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SUMMARY ON ATOMIC BEAMS, SOURCES, JETS AND STORAGE CELLS

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As an old user of polarized sources and beams, I am very pleased to contemplate the recent advances in spin physics, largely due to the progress of atomic sources. Polarized beams represent a real need for actual and future physics. After the enthusiasm of the 60's during which low energy nuclear physics obtained excellent and new results with polarized projectiles, a pessimistic period appeared. Theoreticians of high (and intermediate) energy physics strongly asserted that beyond 1GeV spin physics had almost no interest. The first experiments at Argonne, then at Saclay, Triumf, Sin, Los Alamos, proved on the contrary, that the "spin-parameters" are essential to get deep understanding and constrain any model. Actual efforts to prepare "Siberian-snakes", or other spin conserving (or polarization creating) systems at very high energies, show that the necessity of intense polarized beams (and targets) is recognized at all energies.

The second subject which satisfied a veteran of polarized atomic beams is the remarkable evolution of jets and sources over the last few years. Nuclear laboratories widely contributed to improvements and new developments, but we must be pleased with the essential contributions of a more and more vigourous atomic physics community, which brought us original ideas and allowed deeper and deeper understanding of facts, which looked like recipes more than scientific analysis in the years 50-60. In particular, the idea of the ultracold confined atoms of high density strongly restarted the imaginations.

This workshop of Montana should appear in the future as representative of the strong and hopefully rapid transition between the "step by step" improvements of the old recipes and the real applications of new ideas toward VERY HIGH intensity sources.

Three essential subjects have been developed at this meeting for pulsed or d.c.atomic beam sources :

1 - Increase of the <u>intensities</u> and <u>decrease</u> of the atomic jet temperature
2 - Improvement of the <u>matching</u> between a jet and its final focussing (after polarization) in an ionizer.
3 - Creation of the new ionizers of a high efficiency for both negative and positive polarized hydrogen (or deuterium) beam.

This is obtained by optimizing each of four factors :

$$I\ \text{final} = I\ (\text{atomic beam}) \times \frac{1}{v} \times m_t \times \eta\,(\text{ionizer}) \quad (1)$$

where v is the mean velocity of the atomic beam; m_t a matching coefficient between the origin of the beam and the ionizer, η the efficiency of the ionizer.

[This summary will refer only to papers presented at this workshop. For complete review and references, see for example the review paper of W.Grüebler at Osaka].

1. ATOMIC BEAMS

1.1 The first simple idea for increasing the intensity of a polarized source was the cooling of the atoms at the level of their production. People hoped to profit by two gain factors (see W.H. Haeberli paper).

a) - The density in an ionizer is proportional to the inverse of the mean velocity of the atoms.

b) - The number of atoms which can be focussed inside the given emittance of an ionizer is proportional to the maximum solid angle (Ω) of the focussing lens, in turn proportional to the inverse square of the velocity :

$$I_f \cong \rho_f \cong (v^{-1}) \times (v^{-2}) \cong T^{-3/2} \quad (2)$$

1.2. The final issue is not so successful. The important hard work devoted to the cooling at SIN, ETH, BNL, Saclay, has clearly demonstrated unclear phenomena which make I_f vary very differently from (2). The number of atoms produced as a function of T shows unexplainable variations and a general trend to a serious decrease.

1.3. Local cooling of atoms after warm production, either inside a continuous geometry or in a special separate device (accomodator), exhibits unstable or irreproducible regimes. In particular in one and the same temperature range very different variations of (I) are observed as the temperature is increased or decreased. Careful examination of those variations shows almost an independence of those variations as a function of the inner covering materials in the cooling regions. It conveys the idea that surface effects give rise to an important recombination of the atoms, related probably to very small concentration of impurities in the gas (see reports of BNL, SIN, ETH).

1.4. Magic mixings of gas seem to allow a partial compensation of the recombining effects, permitting a partial recovery of the intensity. See for example the paper of P.A.Schmelzbach, where they get good results around 35°K with an admixture of N2. Similar variations were observed at BNL (see Herschcovitch's paper), but the clean geometrical separation between the first cooling ($\cong$ 80°K, Teflon) and the final very cold accomodator proved to be efficient in limiting the distance covered by the atoms in the catastrophic temperature range (90°K to 30°K).

1.5. The fundamental thermodynamics of very cold (H_o, D_o) jets is not yet well understood and efforts for a better comprehension are welcomed (T.Niinikovski). The quality of the velocity spectra measured at BNL and ETH should allow improvements of the models of jet formation.

1.6. My own conclusions are the following :

1.6.1. It seems necessary in the cooling devices to go as quickly as possible to the very cold region, trying to shorten or cut the large unclear zone of "transition temperatures" (90°K to 30°K).

