

Heating and Current Drive Studies In the ARIES Program

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Peer Review of the ARIES Program

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Heating and Current Drive Analysis is Critical

- Determine and understand **current drive power** requirement, a critical element in systems analysis for the power plant COE.
- 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.**
- Identify (and resolve) issues and areas for further research.

RF Heating and Current Drive Analysis for ARIES Motivates Extension of Physics Models to Power Plant Regimes

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

- **Wave absorption physics:**
 - Cold ion ($k_x r_i \ll 1$), warm electron dispersion relation
 - Thermal ion and electron effects in field polarization terms when calculating linear damping decrement a long rays
 - **Energetic ion species (e.g., alphas) are treated either as hot Maxwellian 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)
 - **Extended j/p scaling to low aspect ratio regimes [ARIES-ST, NSTX]** [A feature unique to CURRAY]
 - Developed algorithm to maximize alignment of driven to equilibrium j-profile
- Coupled to high-precision equilibrium geometry (JSOLVER)

Overview of Current Drive Scenarios for ARIES Power Plants

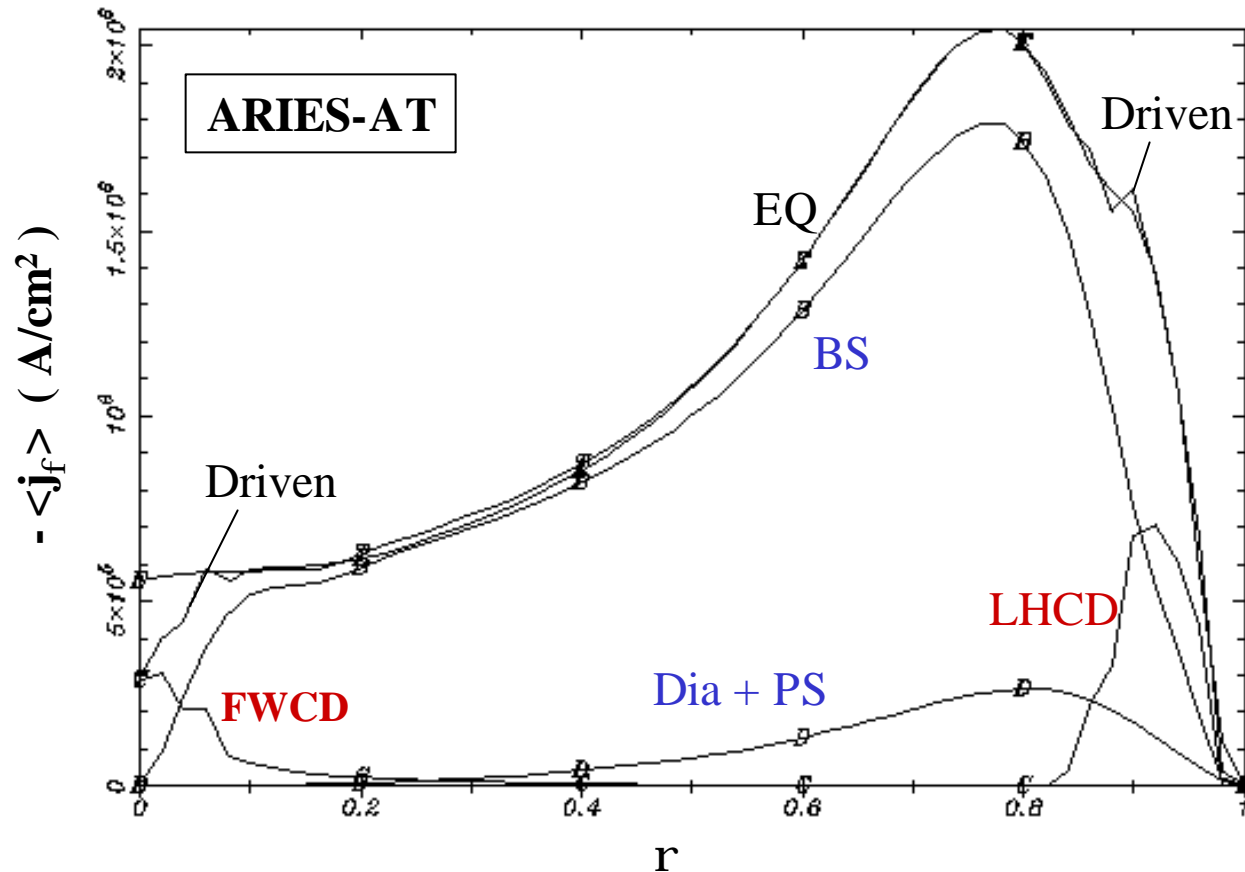
ARIES-AT requires much less current drive power than ARIES-RS because of much better bootstrap alignment.

