Design study of RWM control system on JT-60SA

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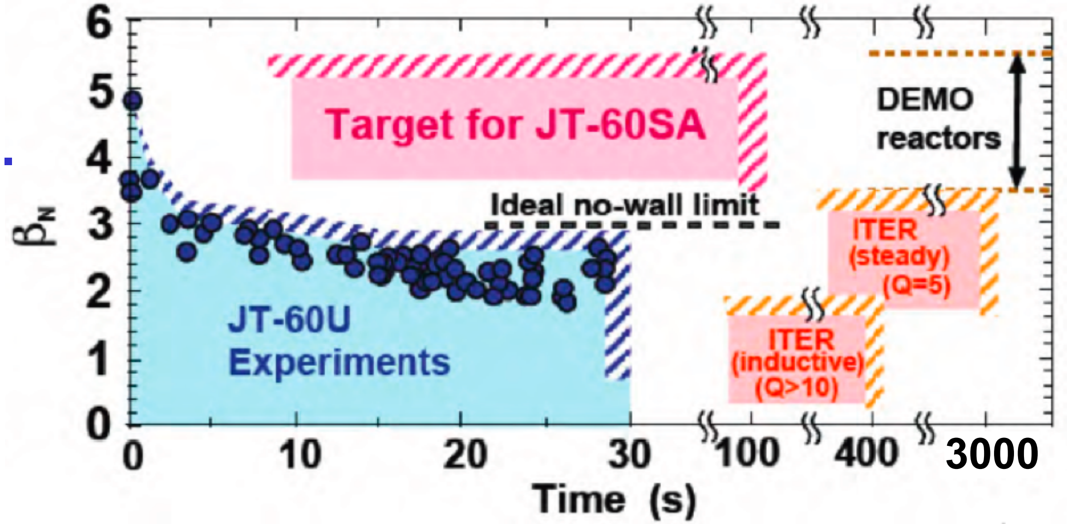
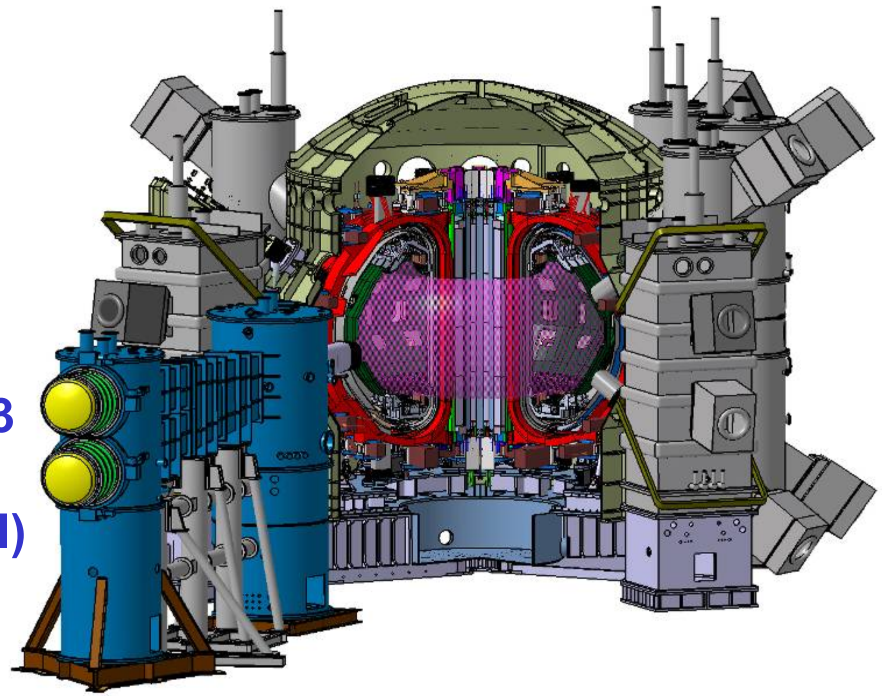
Introduction

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

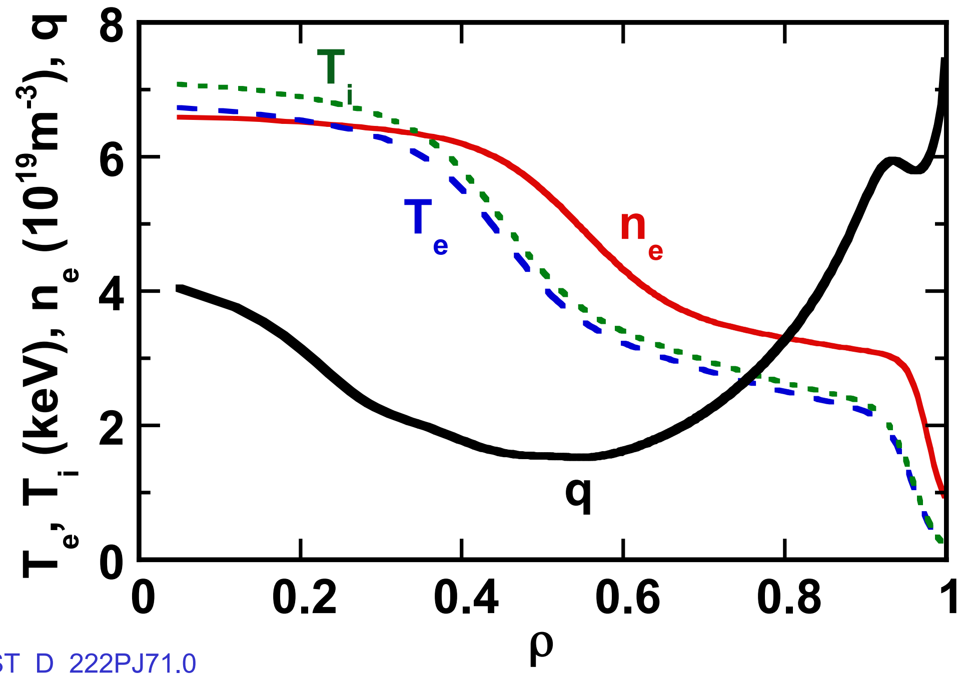


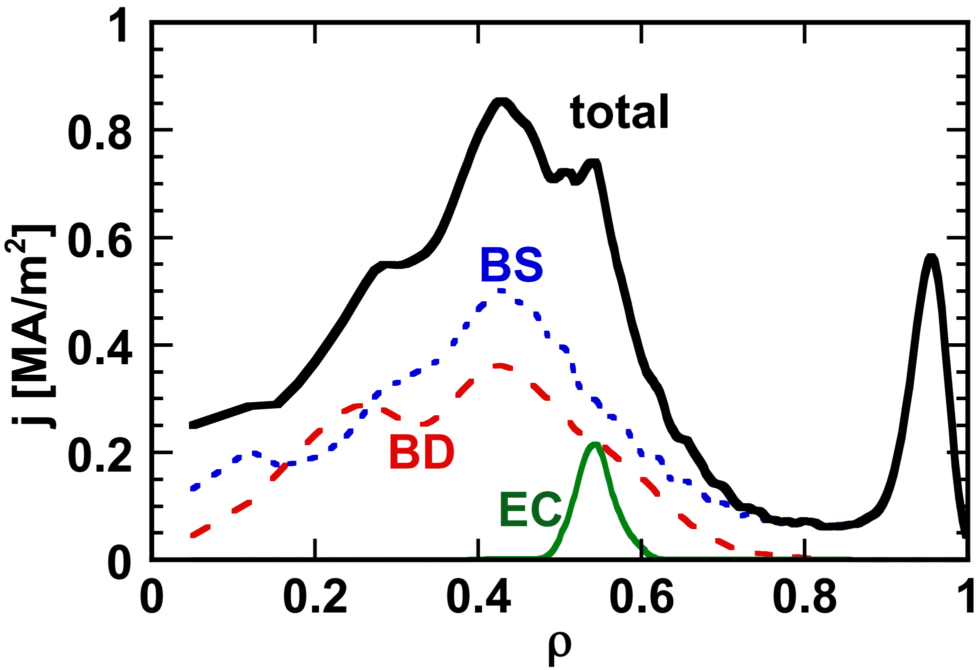
- **For High beta operation, RWM stabilization is necessary.**
  - Stabilization by rotation
    - Not sufficient because of ELM, FB, EWM…
  - RWM active control system
    - RWM control coil (fast control) Simultaneously stabilization of n=1,2,3 RWM
    - Error field correction coil (slow control) also used for ELM control



High beta full non-inductive operation

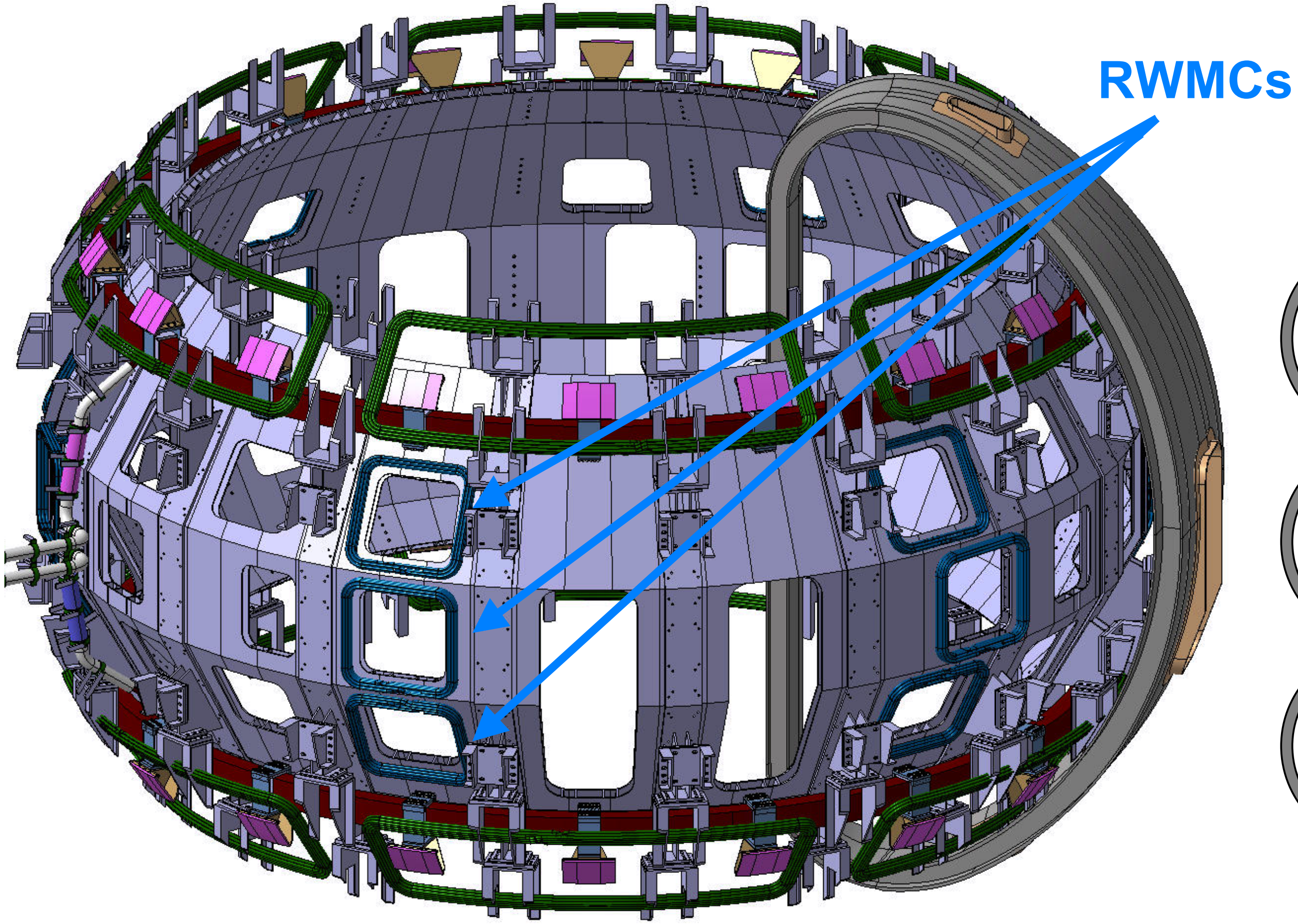
- Full current drive with I_p=2.3 MA, B_t=1.7 T, β_N = 4.3, f_{GW} = 0.85, f_{BS} = 0.68 for H_{H98y2} = 1.3 with P_{tot} = 37 MW.
- p(r) and j(r) are consistent with the ACCOME analysis, where q_{min} ~ 1.6.
- Normalized parameters are close to those required in DEMO (Slim CS)
- Stable for n≤4 kink-balloning mode with ideal wall (MARG2D)

