# Current Drive and Heating on ARIES-RS/AT, and FIRE-AT

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**Heating and Current Drive Breakout Session**

**Burning Plasma Workshop II**

**May 1-3, 2001**

**General Atomics**

# OUTLINE

- ARIES-RS and ARIES-AT H&CD Scenarios
  - RF system requirements
  - Choice of wave launchers
- RFCD assessment for FIRE AT modes, based on ARIES experience:
  - without wall stabilization, moderate beta normal
  - with wall stabilization, high beta normal
- Issues and Conclusions

# Heating and Current Drive Analysis Objectives for ARIES

- Determine and understand current drive power requirement, a critical element in systems analysis for the power plant economics.

- Select most viable current drive schemes for maintaining high performance, MHD-stable plasma equilibria, according to:

  1. **Core accessibility**
  2. **Current drive efficiency**
  3. **Profile control capability**
  4. **Experimental data base and physics understanding**
  5. **Power generation efficiency**
  6. **Dual capability of current drive and auxiliary plasma heating**
  7. **Core compatibility of in-vessel components.**

- Determine current drive source and power launcher requirements,

  **e.g., frequency and spectrum for RF launchers,**
  **beam energy and injection angle for NBI systems,**

  **and** select launcher configuration compatible with fusion core.

- Identify (and resolve) issues and areas for further research.

# Physics Models Used in
# RF Heating and Current Drive Analysis for ARIES

Main analysis tool is the CURRAY ray tracing code (developed with GA), with state-of-the-art features:

- Wave absorption physics:
  - **Cold ion ($k_x \rho_i << 1$), warm electron dispersion relation**
  - **Thermal ion and electron effects in field polarization terms when calculating linear damping decrement along rays**
  - **Energetic ion species (e.g., alphas) are treated either as <u>hot Maxwellian</u> or having slowing down distribution**
  - **Calculates absorption profiles, due to cyclotron resonance, Landau and TTMP processes, for all species**
- Current drive physics:
  - **Calculates local driven electron currents**
  - **Developed normalized j/p efficiency formulas due to Ehst-Karney and Chiu-Mau (relativistic correction)**
  - **Self-driven current [= bootstrap + diamagnetic + Pfirsch-Schlutter] is calculated for multiple ion species for all collisional regimes on exact equilibrium and self-consistent (p, n, T) profiles.**
  - **Developed algorithm to maximize alignment of driven to equilibrium j-profile**
- Coupled to high-precision equilibrium geometry (JSOLVER)

# Current Drive Scenarios for ARIES-RS/AT 1-GWe Power Plants

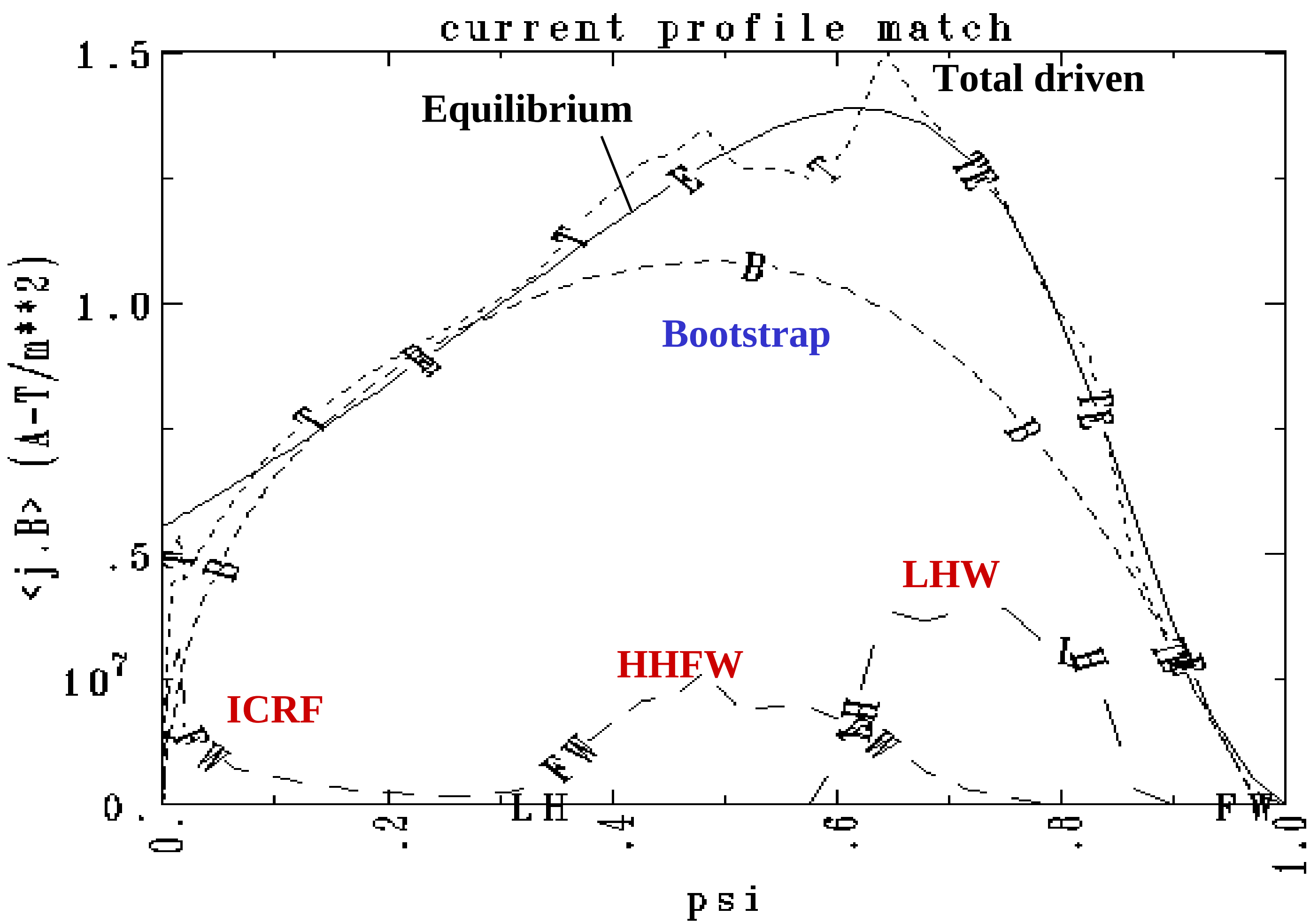
**ARIES-AT requires much less current drive power than ARIES-RS because of much better bootstrap alignment.**

