Plans for MHD control in KSTAR

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On behalf of the KSTAR team

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Outline

I. In-Vessel Control Coils (IVCC) system
   - IVCC system is to be implemented in KSTAR, as an actuator to provide the control of vertical & radial position control, field error correction (FEC), and resistive wall mode (RWM) feedback stabilization.

II. Physical Requirements
   - Vertical and radial position control coil
   - FEC coil
   - RWM control coil
   - Other possible application including ELM control

III. Neoclassical Tearing Mode control using ECCD
   - Active suppression of m/n = 3/2 and 2/1 NTMs will be pursued by using a 170GHz (2nd harmonic resonant with KSTAR reference scenario of which toroidal field is 3.5 T at magnetic axis) ECCD system for KSTAR. Results of a preliminary study and a prototype of control system are presented.

IV. Issues and future works
   - KSTAR operation schedule is presented. Remained issues and future works of MHD control on the basis of this schedule is addressed.

V. Summary

In-Vessel Control Coils System

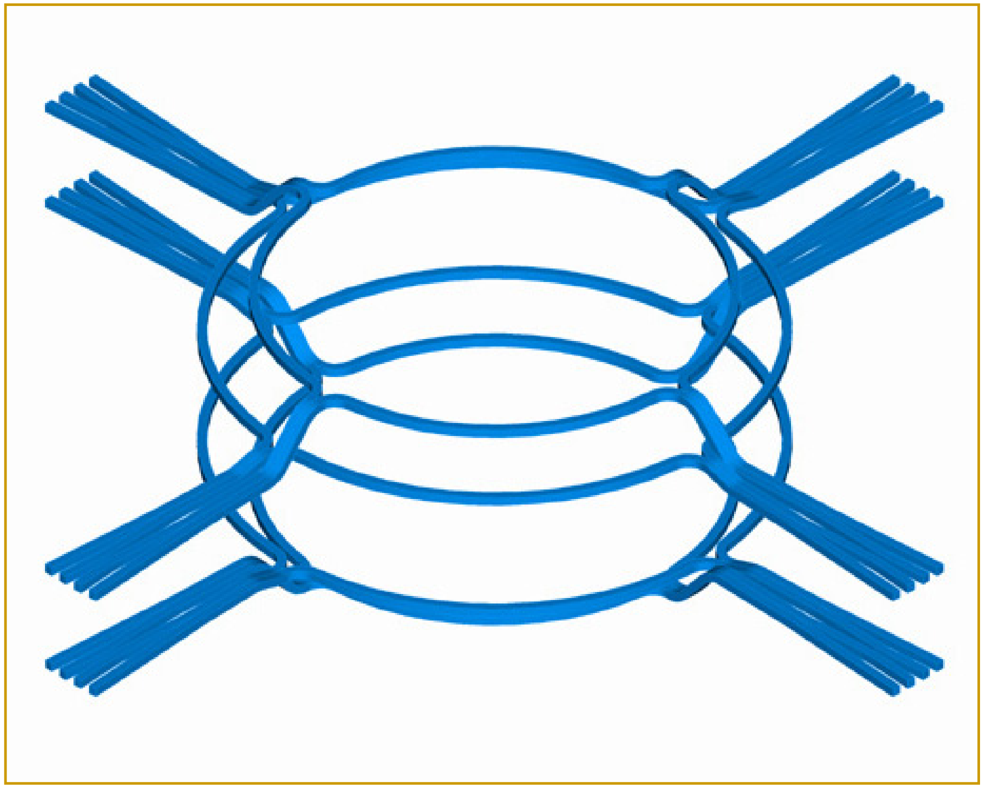
Plasma control capability of the KSTAR IVCC system

- **Main functions:**
  - **Vertical position control (n = 0)**
  - **Radial position control (n=0)**
  - **Field error correction (FEC) (n ≥ 1)**
  - **Resistive Wall Mode (RWM) feedback stabilization (n ≥ 1)**

- **Additional possible control capabilities are under study.**
  - **Type-I ELM control**
  - **Tearing mode control**
  - **Local plasma rotation control**
  - **Impurity control**

A schematic of KSTAR In-Vessel Control Coils (IVCC) system

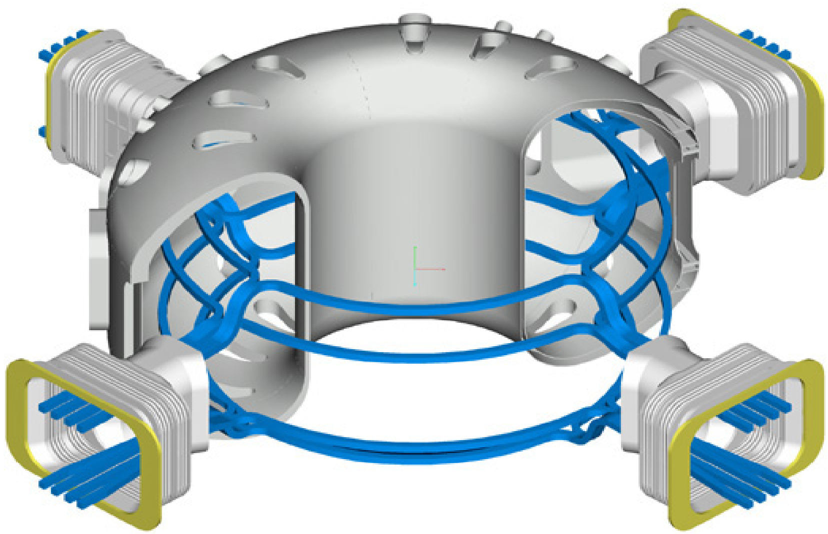
- IVCC is a unified coil system using toroidal segmentation concept



- **Each In-Vessel Control Coil is divided into four toroidal segments (at 4 positions in a poloidal section at p1, p2, p3, and p4, total 16 segments)**
- **Each segment is deformed to have lead parts, of which a proper connection can give a loop for plasma position control, FEC/RWM control.**

Advantages of the Segmented IVCC design are

- Simplification in the fabrication and installation.
- Improvement in the reliability of the coil system.
- Easy maintenance and repair.
- Saving in in-vessel space.
- More improved plasma control flexibility.

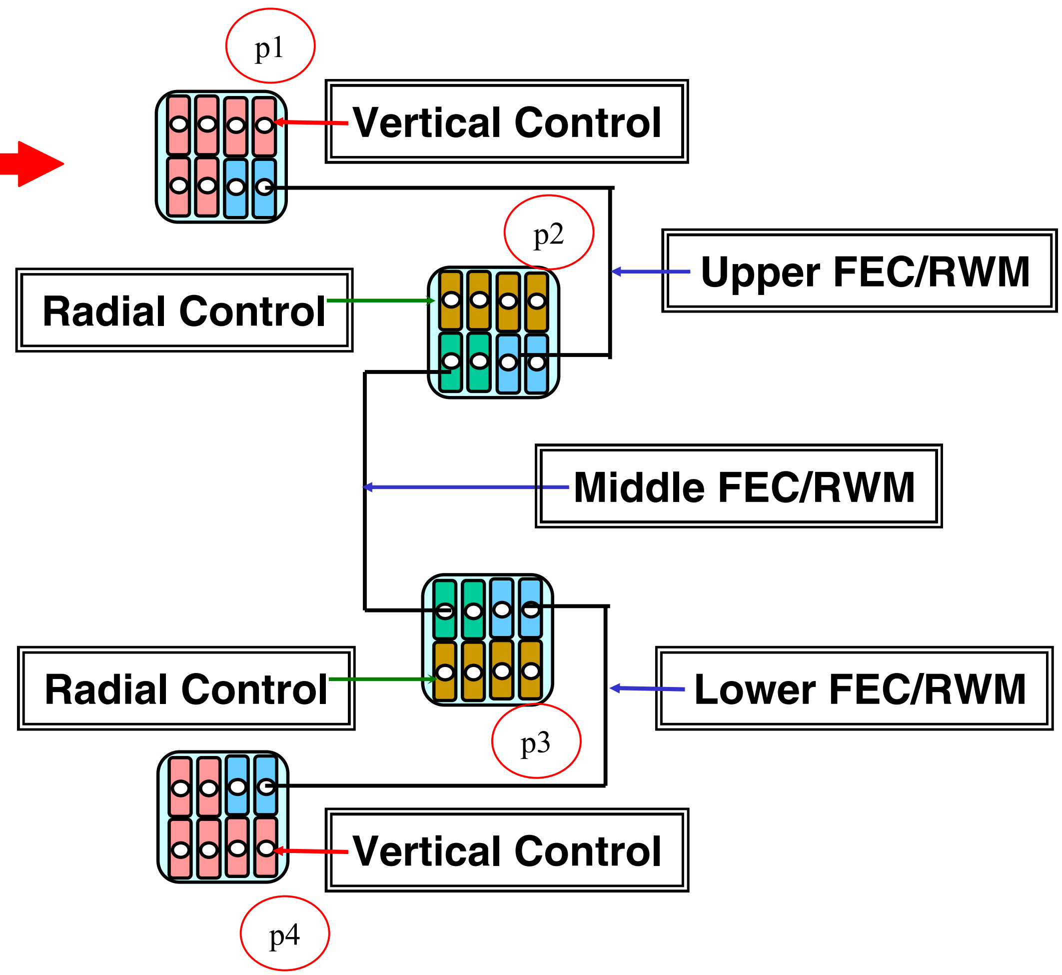


IVCC Installation is performed through three NBI and one RF type ports after main device assembly

