Design Studies on Split and Segmented-Type Helical Coils for FFHR

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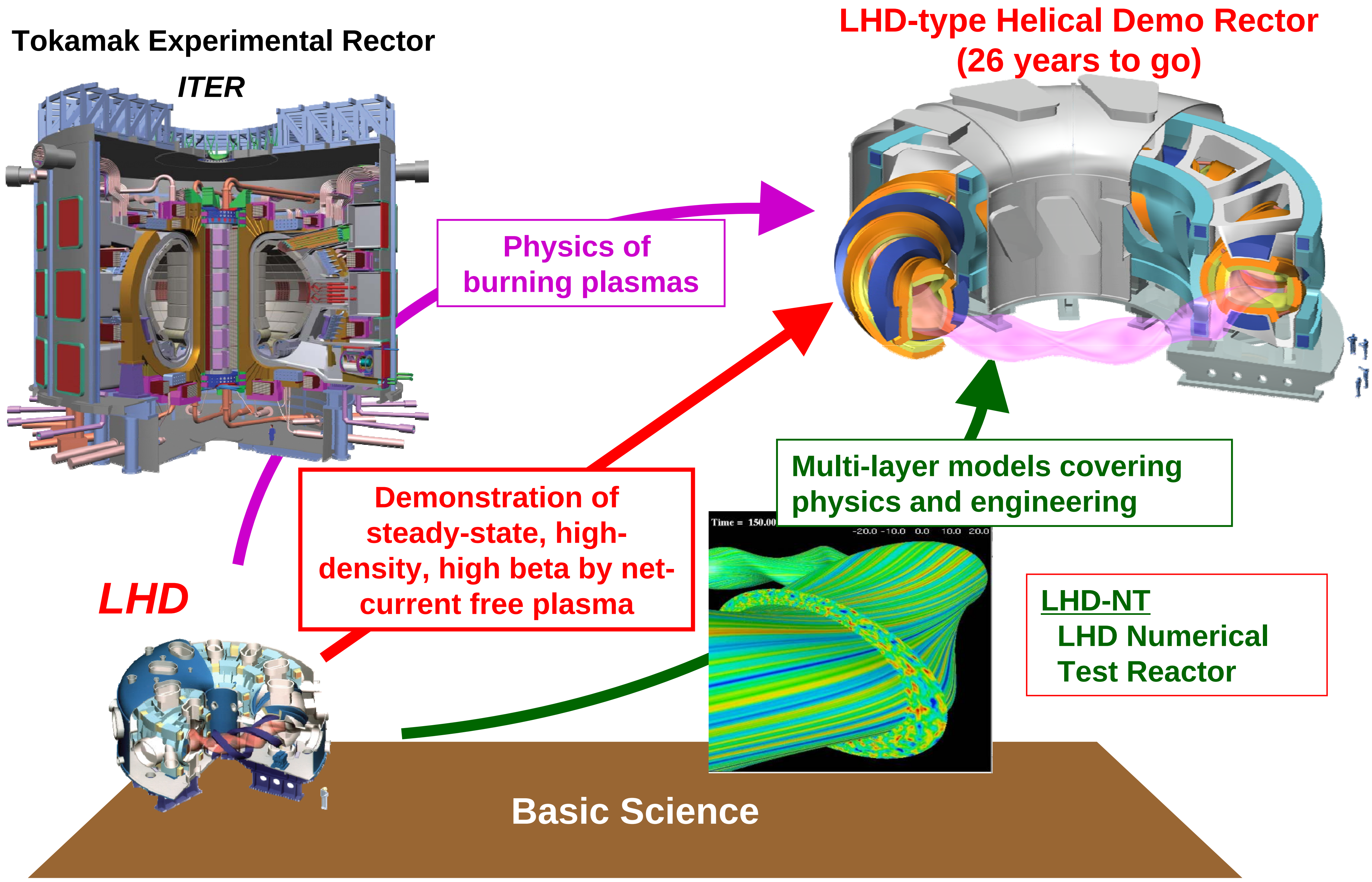
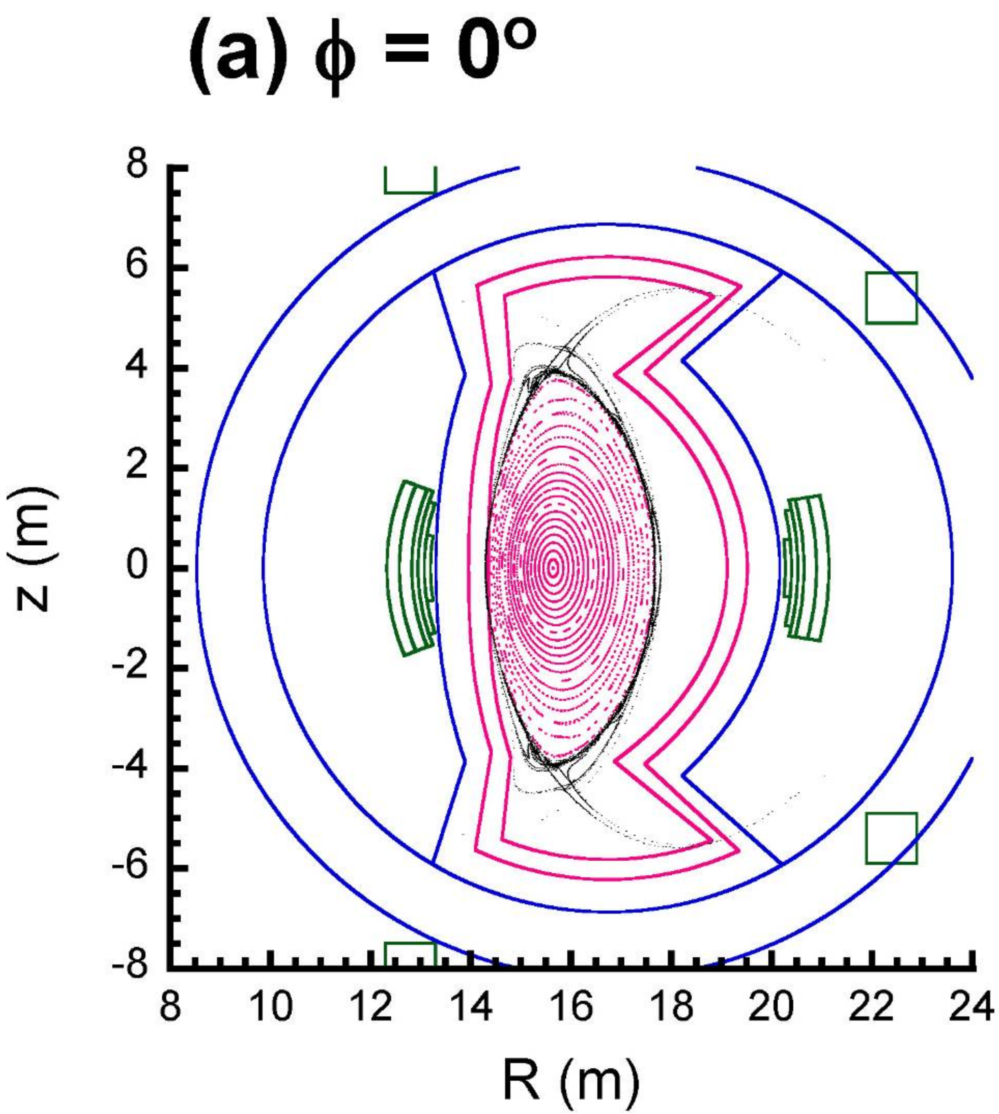
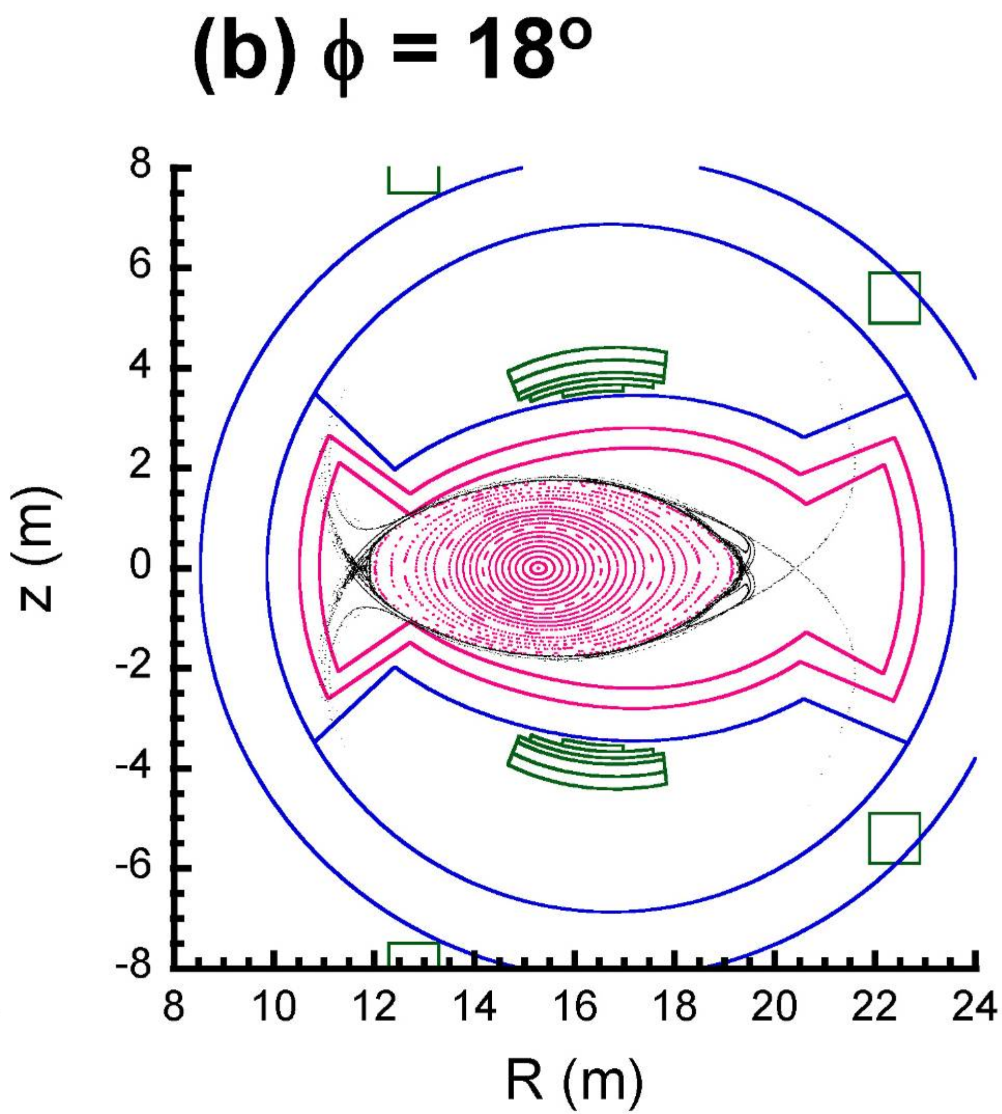
Realization of Helical Demo-Reactor Based on LHD



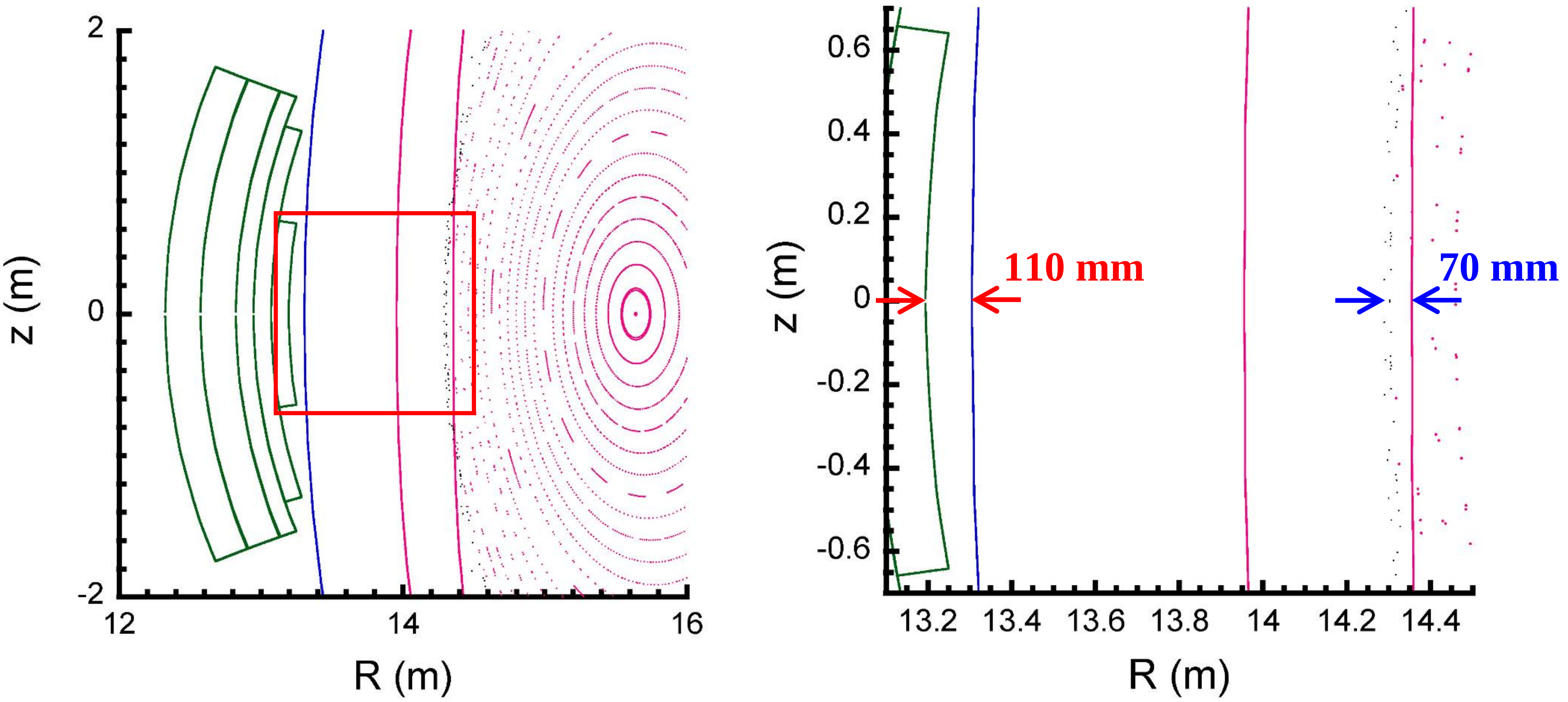
Vacuum Magnetic Surfaces of FFHR-2m2 Type-D





R_c = 16.74 m , γ = 1.2, α = +0.1, R_p = 15.45 m, B_p = 4.84 T, j_{HC} = 26 A/mm^2
Stored magnetic energy = 145 GJ

Vacuum Magnetic Surfaces of FFHR-2m2 Type-D



- **Interference of ergodic layers with blankets : ~70 mm**
- **Clearance of $\Delta_{HC\text{-}VV}$ = 110 mm really enough?**

Is it possible to obtain magnetic surfaces with better symmetry and larger clearances?

