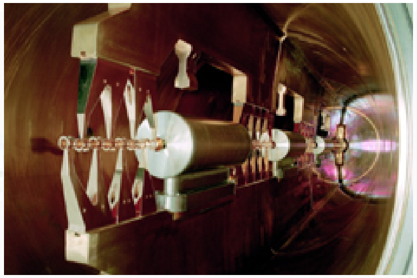
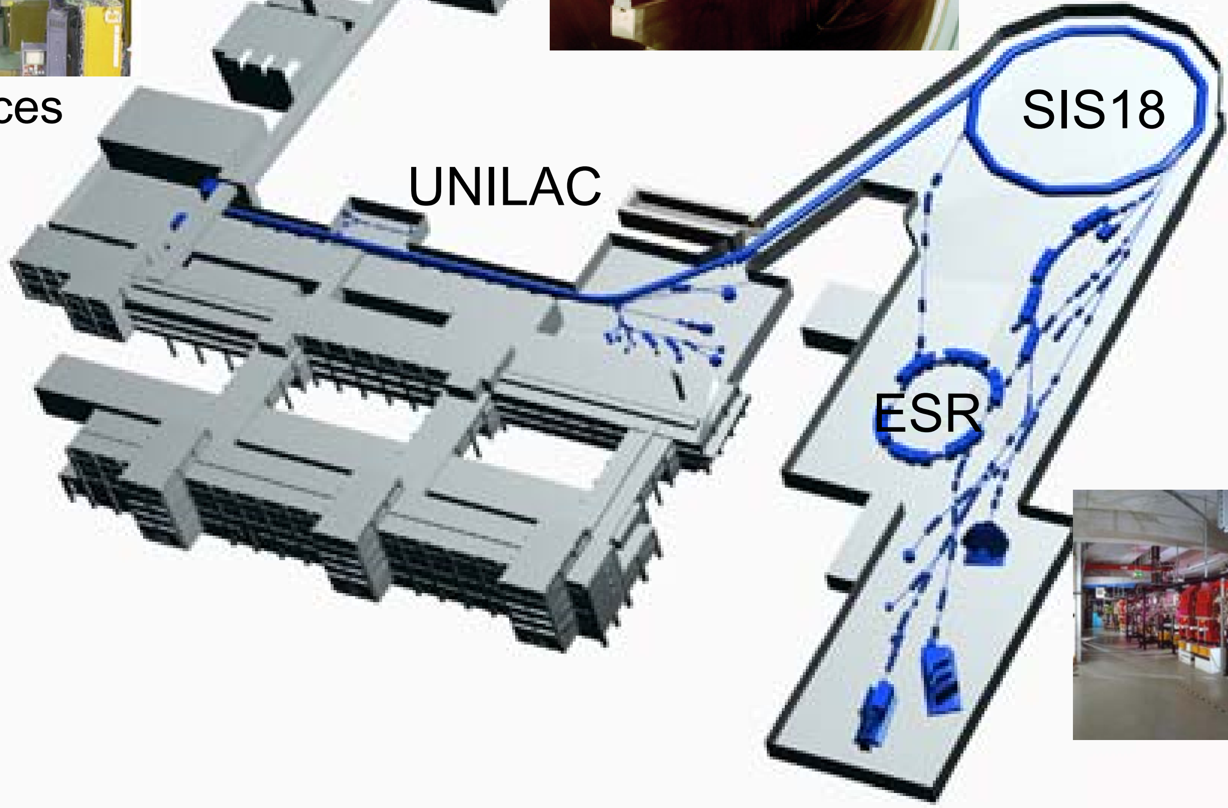
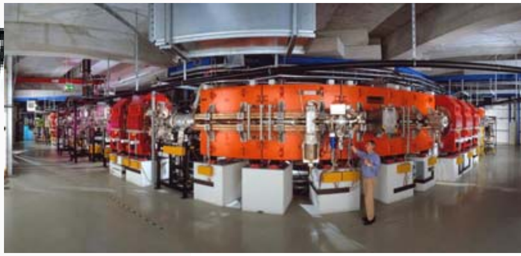
- Requirements at SIS injection
- Conceptual layout of emittance splitting section (brief)
- Beam dynamics tools
- Magnetized beams
- Procedure to apply
- PARMT simulations
- Set-up for experimental proof of principle, required components
- Additional application: beams from ECR

GSI Accelerator Facilities

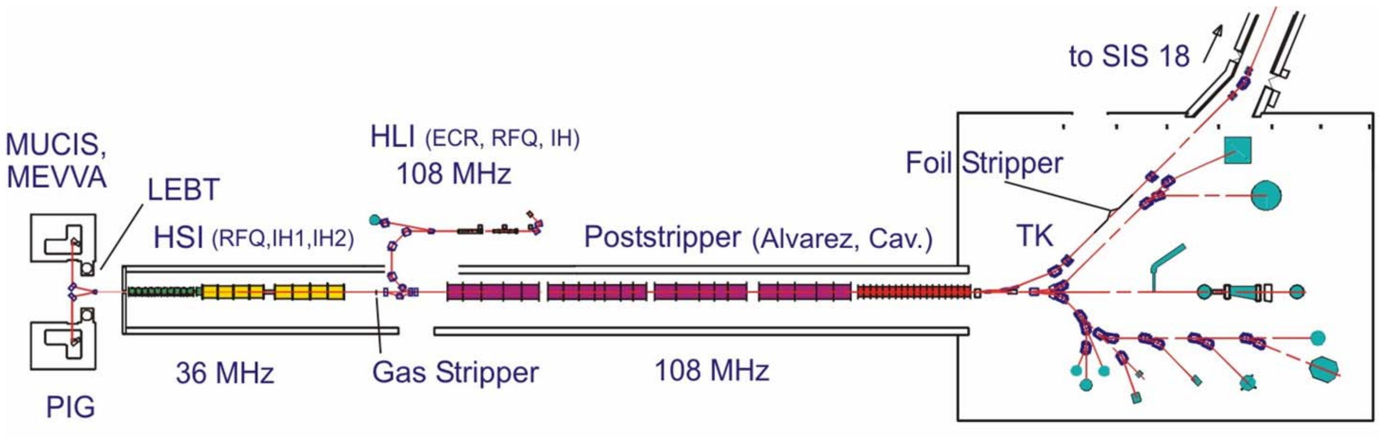
Ion Sources







UNILAC as Injector for SIS Synchrotron



<u>Figures of merit for an injector:</u>

- small emittance
- high current

→ <u>high ratio current / emittance ≈ Brilliance</u>

UNILAC in the Press

BILD FRANKFURT ✱ 5. OKTOBER 2010

Fotos: PICTURE-ALLIANZE/DPA

Hier wird der Urknall erforscht

Darmstadt – **Was geschah eine Tausendstelsekunde nach dem Urknall? Wie wurde die Welt eine brodelnde Ursuppe, sind verschiedene Arten von Materie aufgebaut, z. B. die unerforschte dunkle Materie?**

Das soll ein neues Forschungszentrum in Darmstadt klären. Gestern unterschrieben 9 Staaten aus Asien, Ost- und Westeuropa den Vertrag über Bau und Betrieb. Startschuss für den Teilchenbeschleuniger „FAIR"*!

Das Ding funktioniert wie eine Kanone, ist nur viel größer (120 Meter lang, 2 Meter Durchmesser). Da werden kleine Atome mit hohen Spannungen beschleunigt, in einen Ring geschleudert, auf andere Materialien geschossen. Durch die Aufprallwucht werden sie zertrümmert, können untersucht werden.

„Im Universum steckt noch viel unbekanntes Zeug", sagt Ingo Peter, Sprecher des Helmholtzzentrums für Schwerionenforschung, auf dessen Gelände das Mega-Projekt entsteht. „FAIR" baut auf eine bestehende Anlage auf, kann immer weiter ausgebaut werden.

1,2 Mrd Euro kostet es. „Hessen hat sich als Standort bereiterklärt, 94 Mio Euro in den Bau zu investieren", so Hessens MP Volker Bouffier (CDU). 178 Mio steuert Russland bei. 3000 Forscher in 40 Ländern tüfteln an der Anlage. Der eigentliche Tiefbau beginnt aber erst im Winter 2011/12. **jak**

