A Hot-ion-mode rf-driven Tokamak via Alpha Channeling

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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. An important role for rf physics, technology, and modeling

Outline

1. Utility of Alpha Channeling -- ARIES operating point
2. Physics of Alpha Channeling
3. Summary of Experimental Progress -- TFTR campaign
4. Indicated directions

Reactor designs around Aries I operating point

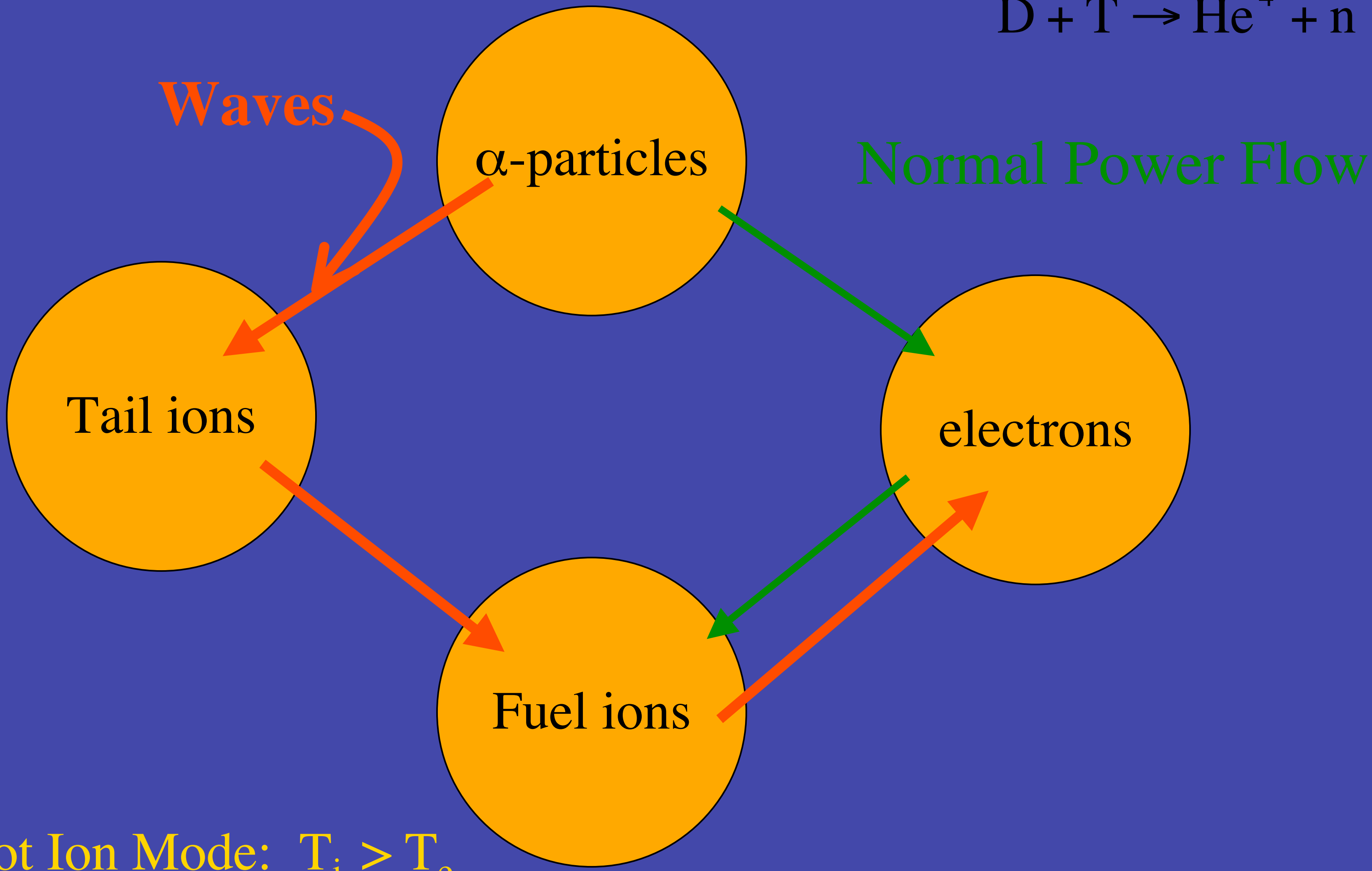
	no channeling		channeling	
	cd	P	75%	75%
T_i(keV)	20	15	20	15
T_e(keV)	20	15	12	12
n(10^{14} cm^{-3})	1.2	1.8	1.8	2.1
τ_i(s)	2	2	2	1
τ_e(s)	1	0.7	0.3	0.5
P_f (W cm^{-3})	4.7	6.1	10.9	9.7

