Toroidal confinement of non-neutral plasma

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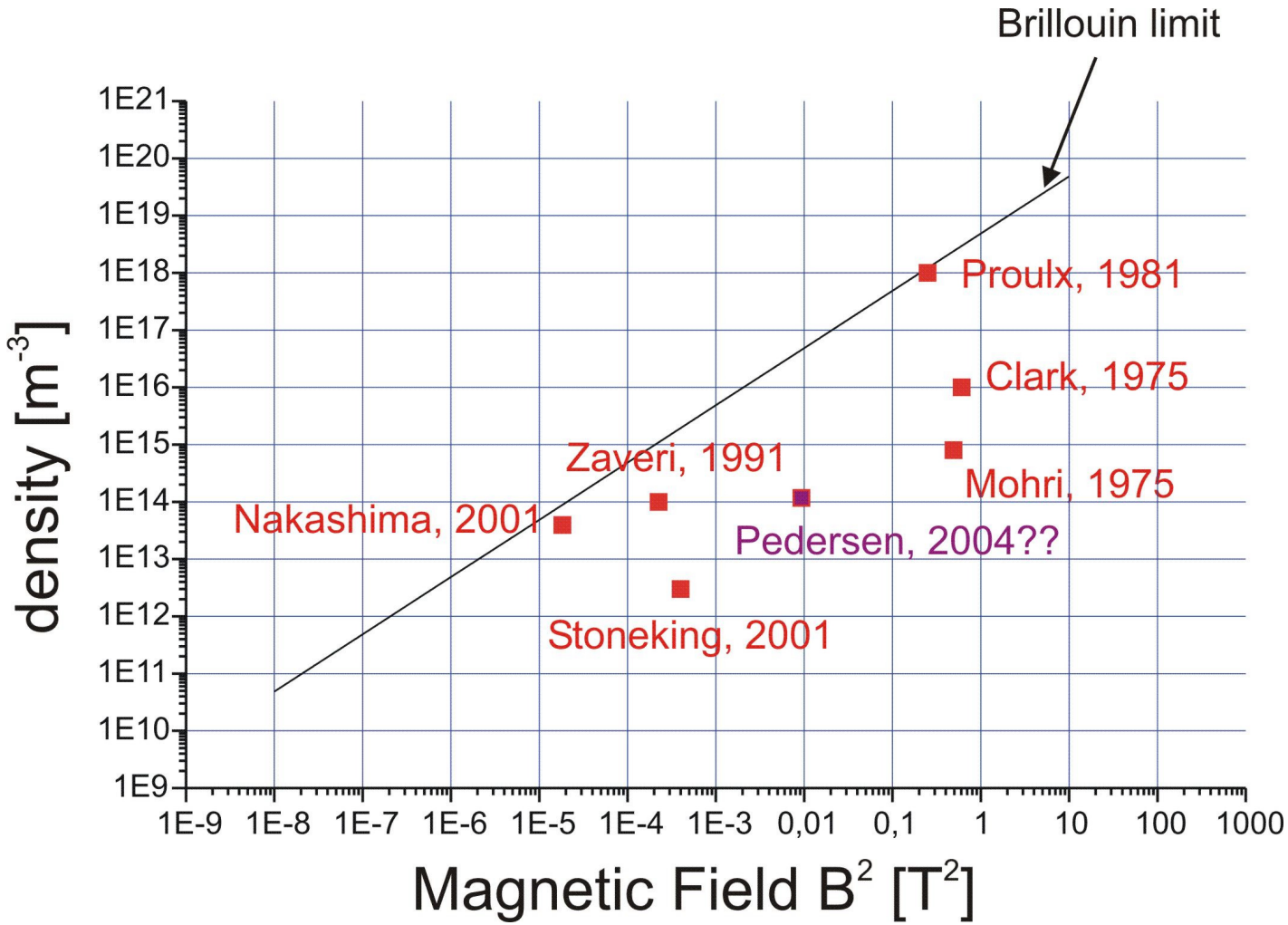
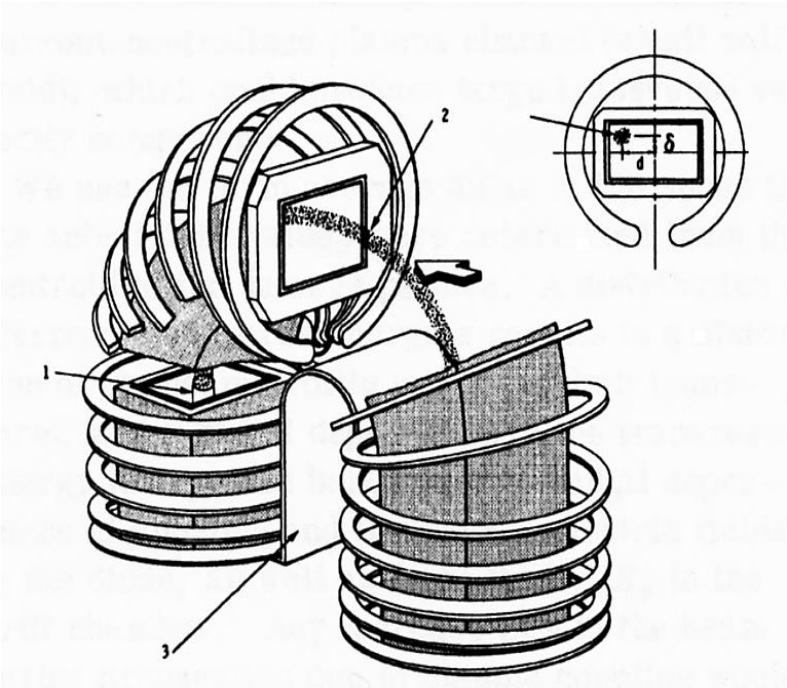
- Experiments with toroidal non-neutral plasma
- Magnetic surfaces
- CNT and IAP-high current ring
- Conclusion

Experiments with toroidal non-neutral plasma



- J. Benford (Physics int. company, USA, 1973)

- intense relativistic electron beams
- Major drift RxB and not ExB
- R=20.5 cm, r=11.5 cm
- I = 60 – 90 kA, 100 ns, 350 – 540 keV
- Magnetic field 2.8 – 9.2 kG
- 1 Torr nitrogen, 80% transport efficiency, fractional current neutralization 97%



- W. Clark (Maxwell Lab., California, USA, 1975)

- relativistic electrons, densities ~ 10^{10} cm^{-3}

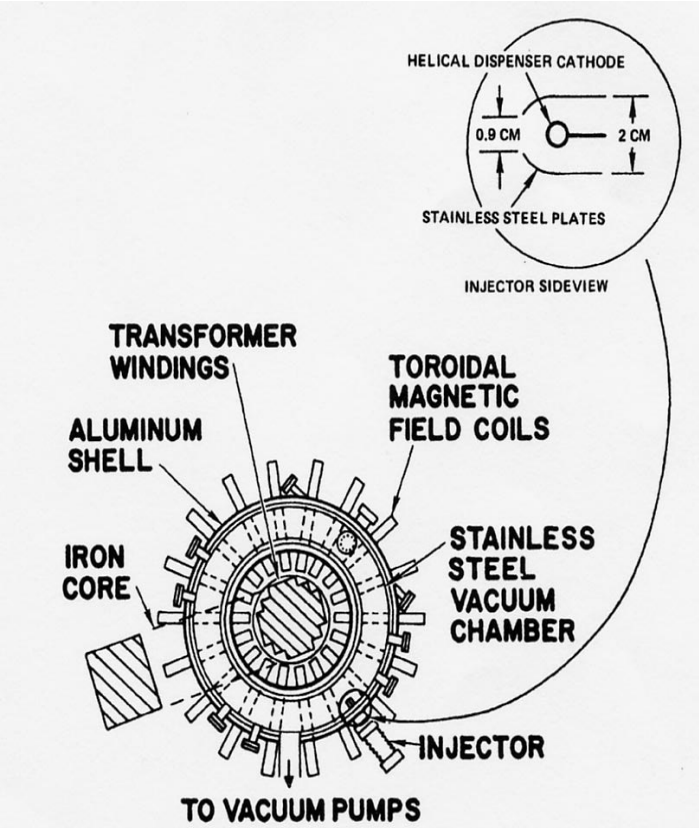
- magnetic field, 7.8 kG + vertical field for stabilizing