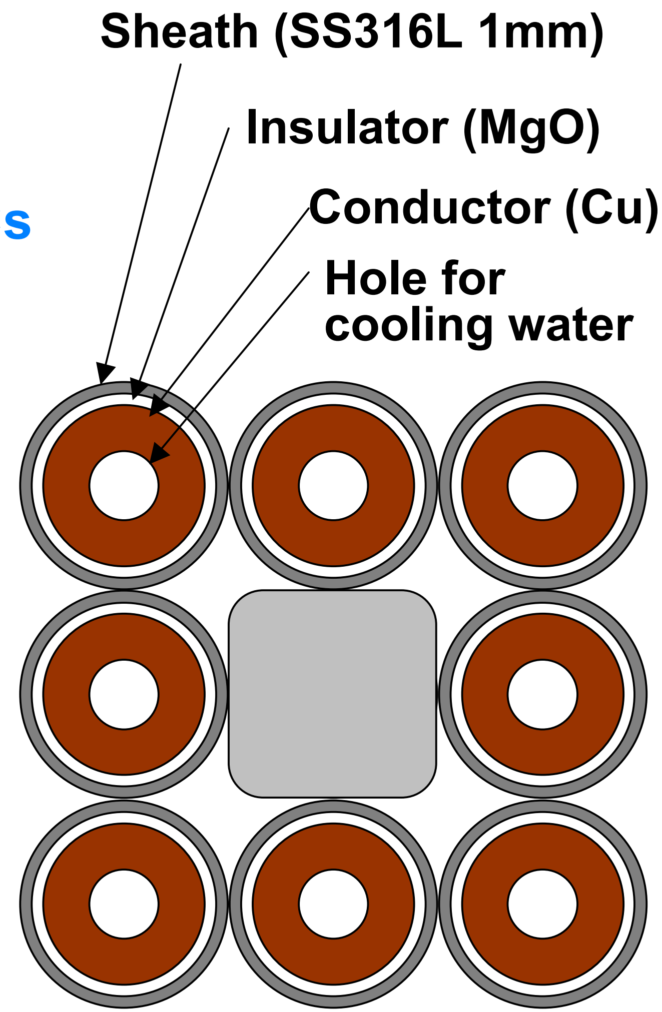




RWM Control Coils

- 3 poloidal x 6 toroidal = 18
- 8 turns
- 2.5kA/turn (20 kAT)
- Conductor: Mineral insulation (MI) cable





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RWMC current requirement derived from VALEN results

VALEN shows the JT-60SA RWMC of present design can stabilize RWM for β_N ~4.3 (C_β ~ 0.90)

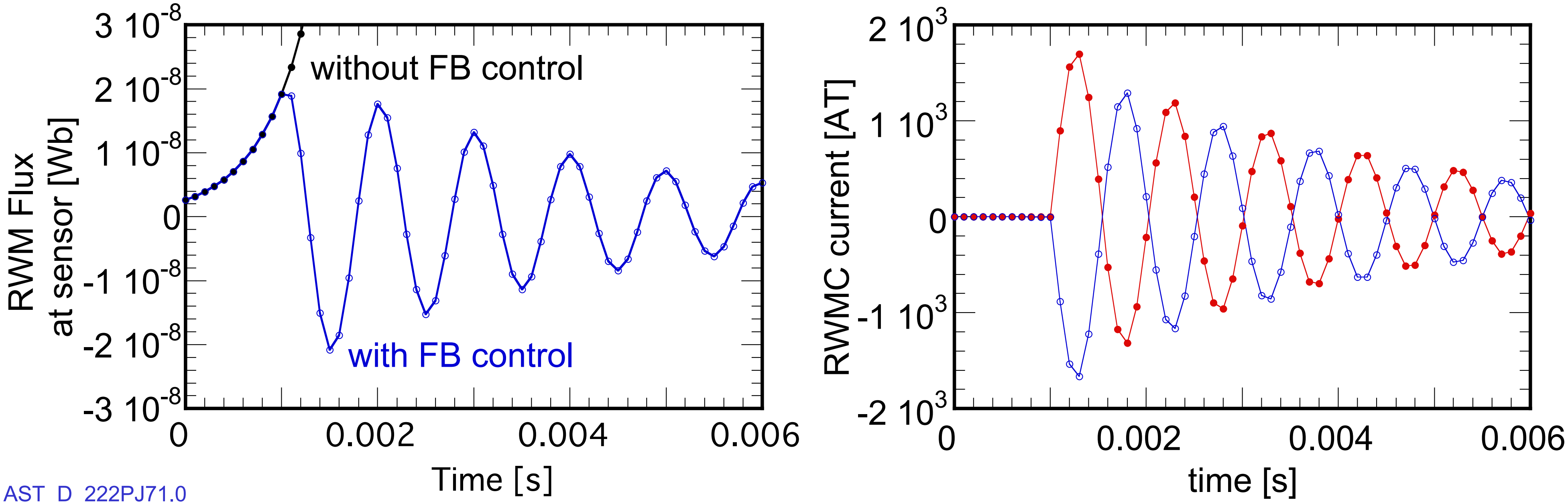
The maximum current of RWM control coils is estimated at about 1.7 kAT.

- •Maximum current of RWMC of present design is 20kAT.

However this current requirement is optimistic because,

- Stabilizing plate with the single wall configuration (Double wall for present design)
- without sheath (with 1mm SS sheath for present design)

Simulation including actual coil conditions is necessary.

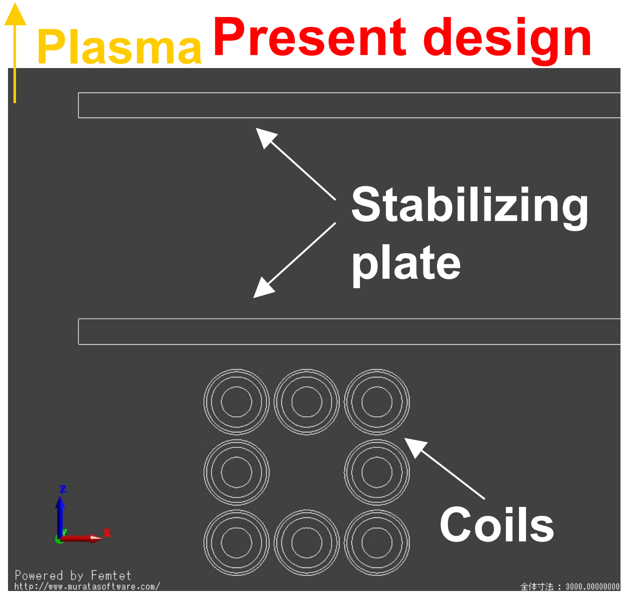


FEM analysis were performed to complement the RWMC current requirement derived by VALEN.

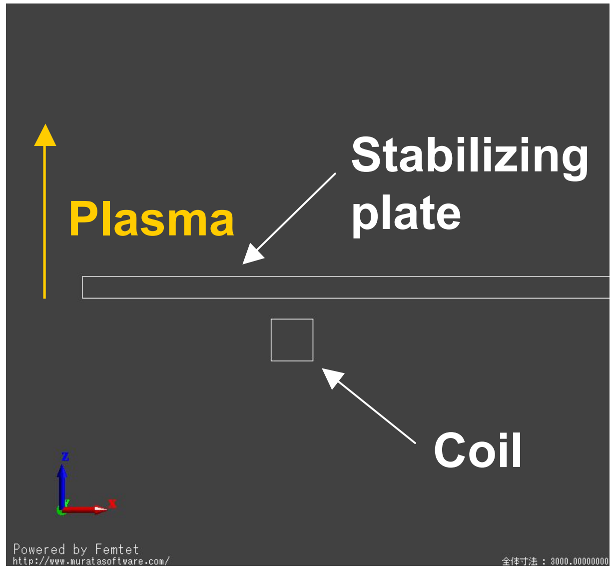
- **2D FEM analysis performed for VALEN RWMC configuration and present design.**

		VALEN	Present design
Coil	Turn	1	8
	Conductor size	400 mm^2	200 mm^2
	Coductivity	5.0e7 S/m (Cu)	5.977e7 S/m (Cu)
	Sheath thickness	no	1 mm (SS316L)
	Coil current	20kAT (20kA x 1 turn)	20kAT (2.5 kA x 8 turn)
SP	Number of SP	1	2
	SP thickness	10 mm	10 mm
	conductivity	2.2e6 S/m (Ferritic steel)	1.35e6 S/m (SS316L)

