Design of RWM Control on JT-60SA

M. Takechi and JT-60SA team

14th Workshop on Active Control of MHD Stability:
Active MHD Control in ITER
9-11 Nov. 2009, Princeton, USA

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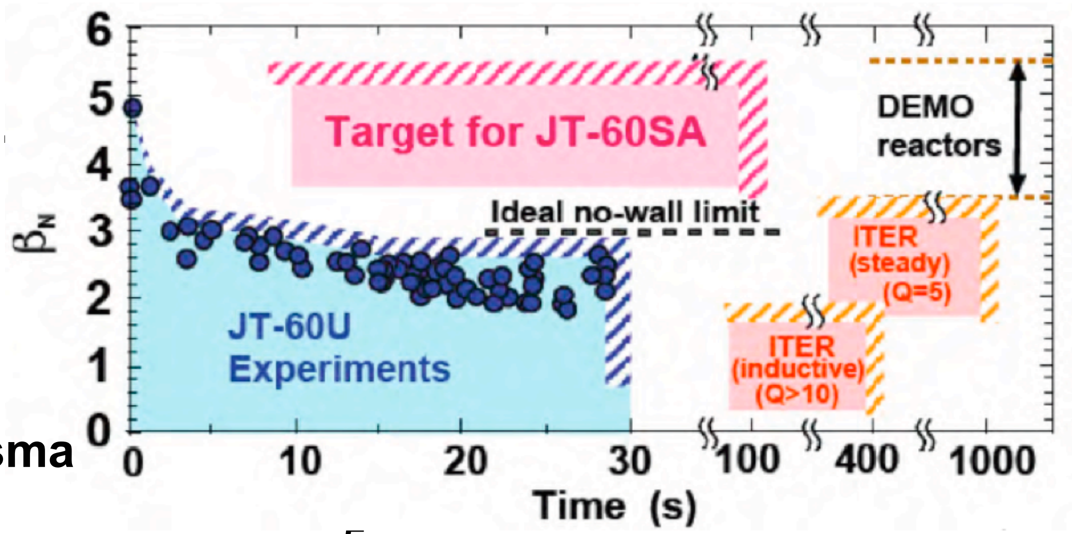
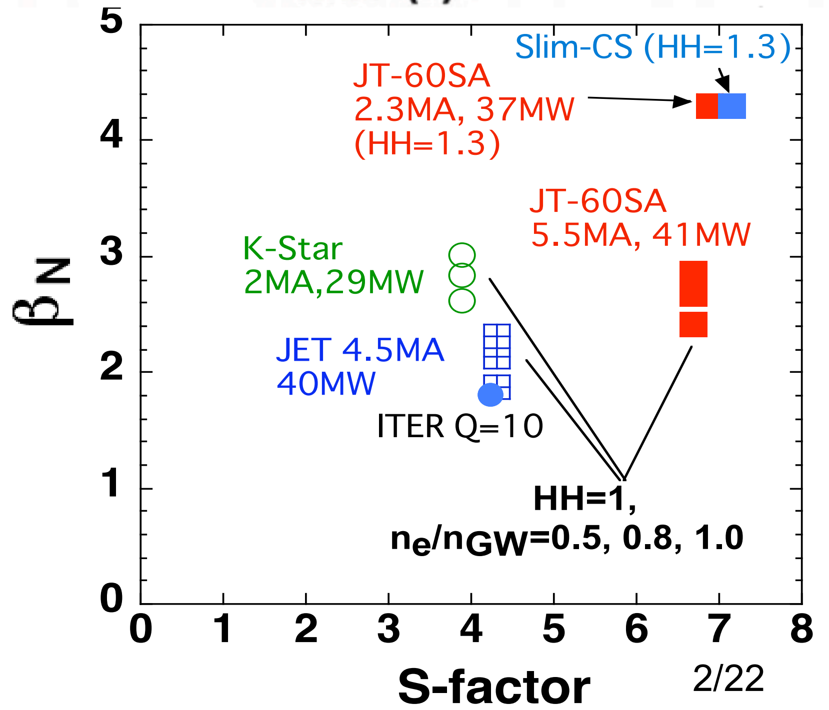
Introduction

- **Mission of JT-60SA is to contribute and supplement ITER toward DEMO**
  - **optimization of ITER operation scenarios.**
  - **steady-state high beta operation.**



JT-60SA allows exploitations of high beta regimes with a DEMO-equivalent high plasma shaping factor of S (= $q_{95}I_p/(aB_t)$) ~7 , the stabilizing shell, and the sufficient additional high power 41 MW for heating and CD.

- **For High beta operation, RWM stabilization is necessary.**
  - **-Stabilization by rotation**
    - **Clarification of stabilization mechanism**
    - **Not sufficient because of ELM, FB, EWM…?**
  - **-RWM active control system**
    - **RWM control coil (Fast control)**
    - **Error field correction coil (Slow control)**
      - **-and also used for ELM control**



JT-60SA
Advanced Superconducting Tokamak
BA-Satellite Tokamak Program

New JT-60SA Outline

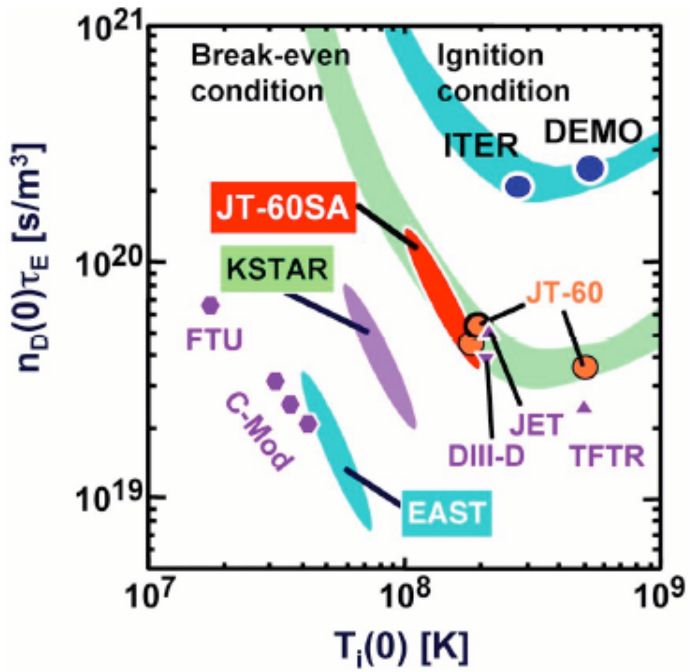
Objectives of the Project

The JT-60SA

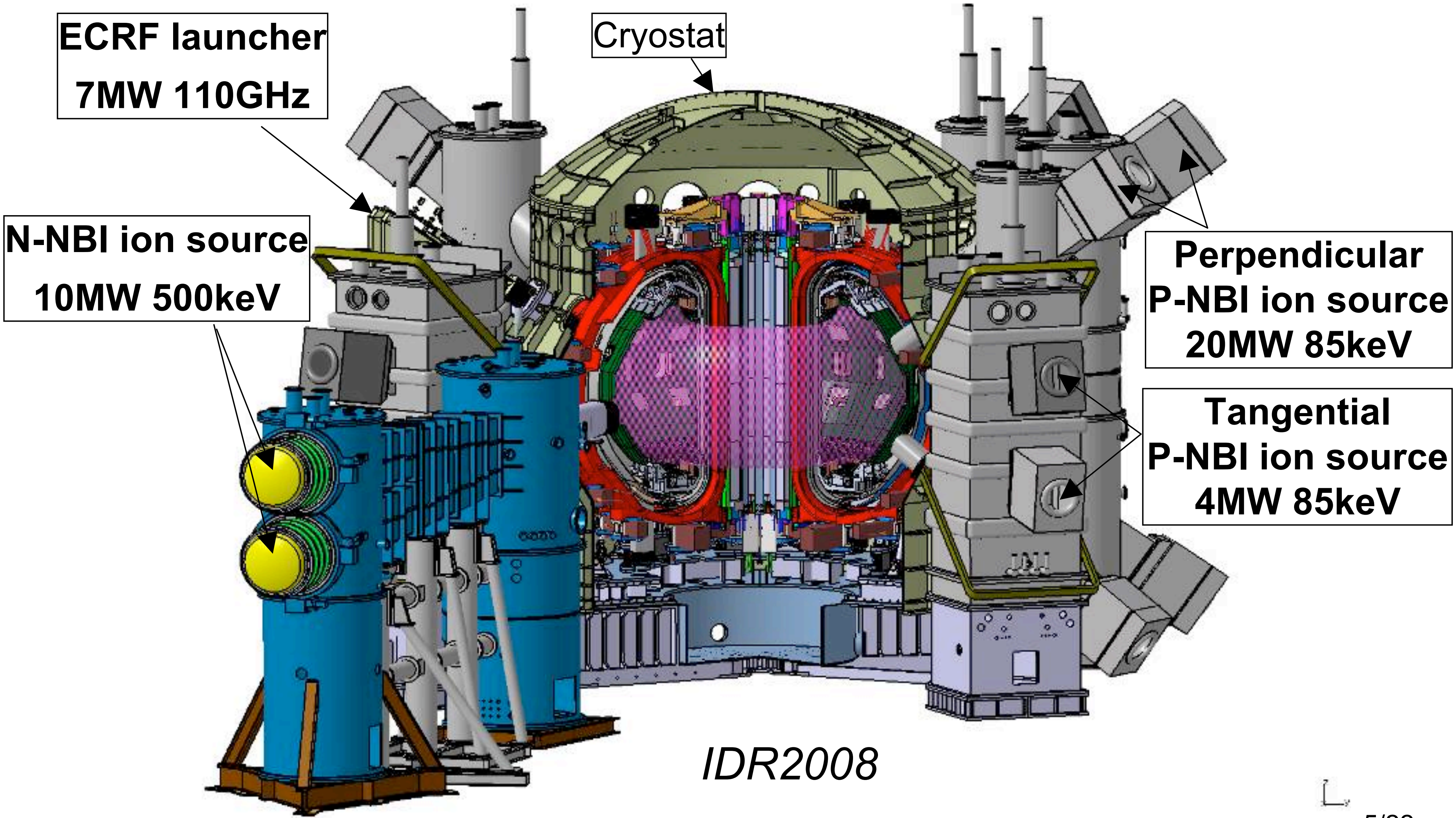
- is capable of confining break-even-equivalent class high-temperature deuterium plasmas (the maximum plasma current of 5.5 MA) lasting for a duration longer than the timescales characterizing the key plasma processes, such as current diffusion and particle recycling, with superconducting toroidal and poloidal field coils.
- should pursue full non-inductive steady-state operations with high values of the plasma pressure exceeding the no-wall ideal MHD stability limits.
- should explore ITER and DEMO-relevant plasma regimes in terms of non-dimensional plasma parameters together with high densities in the range of $1\times10^{20}/m^3$.

