Figure-8 Storage Ring
F8SR
Non Neutral Plasma Confinement in Curvilinear Guiding Fields

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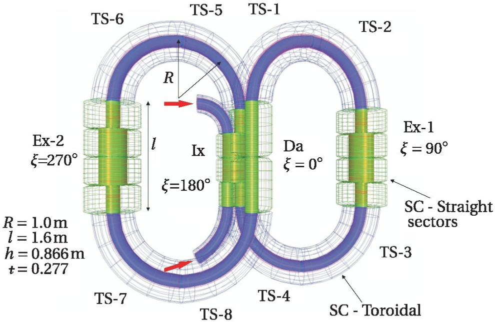
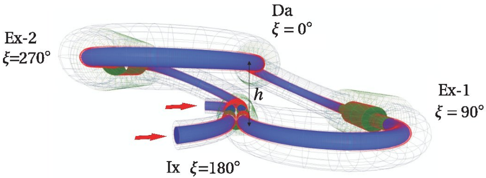
19.04.2013

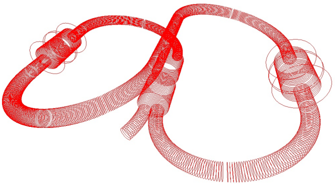
Outline

Superconducting High Current Ion Storage Ring **F8SR**

- Magnetostatic $|\vec{B}| \approx 6\,\mathrm{T}$
- Beam Energy: $W = 150\,\mathrm{keV}\text{-}1\,\mathrm{MeV}$
- Beam Current: $I = 1\text{-}10\,\mathrm{A}$
- Orbital revolution period: $T = 2\,\mu\mathrm{s}$
- Stored Beam Energy & Power:
  $E = 3\,\mathrm{J}$
  $P_{\max} = 1.5\,\mathrm{MW}$





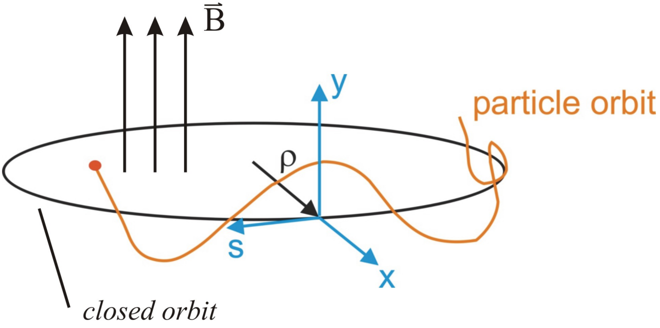


Why to build a new and such crooked Storage Ring - Motivation:

- astrophysical thin target experiments with well sharpened ΔE by electron cooling in a so called *Standard Mode*
- Fusion reactivity studies in a *High Current Mode* such as $\mathrm{p} + {}^{11}\mathrm{B} \rightarrow 3\ {}^{4}\mathrm{He} + 8.7\ \mathrm{MeV}$
- multiple beam(species) experiments in *Collider Mode* down to center of mass collision energies of $100\,\mathrm{eV}$
- space charge compensation by magnetic surface bounded secondary electrons
- multi ionisation of light atoms by an intense proton beam
- beam plasma interaction
- coulomb screening effects

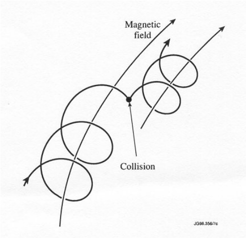
Traditional Storage Ring Concept

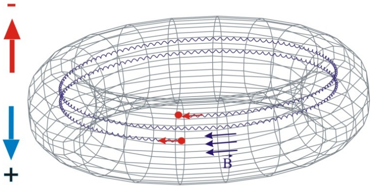
- achieving bending via dipole field
- focussing and corrections via quadrupoles & sextupoles
- closed orbit represents center of beam envelope



Magnetic Guiding Fields

- increasing the field strength up to $\approx 6\,\mathrm{T}$
  $\rightarrow$ fields become guiding fields
- field geometry can be chosen as toroidal.
  problem: still drifts perpendicular to the torus plane





Magnetic Guiding Fields

- to achieve focussing use poloidal field components.
  $\rightarrow$ toroidal field gets a rotational transform ι
  How? $\rightarrow$ bend the torus into a Figure-8
- off plane $\vec{R} \times \vec{B}$ drift vanishes in average due to changing direction of rotaion

