Predictive Analysis of NTM Suppression by 170GHz ECCD in KSTAR

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Index

- Overview of NTM suppression in KSTAR

- Simulations of ECCD optimization
  - Optimization of ECCD vertical launch location
  - Optimal current drive on NTM surfaces by 170GHz ECCD
  - Current drive simulations with different ECCD frequencies
  - Optimization of plasma equilibrium for improved ECCD performance

- Numerical analysis of ECCD phase modulation effect

- Stability analysis of NTMs in KSTAR

- NTM control simulator development
Overview of NTM Suppression in KSTAR

- In future high confinement discharges of KSTAR, onset of NTMs will be inevitable and severely degrade the confinement and also can be a potential risk to disruption.

- For active suppression of NTMs, 170GHz ECCD system will be implemented around year 2010 and 3/2 NTM suppression experiment will be started with initial 1MW ECCD power and 2/1 NTM suppression will be followed.

- We have to predict performance of NTM stabilization under the proposed NTM control environment of KSTAR and should derive optimized control parameters for successful NTM suppression.

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Commission</th>
<th>Phase I</th>
<th>Phase II</th>
<th>Phase III</th>
<th>SUM (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>07 08 09</td>
<td>10 11 12</td>
<td>13 14 15</td>
<td>16 17 18</td>
<td>19 20 21</td>
</tr>
<tr>
<td>EC H&amp;CD (MW)</td>
<td>0.5 (84GHz)</td>
<td>1(0.8) 1(0.8)</td>
<td>1 (0.8)</td>
<td>1 (0.8)</td>
<td>1 (0.8)</td>
</tr>
<tr>
<td>SUM (MW)</td>
<td>22</td>
<td>21</td>
<td>09</td>
<td>08</td>
<td>07</td>
</tr>
</tbody>
</table>

First plasma NTM suppression? (P_{NEF}=2.7MW, P_{LH}=1MW)

- The number in parenthesis is deliverable power to the plasma

- Conceptual design of multi-MW KSTAR ECCD launchers in equatorial port (PPPL)

- KSTAR in-vessel control coils for control of plasma position, field error, RWMs (also expected to be used for ELM & NTM suppression)
Conceptual Design of KSTAR NTM Controller

Plasma radial position movement, non-resonant field injection

NBI

Plasma rotation, \( q \)-profile modification

ECCD launch angle, power, phase modulation

ECCD

(170GHz, max. 4MW)

RT Steering Mirror
(2.8m, -0.3m)

ECE

Algorithm \(^{[1]}\)

Island width, phase

Island width \((w)\)

Island location

Island phase

ECE

NTM Controller
(in the PCS)

Real-time MSE-EFIT
(\( q \)-profile reconstruction)

Diagnostics (MSE, ECE, Mirnov, …)

ECCD deposition location, driven current, profile

TORAY
(offline)

\[ w > w_c \quad w < w_c \]

\[ q = \frac{3}{2}, \frac{2}{1} \] location

IVCC

NB


NUPLEX
NUclear Plasma Experiments

SEOUL
NATIONAL UNIVERSITY
Simulation of Reference NTM Discharge Scenario in KSTAR

- Reference NTM discharge simulation by ONETWO (I_p=2MA, B_T=3.5T, P_{NBI}=14MW for target $\beta_N=2.5$)

  ※ Input $n_e$, $T_e$, $T_i$ profiles for ONETWO are obtained from DIII-D #122906 multiplied by constant factor

### Plasma parameter

<table>
<thead>
<tr>
<th>Reference EFIT</th>
<th>Plasma parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQDISK</td>
<td>g010004.01040</td>
</tr>
<tr>
<td>$B_T$</td>
<td>3.5T</td>
</tr>
<tr>
<td>$I_p$</td>
<td>2.0MA</td>
</tr>
<tr>
<td>$R_0$</td>
<td>1.79m</td>
</tr>
<tr>
<td>$a$</td>
<td>0.5m</td>
</tr>
<tr>
<td>$\kappa_x$</td>
<td>2.0</td>
</tr>
<tr>
<td>$\delta_x$</td>
<td>0.8</td>
</tr>
<tr>
<td>$\beta_N$</td>
<td>2.49</td>
</tr>
<tr>
<td>$\beta_p$</td>
<td>1.33</td>
</tr>
<tr>
<td>$I_i(1)$</td>
<td>0.982</td>
</tr>
<tr>
<td>$q_0$</td>
<td>1.1</td>
</tr>
<tr>
<td>$q_{95}$</td>
<td>3.75</td>
</tr>
</tbody>
</table>

