Simulationsrechnungen zum Niederenergie-Ionenspeicher

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Inhalt:

- Magnetische toroidale Systeme
- Geometrie
- Magnetfeld
- Teilchensimulation
- Ausblick

Magnetische Systeme mit toroidaler Symmetrie

- Gyrationsbewegung

$$\omega_g = qB / m$$

- Drift

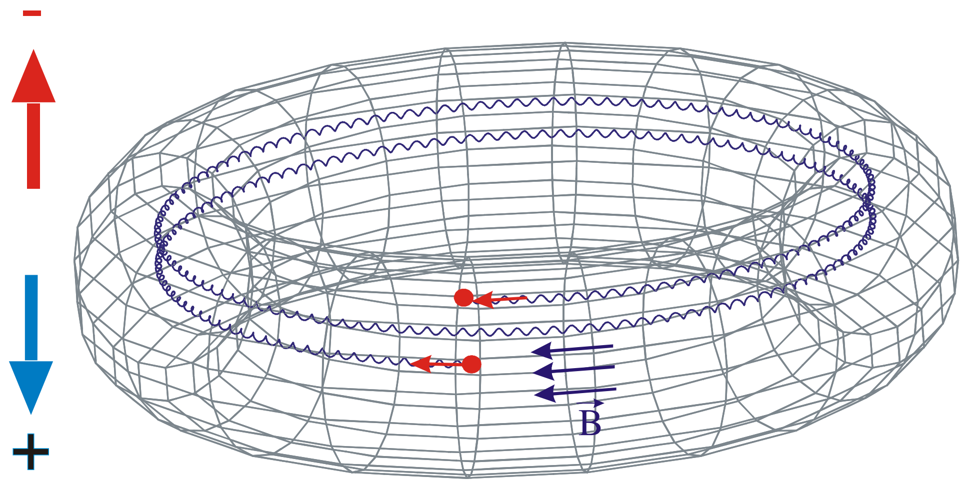
$$\vec{F} \times \vec{B}$$

$$\vec{F} = \vec{F}_c + \vec{F}_{\nabla B}$$

$$\vec{F}_c = m v_{\parallel}^2 / R \cdot \vec{e}_r$$

$$\vec{F}_{\nabla B} = -\mu \cdot grad\ \vec{B}$$

Ladungstrennung aufgrund der Drift



Theorie

Driftgeschwindigkeit und Gyrationsfrequenz bei einer Feldkrümmung:

$$v_{d0} = \frac{m}{qBR}\left[v_{\parallel}^2 + \frac{v_{\perp}^2}{2}\right], \quad \omega_g = \frac{qB}{m}, \quad r_g = mv_{\perp} / qB$$

Bei konstanter Steigung $a = B_z/B_{long}$ in z-Richtung

$$v_d = v_{d0}\frac{1}{1-a^2}, \quad \omega_g = \omega_{g0}\sqrt{1-a^2}$$

Geometrie

Parameter:

