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AN ECR IONIZER FOR AN ATOMIC BEAM POLARIZED SOURCE... WILL IT HELP?

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ABSTRACT

The proposal that an ECR ionizer may be a more efficient replacement for existing electron-bombardment ionizers of atomic beams is discussed. The concern that before ionization occurs such a device would depolarize the $\vec{H}_o$ (or $\vec{D}_o$) beams is investigated and found probably to be unwarranted. Preparations are underway for making a test of such an ECR ionizer on an operating atomic beam source at Karlsruhe.

1. Introduction

At previous meetings in 1981 and 1983 [1,2] Jaccard reported, in his summaries of the discussion on atomic-beam ionizers [3,4], about the interesting idea that an electron-cyclotron-resonance (ECR) discharge might be used. This was suggested as providing the real possibility of much improved ionization efficiency. Such ECR discharge sources were already highly successful in producing both intense D^- beams for plasma fusion devices and intense, highly-charged heavy ion beams for accelerators [5]. They have continued to be improved for these purposes [6,7]. However, Jaccard was quick to point out that there were serious concerns. The electron-cyclotron frequency in magnetic field B, $f_c = eB/2\pi m$, is (within the equality of the g-factor of the electron to 2) identical to the electron spin-flip frequency f_o in the same magnetic field. Adding to the general concern was the experience of several conference participants [4] that polarized atoms in an atomic beam lost their polarization when ionized in the plasma of an r.f. source or a duoplasmatron.

Why do we need another type of ionizer, since the two types now commonly used work rather well? Both, however, have some drawbacks. First, the electron-bombardment (EB) "super-ionizer" [8,9] is most common. Neutral atoms in the polarized beam are stripped by collision with electrons confined in a solenoidal magnetic field. The trapped electron density is typically n_e = 2 to 3 × $10^9/cm^3$, corresponding to effective axial electron currents of 1 A. At best the absolute ionization efficiency of this ionizer is limited to 4 ± 1% because of the space-charge limit on the number of confined electrons. The emerging $\vec{H}^+$ (or $\vec{D}^+$) ion beam typically has a 150 to 200 eV energy spread, because the ions originate at different radii having different electrostatic potentials arising from the electrons' space charge. We have even heard a report from Saclay at this workshop that the measured energy spread from their EB ionizer is 1 keV [10]. Although this device is without question the ionizer of choice now for $\vec{H}^+$ (or $\vec{D}^+$) beams, the resulting beam energy spread contributes significantly to the estimated output beam emittance of ~12π mm•mrad•$(MeV)^{1/2}$ [8]. Furthermore, there is considerable difficulty in bunching these beams at the low ~10 keV injection energies needed for many cyclotrons.

The second, commonly used ionizer originated at Wisconsin [11] and produces <u>only</u> negative ions. This ionizer requires an intense, fast (~40 keV) neutral cesium beam counterflowing with the $\vec{H}_o$ (or $\vec{D}_o$) beam. The output beam energy spread (<10 eV) is much better and the emittance (<10π mm•mrad•(MeV)$^{1/2}$ somewhat better than for the EB-ionizer. The output $\vec{H}^+$ beam polarization is also slightly higher. A pulsed (~1 Hz) version of this source at Brookhaven has been highly successful [12]. When operated in a d.c. mode, there is significant erosion from cesium beam sputtering of components in the atomic beam source. Although it is not yet clear, this may require increased maintenance with the Seattle version of this ionizer [13]. Also the ~2.5 W of cesium-beam power entering through the 5 mm diameter skimmer aperture and impinging on the cooled nozzle and dissociator bottle of the Seattle source is not easily compatible with obtaining atomic beams of temperatures below 77 °K.

By contrast ECR sources produce a plasma which is space-charge neutral, i.e. the number of plasma electrons is equal to the net ionic charge in the plasma. The resulting extracted positive beams have low energy spread, typically <5 eV. There is little experience using low-power ECR sources for hydrogen or deuterium. However, it is estimated that typical ionization efficiencies for H_2 gas range from 50% to 75% for such sources [14]. This is accomplished in an ionization volume which is axially shorter and radially larger than typical for present EB ionizers. This geometry would be highly desirable for the recently developed cooled atomic beams which have large angular divergence and poor spatial overlap with presently designed ionization volumes. Furthermore, ECR heavy-ion sources operate routinely in many laboratories, often for a week or more without touching a control.

Thus we have considered seriously the possibility of using an ECR discharge to ionize polarized atomic beams of H_o, D_o, and He^3. The conclusions from our investigations have been published [15,16]. The present report will provide a summary and some further new details. Finally, there is a brief discussion of a new experimental test of these ideas which is being prepared at Karlsruhe.