1.6.2. The final value for the atom fluxes (ETH, BNL) are not bad (3.3 10^{18}/sr/sec at BNL) but should still be improved (other geometries, pulsing, .. ?).

2. FROM THE JET FORMATION TO THE IONIZER

2.1 Large progress was made in matching the atomic beam emittance and the acceptance of the ionizers (see e.g. Eversheim, Grüebler). The usefulness of many separated sextupoles is not convincing concerning the final intensity, but two focussing devices seem necessary to obtain pure polarized nuclear states at least for deuterium. Each step of improvement concerning a given part of a source should automatically lead to reexamination and optimization of the full matching :

$$[\text{JET}] \Leftrightarrow [\text{FOCUSING}] \Leftrightarrow [\text{IONIZER}]$$

2.2 RF - Transitions necessary to produce the nuclear polarization are routinely used with efficiencies near 100% from the 60's (thanks to A.Abragam !). The adiabaticity criterion will be better and better satisfied with colder atoms and will allow shorten transition devices,
(if $v\downarrow, T\uparrow$, hence $\frac{\Delta B}{\Delta T}\downarrow$, where ΔT = transit time)

2.3 The new qualities of cold atomic jets ($\overline{v}$ and $\frac{\Delta v}{\overline{v}}$ smaller) and of ionizers (see 3.) will necessitate new focussing setups with very large initial solid angles. Solenoïdal lenses could be a first approach (T.Niinikovski) but are far from excellent, due to still serious aberrations (chromaticity, aperture). Other ideas could be tried for very cold atoms (see 4.).

For final adjustments of solid angle, I would suggest that the flux of cold beam systems be measured as a function of the angle near the axis of the emitter.

3. IONIZER

3.1 Classical ionizers (electrons, charge exchange) in their actual long geometry have probably achieved almost their optimum efficiency. Successive improvements brought subsantial gains in intensity. Adjusting many parameters of the source (not only the ionizer),J.Alessi has shown how they went from 7 μA beyond 30 μA (H^-). Intense continuous beam of (H^+, D^+) are currently produced (up to 100 μA, see Karlsruhe, Bonn) and also pulsed currents of few hundreds of microamperes (Saclay).

3.2 Two types of particularly interesting ionizers were described or proposed at this meeting.

3.2.1. **The ring-magnetron-Ionizer**

Even if the basic idea is indeed old, I must mention the beautiful realization presented by J.Alessi et al, of such a large acceptance and high efficiency ionizer. The first result (500 μA, H^-) is fantastic. But it should be fair to know more precisely the density of H_0 focussed in the ring. The foreseen measurements with the old Argonne polarized jet will answer that question, and also will allow the measurements of the polarization.

3.2.1. **The ECR-Ionizer**

The possible use of an ECR-Ionizer (see T.B.Clegg) is an original idea, based on the high predicted efficiency for producing (D^+, H^+), d.c. or pulsed currents. There seems no reason for a depolarizing mechanism in such an ionizer. With efficiencies as large as 20%, everybody can imagine what kind of current could be obtained. We urge the "Karlsruhe-ECR" test ! (maybe at the end of 86 ?).

3.3 My conclusions :

3.3.1. If these two ionizers get final results as it is hoped, all other ionizers of jets will be superceded within two years. Currents will exceed one milliampere (but wait the realistic measurements, with an atomic beam, of the currents and polarizations).

3.3.2. Taking into account the progress of cold beams, the optimum matching would be realized only if these ionizers have a VERY large geometrical transverse acceptance. It seems to be (almost) the case for the RING, but has to be proved for ECR.

3.3.3 In any case the ANL-type ionizers will no longer be suited for large solid angle cold beams (the suggestion by R.Vienet to cut an ionizer into slices might be considered, but it will remain very specific to a particular accelerator).

4. ONE MORE REMARK AND A PERSONAL PROPOSAL

4.1 The most ambitious apparatus described at this meeting is the straight highway to an ultracold atomic cell (8 teslas; T $\cong$ .5K, Extraction 140 GHz, Acceleration $\simeq$ 5K, density 10^{14}/cc).

This unique and important set up due to the Michigan-MIT-Brookhaven collaboration is under construction. No doubt that if this scheme works as is hoped by the authors, it would gain another order of magnitude on the possible densities and temperature for cold jets. Our best wishes for such a bold device !

