IUCF HIGH INTENSITY POLARIZED ION SOURCE*

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I. INTRODUCTION

A major fraction of the experimental program at IUCF has always concentrated on studies of spin degrees of freedom. The newly commissioned electron cooled storage ring/synchrotron will provide unique opportunities in spin physics research which require circulating beam intensities near the limit of ring operation, 10^{16} particles/sec, because target densities and/or reaction cross sections are very low.

In order to meet these experimental requirements we are replacing the existing ANAC source built in 1976 with a modern high intensity source expected to yield in excess of 100μA DC $\vec{H}^+$ and $\vec{D}^+$ ion beams and/or at least 10μA DC $\vec{H}^-$ and $\vec{D}^-$ ion beams. Such a source, coupled with a high-efficiency bunching system and a high-transmission beam line into the first cyclotron, should allow 10^{10} protons to be stored in the Cooler ring in a few seconds. Besides the options of intense positive or negative ion beams and CW or pulsed mode of operation, other source requirements are: low transverse phase space emittance (< 15π mm mrad $\mathrm{MeV}^{1/2}$) to match the cyclotron acceptance, low longitudinal phase space emittance (i.e. energy spread < 10eV) to permit efficient bunching, and proton polarization of 75% or higher, with equivalently high deuteron polarization in both vector and tensor states separately.

Of the various proven state-of-the-art polarized ion source technologies, the system recently built and brought into successful operation at TUNL by T.B. Clegg and associates [1] best meets our needs. In 1989 we began acquiring design specifications from TUNL to build HIPIOS (High Intensity Polarized Ion Source). Based on TUNL's experience, HIPIOS should produce in excess of 100 μA DC $\vec{H}^+$ and $\vec{D}^+$ ion beams. It employs cold (~30 K) atomic beam technology, a proven method for generating intense neutral atomic beams. The ionizer is an electron cyclotron resonance (ECR) device similar to those routinely employed for many years for production of intense beams of heavy ions in high charge states.

II. INITIAL DESIGN AND TESTING

Throughout the design process we have been greatly assisted by the TUNL staff who provided us with all their construction drawings and many useful recommendations based on their operating experience.

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A. Dissociator

The dissociator geometry is a close copy of the TUNL design. The discharge is excited by an ENI OEM-6A, 15 MHz, 600 watt supply and is contained inside a 10 mm OD Pyrex tube. About 35 SCCM of hydrogen gas flows into the discharge tube which has a 20 mm OD Pyrex water jacket. The copper cold nozzle is slipped over a MACOR thermal adapter and is cooled by a CTI 1020 cold head that has a capacity of 10 W at 20 K. The cold nozzle temperature is controlled with a heater and sensor attached directly to the nozzle clamp. As in the TUNL design, N_2 is bled into the nozzle at a flow rate of 0.02 SCCM to prevent recombination on the copper surface.

The dissociator has recently been put into operation without sextupoles, and measurements of the atomic beam velocity have been made using an atomic beam chopper generously loaned to IUCF by Professor W. Gruebler of ETH [2]. Preliminary results indicate that with an H_2 flow rate of about 20 SCCM, and a nozzle temperature of 25 K, 30 K and 40 K, the atomic beam velocity was consistent with a beam temperature of 35 K, 42 K and 54 K respectively.

B. Sextupoles

Conventional sextupole magnets are used to separate the hydrogen atomic spin states hence generating atomic polarization. Two independent magnets with a 26 cm drift space between are used for improved focusing of the atoms into the ionization region. The optics of the first magnet is optimized by using a tapered (14 mm - 28 mm) aperture resulting in a ramped sextupole strength. We have increased the length of the first sextupole by 50% from previous designs to provide the increased integrated sextupole strength recommended. Ray trace calculations predict that this modification should have an effect similar to that obtained by increasing the strength of the shorter magnet - a much more difficult task. We have measured a maximum pole tip field for the tapered sextupole of 7600 G at the design current of 250 Amps, and 5600 G for the second sextupole at the design current of 200 Amps.

C. Rf Transitions

The rf transitions, which convert the atomic polarization to nuclear polarization, utilize the conventional adiabatic fast passage principle causing transitions between particular magnetic substates. One strong field and weak field transi-

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tion pair is located between the sextupoles and another pair between the second sextupole and the ionizer.

