Integrated modeling of island growth, stabilization and mode locking

Consequences for NTM control on ITER

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Outline

What are the consequences of preventing mode locking for NTM control on ITER?

- Rotation of NTMs
- Generalized Rutherford Equation with ECCD stabilization
- Maximum allowed latency
- Effect of misalignment

NTM control on ITER

- ECCD on ITER
  - Four EC launchers spanning 100° toroidal angle
  - Total power 13.3 MW
  - Destabilizing current drive in X-point likely for locked modes

- Full suppression of islands
- No mode locking (rotation should remain finite)

- Latency and alignment requirements?

Rotation

- Rigid body rotation of the island
  - Speed up by viscous coupling with the bulk plasma
  - Slow down by wall interaction

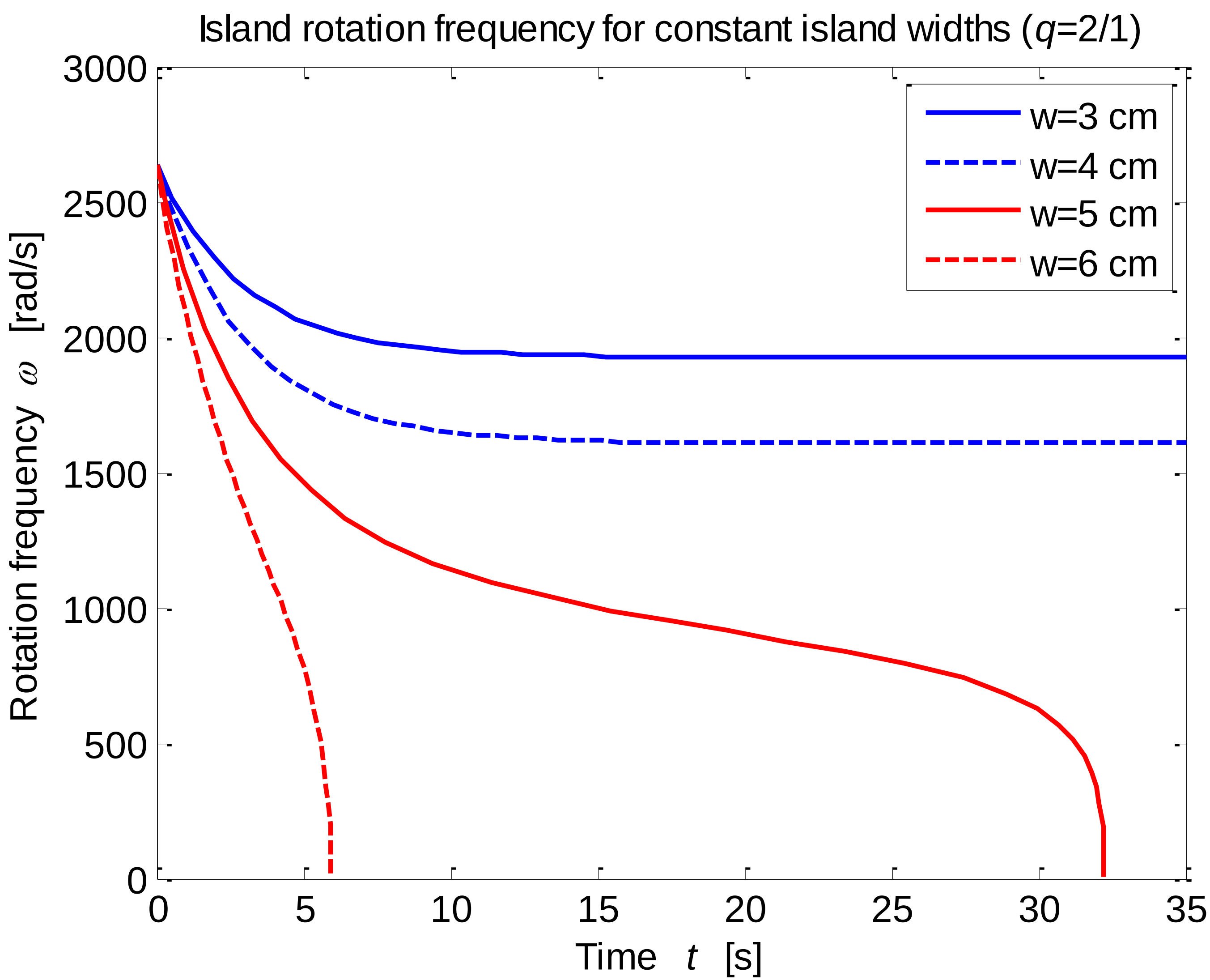
$$\frac{d\omega}{dt} = \left(\frac{\omega_0}{\tau_{M0}} - \frac{\omega}{\tau_M} \right) - \frac{1}{m\tau_{A0}^2 C_W \omega \tau_w} \left(\frac{w}{a} \right)^3$$

$$\tau_M = \frac{\tau_{M0}}{1 + C_M \dfrac{w}{a}}$$

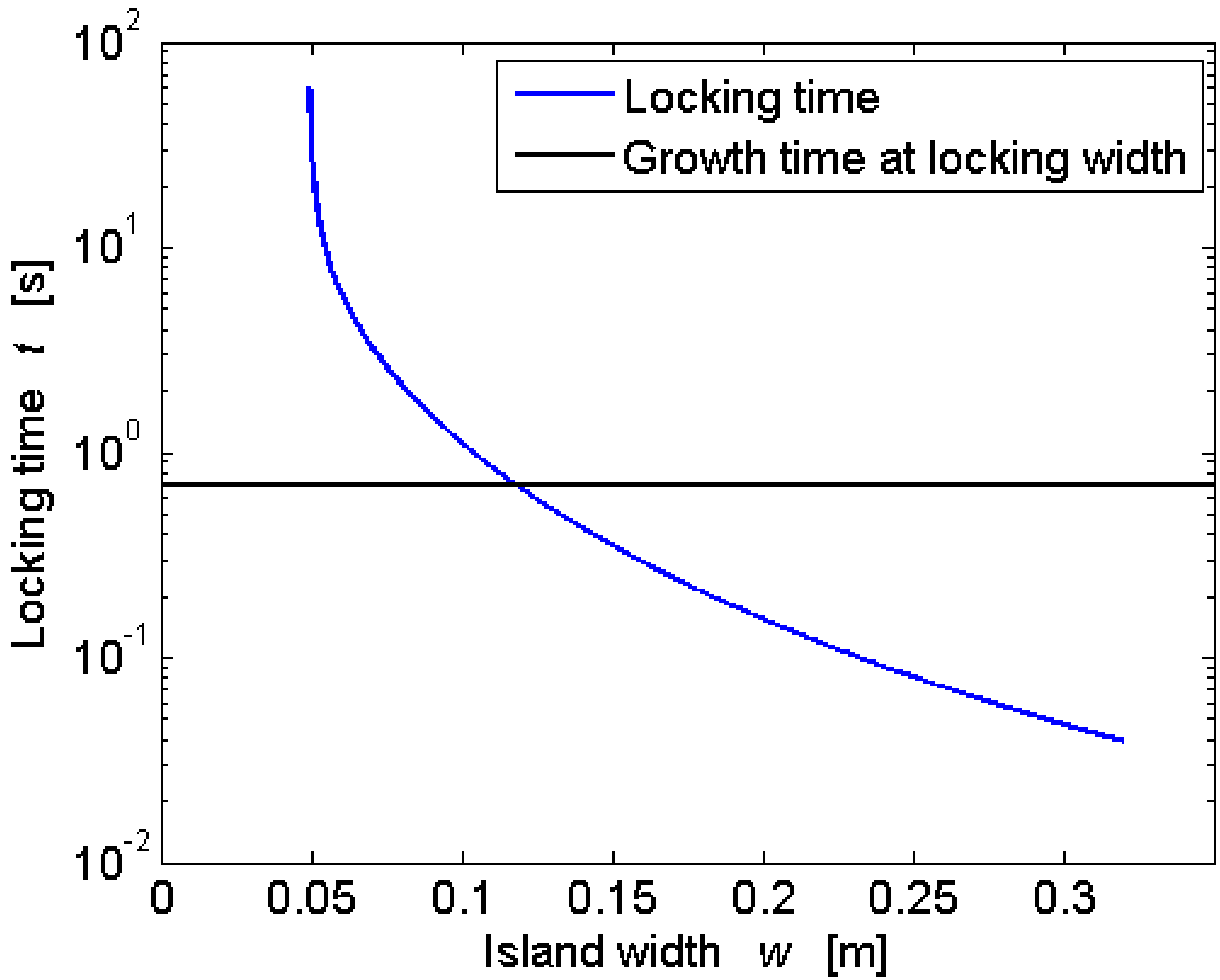
- Islands equal to or larger than 5 cm lock

Rotation model by La Haye et al NF pp. 451 vol 46 2006

Locking of q=2/1 modes



Locking time comparable to growth time



Island growth

- Generalized Rutherford Equation
- Classical growth rate

$$\frac{\tau_r}{r_s}\frac{dw}{dt} = r_s \Delta'_0$$

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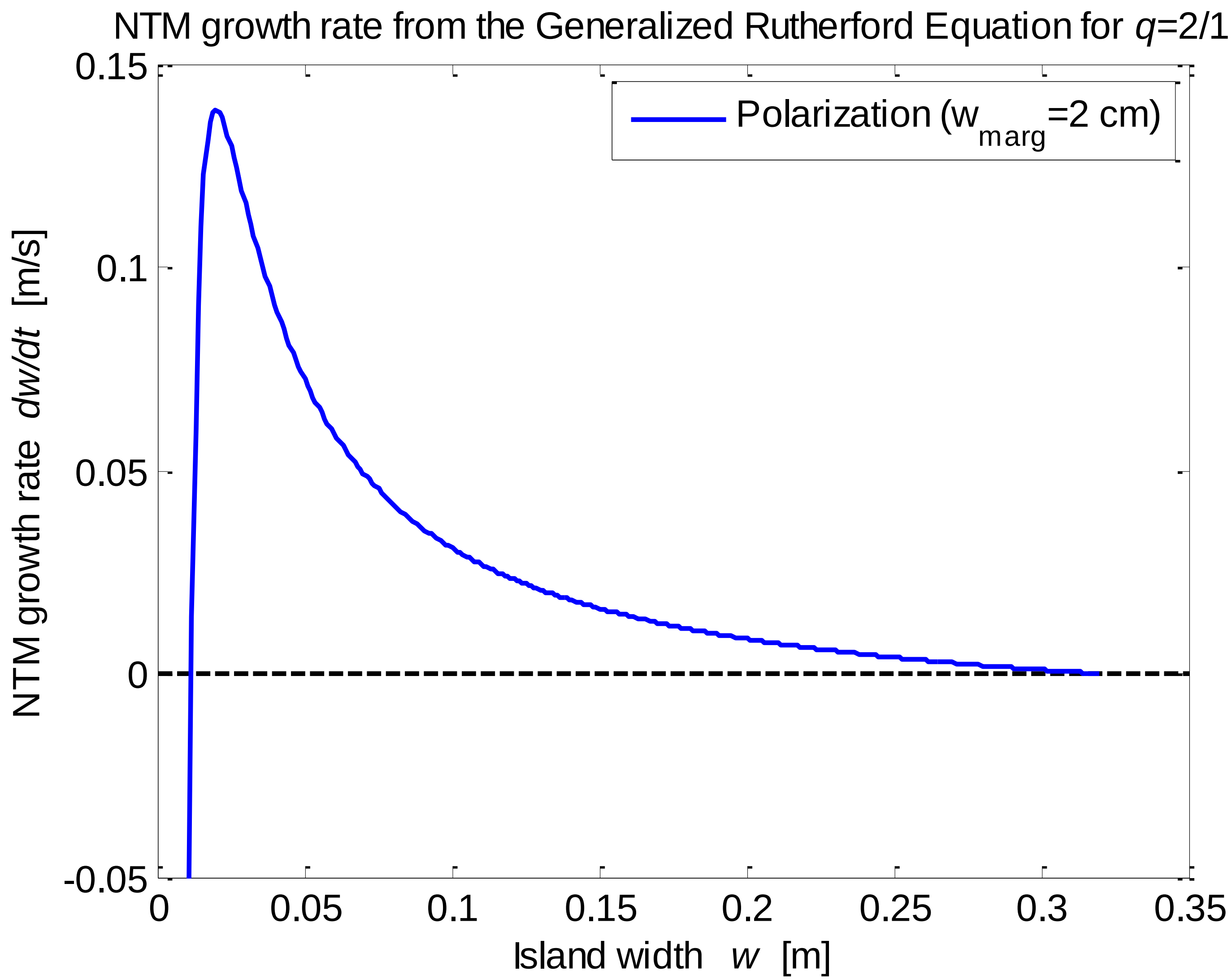
- Classical growth rate found by relating it to the bootstrap term

