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HOW COULD OPERATIONAL CONDITIONS AND BEAM CONTROL DEVICES MAKE AN EXPERIMENT EASIER, EFFICIENT AND MORE PRECISE ?

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Abstract. - *Due to intensity limitations of heavy ions sources, cyclotrons are usually operated in order to obtain the maximum intensities with the highest energy. As a consequence, the beam characteristics and the operating conditions are not completely satisfactory. After defining "reasonable" requirements for operating conditions, the needs for a precise knowledge and some versatility of beam characteristics useful for an experiment are emphasized. These needs are illustrated by some experimental data taken with a 86 MeV per nucleon* ^{12}C *beam.*

I - INTRODUCTION AND GENERAL CONSIDERATIONS ON CYCLOTRONS AS HEAVY IONS ACCELERATORS

In the range of 15 MeV to 200 MeV per nucleon cyclotrons are known to be very efficient accelerators. They can deliver high intensities for various ions, they can have a macro-duty cycle of 100 %, they can cover a large range in energy, their technology is rather well known and reliable, they can now be calculated in a very precise way. The coupling of 2 or 3 cyclotrons can be controlled easily. Finally the power expenses are not too high even for conventional cyclotrons and it appears that for heavy ion acceleration they are the less expensive accelerators in the range of 10 to 200 MeV per nucleon as long as beam requirements are compatible with cyclotrons.

However cyclotrons are characterized by a large number of parameters (mechanical, electrical, magnetic) which have to be set very precisely and with a particular procedure in order to get reproducibility of beam characteristics. Due to the acceleration made through a large number of turns and focusing properties some parameters have to be set with a precision probably better than 10^{-5}, most of them have to be set with a precision of 10^{-4}. In addition these parameters are coupled in such a way that it is rather easy and tempting to roughly compensate an error made on one parameter by a different setting of another parameter. This misseting is usually difficult to identify by looking at beam diagnostics, but can induce a slight variation on beam direction and emittance. These effects are still amplified for the several stage accelerators. However the quality of the components of a cyclotron is such that the stability of the beam characteristics is very high as long as all parameters stay unchanged and this can be controlled by computer. But if even small changes are necessary, because of complex hysteresis effects it is difficult to guaranty a precise reproducibility.

In addition, if cyclotrons are rather efficient accelerators, they are not usually considered as able to deliver high quality beams in terms of emittance and energy resolution. It is usually the case, but this is simply due to the very simple but very rough way that ions are produced by sources located in the center of cyclotron. The ion extraction is not optimized and the maximum phase acceptance used. As a consequence, the intensity can be high, but emittance and energy resolution are then rather poor.

Obviously very large improvements are possible if one use external ion source, with efficient bunching device and precise flat-topping system. But let's consider the general situation, and examine the usual drawbacks of cyclotrons as considered by an experimentalist.

- The precise reproducibility is usually poor and beam delivery times have large fluctuations.

- The continuity of operation is not satisfactory due to heavy ion source lifetime.

- Changing the beam energy takes usually a rather long time.

- The absolute beam energy is usually not known very precisely a priori.

- Because of the intensity limits of heavy ions source the beam emittance is rather high.

- Good energy resolution is not automatically given by cyclotrons for the same reason as above.

- The micro-duty cycle is rather low and time structure is difficult to control.

Obviously a nuclear physicist would like for simplicity to have a beam with an energy resolution of 10^{-4}, an emittance of few millimeter x milliradian, an absolute energy precision of 10^{-4}. He would like also to be able to change the energy within a minute, to have a duty cycle of 100 % for some experiments while short burst (typically 100 ps) would be also very appreciated. Such requirements are very difficult or impossible to meet with cyclotrons. However such requirements are usually not really necessary and reflect only that if the beam characteristics were so, they could be completely ignored. But if a precise knowledge and control of beam characteristics can be achieved in a very convincing way for physicist then these requirements can be much less severe.

