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NEW HEAVY ION ACCELERATORS

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ABSTRACT : Several new or upgraded versions of heavy ion accelerators have recently come into service. A review is made of these machines and tentative conclusions are drawn on the merits of the various types.

INTRODUCTION : The first big heavy ion accelerator has certainly been the HILAC in Berkeley but several other smaller machines were also built in various places a long time ago : ALICE in Orsay for instance already constituted a quite elaborate complex. It was however mainly during the last decade that a large and wide impetus was given to these machines.

Acceleration of heavy ions does not differ in principle from other lighter particles, protons in particular. Charge to mass ratio Q/A however is always smaller than one, which makes acceleration more difficult but also affects the bending radius in a field. Q/A can be chosen from the source but may change during acceleration, by stripping ; this gives to accelerator designers or users an extra flexibility to optimize the operation of a machine. Stripping usually gives a range of charge states among which one selects only a preferred one, thus loosing intensity. This loss is however reduced for the average charge state for which the percentage is the largest. This average charge state Q depends on the energy at which stripping is done and on the nature (foil or gas) of the stripper.

The formula :

$$Q = Z\,(1 - C.\exp\,(-3{,}86\,\sqrt{W}/Z^{0.447}))$$

with $C = 0.9 + 0.0769\,W$ for $W < 1.3$ MeV/A

and $C = 1$ for $W > 1.3$ MeV/A

where Z is the number of charges of the nucleus of energy W, applied to a foil stripper (carbon with equilibrium thickness) for $0{,}4\ \text{MeV/A} < W < 8$ MeV/A was for instance derived by E. BARON* for the case of GANIL.

One finds now heavy ion accelerators of electrostatic type, linear type and circular type.

ELECTROSTATIC ACCELERATORS. TANDEMS

Only a few machines, amongst the biggest, operating around 18 MV will be considered : JAERI (Japanese Atomic Energy Research Institute), NSF (Nuclear Structure Facility) of SERC in Daresbury (UK) and Strasbourg (France). With foil or gas strippers in the terminal, the maximum energy these tandems can deliver is shown on Fig. 1. Table 1 gives a list of typical beams.

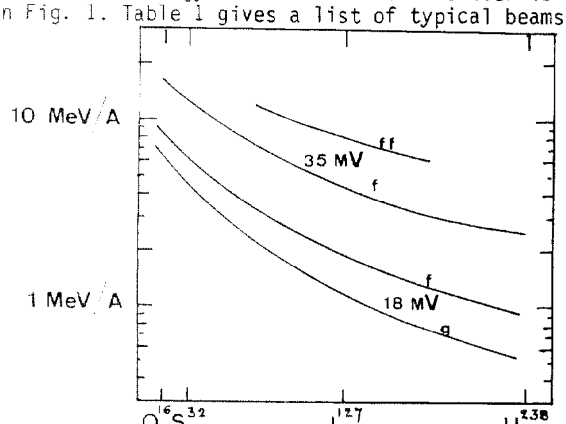

Fig. 1 - Energy of beams obtained from tandems of 18 MV (foil or gas stripper) and predicted for 35 MV (single or double foil).

* E. BARON, private communication. Internal GANIL report n° 79R/146/TF/14.

Table 1

Short list of beams at JAERI and NSF

Ion	Terminal Voltage	Charge State	Analysed current (enA)
B	16.5	4	300
Al	16.5	7	125
Cl	18	9	4800
Fe	16.5	10	180
I	18	7	3800
C	17.6	5	60
O	15	7	400
Ti	18.3	11	37
Ca	18	11	36

Emittances are usually much better than 1πmm mrad. Table II gives an example of short pulses production. Energy spread is normally negligible and the quality limitation only comes from stripping and voltage stabilization, i.e. performance of the electronics ; it can be extremely good. As a whole if limited in energy, electrostatic machines can be considered as giving beams of the best possible quality.

Table II

Iodine pulsed beams at JAERI

Terminal voltage	Peak current	FWHM
13 MV	10 pμA	2.5 nsec
18 MV	12 pμa	1.9 nsec

A few comments may be added on each machine.

