Design of the Actively Cooled Ion Cyclotron Travelling Wave Array System for WEST

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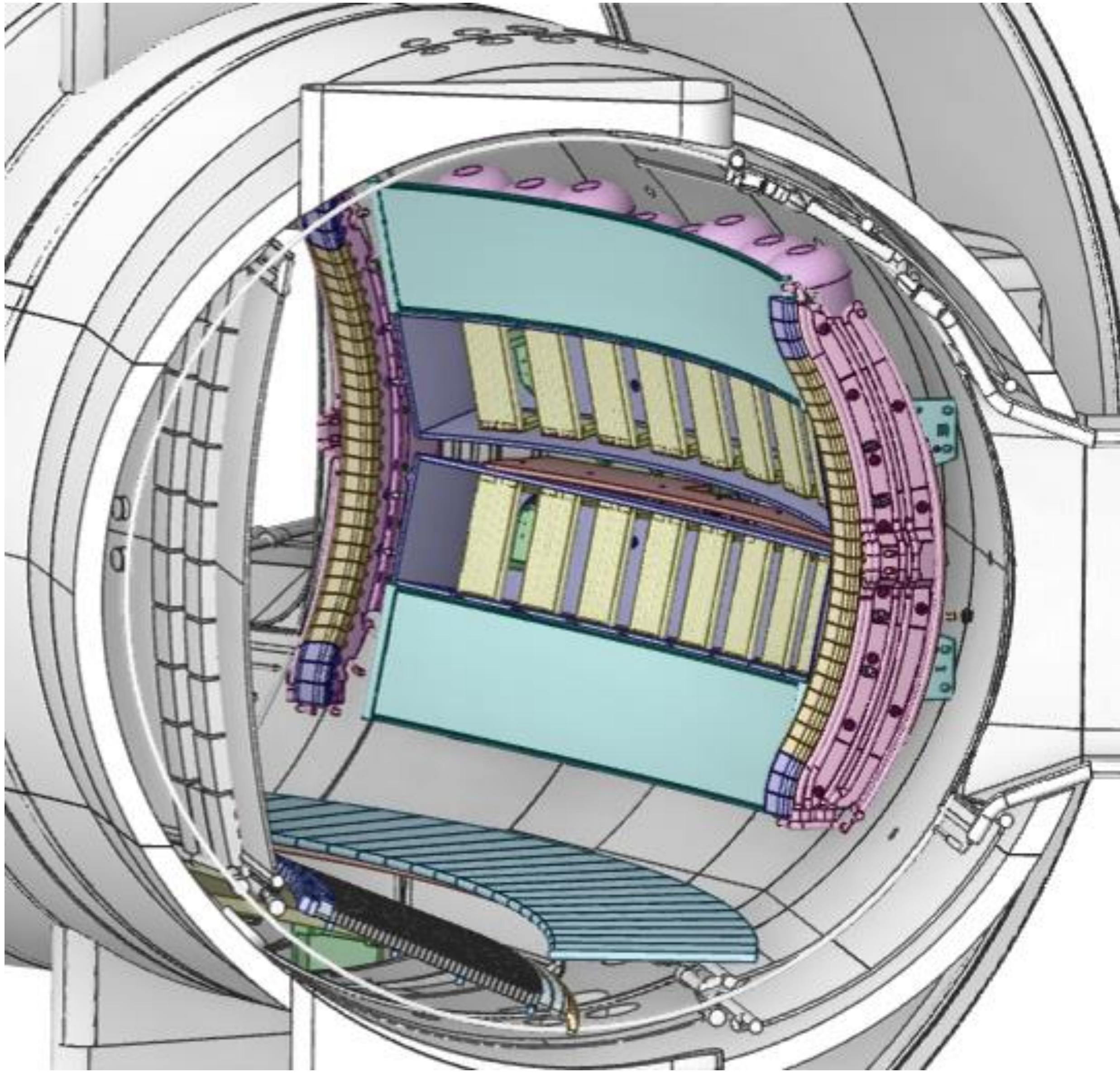


Current Ion Cyclotron launchers have several drawbacks

While ICRF has been proven to be a relevant tool in fusion experiments due to

- No density limit (high-density plasmas)
- Excellent absorption
- Proven experience in various scenarios (heating, wall-conditioning, assisted breakdown)
- Proven technology for CW and modest price/MW (compatible with high field experiments)

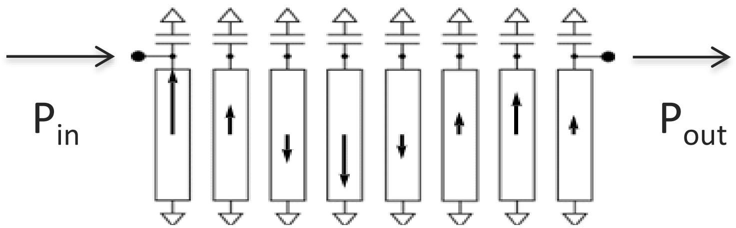
Current ICRF launchers suffer from drawbacks making them incompatible with fusion plants

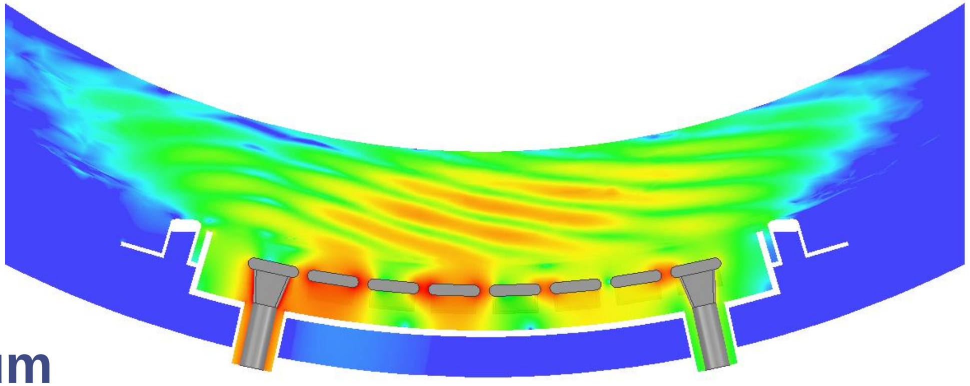
- Low coupling conditions (large strap to fast-wave cut-off distance)
- Undesirable large voltages inside the launchers (Arcs)
- Metallic impurity production (RF sheaths)
- Low Reliability, Availability, Maintainability and Inspectability (RAMI)
- Large launcher volume and weight (a volume necessary for Tritium breeding)

Travelling Wave Array (TWA) launcher for ICRF

An innovative launcher concept for the ICRF

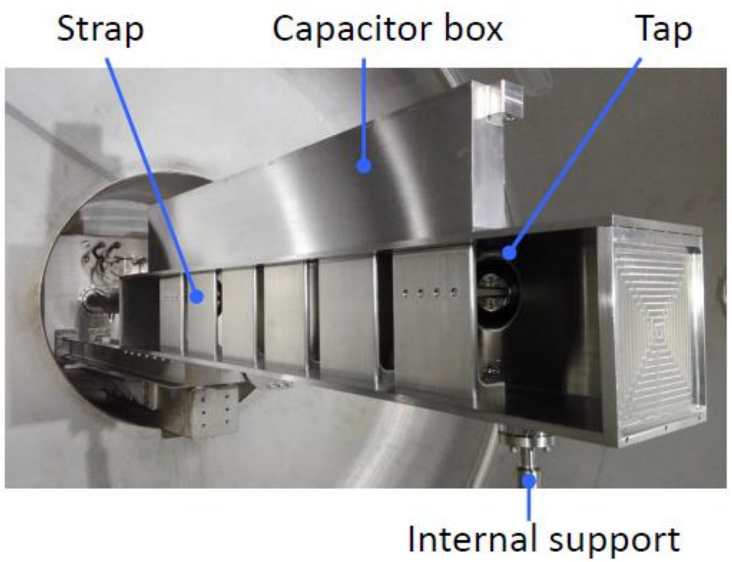
- Array of tuned straps
- RF current is induced by mutual coupling between elements
- No direct feeding of each element
- "*Slow-wave*" RF structure (exciting plasma fast-wave)
- Power *leaks* to the plasma





High-power mock-up successfully tested in 2021 in Vacuum

- 2 MW / 3s, 1.75 MW / 5s and 500 kW / 60s
  - Limited by RF generator only
- No pressure increase during long pulses
- Thermal & electrical responses as expected by modelling



[Chiu 1984 Nucl. Fus. 24]
[Moeller 1994 AIP Conf. Proc 289]
[Ragona 2016 Nucl. Fus. 56]

[Ragona 2022 *Nucl. Fus* 62]

Demonstrating ICRF TWA launcher on WEST plasmas

Expected advantages of TWA launchers in a W-environment

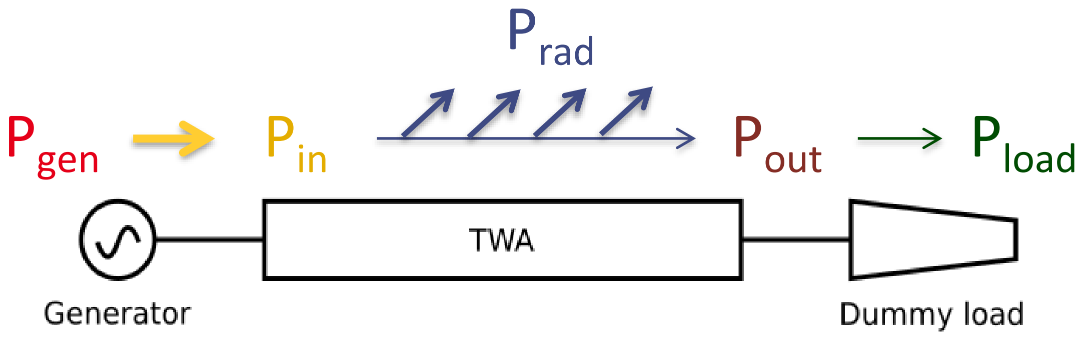
- Increased RF coupling ($k_{//}$ spectrum narrower and of lower value)
  → Plasma can be located further away from the launchers
- Lower electric field
  → Reduced RF sheaths and lower risk of arcs
- Enhanced directivity
  → Reduced parasitic coaxial mode excitation (reduced parasitic uncoupled power/far sheaths)
- Provides operational simplicity (no tuning elements in vacuum)
  → Load-resilient launchers, low reflected power to RF sources
- Fusion power plant compatibility
  → Materials (stainless-steel), reliability, efficiency, reduced radial volume
- Large bandwidth launchers: allows to change RF frequency (power deposition) in real-time
  → Open new operational scenarios!