II - OPERATING CONDITIONS

a) "Delivery time"

The first question which arises from an user is the following : how long is the time necessary to get the beam out of the accelerator and on the target with specified requirements ?

What is a reasonable requirement for this first delivery time ? I would suggest that 3 to 4 hours for the first phase and 1 hour for the second phase would be very reasonable on the following arguments :

- The beam setting can be made early in the morning and by noon we can get the beam on target. The experiment setting can then be done during the day with all the technical support available.

- If this beam delivery time ranges only for 4 hours, in a regular way then I think the experiments will be much better prepared to start as soon as the beam is on the target and the planning for users can be much more tight.

Such a time is rather short to set a complex accelerator system, but this is probably possible if the machine can be set in a very reproducible way using computer control and if the reproducibility is such that it is sufficient to control the beam characteristics (emittance, position, phase, etc...) at few points in the accelerator system and the beam transport.

b) Operating conditions with beam on target

These conditions are mainly subordinated to the ion source life-time which for PIG heavy ions source ranges from 10 to 30 hours. Again what is the reasonable time which can be taken for replacing the used ion source by an other one, and have it running smoothly ? I would suggest that a large effort should be made in order to have a total interruption of less than 20 mn. Again it is very short. But this can probably be achieved if the heavy ion facility is equipped with two injectors or if not, by changing the complete ion source device for which the correct operating conditions have been checked before in a separated magnet in the case of PIG source.

Why 20 mm ? I give this time with respect to the continuity of an experiment specially during the setting time. An interruption of 1 or 2 hours makes a break which is often very bad for the coherence of the experiment set-up and the effective lost of time can be much larger than 2 hours. An obvious solution to this problem is evidently to have an ion source which can run continuously for several days. The ECR ion source will probably meet this requirement within one or two years.

c) Beam sharing

I just mention here that the possibility of sharing the beam on two experimental sites is very useful as long as it is not too complicate to operate and that the beam characteristics are precisely controlled (time structure and emittance). An alternative or complementary way could be to transport reaction products which can be used to test and calibrate detectors.

III - CONTROL AND KNOWLEDGE OF BEAM CHARACTERISTICS

The aim of this section is to point out specific problems related to heavy ion beams specially when accelerated by cyclotrons. Intensity and beam transmission measurements, beam purity, emittance, absolute energy, energy resolution, duty cycle.

- Intensity measurements and beam transmission control

Due to a very high secondary emission of electrons it is well known that precise intensity measurements have to be made with special care. Faraday cups can be designed in such a way that secondary electron emission is negligible. However the current measurements on slits cannot be used for calculating the beam transmission. The solution which usesphase pick-up device to measure the intensity seems very efficient. To get absolute values from such devices, one needs to study very carefully the influence of the beam burst width, and of the shape of the burst, the linearity of the total system and finally a calibration procedure. But these non interceptive probes seem to be well adapted if very low intensities can be measured easily (1 nA for example).

- Beam purity

Due to their acceleration principle, the pertinent parameter for an ion to be accelerated in a cyclotron is the q/m value. While stable operation of cyclotrons needs stability of magnetic field and R.F. frequency of few 10^{-6} it is well known that ions with relative differences of 10^{-4} for their q/m values can be accelerated together. This value of 10^{-4} is only indicative and can depend on R.F. harmonic number, phase selection, etc... To get some idea of such an effect let's consider 200 turns in a cyclotron. Within a rough approximation, neglecting effect due to different trajectories, the total phase shift is $360 \times 200 \times 10^{-4} \times h = 7{,}2° \times h$, h is the harmonic number. Let's take h = 2 or 6 this leads to a total phase shift of 14° or 43° (R.F. unit). The correlated variation in energy depends on the central phase of the beam versus the R.F. phase. Taking an ideal situation where the acceleration per turn is maximum, the integrated energy variation during acceleration is of the order 10^{-3} for h = 2. For h = 6 the variation is much larger (10^{-1}) and then if the cyclotron operates with separated turns it is possible to select one value of q/m with a resolution of 10^{-5} or better. This possibility may disappear in some way if we used a flat-topping device. In any case I will conclude that the measurement of the beam purity must be made, and this measurement have to operate with a relative sensitivity of 10^{-4} to 10^{-6}. This can be achieved by using Rutherford scattering with a gold target for example. In order to get a minimum ratio between reaction cross-section and elastic scattering the measurement has to be made at very forward angle, typically 2 or 3° for ^{12}C at 85 MeV/nucleon. Then, since the different beams have the same energy per nucleon but not the same number of nucleons (in most cases) then the total energy is different and the composition of the beam can be measured. This measure which probably can be done with a plastic scintillator in most cases, has to be integrated to the beam diagnostic system of the accelerator in order to get a reliable beam identification and to optimize the beam purity if it is necessary.

