Heat Flux Reduction by HTS Helical Divertor Coils in the Heliotron Fusion Energy Reactor

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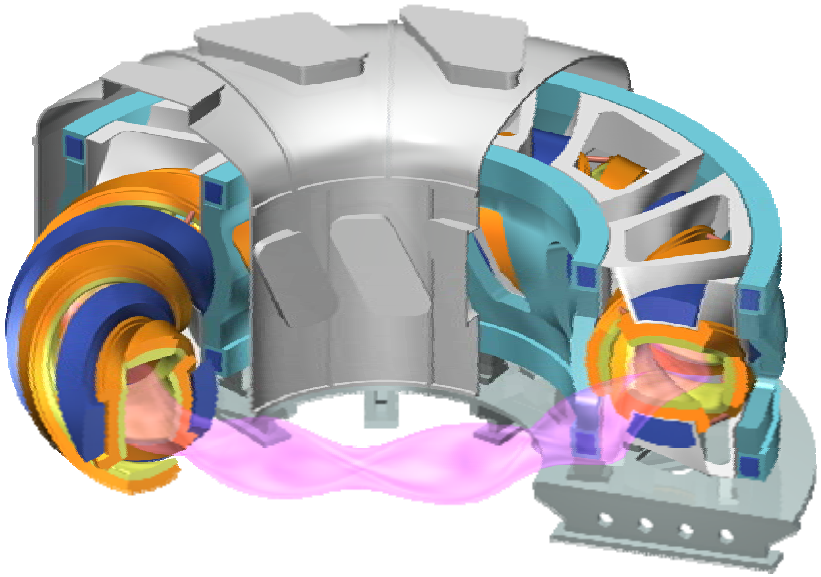
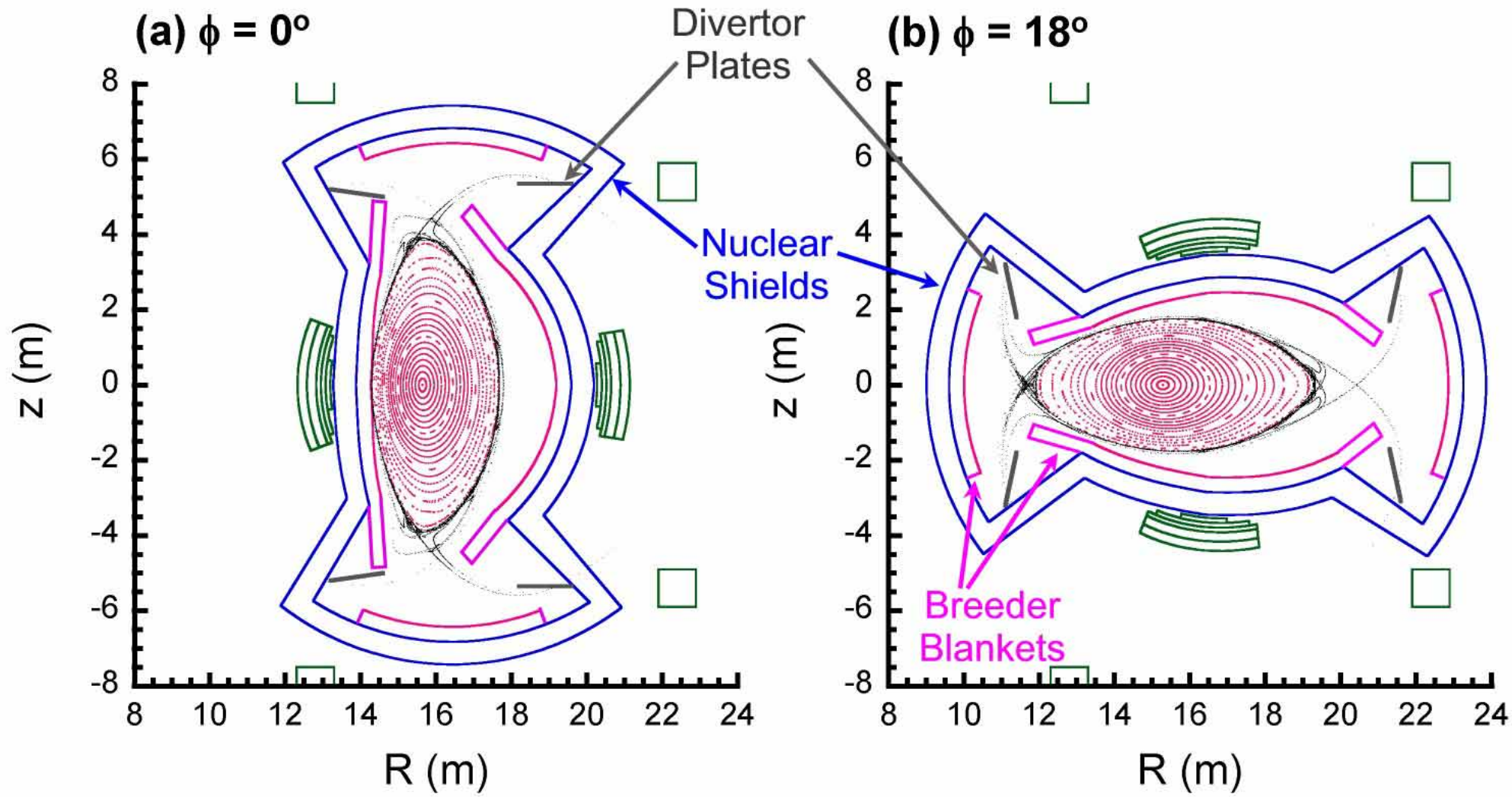
Heliotron Fusion Energy Reactor FFHR



Major Specifications of FFHR-2m2

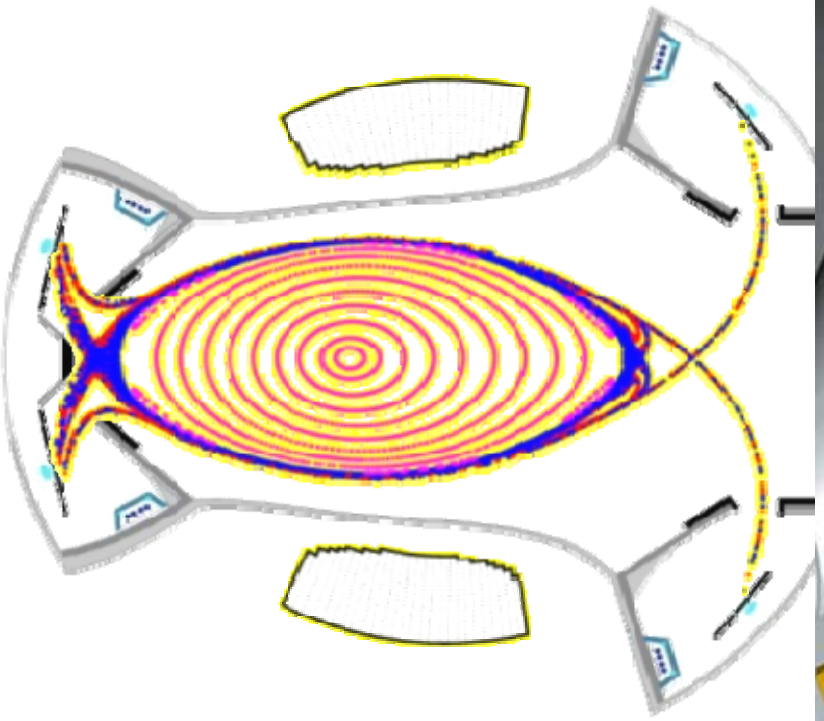
Major / minor radius of helical coils	17.0 / 4.08 m
Helical pitch parameter, γ	1.20
Toroidal magnetic field	5.1 T
Stored magnetic energy	160 GJ
Major / minor radius of plasma	15.7 / 2.5 m
Plasma volume	1970 m^3
Fusion power	3 GW
Neutron wall load	1.5 MW/m^2
Average beta	5.6 %
Confinement improvement factor from LHD	1.3

