Optimization of low-energy beam transport

Kernfysisch Versneller Instituut –
Center for advanced radiation technology (KVI-CART)

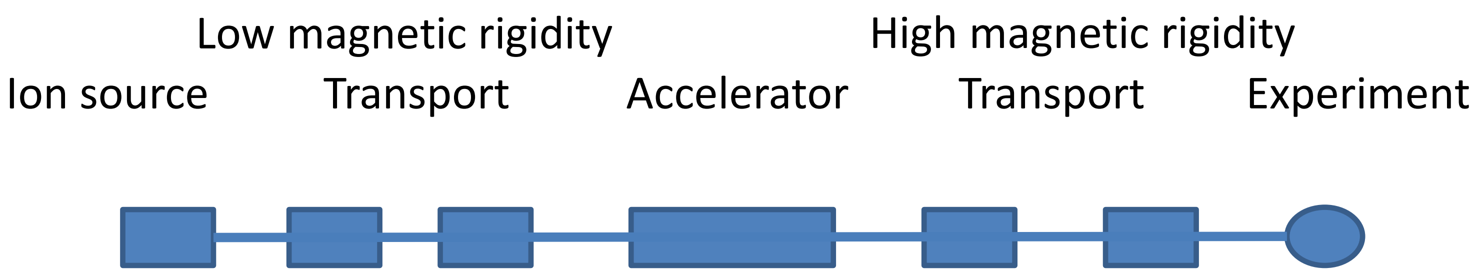
H.R. Kremers, J.P.M. Beijers, S. Brandenburg
Zernikelaan 25, 9747 AA, Groningen.
The Netherlands

content

- Introduction
- KVI- situation (brief)
  - Magnet aberrations and 4rms-emittance growth
- Optimization low energy beam line
  - Quick compensation by an additional sextupole effect?
  - General method to calculate the 4rms-emittance growth
    - Sectupoles
    - Solenoid lens
    - Einzel
  - Conclusions.

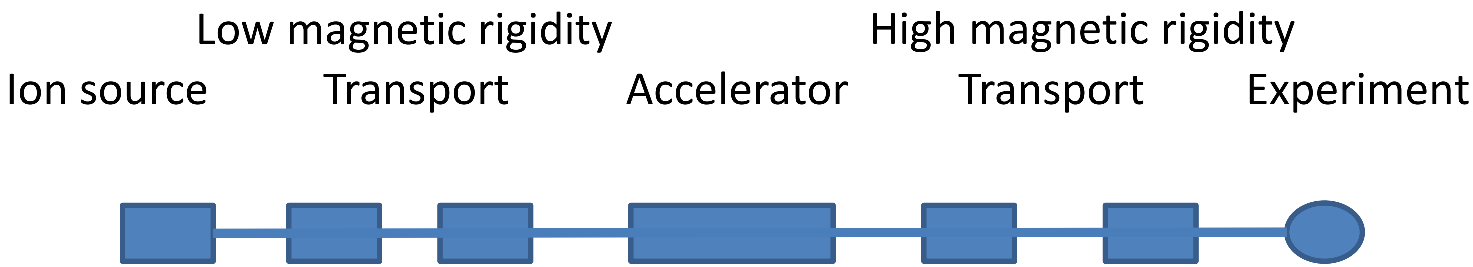
Introduction

Accelerator Laboratories:



Introduction

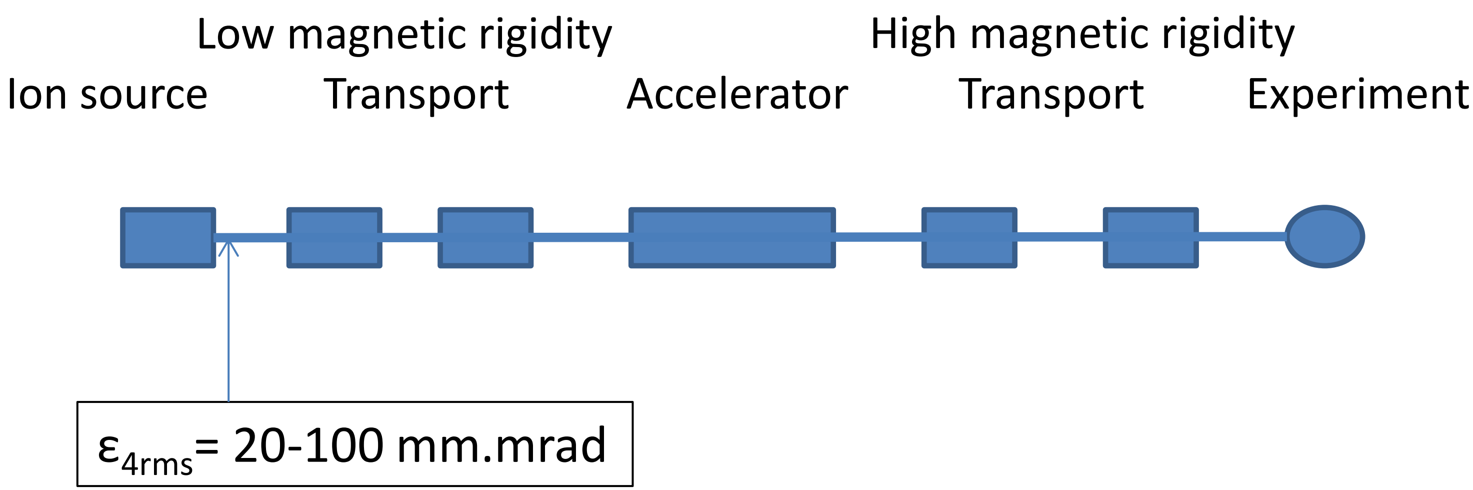
Accelerator Laboratories:



ε_{4rms}= 20-100 mm.mrad

Introduction

Accelerator Laboratories:



Introduction

Accelerator Laboratories:

Low magnetic rigidity | High magnetic rigidity

Ion source | Transport | Accelerator | Transport | Experiment

ε_{4rms}= 20-100 mm.mrad

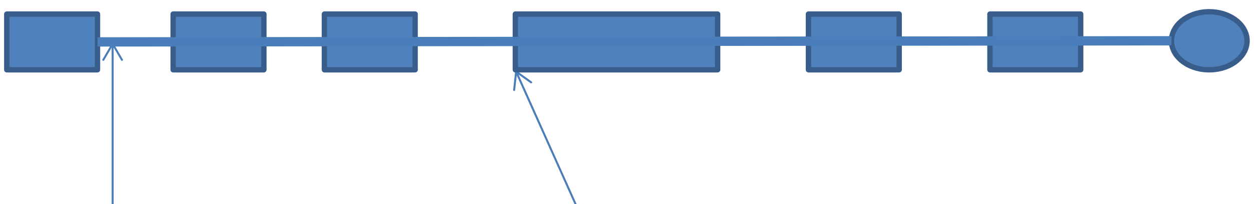
Geometrical acceptance = 100-200 mm.mrad

Introduction

Accelerator Laboratories:

Low magnetic rigidity High magnetic rigidity

Ion source Transport Accelerator Transport Experiment

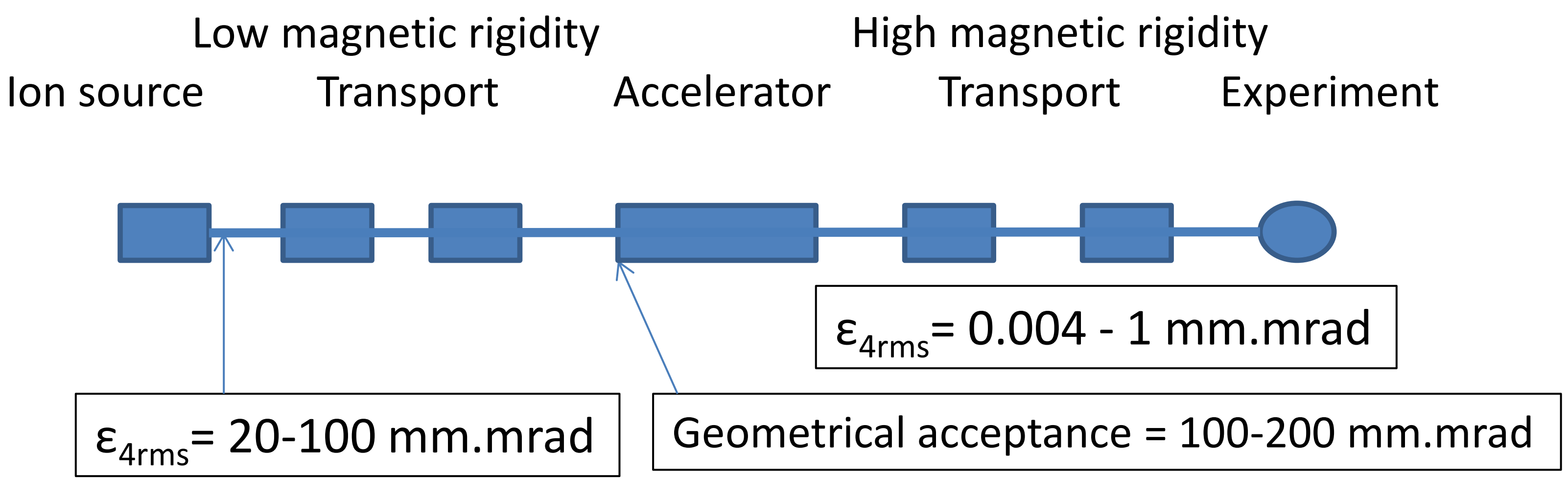


ε_{4rms}= 20-100 mm.mrad

Geometrical acceptance = 100-200 mm.mrad

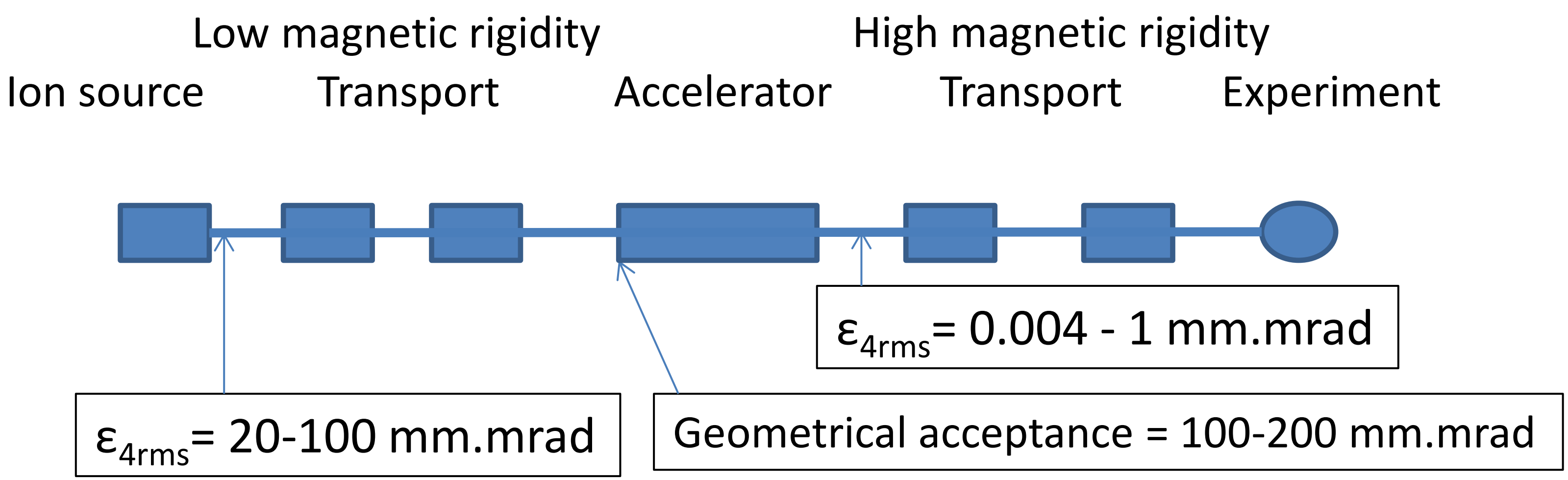
Introduction

Accelerator Laboratories:



Introduction

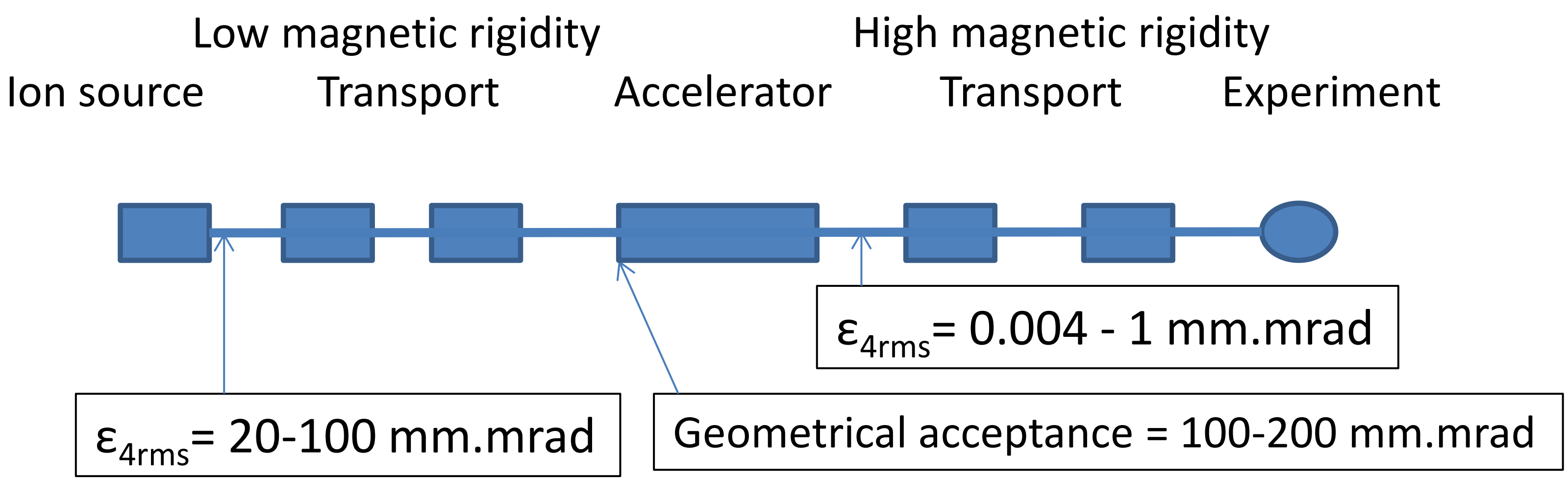
Accelerator Laboratories:



Introduction

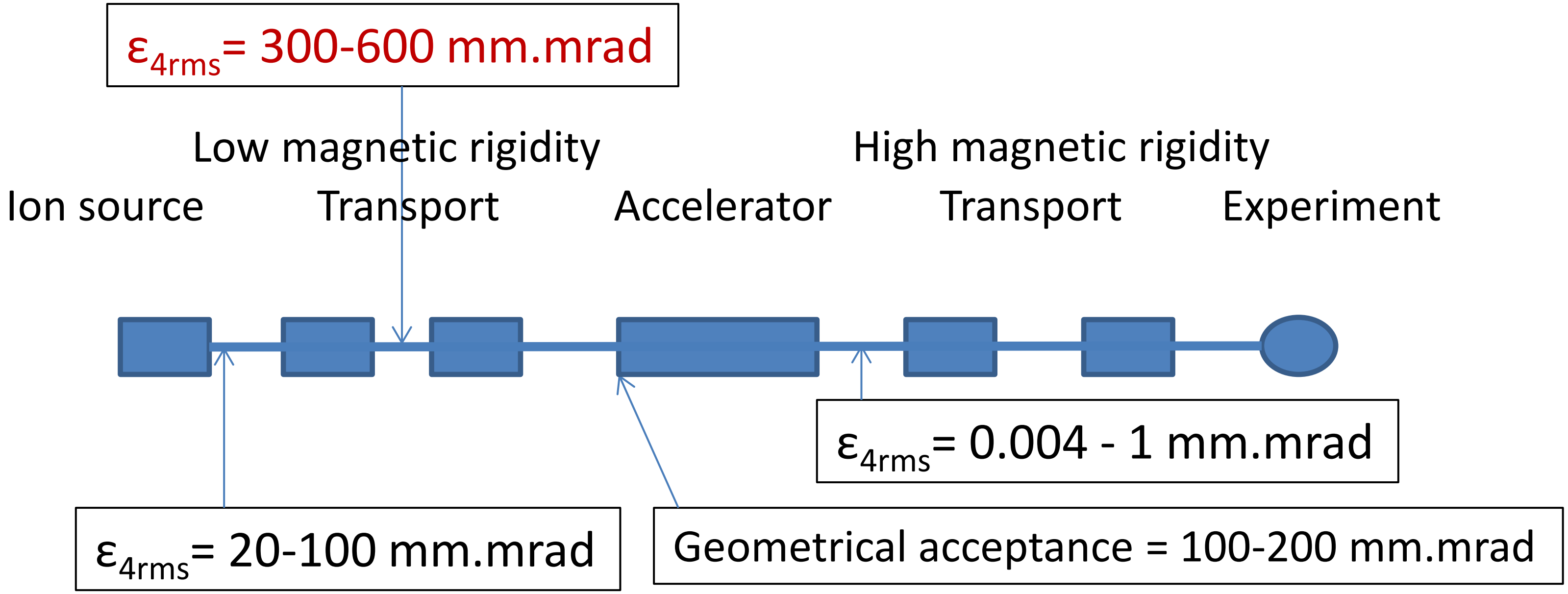
Accelerator Laboratories:

ε_{4rms}= 300-600 mm.mrad



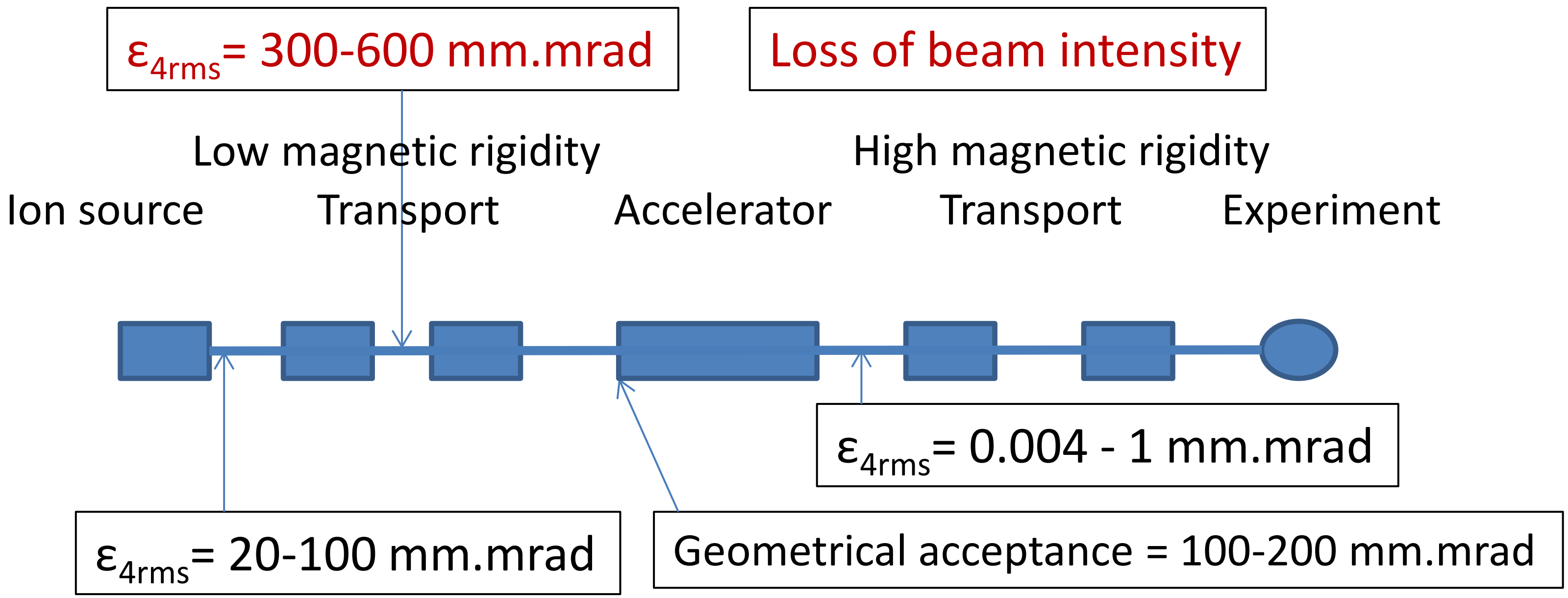
Introduction

Accelerator Laboratories:



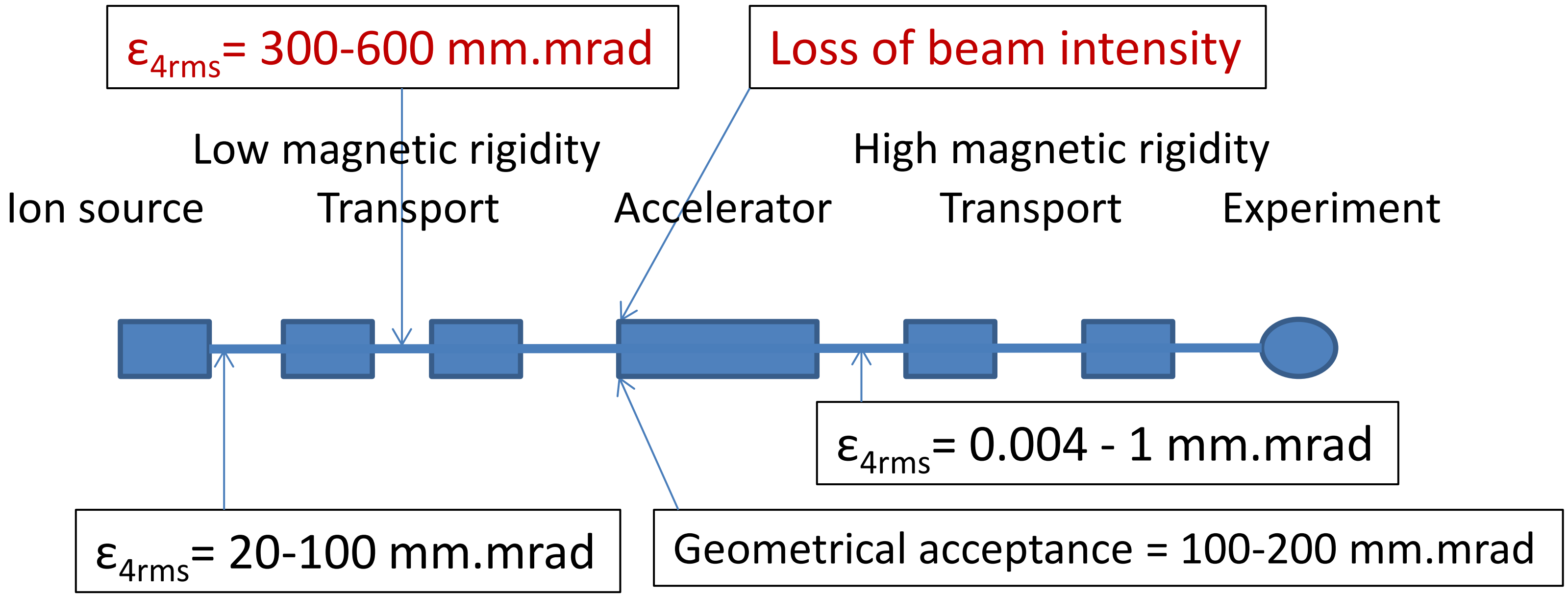
Introduction

Accelerator Laboratories:



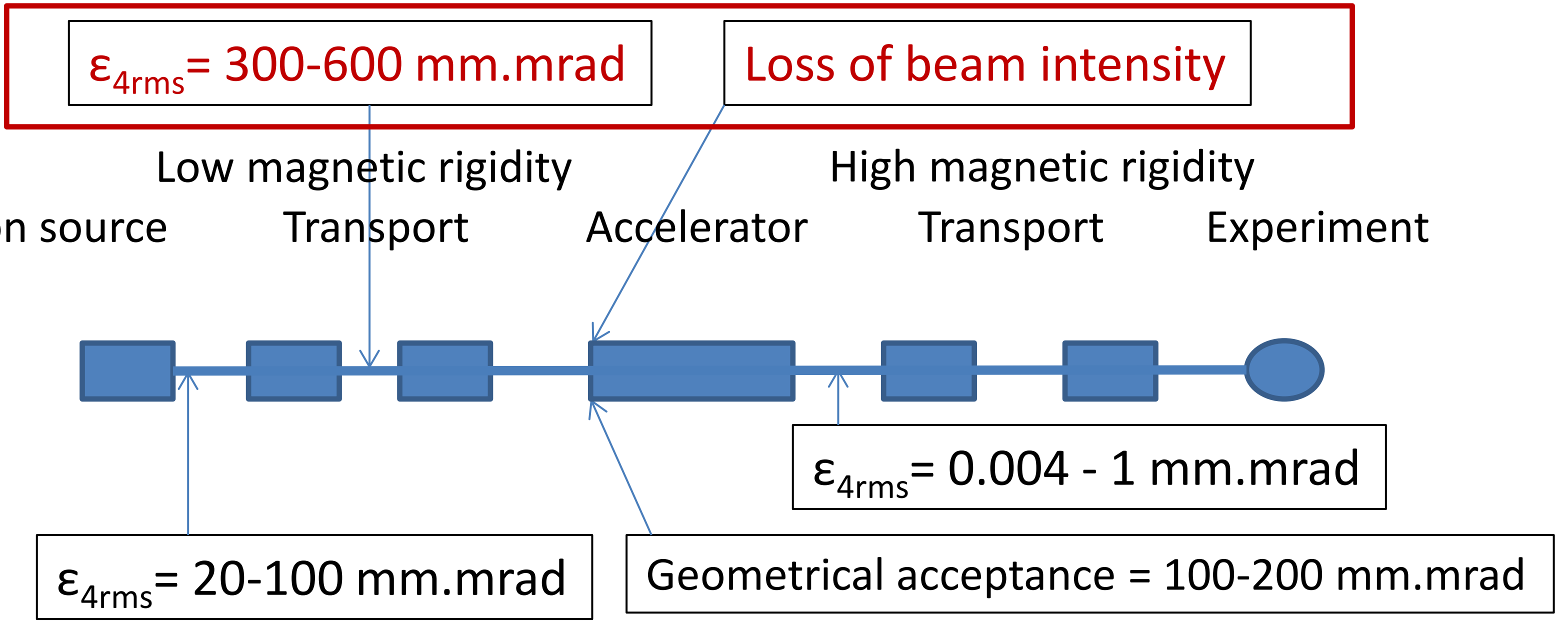
Introduction

Accelerator Laboratories:



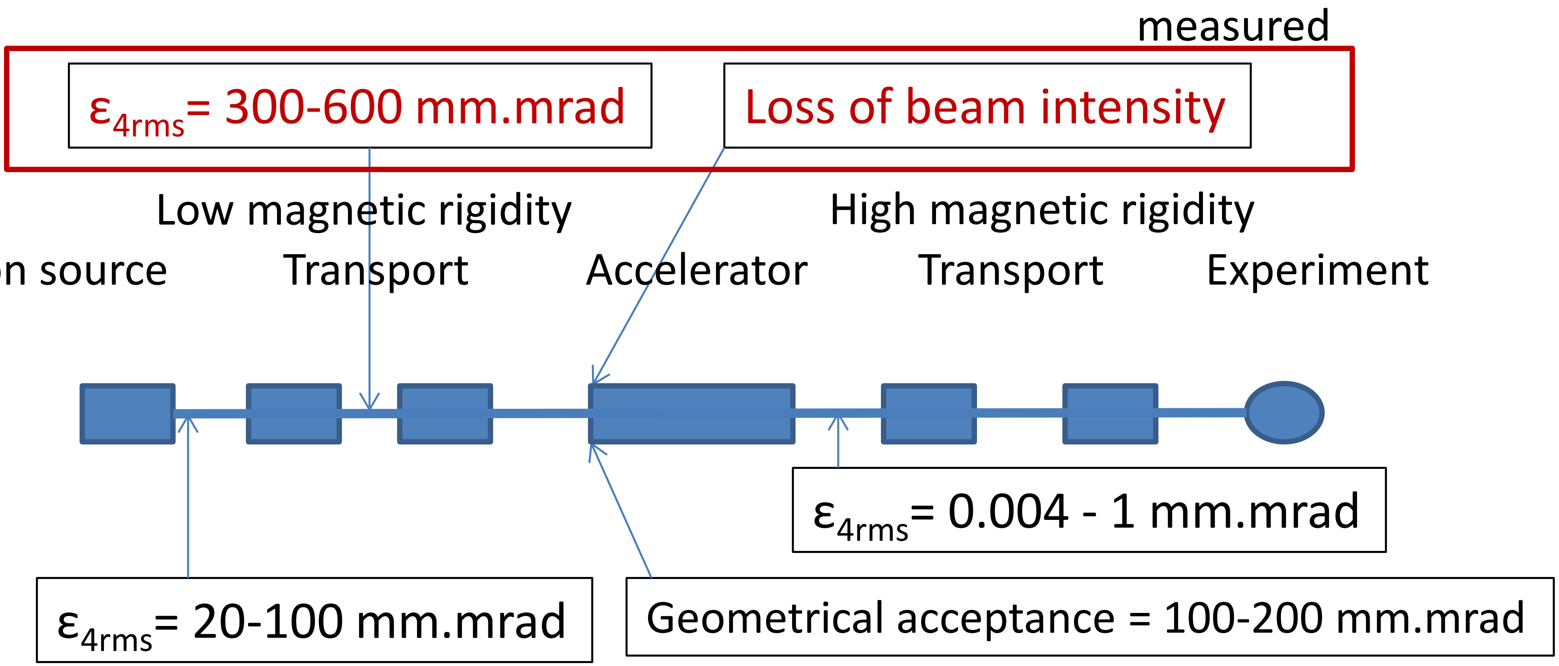
Introduction

Accelerator Laboratories:



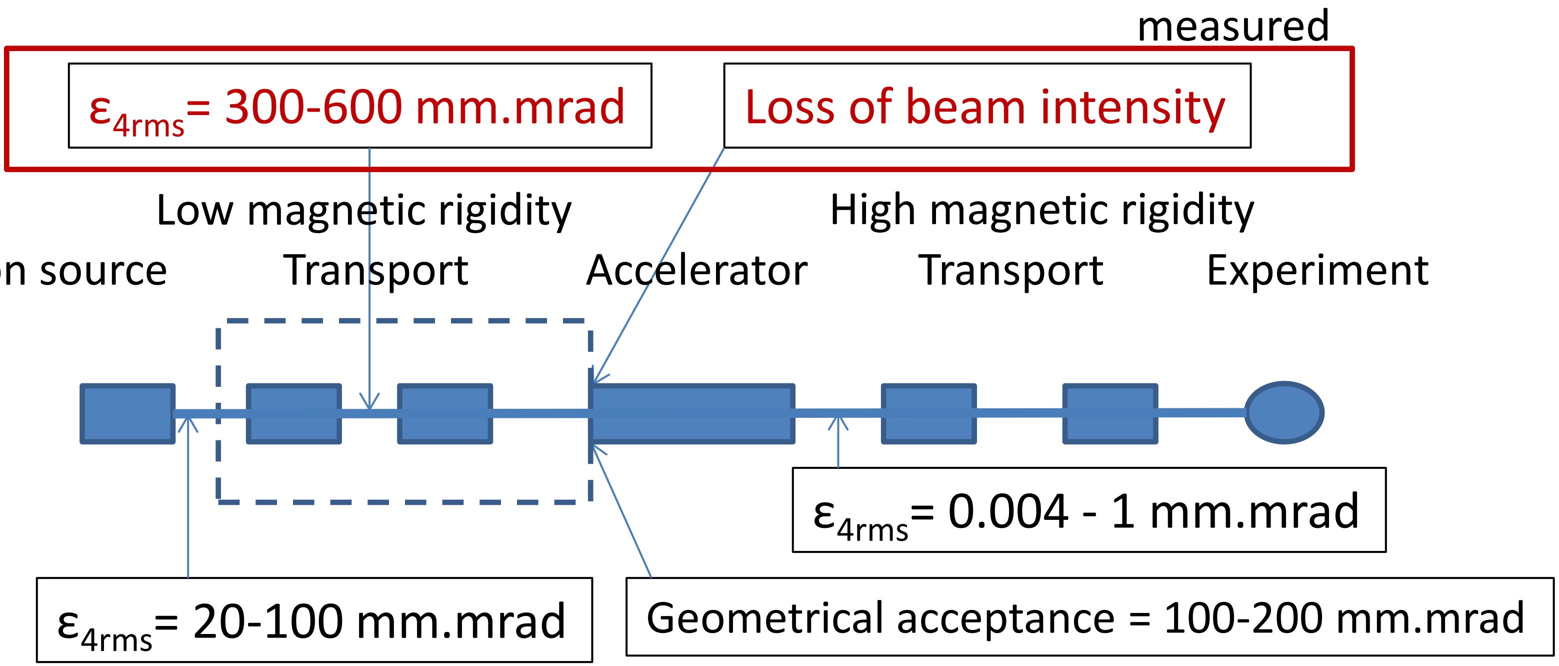
Introduction

Accelerator Laboratories:



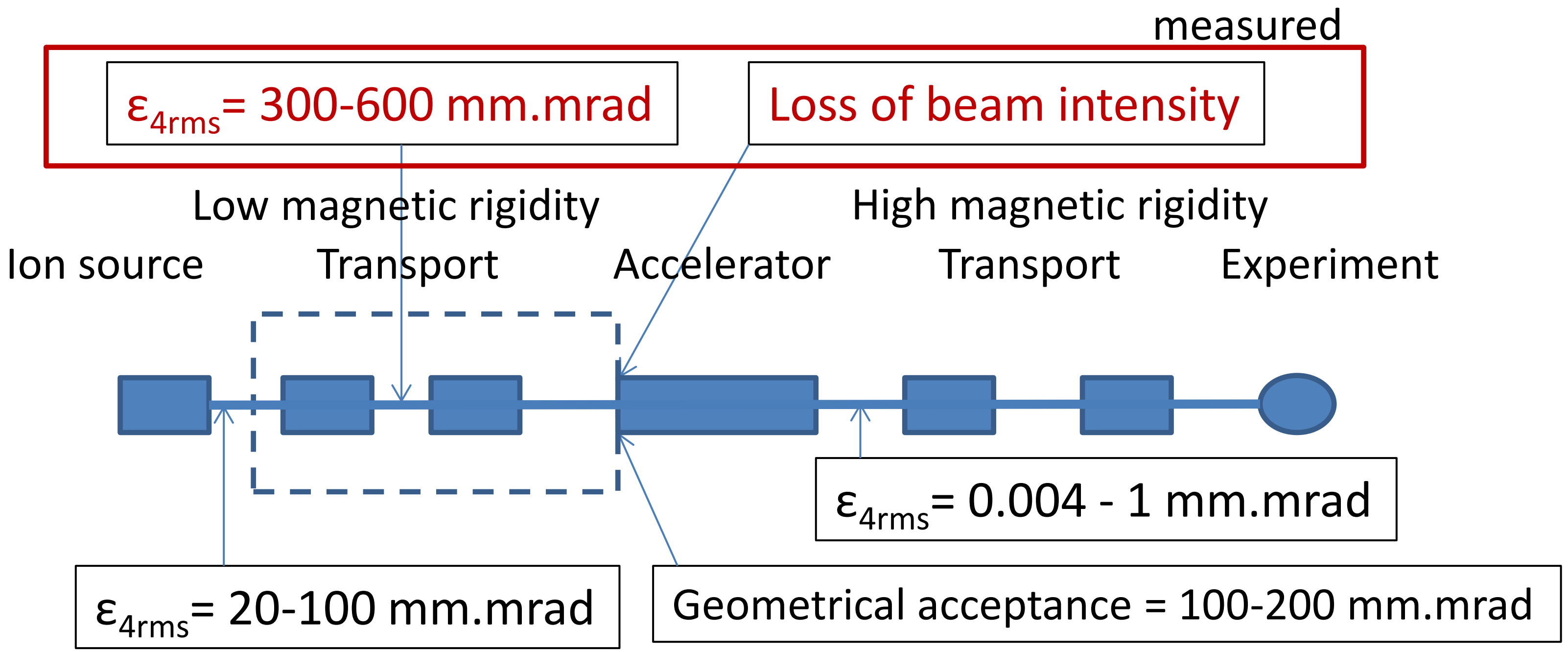
Introduction

Accelerator Laboratories:



Introduction

Accelerator Laboratories:



Challenge: avoid emittance blowup due to:

1. lens aberrations
2. absence of space charge compensation

Introduction

Research emittance growth

- Simulations
  - Particle tracking codes, Raytrace, Track, GPT,

    +: any field configuration. Lorentz3D

    - : slow (equation of motion is calculated for every track)
  - Mapping codes: Transport, GIOS, COSY Infinity 9.1

    +: fast (equation of motion is already in the matrix)

    - : fixed elements.
- Measurements
  - Measurement of emittance
    - Slit grid, Allison scanner:

      - measurement in one plane, integrates over other planes

      + proven technology
    - pepper pot emittance meter:

      + measurement in two planes, cross correlations, slices emittances

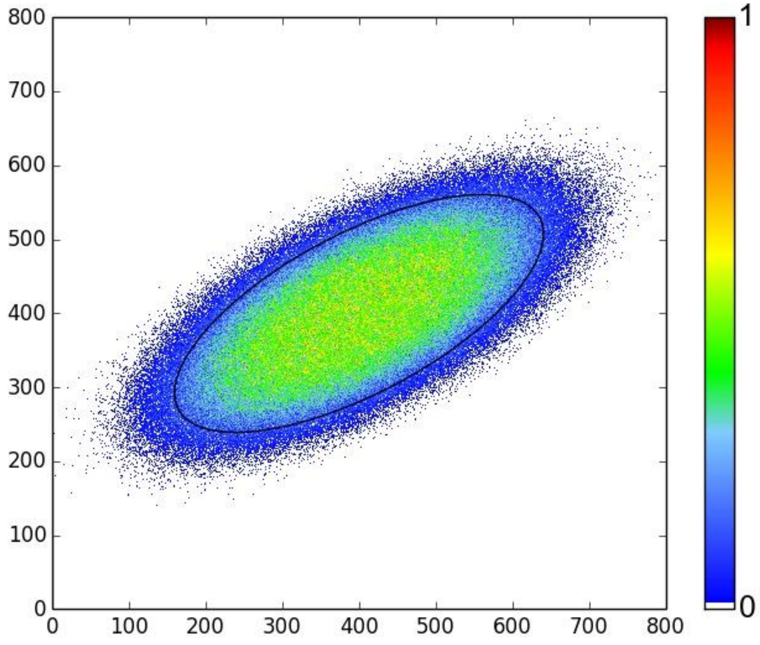
      - Fixed grid

Emittance

university of groningen

kvi - center for advanced radiation technology

Gaussian distribution



$$\sigma_{11} = \iint (x_i - \langle x \rangle)^2 \rho(x, x') dx dx'$$

$$\sigma_{22} = \iint (x'_i - \langle x' \rangle)^2 \rho(x, x') dx dx'$$

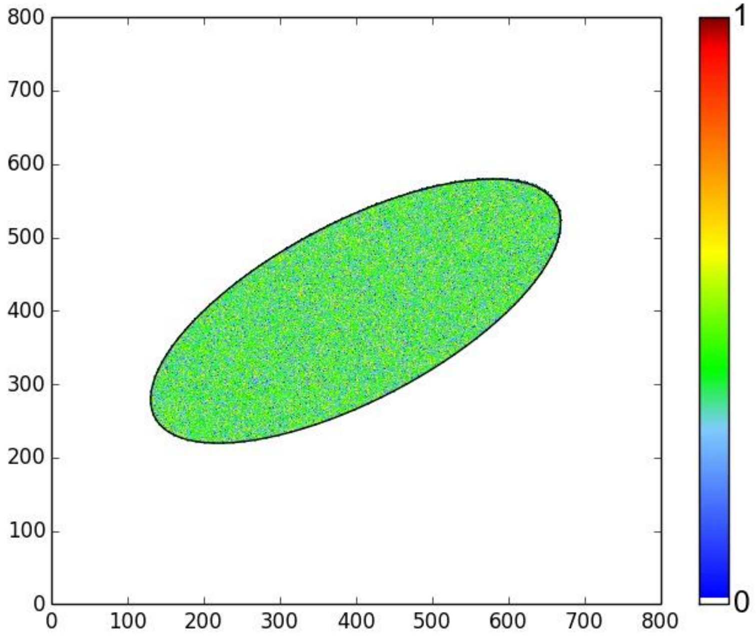
$$\sigma_{12} = \iint (x_i - \langle x \rangle)\,(x'_i - \langle x' \rangle) \rho(x, x') dx dx'$$

$$\varepsilon_{xx'-4rms} = 4 \cdot \sqrt{\sigma_{11}\sigma_{22} - {\sigma_{12}}^2} = \frac{A_{86\%}}{\pi}$$

$$\varepsilon_{xx'-4rms,n} = \varepsilon_{xx'-4rms} \cdot \beta \cdot \gamma$$

Emittance

Gaussian distribution



$$\sigma_{11} = \iint (x_i - \langle x \rangle)^2 \rho(x, x') dx dx'$$

$$\sigma_{22} = \iint (x'_i - \langle x' \rangle)^2 \rho(x, x') dx dx'$$

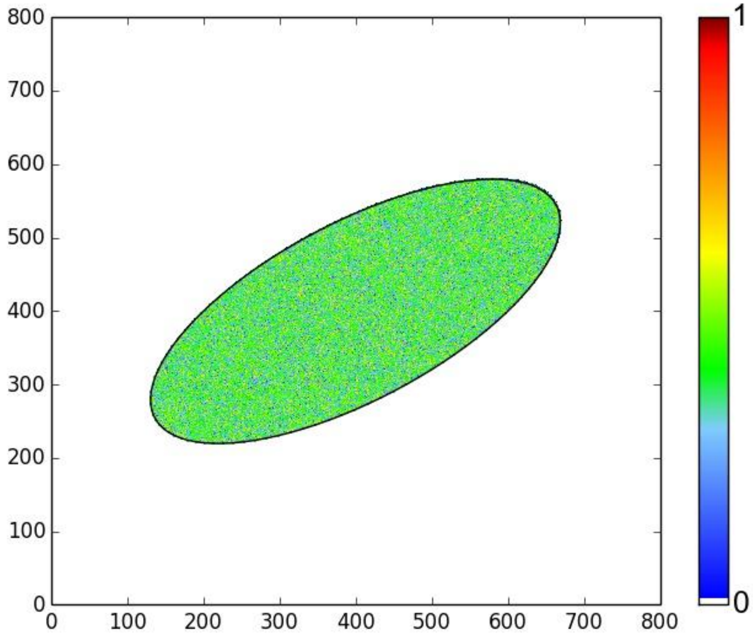
$$\sigma_{12} = \iint (x_i - \langle x \rangle)\,(x'_i - \langle x' \rangle) \rho(x, x') dx dx'$$

$$\varepsilon_{xx'-4rms} = 4 \cdot \sqrt{\sigma_{11}\sigma_{22} - {\sigma_{12}}^2} = \frac{A_{86\%}}{\pi}$$

$$\varepsilon_{xx'-4rms,n} = \varepsilon_{xx'-4rms} \cdot \beta \cdot \gamma$$

Emittance

Gaussian distribution
Uniform distribution



$$\sigma_{11} = \iint (x_i - \langle x \rangle)^2 \rho(x, x') dx dx'$$

$$\sigma_{22} = \iint (x'_i - \langle x' \rangle)^2 \rho(x, x') dx dx'$$

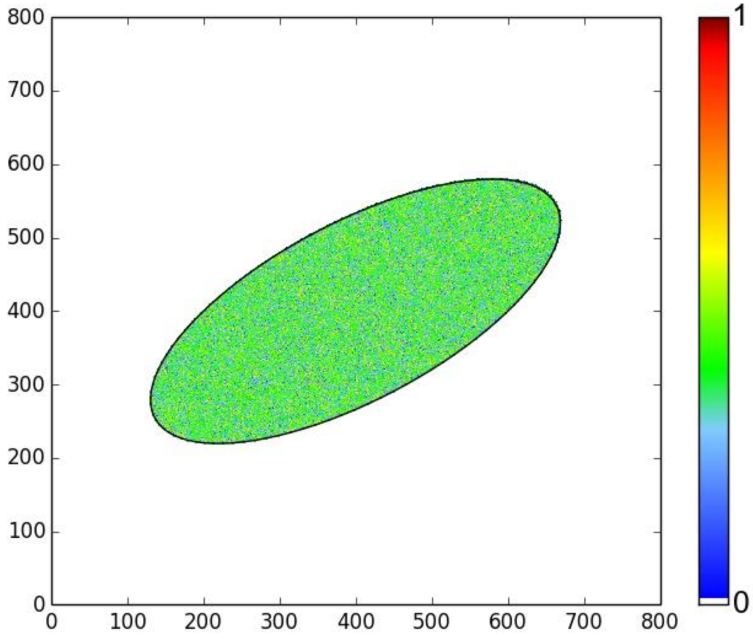
$$\sigma_{12} = \iint (x_i - \langle x \rangle)\,(x'_i - \langle x' \rangle) \rho(x, x') dx dx'$$

$$\varepsilon_{xx'-4rms} = 4 \cdot \sqrt{\sigma_{11}\sigma_{22} - {\sigma_{12}}^2} = \frac{A_{86\%}}{\pi}$$

$$\varepsilon_{xx'-4rms,n} = \varepsilon_{xx'-4rms} \cdot \beta \cdot \gamma$$

Emittance

Uniform distribution
Gaussian distribution



$$\sigma_{11} = \iint (x_i - \langle x \rangle)^2 \rho(x, x') dx dx'$$

$$\sigma_{22} = \iint (x'_i - \langle x' \rangle)^2 \rho(x, x') dx dx'$$

$$\sigma_{12} = \iint (x_i - \langle x \rangle)\,(x'_i - \langle x' \rangle) \rho(x, x') dx dx'$$

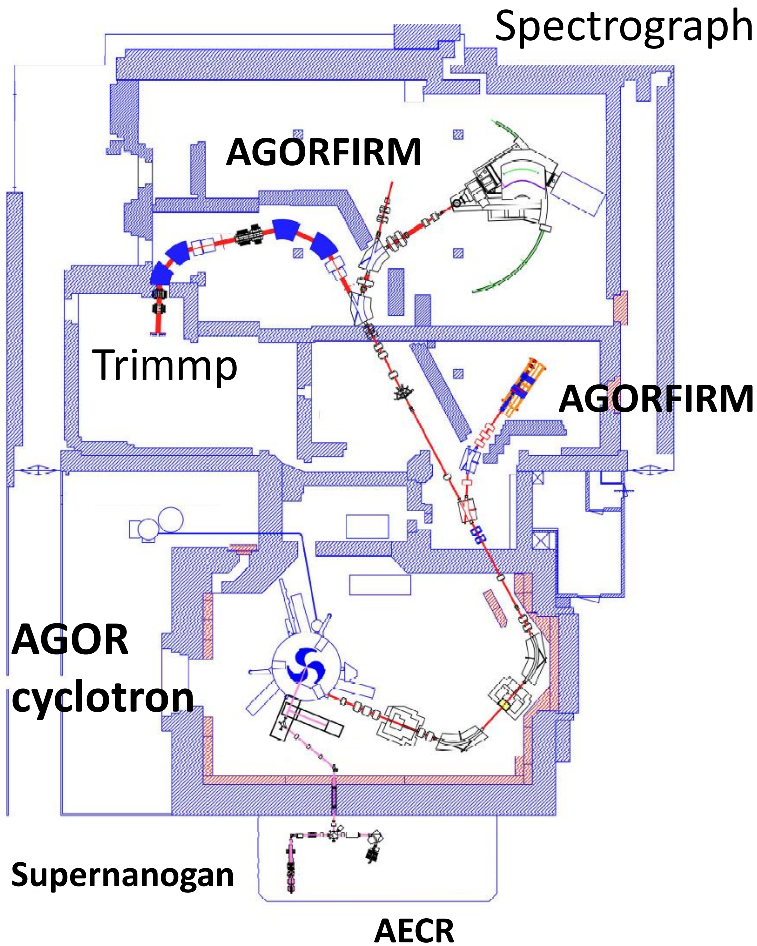
$$\boldsymbol{\varepsilon_{xx'-4rms} = 4 \cdot \sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}{}^2} = \frac{A_{80\%}}{\pi}}$$

$$\boldsymbol{\varepsilon_{xx'-4rms} = 4 \cdot \sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}{}^2} = \frac{A_{100\%}}{\pi}}$$

$$\varepsilon_{xx'-4rms,n} = \varepsilon_{xx'-4rms} \cdot \beta \cdot \gamma$$

KVI-CART facility layout

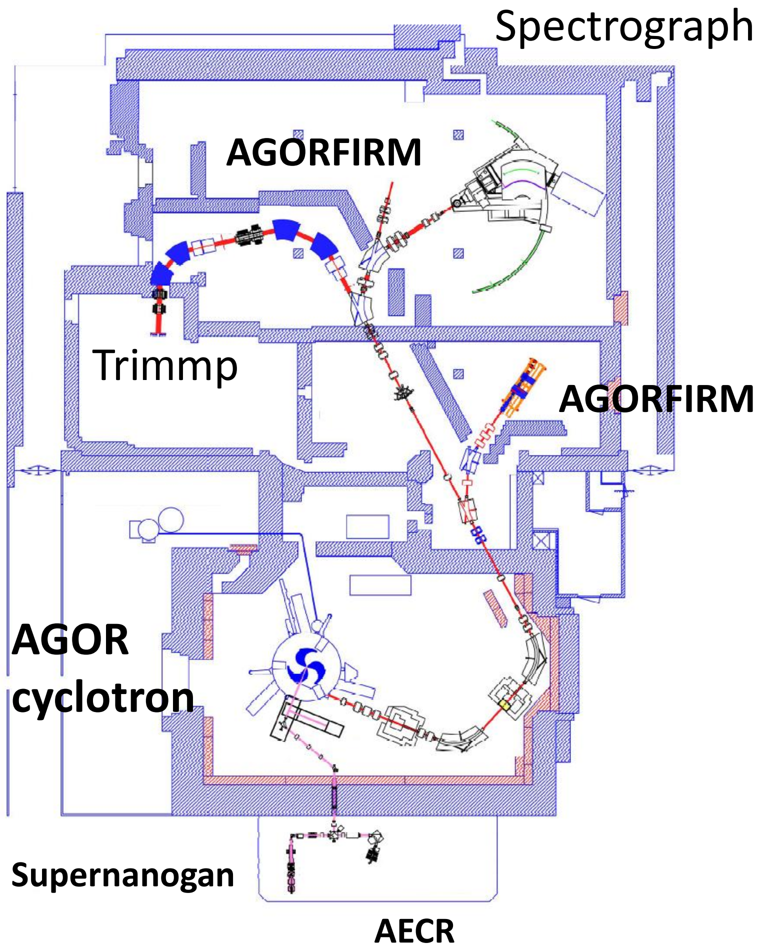
- Top view experimental hall



KVI-CART facility layout

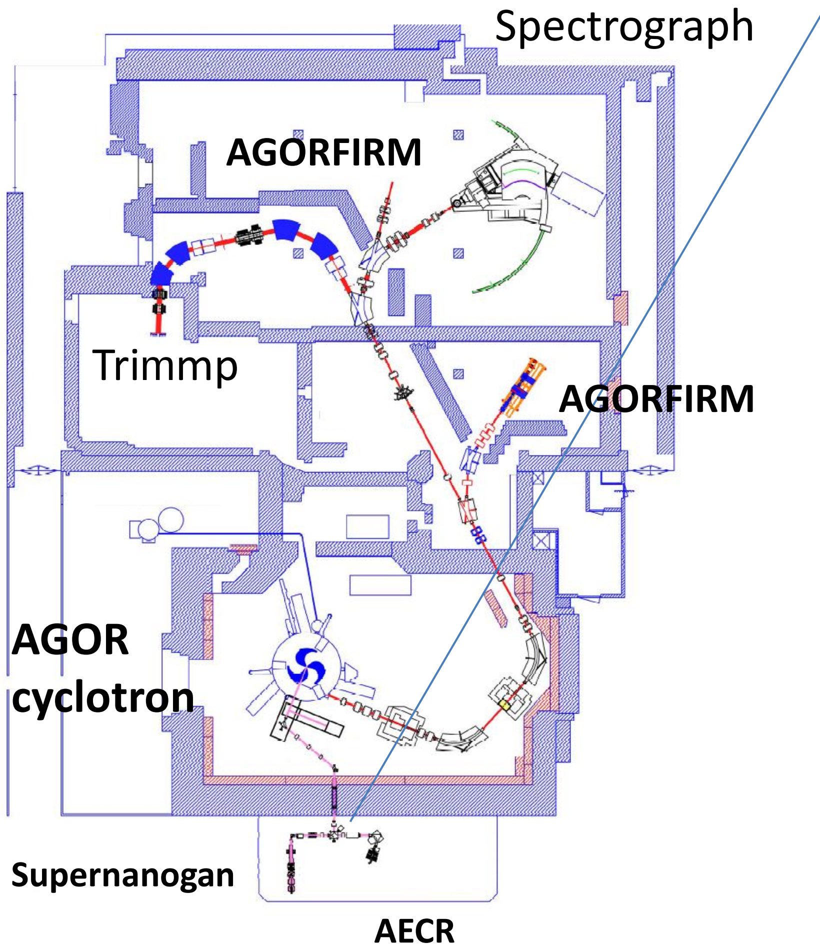
university of groningen / kvi - center for advanced radiation technology

