ICRF Heating for SPARC

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ICRF = Ion Cyclotron Range of Frequencies
SPARC V0: nominal starting point

SPARC V0 technical objectives:

- Burn D-T fuel
- \( Q > 2 \) (with headroom)
- \( P_{\text{fusion}} > 50 \text{ MW up to 100 MW} \)
- Pulsed with 10 s flattop burn (about \( 2 \times \tau_{\text{CR}} \))
- ~1,000 D-T pulses, >10,000 D-D full-power pulses
- ~1 hr D-T pulse repetition rate
- ~15 minutes between D-D shots

\[
\begin{array}{|c|c|}
\hline
\text{Parameter} & \text{Value} \\
\hline
R_0 & 1.65 \text{ m} \\
\alpha & 0.5 \text{ m} \\
\varepsilon & 0.33 \\
\kappa & 1.8 \\
\mathbf{B}_0 & 12 \text{ T} \\
I_p & 7.5 \text{ MA} \\
B_{\text{max}} & 20.9 \text{ T} \\
P_{\text{fus}} & 50-100 \text{ MW} \\
\hline
\end{array}
\]

Desired schedule:

- R&D: 3 years
- Construct: 4 years
- Operate: 5 years
- Decommission: 4 years

ICRF for SPARC
Build upon the success of ICRF on Alcator C-Mod

ICRF system on C-Mod
- \( f = 50-80 \text{ MHz} \) for \( B = 3-8 \text{ T} \)
- 3 antennas (8 straps)
- 8 MW source
- Power to plasma \( \leq 6 \text{ MW} \)

• 20+ years experience of delivering ICRF power for day-to-day tokamak operation
  – Supporting research efforts in most scientific areas;
  – **ICRF physics research**: minority heating, mode conversion heating and flow drive, 3-ion heating, wave detection, fast ion physics, RF sheath physics and full wave modeling.
  – **RF engineering development**: field-aligned antenna, fast ferrite tuning system, etc.

• **Insights and lessons from C-Mod for SPARC**
  – Use tested physics as the main heating method
  – Choose simple and robust design for antennas and transmission lines
  – Set realistic goals for antenna performance
  – Make quick iterative improvements
SPARC V0 plan for the ICRF system

- **Operation frequency: 120 MHz**
  - $^3$He ion cyclotron frequency at $B = 12$ T
  - 2nd harmonic tritium ion cyclotron frequency

- **Number of antennas: 12**
  - Antennas at 4 toroidal locations (3 antennas per location)
  - 4 current straps per antenna

- **Total RF source power: $\geq 50$ MW**
  - Two 2 MW sources for each antenna
  - Max power 4 MW/antenna at $V_{\text{max}} \approx 40$ kV.

- **Total power to plasma: $\geq 30$ MW**
  - Set modest target for antenna performance
  - $\geq 2.5$ MW/antenna at $V_{\text{max}} \geq 30$ kV.

“When you build a bridge, you insist that it can carry 30,000 pounds, but you only drive 10,000-pound trucks across it. And that same principle works in investing building an ICRF heating system.” — Warren Buffett
SPARC with RF transmission lines
Layout of the RF power room
## Key issues for ICRF heating

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3He minority heating will be effective in SPARC D-D plasmas

- **Key parameters for fast wave single-pass absorption:**
  - $\omega = \omega_{c,\text{He}}$
  - 3He fraction $n_{\text{He}3}/n_e$ for wave polarization and power absorption.
  - Doppler width of the IC resonance layer \( \Delta \propto k_{||} \times R_0 \times (\text{tail temperature})^{0.5} \)

- **Experience:**
  - **C-Mod**: D(3He) minority heating worked although not as effective as D(H) minority heating.
  - **JET**: D(3He) heating is the main method and it has excellent absorption.

- **Absorption of D(3He) minority heating on SPARC will be similar to that on JET.**

*Single-pass-absorption formulas from M. Porkolab, the Stix Symposium, 1992.*
$^3\text{He}$ minority heating will be effective in SPARC D-T plasmas

- **Key parameters:**
  - $\omega = \omega_{c,3\text{He}}$
  - $^3\text{He}$ fraction.
  - $T(^3\text{He})$ is as effective as $D(H)$ because of identical $(Z_m/A_m)/(Z_M/A_M)$ of the two species.

- **Experience:**
  - $T-(^3\text{He})$ is a proven heating method in D-T experiments on JET/TFTR.
  - $D(H)$ minority heating is the main heating method on C-Mod.

