Dependency of Gabor Lens Focusing Characteristics on Nonneutral Plasma Properties

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HIC for FAIR Workshop
Riezlern, 14.03.2013

HIC for FAIR
Helmholtz International Center

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Outline

1. Motivation and Introduction
2. Diagnostics
3. Beam Transport Measurements and NNP Studies
4. Summary

1. Motivation and Introduction

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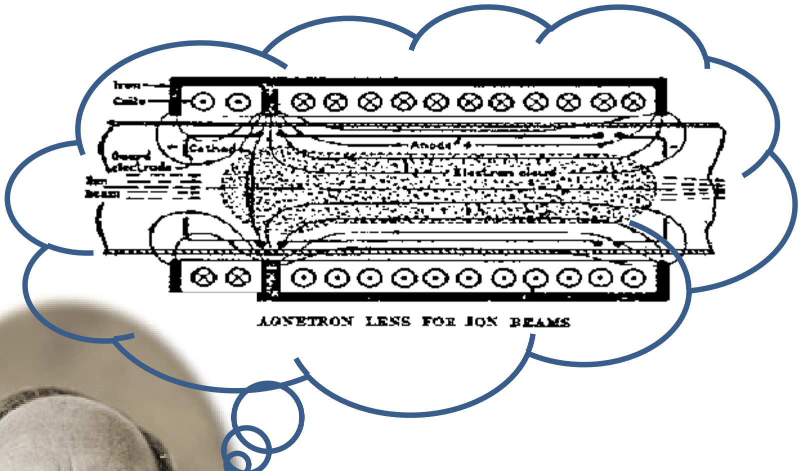
1.1. Relevant to know about Gabor lenses...

...or Gabor lens in a nutshell



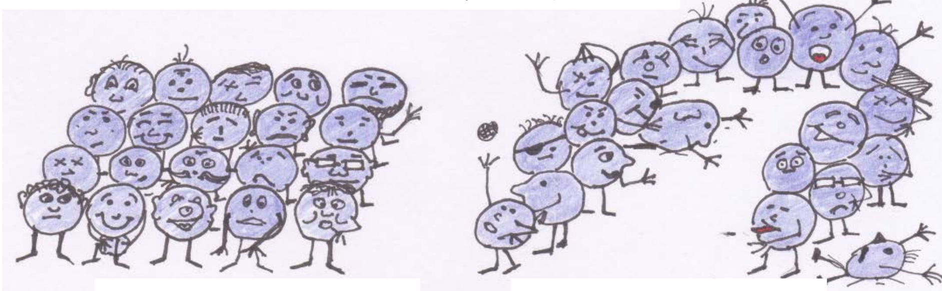
Dennis Gabor
(1900-1979)

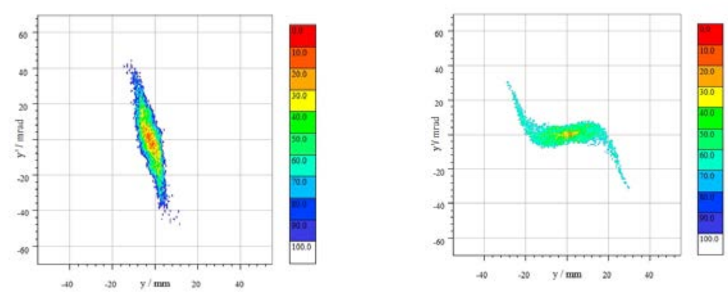
focal length:

$$\frac{1}{f_G} = \frac{qen_e}{2m_i v_i^2 \epsilon_0} l = \frac{en_e}{4\epsilon_0 W_b} l$$

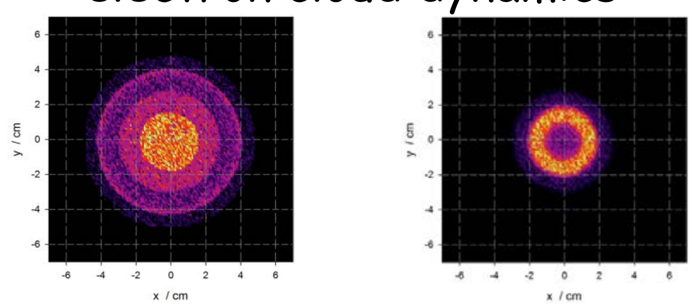
"a beam focusing device that maintains full beam neutralization even for high current beams under all circumstances."

decision on electron distribution





electron cloud dynamics



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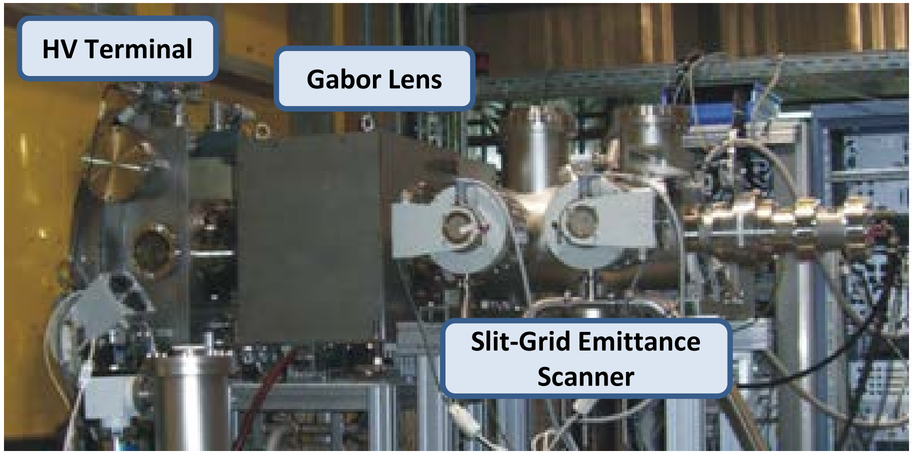
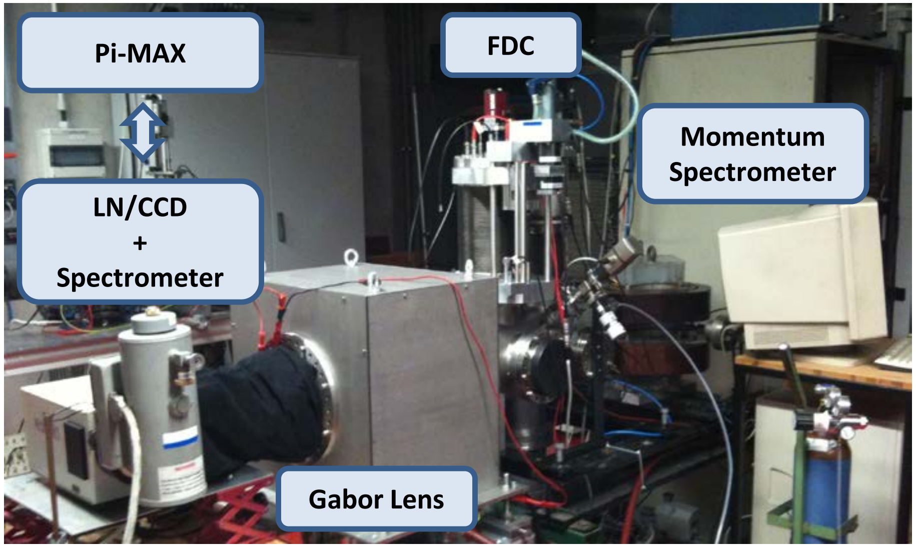
1.2. Investigation of NNP Properties





For the same Gabor lens parameters

Beam Transport Measurements
-- "with beam"
- Beam Emittance
- Electron Density

and

Measurements of NNP Properties
-- "without beam"
- Electron Density
- Electron Temperatur
- Electron Density Distribution

were performed.

2. Diagnostics

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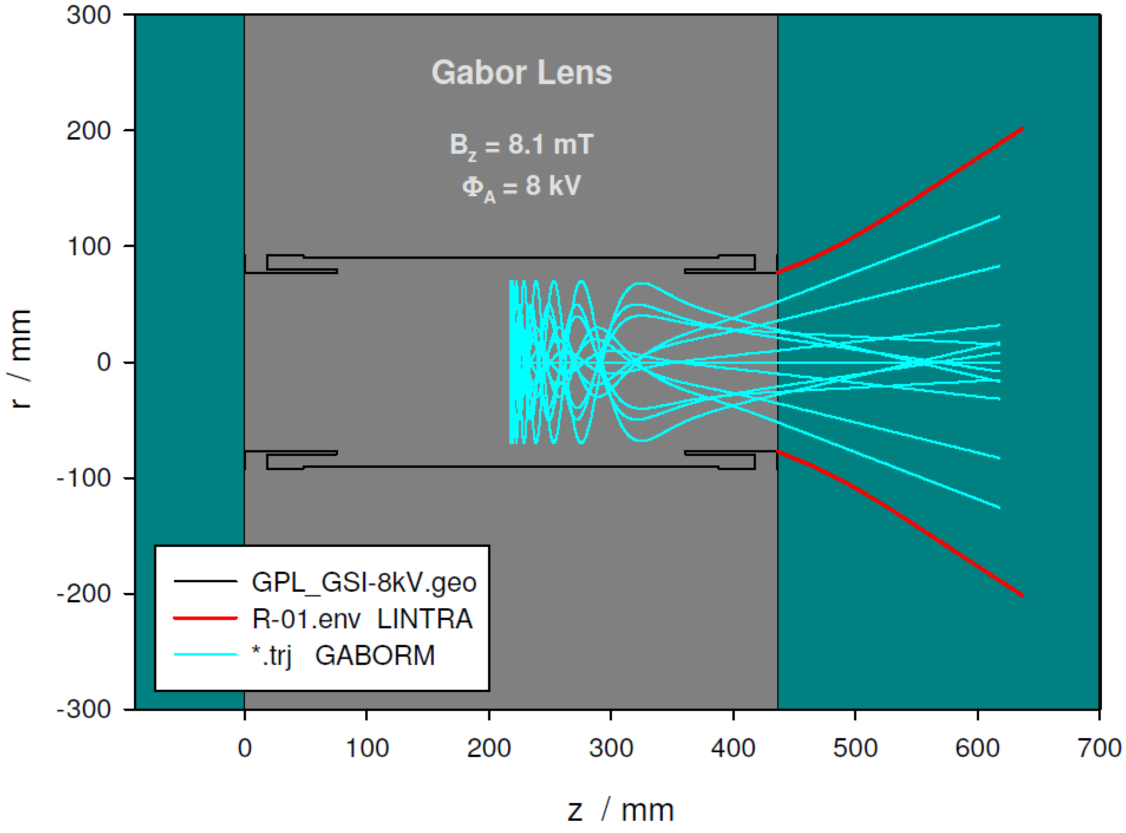
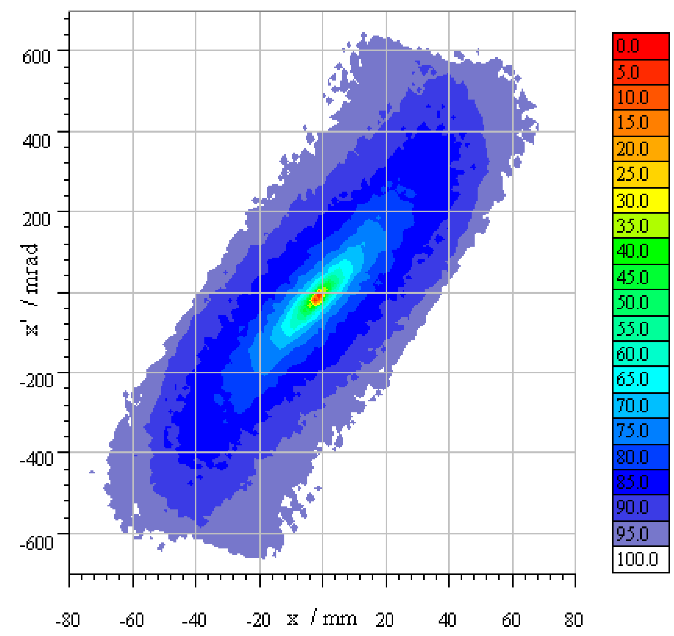
2.1. Density Measurement - without beam

simulation of Ar^+ production assuming a homogeneously distributed residual gas at room temperature 0.025eV (642000 particles)





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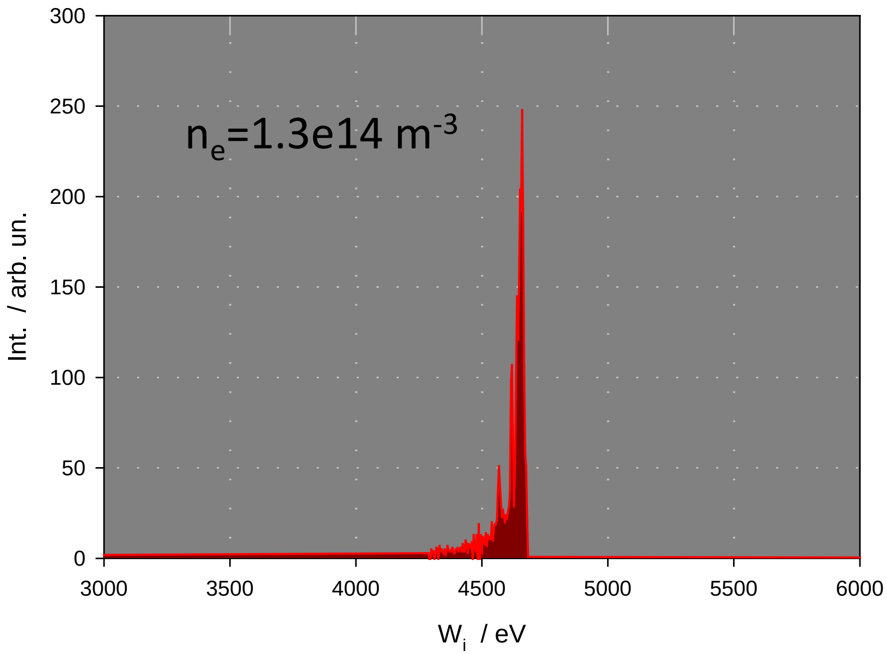
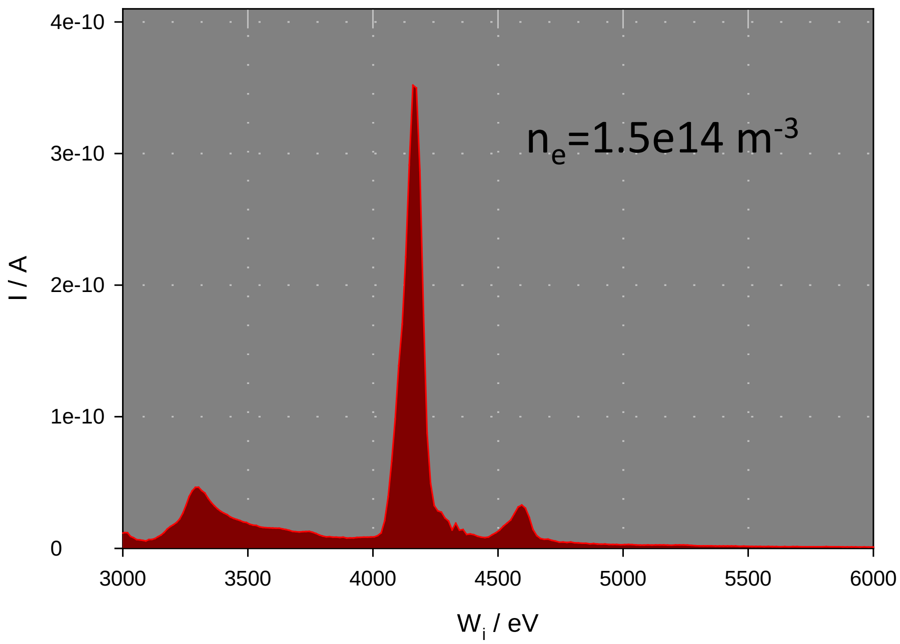
2.2. Density Measurement - without beam

simulated energy spectrum



measured energy spectrum



The residual gas ions gain their kinetic energy $W_i = e\Phi_{ion}$ within the anode potential Φ_{anode} that is reduced by confined electrons. The electron density is than calculated by

$$n_{e,l} = \frac{4\epsilon_0 \cdot \Delta\Phi}{er^2}$$

assuming $\Delta\Phi = \Phi_{anode} - \Phi_{ion}$

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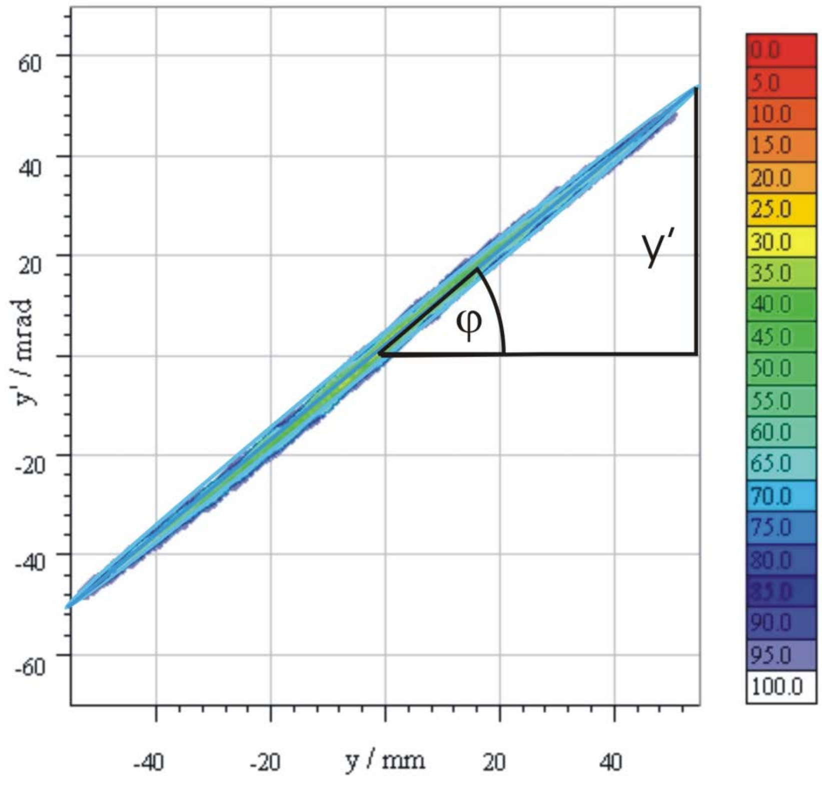
2.3. Density Measurement - with beam

change of angle in the phase space distribution → electron density



$$\varphi = \frac{arctan\frac{2\cdot\alpha}{\beta\cdot\gamma}}{2}$$

$$y' = tan(\varphi)\cdot y$$

$$\frac{1}{f} = \frac{\Delta y'}{y} = k_G^2 = \frac{e n_e l}{4\epsilon_0 U}$$

$$n_e = \frac{4\epsilon_0 U}{e\cdot l}\frac{\Delta y'}{y}$$

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2.4. Light Density Distribution and Symmetry

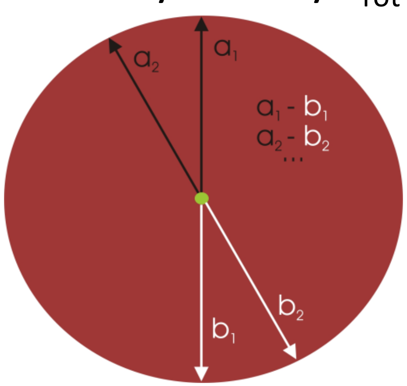
symmetry S_{sym}:

$$S_{sym} = \frac{\mu_I}{\sigma_I^2}$$

$$\mu_I = \frac{1}{N} \sum_{i=1}^{N} \int_0^R I(r, \frac{2\pi \cdot i}{N}) dr$$

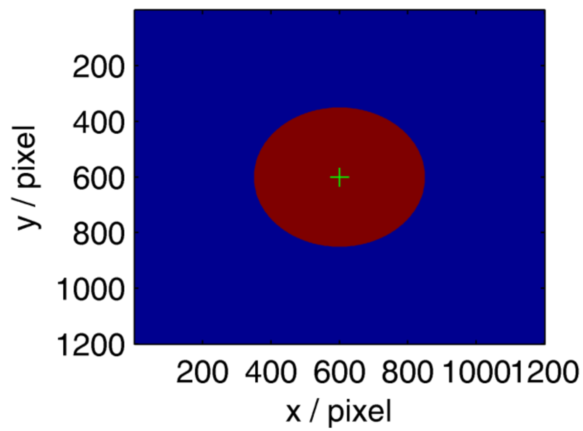
$$\sigma_I^2 = \frac{1}{N} \sum_{i=1}^{N} \left(\int_0^R I(r, \frac{2\pi \cdot i}{N}) dr - \mu_I \right)^2$$

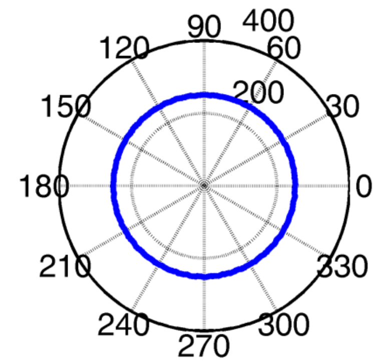
rotational symmetry S_{rot}:

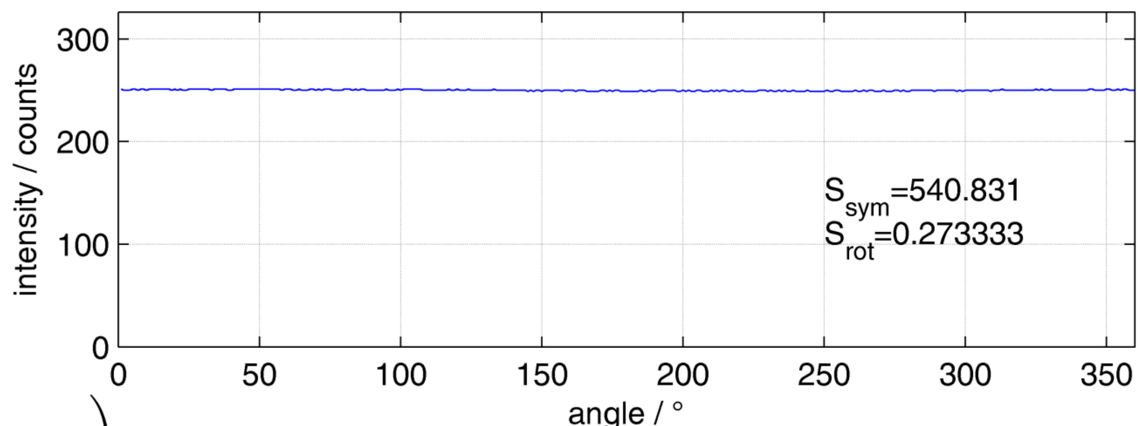


$$S_{rot} = \sum_{i=1}^{N} \left(\sum_{i=1}^{\frac{N}{2}} \int_0^R I(r, \frac{2\pi \cdot i}{N}) dr - \sum_{i=\frac{N}{2}+1}^{N} \int_0^R I(r, \frac{2\pi \cdot i}{N}) dr \right)$$

evaluation of method for symmetry determination







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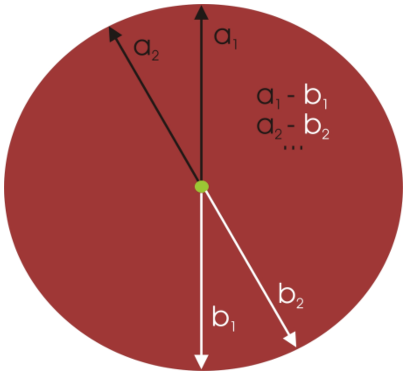

