PLASMA LENS FOCUSING AND PLASMA CHANNEL TRANSPORT FOR HEAVY ION FUSION

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Abstract
The final focus lens in an ion beam driven inertial confinement fusion reactor is important since it sets limiting requirements for the quality of the driver beam. Improvements of the focusing capabilities can facilitate the construction of the driver significantly. A focusing system that is of interest both for heavy ion and for light ion drivers is an adiabatic, current carrying plasma lens. This lens is characterized by the fact, that it can slowly (adiabatically) reduce the envelope radius of a beam over several betatron oscillations by increasing the focusing magnetic field along a tapered high current discharge. A reduction of the beam diameter by a factor of 3 to 5 seems feasible with this focusing scheme. Such a lens can be used for an ignition test facility where it can be directly coupled to the fusion target. For use in a repetitively working reactor chamber the lens has to be located outside of the reactor and the tightly focused but strongly divergent beam must be confined in a high current transport channel from the end of the lens into the immediate vicinity of the target. Laser preionization of a background gas is an efficient means to direct and stabilize such a channel. Experiments have been started to test both, the principle of adiabatic focusing, and the stability of laser preionized high current discharge channels.

1. Adiabatic Plasma Lens Focusing

Active plasma lenses have usually been used as 'thin' lenses [1,2]. 'Thin' in this context means that the beam passage trough the lens requires less than a quarter of a betatron oscillation. A thin lens is characterized by the fact that the focal length of the lens depends on the phase of the betatron oscillation that the particles have reached at the end of the lens. Particles of different energy or charge state are focused to different points. If the focal point is close to the end of the lens, the beam diameter inside the discharge plasma changes significantly. In this case the efficiency of the lens can be enhanced by fitting the discharge diameter to the beam envelope. This can be achieved by tapering the discharge tube and does not affect the ion optical properties of the lens [3]. Such a tapered lens with an adiabatically slow increase of the focusing power can be used as a thin or as a thick lens. A thick adiabatic lens is characterized by the fact, that the focusing field extends over a length of several betatron wavelengths. In this type of lens a reduction of the beam envelope can be achieved independent of the betatron phase with which the ions reach the end of the lens, by reducing the amplitude of the betatron oscillations with the increasing focusing field [4,5]. This provides the possibility of focusing beams with a high momentum spread or beams with particles in mixed charge states. The smallest diameter for a beam of high momentum spread is exactly at the end of the lens. The beam diameter increases rapidly behind the lens. In the adiabatic lens the beam envelope is described by Hill's Equation $d^2/dz^2 = -k^2 r$ with $k^2(z) = Z(z)2eI / a^2(z)\beta mc^3$. Here Z denotes the charge state of the ion, I is the total discharge current in the lens, and a is the radius of the focusing discharge. In the adiabatic approximation $1/k^2\, dk/dz << 1$ a solution can be written in the form $r = C \exp(i\int k\, dz) / k^{1/2}$. If the ratio of the beam radius at the end of the lens r_{out} and at the entrance of the lens r_{in} is $b = r_{out}/r_{in}$ the initial wave number k_{in} has to be decreased by a factor of b^2 to $k_{out} = k_{in}/b^2$ at the end of the lens in order to reduce the radius of the beam envelope by a factor of b. To achieve a beam size reduction of b=3 for typical parameters of a driver beam with m=200 amu, β=0.3, with a discharge current of I=100 kA, and assuming that the beam is stripped from initially Z=+16 to Z=+64 at the end of the lens, the channel has to be tapered down from the entrance radius $a_{in} = 11.25$ mm to an exit radius a_{out} =2.5 mm. This yields a reduction of the beam radius from r_{in} = 7.5 mm to r_{out} = 2.5 mm. The admissible emittance for the beam is determined by the conservation of phase space density over the simple relation $\varepsilon r = ka$, which allows a normalized emittance of 62 mm mrad for the above example.