(a) Density profiles of ion, electron, NBI driven current and bootstrap current ($j_{bs}$ from Sauter's model)

(b) Ion, electron temperature profiles and safety factor profile of reference NTM discharge scenario
Optimization of ECCD Launch Location for NTM Suppression

- Vertical location of ECCD launch location is optimized using a criterion for the optimization figure of merit of driven current profile (measure of profile localization), $I_{EC}/\delta_{EC}^2$ [2]

ECCD launch from the lowest allowable location, $z=-30\text{cm}$, shows maximum profile figure of merit for both $q=3/2$ and $2/1$ surfaces.

(a) ECCD driven current, (b) FWHM of driven current density profile and (c) profile figure of merit

The most highly localized driven current density profiles for $q=3/2$, $2/1$ can be obtained from ECCD launch from $z=-30\text{cm}$ vertical location.
Optimized 170GHz ECCD Parameters for 3/2 & 2/1 NTMs

- Optimal ECCD ray trajectories for \( q = 3/2 \) and 2/1 deposition using 170GHz 2\(^{nd}\) harmonic resonance ECCD in TORAY-GA (\( z_{\text{mirror}} = -30\,\text{cm} \))

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### ECCD Deposition Parameters on \( q = 3/2 \) and 2/1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( q = 3/2 )</th>
<th>( q = 2/1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{\text{mirror}} ) (m)</td>
<td>2.785</td>
<td></td>
</tr>
<tr>
<td>( Z_{\text{mirror}} ) (m)</td>
<td></td>
<td>-0.30</td>
</tr>
<tr>
<td>Poloidal launch angle</td>
<td>63.0(^\circ)</td>
<td>56.9(^\circ)</td>
</tr>
<tr>
<td>Toroidal launch angle</td>
<td>167.6(^\circ)</td>
<td>156.7(^\circ)</td>
</tr>
<tr>
<td>( \rho ) (=deposition center)</td>
<td>0.540</td>
<td>0.724</td>
</tr>
<tr>
<td>( j_{\text{EC}}/P_{\text{EC}} ) (kA/m(^2)/MW)</td>
<td>49.07</td>
<td>44.63</td>
</tr>
<tr>
<td>( I_{\text{EC}}/P_{\text{EC}} ) (kA/MW)</td>
<td>13.65</td>
<td>20.35</td>
</tr>
<tr>
<td>( \delta_{\text{EC}} ) (( \rho ), FWHM)</td>
<td>0.034</td>
<td>0.047</td>
</tr>
<tr>
<td>( \delta_{\text{EC}} ) (cm) *</td>
<td>1.48</td>
<td>1.73</td>
</tr>
<tr>
<td>( I_{\text{EC}}/\delta_{\text{EC}}^2 ) (kA/rho(^2)/MW)</td>
<td>12.06x10(^3)</td>
<td>9.39x10(^3)</td>
</tr>
</tbody>
</table>

* Radial widths in cm unit are calculated in the outboard midplane
Performance of Outboard Deposited 170GHz ECCD is Poor

- Disadvantages of 170GHz ECCD under $B_T=3.5T$
  - Strong effect of electron trapping causes low current drive efficiency (Ohkawa current)
  - Difficulties in determining optimum launch angles
    - Vertical location of resonance point is sensitive to plasma conditions
      - We have to carefully control the poloidal launch angle also
  - In low beta($\beta_N<2$), $q_{95}$ should be reduced to drive current on $q=3/2$
  - In higher beta, current drive width can be broadened

- How can we improve ECCD performance?
  - Move cyclotron resonance layer to inboard region of plasma
    - Reduce $B_T$ or use different ECCD frequency
  - Change $q$-profile (raise $q_{95}$) to move NTM surface to core region
    - High $T_e$ can improve ECCD performance and make 2/1 NTM less dangerous
      - but NTM stability can be degraded from enhanced interactions between MHD activities
  - Increase local $T_e$ around NTM surface by auxiliary heating

