Status of the **F**igure-**8** **S**torage **R**ing **F8SR**

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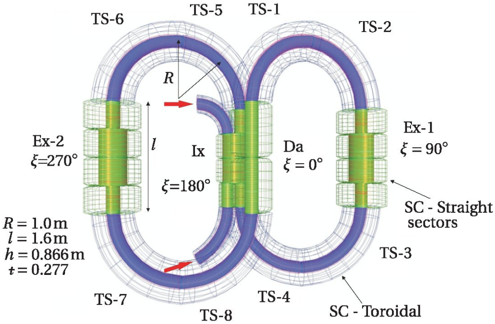
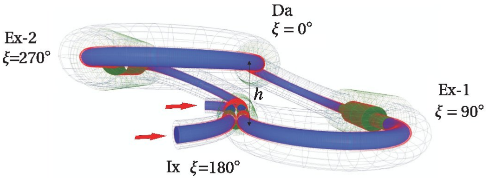
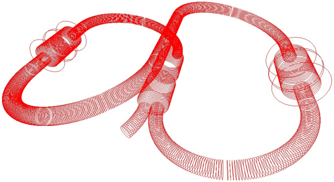
Outline

Superconducting High Current Ion Storage Ring **F8SR**

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







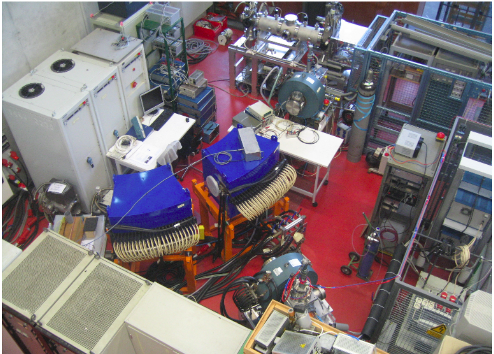
Why to build a new and such crooked Storage Ring - Motivation:

- Fusion reactivity studies in a *High Current Mode* such as $p + {}^{11}B \rightarrow 3\,{}^{4}He + 8.7$ MeV
- multiple beam & particlespecies 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

F8SR Experiments - Setup

Two 30° Toroids, $B_{max} = 0.6\,\mathrm{T}$
Two refurbished injectors, each with:

- terminal, $U_{max} = 20\,\mathrm{kV}$
- volume source, $I \approx 3.4\,\mathrm{mA}$ hydrogen mix, max 50% protons
- faraday-cup + solenoid, $B_{max} = 0.72\,\mathrm{T}$

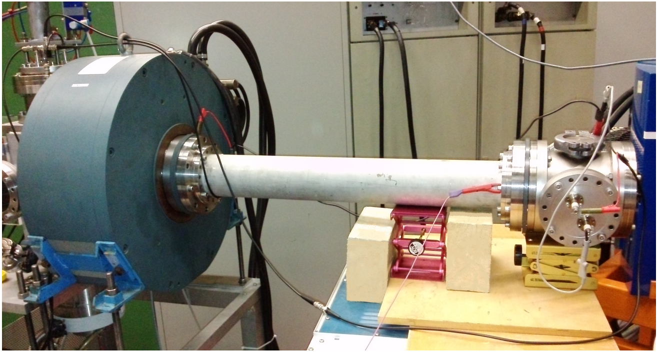


Momentum-Filter

F8SR Experiments - Momentum-Filter

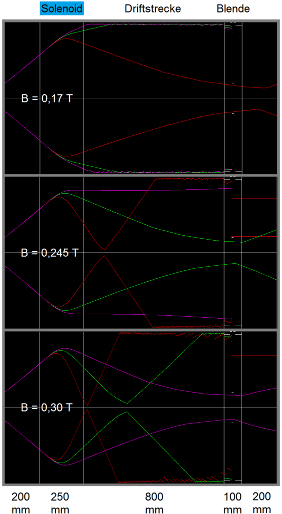
Master Thesis - Heiko Niebuhr:

- Design and construction of a magnetic **Momentum-Filter** for different hydrogen species (H^+,H_2^+,H_3^+)