| Device | ARIES-RS | ARIES-AT |
|---|---|---|
| R (m) | 5.5 | 5.2 |
| A | 4.0 | 4.0 |
| $\kappa$ | 1.89 | 2.18 |
| $\delta$ | 0.77 | 0.84 |
| $I_p$ (MA) | 11.3 | 12.8 |
| $\beta$ (%) | 5.0 | 9.2 |
| $I_{bs} / I_p$ | 0.88 | 0.915 |
| On-axis CD* | ICRF/FW | ICRF/FW |
| Off-axis CD* | HHFW,LHW | LHW |
| Power (MW) | 82.0 | 41.6 |

* **ECCD can be localized at all radii, but was not used here due to low current drive and source efficiencies.**

# Current Drive Scenario for ARIES-RS

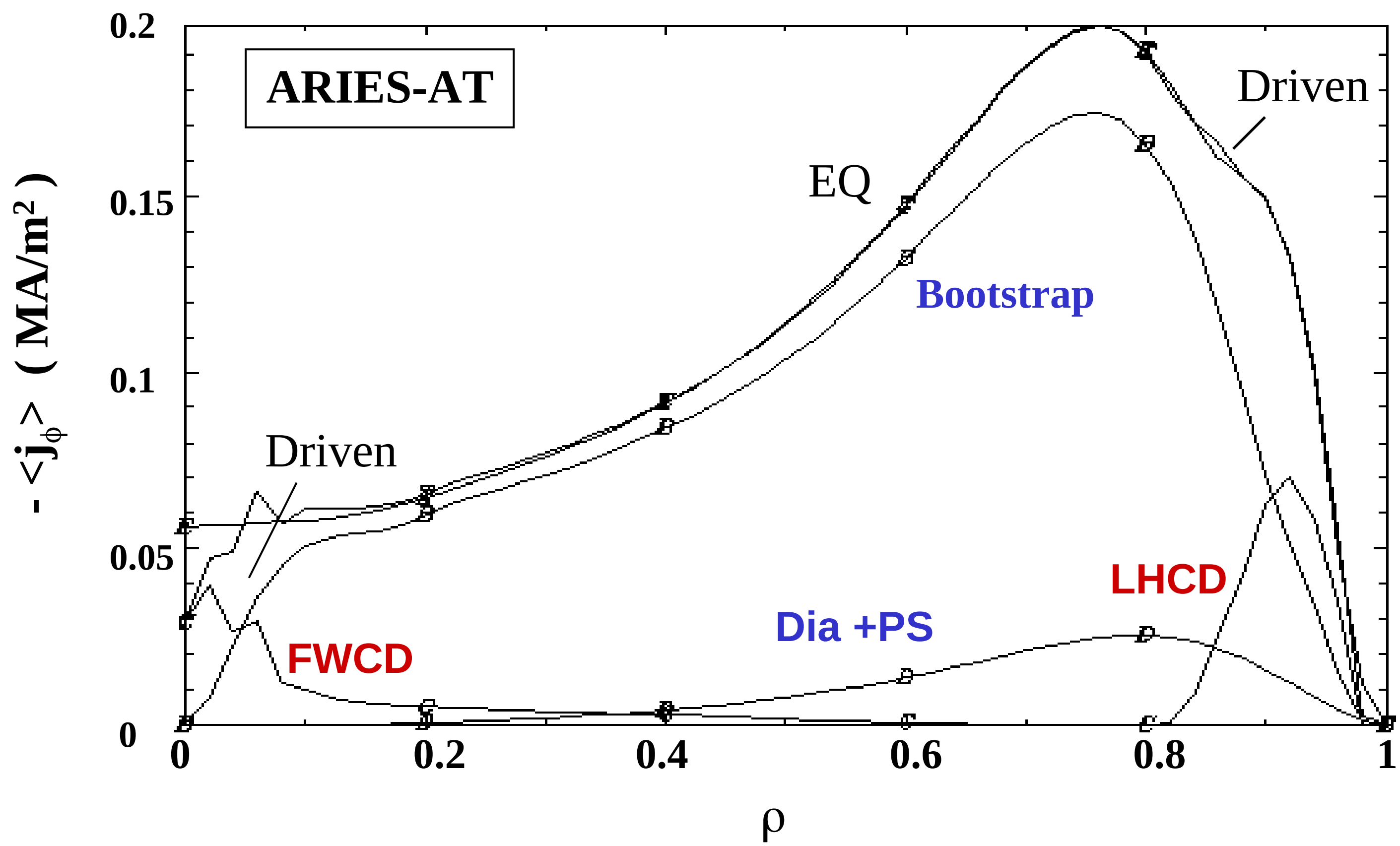
- **3 RF schemes are required to drive the seed currents on ARIES-RS:**
  **(1) ICRF fast waves for on-axis drive: 23.2 MW @ 98 MHz**
  **(2) LH waves for off-axis drive: 47.1 MW @ 3.5 - 4.6 GHz**
  **(3) HHFW (~ 20 $f_{cD}$) for mid-radius drive: 37.6 MW @ 1 GHz**



