Presentation to Committee on a Strategic Plan for U.S. Burning Plasma Research

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Director, Program in Plasma Physics, Princeton University
Associate Director for Academic Affairs, PPPL

April 11, 2018

# Trying for Upside Potential in Controlling Fusion

My Background:
25+ years of recruiting graduate students
40+ years as nuclear fusion researcher -- trying to reach the upside

## Preliminaries -- an educational perspective: Program the non-programmatic

1. A healthy field needs to attract top, creative students.
2. Any strategic plan, particularly at this juncture in the field, must insist on this.
3. Programmatic tasks recruit students who want well-defined career paths.
4. Holding out the upside, uncharted potential of fusion is often needed to recruit top students.
5. What does this mean? While pursuing mainstream ideas, strategically plan for balance.

# Upside potential for Magnetic Confinement Fusion

1. Hot ion mode: $T_i > T_e$
2. Steady state
3. Natural ejection of high-Z impurities (differential confinement)
4. Natural ejection of slow $\alpha$-particles (differential confinement)
5. Disruptions not destructive
6. Direct energy conversion
7. Advanced fuels
8. Engineering compatibility

Double analogy: In MFE, mirror is to tokamak; as in ICF, Z is to NIF.
Toroidal MFE and laser-driven ICF are winning, elegant, scientific solutions.
Open-B systems and capacitor-driven ICF are more engineering compatible.
The further advanced, the more apparent is the importance of engineering compatibility.

One more thing: The reactor development path, if it is to span many decades, ought optimally to have *intermediate applications*.

H. P. Furth, Sci. Am. (1995)

Examples:

1. Steam engines: Hauling coal from coal mines (replacing reluctant horses).
2. ICF: Stockpile stewardship, and discovery science in extreme regimes of density-temperature.
3. MFE -- Open-B and other rotating devices: Legacy nuclear waste and other separations.

# Fusion

*Energy derived from fused nuclei may become widely used by the middle of the next century*

by Harold P. Furth

During the 1930s, when scientists began to realize that the sun and other stars are powered by nuclear fusion, their thoughts turned toward re-creating the process, at first in the laboratory and ultimately on an industrial scale. Because fusion can use atoms present in ordinary water as a fuel, harnessing the process could assure future generations of adequate electric power. By the middle of the next century, our grandchildren may be enjoying the fruits of that vision.

The sun uses its strong gravity to compress nuclei to high densities. In addition, temperatures in the sun are extremely high, so that the positively charged nuclei have enough energy to overcome their mutual electrical repulsion and draw near enough to fuse. Such resources are not readily available on the earth. The particles that fuse most easily are the nuclei of deuterium (D, a hydrogen isotope carrying an extra neutron) and tritium (T, an isotope with two extra neutrons). Yet to fuse even D and T, scientists have to heat the hydrogen gases intensely and also confine them long enough that the particle density multiplied by the confinement time exceeds $10^{14}$ seconds per cubic centimeter. Fusion research since the 1950s has focused on two ways of achieving this number: inertial confinement and magnetic confinement.

The first strategy, inertial confinement, is to shine a symmetrical array of powerful laser beams onto a spherical capsule containing a D-T mixture. The radiation vaporizes the surface coating of the pellet, which explodes outward. To conserve momentum, the inner sphere of fuel simultaneously shoots inward. Although the fuel is compressed for only a brief moment—less than $10^{-10}$ second—extremely high densities of al-

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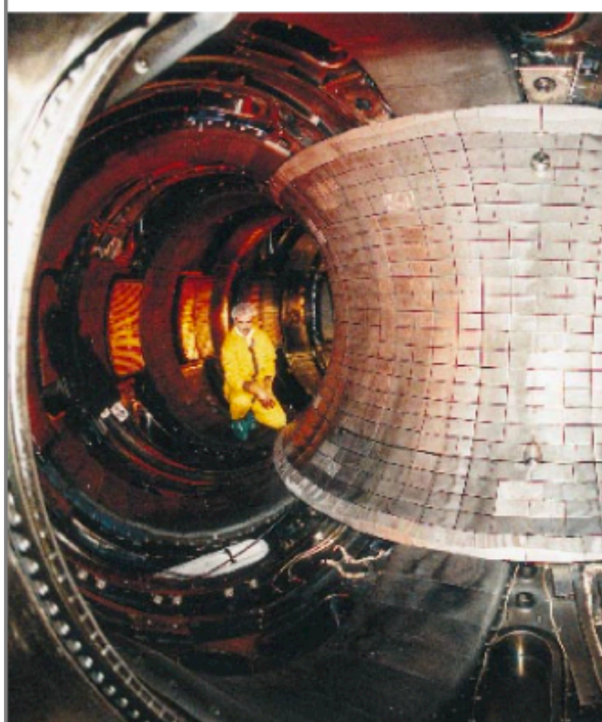






The particles produced as by-products of fusion may be put to another, quite different, use. In this respect, taking a hint from history might be beneficial for fusion's short-term future. Two centuries ago in England, the industrial revolution came about because horses refused to enter coal mines: the first engines were put together to haul out coal, not to power cars or airplanes. John M. Dawson of the University of California at Los Angeles has proposed that during the next 20 to 30 years, while fusion programs are developing a technology for large-scale energy production, they could provide other benefits. For example, the protons formed as by-products of some fusion reactions may be converted to positrons, particles that can be used in medically valuable positron emission tomography scans.

During this phase of special applications, an abundance of new ideas in plasma physics would be explored, ultimately yielding a clear vision about future reactor design. Fifty years from now engineers should be able to construct the first industrial plants for fusion energy. Although far removed from immediate political realities, this schedule matches the critical timescale of 50 to 100 years in which fossil-energy resources will need to be replaced.

**Princeton University**
**Plasma Physics Laboratory - TFTR Physics Program Division**

To: K. M. McGuire    Date: January 24, 1996

From: H. P. Furth    Subject: "TFTR-U"

===================================================================

Your new and very sober vision of "TFTR-U", to be built in the course of four years, at an incremental capital cost of order ~ 100M, is constrained, by its nature, to point along the most direct path towards our ultimate goal of economically profitable fusion power: We seek a practical Tokamak-DEMO -- not some fanciful Tokamak-COUNTER-DEMO, whose main virtue would likely be its slowness to materialize.

**A Tokamak DEMO:**

1. Will have to be cheap and simple, or else the servicing of the interest and the compound interest on the borrowed capital will wipe out any hope of economic gain. (Probable upper limit: $3 Billion.)

2. Will have to benefit from smart-but-simple innovative ideas -- or else the capital cost and interest charges would "run away".

3. Will have to have non-equilibrated fuel-ion and electron populations, with the fuel-ions not necessarily non-Maxwellian in their own velocity-space distribution, but necessarily heated directly by the alphas, e.g., via plasma waves, with the electrons smoothing the temperature gradient from hot fuel-ions to cold walls.

**A TFTR-U:**

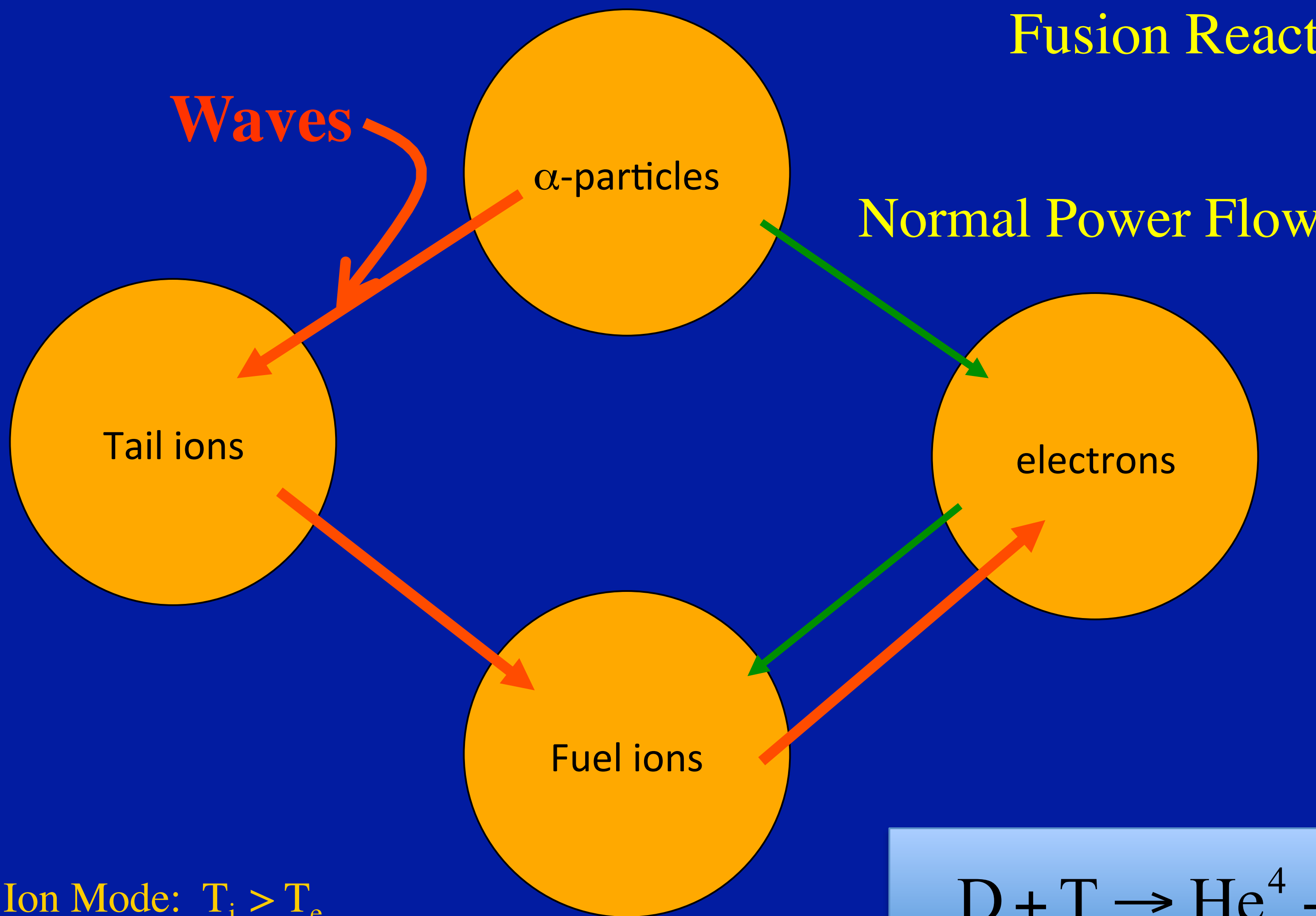
1. Is likely to be cheap and simple, because we don't have spare money for frills or risky engineering ventures -- nor for a pattern of safety-via-bureaucratic committee-work. (Probable upper limit: $150 Million.)