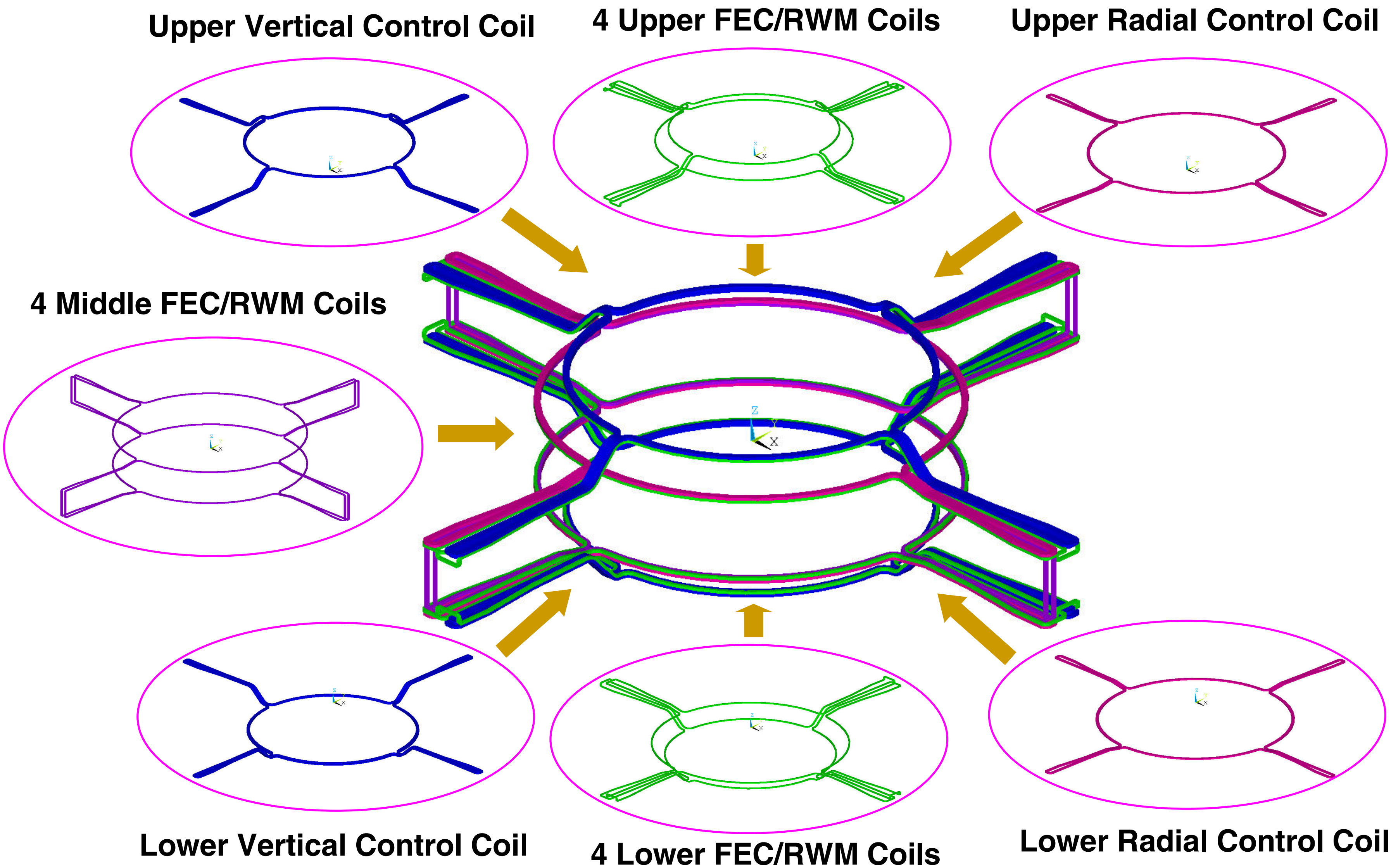
1:10 mock-up of the KSTAR VV & IVCC shows that the installation principle is possible.

Cross sectional view of segments and connection for IC & FEC/RWM control coils

- Each coil segment is composed of 8 copper sub-coils
- Figure shows a poloidal cross sectional view
- Pink sub-coils : connected to be IVC (internal vertical control) coils (2 sets of upper and lower)
- Mud yellow : connected to be radial control coils (upper and lower)
- Green : connected to be middle FEC/RWM control coils
- Blue : connected to be upper and lower FEC/RWM control coils



Connection lines for position control and FEC/RWM coils in 3-D



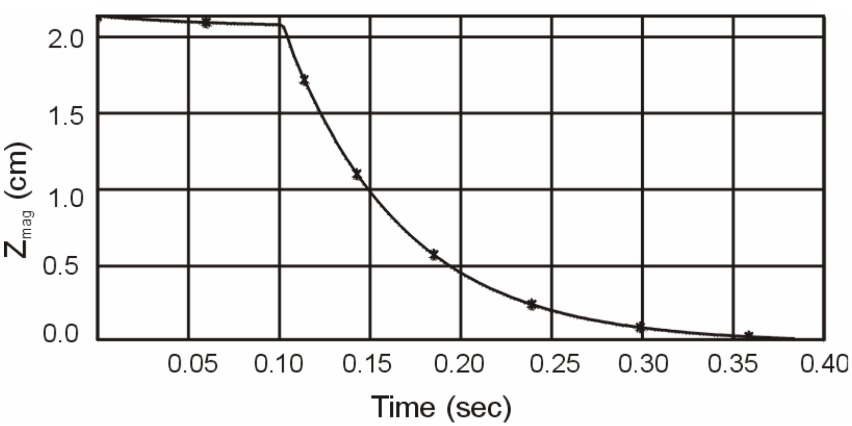
Physical Requirements for

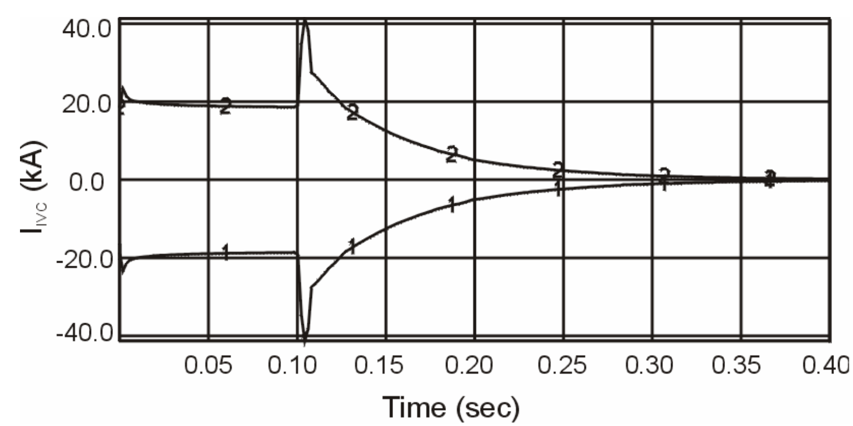
- Plasma Position Control
- Field Error Correction
- Resistive Wall Mode Control

Plasma Position Control

Plasma vertical position control

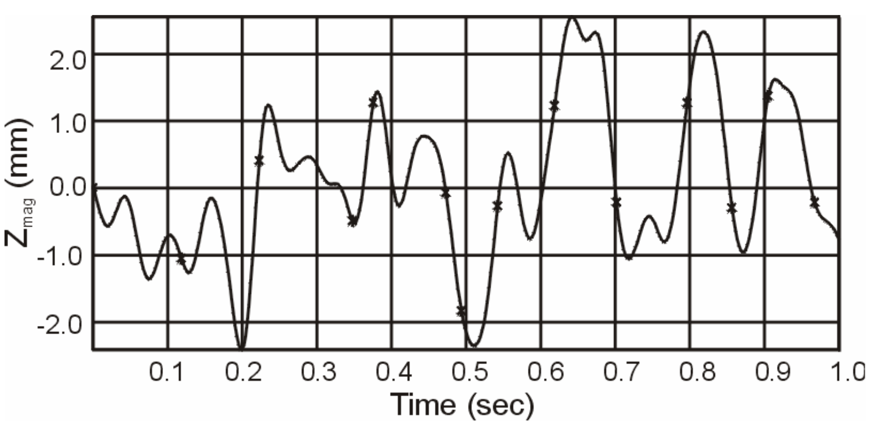
- The fast time-scale (~ 10 msec) plasma postion control is realized by using two pairs of inner control coils (IVC for vertical position control, IRC for radial position control).
- A step response simulation has been used to calculate the **IVC** current to hold a worst plasma (β_N=0.3, $l_i(3)$=1.2, I_p=2.0 MA, κ=2.0) 2 cm above mid-plane, and to bring it back to its original position within 200 msec. The maximum current (voltage) is found to be **42 kA-turns (123 V/turn).**

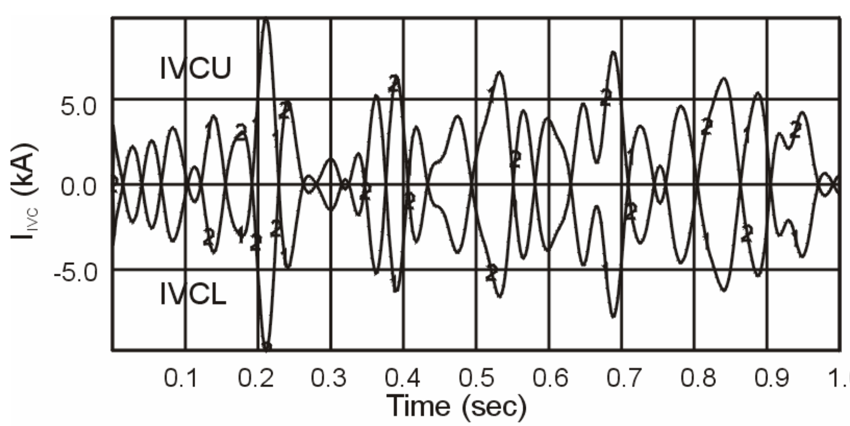




Plasma vertical position control (cont.)

- Random disturbance simulation has been performed to evaluate the **IVC** power supply requirements. The random displacements in Z_{mag} are characterized by $\Delta Z_{rms} = 1$ mm, $\Delta\omega = 1/\tau_z$; $\tau_z = 18.0$ msec ($\beta_N = 0.3$, $l_i = 1.2$). The maximum feedback current (voltage) is found to be **9.8** kA-turns (**8**V/turn).





Plasma radial position control

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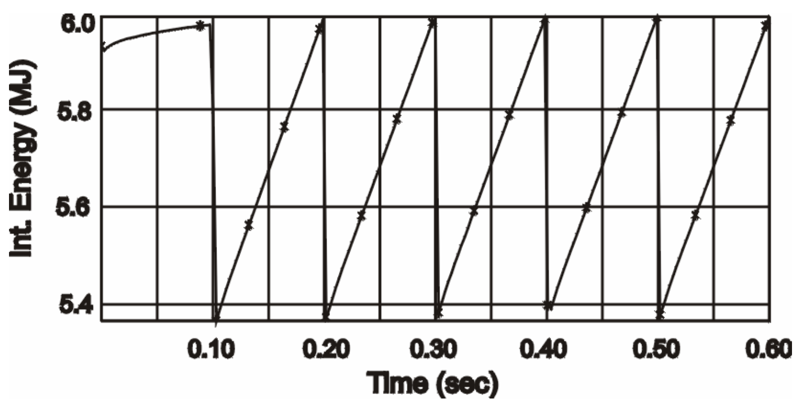
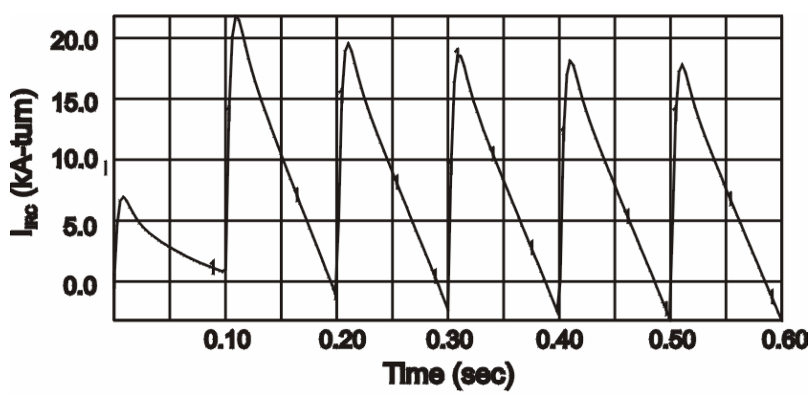
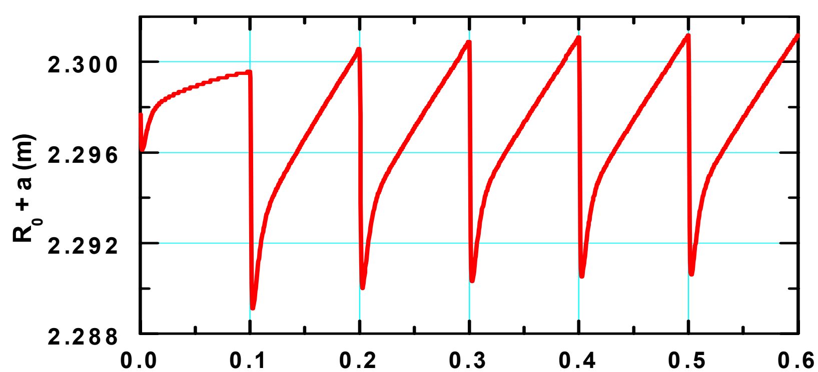
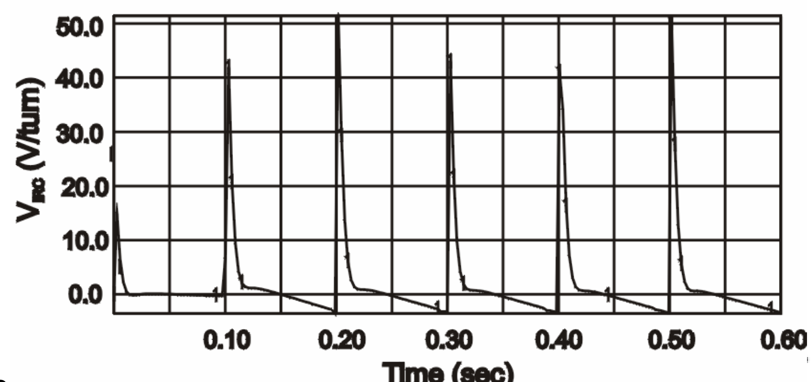
- Power supply requirements for **IRC** are calculated for a high β plasma (β_N = 5.0, l_i= 0.8, I_p = 2 MA) undergoing **10 %** drop in stored energy every 100 msec (~ τ_E) with recovery. This 10% drop is assumed to be worst **recoverable** event. The maximum feedback current (voltage) in **IRC** is found to be **22 kA-turns (52 V/turn).**









