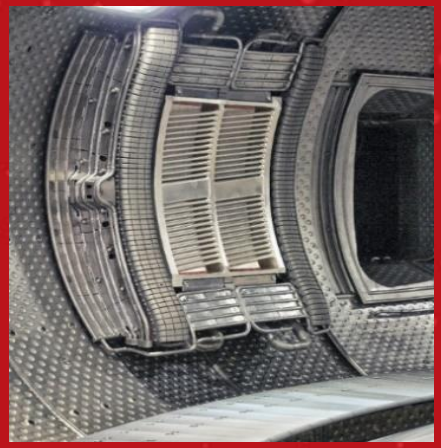
WEST Actively Cooled Load Resilient Ion Cyclotron Resonance Heating System Results

DE LA RECHERCHE À L'INDUSTRIE



J.Hillairet, P.Mollard, L.Colas, J.-M.Bernard, J.-M. Delaplanche, F.Durand, N.Faure, P.Garibaldi, W.Helou, G.Lombard, G.Urbanczyk, Y.Song, Q.Yang, R.Ragona, Z.Chen, Y.Wang, H.Xu, S.Yuan, Y.Zhao, F.Durodié, E.Lerche, C.Bourdelle, C.Desgranges, E.Delmas, R.Dumont, A.Ekedahl, F.Ferlay, M.Goniche, C.Guillemaut, G.T.Hoang, P.Maget, R.Volpe, N.Bertelli, V.Bobkov, C.Klepper, C.Lau, B.Lu, E.Martin, R.Maggiora, D.Milanesio, M.Ono, S.Shiraiwa, K.Vulliez, G.Wallace, and WEST Team

Rapporteur Contribution

Status of the WEST Travelling Wave Array antenna design and results from the high power mock-up

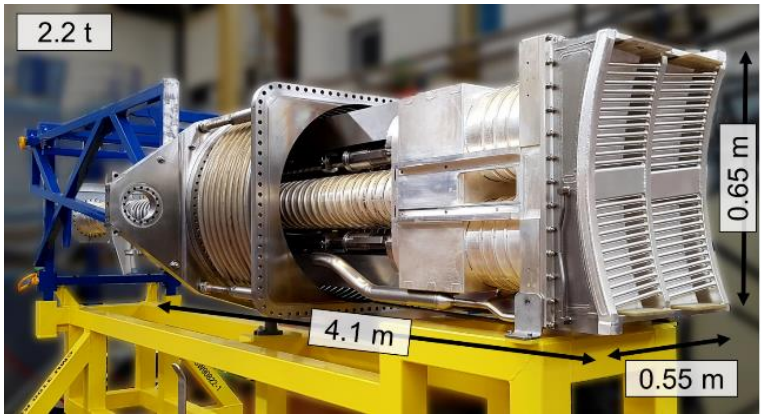
EUROfusion

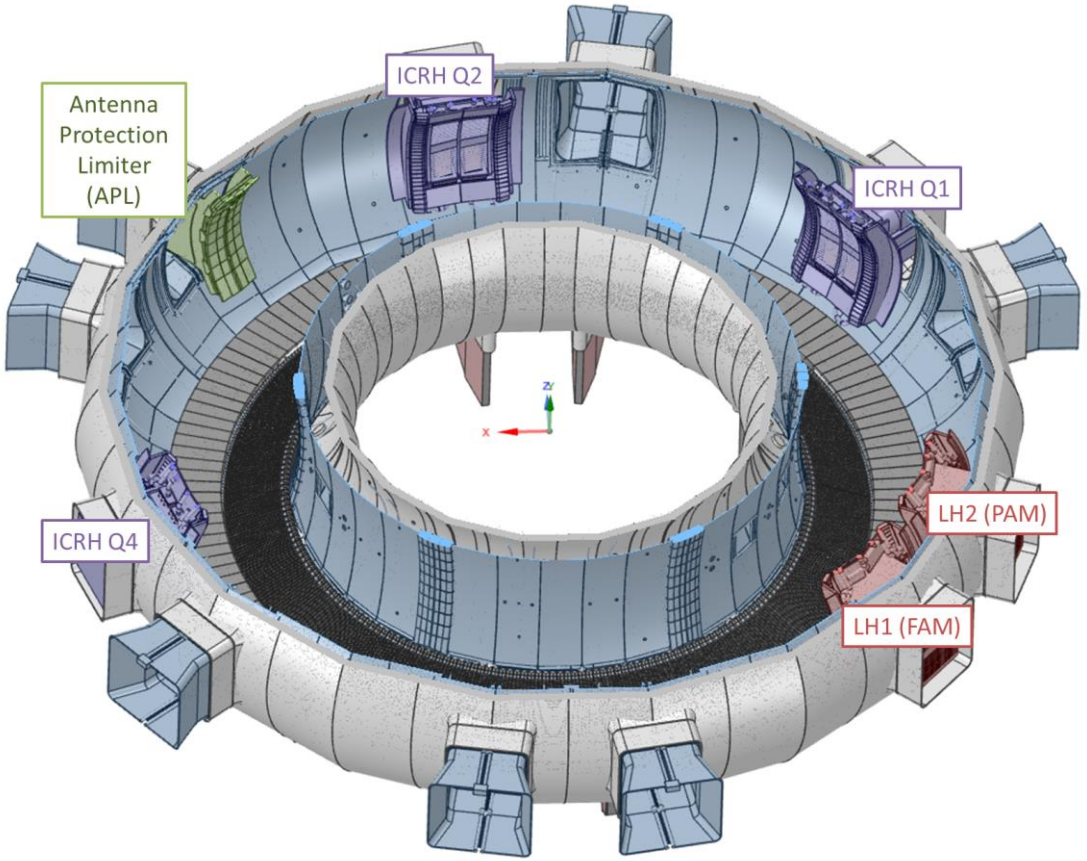
R.Ragona, J.Hillairet, P.Mollard, F.Durand, T.Batal, F.Durodié, C.Yu, Q.Yang, H.Xu, Z.Chen, A.Messiaen, J.-M.Bernard, G.Lombard, J.Ongena, R.Dumont, S.Agzaf,Y.Song, T.Hoang and M. Van Schoor