- Top view experimental hall



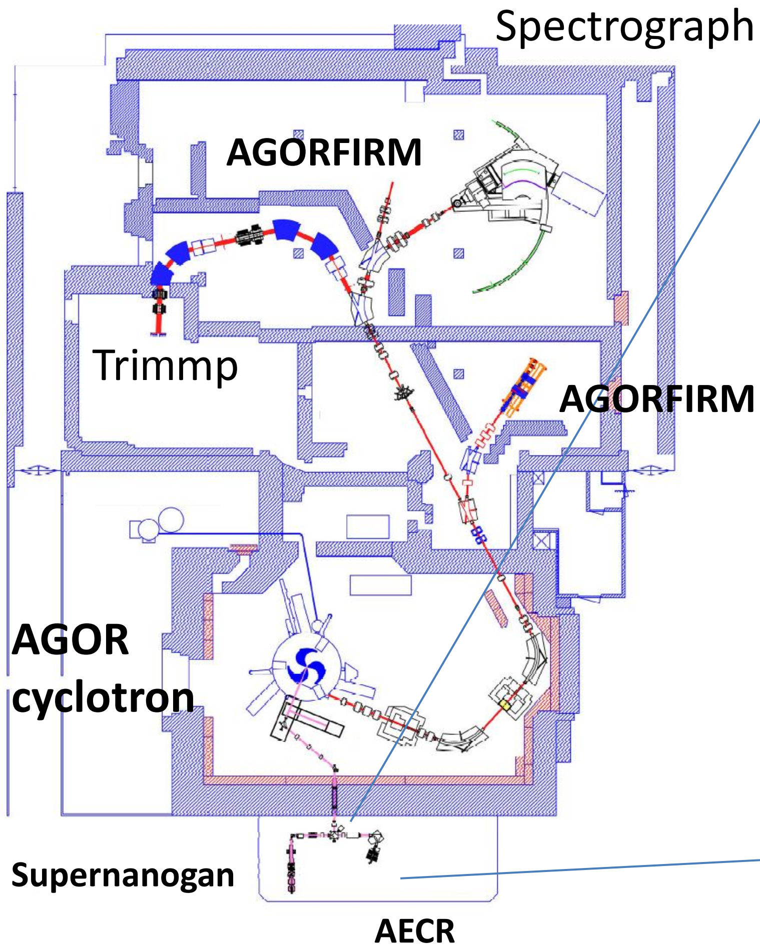
KVI-CART facility layout

- Top view experimental hall



KVI-CART facility layout

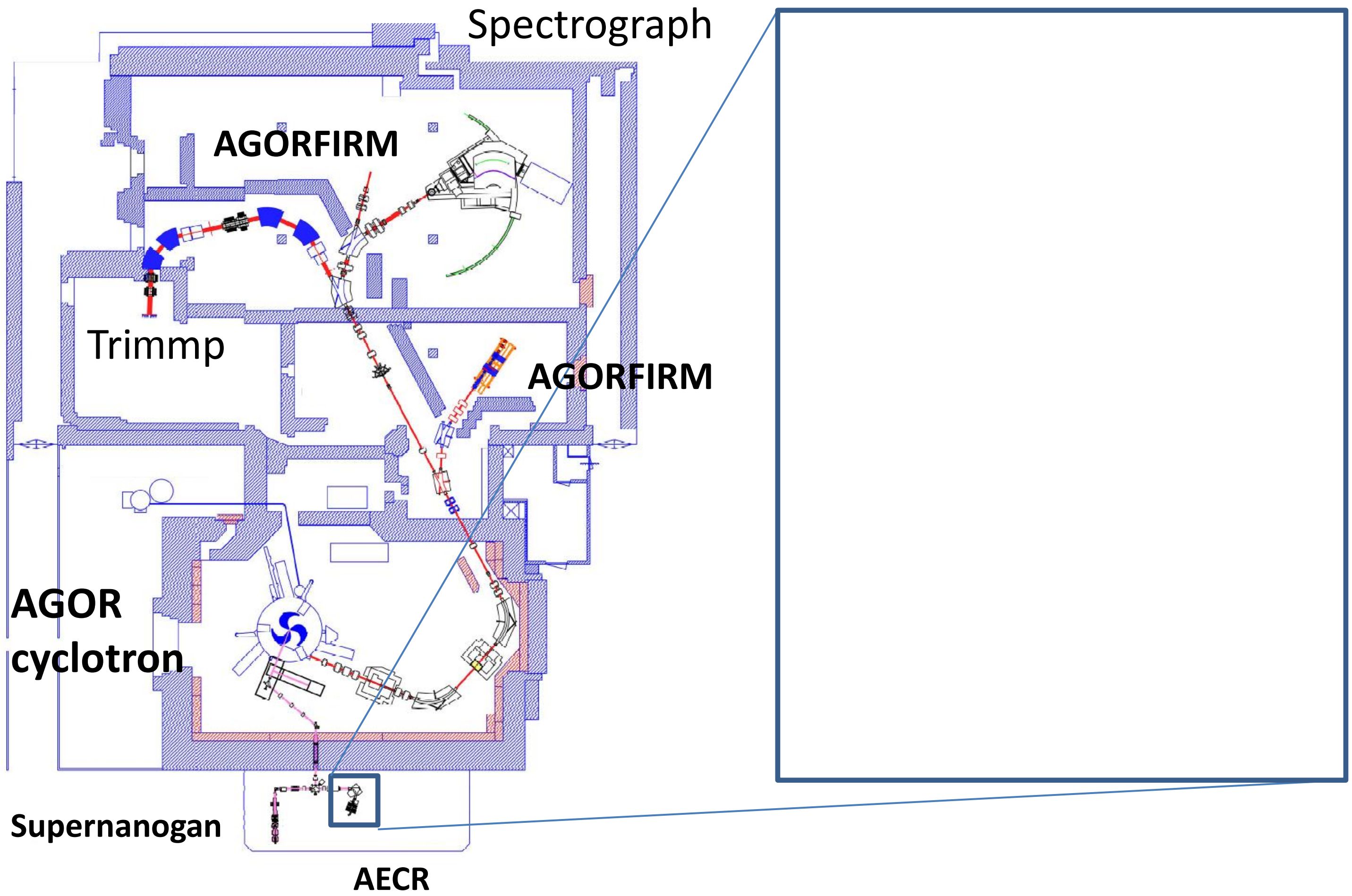
- Top view experimental hall



KVI-CART facility layout

university of groningen
kvi - center for advanced radiation technology

- Top view experimental hall

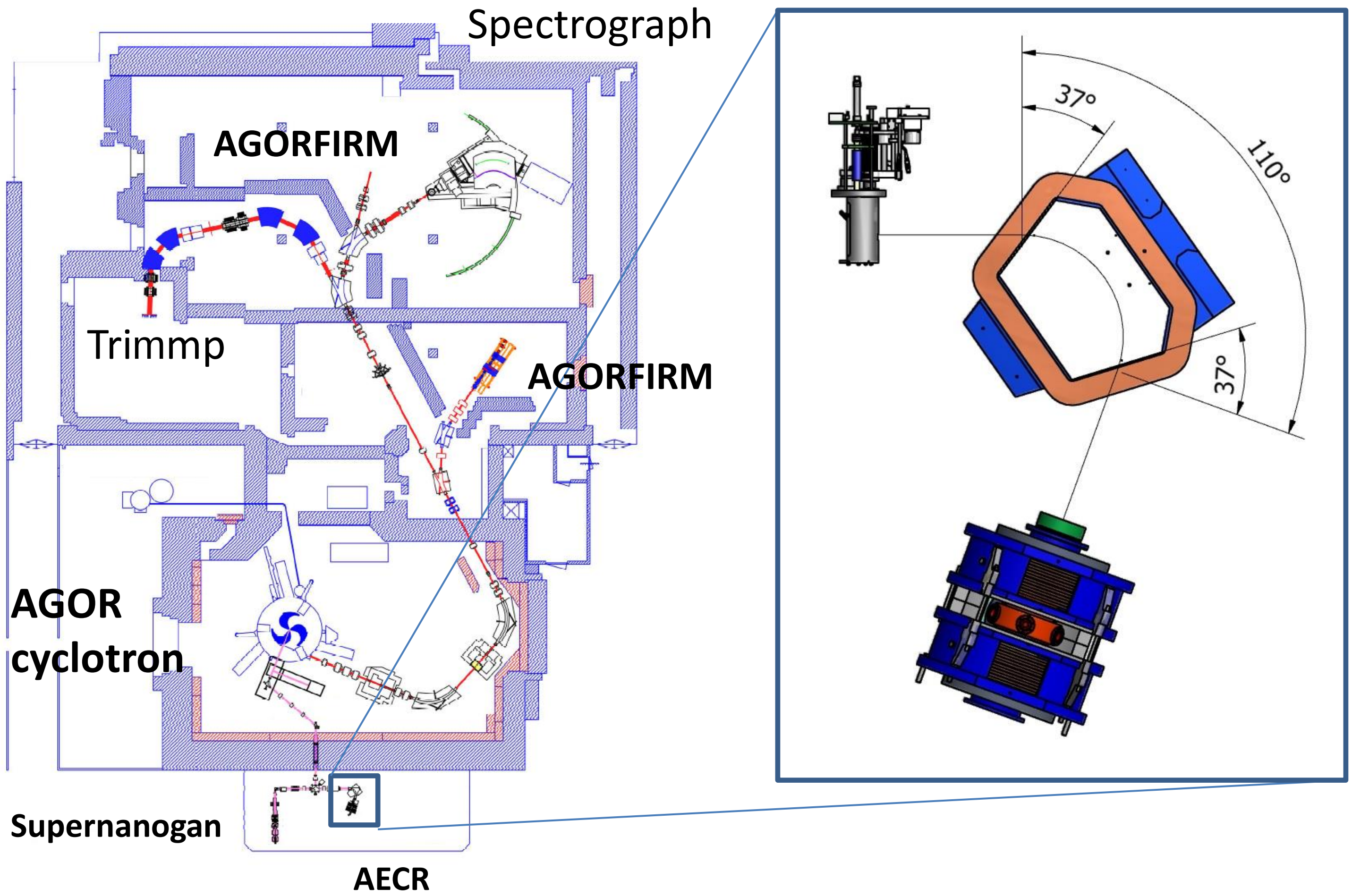


KVI-CART facility layout

university of groningen

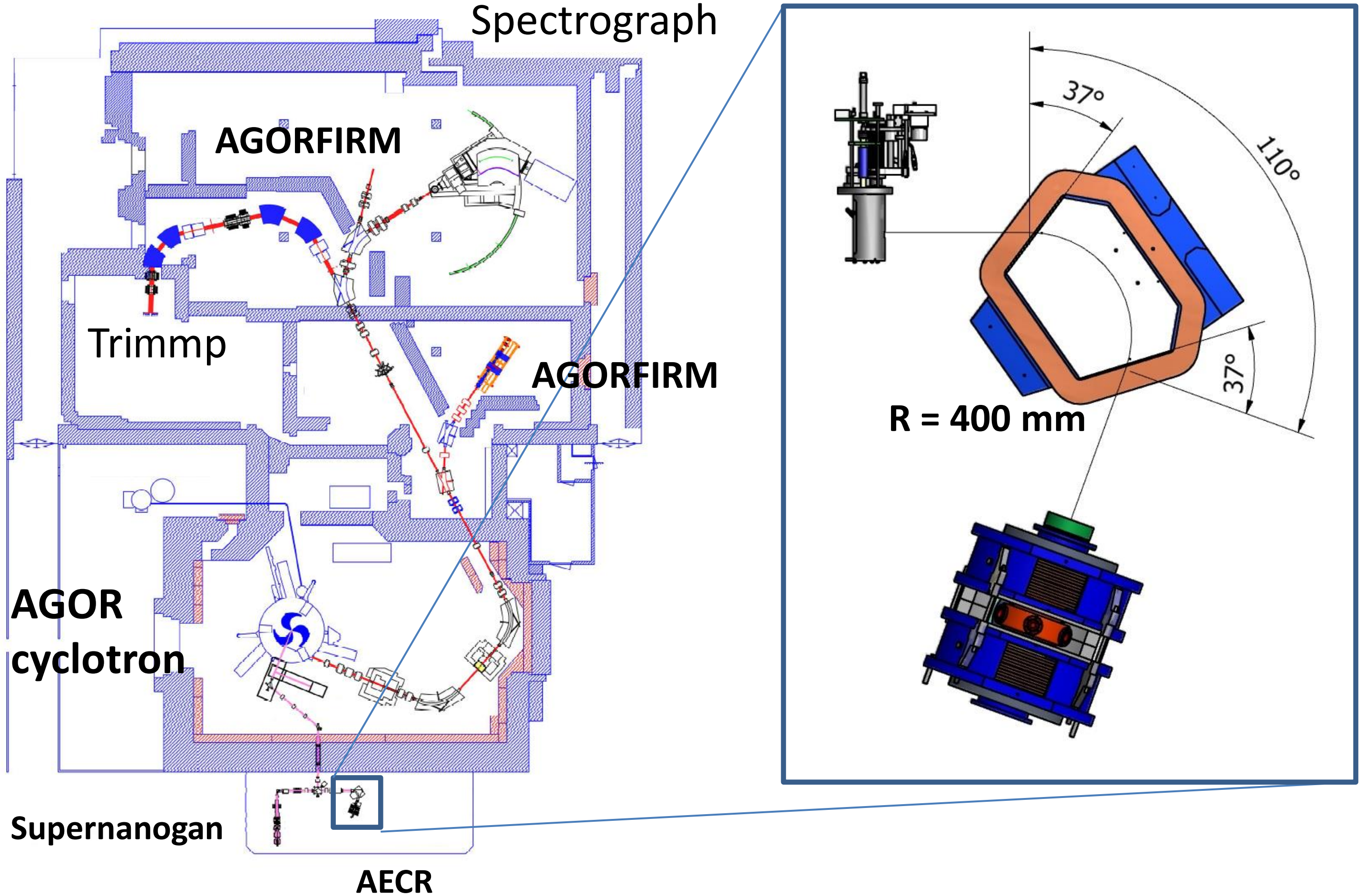
kvi - center for advanced radiation technology