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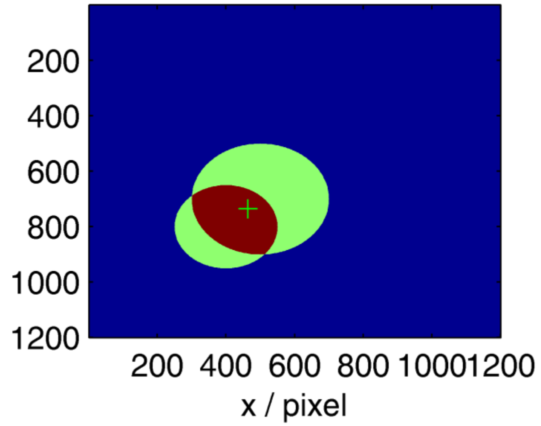

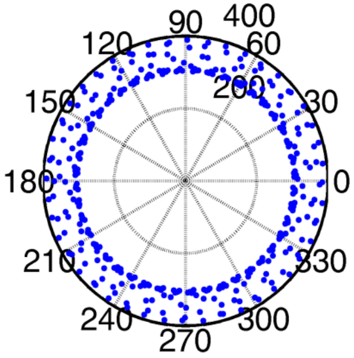

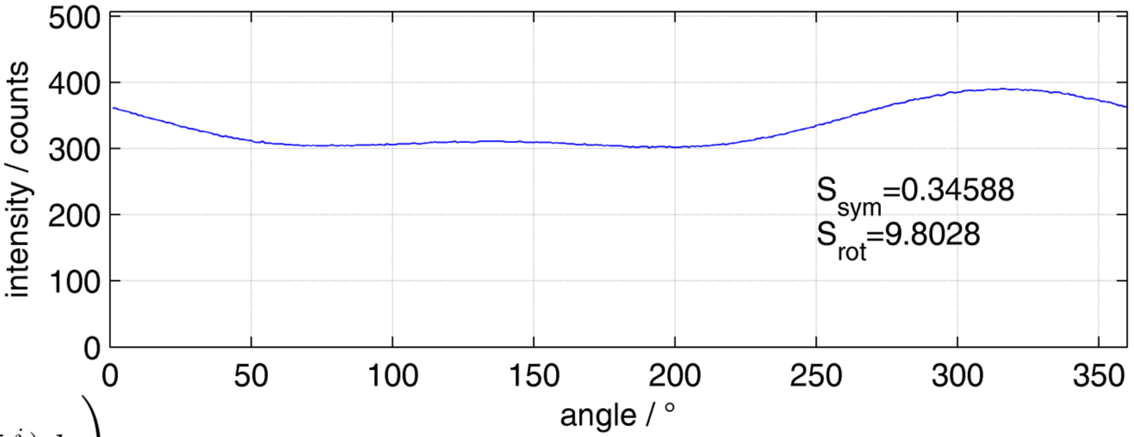

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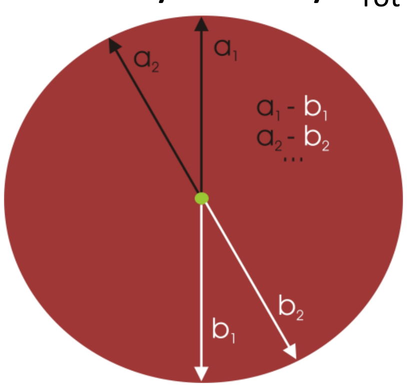

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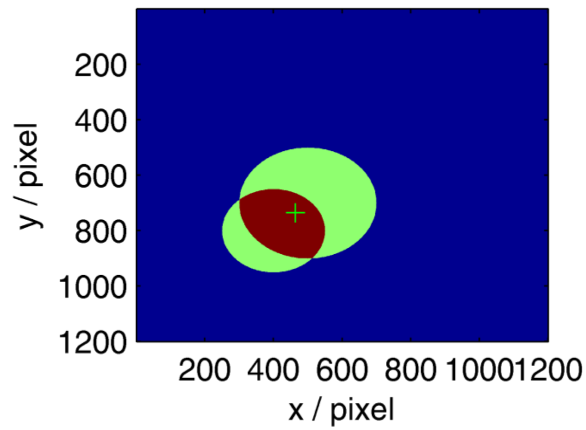
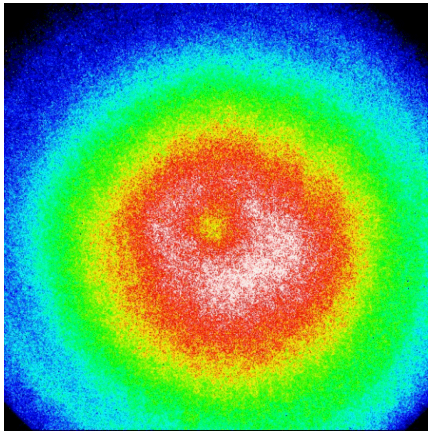
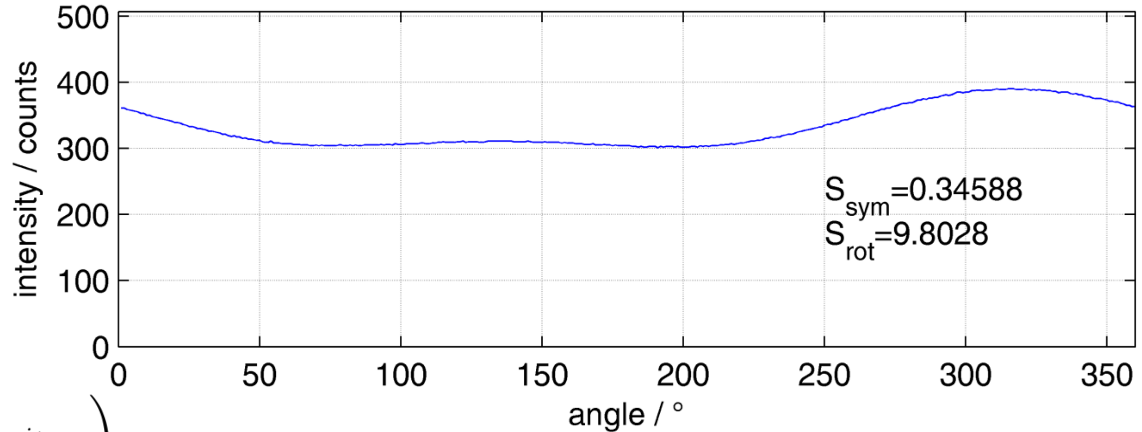
evaluation of method for symmetry determination







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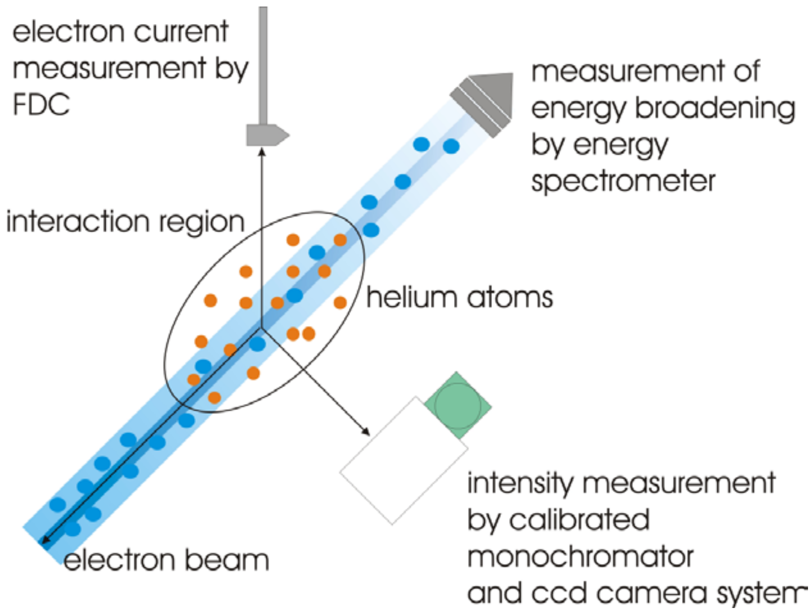
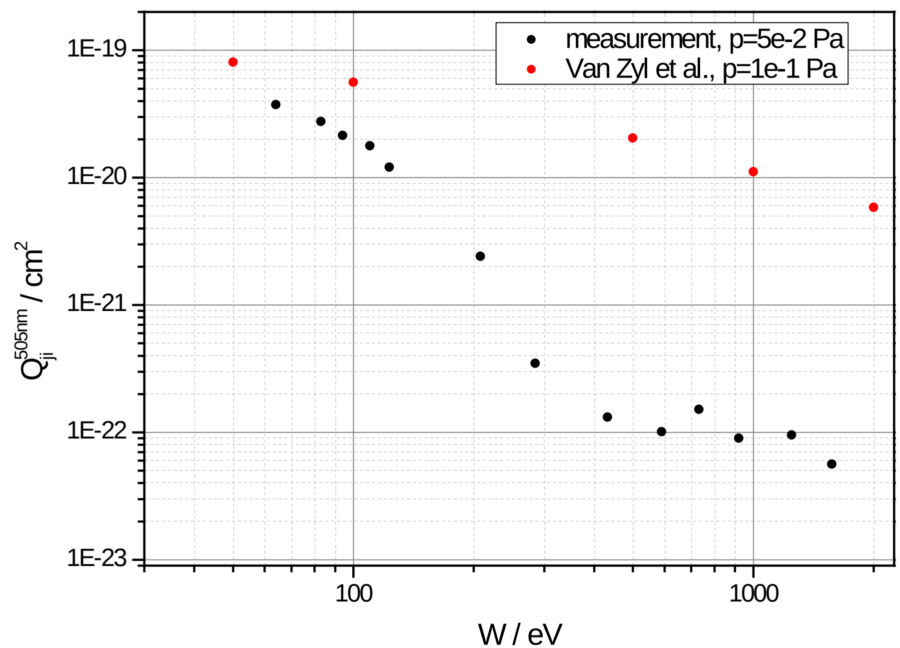
2.5. Electron Temperature Measurement

Temperature measurement by optical emission cross sections assuming a corona regime*:

$$\frac{\Phi_{ij}^{obs}}{\Phi_{ab}^{obs}} = \frac{\int_{E1}^{\infty} Q_{ij}^{opt}(E) exp[-E/kT_e] E dE}{\int_{E2}^{\infty} Q_{ab}^{opt}(E) exp[-E/kT_e] E dE} \xrightarrow{\textit{simplified}} \frac{\Phi_{ij}^{obs}}{\Phi_{ab}^{obs}} = \frac{Q_{ij}^{opt}(E)}{Q_{ab}^{opt}(E)}$$

Measurement of Optical Emission Cross Sections for Helium





*"Application of excitation cross sections to optical plasma diagnostics“, J.B. Boffard, J. Phys. D: Appl. Phys. 37 (2004) R143-R161

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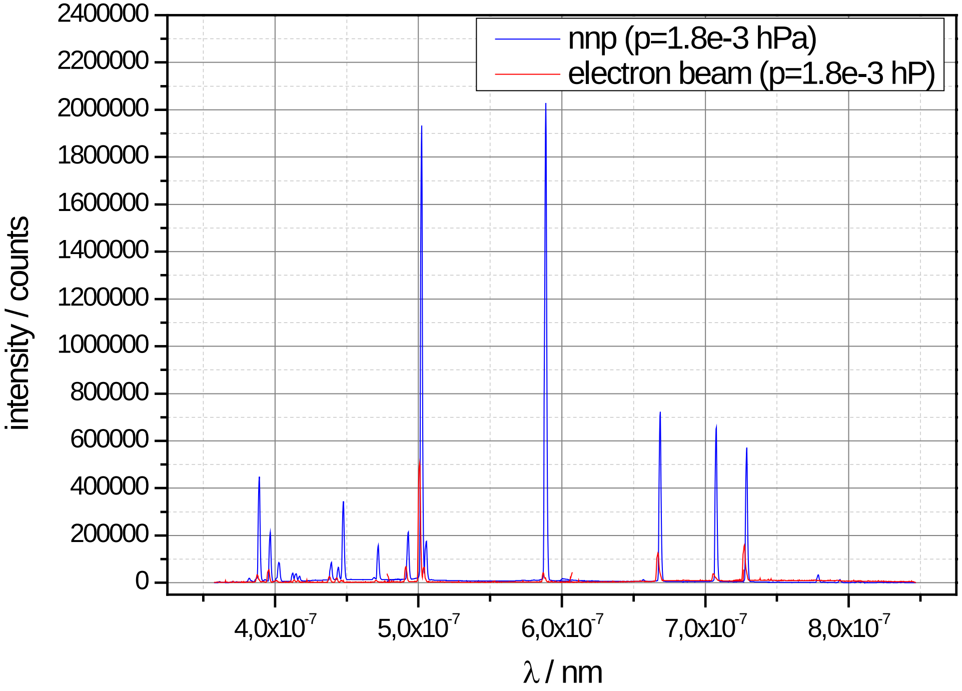
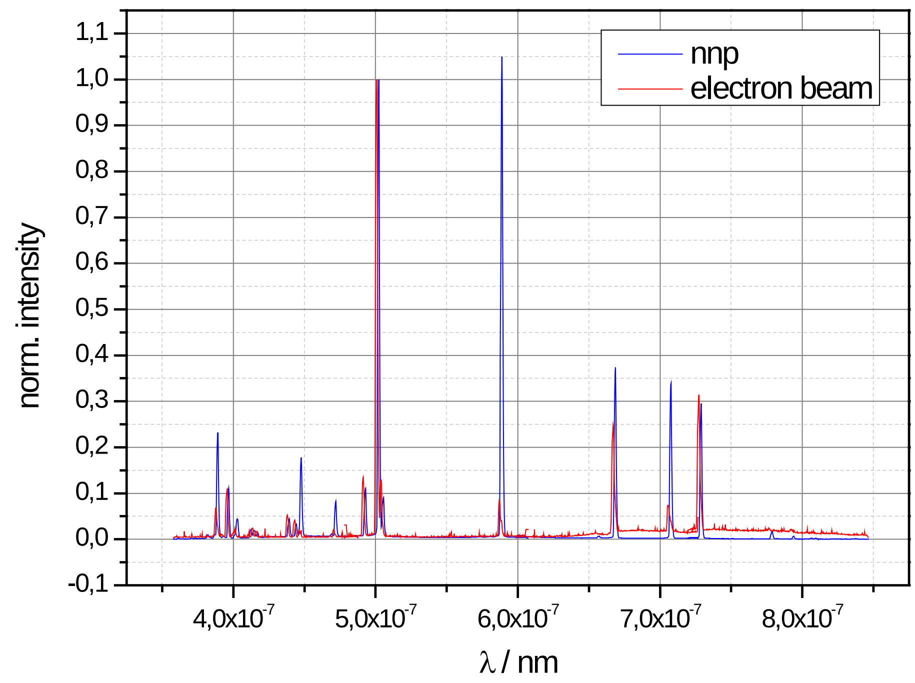
2.5. Electron Temperature Measurement

comparison of plasma emission spectra to line emission of atoms excited by an incident electron beam





3. Beam Transport Measurements and NNP Studies

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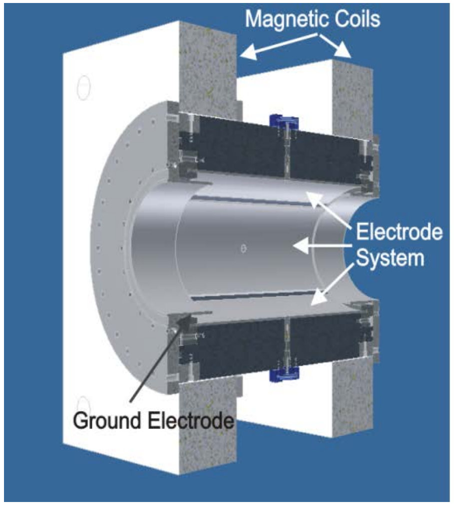
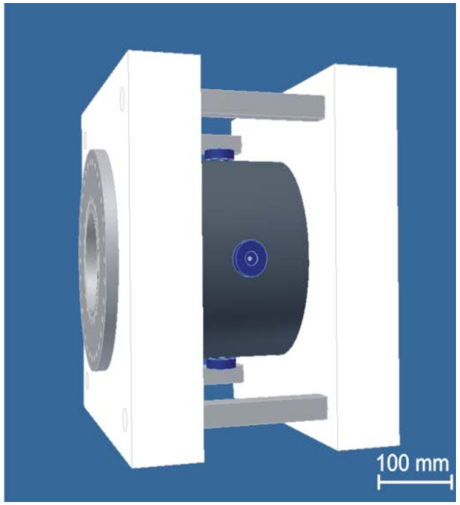
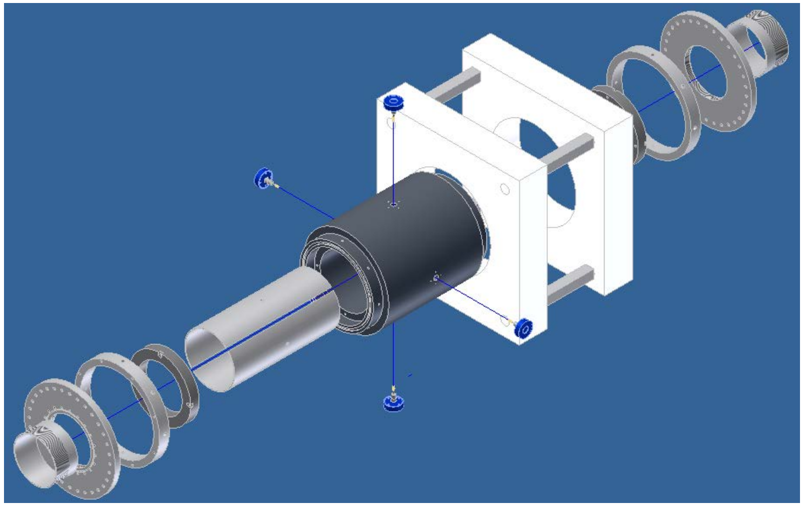
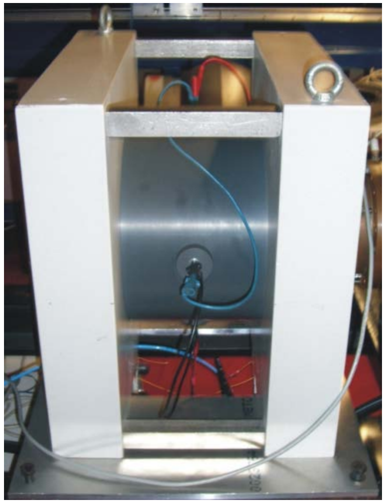
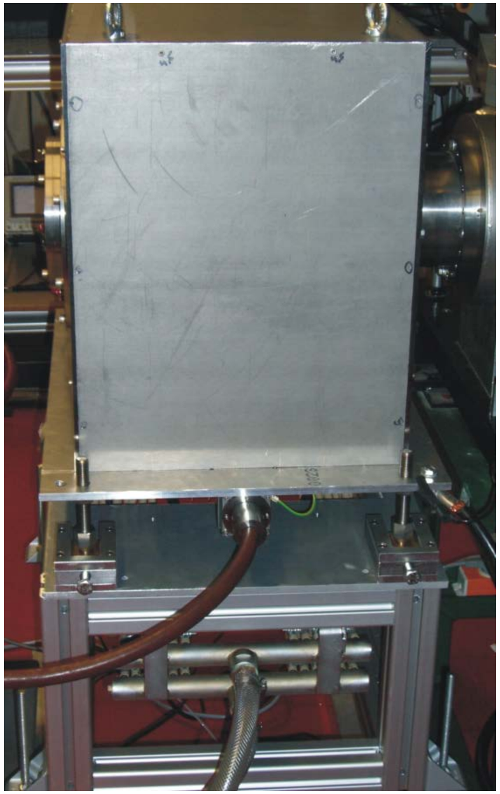
3.1. Gabor Lens - Specifications











geometry:

- r_{anode}: 85 mm
- r_{ground}: 75 mm
- l_{anode}: 340 mm
- L_{total}: 436 mm

maximum field and potential

- $B_{z,max}$: 160 mT (200 mT)
- $\Phi_{A,max}$: 50 kV

material:

- stainless steel
- Vinidur (T_{max}=80°C; 14 kV/mm)

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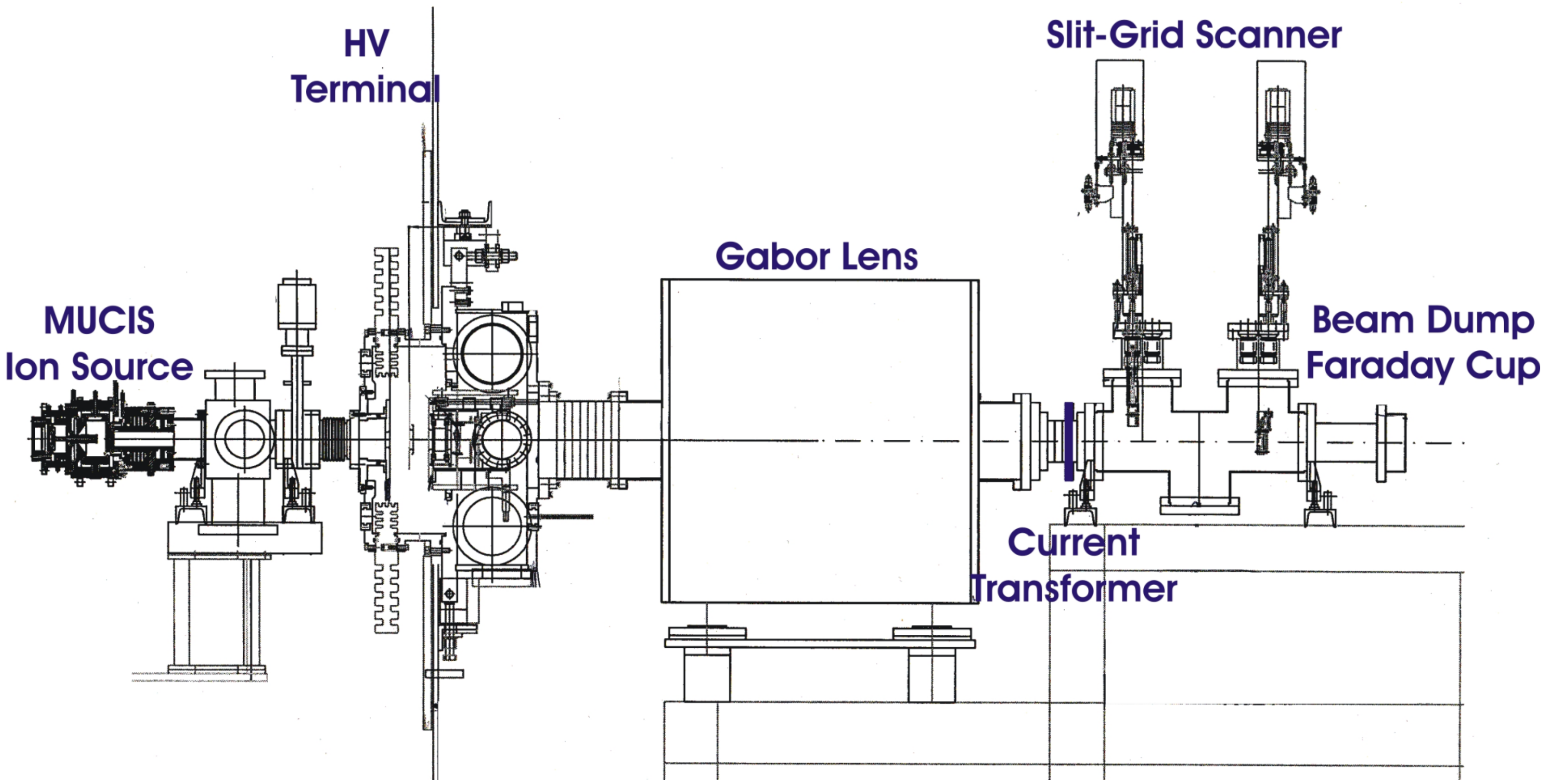
3.2. High Current Test Injector at GSI



beam parameters: pulse length=1.25 ms, pulse delay=1 Hz

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3.3. Results

1. **Low current measurements for studies of the quality of ion optics**
   - He^+, W_B=50.3 keV (12.6 keV/u), I_B=3-5 mA (measured in current transformer behind lens)
   - simulated phase space distributions were "fitted" to results of experiments to study the influence of electron density and electron density distribution of the NNP on the ion beam
   - NNP studies "without beam" in comparison to the results of beam transport measurements
2. **High current measurements for studies of the influence on n_i/n_e-ratio**
   - Installed aperture of 50 mm to save insulator from beam
   - Ar^+, W_B=124 keV (3.1 keV/u), I_B=29-35 mA (measured in current transformer behind lens)
   - NNP studies "without beam" in comparison to the results of beam transport measurements

