# Some unsolved challenges in RF current drive Nathaniel Fisch Department of Astrophysical Sciences Princeton University

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Unsolved problems include current drive in magnetic geometries in which the toroidal magnetic field cannot be assumed to be dominant, current start-up with hyper-resistivity, current drive with oscillating parameters, and synergistic effects between current drive and alpha channeling. These problems are not necessarily straightforward to solve, but there is the potential of significant consequence. Some Unsolved Challenges in RF Heating and Current Drive

- 1. Alpha Channeling How to accomplish?
- 2. Current Drive effects associated with ions
- 3. Neoclassical pinch effects associated with trapped electrons
- 4. High-Efficiency Cyclic Operation
- 5. Combine with Alpha Channeling: Engineering and Physics
- 6. Can Hyper-resistivity be induced?
- 7. Free Energy Complexity Theory



## Reactor designs around Aries I operating point

	no channeling		channeling		
	cd	Р	75%	75%	
T <sub>i</sub> (keV)	20	15	20	15	
T <sub>e</sub> (keV)	20	15	12	12	
n(10 <sup>14</sup> cm <sup>-3</sup> )	1.2	1.8	1.8	2.1	
$ au_{i}(s)$	2.0	2.0	2.0	1.0	
$ au_{e}(s)$	1.0	0.7	0.3	0.5	
P <sub>f</sub> (W cm <sup>-3</sup> )	4.7	6.1	10.9	9.7	

# Advantages of Alpha Channeling

- 1. Because of the increased reactivity at a given confined pressure (and the free current drive), the hot ion mode gives about 30% cheaper COE, compared to aggressively designed reactors.
- 2. The impurities can be removed and the plasma can be fueled easily.
- 3. However, it may be more desirable yet, if electron heat transport is not tamed. Ion transport might eventually be tamed, but maybe not electron transport, in which case having ions hotter than electrons reduces the heat loss substantially.
- 4. The present data base of the top tokamak confinement and heating results supports hot-ion mode operation only.

## Hot-ion Mode RF-Driven Tokamak

Are we prepared?

Perhaps the eventual reactor will be in the hot ion mode.

Does equal temperature mode really extrapolate?

- 1. Top performance results to date (JET, TFTR) achieved in hot ion mode.
- 2. Perhaps ion heat transport will be well-controlled but not electron heat transport

Upside to hot ion mode -- better extrapolation and 30% on COE

- 1. RF energy channeled from alpha particles
- 2. Fusion reactivity can be doubled in hot ion mode.
- 3. RF current drive fueled by alpha channeling.
- 4. Ash removal. Fueling.
- 5. Expedited by possible resonant "ringing" of tokamak.
- 6. Electron heat can be poorly confined.
- 7. Less free energy to drive instabilities.

If the reactor will be in the hot ion mode, then expect Highly rf-driven reactor, possibly with 400 MW or more RF, where RF is first-order physics.

## **RF-Driven** Tokamak

A more essential role for rf physics, technology, and modeling

- 1. Steady state achieved by rf current drive for much of the current.
- 2. Control of transport: plasma fueling and ash removal
- 3. Rf energy channeled from alpha particles.
- 4. Resonant "ringing" of tokamak!
- 5. Highly rf-driven reactor, possibly with 400 or more MW rf, where rf is first-order physics.
- 6. Non-issues: alpha-driven instabilities, poor electron heat confinement or poor alpha particle radial flux.

# **Diffusion Paths**



# **Diffusion Paths**



# Tapping Free Energy in $\alpha$ -Particles







# **TFTR D-Beam MCIBW Experiments**



### 4D information: energy, poloidal angle, pitch angle, time!

# **Experimental Results**

Fisch et al. (1996), Herrmann and Fisch (1997)

Key characteristics of mode-converted IBW verified on TFTR

Detailed verification of diffusion (phased for heating) in  $E-\mu-P_{\phi}$  space

Absolute value of diffusion coefficient appears to be factor of 50 higher than simple ray-tracing theory implies!

Possibility of Exciting Internal Mode

Clark and Fisch, 2000

1.

2.