Rapporteured Contribution

WEST Ion Cyclotron Resonance Heating System

- **3 New Antennas (ICRH Q1/Q2/Q4)**
  - 46 to 65 MHz
  - Actively Water Cooled
  - Load Resilient
  - 2 x 2 straps Antenna
  - W Antenna Limiters
- **ICRH System Specifications**
  - 9 MW/30 s
  - 6 MW/60 s
  - 3 MW/1000 s

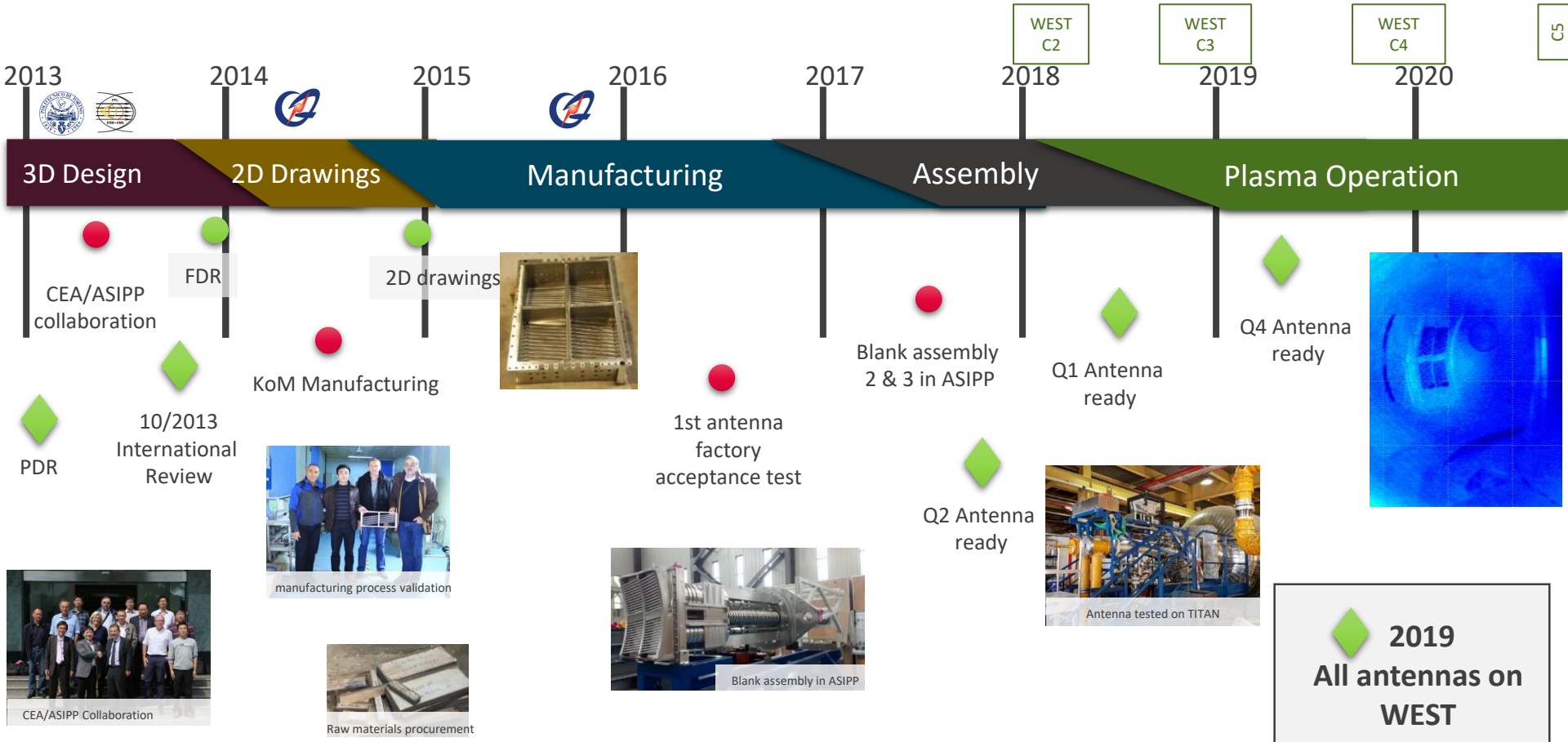




WEST ICRH Antennas are the Result of an International Collaboration

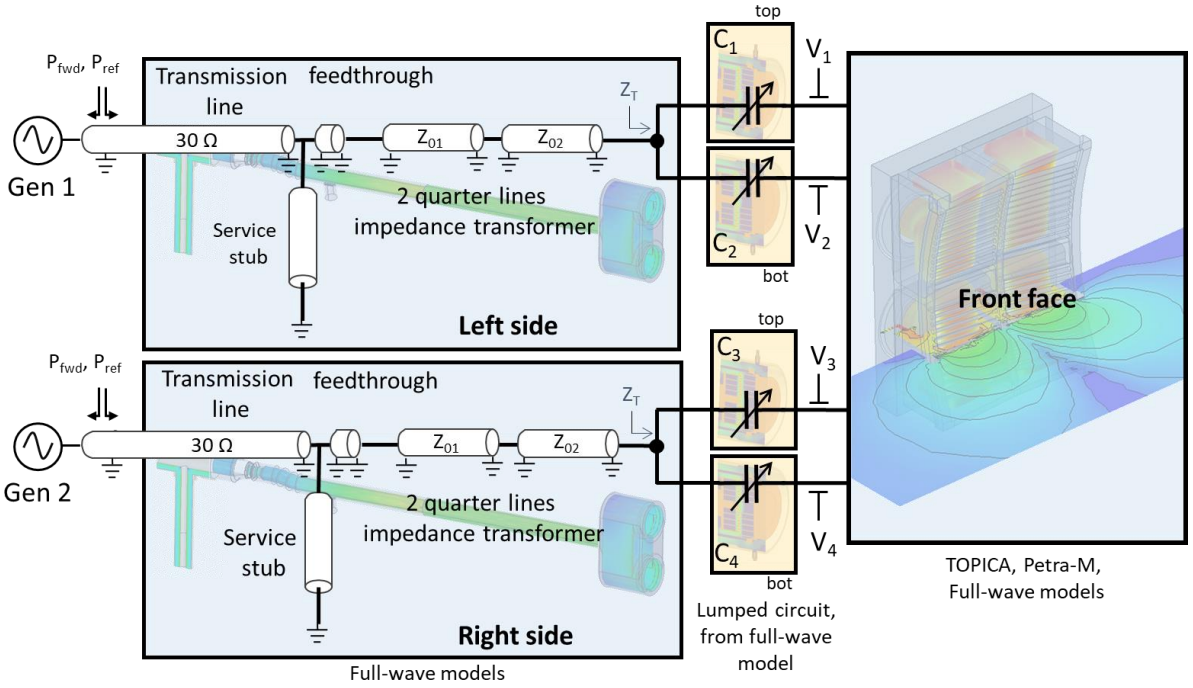
Fruitful and efficient collaboration

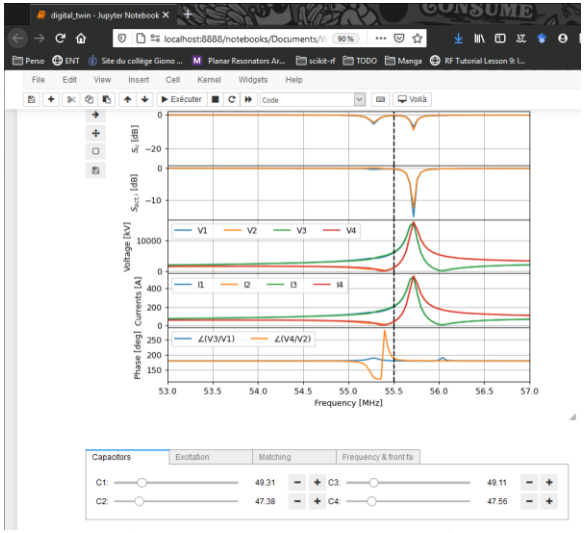
- 2 years from project start to blueprints (>250 parts/ant, >130 remote meetings)
- 2.5 years from raw materials to plasma operation
  - But also: new CODAC, Generator upgrades, etc…



WEST ICRH Antenna Electrical Design and RF Model

- **Load Resilience from Internals Conjugate-T with Matching Capacitors**
