Charged particle beams in strong magnetic fields

Martin Droba

Contens

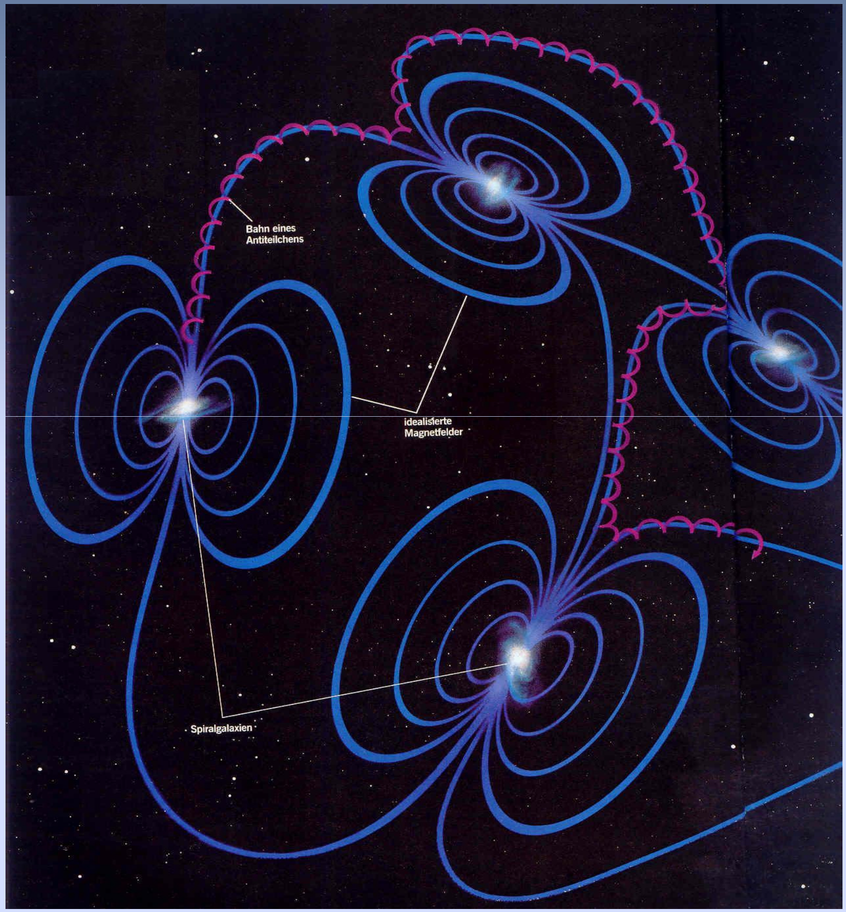
- Solenoid
- Figure-8 Configuration
- Drift motion
- Summary and Outlook

How strong is enough ?

	typicall |B|
Galactic center	1-2 nT
Near the solar center	0,5-1 nT
Halo	0,25 nT
Interstellar space	0,1 nT

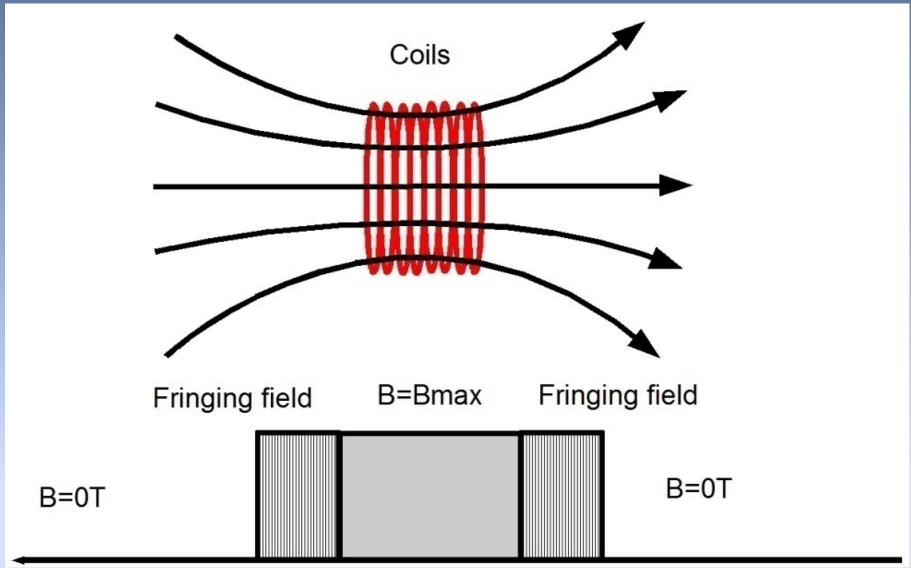
„Galactic Magnetic Field“,
AIP Handbook, 3rd Edition

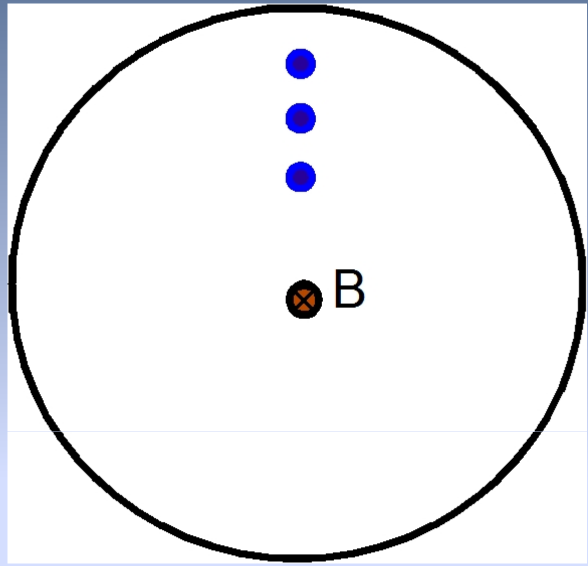
Earth magnetic field	30-60 μT
Gabor-Plasma Lens	6-16 mT
Bruker-focusing Solenoid (Transport Experiments)	0.15 T
ITER	5.3 T
LHC	8.4 T



Spektrum der Wissenschaft, Dossier, Kosmologie

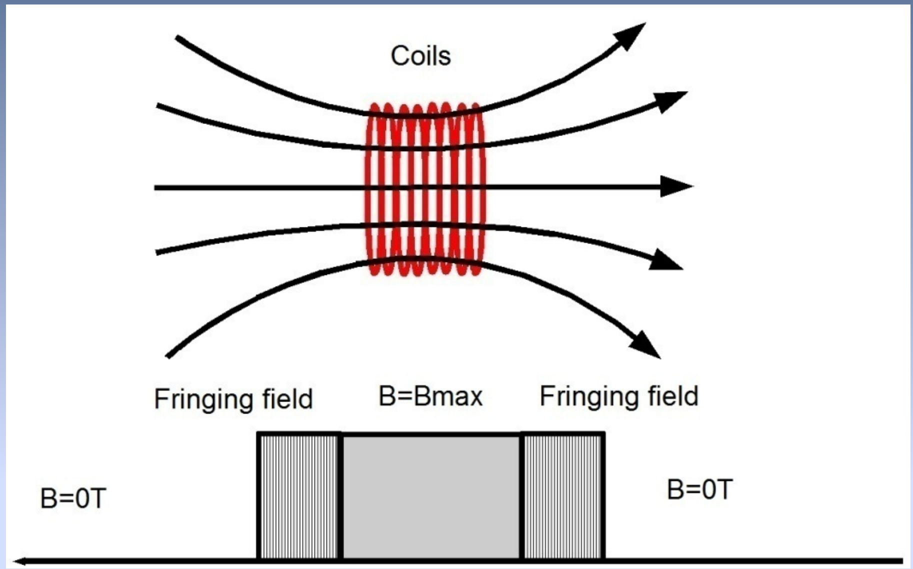
Solenoid 1.