To achieve these objectives, the JT-60SA is designed to realize

- Expanded range of plasma equilibria in divertor configuration
- Enhanced plasma shaping factor typically of S~6-7
- Increased flux swing for an inductive flattop allowing ~100 s
- Divertor targets to stand up to 15 MW/m^2
- Heating power up to 41 MW including 500 keV N-NBI



Bird's View and heating of JT-60SA



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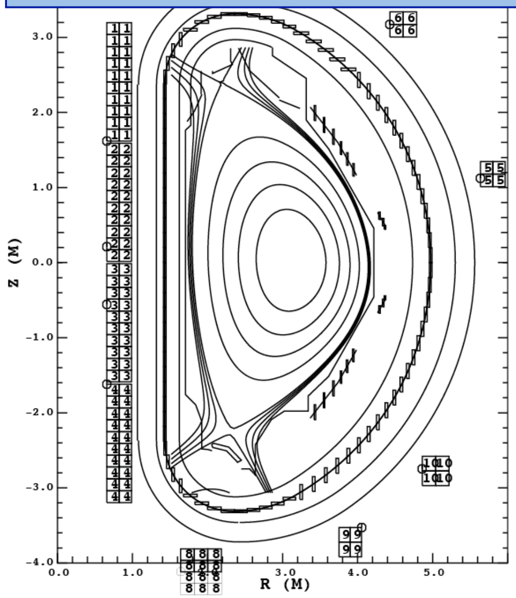
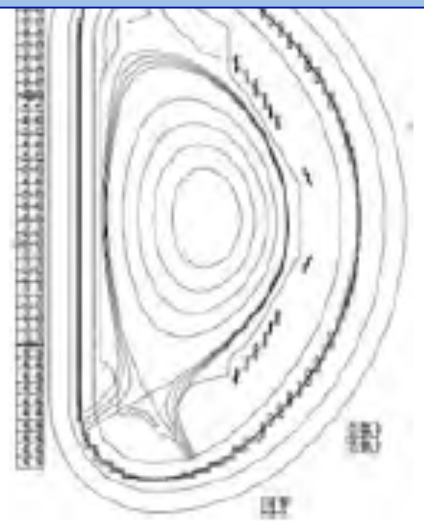
JT-60SA Typical Parameters

Ip=5.5MA, Double Null



Ip=4.6MA ITER-shape



Parameter	Full I_p DN Low A	ITER-Shape SN	High β_N Full CD SN
Plasma Current I_p (MA)	5.5	4.6	2.3
Toroidal Field, B_t (T)	2.25	2.28	1.71
Major Radius (m)	2.96	2.93	2.97
Minor Radius (m)	1.18	1.14	1.11
Aspect Ratio, A	2.5	2.6	2.7
Shape Parameter, S	6.7	5.7	6.9
Elongation, κ_x , κ_{95}	1.95, 1.77	1.81	1.92
Triangularity, δ_x , δ_{95}	0.53, 0.42	0.43	0.51
Safety factor, q_{95}	3.2	3.2	5.7
Normalized beta, β_N	3.1	2.8	4.3
Flattop Duration (s)	100	100	100
Heating power	41 MW	34 MW	37 MW
Assumed HH-factor	1.3	1.1	1.3
Bootstrap current fraction	0.29	0.30	0.66
Electron Density n_e ($10^{20}/m^3$)	0.63	0.91	0.50
Normalized Plasma Density $n_e/n_{Greenwald}$	0.5	0.8	0.66
Thermal Energy Confinement Time τ_E (s)	0.54	0.52	0.26

JT-60SA prepare the devices for research and controlling MHD stability and disruption

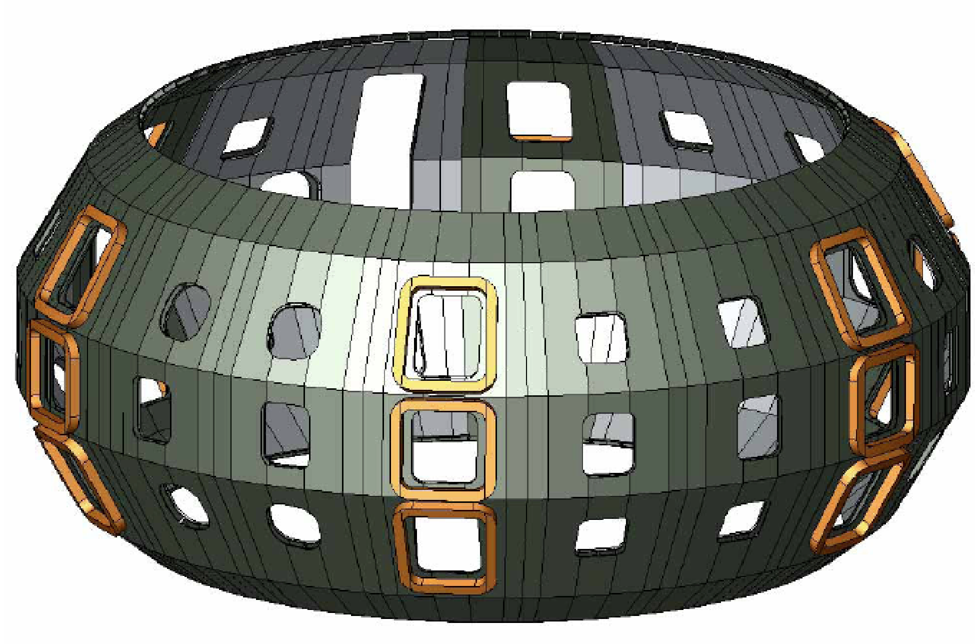
MHD and high energy particle research needs for ITER and DEMO and required device capabilities

Main Issues		ITER	DEMO	Requirements for devices
MHD Siability and Disruption	high β operation boundary	Demonstrate long pulse high β_N ~3 and determine stability boundary	Demonstrate long pulse high β_N >4 .Determine stability boundary. Clarify plasma shape effects	Low-A, strong shaping, NNB
	RWM	RWM Control with internal coils Compatibility with RMP	RWM stabilization with rotation	RWM control-coil CO/CTR/Perp-NB
	NTM	Efficient real time control with ECCD, Compatibility with RMP	Simultaneous stabilization of NTM & RWM at high βN>4	ECCD, NNB, CO/CTR/Perp-NB
	Disruption mitigation	Fast VDE control by VS-coil, Mitigation by large amplitude magnetic fluctuation or Increase of electron density		Fast position control coil, Killer pellets, massive gas injection and helical fields
	Disruption prediction	Develop prediction scheme such as using Neural network	Disruption limits & behavior at high βN & high radiation	Active MHD diagnostics
High Energy particle	AE	Stabilization / Control of AE at high fast ion beta,		High energy & high power NNB
	Transport	Study transport of high energy particles		
	Interaction with MHD modes	Clarify Interaction of high energy ions with various MHD modes		
	NBCD	High energy NBCD	High energy off-axis NBCD	

