LhARA Capture Meeting

11th April 2022

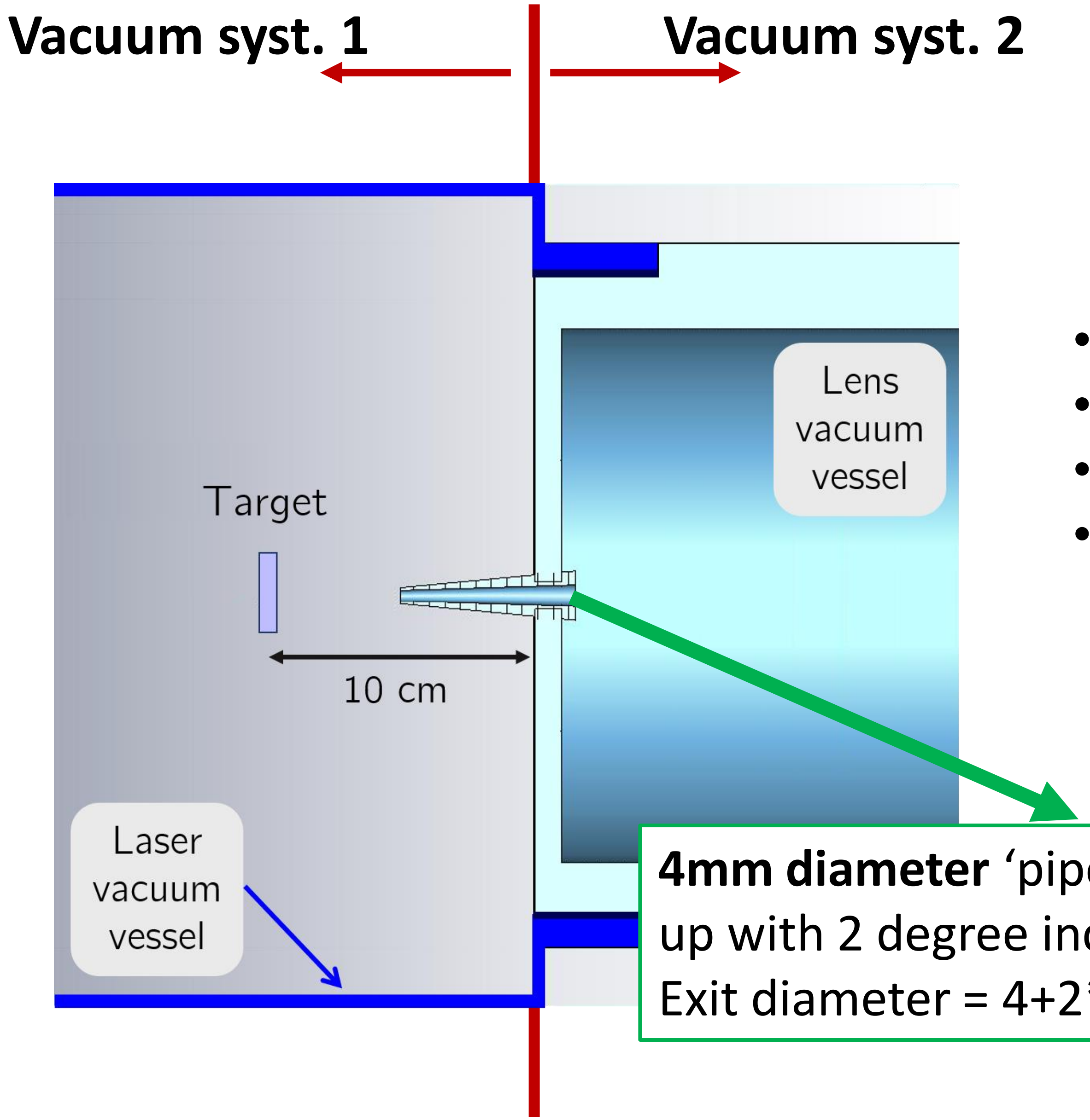
Titus Dascalu

Source/lens interface

Rationale for the source/lens interface

C. Whyte

- 300 l/sec pump
- Base pressure 10^{-5} mBar
- Molecular flow regime



- 300 l/sec pump
- Lower base pressure
- Turbo + NEG pump
- $< \sim 10^{-7}$ mBar

Tube must provide more than 3 orders of magnitude pressure drop

4mm diameter ‘pipe’ **50mm long** tapering up with 2 degree included angle;
Exit diameter = 4+2*(50tan1) = 5.74mm

Rationale for the source/lens interface

C. Whyte

Dushman's Table (straight tube)

$$^{l}/_{a} = {}^{50\text{ mm}}/_{2\text{ mm}} = \mathbf{25}$$

Conductance $C_t = 0.194\ \mathrm{l/s}$

Throughputs (Q) measured at either end of tube are equal (no gas generation inside tube):

$$Q_1 = p_1 S_1 = p_2 S_2 = C_t(p_1 - p_2) = Q_2$$

$$p_2 = p_1 C_t / (S_2 + C_t)$$

$$C_t = 0.018 \rightarrow p_2 = p_1 \times (\mathbf{6 \times 10^{-4}})$$

$$C_t = 0.020 \rightarrow p_2 = p_1 \times (\mathbf{4 \times 10^{-4}})$$

Gabor lenses in development

>20 years of investigations in Frankfurt

NNP
Non Neutral Plasma Physics Group

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Aim: focus high intensity ion beams–improve focusing quality and reduce the emittance growth
(+ space-charge compensation)

GL tested so far:

<30 keV Ar-, He- beams

<130 keV, 35 mA Ar1 beams

Name	Radius	Length	r/l	Ref.	ϕ_A
small GL	0.054 m	0.16 m	0.3375	[2]	6 kV
3-segmented GL	0.054 m	0.4 m	0.135	[3]	6.5 kV
HSI-GL	0.085 m	0.340 m	0.25	[4]	50 kV (r_p=5 cm)
Toroid-GL	0.1 m	0.68 m	0.147	[5]	
GL2000	0.075 m	2 m	0.0375	(*)	30 kV

Table 1: Aspect ratio of the Gabor Lenses designed by the NNP Group
(*) under construction

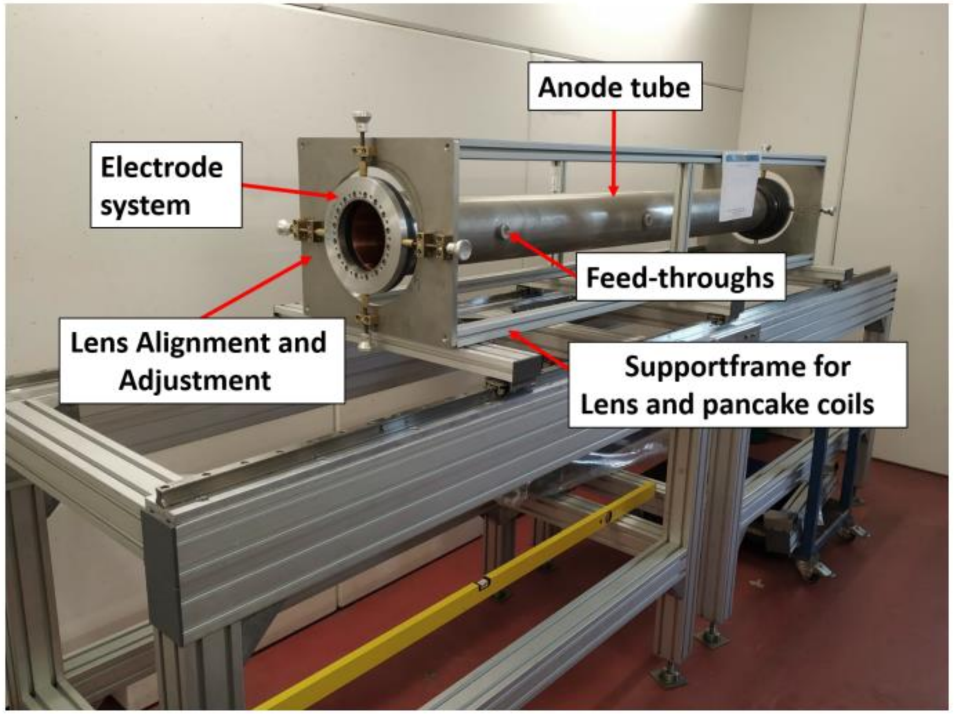


Figure 4: Picture of the present experimental setup of GL2000 (October 2018).

"The formation of an electron cloud in the GL2000 is expected to take at least longer than in the previously investigated lenses."

http://dx.doi.org/10.23732/CYRCP-2020-007.143

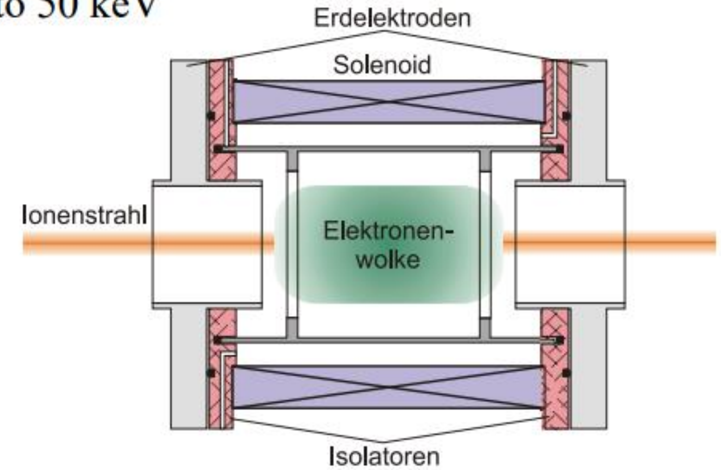
Types of lenses at IAP, Frankfurt

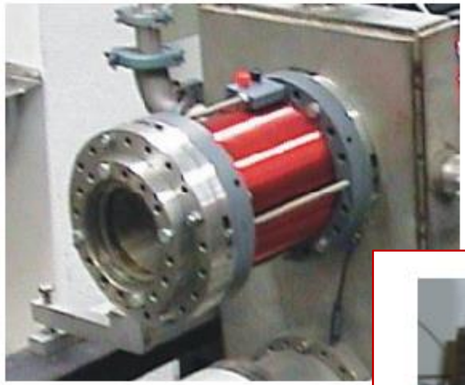
Gabor lens for beam energies up to 50 keV

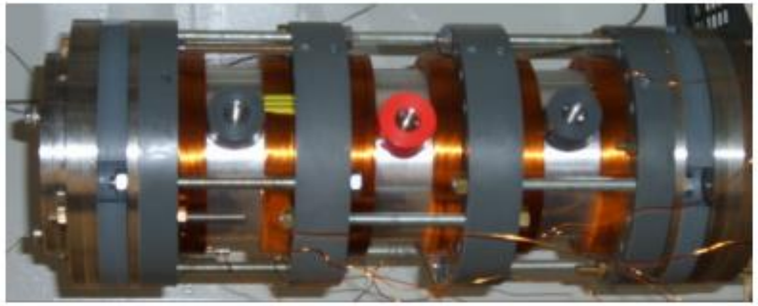
lens properties:

$\Phi_{A,max} = 6.5kV$

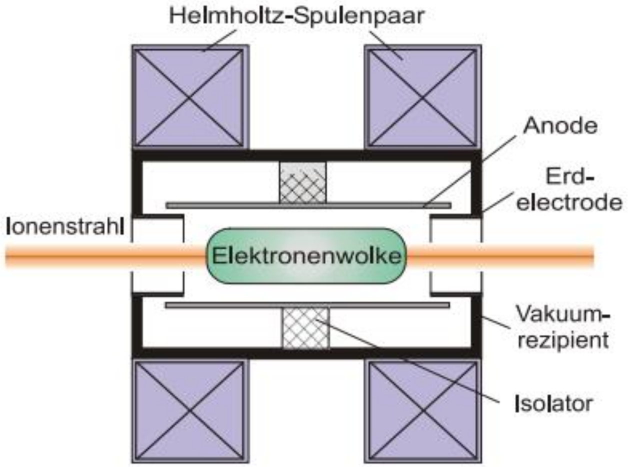
$B_{z,max} = 48mT$







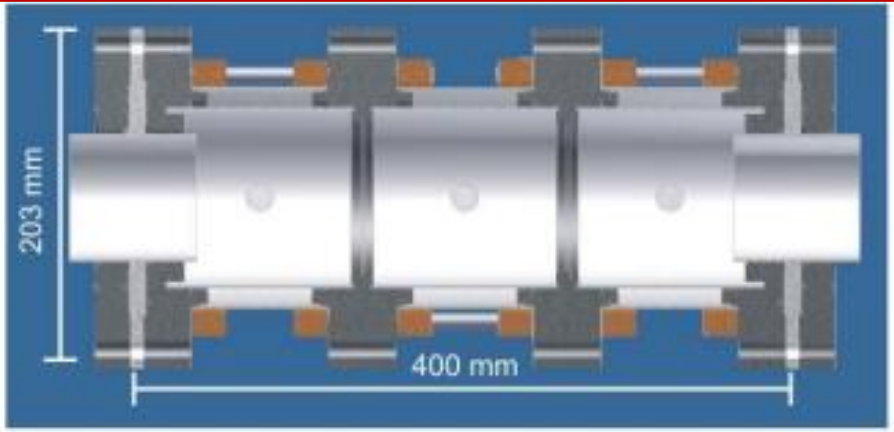
high field Gabor lens for beam energies up to 500keV



lens properties :