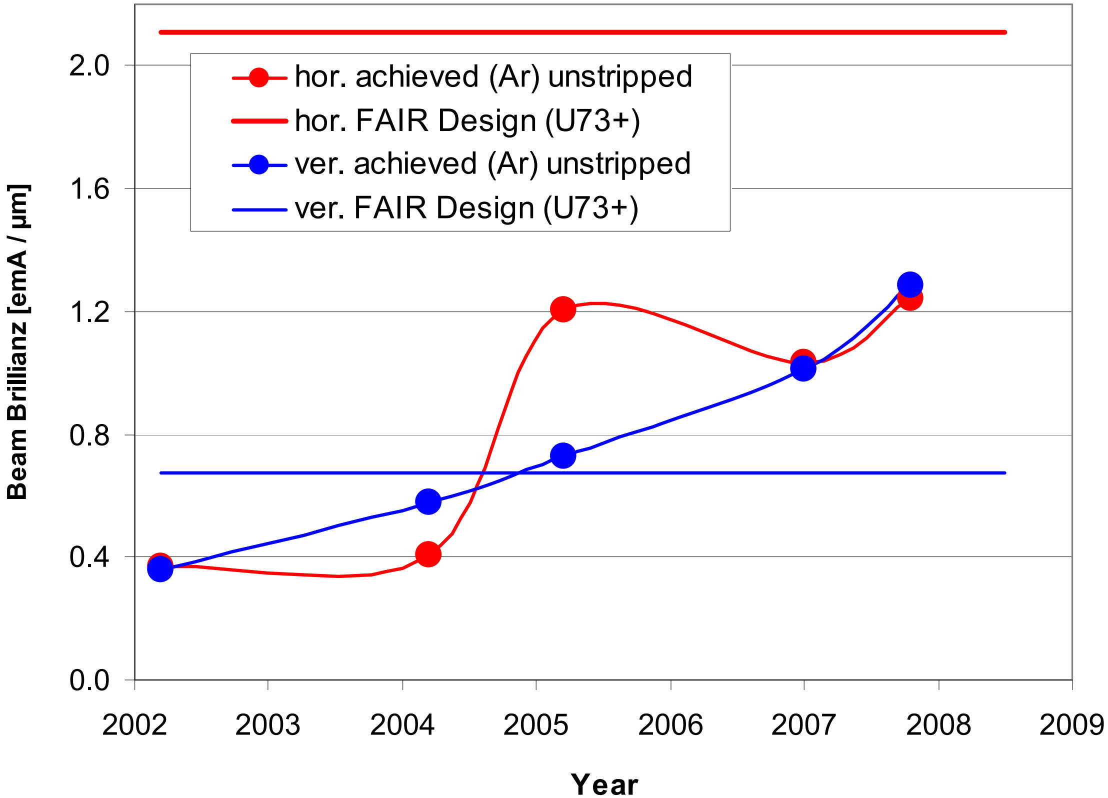
Das 3-D-Modell der geplanten Anlage mit Beschleuniger-Ring. Sie soll ab 2017 Ionenstrahlen liefern

(* englisch für Facility for Antiproton and Ion Research in Europe, dt.: Anlage für Antiprotonen- und Ionenforschung)

Development of Horizontal and Vertical UNILAC Beam Brilliances

Brilliance Definition:

$B_{x/y}$:= (q/A)*Current / Emittance$_{x/y}$



- achieved hor. & ver. UNILAC brilliances are similar
- horizontally we are not ok
- vertically we are ok

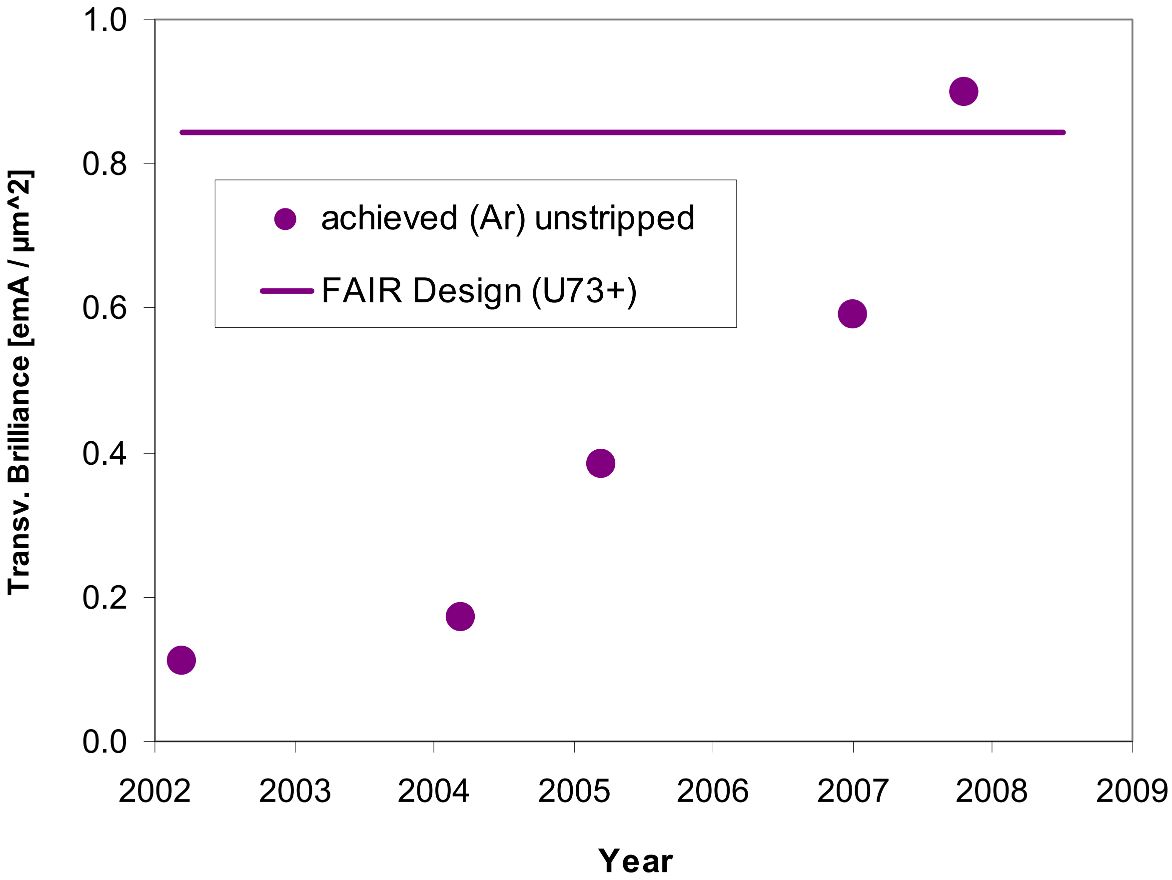
Transverse Beam Brilliance Definition

- Horizontal and vertical brilliances are defined separately
  - $B_x = (q/A) * I / E_x$
  - $B_y = (q/A) * I / E_y$

- Now define one single transverse brilliance as
  - $B_\perp = (q/A) * I / (E_x * E_y)$

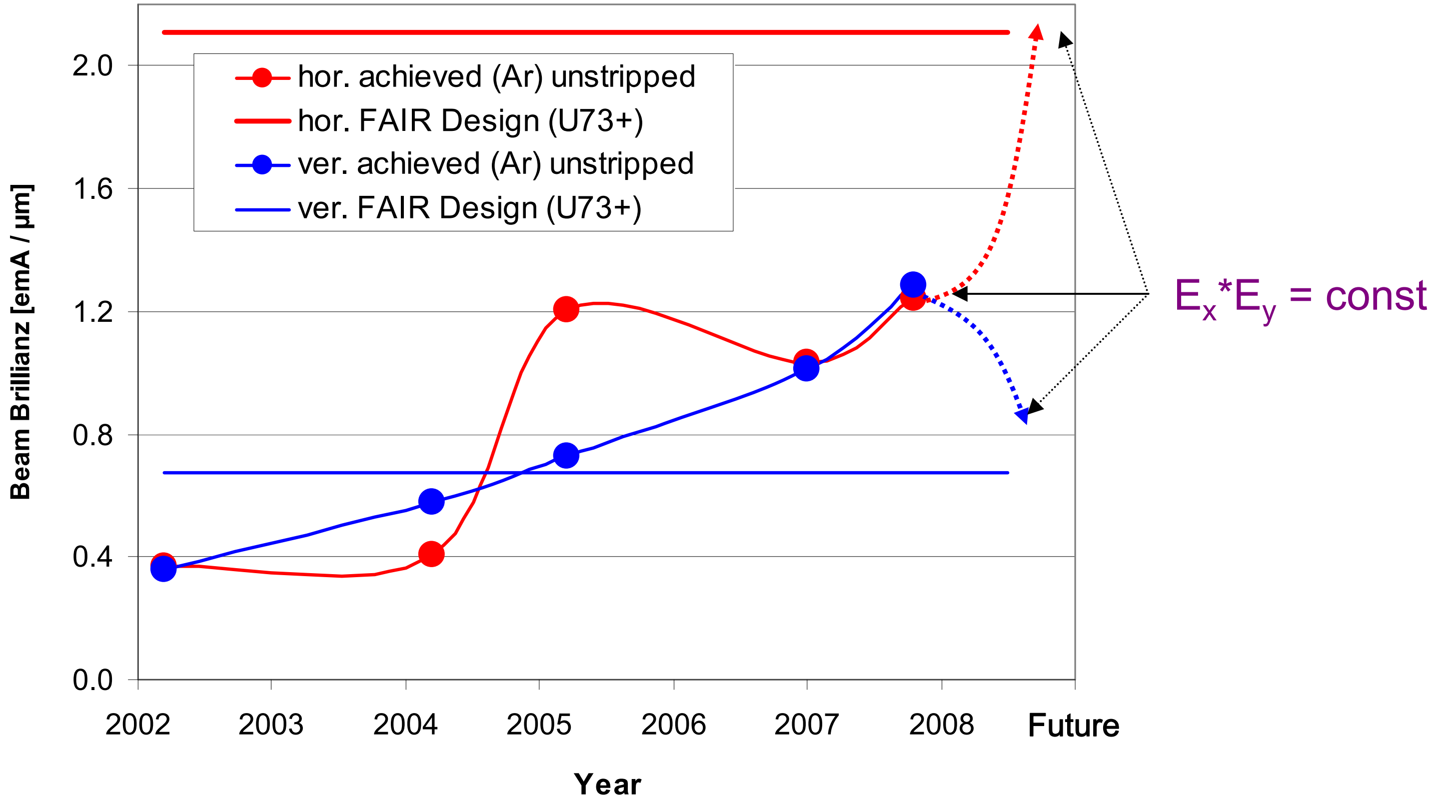
Development of Transverse UNILAC Beam Brilliance