- Top view experimental hall



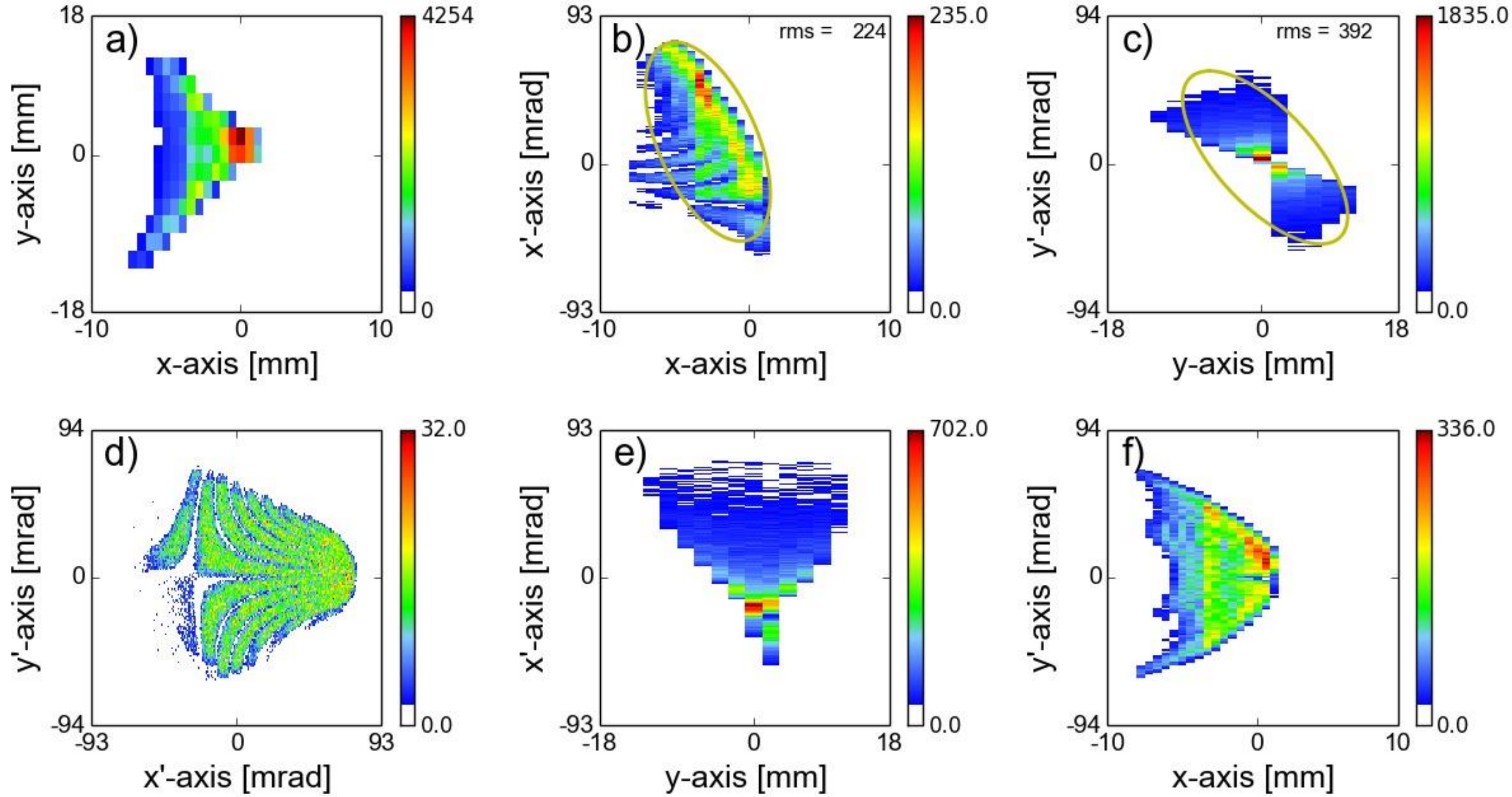
KVI-CART facility layout

- Top view experimental hall



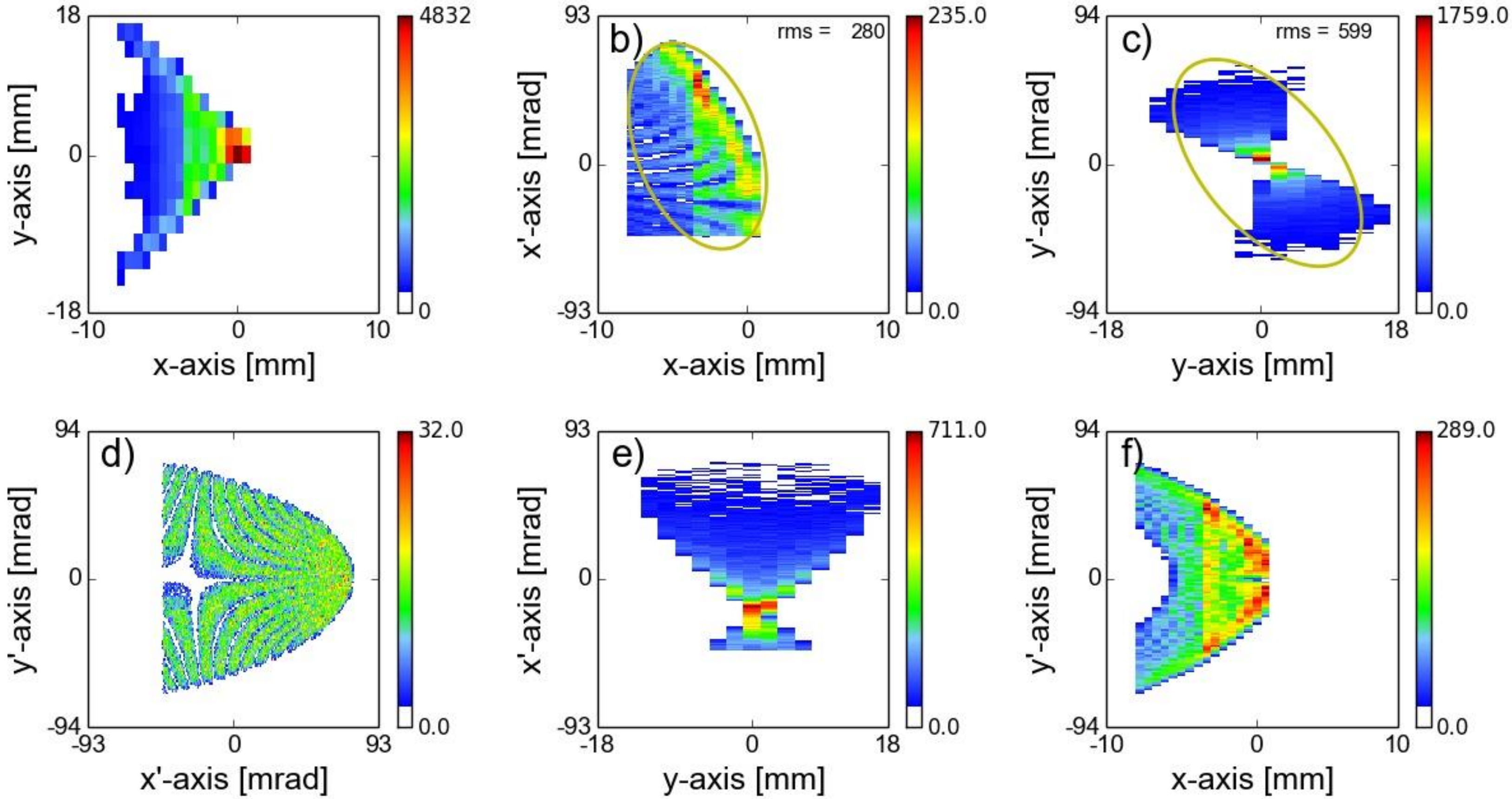
Measured and simulated

- Simulated phase-space projections of a 25 kV He^{1+} validated by measurements



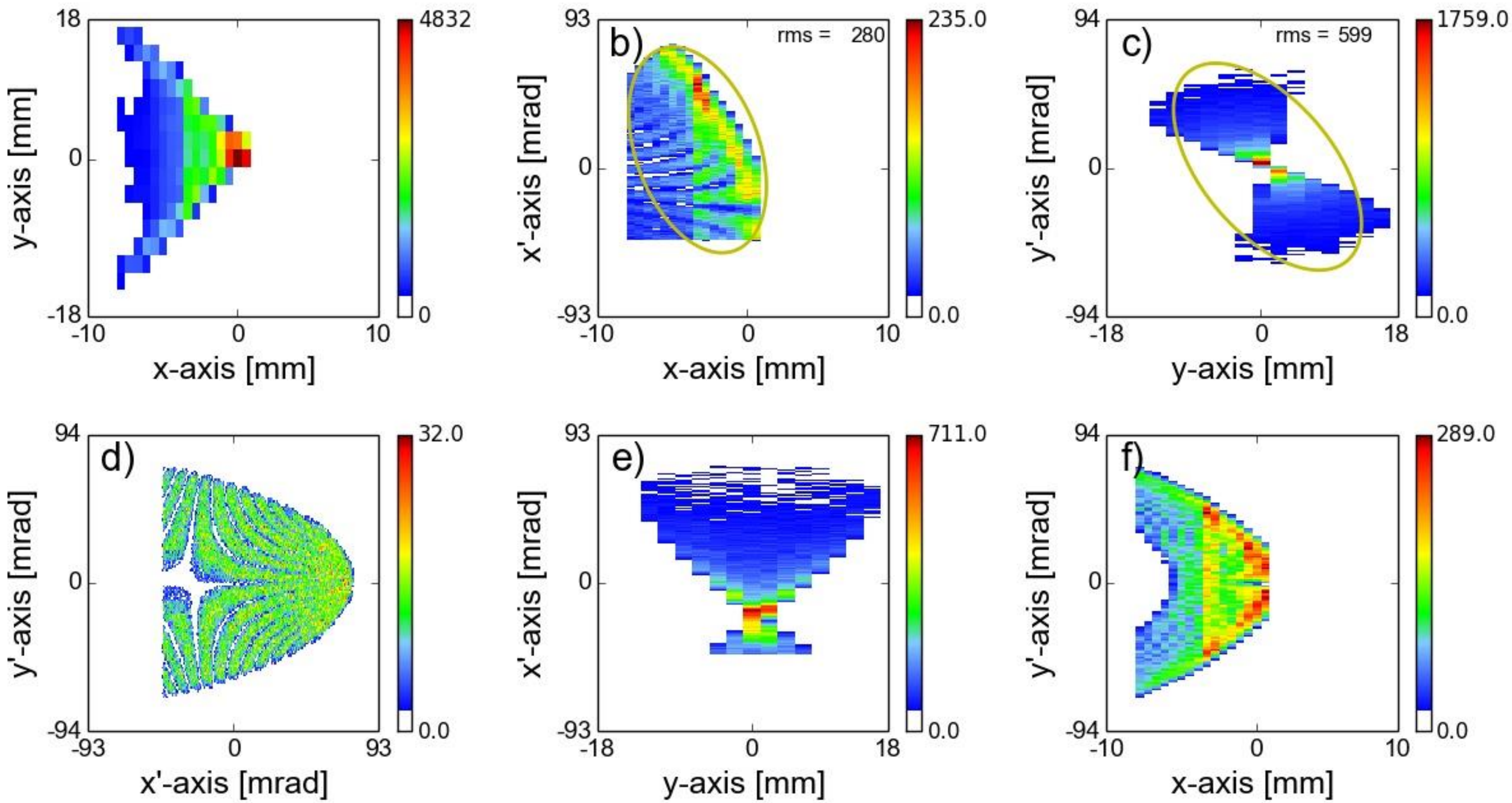
Measured and simulated

- Simulated phase-space projections of a 25 kV He^{1+} validated by measurements

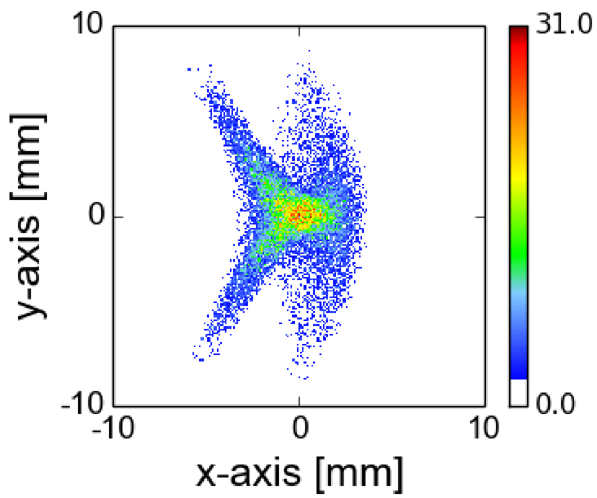


Measured and simulated

- **Simulated phase-space projections of a 25 kV He^{1+} with phase space cutoffs** validated by measurements



- Conclusion:
  - Higher order components (y|x'y') , (x|y'y') and (x|x'x') identified
  - Strengths : 5.3, - 2.4 and -0.9 respectively.
  - Ion displacement in image plane due to aberrations are 26, 12 and 5 times larger than first order imaging. Image = aberration

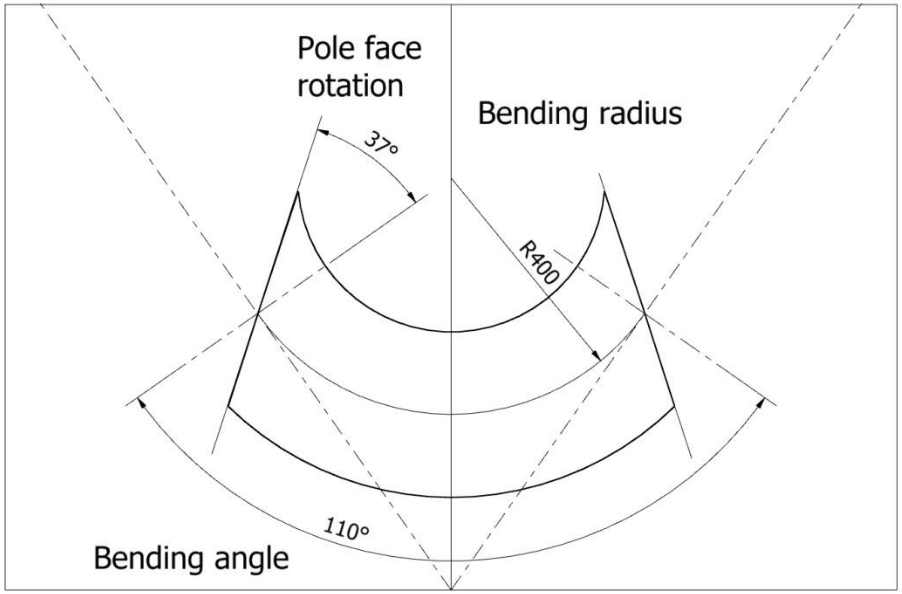


25 kV He^{1+} with phase-space cutoffs

- How to fix the aberrations

- Method to calculate the emittance growth

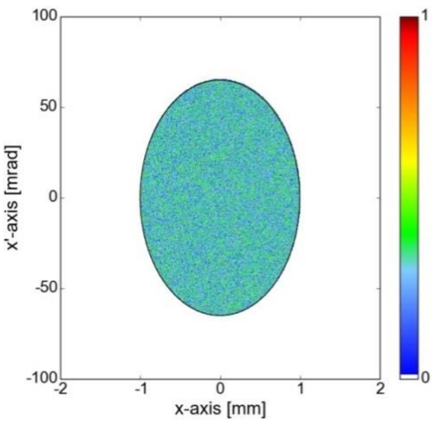
- Apply this method to:
  - Add sextupoles
    - sextupoles
  - Add field lenses
    - Solenoid
    - Einzel lens

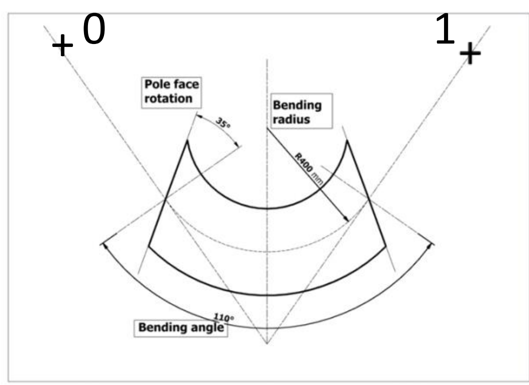


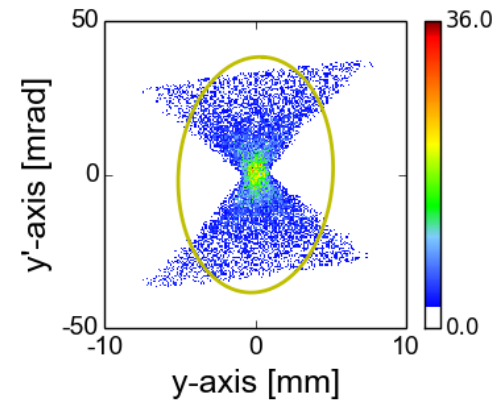
Optimization of low-energy beam transport.

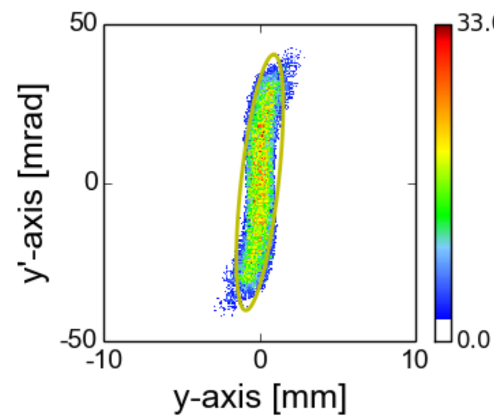
Method to calculate the 4-rms emittance growth

X_0 $X_1 = M^{(k)} \cdot X_0$ X_1









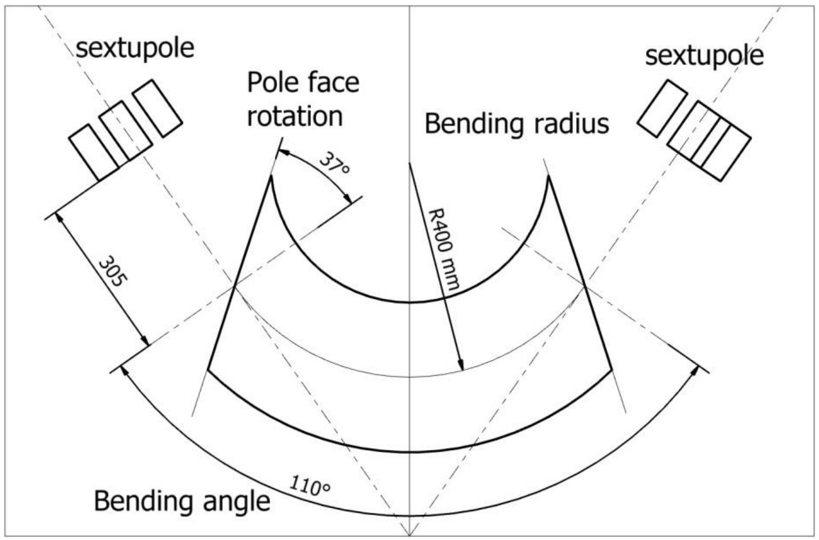
4rms = 65 mm.mrad

Area = 65.p mm.mrad

No difference with or without ion distribution in extraction aperture

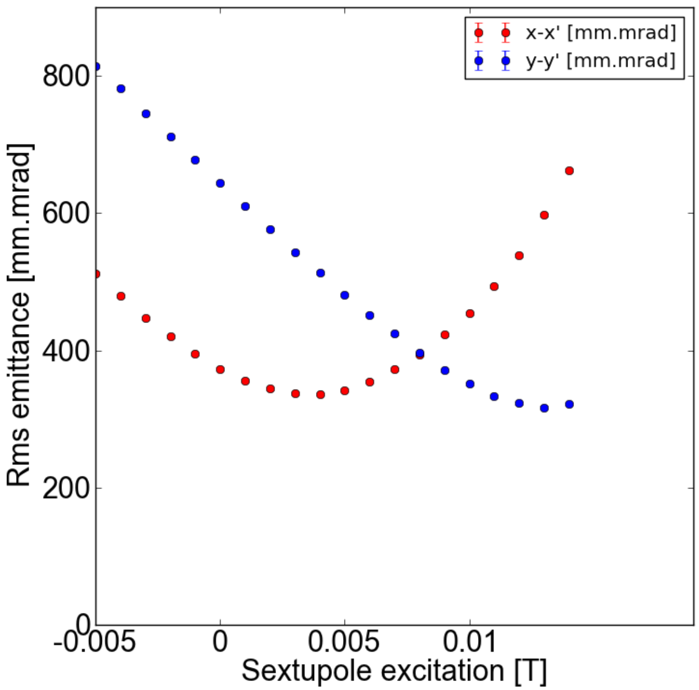
Dipole with an additional two Sextupoles

- Top view analyzing magnet



4RMS emittance 21 H^{1+}

as function sextupole excitation



(y|x'y')	(x|y'y')	(x|x'x')	
5.3	-2.4	-0.9	aberrations dipole
-5.3	+2.7	-2.7	compensation sextupoles 0.013T
0	+0.3	-3.6	dipole corrected with sextupoles

- **Compensation by sextupoles** and small pole face adjustement

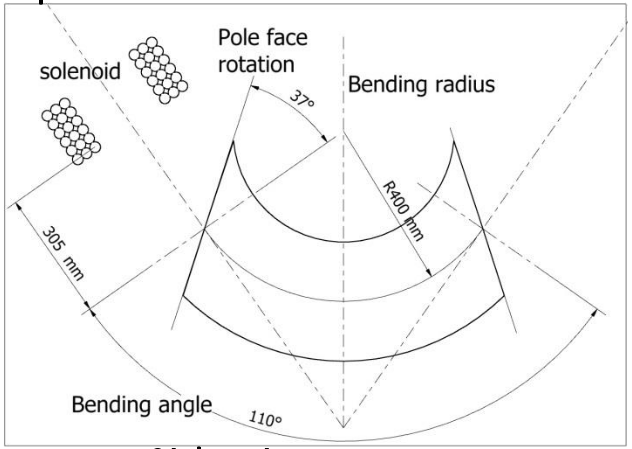
$\Theta_1 = x_1$	%	$\Theta_1 = x'_1$	%	$\Theta_1 = y_1$	%	$\Theta_1 = y'_1$	%	ID coeff
1.01E+00	100	2.19E+00	3					$(\theta\|x)$
-3.74E-08	0	9.94E-01	100					$(\theta\|x')$
				-1.01	100	-1.26	2	$(\theta\|y)$
				-3.36E-10	0	-0.99	100	$(\theta\|y')$
-3.011	1226							$(\theta\|x'^2)$
-15.615	407							$(\theta\|x'^3)$
36.2	944							$(\theta\|x'y'^2)$
				-36.3	943			$(\theta\|x'^2y')$
				-34.4	893			$(\theta\|y'^3)$
-173	289							$(\theta\|x'^2y'^2)$
-155	260							$(\theta\|y'^4)$
				119	197			$(\theta\|x'^3y')$
				629	1044			$(\theta\|x'y'^3)$
1857	198							$(\theta\|x'y'^4)$
				-3191	339			$(\theta\|x'^2y'^3)$
				-1669	177			$(\theta\|y'^5)$

Conclusion:

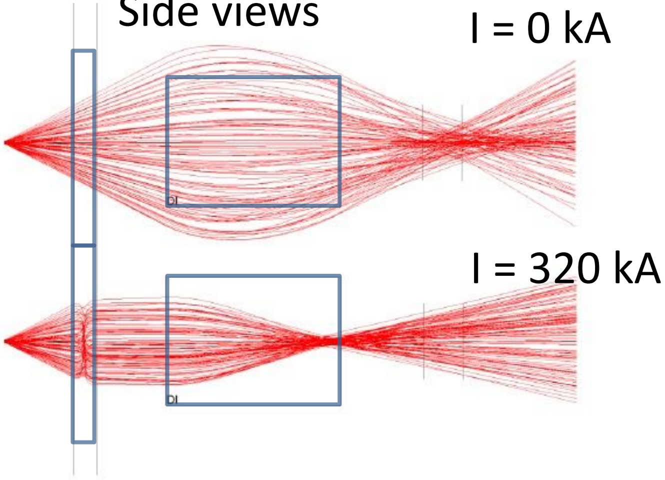
1. Yes, second order is partially compensated. However large higher order terms.