The JAERI vertical folded tandem[1] has been designed by NEC to reach 20 MV ; 18.5 MV obtained in October 82 is now a normal running level. On this machine is used a method of glow discharge conditioning developed by Pr. ISOYA[2] which seems there quite satisfactory (installed in Japan, this tandem is equipped with antiseismic dampers).

The NSF vertical tandem[3] was completely designed in Daresbury. Its final rating should be up to 30 MV. Some accident during early conditioning introduced a very long delay in the operation, dust having been deposited along the tube. Nowadays, that as well as a temperature problem seem to be overcome ; 18 MV have been reached late 1982 with the hope to go above 20 MV soon.

The Strasbourg machine was a horizontal HVEC tandem of 13 MV, modified and upgraded in the laboratory by Dr. M. LETOURNEL. The improvement results from the application of two major guide lines. The first was to reduce the gradient on the tube by limiting the length of dead section and redesigning the potential distribution in order to protect completely the tube against discharges which must find another more direct flow path. The second line was the use of discrete electrodes between the column and the vessel : with them the 1/r potential distribution can be made more linear but a careful choice of the shape of these electrodes also gives a more stable configuration of the stored energy which is also slightly reduced.

The same methods are applied in a new project, called VIVITRON[4], horizontal tandem designed for 35 MV. The expected energies for such a machine were given on Fig. 1 : due to the increased energy of stripping, the final energy goes up quite rapidly for heavy ions (somewhat like $V^{3/2}$). One might also consider using several stripping processes but the intensity is then reduced and the beam quality can be slightly degraded.

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LINEAR ACCELERATORS

A first big heavy ion linear accelerator has been the hilac then converted into SUPER HILAC in Berkeley. It is now exclusively used in conjunction with the BEVATRON and will be mentioned with it.

During the past decade a very big machine, the UNILAC was developed in Germany under the initial guidance of Prof. Ch. SCHMELZER. Fixed frequency linacs are by nature machines with fixed velocity, i.e. fixed energy per nucleon. Such a property, perfectly satisfactory for an injector cannot satisfy the needs for experimental physics. The use of several accelerating cavities (Wideroë and Alvarez types) allows by stopping some of them to obtain several steps in energy. Operation of tanks at reduced level may also give some intermediate energy. In order to fill the gaps in between, individual single gap cavities adjustable in amplitude and phase are, in the UNILAC, added to the tanks. Under these circumstances, the energy produced by the UNILAC in its original version was about 10 MeV/A for heaviest ions, going up slightly for lighter ions.

Progressively, during 1982, an upgraded version of UNILAC[5] has been put into operation, raising that energy to 19 MeV/A for uranium and more than 20 for lighter ions ($A < 150$) : two Alvarez cavities have been added, giving at their output an energy of 11.4 MeV/A ; with the use of a second stripper (thick foil of 300 $\mu g/cm^2$) very high charge states can be reached and the efficiency of the single gap cavity resonators section becomes very high. Thanks to an improvement of the source (anode slit height increased from 15 to 45 mm) and low energy beam transport system, intensities have been considerably improved by a factor of almost ten. Table III gives a set of beams available at the UNILAC. Typical transverse emittance for most beams is 5πmm mrad and $\Delta W.\Delta t$: 1.5. 10^{-5} sec eV/A. The minimum bunch width achievable with the rebuncher system is 150 psec.

Table III

A few out of 42 beams produced at UNILAC

Ion	Charge state	Average intensity (pnA)
N	5	2000
Ar	10/18	1600
Ti	12	200
Fe	14	450
Ge	15	20
Kr	17/34	120
Mo	18	25
Xe	21	120
Sm	32	10
Pb	36	20
U	40/68	50

In order to improve the operation a new computer controlled system has been developed. Focusing in the Wideroë section according to automatic emittance measurements from the source will be done automatically. Similar program will be made for the post stripping section and experimental area. A fast switching system will be prepared for the proposed heavy ion synchrotron facility SIS.