- Emittance

It will be illustrated in a next section that the direction of the beam has to be known and stable with a precision probably better than 1/10 degree or 1,7 mr. If we take an emittance of 15 mm-mr, and a beam size of 3 mm the angular aperture is 5 mr. This means that not only the mean beam direction has to be known precisely but also the intensity distribution inside the beam angular aperture. The conclusion is rather straight- forward. It will be very useful, and almost necessary to measure the intensity distribution inside the emittance just in front of the target. An intensity dynamics of 100 or more, seems necessary to detect eventual significant halos. This can be done in a rather simple way using computer or microprocessor controlled emittance monitor.

- Absolute energy

The absolute energies can be measured by different ways (magnetic deviation, time of flight). Due to the recent and impressive improvements in the phase pick - up devices, I think that energy measurements should be made systematically by both ways, in order to get always a cross-check which is convincing.

- Energy resolution

Again, this concept is too general. Due to the large kinematic effect, we should probably talk in terms of energy distribution. This is usually made by a magnet, with an object which have a size comparable to the slit aperture which defines the energy distribution limits. The problem is not very simple. In other words one would like to know the intensity distribution of the beam versus energy and space, and the eventual correlation between these two parameters. This could be provided by a beam profiler placed at the focal plane of the analysing magnet and by movable slits which could select the contribution of the different regions of the object.

- Duty cycle

The duty - cycle is not easy to predict a priori and has to be measured. Let's only mention the macro-duty cycle of the ions source, and the mean profile of intensity when the ion source is switched on or off. This is easy to display. A second factor is the time - distribution in the beam burst. This can be analysed easily by a counter using Rutherford scattering. The third factor is the fluctuation of the number of particles inside the different beam bursts. We observed in Grenoble very large fluctuations which were attributed to relaxation phenomena inside the ion source. These fluctuations can be very large (a factor of five or ten). The pertinent way to display this intensity distribution inside the beam burst and among the consecutive bursts is depending mainly on the experiment requirements.

IV - VARIATION OF BEAM CHARACTERISTICS

When setting or performing experiments, in most cases physicists need to change beam intensities by very large factor due to variations of cross - section with detection angle. In addition, the beam requirements which can be severe for one part of the experiment (duty-cycle, energy resolution and/or emittance in its size or profile), can be much less tight for the other parts of the same experiment. In this section these different points are developped.

- Intensity, Emittance, Resolution

When setting counters very often it is not obvious to separate the influence of these three factors. For example a bad energy resolution in a counter can be due to pile-up, to the beam energy spread or to a kinematic effect related to the emittance. This means that it would be very useful to change the intensity by a factor of 100 or even 1 000 without changing emittance and resolution. This could be done by an appropriate device (for example a plate with small holes uniformly distributed) placed in the low energy part of the accelerator system in order to minimize the pollution of the beam by reaction products and the effect of multiple scattering on the hole edges. It would be also very helpful to vary in a very fast way the size or even the shape of emittance by an appropriate procedure, and have an immediate control near the target. Changing the energy resolution is straighforward. But energy distribution and not only the mean energy width has to be known.