$$\Delta'_0 = -\Delta'_{BS}\,(w = w_{sat})$$

Bootstrap term models



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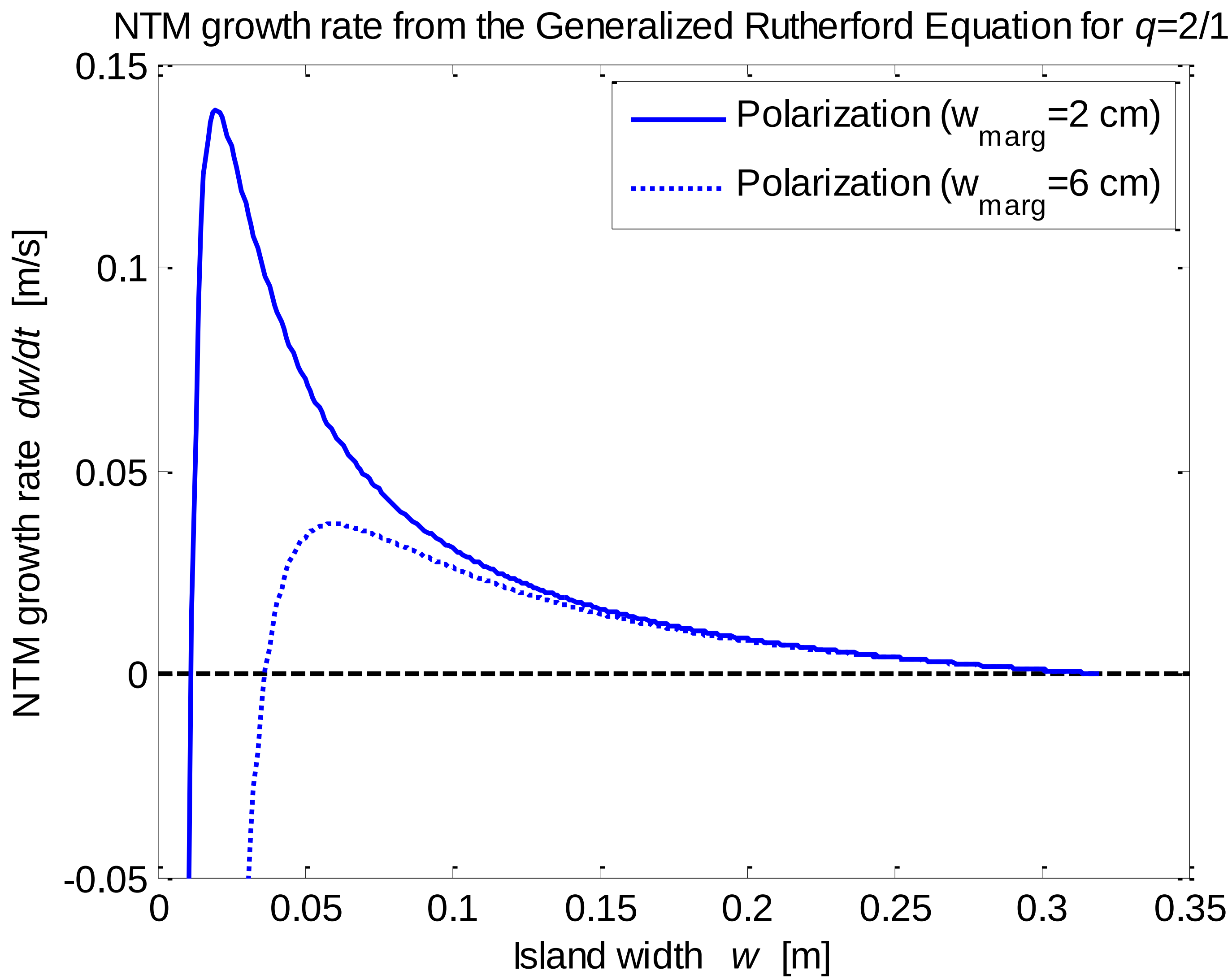

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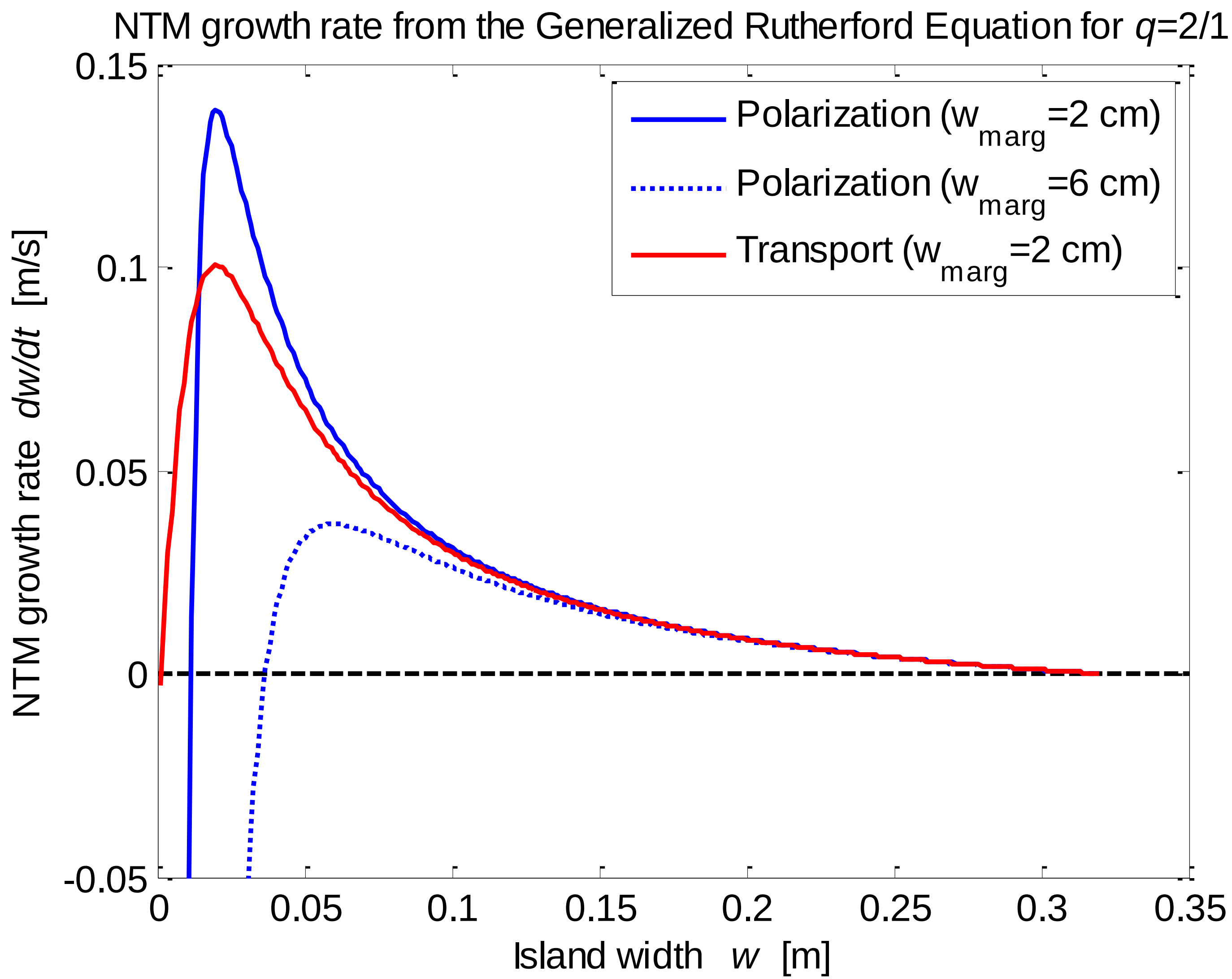

