RESULTS OBTAINED FROM ALICE AND FUTURE PROSPECTS

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ABSTRACT

An accelerator for $75(Q/A)^2$ MeV/amu heavy ion beams with ability to produce by stripping a rather large Q/A ratio - at least 0.285 in the 40 - 80 mass range - is now in operation in Orsay. As previously described, ALICE consists of a Linac ($Q/A \geqslant 0.08$) acting as an injector at 1.15 MeV/amu and a sector-focused isochronous cyclotron.

505 MeV Kr^{24+}, 475 MeV Kr^{23+} (10^{-10} - $2 \cdot 10^{-10}$ A particle current) and 227 MeV Ar^{11+}, 300 MeV Ar^{13+} ($4 \cdot 10^{-9}$ - $8 \cdot 10^{-9}$ A particle current) are the most used beams since 1971, with an operation time of about 70%.

Different improvements of the conceptual design have been needed to obtain these results, the principal one being on the platform where the PIG ion source has been put in an analysing magnet (5 kG) with an improved vacuum (10^{-6} Torr). The efficiency of the main components is discussed, and some future improvements are proposed. With a view to satisfying an increasing demand, a new beam transport system has been designed (9 lines) and its installation is planned for December, 1972.

At least some ideas about the prospects of the machine, in view of increasing its ability to accelerate heavier ions, are briefly exposed.

INTRODUCTION

In order to satisfy the demand of heavy ion physics research, the Orsay Institute of Nuclear Physics decided seven years ago to build the ALICE machine. It was felt necessary to extend the performance of the $75(Q/A^2$ MeV/amu cyclotron to ions heavier than C^{4+}, O^{5+} and N^{5+}.

The classical ion source limitations to charge states near 10 and absence at this time of other capabilities (such as the laser sources or Doñetz source that are studied today but with which it is too early to design an accelerator) led to producing the high charge states by stripping a 1.15 MeV/amu beam given by a Linac used as an injector.

Compared to more important machines which very soon are going to accelerate up to 10 MeV/amu uranium ions (Super-Hilac, Darmstad, U_{400} Dubna), ALICE appears a more modest machine, allowing acceleration of rather heavy masses (Krypton-84) with a charge/mass ratio equal to 0.28 for the heaviest mass.

STATUS REPORT

Test Schedule

ALICE[1,2] was under assembly at the time of the Cyclotron Conference of 1969. The injection Linac was only tested with N^{2+} produced by a duoplasmatron ion source on the 150 kV platform. The PIG ion source and beam transport were being assembled.

The first tests of the beam transport started in January 1970, and a first argon beam was stripped, accelerated on the 13 charge state and extracted from the cyclotron in March (Fig.1). The intensities did not exceed 10 nA for Ar^{13+} and 0.2 nA for Kr^{21+}. We will see (second section) how the different efficiencies were distributed; without being exactly equal to the computed values, none of them showed important differences, and it was obvious that to improve the performance it was necessary to improve the current provided by the ion source.

The results obtained by Passyuk[3] at Dubna on this type of source and those obtained with the adjustment of this source on our cyclotron resulted in a considerable increase of intensity, provided that care was taken of some very critical points: a magnetic field larger than 4.5 kG, a pressure in the range of 10^{-6} Torr, an extraction slit instead of a circular hole, and a very early charge state analysis.