2. Application to an Ignition Test Facility

An application of an adiabatic plasma lens for an ignition test facility is sketched out in fig. 1. The adiabatic lens as the central element of the final focus system is located inside the reactor chamber and directly connected with the fusion target. Depending on the required uniformity of target illumination one or several lenses can be used. Since the adiabatic lens is not capable of a sufficiently high focusing ratio, a conventional quadrupole lens is necessary to match the ion beams from the accelerator to the entrance of the adiabatic lens. A lens that reduces a beam from a radius of 7.5 mm to a 2.5 mm spot radius on the target needs a length of about 1.7 m to fulfill the adiabaticity condition. This distance is the length of one betatron oscillation at the entrance of the lens or of nine betatron wavelengths at the exit of the lens, for a discharge current of 100 kA, an ion mass of 200 amu, and a velocity of 0.3 c. Such a lens has an acceptance angle of ±30 mrad. The large acceptance angle, the space charge neutralization and the insensitivity to beam emittance of the adiabatic lens make the entrance of the tapered discharge an ideal place to combine several driver beams. The main advantages of this focusing scheme are that it is achromatic and allows therefore a fast drift compression of the ion bunches, and that it can focus beams with very high emittance which allows to reduce the final ion energy. Since this scheme does not depend on ballistic focusing the vacuum requirements for the target chamber are low. The disadvantage, that the lens has to be replaced after every target explosion is relatively minor for an ignition facility with a few shots per day.

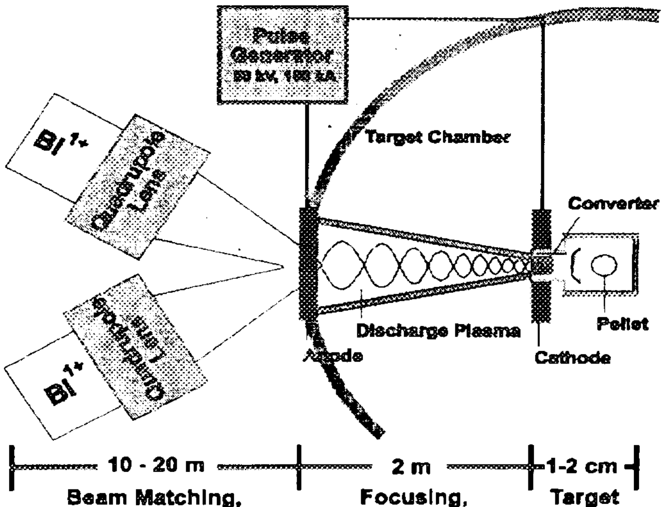

Fig.1 Schematic layout of a target chamber for an ignition facility using adiabatic focusing.

3. Experimental Test of an Adiabatic Plasma Lens

One of the most important characteristics of an adiabatic plasma lens is its capability to focus high emittance beams. Therefore the focusing properties and the transmission of the lens for high emittance beams are important topics in an experimental test. An electrostatic quadrupole injector (ESQ) capable of producing a singly charged potassium beam at an energy of up to 2 MeV was used to test the focusing properties. The short ion range in solid matter does not allow windows in the beam path at this energy. Therefore a three stage differential pumping system was used to reduce the pressure in the discharge tube of 1 Torr helium over a distance of 135 mm to 10^{-6} Torr at a free beam aperture of 5 by 15 mm. An electrical diagnostics using a Faraday cup was chosen to measure the intensity of the transmitted beam in spite of problems caused by the electromagnetic noise of the discharge, because this diagnostics provides a good temporal resolution. A spatial resolution of the beam profile behind the discharge can be achieved by a pinhole that can be moved across the exit aperture of the lens. A schematic representation of the plasma lens, the differential pumping system and the diagnostic system is shown in fig. 2. Experiments were performed with beams of 1.1 and 1.5 MeV ion energy. The 360 mA current of the 1.1 MeV potassium beam at the entrance of the differential pumping system is reduced to about 5 mA at the entrance of the discharge. Without discharge gas the pinhole with a diameter of 0.5 mm at the end of the discharge tube with a length of