$\Phi_{A,max} = 65kV$

$B_{z,max} = 220mT$



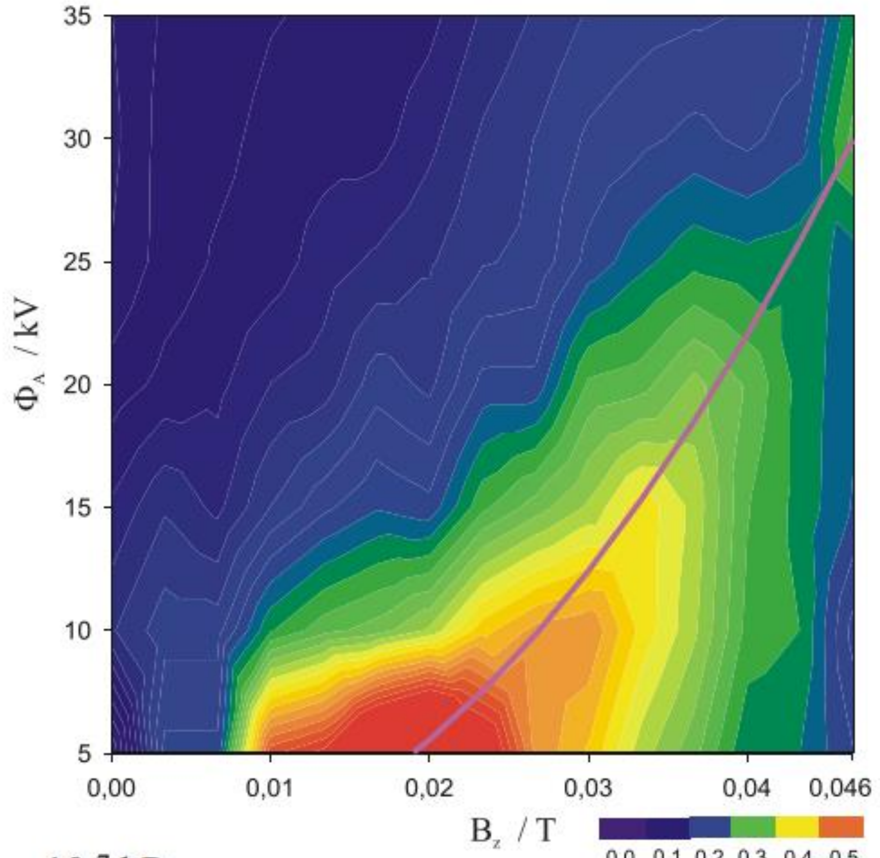
O. Meusel, 2010

K. Schulte, 2006

Beam transport measurements

1.2 mA, 440 keV, He^+ beam

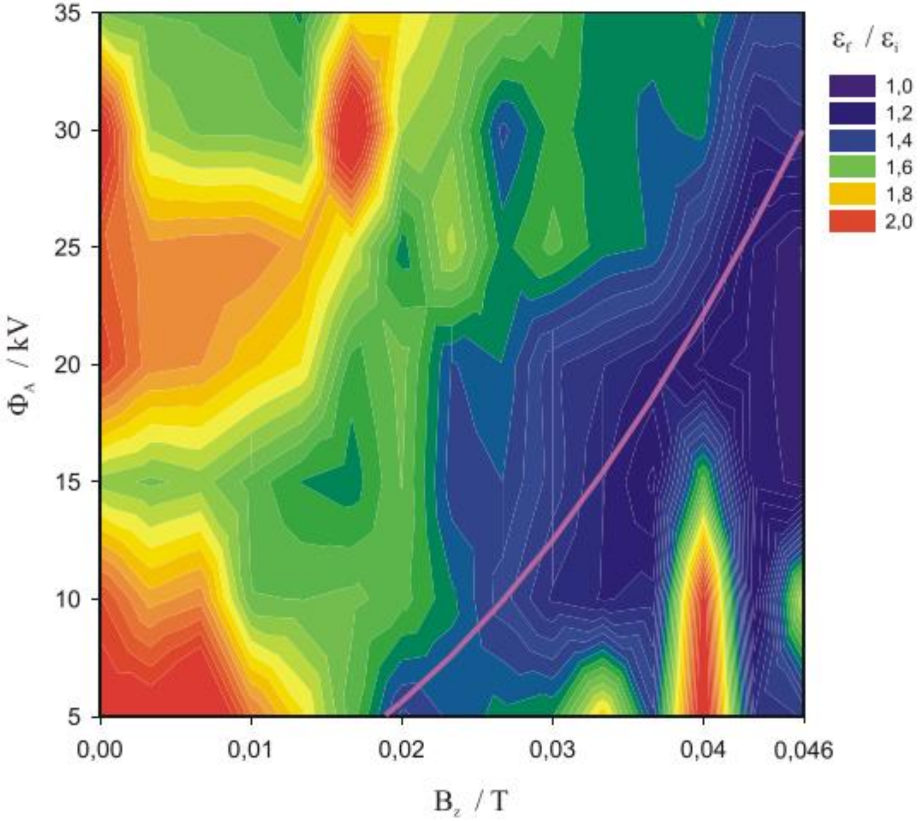
Lens filling degree



p = 10^{-7} hPa

$$\kappa_r = \frac{n_{e.\exp}}{n_{e,theo}}$$

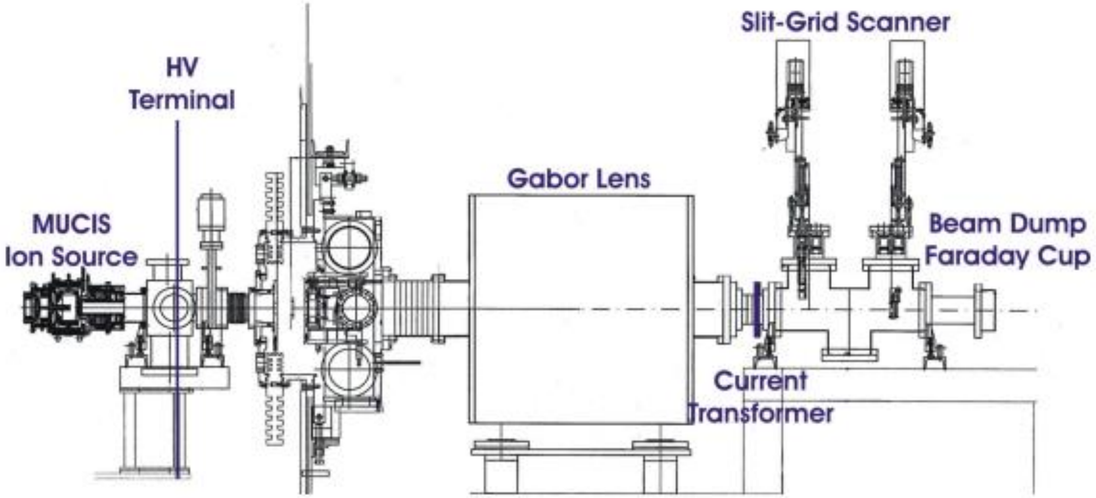
Beam emittance growth

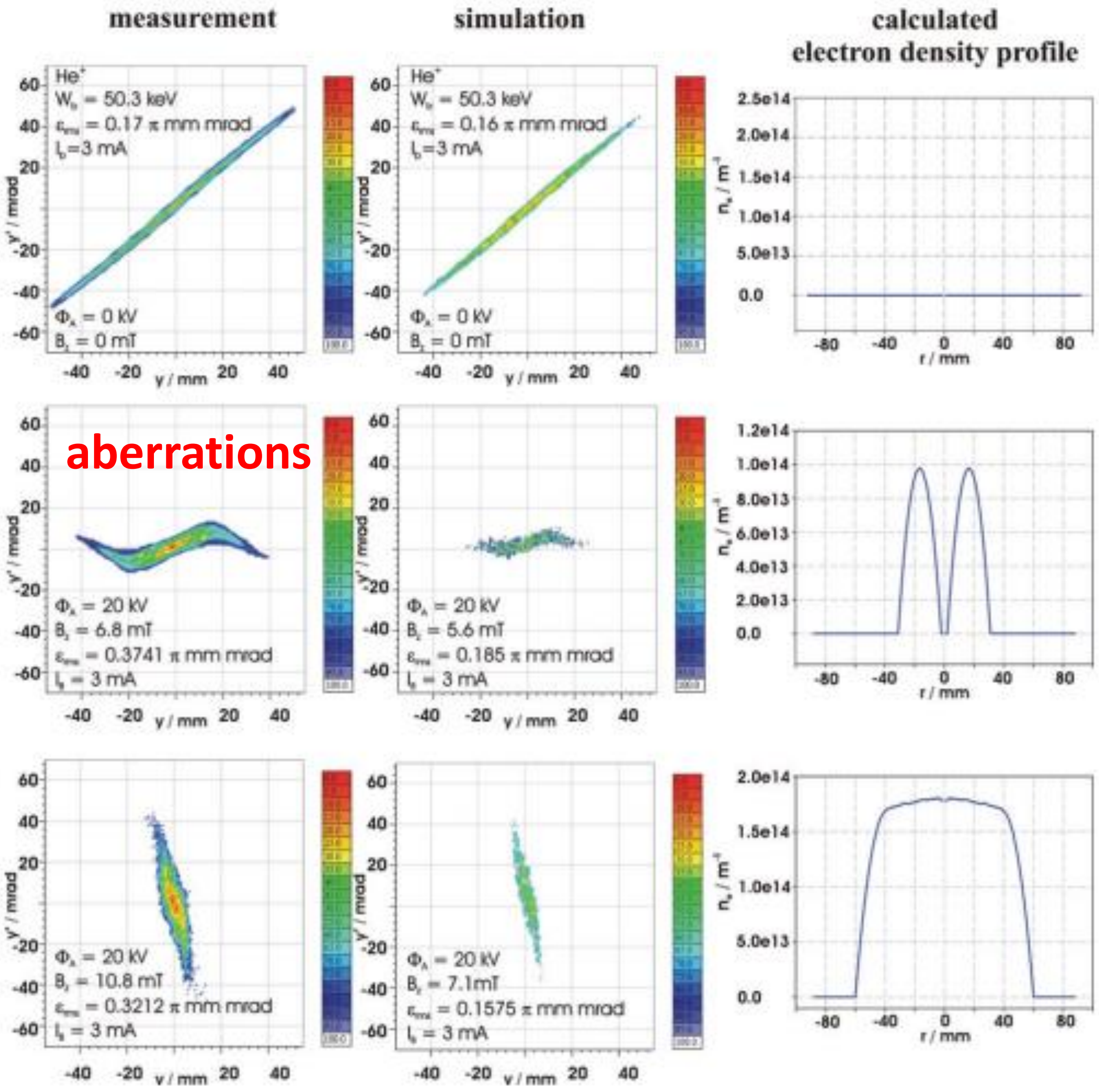


O. Meusel, HIAT2012

Beam transport measurements

GSI, 2012 IPAC2013, THPWO021





He+ beam, emittance dominated transport (test performance of the lens as focusing device)

Beam transport measurements

GSI, 2012 IPAC2013, THPWO021

- Ar^+ beam
- space-charge dominated transport (ion number density ~ order of the electron density)
- secondary electron production from beam losses on the beam pipe)

- **secondary electron production**
- focusing strength increases with ion beam current

