Demonstration of a Travelling Wave Array antenna for Ion Cyclotron Resonance Heating in WEST

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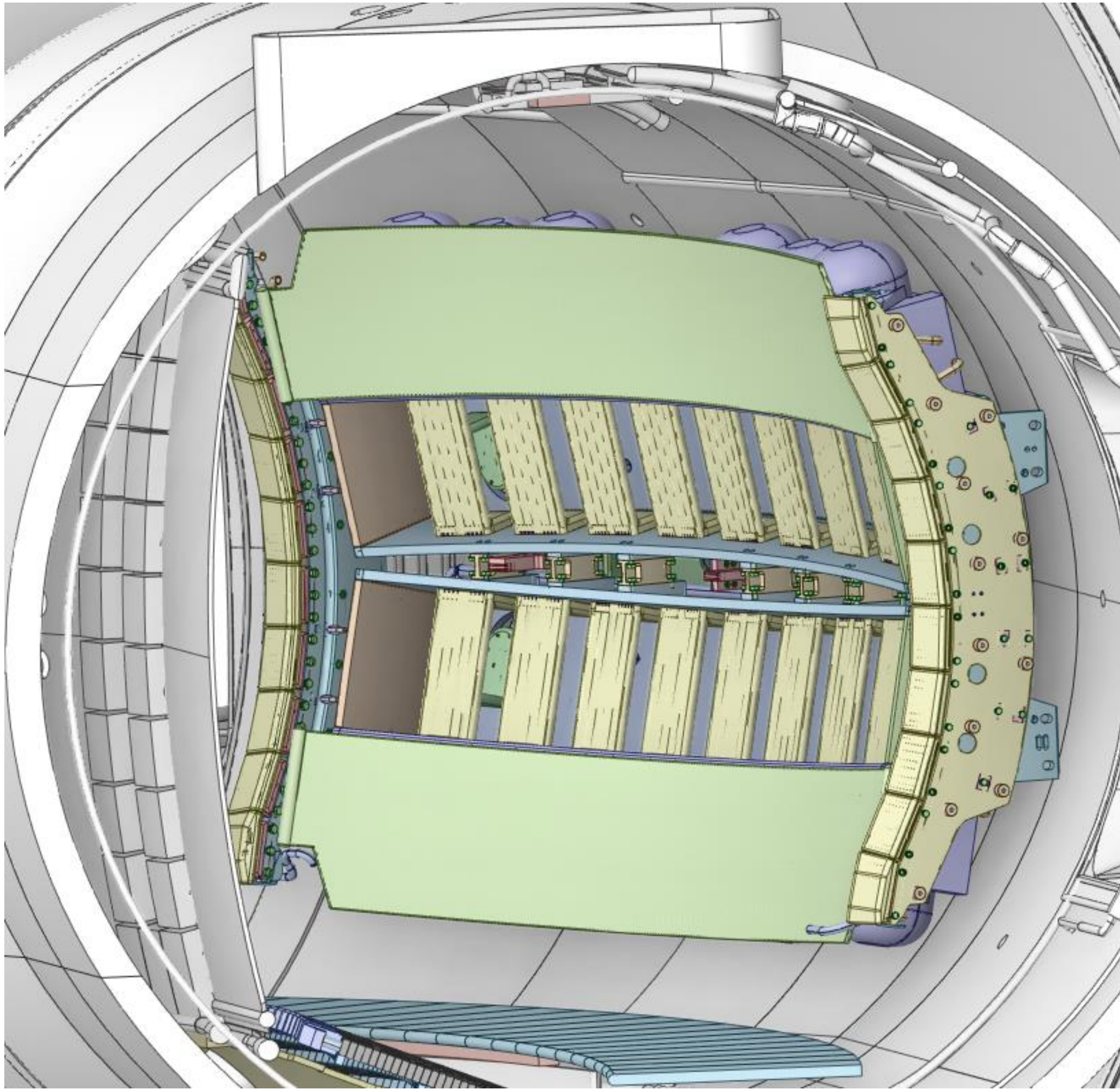
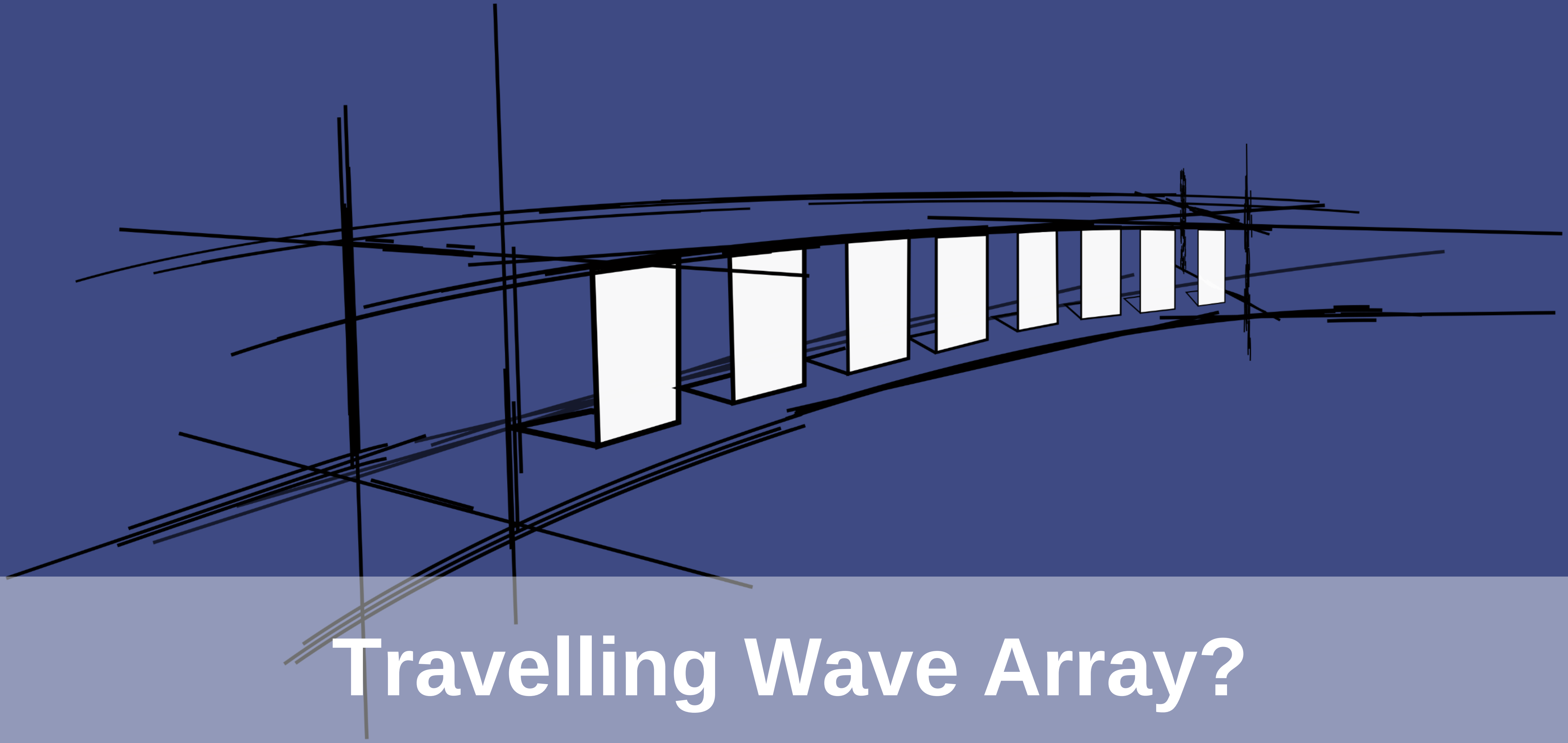


EUROfusion Science Meeting on Status of Enabling Research Projects
ENR-TEC.02.CEA



Travelling Wave Array?

