Beam dynamics in the Figure-8 magnetic field

Beam Dynamics meets Magnets,
1st XBEAM-XRING Workshop,
Darmstadt 2-4, December 2013,

Martin Droba.

Scientific frame → Low energy, 3D Fields

Beam Dynamics and Magnets

$$H(P,Q) = \frac{\left(P(Q,p) - qA(Q)\right)^2}{2m} + q\Phi(Q)$$

$$\vec{P} = m\vec{v} + q\vec{A}$$

equivalence of **mechanical momentum** and **vector potential**

$$\dot{Q} = \frac{\partial H(P,Q)}{\partial P}, \dot{P} = -\frac{\partial H(P,Q)}{\partial Q}$$

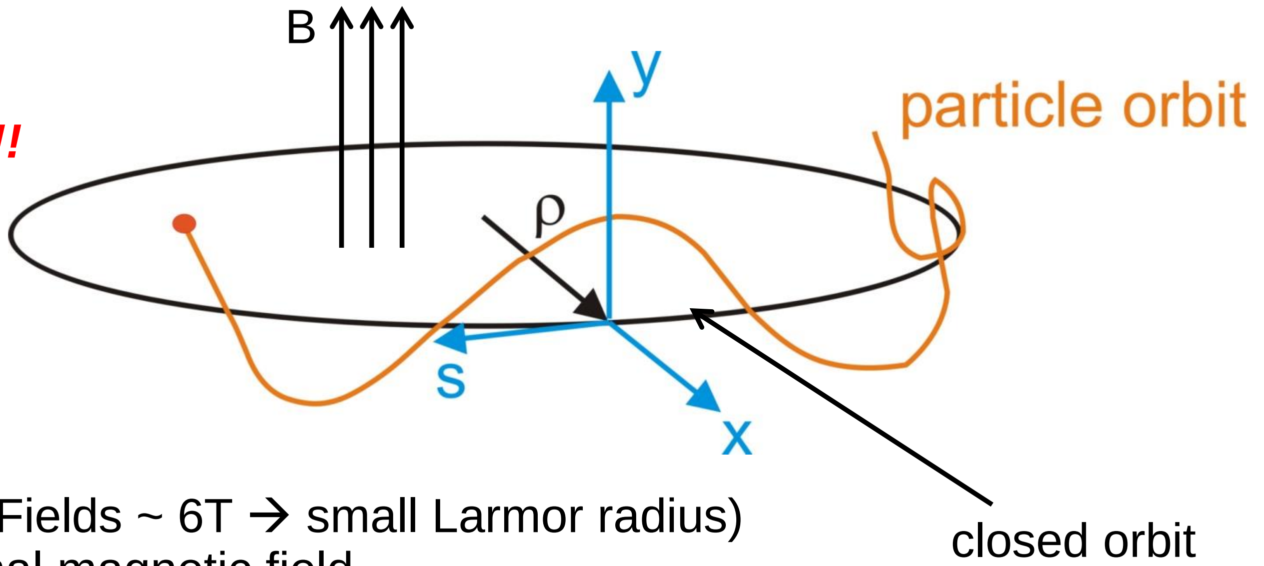
P,Q – cannonical coordinates

NNP Non Neutral Plasma Physics Group

Low Energy Storage Ring magnetic confinement

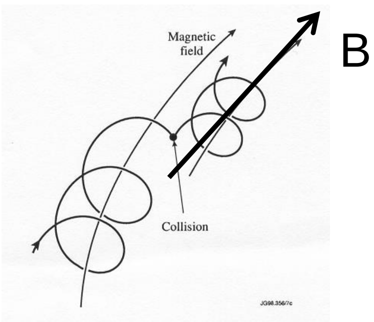
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

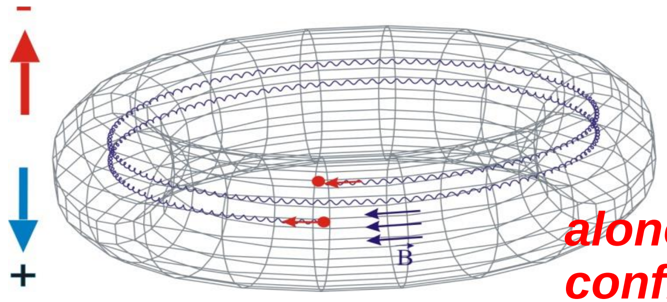
- Bending – dipol field
  alone isn´t enough!!!
  confinement in y?
- Focusing –
  - quadrupoles
  - sextupoles



- Guiding fields (higher Fields ~ 6T → small Larmor radius)
- Focusing by longitudinal magnetic field

but Drifts !!!

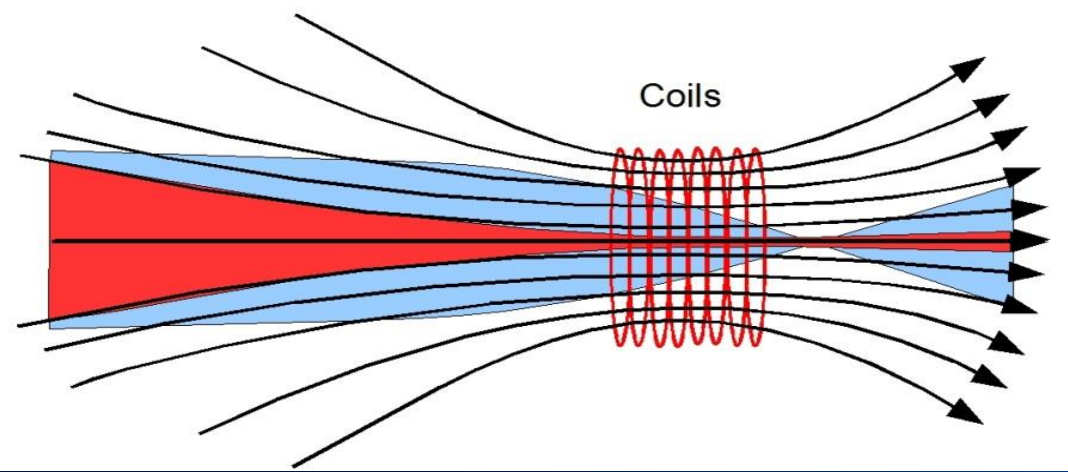




alone isn´t enough!!!
confinement in y?