Present design

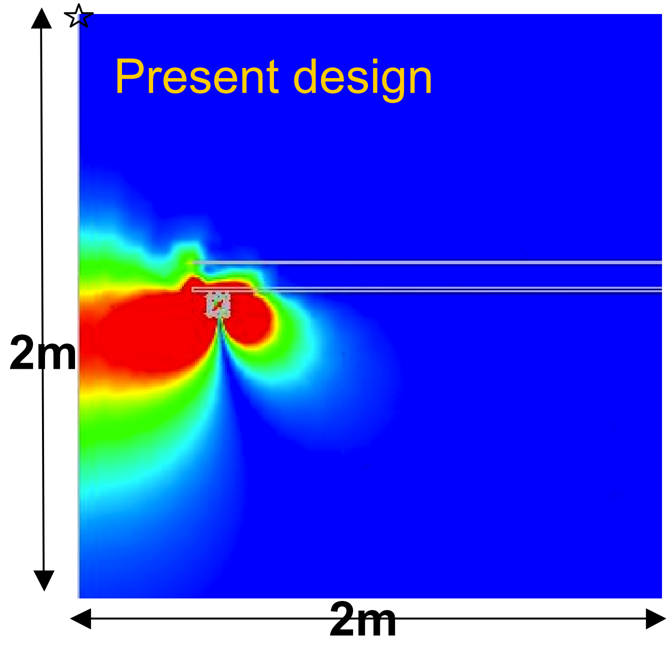


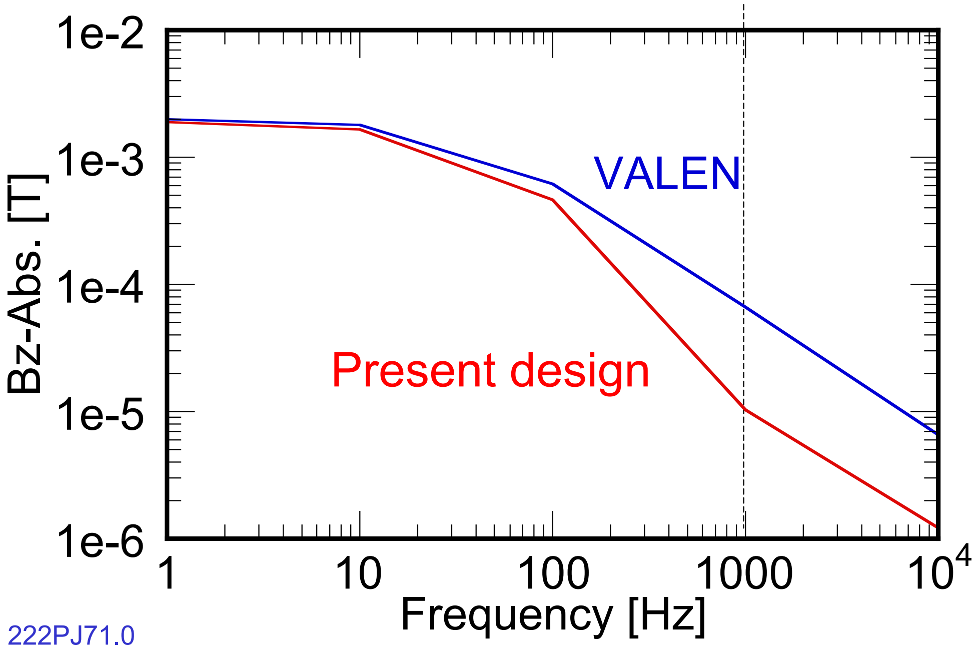
VALEN model

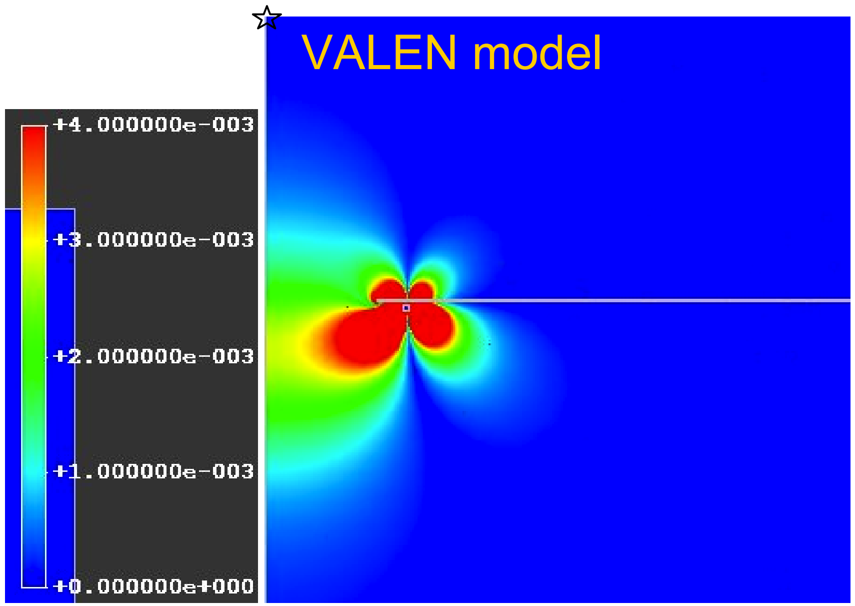


RWMC current requirement has been estimated by comparison of VALEN and present configuration

- Bz around the q = 3 surface (indicated by star in left figures) induced by both configuration with 1kHz and coil current of 20 kAT are compared.
- Bz for the present design is 6.4 times smaller than that for VALEN model.
- RWMC current requirement of 20kAT is estimated including reasonable time delay and noise.
- Shielding effect of SP with double wall configuration is huge!

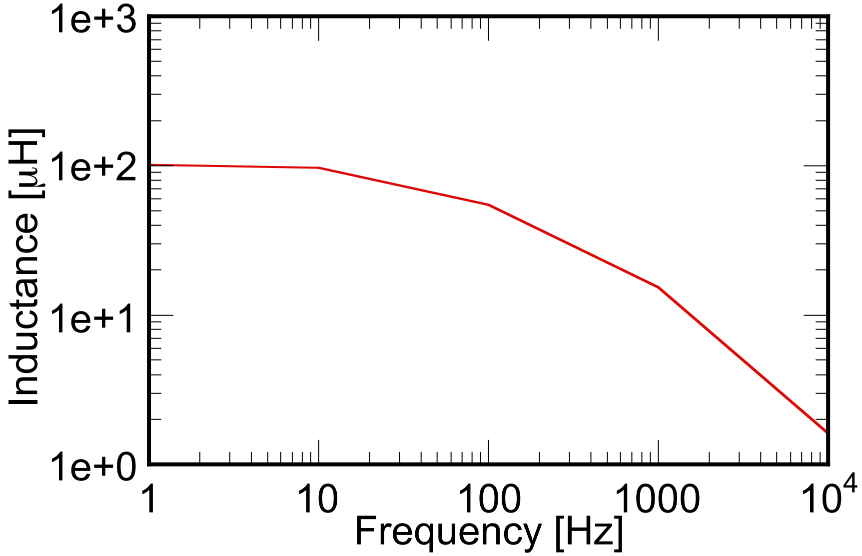


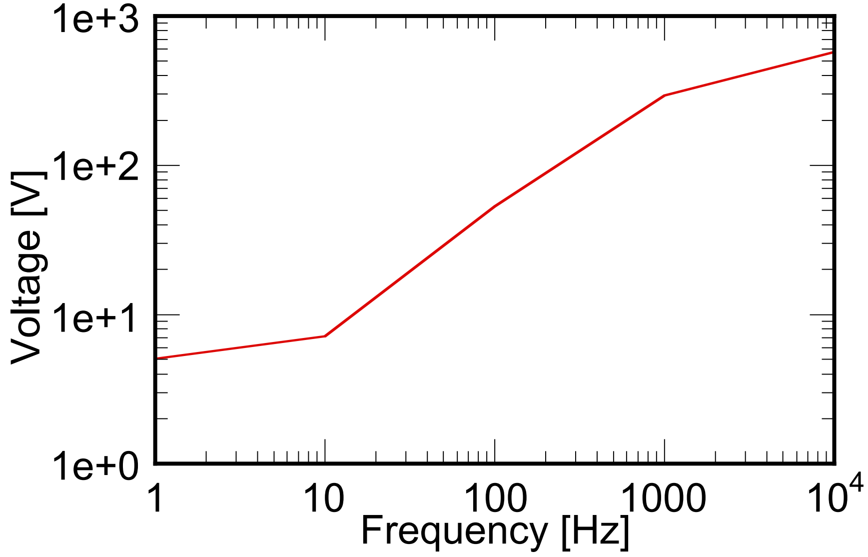




RWMC voltage requirement has been estimated with FEM analysis

- **Voltage at RWMC is 293 [V] for 1kHz and 20kAT current**
- **Voltage at MIC feeder in the VV is 50 [V] for 1kHz**
- **Voltage of 50m x 2 feeder (200 mm^2 cross-section) outside the VV is 12.5 [V]**
- **293 + 50 + 12.5 = 355.5 -> 400 [V]**





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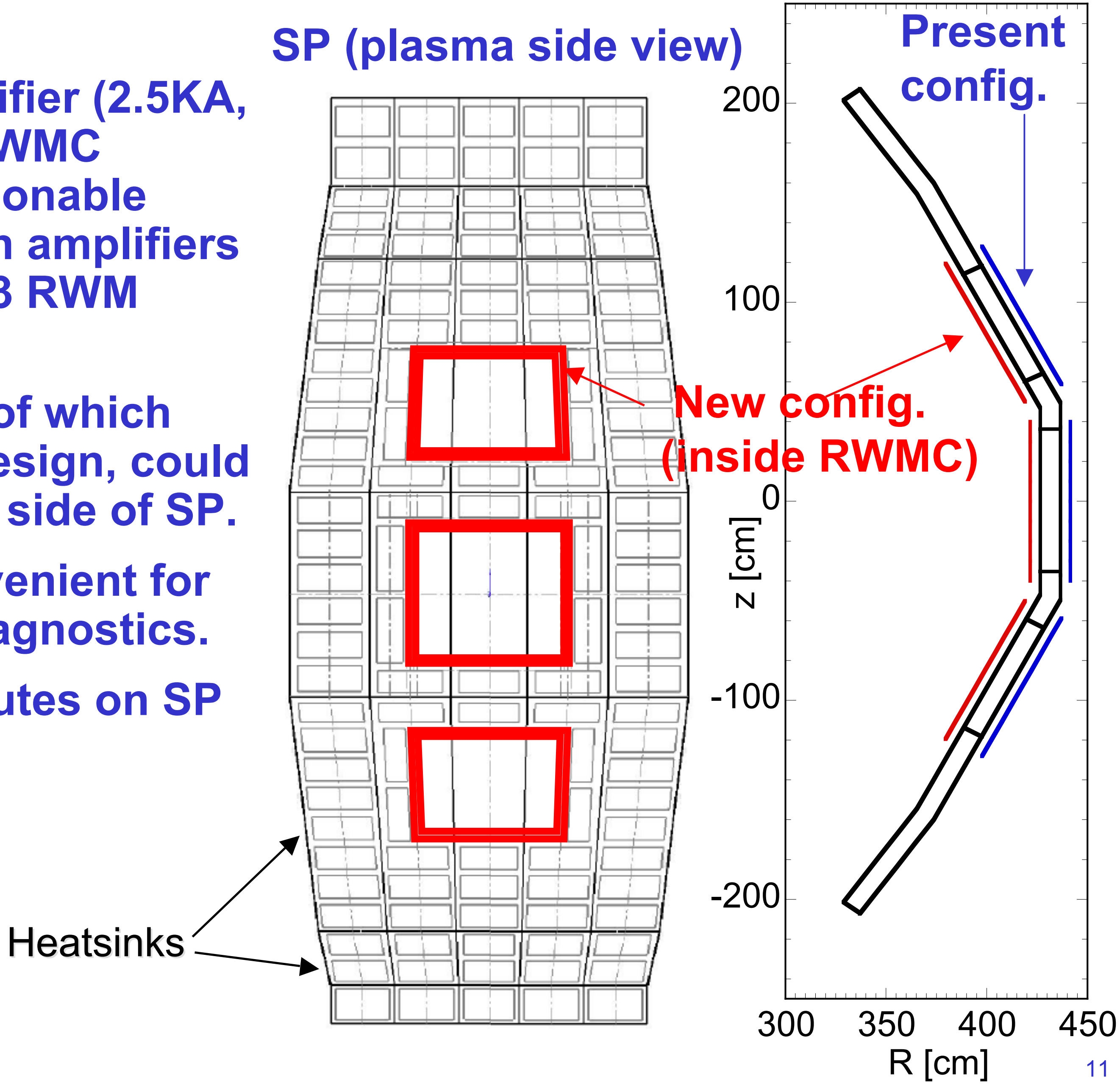
New configuration of one or two turns RWMC at the plasma side of SP is proposed.

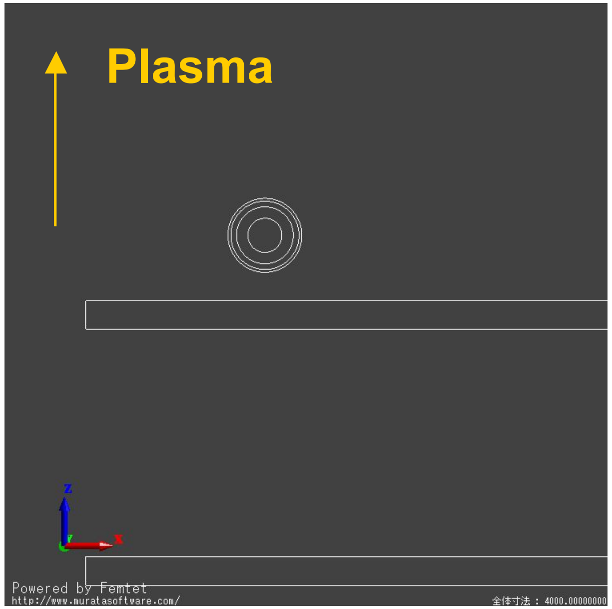
- The requirements of amplifier (2.5KA, 400V, 1kHz) for present RWMC configuration are not reasonable because we need eighteen amplifiers for simultaneously n=1,2,3 RWM stabilization.
- One or two turns RWMC, of which size is same as present design, could be installed at the plasma side of SP.
- Inside RWMC is also convenient for RWMC installation and diagnostics.
- We will try to keep the routes on SP for larger inside RWMCs.



