# Methods of rf Current Drive

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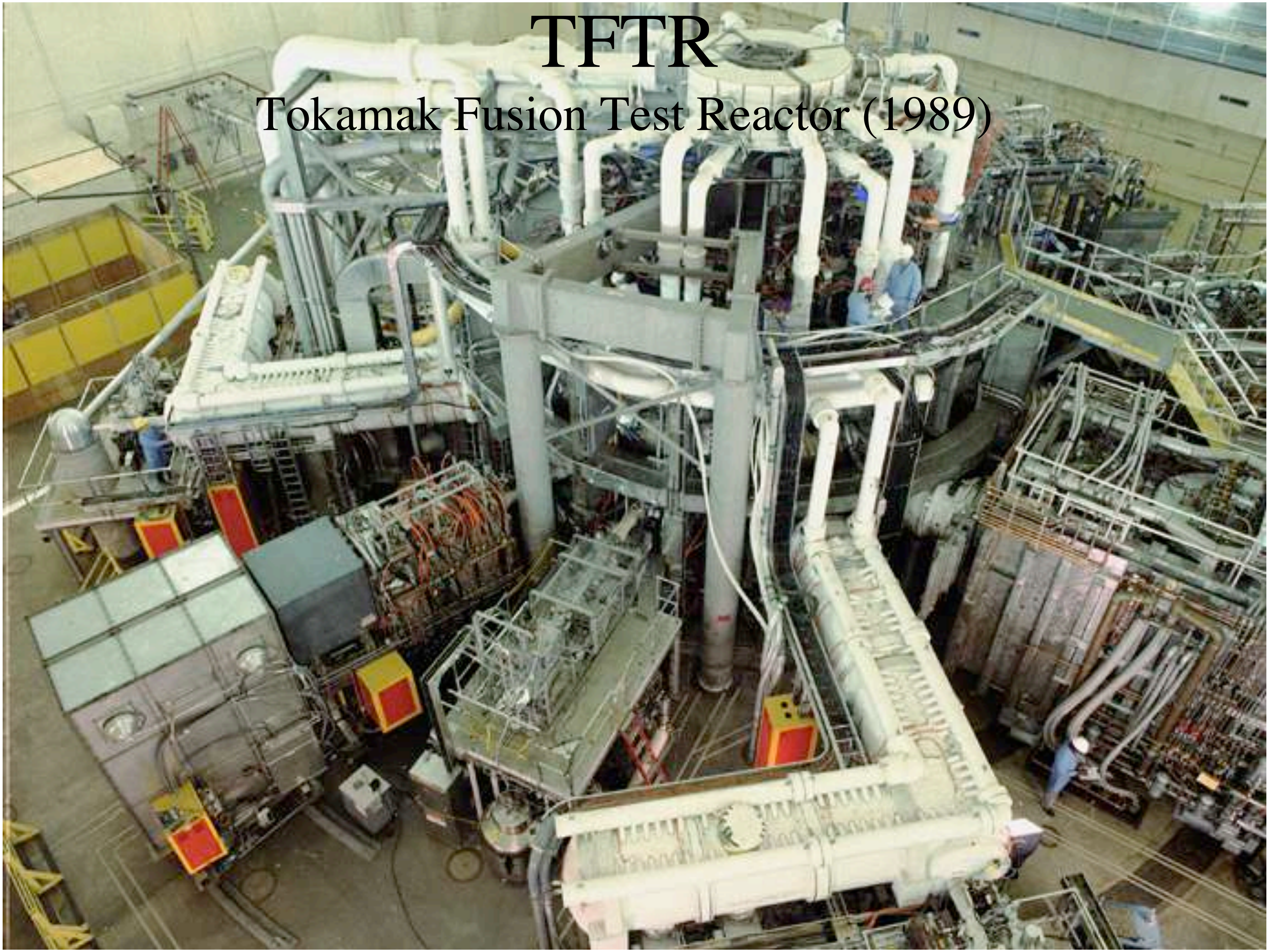
Radio frequency waves can penetrate thermonuclear plasmas, depositing momentum and energy with great selectively: in select resonant ions or electrons, in select resonant regions, and with select momentum.

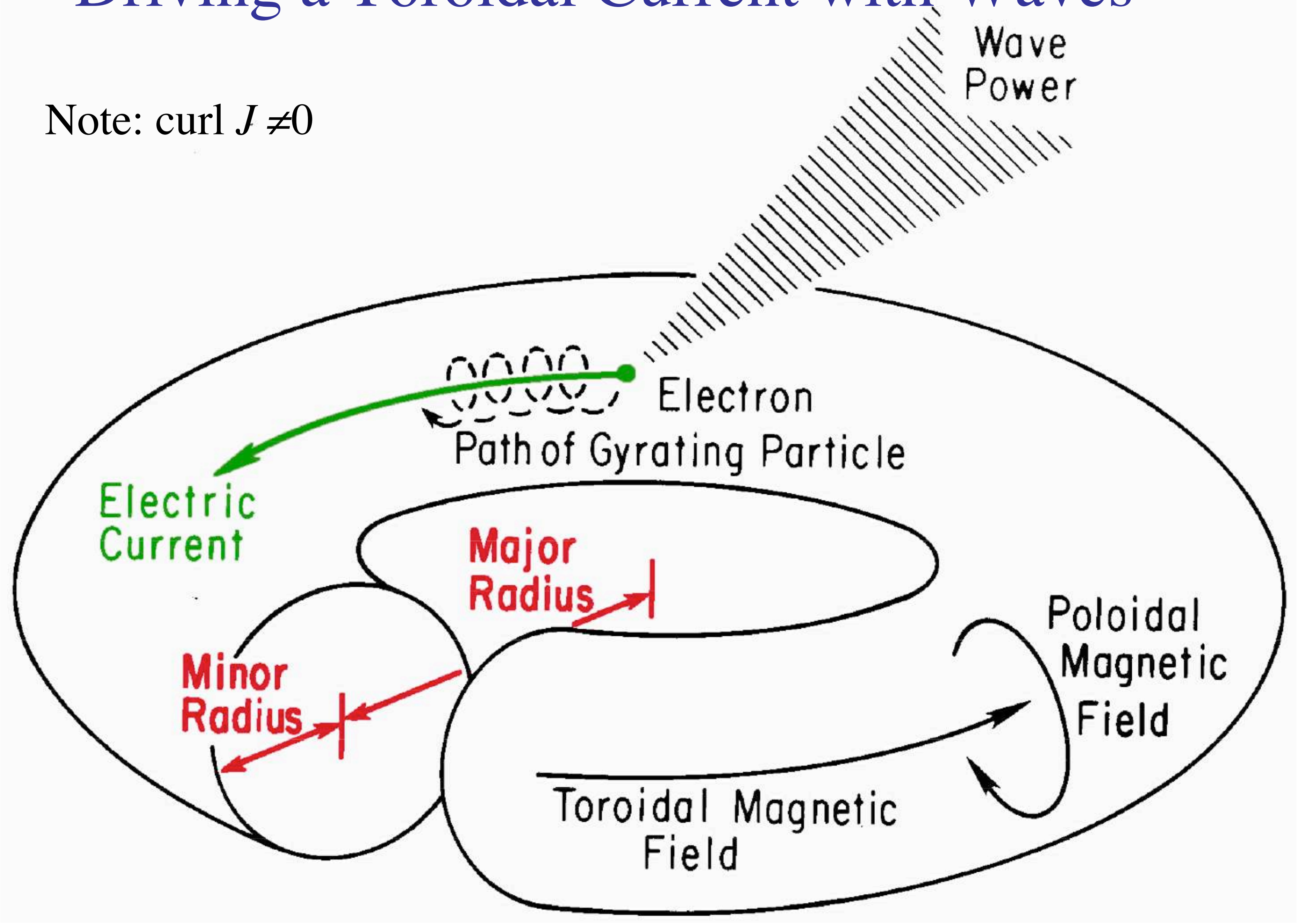
# TFTR

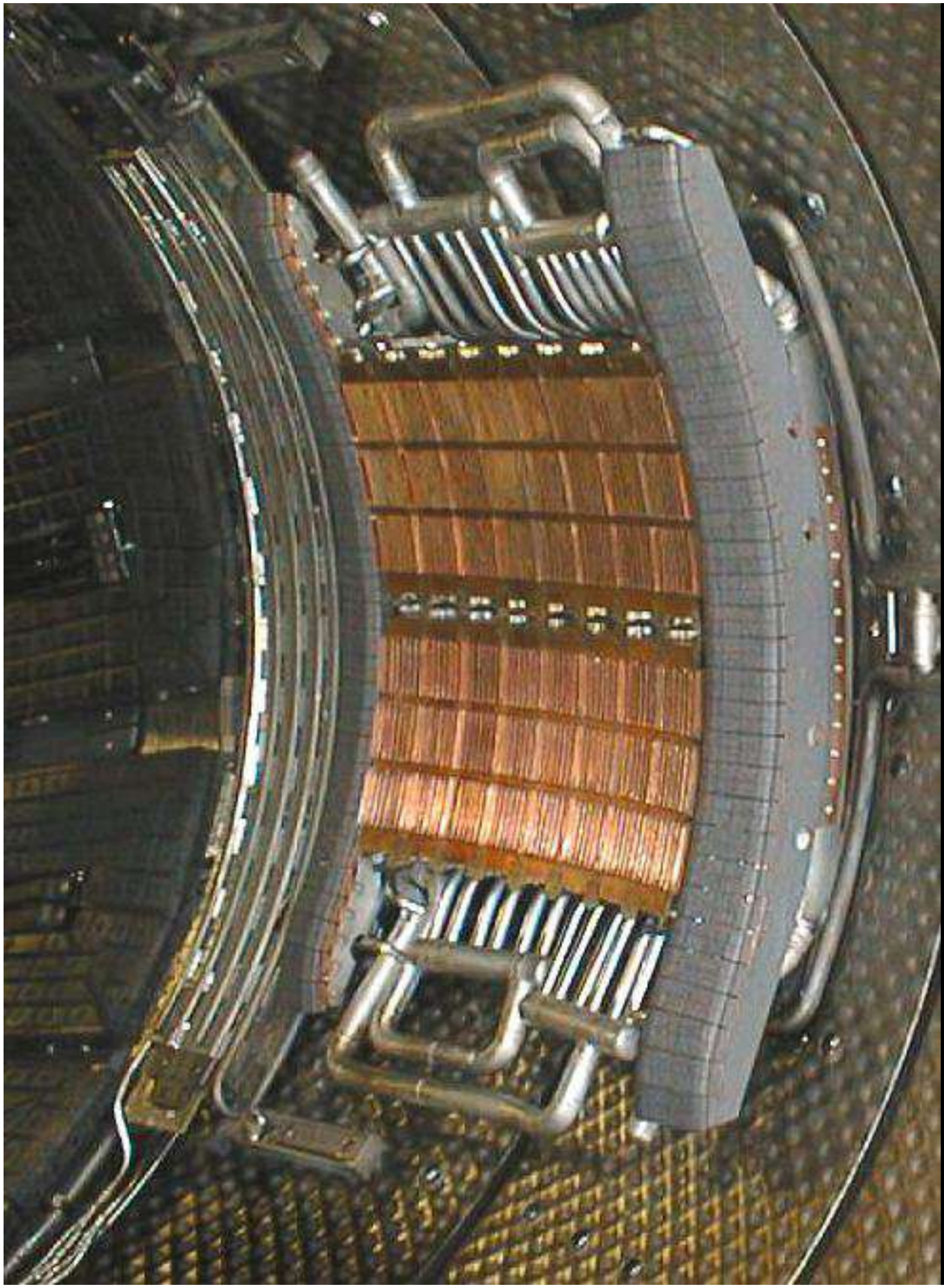
## Tokamak Fusion Test Reactor (1989)