- Shape of 170GHz 2nd harmonic resonance layer (pink) in $\beta_N=3.5$(left) and $\beta_N=2.5$(right) plasmas.
  Contours of $q=3/2$(green) and $q=2/1$(blue) surfaces in $\beta_N=3.5$(solid) and $\beta_N=2.5$(dashed) plasmas.
ECCD utilizing 110GHz O-wave fundamental harmonic resonance exhibits higher driven current than 170GHz ECCD but the profile figure of merit, $I_{EC}/\delta_{EC}^2$, is reduced from broad profile

$\rightarrow \delta_{EC}$ is too broad

- Optimal ECCD ray trajectories & driven current density profiles for $q=3/2$ & $2/1$ deposition using 110GHz 1st harmonic resonance ECCD in TORAY-GA ($z_{mirror}=-30\text{cm}$)

<table>
<thead>
<tr>
<th>ECCD Deposition Parameters on $q=3/2$ and $2/1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{mirror}$ (m)</td>
</tr>
<tr>
<td>$Z_{mirror}$ (m)</td>
</tr>
<tr>
<td>Poloidal launch angle</td>
</tr>
<tr>
<td>Toroid. launch angle</td>
</tr>
<tr>
<td>Rho (=deposition center)</td>
</tr>
<tr>
<td>$j_{EC}/P_{EC}$ (kA/m²/MW)</td>
</tr>
<tr>
<td>$I_{EC}/P_{EC}$ (kA/MM)</td>
</tr>
<tr>
<td>$\delta_{EC}$ (rho, FWHM)</td>
</tr>
<tr>
<td>$\delta_{EC}$ (cm)</td>
</tr>
<tr>
<td>$I_{EC}/\delta_{EC}^2$ (kA/rho²/MM)</td>
</tr>
</tbody>
</table>

* Value in brackets are from 170GHz ECCD
**120GHz ECCD for 3/2 NTM under 3.5T Equilibrium**

- By increasing the frequency of 110GHz O-wave 1st harmonic ECCD from 110GHz to 120GHz, improved current drive on 3/2 NTM is possible.

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**ECCD Deposition Parameters on q=3/2**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{mirror}}$ (m)</td>
<td>2.785</td>
</tr>
<tr>
<td>$Z_{\text{mirror}}$ (m)</td>
<td>-0.30</td>
</tr>
<tr>
<td>ECCD frequency</td>
<td>110GHz, 120GHz</td>
</tr>
<tr>
<td>Poloidal launch angle</td>
<td>90.0°, 76.0°</td>
</tr>
<tr>
<td>Toroidal launch angle</td>
<td>169.3°, 171.81°</td>
</tr>
<tr>
<td>$R_0$ (deposition center)</td>
<td>0.540, 0.541</td>
</tr>
<tr>
<td>$J_{\text{EC}}/P_{\text{EC}}$ (kA/m²/MW)</td>
<td>107.11, 135.56</td>
</tr>
<tr>
<td>$I_{\text{EC}}/P_{\text{EC}}$ (kA/MM)</td>
<td>74.24, 60.92</td>
</tr>
<tr>
<td>$\delta_{\text{EC}}$ (rho, FWHM)</td>
<td>0.087, 0.055</td>
</tr>
<tr>
<td>$\delta_{\text{EC}}$ (cm)</td>
<td>3.83, 2.45</td>
</tr>
<tr>
<td>$I_{\text{EC}}/\delta_{\text{EC}}^2$ (kA/rho²/MM)</td>
<td>9.79x10^3, 19.97x10^3</td>
</tr>
</tbody>
</table>

* Radial widths in cm unit are calculated in the outboard midplane.
128GHz ECCD for 2/1 NTM under 3.5T Equilibrium

- By increasing the frequency of 110GHz O-wave 1st harmonic ECCD from 110GHz to 128GHz, improved current drive on 2/1 NTM is possible.