2. Typical ECR Ionizer Design Parameters

In order to understand the design details of an ECR ionizer, it is convenient to consider a small ECR source built several years ago at Jülich [17] and shown in Fig. 1. Although the purpose of this source, and many others, was the production of highly charged heavy-ion beams, it is very similar to the device which will be needed to ionize polarized beams. The Jülich source operated at 2.45 GHz, the microwave oven frequency. It utilized a coaxial pair of coils of approximately 15 cm inside diameter and separated by ~18 cm. These produced a double-peaked, axial mirror field for confining the electrons of the ECR plasma. The radial electron confinement was aided by a permanent magnet hexapole having its axis coincident with that of the two coils and the extracted beam. Indeed the extra confinement provided by the hexapole was necessary to allow the ECR plasma discharge to operate at pressures below ~10^{-4} Torr. The resulting 875 G ECR resonance zone was a roughly egg-shaped shell and crossed the axis in two places. At these locations the axial slope of the static magnetic field was >50 G/cm.

The base vacuum needed for clean operation of the source was <10^{-7} Torr and the optimum pressure for producing the highly charged, heavy-ion beam was ~8 x 10^{-6} Torr. This should be compared with the effective pressure of ~6 x 10^{-6} Torr inside a polarized atomic beam of flux 2 x 10^{16} atoms/sec and average atomic velocity of 750 m/sec. This flux characterizes

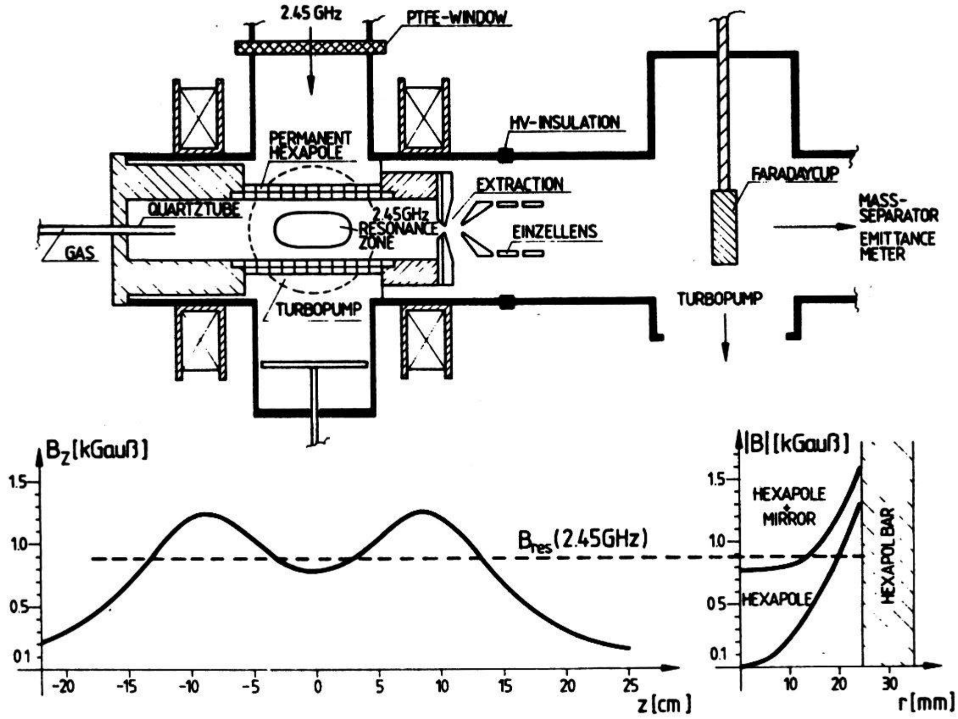

Fig. 1 Schematic of the ECR test source at Jülich taken from ref. 17.

the central region of the cooled atomic beams being used now at SIN and ETH [18,19].

Only 50W of power was needed to produce the required ECR discharge in the Jülich source. Assuming that the confined ECR plasma occupied a roughly cylindrical minimum volume 10 cm long and ~2.5 cm in diameter, then the average power incident on the plasma was $\bar{s} \leq 2$ W/cm^2. Assuming further that the system acted, as is believed for ECR sources [14], as a multimode non-resonant cavity with $Q \cong 1$, then one finds that the local r.f. magnetic field was randomly oriented having a component perpendicular to the static B-field of $B_1 \leq 0.1$ G.