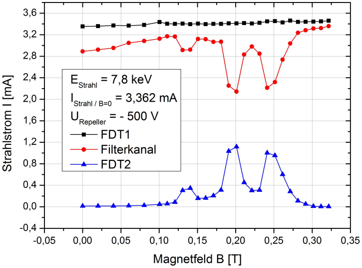


F8SR Experiments - Momentum Filter

Simulations of hydrogen species H^+,H_2^+ ,H_3^+ with *LINTRA*

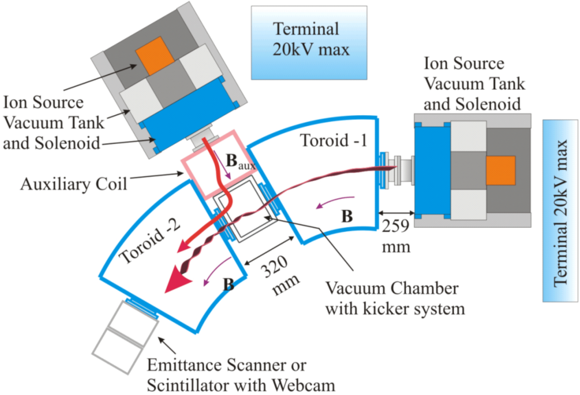


Measurements:
beam current in Faraday-Cups
FDT1: in front of solenoid
FDT2: behind filter-aperture
filterchannel: grounded via ampèremeter, $I \sim$ losses



F8SR Experiments - Injection

Injection simulations to determine air-core-coil parameters done (sim.-code *segments*). $B = 0.2 - 0.3\,\mathrm{T}$
Coil-design and construction is upcoming.

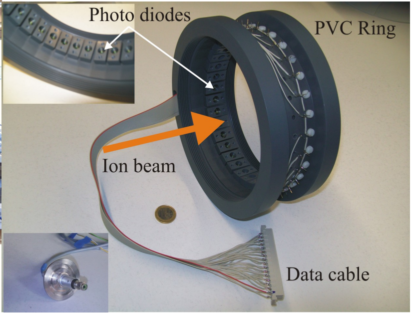


Beam Diagnosis

F8SR Experiments - Diagnosis

Master-Thesis Adem Ates: Non invasiv beam diagnosis via residual gas monitor in high magnetic fields

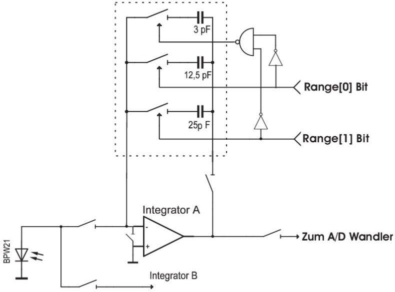
- movable ring of azimutal photodiodes for visible light

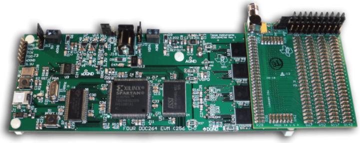


F8SR Experiments - Diagnosis

construction of a rapid recording electronics is done

- 20bit , 256 channels, direct current input & Analog-to-digital converter
- available capacitors: 3pF; 12,5pF; 25pF; 37,5pF ; up to 150pC
- integration times: 160 $\mu\mathrm{s} - 1\,\mathrm{s}$
- input currents: $\mathrm{fAs} - \mu\mathrm{As}$
- continous measurement via two way input channel



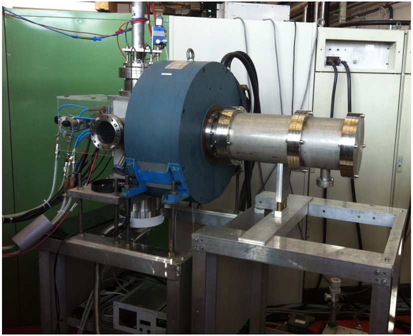


DDC264EVM

F8SR Experiments - Diagnosis

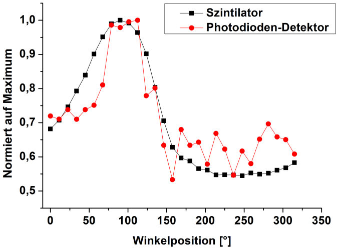
Testing setup:

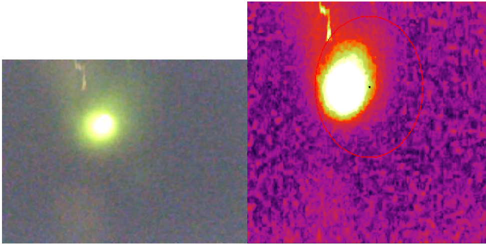
- extraction voltage: $6.5\,\mathrm{kV}$
- beam current: $1\,\mathrm{mA}$
- solenoid field: $0.33\,\mathrm{T}$
- residual gas pressure: $10^{-5}\,\mathrm{mbar}$ nitrogen



F8SR Experiments - Diagnosis

- measurement of a He-beam
- comparision with an invasive phosphor screen





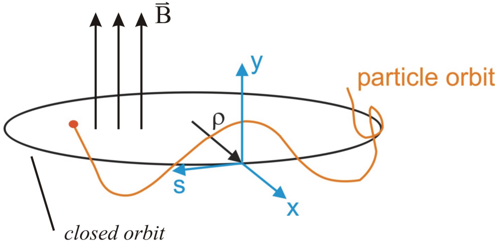
setting up a full diagnosis software with a algorithmical back transformation beam monitoring is the next step

Theory & Simulations

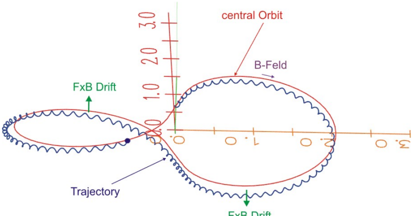
Theory & Simulations

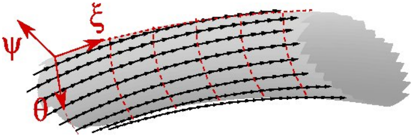
Closed Orbit Studies

Traditional Rings, focussing & corrections → Dipole, Quadrupoles



F8SR → Guiding-Fields





Complex magnetic field geometry inhibits traditional transport description via matrices & fixpoints

→ find analogous description to interlink
In magnetic coordinates (Boozercoordinates) ψ,θ,ξ
→ canonical variables for Drift-Hamiltonian:

$$\theta,\ P_\theta = \frac{q\psi}{2\pi}$$

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

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

For stable orbits the canonical variables must obey;

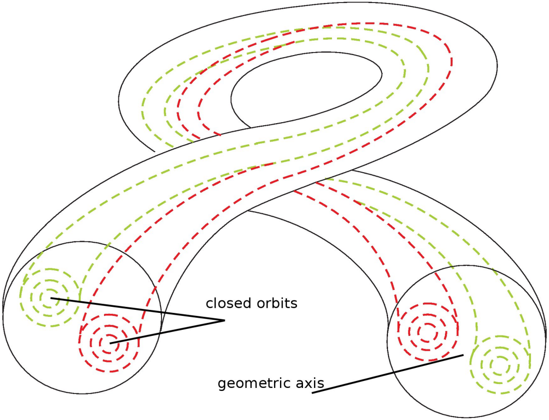
$$\frac{\mathrm{d}P_\theta}{\mathrm{d}t} \stackrel{!}{=} 0$$

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} \stackrel{!}{=} 0$$

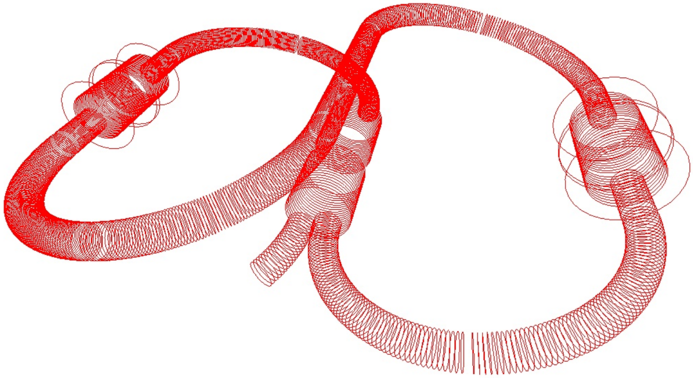
$$\frac{\mathrm{d}P_\theta}{\mathrm{d}t} = -\left[q\frac{\partial\phi}{\partial\theta} + \left(\mu + \frac{mv_\parallel^2}{|\vec{B}|}\right)\frac{\partial|\vec{B}|}{\partial\theta}\right]$$

