F8SR - Ein Hochstromspeicherring für leichte Ionen

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Motivation

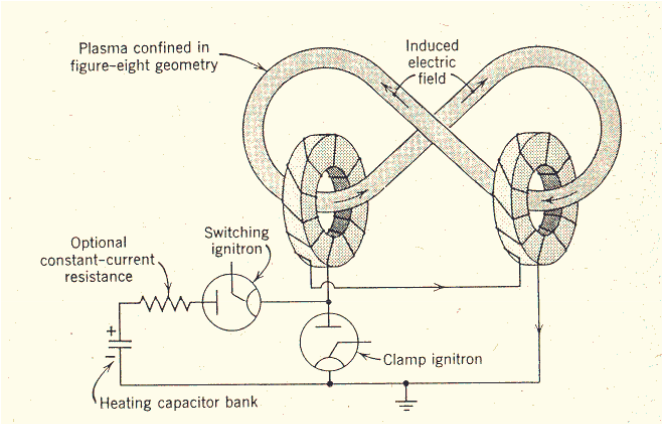
- Einschluss im Magnetfeld - Speicherrung

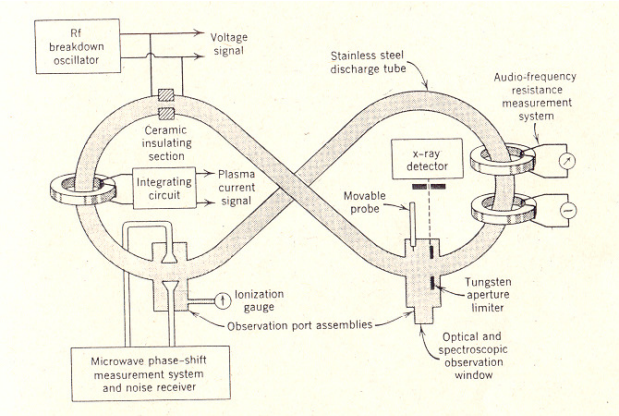
  - longitudinales Führungsfeld
  - Gyration
  - gekrümmtes Feld
  - Driften (RxB, gradB, ExB...FxB)
  - Raumladungskompensation

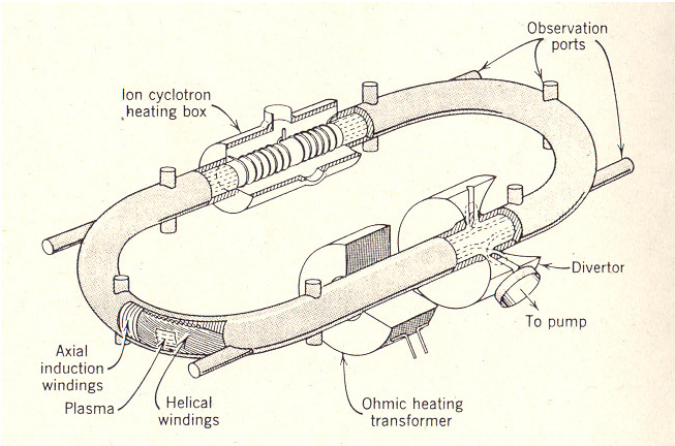
Einschluss in longitudinalem Magnetfeld

- Projekt Matternhorn
- Fusionsforschung - Stellarators, Tokamaks
- LEPTA –Ring
- CNT – Columbia Non-neutral Torus
- MECO Projekt
- Elektronenstrahlen für Plasmaheizen
- Elektronkühler, Detektoren

Projekt Matternhorn (1951-1958)

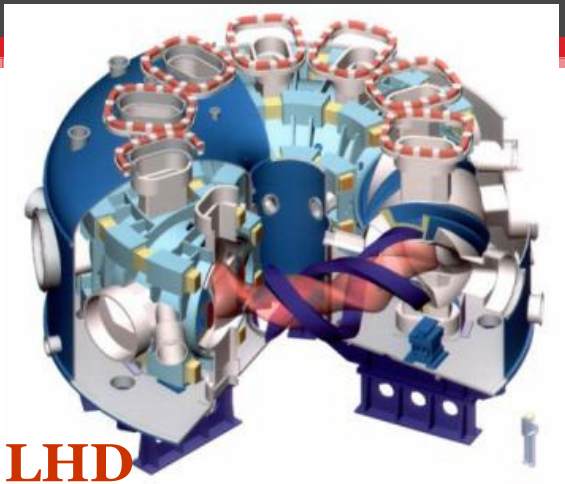




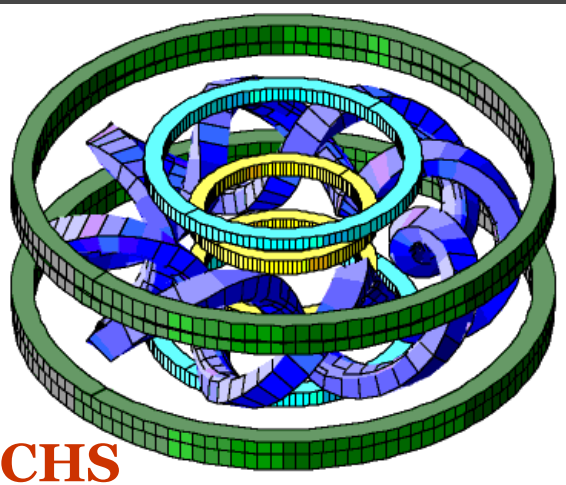


Plasmaeinschluss – [ms] Bereich, induziertes Magnetfeld die natürliche Rotation der Feldlinien auf der Flussfläche wird aufgehoben

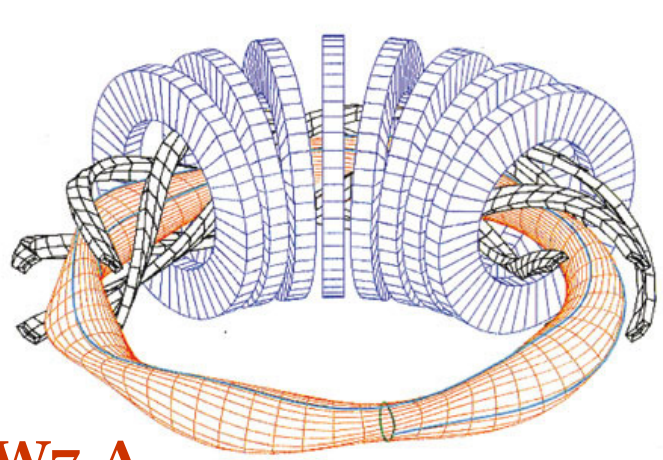
"runaway electrons" – Einschluss in sekunden



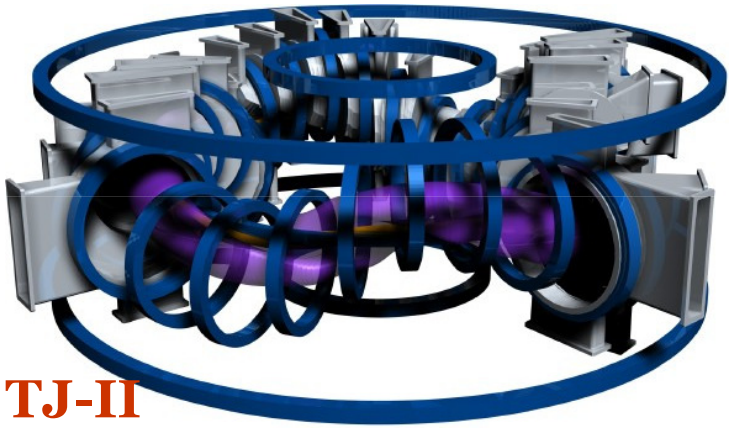
LHD



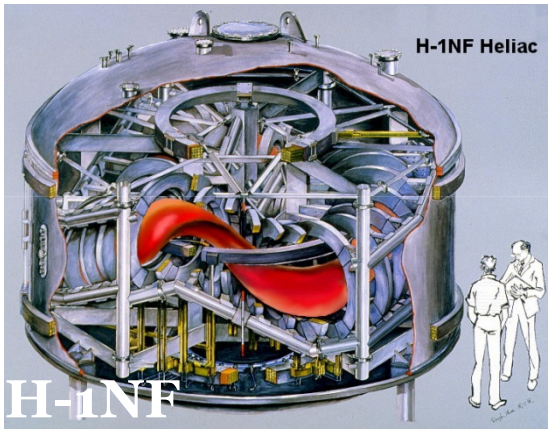
CHS



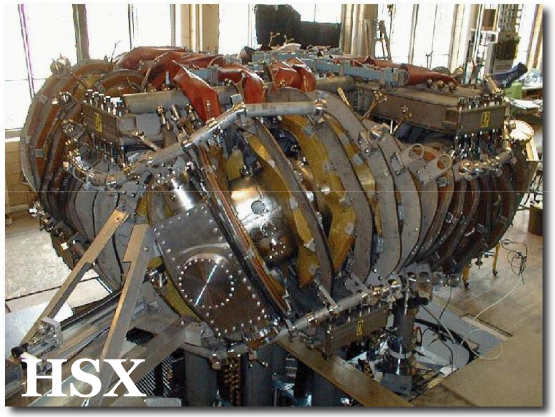
W7-A



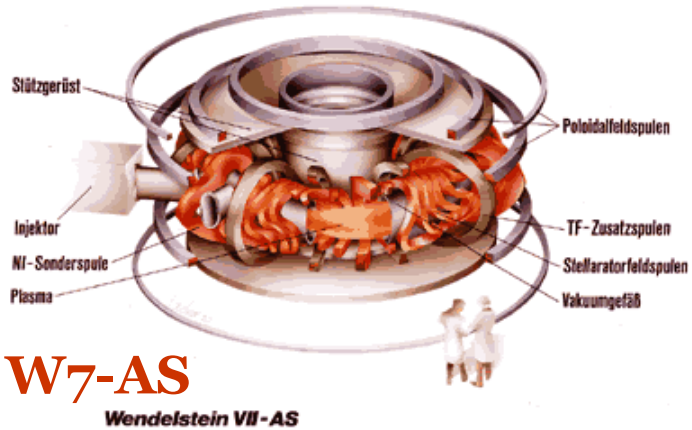
TJ-II



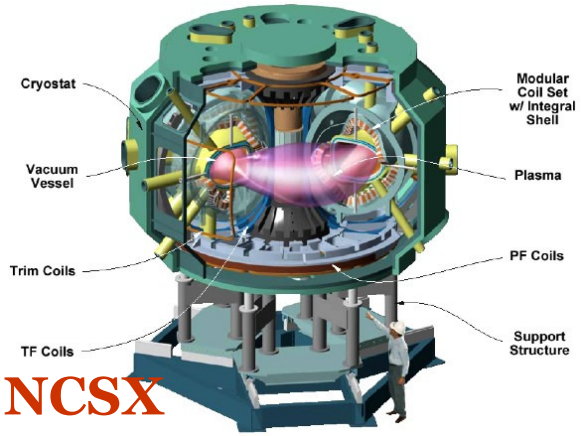
H-1NF



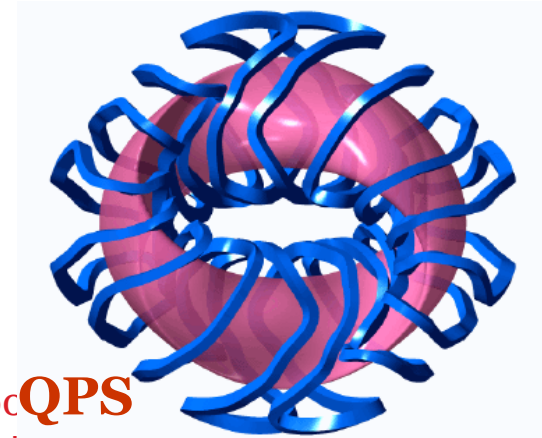
HSX



W7-AS

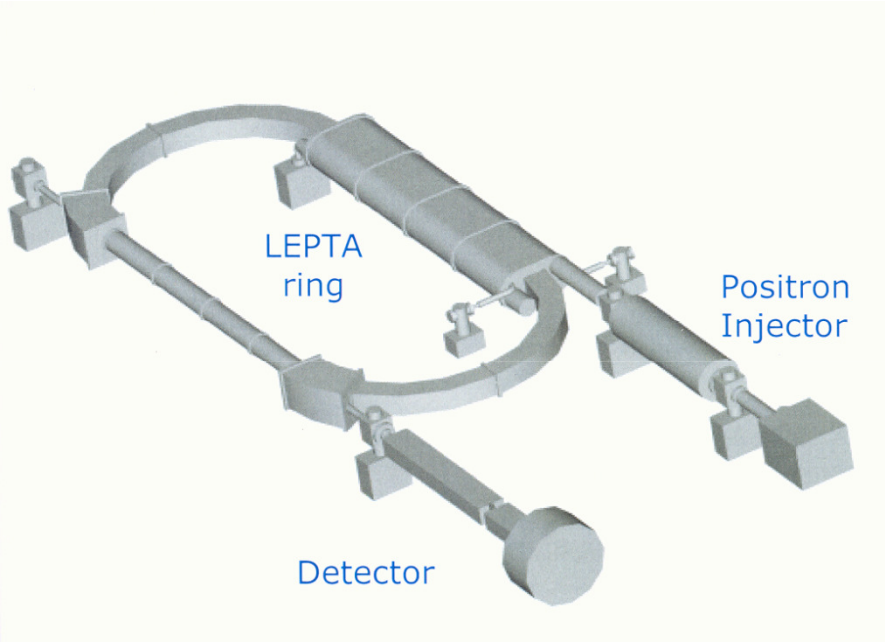


NCSX



QPS

LEPTA (Low Energy Positron Storage Ring)