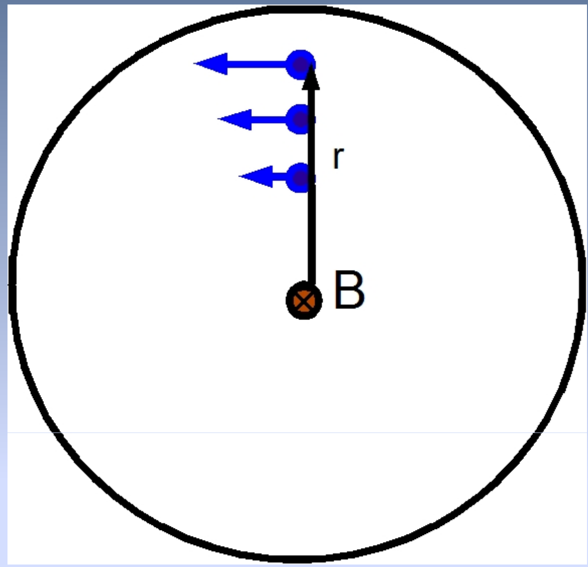




3 charged particles moving parallel

Solenoid 1.





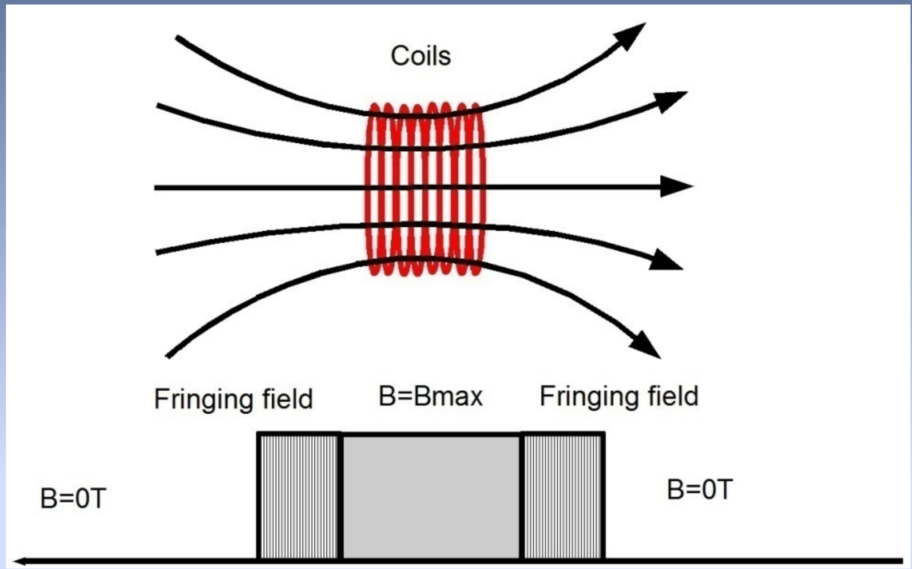
3 charged particles moving parallel

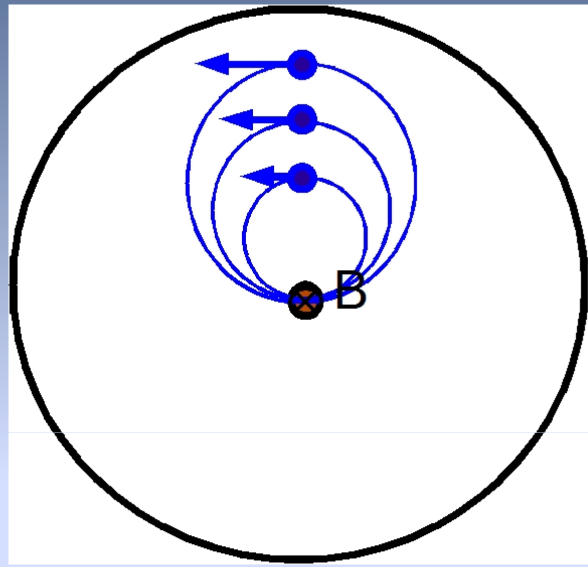
$$v_\varphi = qA_\varphi / m = qB_{\max} \cdot r / 2$$

transversal kick

$$r_L = \frac{mv_\varphi}{qB}$$

Solenoid 1.





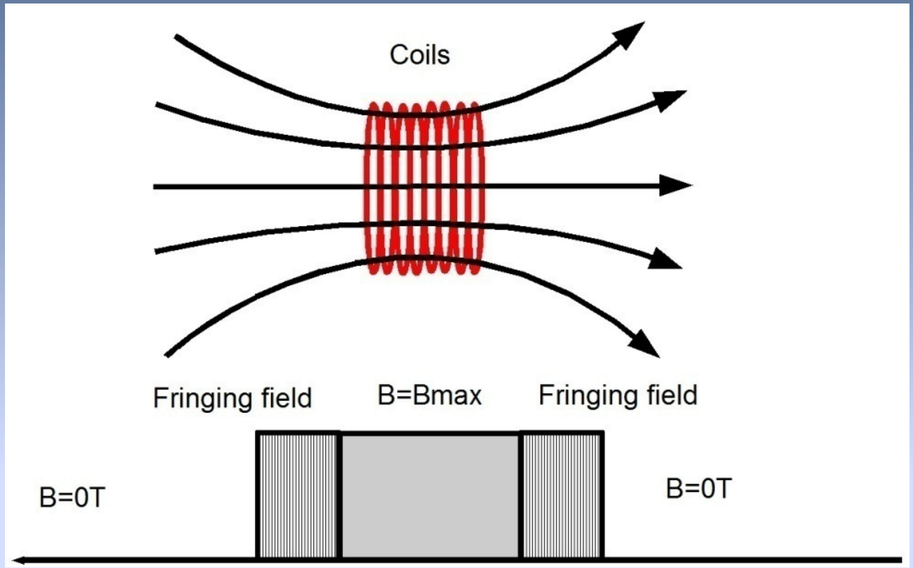
3 charged particles moving parallel

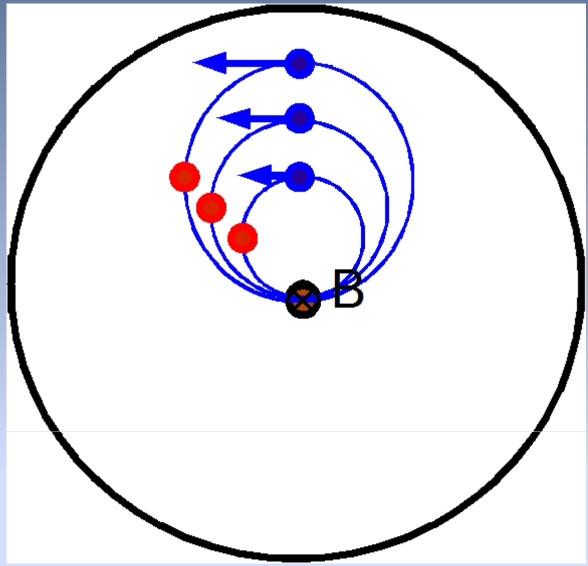
transversal kick

$$v_\varphi = qA_\varphi / m = qB_{\max} \cdot r / 2$$

$$r_L = \frac{mv_\varphi}{qB} \qquad r_L = \frac{r}{2}$$

Solenoid 1.