Perhaps  $\alpha$ -channeling effect can be achieved even at low power





 $\omega - n_{\varphi}\omega_{\varphi} - m\omega_{\theta} = 0$ 

 $dP_{\varphi}$  $rac{n_{arphi}}{\omega}$ dE $\frac{d\mu}{dE}$ ()

# Destiny of trapped electrons under LHCD

- 1. RF Pinch effect: Canonical angular momentum of trapped electrons is conserved, so electrons must change vector potential upon absorbing wave momentum (Fisch and Karney, 1981).
- 2. But electron pinch is not a steady state option.
- 3. Do rotation measurements (Rice, 2008) inform on destiny of trapped electrons through radial electric field?
- 4. More generally, an open challenge is LHCD in ST. Use 5D.
- 5. Suggestion: Use adjoint formalism to calculate Green's function response for linear absorption.

### MIT LHCD Experiment (2008)

#### Counter-Current Core Toroidal Rotation with LHCD

Counter-current increment in V<sub>b</sub> Time scale for V<sub> $\phi$ </sub> evolution much longer than  $\tau_E$  or  $\tau_{\phi}$  (~35 ms) but similar to the current relaxation time,  $\tau_{CR}$  ~ 250 ms. similar drop in internal inductance (broadening of current profile) peaking of central electron density peaking of core electron and ion Comparison of two discharges, temperature with and without LHCD 0.75 0.70 0.70 10<sup>20</sup>/m<sup>3</sup> 0.65 0.65 10<sup>20</sup>/m<sup>3</sup> <n<sub>e</sub>> 0.60 0.60 0.55 0.55 0.50 n 3.0 0.45 2.8 ke∨ T<sub>e</sub>(0) 2.6 0.4 2.4 ¥ 0.3 LH 2.2 0.8 0.1 0.0 0.6 ΜM 1.48 0.4 LH 1.46 0.2 0.0 1.44 1.42 Δl 1.45 1.40 1.40 1.38 1.35 1.30 -10 V<sub>Tor</sub>(0) km/s km/s -10 -20 ΔV -20 -30 V<sub>Tor</sub>(0) -30 -40 0.6 0.8 1.0 1.2 1.4 1.6 1.2 1.4 1.6 0.6 0.8 1.0 t (s) t (s)

Ince-Cushman et al (2008), Rice et al (NF, 2009)

Minority ion Cyclotron Current Drive Effect (MiCCD) Use waves to get counter-streaming ions



### Minority ion Cyclotron Current Drive

Sawtooth control by ICRF waves Ion Cyclotron Current Drive

How to affect sawtooth :

 $\odot$  EF

- ✓ High central fast particle pressure: stabilisation
- ✓ Local modification of current profile at R<sub>INV</sub>: destabilisation or stabilisation



- Toroidally directed ICRF waves : co or counter current propagation
- ✓ Finite k<sub>//</sub> ⇒ asymmetric coupling to ions and electrons in v<sub>//</sub>-space ⇒ dipolar ICCD (Fish, Nucl. Fusion, 1981)
- Effect will depends on:
  - ✓ Toroidal direction of the wave
  - ✓ Location of R<sub>res</sub> versus R<sub>inv</sub>



bletr

2 M.L. Mayoral, 45th Meeting of the Division of Plasma Physics, Albuquerque, October 27-31, 2003 U

erque, October 27-31, 2003 UKAEA

Note: MiCCD effect is complicated if

- 1. absorption straddles resonance
- 2. Ion trapping

Thus, other current drive effects may dominate

Hellsten et al., PRL, 1995 Carlson et al., PP, 1998

## LHCD Power Required

 $P_{\rm rf}$ 15  $\overline{P_f} \simeq \overline{J/P_d} (n_{14}T_{10}a_1R_1)^{1/2}(3T_{10}-2)$ 

Design 1 (small and cold)	Design 2 (large and hot)		
$T_{10} = 1$	$T_{10} = 2$		
$n_{14} = 1$	$n_{14} = \frac{1}{3}$		
$a_1 = 3$	$a_1 = 5$		
$R_1 = 8$	$R_1 = 13$		
$P_f \simeq 1.8  \mathrm{GW}$	$P_f \simeq 3.3  \mathrm{GW}$		
$H \simeq 1.5 \text{ MW/m}^2$	$H \simeq 1 \text{ MW/m}^2$		
$\frac{P_{\rm rf}}{P_f} \simeq \left(\frac{15}{J/P_d}\right) 20\%$	$\frac{P_{\rm rf}}{P_f} \simeq \left[\frac{15}{J/P_d}\right] 3\%$		

# Tokamak Recharge or "Oscillating Current Drive"

Suppose that current is generated under one set of conditions, but then allowed to relax under a different set of conditions. What is the current-drive efficiency?