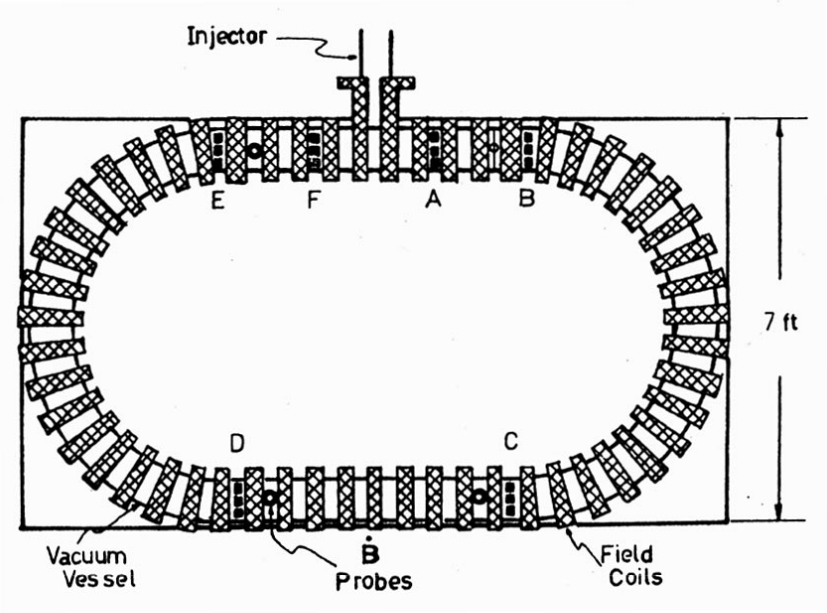
- 10keV, 300ns, L=18.12 m
- Elektronenkühlung ->Positronfluss
- Positronium
- Anti-hydrogen “in-flight”
- Einschluss -> 100s

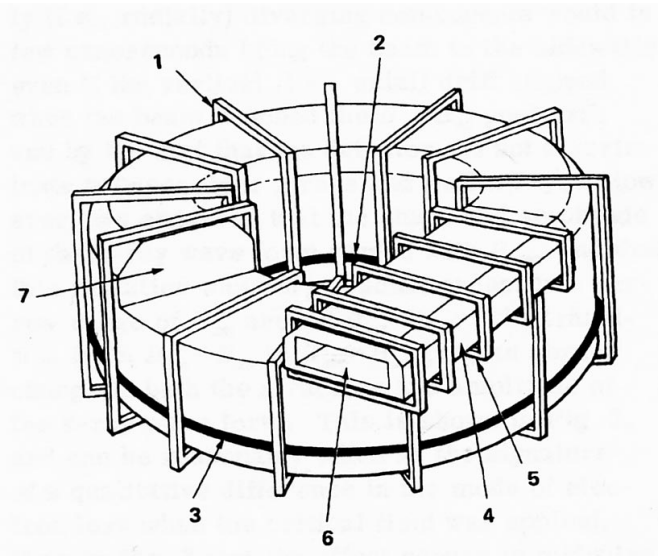
- P.Gillad (Cornell University, USA,1974)

- relativistische Elektronstrahl (50 ns, 400 kV, 20 kA)
- 3.8 kG, trapping für 300 ns, Gasdruck 1.5 Torr
- R=91cm, r=6.35cm

- J. Benford (Physics int. company, California, USA, 1974)

- Injektor für relativistische Elektronenstrahlen (10 kA, 40 ns, 0.96 – 1.75 MeV)
- Toroidale Feld 2.35 kG
- Driftkompensation durch verticale Dipolfeld 400-800 G
- Stickstoffgas – 1000 Torr schnelle Raumladungskompensation

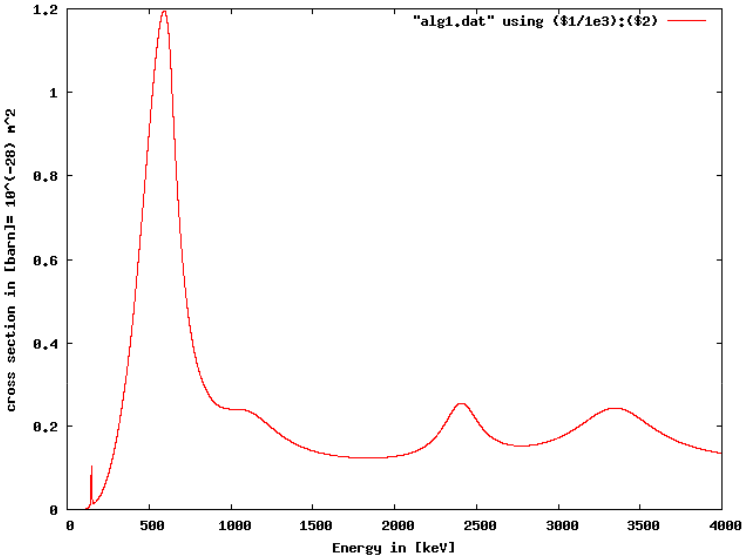


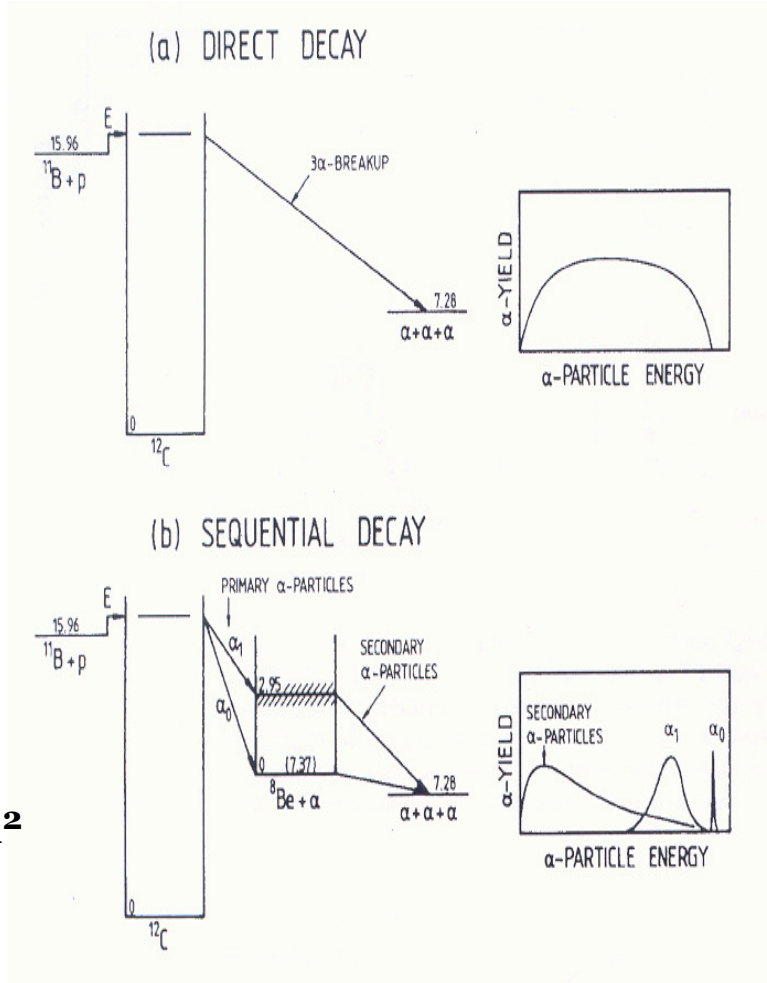


Hochstromspeicherring

- Speicherringe mit longitudinalem Magnetfeld (W~100 AkeV – 1AMeV)
- Fusionsquerschnitte
- Mehrteilchenreaktionen – Multispezies
- Sekundärteilchenspeicherung
- Multi-Ionisationsprozesse von leichten Atomen bei Wechselwirkung mit intensiven niederenergetischen Protonenstrahlen
- Raumladungskompensation – Restgaselektronen
  Elektronenstrahl
- Strahlkühlung, Kristalline-Strahlen

^{11}B+p Reaction





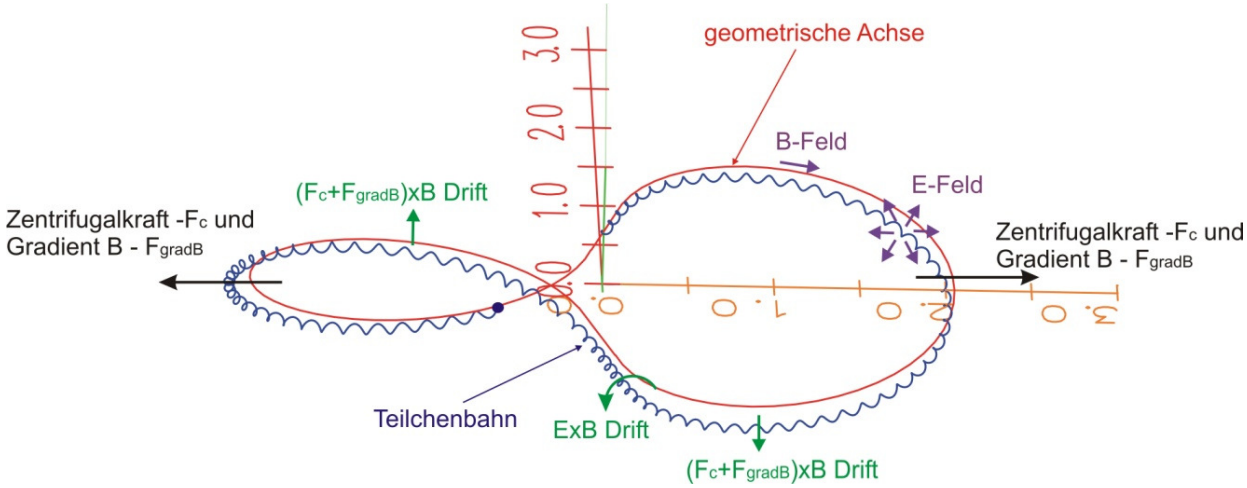
Fusionsreaktion

^{11}B+p -> 3α (8.7MeV);