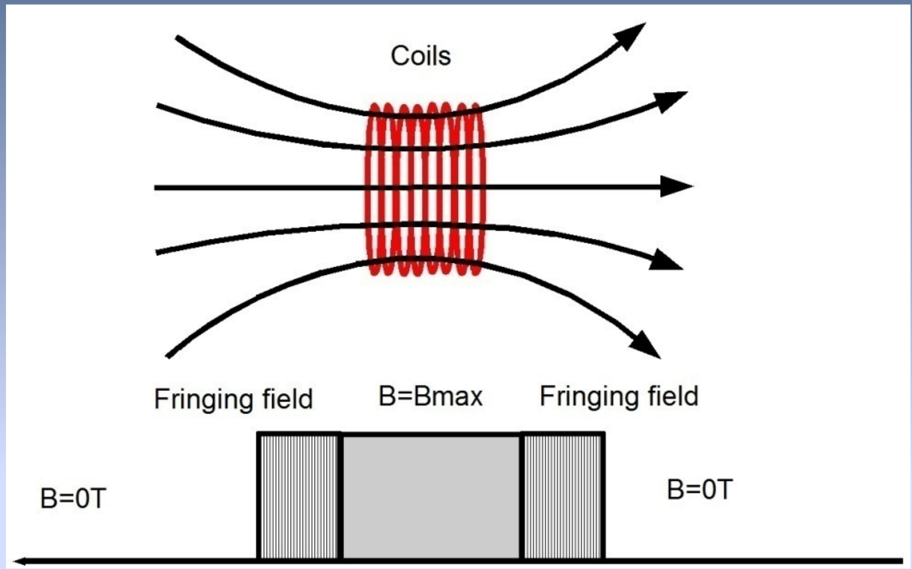
3 charged particles moving parallel

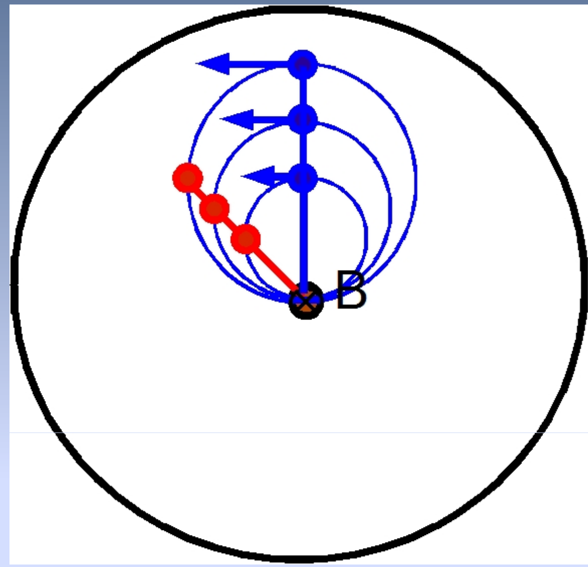
$$v_\varphi = qA_\varphi / m = qB_{\max} \cdot r / 2$$

transversal kick
new position

$$r_L = \frac{mv_\varphi}{qB} \qquad r_L = \frac{r}{2}$$

Solenoid 1.





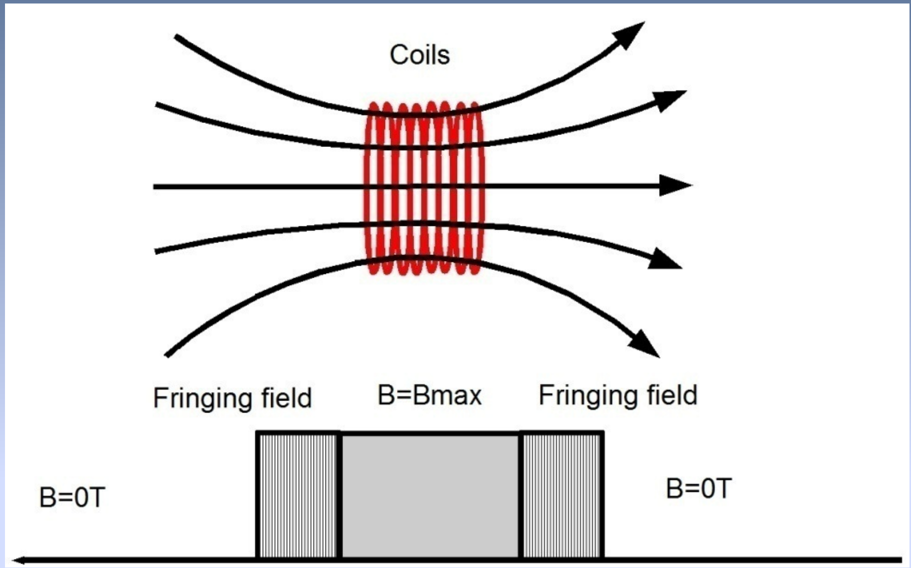
3 charged particles moving parallel

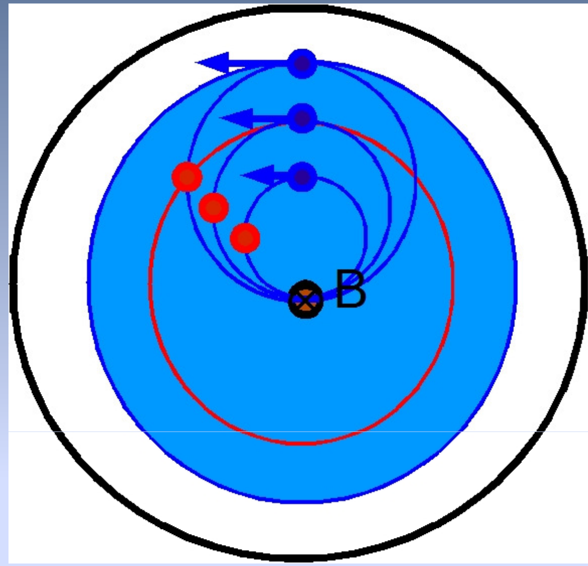
$$v_\varphi = qA_\varphi / m = qB_{\max} \cdot r / 2$$

transversal kick
new position

$$r_L = \frac{mv_\varphi}{qB} \qquad r_L = \frac{r}{2}$$

Solenoid 1.





3 charged particles moving parallel

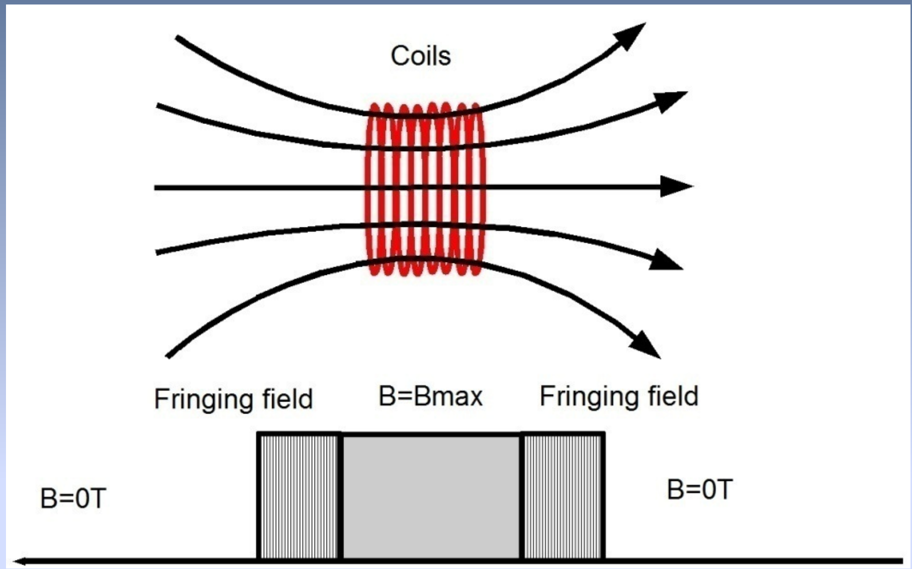
$$v_\varphi = qA_\varphi / m = qB_{\max} \cdot r / 2$$