Device	ARIES-RS	ARIES-ST	ARIES-AT
R (m)	5.5	3.2	5.2
A	4.0	1.6	4.0
I_p (MA)	11.3	28.4	12.8
β (%)	5.0	50.4	9.2
I_{bs} / I_p	0.88	0.96	0.915
On-axis CD*	ICRF/FW	Potato Orbit	ICRF/FW
Off-axis CD*	HHFW,LHW	NBI(120 keV)	LHW
Power (MW)	82.0	27.6	35.0

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

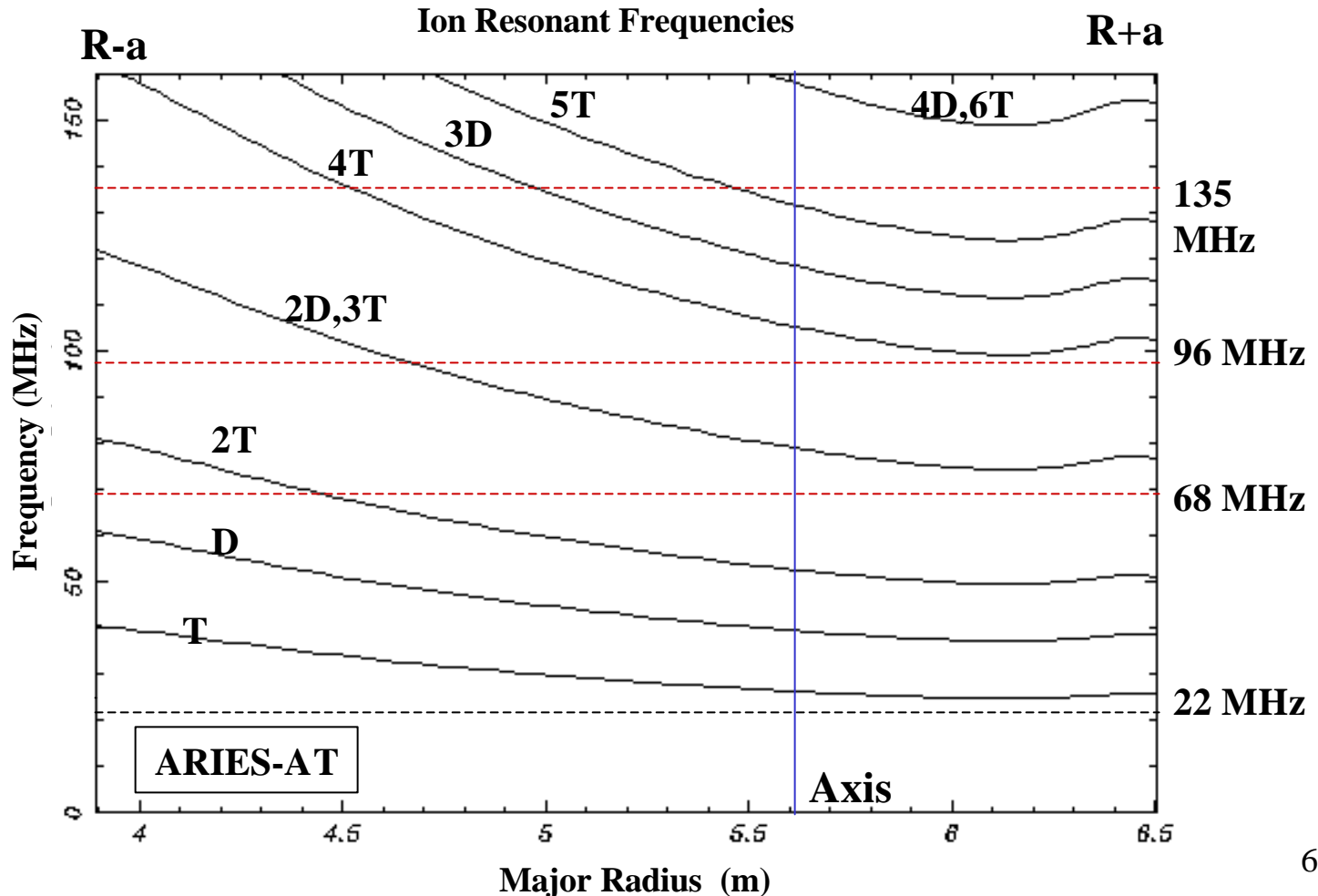
Target Equilibrium Can be Maintained with RF- and Self-Driven Currents

- Self-driven current [= bootstrap + diamagnetic + Pfirsch-Schluter] is calculated for multiple ion species for all collisional regimes on exact equilibrium and self-consistent (p , n , T) profiles.
- **2 RF schemes** are required to drive the seed currents on ARIES-AT:
(1) ICRF fast waves for on-axis drive: (2) LH waves for off-axis drive.



