ECRH and ECCD studies for DEMO and for a volumetric neutron source (VNS)

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OUTLINE

- Design activities for both a **demonstration power plant** (DEMO) and a **volumetric neutron source** (VNS) for component testing and qualification are under way in EUROfusion [Federici 21, 23]
- For both machines:

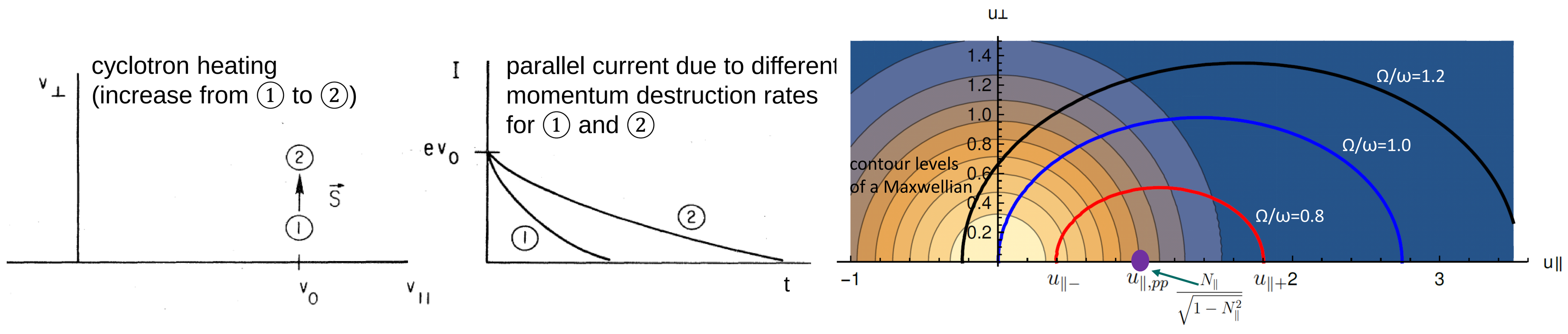
1) ECCD for bulk current drive → **how far can the ECCD efficiency be optimized**?

2) ECCD for **stabilization of neoclassical tearing modes**

- Extensive scans performed with the code Torbeam; evaluation of beam scattering with the wave-kinetic-equation-solver WKBeam

ELECTRON CYCLOTRON CURRENT DRIVE

ECCD in DEMO scenarios relies mostly on the acceleration of passing electrons far from the trapped/passing boundary (**Fisch-Boozer mechanism** [Fisch & Boozer 80])



Resonance condition: Fundamental role of **relativistic effects** and **Doppler shift**

$$\omega - \frac{n\Omega_c}{\gamma} - k_\parallel v_\parallel = 0 \quad \rightarrow \quad \gamma - n\overline{\Omega} - N_\parallel u_\parallel = 0 \quad \text{with } \overline{\Omega} = \Omega_c/\omega \text{ and } u = \gamma v/c$$

Resonance curves **in velocity space** are **ellipses** intersecting the $u_{||}$ axis at

$$u_{\parallel,\mp} = \frac{nN_\parallel\overline{\Omega} \mp \sqrt{n^2\overline{\Omega}^2 - (1-N_\parallel^2)}}{1-N_\parallel^2} \quad \Rightarrow \quad \text{resonance possible if } n\overline{\Omega} \geq \sqrt{1-N_\parallel^2}$$

Increasing $N_{||}$ **moves the absorption location** to the LFS and **shifts the resonance on more energetic electrons** (less collisional) → higher current drive efficiency, weaker absorption → basic scaling for CD efficiency: $\eta_{CD} \propto T_e/n_e R$

The **maximum ECCD is a trade-off** between two competing effects

- Need for high-energy (low-collisionality) electrons → **favours resonance on the tail** of the distribution
- Need for sufficiently high absorption → **favours resonance on the bulk**