Reduced impurity production

Two possible TWA RF power feeding schemes

Direct feeding

- Simplest configuration, aims at demonstrating:
  - Coupling performance
  - Load resilience
  - RF Sheath minimization
  - Spectrum optimization
  - Assess high power performance
  - Test frequency changes and RT control



$P_{rad}=P_{in}-P_{out}$ and $P_{in}=P_{gen}$

$P_{rad}=P_{gen}$ only if $P_{load}=0$

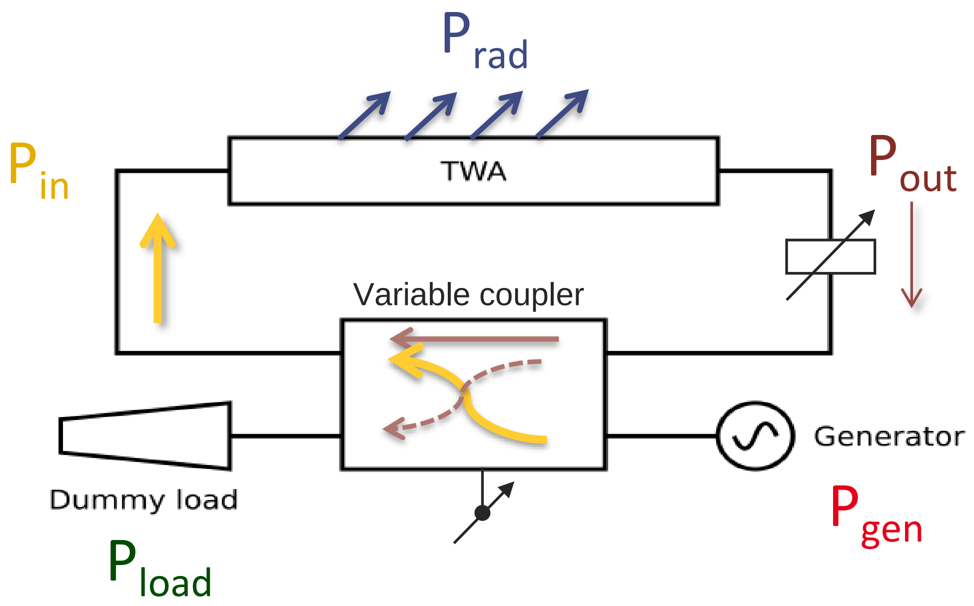
Uncoupled power is lost (unless very long structure is used)

Resonant Ring feeding

- Allows recirculation of uncoupled power
- Optimal power efficiency:

  $P_{rad}=P_{gen}$ when $P_{load}=0$ (by tuning)

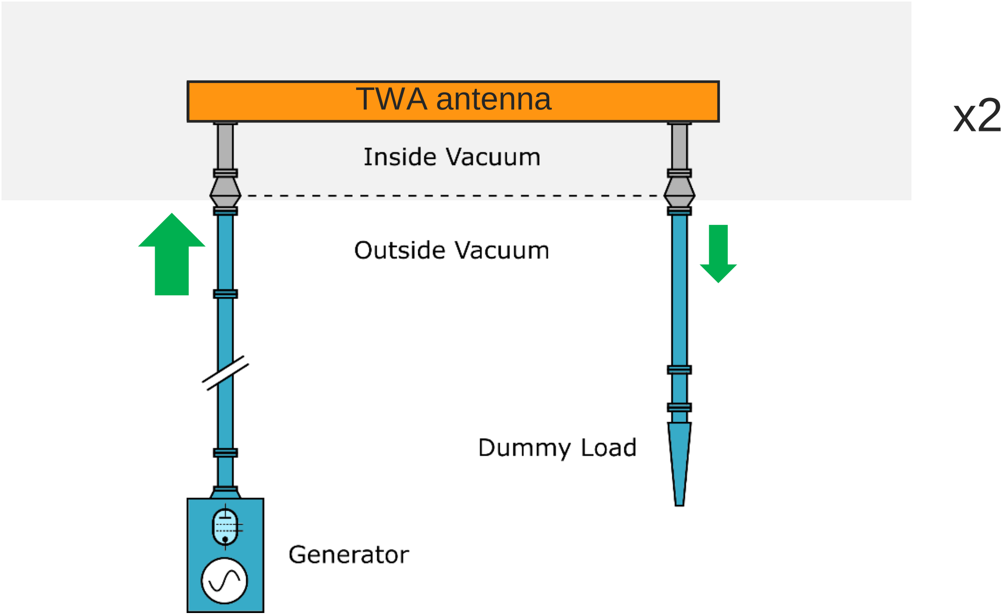
- Relevant to fusion plant



WEST TWA Project — Staged Approach

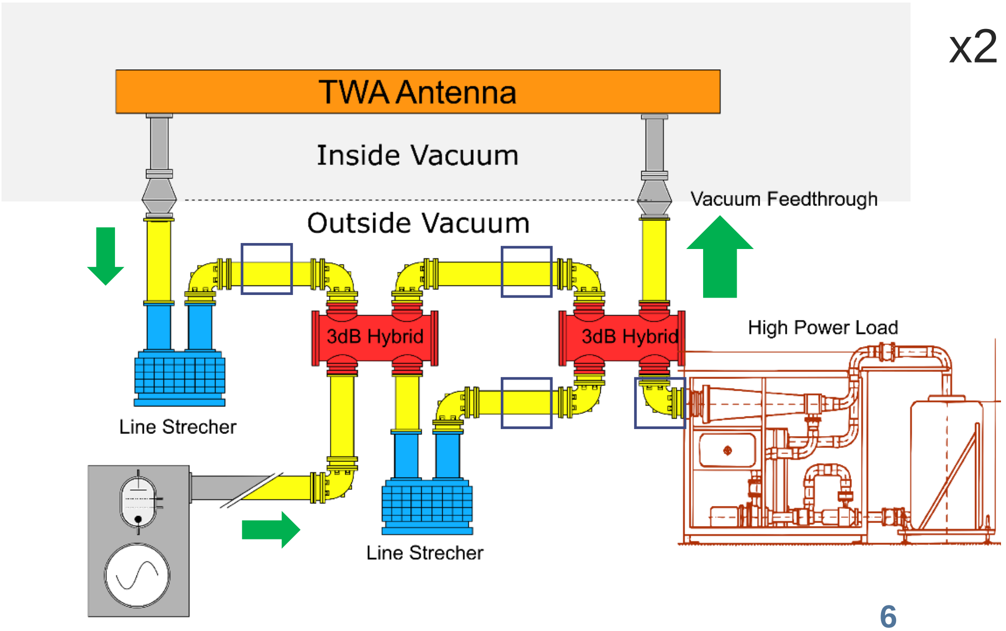
Phase 1: Direct Feeding

- Actively cooled launchers (2 rows of straps)
- Each TWA launcher directly fed by one ICRF Generator
  - Uncoupled Power is transferred to dummy loads
- Performances and operational space characterization
- *Walk-away* ICRF system demonstration



Phase 2: Resonant Ring Feeding

- Uncoupled Power is recirculated back to the launchers
  - Larger ROG operation
  - Maximize Power Efficiency
- Requires additional ex-vessel components:
  - 4 x 3dB Hybrid
  - 4 x Phase Shifters (Line Stretchers)
  - Additional lines and bi-directional couplers