- **Absorption of $T(^3\text{He})$ minority heating on SPARC will be similar to $D(H)$ on C-Mod.**

![Absorption Coefficient vs Minority Fraction](chart)

$T(^3\text{He})$ single pass absorption is as good as $D(H)$ on C-Mod
Synergy of 2\textsuperscript{nd} harmonic T heating and $^3$He minority heating will lead to excellent core absorption in SPARC D-T plasmas

- **Key parameters:**
  - $^3$He minority heating can start at low temperature and then drive up tritium $\beta_T$.
  - 2\textsuperscript{nd} harmonic T heating ($\omega = 2\omega_{c,T}$) is self-boosting: the higher $\beta_T$, the better absorption.

- **Experience:**
  - Combined heating has been shown to work well in D-T plasmas on both TFTR and JET.

- **D-T($^3$He) heating will be utilized for ICRF heating in SPARC D-T plasmas $\rightarrow$ Core wave absorption will be excellent.**

On JET, $4\%$ $^3$He greatly increased neutron emission over heating with 2\textsuperscript{nd} harmonic T only. [From D. Start et al, Nuclear Fusion 39, 321 (1999)]
Antenna loading is often the limiting factor for the maximum power a system can deliver.

On most tokamaks, loading $\propto \exp(-k_{||}d)$
- Where $d$ is distance from antenna to the cutoff layer, $n_{\text{cutoff}} \approx 0.5-1 \times 10^{19} \text{ m}^{-3}$ and $k_{||}$ is determined by antenna geometry and operation phase.

SPARC and C-Mod have $d \approx 0 \rightarrow$ inherent high loading
- On C-Mod, ICRF cutoff is in the limiter shadow, and antenna loading is always high, only varying with some 2nd order effects, e.g., pedestal height/width.
- On SPARC, $n_e/n_G \sim 0.3 \rightarrow n_e \approx n_{\text{cutoff}}$ in front of the antennas, i.e., a similar situation to that on C-Mod.
- This is as good as it gets for antenna loading.
Optimizing \( k_{\parallel} \) to achieve both good absorption and coupling

- \( k_{\parallel} \) is an important parameter
  - Set by phase difference and spacing between adjacent antenna straps.
- **SPARC**: plenty of headroom for \( k_{\parallel} \) to have both good heating and good coupling
  - More advantageous than most other tokamaks
- We can optimize \( k_{\parallel} \) through an integrated antenna/machine design.
  - Choice of \( k_{\parallel} \) sets approximate antenna size;
  - Need to integrate tokamak port design with antenna installation, antenna radial movability and accessibility for maintenance.

\[
\begin{align*}
\text{Smaller } k_{\parallel}, \text{ better coupling} & \\
\text{Larger } k_{\parallel}, \text{ better absorption} & \\
k_{\parallel} \sim 15 \text{ m}^{-1} \text{ at } R_0 & \rightarrow k_{\parallel} \sim 11 \text{ m}^{-1} \text{ at antenna} \rightarrow \text{toroidal extension } \sim 0.6 \text{ m for the 4 straps at } [0, \pi, 0, \pi] \text{ phase.}
\end{align*}
\]
Impurity generated by ICRF heating will be mild on SPARC

• **Methods to deal with the impurity issue associated with ICRF heating**
  – Minimize parasitic RF field $\rightarrow$ ICRF heating in conditions with good absorption and coupling.
  – Run plasma regimes that have high tolerance for impurities $\rightarrow$ For example, I-mode.
  – Minimize $E_\parallel$ $\rightarrow$ C-Mod field-aligned antenna.
  – Minimize RF image currents $\rightarrow$ AUG 3-strap antenna and C-Mod 3-strap operation.
  – Other knobs: puffing noble gases in front of antennas, boronization, etc.
  – On JET, ICRF has been used to tailor impurity profiles in NBI heated H-mode plasmas.

• **SOL ICRF physics is an active research area**
  – ITPA IOS-5.1 has joint experiments on EAST, JET and ASDEX-upgrade, plus ICRF SOL modeling.

• **SPARC**
  – Excellent core absorption and good coupling $\rightarrow$ Low parasitic RF field
  – Likely I-mode operation (from C-Mod experience) $\rightarrow$ High tolerance for impurities
  – Antenna design will be based on the latest understanding of ICRF SOL physics
Summary: ICRF heating for SPARC

• ICRF heating will have excellent power absorption and good coupling. Impurity will not be a serious issue.
• Use integrated machine + antenna design for system optimization.
• Set a conservative performance target for reliable total antenna power.
• Help from the community is welcome
  – Physics: core RF physics modeling, RF SOL modeling for coupling and impurities
  – Diagnostics: wave detection, fast ions detection and edge profiles
  – Engineering: antenna design and modeling, RF transmission lines (transient matching and arc detection) and power systems, etc.

SPARC open meeting: Today (11/6) at 5PM, Room C123, Convention Center
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