$$\varphi = 72^{\circ}$$

h = 0.6 m

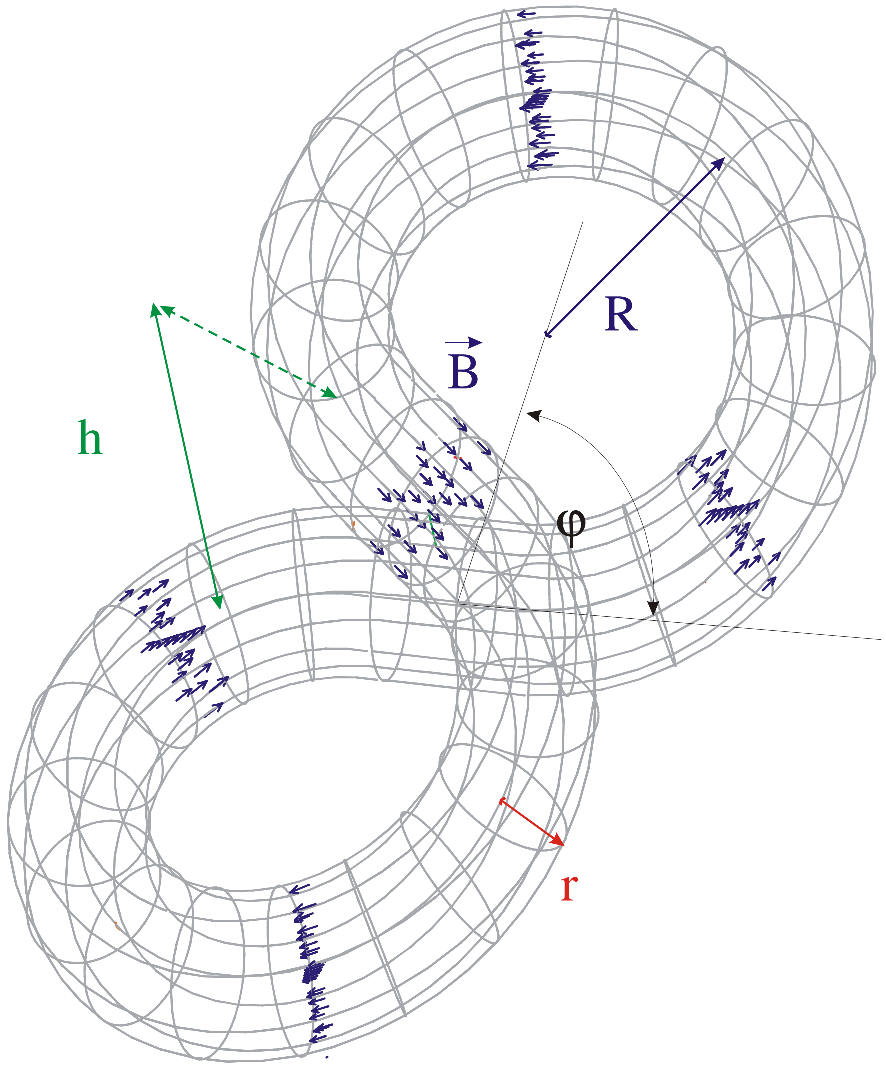
r = 0.25 m

R = 1 m

Steigung:

a) Linear

b) cos-Funktion



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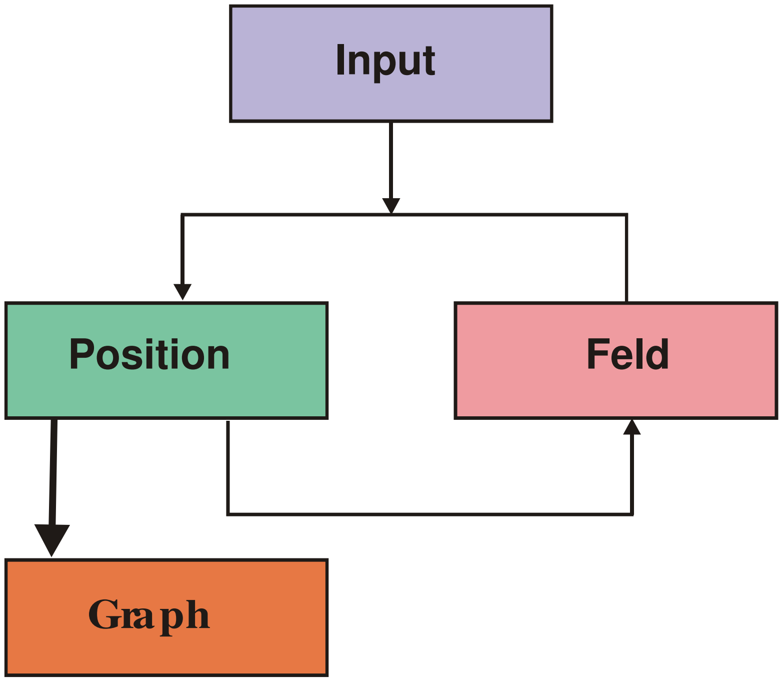
Teilchensimulation

- Feldberechnung – Biot-Savart Gesetz

$$\vec{B} = \int \frac{\mu I}{4\pi} \frac{d\vec{l} \times (\vec{r} - \vec{r}')}{\left|\vec{r} - \vec{r}'\right|^3}$$