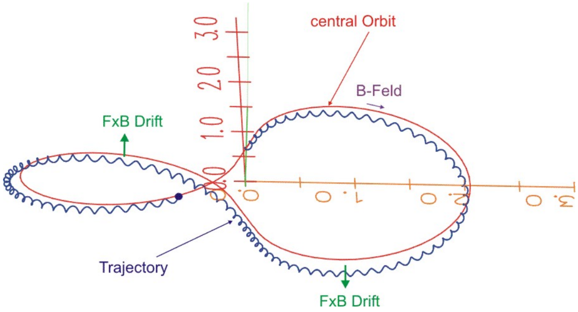
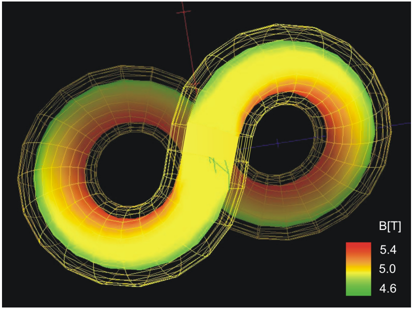


Figure-8 Storage Ring (**F8SR**)

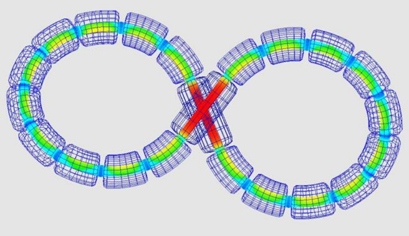
Studied Figure-8 Concepts

idealised mathematical design



- to see formation of magnetic surfaces
- first single particle dynamics

segmented design



- first step for a concrete realisation
- lower costs, contruction benefits
- problems with gaps and field discontinuities

Latest Figure-8 Design

- realisation ideas of: Injection-,Experimental- & Diagnosisarea
- Magnetostatic $|\vec{B}| \approx 6\,\mathrm{T}$
- Beam Energy: $W = 150\,\mathrm{keV}$-$1\,\mathrm{MeV}$
- Beam Current: $I = $ 1-10 A
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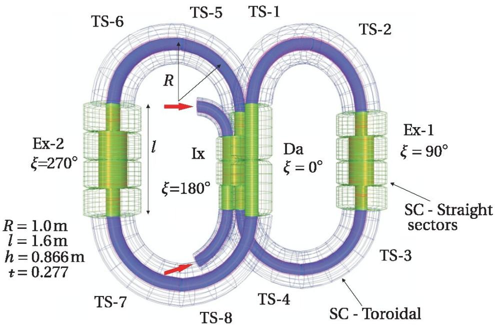
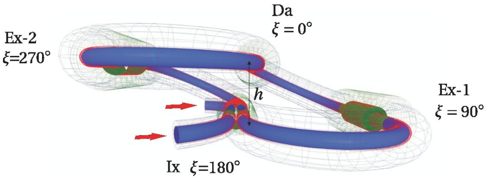
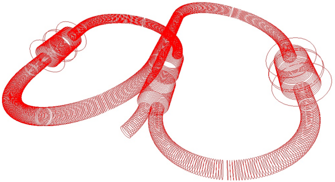
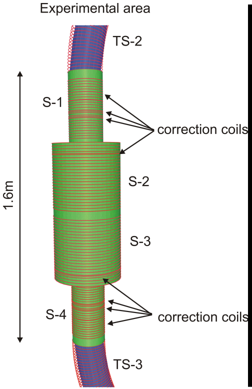
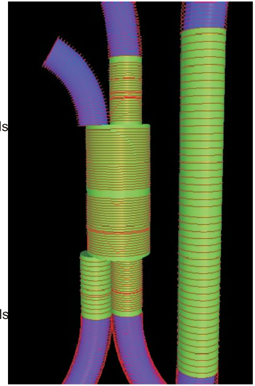