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \frac{2\pi}{q}\left[q\frac{\partial\phi}{\partial\psi} + \left(\mu + \frac{mv_\parallel^2}{|\vec{B}|}\right)\frac{\partial|\vec{B}|}{\partial\psi}\right] + t\frac{\mathrm{d}\xi}{\mathrm{d}t}$$

- fixpoint studies with multipole expansion within the fieldmap are ongoing
- conventional 2d multipole expansion investigations do not satisfy the complex field geometry


closed orbits
geometric axis

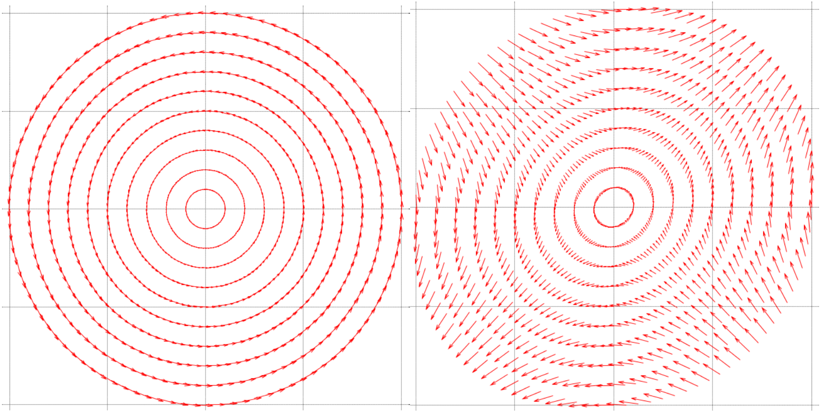
Field Imperfections & Error Studies



Construction always has coil missalignment → interfering multipole fields

Since $\vec{B}$ has components: $B_\psi = 0$, B_ξ, B_θ

Superposing a **poloidal** (B_θ) and **multipole** field. What do we get?



$$\vec{B} = \vec{B}_\theta + \vec{B}_{\text{quad}}$$

$$\vec{B}_\theta = \hat{B}_\theta \begin{pmatrix} -\sin\theta \\ \cos\theta \end{pmatrix} \; \vec{B}_{\text{quad}} = \frac{\hat{B}_{\text{q}} r}{a} \begin{pmatrix} \sin\theta \\ \cos\theta \end{pmatrix}$$

One obtains points with $|B| = 0 \rightarrow$ analytically solvable:

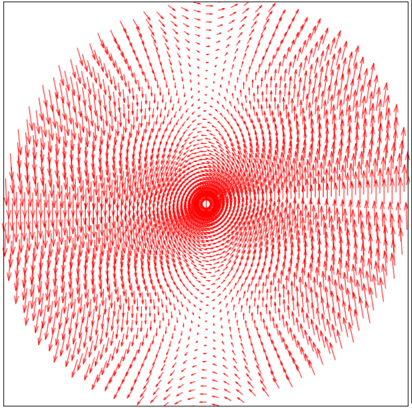
superposed **quadrupole**:

$$\left\{\theta = \frac{\pi}{2}, \quad r = \frac{\hat{B}_\theta}{\hat{B}_{\text{q}}} a\right\}; \left\{\theta = \frac{3\pi}{2}, \quad r = \frac{\hat{B}_\theta}{\hat{B}_{\text{q}}} a\right\}$$