Objectives of the WEST TWA launchers project

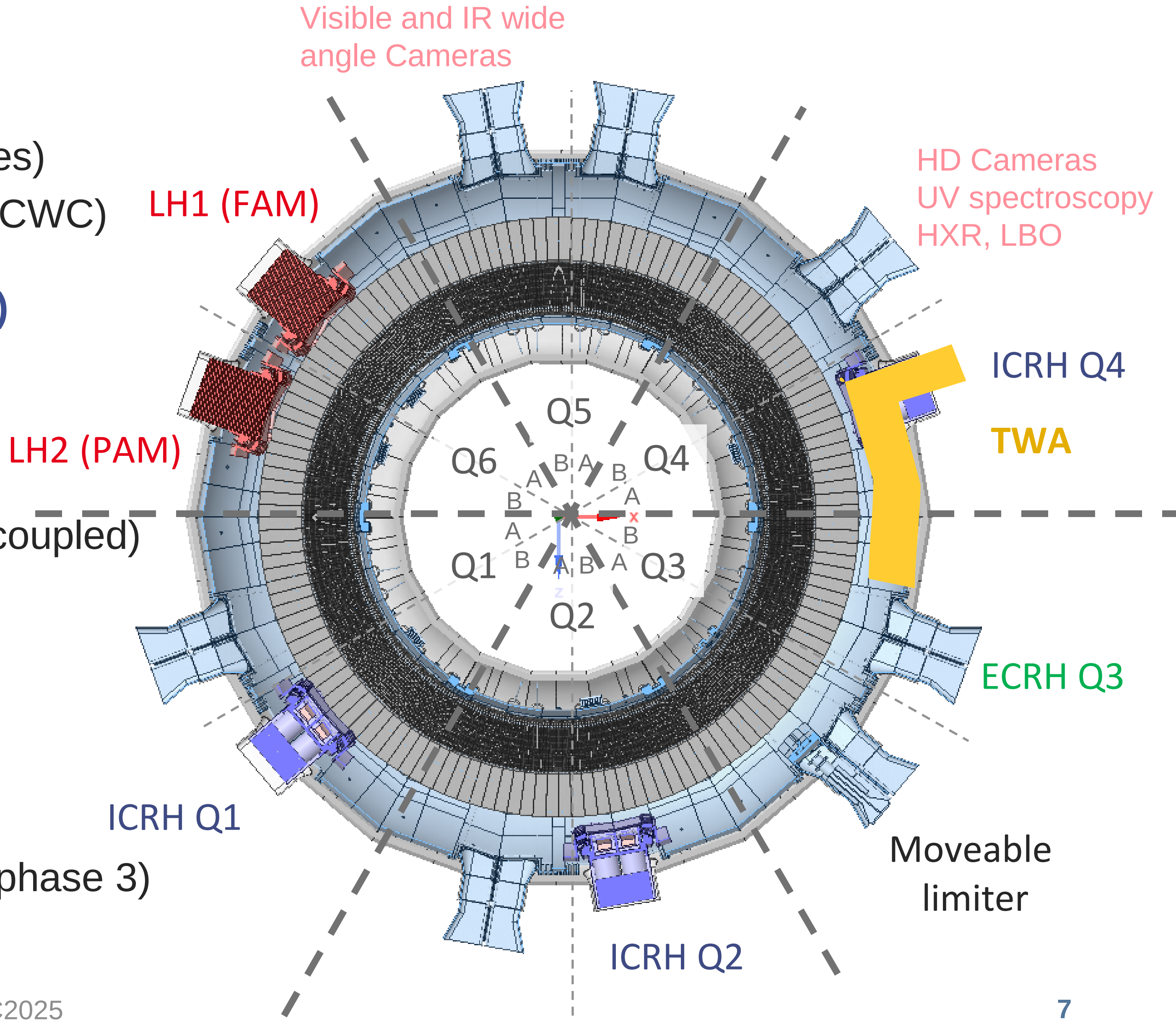
Two poloidal rows

- Replacing one ICRF launcher (Q4)
- CW/actively cooled launchers (WEST long pulses)
- Compatible with all WEST plasma scenarios (+ICWC)

Launchers RF *input* power design targets (2 rows)

- Direct feeding phase
  - 3.0 MW / 30 s (1.5 MW/ant)
  - 1.0 MW / CW (0.5 MW/ant)
- Resonant ring feeding phase (50% single pass coupled)
  - 6.0 MW / 30 s
  - 2.0 MW / CW
- Limited by plant/lines/feedthroughs

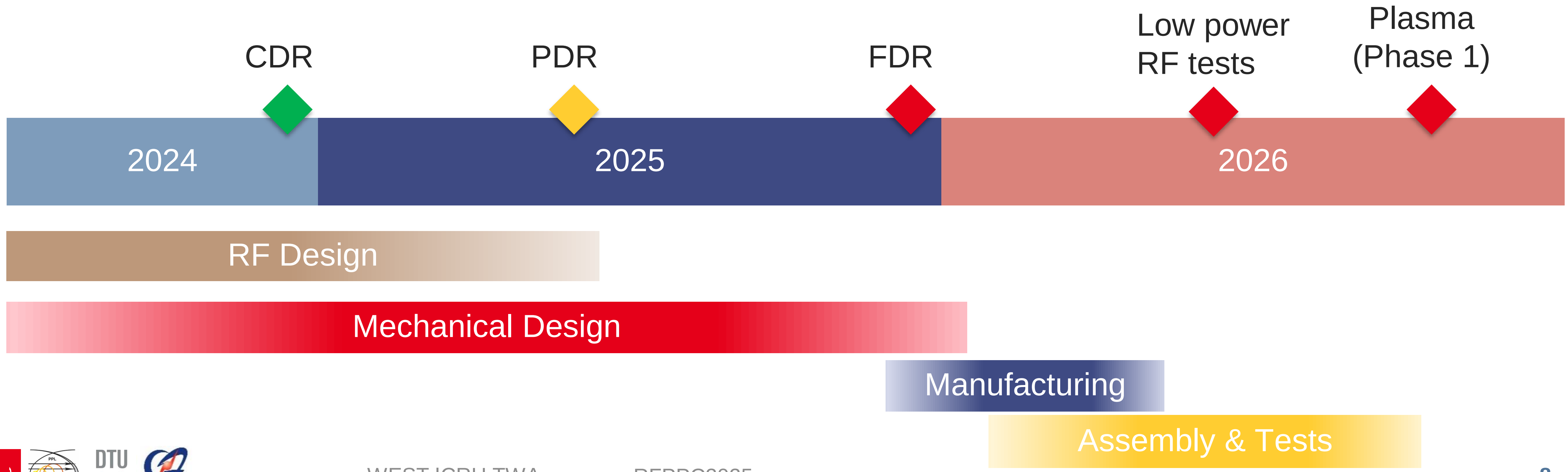
- Material: bare Stainless-Steel
  - No coating (fusion plant relevance)
- Eventually integrated inside a wall/blanket (WEST phase 3)



WEST TWA Project – Deliverables Planning & Main Milestones

- CDR December 2024
- PDR July 2025
- FDR December 2025
- Launchers manufacturing end 2025-beg. 2026
- Shipping, assembly and testing at IRFM from beg-to-mid 2026
- Tested in WEST plasmas in 2026

Performed with an increasing help of ASIPP for modelling, 3D/2D design and manufacturing

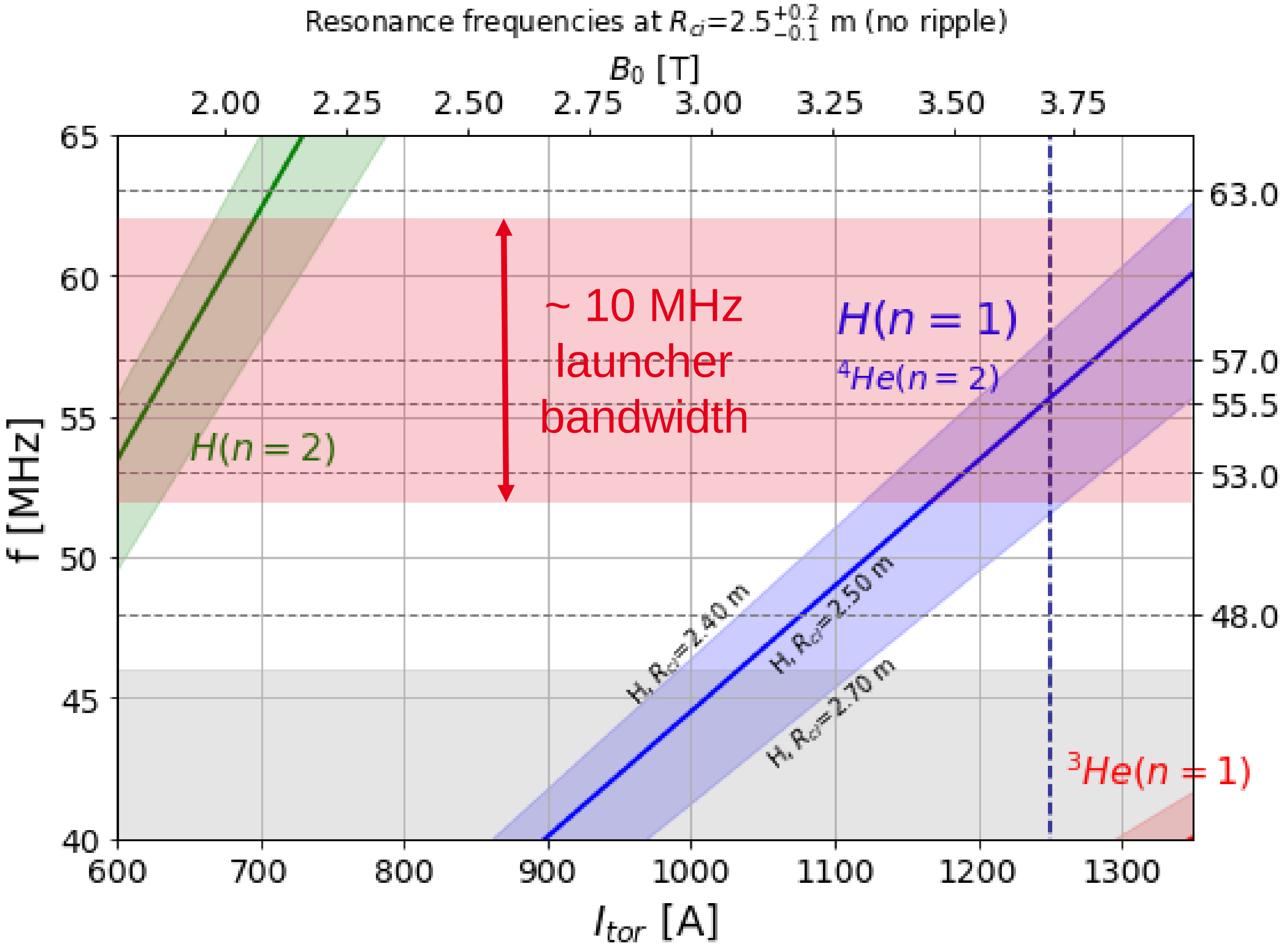


WEST TWA launchers operate within a ~10 MHz bandwith

- Main scenario D(H) @ 3.7 T: 55.5 MHz
  - Higher frequencies allow H(n=2) scenarios at half-field
- TWA Launchers have a ~ 10 MHz bandwidth (more on this later)