- R=0.5 m, r=0.081 m, vacuum 10^{-9} Torr

- Diocotron modes $f \approx Q / 8\pi^3 R r \varepsilon_0 B$

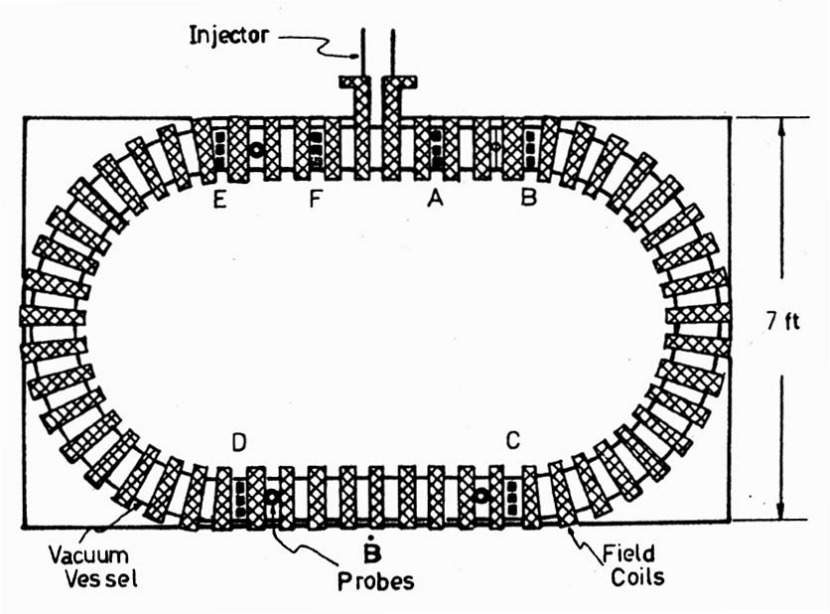
- oscillation after 200 µs → ion resonance instability

- I~20A



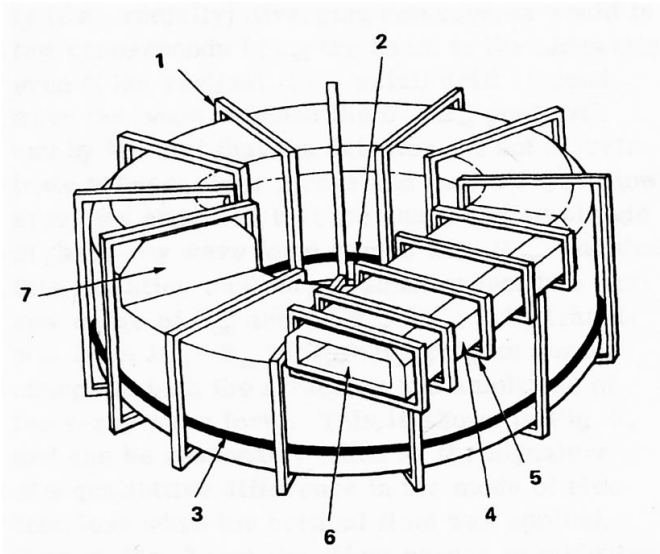
- P.Gillad (Cornell University, USA,1974)

- injection of relativistic electron beam (50 ns, 400 kV, 20 kA)
- 3.8 kG, trapping for 300 ns, pressure 1.5 Torr
- R=91cm, r=6.35cm



- J. Benford (Physics int. company, California, USA, 1974)

- injection of relativistic electron beam (10 kA, 40 ns, 0.96 – 1.75 MeV)
- Toroidal field 2.35 kG
- Drift control with vertical magnetic field 400-800 G
- Nitrogen gas – 1000 Torr → to provide rapid charge neutralization



- A. Mohri (Nagoya University, Japan, 1975)

- Magnetic field ~ 7 kG, + vertical magnetic field
- Lifetime ~ 20 μs, beam was not hollow
- Vacuum 6×10^{-7} Torr, $I_{current}$=300 A, density ~ 8×10^{8} cm^{-3}
- Radial electric field ~ 4×10^{3} V/m
- Ion resonance instability ? (Buneman, Levy, Daugherty)
- Low ion density → azimuthal wave mode l=1

$$\omega_e = n_e e / 2\varepsilon_0 B \cong \left(\Omega_E^2 + \frac{1}{4}\Omega_c^2 \right)^{\frac{1}{2}} - \frac{1}{2}\Omega_c = \Omega_i \,, \quad \Omega_E^2 = Z n_e e^2 / 2\varepsilon_0 m_i$$

- higher vertical field → displacement to major axis → excentricity → diocotron oscillations → hard-x-ray bursts → second instability

