

Methods of rf Current Drive

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

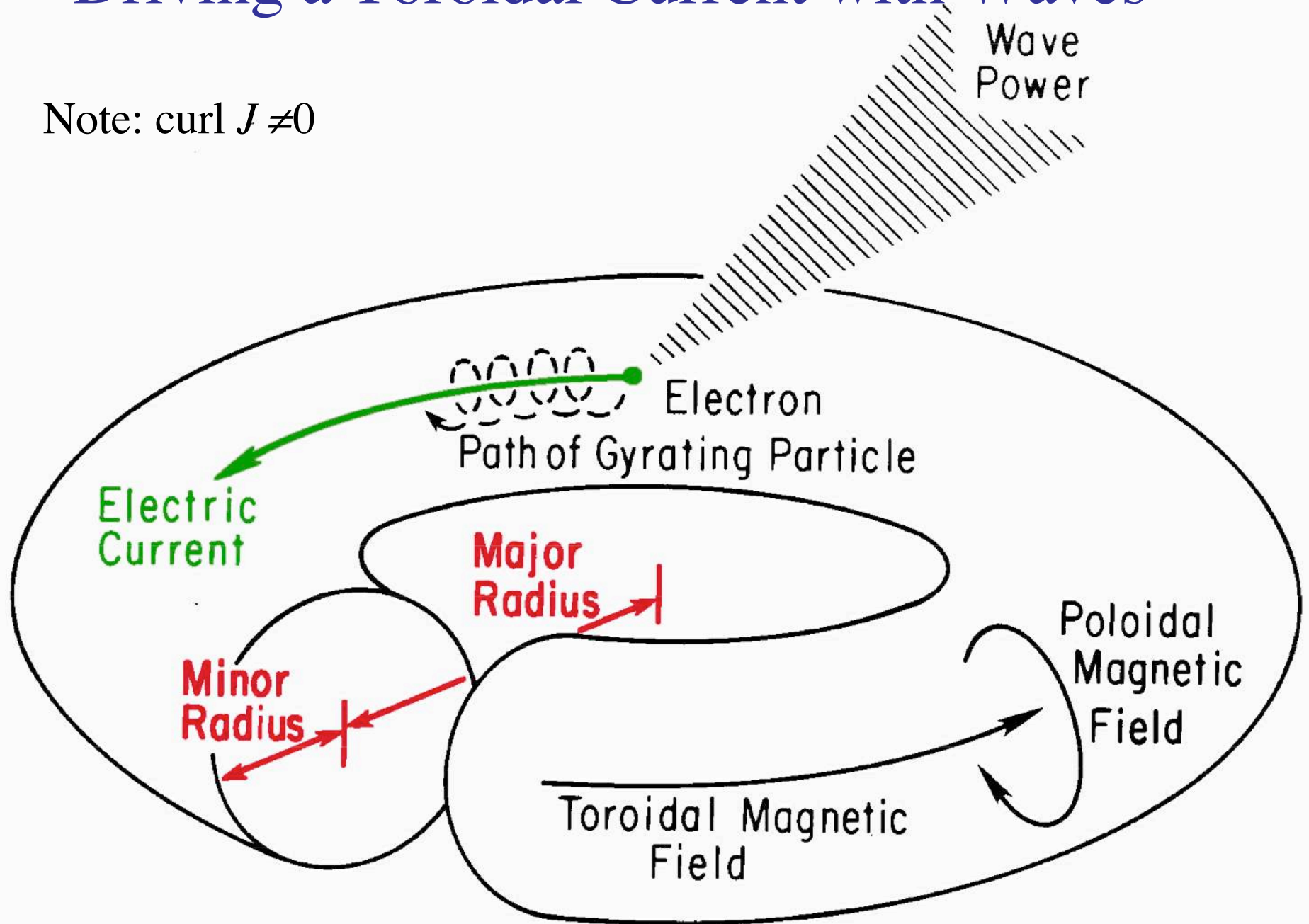
TFTR

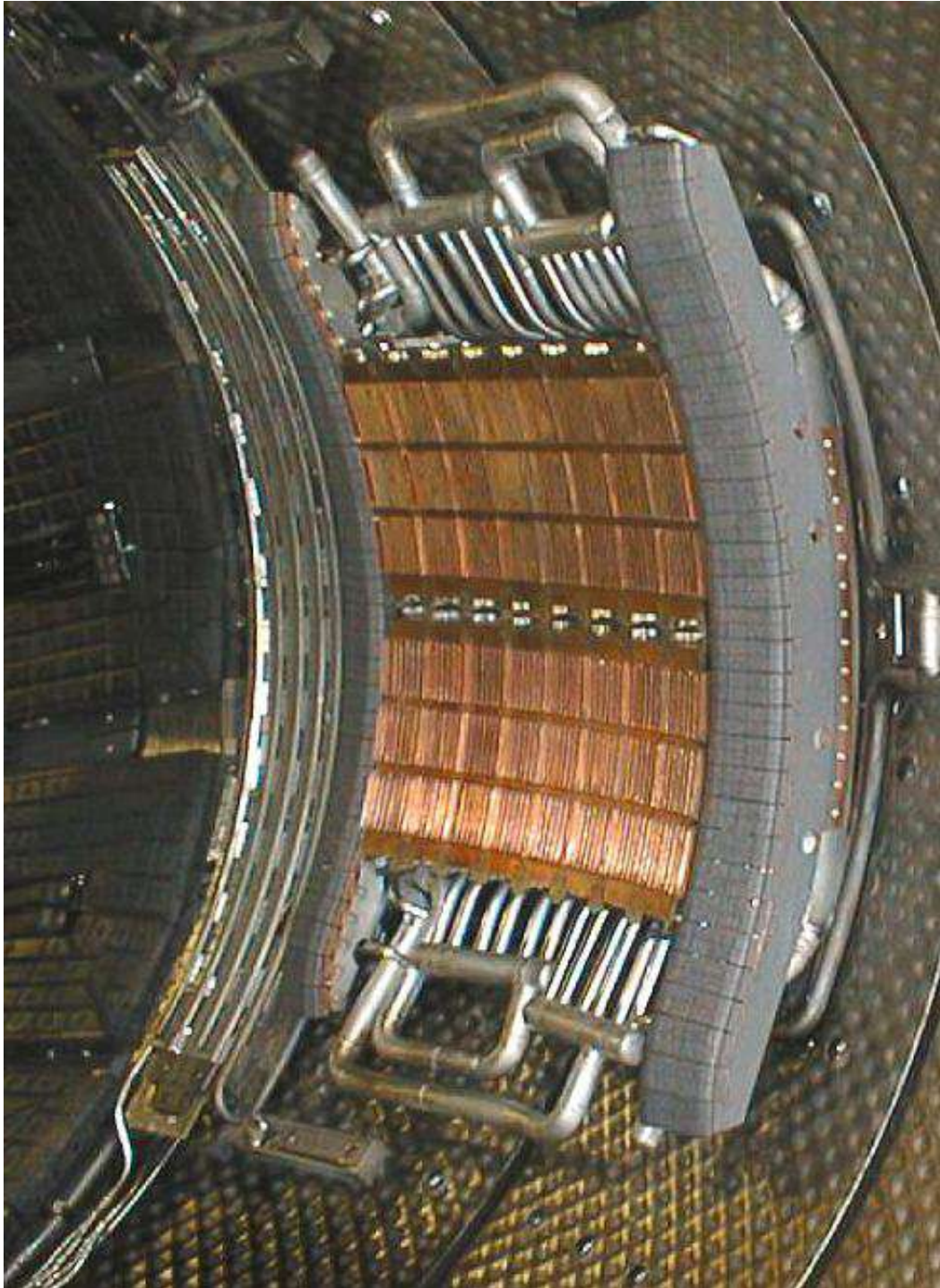
Tokamak Fusion Test Reactor (1989)



Driving a Toroidal Current with Waves

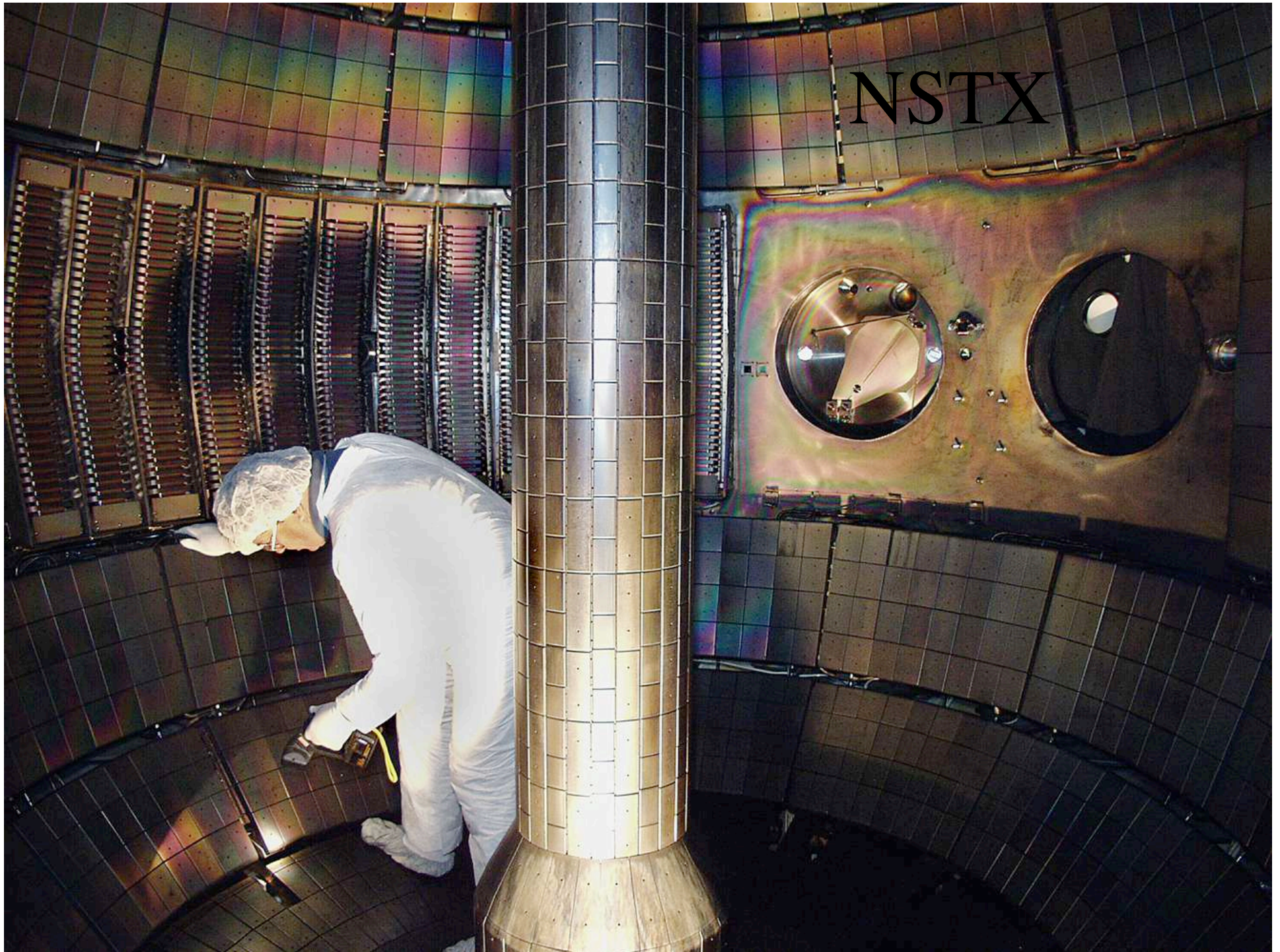
Note: $\text{curl } J \neq 0$





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

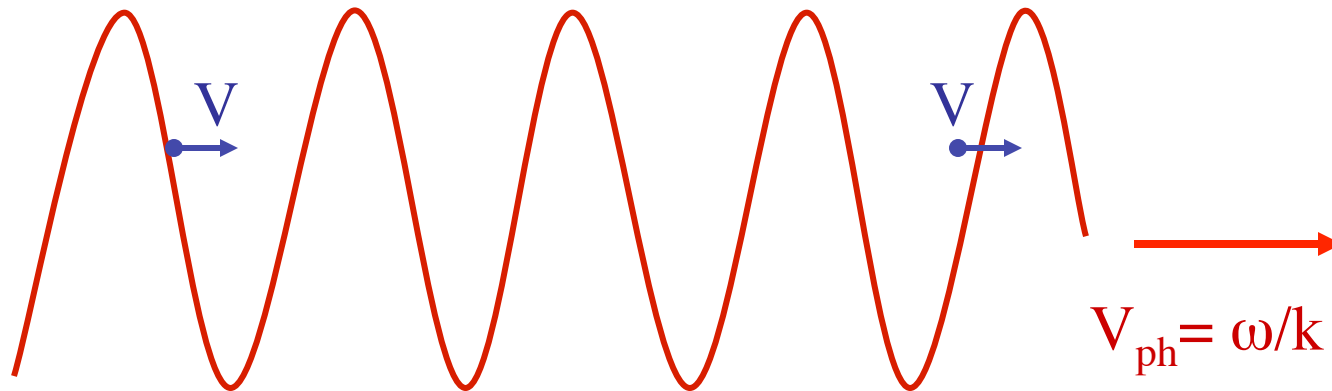
Select particles in 6D velocity-configuration space