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Field Error Correction

Field error calculation

- Definition of Fourier harmonics A_{mn} and $A_{3\text{-mode}}$

$$c_{mn} = \frac{1}{2\pi^2 B_0} \int_0^{2\pi}\int_0^{2\pi} B_r \cos(n\phi - m\theta)\,d\theta\,d\phi,$$

$$s_{mn} = \frac{1}{2\pi^2 B_0} \int_0^{2\pi}\int_0^{2\pi} B_r \sin(n\phi - m\theta)\,d\theta\,d\phi,$$

$$A_{mn} = \sqrt{c_{mn}^2 + s_{mn}^2},$$

$$A_{3-\text{mode}} = \left[A_{21}^2 + 0.8\,A_{31}^2 + 0.2\,A_{11}^2\right]^{1/2}$$: based on DIII-D scaling

B_0 : magnetic field at the geometrical axis (3.5 T for KSTAR)

- B_r : error field component normal to (2, 1) surface, over which the integration is carried out
- Correction current then calculated to reduce the estimated field error below the following threshold values for locked modes;

$$A_{21} = 1\times10^{-4},\ A_{m1} = 2\times10^{-4}\ (m = 1,\ 3,\ 4),$$

$$A_{42} = 2\times10^{-4},\ A_{m2} = 4\times10^{-4}\ (m = 3,\ 5),\ \ A_{3-\text{mode}} = 2\times10^{-4}$$

Field error calculation (cont.)

- Field error magnitude calculated, considering possible all sources;
  - PF coil winding irregularities
  - Bus and lead wires
  - Welded joints of V V
  - PF &TF coil misalignments and manufacturing error (shift, tilt)

* total 232 sources considered

Calculated field error from PF winding

KSTAR

PF No	A_{11}	A_{21}	A_{31}	A_{41}	A_{3-mode}
1	2.10	2.74	0.22	0.89	2.91
2	0.11	0.01	0.09	0.05	0.09
3	0.34	0.05	0.18	0.05	0.23
4	0.35	0.11	0.18	0.02	0.25
5	1.16	1.04	0.35	0.28	1.20
6	0.89	0.24	0.32	0.07	0.55
7	0.13	0.64	0.22	0.07	0.67

($* 10^{-5}$)

- ✓ Considered PF coil currents are at Start Of Flattop (SOF), when plasma density and rotation allow lower field error, of reference discharge condition as

PF No.	1	2	3	4	5	6	7
coil current (MAt)	-3.546	0.126	0.194	0.358	1.426	-0.561	-0.845

- ✓ ~ 10 % of the threshold value

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Field error from PF and TF bus-lines

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(* 10^{-6})

coil	A_{11}	A_{21}	A_{31}	A_{41}	A_{3-mode}	A_{32}	A_{42}	A_{52}
CS1	7.37	2.82	0.56	0.38	4.37	0.25	0.12	0.04
CS2	4.95	1.13	0.61	0.24	2.54	0.27	0.18	0.05
CS3	10.42	2.06	1.36	0.49	5.24	0.53	0.26	0.11
CS3	3.03	1.39	0.72	0.32	2.05	0.30	0.14	0.07
CS4	5.91	0.71	0.83	0.16	2.83	0.31	0.08	0.08
CS4	1.69	0.79	0.42	0.18	1.16	0.17	0.08	0.04
PF5	1.24	0.59	0.30	0.10	0.85	0.18	0.06	0.04
PF5	0.56	0.25	0.13	0.04	0.37	0.05	0.02	0.01
PF6	0.11	0.05	0.03	0.02	0.07	0.05	0.01	0.01
PF6	0.28	0.20	0.09	0.03	0.25	0.06	0.02	0.01
PF7	0.51	0.50	0.29	0.09	0.61	0.25	0.08	0.04
TF	1.69	0.81	0.34	0.13	1.15	0.30	0.10	0.03

- This is calculated on the basis of 1MAt coil currents
- The results show ~ 1 % of threshold values : minor field error source
  - Field error from PF bus-line is proportional to PF coil current.

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Field error from vacuum vessel weld joints ($\mu_r > 1$)

- For SOF (Start of Flattop) coil current :

($* 10^{-5}$)

μ_r	A_{11}	A_{21}	A_{31}	A_{41}	A_{3-mode}	A_{32}	A_{42}	A_{52}
1.05	0.30	0.20	0.16	0.09	0.28	0.08	0.04	0.02
1.10	0.57	0.42	0.32	0.15	0.56	0.17	0.10	0.03
1.15	0.87	0.62	0.44	0.24	0.83	0.20	0.14	0.10
1.20	1.17	0.82	0.59	0.33	1.11	0.28	0.17	0.14
1.25	1.47	1.07	0.71	0.37	1.41	0.37	0.21	0.13
1.30	1.72	1.25	0.85	0.46	1.65	0.44	0.25	0.17

- It makes field error ~ 10 % of the threshold value.
- Field error is proportional to the deviation of relative permeability from unity.

3-Mode Harmonics for 2mm installation errors

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(1.0E-6)

PF	Shift	Tilt	Elongation
1	13.12	9.17	0.0017
2	10.02	6.85	0.0018
3	7.71	4.74	0.0010
4	5.73	3.31	0.0008
5	4.28	1.49	0.0009
6	8.43	4.33	0.0010
7	8.19	5.93	0.0014

- Gives max. ~10% of field error threshold

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Field error from manufacturing and misalignment should be treated statistically

- Using the random number simulation (1000000 ~ 1500000 sampling) to reduce the calculation size

- Normal distribution

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{x^2}{2\sigma^2}\right)$$

$$\int_{-\sigma}^{\sigma} f(x)dx = 0.6827$$

σ : standard deviation

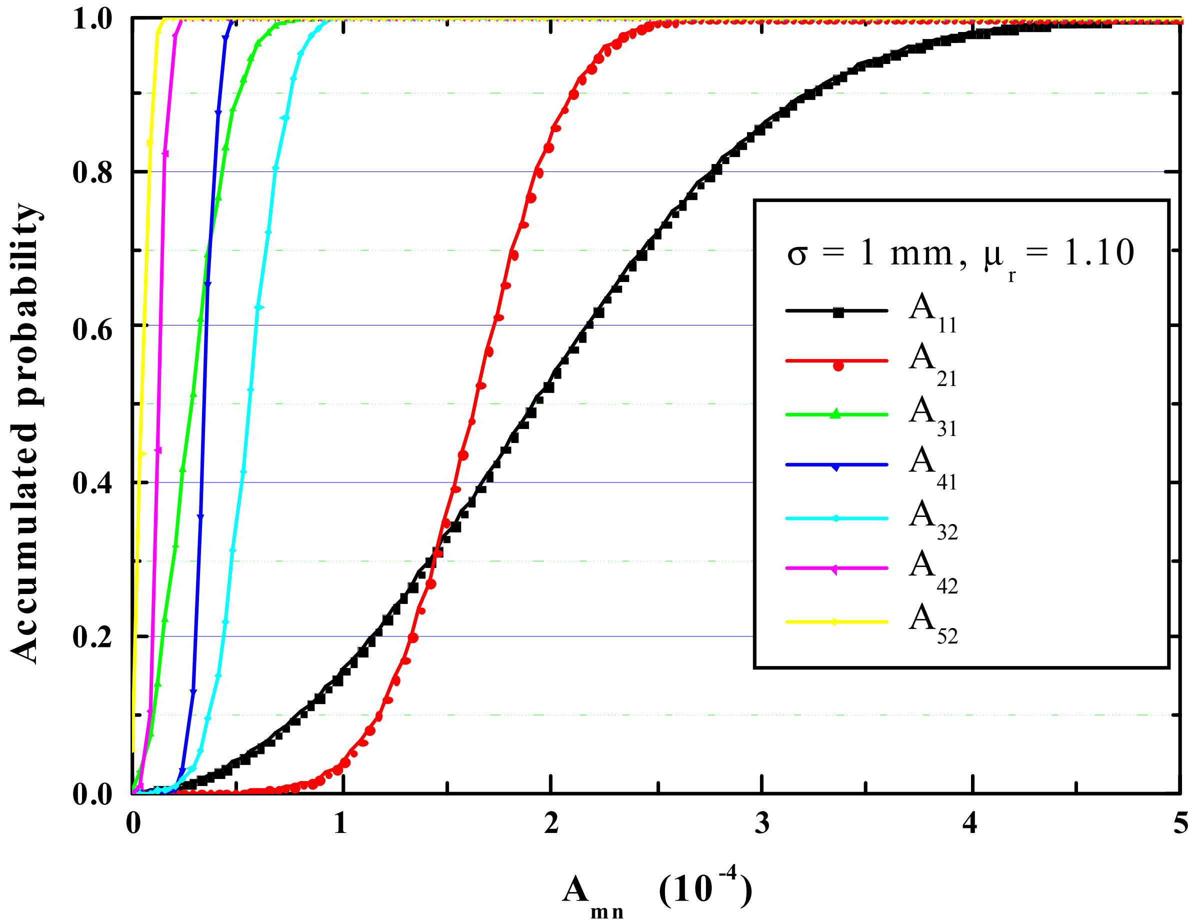
The real distribution will be somewhere between these two distributions.
In this calculation, we use normal distribution since it produce bigger error.

