Physics 87 — Class 4

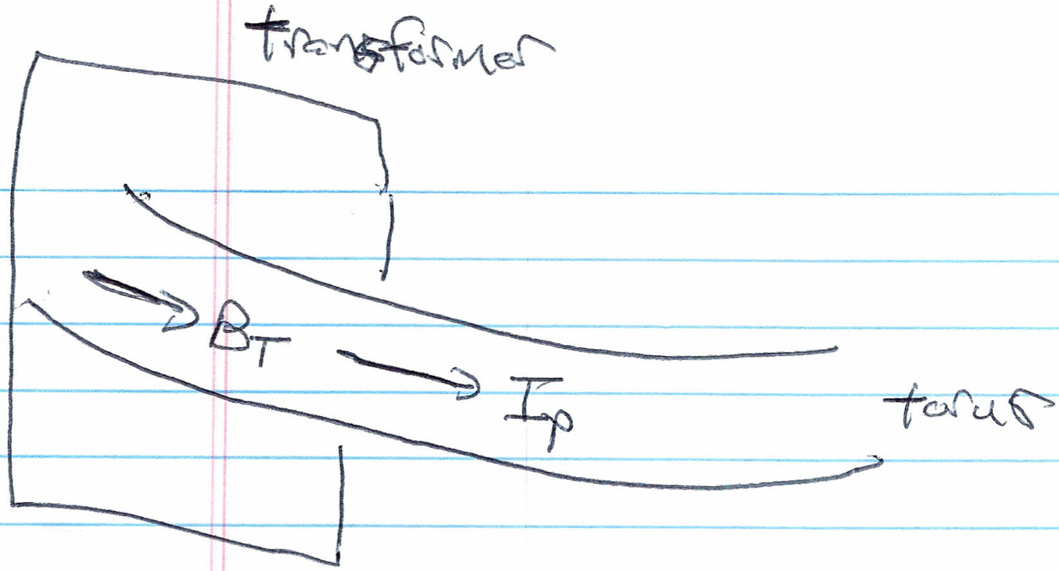
From RFP → Tokamak

- Toroidal Pinch :
  - $q(r) = \frac{r B_T}{R B_\theta} < 1$, $q' < 0$
  - kink / MHD turbulence ⇒ drive "dynamo" ⇒ poloidal currents
  - Taylor state → self-organization

∴ Reversed Field Pinch 'finds' constrained minimum energy state at price of degraded confinement.

- Enter the tokamak!

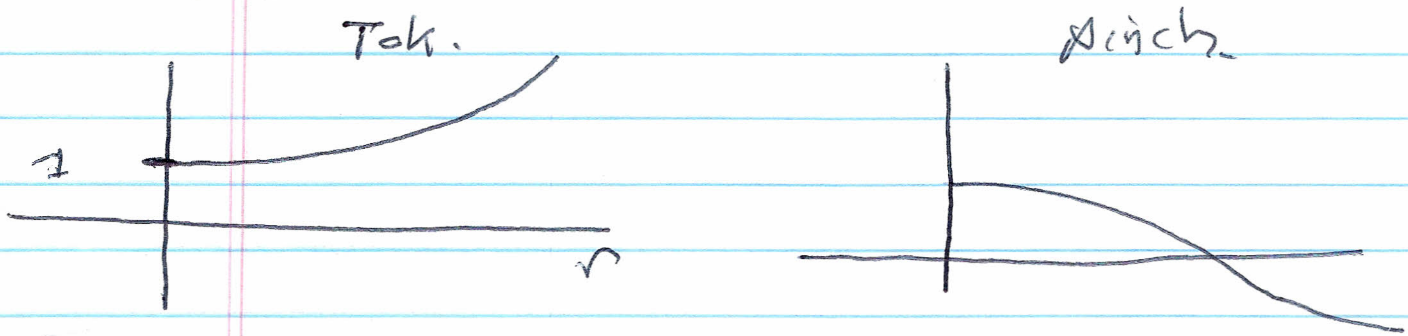
- Russian : toroidal magnetic chamber
- T3 : mid 60's , Kurchatov Inst., Moscow
- [illegible]
  A. Sakharov, I. Tamm, Artzimovich, Leontovich



so what is difference from pinch ?

- strong B_T $\qquad B_T \gg B_\theta$
 vs $B_T \sim B_\theta$

- $q = \frac{r B_T}{R B_\theta} > 1$, $q' > 0$



- tokamak is more "macroscopically" stable

⇒ not in a state of MHD turbulence

- why? → resonances

$q(r)$ → pitch of magnetic field line

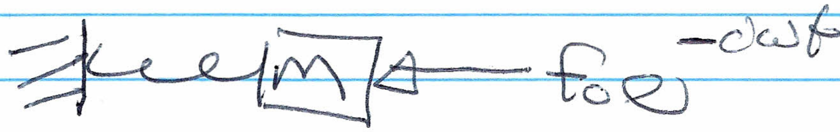
and

periodic perturbation (in torus):

$$\underline{\tilde{B}} = \sum_{m,n} \underline{\tilde{b}}_{m,n} \, e^{i(m\theta - n\phi)}$$

so

resonance when $q = m/n$, especially low m.

i.e. resonance: 

$\omega \sim \sqrt{k/M}$

here: space.