2. Has to try out ideas that are innovative (or else it will have no vital role), and has to focus on ideas that are practical -- because there is no money for stunts and frills.

3. Has to be able to try out simple versions (or explicit-physics-based analogues for direct alpha-particle heating of the fuel ions. The latter requirement will, incidentally, drive the development of our capability for computer-modeling in terms of "first-principles" physics understanding.

# One Upside: "α-Channeling"

## Power Flow in a Fusion Reactor




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

Get Hot Ion Mode: $T_i > T_e$

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

# Outline of the Argument

1. Rotating magnetized plasma confinement may enable upside potential to fusion.

2. Central to rotation is creating radial potential, by moving charge across field lines.

3. This might be accomplished by alpha channeling, which has other desirable features.

4. There are many unanswered basic scientific questions regarding cross-field charging.

5. Many of these questions can be posed and answered most easily in linear devices.

6. Linear, rotating plasma devices can be used for separations.

7. This suggests a fundamental physics program with high upside potential for magnetic fusion, with intermediate applications in other areas, both curiosity and applications driven, and, at least in the linear limit, relying upon relatively easy to build devices.

# 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 |
| $\tau_i$(s) | 2.0 | 2.0 | 2.0 | 1.0 |
| $\tau_e$(s) | 1.0 | 0.7 | 0.3 | 0.5 |
| $P_f$ (W $cm^{-3}$) | 4.7 | 6.1 | 10.9 | 9.7 |

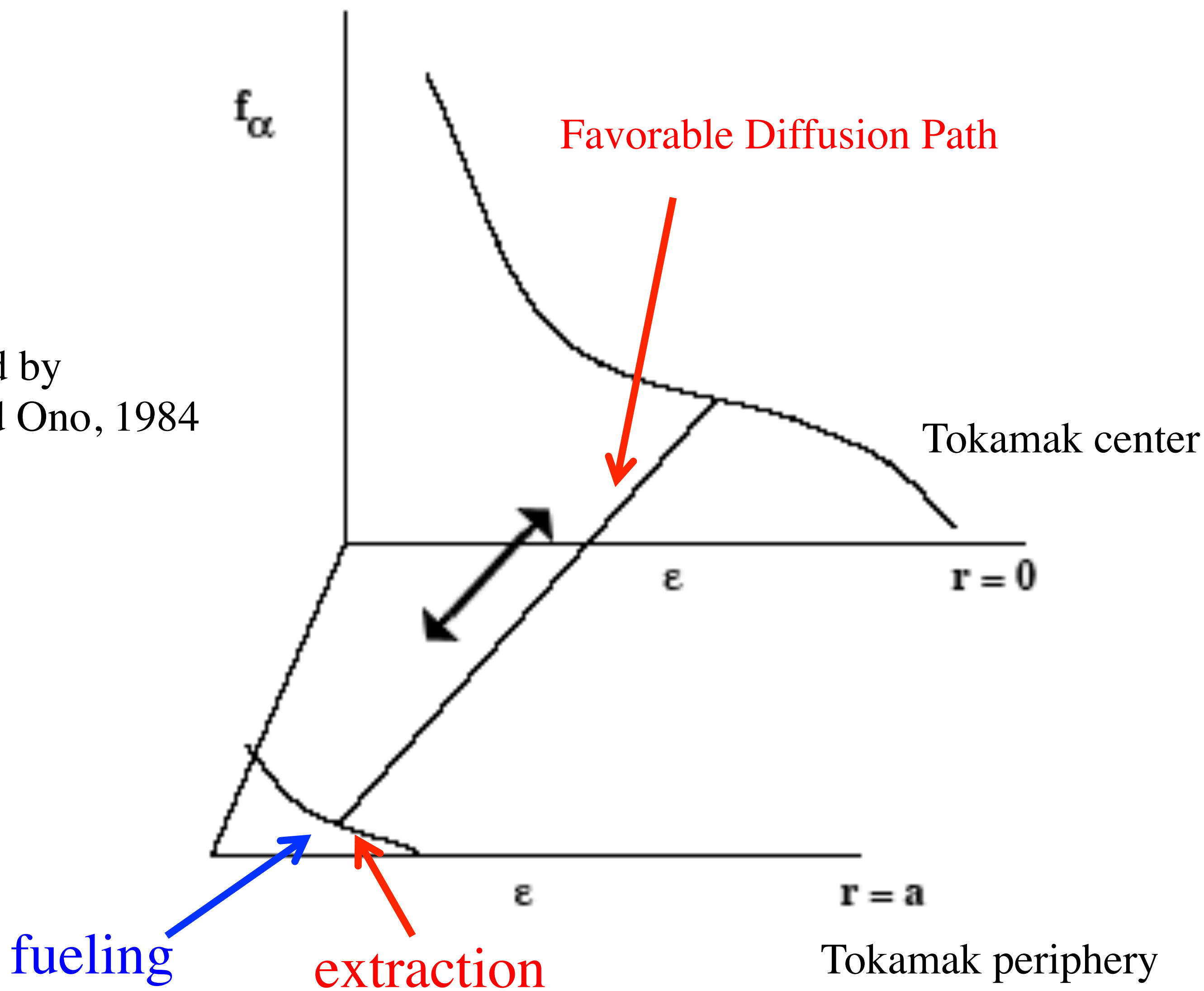
make virtue of low electron heat confinement time

Fisch and Herrmann (1994)

Snyder, Herrmann and Fisch (1994)

# Extracting Free Energy

Motivated by
Wong and Ono, 1984



# Advantages of Alpha Channeling

1. Hot ion mode gives about 30% cheaper COE, compared to aggressively designed reactors, due to increased reactivity at given confined pressure (and free current drive).

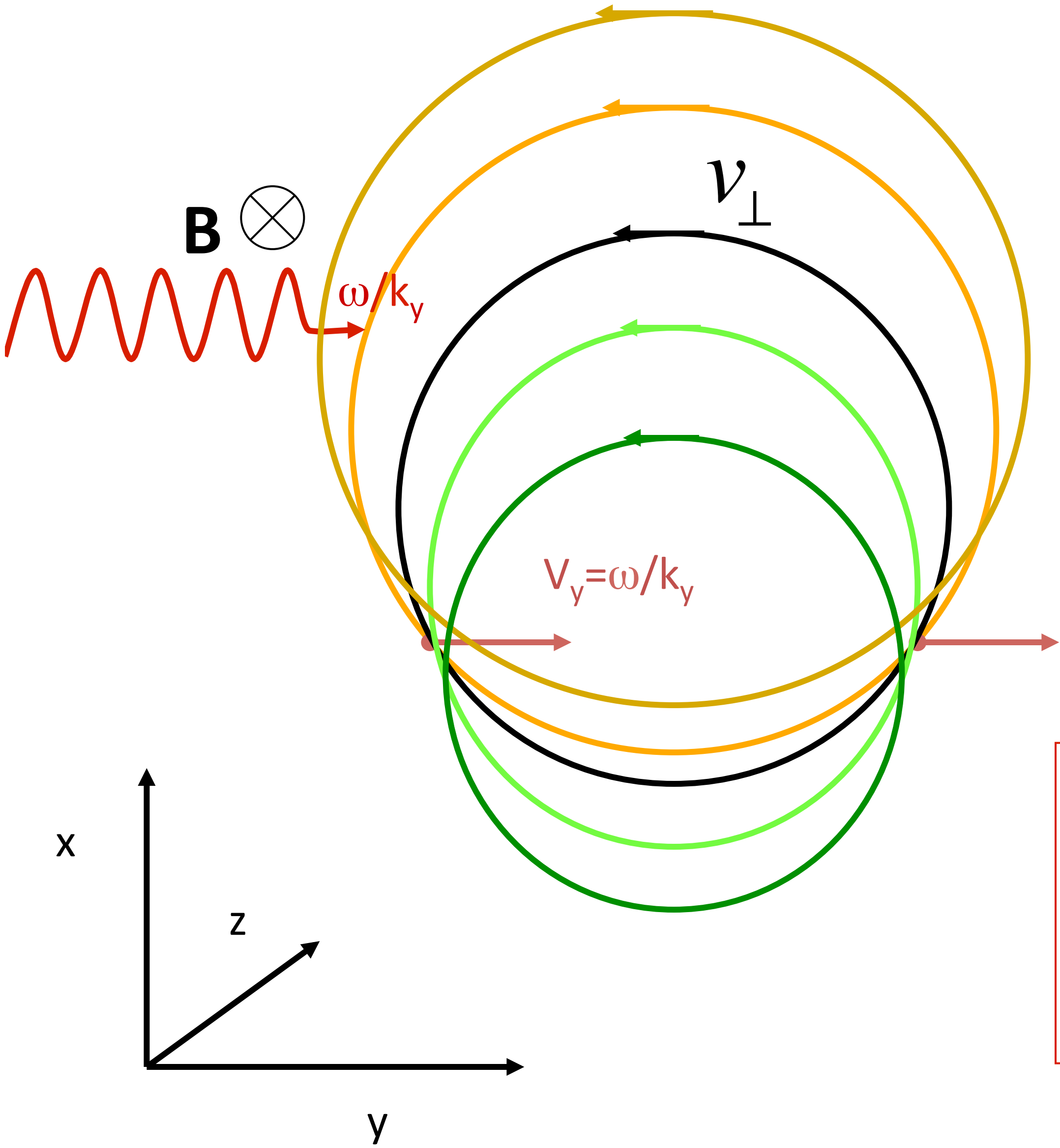
2. Impurities removed and plasma fueled automatically.

3. Ion transport might eventually be tamed, but maybe not electron transport, so having ions hotter than electrons reduces heat loss.