# Current Drive Scenario for ARIES-AT

- **2 RF systems are required to drive the seed currents on ARIES-AT:**
  **(I) ICRF fast waves for on-axis drive: 4.7 MW for 0.15 MA**
  **(2) LH waves for off-axis drive: 36.9 MW for 1.1 MA**
  **(3) Better Bootstrap alignment eliminates need for 3rd CD system.**

$\gamma_{CD} = 0.32 \times 10^{20}$ **A-T/W/m²**



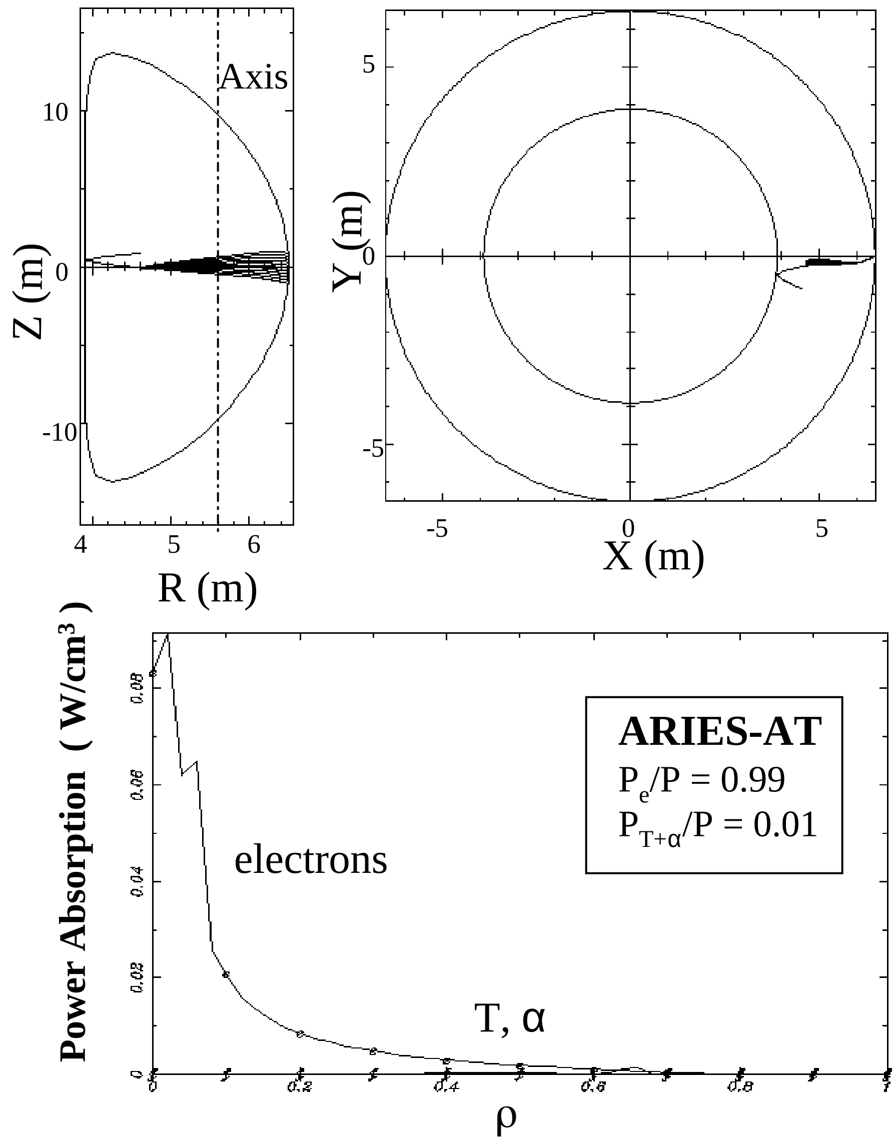
# ICRF Fast Wave Drives On-axis Seed Current

- Wave frequency is chosen to place $4f_{cT}$ resonance at $R > R_o+a$, and $2f_{cD}$ resonance at $R << R_{axis}$, to minimize ion and a absorption.

- Launcher is located on outboard midplane with $N_{||} = 2$ spectrum for best current profile alignment.

- Plasma & wave parameters :

  $T_{eo}$ = 29 keV, $n_{eo,20}$ = 2.95,
  $Z_{eff}$ = 1.8
  f = 96 MHz, $N_{||}$ = -2.0.
  $P_{cd}$ = 4.7 MW

