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

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Presented by: Walid Helou

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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Summary & potential common interest with particle-accelerator community

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).
Objective: nuclear fusion power plant.

\[ D + T \rightarrow \alpha (3.5 \text{ MeV}) + n (14.1 \text{ MeV}) \]

Electricity

Nuclear fusion reactor very attractive:
- No long-term nuclear waste.
- Runaway reactions are impossible.
- Reduced CO₂ emissions.
- T bred from Li in-situ.
- D and Li largely abundant.

However: need to overcome Coulomb forces, this requires \(~10-20\text{ keV} \equiv \sim150\times10^6 \text{ °C}\).


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).
General configuration:

- RF tubes
- Transmission lines
- Antenna Tuning Unit, when required
- Plasma-wave

$Z_{in,\text{antenna}} \neq Z_0 \rightarrow$ Power reflection.

$V_{\text{max}} \uparrow, I_{\text{max}} \uparrow$: arcing, overheating.

Reflection + losses: efficiency $\downarrow$.

System’s safety altered.

Impedance-matching is crucial.

$\rightarrow$ Wave-particles resonance.

$\rightarrow$ Current-drive or heating.
## MW-range electromagnetic heating and current-drive systems in nuclear fusion

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

### This talk

Generally, heating

Generally, current-drive

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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:

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>ICRF</td>
<td>~10 MW / 1.5s / 3 antennas, ~4 MW / 1s / 1 antenna.</td>
</tr>
<tr>
<td>LHRF</td>
<td>3.8 MW / 5s / 1 antenna, 2.7 MW / 78s / 1 antenna.</td>
</tr>
<tr>
<td>ICRF+LHRF</td>
<td>6.2 MW / 150 s.</td>
</tr>
</tbody>
</table>

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

9” rigid coaxial lines (Z₀=300Ω)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torus major radius</td>
<td>2.5 m</td>
</tr>
<tr>
<td>Torus minor radius</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Toroidal field</td>
<td>3.7 T @ R=2.5m</td>
</tr>
<tr>
<td>Plasma current</td>
<td>Up to 1 MA</td>
</tr>
<tr>
<td>ICRF power</td>
<td>Up to 9 MW</td>
</tr>
<tr>
<td>LHRF power</td>
<td>Up to 7 MW</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>Up to 1000s</td>
</tr>
</tbody>
</table>
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Particularities of the high power CWRF systems in nuclear fusion

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Summary & potential common interest with particle-accelerator community
Plasma-waves and implications on the RF system

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

$$\text{Stix tensor: } K = \begin{bmatrix} S & jD & 0 \\ -jD & S & 0 \\ 0 & 0 & P \end{bmatrix}$$

$$x \sim e^{-\frac{x}{L_{ev}}}$$

$D_{co}$

$\alpha_e > \alpha_{e,co}$

$\alpha_e = \alpha_{e,co}$

$\alpha_e < \alpha_{e,co}$

$\alpha_e = \alpha_{e,co}$

Excite proper plasma-wave $\rightarrow$ Proper antenna polarization.
Some particularities of the high power electromagnetic systems used in nuclear fusion

- High vacuum (<$10^{-5}$ Pa) & high temperature (~200°C) environment.
- Eddy currents $\rightarrow$ 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. $n_e$ $\uparrow$ by gas-puffing), optimize plasma shape, etc. in order to $V \downarrow / I \downarrow / |\Gamma| \downarrow$, 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.
  - 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

- $R \propto P/I^2 \propto P/V^2 \rightarrow R \propto \text{crucial.}$
- $|\Gamma_{\text{strap}}| > 0.9 \rightarrow \text{Matching mandatory.}$
- $Q \sim \omega R > 1 \rightarrow \text{Sensitive matching.}$
- $R \text{ very non-stationary.}$

Arrows indicate RF current direction

- Vacuum capacitor.
- Vacuum flange.
- RF feedthrough.
- $\lambda/4$ service stubs.
- 2-stage $\lambda/4$ imp. transf. (3 $\rightarrow$ 30Ω).

- $R_0/R$ \hspace{1cm} $R/R_0$

$VSWR_{\text{max}}$ \hspace{1cm} Typical $R$ variation

Non-resilient

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

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

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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).

RF diagnostics & securities.
- Vacuum measurements.
- Spectroscopic measurements.