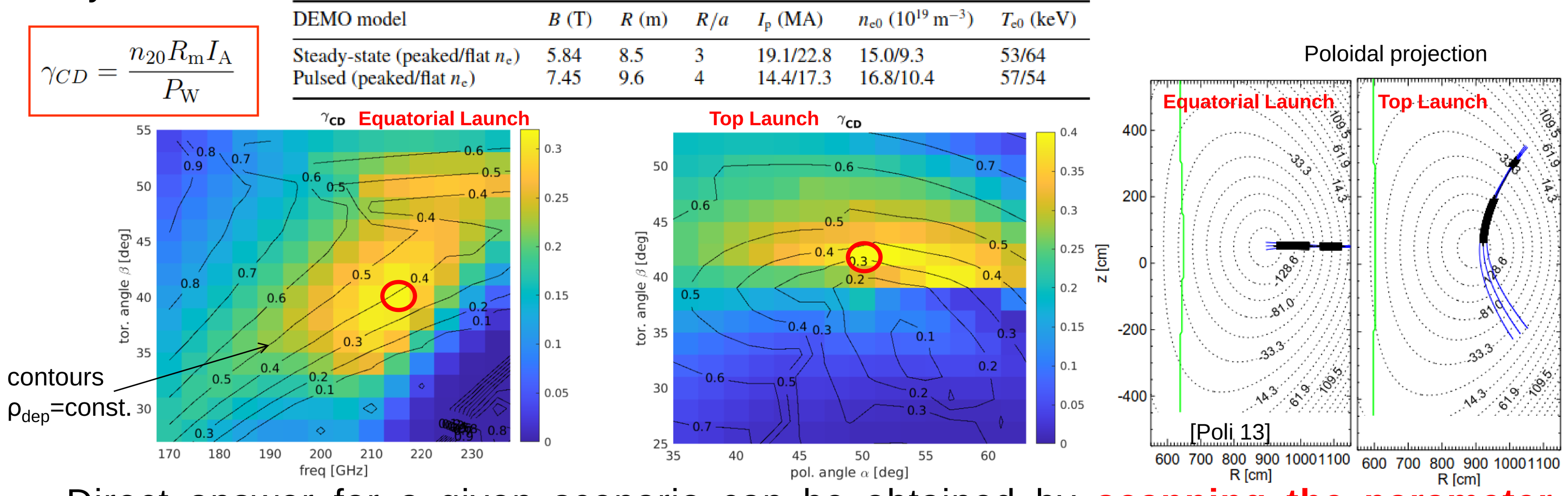
This balance is **exploited in the code HARE** (Hare Analyses Reactor Eccd) [Poli 18] for a **fast evaluation of ECCD given machine parameters**

OPTIMIZATION OF BULK CURRENT DRIVE

Example from previous DEMO analysis [Poli 13]: **How much current can be driven by EC waves?**

$$\boxed{\gamma_{CD} = \frac{n_{20}R_\mathrm{m}I_\mathrm{A}}{P_\mathrm{W}}}$$

DEMO model	B (T)	R (m)	R/a	I_p (MA)	n_{e0} (10^{19} m^{-3})	T_{e0} (keV)
Steady-state (peaked/flat n_e)	5.84	8.5	3	19.1/22.8	15.0/9.3	53/64
Pulsed (peaked/flat n_e)	7.45	9.6	4	14.4/17.3	16.8/10.4	57/54



