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ECE diagnostics for NTM detection and tracking in fusion reactors

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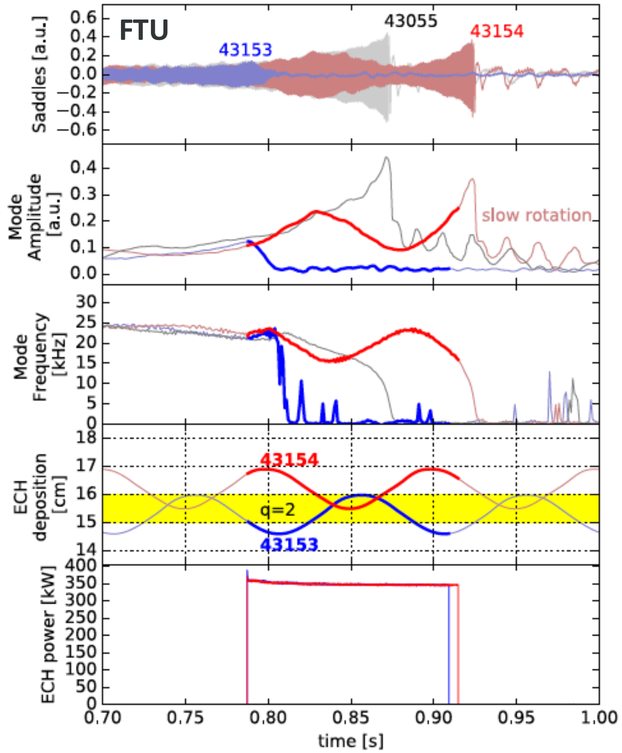
Contents

- Introduction to Neo-classical Tearing Modes and their control
- Focus on (Quasi-)In-Line control strategy => Oblique ECE line of sights (LOS)
- Advantages/Issues of Oblique ECE LOS in DEMO-like reactor
- Introduction of a novel diagnostic concept and control strategy.

Introduction

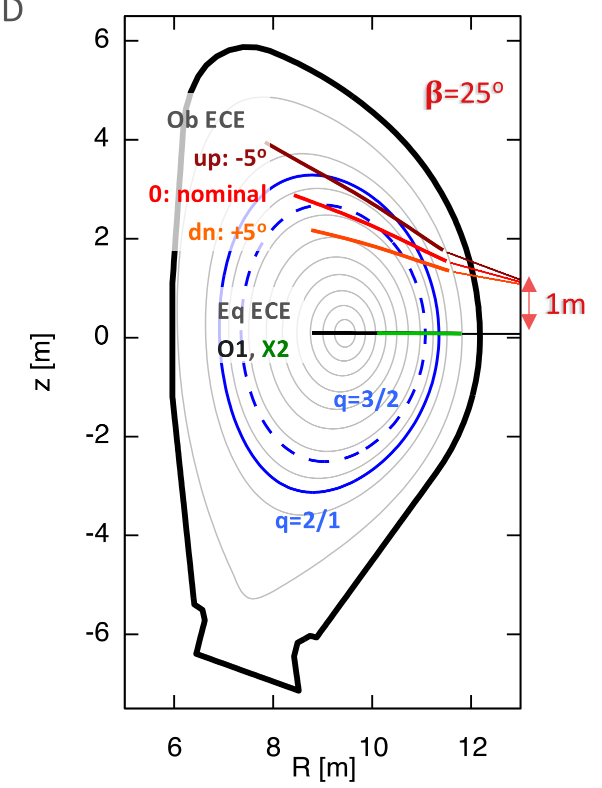
- In magnetically confined plasmas, a *tearing mode* breaks the magnetic surfaces forming a 'magnetic Island'. Islands reduce the confinement, and in some cases can lead to a disruption.
- Possibility to stabilize/suppress via localized **EC heating power and current drive**
- Alignment is critical:
  - Deposition **far** from instability has negligible effects
  - Deposition **near** the Island can partly stabilize
  - **well aligned/overlapping** can suddenly suppress it
- Need of RT Control of ECH/CD deposition



G.Pucella et al., NF 62 (2022) 042204

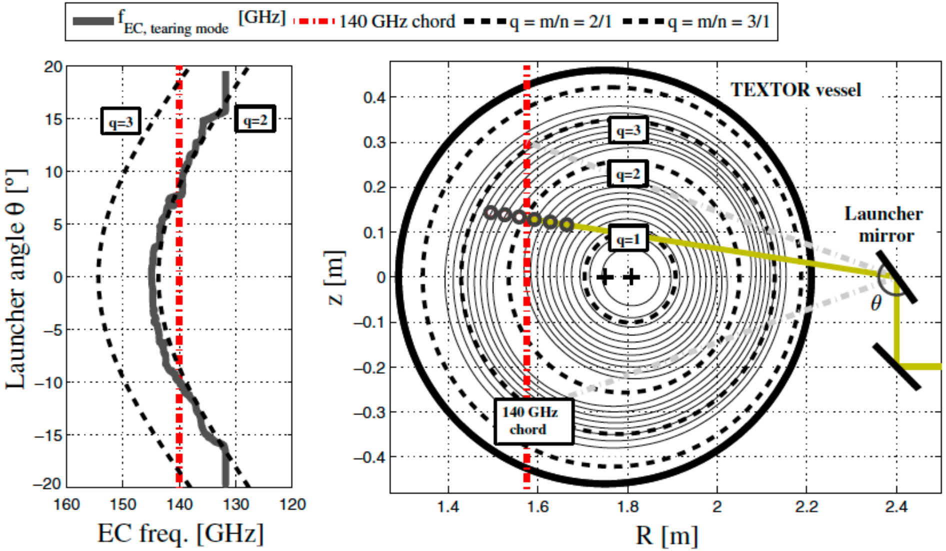
ECH/CD and ECE systems in a DEMO-like reactor