# Driving a Toroidal Current with Waves

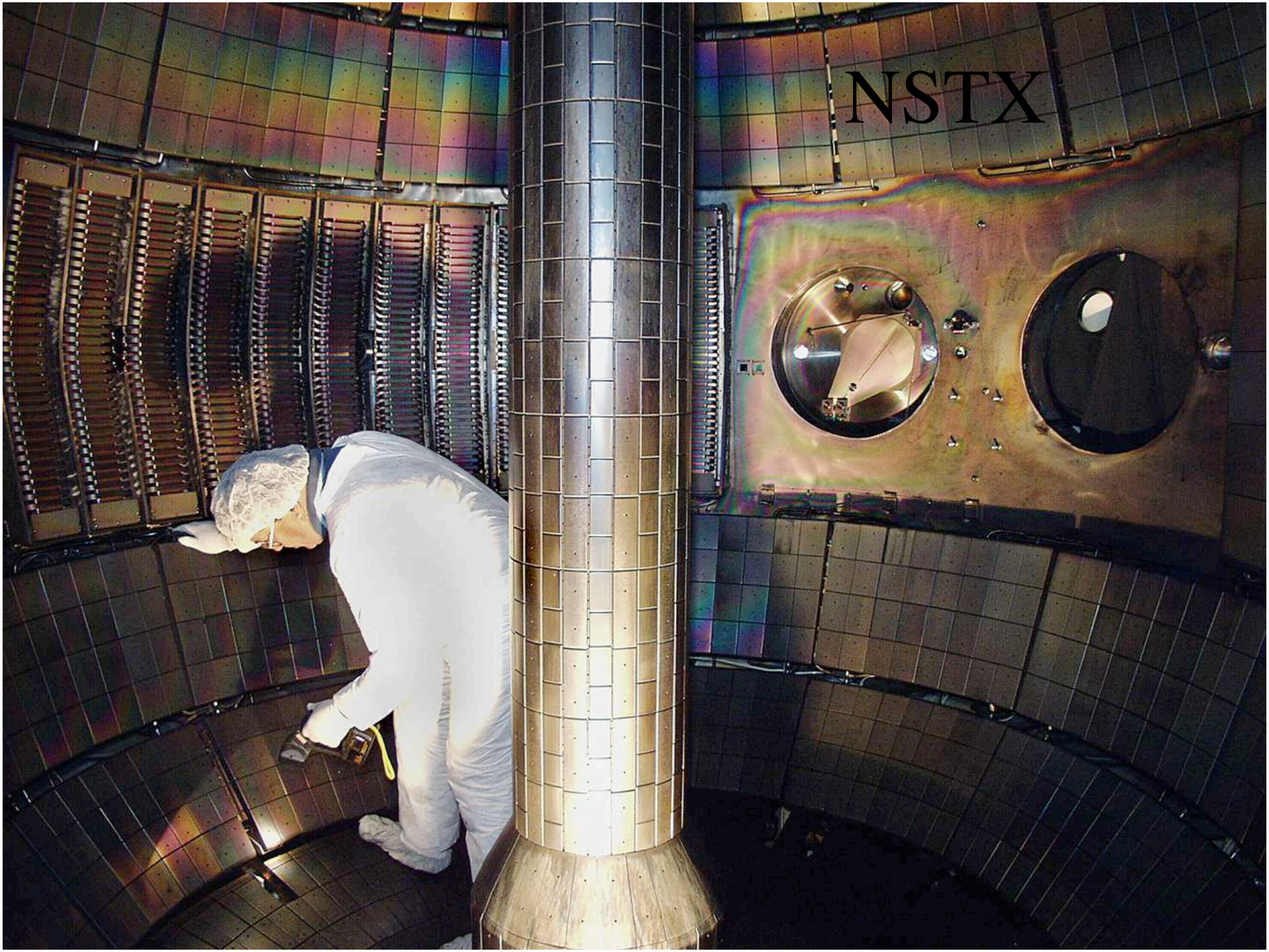
Note: curl $J \neq 0$





# 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
"α− Channeling effect"

**Trend to "phase space engineering"**

**Detailed control of rf-induced fluxes in 12-D**

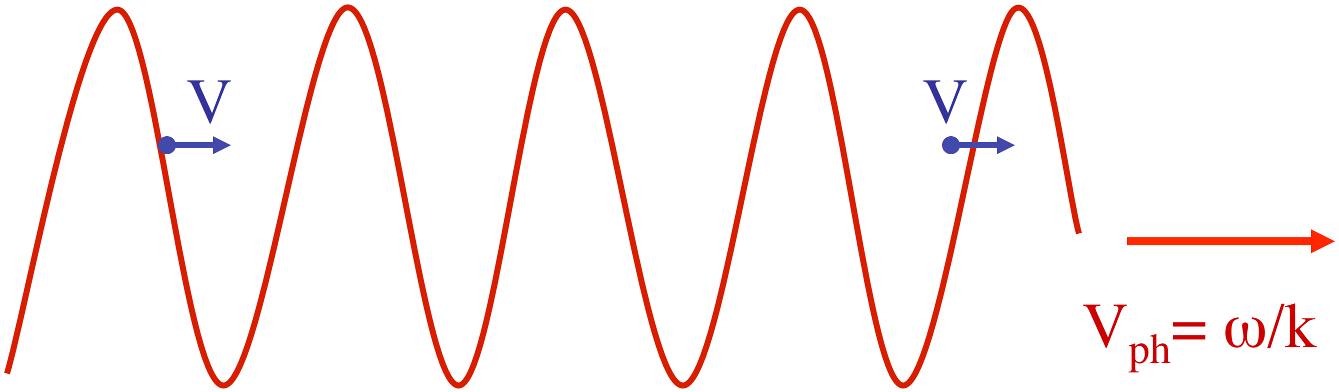
**Select particles in 6D velocity-configuration space**

**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 $v_{ph} < v_T$ |
| 1971 | Bickerton *et al*. -- bootstrap effect |
| 1971 | Hirano -- glass tube |
| 1973 | Klima, Midzuno, theory of momentum input |
| 1976 | Fukuda et al -- synchromak |
| 1978 | Start et al -- neutral beams on Levitron |

# (Resonant) Radio Frequency (RF) Current Drive Effect



Resonance condition

$$\omega - \vec{k}\cdot\vec{v} = 0$$

$$\mathrm{v} \longrightarrow \mathrm{v} + \Delta\mathrm{v}$$

$$J = en\Delta\mathrm{v}$$

$$\Delta E = mn\mathrm{v}\Delta\mathrm{v}$$

$$P_{\mathrm{D}} = \nu\Delta E$$

$$\Longrightarrow$$

$$\boxed{J/P_{\mathrm{D}} = e/m\,\mathrm{v}\,\nu(\mathrm{v})}$$

$$\nu(\mathrm{v}) \approx \mathrm{v}^{-3}$$

Fisch (1978)

# Example of Resonance: The Traveling Plasma Wave

$$\nabla \bullet \vec{E} = 4\pi e(n_0 - n_e) = -4\pi e\tilde{n}$$

Poisson’ s equation

$$\frac{\partial}{\partial t} n_e + \nabla \cdot n_e v = 0$$

Particle conservation

$$\frac{\partial}{\partial t} n_e m v + \nabla \cdot n_e m v v = eE$$

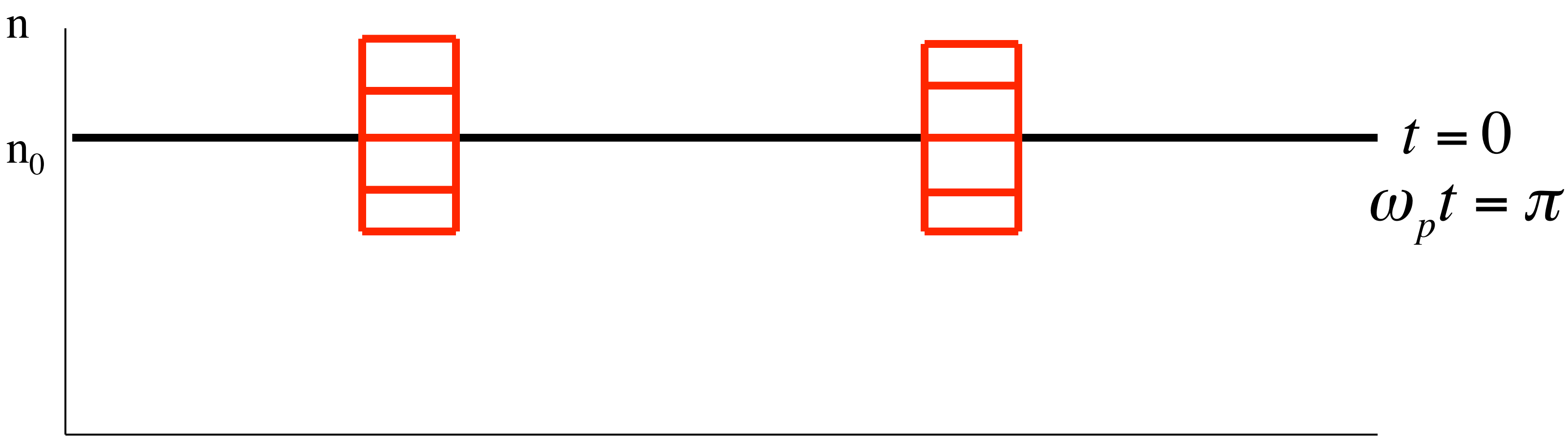
Momentum conservation

⇒

$$\boxed{\frac{\partial^2}{\partial t^2}\tilde{n} + \omega_p^2 \tilde{n} = 0}$$

$$\boxed{\tilde{n} = A(\vec{r})\cos\omega_p t + B(\vec{r})\sin\omega_p t}$$

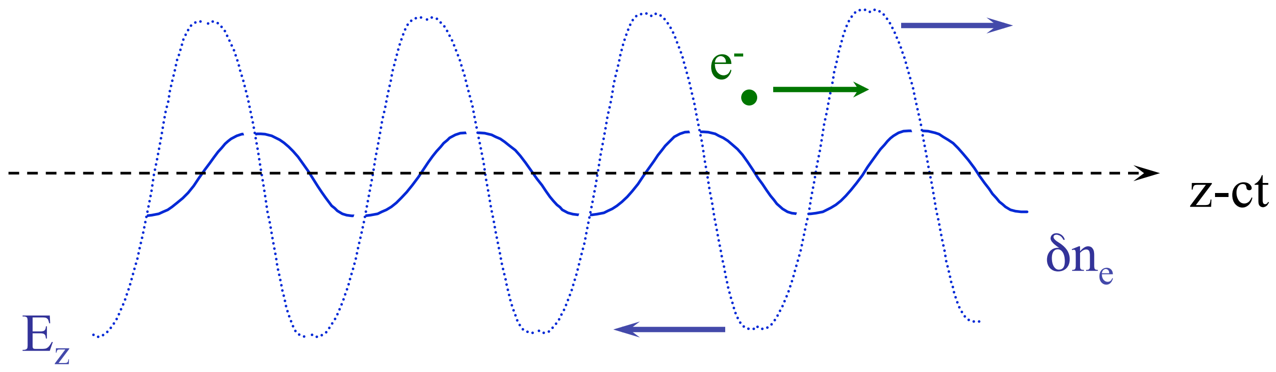
# Plasma Oscillation



Make traveling wave:

$$\boxed{\Phi(x,t) = A(x)\cos[\omega_p\,(t - x/c)]}$$

# Electron acceleration in a plasma wave

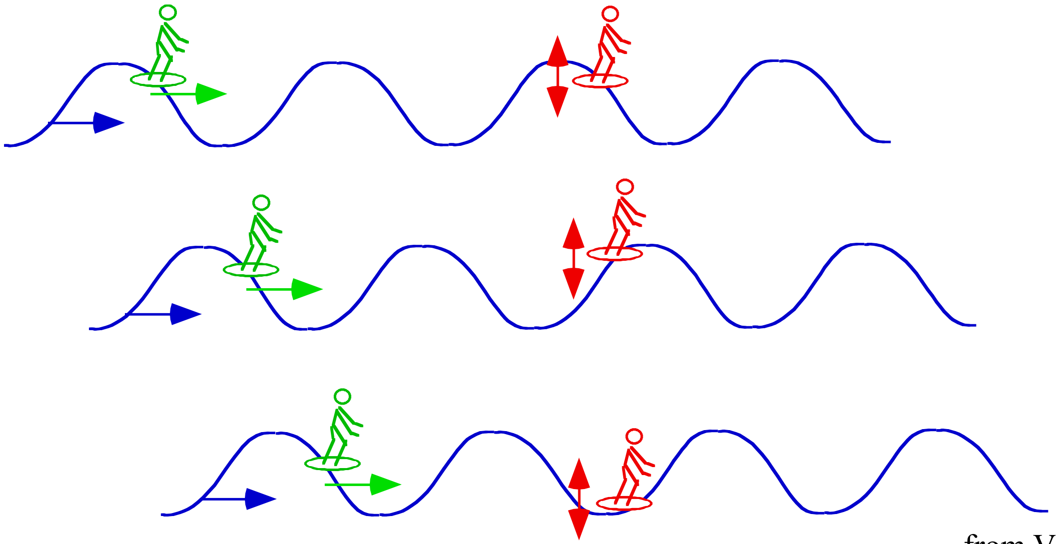


phase velocity -- arbitrary

Accelerate to TeV

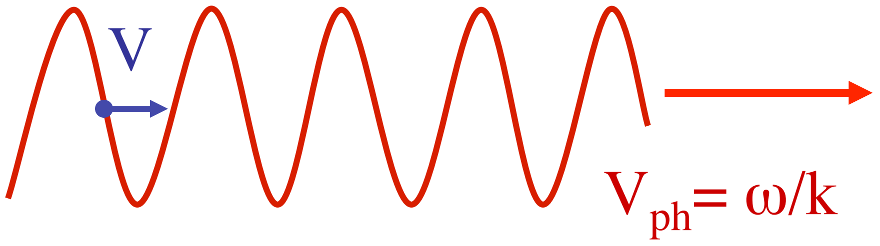
Tajima and Dawson (1979)

Analogy:



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

## Plasma Accelerator

High fields, No breakdown

(Tajima and Dawson, 1979)

$$\nabla \bullet \vec{E} = -4\pi e\tilde{n}$$

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

$$k = \frac{\omega_p}{c}$$

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

**Example**

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

eE=100 GeV/m

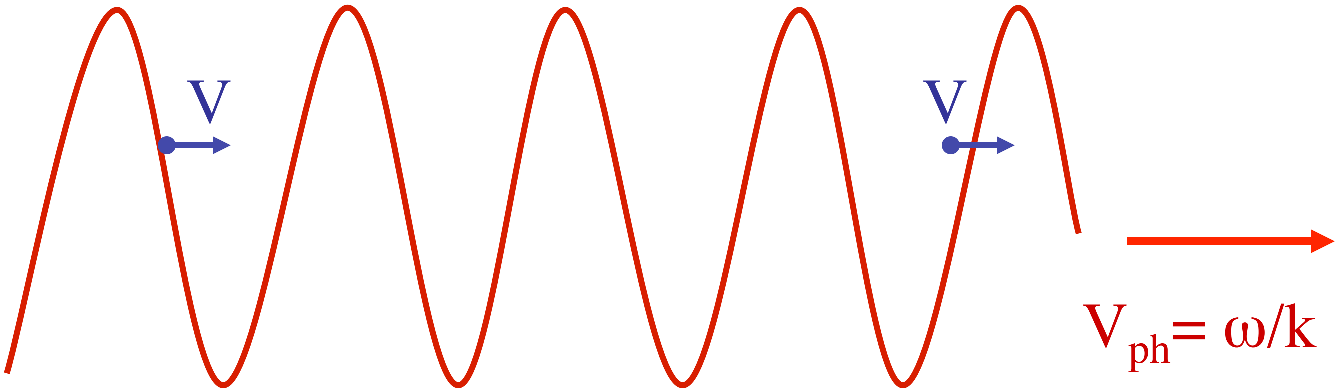
Note: For v << c , $\frac{v_{osc}}{c} \approx \frac{\tilde{n}}{n_0}$

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

# Resonant Surfers

Not-resonant surfers $V \neq V_{ph}$

# (Resonant) Radio Frequency (RF) Current Drive Effect



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$$\nu(\mathrm{v}) \approx \mathrm{v}^{-3}$$

Fisch (1978)

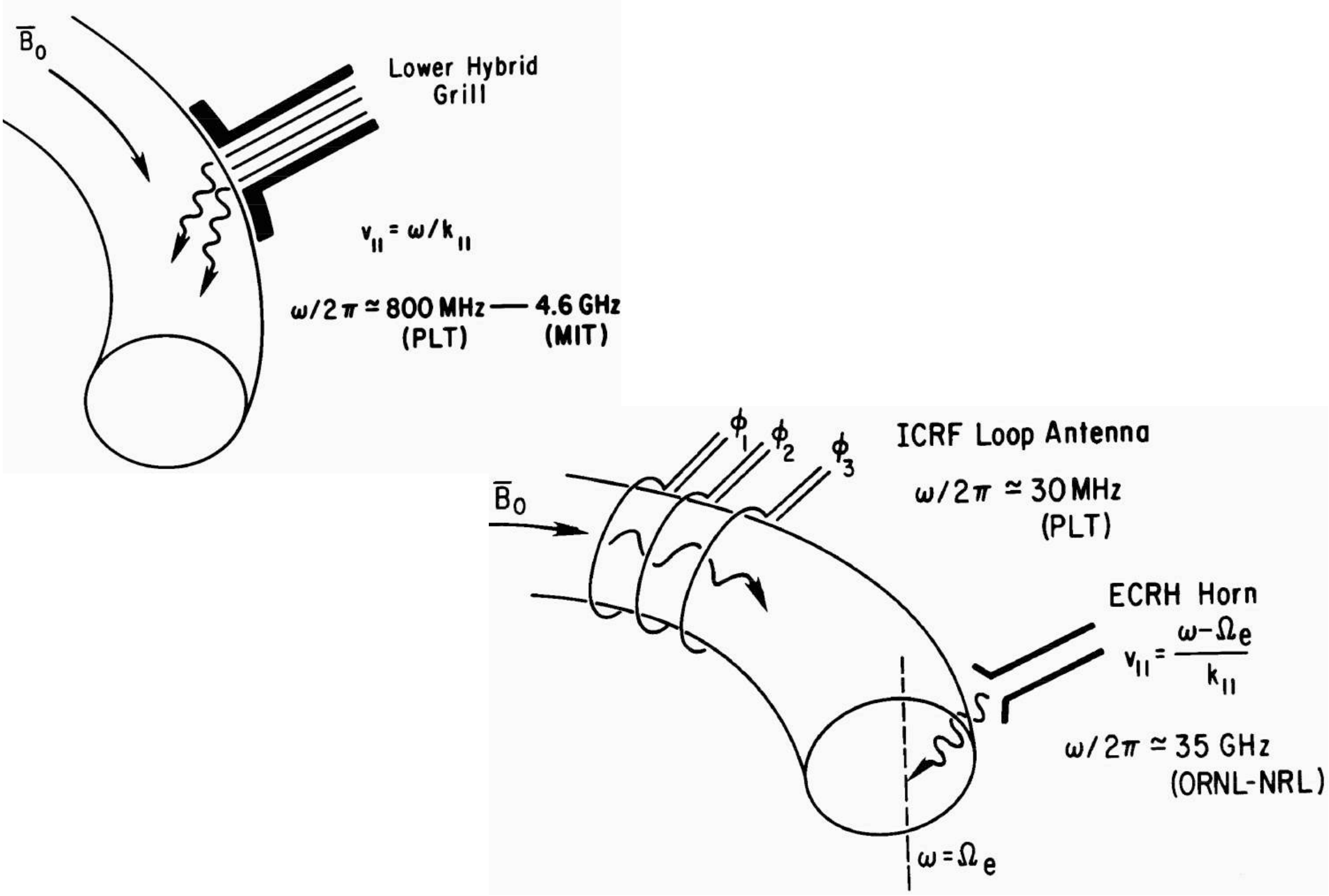
# Pushing Particles with Waves

1. Parallel to B-field: Current Drive by Resonant Interactions
    - Current Drive Predictions
    - New Transport Quantities
    - Experimental Confirmations
    - Implications: practical and basic