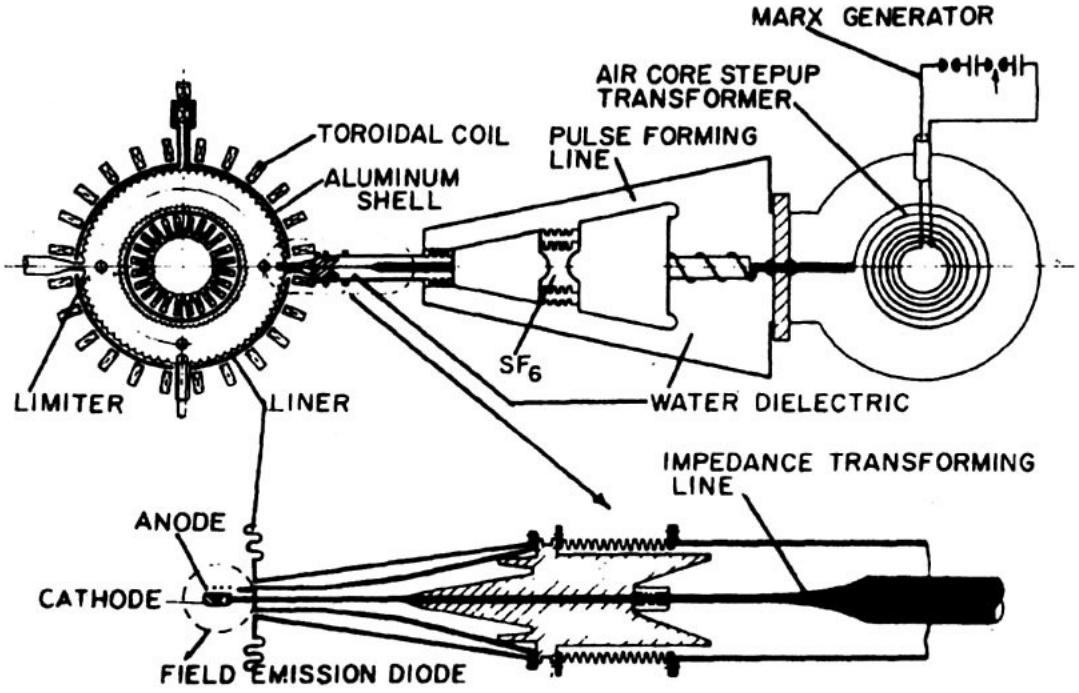
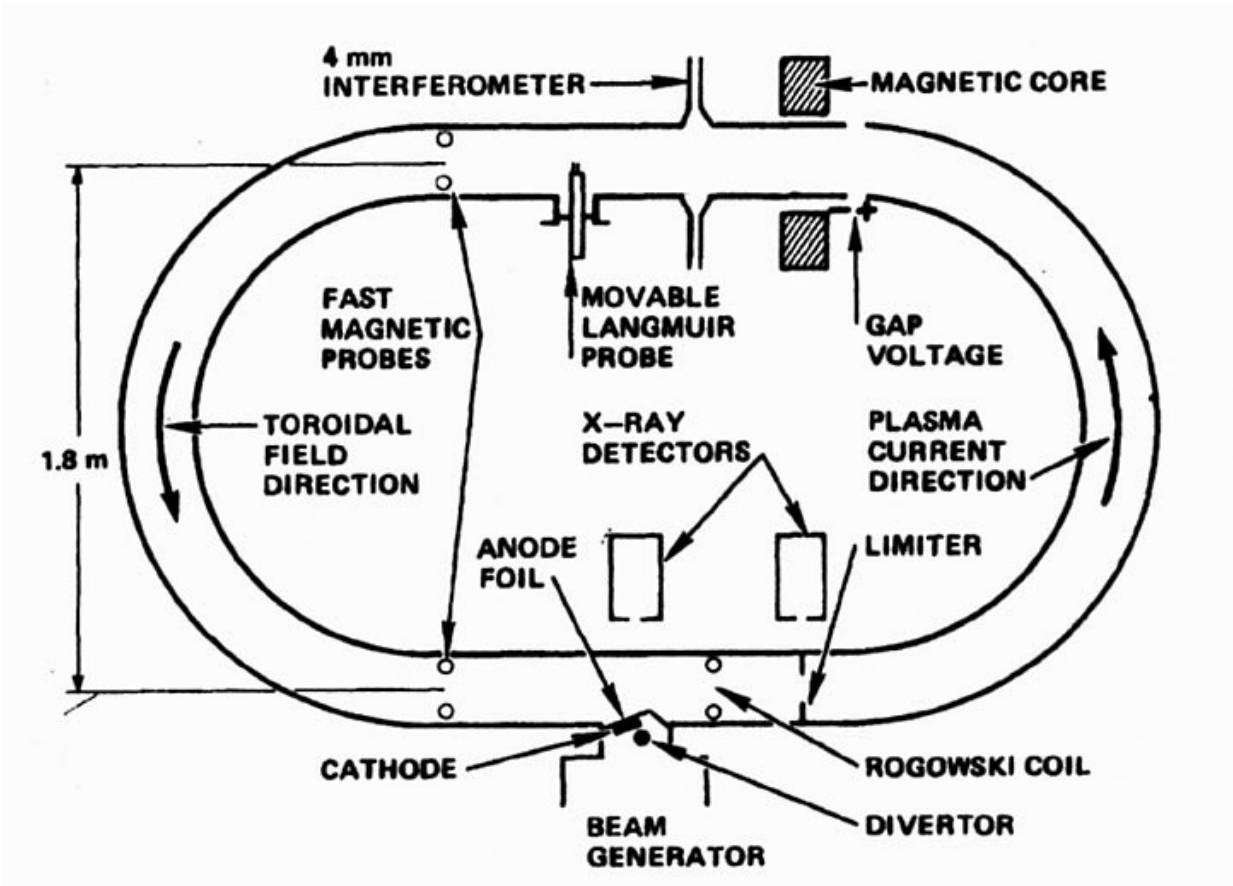


FIG. 1. Schematic view of the experimental setup.

- G. A. Proulx (Cornell University, USA, 1981)

- Relativistic electron beam
- Magnetic field 5 kG, r=6.3 cm, circumference 8 m
- Plasma was produced by an ohmic heating system
- Plasma currents ~ 400 – 1000 A, density 10^{12} – $2x10^{13}$ cm^{-3}
- Plasma temperature 10 – 20 eV
- Discharges in hydrogen, argon, nitrogen
- Confinement time 3 – 30 μs, no dependence on toroidal field or plasma current
- Injected beams, I ~ 10 kA, 400 keV, 50 ns


4 mm
INTERFEROMETER
MAGNETIC CORE
FAST
MAGNETIC
PROBES
MOVABLE
LANGMUIR
PROBE
GAP
VOLTAGE
TOROIDAL
FIELD
DIRECTION
X–RAY
DETECTORS
PLASMA
CURRENT
DIRECTION
1.8 m
ANODE
FOIL
LIMITER
CATHODE
ROGOWSKI COIL
BEAM
GENERATOR
DIVERTOR

- *Puravi Zaveri (Bhat, India,1991)*

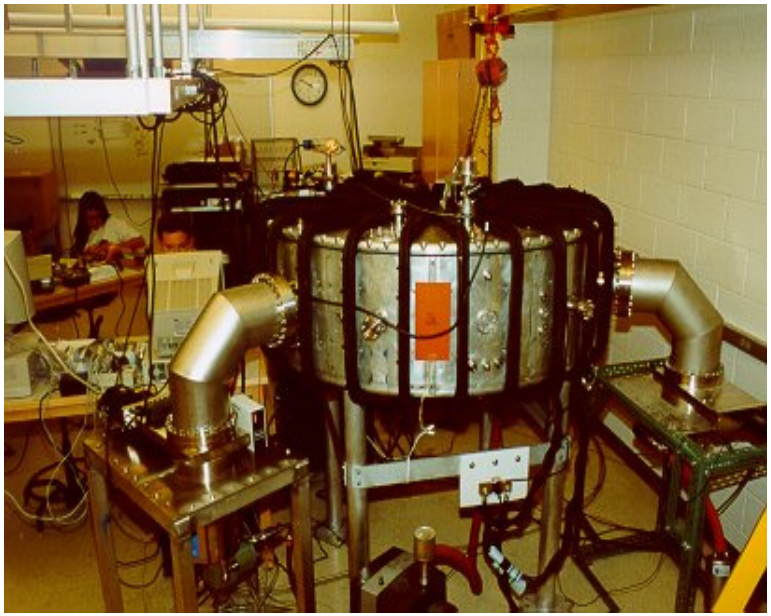
- *But strong ExB drift ->rotation overcomes curvature drift*
- *Equilibrium -> closer to the inboard conducting shell*
- *Strong toroidicity->strong distortion of the surfaces ->large elipticity and triangularity*
- *B <40,150>G*
- *Pressure $4x10^{-7}$ Torr, I=150 mA, density=$10^8 cm^{-3}$,confinement time 2-2.5 ms*
- *Theory->Only 3μs to reach the chamber wall due to (grad B) drift*
- *Diocotron instability*
- *Charge injection 15μs, grad B drift ~ 10^6 m/s, ExB drift ~ 10^8 m/s*

- M. R. Stoneking (Lawrence University, Wisconsin, USA, 2001)