- Bewegungsgleichung

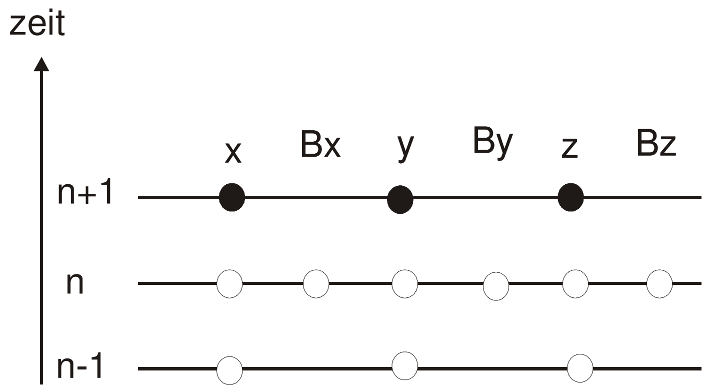
$$m \frac{d^2\vec{r}}{d\ t^2} = q\vec{v} \times \vec{B}$$



Numerische Methoden

- Numerische Integration
- FDTD – Methode

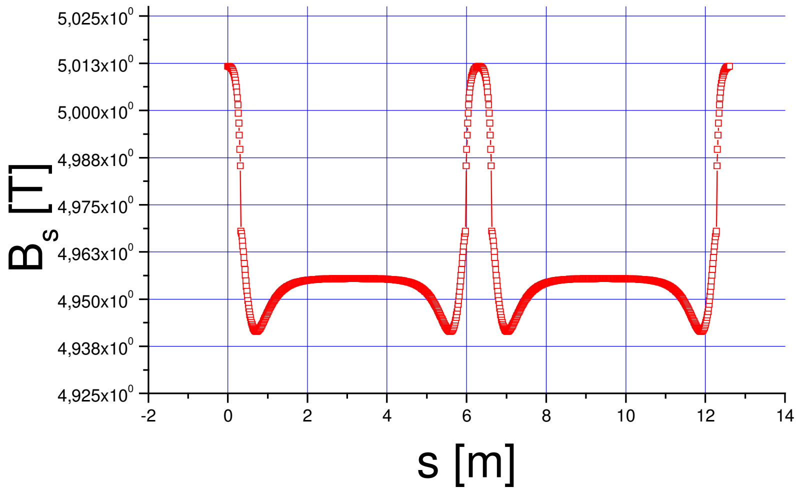
„leap-frog“ Verfahren

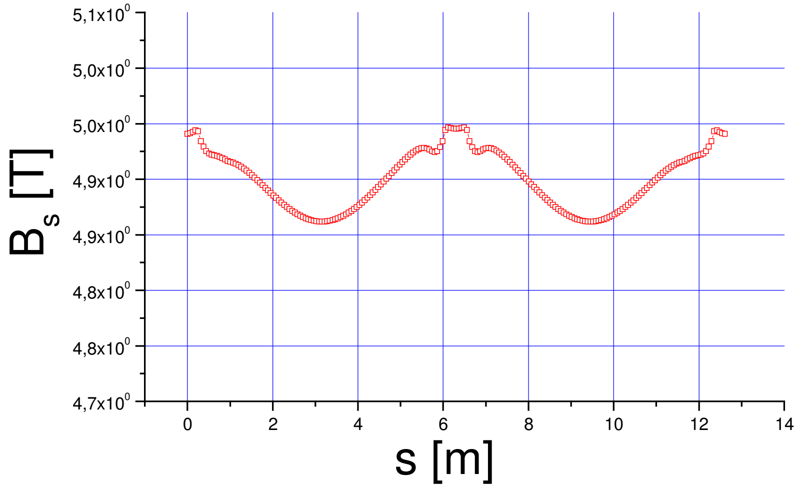


$$\frac{x_{n+1}}{\Delta t^2} - B_{z,n}\frac{q}{m}\frac{y_{n+1}}{2\Delta t} + B_{y,n}\frac{q}{m}\frac{z_{n+1}}{2\Delta t} =$$