WEST ICRH TWA launchers bandwith specification

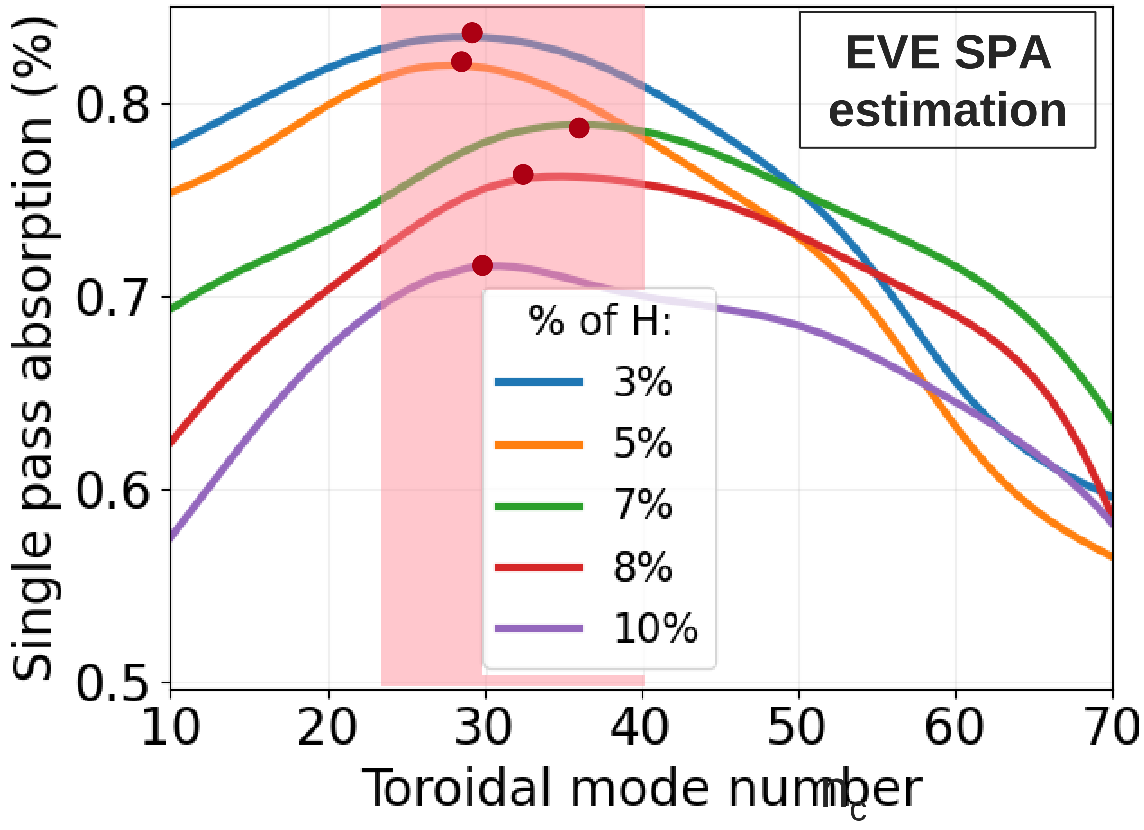
57 +/- 5 MHz



Single Pass Absorption (SPA) max. for toroidal modes [25-40]

For Hydrogen concentration between 3 to 10%

- EVE modelling show an optimum of the SPA for toroidal mode numbers (n_c) between 25 to 40
- As n_c increases, power damped by electron increases
- Larger n_c broadens the power deposition profile



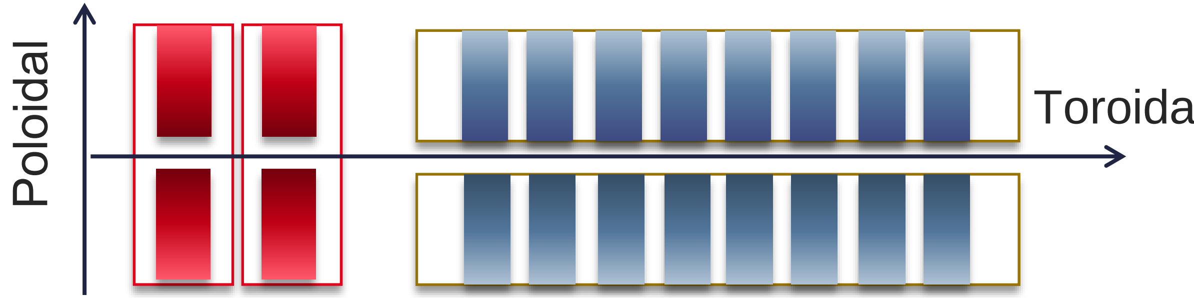
Lower toroidal modes favoured: n_c 25 to 30 ($k_{//0}$ 8 to 10 rad/m)

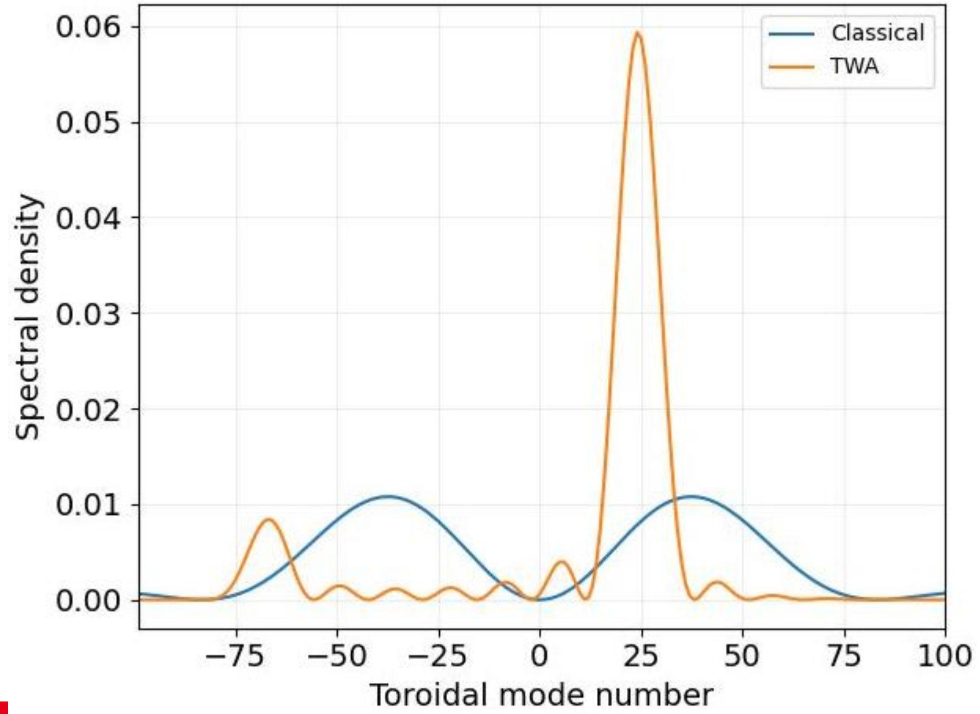
[Dumont2009] [Lara Hijazi, this conference]

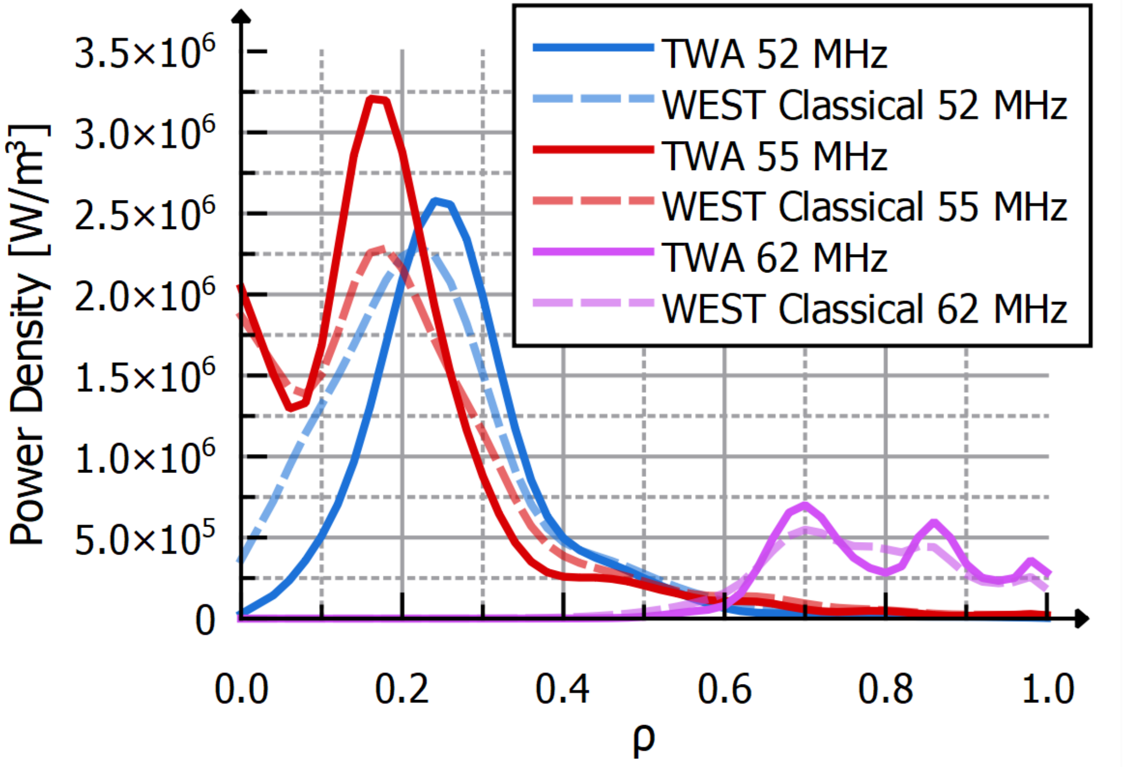
TWA launchers have a narrower radiated spectrum