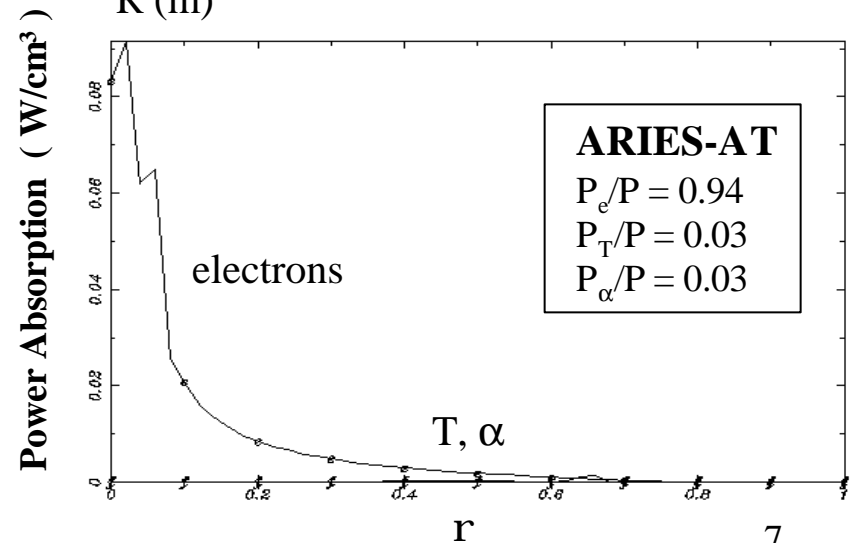
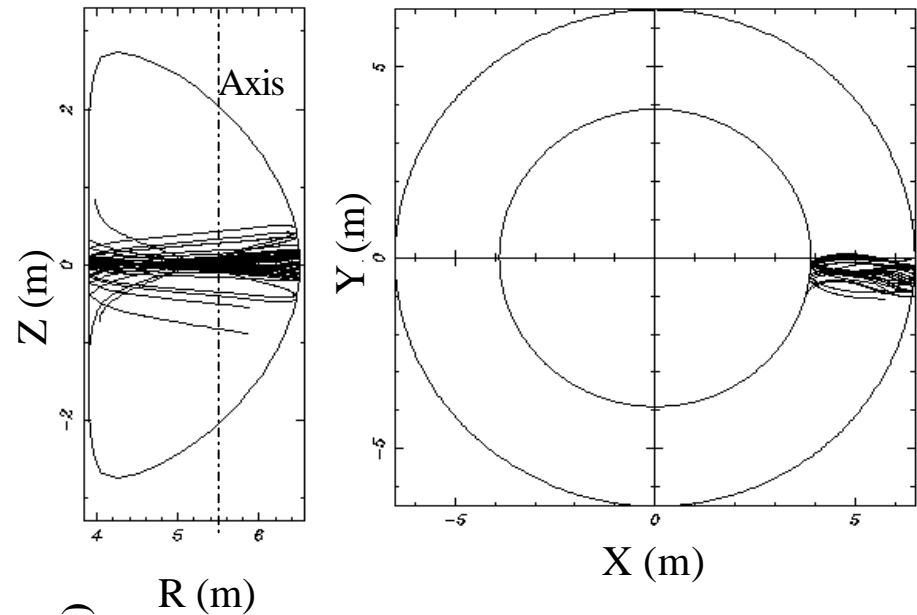
Frequency Options for Fast Wave On-Axis CD

- Criteria : Avoid ion and α absorption \longrightarrow no resonance on OB side
Reasonable antenna size \longrightarrow higher frequency
- 68 MHz, 96 MHz, and 135 MHz appear feasible; similar power requirements
- Use 68 MHz as reference in ARIES-AT.



ICRF Fast Wave Drives On-axis Seed Current

- Wave frequency is chosen to place $2f_{cD}$ resonance at $R > R_o + a$, and $2f_{cT}$ resonance at $R \ll R_{axis}$, to avoid ion and alpha absorption.
- Launcher is located on outboard midplane with $N_{||} = 2$ spectrum for best current profile alignment.
- Plasma & wave parameters :
 $R = 5.2 \text{ m}$, $A = 4$, $\kappa = 2.2$, $\delta = 0.8$,
 $B_o = 5.9 \text{ T}$, $I_p = 13 \text{ MA}$, $\beta_N = 6.0$,
 $T_{eo} = 29 \text{ keV}$, $n_{eo,20} = 2.95$,
 $Z_{eff} = 1.8$
 $f = 68 \text{ MHz}$, $N_{||} = -2.0$.