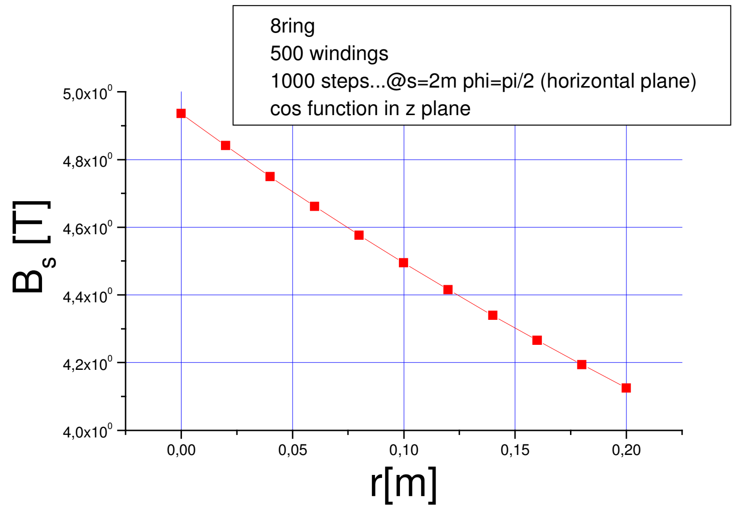
$$\frac{2x_n}{\Delta t^2} - \frac{x_{n-1}}{\Delta t^2} - B_{z,n}\frac{q}{m}\frac{y_{n-1}}{2\Delta t} + B_{y,n}\frac{q}{m}\frac{z_{n-1}}{2\Delta t}$$

Magnetfeld





- Symmetrisch
- 2% Schwankung auf der Achse
- 1/R – Abhängigkeit in radialer Richtung



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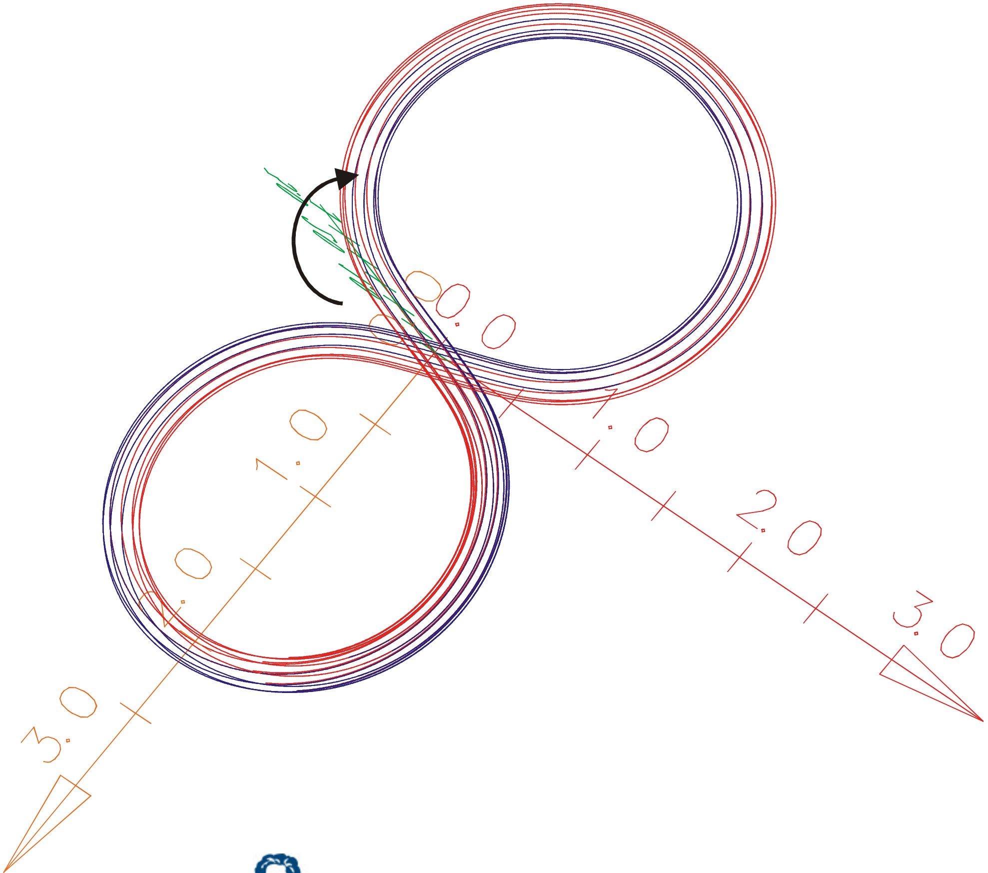
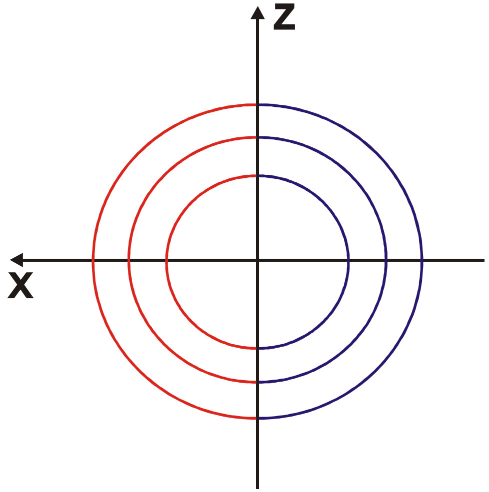
Rotation-Symmetrie