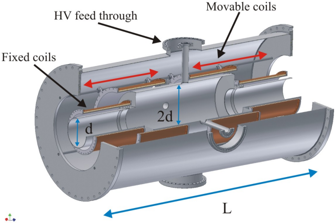


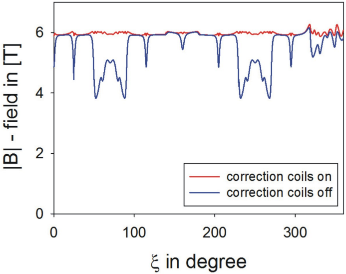
Latest Figure-8 Design





Preliminarily designs





followed by field analysis and repetitive construction designs to optimise the compromise:
beam transport≠experimenter liberties

Numerical Magnetic Field Transformation, Analysis & Particle Simulation

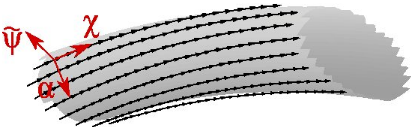
Simulation Method

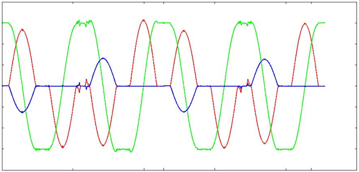
- once the magnetic fluxdensity is high, a guiding center approximation can be done
- for stable long-term simulations the use of symplectic algorithms becomes clear (bounded error range)
- to switch in a symplectic form of canonical coordinates one needs to get magnetic fluxcoordinates
  (in particular: Boozercoordinates ψ, θ, ξ)
- in the end - combined with particle in cell (PIC) methods to establish simulations

Establishing Magnetic Fluxcoordinates

- conventional mapping: fieldline-tracing-method gives periodical functions :

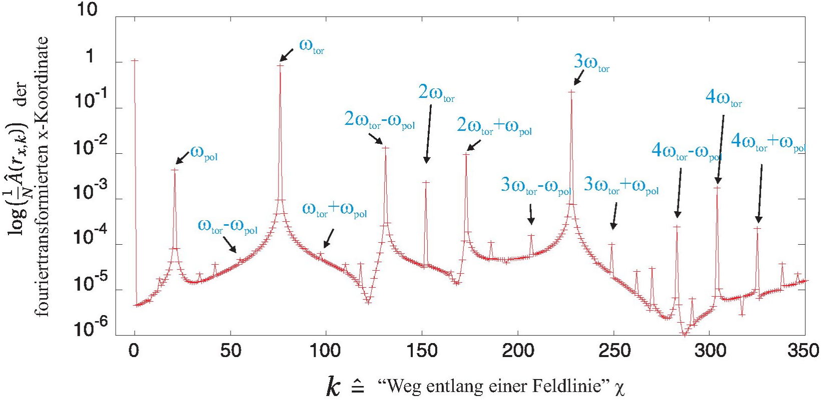
$$\begin{array}{ccc} r_x(\chi) & r_y(\chi) & r_z(\chi) \\ B_x(\chi) & B_y(\chi) & B_z(\chi) \\ A_x(\chi) & A_y(\chi) & A_z(\chi) \end{array}$$





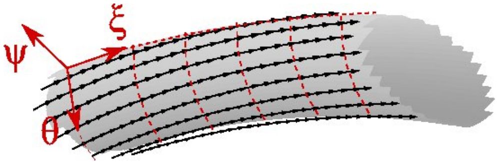
Establishing Magnetic Fluxcoordinates

1D-forward fouriertransformation gives frequency spectrum which has to be analysed



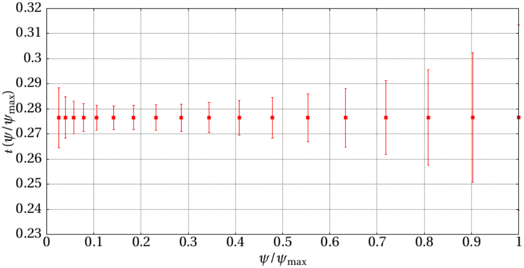
Establishing Magnetic Fluxcoordinates

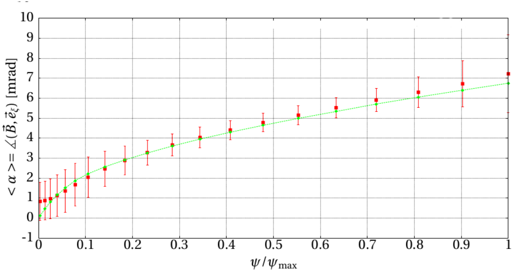
- 2d-backward Fast-Fourier-Transformation and frequency splitting establishes curvilinear (non-orthogonal) magnetic fluxcoordinates (Boozercoordinates) propagating by 2π
  $\vec{r}(\psi, \theta, \xi) \quad \vec{B}(\psi, \theta, \xi) \quad \vec{A}(\psi, \theta, \xi)$
  $\rightarrow$ Co- and contravariant vector components
  $B_\psi, B^\psi, B_\theta, B^\theta, B_\xi, B^\xi$