- A DEMO-like reactor *[M.Q. Tran FED 2022]* will be provided of dedicated ECH/CD (@f=170 GHz) launchers for NTM control:
  - RT steerable antennas
  - Large toroidal angle of injection (current drive)
  - Launching point at z=1m above equatorial plane
- O1/X2 ECE radiometers installed in equatorial port
  - to align ECH/CD NTM antennas need RT evaluation of equilibrium reconstruction and of beam propagation
- Options for Island detection and tracking:
  - To equip ECH/CD launchers with collinear ECE radiometers (**In-Line**)
  - To install (shifted) additional RT steerable antennas equipped with ECE (**Quasi-In-Line)**
  - In both cases ECE diagnostics will have oblique LOS



In-Line strategy

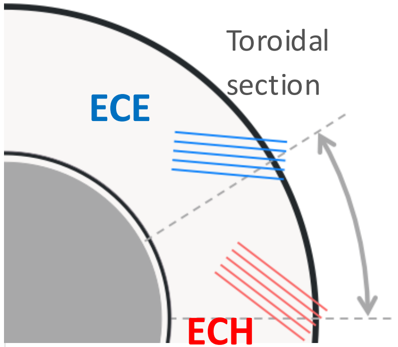
- Alignment is based on $f_{ECH} - f_{ECE,Island}$ ->0 [GHz]
- Robust control strategy based on measurements of $f_{ECE,Island}$: *detected Island position along ECE LOS*
- Collinear ECE shares same antenna with ECH source (**In-Line**): plasma volume emitting ECE (at $f=f_{ECH}$) is the same plasma volume would absorb the ECH/CD beam power injected from the antenna (reciprocity).
  - Need of FADIS technologies to separate emitted (μW) ECE and ECH/CD power (MW)



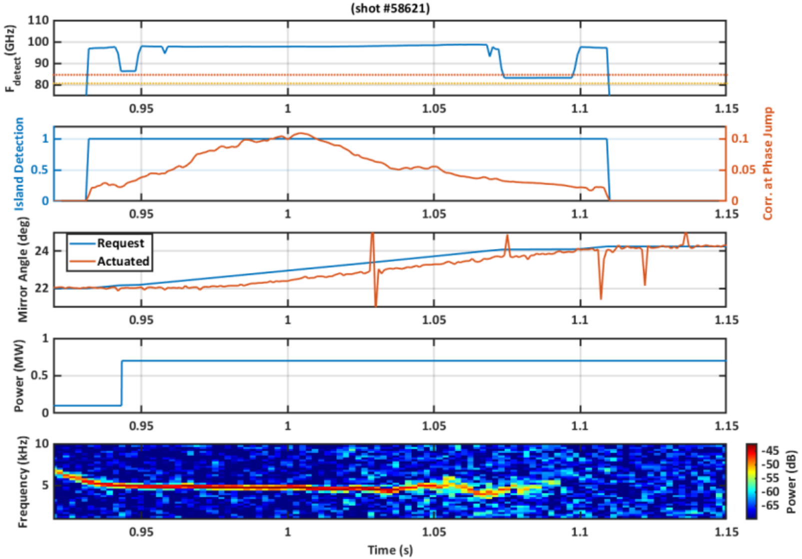
B. A. Hennen et al., PPCF 52 (2010) 104006, **TEXTOR**

Quasi-In-Line strategy

- Avoid the need of FADIS by exploiting toroidal symmetry
- Use of additional RT steerable antennas (parallel to ECH/CD ones) toroidally displaced and equipped with ECE.
  - **Quasi-In-Line**: Proof of principle demonstrated in TCV *[N.Rispoli, FED 146 (2019) 666-670]*



- Synchronous steering of ECE and of ECH/CD antennas
- ECH source firing
- When ECE sees $f_{Island} \sim f_{ECH}$ Island is completely suppressed



[C.Sozzi, IAEA-FEC 2023], **TCV**

Spatial Resolution of different ECE LOS in a DEMO-like reactor

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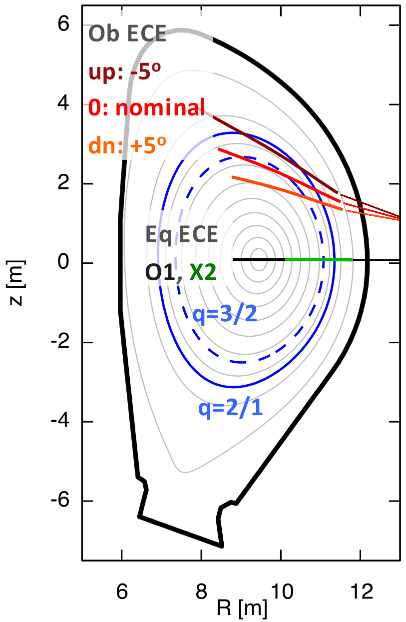
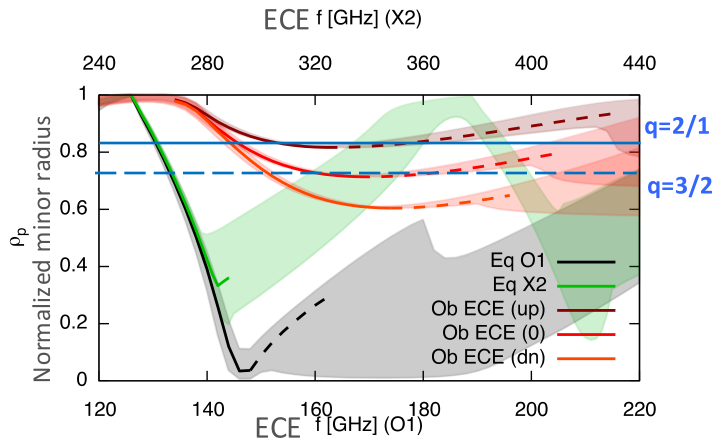
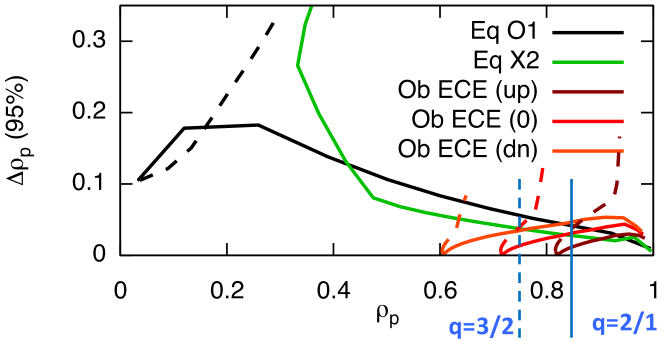
- Simulations in DEMO-like with SPECE *[D.Farina et al. AIP Conf Proc 988 2008]* for ECE on equatorial LOS (O1, X2) and on Oblique LOS (O1) for I-L/Q-I-L control



