Wed-Af-Po3.17-09 [37]: Analysis of Mechanical Behavior of the KSTAR CS Magnet during Long Pulse Plasma Discharges

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KSTAR

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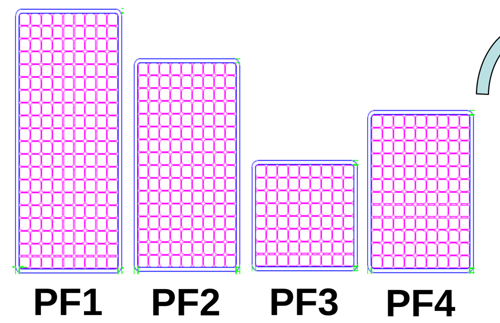
Abstract : The strain and displacement of the CS magnet are monitored in real-time, limiting the min. compression as an important parameter of the interlock system for the safe operation. The equivalent force methodology of a simplified multi-spring system was developed to analyze the displacement of the CS magnet. The equivalent force is based on the plasma and PF coils currents during plasma discharge. The estimated displacements by the developed method agreed fairly well with the measured displacements of the long pulse plasma discharges in 2017 and 2018 campaigns. The analyzed displacement can be used to simply estimate the remaining preload on the coils. This approach contributes to the development of advanced operation scenarios for large plasma current and long pulse discharges. By applying this algorithm to the plasma control system, the CS magnet can be controlled more safely during KSTAR

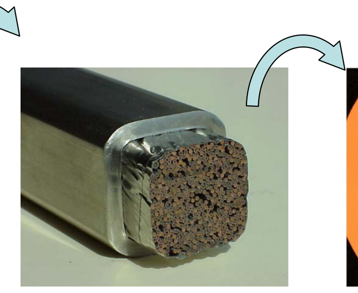
1. Introduction

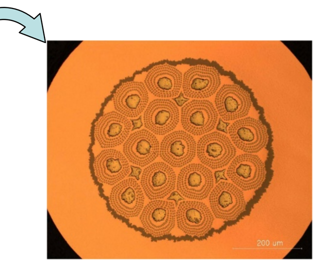
- The KSTAR CS magnet consists of four pairs of CS coils stacked with up-down symmetry, preloading and supporting structures.
- Preloading was applied as 7.2 MN by wedge system with thermal expansion of the structures during assembly in 2006 and the min. residual preloading is about 6.5 MN after cool-down.
- For the safety, the min. preloading should be greater than 0.65 MN during plasma operations.

Parameters of CS Magnet	Values
No. of CS coils	8
Mean radius of coils, R_m	570.0 mm
Inner radius of coils, R_i	454.8 mm
Outer radius of coils, R_o	685.2 mm
Overall height of coils	2948.5 mm
No. of turns per pancake	9
No. of pancakes (PF1/PF2/PF3/PF4)	20/16/8/12
Peak current in conductor	25 kA