Guiding magnetic fields

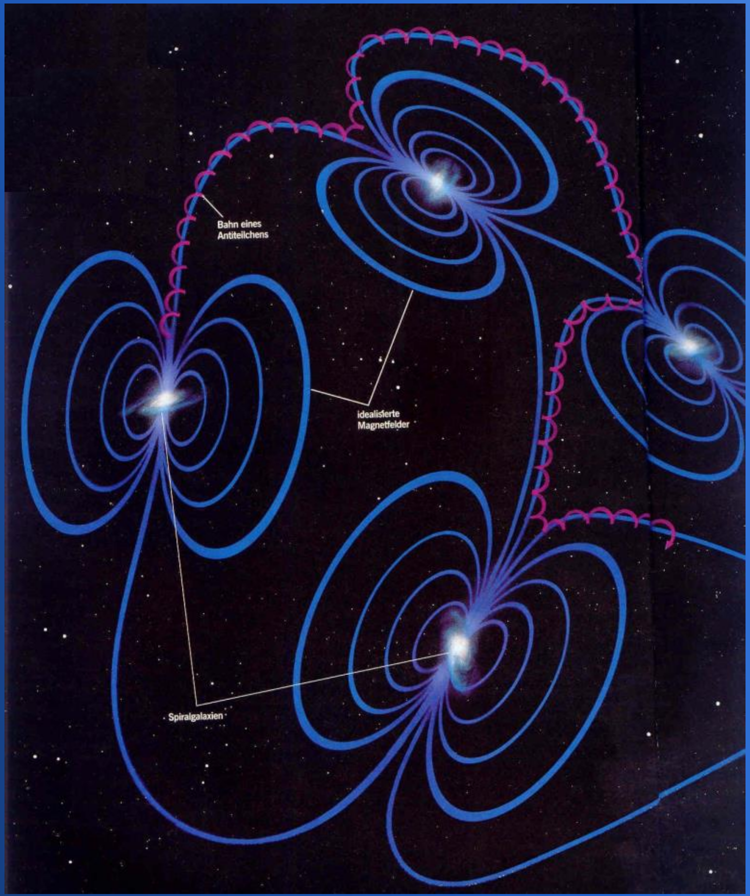
Example: magnetic Solenoid with
charged particle beam (protons & electrons)



Electrons(red) – guided

Protons(blue) – not guided – focusing by fringing fields?

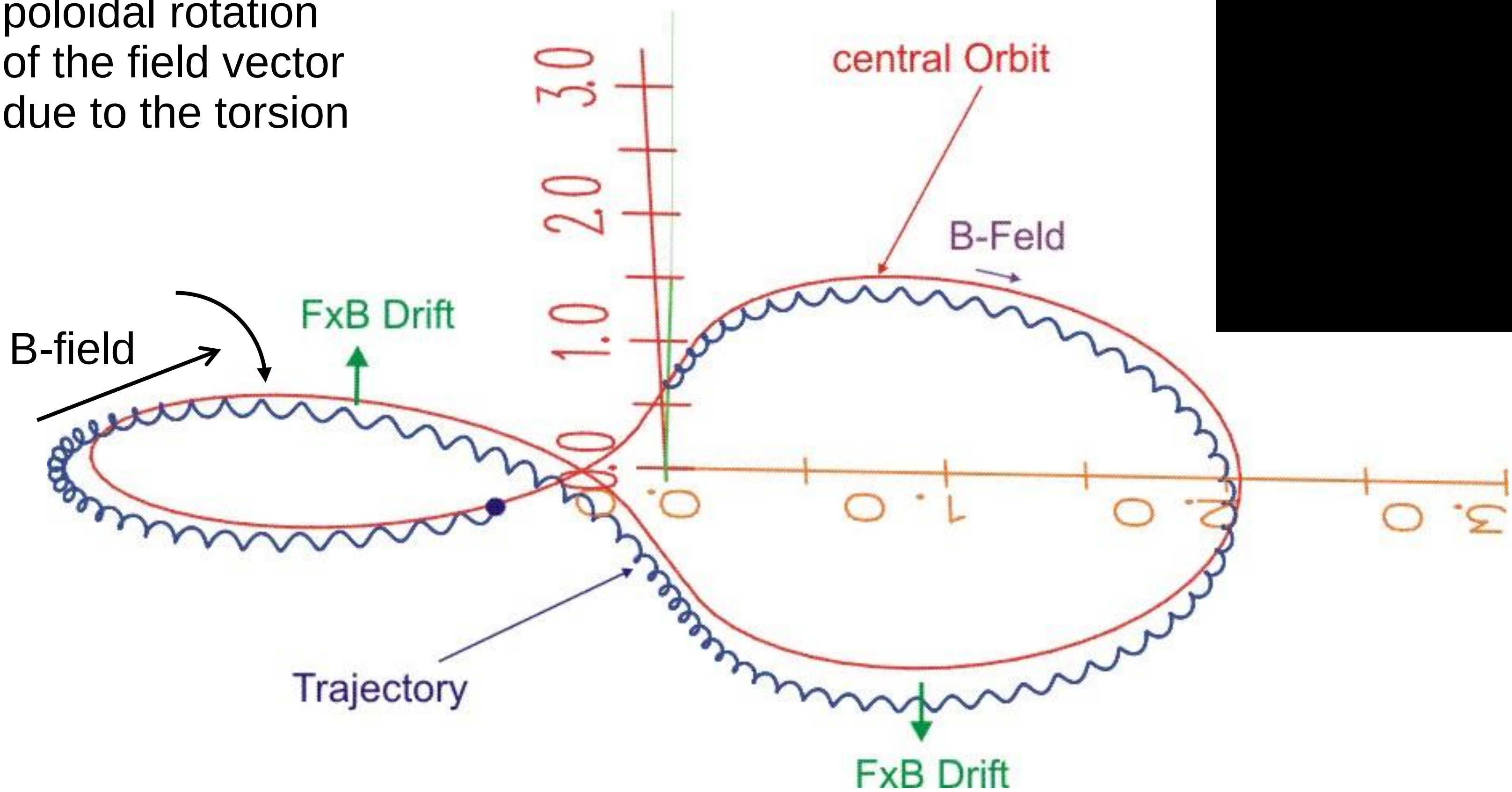
BUT same field !!! mv ←→qA ?



Spektrum der Wissenschaft, Dossier, Kosmologie

Figure-8 geometry

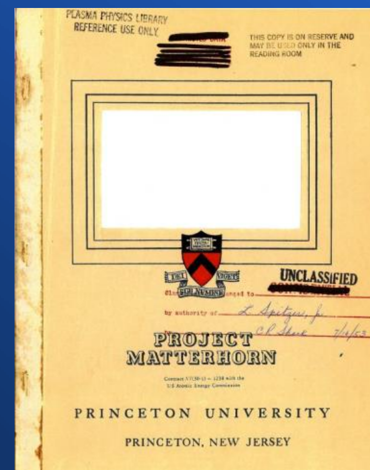
additionally
poloidal rotation
of the field vector
due to the torsion