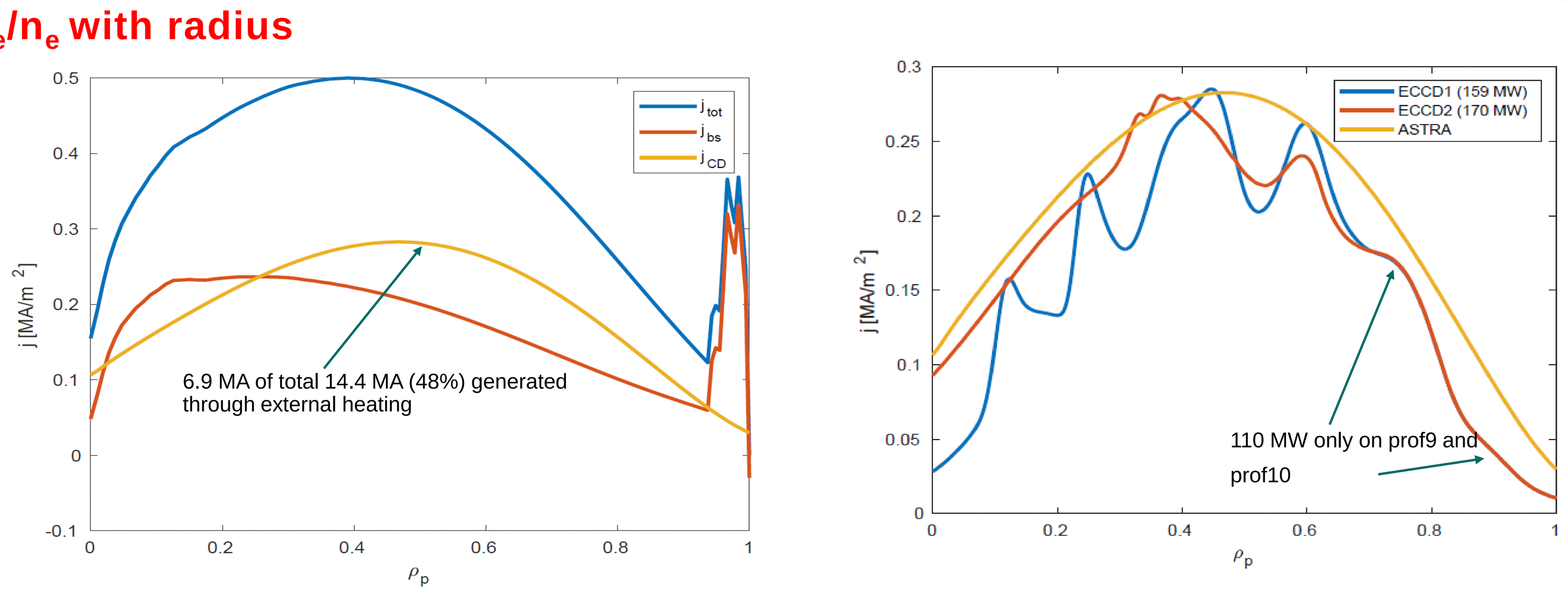
Direct answer for a given scenario can be obtained by **scanning the parameter space** (injection position, injection angles, wave frequency)

Increase in ECCD efficiency for top launch **recently demonstrated at DIII-D** [Chen 22]

STEADY STATE WITH ECCD ONLY IN DEMO?

ASTRA steady-state scenario: B=5.8 T, R=8.4 m, a=2.88 m, Z_{eff}=1.48, strong off-axis CD assuming 50 kA/MW

High central ECCD deteriorates with radius due to trapped particles and **decreasing T_e/n_e with radius**



"Synthetize" the required CD profile with ECCD: **Required heating power** (> 170 MW) **too high** ☹ [Poli 24]