$k_{//0}$ specification → 8 straps → narrower spectrum

- Reduced higher $k_{//}$ components
  → Increase coupling
- Reduced lower $k_{//}$ components
  → Less parasitic (coaxial) modes (↓ impurity)





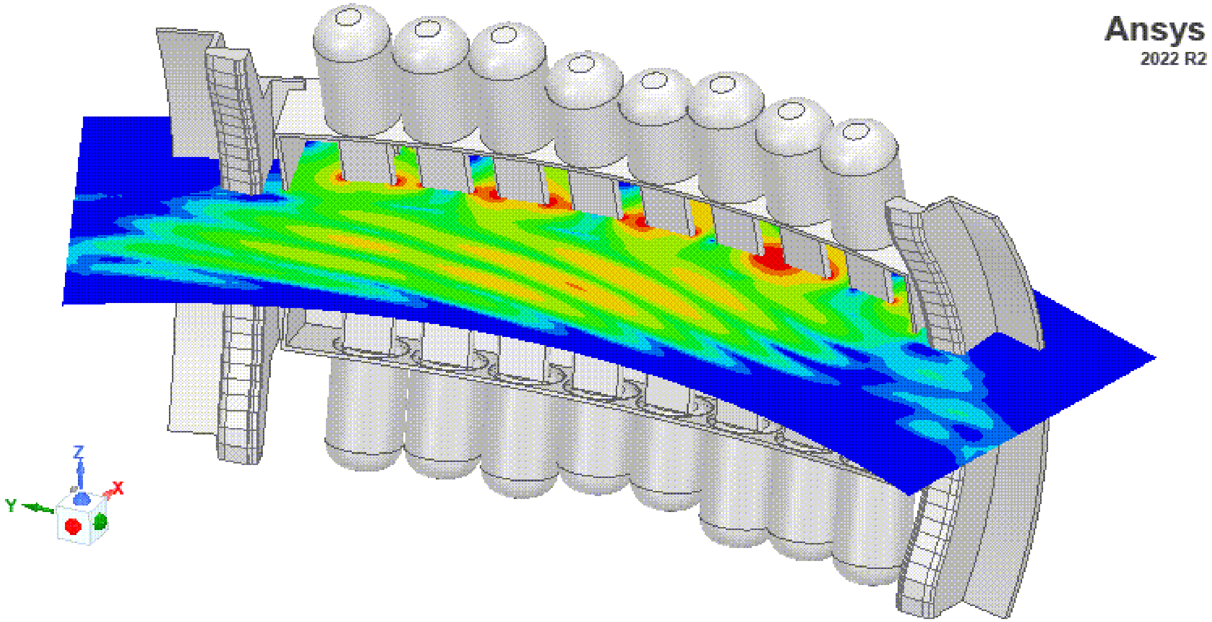


Launcher design performed with state-of-art 3D RF modelling

- 3D inhomogeneous and anisotropic cold plasma
  - Using WEST equilibria and density profiles
  - Solved in HFSS
  - Absorption mimicked with artificial losses

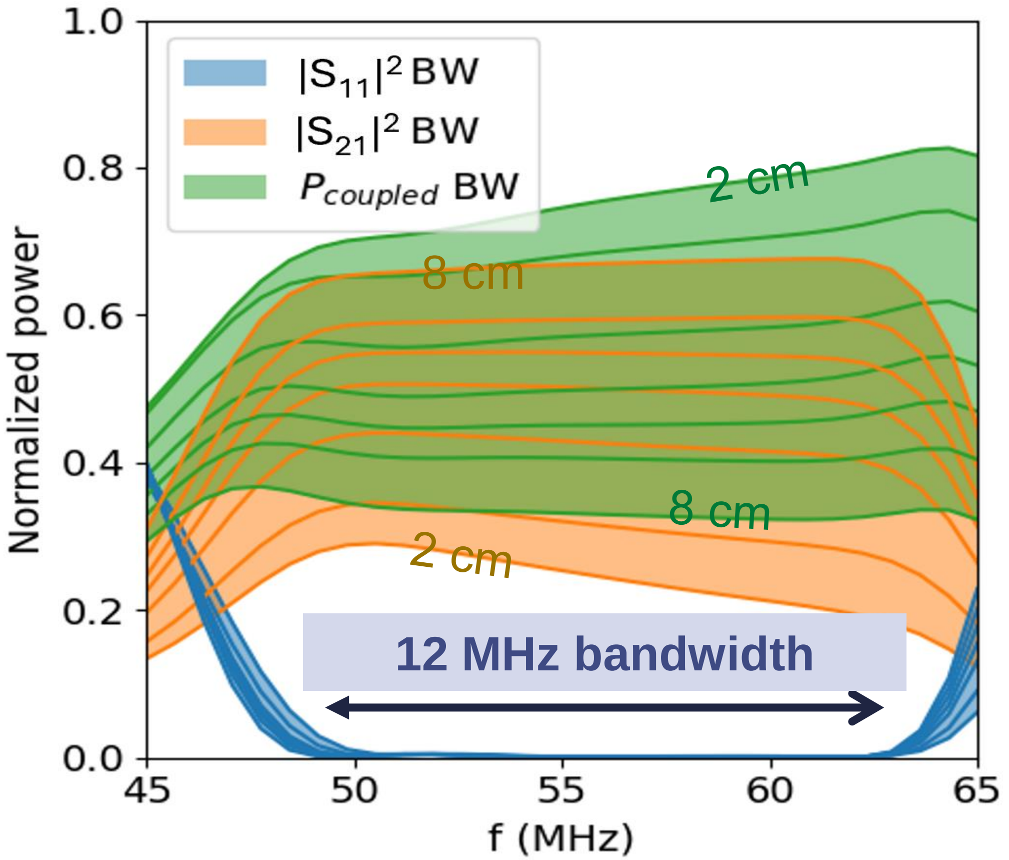
- Optimized to minimize E-field (2.5 MV/m) at max power
  - Designed for Phase 2 in mind (< 3.5 MW input)
    - Brings large margins for phase 1 (< 2 MW input)
  - Sensibility studies on capa. and assembly tolerances
  - Radiated spectrum minimized in [$-k_0$; k_0]

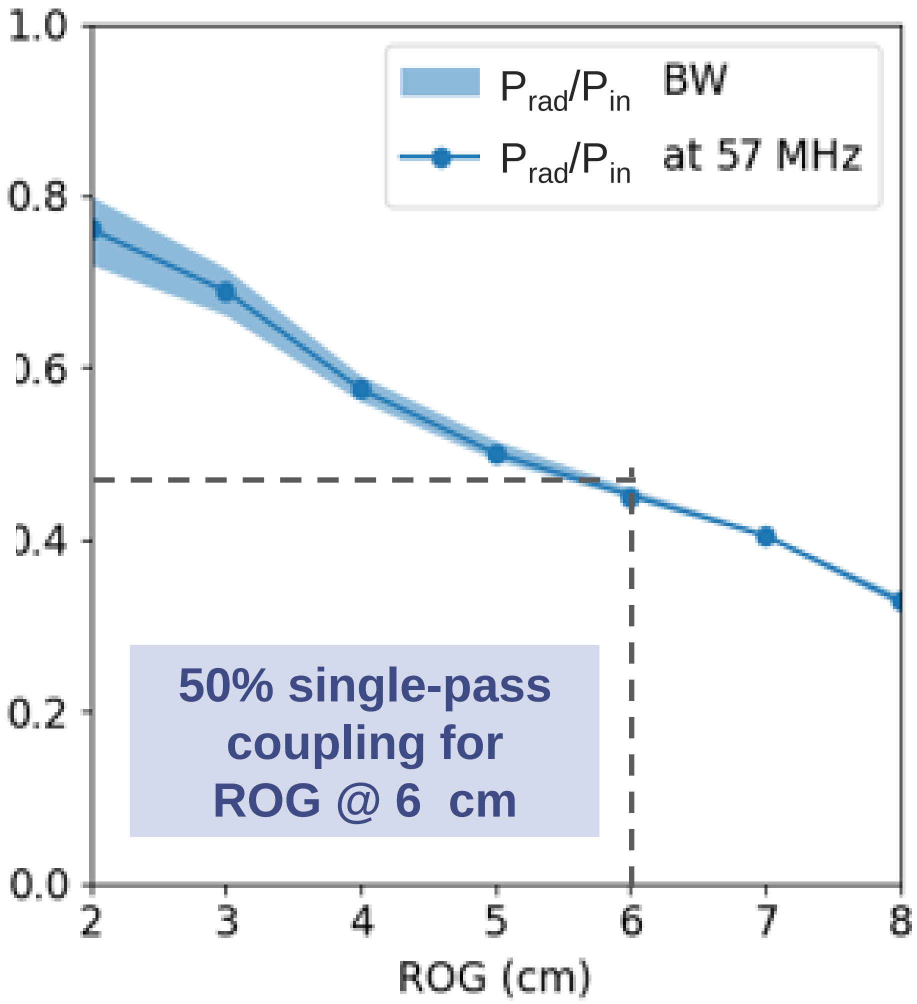
- RF Losses: ~6% Pin
  - Mostly located in box and straps (stainless-steel)



WEST TWA launchers are resilient and ~12 MHz bandwidth

- Launcher bandwidth: 50-62 MHz (SWR<1.2:1)
- Launched spectrum barely sensible to ROG and mech.tol.
- Coupling for large Radial Outer Gap (ROG)