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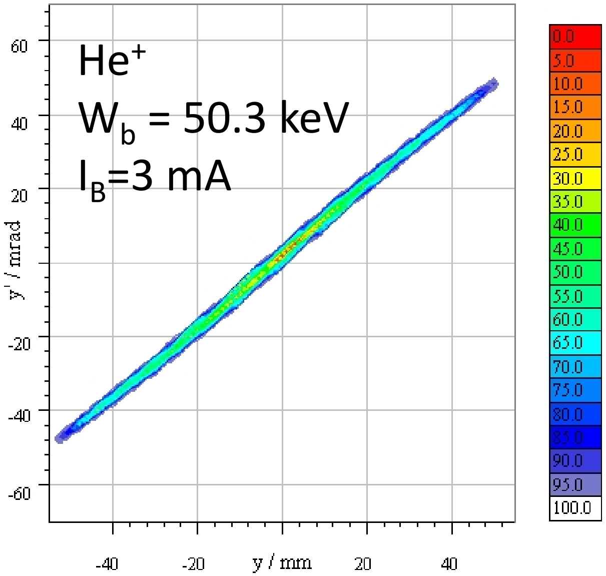
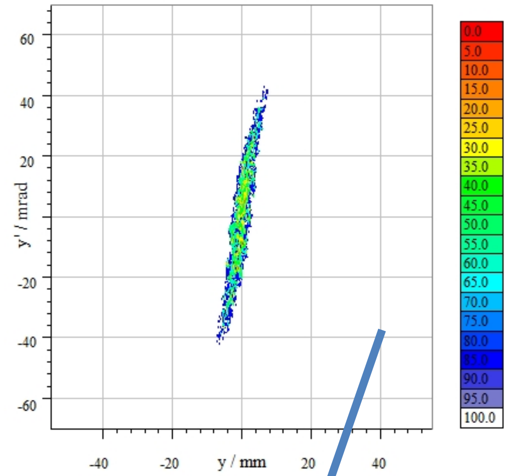
3.3. Low Current Measurements

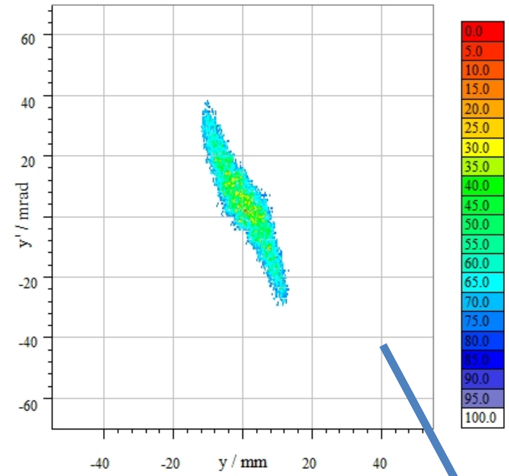
drifted beam

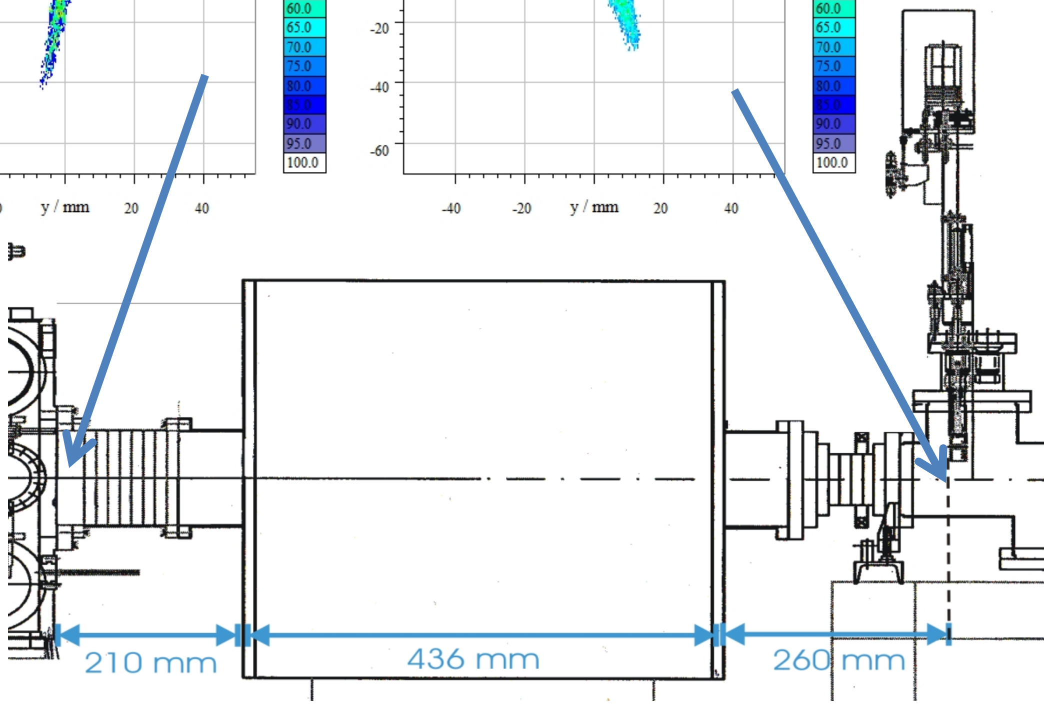


input emittance



transported beam





Φ_A= 0 kV
B_z= 0 mT
$\varepsilon_{100\%}$= 3568.24 mm mrad
$\varepsilon_{97\%}$= 122.25 mm mrad
ε_{rms}= 0.16558 π mm mrad
ω =2.25869
n = 1

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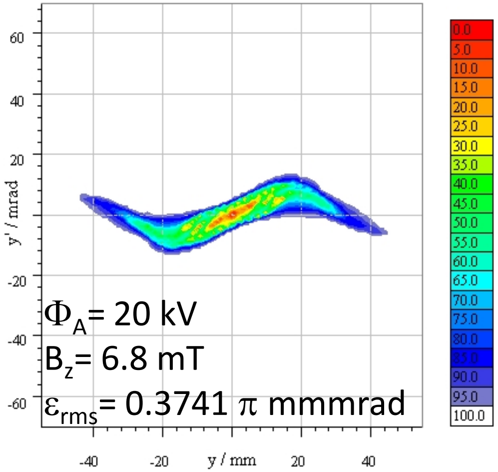
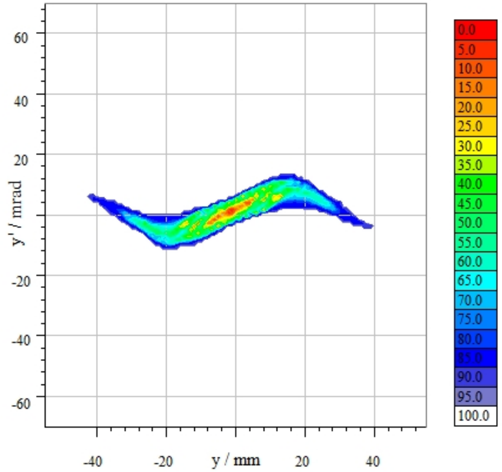
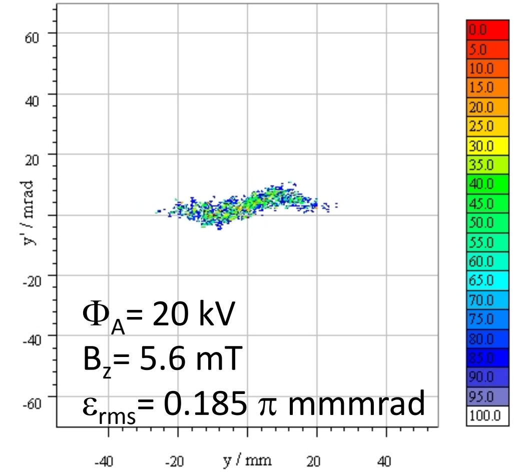
3.3. Low Current Measurements

beam transport measurement

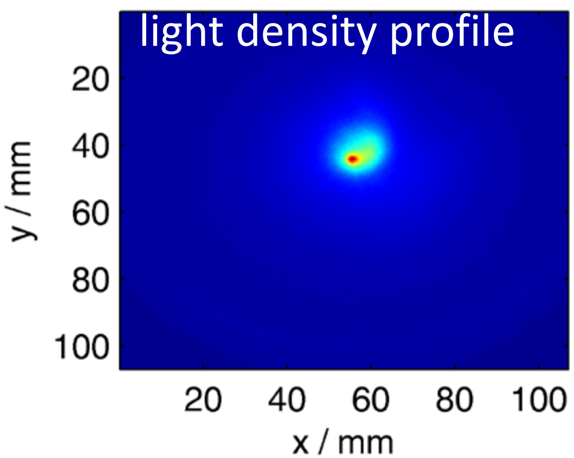


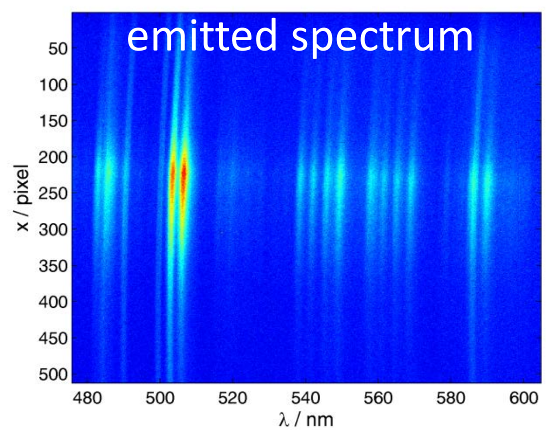


numerical simulation

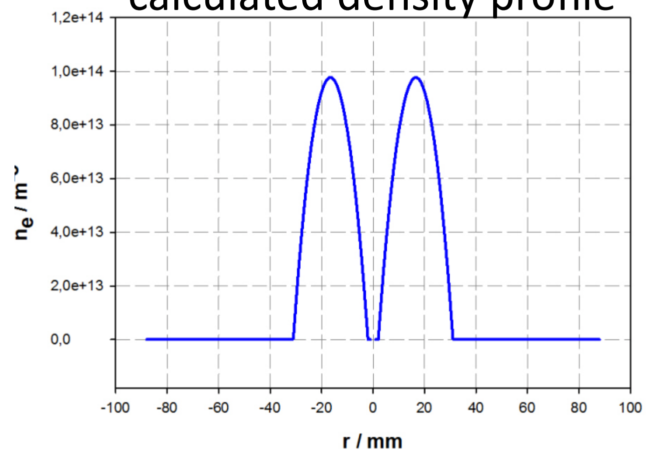


NNP diagnostics





calculated density profile



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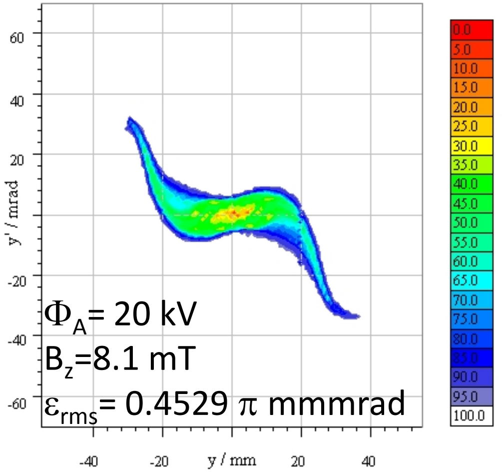
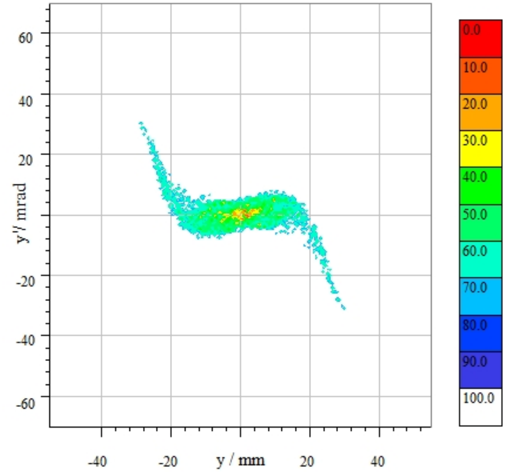
3.3. Low Current Measurements

beam transport measurement





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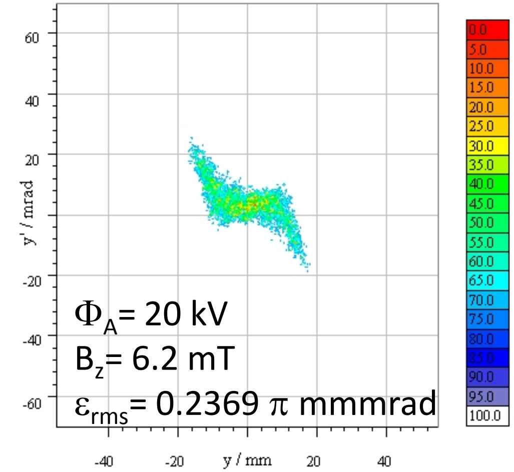

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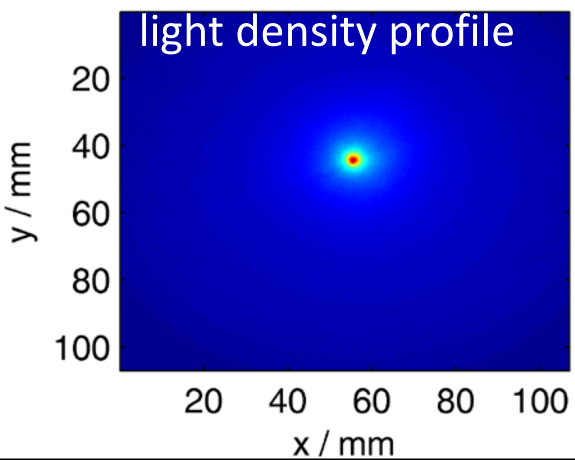

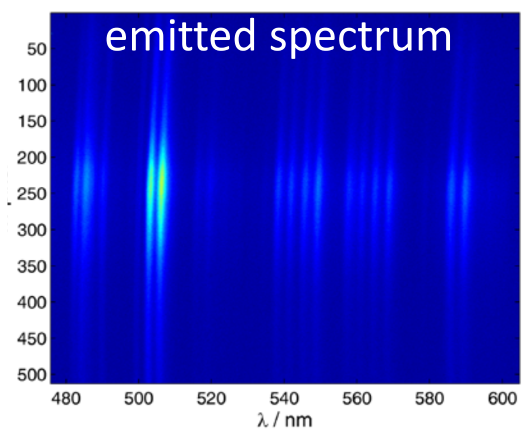

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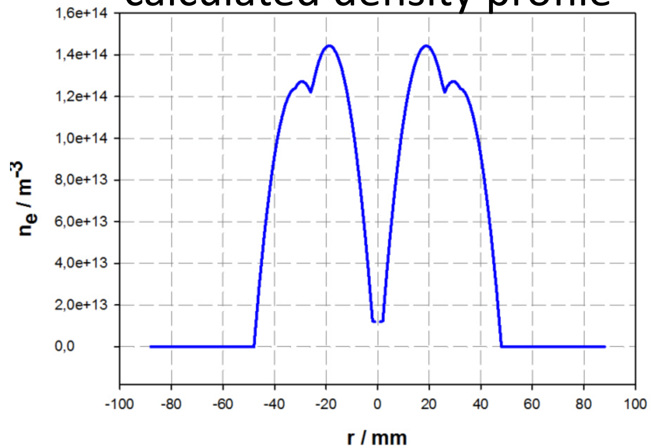

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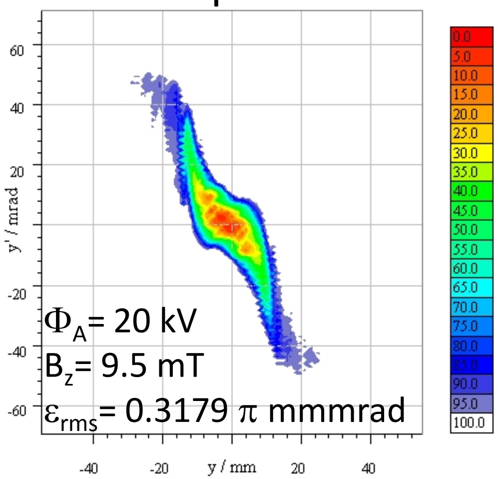
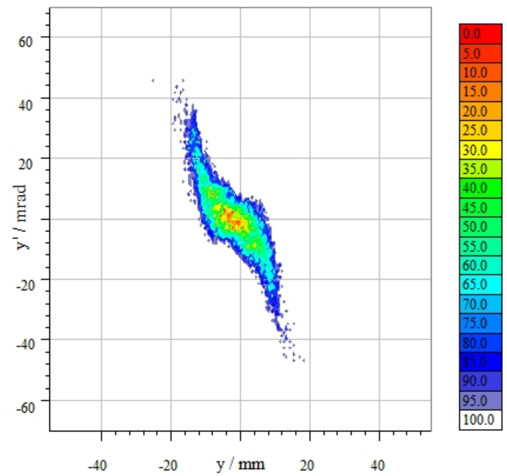
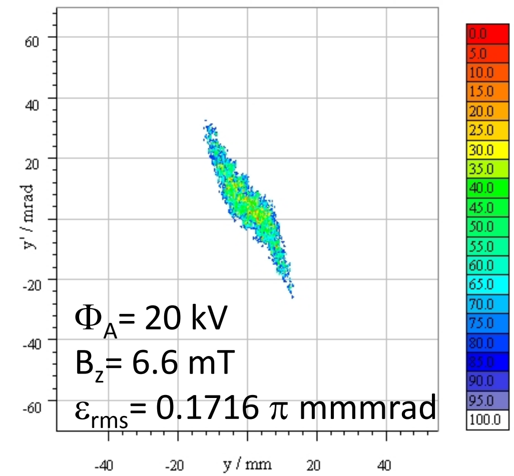
3.3. Low Current Measurements

beam transport measurement

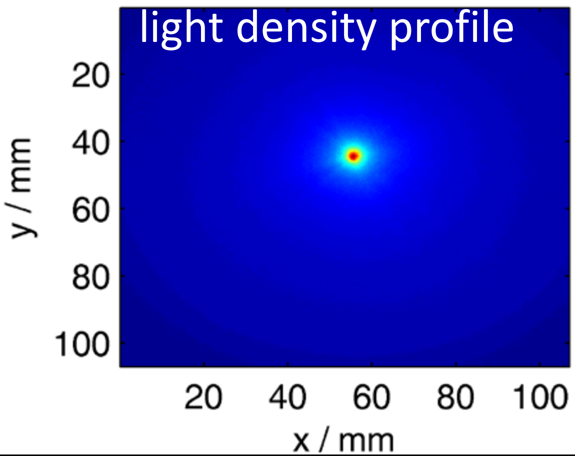


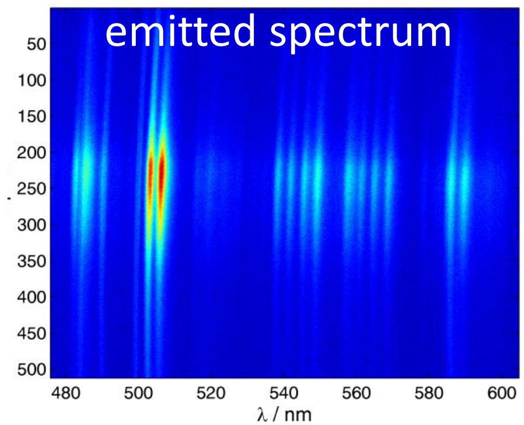


numerical simulation



NNP diagnostics





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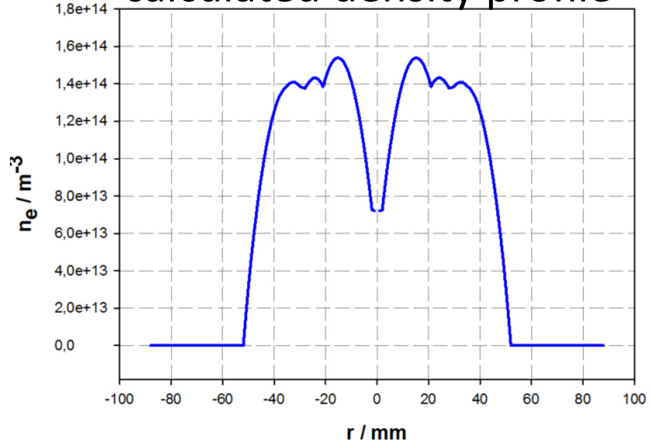