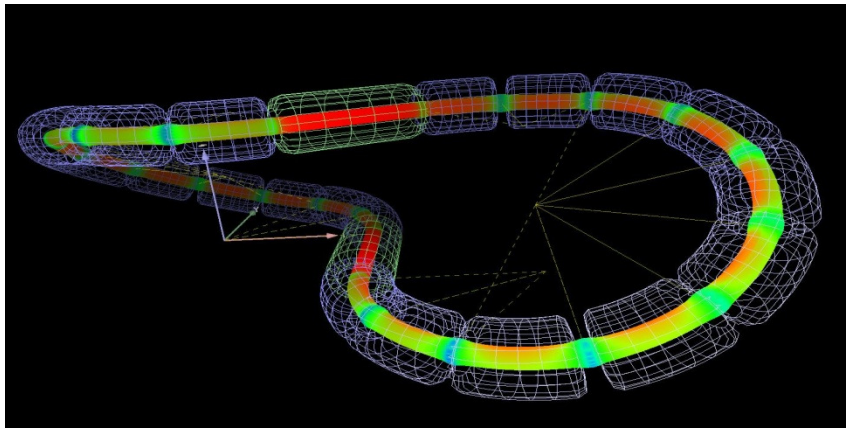
Reaktionsquerschnitt $\sigma_{max} \sim 10^{-28}$ m²

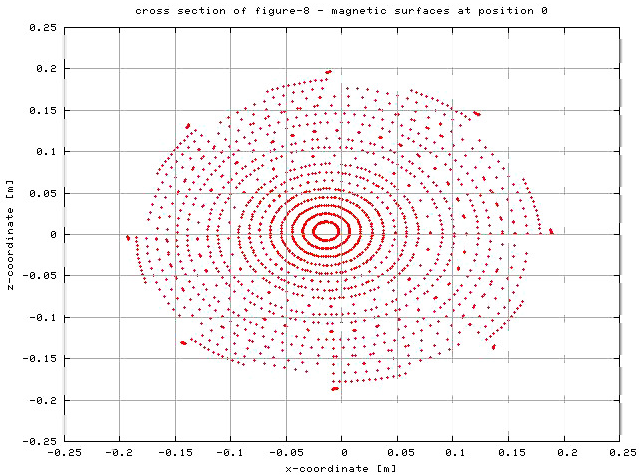
Relaxationsprozesse – Strahl zur NNP

Figure-8 Hochstromspeicherring



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





Zyklotronfrequenz ω_c [s^{-1}] @5T	$4.8 \cdot 10^8$
Brillouin-Limit n_B [m^{-3}]	$6.6 \cdot 10^{16}$
Strahlradius a [m]	>0.02
Debye-Länge [m]	$3 \cdot 10^{-4}$
ExB Rotationsfrequenz [s]	$5.2 \cdot 10^{-10}$
UHV ($n \sim 10^{12}\ m^{-3} \sim 4 \cdot 10^{-11}$ hPa) Stoßfrequenz τ_c[s]	12.5
NNP Einschlusszeit in toroidalen Magnetfeldern (Crooks 1994)	$\tau \approx \tau_c \cdot (R/\lambda_D)^2$
NNP Einschlusszeiten auf magnetischen Flächen (Pedersen 2003)	$\tau \approx \tau_c \cdot (a/\lambda_D)^4$

Simulationsprogramme

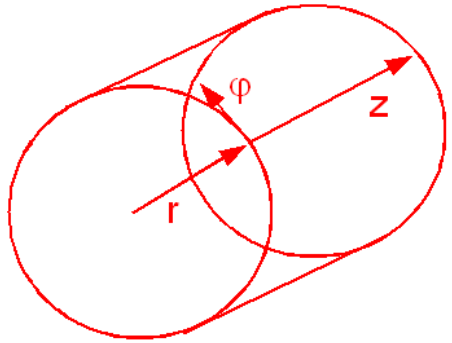
- **Magnetfeld – Biot-Savart solver**
  (Predictor-Corrector method, Field-line integration –1D information)
- **Frequenzdekomposition – FFT (1D => 2D)**
- **Generierung von numerischen Gitter – in Clebsch-Koordinaten**
  ψ<0,1>, θ<0,2π>, ξ<0,2π>
- **Poissongleichung (PIC – Particle in cell)**
- **Bewegungsgleichungen in Guiding-center-Koordinaten**

Parallele Rechnercluster CSC (Centre for Scientific Computing) http://www.csc.uni-frankfurt.de

Bis zu 60 Prozessoren, 10Mio Makroteilchen

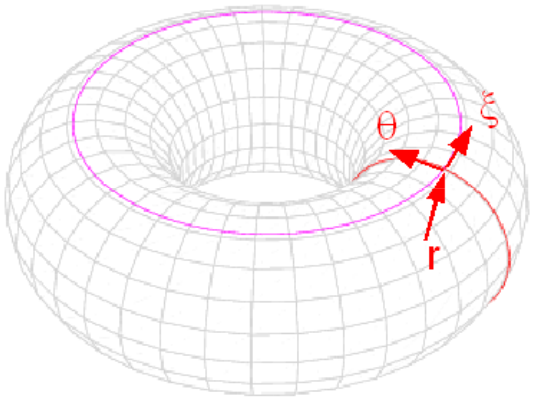
Cylindrische Koordinaten

r, φ, z



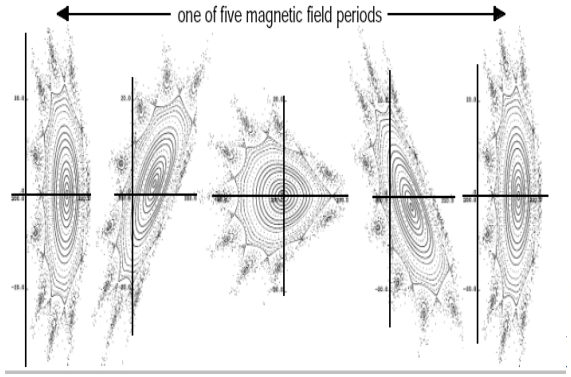
Toroidale Koordinaten

r, θ, ξ



Magnetische Koordinaten
(Clebsch, Boozer.....)

$\psi, \theta, \xi \qquad \psi, \alpha, \chi$



IAP

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FRANKFURT AM MAIN

Koordinatensystem – Guiding center

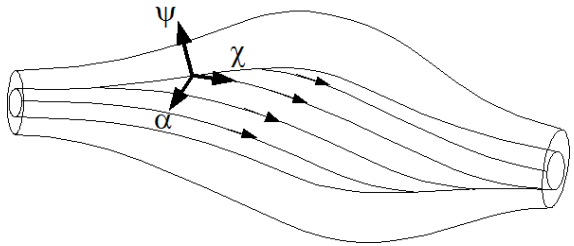
Poloidale Winkel $\theta \in <0,2\pi>$

Toroidale Winkel $\xi \in <0,2\pi>$

Normierte magnetische Flusskoordinate $\tilde{\psi} \in <0,1>$, $\tilde{\psi} = \frac{\psi}{\psi_{max}}$

Kontravariante Representation $\vec{B} = 2\pi\vec{\nabla}(\theta - \imath\xi) \times \vec{\nabla}\psi$

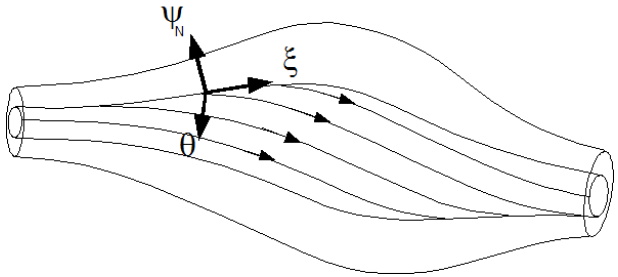
Kovariante Representation $\vec{B} = \vec{\nabla}\chi = g\vec{\nabla}\xi$