VOLUMETRIC NEUTRON SOURCE

Main VNS parameters: B=5.6 T, R=2.67 m, a=0.63 m, Z_{eff}=1.2

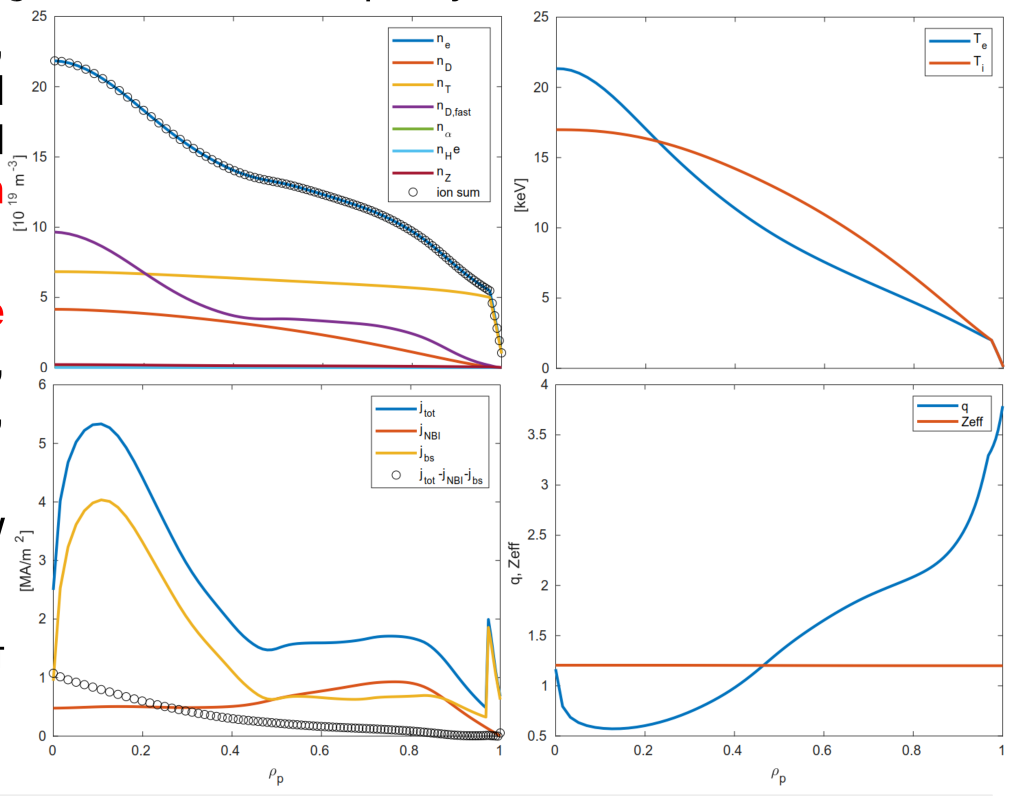
DT reactions mainly from beam-target collisions, but partly also from thermal bulk

Goal: Test and qualify blanket, plasma-facing components and tritium cycle at a **10-20 dpa** level and comparatively **low tritium consumption**

EC as actuator for **current profile control, NTM stabilization**, control of W accumulation, keeping T_e high

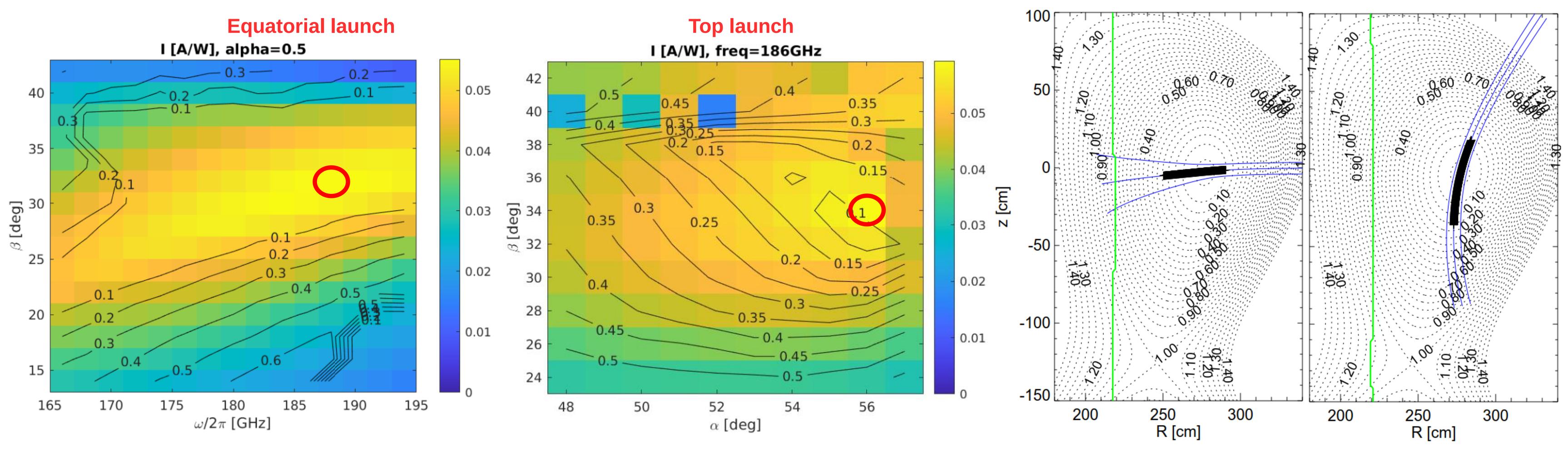
Installed EC power: ca. 10 MW (provisional value)