Another interesting heavy ion linac recently commissioned is the RILAC (RIKEN linac) in Japan, near Tokyo at the Institute of Physical and Chemical Research (RIKEN). This linac is a variable frequency linac [6] operated in the range 16 to 54 MHz (0,5 to 4 MeV/A). This completely new technological development, maybe expensive, seems to be very successful. This linac was designed to serve as an injector into a big separated sector cyclotron as will be mentioned later.

BEVALAC[7]

The use of the old bevatron to accelerate up to relativistic energies the beams produced by the SUPER HILAC started more than ten years ago. This type of operation has now become routine, sharing time between nuclear physics (2/3) and radiotherapy (1/3). A major improvement programme has recently been performed to extend the ranges of ions accelerated up to the heaviest. The vacuum had first to be improved from 10^{-5} to 10^{-8} pascal (10^{-7} to 10^{-10} Torr) to permit the survival of heavy ions over long periods ; fortunately, owing to the large size of the vacuum chamber, cryogenic pumping could be extensively used. A second spectacular development has been a rapid switching (particles and energy) to make use of the patient set up times (30 minutes for 2 minutes treatment) for an almost continuous nuclear physics running : beam line can be changed in 30 sec and energy in 1 min. A new RFQ linac on the local bevatron injector for Ne, Si and Ar beams used for therapy will still alleviate the load on the Super Hilac and improve even more the flexibility.

Table IV gives a list of some of the beams which can be produced. For very weak beams, adjustments are made with the help of a tracer having Q/A very close in value; with only slight corrections, the desired particles can then be obtained.

SYNCHROCYCLOTRON[8]

The advent of isochronous cyclotrons which extended to much higher energies the range of these machines has significantly reduced the development of synchrocyclotrons. It would not be fair, however, not to mention the CERN S.C., built in 1957 which, after having for many years been limited to the acceleration of protons was in 1974 extended to heavier particles. After only Q/A = 1/2 it can accelerate now particles down to Q/A = 0.3. Even restricted to relatively light particles, and despite its macrocycle which reduces the average intensity, CERN S.C. appears as a very powerful tool for light or medium ions in the intermediate energy range.

Table IV

Short list of beams at the BEVALAC

Ion	Charge state	Extr. intensity (ppp)	Energy
N	10	1×10^{10}	2.1 GeV/A
Ar	18	1×10^{9}	1.9 GeV/A
Fe	24	1×10^{8}	1.7 GeV/A
La	47	2×10^{6}	1.3 GeV/A
Au	61	2×10^{4}	1.1 GeV/A
U	68	2×10^{4}	1.0 GeV/A

CYCLOTRONS *

The most common big accelerators for heavy ions are nowadays cyclotrons. Several machines of this class have been built or are in the course of being built. Various versions exist : big cyclotrons are usually part of a complex which can comprise :

- electrostatic machine + cyclotron + ...
  cyclotron + cyclotron + ...
  linac + cyclotron.

In the first category are VICKSI in Berlin, ORIC I in Oak Ridge and IUCF at Bloomington, Indiana.

The maximum energy a cyclotron can give is usually expressed with the use of the K factor as $W_{max} = K\,Q^2/A$. K is an expression of the bending limit of the magnetic field. The energy limit depends on Q.

In the case of a Separated Sector Cyclotron, injection and extraction are at fixed radii so that the machine acts as an energy multiplier. In order to fully use

* Data sheets from cyclotrons and synchrocyclotrons can be found in the Proceedings of the International Conferences on Cyclotrons. In particular for the IXth Conference (Caen) : Editions de Physique, Paris, Ed. 1981.

the capability of such a machine, injection has to be made at an energy where the charge state produced by stripping just fits the bending limit. Stripping usually gives several charge states, of course, and what is necessary is just that the requested one exists at an acceptable level. The different properties of gas and foil can help to satisfy this requirement. Nevertheless the choice of the optimum injector for an SSC is a difficult problem and various philosophies exist.