<table>
<thead>
<tr>
<th>ECCD Deposition Parameters on $q=2/1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{mirror}}$ (m)</td>
</tr>
<tr>
<td>$Z_{\text{mirror}}$ (m)</td>
</tr>
<tr>
<td>ECCD frequency</td>
</tr>
<tr>
<td>Poloidal launch angle</td>
</tr>
<tr>
<td>Toroidal launch angle</td>
</tr>
<tr>
<td>$R_0$ (deposition center)</td>
</tr>
<tr>
<td>$j_{EC}/P_{EC}$ (kA/m²/MW)</td>
</tr>
<tr>
<td>$I_{EC}/P_{EC}$ (kA/MW)</td>
</tr>
<tr>
<td>$\delta_{EC}$ (rho, FWHM)</td>
</tr>
<tr>
<td>$\delta_{EC}$ (cm) *</td>
</tr>
<tr>
<td>$I_{EC}/\delta_{EC}^2$ (kA/rho²/MW)</td>
</tr>
</tbody>
</table>

* Radial widths in cm unit are calculated in the outboard midplane.

- Optimal ECCD ray trajectories & driven current density profiles for $q=2/1$ deposition using 128GHz O-wave 1st harmonic resonance ECCD from TORAY-GA.

Resonance layer is moved to inboard side.
**B_T = 2.5T, I_p = 1.4MA Equilibrium for 3/2 NTM with 170GHz ECCD**

- ECCD figure of merit can be greatly increased in case of inboard deposition by eliminating the current drive degradation by electron trapping which is majorly occurred in outboard region (I_p = 1.4MA, B_T = 2.5T, 170GHz ECCD)

### ECCD Deposition Parameters on q=3/2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R_{mirror} (m)</td>
<td>2.785</td>
</tr>
<tr>
<td>Z_{mirror} (m)</td>
<td>-0.30</td>
</tr>
<tr>
<td>Poloidal launch angle</td>
<td>63.0°</td>
</tr>
<tr>
<td>Toroidal launch angle</td>
<td>167.6°</td>
</tr>
<tr>
<td>Rho (deposition center)</td>
<td>0.540</td>
</tr>
<tr>
<td>(\delta_{EC}/P_{EC} ) (kA/m²/MW)</td>
<td>49.07</td>
</tr>
<tr>
<td>(I_{EC}/P_{EC} ) (kA/MM)</td>
<td>13.65</td>
</tr>
<tr>
<td>(\delta_{EC} ) (rho, FWHM)</td>
<td>0.034</td>
</tr>
<tr>
<td>(\delta_{EC} ) (cm) *</td>
<td>1.48</td>
</tr>
<tr>
<td>(I_{EC}/\delta_{EC}^2 ) (kA/rho²/MM)</td>
<td>12.06x10²</td>
</tr>
</tbody>
</table>

* Radial widths in cm unit are calculated in the outboard midplane.
**ECCD Deposition Parameters on \( q = \frac{3}{2} \)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tr>
<td>( R_{\text{mirror}} ) (m)</td>
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</tr>
<tr>
<td>( Z_{\text{mirror}} ) (m)</td>
<td>-0.30</td>
</tr>
<tr>
<td>Poloidal launch angle</td>
<td>56.9°</td>
</tr>
<tr>
<td>Toroidal launch angle</td>
<td>76.0°</td>
</tr>
<tr>
<td>( \rho_{\text{center}} )</td>
<td>0.724</td>
</tr>
<tr>
<td>( \delta_{\text{EC}} ) (cm)</td>
<td>0.92</td>
</tr>
<tr>
<td>( \delta_{\text{EC}} ) (RFHM)</td>
<td>0.047</td>
</tr>
<tr>
<td>( \delta_{\text{EC}} ) (cm) *</td>
<td>1.73</td>
</tr>
<tr>
<td>( I_{\text{EC}}/P_{\text{EC}} ) (kA/MW)</td>
<td>44.63</td>
</tr>
<tr>
<td>( I_{\text{EC}}/P_{\text{EC}} ) (kA/MM)</td>
<td>20.35</td>
</tr>
<tr>
<td>( I_{\text{EC}}/\delta_{\text{EC}}^2 ) (kA/rho^2/MM)</td>
<td>9.39x10^3</td>
</tr>
</tbody>
</table>

* Radial widths in cm unit are calculated in the outboard midplane.