Fisch and Herrmann, 1994

Power Flow in a Fusion Reactor

Advantages of "α-Channeling"

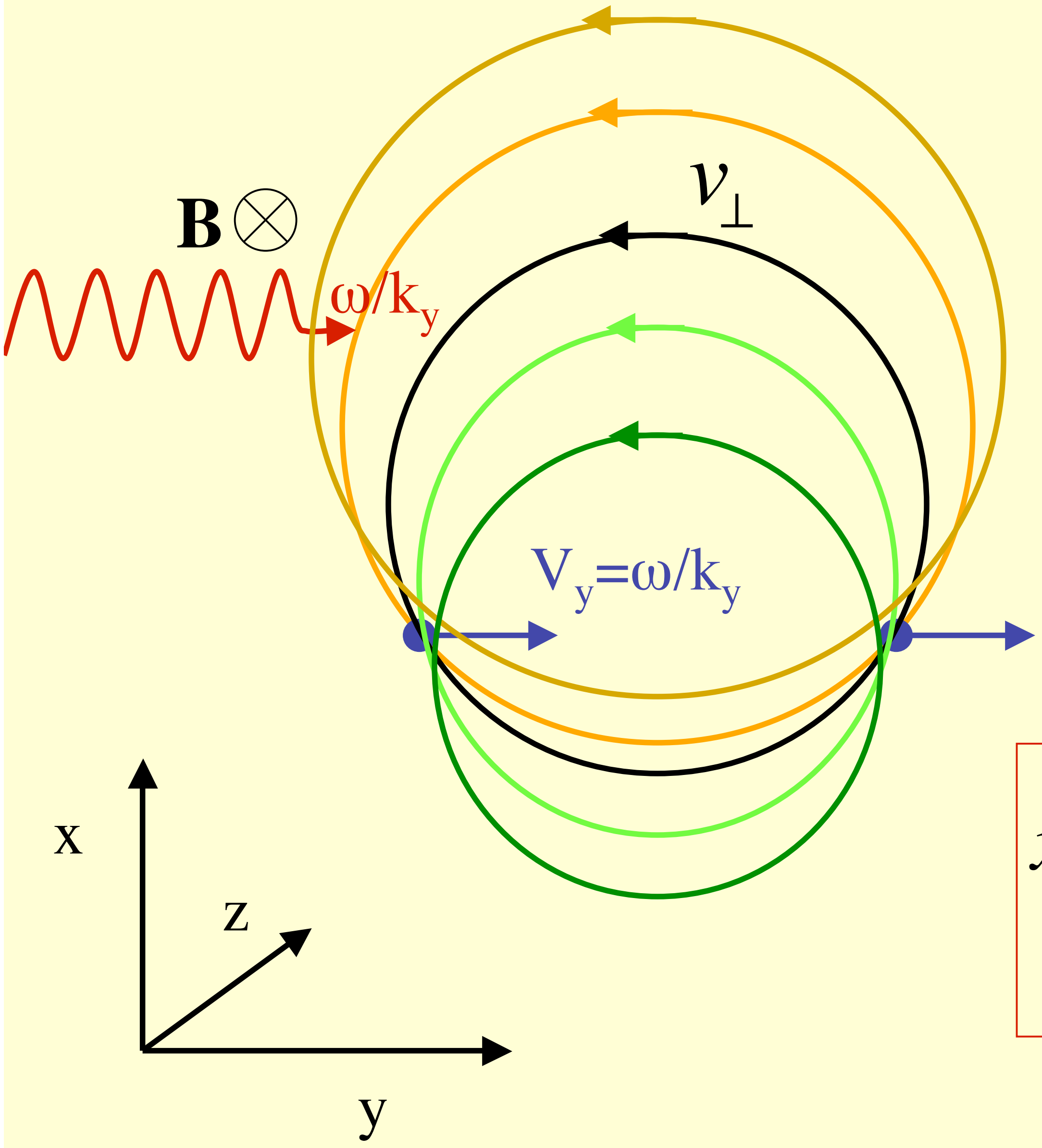
$D + T \rightarrow He^4 + n$



Get Hot Ion Mode: $T_i > T_e$

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

Diffusion Paths



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

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