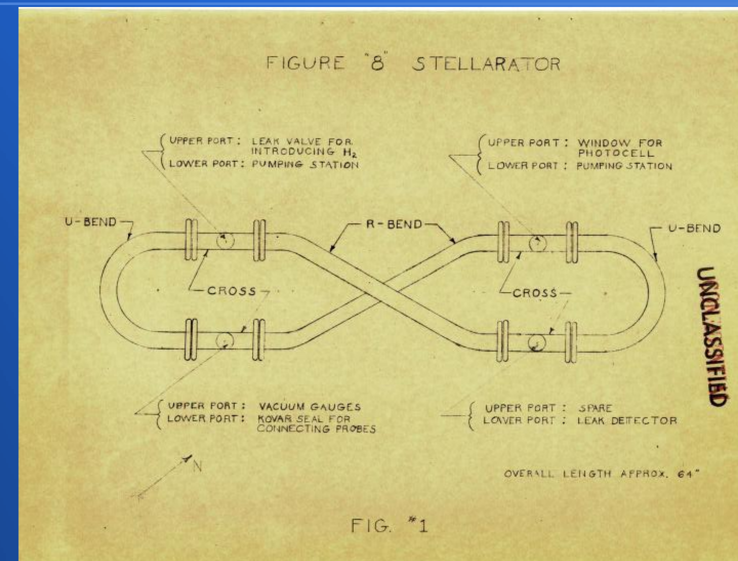


1st Stellarator

- Project Matternhorn
- *Princenton University*

Lyman Spitzer



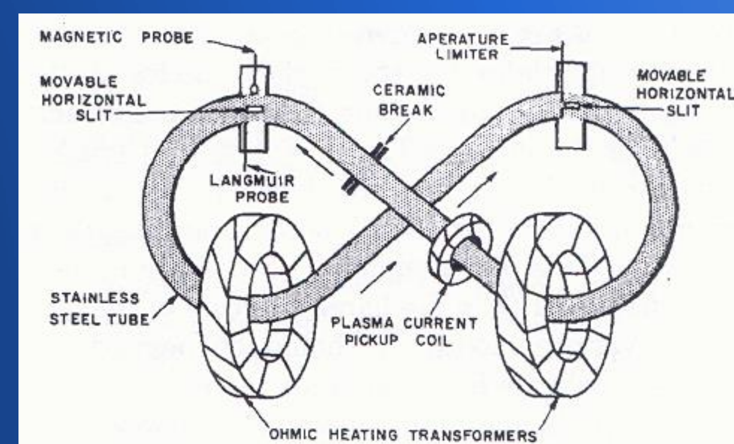


- Ohmic heating - Transformers
- High electron current kA->MA
- Disruption – instabillities

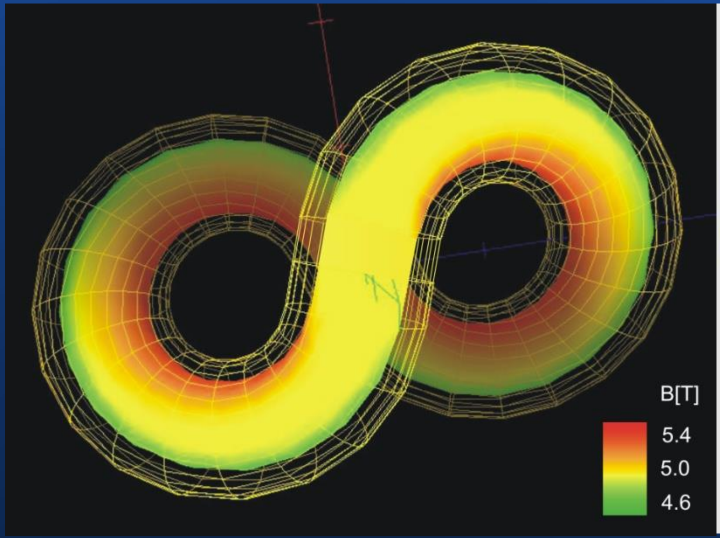
magnetic self fields

(*however, after disruption observation of long time confined runaway electrons → beam like!!!*)