**ECCD figure of merit can be greatly increased in case of inboard deposition by eliminating the current drive degradation by electron trapping which is majorly occurred in outboard region (\( I_p=1.35 \text{MA}, B_T=2.35 \text{T}, 170 \text{GHz ECCD} \))**
Summary of Current Drive Performances

Driven current densities from optimized plasma equilibrium exhibits the most highly enhanced ECCD performance.

- 170GHz ECCD under $B_T=3.5T$
- From frequency optimization ($f_{ECCD}=120\text{GHz}$ for 3/2 NTM, $f_{ECCD}=128\text{GHz}$ for 2/1 NTM)
- From equilibrium optimization ($I_p=1.4\text{MA}$, $B_T=2.5T$ for 3/2 NTM, $I_p=1.35\text{MA}$, $B_T=2.35T$ for 2/1 NTM)
Modified Rutherford Equation for KSTAR NTM Stability Analysis

- Compact form of modified Rutherford equation for NTM stability analysis

\[
\frac{\tau_R}{r_s} \frac{dw}{dt} = \Delta r_s + \delta \Delta' r_s + a_2 \frac{L_q}{w} \left[ 1 - \frac{w_{marg}^2}{3w^2} - K_1 \left( \frac{j_{ec}}{j_{bs}} \right) \right]
\]

1st Conventional tearing mode stability: assumed as \( \Delta r_s - m \) for \( m/n \) NTM

2nd Tearing mode stability enhanced by ECCD: Westerhof's analytic model is used with no-island assumption

3rd Destabilization from perturbed bootstrap current: \( a_2 \) is fitted by inferred size of saturated NTM island from ISLAND

4th Stabilizing effect from small island & polarization threshold: assumed as \( w_{marg} \leq 2 \epsilon^{1/2} \rho \) (FWHM of driven current profile) \( \leq \frac{1}{2} \)

5th Stabilization from replacing bootstrap current by ECCD: effectiveness of current drive, \( K_1 \), is calculated from Perkins' current drive model

\[
K_1(x, \tau, o, \epsilon) = \text{func} \left[ \begin{array}{c}
\text{size of current drive,} \\
\text{phase modulation, phase delay,} \\
\text{positional misalignment}
\end{array} \right]
\]

\( x = \frac{w}{\delta_o}, \ e : \text{positional misalignment (}= (r - r_c)/\delta_o) \) \\
\( \delta_o : \text{FWHM of driven current profile,} \ o : \text{phase delay (rad)} \) \\
\( \tau : \text{fractional ‘ON’ time of modulation (0 \leq \tau \leq 1)} \)

Evaluation of $\delta \Delta' r_s$ and Fitting of $a_2$ in MRE

- Enhancement of tearing mode stability from $j_\parallel$ modification by ECCD is evaluated from analytic model [4]

$$\delta \Delta' r_s \approx -\frac{5\pi^{3/2}}{32} a_2 \frac{L_y}{\delta_e} F(x) \frac{j_{ec}}{j_\parallel}$$

with

$$F(x) = \tau - 2.43 e + 1.40 e^2 - 0.23 e^3$$

- Shaping parameter $a_2$ is fitted by inferred size of saturated NTM island from ISLAND [5]

  - Under the KSTAR reference NTM discharge, widths of saturated 3/2 and 2/1 NTMs are inferred from quasi-linear ISLAND module and $a_2$ is fitted from growth rates of NTMs with no-ECCD

  From ISLAND,
  \[ w_{32\text{sat}} = 4.5\text{cm} \]
  \[ w_{21\text{sat}} = 10.5\text{cm} \]

  Fitted shaping parameters, $a_2$, from NTM growth rates calculated by MRE

  \[ a_2 = 2.1 \text{ (for 3/2 NTM)} \]
  \[ a_2 = 3.9 \text{ (for 2/1 NTM)} \]

Numerical Analysis of Phase-Modulated ECCD Effectiveness

- ECCD effectiveness, $K_1$, is calculated by using F.W. Perkins' current drive model [6]

