Some Unsolved Challenges in RF Heating and Current Drive!

1. Alpha Channeling – How to accomplish?!

2. Current Drive effects associated with ions!

!

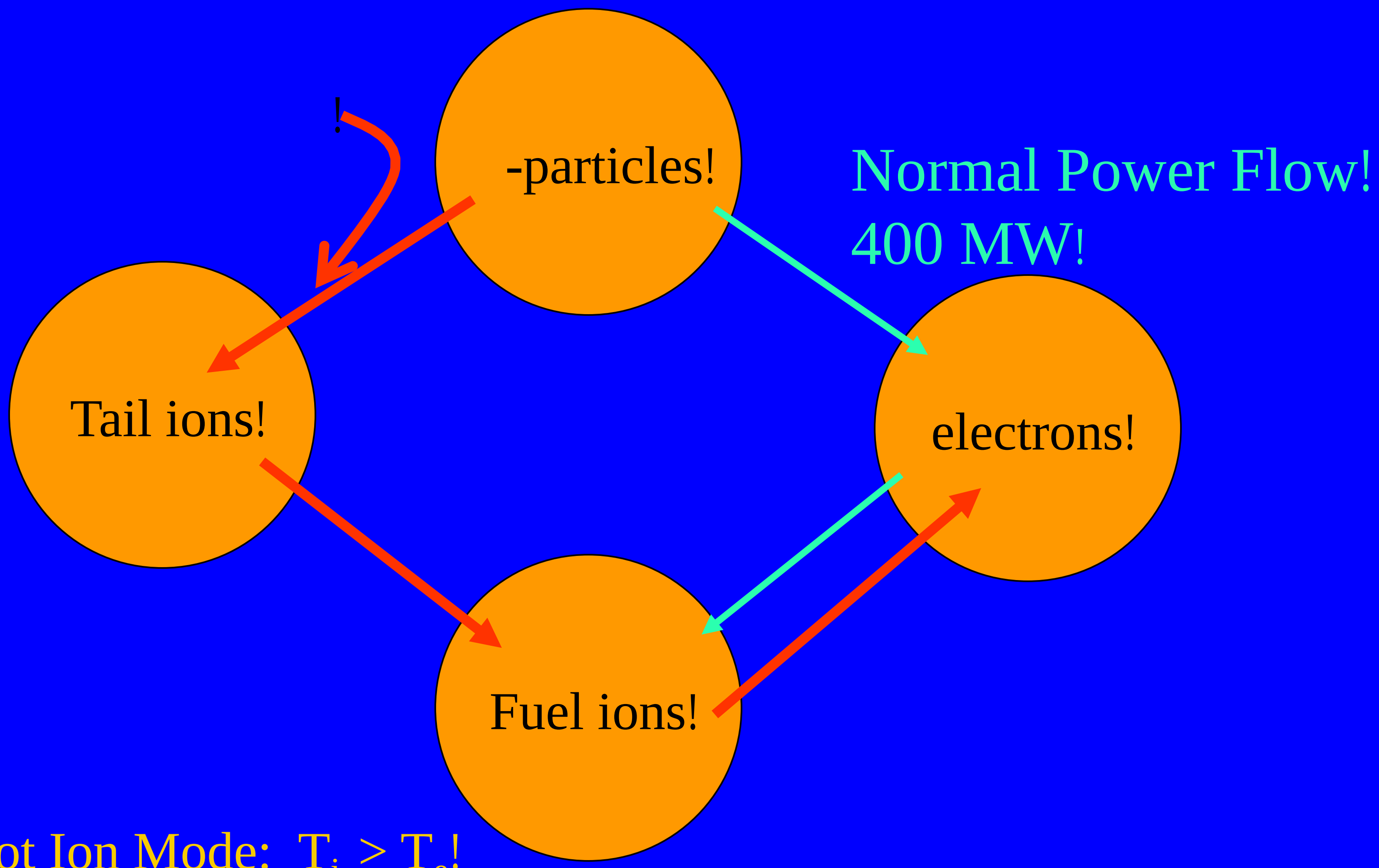
3. Neoclassical pinch effects associated with trapped electrons!

!

4.

Power Flow in a Fusion Reactor

Advantages of -Channeling



Get Hot Ion Mode: $T_i > T_e$!

75% of power to ions P_f 2 P_f!

Reactor designs around Aries I operating point

T_i(keV)	20	15	20	15
T_e(keV)	20	15	12	12
n(10^{14} cm^{-3})	1.2	1.8	1.8	2.1
$_i$(s)	2.0	2.0	2.0	1.0
$_e$(s)	1.0	0.7	0.3	0.5
P_f (W cm				

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

5/'!6'!7/'7&/'-8!!
9'/%&7,!:%'!';'":<&(!/'&$:#/!6)((!='!)"!:%'!%#:!)#"!0#-'›!