- Unit distribution

$$f(x) = \begin{cases} \frac{1}{2\Delta}, & -\Delta < x < \Delta \\ 0, & \text{otherwise} \end{cases}$$

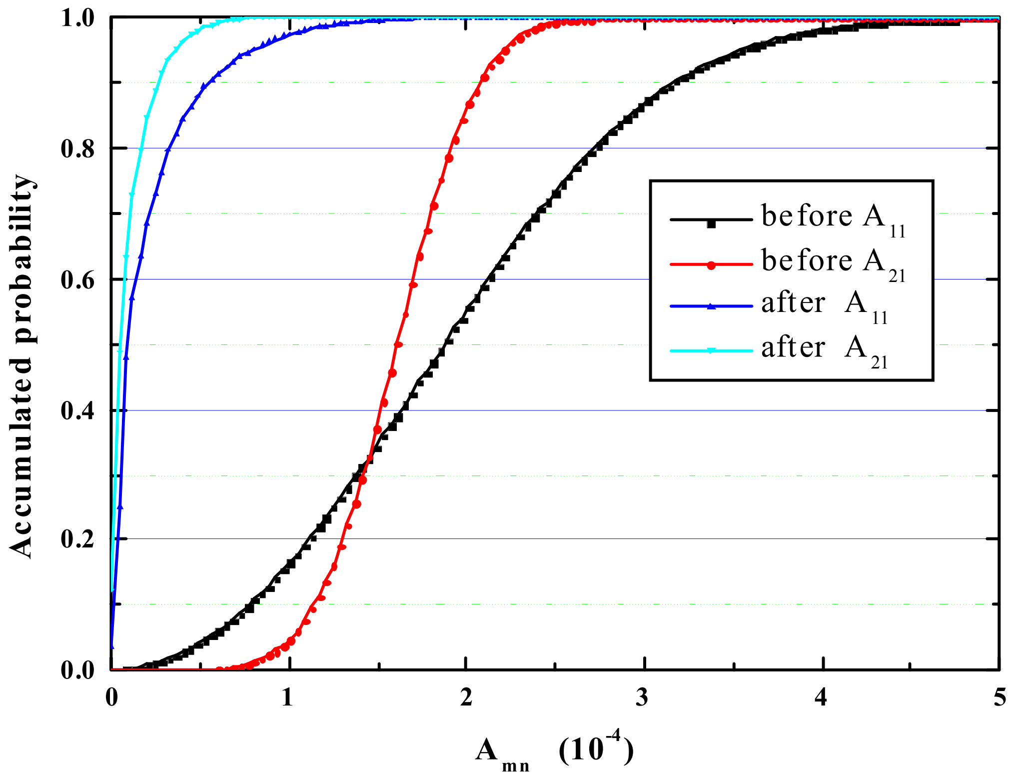
Δ : the accuracy of alignment

Calculated field error considering all the sources



- 1/1 and 2/1 modes are expected to be biggest.

Field error correction current requirement is calculated



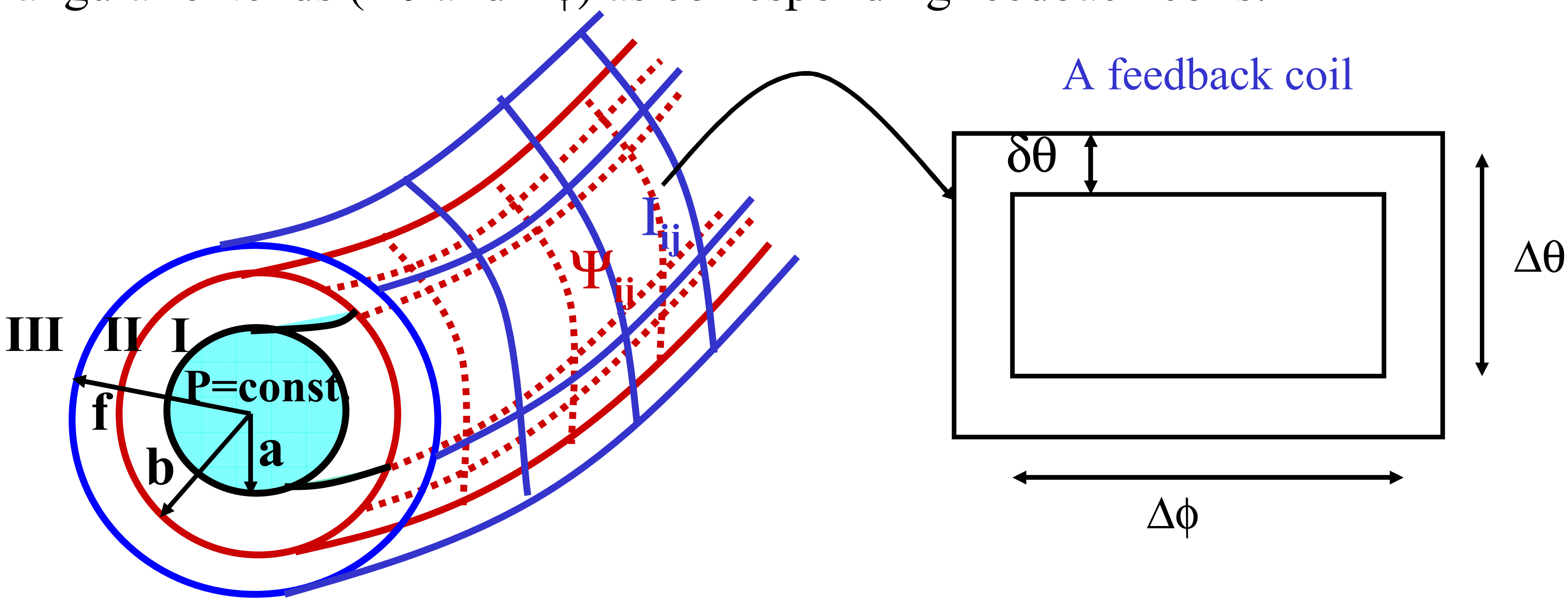
Before and after error correction with the correction current limit 6.5 kA when σ=1 mm, μ_r=1.10

- Maximum 13 kA of correction current is necessary to correct field error up to n = 2 mode with 99.8 % confidence when standard deviation σ = 1.5 mm, magnetic permeability of the welded joint $\mu_r = 1.10$

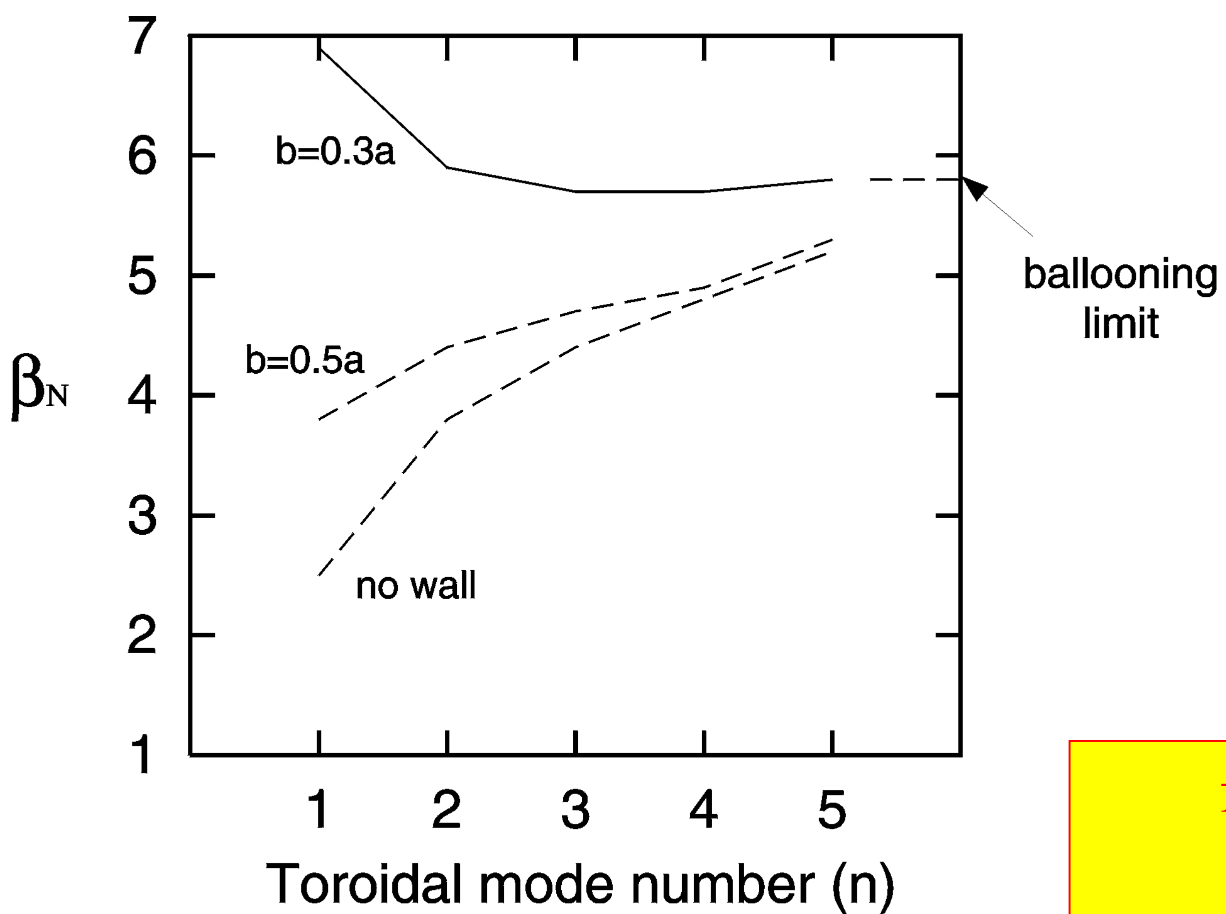
Resistive Wall Mode Control

RWM control – model for calculation

- A **toroidal, circular, surface plasma model (r=a)** with **resistive wall** at **r=b** and **feedback coils** at **r=f** is considered. Feedback coils and resistive wall are modeled by **surface current distributions** at r=b and r=f, respectively.
- **Sensors** are assumed to be located at r=b with same poloidal and toroidal angular extends (Δθ and Δϕ) as corresponding feedback coils.



Idel MHD stability for the reversed-shear mode



- Ballooning stable up to $\beta_N = 5.8$
- Continuous conformal wall with plasma-wall separation b < 0.3a can make kink limit to exceed ballooning limit

for KSTAR b ~ 0.15a

✓**RWM control is important to get a high-beta plasma**

Passive stabilization by toroidal plasma rotation

KSTAR

♦ **Toroidal rotation frequency in KSTAR**

calculated by balancing momentum input by NBI & momentum loss by anomalous transport and assuming $\tau_M \sim \tau_E$ with τ_E by ITER-89 scaling

$$\omega_f / \omega_A = (V_B P_B q \cos\psi_B \tau_M)/(V_A V_P \langle n\rangle eV_B)$$

$$\sim 0.015 \; H_{factor} P_B^{1/2}(MW) / \langle n\rangle^{1/2} \quad (10^{20}\ m^{-3})$$

$$\sim 0.069$$

where $\omega_A = V_A/2\pi Rq$, Alfven frequency, and we assumed the KSTAR parameter values,

V_B = 120 keV, $\psi_B \sim 30^o$, V_P = 16 m^3 , P_B = 2.7 MW (baseline NBI power),

$\langle n\rangle$ = 0.5 x 10^{20} m^{-3}, and H = 2.