- **Antenna RF model combines full-wave and lumped elements circuits (deduced from full-wave)**
  - Front-face plasma coupling obtained from bespoke codes (TOPICA, Petra-M) or commercial software
  - Built with open-source Python package scikit-rf and can be used interactively in live in the control room



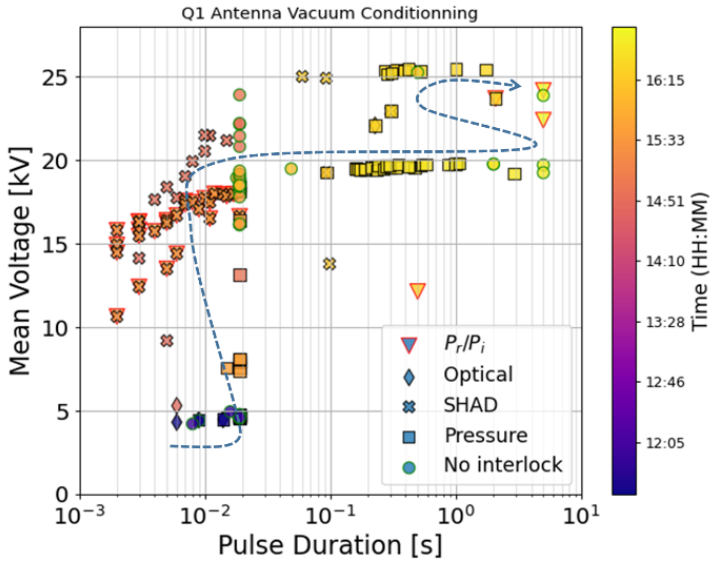


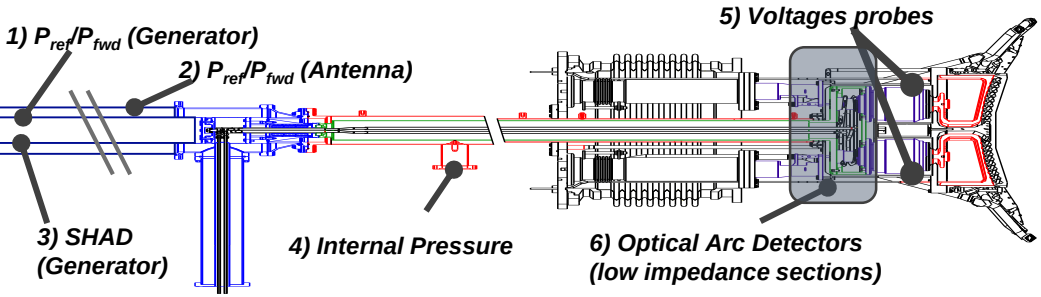
scikit-rf
Object Oriented RF Engineering

WEST ICRH Antennas are Protected by Several Systems

A Combination of Protection Systems (10 to 50 µs response times)

1. P_{ref}/P_{fwd} Generator
2. P_{ref}/P_{fwd} Antenna
3. Sub-Harmonic Arc Detection (SHAD)
4. Internal Pressure (outgassing)
5. Voltage Probes
   - Voltages & Current limits (fast overshoots during disruption)
   - Toroidal and Poloidal Unbalance
6. New: Optical Arc Detectors (8 fibers/antenna)