Oblique LOS almost tangential to rational surfaces => Improves resolution close to the rational surface:

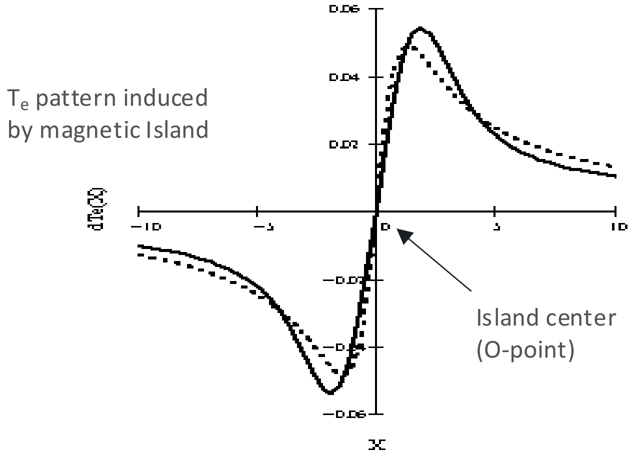
- smaller ($\partial\rho/\partial f_{ECE}$)
- Reduced radial ECE channel width ($\Delta\rho_p$)

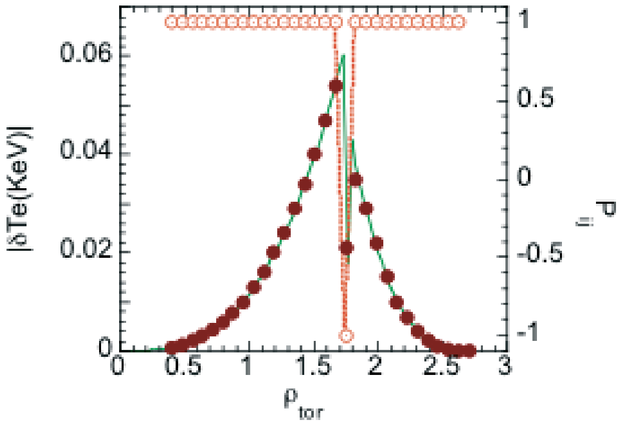




NTM detection by cross-correlation on different ECE LOS

- Improved resolution has an impact on the Island detection
- Simulated perturbed/unperturbed profiles to provide “synthetic” ECE channels in DEMO-like *[N. Rispoli et al. FED (2017) 628-631]*
- Applied *Berrino* Detection algorithm to synthetic data
- Island localization based on cross-correlations $P_{i,j}$ of ECE (<0, π-jump)

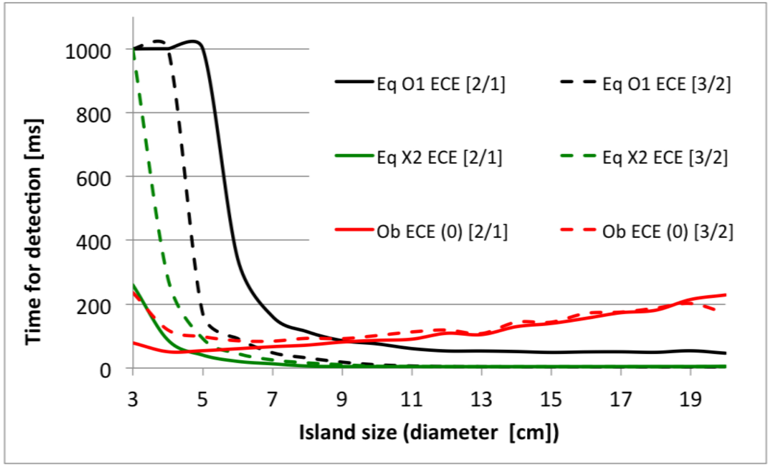


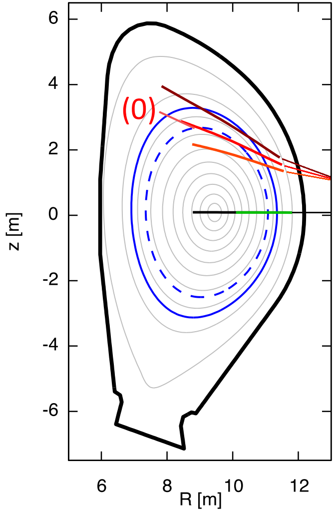


From J. Berrino et al., NF 45 (2005) 1350-1361

NTM detection by cross-correlation on different ECE LOS

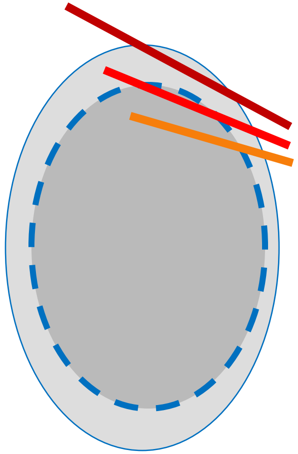
- Equatorial ECE show long detection times of small Islands not compatible (~1s) with control purposes
- Oblique ECE results in earlier detection