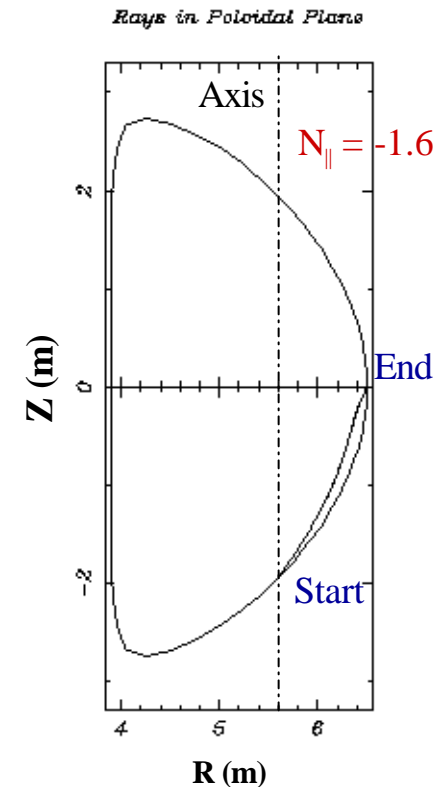
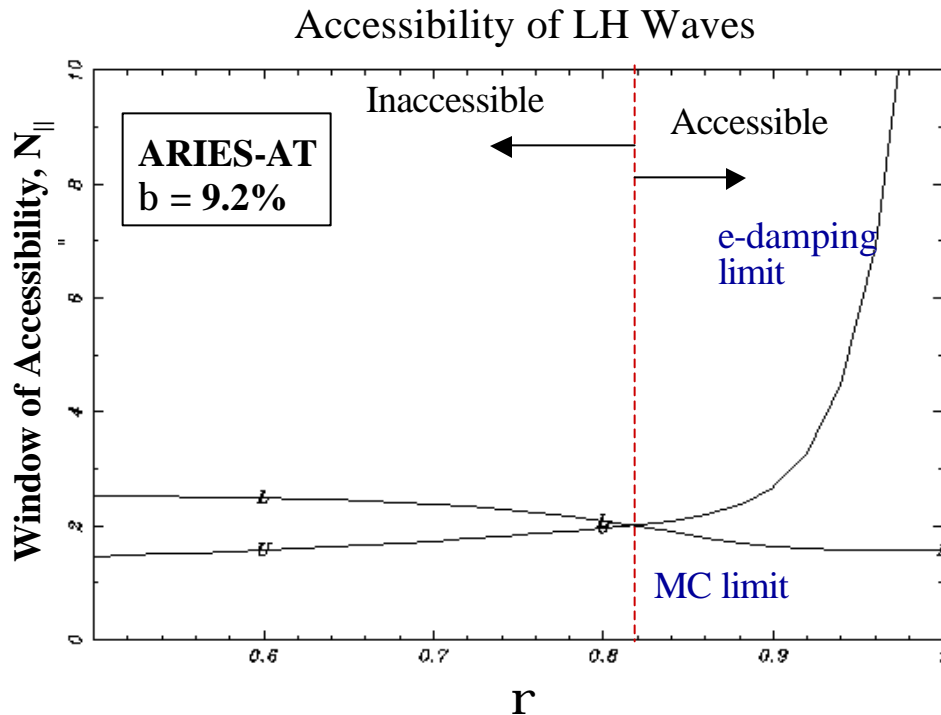


LH Wave Penetration is an Issue in High-b Plasmas

- Frequency = 3.6 GHz [$> 2 \times f_{LH}(r=0.8)$]
 - Less than 1% 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 $r > 0.8$ for the high-b AT equilibrium. [$b \sim (f_{pe}/f_{ce})^2$]

Low $N_{||}$ rays encounter mode conversion to fast wave at $r > 0.8$ and propagates back to edge; higher $N_{||}$ rays get totally damped before reaching $r = 0.8$.

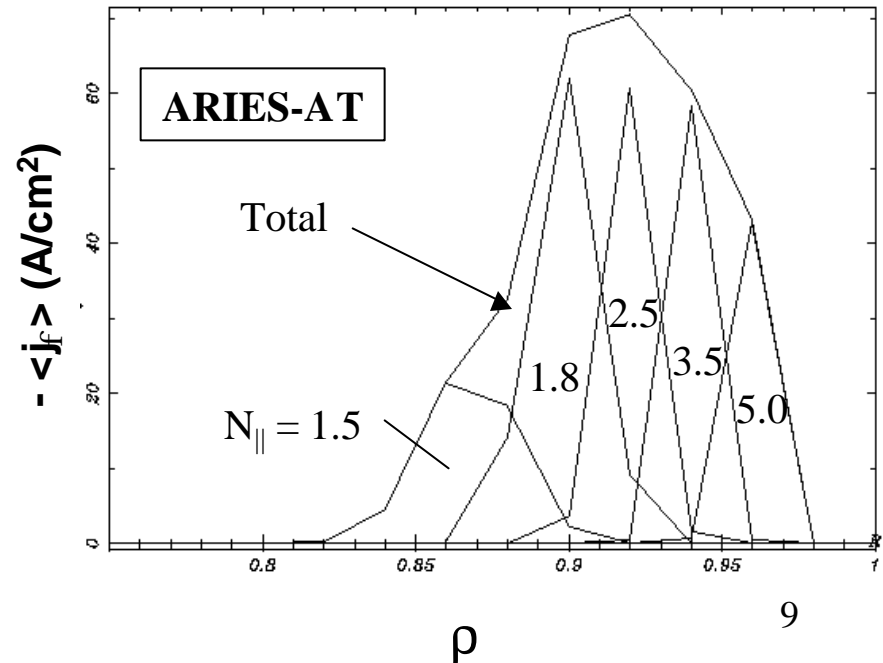


Off-Axis Current Drive Requires Tailored LH Power Spectrum

- Five waveguide modules, each launching a different N_{\parallel} spectrum, are used to drive the required off-axis seed current profile. These are located about 90° ($\sim 2\text{m.}$) below the outboard midplane.
- Extended physics model found a absorption to be negligible for off-axis drive at $\rho > 0.8$. Frequency can be lowered for high N_{\parallel} launch at outer plasma region, thus easing design of waveguide launcher.

