* **1988 – Palkovic – Measurements on a Gabor lens for neutralising and focusing a 30 keV proton beam**
  + Given a particular beam charge density, one designs the Gabor lens to have plasma densities which are much larger. Thus, the beam charge density is a small perturbation on the motion of the plasma.
  + Study a 30 keV H- beam to be matched into an RFQ (focus the beam from a duoplasmatron on the initial stage of the Fermilab linac)
  + The design of the lens is similar to the one proposed by Gabor.
  + The magnetic flux tubes are also equipotential electric surfaces.
  + Emittance is measured both upstream and downstream of the lens with two slit emittance probes.
  + Stable operation of the lens has been observed for periods of 24 hours.
  + The discharge current from the lens anode is less than 1 mA at 10 kV.
  + A growth factor of about 4 is seen in the rms emittance and about 3 in the 90% emittance. Computer simulations show the rms emittance growing by a factor of 3 in the short drift between the source and the entrance to the lens.
  + It is not known how much growth occurs in the second drift or whether lens aberrations are causing the emittance growth.
  + A decrease of the rms emittance measured at the second probe by a factor of 2 is seen as the strength of the lens is increased. The 90% emittance seems to be independent of the lens strength.
  + The angular distribution is sharply peaked at the second probe.
  + They have investigate the time dependence of the emittance over the length of the beam pulse (90 micro-seconds). The emittance changes due to variations in the DC current of the source.
* **1992 – Pozimski – EPAC – First experimental studies of a Gabor-Plasma-Lens**
  + A compact lens has been built and tested
  + One way to reduce the perveance of a positive ion beam without reduction of the beam current is the space charge compensation by electrons
  + Magnetic elements (solenoids, quadrupoles, dipoles) preserve or even enhance space charge compensation but they suffer from the weak focusing for low velocity or high mass ions
  + Assuming a homogeneous magnetic field and electron production, the resulting electron density is homogeneous too. This leads to a linear radial dependence of the focusing force needed for **aberration free focusing**
  + **Filling mechanism:**
    - Electron production by collisions of the beam ions with the residual gas. This mechanism always take place and will usually produce electrons near the axis. The time needed to fill the lens is mainly a function of the residual gas pressure.
    - Production of electron by a hot cathode. Not sure that the electrons reach the central area of the lens.
    - Production of electrons by a gas discharge (very efficient). There seems to be no way to control the production density in different regions inside the lens.
  + Numerical simulations have shown that the electrons move from regions with an electron density higher than the radial limit for trapping into outer regions with lower density ---> **homogenisation** of electron density
  + Discharge experiments:
    - The type of gas does not change the discharge behaviour significantly
    - At low pressure (up to 10^-6 hPa) the discharge current is approximately proportional to U^3/2
    - In the range 10^-4 to 10^-5 hPa, the dependence of the discharge current on voltage and magnetic field shows maxima (optimum values of mean free path and electron accelerating voltage)
    - At pressures higher than 10^-4 hPa, the discharge current increases rapidly
  + Measurements of the potential depression (no ion beam)
    - Use an on-axis energy spectrometer with the gas discharge on
    - The ion energy contains information on the potential distribution and filling rates
    - Assuming that the maximum ion energy is gained by ions created near the axis, the corresponding potential value gives a lower limit for the degree of lens filling (~40%)
  + Experiments with an ion beam
    - Previous measurements by other groups have shown beam aberrations and severe emittance growth due to incomplete and inhomogeneous electron filling
    - They managed to focus the beam with a negligible emittance growth
    - The measured focal length was 4 times larger than the theoretical value ---> the lens was filled only to about 25% of the radial trapping limit
  + Need to account for the diffusion of electrons over magnetic field lines
  + Wide spectrum of behaviour in several experiments
  + Sometimes emittance growth by a factor of 4 occurred
* **1996 – Pozimski – Investigation of space charge compensated transport by use of a Gabor plasma lens**
  + Two experiments: determination of the plasma density by examination of the light emitted by the plasma; measure the focusing capabilities using a 10 keV He+ beam
  + The light emitted by the plasma is caused by collisions between the residual gas and the captured electrons.
  + Density measurements:
    - The intensity of the emitted light is strongly peaked on the lens axis, so the electron density is assumed to be distributed in a similar way.