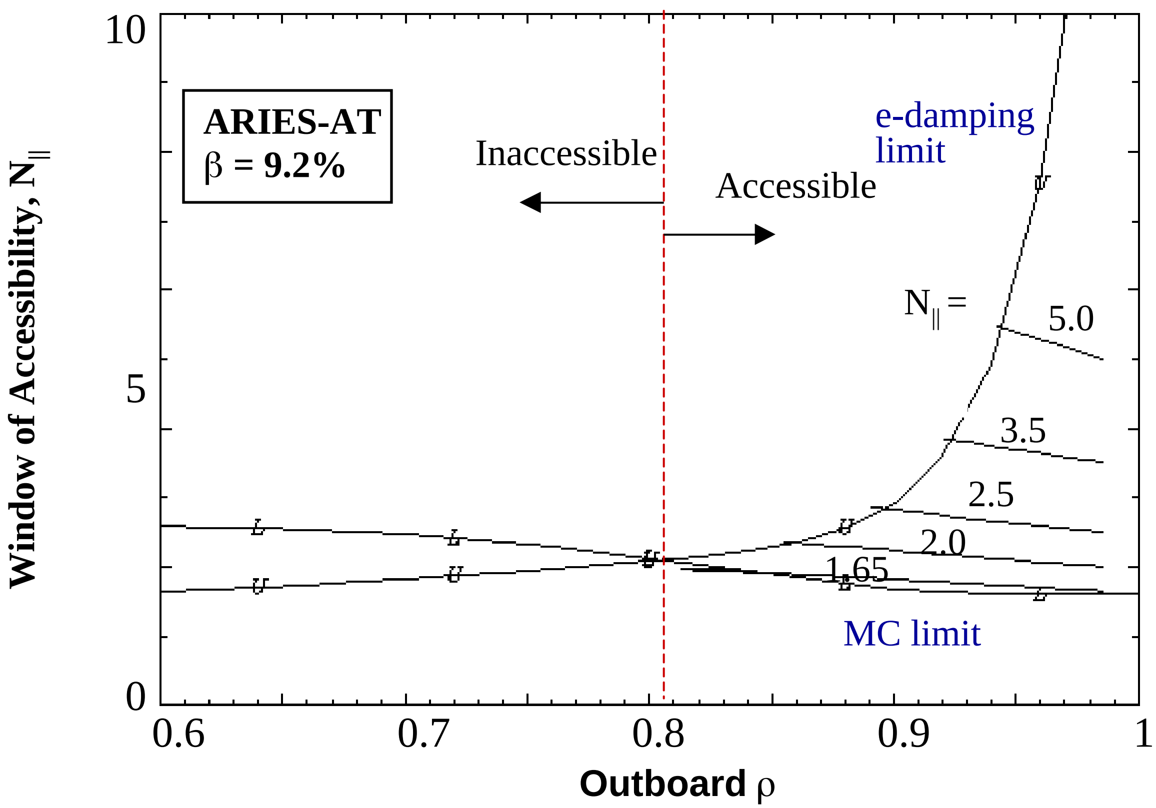


# LH Wave Penetration is an Issue in High-β Plasmas

- **Frequency = 3.6 GHz [ > 2 x $f_{LH}$ (r=0.8) ]**
  - **Less than 1% a absorption, even though f=9.3 GHz to eliminate a-damping.**
- **There is a window in $N_{||}$ for accessibility to the core:**

$$[\, 1 + (f_{pe}/f_{ce})^2 \,]^{1/2} + f_{pe}/f_{ce} < N_{||} < 7.0/T_e^{1/2}\ (\text{keV})$$

- **Penetration is limited to ρ > 0.8 for the high-β AT equilibrium. [ $\beta \sim (f_{pe}/f_{ce})^2$ ]**
  **Low $N_{||}$ rays encounter mode conversion to fast wave at r > 0.8;**
  **higher $N_{||}$ rays get totally damped before reaching ρ = 0.8.**



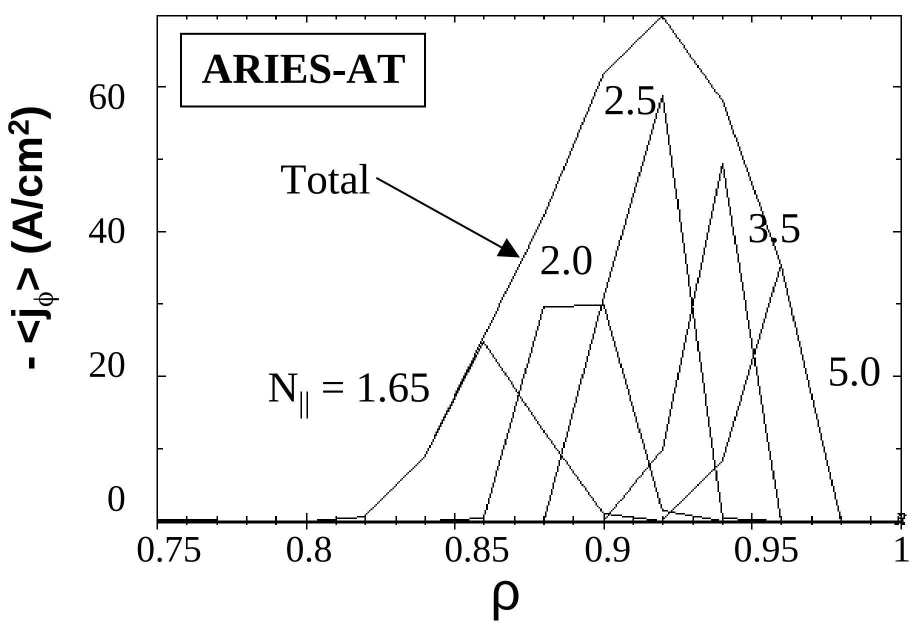
# Off-Axis Current Drive Requires Tailored LH Power Spectrum

- Five waveguide modules, each launching a different $N_{||}$ spectrum, are used to drive the required off-axis seed current profile. These are located about $90^o$ (~2m.) below the outboard midplane.

- Extended physics model found α absorption to be negligible for off-axis drive at ρ > 0.8. Frequency can be lowered for high $N_{||}$ launch at outer plasma region, thus easing design of waveguide launcher.