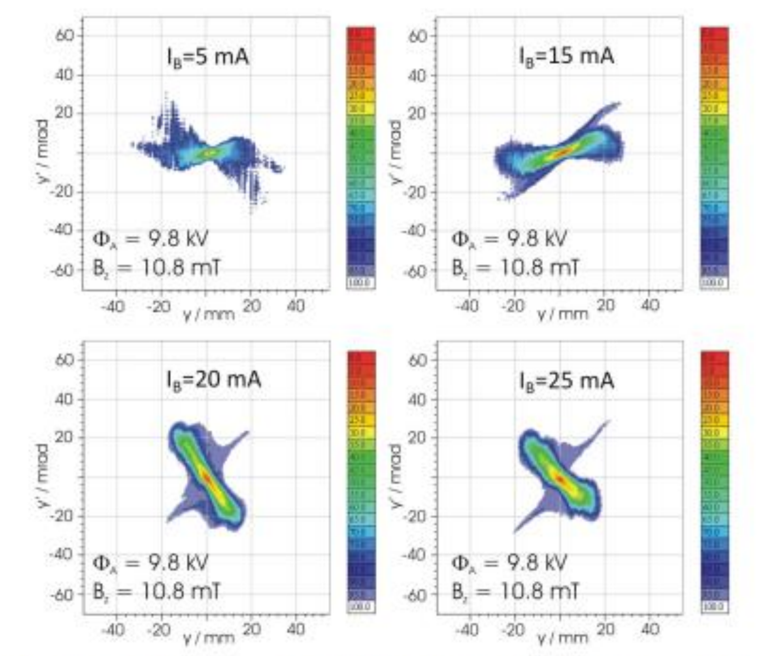
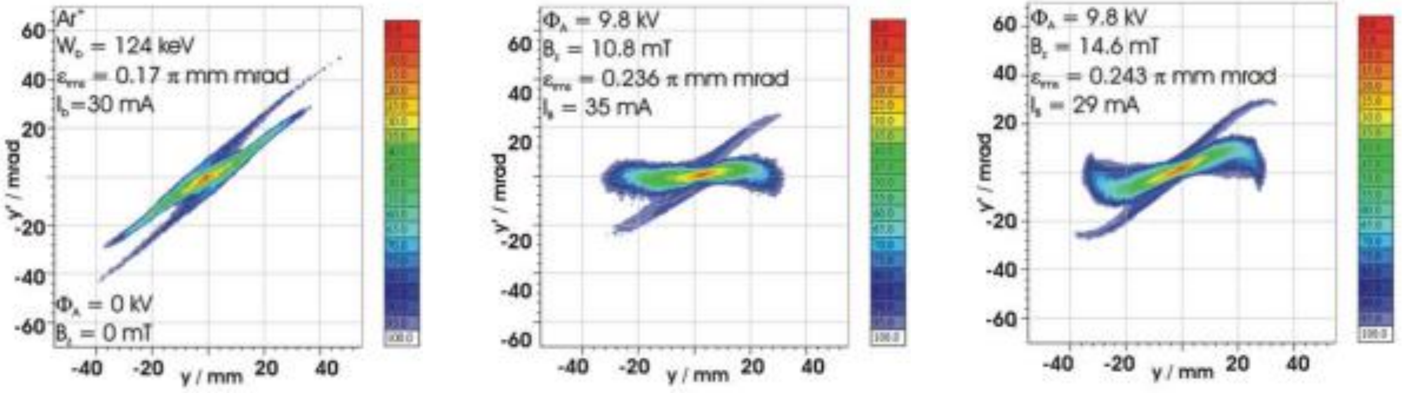
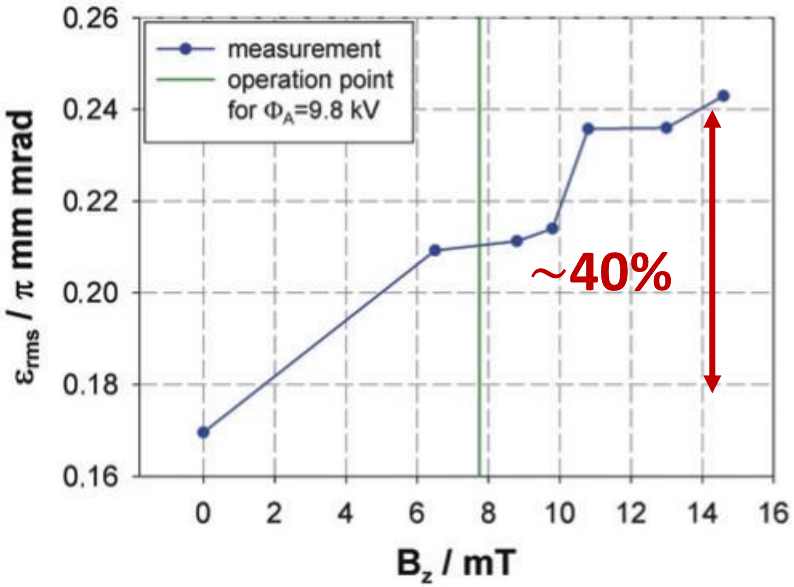


Figure 3: Influence of the ion current on the focusing performance of the lens.

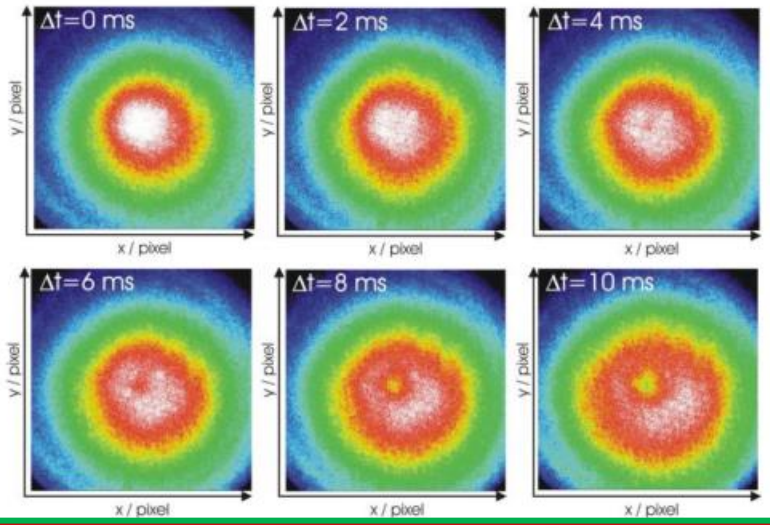


Increasing B_z

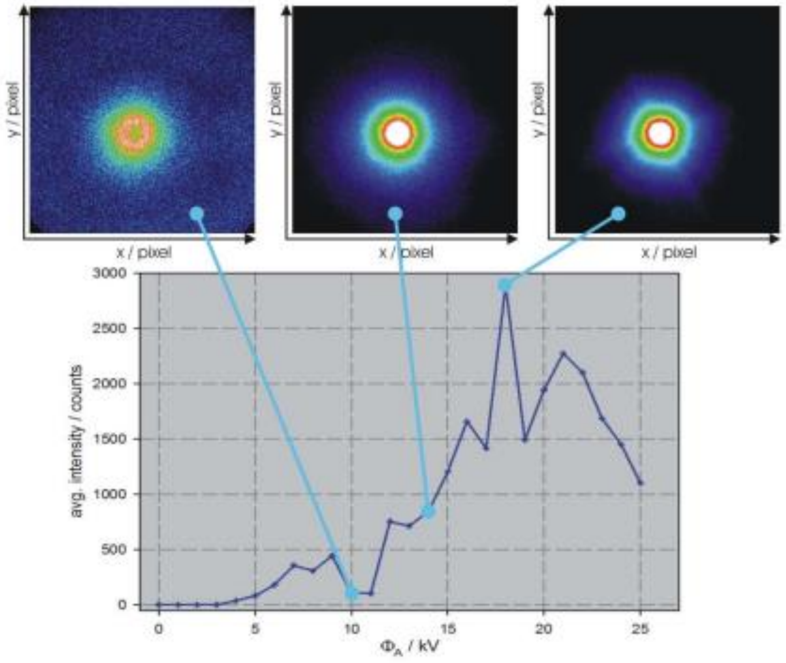


Other diagnostics

Optical measurements

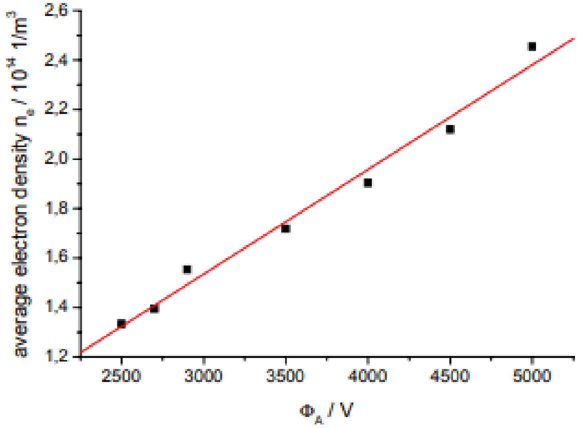


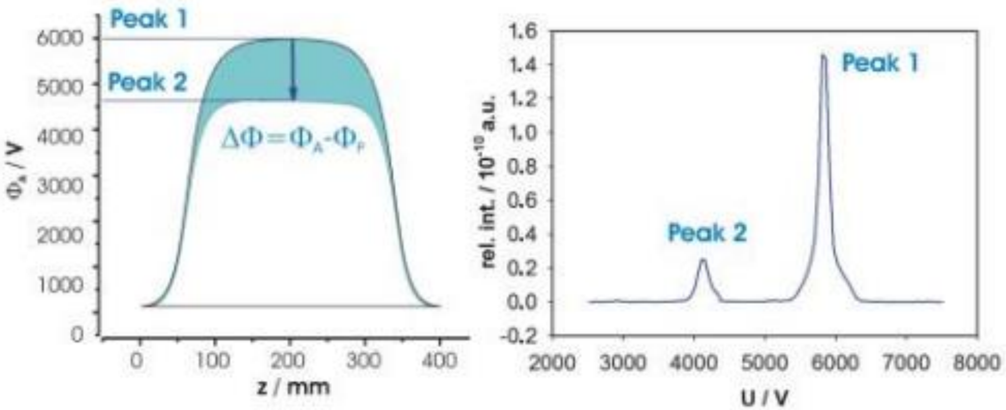
IPAC2011, THPS034

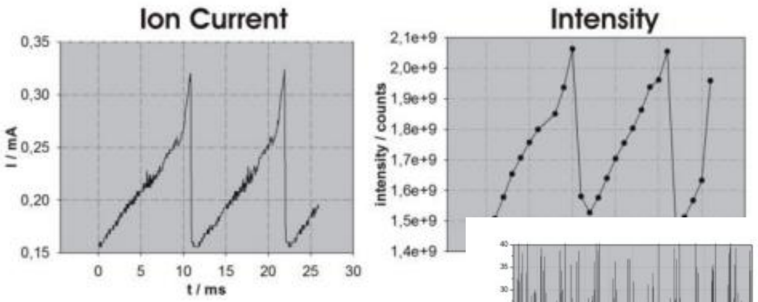


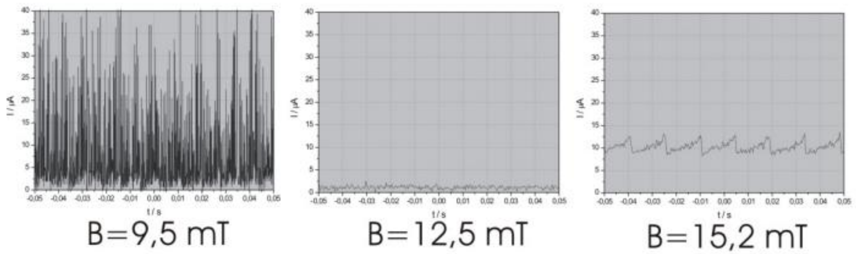
arXiv:1309.4654

Momentum spectrometer







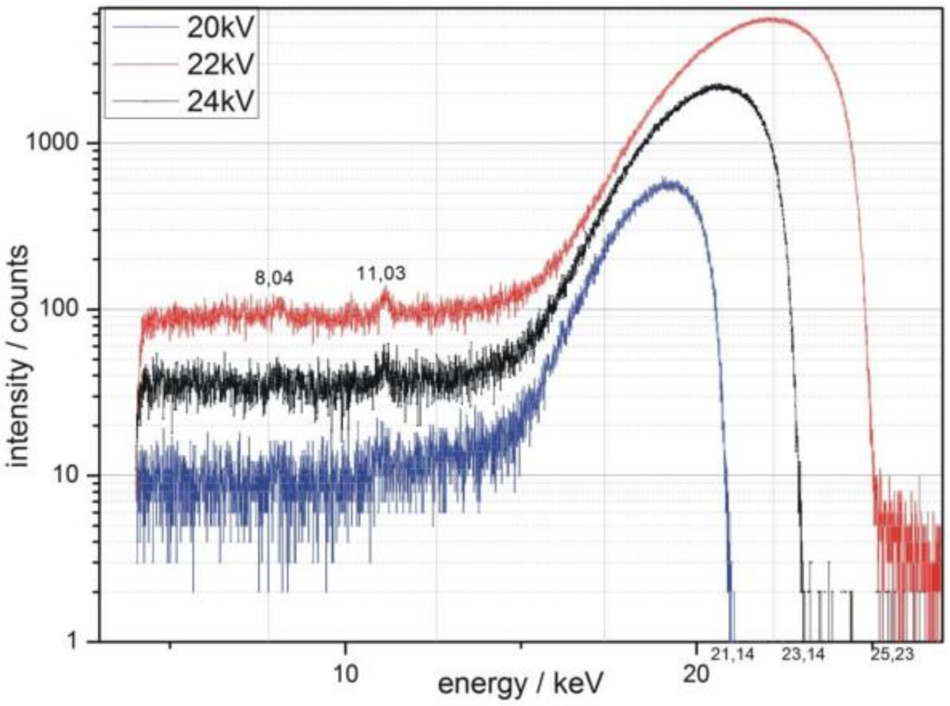


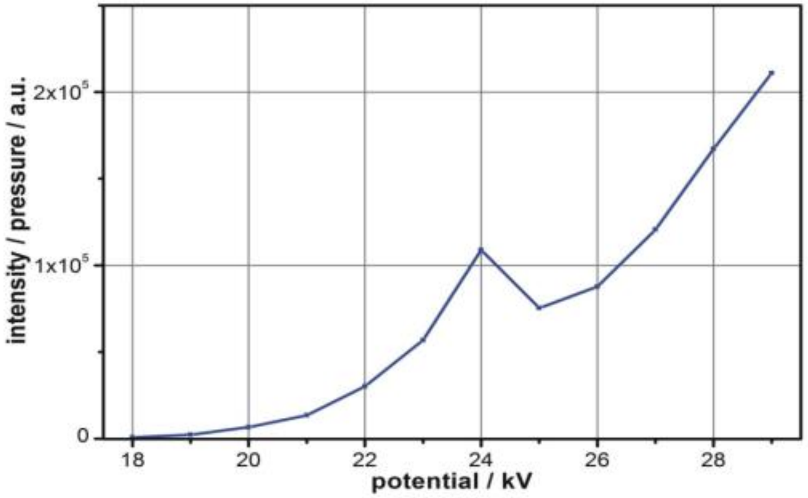
Faraday cup (ion current)