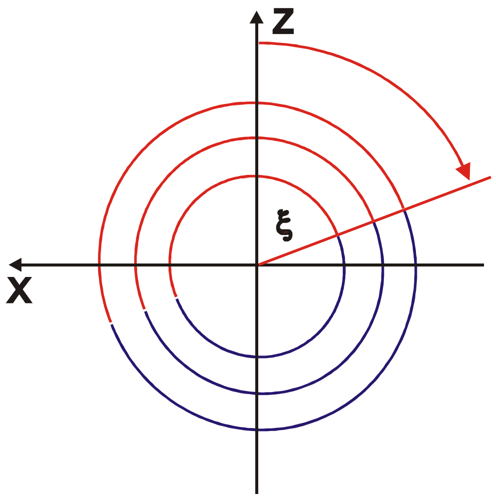
Drehung der magnetischen Flächen



Magnetische Flächen
Anfang



Magnetische Flächen
nach einem Umlauf



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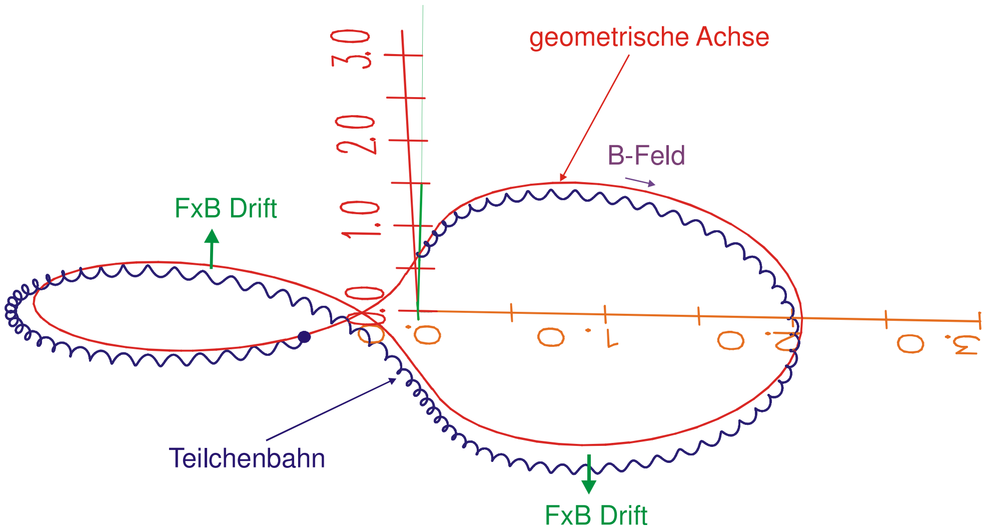
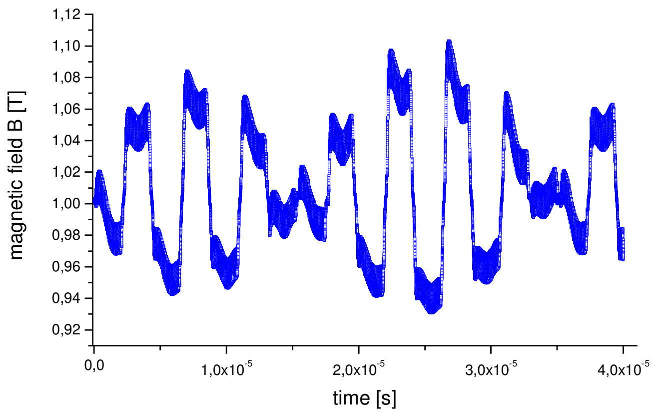
Einzelnteilchenbewegung