- Duty-cycle and time structure

The macro-duty-cycle can be varied easily, when the time "on" needed ranges from 1 ms to 100 ms, because it's usually simple to control the ion source in such a time scale. In the 1 to 500 µs range, an electric deflection in the low energy part of the accelerator is possible. The extraction of a single turn or several turns does not affect the quality of the

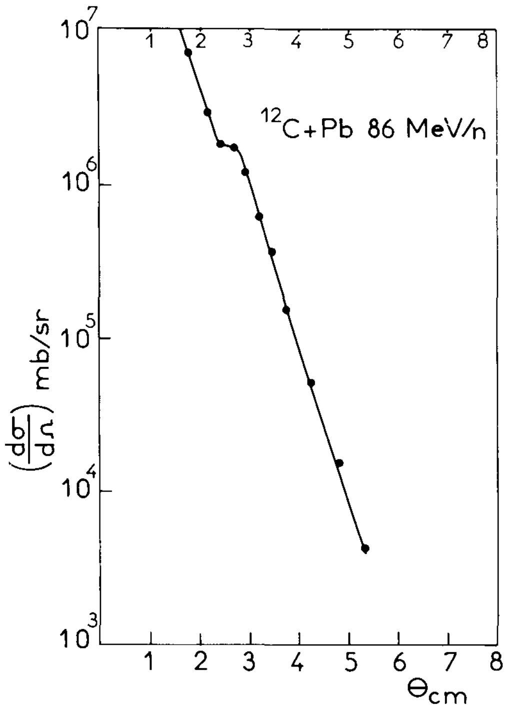

Figure 1 : Angular distribution of elastic scattering cross - section.

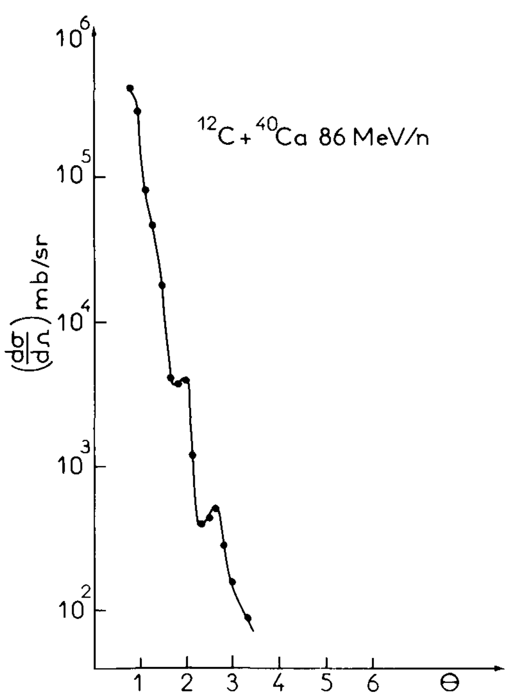

Figure 2 : Angular distribution of elastic scattering cross - section. Note the small shoulders on the curve which are converted to oscillations in the representation of figure 3.

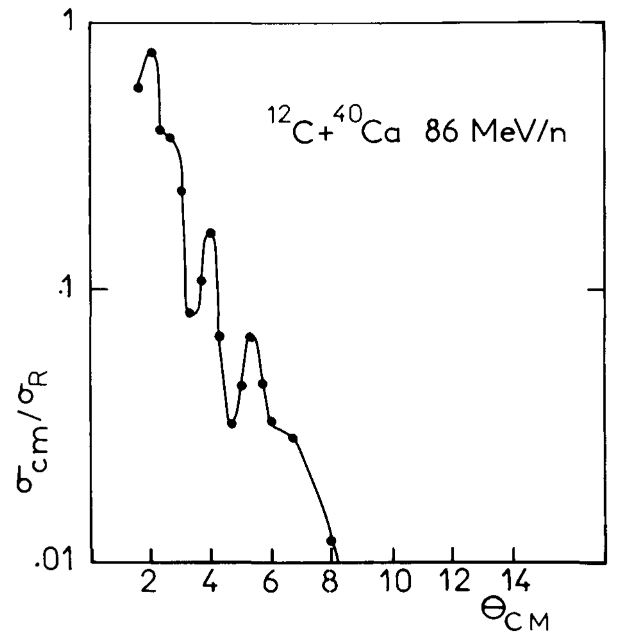

Figure 3 : σ/σ_R is the ratio between the elastic cross-section as measured and the cross - section predicted by a pure coulomb interaction between the ions. The position of these oscillations is very important for determining interaction potential.