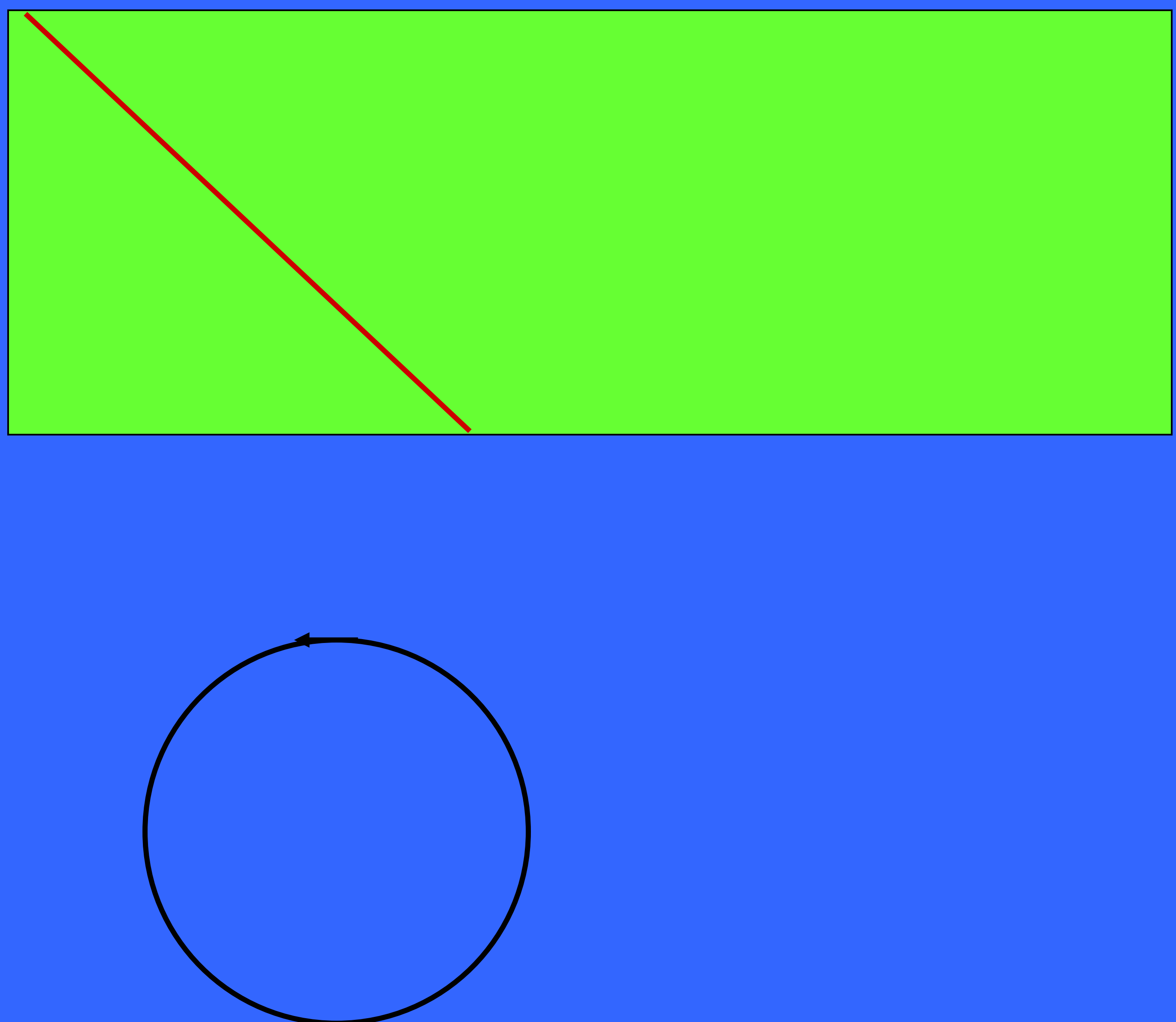
1. RF energy channeled from alpha particles
2. Fusion reactivity can be doubled in hot ion mode.
3. RF current drive fueled by alpha channeling.
4. Ash removal. Fueling.
5. Expedited by possible resonant ringing of tokamak.
6. Electron heat can be poorly confined.
7. Less free energy to drive instabilities.

Highly rf-driven reactor, possibly with 400 MW or more RF, where RF is first-order physics. !