If we decrease the helical pitch parameter γ

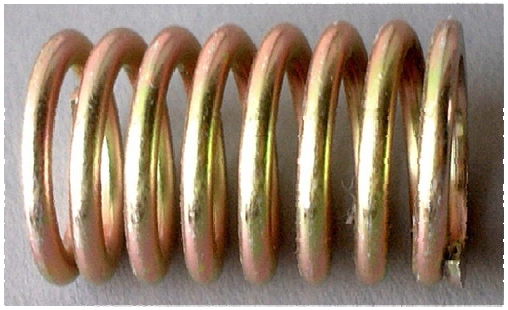
$$\gamma = \frac{m}{\ell}\frac{a_c}{R}$$

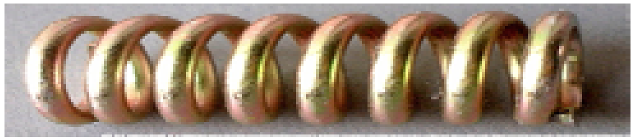
m : Toroidal Pitch Number (= 10)

ℓ : Poloidal Pole Number (= 2)

a_c : Minor Radius of HC (= 3.22)

R : Major Radius of HC (= 14.0)

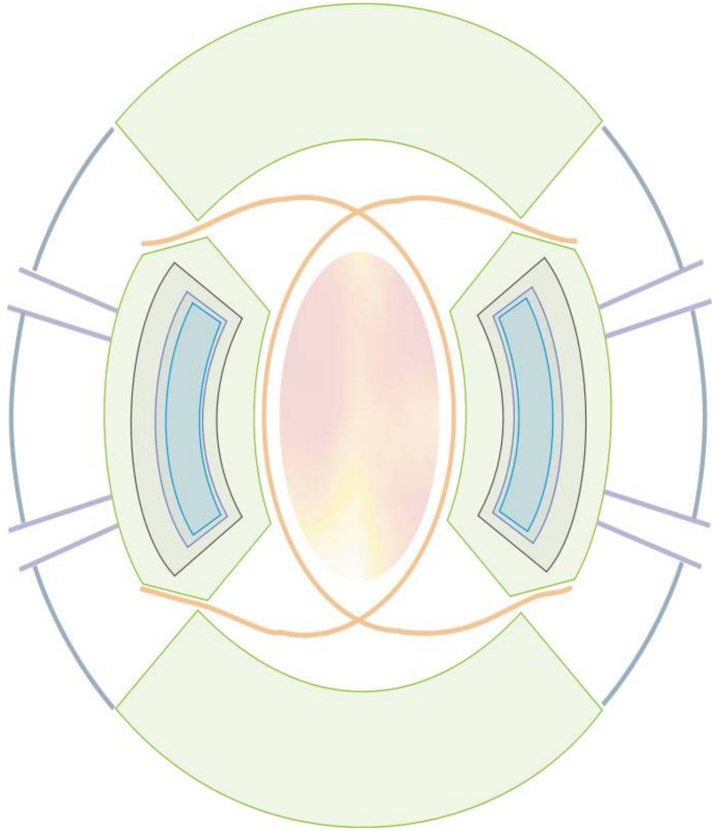




γ = 1.25 ➔ 1.20 ➔ ~ 1.0

LHD FFHR-2m2 FFHR-2S (Type-I)

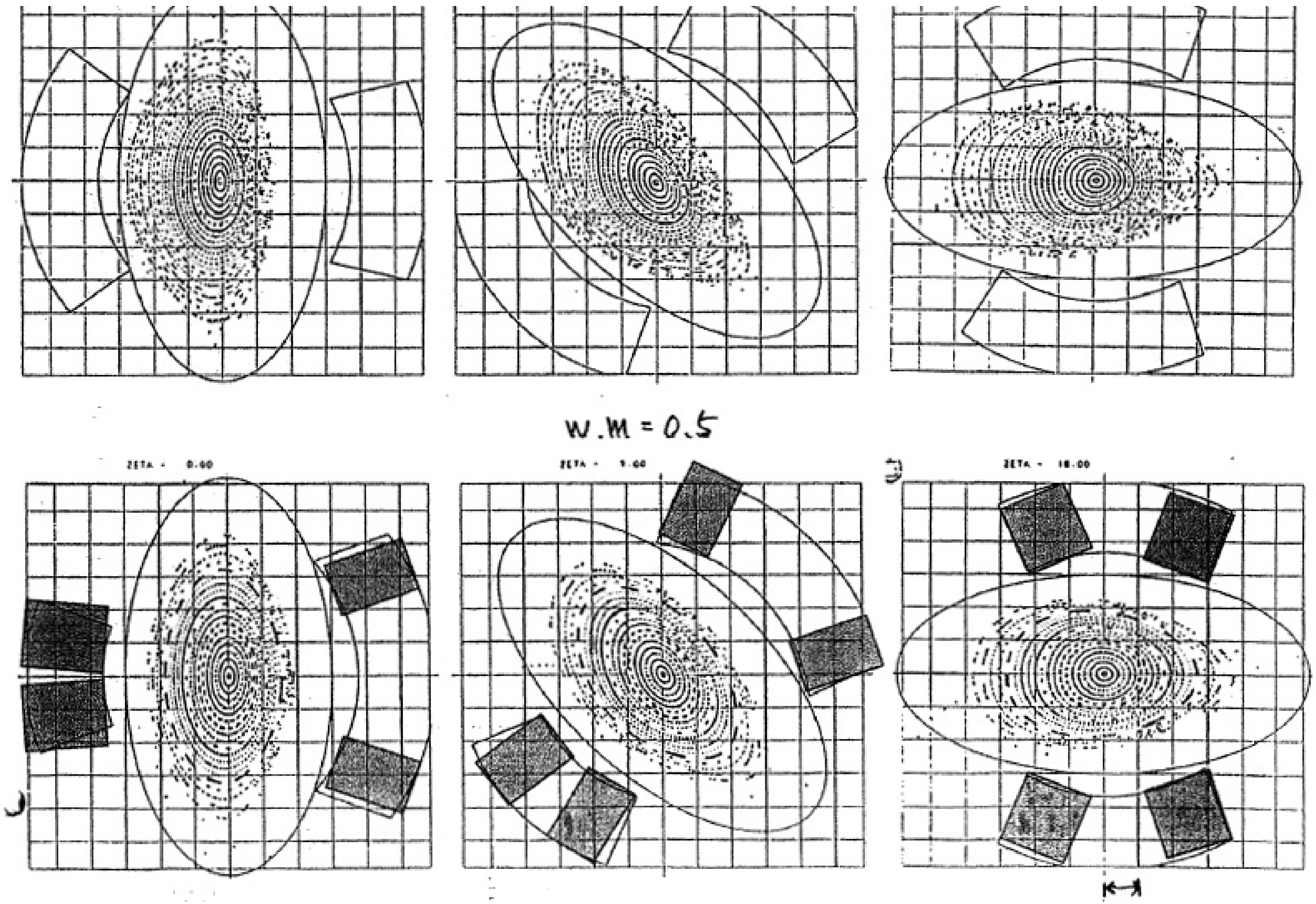
- **Larger clearances between the ergodic region and blankets**
- **Smaller magnetic surfaces**



An Orthodox Image of Heliotron Reactor

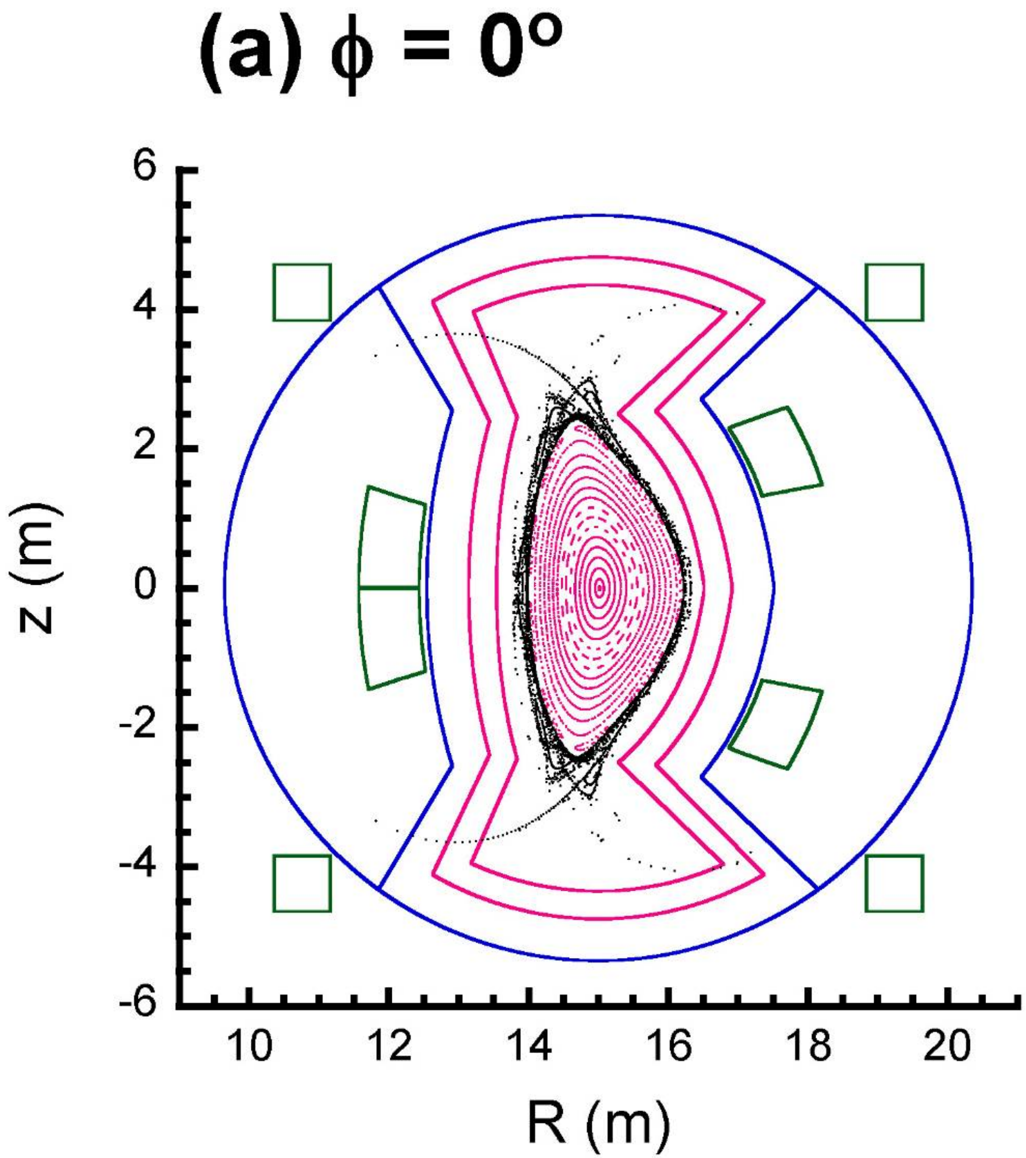
A. Iiyoshi

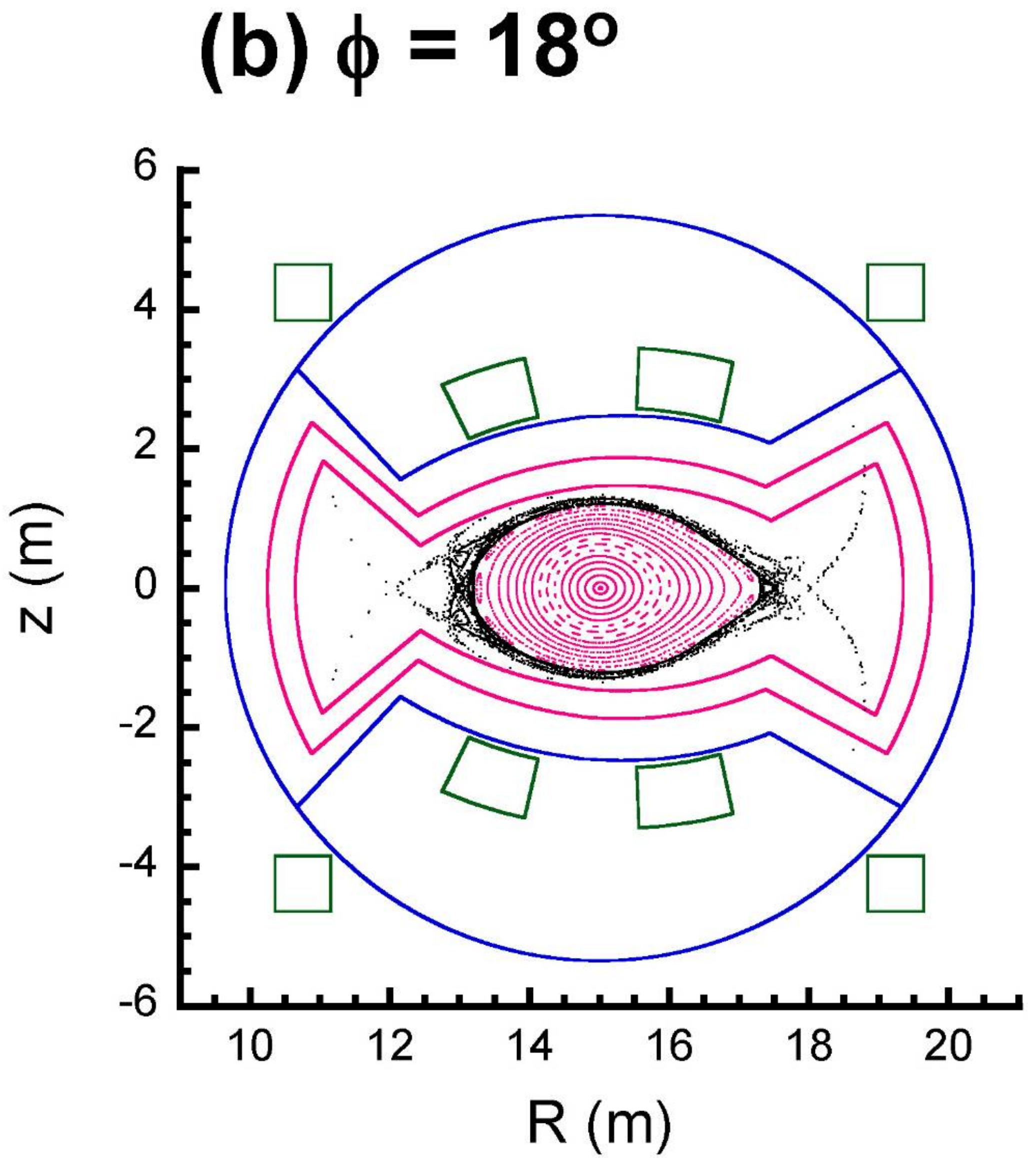
Helical symmetry is improved by increasing/decreasing current density of helical coils at the inboard/outboard side



K. Nishimura and M. Fujiwara, "Symmetrized Magnetic Field Configuration of Low-Aspect Ratio Helical System" JPSJ 64 (1995) pp.1164-1171.