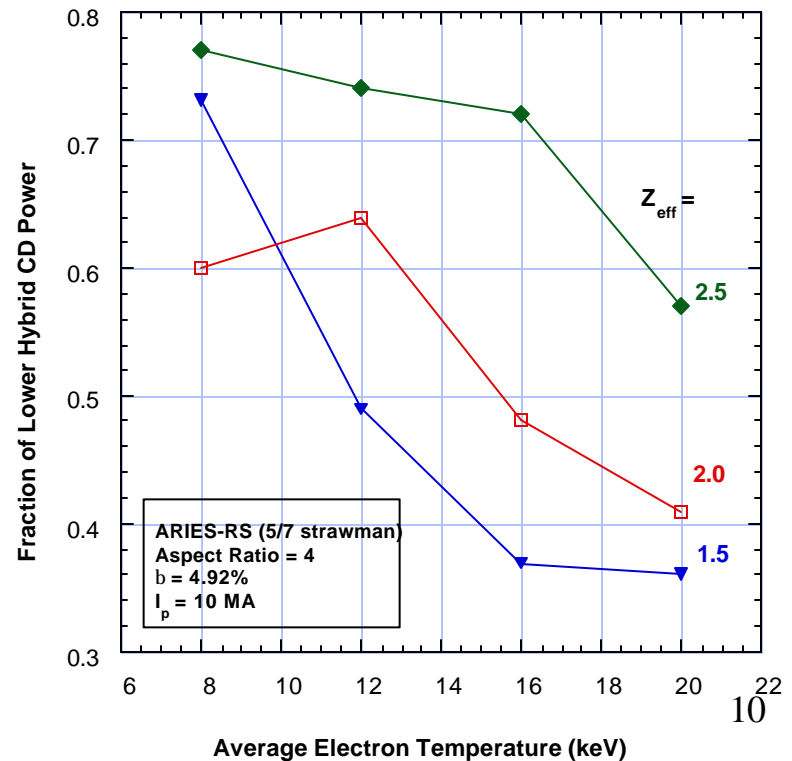
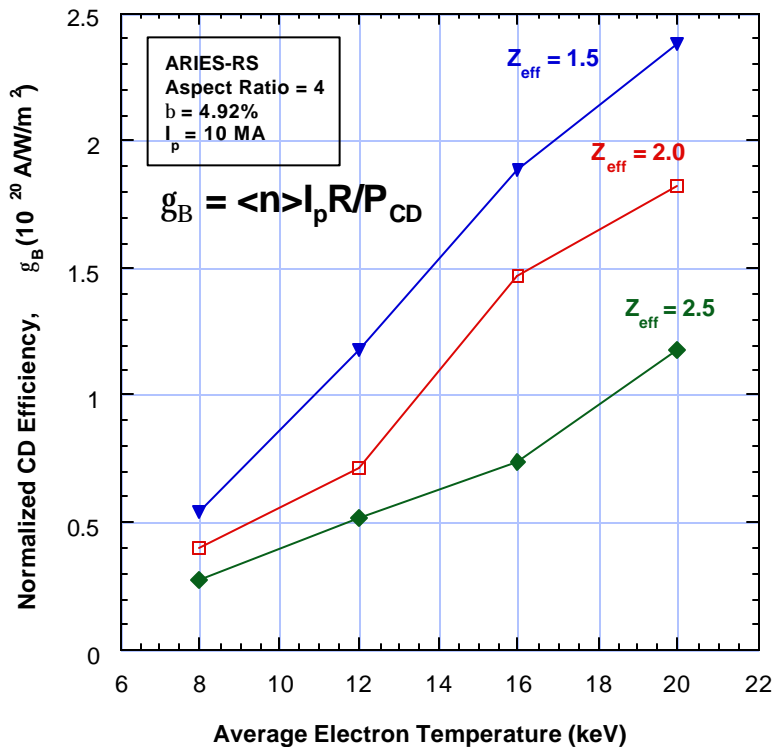
- The tailored LH spectrum has following parameters:

$f(\text{GHz})$	N_{\parallel}	$P(\text{MW})$	I_{cd}/I_{sd}
3.6	1.5	2.41	0.15
3.6	1.8	4.92	0.28
3.6	2.5	6.29	0.25
3.6	3.5	8.36	0.20
2.5	5.0	9.02	0.12