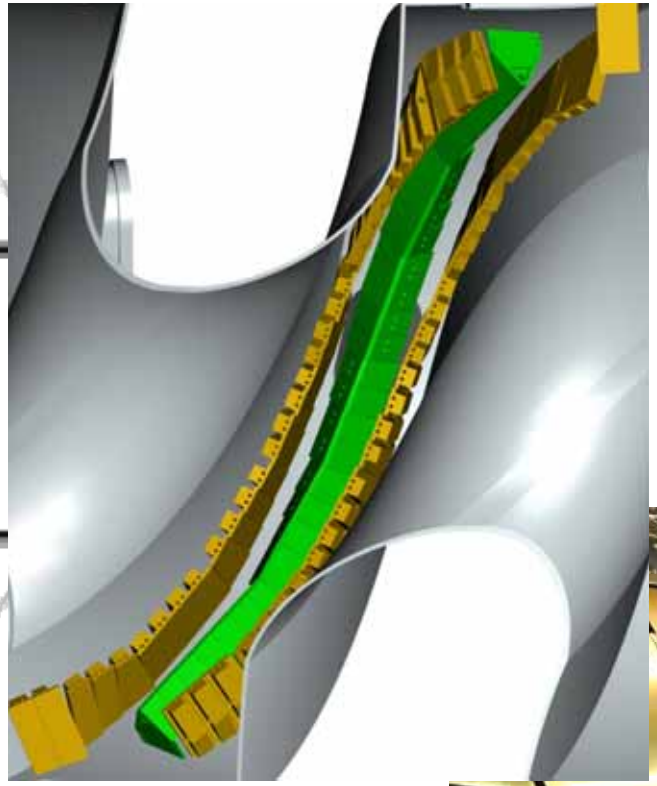
Vacuum Magnetic Surfaces of FFHR-2m2



- Heliotron configuration possesses built-in helical divertors with four clear legs
- Divertor tiles are protected by blankets from direct irradiation of neutrons
- Divertor heat flux (~10 MW/m^2) is as severe as that in tokamaks
  - ➔ Detached plasma should be realized to reduce the heat flux

Upgrade of Closed Divertor in LHD





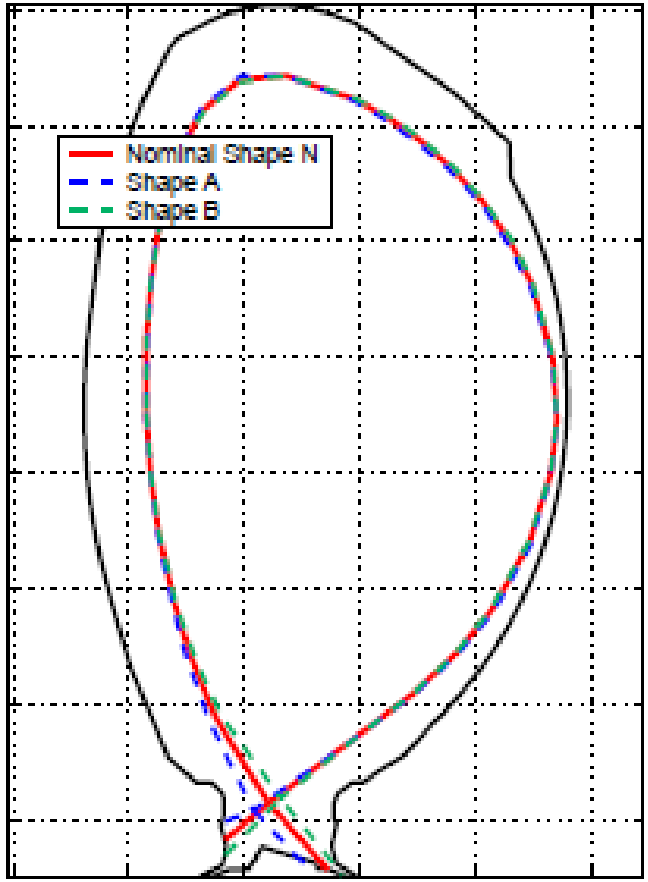
Courtesy of S. Masuzaki & M. Shoji

Closed divertor

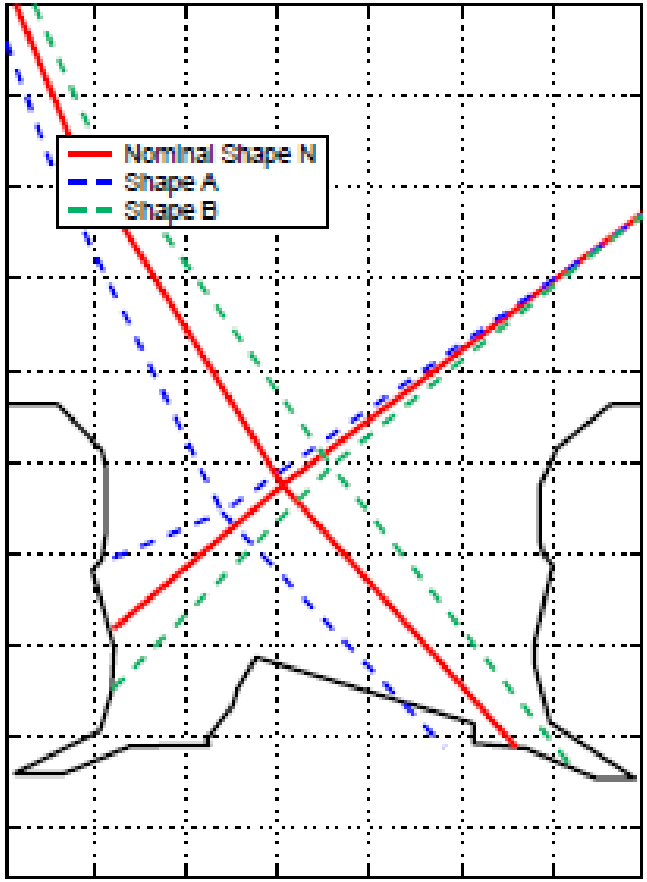
Upgraded in 2010 (14th exp. campaign)

Two inboard sections (without cryo-pump)