Punchline:

- RFP has $m=1$, n resonances $10 < n < 20$ ⇒ MHD turbulence

- tokamak has isolated $q = 2/1$ etc. resonance.

∴ tokamak is ~ MHD quiescent

Outcome:

- T > 500 eV ; more than double pinch effort best
  τ_E ~ several 10's msec.
- Measurement a collaboration of U.K. Team and USSR experiment (D. C. Robinson).
  ⇒ first notable case of international collaboration in fusion

Thereon: - Tokamak assumed lead & held it among MFE concepts

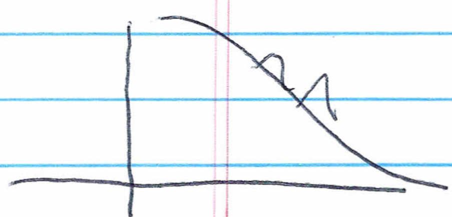
- caveat W7-X.

→ Advent of tokamak got emphasis <u>on</u> transport, off of stability

⇒ confinement physics.

~ "Bohm Barrier"

→ picture: confinement limited by small scale fluctuations



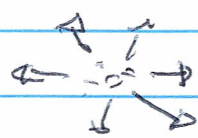
"microinstabilities"

(circa 50's)

→ origin: { ∇n, ∇T, etc. ; geometry }

→ produce effective diffusion coefficient

$D \sim (\Delta r)^2/\tau$



$\tau_E \sim a^2/D$

↳ critical to Lawson criterion

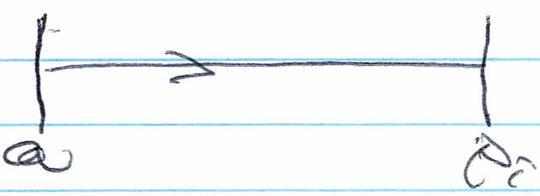
→ What is the effective diffusion coefficient for confined plasma?

- Measurement suggest:

  $D > D_{colln}$ ⇒ micro-turbulence

- $D \simeq \frac{cT}{16 B}$ ⇒ "Bohm Diffn" (after David Bohm)

  $\sim \rho_i v_{Thi}$

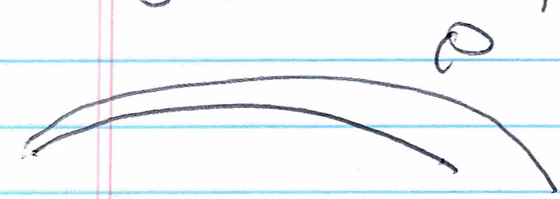


not good ⇒ $10^5 \to 10^6\ cm^2/sec$

⇒ $D \uparrow$ with T, $1/B$ scaling

⇒ no scale dependence.

- origin: isotope separation



but collective effects ⇒ scattering

fit to Bohm formula, circa 1949.

- Aside: Bohm story

⇒ D_{Bohm} fit various early experiments creating pessimistic view of early scaling trends.

→ T3 broke Bohm barrier ⇒ confinement significantly better. Why was unclear at that point.

→ $D \sim \left(\frac{\rho_i}{a}\right)^{\alpha} D_B$

Gyro-reduced Bohm $\alpha = 1$

⇒ confinement story TBC.

⇒ Tokamak quickly adopted, other tokamak experiments begin, world wide.

→ Early Issues in Tokamak Research

— stability / disruptions:

avoid running $q_L \sim 2, \sim 3$.

— low efficiency of P_{OH}

$P_{OH} \sim \eta J^2$ $(\sim I^2 R)$

$\eta \sim 1/T^{3/2}$

∴ Ohmic heating less effective as temperature rises.

⇒ NBI, RF heating

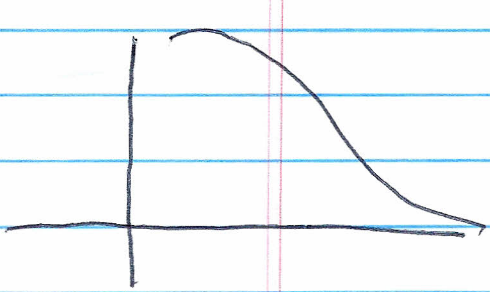
i.e. PLT — late 70's several keV

*— Density profile / pinch

Why does density peak when particles deposited at edge?

⇒ Convection / up-gradient

(gas-puff)



$$\frac{\partial n}{\partial t} = -\frac{\partial}{\partial r}\left[-D\frac{\partial n}{\partial r} + Vn\right]$$

$V < 0$!

What drives V? ⇒ ∇T, Q

i.e. outward, down-gradient heat flux drives up-gradient particle flux!

⇒ pinch, a la' chemotaxis

Next: Physics of Microturbulence.