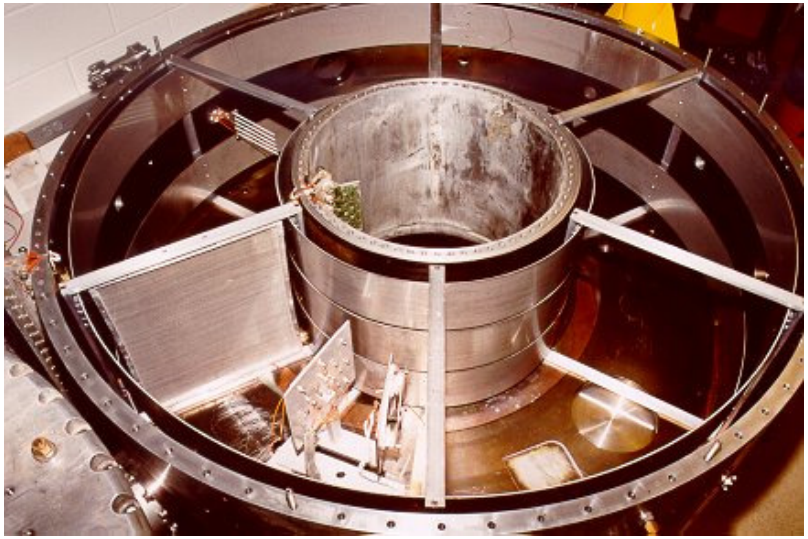
- electron plasma, partial torus, horizontal electric field *E=5-10 V/cm (larger than by Bhattacharyya ~ 1.4 V/cm for the same charge ~ 8.1 nC ~5x10^{10} electrons)*

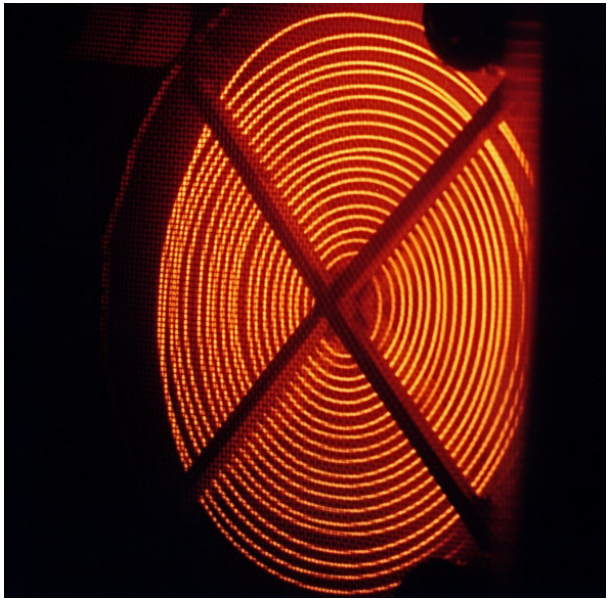
- *Vacuum chamber 3mm Al, square poloidal cross-section, R=0.5m*

- *Electron poloidal ExB drift frequency 240 kHz*
- *B = 196 G, typically energy W=100-200 eV*



- *Electron source – 0.5mm tungsten spiral – 22 turns - I=10.2A - T=1900K*
- *Pressure 10^{-6} Torr, I=150 mA, density=$3.1 \times 10^{6} cm^{-3}$,confinement time 0.1 ms*
- *At small electric field → no evidence of traping*
- *Some evidence of low frequency oscilation → ion resonance → possible diocotron modes → modification with horizontal electric field*





- C. Nakashima (University of Tokio, Japan, 2001)

- R=59 cm, height h=90 cm, internal ring conductor R0=30 cm (ring current ~ 7.875 kAT
- Pressure ~ $3x10^{-7}$ Torr, W ~ 2 keV
- I ~ 10 mA
- Magnetic field toroidal ~ 3 G, poloidal ~ 40 G
- Trapping 3 µs (2 keV), low-energy electrons (5 eV) is magnetized in trapping region and moves on magnetic surfaces
- plasma temperature 60 eV

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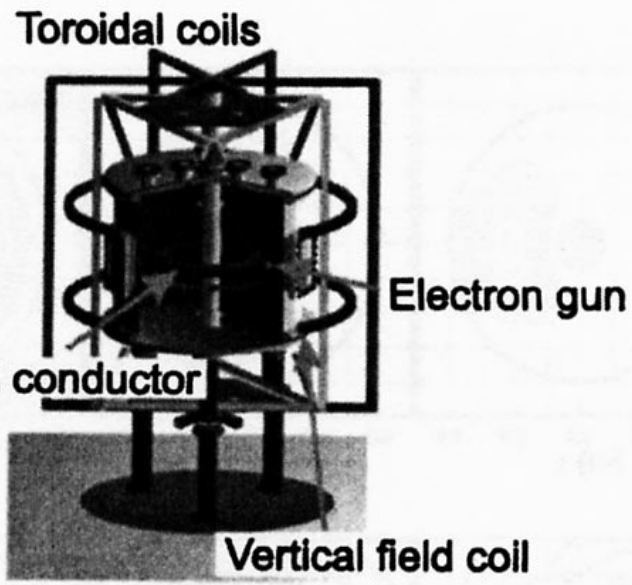
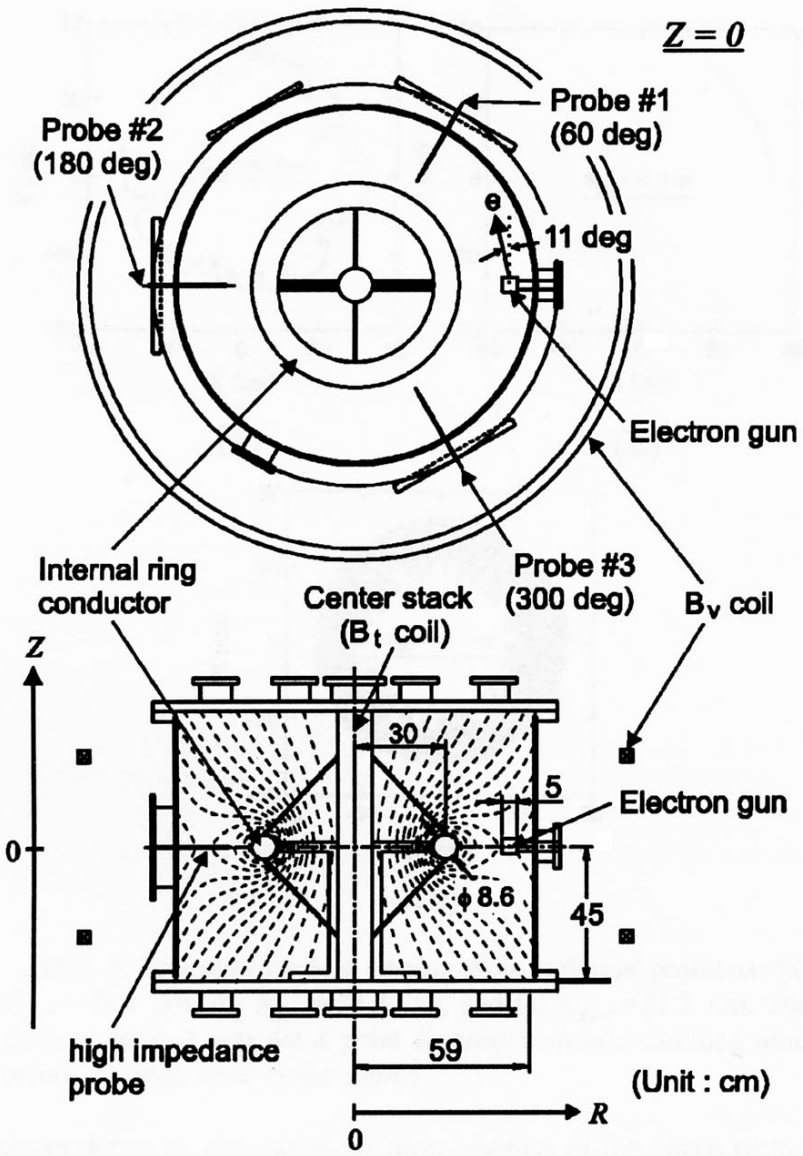




Magnetic coordinates for stellarator fields

Magnetic surface:

If a magnetic field line stays within a surface, coming arbitrarily close to any point on the surface, then that surface is a magnetic surface.

