Overview of the high-power CW RF systems of the WEST tokamak and new developments

CWRF2018, 26/06/2018

Presented by: Walid Helou

W. Helou, L. Delpech, P. Mollard, F. Záček, R. Abdeddaim, J. Achard, J. Adamek, A. Armitano, G. Berger-By, J.-M. Bernard, P. Bienvenu, O. Bogár, N. Charabot, L. Colas, J.-M. Delaplanche, P. Dumortier, F. Durodié, A. Ekedahl, F. Ferlay, M. Goniche, J. Havlicek, J. Hillairet, K. Hoffmann, V. Kabourek, G. Lombard, D. Milanesio, J. Preinhaelter, M. Prou, P. Sabouroux, D. Sesták, G. Tayeb, R. Volpe, K. Vulliez, Q. Yang, J. Zajac

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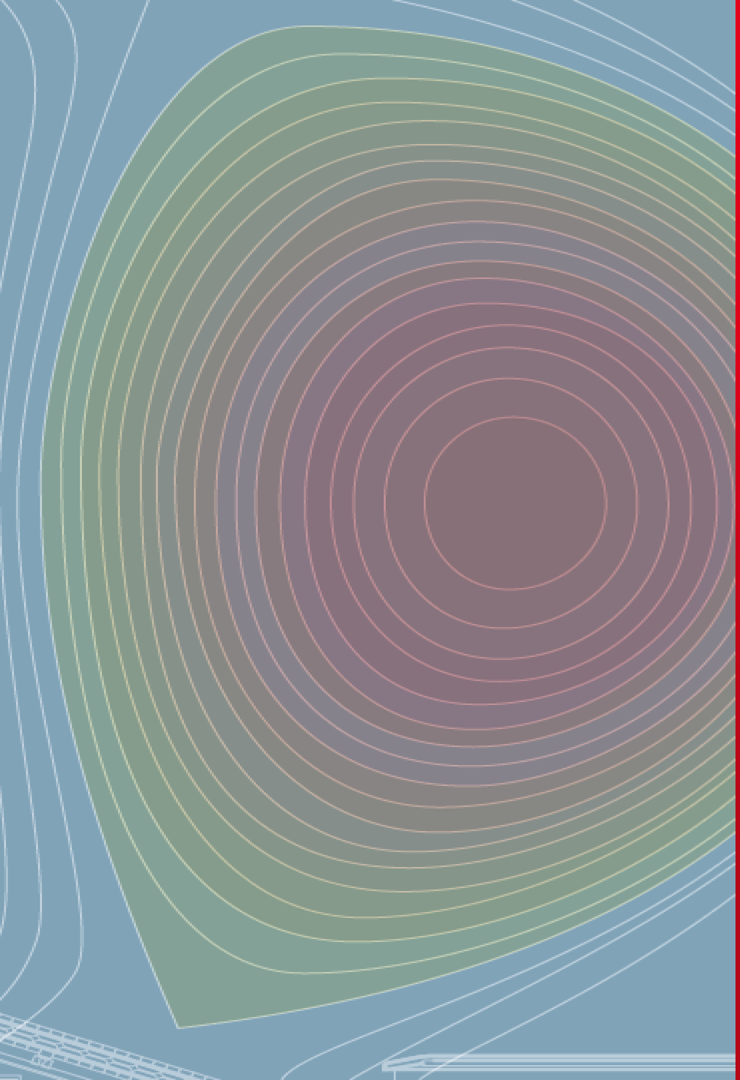


IRFM, nuclear fusion & WEST tokamak

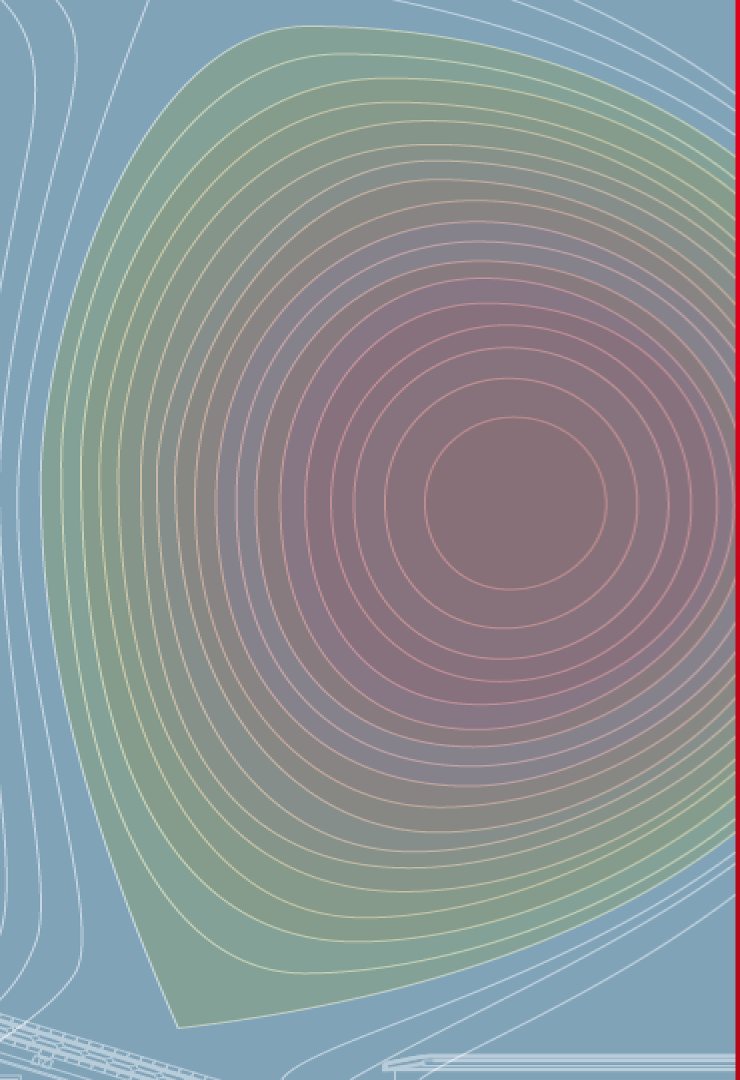
Particularities of the high power CWRF systems in nuclear fusion

WEST ICRF system

WEST LHRF system

IRFM new developments at LHRF

Summary & potential common interest with particle-accelerator community



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Institut de Recherche sur la Fusion par confinement Magnétique (IRFM)

- Institute at the Fundamental Research Division of the French Alternative Energies and Atomic Energy Commission (CEA).
- Localized at CEA-Cadarache site (close to Marseille, south of France).
- IRFM Staff: ~250 (~10% CEA-Cadarache staff), ~220 permanent, ~30 PhD postdocs and trainees.
- Works on physics & technology for nuclear fusion by magnetic confinement.
- Main experimental device: WEST tokamak.
- Also works for the International Thermonuclear Experimental Reactor (ITER) & other fusion devices worldwide (Europe, China, Korea, Japan, USA, India).

Nuclear fusion

- Objective: nuclear fusion power plant.

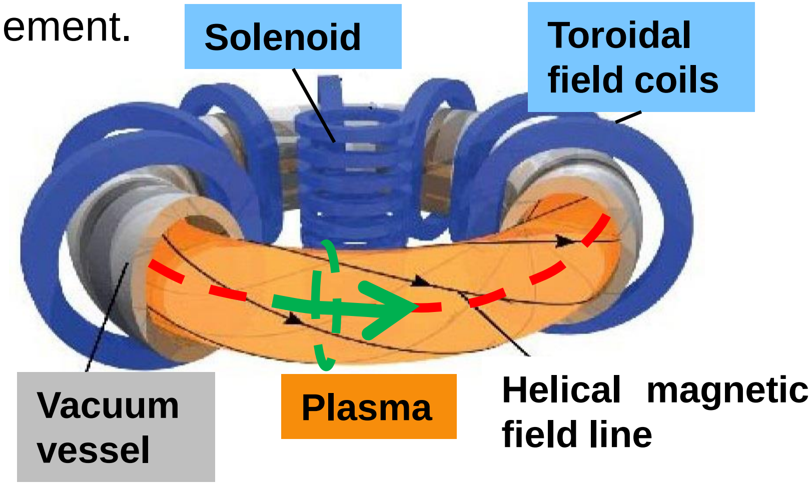
$$D + T \rightarrow \alpha\,(3.5\ \text{MeV}) + n\,(\underbrace{14.1\ \text{MeV}}_{\text{Electricity}})$$

- Nuclear fusion reactor very attractive:
  - No long-term nuclear waste.
  - Runaway reactions are impossible.
  - Reduced CO_2 emissions.
  - T bred from Li in-situ.
  - D and Li largely abundant.