- The tailored LH spectrum has following parameters:

| f(GHz) | $N_{\parallel}$ | P(MW) | $I_{cd}/I_{sd}$ |
|---|---|---|---|
| 3.6 | 1.65 | 3.06 | 0.15 |
| 3.6 | 2.0 | 4.40 | 0.20 |
| 3.6 | 2.5 | 8.22 | 0.30 |
| 3.6 | 3.5 | 8.87 | 0.20 |
| 2.5 | 5.0 | 12.39 | 0.15 |



# ARIES and FIRE have Different Design Features

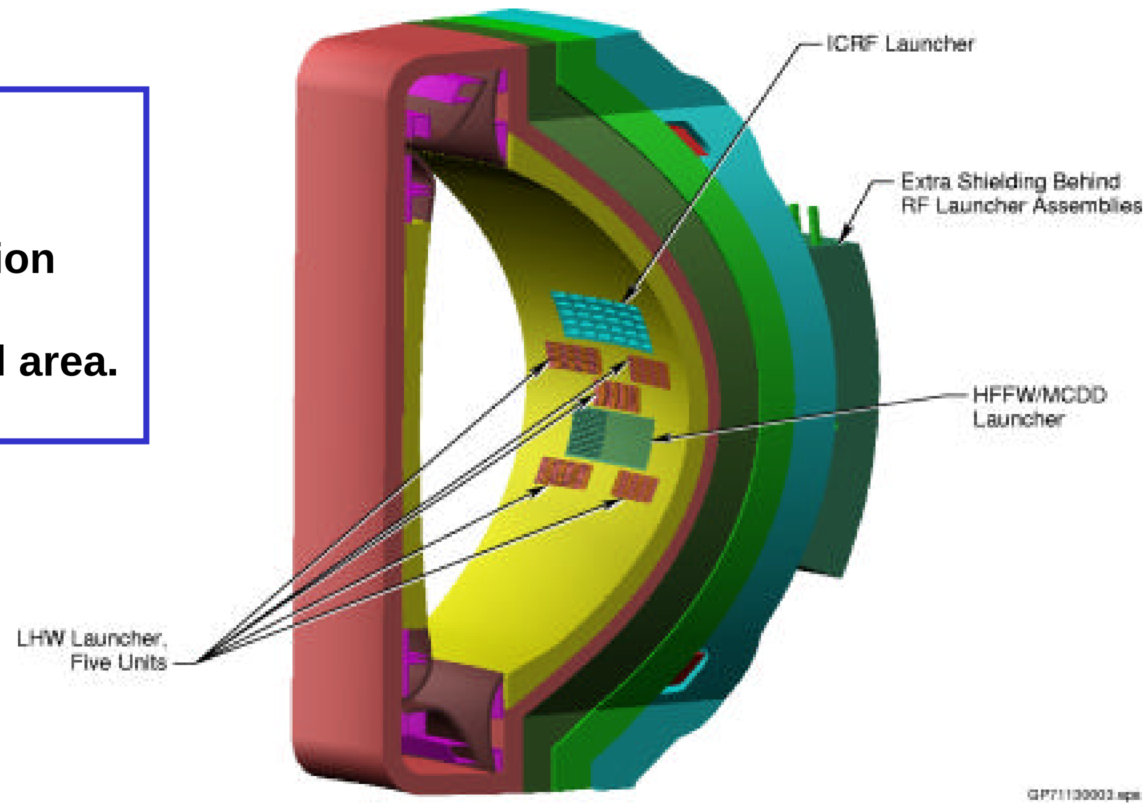
| ARIES | FIRE |
|---|---|
| • Single mode of operation | Multiple Modes (Elmy-H, AT with and w/o wall stabilization, D and DT) |
| • RF power exclusively for CD | RF power heat ions and drive current at same time; depends on operating mode |
| • Large size and high β → strong single-pass damping | smaller size and lower β → weaker single-pass damping |
| • Incorporate innovative concepts for launchers | Use conventional launchers |
| • Minimal launcher port size | Port size not crucial consideration |

# ALL RF Launchers Fit in One Blanket Sector on ARIES

- To minimize intrusion in power core requires RF launchers with high power density ($MW/m^2$) capabilities.
  - ICRF/FW : Folded waveguide [ ORNL ]
  - LHW : Active/passive waveguide grille [ ITER-EDA ]

**In ARIES-RS:**

**Total first-wall penetration**
**= $2.53\ m^2$**
**= 0.6% of wall area.**




**Implications for FIRE: Use loop antennas for ICRF/FW, as port size is not a crucial consideration.**

## CD Requirements are Substantial for FIRE-AT w/o Wall Stabilization

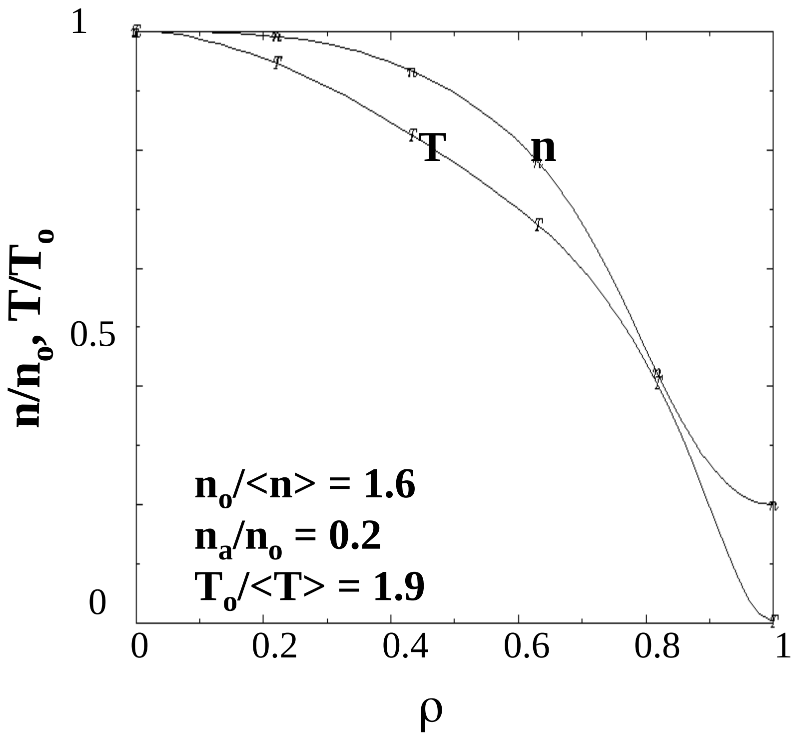
- Based on a FIRE-AT mode equilibrium (from Kessel), amount of current to be driven is **2.29 MA**, for the following parameters:

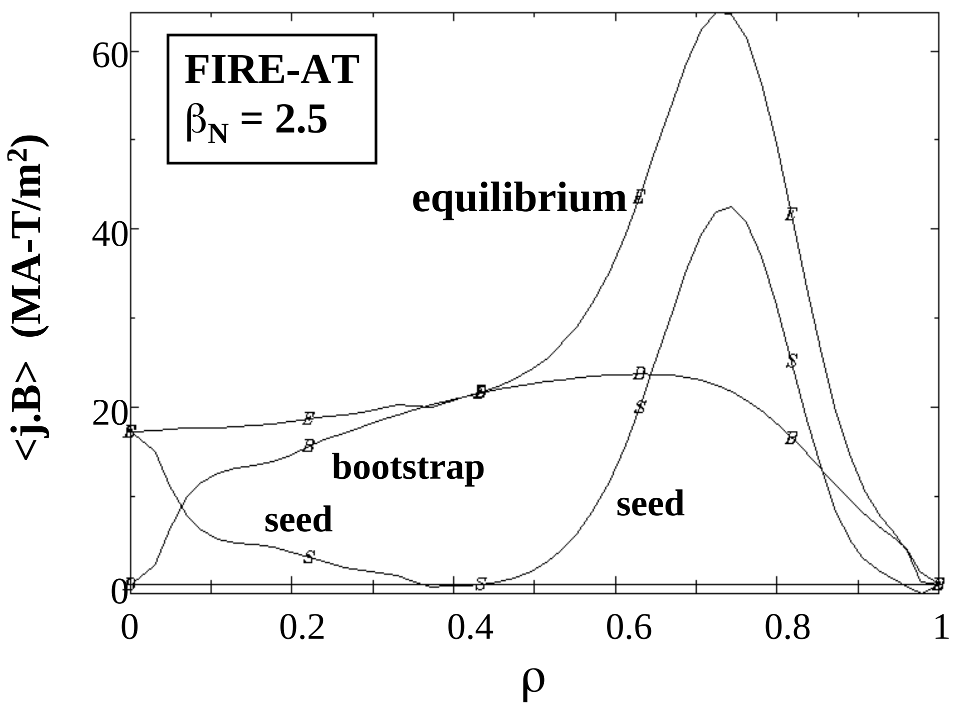
  $R = 2$ m, $a = 0.52$ m, $B_o = 8.5$ T, $I_p = 5.34$ MA,

  $T_{eo} = 19.9$ keV, $n_{eo} = 3.34\times10^{14}$ cm$^{-3}$, $Z_{eff} = 1.41$ (1.3% Be , 17.2% He)

  $\beta = 2.98\%$, $\beta_N = 2.54$ (w/o wall stabilization of kink) , $I_{BS}/I_p = 0.57$

  High edge density : $n_e(a) / n_{eo} = 0.2$



# CD Power Requirement is Substantial

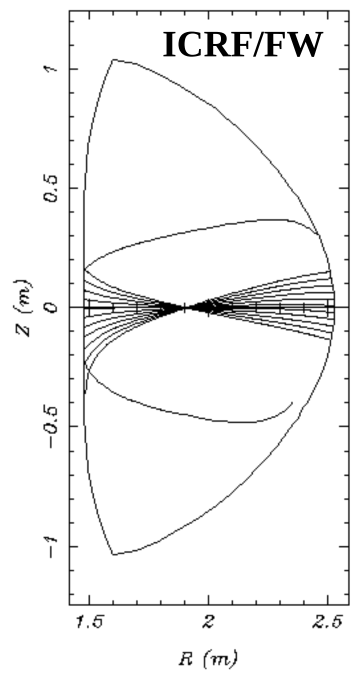
- **On-axis CD:**
  **ICRF/FW @ 3.6 MW**
  **100 MHz, $N_{||} = 2$**
  **$P_{Be}/P = 0.23$, $P_T/P = 0.16$**

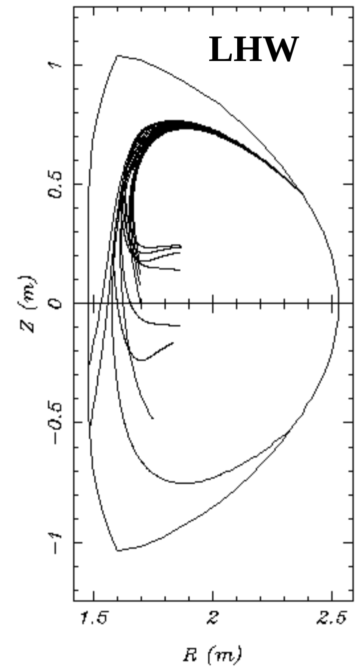
- **Off-axis CD:**
  **LHW @ 17.7 MW, $P_\alpha/p = 0.03$**
  **4.6 MHz**
  **$N_{||o} = 1.85$**
  **$\Delta N_{||} = 0.3$**
  **Launched from 60° above midplane***