- $B_{\perp}$ ok
- B_y ok
- B_x not ok

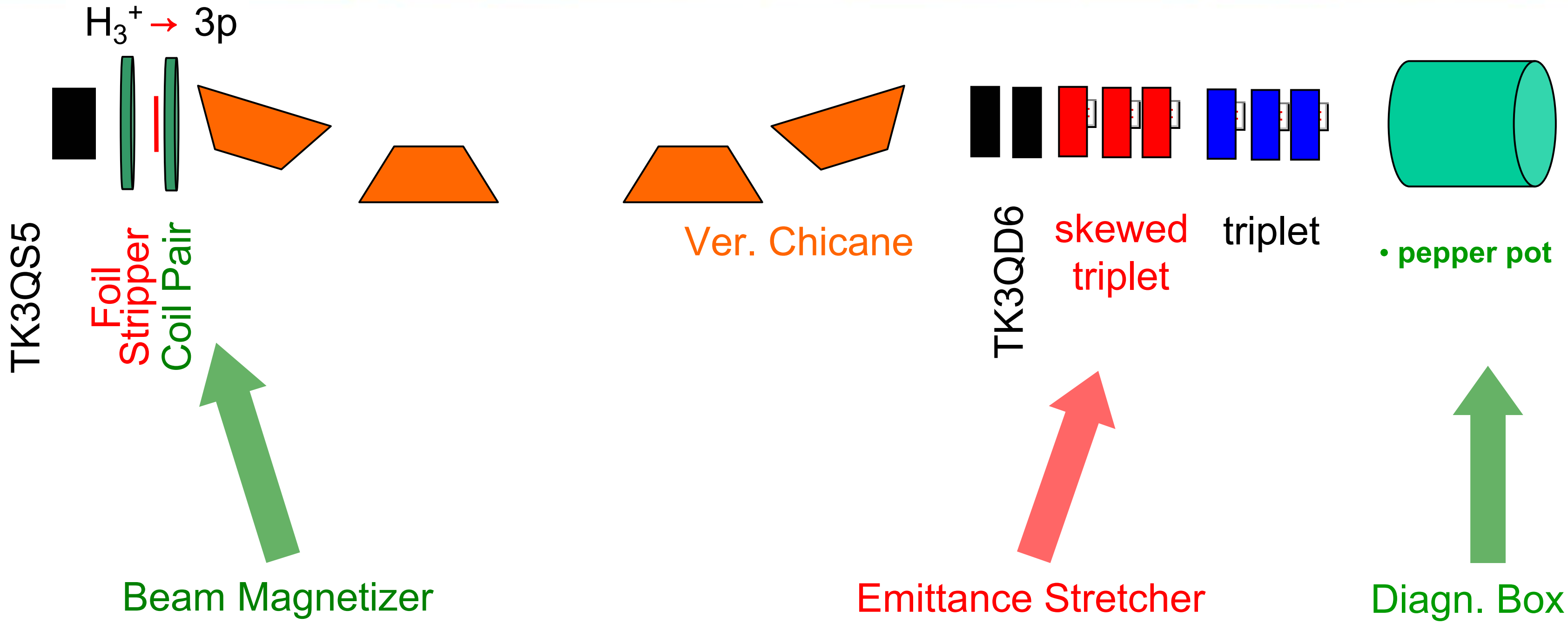


How to Meet Horizontal and Vertical Design Brilliances ?

- present UNILAC brilliances are equal
- pushing both brilliances over hor. design value : quite hard & not really required
- emittance transfer from horizontal to vertical plane should help
- transfer should preserve E_x*E_y



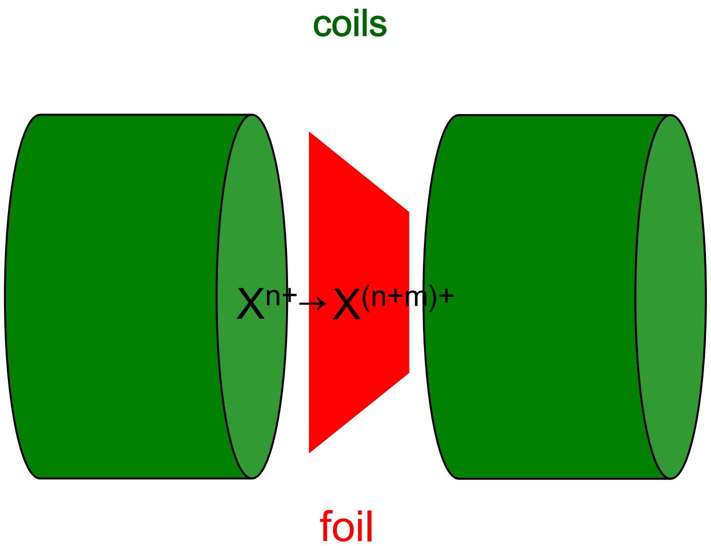
Conceptual Layout of an Emittance Splitter in the UNILAC

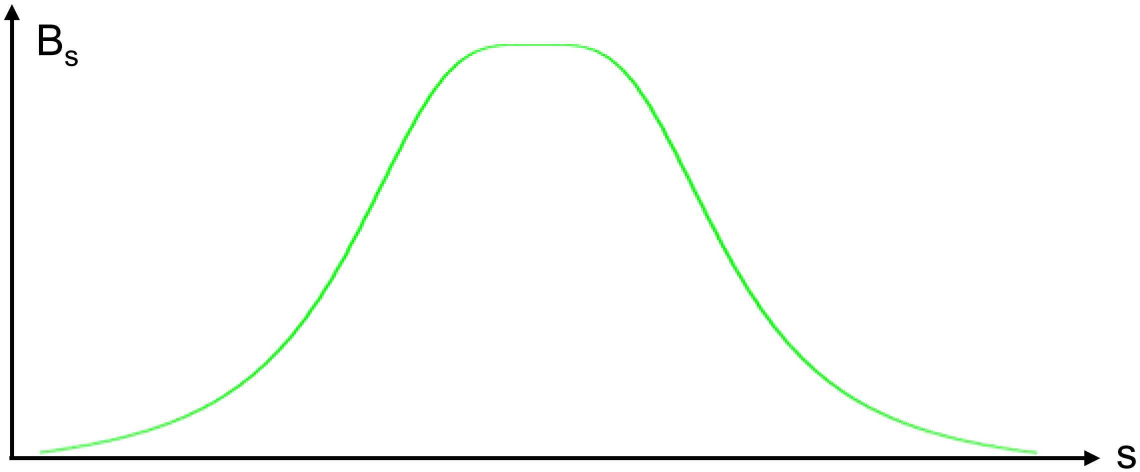


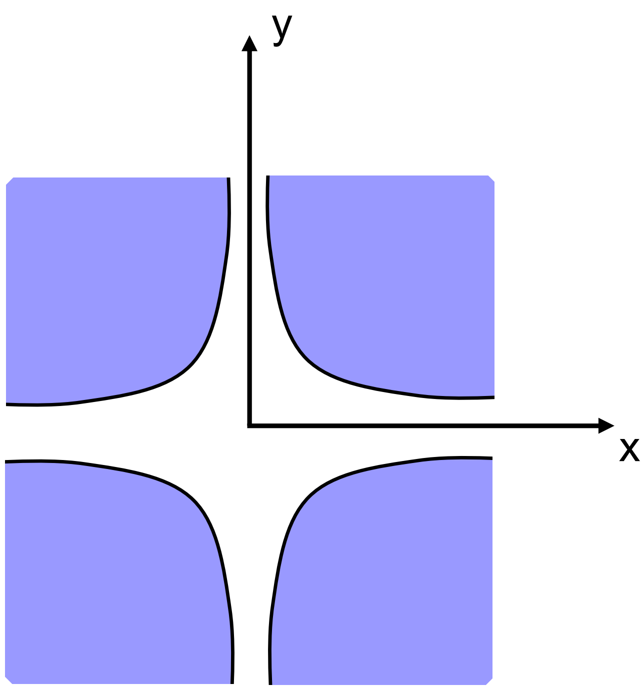
- Splitter integrated around existing Charge State Separator
- Splitter comprises :
  - coil pair (B ≈ few T)
  - skew triplet + doublet or triplet
  - diagnostic box with pepper pot