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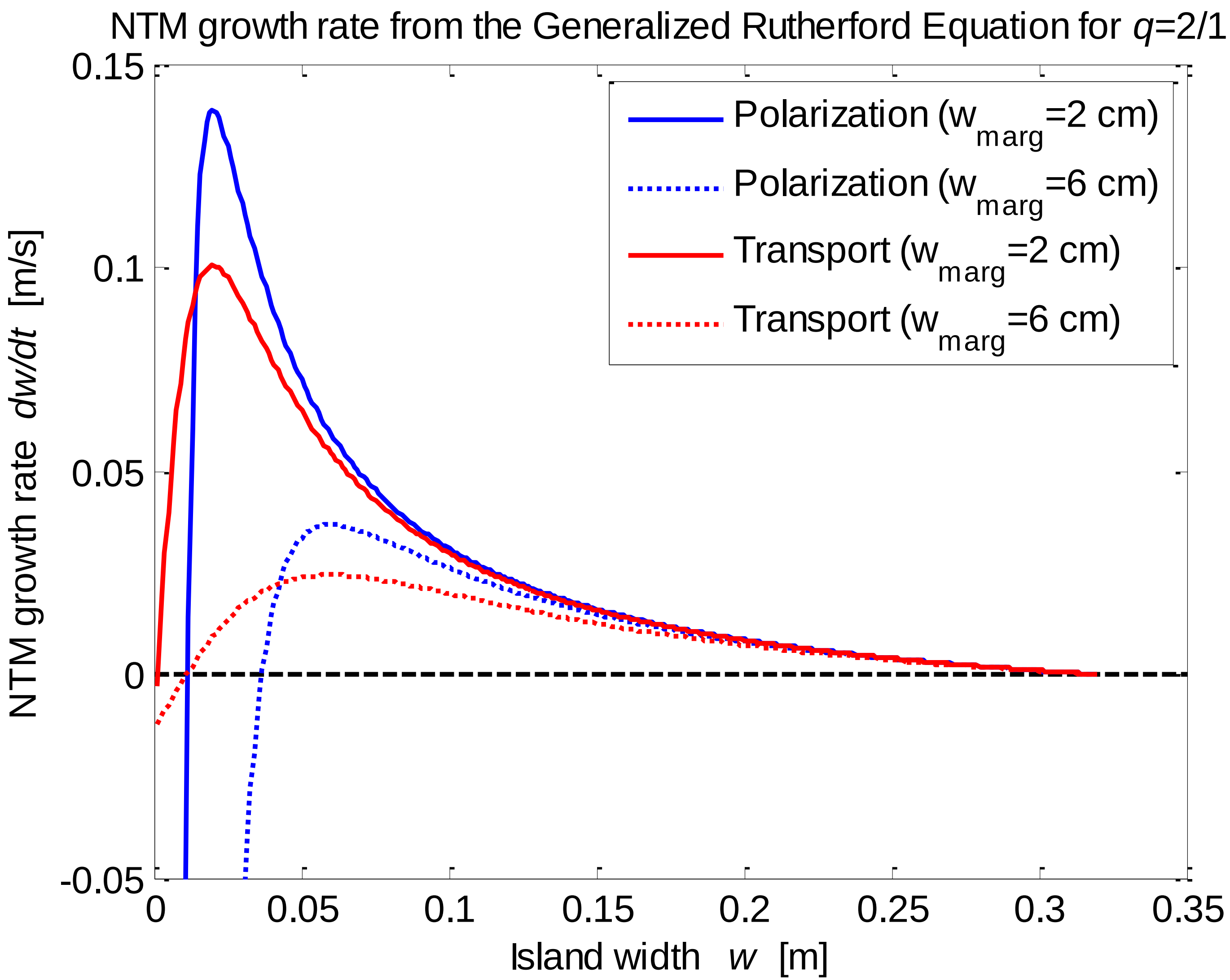

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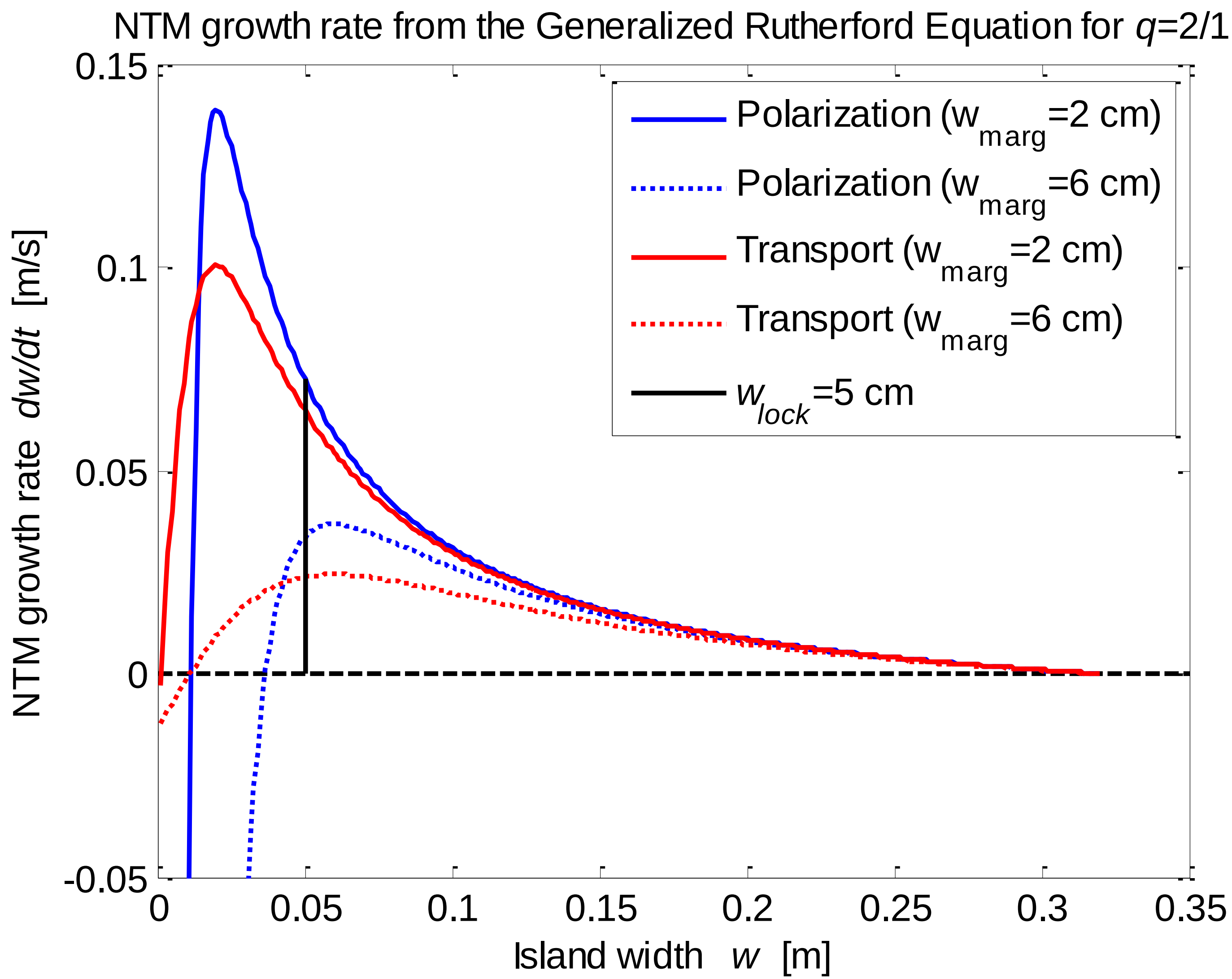
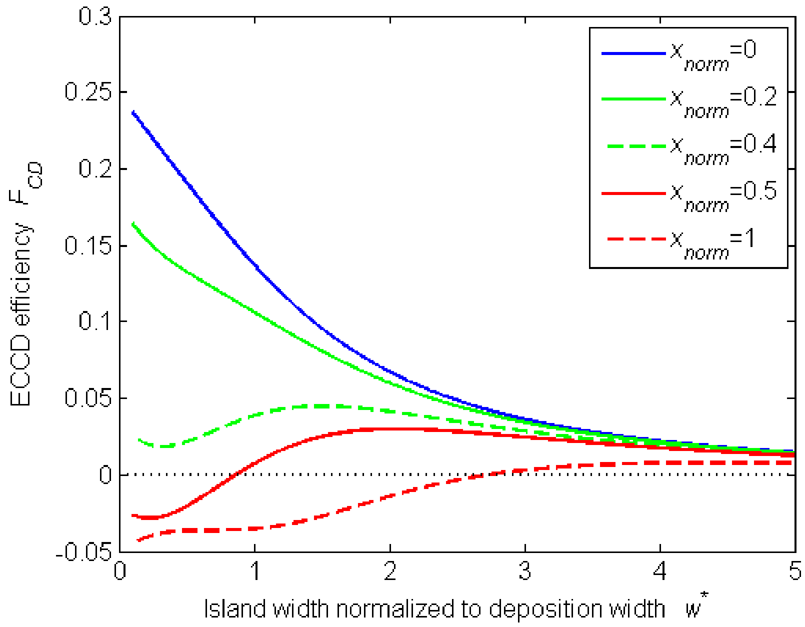


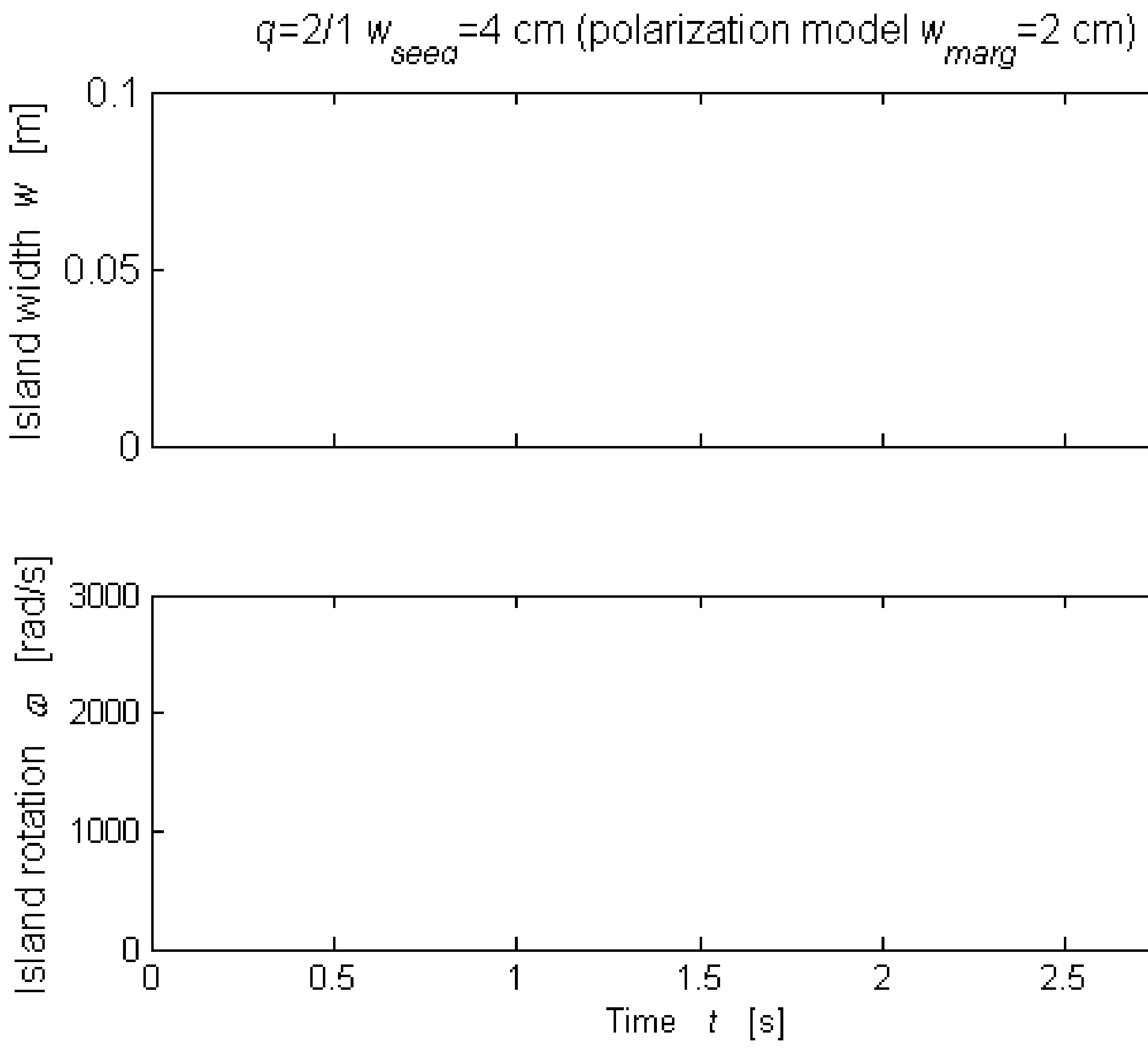
Electron Cyclotron Current Drive

$$\frac{\tau_r}{r_s}\frac{dw}{dt} = r_s\Delta'_0 + r_s\Delta'_{BS} + r_s\Delta'_{CD}$$

$$r_s\Delta'_{CD} = -K_{CD}P_{EC}\,F_{CD}\left(w^* = \frac{w}{w_{dep}},\, x_{norm} = \frac{x_{dep}}{\max(w, w_{dep})}\right)$$