Issues with oblique ECE LOS in a DEMO-like reactor

- NTM detection/localization codes from ECE are developed for equatorial LOS
- Patterns of T_e fluctuations at ECE frequencies are different if seen from an Oblique LOS
- Pattern depends on the number (0,1,2) of intersection with the m/n rational surface



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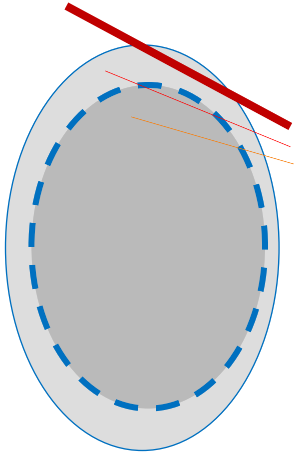

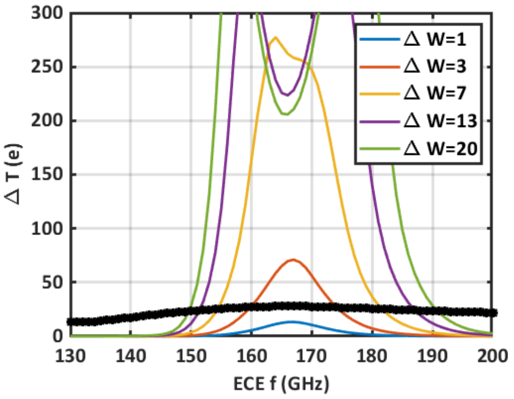

No intersections:

No localization of the Island

No information for steering the launcher

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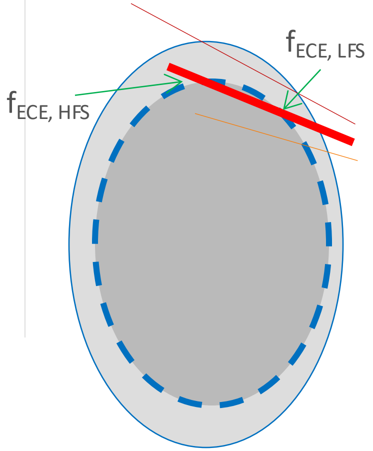

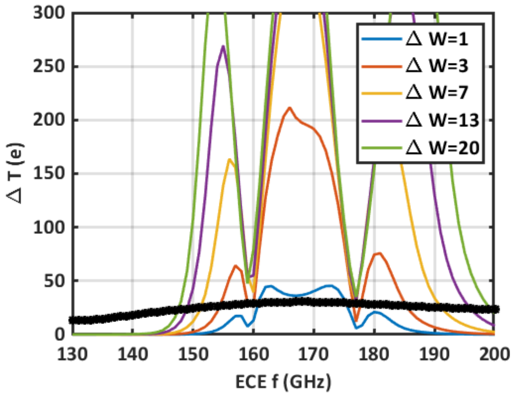

Two intersections:

Double localization of the Island

Typical condition is

$$f_{ECE,\ HFS} \geq f_{ECH} \geq f_{ECE,\ LFS}$$

No clear indication to move antenna outward or inward

Issues with oblique ECE LOS in a DEMO-like reactor

- NTM detection/localization codes from ECE are developed for equatorial LOS
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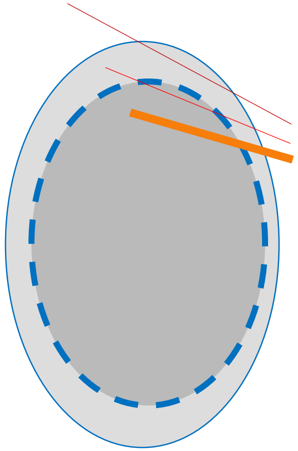

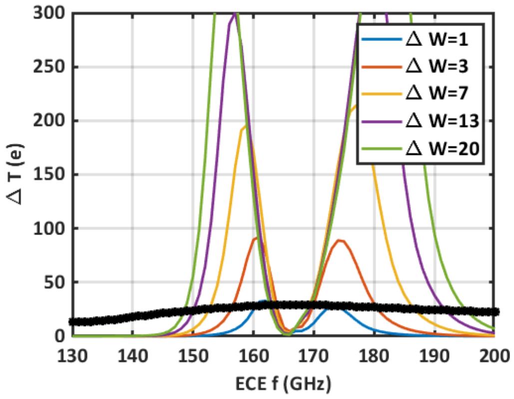

One intersection:
Similar to the case of Equatorial LOS

Issues with oblique ECE LOS in a DEMO-like reactor

- NTM detection/localization codes from ECE are developed for equatorial LOS
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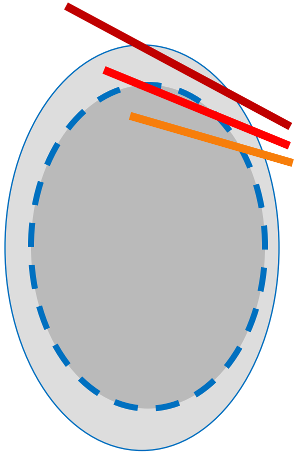
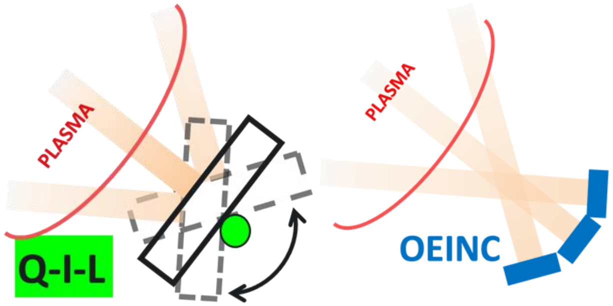