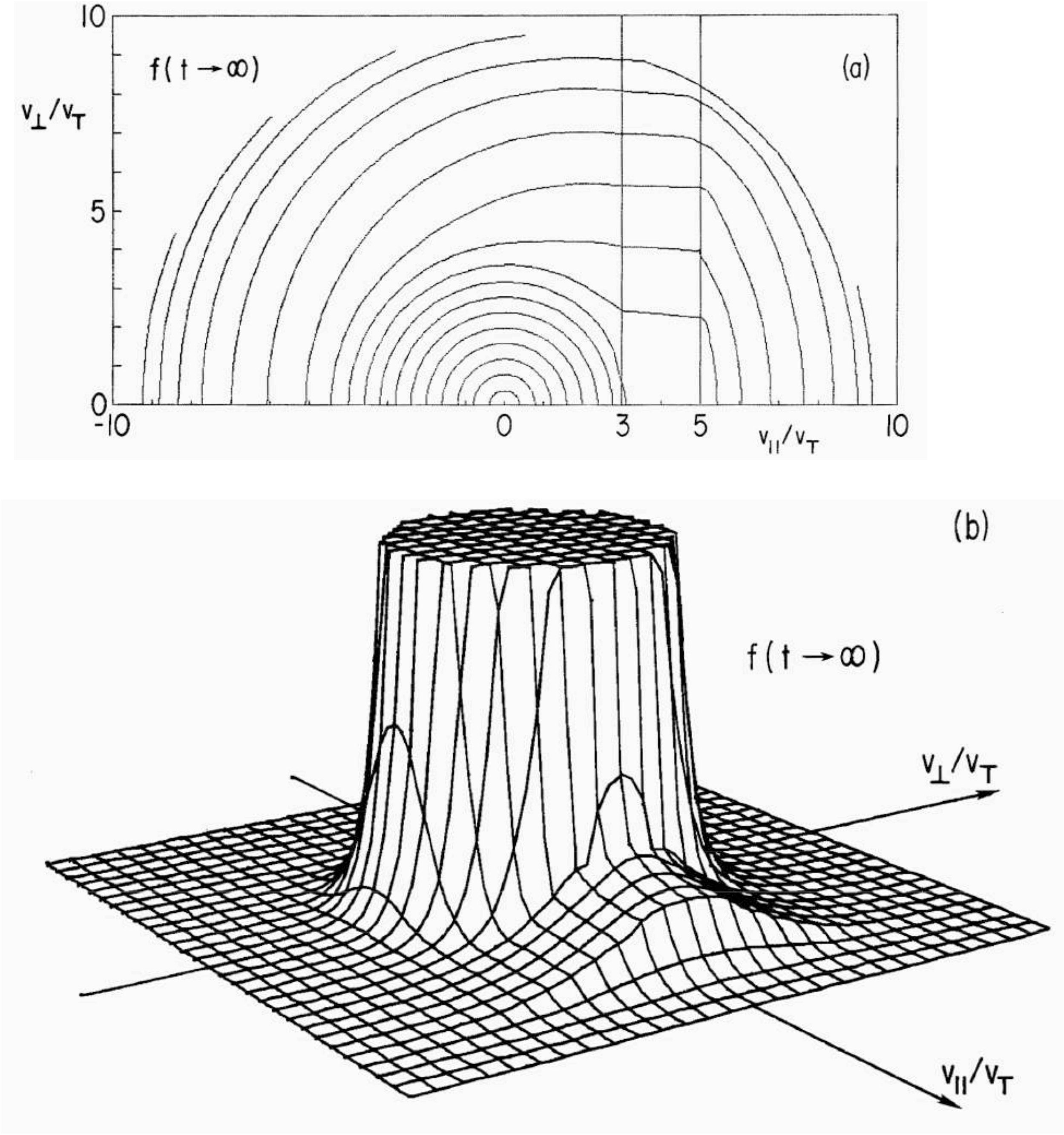
2. Perpendicular to B-field: Constrained transport
    - wave diffusion paths in velocity-configuration space
    - Use of free energy in inhomogeneous plasma "$\alpha$ channeling"
        - a. tokamak
        - b. mirror
    - Experimental Confirmations
    - Implications: practical and basic