Divertor Sweeping in JET



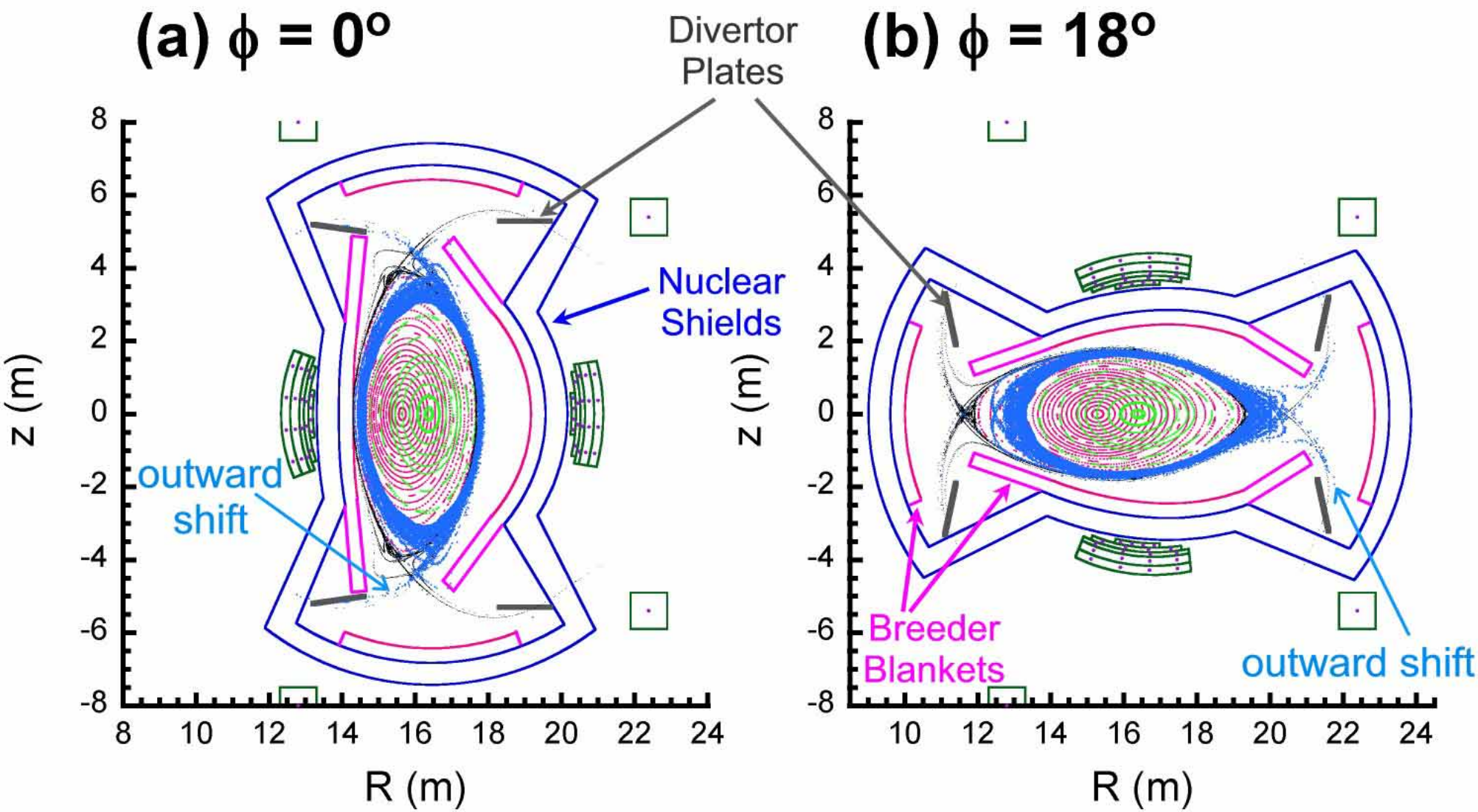
(a) Nominal and varied shapes.



(b) Divertor region.

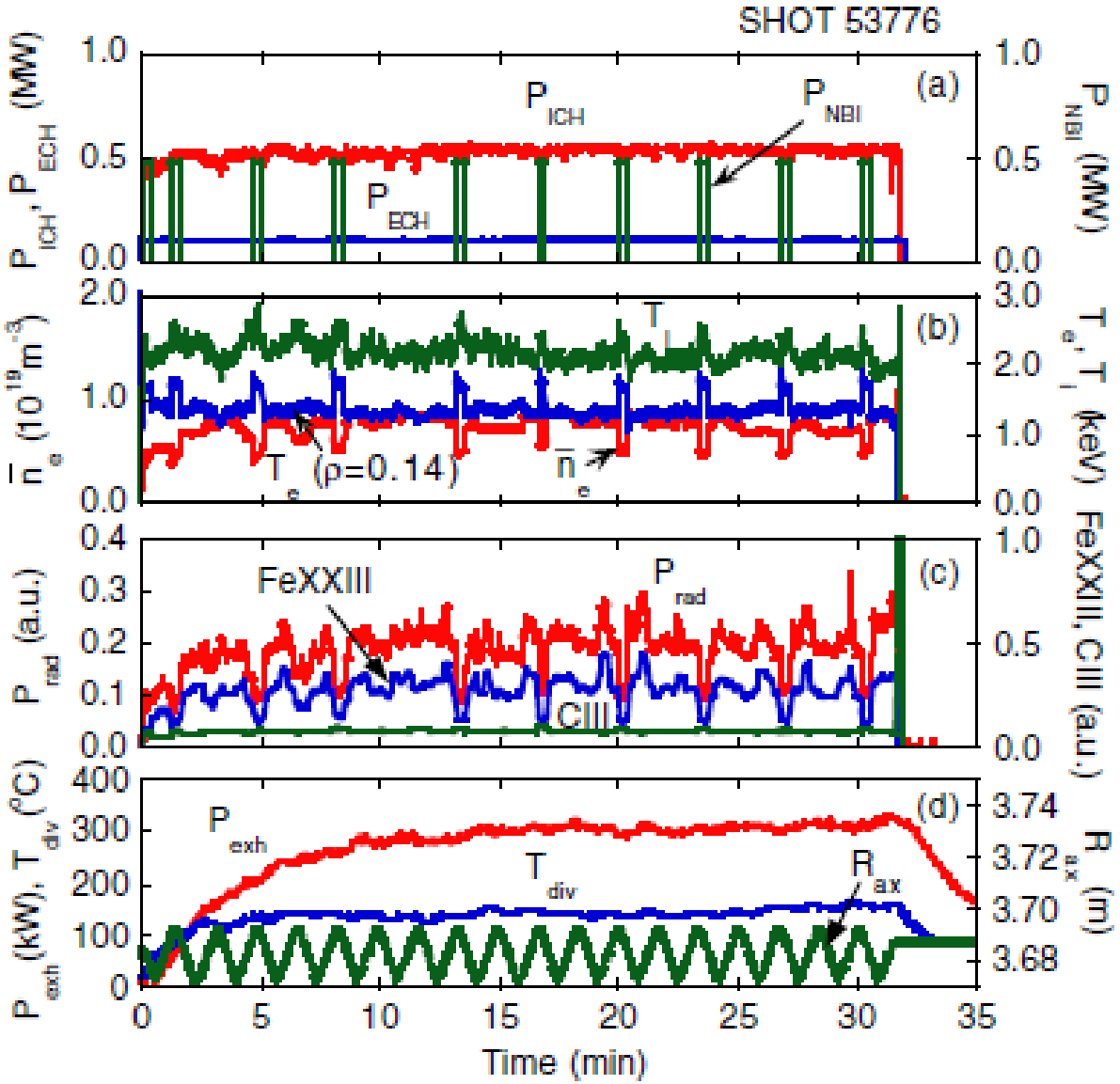
A. Pironti et al., "A new algorithm for strike-point sweeping at JET",
34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007
ECA Vol.31F, P-5.116 (2007)