Kanonische Variablen

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

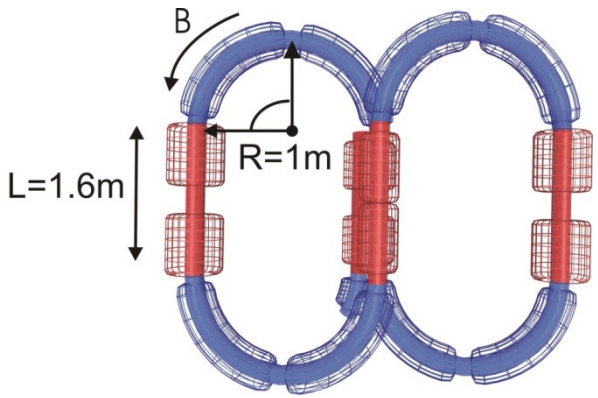
$$g = \frac{\mu_0 G}{2\pi}$$



Drift Hamiltonian

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

F8SR – Strahldynamik in starken gekoppelten Magnetfeldern



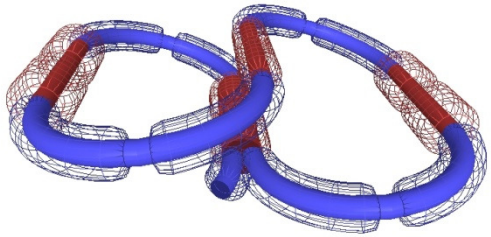
Strahlenergie: $W_b = 150\text{keV}$

Strahlstrom: $I = 10\text{A}$

Umlaufzeit: $t = 2\mu s$

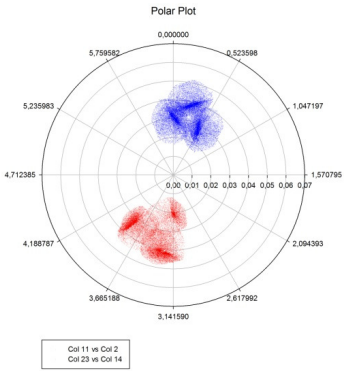
Gespeicherte Energie und Peakleistung

$E = 3\text{J} \Rightarrow P_{peak} = 1{,}5\text{MW}$

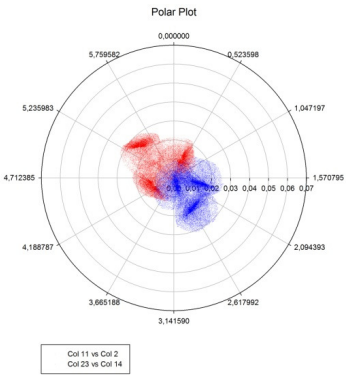


- Rot – Strahl parallel zum B-Feld
- Blau – Strahl antiparallel zum B-Feld

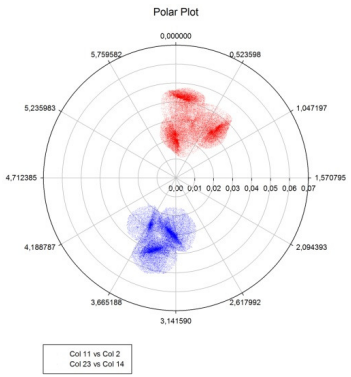
Injektion



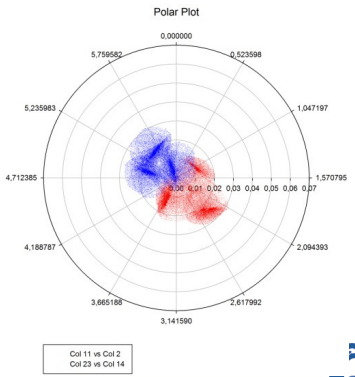
$\pi / 2$ - Experiment



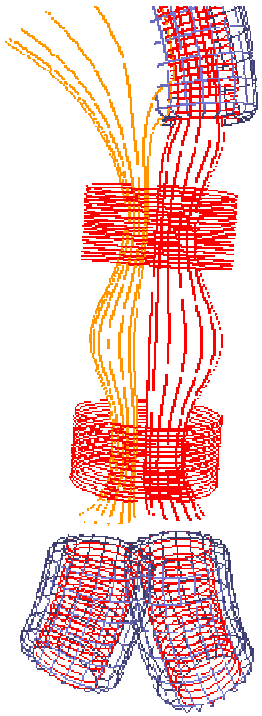
π – Brücke

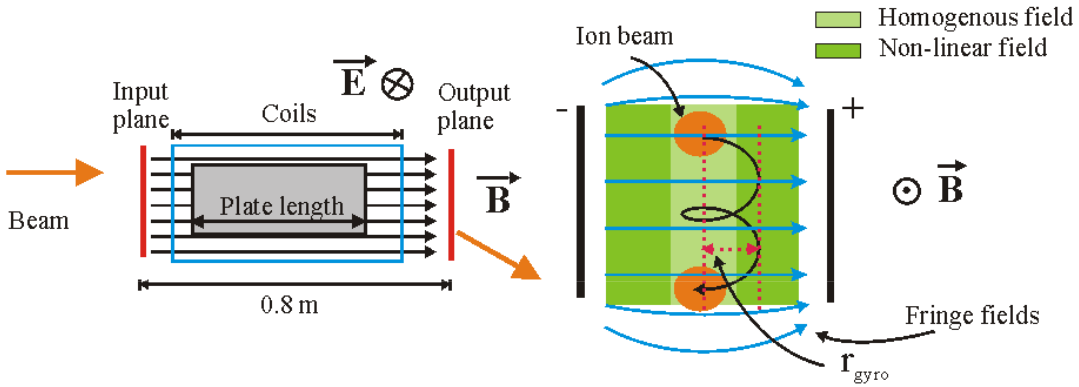


$3\pi / 2$



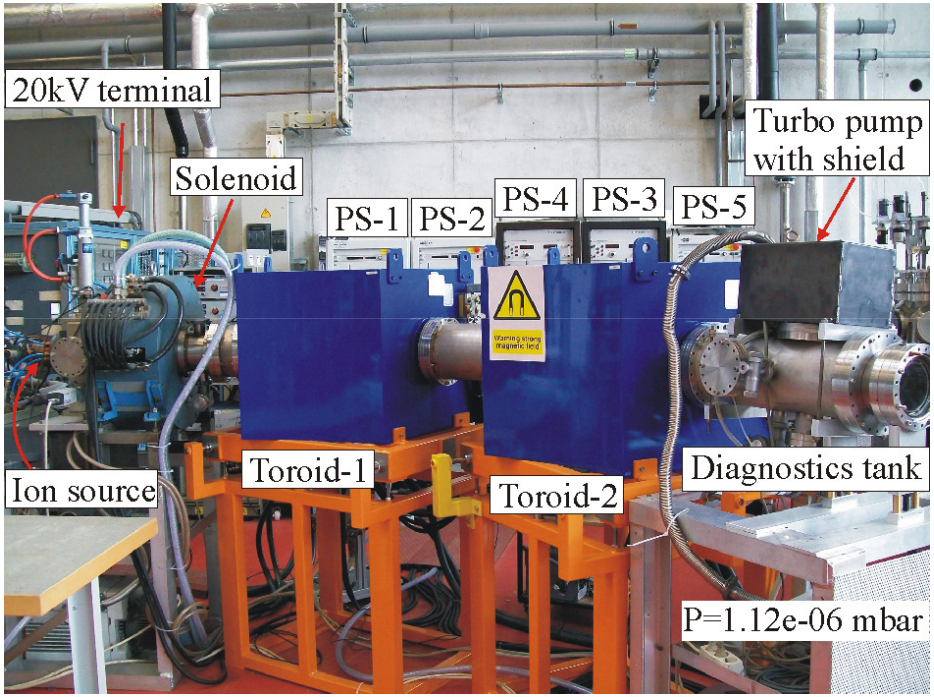
Injektionssystem





- Anpassungskanal
- ExB - Kickersystem

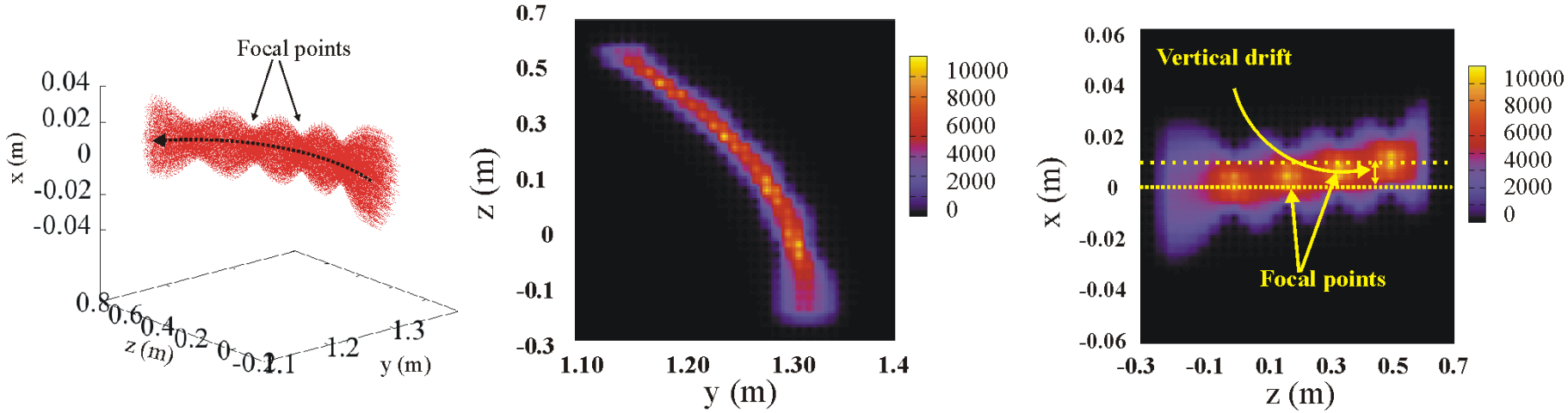
Toroidale Strahltransportexperimente



- Strahlinjektion
- Strahltransport
- Simulation-Experiment Vergleich
- Diagnose
- Abschirmung

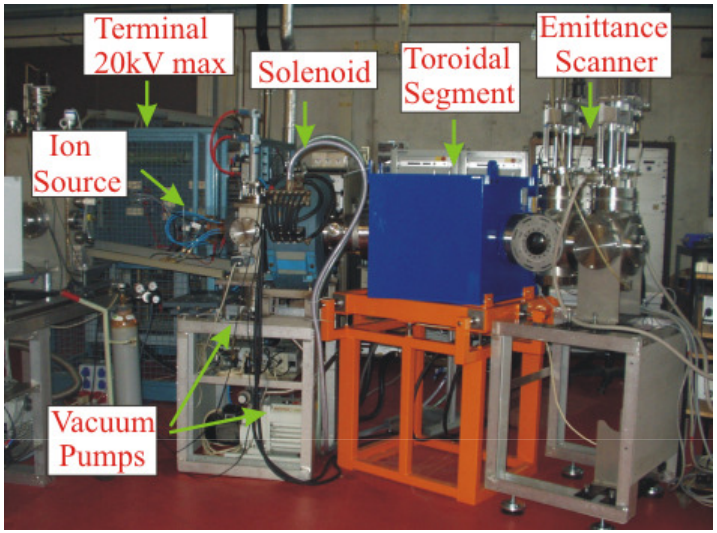
Strahltransport in gekrümmten Magnetfeldern

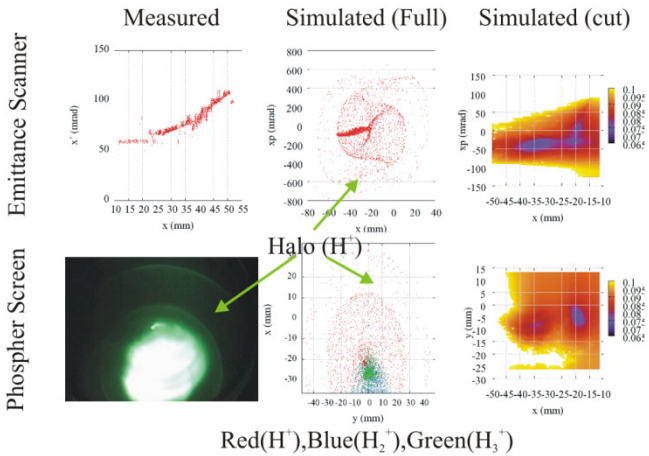
- Simulation Code TBT(toroidal beam transport)
- PIC Routine, Multispecie
- Realistische Feldern -> file input
- 10^6 Macro-particles (CSC cluster)
- 50*50*180 Grid points



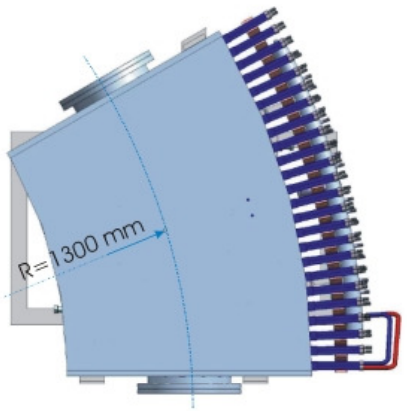
Beispiel : proton 10keV B~0.6 T Drift ~15 mm

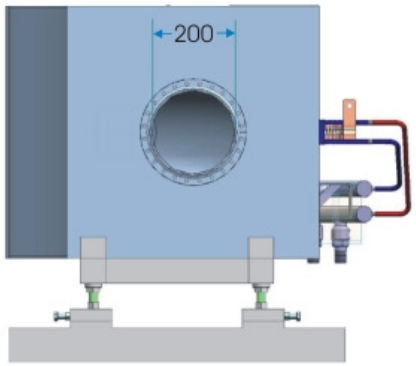
Toroidaler Strahltransport – skaliertes Experiment



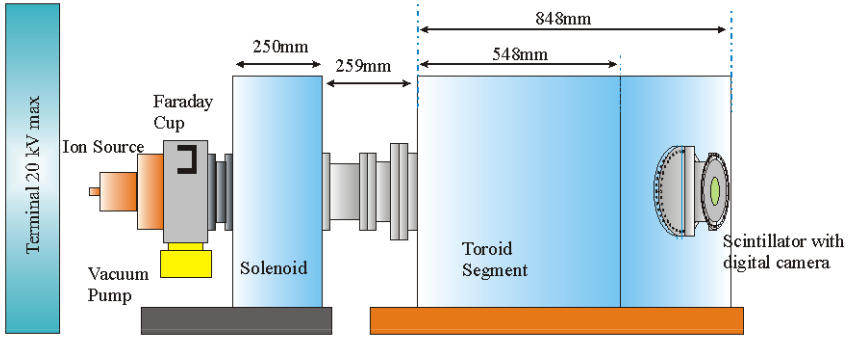


Strahlenergie	2 – 15 keV
Strahlstrom	0 – 5 mA
Ionen	He^+, p, H_2^+, H_3^+
|B|max	0,6 T
Krümmungs-winkel	30°
Krümmungs-radius	1,3 m

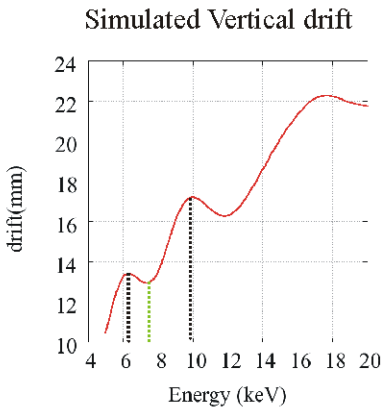


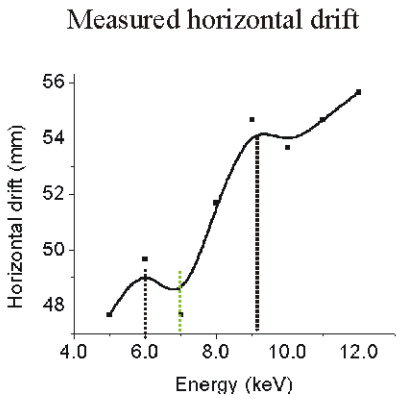


Messungen - Strahlenergievariation



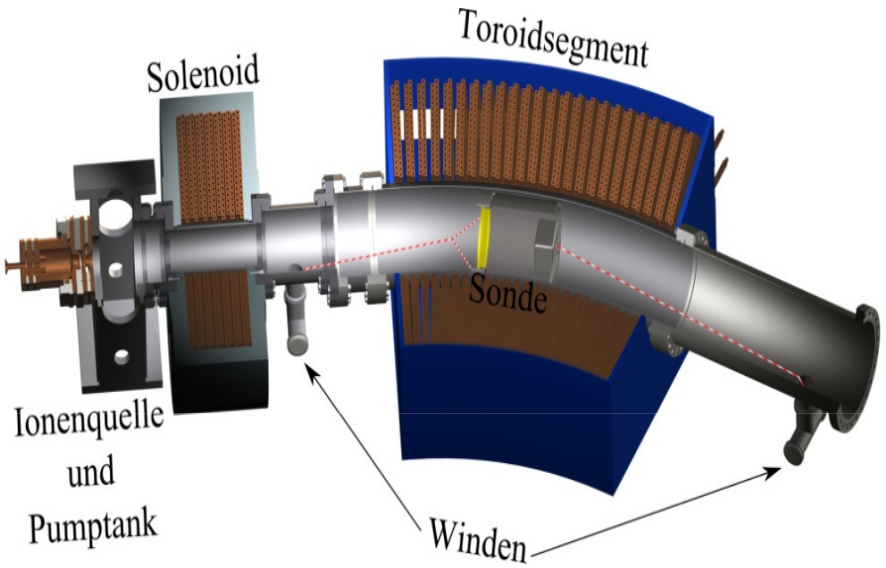
Diagnose – statisch
Im Randfeld des Toroids
Verticale Drift ~ horizontale Position