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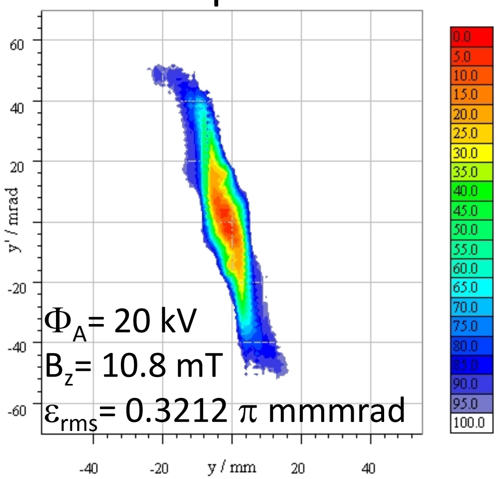
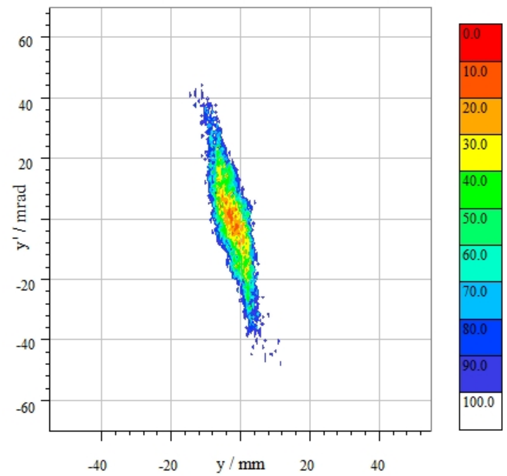
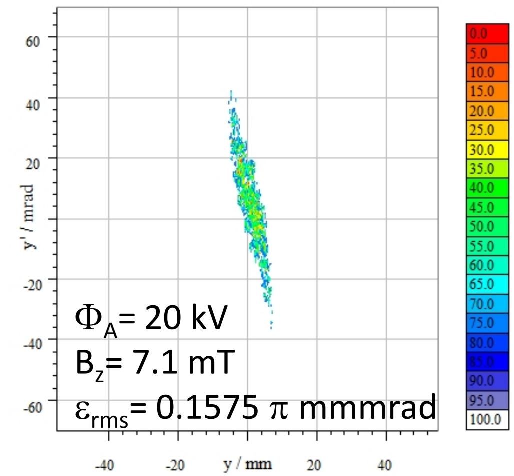
3.3. Low Current Measurements

beam transport measurement

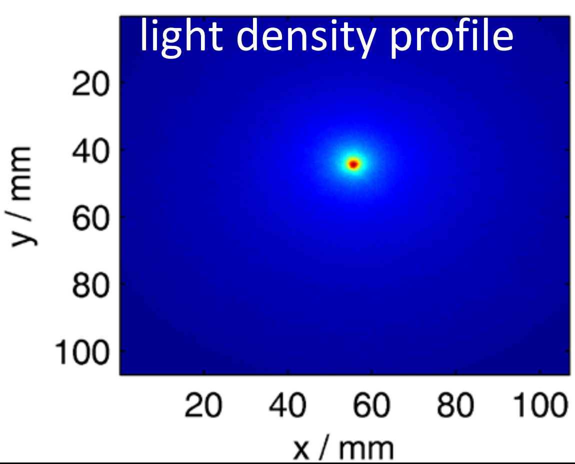


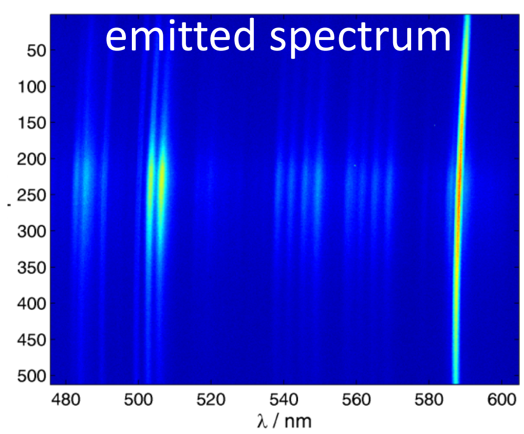


numerical simulation

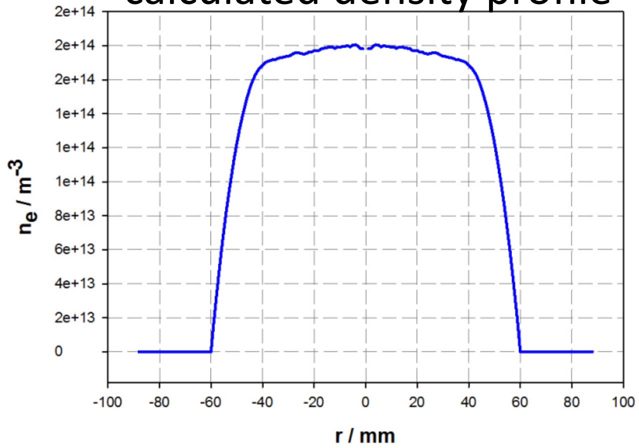


NNP diagnostics





calculated density profile



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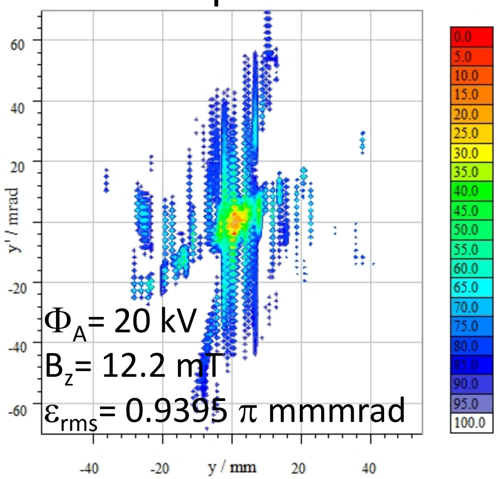
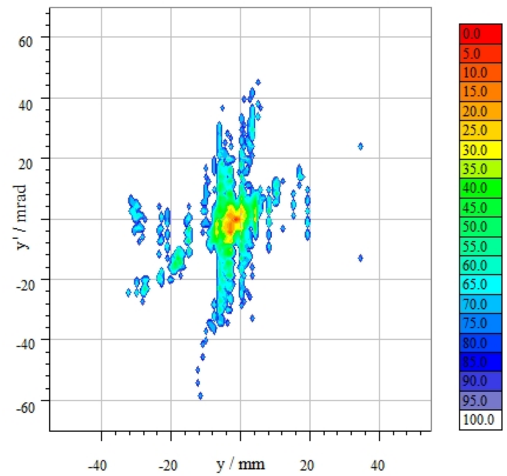
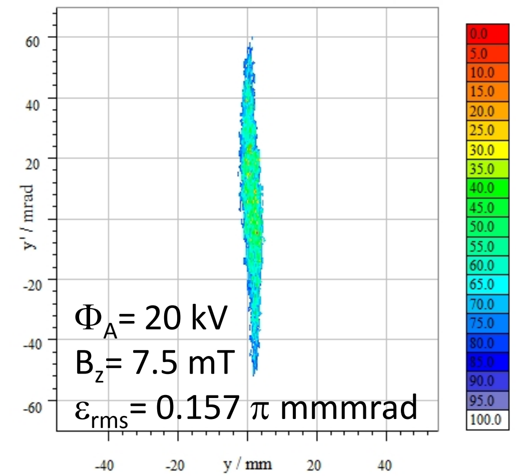
3.3. Low Current Measurements

beam transport measurement

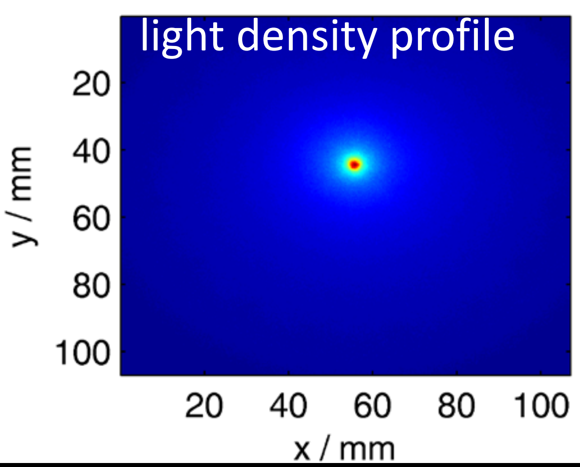


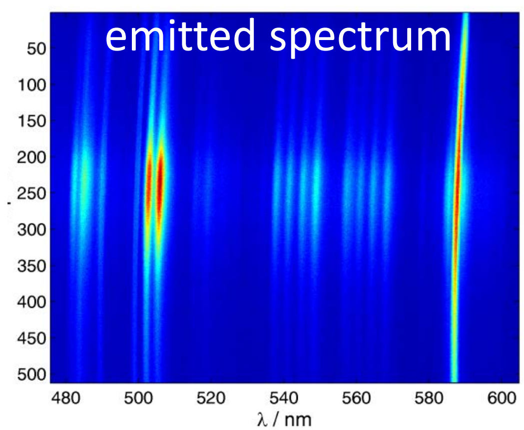


numerical simulation

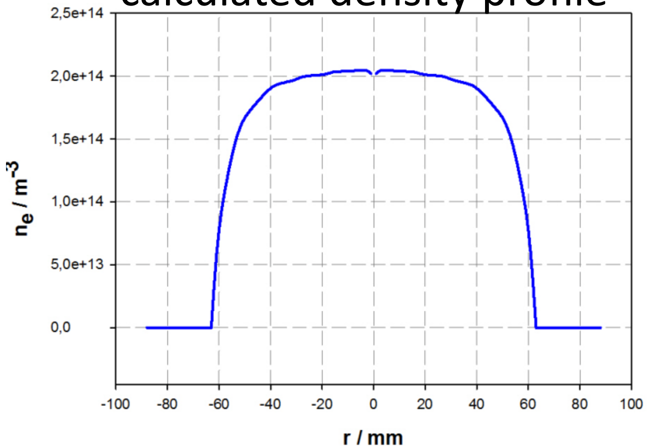


NNP diagnostics



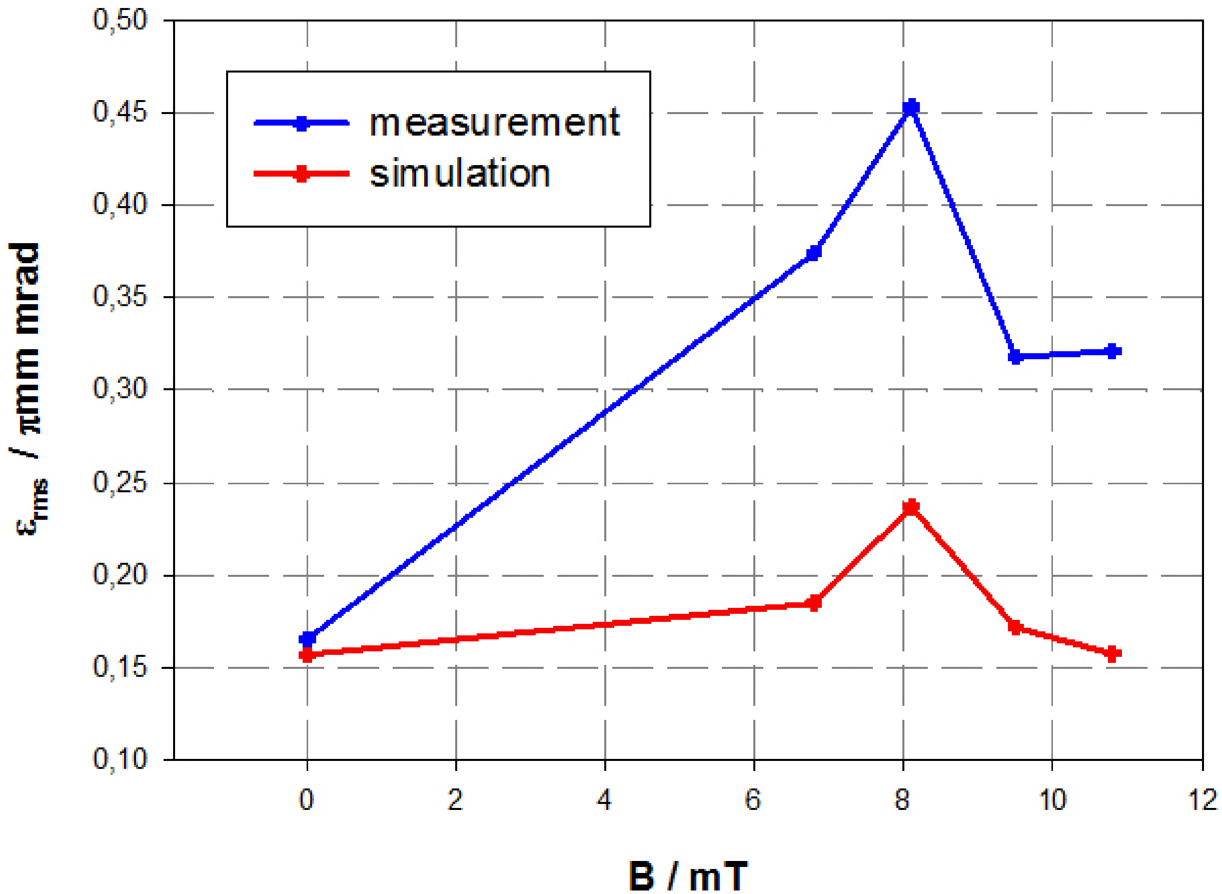


calculated density profile



3.3. Low Current Measurements

comparison of measured and calculated rms-emittance



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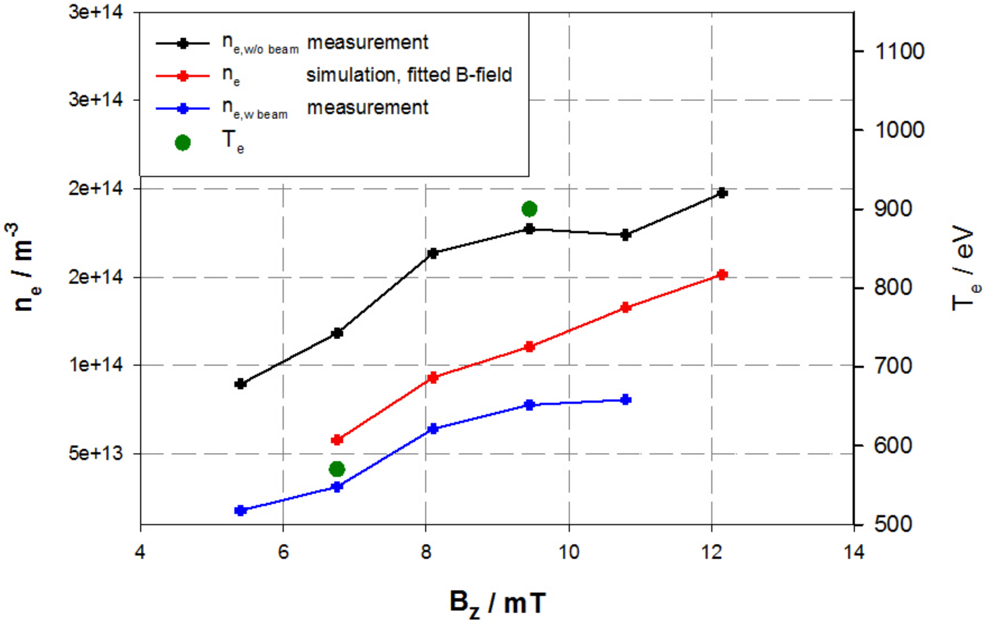
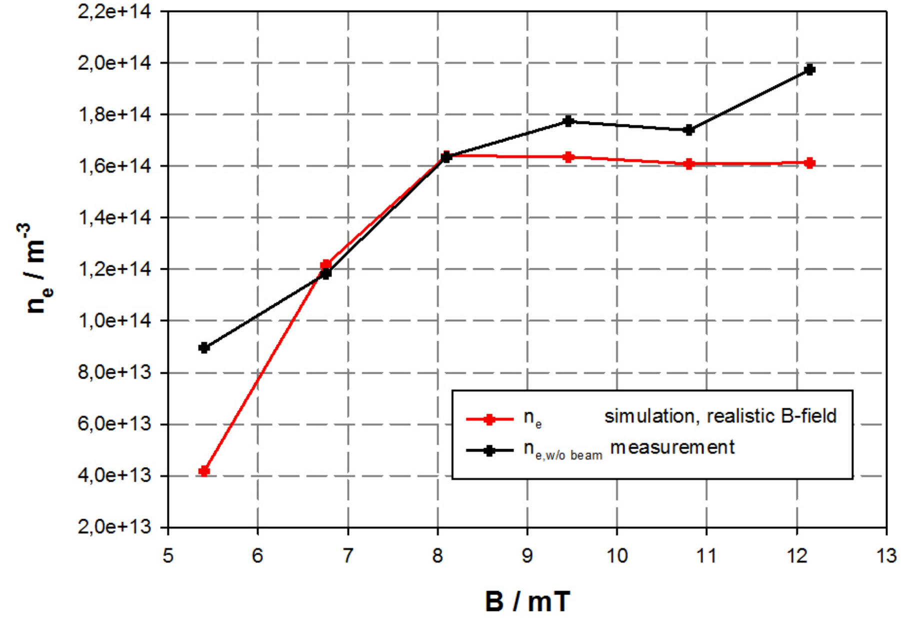
3.3. Low Current Measurements - Electron Density

comparison of calculated and measured electron densities as well as the measured electron temperature



measured electron density in comparison with calculated electron density for realistic field configuration of Gabor lens



preliminary results for electron temperature measurement as discussed before

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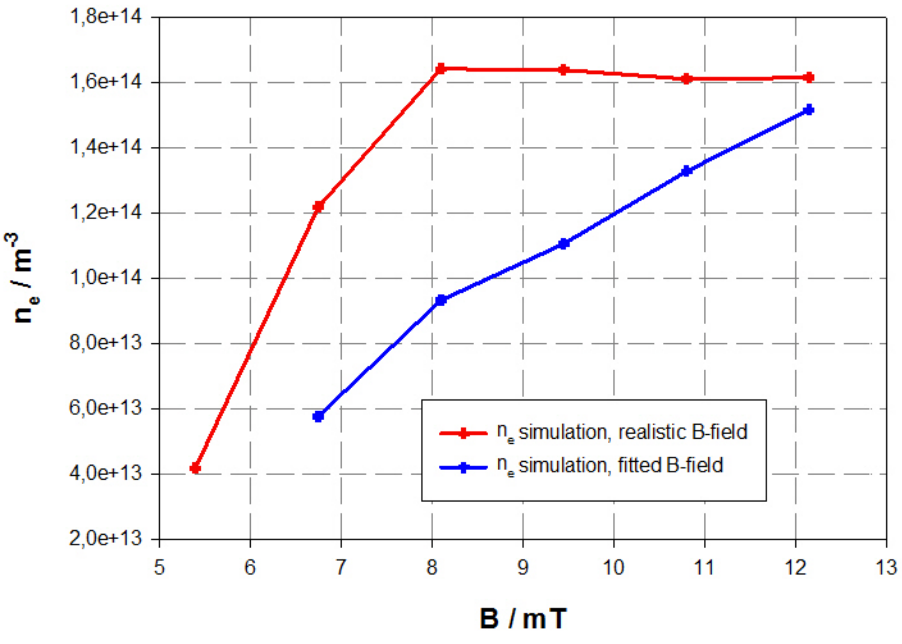
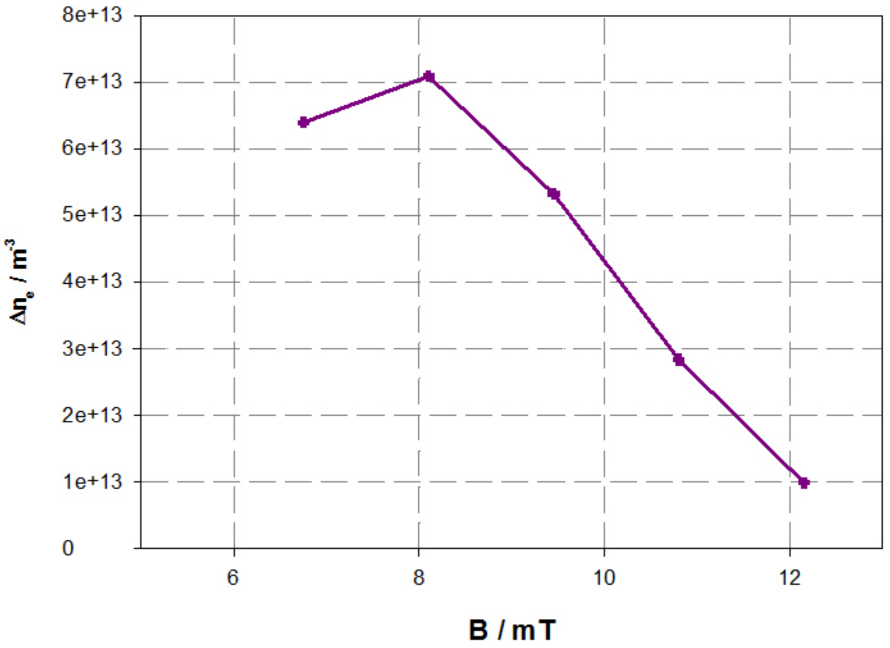
3.3. Low Current Measurements

comparison of calculated electron densities



"missing" electron density



Because of this result another evaluation of the studies on NNP "without beam" in comparison with numerical simulation calculated with ***realistic field configuration*** of Gabor lens has been made.

