State of the Eight - Non Neutral Plasma Confinement in Curvilinear Figure-8 Guiding Fields

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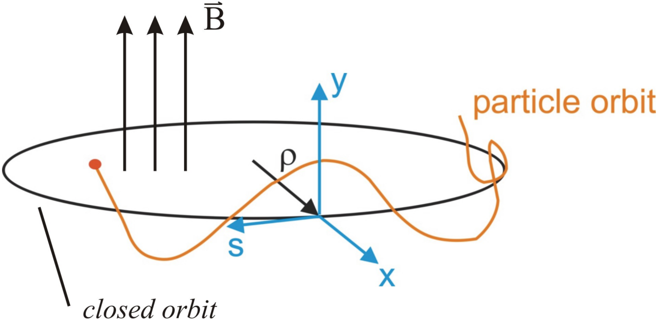
Content

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 p $+ {}^{11}$B $\rightarrow 3\ {}^{4}$He $+$ 8.7 MeV
- multiple beam(species) experiments in *Collider Mode* down to center of mass collision energies of $100\,\mathrm{eV}$
- multi ionisation of light atoms by intense proton beam
- beam plasma interaction
- coulomb screening effects

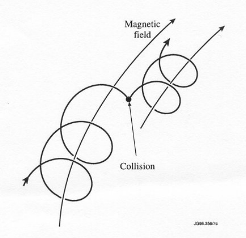
Traditional Storage Ring Concept

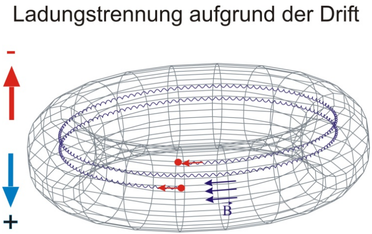
- achieving bending via dipole field
- focussing and corrections via quadrupoles & sextupoles
- closed orbit represents center of beam envelope



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 in y-axis





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

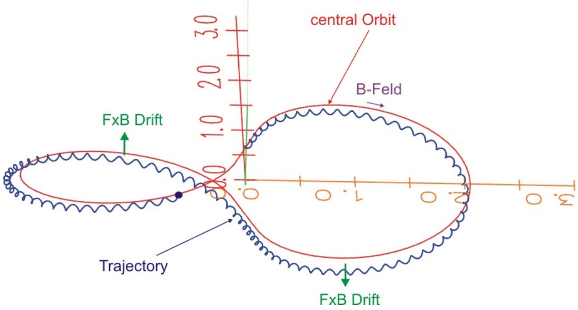
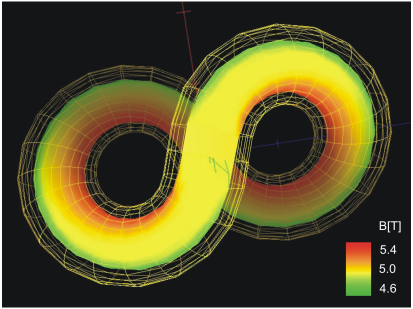


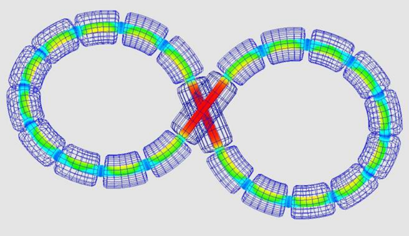
Figure-8 Storage Ring (**F8SR**)

Studied Figure-8 Concepts

idealised mathematical design

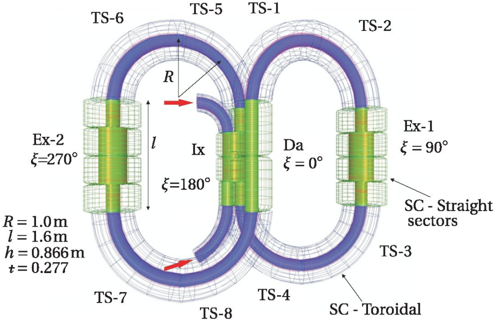


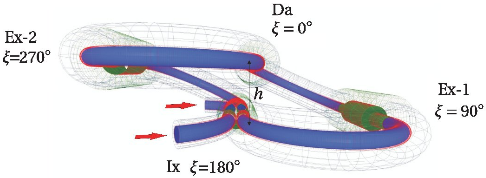
segmented design: lower costs, contruction benefits