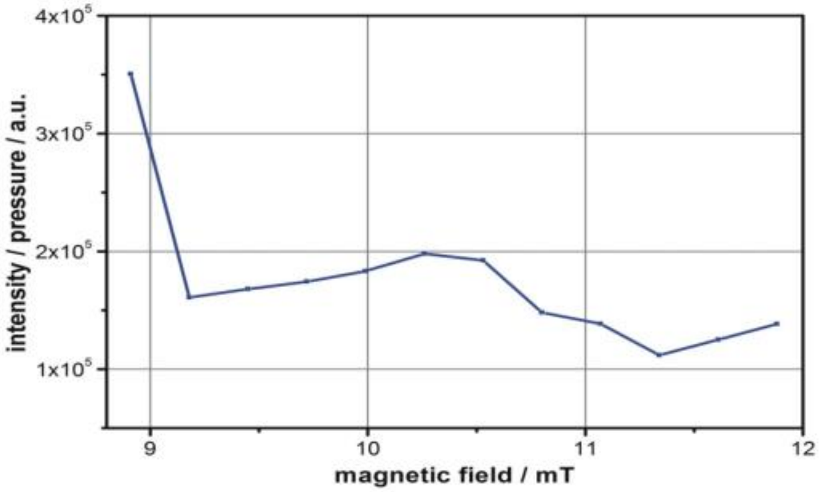
Other diagnostics

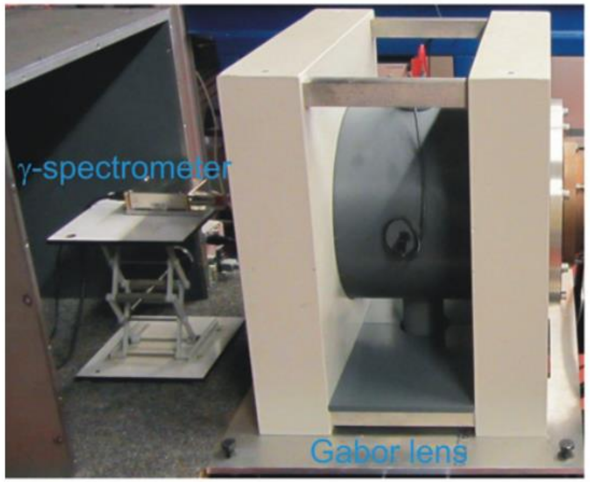
IPAC2012, TUPPC007

emitted bremsstrahlung spectra

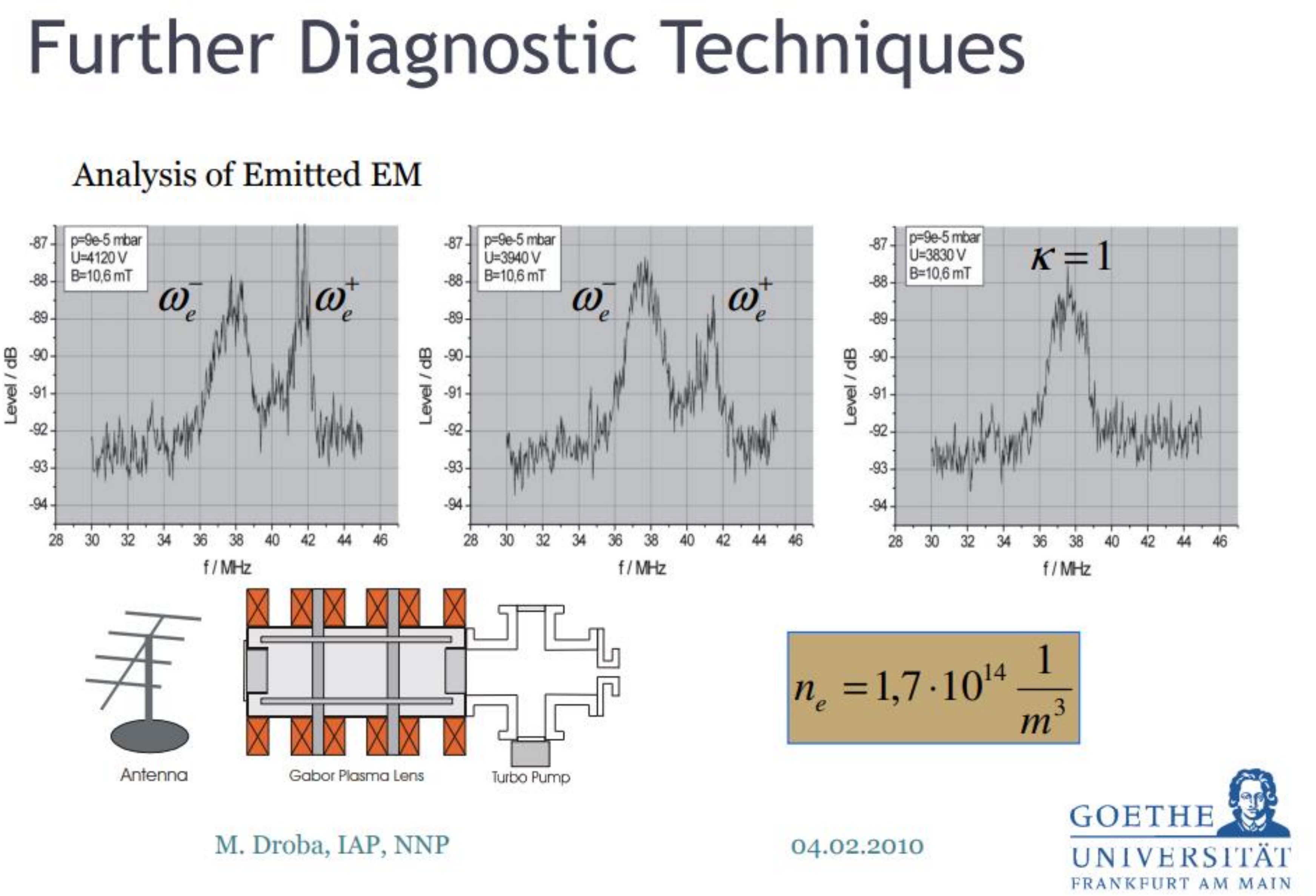




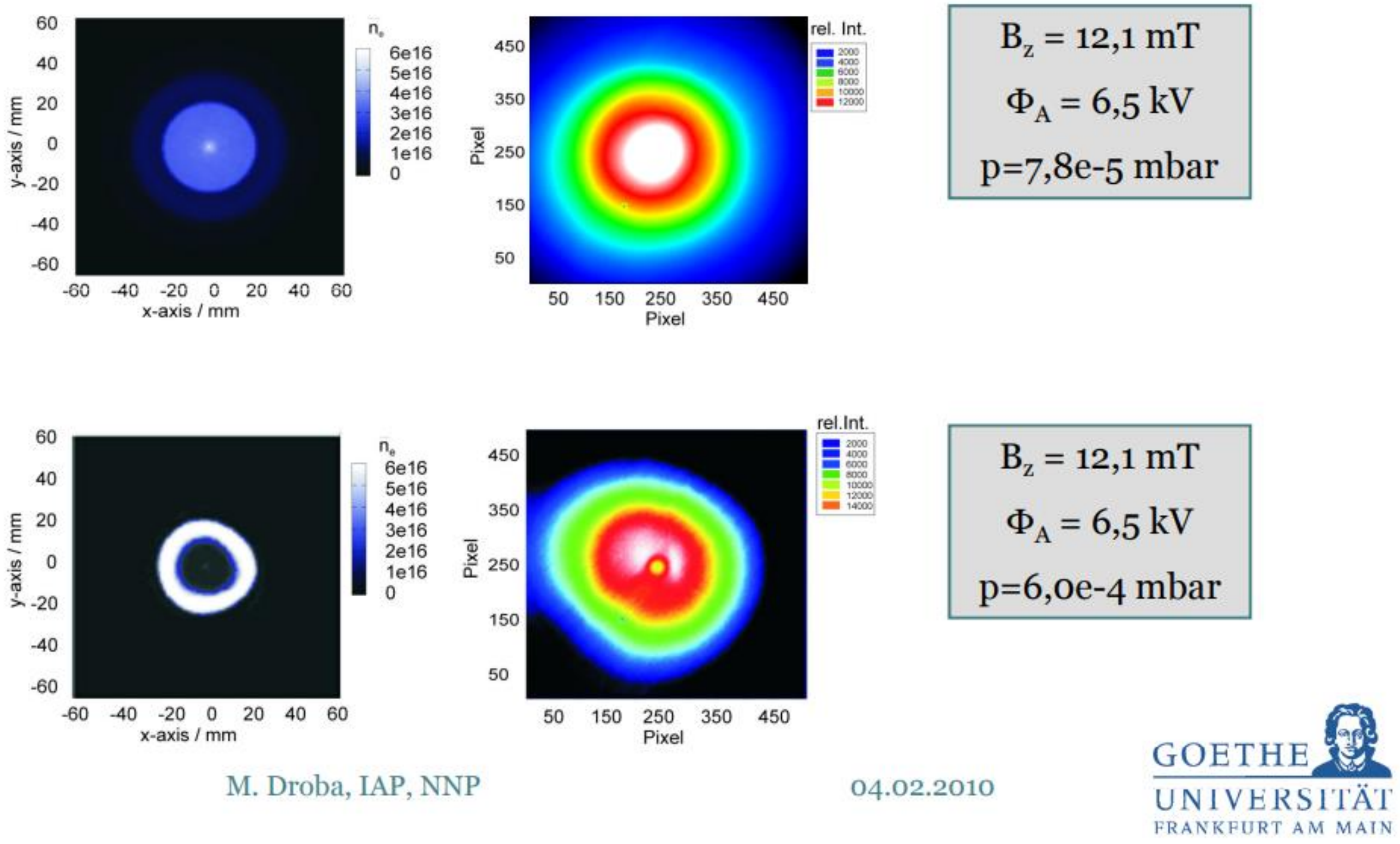




Other diagnostics



Electron density highly sensitive to background gas pressure



Residual gas pressure is linked to the formation of plasma instabilities.

Conditioning procedure

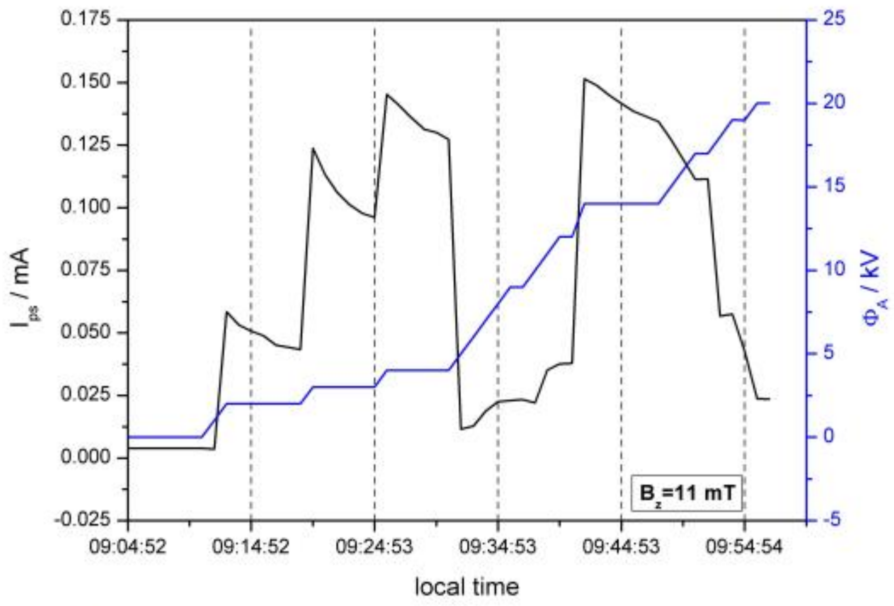


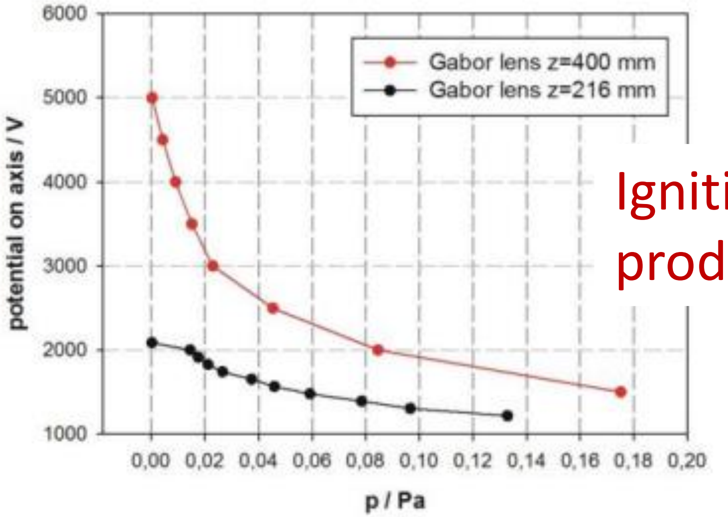
Figure 3: Example of high-voltage conditioning procedure for the prototype Gabor lens. I_{ps} denotes the power supply current.