- However: need to overcome Coulomb forces, this requires ~10-20 keV (≡ ~150x10^6 °C).

Plasma heating & confinement and tokamaks

- ~10-20 keV → Plasma state. Plasma needs confinement.
- Tokamak:
  - Magnetic confinement.
  - Requires plasma current (I_p).
- I_p can be inductively generated.
- I_p also heats the plasma by Joule effect.

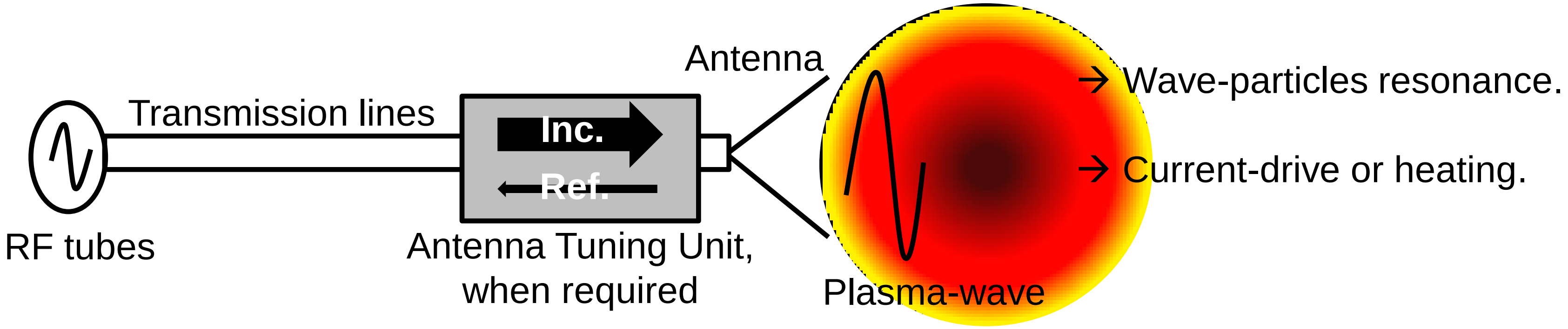


- However:
  - Plasma resistivity ↘ with the temperature → I_p insufficient to reach ~10-20 keV.
  - Inductive I_p has finite duration → Tokamak is intrinsically pulsed device.

➡ Steady-state tokamak reactor requires auxiliary heating & current-drive (CD) systems (electromagnetic + other such as Neutral Beam Injectors).

MW-range electromagnetic heating and current-drive systems in nuclear fusion

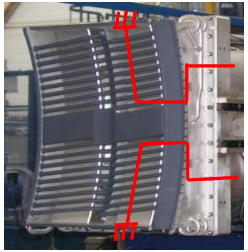
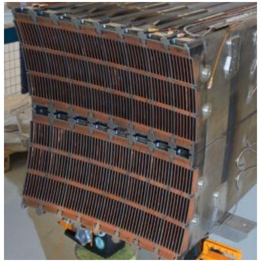
- General configuration:



- $Z_{in,antenna} \neq Z_0$ → Power reflection.
  - V_{max} ↗, I_{max} ↗: arcing, overheating.
  - Reflection + losses: efficiency ↘.
  - System's safety altered.

  } Impedance-matching is crucial.

MW-range electromagnetic heating and current-drive systems in nuclear fusion

Frequency	Ion Cyclotron Range of Freq. (ICRF, ~30-120 MHz)	Lower Hybrid Range of Freq. (LHRF, ~1-10 GHz)	Electron Cyclotron Range of Freq. (ECRF, ~50-200 GHz)
Tubes	 Tetrodes	 Klystrons	 Gyrotrons
Trans. lines	 Rigid coaxial lines	 Rectangular/circular, mono-mode/oversized waveguides	 Circular oversized and corrugated waveguides
Antennas	 Phased arrays of electrically small loops	 Phased arrays of rectangular waveguides	 Quasi-optical mirrors

Generally, heating — Generally, current-drive

This talk

WEST tokamak (formerly Tore Supra)

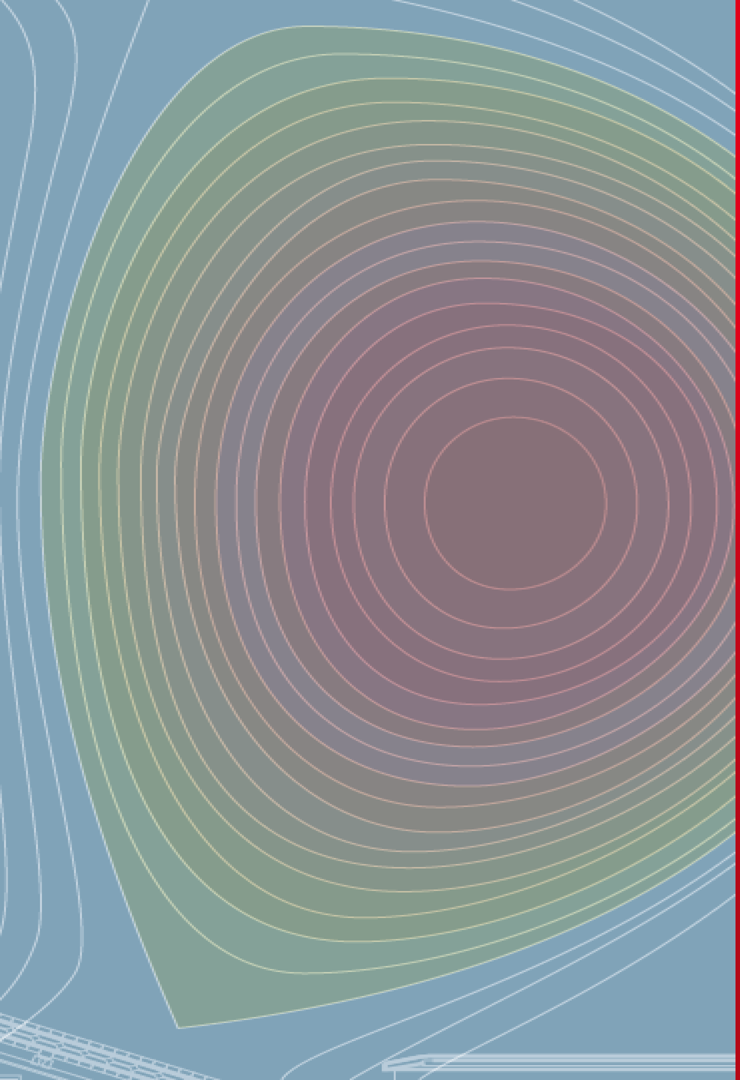
- Tore Supra (1st plasma in 1988): a pioneer in long pulse operation.
  - Superconducting toroidal coils.
  - Pressurized water loops.
  - Actively cooled plasma facing units.
  - 15 MW of CWRF power.
- World record of injected/extracted energy in a tokamak (6 min, 1GJ in 2003).
- Reached coupled RF power:

ICRF	~10 MW / 1.5s / 3 antennas, ~4 MW / 1s / 1 antenna.
LHRF	3.8MW / 5s / 1 antenna, 2.7MW / 78s / 1 antenna.
ICRF+LHRF	6.2 MW / 150 s.

- Tore Supra upgraded to WEST (1st plasma in December 2016).