4.2. Proposal for a new focussing-transport system (for T≤6K)

4.2.1 Nothing magic in this basic idea suggested by G.Clausnitzer as early as 1966, of a "total reflection" magnetic surface (s). A surface (see Fig.1) is built of the ends of iron foils in between which are wound wires of alternating currents (very intense short pulsed or supraconducting d.c. wires). The properties of the magnetic fields near (s), i.e. near the alternate (±) thin poles are obvious : the magnitude of B is almost constant and maximum along (s) and decreases very sharply perpendicular to (s), approaching zero after a distance comparable to the step (e)

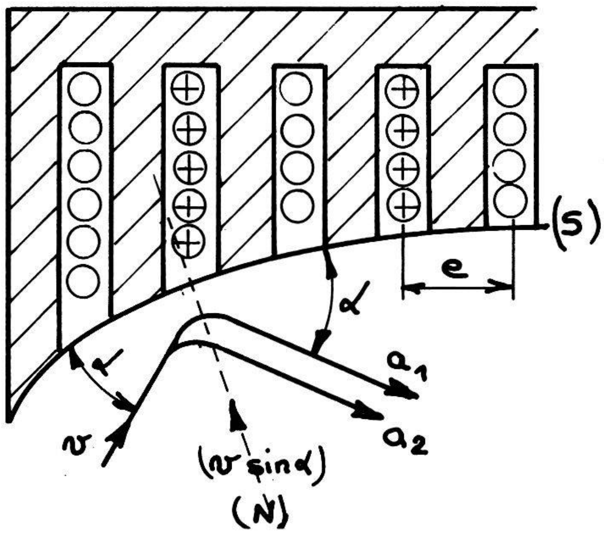


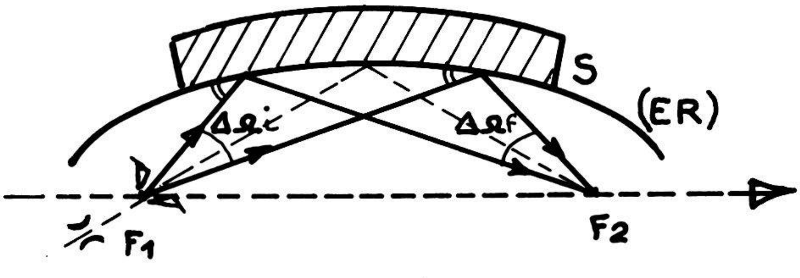
Fig.1

Each atom with electronic spin (+) will be deflected around the perpendicular (N) to (S), providing that its transverse energy (E_T) obeys the condition :

$$E_T = \frac{1}{2} mv^2 \sin^2\alpha = E_o \sin^2\alpha \quad \leq \mu|B| \max \quad (3)$$

where (E_T, E_o) are the transverse (resp.total) energy of the atom. This is **the total reflection** condition. Two atoms (a_1, a_2) with different velocities will leave the vicinity of (s) with almost parallel trajectories (Δa_1a_2 = chromatic aberration (c.a.) $\lesssim$ e). If $\alpha \lesssim 30°$, the major part of an atom jet of ≅ 5K will be deflected for B ≅ 2 teslas.

4.2.2 If(s)is **part** of an **ellipsoïd of revolution** (ER) (see Fig.2), all atoms with electronic spin (+) emerging from a source point located at a focus (F_1) will be



deflected by (s) toward the second focus (F_2). The magnification ($\Omega i \rightarrow \Omega F$) will be related to the choice of the part (s) of the (ER) used for reflection. Residual chromatic aberration will spread the lateral dimension in (F_2).

4.2.3. Two such devices having focus (F_1,F_2) and (F_2,F_3), symmetric to a plane (π), will suppress the aberration (c.a.) when used in succession (to 1st order) (see Fig.3). Vicinities of F_2 and F_3 will contain the adiabatic (RF) transitions creating the nuclear polarizations (eventually pure states, transition in F_2).

4.2.4. Such a magnetic deflection can be used for driving, focussing, storing, and also for matching (with two different E.R.) the emittance of the jet to the acceptance of a given ionizer (if large enough).

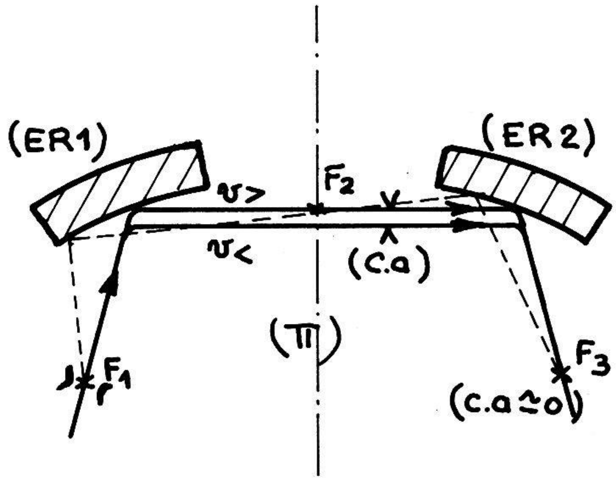


Fig.3

Those open focussing-cells would make the pumping quite easy !.
But: Very cold atoms are needed !