4. Present data base of the top tokamak confinement and heating results supports hot-ion mode operation only.

5. Deleterious instabilities stabilized by removal of $\alpha$ free energy.

# Diffusion Paths




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

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

$$\Omega \equiv eB/m$$

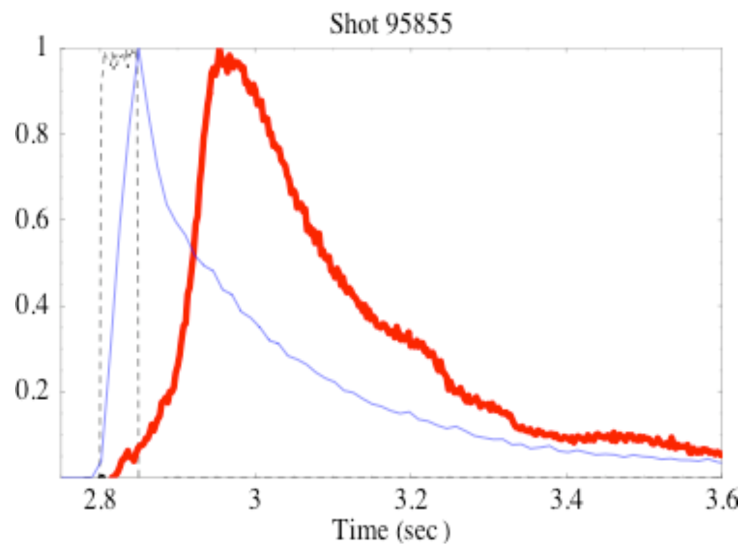
$$\Delta E = m v_y \Delta v_y$$

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

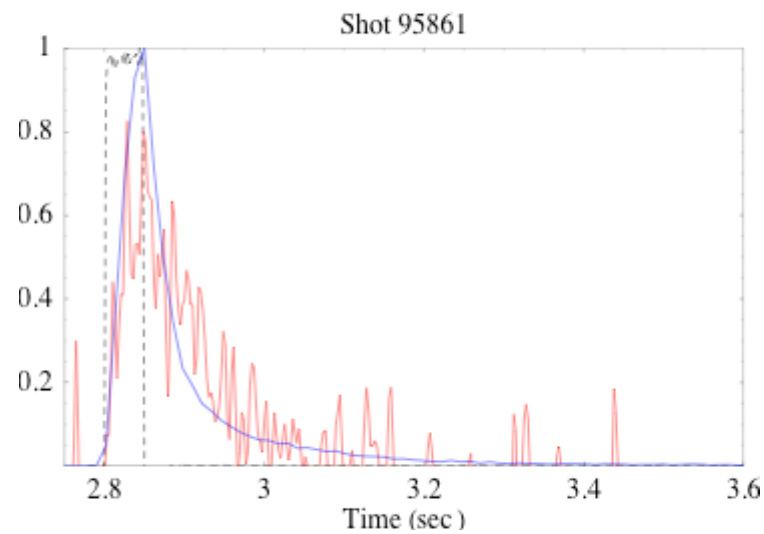
Fisch and Rax, 1992

# TFTR Experiment: Surprise Loss Rate Dependence on $P_{rf}$

With $P_{rf}$ = 3.2 MW




With $P_{rf}$ = 1.0 MW




Beam (black), neutrons (blue), & losses (red)

Energy diffusion coefficient of lost particles : $D_{\varepsilon} \sim 25\ \mathrm{MeV}^2/\mathrm{sec}$ !!

Figures from Herrmann Thesis (1998)

Comment: a very under appreciated experiment

# Hot-ion Mode RF-Driven Tokamak

Vision: 400 MW or more re-circulating RF; RF is first-order physics

Present best results extrapolate to Hot ion mode

1. Top performance results to date achieved in hot ion mode
2. Ion heat transport might be controlled but not electron heat transport

Upside to hot ion mode -- confidence in 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.

# 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

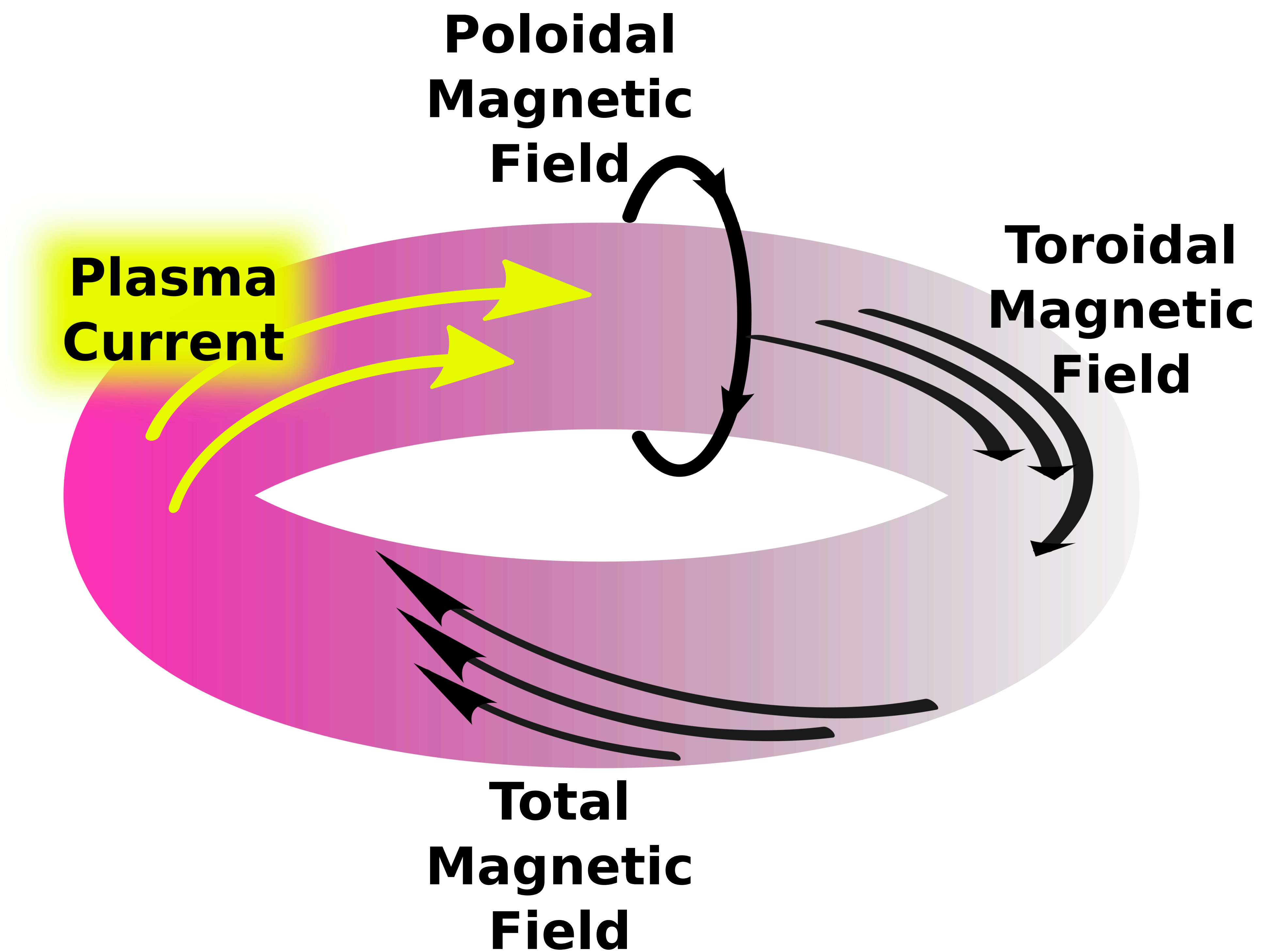
1990's: More detailed positioning of plasma current

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

1990's: Exploit coupled diffusion of particles in velocity and position
"$\alpha$- channeling effect"

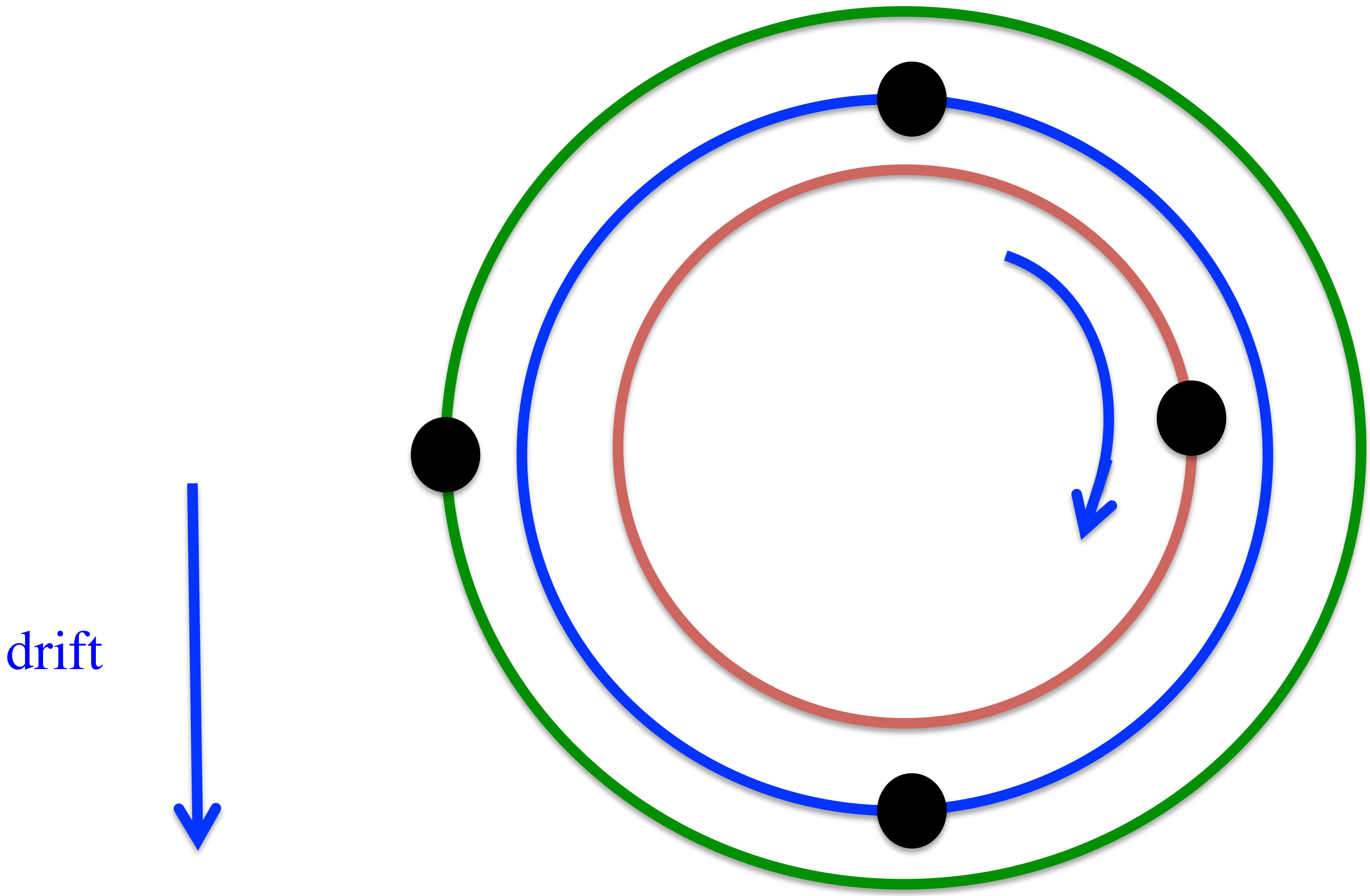
## Trend to "phase space engineering"