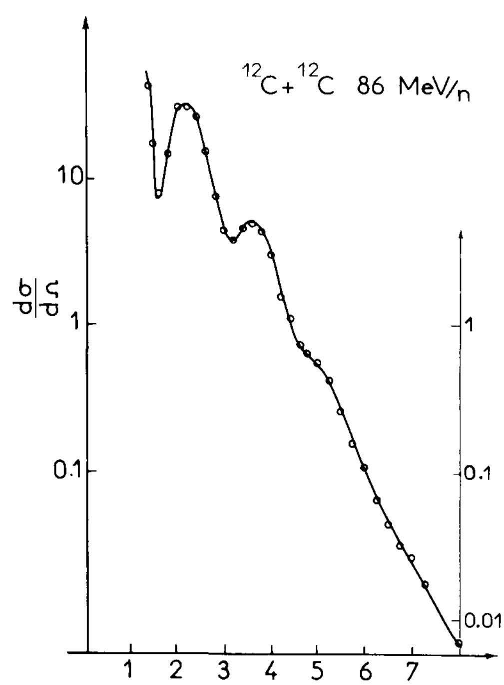

Figure 4 : Angular distribution of elastic scattering cross - section.

intensity distribution. But in the case of selecting 1 burst out of 3, 4 or 5 one needs an electric deflection placed on the beam fully accelerated unless single turn extraction can be achieved with such a high quality that the relative contribution of parasitic burst is kept less than typically 10^{-3}.

For time of flight measurements very short bursts (0.2 ns wide) are really useful. This can probably be obtained by phase selection, but then intensities will be reduced. For coincidence experiments the maximum duty-cycle is suitable. The use of flat-topping device can provide a large improvement with a maximum value of around 10 %.

- Energy

When starting an experiment, the calibration of detectors can be very important. If the detector response is linear, one point is theoretically sufficient. In fact the calibration has usually to be very precise in a narrow range for most of cases. This calibration could be very easily obtained if the beam energy could be varied by quantities of the order of 2 to 5 % and precisely measured. This can be achieved either by degrading the energy of the beam by a foil or by changing the cyclotrons setting. The second way which does not degrade the beam qualities, has to be experimental in a systematic way. This goal does not seem too far away. I am convinced that if the variation of cyclotrons parameters is smooth as it should be and if the qualities of the beam can be checked precisely on the target, this setting change can be made safely within 30 to 60 mm.

V - A TYPICAL EXPERIMENT

In figures 1, 2, 3, 4, 5, 6, some of the experimental data taken at CERN, with the 86 MeV/n ^{12}C beam are displayed. The aim of this experiment was to measure elastic and inelastic scattering cross-sections and the projectile fragmentation processes. Experimental data can suggest several remarks.

a) The cross-section can vary by 4 orders of magnitude within 3 degrees (figure 3), 2 orders of magnitude within 1°. A variation of 1/10 of a degree induces a relative variation of 1.6. In order to get the true mean angle of the measurements, the intensity distribution within the beam angular