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

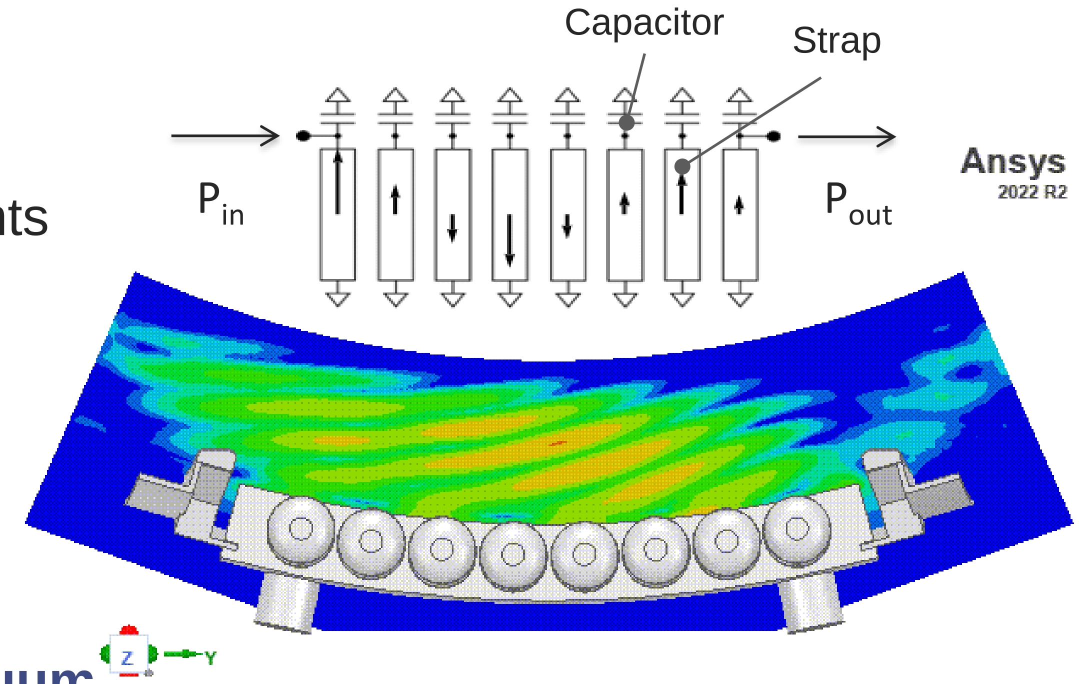
Current ICRF launchers suffer from drawbacks making them incompatible with fusion plants

- 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

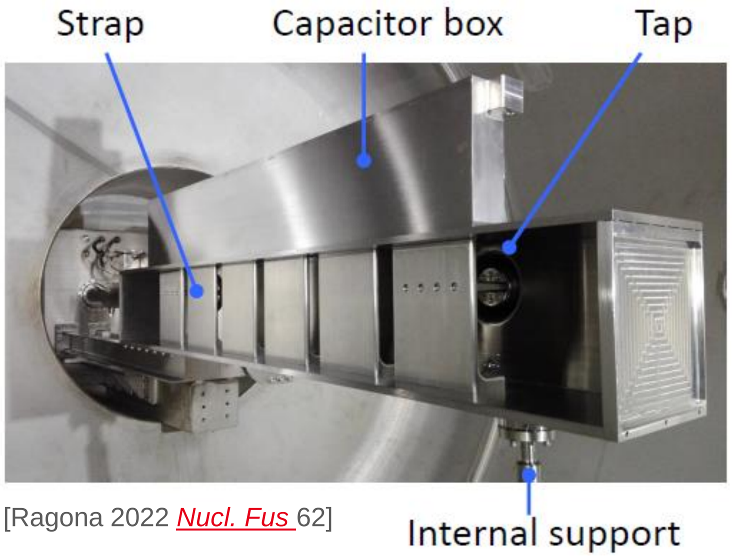
An innovative launcher concept for the ICRF

- Array of tuned straps
- RF current is induced by mutual coupling between elements
- No ceramic in the capacitors (parallel-plate like)
- 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



[Ragona 2022 Nucl. Fus 62]

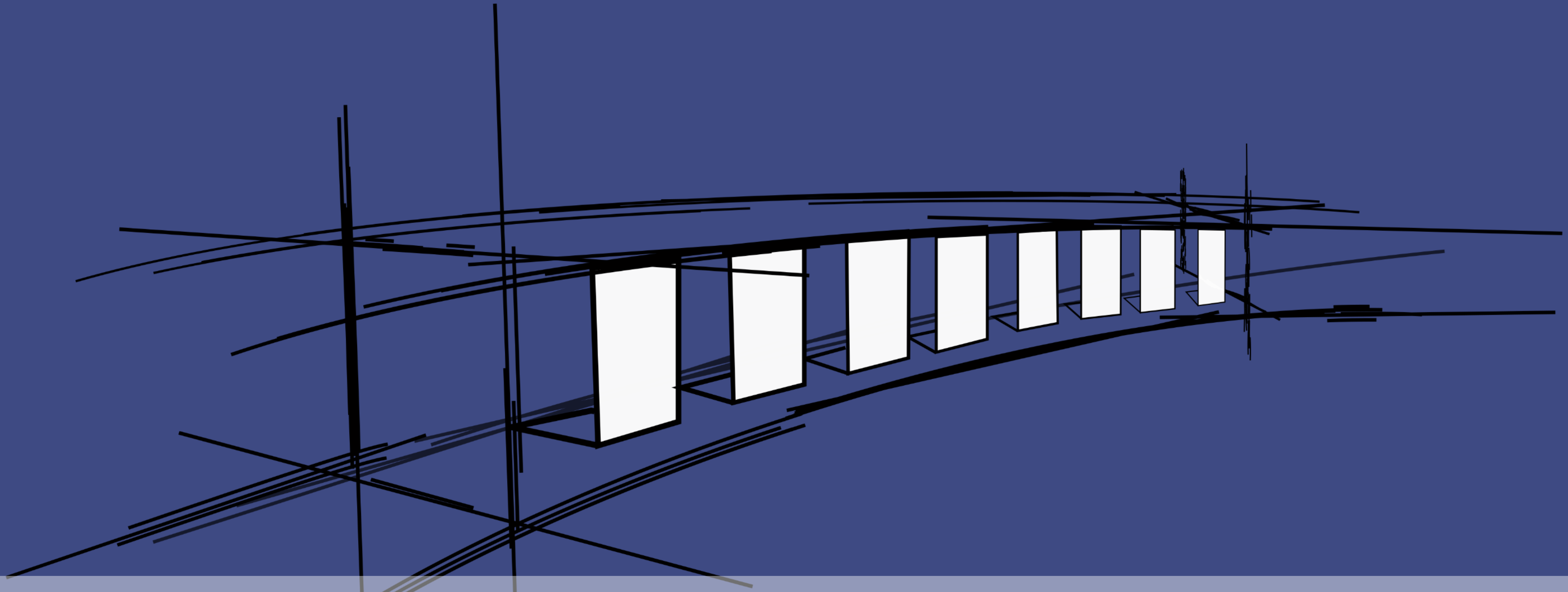
[Chiu 1984 Nucl. Fus. 24]
[Moeller 1994 AIP Conf. Proc 289]
[Ragona 2016 Nucl. Fus. 56]

Next step: demonstrating ICRF TWA 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