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

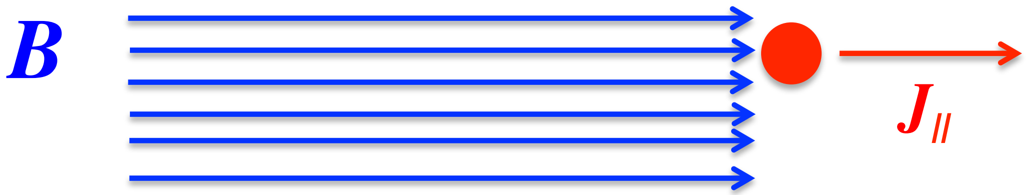

Poloidal Magnetic Field
Toroidal Magnetic Field
Plasma Current
Total Magnetic Field

Poloidal Magnetic Field produces swirling to stabilize drift

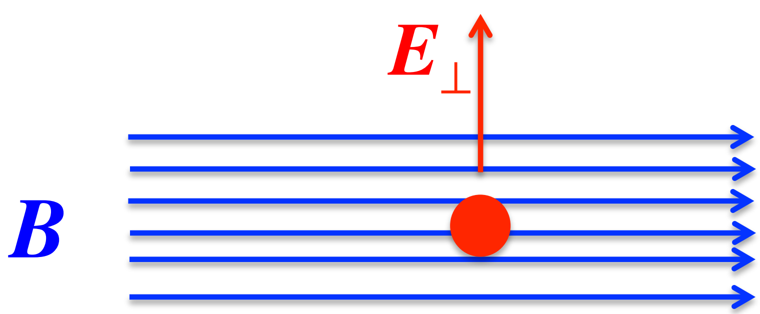
But so does  radial electric field!



# Methods of Producing "Rotational Transform"




Magnetic: Parallel current induced by pushing charge along field
Electron current is impeded by collisions with ions




Electric: Perpendicular voltage induced by pushing charge across field
But collisions do not restore charge neutrality
(caveat: field lines could move)

# Wave-driven Rotating Torus

Rax, Gueroult, and Fisch (POP, 2017)

Rotational transform produced by radial electric field
Waves generate radial electric field ($\alpha$-channeling effect)
Pick radial potential negative MeV – direct conversion

Two questions:

1. How much stored energy?
2. How much dissipation?

Answers

1. Stored energy small – quick release not damaging!
2. Dissipation small for skinny torus.

*Some Advantages:*

*a. No runaways*
*b. Possibility of natural hot ion mode*
*c. Possibility of natural impurity control*

*Caveat: Many things to check:*

Perpendicular conductivity (*in commonality with centrifuges)*
Stability and transport
Major radial force balance [Ochs and Fisch (POP, 2017)

# Impurity Concentration Effect in transverse B field

$$n_i(x) = n_b(x)^{\left(Z_i / Z_b\right)}$$

Taylor, 1961

What about in a potential, like gravity, or centrifugal forces?

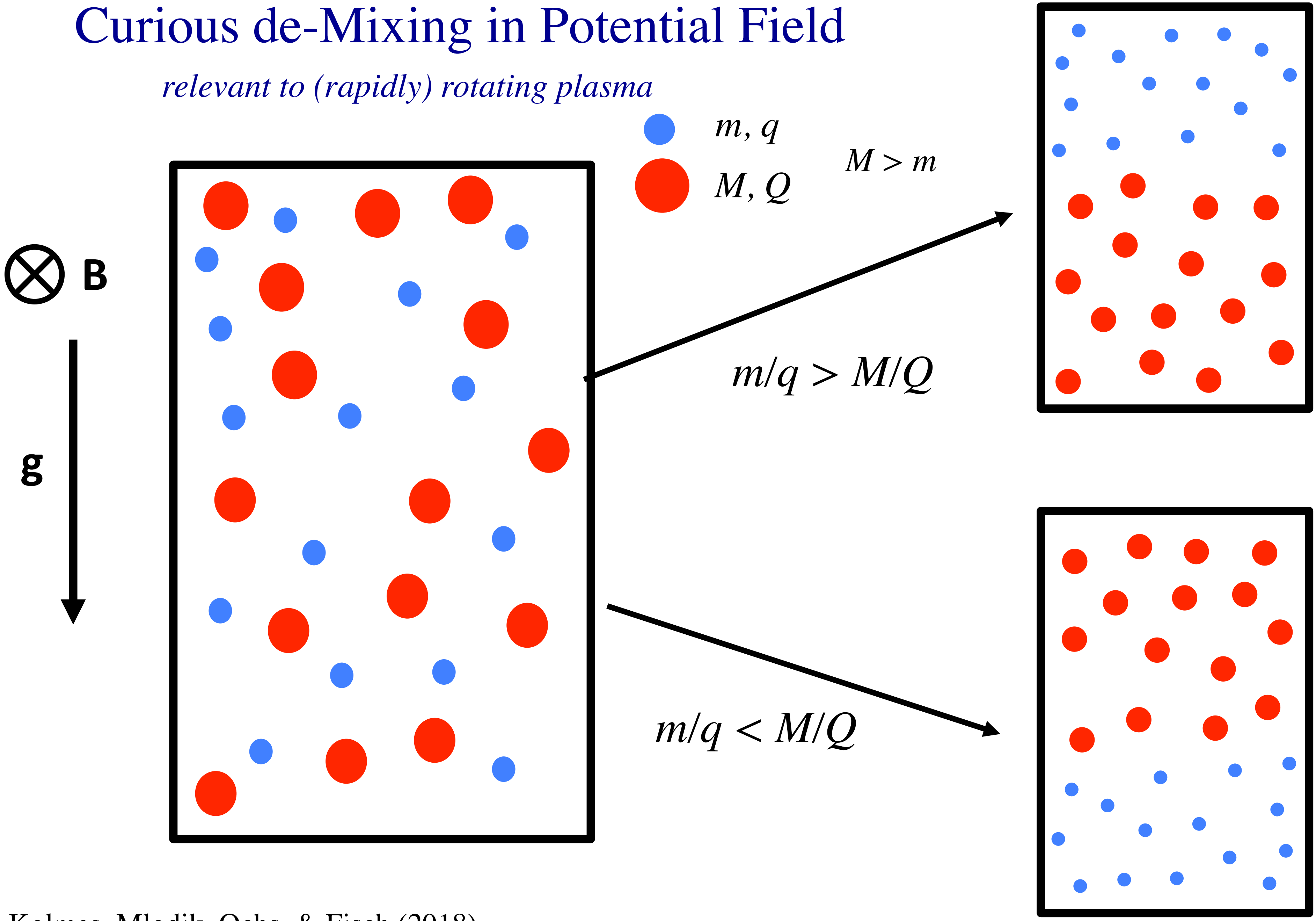
$$\left[n_a(x)\mathrm{e}^{-\Phi_a/kT}\right]^{1/Z_a} \sim \left[n_b(x)\mathrm{e}^{-\Phi_b/kT}\right]^{1/Z_b} \sim \left[n_c(x)\mathrm{e}^{-\Phi_c/kT}\right]^{1/Z_c}$$

→ interesting effects in rotating magnetized plasma.

$$\Phi \sim mgy; \quad \Phi \sim m\Omega^2 r^2 / 2$$

# Curious de-Mixing in Potential Field

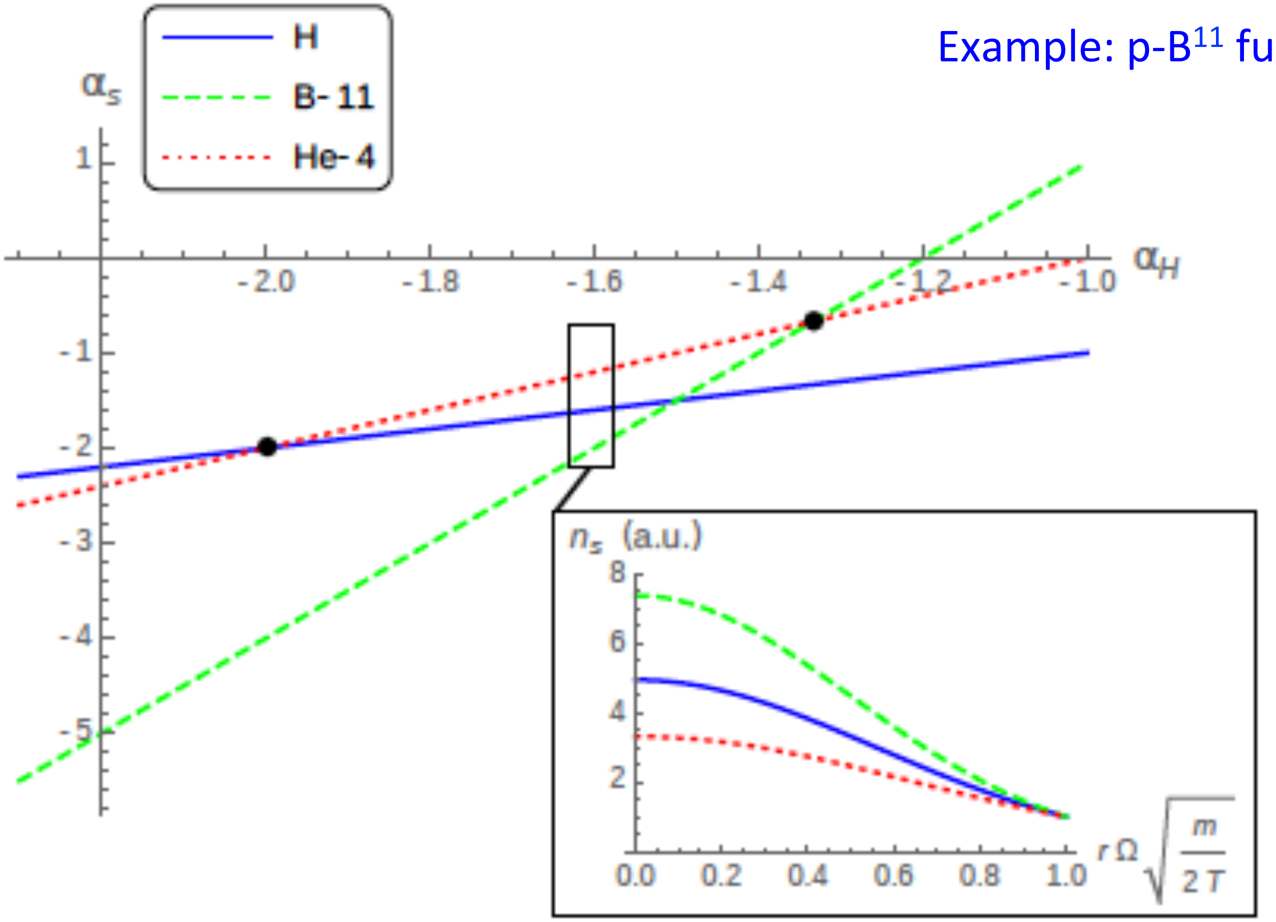
*relevant to (rapidly) rotating plasma*




Kolmes, Mlodik, Ochs, & Fisch (2018)