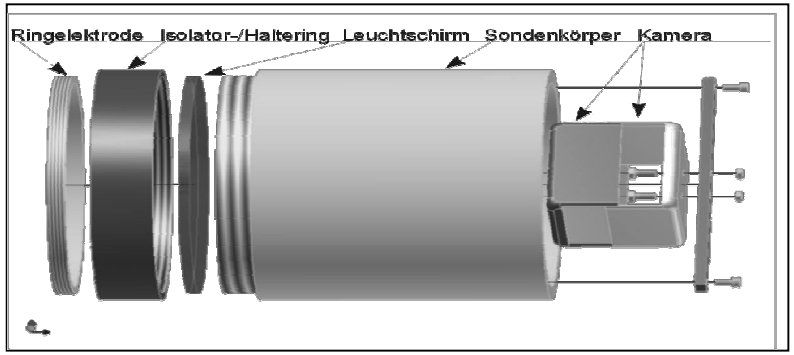


Kopplung der vertikalen und horizontalen Ebenen

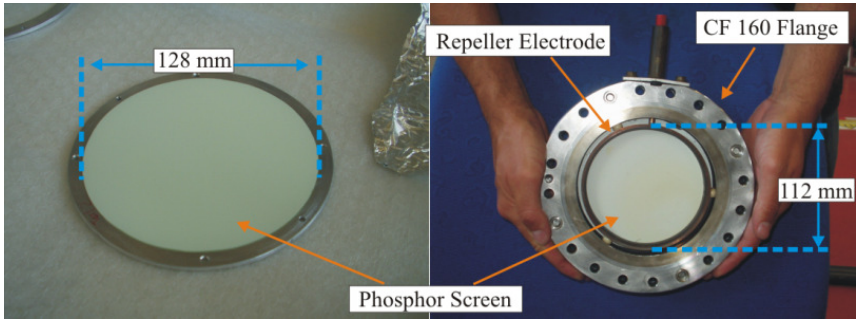
Optische Strahldiagnose

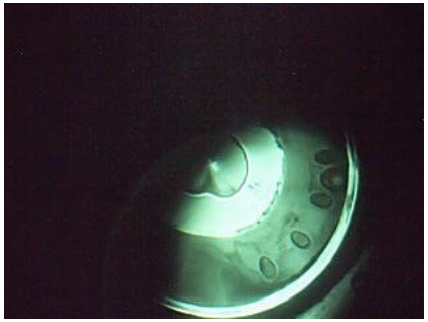


Aufbau der Sonde

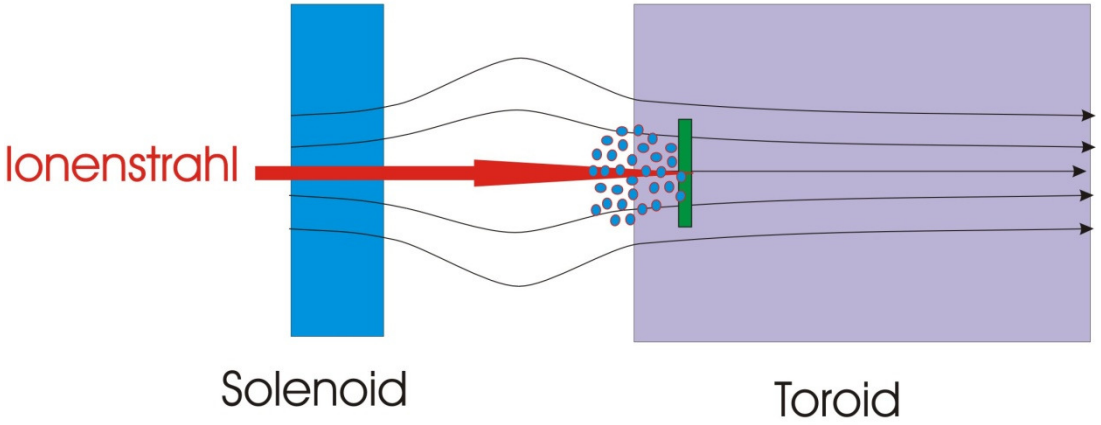


Länge: ca. 220 mm
Durchmesser: 180 mm
Gewicht: ca. 3 kg
Material: Aluminium, PVC

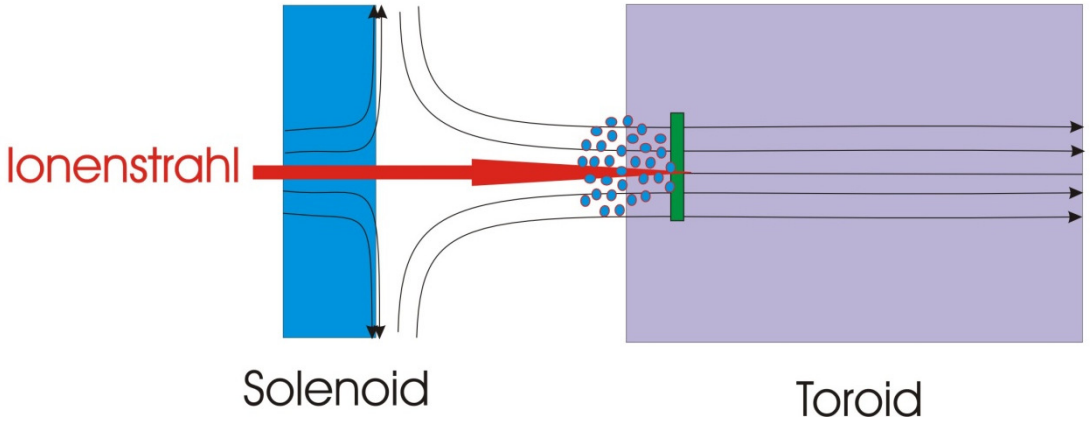




Magnetische Flasche



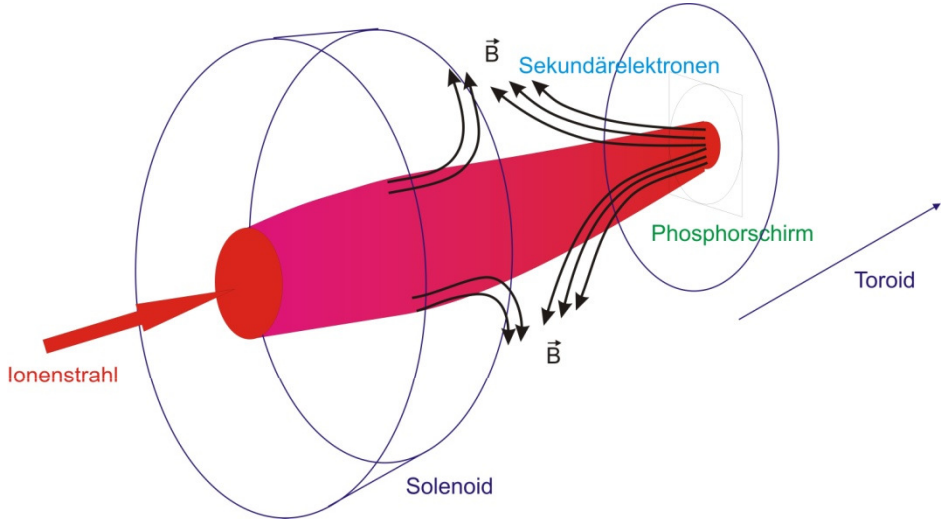
Cusp

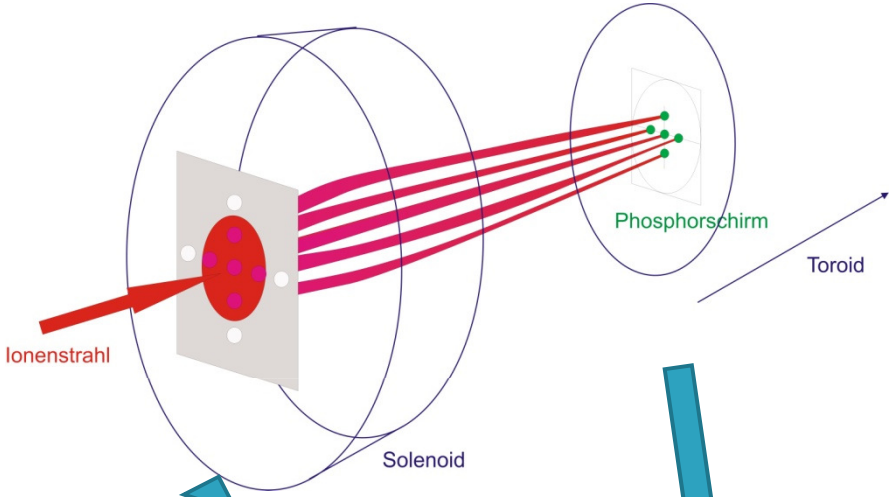


Strahlinduzierte NNP

Eingeschlossene Elektrone
Beeinflussung des Strahl-
transports

Strahlinduzierte NNP

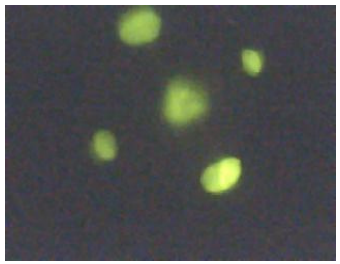




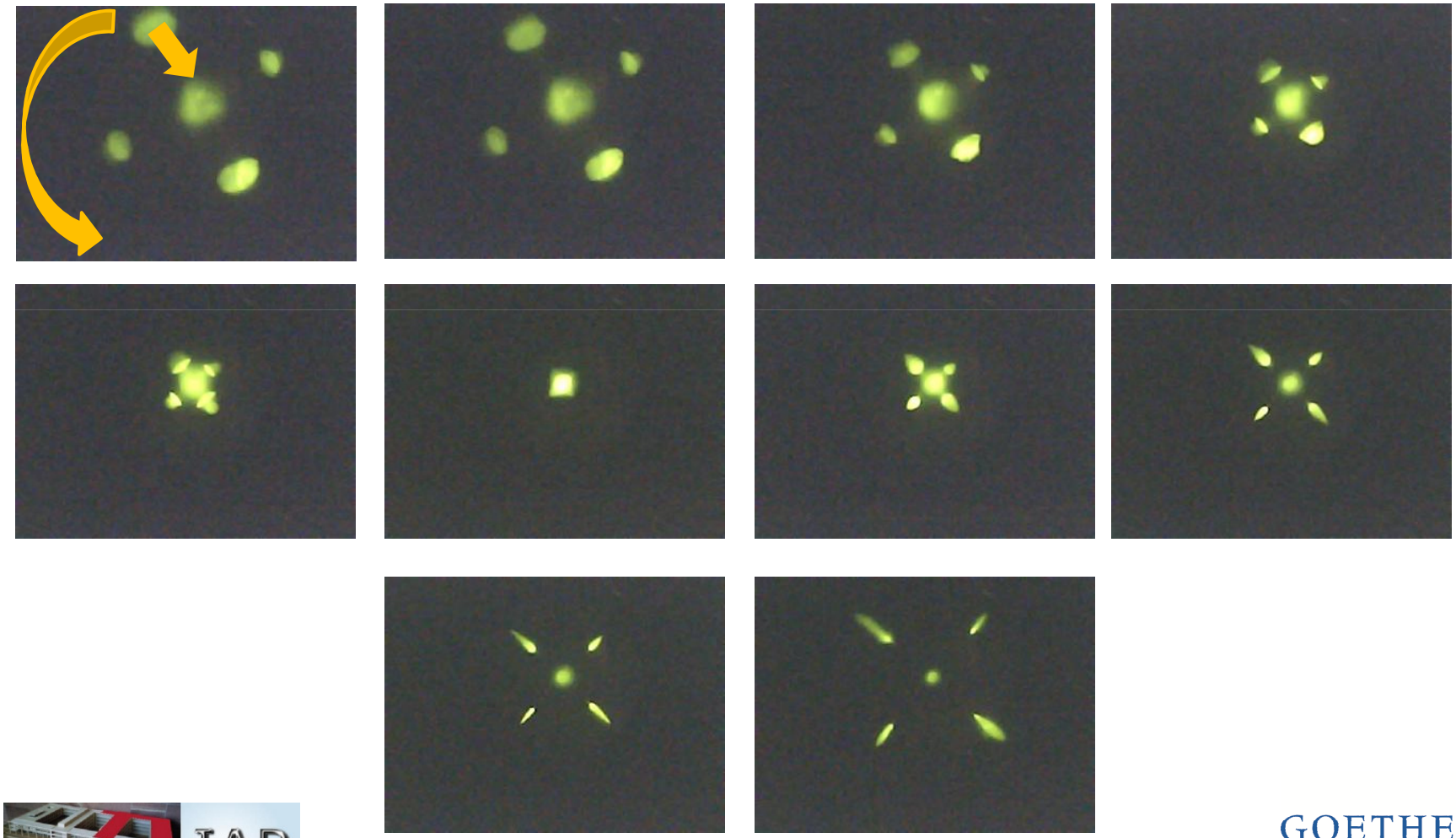
- Strahlblende am Eingang
- Durchmesser der Löcher