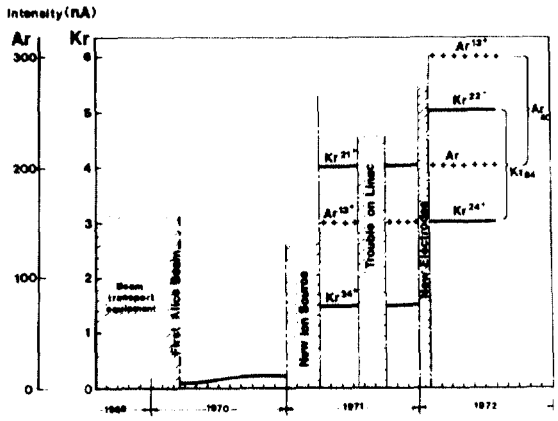


Fig.1

A new installation[4] taking into account these points was designed and tested in March 1971. Final intensities have been multiplied by a factor of 20 to 30 (which allowed the acceleration of Kr^{24+}). Nevertheless, this value is low if it is known that the injected beam in the Linac has been multiplied by a factor of 100. When we obtained these results, we thought that the ion source emittance could explain this discrepancy but some investigations showed that the Linac angular acceptance and perhaps a lack of alignment could account for this loss (cf. second section).

During the tests, two severe failures in the Linac cooling system happened, stopping the machine: this system, designed for a 250 kW total dissipation power, proved inadequate on one of the short-circuits. A quick repair limited the shutdown to one month. But last year, at the beginning of summer, a new accident on the same "leg" required the construction of a new one and stopped the machine again for three months. With this incident it was realized that the last 15 drift-tubes were also damaged because of bad thermal conductivity between them and the cooling pipe. The last 10 drift-tubes were removed and replaced by a new set cooled by a direct water circulation around them.

An increase of intensities was obtained after this operation (Fig.1). It was due on the one hand to the focusing grids which were made thinner to improve the transparancy, and on the other hand to the vacuum improvement at drift-tube level. It can be thought indeed that the over-heated drift-tubes were producing local damage on vacuum, which decreased the Linac efficiency by charge exchange phenomena.

The duty-cycle is limited to 30%, which assumes a 100 kW dissipation power in the Linac.

Results

Table I gives the standard values obtained during this year for several ions on the physicist's target (electrical current).

Table I. Values of beam intensity and energy

Ion	Charge	Intensity Linac exit μA	Energy MeV	Stripped charge	Stripping efficiency %	Energy cyclo. exit MeV	Intensity on Physicist's target 10^{-3} μA
C	2	50	12	Non actually used			
N	2	50	14				
O	2	50	16				
Ne	2	50	20				
Ar	4	40	40	11 12 13	22,2 33,7 25,2	227 270 300	100 - 150
Kr	8	3	84	21 22 23 24	23 17 7 3	396 430 475 505	3 - 5 3 - 5 3 - 5 3 - 2

It is shown that only Ar and Kr ions have been accelerated with ALICE. There are two reasons for this: first, the demand for research of super-heavy elements, second the actual cyclotron RF amplifier which does not allow obtaining all the cavity frequency range. A new amplifier[5] using a power tetrode (100 kW) and a Marconi amplifier (1 kW) will be installed in 1973. Then 290 MeV N^{7+}, 230 MeV O^{7+}, 220 MeV Ne^{8+} beams will be able to be accelerated with an expected 50-100 10^{-9} A (particle current).

Machine Operation

From the source platform modification (April 1971) to June 1972, the machine schedule is distributed as follows:

- 51% on cyclotron
- 47% on ALICE
- 1.6% on Linac

The ALICE time can be split into:

- 65% beam time
- 11% failures
- 24% maintenance and adjustment operations

The important improvement obtained on ALICE can be expressed by the following schedule time since January 1972:

- 33% on cyclotron
- 64% on ALICE
- 3% on Linac

with for ALICE:

- 14% maintenance
- 85% operation with: (9.8% failures
  (7.5% source changes
  (3.4% ion and energy changes
  (79.3% beam time

The time of source change is less than half an hour, adjustments included. The source life-time is 20-24 h for Ar, 8-12 h for Kr.

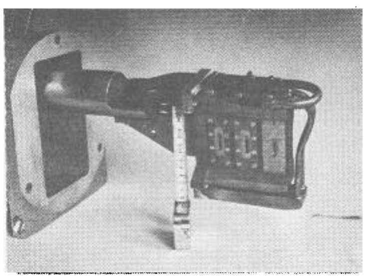


Fig.2 - Multibody ion source

A multibody ion source[4] (Fig.2) with three bodies has been tested during this year. It gives the same intensities as the normal ion source and avoids two changes. It is now in usual operation and some copies are in construction.