Configuration Modification by Split-Type Helical Coils: "FFHR-2S Type-I" (2008 design)



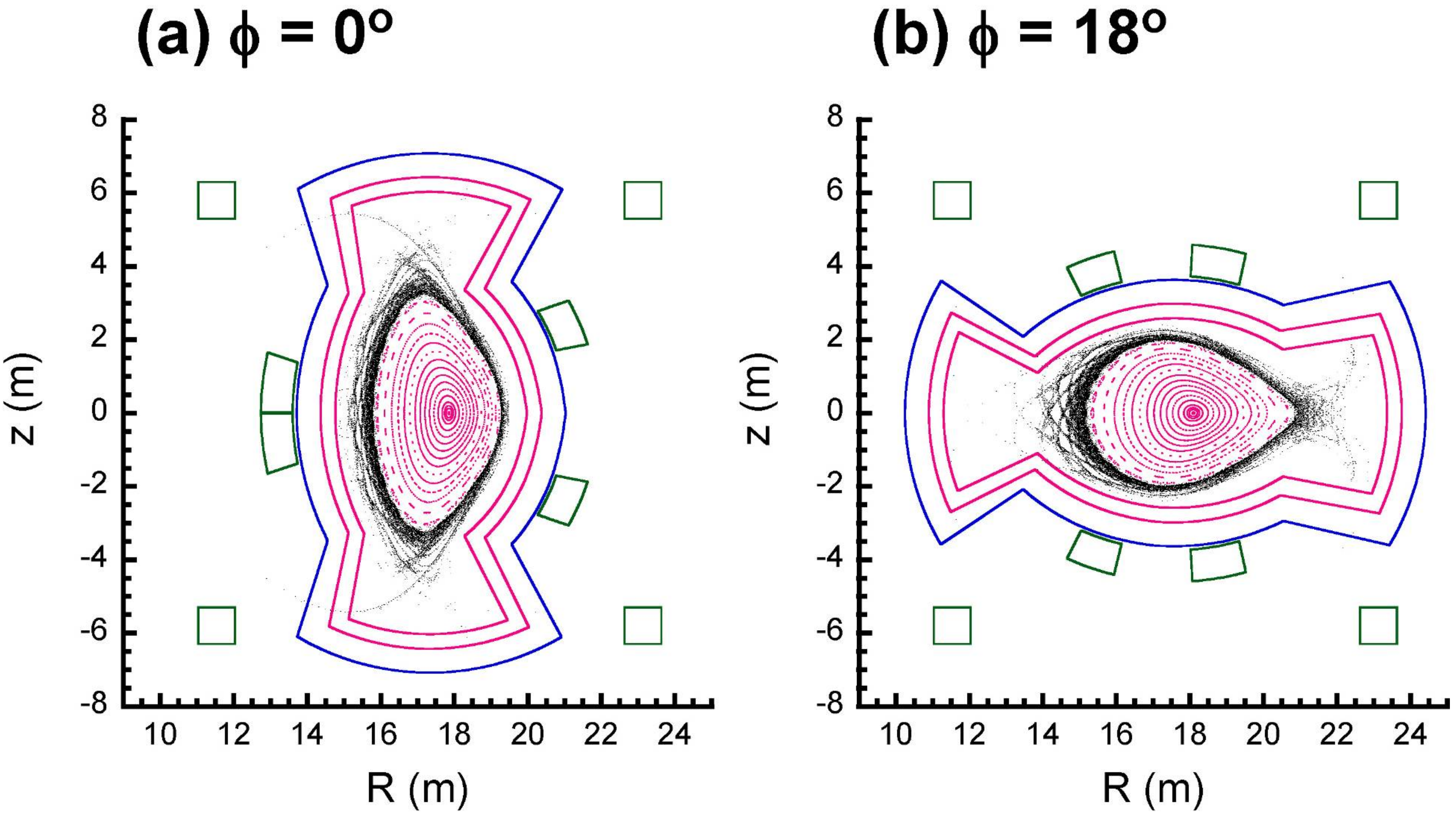


R_c = 15.0 m , γ = 1.0, α = +0.1, R_{axis} = 15.0 m, B_{axis} = 6.0 T, j_{HC} = 30.0 A/mm^2, a_{PC} = 6.0 m

HC : 45.0 MA, OV : -17.55 MA, IV : 0 MA

Stored magnetic energy = 143.2 GJ

Configuration Modification by Split-Type Helical Coils: "FFHR-2S Type-II" (2008 design)

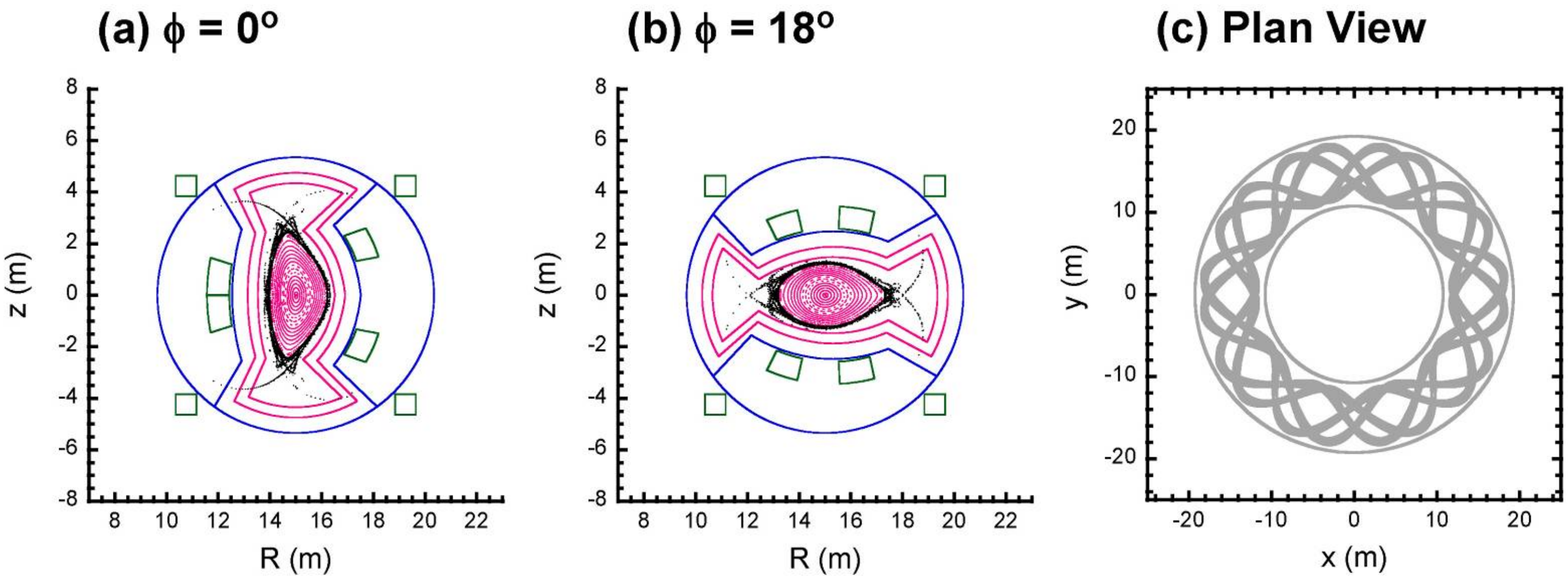


R_c = 17.33 m , γ = 1.2, α = +0.1, R_{axis} = 18.0 m, B_{axis} = 4.3 T, j_{HC} = 26.0 A/mm^2 , a_{PC} = 8.2 m

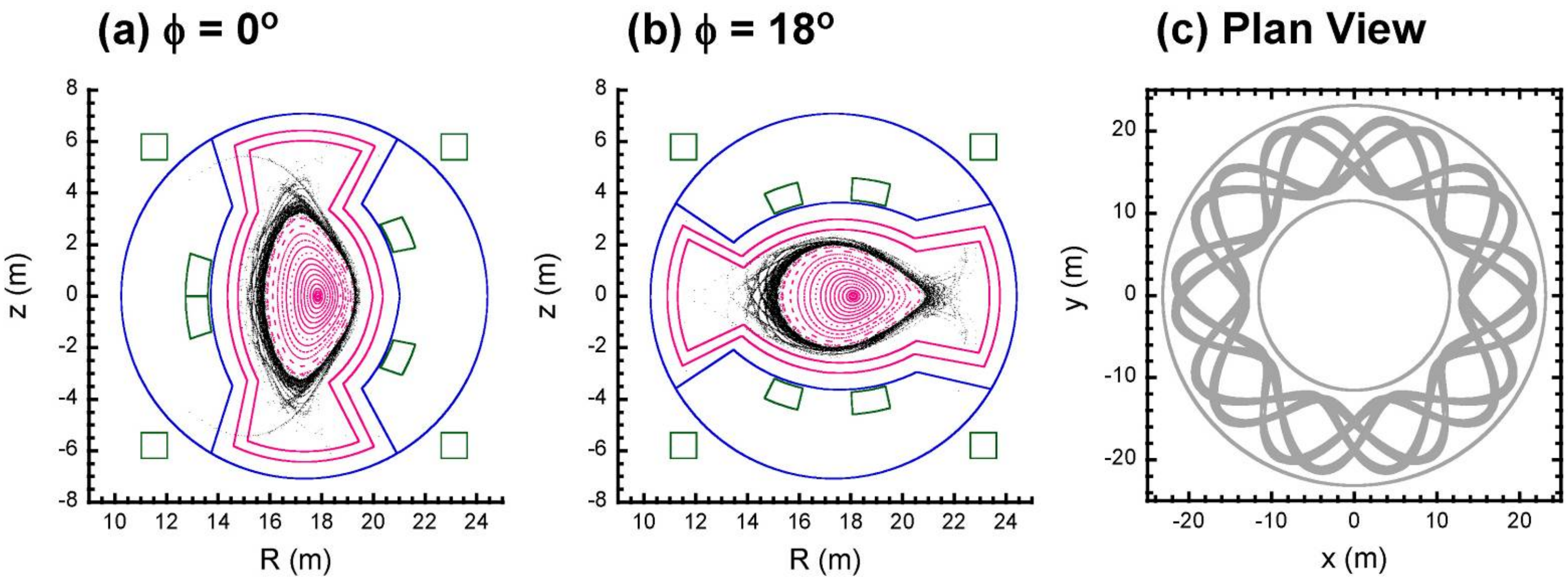
HC : 38.72 MA, OV : -18.30 MA, IV : -13.29 MA

Stored magnetic energy = 136.3 GJ

Two Options of FFHR-2S: Type-I & Type-II



Smaller size and higher field
➔ reduction of total mass with comparable fusion power

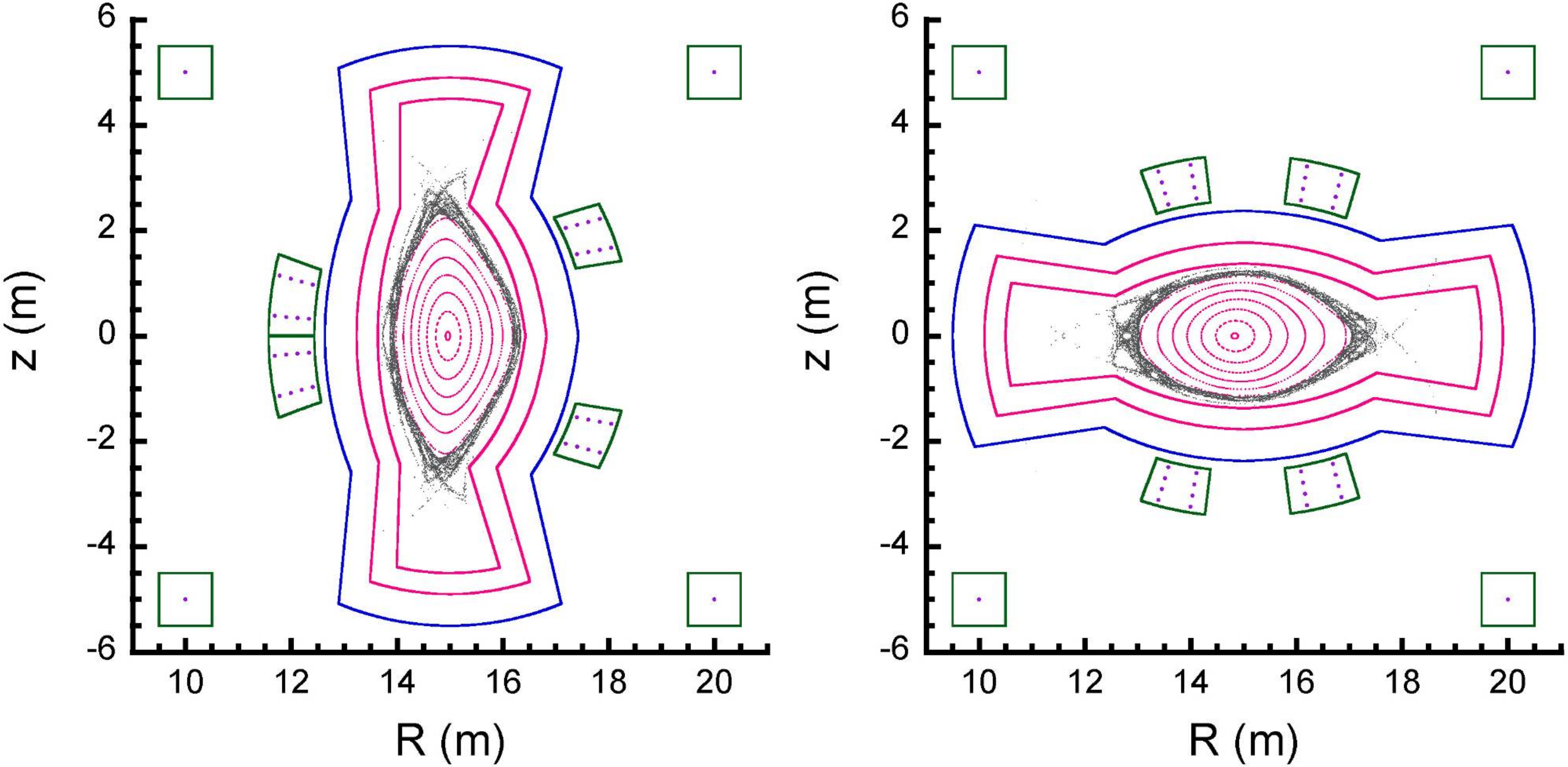


Large magnetic surfaces with outward-shifted configuration
➔ suitable for SDC operation?

ICRF antenna has good accessibility for FFHR-2S
K. Saito et al., to be published in Plasma and Fusion Res.