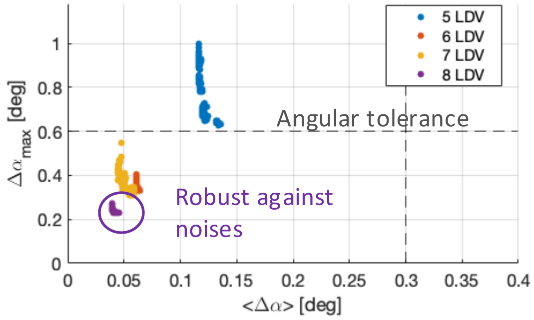
A moving antenna will see different conditions when aligning to the Island

=> in some cases, fall in conditions not providing clear information for alignment

Oblique ECE Imaging for NTM Control (OEINC)

- RT steerable ECE antennas **(Q-I-L)** can be replaced by a set of fixed antennas (**OEINC**) looking at different plasma volumes –possibly integrated in a single mechanical component-
  - Reduce moving parts faced to plasma
  - Avoid localization problems
- This Imaging diagnostic must cover the steering range of the ECH/CD launcher
- From OEINC information, it is possible to **solve an Inverse problem** and directly estimate the optimum angle for ECH/CD antenna alignment.
- In a DEMO-like reactor, Imaging with 8 ECE LOS fits the resolution requirements under noisy detection. *[N. Rispoli et al., 33th SOFT being submitted to FED]*

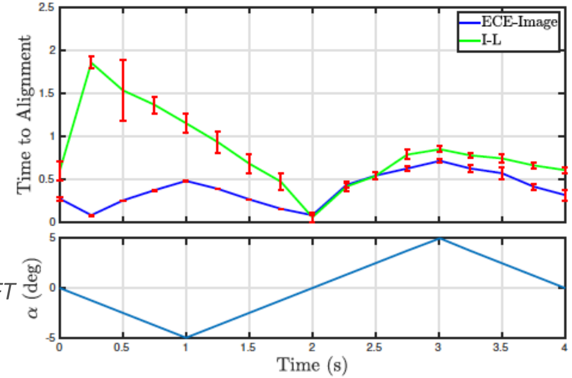




SUMMARY

In a DEMO-like reactor, magnetic measurements (fast, and equilibrium) can suffer of high disturbances, and complex evaluation in RT (Equilibrium Reconstruction, Beam propagation) may result in low resolution => use alternative diagnostics (e.g. ***ECE*** or SXR).

- *Oblique LOS ECE* are more sensitive than equatorial to magnetic Island and can ensure *faster reaction*.
- Technical difficulties of integration of ECE in ECH antenna (**In-Line**) can be avoided using toroidally displaced RT steerable ECE antennas (**Quasi-In-Line**).
- Significant reduction of moving parts faced to plasma with adoption of an Imaging diagnostic
- An Oblique ECE Imaging diagnostics (**OEINC**) made up of fixed antennas can replace the RT ECE antennas
  - a large impact on the control strategy, which will become more robust and capable of performing a faster ECH/CD alignment.



N. Rispoli et al., 33th SOFT being submitted to FED

Thank you all for attention!

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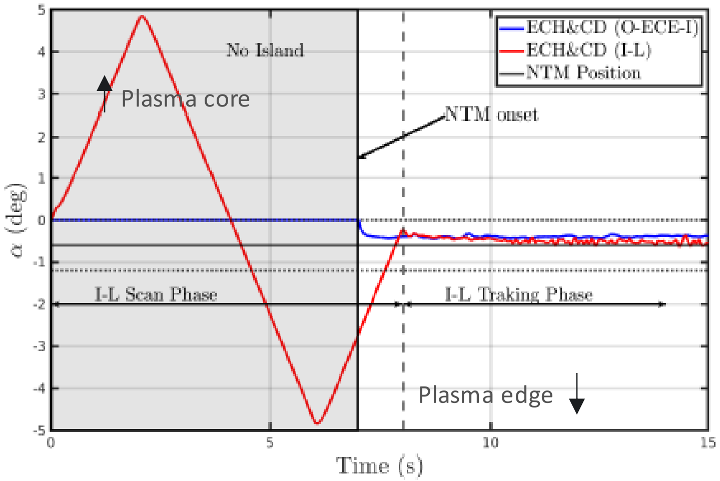
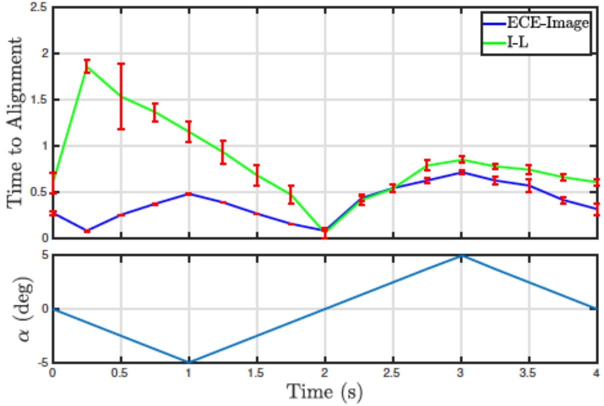
BACK-UP SLIDES

Performances with OEINC

- In a DEMO-like reactor, a limited number (8) of los can provide sufficient resolution for NTM control purposes.
- This leads to faster alignment with respect to Q-I-L, I-L solutions.
- Improvements on redundance, robustness and reliability