ENR TEC for the WEST TWA

Objectives of the WEST TWA launchers project

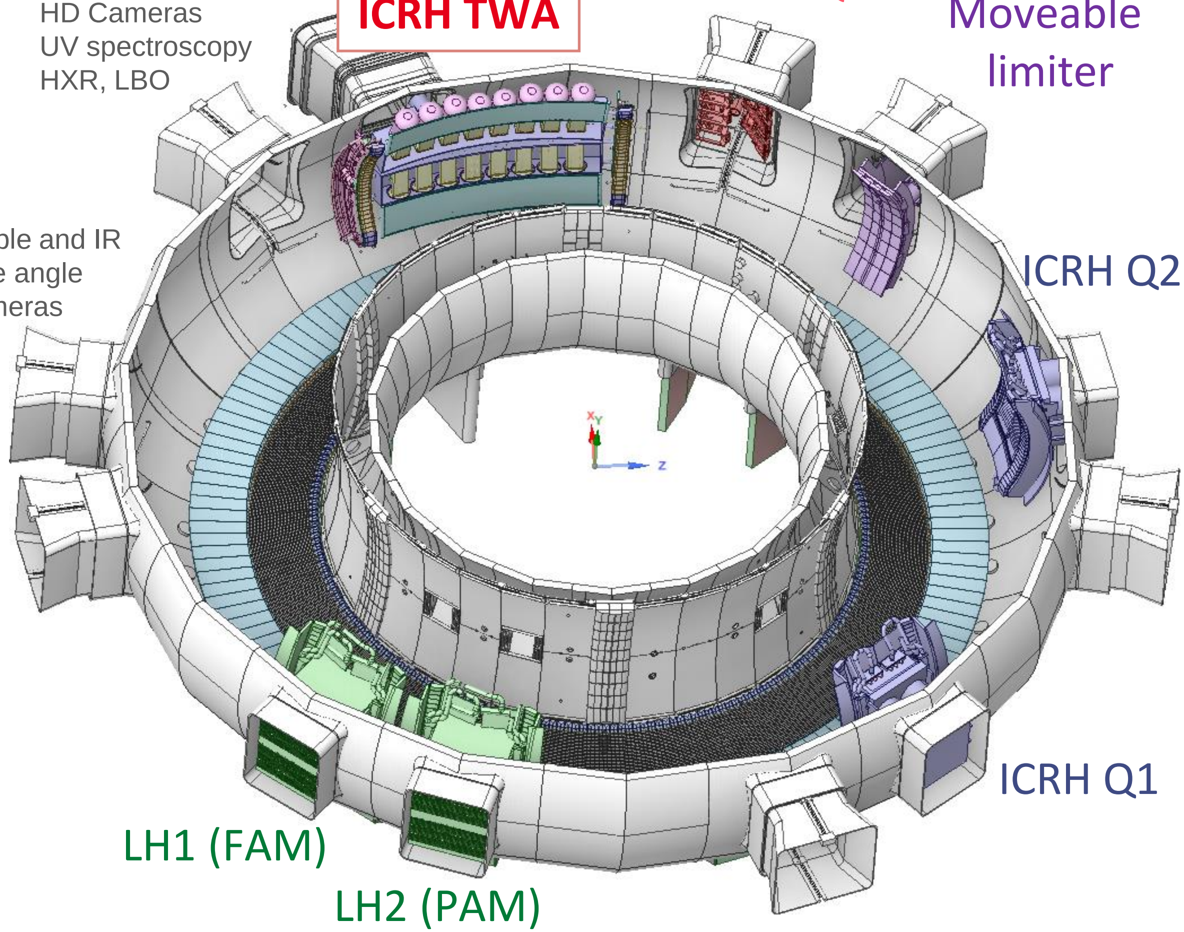
Two poloidal rows

- 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)

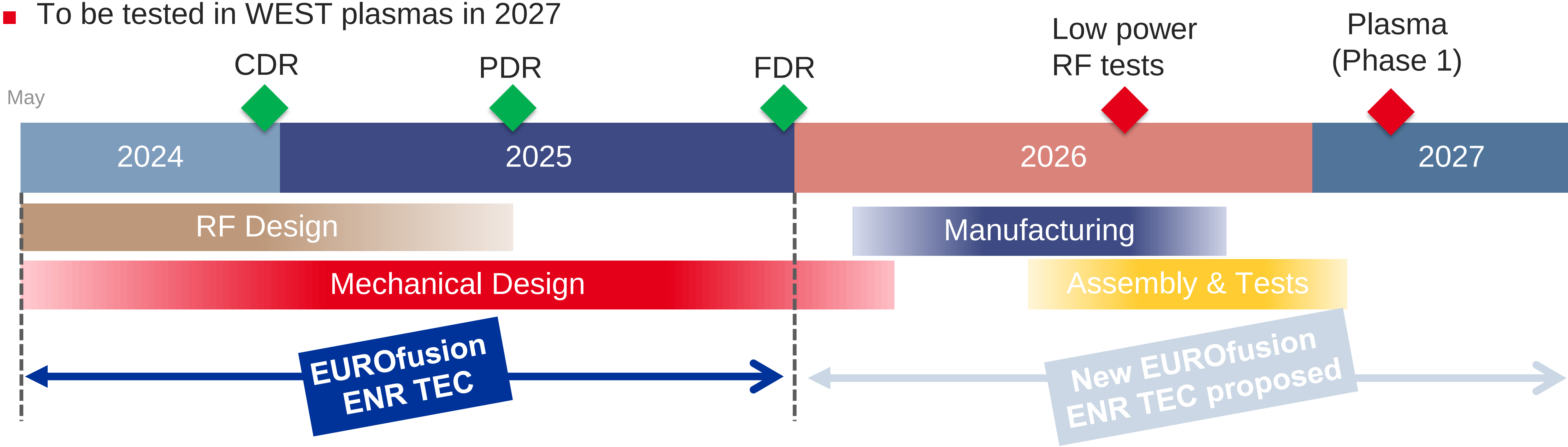
- Direct feeding phase
  - 3.0 MW / 30 s (1.5 MW/ant)
  - 1.0 MW / CW (0.5 MW/ant)
- Resonant ring feeding phase (higher net efficiency)
  - 6.0 MW / 30 s
  - 2.0 MW / CW
- Max perf limited by current WEST plant/lines/feedthroughs
- Fusion plant relevant materials
  - Bare Stainless-Steel (no coating)
  - No ceramics

EUROfusion ENR TEC



WEST TWA Project – Deliverables Planning & Main Milestones

- ENR Project started May 2024
  - CDR December 2024
  - PDR July 2025
  - FDR December 2025
- Launchers manufacturing beg. 2026
- Shipping, assembly and testing at IRFM from beg-to-mid 2026
- To be tested in WEST plasmas in 2027