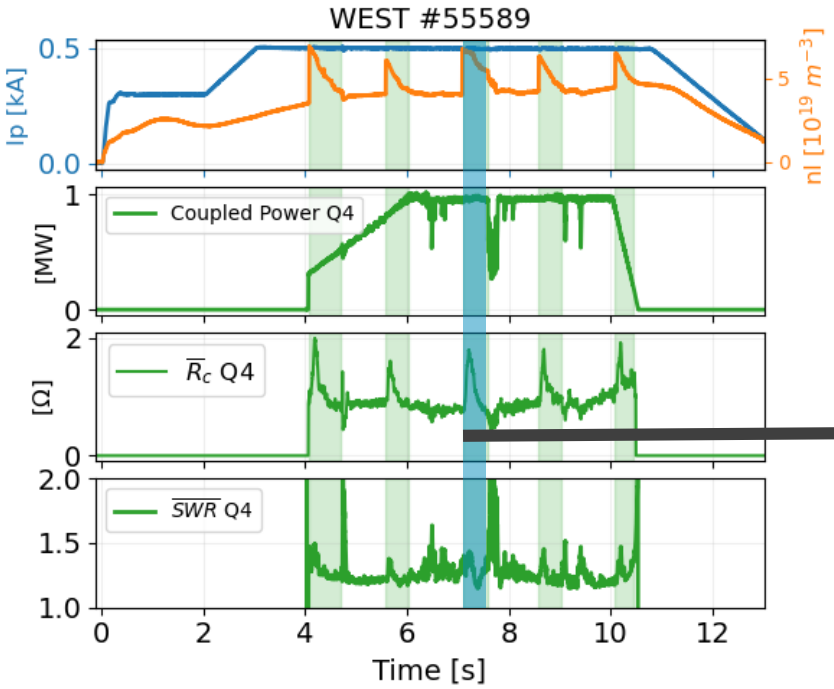
- All Systems can trigger during commissioning and plasma operation…
- …but not at the same time: different locations & breakdown mechanisms
- ➔ **Several protections needed to detect as soon as possible**
- ➔ **No significant damage observed on antenna**

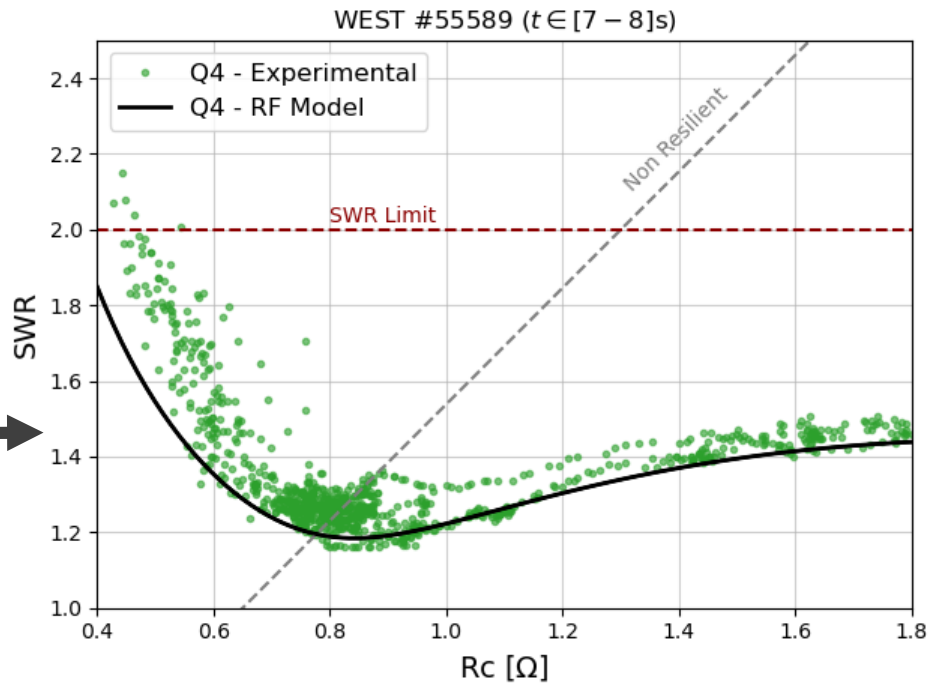
WEST ICRH Antenna Load Tolerance Demonstrated

Load-Tolerant Antenna Electrical Circuit (Internal Conjugate-T)

- Coupled Power is tolerant to important changes in plasma loading
- RF Model is in good agreement with experimental data