Configuration Optimization of FFHR-2S Type-I (2009 design)

(a) ϕ = 0°　　　　(b) ϕ = 18°

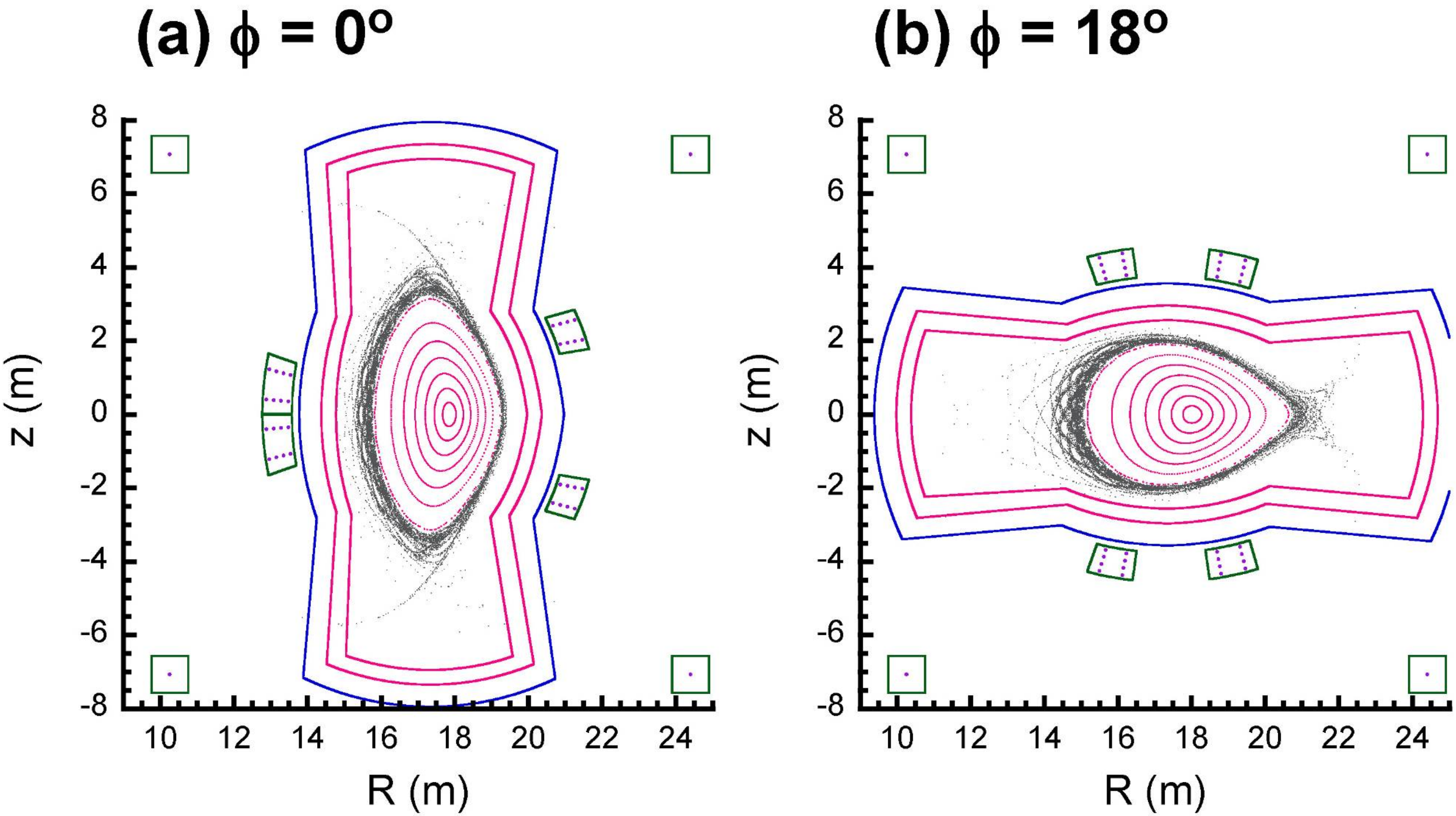


R_c = 15.0 m , γ = 1.0, α = 0, R_{axis} = 15.0 m, B_{axis} = 6.0 T, j_{HC} = 30.0 A/mm^2 , a_{PC} = 7.07 m

HC : 45.0 MA, OV : -27.9 MA, IV : -27.0 MA

Stored magnetic energy = 165 GJ

Configuration Optimization of FFHR-2S Type-II (2009 design)



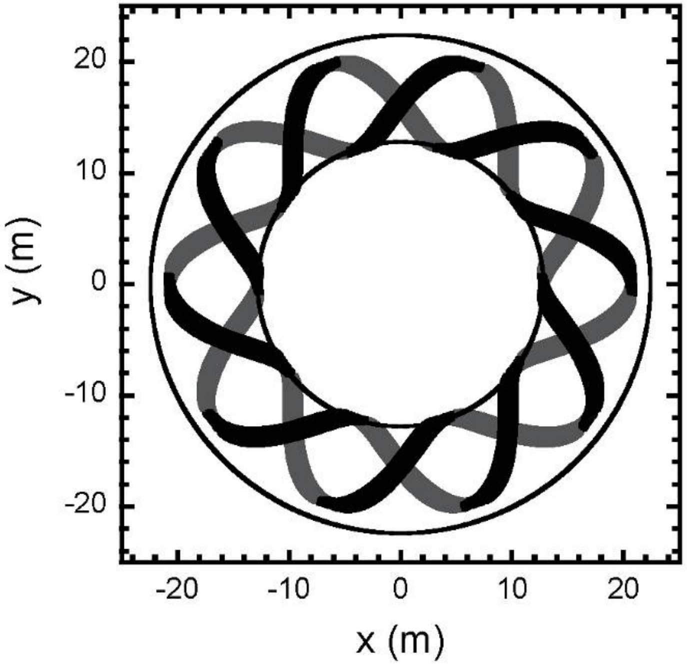
R_c = 17.33 m , γ = 1. 2, α = 0, R_{axis} = 18.0 m, B_{axis} = 4.3 T, j_{HC} = 30.0 A/mm^2 , a_{PC} = 10.0 m

HC : 38.72 MA, OV : -24.40 MA, IV : -19.36 MA

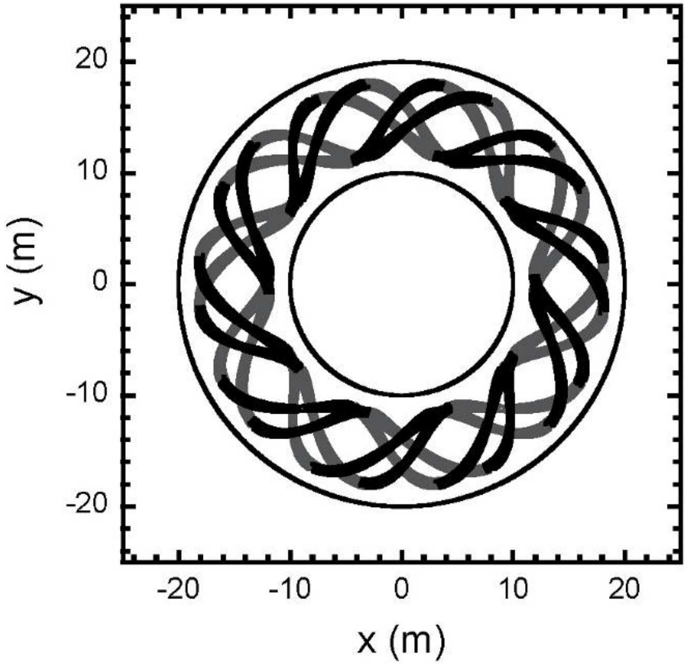
Stored magnetic energy = 177 GJ

Comparison of Coil Configurations

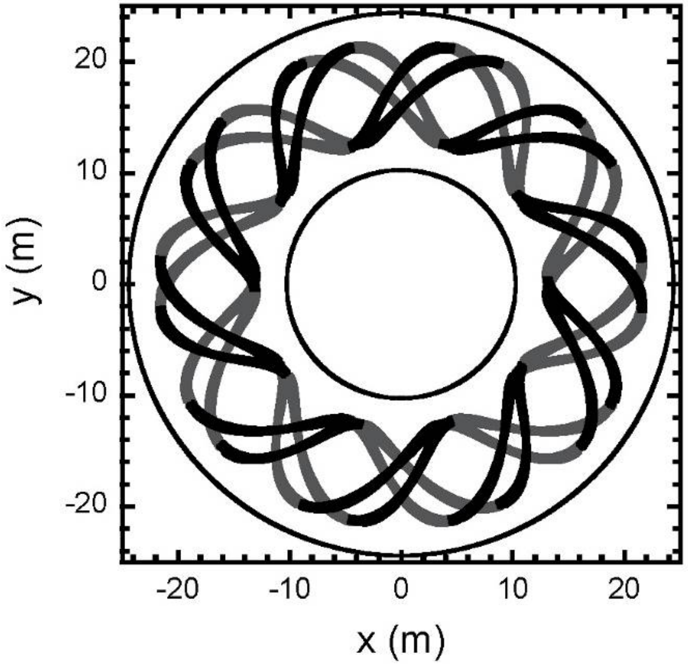
(a) FFHR-2m2 Type-D



(b) FFHR-2S Type-I



(c) FFHR-2S Type-II

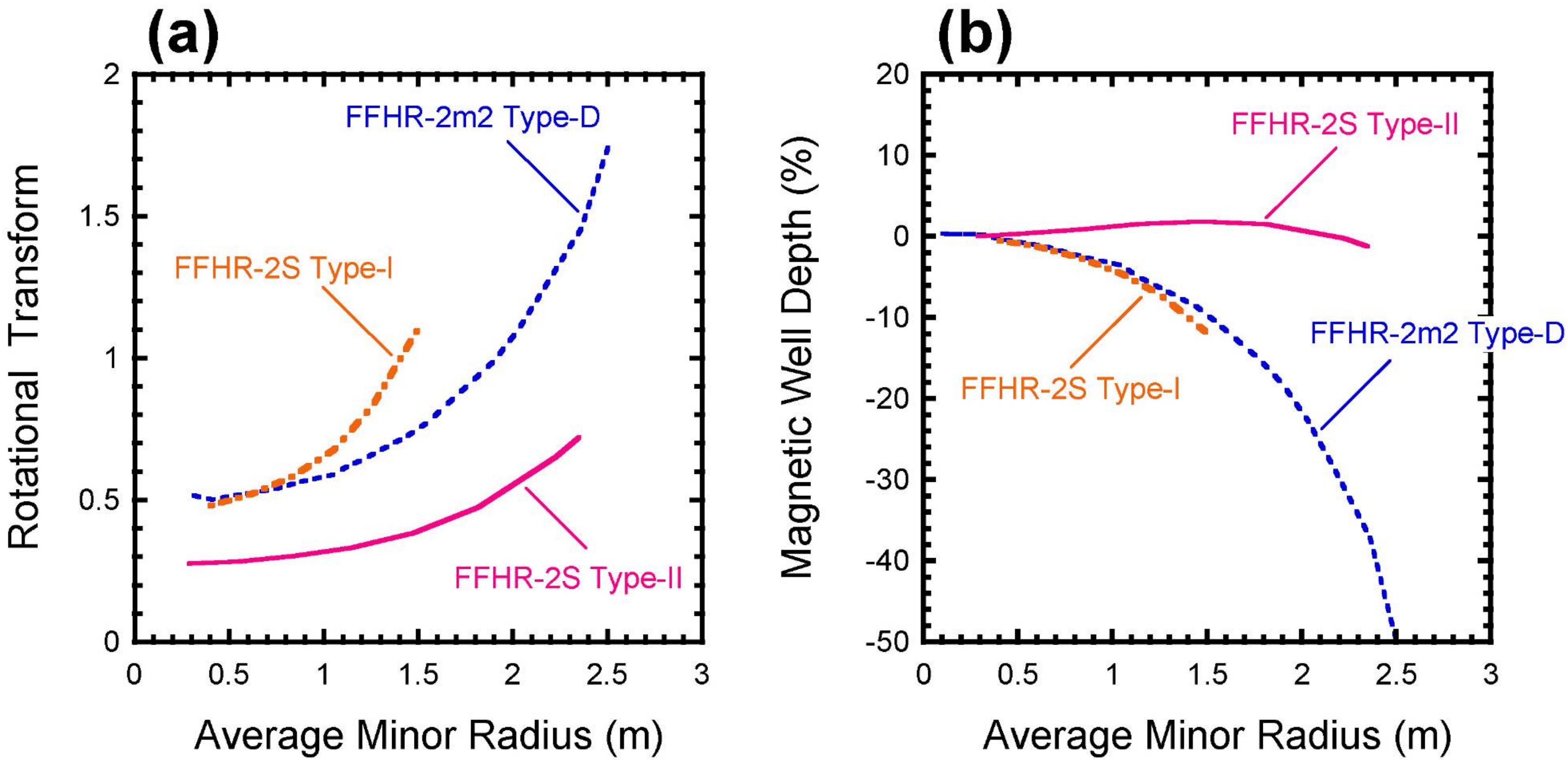


R_c = 17.33 m, a_p = 4.16 m,
γ = 1.20
B_{axis} = 4.84 T, a_p = 2.5 m
W = 145 GJ

R_c = 15.0 m, a_c = 3.0 m,
γ = 1.0
B_{axis} = 6 T, a_p = 1.5 m,
W = 165 GJ

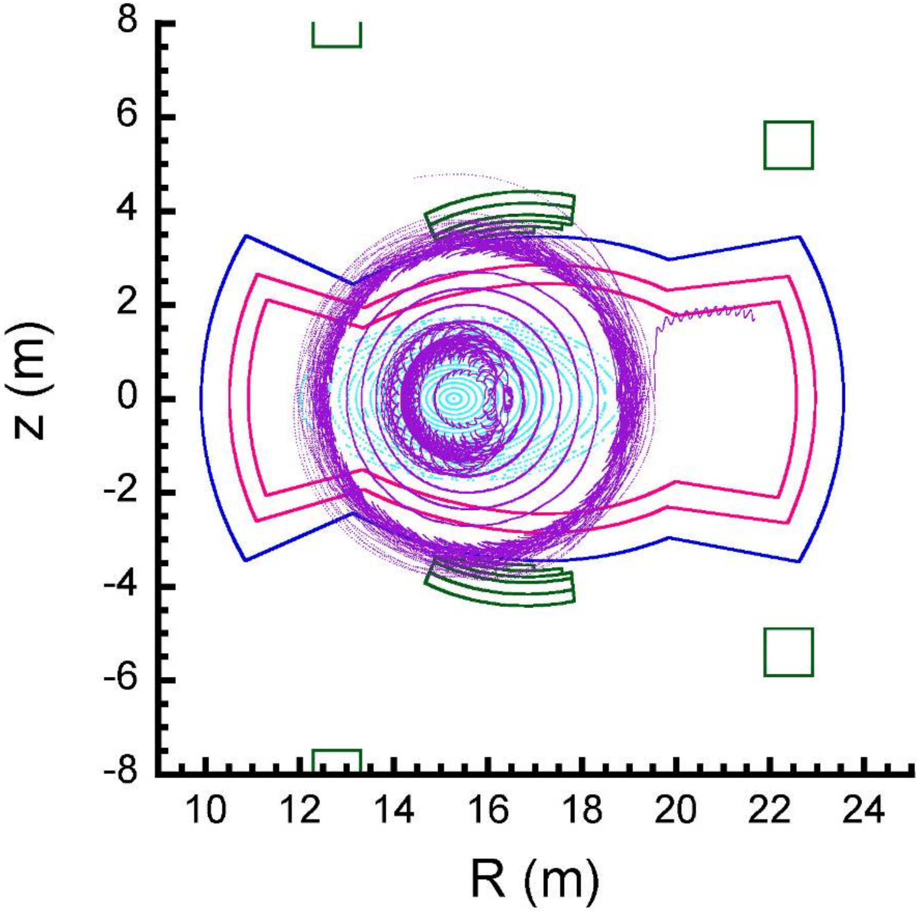
R_c = 17.33 m, a_c = 4.02 m,
γ = 1.2
B_{axis} = 4.3 T, a_p = 2.3 m,
W = 177 GJ