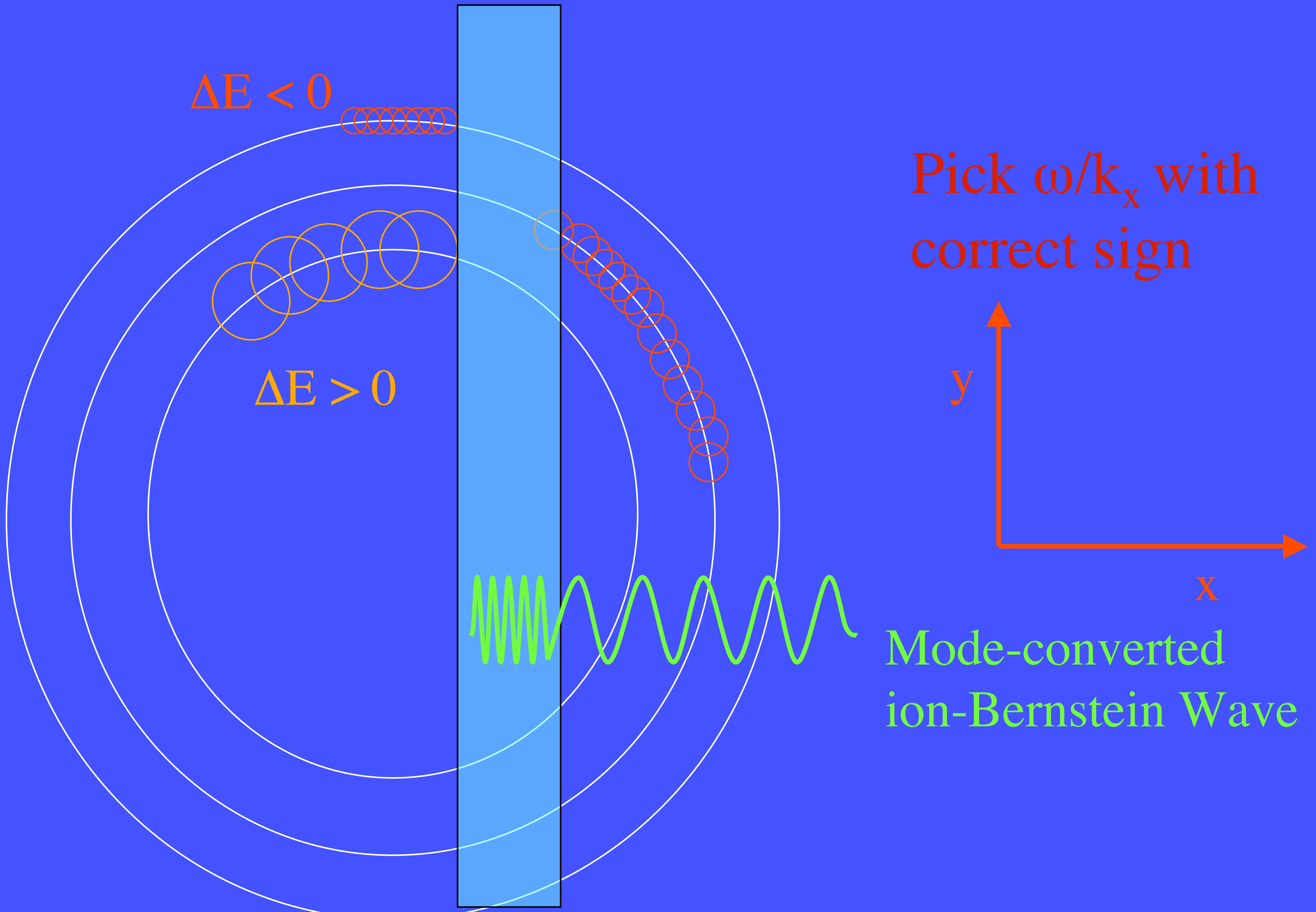
$$\Omega \equiv eB/m$$

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

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

Fisch and Rax, 1992

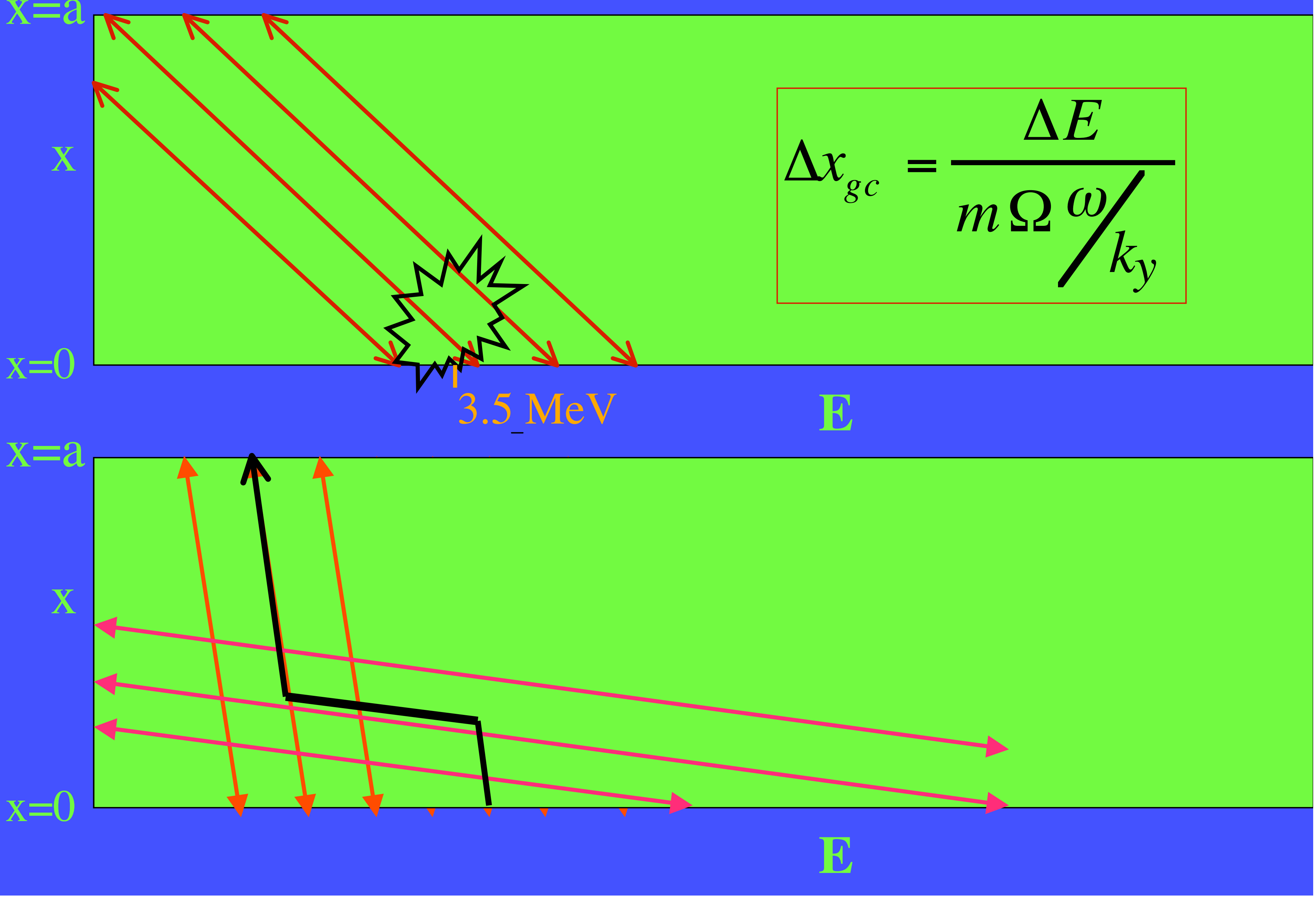
Tapping Free Energy in α-Particles



Pick ω/k_x with correct sign

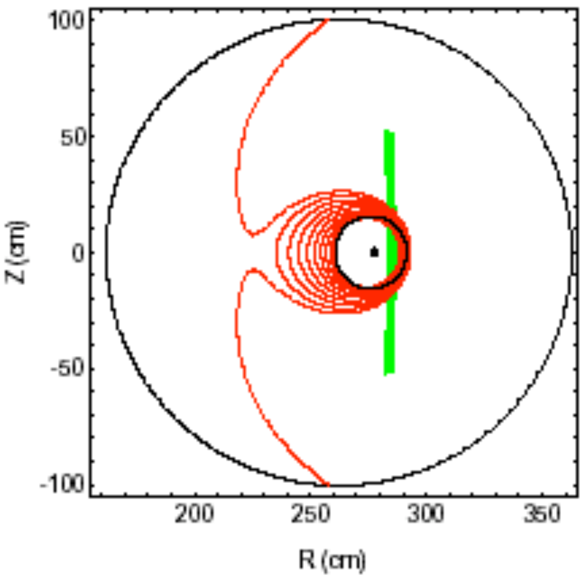
Mode-converted ion-Bernstein Wave