$$\mathrm{SWR} = \frac{1+\sqrt{P_r/P_f}}{1-\sqrt{P_r/P_f}}.$$

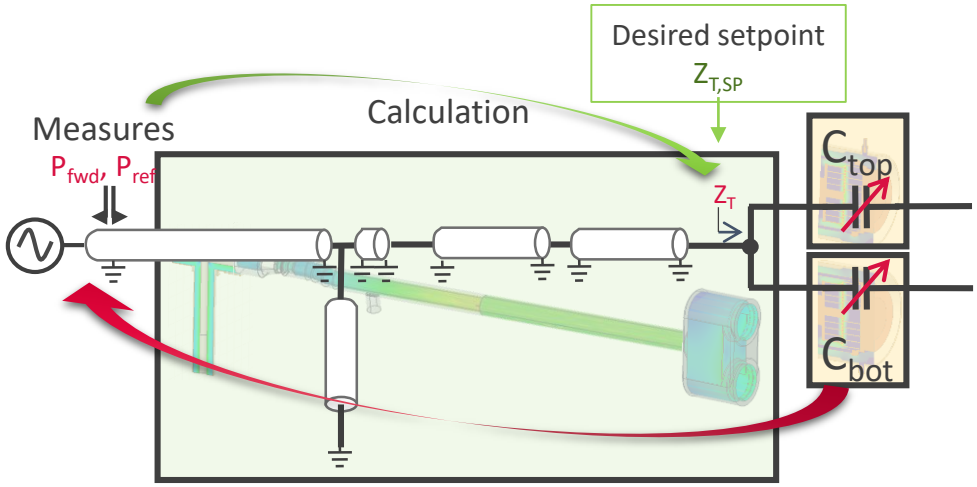


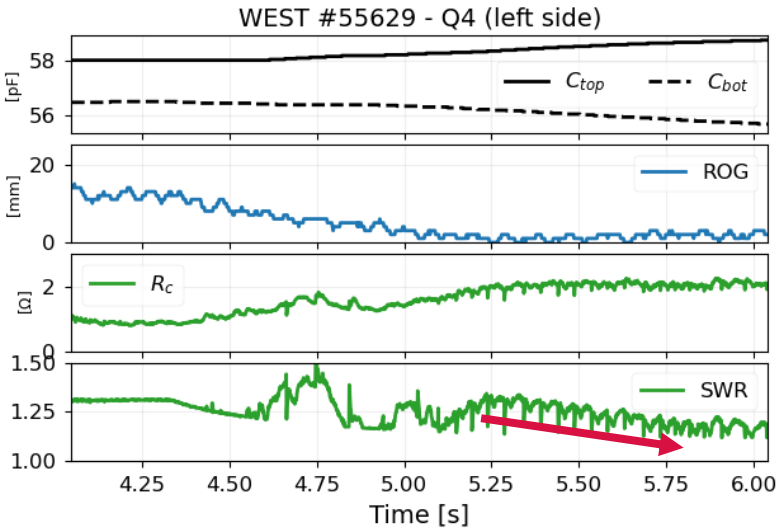


Automatic Matching Demonstrated

Real-time Matching Feedback Control Demonstrated

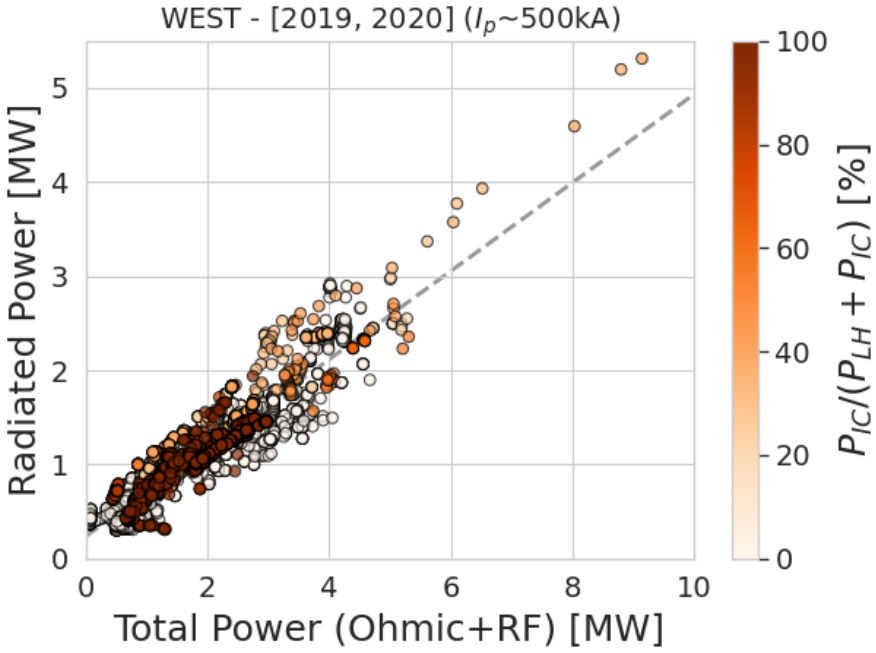
- Similar Control Scheme to JET ILA
- Capacitors actuated to minimize difference between desired impedance $Z_{T,SP}$ and calculated Z_T

