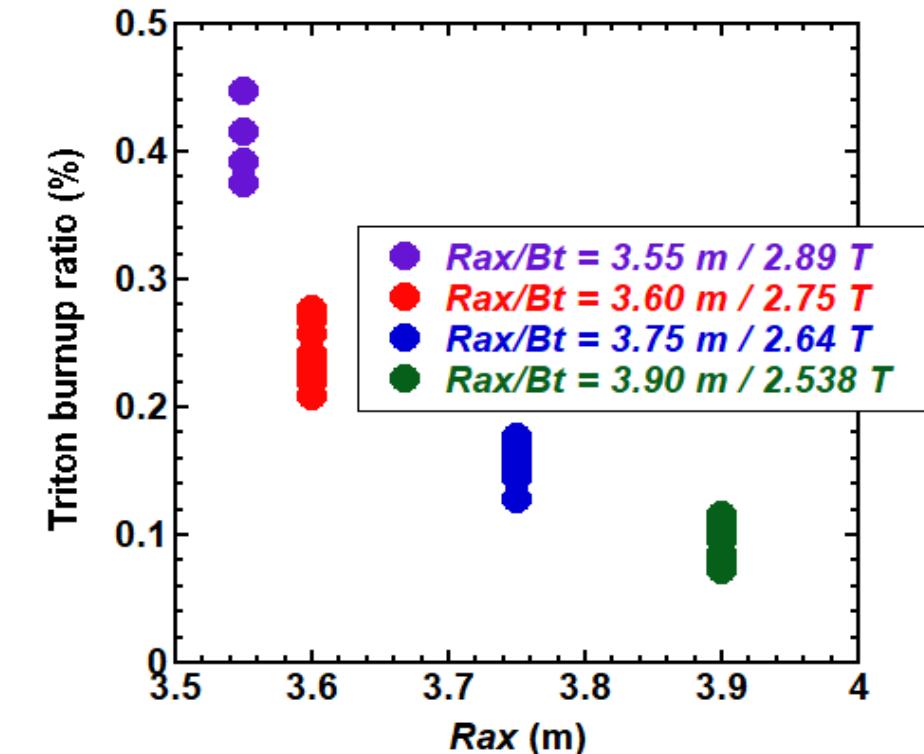
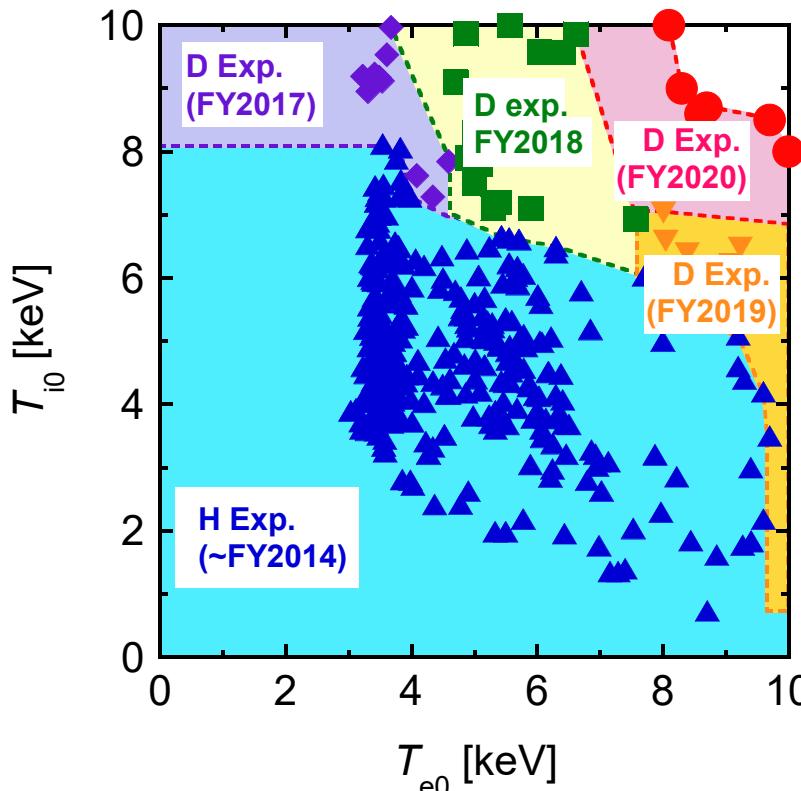
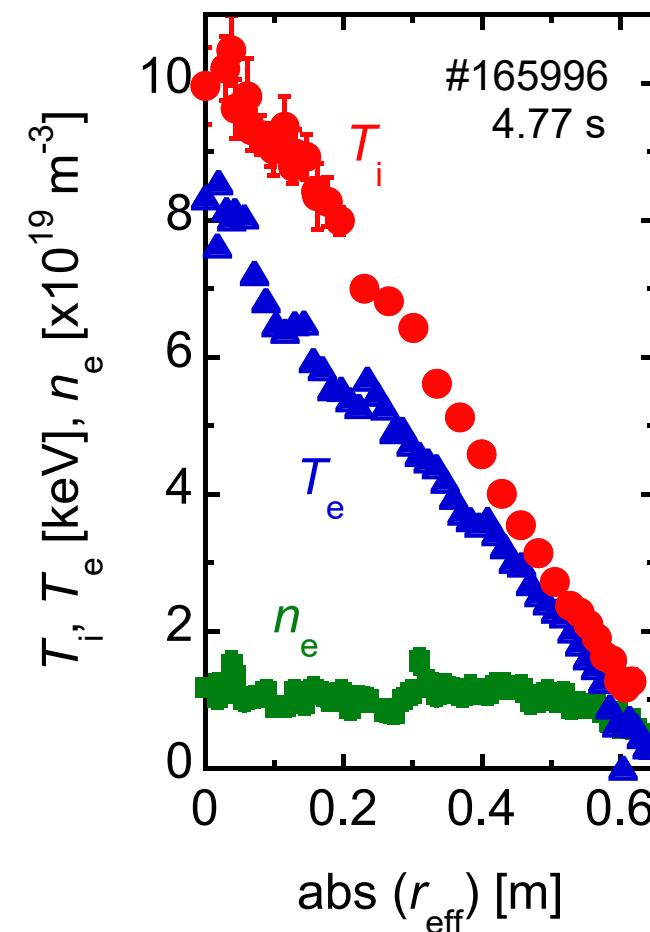
FUSION POWER ASSOCIATES
42nd Annual Meeting and Symposium
“Pathways to Fusion Power”
December 15-16, 2021
Grand Hyatt Washington
/ Remote Participation

The Large Helical Device (LHD)

NIFS (Toki, Japan)



Highlights of plasma experiments in LHD (1)

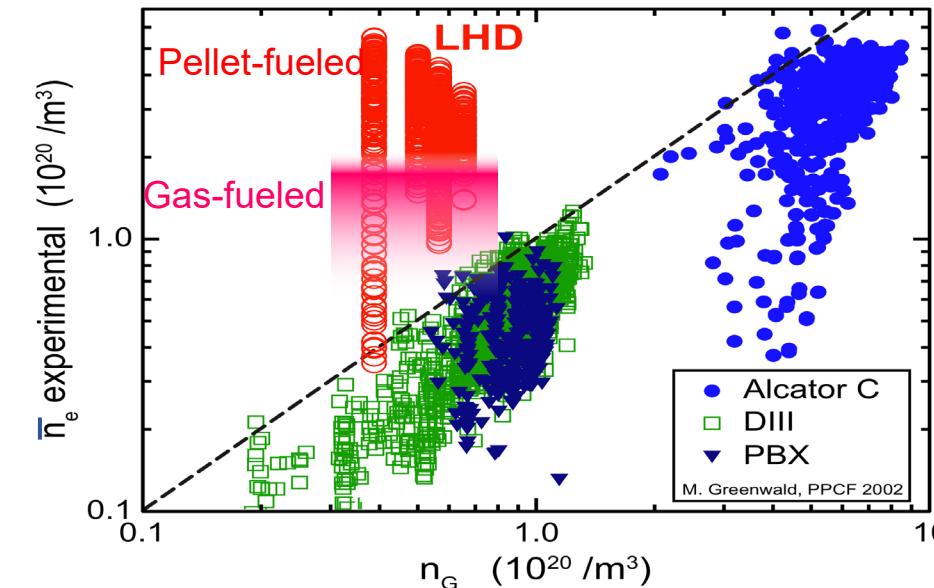


Triton burnup ratio $\sim 0.45\%$
Confinement of energetic ions is comparable
to tokamaks of similar minor radius