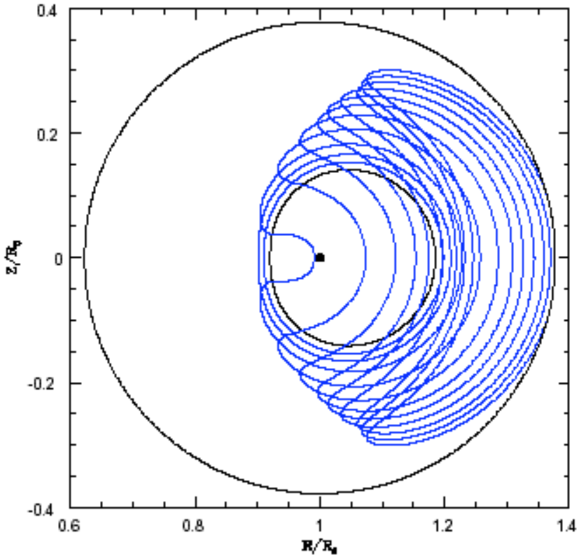
Diffusion Paths with 2 Waves: Highly Constrained Stochastic Motion



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

Wave-Particle Interaction Physics





$$\omega - k_{\parallel} v_{\parallel} = \Omega_{\alpha}$$

$$\frac{dP_{\varphi}}{dE} = \frac{n_{\varphi}}{\omega}$$

$$\frac{d\mu}{dE} = \frac{e}{m\omega}$$