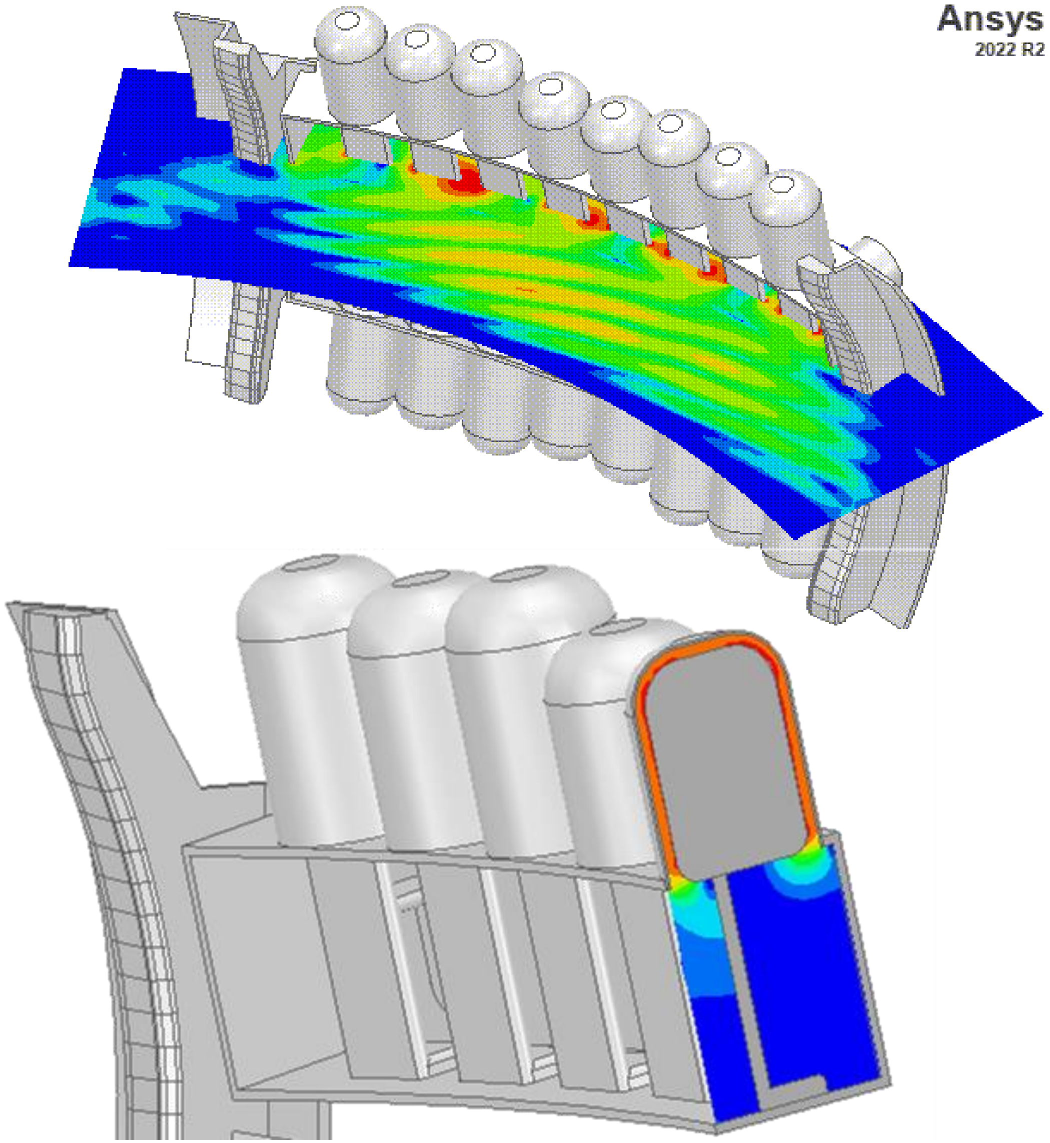


Launcher design performed with state-of-art 3D RF modelling

- 3D inhomogeneous and anisotropic cold plasma
  - Using WEST equilibria and density profiles
  - 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 margin for phase 1 (< 2 MW input)
  - Sensitivity analysis on cap. and assembly tolerances
  - Radiated spectrum minimized in $[-k_0; k_0]$

