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THE SODIUM CURTAIN BEAM PROFILE MONITOR OF THE ISR

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The instrument displays the cross-section image of the ISR proton beam on a television screen. Beam density distributions across the horizontal or the vertical axis as well as their simultaneous perspective display (i.e. mountain range) are displayed on an oscilloscope. The monitor does not impair the ultrahigh vacuum of the ISR nor does it destroy or degrade the proton beam. The beam image is formed by extraction and acceleration of electrons produced by the beam in a thin curtain-shaped sodium vapour jet, on to a fluorescent screen. The curtain is inclined at 45° to the vertical in order to obtain the horizontal and the vertical profile simultaneously. The geometrical definition of this apparatus is better than 1 mm.

Introduction

The development of a device for the measurement of the dimensions and the charge distribution of the ISR proton beam has been completed. The sensitivity of the device had to be such as to permit operation during the setting up of the ISR (few mA) and not to saturate at the highest design current (20 A). It should operate continuously and should neither degrade the ultrahigh vacuum of the ISR nor perturb the beam.

The problem was solved by using the ionization electrons coming from a collimated, (almost two dimensional) gas jet crossing the ISR vacuum chamber as the signal source for the proton beam dimensions and charge distribution. The plane of the gas jet injected into the vacuum chamber of the ISR is at 45° to the vertical and to the beam and the electrons produced in the gas are extracted vertically and are accelerated on to a fluorescent screen where they produce a 1:1 image of the cross-section of the beam. One can compare the gas jet (curtain) to a mirror held by an observer situated above the beam pipe and who wants to look along the beam (figure 1).

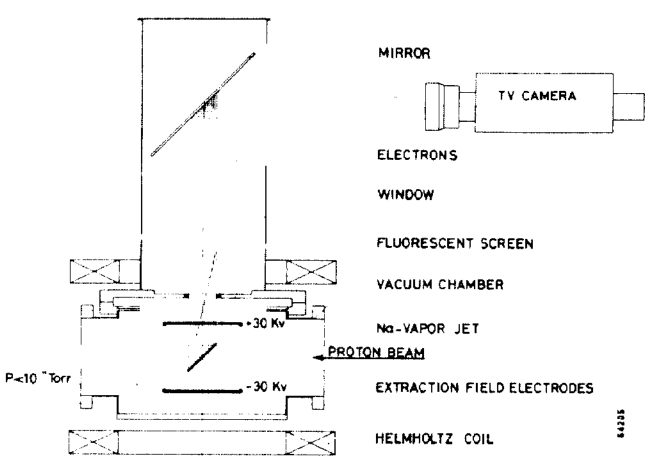

Fig. 1 : Principle of operation

Description of the monitor

The monitor consists of three main parts: the gas curtain generator, the electron extraction chamber and the television camera with associated electronics for the signal treatment.

The parameters of these components are tightly interconnected and are the result of a number of compromises, the limitations being of a physical, technological or commercial nature.

Gas curtain generator :

The minimum observable current in the ISR, the geometrical definition, the value of the extraction voltage, the phosphor efficiency and the sensitivity of the television camera define the size, the density and the divergence necessary for the gas curtain. Our need was a 0.7×64 mm^2 gas jet with 0.7 mrad maximum divergence and a minimum density equivalent to a pressure of 10^{-7} torr. In view of a possible time definition higher than that of a television camera working with 625 lines/50 half frames per second, we set our aim at 10^{-4} torr. Such high jet intensities can only be achieved by means of a supersonic flow, where some of the random thermal motion of the gas atoms is converted into an ordered motion. This process takes place when there are enough collisions between the atoms of the gas during the outflow from a pressurized vessel. However, the effect of the ordered motion is lost when this "jet" encounters too many particles on its passage from the source to the point of utilisation. Therefore a very powerful pumping system is needed if one wants to produce a dense molecular beam of large dimensions.[1] In fact, the only way to pump such high gas flow rates is to condense the gas. Consequently sodium vapour was chosen as an "easily" condensable gas which satisfies another imposed boundary condition, namely that the vapour pressure of the condensed gas at room temperature is lower than the 10^{-9} torr which was initially the design pressure for the ISR.