Each strong field transition consists of a magnetic field transverse to the beam direction (85 G for deuterons, 150 G for protons) and an rf magnetic field (330MHz, 400MHz, 460MHz for deuterons and 1485MHz for protons) generated by a cavity. Each weak field transition consists of a magnetic field of 10 G transverse to the beam direction and an rf magnetic field of 15 MHz generated by a small coil with its axis along the beam. The strong field transition is shielded from the fields of the sextupole magnet by a 1.6 mm thick iron field clamp. The weak field transitions are located inside a cylinder of magnetic shielding to prevent interference from other magnetic fields.

The mechanical design of the cavities follows the design of Robinson et al. [3]. For driving the cavities, we opted to change from a medium power signal generator to a self-oscillating loop utilizing the cavities self-resonance and a high gain amplifier. After phase adjusting the output of the cavity with the input we were able to operate from 500 milliwatts to over 5 watts.

Assembly of the 330 MHz and the 400 - 460 MHz dual unit has been completed and development is continuing to enhance their operating characteristics. Data taken thus far show we have approximately 10 G per square root of rf watt.

D. ECR Ionizer

The ECR ionizer design follows the now standard configuration employed in several recently commissioned polarized ion source systems [4,5]. A polarized atomic beam is ionized while passing through a resonantly excited electron plasma confined radially by a permanent magnet hexapole and longitudinally by solenoidal mirror coils. Our ionizer closely follows the TUNL design which has the hexapole magnet mounted within a vacuum chamber on which the external mirror solenoids and return yoke are assembled. We have, however, made several modifications to the basic configuration to address special requirements for our application, accomodate competing technical requirements, and incorporate improvements resulting from source commissioning work at TUNL.

A primary technical consideration involves the design and mounting of the permanent magnet (SmCo) hexapole, which can be damaged by plasma or beam heating above 300 ^{o}C or by exposure to the hydrogen gas in the ionizer vacuum chamber. An ECR chamber pressure less than 0.1 uTorr is required. A further complication is that the internal structure (hexapole magnet, pre-buncher, and extraction electrodes) of the ECR ionizer is isolated from and operated at 20 kV above platform ground to provide an extraction gradient. This allows the majority of the ion source apparatus to remain at ground potential, and also simplifies the pre-bunching of the low energy dc beam from the ionizer for later injection into the IUCF cyclotrons.

To meet the competing requirements of vacuum, temperature, rf and high voltage constraints on the mounting of the hexapole structure, it was decided to vacuum encapsulate the permanent magnets in thin walled (0.5 mm) stainless steel cans welded onto thicker ring brackets to form the hexapole field configuration. The magnets are inserted into the welded structure following fabrication, mapped and shimmed to minimize other multipole field components, and then epoxy impregnated. This structure is supported from one end of the ECR vacuum chamber by six 2.5 cm diameter ceramic insulators. A separate freon cooled copper heat shield is mounted inside the hexapole structure to conduct the heat generated by the plasma and rf ($\leq$ 150 watts) away from the magnets. This overall design provides for an open geometry permitting good radial and axial pumping in the region of the ECR plasma.

The rf generator for the ECR plasma will operate over a range of 2.6 to 4.7 GHz at 150 watts. The system will consist of a voltage controlled oscillator based on an Avantec HTO-2600 oscillator and AGT-8235 variable gain preamplifier. Final amplification of the microwave system is provided by a Keltec TWTA 200 watt amplifier. Power will be fed into the ECR chamber via Heliax coaxial cable to an internally mounted horn using a waveguide adapter at the chamber. We expect to achieve higher beam intensities and polarizations at the higher frequencies, as reported by the TUNL group.

E. ECR Extraction and Acceleration

Extraction of positive ions from the ECR plasma region will take place in an axial (solenoidal) magnetic field of about 1 kG, using a computer designed electrostatic electrode system. The ECR extraction beam energy will be relatively low, 1-2 keV, to permit efficient prebunching using a low-voltage ramp waveform. The low-energy beam will drift in the uniform solenoid field for about 30 cm to achieve bunch formation at the second acceleration stage (to 20 keV beam energy) at the termination of the solenoid field. The solenoid field provides preferential focusing of the proton beam relative to the underfocused nitrogen ions, allowing for early rejection of much of the large nitrogen component which originates from the nitrogen buffer gas used to create the ECR plasma.