    - Varying the potential on the central electrode: the form of the radial density distribution seems to be constant and the height growths linear in a first approximation except for the lowest fields where the gas discharge is off
    - Varying the external magnetic field: the intensity rises more than linear for low fields and then levels off.
  + Beam measurements:
    - The emittance was measured after the lens with the lens off and on.
    - Simulations were done for the emittance after the lens using the ‘peaked’ electron density and using a homogeneous electron density
    - The experiments indicate that the electron density is between the two cases
  + Comparison between the measured emittance and the calculated emittance show in focusing strength and in aberration forecast a better result for the peaked than for the homogeneous distribution.
    - Additional electrons produced by the beam travelling through the lens (??)
    - Influence of the beam potential on the plasma (??)
* **1998 – Ivanov – Plasma lens with a current density depended on external magnetic field**
  + Ion beam focusing by an azimuth magnetic field of longitudinal current in plasma
  + The current radius is determined by the outer nonhomogeneous longitudinal magnetic field.
  + A plasma gun is assumed – the current in the plasma is supplied by an electrode
  + The plasma current lens is placed in an external non-homogeneous longitudinal magnetic field which can change the radius of the current channel.
  + Simulations show that all the protons in a beam are focused at the same point.
  + The outer magnetic field distribution is optimised to put together all ions in focus.
  + When the solenoid is switched on, the current channel radius decreases.
  + A 5 MeV proton beam was transported through the plasma at various time moments after the discharge of the plasma gun. A focussing effect was observed at microseconds after the plasma discharge which coincided with the maxima of the measured plasma current.
  + Simulation of proton trajectories gives similar final beam radius as the measured one.
  + The majority of the protons go out of the current channel and do not reach the focus.
  + The optimised external magnetic field was not on during the measurements.
* **2002 – Soloshenko – Space-charge lens for focusing negative ion beams**
  + Performed estimations of the focal length and experimental demonstration of H- focusing.
  + Demonstrated the focusing of negative ions in two regimes: when the gas ionisation is performed mainly by the beam ions and in the regime of non-self-maintained discharge. In the last case, the working pressure is low enough that the loss of negative ions in the lens are negligible.
* **2004 – Chekh – Static and dynamic characteristics of plasma lens with modified magnetic field geometry**
  + Reports results of investigations of a plasma lens with modified configuration of magnetic field lines which minimises the axial and radial field gradients in the central region of the lens.
  + The focusing properties of the lens significantly depend on the beam current, on the mode of power supplying to the electrodes and on the magnetic field strength.
  + The maximum radial field gradient was decreased by a factor of 6 with permanent magnets in comparison with the field configuration given by current coils.
  + Investigations used two beam currents: 40mA and 400mA.
  + The introduction of a Langmuir probe close to the electrodes resulted in an almost total loss of the focusing properties, while such an influence was not observed when introducing the probe in a region near the axis.
  + At low magnetic field strength, the medium in the plasma lens may be characterised as a sufficiently unstable one – they observed high-frequency noises and strong breakups in the focusing process.
  + In the pulsed mode, the sharpness of the focusing is weaker at low beam intensity. No differences were observed at high beam intensity between dc and pulsed modes.
  + In dc mode, the lens provides a more efficient and stable focusing, quicker coming to an operation regime.
  + One may assume that the glow discharge forms a preliminary density of electron space charge in the lens. This results in easier and faster forming of the main plasma medium. The presence of the discharge is evidenced by the directly observed diocotron oscillations modulated at a frequency of an ionization instability.
* **2005 – Goncharov - Effect of the electrostatic plasma lens on the emittance of a high-current heavy ion beam**
  + The paper describes measurements of the emittance growth for a 32keV, 50mA Cu2+ ion beam through a permanent-magnet electrostatic plasma lens.
  + Lens specifications: D=7.4cm, L=14cm, up to 5.5kV anode voltage, B=12.6mT, p<2e-5 Torr; The focusing properties of the lens have been reported previously.
  + The magnetic field configuration was determined by numerical calculations to minimise field gradients. According to theory, such a configuration suppresses plasma noise and removes spherical aberrations.