Divertor Sweeping with Magnetic-Axis Shift



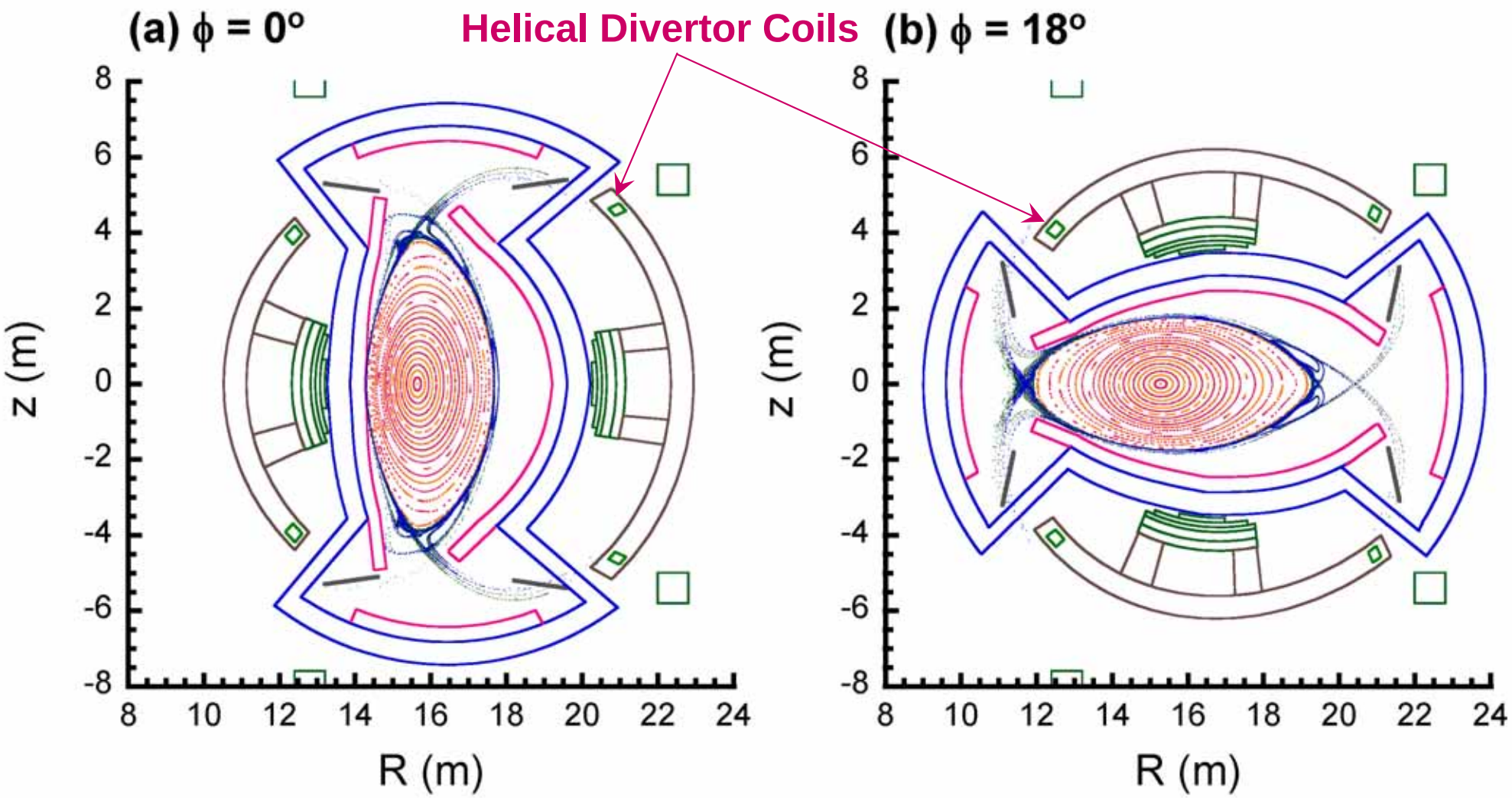
- Y. Nakamura et al., "Impact of real-time magnetic axis sweeping on steady state divertor operation in LHD", Nuclear Fusion 46 (2006) 714–724.
- Large shift of magnetic axis ➔ Fluctuation of fusion power, AC losses in the main coils

Divertor Sweeping with Magnetic-Axis Shift (LHD)



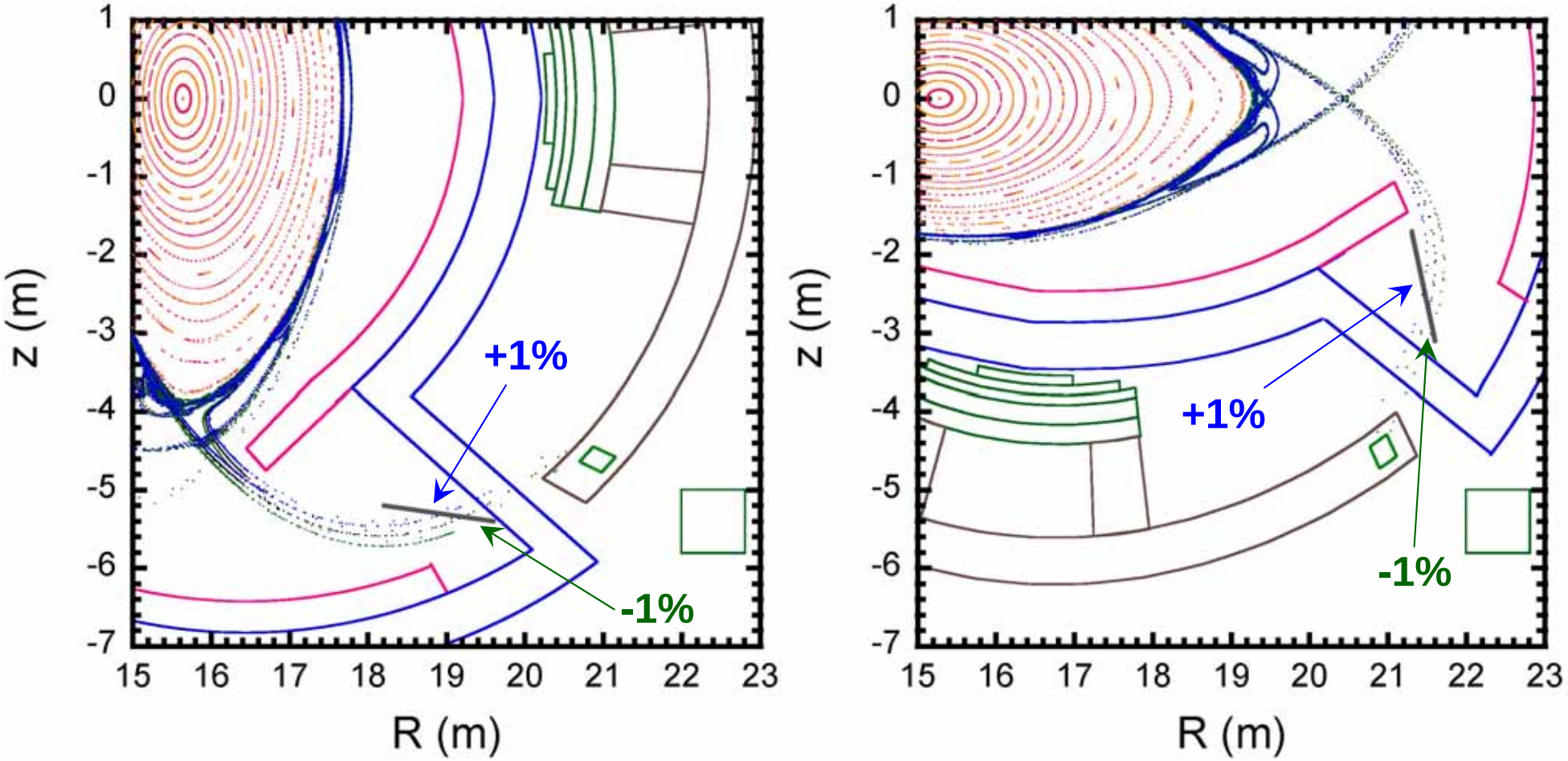
➢ **Y. Nakamura et al., "Impact of real-time magnetic axis sweeping on steady state divertor operation in LHD", Nuclear Fusion 46 (2006) 714–724.**