VICKSI is in routine operation in Berlin since 1979 with a 6 MV Van de Graaff injector then available at the Hahn Meitner Institute[9]. Table V shows a list of heavy ions accelerated so far. One cannot miss to note that energies are always a multiple of 100 MeV. A closer look would show that they do not correspond to the bending limit (K = 128). In fact with a 6 MV VdG and an energy multiplication of 17 in the SSC the final energy which can be obtained is limited by injection voltage to 6 x 17 Qs ≃ 100 Qs where Qs is the charge state at the source.

Table V

Short list of beams at VICKSI

Ion	Energy (MeV)	Intensity (pnA)
B	45-100	50
C,N	45-300	500 - 0.2
O	45-200	500 - 50
Ne	45-400	500 - 0.2
Ar	55-500	150 - 0.1
Kr	120-500	100 - 0.1

From the start, a better injector had been foreseen but the choice was not made. A proposal of building a smaller superconducting cyclotron was given up for lack of man power and long construction time. Decision was then officially taken and approved in 1981 to buy a 8 MV tandem which will be installed in the second half of 1983. With this new injector, run at full voltage for mass range around 55 and down to 6.5 or 7.5 MV for higher or lower masses the energy mass curve which will be accessible is shown on Fig. 2, corresponding to the bending limit.

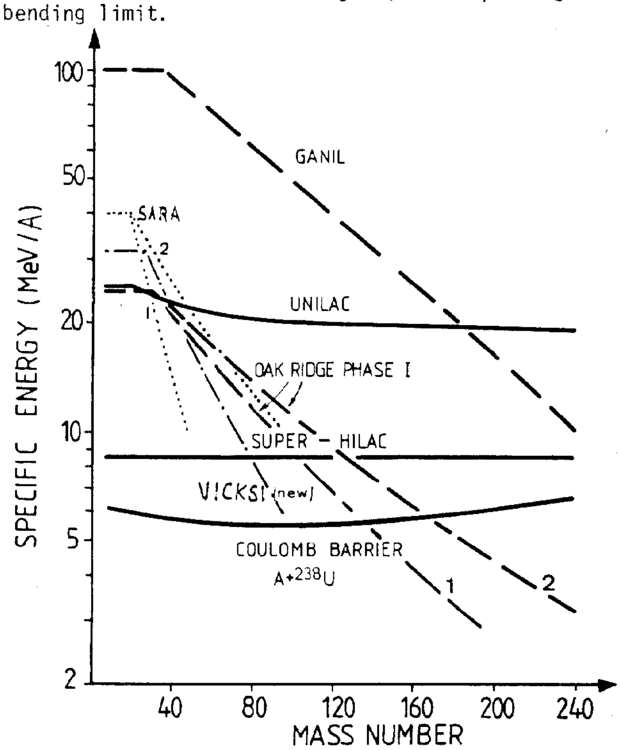

Fig. 2 - Energy obtained from various machines 1 and 2 curves for ORIC I correspond to 18 MV and 25 MV tandem voltage. 1 and 2 for SARA correspond to normal or ECR sources.

Already now, however, VICKSI has proved to be a very good machine with an elaborate computer control system. Change of ion species or large change in energy normally requires ten hours, which seems very long compared to the extraordinary performance of the Bevalac but is still very good and acceptable for physics experiments.

The Holifield Facility, Tandem + ORIC Phase I shows a different solution for the choice of an injector[10]. AVF cyclotron ORIC of K = 100 was among the first to be built. In operation since 1962-1963, it was originally run with an internal source. In 1974 a decision was made to implement it with a new big tandem injector. Here, the solution chosen was to make injection by stripping inside the cyclotron (the access is not easy in an AVF as it is in an SSC). The stripping method allows also the optimization of injection radius and of energy gain according to ion and energy.

Fig. 2 shows, besides VICKSI, the ORIC curves corresponding to 18 and 25 MV tandem operation.

Despite the additional complication of stripper foil accurate positionning for injection, ORIC is now running very smoothly and the set-ups are found much easier than expected. Reproducibility is excellent.