- High-voltage conditioning to remove contamination.

doi:10.18429/JACoW-IPAC2014-MOPRI088

Plasma production

- Electrons are considered to be created by **impact ionisation of the residual gas atoms**
- 'Short' filling times cannot be explained by the sole interaction of the electrons with the residual gas
- Electron losses on the anode as further production mechanism => x-ray radiation detected



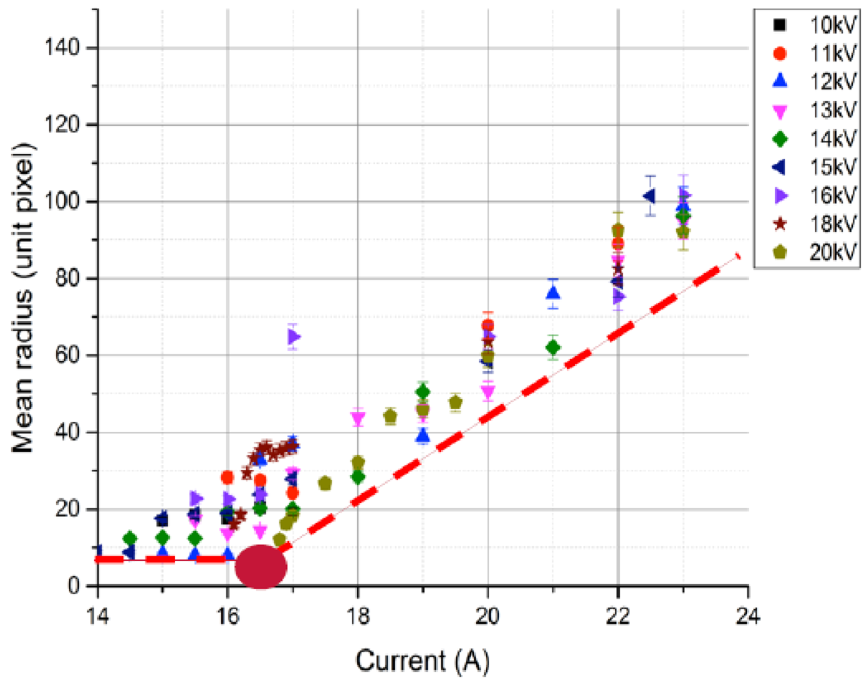
Ignition = electron production > losses

Figure 4: Ignition curves for different lengths of space charge lenses.

Reminder on the prototype from Imperial

Imperial College London

Beam Test in Surrey (2/3) [8]



The lens starts working at a given combination of High Voltage – Solenoid Current

Development of a control system

IPAC2017, MOPAB039

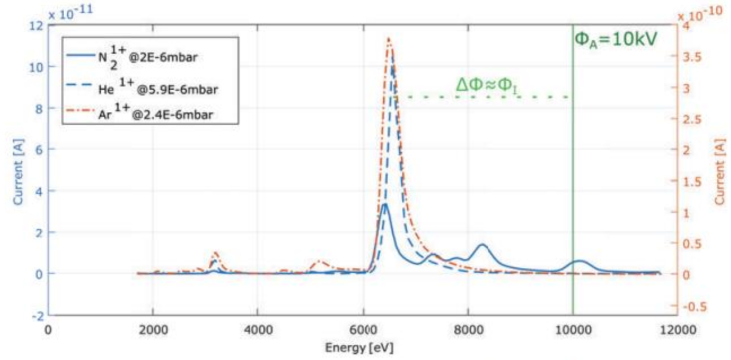
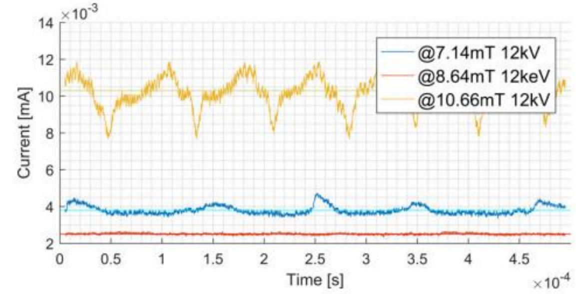


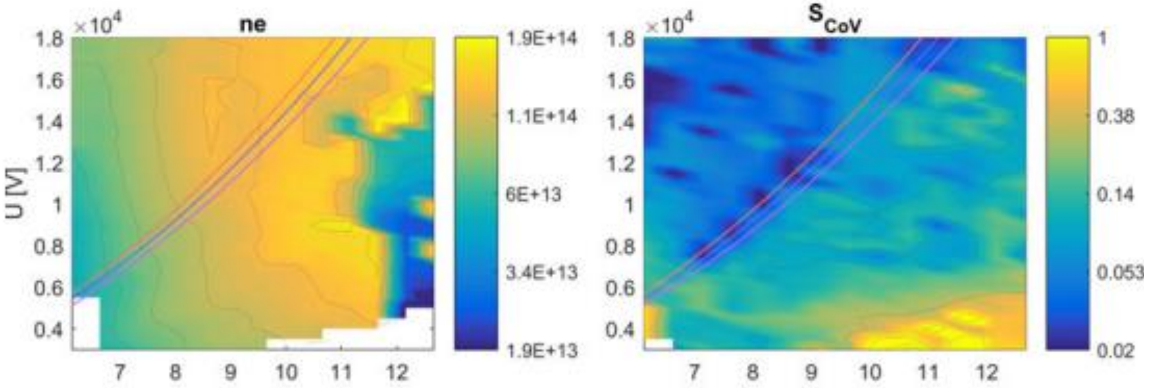
Figure 3: Energy spectra of He^{1+},N_2^{1+},Ar^{1+}-ions at operation point $\Phi_A = 10\,\text{kV}$, $B_z = 8.1\,\text{mT}$.

→ $\boldsymbol{n_e}$

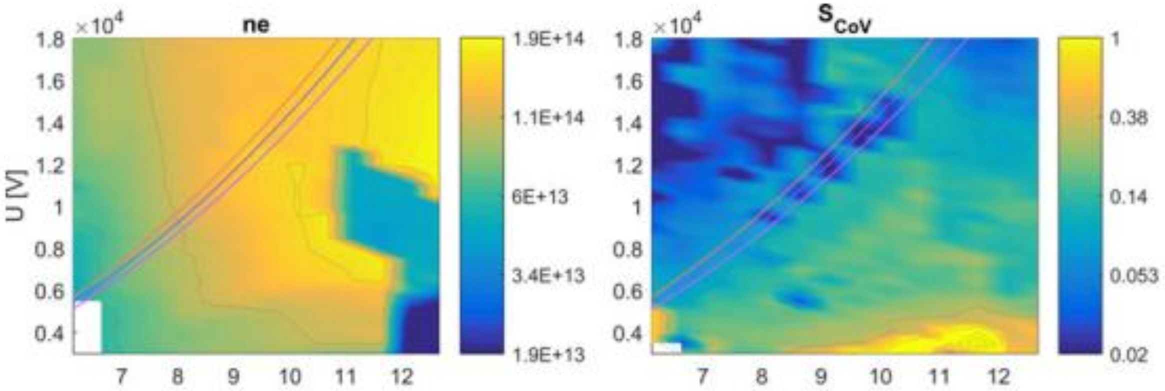


→ $S_{CoV} = \frac{\sigma_c}{\mu_c}$

- 3-D maps measured
- General concept for control system designed
- Implementation and test with beams to follow



Residual gas 5.9×10^{-6} mbar



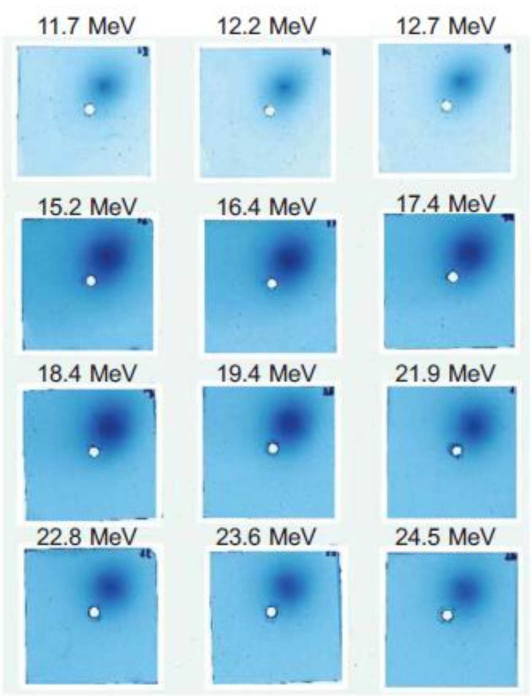
17.7×10^{-6} mbar helium

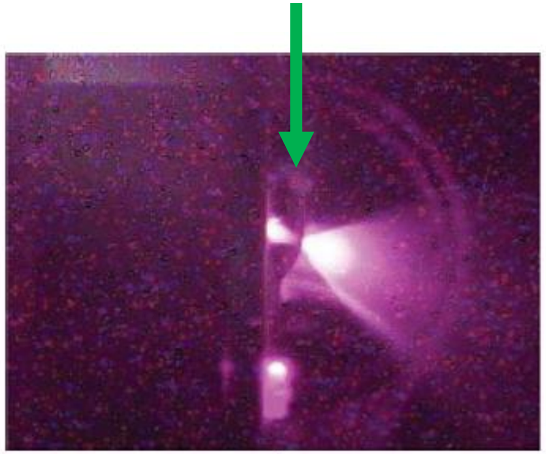
Alternative focusing devices

Pulsed high-field solenoids

Worst-case-scenario: a few $\times 10^{11}$ protons transported

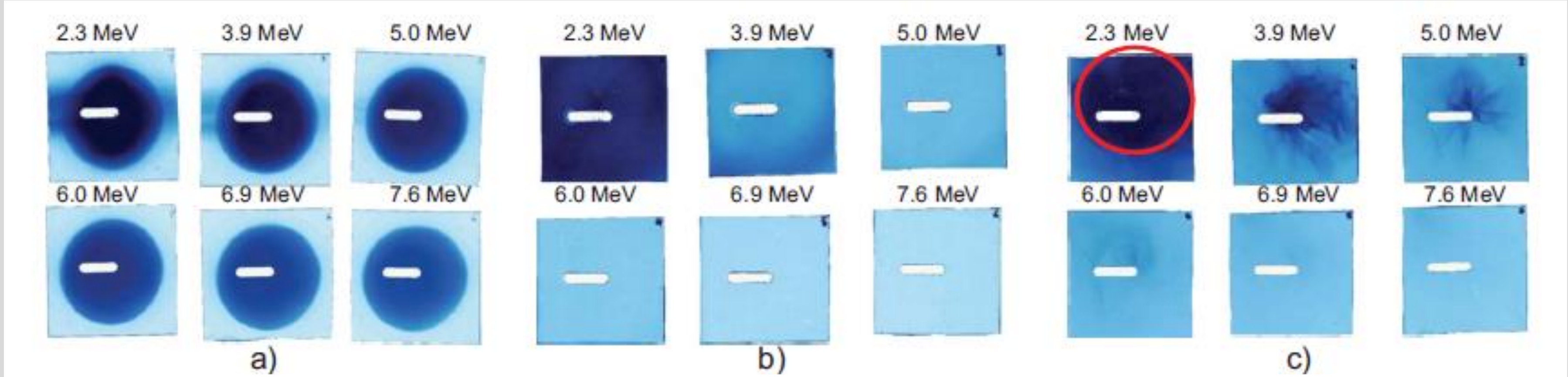
- 2.3 MeV, 10^{12} protons collimated
- 8.6 T (tested up to 15 T), 44 mm diameter solenoid, 17 mm from the target
  - Higher solenoid currents (>19 kA) were associated with stronger arcing due to the expanding plasma entering the solenoid
- Stronger focusing than expected from ptcl. tracking
  - Due to comoving electron space-charge (r<1mm) on solenoid's axis
- 130 mm from solenoid exit to RCF stack
- Strong eddy currents (induced in the gold foil by the solenoid) led to bending of the **target**





a)