  + Plasma is formed by the ion beam by secondary electron emission from the lens electrodes.
  + Beam emittance is measured using the “pepper pot” technique.
  + The central part of the beam is almost completely focused and the ion trajectories at the periphery are distorted by spherical aberration.
  + Measurements showed no significant increase in beam emittance due to the plasma lends when the lens is optimally focused.
  + However, in the focusing regime with considerable dynamic aberrations, almost complete loss of periodic structure of the pepper-pot emittance pattern is observed, indicating substantial emittance growth.
* **2005 – Pozimski – Space charge lenses for particle beams**
  + Plasma lenses are better than conventional systems for a degree of lens filling above 17%
  + Presented simulations show that the local density values can be reached locally.
  + Significant improvements in the lens operation are caused by a reduction in the residual gas pressure.
  + Comparison of experiments and simulations shows good agreement concerning both focusing strength and linearity of phase space transformation.
  + Not enough theory to describe the space charge density is available. Additional effects are: charge production, thermalization of the space charge ensemble, diffusion of particles across magnetic field lines.
  + The use of space-charge lenses is advantageous for filling factors higher than 0.17 using internal filling and higher than 0.26 for external electrons.
  + Numerical simulations
    - For each grid point, the local electric field is calculated from the confinement condition and then compared to the existing electric filed generated by space charge ---> a new local electric field is calculated until convergence
    - A thermalization of the space charge along the magnetic field lines is assumed (an electron temperature must be assumed)
    - The simulation calculates the electron temperature for a given longitudinal loss current
    - Space charge density as a function of r and z is obtained: while in the centre of the lens the theoretical density is nearly reached (~70%), the strong influence of the electrodes on the longitudinal and radial elongation of the cloud is clearly visible.
  + Experiments
    - Source emittance is measured at the entrance of the LEBT system (use for beam transport calculations)
    - The predicted emittance growth is smaller than the measured one
    - The space charge density is almost homogeneous (+-3%) ---> negligible aberrations caused by nonlinear focusing fields
    - Measurements give an average density of 8x10^13 particles per cubic meter.
    - The data shows a local maximum degree of lens filling of 70% for the radial enclosure and 90% for the longitudinal trapping. The average degree of lens filling was (38%, 49%) [79% of the value obtained in simulation] and (49%, 61%) [exactly as predicted by simulation] for the two Gabor lenses (radial, longitudinal).
* **2006 – Goncharov – Electrostatic plasma lens for accelerator injection application**
  + Indications that for optimal focussing conditions the lens does not increase the beam emittance nor the beam noise for beam current intensities up to 250 mA/cm^2.
* **2008 – Schulte – Optical diagnostic on Gabor plasma lenses**
  + Experiments using a high field Gabor lens have shown a correlation between the thermalisation of the enclosed electron cloud and the focussing quality.
  + A nonuniform energy distribution of the confined electron cloud leads to a Diocotron instability and therefore a change of the radial electron density profile. The resulting nonlinear focussing field forms the observed aberrations.
  + A three segmented Gabor lens was constructed
  + Observed light emitted by the interaction of electrons with the residual gas
  + Evaluate the temperature and density distribution of the NNP
  + In the case of similar strengths in longitudinal and radial confinement the NNP is assumed to be thermalized and its beam focussing quality is free of aberrations.
  + Measured emittance growth for range of electric potential and magnetic field
  + Emitted ions are detected by a Faraday cup and by a momentum spectrometer to determine the ion current and their energy
  + Besides the external fields, it has been proved that the r**esidual gas pressure** and the involved **electron collision frequency** are crucial confinement parameters as well.
  + For each magnetic and electric adjustment, it is possible to find a pressure range that improves the trapping efficiency.
  + Diocotron instability is seen in both numerical simulations and experiment.
  + Because of low electron densities (10^14 m^-3) and by absence of important recombination processes the **NNP cannot be assumed to be in thermodynamic equilibrium**
  + The plasma column could be described in **corona equilibrium.**
  + But with similar strengths in longitudinal and radial confinement, the NNP performs a transition to a state of **thermalisation.** In this context, thermalisation means a homogeneous distribution of electrons in the lens and **equality of longitudinal and radial average kinetic energies.**
  + Then the Boltzmann distribution is valid and the method of temperature measurement by comparison of different intensity levels can be used (Hans R. Griem, Plasma Spectroscopy, 1964).