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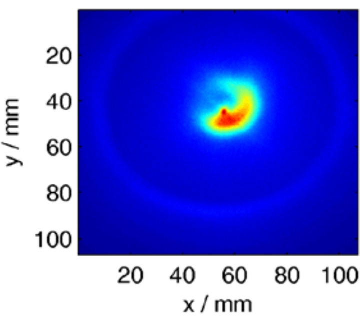
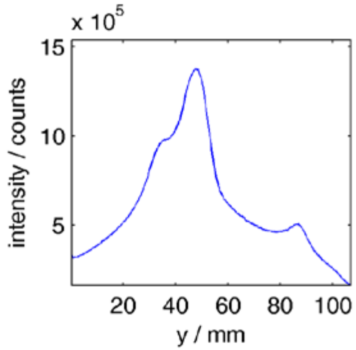
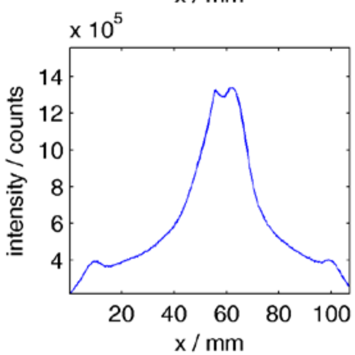
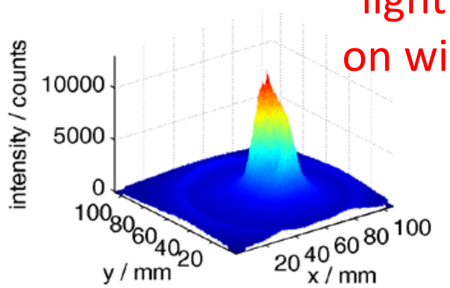
3.3. Low Current Measurements

light density profile

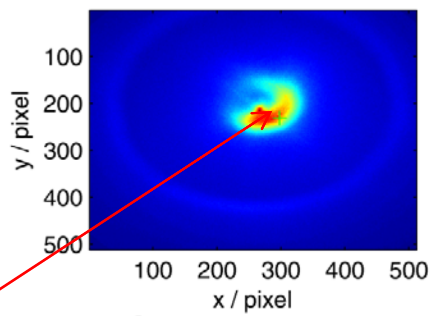




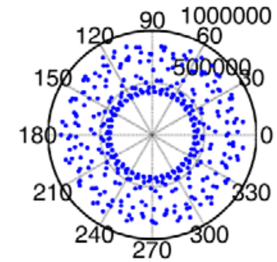


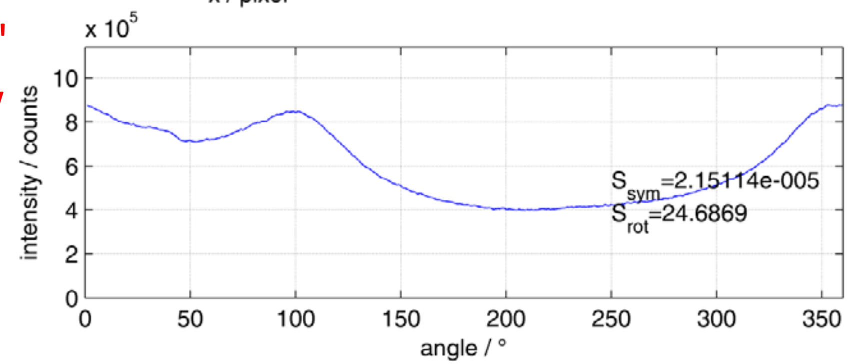


symmetry of plasma cloud

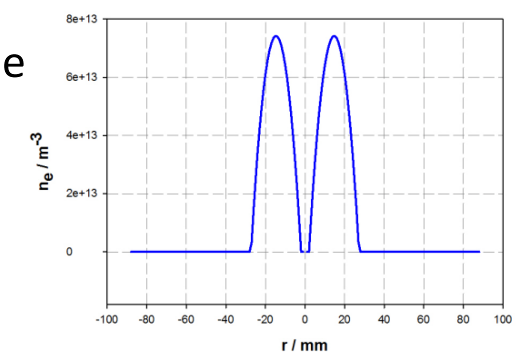


"light spot" on window





calculated electron density profile



parameter setup:
Φ_A=20 kV
B_z=5.4 mT
P=9.6e-6 (He)

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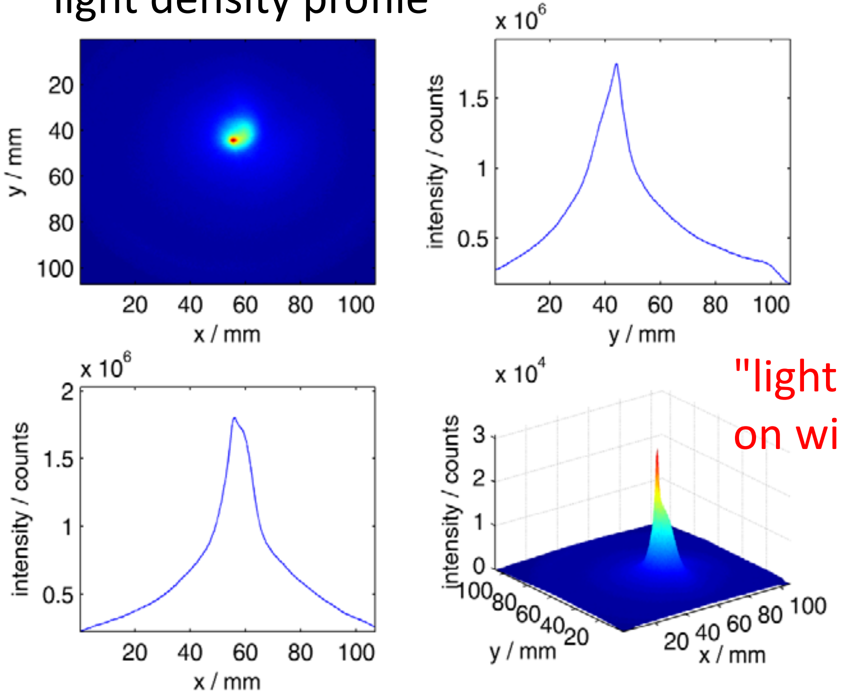
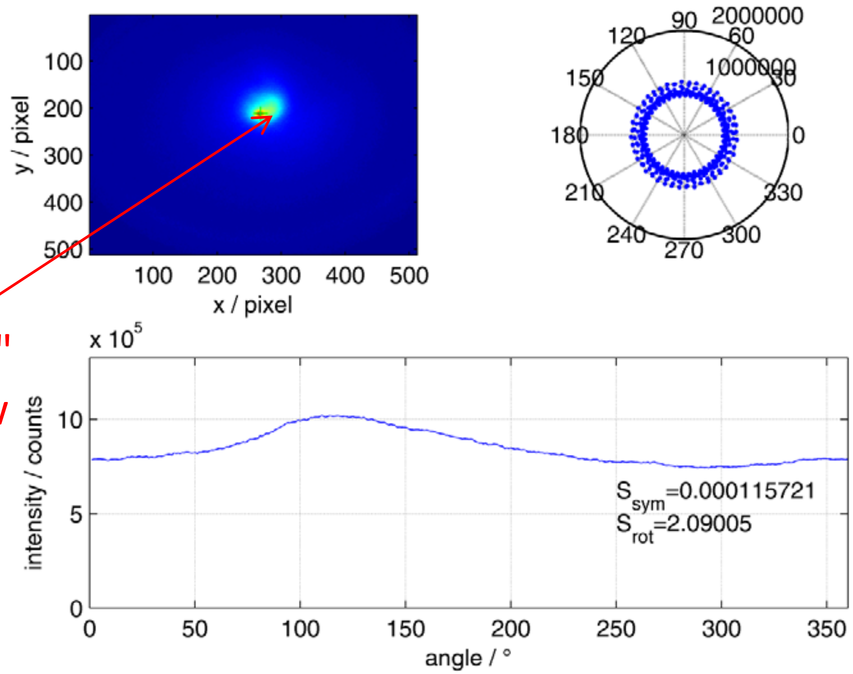
3.3. Low Current Measurements

light density profile

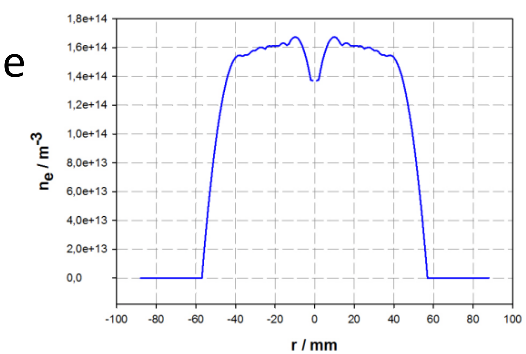


symmetry of plasma cloud



"light spot"
on window

calculated electron density profile



parameter setup:
Φ_A=20 kV
B_z=6.8 mT
P=9.6e-6 (He)

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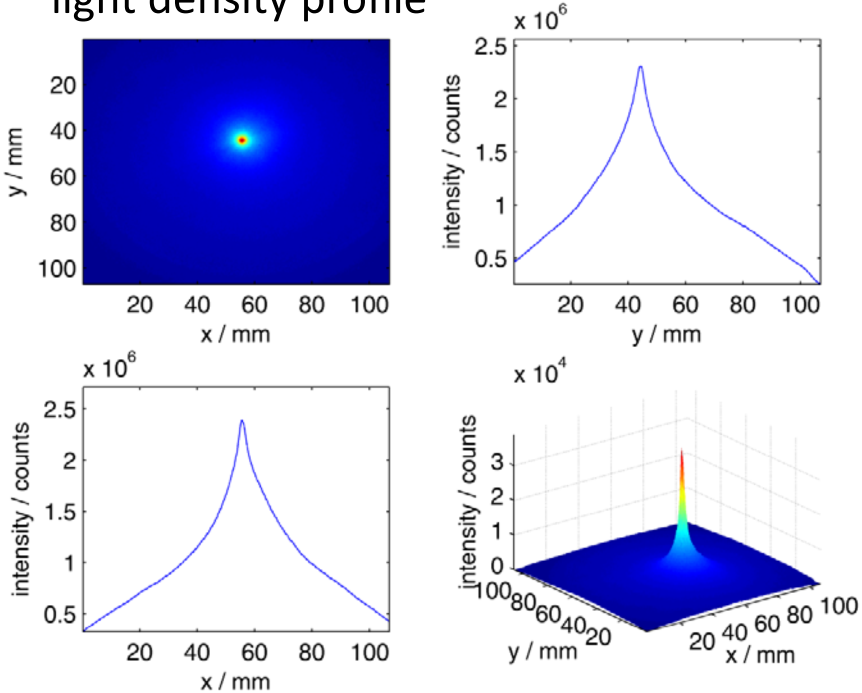
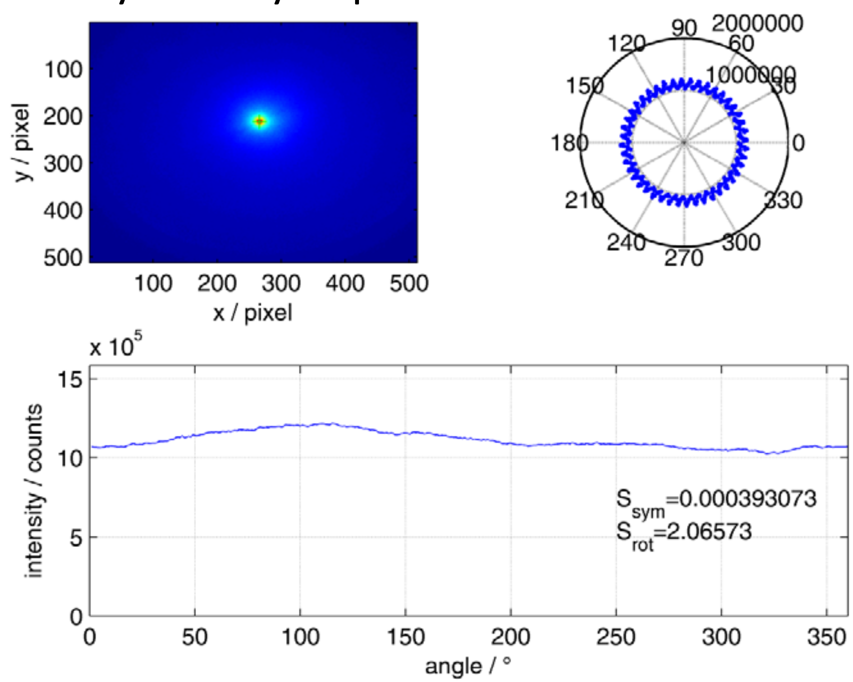
3.3. Low Current Measurements

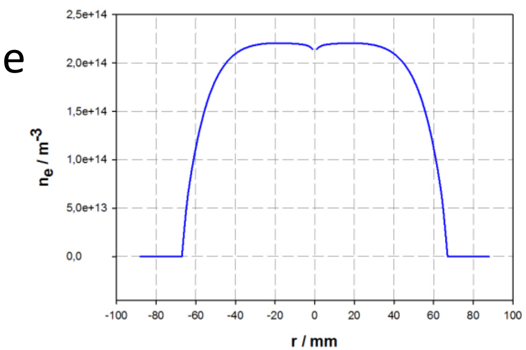
light density profile



symmetry of plasma cloud



calculated electron density profile



parameter setup:

Φ_A=20 kV

B_z=8.1 mT

P=9.6e-6 (He)

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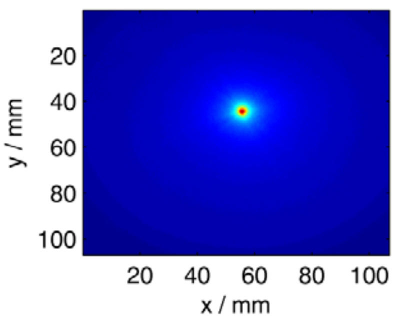
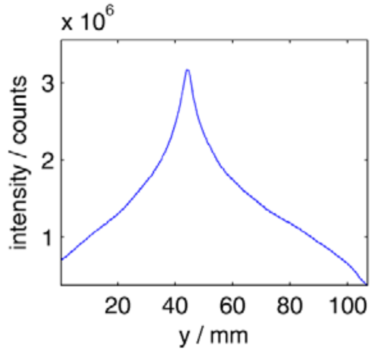
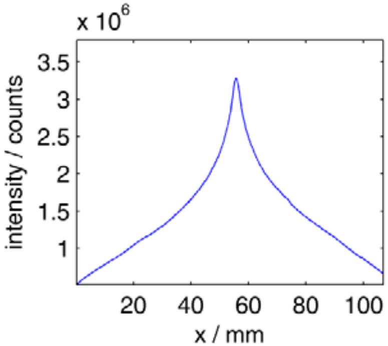
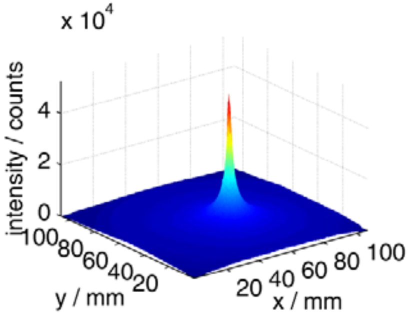
3.3. Low Current Measurements

light density profile

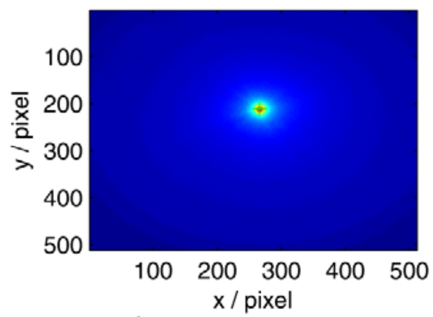


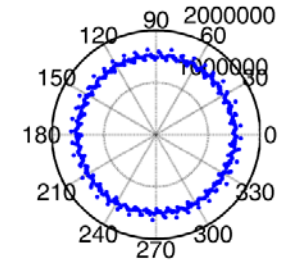


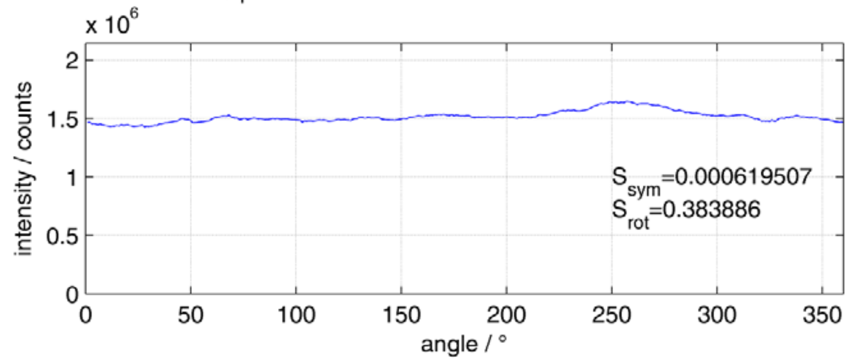




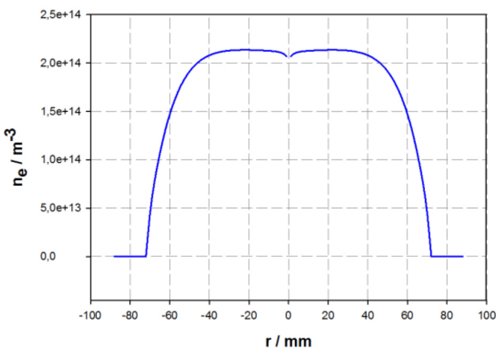
symmetry of plasma cloud







calculated electron density profile



parameter setup:
Φ_A=20 kV
B_z=9.5 mT
P=9.6e-6 (He)

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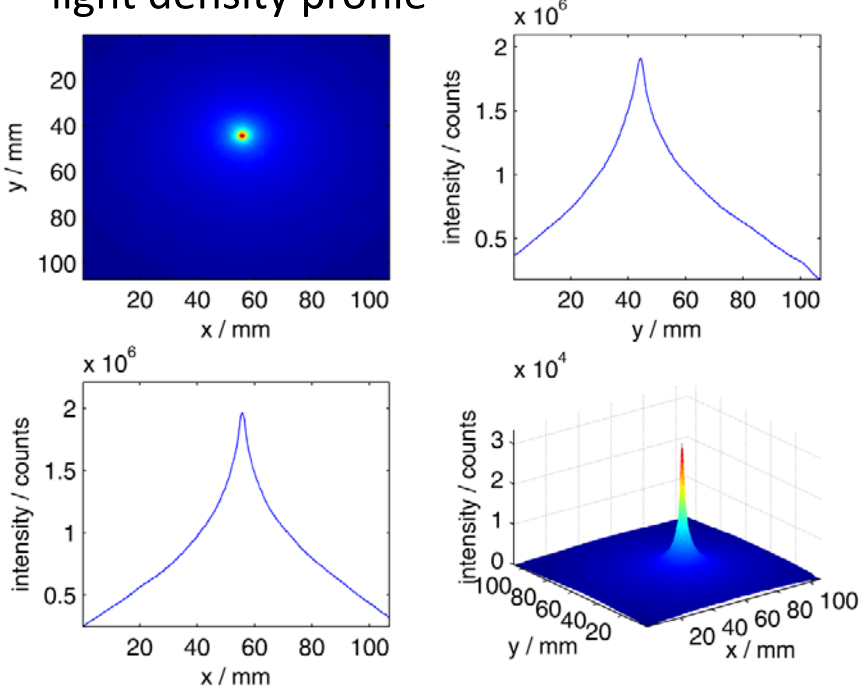
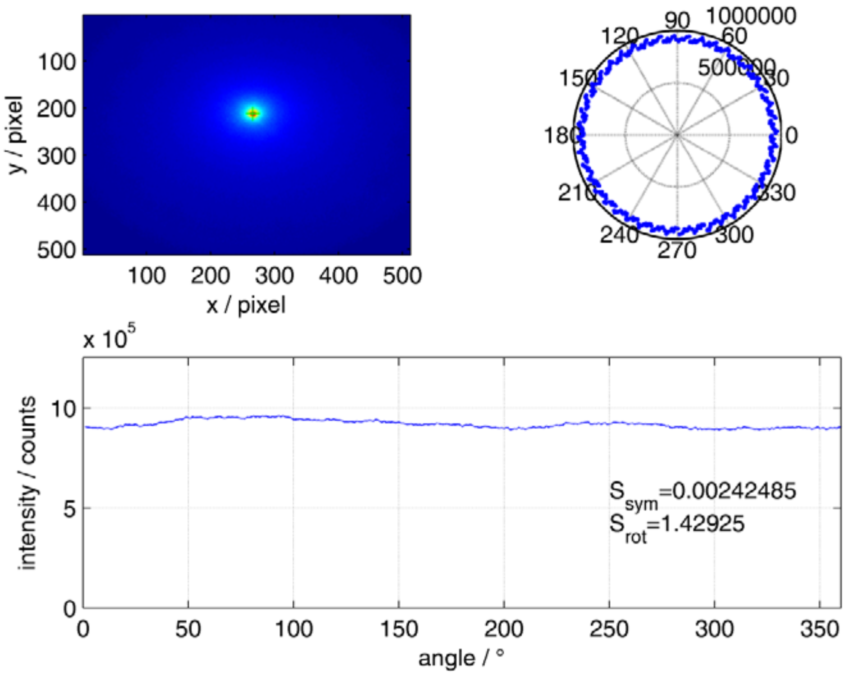
3.3. Low Current Measurements

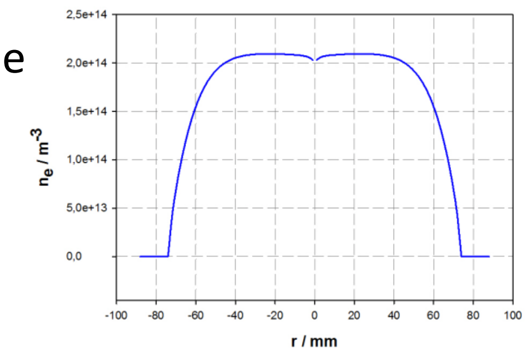
light density profile



symmetry of plasma cloud



calculated electron density profile



parameter setup:

Φ_A=20 kV

B_z=10.8 mT

P=9.6e-6 (He)

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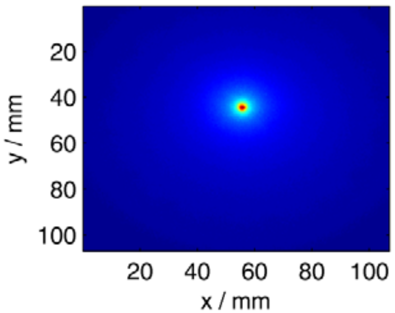
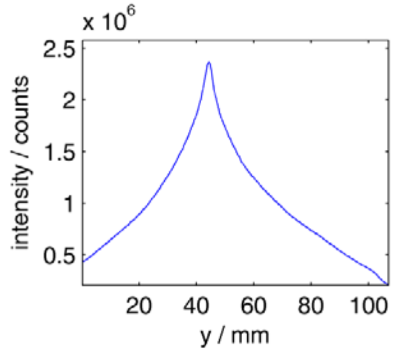
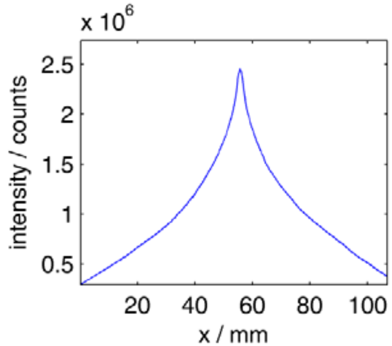
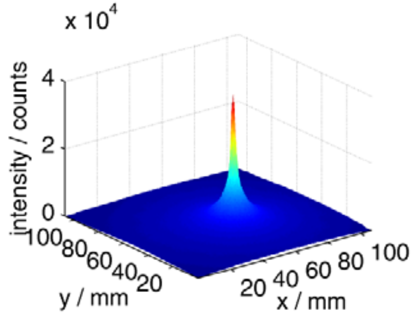
3.3. Low Current Measurements

light density profile

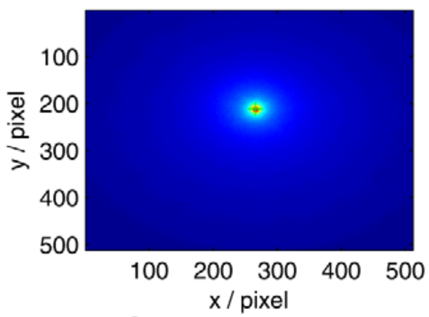


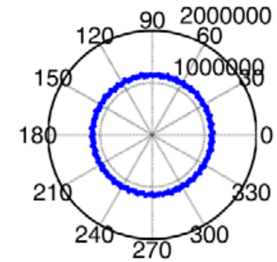


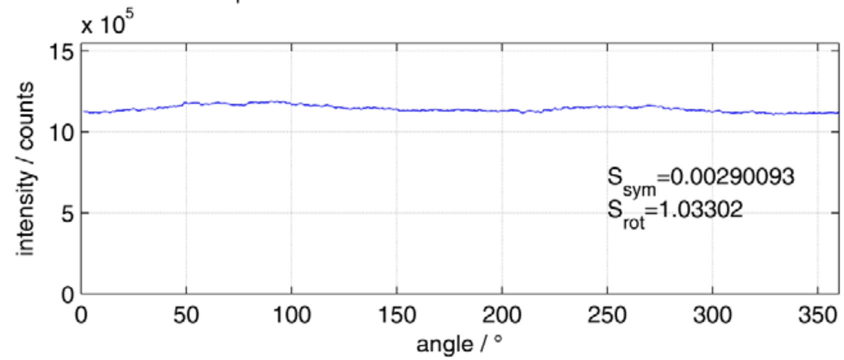




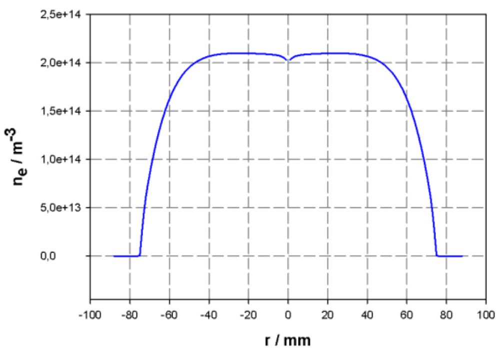
symmetry of plasma cloud







calculated electron density profile



parameter setup:
Φ_A=20 kV
B_z=12.2 mT
P=9.6e-6 (He)