Simulation example



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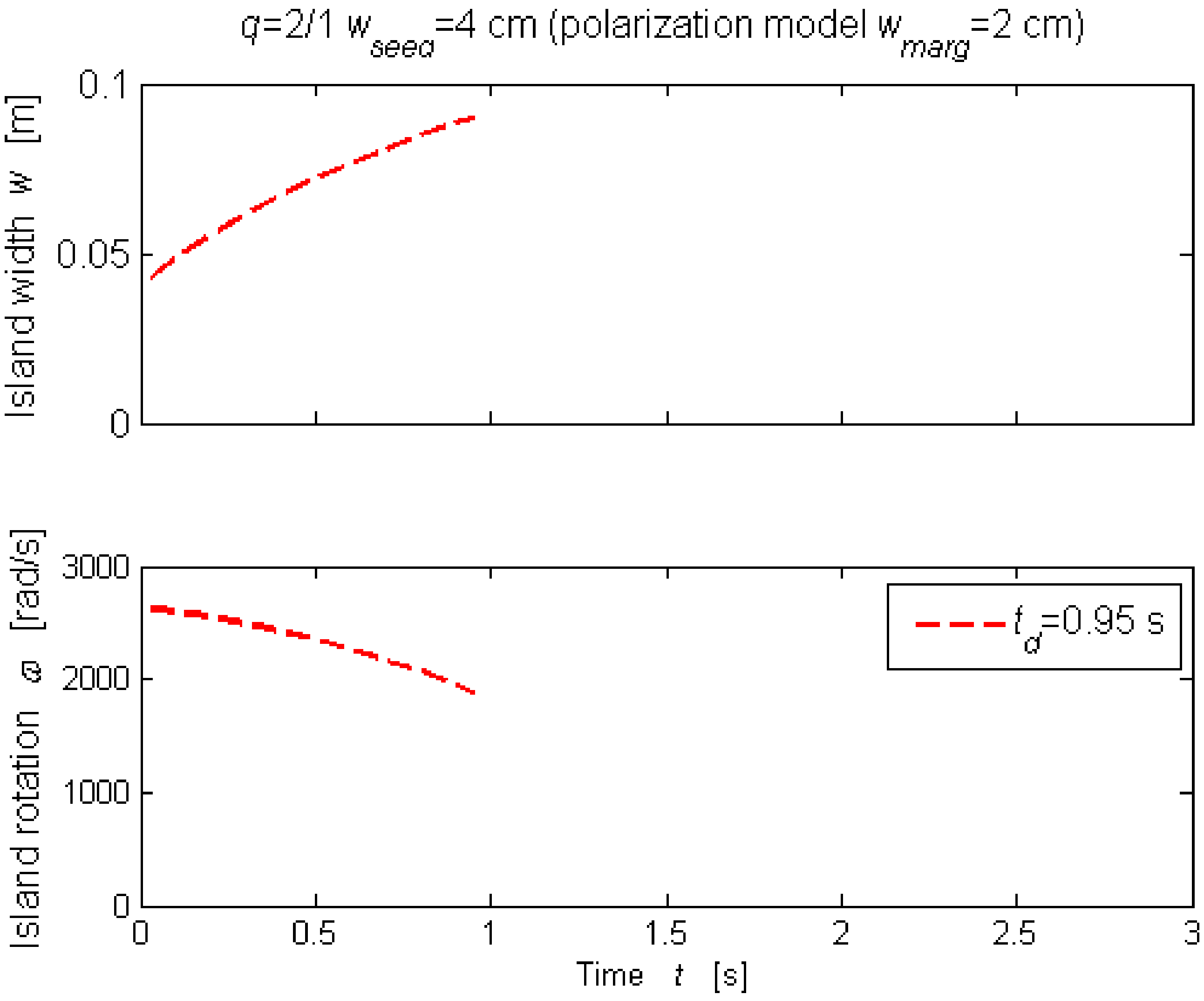

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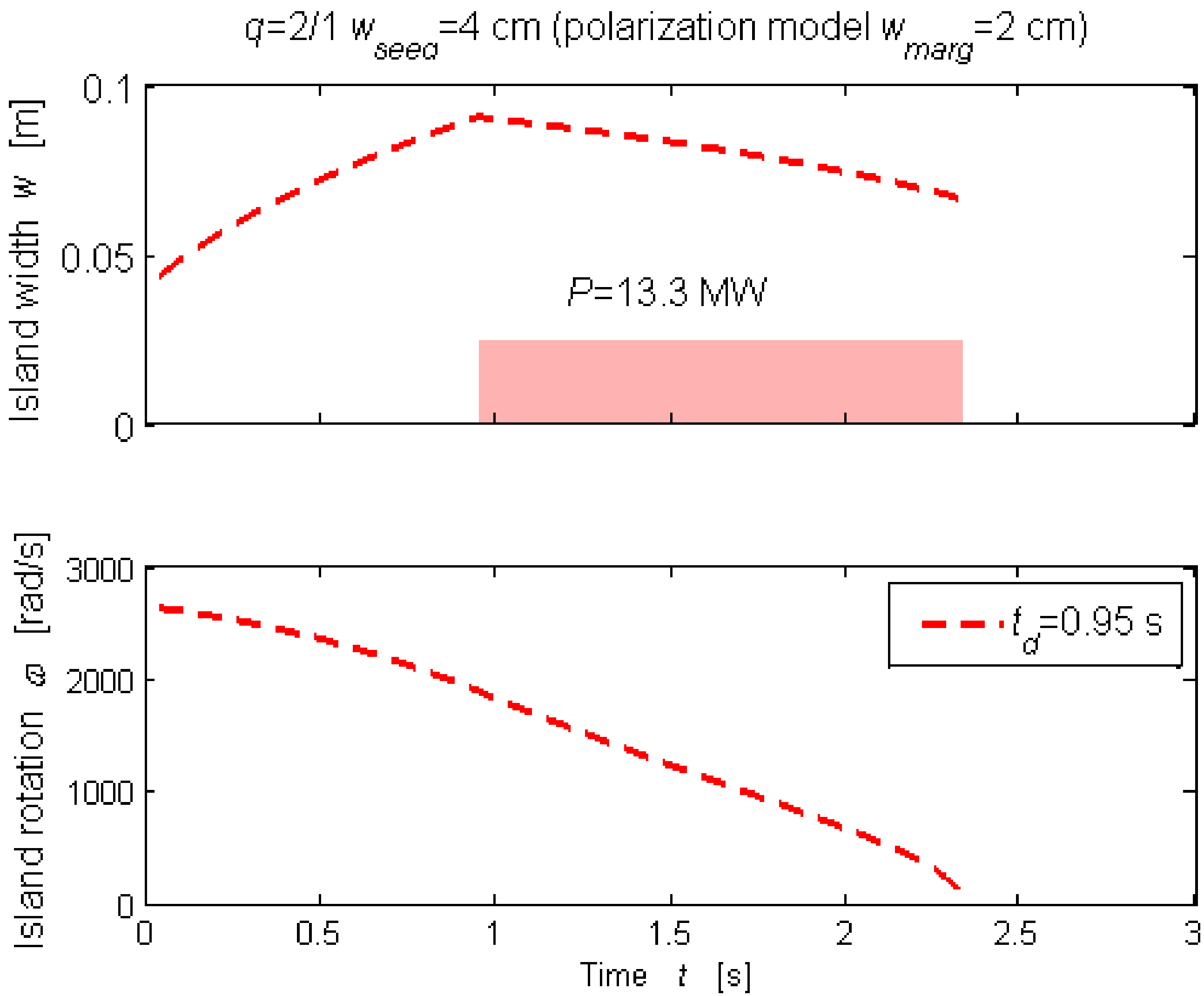