  + Density measurement:
    - The trapped electrons reduce the externally set potential and influence the electric field. The ion energy measured by the momentum spectrometer yields information about the average electron density.
    - There are different regions of ion production within the electron plasma.
    - The linear dependence between the average electron density and the anode potential is in agreement to the measurement.
* **2009 – Meusel – PhD Thesis – Focusing and transporting ion beams with space charge lenses**
  + The previous mechanisms of externally filling the lens were replaced with production mechanisms inside the lens.
  + Improvements in the performance of the lens were possible through computer software which optimizes the lens parameters for a larger filling factor.
  + The imaging capabilities still fall short of expectations.
  + They had an existing prototype and built two others to investigate their performance.
  + The theoretical description overestimates the electron cloud density. Thus, a numerical model is presented which determines the electron density distribution in a self-consistent matter.
  + A Helmholtz coil is used for creating the magnetic field to allow for transverse diagnosis of the NNP.
  + Assumptions (R.C. Davidson)
    - NNP **plasma is cold** (the thermal speed of electrons is negligible compared to their drift speed)
    - Diamagnetic field caused by the rotation of the plasma is negligible
    - Homogeneous cloud with no ions
  + Two solutions for the angular frequency: one corresponds to the cyclotron frequency of the electrons moving in circular path around the magnetic field lines; the other corresponds to ExB rotation of the plasma column. The filling factor is represented by an inverted quadratic as a function of the angular frequency.
  + Brillouin flow corresponds to a filling factor of 1 and to a rigid rotation of the plasma cloud.
  + The two theoretical confinement conditions are not linked together.
  + The operation point of the lens is defined as the condition for equality between the two densities obtained from the confinement conditions in the longitudinal and radial directions.
  + The radial density condition neglects the radial electric field given by Laplace’s boundary conditions (from the external electric field). This is considered in the numerical simulations.
  + Numerical simulation shows that the electron density is lower than predicted by the radial enclosure condition even when the influence of the outer field is reproduced.
  + The simulation shows loss channels between the anode and the ground electrodes (region of zero potential). Thus, the maximum radius of the NNP can be approximated by the radius of the ground electrodes. The longitudinal filling factor is maximal when the radius of the ground electrodes matches the radius of the anode. However, because of high-voltage sparks, a minimum distance needs to be kept between the two components. For a high field Gabor lens, the ratio can approach 2 which results in a longitudinal filling factor of about 0.6
  + The electrons are free to move along the magnetic field lines. Once their KE has been converted into enough PE, the electrons can escape the trapping potential.
  + The **thermalisation** of the plasma takes place if the time that electrons spend in the lens is higher than the thermal relaxation time (related to the plasma temperature and density). The time spent by an electron inside the lens can be estimated from loss current. Thus, one can plot the loss current as a function of the plasma temperature.
  + A reduction in the electron density in the lens centre is seen when increasing the plasma temperature.
  + The main electron production mechanism is considered to be the residual gas ionisation. For He, the total cross-section for ionisation is maximum at an electron temperature of about 100 eV. By considering RGA ionisation from electrons, from other RG ions or from the beam ions, the lens filling time is calculated to be about 350 ms.
  + The plasma temperature is determined by a spectroscopic method (assumes local thermal equilibrium): measure the intensity and wavelength of two emission lines.
  + LTE is violated by the lack of recombination processes such as three-body recombination and dielectric capture. In addition, the ion current from the lens leads to a constant outflow of energy from the NNP.
  + Since the KE of electrons is determined by the external fields separately in longitudinal and radial direction, the term temperature is no longer permissible as a system property.
  + The measured average KE of electrons is 2 to 3 orders of magnitude lower than the calculated ones. As the anode potential increase, there is only one data point which shows possible agreement.
  + A new ion source is investigated to determine the input emittance.
  + The beam transport measurements are done with 2 Gabor lenses one after the other (operated separately or at the same time)
  + The degree of compensation in the drift is calculated by comparing the measured emittance with numerical simulation. The result is 0.95 and a compensation degree of 1.0 is assumed inside the lenses.
