# EXPERIMENTS WITH STABLE CONFINED ELECTRON COLUMNS

K. I. Thoma*, V. Britten, M. Droba, O. Meusel, H. Podlech, B. Scheible, K. Schulte
Goethe-University Frankfurt

*Abstract*

Gabor Lenses were invented for focusing ion beams by the electric field of a confined electron column. In synchrotrons spontaneously occurring electron clouds have an influence on the beam dynamics. Instabilities of single or multi bunches, emittance growth, excessive energy deposition, particle losses, interferences with diagnostic and gas desorption from chamber walls can appear. As a consequence of these interactions between ions and electrons, the beam is deflected or, in worst case, lost. If an ion beam bunch passes a confined electron column in a Gabor Lens these impacts can be studied as well. Collisions of the ions with the electron ensemble will lead to oscillation effects on the cloud and have an influence on the bunch train. These interaction effects will be increased by the number of bunches and their frequency and can be modified by the plasma parameters, temperature and density, of the electron column. If it is possible to damp the excitation of the confined electron column space charge compensation could be provided.
To study these impacts and interactions Gabor Lenses are built. In 2018 a new lens called Gabor Lens 2000 is constructed. This 2 m long lens can hold an electron column with an aspect ratio smaller than 0.1. Single pass experiments with ion beams will be performed under different temperature and density of the plasma and also different frequencies of the train.

## INTRODUCTION

The development of the Gabor Lens (GL) by Dennis Gabor in 1947 opened up a new field of research for the investigation and usage of statically enclosed electron clouds. These electron clouds are plasmas of a single particle species – the so-called non-neutral plasma (NNP).
In Gabor Lenses a homogenous magnetic field created by a solenoid confines electrons in transverse direction, while a potential well created by a cylindrical electrode system confines them longitudinally (see picture 1).

### *Research with the Gabor Lens*

Experiments with Gabor Lenses were done for several reasons. It is possible to inject an ion beam into the Gabor Lens and observe interactions between electron clouds and ion beams. The focal length of the lens as well as the charge exchange and recombination of the particles can be determined.
With the Gabor Lens it is possible to focus highly intensive ion beams. Improving the focusing quality and reducing the emittance growth is the main emphasis in the application of this electron trap. It is also possible to achieve space charge compensation with correctly adjusted lenses.
Furthermore, the non-neutral plasma is examined with the Gabor Lens. The plasma parameters, density distribution and temperature, can be determined.

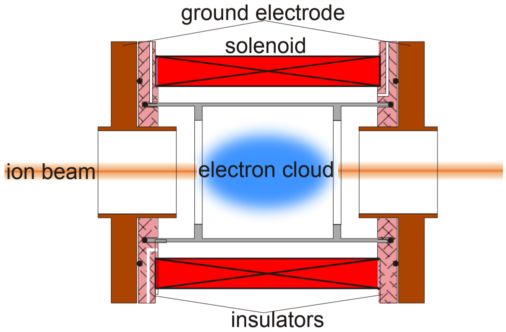


Figure 1: Basic principle of a Gabor Lens.
red: solenoid for magnetic field, brown: ground electrode, grey: anode for applying a potential, blue: electron column, orange/red: positive ion beam [**2**]

## DIFFERENT GABOR LENSES UNDER INVESTIGATION

Several concepts of Gabor Lenses have been designed [**2**]-[**5**]. Here, the aspect ratio of the GL is a decisive parameter for the confinement behaviour of the non-neutral plasma. Different sizes of lenses have been tested and correspondingly different radius to length ratios were assumed. The following table will give an overview of the GL tested so far:

| **Name** | **Radius** | **Length** | **r/l** | **Ref.** |
|---|---|---|---|---|
| small GL | 0.054 m | 0.16 m | 0.3375 | [**2**] |
| 3-segmented GL | 0.054 m | 0.4 m | 0.135 | [**3**] |
| HSI-GL | 0.085 m | 0.340 m | 0.25 | [**4**] |
| Toroid-GL | 0.1 m | 0.68 m | 0.147 | [**5**] |
| GL2000 | 0.075 m | 2 m | 0.0375 | (*) |

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

The first four GL's in the table have already been tested at NNP Group. Following the research results are briefly presented:

- small GL: The lens has a maximum potential of $\phi_{\mathrm{A,max}} = 6\,\mathrm{kV}$ and a maximum magnetic field of $\mathrm{B}_{\max} = 30\,\mathrm{mT}$. The magnetic field is created by

* thoma@iap.uni-frankfurt.de

solenoidal windings. With this lens it was possible to focus Ar- and He-beams up to 30 keV and space charge compensation in the transport channel has been reached.
- 3-segmented GL: This GL is a 3-segmented lens for the creation of a longitudinal gradient in the magnetic field. It has three separated ports for the potential and also three independent magnetic solenoids. With the feed-throughs through the anode tube optical diagnostics is possible and advanced diagnostic concepts have been developed.
- HSI-GL: The maximum potential of the anode is $\phi_{A,max}$ = 50 kV and the maximum of the magnetic field is $B_{max}$ = 160 mT. With this lens a plasma radius of r = 5 cm is created. A segmentation in radial direction of the potential makes it possible to get an asymmetric confinement. This lens was tested at GSI/FAIR Darmstadt and focused intense $Ar^1$ – beams in accelerators up to 130 keV and 35 mA. With HSI-GL the effective focusing quality of a GL has been proofed and possible reduction of emittance growth has been observed (under assumption of 100 % transmission) (see picture 2).

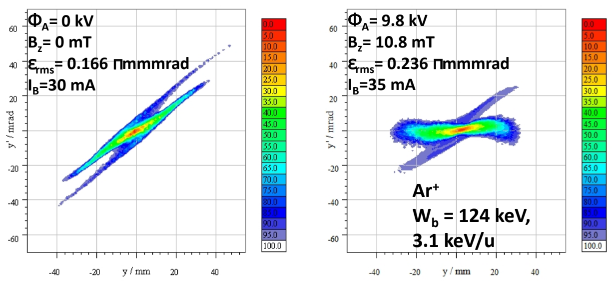


Figure 2: Focusing an ion beam with a Gabor Lens – Emittance growing factor 1.38 [**4**].

- Toroid-GL: This type consists of a toroidal magnetic confinement and a 30 degree-bent anode. With the Toroid-GL electron trapping in an asymmetric potential and magnetic field is possible. The experiments found that the light density distribution of the excited residual gas atoms at the inner edge of the anode tube was significantly more intensive (see picture 3). Thus, a shifted electron density distribution towards the higher magnetic field could be confirmed. A next step could be an application of the toroid GL as a toroidal ion beam guiding device.

GL2000 has the lowest aspect ratio with longest on-axis distance of all lenses designed to date. GL2000 is under construction right now and will be tested till the end of 2018.

## GL2000

GL2000 opens up a new field in research with Gabor Lenses. It is planned to confine the largest stable electron column.

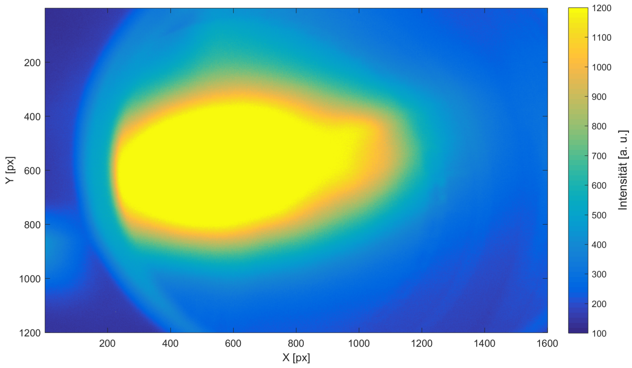


Figure 3: Shift of the light density distribution - the light density distribution is more intensive towards the inner edge of the beam tube [**5**].

The anode of the lens is a 2 m long stainless steel tube with a radius of 75 mm. The copper made electrodes are grounded and the potential well is up to 30 kV. The magnetic field of the lens is created by 23 water-cooled copper coils in pancake configuration. The coils are held by a manufactured frame and can therefore be aligned radially to the anode tube and moved longitudinally to it.

Plasma diagnostics such as emittance measuring systems, Faraday Cups, CCD cams, monochromators, momentum spectrometers and also insitu diagnostic will help to determine the plasma parameters in the lens. It is provided with six feed-throughs for various measurements.

Due to the aspect ratio of 0.0375, the confinement of the electron plasma will be a challenge. Because of the long anode tube, the resulting electric field in the tube is nearly zero and the electrons have a lower kinetic energy. Consequently, there are less impact ionizations and less electron productions. The formation of an electron cloud in the GL2000 is expected to take at least longer than in the previously investigated lenses.