The stripping foils (20 μg/cm^2 carbon films) are laid on C-shaped tungsten frames with a 0.5 mm diam tungsten wire constituting the fourth side. A magazine (Fig.3), similar to that of a slide projector, contains 49 targets, and a few seconds are required to change from one to another. The foil must be changed every 24 h for Ar, for which it receives about 10 μA; with Kr where the intensity does not exceed 1 μA, no destroying has been noticed.

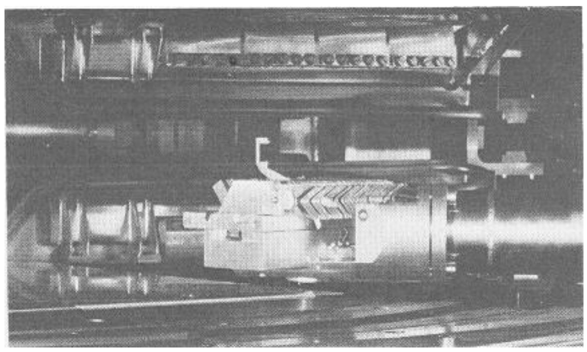


Fig. 3 - Stripping magazine

EFFICIENCY

The ALICE efficiency (ratio between the intensity extracted from the cyclotron and the intensity injected into the Linac) is actually near $3 \cdot 10^{-4}$. This is a low value compared to the 10^{-2} computed value (which has to be reduced by the isotopic abundance ratio). In the following sections, we try to explain this difference by giving first, the initial conditions on the Linac injected beam, and second, the efficiency of each part of the machine.

Ion source - Linac injected beam

The platform modification[4] consisted in placing the ion source in a 17 cm gap analysing magnet. The maximum magnetic field is 6.8 kG which will allow a higher extraction voltage in the future. With the actual 30 kV, the magnetic field is 5.1 kG.

A 20 x 0.8 mm molybdenum source slit and a "Berkeley type" extractor (two strips at 45° separated by 2 mm) are located 2.5 mm apart.

A $3.5 \cdot 10^{-6}$ Torr pressure with the source in operation is obtained with a 6000 ℓ/sec oil diffusion pump.

With a pulse rate of 200 c/sec (1.3 msec pulse length every

5 msec) the mean currents obtained at the exit of the platform are:

for Krypton:	60 μA	(standard value)	-	120 μA
for Argon:	400 μA	(" ")	-	1 mA

These results depend very strongly on the extractor position and its condition. The beam destroys rather quickly the extractor strips which have to be replaced every week.

Two electrostatic lenses lead the beam to the entrance of the Linac, and the last one gives a well-focused beam on the first gap. Emittances[4] have been measured just at the entrance of this last lens; they are function of arc current and for 2 A their values are 400 mm.mrad in the vertical plane and 700 mm.mrad (80% current) in the horizontal plane.

Fig. 4 shows the phase space figures on the first gap, computed from the figures obtained before the lens. Note also that this spot size has been checked by a measurement on a diaphragmed Faraday cup (ϕ = 14 mm for total current).

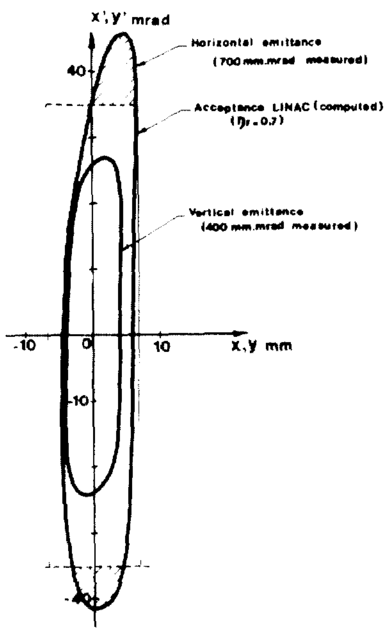


Fig. 4

The separation between the different charge states that we can sweep by changing the magnetic field makes the current values correct for the Linac efficiency computations.