Antenna validation before installation in the tokamak & accelerate commissioning on plasma
Detection within ~30 µs. Power tripping during ~30 ms 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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IRFM new developments at LHRF

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 mm²).
  - 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 $\phi$-shifter.

- $\text{TE}_{10} - \text{TE}_{30}$ mode converters and H-plane septa (vertical power splitting).

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

- 16 klystrons (8 per antenna).

Specs for a klystron:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>3.7 GHz ± 5 MHz</td>
</tr>
<tr>
<td>Power / 1000s</td>
<td>700 kW (VSWR&lt;1.1:1)</td>
</tr>
<tr>
<td></td>
<td>600 kW (VSWR&lt;1.4:1)</td>
</tr>
<tr>
<td>Efficiency</td>
<td>38-44%</td>
</tr>
<tr>
<td>Gain min</td>
<td>50 dB (5 cavities)</td>
</tr>
</tbody>
</table>

- 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.
- \( I_{\text{beam}} \) > 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.

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.

- LHRF metamaterial low-power loads:
  - Pre-qualification of LHRF antennas

mW prototype tested @ COMPASS tokamak

3D printed (metal) waveguide feeder
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Summary & potential common interest with particle-accelerator community
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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
### Heating at ICRF ($\sim$ 50 MHz)

Ion cyclotron resonance:

$$\omega - N\omega_{c,i} - \frac{k_z v_{z,i}}{\omega} = 0$$

### Current-Drive at LHRF ($\sim$ 5 GHz)

Landau resonance:

$$\begin{align*}
\omega - N\omega_{c,e} - k_z v_{z,e} &= 0 \\
\Rightarrow \frac{\omega}{k_z} &= v_{z,e}
\end{align*}$$

### Plasma-wave

- **Fast Wave (FW)**
  - Frequency ($f_0$)
    - $\omega = N\omega_{c,i}$ at required resonance layer ($\omega_{c,i} \propto B_{\text{static}}$).
    - $n_{e,co}$ $\downarrow$ when $f_0 \uparrow$
  - Polarization
    - $E \parallel y$-axis
    - $\rightarrow$ FW: suitable for IC resonance.
  - Spectrum
    - Typically, symmetric spectrum.
    - $|k_z M| \sim 5$-$15 \text{ m}^{-1}$.
    - $n_{e,co}$ $\uparrow$ when $|k_z| \uparrow$.
  - Typical $n_{e,co}$ & $L_{ev}$
    - $n_{e,co} \sim 10^{18}$-$10^{19}$ m$^{-3}$ ($D_{co} \sim 5$-$15$ cm)
    - $L_{ev} \sim 10$ cm.

- **Slow Wave (SW)**
  - Frequency ($f_0$)
    - $n_{e,co}$ depends only on $f_0$:
      - $n_{e,co}$ $\downarrow$ when $f_0 \downarrow$
  - Polarization
    - $E \parallel z$-axis
    - $\rightarrow$ SW: suitable for Landau resonance.
  - Spectrum
    - Asymmetric spectrum.
    - $|N_{zM}| > 1$ (absorption & propagation).
      - Typically: $|N_{zM}| \sim 2$.
  - Typical $n_{e,co}$ & $L_{ev}$
    - At 5GHz: $n_{e,co} = 3.1 \times 10^{17}$ m$^{-3}$.
    - $L_{ev} \sim 5$ mm.
Need for array antennas

Example: LHCD case at 5 GHz ($\lambda_0=60$mm)

- Use a single radiator $\rightarrow$ Technically non-trivial.
- Spatial sampling $\rightarrow$ Phased array antennas.

Sampling:
- Spectrum periodization & grating lobes.

Directivity $\downarrow$
ICRF case: R a very sensitive & variable parameter

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

- Edge density profile hardly controllable → Same for R.

- Transitions of plasma confinement modes & plasma edge instabilities impact much edge density profile & R.
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: $VSWR < VSWR_{\text{max}} \approx 2$):
    → 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)

![Graph showing typical R variation and VSWR curves](image)
The “T” locations

Capacitor: cylindrical concentric electrodes (with V-probes)

Bridge: ~3-branch node

Imp. transformer

RF window

Service-stub

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.
  - $S_{\text{front-face}}$ interpolation.

- SIDON solves the RF network every $\Delta t = 1 ms$.
  - $Z_{T,R} = 3 + 0.4j \Omega$

- Feedback control can be activated.

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

- Load-resilience

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