  2mm - Horizontal

  3mm und 4mm - Vertikal



- He – Strahl 8 keV
- Fokussierende Solenoid 0.4T – 0.52T (Rotation+Fokussierung)



IAP

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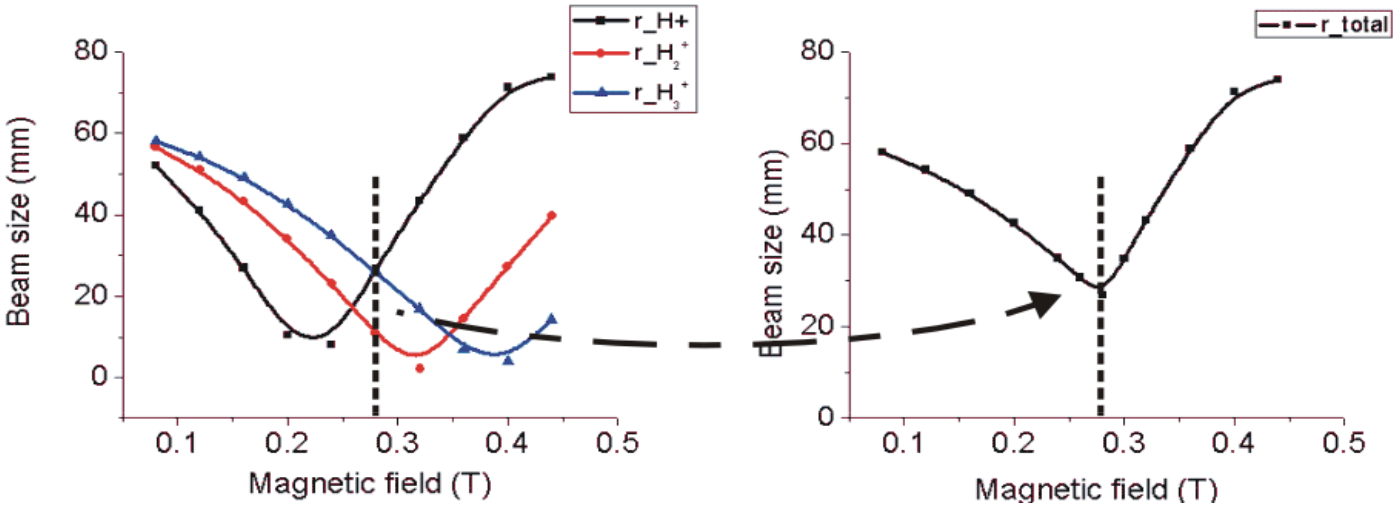
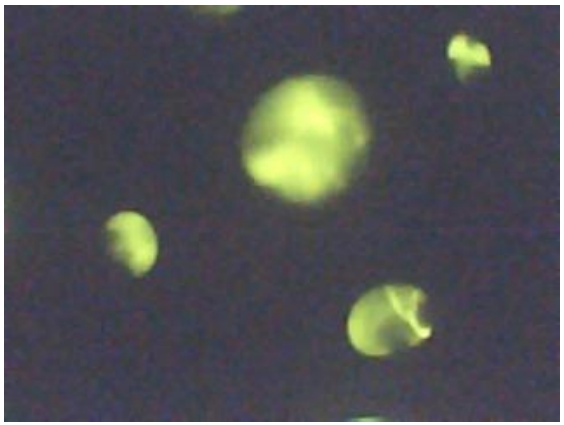
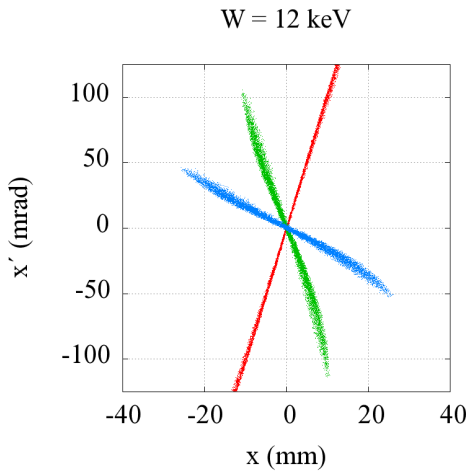
- p – Strahl 8 keV (auch Komponenten H_2^+, H_3^+)
- Solenoidales Magnetfeld varriert







IAP

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- p – Strahl 8 keV (auch Komponenten H_2^+, H_3^+)
- Solenoidales Magnetfeld varriert

Proton

H_2^+,

H_3^+

IAP

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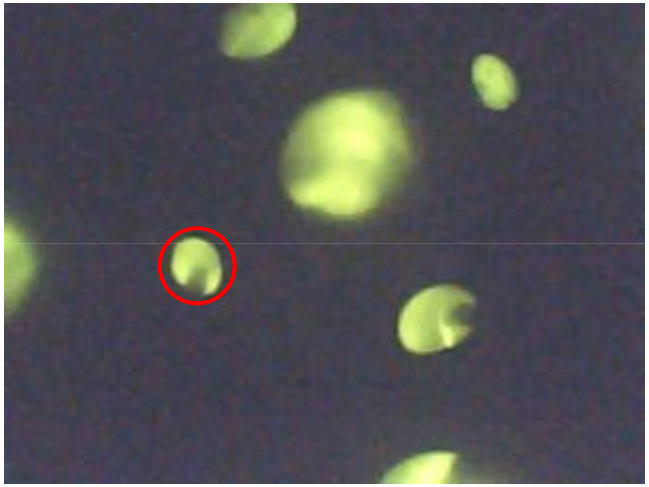
- p – Strahl 8 keV (auch Komponenten H_2^+, H_3^+)
- Solenoidales Magnetfeld varriert



Proton

H_2^+,

H_3^+

IAP

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

- p – Strahl 8 keV (auch Komponenten H_2^+, H_3^+)
- Solenoidales Magnetfeld varriert

Proton

H_2^+,

H_3^+

IAP

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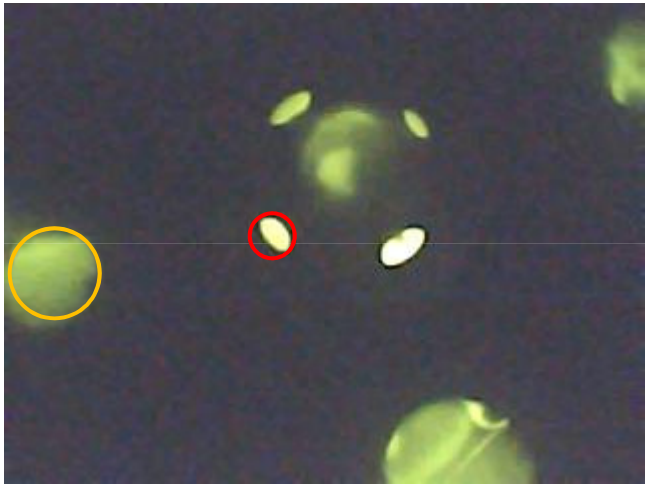
- p – Strahl 8 keV (auch Komponenten H_2^+, H_3^+)
- Solenoidales Magnetfeld varriert



Proton

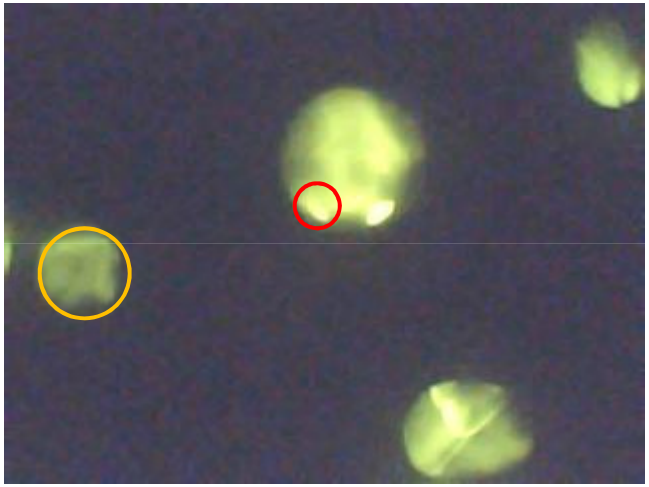
H_2^+,

H_3^+

IAP

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

- p – Strahl 8 keV (auch Komponenten H_2^+, H_3^+)
- Solenoidales Magnetfeld varriert



Proton

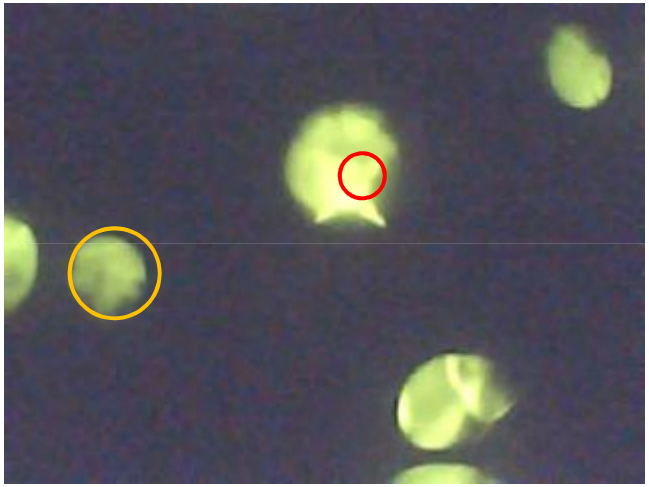
H_2^+,

H_3^+

IAP

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

- p – Strahl 8 keV (auch Komponenten H_2^+, H_3^+)
- Solenoidales Magnetfeld varriert



Proton

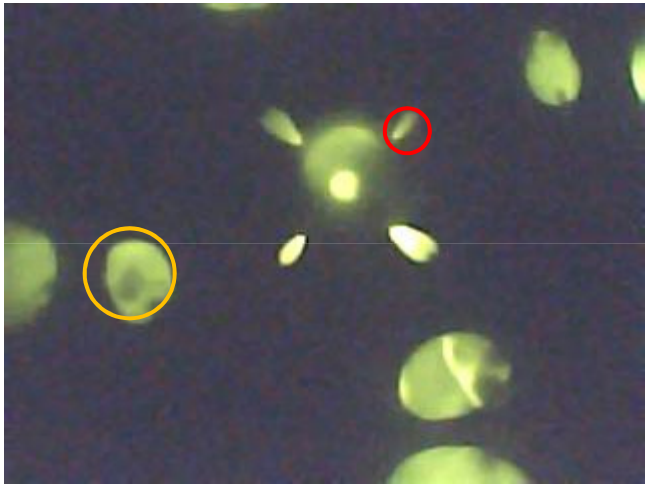
H_2^+,

H_3^+

IAP

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

- p – Strahl 8 keV (auch Komponenten H_2^+, H_3^+)
- Solenoidales Magnetfeld varriert