Hardware design of RWM Control

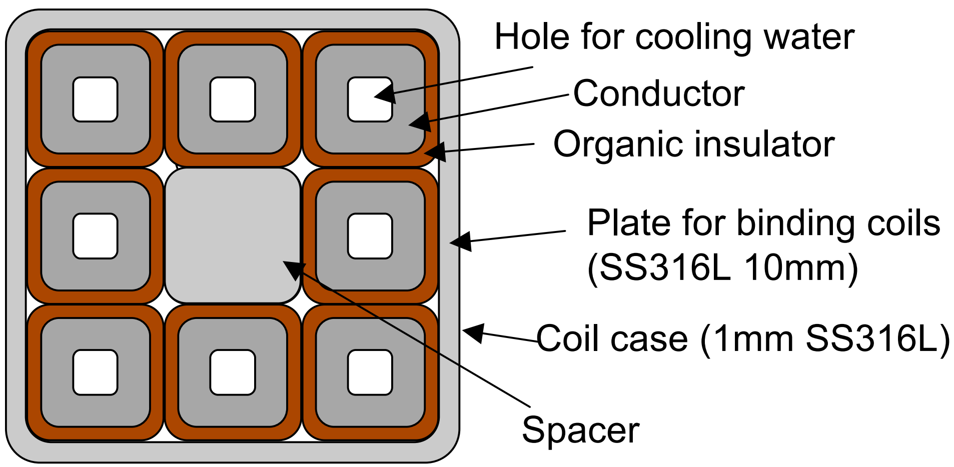
JT-60SA Advanced Superconducting Tokamak BA-Satellite Tokamak Program

Design status of RWM Control Coils

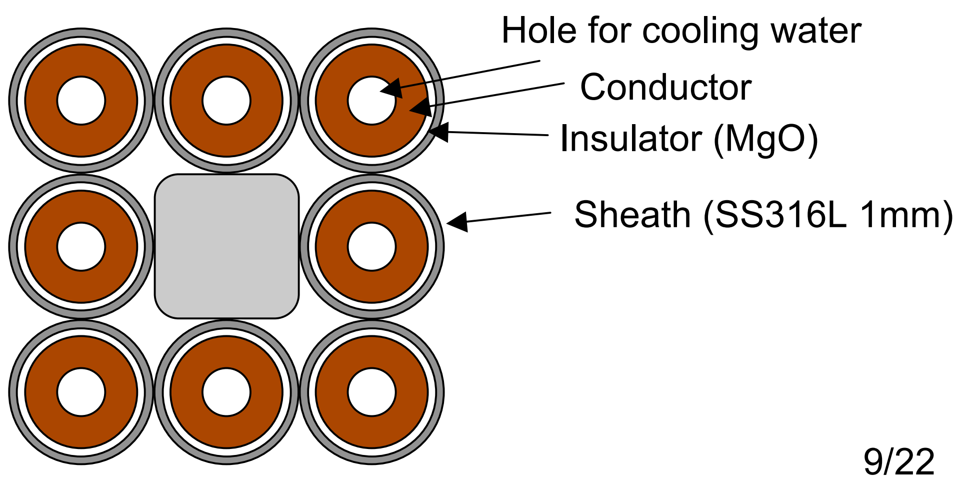


- 3 poloidal x 6 toroidal = 18
- 8 turns
- 2.5kA/turn (20 kAT)
- Two type of design is considered
  - Hollow conductor with organic insulator (original design)
  - Mineral insulation (MI) cable (current design)
- The design of coils at the plasma side of SP is also considered

Original design (hollow conductor)



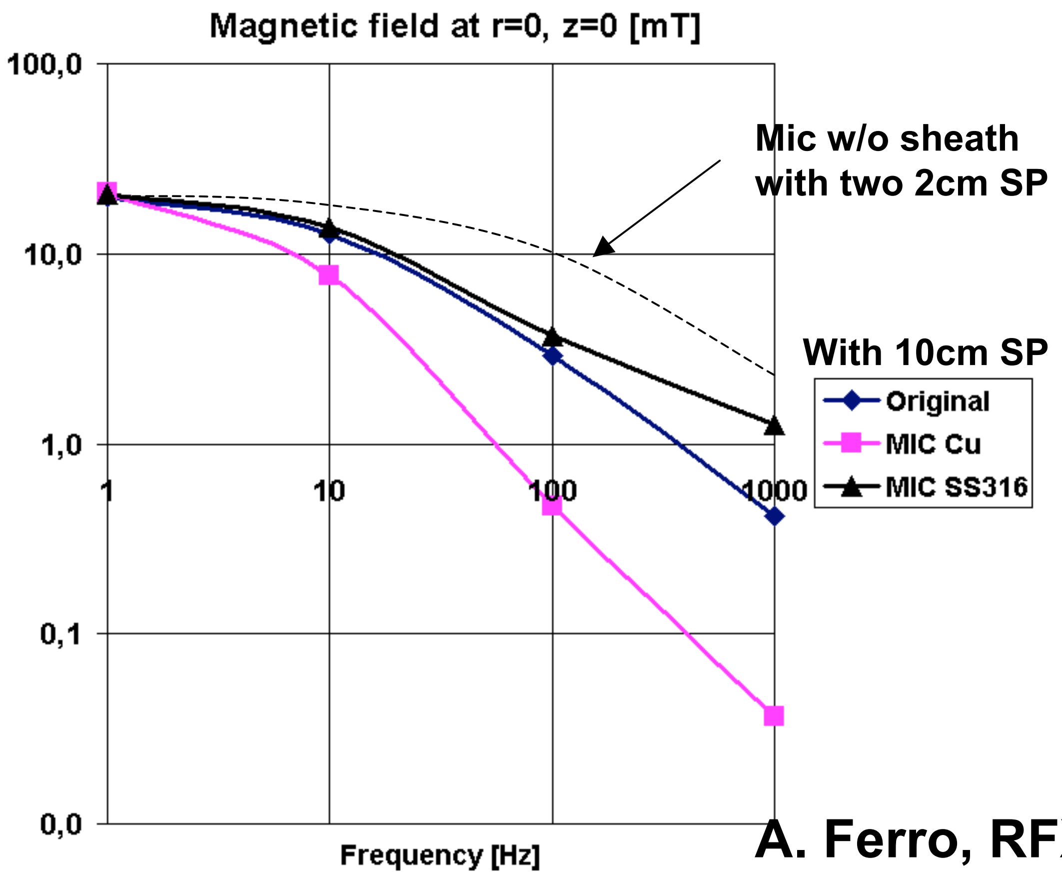
Current design (MIC)



FEM analysis of a sector coil

FEM analysis was performed to evaluate the magnetic field induced by sector coils.

-> Thanks to this calculation, the effect of the sheath of the coils becomes clear.



We considered we will make sector coils with existing MIC with Cu sheath.

However, the magnetic field induced by MIC with Cu sheath decreases strongly as frequency increase due to the higher conductivity of the Cu respect to SS316.

Therefore we need MIC with sheath of high conductivity.

-> We looked for the company which can make MIC with SS for high current (2.5kA)

A. Ferro, RFX

Improvement and R&D of MIC

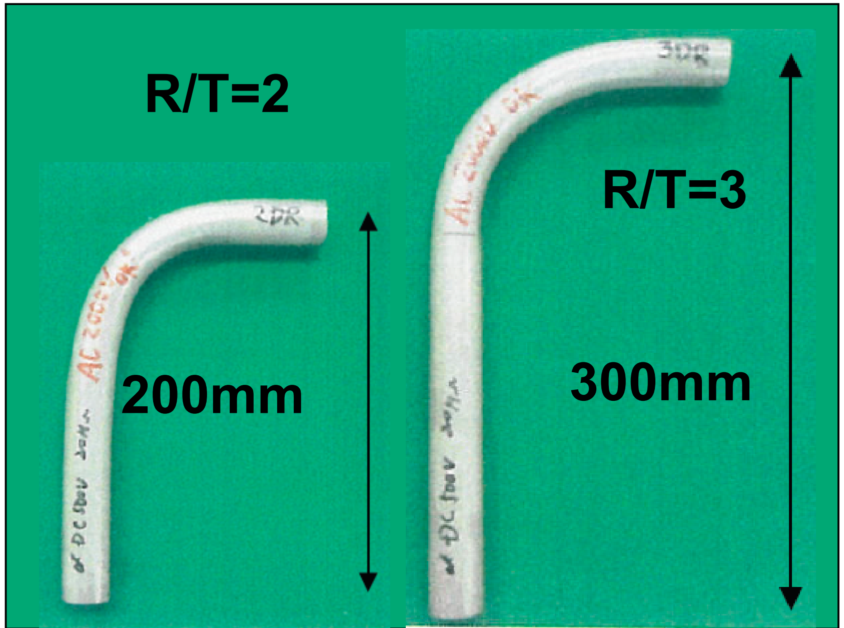
- Okazaki manufacturing company
- Insulator: MgO
- Water cooled
- 2.5kA DC continua
- Φ2.6cm
- Sheath: SS316L 1mm

Copper sheath

SS sheath

R&D of MIC with SS sheath has been launched by Okazaki and JAEA.