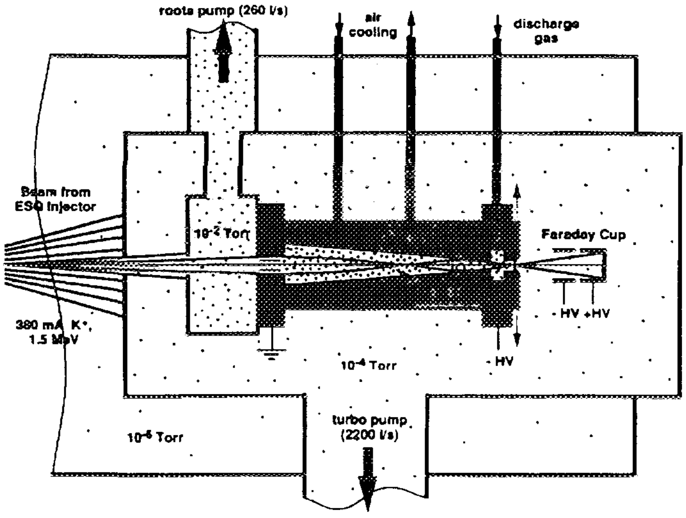

Fig. 2 Set up for a test of adiabatic plasma lens focusing of an 1.5 MeV potassium beam.

300 mm reduces the particle current to a calculated value of 16 μA. The measured value of 21 μA can be explained by a partial stripping of the ions in a small amount of rest gas. At the working gas pressure of 1 Torr helium in the lens the gas is not only stripped to the equilibrium charge state of +1.8 but the transmission is strongly reduced by scattering. The microdivergence of the beam after passage through the gas is 36 mrad (full angle for 90% of beam intensity) and the intensity in the pinhole is reduced to 5.6 μA. By pulsing a current of 5.9 kA through the discharge tube the beam intensity in the pinhole can be enhanced by a factor of 20 to 112 μA. At the higher ion energy of 1.5 MeV an enhancement during the current pulse by a factor of 26 from 7.6 μA to 200 μA was found. The experimental results are in good agreement with simulations of the focusing which include the initial beam conditions, stripping, and the emittance increase by scattering. The large intensity increase in spite of the strong scattering of the ions in the discharge gas and the presents of different charge states indicate, that the adiabatic focusing works as expected. Further experiments are planned to measure the transmission trough the lens and the intensity profile of the beam behind the lens.

4. Application to a Fusion Power Reactor

In contrast to an application in an ignition test facility the destruction of the lens with each pellet explosion can not be tolerated for a power reactor. Therefore the adiabatic lens has to be located outside of a reactor chamber. A schematic reactor layout using an adiabatic lens is sketched out in fig. 3. The focused beam is guided from the end of the lens to the target by a high current discharge channel. The envelope radius of the beam in this channel has to be the same as at the end of the lens and determines the spot radius on the target. Since lens and channel require the same discharge current, they can be driven by a single current pulse generator. One or, to reduce the circuit inductance, several current return channels are required from the target back to the generator. Fig. 3 sketches two transport channels from opposite sides and two return current channels perpendicular to the transport channels. Laser preionization of a background gas in the mbar pressure regime inside the reactor chamber is used to stabilize and direct the transport channels. An excimer laser pulse energy of less than 10 J is sufficient for this purpose. Besides the advantages of achromaticity and the possibility to focus high

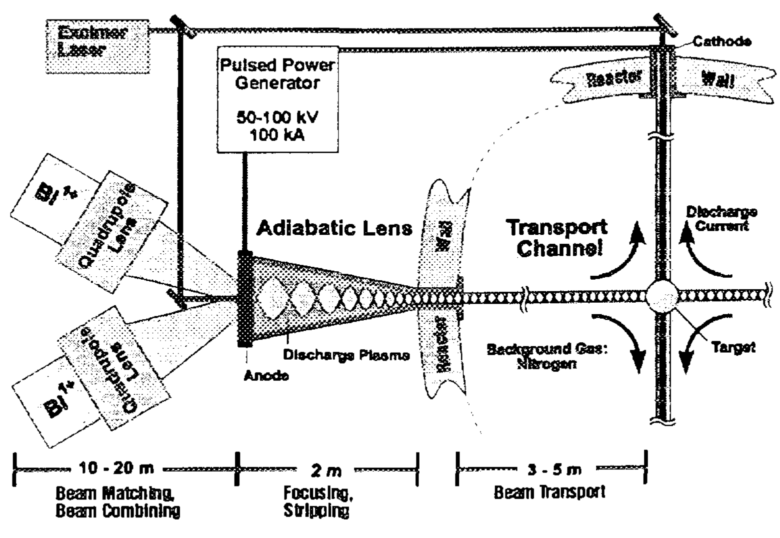

Fig. 3 Schematic layout of a reactor chamber using adiabatic focusing and discharge channel transport.