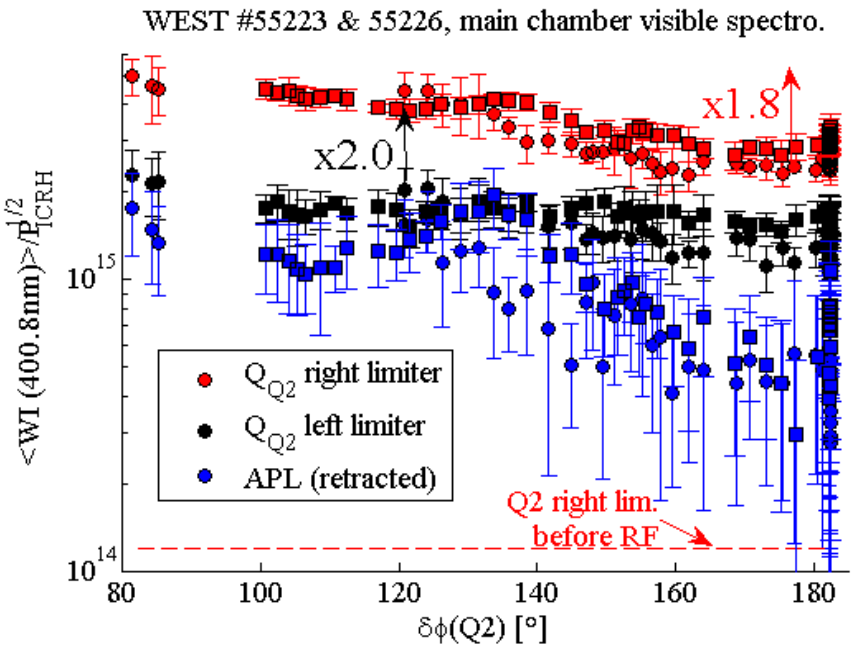




RF-Induced Radiated Power and Impurity Production

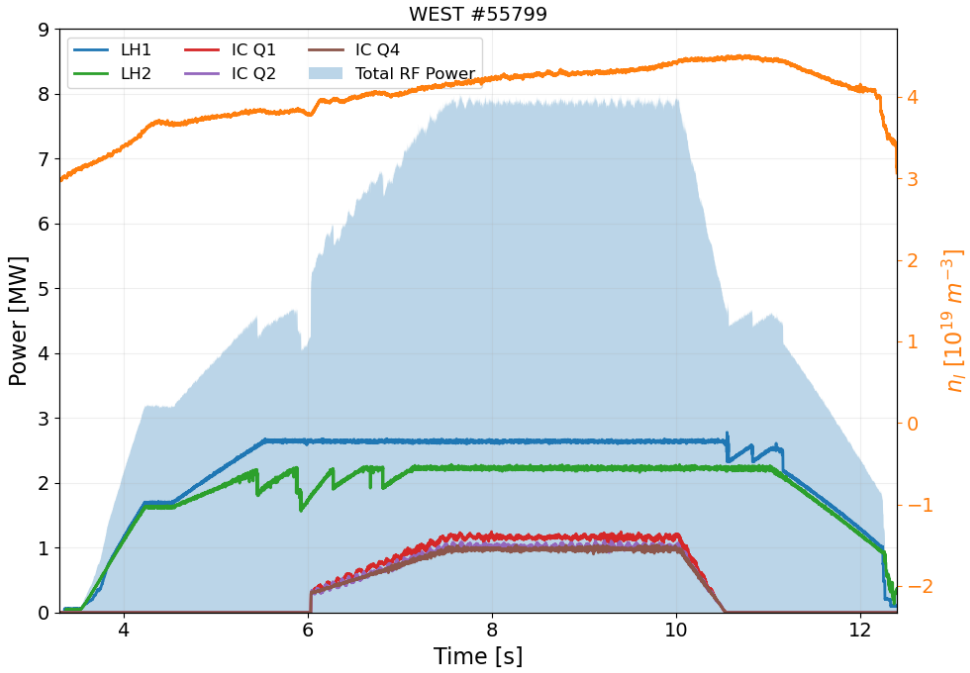
- **In Nominal Conditions (5-10% $n_H/(n_H+n_D)$ for H-minority Heating Scenarios and Dipole Phasing)**
  - Radiated power measured in 2019 and 2020 scales with Total Power (Ohmic + RF)
  - ...but central T_e is generally lower with ICRH only than with LHCD only
- **Gross Erosion Measured on W Antenna Limiter Increases when ICRH Antenna are used**
  - Especially if Toroidal Phase Departs from Dipole
- **The Specific Role of ICRH on W-PFCs to the W Concentration in the Plasma Core Still Under Assessment**
  - Complex interplay between Source Locations, SOL Transport and Plasma Core Temperature and Density.
  - New low-Z materials Antenna Lateral Limiters are under design and will be installed progressively for all antennas.

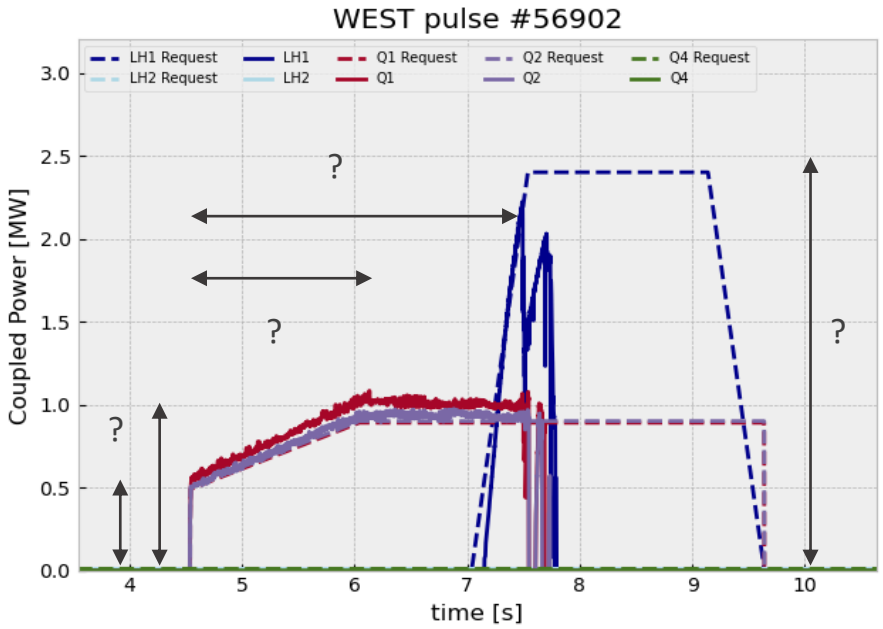




Combined Operation ICRH+LHCD Possible but Tricky

- **Simultaneous High Power LHCD + ICRH Operation Have been Achieved**
  - So far up to 7.8 MW RF Coupled Power for few seconds
- **But Combined Operation often plagued with Interferences between System**
  - SOL Modifications that impact RF coupling, Hot Spots, …
  - Future work will focus on optimizing combined RF Power scenarios





Conclusions

WEST ICRH System has been upgraded to allow long-pulse operation and load-resilience

- **A unique combination**
  - That no ICRH system before ITER has had to deal with simultaneously
- **3 new ICRH antennas have been designed and manufactured**
  - In collaboration with European laboratories and ASIPP
- **The 3 antennas have been successfully operated together on plasma in 2019 and 2020**
  - The load resilience capability has been demonstrated.
  - The antenna feedback controls (phase, matching) successfully used.
- **High confinement mode transitions identified on WEST obtained with both LHCD + ICRH**
  - Future work will concentrate on optimizing combined RF heating scenarios:
  - Maximize Central Temperature and Minimize Radiated Power

Status of the WEST Travelling Wave Array antenna design and results from the high power mock-up

(ENR-MFE19.LPP-ERM-KMS-03)