- Vending test (already started); R/T=2, 3
  Withstand voltage test; 2kV 1min no problem
  X-ray inspection; Thickness of insulator keeps uniform.
- Connecting MICs together (also connecting MICs inside VV)
- Heating test (300ºc)
- Leak test
- We will finish this R&D until Feb 2010

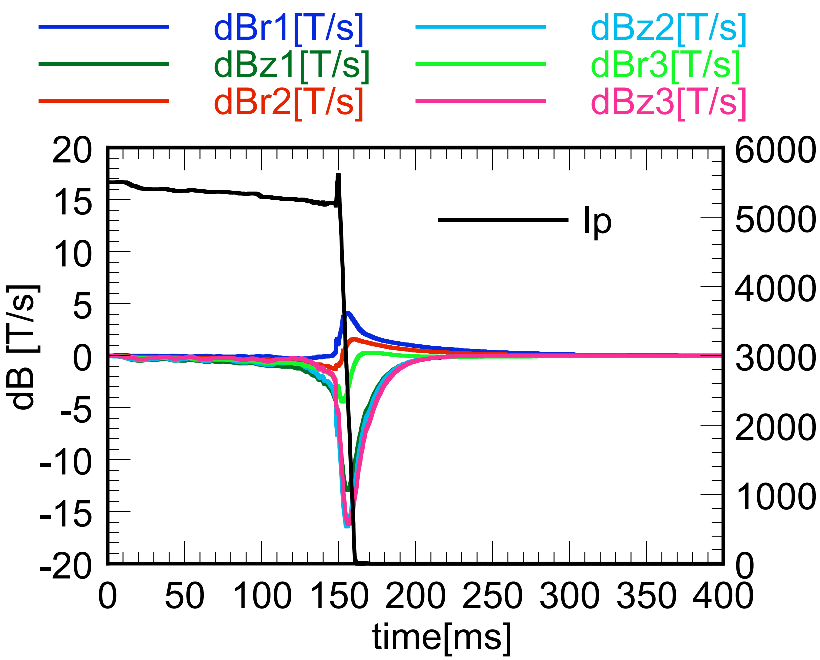


EM Force of RWM coil at disruption

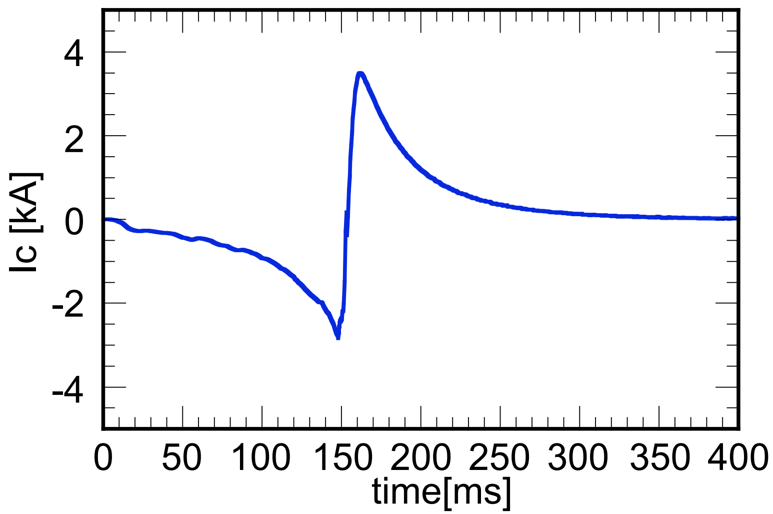
Evaluation of EM Force of RWM coil at disruption has been started with DINA code.

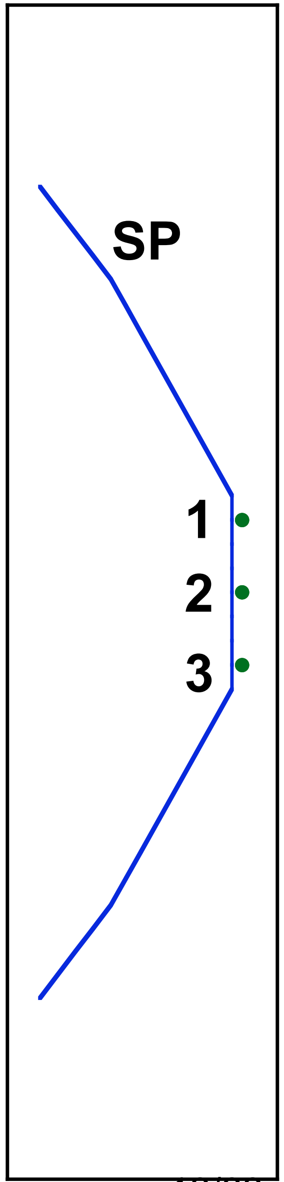
- **EM Force at coils**
- **EM Force at feeders in the case of no insulation between coil sheath and VV, SP.**
- **EM Force at coils at the plasma side of SP**