On axis: $\omega_{ce}/2\pi$=157 GHz, $\omega_{pe}/2\pi$ =133 GHz → **large refraction**



BULK ELECTRON CYCLOTRON CURRENT DRIVE

Total current in VNS scenario I_p=2.54 MA, steady-state discharge targeted



Ratio T_e/n_e smaller by a factor 3-4 with respect to DEMO, but major radius smaller by a similar factor → **comparable ECCD efficiency as in DEMO**

Torbeam scans show a **moderate increase** of the ECCD efficiency **for top launch**

HARE prediction **very close to optimum current**, although for **slightly different injection conditions**

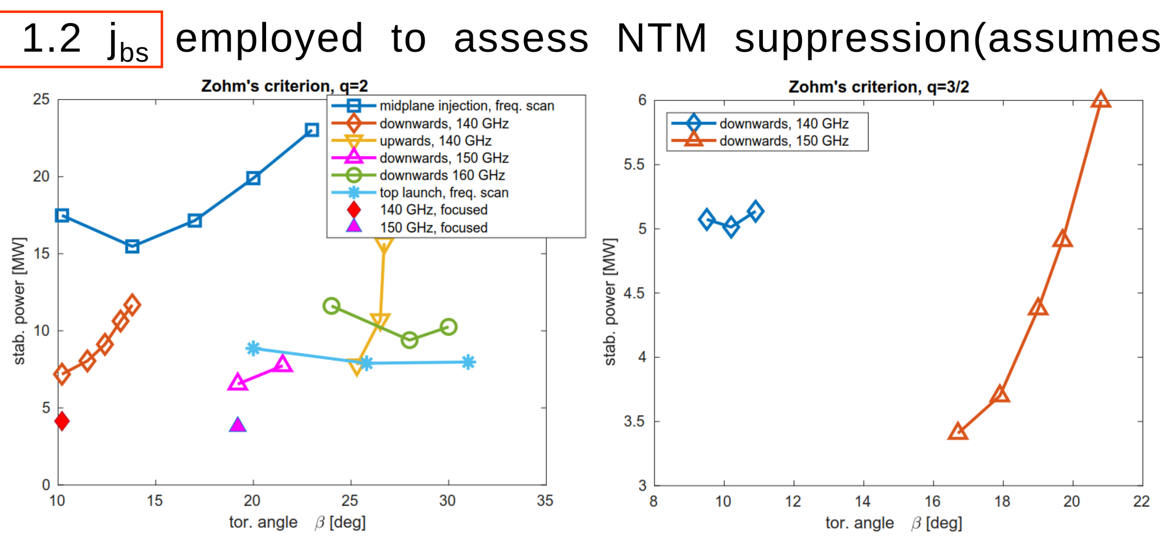
(R,Z) [cm]	(α,β)	freq. [GHz]	I_{CD} [kA/MW]	$N_\parallel$
(350, 0)	(0.5°, 34°)	188	55.17	0.706
(370, 0)	(0.5°, 32°)	188	55.19	0.707
(350, 80)	(43°, 34°)	191	58.57	0.704
(330, 100)	(56°, 34°)	186	59.16	0.670
HARE		195	59.69	0.620