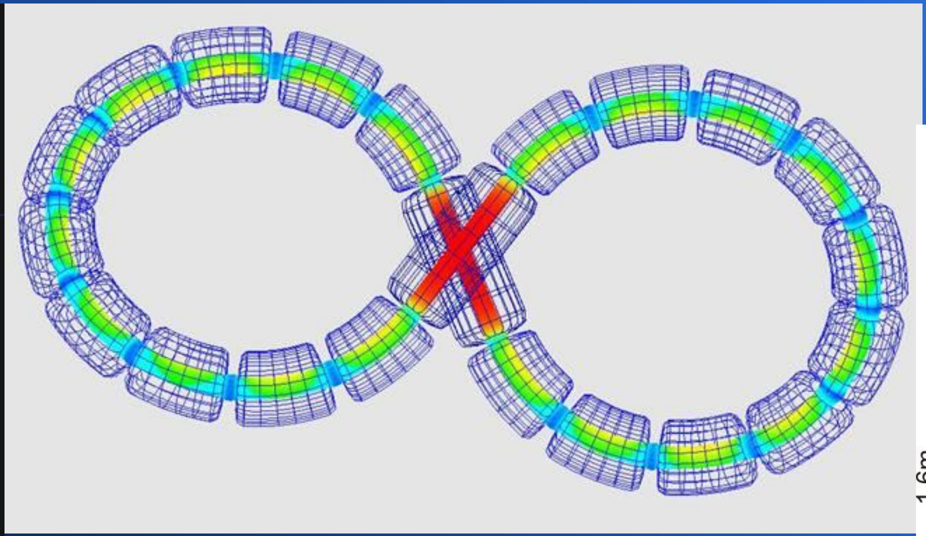
1950-1960



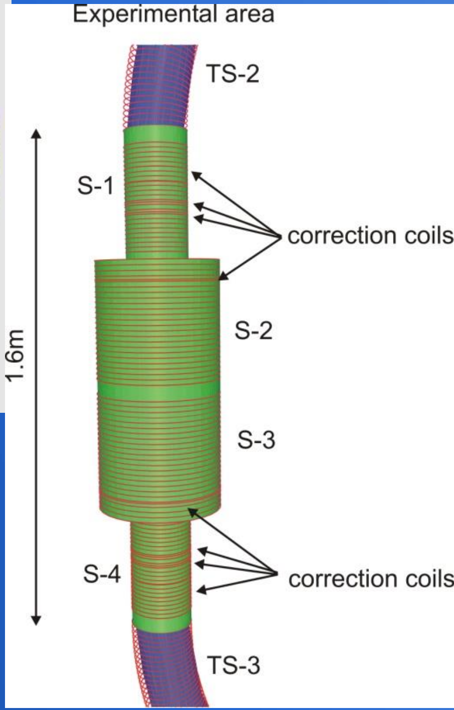
Practical vs Ideal



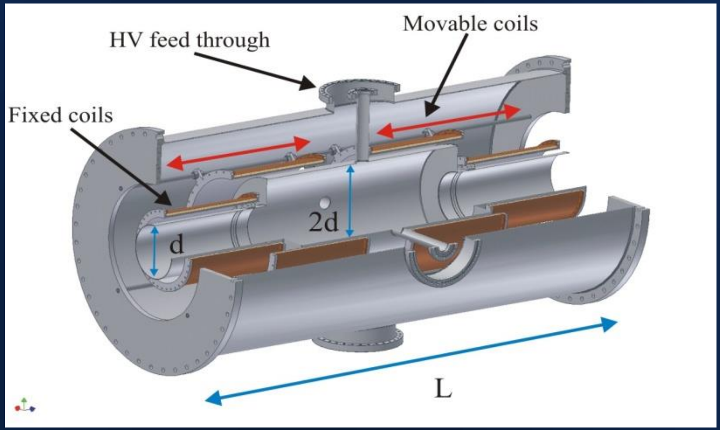
Ideal shape

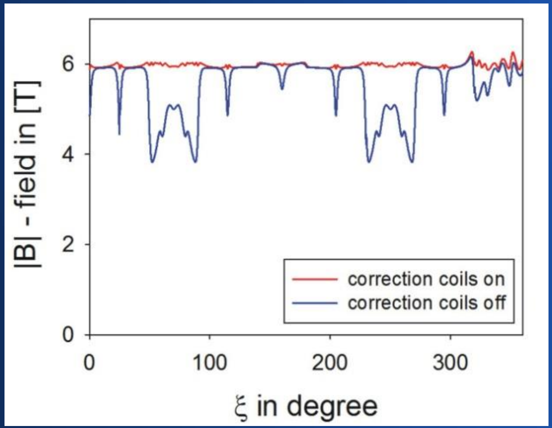


Segmented design

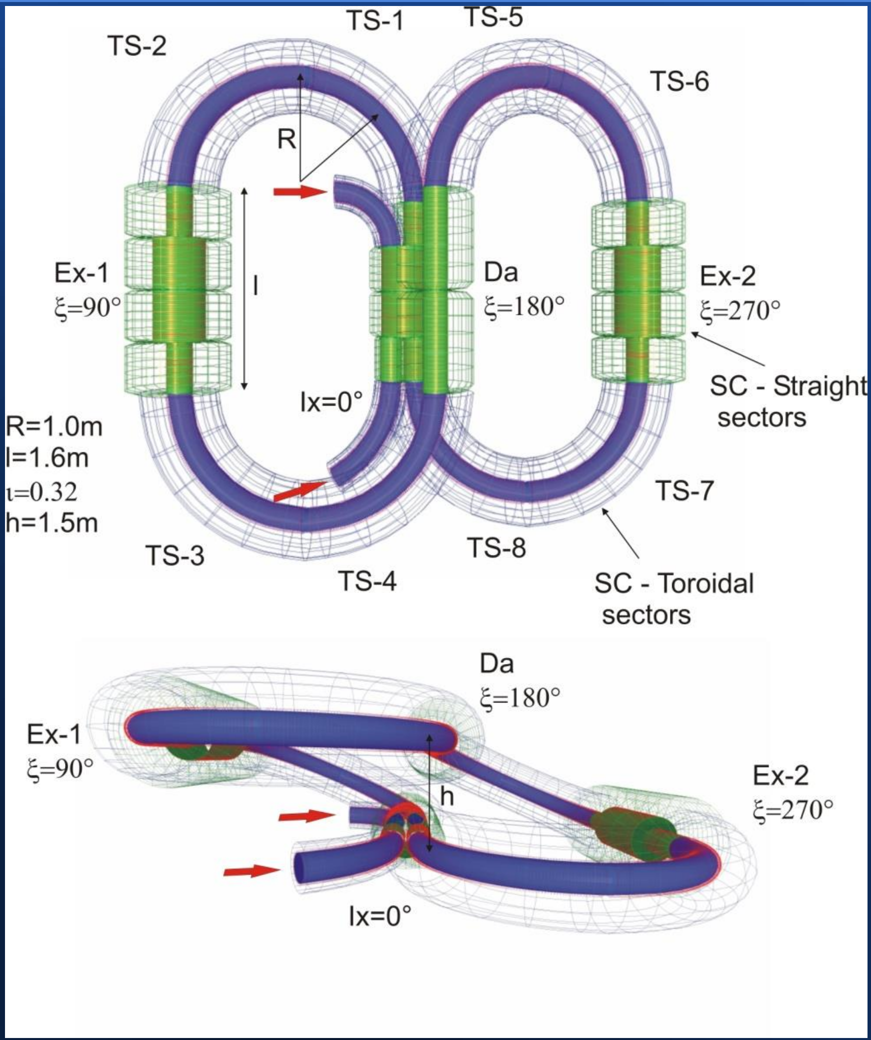


Correction coils





Design Example



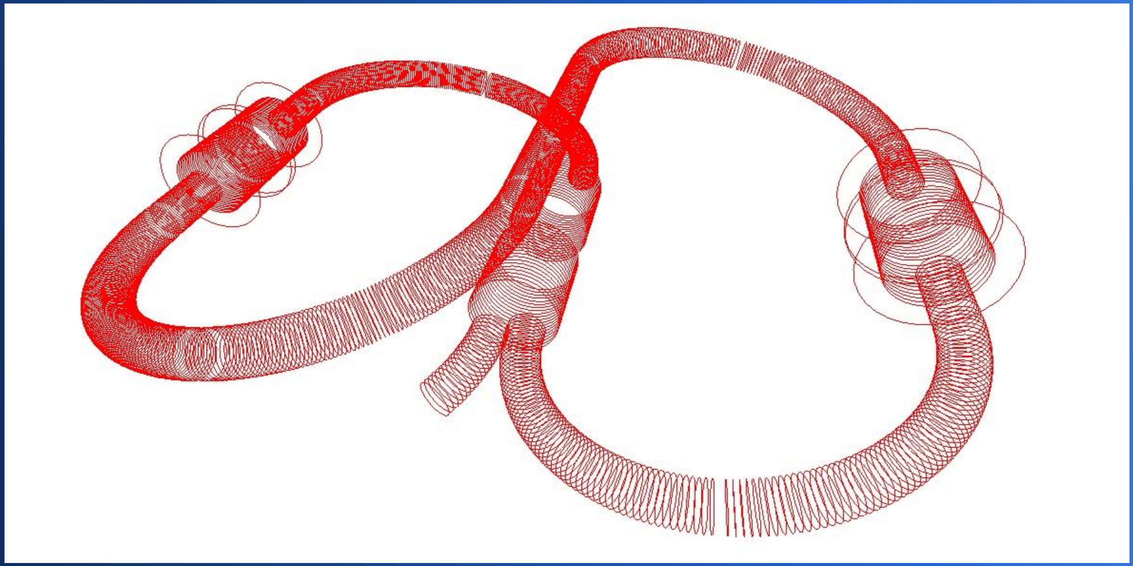
Beam Energy: W_b = 150keV

Beam current: I = 10A

Revolution time: t = 2µs

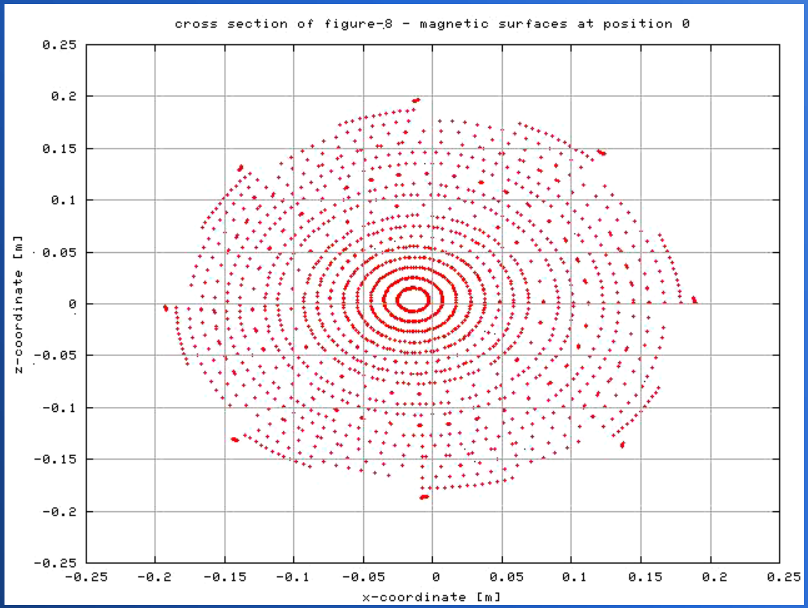
Stored beam Energy and Power

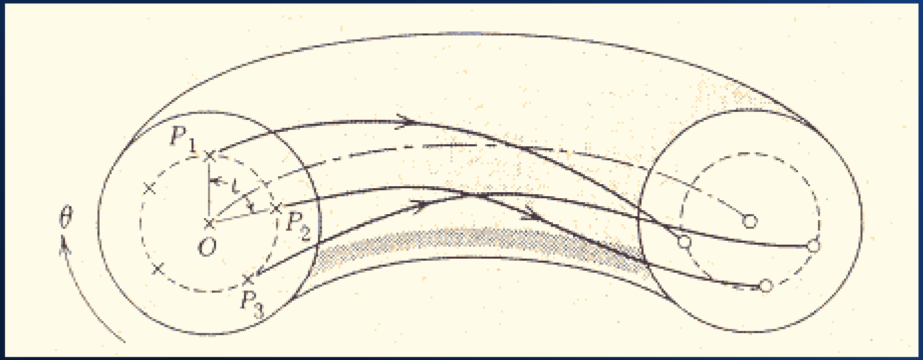
E = 3J P_{peak} = 1,5MW



Mapping of nested magnetic flux surface

- magnetic field vector following
- over many turns around figure-8
- in equidistant step of $d\chi = Bdl$

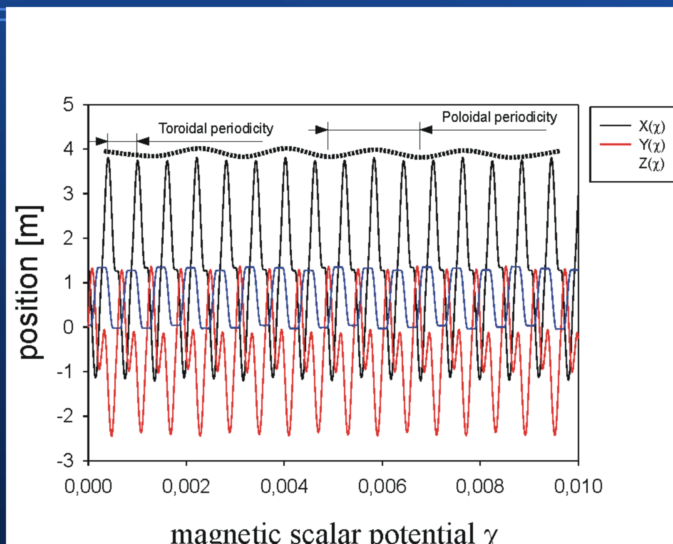




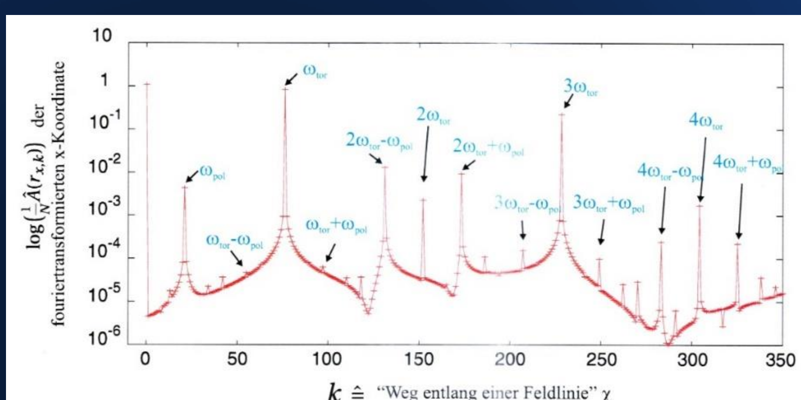
virtual flight along ideal figure-8 structure