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

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

$$v \rightarrow v + \Delta v$$

$$J = en\Delta v$$

$$\Delta E = mnv\Delta v$$

$$P_D = \nu \Delta E$$



$$\frac{J}{P_D} = \frac{e}{m} \nu v(v)$$

$$\nu(v) \approx v^{-3} \quad \text{Fisch (1978)}$$

Example of Resonance: The Traveling Plasma Wave

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

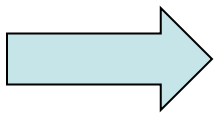
Poisson's equation

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

Particle conservation

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

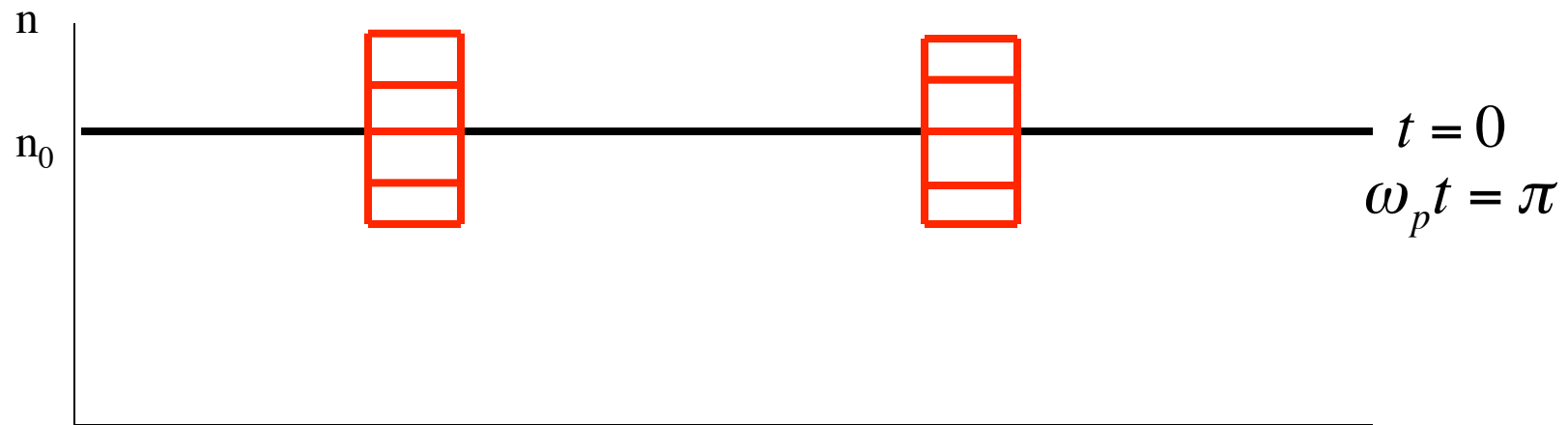
Momentum conservation



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

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

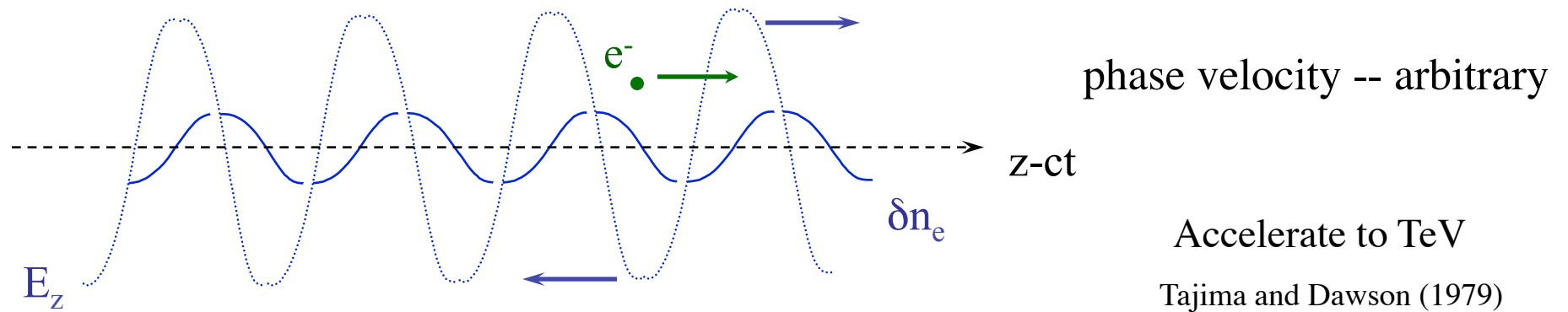
Plasma Oscillation



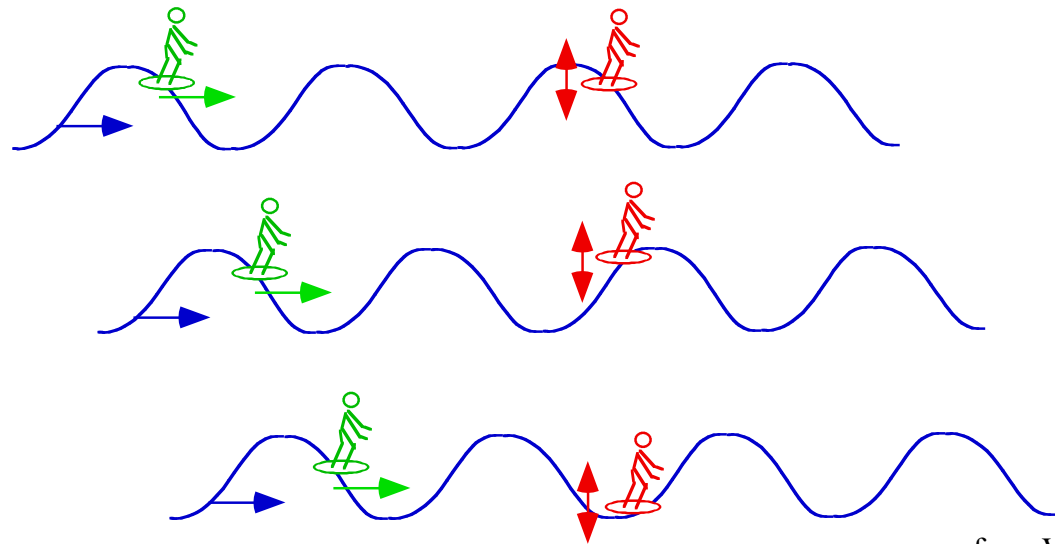
Make traveling wave:

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

Electron acceleration in a plasma wave



Analogy:



from V.Malka

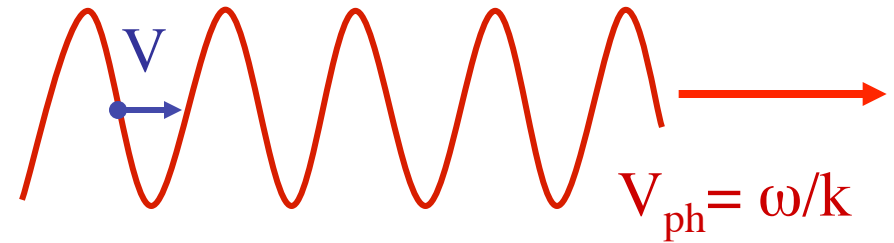
Accelerating Gradient in Plasma

Conventional Accelerator

Gradients ~ 20 MeV/m at 3GHz

1 TeV Collider requires 50 km

Peak gradients limited by breakdown



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

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

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

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

Plasma Accelerator

High fields, No breakdown

(Tajima and Dawson, 1979)

Example



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

$$eE = 100 \text{ GeV/m}$$

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

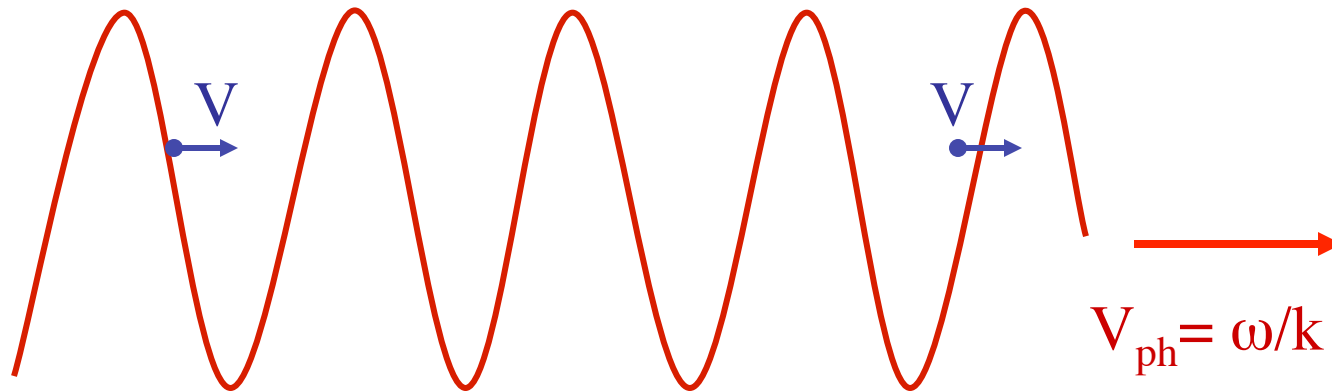
Particles accelerated to relativistic energies, even as plasma motion is not

Resonant Surfers



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

(Resonant) Radio Frequency (RF) Current Drive Effect



Resonance condition

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

$$v \rightarrow v + \Delta v$$

$$J = en\Delta v$$

$$\Delta E = mnv\Delta v$$

$$P_D = \nu \Delta E$$



$$\frac{J}{P_D} = \frac{e}{m} v \nu(v)$$

$$\nu(v) \approx v^{-3} \quad \text{Fisch (1978)}$$

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 “ α channeling”

a. tokamak

b. mirror

Experimental Confirmations

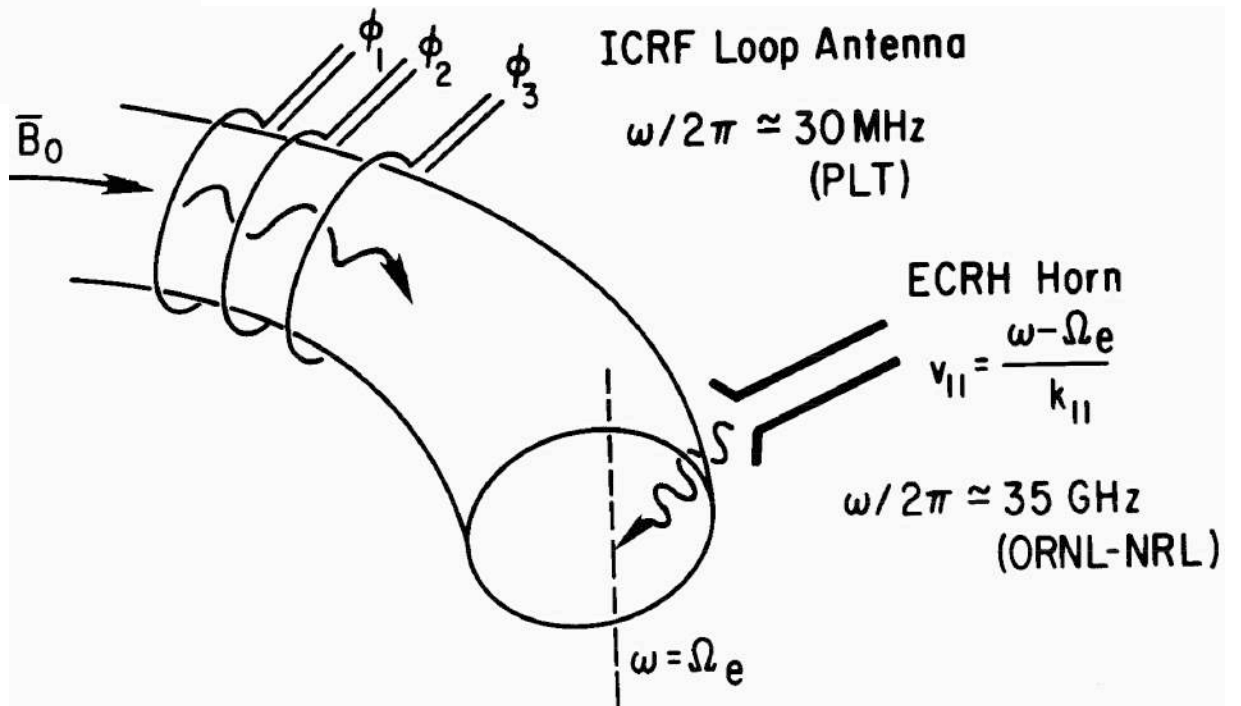
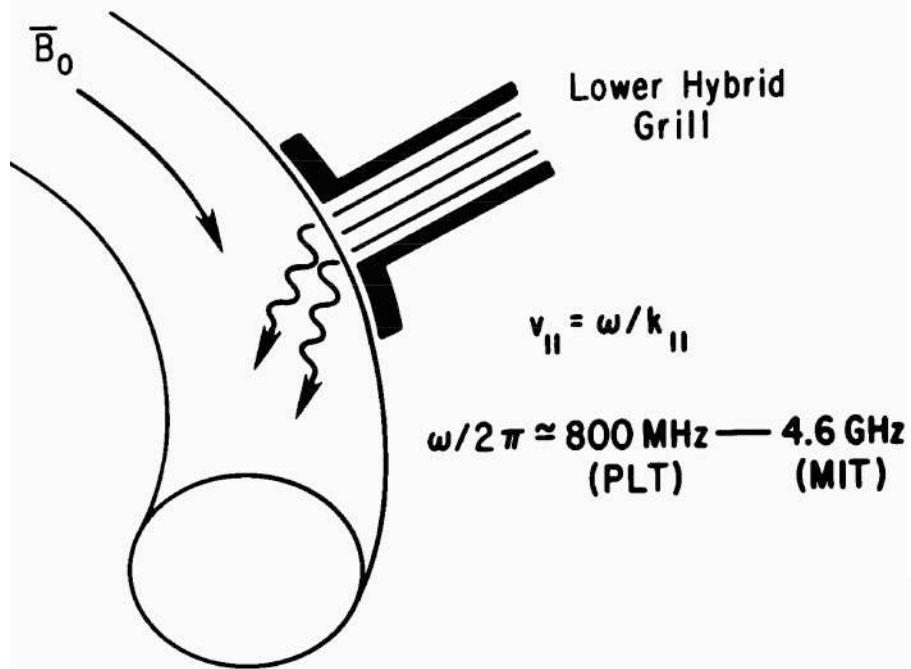
Implications: practical and basic