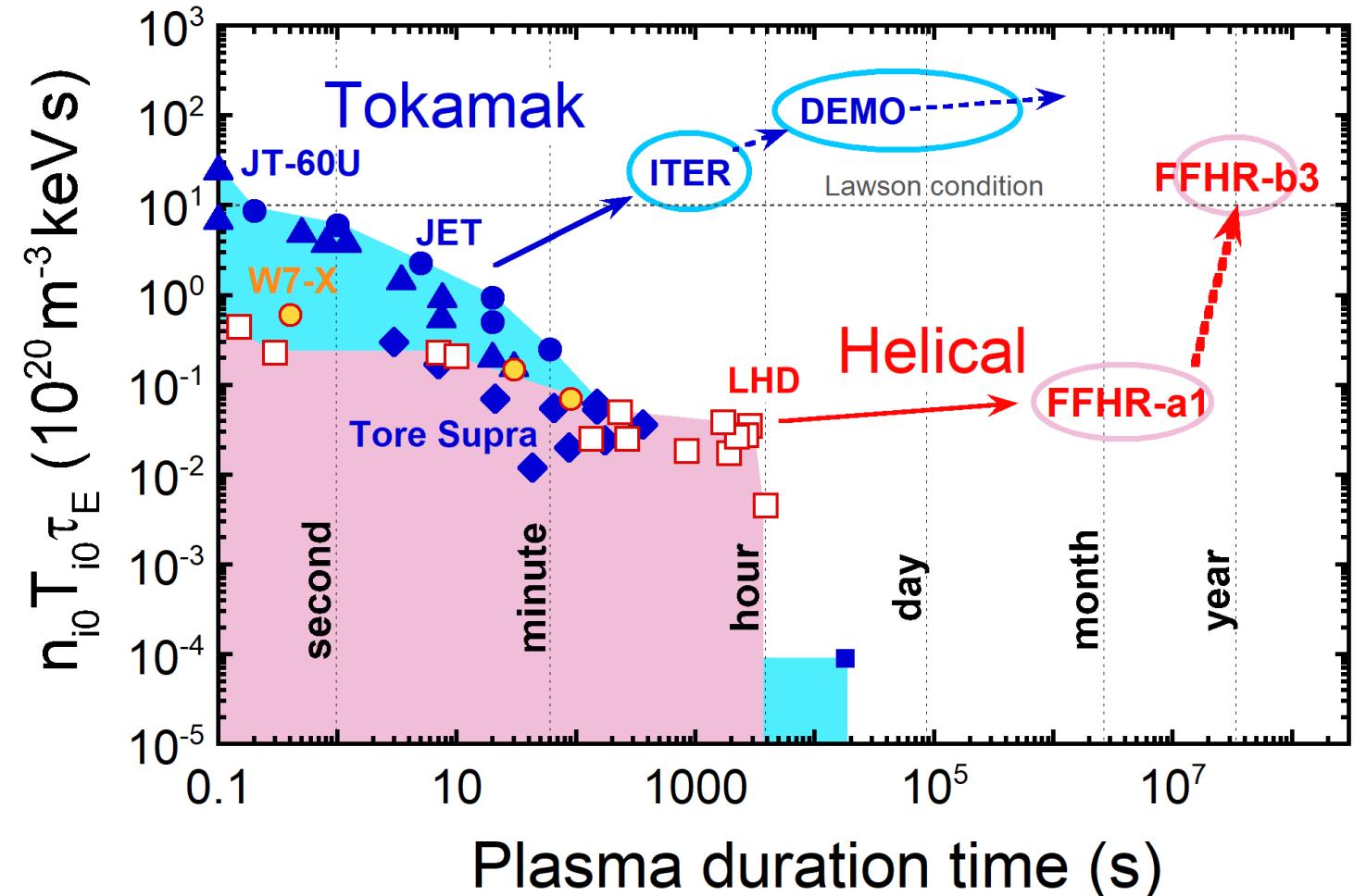
K. Ogawa et al., Nucl. Fusion 59 (2019) 076017

Simultaneous achievement of 10 keV ion and electron temperatures is now being explored

Highlights of plasma experiments in LHD (2)



High-density discharge is available in LHD



Duration of steady-state plasma can be extended in LHD and the next-generation helical device
Then, a scaleup to a reactor

> 25 Years of Design Studies on the LHD-type Heliotron Fusion Reactor “FFHR”

Plasma

- Steady-state
- No disruption

Magnet

- Continuously wound helical coils
- HTS
- High-current density
- Joint-winding

Divertor

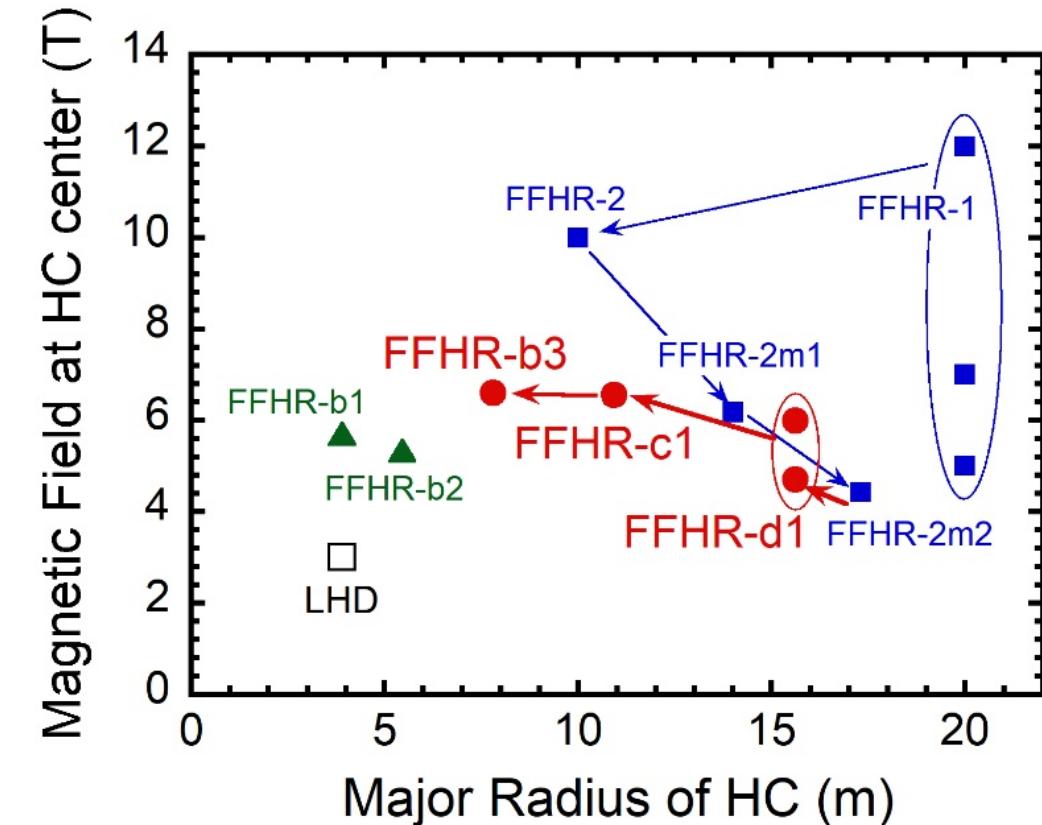
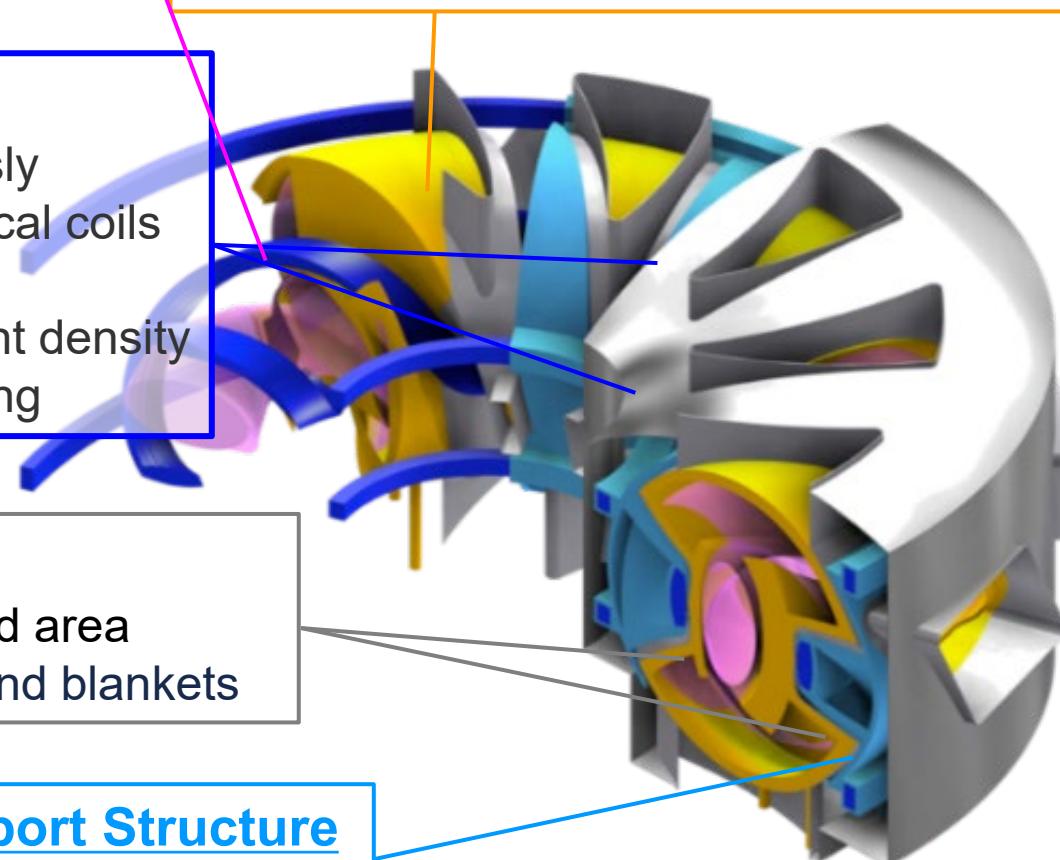
- Large wetted area
- Placed behind blankets