FEM analysis of plasma side 1-turn configuration

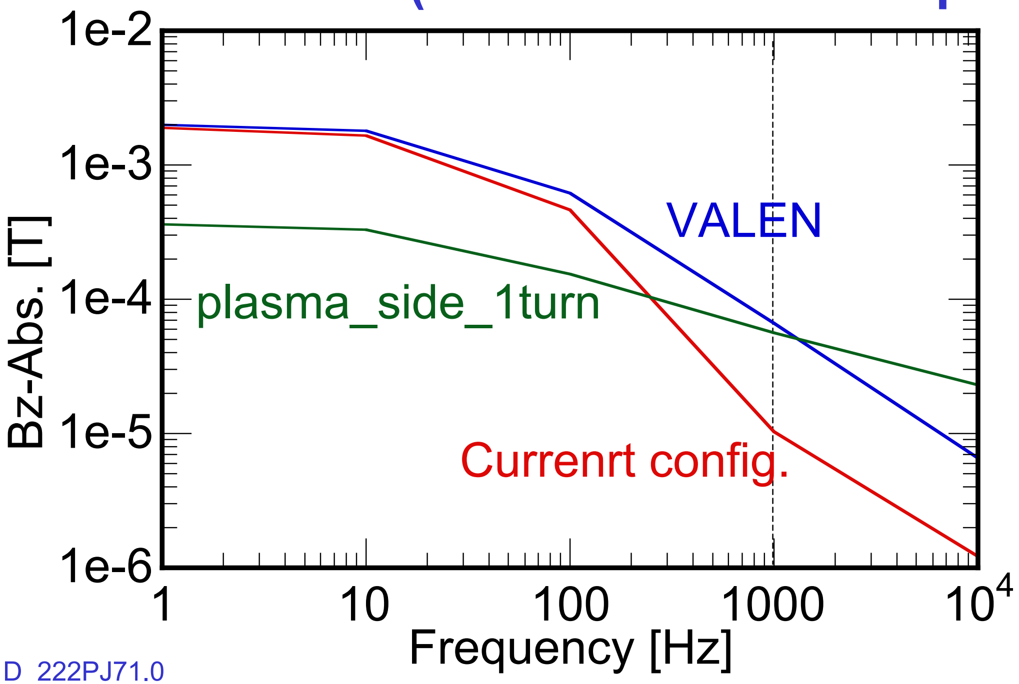
		VALEN	Current config.	Plasma side 1-turn
Coil	Turn	1	8	1
	Conductor size	400 mm^2	200 mm^2	<-
	Coductivity	5.0e7 S/m (Cu)	5.977e7 S/m (Cu)	<-
	Sheath thickness	no	1 mm (SS316L)	<-
	Coil current	20kAT (20kA x 1 turn)	20kAT (2.5kA x 8 turn)	2.5kA (2.5kA x 1 turn)
SP	Number of SP	1	2	<-
	SP thickness	10 mm	10 mm	<-
	conductivity	2.2e6 S/m (Ferritic steel)	1.35e6 S/m (SS316L)	<-

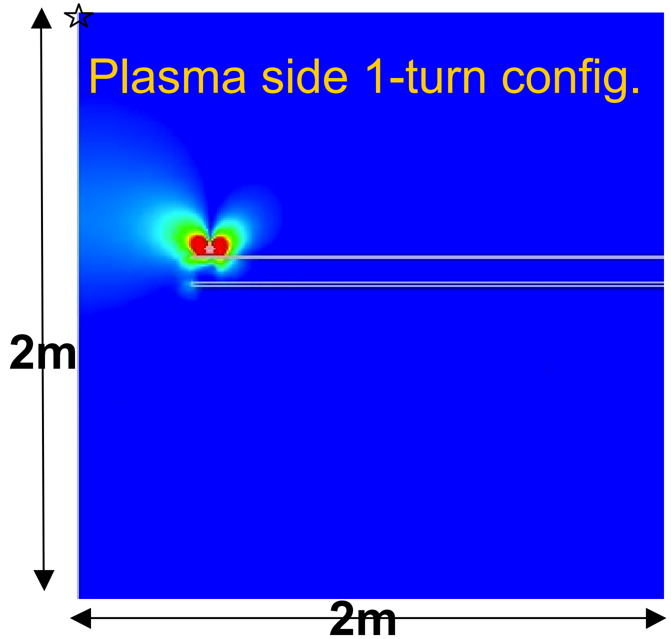
Plasma side 1-turn

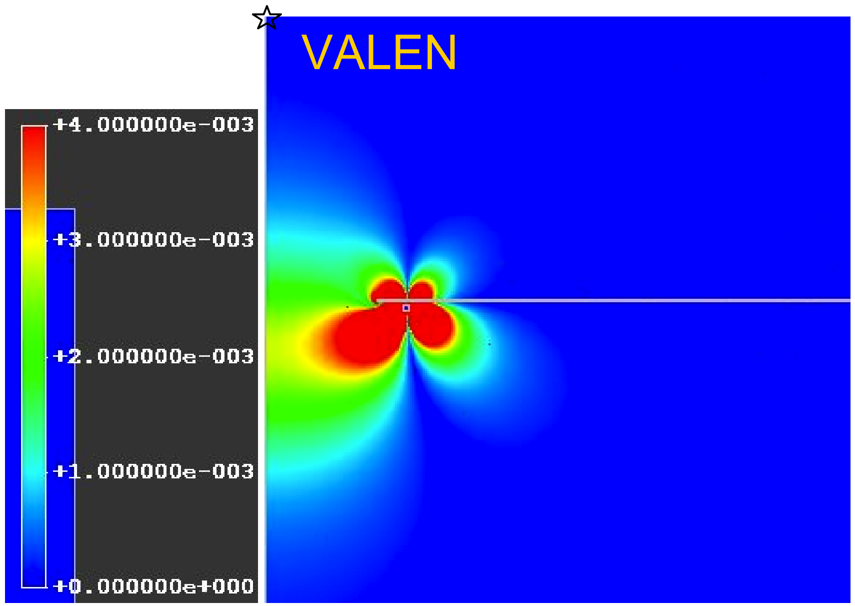


Requirement of power supply is significantly reduced for plasma side 1 turn RWMC

- Bz around q = 3 with 1kHz are calculated for
  - 1-turn RWMC at plasma side (2.5 kAT),
  - 8-turns RWMC of present configuration (20kAT),
  - 8-turns RWMC of VALEN configuration (20kAT).
- Bz of plasma side 1-turn configuration is,
  - 84% of that for VALEN model
  - five times larger than that of outside 8-turns
- Current and voltage are evaluated as ~2kAT and ~6 V at RWMC (20kAT and 300V for present conf.)



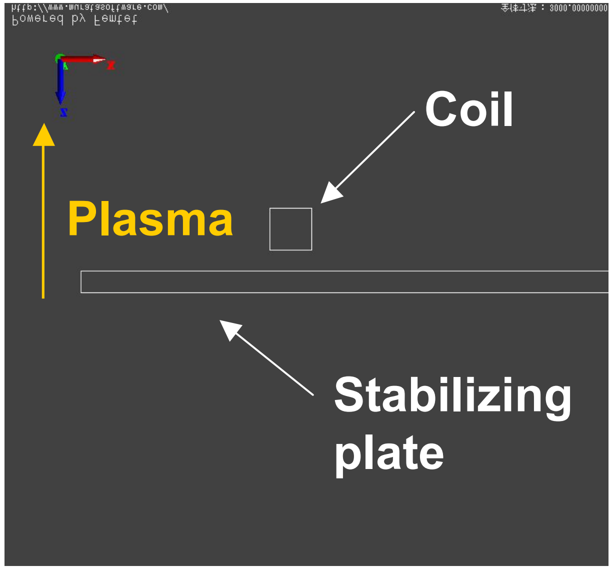


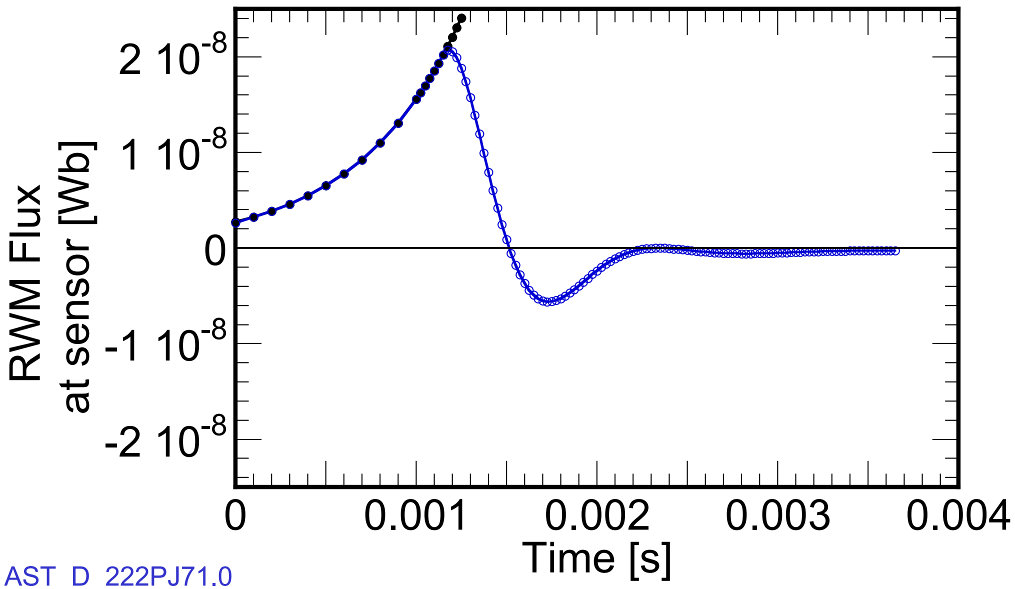


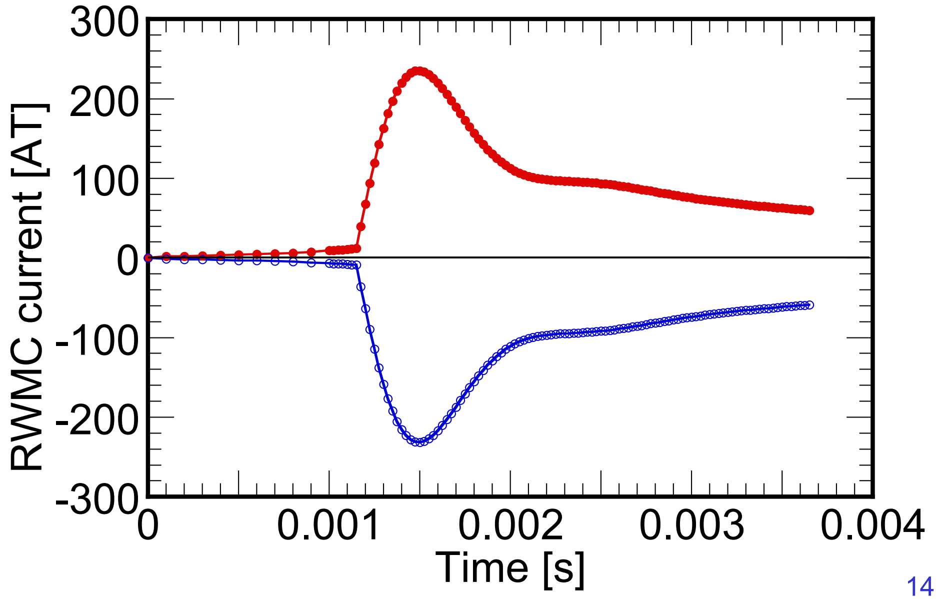
VALEN results for the plasma side 1-turn RMWC

- Maximum Current: ~240 AT
- Maximum voltage: ~2.1 V
- Conductor without sheath.
- Single wall configuration of SP (not so effective)