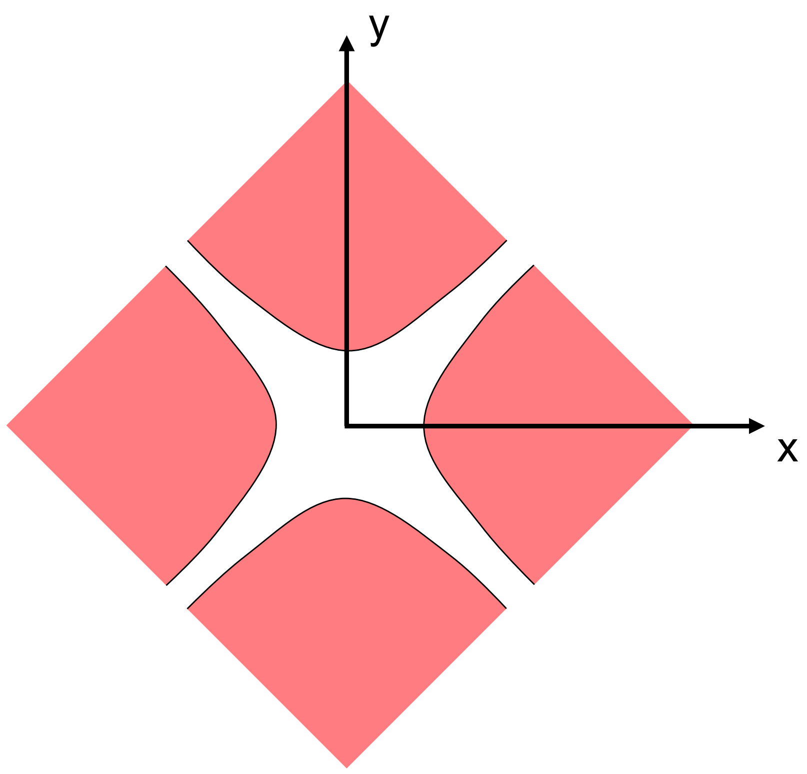
stripping inside long. B-field

long. B-field couples x & y motion









normal quadrupole

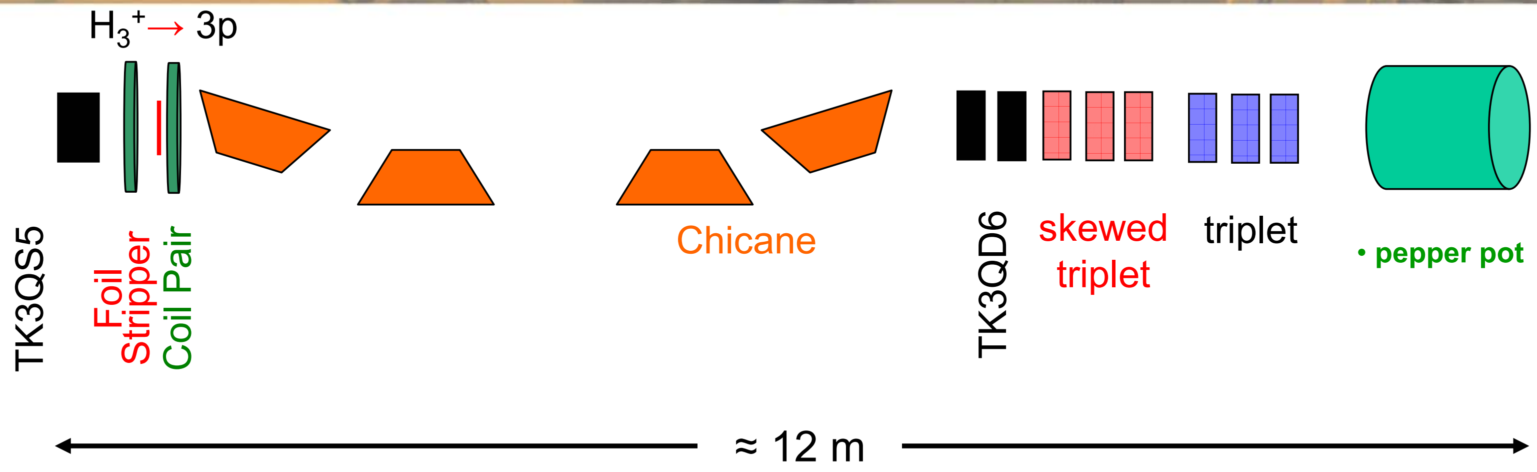
no x-y coupling

skew →

tilted by 45°

x-y coupling

Demonstrator for Emittance Splitter in the UNILAC



<u>Set-up for testing:</u>

- low current $H_3^+ \rightarrow$ proton beam (B = 0.8 T)
- no space charge
- low magnetic fields
- required equipment might be available on-site
- simulations: no losses, ΔE_x = - 41%, ΔE_y = +142%

Emittance Splitting: Beam Dynamics Tools

- the following tools deal with beam rms properties
- concepts hold for total emittances, beam sizes, etc...
- linear elements, to avoid emittance growth from non-linear elements

emittances defined through beam's second moments :

- a_i, b_i : two coordinates of particle i
- <ab>: mean of product $a_i b_i$
- C is moment matrix (symmetric)

$$C_x = \begin{bmatrix} <xx> & <xx'> \\ <x'x> & <x'x'> \end{bmatrix}, \quad E_x^2 = det\, C_x$$

$$C_y = \begin{bmatrix} <yy> & <yy'> \\ <y'y> & <y'y'> \end{bmatrix}, \quad E_y^2 = det\, C_y$$

Emittance Splitting: Beam Dynamics Tools

assumption: x & y plane are decoupled

linearly transport from point_1 → point_2 through matrices :

$$\begin{bmatrix} x \\ x' \end{bmatrix}_2 = M_x \begin{bmatrix} x \\ x' \end{bmatrix}_1 \qquad M_x = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}, \quad det\, M_x = 1$$

beam moments transport by matrix equation :

$$C_{x2} = M_x\, C_{x1}\, M_x^T$$

analogue in y

Emittance Splitting: Beam Dynamics Tools

If x & y plane are decoupled :

$$M = \begin{bmatrix} m_{11} & m_{12} & 0 & 0 \\ m_{21} & m_{22} & 0 & 0 \\ 0 & 0 & m_{33} & m_{34} \\ 0 & 0 & m_{43} & m_{44} \end{bmatrix}, \quad det\,M = det\,M_x \cdot det\,M_y = 1 \cdot 1 = 1$$

- E_x and E_y are preserved separately
- x-y coupling moments are zero
- non-coupling elements: drift, dipole, quadrupole, rf-gap
- transport in x calculated w/o knowledge on beam properties in y

- to change E_x and/or E_y, coupling elements must be non-zero :
  - solenoids
  - tilted (skewed) quadrupoles or dipoles
  - *non-linear magnets not considered here*

Emittance Splitting: Beam Dynamics Tools

<u>if x & y plane might be coupled</u>

→ generalization to 4d equations :

$$E_{4d}^2 = det \begin{bmatrix} <xx> & <xx'> & <xy> & <xy'> \\ <x'x> & <x'x'> & <x'y> & <x'y'> \\ <yx> & <yx'> & <yy> & <yy'> \\ <y'x> & <y'x'> & <y'y> & <y'y'> \end{bmatrix} = det\, C$$

transport of moments from 1 → 2 as usual:

$$\begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_2 = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{bmatrix} \begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_1 , \quad det\, M = 1$$

$$C_2 = M\, C_1\, M^T$$

Emittance Splitting: Beam Dynamics Tools

$$E_{4d}^2 = det \begin{bmatrix} <xx> & <xx'> & <xy> & <xy'> \\ <x'x> & <x'x'> & <x'y> & <x'y'> \\ <yx> & <yx'> & <yy> & <yy'> \\ <y'x> & <y'x'> & <y'y> & <y'y'> \end{bmatrix} = det\, C$$

- E_{4d} is preserved for even solenoids, tilted dipoles & quadrupoles; all tilt angles
- These elements couple x & y plane and produce x-y correlations
- $E_x \cdot E_y \geq E_{4d}$
- $E_x \cdot E_y = E_{4d}$ holds just for zero x-y correlation
- although E_{4d} is preserved, $E_x \cdot E_y$ increases if x-y correlation is produced

Emittance Splitting: Beam Dynamics Tools

Transport matrix of a solenoid, length L, and field strength B :

$$M_{Solenoid} = \begin{bmatrix} C^2 & \frac{SC}{K} & SC & \frac{S^2}{K} \\ -KSC & C^2 & -KS^2 & CS \\ -SC & -\frac{S^2}{K} & C^2 & \frac{SC}{K} \\ KS^2 & -SC & -KSC & C^2 \end{bmatrix}$$

$$K = \frac{B}{2(B\rho)}$$

$$C = cos(KL)$$

$$S = sin(KL)$$

Transport matrix of a thin hor. foc. quadrupole, rotated clockwise by -45°, focusing length 1/q :

$$M_{SkewQuad} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & -q & 0 \\ 0 & 0 & 1 & 0 \\ -q & 0 & 0 & 1 \end{bmatrix}$$

Symplectic Transformations

- drifts, gaps, tilted quads & dipoles, solenoids are "symplectic" :

$$M^T J M \; = \; J$$

$$J \; := \begin{bmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{bmatrix}$$

- symplectic transformations preserve two quantities :
  - $E_{4d}^2 \; = \; det\, C$
  - $Trace\{JCJC\}$

see for instance prst-ab **6** 104002 (2003)

Symplectic beam lines :

- preserve E_{4d}
- change simultaneously E_x & E_y :
  - no initial x-y correlations → E_x & E_y generally increase in x-y coupling devices
  - initial x-y correlations → E_x & E_y might be decreased by lowering correlations
- allow swapping $E_x \leftrightarrow E_y$

But

- symplectic beam lines do not change the "emittance splittability" of a beam
- "regular" beams are not "splittable"
- "regular": distributions as generally used for simulations (no inter-plane coupling)
- splittablity related to $Trace\{JCJC\}$, how ??????