Blanket

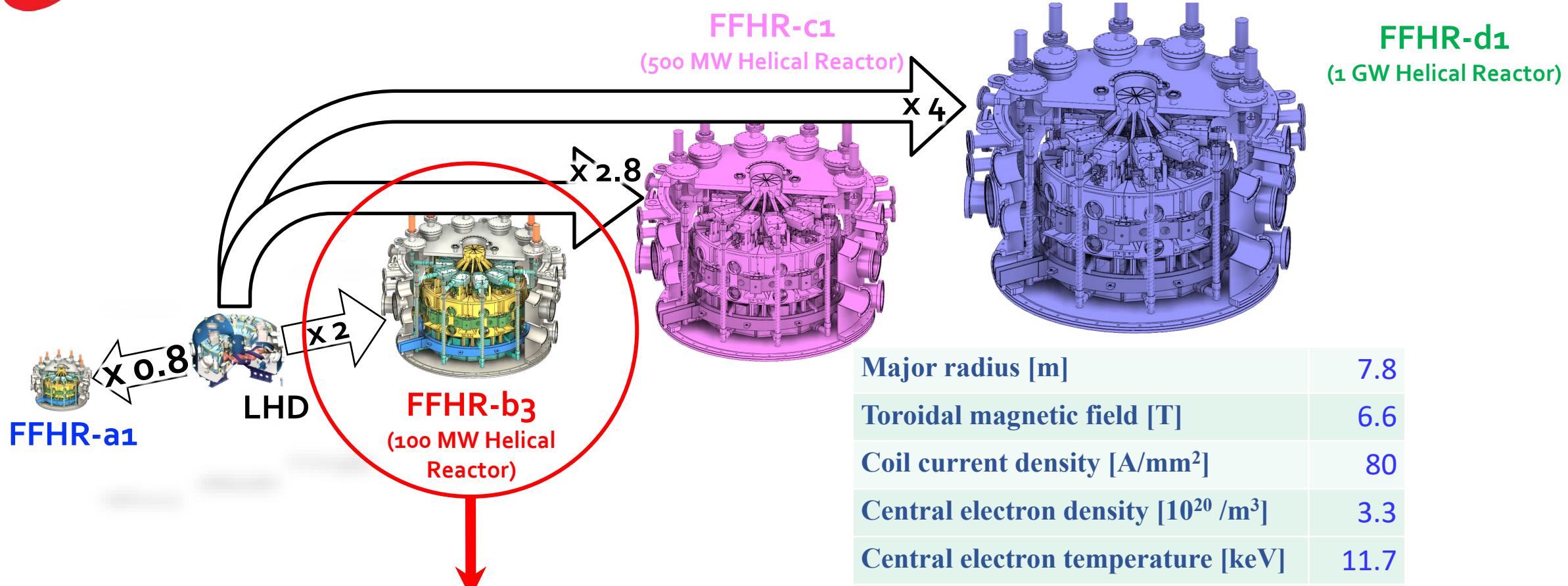
- Molten-salt and/or liquid metal
- RAFM and/or Vanadium alloy
- Easy maintenance through large ports

EM Support Structure

- Topology optimization



New Strategy for Early Realization of the Heliotron Reactor



Early realization of the heliotron reactor with

- Double size of LHD ($R = 7.8$ m)
- Configuration optimization
- Innovation for reactor engineering
- ➔ 100 MW net electricity production

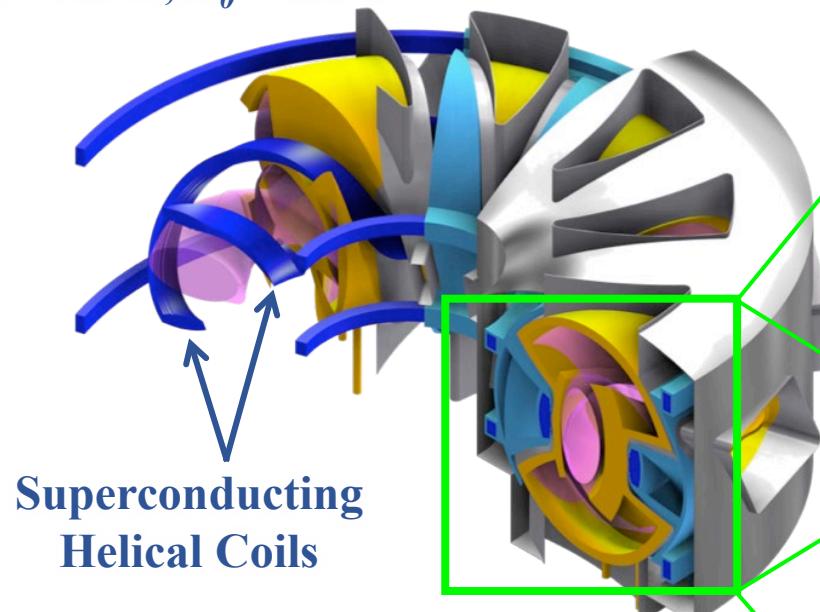
Major radius [m]	7.8
Toroidal magnetic field [T]	6.6
Coil current density [A/mm ²]	80
Central electron density [10 ²⁰ /m ³]	3.3
Central electron temperature [keV]	11.7
Central beta value [%]	5.0
Fusion output [MW]	469
Fusion gain (Q)	14
Neutron wall load [MW/m ²]	0.69
Net electricity output [MW]	106
Stored magnetic energy [GJ]	47.2

High-Temperature Superconducting Magnet

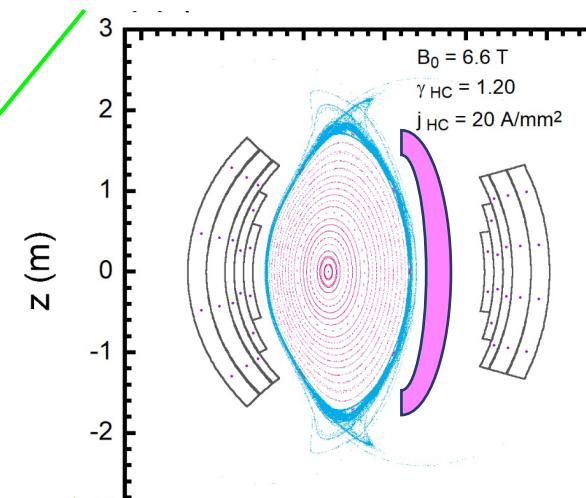
(proposed: 2002, primary option: 2014)