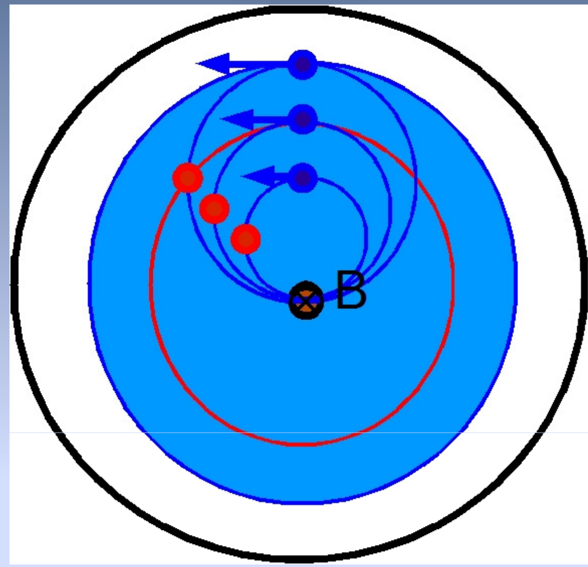
transversal kick
new position
smaller beam radius

$$r_L = \frac{mv_\varphi}{qB} \qquad r_L = \frac{r}{2}$$

Rotation + Point symmetry

Solenoid 1.





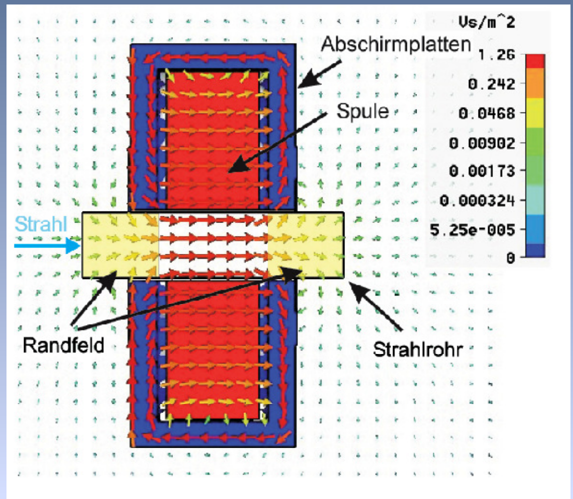
Due to the energy conservation
V_z change – dependent on radial
Position
Effects on focusing?
Space charge effects?
Reflection?

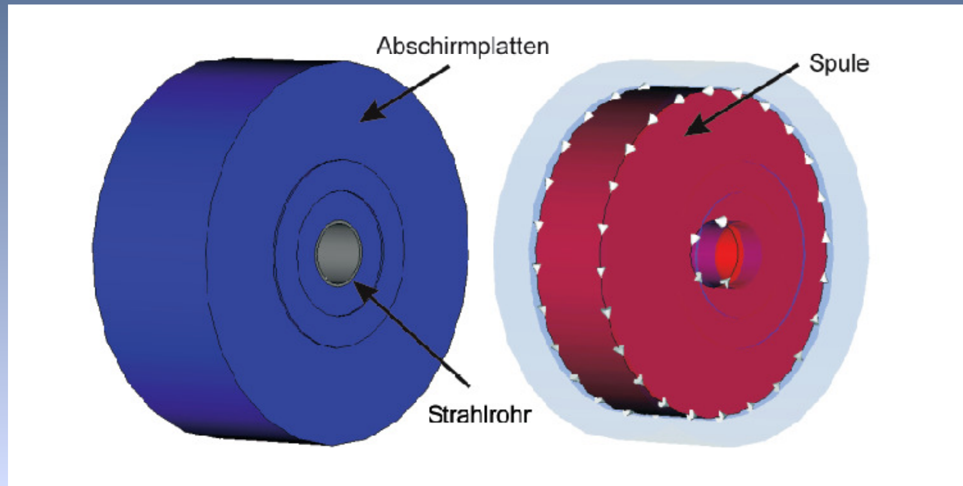
$$v_\varphi = qA_\varphi / m = qB_{\max} \cdot r / 2$$

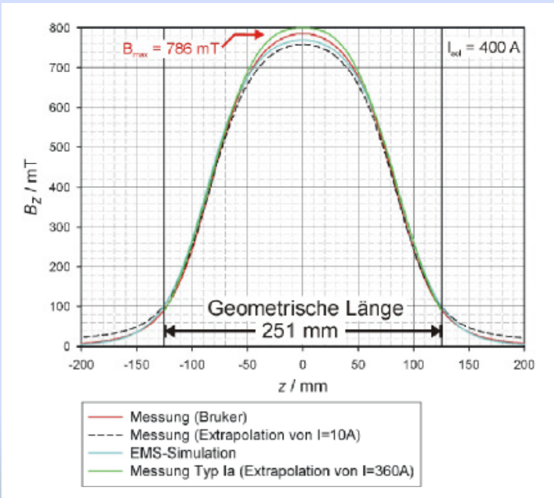
$$r_L = \frac{mv_\varphi}{qB} \qquad r_L = \frac{r}{2}$$

Rotation + Point symmetry

Solenoid 2.







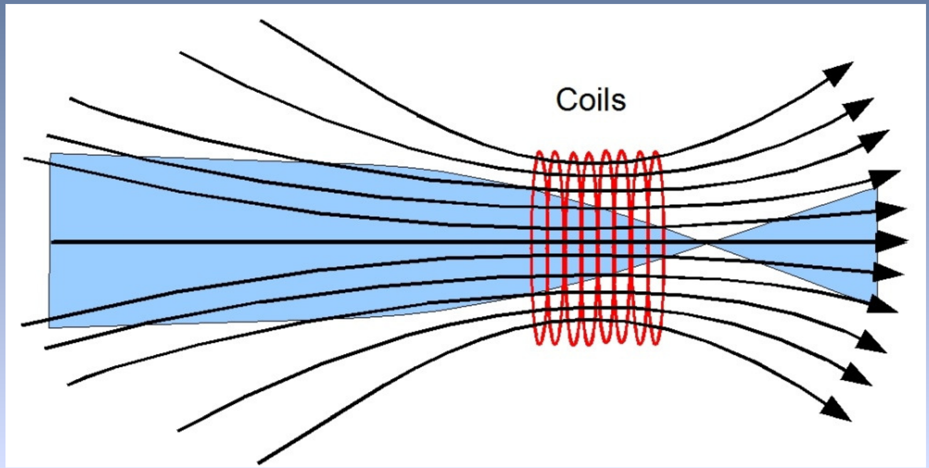
Typicall settings for focusing of protons:

$$L < v_z \cdot \frac{2\pi}{\omega_{c,p}} \cdot \frac{1}{2}$$

But for electrons:

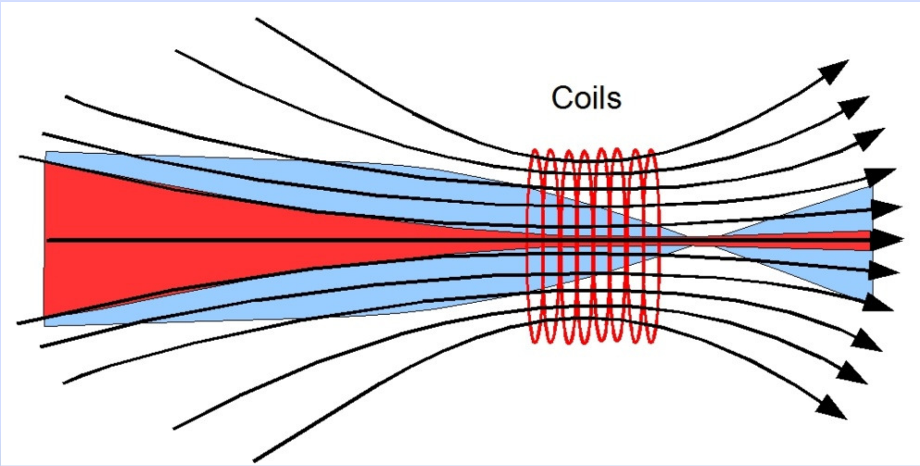
$$L_{eff} >> v_z \cdot \frac{2\pi}{\omega_{c,e}} \cdot \frac{1}{2}$$

Solenoid 2.