♦ **Rotational stabilization might be possible**

$(\omega_f / \omega_A)_{threshold} \sim 0.033$ for TPX passive plate, similar to KSTAR

(cf. D.J. Ward, Phys. Plasmas **3** 3653 (1996))

* **FEC is important, to avoid the rotation damping by field error amplification above no-wall beta limit**

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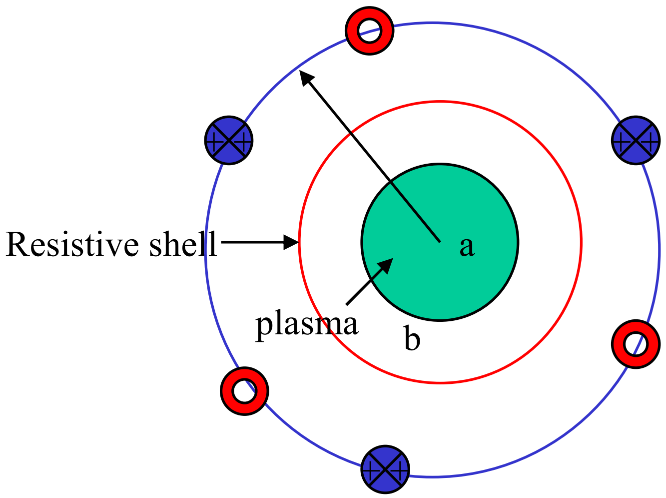
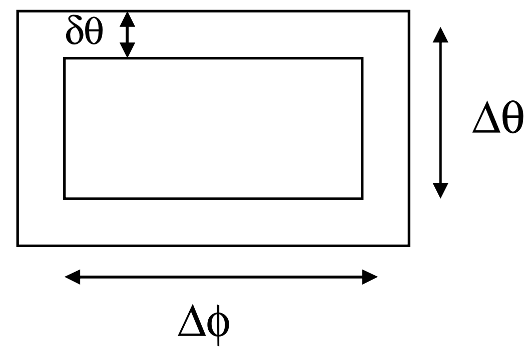
Active control of resistive wall mode : I. cylinder model



Feedback coils (current density distribution)

A feedback coil is



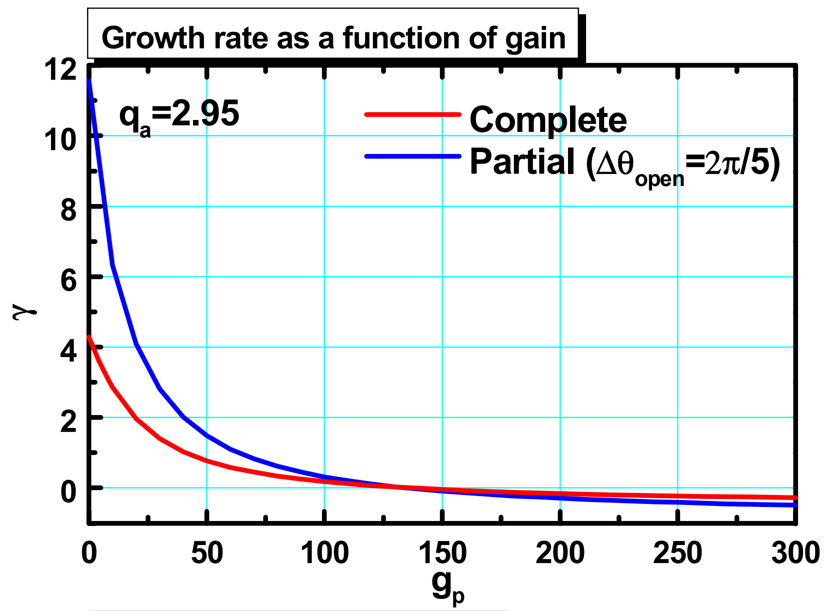
An eigenvalue equation set of RWM growth rate including feedback coil effect is

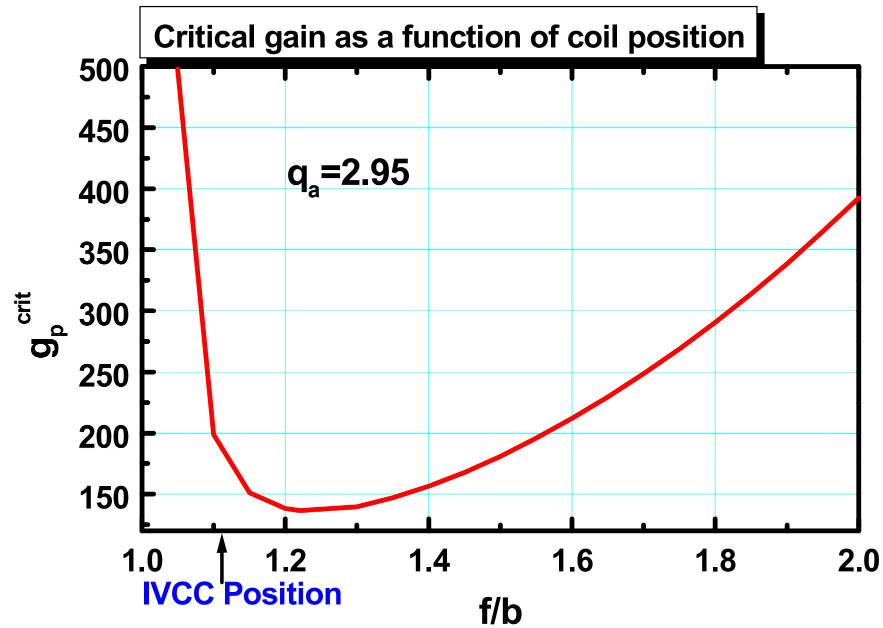
$$(\overleftrightarrow{A} - \overleftrightarrow{B}\gamma - \overleftrightarrow{C}\gamma^2)\bullet\vec{\zeta} = \vec{0} \text{ where}$$

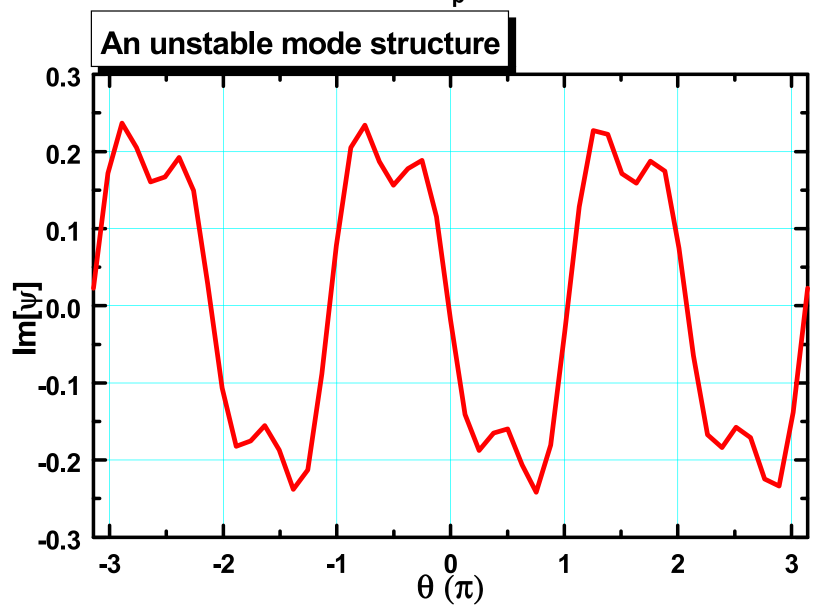
$$C_{lm}\zeta_m = (1/f)U^T_{lk}g_d{}^{kn}\Phi_{ni}\delta_{ij})[\psi_{jm}]_{r=b}\zeta_m$$

$$B_{lm}\zeta_m = (\mu_0\sigma_{lk}\delta_{kj} + 1/f[U^T_{lk}g_p{}^{kn}\Phi_{ni}\delta_{ij}][\psi_{jm}]_{r=b} + i\delta_{lk}[\frac{\partial\psi_{km}}{\partial r}]^{r=f+\varepsilon}_{r=f-\varepsilon})\zeta_m$$

$$A_{lm}\zeta_m = (1/f)[U^T_{lk}g_I{}^{kn}\Phi_{ni}\delta_{ij})[\psi_{jm}]_{r=b}\zeta_m$$







The required feedback current is estimated to be 2.4 kA-turns.

$$I_k = \frac{\delta\theta}{2R_0\Delta\phi\mu_0} g_p \Phi_k$$
$$\approx -200 \times (\pi/30) \times (\pi/6) \times 0.53 \times B_r/\mu_0$$
$$\approx 2.4 \ \text{kA}$$

Other possible applications of KSTAR IVCC for advanced physics studies are

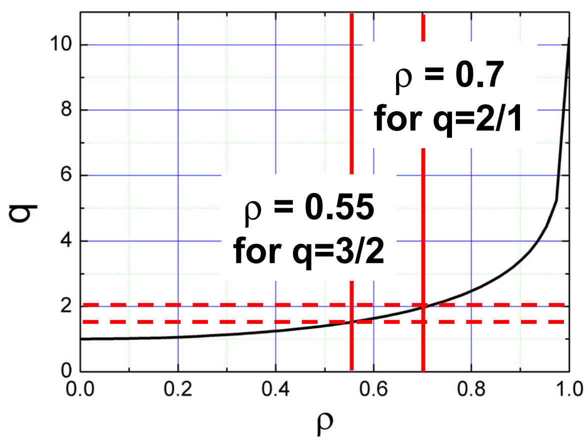
- **Edge Localized Mode control**
  - ELM suppresion by n=1 or 2 (due to the geometry of the IVCC system) resonant magnetic perturbation with currents up to 6 kA (ref. DIII-D case : 4 kA)
- **Tearing mode control**
  - Suppression/generation of tearing modes by resonant or non-resonant helical magnetic perturbations
- **Plasma rotation and transport control**
  - Local & temporal reduction of plasma rotation by magnetic islands generated using helical perturbation
  - Fluctuation suppression by local flow shear
  - Need to check the possibility of the enhancement of electron transport or the destabilization of tearing or NTM modes.
- **Impurity transport control**
  - Static island generation near plasma edge

Neoclassical Tearing Mode Control : a preliminary work

NTM control- EFIT equilibrium profiles used in TORAY-GA code

KSTAR

- Reference Plasma: The reference Double Null (DN) plasma parameters are presented in Table 1 (column 2). The EFIT model developed at GA was used to produce an equilibrium close to these parameters.



Plasma Parameters	KSTAR Reference DN Equilibrium	Reference EFIT	High *li* EFIT
Eqdsk File	--	g010004.01020	g010004.01000
B_ϕ	3.5 T	3.5 T	3.5 T
I_p	2.0 MA	2.0 MA	2.0 MA
R_o	1.8 m	1.79 m	1.79 m
a	0.5 m	0.501 m	0.499 m
κ_x	2.0	2.00	2.01
δ_x	0.8	0.80	0.80
β_ϕ	4%	4%	4%
β_n	3.5	3.53	3.51
$l_i(1)$	--	1.01	1.14
$l_i(3)$	0.8	~ 0.8*	~ 0.9*
q_{95}	--	3.9	3.83

* EFIT calculates *li*(1); *li*(3) ~ 0.8 * *li*(1); (--) Information not available

From J. Leuer, GA Engineering Physics Memo (July 30, 2004).