Helical Fusion Reactor, FFHR-b3

$$R_0 = 7.8 \text{ m}, B_0 = 6.6 \text{ T}$$

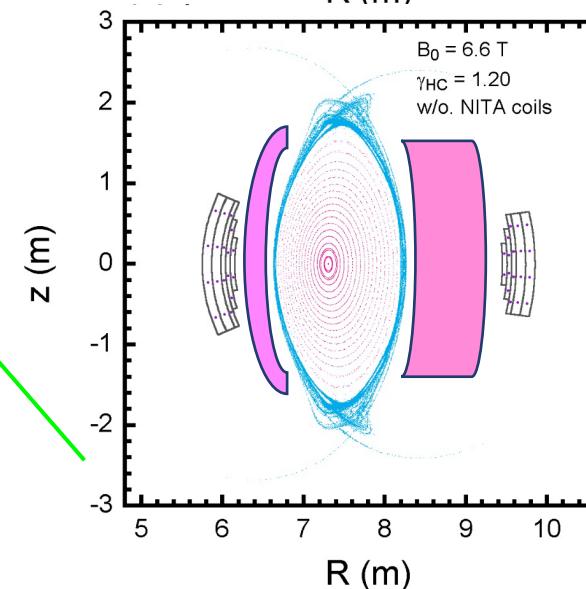


Superconducting
Helical Coils



Low-Current Density (LTS)
 20 A/mm^2

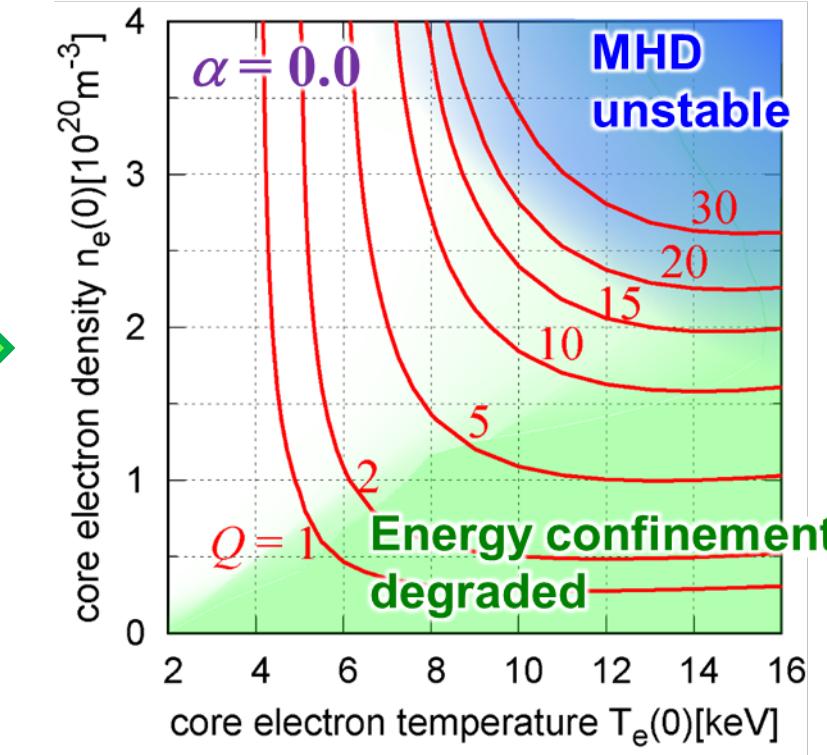
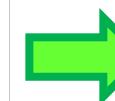
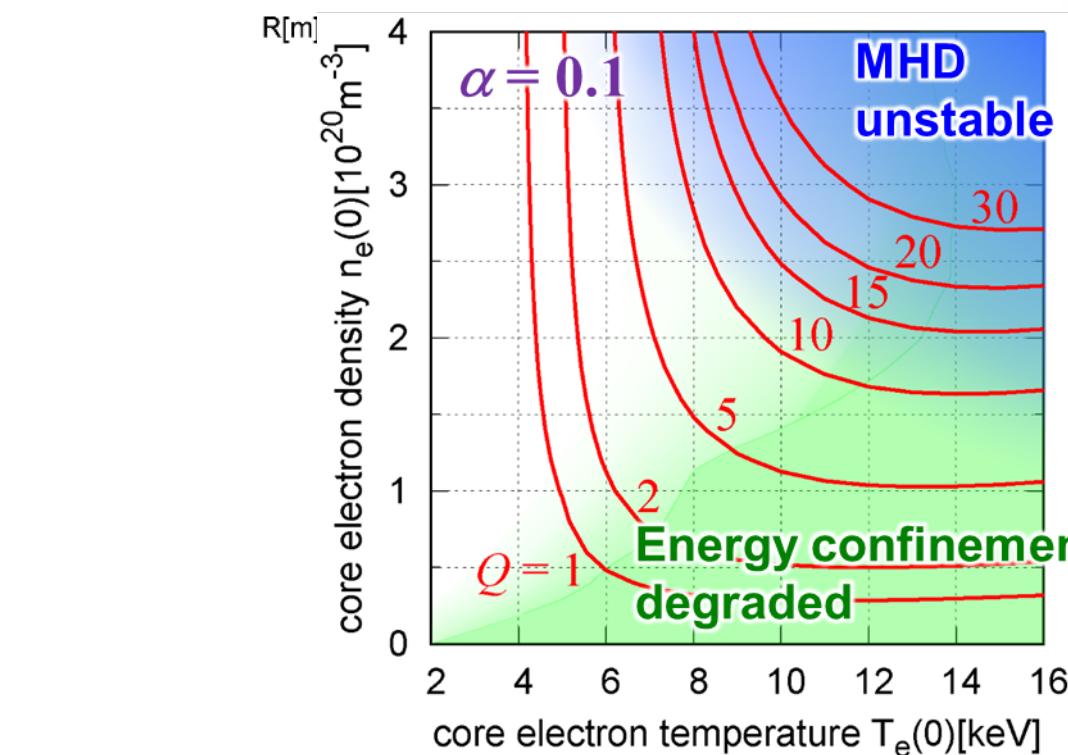
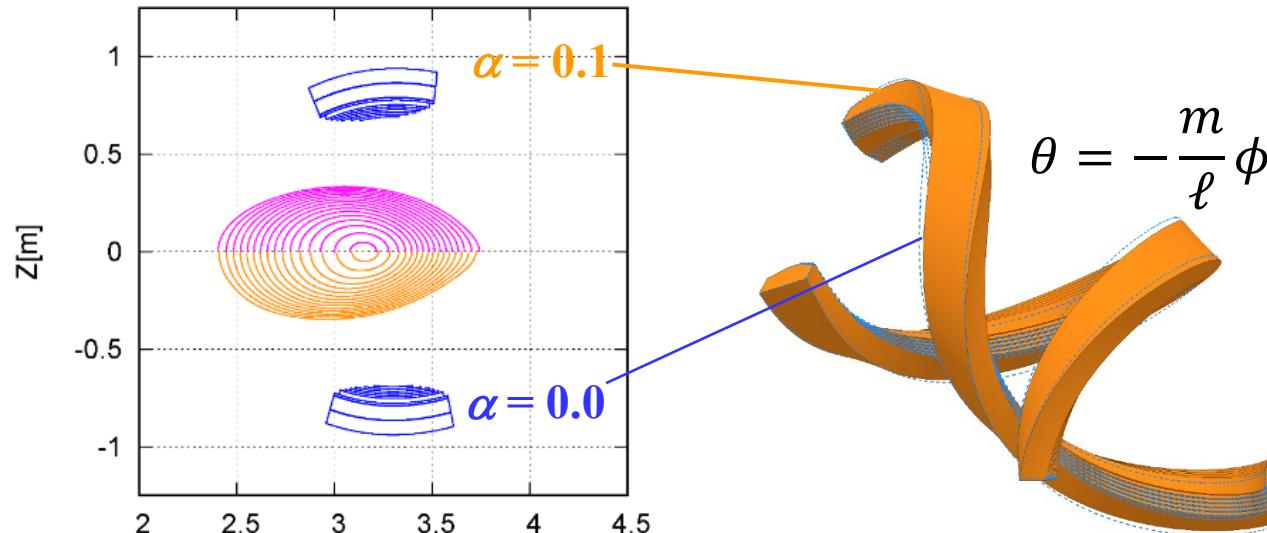
High-current density is
a key factor for HTS



High-Current Density (HTS)
 80 A/mm^2

Other key factors for selecting HTS magnet

- Joint winding of segmented conductors
- High plant efficiency
- Low helium consumption



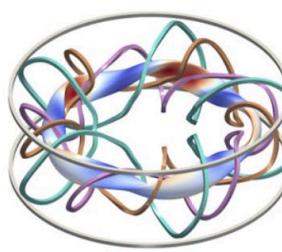
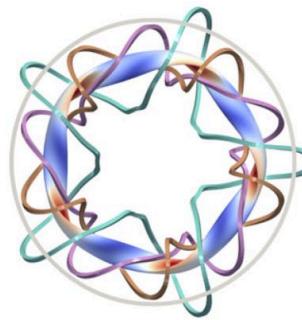
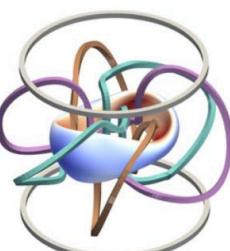
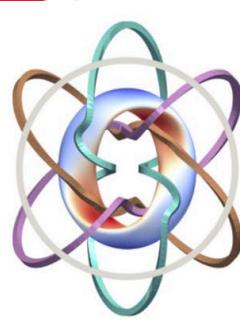
T. Goto et al., Nucl. Fusion 59 (2019) 076030

$$\theta = -\frac{m}{\ell} \phi - \alpha \sin \left(\frac{m}{\ell} \phi \right)$$

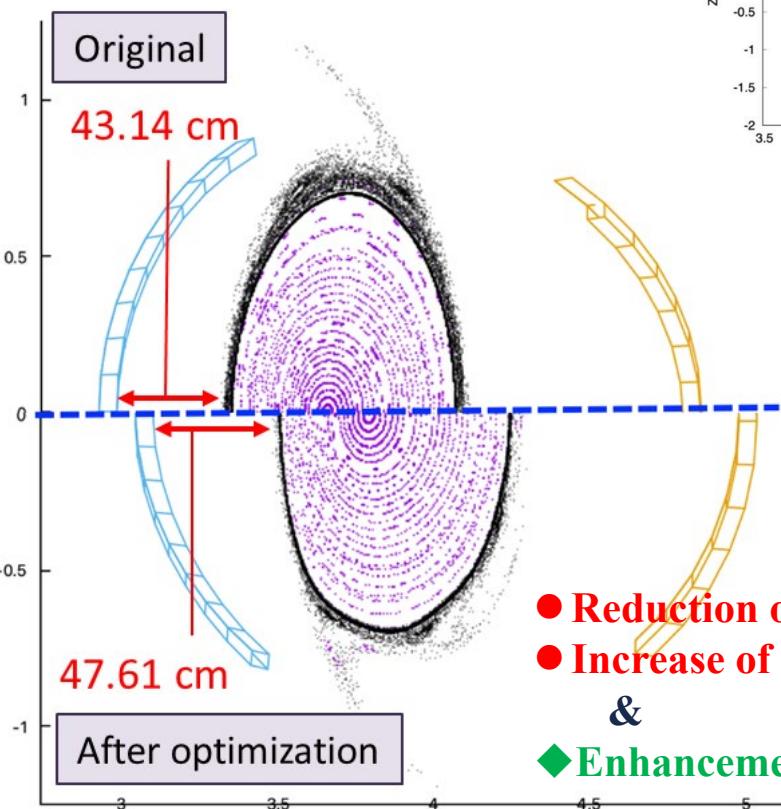
A pair of helical coils

= double helix (obeying the law of nature, like DNA)