Comparison of Magnetic Field Properties

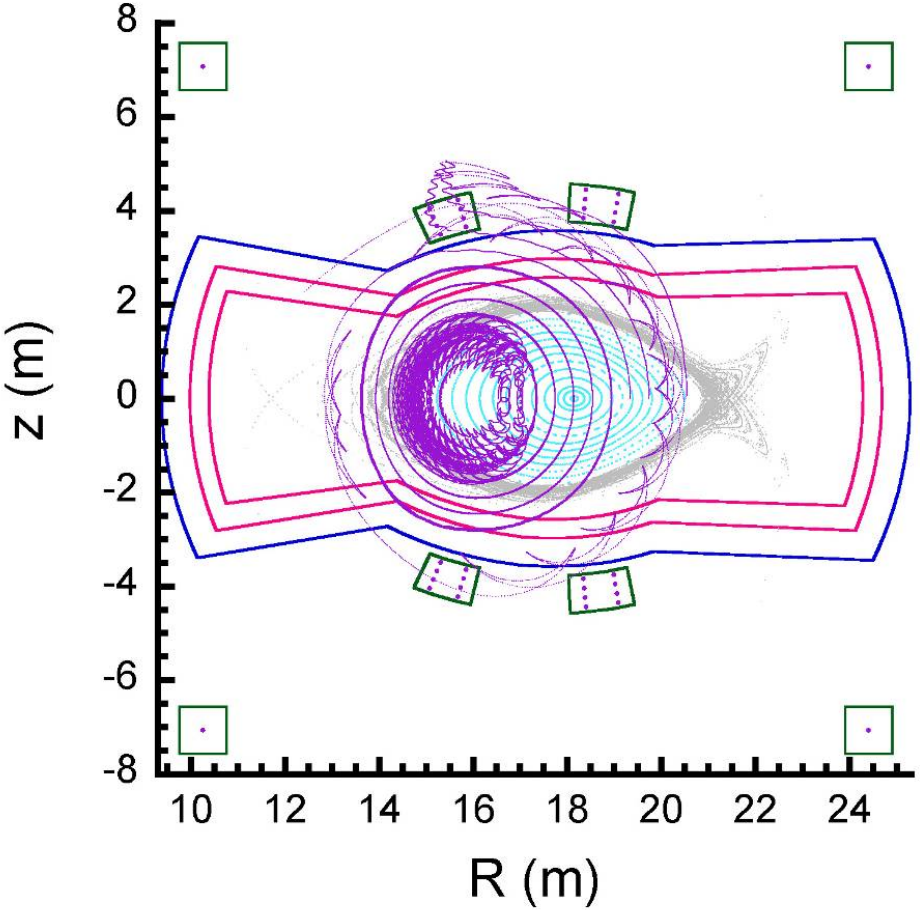


Comparison of Particle Orbits

FFHR-2m2 Type-D



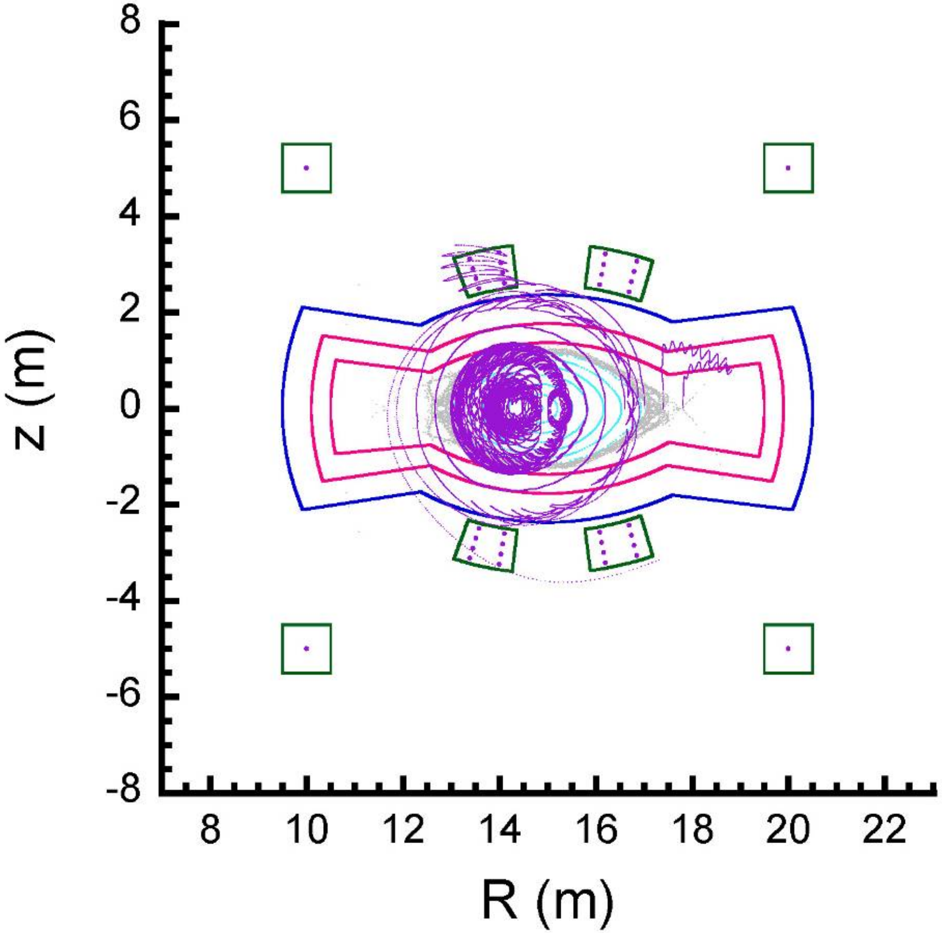
FFHR-2S Type-II ($\alpha = +0.1$)



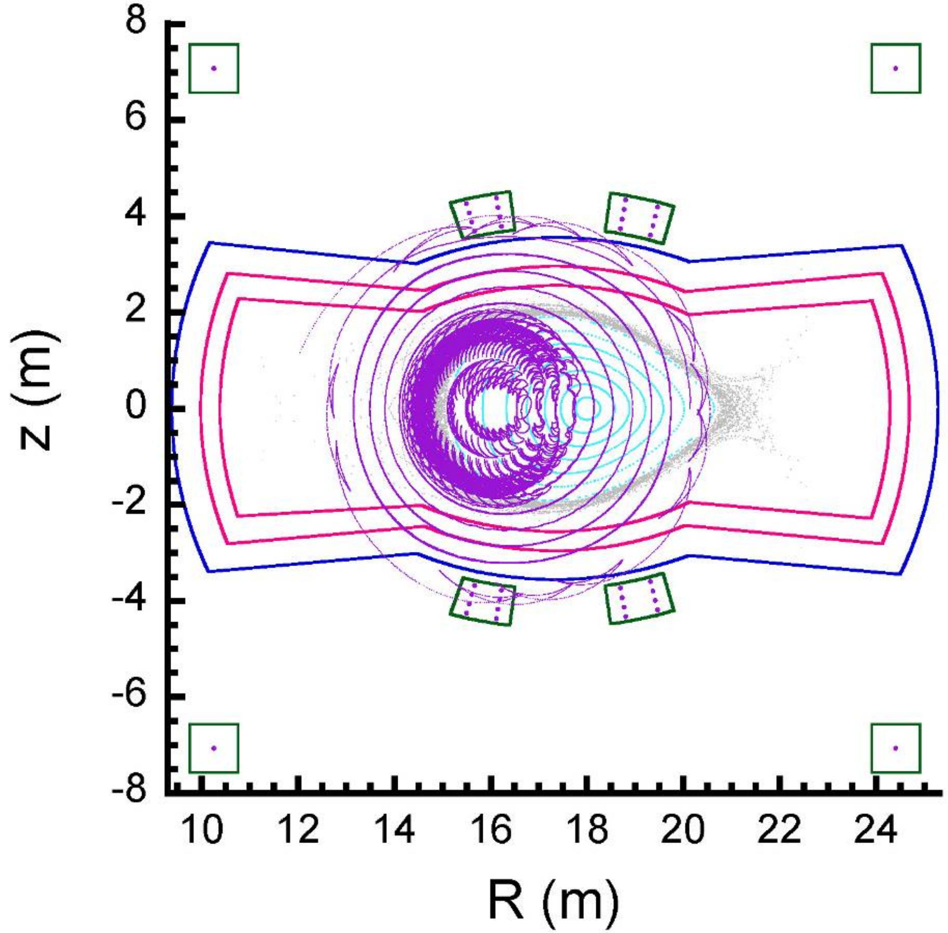
- **Drift orbits of alpha particles with 90 degrees pitch angle**
- **Good confinement with inward shifted configurations of FFHR-2m2**
- **Not good confinement with outward shifted configurations of FFHR-2S with a pitch modulation parameter $\alpha = +0.1$**

Comparison of Particle Orbits

FFHR-2S Type-I (α = 0)

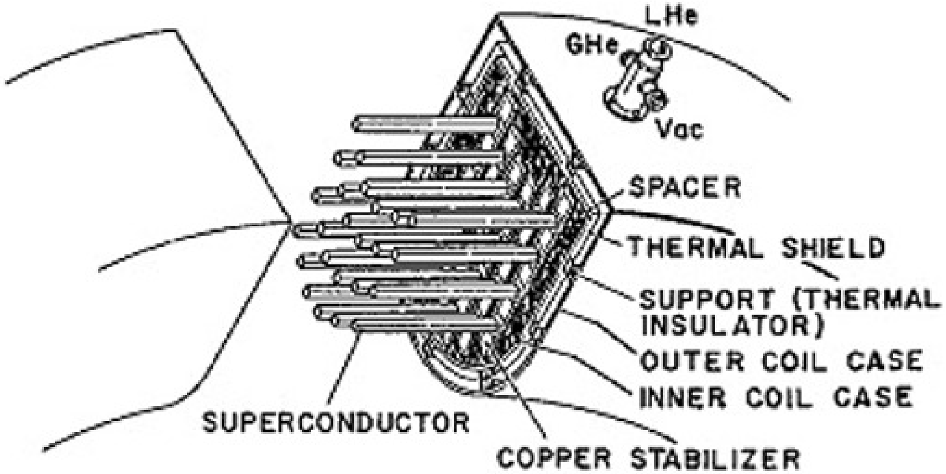


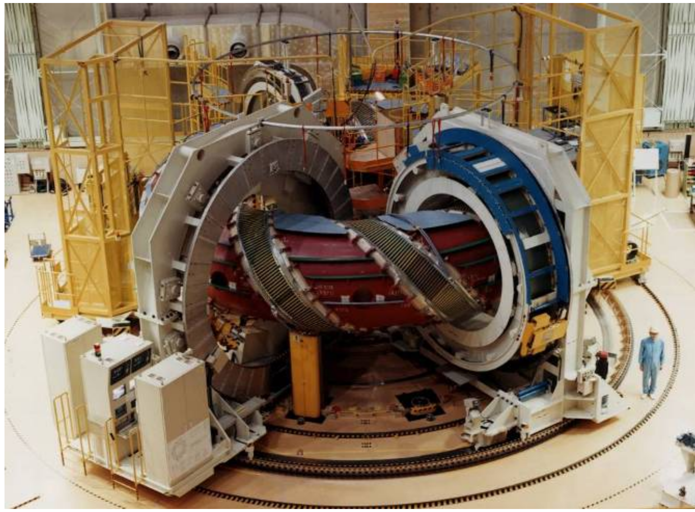
FFHR-2S Type-II (α = 0)



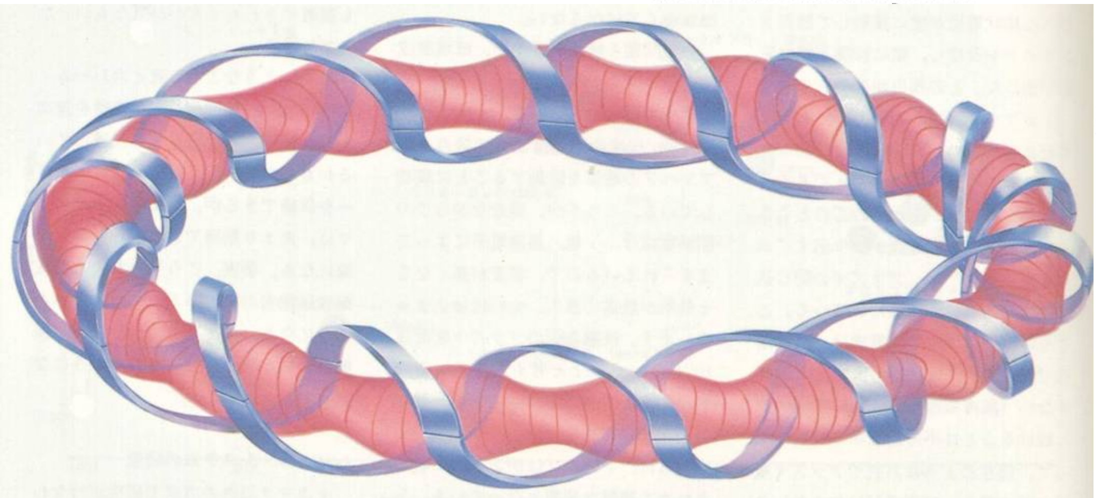
- **Confinement is improved for FFHR-2S with α = 0**
- **High-density core plasma might be heated by injecting ECH and/or neutral beams from the inboard side of the torus**

Proposal of Segmented Fabrication of Helical Coils





Winding Machine for the LHD Helical Coils (Continuous Conductors)



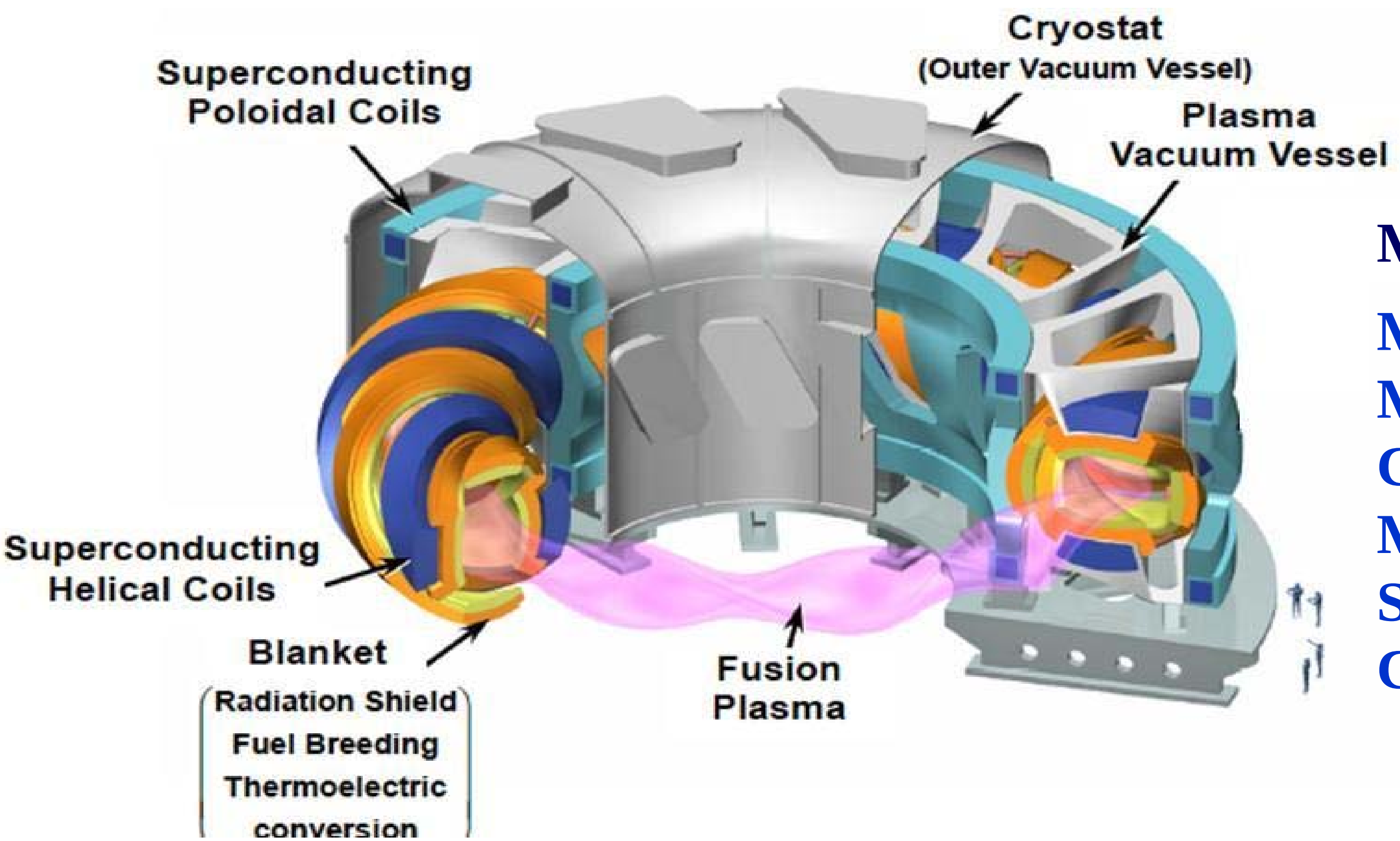
Concept of Demountable Helical Coils

K. Uo et al., Proc. 14th Symposium on Fusion Technology (1986) 1727-1732.

➔ Renewal of the idea with high-temperature superconductors (HTS)