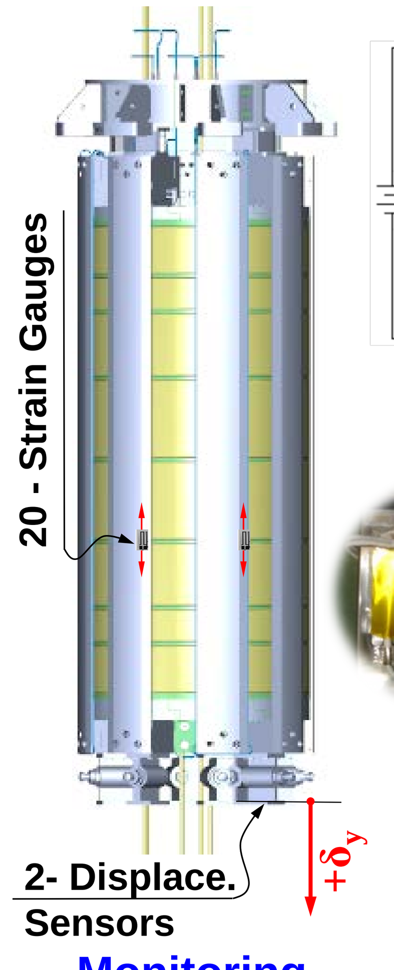
Cross Section of CS Coils


CICC

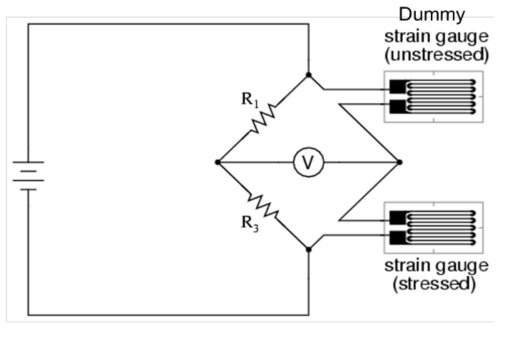

Nb_3Sn strand

2. Measurement of Mechanical Behaviors of CS Magnet

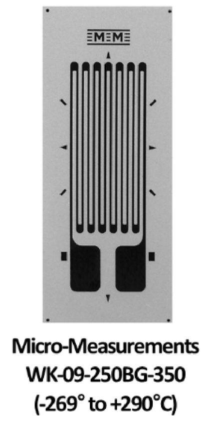
- Twenty cryogenic strain gauges on the shell and two displacement sensors at the CS magnet bottom were installed for monitoring of the mechanical behavior of the CS Magnet.