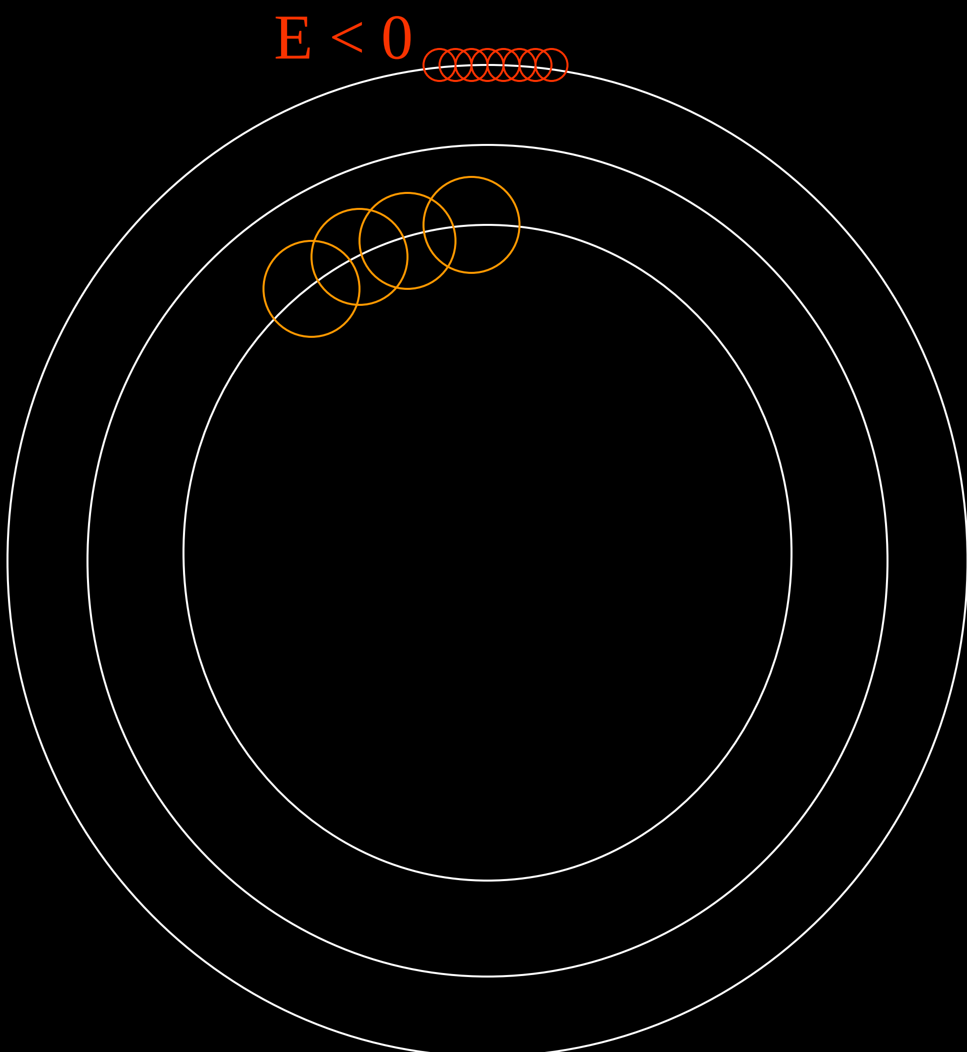
RF-Driven Tokamak!

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.

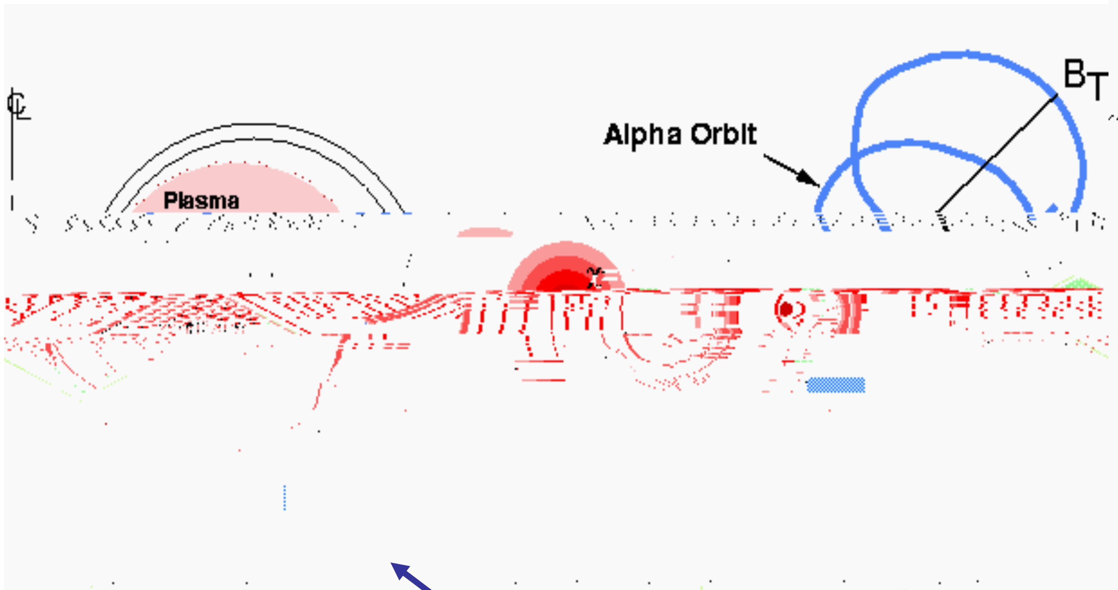
Diffusion Paths!