3. The Problem of Possible Depolarization

The ECR plasma device described above is convenient for trying to understand if atomic beam depolarization is probable before ionization occurs. Such depolarization, if present, will most likely arise from flipping the spin of the atomic electron. Simultaneous nuclear depolarization could then occur via the electron-nuclear hyperfine coupling.

One well-understood method for flipping the electron spin is via adiabatic fast passage [20]. The Abragam-Winter criterion

$$\frac{1}{B_1}\frac{dB}{dt} \ll \gamma_J B_1 \qquad (1)$$

must be satisfied for this to occur. Here dB/dt is the true rate of change of the magnetic field experienced by the atom, and $\gamma_J = 0.28 \times 10^7$/Gauss-sec is the electron gyromagnetic ratio. For the conditions in the source at Jülich and using an average atomic beam velocity $\bar{v} = 750$ m/sec typical of the latest 35° K source at SIN and ETH [18], then

$$\frac{1}{B_1}\frac{dB}{dt} = \frac{1}{B_1}\frac{dB}{dz}\bar{v} = \left(\frac{1}{0.1G}\right)(50\ \mathrm{G/cm})(0.75 \times 10^5 \mathrm{cm/sec}) = 37.5\ \mathrm{MHz}. \quad (2)$$

When compared with $\gamma_J B_1 = 0.28$ MHz, we see that the necessary criterion of eq. (1) is strongly violated. Therefore depolarization via adiabatic fast passage, caused by the applied 2.45 GHz r.f. field, seems very unlikely.

But could the Abragam-Winter criterion be satisfied near the B-field minimum between the coils where $dB/dt \cong 0$ but is still monotonically decreasing or increasing? To estimate the possible depolarization there, consider again the axial B-field distribution of Fig. 1. Assume also that there is an unknown plasma frequency of amplitude equal to 30% of that at the driving frequency, i.e. $B_{1p} = 0.03$ G at frequency $f_p \cong eB_{min}/2\pi m$. Recall that $B_{1p} \propto (\bar{s}Q)^{1/2}$ where Q is the quality factor of the nonresonant ECR plasma chamber and $(\bar{s}Q)$ is the local power density. Assuming that Q=1, one finds that the power present at f_p in the unwanted plasma oscillation must be ~10% of the input power, or $\simeq 5$ W, and that locally $\bar{s} \simeq 0.2\ \mathrm{W/cm^2}$. Then the dangerous "resonance" zone, where the axial field is within one linewidth $\Delta B = 2B_{1p}$ from B_{min}, extends over a finite axial length Δz and will be traversed by the cooled atomic beam in a time $\Delta t = \Delta z/\bar{v}$. An ionizer operating at $f_c = 2.45$ GHz will have $\Delta t \cong 0.9$ μsec. This time is somewhat shorter than the minimum spin-flip time of 6 μsec. In the rotating frame of ref. [20], spin flip can occur in a time no shorter than one-half the Larmor period for precession around $B_{1p} = 0.03$ G.

What depolarization might result? For small precession angles θ around B_{1p} the resulting polarization $P = P_o \cos\theta \cong P_o(1-\theta^2)$ and the depolarization $(P_o - P) \cong \theta^2 P_o$. But θ is proportional to the ratio of the time Δt in the "bad" region $(\propto B_{1p}^{1/2})$ to the spin-flip time $(\propto B_{1p}^{-1})$. Thus for the conditions above we find $\theta^2 \cong 0.2$, and depolarization may be significant. The depolarization scales as $\theta^2 \propto B_{1p}^3 \propto (\bar{s}Q)^{3/2}$. Clearly if the local power density in this particular plasma oscillation is so large, because either $\bar{s}$ or Q is large, then there is reason for concern.

The ECR plasma is space-charge neutral with equal densities of electrons and ions, $n_e = n^+$. If e and m are the electron charge and mass and ε_o is the permittivity of space, we see from the expression for the plasma frequency $f_p = (1/2\pi)(n_e e^2/\varepsilon_o m)^{1/2}$, that there is a limit

$$n_e{,}\max = 4\pi^2 f_c^2 \varepsilon_o m/e^2 \quad (3)$$

for the electron density in the plasma. For densities greater than this, the input r.f. power will not penetrate effectively into the plasma. At lower input r.f. power with $n_e \lesssim 0.1\ n_e{,}\max$ the power spectrum in the ECR plasma will be relatively simple such that f_c is dominant, as shown in Fig. 2a. For higher input powers, the accelerated plasma electrons radiate and plasma oscillations at other frequencies appear, as shown qualitatively in Fig. 2b. The situation in a driven ECR plasma is not understood well theoretically [6,21]. The total power is dispersed over a continuum of frequencies [22] ranging between $0 < f < f_p$ and $f_c < f < f_{uh}$, depending on the relative orientation of the momentum of the plasma wave and the local B-field. Here the upper hybrid frequency f_{uh} characterizes the plasma oscillation perpendicular to the static B-field, and is given by $f_{uh}^2 = f_p^2 + f_{ECR}^2$ [22]. As the power increases, the reemission of radiation significantly lowers the plasma radiation resistance and broadens the frequency spectrum of oscillations, thereby lowering the overall Q of the plasma chamber and reducing the magnitude of B_1 for all frequencies.