### *Possible applications of GL2000*

GL2000 was developed to confine a long and stable electron cloud. The subsequent diagnostics will characterize the electron plasma as comprehensively as possible and determine the plasma parameters and formation of the longitudinal plasma instabilities.

In the next step, pencil beam experiments will be performed to determine the focal length of the lens. Then beam experiments with highly intense positive ions will be implemented. These ion beams are dominated by space charge and will provide information about the space charge compensation by passing the electron column. The emittance growth can be estimated transversal and longitudinal.

The interaction between electron cloud and ion beam gives information about optimal GL settings for ion beam guiding without losses.

Also new physical effects are expected compared to a series of many small lenses. The shorter, already characterized and functional Gabor Lenses can also be used for beam focusing.

However, the disadvantage is that much more electronics would be required, as each laboratory lens would have to be equipped with its own power supplies and magnets. Furthermore and much more important, the electron cloud would always be constant in density only within the respective lens. Thus, there would be no constant focusing effect on the ion beam due to a chain of Gabor Lenses.

### *Focusing a positive Ion Beam with GL2000*

The transit time of a relativistic ion beam through the 2 m long Gabor Lens is with v=c according to $v = \frac{l}{t}$ about $t_r = 6,67 \cdot 10^{-9}$ s.

The plasma frequency of the electron plasma inside the lens is $\omega_{PE} = 2\pi f = \sqrt{\frac{n_e \cdot e^2}{\epsilon_0 \cdot m_e}} = 564,15$ MHz $T_P = \frac{2\pi}{\omega_{PE}} = 1,7 \cdot 10^{-9}$ s, if the density is assumed to be $n_e = 1 \cdot 10^{14}\,m^{-3}$.

If the transit time $t_r$ of the ion beam is equal to the response time of the electron cloud, expressed by the plasma frequency $\omega_{PE}$ and the beam bunch frequency is below $\omega_{PE}$, the focusing of space charged and emittance dominated beam transport should be possible.

## PRESENT STATUS AND OUTLOOK

GL2000 has been designed since the beginning of 2018 and is currently being assembled. The status of the experimental setup can be seen in Figure 4. The lens is adjusted on a frame and mounted on a rack. The frame can be moved on the rack and later holds not only the lens but also the 23 longitudinally movable copper coils.

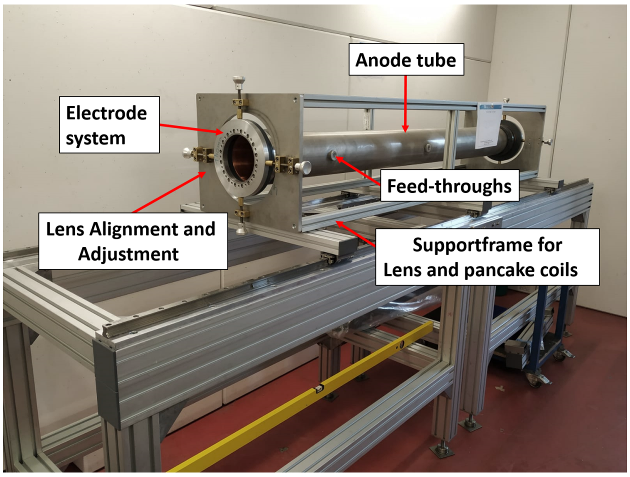


Figure 4: Picture of the present experimental setup of GL2000 (October 2018).

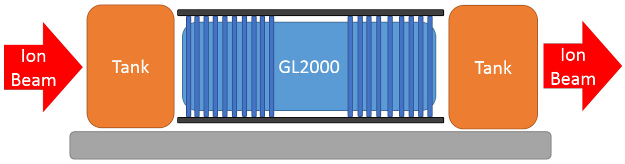


Figure 5: Schematic structure of the experimental setup

After the coils have been mounted on the experiment, the tanks for pumps and diagnostic instruments are to be connected. Following, the first experiments will be carried out at the beginning of 2019. Figure 5 shows a schematic representation of the finished setup. The red arrows represent the ion beam, which passes through the first tank before it is guided through the Gabor Lens and can then be detected in the second tank.

## ACKNOWLEDGEMENTS

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