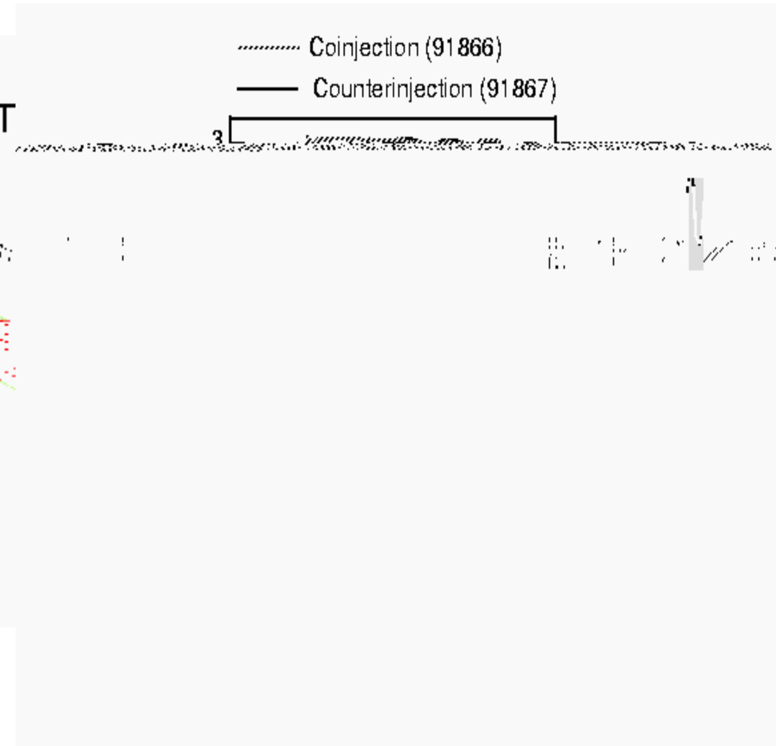


Tapping Free Energy in -Particles



TFTR D-Beam MCIBW Experiments!





Zweben s lost alpha detectors!

Darrow, 1996!

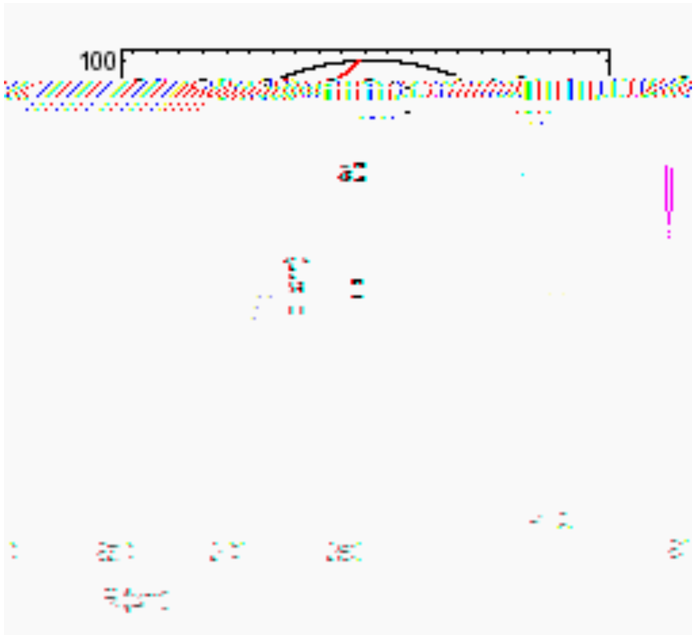
4D information: energy, poloidal angle, pitch angle, time!

Experimental Results

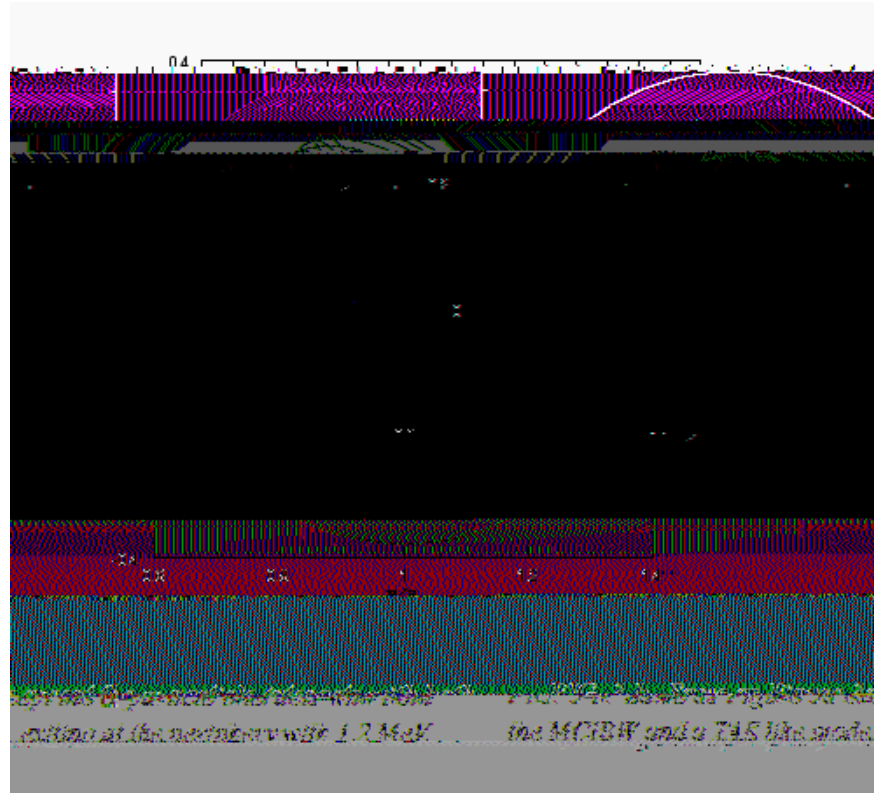
1. !Key characteristics of mode-converted IBW verified on TFTR!