Field as a function of particle position



- Kurzzeit-Simulation (1-10 Umläufe)
- Stabile Bewegung
- Übereinstimmung mit der Theorie

Einschussebene

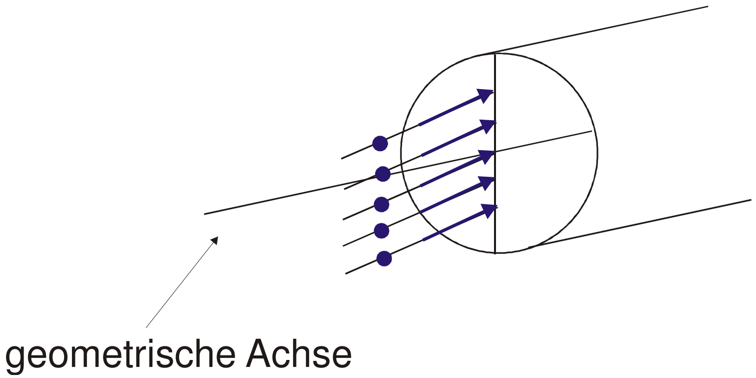
v_{long}/v_{trans} = const

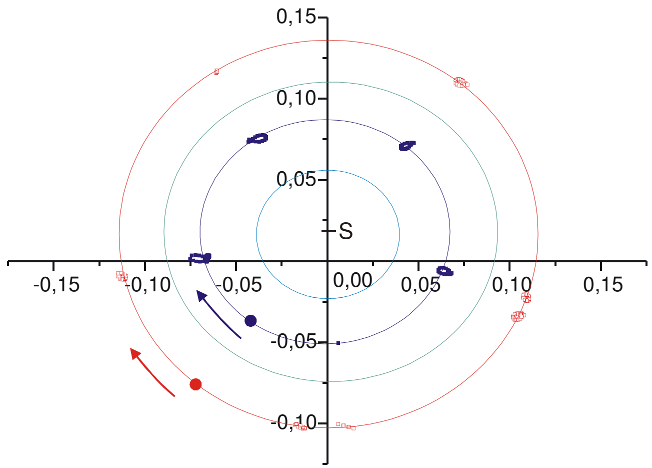
W = 150 keV

B = 5 T

R = 1 m

R1=0.25m





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Einschusswinkel

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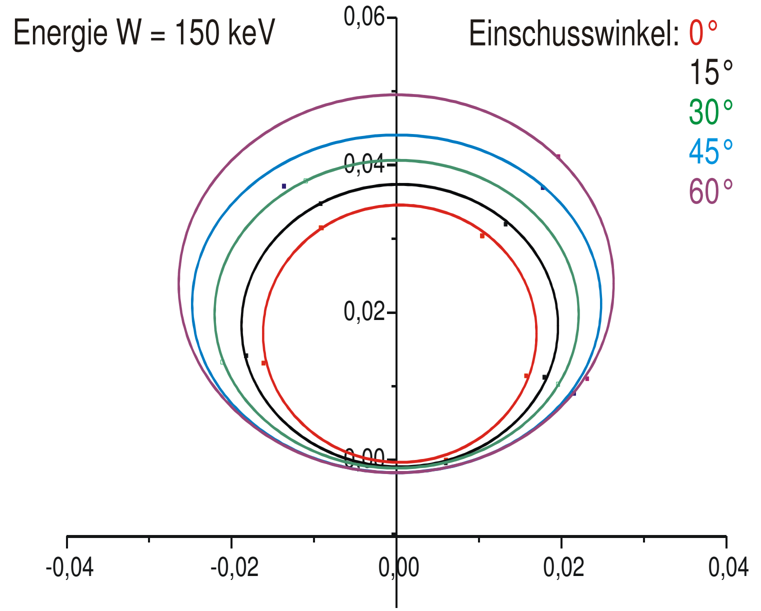

