Methods of rf Current Drive

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Radio frequency waves can penetrate thermonuclear plasmas, depositing momentum and energy with great selectively: in select resonant ions or electrons, in select resonant regions, and with select momentum.

TFTR

Tokamak Fusion Test Reactor (1989)

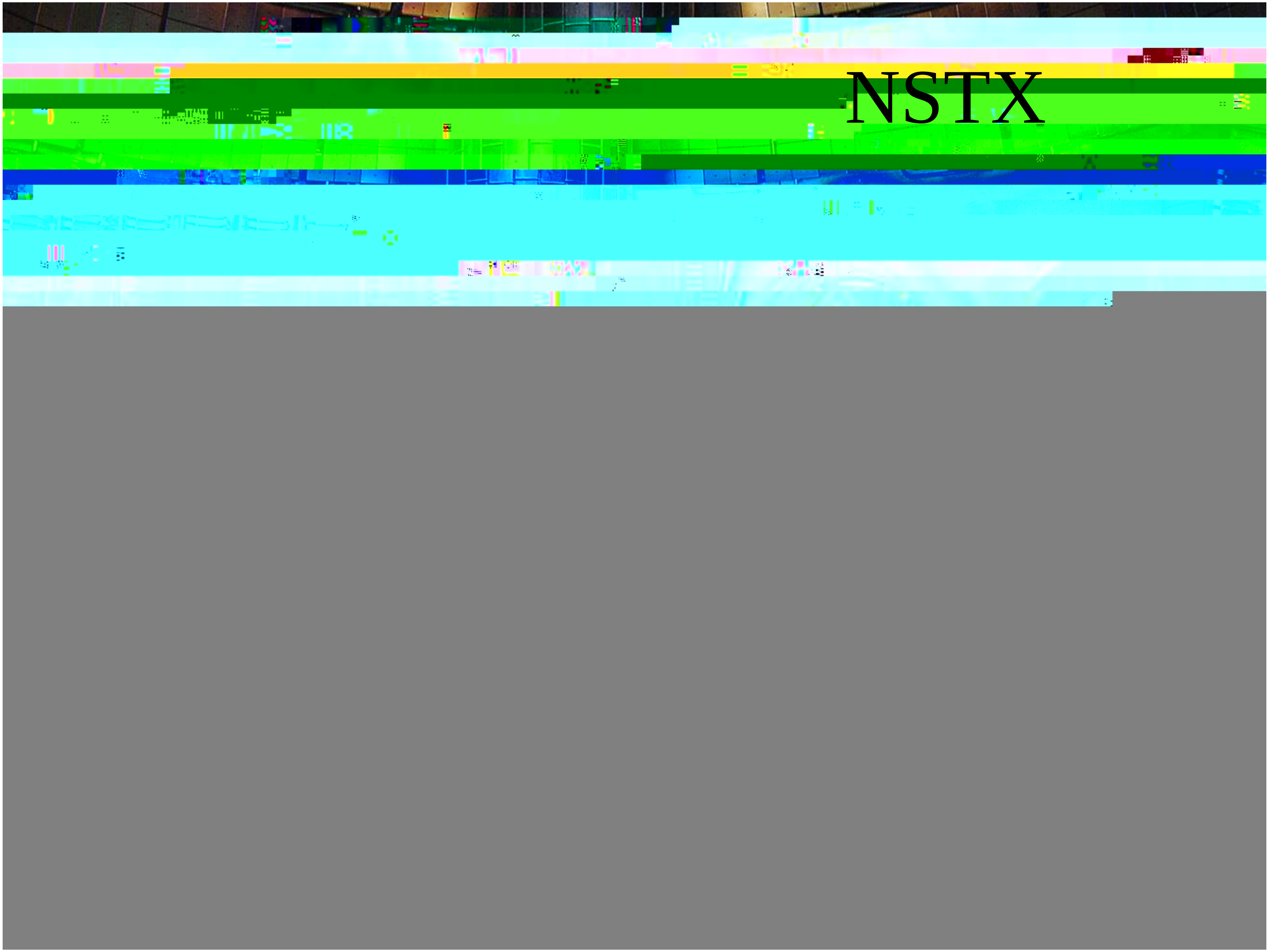
Driving a Toroidal Current with Waves

Note: curl $J \; ! 0$

How are these plasma waves excited?

Example:
Tore Supra LH Grill
4 MW
1000 s
3.7 GHz

NSTX



Uses of RF Waves in Magnetic Confinement Fusion Devices seeking ever increasing control of plasma

1970's: Heat Plasma to Thermonuclear Temperature:

Ion Cyclotron, Lower Hybrid, Electron Cyclotron Waves

1980 s: Drive Mega-amps of plasma current

LHCD, ECCD, MiCCD current drive

1990's: More detailed positioning of plasma current

Use LHCD, ECCD to control of NTM, sawteeth, plasma current profile

1990 s: Exploit coupled diffusion of particles in velocity and position
! !   Channeling effect"

Trend to !phase space engineering"!

Detailed control of rf-induced fluxes in 12-D!
!Select particles in 6D velocity-configuration space !
!Select flux vector in 6D velocity-configuration space !

Early Current Drive Work

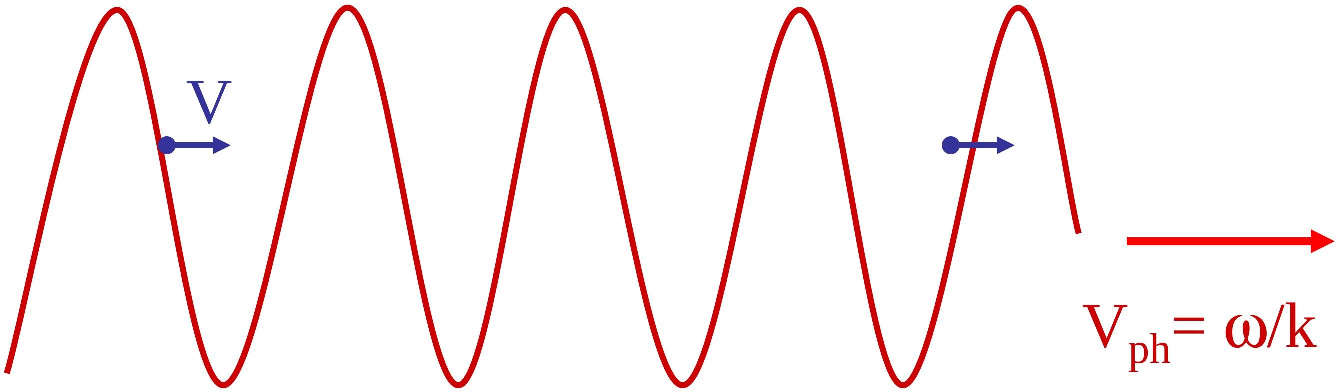
1952 Thoneman *et al.* -- glass tube

1966 Yoshikawa and Yamato -- C- Stellarator (200 s)

1970 Ohkawa -- Neutral beams, $v < v_T$

1971 Wort -- waves $v_{ph} < v$

(Resonant) Radio Frequency (RF) Current Drive Effect



v v v

$$J = en \quad \text{v}$$

$$E = mn\text{v} \quad \text{v}$$

$$P_D = \nu \Delta E$$

Example of Resonance: The Traveling Plasma Wave

$$\vec{E} \qquad 4\,!\,e(n_0 \qquad n_e) \qquad 4\,!\,e\tilde{n}$$

Poisson s equation

$$\frac{\partial}{\partial t} n_e \qquad\qquad n_e v \qquad 0$$

Particle conservation

$$\frac{\partial}{\partial t} n_e m v \qquad\qquad n_e m v v \qquad eE$$

Momentum conservation

$$\frac{\;^2}{t^2}\tilde{n} \qquad\qquad {}_p^2\,\tilde{n} \qquad 0$$

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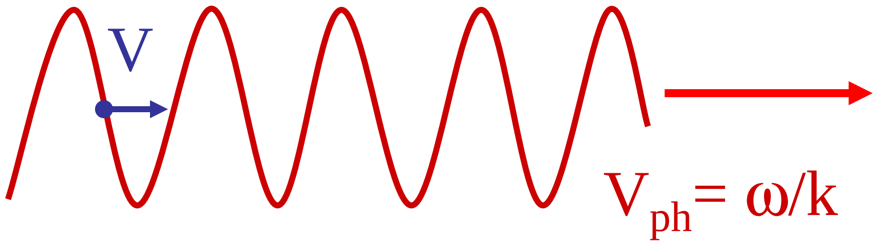
Electron acceleration in a plasma wave

from V.Malka

Accelerating Gradient in Plasma



Conventional Accelerator

Gradients ~ 20 MeV/m at 3GHz

1 TeV Collider requires 50 km

Peak gradients limited by breakdown

$$\nabla \quad \vec{E} \quad -4\,!\,e\tilde{n}$$

$$\tilde{n}_{MAX} \approx n_0$$

$$k \quad \frac{!_p}{c}$$

$$eE_{MAX} \approx \sqrt{n_0}\,GeV/cm$$

Plasma Accelerator

High fields, No breakdown

(Tajima and Dawson, 1979)