3. Open questions

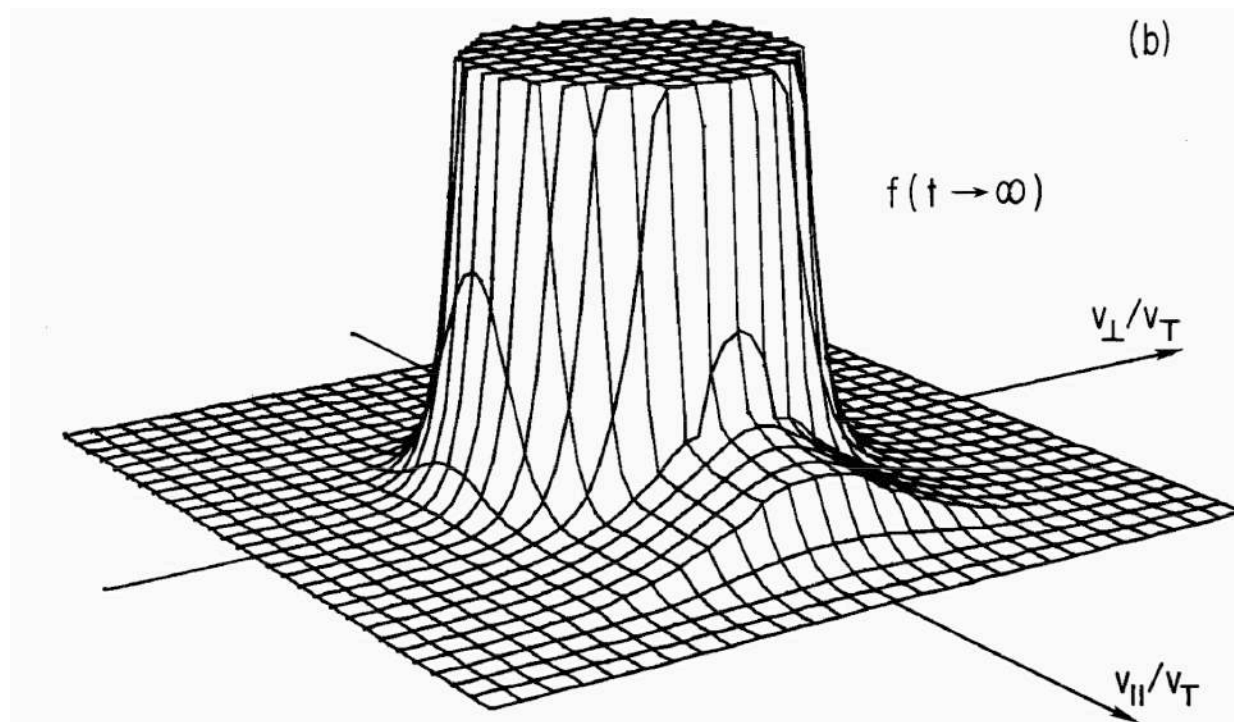
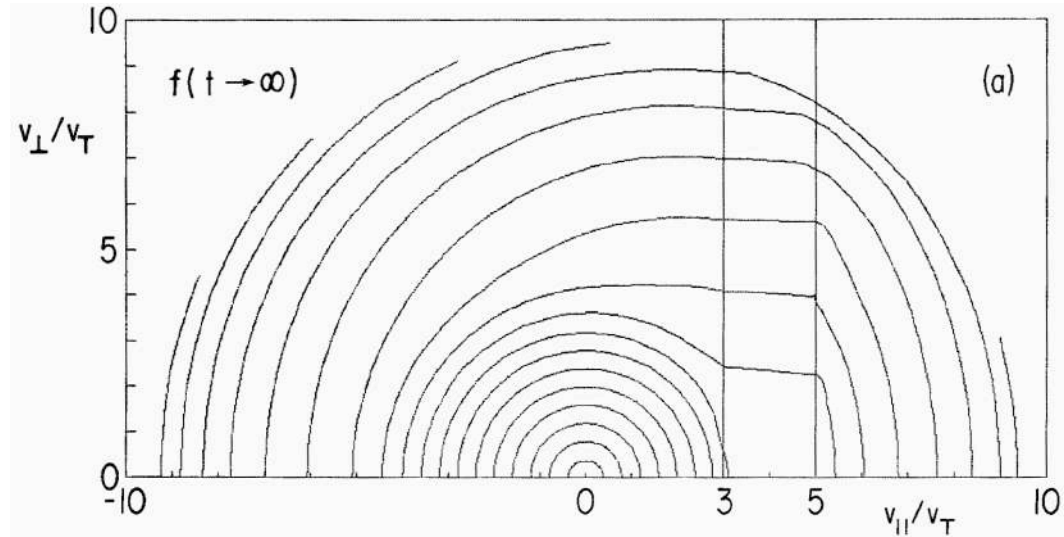
New Physics