# Differential de-confinement of particles of intermediate mass and charge

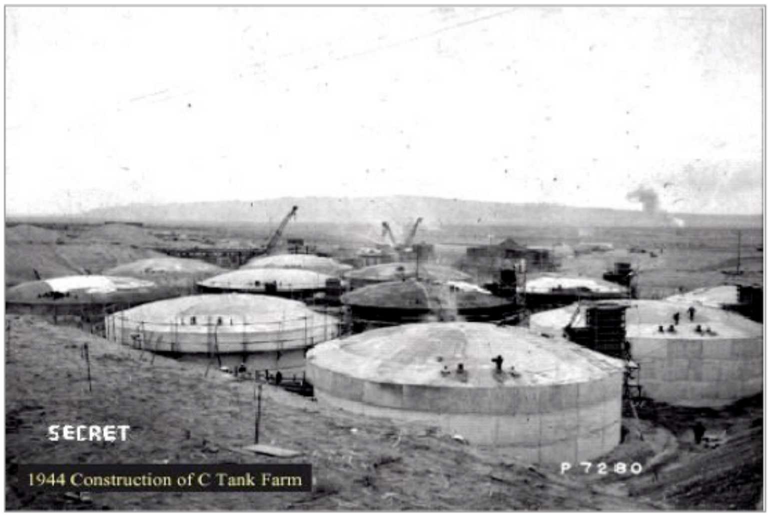
Example: p-$B^{11}$ fusion




Rotation regime for pushing alpha particles to periphery

Kolmes, Ochs, and Fisch (POP, 2018)

# Legacy Waste at Hanford
## (from US nuclear weapons program)




Single shell tanks constructed in 1944

Waste treatment plant in 2005

- 177 tanks contain 54 million gallons of high level waste with 194 MCi total radioactivity
- Tanks are decades past planned lifetime. Decades remain until they are fully processed.

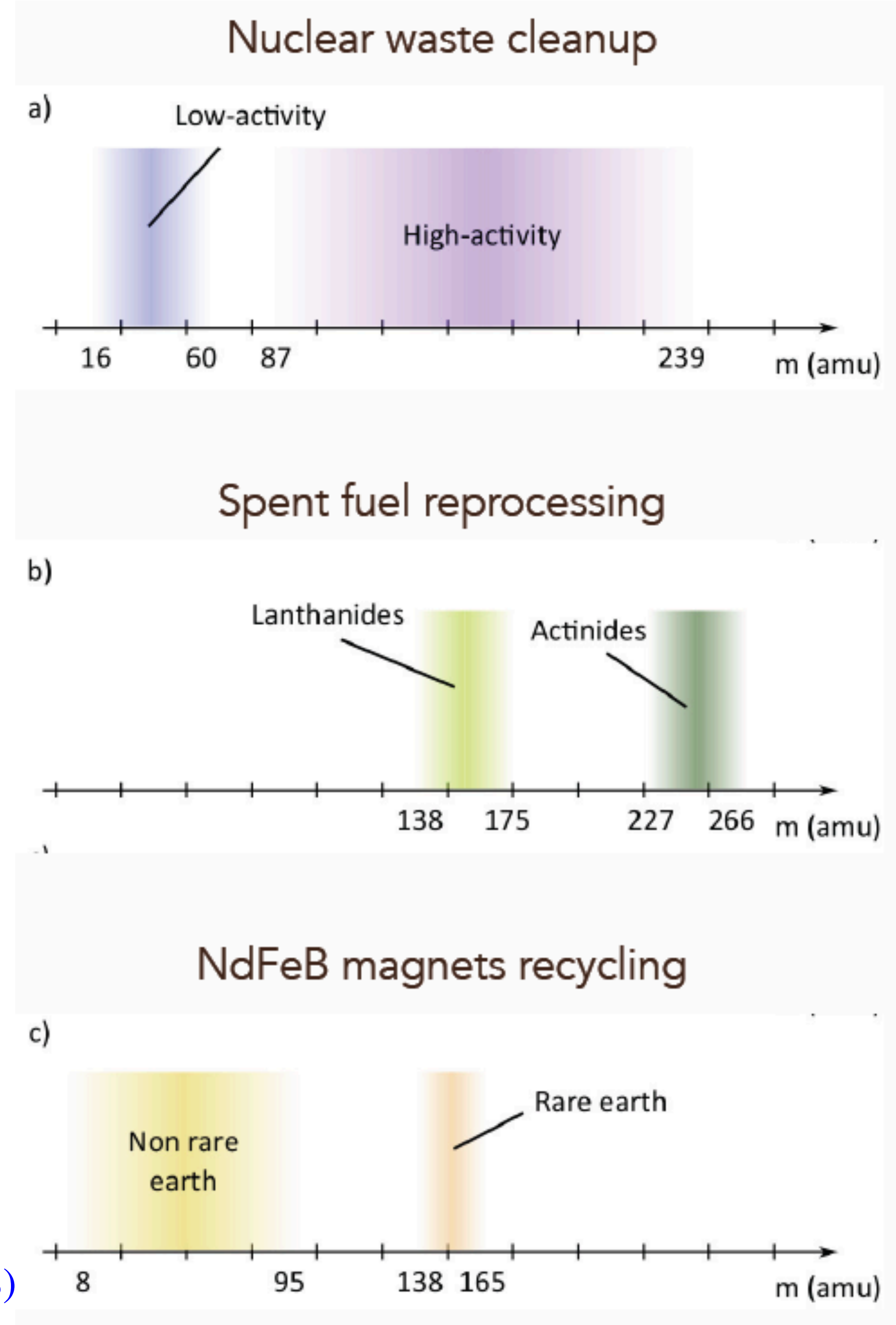
River Protection Project System Plan, Revision 5 (2010)

Three important applications for high-throughput mass separation that could exploit large atomic mass differences