Linac efficiency

It is given by the product:

$$\eta = \eta_r^2 \cdot \eta_\phi \cdot \eta_t \cdot K \cdot F$$

with:
- η_r : radial efficiency
- η_ϕ : phase
- η_t : grid transparency
- K : Buncher multiplying factor
- F : form factor of RF pulse

- Phase efficiency: $\eta_\phi = 0.21$
- Buncher factor:

K = 2.7 with the first harmonic
3.3 " the second "

These values are in good agreement with the measurements. It is difficult to check η_ϕ, but the good value for the buncher implies that a 75° phase interval is accepted by the Linac:

- grid transparency: $\eta_t = 0.685$
- form factor of RF pulse: 0.9
- radial efficiency: η_r depends a lot on the beam diameter

At the construction of the Linac, no program of the motion of particles in real electric field existed. So the grid separation was chosen, according to the results obtained with the "Berkeley grid", which explains the 1/3 value for the grid separation/drift-tube diameter ratio ($\gamma = c/d$). Later, a program[6] called MORAD allowed the computing of real paths and consequently the η_r efficiency, the external beam emittance and the energy spread.

Before the platform modification, the injected beam had an 89π mm.mrad emittance (10.8 mm beam diam). For this value and with the grid set $\gamma = 1/3$, the MORAD program (Fig.5) gives a η_r value equal to 0.45, which gives a total efficiency of 8.6% and an emittance value of 105π mm.mrad. These were in good agreement with the experimental results: $\eta = 10\%$ and $\varepsilon = 95\pi$ mm.mrad.

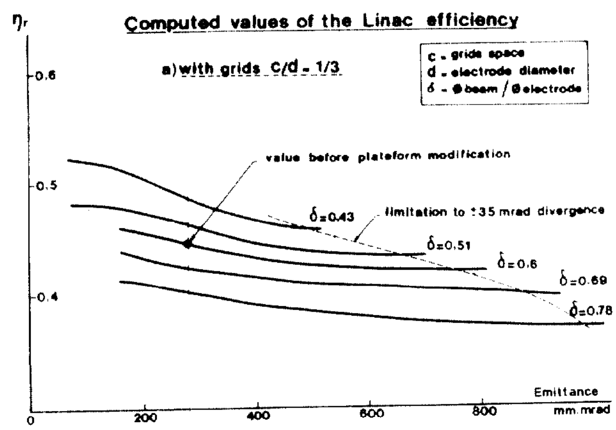


Fig. 5

The large value of the emittance and also the aim of increasing the efficiency led to computing with the MORAD program, a better grid-focusing system.[6] It was shown that the emittance could decrease if the grid separation were reduced (the drift-tube diameter is increasing and the choice of $\gamma = 1/3$ requires the grid separation to increase too; this induces an emittance increase for trajectories wound around the grids) and that radial efficiency η_r was also better (Fig.6). This figure plots the η_r values versus the injected beam emittance (with a limitation on the divergence to ±35 mrad) for a constant grid separation (c = 5 mm).

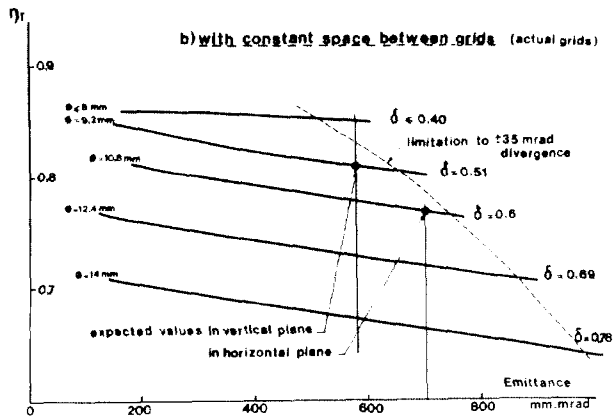


Fig. 6

From this work, a new set of grids was designed and the optics of the new platform took into account these computations, by the use of a last lens very near the Linac to focus the beam.