  + For only one lens operating, an emittance growth factor of 1.95 is observed (including the drift range). Beam aberrations occur close to the axis, but the transformation is linear to a good approximation. Simulation and experiment give similar phase space distributions.
    - For a beam radius of 20mm, the electron density obtained from simulation is constant up to a variation of 1.5%.
    - The simulated average electron density was 48% / 63% of the theoretical values given by the confinement conditions (radially/longitudinally).
    - The measured average electron density was 38% / 49% wrt. theory.
  + The second lens is also switched on to focus the beam on the emittance scanner. The transformation is highly linear. Aberrations occur again in the area close to the axis.
    - A possible cause for aberrations could be a decrease in the space charge density with very small radii.
    - The measured emittance growth was 3.54.
    - The simulation shows the same orientation of the phase space distribution, but without the near-axis aberrations.
    - From the measure focal distances, the electron densities in the two lenses were 7.9e13 and 1.4e14 1/m^3.
    - The simulated average electron density was 34% / 61% of the theoretical values given by the confinement conditions (radially/longitudinally).
    - The measured average electron density was 34% / 61% wrt. Theory. (perfect agreement with the simulation).
  + All the measurements are collated together and show a scan of the parameter space (anode potential, magnetic field) in terms of
    - The mean electron density – this is maximum in the neighbourhood of the lens work function, though some additional features can be seen
    - The filling factor – it is highest around the work function of the lens. However, it increases until the maximum and then decreases further along the work function.
      * An average filling factor of 38% is obtained for the operational parameters of the lens being tested.
    - Emittance growth – the imaging properties of the electron cloud go beyond the work function of the lens. However, the region of minimum growth coincides with the regions of maximum filling factor and high electron density
  + Inducing collective instabilities was tried by a fast change (100 us) of the anode potential. The anode potential was ramped from 500V to 2000V. However, because of the non-zero initial value, a thin NNP is present at t=0. The construction time of the NNP was implied to be less than 50us. This does not correspond to any theoretically determined filling times.
    - No aberrations were seen during the temporal variation of the longitudinal filling factor.
    - The ion beam radius changes simultaneously with the anode voltage change.
* **2010 – Drozdowskiy – Investigation of the formation of a hollow beam in the plasma lens**
  + A discharge plasma lens is described
  + The current distribution changes significantly during the discharge. The current is approximately constant for a limited time, so the lens can be used for focusing for beams of about 1ms or less.
  + Special shape beams can be produced by the lens if it is used in the non-linear regime. Precisely the lens can be used to create hollow beams.
  + A paraxial beam with zero emittance is converted into a tube for an azimuthal magnetic field distribution given by B = a + br in the plasma lens. This can correspond in practice to the size of the homogeneous core of the discharge current being much smaller than the size of the beam.
  + Experiments resulted in the observation of tubular ion beams of relatively small diameter (less than 1cm)
* **2010 – Dobrovolskiy et al. - Recent advances in plasma devices based on plasma lens configuration for manipulating high-current heavy ion beams**
  + Design of a cylindrical plasma source for ion treatment of substrates (the magnetic system is based on permanent magnets). The device was adapted for focusing of intense negatively charged ion beams.
  + Both the spatial distribution of the potential inside the lens and a photo of the plasma discharge show two maxima. A ring-shaped maximum is seen near the central axis, rather than on the axis. A second maximum is seen near the perimeter of the discharge.
  + The potential distribution on the axis is seen to depend on pressure.
* **2011 – Schulte – Studies on electron cloud dynamics for an optimised space charge lens design**
  + New space charge lens prototype was designed and constructed (50 kV, 436 mm, 75mm)
  + Instabilities were observed far from the work function of the lens (ratio of external electric and magnetic field strengths)
  + The field and the pressure dependency of the plasma state is strongly coupled with a variation in the electron production rate.
  + A time-resolved diagnostic was developed.
  + The evolution of the diocotron instability occurs within **nanosecond to millisecond time scales**. In the case of an unstable electron cloud the detected ion current shows a periodic structure.
  + The measure ion current, the intensity and symmetry of the light density distribution are strongly correlated.