Proton beam :

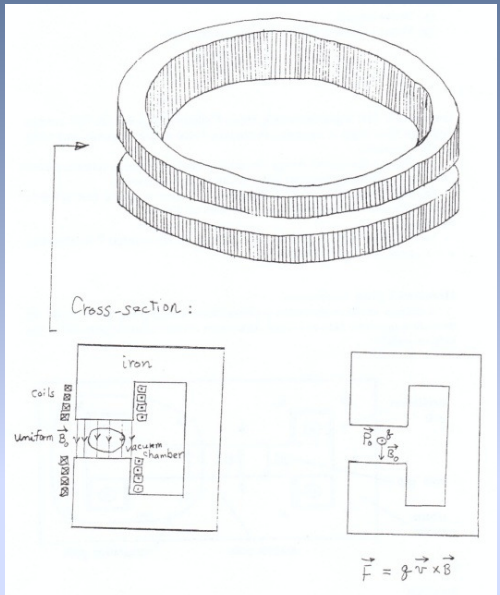
Fringing field kick rotation
Focusing fringing field kick

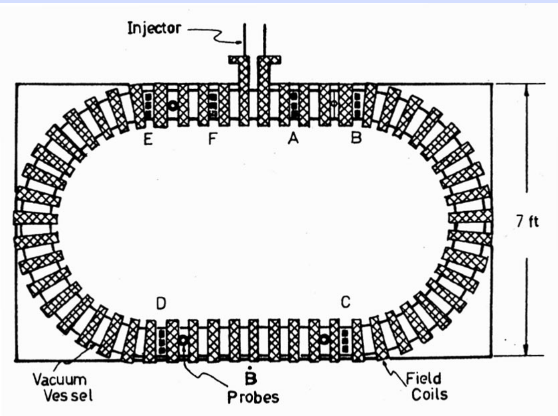


Electrons :

Fringing field far away guiding
Fields reflection (magnetic bottle)

Storage ring?





- Uniform magnetic field B_0 circular trajectory

$$P_0 = qB_0\rho$$

- Cyclotron frequency:

$$\omega_0 = \frac{qB_0}{\gamma m}$$

Why not electric bends?

$$\frac{\rho_E}{\rho_B} = 300\frac{B[T]}{E[MV/m]}\cdot\frac{v}{c}$$

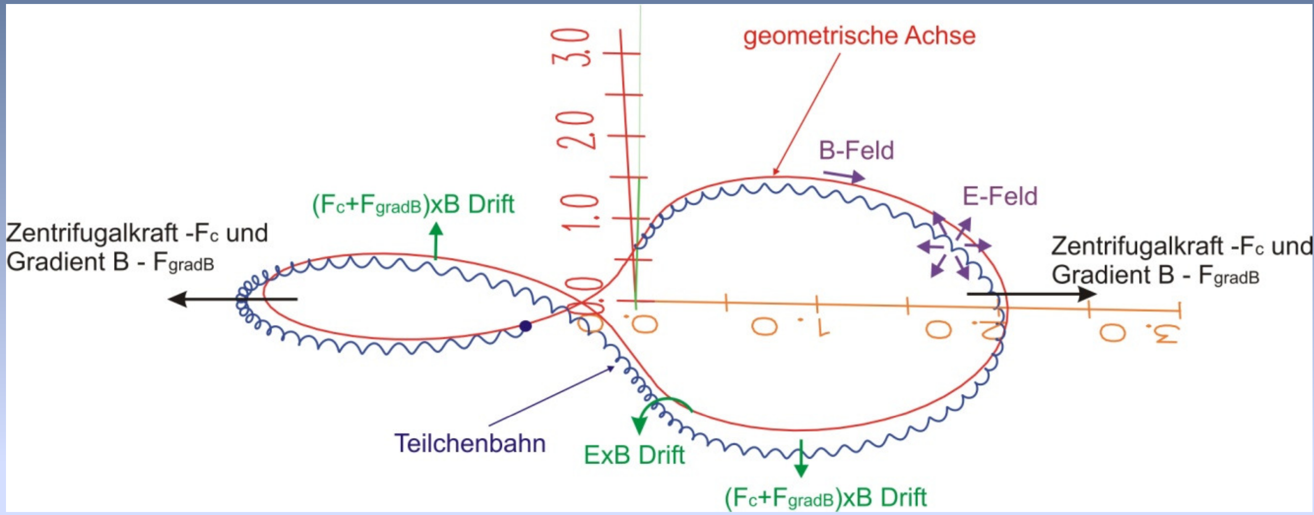
Deviation in y-direction instable
solution ->other magnetic components

Longitudinal magnetic field:

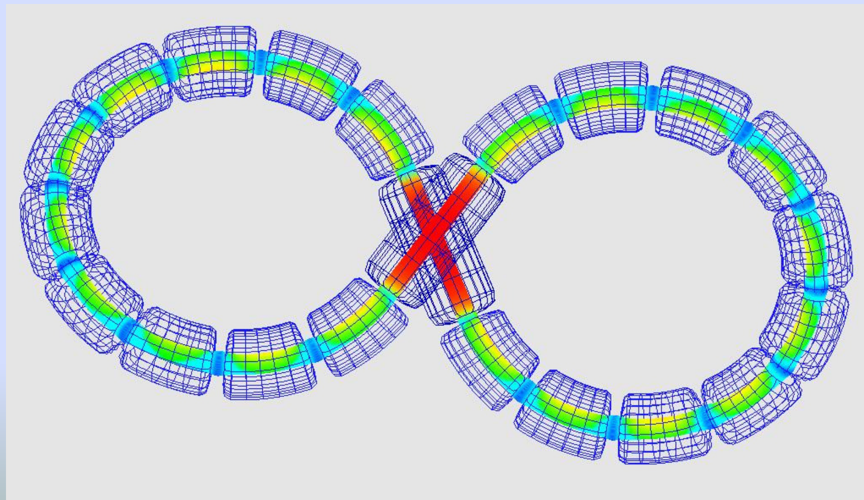
RxB drift in vertical direction

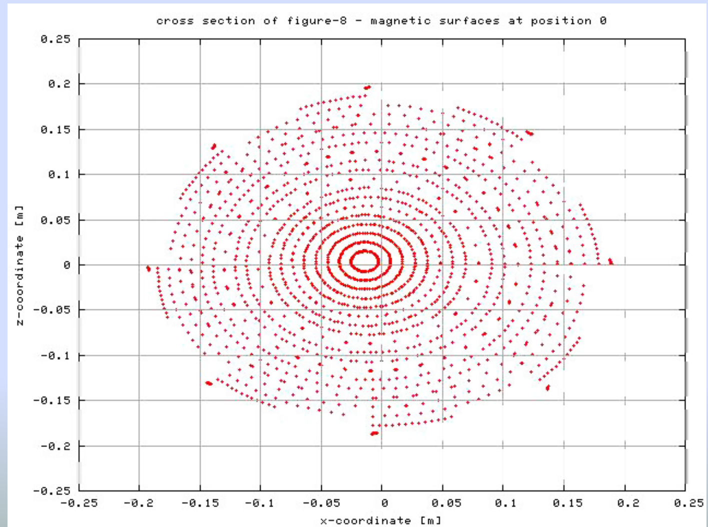
Solution->Twisting of field lines -> compensation of drifts