Take advantage of separation of time scales:  $\tau_c \ll J/(dJ/dt) \ll L/R$ 

$$\frac{dJ}{dt} + \frac{J}{\tau_g} = \frac{J_{rf}}{\tau_g} \qquad \qquad \frac{dJ}{dt} + \frac{J}{\tau_r} = 0 \qquad \qquad E = \eta \left( J - J_{rf} \right)$$





compare: Peysson, Bae, Calabro (this conference)

### Cyclic Operation

$$J_{\max} - J_{\min} \approx J_{\max} \frac{T_r}{\tau_r} \approx J_{rf} \frac{T_g}{\tau_g}$$
$$J_{\max} \approx J_{\min} \approx J_0$$
$$\frac{T_r}{T_g} \approx \frac{J_{rf} \tau_r}{J_0 \tau_g} >> 1$$
$$W_c = P_d T_g \approx \frac{J_{rf}}{\langle J/P_d \rangle_g} T_g$$

$$\left\langle J/P_{d}\right\rangle_{avr}\cong W_{c}/\tau_{r}\cong \left\langle J/P_{d}\right\rangle_{g}\frac{\tau_{r}}{\tau_{g}}$$

periodic

Minimum variation in J

maximize relaxation stage

Energy dissipated

Average efficiency

$$\frac{\tau_r}{\tau_g} , \frac{T_r}{T_g} , \frac{J_{rf}}{J_0} >> 1$$

**Optimizing Current Drive Efficiency** 

$$\left\langle J/P_{d}\right\rangle_{LH} = \frac{-e v_{\parallel}^{2}}{v_{0}(5+Z_{i})}$$

$$\langle J/P_d \rangle_{avr} \cong \left[ J/P_d \right]_{Z=1} \frac{\tau_r}{\tau_g (Z=1)} \frac{6Z_g}{5+Z_g}$$

Note: factors are multiplicative, so get factor of say several in high-Z and further factor of several in low-n. Could also get factor of several by cycling  $T_e$ . The higher peak power required is balanced by the higher current drive efficiency to the extent that low-n is utilized.

### Synergies with Alpha Channeling Open question: What are the engineering implications?

### **Current Generation Stage**

Low density to optimize current drive efficiency Low  $T_e$  and high  $Z_{eff}$  to minimize  $\sigma$ 

But these are just the conditions for hot ion mode! Also, these are also conditions for proven LHCD

Two Possible optimizations

- 1. Optimize for current drive only, say  $T_e = T_i = 5$  keV,  $n_e = 10^{13}$ . In this case LHCD can be used efficiently.
- 2. Optimize for both current drive and fusion production via hot ion mode, say  $T_e = 15$  keV,  $T_i = 30$  keV,  $n_e = 10^{13}$ . In this case, LHCD can be used to drive the current, and ion heating can separately provide the hot ion mode, or, better yet, a different wave mechanism can produce both the current and the hot ion mode via alpha channeling.

Fisch, JPP (2010)

### RF-induced Hyper-resistivity? (probably absurd, but it would be very useful)



If current carriers follow field lines, can one add to field line length to increase resistivity?
If so, is there a fundamental maximum increase? Shouldn't there be a limit to the length after which fine scales are averaged over?
If so, wouldn't the resistivity increase be larger for Ohmic currents?
What would be the cost of increasing the resistivity?



Free energy is due to equalizing population inversion Diffusion over resonant wave region: Not entropy conserving Recall Lecture by Professor J. M. Rax



Rearrangement of Phase Space in Plasma



- 1. Current drive
- 2. One-way wall
- 3. Coupled diffusion in position-velocity: "alpha-channeling"



Initial energy distribution

Entropy conserving

### Free Energy under Phase Space Rearrangement



$$\mathcal{E} = n_g \mathcal{E}_g + n_1 \mathcal{E}_1 + n_2 \mathcal{E}_2$$
  
minimized for:  $n_g > n_1 > n_2$   
more generally, minimize:  $\mathcal{E} = \vec{n} \cdot \vec{\mathcal{E}}$   
using  $\pi$ -pulse excitations  $v_{ij}$ 

Example: for  $n_1 > n_2 > n_3$  t=0:  $n_3 n_2 n_1$ 

To release free energy, apply 3 (ordered)  $\pi$ -pulses (to exchange densities)