3. Open questions
    - New Physics
    - Hot ion mode reactor

# RF Methods of Heating and Current Drive

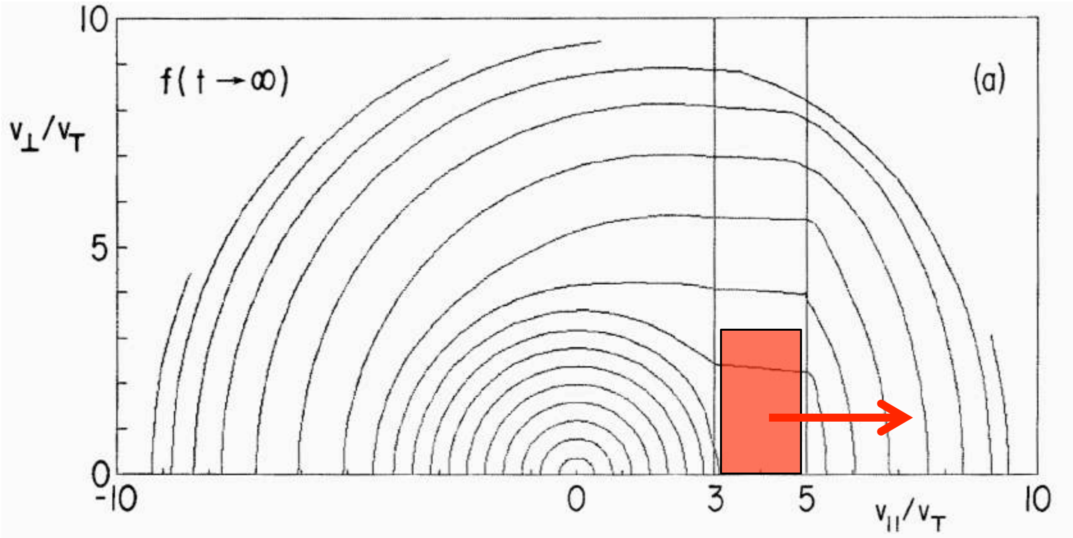


# Electron Distribution Function -- LHCD

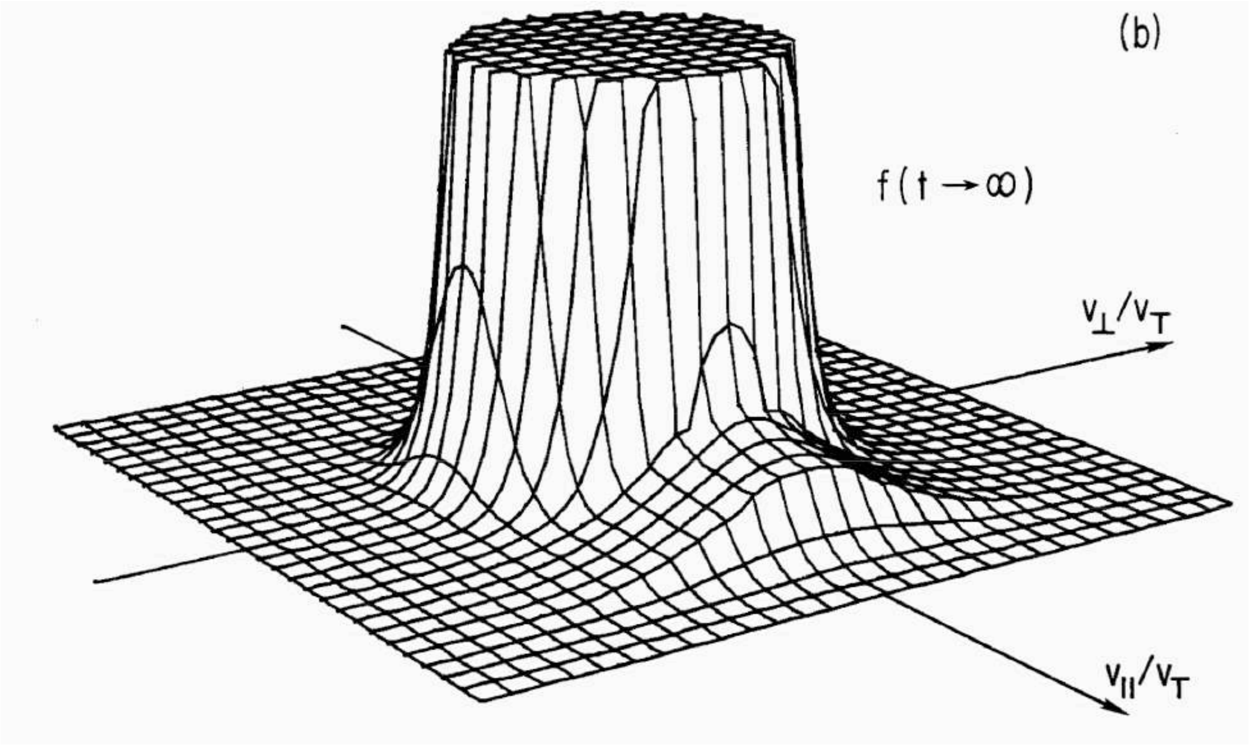


Karney and Fisch, 1979

# Electron Distribution Function

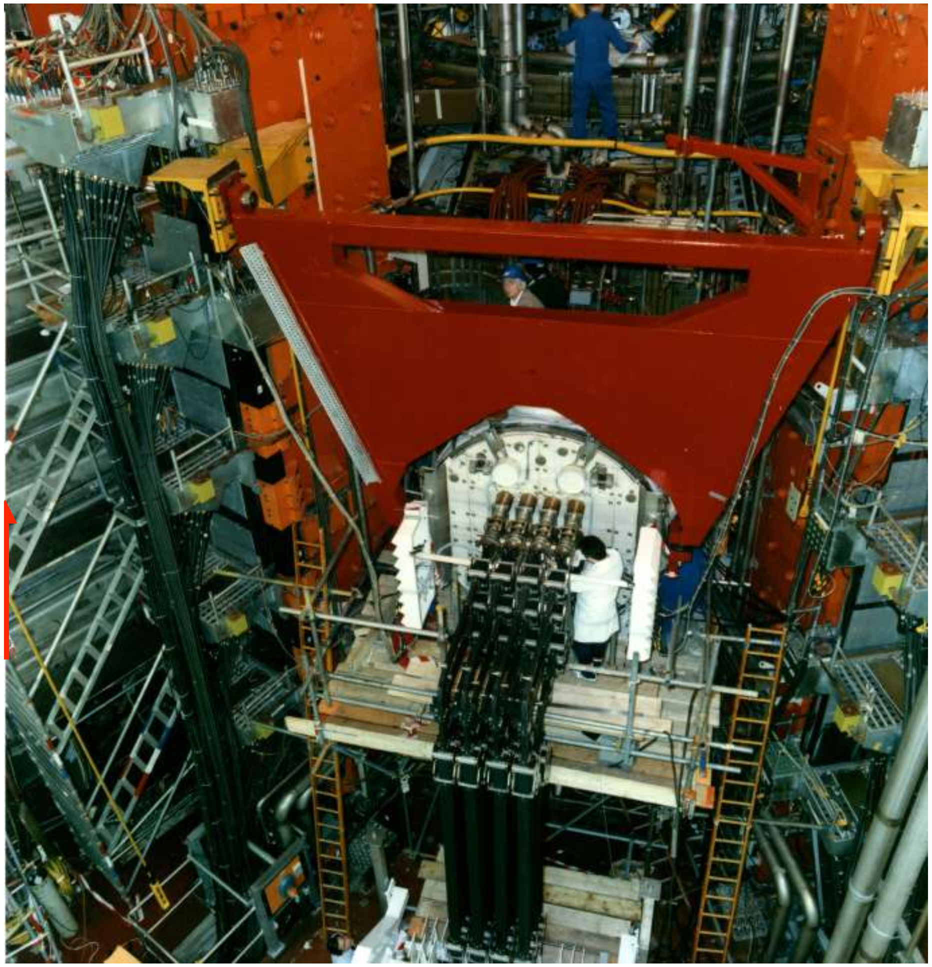


Localize **S**(**v**)
Resonance condition
Dispersion relation

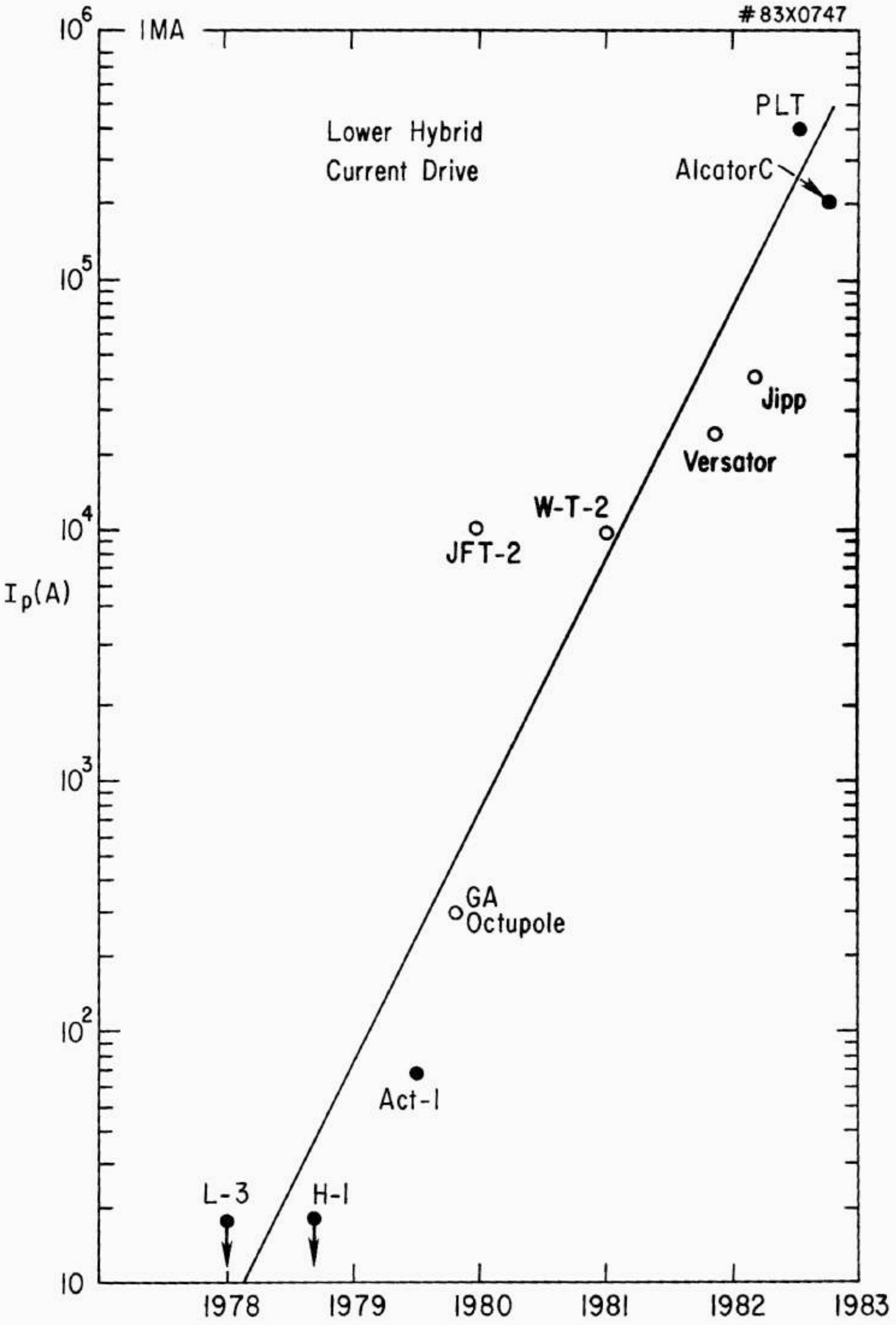


Karney and Fisch, 1979

# Progress in Current Drive



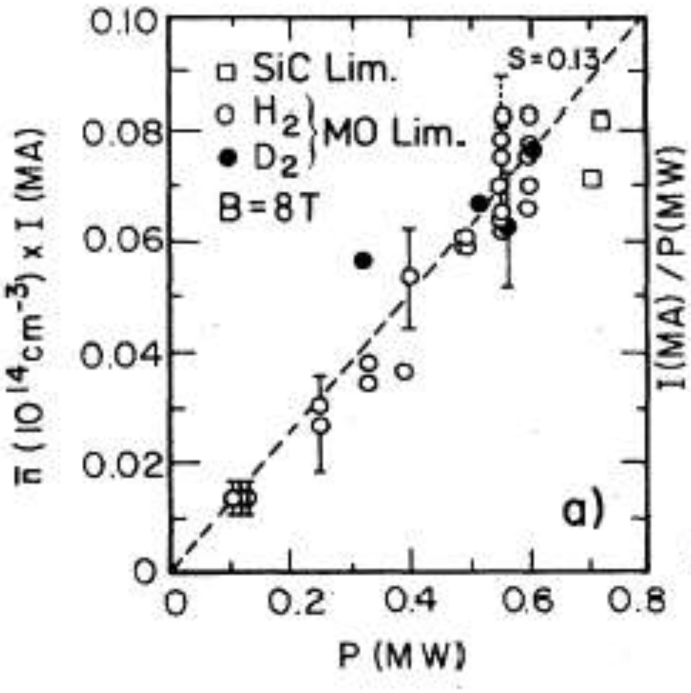
JET (2001)



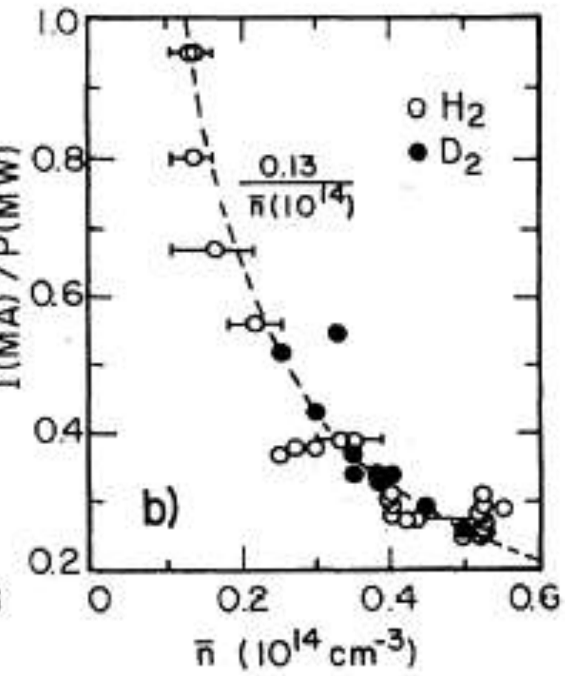
# Alcator C

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

Porkolab et al, 1984



Line-averaged density times current vs. power

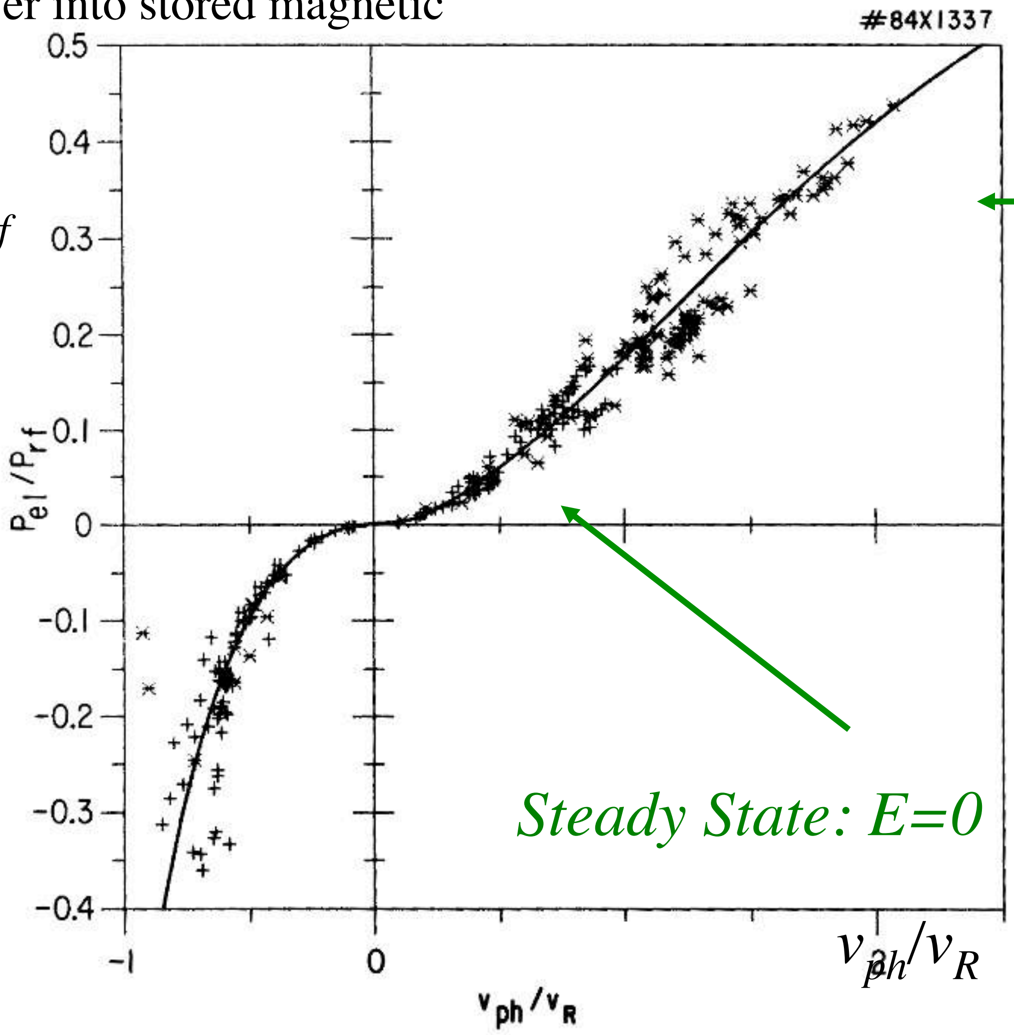


Efficiency vs. density

# Theory and Demonstration of the Current Drive Effect with PLT Data

$P_{el}$ is power into stored magnetic energy

$P_{el}/P_{rf}$



*Ramp-up: E<0*

*Steady State: E=0*

$v_{ph}/v_R$

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)

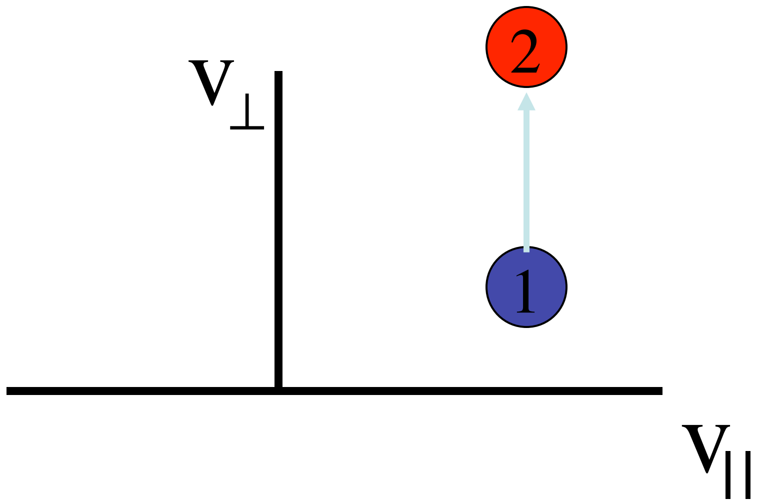
$v_R$ = runaway velocity

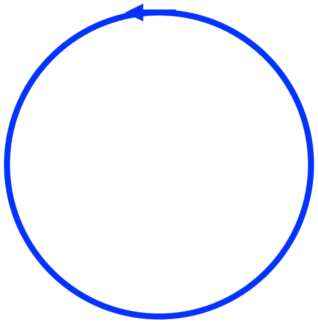
Verification *in detail* proves classical picture of electron collisions!

# Tokamak East

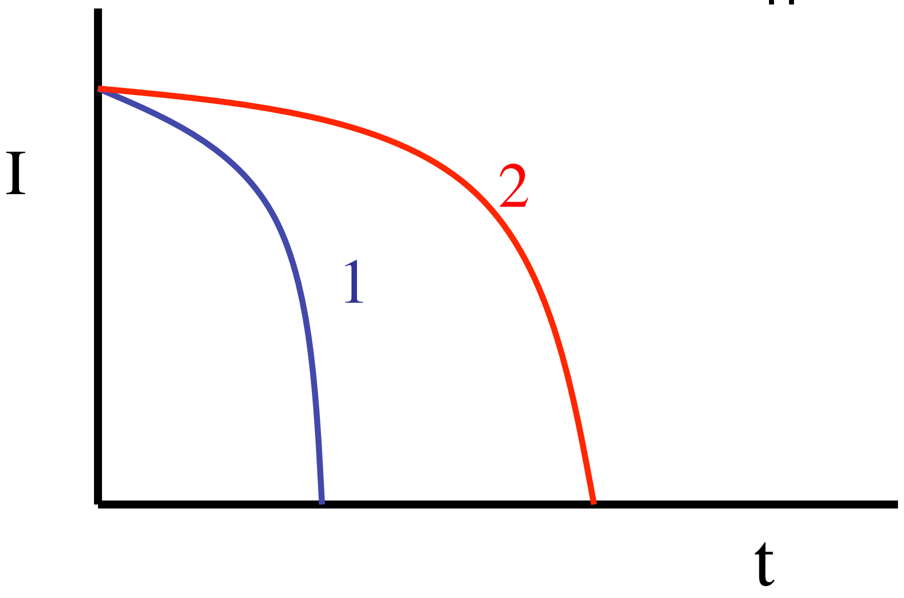
LHCD with very long pulse -- time scales for pinch effects
Low frequency ICRF with 4T  (internal mode excitation)

# Electron Cyclotron Current Drive Effect





Cyclotron motion



$$\omega - \vec{k}\cdot\vec{v} = n\Omega$$

$$\Omega \equiv eB/m$$

Fisch and Boozer, 1980

# Method of Calculating $J/P_D$

$$J(t) = \int_0^t \frac{P(\tau)}{\varepsilon_2 - \varepsilon_1} \left\langle q \mathrm{v}_{\|}(t-\tau, v_2) - q \mathrm{v}_{\|}(t-\tau, v_1) \right\rangle d\tau$$

$$= \lim_{v_2 \to v_1} \int_0^t d\tau P(\tau) \frac{S \cdot (\partial / \partial v) \left\langle q \mathrm{v}_{\|}(t-\tau, v_1) \right\rangle}{S \cdot (\partial / \partial v) \varepsilon_1}$$

Suppose constant $P(t) = P_D$

$$\varepsilon = mv^2 / 2$$

$$\boxed{\frac{J}{P_D} = \frac{S \cdot (\partial / \partial v) \int_0^{\infty} \left\langle q \mathrm{v}_{\|}(t, v) \right\rangle dt}{S \cdot (\partial / \partial v) \varepsilon}}$$

# Langevin Equations

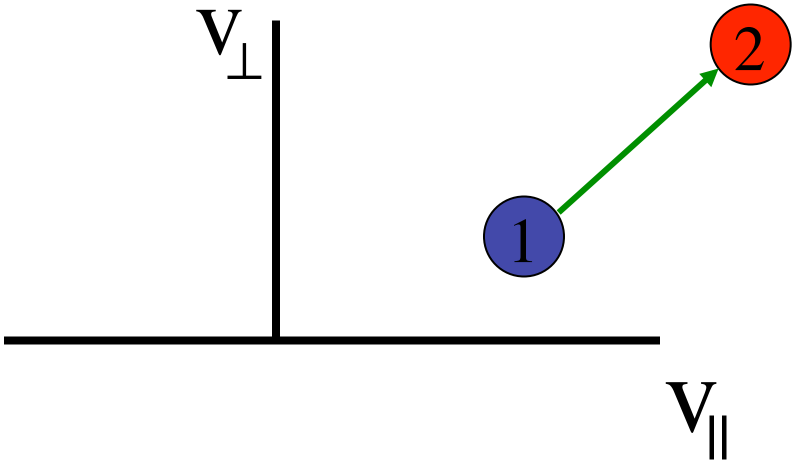
$$\frac{\partial f}{\partial t} = C(f,f) + C(f,f_i) \qquad C(f,f_i) = \frac{\Gamma}{2v^3}\frac{\partial}{\partial \mu}(1-\mu^2)\frac{\partial}{\partial \mu} f$$