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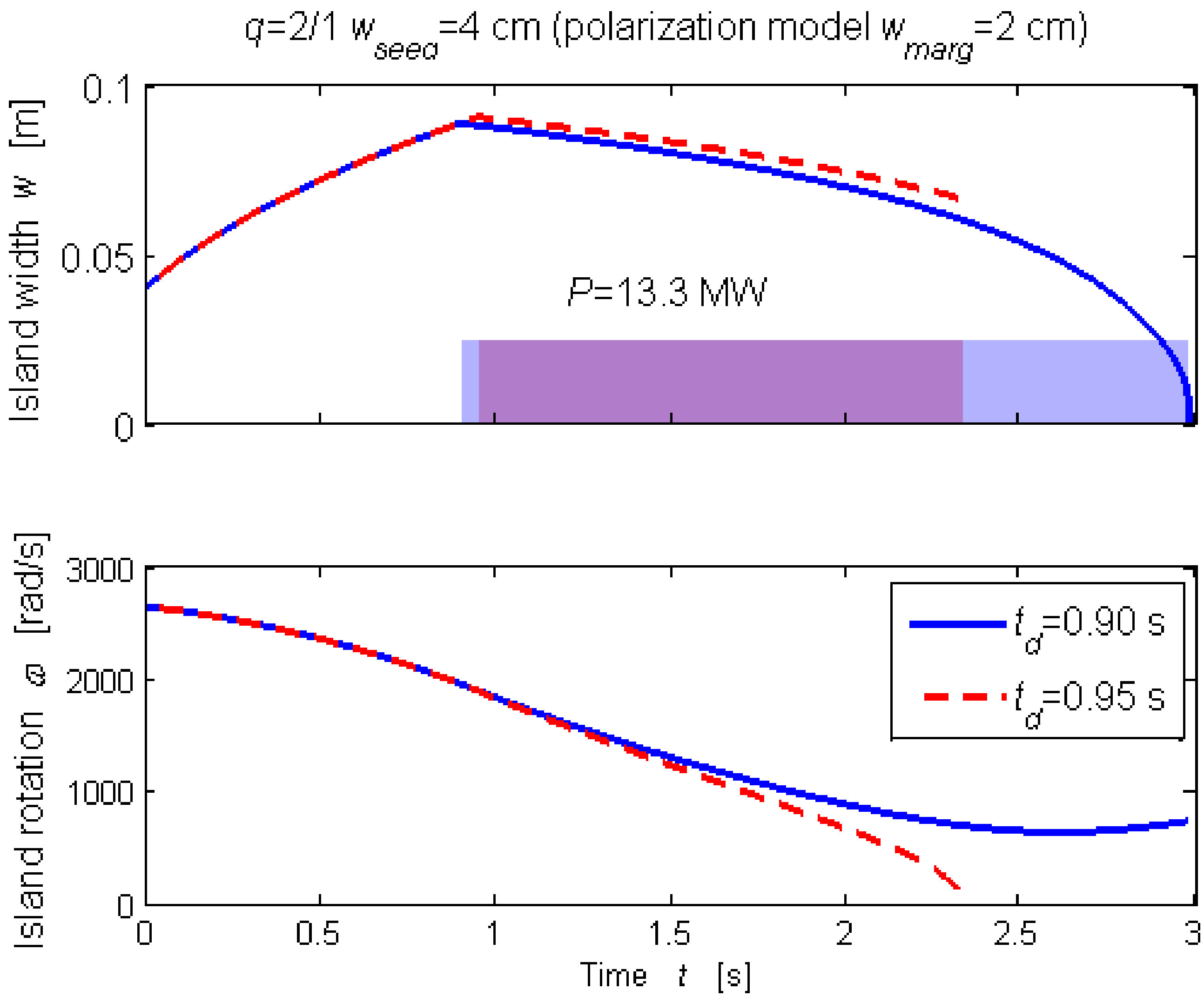
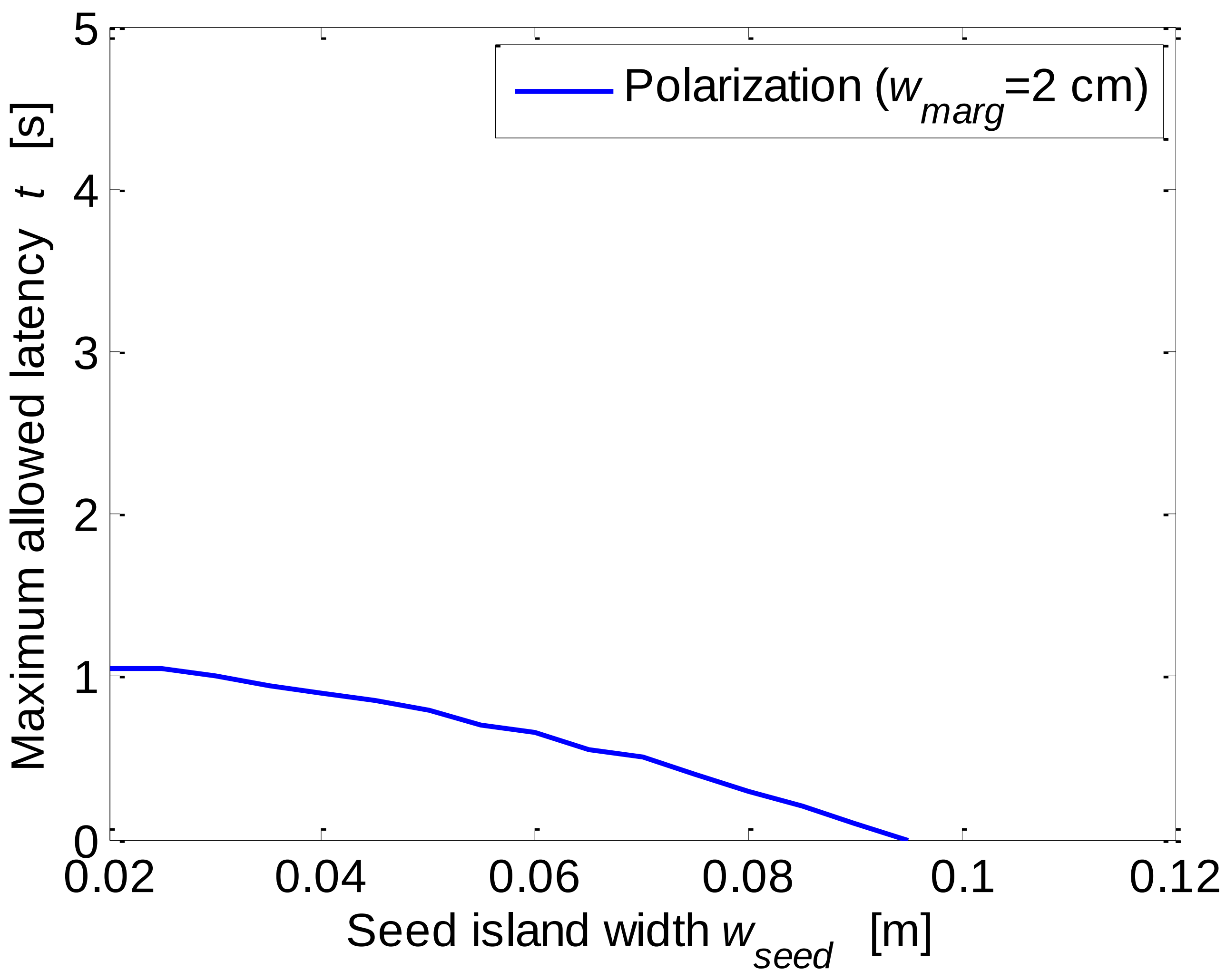


Maximum allowed latency



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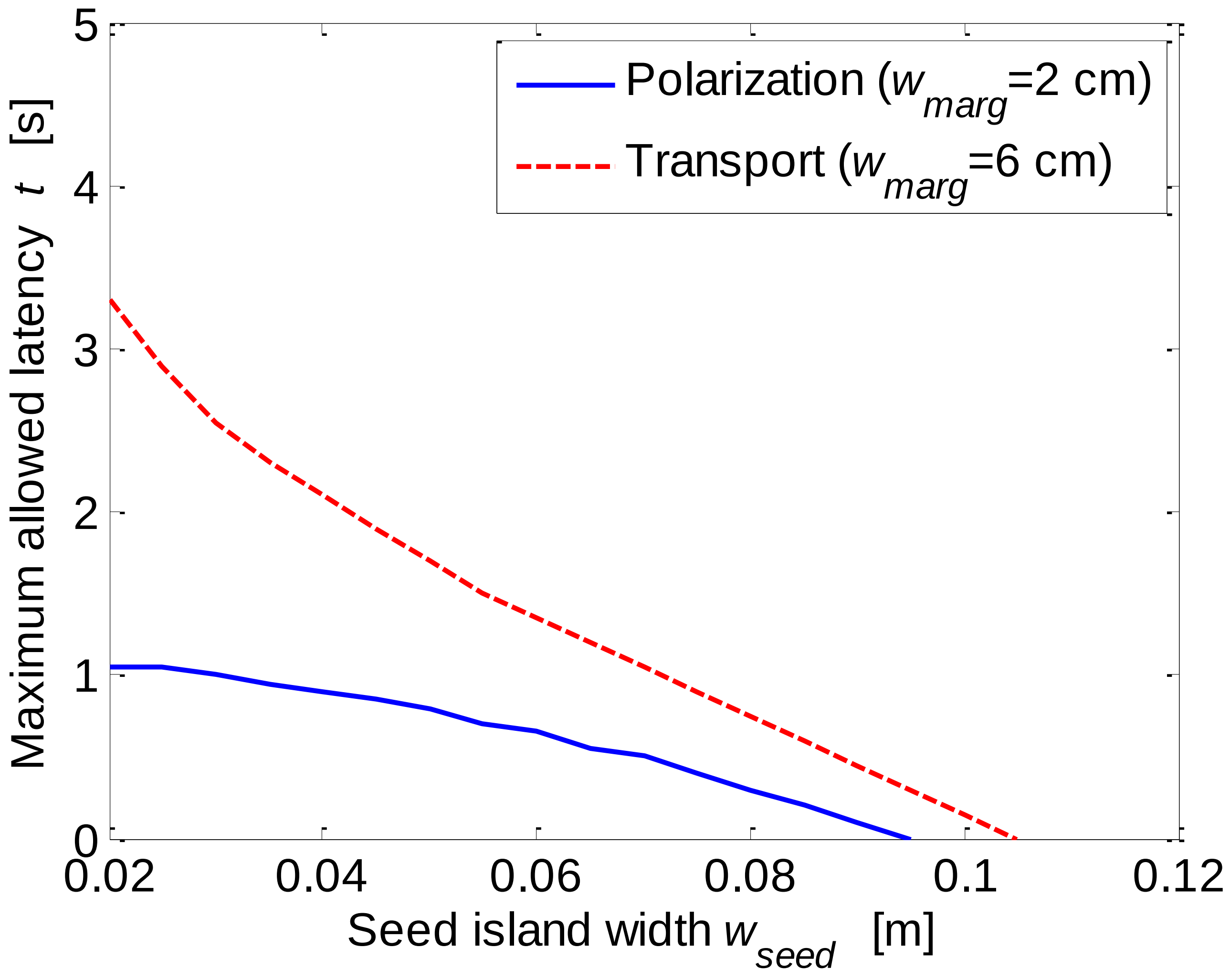
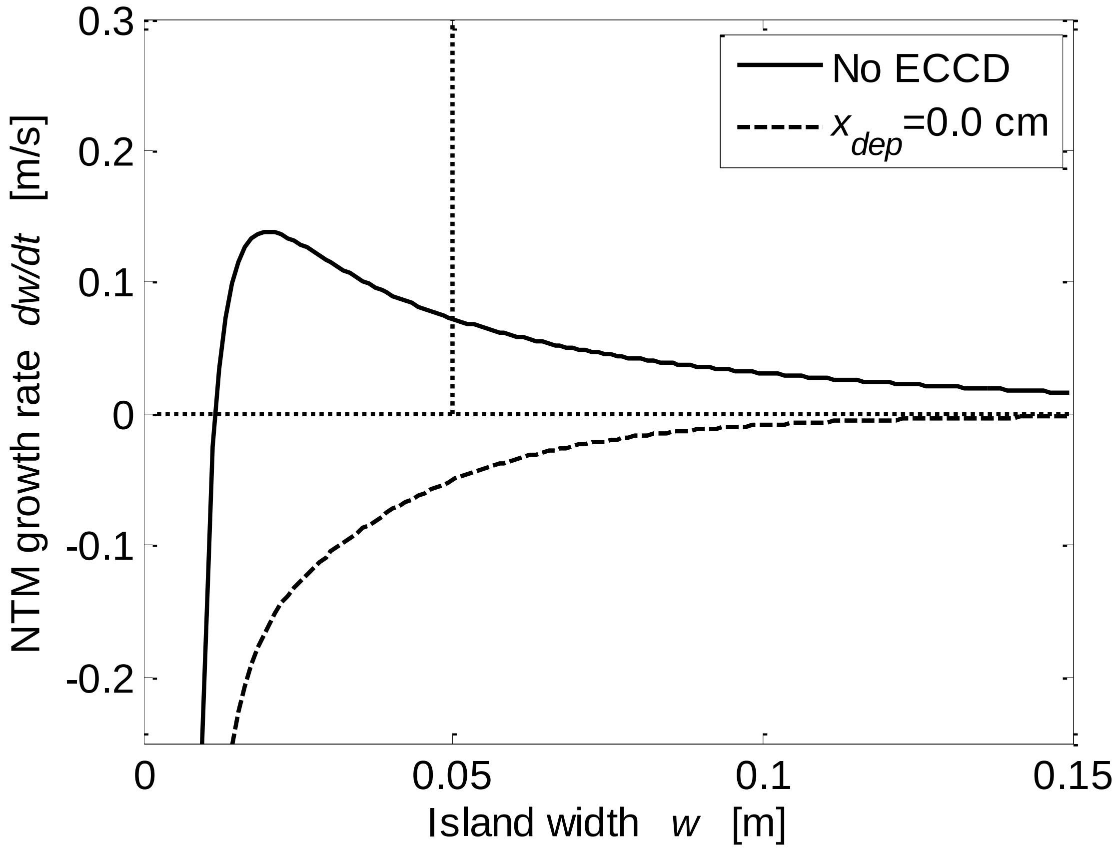