Divertor Sweeping with Helical Divertor Coils



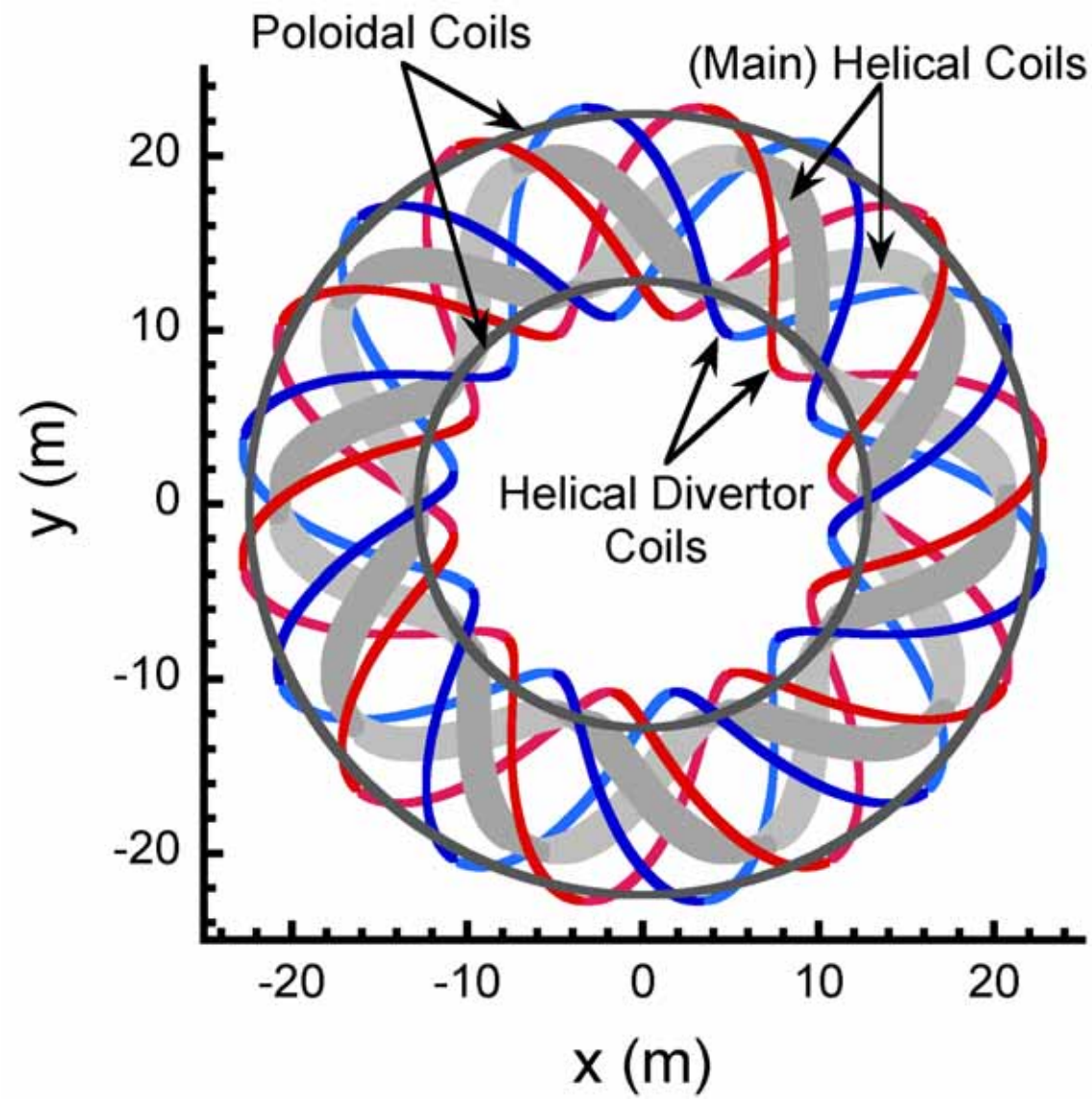
- Strike points on divertor plates are effectively swept with AC operations of "Helical Divertor Coils" with 1-2% amplitude of main helical coil currents
- Magnetic surfaces (and the main plasma) are not affected by divertor sweeping

Divertor Sweeping with Helical Divertor Coils

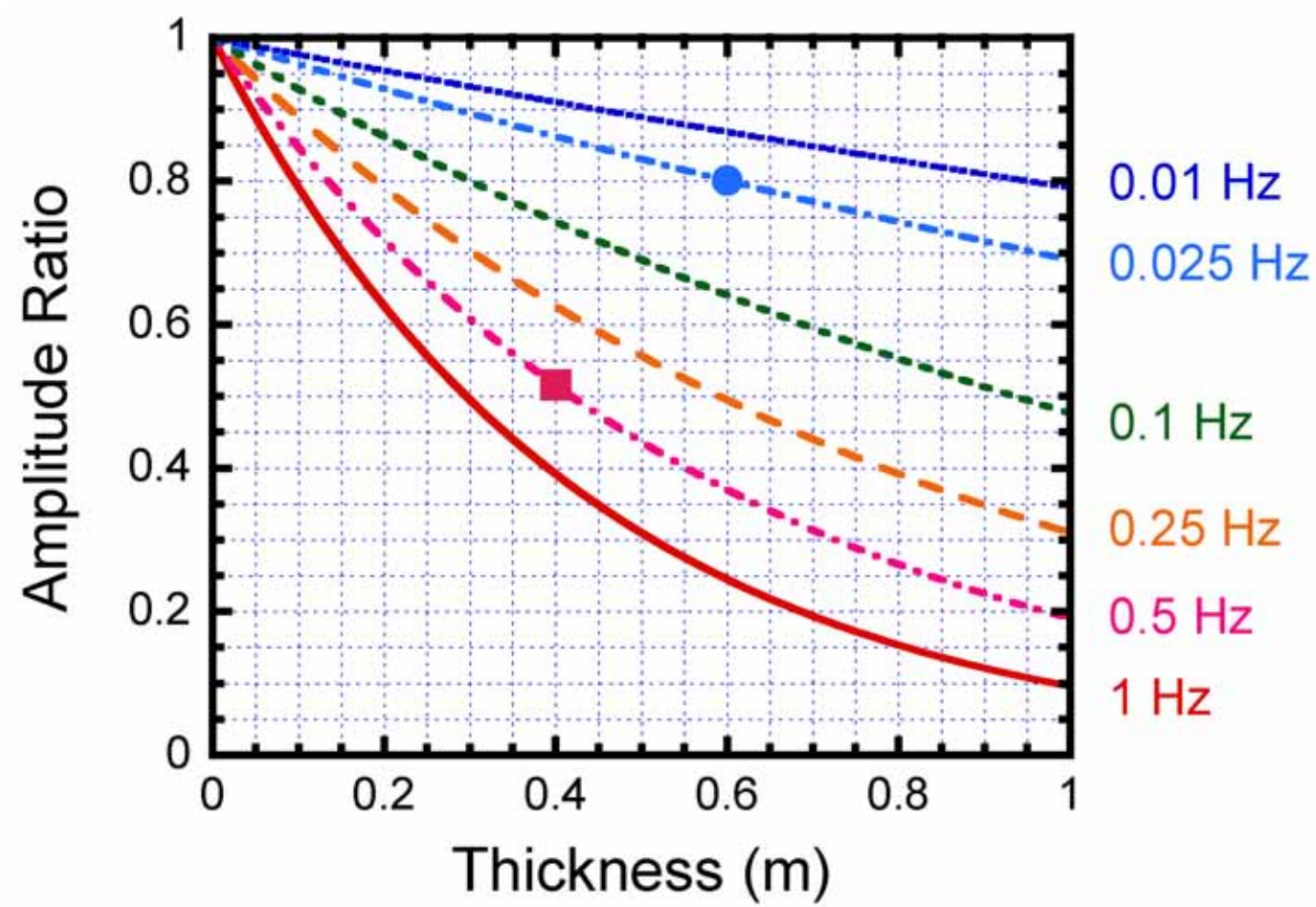


- Divertor power flow : ~ 600 MW (with 3 GW fusion power)
- Sweeping width of strike points : ~800 mm (with ±1% amplitude)
- Total length of divertor legs : ~ 900 m ➔ Total wetted area : ~700 m^2
- Divertor heat flux : <1 MW/m^2 (on time average)

