Discussion Starter: Developing the RFP Reactor Concept

John Sarff
UW-Madison
The RFP is best known as a high beta, compact fusion reactor option

- Since 1990, the TITAN system study has defined the RFP development target
- TITAN concept has attractive/novel features:
  - Steady-state, via oscillating field current drive
  - High core radiation for power handling, uniform on first wall surface
  - Single-piece maintenance
  - Low cost-of-electricity (COE) projection

### TITAN Parameters

- \( a = 0.6 \text{ m} \)
- \( R = 3.9 \text{ m} \)
- \( I = 18 \text{ MA} \)
- \( \beta_\theta = 23\% \)
- \( \tau_E = 0.15 \text{ s} \)
- 2300 MW fusion
- 970 MW net elec.
TITAN is very compact … on purpose, to assess the potential benefits of a compact fusion power core

TITAN wall loading:
• 18 MW/m² neutrons
• 4.6 MW/m² radiation
Recent re-analysis of the TITAN system shows a new COE minimum at lower wall loading

- The TITAN system code was reactivated, updated, and “validated” (R. Miller)
- Minimum COE point shifts from ~ 18 MW/m\(^2\) to ~ 12 MW/m\(^2\)
- More striking is the flat COE beyond a threshold \(P_n/A \sim 5\) MW/m\(^2\)

COE levels out where plasma minor radius ~ blanket thickness

Ron Miller, Decysive Systems

If compactness does not yield reduced COE, what are the RFP’s advantages in solving fusion’s challenges?
The RFP’s relative simplicity could greatly enhance the reliability and maintainability of a fusion power core

- Reduced magnetic field at magnets (not average $B$ in the plasma!)
- Possibility for ohmic heating to ignition, without complex auxiliary heating apparatus facing a burning plasma
- While the projected cost of electricity saturates for $P_n/A > 5 \text{ MW/m}^2$, (shielded) copper magnets and simple heating could greatly improve reliability and maintainability relative to a comparable-size high beta tokamak/stellarator
- High beta permits access to compact core with very high wall loads and “true” single-piece maintenance, if material feasibility (and confinement) is resolved
- Major issues that need to be resolved:
  - Confinement at reactor parameters
  - Current drive consistent with confinement requirements
  - Self-consistent plasma-boundary interface
  - Disruptions/terminations (but probably not runaway electron generation)
  - Complexity associated resistive-wall-mode control
A $P_n/A \sim 5 \text{ MW/m}^2$ RFP system would operate well within copper magnet capability.

- $B_{\text{coil}} = B(a)$ for illustration below

Figure from FESAC “Priorities, Gaps and Opportunities: Towards a Long-Range Strategic Plan for MFE”
Single-piece maintenance a game-changer? Is this spoiled at tokamak-like wall loads?

- TITAN blanket cooling tubes also serve as the toroidal field coil.

1. VACUUM TANK LID
2. UPPER OH COILS
3. UPPER HOT SHIELD
4. TORUS ASSEMBLY

TITAN maintenance (once/year)
Projection of system size and $B$ for varied wall loads

- Power scaling for ohmic heating, taking $T$ fixed ($\sim$10-15 keV)

\[
P_f \sim n^2 V \sim n^2 a^2 R \sim \beta^2 B^4 a^2 R \sim \beta^2 I^4 R/a^2 \sim \left( \frac{\beta^2 I^4}{a^3} \right) \frac{R}{a^2}
\]

\[
P_\Omega \sim I^2 R/a^2
\]

- Scale with fixed $P_f$ and $\beta$ to different wall load and aspect ratio

|         | $R / a$       | $P_n / 4\pi^2 aR$ [ MW/m²] | $I_p$ [ MA] | $|B(a)|$ [ T] | $n / n_G$ (fixed T) | $\beta_\theta$ [%] | $P_\Omega$ (sustained) |
|---------|---------------|-----------------------------|-------------|--------------|---------------------|-------------------|---------------------|
| TITAN   | 3.9 / 0.6 = 6.5 | 20                          | 18          | 6.0          | 0.63                | 22                | 30                  |
| TITAN $R/a$ | 7.8 / 1.2 = 6.5 | 5                           | 22          | 3.7          | 0.73                | 22                | 23                  |
| Moderate $R/a$ | 6.1 / 1.53 = 4.0 | 5                           | 26          | 3.4          | 0.89                | 22                | 15                  |
| Moderate $R/a$ | 6.1 / 1.53 = 4.0 | 5                           | 30          | 3.9          | 0.5 T=13 keV        | 15                | 20                  |