The experimental results have been improved for the emittance, but unfortunately not for the efficiency:

ε_H = 48π mm.mrad (80% current)) computed value
ε_V = 65π mm.mrad (" ")) 40π mm.mrad

η = 4.8% for Ar and 3.6% for Kr

With the new cooled drift-tubes and an improved grid transparency (0.8), by using a thinner tungsten strip for the grids ($2.5\ 10^{-2}$ mm), we obtained a total efficiency value of:

η = 6.75% for Ar and 6.5% for Kr.

Fig.6 shows that with the beam emittance of the new ion source (above paragraph), the η_r value is equal to 0.7, which means a total efficiency of 25%. So there is a large gap between experimental and computed values.

A first reason can be a lack of alignment in the vertical plane. To have an aligned beam before the last lens, we have to put some voltage on the electrostatic deflecting plates. This lack can explain the difference between vertical and horizontal emittance.

The second one is a bad angular acceptance of the Linac: Fig.4 shows the beam emittance plots and the computed acceptance values. It can be seen that only 20% is lost in the horizontal plane and nothing in the vertical plane. This estimate is checked by a measurement on a Linac internal target (after the 10th drift-tube) that we can use without RF. Taking into account the diaphragm effect of these ten drift-tubes, the computed value for the intercepted beam would be 33% in the horizontal plane and 65% in the vertical plane, i.e. a 21% mean value measurement on the internal target gives 25 to 30%. So, the total efficiency should be 20% if all phase space was accepted.

Recent measurements give more information on this point. Electrostatic deflecting plates allow translating the beam before the last lens, which transforms this motion into an angular one. The phase space is translated along the $\dot{y}$ axis. The measurements showed that a 10 mrad horizontal translation does not affect the accelerated beam value, but a 10 mrad vertical one decreases the beam by a factor of 2. To understand this result, it must be supposed that the divergence acceptance is less than 35 mrad; so a very large divergence, as the horizontal one, has always a part of it which is accepted, while a smaller divergence, as the vertical one, is diaphragmed.

Lately, the grids of the three first drift-tubes (4 strips), have been replaced by better focusing grids (8 strips). No increase on the efficiency has been noticed but a translation of the same 10 mrad phase interval leads to a beam decrease of only 1.3, which would mean maybe a better acceptance.

Finally, it is not sure that the grid transparency has really the 0.8 value. For example, the first grids which had a 0.685 transparency theoretical value had in fact 0.48 due to their deformation by heating into the beam.

To conclude, it can be seen that these reasons can easily explain the efficiency reduction by a factor of 3. Our present investigations aim at a complete understanding of these and, of course, an attempt to improve again the emittance.

Beam transport efficiency up to stripping foil

It must be remembered that the beam is carried 27 m and focused on a stripping foil,[2] the size of which depends on the cyclotron acceptance (turn separation, dee aperture, electrostatic deflector height).

The Courant and Snyder invariant gives the whole $y,\dot{y}$ and $z,\dot{z}$ stripped particle positions in the vertical and horizontal phase space:

$$\frac{y^2 + (\alpha y + \beta\dot{y})^2}{\beta} = A.$$

If we take the example of 14 kG Kr^{23+}, the α and β coefficients corresponding to the equilibrium orbit (Program CYCLOPS) have the values:

$\alpha_H = -0.005 \qquad \alpha_V = 0.07$ (cyclotron units)

$\sqrt{\beta_H} = 1.10 \qquad \sqrt{\beta_V} = 2.77$

They determine the acceptance Figs.7a and 7b.