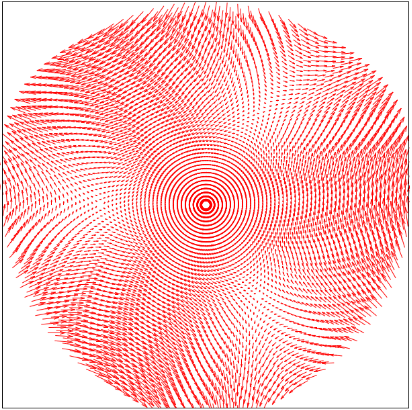
superposed **sextupole**:

$$\left\{\theta = \frac{\pi}{3}, \quad r = \sqrt{\frac{\hat{B}_\theta}{\hat{B}_{\text{q}}} a}\right\}; \left\{\theta = \pi, \quad r = \sqrt{\frac{\hat{B}_\theta}{\hat{B}_{\text{q}}} a}\right\}; \left\{\theta = \frac{5\pi}{3}, \quad r = \sqrt{\frac{\hat{B}_\theta}{\hat{B}_{\text{q}}} a}\right\}$$

poloidal + quadrupole
$\rightarrow$ Quadrupoles around $|B| = 0$
Poloidal around center area

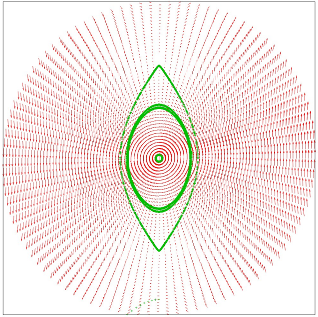


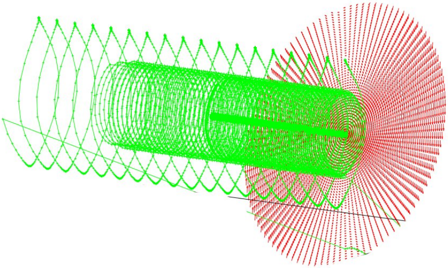
poloidal + sextupole



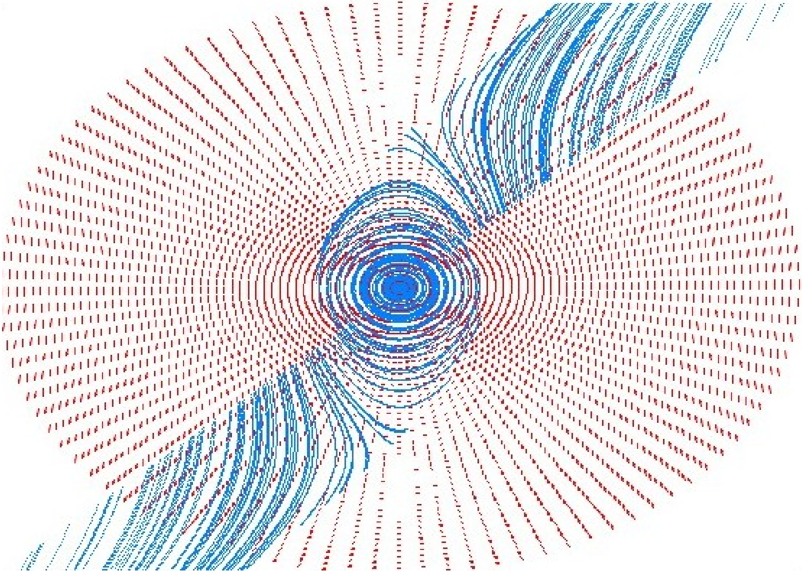
Influence on particle transport?