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

$$\frac{dP_{\varphi}}{dE} = \frac{n_{\varphi}}{\omega}$$

$$\frac{d\mu}{dE} = 0$$

Experimental evidence

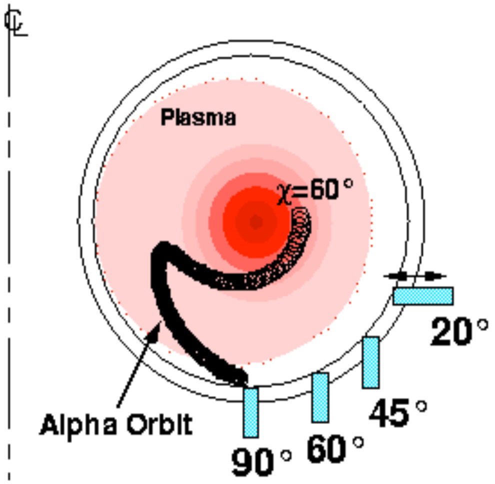
1. k-parallel flip of MCIW on TFTR
   (Valeo and Fisch, 1994; Fisch et al., 1996)

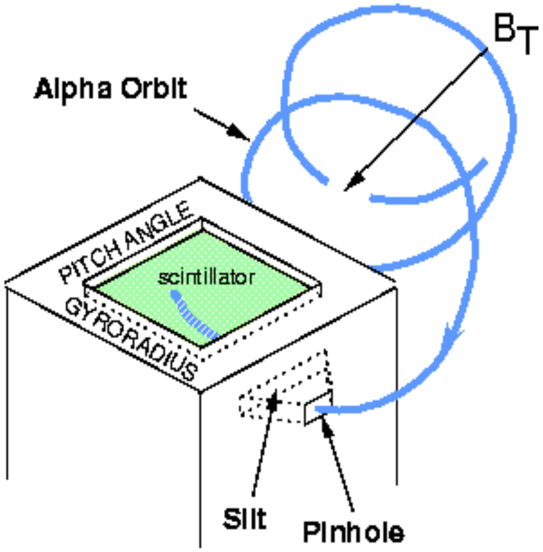
2. Wave-induced pinch effect on JET
   (Eriksson et al, 1998)