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Geometry for 170 GHz ray tracing and EC-wave injection angles

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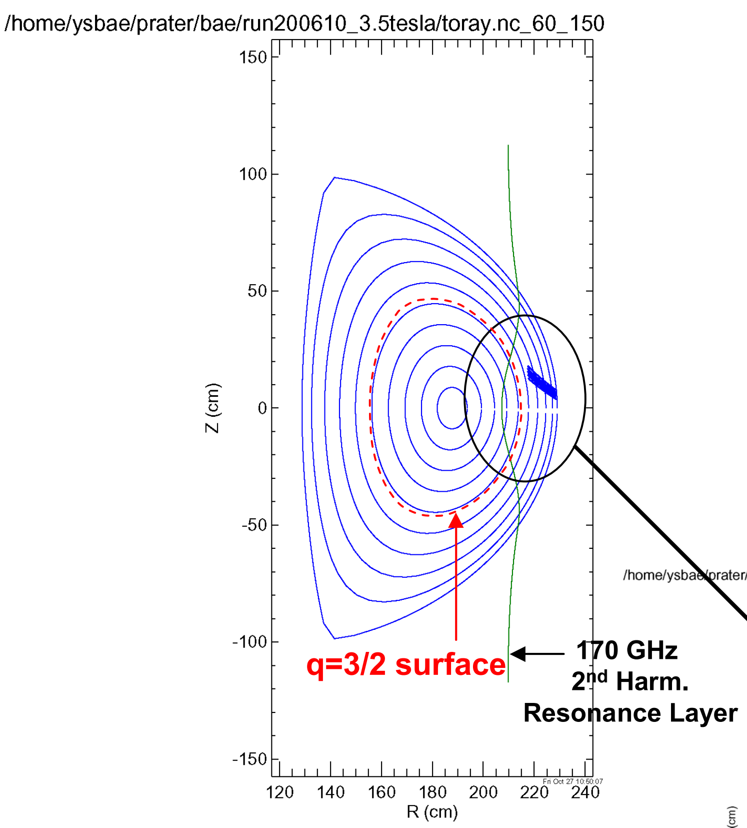
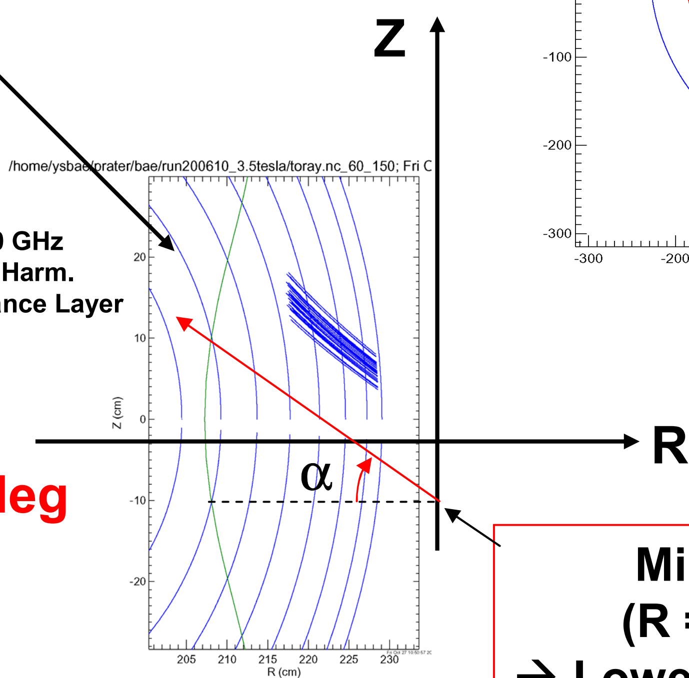
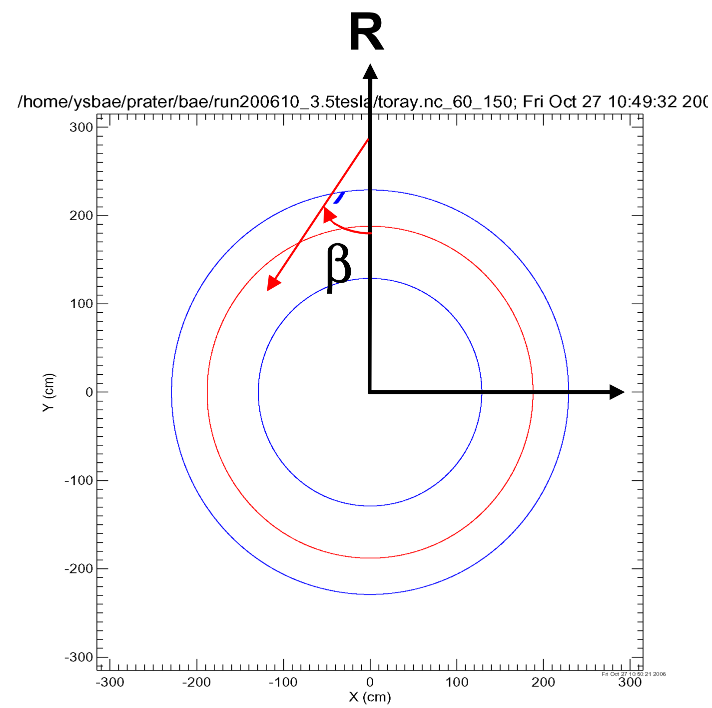




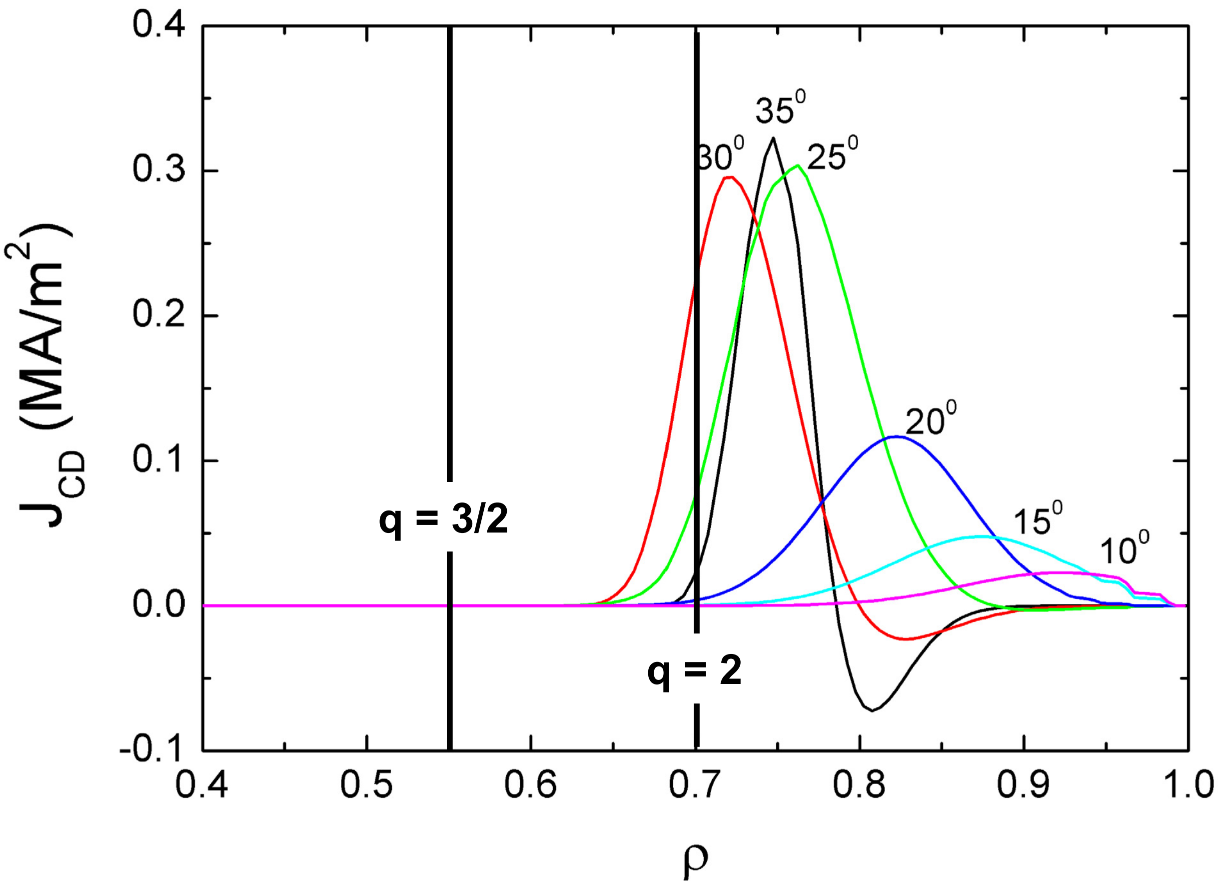


α: poloidal angle
β: toroidal angle

e.g. α = 30 deg, β = 30 deg

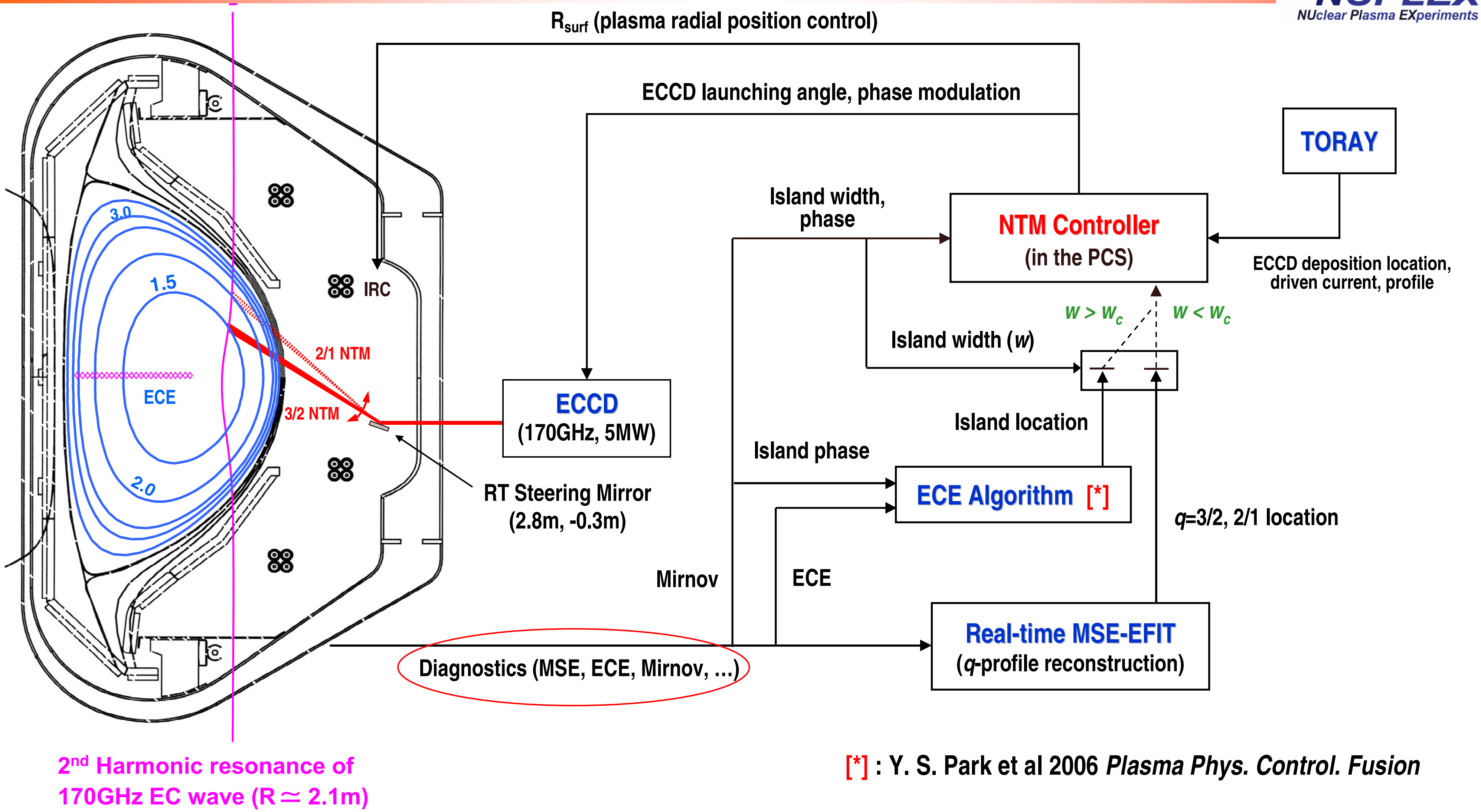
Mirror pivot position
(R = 2.8 m, Z = -0.3 m)
→ Lower row in Equatorial Port

Driven current density profiles (β = 30 deg)



Profiles of the driven current density for poloidal launched angles and for 5 MW of EC power injected as X2-mode with β = 30 deg. When α is around 30 deg, the current induced on the q = 2 surface is highest.