emittance beams this focusing scheme simplifies the protection of the beamlines from debris in the reactor by reducing the number and area of the entrance ports for the beams to a minimum and, the background gas reduces the stress of the first reactor wall.

5. Investigation of Discharge Channel Generation by Laser Preionization

The feasibility of the discharge channel transport of the focused ion beams is crucial for the applicability of the adiabatic focusing to a fusion power reactor. Earlier experiments[6,7] addressing the creation of laser preionized discharge channels, and the ion beam transport in such channels were done using narrow, insulating discharge tubes, which reduce breakdown problems and increase the channel stability. For the experiments described here a metal discharge chamber with a crossection of 25 cm by 25 cm and a gap between the electrodes of 40 cm was used. The electrodes were mounted electrically insulated from the chamber on Plexiglas flanges. A KrF laser with a wavelength of 248 nm and a pulse energy of up to 100 mJ in a 20 ns pulse, focused to a parallel beam of 5 by 5 mm crossection was used for the preionization. The laser ionizes a channel in the discharge gas mixture of 10 Torr N_2 and 0.2 Torr benzene. The laser light, that is not absorbed in the discharge gas, is used to trigger a sparkgap, which discharges a capacitor of 0.15 µF at a voltage of 10 kV into the laser ionized channel. The resulting discharge current of 1 kA improves the conductivity in the plasma channel. With a delay of 10 to 50 µs the main capacitor bank of 4.8 µF, charged to a voltage of 30 kV, is discharged into this channel. This high current discharge is diagnosed with pickup probes to measure the current distribution in the discharge chamber, and with a gated CCD camera with a time resolution of 2 ns to investigate the stability of the discharge. A typical current wave form of the total discharge current and of the current enclosed in a channel with 36 mm radius are shown in fig. 4. The peak current of the discharge is reached 3.8 µs after the ignition of the main discharge and reaches a value of 63 kA out of which 55 kA are flowing in the central channel. Measured from the light distribution the current channel has a half width of 6 mm radius after 3.8 µs and is slowly expanding. Pictures with an exposure time of 8 ns, taken at different times of the discharge, show a high reproducibility and no signs of hydrodynamic instabilities. These channels seem to be well suited for heavy ion beam transport.

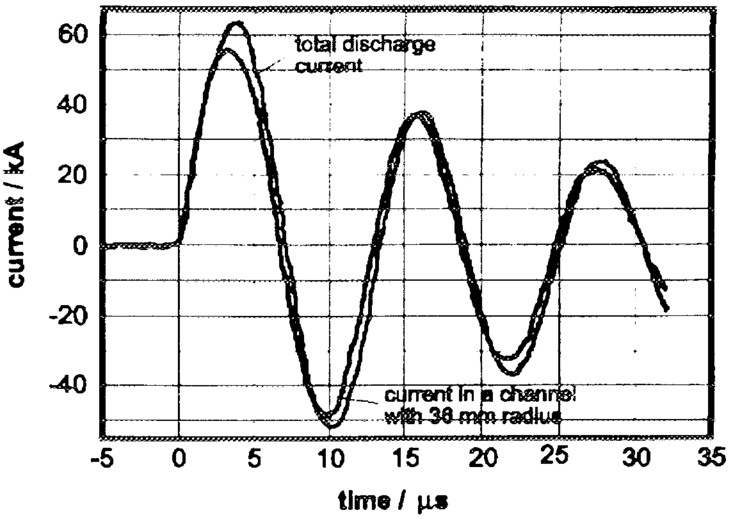

Fig. 4 Total discharge current and current enclosed in a laser preionized channel with a radius of 36 mm.

6. Acknowledgments

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