Example

$n_0 = 10^{18}\text{cm}^{-3}$

eE=100 GeV/m

Note: For v << c , $\frac{v_{osc}}{c} \approx \frac{\tilde{n}}{n_0}$

Particles accelerated to relativistic energies, even as plasma motion is not

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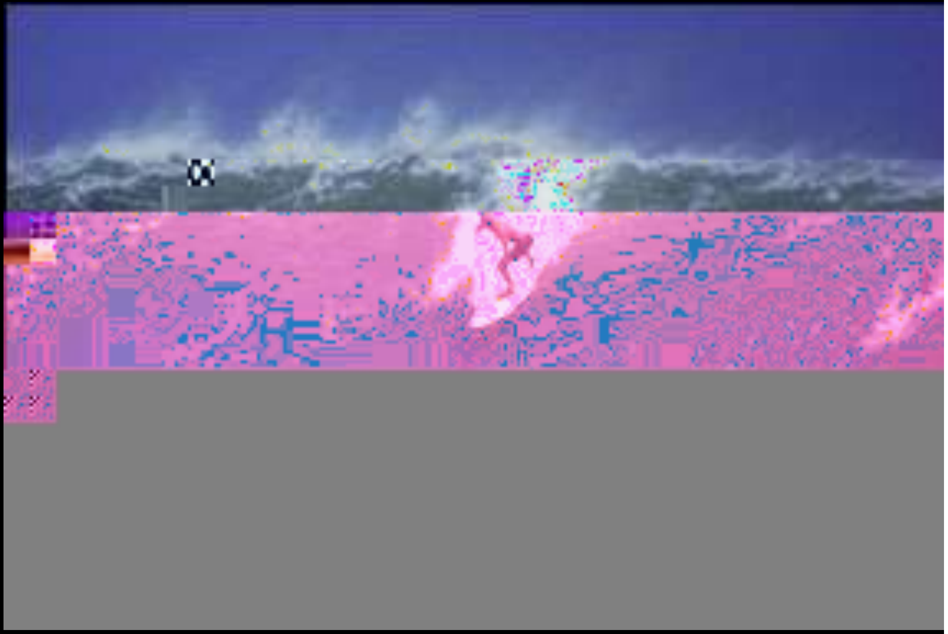
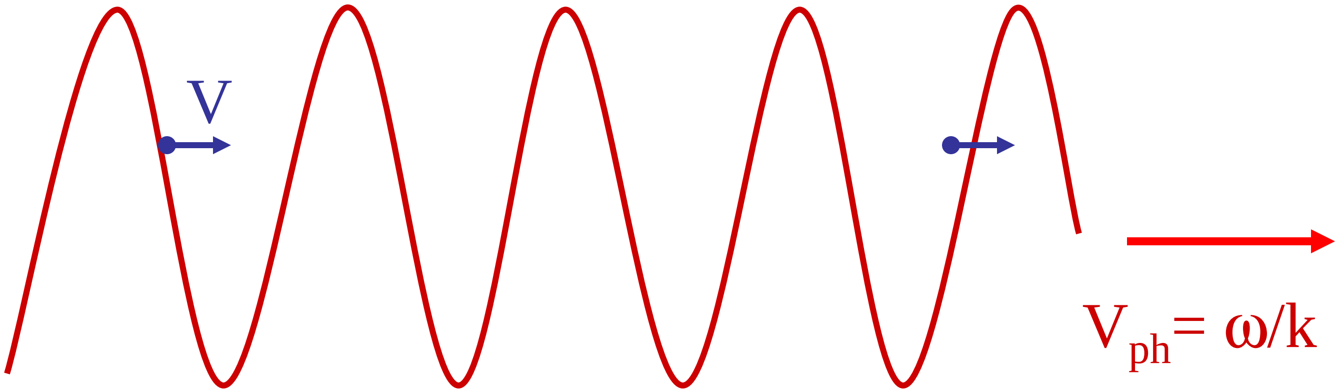


