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High Intensity Lithium Beam for Zeeman Spectroscopy.

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The Zeeman splitting of neutral lithium introduced to a hot plasma as a beam may be used to determine both the magnitude and direction of the local magnetic field. Dye lasers can improve the sensitivity of the method, either by resonance fluorescence or by intracavity absorption. A limit on the applicability of this diagnostic is set by the lithium density in the plasma. A high density, 80 kV lithium beam has been developed to access plasmas of larger dimension and/or higher densities, or to permit measurements with better time resolution than with previous beams. The beam utilises a high density lithium ion source. Diagnostics include 2-D ion beam profiling, Faraday cup, magnetic analyzer and a 'pepperpot' probe for measurements of beam intensity, composition and divergence. Beam currents presently exceed 10 mA in a ≤ 2 cm diameter beam with a divergence of several milliradians.

1. INTRODUCTION.

Measurement of the local magnetic field vectors in hot plasmas is not a routine diagnostic in present experiments. Several measurements of the safety factor q have been made in tokamaks, notably by laser scattering[1] and by following the trajectories of charged particles,[2] and also by Zeeman spectroscopy of injected species.[3,4] Other Zeeman splitting magnetic field diagnostics are in preparation,[5] or are ready to be applied to low density magnetic confinement devices.[6]

This paper describes a diagnostic system to measure the local magnetic field vectors in plasmas of relatively high electron densities ($\lesssim 10^{20}$ m^{-3}) with millisecond time resolution. The requirement to measure the local magnetic field strength <u>and</u> direction is peculiar to higher beta confinement systems such as the Reversed Field Pinch,[7] in which the plasma magnetic fields differ greatly from their vacuum configurations, and no dominant component exists. In contrast, for a low beta tokamak, it suffices to ascertain the field direction since the field strength is dominated by the strong toroidal magnetic field, although the field angle is small and must be accurately determined.

The key to this measurement is to provide a sufficient population of atoms whose Zeeman splitting can be measured in the available time for observation. The lithium atoms in the beam will be excited and ionized by plasma electrons and ions, and will also undergo charge exchange. A 1-D simulation code estimates the atomic level populations in the remaining neutral lithium at each location. For a typical plasma of central density $5*10^{19}$ m^{-3}, central electron temperature of 500 eV, and a radius of 0.2 m, only a fraction of 1 % of the 80 kV particles introduced at the plasma edge will penetrate to the center as ground state atoms. Thus one wishes to use a beam of high density for this diagnostic. This paper describes such a beam, and mentions some of the laser enhanced detection schemes for the lithium Zeeman spectroscopy

Lithium was selected for this diagnostic for several reasons. First, lithium is a low-Z element, and thus has a minimal effect on the average ion charge of the plasma. Second, a resonance transition can be used for the measurement. Also, this transition is at a wavelength that is accessible to dye lasers, which can increase the detection sensitivity, either by resonance fluorescence[4] or by intracavity absorption.[5] The Zeeman splitting of lithium is shown in Fig. 1. The measurement of the magnetic field strength involves determination of the wavelength splitting between components, while for a field direction measurement one needs to ascertain the polarization direction of a (preferably field insensitive) component.

II. LITHIUM ION SOURCE.

The lithium ion source for this diagnostic beam must produce rather cold ions, so that a well collimated beam can be extracted. It must also provide a sufficient density of ions so that cw currents extracted will far exceed the ~1 mA/cm^2 extracted from the usual aluminosilicate lithium ion sources.[8,9]

A suitable ion source has been developed;[10] only a brief description is given here. The source (Fig. 2) is a modified two species duopigatron. An arc is drawn in the working gas (usually helium) between the anode and cathode. The plasma thus formed flows through the anode aperture into the expansion cup, which contains metallic lithium. The plasma heats and ionizes the lithium, which can then be extracted. Apertures are employed to regulate the quantity of lithium ions available for extraction. The lithium fraction in a low voltage extracted beam has been ascertained by magnetic mass analysis to be 70-80 %. The extracted current density exceeded 15 mA/cm^2 at 1 A arc current (maximum 10 A) during these low voltage mass analysis tests.