  + Experimental results implicate that there are different regions of ion production within the electron plasma ---> 2 peaks: peak 2 is a result of the ion production in a sheath at the anode surface. In this region, the produced electrons are rapidly attracted and do not contribute to the average density. The average density is measured from peak 1 from the reduced kinetic energy of the extracted residual gas ions.
  + Conventional diagnostic methods for determining the electron temperature are not suited for the nonneutral plasma.
  + Investigated a method based on optical-emission cross sections (direct relation between the emitted atomic lines and the electron energy)
    - Clear discrepancy of the results in electron temperature between the experimental data and numerical prediction.
* **2011 – Schulte – Investigation of diagnostic techniques on a nonneutral plasma**
  + Two regions of ion production within the plasma – confirmed by experiment and numerical simulation.
  + The measured average electron densities are in good agreement with numerical values.
  + J.B. Boffard, “Application of excitation cross sections to optical plasma diagnostics” (2004)
  + Clear discrepancy seen in experimental data when compared to numerical results.
  + Results show a dependency of the detected photon flux on the residual gas pressure. This pressure dependency affects the optical-emission cross sections and might be the reason for the discrepancy above.
* **2013 – Meusel – Experimental studies of stable confined electron clouds using Gabor lenses**
  + Advantages of Gabor lenses:
    - Mass independent focussing strength
    - Space charge compensation of the ion beam
    - Reduced magnetic and electric fields compared to other devices
  + Collective phenomena result in aberrations and emittance growth
  + Simulation with two numerical codes:
    - 2d hydrodynamics code with the loss current as a free parameter
    - 3d PIC code ---> gives the most probably equilibrium state
  + Trapping efficiency and emittance growth measured for a range of electrostatic potential and magnetic fields
  + The emittance growth along the work function is negligible.
  + Following the work function, the filling factor reaches 50%. Increasing the magnetic field and the anode voltage along the optimum work function leads to a decrease of the trapping efficiency. This may be explained by the raise of the electron temperature.
* **2013 - Schulte - PhD Thesis**
  + Plasma instabilities are observed in the regime of unbalanced confinement conditions or at high residual gas pressure.
  + Nonneutral plasmas show a similar collective behaviour as described for quasi-neutral plasmas (Debye shielding, plasma frequency, plasma instabilities)
  + Gabor lens typical space charge: density 10^14 m^-3 and **temperature T~100 eV**
  + The electron cloud in a Gabor lens meets all the conditions for a plasma.
    - **Plasma frequency ~ 563 MHz** (above which the plasma becomes transparent for EM waves)
  + **Detailed theory is described**
  + The maximum electron density for longitudinal confinement is calculated considering the **neutralization factor f** (Ions are created by electron impact ionization and despite being extracted from the plasma due to the positive anode potential, they will form a neutralising background)
  + Loss channels between the anode and the ground electrode lower the maximum radial expansion of the plasma column to the radius of the ground electrode.
  + One can define a configuration rule for the lens when n\_e,r = n\_e,l giving the relation between the magnetic field and the applied potential
  + Since the interaction of electrons with residual gas atoms is not negligible, the **temperature of the NNP is best described by a flow equilibrium** that is achieved due to all energy gain and loss processes of the electrons.
    - An electron gains KE in the electric field between two collisions
    - Energy loss in collision, plus change in momentum direction
  + Ion-electron collisions
    - Radiative recombination is negligible
    - Electron-impact ionisation also negligible
  + The description of plasma by a few thermodynamic variables is not possible since the plasma is not in complete thermodynamic equilibrium. The density of the electron cloud in a Gabor lens is much lower than the density required for Local Thermodynamic Equilibrium.
  + Low-density laboratory plasmas are better described by the Steady-State Corona Model where only a few atomic processes are balanced: ionisation and recombination, collisional excitation and spontaneous decay.
  + Due to the long confinement times, the electrons are assumed to have a Maxwellian distribution.
  + Electron density is low enough that the main atomic excitation processes are a result of electron-atom collisions while these levels depopulate by spontaneous decay.
  + The electron impact ionisation and the recombination of ion electron pairs is not balanced ---> ions are extracted from the lens due to the anode potential
  + Electron production
    - Main production process ---> residual gas ionisation by electrons, residual gas and beam ions
    - The experimentally observed short filling times (in the order of >ms) for the Gabor lens operated as a stand-alone system cannot be explained by the interaction of electrons and ions within the residual gas alone.