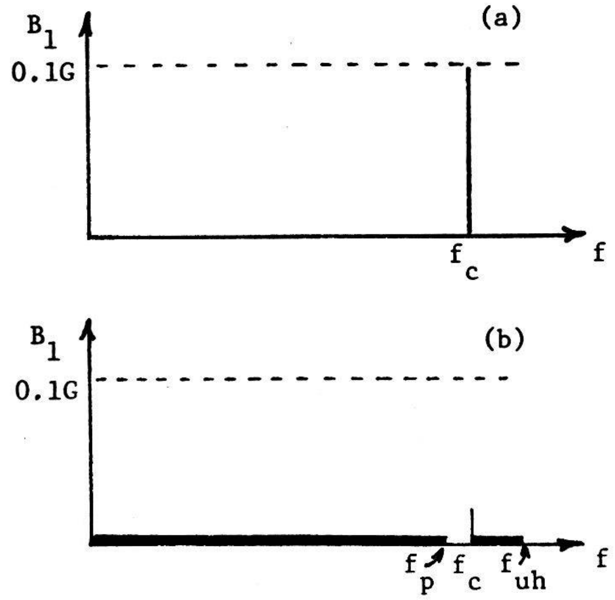

Fig. 2 Spectra for the r.f. magnetic field versus frequency in an ECR source plasma showing qualitatively the differences between the situations for a) low input power such that $n_e < 0.1\ n_{e,max}$ and b) high input power such that n_e is approaching $n_{e,max}$. The frequency spectrum in a) is expected because it approximates the situation in vacuum. In b) the driving frequency f_c couples with f_p to disperse the power over two broad bands, although the exact power distribution is not well understood for the ECR source plasma.

Is it possible then that there will be a plasma oscillation in the ECR chamber of frequency and amplitude to cause depolarization? As seen above, one requires an oscillation with local power density approaching 0.2 W/cm^2 or greater. Furthermore, to flip the spin, there must be a constant phase relationship between its precession and the driving r.f. field for the duration of the spin-flip time. This phase will be constant if

$$f_o \tau_{flip} - (f_o + \Delta f)\tau_{flip} < 1 \text{ revolution.} \tag{4}$$

If this difference increases, the spin will slip completely out of phase. Thus $\Delta f \tau_{flip} < 1$ or $\Delta f < 1/\tau_{flip} = \gamma_J B_1$ and the power must be concentrated in a fractional linewidth of

$$\frac{\Delta f}{f_o} = \frac{\gamma_J B_1}{\gamma_J B_o} \simeq 10^{-4}. \tag{5}$$

It seems extremely unlikely, in the complicated magnetic field of the nonresonant ECR chamber of Fig. 1, that one would concentrate ~10% of the local power density in such a narrow band of the total ~2.5 GHz frequency spectrum. If there were unexpectedly such a narrow depolarizing resonance, it seems likely that one could tune the ionizer parameters to avoid it.

Thus from these semiquantitative arguments we conclude that for up to 50W of total power into the ionizer considered here, significant depolarization seems very unlikely. This conclusion remains valid even if $Q \cong 10$ for the ECR chamber.

Finally, it is important to realize that we have been discussing here the flipping of the atomic electron's spin, while the dangerous condition for the application to a polarized source is that the nuclear spin be flipped. Because of the strong axial B-field required by the ECR ionizer, the electron and nuclear magnetic moments are largely decoupled. For example, at the field of 1200 G typical of most EB ionizers, the ratios of the nuclear and electron spin-flip probabilities are $P(\mu_p)/P(\mu_e) = 0.08$ for $H_o(1S)$ and $P(\mu_d)/P(\mu_e) = 0.006$ for $D_o(1S)$. This gives the ECR ionizer a significant added margin of safety.

4. The Question of Ionization Efficiency

The efficiency of an ECR ionizer for a slow neutral, atomic beam of $H_o(1s)$ or $D_o(1s)$ can be estimated from a comparison with the EB ionizers used now. Assuming an electron energy distribution in the ECR plasma similar to that in the EB ionizer, then the important quantity to compare is the electron density n_e in the two devices. In the ECR ionizer, n_e depends on f_c, on the input power density $\bar{s}$, and on the local pressure.