Magnetized Beams

- no emittance splitting with skewed quads/dipoles or solenoids only
- to make beam splittable → apply non-symplectic action

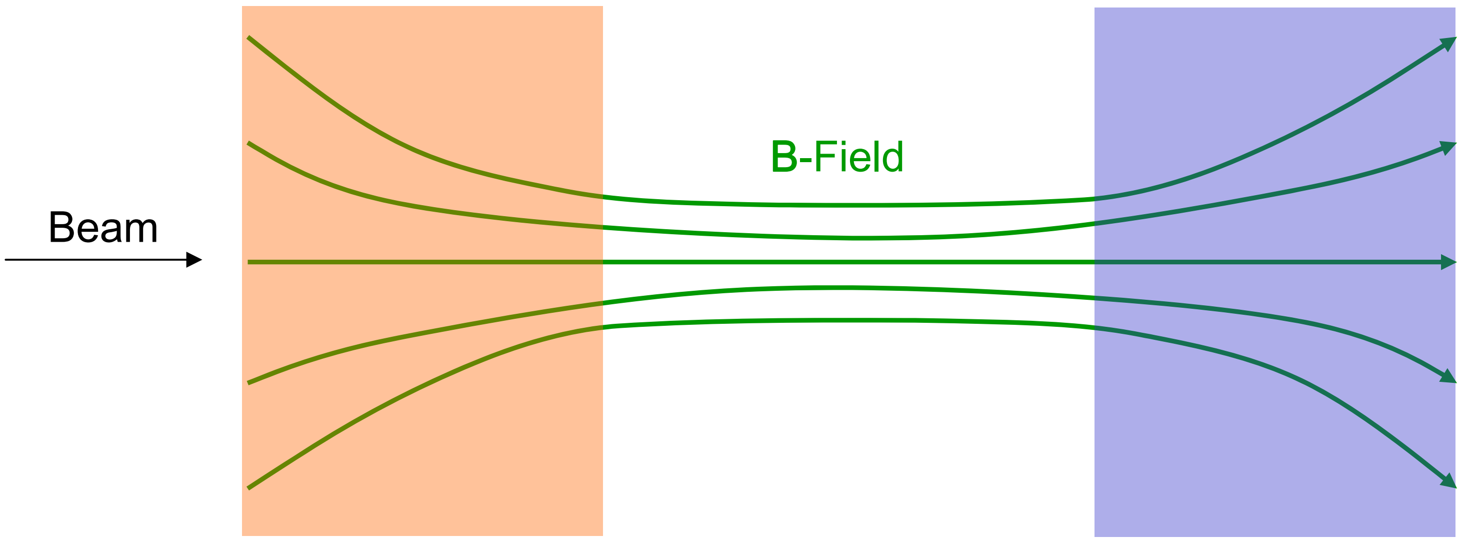
<u>solenoid fringe field:</u> non-symplectic transformation, changing $Trace\{JCJC\}$, E_{4d} preservation

$$M_{SolFringe} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & +K & 0 \\ 0 & 0 & 1 & 0 \\ -K & 0 & 0 & 1 \end{bmatrix}$$

K(in) = -K(out)

$$K = \frac{B}{2(B\rho)}$$

Magnetized Beams



- transverse kick by transverse fringe
- non-symplectic transformation
- $\Delta x_i' \sim y_i$, $\Delta y_i' \sim -x_i$,
- each particle gets angular momentum
- $L_i = r_i \times p_i \sim x_i y_i' - x_i' y_i$

- spiraling around **B**
- non-symplectic

- -(transverse kick) by –(transverse fringe)
- kick removes $\mathbf{L}_i$
- complete solenoid is symplectic again

(follows from div **B** = 0)

change of beam's Bρ prevents kick-cancellation

→ beam experiences non-symplectic transformation

→ beam is "magnetized" (splittable) at solenoid exit

Magnetized Beams

- Magnetized beams are splittable

- "Magnetizatized" and "x-y correlated" are not the same !!!

- x-y correlated beams can be magnetized or not

- Beam lines made just from solenoids, skewed quads & dipoles, drifts, gaps :
    - can change x-y correlations
    - can not change $Trace\{JCJC\}$
    - preserve the magnetization, i.e. the "splittability"

Magnetized Beams

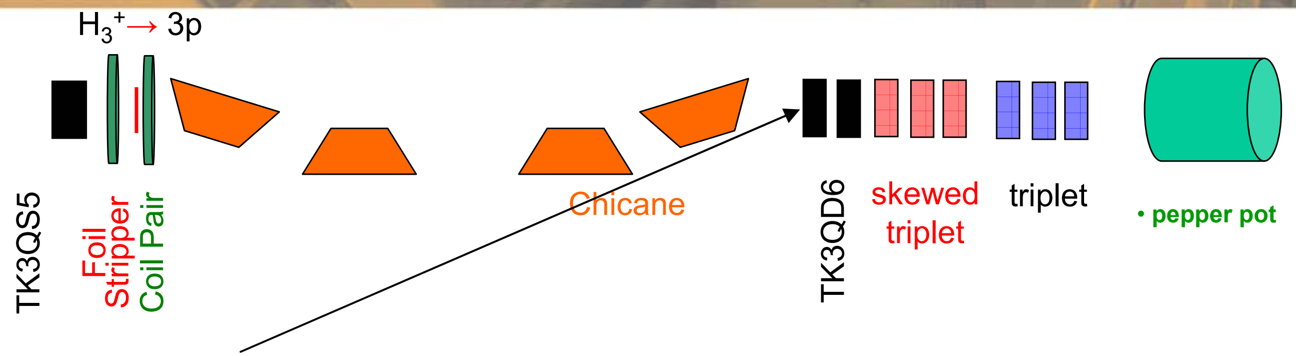
- electron guns inside a solenoid provide magnetized beams
- e-linacs: emittance ratios of $E_x/E_y \approx 50$ were achieved (D. Edwards, XXth LINAC Conf., Monterey)
- proposal to apply this principle to ion beams :
  - stripping inside long. magn. field
  - non-symplectic action → transverse emittance splitting possible

remark: beams from ECRs are magnetized and can be split

Procedure of Emittance Splitting in the UNILAC (1)

- switch off the skew triplet and the normal triplet
- place the stripping foil inside a long. B-field (0.n T) produced by coil pair
- proton beam behind coil/foil combination :
  - magnetized, emittance splitting possible
  - inter-plane correlations, i.e. $E_x \cdot E_y \geq E_{4d}$

Procedure of Emittance Splitting in the UNILAC (2)



- at entrance TK3QD6: measure full 4d beam's second moment matrix C_1, i.e. 10 values

$$C_1 = \begin{bmatrix} <xx> & <xx'> & <xy> & <xy'> \\ <x'x> & <x'x'> & <x'y> & <x'y'> \\ <yx> & <yx'> & <yy> & <yy'> \\ <y'x> & <y'x'> & <y'y> & <y'y'> \end{bmatrix}_{TK3QD6_{in}}$$

C is symmetric !

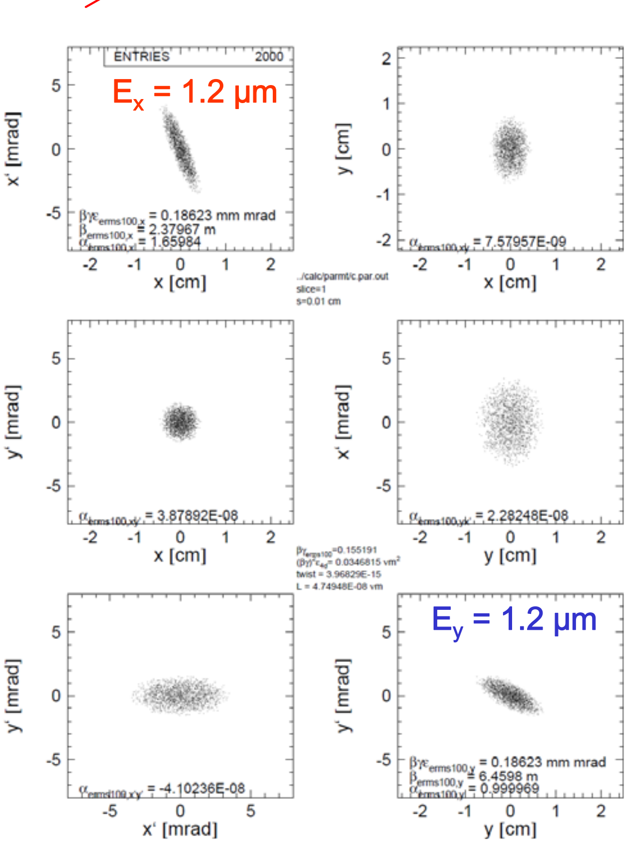
- set TK3QD6 and skew triplet to provide transport of beam moments $C_2 = M\, C_1\, M^T$ with

$$C_2 = \begin{bmatrix} <xx> & <xx'> & 0 & 0 \\ <x'x> & <x'x'> & 0 & 0 \\ 0 & 0 & <yy> & <yy'> \\ 0 & 0 & <y'y> & <y'y'> \end{bmatrix}_{Skew_{out}}$$

and minimized $det \begin{bmatrix} <xx> & <xx'> \\ <x'x> & <x'x'> \end{bmatrix}_{Skew_{out}}$ at skew exit