WEST tokamak

Torus major radius	2.5 m
Torus minor radius	0.5 m
Toroidal field	3.7 T @ R=2.5m
Plasma current	Up to 1 MA
ICRF power	Up to 9 MW
LHRF power	Up to 7 MW
Pulse duration	Up to 1000s

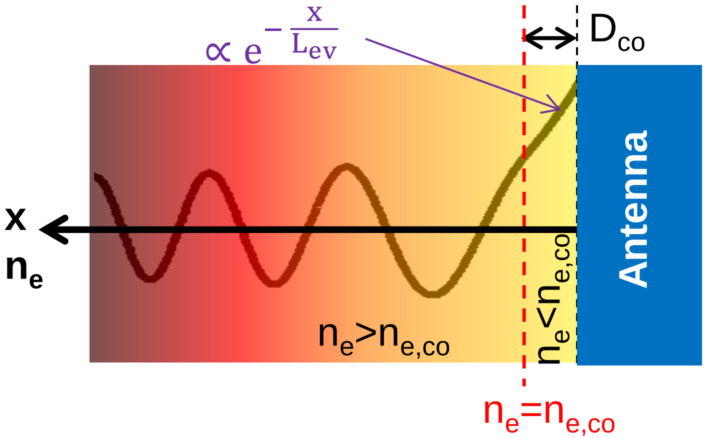


- IRFM, nuclear fusion & WEST tokamak
- **Particularities of the high power CWRF systems in nuclear fusion**
- WEST ICRF system
- WEST LHRF system
- IRFM new developments at LHRF
- Summary & potential common interest with particle-accelerator community

- Magneto-plasma: gyrotropic dielectric.
- Birefringence:
  - Slow-Wave.
  - Fast-Wave.
- Excite proper plasma-wave → Proper antenna polarization.
- Generally required: $|N_z| > 1$ → Particular phased-arrays, typically interspaces ~$\lambda_0/10$.
- Challenge of antenna-plasma coupling:

Stix tensor:

$$\mathbf{K} = \begin{bmatrix} S & jD & 0 \\ -jD & S & 0 \\ 0 & 0 & P \end{bmatrix}$$



Some particularities of the high power electromagnetic systems used in nuclear fusion

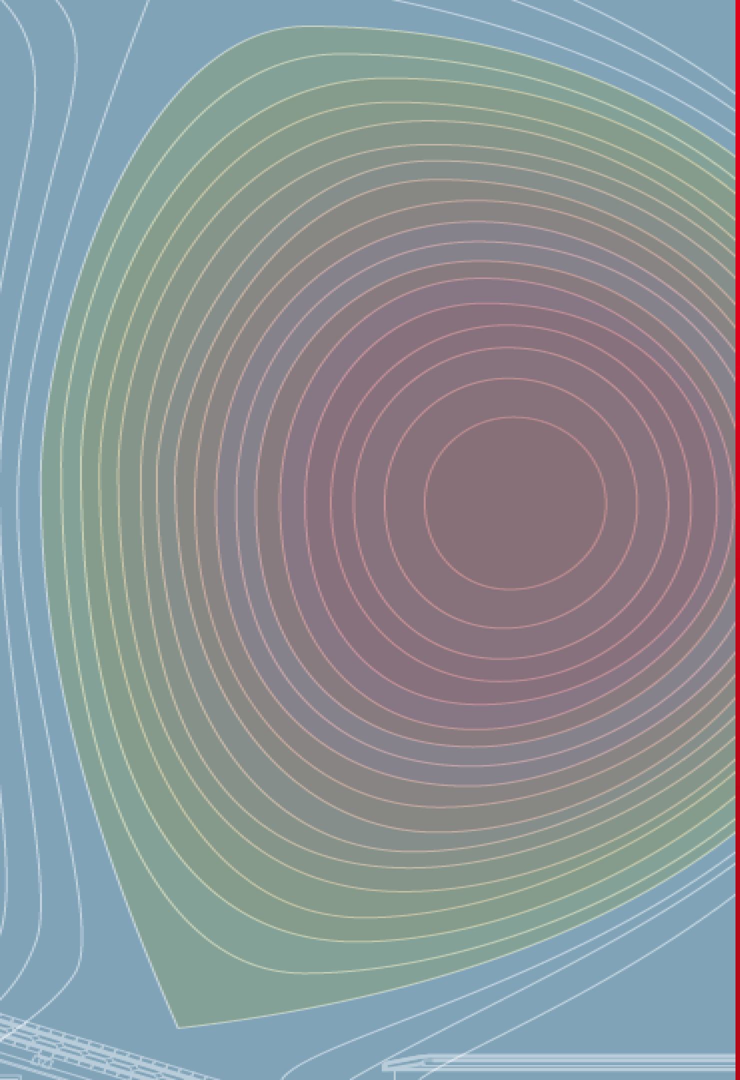
- High vacuum ($<10^{-5}$ Pa) & high temperature (~200°C) environment.
- Eddy currents → Large forces & torques (~500 N.m in ms-time scale, ex: plasma transients).
- Large heat fluxes (~MW/m^2).
- Nuclear-safety constraints & compatibility with remote handling (ex. on ITER).
- Need to excite proper plasma-waves. Need for proper phased-arrays with proper polarization.
- Need to optimize edge electron density profile (ex. n_e ↗ by gas-puffing), optimize plasma shape, etc. in order to V↘ / I↘ / |Γ|↘, and optimize power coupling.

Some particularities of the high power electromagnetic systems used in nuclear fusion

- Very non-stationary plasma → Harsh non-stationary RF loading. Real-time controlled &/or intrinsically immune (*aka* load-resilient) impedance matching required.

- High/CW RF currents (~kA / ~1000s). Thermomechanical considerations & active cooling.

- High electric fields (~MV/m). Need for arc detection systems (VSWR-based, optical, acoustic, ratio between RF signals, RADAR-based, S-matrix based *aka* SMAD, SHAD, etc.).



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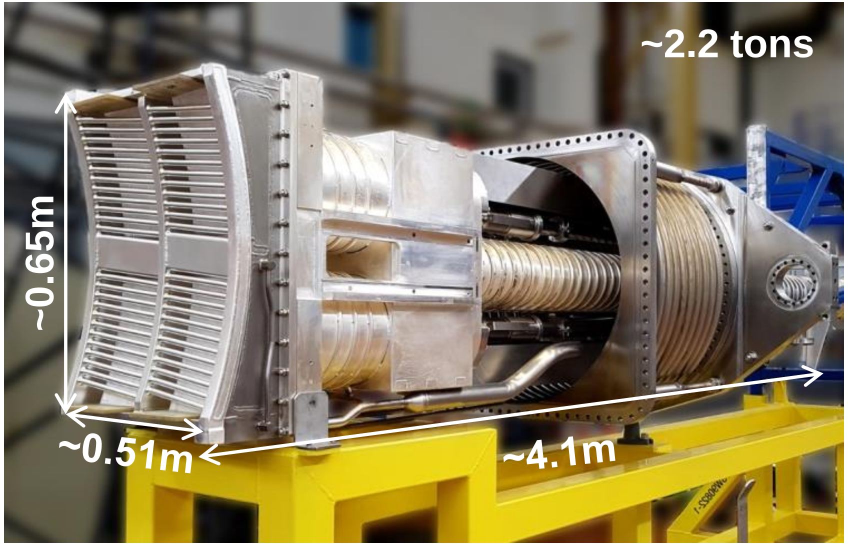
Summary & potential common interest with particle-accelerator community

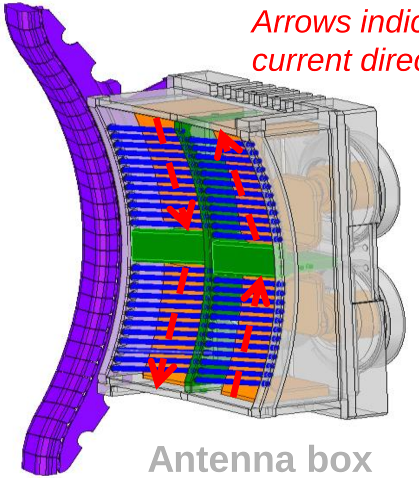
Three identical high power CW ICRF antennas

- Features:
  - Per antenna: 3MW/30s or 1MW/1000s, 2 power inputs.
  - 48-60 MHz.
  - Load-resilience with VSWR < 2:1.
  - Symmetric spectrum & $|N_{z,M}|$~10.
  - Water actively cooled (70°C/30 bar).
  - Vacuum compatible (10^{-5} Pa, ~150°C).