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

$$\frac{\partial \langle \mu \rangle}{\partial v} = (1+Z_i)\frac{\langle \mu \rangle}{v} \Rightarrow \frac{\langle \mu \rangle}{\mu_1} = \left(\frac{v}{v_1}\right)^{(1+Z_i)}$$

$$\int_0^\infty q v_\parallel \, dt = \frac{q\mu_1}{\Gamma}\int_0^\infty \left(\frac{v}{v_1}\right)^{(4+Z_i)} dv = \frac{q\mu_1 v_1^4}{(5+Z_i)\Gamma} = \frac{-e\,\mathrm{v}_\parallel \mathrm{v}^3}{\Gamma(5+Z_i)}$$

# Generalized RF Current Drive Effect



$$\omega - \vec{k} \cdot \vec{v} = n\Omega$$

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

$$P_D = \int d^3v \, \overline{S} \cdot \overline{\nabla} \varepsilon$$

$$\varepsilon \equiv m v^2 / 2$$

New "transport quantity" for current drive

$$\Psi = \int_0^\infty e v_\parallel(t) \, dt$$

$$\boxed{\Psi(v_\parallel, v_\perp) = \frac{-e v_\parallel v^3}{\nu_0 (5 + Z_i)}}$$

Green's function: Fisch and Boozer, 1980
Adjoint formalism: Antonsen and Chu, 1982

# Generalized Transport Quantities

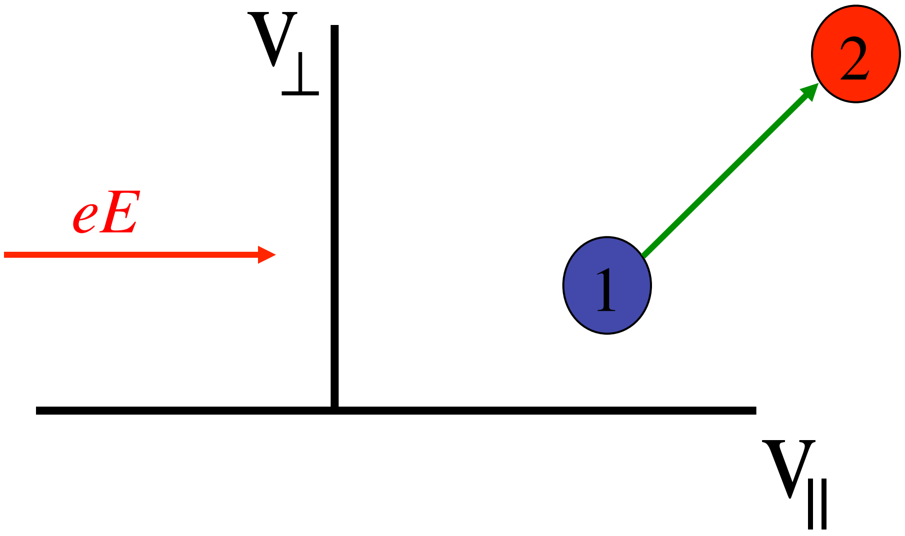
Associate transport quantity with each point in 2D velocity space

1. Current Drive Efficiency

Generalizes Spitzer conductivity

2. Runaway Probability

Generalizes Dreicer velocity



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

Fisch (1985); Fisch and Karney (1985); Karney and Fisch, 1986

# 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

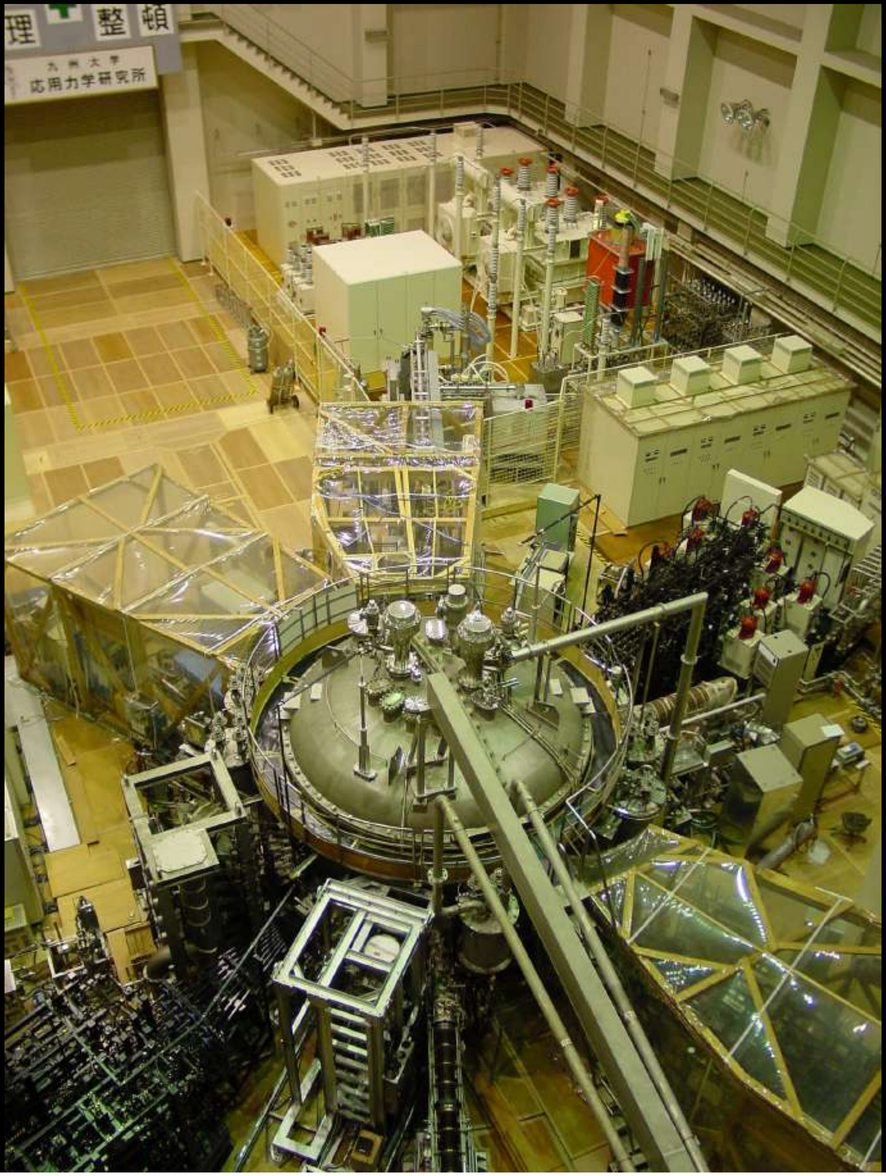
C-Mod tokamak (MIT) :  LHCD
TRIAM ( Japan):  several hours LHCD
T-10 (Russia): ECCD , sawteeth
TCV tokamak --- ECCD steady state, sawteeth
ASDEX (Germany): ECCD stabilization of tearing modes
Wendelstein 7-AS Stellarator: ECCD
Frascati FT-U (Italy):  LHCD, ECCD stabilization of sawteeth, tearing modes
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*

5 hour 16 minute (19,000 s) LHCD discharge



| | |
|---|---|
| **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)

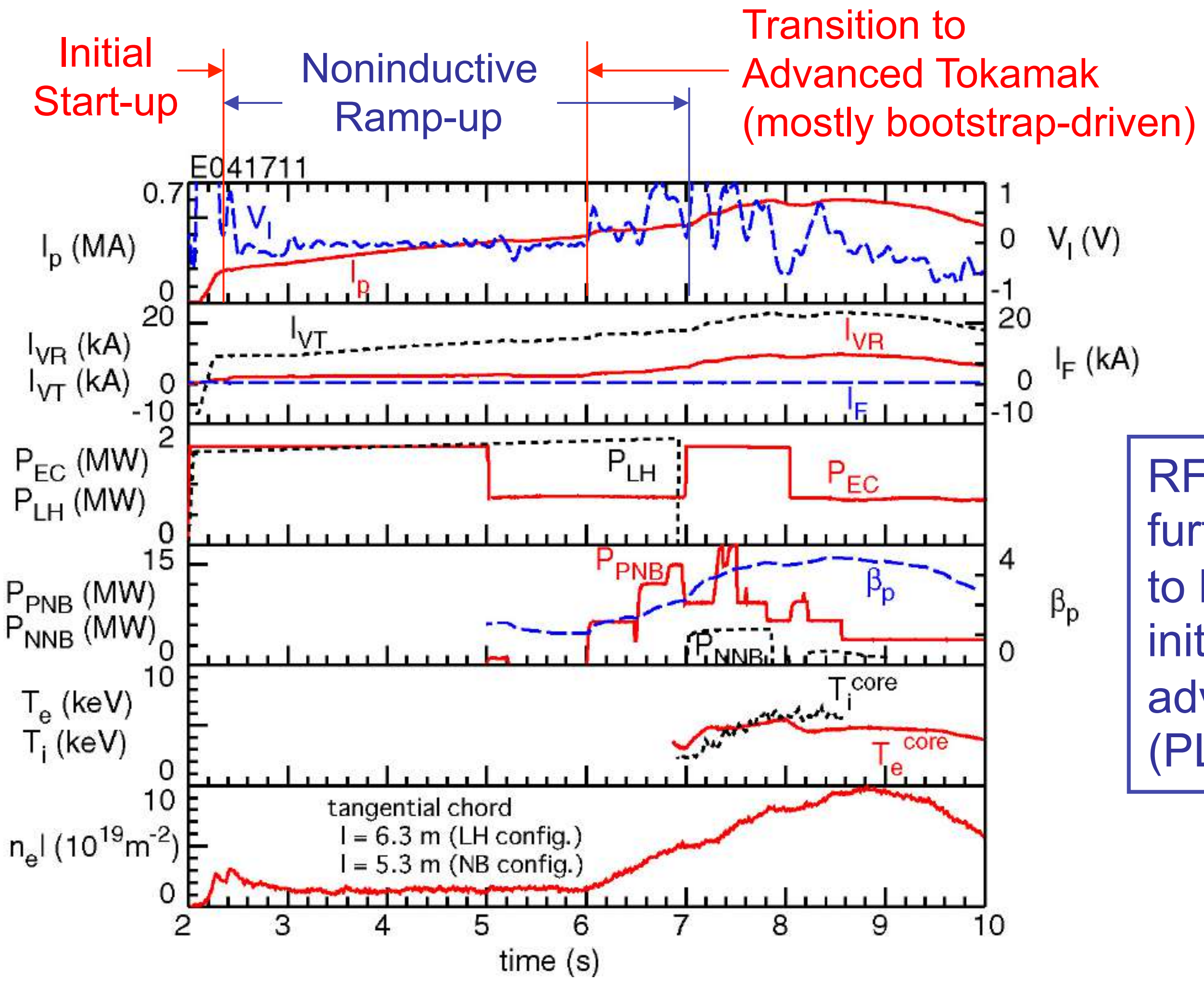
| | | |
|---|---|---|
| 8.2 GHz | 400 kW | 16 Klystrons |
| 2.45 GHz | 50 kW | 1 Klystron |

Electron Cyclotron Waves

| | | |
|---|---|---|
| 170 GHz | 200 kW | 5 sec |

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

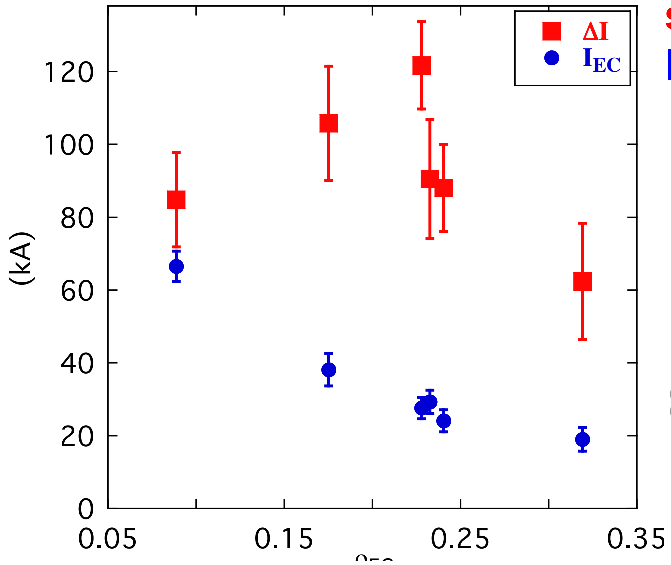
Y. Takase, et al.,
IAEA 2002



JT-60U

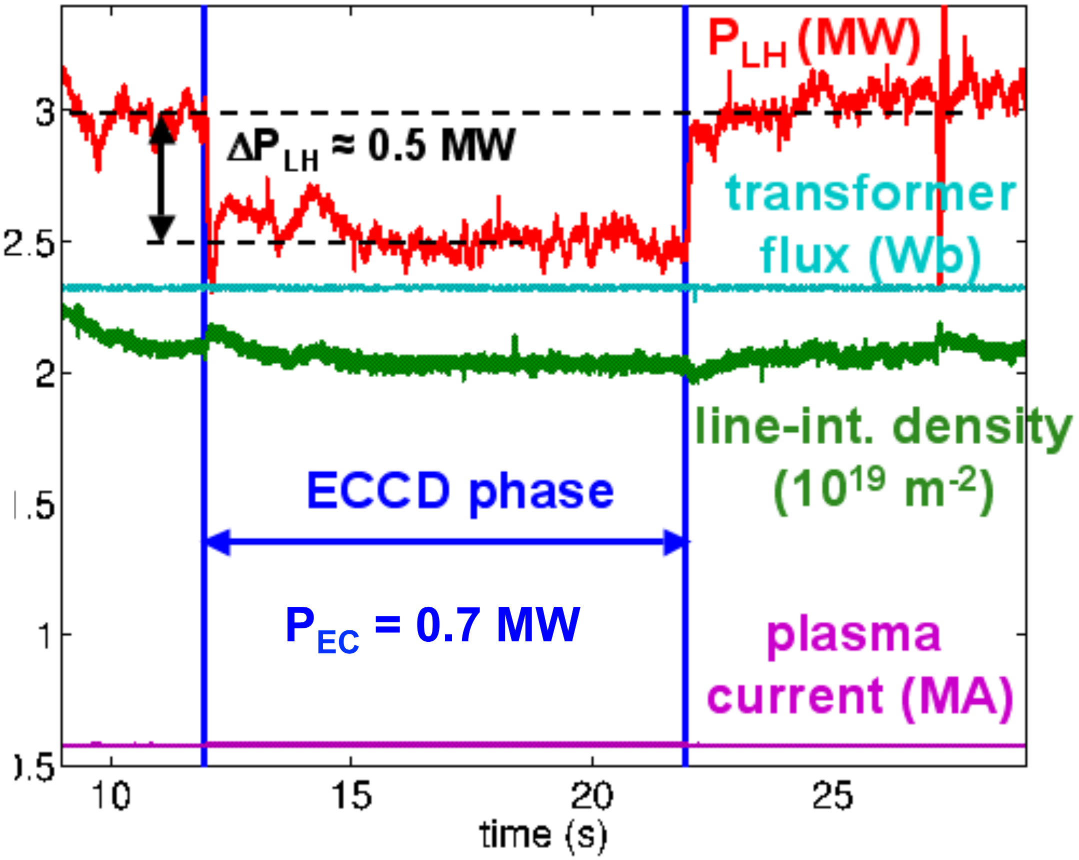
RFCD can be used for further current ramp-up to bridge the gap between initial start-up and NB-heated advanced tokamak phases ($P_{LH} > 1$MW for JT-60U)