Not-resonant surfers $V ! V_{ph}$

(Resonant) Radio Frequency (RF) Current Drive Effect



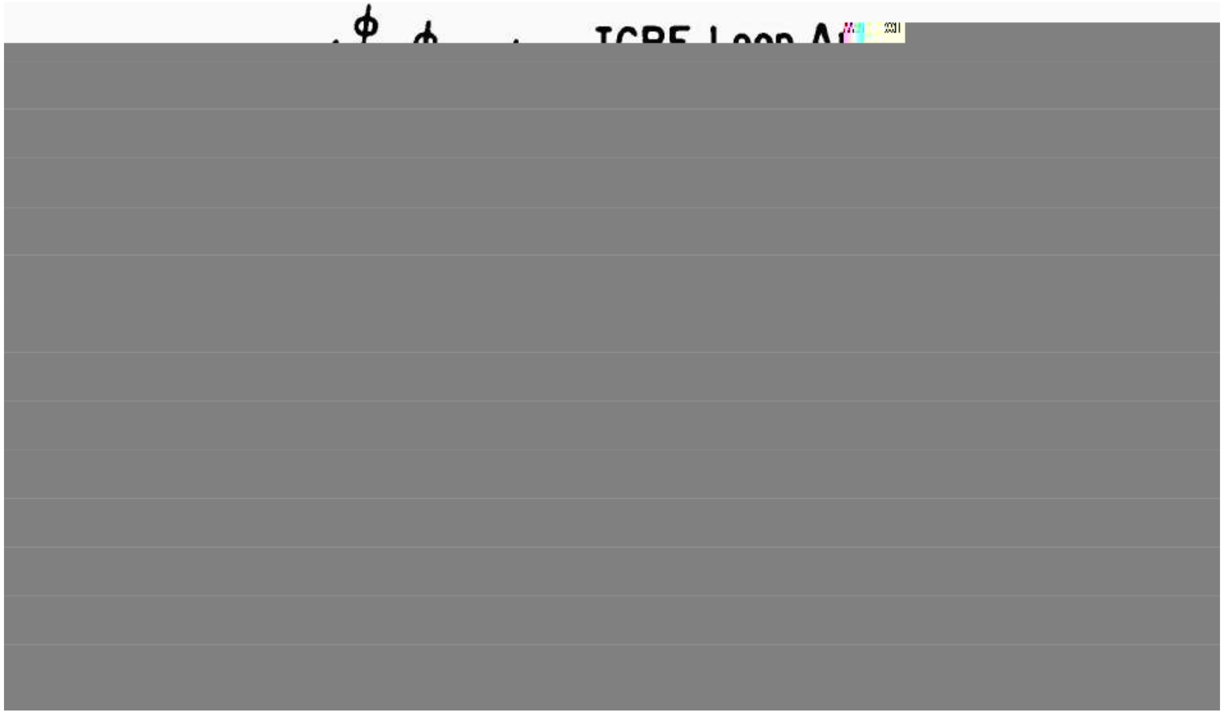
$$v \qquad v \qquad v$$

$$J = en \quad v$$

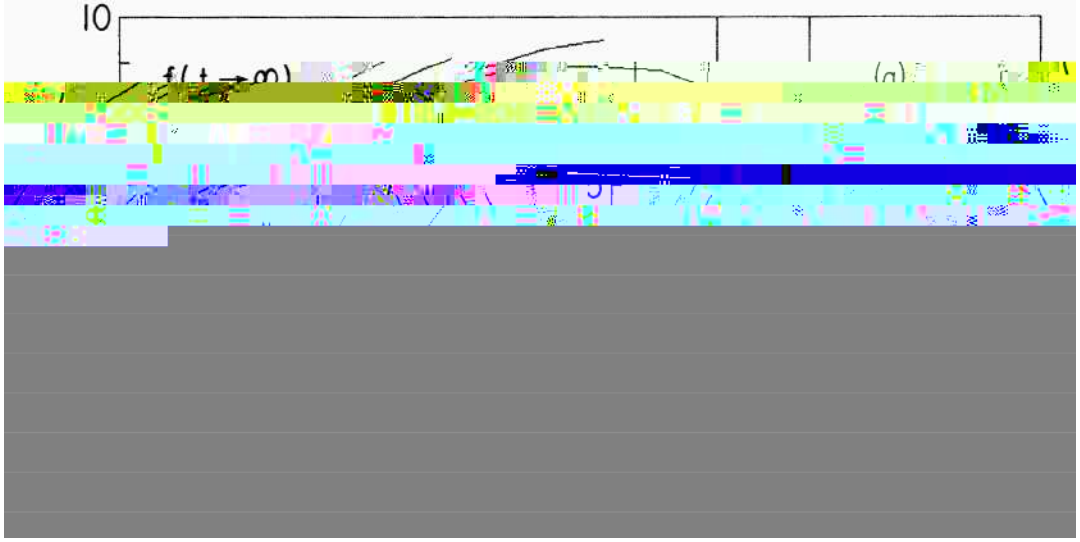
$$E = mnv \quad v$$

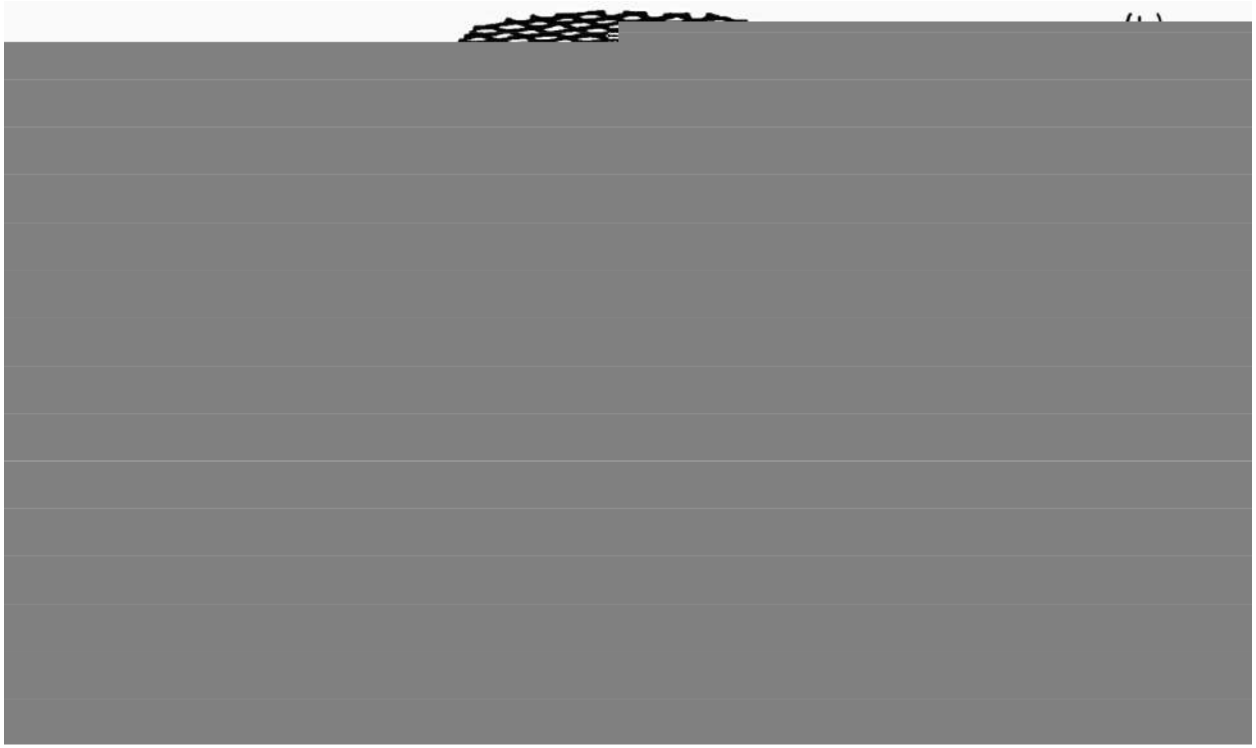
$$P_D = \nu \Delta E$$

RF Methods of Heating and Current Drive



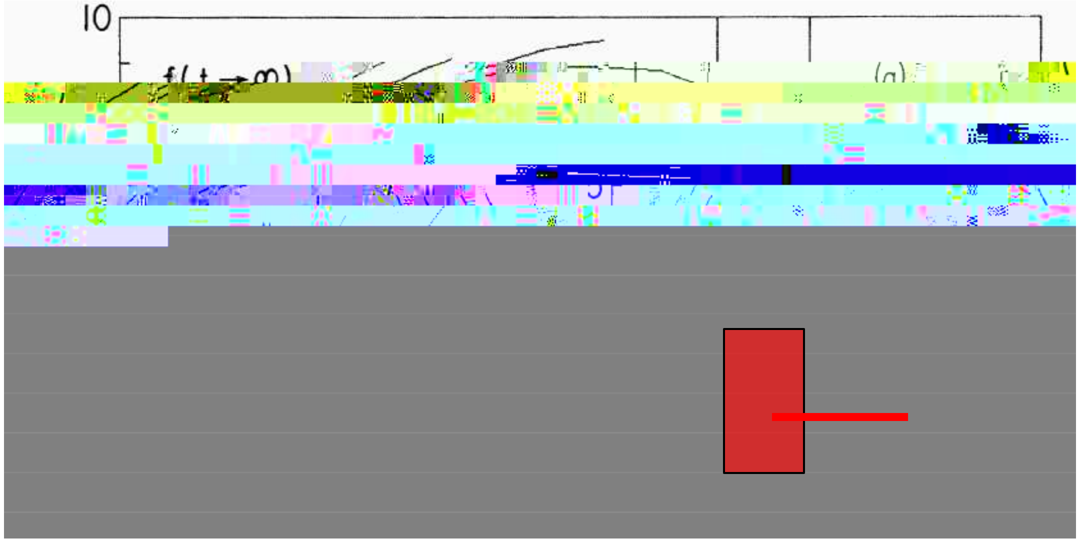
Electron Distribution Function -- LHCD

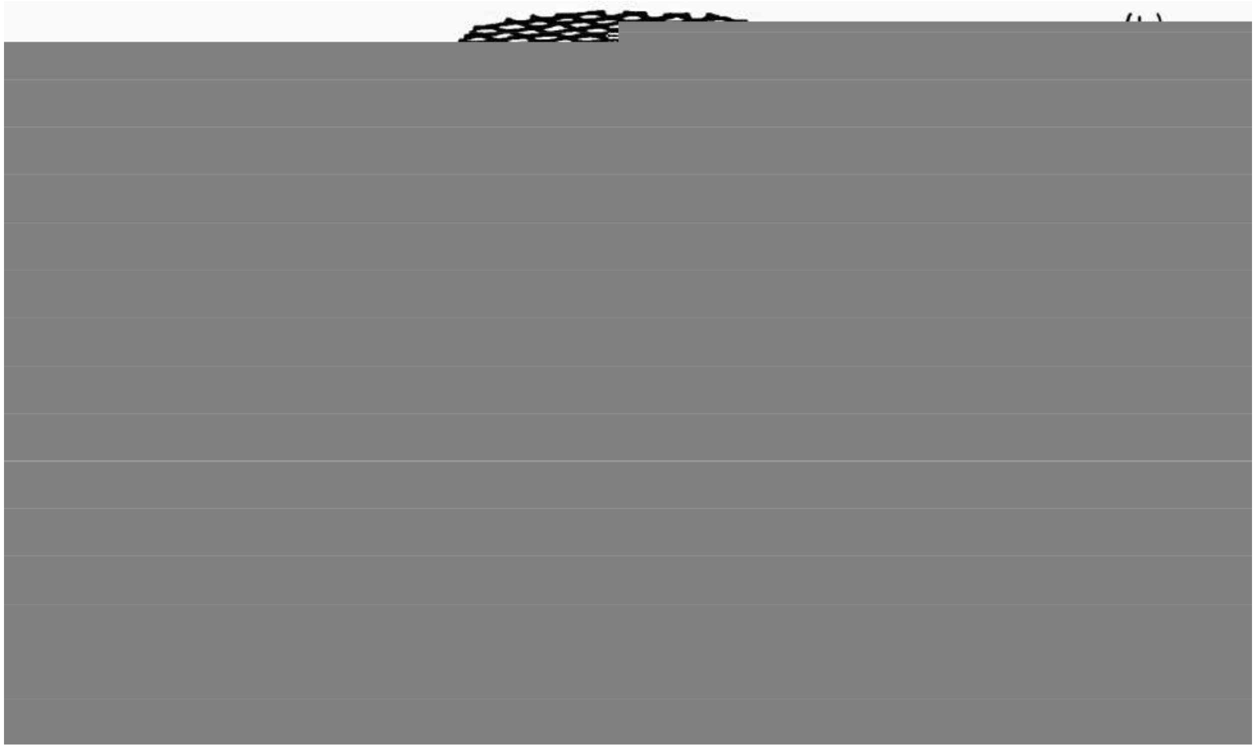




Karney and Fisch, 1979

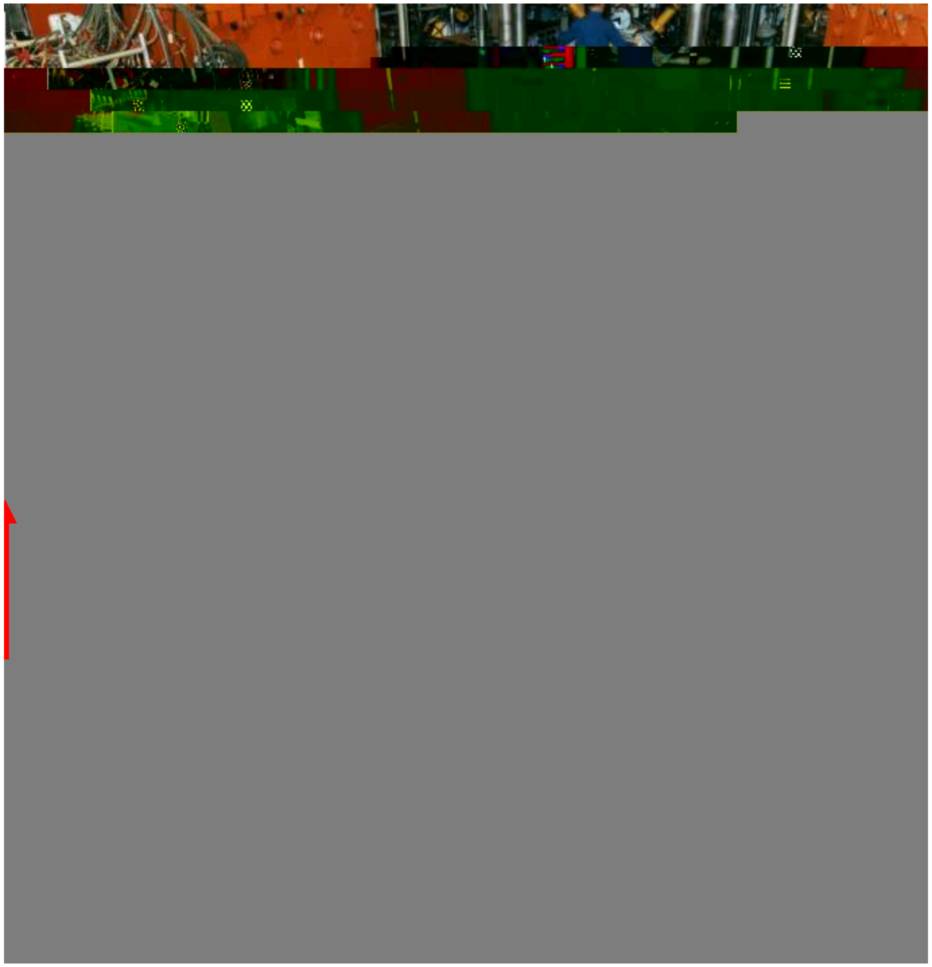
Electron Distribution Function