Numerical calculations vs. Theory

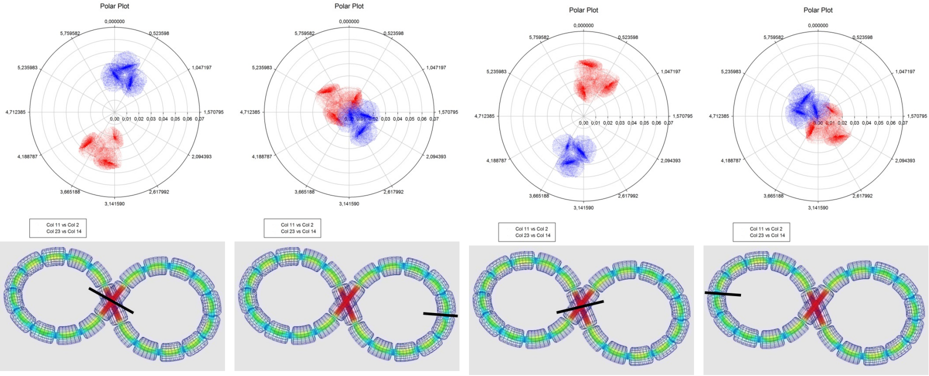
- coordinate transformation with 20 magnetic surfaces in total
- interesting parameters of boozercoordinates were cross checked: rotational transform $t = 0.277$ and for instance $\alpha = \measuredangle(\vec{B}, \vec{e}_\xi)$





Beam Dynamics in F8SR

Co- and contratraveling ion beams

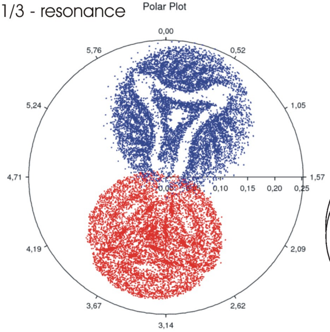


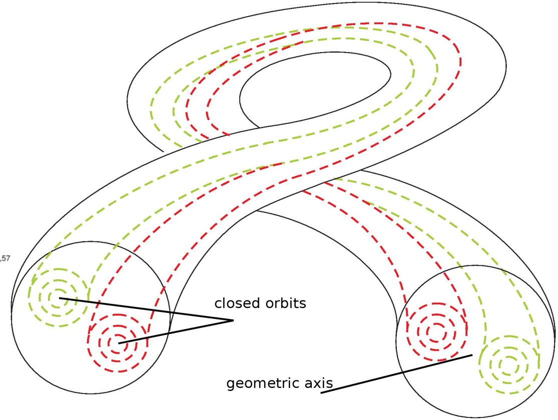
$\xi = 0^{\circ}$ $\xi = 90^{\circ}$ $\xi = 180^{\circ}$ $\xi = 270^{\circ}$

Dynamics of Driftsurfaces via Symplectic Single Particle Simulation

closed orbits depends on: injection position, beam energy
$\rightarrow$ obits need to be evaluated by simulations

1/3 - resonance





Experiments at Goethe University Institute of Applied Physics (IAP)