The ray trace code BEAM3D specifically designed for ECR extraction at Michigan State University was installed on the IUCF VAX computer system with the invaluable help of T. Antaya of MSU. For a given axially symmetric electric and magnetic field configuration (calculated from any electrode and coil geometry using the POISSON group of codes), the BEAM3D code performs exact 3D ray tracing for any multi-species ion beam, includingspace charge and finite ion temperature effects. Optimization of the beam extraction, focusing and acceleration geometry for minimum beam phase space and maximum transmission of protons has been performed for HIPIOS.

F. Buncher

A prototype of the wideband, ramp-waveform pre-buncher which follows the ECR was built and tested at low power by Lars Hermansson, a visiting engineer from The Svedberg Laboratory in Uppsala, Sweden. In order to compress 90% of the beam from the source into the $\pm 3°$ cyclotron phase acceptance, this buncher should have a linearity of $\pm(30/n)\%$ of the voltage amplitude over 90% of the fundamental rf period, where $n = 1,2,3$ is the pulse-selection ratio (subharmonic). A buncher with this linearity specification should ideally produce a beam phase width of less than $\pm 30°$ at the entrance to the resonant buncher in the 600 kV beam line to the cyclotron and the nonlinearity resulting from the sinusoidal waveform of this second buncher should result in less than $\pm 1°$ beam phase width at the cyclotron (neglecting all other effects). Test results show that the design specifications for the most part have been met or exceeded.

G. Control System

We made the decision not to use the existing cyclotron control systems for HIPIOS since their limited functionality and numerous obsolete components placed limits on the proposed expansion. Instead, we are implementing a new system that will operate in parallel with the present controls and provide a platform for future facility expansion.

Hardware controls are based on the use of Allen Bradley programmable logic controllers (PLC's) for vacuum and interlock systems, and VME modules for analog readout and control of temperatures, voltages, currents, and vacuum levels. Direct control of the VME systems is provided by a VAX RT300 controller supplied by AEON.

Because the HIPIOS terminal operates at 600 KV potential, special care will be been taken to minimize the possibility of damage during sparking. These efforts include placing intelligent modules at ground potential, ensuring that all I/O racks are EMI sealed, and that all cabling uses EMI connectors with Tanszorb protectors. VME optical links will provide the necessary control isolation up to the terminal.

To drive the VME hardware we will use the graphically oriented workstation based software system marketed by Vista Control Systems, Inc. [6], chosen because of our familiarity with their VAX/VMS product line, the ease of accessing the existing control system PDP-11s running RSX via Decnet, their support of VME hardware and our judgment that the system is well suited to the comparatively small nature of our project. At present we are learning how to use the Vista system, writing low level handlers for specific VME modules and creating simple applications.

X-Windows terminals will be used to provide multiple access points to the control system for operation and maintenance - directly in the terminal, for example. We will also provide services similar to those now available to the cyclotron operator, such as DAC setup and scaling, DAC and ADC archiving and limits checking.

H. Power Supply Modifications

To reduce the size, weight, and power consumption of power supplies for the source, a commercial line of 5 and 6 kW switching mode power supplies for powering the magnet loads has been evaluated for performance. While stability was found to be acceptable, the high harmonic content of the three phase line currents (especially at light loading) was excessive (in excess of 110% Total Harmonic Distortion, THD). Since the AC system is alternator driven and presents higher than average source impedance (as opposed to a normal AC distribution network), AC line voltage distortion could be well in excess of acceptable limits (3-5% THD). The manufacturer agreed to a modification of the units by adding a filter choke to the DC output of the rectifier bridge. This lowered current distortion to about the 35% THD level while AC RMS line current dropped 30%.

Because of the high stability requirement for the ECR electrostatic extraction elements (better than 100PPM), the extraction high voltage supplies have had remote sensing modifications designed, installed, and tested. These modifications compensate for the voltage variation that would normally be seen at the load due to changes in beam loading as a consequence of having a 180 KΩ series surge resistor in the high voltage load cable. Worst case voltage variations at the element of 1% have been reduced to .02% by use of this remote sensing technique.

III. ACKNOWLEDGMENTS

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IV. REFERENCES

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