2. !Detailed verification of diffusion (phased for heating) in E- -P !space

Absolute value of diffusion coefficient appears to be factor



$$k_{\|} \mathrm{v}_{\|} =$$

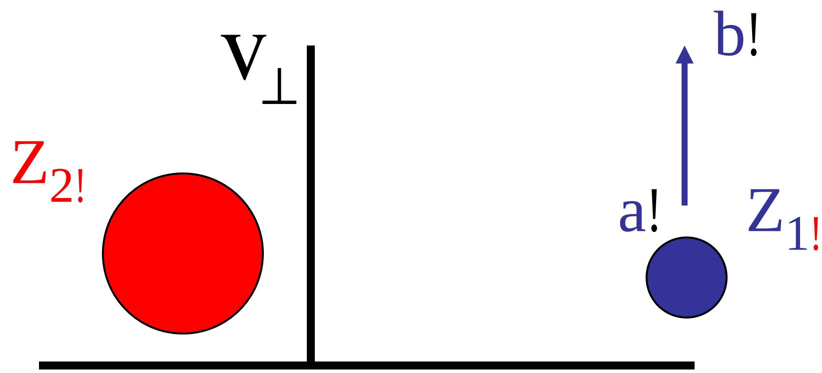


$$\frac{\quad}{\quad} =$$

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

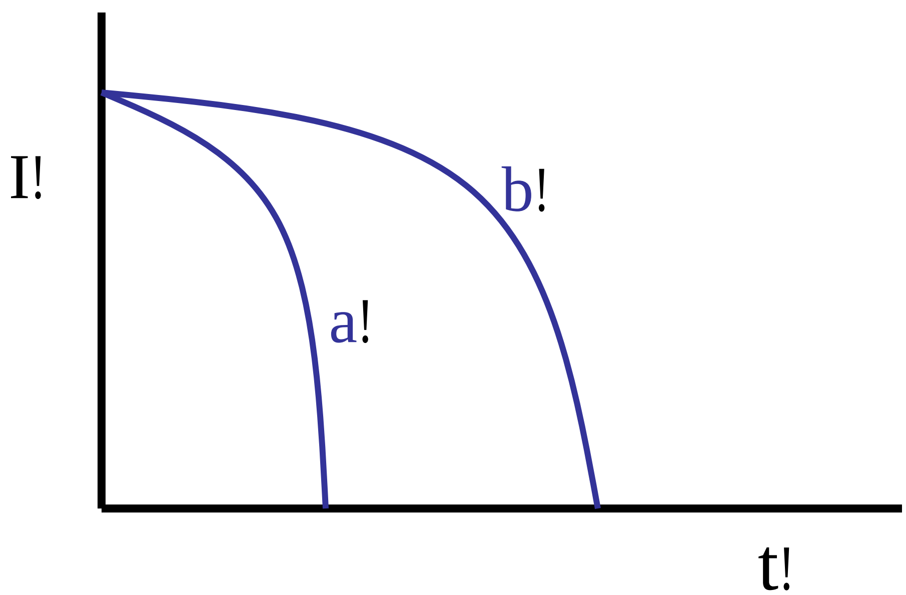
Minority ion Cyclotron Current Drive Effect (MiCCD)!



Zero ion current ! ⇒

Non-Zero electron current!

if Z_2 # Z_1 !