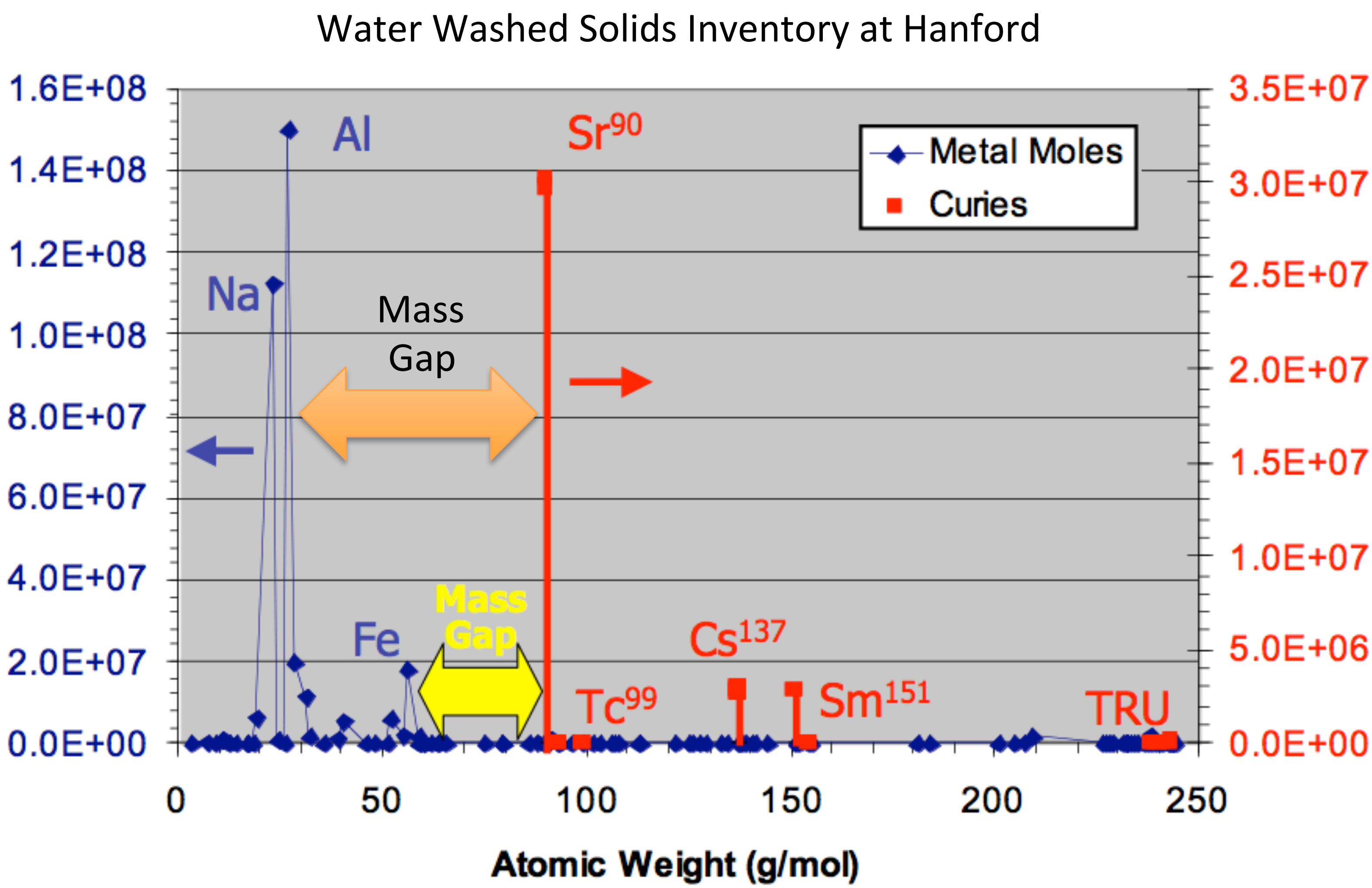
Guardian sustainable business

Rare earth mining in China: the bleak social and environmental costs



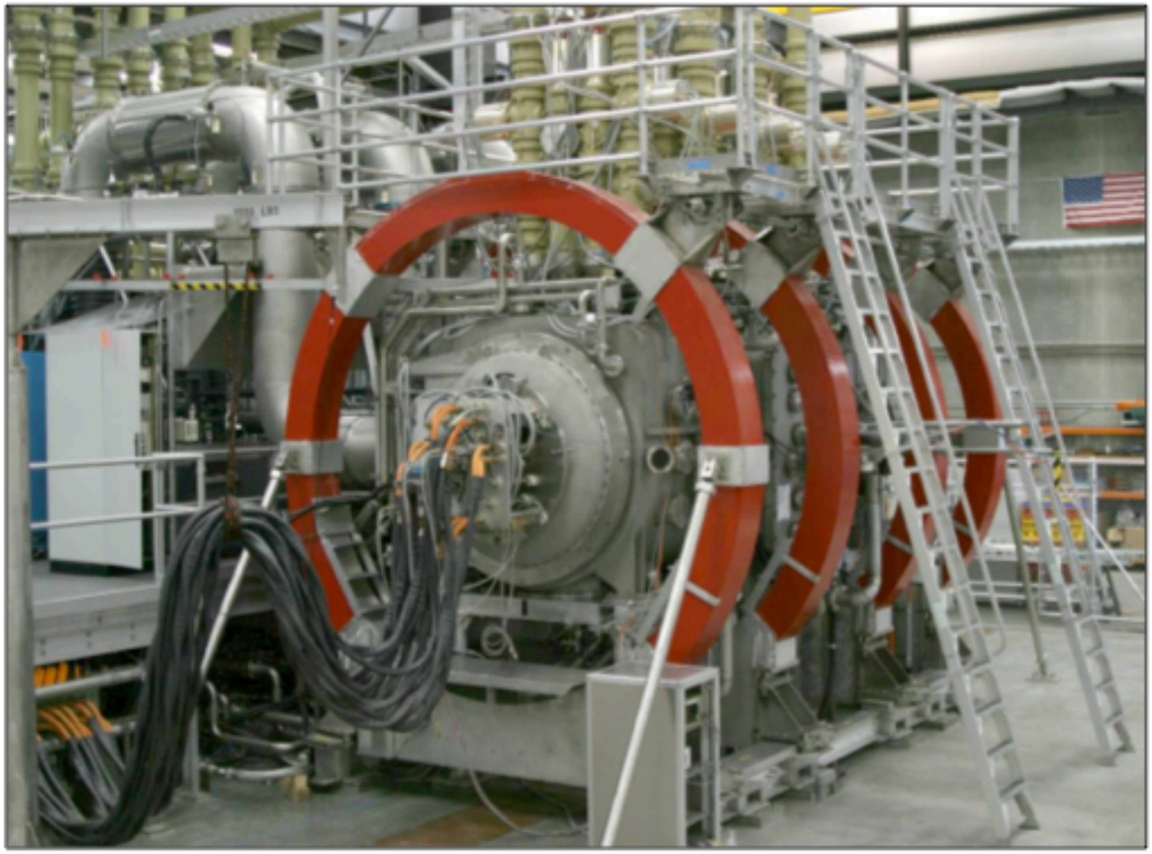

Gueroult, Rax and Fisch, PPCF (2018)
Gueroult, Rax and Fisch, J. Cleaner Production (2018)

# Plasma mass filters can exploit "mass gap" to separate bulk elements from radioactive ones




B. Cluggish, "Technical Overview of Archimedes Filter." Archimedes Workshop at General Atomics, 2006.

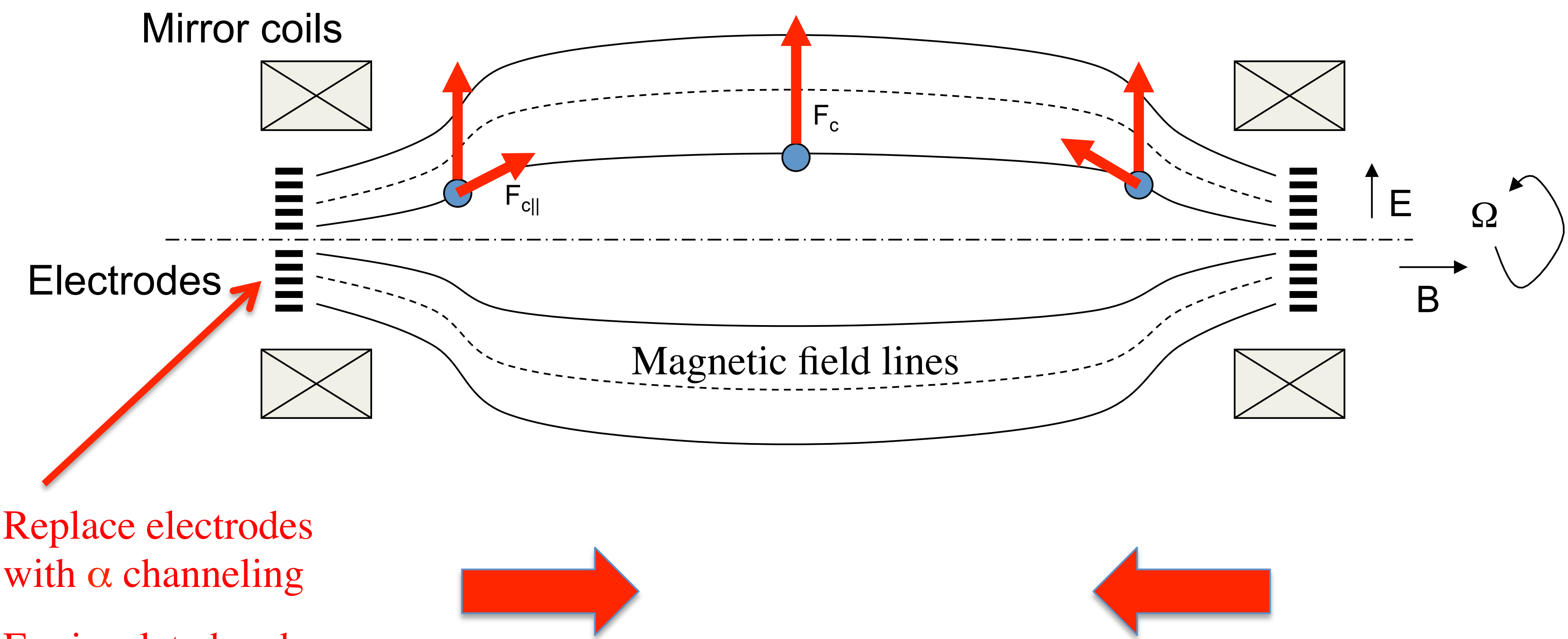
# Archimedes Demo was built to prove concept at scale



| Demo Design Parameters | |
|---|---|
| Plasma Radius (m) | 0.4 |
| Plasma Length (m) | 3.9 |
| Magnetic Field (G) | 1600 |
| RF Frequency (MHz) | 4 |
| RF Power (MW) | 3 |
| Plasma Density ($10^{19}$ $m^{-3}$) | 2.0 |
| Throughput (ion-mol/s) | 0.1 |
| Electrode Voltage (V) | 600 |
| Ion Temperature (eV) | 13 |
| Test Duration (s) | Steady State |

B. Cluggish, "Technical Overview of Archimedes Filter**."** Archimedes Workshop at General Atomics, 2006.

# Centrifugal Confinement Fusion or Separation




Replace electrodes with α channeling

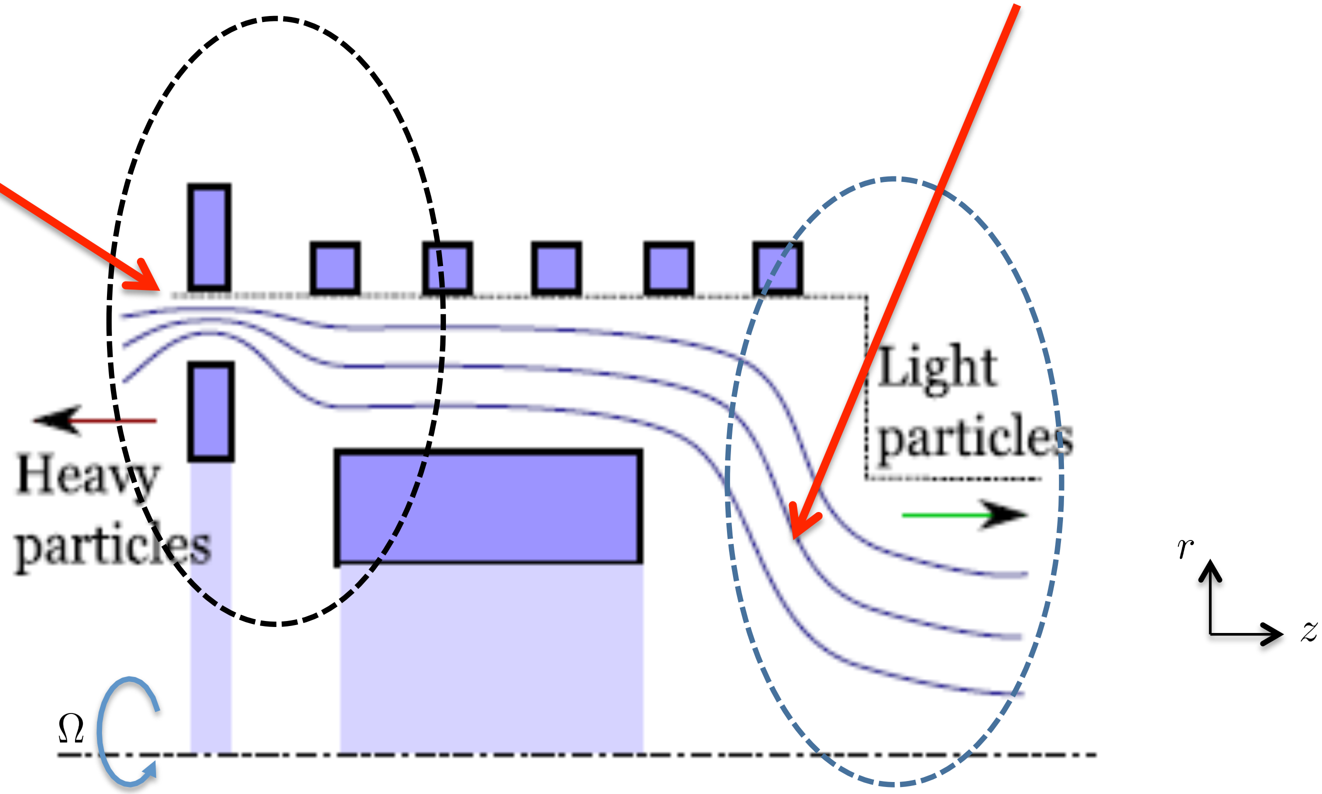
For insulated ends, potential maintained against perpendicular conductivity

*Centrifugal forces (mass dependent)*
push charged particles from: low radius region
to high radius regions

# One Possible Improvement:
# Magnetic Centrifugal Mass Filter

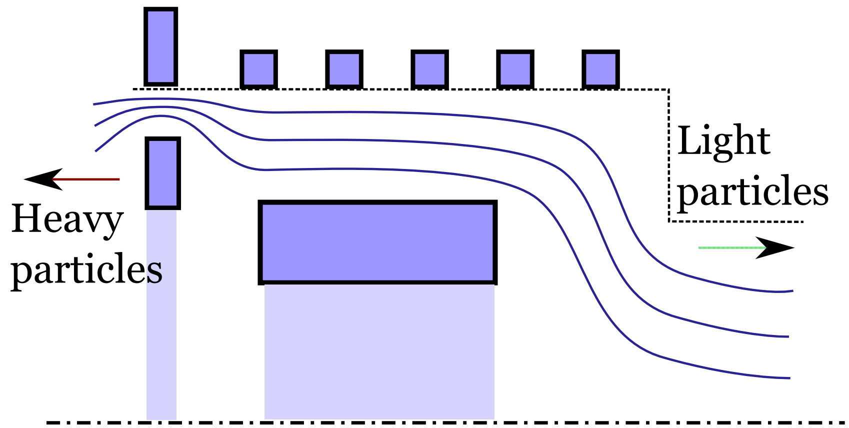
Centrifugal force on heavy ions overcomes the magnetic mirror force.

