HEAVY ION FOCUSING USING A GABOR LENS INSIDE A DRIFT TUBE STRUCTURE

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Abstract

Space-charge lenses based on confined non-neutral plasmas, such as electron clouds, provide strong, axially symmetric focusing for high-intensity ion beams (Table 1) and serve as an alternative to conventional quadrupole magnets. The so-called Mobley drift tube integrates a Gabor Lens (GL) into a drift tube of a linear accelerator, enabling beam focusing within an accelerating RF structure. The confined electron cloud does not come into direct contact with the accelerating field; a re-entrant snout geometry is introduced and optimized to minimize the RF field amplitude in the region where the electron cloud forms. Confinement of sufficiently high electron density is achieved in the beam pipe of the drift tube without any external electron source, relying solely on self-sustained processes. This contribution presents simulations and RF measurements of an RF- and vacuum-compatible prototype Mobley drift tube designed for heavy-ion beams, providing insight into the operational feasibility and focusing performance of Gabor lenses integrated in LINAC drift tubes.

INTRODUCTION

A Gabor-lens [1–3] consists of a positively charged cylindrical electrode, a radial magnetic field and ground electrodes designed to capture and confine the generated, rotating electron clouds that focus and transport the hadron beams [4, 5]. The original concept of the lens envisaged the use of a longitudinal magnetic field generated by a solenoid coil for the radial confinement, in this case a Helmholtz coil configuration is used.

In heavy ion accelerator facilities operating in the low [6] up to high β range [7, 8], various types of focusing elements are used, such as magnetic quadrupoles or solenoids. These magnetic quadrupoles can be positioned inside a drift tube in a linear accelerator or outside the cavity. The alternative is the Mobley drift tube [9], which integrates a Gabor-lens into a drift tube. Drift tubes with internal magnetic focusing elements (single, double or triple quadrupole lenses) are now installed in many different LINACs, but the construction, operation or repair of these internal lenses presents a challenge. In addition to focusing and transporting heavy-ion beams, it is also possible to study the interaction of an electron shower between two drift tubes. The electron shower can be activated with the described Mobley-Gabor lens for detailed experiments involving threshold measurements.

Table 1: Heavy Ion Beam Parameters

Parameter	**Unit**	**Value**
Ion		U^{28+}
Max. current	mA	15.0
Input beam energy	MeV/u	1.358
Beam pulse length	ms	≤ 1.0
Beam repetition rate	Hz	≤ 10

MOBLEY-GL AND RF

The Mobley-Gabor lens (see Fig. 1) is an improvement of the Gabor-lens, as it is located in a linear accelerator and within a accelerating RF-field. The electric field in the accelerating gap increases in accordance with the RF period. The field has not yet reached its peak when the particle beam enters the accelerating gap, and by the time it leaves the gap, the field has already begun to decrease again. The end plates of the drift tube are the ground electrodes of the Gabor lens.

The general design of a Gabor lens uses a solenoid to ensure radial confinement via a longitudinal magnetic field. The Mobley drift tube required a design change from the

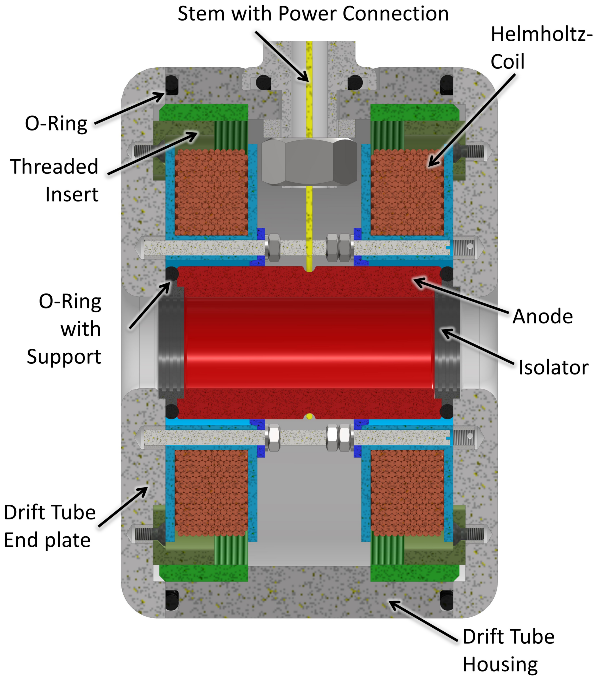

Figure 1: Test setup of a Mobley-drift tube with integrated Gabor lens (anode, isolation, end plate of the drift tube, Helmholtz coil) into a drift tube of a linear accelerator.