The design value of vertical oscillation (Fig.7a) was 15 mm in order to have 10 mm at the electrostatic deflector where the H.V. plate is only 20 mm height. The dee aperture (4.5 cm) allows a larger oscillation and consequently a larger emittance for the beam (163π mm.mrad). Actually, to take into account the beam emittance, the stripping foil height has been increased to 20 mm (acceptance 32π mm.mrad).

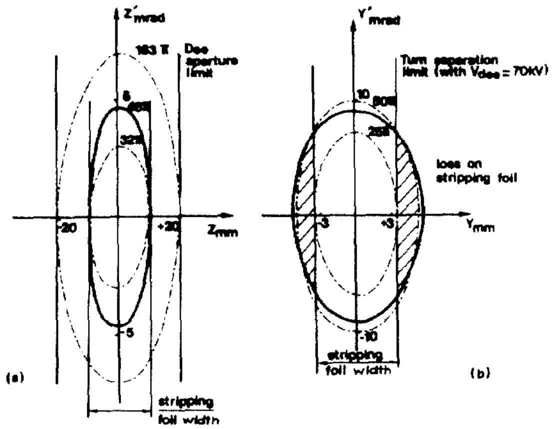


Fig. 7

In the radial plane (Fig.7b), one sees that the design value of the acceptance (25π mm.mrad) fixed by the turn-separation (7 mm) may be increased, with the condition, of course, to increase only the beam divergence on the stripping foil.

The beam transport system[2] designed for a 22π mm.mrad acceptance has a 100% efficiency but now, with the actual emittance (ε_V = 65π mm.mrad, ε_H = 48π mm.mrad), some losses appear.

The program OPTICS, computing the envelope of the trajectories and the magnetic field gradient values, gives for a 48π mm.mrad emittance the following values for beam dimensions on the stripping foil:

(y_{MAX} = 5 mm (z_{MAX} = 10 mm

($\dot{y}_{MAX}$ = 8.92 mrad ($\dot{z}_{MAX}$ = 4.77 mrad

With 30% loss in the beam transport, these phase figures assume a 17 mm vertical oscillation amplitude that is accepted by the dee, but not by the electrostatic deflector.

The computations are in rather good agreement with the measurements: actually, 30% of the Linac beam can be put on the stripping foil and the experimental values of the focusing elements are very near the computed values.

According to the computations, the efficiencies are distributed as follows:

- 70% for the horizontal plane in the beam transport
- 70% " " " " on the stripping foil
- 88.5 to 88% for the vertical plane on the stripping foil (with 65π mm.mrad)
- 80% since the emittances are taken for this percentage of the total current

giving 35% for the total.

Stripping foil to cyclotron external beam efficiency

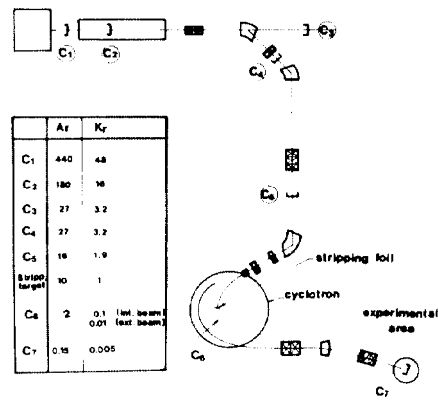
There is nearly no problem with this last efficiency. The computed value can be reduced to:

- η_r, stripping efficiency, that has been measured[7] for Ar and Kr (see Table I)
- η_{RF}, RF acceptance[2] estimated between 20% and 30%, according to the cyclotron frequency and dee voltage. The beam fine structure has been measured: 36° phase interval, with a visible modulation due to the difference between cyclotron and Linac frequencies.
- η_{ext}, extraction efficiency which is about 30% usually for the cyclotron.
- η_{iso}, isotopic efficiency (100% for Ar, 57.9% for Kr).

On the whole, $\approx 10^{-2}$ efficiency for the internal beam and $3 \cdot 10^{-3}$ for the external beam (for Kr^{21+}).