Centrifugal force is not sufficient to confine energetic light ions.




A. J. Fetterman and N. J. Fisch (2011)

# MCMF Advantages




Confinement condition only depends on mass

$$W_{\|0} < W_{\perp 0}\left(R_m - 1\right) + W_{E0}\left(1 - R_r^{-1}\right).$$

$$R_m = B_m/B_0 \quad R_r = r_0^2/r_m^2 \quad W_{E0} = m\Omega_E^2 r^2/2 \quad \Omega_E = -E_r/rB_z$$

1. Output streams collected axially over a smaller area
2. Plasma source can be on field lines
3. Works much better on large mass differences (less proliferative)

## Summary of the Argument -- a Program for *"Differential"* Magnetic Confinement

1. Rotating magnetized plasma confinement may enable upside potential to fusion.

2. Central to the rotation is creating a radial potential, by moving charge across field lines.

3. This might be accomplished by alpha channeling, which has other very desirable features.

4. But there are many unanswered questions – and many curiosities – particularly in cross-field charging and transport – either by waves or through collisional effects.

5. Parallel plasma conductivity well demonstrated – not so perpendicular conductivity.

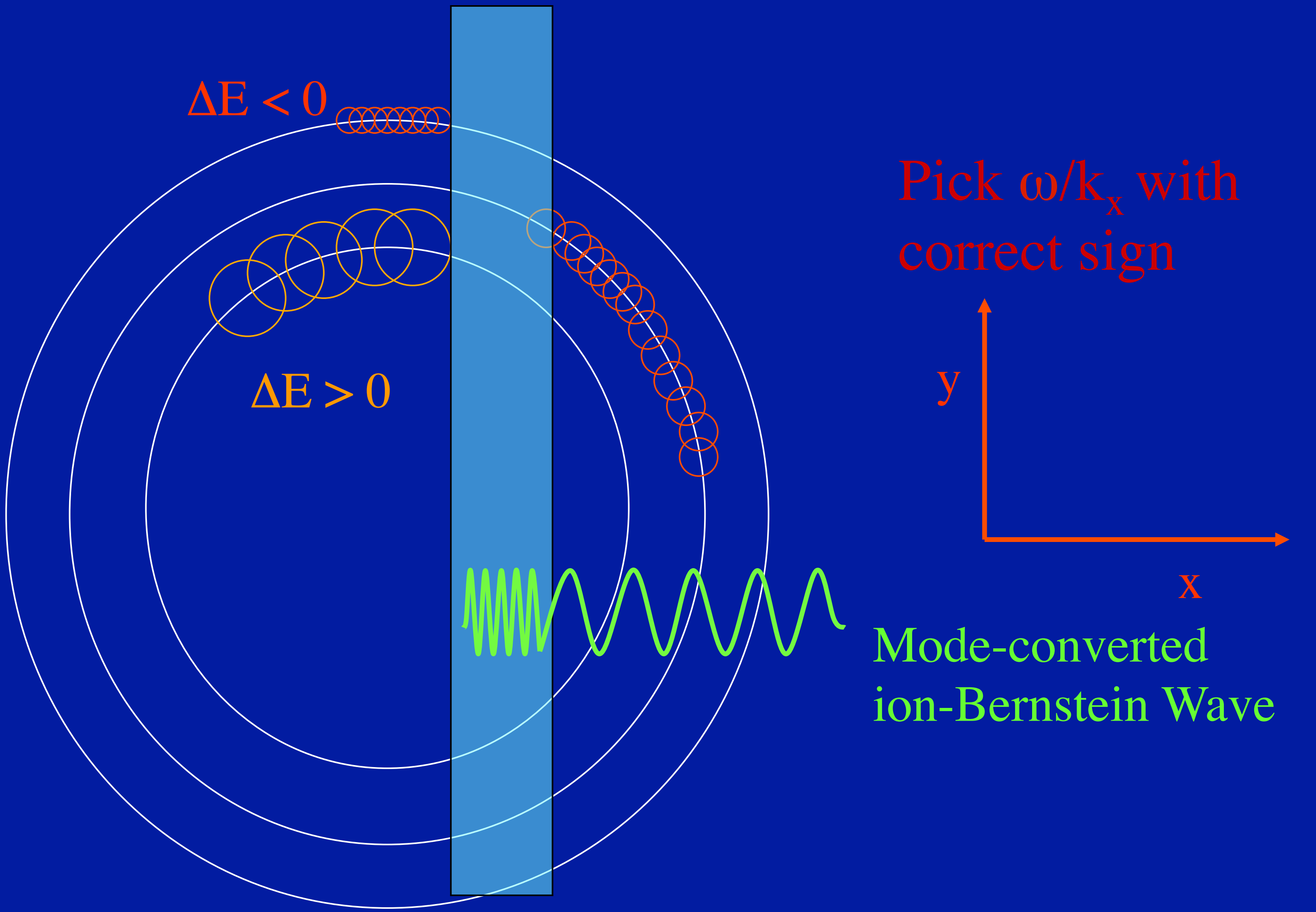
6. Linear, rotating plasma devices can be used both for separations and nuclear fusion.

7. Many fundamental physics (conductivity and differential transport) and technology questions (radial potential) can be posed and answered most easily in linear devices.

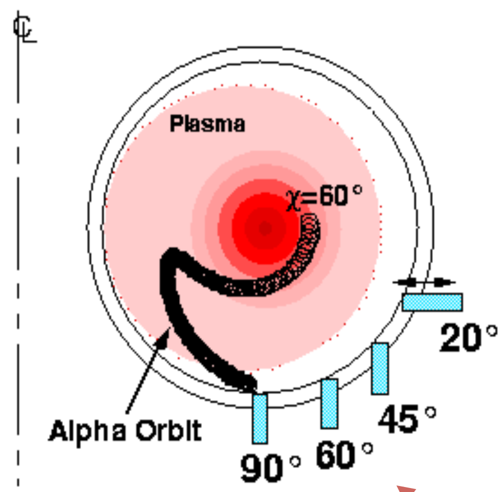
8. This suggests a fundamental physics program with high upside potential for magnetic fusion, with intermediate applications in other areas, both curiosity and applications driven, and, at least in the linear limit, relying upon relatively easy to build devices.

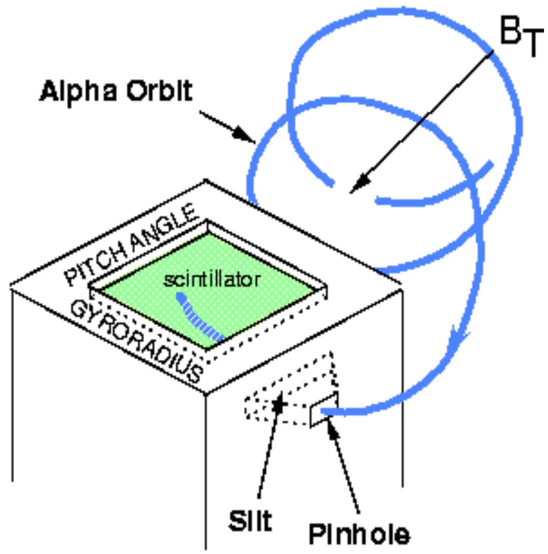
[redacted]