Stellarator:

Magnetic surface created entirely by external coils – no need for a net plasma current or solid conductors immersed in the plasma

Why care about magnetic surfaces?:

Novel plasma physics – equilibrium and stability is different from previously studied configuration

Confines both quasi-neutral and single component plasma

Injection of toroidal pure electron plasma is easier than in pure toroidal field

Magnetic coordinates for stellarator fields

Boozer-like coordinates → field line trace →

- Rotational transformation ι
- Toroidal and poloidal currents flow

$$\chi = \int \vec{B} d\vec{l}$$

- covariant representation (assumption of scalar

$$\vec{B} = \vec{\nabla}\chi + \beta\vec{\nabla}\psi_T$$

- pressure MHD equilibrium → **j**

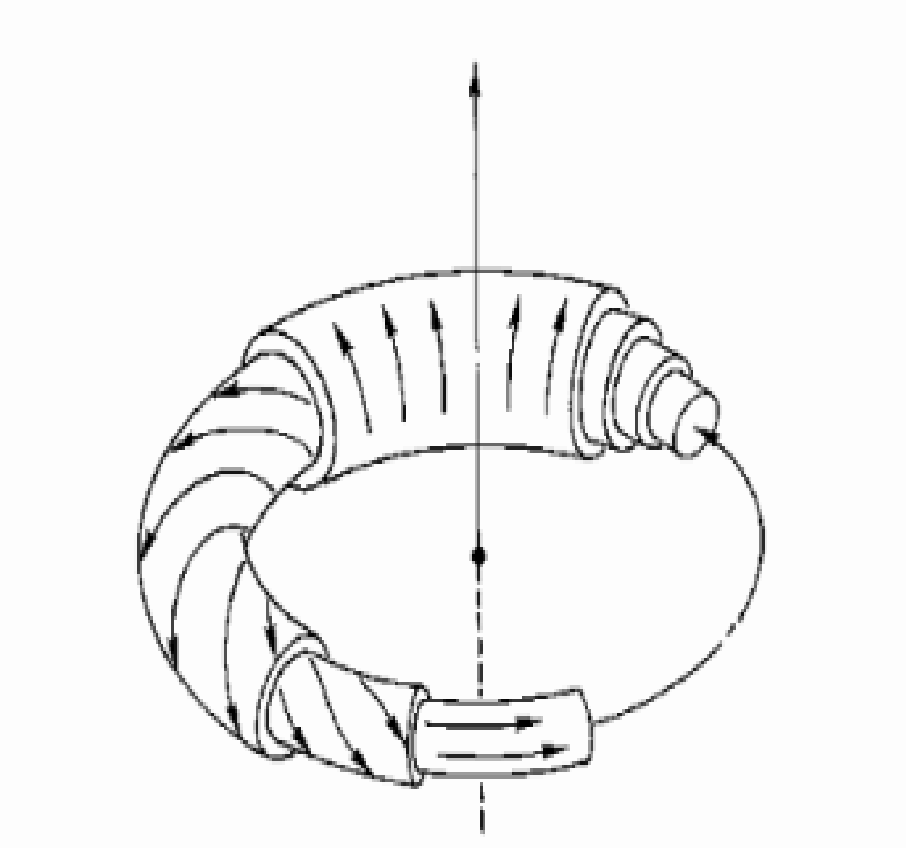
$$\vec{j} \cdot \vec{\nabla}\psi_T = 0$$

- Magnetic field on flux surface

→ $\vec{B} = \vec{\nabla}_{\parallel}\chi_0$

- Contravariant representation

$$\vec{B} = \vec{\nabla}\psi_T \times \vec{\nabla}\theta_0$$



CNT – non neutral plasma device

CNT – non neutral plasma device

Main parameters:

Major radius	0.3m	Minor radius	0.1m
Magnetic field	0.2T	Rot.transform.	0.06-0.3
Field line shear	0-20%	T_e	1-50eV
n_e	10^7-10^8 cm^{-3}		

-Diocotron modes can be stabilized either by Landau damping

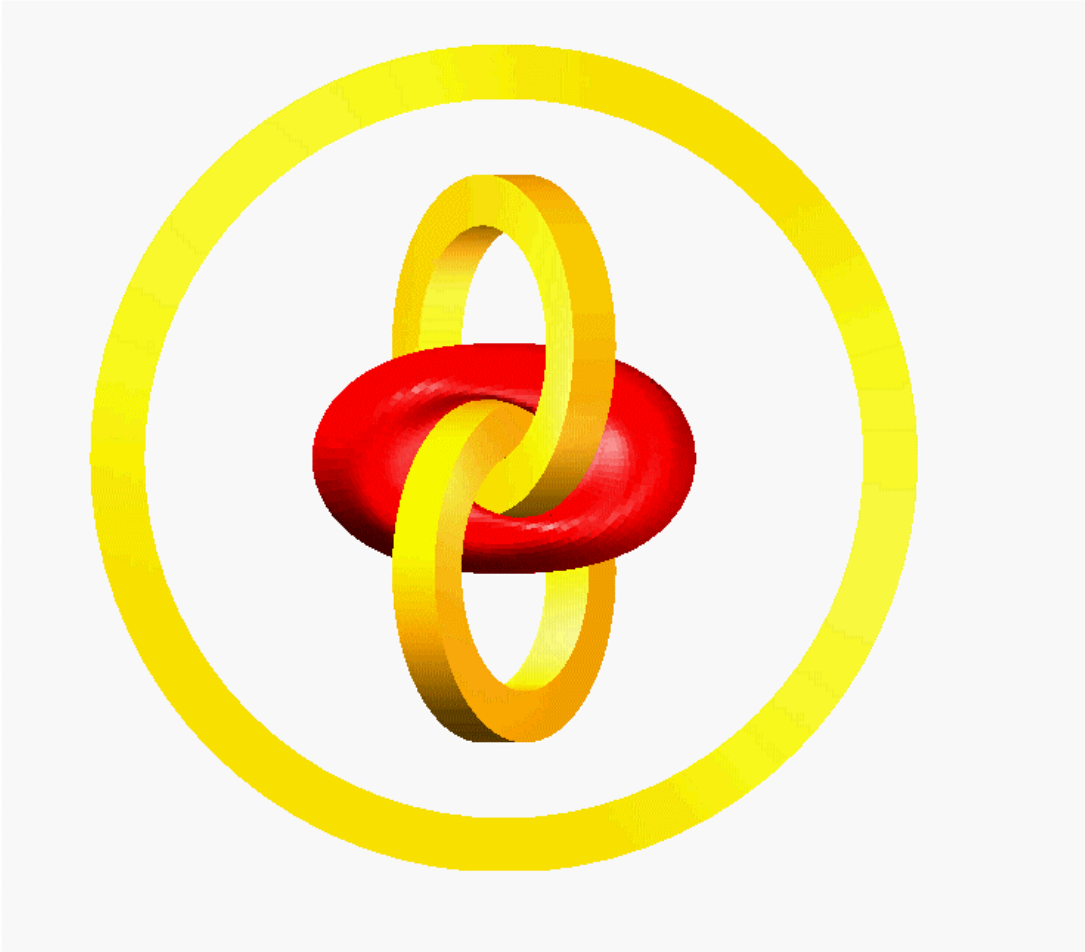
$$R/(\iota\lambda_D)\cdot\sqrt{n/n_B} << 1, \quad \lambda_D = \sqrt{\varepsilon_0 T_e/(e^2 n_e)}, \quad n_B = \varepsilon_0 B^2/(2m_e)$$