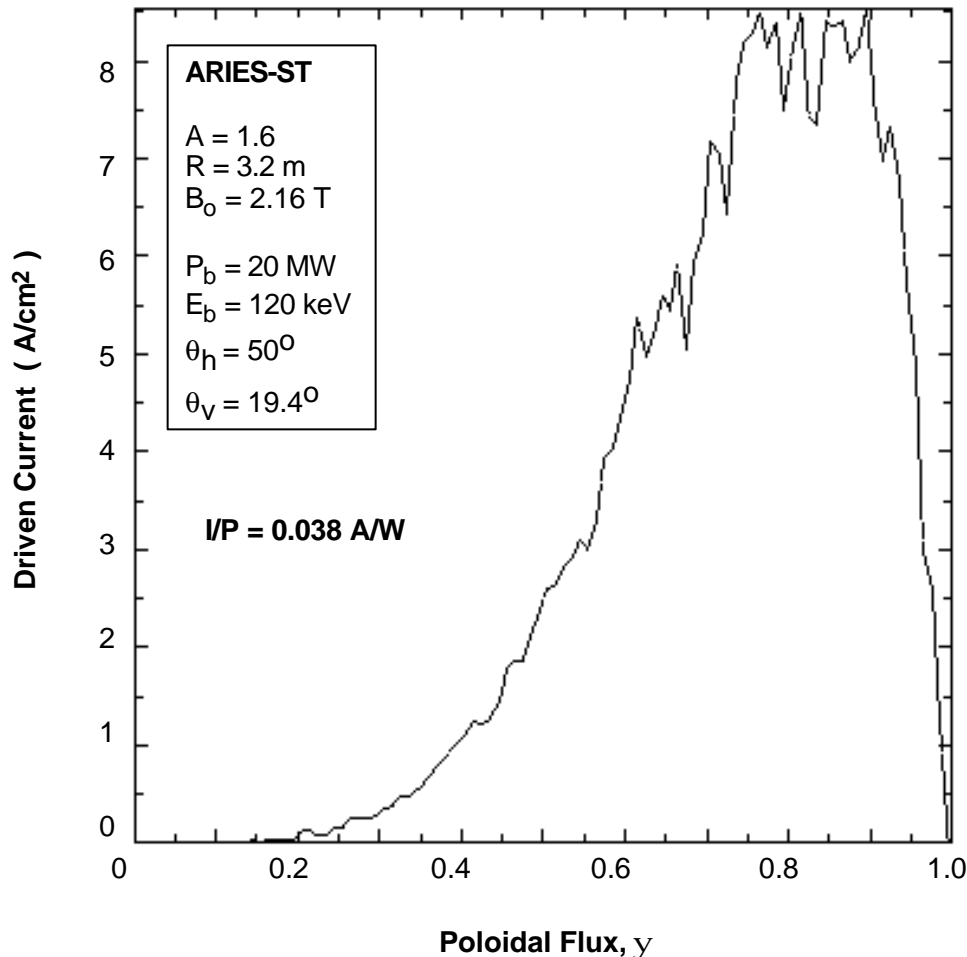
Enhanced Core Radiation Impacts Current Drive Power Requirement

- High f_{rad} operation with impurity injection and/or radiative mantle was examined for ARIES-RS in order to reduce divertor heat load.
- Higher Z_{eff} has two major effects on current drive:
 - Increased collisionality results in modified bootstrap current profile;
 - Lower current drive efficiency
- In ARIES-RS, higher Z_{eff} reduces normalized current drive efficiency, and leads to higher off-axis current drive power.



ARIES-ST Uses Neutral Beams to Drive Off-Axis Seed Current

- NBI was used because: (1) lack of penetration with LHW and HHFW, and (2) need of toroidal rotation drive for kink stabilization.



- 5% I_p driven by 32 MW @ 120 keV, R_{tang} = 4.0 m.
- Generated rotation:
 <V_φ> ~ 80 km/s ~ 4% V_a
 Rigid-body assumption.
- NBCD analysis done by NFREYA with large r/R correction.
- Small on-axis seed current driven by potato-orbit particles --- a topic of on-going research.

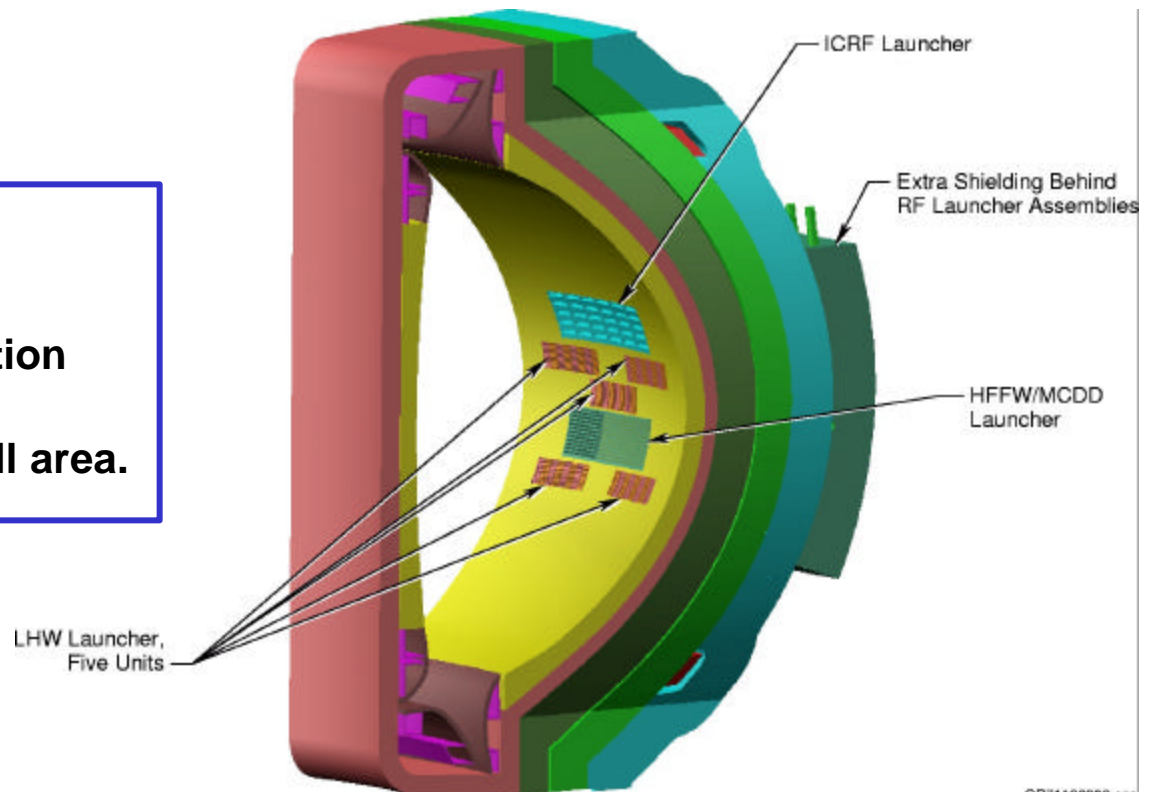
ALL RF Launchers Fit in One Blanket Sector

- 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]

→ All launcher modules fit in one special blanket sector with minimal impact on blanket performance.