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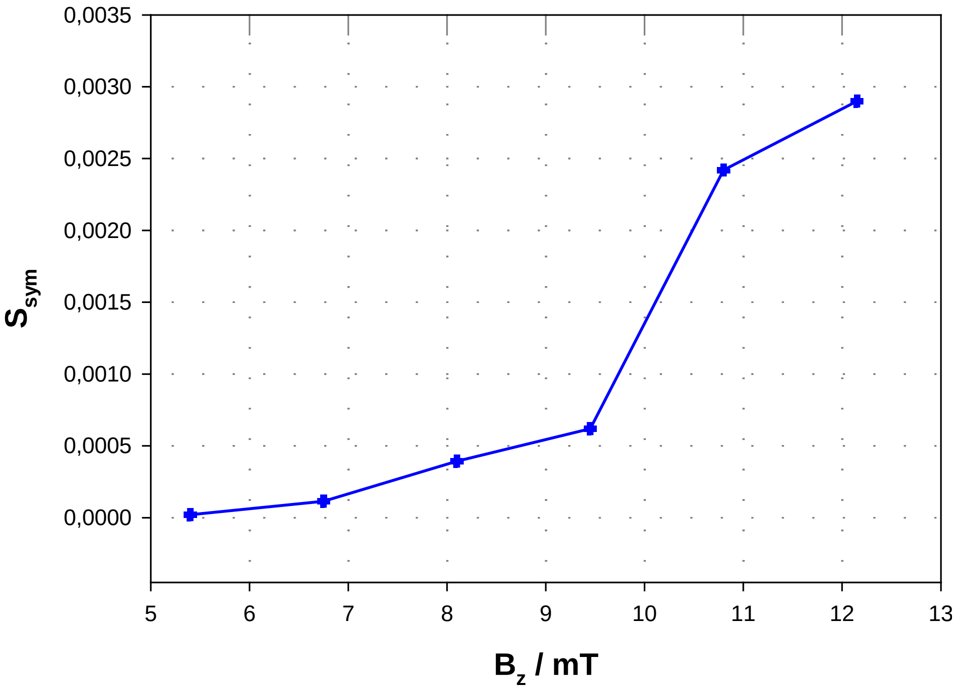
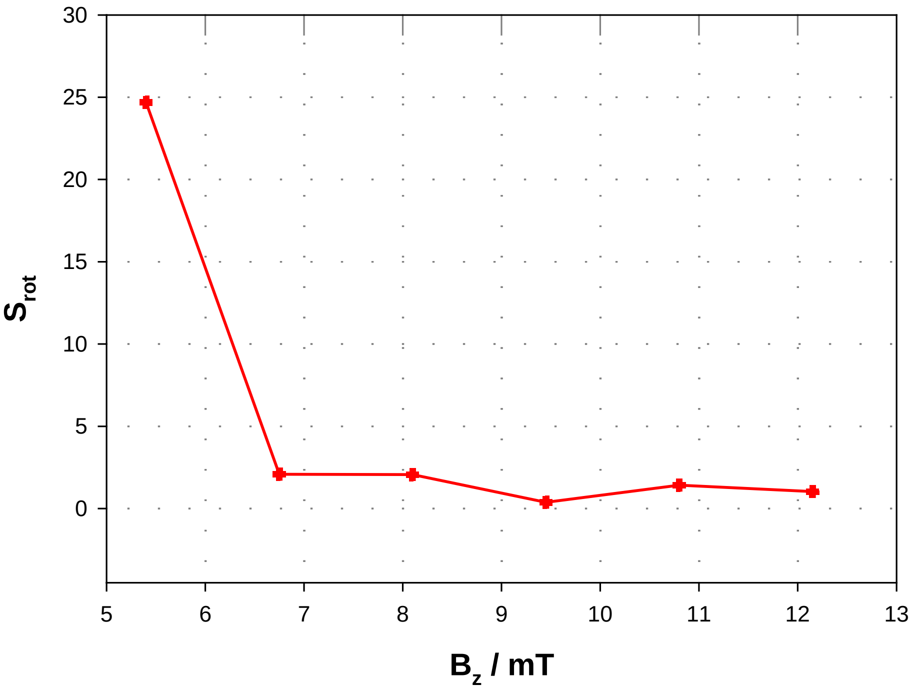
3.3. Low Current Measurements

symmetry



rotational symmetry



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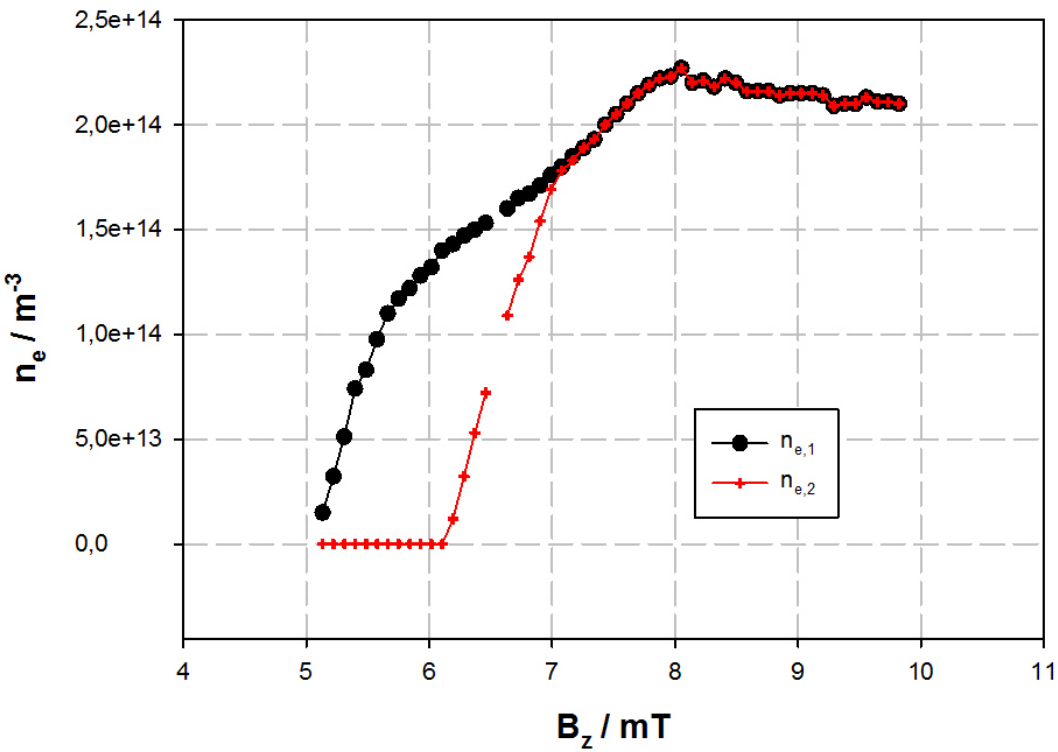
3.3. Low Current Measurements

simulated maximum electron density



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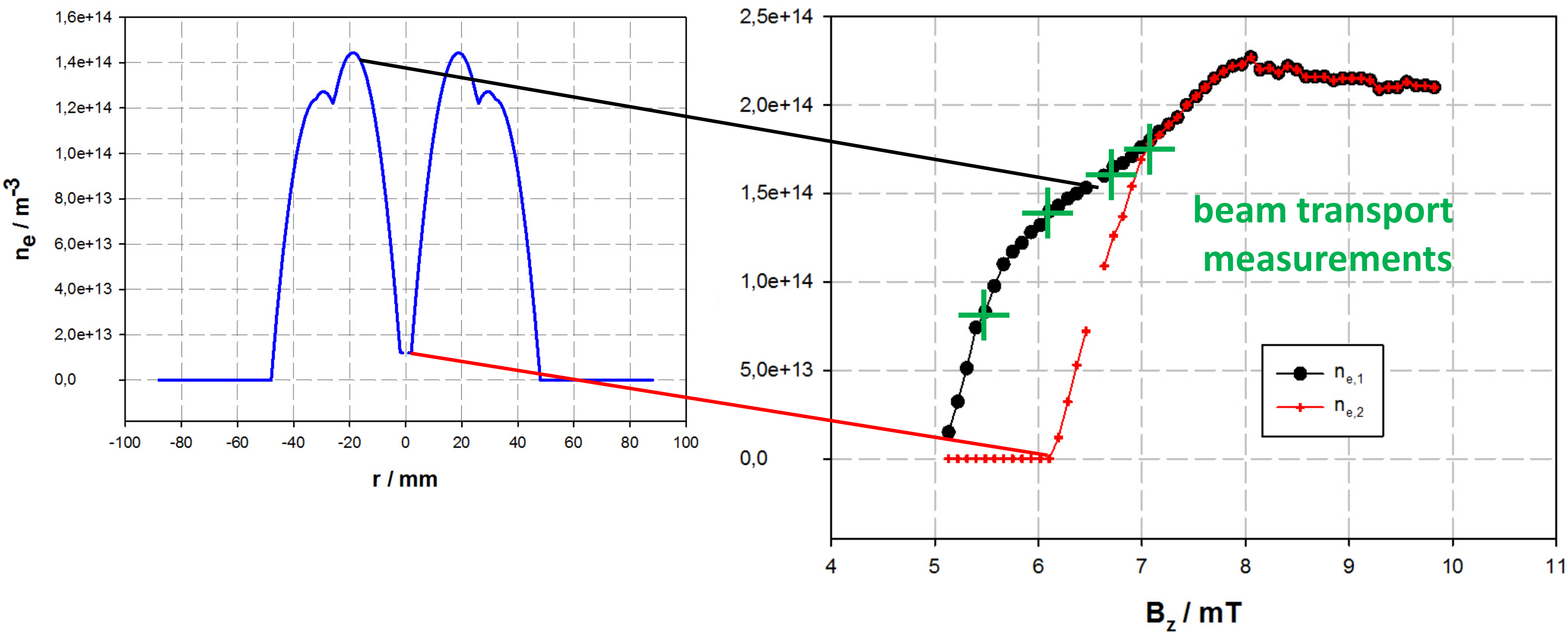
3.3. Low Current Measurements

simulated electron density distribution

simulated maximum electron density



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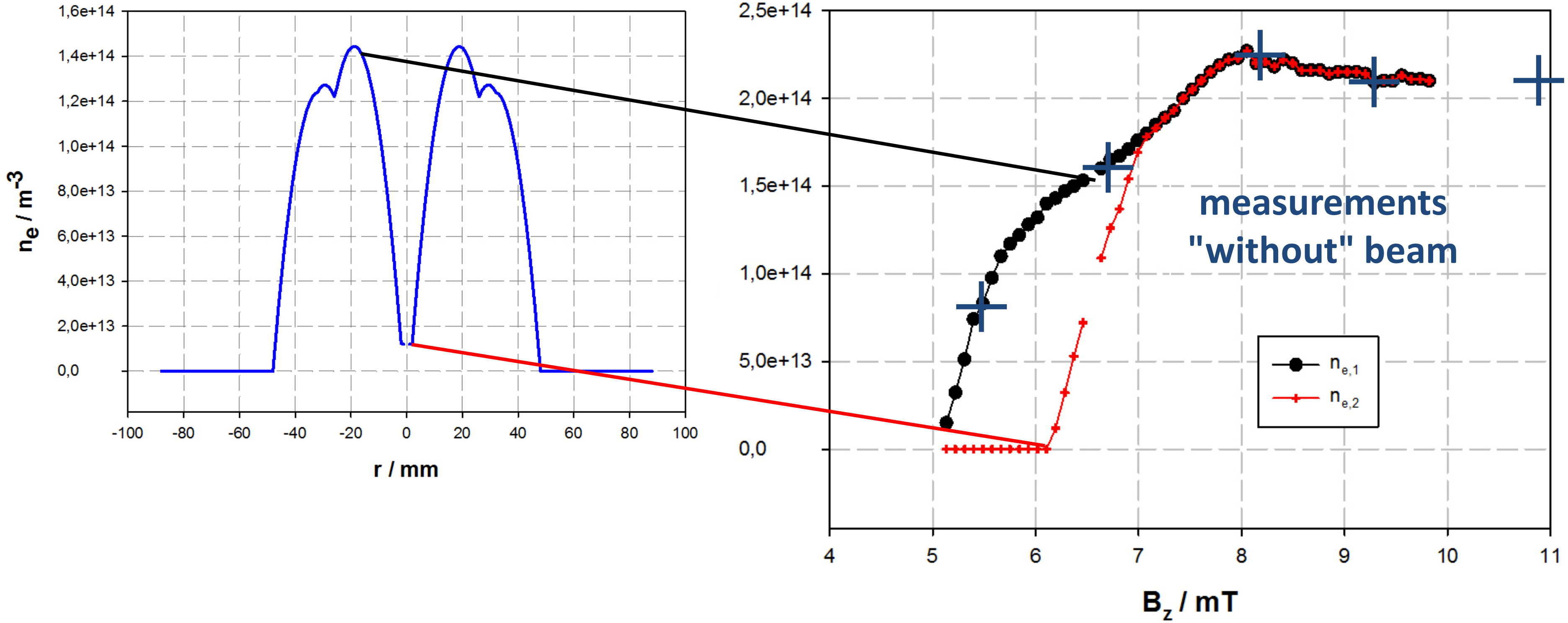
3.3. Low Current Measurements

simulated electron density distribution

simulated maximum electron density



carefully asking: *beam-driven instability?!*

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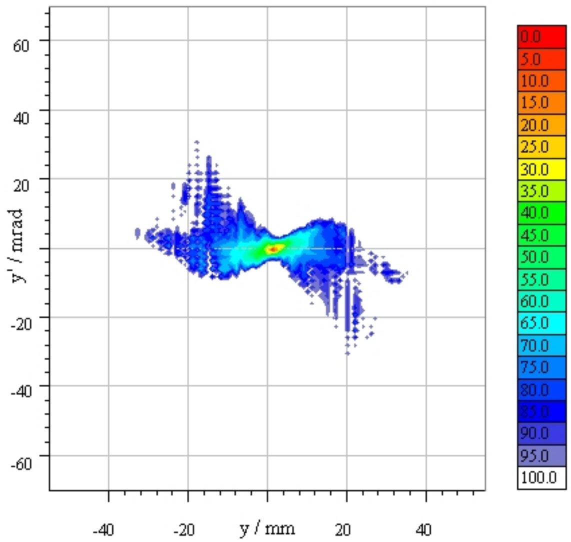
3.4. High Current Measurements - e^- Production

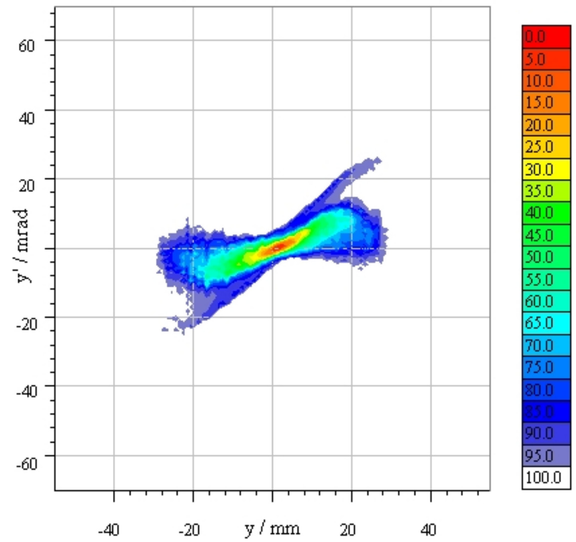
Influence of ion beam current / electron production rate on focusing strength ?!

$$\frac{n_i}{n_e} = 0,07$$



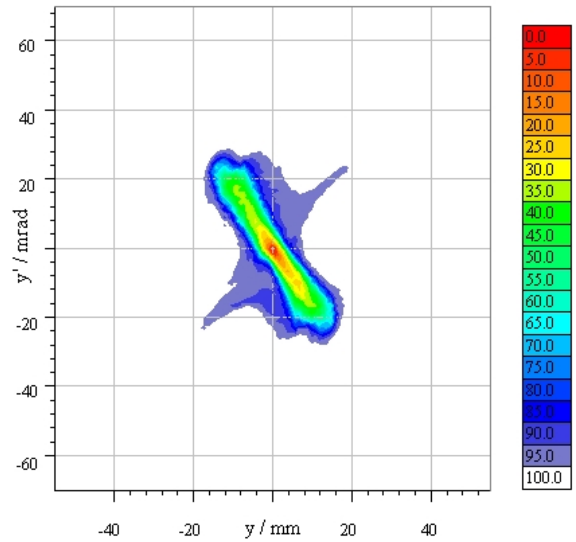
I_B=5 mA

$$\frac{n_i}{n_e} = 0,20$$



I_B=15 mA

$$\frac{n_i}{n_e} = 0,26$$



I_B=20 mA

lens parameters:
Φ_A= 9.5 kV
B_z= 9.7 mT

beam parameters:
Ar^+
W_B=88 keV (2.2 keV/u)

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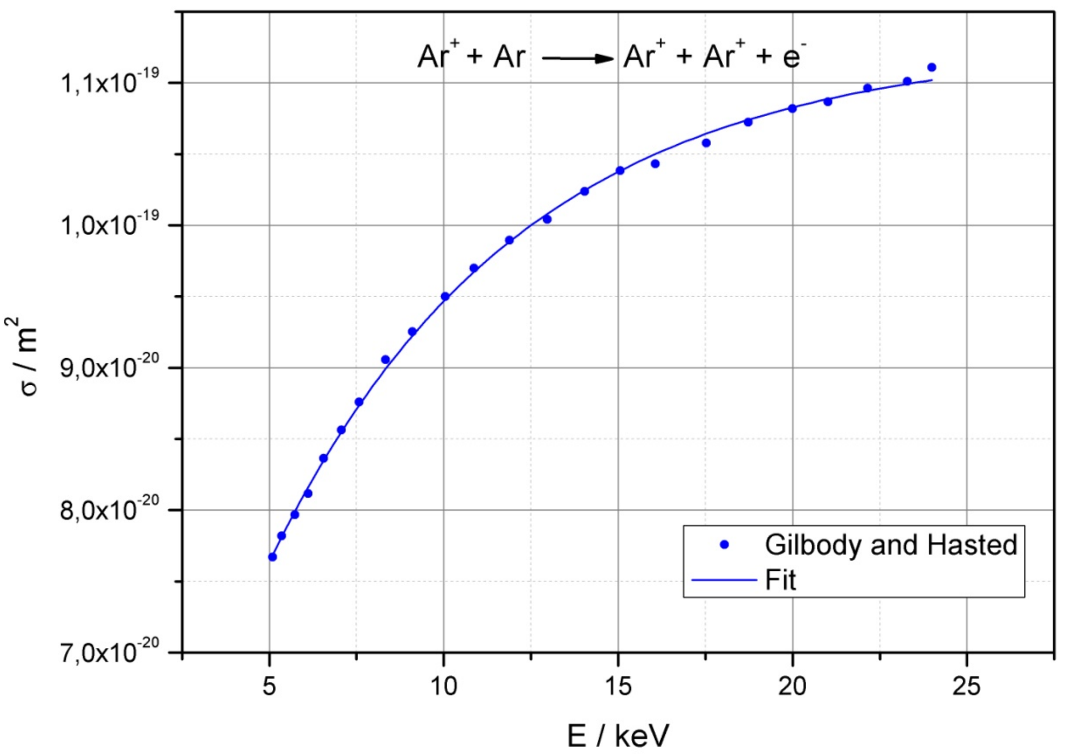
3.4. High Current Measurements - e^- Production

Ionization Cross Section



I_B = 5 mA --> $n_i = 2.45\ 10^{13}\ m^{-3}$:
$\nu_{in} = n_n\ \sigma(24keV)\ v_i = 2161$ Hz
$dn/dt = \nu_{in}\ n_i = 5.3\ 10^{16}\ m^{-3}s^{-1}$

--> **$6.61\ 10^{13}\ m^{-3}$** within 1.25 ms

I_B=15 mA --> $n_i = 7.35\ 10^{13}\ m^{-3}$:
$dn/dt = \nu_{in}\ n_i = 1.59\ 10^{17}\ m^{-3}s^{-1}$

--> **$2\ 10^{14}\ m^{-3}$** within 1.25 ms

I_B=20 mA --> $n_i = 9.81\ 10^{13}\ m^{-3}$:
$dn/dt = \nu_{in}\ n_i = 2.12\ 10^{17}\ m^{-3}s^{-1}$

--> **$2.65\ 10^{14}\ m^{-3}$** within 1.25 ms

beam parameters:
Ar^+, W_B=88 keV (2.2 keV/u) --> v_i=650 10^3 m/s

lens parameters:
Φ_A= 9.5 kV, B_z= 9.7 mT, $n_{e,theo,max}=3.9\ 10^{14}\ m^{-3}$, $n_{e,simu,max}=1.15\ 10^{14}\ m^{-3}$