The gas curtain generator was constructed to have the following characteristic numbers : Knudsen number of the source vapour 0.01, slit length 64 mm. This implies a gas flow of one g/s to be generated by a heating power of 4.2 kW. Therefore the heating and condensation facilities were designed for a power of 5 kW. The principal parts of the source are shown in figure 2.

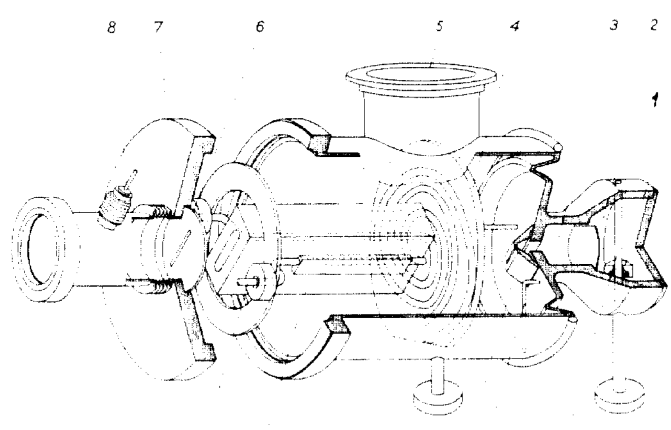

Fig. 2 : Exploded view of the sodium curtain generators

Sodium vapour is generated in the boiler (2) and superheated in a chamber (3). This part of the boiler is made out of a high nickel alloyed steel (Nimonic 75). On its outer surface there are grooves in which the coaxial heating elements (2 mm in diameter) plus some spare ones are embedded. These thermocoaxial cables are pressed down in their grooves by small stainless steel bars and are covered with a 2 mm thick nickel layer deposited by means of plasma spraying.

Beam shaping elements

The exit nozzle (11) which has a slit width of 0.7 mm, a length of 64 mm and a lip length of 0.2 mm is screwed to the super-heater chamber. A copper foil is interposed to make a seal and to assure a good thermal contact. The beam scraper (6) is housed in the cover (7). Its slit, which has the same dimension as that of the nozzle is heated by a thermocoaxial cable to a temperature where clogging by sodium is excluded. A second collimation slit is not represented in the figure. A shutter (8) which can be actuated via a stainless steel bellows can block the passage of the sodium beam.

Condensation and pumping system

If the residual partial pressure of sodium is to stay below 10^{-5} torr, sodium vapour must be pumped by the condensation surfaces with a sticking factor approaching unity. The first experiments, where large copper condensation surfaces were installed have revealed that the partial pressure of sodium was too high and that beam - background scattering occurred. Therefore investigations on the condensation behaviour have been undertaken in order to determine the influence of the substrate surface and its temperature as well as the influence of the flux ratio of sodium vapour to the residual gas arriving on the surface.[2]

The experiment has shown that it is possible to obtain film condensation on copper plates which are either silver or gold plated. We think the reason for this film condensation depends on the fact that the oxides of gold and silver are already decomposed at the bakeout temperature and that the sodium vapour arrives on the clean metallic surface where it is bound by the noble metal. Furthermore, the sticking coefficient was determined as a function of the ratio of the flux of sodium to the flux of residual (predominantly H_2) gas molecules.

The measurements have shown that the sticking coefficient decreases with a decreasing Na/H_2 flux ratio. We see the reason for this behaviour in that at a low flux ratio the substrate surface is covered by physically adsorbed hydrogen, which impedes the full accommodation of the arriving sodium atoms. The measurements did not show any dependence on the substrate temperature. We conclude, therefore, that sodium condenses on clean metallic surfaces and on clean sodium covered surfaces with a sticking probability of unity.

As a consequence of the above measurements, the condensation surfaces were kept just sufficiently big for the desired pumping speed and the partial pressure of the non-condensable gases had to be kept low. Therefore a good pumping speed system has been installed consisting of an ion pump with a pumping speed of 400 ℓ/s and a turbomolecular roughing pump. The residual gas pressure has thus been maintained below 10^{-9} torr. This has been measured by an ionization gauge and the residual gas composition was checked by a mass spectrometer. The partial sodium vapour pressure in the vessel was measured by two gauges, which were permanently heated to 200°C in order to impede the condensation of sodium vapour on them. As can be seen from figure 2, most of the sodium vapour is condensed on a thick copper disc (4), cooled by an oil circuit. In the middle of this disc is an opening which is just big enough so that the biggest sodium droplets cannot clog it. The rest of the vapour condenses on the cooled plates (10) surrounding the beam. Since the power dissipation per unit of surface is high, the cooling circuit, consisting of a single copper tube (9) was embedded in the copper plates and silver brazed under vacuum. In order to prevent the dissolution of the silver solder by the sodium, all silver brazed parts were nickel plated.