Effect of misalignment on island growth



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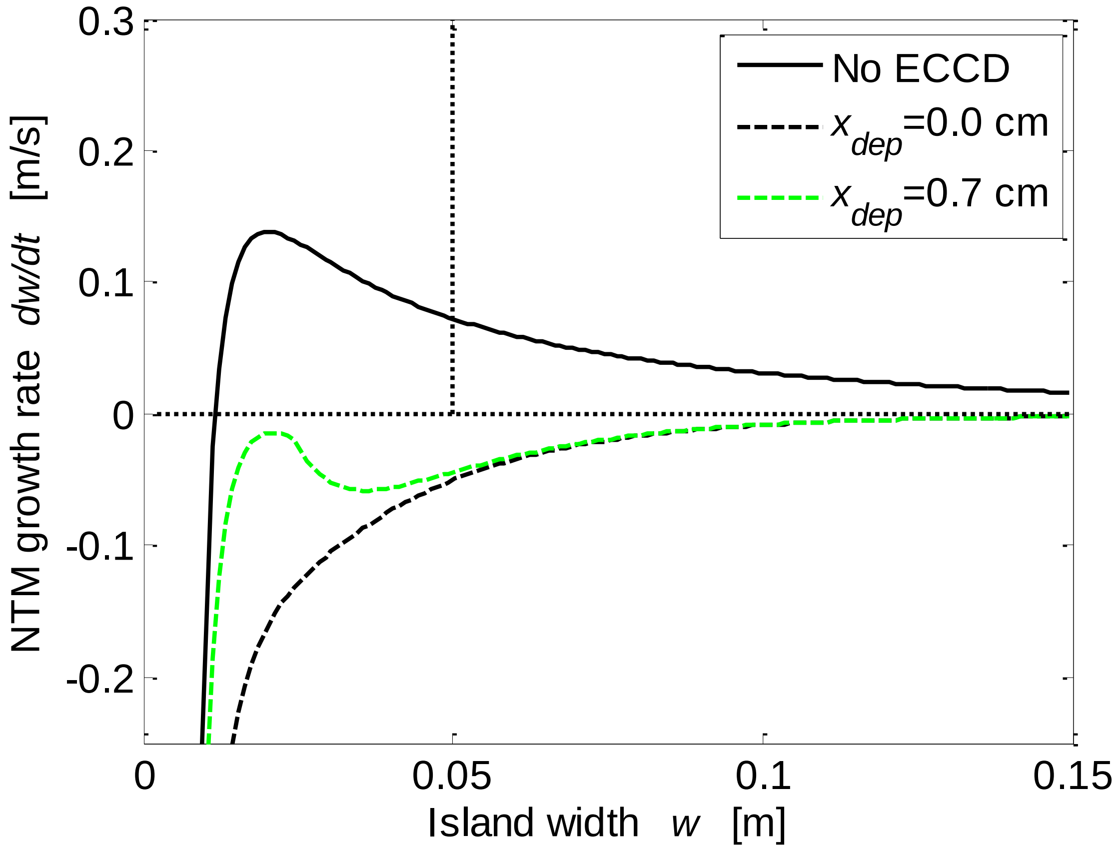

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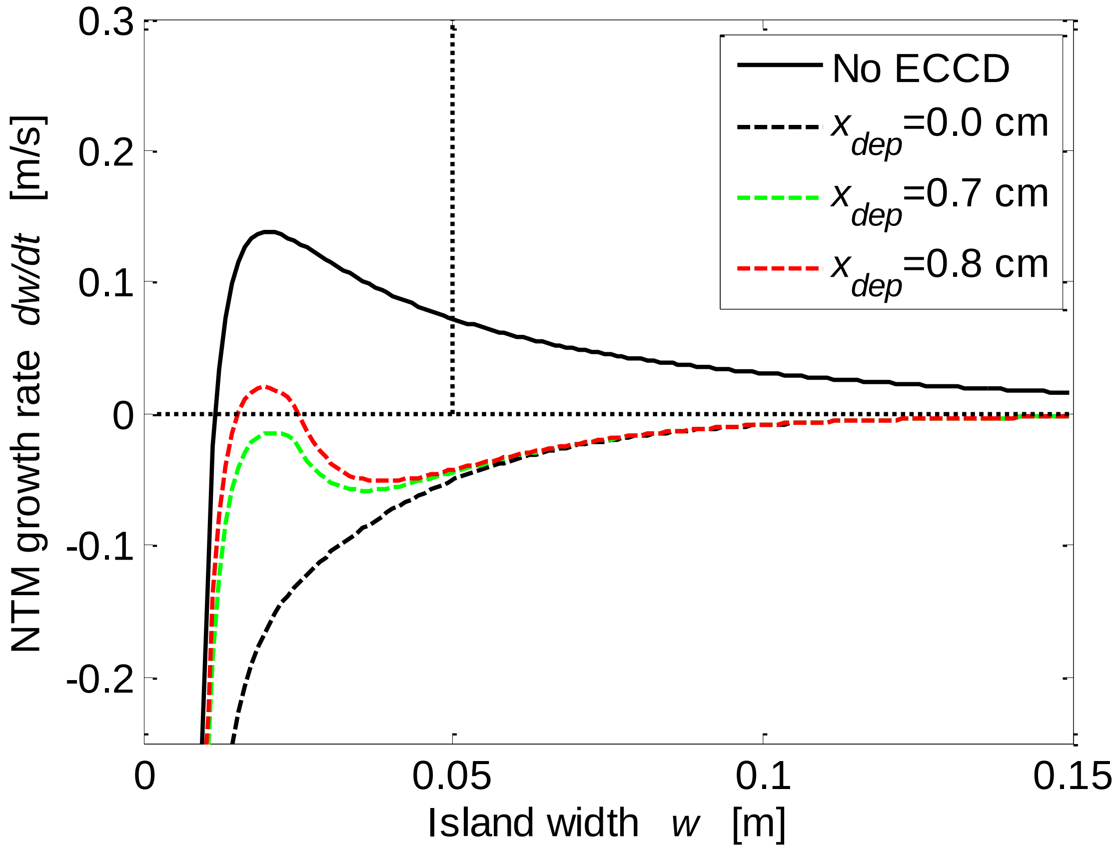

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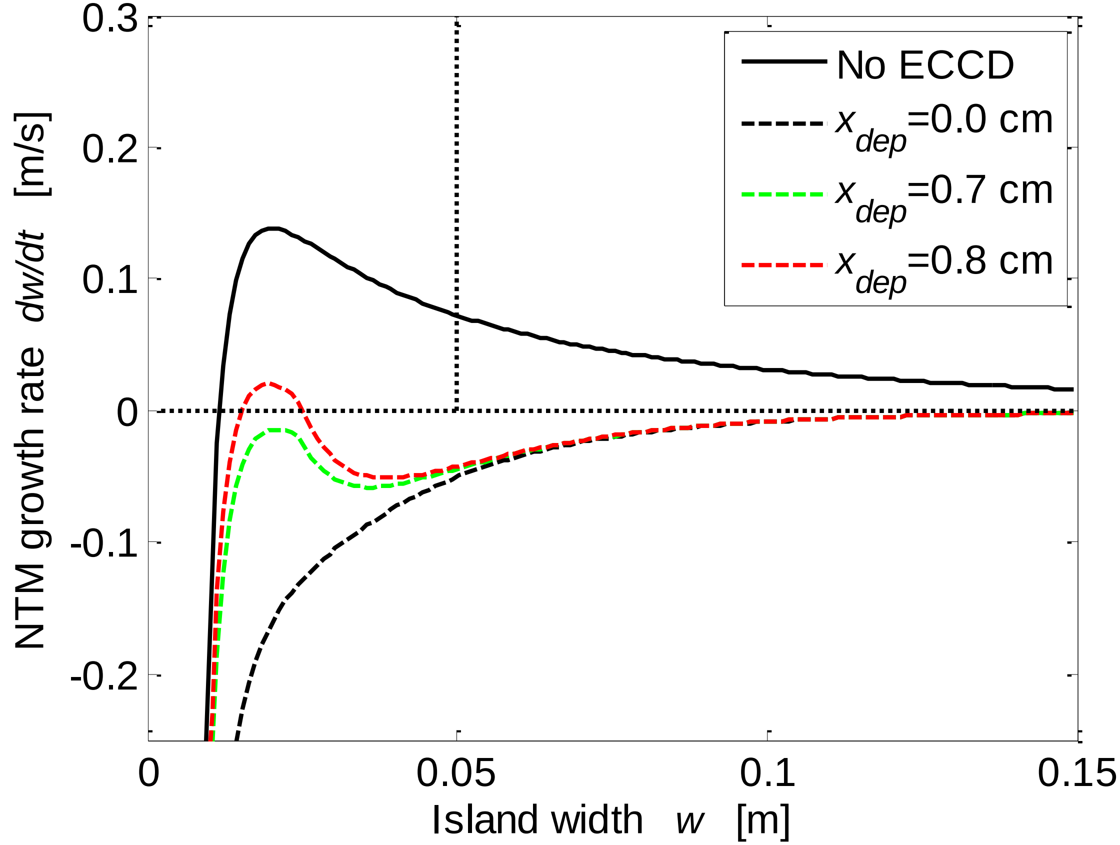

- Maximum allowed deviation 0.7 cm to 1.0 cm

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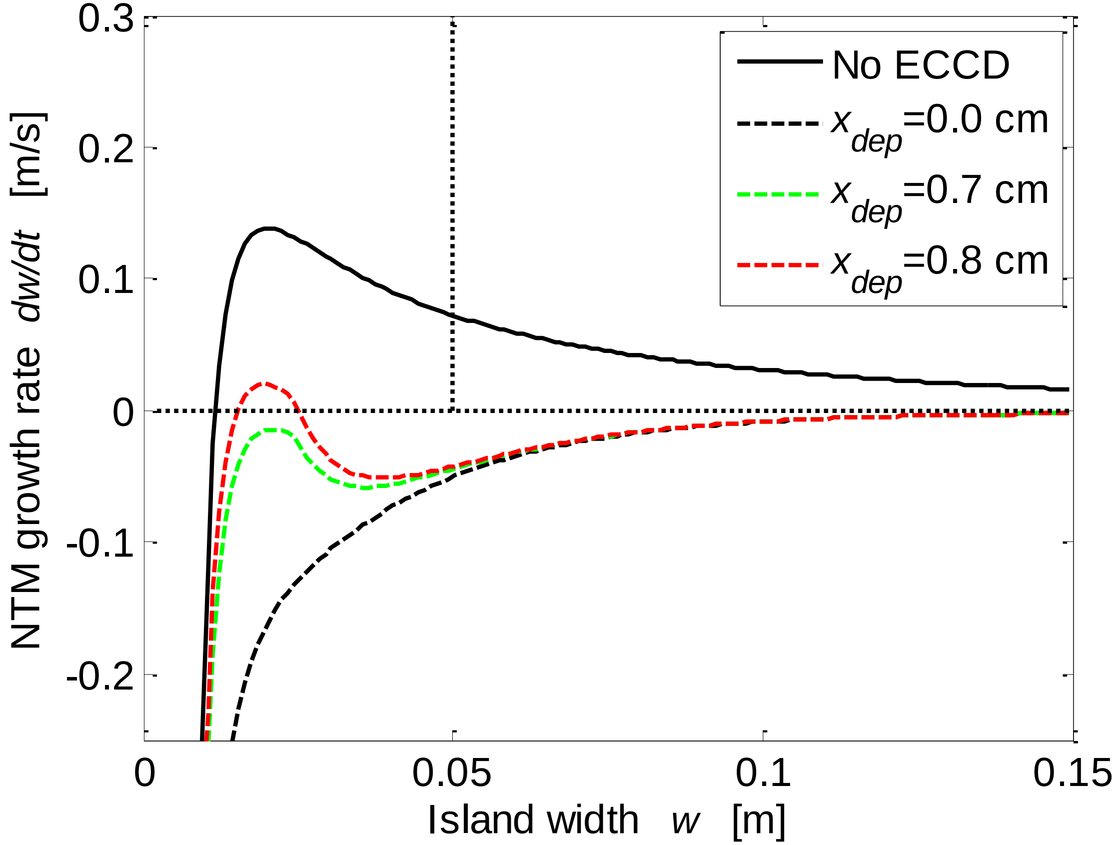