Derivation of magnetic field at sector coil



Induced current of the sector coil at disruption

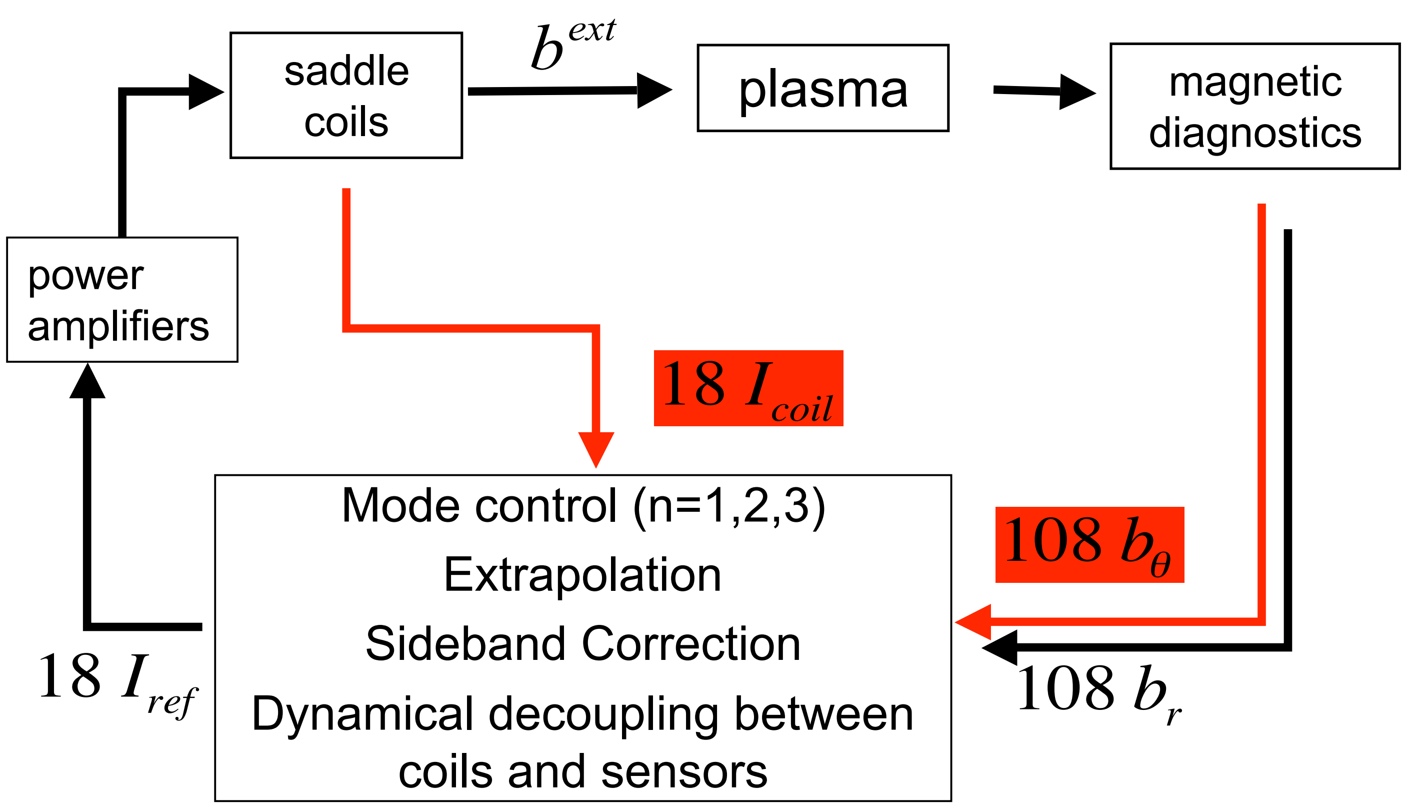




Sensors and Feedback control

Magnetic sensors; 6 x 18 x 2 = 216 channel

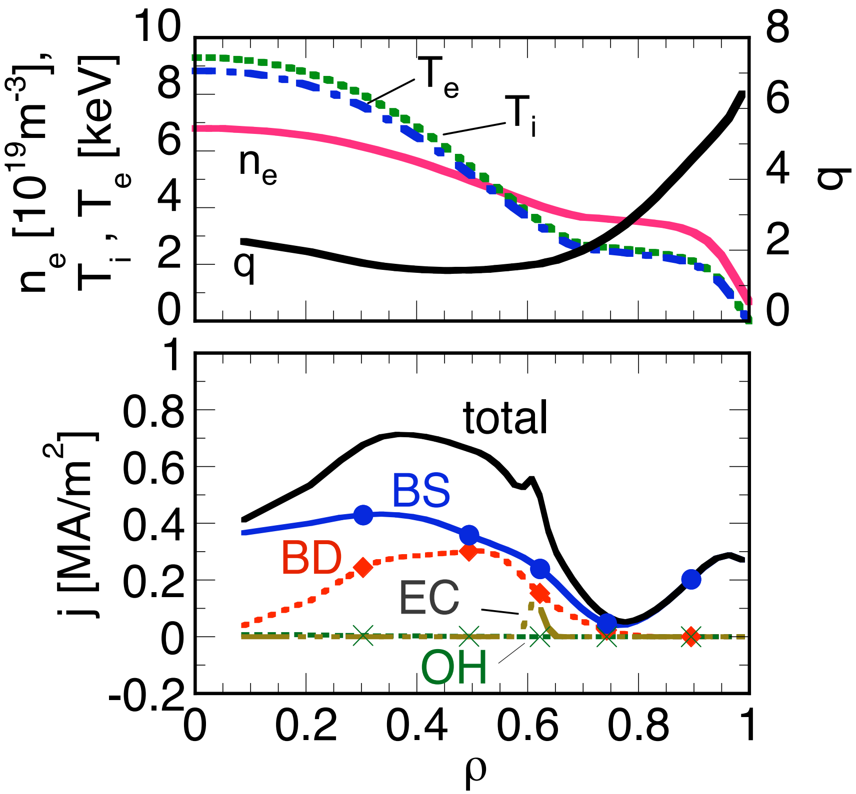
- 6 magnetic sensors in the toroidal direction for n=3 RWM control
- 18 magnetic sensors in the poloidal direction for m=9 RWM control
- Biaxial (Bq and Br) sensors for Mode control, sideband correction and the dynamical decoupling between coils and sensors.

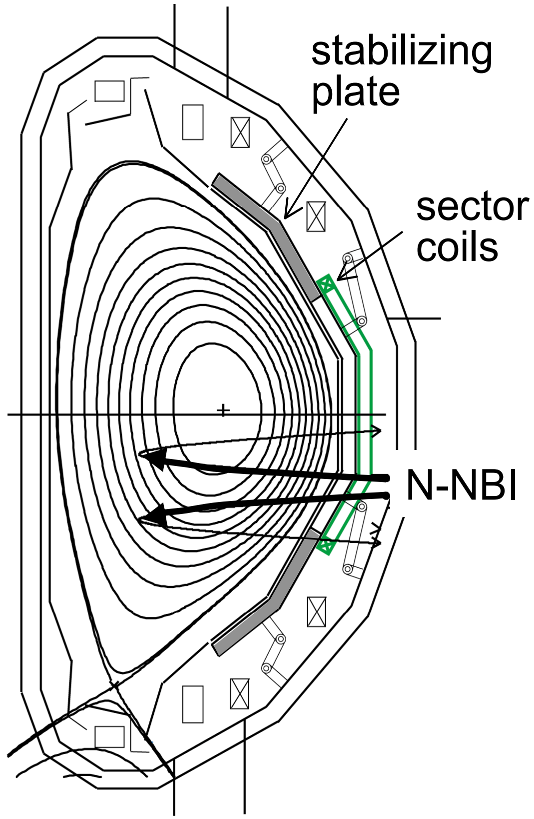


RWM Control Simulation

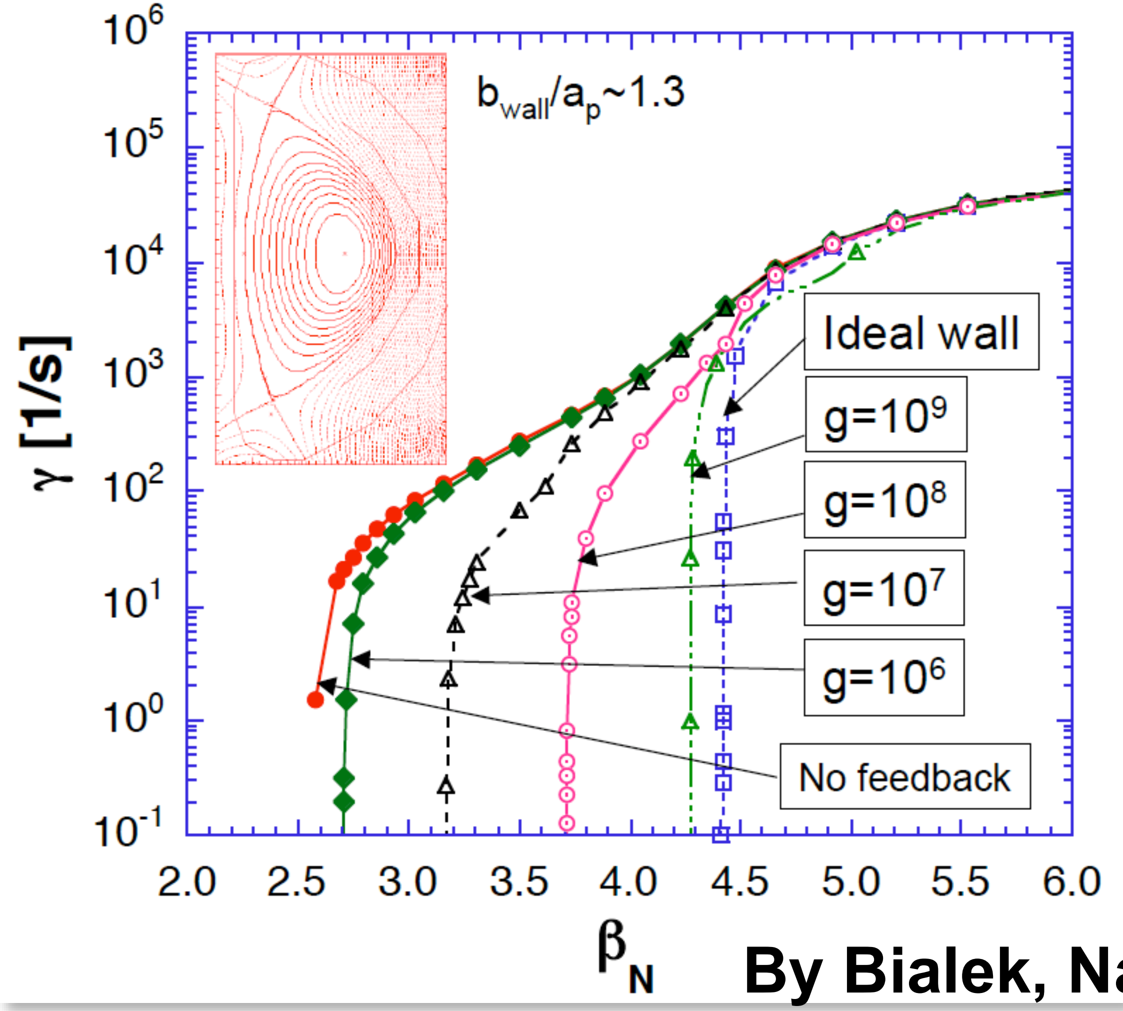
High beta full noninductive operation

- 2.4 MA full current drive with A = 2.65, β_N = 4.4, f_{GW} = 0.86, f_{BS} = 0.70 for H_{H98y2} = 1.3 with P_{tot} = 41 MW [Note that JT-60SA design and plasma are the previous version]
- p(r) and j(r) consistent with the ACCOME analysis, where q_{min} ~ 2.1.
- Normalized parameters are close to those required in DEMO (J05, slim CS)
- No-wall limit $\beta_{N\ no\text{-}wall}$ ~ 2.56, Ideal-wall limit $\beta_{N\ ideal\text{-}wall}$ ~ 4.42,





Simulation with VALEN code



- $V_{coil} = G_p \Phi_{sensor}$
- G_p is proportional gain.
- Φ_{sensor} is perturbed poloidal flux measured by poloidal field sensor placed at center of each coil.
- JT-60SA design and plasma are the previous version.
- $\beta_{N\ no\text{-}wall}$ = 2.56, $\beta_{N\ ideal\text{-}wall}$ =4.42

By Bialek, Navratil: Columbia U.

- **Maximum critical β_N with active feedback control for the present design of JT-60SA plasma is 4.26, which corresponds to C_β = 0.91**

Required current for RWM control

The maximum current of RWM control coils calculated with VALEN is about 1.7 kA (Maximum current of 20kA for current design).