Proton

H_2^+,

H_3^+

IAP

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- p – Strahl 8 keV (auch Komponenten H_2^+, H_3^+)
- Solenoidales Magnetfeld varriert

Proton

H_2^+,

H_3^+

IAP

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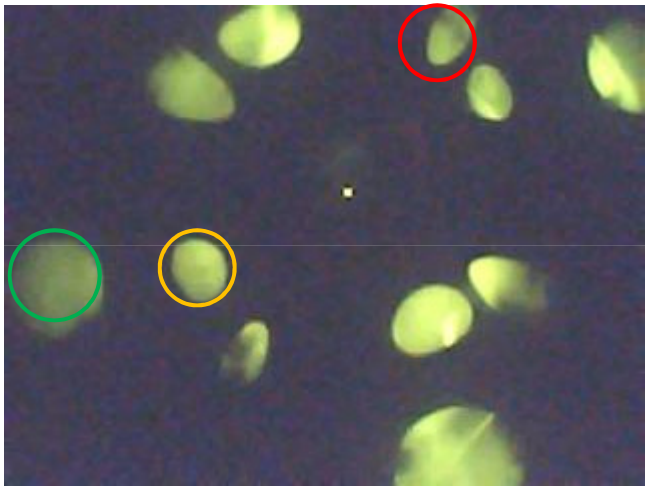
- p – Strahl 8 keV (auch Komponenten H_2^+, H_3^+)
- Solenoidales Magnetfeld varriert



Proton

H_2^+,

H_3^+

IAP

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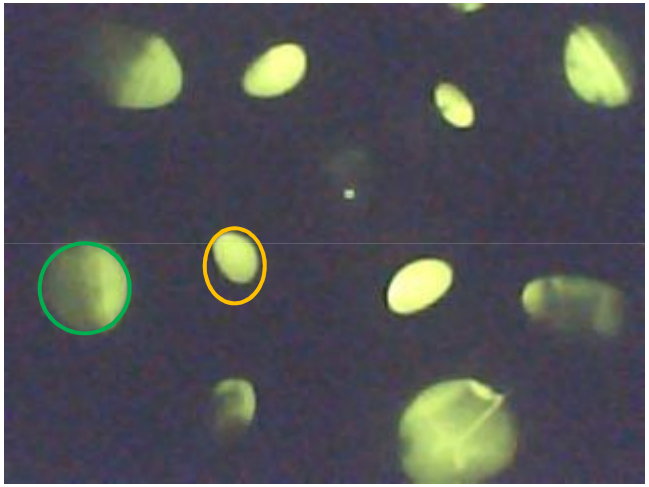
- p – Strahl 8 keV (auch Komponenten H_2^+, H_3^+)
- Solenoidales Magnetfeld varriert

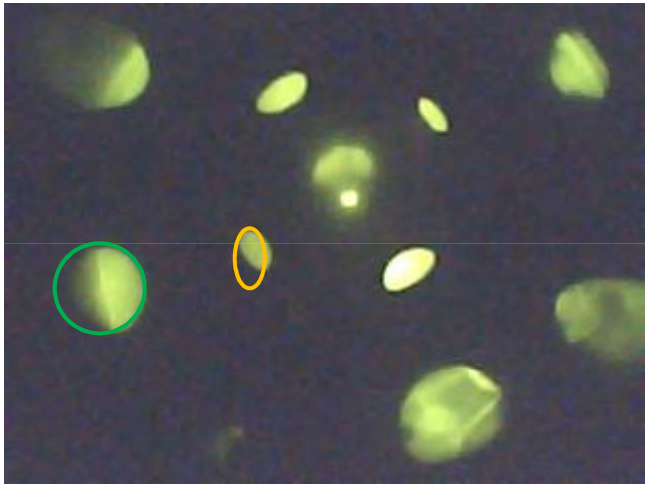


Proton

H_2^+,

H_3^+

- p – Strahl 8 keV (auch Komponenten H_2^+, H_3^+)
- Solenoidales Magnetfeld varriert



Proton

H_2^+,

H_3^+

IAP

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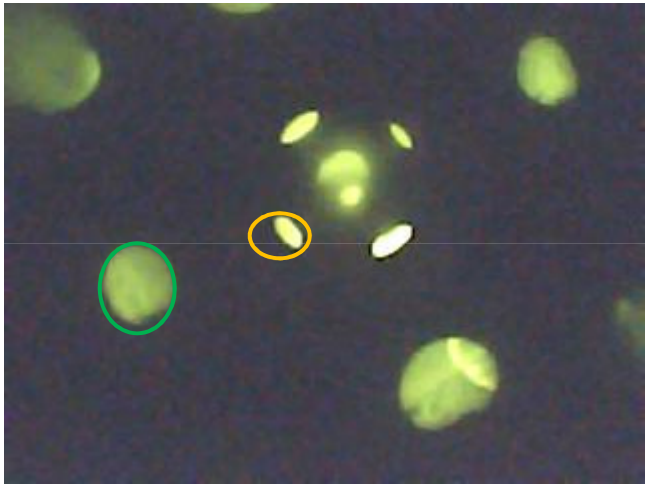
- p – Strahl 8 keV (auch Komponenten H_2^+, H_3^+)
- Solenoidales Magnetfeld varriert



Proton

H_2^+,

H_3^+

IAP

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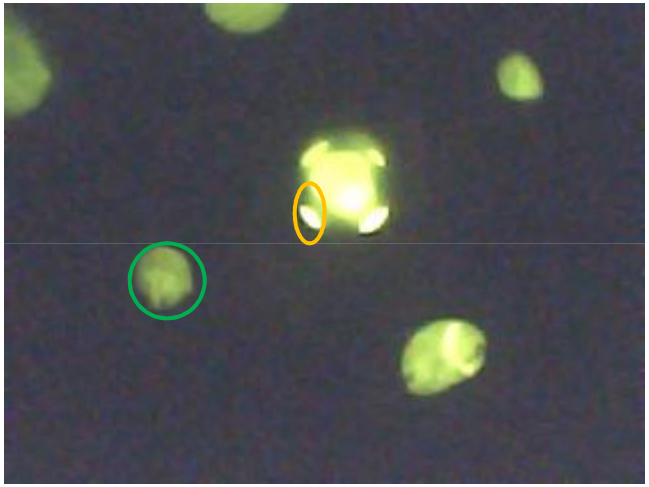
- p – Strahl 8 keV (auch Komponenten H_2^+, H_3^+)
- Solenoidales Magnetfeld varriert



Proton

H_2^+,

H_3^+

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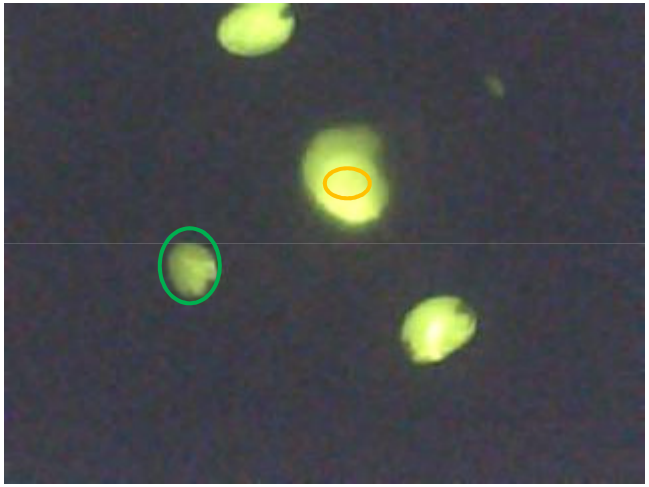
- p – Strahl 8 keV (auch Komponenten H_2^+, H_3^+)
- Solenoidales Magnetfeld varriert



Proton

H_2^+,

H_3^+

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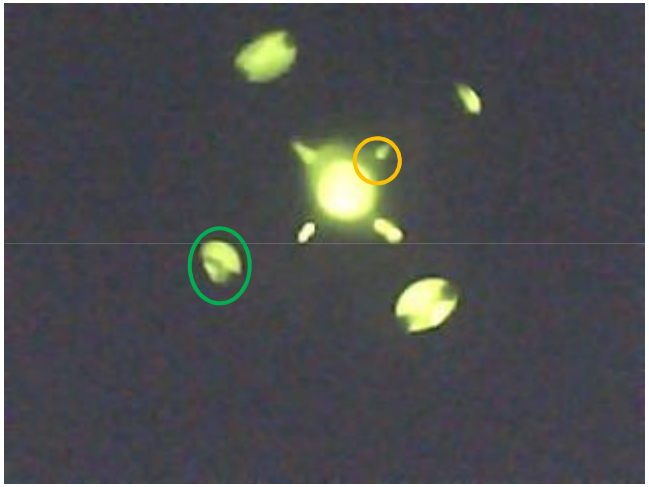
- p – Strahl 8 keV (auch Komponenten H_2^+, H_3^+)
- Solenoidales Magnetfeld varriert



Proton

H_2^+,

H_3^+

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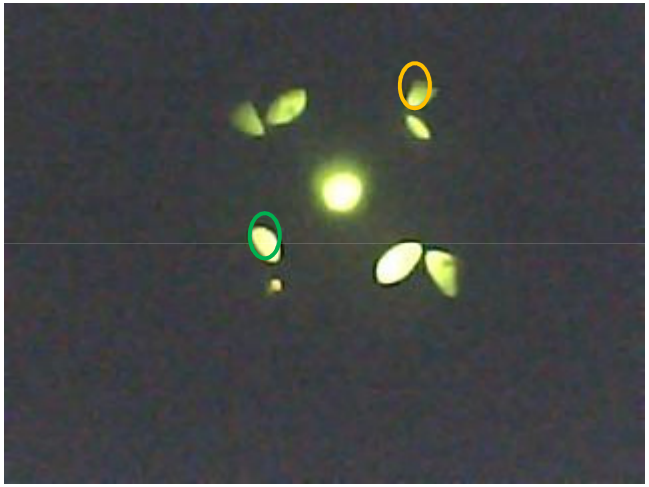
- p – Strahl 8 keV (auch Komponenten H_2^+, H_3^+)
- Solenoidales Magnetfeld varriert