Temperature control and sodium transfer system

The condensation plates are maintained above the melting temperature of sodium at 97.7°C. This is done b[y] regulating, on the one hand, the flow rate of the oil circuit, and on the other, the power in the coaxial heating elements, which are also embedded on the condensation plates. All heaters are regulated continuousl[y] by triac controllers. The sodium temperature in the boiler is measured by a thermocouple fixed at the bottom of the tube (13). The tube (13) also guides a float (1) with a permanent ring magnet inside. A hollow cylinder in soft iron suspended in the tube can follow the movements of the float indicating the sodium level in the boiler. In the condensation vessel the level of sodium is measured by a nickel plated copper bar (12) on which a thermocouple has been fixed near the middle. When the point of the bar dips into the liquid sodium, a temperature change is recorded which in turn is linked to the sodium level in the condensation chamber.

The sodium transfer and filling system is shown schematically in figure 3. The sodium which is condensed in the vessel (2) is pumped back to the boiler (3)

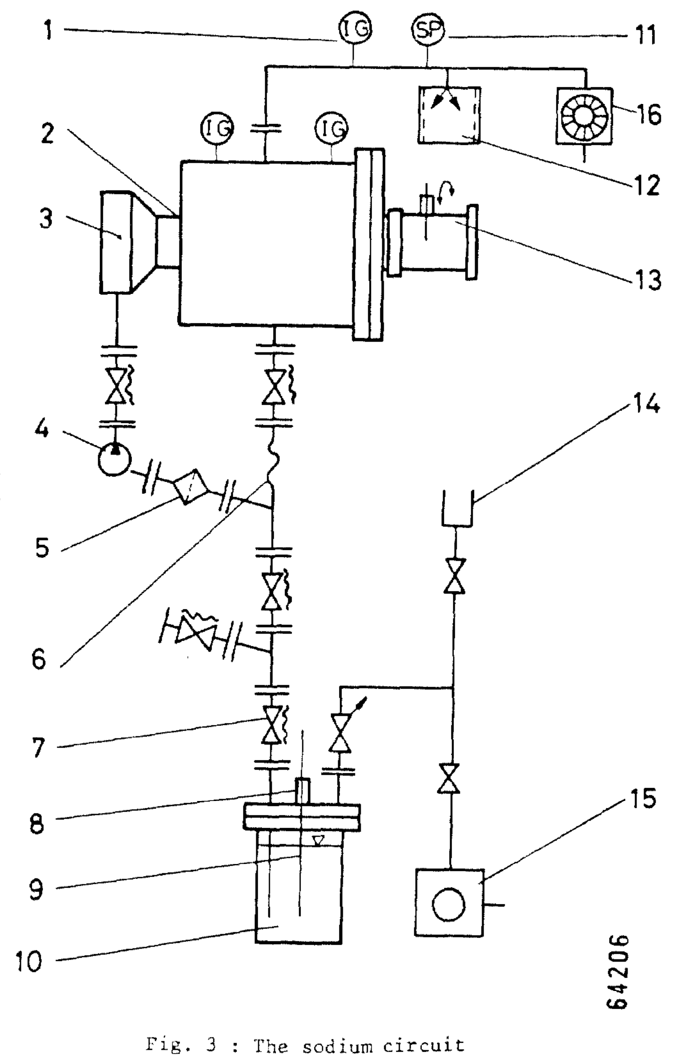

Fig. 3 : The sodium circuit

by a small electromagnetic pump (4) yielding a pressure of several hundred torr and a flow rate of several grams per second. One of the main impurities of the sodium circuit is sodium oxide. The solubility of sodium oxide in sodium decreases with decreasing temperature so that a danger exists in that it precipitates in the cooler places where it can clog the tubing (e.g. the sodium pump). Therefore, the sodium is continuously cleaned by a filter of sintered stainless steel (5) having a pore diameter of 5 microns. The filter is maintained at the temperature of 130°C, which favours the precipitation of sodium oxide. Sodium is filled into the boiler by forcing it up from the reservoir (10) by means of 100 torr pressure of pure argon. The sodium level in the reservoir is determined by the electric resistance measurement of a stainless steel wire plunged into the sodium.