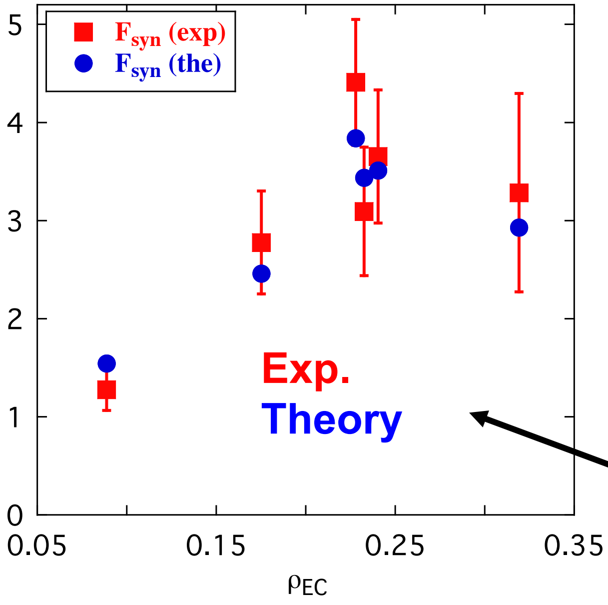
# TORE SUPRA: First demonstration of EC+LH synergy



synergy current (measured)

linear current (computed)

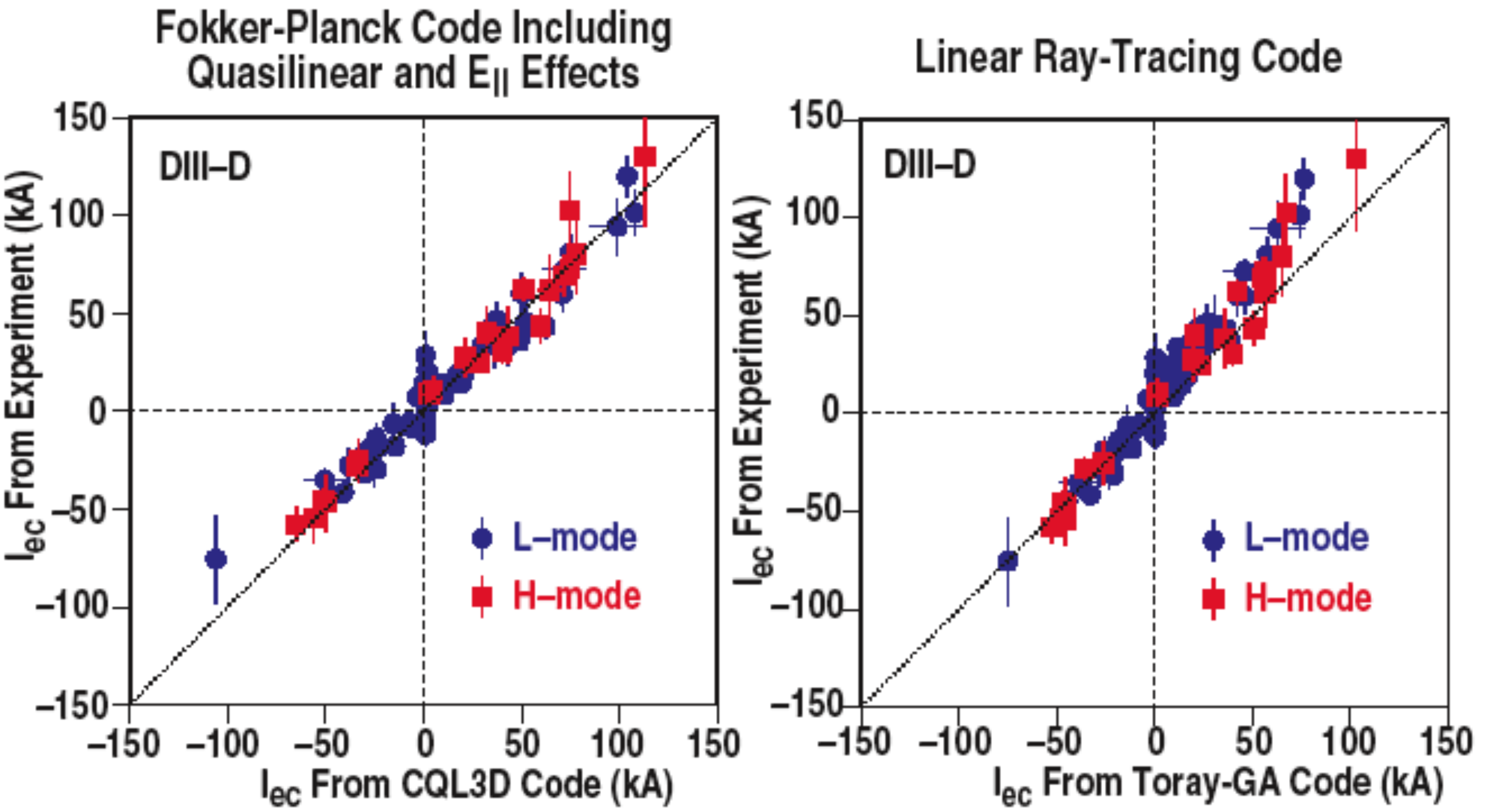




**ECCD efficiency enhancement factor**

G. Giruzzi et al, PRL **93**, 255002 (2004)

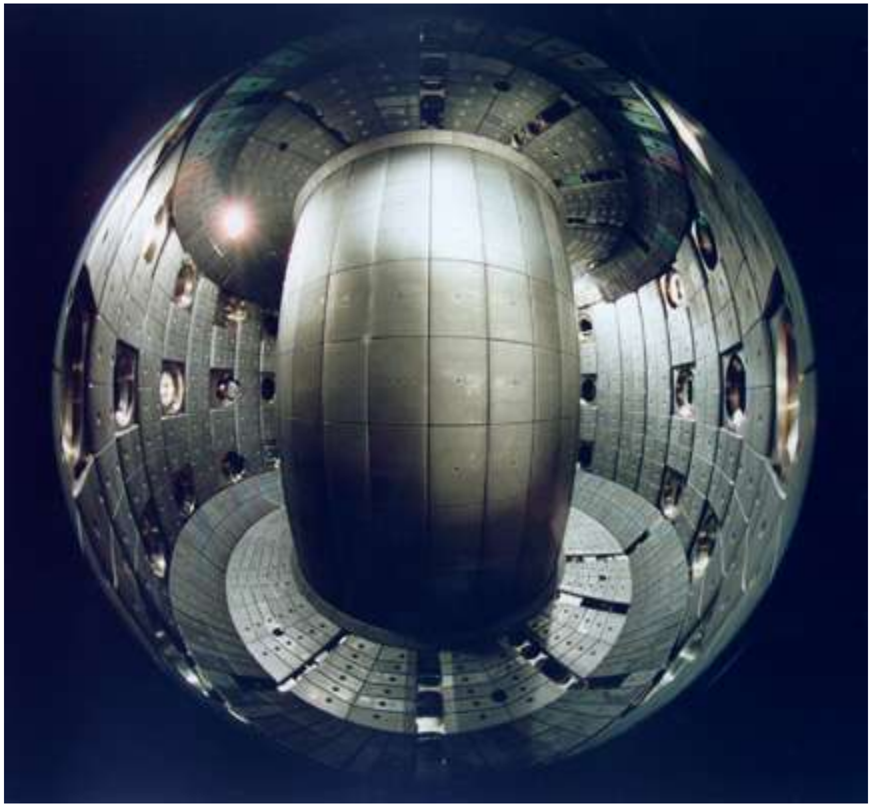
# MEASURED ECCD AGREES WITH THEORY

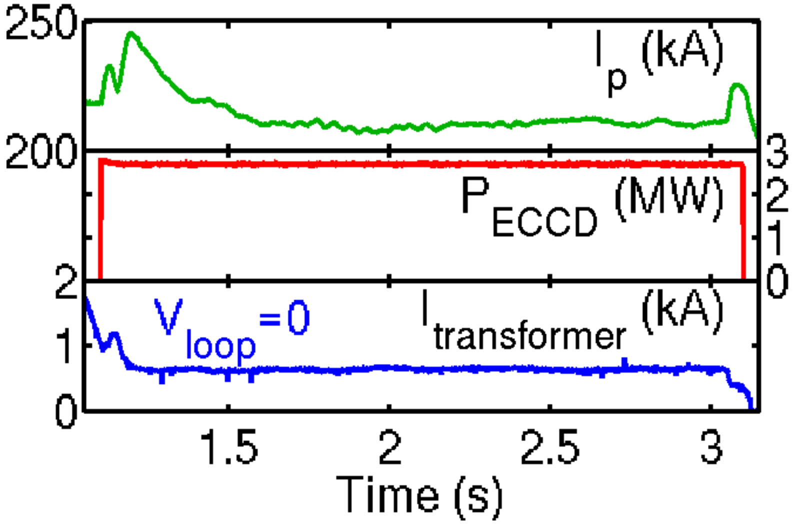


Comparison: DIIID data with computations
from C. C. Petty, Nuclear Fusion (2002)

CQL3D: Harvey and McCoy (1992)
TORAY: Kritz et al (1982); Matsuda (1989)

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





S. Coda et al. (2000)

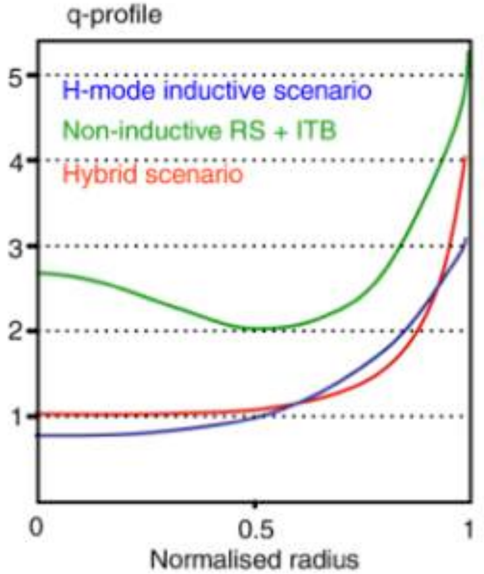
also e.g. *Steady-state non-inductive eITB with off-axis co-ECCD*
M.A. Henderson et al, Phys. Plasmas **10**, 1796 (2003

LHCD for current profile control in JET

J. Mailloux, 16th Topical Conference of RF Power in Plasma (2005)

## 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

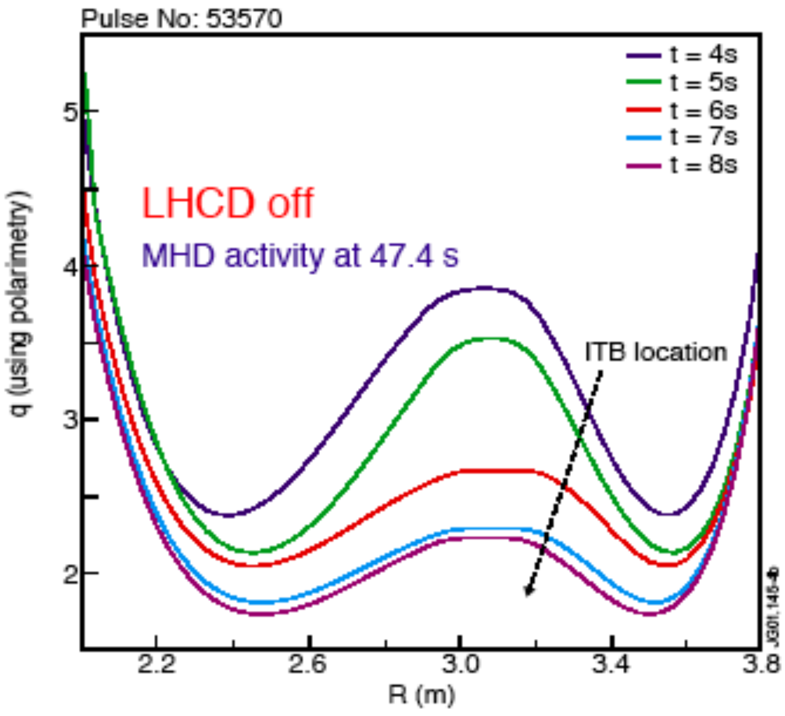
**In JET, key tool for this application is LHCD**

# JET Control of ITB with LHCD

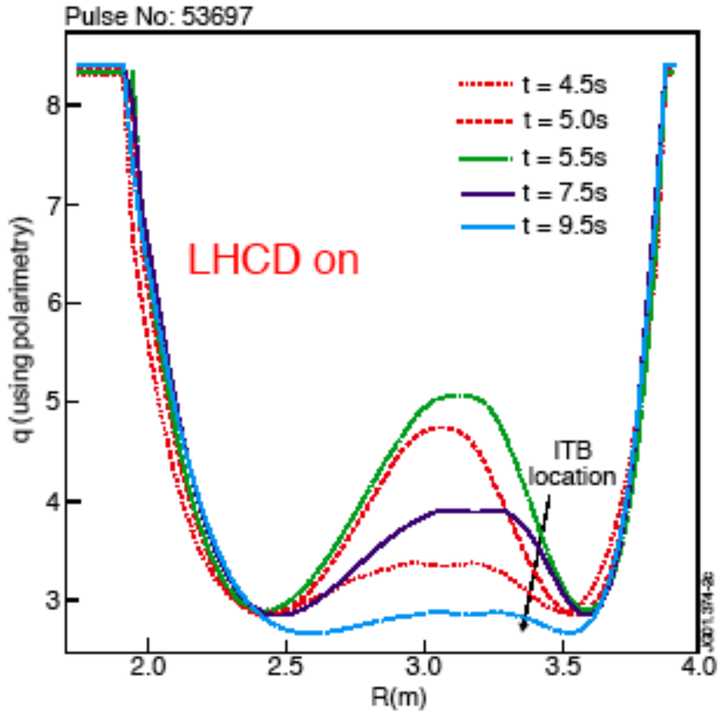
EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