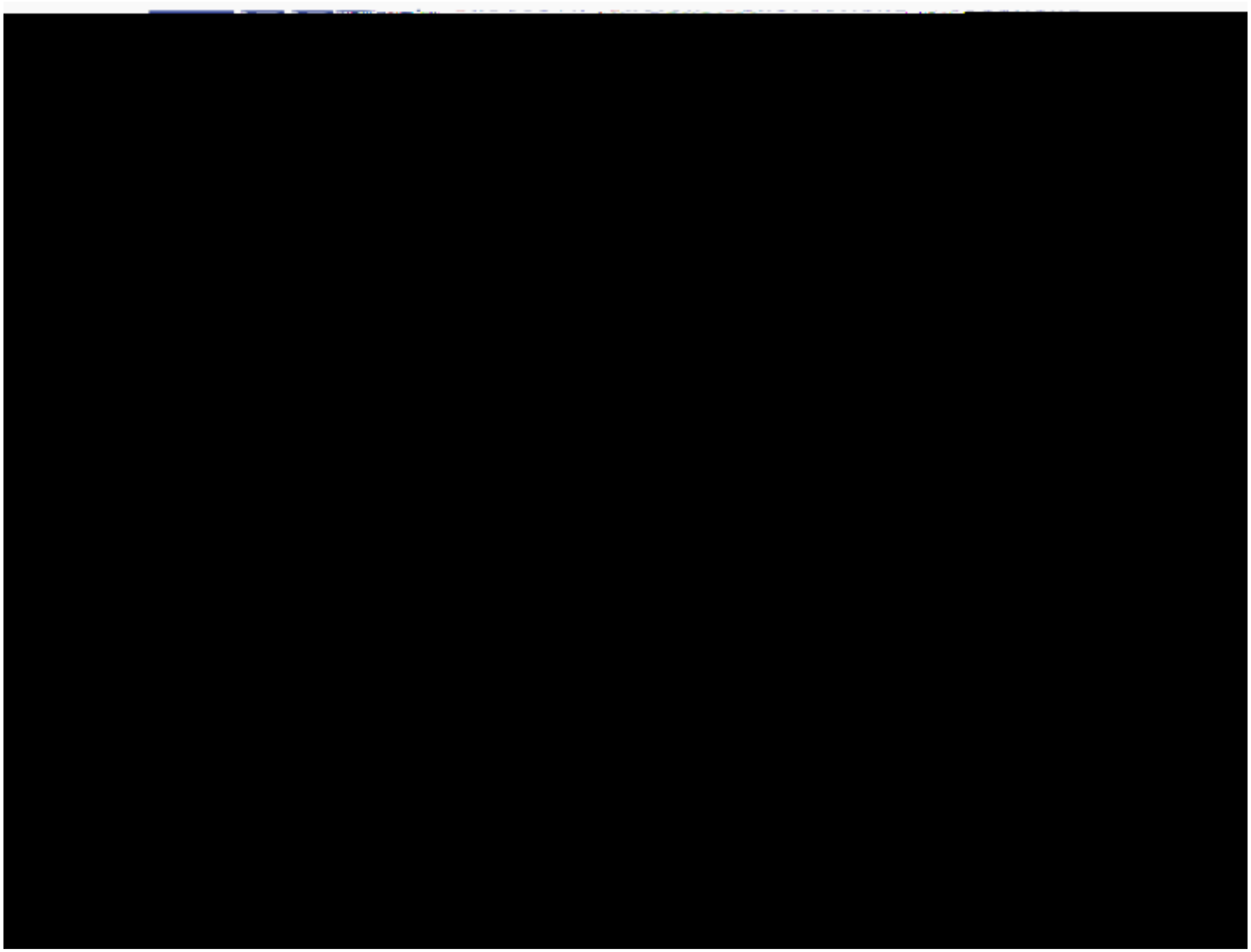


! ! $\vec{} \cdot \vec{v}$ n#

$\Omega \equiv$ /

Fisch, 1981!