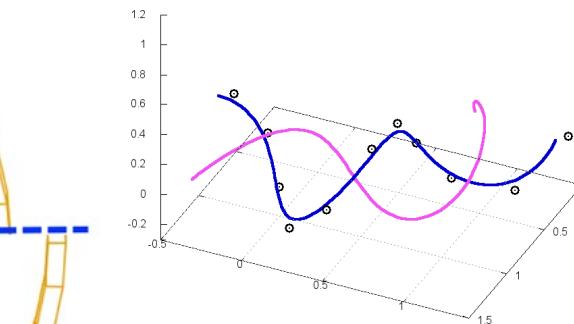
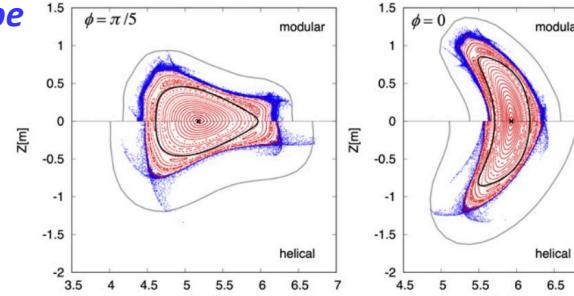
Slight change of winding path makes simultaneous improvements of confinement and MHD



Advanced stellarator configuration can be reproduced by continuous helical coils with helical divertor legs



- Reduction of neo-classical transport
- Increase of MHD stability
- &
- ◆ Enhancement of blanket space



OPTHECS

Main code
Genetic algorithm/Gradient method (LM)

vacuumf-xs

Biot-Savart's law

mixBFs

Summation of B by different coils

tracer3

Field-line tracing (core)

dvfoot

Field-line tracing (edge)

boundFT

Conversion from points to surface

c2cpls

Coil and plasma geometry analysis

VMEC

3-D MHD equilibrium

gcbooz

Guiding-center orbit

nd11-mc

Mono-energetic neoclassical D_{11}

proxy

Turbulence-related quantities

boozmn2gnet

Data conversion

Coil-shaping

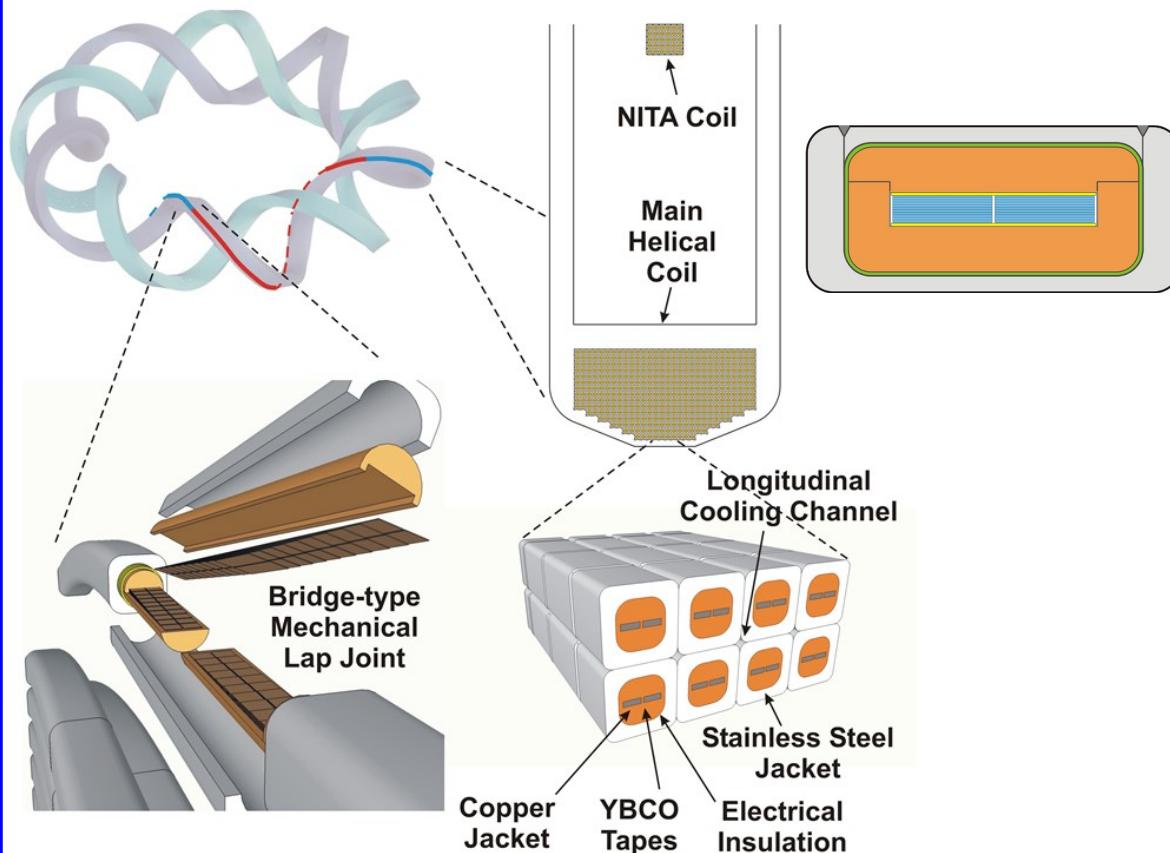
Boundary-shaping

H. Yamaguchi et al., Nucl. Fusion 61 (2021)

Engineering design options : Magnet

Option 1 : HTS STARS Conductor

- Simple stacking of REBCO tapes
- Mechanically robust
- Joint-winding of conductor segments



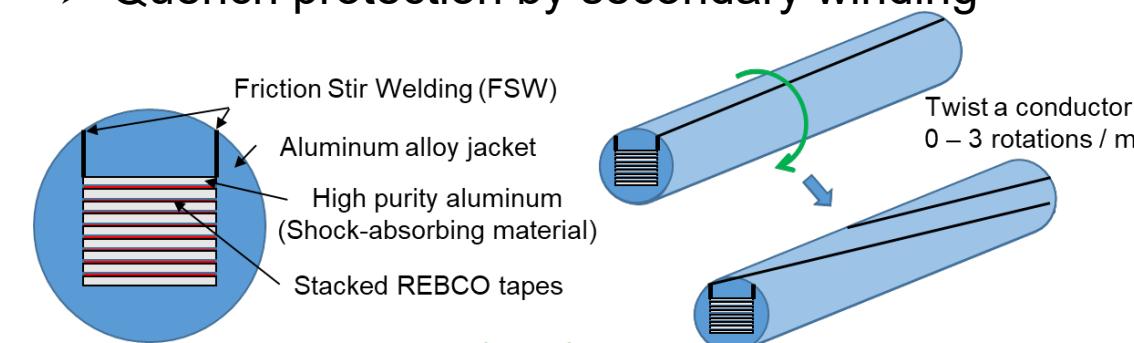
N. Yanagi, Nucl. Fusion 55 (2015) 053021

Y. Terazaki, IEEE Trans. Appl. Supercond. 25 (2015) 4602905

S. Ito, et al., Fusion Eng. Des. 146 (2019) 590

Option 2: HTS FAIR Conductor

- Twist-stacking of REBCO tapes
- Flexible during winding (aluminum alloy)
- Quench protection by secondary winding