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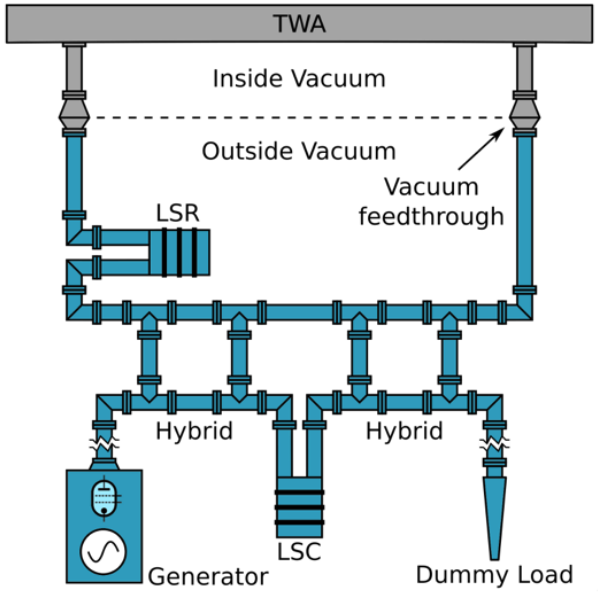
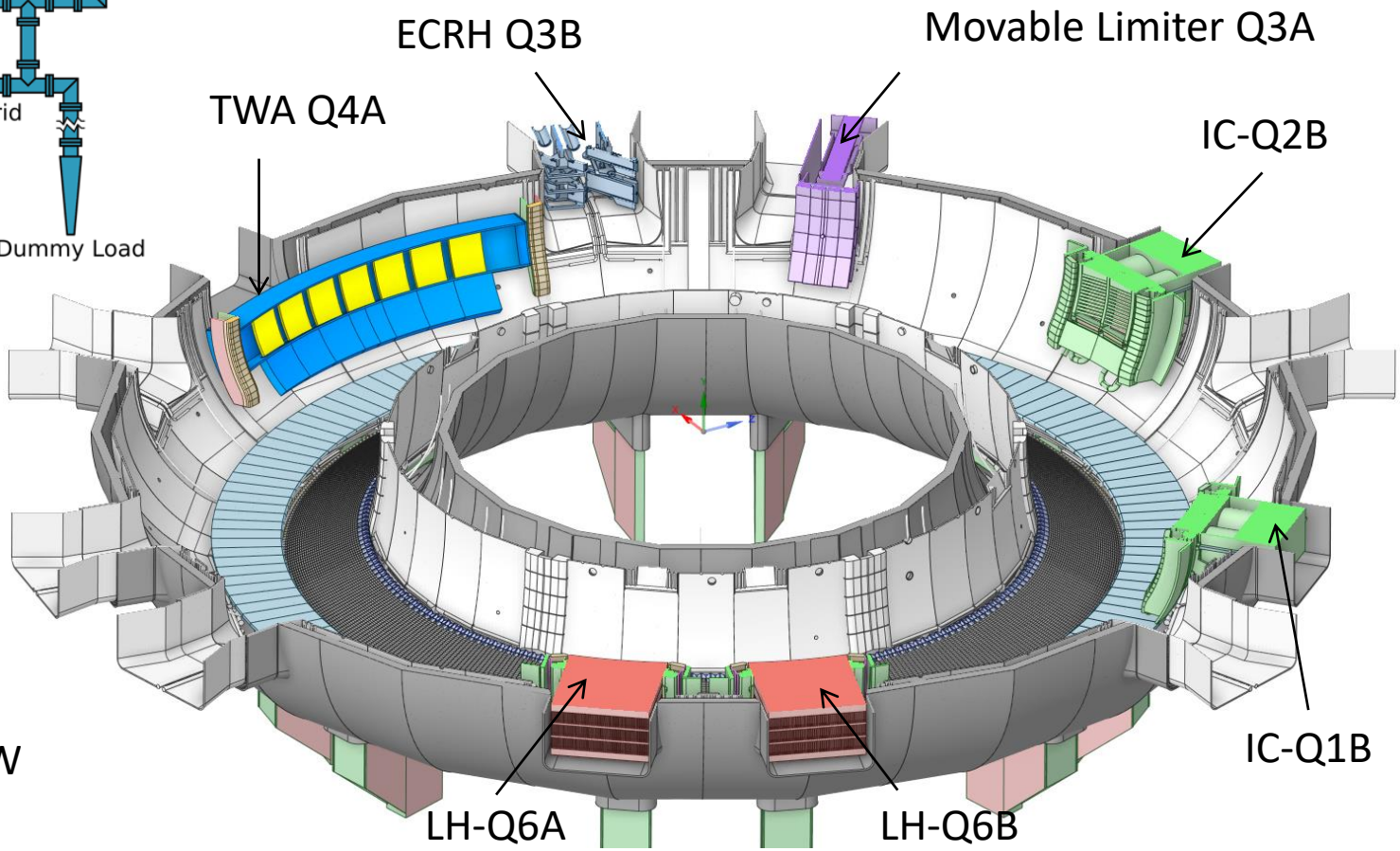
TWA on WEST



Two rows separated poloidally:

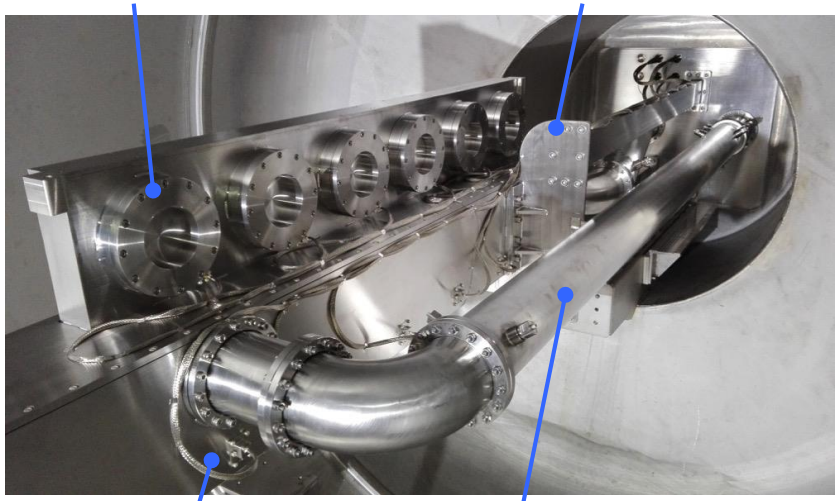
- 7 straps
- 1.5MW-30s & 0.5MW-1000s
- resonant ring feeding