H. Hashizume et al., *J. Plasma Fusion Res. SERIES* 5 (2001) 532.

LHD-type Fusion Energy Reactor FFHR



Main Parameters of FFHR

Major radius	14-18 m
Minor radius	3-4 m
Central field	4~6 T
Maximum field	<13 T
Stored energy	120-150 GJ
Conductor current	~100 kA

Options for SC Materials

LTS ➔ Nb_3Al, Nb_3Sn, V_3Ga

HTS ➔ REBCO
(RE-123 based coated-conductor; YBCO, GdBCO)

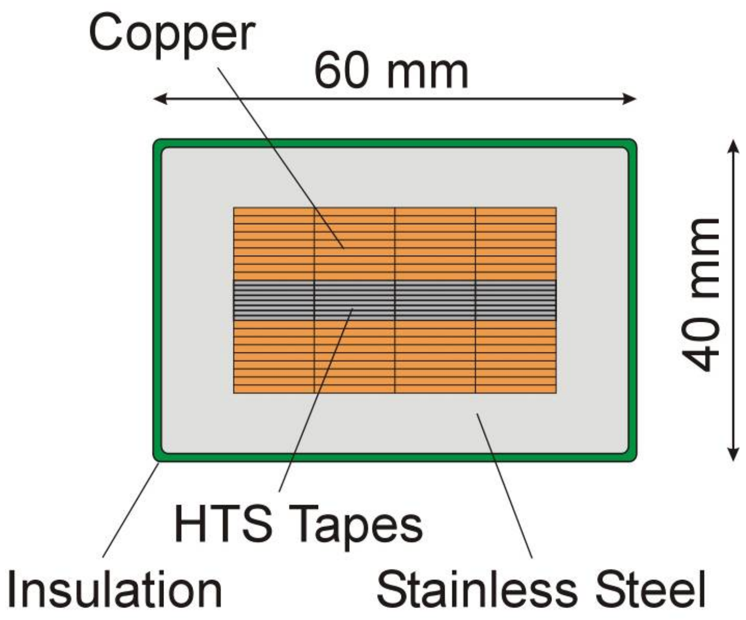
Options for Conductor Type and Cooling Method

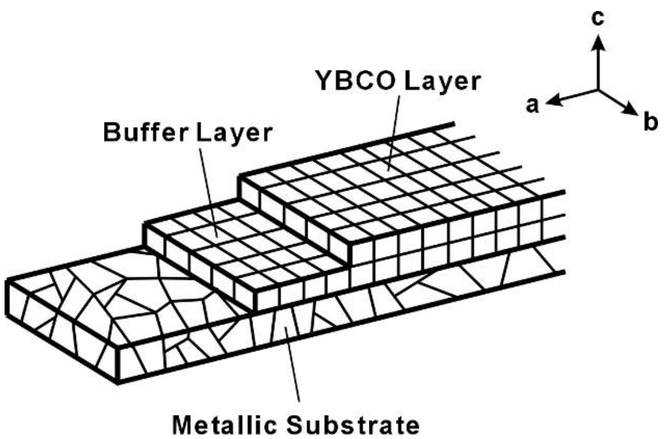
CICC (force-cooling) ➔ LTS (1st Option)

Solid (indirect cooling) ➔ LTS (2nd Option)

HTS (3rd Option)

Proposal of HTS Conductor for FFHR

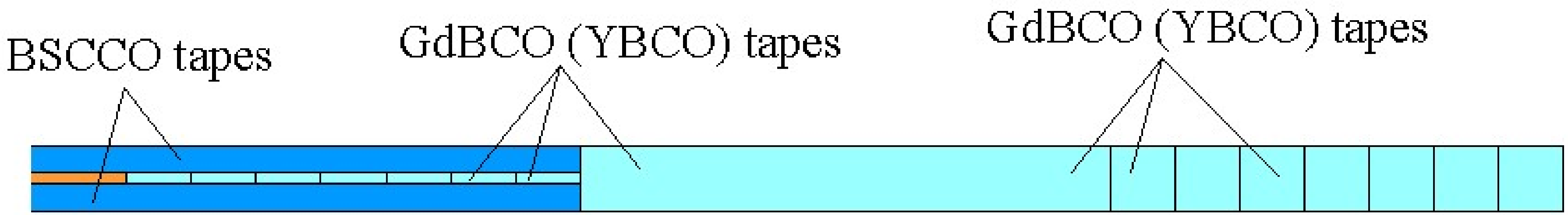


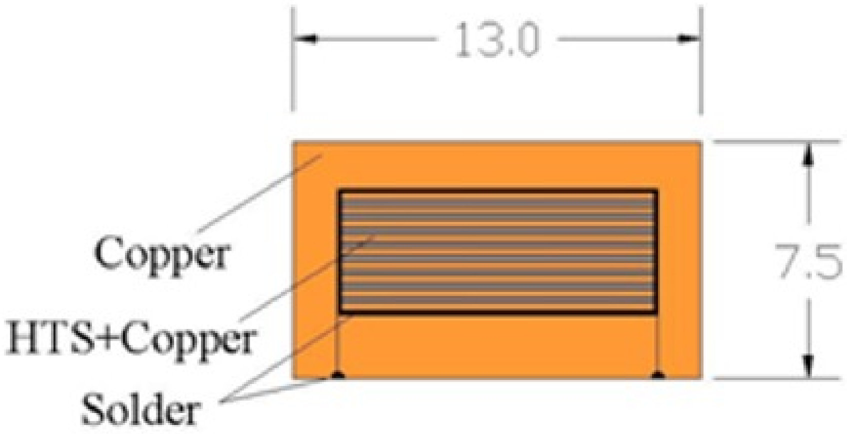


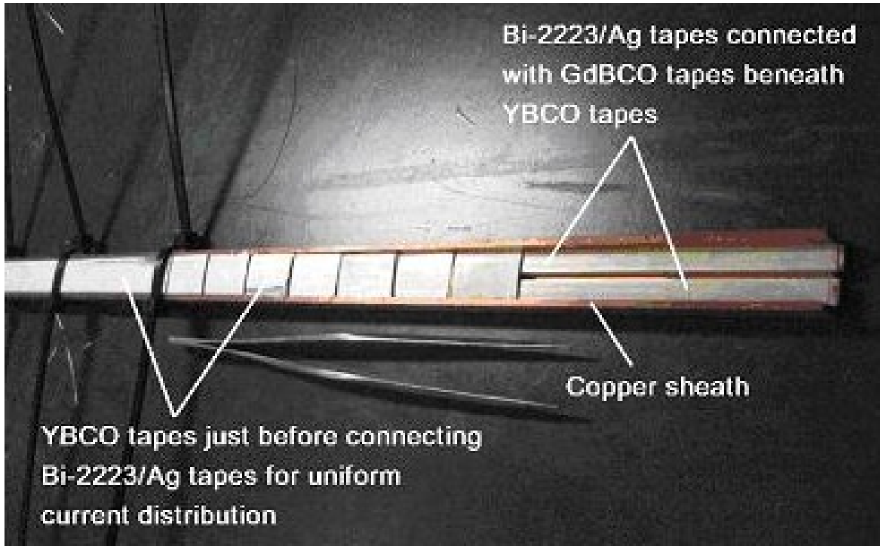
Major Specification of HTS Conductor

Superconductor	**REBCO**
Conductor size	**60 mm × 40 mm**
Operation current	**100 kA**
Maximum field	**~13 T**
Operation temperature	**20 – 30 K**
Current density	**~40 A/mm^2**
Number of HTS tapes	**100**
Bending strain	**0.4% (Conductor)** **0.05% (HTS part)**
Maximum hoop stress	**~370 MPa**
Copper to HTS ratio	**7.0**
Outer jacket	**S.S. or Al-alloy**
Cooling method	**Indirect cooling**

10 kA-Class HTS Conductor (YBCO & GdBCO)

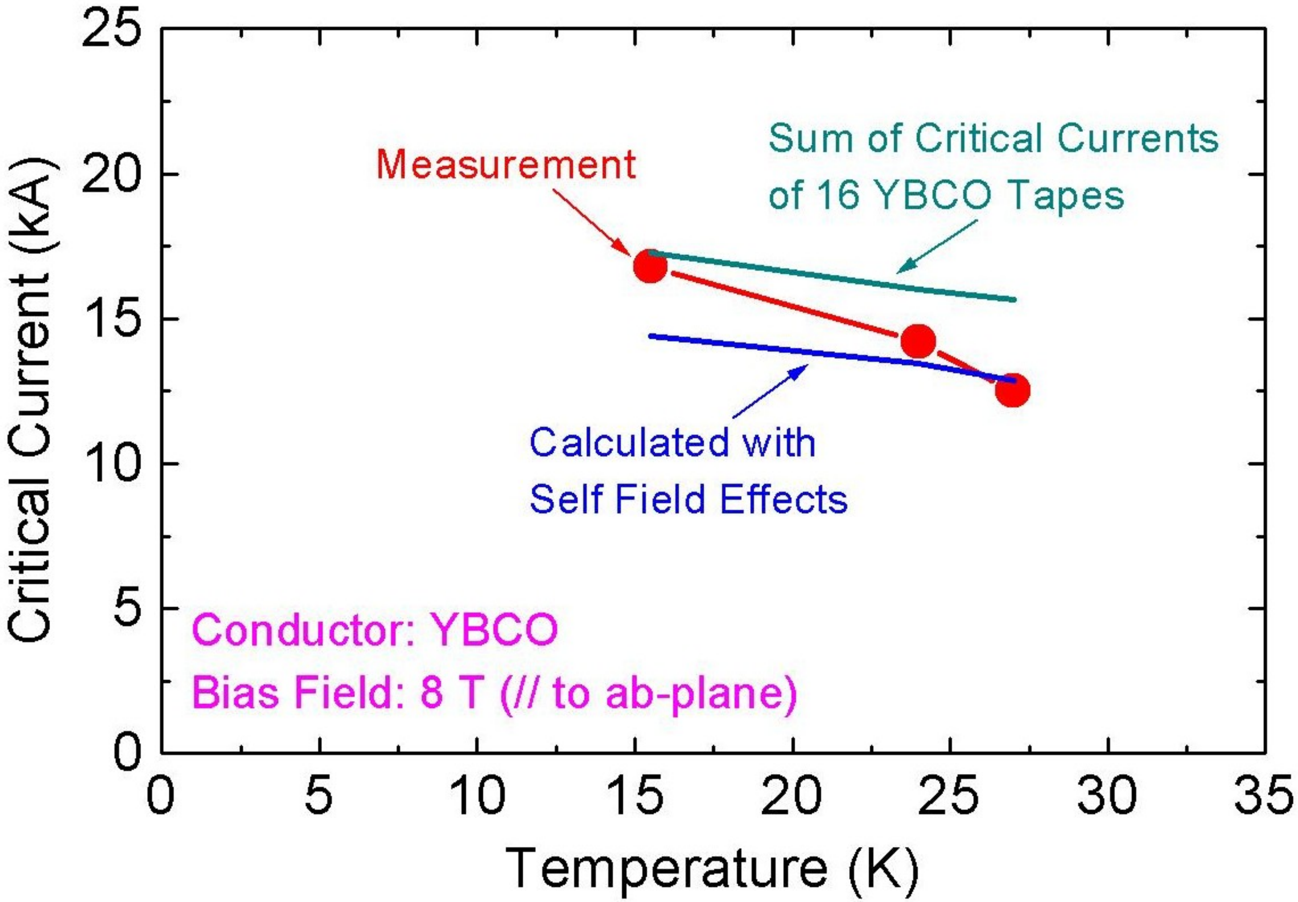


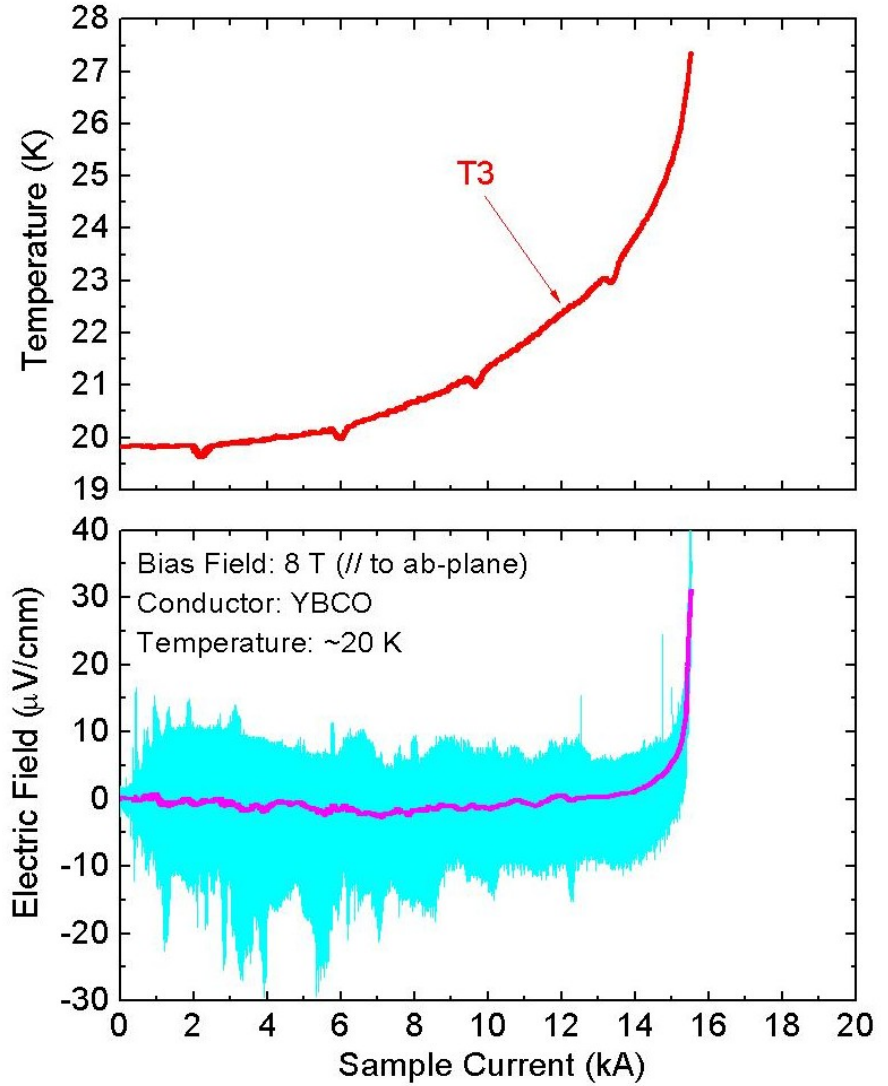




Superconductor	**YBCO & GdBCO**	
Conductor size	**13.0 mm × 7.5 mm**	
Critical current of a tape	**210 A (YBCO)**	
(@77 K, s.f.)	**190 A (GdBCO)**	**➔700 A for recent short samples**
Width / thickness of a tape	**10 mm / 0.1 mm**	
Thickness of REBCO layers	**~1 μm**	**➔ ~3 μm**
Supplier	**ISTEC-SRL**	
Number of HTS tapes	**16**	**➔ > 50 kA**
Critical current at 20 K	**15 kA (20 K, 8 T)**	