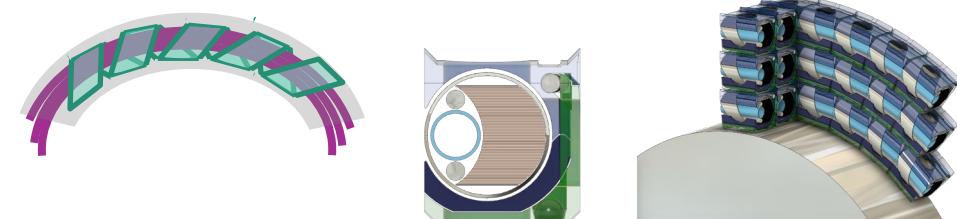


T. Mito et al., J. Phys. Commun. 4 (2020) 035009

Y. Onodera et al., J. Phys. Conf. Ser. 1559 (2020) 012118

Option 3: HTS WISE Conductor

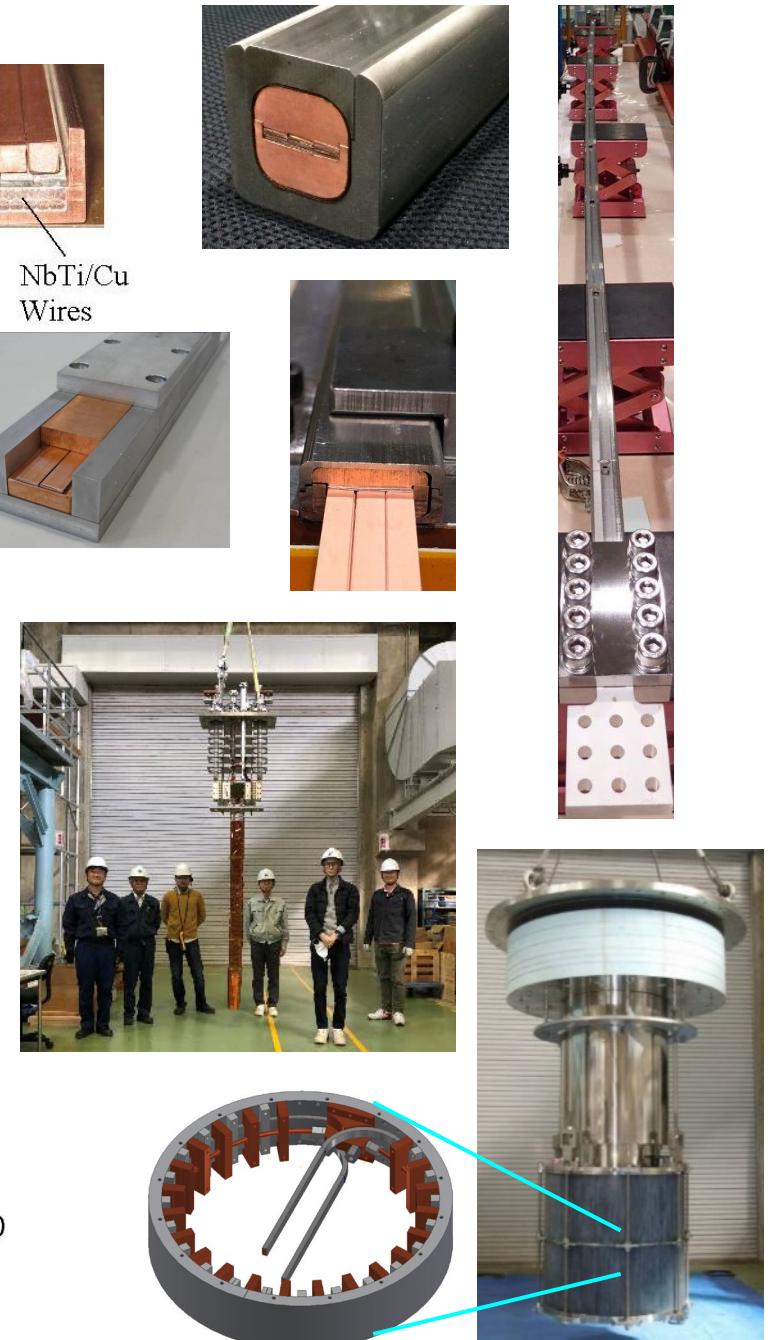
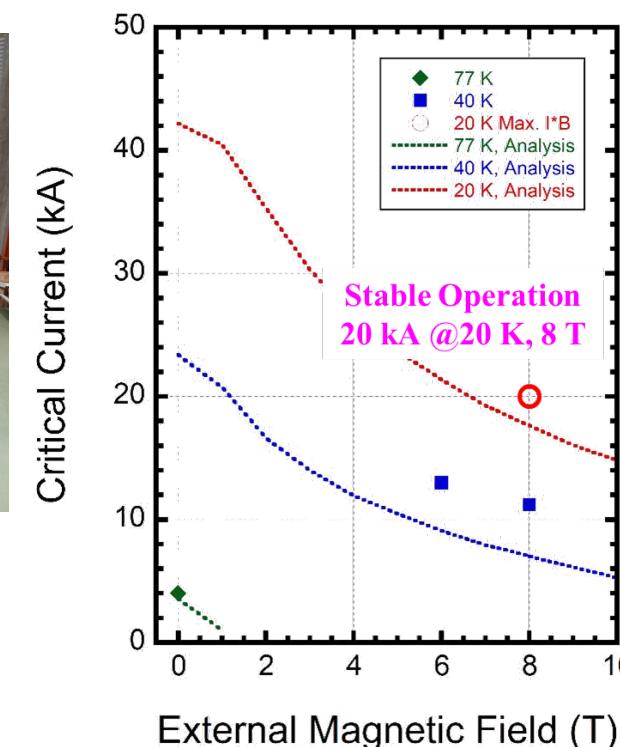
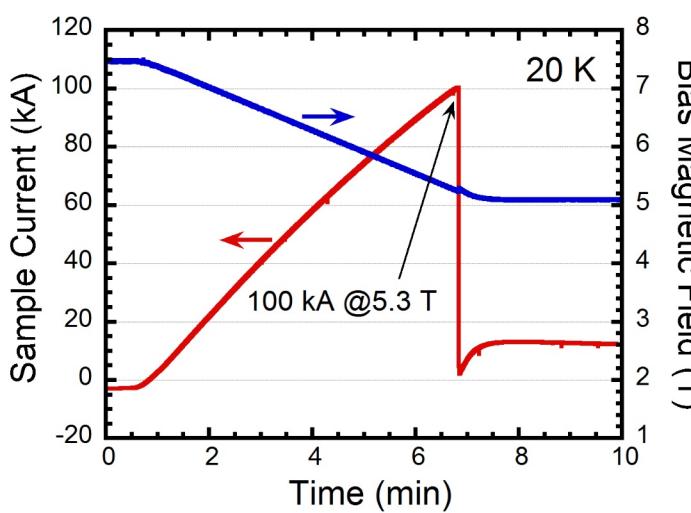
- Simple stacking of REBCO tapes
- Super-flexible during winding
- Impregnation by low-temp. metal (no insulation)



S. Matsunaga et al., IEEE Trans. Appl. Supercond. 30 (2020) 4601405

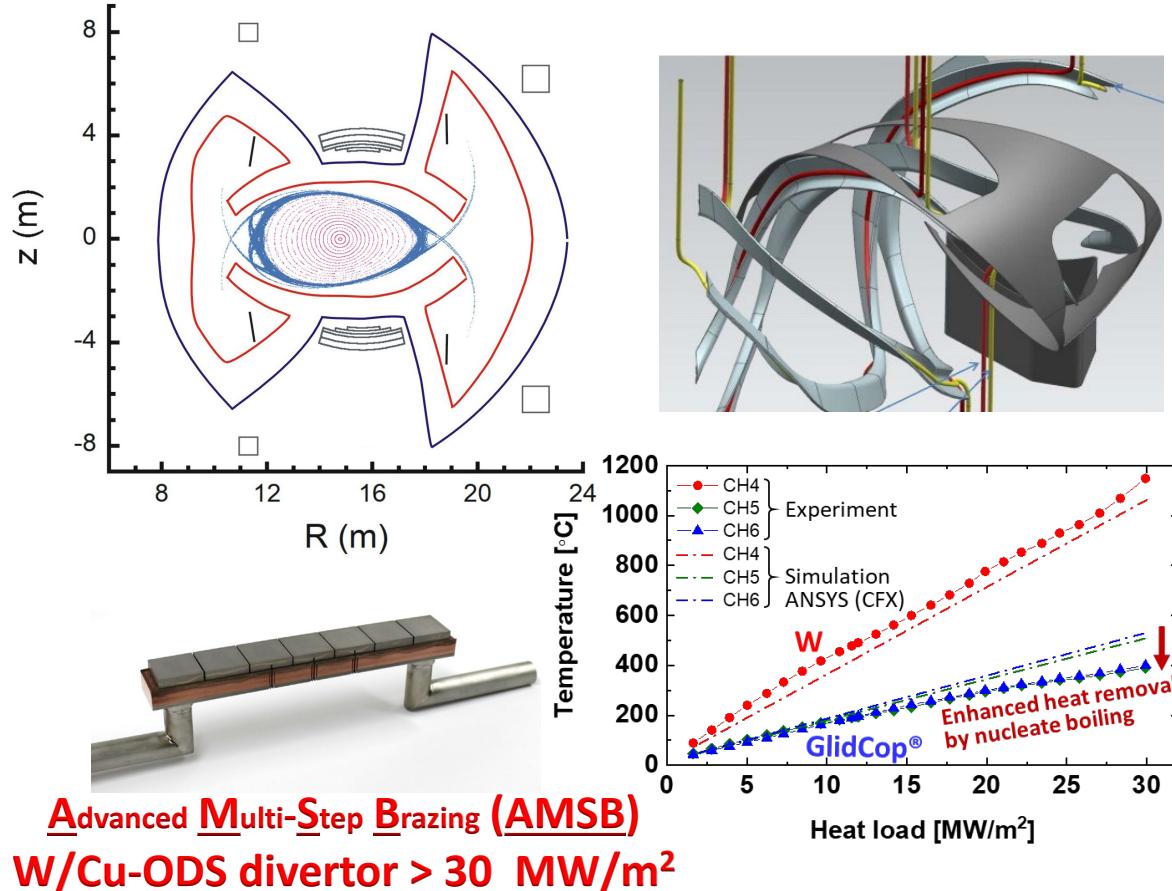
HTS STARS Conductor Development at NIFS

2003-2006 : LTS / HTS hybrid conductor
2006-2007 : 10-kA-class STARS prototype conductor
2007-2008 : 15-kA-class STARS prototype conductor
2012-2013 : 30-kA-class STARS prototype conductor
2013-2014 : 100-kA-class STARS prototype conductor
2019-2021 : 20-kA-class STARS actual conductor with LBW