Dipole with an additional solenoid

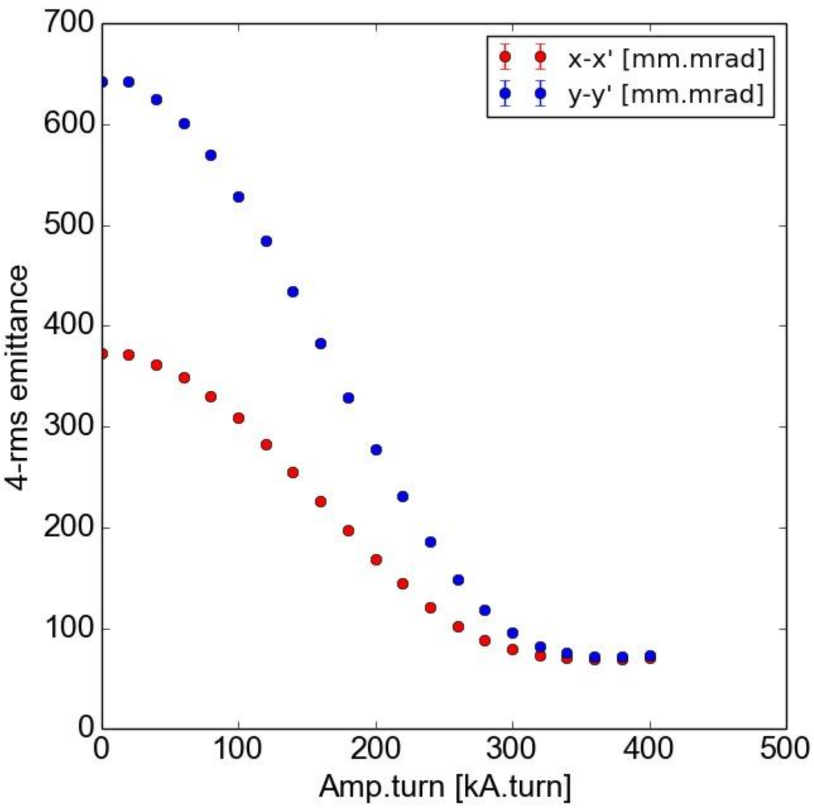
- Top view



Side views

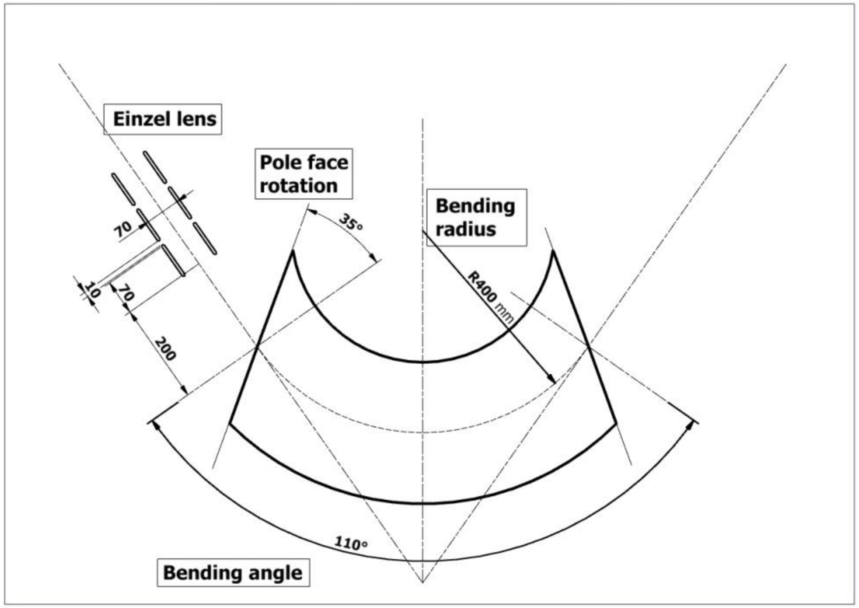


21 kV H^{1+}



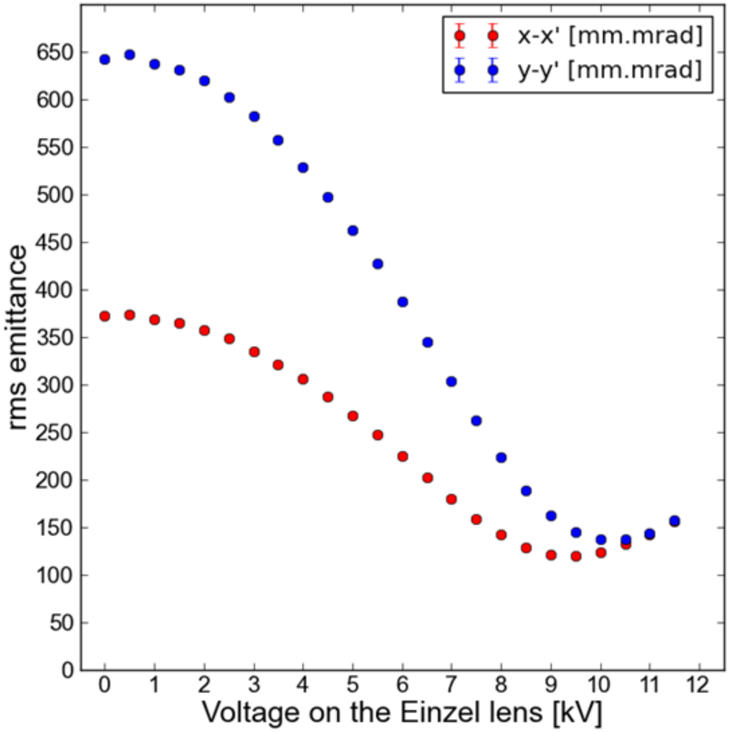
Dipole with additional einzel-lens

- Top view analyzing magnet



4RMS emittance 21 kV H^{1+}

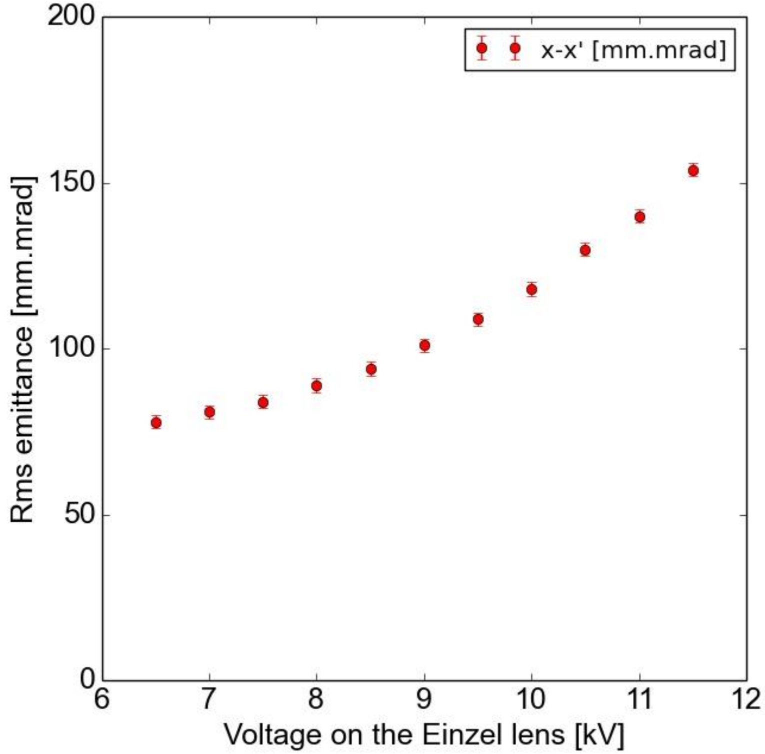
as a function of the Einzel lens potential



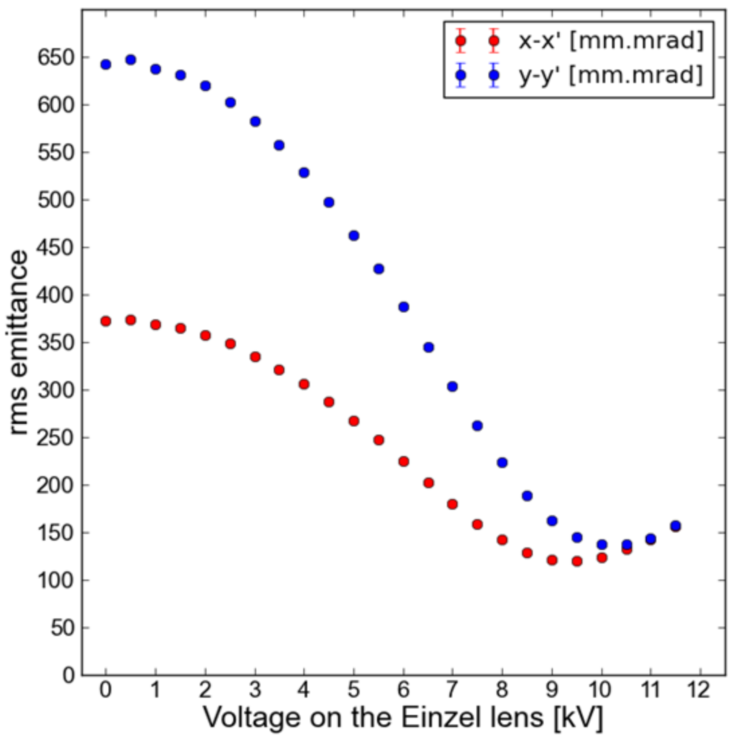
Optimization of low-energy beam transport.

Detail : In the image plane of the dipole remnant 4-rms emittance generated by the einzel lens.

4-rms emittance growth
due to einzel lens , 21 kV H^{1+}



4-rms emittance in image plane dipole of a 21 kV H^{1+} beam



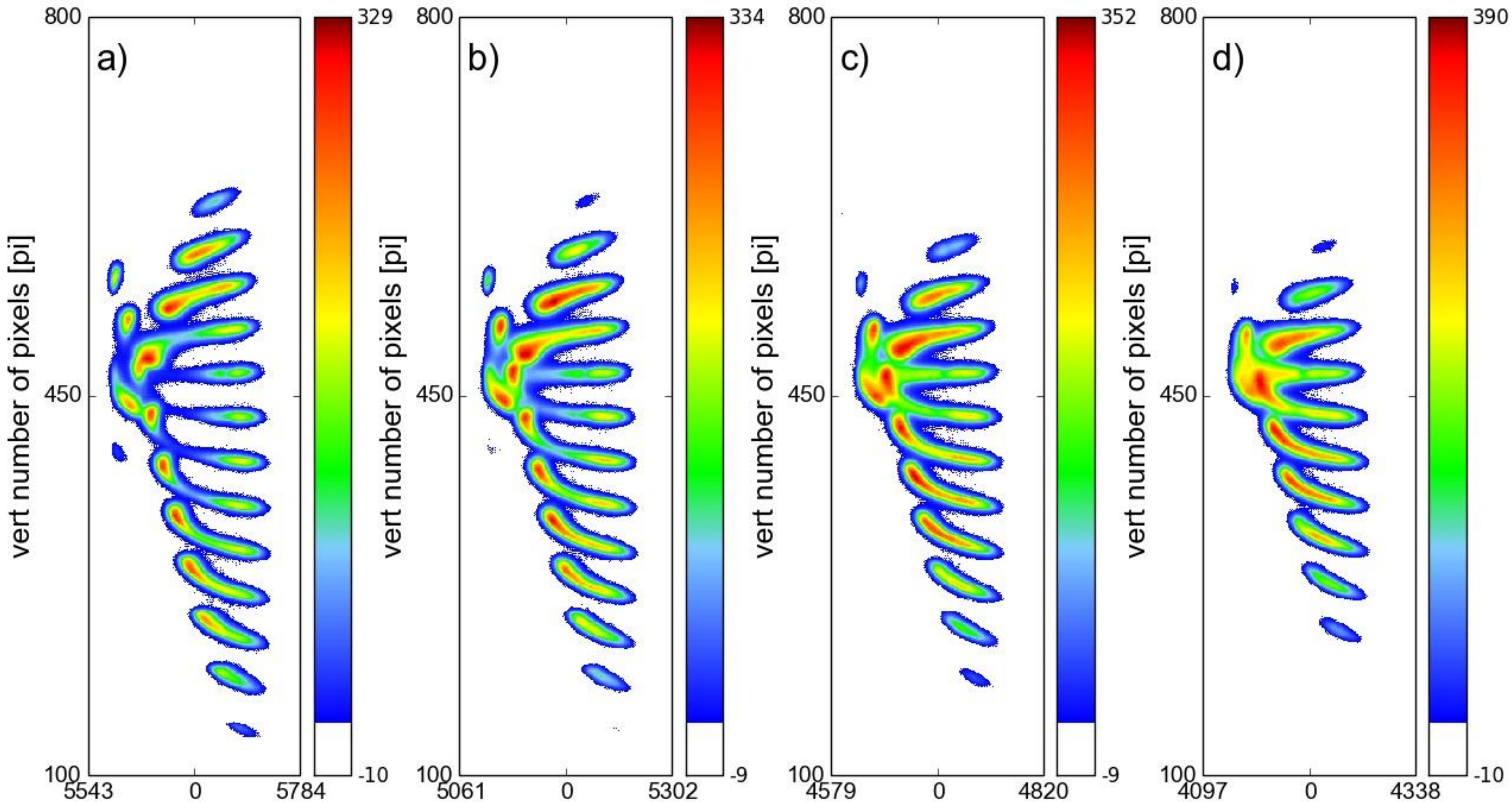
Conclusions:

1) Solenoid option is the best option. However 500 kA.Turn is difficult to integrate in existing setup.
2) Einzel lens reduces the emittance growth roughly with factor of 3 in both planes.
3) Diameter of the Einzel lens should be larger than 70 mm diameter.
4) Design strategy for a low energy beam-lines to accept beams with large divergence:
    1) First, reduce the fringe fields as much as possible and included additional correction.
    2) Secondly, calculate which coefficients causes the aberrations and change the phase-space upstream such that the effect of fringe fields on the beam phase-space is minimized.