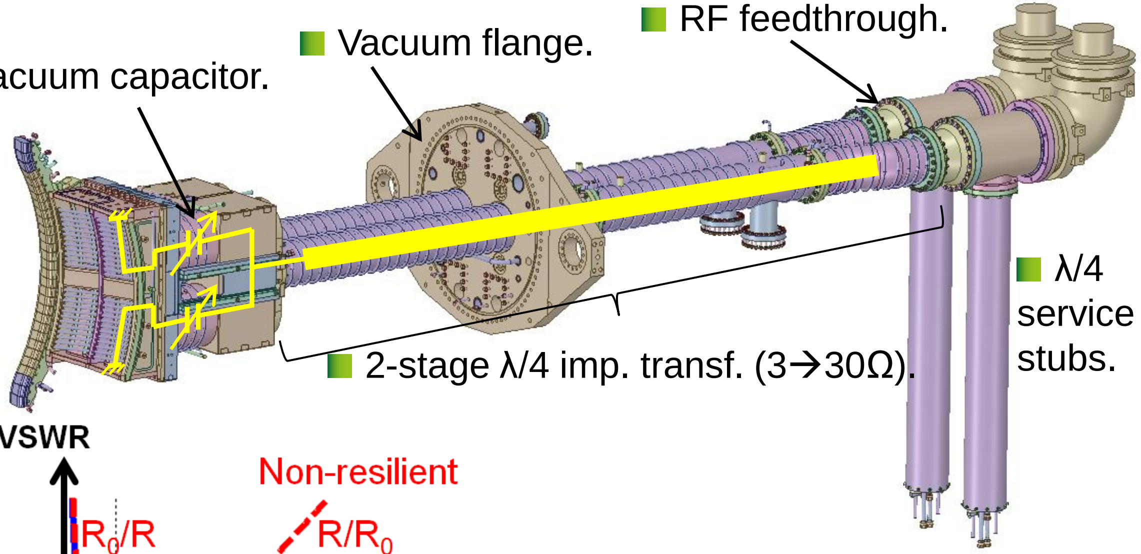
- RF measurements (amplitude & phase):
  - Voltage probes at straps inputs (vacuum compatible).
  - Directional couplers (P_i, P_r) at antennas inputs.

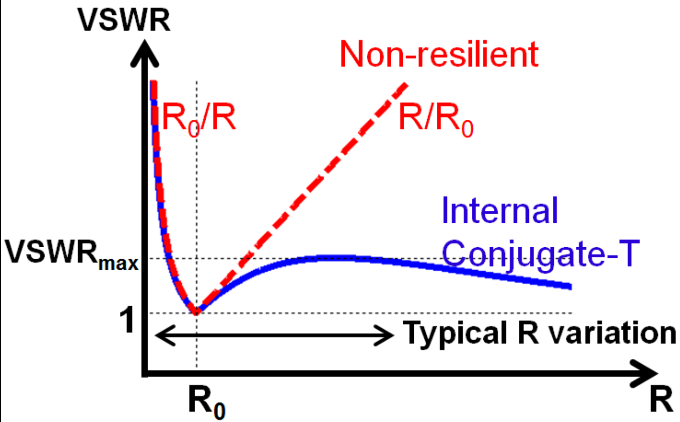
WEST ICRF antennas & their load-resilience



Antenna box
Straps or loops (Z_s=R+jLω)
Septa, Faraday screen, Limiters

- $R \propto P/I^2 \propto P/V^2$ → R ↗ crucial.
- $|\Gamma_{strap}|$>0.9 → Matching mandatory.
- Q~Lω/R>>1 → Sensitive matching.
- R very non-stationary.

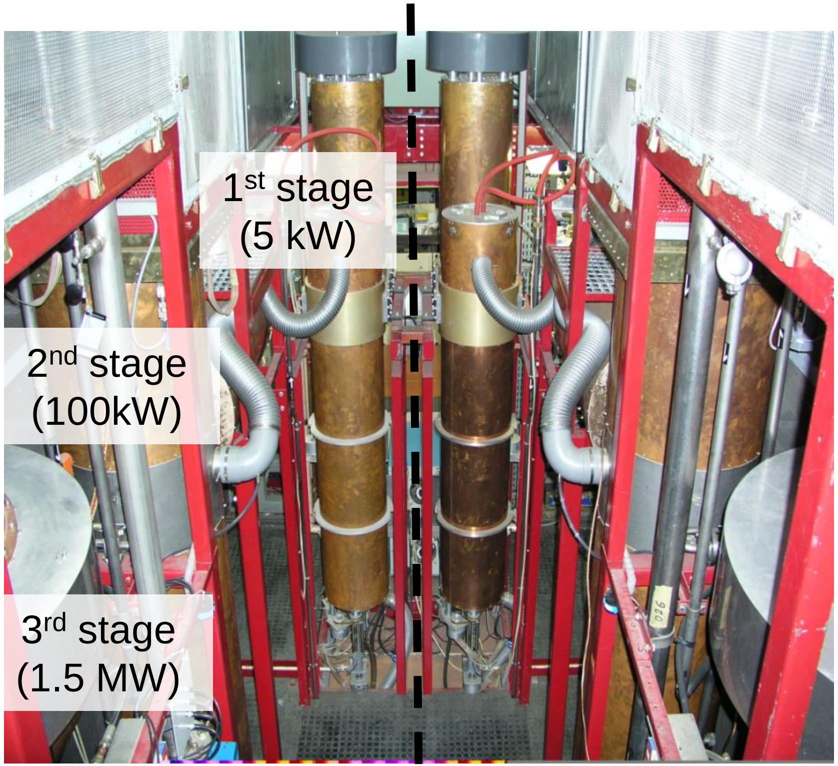




- Internal Conjugate-T matching → Load-resilience against RF loading variations (ms & sub-ms).

High power CW ICRF generators

- 3 modules (1 module / antenna), 1 module ≡ 2 generators (1 generator / ½ antenna).
- Each generator:
  - Solid state amplifier (200W).
  - 3-stage tetrodes.
- Control system with ~10 µs time-scale:
  - FPGA calculations.
  - Inputs: dissipated power, grid & anode currents, P_i & P_r, arc detection, etc.
  - Outputs: power trips, regulation & limitation (ex. power is reduced if P_r>200kW).



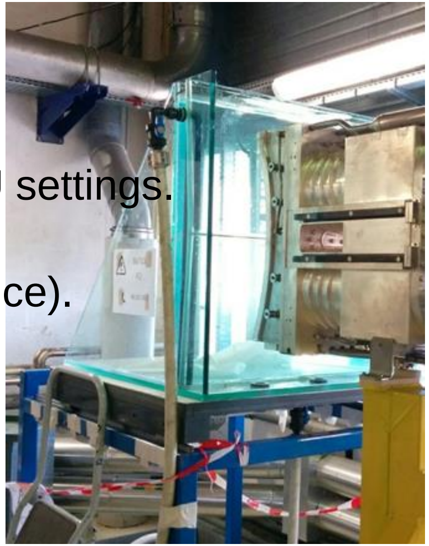
TITAN: ICRF antenna pre-qualification testbed @ IRFM

- TITAN vacuum chamber:
  - Vacuum leak tests (10^{-5} Pa, ~150°C).
  - High CW RF voltages/currents tests (~30kV/915A peak @ straps inputs).

- Low-power dummy load (~mW, tests using VNA) :

Radially moveable (0-10cm) aquarium, hosting high $|\varepsilon_r|$ media ($BaTiO_3$ mixtures, optimized salty water).

- Validate RF design.
- Check frequency range.
- Fill look-up tables with ATU settings.
- Assess load-resilience (sweep antenna/load distance).



Antenna validation before installation in the tokamak & accelerate commissioning on plasma

Arc detection in the ICRF system

- Detection within ~30 µs. Power tripping during ~30ms before reapplication.
- Arc detection systems:
  - V_r/V_i at antenna & generators (VSWR $_{threshold}$~4).

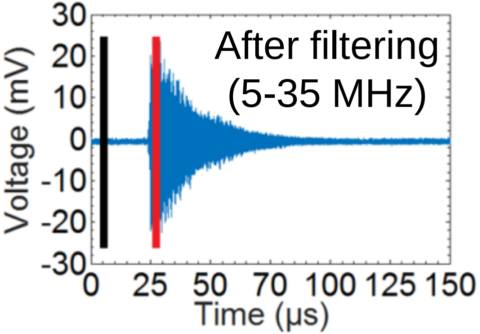
    ⚠ But do not protect the full system (ex. low-Z regions).