Engineering design options : Divertor

Option 1: W/Cu + water cooling = helical divertor



Flattening of strike points < 20 MW/m² (even w/o detachment)

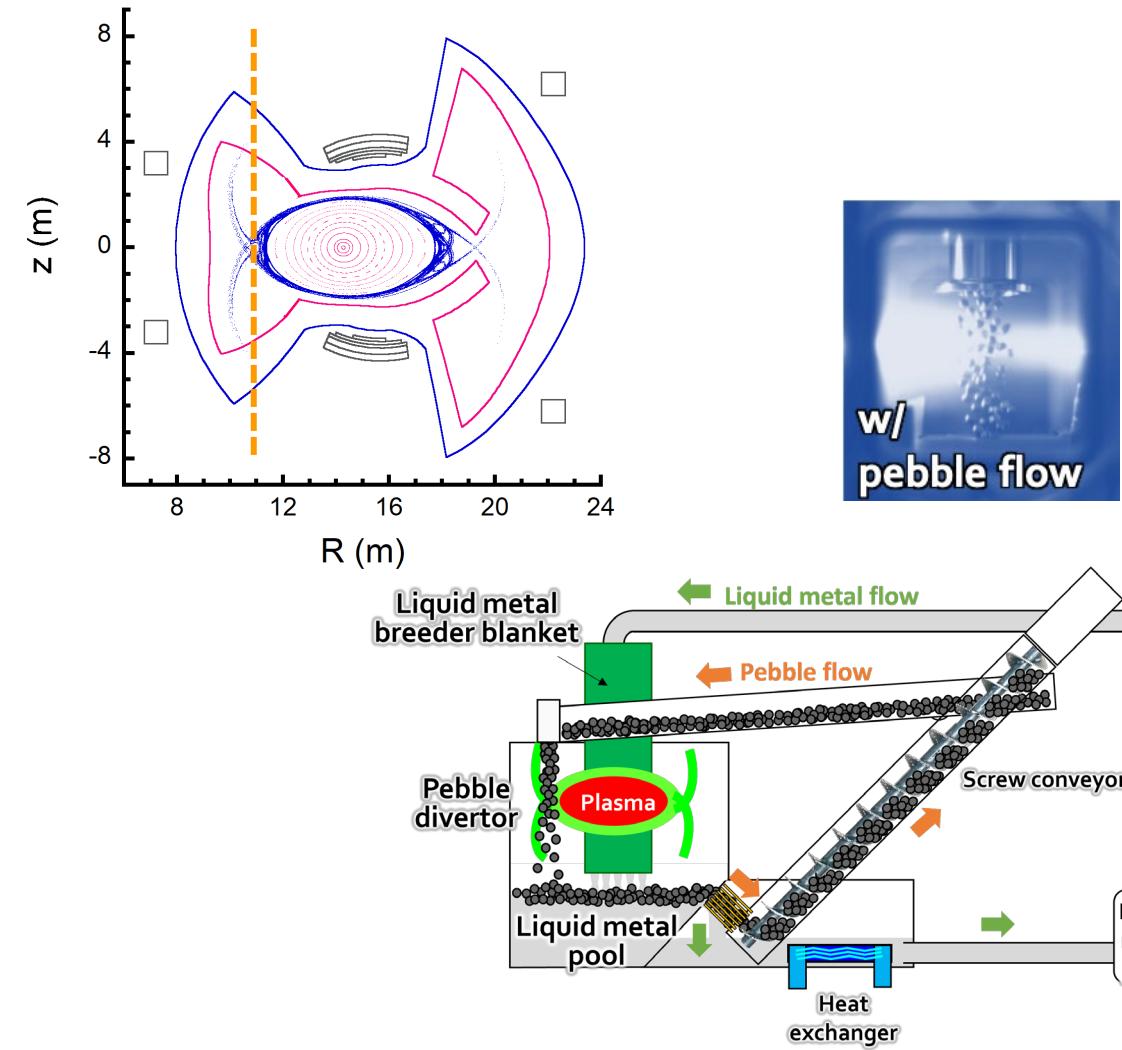
Divertors are shielded from 14 MeV neutrons by blankets

M. Tokitani et al., Nucl. Fusion 61 (2021) 046016

Y. Hamaji et al., Nucl. Mater. Energy 18 (2019) 321

N. Yanagi, J. Fusion Energy 38 (2019) 147

Option 2: Pebble + liquid metal = ergodic limiter divertor



Concentration of strike points at inboard sections
Pebble (fusible Sn or ceramic)

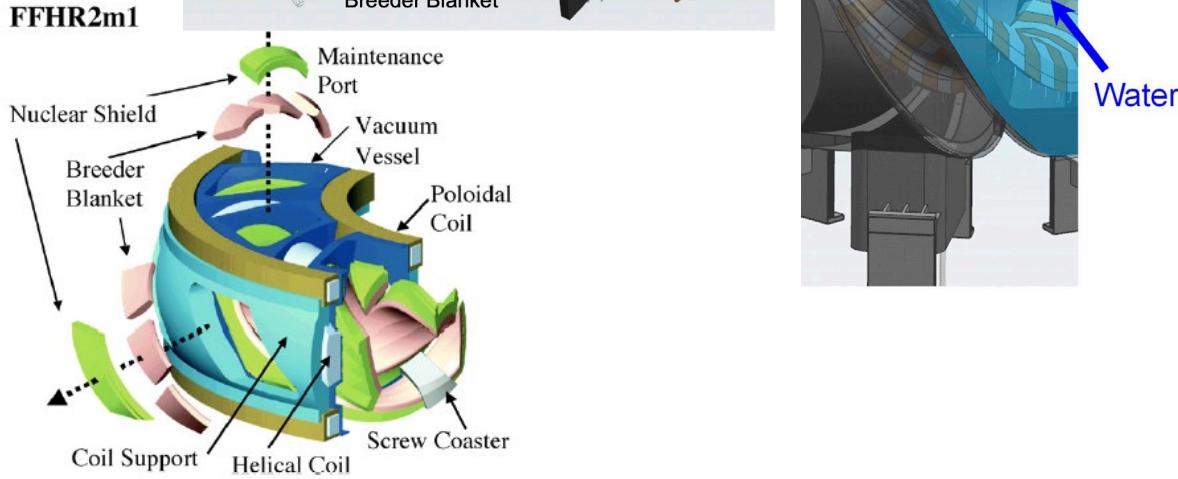
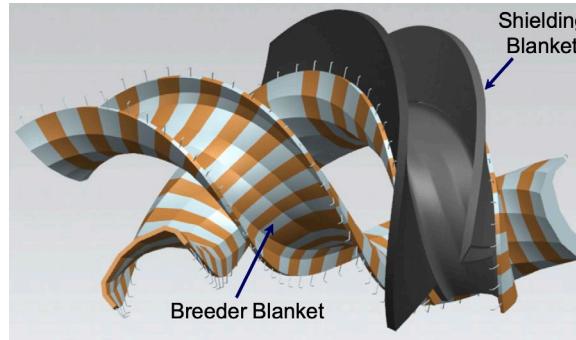
Engineering design options : Blanket

Option 1: Helically segmented

Molten salt (FLiNaBe)

Maintenance by remote handling

Screw-coaster and aquarium method



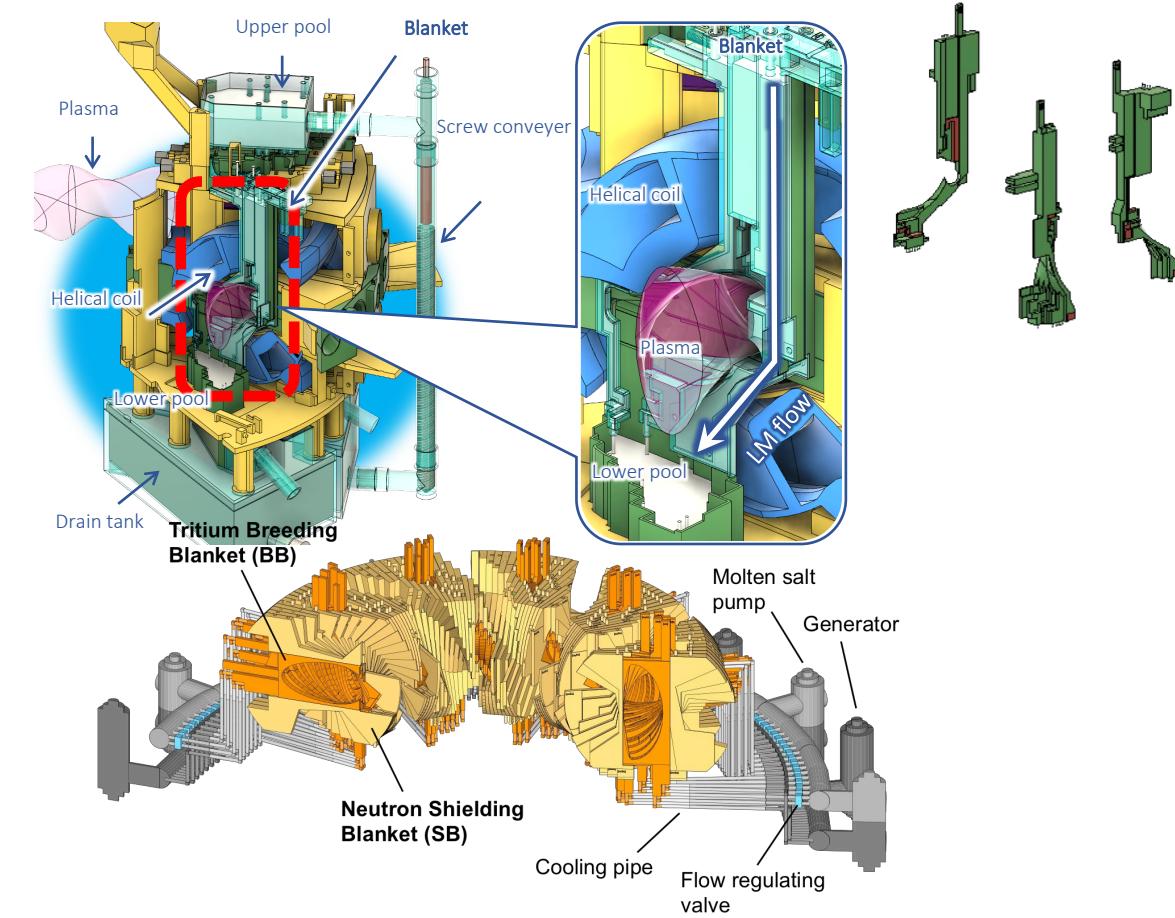
A. Sagara, Fusion Eng. Des. 81 (2006) 1299