Temperature Dependence of Critical Current

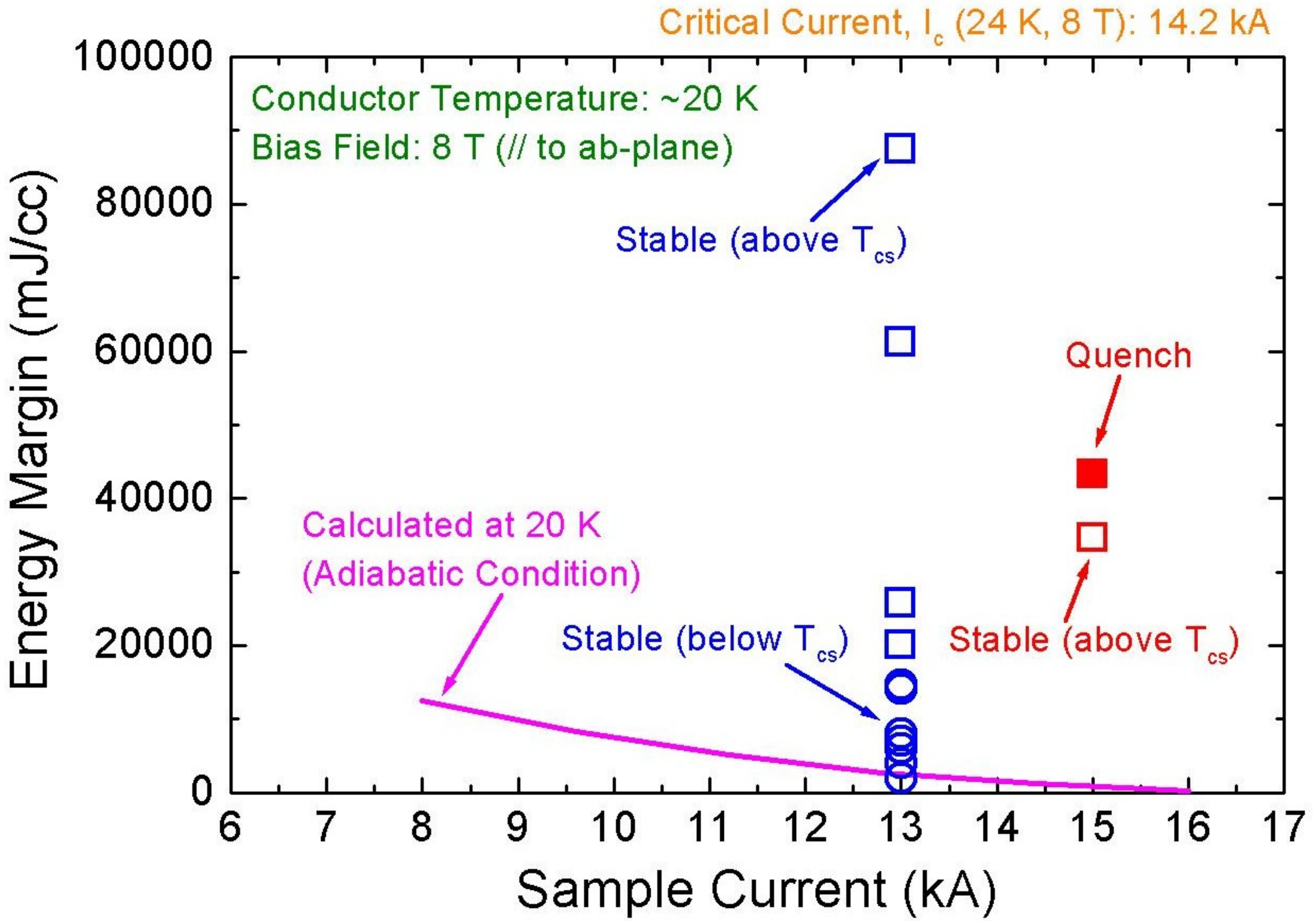


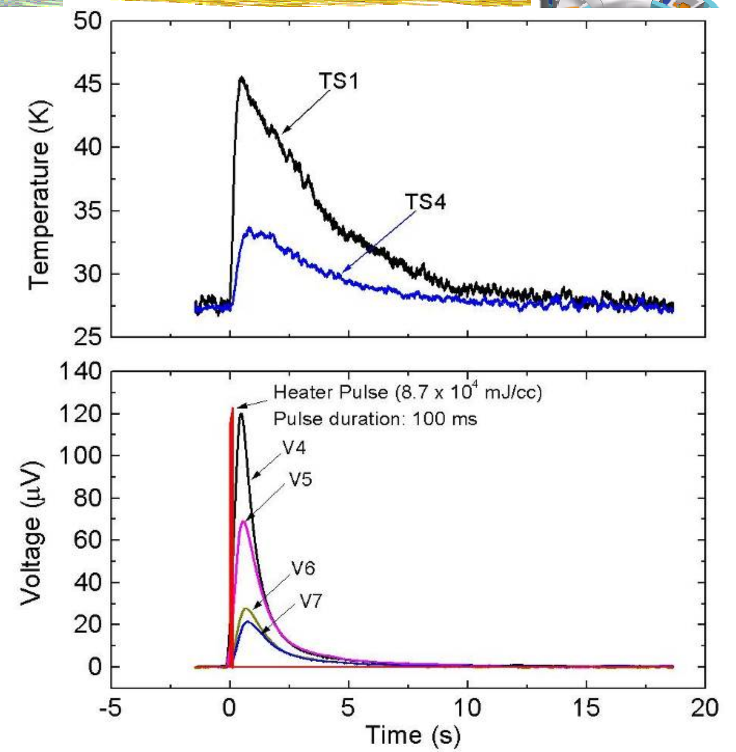


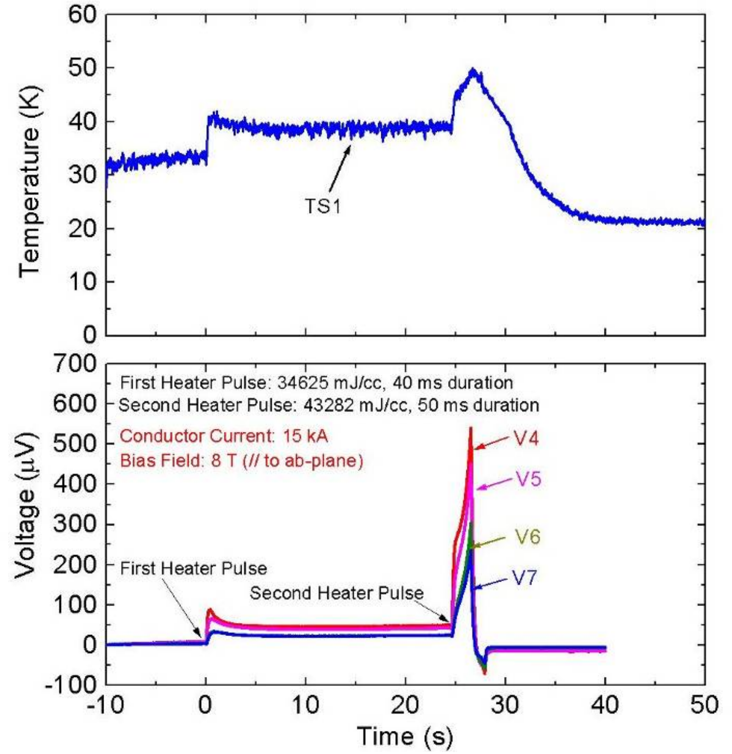
● **Critical current was measured with bias magnetic field. Measurement error was relatively big due to the electrical noise and insufficient temperature control.**

➔ **Second experiment is being planned in 2009**

Stability Tests

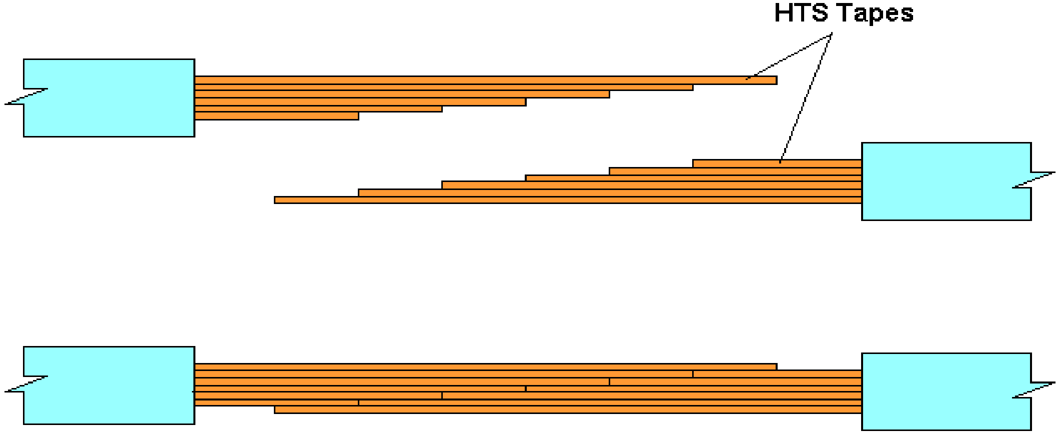


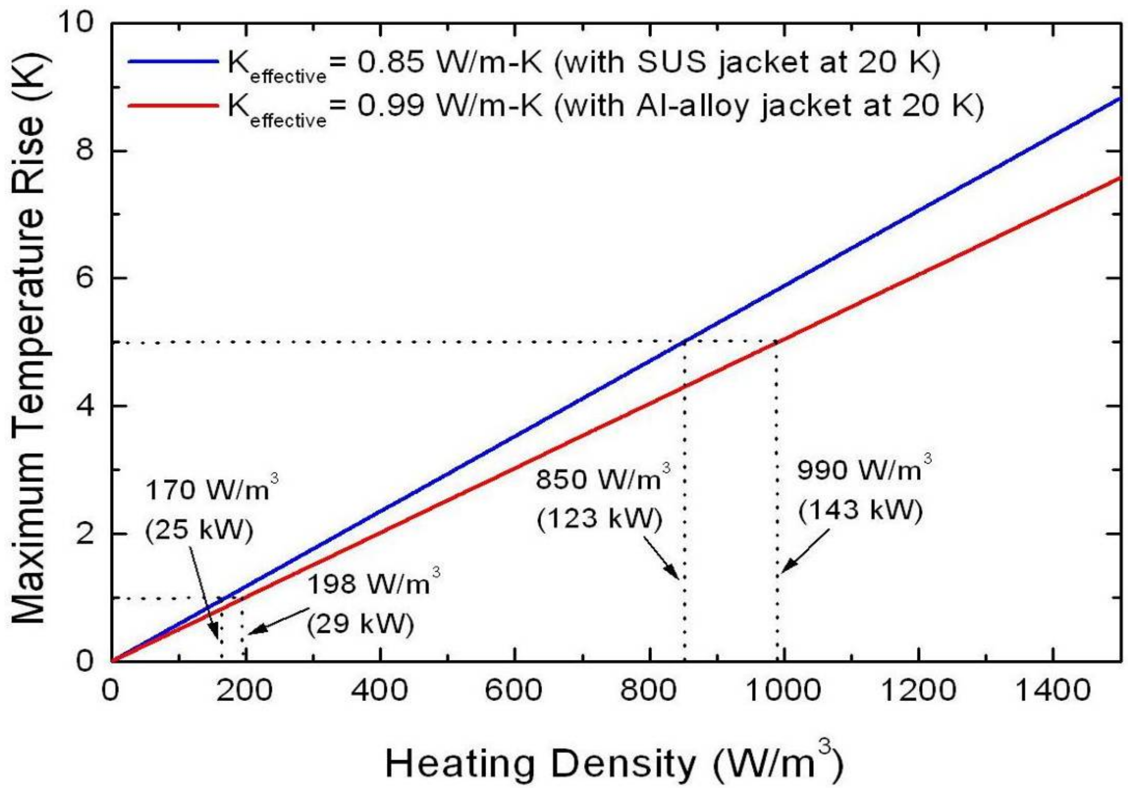


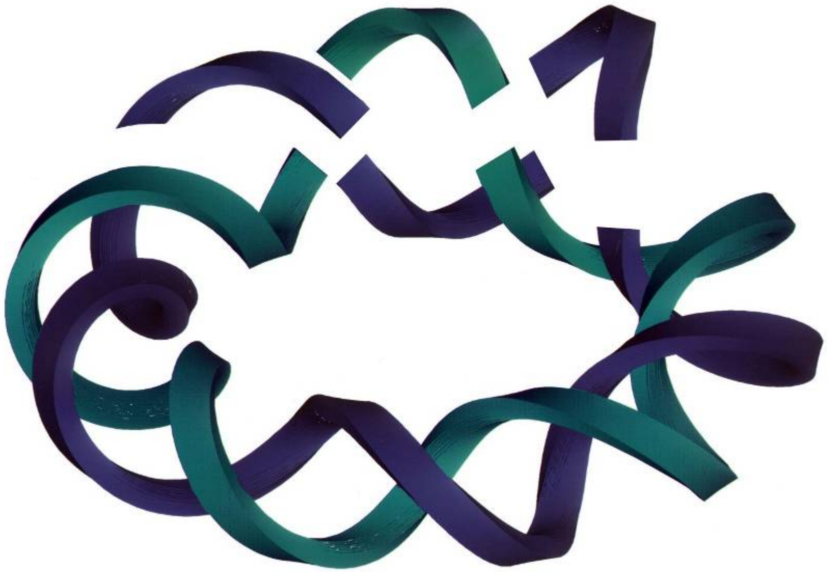


- **Stability margin was confirmed to be 2 orders of magnitude higher than that of LTS large-scale conductors.**