Hot ion mode reactor

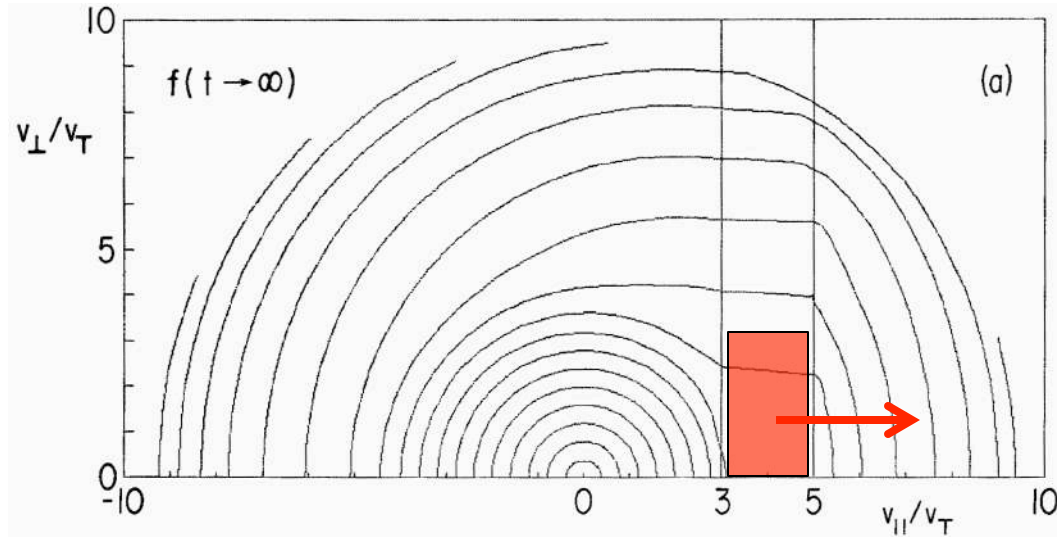
RF Methods of Heating and Current Drive



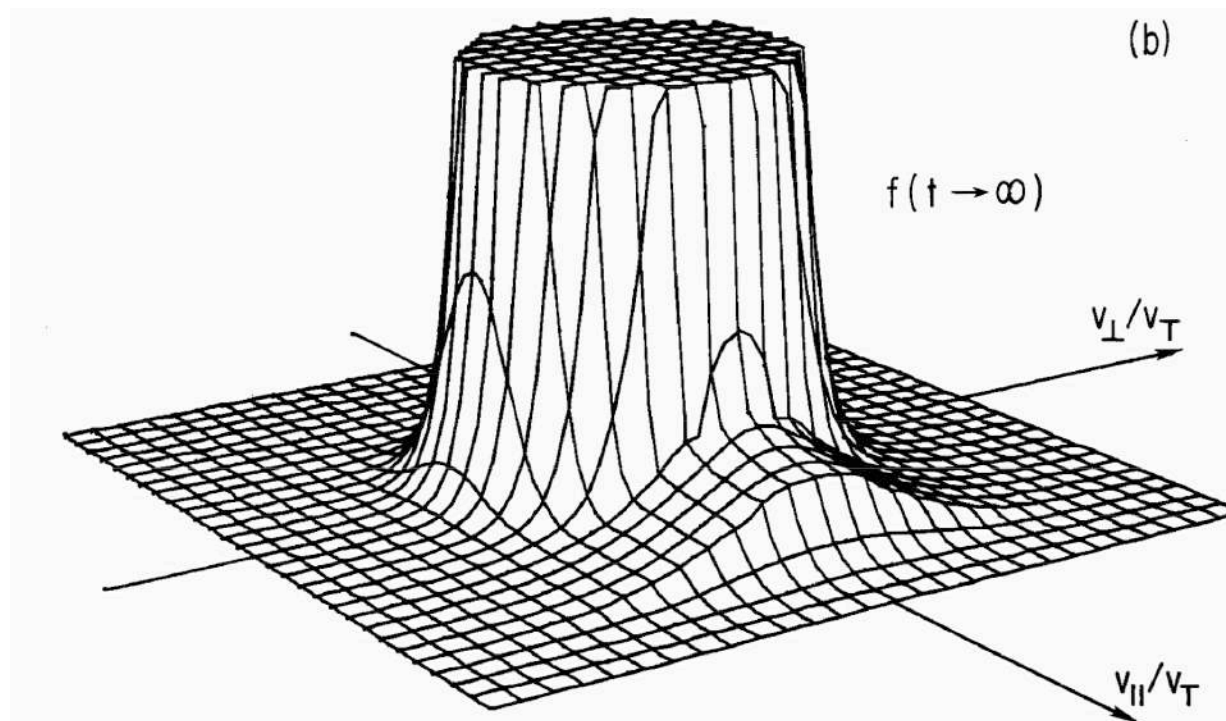
Electron Distribution Function -- LHCD



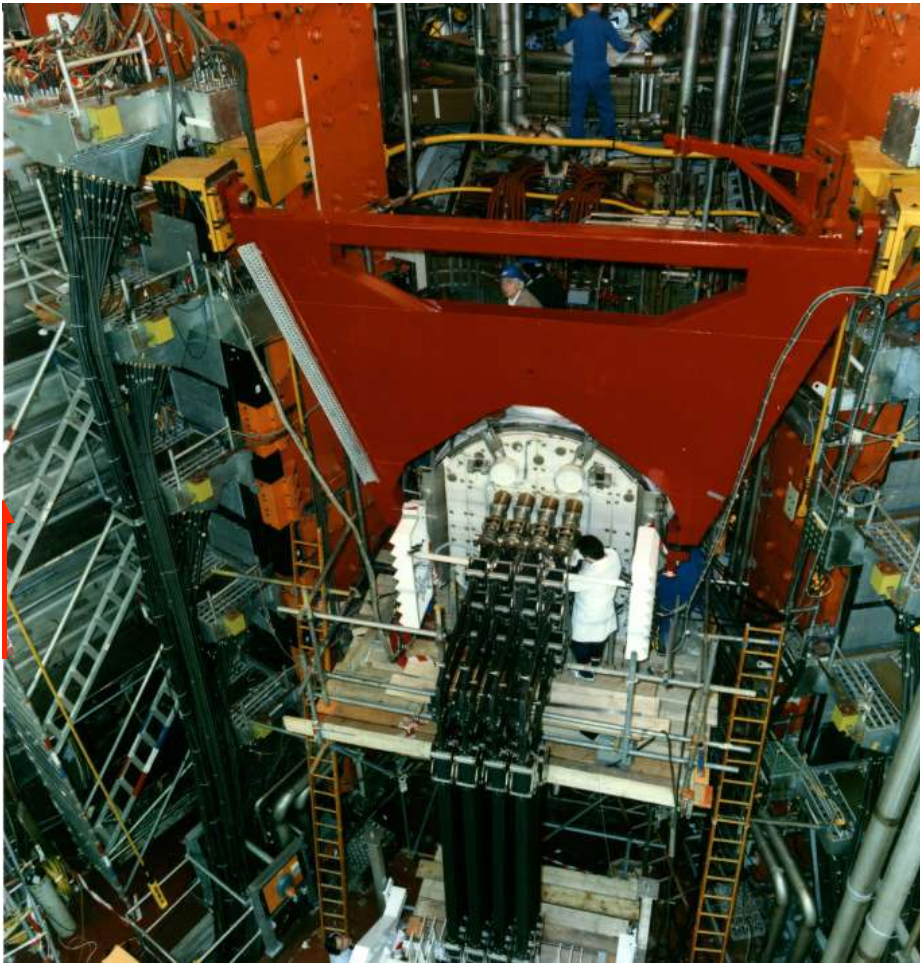
Electron Distribution Function



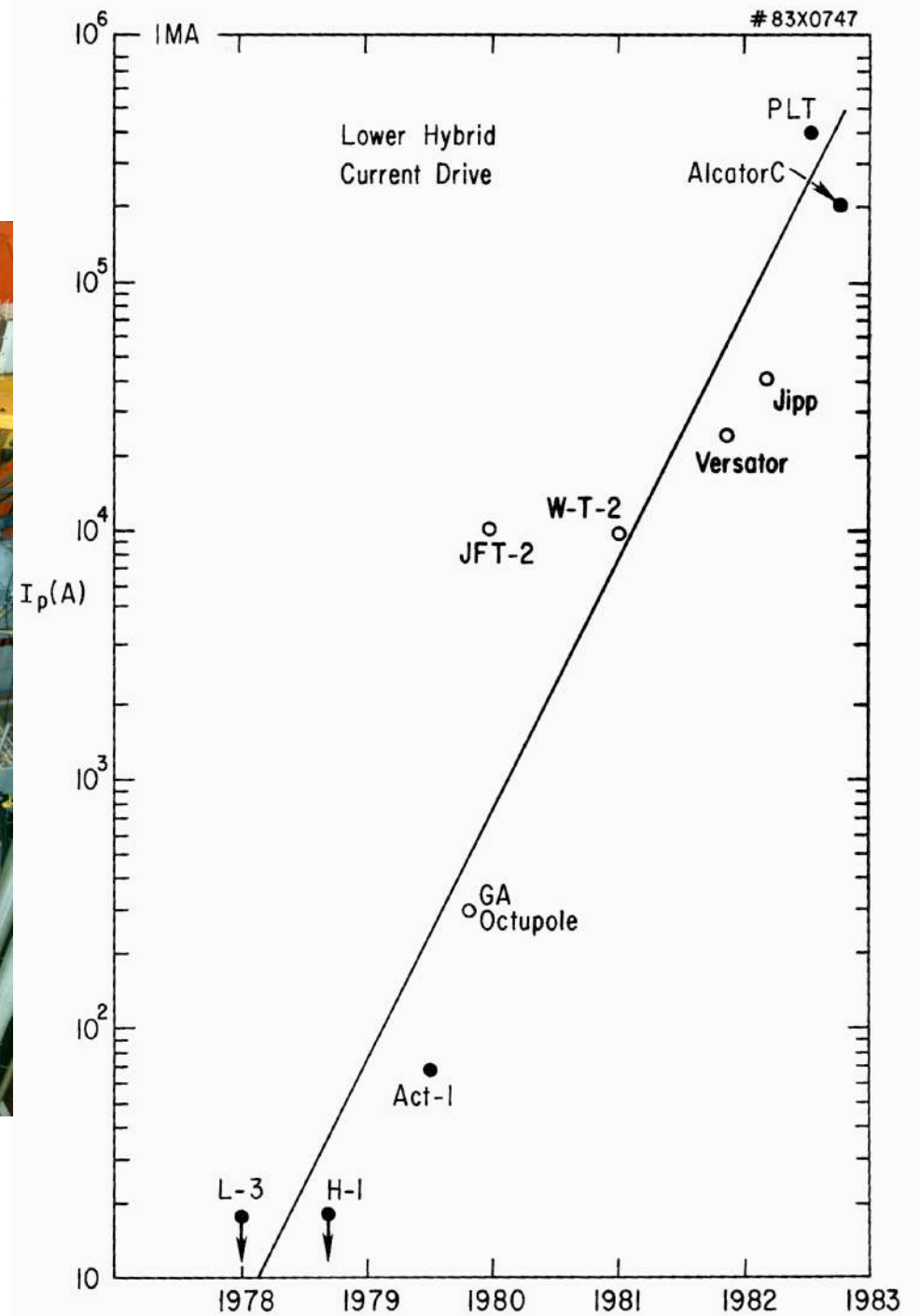
Localize $S(v)$
Resonance condition
Dispersion relation



Progress in Current Drive



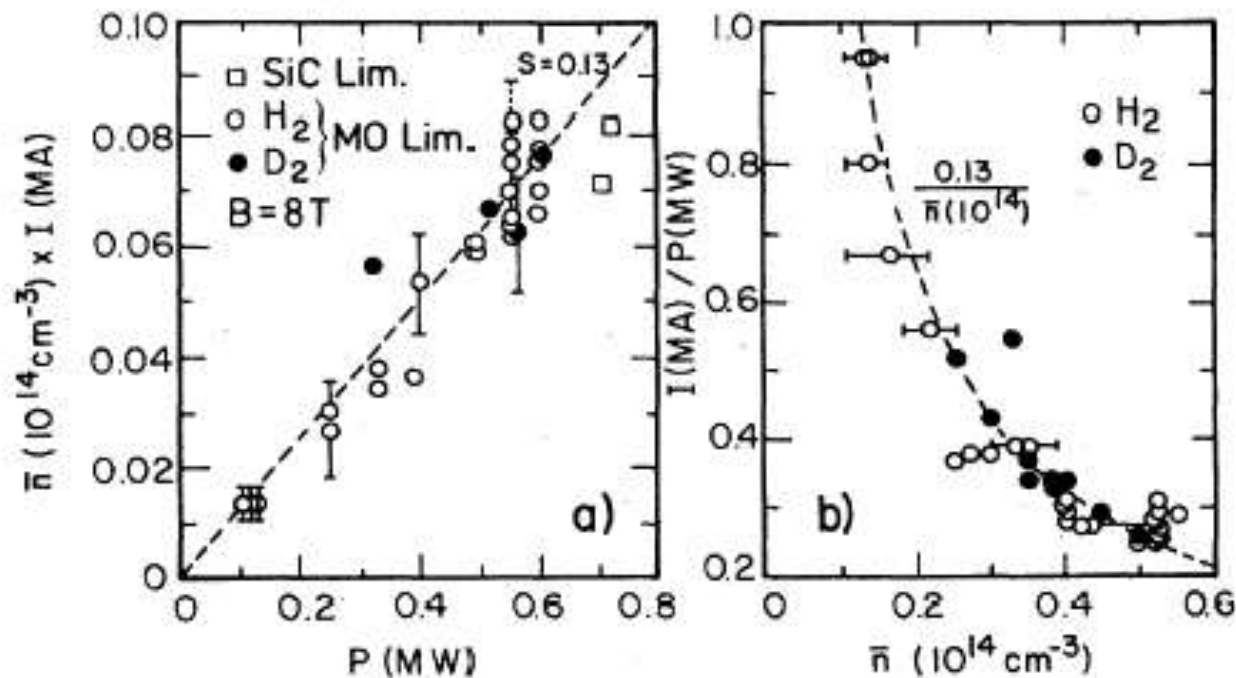
JET (2001)



Alcator C

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

Porkolab et al, 1984



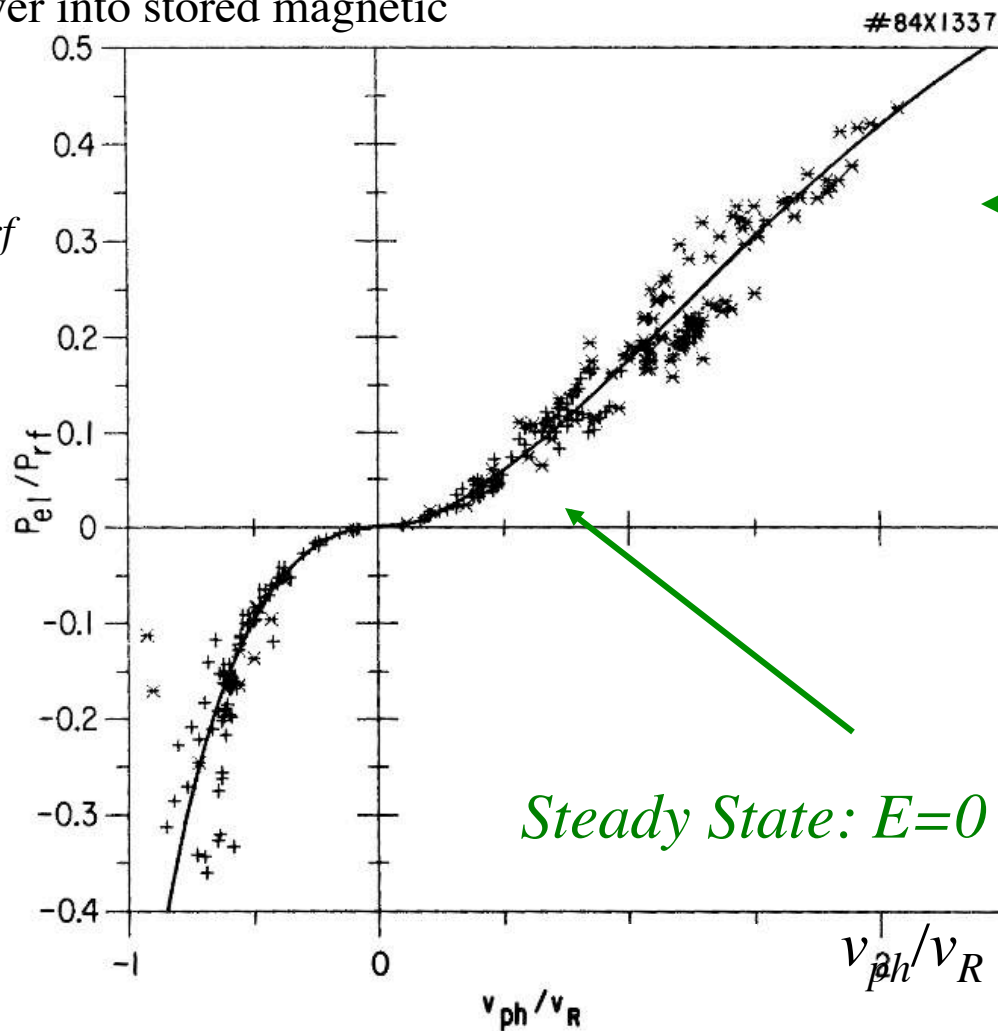
Line-averaged density
times current vs. power

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: $E < 0$

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

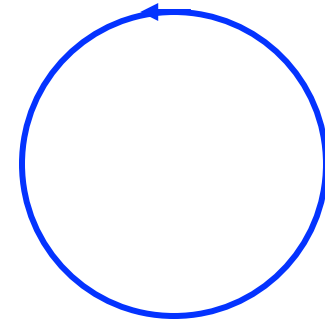
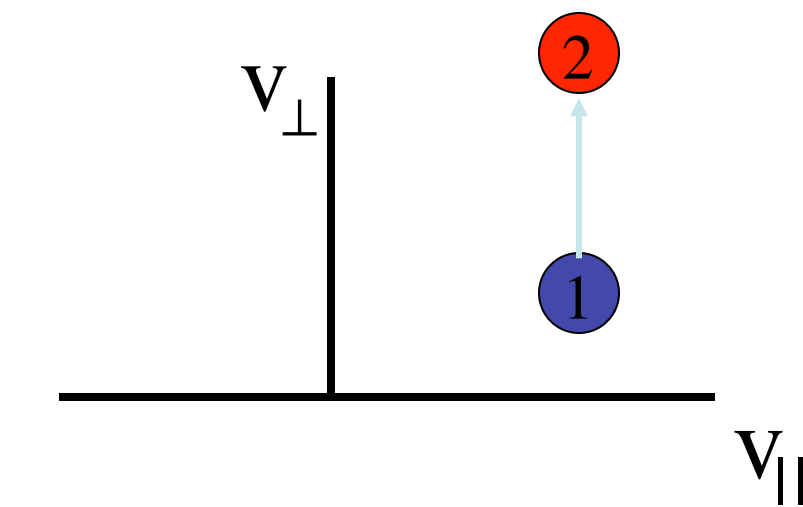
Verification *in detail* proves classical picture of electron collisions!

Tokamak East

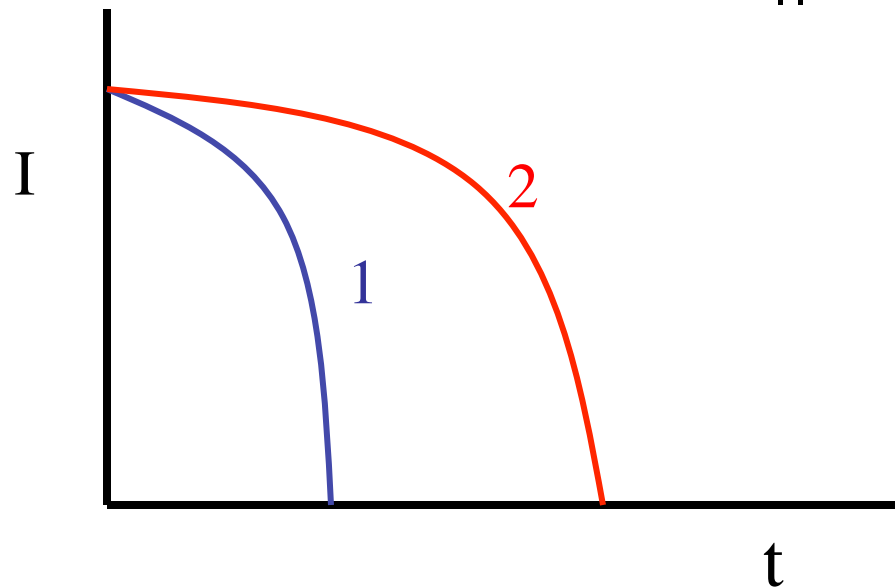


LHCD with very long pulse -- time scales for pinch effects
Low frequency ICRF with 4T (internal mode excitation)

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

$$J(t) = \int_0^t \frac{P(\tau)}{\varepsilon_2 - \varepsilon_1} \langle q v_{\parallel}(t - \tau, v_2) - q v_{\parallel}(t - \tau, v_1) \rangle d\tau$$

$$= \lim_{v_2 \rightarrow v_1} \int_0^t d\tau P(\tau) \frac{S \cdot (\partial / \partial v) \langle q v_{\parallel}(t - \tau, v_1) \rangle}{S \cdot (\partial / \partial v) \varepsilon_1}$$