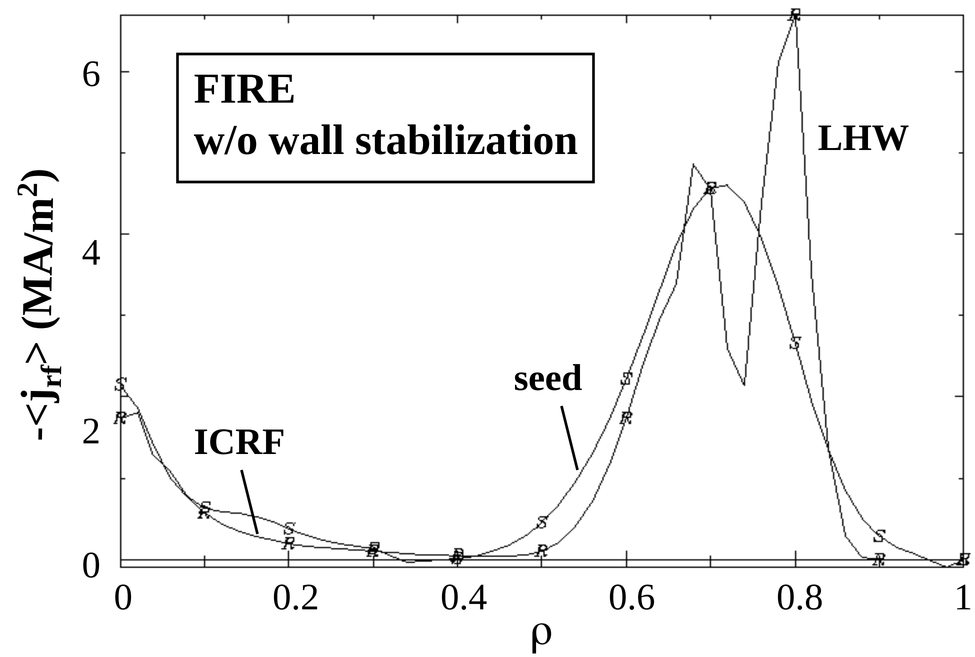
  *** Above midplane launch is required for deeper penetration.**

- **Reasonable alignment with seed current profile is obtained.**

  - **Total Power ~ 21 MW**
  - **Efficiency is $\gamma_{cd}$ ~ 0.44.**

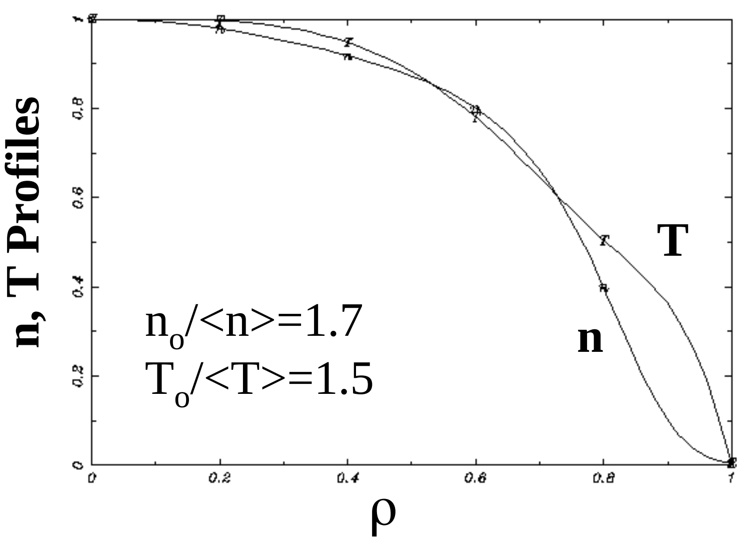


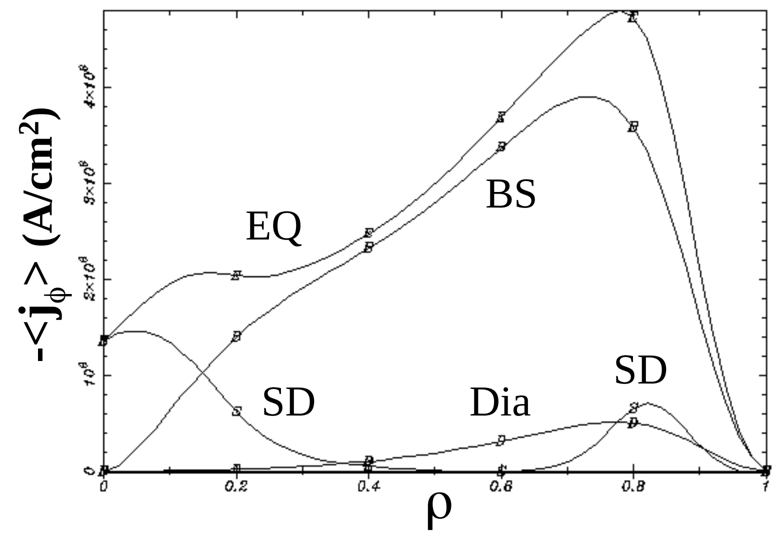



# CD Power Assessment for FIRE High-$\beta_N$ AT Mode

- Based on a FIRE DT-burning AT mode equilibrium (from Kessel):
  $R = 2$ m, $a = 0.52$ m, $B_o = 6.75$ T, $I_p = 4.50$ MA,
  $T_{eo} = 13.9$ keV, $n_{eo} = 5.10\times10^{14}$ cm$^{-3}$, $n_{ea}/n_{eo} \sim 0$, $Z_{eff} = 1.38$,
  $\beta = 5.62\%$, $\beta_N = 4.38$ (with wall stabilization of kink)
  $I_{BS}/I_p = 0.93$, $I_{seed} = 0.35$ MA