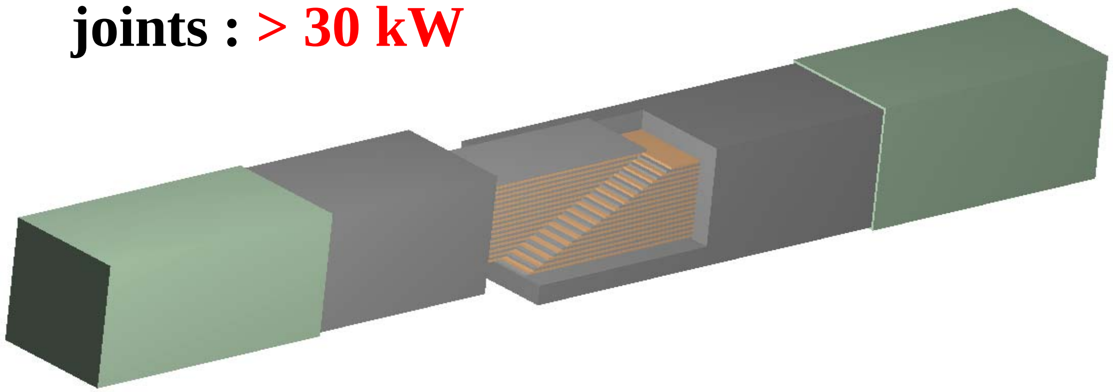
Required Refrigeration Power for Joints



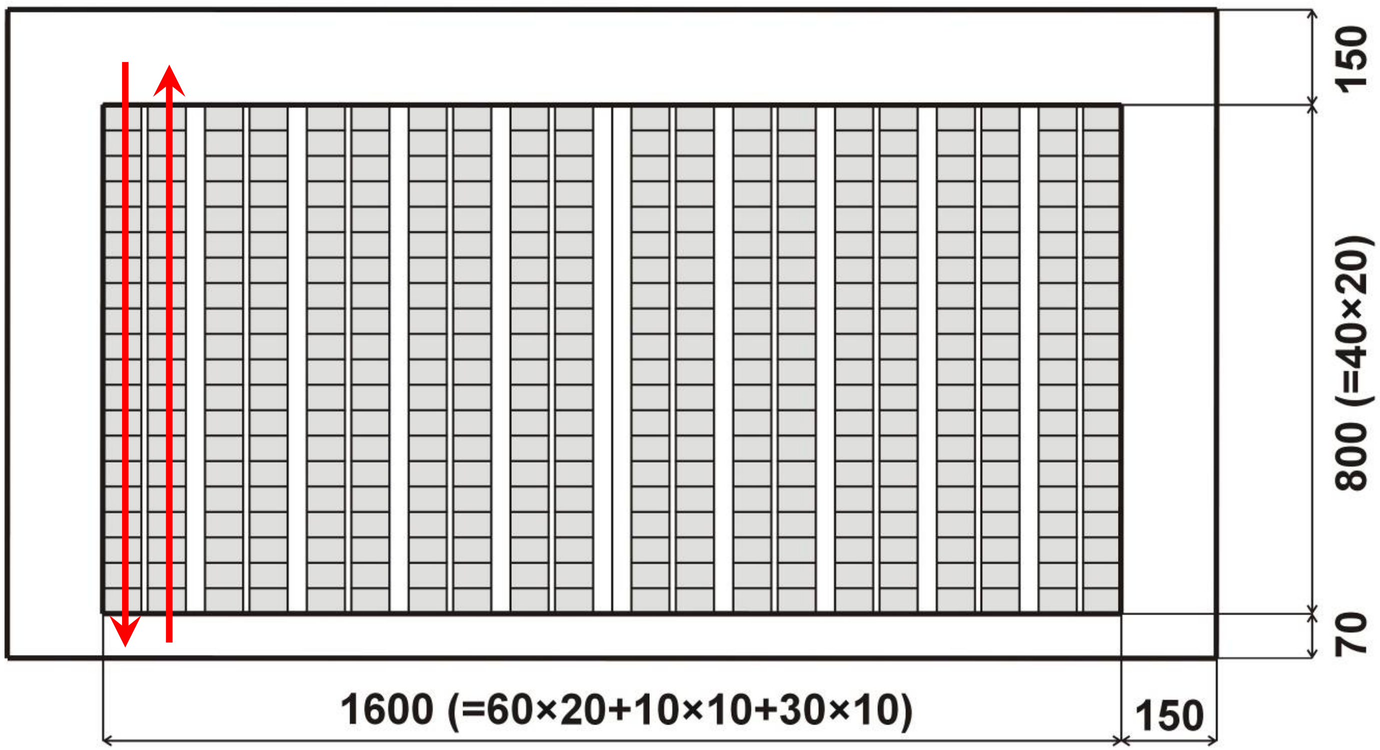


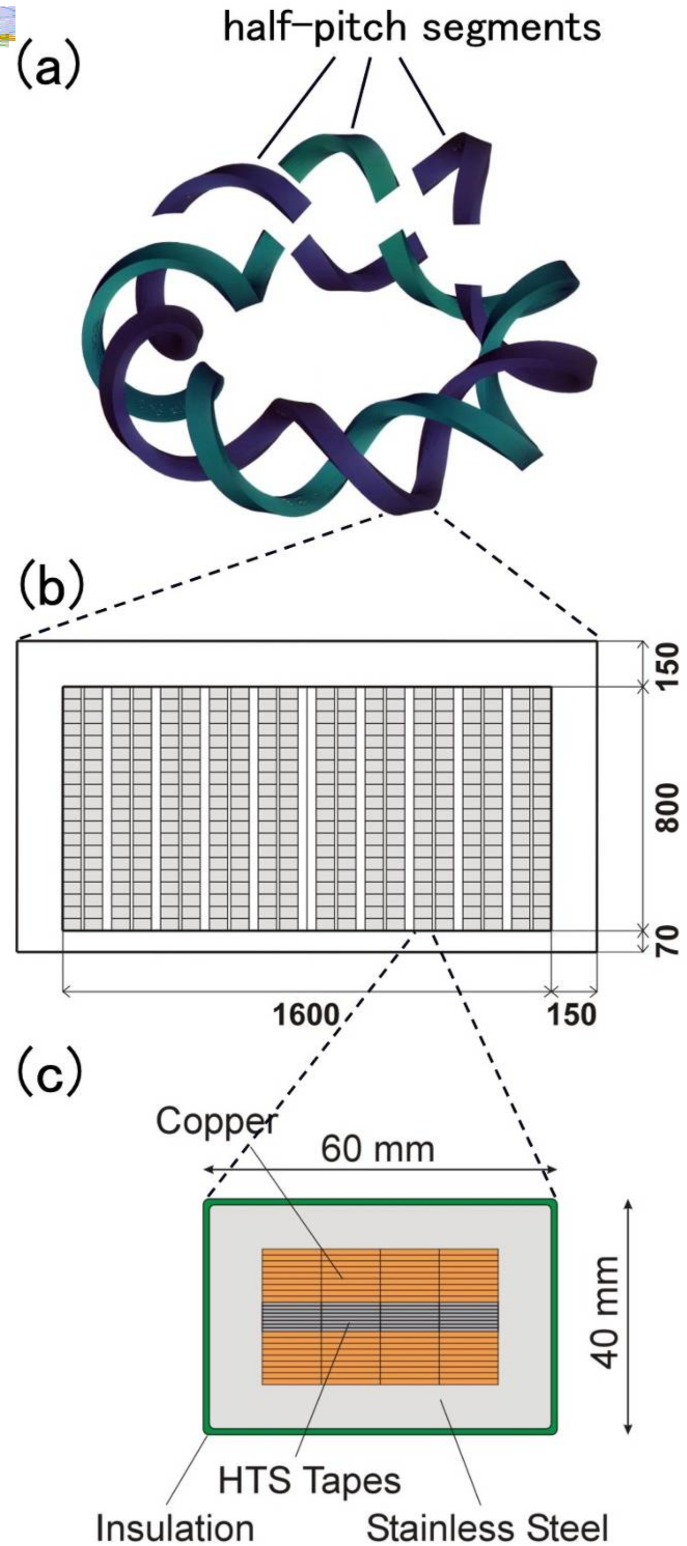


Joint resistance : > 0.06 nΩ
Additional refrigeration power for 8000 joints : > 30 kW



Double-pancake windings of helical coils using HTS conductors



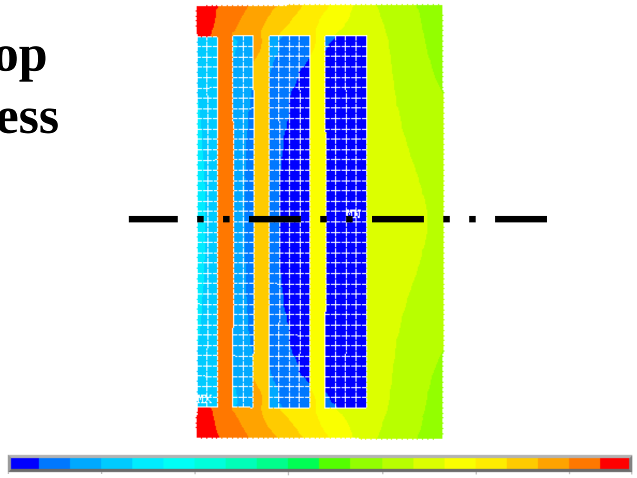


- Ten double pancakes (400 turns of conductors)
- Windings : 1600 mm × 800 mm ($j = 30$ A/mm^2)
- Thinner top cover and addition of bottom plate
- Divided into ten blocks for protection
- Possible to apply only with segmented fabrication

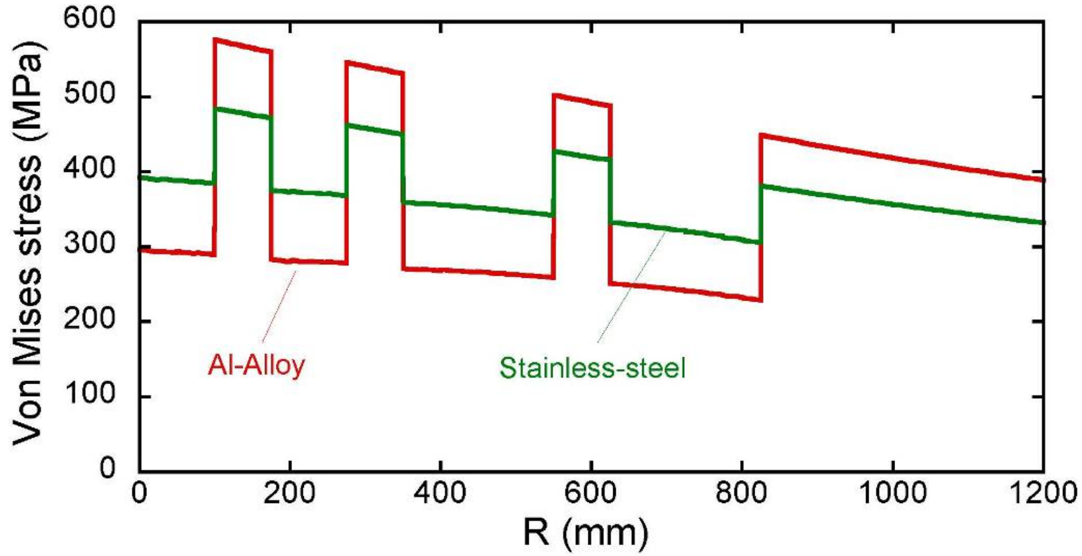
Mechanical Analysis of Stresses inside the Helical Coil Pack (using ANSYS)

(by Romain Champailler)

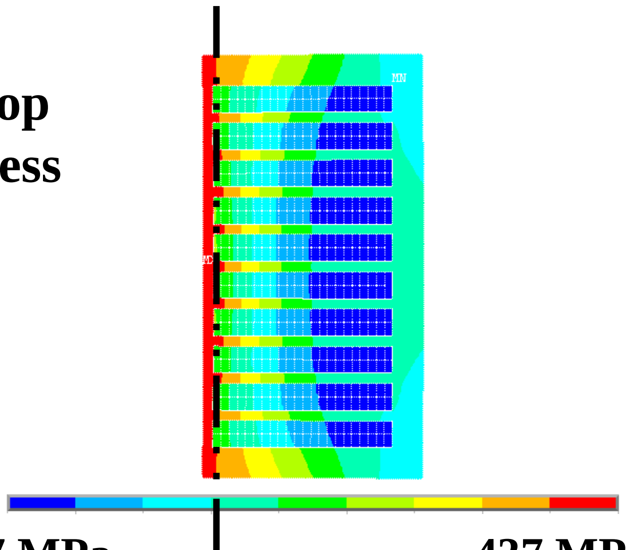
Hoop Stress



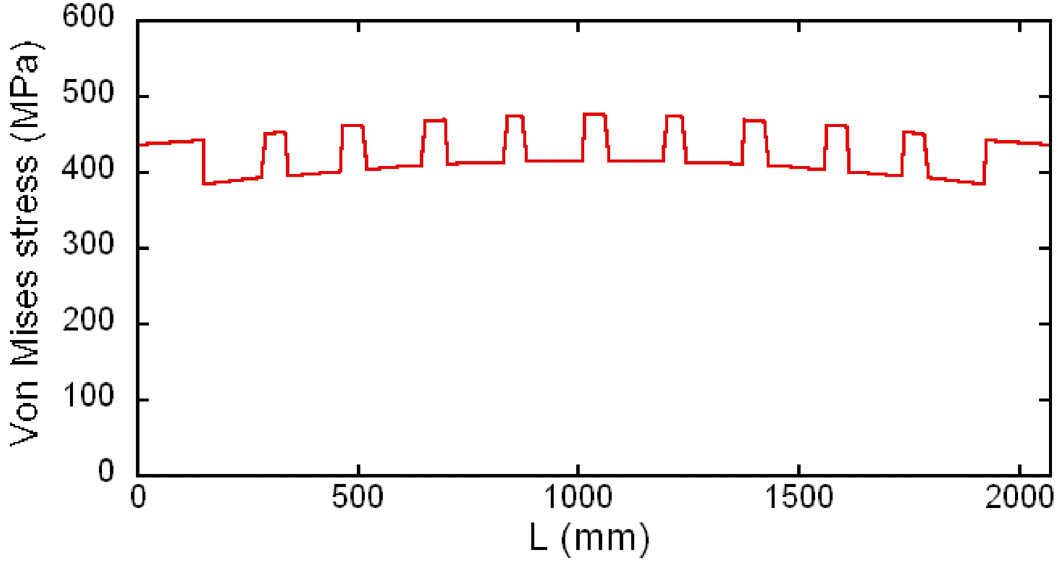
195 MPa **491 MPa**



Hoop Stress



297 MPa **437 MPa**



Summary

- **Split-type helical coils possess remarkable features for configuration optimization of heliotrons**
  - Type-I : Smaller major radius, higher field, lower weight
  - Type-II : Larger minor radius with magnetic well
  - Drift orbits of deeply trapped particles can be improved by lowering helical pitch modulation parameter ($\alpha = 0$)
- **Segmentation of helical coils with HTS conductors is feasible**
  - Simple stacking of REBCO HTS tapes for 100 kA conductors
  - 10 kA-class conductor samples were successfully tested
  - Helical coils might be assembled with half-pitch modules
  - Double-pancake windings can be applied with segmented fabrication