-or by magnetic shear

-electrical current -> change in the magnetic field $\delta B/B \approx (n_e/n_B)^2\left(\frac{a}{c/\omega_c}\right)^2$

-equilibrium → self-consistent equation $\nabla^2\phi = \frac{e}{\varepsilon_0}N(\psi)\exp\left(\frac{e\phi}{T_e(\psi)}\right)$

Magnetic configuration of CNT-device



IAP study of high current ring

Main parameters:

Major radius R	0.5-1.0m
Minor radius r	0.1-0.25m
Magnetic field B	0.1-1.0T
Rot. transform.	~ 0.37

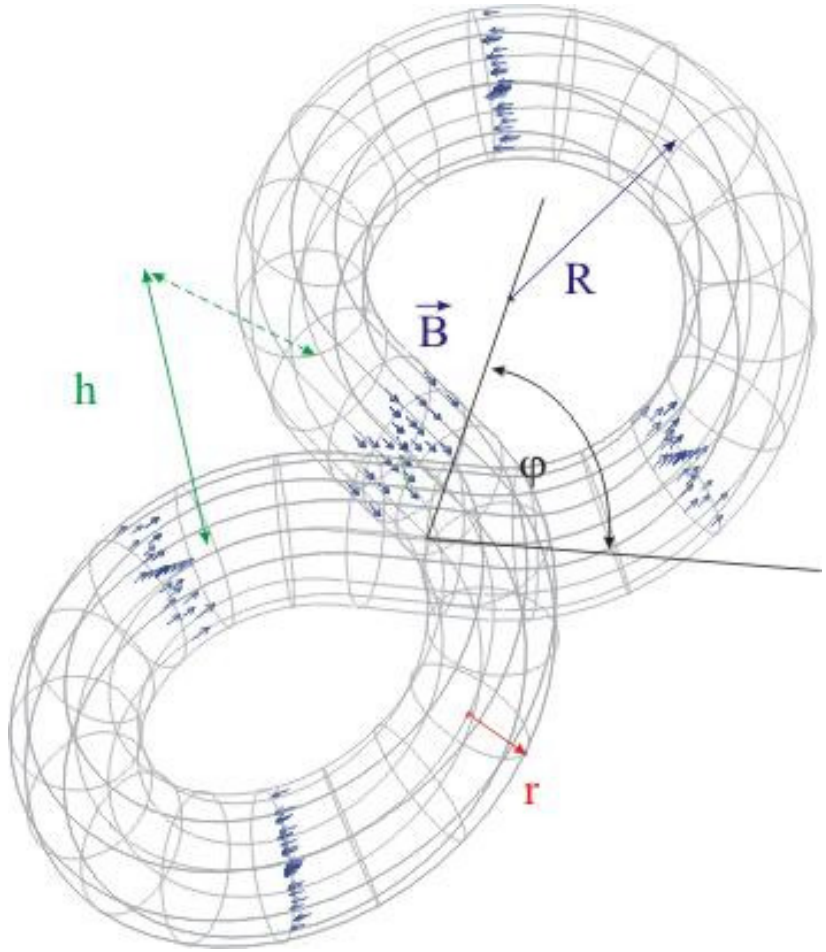
Single particle motion – stable

Twisting of magnetic field lines

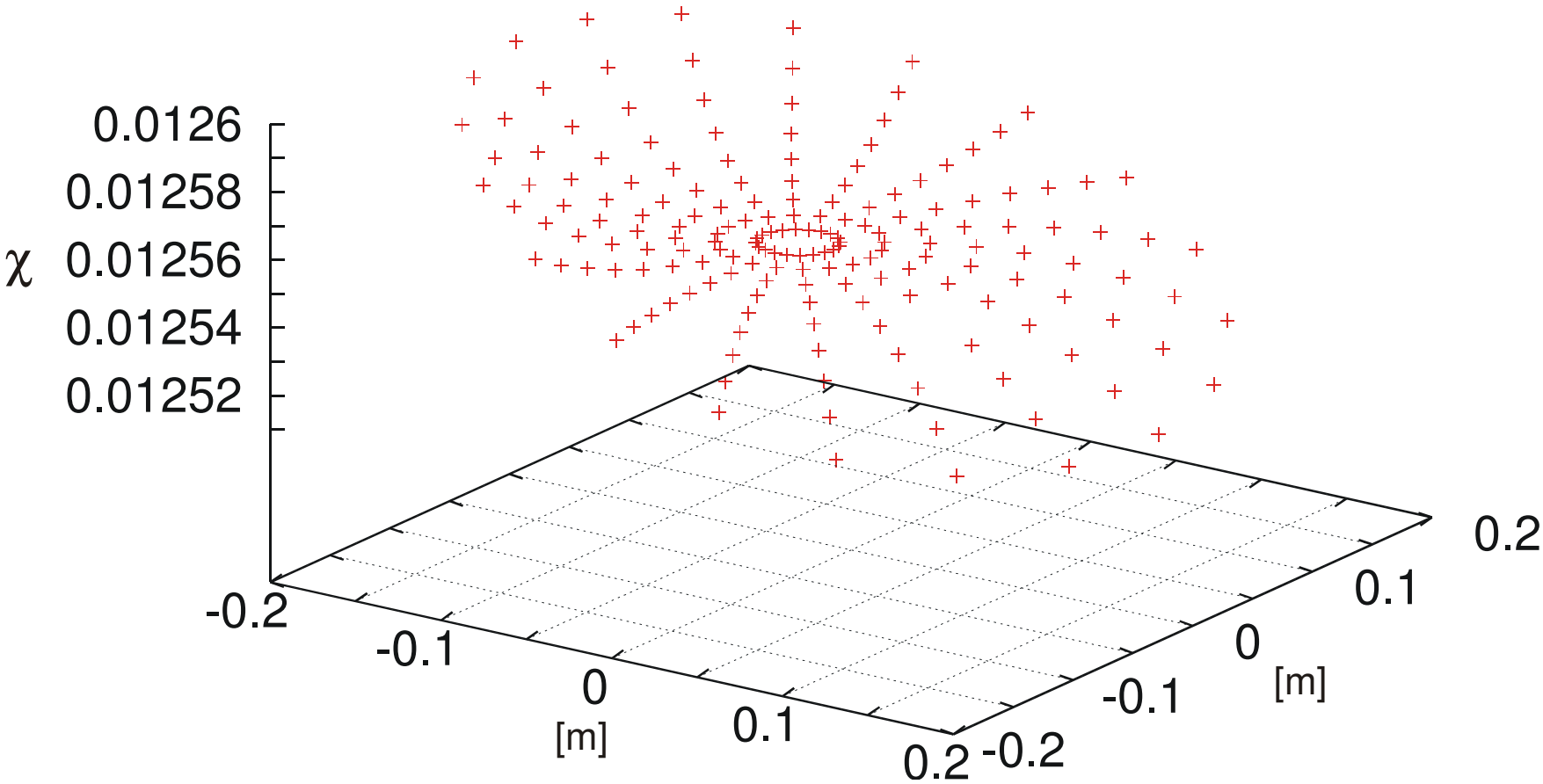
(cca 134° in 1 toroidal turn)