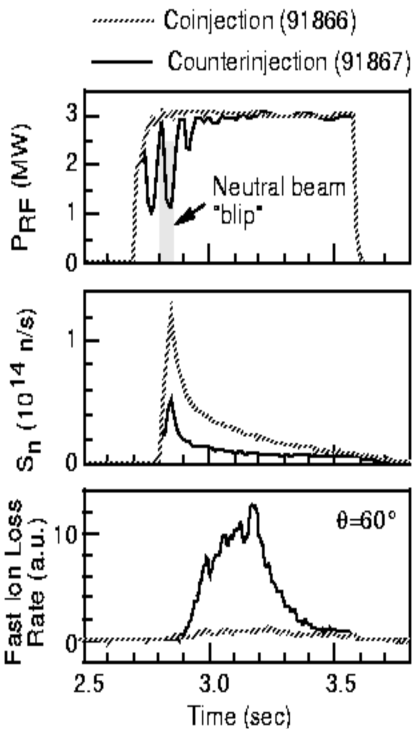
3. Alpha-channeling Experiments on TFTR

TFTR D-Beam Experiments

Strong loss signals of energetic ions were detected by TFTR lost alpha scintillation detectors during MCIBW experiments [Figures from Darrow (1996)].







Substantial losses seen only with counter-going D injection and uncorrelated with neutron rate implies accelerated D-beam ions and not charged fusion products being lost.

Conundrum

1. The Alpha Channeling Effect on TFTR is highly constrained.
2. 80 K deuterium Beams arrive at the detectors with the proper energy (2.2 MeV), the proper poloidal angle (60^0), the proper pitch angle (co-streaming with mostly perpendicular energy), but by a factor of 50 not the right diffusion coefficient for MCIBW.

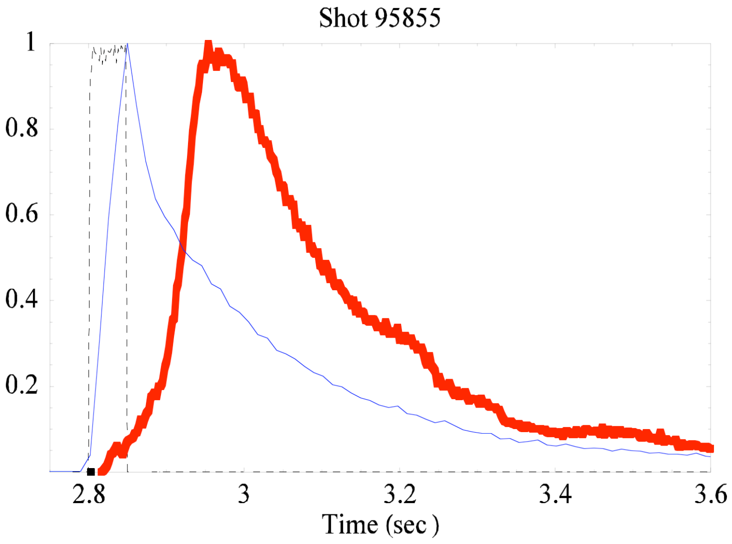
resolution

1. The only explanation appears to be an internal mode with the same toroidal mode number.
2. Recent work by Gorelenkov suggests that internal modes on NSTX are of same branch as required modes on TFTR.

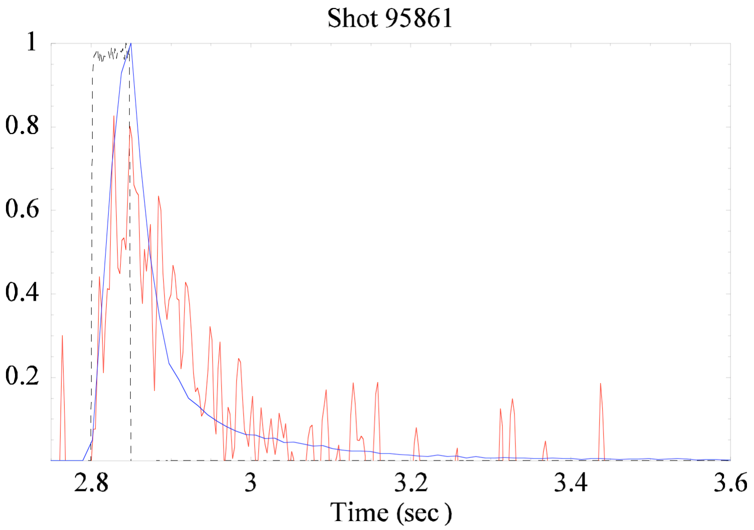
Loss Rate Dependence on P_{rf}

Beam (black), neutrons (blue), & losses (red) [Figures from Herrmann (1998)]