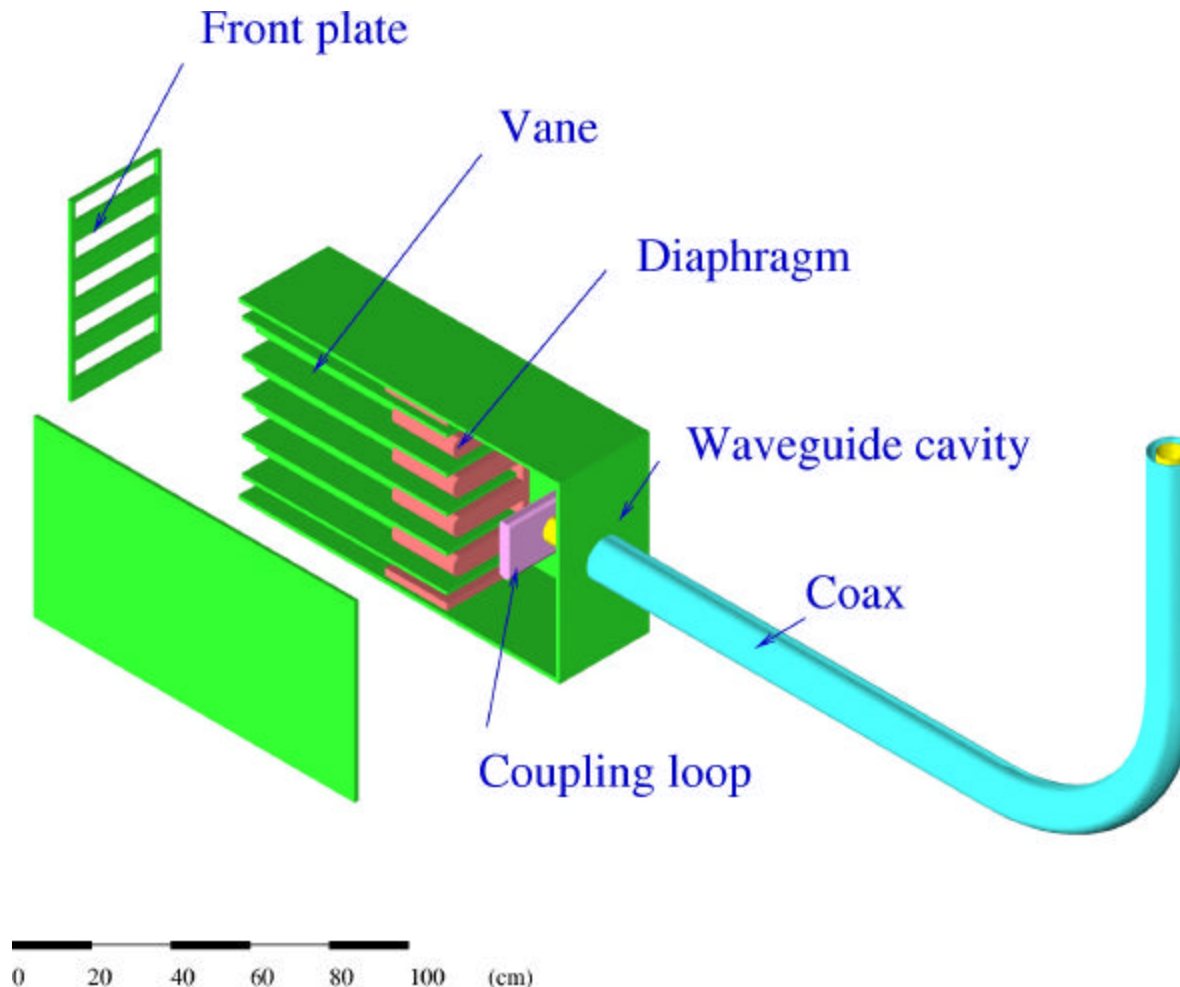
In ARIES-RS:

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



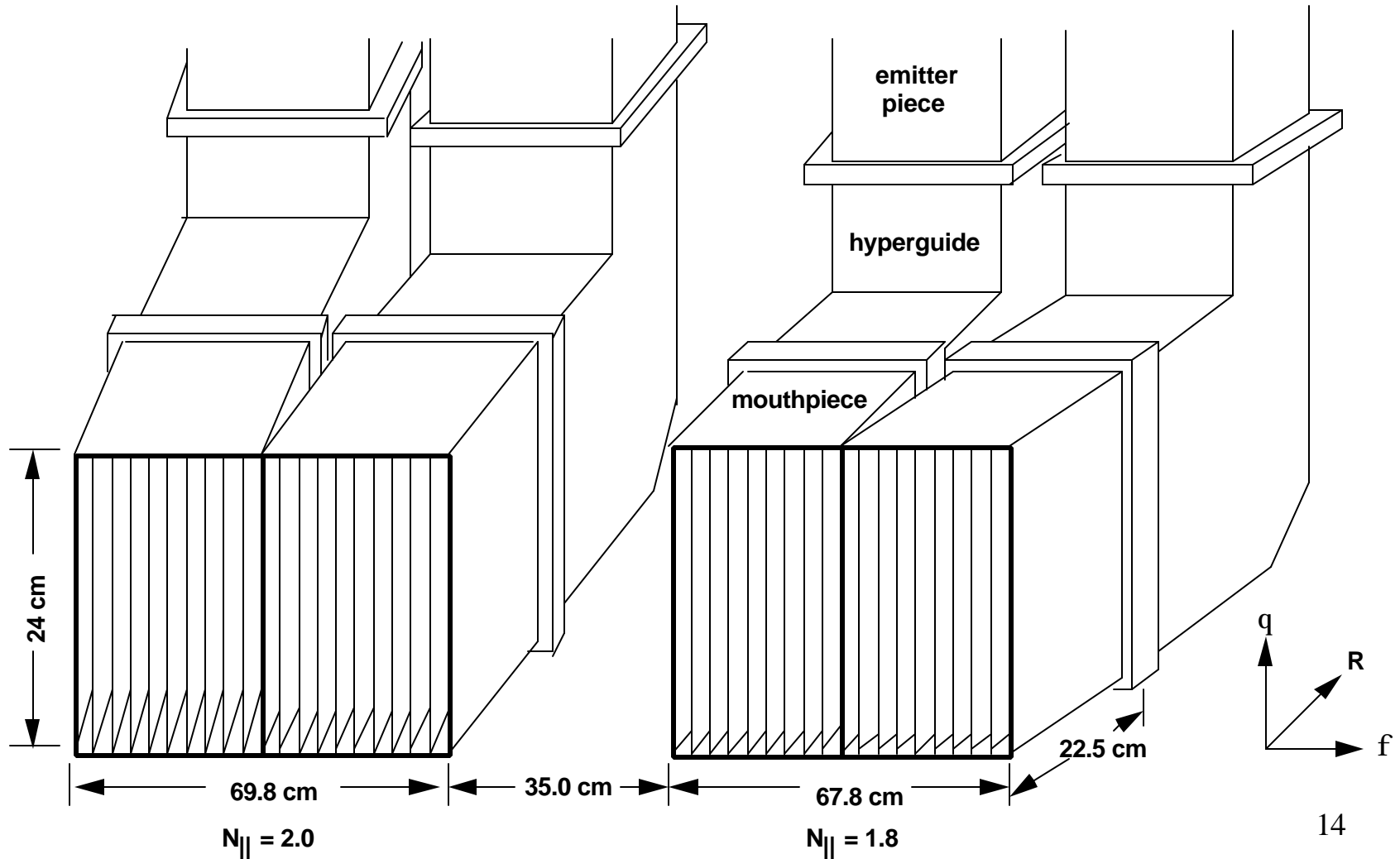
Single Folded Waveguide Launcher and Coax Feed

- Capacitive diaphragm reduces radial thickness of waveguide, and provides extra shielding; voltage can be lowered by proper shaping.



Front View of LH Launcher Modules for ARIES-RS

- Each base unit consists of an active/passive waveguide pair modeled after ITER-EDA.
- * The 4.6 GHz LH launcher array consists of 4 units, 2 for $N_{||}=2.0$ spectrum and 2 for $N_{||}=1.8$ spectrum.
- * Total power transmitted = 20 MW; Directivity = 0.7.



Issues and Areas for Future Research

- Heating and Current Drive:
 - LHW penetration is limited in high- β plasma; HHFW is a possibility, but needs innovative antenna concept;
 - Investigate the dynamics of RF current profile control --- modeling, and physics and technological constraints
 - Refine modeling capability to self-consistently determine MHD stable equilibrium with bootstrap and externally driven currents;
 - Use wave spectrum calculated for RF launcher in ray tracing analysis;
 - Study roles of RF in rotation generation and transport barrier control
- RF Launcher:
 - EM field analysis inside folded waveguide in realistic geometry, and experiments in a tokamak environment
 - Detailed launcher cooling and thermal stress analysis
 - Structural material choice in SiC environment : SiC with metal coating
 - Wave coupling and loading during plasma transients

Interactions with Community and Publications

- The CURRAY code was developed jointly with General Atomics, and is used for ARIES study, fast wave experiments on DIII-D, and NSTX HHFW studies.
- The use of FWCD in ARIES partially motivated FWCD experiments on DIII-D in the mid-90's.
- Interactions with GA RF physicists led to the extension of RF and NBI j/p scalings to low aspect ratio regime for spherical tori.
- Interactions with ORNL RF Group were beneficial in the design of folded waveguide launchers on ARIES-RS.
- UCSD will co-host 14th RF Topical Conference in 2001.
- Number of authored and co-authored papers on related topics: 6 in peer-reviewed journals, and 6 in conference proceedings in the last five years.