The maximum intensity of the sodium beam delivered by the described generator is about 10^{20} atoms/sr.s (equivalent to $\approx 10^{-5}$ torr pressure), was measured by a Langmuir-Taylor platinum ribbon detector and has a performance better than that of any generator reported to date. Though inferior by a factor of 10 to our expectations, it is quite sufficient at the moment. With the TV observation the usual working pressure is $\approx 10^{-7}$ torr.

Observation chamber

The high voltage electrodes serving to extract electrons formed by ionization of the sodium curtain, are contained in a vacuum box inserted into the ISR ring (figure 4). The electrodes (1) are made of titanium which shows very low cold emission. A proton current of 5 mA yields an electron current of only $\approx 2.10^{-13}$ A, with the sodium curtain at its normal intensity of 10^{-7} torr, a fact which emphasises the necessity for low cold emission from the extraction electrodes. The insulators carrying the electrodes are protected by metallic shields against an eventual sodium deposit. The upper positive electrode carries a quartz plate with an aluminized type P 22 B phosphor deposited on its lower surface. This phosphor was chosen because of its high energy conversion efficiency (25%) and good colour match to the TV camera photo-cathode. To prevent sodium being deposited on the phosphor (which would destroy it), the upper electrode is permanently heated to ≈ 120°C by a thermocoaxial cable embedded in a groove machined into the electrode. The strength of the extracting electric field is about 4.5 kV/cm, a value that permits the distortion of the beam image, due to the space charge field of the proton

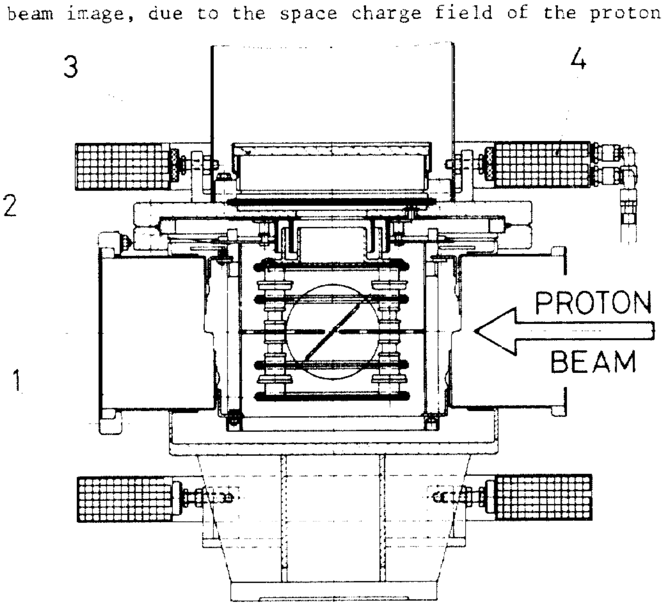

Fig. 4 : The observation box, cross-section

beam itself, to be kept within 1 mm, up to the highest design current (20 A). The normal potentials of the upper and lower electrodes are respectively ± 30 kV; two additional intermediary electrodes at ± 15 kV help to homogenise the electrical field. Stray light coming from vacuum gauge cathodes is screened by a labyrinth (2). The fluorescent screen is observed via a quartz window (3). A calibration grid is laid over the fluorescent screen and everything is aligned with respect to the ISR reference frame to about 0.2 mm.

The electrons which are ejected by the proton beam from the sodium atoms have a certain initial velocity, and would normally follow a parabolic path and would not be collected at the same spot as for electrons with zero initial velocity. A magnetic field of ≈ 300 gauss parallel to the electric field is created by a couple of coils (4) and contains electrons of up to 20 eV within a 0.5 mm radius around the ideal projection point. There are less than 10% electrons having energies higher than 20 eV. The effect of this magnetic field on the ISR is compensated by a small magnet on each side of the observation chamber.