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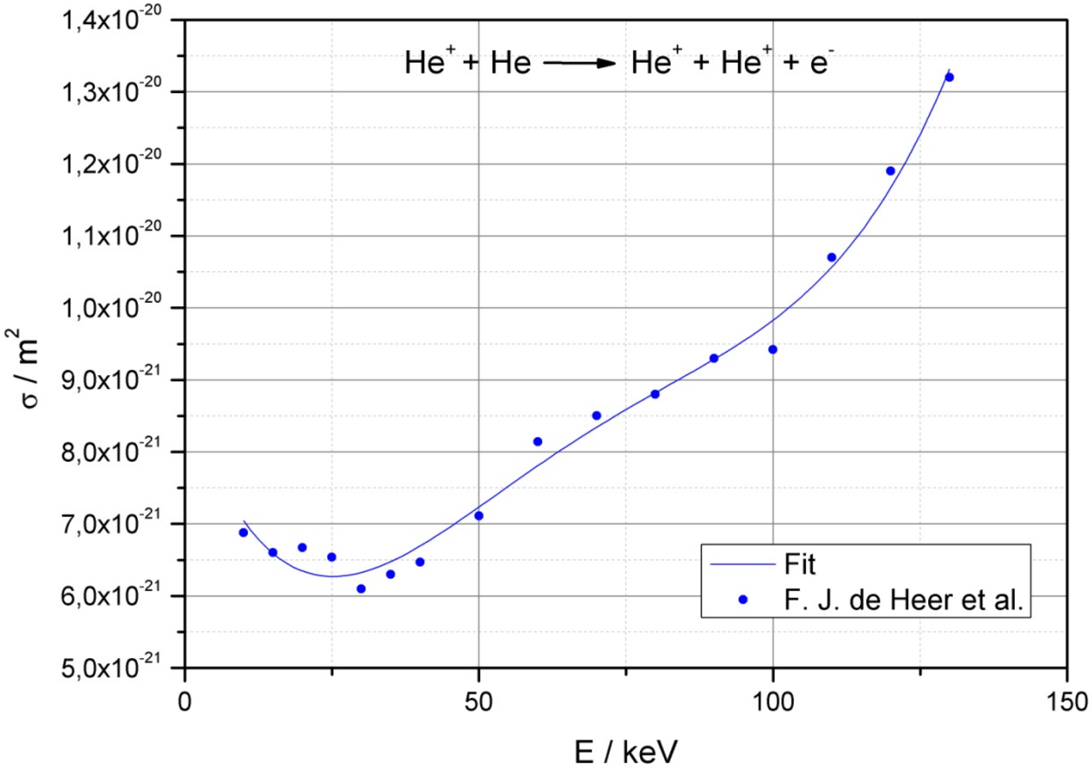
3.4. High Current Measurements - e^- Production

Ionization Cross Section



Comparison:

$\mathbf{I_B = 3\ mA}$ --> $n_i = 4.84\ 10^{12}\ m^{-3}$:
$\nu_{in} = n_n\ \sigma(50\ keV)\ v_i = 2612\ Hz$
$dn/dt = \nu_{in}\ n_i = 1.26\ 10^{16}\ m^{-3}s^{-1}$

--> $\mathbf{1.58\ 10^{13}\ m^{-3}}$ within 1.25 ms

Other e^- production processes like

secondary thermal ions on chamber wall (charge exchange)

or

beam ions strinking ground vessel

are neglected.

beam parameters:

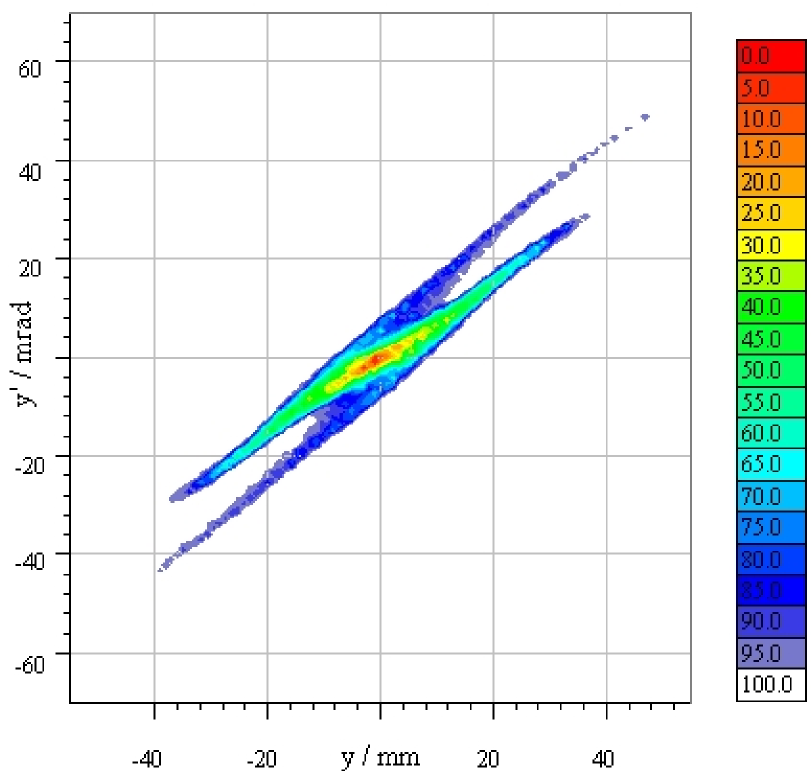
He^+, W_B=50.3 keV (12.6 keV/u) --> v_i=1.6 10^3 m/s

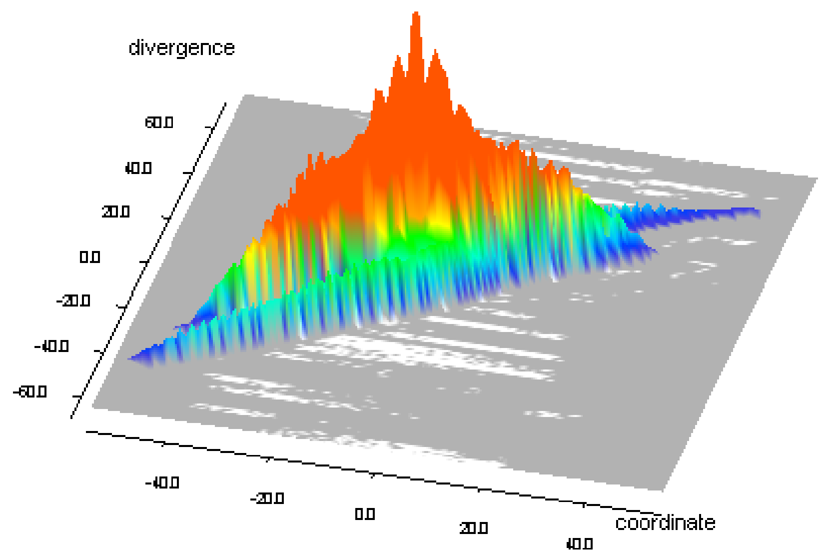
lens parameters:

Φ_A= 20 kV, B_z=12.2 mT, $n_{e,theo,max}$=7.9 $10^{14}\ m^{-3}$, $n_{e,simu,max}$=2 $10^{14}\ m^{-3}$

3.4. High Current Measurements

drifted beam





Ar^+
W_b = 124 keV, 3.1 keV/u
I_B=30 mA

Φ_A= 0 kV
B_z= 0 mT
$\varepsilon_{100\%}$= 1860.69 mm mrad
$\varepsilon_{97\%}$= 269.8 mm mrad
ε_{rms}= 0.16558 π mm mrad
ω =3.45
n = 3

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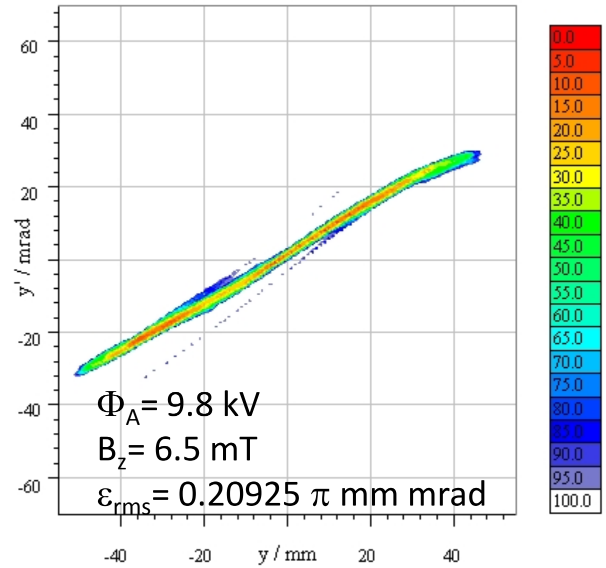
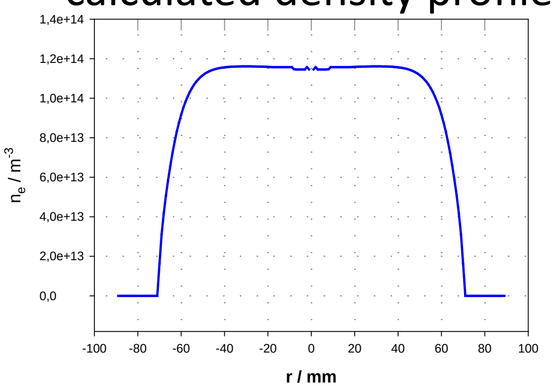
3.4. High Current Measurements

beam transport measurement

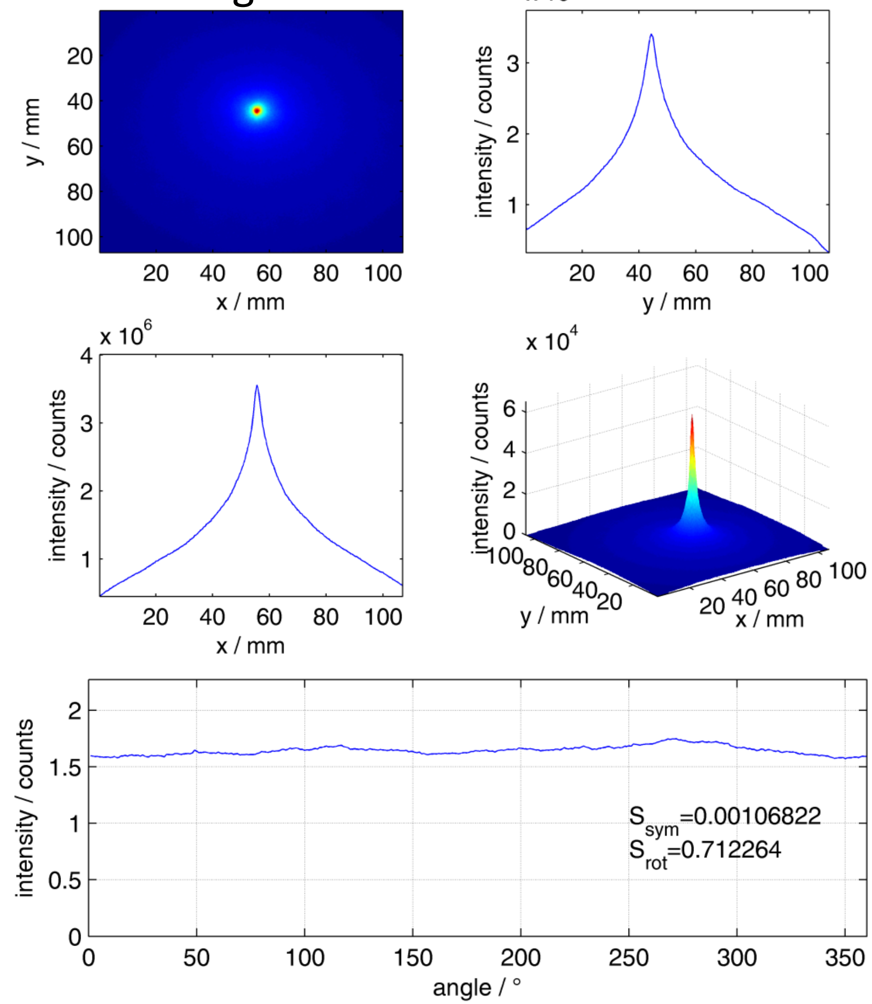


Φ_A= 9.8 kV
B_z= 6.5 mT
ε_{rms}= 0.20925 π mm mrad

calculated density profile



NNP diagnostics



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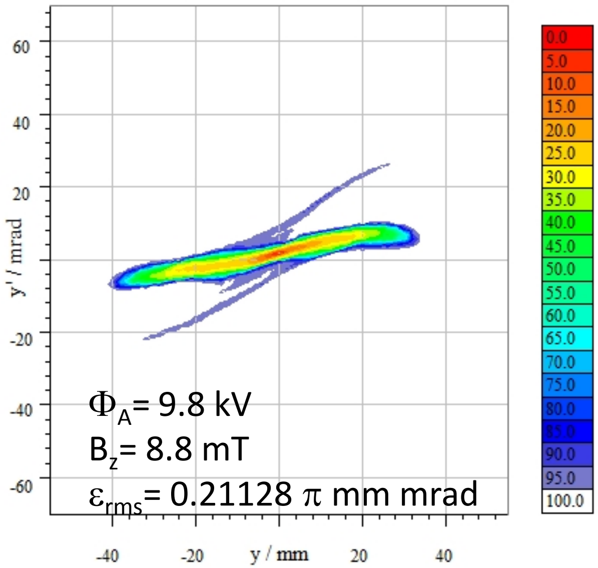
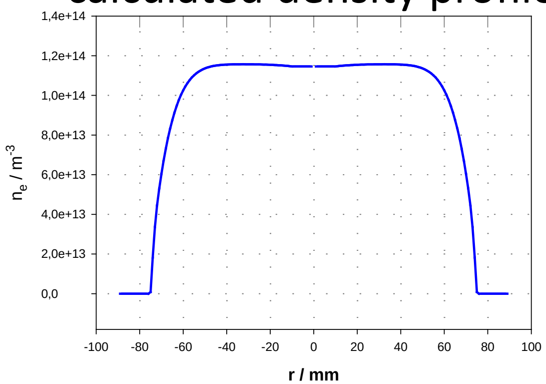
3.4. High Current Measurements

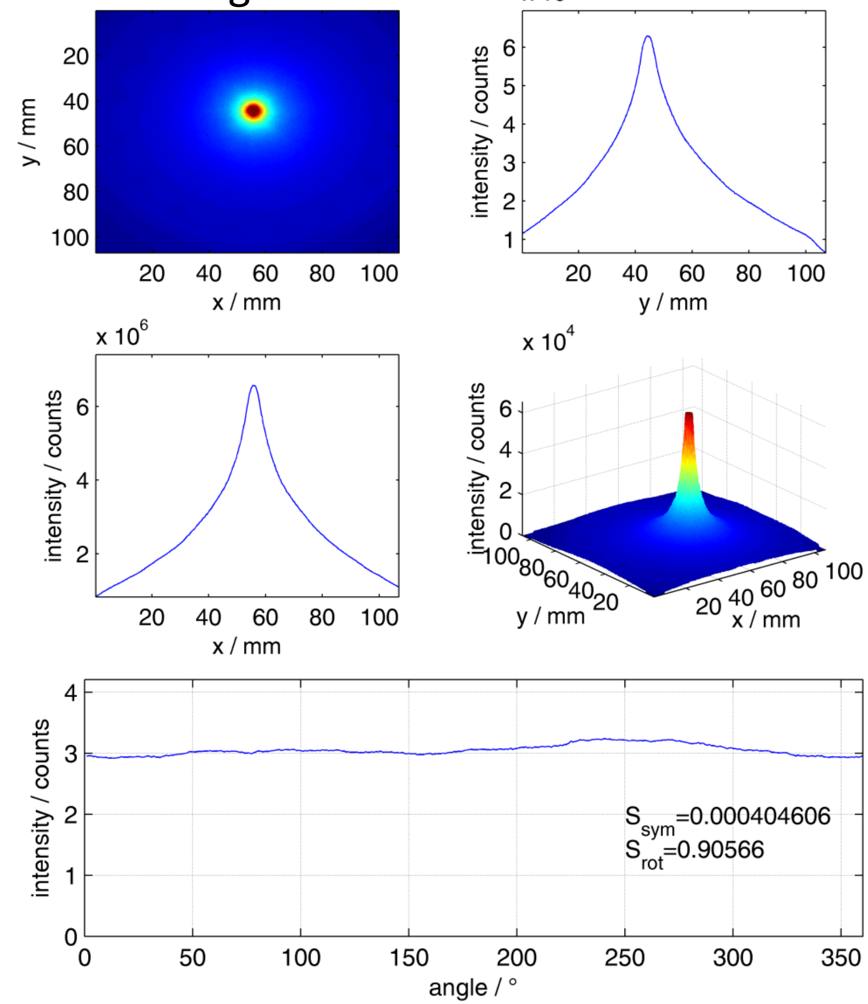
beam transport measurement



calculated density profile



NNP diagnostics



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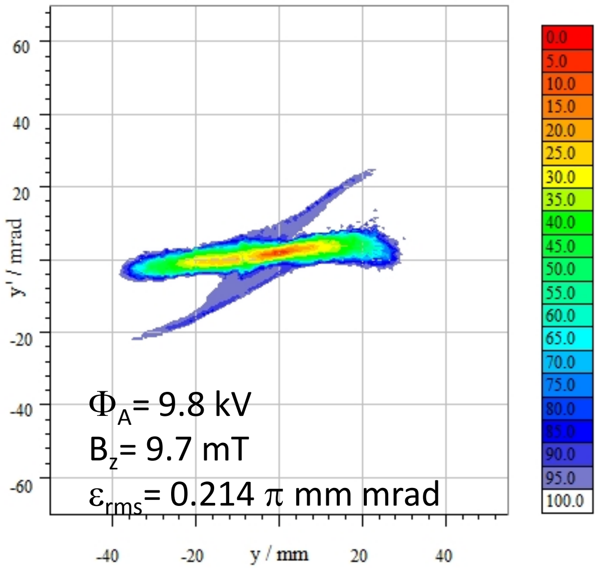
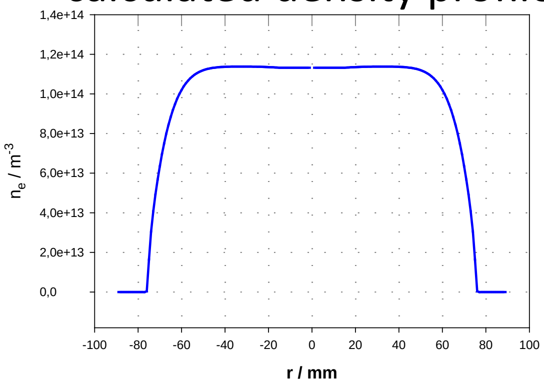
3.4. High Current Measurements

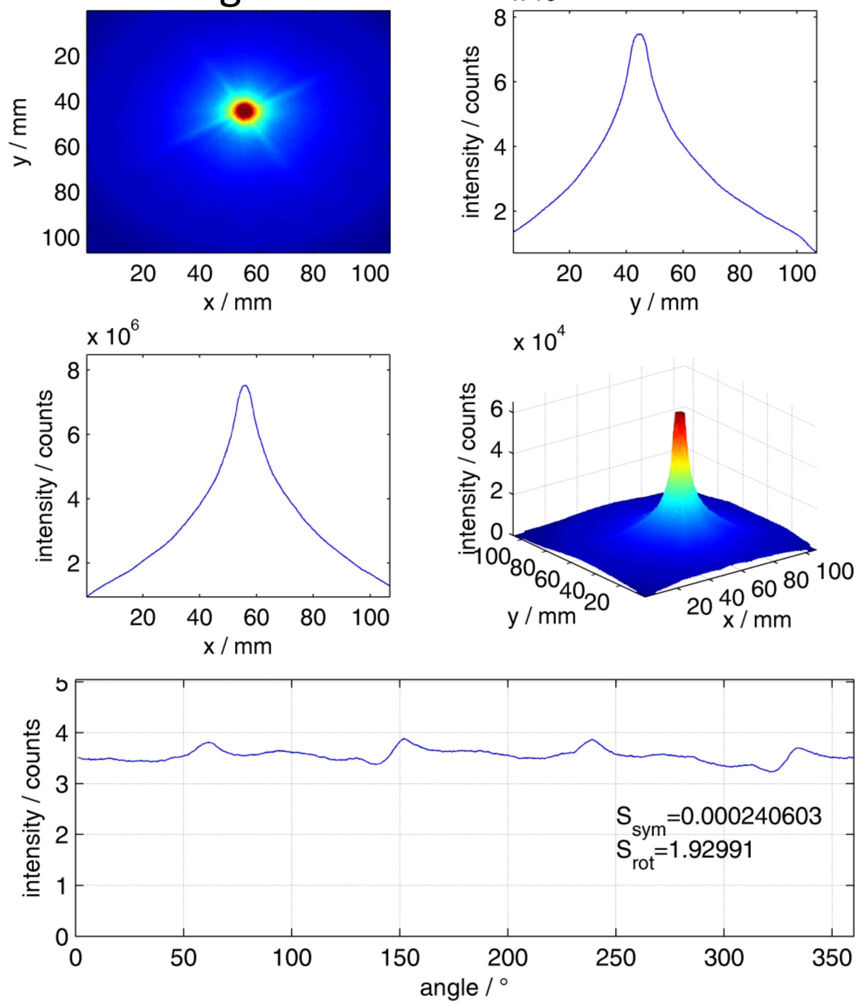
beam transport measurement



calculated density profile



NNP diagnostics



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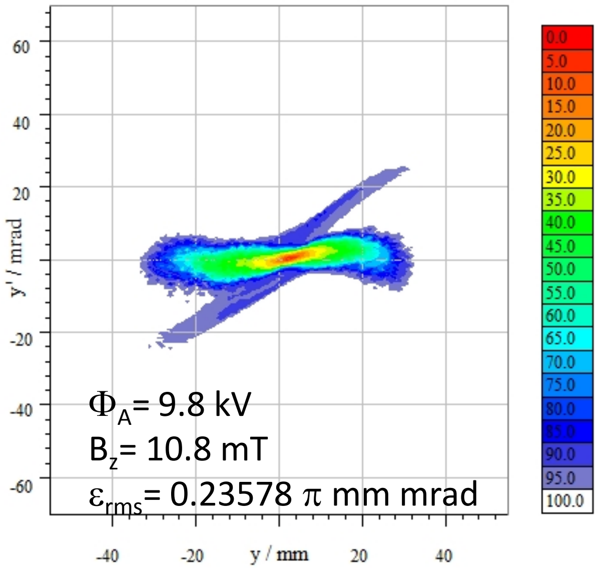
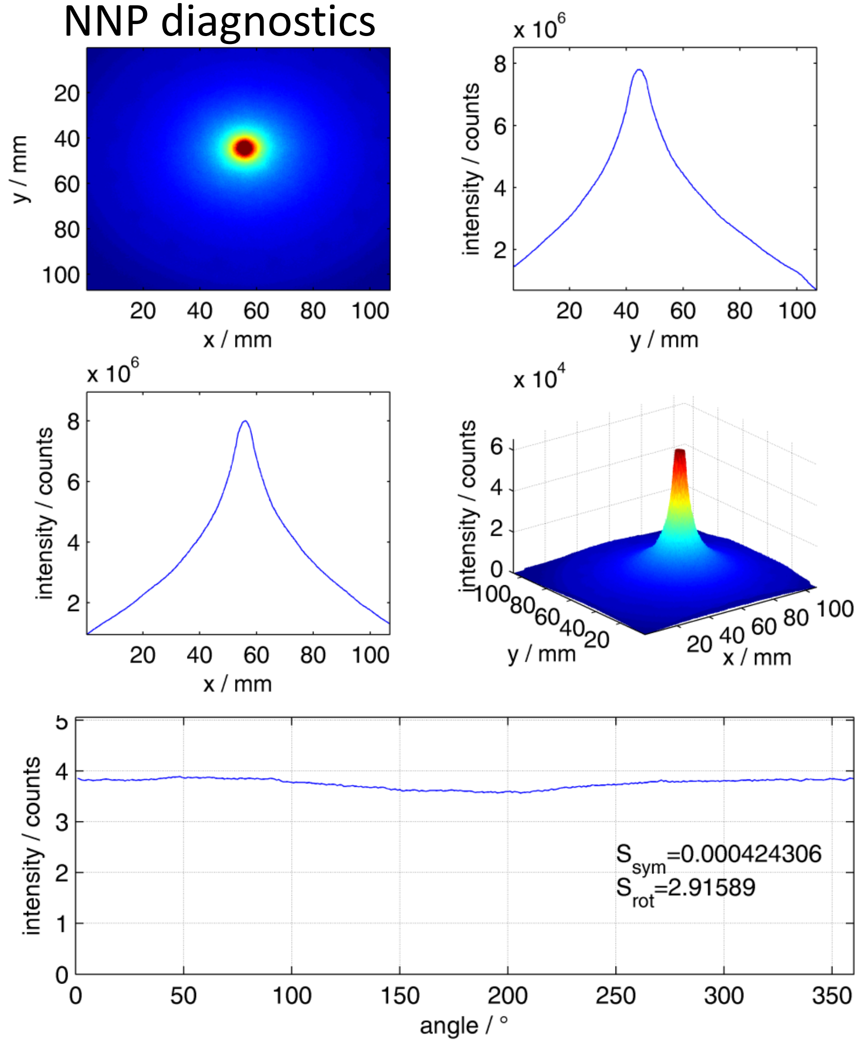
3.4. High Current Measurements