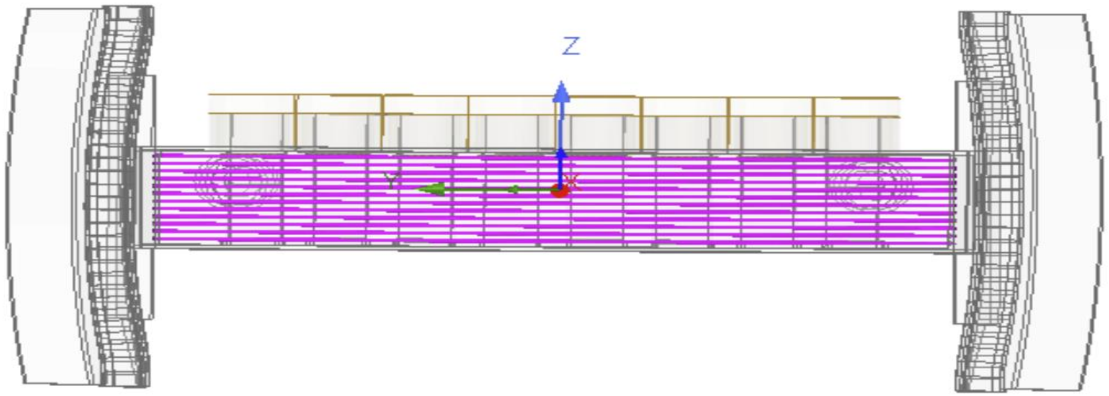


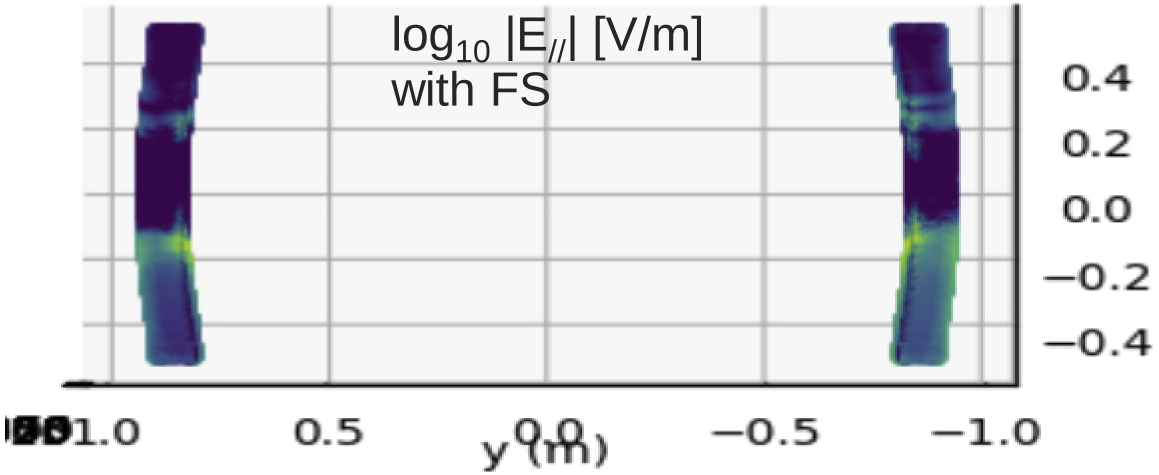
 [R.Ragona2025] [R.Ragona, this conference]

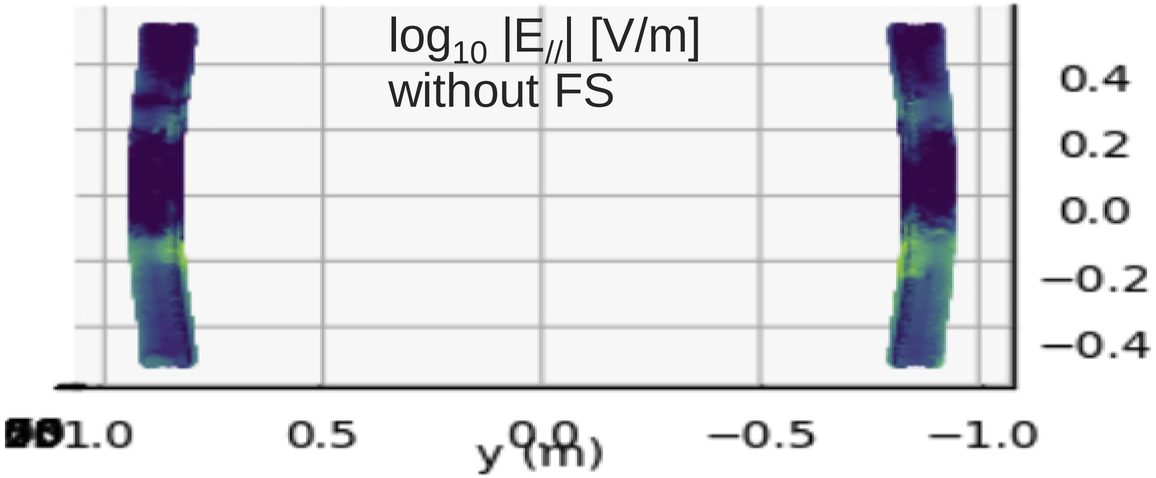
On the requirement (or not) of a Faraday screen

Comparing RF fields from with/without horiz. bars

- No difference in the launcher's RF responses
- No difference in the radiated spectrum
- No large difference of fields:
  - Even small advantage in average and max fields for the shield-less antenna.
- Mechanical complexity (actively cooled)





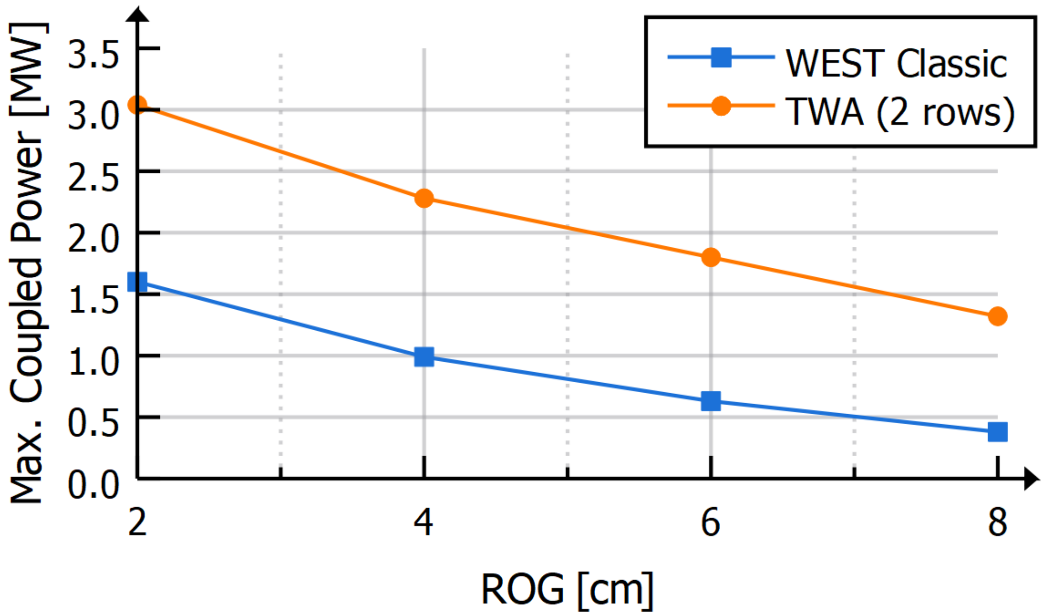


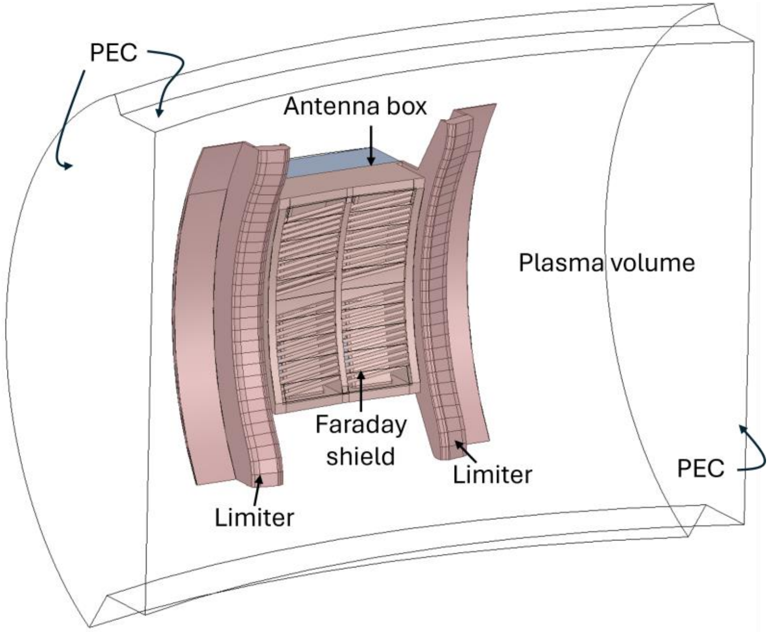
No Faraday Screen

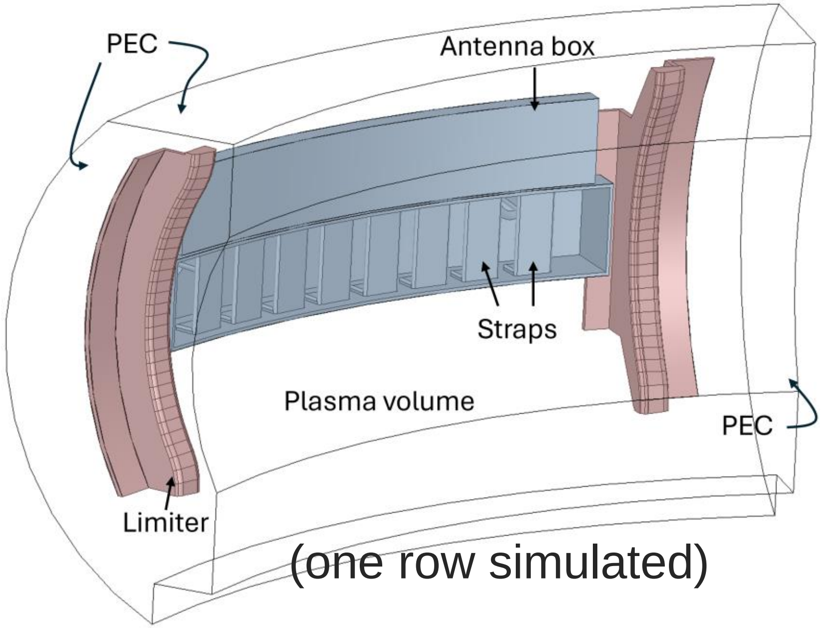
More than 200% coupled power increase with TWA vs WEST classic antennas