Plan View of the SC Magnet System



Skin Effect of the Nuclear Shield



- **Sweeping frequency 0.025 Hz ➔ 20% reduction with 600 mm thickness**
  ➔ Concern of thermal fatigue with 40 s cycles
- **Sweeping frequency 0.5 Hz ➔ 50% reduction with 400 mm thickness**
- **Leveling of erosion is expected even with quasi steady-state sweeping**

Temperature Distribution in Divertor Tiles
(One-Dimensional Heat Diffusion)

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2}$$

Tungsten thickness: 8 mm

Local heat flux: 10 MW/m^2 in 8 cm width

Sweeping width: 800 mm

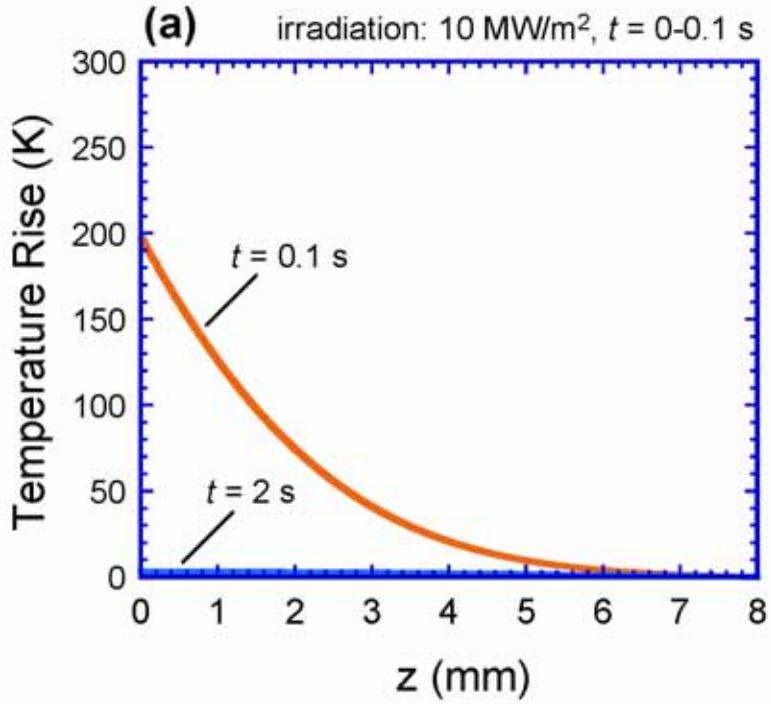
Sweeping frequency: 0.5 Hz

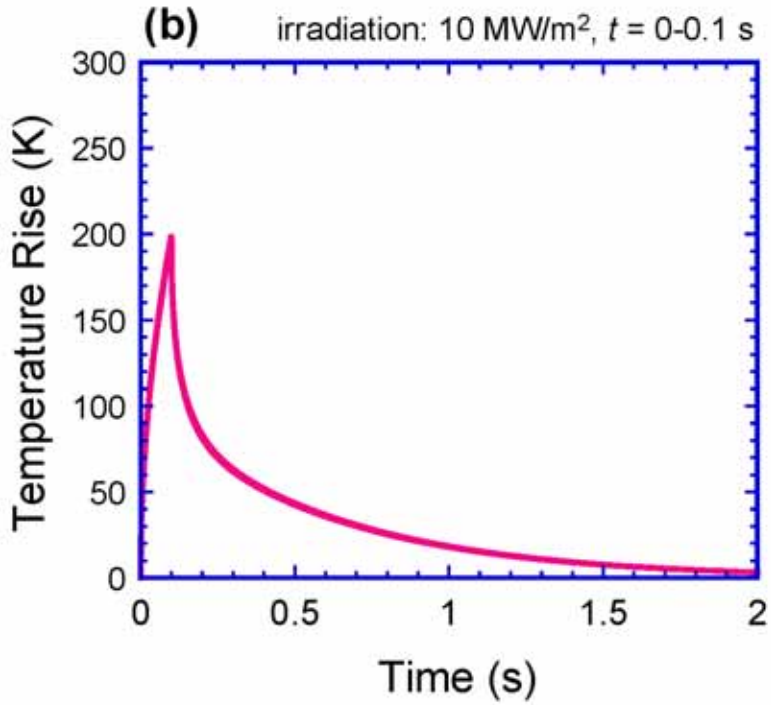
(0.1-s irradiation in 2-s cycle)

The cooling-water temperature is fixed

ΔT @z = 0 mm ~ 200 K
ΔT @z = 7 mm ~ 0 K

➔ Thermal cycle may not be significant…
➔ Should be further studied with FEM





Temperature Distribution in Divertor Tiles (2)
(One-Dimensional Heat Diffusion)

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2}$$

Tungsten thickness: 8 mm

Local heat flux: 10 MW/m^2 in 8 cm width

Sweeping width: 800 mm

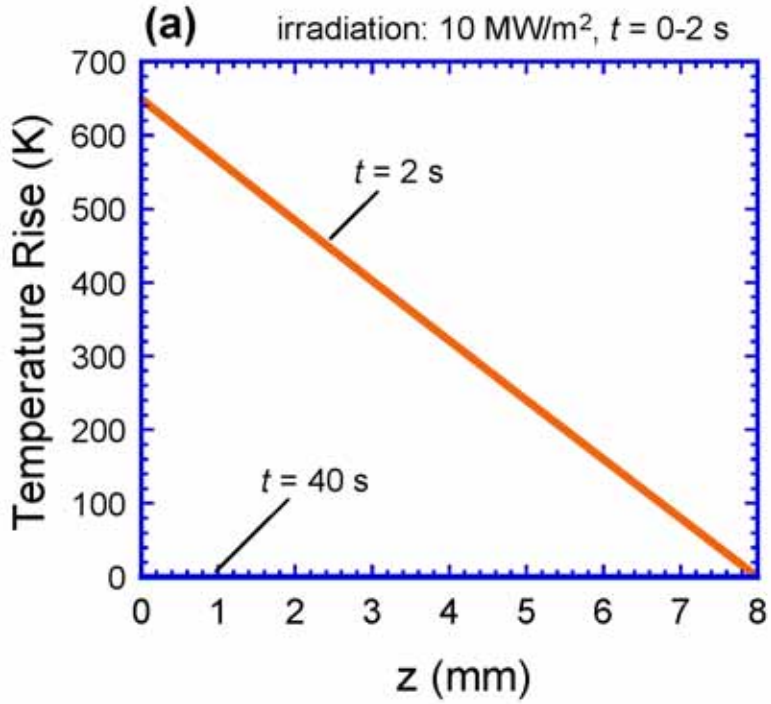
Sweeping frequency: 0.025 Hz

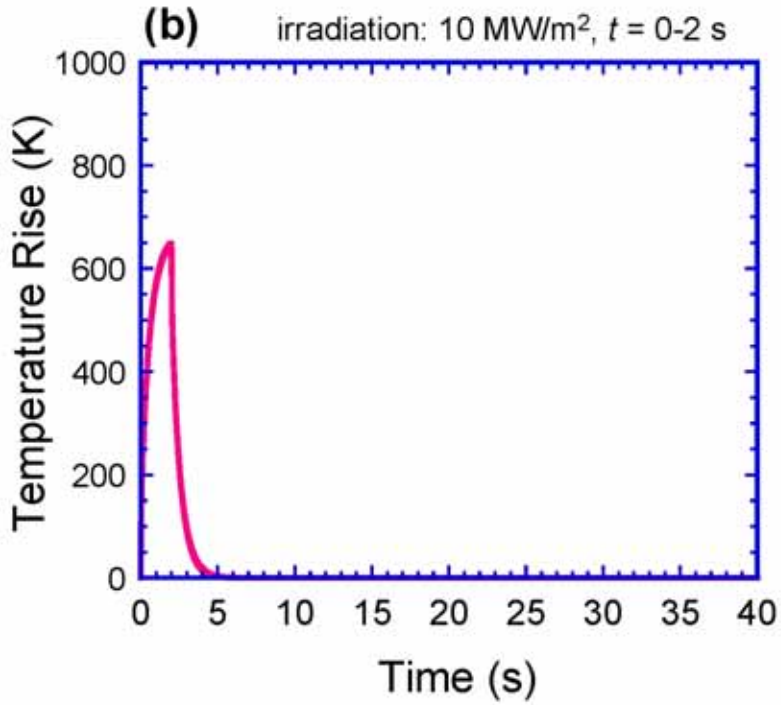
(2-s irradiation in 40-s cycle)