Karney and Fisch, 1979

Progress in Current Drive

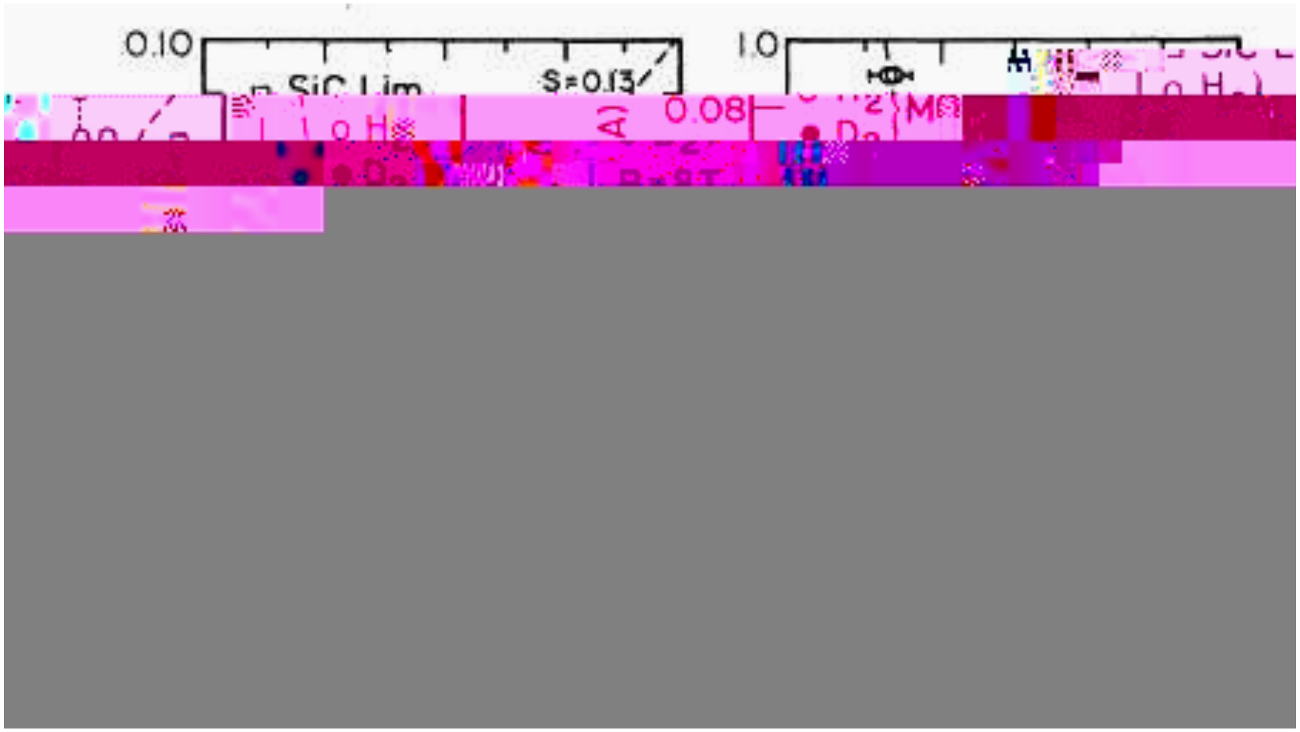


JET (2001)

Alcator C

Current drive efficiency at B=8T shows n^{-1} scaling

Porkolab et al, 1984



Line-averaged density times current vs. power

Efficiency vs. density

Theory and Demonstration of the Current Drive Effect with PLT Data

P_{el} is power into stored magnetic energy

Ramp-up: $E<0$″

P_{el}/P_{rf}

Karney, Fisch and Jobes (1985)

Corroborated on:

ASDEX: Leuterer (1991)
PBX: Giruzzi; Bernabei (1997)
HT-7: Chen (2005)

Also note ECCD consistency
DIII-D: Petty (2002)