New VALEN model







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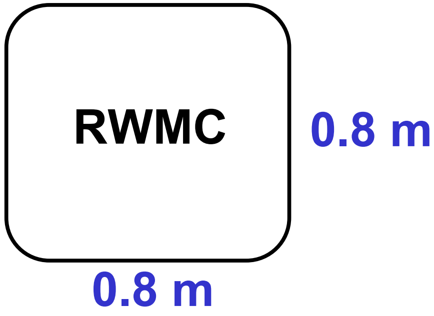
EM force analysis during disruption with DINA code

- Outside eight turn RWMC
- Inside one turn RWMC
- As the initial plasma for DINA simulation we adopted the 5.5 MA plasma equilibrium at end of burn.
- Total EMF = EMF [N/m] x length(0.8) [m] x n(1 or 8) [turn]

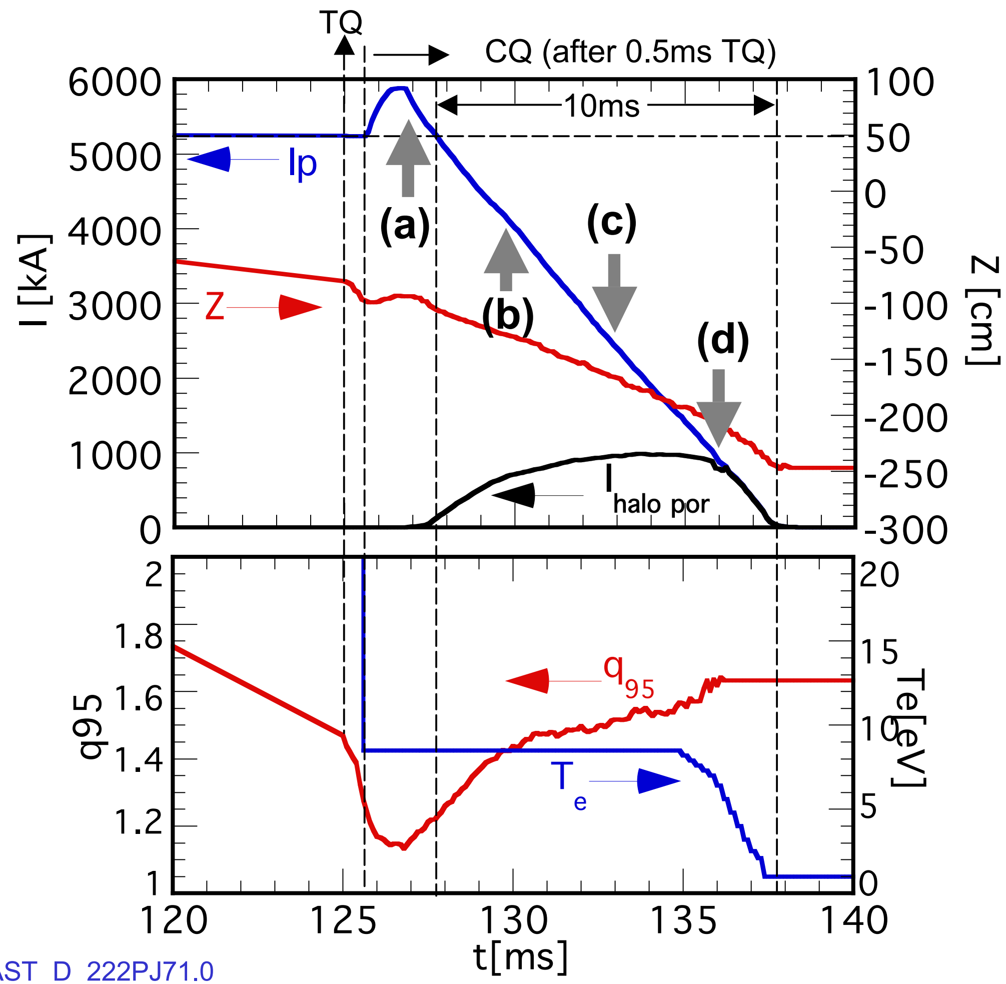


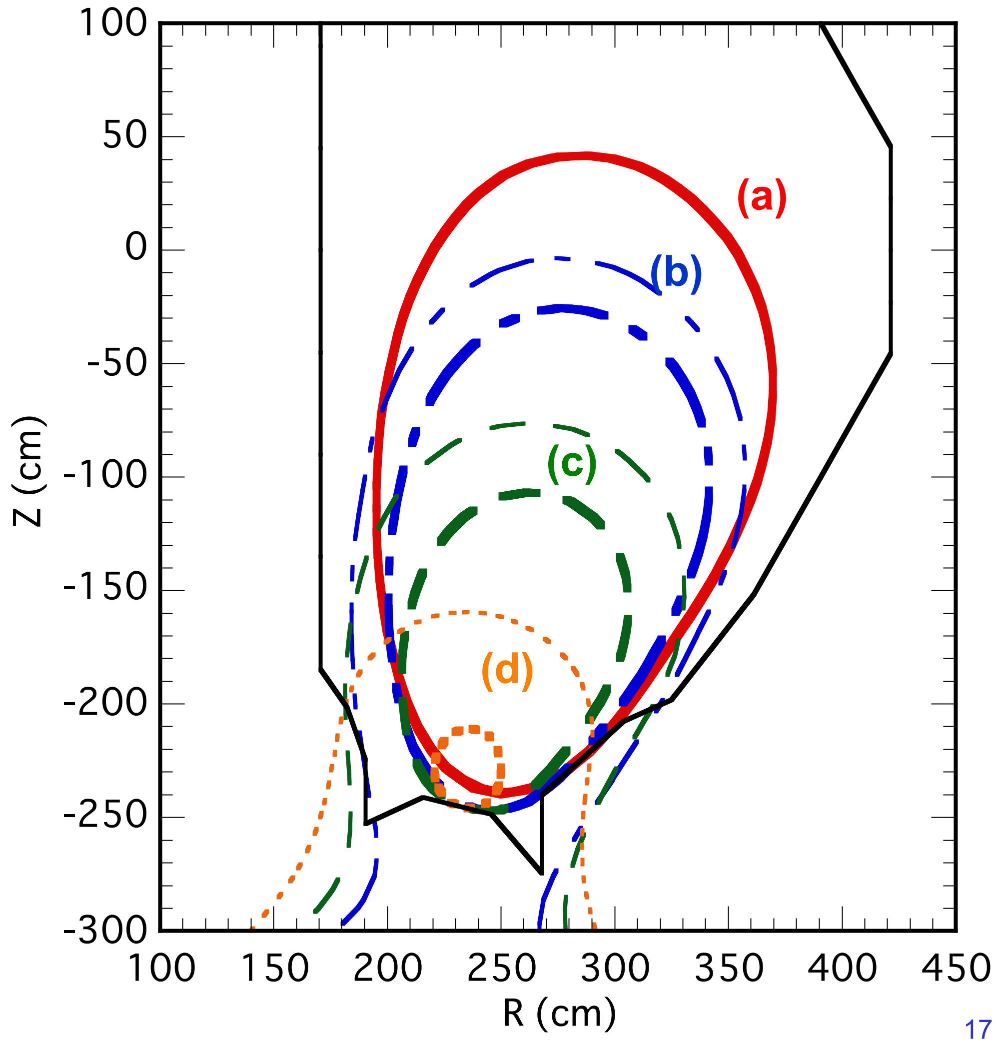
I_p	5.5MA
β_p	0.83
l_i	0.71
κ	1.86
a	1.14m
R_{cur}	2.97m
Z_{cur}	0.034m
q_{95}	2.70
T_e	9.1keV
Z_{eff}	2.0
n_e	$5\times10^{19}m^{-3}$

Event	Conditions Event
Downward VDE Disruption	• Caused by vertical instability due to loss of control. • Disruption (thermal quench) starts at q_{edge}=1.5. • Current quench starts 0.5 ms after thermal quench. • Plasma Current decreases linearly in 10 ms.
Major Disruption (MD)	• Plasma stays at center when disruption (thermal quench) starts. • Current quench starts 0.5 ms after thermal quench. • Plasma Current decreases linearly in 4 ms.

Downward VDE with τ_{CQ}=10ms

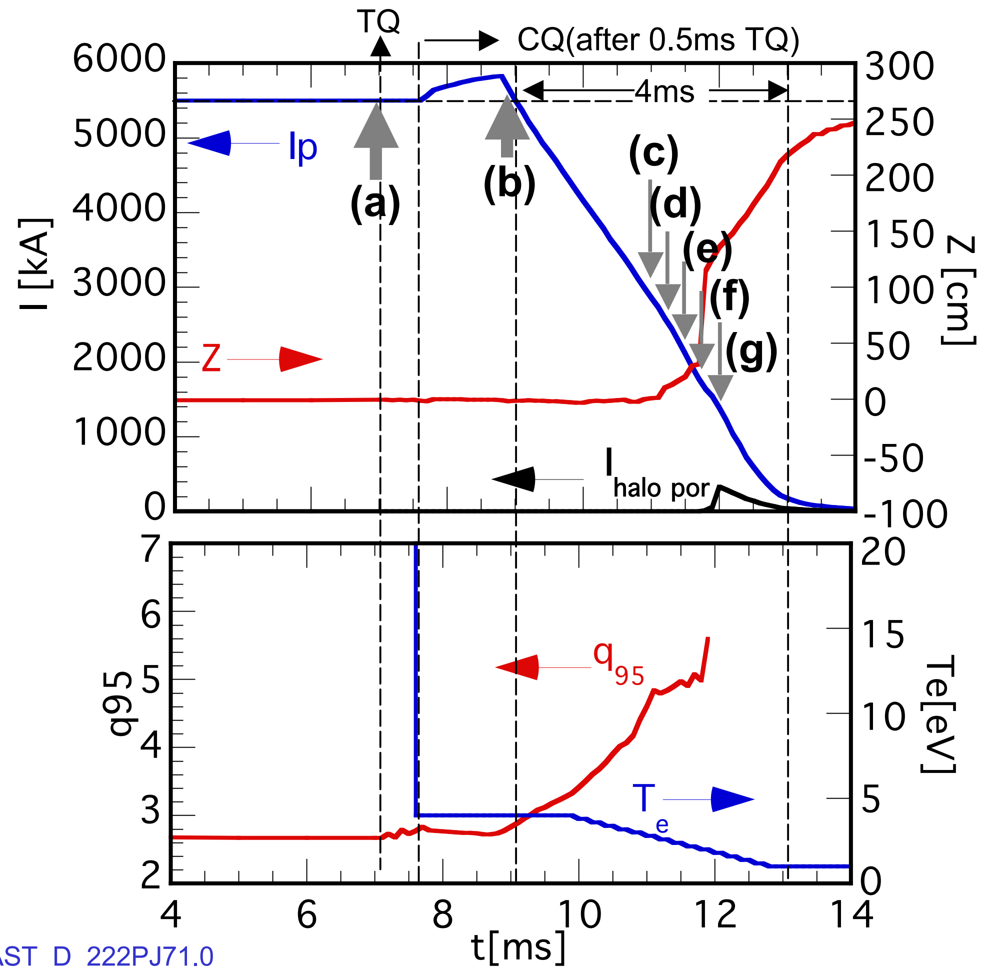
- Current quench time is adjusted by changing Te.
- All coils are supposed to be short-circuited.