Poincare map

Decomposition – Boozer coordinates



1D Frequency spectra



splitting

2D spectra
poloidal θ
toroidal ξ

ratio → poloidal rotaion ι

Backward 2D FFT

establishment of coordinate system for 1 surface (ψ=const, enclosed flux is constant)

A.Boozer, *Rev.Mod.Physics,Vol 76 (2004)*

Boozer coordinates

$$\vec{B} = \nabla\chi \quad \vec{B} = \nabla\psi \times \nabla(\theta - \iota\xi)$$

covariant representation

contravariant representation

Drift Hamiltonian for guiding center approximation

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

μ Adiabatic invariant associated with fast gyromotion

→ Equation of motion

J.R.Cary, *Rev.Mod.Physics,Vol 81 (2009)*

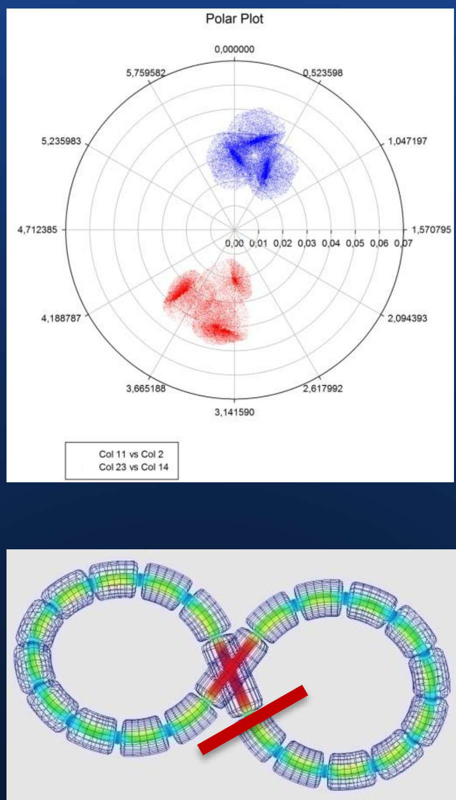
Simulation

- Guiding center approximation
- Particle-in-cell simulations (PIC)
- Boozer coordinates