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

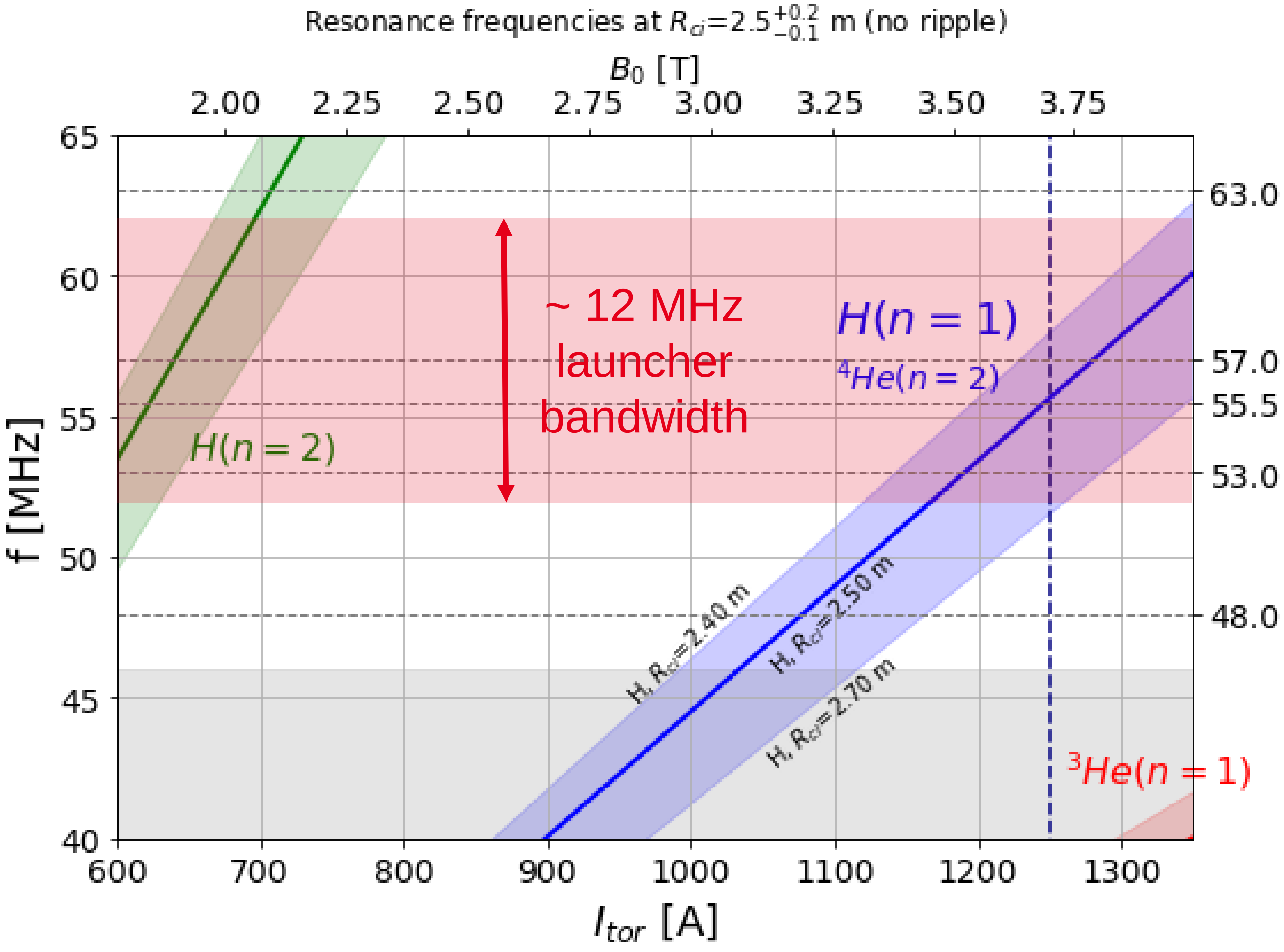


WEST TWA launchers operate within a ~12 MHz bandwith

- 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

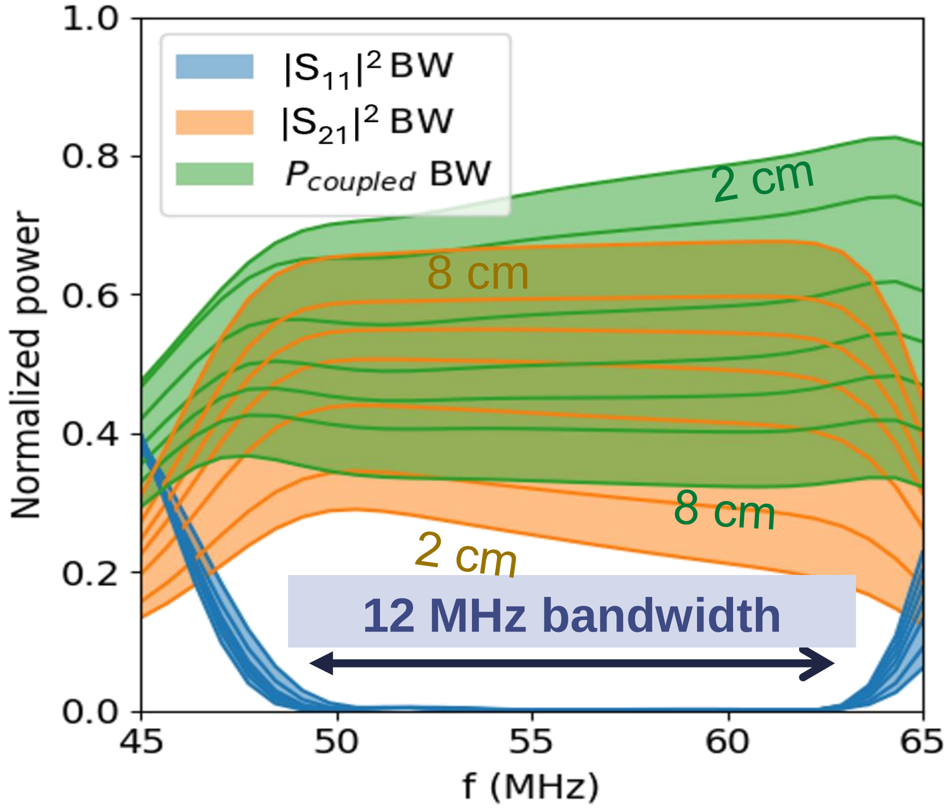
WEST ICRH
TWA launchers bandwith

57 +/- 5 MHz

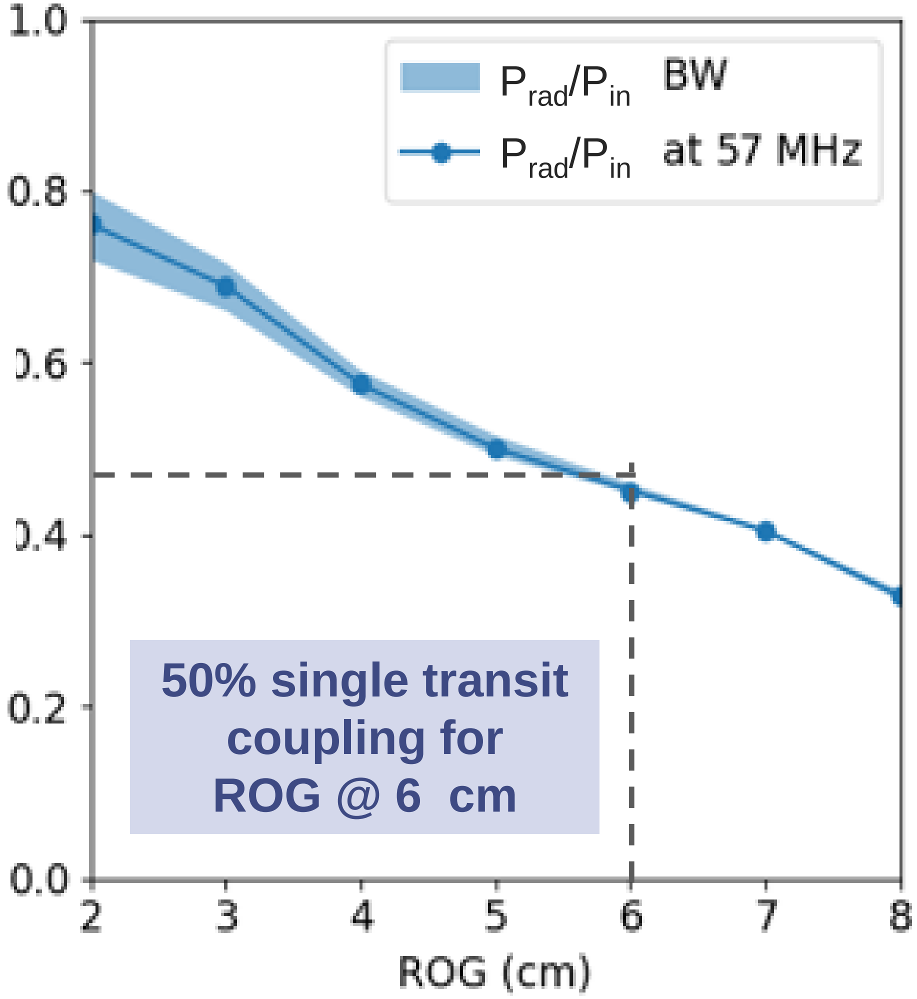


WEST TWA launchers are resilient and ~12 MHz bandwidth

- Launcher bandwidth: 50-62 MHz (SWR<1.2:1)
- Launched spectrum barely sensitive to ROG and mech.tol.
- Coupling for large Radial Outer Gap (ROG)
- **No matching needed —> allows RT change of frequency!**



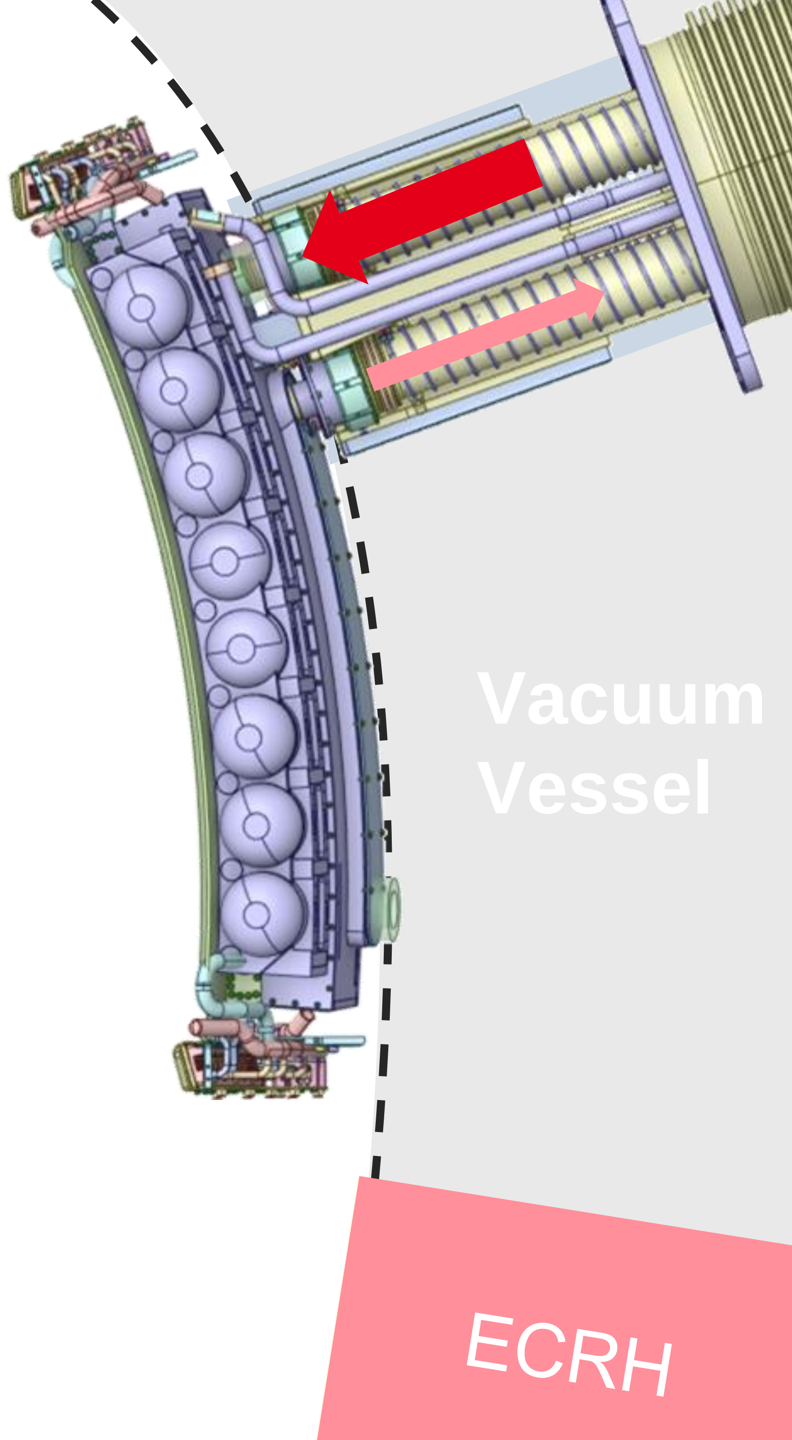
ratio P_{rad}/P_{in} (1 row)



[R.Ragona, this conference]