Simulations with $\hat{B}_\theta = \hat{B}_\mathsf{q} = 0.1\% \hat{B}_\xi$

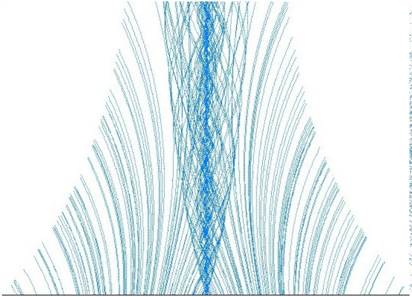




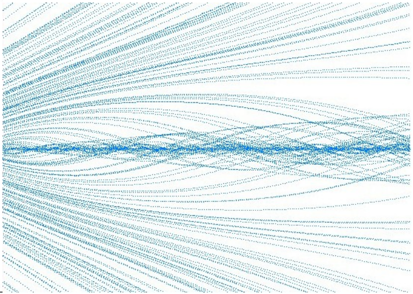
front view



top view



side view



→ certain aperture at a specific slice

→ dynamic aperture along the ring axis

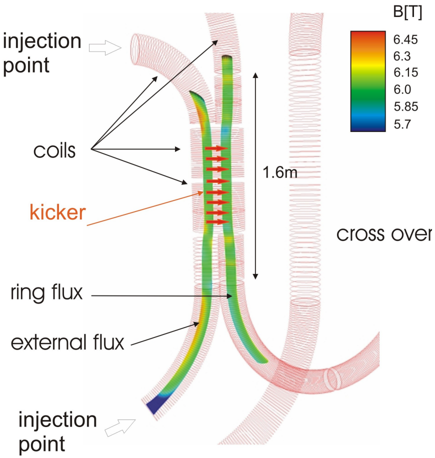
Acceptance of the confinement area is reduced

→ areas of particle loss

Injection via Adiabatic Compression

Injection via Adiabatic Compression

Concerning the canonical momentum
$\vec{p} = m\vec{v} + q\vec{A}$
even if $\vec{v} || \vec{B}$ at injection point one obtain
$\Delta\vec{A} \rightarrow \Delta\vec{v}$ during entering
$\rightarrow$ radius of acceptance
$r = \frac{2mv_{||}}{qB}$
$r|_{B\,=\,6\,\mathrm{T}} = 8\,\mathrm{mm}$

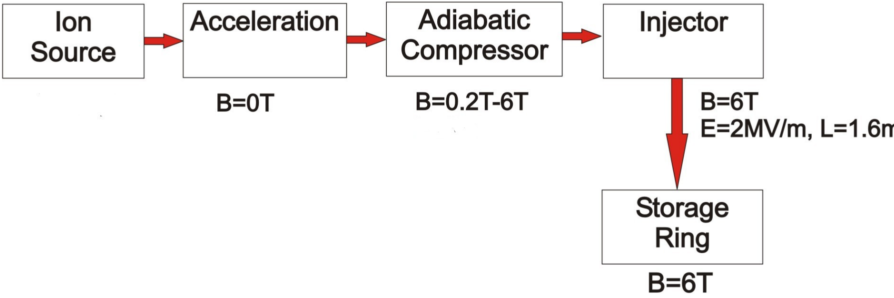


Injection via Adiabatic Compression

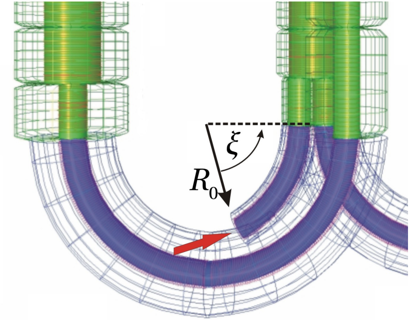
- the facing problem is a smooth field transition

magnetic moment $\mu = \frac{mv_\perp^2}{2B}$ must be constant
$\rightarrow$ adiabatic invariant

$$\frac{\mathrm{d}B}{\mathrm{d}t} = \underbrace{\frac{\partial B}{\partial t}}_{=0} + v_z \frac{\partial B}{\partial z} < B\frac{\omega_c}{2\pi} = \frac{qB^2}{2\pi m} \rightarrow v_z \frac{\Delta B}{\Delta z} < q\frac{B^2}{2\pi m}$$

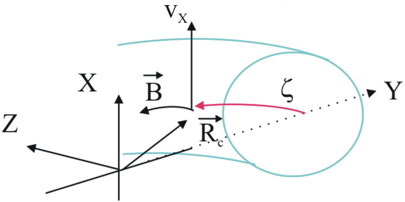


Injection via Adiabatic Compression



due to the gradient $\frac{\Delta B}{\Delta s} \rightarrow B(x, y, z) \rightarrow B(\xi)$

Injection via Adiabatic Compression



$$\vec{v}_\mathrm{d} = \frac{1}{q}\frac{\vec{F}\times\vec{B}}{B^2} \qquad \vec{F}_\mathrm{c} = \frac{mv_\parallel^2}{R_\mathrm{c}} \rightarrow \vec{v}_\mathrm{d} = \frac{mv_\parallel^2}{qB^2}\frac{\vec{R}_\mathrm{c}\times\vec{B}}{R_\mathrm{c}^2}$$