The sodium curtain generator is attached to the observation chamber and is perpendicular to the ISR beam pipe axis. The sodium jet, after having crossed the observation chamber, enters the condensation chamber whose walls are cooled to − 40°C. This chamber contains the Langmuir-Taylor platinum ribbon detector which measures the sodium jet density. In order to protect the ISR vacuum chamber from eventual Na migration, cold traps were fitted in the ISR at each side of the beam profile monitor. Analysis of the rest gas composition 1 metre up or downstream from the observation chamber, did not show any trace of sodium. The sodium curtain at its normal operating pressure of 10^{-7} torr and having a thickness of 10^{-3} m, represents a gas target of 10^{-10} torr m, as seen by the proton beam. The ISR rest gas represents $\approx 10^{-11}$ torr × 10^{3} m = 10^{-8} torr m. These figures show that the sodium curtain does not perturb the ISR.

Television camera and the signal treatment

With 10^{-7} torr in the sodium beam, we obtain $2.5.10^{-13}$ A of ionization electrons for 5 mA of proton beam. After acceleration to 30 kV, these electrons strike the fluorescent screen. There, each electron produces about two thousand photons. The extraction system acts at the same time as an image intensifier! This welcome gain compensates the light losses due to the limited solid angle acceptance of the TV camera objective.

Nevertheless, the quantity of light falling on the photocathode of the camera tube corresponds to starlight illumination so the TV camera tube chosen was a SEC tube with one stage of image preamplification, sold by the French firm Thomson-Houston under the name of the Super Esicon. The sensitivity and definition of this tube are quite sufficient for our purpose. Its main defect is the fragility of the secondary emission target to light overexposure. The camera head amplifier and the scanning circuit is equipped with vacuum tubes because of the relatively high radiation level ($\approx 3.10^{4}$ rad/year at the beam pipe level).

The light collection is ensured by a telephoto lens (f = 135 mm, 1/F number = 1.5). After a few months of operation, the glass of the lens becomes brownish due to radiation. It is possible to remove this coloration almost completely by exposing the lens elements to ultraviolet radiation for about a week. We have had a lens operating in this way for more than 4 years before it became unusuable.

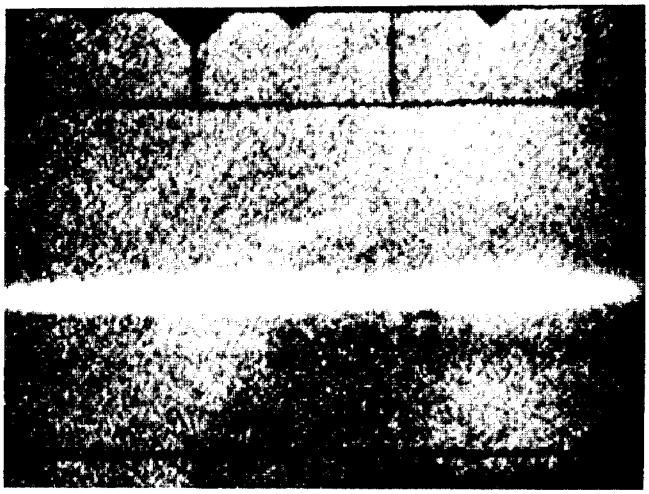

Fig. 5 : Cross-section of a stacked proton beam as seen on the TV monitor

Figure 5 shows the picture of a stacked beam as seen on the television monitor. On the top and bottom of the picture the calibration grid can be seen. The distance between the vertical bars is 20 mm. The distance between the horizontal bars is 40 mm. The background light is due to the electrons coming from the rest gas. This can be used for measuring a horizontal profile alone if, for example, the sodium generator is not operating. Representation of either horizontal or vertical beam density profiles on an oscilloscope as well as the perspective view of the beam density distribution is used more than the picture on the TV monitor. The circuits for different types of presentation are push-button selected.

The horizontal profile is obtained by using a horizontal sweep of ≈ 60 μs duration, putting the video signal on the vertical axis and deblocking (brightening) the line which we desire to observe. The speed of the sweep is adjusted so that one division of the oscilloscope's calibration grid corresponds to say, 20 mm in real space. For this purpose the picture of the calibration grid inside the observation chamber is used as the reference.