Minority ion Cyclotron Current Drive



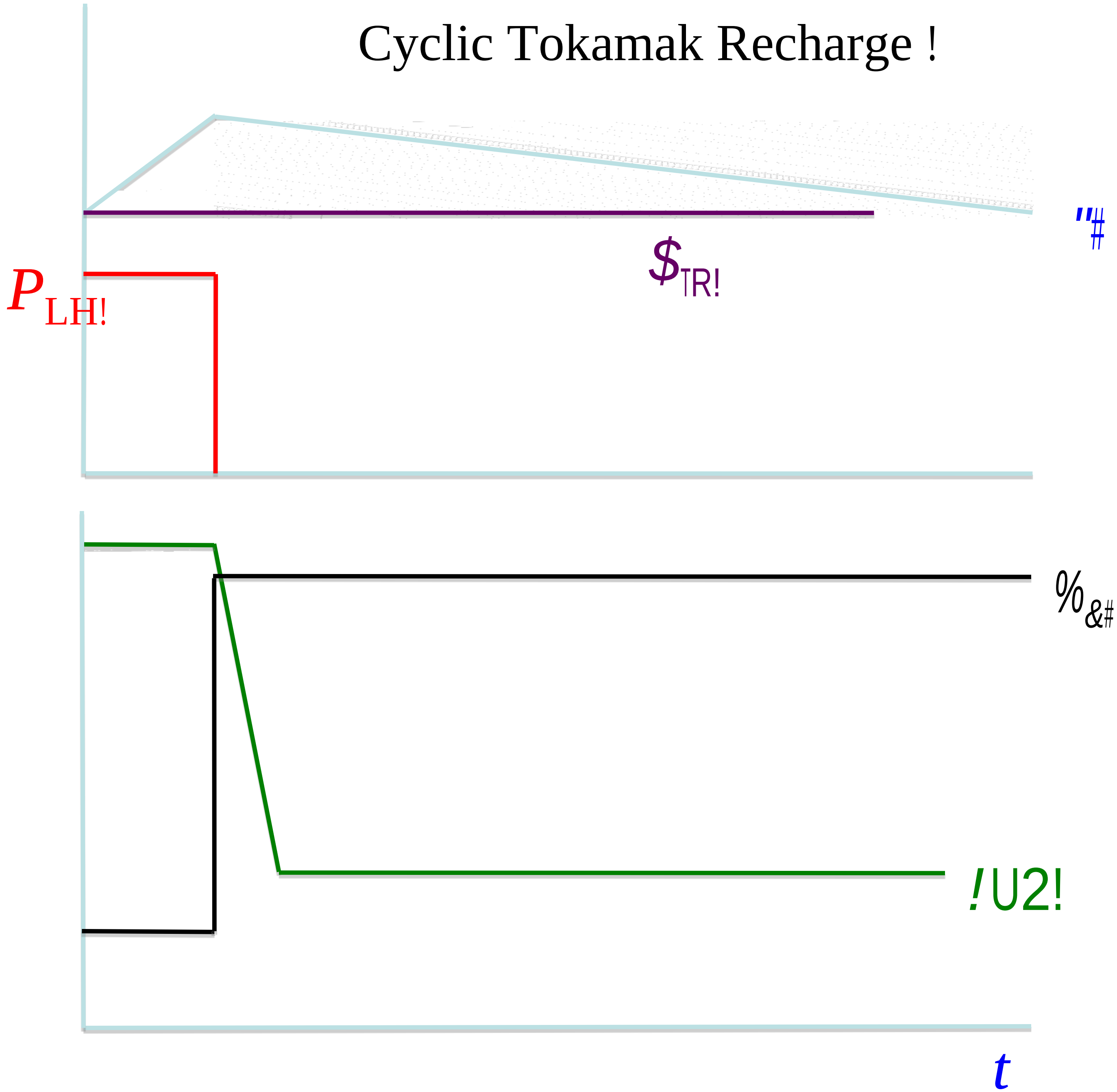
Note: MiCCD effect is complicated if

1. absorption straddles resonance
2. Ion trapping

LHCD Power Required!

Tokamak Recharge or Oscillating Current Drive !

Cyclic Tokamak Recharge !



compare: Peysson, Bae, Calabro (this conference)!

Cyclic Operation"

$$J \quad - J \quad \approx J \quad \frac{T_r}{\tau_r} \approx J_{rf} \frac{T_g}{\tau_g}$$

periodic!

$$J \quad \approx J \quad \approx J$$

Minimum variation in J

$$\underline{\quad} \approx \frac{\tau}{{}_0\tau} >> 1$$

maximize relaxation stage!

$$\frac{J}{\langle J/P \quad \rangle} \; T$$

Energy dissipated!

$$\langle \; / \quad \rangle \qquad \#$$

Optimizing Current Drive Efficiency:

$$\left\langle J/P_d \right\rangle_{LH} \qquad \frac{e}{Z_i}$$

$\left\langle J/P_d \right\rangle$

RF-induced Hyper-resistivity? "

(probably absurd, but it would be very useful)

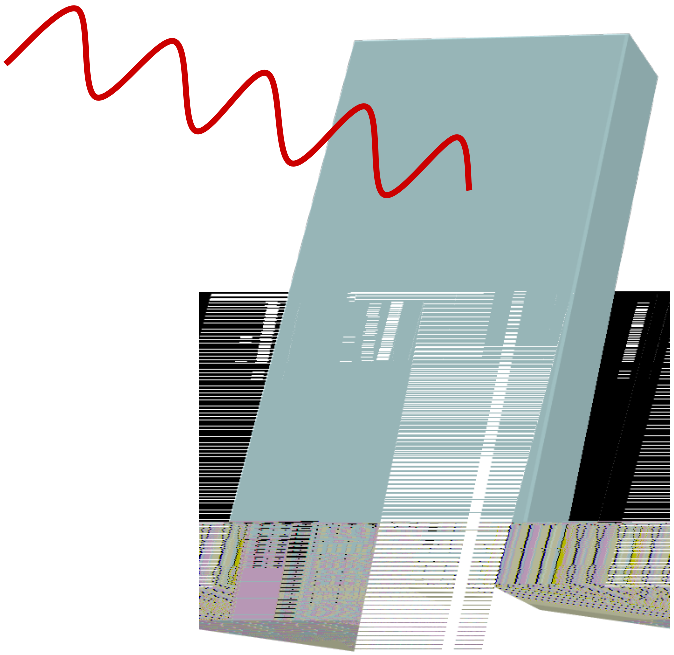
If current carriers follow field lines, can one add to field line !
!length to increase resistivity?!

If so, is there a fundamental maximum increase?!
!Shouldn’t there be a limit to the length after which !
!fine scales are averaged over?!