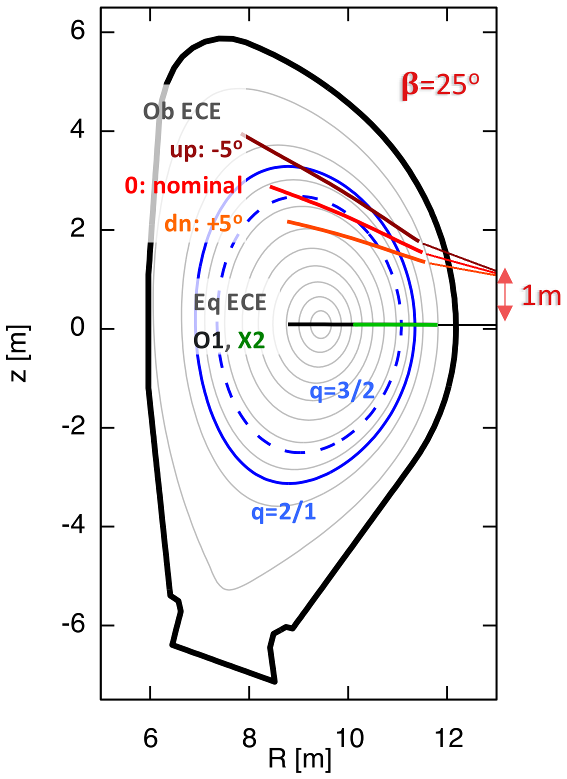


N. Rispoli et al., 33th SOFT being submitted to FED

ECH/CD and ECE systems in a DEMO-like reactor

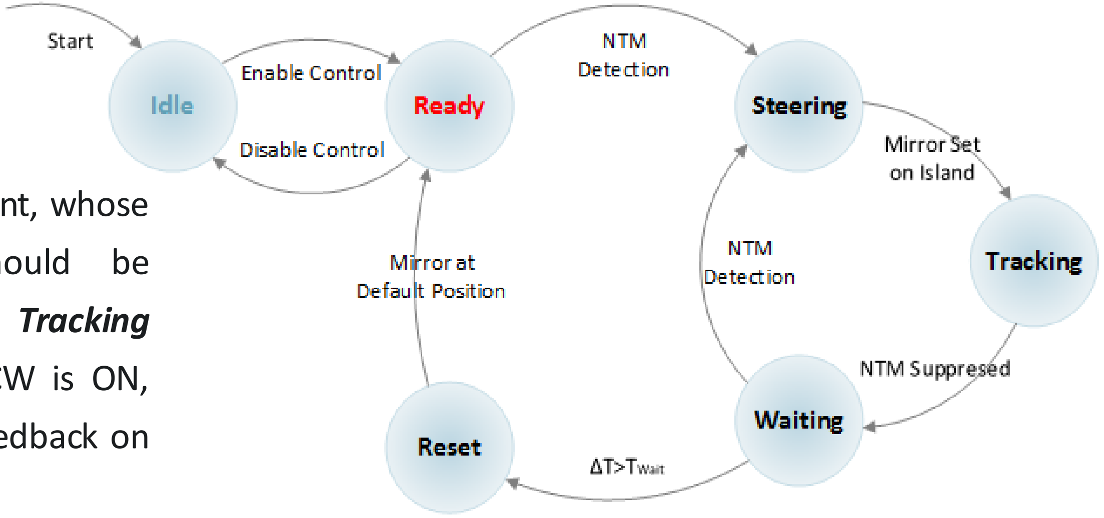
- A DEMO-like reactor *[M.Q. Tran FED 2022]* will be provided of dedicated ECH/CD (@f=170 GHz) launchers for NTM control:
  - Relevant toroidal angle of injection (current drive)
  - Launching point at z=1m above equatorial plane
- O1/X2 ECE radiometers installed in equatorial port -> RT equilibrium reconstruction and beam propagation codes to align ECH/CD NTM antennas
- Simple and robust control strategies based on In-Line principle:
  - To equip ECH/CD launchers with radiometers
  - To install additional RT steerable antennas **Quasi-I-L**
- Oblique los ECE

Parameters	Values
R_0, a [m]	8.94, 2.88
A, k_{95}, ∂_{95}, q_{95}	3.1, 1.65, 0.33, 3.94
I_P [MA], B_T [T]	18.3, 5.74
<T_e> [keV], <n_e> [$10^{19}m^{-3}$]	11.3, 8.06
ECH/CD (bulk, NTM) [MW]	50, 30
NBI, ICRF [MW]	50, 30-50
P_{Fus}, $P_{el, net}$ [MW]	2000, 500



Further developments of OEINC with Machine Learning

- OEINC opens to the possibility of developing Deep Learning algorithms to provide detailed information about the Island: (relative) position, width, rotation frequency and phase.
- ECW antenna is aligned on the basis of the OEINC estimate. Leading to a finite alignment error (***Steering***), but ensuring good efficiency



The finite resolution of the alignment, whose effect on the stabilization should be evaluated, can be solved adding a ***Tracking*** state in the control logic: once ECW is ON, alignment is optimized from the feedback on the Island width.

Control Strategies for ECH alignment

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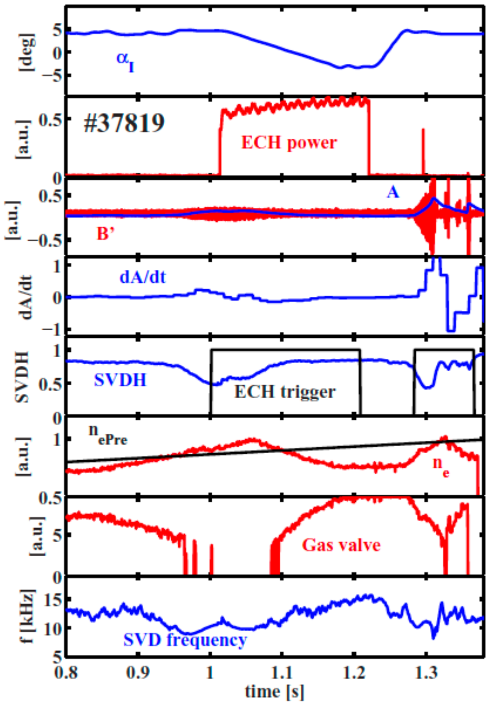
Feedback on	Diagnostics	Real Time Codes	Comments	Burning plasmas
W (Island width)	Mirnov	Fluctuation amplitude	Evaluate the Island response to ECH (on)	Reliability of Mirnov Power consuming
Radial position ($\rho_{ECH} - \rho_{Island}$)	Mirnov, Equatorial ECE	Equilibrium Reconstruction ECH Beam propagation Island radial localization and (m,n) identification *ECH deposition localization*	RT codes required for evaluating ρ_{ECH} And properly drive ECH antenna (ρ->α)	Reliability of Mirnov Reliability of RT codes
Relative position ($f_{ECH} - f_{Island}$)	Oblique ECE (In-Line)	Island localization along the ECE los	ECH antenna equipped with dedicated radiometer	Development of devices to separate emitted plasma radiation from ECH back reflected