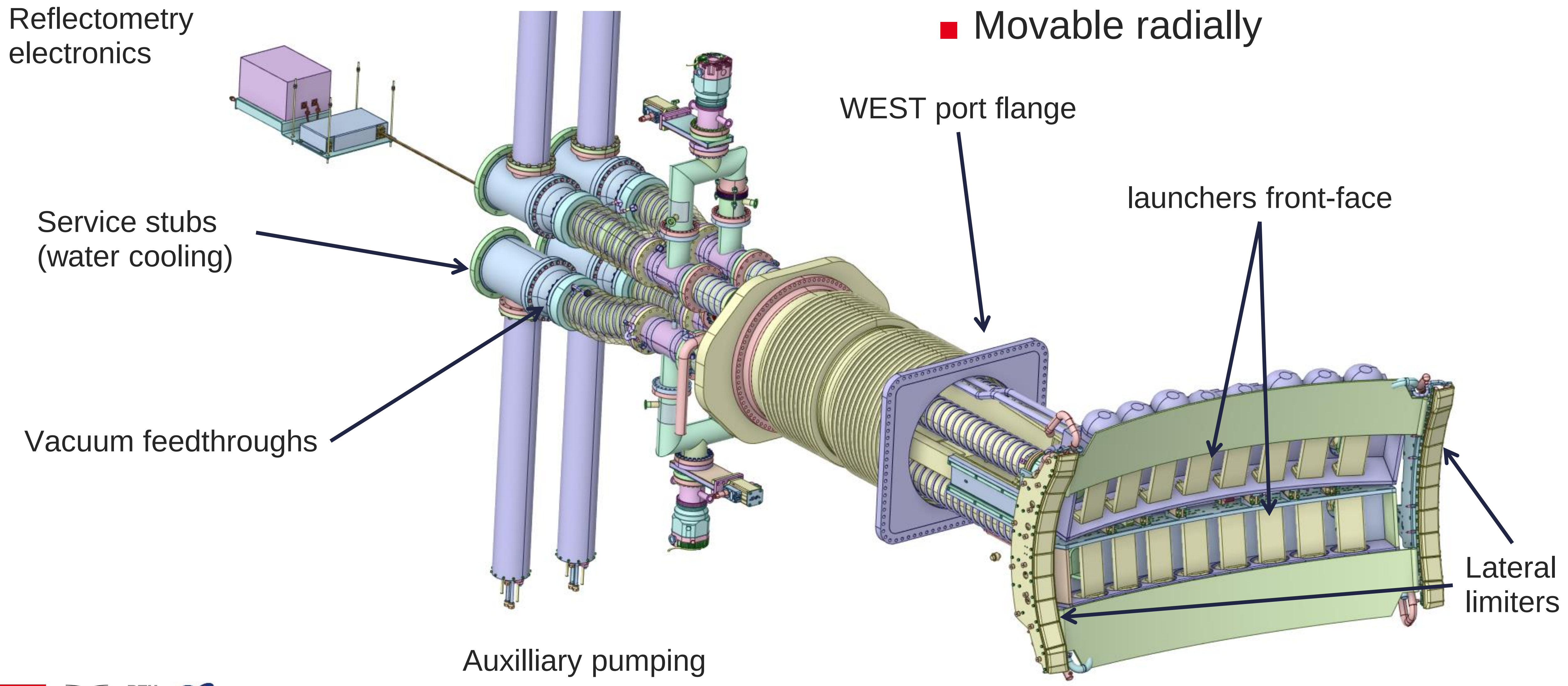
Mechanical challenges

- Water cooling everything!
  - Challenging despite experience with WEST ICRH CW launchers
- Cantilevered launcher
  - Requires proper design for disruption and VDE loads
- Available space inside port and vac. vessel limit components size
- Assembly
  - Front-face to be assembled inside the torus
  - Designed to minimize operations and risks inside the vacuum vessel