## q-profile relaxation with/without LHCD

**53570 $B_T$=2.6T Ip=2.2MA**



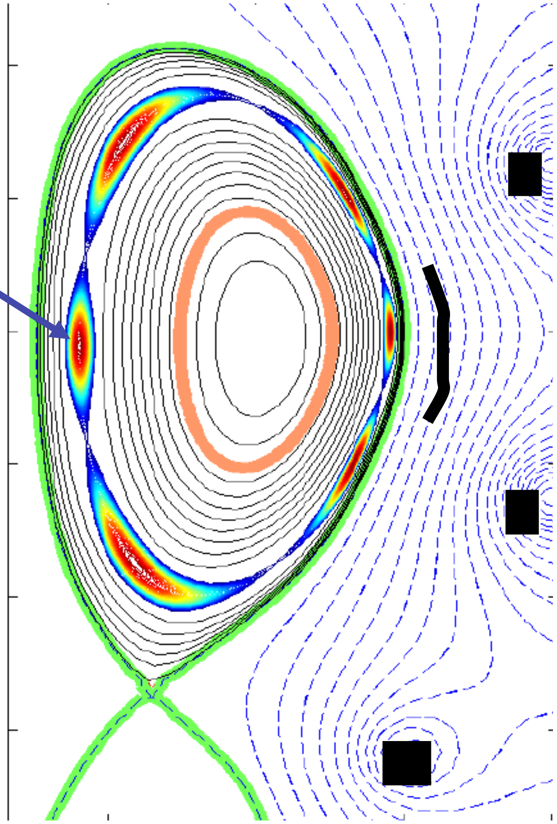
**53697 $B_T$=3.4T Ip=1.8MA**



Inner ITB linked with negative shear region

*D. Mazon et al, PPCF 44 (2002) 1087*

# Importance of Stabilizing Neoclassical Tearing Modes



island

**Neoclassical tearing modes reconfigure local equilibrium magnetic field into trapping helical chains of plasma known as magnetic islands**

**Islands permit heat to flow more easily.**

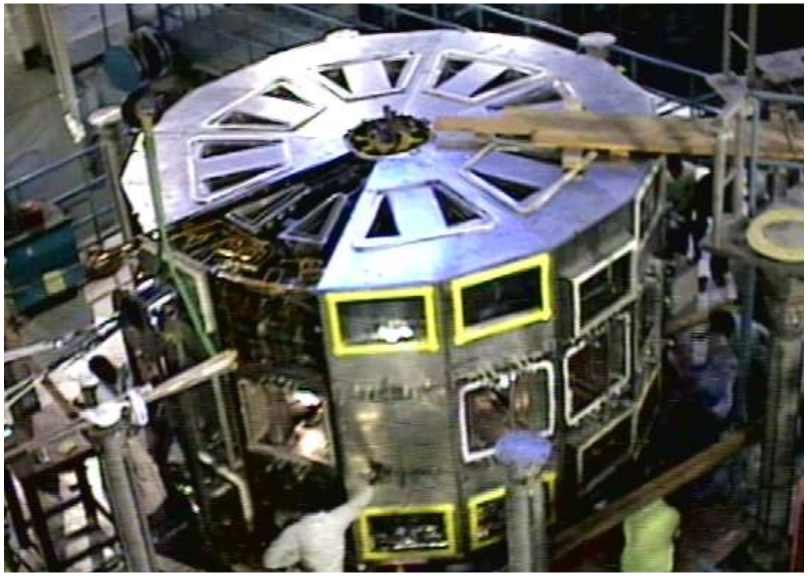
## Issues for ITER

Stabilizing the 2/1 island

Stabilizing multiple islands of varying helicity

See e.g. LP1.00051 Saturated Widths of Magnetic Islands in Tokamak Discharges, F. HALPERN, G. BATEMAN, A.H. KRITZ

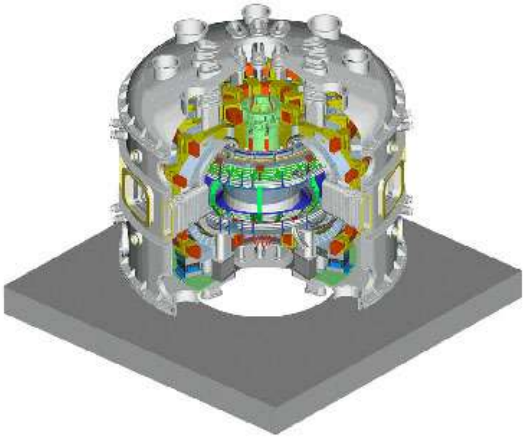
# New Superconducting LHCD- driven tokamaks



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

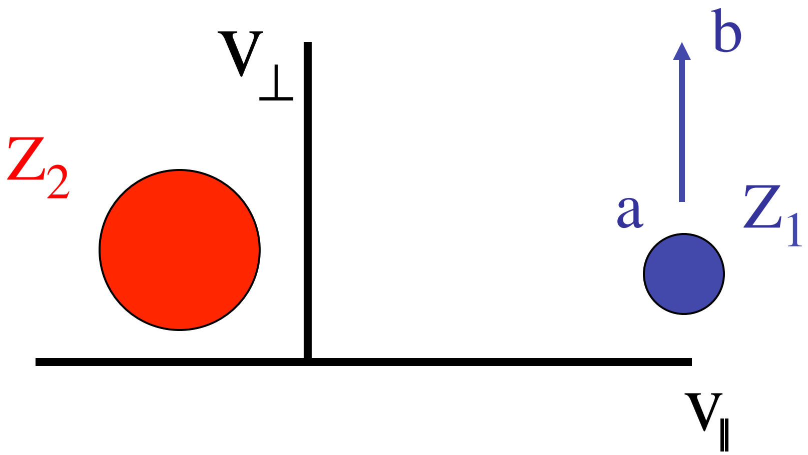
EAST China (1000 s)
(R=1.95 m, 1-1.5 MA, 4 MW, 4.6 GHz LHCD)

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 Effect (MiCCD)

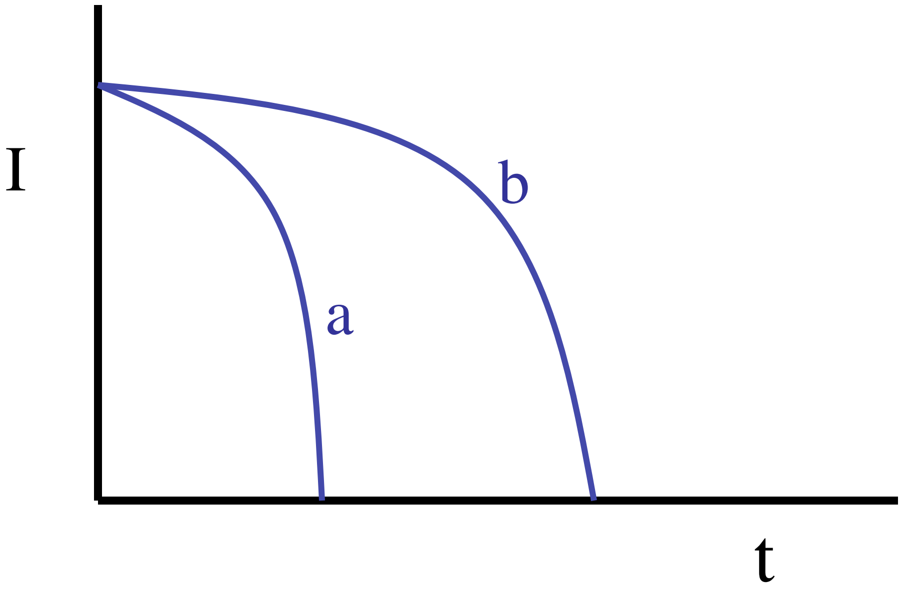
## Use waves to get counter-streaming ions



Zero ion current ⇒

Non-Zero electron current

if $Z_2 \neq Z_1$

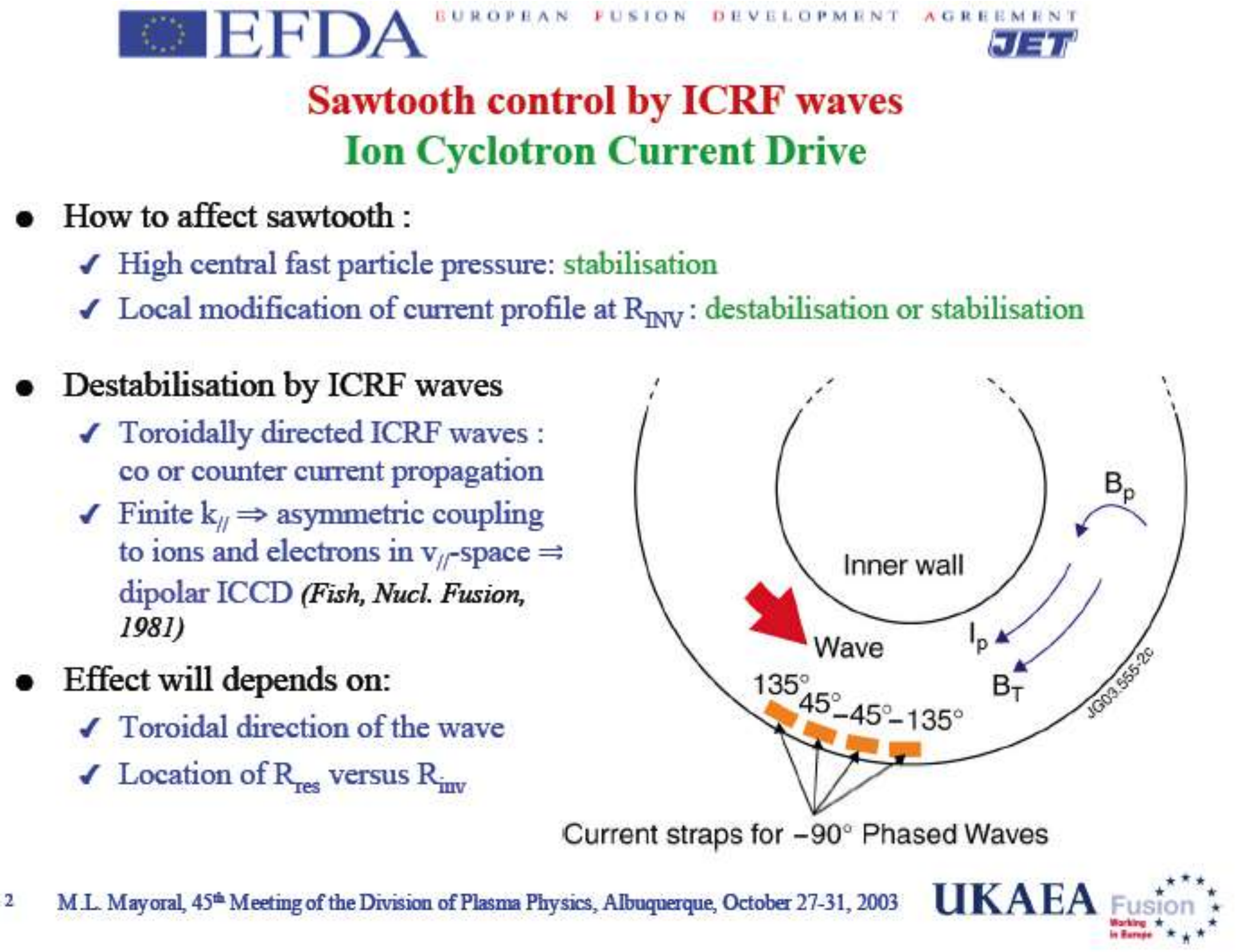


$$\omega - \vec{k} \cdot \vec{v} = n\Omega$$

$$\Omega \equiv eB/m$$

Fisch, 1981

# Minority ion Cyclotron Current Drive



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## Sawtooth control by ICRF waves
## Ion Cyclotron Current Drive

- How to affect sawtooth :
  - ✓ High central fast particle pressure: stabilisation
  - ✓ Local modification of current profile at $R_{INV}$ : destabilisation or stabilisation
- Destabilisation by ICRF waves
  - ✓ Toroidally directed ICRF waves : co or counter current propagation
  - ✓ Finite $k_{//}$ ⇒ asymmetric coupling to ions and electrons in $v_{//}$-space ⇒ dipolar ICCD *(Fish, Nucl. Fusion, 1981)*
- Effect will depends on:
  - ✓ Toroidal direction of the wave
  - ✓ Location of $R_{res}$ versus $R_{inv}$

Current straps for −90° Phased Waves

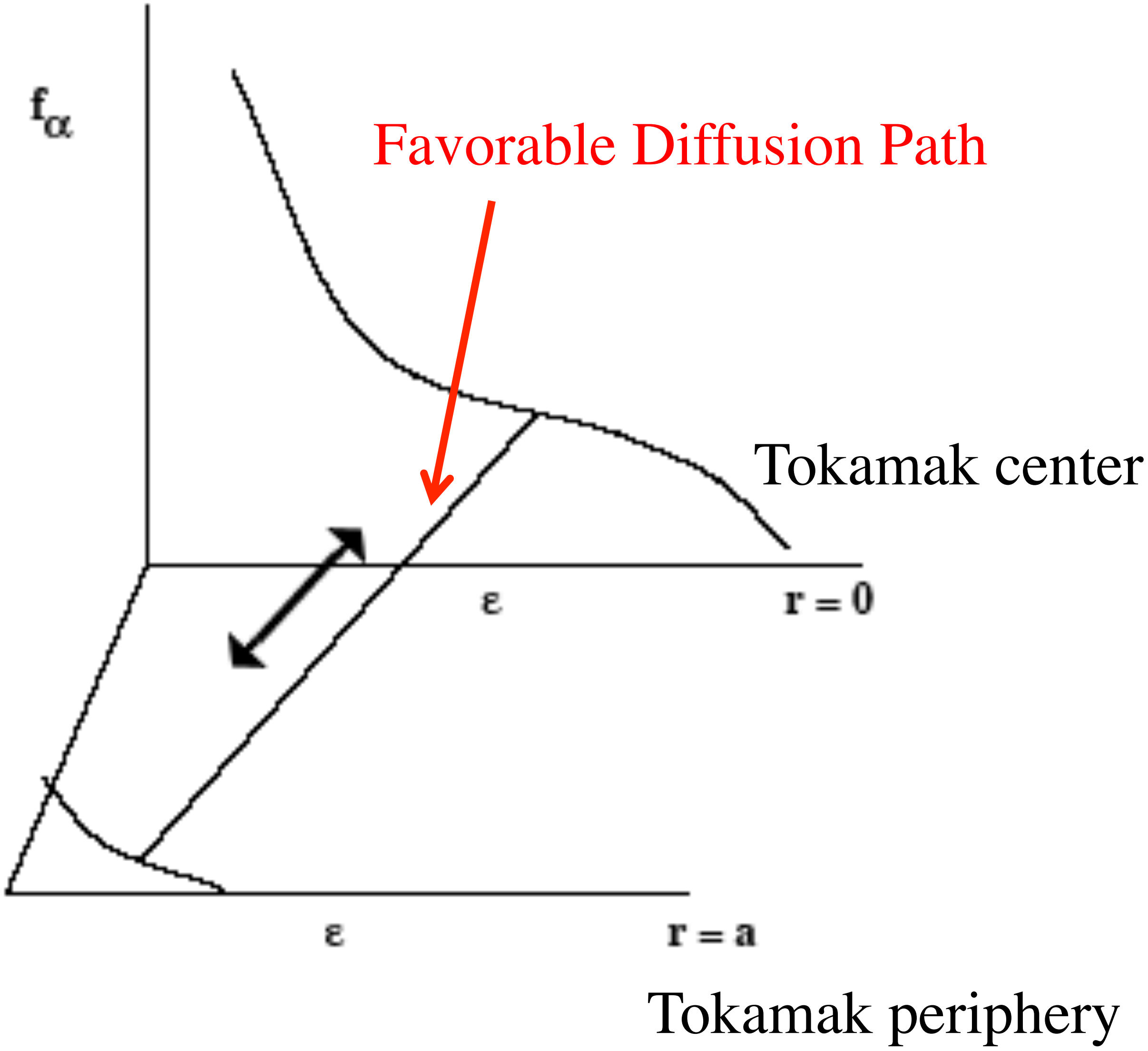
2 M.L. Mayoral, 45th Meeting of the Division of Plasma Physics, Albuquerque, October 27-31, 2003