Applying this to the actual numbers of BNL, with an initial cone having in (F_2) an angle α 1/2 $\approx$ 15° would produce densities greater than $\cong 5.10^{12}$/cc at 5°K-($\Omega_i \cong .2$ Ster).

5. STORAGE CELLS

5.1 The need for pure polarized hydrogen of large enough densities was clearly examined by W.Haeberli, L.Dick, W.Kubischta for physics inside storage rings or accelerators. The desired luminosity would be obtained in many cases if the integrated thickness of polarized atoms is at least $10^{13}/cm^2$. W.Haeberli showed us the possibility of using a storage cell, i.e. a mechanical box with a continuous escape flow as small as possible. He pointed out the low rate of depolarization by scattering on the walls of an appropriate material (old measurements at Wisconsin indicated a relative depolarization of 25% after $\cong 10^3$ collisions). This scheme necessitates a large feeding flow, and a continuous measurement of the polarization inside the cell (monitoring of P).

5.2 The magnetic bottle built by H.Hess for the purpose of maintaining the density of atoms and simultaneously decreasing the temperature is exciting, even if the specific goal (Bose-Einstein condensation) differs from our concerns. We should imagine such a tube (but of larger dimensions) crossing the vacuum chamber of a storage ring with the same kind of superposed solenoïds (longitudinal confinment) and quadrupoles (transverse confinment). Firing the solenoïds in succession allows one to imagine the following possibilities :

a) - Create a magnetic bottle outside the interaction region and fill it with very cold atoms. Eventually compress this bubble (by increasing the magnetic fields).

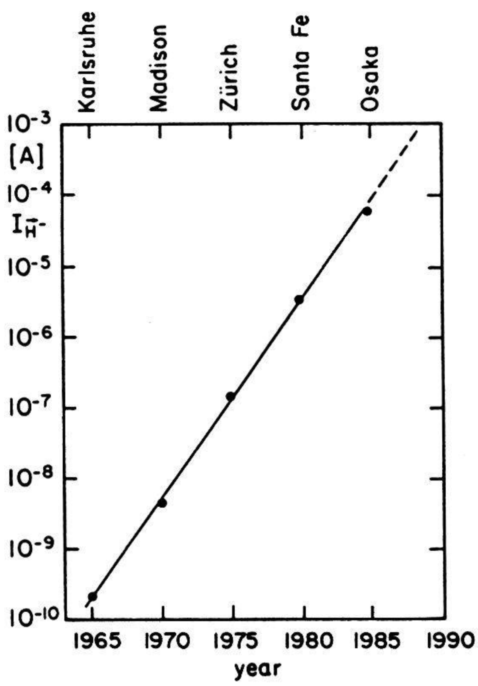
b) - Translate this magnetic bottle to the interaction region for the crossed beam-bubble experiment (switching on and off individual solenoids)

c) - Prepare a new (lateral) bottle and fill in a "fresh" atom bubble, etc.... In such a scheme, longitudinal magnetic fields act like movable pistons. Confining at each step a few times 10^{15} cold atoms could produce densities over $10^{13}/cm^3$.

5.3 In both cases, the destruction of cold atoms by the interacting beam should be carefully examined. Ionization and elestic cross-sections of the primary charged beam are very energy dependent and the lifetime of "bubbles" very different for different energies and intensities of the interacting projectiles.

6. CONCLUSIONS

I claimed in 1966 at Saclay meeting on sources that... "within a few years we can hope to achieve polarized beams of milliamperes...". The reality thereafter was small and painful gain factors only were obtained for many years, until the first serious cooling (Argonne) was achieved, and new developments were initiated by the atomic physics of ultracold atoms.



Today, more than one milliampere 65% polarized source does exist in Moscow (serious competition with optical pumping, see the summary of E.Steffens and the Osaka proceedings !). This is a pulsed current (but with probably too short pulses). Within two years atomic beams with fair focussing lenses and efficient ionizers (ECR, RINGS) will achieve still more intense currents.

At this point we can contemplate the famous log-diagram shown at the Osaka conference by W.Gruebler (also valid for (H^+, D^+) with a difference of almost an order of magnitude at this time).

If we believe in this magic figure and extrapolate, the final limitation in intensity in polarized protons would be in 1991 the space charge limit of all existing machines !

Would the polarized source community be unemployed after 1991 ? or would after this time new improvements in sources or jet intensities (and densities) be used for completely different purposes than nuclear or elementary particle physics ??