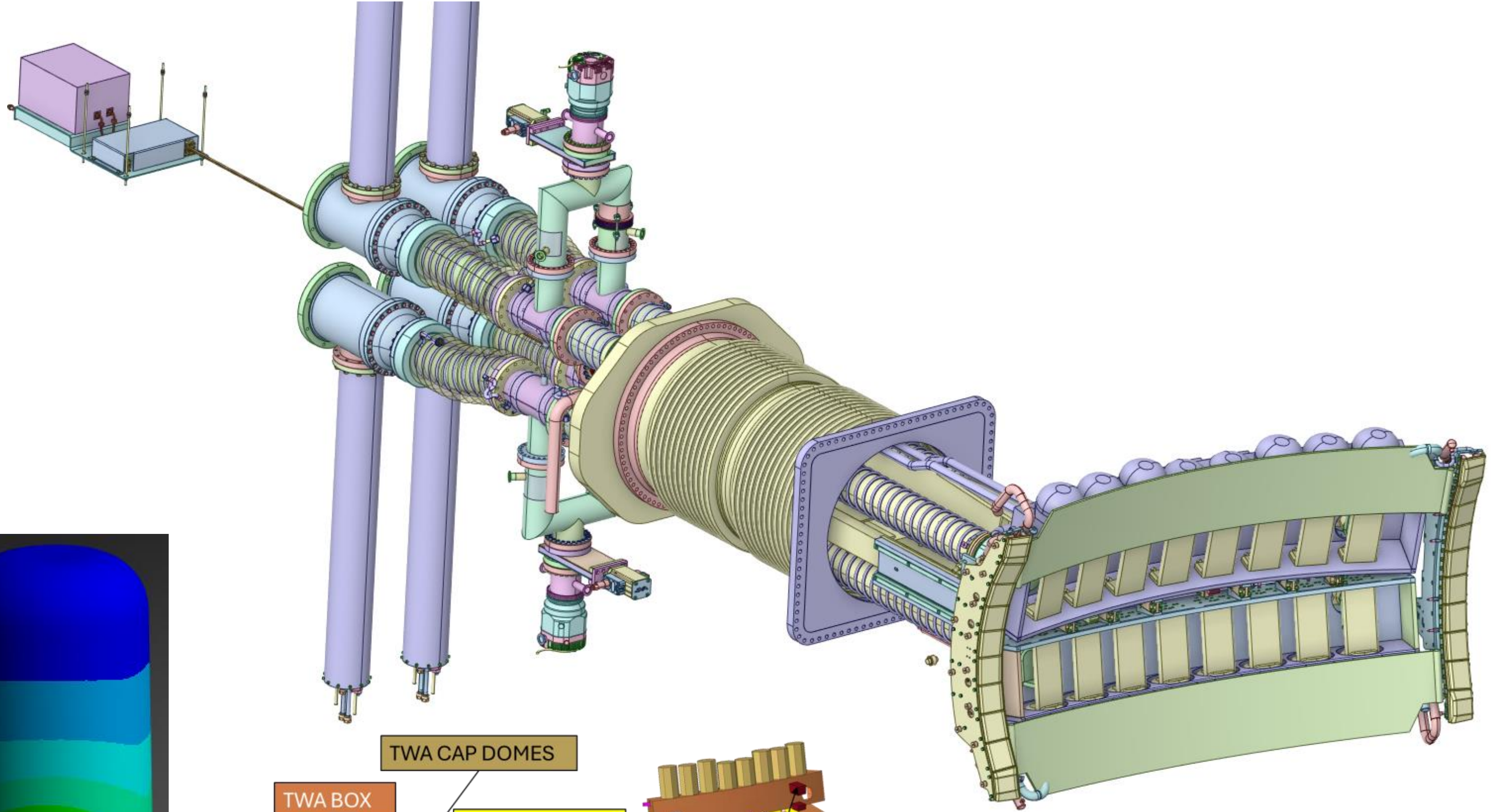
Mechanical Design Overview

- Designed for CW operation
- Fully actively cooled (30 bars)
- Movable radially

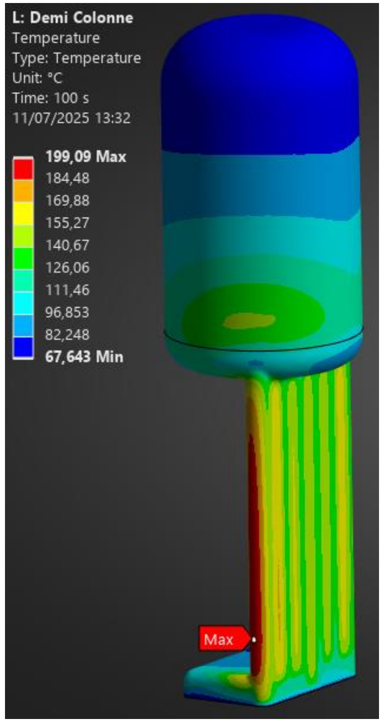


Mechanical Loads

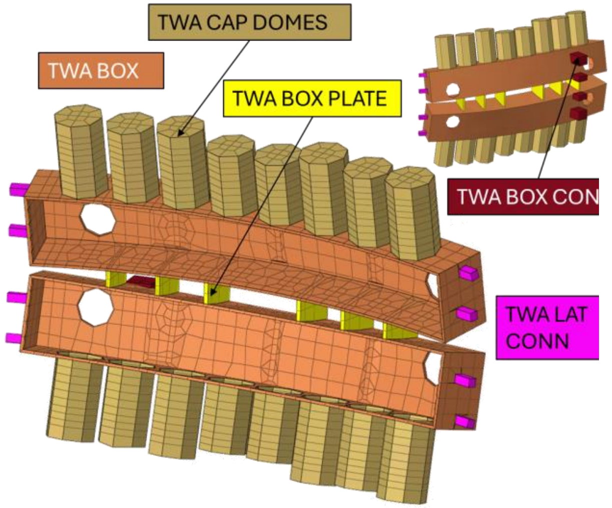
- Plasma radiation (10 MW)
- Convective loads
- RF loads
- Weight and VDEs