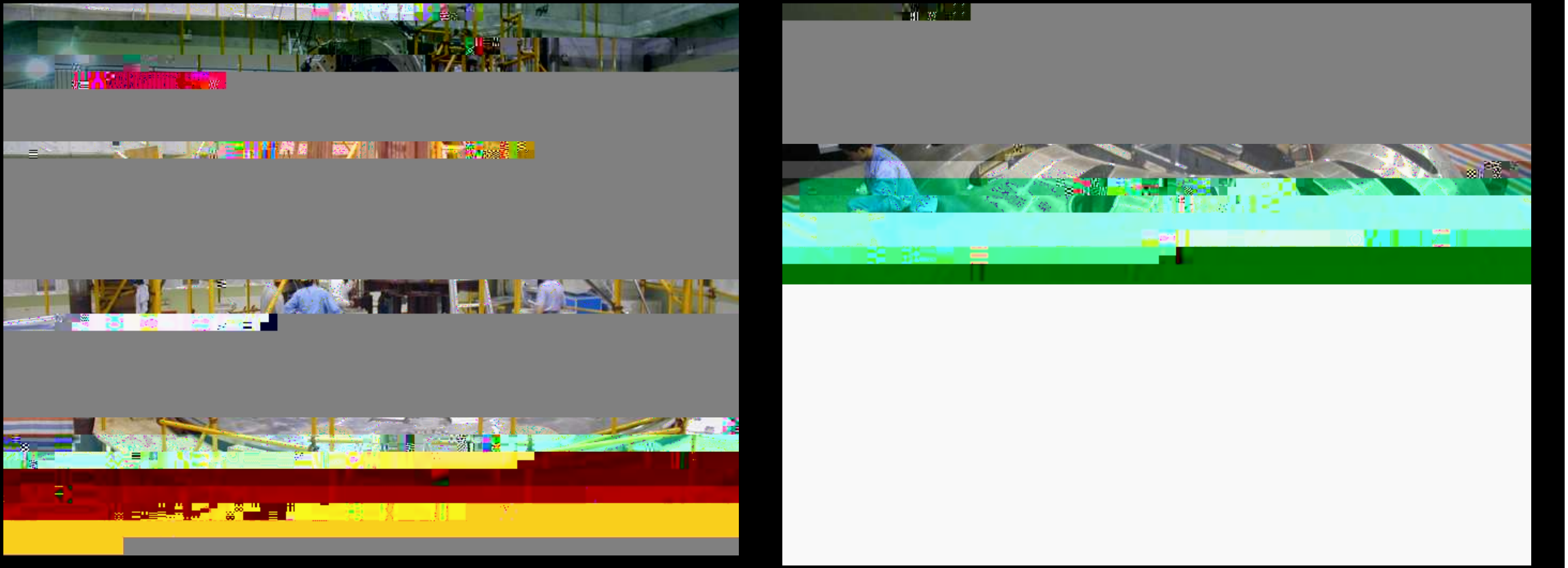
Steady State: $E=0$″

v_{ph}/v_R

v_R = runaway velocity

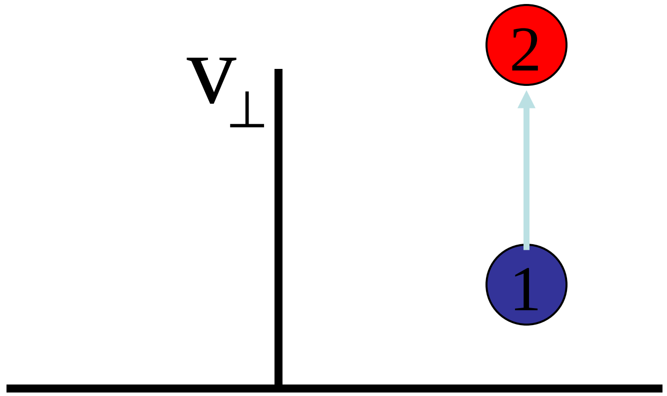
Verification *in detail* proves classical picture of electron collisions!

Tokamak East



LHCD with very long pulse -- time scales for pinch effects
Low frequency ICRF with 4T (internal mode excitation)

Electron Cyclotron Current Drive Effect



$$! - \vec{k}\cdot\vec{\mathrm{v}} \quad n\Omega$$

$$\Omega \equiv$$

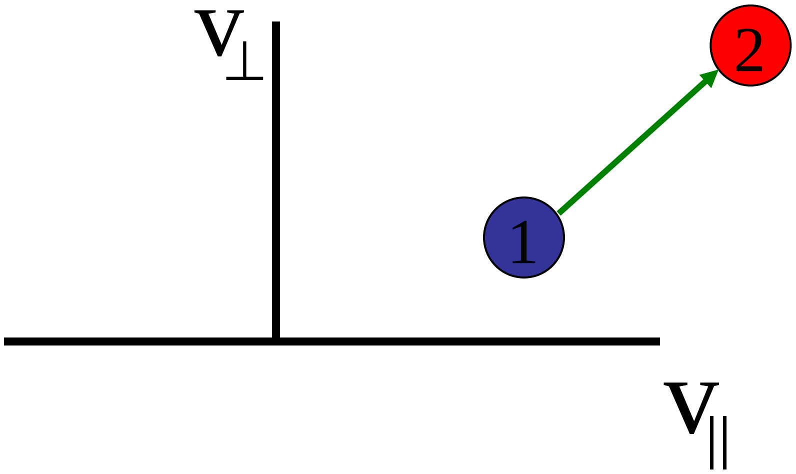
Langevin Equations

$$\frac{\partial f}{\partial t} \quad C(f,f) \quad C(f,f_i) \qquad C(f,f_i) \quad \frac{}{2v^3}\,\frac{}{\mu}(1 \quad \mu^2)\frac{}{\mu}\, f$$

$$\frac{\partial v}{\partial t} \quad -\frac{\Gamma}{2v^3}v \qquad\qquad \frac{\partial\langle\mu\rangle}{\partial t} \quad -\frac{\partial}{\partial t}\frac{\Gamma}{2v^3}\int\mu\frac{\partial}{\partial\mu}(1-\mu^2)\frac{\partial}{\partial\mu}f \quad \frac{\Gamma}{2v^3}(1 \quad Z_i)\langle\mu\rangle$$

$$\frac{!\langle\mu\rangle}{!v} \quad (1 \quad Z_i) \; \frac{\mu}{}$$

Generalized RF Current Drive Effect



$$! - \vec{k}\cdot\vec{v} \quad n\Omega$$

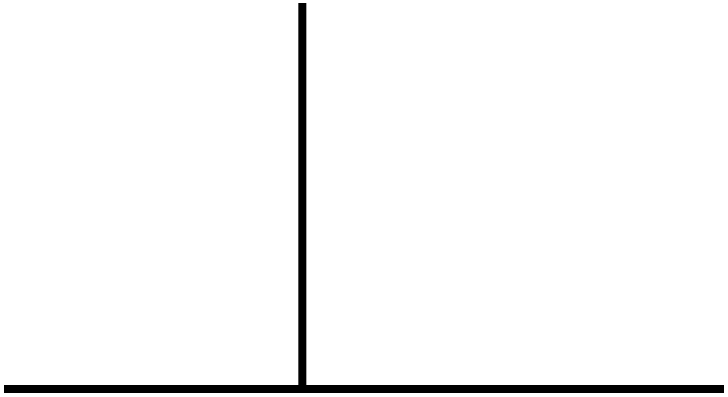
$$J \quad \int d^3v\, \overline{S}\cdot\overline{\nabla}\,\Psi$$

$$P_D \quad d^3v\, \bar{S}\cdot\nabla$$

Generalized Transport Quantities

Associate transport quantity with each point in 2D velocity space

1. Current Drive Efficiency



2. Runaway Probability

3. Energy flow to stored magnetic energy $W_{el} \quad \int_0^\infty ev \cdot E\, dt$

Conclusions From Current Drive Campaign

A. Current drive effect established as a tool

   1. Precise control over RF Absorption.
   2. New transport quantities demonstrated.
   3. Contemplate steady-state tokamak reactors.

B. Fundamental physics established

   1. Slowing down equations of fast electrons not hitherto tested since Spitzer conductivity not sensitive to fast electrons.
   2. But the transport quantities verified are far more detailed than Spitzer conductivity (integrated quantity).
   3. Verification *in detail* therefore resolved the question whether classical Coulomb collisions govern superthermal electrons!