Proton

H_2^+,

H_3^+

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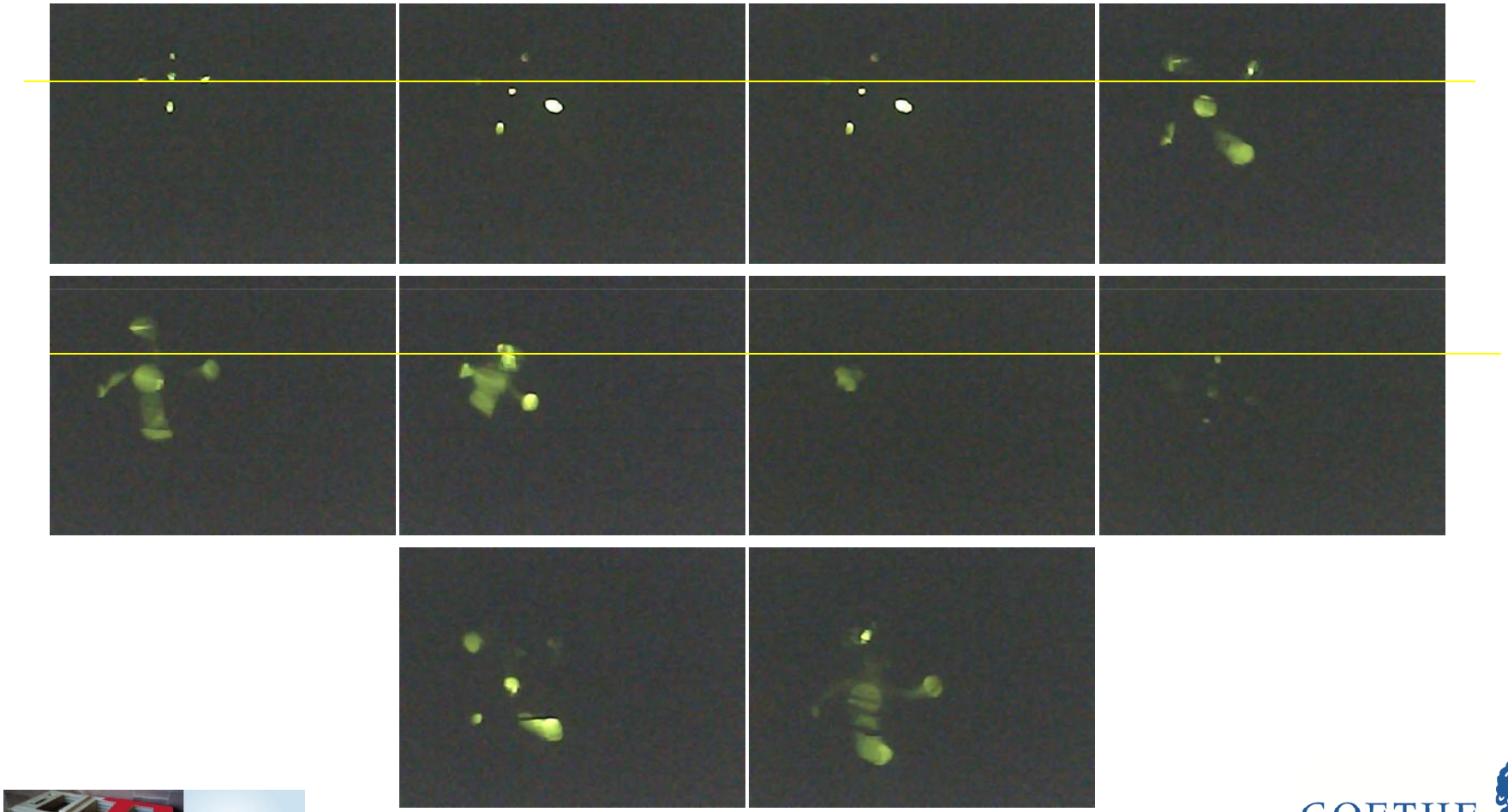
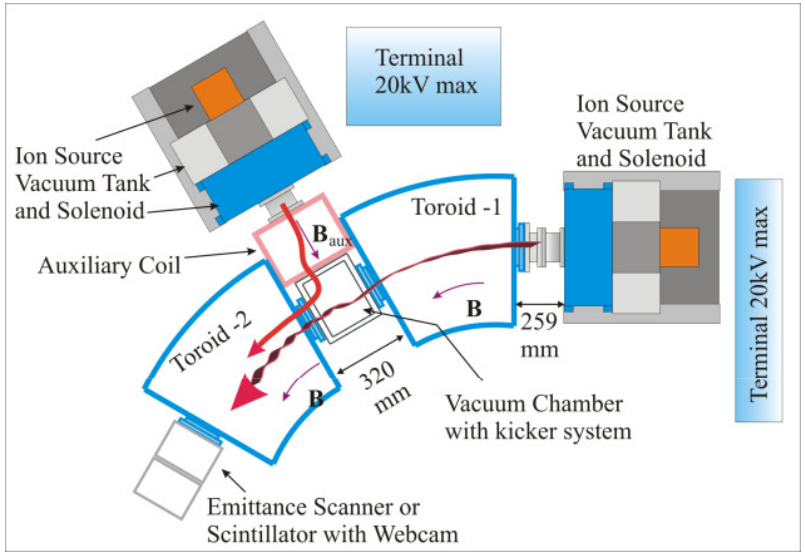
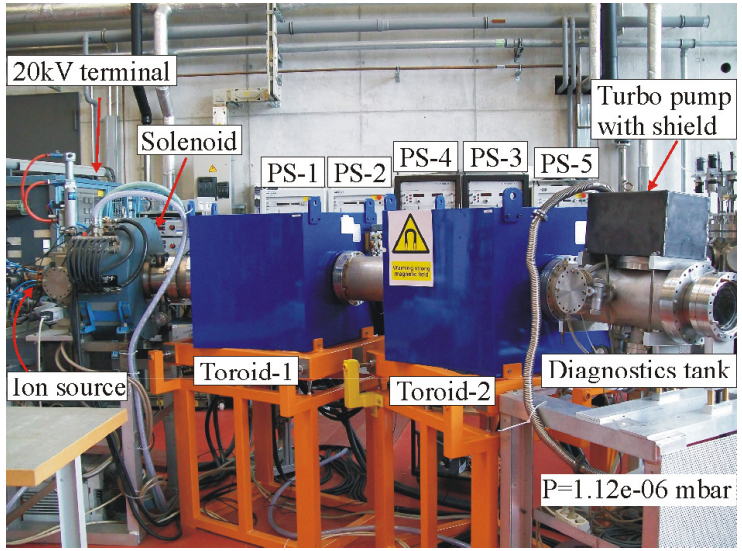
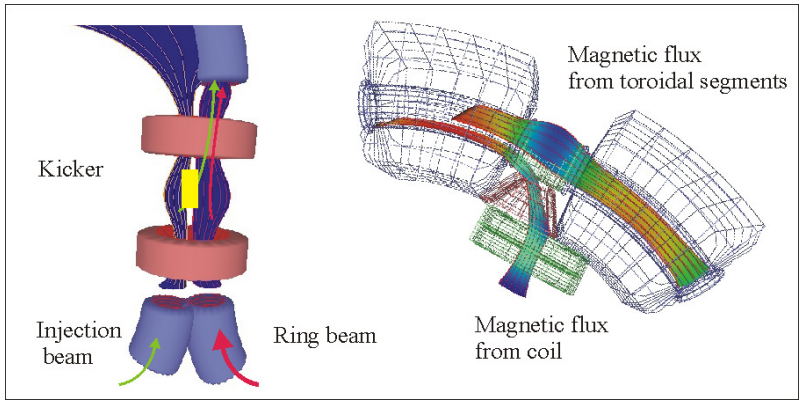
- He – Strahl 8 keV, Solenoid B=0.26T , Toroid B=0.53T
- Schirm longitudinal bewegt entlang der Achse position1- position10

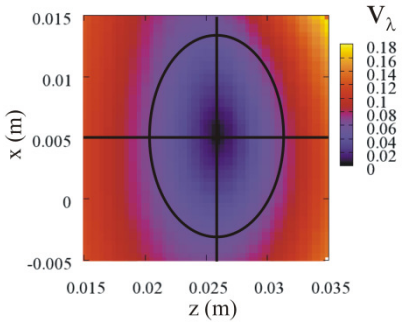


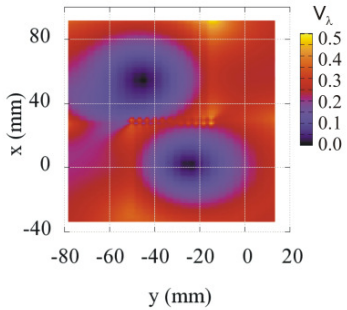
Injektionsexperiment



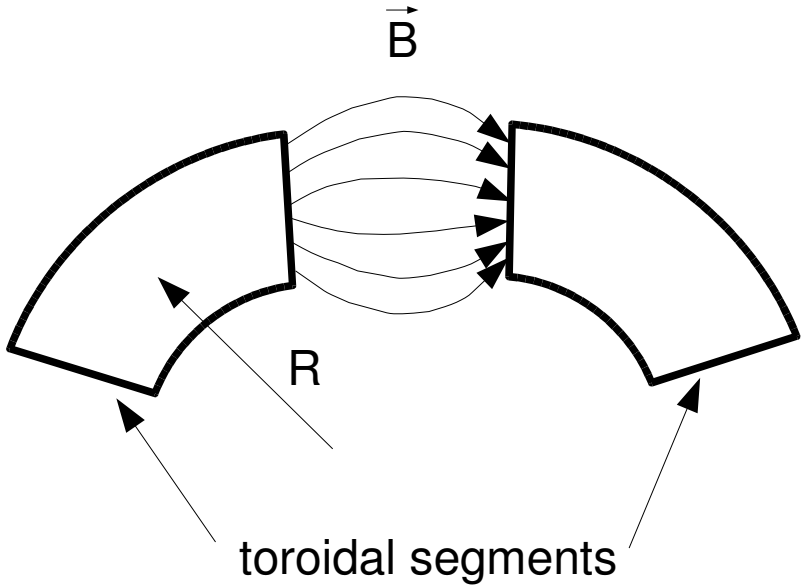








Ausblick – Toroidale Transport



- Kompensations-elektronen in Spiegelkonfiguration
- Driften – ExB, Zentrifugalkraft, grad B Umverteilung der Impulse

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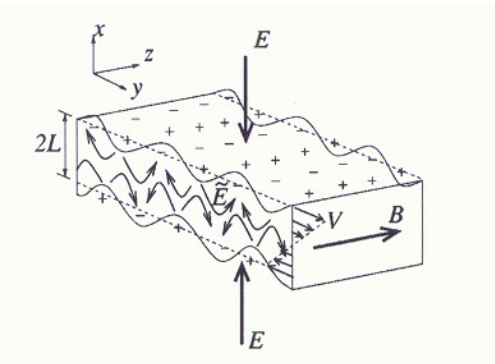
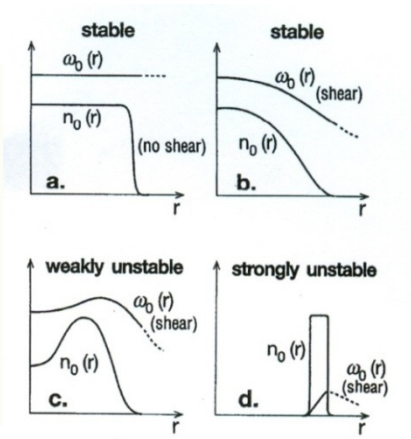
Ausblick - Stability

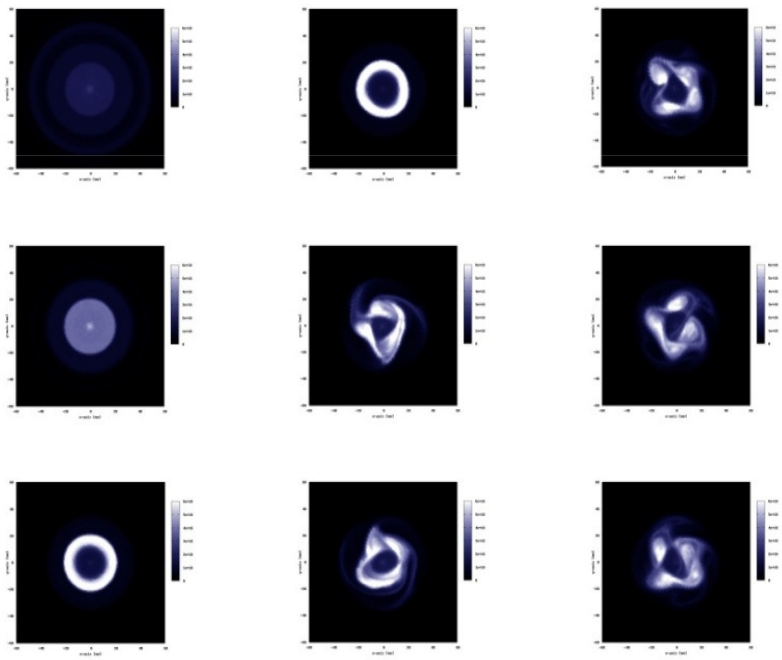
- Raumladung -> ExB Bewegung

Hohlprofil -> Diocotroninstabilität

Kink- instabilität







Ausblick

- Untersuchung von Raumladungskompensation im toroidalen Strahltransport
- Untersuchung von Strahlinstabilitäten
- Aufbau von Injektionsexperiment
- Weiterentwicklung der optischen Strahldiagnose