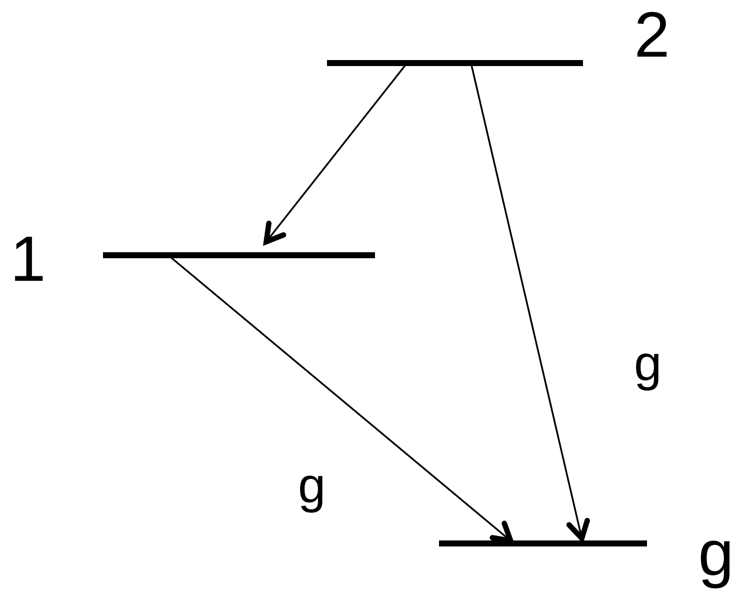
Bump-on-tail Instability!

Bump-on-tail Instability!

Rearrangement of Phase Space in Plasma



Free Energy under Phase Space Rearrangement



$$\varepsilon = n_g \varepsilon_g + n_1 \varepsilon_1 + n_2 \varepsilon_2$$

minimized for: n_g n_1 n_2

→ →

more generally, minimize:

using -pulse excitations ij

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

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

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

Example!

Example (continued)

Apply 21, 20, 10)

Best strategy

Initial	!W_0 = 22	0!	!	2	!	5
Step 1	!W_1 = 35/2	0!	!	7/2	!	7/2
Step 2	!W_2 = 21/2	7/4	!	7/2	!	7/4!
!						
Step 2	!W_3 = 77/8	21/8	!	21/8	!	7/4

21, 10, 20, 21) !

Poor strategy

Step 1	!W_1 = 35/2	0!	!	7/2	!	7/2
Step 2	!W_2 = 63/4	7/4	!	7/4	!	7/2!
!						
Step 3	!W_3 = 49/4	21/8	!	7/4	!	21/8!
!						
Step 4	!W_4 = 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 { $_{ij}$} that minimizes: $\vec{\ } \cdot \vec{\varepsilon}$

Continuous: Let

$$\frac{\partial (,)}{\partial} = \# \quad (, ',)\left[(',) - (,) \right]$$

$$K \qquad = K$$

$$(, ',) \quad 0$$

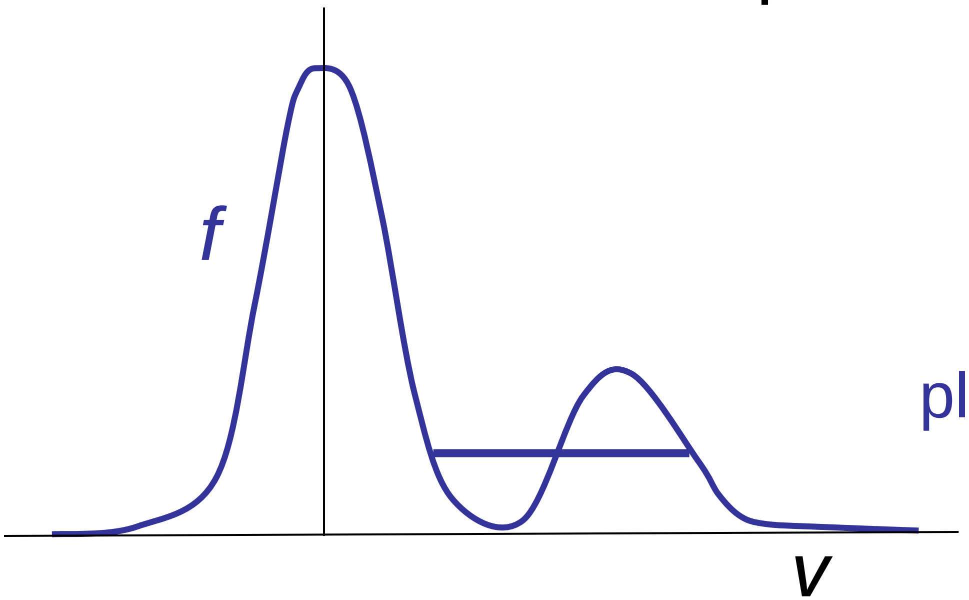
$$W(t) \quad \# \, \varepsilon(v) f(v,t) dv$$

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

Note the H-theorem:

$$— \int \ (,)^2 \quad \# \ 0$$

Bump-on-tail Instability



plateau solution