With P_{rf} = 3.2 MW

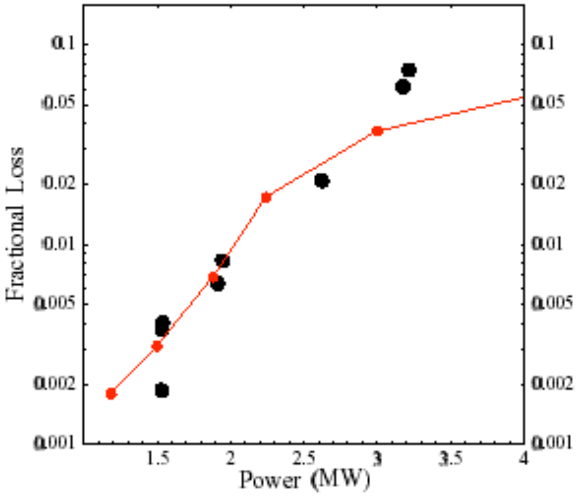


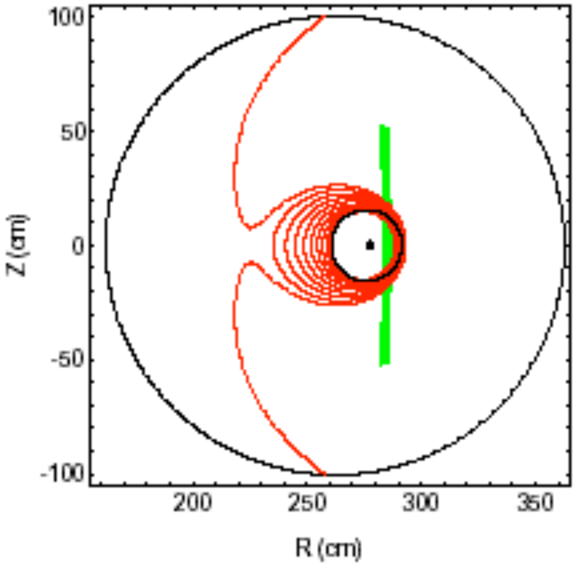
With P_{rf} = 1.0 MW



Energy diffusion coefficient of lost particles estimated to be $D_\varepsilon \sim 25\ \mathrm{MeV}^2/\mathrm{sec}$.

Anomalously Large Diffusion





Explanations

1. Superadiabaticity

   Helander and Lisak, 1992

   but unlikely for mcibw

2. Contained Mode

Experimental Results

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

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

2. Detailed verification of diffusion (phased for heating) in E-μ-P_ϕ space (4-D in pitch angle, poloidal angle, energy and time)

Quizzical Observation:

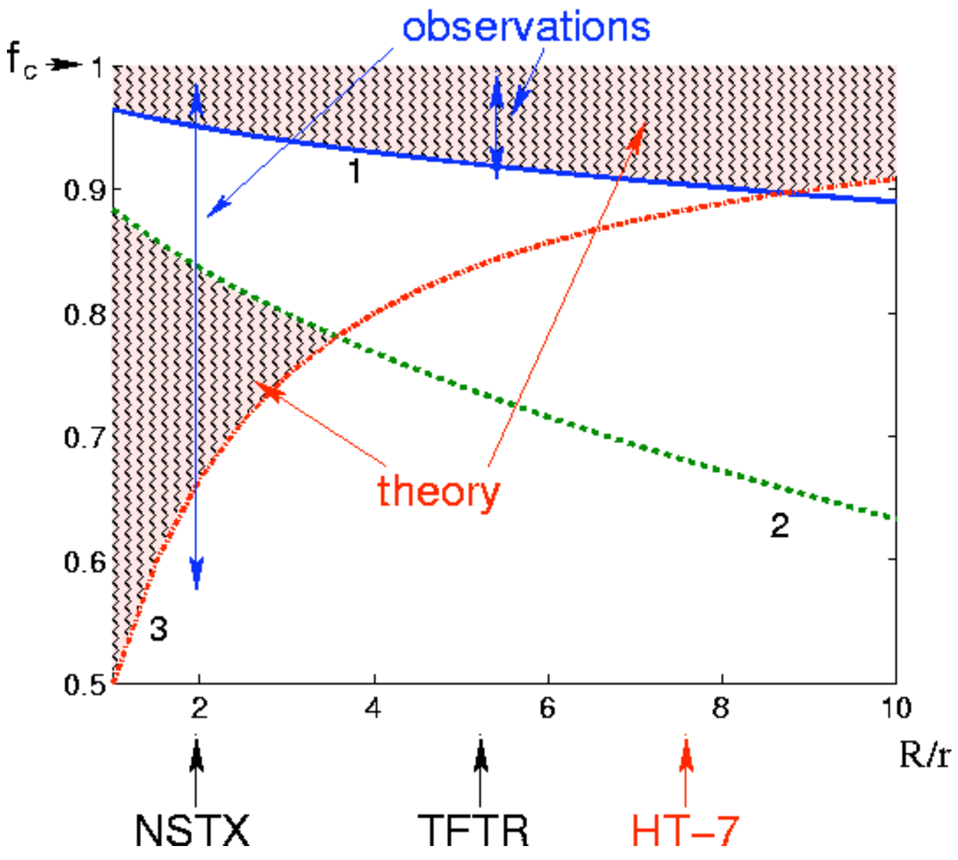
Absolute value of diffusion coefficient appears to be factor of 50 higher than simple ray-tracing theory implies!