Scaling consistent with analysis using TITAN systems code
Ohmic heating power balance for $I_p=30$ kA, $R/a=4$, $\beta_\theta=15\%$ with neutron wall load of $5 \text{ MW/m}^2$ @ $2.3 \text{ GW}$ fusion power.

\[ \frac{J}{B} \sim 1 - r^4 \]

\[ T \sim 1 - r^2, \quad n \sim 1 - r^8 \]

\[ Z_{\text{eff}} = 2, \quad Z_{\text{neo}} = 2 \]

\[ \tau_E = \frac{3nT_e}{P_\Omega - P_{\text{brem}} - P_{\text{synch}}} \]

\[ \chi_{\text{eff}} = \frac{a^2}{4\tau_E} \]
Confinement required for RFP ohmic ignition

RFP Ohmic Ignition -- Required Energy Confinement Time [s]

- $n/n_\text{GW}$
- $Q=50$
- $Q=100$
- $\beta_{\text{pol}}=0.2$
- $\beta_{\text{pol}}=0.05$
- Sealed/ITER

$P_\text{fus}=2.3 \text{ GW}$, $P_{n/A}=5 \text{ MW/m}^2$, $l_p=30 \text{ MA}$, $a=1.53 \text{ m}$, $R/a=4.0$, $<B>=5.6 \text{ T}$, $B(a)=3.9 \text{ T}$, $B_{\text{coil}}=3.0 \text{ T}$, $Z_{\text{eff}}=2$, $Z_{\text{neo}}=2$
A scaling for the stochastic RFP?

- MST and RFX both see a trend of increasing $T_e$ with $I_p$

  \[ T_e(0) \sim I_p^{0.67} \left( \frac{n}{n_{GW}} \right)^{-0.51} \] (MST, Stoneking et al)

  \[ T_e(0) \sim I_p^{0.69} \left( \frac{n}{n_{GW}} \right)^{-0.31} \] (RFX, Innocente et al)

  \[ T_e(0) \sim I_p^{0.93} \left( \frac{n}{n_{GW}} \right)^{-0.35} \] (RFX-Mod, CMC, Innocente et al)

- For stochastic transport scaling with Lundquist number

  \[ \chi \sim \nu_{th} L_{ac} (\tilde{b} / B)^2 \sim T^{1/2} a S^{-2\alpha} \]

- Balancing ohmic heating and conduction yields

  \[ T \sim a^{\frac{1+2\alpha}{3-3\alpha}} Z_{\Omega}^{\frac{1-2\alpha}{3-3\alpha}} I_p^{\frac{1+\alpha}{3-3\alpha}} \left( \frac{n}{n_{GW}} \right)^{\frac{-(1+\alpha)}{3-3\alpha}} \]

- For $\alpha \approx 1/3$ (for minor radius scaling), with MST’s trend $T_e(0) = 5.0 a^{0.83} I_p^{0.67} \left( \frac{n}{n_{GW}} \right)^{-0.51}$

- (Caveats: profiles, $Z_{eff}$, validity of $S$-scaling, ...)
Possibility that stochastic transport is acceptable? (i.e., is the “standard” RFP acceptable?)
What should next steps be on the RFP development path?

- Build on progress in last decade in improved confinement, control of resistive wall modes, and demonstrated high beta.
- MST is not saturated in its capabilities, but its limits in current and pulse length are being felt, while RFX shows transformational new trends at high current.
- Resolution of high priority issues in confinement and sustainment requires higher current, longer pulse length.

Conceptual development path for the RFP, output from TAP/ReNeW.

- RELAX, …
- Extrap-T2R, now KTX!
Some suggestions for today’s discussion

- Is a pulsed fusion system acceptable? Is a pulsed RFP better/worse than a pulsed tokamak? How to answer?

- How to assess the virtues of ohmic ignition and copper magnets in realizing the *essential* need for reliability and maintainability of a fusion reactor? Are systems studies to date realistic in addressing/costing RAMI (reliability, availability, maintainability, inspectability)?

- How to integrate boundary control (heat, particles)? Sensitive need for maintaining close proximity to conducting shell/feedback coils?

- RFP plasmas do not “disrupt” the same way as tokamak plasmas, but like all plasma systems, they will “terminate.” What are consequences?

- What is the appropriate next (large) step from present-day facilities?

- How to promote the RFP development path? Robust solution to RAMI? Neutron source? Materials and boundary interface?

Or whatever points you’d like to raise…