Control Strategies. Feedback on W (A)

FTU

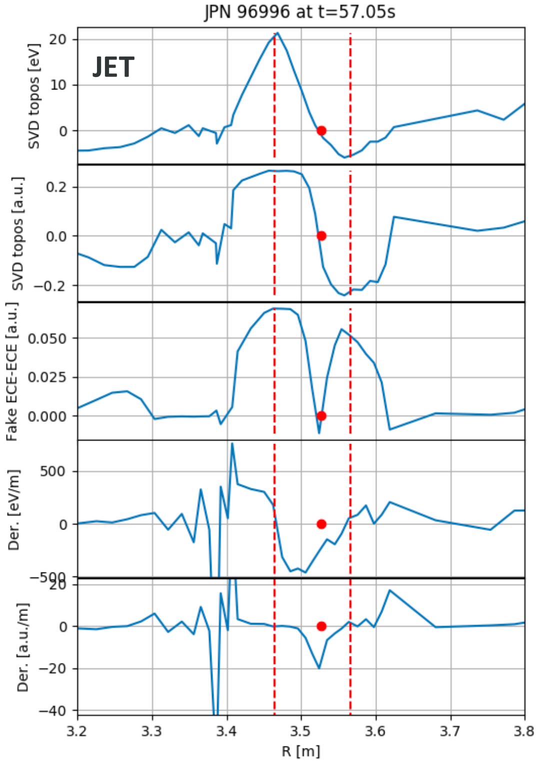


C.Sozzi et al., NF 55 (2015) 083010

- Minimal control system based on the Island response to ECW (on)
- Diagnostics to estimate A amplitude fluctuations (Island width, W)

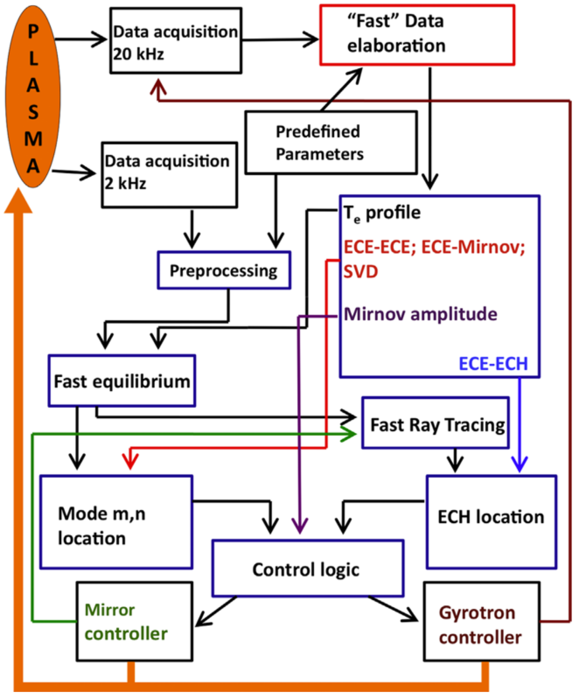
In Burning plasmas:

- Power consuming method (ECW on with low efficiency)
- Amplitude from in-vessel magnetic coils: subject to hard environment => Develop alternative diagnostics: e.g. SVD on **equatorial ECE** data



Control Strategies. Feedback on ρ_{ECW} - ρ_{Island}

FTU



E. Alessi et al., NIMA 720 (2013) 186-188

Complex control strategy needs measurements and/or estimates of ECH absorbing plasma volume (ρ_{ECW}) and of Island position (ρ_{Island}):

- Main diagnostics are fast Magnetic and **Equatorial ECE**
- Equilibrium reconstruction can provide an estimate of ρ_{Island} and is necessary to aim ECH antenna from localization along an equatorial line of sight (los)
- RT ECW beam propagation to estimate ρ_{ECW} (direct RT measurement not demonstrated yet)
- Bayesian assimilation of both actual measurements and of synthetic estimates.

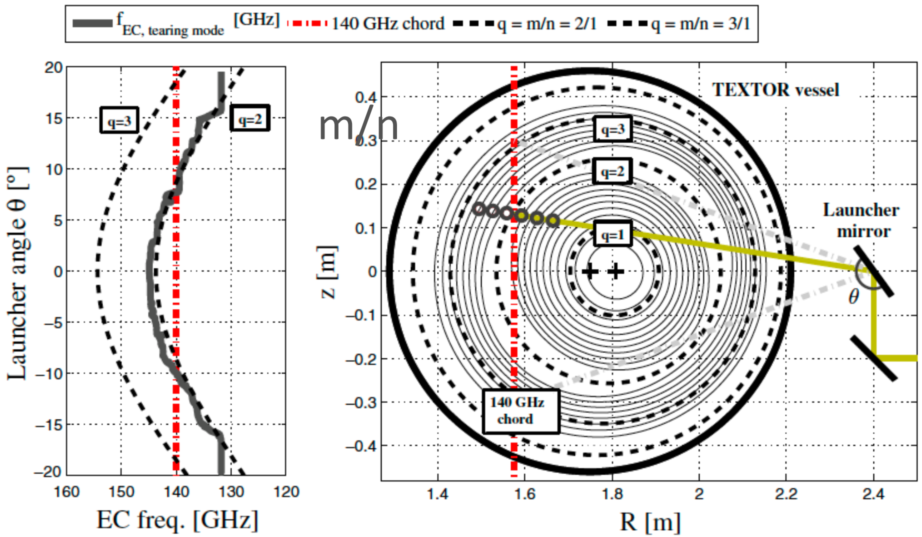
In Burning plasmas:

- Fast magnetics may have low reliability
- RT codes can fall in error/ have low resolution

Control Strategies. Feedback on f_{ECW} - f_{Island}

- ECE shares same antenna with ECW source (**In-Line**)
- Exploit (quasi-)reciprocity between plasma emitted ECE and injected ECW beam power
- More robust control strategy based on measurements of f_{Island}: detected Island position along ECE los

TEXTOR



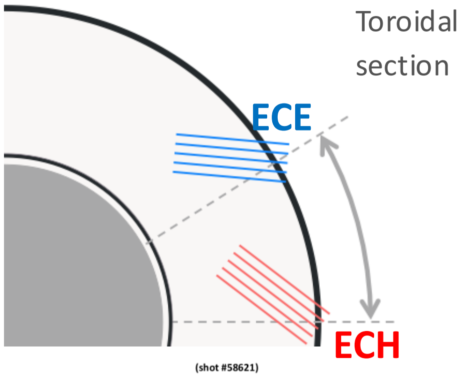
B. A. Hennen et al., PPCF 52 (2010) 104006

In-Line: Technologies for separating emitted (μW) ECE and injected (MW) ECW

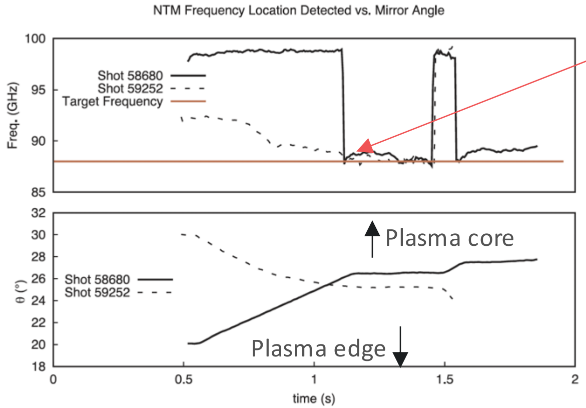
- worsening SNR [H. van der Brand NF 2019], may require further reference signal (Magnetic, SXR)
- ECW antennas dedicated to NTM stabilization are not equatorial
- Which los is better to detect NTMs?

Quasi-In-Line ECE for NTM control

- To exploit toroidal symmetry to reduce back-reflection helps avoiding FADIS
- Two similar antennas toroidally displaced, one for ECE and one for ECH
- In-line alignment control applied to the ECE (and ECH) antenna
- Proof of principle demonstrated in **TCV** *[N.Rispoli, FED 2019]*



Predefined angular scan stopped when $f_{ECH} - f_{Island} = 0$

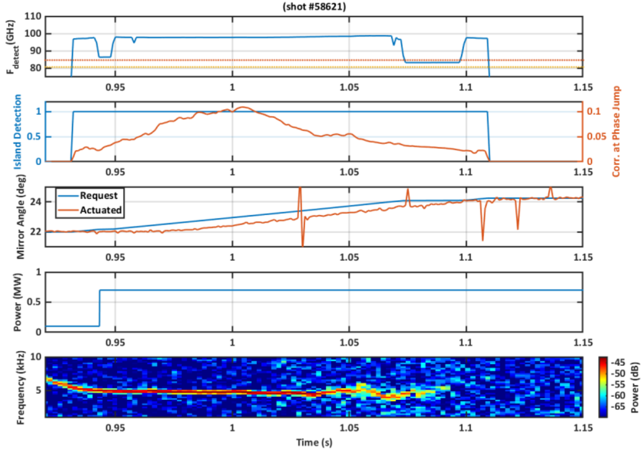


Test with

ECH/ECE antennas linked and ECH on

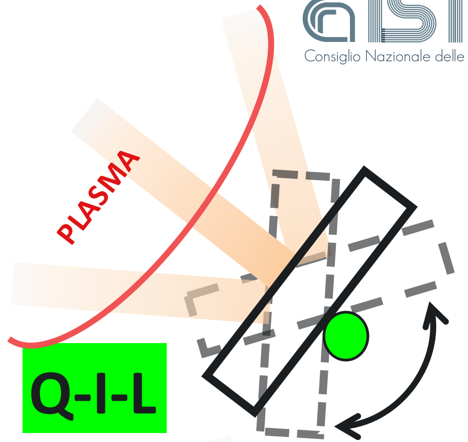
NTM is suppressed when $f_{ECH} - f_{Island,ECE} = 0$

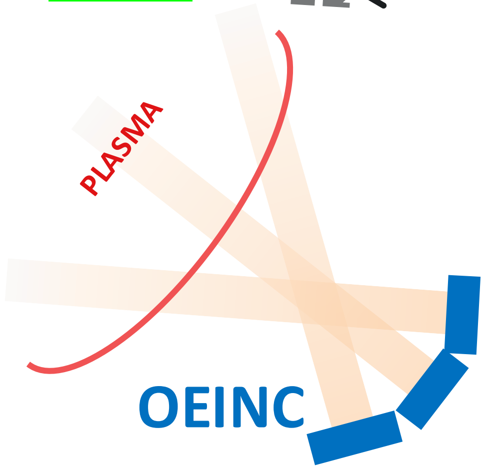
[C.Sozzi, IAEA-FEC 2023]



Oblique ECE Imaging for NTM Control (OEINC)

- RT steerable ECE antennas (**Q-I-L**) can be replaced by a set of fixed antennas (**OEINC**) looking at different plasma volumes –possibly integrated in a single mechanical component-
  - Reduce moving parts faced to plasma
  - Avoid localization problems
- This Imaging diagnostic must cover the steering range of the ECH/CD launcher
- From OEINC information, it is possible to **solve an Inverse problem** and directly estimate the optimum angle for ECH/CD antenna alignment.
- In a DEMO-like reactor, Imaging with 8 ECE LOS fits the resolution requirements. It results in faster detection and ECH/CD alignment *[N. Rispoli et al., 33th SOFT being submitted to FED]*





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