Suppose constant $P(t) = P_D$

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

$$\frac{J}{P_D} = \frac{S \cdot (\partial / \partial v) \int_0^{\infty} \langle q v_{\parallel}(t, v) \rangle dt}{S \cdot (\partial / \partial v) \varepsilon}$$

Langevin Equations

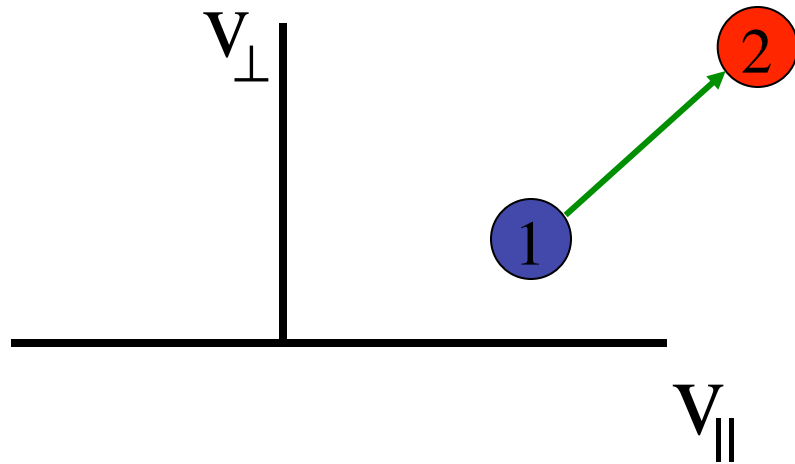
$$\frac{\partial f}{\partial t} = C(f, f) + C(f, f_i) \quad C(f, f_i) = \frac{\Gamma}{2v^3} \frac{\partial}{\partial \mu} (1 - \mu^2) \frac{\partial}{\partial \mu} f$$

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

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

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

Generalized RF Current Drive Effect



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

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

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

$$\varepsilon \equiv mv^2/2$$

New “transport quantity”
for current drive

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

$$\Psi(v_{\parallel}, v_{\perp}) = \frac{-e v_{\perp} v_{\parallel}^3}{v_0(5 + Z_i)}$$

Green's function: Fisch and Boozer, 1980

Adjoint formalism: Antonsen and Chu, 1982

Generalized Transport Quantities

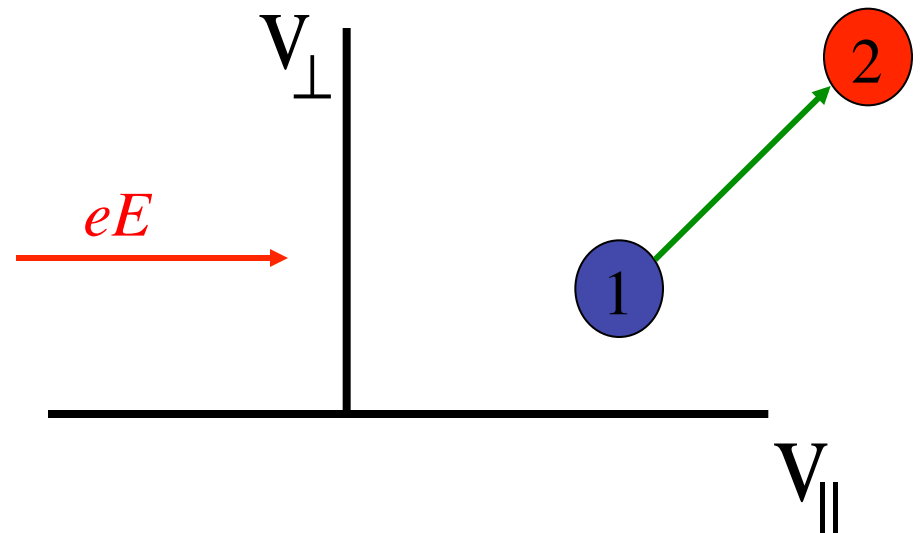
Associate transport quantity with each point in 2D velocity space

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-60 and JT60-U (Japan) -- 3 MA 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 DIII-D tokamak; ECCD, ITB, mode suppression

Princeton spherical torus: NSTX (HHFWCD)

New Steady-State Superconducting Lower-hybrid driven

SST (India)

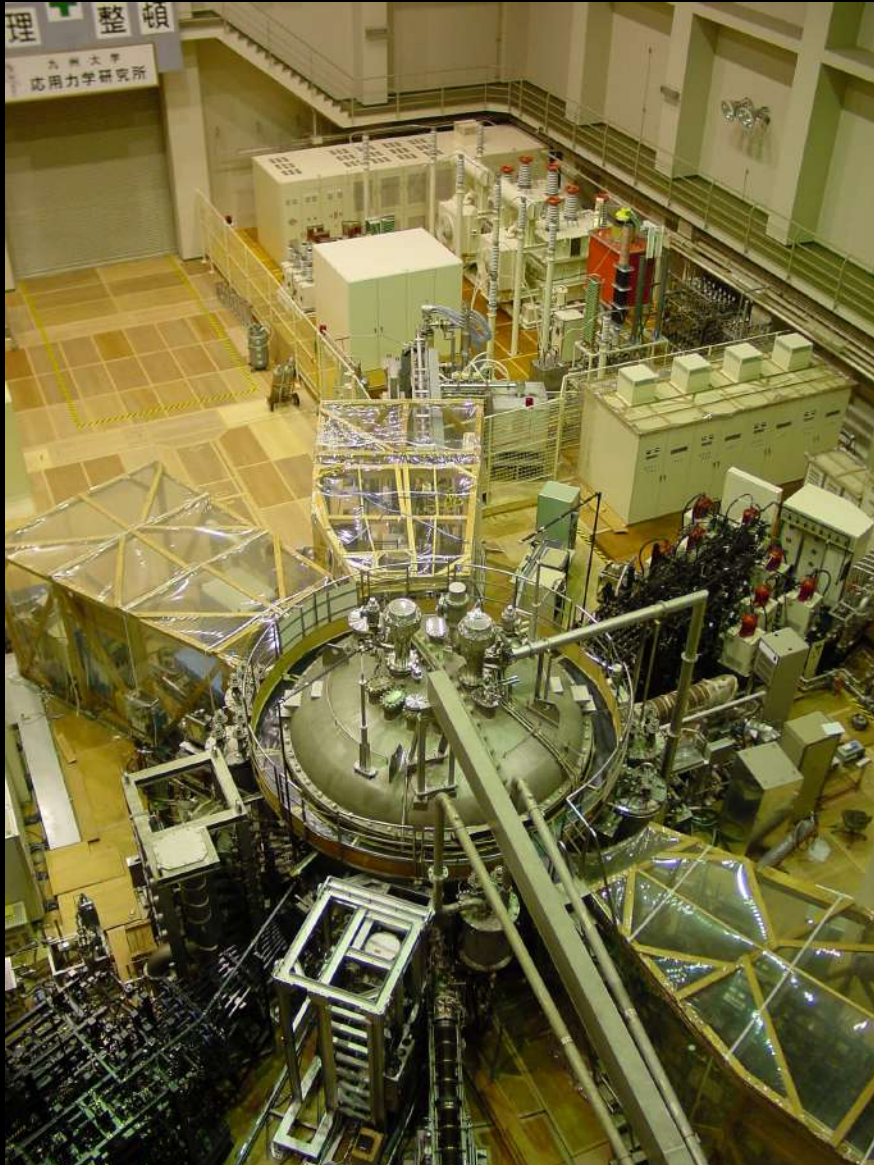
KSTAR (Korea)

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

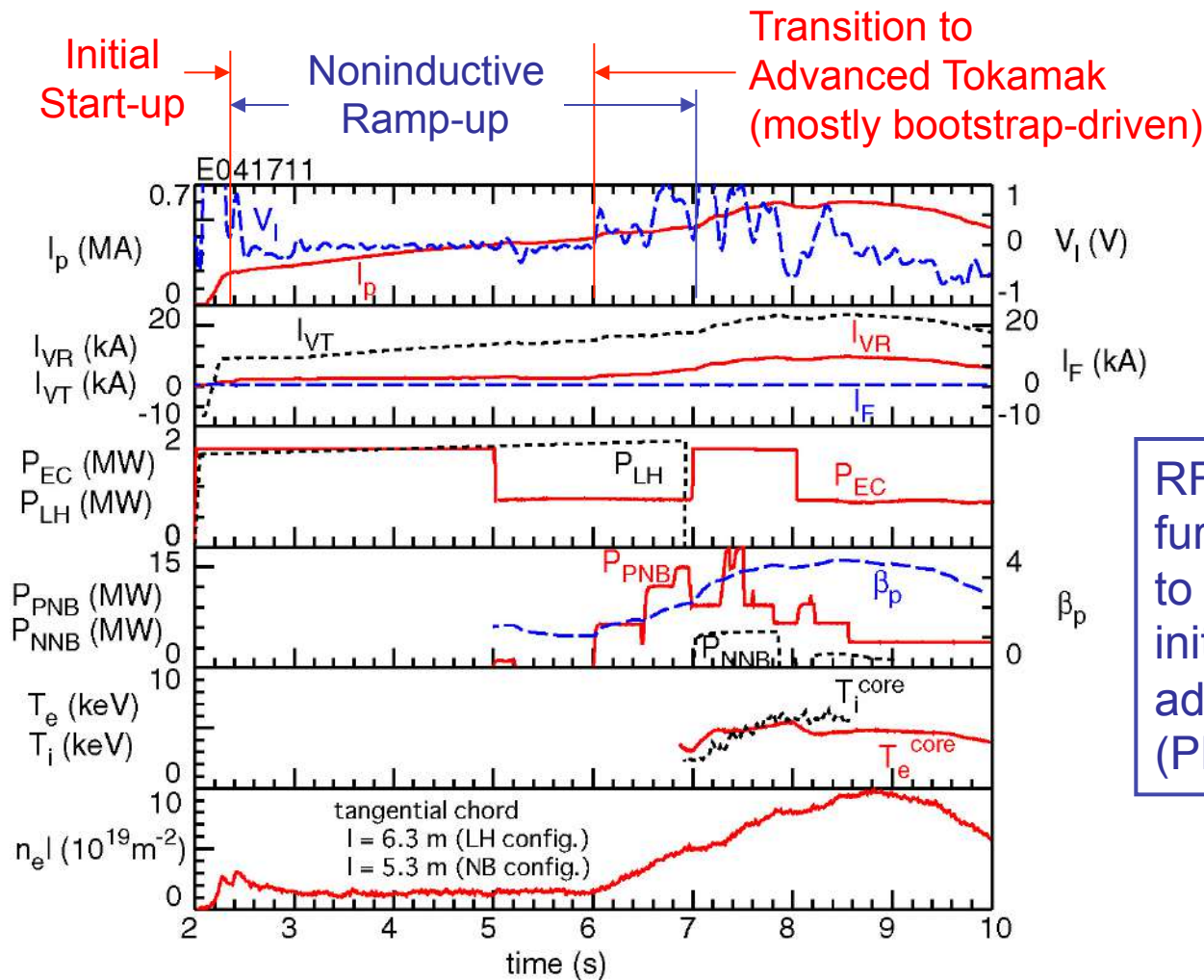
170 GHz 200 kW 5 sec

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

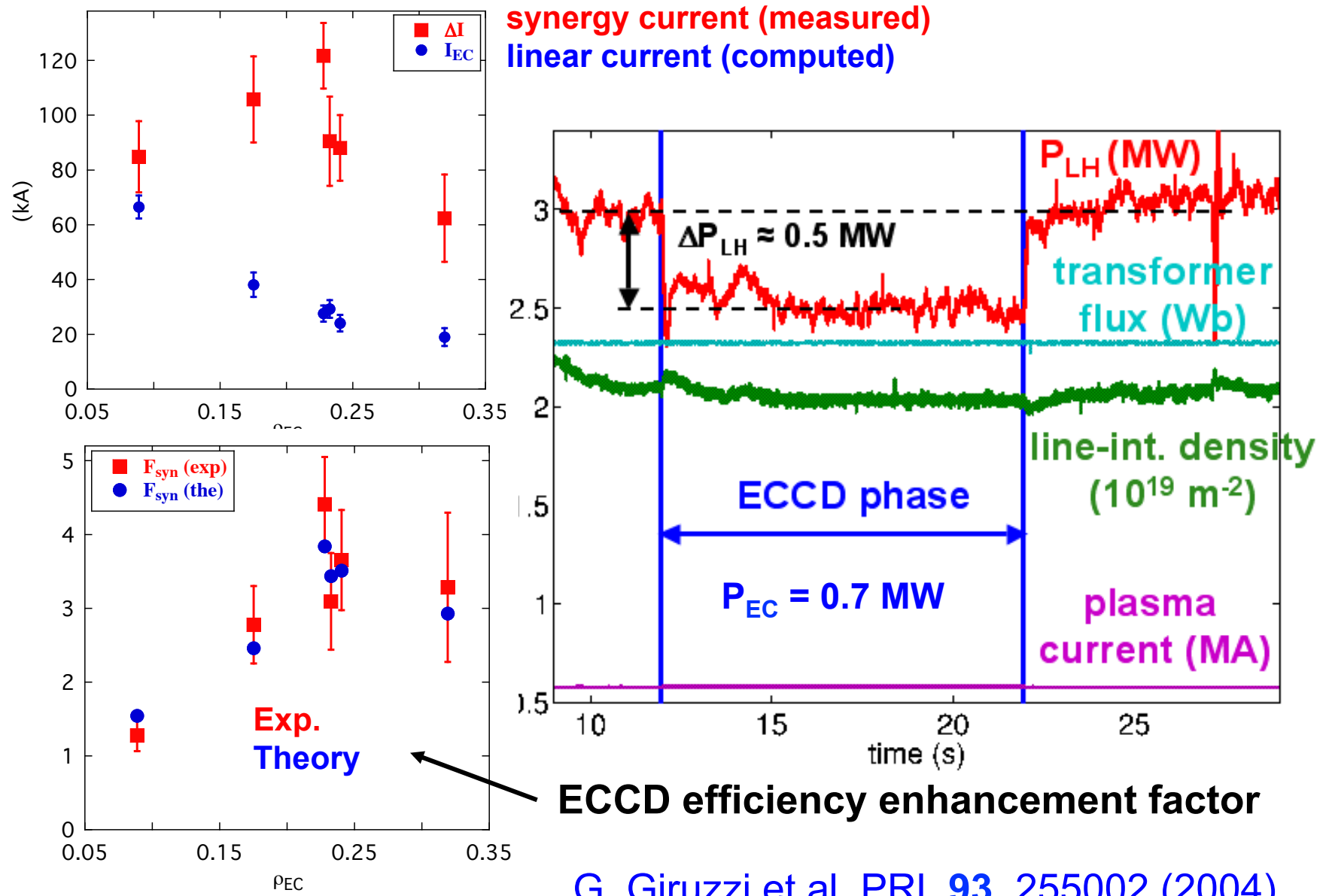
Y. Takase, et al.,
IAEA 2002

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 (PLH > 1MW for JT-60U)