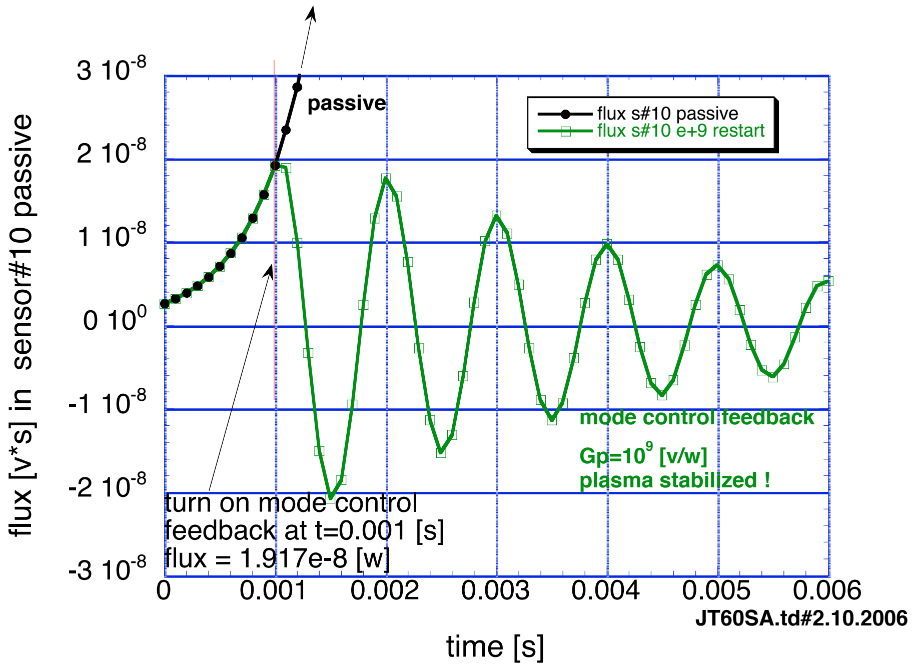
Feedback (Gp=10^9V/Wb) starts at t=0.001s when we have 2 gauss at sensor.

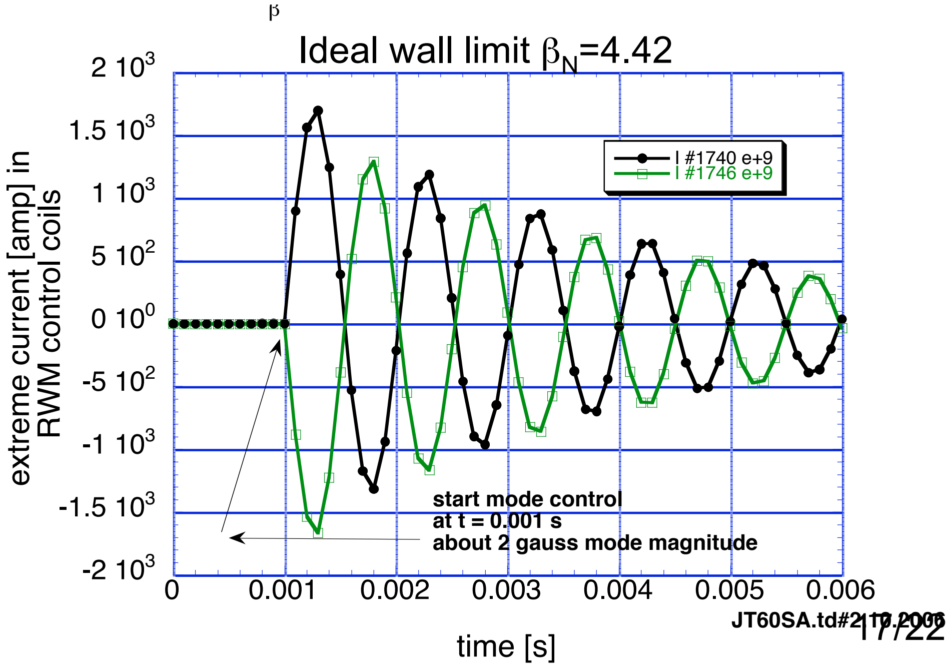
These results are optimistic because,

- without sheath effect
- 1 turn coil
- with out time delays (Ideal power supply and no delay of calculation)
- without noise

More current needs for actual RWM stabilization

(For example, with 1ms delay maximum current is ~12kA)





New activities for identification of RWM control requirements

Starting from the existing collaboration with Consorzio RFX on RWM physics and control, because the JT-60SA project is conducted under the BA Satellite Tokamak Programme by Europe and Japan

- Calculation of effect of MIC sheath on induced magnetic field was done (shown before).
- RFX experiment with reduced coil sets for mode rigidity study has been started.
- RWM control simulations with CarMa code are under consideration with the help of Cassino University.

Experiment of RWM control with reduced control coils of RFX

The sector coils for RWM control of JT-60SA are covered plasma surface much smaller than existing systems (DIII-D, NSTX, RFX,…)

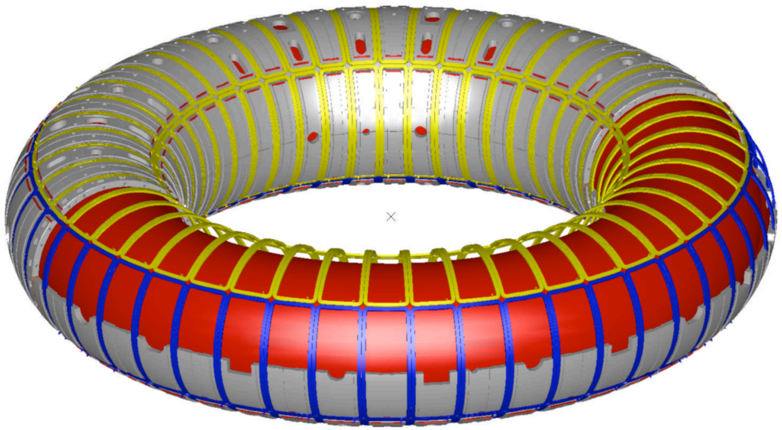
We have to pay attention to issue of mode-rigidity

Issue of mode non-rigidity

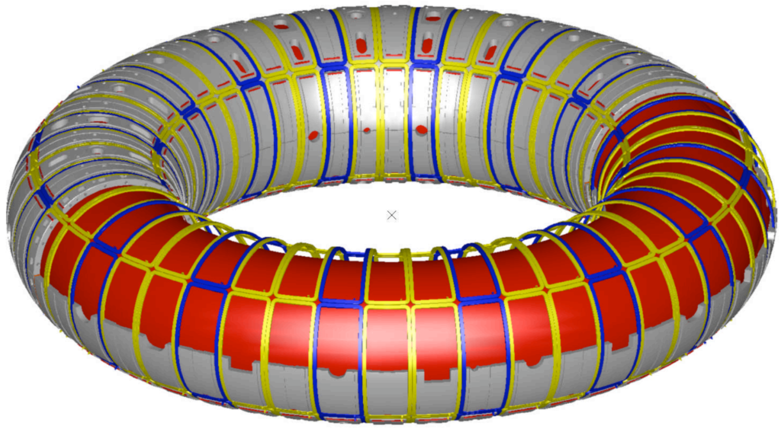
- Mode deformation
- Induced side band mode due to small coil area

RFX experiments with reduced coil sets for mode rigidity (mode deformation) study has been started.