Conceptual Design of KSTAR NTM Control System



[*] : Y. S. Park et al 2006 *Plasma Phys. Control. Fusion*

Calculation of MRE Under KSTAR Ref. DN Equilibrium

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NUPLEX NUclear Plasma EXperiments

- **Modified Rutherford Equation :**

$$\frac{\tau_R}{r}\frac{dw}{dt} = \underbrace{\Delta' r}_{(1)} + \varepsilon^{1/2}\underbrace{\left(\frac{L_q}{L_p}\right)}_{(2)}\beta_p \frac{r}{w}\left[\underbrace{\frac{w^2}{w^2+w_d^2}}_{(3)} - \underbrace{\frac{w_{pol}^2}{w^2}}_{(4)} - \underbrace{\frac{8q\delta_{EC}}{\pi^2 w}\left(\eta\frac{j_{EC}}{j_{BS}}\right)}_{(5)}\right]$$

Where each term is related to (1) Conventional tearing mode stability, (2) Profile scale lengths, (3) Transport threshold, w_d (4) Polarization threshold, w_{pol}

- **Finally, the term of (5) is our concerned and a function of the ratio of external current and bootstrap current. Others are functions of equilibrium quantities.**

$$\Gamma_{EC} \propto -K_1\left(\frac{w}{\delta_{EC}},\frac{\Delta R}{\delta_{EC}}\right)\frac{j_{EC}}{j_{BS}}$$

where rf current efficiency, $\eta = \eta_0(1+2\delta_{EC}^2/w^2)^{-1}\exp[-(5\Delta R/3\delta_{EC})^2]$

δ_{EC} : FWHM of Gaussian RF current density profile

ΔR : offset between center of current drive and center of island

By numerical estimation of K_1 by F.W. Perkins [*] ,

[*] : F.W. Perkins et al 2000 *Bull. of APS*

$$K_1\left(\frac{w}{\delta_{EC}},\frac{\Delta R}{\delta_{EC}}\right) \approx \left(\frac{8q\delta_{EC}}{\pi^2 w}\eta\right)\frac{j_{EC}}{j_{BS}}$$ in case of un-modulated ECCD

$\delta_{EC} = 0.03\ m,\ \eta_0 = 0.4$ are assumed in ideal alignment case ($\Delta R = 0$)

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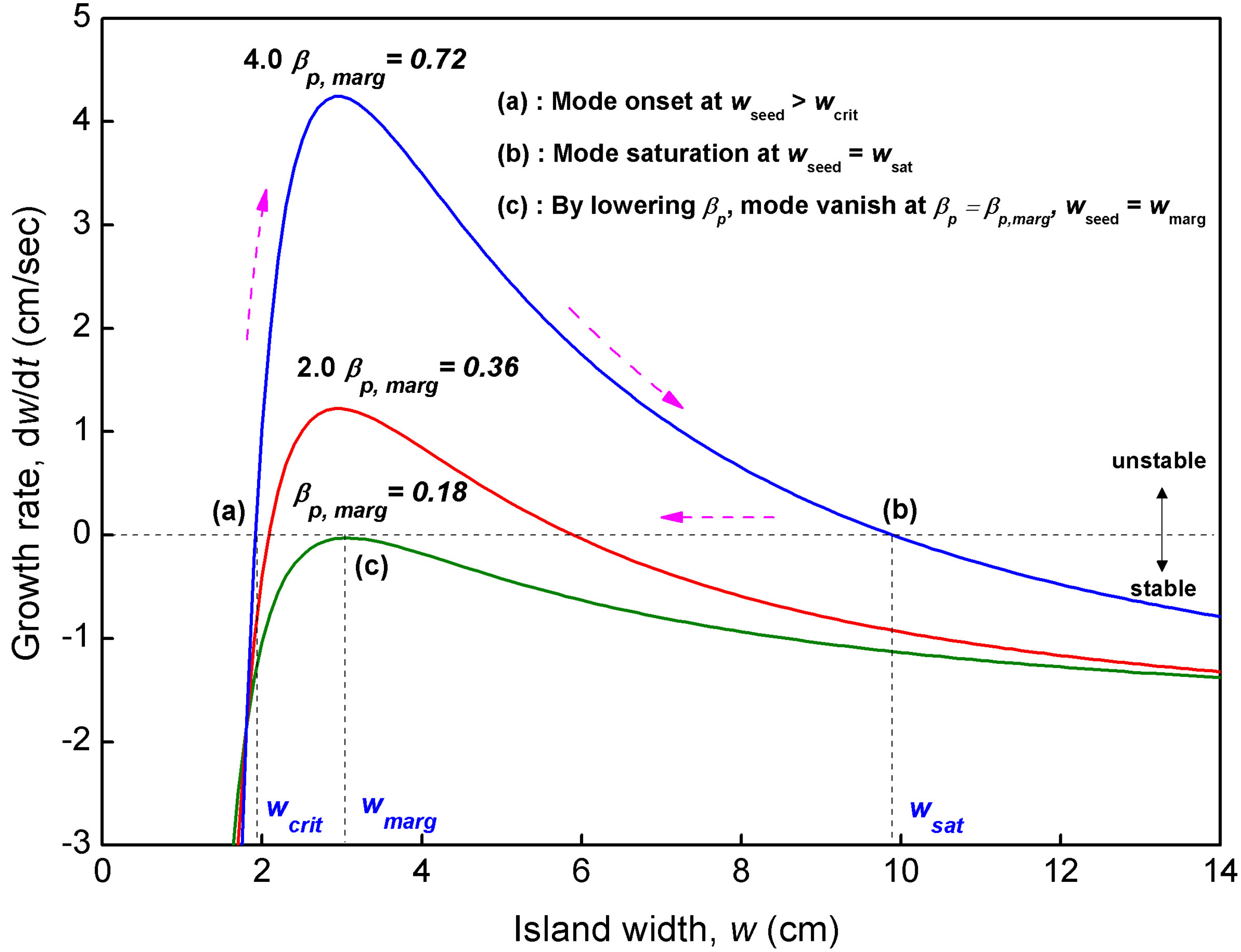
Marginal Stability Limit of 3/2 NTM in KSTAR DN plasma of reference scenario : $\beta_{p,marg} = 0.18$



$m/n = 3/2$

$\Delta' r_s = -3$

$\varepsilon = 0.217$

$r_s = 0.39\ m$

$L_q/L_p = 4.46,\ 4.35,\ 4.30$

$w_{pol} = 1.8\ cm$

$\tau_R = 62\ sec$

β_p is assumed to be decreased with increasing island size (β_p is ~25% decreased at saturated island)

L_p is assumed to be increased as increasing island size (L_p is ~80% increased at saturated island because the pressure profile is broaden by increasing island size)

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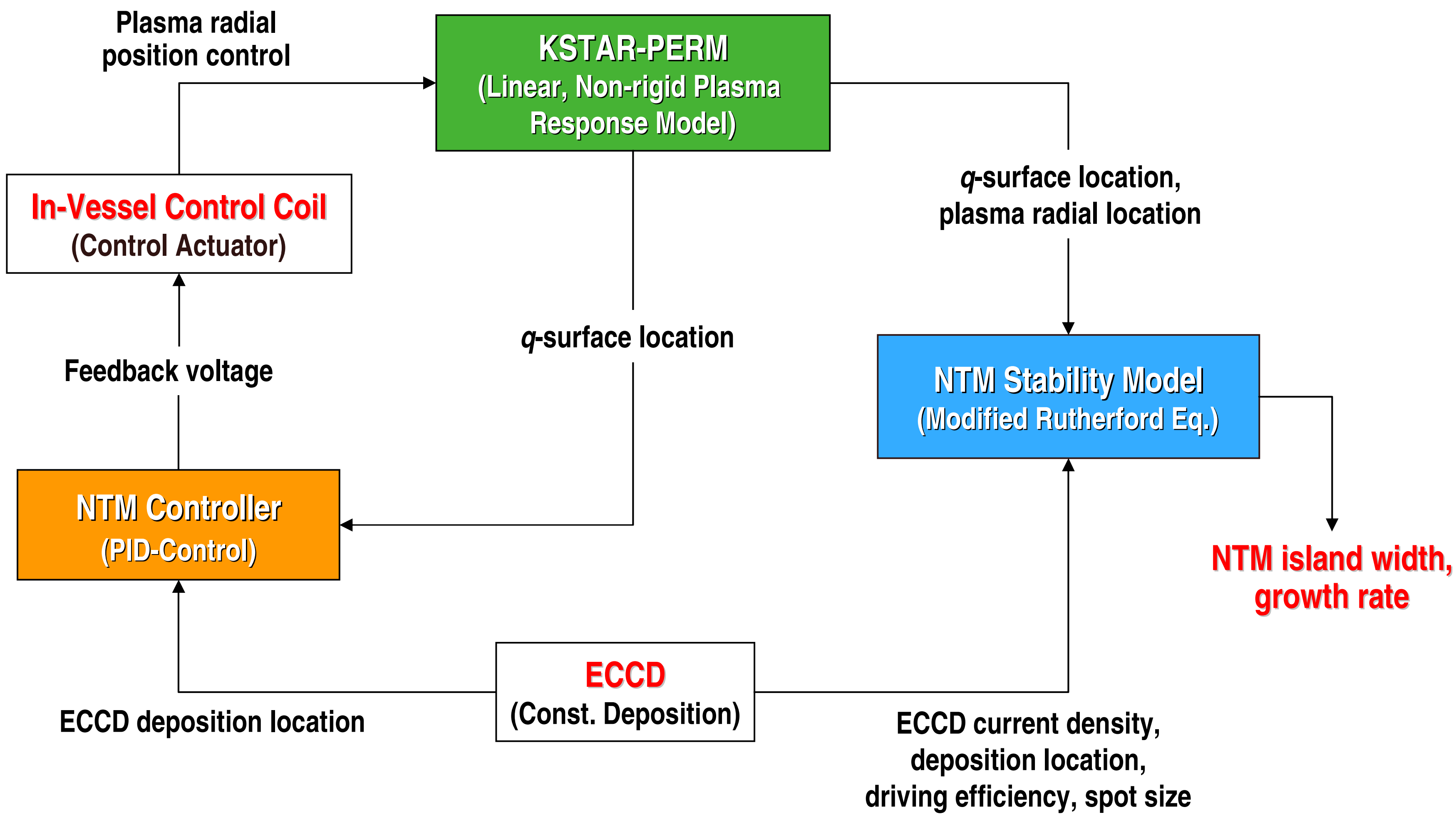
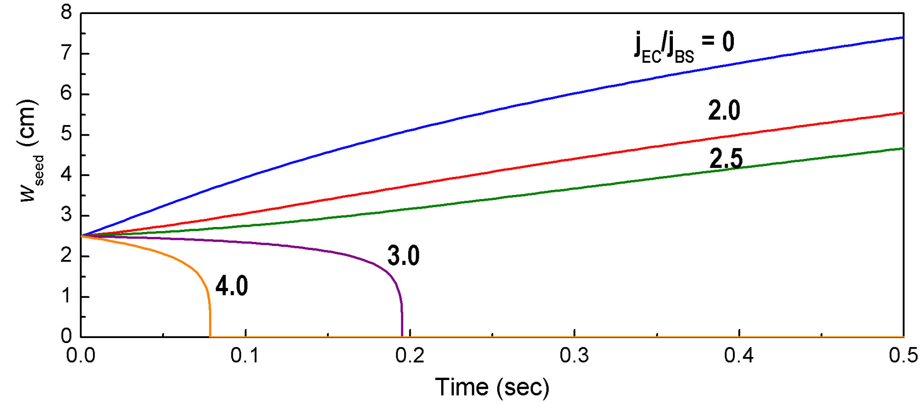
Diagram of Prototype KSTAR NTM Control Simulator