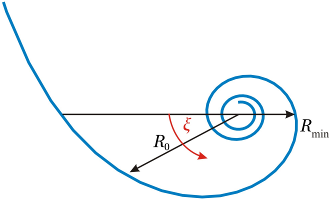
drift velocity coming from $R \times B$ drift

$$v_x = \frac{mv_\parallel^2}{qB(\xi)R}$$

$v_x \overset{!}{=} \text{const.}$

$\rightarrow B(\xi)\cdot R(\xi) \overset{!}{=} \text{const.}$

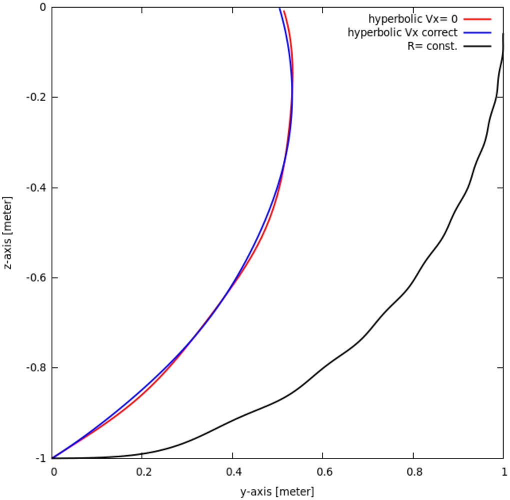
$B(\xi) = a_1 \cdot \xi \qquad R(\xi) = a_2 \cdot \frac{1}{\xi}$



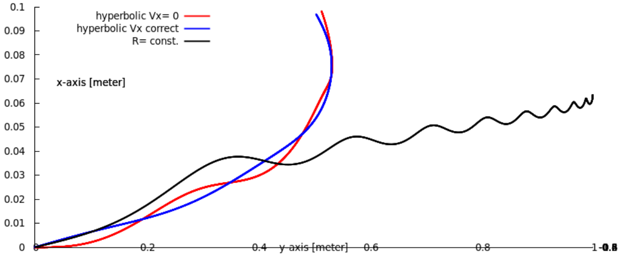
hyperbolic spiral transport channel

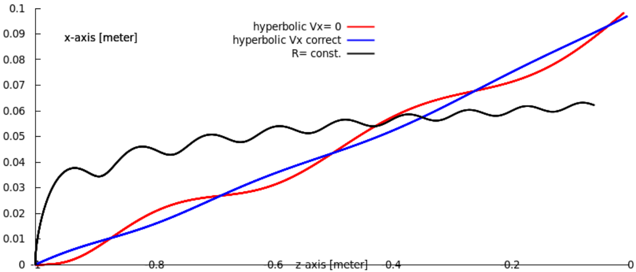
Injection via Adiabatic Compression

Single particle simulations, $\vec{v} = \vec{v}_x + \vec{v}_{||}$



Injection via Adiabatic Compression





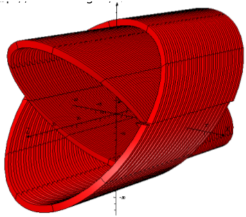
Injection via Adiabatic Compression

Another possible solution to compensate the drift is by adding a dipole component

$$x(\theta) = R.\cos(\theta)$$

$$y(\theta) = R.\sin(\theta)$$

$$z(\theta) = \frac{h\theta}{2\pi} + \frac{R}{\tan\alpha}\sin(n\theta + \varphi_0)$$



[S.Sheehy,BeamDynamicsMeetsMagnets 2013]

$\rightarrow$ to be investigated

Outlook

- commissioning of the injection experiment when the coil is ready
- design of the adiabatic injection section for the latest F8SR type
- high current beam transport simulations
- target fusion cross section simulations

Thank you for listening!