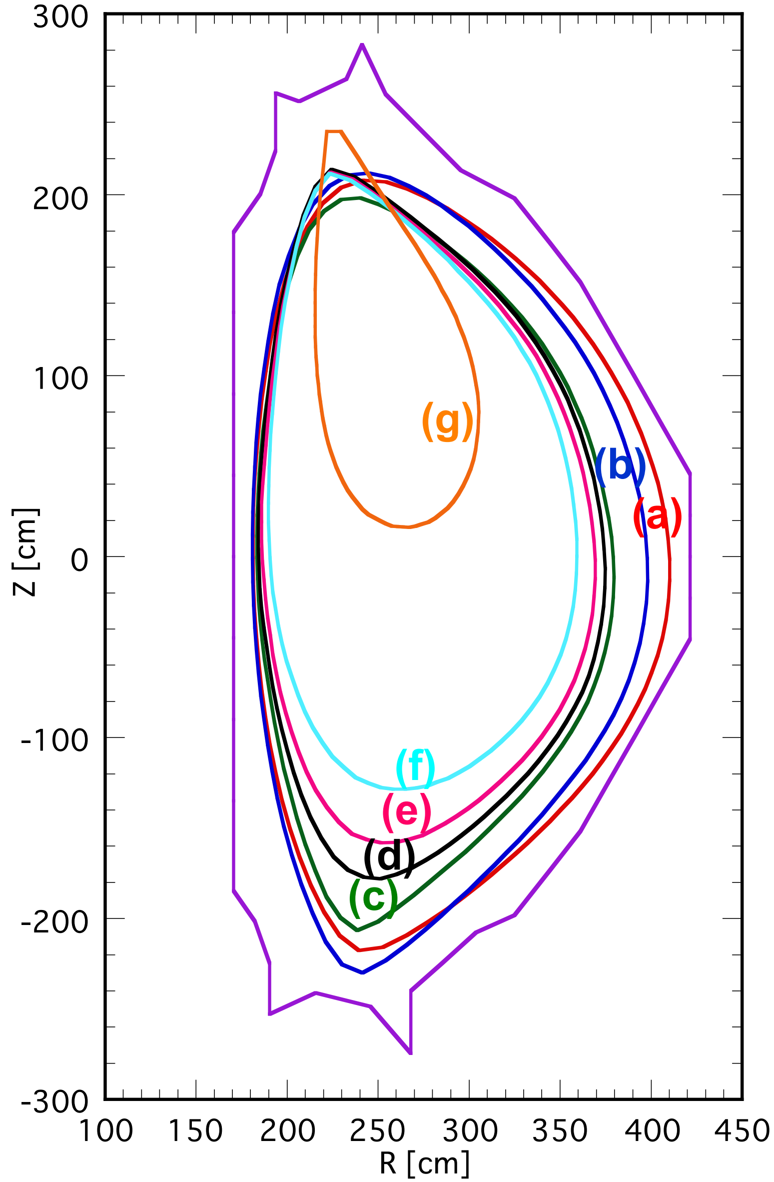




MD with τ_{CQ}=4ms

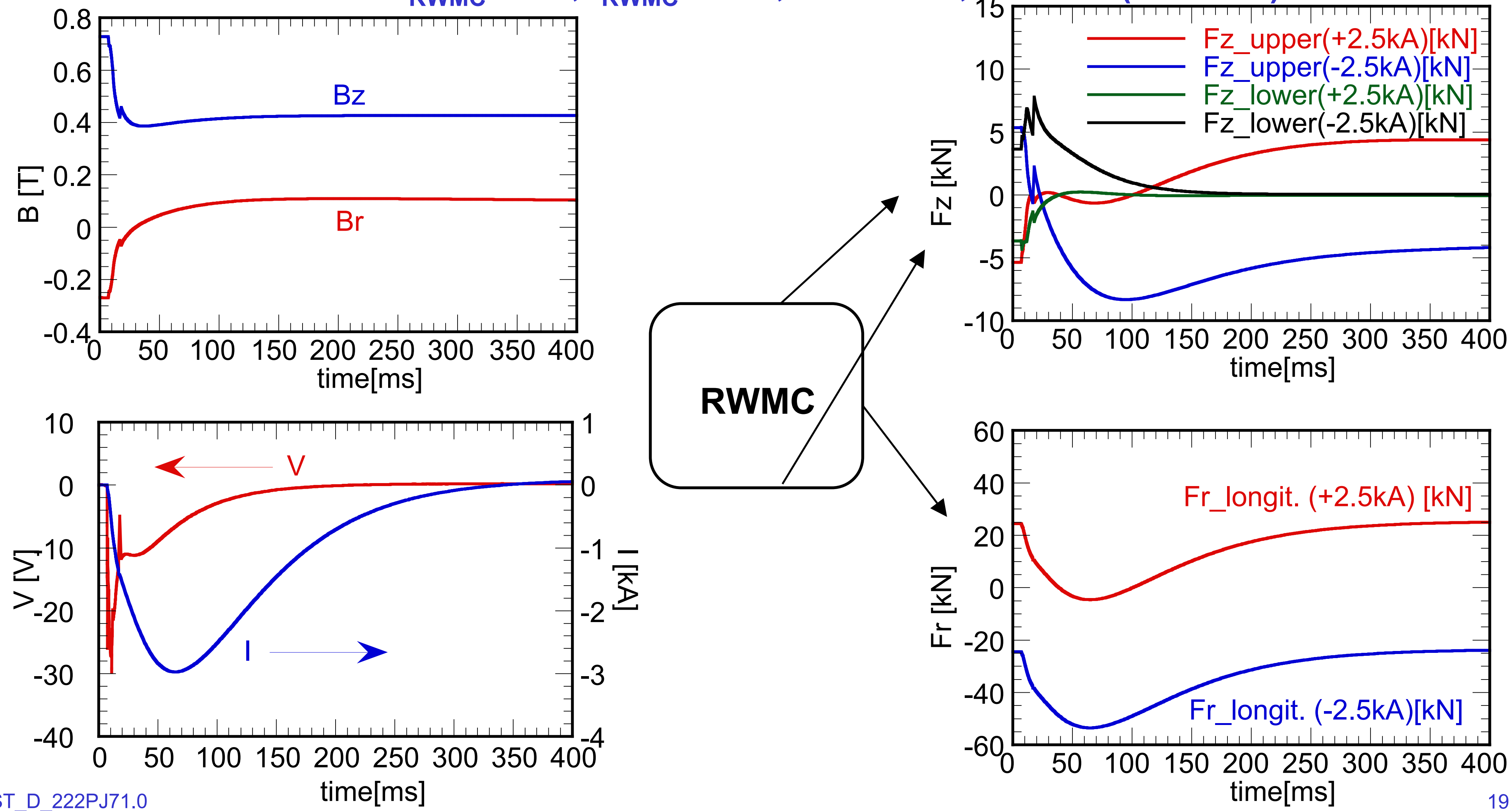
- **When thermal quench occurs, plasma is still at the center.**





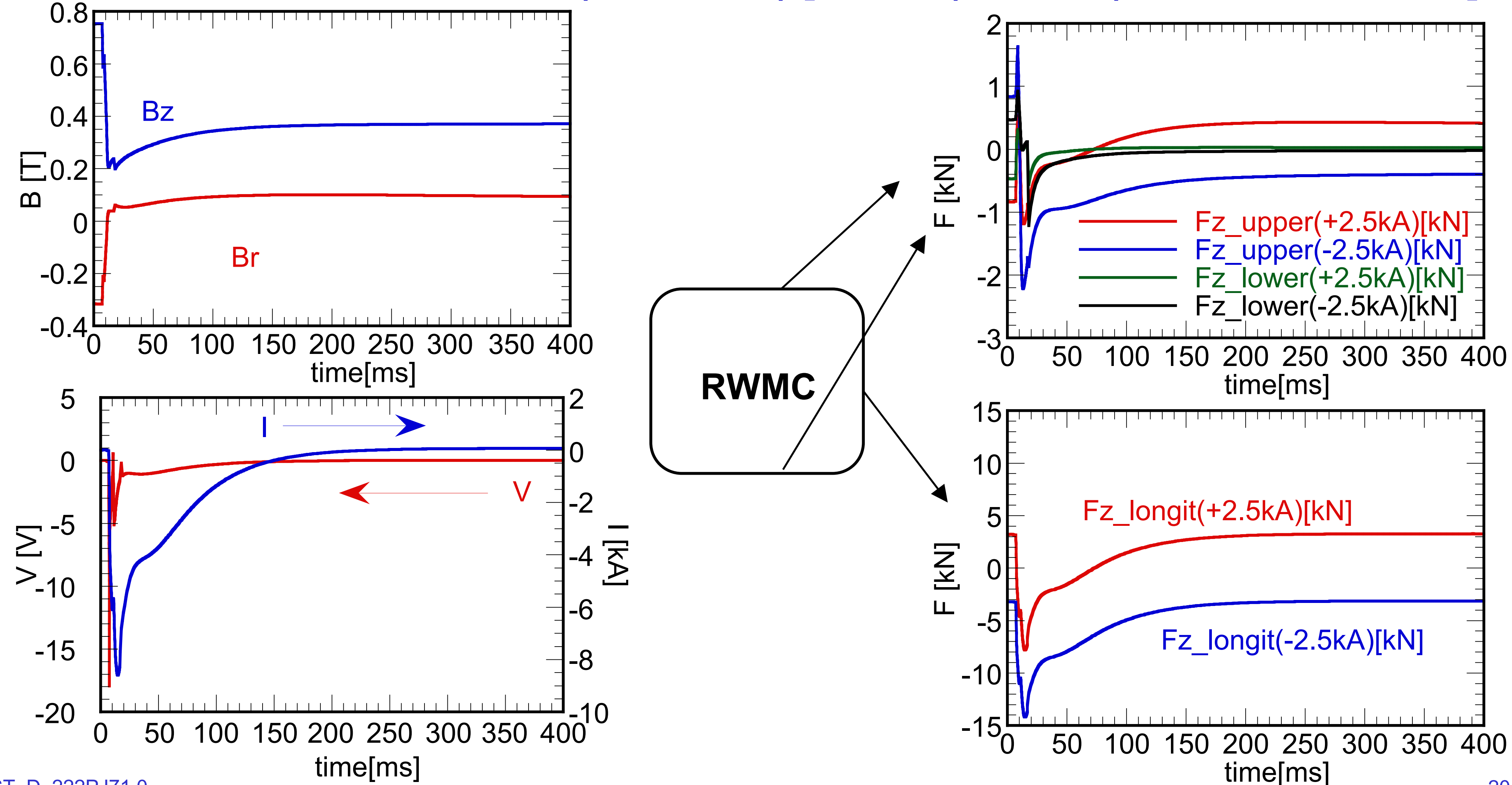
Example results of RWMC EMF at disruption ~Upper Outside RWMC (8-turn), MD with τ_{CQ}=4ms~

- Magnetic fields at RWMC are calculated by DINA code.
- Fr at longitudinal conductor of RWMC is largest due to Bt.
- Maximum value: V_{RWMC}~30V, I_{RWMC} ~3kA, total EMF; F~53kN (8.3kN/m)