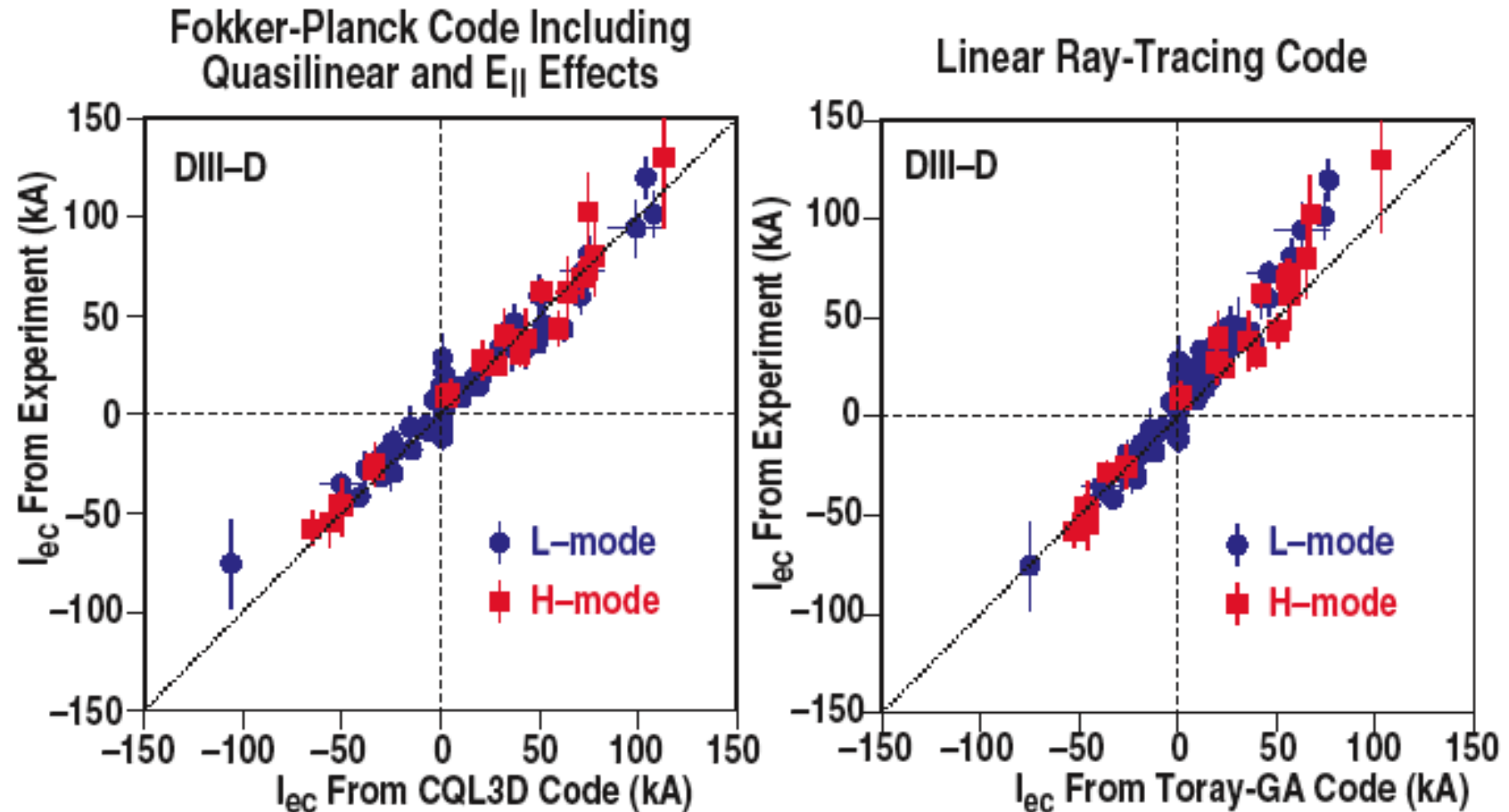


TORRE SUPRA: First demonstration of EC+LH synergy



Heating and Current Drive by Electron Cyclotron Waves
R. Prater, Review Talk DPP03

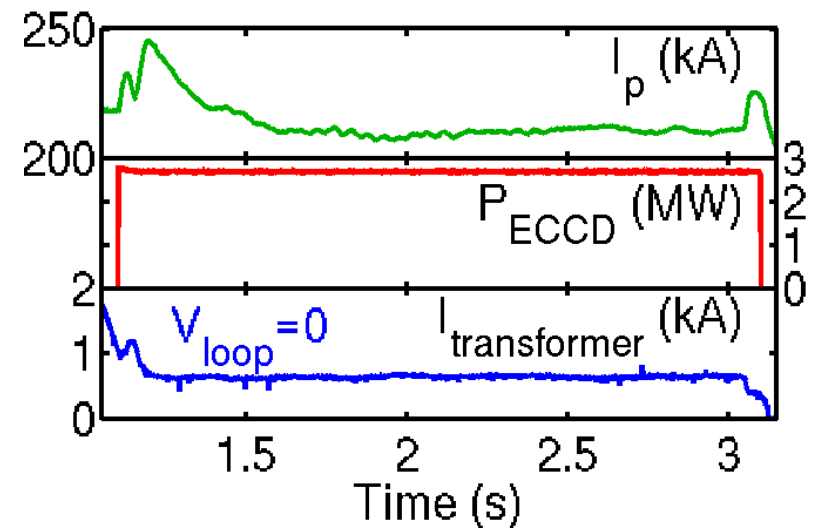
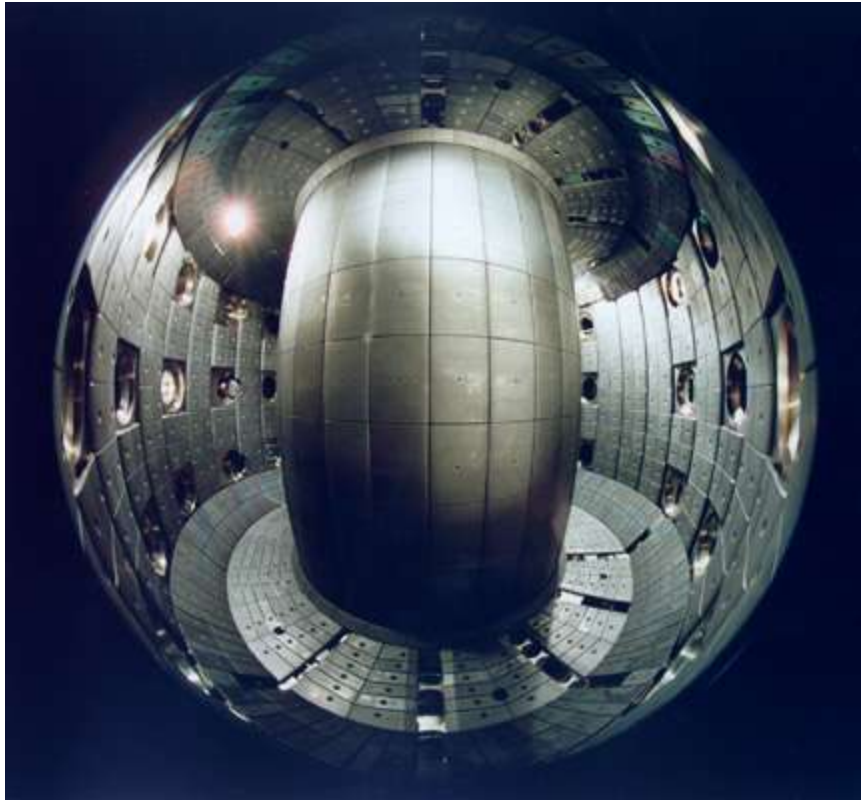
MEASURED ECCD AGREES WITH THEORY



Comparison: DIII-D 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)



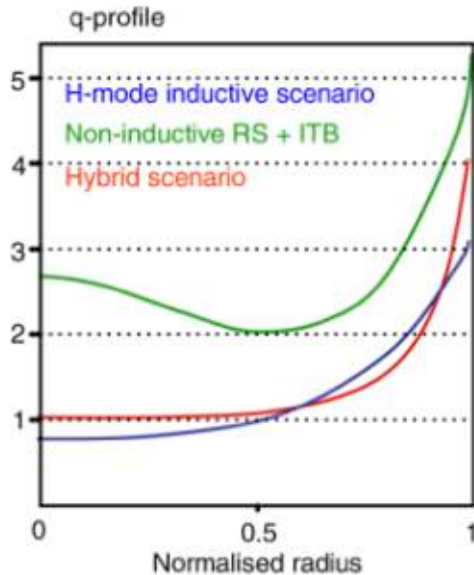
S. Coda et al. (2000)

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 $q_{95} \sim 3-4$,
with low positive or weak negative magnetic shear

ITER 'non-inductive' scenario:

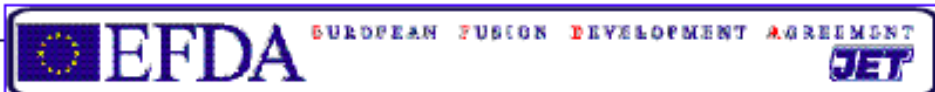
100% NI current, with $> 50\%$ BS current
candidates: plasmas with $q \gg 1$, $q_{95} \sim 5$, with negative magnetic shear

→ 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

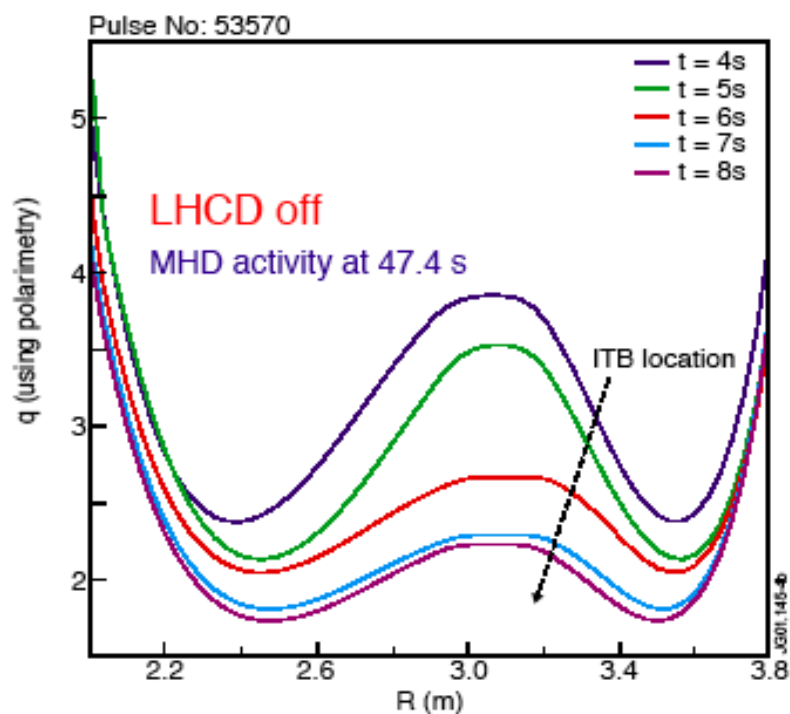
In JET, key tool for this application is LHCD