NTM STABILIZATION

EC waves stabilize neoclassical tearing modes by replacing the missing bootstrap current

Zohm's criterion $\boxed{j_{ECCD} > 1.2\ j_{bs}}$ employed to assess NTM suppression(assumes power modulation)

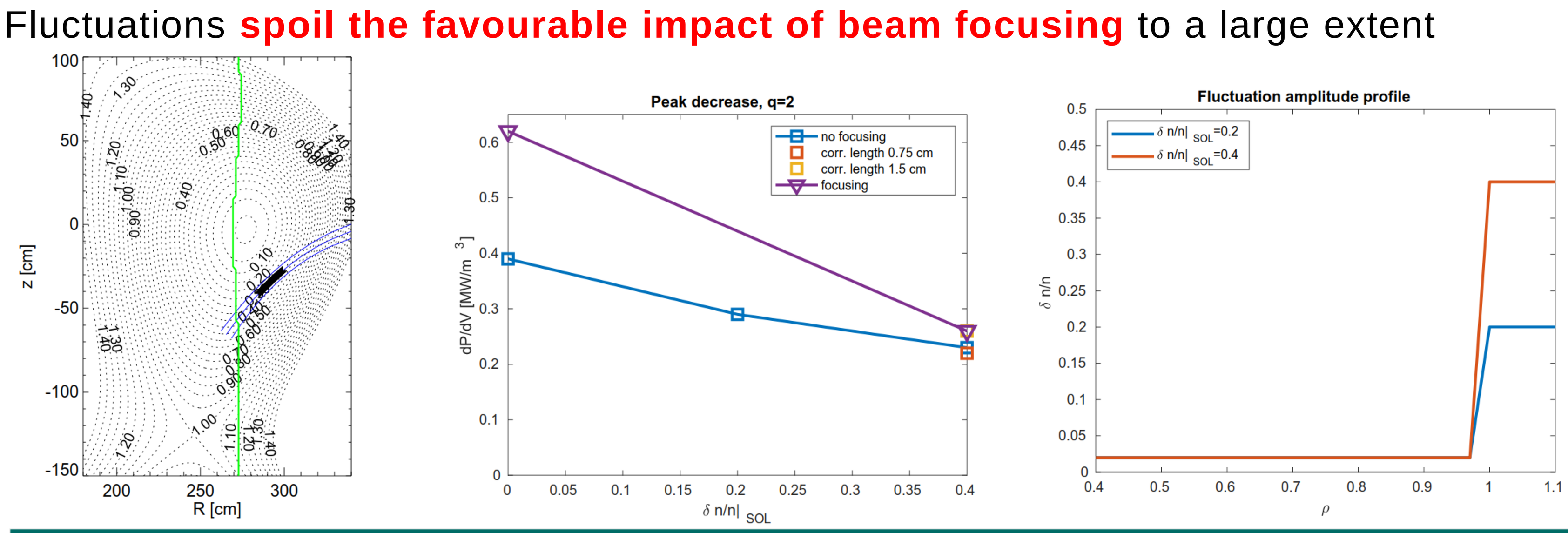
Optimum conditions for NTM stabilization different from those for maximum bulk current drive: current density to be optimized → lower frequency, smaller $N_{||}$



Injection **tangential to the rational surface increases localization of power deposition**, profits from focusing, but is particularly **prone to deposition broadening** due to beam scattering off density fluctuations

Effect of scattering evaluated using the wave-kinetic-equation solver WKBeam ← **large uncertainties in the turbulence parameters** (amplitude, correlation length)

Fluctuations **spoil the favourable impact of beam focusing** to a large extent



SUMMARY

DEMO: Economically efficient ECCD in a DEMO power plant remains a challenge

VNS: (i) good ECCD efficiency (ii) NTM stabilization should be feasible with an installed power of 10 MW (iii) engineering constraints not taken into account yet, but do not appear to be critical

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