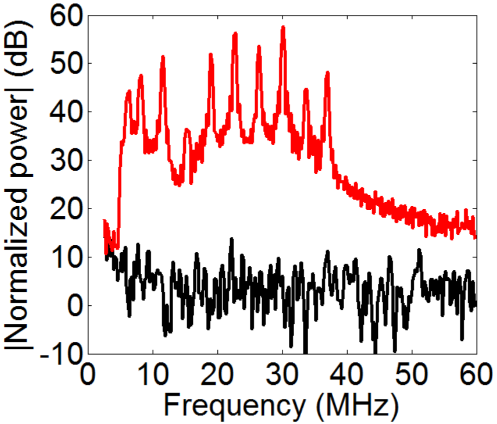
  - Optical arc detection @ low-Z regions.
  - Sub-Harmonic Arc Detection (SHAD):

+ Under development: FPGA-based SHAD for discrimination between arcs and spurious noise.

Undetected arcs

⚠ Complementary arc detection systems are required.





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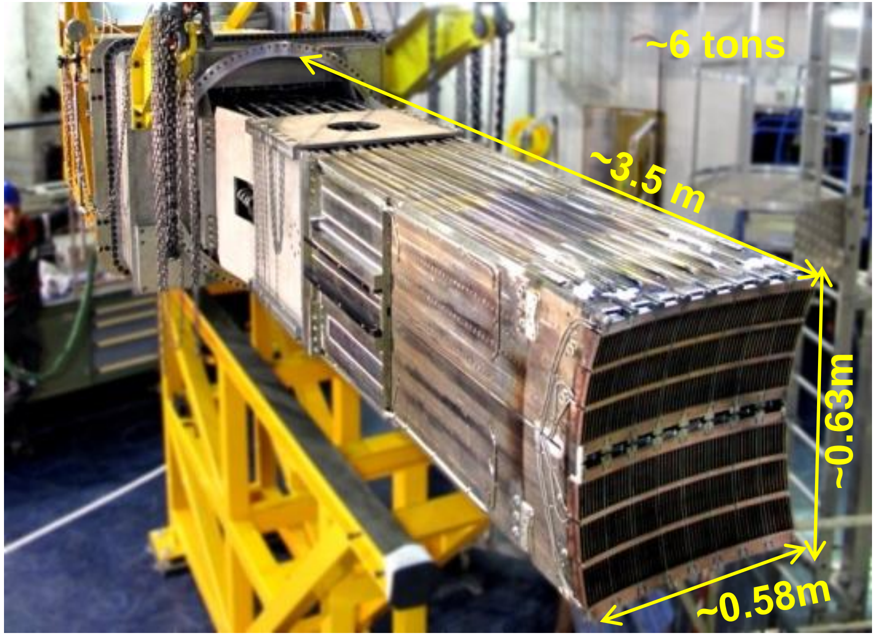
Summary & potential common interest with particle-accelerator community

Two similar high power CW LHRF antennas

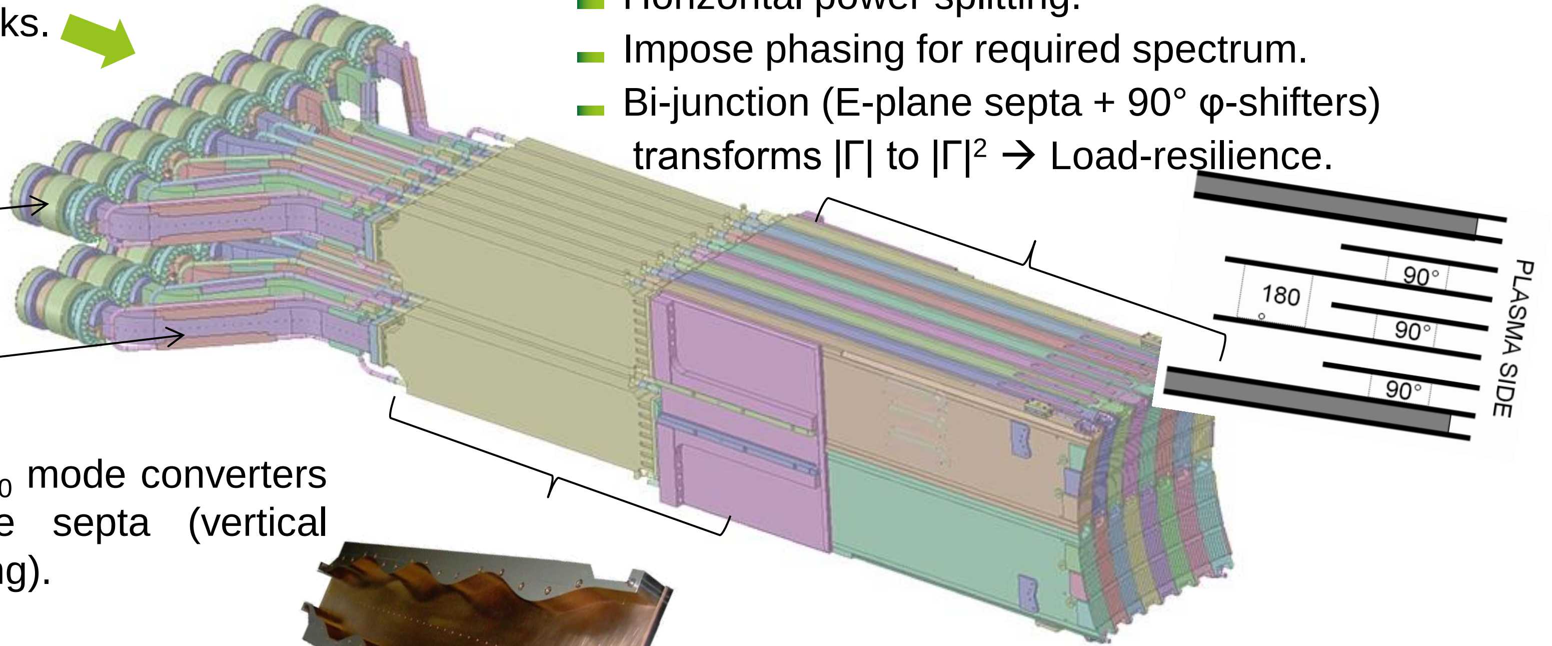
- Features:
  - 3.7 GHz. 3-4MW / 1000s.
  - ~300 reduced-height waveguides (~70x8 mm^2).
  - Directional spectrum & $|N_{z,M}|$~2.
  - Water actively cooled (150 °C / 30 bars).
  - Vacuum compatible (10^{-5} Pa, ~150°C).

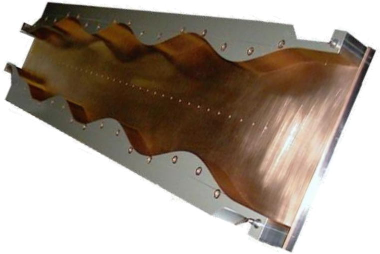


Typical components of a WEST LHRF antenna

- 3dB splitters, directional couplers, DC blocks.
- BeO pill-box RF window.
- Step φ-shifter.
- TE_{10} - TE_{30} mode converters and H-plane septa (vertical power splitting).

- Multi-junctions (E-plane septa, step φ-shifters):
  - Horizontal power splitting.
  - Impose phasing for required spectrum.
  - Bi-junction (E-plane septa + 90° φ-shifters) transforms |Γ| to $|\Gamma|^2$ → Load-resilience.





High power CW LHRF generators

- 16 klystrons (8 per antenna).

- Specs for a klystron:

Frequency	3.7 GHz ± 5 MHz
Power / 1000s	700 kW (VSWR<1.1:1) 600 kW (VSWR<1.4:1)
Efficiency	38-44%
Gain min	50 dB (5 cavities)

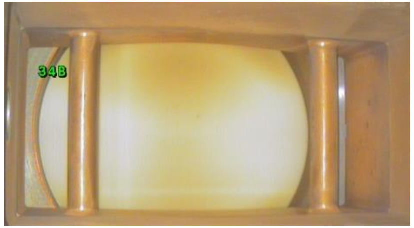
- Each klystron features a dual-output followed by BeO RF windows and a power combiner.