JET Control of ITB with LHCD

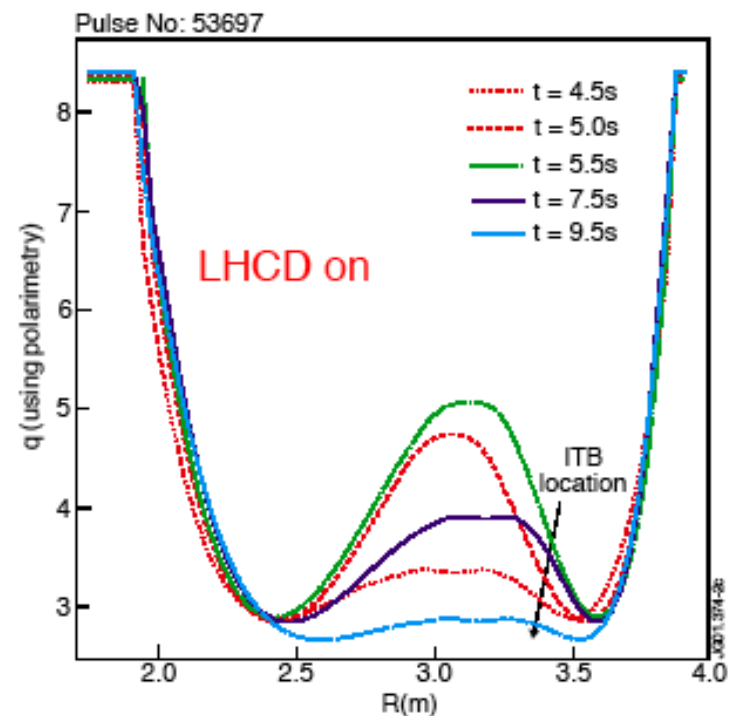


q-profile relaxation with/without LHCD

53570 $B_T=2.6T$ $I_p=2.2MA$



53697 $B_T=3.4T$ $I_p=1.8MA$



Inner ITB linked with negative shear region

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

Importance of Stabilizing Neoclassical Tearing Modes

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

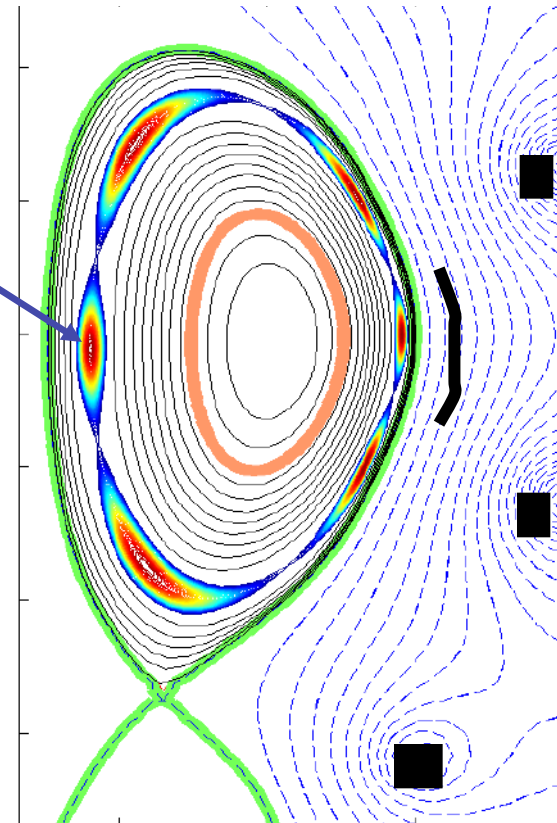
Islands permit heat to flow more easily.

Issues for ITER

Stabilizing the 2/1 island

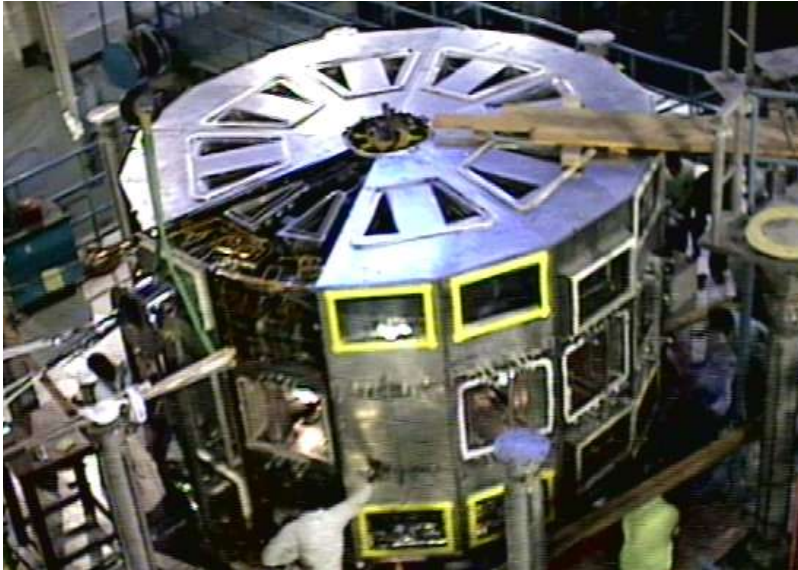
Stabilizing multiple islands of varying helicity

island



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



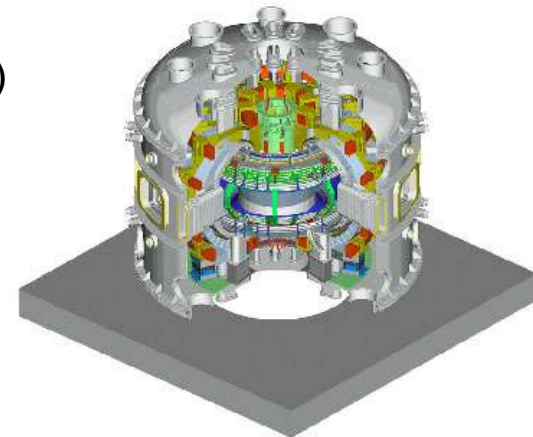
SST-1 India (1000 s)
($R=1.1$ m, 220 kA, 1 MW, 3.7 GHz LHCD)



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

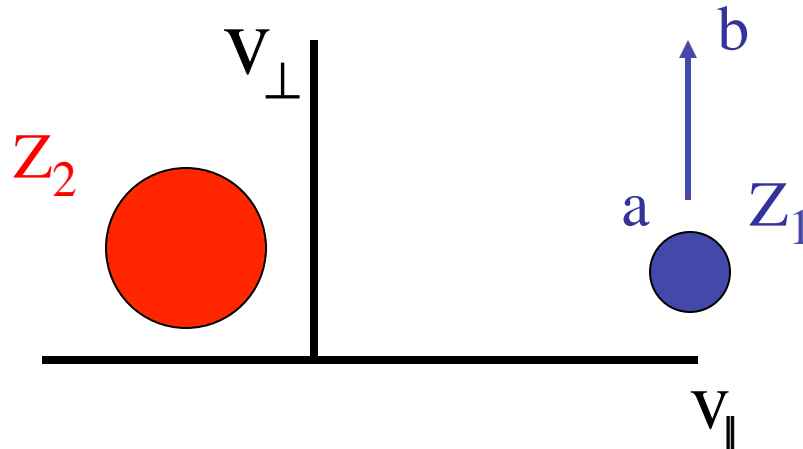


KSTAR Korea (20-300 s)
 $R=1.8$ m, 2 MA
1.5 MW LHCD (2014)
0.5 MW ECCD (2008)
3 MW ECCD (2014)



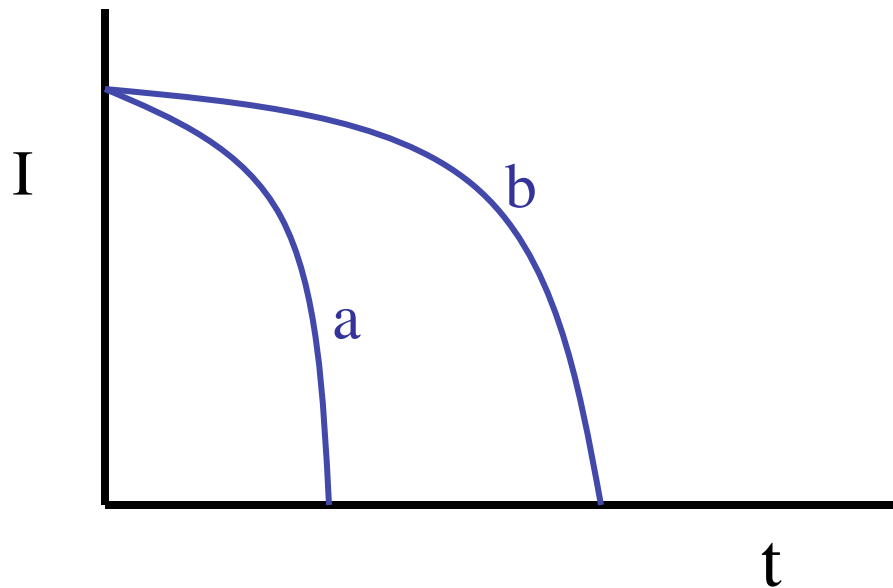
Minority ion Cyclotron Current Drive Effect (MiCCD)

Use waves to get counter-streaming ions



Zero ion current $\Rightarrow$

Non-Zero electron current
if $Z_2 \neq Z_1$



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

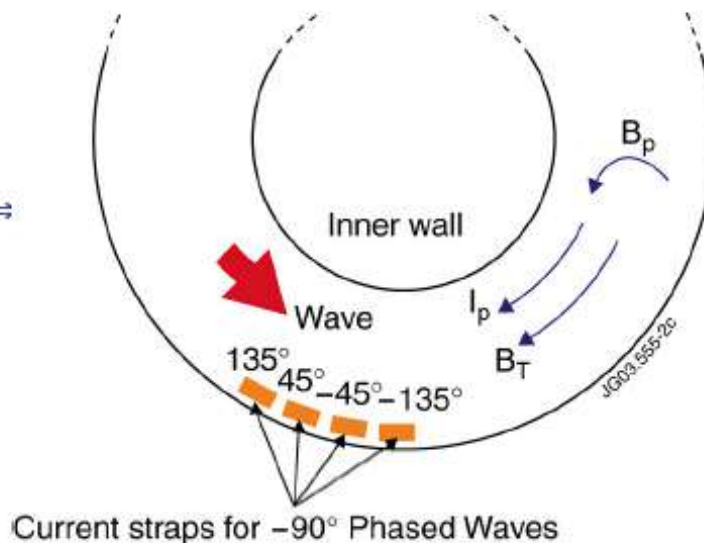
$$\Omega \equiv eB/m$$

Minority ion Cyclotron Current Drive



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 $k_{||} \Rightarrow$ asymmetric coupling to ions and electrons in $v_{||}$ -space $\Rightarrow$ dipolar ICCD (*Fish, Nucl. Fusion, 1981*)
- Effect will depends on:
 - ✓ Toroidal direction of the wave
 - ✓ Location of R_{res} versus R_{inv}