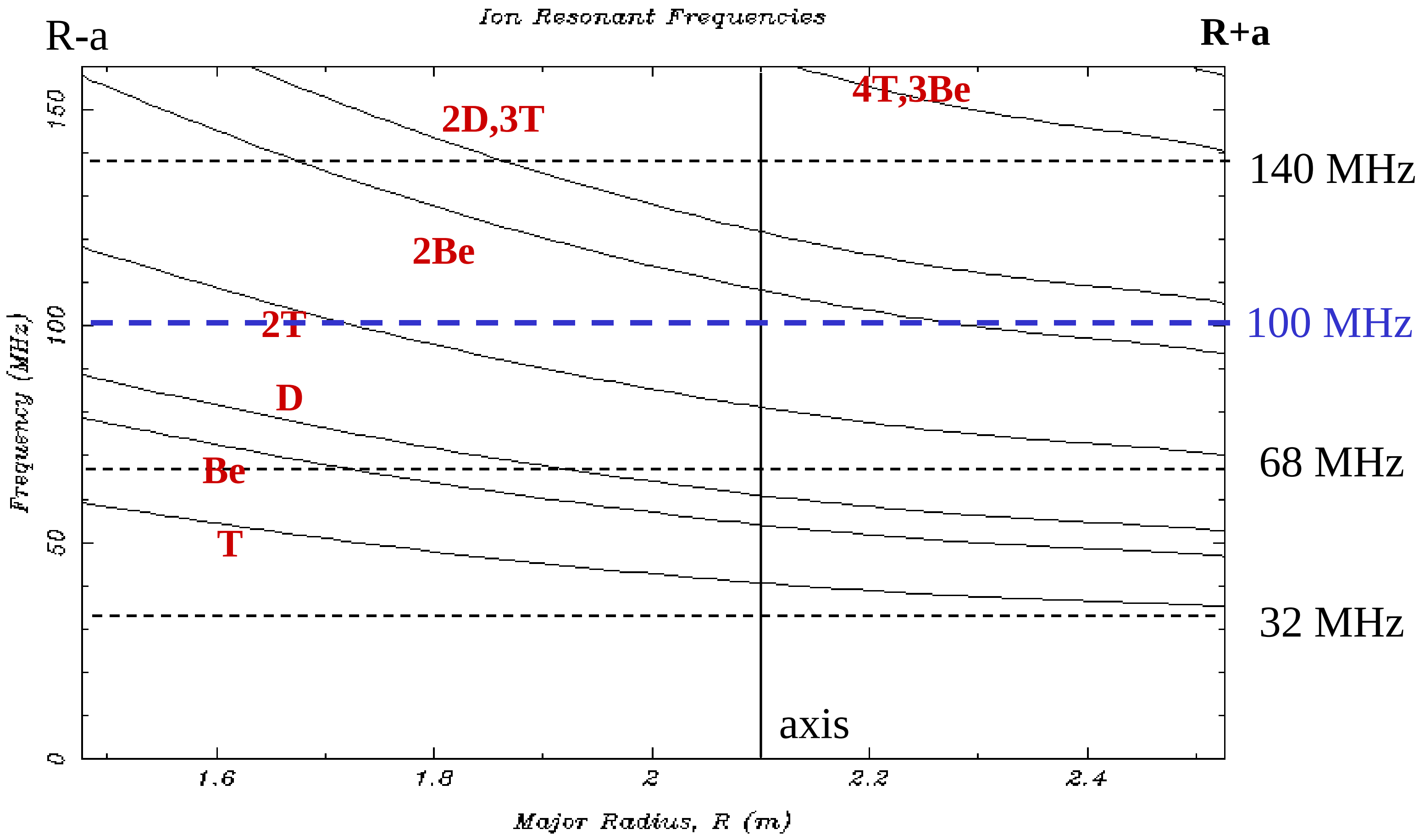



- Using ICRF to drive on-axis seed (0.1 MA), and LHW to drive off-axis seed (0.25 MA), total CD power can be as low as 7.3 MW !!
  - The CD power will rise as edge density is raised.

## Frequency Windows for Fast Wave Heating and CD

- **In the ICRF, fast wave power is absorbed by both electrons and ions (D, T, H, Be, $\alpha$), because of weak single-pass absorption, and 1-3% Berylium present.**
  - **Partition of power among electron and ion species varies with frequency and $N_{||}$.**
- **Antennas used for both H & CD should be designed for a finite frequency range of operation, which should be carefully determined.**



## CD and Profile Control Issues for FIRE AT Modes

- Realistic edge n,T profiles are required to accurately assess LH off-axis CD power. Linear results should be benchmarked with QL analysis.

- Species heating and current profile control while accessing flattop AT modes is critical, and modeling in conjunction with transport codes will be useful.

- The effect of berylium impurity (1-3%) should be taken into account when assessing ICRF fast wave H & CD.

- For LH off-axis CD, interaction with energetic alphas should be studied in more detail.

# Conclusions and Discussions

- RFCD power was assessed for example FIRE-AT equilibria both with and without wall stabilization.
  - For $\beta_N$ = 2.5 case, $P_{cd}$ ~ 20 MW.
  - For $\beta_N$ = 4.4 case, $P_{cd}$ > 7 MW depending on edge conditions.

- It appears that ICRF/FW and LHW are adequate for sustaining the target equilibria. The required power is dominantly LH.

- Antennas used for both heating and CD should be designed for for operating in a chosen range of frequencies.

- Current profile control during transients for AT flattop is critical and should be investigated and modeled.

- More experimental data base on Alcator C-Mod that involves access to AT mode with LHW will be useful.