 $v_{21}$ :  $n_3 n_1 n_2 v_{1g}$ :  $n_1 n_3 n_2 v_{21}$ :  $n_1 n_2 n_3$ 

Free Energy under constrained Phase Space Rearrangement

minimize:  $\mathcal{E} = \vec{n} \cdot \vec{\mathcal{E}}$ 

### under phase space conservation

for atoms, use  $\pi$ -pulse excitations  $\nu_{ij}$ : solution sequence  $(\nu_{ij1}, \nu_{ij2}, ...)$  for plasma, use Hamiltonian forces: "Gardner restacking"

### under diffusion constraint the free energy is not so easily found

for example: apply sequence  $(v_{10}, v_{21})$  under diffusion constraint

	$\epsilon_0$	$\boldsymbol{\epsilon}_1$	$\epsilon_2$
Initial	n <sub>o</sub>	n <sub>1</sub>	n <sub>2</sub>
Step1	( n <sub>1</sub> +n <sub>0</sub> )/2	( n <sub>1</sub> +n <sub>0</sub> )/2	n <sub>2</sub>
Step2	( n <sub>1</sub> +n <sub>0</sub> )/2	( n <sub>1</sub> +n <sub>0</sub> )/4 + n <sub>2</sub> /2	( n <sub>1</sub> +n <sub>0</sub> )/4 + n <sub>2</sub> /2

Fisch and Rax, 1993

			Example		
		$E_0 = 0$	ε <sub>1</sub> = 1	$\epsilon_2 = 4$	
Initial	$W_0 = 22$	$n_0 = 0$	n <sub>1</sub> = 2	n <sub>2</sub> =5	
Step 1	$W_1 = 12$	5/2	2	5/2	Apply $(v_{20}, v_{21})$
Step 2	$W_2 = 45/4$	5/2	9/4	9/4	
		$\epsilon_0 = 0$	ε <sub>1</sub> = 1	$\epsilon_2 = 4$	
Initial	$W_0 = 22$	0	2	5	Apply $(v_{10}, v_{20}, v_{21})$
Step 1	$W_1 = 21$	1	1	5	Better strategy
Step 2	$W_2 = 13$	3	1	3	
Step 3	$W_3 = 10$	3	2	2	

Strategy 1: Diffuse particles first between similar population levels

		Exar	nple (continued)		
		$\varepsilon_0 = 0$	ε <sub>1</sub> = 1	$\epsilon_2 = 4$	
Initial	$W_0 = 22$	0	2	5	Apply $(v_{21}, v_{20}, v_{10})$
Step 1	$W_1 = 35/2$	0	7/2	7/2	Best strategy
Step 2	$W_2 = 21/2$	7/4	7/2	7/4	
Step 2	$W_3 = 77/8$	21/8	21/8	7/4	
		$\varepsilon_0 = 0$	ε <sub>1</sub> = 1	$\epsilon_2 = 4$	
Step 1	$W_1 = 35/2$	0	7/2	7/2	$(\mathbf{v}_{21}, \mathbf{v}_{10}, \mathbf{v}_{20}, \mathbf{v}_{21})$
Step 2	$W_2 = 63/4$	7/4	7/4	7/2	Poor strategy
Step 3	$W_3 = 49/4$	21/8	7/4	21/8	
Step 4	W <sub>4</sub> = 175/16	21/8	35/16	35/16	

Strategy 2: Deplete particles first from high energy levels

Statement of the Problem

Discrete: Find the sequence  $\{v_{ij}\}$  that minimizes:  $W = \vec{n} \cdot \vec{\epsilon}$ 

Continuous: Let 
$$\frac{\partial f(v,t)}{\partial t} = \int K(v,v',t) \Big[ f(v',t) - f(v,t) \Big]$$
$$K(v,v',t) = K(v',v,t)$$
$$K(v,v',t) \ge 0$$
$$W(t) = \int \varepsilon(v) f(v,t) dv$$

Then find K that minimizes  $W(t \rightarrow \infty)$ .

Note the H-theorem:

$$\frac{d}{dt}\int f(v,t)^2 dv \le 0$$



Some Unsolved Challenges in RF Heating and Current Drive

- 1. Alpha Channeling How to accomplish?
- 2. Current Drive effects associated with ions (optimize)
- 3. Neoclassical pinch effects and CD in ST
- 4. High-Efficiency Cyclic Operation1. What are the physical mechanisms for asymmetry2. Can Hyper-resistivity be induced?
- 5. Combine with Alpha Channeling1. What are the Engineering implications2. What are the associated physics issues?
- 6. Free Energy Complexity Theory