When one desires to observe the vertical beam profile at a certain radial position, the circuit is arranged as in figure 6. A vertical sweep generator

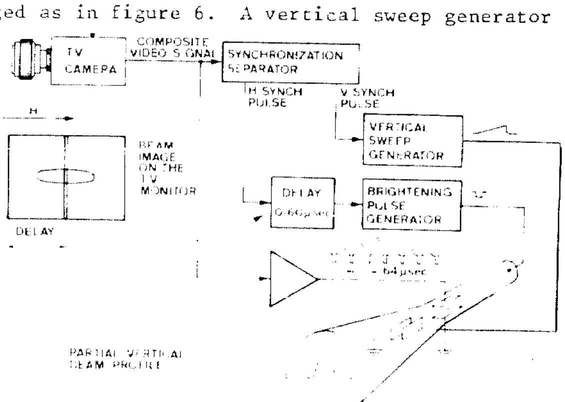

Fig. 6 : Oscilloscope connected for observation of partial vertical profile

(connected to the horizontal deflection plates) displays one frame of the picture. The brightening pulse (1-5 μs) is delayed in order to display the vertical profile of the beam at the desired radial position only. This position can be indicated on the monitor when connected for the observation of the horizontal, i.e. radial beam profile. The oscillogramme one obtains is shown on figure 7.

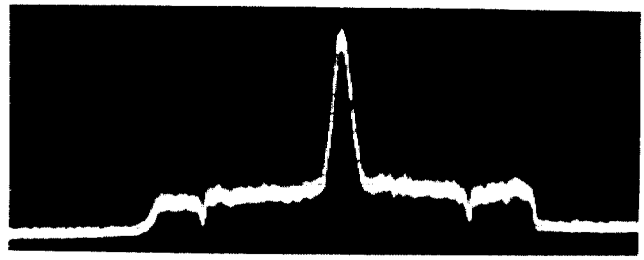

Fig. 7 : Vertical beam profile. The pedestal is due to the electrons from the rest gas. Indentations in the pedestal are the ± 20 mm fiducial marks.

Connecting the different sweep generators in the manner shown in figure 8, one obtains the perspective display. It helps the visualization of the charge distribution within the proton beam very well. A typical display is shown in figure 9.

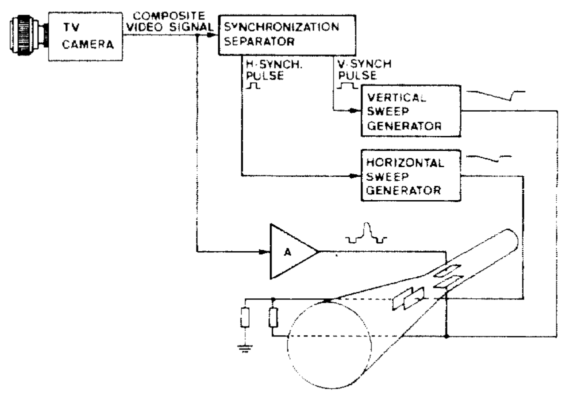

Fig. 8 : The circuit for perspective display of the proton beam density distribution

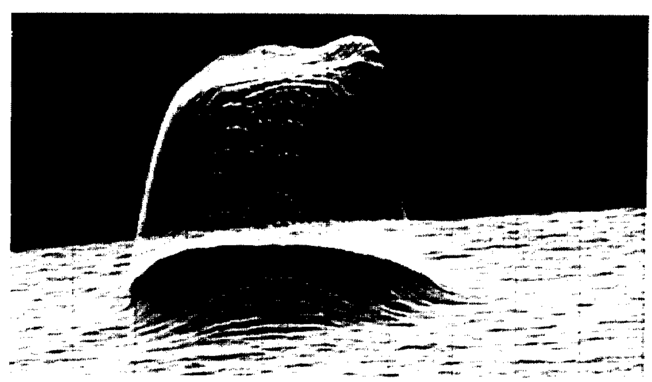

Fig. 9 : Perspective display of the charge distribution inside the proton beam

Note : Two monitors have been built and have been in practically constant use for the last few years. The sensitivity and the geometrical definition are inside the design limits. The reliability is very good for such a complex instrument.

References

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