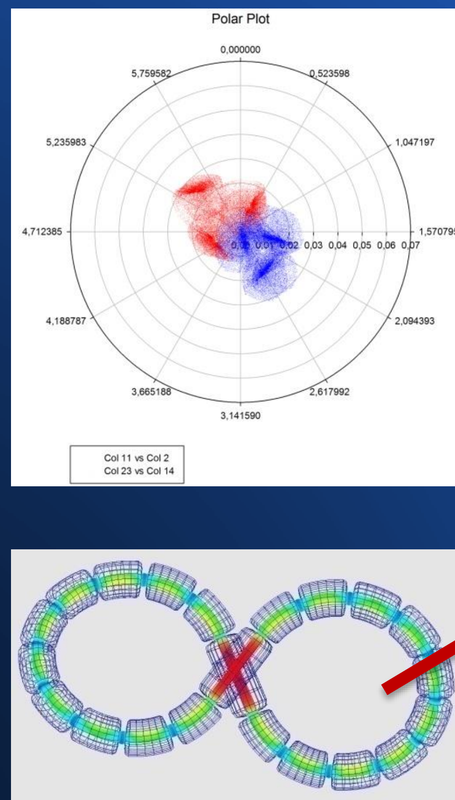
  (non-orthogonal for *vacuum fields*)
- Parallel programming