Drifts



- **R ~ 1m**
- **r ~ 0.15m**
- **L ~ 10m**
- **22 Segments**
- **h ~ 1m**
- **B ~ 5T**
- **I ~ 10A**





Motivation

Multi ionisation of light atoms by intense proton beam (W~150 keV)

Fusion cross sections (^{11}**B+p -> 3α (8.7MeV) fusion cross section σ~10^{-28}m^2**)

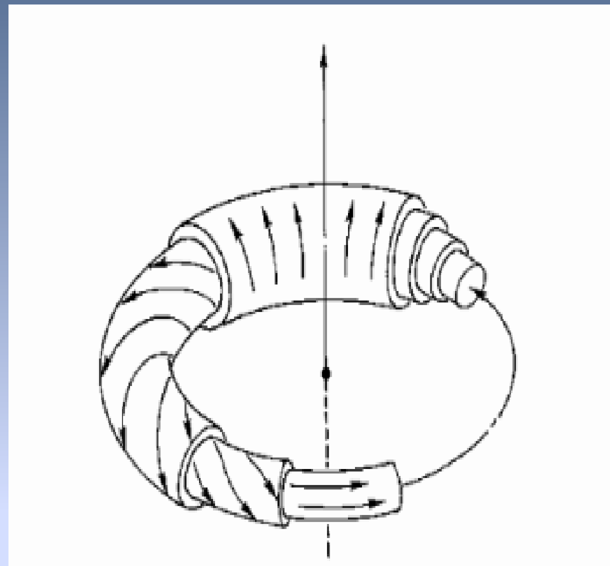
Space charge compensation – electrons – moving
trapped

Cooling processes, Crystalline beam

Multi species interaction

Coordinate system – Guiding center

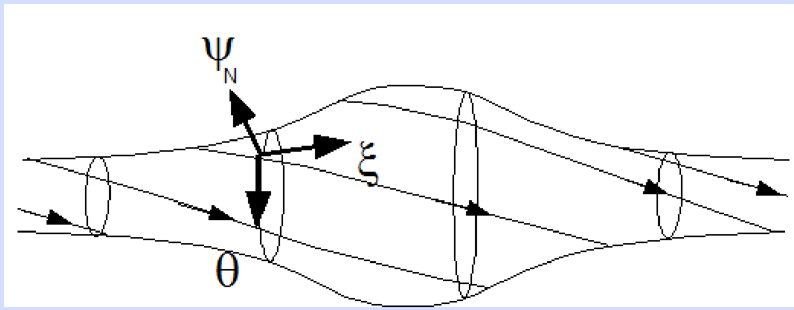
Poloidal angle $\theta \in <0,2\pi>$
Toroidal angle $\xi \in <0,2\pi>$
Normalised magnetic flux coordinate $\tilde{\psi} \in <0,1>$, $\tilde{\psi} = \frac{\psi}{\psi_{max}}$
Contravariant representation $\vec{B} = 2\pi\vec{\nabla}(\theta - \iota\xi) \times \vec{\nabla}\psi$
Covariant representation $\vec{B} = \vec{\nabla}\chi = g\vec{\nabla}\xi$



Canonical variables

$$\theta,\ P_\theta = \frac{q\psi}{2\pi}, \xi,\quad P_\xi = \frac{\mu_0 G}{2\pi|B|} m v_{||} - \iota\frac{q\psi}{2\pi}$$

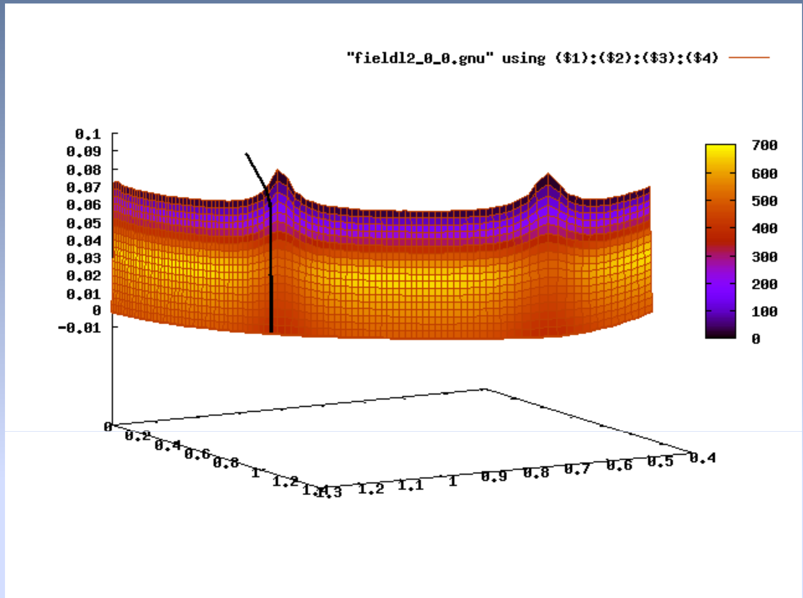
$$g = \frac{\mu_0 G}{2\pi}$$

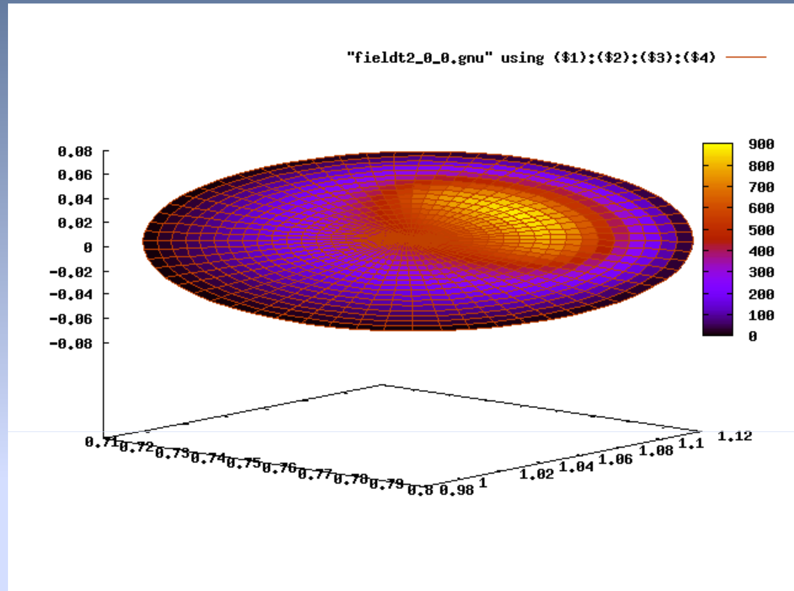


Drift Hamiltonian

$$H = \frac{1}{2m}\frac{\left(P_\xi + \iota P_\theta\right)^2 (2\pi)^2 |B|^2}{{\mu_0}^2 G^2 m^2} + \mu|B| + q\phi$$