- Driven current density averaged over a volume element of helical flux

$$J(\Phi, x, \tau) = \frac{\langle j_{\text{cd}} \rangle}{j_{\text{cd}}} = \frac{1}{V'(\Phi)} \int \frac{M(\alpha, \tau)}{\sqrt{\Phi + 1 + \cos(m\alpha)}} \exp\left(-x^2\left(\Phi + \frac{1 + \cos(m\alpha)}{2}\right)\right) d\alpha$$

- Current drive effectiveness, $K_1$, can be calculated as

$$K_1(x, \tau) = \frac{1}{C_2} \int_{-1}^{\infty} W(\Phi) J(\Phi, x, \tau) d\Phi$$

- Distribution of weighting function values over island helical flux (red: stabilization, blue: destab.)

- 50/50 modulated ECCD current density driven over non-dimensional helical flux of island

- $K_1$ in various schemes of current drive can be described such as
  
  I: misaligned
  II: phase delayed
  III: misaligned & phase delayed

Current Drive Effectiveness of Continuous & Modulated ECCD

\[ K_1 = 0.603 \text{ with } w/\delta_{\text{ec}} = 1.6, \Delta R/\delta_{\text{ec}} = 0 \]

\[ \tau = 1 \quad \text{(Continuous)} \]

\[ \max. K_1 = 0.866 \text{ with } w/\delta_{\text{ec}} = 1.1, \tau = 0.58, \Delta R/\delta_{\text{ec}} = 0 \]

\[ \tau < 1 \quad \text{(Modulated)} \]

\[ \text{~44% increase in } \max. K_1 \text{ by modulation} \]

\[ K_1 \text{ versus relative size of island & positional misalignment} \]

\[ K_1 \text{ versus modulation duty factor & relative size of island} \]

\[ \Delta R/\delta_{\text{ec}} = 0.0, 0.5, 1.0, 1.5, 2.0 \]

\[ K_1 \text{ vs } w/\delta_{\text{ec}} \]

\[ K_1 \text{ vs } \tau \]

\[ w/\delta_{\text{ec}} = 0.1, 1.0, 5.0, 10.0 \]
3/2 NTM stability predicted for the target KSTAR NTM discharge (170GHz X2 ECCD)

- Input parameters in MRE

\[
\begin{align*}
\Delta R &= 0 \text{ (=ideal alignment)} \\
\Delta' r_s - m &= -3 \\
L_q &= 31.52 \text{ cm} \text{ (from EFIT)} \\
\delta_{ec} &= 1.48 \text{ cm} \text{ (from TORAY-GA)} \\
j_\parallel &= 185.05 \text{ A/cm}^2 \text{ (from EFIT)} \\
j_{bs} &= 41.66 \text{ A/cm}^2 \text{ (from ONETWO)} \\
j_{ec}/P_{ec} &= 4.91 \text{ A/cm}^2/MW \text{ (from TORAY-GA)} \\
w_{marg} &= 2.23 \text{ cm} = 2 \epsilon^{1/2} \rho_i \text{ (from EFIT)} \\
a_z &= 2.1 \text{ (Inferred from ISLAND calculation)}
\end{align*}
\]

The initial ECCD power of KSTAR (=1MW) can be enough for complete stabilization of predicted 3/2 NTM having \( w_{marg} \equiv 4.5 \text{ cm} \).
2/1 NTM stability predicted for the target KSTAR NTM discharge (170GHz X2 ECCD)

- Input parameters in MRE
  \[ \Delta R = 0 \] (ideal alignment)
  \[ \Delta r_s - m = -2 \]
  \[ L_q = 22.83 \text{ cm} \] (from EFIT)
  \[ \delta_{ec} = 1.73 \text{ cm} \] (from TORAY-GA)
  \[ j_\phi = 156.69 \text{ A/cm}^2 \] (from EFIT)
  \[ j_{bs} = 36.95 \text{ A/cm}^2 \] (from ONETWO)
  \[ j_{ec}/P_{ec} = 4.46 \text{ A/cm}^2/\text{MW} \] (from TORAY-GA)
  \[ w_{marg} = 1.81 \text{ cm} = 2\varepsilon^{1/2}\rho_{li} \] (from EFIT)
  \[ a_z = 3.9 \] (Inferred from ISLAND calculation)