doi:10.1063/1.3299391

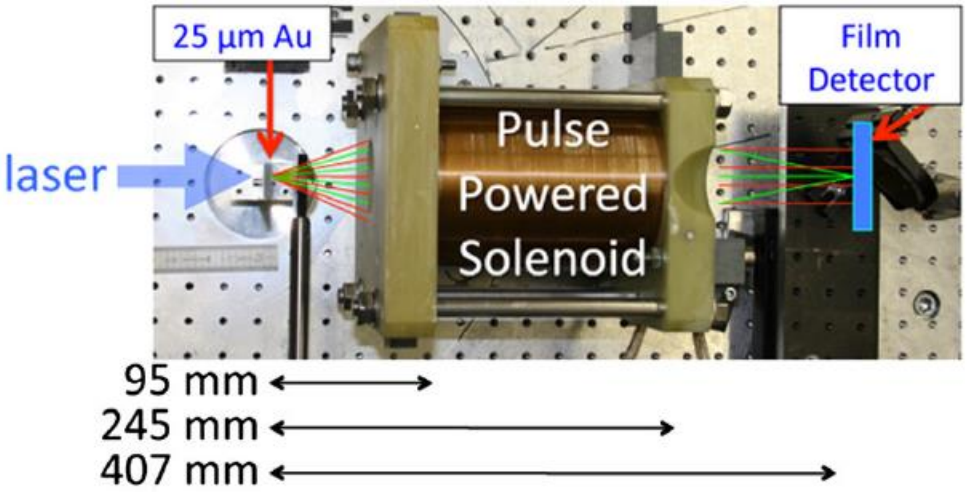


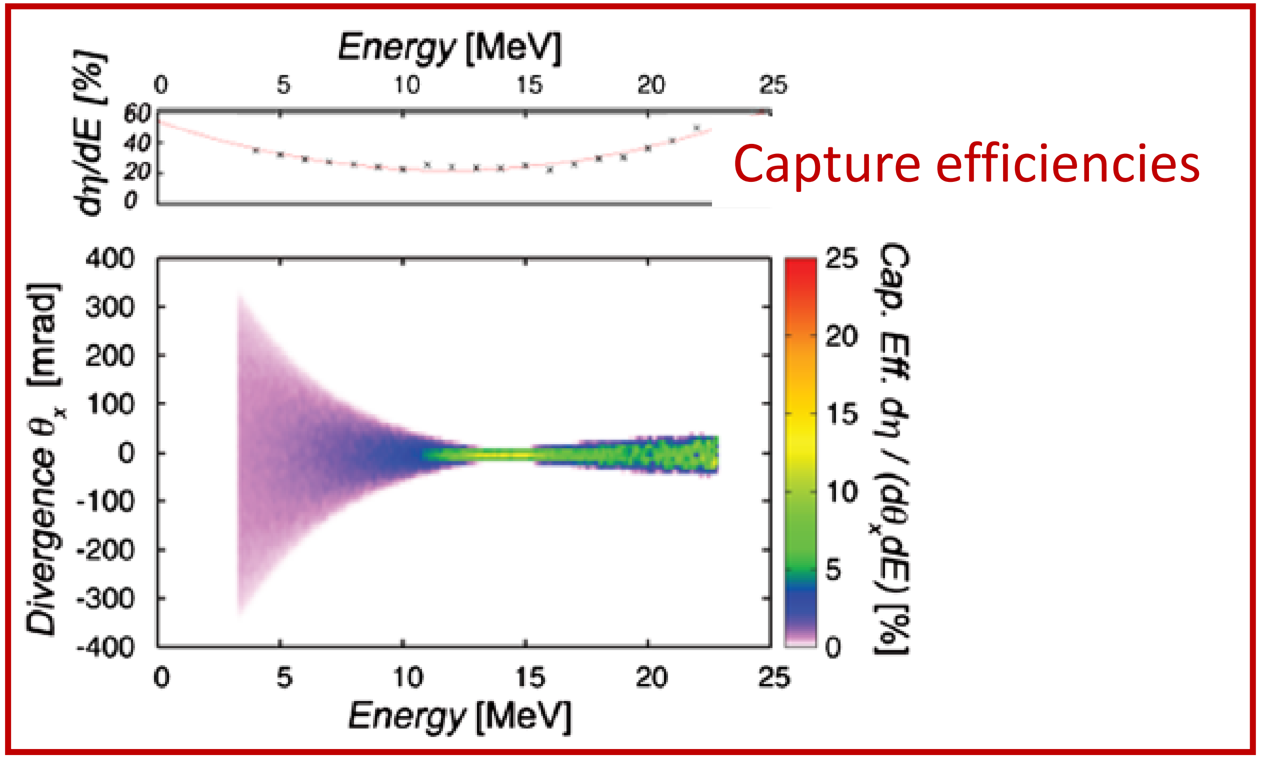
40 mm from target

241 mm from target, solenoid OFF

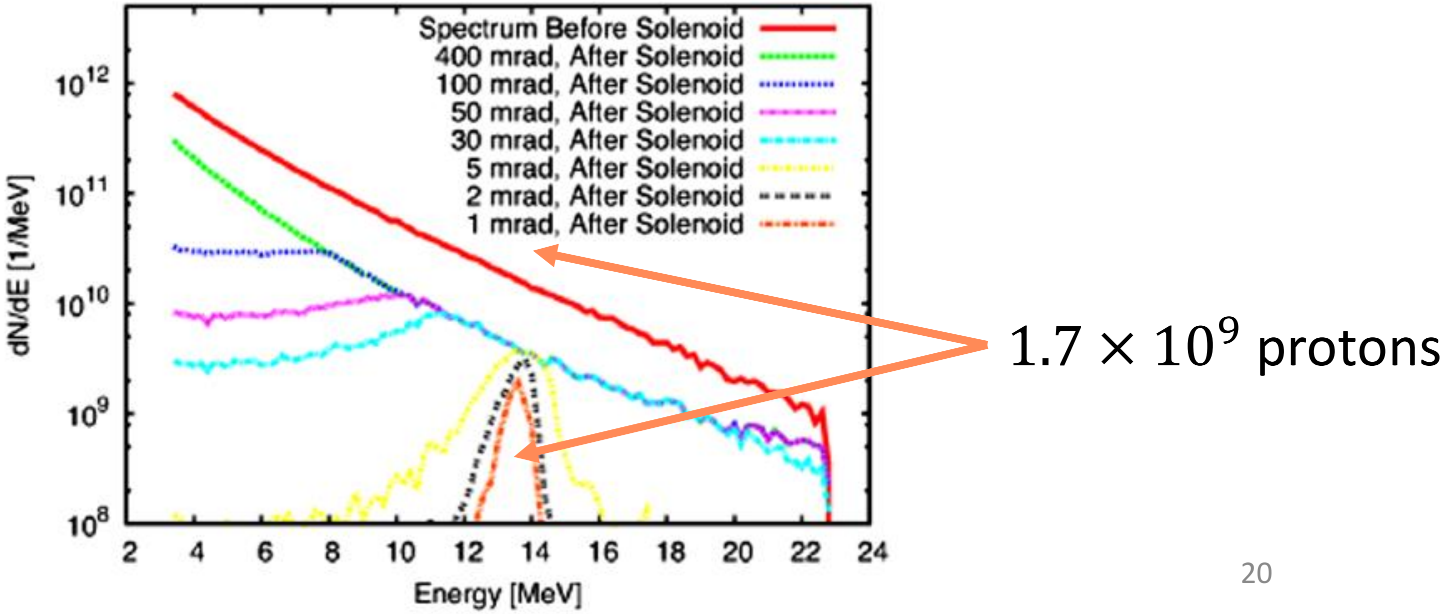
241 mm from target, solenoid ON

Pulsed high-field solenoids





- $2\text{x}10^{12}$ protons (3.7–23 MeV) accelerated from the foil
- 48 mm bore, 8.5 T (tested up to 16 T)

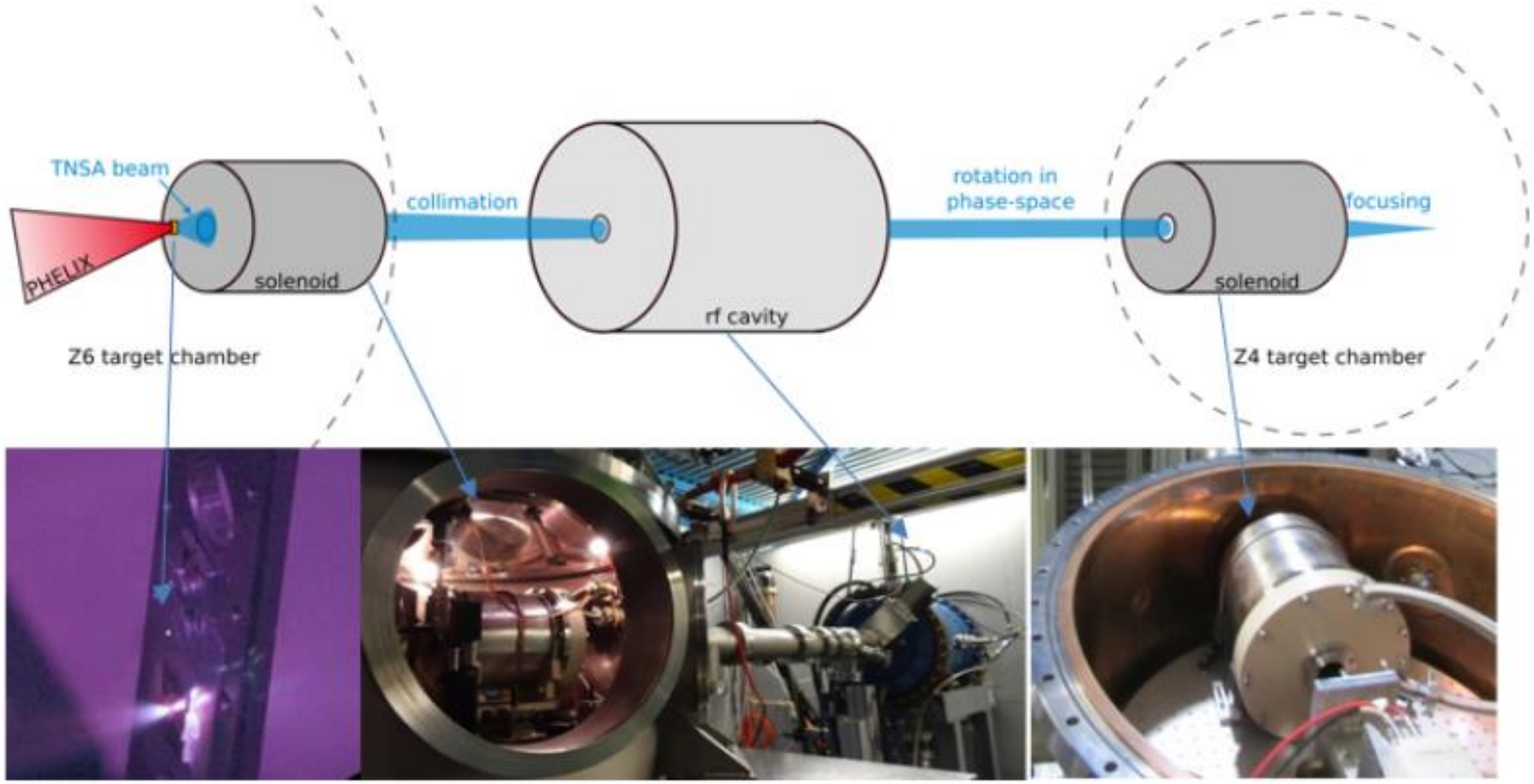


DOI: 10.1103/PhysRevSTAB.14.121301

Pulsed high-field solenoids

GSI Helmholtzzentrum für Schwerionenforschung GmbH

LIGHT beamline at GSI

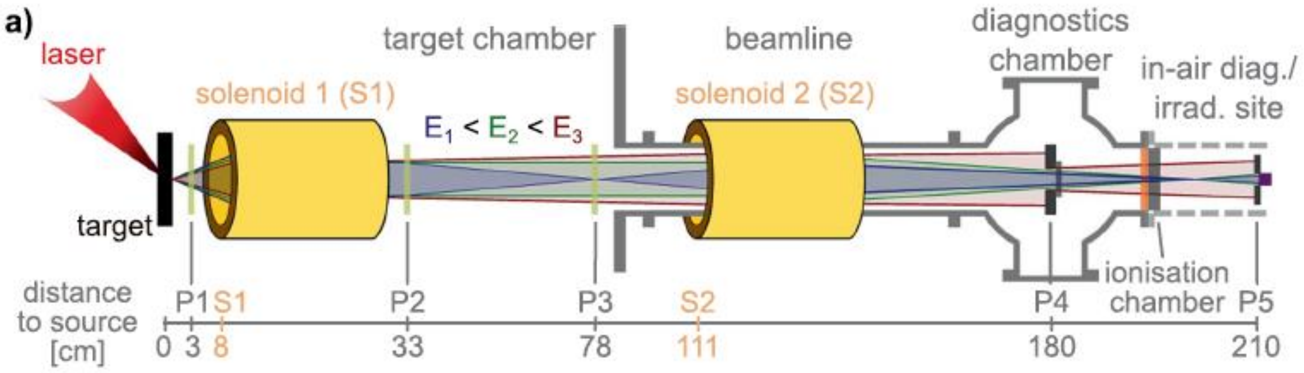


DOI: 10.1103/PhysRevSTAB.16.101302

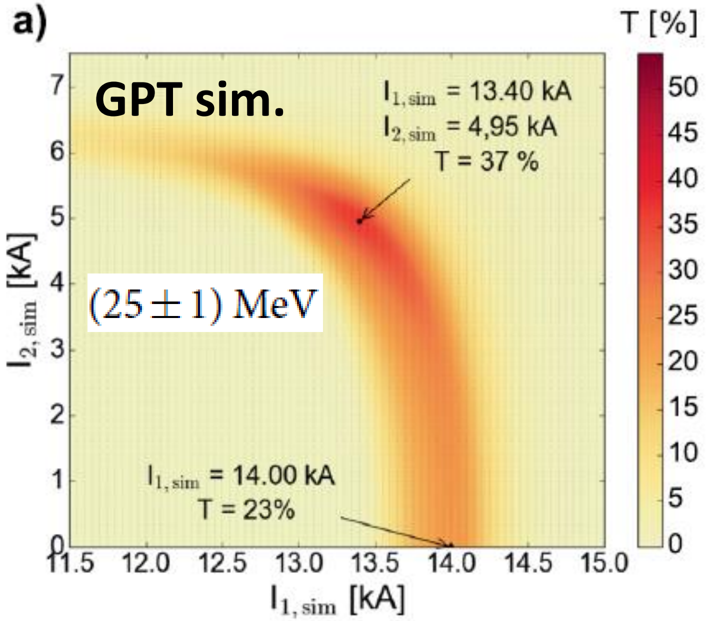
DOI: 10.1103/PhysRevSTAB.17.031302

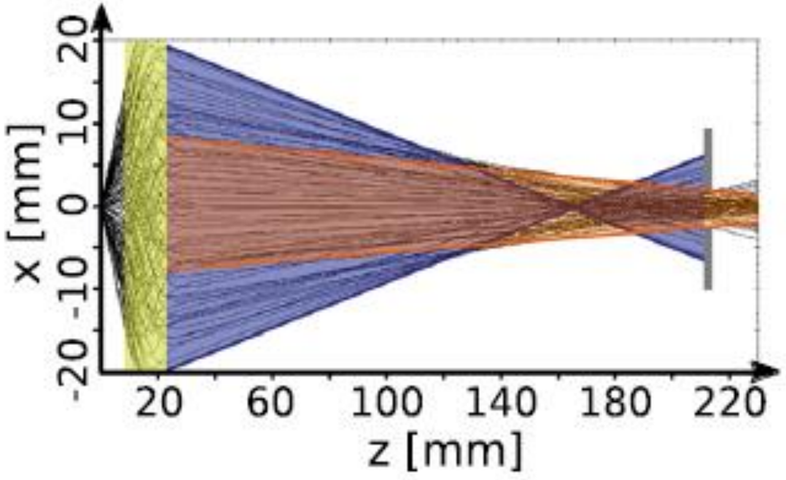
Pulsed high-field solenoids

5.7×10^9 protons at source (25±1 MeV)