This computation is in agreement with the measurement since with 1 μA Kr^{8+} on the stripping foil, 100 nA Kr^{21+} are accelerated (electrical currents) to the electrostatic deflector. In this case, the external beam is only 10 nA which means that η_{ext} is less than usual. We explain this by the too large vertical amplitude taken by the beam because of the emittance (Fig.7a), as was explained above. It has been noticed that a worse focusing of the beam on the stripping foil degrades the internal beam, but not so much the external one.

To summarize all these losses, Fig.8 shows a typical current distribution. These results indicate that an improvement can be obtained only when the beam emittance will be reduced, and future developments must aim at this point.



	Ar	Kr
C_1	440	48
C_2	180	16
C_3	27	3.2
C_4	27	3.2
C_5	16	1.9
Stripp. target	10	1
C_6	2	0.1 (int. beam) 0.01 (ext. beam)
C_7	0.15	0.005

Fig.8

Importance of the pressure

The transparency of ALICE is considerably affected by charge exchanges if the pressure is not low enough. A decrease by a factor of at least 10 in one instance where one of the pumps failed was observed. Measurements were undertaken, but the errors might be quite large since one should in fact have several vacuum gauges to know the pressure gradient. Fig.9a shows the beam losses as a function of the pressure in the interval between the ion source platform and the Linac entrance (2.6 m) (measurement on the Linac beam).

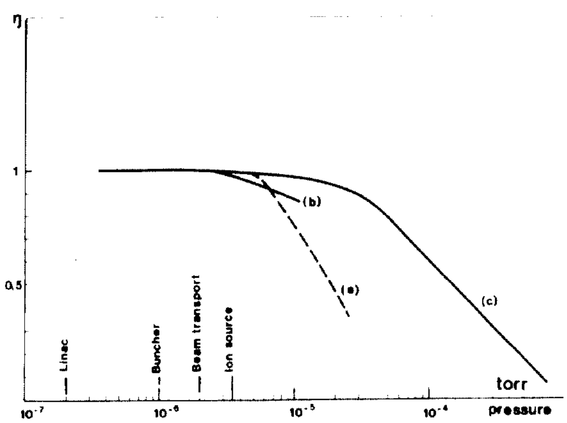


Fig.9

Fig.9b shows the losses when the pressure is varied in the Linac tank and Fig.9c refers to the first part of the beam transport system (6 m).

The standard pressure values when the Linac is in normal operation are shown on the curves.

MACHINE IMPROVEMENTS

The aims of the future improvements are to increase both the machine transparency and the beam intensity.

Reduction of the horizontal emittance after the platform

We actually use an unstabilized extractor power supply which causes a horizontal emittance increase as soon as the output current exceeds 100 mA (peak value). This leads to a limitation of the arc current (1.5 A average current) and of the source slit to 0.8 mm. By the month of December, we will have a 50 kV - 100 mA power supply stabilized to 1 part in 10^4.

We tried a pulsed extraction, which improved the intensity by a factor of two, but a lack of reliability of the power supply led us to abandon it at the moment.

Cyclotron frequency tuned buncher[8]

In order to avoid the loss of bunches arriving out of the accelerating phase interval in the cyclotron, we thought that at the ion source platform level, the ions could be packed in one single bunch at the RF cyclotron frequency. The actual Linac buncher which brings the ions inside the 21° Linac phase acceptance would be left, and a phase control system between buncher and cyclotron would be needed. This buncher would decrease the actual energy modulation of the beam which, when injected, has to pass through the dee and is thus slightly sweeping the stripping target. It would also produce a stable fine structure extracted beam, which is necessary for time-of-flight experiments. The increase in intensity will depend mainly on the buncher efficiency; it is clear that a bunching over 90° would not bring any improvement, but a bunching interval of 36°, which is a severe requirement, would deliver a single bunch.

Improvement of the cyclotron extraction efficiency

After the electrostatic deflector, the beam is focused by two magnetic channels, reducing the beam spot size at the exit window of the cyclotron. But we know that they stop a part of the beam and in addition that the consecutive bunches extracted by the deflector with an energy spread are too much analysed. In the near future (December 1972), they will be improved.