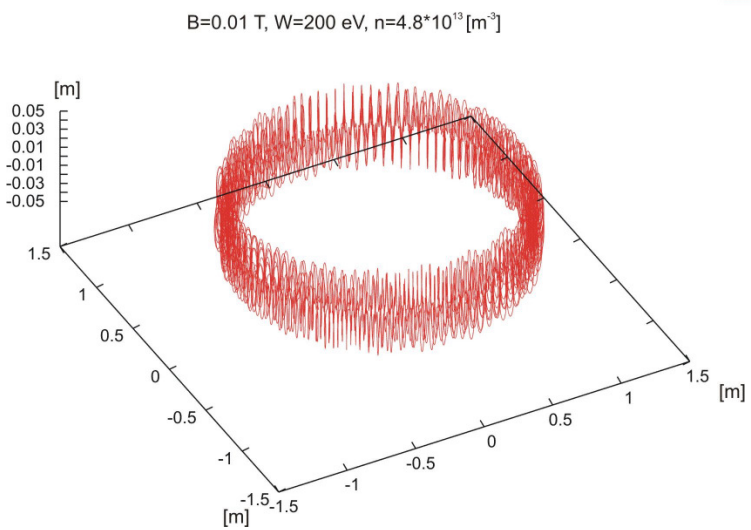
Electric field study – ideal conducting walls

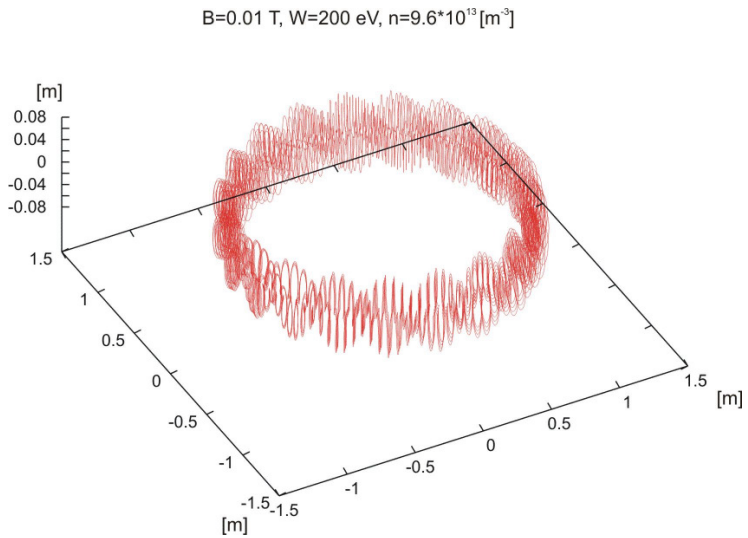
ExB drift dynamics

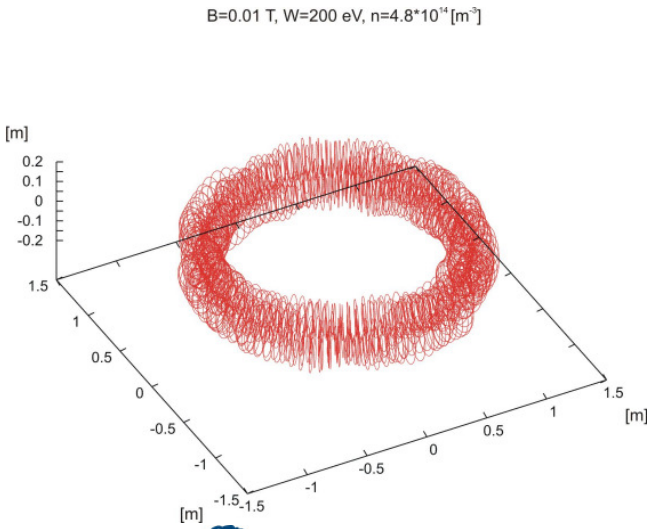


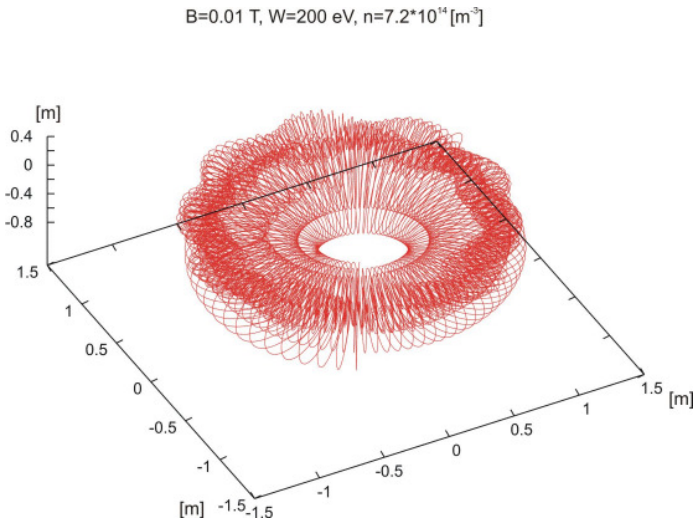
χ – parameter in 1 turn around the 8-figure ring

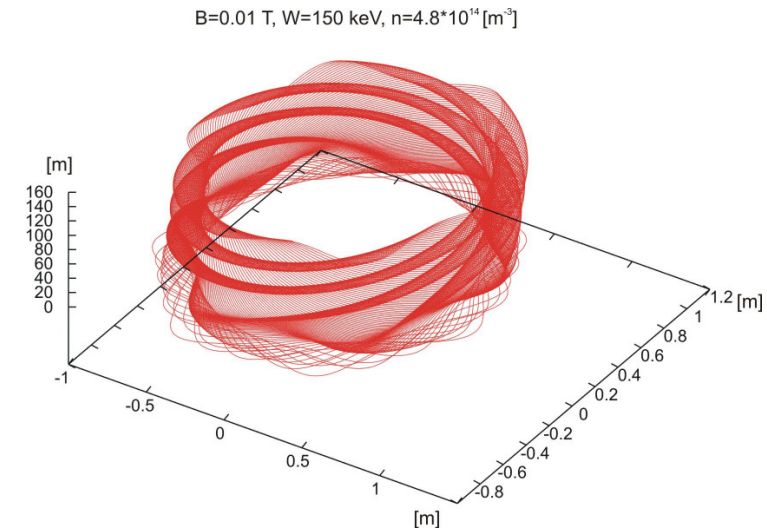


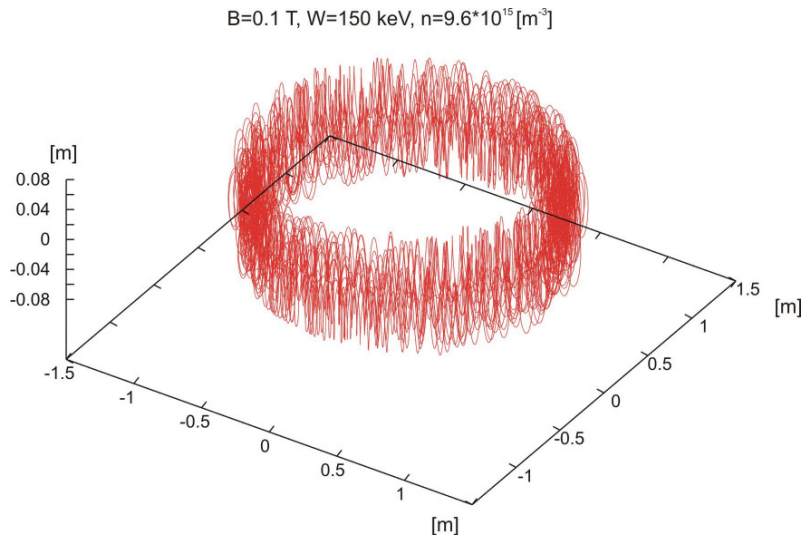

B=0.01 T, W=200 eV, n=4.8*10^13 [m^-3]
[m]
0.05
0.03
0.01
-0.01
-0.03
-0.05
1.5
1
0.5
0
-0.5
-1
-1.5
[m]
-1.5
-1
-0.5
0
0.5
1
1.5
[m]