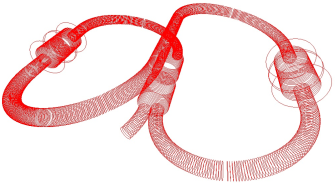


Latest Figure-8 Design

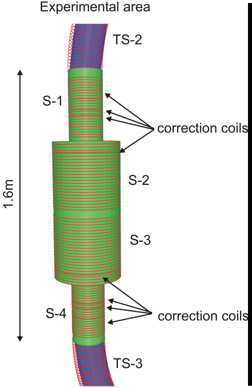
- realisation ideas of: Injection-,Experimental- & Diagnosisarea
- Magnetostatic $|\vec{B}| \approx 6\,\mathrm{T}$
- Beam Energy: $W = 150\,\mathrm{keV}$-$1\,\mathrm{MeV}$
- Beam Current: $I = 1$-$10\,\mathrm{A}$
- Orbital revolution period: $T = 2\,\mu\mathrm{s}$
- Stored Beam Energy & Power: $E = 3\,\mathrm{J}$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

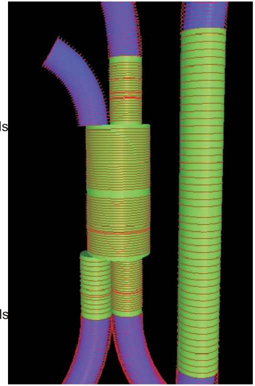




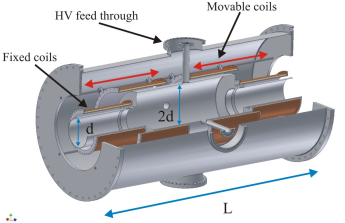


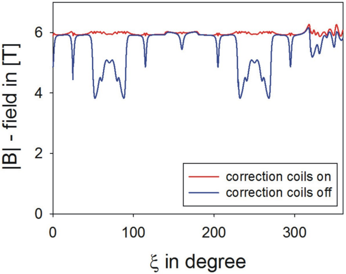
Latest Figure-8 Design





Preliminarily designs





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

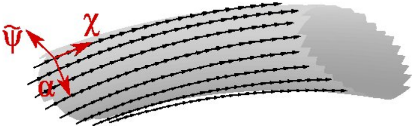
Numerical Magnetic Field Transformation, Analysis & Particle Simulation

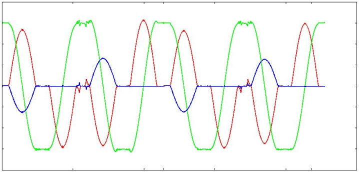
Simulation Method

- once the magnetic fluxdensity is high, a guiding center approximation can be done
- for stable long-term simulations the use of variational symplectic algorhytms 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

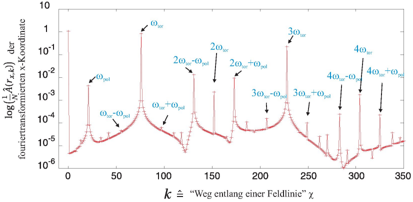
Establishing Magnetic Fluxcoordinates

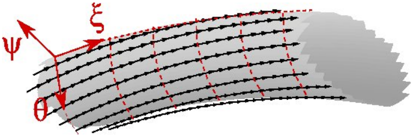
- conventional mapping: fieldline-tracing-method gives periodical functions :
  $r_x(\chi)$ $r_y(\chi)$ $r_z(\chi)$ $B_x(\chi)$ $B_y(\chi)$ $B_z(\chi)$ $A_x(\chi)$ $A_y(\chi)$ $A_z(\chi)$





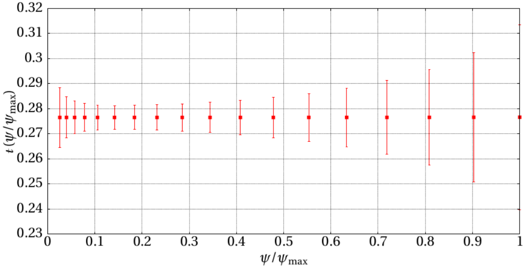
- 1d-forward, 2d-backward Fast-Fourier-Transformation and frequency analysis establishes curvilinear (non-orthogonal) magnetic fluxcoordinates (Boozercoordinates) propagating by 2π
  $\vec{r}(\psi,\theta,\xi)$ $\vec{B}(\psi,\theta,\xi)$ $\vec{A}(\psi,\theta,\xi)$
  $\rightarrow$ Co- and contravariant vector components B_ψ, B^ψ, B_θ, B^θ, B_ξ, B^ξ