III. ACCELERATOR, BEAM DIAGNOSTICS AND NEUTRALIZATION.

The ion source parameters provided input to a particle simulation code[11] to design an 80 kV accelerator with minimal divergence and high (tens of mA) extracted current. This voltage was chosen as a compromise between efficient neutralization of the Li$^+$ beam, plasma penetration and spatial resolution along the beam during fluorescence decay. The stainless steel electrodes were machined using a numerically controlled lathe. Lithium deposition on the electrodes during operation causes the beam current to decrease and the divergence to increase over typically several minutes of operation. This problem was greatly alleviated by heating the electrodes to several hundred degrees centigrade, exceeding the melting point of lithium. Various other structures are designed to limit lithium deposition problems. Lithium deposition on insulators in the accelerating gap region is still an occasional problem, but the beam can run steady state for over an hour. The ion source and accelerator are pumped by a 1500 l/s turbomolecular pump. The ion beam is analysed by a set of vanes which swing through the beam and provide a two-dimensional profile of the ion density. This profiler can be inserted at several locations along the beam path, including in front of and immediately behind the beam bending magnet. Thus the ion beam dynamics can be optimized, and profile evolution can be studied.

A 'pepper pot' probe is employed to evaluate the time average spatial power density and divergence of either ions or neutrals. This probe consists of a disc with a set of small holes to sample parts of the beam. A Kapton[12] foil is placed down stream, and is discolored by the beam particles. The extent of the discoloration is a measure of the beam power density, while the spot sizes reflect the local divergence. A Faraday probe and thermal detectors are also available.

The beam is neutralized in a recirculating sodium cell. Sodium is used since the required operating temperature is much lower than would be required for resonant charge exchange in lithium, while the cross-sections are comparable. Also, any neutralizer atoms which drift into the measurement region will not be confused with beam atoms.

IV. BEAM OPERATION.

The main effort in beam operation has been in achieving a high current density condition with small divergence. The 80 kV design voltage has been reached, and beams of up to 30 mA (limited by the power supply) have been extracted. The beam current increases with increasing arc current in the ion source, with a 2 A arc current being typical for present experiments. Lithium vapor in the accelerating gap is a major problem: various apertures, gap lengths and pumping speeds have been studied to achieve the best beam parameters. As expected, the extracted current increases with larger expansion cup apertures, and with shorter extraction gaps, though both of these variations imply a much larger breakdown and lithium deposition problem. The beam operates continuously, with a typical divergence of several milliradians, and a beam diameter of ≤ 2 cm as measured 1.5 m from the accelerator.

The lithium ion beam needs to be bent prior to neutralization to achieve a collinear fluorescence configuration (see section V). An angle of thirteen degrees has been chosen, and the required hardware has been tested and is being installed. The neutralizer will be moved downstream of this bending cavity, and will be pumped by a second 1500 l/s turbomolecular pump. Efforts to produce a better recirculating neutralizer for the beam are in progress in collaboration with other LANL groups.

V. DYE LASER ENHANCED DETECTION.

It is possible to determine the local magnetic field by analysing the emitted light from plasma excitation of the beam.[3] However, dye lasers permit at least two schemes for improved sensitivity and time response.

Collinear dye laser resonance fluorescence has been chosen as the first enhanced detection system for our experiment. A dye laser is to be aligned along the atomic beam: fluorescence will be observed when the wavelength and polarization of the laser are appropriate for the local magnetic field strength and direction. Fast (30 kHz) wavelength sweeping of a dye laser has been implemented in our laboratory using the electro-optic tuning scheme of Telle and Tang,[13] while polarization rotation has been demonstrated using a lithium niobate crystal.[14] Thus good time resolution can be achieved, provided a sufficient number of lithium atoms remain in the ground state at the measuring location. Intracavity absorption[5] remains an option for laser enhanced detection, but the existing beam divergence and diagnostic access preclude its immediate utilization. Both ICA and crossed beam resonance fluorescence would have the advantage of exact spatial localization, but would be limited to a single point in space; collinear fluorescence can provide single discharge profiles of the magnetic field, but with reduced spatial accuracy due to the finite lifetime of the excited state.