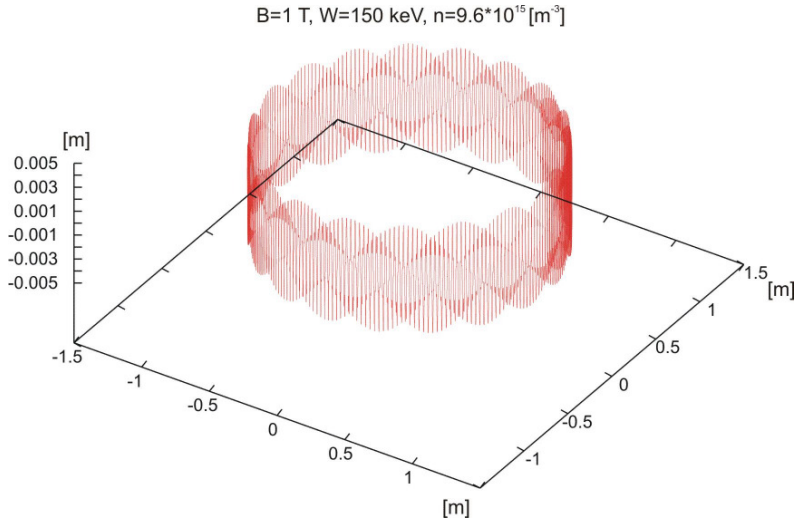

B=0.01 T, W=200 eV, n=9.6*10^13 [m^-3]
[m]
0.08
0.04
0
-0.04
-0.08
1.5
1
0.5
0
-0.5
-1
-1.5
[m]
-1.5
-1
-0.5
0
0.5
1
1.5
[m]

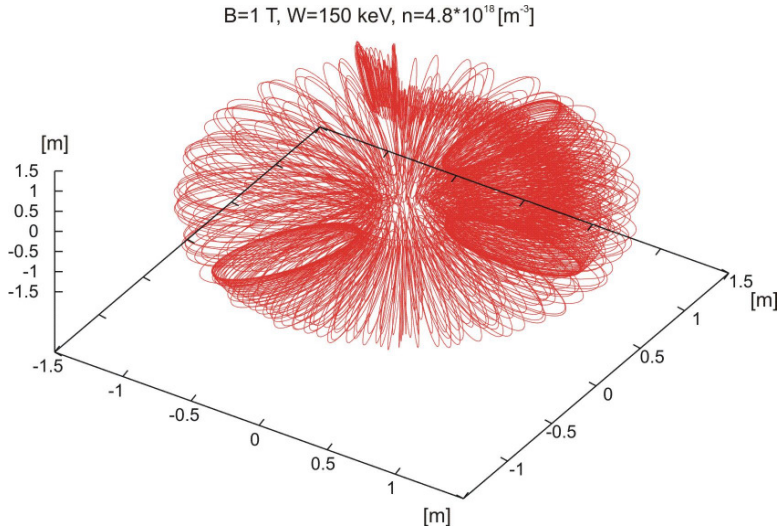

B=0.01 T, W=200 eV, n=4.8*10^14 [m^-3]
[m]
0.2
0.1
0
-0.1
-0.2
1.5
1
0.5
0
-0.5
-1
-1.5
[m]
-1.5
-1
-0.5
0
0.5
1
1.5
[m]


B=0.01 T, W=200 eV, n=7.2*10^14 [m^-3]
[m]
0.4
0
-0.4
-0.8
1.5
1
0.5
0
-0.5
-1
-1.5
[m]
-1.5
-1
-0.5
0
0.5
1
1.5
[m]


B=0.01 T, W=150 keV, n=4.8*10^14 [m^-3]
[m]
160
140
120
100
80
60
40
20
0
-1
-0.5
0
0.5
1
[m]
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
[m]


B=0.1 T, W=150 keV, n=9.6*10^15 [m^-3]
[m]
0.08
0.04
0
-0.04
-0.08
-1.5
-1
-0.5
0
0.5
1
[m]
1.5
1
0.5
0
-0.5
-1
[m]


B=1 T, W=150 keV, n=9.6*10^15 [m^-3]
[m]
0.005
0.003
0.001
-0.001
-0.003
-0.005
-1.5
-1
-0.5
0
0.5
1
[m]
1.5
1
0.5
0
-0.5
-1
[m]


B=1 T, W=150 keV, n=4.8*10^18 [m^-3]
[m]
1.5
1
0.5
0
-0.5
-1
-1.5
-1.5
-1
-0.5
0
0.5
1
[m]
1.5
1
0.5
0
-0.5
-1
[m]

Particle motion in toroidal ExB field

Summary

- Toroidal confinement of non-neutral plasma (electrons)
- Confinement on magnetic surfaces
- CNT and IAP-high current ring

IAP study for high current ring

- B=1T, r=0.25m, R=0.5m

- Electrons

$$\omega_g = qB/m = 1.76 \cdot 10^{11} Hz$$

$$r_g = m/qB \cdot v_\perp = 5.7 \cdot 10^{-12} \cdot v_\perp [m]$$

$$v_{d0} = \frac{m}{qBR}\left[v_\parallel^2 + \frac{v_\perp^2}{2}\right] = \frac{5.7 \cdot 10^{-12}}{\sqrt{1-\frac{v^2}{c^2}}}\left[v_\parallel^2 + \frac{v_\perp^2}{2}\right]$$

Protons

$$\omega_g = qB/m = 9.6 \cdot 10^{7} Hz$$

$$r_g = m/qB \cdot v_\perp = 1.04 \cdot 10^{-8} \cdot v_\perp [m]$$

$$v_{d0} = \frac{m}{qBR}\left[v_\parallel^2 + \frac{v_\perp^2}{2}\right] = 1.04 \cdot 10^{-8}\left[v_\parallel^2 + \frac{v_\perp^2}{2}\right]$$

$$v_E = \frac{1}{B^2}[E \times B]$$

Theory

- K. Avinash (Bhat, India,1991)

- drift surfaces shifted toward the major axis ~ $r/R(\omega_p/\omega_c)^2$
- in the absence of the conducting shell, the force along major radius could be balanced by an externally applied electric field
- question: as the walls of vessels are never perfect conducting, what happens to the shifted equilibrium in the presence of finite resistivity of the walls? → resistivity destroy imaging charges → grow of diocotron modes → instability

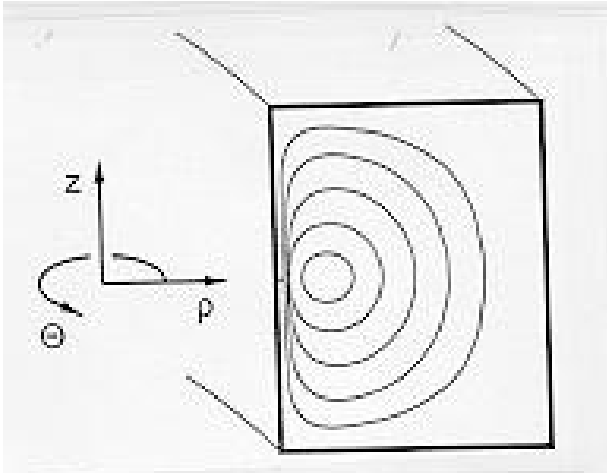


FIG. 9. Five maximum energy states for waterbag model.