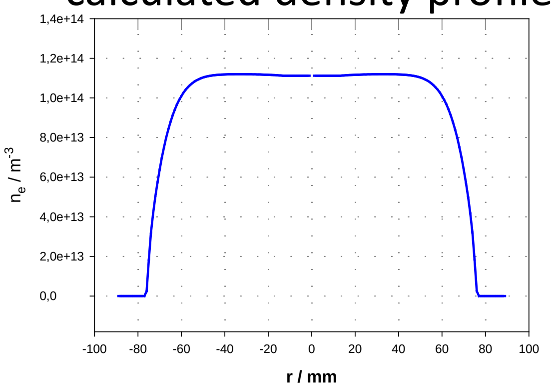
beam transport measurement



NNP diagnostics



calculated density profile



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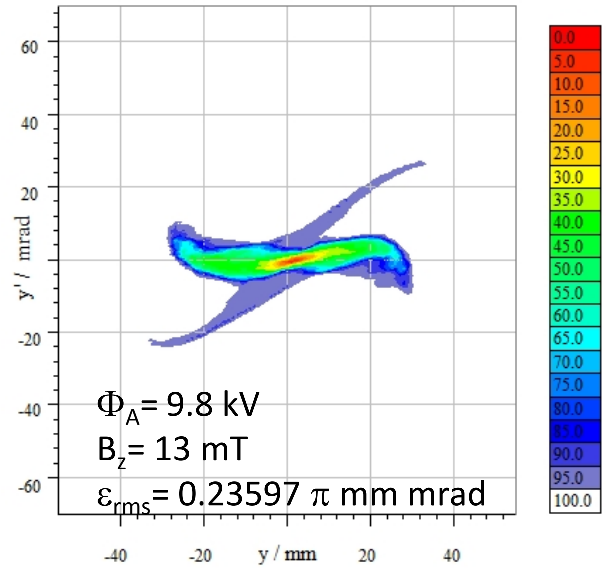
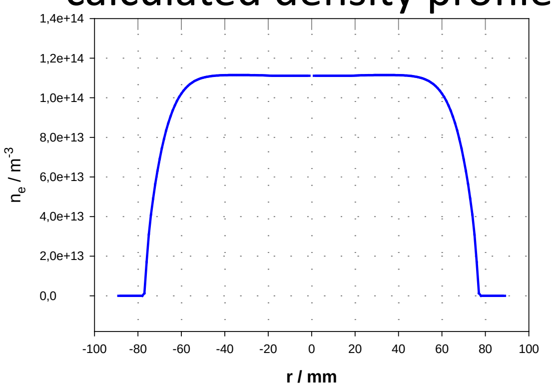
3.4. High Current Measurements

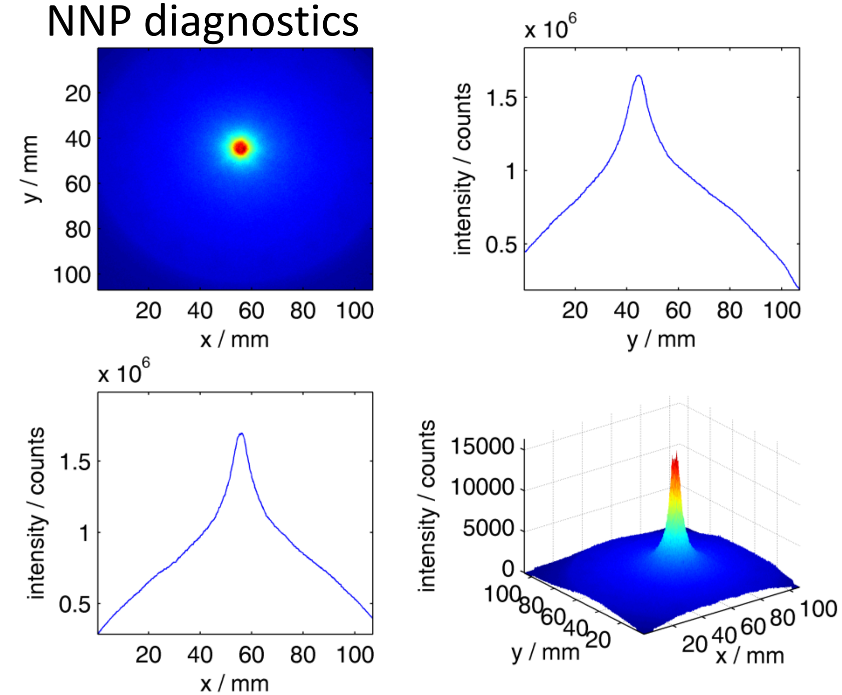
beam transport measurement

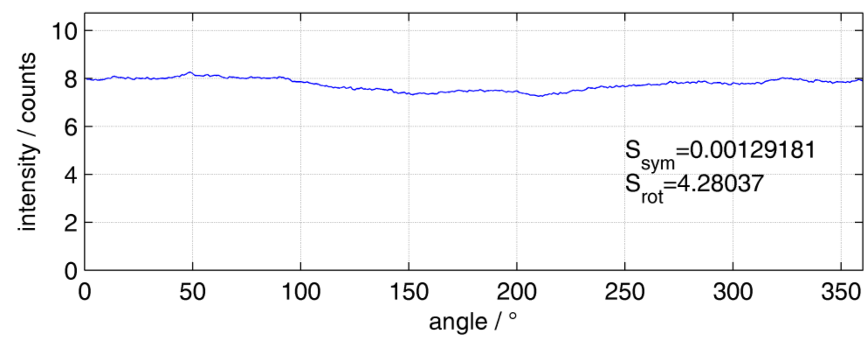


calculated density profile



NNP diagnostics





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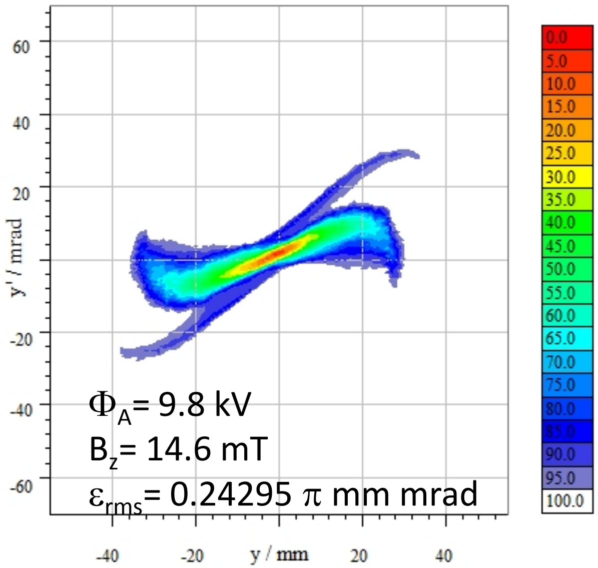
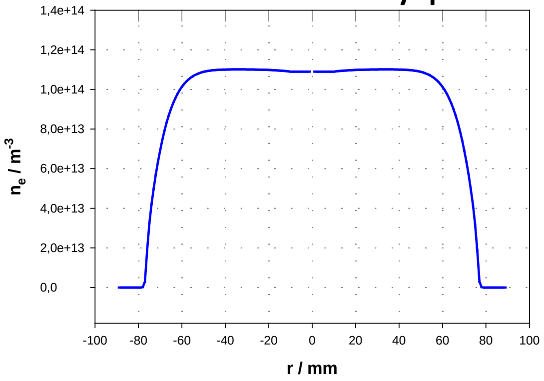
3.4. High Current Measurements

beam transport measurement



calculated density profile



NNP diagnostics

NNP fluctuated,
measurement not possible

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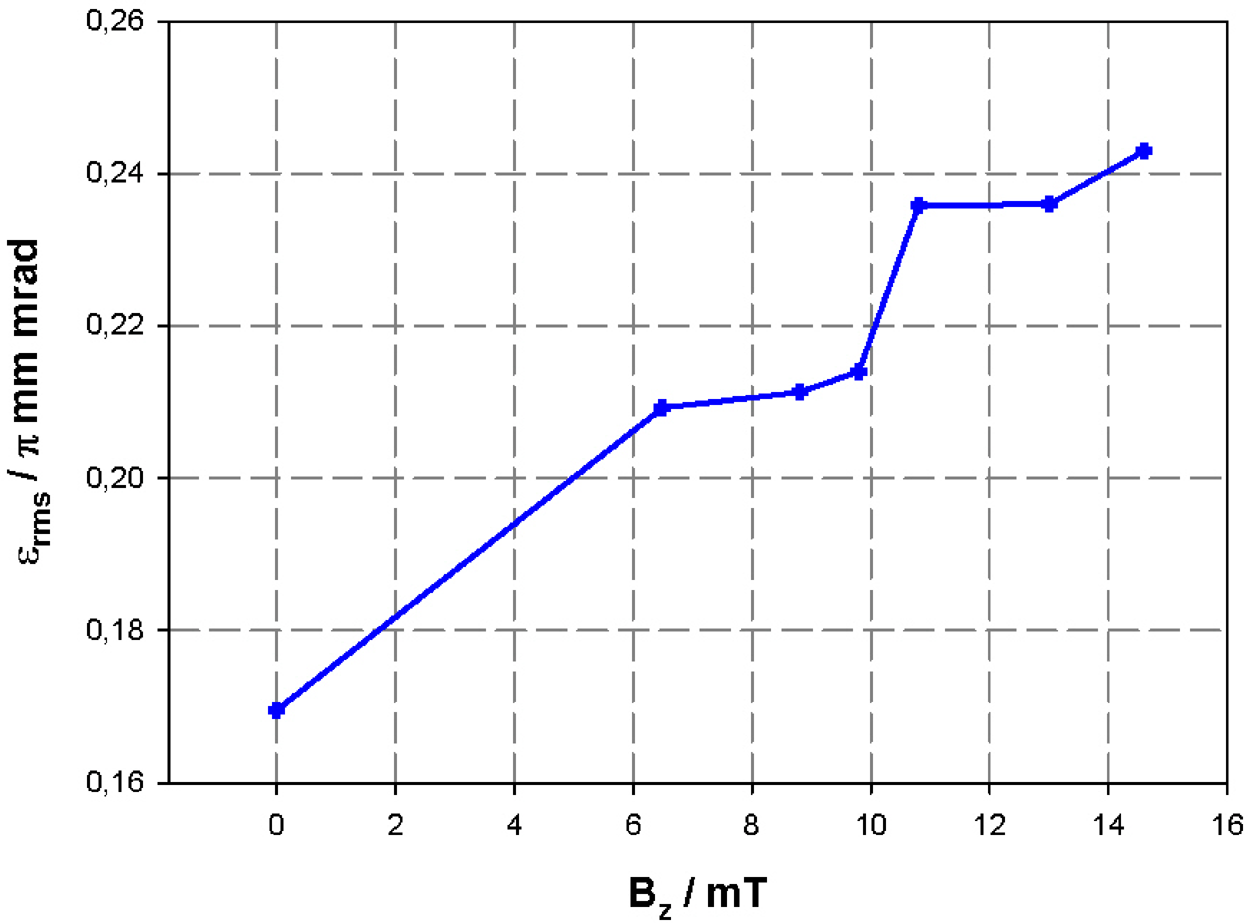
3.4. High Current Measurements

measured rms-emittance



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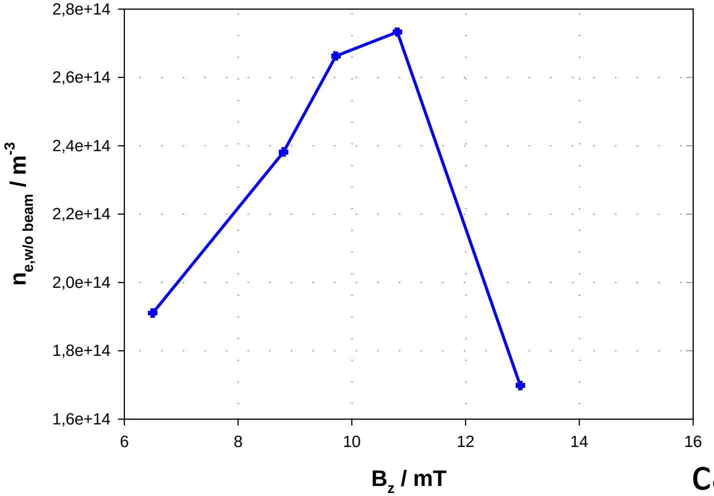
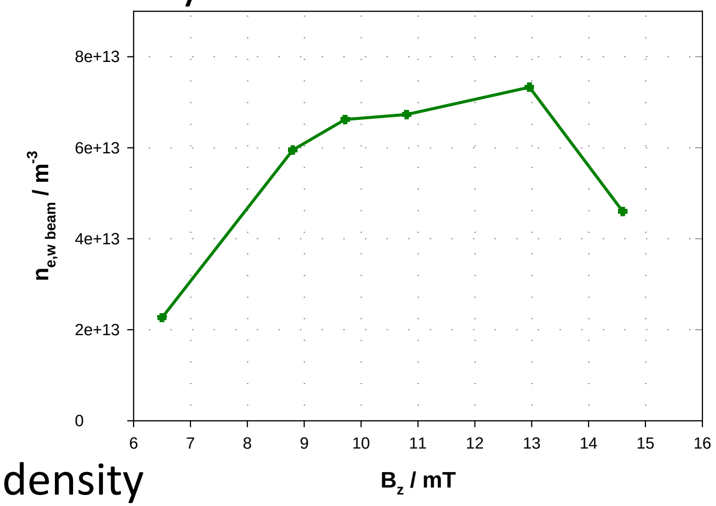
3.4. High Current Measurements

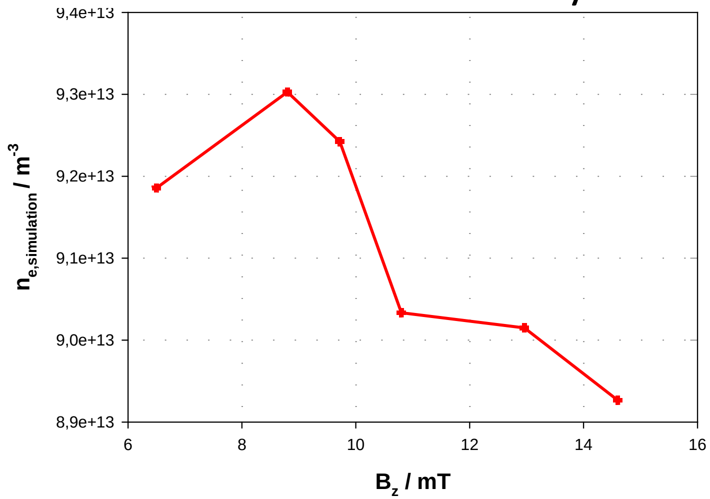
density measurement "without" beam



density measurement "with" beam



calculated density



strong discrepancy between measurement and simulation

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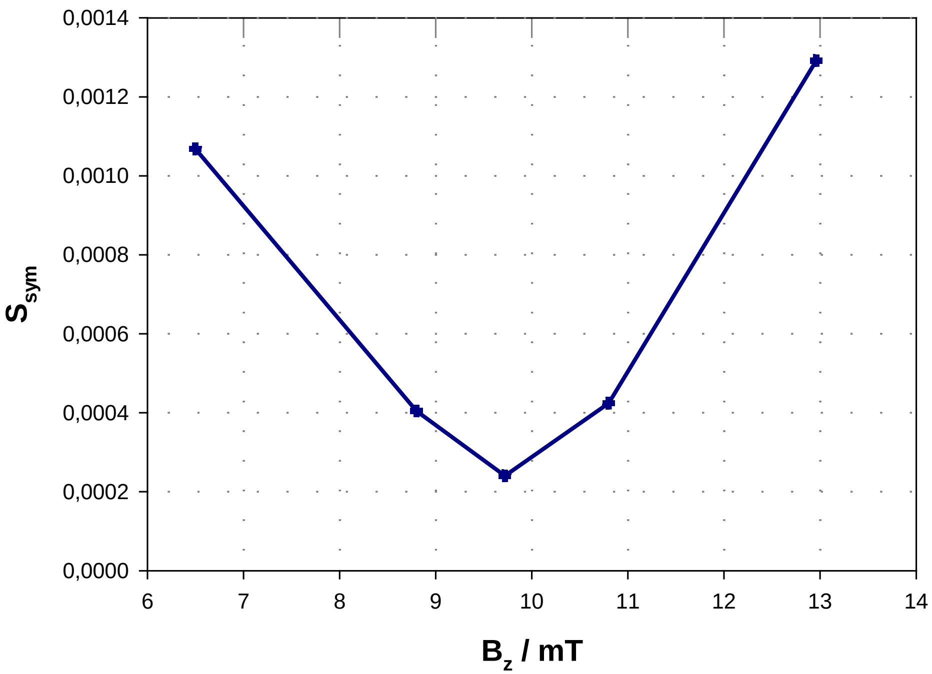
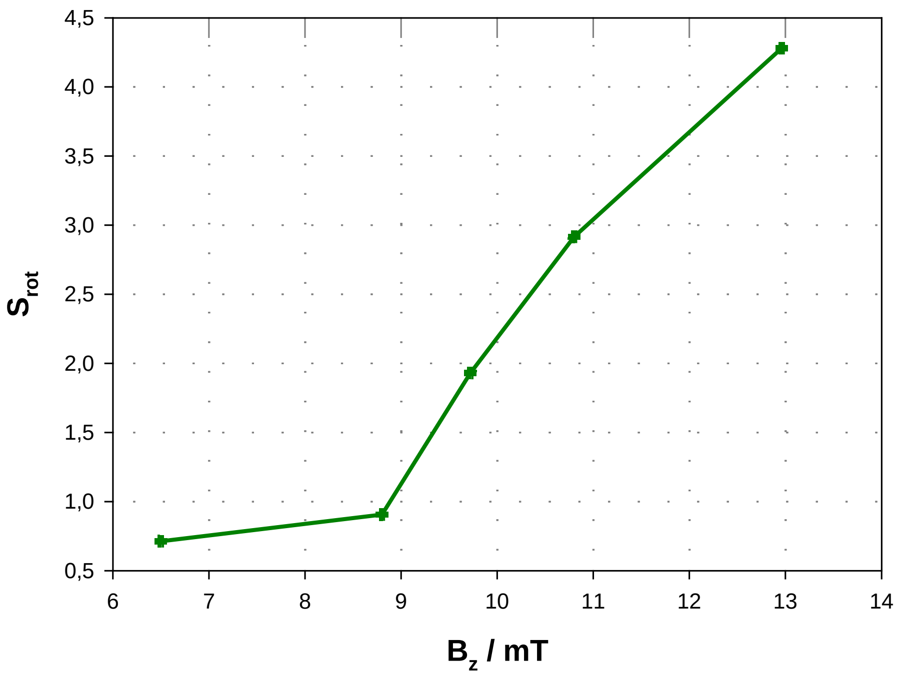
3.4. High Current Measurements

symmetry



rotational symmetry



4. Summary

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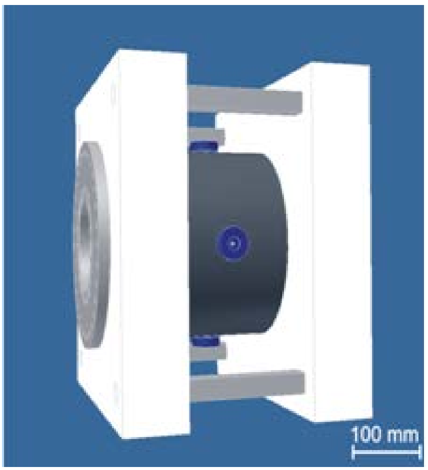
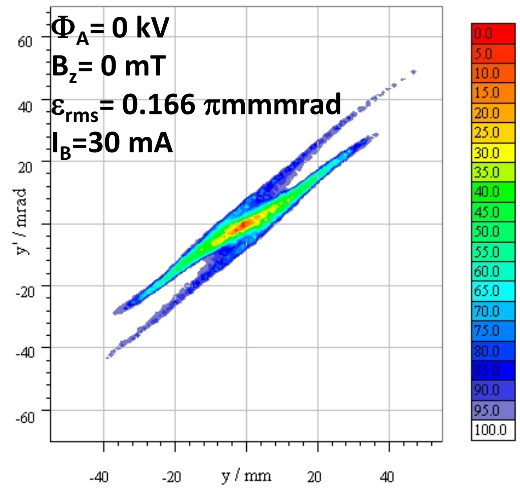
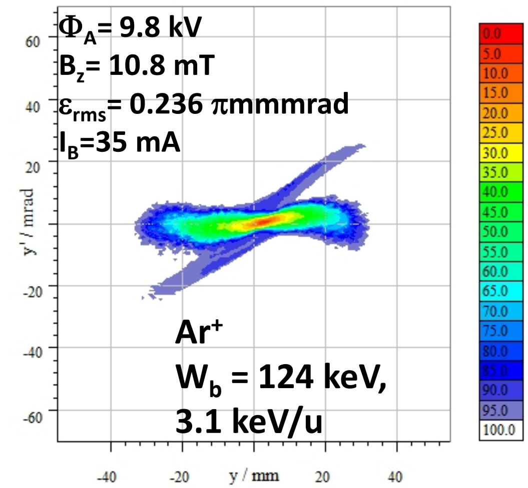
4.1. Summary

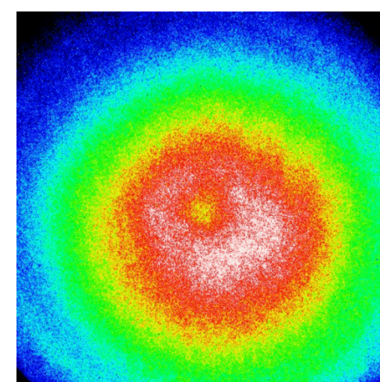
- Design and performance studies of prototype lens for GSI







- Development and evaluation of non-interceptive diagnostic methods
  - electron density measurement
  - temperature measurement
  - electron density distribtion - symmetry and dynamics



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Thank you for your attention!