N. Yanagi, J. Fusion Energy 38 (2019) 147

Option 2: Toroidally segmented = cartridge-type

Functional liquid metal

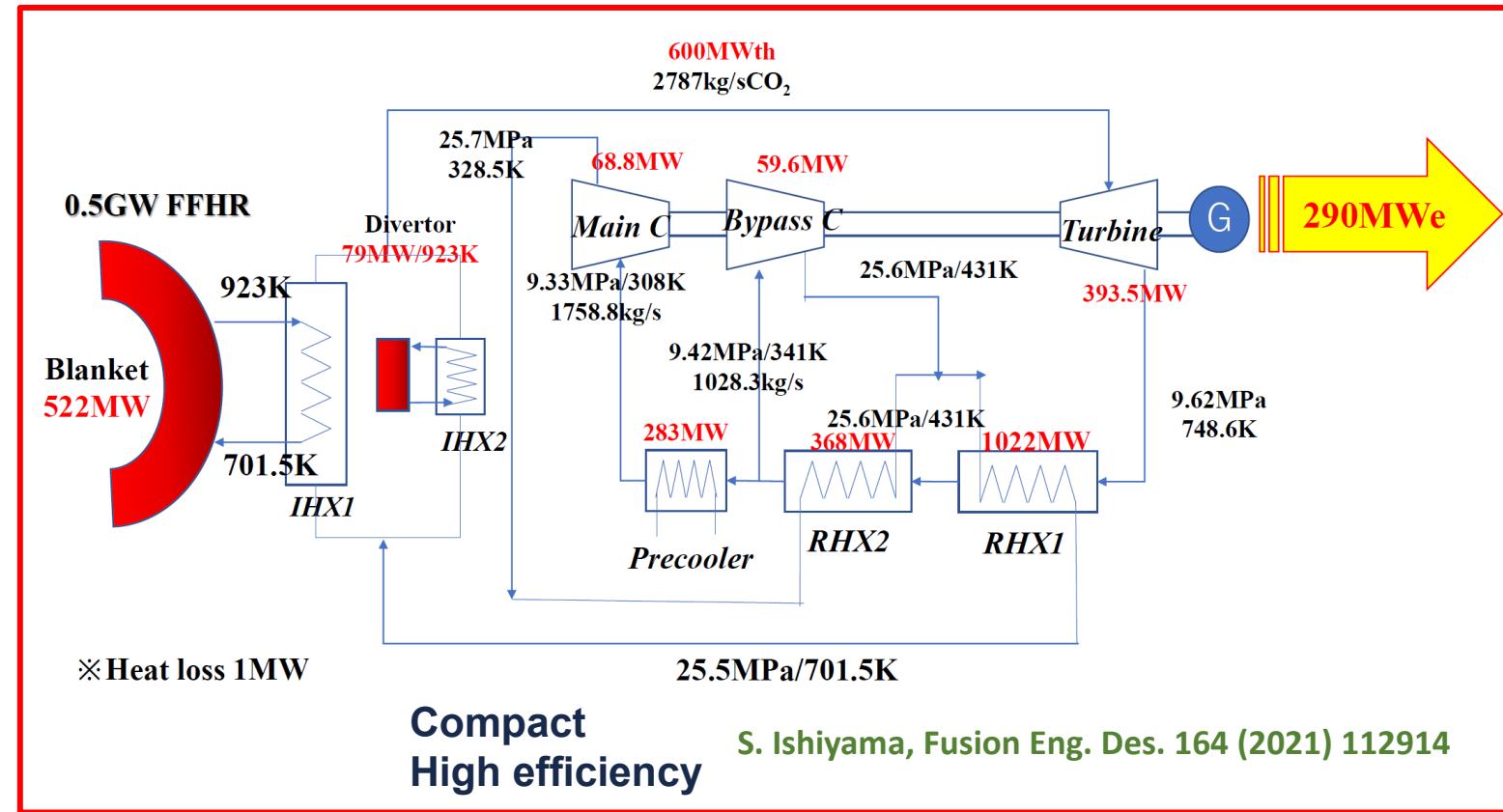
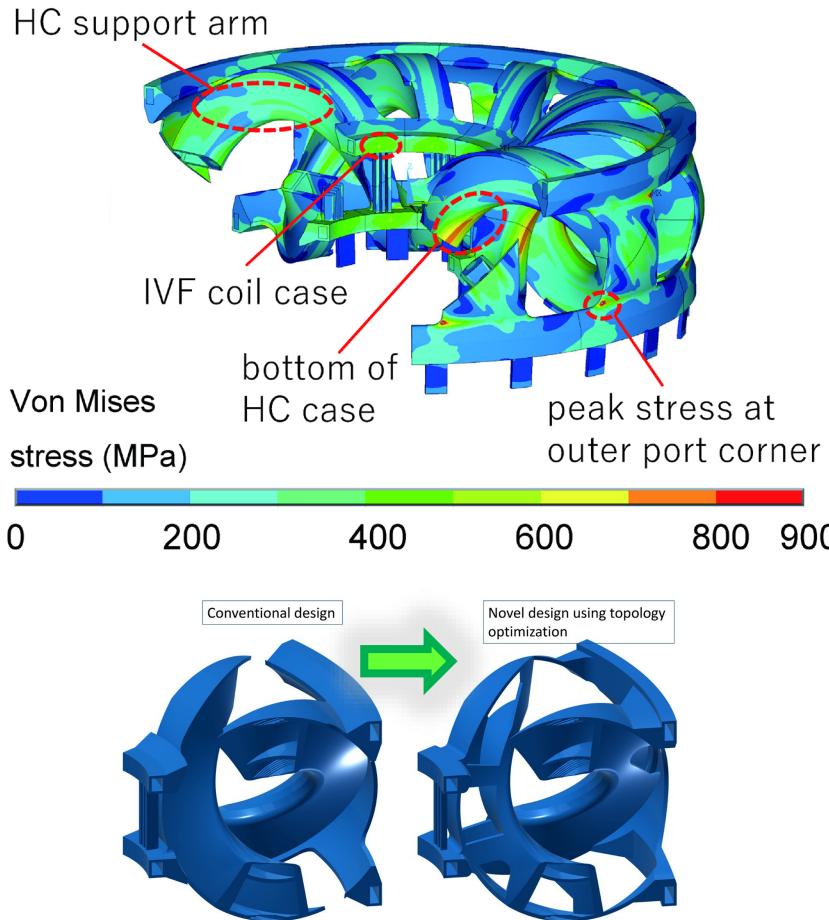
Maintenance by external handling



J. Miyazawa, Nucl. Fusion 61 (2021) 116030

J. Miyazawa, Fusion Eng. Des. 136 (2018) 1278

Electromagnetic supporting structure / SCO_2 turbine generator



Stress distribution in electromagnetic supporting structure is analyzed by FEM
Topology optimization confirms >25% weight reduction

- The LHD-type heliotron fusion reactor **FFHR-b3** is proposed aiming at **100 MWe** production with double the size of LHD
- Configuration optimization is examined to improve plasma confinement, MHD, and blanket space
- Engineering design is progressing with options for the magnet, divertor, and blanket
- HTS conductors are being developed with high current density **80 A/mm²**

- *Superconducting operation of LHD will come to an end in spring 2023... by termination of the budget “Projects to Promote Large Scientific Frontiers”*
- *NIFS will be promoting more academic research on fusion science, extending interdisciplinary research, contributing more on Japanese DEMO*
- *Engineering design of the heliotron fusion reactor will be continued by Helical Fusion Co., Ltd. (coming soon...)*