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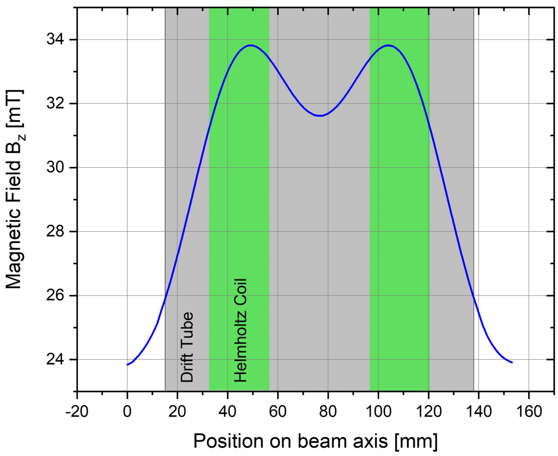

Figure 2: Simulated magnetic field distribution of the Helmholtz coils on the beam axis. In gray is the drift tube and in green the position of the Helmholtz coils.

solenoid to a pair of Helmholtz coils to establish an electrical connection to the anode.

The anode is the beam pipe of the drift tube and has the same diameter as the aperture of the end plates [10]. There is an electrical isolation between the anode and the end plates of the drift tube. The isolators are also equipped with grooves to prevent leakage currents, and PEEK was the preferred material due to its excellent vacuum, thermal and insulating properties. The end plates of the drift tube can be mounted so that all options are available during experiments, such as adjusting the gap length, changing the Helmholtz coils or modifying the geometry of the insulators. In the standard Helmholtz coil configuration, two parallel, identical coils are positioned at a distance equal to their radius R_a and are both supplied with current I in the same direction. This setup had to be modified by increasing the distance between the coils to accommodate the screw connection and the electrical wiring. As a result, the normally homogeneous magnetic field along the axis has a local minimum (see Fig. 2). The Mobley-drift tube including the Gabor-lens, Helmholtz coils and geometry of the drift tube is shown in Fig. 3 and the parameters are summarized in Table 2. The field gradient of a comparable quadruple singlet magnet of the same length is 53.15 T/m, at 1200 A and with a single-layer winding scheme. The focal length of a Gabor-lens f can be approximated as a thin lens, and assuming a cylindrical, homogeneously distributed electron cloud [3]:

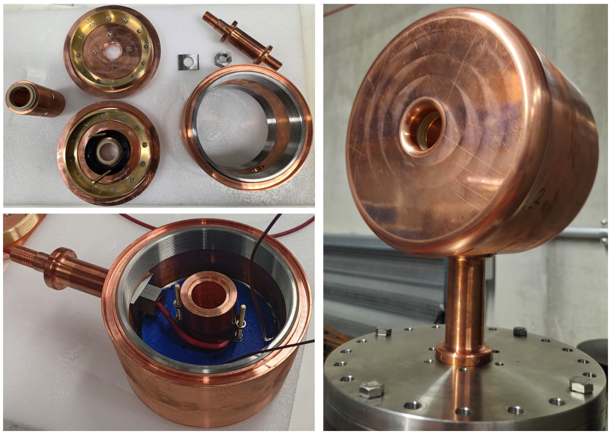

Figure 3: (top left) Components and complete assembly of the Mobley-drift tube. (bottom left) One Helmholtz coil and the electrical connection to the anode. (right) Final assembly on the vacuum leak detector.

Table 2: Design Parameters of the Mobley-Drift Tube

Parameter	**Unit**	**Typ-1**
Anode potential Φ_A	kV	5.0
Anode radius r$_A$	mm	15.0
Magnetic field B$_z$	mT	31.0
Helmholtz coil:		
– Radius R_a	mm	49.3
– Distance a	mm	64.0
– Windings N	#	300
– Current I	A	10.0
Eff. length $L_{\mathrm{eff,GL}}$	mm	95.5
Aspect Ratio S		0.156
Electron density n_e	$\times 10^{14}$ m^{-3}	1.048
Drift tube:		
– Diameter	mm	180.0
– Aperture diameter	mm	30.0
– Length	mm	123.1

$$\frac{1}{f_{GL}} = k^2 L = \frac{n_e e}{4\epsilon_0} \frac{L}{W_b}. \tag{1}$$

with n_e as the electron density, L the length of the Gabor-lens (distance between the two ground electrodes, in this case the end plates) and W_b is the energy of the beam in units of [eV]. The deflection angle of charged particles by the Gabor lens can be expressed directly in terms of the focal length, because particles at an entrance distance d from the lens are bent by an angle Θ_{GL} according to the thin-lens approximation:

$$\Theta_{GL} \approx -\frac{d}{f_{GL}}. \tag{2}$$

LINAC Structure

In current applications, the Gabor lens is used for static focusing or for beam transport of light to heavy ions. The Mobley drift tube described is used to focus the particle beam during pulsed operation within a linear accelerator. The repetition rate, pulse width and also the amplitude of the RF power in the LINAC must be individually adjustable for different particle beams. For this reason, rapid modification of the electron cloud within the Mobley drift tube is of crucial importance.