Outside only; 1 x 48



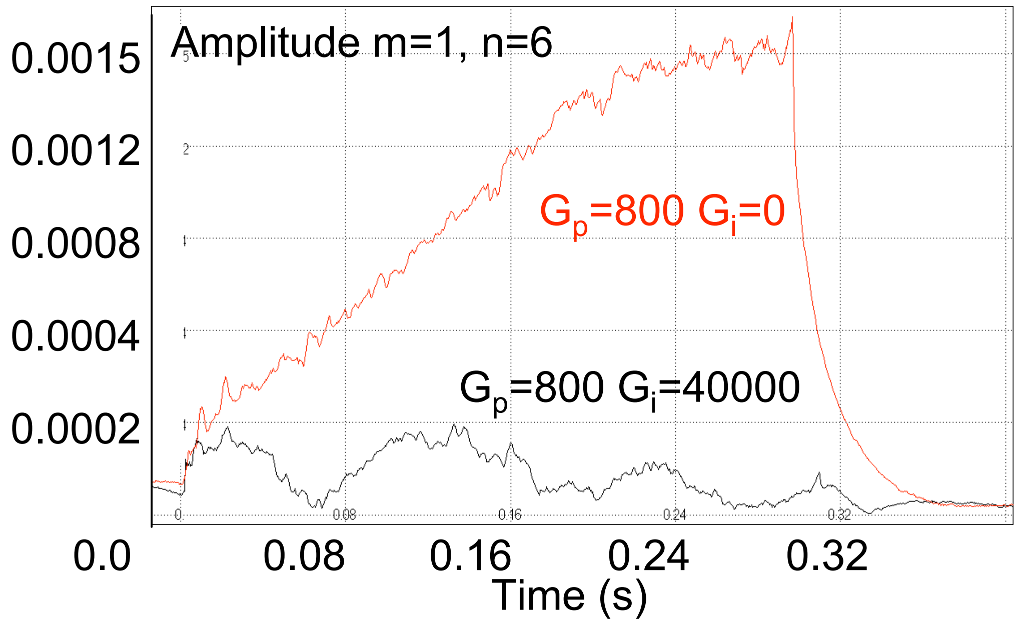
Reduced toroidally; 4 x 16



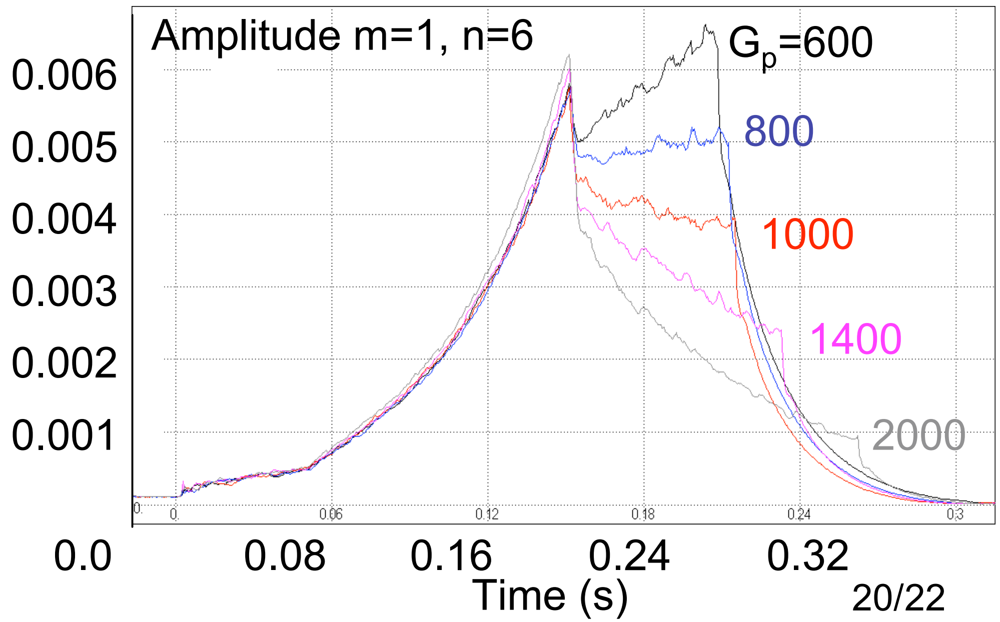
Experiment of RWM control with reduced control coils of RFX (continue)

- **Preliminary study of RWM control with inner or top toroidal array only has been performed.**
- **RWM can be stabilized with reduced (covered 25% of plasma surface) coil sets.**
- **Further experiments are nessesary because the area of plasma surface covered with sector coils of JT-60SA is less than 10% of low field side area.**
- **How much can we reduce the area of control coils?**

The (1,-6) RWM amplitude controlled with only the top toroidal array from the beginning of the discharge.



Full gain scan on control of (1,-6) using only the inner toroidal array. Controls are turned on at t=0.20s



RWM control simulations with CarMa code for JT-60SA

CarMa code (=CARIDDI + Mars-F) can treat

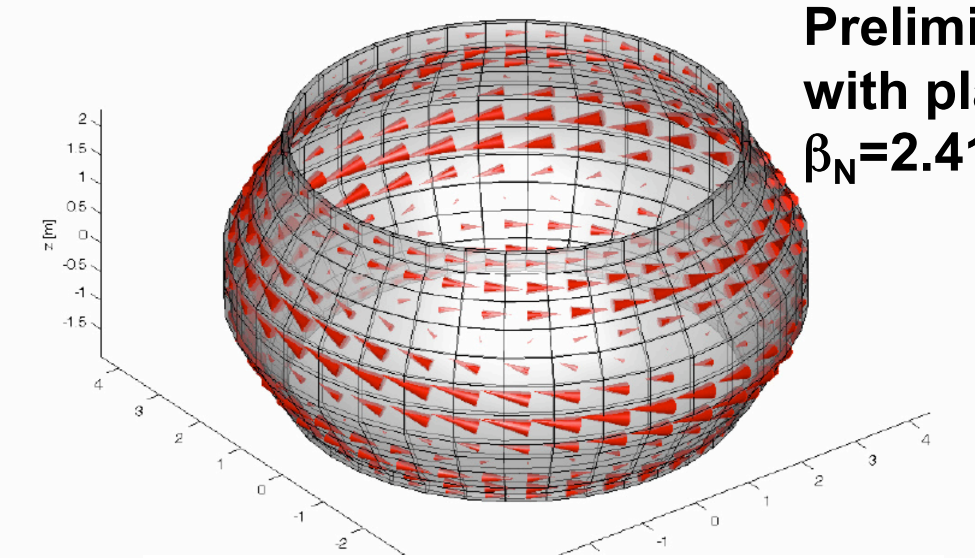
- 3D features of conducting structures (SP, VV, …)
- Feedback Active control
- Plasma Rotation

Active stability analysis for

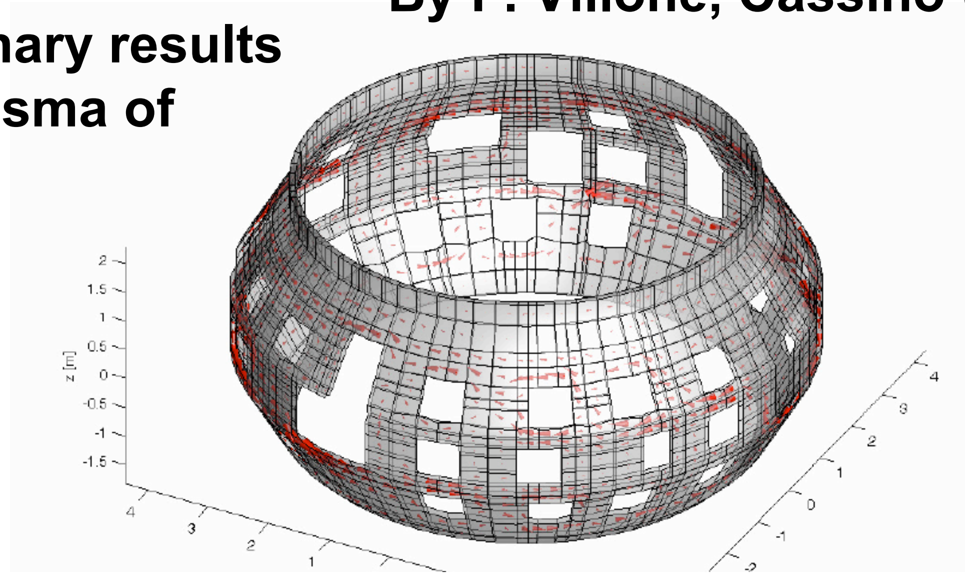
- Estimation of voltage, current and frequency of power supply
- Optimization of controller

By F. Villone, Cassino U.

Preliminary results with plasma of β_N=2.41



Vacuum vessel + stabilizing plate
n=1 RWM growth rate γ ~ 10 s^{-1}



Vacuum vessel + stabilizing plate with holes
n=1 RWM growth rate γ ~ 17 s^{-1}

Summary

JT-60SA project

- The project mission of JT-60SA is to contribute to early realization of fusion energy by supporting exploitation of ITER and by complementing ITER for DEMO.

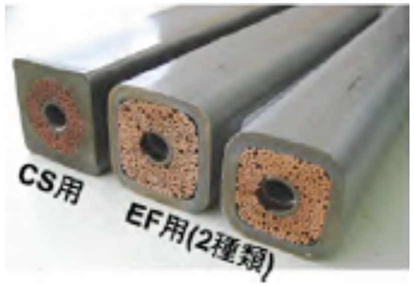
RWM control system

- RWM analysis by VALEN code shows stability of JT-60SA steady state plasma reach to β_N = 4.3.
- Required current for RWM control was estimated from VALEN results. More careful simulation with actual conditions needs to obtain the actual current
- MIC is considered as the conductor of the sector coils.
- The company which have potential to make MIC with SS was found and R&D of MIC has been started.
- EM force of RWM control coils during disruption is evaluated with DINA code.
- RWM control simulations with CarMa code are under consideration for estimation of voltage, current and frequency of power supply and optimization of controller.
- RFX experiment with reduced coil sets for mode rigidity study has been started.