  typical 100 processors

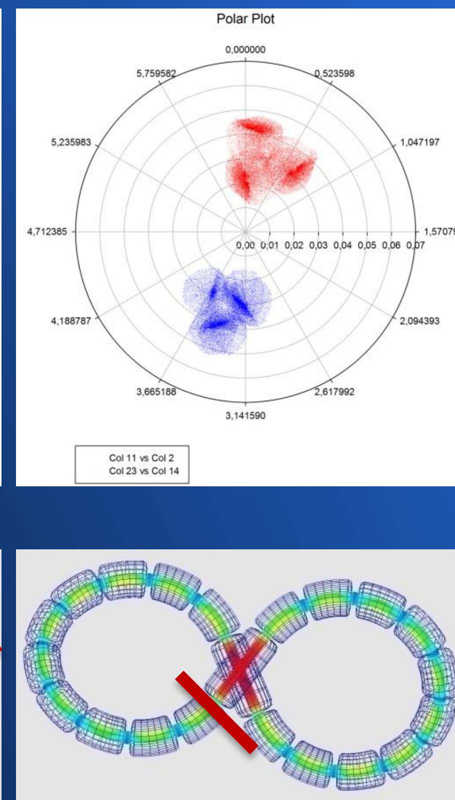
Dynamic - Simulation



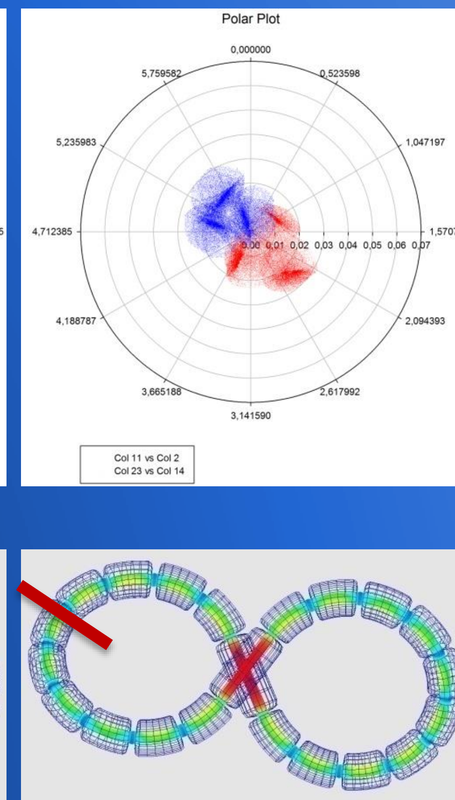
ξ=0°



ξ=90°



ξ=180°



ξ=270°

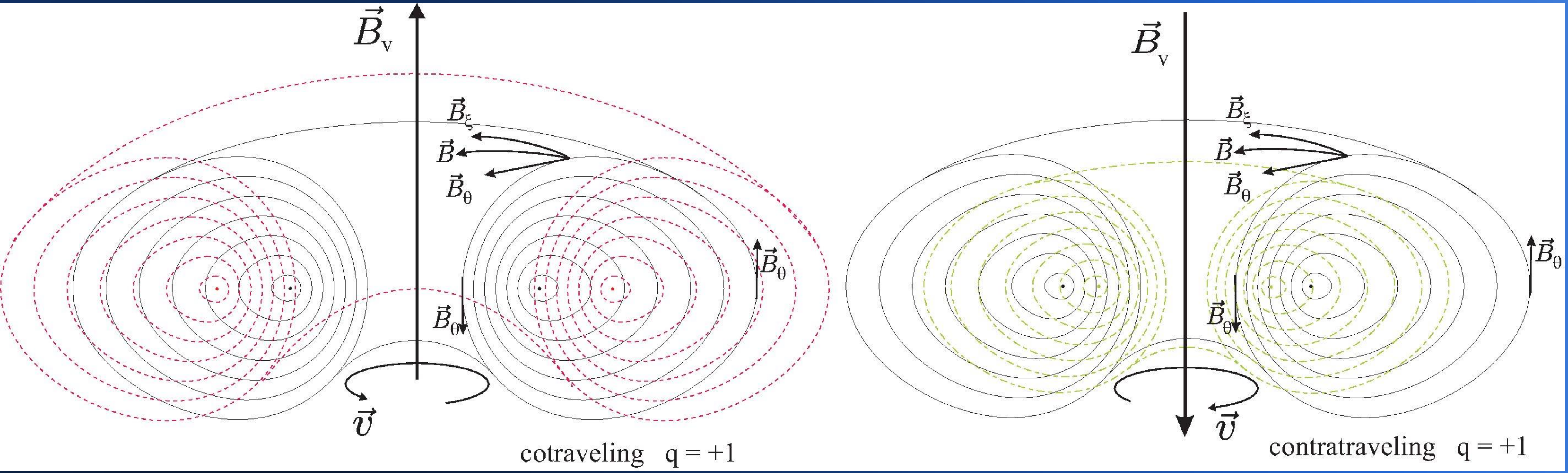
drift surface

magnetic flux surface → mass-less particle →stable phase space

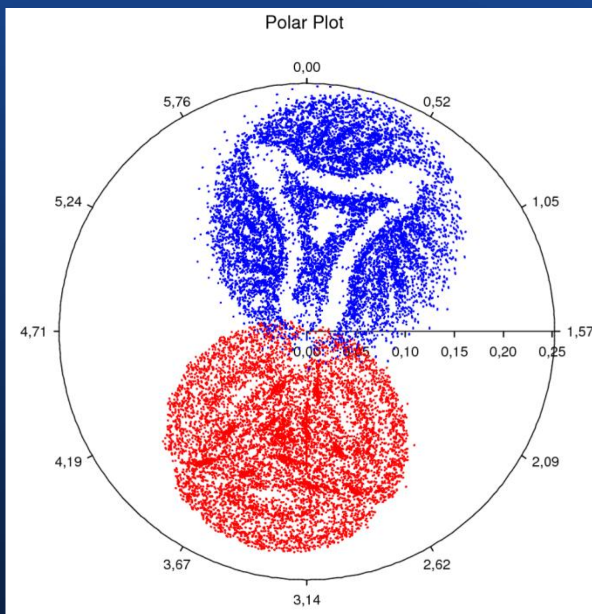
correction for momentum effects

(centripetal force, FxB drifts) → drift surface

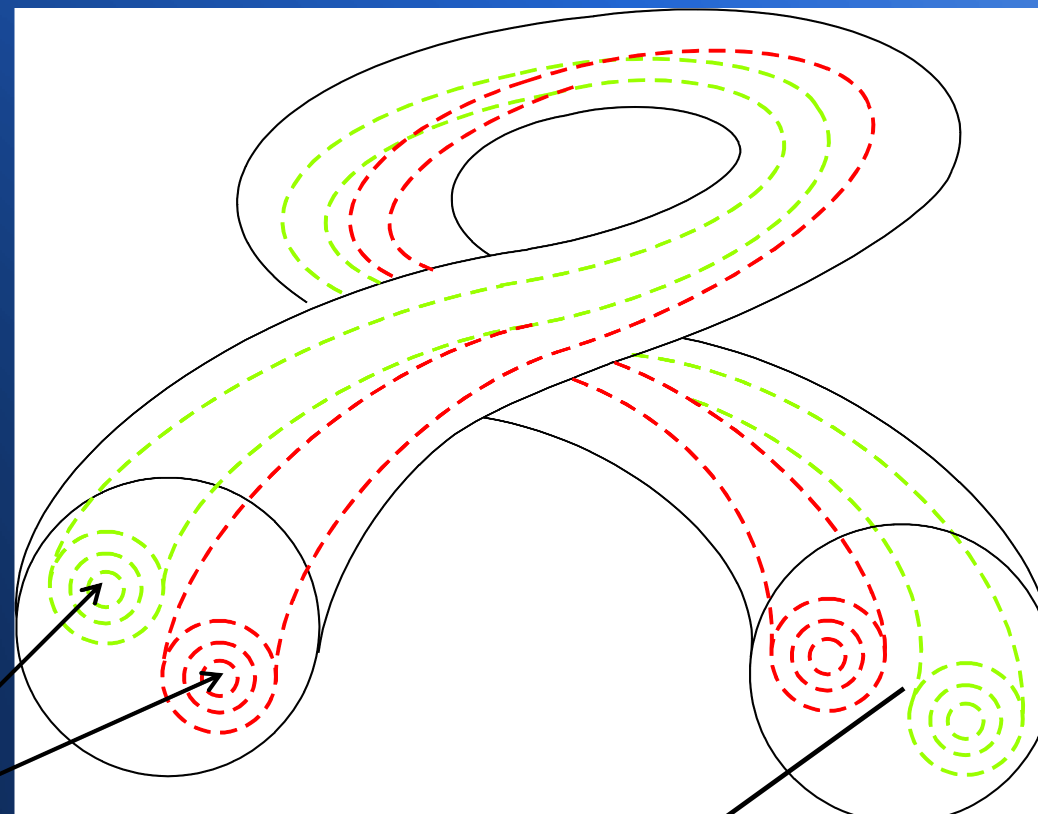
$$mv \to qA$$
$$m\nabla \times v \to q\nabla \times A$$
$$B_v = \frac{m}{q}\nabla \times v$$