  + Electron loss
    - The electron losses in the longitudinal direction are theoretically described by a loss current which increases exponentially with the plasma temperature.
    - The major radial loss process is assumed to be the transport of electrons across the magnetic field lines by particle collisions.
    - Experimental investigation by detection of the emitted X-ray spectrum with a gamma-spectrometer. Only the radial losses on the anode or longitudinal losses on the ground electrode may produce the detected Bremsstrahlungs spectra.
  + Simulation codes
    - 2d hydrodynamics code – loss current used as free parameter, no radial loss. No collisions ---> results in an equilibrium density distribution
    - 3D PIC code – uses a constant number of macroparticles, the macrocanonical state is approaching the most probable equilibrium state (can simulate evolution of Diocotron instability)
  + The presented results work with the normalised rms-emittance
  + Kurtosis measures the “peakedness” of a distribution (ratio of the 4th momenta and squared 2nd momenta of the distribution)
  + Perveance – represents the strength of acting space charge forces
  + Plasma instabilities
    - Two types of instabilities seen: inhomogeneity of the electron density in longitudinal direction and a hollow profile associated with the diocotron instability
    - Diocotron: at strong magnetic fields, the gyration radius of the electrons becomes smaller and the column is more compressed ---> the confinement condition given by the anode potential is locally exceeded and thus electrons can escape this region ---> a hollow profile occurs providing the basis for the diocotron instability
  + Two quantities are observed:
    - The extracted residual gas ion current
    - The photons emitted from the plasma
  + Instability observed: the light density evolves from a previously homogeneous to a hollow distribution within **10ms.** This process repeats every 10 to 11 ms and can be described as a pulsing of the plasma cloud.
    - The ion current and intensity never drops to zero during this variation. Therefore, it does not represent a destructive mode of a plasma instability.
  + The electron temperature is measured by using optical-emission cross sections. The comparison of emission spectra of He produced by an incident electron beam and by the nonneutral plasma shows that only specific transitions agree for the value of intensity. Only two transitions were chosen for the electron temperature measurement.
  + Used a separate electron beam and He gas chamber to measure the optical-emission cross-section for several transitions.
    - Benchmark against previous experiment not ideal (20% to 100% deviations)
  + NNP temperature
    - 428 eV were obtained far from the operation point of the lens, while 69 eV and 29 eV were measured for lens parameters close to the operation point.
    - Far away from the operation point, the results of the simulation and the experiments strongly disagree
    - Close to the operation point, the numerical and experimental results match only for very low electron loss currents as input for the numerical calculations
  + Beam transport measurements
    - The lens is placed after an ion source (He and Ar beams)
    - The emittance of the ion beam was measured behind the Gabor lens with a slit-grid emittance scanner
    - A current transformer is placed right behind the lens to measure the beam current
    - If the lens is already conditioned and the vacuum system is vented, it takes **around 30-50 minutes** until the lens is ready for operation.
    - Beam transport measurements are compared to the results obtained from plasma diagnostics
    - Two sets of measurements: low current He beam (emittance dominated transport) and higher current Ar beam (space charge dominated transport, the ion density becomes comparable to the confined electron density)
    - The input emittance was obtained by tracking back the beam through drift space from the slit-grid scanner
    - The calculated phase space distributions did not represent the measured ones very well due to overestimation of the electron density.
      * The beam radius is underestimated by the numerical simulation, but the shape of the phase space distribution is in good agreement with the measurement.
    - With increasing magnetic field, the hollow electron distribution becomes more homogeneous and the phase space distribution shows less aberrations.
    - Increasing the magnetic field above the operation point drives the plasma cloud to be unstable as seen in the emittance measurement.
    - The measured emittance growth close to the operation point is less than a factor of 2.
    - Indication that the beam is influencing the nonneutral plasma and for this reason the actual electron density during the beam transport measurements is reduced.
    - During the experiments, an increased incidence of high-voltage breakdowns caused by spark-overs was observed.
    - In the case of a high current ion beam the production of secondary electrons increases by interaction with the electron cloud. The number of electrons produced per beam pulse is of the same order as the number of electrons confined inside the lens.