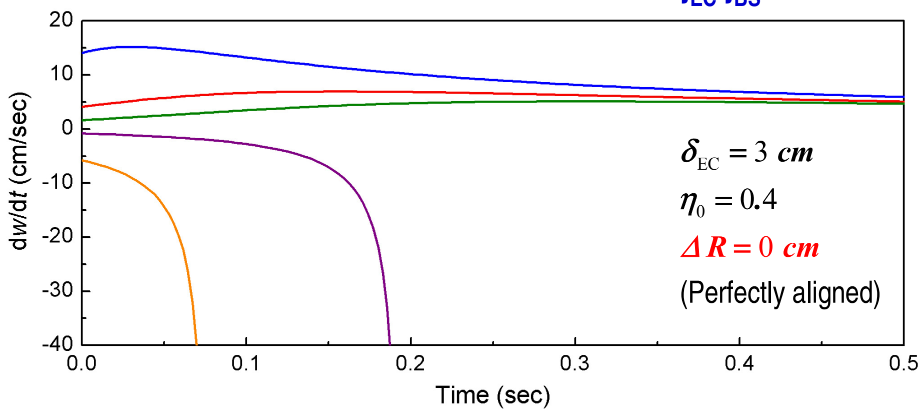
Calculation results

- Calculation with a prototype control simulator shows that the ratio of ECCD and Bootstrap current $j_{EC}/j_{BS} \sim 3$ can stabilize the 3/2 NTM at reference KSTAR DN discharge

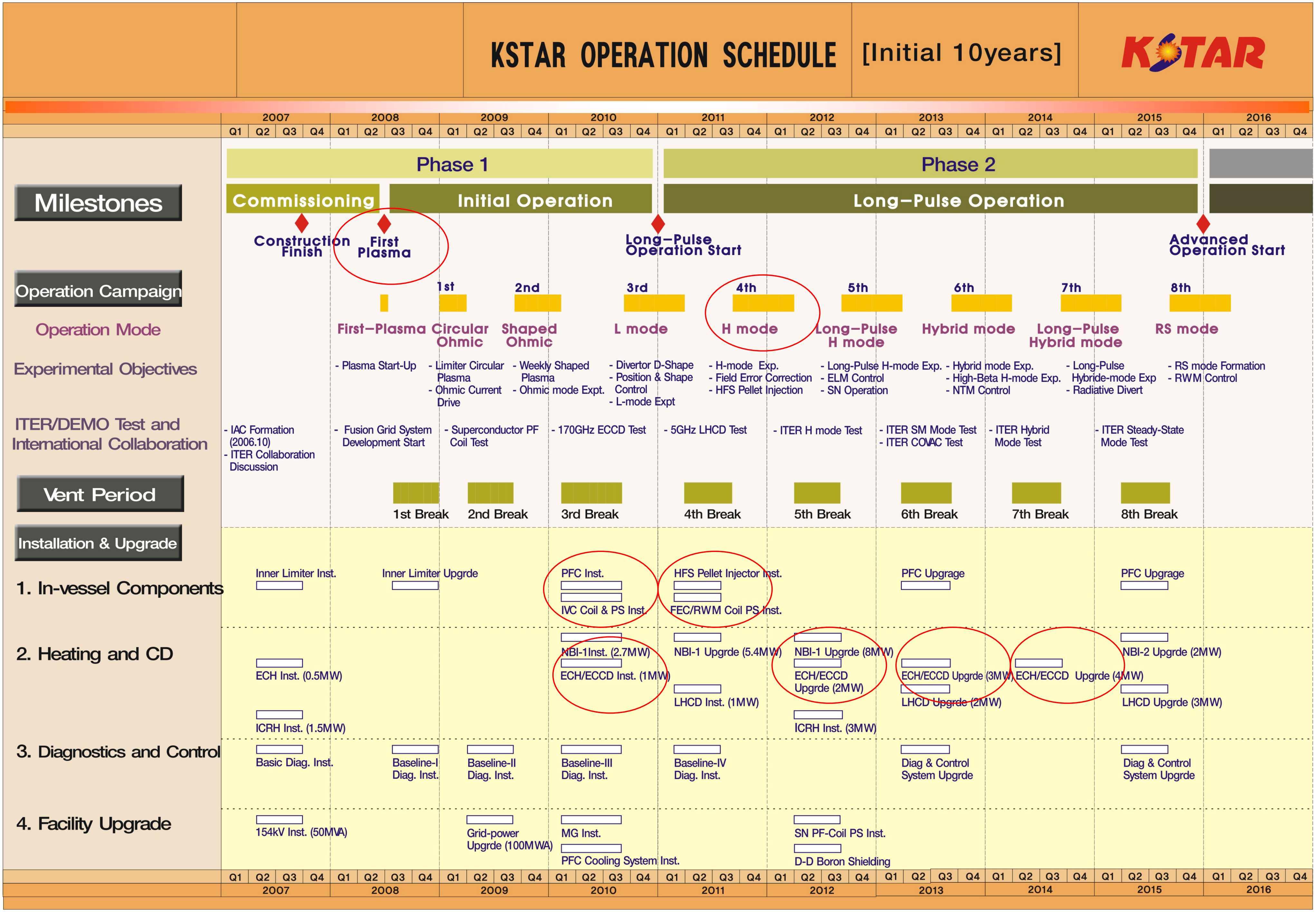
- Growths of seed islands under different j_{EC}/j_{BS}



- Growth rates of seed islands under different j_{EC}/j_{BS}



Issues and future works



KSTAR OPERATION SCHEDULE [Initial 10years]
KSTAR
2007 2008 2009 2010 2011 2012 2013 2014 2015 2016
Q1 Q2 Q3 Q4
Phase 1
Phase 2
Milestones
Commissioning
Initial Operation
Long-Pulse Operation
Construction Finish
First Plasma
Long-Pulse Operation Start
Advanced Operation Start
Operation Campaign
1st
2nd
3rd
4th
5th
6th
7th
8th
Operation Mode
First-Plasma
Circular Ohmic
Shaped Ohmic
L mode
H mode
Long-Pulse H mode
Hybrid mode
Long-Pulse Hybrid mode
RS mode
Experimental Objectives
- Plasma Start-Up
- Limiter Circular Plasma
- Ohmic Current Drive
- Weekly Shaped Plasma
- Ohmic mode Expt.
- Divertor D-Shape
- Position & Shape Control
- L-mode Expt
- H-mode Exp.
- Field Error Correction
- HFS Pellet Injection
- Long-Pulse H-mode Exp.
- ELM Control
- SN Operation
- Hybrid mode Exp.
- High-Beta H-mode Exp.
- NTM Control
- Long-Pulse Hybride-mode Exp
- Radiative Divert
- RS mode Formation
- RWM Control
ITER/DEMO Test and International Collaboration
- IAC Formation (2006.10)
- ITER Collaboration Discussion
- Fusion Grid System Development Start
- Superconductor PF Coil Test
- 170GHz ECCD Test
- 5GHz LHCD Test
- ITER H mode Test
- ITER SM Mode Test
- ITER COVAC Test
- ITER Hybrid Mode Test
- ITER Steady-State Mode Test
Vent Period
1st Break
2nd Break
3rd Break
4th Break
5th Break
6th Break
7th Break
8th Break
Installation & Upgrade
1. In-vessel Components
Inner Limiter Inst.
Inner Limiter Upgrde
PFC Inst.
IVC Coil & PS Inst.
HFS Pellet Injector Inst.
FEC/RWM Coil PS Inst.
PFC Upgrage
PFC Upgrage
2. Heating and CD
ECH Inst. (0.5MW)
ICRH Inst. (1.5MW)
NBI-1Inst. (2.7MW)
ECH/ECCD Inst. (1MW)
NBI-1 Upgrde (5.4MW)
LHCD Inst. (1MW)
NBI-1 Upgrde (8MW)
ECH/ECCD Upgrde (2MW)
ICRH Inst. (3MW)
ECH/ECCD Upgrde (3MW)
LHCD Upgrde (2MW)
ECH/ECCD Upgrde (4MW)
NBI-2 Upgrde (2MW)
LHCD Upgrde (3MW)
3. Diagnostics and Control
Basic Diag. Inst.
Baseline-I Diag. Inst.
Baseline-II Diag. Inst.
Baseline-III Diag. Inst.
Baseline-IV Diag. Inst.
Diag & Control System Upgrde
Diag & Control System Upgrde
4. Facility Upgrade
154kV Inst. (50MVA)
Grid-power Upgrde (100MWA)
MG Inst.
PFC Cooling System Inst.
SN PF-Coil PS Inst.
D-D Boron Shielding

Issues and future works

- Before year of 2010, we should establish/install the control algorithm for IVCC and NTM control since IVCC and Power Supply (PS) for position control and ECCD (baseline) will be installed during year of 2010 and PS for FEC/RWM control will be installed in year of 2011.
- Studies on field error measurement and correction algorithm are underway.
- Suppression of type-I ELM using a sub-coil of IVCC system is under search.
- More calculation, especially bootstrap current, is needed to know required power for NTM control.
- Control of another MHD activity, such as Sawtooth and disruption, will be required.

Summary

- IVCC are to be implemented in KSTAR, as an actuator to provide the control of vertical & radial position, FEC, and RWM feedback stabilization.
- Physical requirements for plasma position control, FEC, and RWM control are calculated and the results are already adopted in IVCC and PS design value. Applications of IVCC for another MHD activities control are considered.
- A preliminary work for NTM suppression using 170 GHz ECCD is done. More calculation is needed to know required power for NTM control.