Examples of Further Development of RF Current Drive

JT-60and JT60-U (Japan) -- 3MA LHCD 800 kA ECCD, ITB sawteeth stabilization (2001)
JET (England) -- 3 MA LHCD, ITB with LHCD, Minority Species CD. ITB
Tore Supra (France) -- 1000 s LHCD, ITB; 330 s, 1 GJ, LHCD (2004), ECCD Synergy

C-Mod tokamak (MIT) : LHCD
TRIAM (Japan): several hours LHCD
T-10 (Russia): ECCD , sawteeth
TCV tokamak --- ECCD steady state, sawteeth
ASDEX (Germany): ECCD stabilization of tearing modes
Wendelstein 7-AS Stellarator: ECCD
Frascati FT-U (Italy): LHCD, ECCD stabilization of sawteeth, tearing modes
General Atomics DIIID tokamak; ECCD, ITB, mode suppression
Princeton spherical torus: NSTX (HHFWCD)

New Steady-State Superconducting Lower-hybrid driven
SST (India)
KSTAR (Korea)
HT-7 and HT7-U !East" (China)

Superconducting tokamak TRIAM-1M (Kyushu, Japan)

TRIAM, Advanced Fusion Research Center
Courtesy H. Zushi

Major radius!	**0.84 m!**
Minor radius!	**0.12 m!**
Toroidal field!	**8 T (Steady State)!**

TF coils : Nb_3Sn (superconductor)
PF coils : Cu (normal conductor)

Current drive

Lower Hybrid Waves (CW)

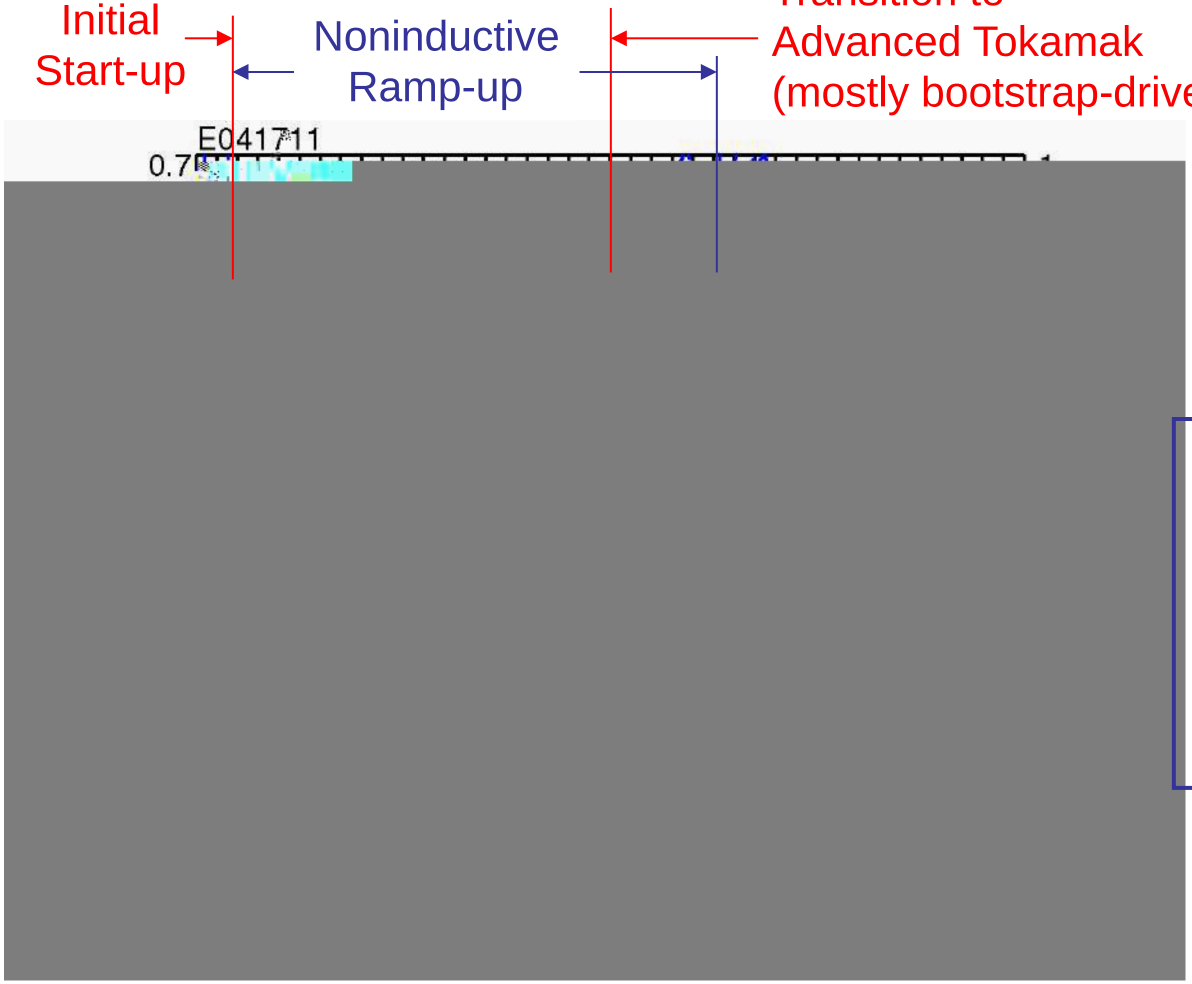
8.2 GHz	400 kW	16 Klystrons
2.45 GHz	50 kW	1 Klystron

Electron Cyclotron Waves

170 GHz 200 kW 5 sec

Demonstration of Full Scenario from Start-up to Advanced Tokamak without OH Transformer

Y. Takase, et al., " IAEA 2002"



Initial Start-up

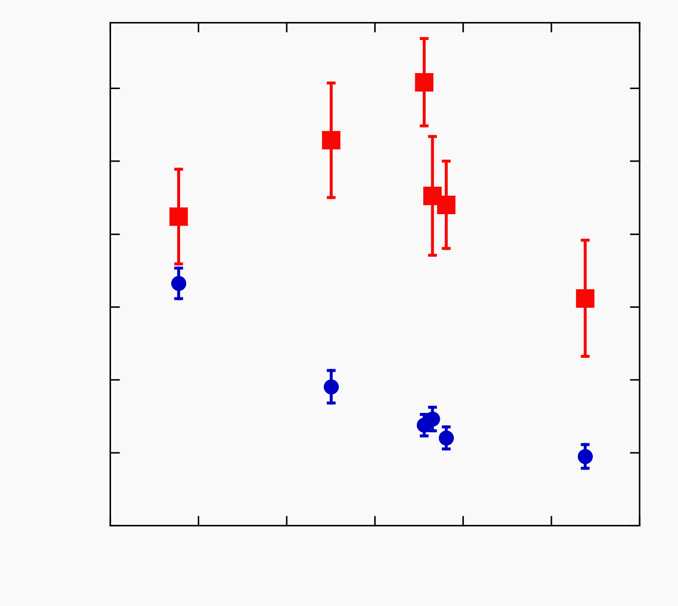
Noninductive Ramp-up

Transition to Advanced Tokamak (mostly bootstrap-driven)