- use last triplet to re-match envelope for further transport

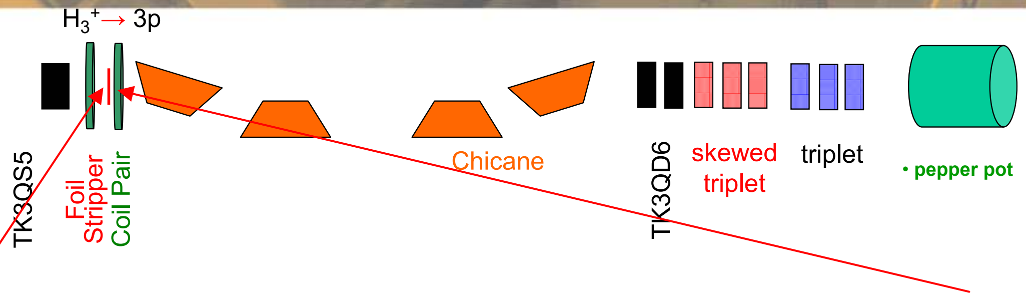
Simulations with PARMILA-Transport



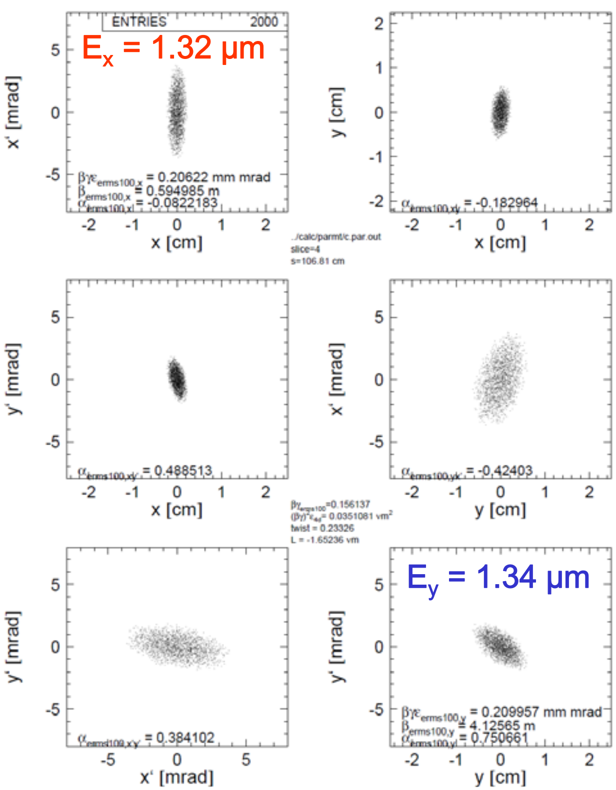
Simulations assume :

- H_3^+, 11.4 MeV/u, low current, no space charge
- initial Gaussian distribution, no x-y correlations
- rms momentum spread 0.1%, (from measurements)
- rms emittance hor./ver. 1.2 μm (from measurements)
- B = 0.8 T
- angle scattering at stripper foil
- 2nd order transport in dipoles (dispersion, 6-pole fringes)
- existing aperture limits (chambers, irises, ...)

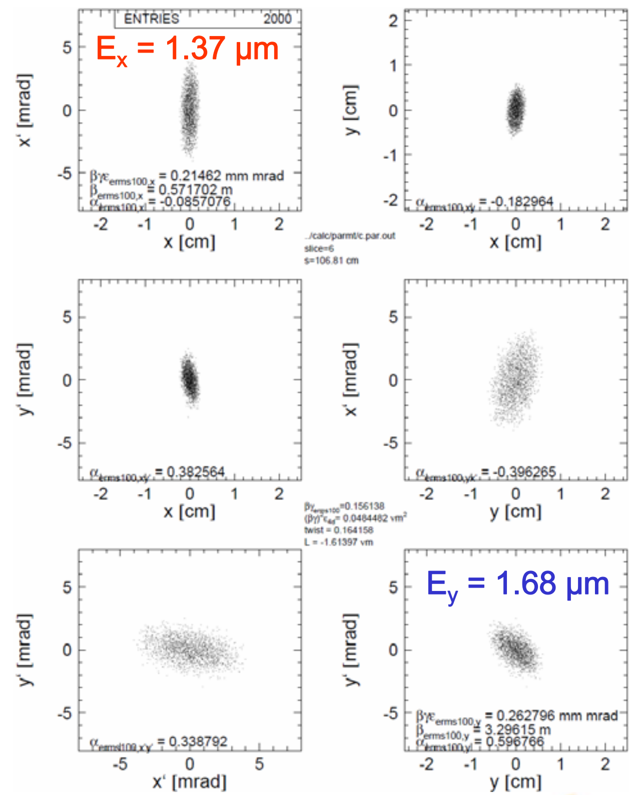
Inside Coil Pair, i.e. on Stripping Foil



before foil scattering



after foil scattering



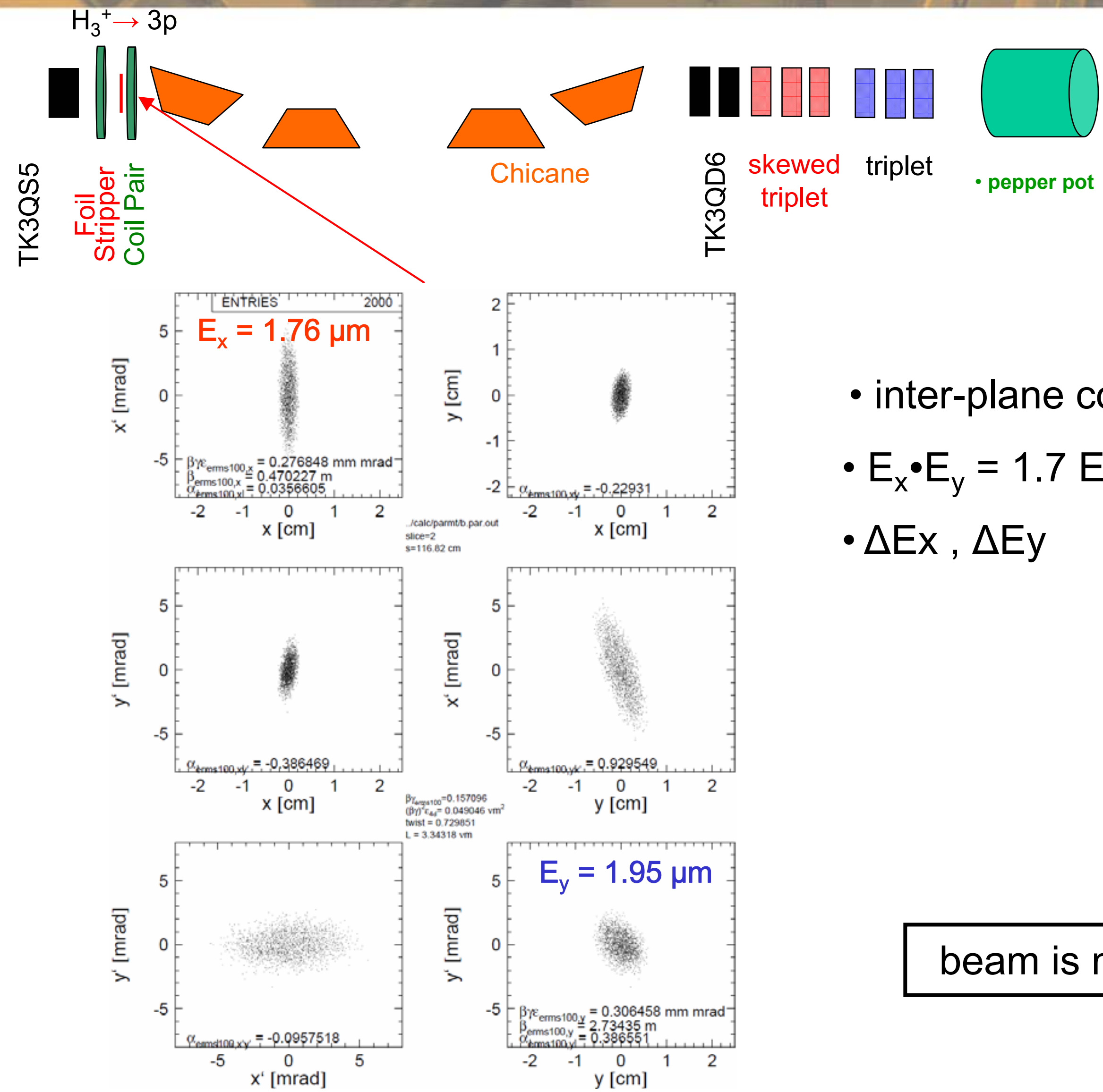
long. B-field:

- x-y correlations
- $\Delta E_{4d} = 0$!
- $E_x \cdot E_y = 1.2\ E_{4d}$
- ΔEx , ΔEy

Foil Scattering:

- $\Delta E_{4d} = 38\%$
- ΔE_x , ΔE_y

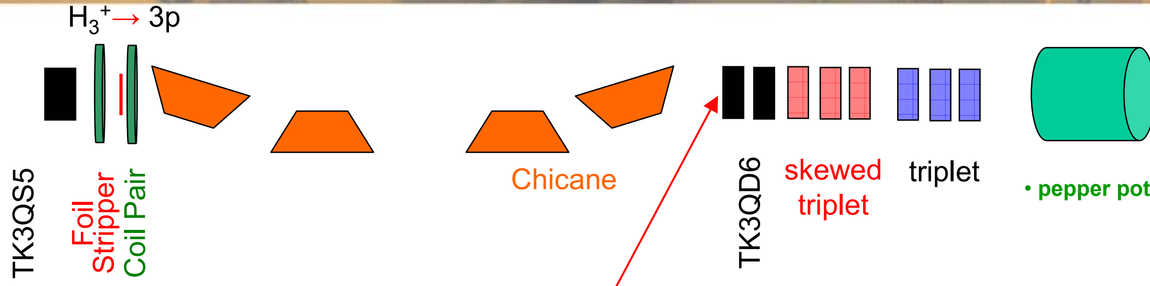
Exit of Coil Pair

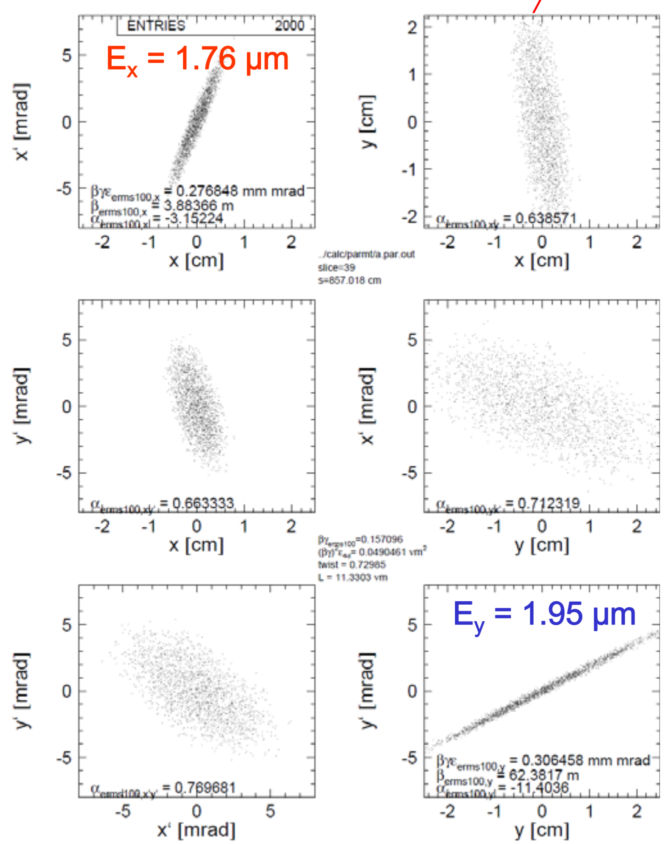


- inter-plane correlations
- $E_x \bullet E_y = 1.7\ E_{4d}$
- ΔEx , ΔEy

beam is magnetized

Entrance to TK3QD6

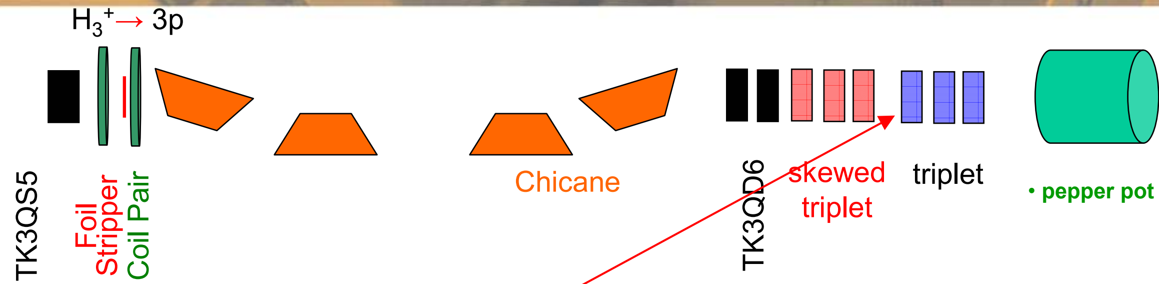


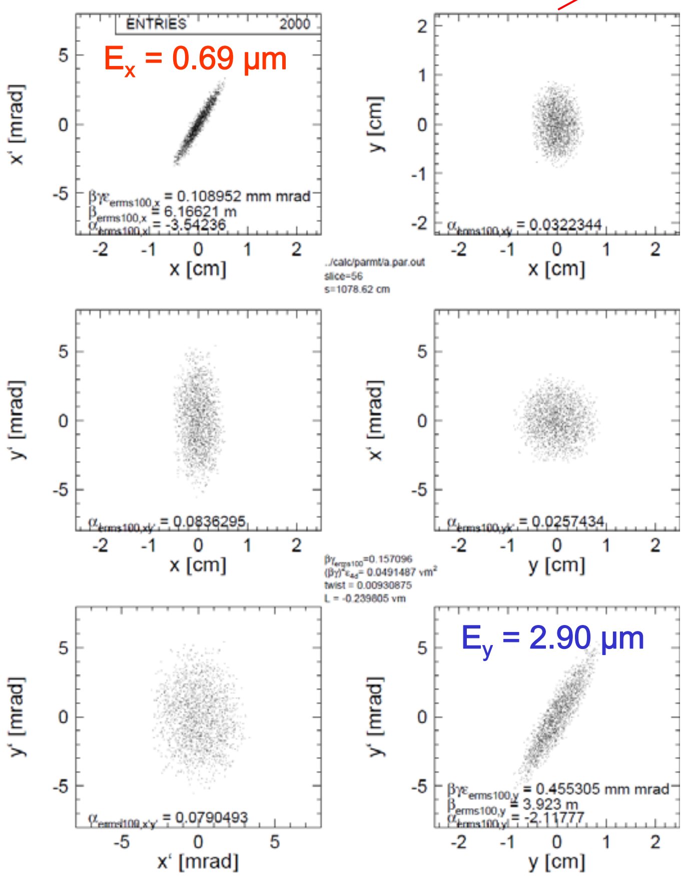


- inter-plane correlations
- $E_x \bullet E_y = 1.7\ E_{4d}$
- evaluation of beam moment matrix
- setting TK3QD6 and skew triplet ...

beam is magnetized

Entrance to First Normal Quadrupole





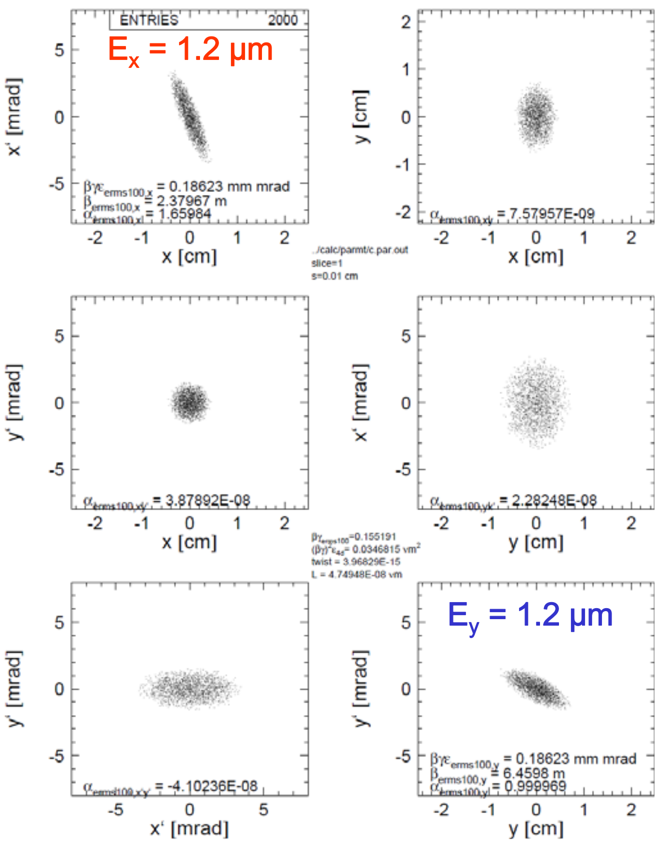
- x-y correllations almost fully removed
- $E_x \cdot E_y = 1.01\ E_{4d}$
- $E_x / E_y = 0.24$

beam is magnetized

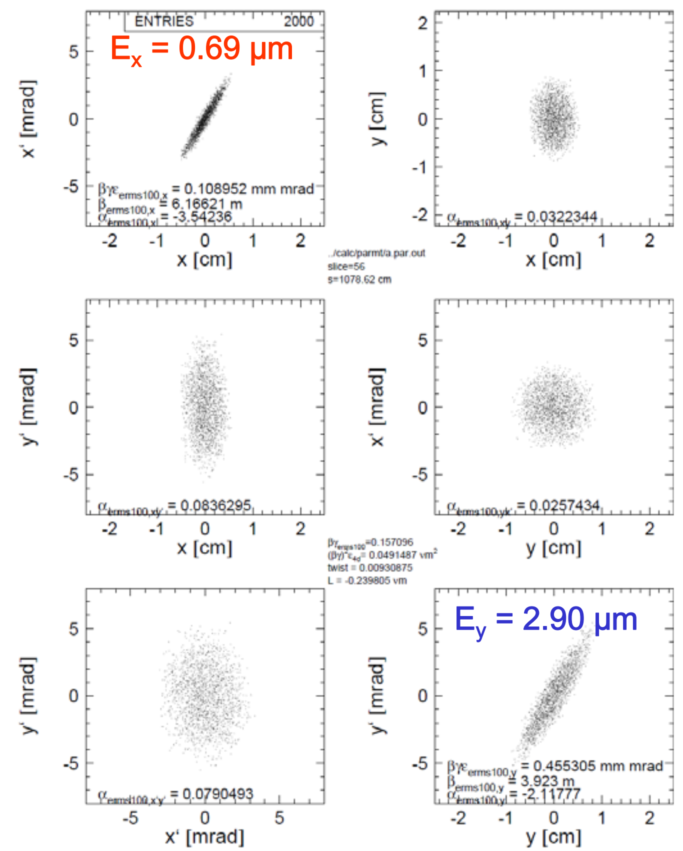
!! splitting did not remove magnetization !!

Comparison: Before/After Section

entrance (H_3^+):



exit (p):



Balance:

- Transmission: 100 %
- ΔE_x: - 41 %
- ΔE_y: +142 %
- ΔE_{4d}: + 42 %
- magnetized !