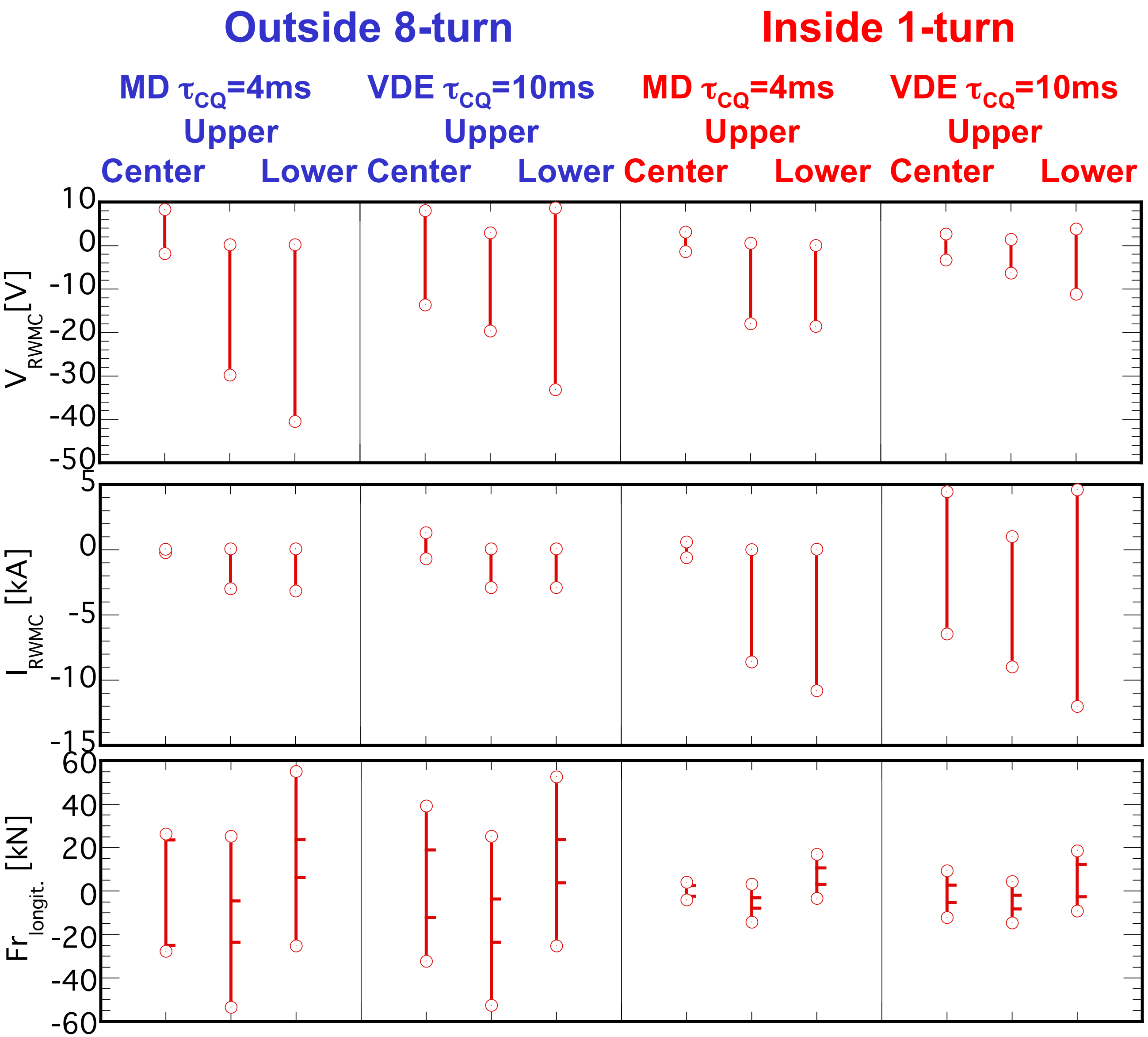


Example results of EMF of RWMC at disruption ~Upper inside RWMC (1-turn), MD with τ_{CQ}=4ms~

- **Maximum voltage: ~18V [~30 V for outside 8 turn]**
- **Maximum current: ~8.6kA [~3A for outside 8 turn]**
- **Maximum EMF: total 14 kN (17.5 kN/m) [~53kN (8.3kN/m) for outside 8 turn]**



Maximum absolute values of voltage, current and EM force are evaluated



Max absolute value	
Outside 8-turn	**Inside 1-turn**
40.4 V MD τ_{CQ}=4ms Lower	**18.6 V** MD τ_{CQ}=4ms Lower
3.1 kA MD τ_{CQ}=4ms Lower	**12.0 kA** DW VDE τ_{CQ}=10ms Lower
53.5 kN MD τ_{CQ}=4ms Upper	**14.7 kN** DW VDE τ_{CQ}=10ms upper

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RWM experiment with reduced coils on RFX-mod

RWMC 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

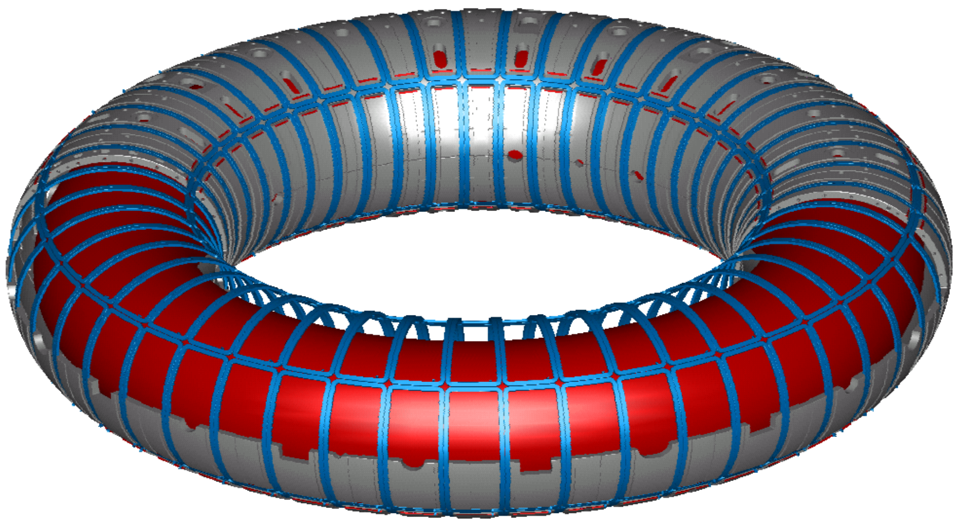
- Mode deformation
- Side band mode destabilization

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

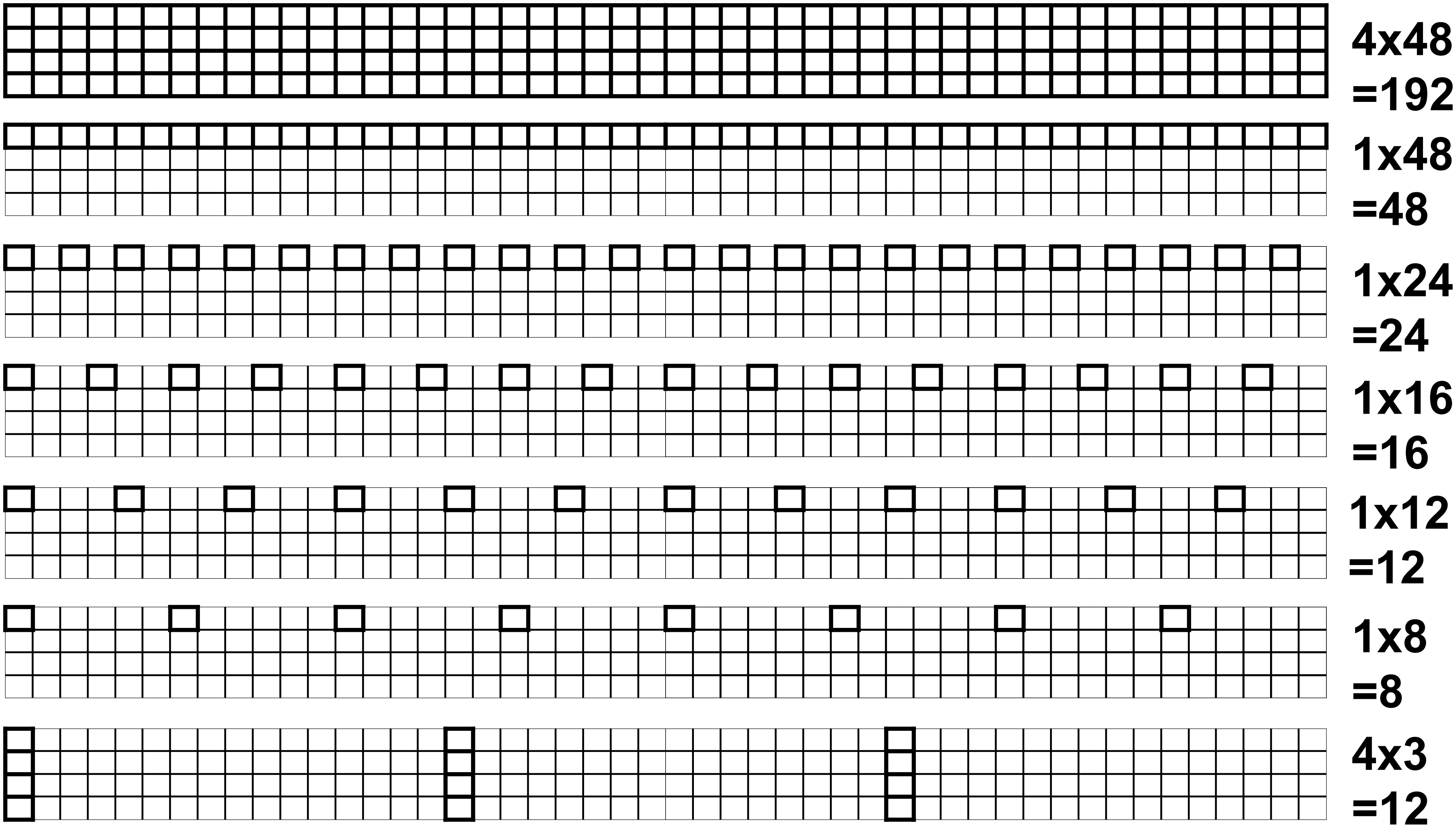
R=2m, a=0.459,
Ip> 1.5 MA (up to 2MA)

Active coil
4(poloidal)X48(troidal)=192 coils
60 (4 layers x 15 turns) turns
I_{nom}=400 A (0.3s), V_{nom}=650 V

Passive structure:
$t_{Bv,shell}$= 50 ms, $t_{Bv,eff} \approx$ 62 ms



Coil configuration for RWM control study with reduced coils on RFX-mod



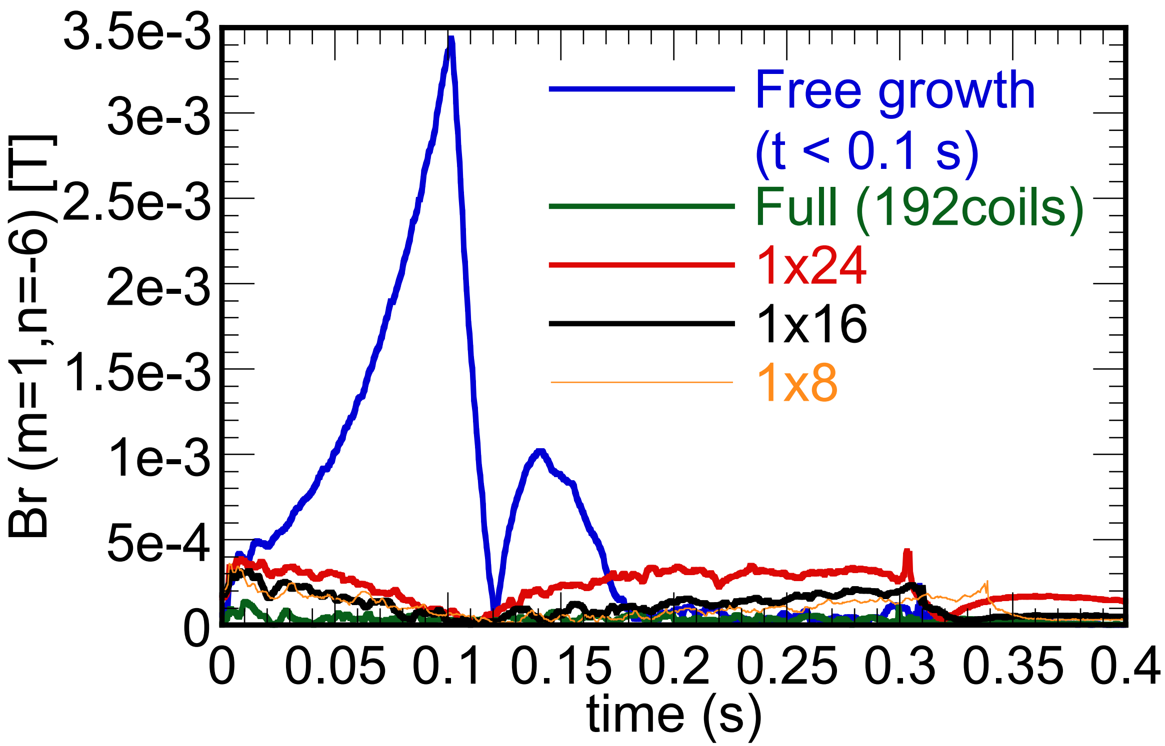
Coverage rate of each coil configuration for RWM control study with reduced coils on RFX-mod