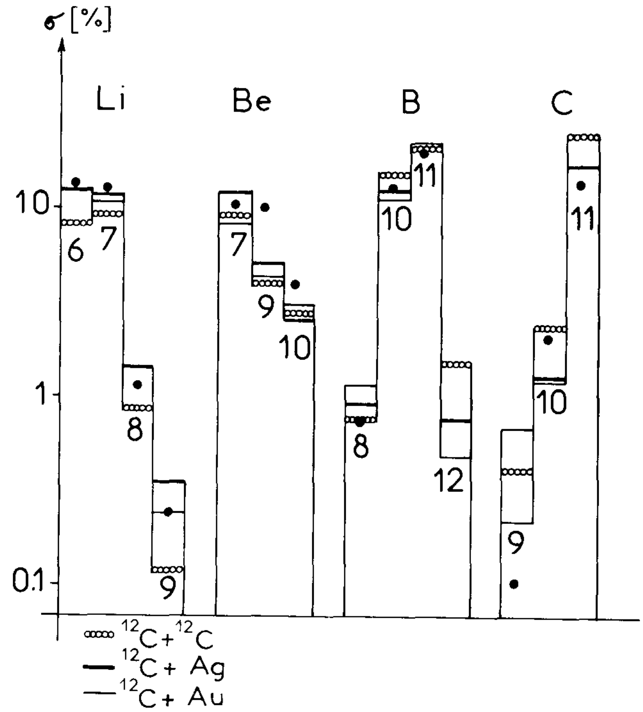

Figure 5 : Relative production of different elements and isotopes for ^{12}C, Ag, Au, targets.

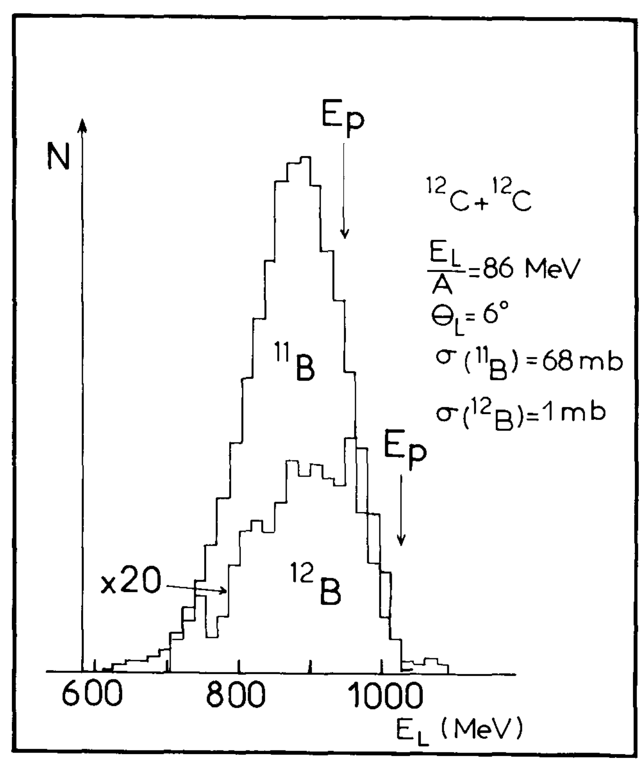

Figure 6 : Energy spectra for ^{11}B and ^{12}B isotopes. The arrows noted Ep correspond to energies of ^{11}B and ^{12}B having the beam velocities.

aperture has to be known. This remark is connected with large beam intensity variations, emittance requirements (profile and stability).

b) At very forward angle (i.e. 1.7°), the elastic scattering cross-section is very large (10^4 barns per steradian) while the total reaction cross-section is only of the order of 1 barn. This large ratio is convenient in order to analyse the beam composition with a large dynamics. A contaminant with a relative abundance of 10^{-4} or 10^{-5} can probably be measured in good conditions.

c) In figure 5 it can be shown that the production of different isotopes can be quite different. The relative cross-sections are different here by factors of 100, but could be different by larger factors and this justifies the beam purity requirements. For example the ^{12}B cross-section would be completely wrong if only 1 % of ^{14}N beam would have polluted the ^{12}C beam.

In figure 6 energy spectra for ^{11}B and ^{12}B are displayed and are compared with the energy corresponding to ions having the projectile velocities. The differences are small and a good energy calibration is needed. An energy variation of the beam would have given a good test of the linear response of detectors on the whole range of observed energies and for different species of emitted ions.