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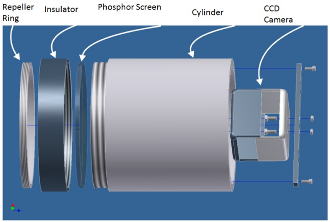
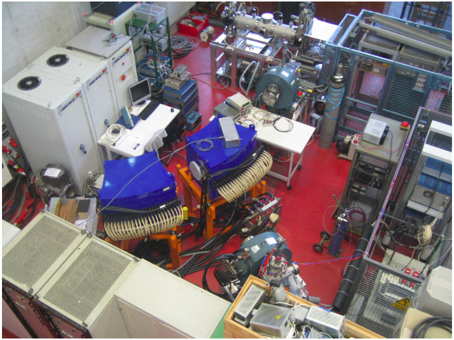
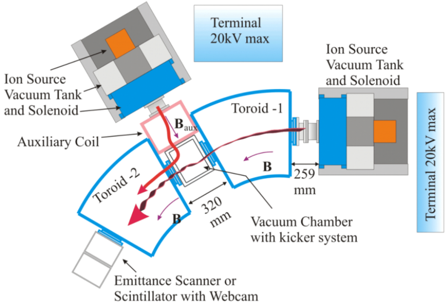
- emittance scanner: *transversal kick of beam in fringing field of toroid - position dependend*
- scintillator detector:
  - *mapping of beam motion in toroidal field*
  - *evidence of expected beam drift*
  - *detection of multi component beam focussing*
- transport through 2 toroids : *existing energy pass-band for optimum transition*



Exp.Setup for Toroidal Beam Transport & Injection Studies

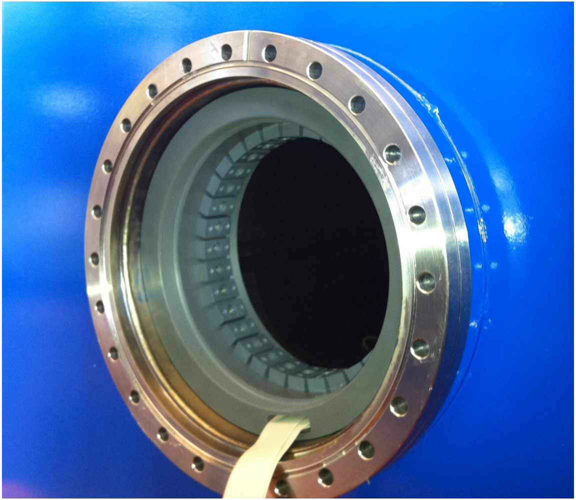
- a second injector (ion-source + solenoid) was refurbished
- two faraday cups were build & installed for momentum filter studies in order to prepare single particle species injection [H.Niebuhr]
  → important for comparable closed orbit simulations





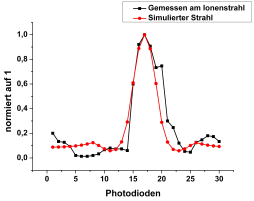
planned setup for injection experiments [N.Joshi]

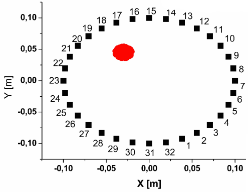
Non-destructive Diagnostics via Residual Gas Monitor



Non-destructive Diagnostics via Residual Gas Monitor

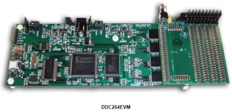
Measured residual gas luminescence of H-ionspecies with simulation reconstruction





actual studies for online data aquisition between photodiodes and evaluationboard:

- 256 channels
- femtoampere currents
- integration times 160 μs-1 s



[Adem Ates]

Outlook

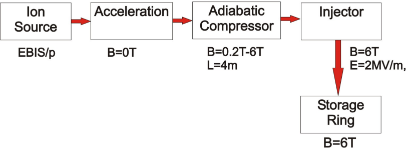
Adiabatic Compressor for Injection

- the facing problem is a smooth field transition

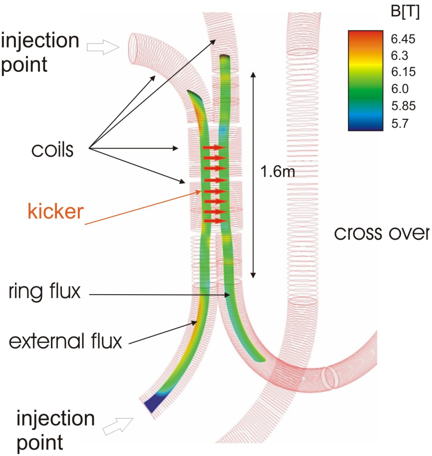
$$\mu = \frac{mv_\perp^2}{2B} \text{ must be constant}$$

$$\frac{\mathrm{d}B}{\mathrm{d}t} = \underbrace{\frac{\partial B}{\partial t}}_{=0} + v\frac{\partial B}{\partial x} < B\frac{\omega_c}{2\pi} =$$

$$\frac{qB^2}{2\pi m} \rightarrow v\frac{\Delta B}{\Delta z} < q\frac{B^2}{2\pi m}$$