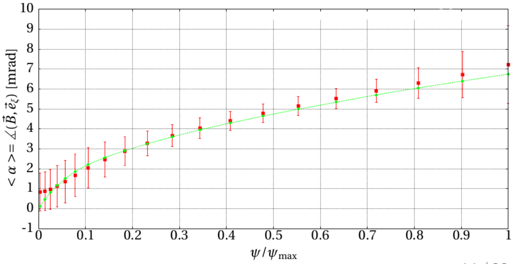




Numerical calculations vs. Theory

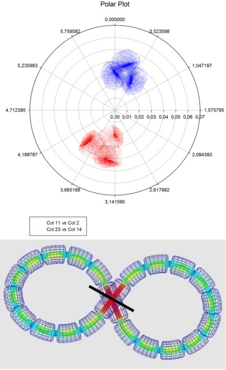
- coordinate transformation with 20 magnetic surfaces in total
- interesting parameters of boozercoordinates were cross checked: rotational transform $\iota = 0.277$ and for instance $\alpha = \measuredangle(\vec{B}, \vec{e}_\xi)$



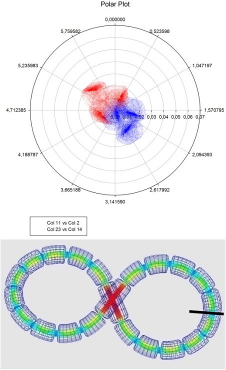


Beam Dynamics in F8SR

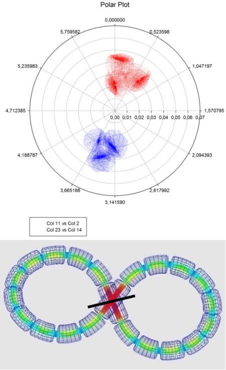
Co- and contratraveling ion beams



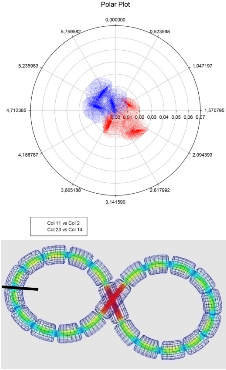
$\xi = 0^\circ$



$\xi = 90^\circ$



$\xi = 180^\circ$

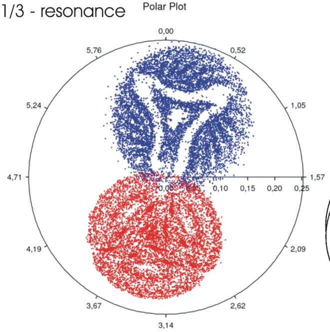


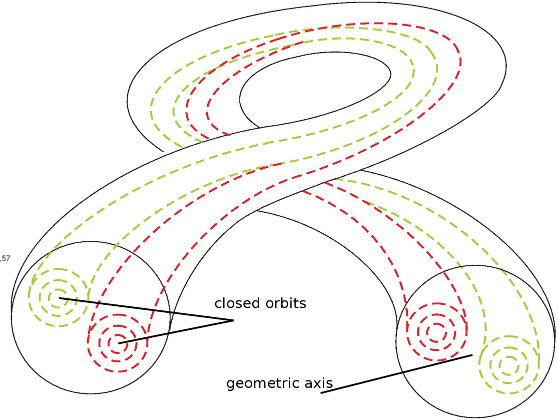
$\xi = 270^\circ$

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

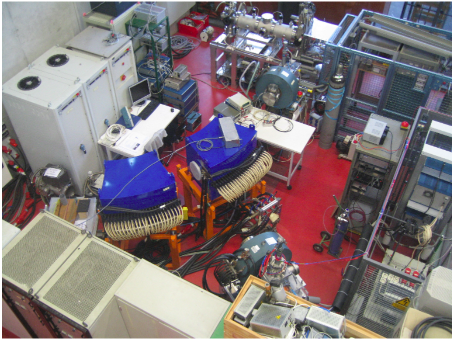


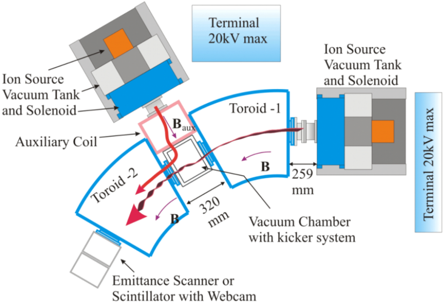


Experiments at IAP

Exp.Setup for Toroidal Beam Transport & Injection Studies

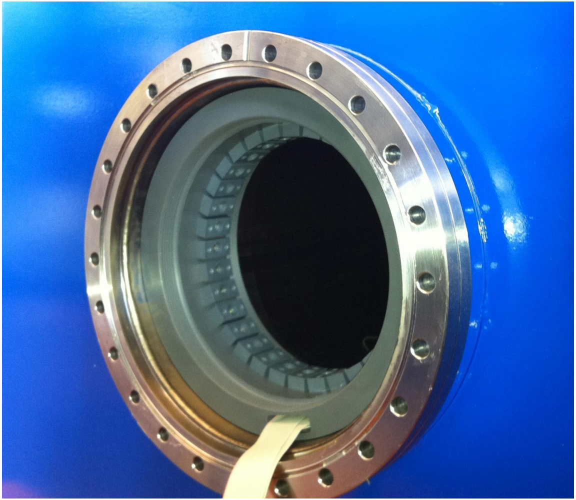
- a second injector (ion-source + solenoid) was refurbished
- two faraday cups were build & installed for momentum filter studies in order to prepare single particle species injection [H.Niebuhr]





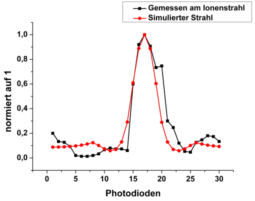
planned setup for injection experiments [N.Joshi]