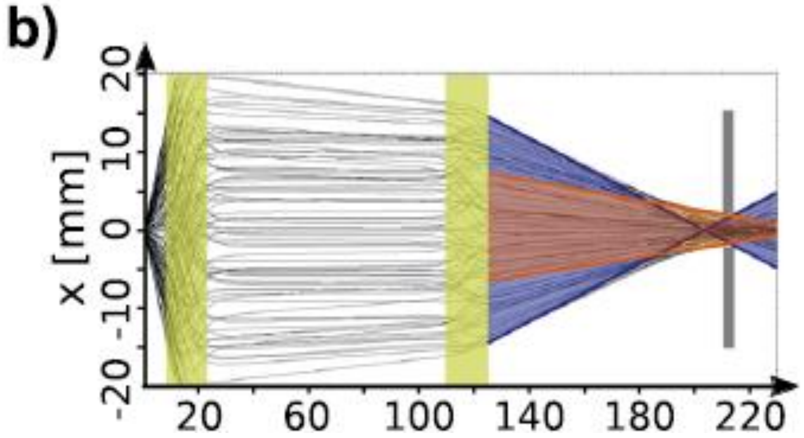
- < 19.5 T, 2 or 3 pulses/min.
- S1, S2: 40 mm bore diameter
- 14° half-angle geometrical acceptance
- Measured transmission (18.6 MeV protons)
  - 50.6% (dual solenoid)
  - 28.6% (single solenoid)





Particle loss due to single solenoid

- Limited aperture
- Spherical aberrations (**highly divergent protons** travel closer to the windings)

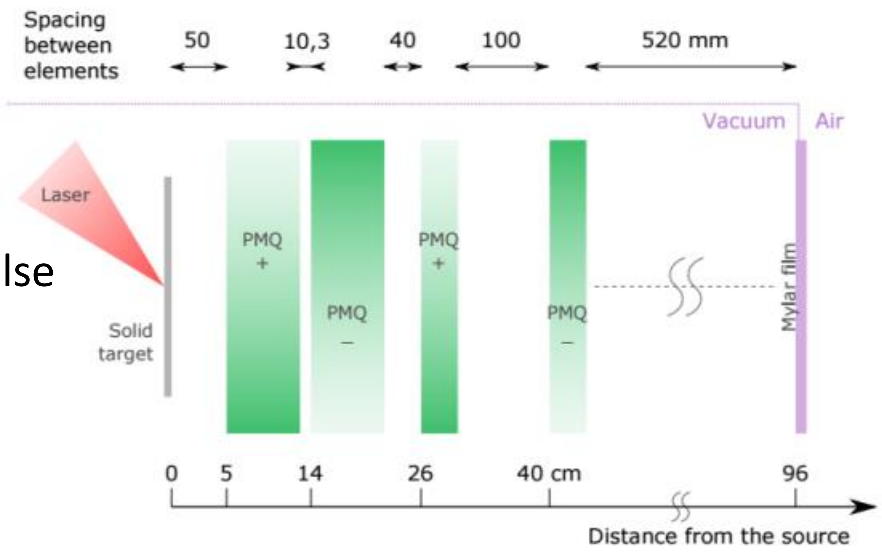


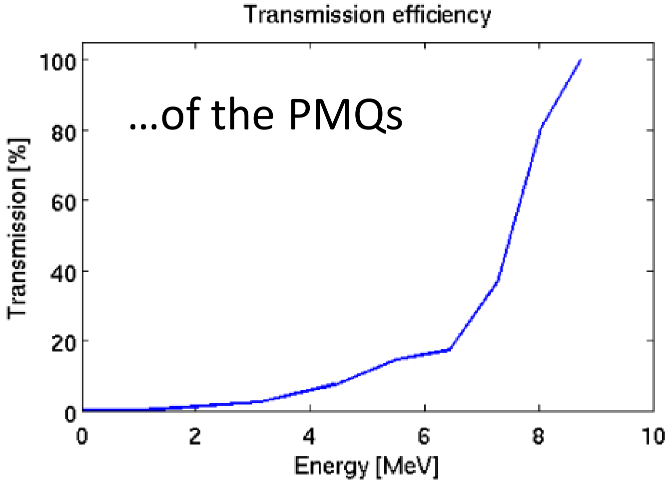
https://doi.org/10.1038/s41598-020-65775-7

Permanent Magnet Quadrupoles (PMQs)

Laboratori Nazionali del Sud

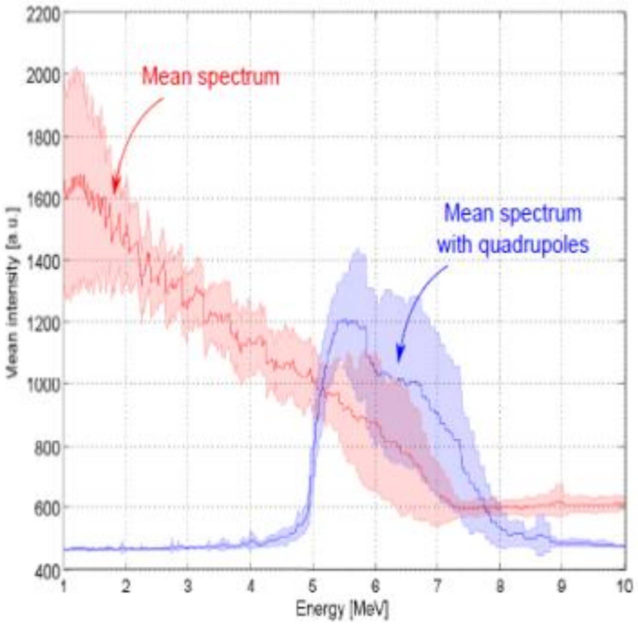
$\sim 5 \times 10^9$ protons/pulse (<8.9 MeV)





(Optimised for 6.5 MeV)

- Halbach design PMQs
- Focus <20 MeV protons
- 20 mm bore diameter
- 2 quads. 80 mm long, 103 T/m
- 2 quads. 40 mm long, 98 T/m

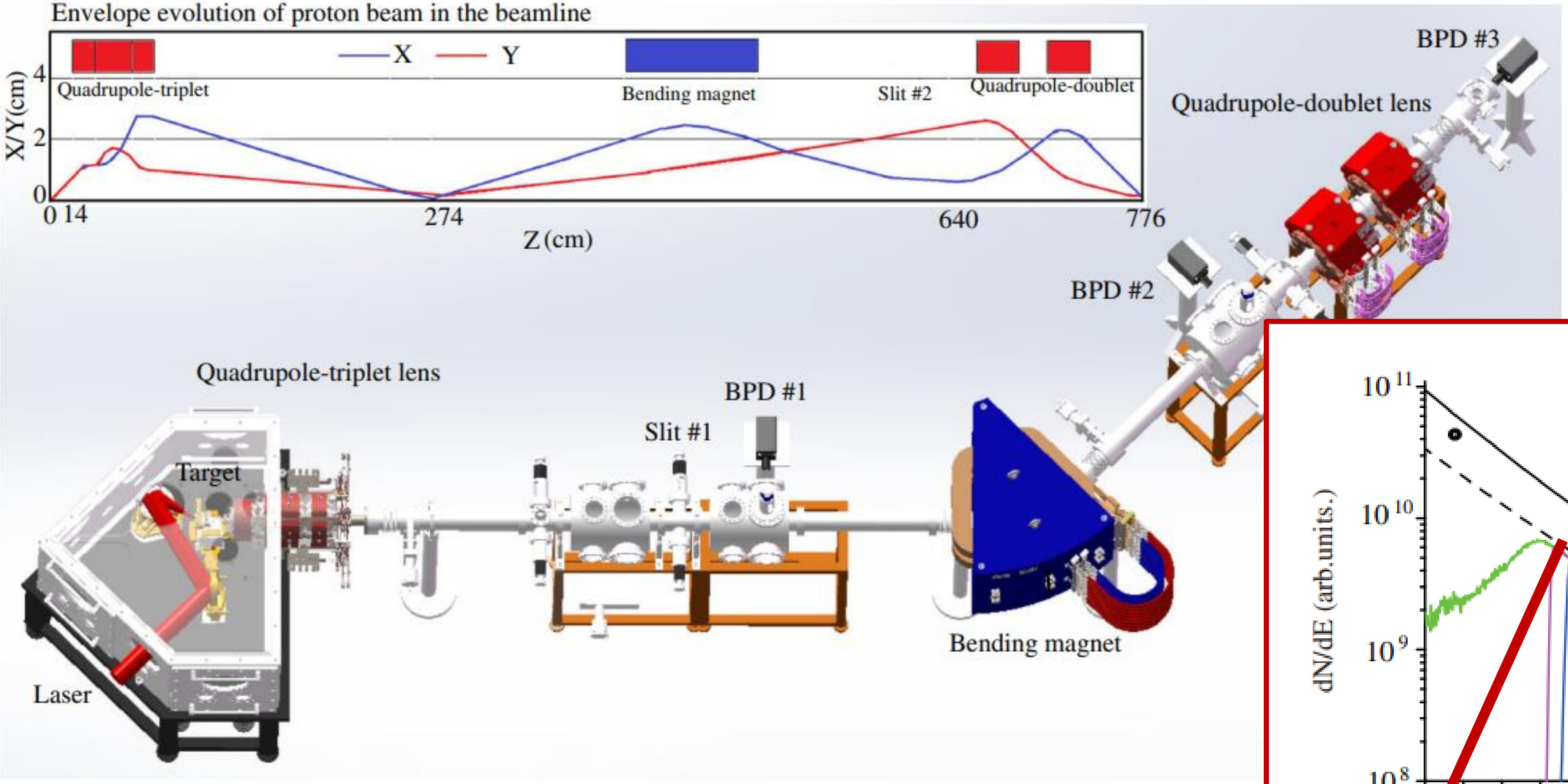


doi:10.1088/1748-0221/11/07/T07005

Quadrupole-triplet lens

DOI: 10.1103/PhysRevAccelBeams.22.061302
DOI: 10.1103/PhysRevAccelBeams.23.121304

CLAPA



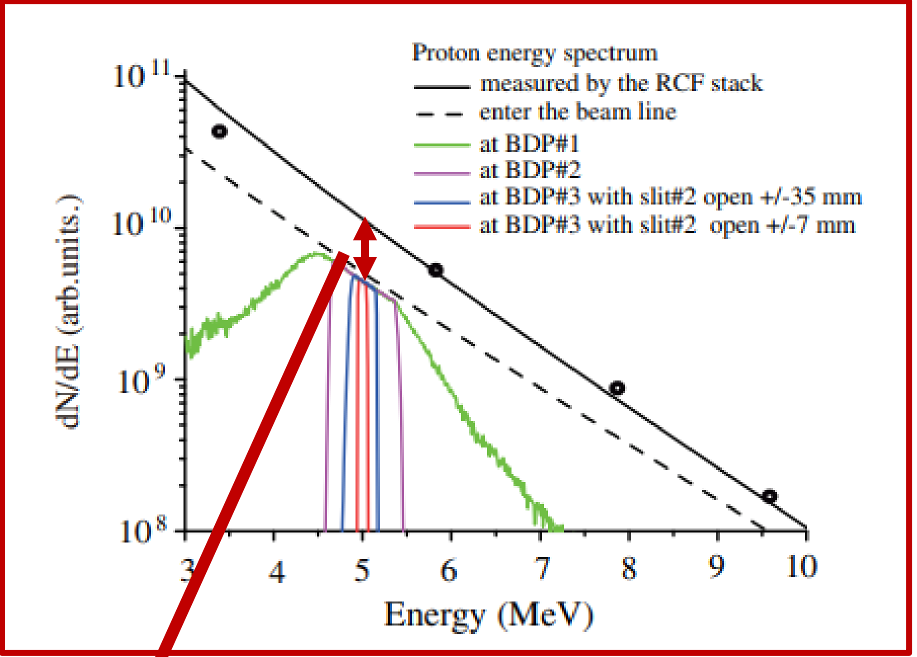


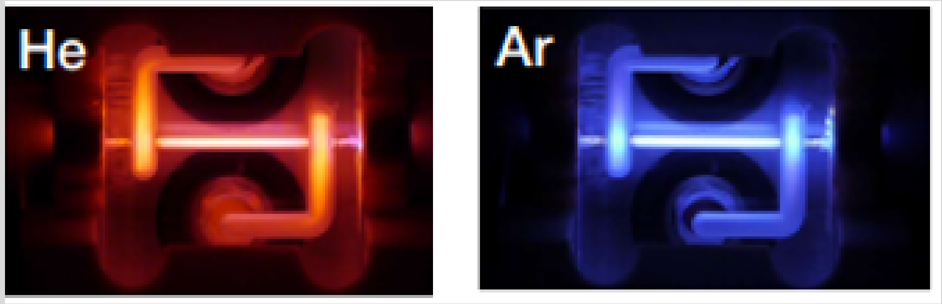
TABLE I. The CLAPA beam line parameters.