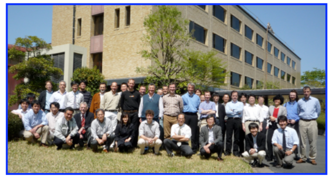
Procurements are on schedule towards the first plasma in 2016

PF Coil Manufacture Building

PF Conductor Manufacture Building with *630 m long line for jacketing*

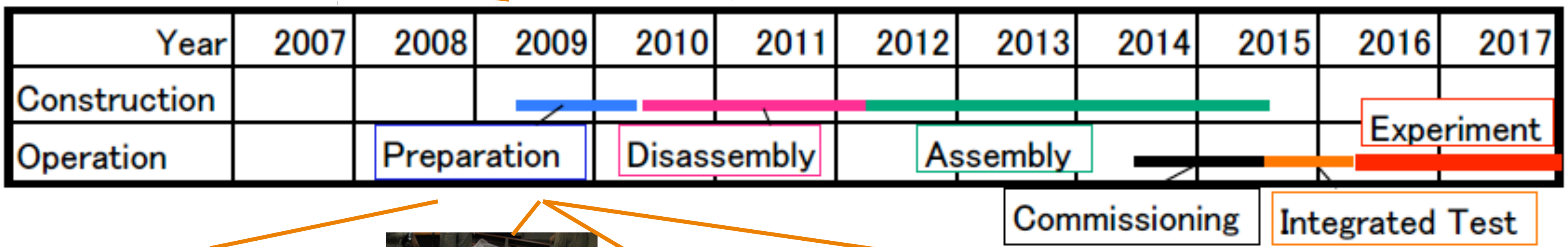


Cu Dummy Conductor

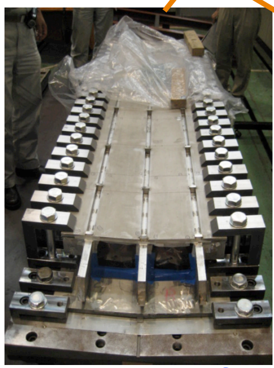


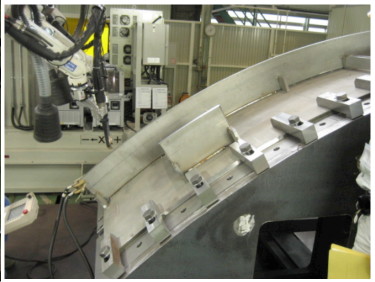
TCM-5 (2009.April, Naka)

TCM-6 (2009.Sep.Madrid)



Material for V.V.





Prototype of VV and welding test


JT-60SA Research Plan

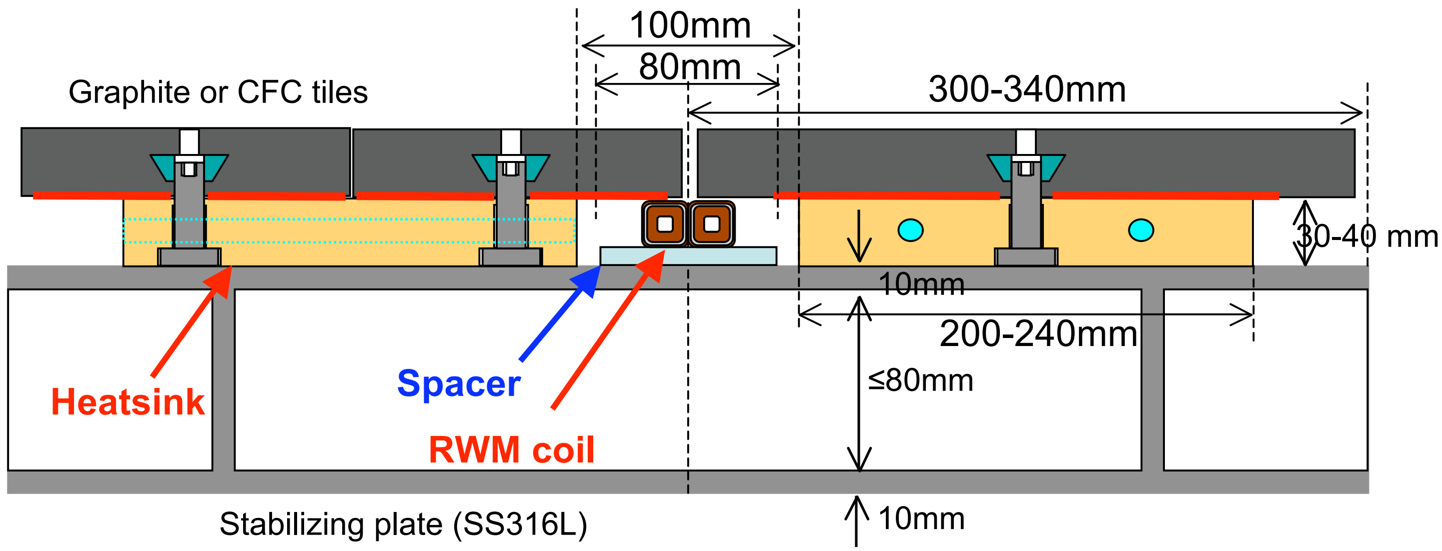
– Research Objectives and Strategy –

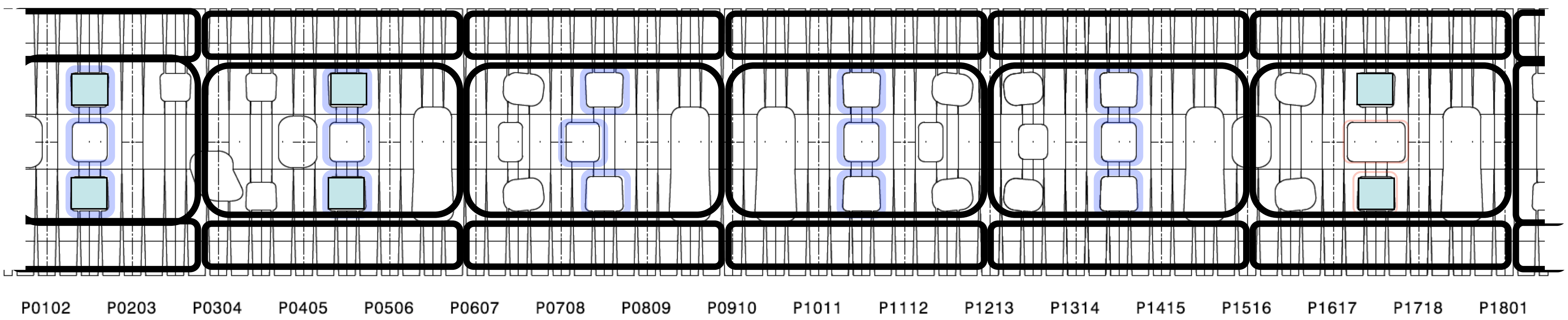
Version 1.0
2009, May 11

JT-60SA Physics Unit
JAEA Home Team

JT-60SA Research Plan

Example of internal sector coil





Required current for RWM control

Rough estimation of coil current from VALEN results.

- **Turn on mode control feedback at detection of RWM at ~2 gauss mode amplitude (t=0.001s)**
- **Time delay is supposed to be 1ms**
- **Mode control starts at t=0.002s,**

  14/2 x 1.7 ~ 12 kA

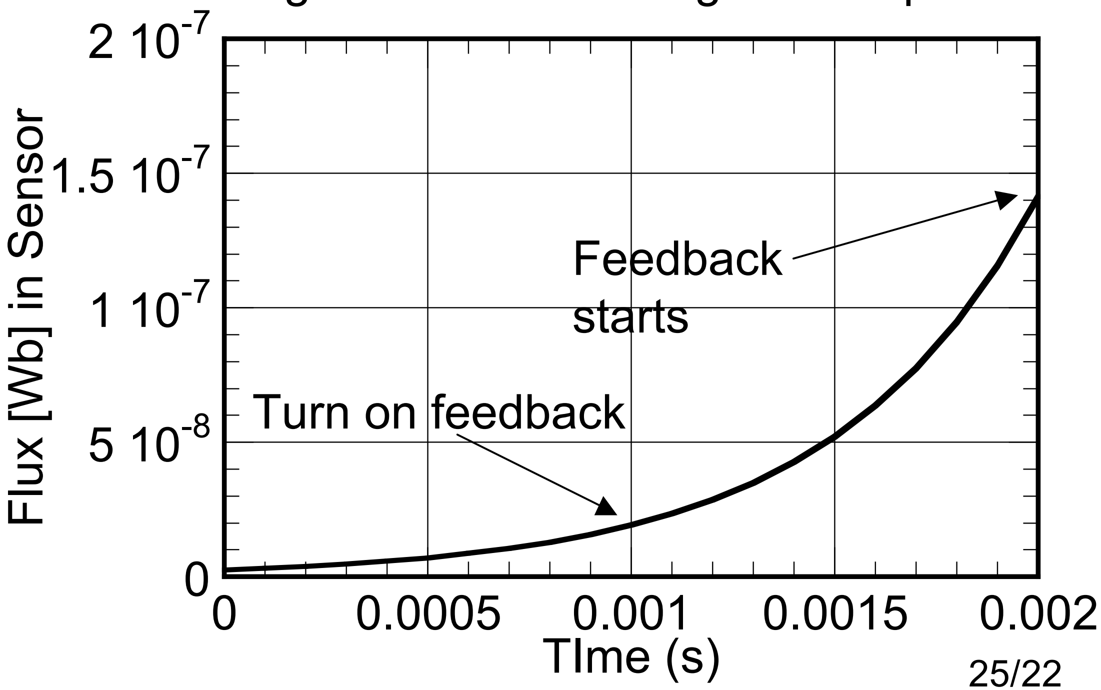
  Designed value of maximum control coil current is 20kA.

More careful simulation with actual conditions needs to obtain the accurate nessesary coil current

- **turn numbers of coil,**
- **delay time,**
- **mode amplitude at detection,**
- **with sheath of coil,**
- **with noise**

  Specification of power supply will be determined after calculation.

Free growth of RWM magnetic amplitude



Error Field correction : (1) EFCC

Current EFCC map on vacuum vessel

Toroidally :6
Poloidally :3 = 2(Upper and Lower coils)
+ 1(mid-plane coil)