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



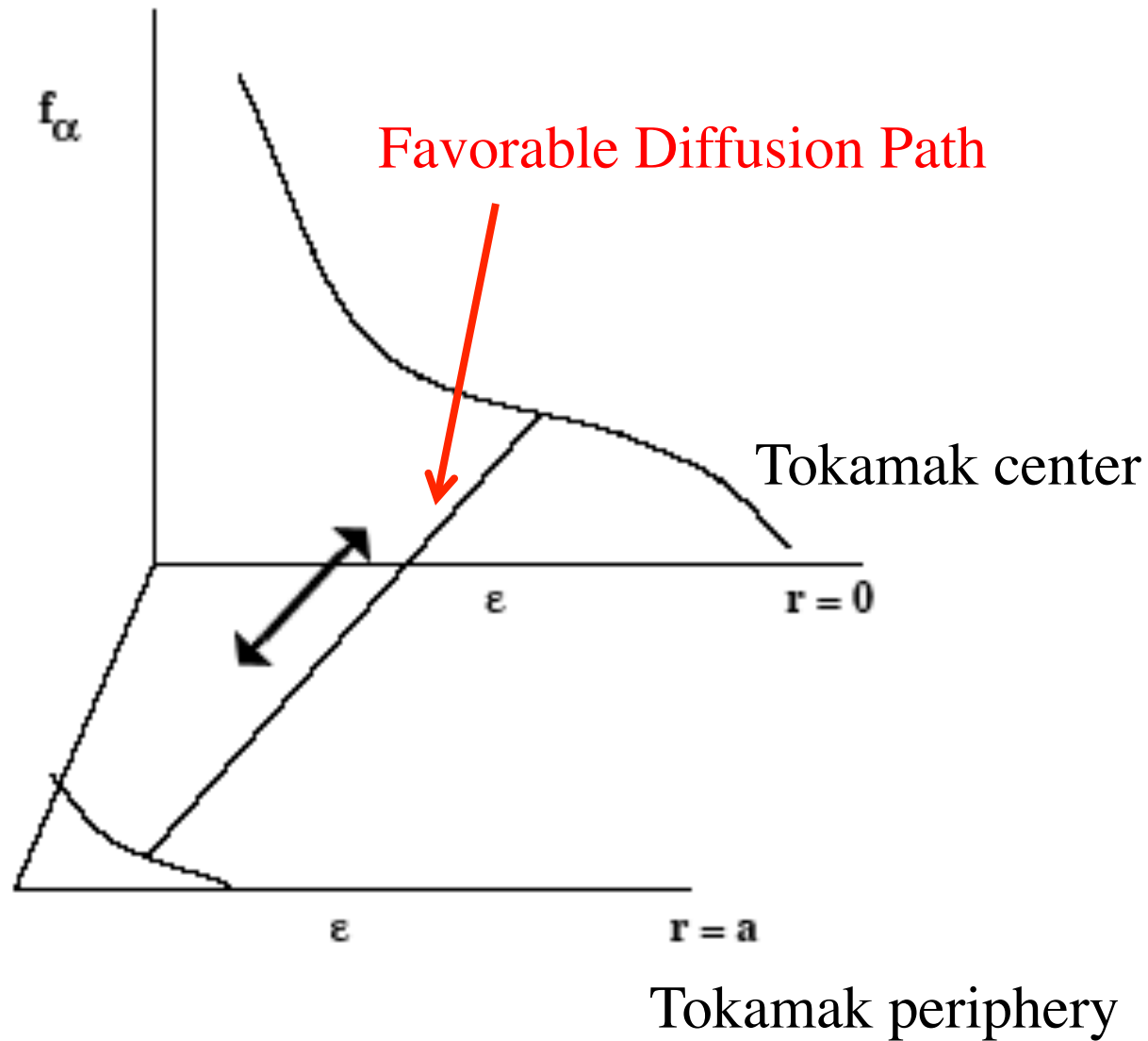
Note: MiCCD effect is complicated if

1. absorption straddles resonance
2. Ion trapping

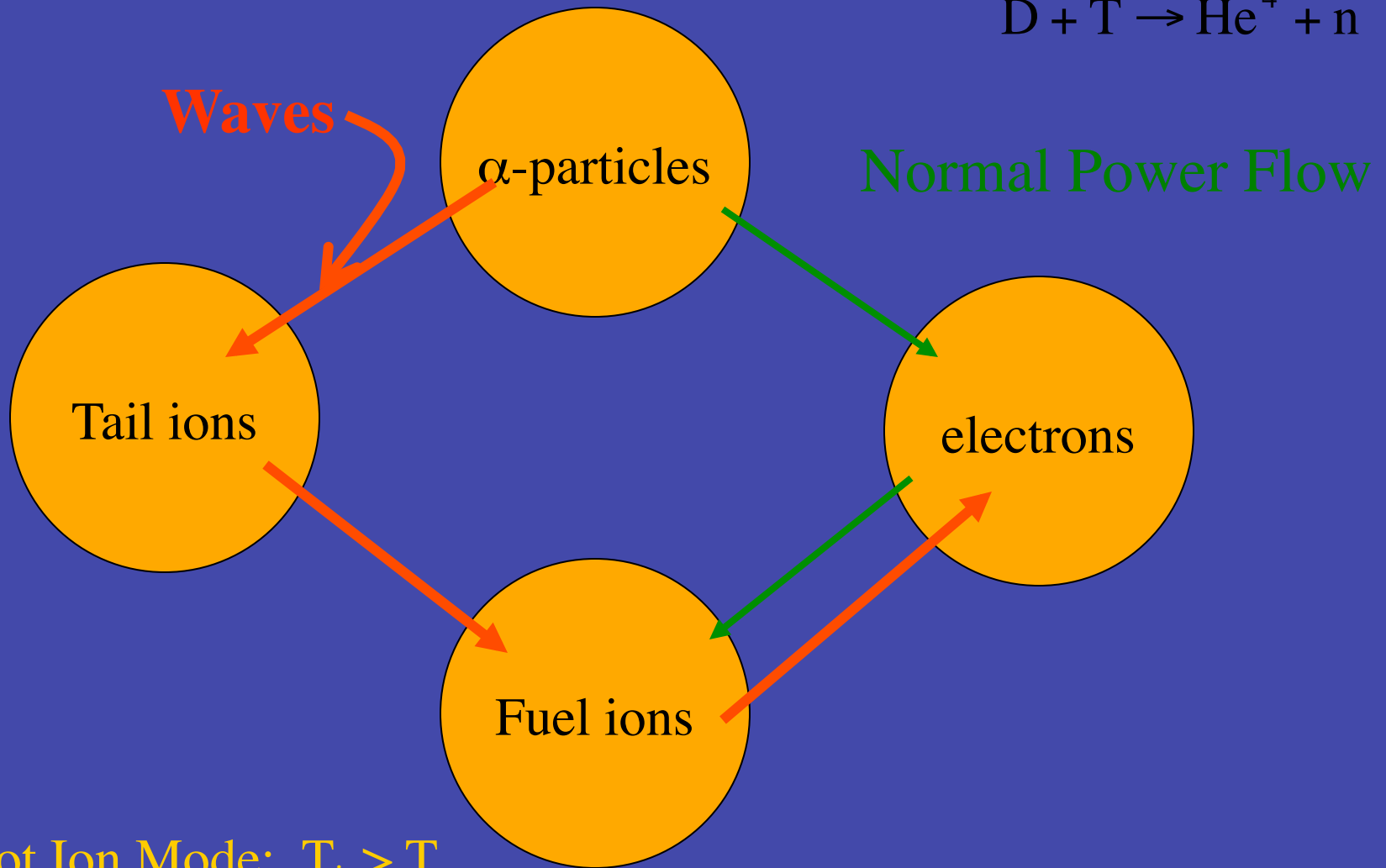
Thus, other current drive effects may dominate

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

Extracting Free Energy

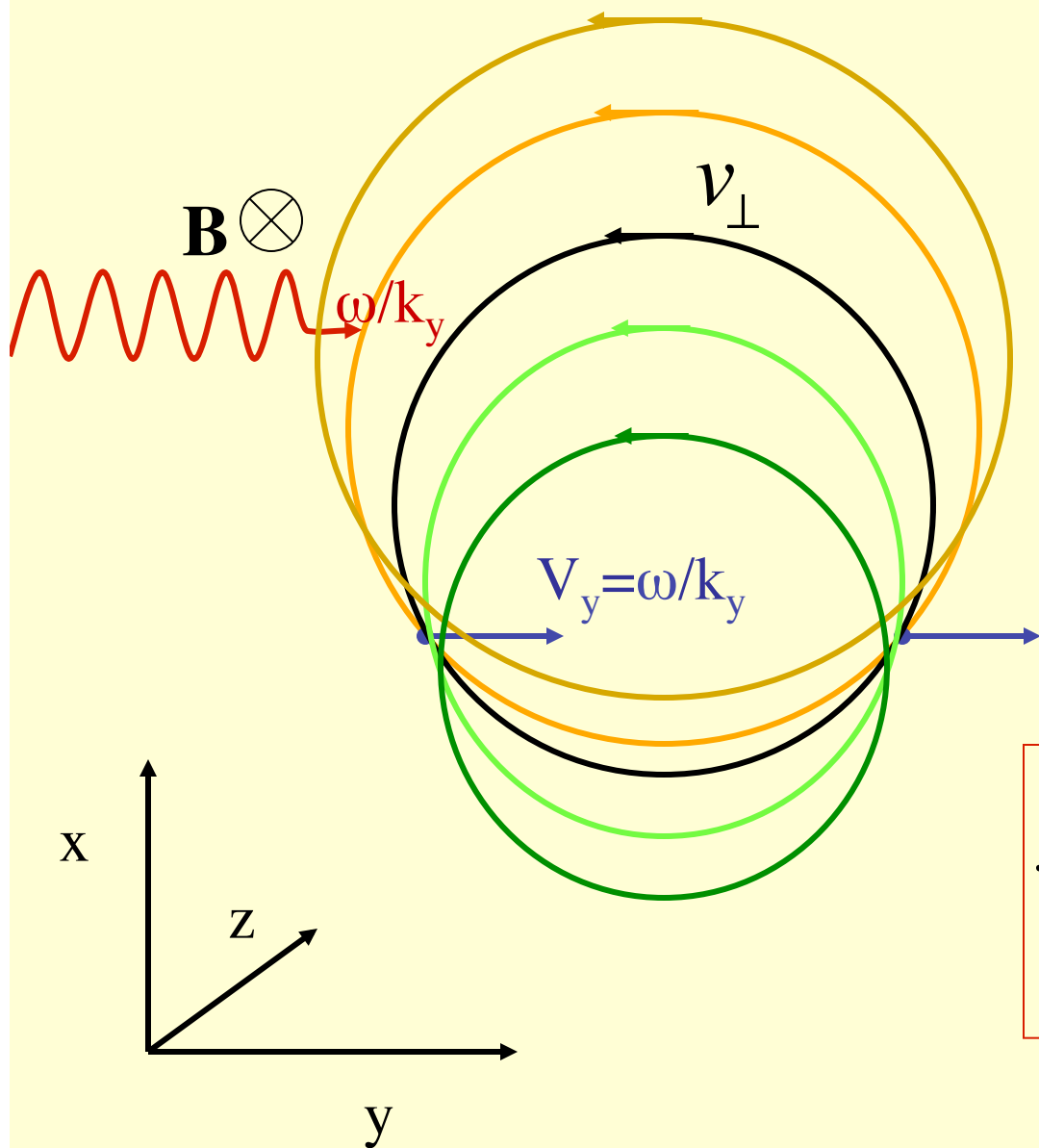


Advantages of “ α -Channeling”



Get Hot Ion Mode: $T_i > T_e$
75% of α power to ions $\Rightarrow P_f \rightarrow 2 P_f$

Diffusion Paths



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

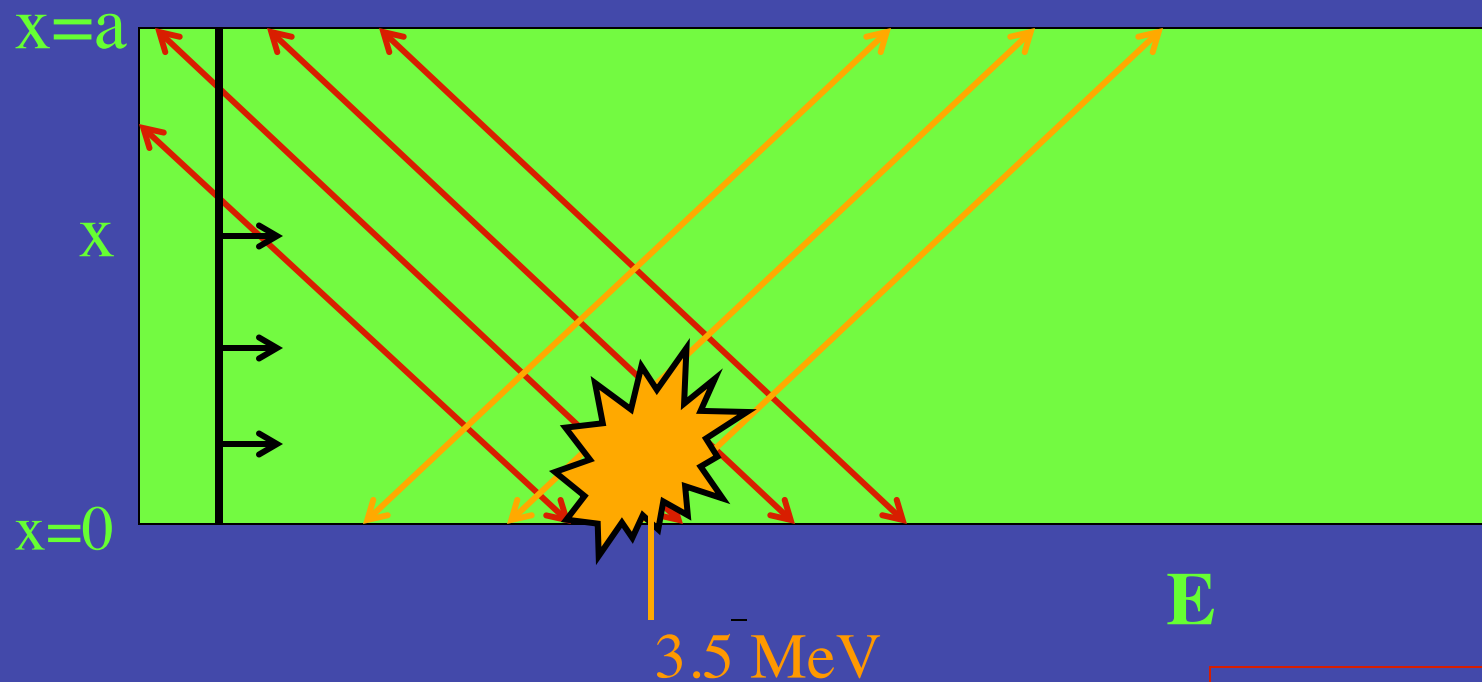
$$x_{gc} \rightarrow x_{gc} + \Delta v_y / \Omega$$

$$\Omega \equiv eB/m$$

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

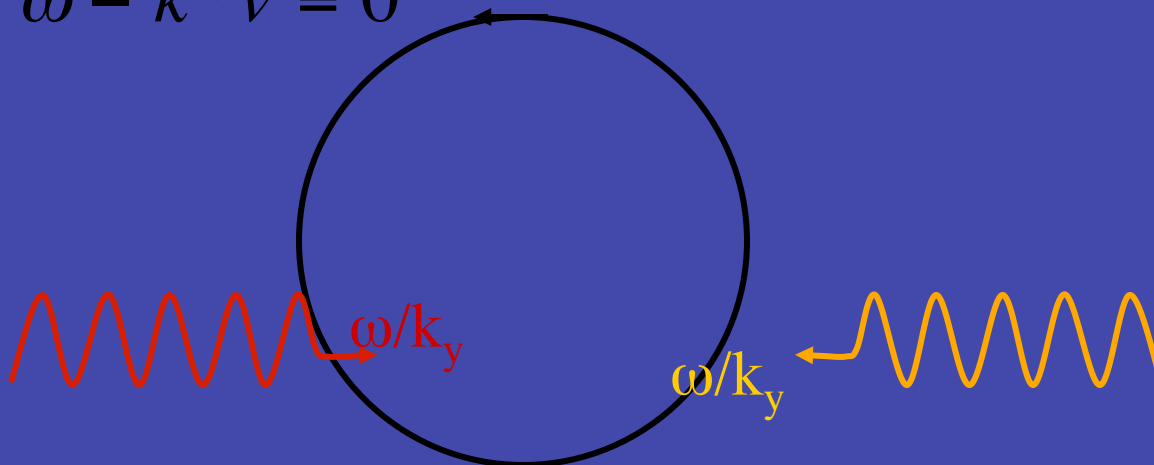
$$x_{gc} \rightarrow x_{gc} + \frac{\Delta E}{m \Omega \omega / k_y}$$

Diffusion Paths



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

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



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