Type	Length	Aperture	Max B	# turns	Current
Q1	100 mm	30 mm	5 KGs/cm	16	300 A
Q2	200 mm	64 mm	2.5 KGs/cm	20	540 A
Q3	100 mm	64 mm	2.5 KGs/cm	20	540 A

±50 mrad collection angle

88% transmission through triplet

Active plasma lenses



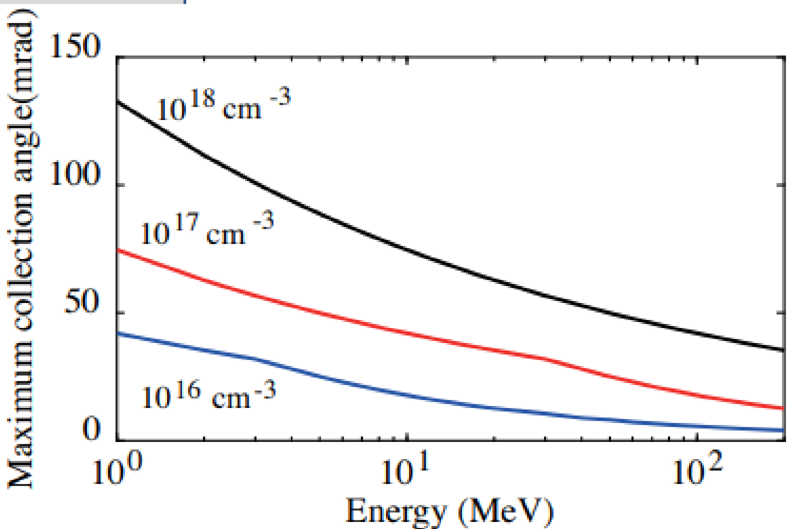
DOI: 10.1103/PhysRevAccelBeams.24.121306

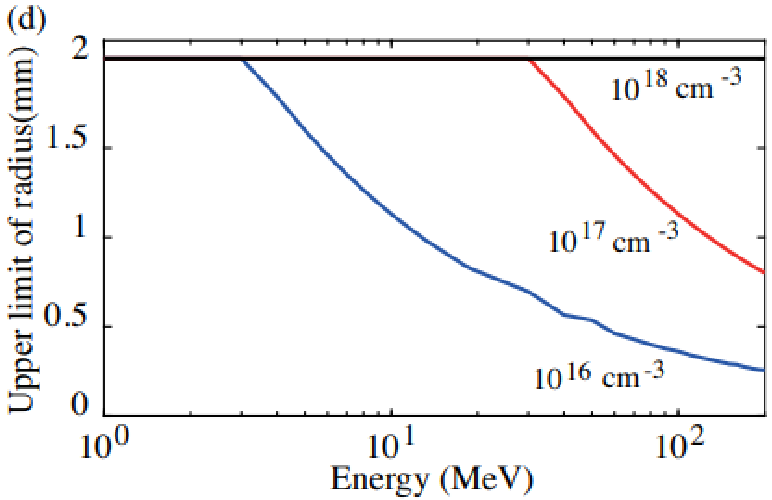
- Promising for electron beam focusing
- < 1 mm-diameter gas-filled capillaries
- Field gradients of few kT/m
- Sensitive to beam-driven plasma wakefields

DOI: 10.1103/PhysRevAccelBeams.24.031301

Designing of active plasma lens for focusing laser-plasma-accelerated pulsed proton beams

- Previous APLs (r > 1 cm) tested at CERN and GSI limited by z-pinch effect
  - Upper limit for the focusing strength
- Upper limit on number of protons that can be focused: $N \ll 2.8 \times 10^7 \times$ rms beam length [μm]
- Influence by the self-driven wakefields can be acceptable
- Optimisation for APL 4 mm from the source results in the following constraints:





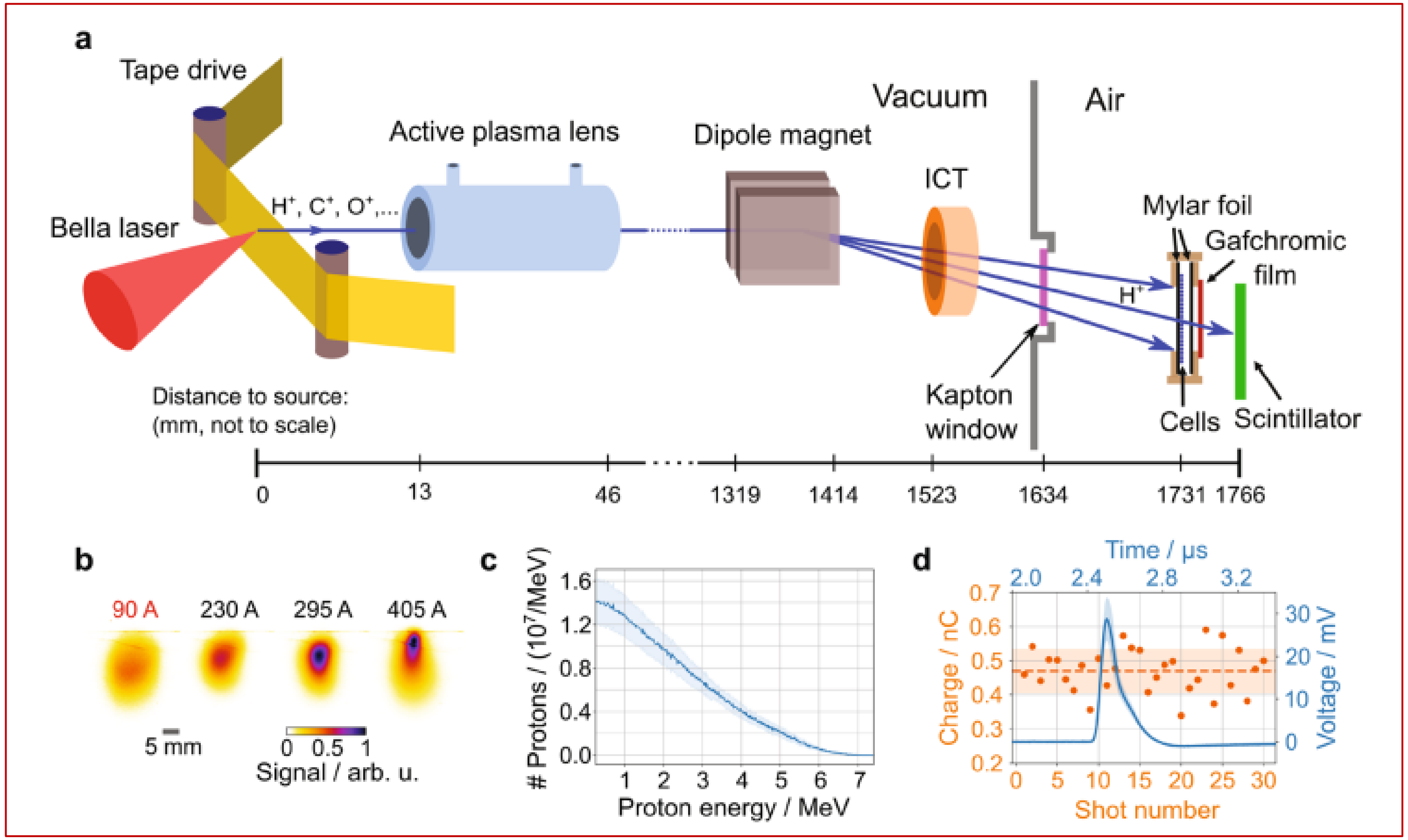
Active plasma lenses

https://www.nature.com/articles/s41598-022-05181-3

Article | Open Access | Published: 27 January 2022

A new platform for ultra-high dose rate radiobiological research using the BELLA PW laser proton beamline

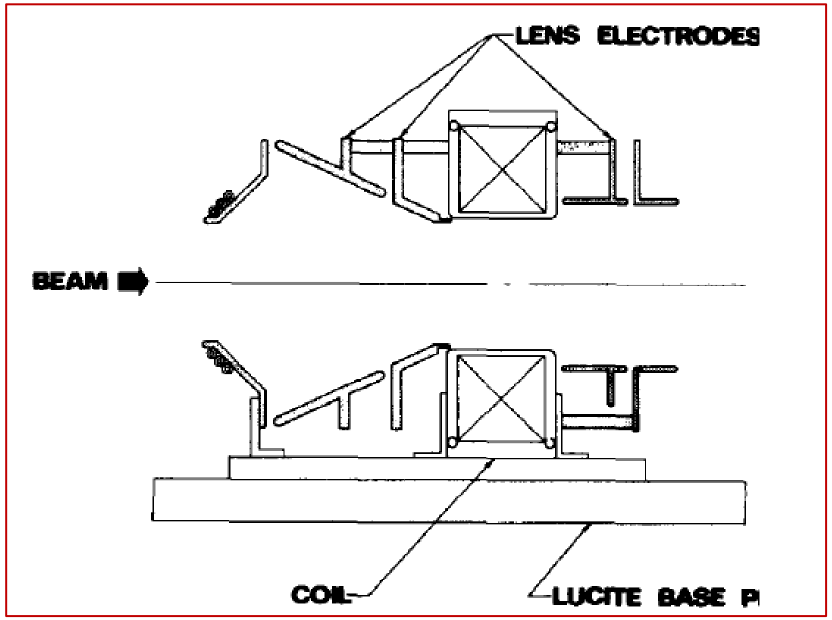
- 1 mm-diameter Ar gas-filled capillary, 33 mm length
- 13 mm behind the tape drive target
- ~0.2% transport efficiency through the APL (protons >1.5 MeV)

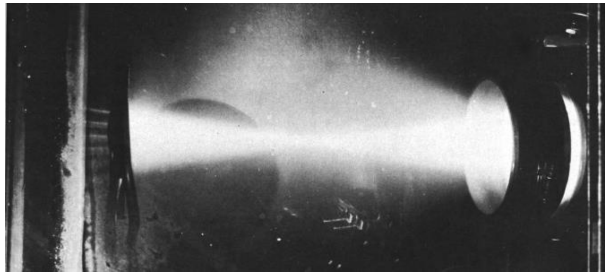


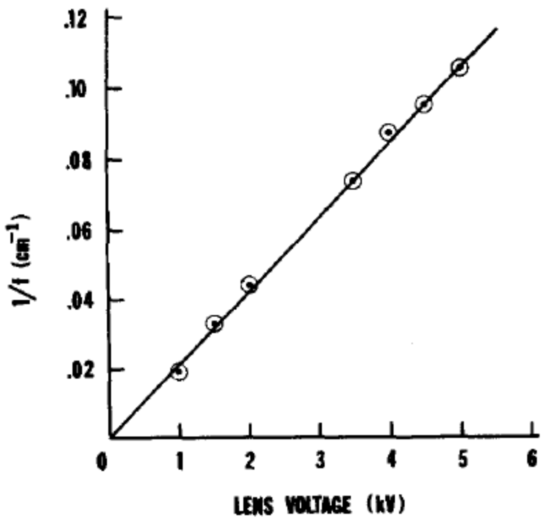
APL

DOI: 10.1103/PhysRevLett.115.184802

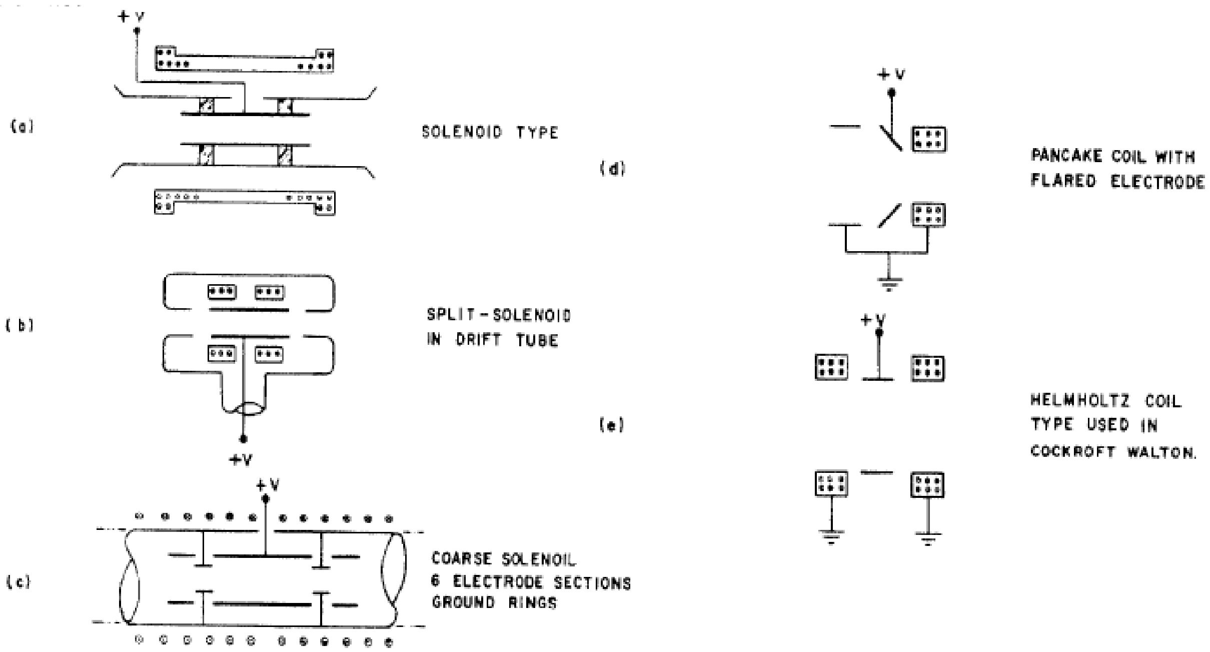
Historical development of the plamsa lens







Booth, 1978



Lens	Electrode R(in.)xL(in.)	B(gauss) at center	V(kV) Op. Range	Fth/Fex*
(a)	1-7/16 x 11	377	5-20	.58
(b)	1-7/16 x 4½	585	5-20	.81
(c)	2 x 72	110	1-2	~3/4
(d)	(1½-2) x 1	200	1-10	-
(e)	2-5/8 x 2	100	1-12	-

*Ratio of theoretical (Eq.(5)) to measured focal length
Lenses (d) and (e) work, but have not been measured yet.

Mobley, 1979