Example of interlocks in the LHRF system

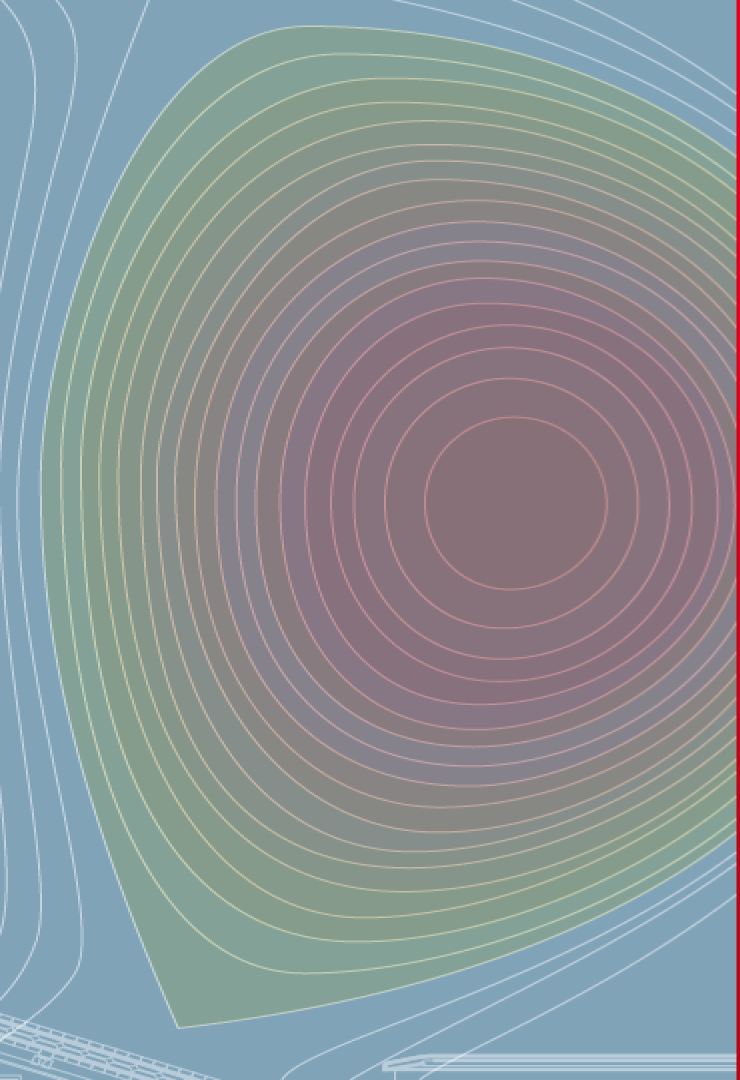
- Power tripped (~10µs) and switched-off, if:
  - Vacuum in klystron > threshold.
  - I_{beam} > threshold.
  - P_r @ klystron > 7 kW.
  - Arc (optical detection) @ klystrons RF windows. Maximum allowed trips: 1.

- Power tripped (~10µs) and reapplied (after ~10ms), if:
  - Arcs (optical detection) @ antennas RF windows or splitters dummy loads. Maximum allowed trips: 7.
  - P_r/P_i @ antenna > 0.2. Maximum allowed trips: 100.

Arc detection @ RF windows is essential



- Power reduced, if:
  - Copper level increases in the tokamak.
  - Antennas front-face temperature > threshold (infrared camera security).



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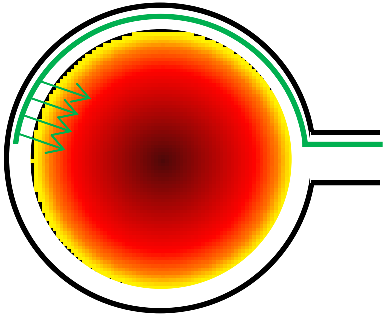
Summary & potential common interest with particle-accelerator community

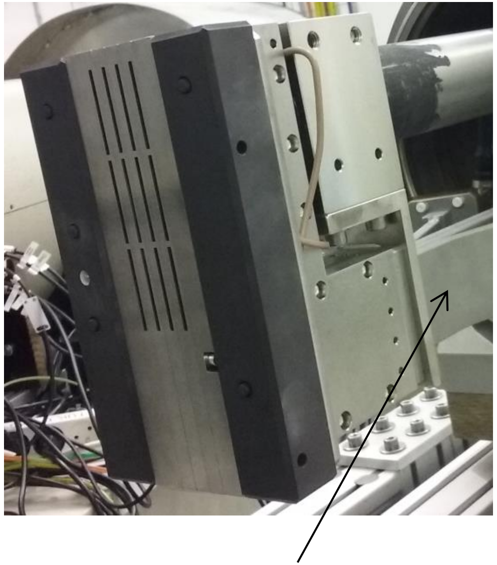
New LHRF antenna concepts & LHRF low-power dummy loads

- LHRF slotted waveguide antenna array:

  - Off-port extension.
  - Wave-coupling from limited-access regions.

mW prototype tested @ COMPASS tokamak

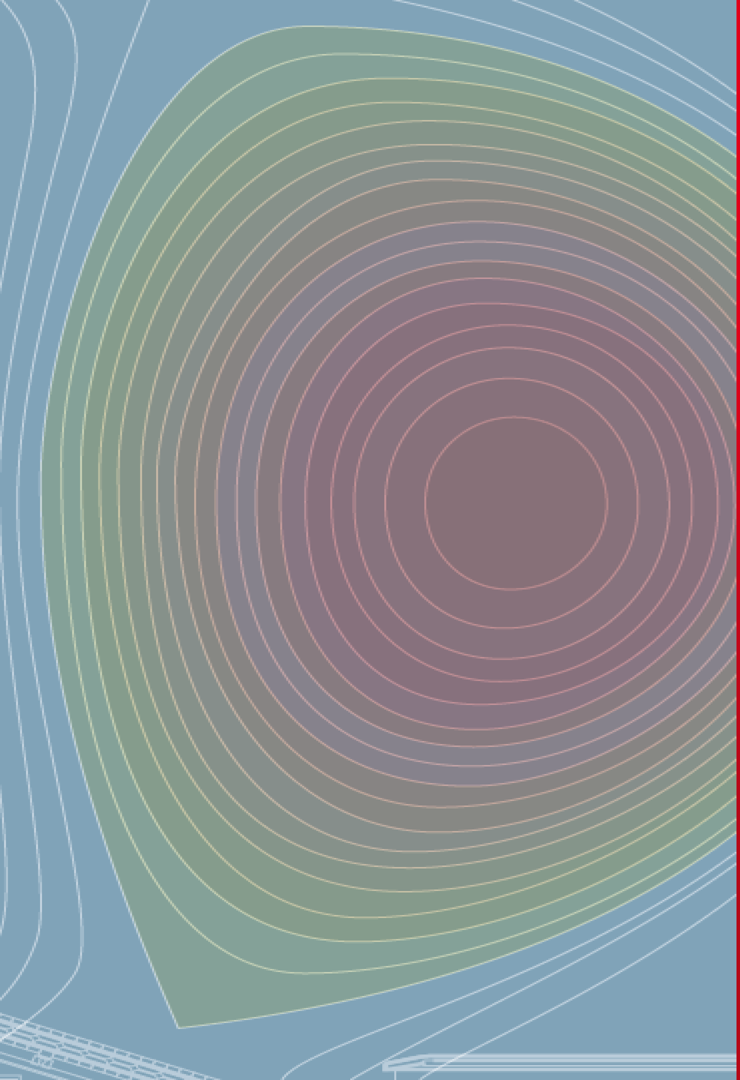




3D printed (metal) waveguide feeder

- LHRF metamaterial low-power loads:

  - Pre-qualification of LHRF antennas



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Summary & potential common interest with particle-accelerator community

- Very particular high power CW RF systems in nuclear fusion:
  - High vacuum / temperature environment.
  - Large heat and electromechanical loads.
  - Very particular phased-arrays.
  - Challenge of antenna-plasma coupling.
  - Harsh non-stationary RF loading.
  - High RF voltages/currents.
  - Arc detection aspects.

- Potential common interest with particle-accelerator community, ex:
  - Commissioning procedures & pre-qualification tests.
  - Impedance-matching problematics.
  - RF arc modeling, detection & discrimination from noise source.