- Maximum allowed deviation 0.7 cm to 1.0 cm
- No effect on latency

Conclusions

Due to limited actuator span, mode locking should be avoided

- Dependence of rotation on width requires combined model
- Maximum allowed latency in order of 1 second
- Maximum allowed deviation 0.7 cm to 1.0 cm from GRE
  - Misalignment does not affect latency
- Similar results for 3/2 NTM
- Results relevant for design of ITER NTM controller
  - Reported mirror settling time of 2.5 s is longer

Terminology

- Maximum allowed latency = the longest time between island seeding and start of ECCD deposition that results in full suppression of the island before mode-locking
- Mode-locking = stop of the island rotation, this means that the island locks to the error fields
- x_dep = radial misalignment related to the resonant surface posistion
- Island width = Average of island width on LFS and HFS in the equatorial plane
- Locking time = the time it takes for an island of constant width to stop rotating

Bootstrap models

$$f_{tra}(w, w_{marg}) = \left(\frac{w^2}{w^2+w_{marg}^2}\right)$$

$$f_{pol}(w, w_{marg}) = \left(1 - \frac{w_{marg}^2}{3w^2}\right)$$

Simulation parameters

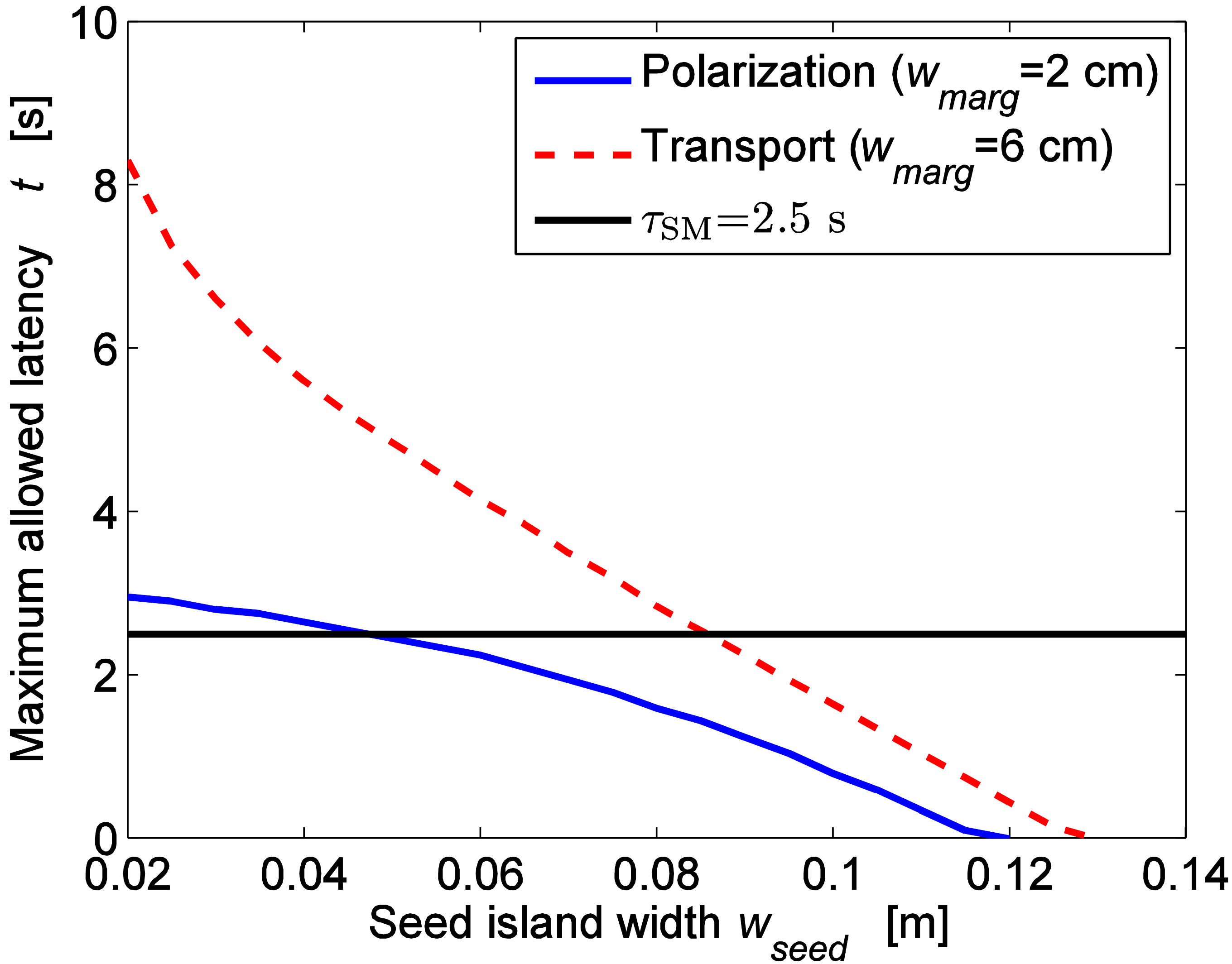
	Constants and ITER parameters		
μ_0	$4\pi \cdot 10^{-7}\ \frac{N}{A^2}$		Permeability of free space[68]
R_0	6.2 m		Major radius[57]
a	2.0 m		Minor radius[57]
κ	1.7		Plasma elongation[57]
Z_{eff}	1.7		Effective charge[69][70][71][72]
	NTM parameters $q = 2/1$	$q = 3/2$	
r_s	1.55 m	1.3 m	Position of the resonant surface[22]
$j_{BS}(r_s)$	$73\ \frac{kA}{m^2}$	$94\ \frac{kA}{m^2}$	Bootstrap current(**cite Bertelli forthcoming**)[63]
$T_e(r_s)$	5.6 keV	7.6 keV	Electron temperature[22]
$B_p(r_s)$	0.97 T	1.07 T	Poloidal magnetic field[22]
$L_q(r_s)$	0.87 m	0.88 m	Gradient length of the q-profile[22]
w_{marg}	2-6 cm	2-6 cm	Marginal island width[6](**cite Bertelli forthcoming**)
w_{sat}	32 cm	25 cm	Saturated island width[6]
w_{dep}^{LSM}	2.4 cm	3.7 cm	Deposition width at flux surface with LSM TORBEAM simulation by Bertelli et. al.
$j_{CD,W}^{LSM}$	$1.32 \cdot 10^{-2}\ \frac{A}{m^2W}$	$1.22 \cdot 10^{-2}\ \frac{A}{m^2W}$	Current drive density per watt with LSM TORBEAM simulation by Bertelli et. al.
w_{dep}^{USM}	3.9 cm	5.5 cm	Deposition width at flux surface with USM TORBEAM simulation by Bertelli et. al.
$j_{CD,W}^{USM}$	$9.62 \cdot 10^{-3}\ \frac{A}{m^2W}$	$1.07 \cdot 10^{-2}\ \frac{A}{m^2W}$	Current drive density per watt with USM TORBEAM simulation by Bertelli et. al.
$\epsilon = \frac{r_s}{R_0}$	0.25	0.21	Inverse aspect ratio
η_{NC}	$1.44 \cdot 10^{-8}\ \Omega m$	$7.73 \cdot 10^{-9}\ \Omega m$	Neoclassical conductivity (equation 2.4)
τ_r^*	293 s	383 s	Resistive time scale (equation 2.3)

	$q = 2/1$	$q = 3/2$	
ω_0	$420 \cdot 2\pi$ rad/s	$578 \cdot 2\pi$ rad/s	Result of ITER scenario 2 simulations
τ_{A0}	3.0 μs		Assumes toroidal rotation of the island
τ_{M0}	$\tau_E = 3.7$ s		Equal to ITER energy confinement time
τ_w	0.188 s	0.125 s	Resistive wall simulations with VALEN
C_1	$\frac{1}{14}$	$\frac{1}{29}$	Obtained through fits on DIII-D shots
C_2	20	12	Obtained through fits on DIII-D shots

Simulation details

- Seed island size varied
- Delay between seeding and start of ECCD varied
- Largest delay that still results in full suppression before locking is the maximum allowed latency
- Simulation scenarios
  - Polarization 2 cm
  - Transport 6 cm
- Resolution: dt=50 ms and dw_seed=0.5 cm
- Implemented in MathWorks Simulink
  - Runga-Kutta 5th order with 4th order error estimate (var. step)
  - Rel error 1e-6