The cooling-water temperature is fixed

ΔT @z = 0 mm ~ 650 K
ΔT @z = 7 mm ~ 80 K

➔ Is this still accepted?
➔ Will be further studied with FEM

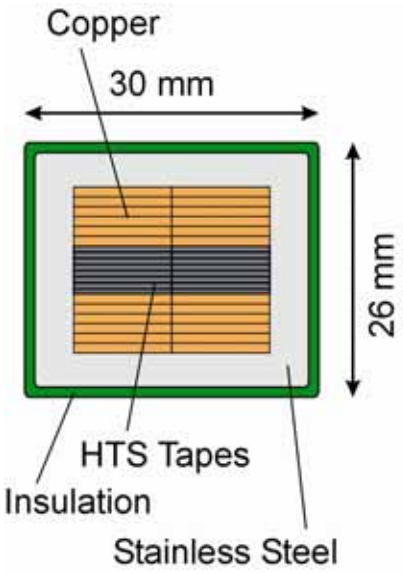




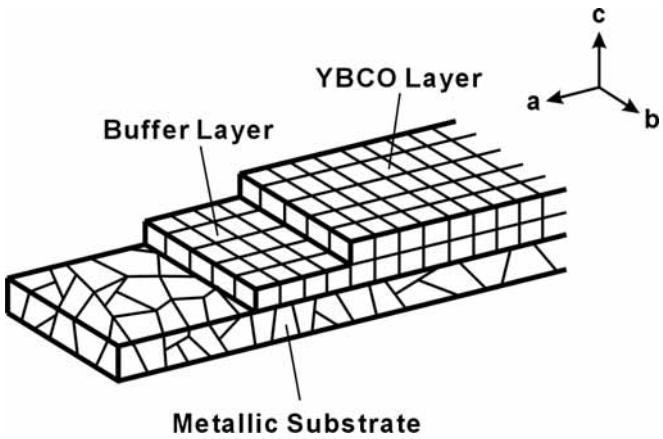
High-Temperature Superconductors (HTS) to be Applied for the Helical Divertor Coils

- Total current of 750 kA (2% of main helical coil currents) = 30 kA ✕25 turns
- YBCO-based HTS conductor : probable candidate also for the main helical coils
- Could be constructed in segments (jointed onsite and remountable)
- AC operations of 0.5 Hz : no problem for HTS at 30 K or higher
- R&D successfully started with 10 kA-class YBCO conductors