Thank you for your attention

Your collaboration is welcome

Commissariat à l'énergie atomique et aux énergies alternatives
Centre de Cadarache | 13108 Saint Paul Lez Durance Cedex
T. +33 (0)4 42 25 46 59 | F. +33 (0)4 42 25 64 21

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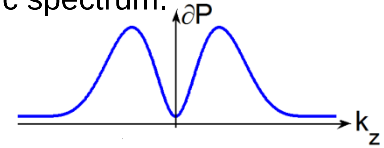
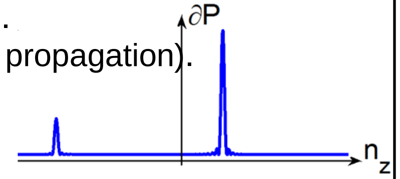
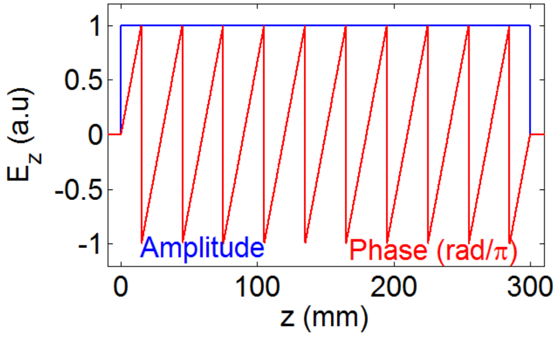
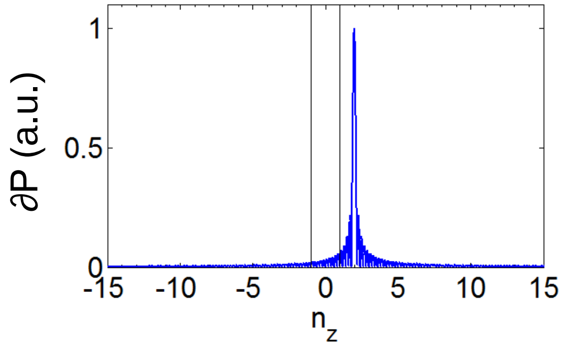
Wave-particle interactions and plasma-waves (plane-wave formalism)

	Heating at ICRF (~ 50 MHz)	Current-Drive at LHRF (~ 5 GHz)
Wave-particle resonance	Ion cyclotron resonance: $\omega - N\omega_{c,i} - \underbrace{\cancel{k_z v_{z,i}}}_{\ll\omega} = 0$	Landau resonance: $\omega - \underbrace{\cancel{N\omega_{c,e}}}_{N=0} - k_z v_{z,e} = 0 \rightarrow \frac{\omega}{k_z} = v_{z,e}$
Plasma-wave	Fast Wave (FW)	Slow Wave (SW)
Frequency (f_0)	• $\omega = N\omega_{c,i}$ at required resonance layer ($\omega_{c,i} \propto B_{static}$). • $n_{e,co}$ ↘ when f_0 ↗	• $n_{e,co}$ depends only on f_0: $n_{e,co}$ ↘ when f_0 ↘
Polarization	**E** // y-axis → FW: suitable for IC resonance.	**E** // z-axis → SW: suitable for Landau resonance.
Spectrum	• Typically, symmetric spectrum. • $\lvert k_{zM}\rvert$~ 5-15 m^{-1}. • $n_{e,co}$ ↗ when $\lvert k_z\rvert$ ↗. 	• Asymmetric spectrum. • $\lvert N_{zM}\rvert$>1 (absorption & propagation). Typically: $\lvert N_{zM}\rvert$~2. 
Typical $n_{e,co}$ & L_{ev}	• $n_{e,co}$~10^{18}-10^{19} m^{-3} (D_{co}~5-15 cm) • L_{ev} ~10 cm.	• At 5GHz: $n_{e,co}$=3.1x10^{17} m^{-3}. • L_{ev} ~ 5 mm.

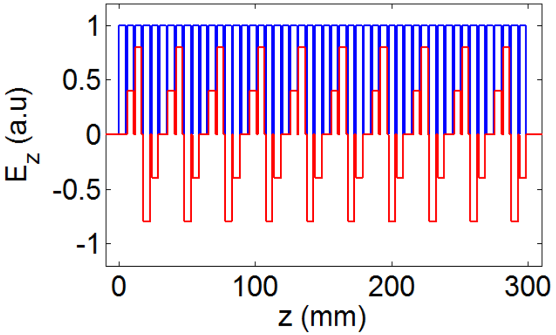
Need for array antennas
Example: LHCD case at 5 GHz (λ_0=60mm)

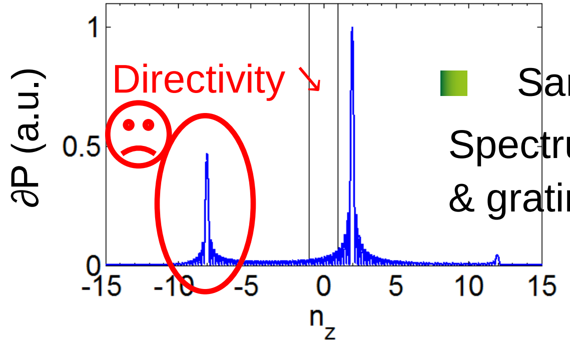
- Use a single radiator → Technically non-trivial.





- Spatial sampling → Phased array antennas.





- Sampling:

Spectrum periodization & grating lobes.

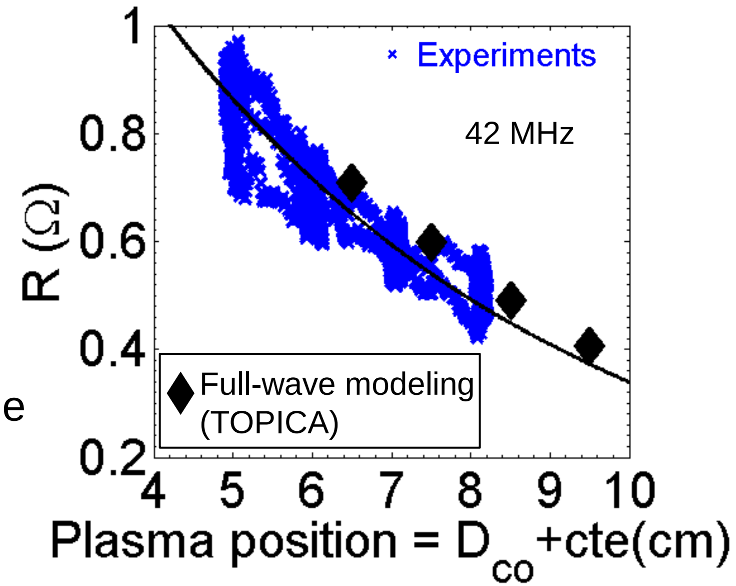
ICRF case: R a very sensitive & variable parameter

- R very much dependent on edge density profile (D_{co} & ∇n_e).

- Edge density profile hardly controllable
  → Same for R.

- Transitions of plasma confinement modes & plasma edge instabilities impact much edge density profile & R.

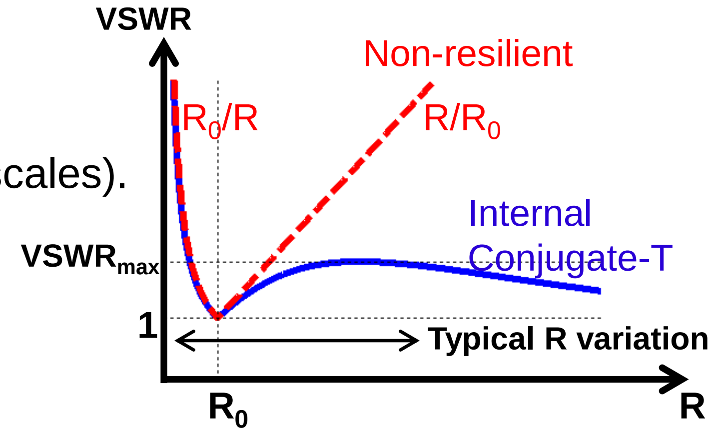
JET tokamak (ILA antenna)



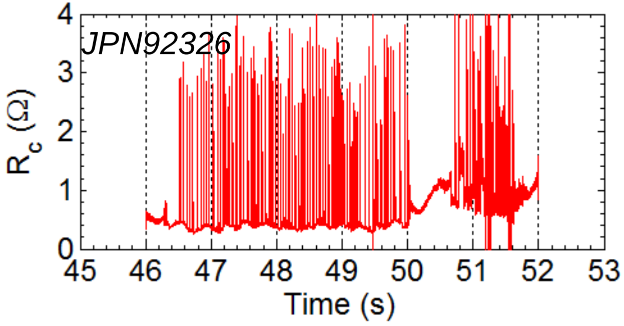
ICRF case: need for load-resilient ATU &/or real-time control

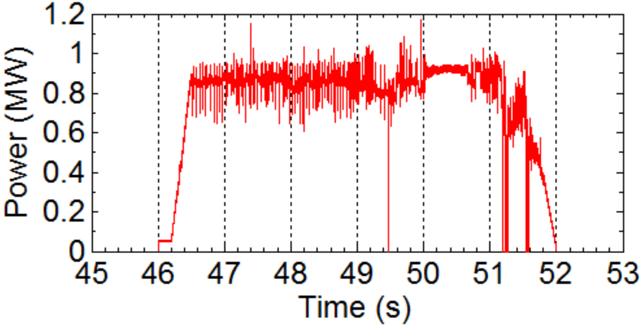
- Straps matched separately for R_0 with fixed 2-port lossless ATU: VSWR=R_0/R, or R/R_0.