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

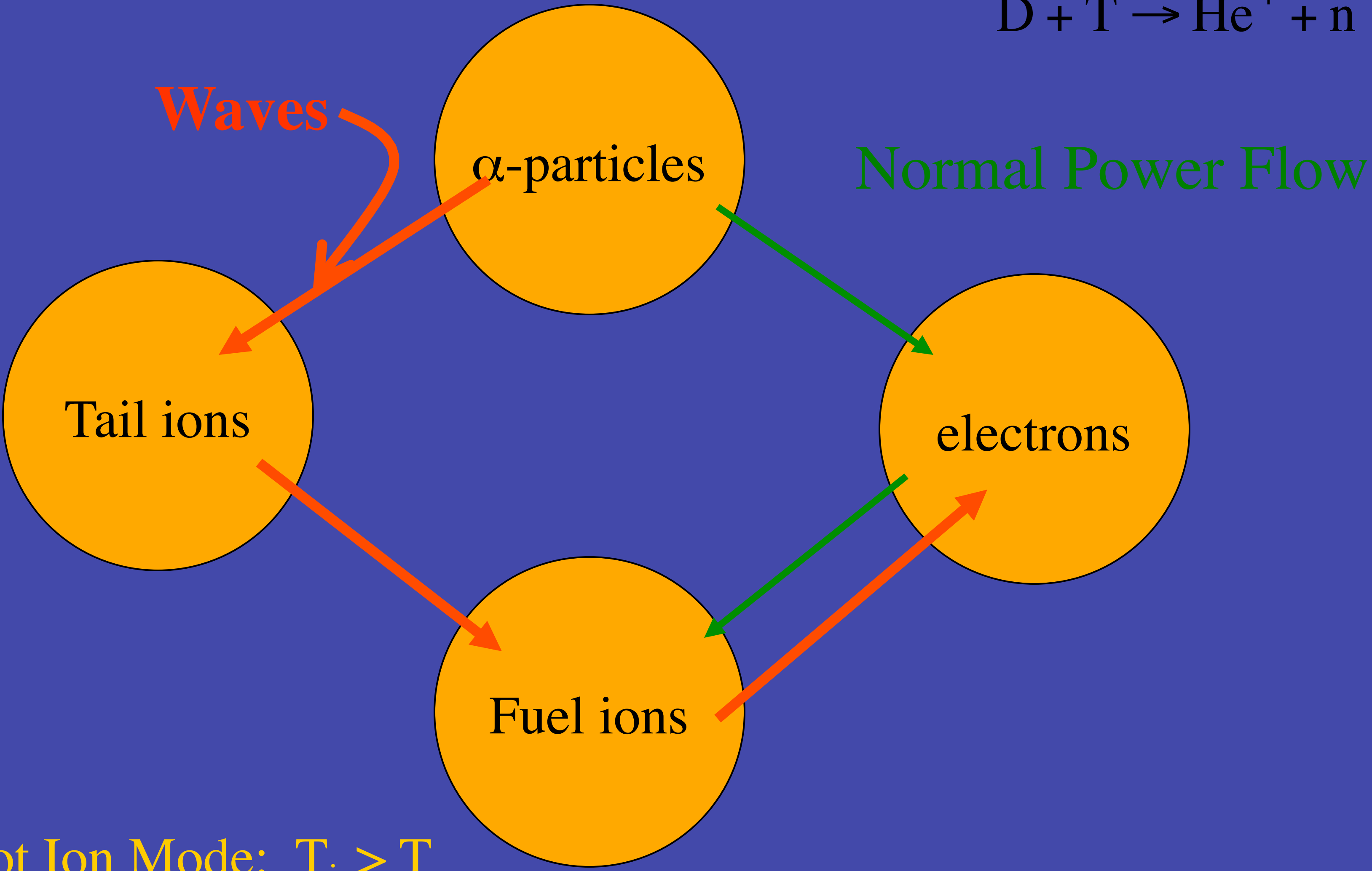
# Extracting Free Energy



# Power Flow in a Fusion Reactor

## Advantages of “α-Channeling”

$D + T \rightarrow He^4 + n$



Waves

α-particles

Normal Power Flow

Tail ions

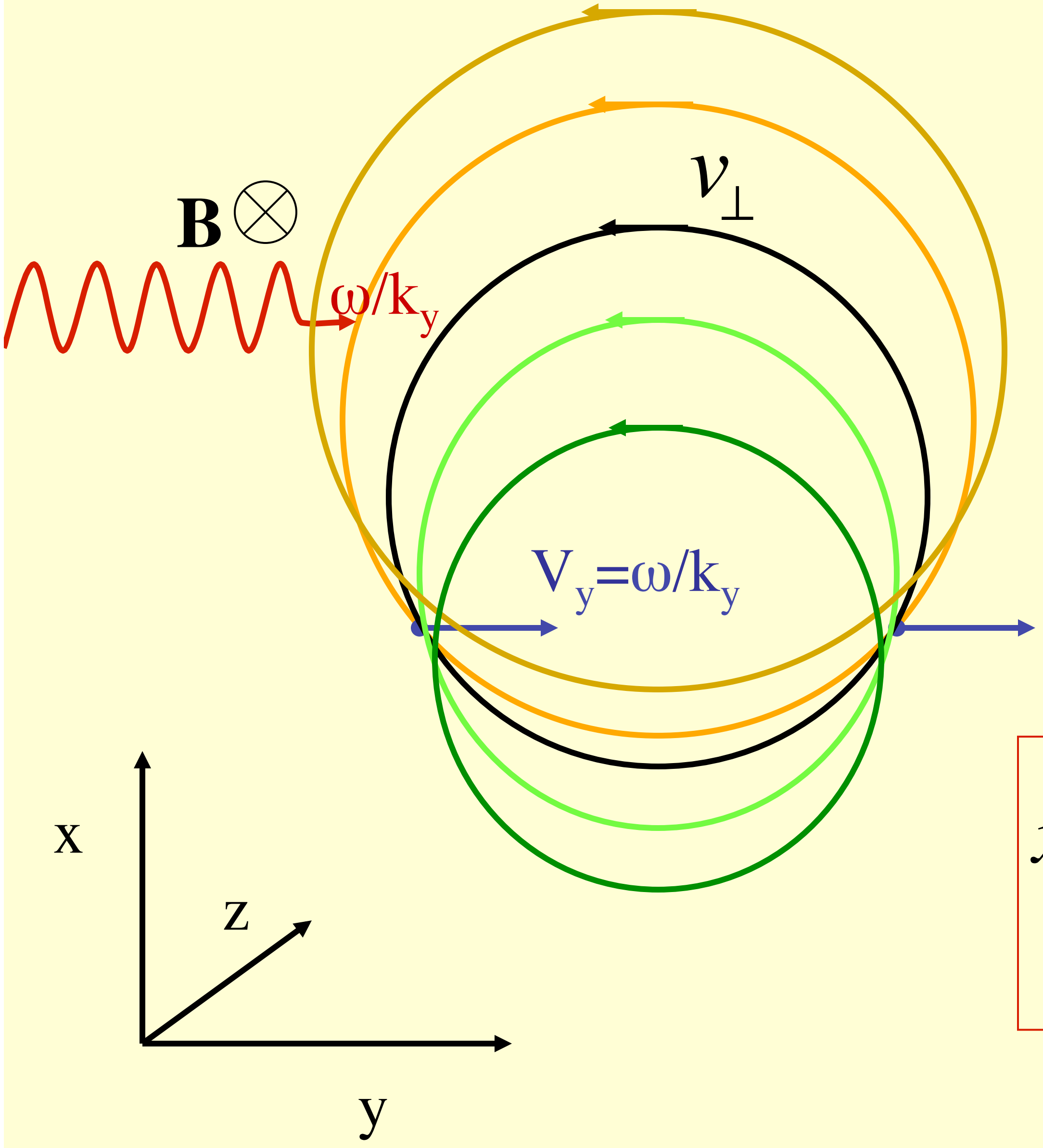
electrons

Fuel ions

Get Hot Ion Mode: $T_i > T_e$

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

# Diffusion Paths



$$v_y \rightarrow v_y + \Delta v_y$$

$$x_{gc} \rightarrow x_{gc} + \Delta v_y / \Omega$$

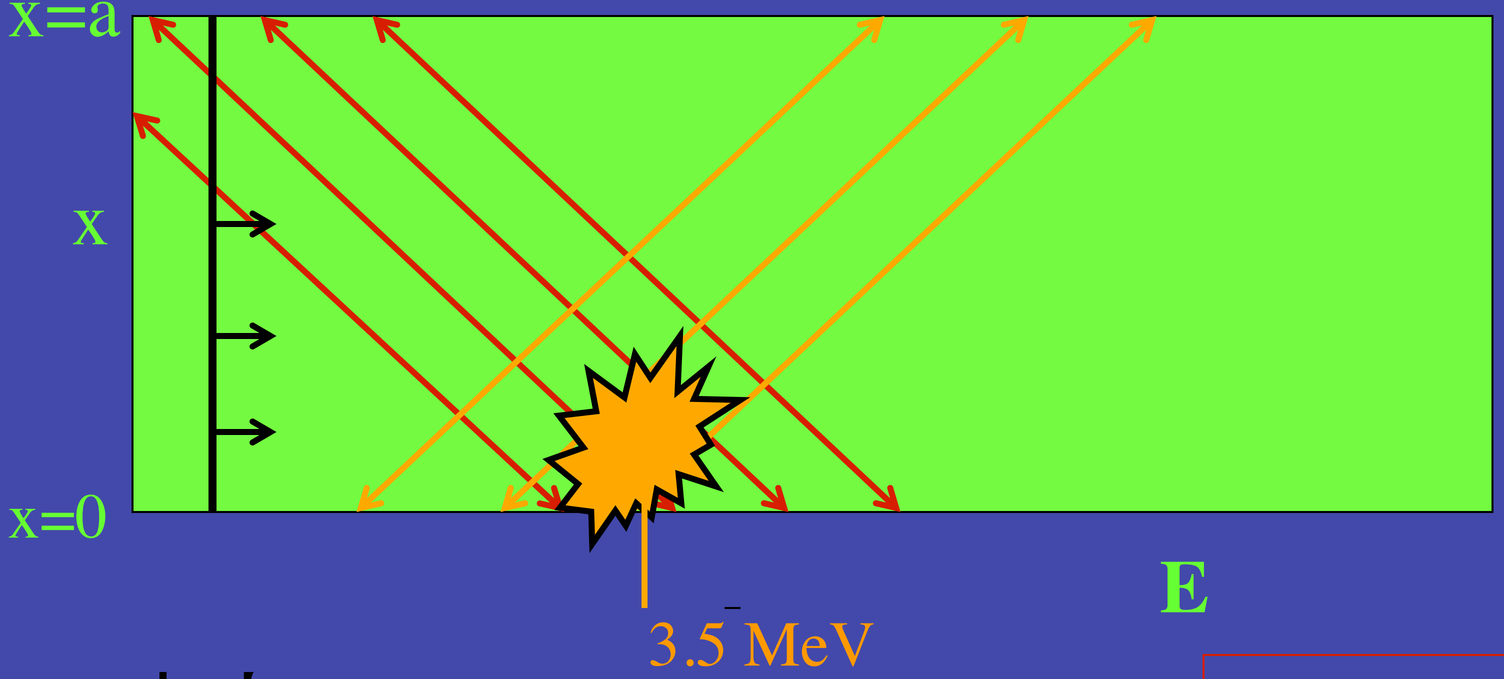
$$\Omega \equiv eB/m$$

$$\Delta E = m v_y \Delta v_y$$

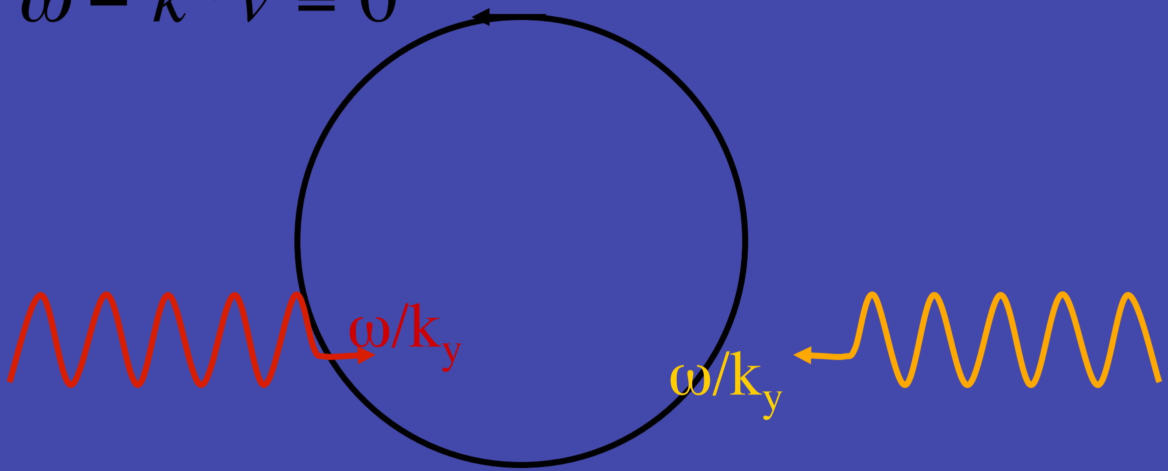
$$\boxed{x_{gc} \rightarrow x_{gc} + \frac{\Delta E}{m\Omega \, \omega / k_y}}$$

Fisch and Rax, 1992

# Diffusion Paths



$$\omega - \vec{k}\cdot\vec{v} = 0$$



$$\boxed{\Delta x_{gc} = \frac{\Delta E}{m\Omega\, \omega/k_y}}$$

# 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. *RF Current drive* is now a basic tool on essentially all tokamaks, present and planned, utilizing CD either to achieve confinement, stabilize unwanted instabilities, or sustain transport barriers..
2. Associating a current drive function to each point in phase space gives the current drive efficiency of driving particles from one point in phase space to another.
3. Using the resonant ponderomotive potential with a sign reversal one might build a "Maxwell Demon-like" current source with potentially higher efficiency yet (but phase-space conservation limits efficiency and suitable waves need to be identified).
4. Free energy in the confined inhomogeneous plasma can be extracted to do useful work, like *alpha channeling* for hot-ion mode, or driving current.

For further aspects: see Lecture by Jean Marcel Rax