- Thank you for your attention

Measured

- Measurements 25 kV He^{1+} beam



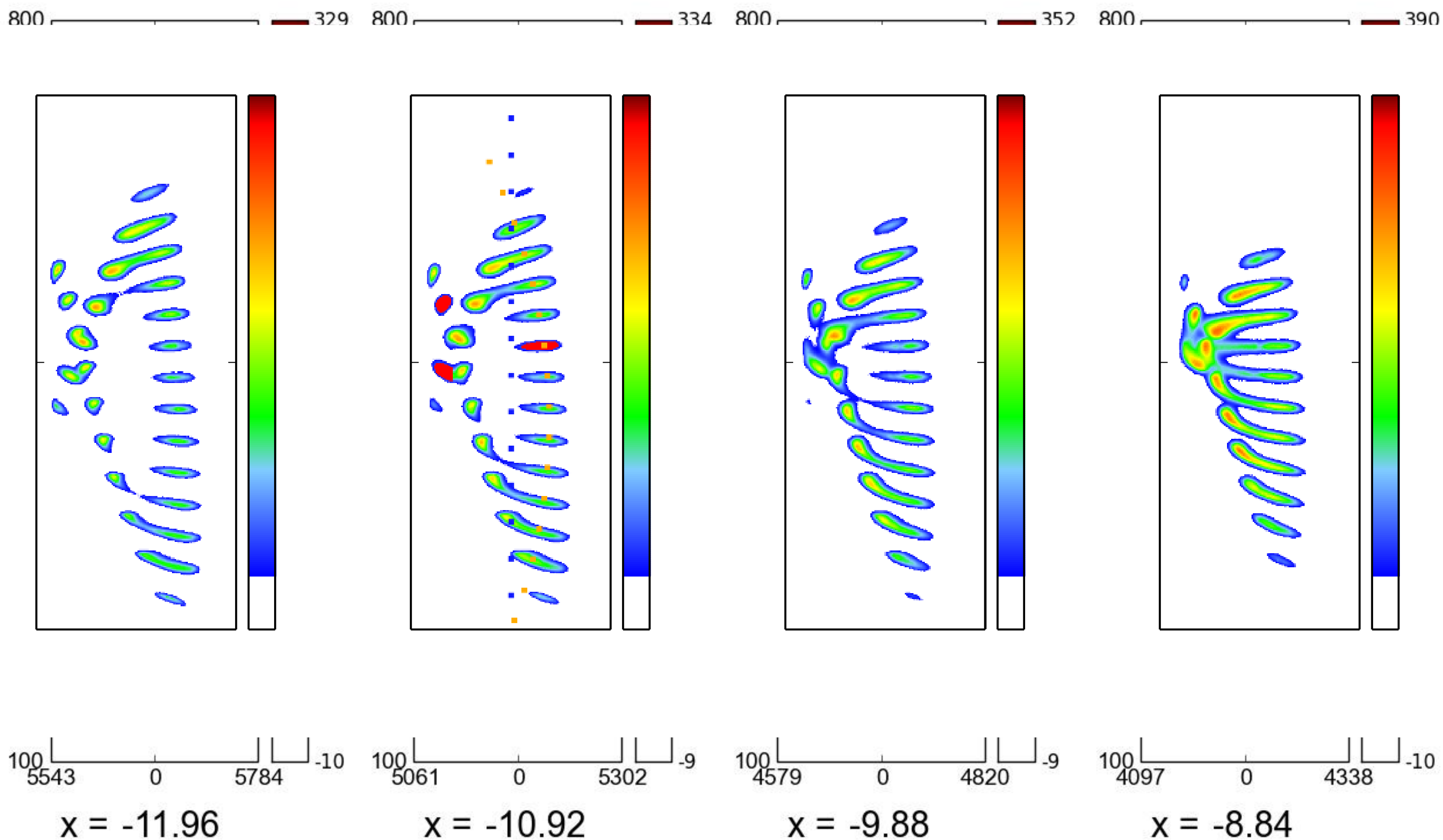
x = -11.96   x = -10.92   x = -9.88   x = -8.84

Measured

university of groningen

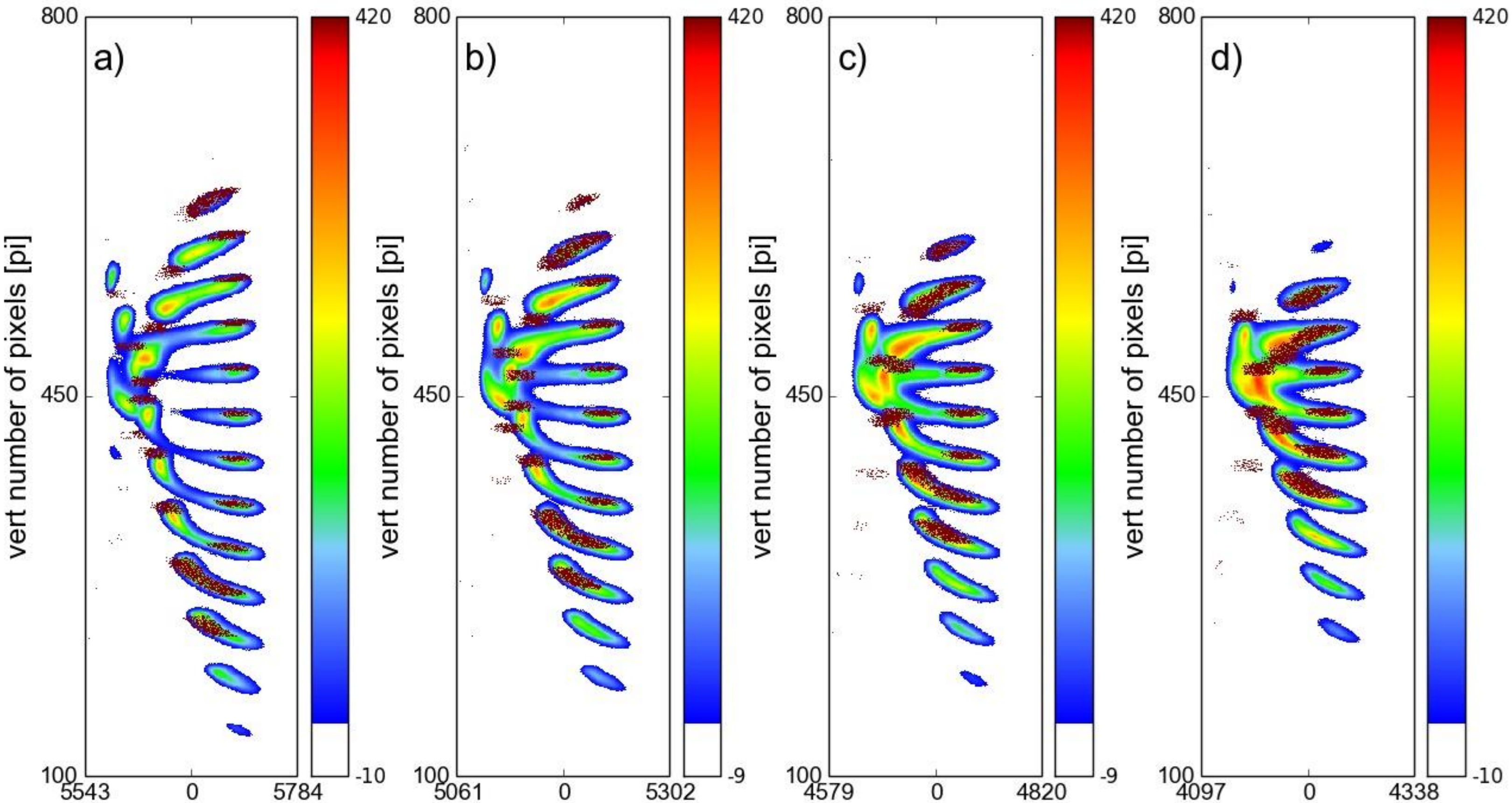
kvi - center for advanced radiation technology

- Measurements 25 kV He^{1+} beam



Measured

- Measurements 25 kV He^{1+} beam

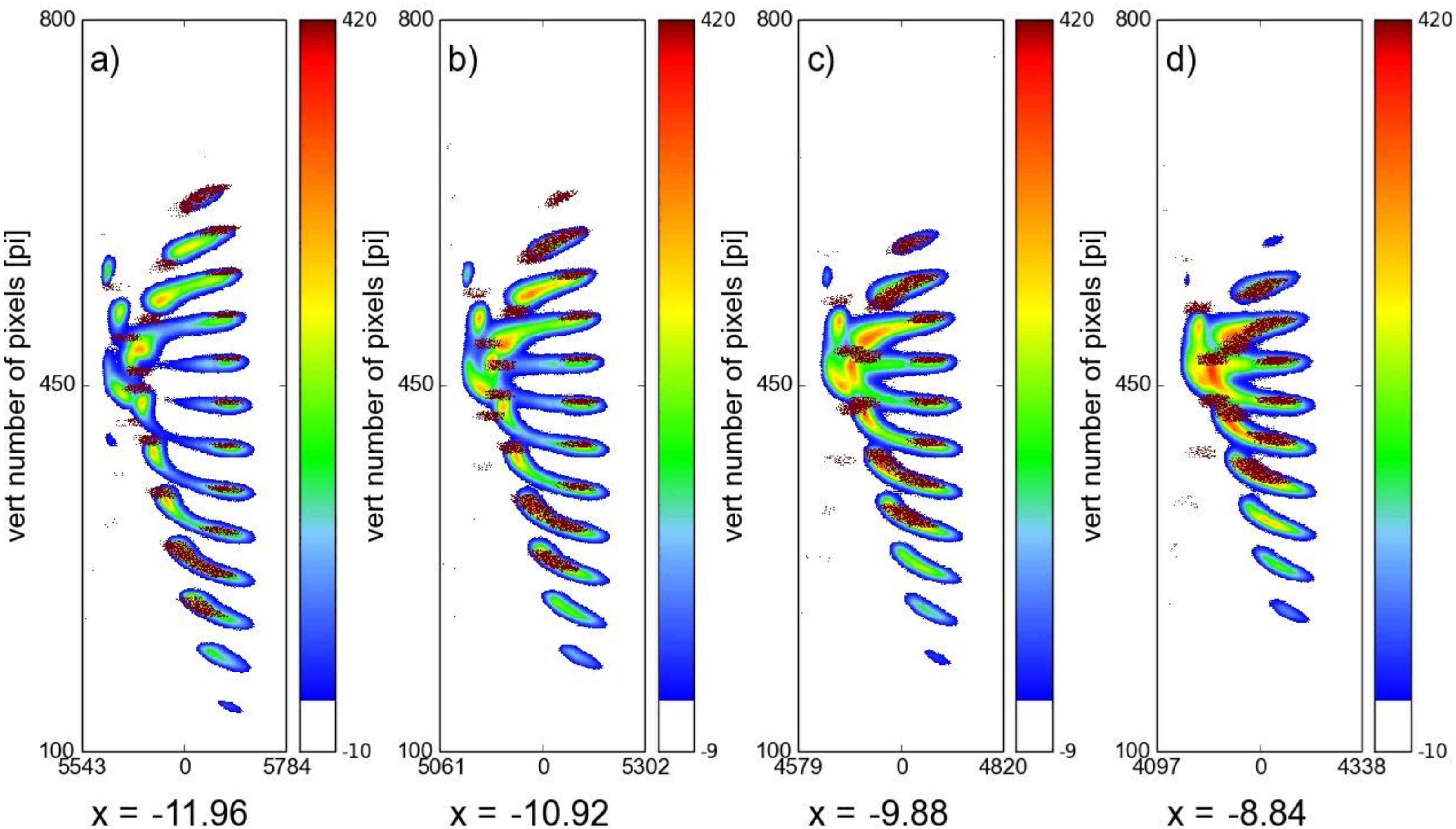


x = -11.96 x = -10.92 x = -9.88 x = -8.84

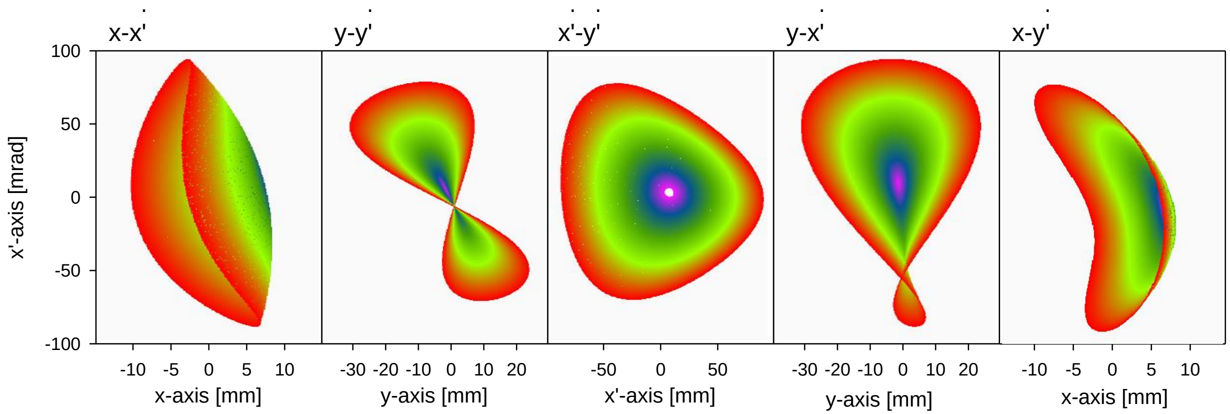
Measured

- Measurements combined with simulations of a 25 kV He^{1+} beam

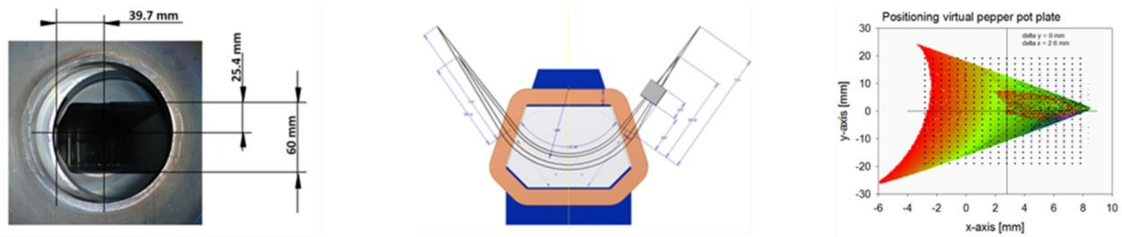
Measurements 25 kV He^{1+} beam



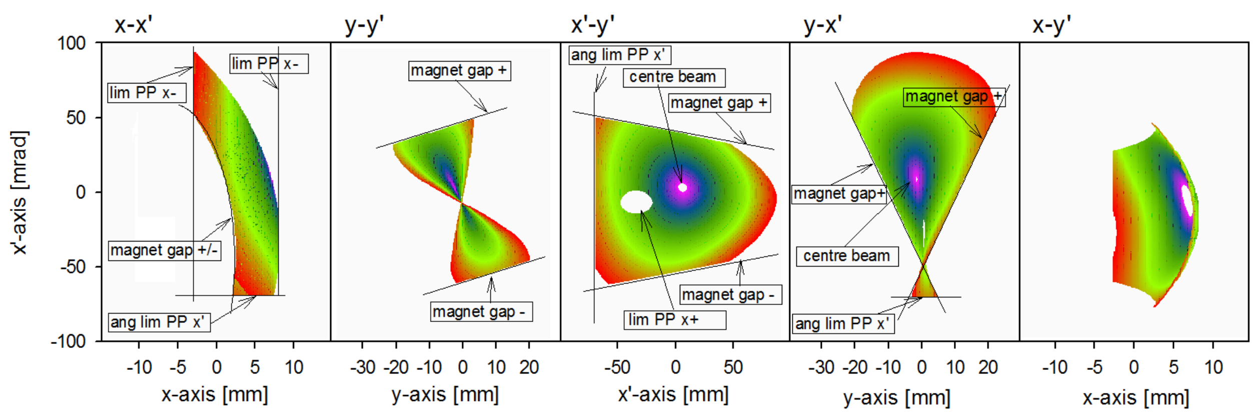
Simulated influence of limiters on projections



Complete beam



The limitations



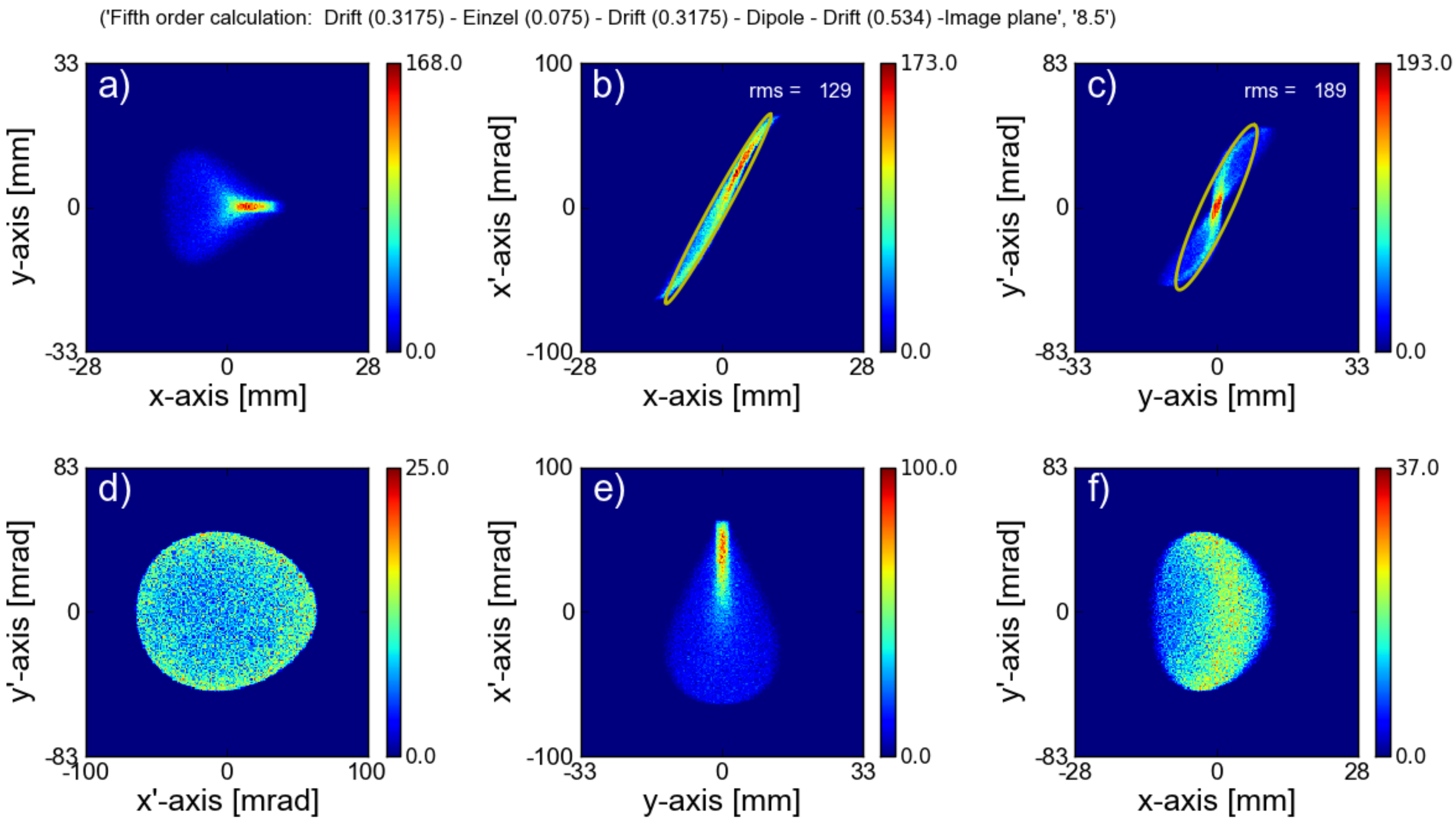
Effects on projections

Optimization of low-energy beam transport.