Coupled power evaluated for a WEST-representative plasma

- Example for #56898 (500 kA/LSN)
  - Benchmarked with experimental data
  - ROG scan (shifted profiles)
- WEST classic antenna limited at 28 kV/915 A on capacitors (op.rules)
- TWA input power is fixed to 2 MW (generator limit)







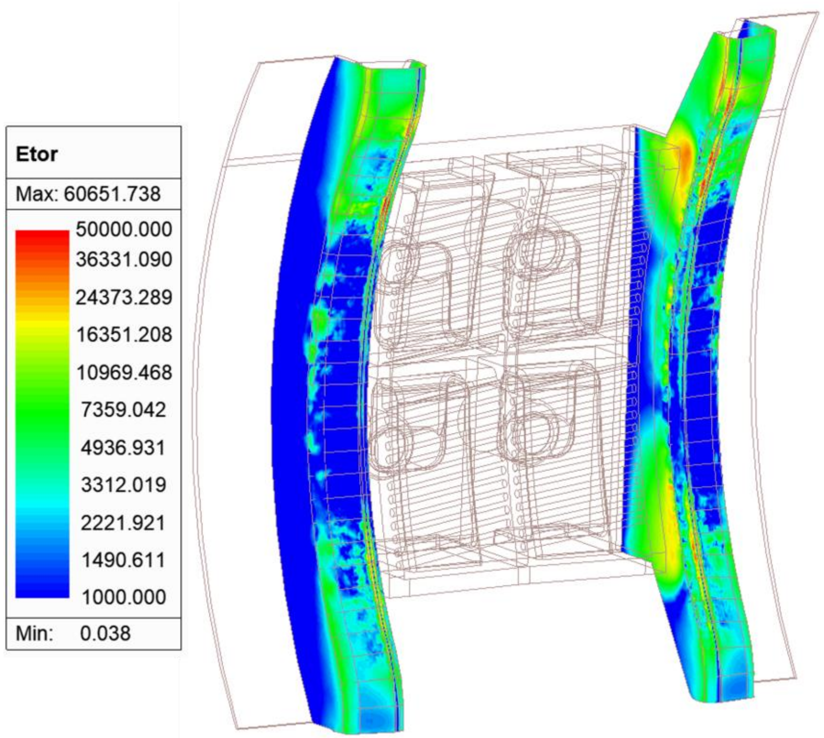
[Maquet2024]
[Ragona2025]

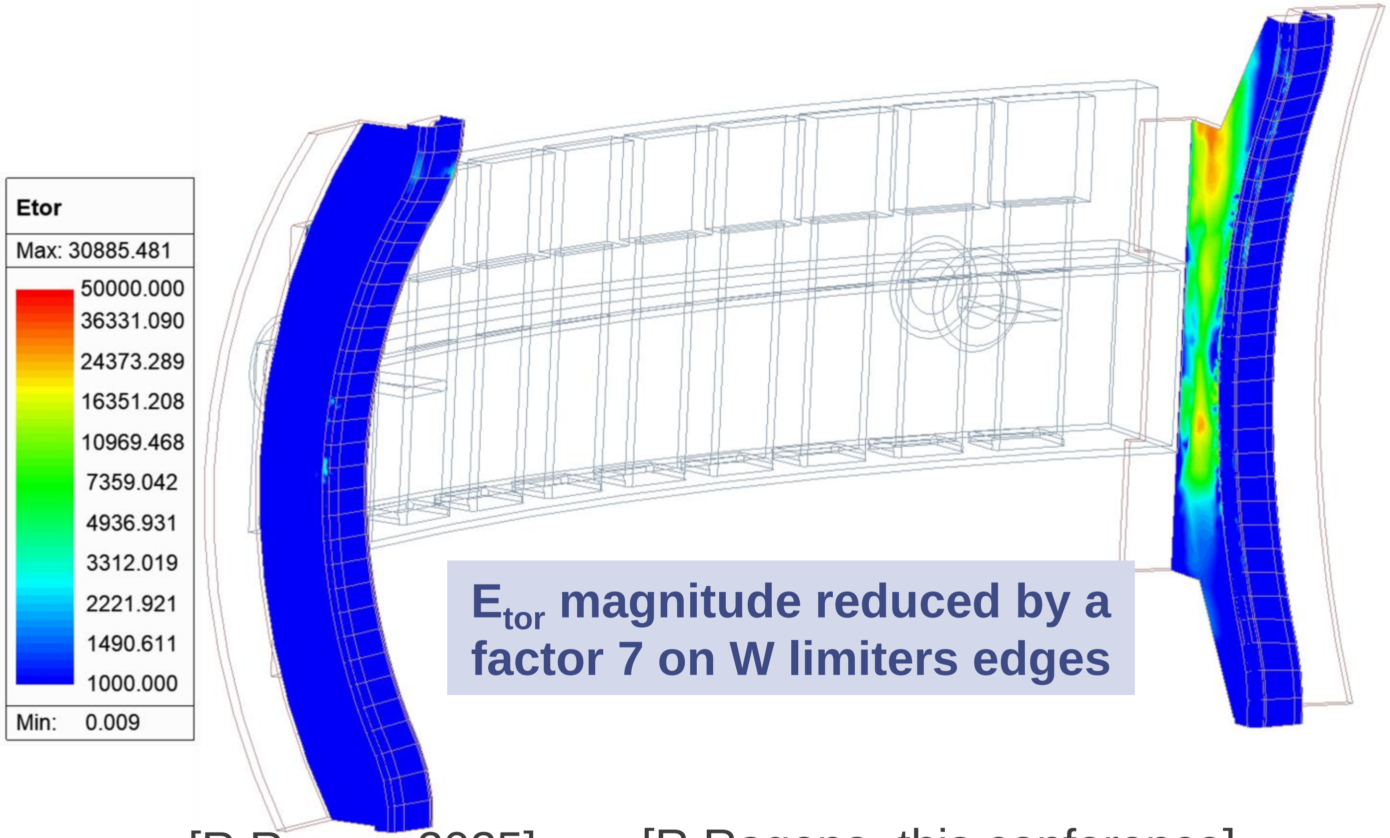
(one row simulated)

TWA lower electric fields will reduce RF sheaths

For the same coupled power

- RF-sheath voltages are proportional to parallel electric field (E//)
  - RF-sheath voltages modelling successfully benchmarked for WEST classical antenna
- E// on the limiters surrounding the TWA are reduced by a factor up to 7 vs classic antenna



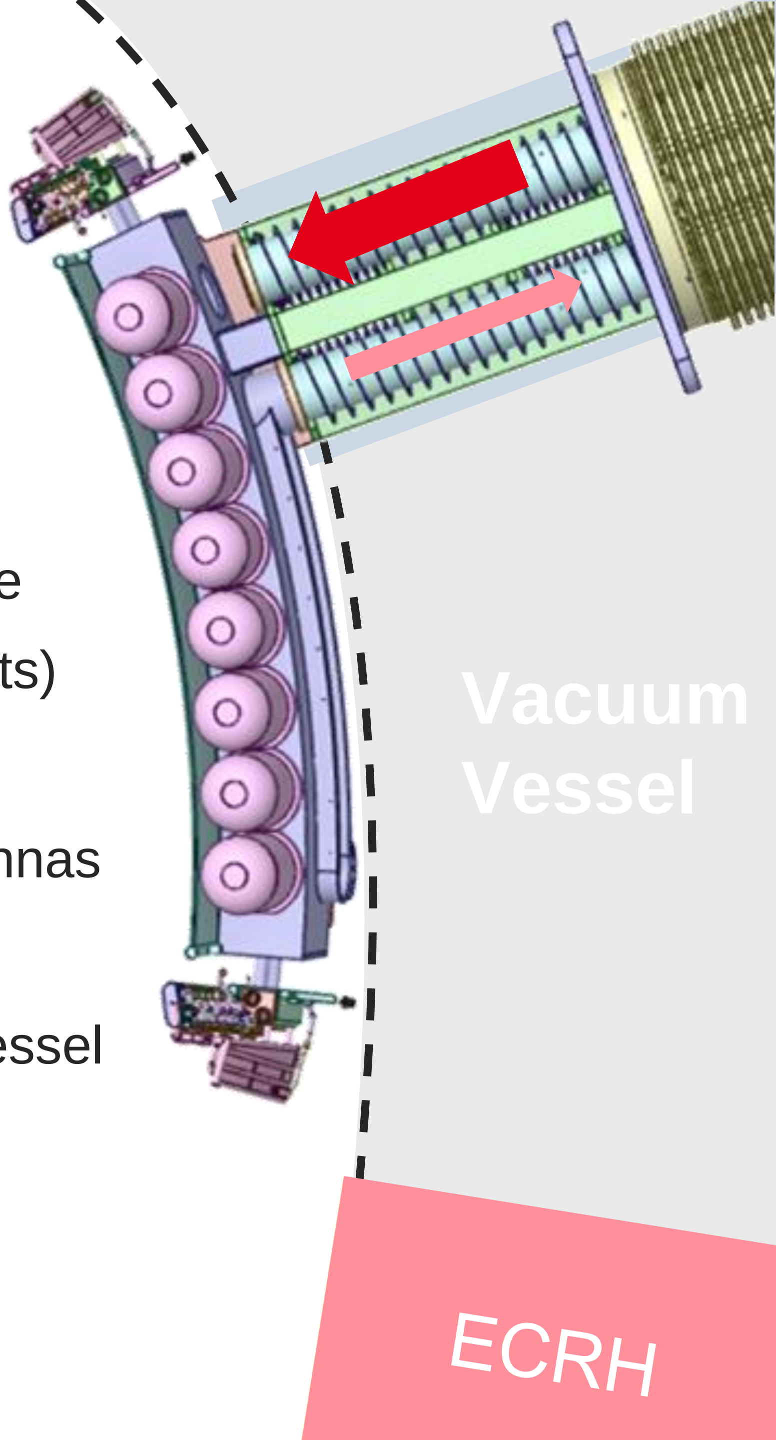


E_{tor} magnitude reduced by a factor 7 on W limiters edges

[R.Ragona2025] [R.Ragona, this conference]