NEW EQUIPMENT

We actually have only 3 beam lines at the exit of the cyclotron, one of which is being abandoned due to the bad optical properties and lack of room, and a second one equipped with an analysing magnet. This situation had to be improved since most of the experimental equipment has to be removed after the experiment, leading to a loss of time.

Since radiation controls have shown that the actual shielding can be reduced, we designed a new layout for the beam lines using the actual experimental area plus a part of the Linac building.

There are 9 lines and a new switching magnet (Fig. 10).

Lack of room and a poor budget led to the use of a unique pair of quadrupoles for all the lines which can be displaced on rails from one line to another in about half an hour. Each line has its own pumping system, which consists of 350 and 650 ℓ/sec SNECMA turbomolecular pumps.

The whole set is actually manufactured and will be assembled in December, 1972. The shutdown period is planned not to exceed 3 months.

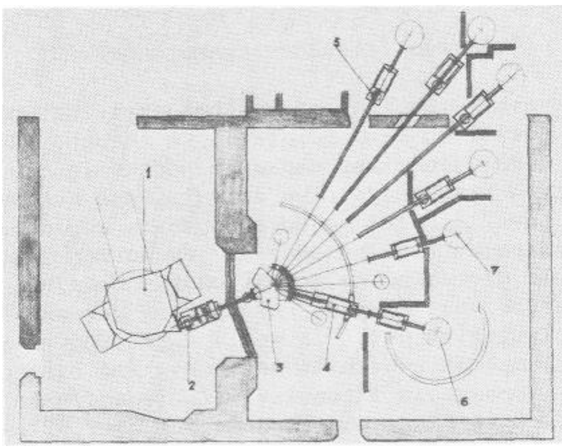


Fig.10

1. Cyclotron
2. Steering magnet
3. Switching magnet
4. Rotating pair of quadrupoles
5. Pump
6. Analysing magnet
7. Chamber of reaction

NEW IONS

Apart from ions like C, O, N, Ne, which have not yet been accelerated by ALICE and for which the demand is constantly increasing, the production of metallic ions (Ca, Ge, Se, etc is also required, which means the use of a different source. A source with furnace (Fig.11) was recently tested on the platform; the stainless steel body which is not cooled, reaches temperatures around 1000°C. In the near future, Ca and Se ions will be accelerated. Simultaneously, a similar source with furnace is being tested on a magnet, allowing charge state analysis.

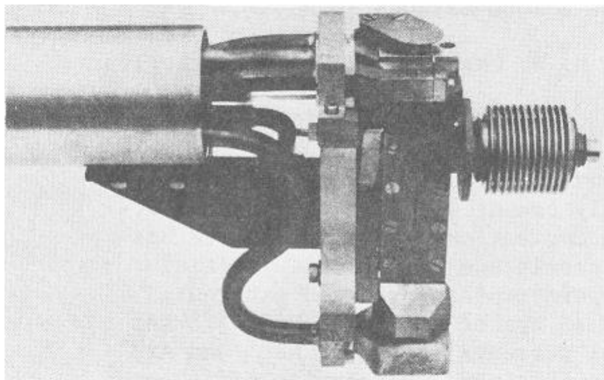


Fig.11

FUTURE PROJECT

For the future developments of heavy ions physics, it is possible to envisage the building of a 10 MeV/nucleon separated sector machine; however, a low-cost modification[9] of ALICE can bring it to a nearly comparable energy for all ions up to uranium.

It would mainly consist in lowering the Linac charge-to-mass ratio to 0.045 and increasing the cyclotron pole tip diameter to 3 m with a 20 kG average magnetic field. Such a machine would then have a maximum energy of 350 Q^2/A MeV. The interest would be to keep the building and its equipment and a number of parts such as RF transmitter and tank for the Linac, beam transport system, cyclotron RF transmitter, vacuum pumps, beam lines, etc.

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