drift surface
closed orbits



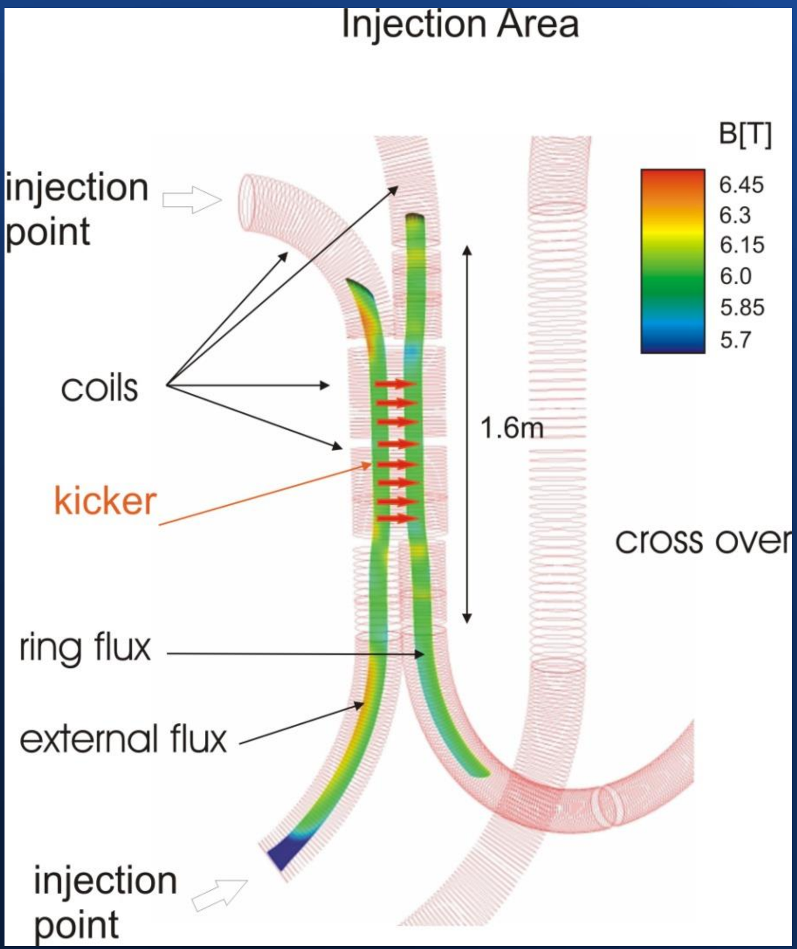
1/3 resonance → resonant islands

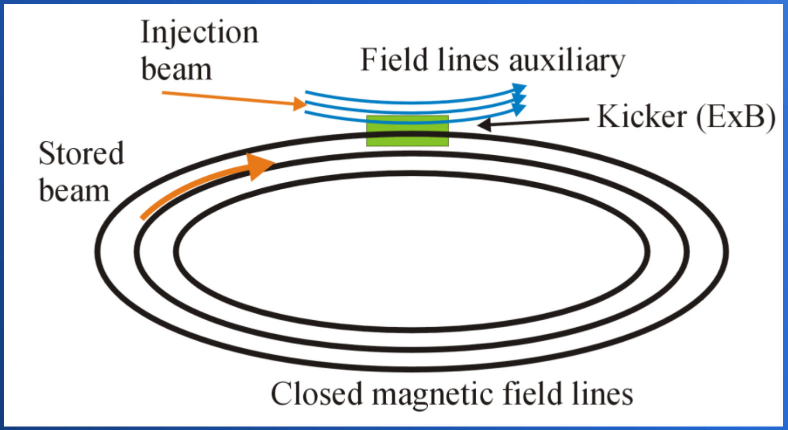


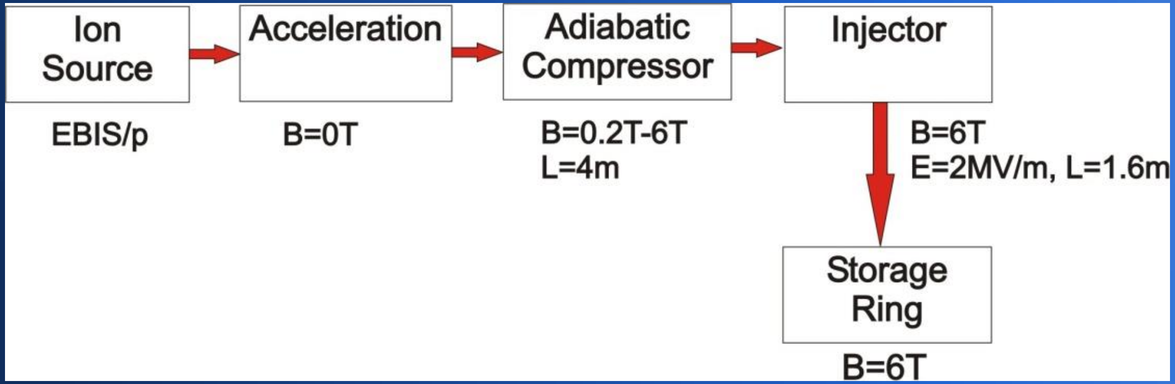
Closed orbits

Geometric axis

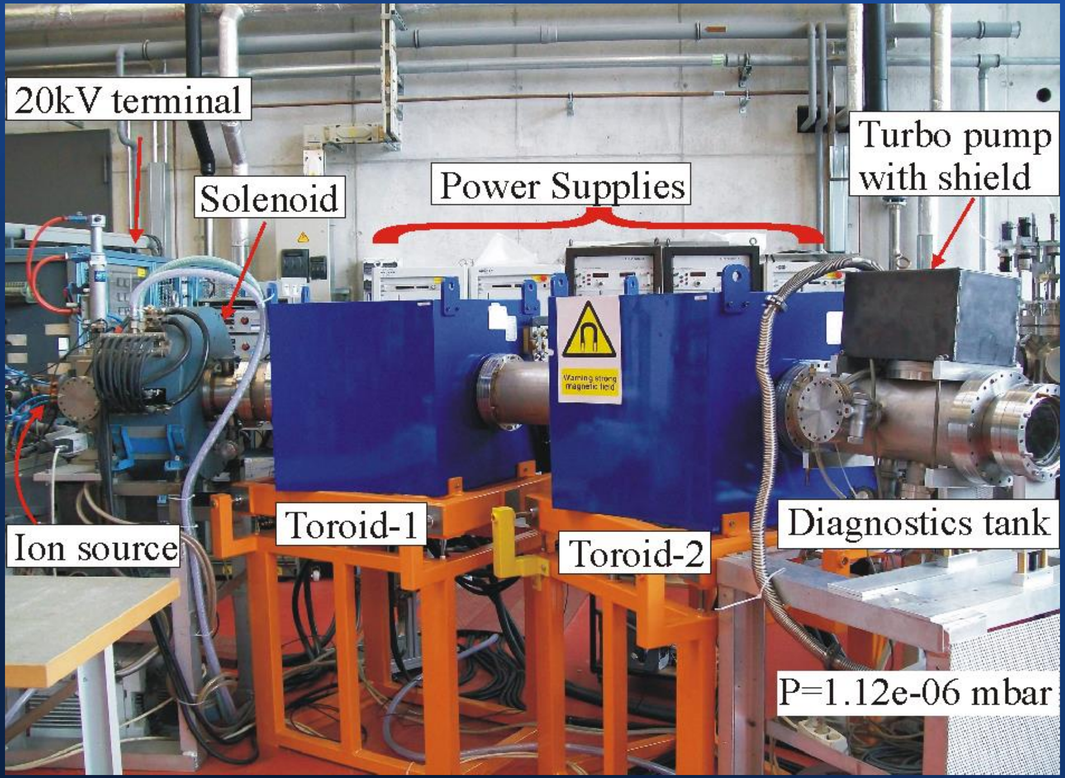
Injection

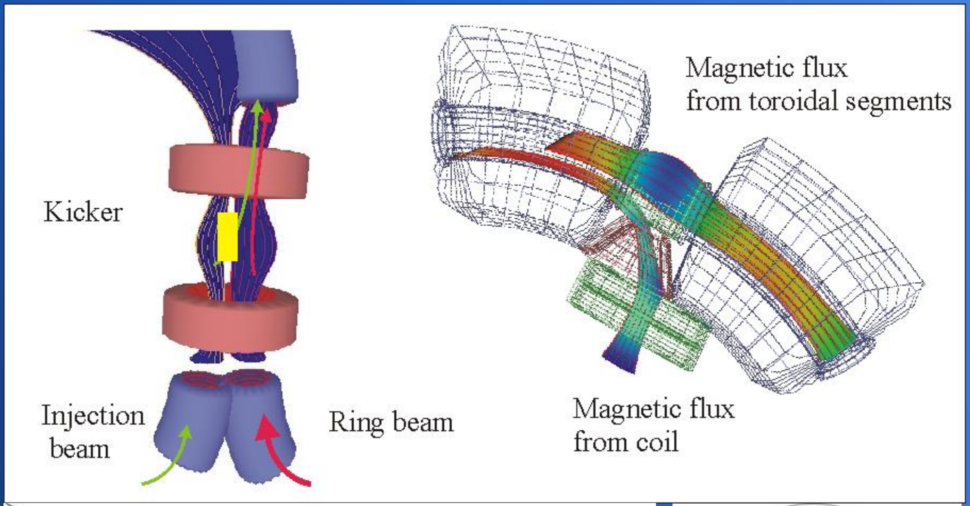

Injection Area
B[T]
6.45
6.3
6.15
6.0
5.85
5.7
injection point
coils
kicker
1.6m
cross over
ring flux
external flux
injection point

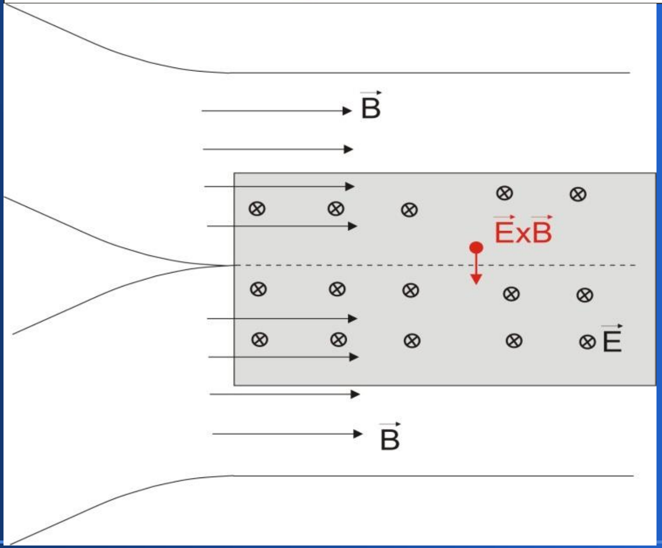

Injection beam
Field lines auxiliary
Kicker (ExB)
Stored beam
Closed magnetic field lines

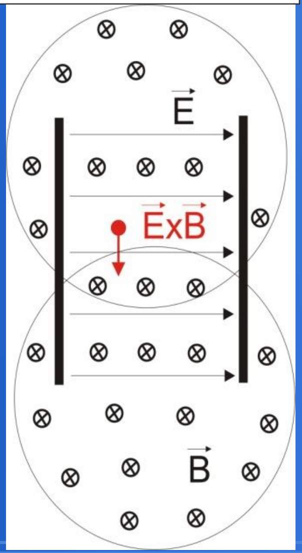

Ion Source
EBIS/p
Acceleration
B=0T
Adiabatic Compressor
B=0.2T-6T
L=4m
Injector
B=6T
E=2MV/m, L=1.6m
Storage Ring
B=6T

Scaled Experiments (room temperature)









Ion source - H^+ , H_2^+, H_3^+, He^+
Room temperature toroids B ~ 0.6T

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Thank you for your attention !!!

IAP