Fixpoints & Multipole expansion

Choose a certain point as a possible fixpoint
$\rightarrow$ interpolate the field at points on concentric circles
$\vec{B}_{\text{res}} = \vec{B}_{\perp} - \vec{B}_{\perp,0}$
where $\vec{B}_{\perp} = B^{\theta}\vec{e}_{\theta}$
$\rightarrow$ start multipole expansion

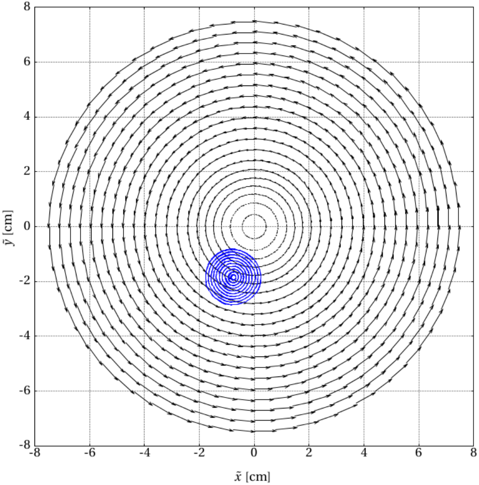
$$C_n = \frac{1}{Mr_0^{n-1}} \sum_{m=1}^{M} (B_y + iB_x)_m e^{-i\phi_m(n-1)}$$

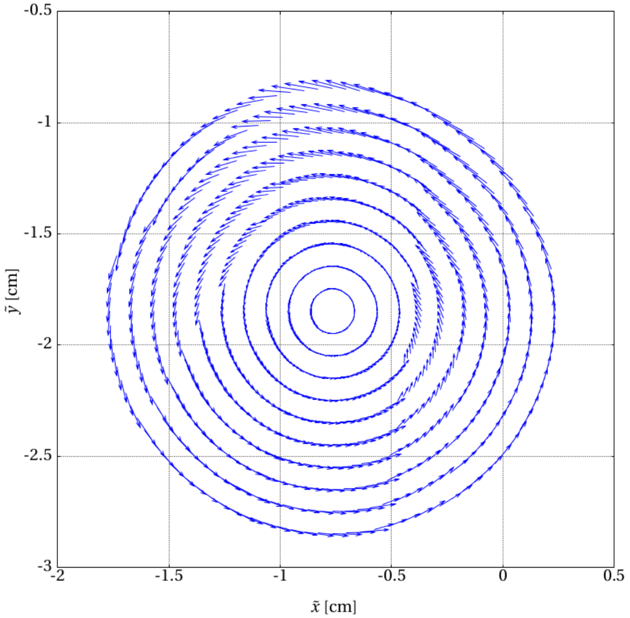
where

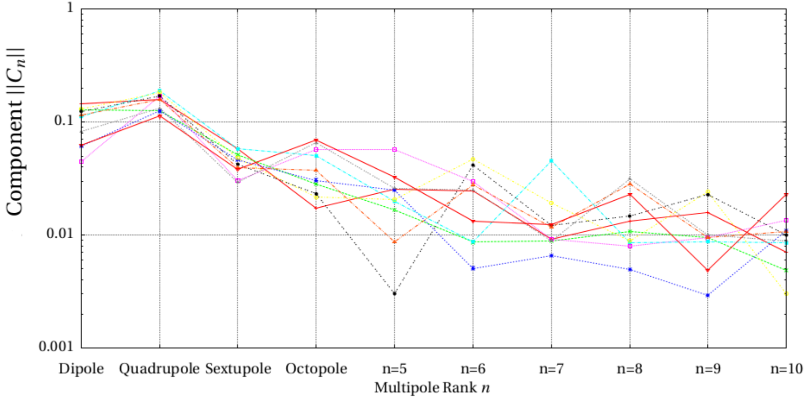
	dipole	quadrupole	sextupole	...
$n =$	1	2	3	...

For a poloidal field $\vec{B} = B \begin{pmatrix} -\sin\theta \\ \cos\theta \end{pmatrix}$ one gets $C_n = 0 \quad \forall \; n$

Slice of the mesh ("beam tube")
black= $\vec{B}_\theta$ component
blue: $\vec{B}_{\text{res}}$




-0.5
-1
-1.5
-2
-2.5
-3
-2
-1.5
-1
-0.5
0
0.5
$\tilde{y}$ [cm]
$\tilde{x}$ [cm]



$\rightarrow$ small or almost none amount of multipole components

problem: this kind of multipole expansion lacks 3rd dimension

$B^\theta \vec{e}_\theta$ is just a projection 3d $\rightarrow$ 2d