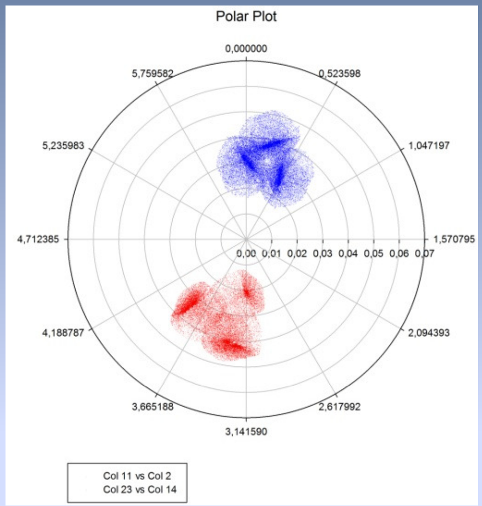
Numerical mesh

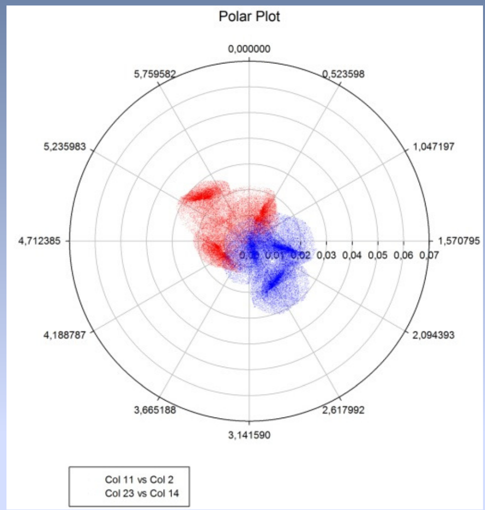


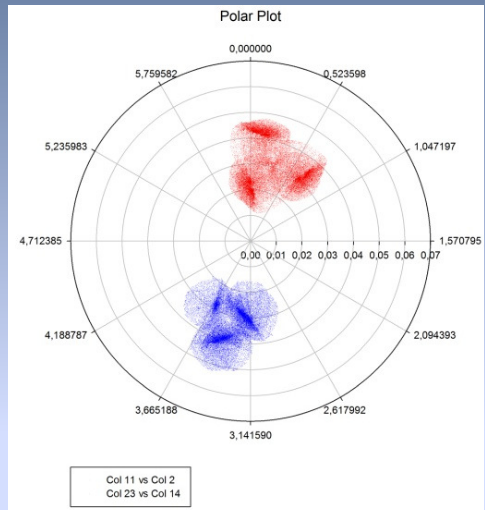


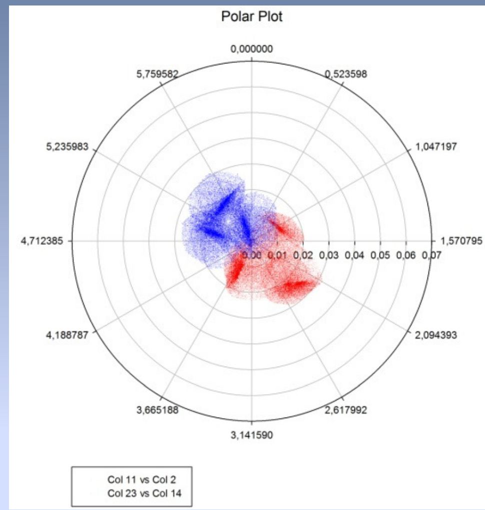
E,B fields and derivates on mesh points -> approximation between the points
Space-charge effects -> PIC (Particle in Cell)
Simulation running parallel on different processors (CSC-Center for Scientific Computation)