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

Machine	Most unstable mode	Number of coils (poloidal)	Number of coils (toroidal)	Coverage
RFX	m=1,n=-6	4	48	100%
		1	48	25%
		1	24	12.5%
		1	16	8.3%
		1	12	6.25%
		1	8	4.2%
		4	3	6.25%
JT-60SA	m=3,n=1	3	6	6.8%

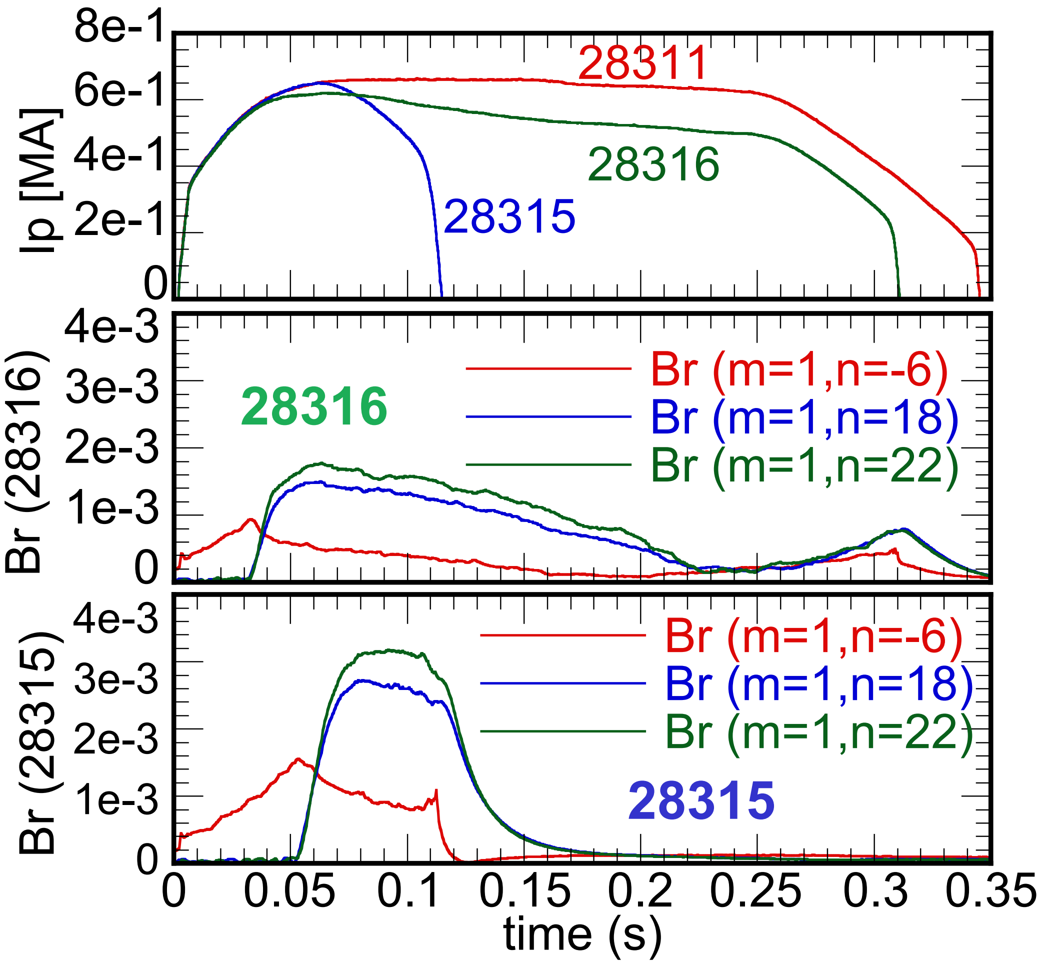
RWM can stabilized with small number of coils

- Control of m=1, n=-6 RWM, which is the most unstable mode, with reduced sets of coils
- RWM control starts from the beginning of the shot.
- Other modes are stabilized with full set of coils.
- m=1, n=-6 mode is suppressed (except for 1x12).
- Gain increase as coil number decrease.



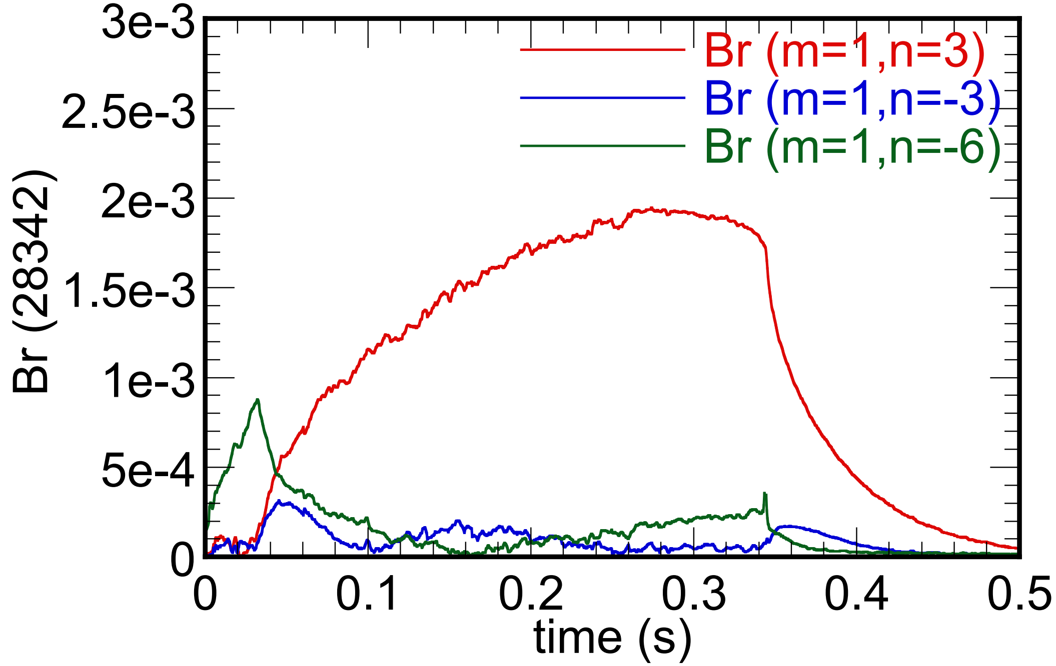
Sideband modes degrade or terminate the plasma

- scan of initial n=1, m=-6 RWM amplitude at the start time of control with 1x8 coils.
- Control of m=1, n=-6 mode starts,
  from beginning (28311),
  at Br=9.6G, t=30ms (28316),
  at Br=15.6G, t=50ms (28315)
- Without sideband control of m=1, n=18,22 on 28315 and 28316.
- n=18,22 modes of 28315 is larger than that of 28316. Plasma was terminated on 28315.



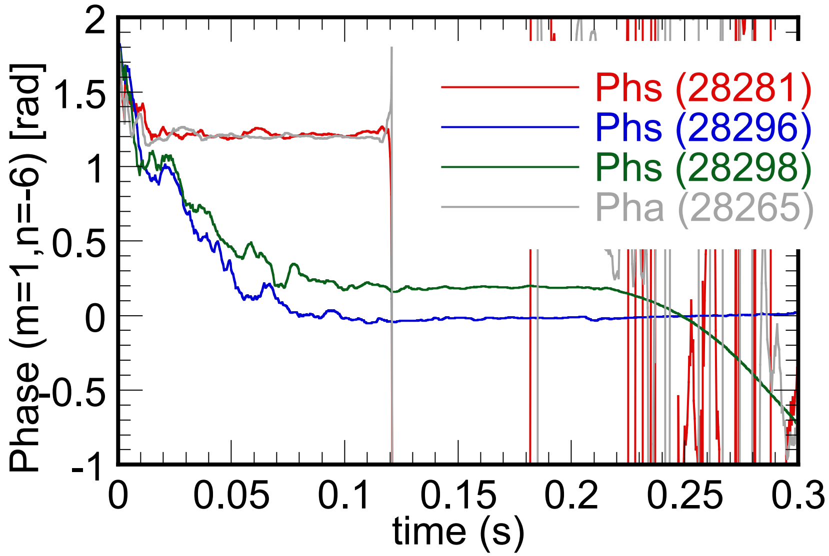
RFA of sideband mode was observed

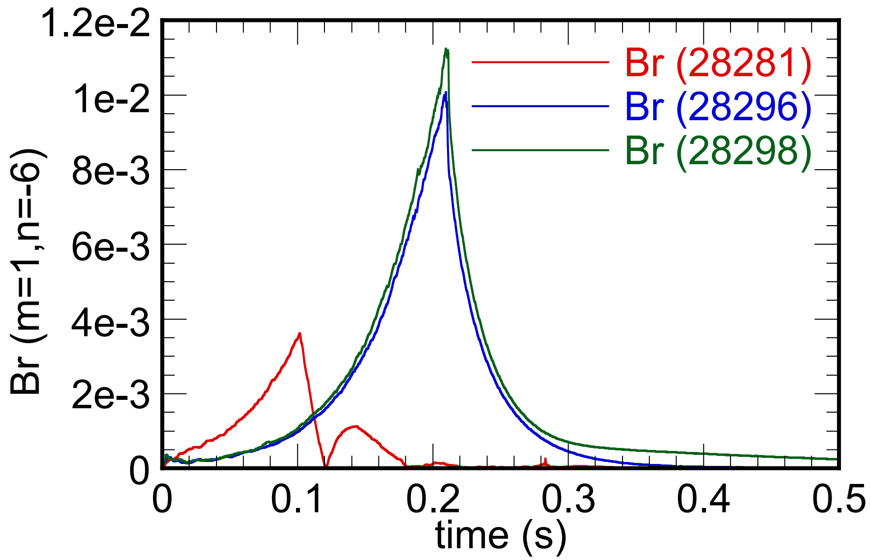
- m=1, n= ±3 modes are sidebands of m=1, n=-6
- m=1,n=+3 mode is marginally stable and m=1,n=-3 mode is stable.
- m=1,n=-6 RWM stabilization starts at t=0.03s without control of m=1, n= ±3 modes
- m=1,n=+3 mode was amplified.
- m=1,n=-3 mode was not amplified.



RWM slipped and not be stabilized with 1x12 configuration

- On 28281, m=1, n=-6 RWM growth until 0.1s and suppressed with full system.
- However, with 1x12 coils on 28296, the mode cannot be suppressed, because the nodes of the mode fit the coil positions.
- The mode slipped to its comfortable toroidal position (phase) and growth almost freely.
- Toroidal position (phase) of control coil was changed Pi/12 between 28296 and 28298.
- Comfortable toroidal position of RWM on 28298 is shifted and growth earlier than that of 28296, because the mode of 28298 reach to the its comfortable position earlier than that of 28296.
- Similar problem will occur for n=3 control on JT-60SA?





Summary

RWM control system design.

- Evaluation of RWM power supply requirements were performed with VALEN simulation and FEM analysis
- New RWMC configuration of plasma side RWMC has been proposed.
- EM force analysis at disruption were performed with DINA code.

RFX experiment with reduced coil sets for mode rigidity study.

- RWM can be stabilized with very few coils.
- Large sideband effect was observed.
- RFA is observed and terminated the plasma.
- RWM slipped and run away to its comfortable phase and growth almost freely if the phase of node is fit to the coils.

Ongoing and future works

1. Engineering
   - 3 D FEM stress and temperature analysis of RWMC.
   - Strength test of MIC

2. RFX experiment with reduced coil sets for mode rigidity.
   - Tokamak discharge

3. RWM control simulations with CarMa.
   - with three dimentional structure of SP, VV, coils.
   - Actual magnetic sensors at actual position, actual delay time

Mode control scheme, sensor,…