Experimental Set-up for Proof of Principles

built a set-up for experimental demonstration of simulated case ($H_3^+ \rightarrow 3p$) :

- Coil pair :
  - B_o = 0.77 T
  - L_{eff} = 40 cm; i.e. R_{Coil} = 29 cm

- 6 "Bokemeier" Coils
- $R_{Coil} \approx$ 28 cm
- $A_{conductor} \approx$ 50 cm^2
- $L_{yoke} \approx$ 4.75 cm
- B_{max} to be measured

- 2 Triplets :
  - $R_{app} \geq$ 40 mm
  - $B' \cdot L_{eff} \geq$ 3 T

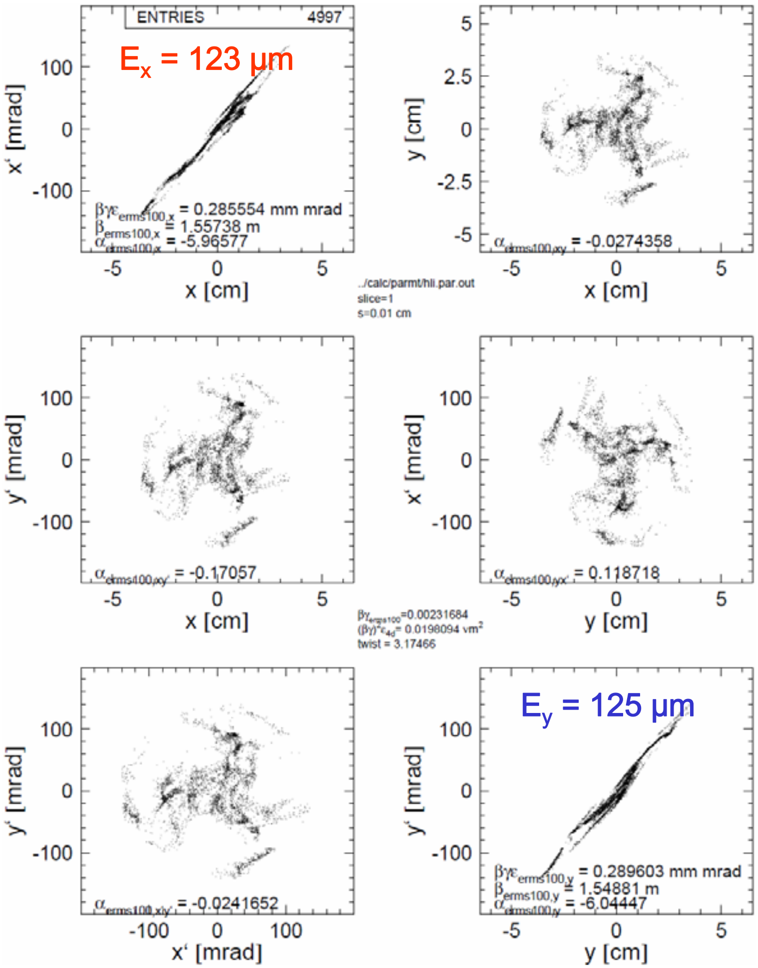
- 2 "Injection Triplets"
- $R_{ap} \approx$ 40 mm
- $L_{eff} \approx$ 20/40/20 cm
- $B'_{max} \approx$ 15 T/m

- 1 Triplet "E-12_156"
- $R_{ap} \approx$ 50 mm
- $L_{eff} \approx$ 35/60/40 cm
- B'_{max} to be measured

- Pepper pot device → improvements, but further testing required

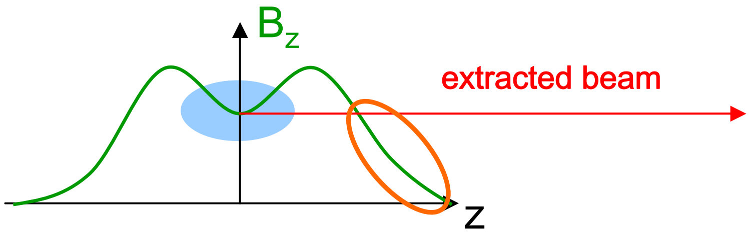
ECR LEBT

beam after extraction from ECR



courtesy P. Spädtke

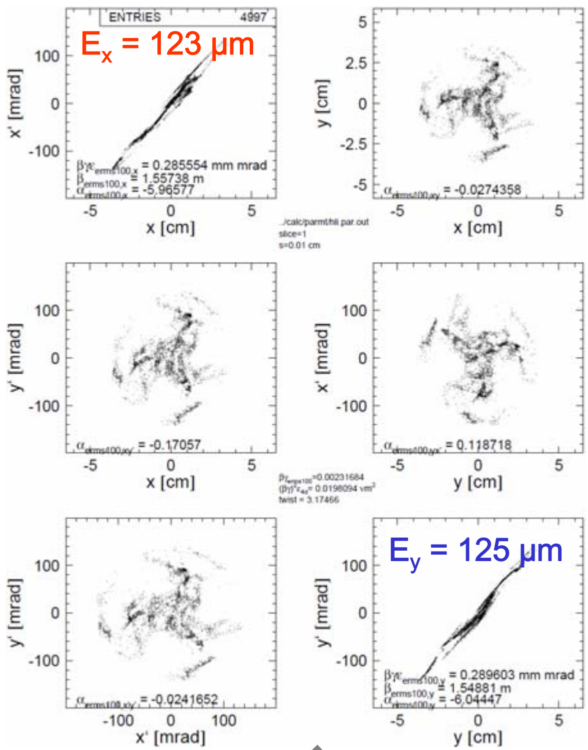
confining in long. B-field:



- ECR-extracted beam has x-y correlations
- $E_x = E_y$
- $E_x \bullet E_y = 4.2\ E_{4d} \geq E_{4d}$ (from correlations)
- ECR-extracted beam is magnetized
- beam is "emittance splittable"

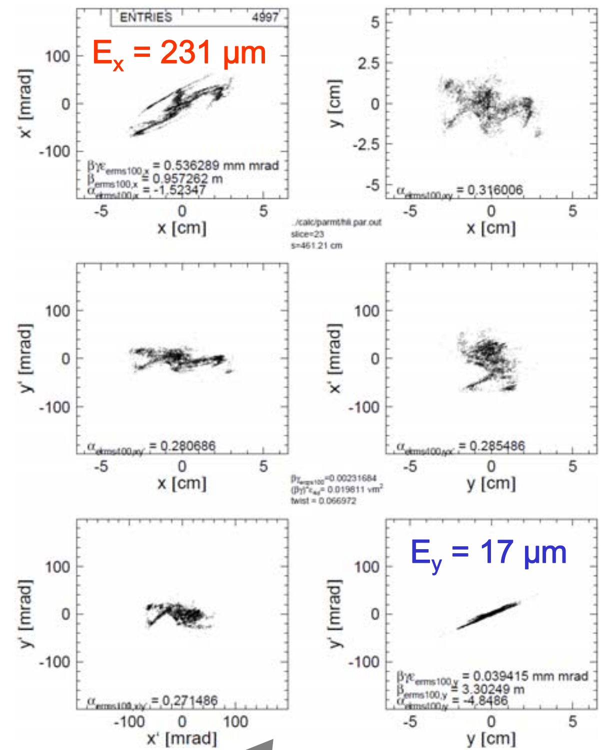
Emittance Splitting of an ECR Beam

directly after ECR extraction



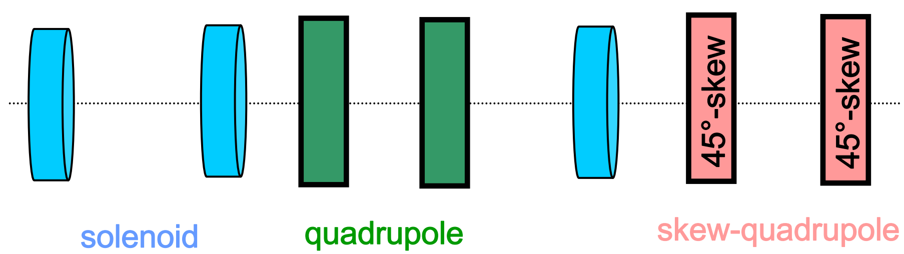
- E_x = 123 µm
- E_y = 125 µm
- $E_x \bullet E_y$ = 4.2 E_{4d}

after emittance splitter

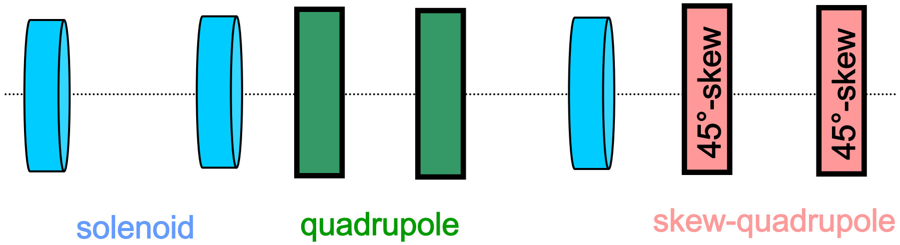


- E_x = 231 µm
- E_y = 17 µm
- $E_x \bullet E_y$ = 1.1 E_{4d}
- $E_x \bullet E_y$ red. by factor 4 !!

ECR-LEBT Emittance Splitter



Emittance Splitting of an ECR Beam



- ECR beams are used at therapy accelerator facilities
- split emittance beams could be injected into the synchrotron
- split emittances will increase MTI efficiency

Summary

- Emittance splitting might improve synchrotron injection efficiency without :
  - primary beam current increase
  - beam collimation
- Method requires long. B-field along stripper and 3 skewed quads
- Simulations (low current, light ions): hor. emitt. reduction by n•10% possible
- Experimental proof of principle using $H_3^+ \rightarrow 3p$ along UNILAC proposed
- Additional application → ECR beams (no stripper required)

- *Might be applicable also along mod. HSI-Alvarez section ($U^{4+} \rightarrow U^{37+}$) :*
  - *lower B-field (≈ 2 T) w.r.t. stripping $U^{27+} \rightarrow U^{73+}$ at 11.4 MeV/u*
  - *simulations needed:*
    - *does split beam survive transport to SIS ?*
    - *what beam is really required at SIS injection (I, q, E_x, E_y, ΔT_{pulse}) ?*