Possibility of Exciting Internal Mode

Clark and Fisch, 2000

Perhaps α-channeling effect can be achieved even at low power

Further Supporting Evidence for the TFTR High-Q Contained Mode



Regions of allowed CAE frequencies

The CAE modes observed in NSTX belong to the same branch responsible for the ICE instabilities in tokamaks with high aspect ratio, which may however exist at a fraction of the fundamental ion cyclotron frequency in STs. The polarization unambiguously identifies these modes as the compressional Alfven branch.

Gorelenkov et al, 2004

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 (Catto, 1988).
7. Indicated directions:
    1. 1-D radial modeling
    2. rf-coupling to internal mode
    3. Identification of ITER experiments

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Simulation of alpha channeling in a reactor

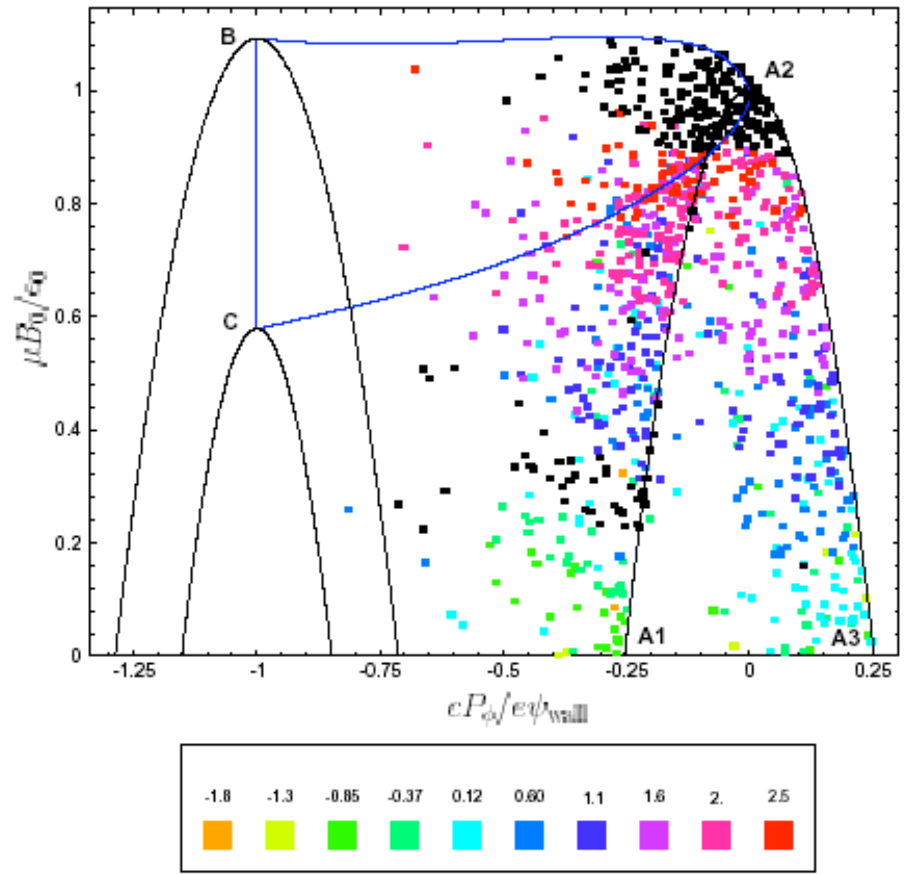

FIG. 1. (color) Energy extracted (MeV) by the IBW vs. initial location of particle in constants-of-motion space.

Herrmann and Fisch, 1997