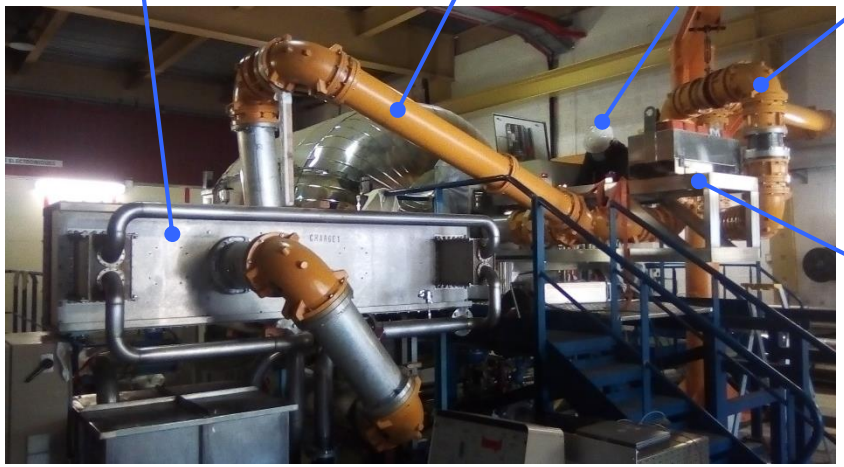


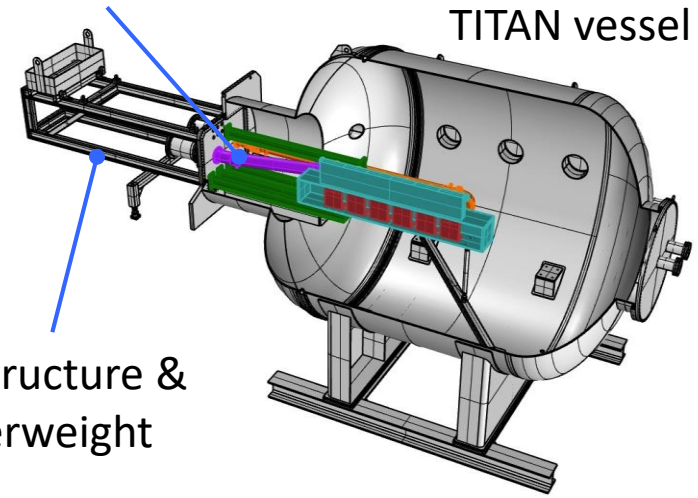
All elements are in Stainless Steel

Water cooling for CW operation

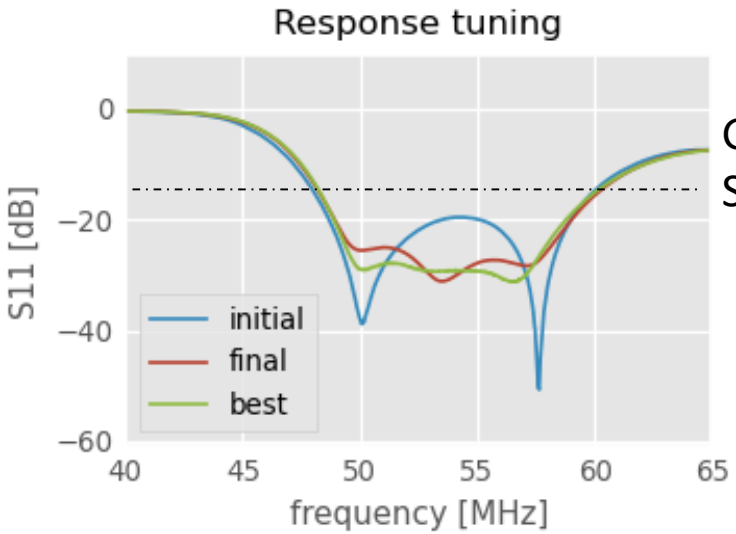
TWA mock-up in TITAN (March 2021)







Preliminary results & next steps



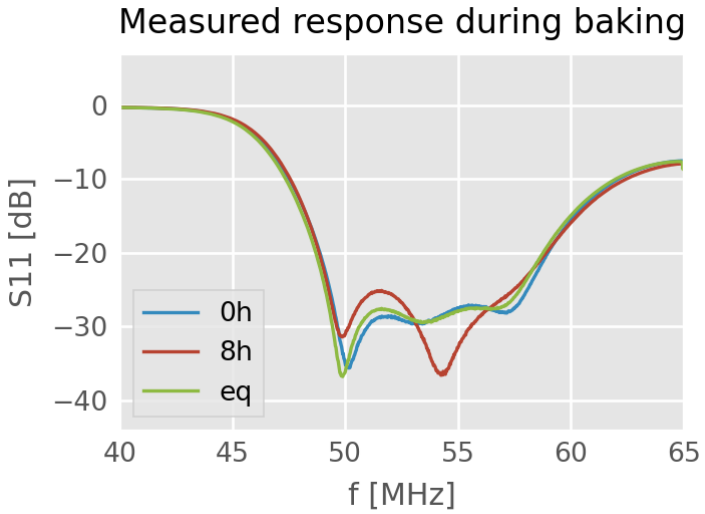
Generator
SWR 1.5:1

Movable trimmers

Wide band at low SWR

Resilience to thermal and mechanical deformation

Coax/strap
0h – 21/21 °C
8h – 180/100 °C
eq – 220/220 °C



Next steps:

- RF conditioning
- Voltage stand-off
- High power envelope (2 MW/10 s & 500 kW/120 s)
- Differential deformations (RF losses)