10 kA-class HTS conductor



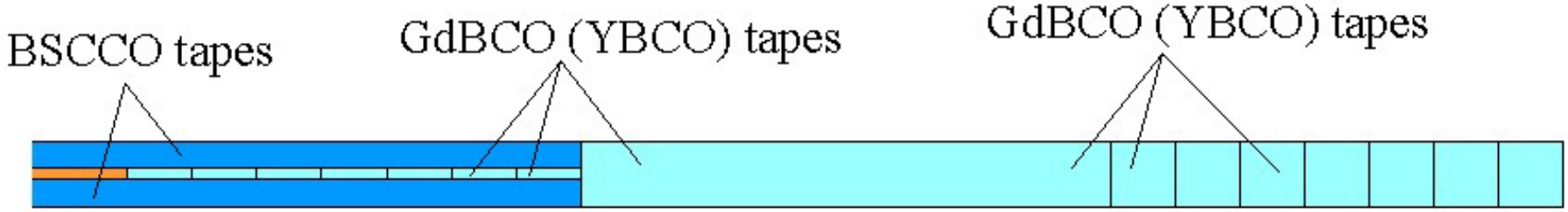
30 kA-class HTS conductor design

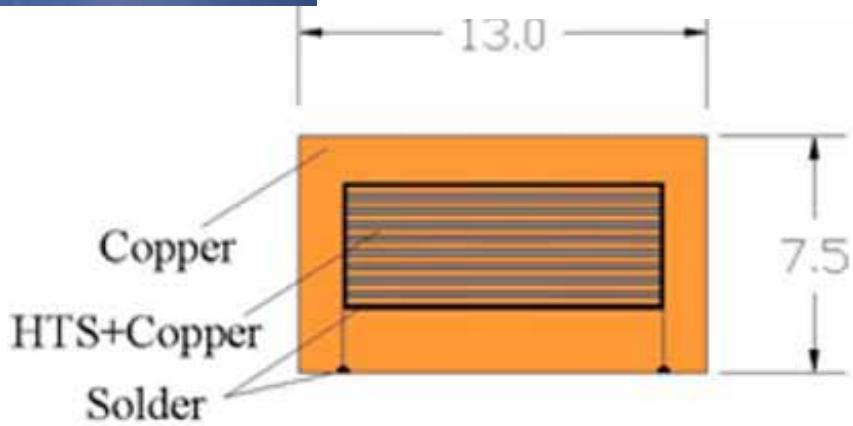


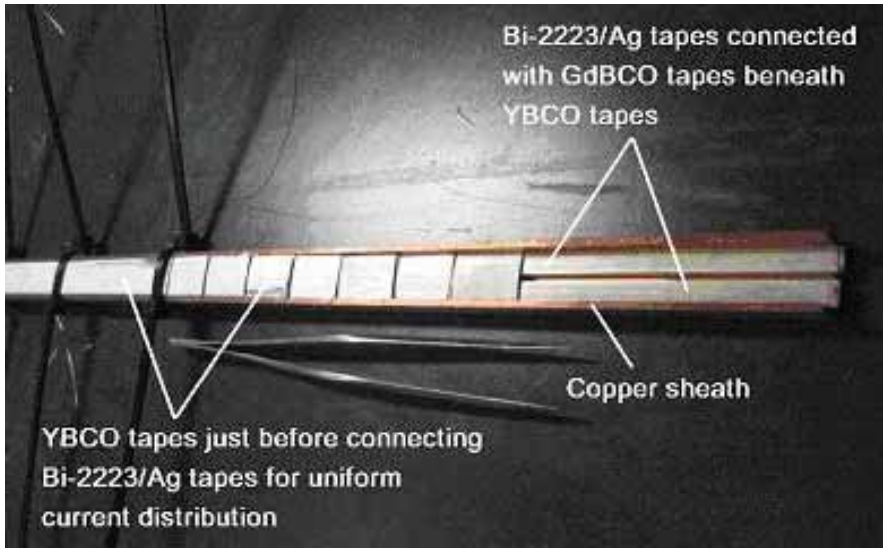
Structure of YBCO tape

Segmented fabrication of helical coils

10 kA-Class YBCO Conductor

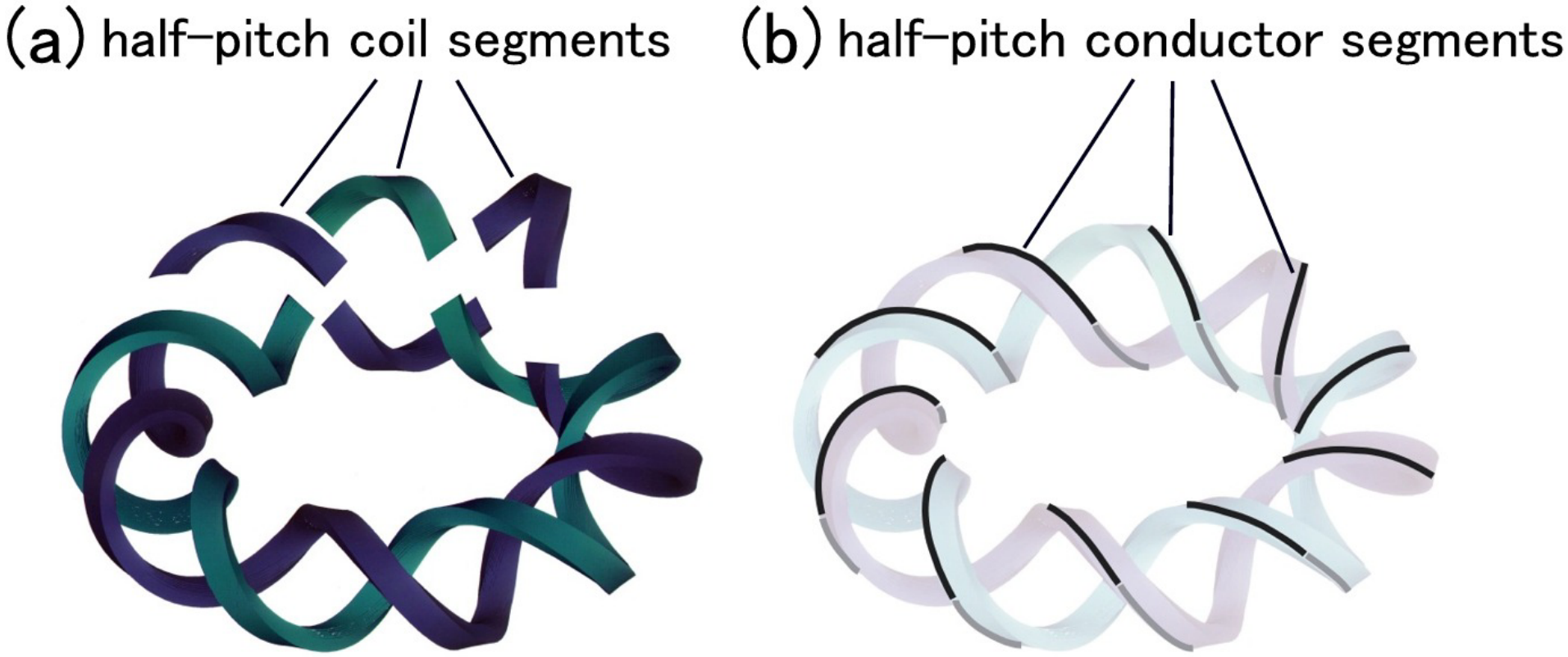






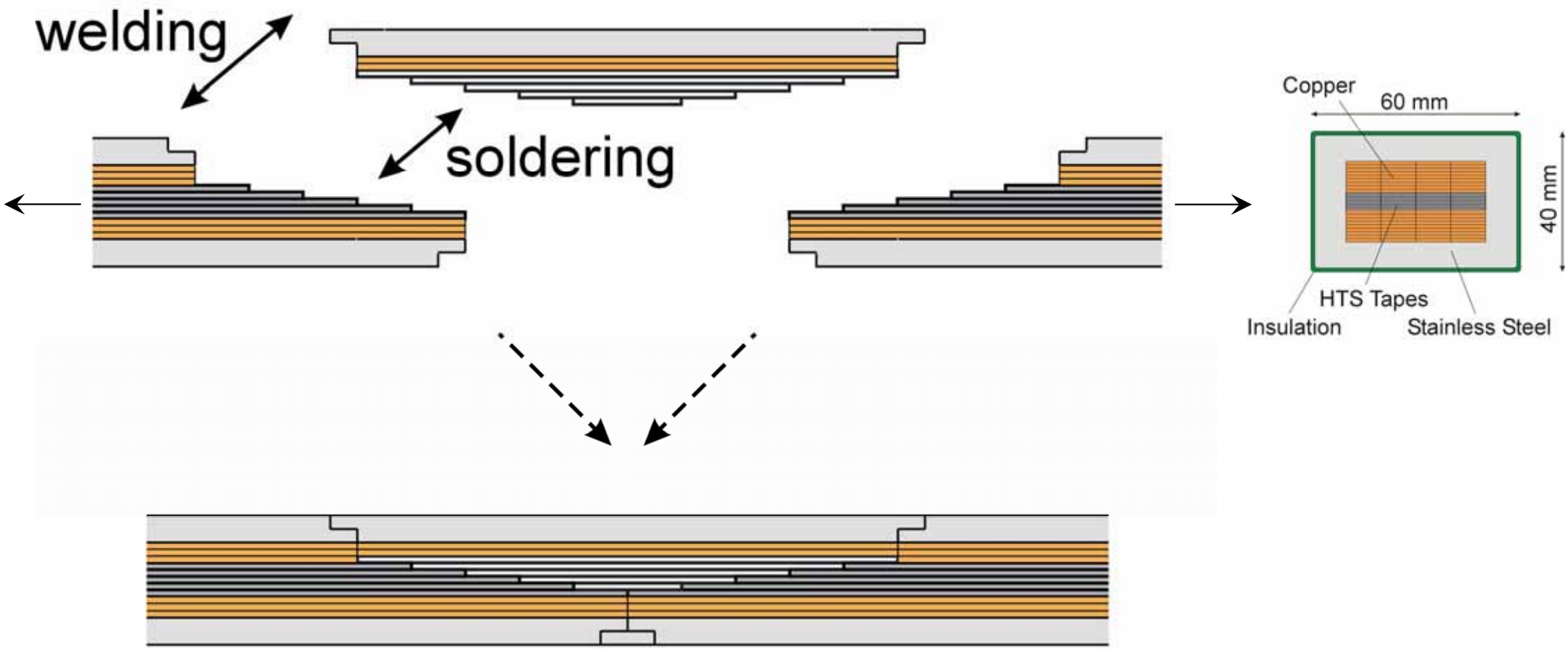
Superconductor	**YBCO & GdBCO**
Conductor size	**13.0 mm ✕ 7.5 mm**
Critical current of a tape (@77 K, s.f., 10 mm wide)	**~200 A → 1000 A**
Width / thickness of a tape	**10 mm / 0.1 mm**
Thickness of REBCO layers	**~1 μm → ~3 μm**
Supplier	**ISTEC-SRL**
Number of HTS tapes	**16**
Critical current at 20 K, 8T	**15 kA → > 75 kA**
Stability margin	**~40 J/cc**

Proposal of Segmented Fabrication of Helical Coils (2)



- A number of half-pitch conductors will be prefabricated and transported
- Each conductor will be formed into a helical shape on site and installed into the helical coil cans
- The joint will be made by soldering and welding

Proposal of Segmented Fabrication of Helical Coils (3)



Joint resistance (per joint) : ~0.12 nΩ (measured for 50 mm)
Number of joints : 8000
Required power for 20 K cooling : ~1.5 MW (@ R.T.)

Summary

- New divertor sweeping scheme is proposed for the heliotron fusion energy reactor FFHR with "Helical Divertor Coils"
- AC operations of HDC with 1-2% of the main HC currents effectively disperse strike points without affecting the core plasma and the heat flux could be < 1 MW/m^2 on time average
- Leveling of erosion (even with quasi steady-state sweeping) prolongs the replacement cycle of divertor tiles
- YBCO-based high-temperature superconductors (HTS) could be applied with segmented fabrication for fabricating HDC

Future Work

- Temperature rise of divertor tiles should be checked carefully
- Flux expansion in steady-state will also be explored