Devil in the (mechanical) details?

- Launchers initially envisaged between 2 ports
  - No more possible with the addition of the new ECRH system
  - Requires a cantilevered antenna
  - Requires proper design for disruption and VDE loads
- Available space inside port and vac. vessel limit components max size
  - and the max power with RR (but also constrained with feed-thoughts)
- Water cooling everything!
  - Always challenging despite experience with WEST ICRH CW antennas
- Assembly
  - Mount (and test) a maximum number of components outside the vessel
  - Minimize operations and risks inside the vacuum vessel



Exciting Experimental Programme Ahead!

Commissioning

- Characterize the coupling and voltages vs plasma distance

Coupling physics

- Code validation vs plasma equilibrium properties

Heating Efficiency and fast ion physics

- Effect of poloidal phase difference on heating efficiency
- Synergies between 2 RF frequency (top and bottom rows)
- Fast-ion losses characterization and possible mitigation techniques (frequency sweeping)
- Investigate turbulence control with TWA generated fast ions.
- Operation and synergy with other heating systems (LH, EC, classical IC antennas)

RF sheaths and Impurity production

- Compare impurity generated by classic WEST IC antenna vs TWA
- Investigate poloidal phasing effects
- ITER-relevant ROG operation
- Investigate SW propagation and LH power losses at high power

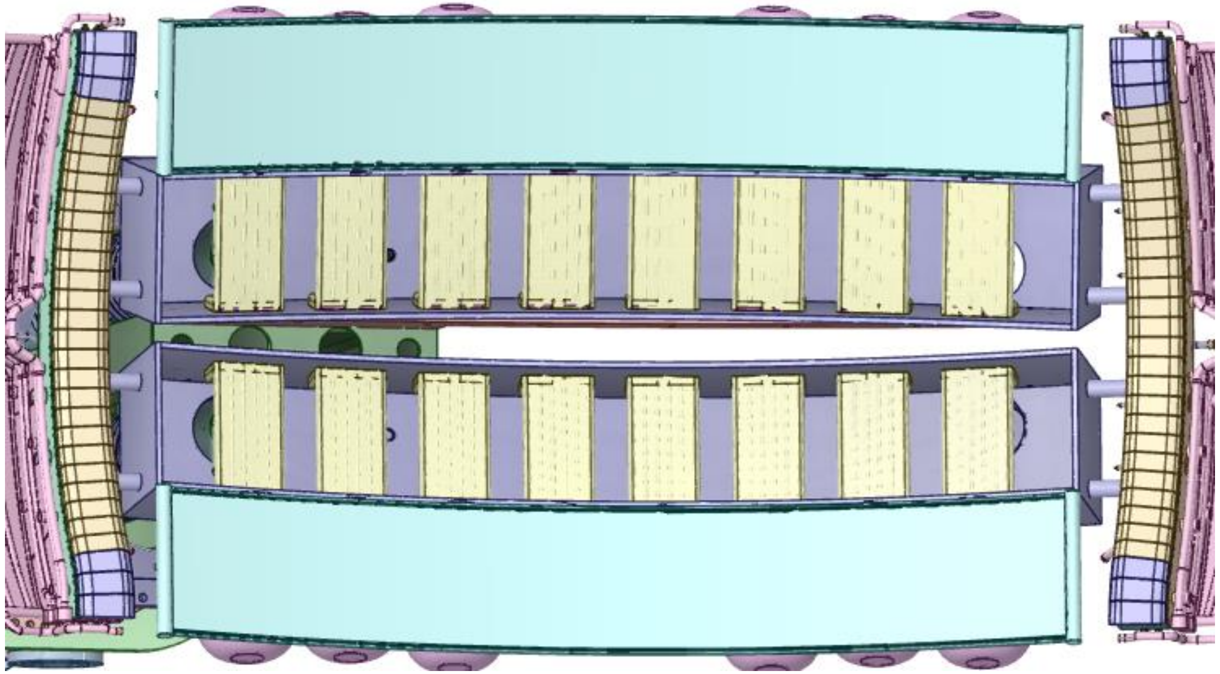
(Real-time) RF frequency change

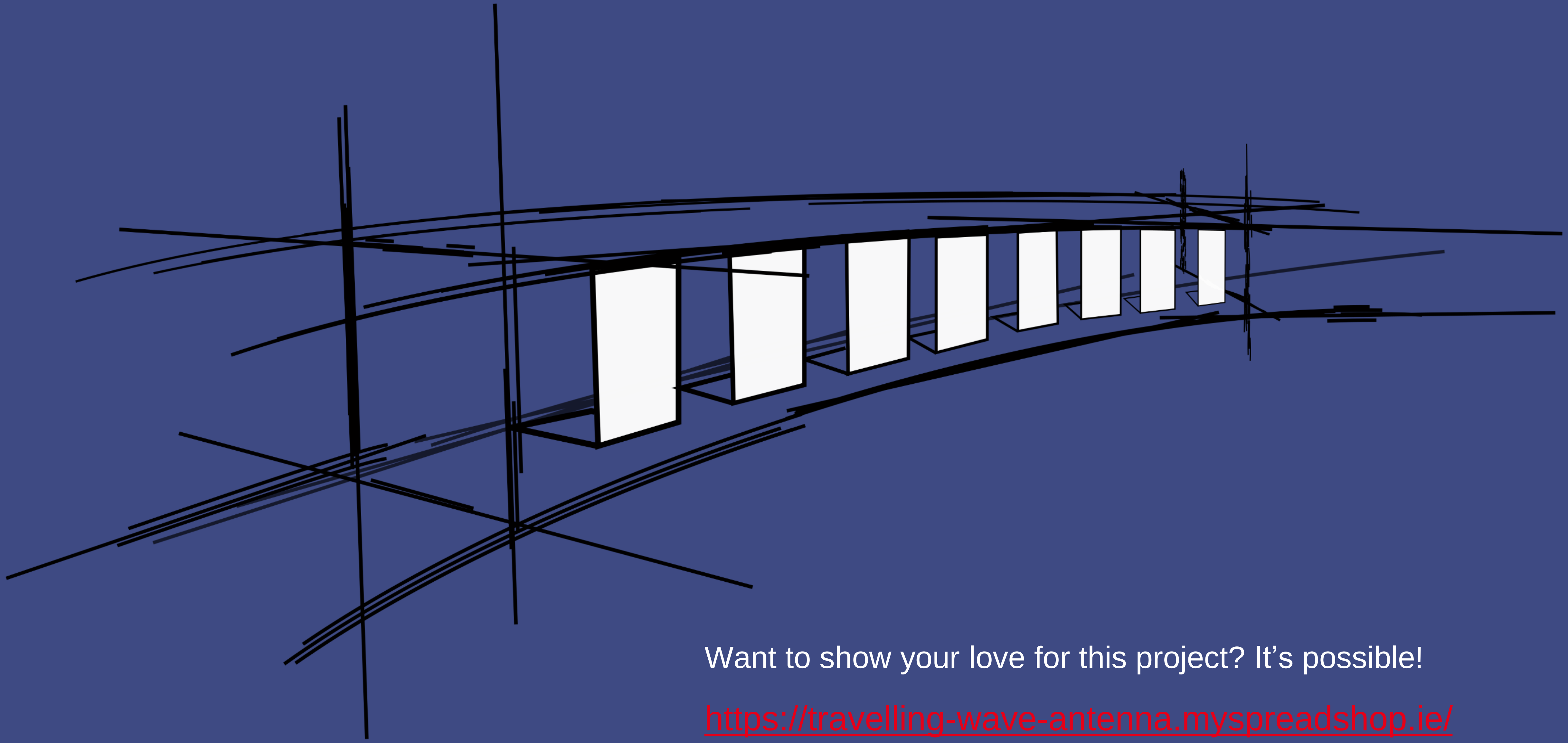
- Power deposition control or sweeping
- Multi frequency operation: core heating + frequency sweeping to control sawtooth
- Assess CD capabilities

And probably much more!

Summary and next steps

- On-going design of 2 WEST TWA ICRF launchers
  - Objective is to test in 2026
- A project staged in two phases
  - Direct feeding
  - Resonant Ring feeding
- Launchers RF design complete
- Mechanical engineering on-going
  - Cantilevered launchers
  - CW operation = actively cooled!





Want to show your love for this project? It’s possible!

https://travelling-wave-antenna.myspreadshop.ie/