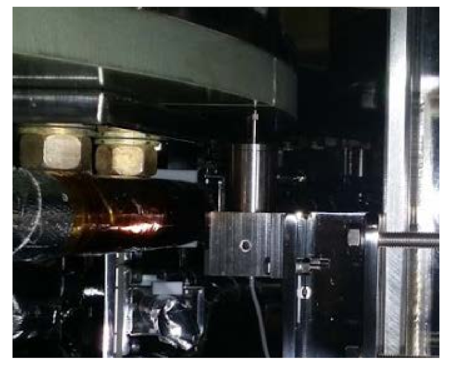


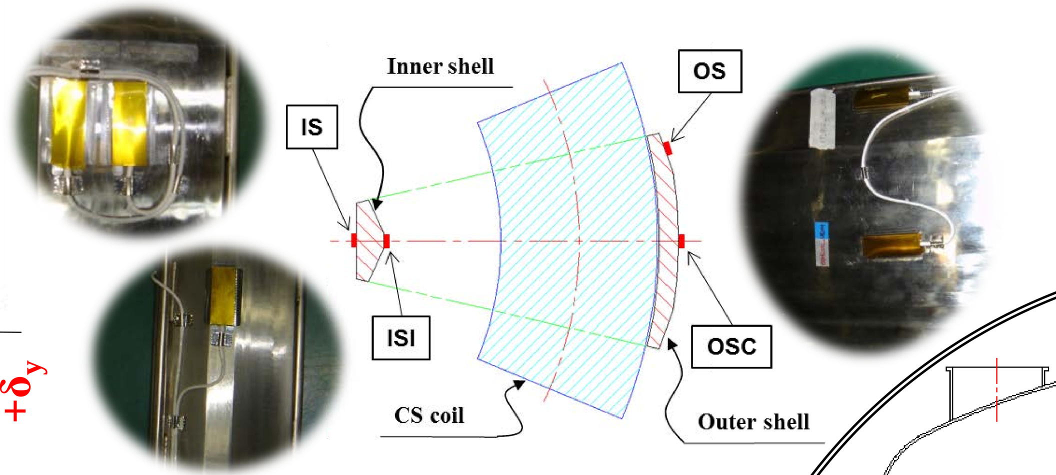
Monitoring System



Active-Dummy Strain Gauges



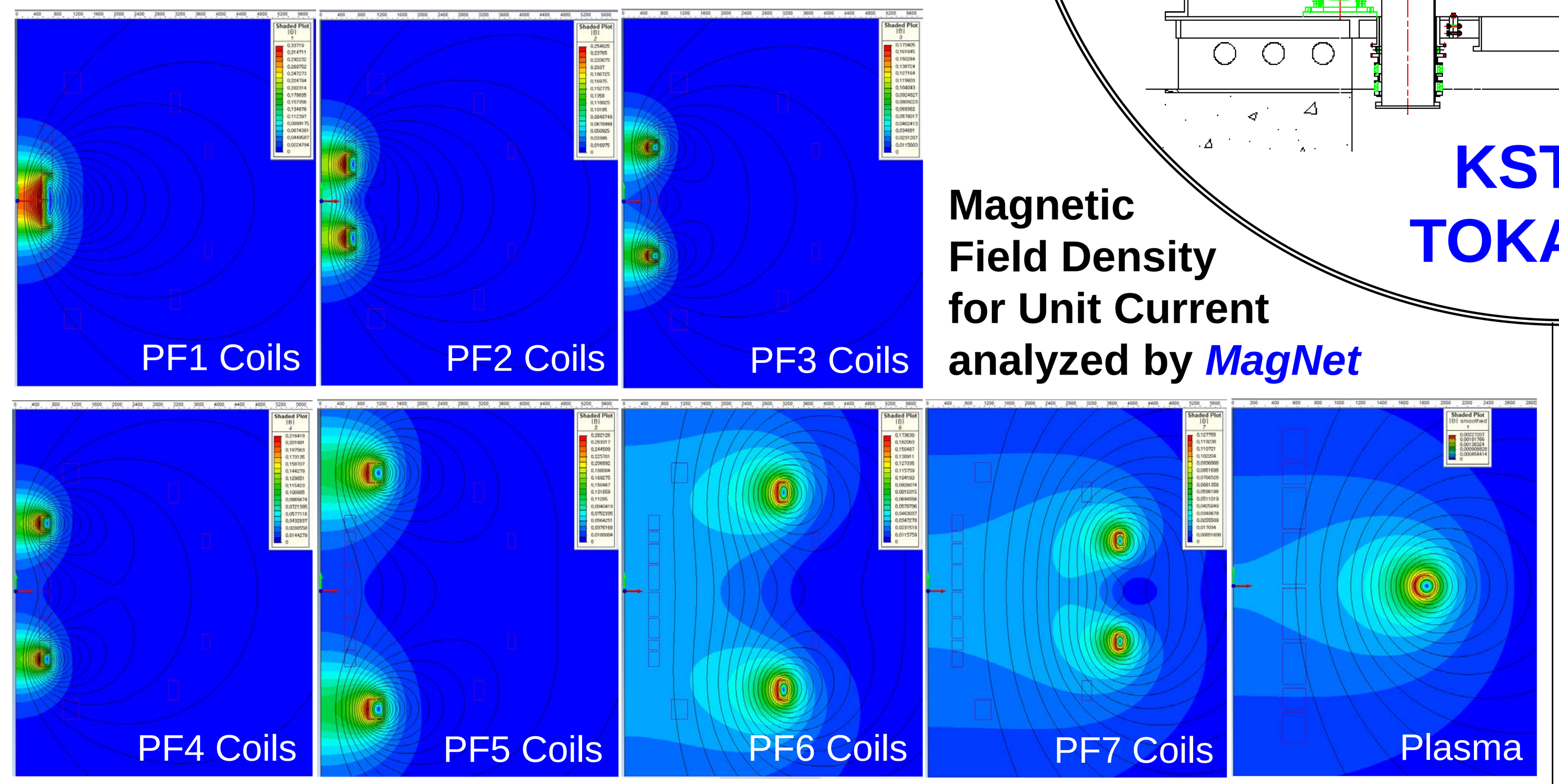

Displacement Sensor



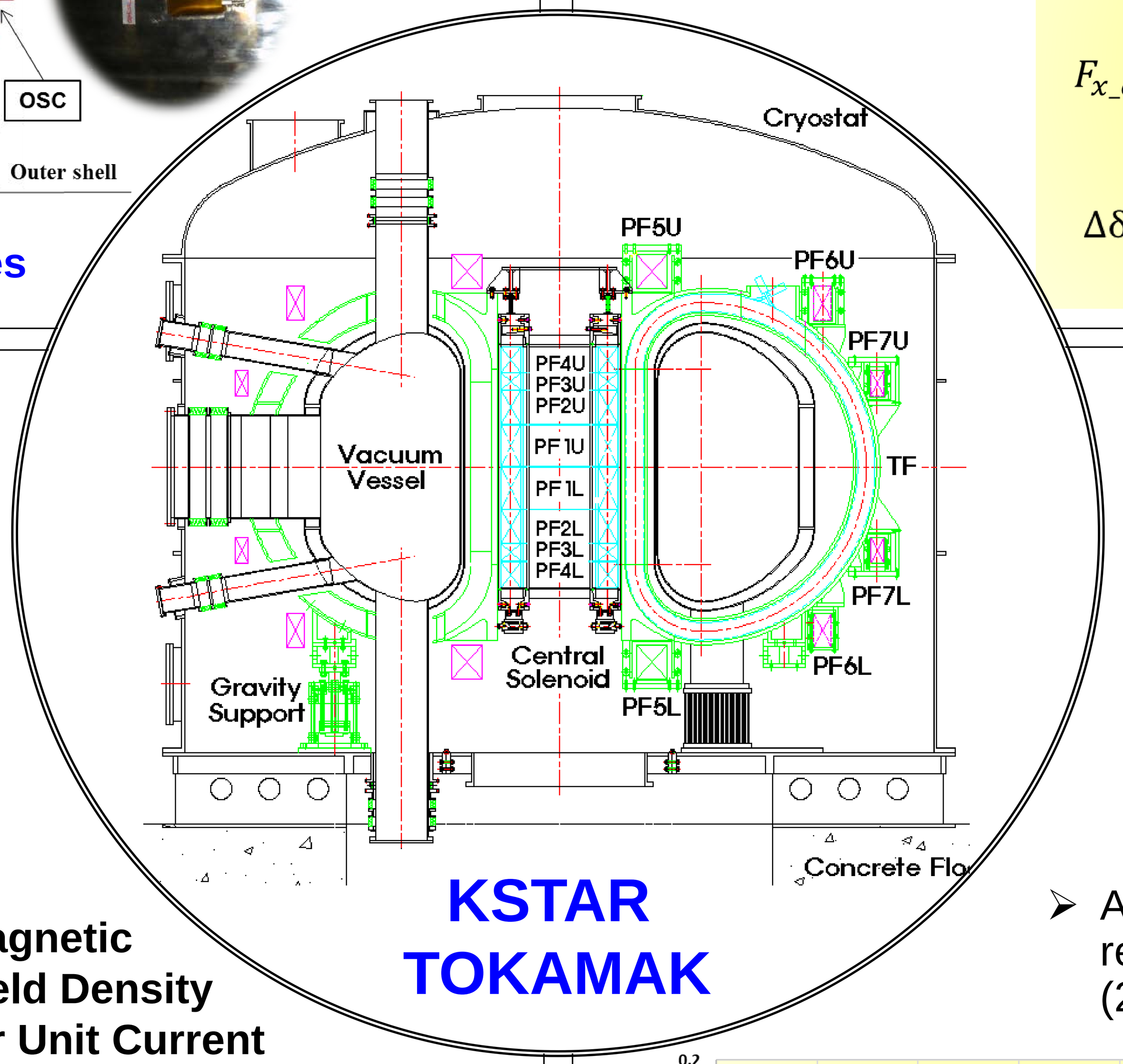
Location of Strain Gauges

3. Database for EM Force Calculations

- Magnetic fields were analyzed for unit current (1 kA /turn) of each PF coil and plasma. A database of magnetic fields at the central point of every CICC for unit current of each coil and plasma were built to calculate EM force quickly.



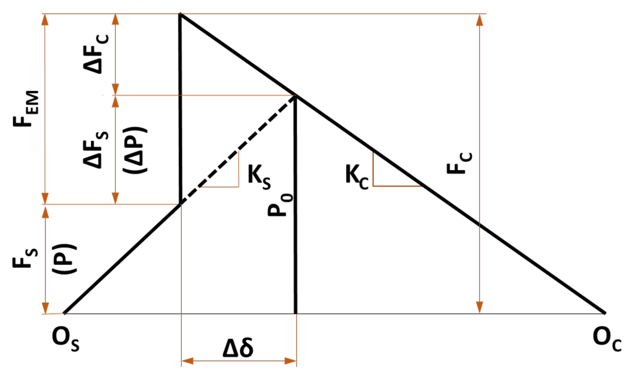
Magnetic Field Density for Unit Current analyzed by *MagNet*



KSTAR TOKAMAK

4. Mechanical Characteristics of CS Magnet

- The stiffness of the CS Magnet was estimated under the cryogenic state (4K) based on the linear elasticity.
  - CS Coil Stiffness, K_C = 5.0 MN/mm
  - Structure Stiffness, K_S = 5.6 MN/mm
- **Joint Diagram** for bolted joints was introduced to solve the complex force problem of the CS coil assembly.
- The equivalent vertical force, ***Feq***, was proposed to calculate the displacement of the CS magnet during plasma discharge.