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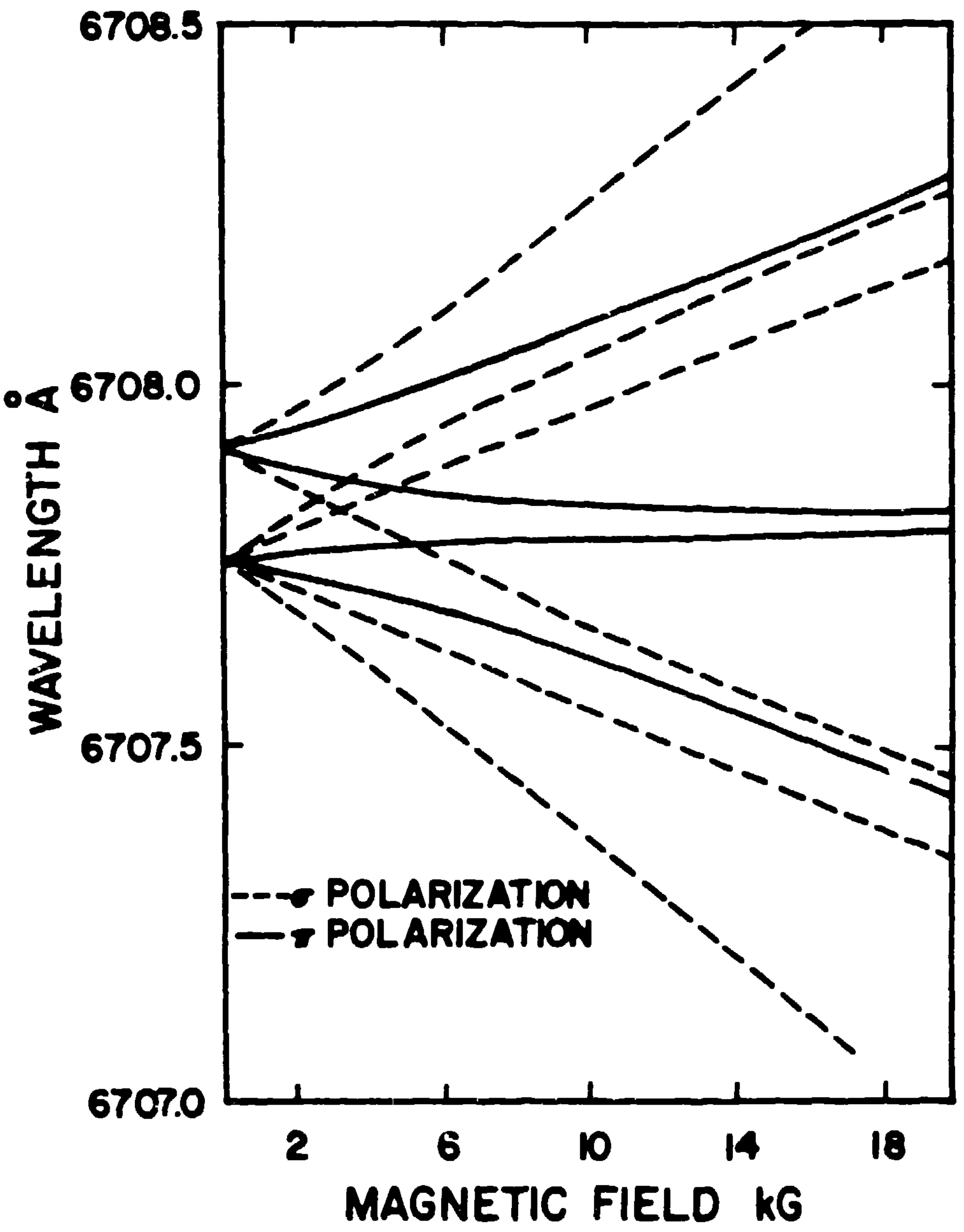
FIG. 1. Zeeman splitting in lithium.