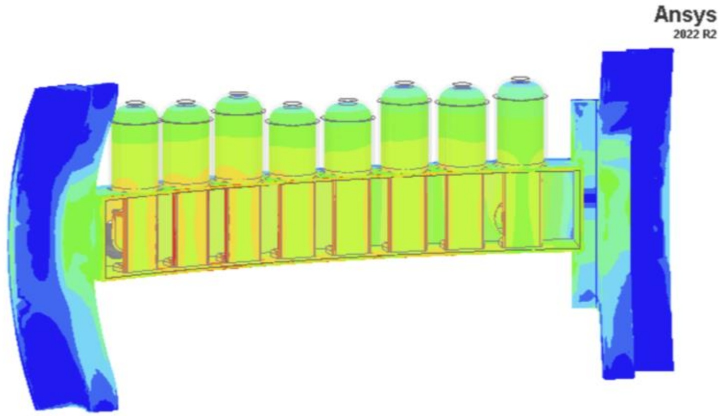


Plasma radiation modelling



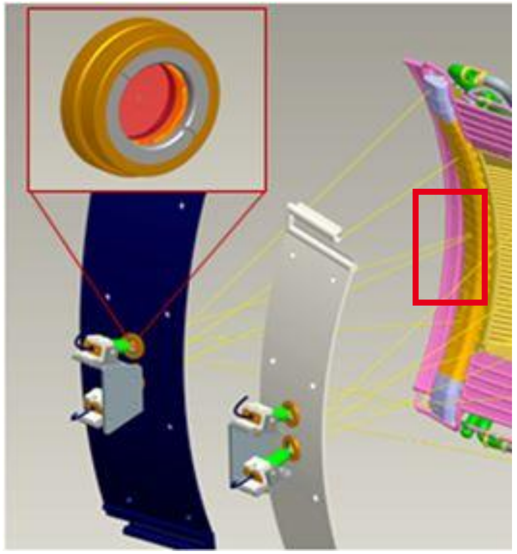
1 MW/CW

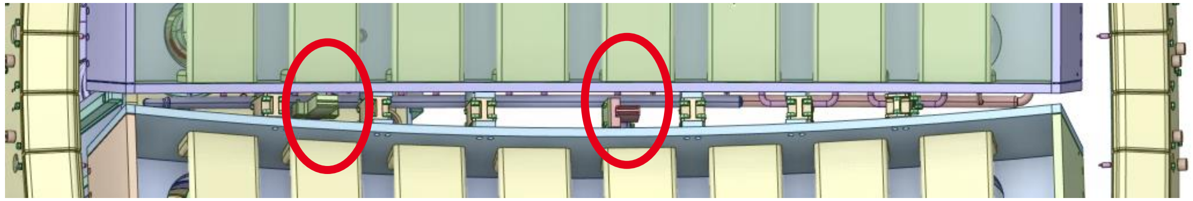


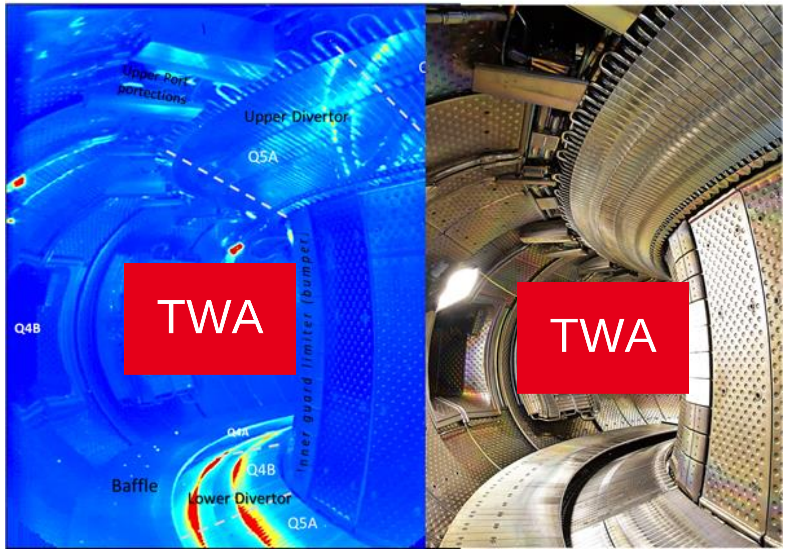


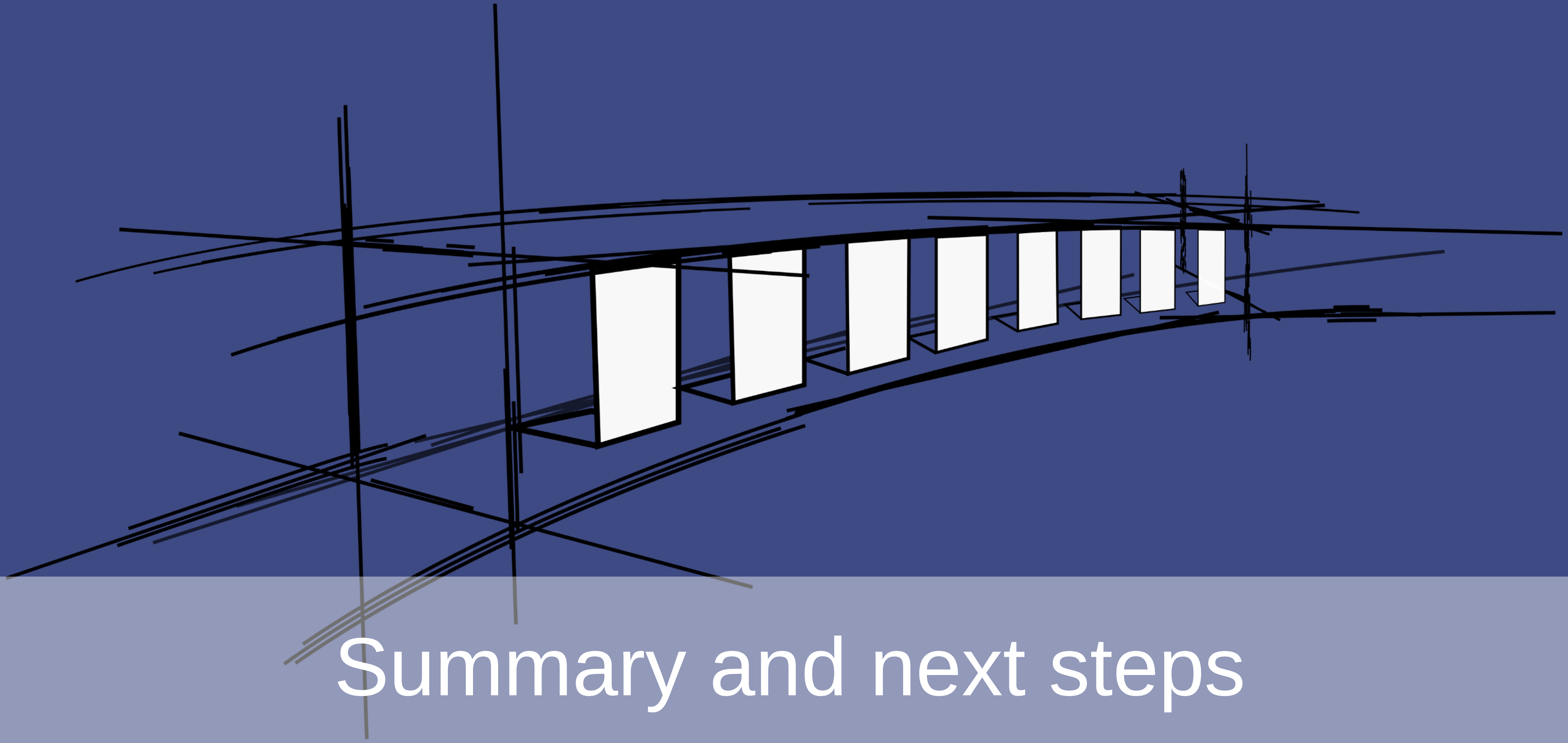
Diagnostics

- RF Measurements
  - RF input/output power
  - Strap electric field
- Visible Spectroscopy (left side only)
  - Same line of view than current views
- Reflectometry
  - Two measurements locations (equatorial plane, at max and min ripple)
- Arc detection
  - From RF measurements
- Infrared Monitoring
  - Wide angle view: totality of the launcher
  - Direct view: partial coverage (same FOV WEST IC launcher)



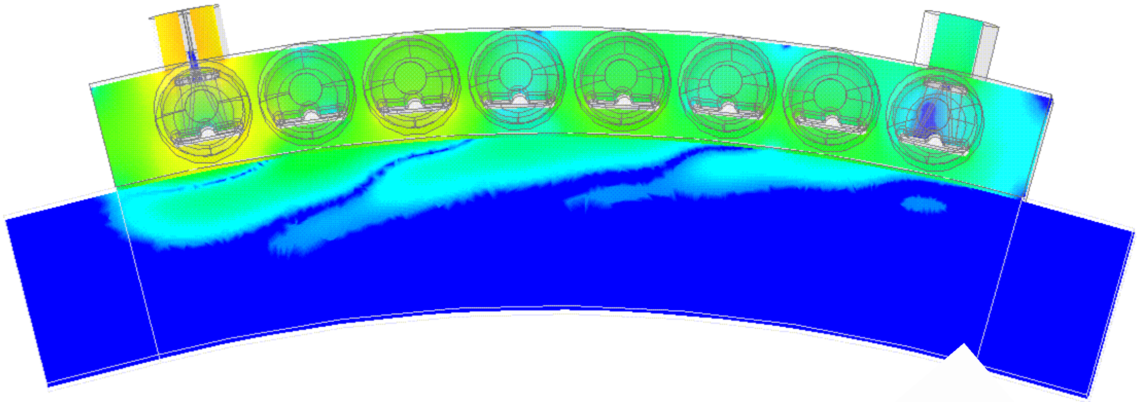




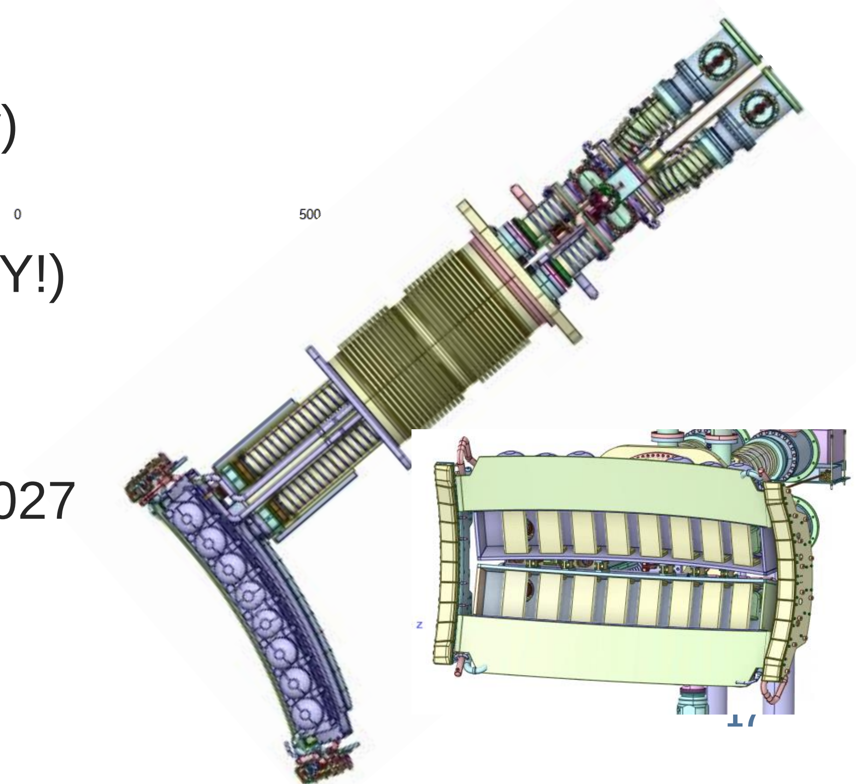


Summary and next steps

An Ion Cyclotron Traveling Wave Array System has been designed for WEST



- 2 WEST TWA ICRF launchers
- Project staged in two phases
  - Direct feeding (this ENR TEC)
  - Resonant-Ring feeding in a future phase 2
- RF designed completed
  - Specified for 6.0 MW (2 launchers: upper and lower)
  - Lower electric field and RF sheath excitation (less high Z impurity)
  - Large bandwidth launchers (12 MHz): new operation domain !
- Mechanical design almost finished (in less than 1.5 year with < 6 PPY!)
  - Cantilevered launchers
  - CW operation = actively cooled!
- Objective is to manufacture in 2026 and test on WEST plasmas in 2027



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 launchers)

RF sheaths and Impurity production

- Compare impurity generated by classic WEST IC launcher 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 of TWA-related WP-TE proposals

- Several experiments have been proposed in the frame of WP-TE related to the TWA (2027)
- All collaborators are welcome !

Name	PI	WP-TE	
Comparing W production and core plasma contamination by 2x2 strap Ion Cyclotron Antenna and TWA	L.Colas	RT-06	P1
LH Power Loss Characterization at high coupling with TWA	V.Maquet	RT-06	P2
TWA Frequency Sweeping	R.Ragona	RT-09	P2
TWA Bi-Frequency Heating for Long Pulse operation in WEST	V.Maquet	RT-08	P2
TWA dual-frequency operation as a flexible tool to tailor fast ion populations and excite Alfvén Eigenmodes	S.Mazzi	RT-09	P2
TWA poloidal phase scan for impurity minimization in WEST	V.Maquet	RT-06	P1
TWA+EC+LH synergy in view of H-mode and Long Pulse operation in WEST	V.Maquet	RT-08	P2
ICWC operation with TWA	R.Ragona	RT-06	P2
Fast-ion stabilization of ITG in WEST with TWA	R.Ragona	RT-09	P2