Joint Diagram of Coils and Structure

$$F_{EM} = \Delta F_S + \Delta F_C = \Delta\delta \cdot K_S + \Delta\delta \cdot K_C = \Delta\delta (K_S + K_C)$$

$$\Delta\delta = \frac{F_{EM}}{K_S + K_C}$$

$$F_{y\_eff} = \sum_{i=1}^{4}\left(F_{y\_PFi}\sum_{j=1}^{i}\frac{H_j}{H}\right)$$

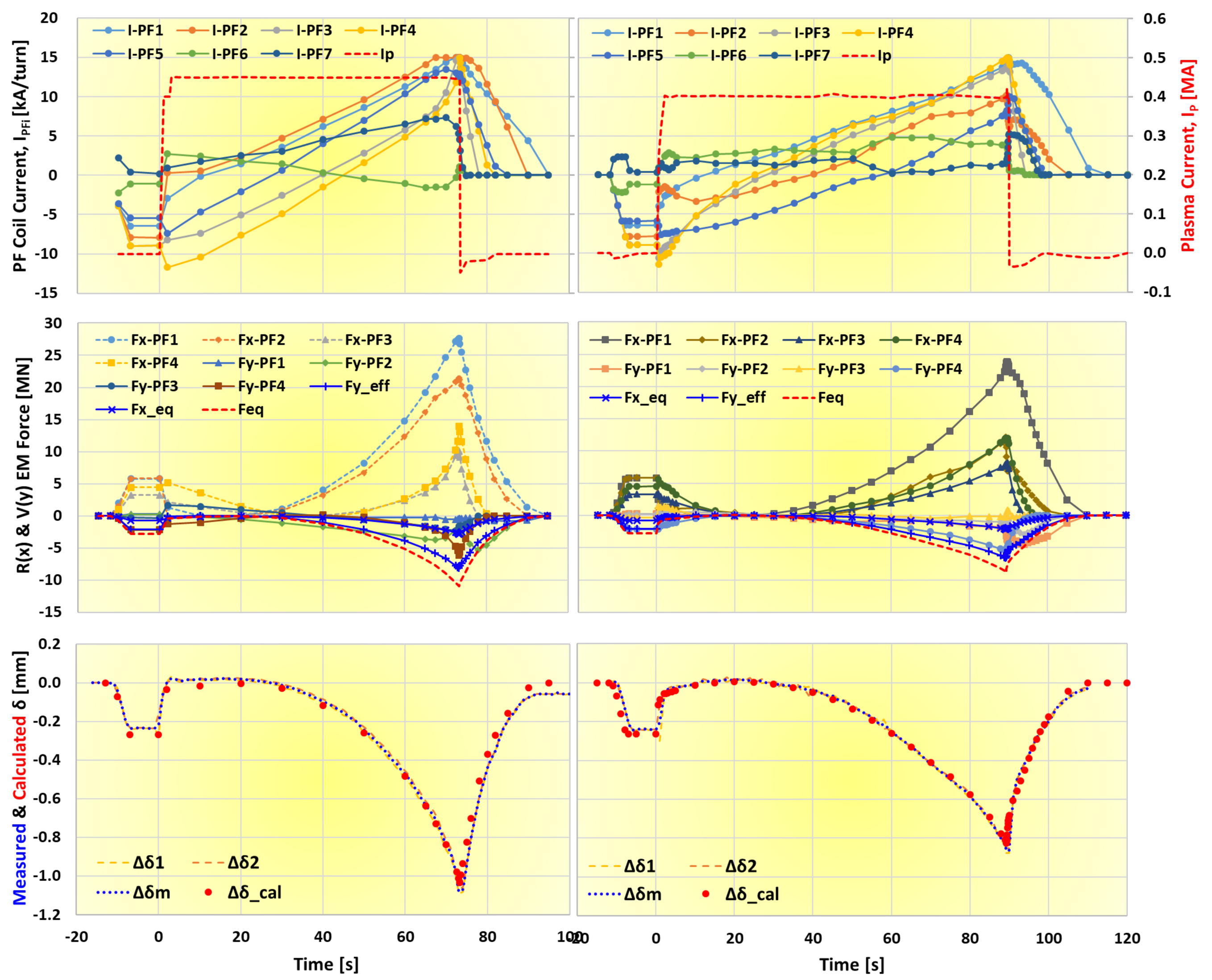
$$F_{x\_eq} = -\nu_{\theta y} R \frac{E_y}{E_\theta}\sum_{i=1}^{4}\frac{F_{x\_PFi}}{H_i}$$

$$\Delta\delta = \frac{F_{eq}}{K_{eq}} = \frac{F_{x\_eq} + F_{y\_eff}}{K_C + K_S}$$

Where, F_{y_PFi} and F_{x_PFi} are the vertical and radial forces of the i-th PF coils. Hi is the height of the i-th PF coil and H is the total height of CS coils. R, K and ν are mean coil radius, stiffness and Poisson's ratio, respectively.