    - Clear indication that the **focusing strength of the lens changes with the ion beam current (5 mA to 25mA) when the lens parameters are kept the same (the confined electron density also probably changes).** 
      * However, this is just qualitative evidence since the ion source parameters (filament current, extraction and post-acceleration voltage) changed during the measurements
      * Another possible explanation is the reduction of the electron loss channels due to the positive potential of the ion beam. The beam potential creates a barrier at the entrance and exit of the lens.
    - A parallel beam is obtained for a specific magnetic field and the emittance grows only by a factor of 1.38. The beam profile transitions from a Gaussian to a more homogeneous distribution.
  + The confinement efficiency of the lens in case of space charge dominated transport is higher than for the emittance dominated beam transport.
    - The confinement efficiency at the operation point of the lens is the same in both experiments (I.e. independently of the ion species, the ion beam current, and the residual gas in the beam line) (??)
    - The confinement efficiency is lower than determined in previous experiments done by others.
* **2014 – Shnain – Computations on Gabor lens having two different field distributions**
  + It uses a paraxial-ray equation which describes the paths of charged particles moving through rotationally symmetric electrostatic fields given by the potential V(z).
    - The charge to mass ratio does not appear in the equation ---> same trajectories for all ions
    - The equation is homogeneous in V ---> an equal increase in V at all points does not change the trajectories
    - The equation is homogeneous in r and z
  + Another equation describes the motion of an electron in an axially symmetric magnetic field.
    - The motion is not dependent on the sign of the magnetic field density
  + The two equations are combined (non-relativistic treatment)
  + Approximate models for the axial field distribution
    - The rectangular model – step function (for the electrostatic field)
    - The Glaser field model – B\_max / (1+ (z/a)^2) (for the magnetic field)
  + The focal length is seen to increase between linearly and quadratically with V
* **2014 – Gabor lenses for focusing and energy selection of laser-driven ion beams in radiobiological experiments (MRes Thesis)**
  1. As well as generating ions, plasma acceleration also yields electron beams from the front and rear of the target surfaces.
  2. Dose = Absorbed Energy / Mass
  3. Relative Biological Effectiveness = Dose\_reference / Dose\_alternative (ratio between the doses of two types of radiation that cause the same amount of biological damage); reference dose is given by photon radiation
  4. No significant difference was found for the RBE between laser-driven sources and conventionally accelerated protons.
  5. There is yet to be a comprehensive investigation of the effects of varied monoenergetic ion beams on in vitro cells.
  6. As the Gabor lens requires much lower magnetic fields than the quadrupole or solenoid systems, it offers a scalable solution that could be implemented for high-energy ion beams needed for therapeutic use.
  7. If the electron densities required for longitudinal and transverse confinement are made equal, the anode voltage required for confinement is given by V\_A = (e r\_A^2 / 8 m\_e) B^2; r\_A is the anode radius. Then, the focal length is 1/f = (e B^2 / 8 m\_e U\_B) l; U\_B is the total acceleration potential of the ions (m\_p v^2 / 2q)
  8. The focal length of a Gabor lens is proportional to the energies of the ions within the beam ---> much weaker magnetic fields are required for focusing particles with a Gabor lens than its magnetic-based alternatives.
  9. When compared to a solenoid: B\_GPL = B\_sol \* sqrt(Z\*m\_e/m\_ion)
  10. GPT – General Particle Tracer – charge particle trajectories and dynamics inside determined electromagnetic fields
  11. In order to achieve focusing of the ions of the same KE at the same focal length, they must experience the same field from the electron cloud ---> a **homogeneous electron distribution** is needed within the lens. (The solenoid magnetic field must be approx. Homogeneous in the active region of the lens to achieve a homogeneous electron distribution)
  12. The proportion of the beam entering the lens is a function of the anode diameter and the target to lens separation.
  13. The electron density is capped by the power supply that will be used experimentally. 630 kV power supplies are readily available and were used previously in theory calculations.
  14. To focus and energy select proton beams of the radiobiological order (~10MeV), longitudinal distances of about 2.0m were used. As higher energies have greater focal length, increasing the distance would allow the selecting of higher energy beams.