V - CONCLUSION

In this paper I tried to give some reasonable requirements for cyclotron operation and beam controls, the main requirement being a very precise control and knowledge of beam characteristics in the target region (spatial distribution, emittance, time structure, absolute energy and energy width). Another important requirement is the possibility to change the beam energy or the emittance profile using a fast procedure. All these improvements seem to be feasible with the existing technics taking advantage in particular of the computer control of accelerators, beam transport, and beam diagnostics.

The other line of improvement is certainly to develop external ion sources which give a low emittance beam. In correlation one has to inject inside a very small phase width, or to use a flat -

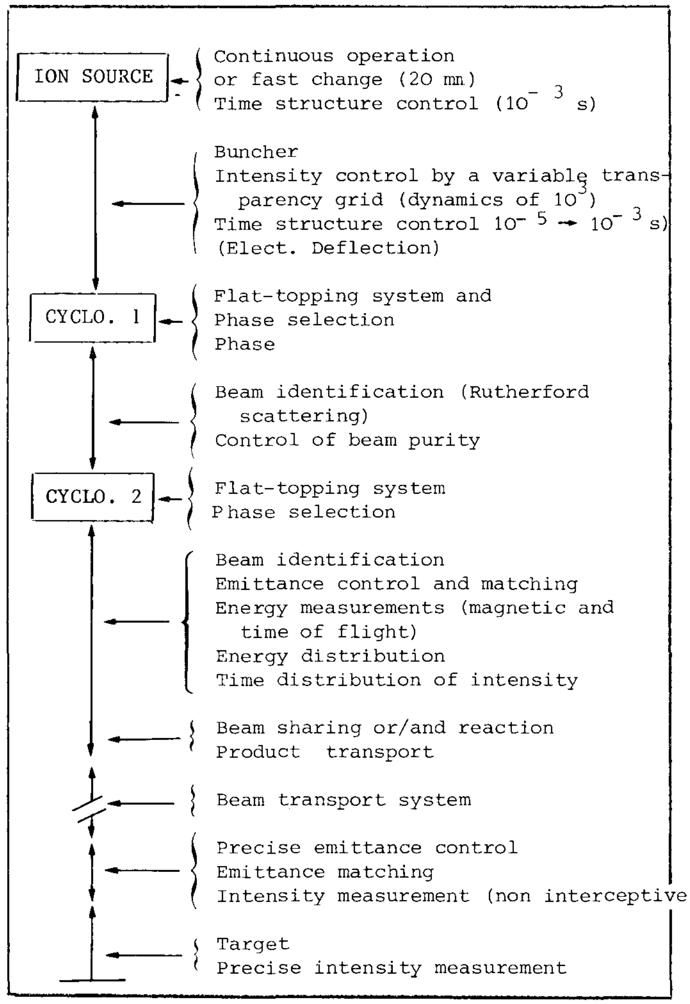

Figure 7 : In this scheme are summarized the devices and requirements which would be necessary for a 2 cyclotron system.

topping system in order to get a constant acceleration per turn for all particles. Then the turns keep separated and the precise control fo the machine is much easier.

With these new developments, cyclotrons can probably become so precise and so versatile that they will be comparable to electrostatic machines except for the important point of duty-cycle.

Obviously the importance of this factor depends strongly on the experiment type. But it seems to me that even using flat-topping system the micro duty-cycle is limited at 10 %. Would it be possible to build storage rings which eventally could be used not only to smooth the time structure, and have duty cycle of 50 % but also to eventually reduce the emittance by special cooling procedure analog to the ones used to cool anti-proton beams ?

" DISCUSSION "

M. LANGEVIN : What part of your requirements for physicists the perfect cyclotron seems to be hopeful and what part seem to be hopeless in the near future.

J.M. LOISEAUX : I think that concerning the beam control requirements, they can be fulfilled quite easily. For versatility and operational conditions, the requirements are probably more difficult.