5. Analysis of the Long Pulse Plasma Discharges

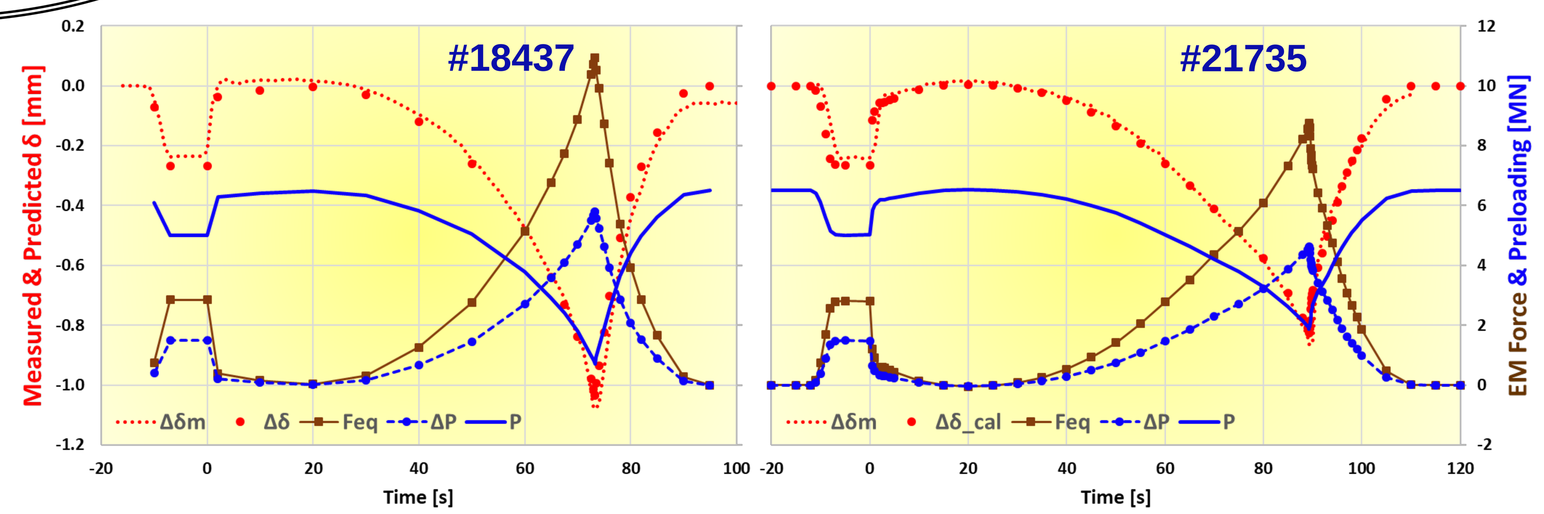
- Long Pulse Plasma Discharges in 2017 and 2018 campaigns.



#18437(~73 s)
#21735 (~90 s)

6. Prediction of Mechanical Behaviors

- The variations of preloading and displacement during the long pulse plasma discharges were predicted using the proposed equivalent EM force. The predicted displacements, **Δδ** are reasonably well in agreement with the measured displacements, **Δδm**.
- The measured displacements after the end of shot did not converge to zero. There might be nonlinear phenomena like slip.
- At the end of plasma, the minimum preloads were remained 0.71 MN (11%) for #18437 and 1.86 MN (28%) for #21735.



7. Conclusions

- The vertical displacement of the CS bottom can be well predicted by the proposed equivalent vertical EM force which is calculated with PF coils and plasma currents.
- This approach will contribute to develop advanced operation scenarios for the long pulse and high plasma current discharges. It can be also applied to a real-time plasma control system.
- Some deviation between the measured data for strains and displacements will be investigated by further experiments.

Shot #	Peak [s]	Δδm [mm]	Δδ_cal [mm]	Fx_eq [MN]	Fy_eff [MN]	Feq [MN]	ΔP [MN]	P [MN]
18437	73.3	-1.08	-1.03	2.83	8.12	10.95	5.79	0.71
21735	89.3	-0.86	-0.83	2.13	6.63	8.76	4.64	1.86

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