FIG. 2. High current lithium ion source and accelerator.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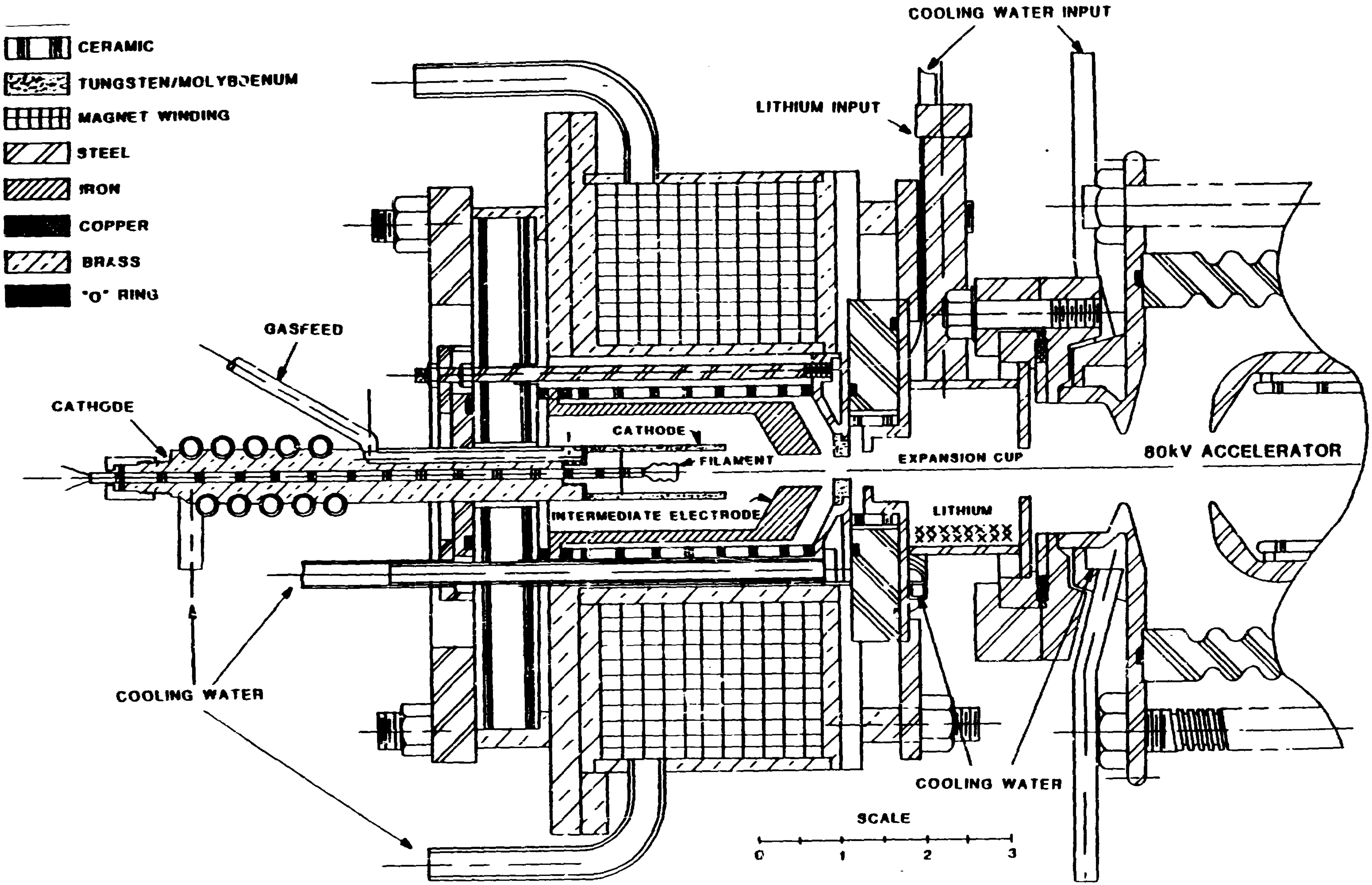
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