ECCD power of ~2.8MW can stabilize the predicted 2/1 NTM having \( w_{\text{marg}} = 10.5 \text{ cm} \)

→ For both 3/2 & 2/1 NTMs, phase modulation of 170GHz ECCD is not effective because of its narrow driven current profile & effect of \( \delta \Delta r_s \) reduction by modulation
Phase Modulation is Effective Only in Broad $\delta_{\text{EC}}$ ECCD

- 2/1 NTM stability predicted for the target KSTAR NTM discharge (110GHz O1 ECCD)

- Input parameters in MRE

\[
\begin{align*}
\Delta R &= 0 \quad (=\text{ideal alignment}) \\
\Delta' r_s - m &= -2 \\
L_q &= 22.83 \text{ cm} \quad (\text{from EFIT}) \\
\delta_{\text{ec}} &= 3.21 \text{ cm} \quad (\text{from TORAY-GA}) \\
j_{b_s} &= 36.95 \text{ A/cm}^2 \quad (\text{from ONETWO}) \\
j_{ec}/P_{ec} &= 5.99 \text{ A/cm}^2/\text{MW} \quad (\text{from TORAY-GA}) \\
w_{m\text{arg}} &= 1.81 \text{ cm} \quad (=2\varepsilon^{1/2}/\rho_{ph}) \quad (\text{from EFIT}) \\
a_2 &= 3.9 \quad (\text{Inferred from ISLAND calculation})
\end{align*}
\]

In case of 110GHz ECCD which has broad profile width (>3cm), phase modulation can reduce the minimum ECCD power required for marginal stability of 2/1 NTM.
Prediction of 2/1 NTM Stability by 128GHz ECCD (2MA, 3.5T)

- 2/1 NTM stability predicted for the target KSTAR NTM discharge (128GHz O1 ECCD)

- Input parameters in MRE

\[ \Delta R = 0 \quad (= \text{ideal alignment}) \]
\[ \Delta' r_s - m = -2 \]
\[ L_q = 22.83 \text{ cm} \quad (\text{from EFIT}) \]
\[ \delta_{ec} = 1.59 \text{ cm} \quad (\text{from TORAY-GA}) \]
\[ j_{\|} = 156.69 \text{ A/cm}^2 \quad (\text{from EFIT}) \]
\[ j_{bs} = 36.95 \text{ A/cm}^2 \quad (\text{from ONETWO}) \]
\[ j_{ec}/P_{ec} = 7.97 \text{ A/cm}^2/\text{MW} \quad (\text{from TORAY-GA}) \]
\[ w_{marg} = 1.81 \text{ cm} \quad (= 2e^{1/2} \rho_{th}) \quad (\text{from EFIT}) \]
\[ a_2 = 3.9 \quad (= \text{Inferred from ISLAND calculation}) \]

In case of 128GHz ECCD, ~2MW ECCD power can be enough for complete suppression of 2/1 NTM.
• 2/1 NTM stability predicted for the equilibrium optimized for 3/2 NTM (170GHz X2 ECCD)
SIMULINK Based KSTAR NTM Control Simulator

- KSTAR NTM Stability Model (modified Rutherford Eq.)

- Prototype KSTAR NTM Control Simulator
NTM Control Simulation Results

- **3/2 NTM suppression simulation**
  - Control simulation under different amount of EC-driven current
  
  - Control simulation under different size of seed island
  - Control simulation under different controller gain (positional offset minimization from plasma radial movement)
Summary

- NTM stabilities are analyzed by construction of modified Rutherford equation under the proposed KSTAR environment
- Reference NTM discharge scenario in KSTAR is developed from ONETWO simulation
- ECCD ray-tracing analysis is performed for the various ECCD schemes by using TORAY-GA
- ECCD effectiveness is analyzed for various deposition schemes including modulated phase effect
- 3/2 NTM which is expected to have small saturated size (~4.5cm) can be completely stabilized by using only 1MW initial ECCD power in KSTAR, but large size 2/1 NTM requires ~2.8MW ECCD power for stabilization
- ECCD launch under low $B_T$ equilibrium is expected to greatly increase current drive performance and can reduce the minimum power required for complete mode suppression to ~1MW for both NTMs