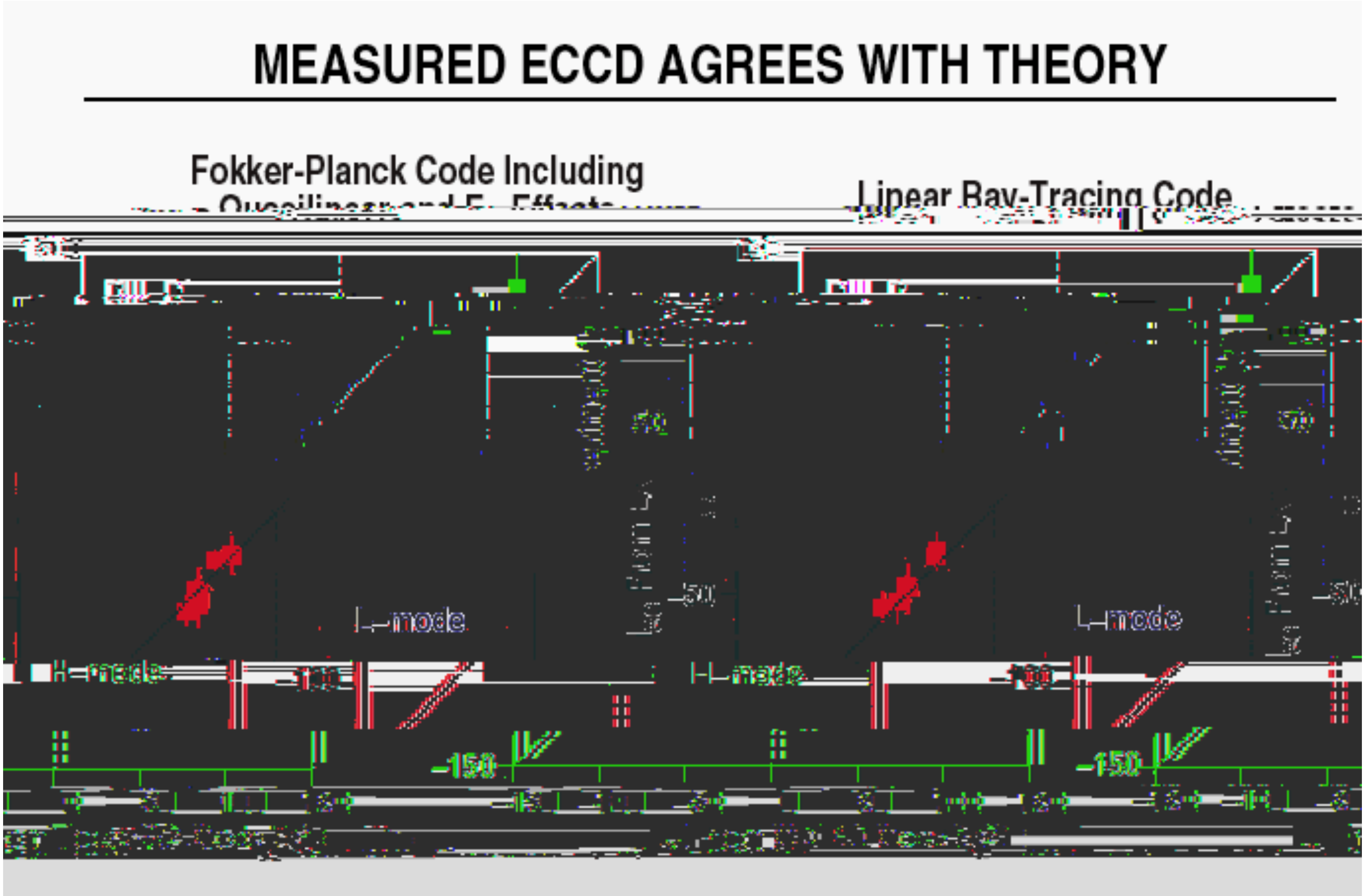
JT-60U

RFCD can be used for further current ramp-up to bridge the gap between initial start-up and NB-heated advanced tokamak phases (PLH > 1MW for JT-60U)

TORE SUPRA: First demonstration of EC+LH synergy



Heating and Current Drive by Electron Cyclotron Waves

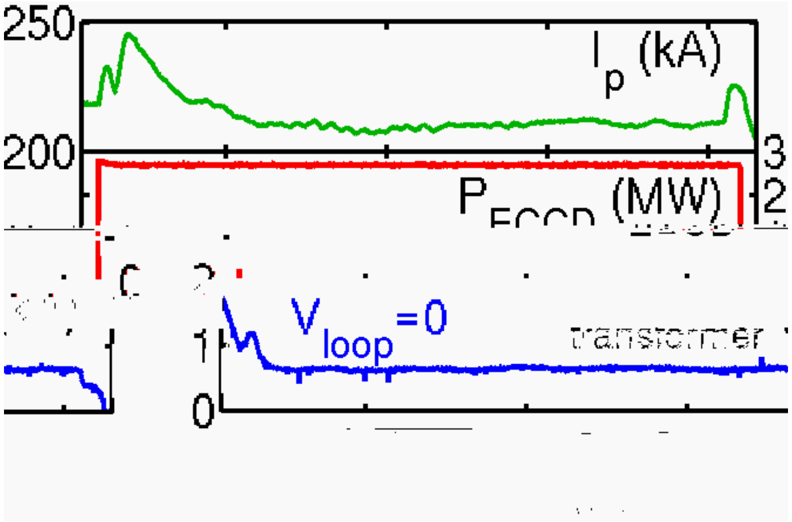


MEASURED ECCD AGREES WITH THEORY

Fokker-Planck Code Including

Linear Ray-Tracing Code

Full Steady-State Current by ECCD in TCV
(record 210 kA)"

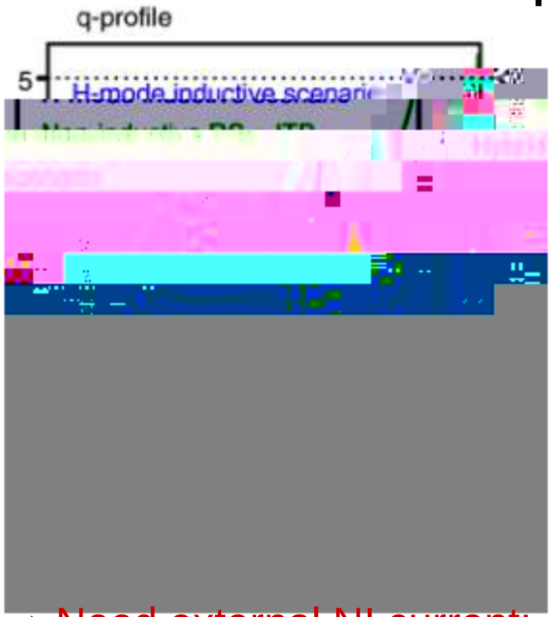


S. Coda et al. (2000)"

also e.g. *Steady-state non-inductive eITB with off-axis co-ECCD*"
M.A. Henderson et al, Phys. Plasmas **10**, 1796 (2003"

ITER ‘non-inductive’ and ‘hybrid’ scenarios: rely on non-inductive (NI) current

JET Task Force S2 mission: plasmas suitable for ITER non-inductive and hybrid scenarios



B. Green, ITER: burning plasma physics experiment, PPCF 45 (2003) 687

ITER ‘hybrid’ scenario:

~50% NI current, with ~20% self-generated bootstrap current

candidates: plasmas with safety factor (q) > 1 and q_{95}~3-4,
with low positive or weak negative magnetic shear

ITER ‘non-inductive’ scenario:

100% NI current, with >50% BS current

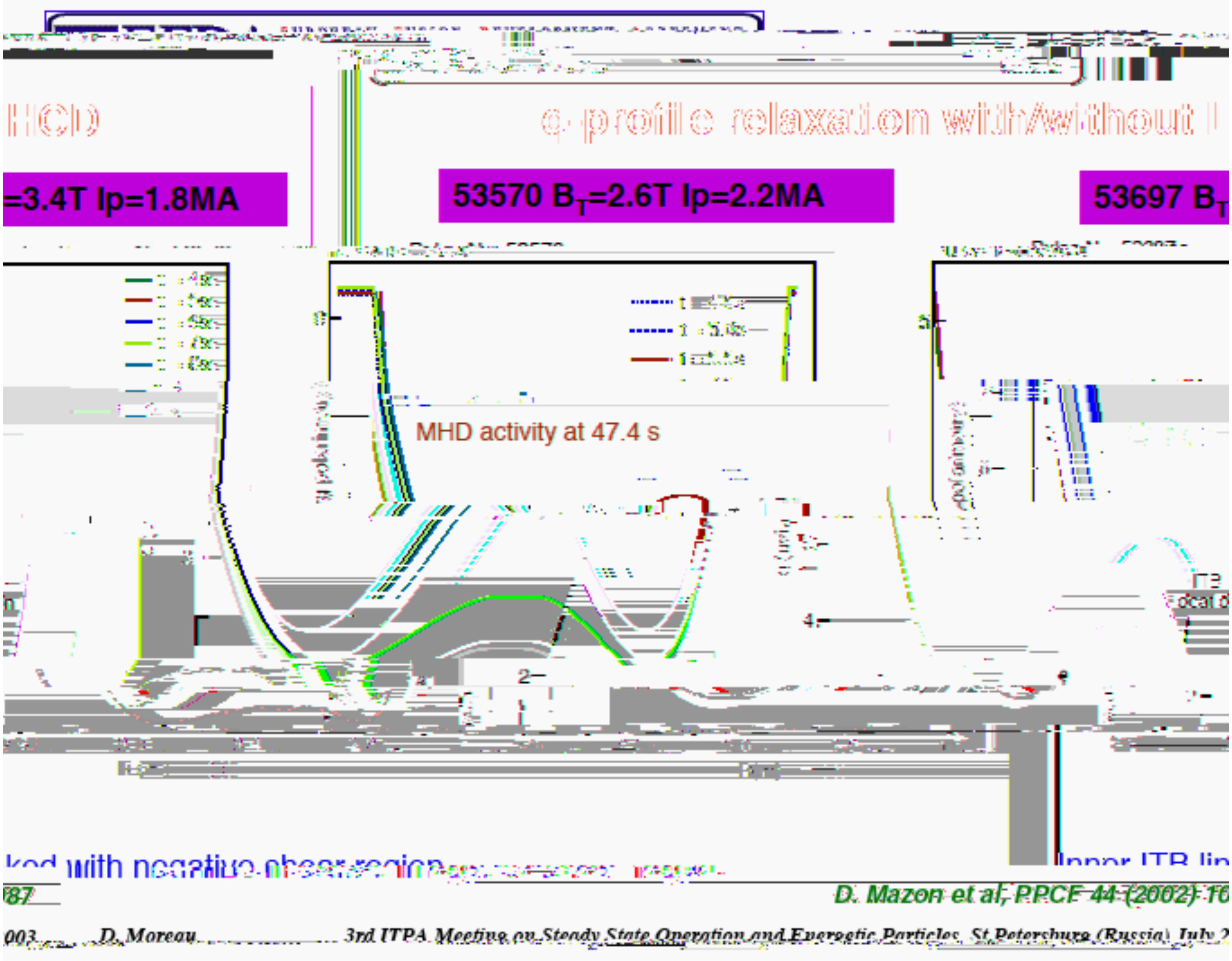
candidates: plasmas with q >> 1, q_{95}~5, with negative magnetic shear