university of groningen

kvi - center for advanced radiation technology

Result in phase-space of the Einzel lens



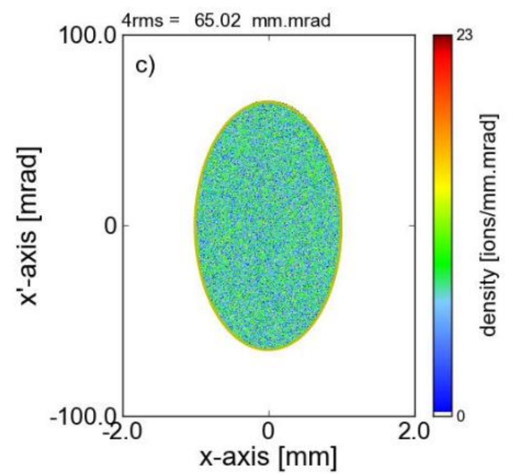
Simulated

- Theoretical model of the setup $X_1 = M_T \, . \, X_0$

Transfer matrix: M_t

x_1	%	x'_1	%	y_1	%	y'_1	%	$(x,x',y,y',\delta,l)_0$
0.82648	24	2.26816	5.8	0	0	0	0	100000
1.668E-06	0	1.20995	108	0	0	0	0	010000
0	0	0	0	-0.85078	9.2	-1.258137	3.8	001000
0	0	0	0	9.100E-02	35	-1.040819	110	000100
-1.3220	0	-0.84624	0	0	0	0	0	200000
-2.0211	-2	-1.6758	0.1	0	0	0	0	110000
-0.94047	33	-1.1015	3.4	0	0	0	0	020000
0	0	0	0	1.96766	0	-3.98394	0	101000
0	0	0	0	3.85987	1.5	-3.84397	0.4	011000
0	0	0	0	5.16242	2	5.65309	0.6	100100
0	0	0	0	5.34891	71	3.59906	13	010100
-3.35827	0	-5.66803	0	0	0	0	0	002000
-3.03125	3	-6.27946	0.6	0	0	0	0	001100
-2.43596	86	-3.12330	9.8	0	0	0	0	000200

X_0: KV distribution



Simulated

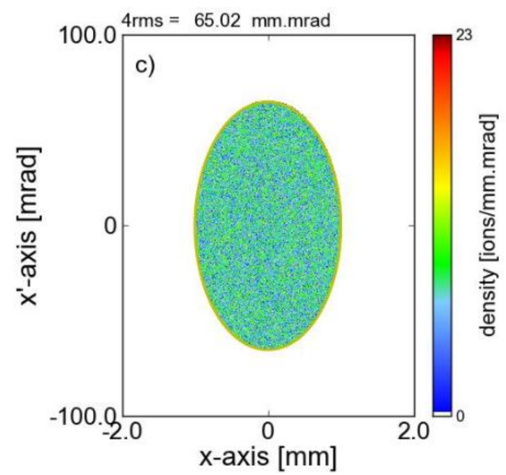
- Theoretical model of the setup $X_1 = M_T \cdot X_0$

Transfer matrix: M_t

$$\theta_1 = (\theta/x)x_0 + (\theta/x')x'_0 + (\theta/y)y_0 + (\theta/y')y'_0 + (\theta/xx)x_0^2$$
$$+ (\theta/xx')x_0x'_0 + (\theta/x'x')x'^2_0 + (\theta/xy)x_0y_0 + (\theta/x'y)x'_0\,y_0$$
$$+ (\theta/xy')x_0y'_0 + (\theta/x'y')x'_0\,y'_0 + (\theta/yy)y_0^2 + (\theta/yy')y_0y'_0 + (\theta/y'y')y'^2_0$$

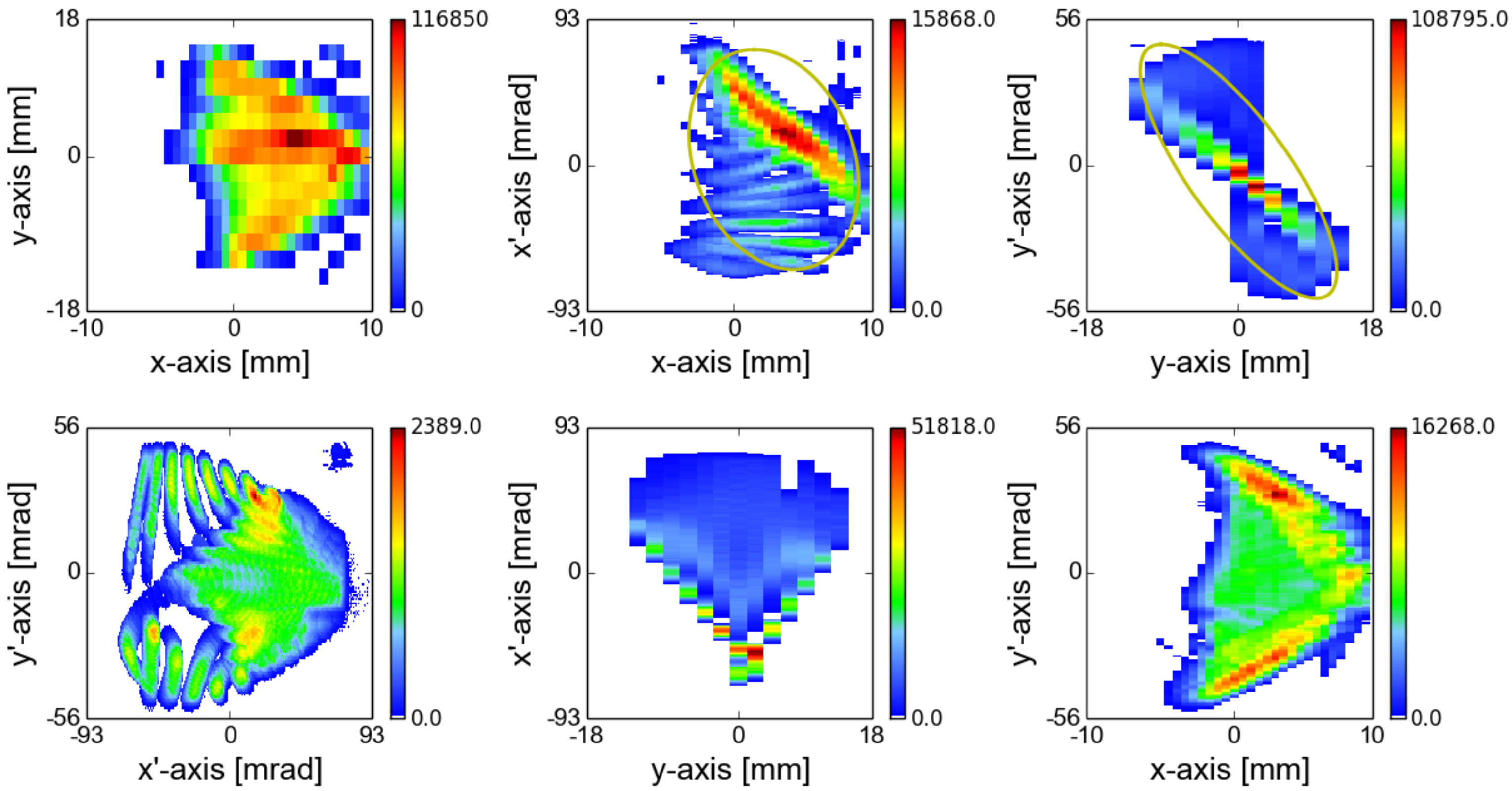
x_1	%	x'_1	%	y_1	%	y'_1	%	$(x,x',y,y',\delta,l)_0$
0.82648	24	2.26816	5.8	0	0	0	0	100000
1.668E-06	0	1.20995	108	0	0	0	0	010000
0	0	0	0	-0.85078	9.2	-1.258137	3.8	001000
0	0	0	0	9.100E-02	35	-1.040819	110	000100
-1.3220	0	-0.84624	0	0	0	0	0	200000
-2.0211	-2	-1.6758	0.1	0	0	0	0	110000
-0.94047	33	-1.1015	3.4	0	0	0	0	020000
0	0	0	0	1.96766	0	-3.98394	0	101000
0	0	0	0	3.85987	1.5	-3.84397	0.4	011000
0	0	0	0	5.16242	2	5.65309	0.6	100100
0	0	0	0	5.34891	71	3.59906	13	010100
-3.35827	0	-5.66803	0	0	0	0	0	002000
-3.03125	3	-6.27946	0.6	0	0	0	0	001100
-2.43596	86	-3.12330	9.8	0	0	0	0	000200

X_0: KV distribution



Measured

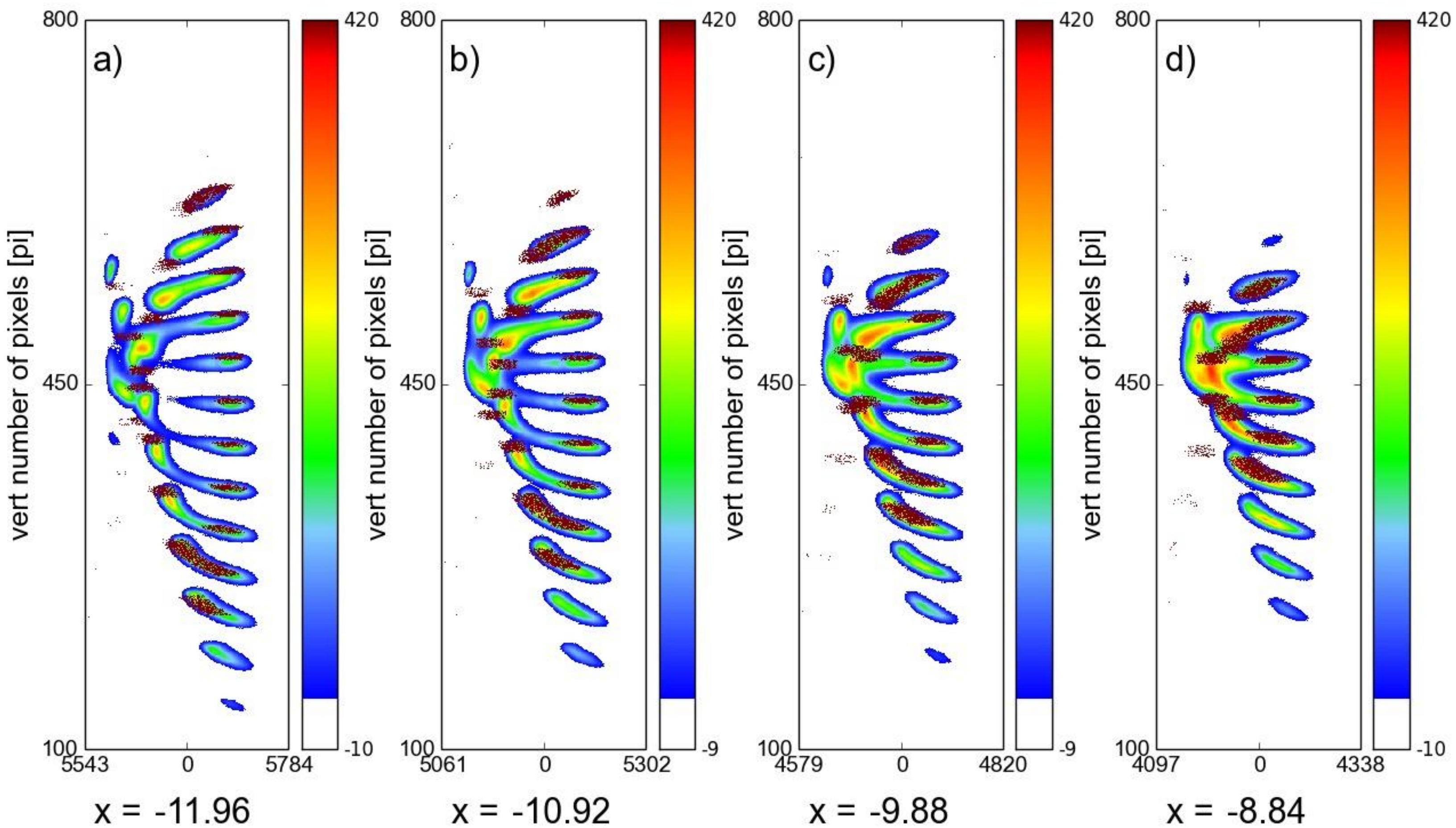
- Measured phase-space projections He^{2+} beam



$$\varepsilon_{xx'-4rms} = 387\ mm.mrad$$
$$\varepsilon_{yy'-4rms} = 359\ mm.mrad$$

Measured and simulated

- Measurements combined with simulations of a 25 kV He^{1+} beam

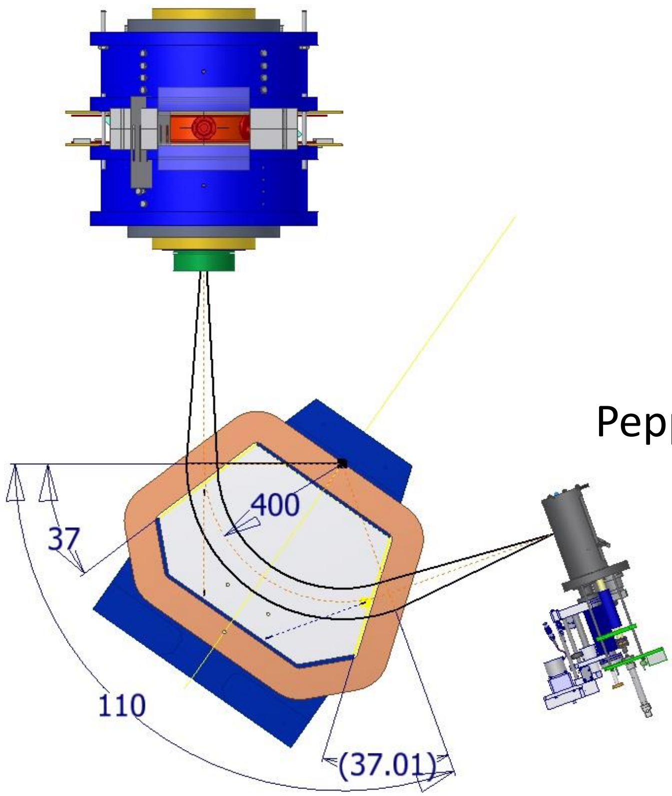


Ion source

AECR (LBNL type)
34 kV Extraction Voltage

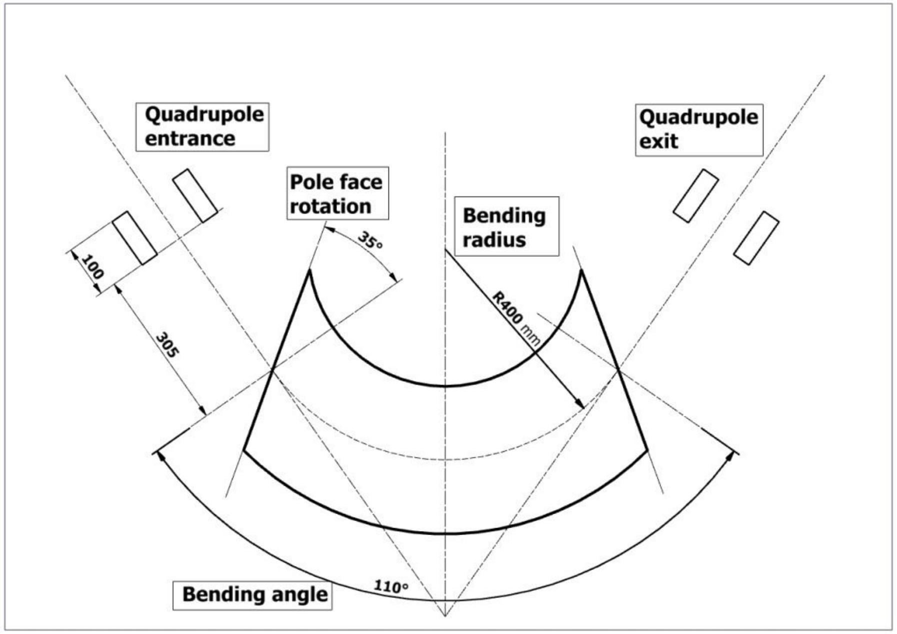
Pepper pot emittance meter

Bending radius = 0.4 m
Bending angle = 110 deg



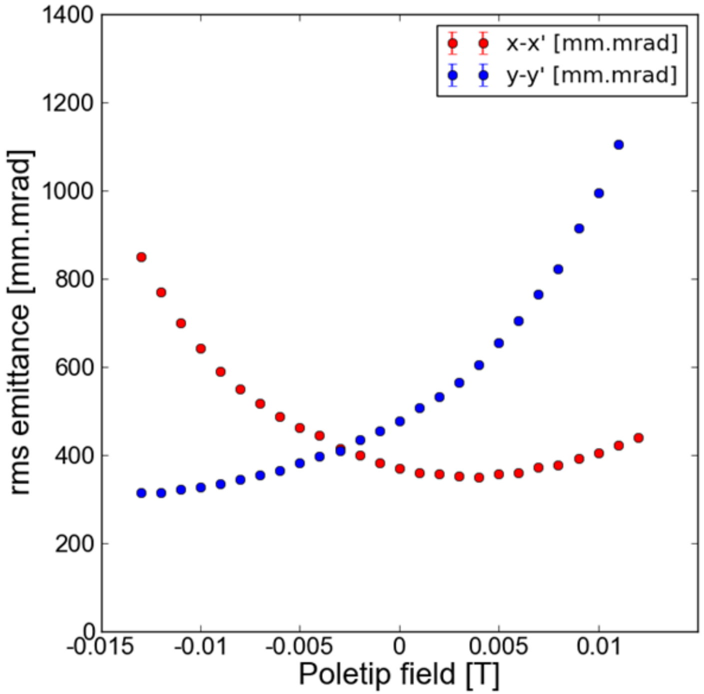
Dipole with an additional two quadrupoles

- Top view analyzing magnet



4RMS emittance 24.5 He^{1+}

as function of the quadrupole excitation



- Possible options to fix.

- Minimize the aberration
  - Add sextupoles
    - **Pole curvature**
    - Add sextupoles