The production of electrons and the dynamics of electrons within Gabor lenses have been studied in detail in [4, 11, 12]. These studies show that an electron cloud can form within a timescale of [µs], and this formation rate is sufficient for pulsed beam operation, i.e. non-CW operation. Furthermore, between the individual beam pulses, which may also have different ion types, pulse lengths and repetition rates

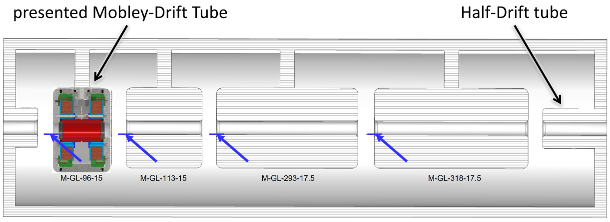

Figure 4: RF-cavity with four Mobley-drift tubes. The first drift tube is shown as an example. Half-drift tubes are on both end plates of the tank. The position of the simulated electric fields are marked.

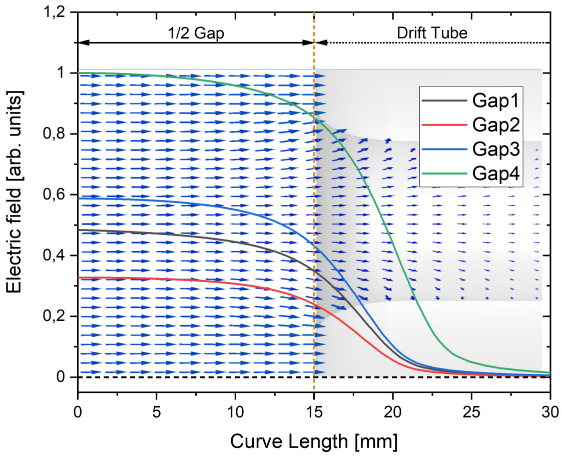

Figure 5: Optimized re-entrant snout to minimize the RF field amplitude in the aperture of the drift tube to the electron cloud, simulated with CST-EM-Studio [13].

the electron cloud must be mitigated; dynamic behaviour is sufficient.

In this test cavity (see Fig. 4), a separate accelerating voltage is required for each gap, in order to be able to study the impact of different RF-field amplitudes on the electron ensemble. In a real LINAC accelerator, gap voltages with different amplitudes are also present for each accelerating gap. The strength of the electric field from the centre of the gap into the drift tube directly at the surface of the aperture is shown in Fig. 5. The re-entrant snouts are optimised to geometrically separate the RF from the electron cloud, i.e. the electric field is minimised. Without a sufficient re-entrant snout, the Gabor lens does not work [9].

Multipacting

Multipacting is a phenomenon that occurs in all RF cavities, whereby a large number of electrons are accelerated in an electric field within the accelerating gap, absorbing energy from the RF field in the process. These electrons therefore prevent an increase in the coupled RF power or the stored energy within a cavity. In the acceleration gap, with the applied RF field, these electrons oscillate and collide with the surface of the drift tube, generating X-rays [14]. The Mobley drift tube allows active investigation of multipacting between two drift tubes by weakening the magnetic field of a single Helmholtz coil. Thermal electrons leave the electron cloud on the side of the weakened magnetic field, are accelerated by the electric field, and collide with the neighbouring drift tube, generating an electron cascade or X-ray radiation. In addition to determining the threshold for multipacting between drift tubes, it is also possible to investigate different pressures within the cavity, gases from the surface and, thereby, the interaction with the electron cascade.

OUTLOOK

The test cavity is shown in Fig. 6 will be equipped with four additional Mobley drift tubes, as well as half-drift tubes, also of the Mobley type. The Mobley drift tubes, with their internal electron clouds, are being investigated in terms of the different amplitudes of the electric fields in the accelerator gap and their focusing properties. The next step with the Mobley drift tubes will be to demonstrate particle acceleration in combination with focusing. The determination of the threshold value for the multipaction as a function of the HF amplitude, the residual gas and the parameters of the Mobley drift tube can be investigated in detail.

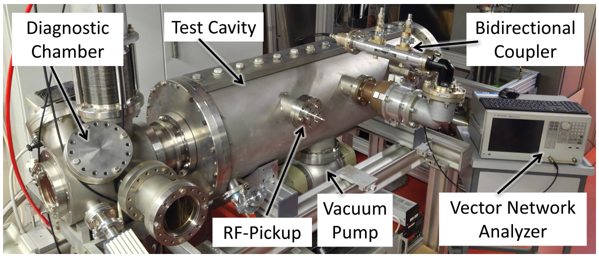

Figure 6: The test cavity is equipped with HF sensors and vacuum components and is ready for the installation of the Mobley drift tube.

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