→ Need external NI current:

- to prepare favourable q profile
- to sustain q profile on timescale required
  - ▹ location must be compatible with current and pressure profiles, i.e. off-axis CD required

In JET, key tool for this application is LHCD

JET Control of ITB with LHCD



HCD

q-profile relaxation with/without

=3.4T Ip=1.8MA

53570 B_T=2.6T Ip=2.2MA

53697 B_T

MHD activity at 47.4 s

ked with negative shear region

Inner ITB lin

D. Mazon et al, PPCF 44 (2002) 16

003 D. Moreau 3rd ITPA Meeting on Steady State Operation and Energetic Particles, St Petersburg (Russia), July 2

Neoclassical tearing modes reconfigure

New Superconducting LHCD- driven tokamaks

SST-1 India (1000 s)
(R=1.1 m, 220 kA, 1 MW, 3.7 GHz LHCD)

EAST China (1000 s)
(R=1.95 m, 1-1.5 MA, 4 MW, 4.6 GHz LHCD)

KSTAR Korea (20-300 s)
R=1.8 m, 2 MA
1.5 MW LHCD (2014)
0.5 MW ECCD (2008)
3 MW ECCD (2014)

Minority ion Cyclotron Current Drive

EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

Sawtooth control

Note: MiCCD effect is complicated if

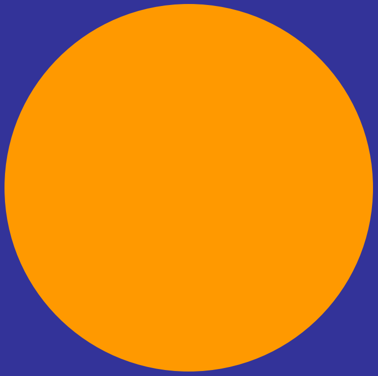
1. absorption straddles resonance
2. Ion trapping

Thus, other current drive effects may dominate

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

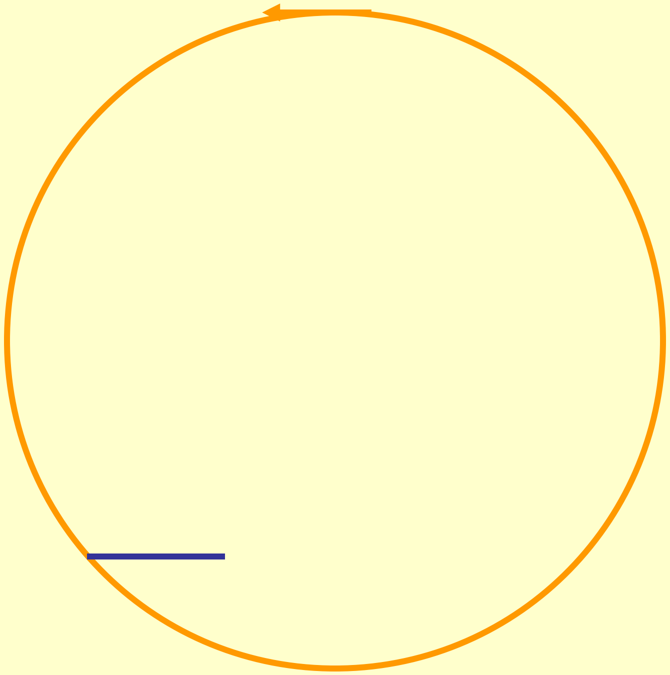
Power Flow in a Fusion Reactor

Advantages of ! ! -Channeling"



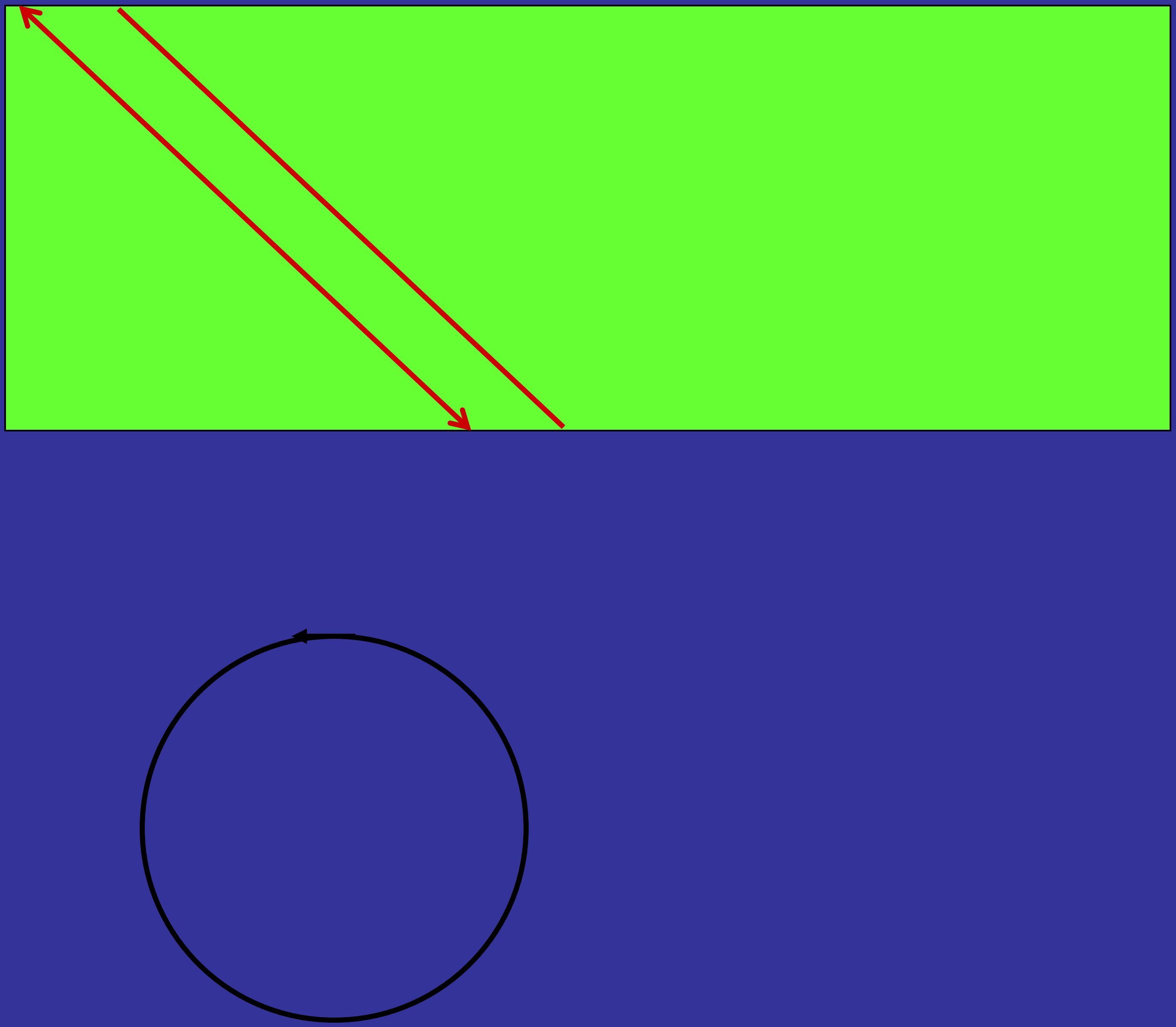
Get Hot Ion Mode: $T_i > T_e$

75% of ! power to ions % $P_f \rightarrow 2\, P_f$



v_y v_y v_y

Diffusion Paths



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.

Summary

1.!