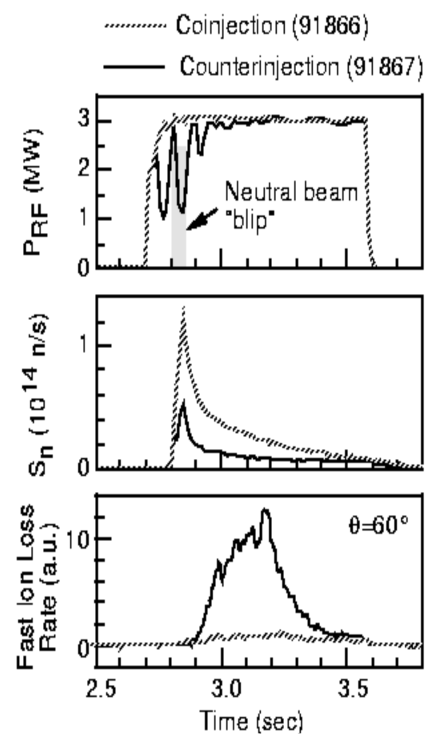
# Tapping Free Energy in α-Particles



# TFTR D-Beam MCIBW Experiments



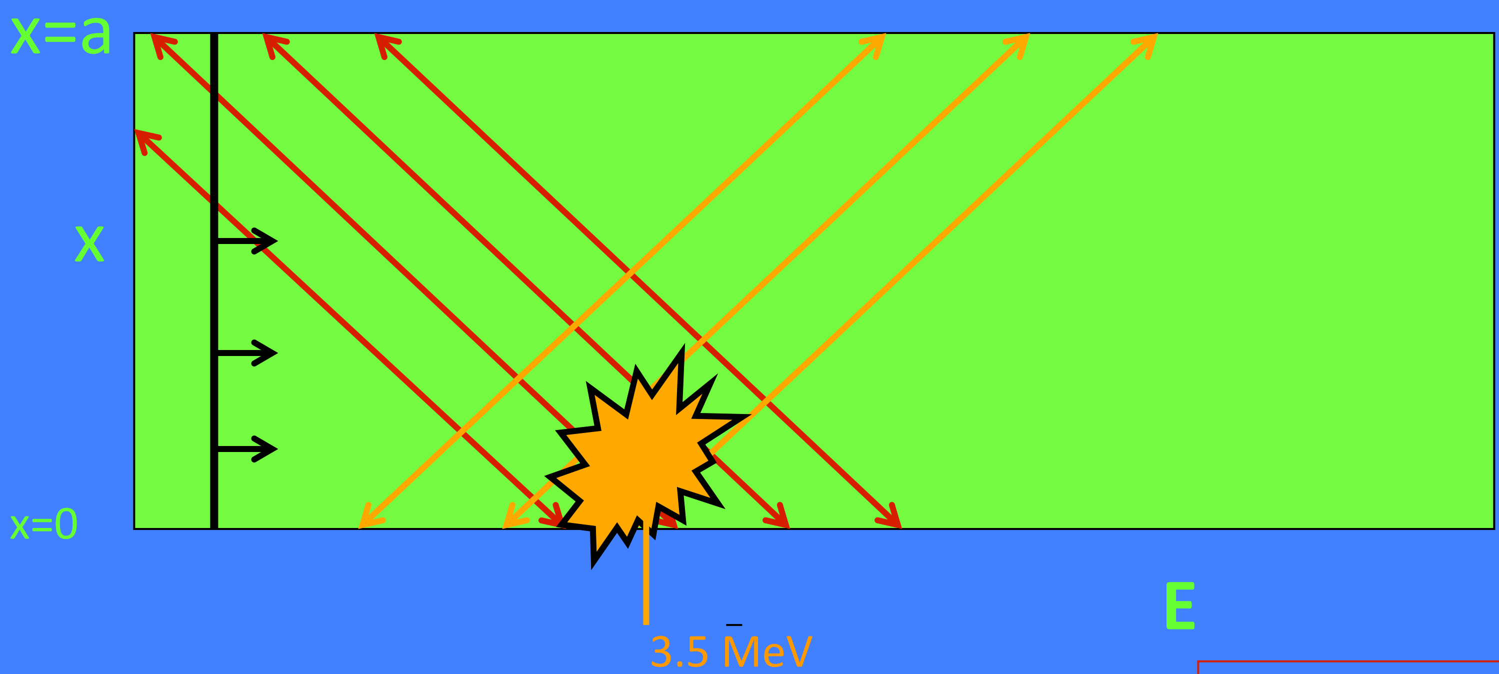




Zweben's lost alpha detectors

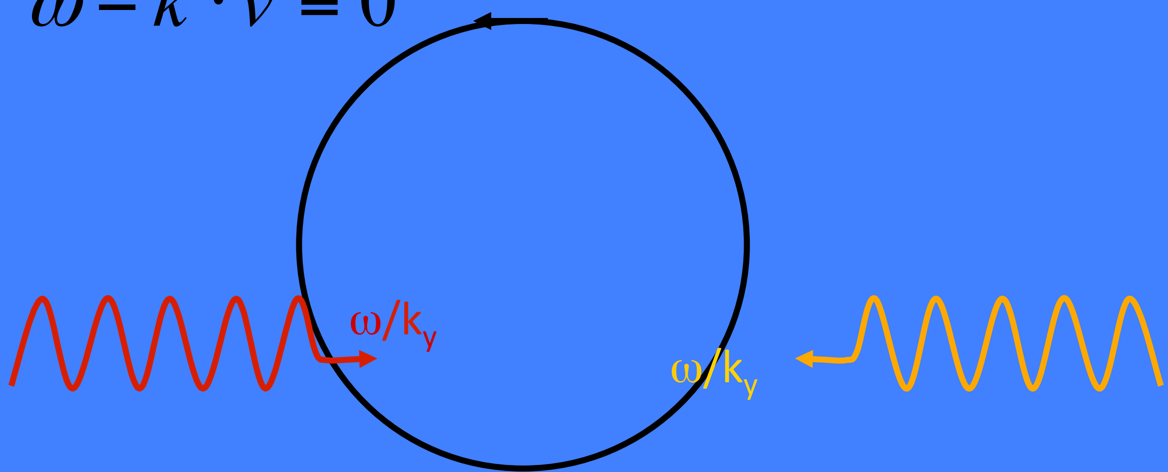
Darrow, 1996

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

# Diffusion Paths




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




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

# Production of Thermonuclear Power by Non-Maxwellian Ions in a Closed Magnetic Field Configuration*

J. M. Dawson, H. P. Furth, and F. H. Tenney
*Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08540*
(Received 15 March 1971)

A toroidal plasma heated by an energetic neutral beam (thus consisting of an energetic ion component and a lower-energy bulk plasma) can produce net thermonuclear power under conditions far less restrictive than Lawson's criterion.

A thermonuclear plasma with a Maxwellian ion distribution must meet Lawson's minimum condition[1] on $n_i \tau_E$ (the product of ion-density and plasma-energy confinement time) in order to generate sufficient thermal power to recreate the electrical power invested in producing the plasma. We will consider the generalization of Lawson's criterion for the case where the bulk-plasma temperatures $T_e$ and $T_i$ are maintained by injection of a neutral beam that gives rise to an energetic ion component of density $n_h \ll n_i$ and initial energy $W_0 \gg T_e, T_i$.

## Some Prefatory Notes for the Invited TFTR Paper at the Pittsburgh APS Meeting.

(Memo from Harold Furth to Rich Hawryluk, 11/10/97) H.9.

HYPOTHESIS:

- Electron-energy confinement is subject to "Bohmlike" diffusion.
- Ion-energy-confinement is not subject to "Bohmlike" diffusion.
- This marked distinction between ions and electrons does not become apparent, as long as plasma-particle collisions are clamping $T_i$ tightly to $T_e$.
- But, when $T_i$ is driven up vigorously enough by direct ion-heating, then it becomes obvious that ion-energy confinement is not really constrained by Bohm.
- Whether the ions are Maxwellian amongst themselves, is relatively unimportant.
- For fusion-energy release, the critical non-Maxwellian feature is that $T_i$ is not dependent on collisional heating through the transfer of thermal energy by way of $T_e$.

LESSON:

- Fusion reactors should strive to put the $\alpha$-energy directly into the fuel ions – where it will be well-confined, limited mainly by classical collisional coupling between the electrons and the somewhat hotter ions. The "Bohmlike" transport of plasma energy to a "limiter" constitutes an incidental benefit, if sputtering of wall material is a problem.

**PRINCETON UNIVERSITY**
**PLASMA PHYSICS LABORATORY**

To: Nat Fisch

From: Harold P. Furth

Date: January 28, 2000

Subject: Comments on Scott Hsu's Ph.D. Thesis topic "Local Measurement of Non-classical Ion Heating During Magnetic Reconnection in MRX"

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Nat:

As you know, in the D-D Fusion experiments of 45 years ago, "Non-Classical Ion Heating" (with the electron temperature much lower) was the cause of optimistic announcements of success in "thermonuclear fusion". These claims were later disproved via the observation that $T_e << T_i$.

More recently, thanks to your own work with your graduate students, the idea of fusion reactors with $T_e << T_i$ has come to look like a reasonable approach to the "economic feasibility" of fusion power.

Scott Hsu's work on magnetic reconnection thus may turn out to shed light on the past – as well as the future – of fusion research.

Cc:
Scott Hsu
Masaaki Yamada

# How much energy is stored in rotation?

$$\frac{v_D}{v_E} \sim \frac{\left( mv^2 \big/ RqB \right)}{\left( E \big/ B \right)} = \frac{a}{R} \frac{mv^2}{qaE}$$

But energy in rotation ~ 1/B.
Typical B → subsonic rotation.

$$\frac{v_D}{v} \sim \quad mv^2 \big/ RqBv = \frac{\rho}{R}$$

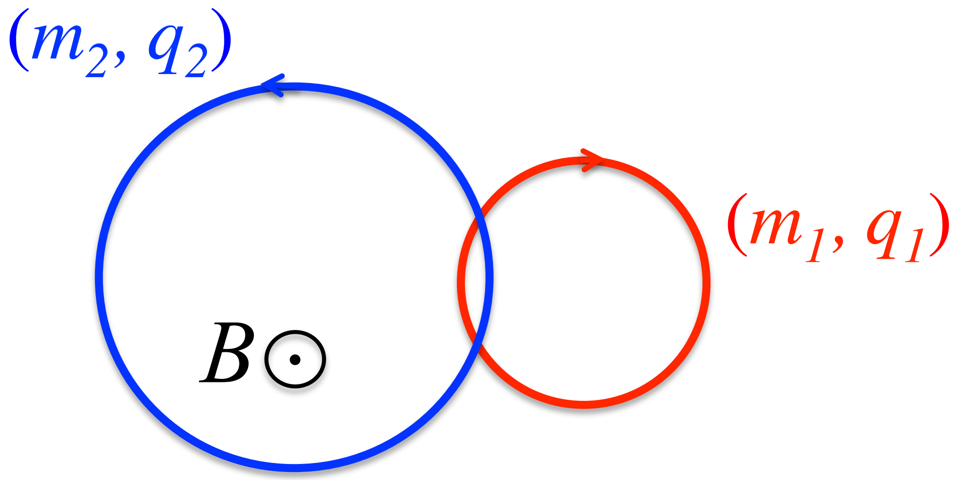
compare

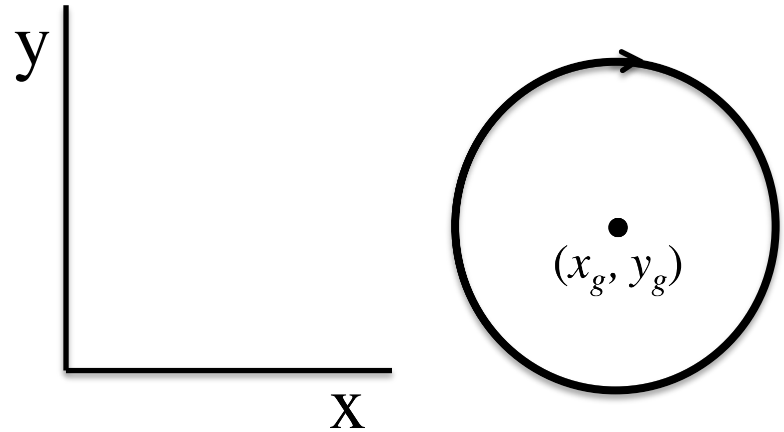
$$\frac{B_\vartheta}{B} \sim 0.1$$

So rotation energy is small compared to thermal energy like poloidal field energy is to total field energy.

But field energy is about 25 times larger than particle energy.

# Perpendicular collisional transport is ambipolar




$$m_2 \Delta v_{y2} + m_1 \Delta v_{y1} = 0$$

$$\Delta x_g = \frac{\Delta v_y}{\Omega}, \quad \Omega = \frac{qB}{m} \implies m \Delta v_y = qB \Delta x_g$$

$$\implies \boxed{q_2 \Delta x_{g2} + q_1 \Delta x_{g1} = 0}$$

Conservation of momentum in y direction means no net transport of charge in x direction