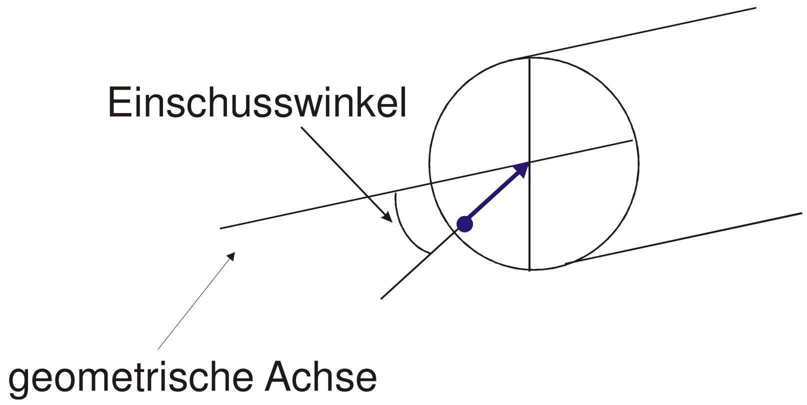

Ausblick

- Mehrteilchensimulation
- Raumladung
- Form der Magnetspulen
- Stabilität

New parameter set

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

- Electrons

Protons

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:

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

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

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

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

Experiments and Theory of non-neutral plasma

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

- relativistic electrons, densities ~ 10^{10} cm^{-3}, potential well ~ 300 kV
- toroidal magnetic field, 7.8 kG, rise time 2 - 3.5 ms, + vertical field for stabilizing
- R=0.5 m, r=0.081 m, Al shell 2.1 cm, vacuum 10^{-9} Torr
- Diocotron modes $f \approx Q / 8\pi^3 Rr\varepsilon_0 B$
- 2 probes
    1. Circular stain-less disk mounted flush with the vacuum wall, but electrically insulated from it…terminated 50 Ohm cable to osciloscop…imaging charges detection
    2. High impedance voltage probe….0.5 mm wire covered with an insulated glass sheath except for the tip which is exposed to the electron cloud, measuring potentials up to ~ 100 kV
- oscillation after 200 μs → ion resonance instability ?

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

- 2 stage Marx generator (100 kV, 5 kJ)
- Magnetic field ~ 7 kG, + vertical magnetic field
- Lifetime of the beam current fluctuated from run to run…longest ~ 20 µs, beam was not hollow
- Vacuum 6×10^{-7} Torr, $I_{current}$=300 A, density ~ 8×10^{8} cm^{-3}, potential well ~ 1.1×10^{4} V
- Radial electric field ~ 4×10^{3} V/cm
- Dump not observed in high gas pressure ~ 0.2 Torr
- Current at the onset of the dump was nearly constant over a wide range of pressure
- 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

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

- *Electrons should be lost due to curvature drift*
- *But strong ExB drift ->rotation overcomes curvature drift*
- *Electrostatic hoop forces tend to expand ring*
- *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*
- *Single particle to collective behaviour (*$I_{critical}$*=1 mA)*

- *T.S.Pedersen (Colombia University, New York, USA,2002)*

-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 $\delta B/B \approx (n_e/n_B)^2\left(\frac{a}{c/\omega_c}\right)^2$

- 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

- 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*
- *Coils 24 evenly spaced bundles of 4 turns each, connected in series*
- *2 interleaved sets (12 bundles each) are wound with opposing helicity → net toroidal current = 0*
- *Electron source – 0.5mm tungsten spiral – 22 turns - I=10.2A - T=1900K*
- *Pressure 10^{-6} Torr, I=150 mA, density=3.1x10^{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*

Magnetic coordinates for stellarator fields

- X.Bonnin (Greifswald, Germany, 2003)

- Boozer-like coordinates → field line trace → $\chi_0 = \int \vec{B} d\vec{l}$
- Definition of flux surfaces
- Rotational transformation ι
- Toroidal and poloidal currents flow

- F.Alladio (Frascati, Italy, 1995)

- $d\chi_0 = \vec{B} d\vec{l}$
- covariant representation $\vec{B} = \vec{\nabla}\chi_0 + \beta\vec{\nabla}\psi_T$ (assumption of scalar pressure MHD equilibrium → **j** flows along flux surfaces → $\vec{j} \cdot \vec{\nabla}\psi_T = 0$)
- Magnetic field on flux surface $\vec{B} = \vec{\nabla}_{\parallel}\chi_0$ →
- Contravariant representation $\vec{B} = \vec{\nabla}\psi_T \times \vec{\nabla}\theta_0$