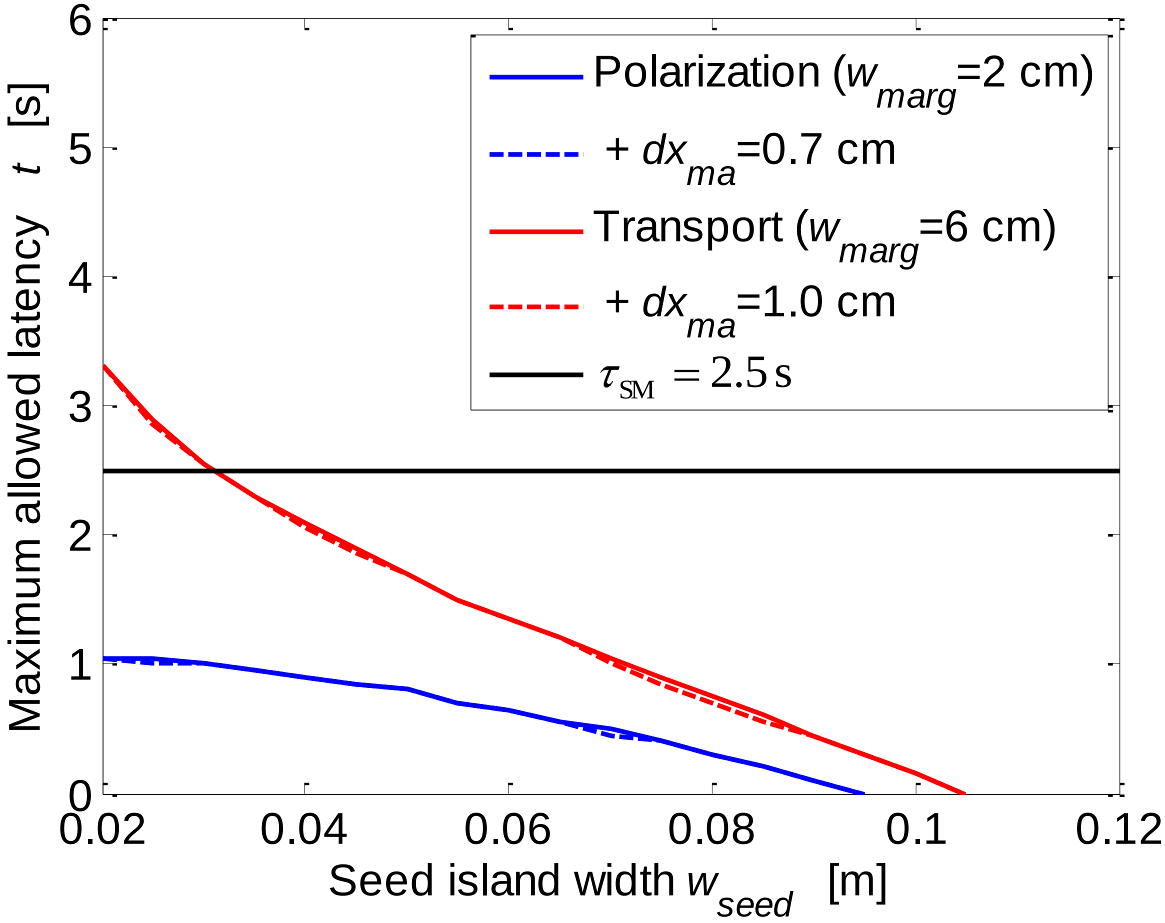
q=3/2 latency



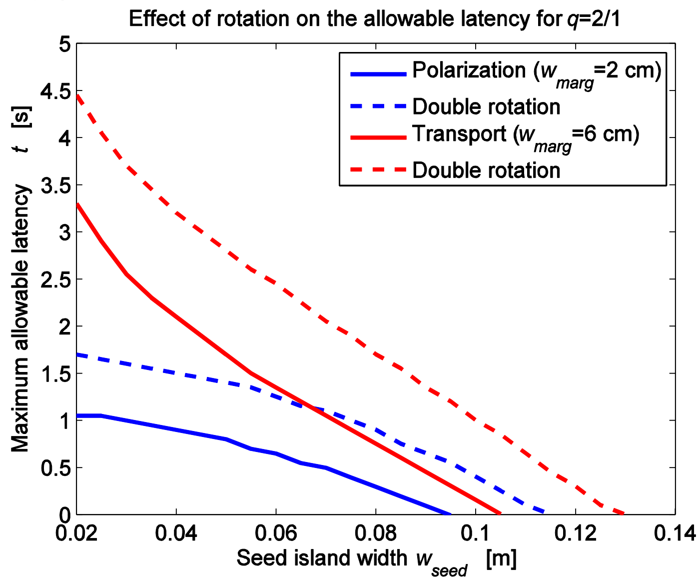
Polarization (w_{marg}=2 cm)
Transport (w_{marg}=6 cm)
$\tau_{\mathrm{SM}}=2.5$ s
Maximum allowed latency t [s]
Seed island width w_{seed} [m]
10
8
6
4
2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14

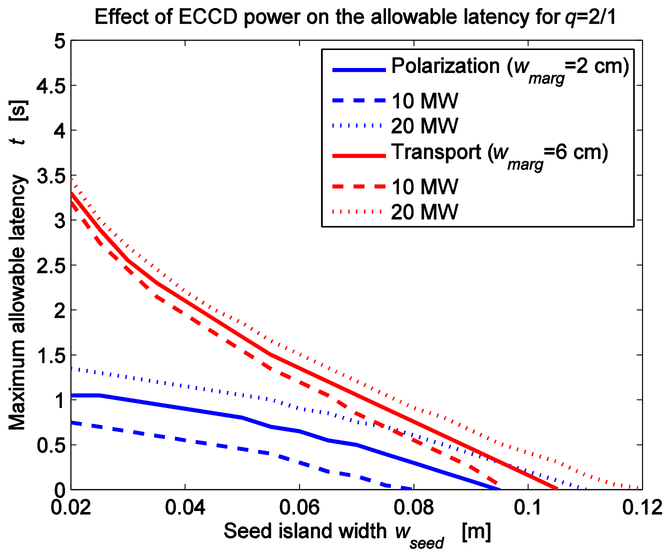
Effect of misalignment on latency

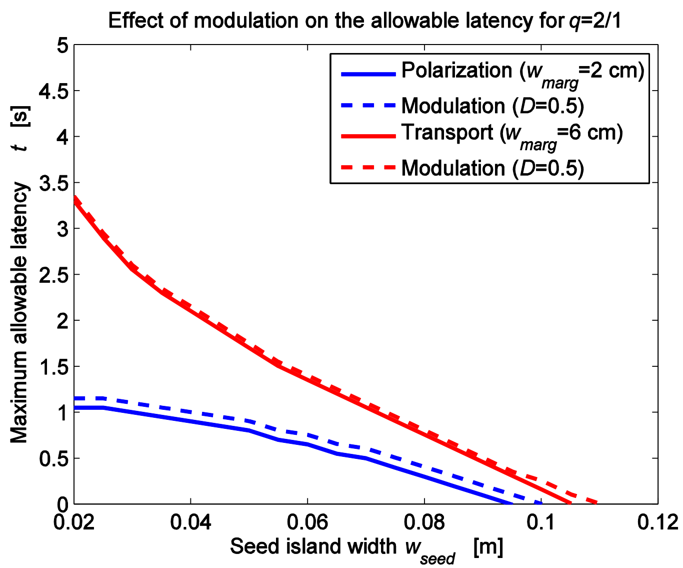
- No effect



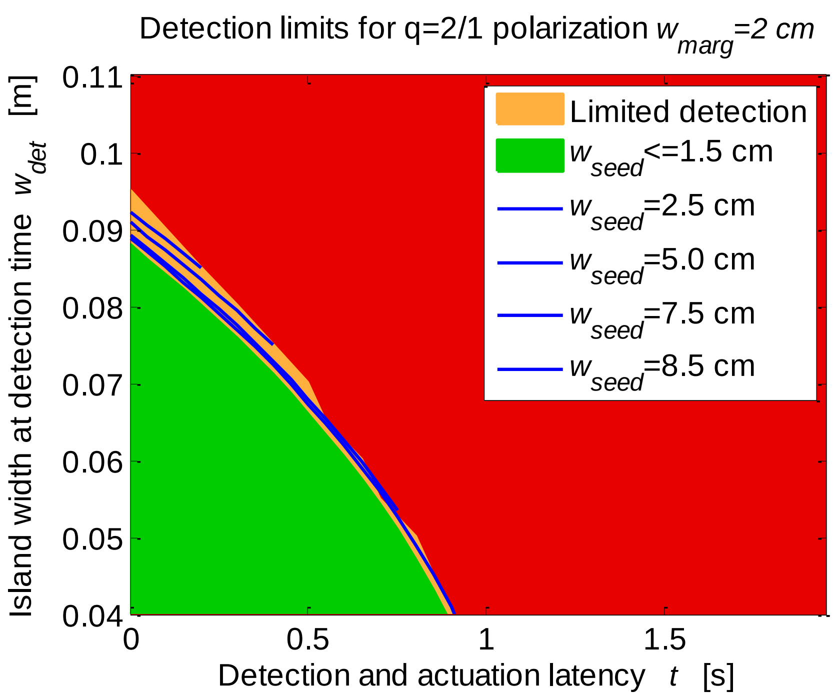
Extra simulations

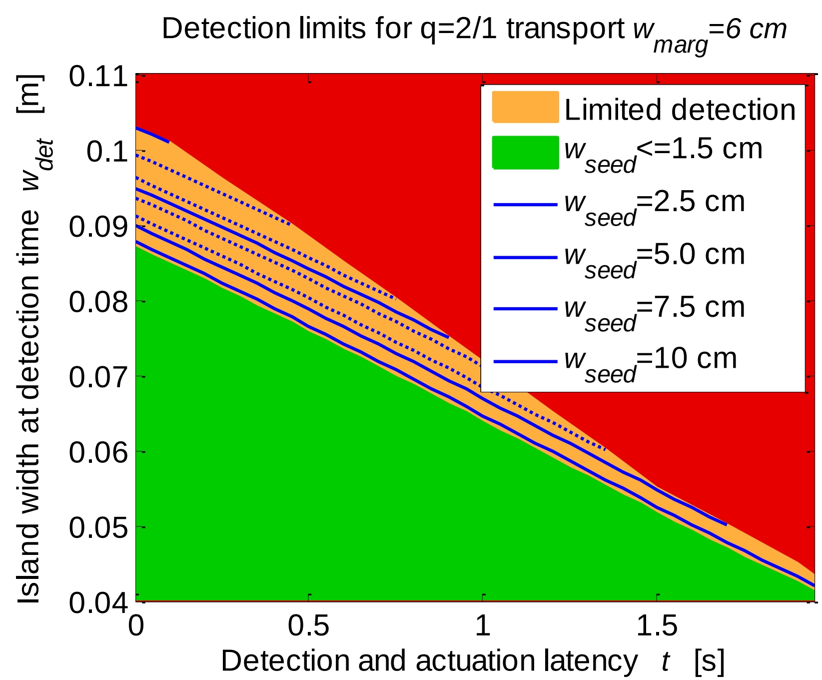






Stabilization maps q=2/1



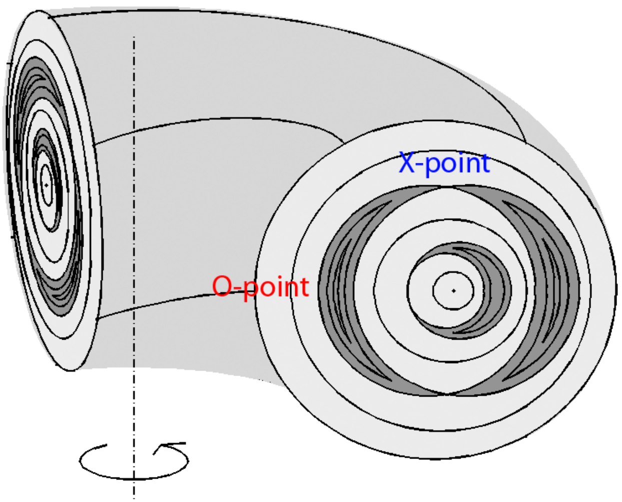


Tearing modes

- Flux surfaces characterized by safety factor

$$q = \frac{m}{n}$$

- Reconnection of magnetic field lines
- Rational values of q
  - q=2/1 (and q=3/2)
- Affected by non-inductive current



Picture from PhD Thesis of I.G.J. Classen (2007)