- Need for:
  - Load-resilient ATU (inherently: VSWR< $VSWR_{max}$~2):
    → Cope with fast loading variations (ms & sub-ms time-scales).
  - Real-time control:
    → Automatically set working point for load-resilient ATU.
    → Relax constraints on load-resilience.

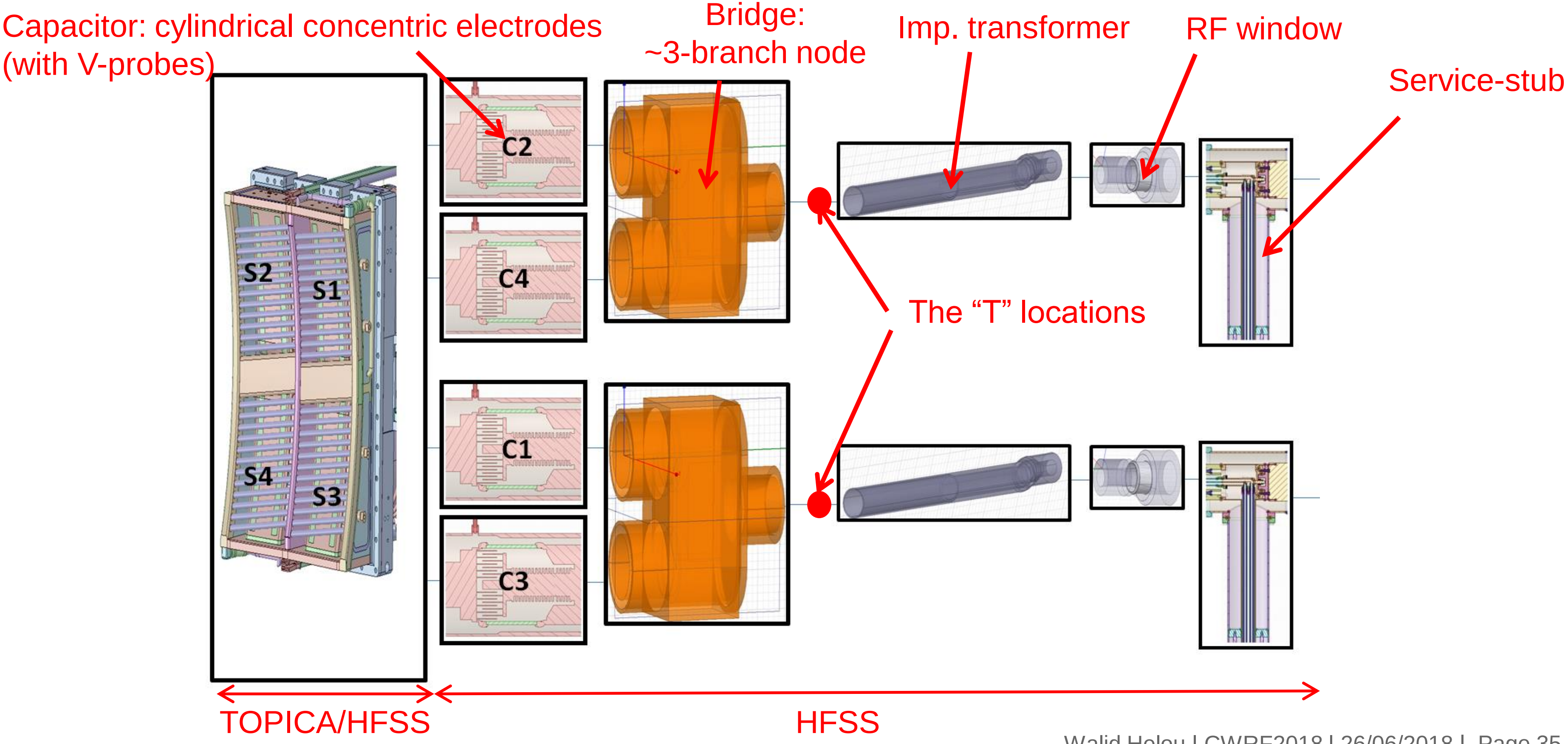


- Example: JET tokamak (ILA antenna)



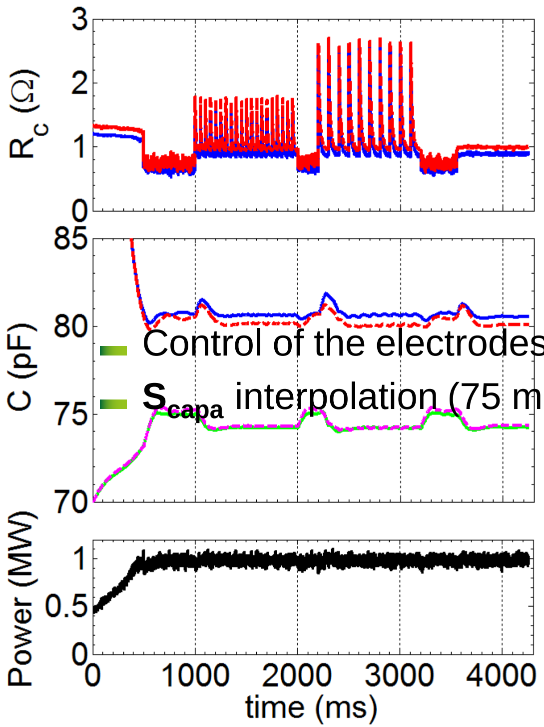


Block diagram of a WEST ICRF launcher as used for SIDON calculations

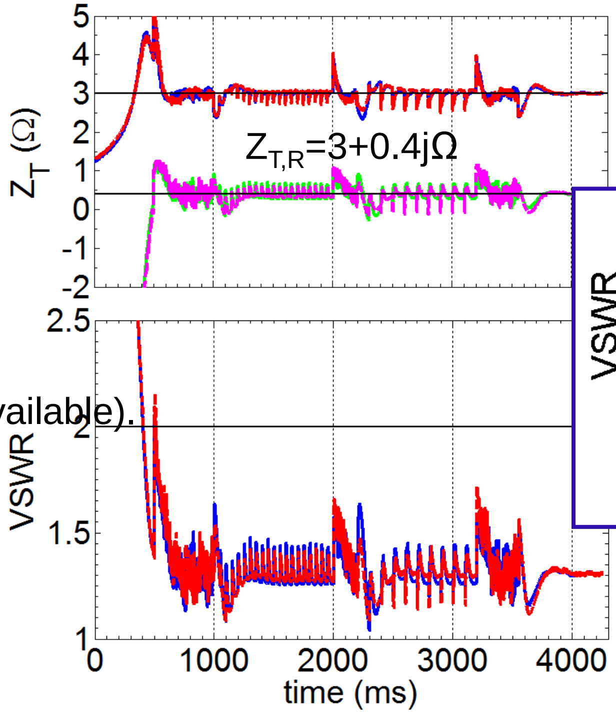


Simulations of operation scenarios for WEST ICRF launchers using SIDON

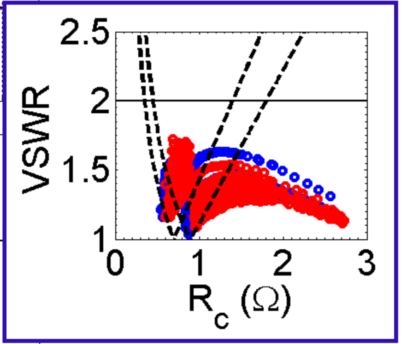
- Scenario is built.
  - $S_{front\text{-}face}$ interpolation.
  - Control of the electrodes overlap.
  - S_{capa} interpolation (75 matrices available).



- SIDON solves the RF network every *Δt=1ms.*



- Feedback control can be activated.



✓ Load-resilience