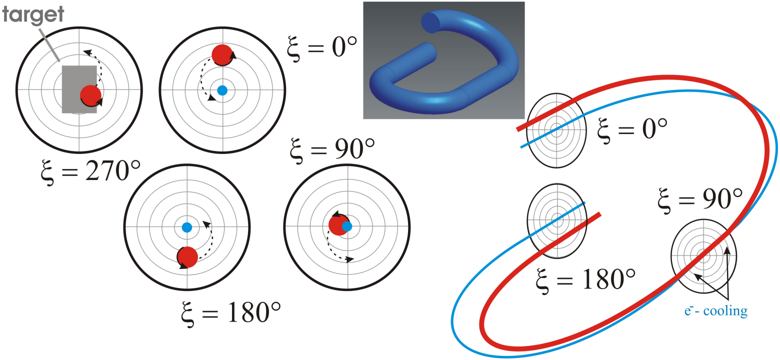
- repetitive coil(current) design with magnetic field analysis is needed



$E \times B$ - kicker $\rightarrow$ rep. rate $4\,\mu\mathrm{s}$, $E = 2\,{}^{MV}/_{\mathrm{m}}$

Standard Mode with Electron Cooler

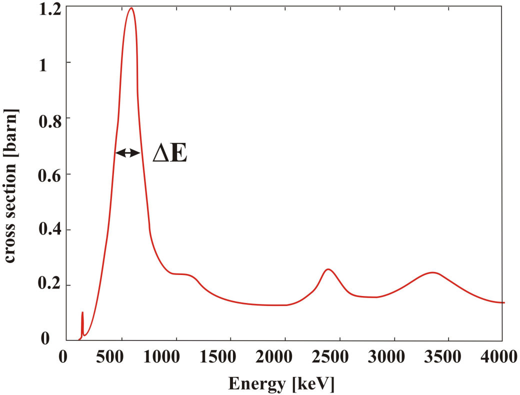
- e$^-$-gun ($E_{\text{kin}} \approx 120\,\mathrm{eV}$) at geometric axis & e$^-$-collector 180° later
- due to high fields e$^-$ are bound to the axis
- ion-beam drifts & rotates into e$^-$-beam simultaneously



→ simulations are planned!

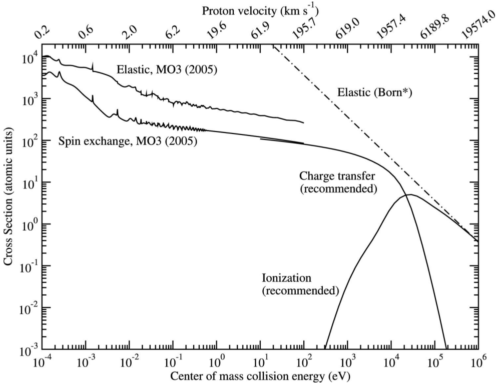
fusion Reactivity Studies in High Current Mode

best fusion cross sections of $p + {}^{11}\mathrm{B} \approx$ 500-600 keV
$\rightarrow$ a proton beam with a wider energy spread ΔE is fully acceptable (e$^-$-cooler off)



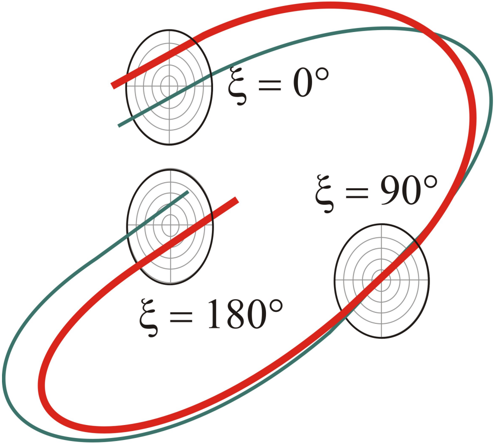
Low Energy Beam Beam Interactions in Collider Mode

Charge transfer problem: $H^+ + H \to H + H^+$



Low Energy Beam Beam Interactions in Collider Mode

→ injecting two beams ($E_{1,2} > 100\,\mathrm{keV}$) with two axis-offsets and $v_1 - v_2 = \Delta v$
→ leads to different closed orbits and collision energies $E_{\mathrm{CMS}} < 100\,\mathrm{keV}$



Thank you for your attention!