Experience has shown [14] that it should be easy with 50W in the source of Fig. 1 to obtain an ECR plasma with $n_e \cong 0.1\ n_{e,max}$. From Table 1 we can see that this gives n_e values ranging from 0.75 to 2.2×10^{10} electrons/cm^3 for f_c between 2.45 and 4.20 GHz. The corresponding B-fields of 875 to 1500 G include the most likely useful range for an ECR ionizer. Comparing with the $n_e \cong 2.5 \times 10^9$ electrons/cm^3 estimated to be available in the best present EB ionizers [23], this gives a gain in efficiency of ~ 3 to ~ 9 <u>for the same ionization volume</u>. For the ECR ionizer this volume is larger radially and shorter axially and may better accommodate the large divergence of the cooled atomic beams. Thus, real gains in ionization efficiency seem possible from increased electron density. Perhaps further gain is available from better geometrical matching with the entering atomic beam.

Table I Parameters and estimated electron densities and ionization efficiency gains for proposed ECR ionizer.

f_{ECR} (GHz)	λ (cm)	B_o (Gauss)	n_e,max (#/cm^3)	0.1 $n_{e,max}$ (#/cm^3)	Est. Efficiency Gain over EB "Superionizer"
2.45	12.2	875	7.5×10^{10}	7.5×10^{9}	3.0
3.36	8.9	1200	1.4×10^{11}	1.4×10^{10}	5.6
4.20	7.1	1500	2.2×10^{11}	2.2×10^{10}	8.8

Another enhancement has been suggested [4]. One can mix small quantities of buffer gas with the ECR plasma to optimize the pressure for maximum output beam intensity. If the added gas were D_2 for $\vec{H}_o$ beams (or H_2 for $\vec{D}_o$ beams), then charge exchange [24] via the process

$$D^+ + \vec{H}_o \rightarrow D_o + \vec{H}^+ \tag{5}$$

would provide higher efficiency than for ionization by electron bombardment alone [25]. For these two processes the output ion current $I \propto n\sigma v$, where n and v are the positive ion or electron density and velocity and σ is the appropriate cross section. Thus their relative effectiveness is shown in Fig. 3 where σv is plotted versus energy. The bands in this graph indicate the approximate ranges of available ion and electron energies in the ECR plasma.

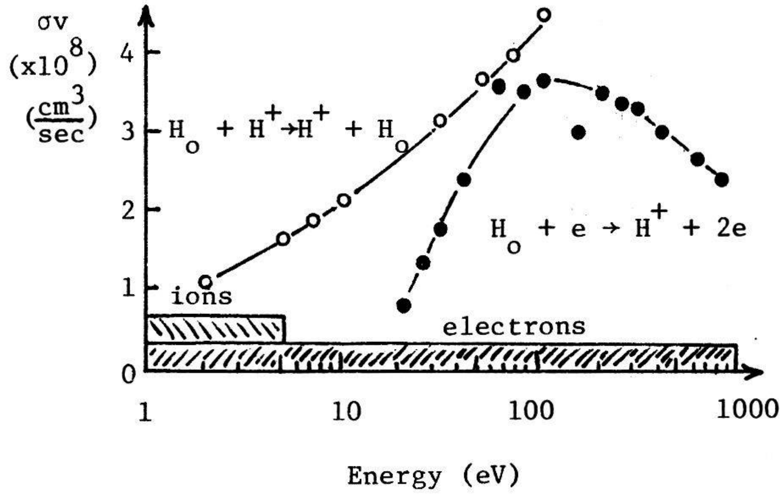

Fig. 3 Comparison of ionization efficiencies of H_o atoms by H^+ ions and electrons, plotted versus incident ion or electron energy. Bar graphs indicate the approximate ranges of ion and electron energies in the ECR plasma. These data imply that only modest gains should be expected when adding D_2 gas to an ECR plasma used to ionize an $\vec{H}_o$ atomic beam.

5. The ECR Ionizer Test at Karlsruhe

To test the above proposals about lack of depolarization and improved ionization efficiency, an ECR test ionizer similar to that in Fig. 1 is being assembled at Karlsruhe [26]. The first tests will determine the efficiency of this ionizer for H_2 gas. When operating successfully, it will be interchanged with the EB "super-ionizer" now installed on the atomic beam source for the Karlsruhe cyclotron. The output beam current and polarization from the ECR ionizer will then be compared with the known present performance. Results are expected before fall 1986.

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