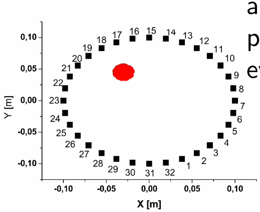
Non-destructive Diagnostics via Residual Gas Monitor



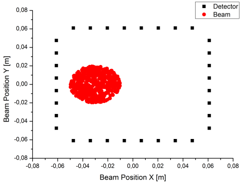
Non-destructive Diagnostics via Residual Gas Monitor

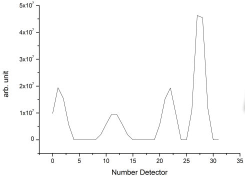
Measured residual gas luminescence of H-ionspecies with simulation reconstruction





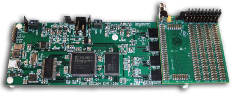
simulated quadratic monitor





actual studies for online data aquisition between photodiodes and evaluationboard:

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



DDC264EVM

[Adem Ates]

Outlook

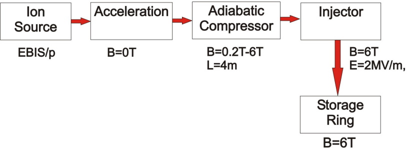
Adiabatic Compressor for Injection

- the facing problem is a smooth field transition

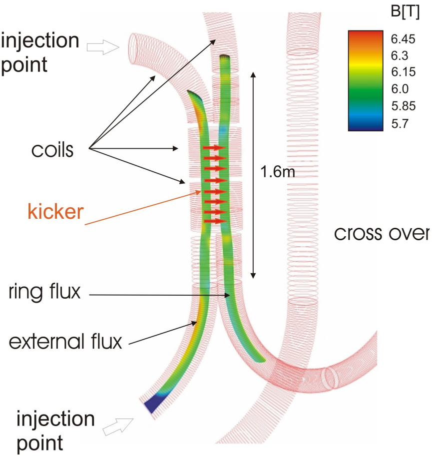
$$\mu = \frac{mv_\perp^2}{2B} \text{ must be constant}$$

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

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



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



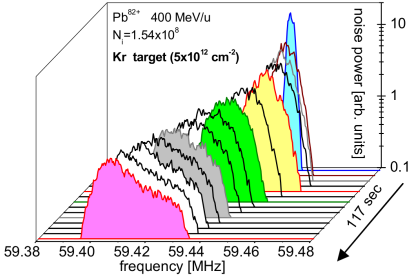
$E \times B$ - kicker $\rightarrow$ rep. rate $4\,\mu\mathrm{s}$, $E = 2\,{}^{MV}/_{\mathrm{m}}$
technical solution doable, see FRANZ chopper

Standard Mode with Electron Cooler

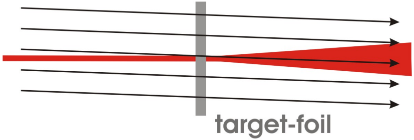
aims:

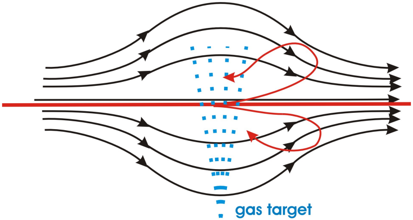
- thin target experiments (foil or gas) as standard application in storage rings
- as a matter of fact: beam energy spreads
- to restore sharp ΔE

  $\rightarrow$ electron cooling (+eventually simple acceleration unit)



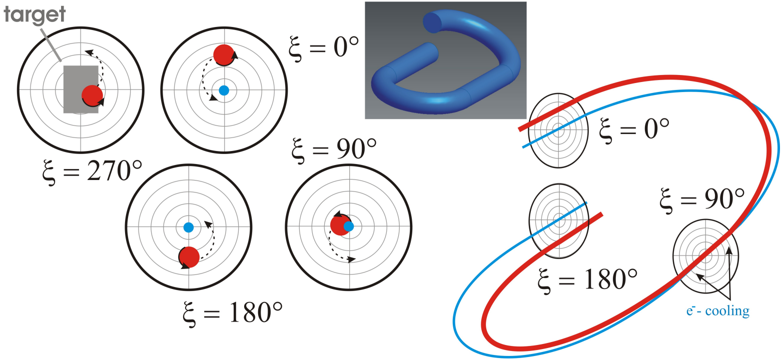
beam-target longitudinal Schottky spectra without cooling [EPAC06-MOPCH075]





Standard Mode with Electron Cooler

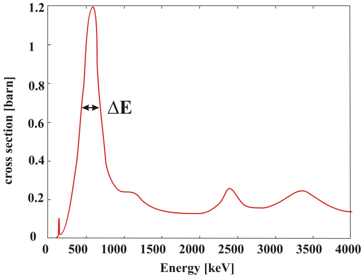
- e⁻-gun ($E_{kin} \approx 120\,\mathrm{eV}$) at geometric axis & e⁻-collector 180° later
- due to high fields e⁻ are bound to the axis
- ion-beam drifts & rotates into e⁻-beam simultaneously

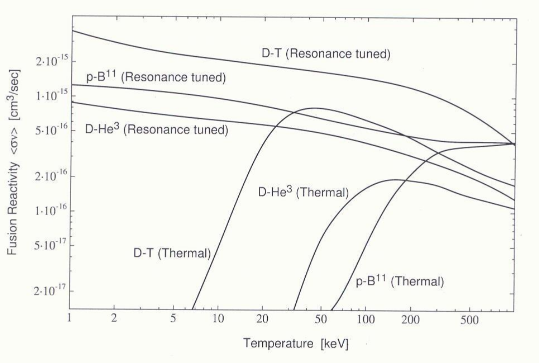


→ simulations are planned!

Fusion Reactivity Studies in High Current Mode

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

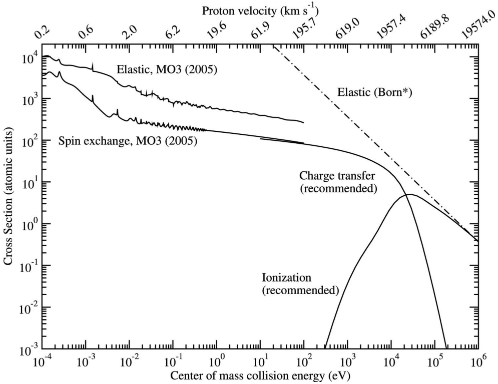




reactivity with resonance tuned proton beam starts earlier than thermal

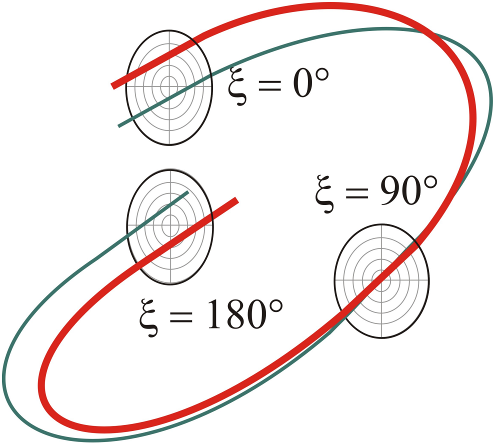
Low Energy Beam Beam Interactions in Collider Mode

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



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!