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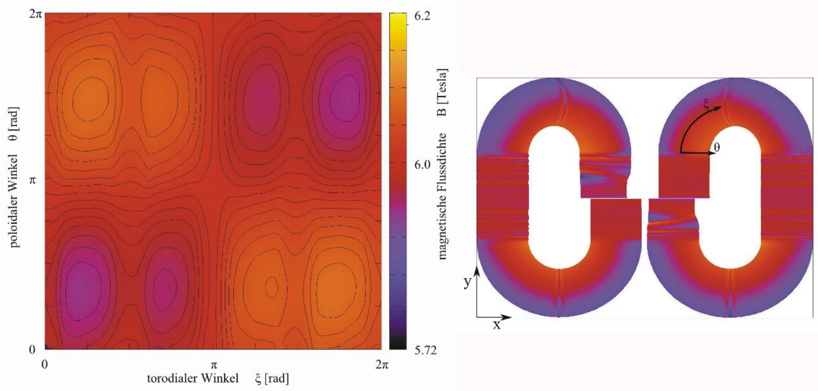
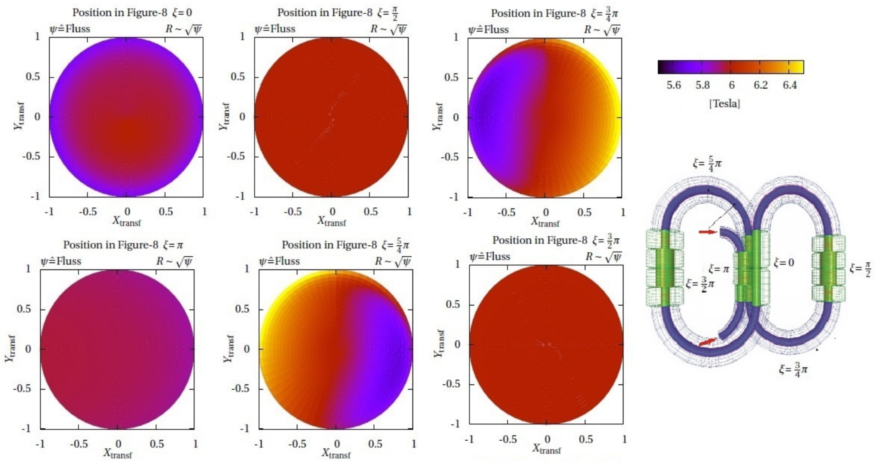
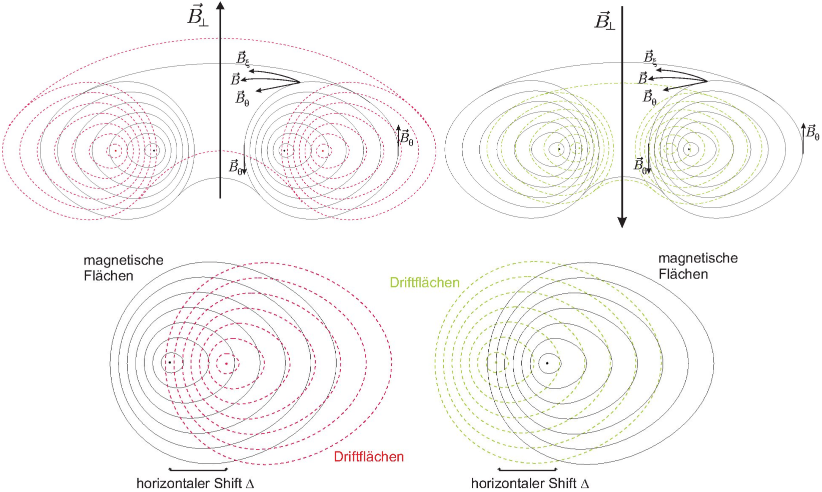
Map of Flux Density



Flux Density Profiles



Driftsurfaces



$$\Delta = \mp \frac{2\pi\beta r_L}{\iota}$$

Drift Hamiltonian & Canonical Variables

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

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

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