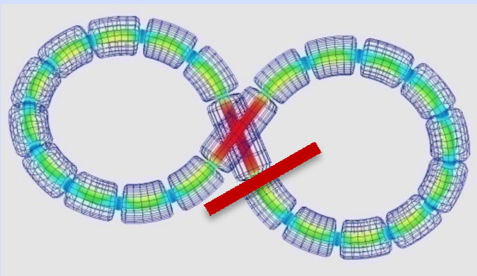
Drift dynamic

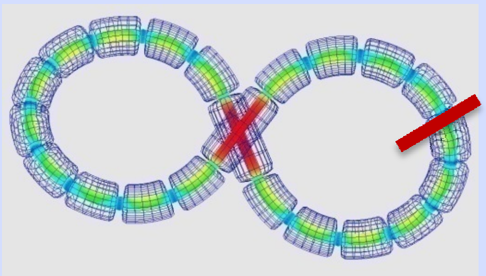


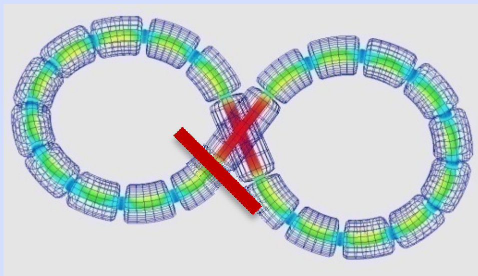


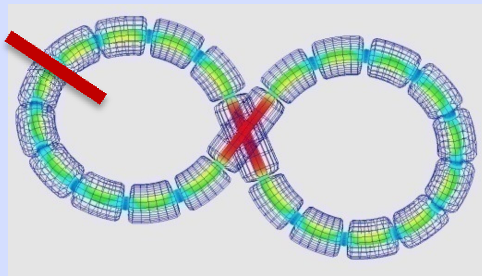






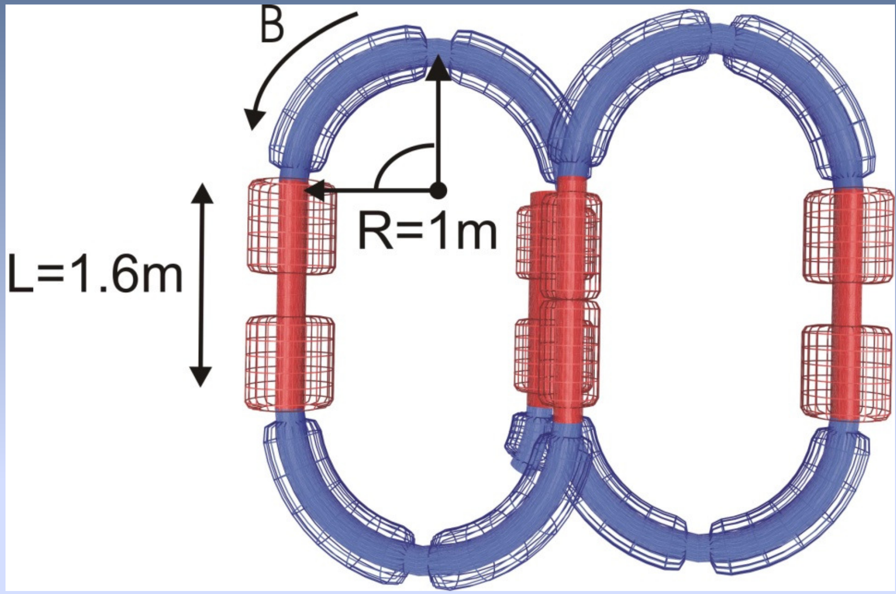


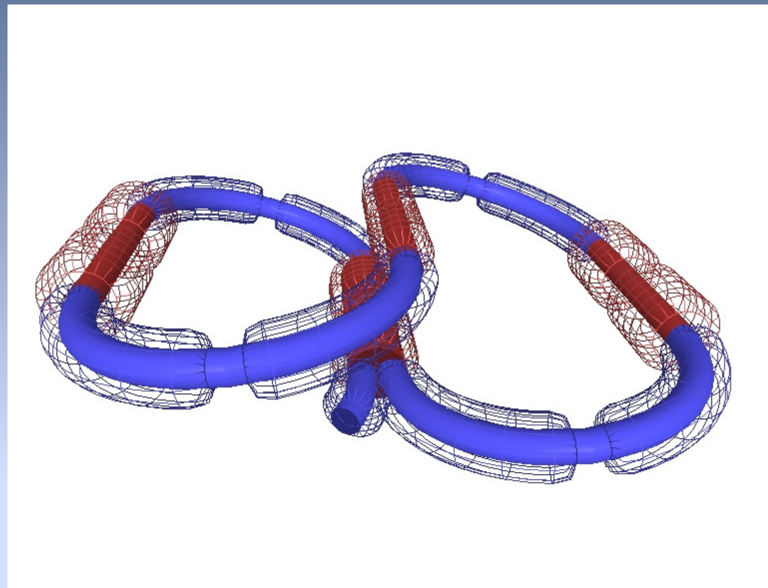


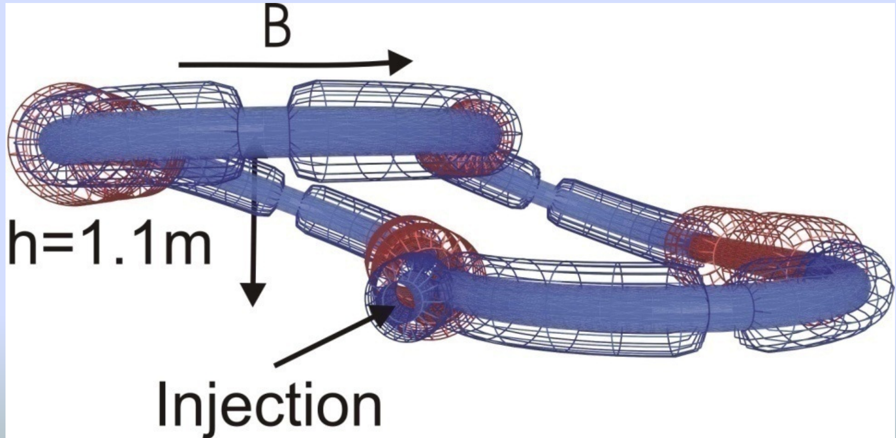


$\xi=0°$ $\xi=90°$ $\xi=180°$ $\xi=270°$

F8SR





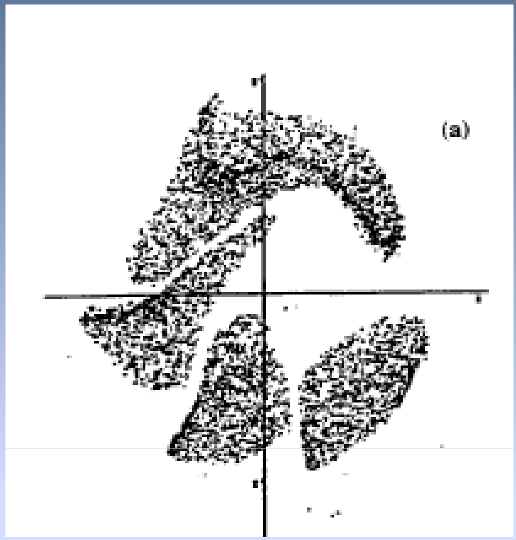


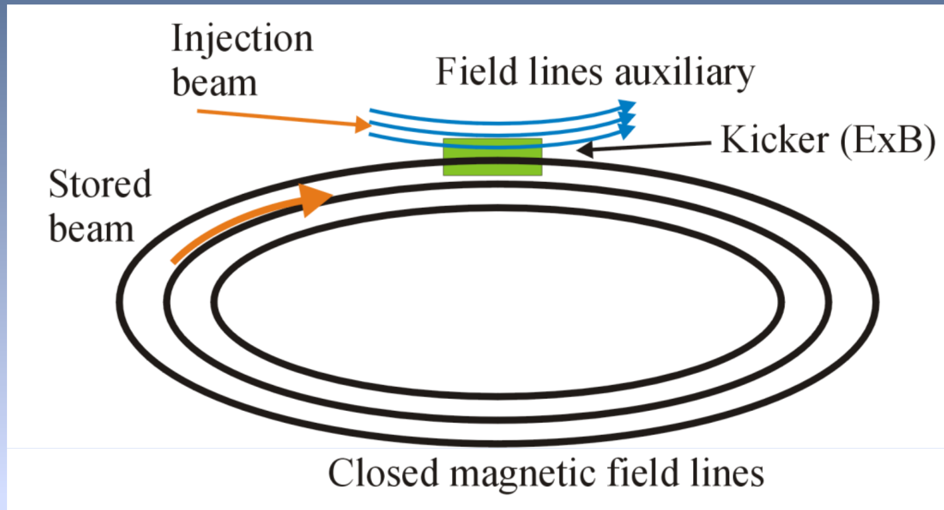
Minimizing of rippled structure

Straight sectors:

-experiments
-injection

Injection systems





Multi-turn Injection. Need to populate different area of phase space.

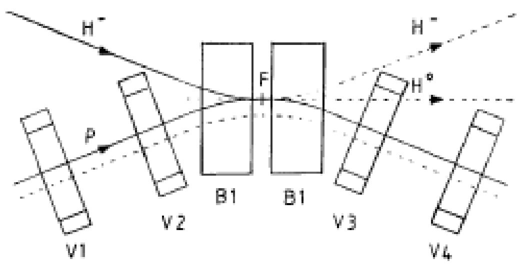


Fig. 6 Optimised H- injection

Laser injection

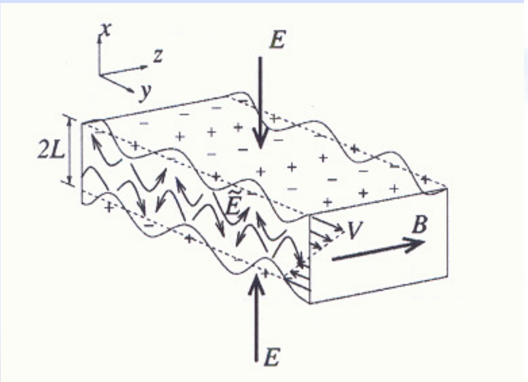
Charge exchange injection

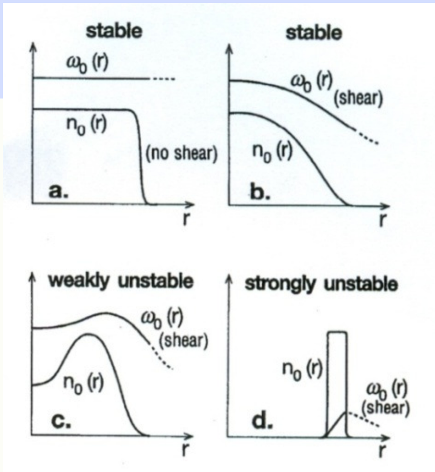
Stability

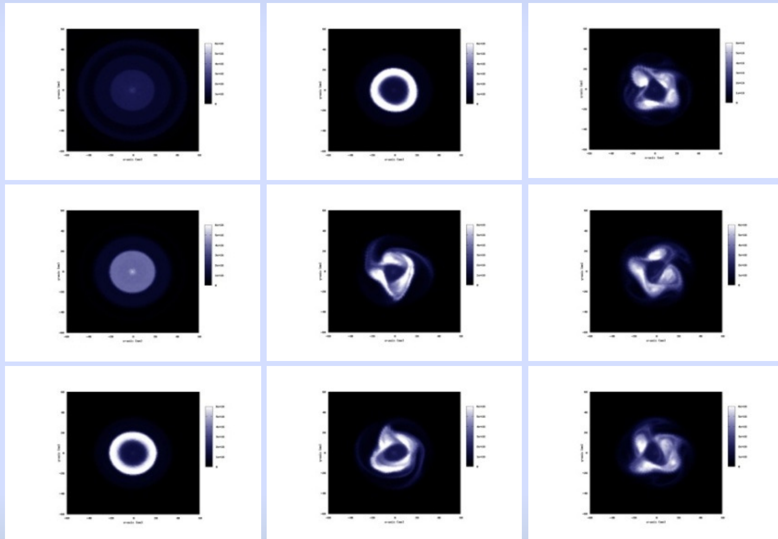
- Space-charge -> ExB motion

Hollow profile -> diocotron instability

Untwisted rotational transform -> kink instability







Summary and Outlook

- How strong is the field -> depending on dimension, observation time and momentum

- Using of strong guiding magnetic fields
  - continuous focusing
  - high transversal momentum acceptance
  - high current (density) beams
    - Transport
    - Accumulation? -> Injection
    - Stability? -> What are the limits?
    - Space charge compensation?