Table VI gives a list of beams accelerated. Though no detailed measurement of emittances have been made, it appears that the transverse emittances are much smaller than with the internal source in ORIC and the energy spread is probably appreciably smaller than 10^{-3}.

Table VI

Short list of beams at ORIC

Ion	Charge state	Energy (MeV)	Intensity (nA)
Be	4	158	30
O	8	402	480
Ni	23	889	20
Cd	25	494	12
Sn	28	613	71

The Indiana University Cyclotron Facility (IUCF) consists of two SSC's in cascade with prior injection from a smaller electrostatic accelerator[11]. Though this complex could accelerate heavier ions, its use has been mostly restricted to protons and deuterons (polarized) and only 10 % of research time is devoted to beams heavier than A = 4 (mainly lithium). The use of an ECR source would, in fact, give quite interesting heavy ion beams, but no definite plan is made in that sense so far.

Cascade cyclotrons from cyclotron injectors are used in SARA and GANIL.

SARA is a simple and economical four sector SSC of K = 160 added to a conventional AVF cyclotron of K = 88 as injector[12]. Table VII gives a list of beams presently available.

Table VII

Beams at SARA

Ion	Charge states	Energy (MeV)	Intensity (enA)
C	3/6	360	400
N	4/7	420	20
O	4/8	480	100
Ne	5/10	600	20
A	7/15	600	2

Beam emittance is smaller than 8πmm mrad, energy spread between 1.5 and 5 10^{-3} with a bunch length ranging from 1.2 to 3 nsec according to adjustments.

SARA started in April 1982 and now eighteen days per month are devoted to physics experiments. An extension of the capability towards heavier ions is foreseen soon from the use of an ECR source. Previous fig. 2 shows the expected performance. Intensities could for instance be 80 enA for 30 MeV/A argon and 20 enA for 11 MeV/A krypton.

GANIL[13] is a complex made of three cyclotrons in cascade : one small injector, flat field cyclotron with an internal source (external ECR source with axial injection will later be an alternate solution) and two identical four sectors SSC's of K = 400 with stripping in between. Optimum stripping is by a factor of 3.5 to use the full bending capability of both SSC's.

Energy curves for GANIL are shown on Fig. 3 for various charge states at injection. The solid limit shows the condition for having an acceptable stripping efficiency (more than 1 % in particle current).

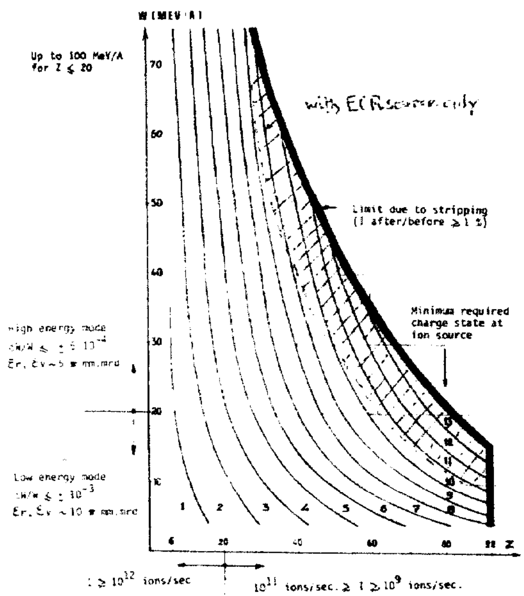

Fig. 3 - GANIL energies versus source charge state. The solid line limit corresponds to a stripping efficiency of 1 %.

One non conventional topic of GANIL is the use of bunch length compression. The phenomenon was originally discovered by MULLER and MAHRT[14] and extensively described by JOHO[15]. There, only the voltage gradient versus radius of the accelerating field in the gap was considered and it was found that the product of the voltage by the bunch length in phase remained an invariant. A closer look at the hamiltonian describing the effect (the fundamental acceleration equation) shows that it is not really the voltage which matters but, to some degree of approximation, the acceleration per gap itself. Instead of changing the voltage, one can then also change the phase : only a slight field correction does the job.

Fig. 4 shows the bunch length in SSC1 of GANIL at injection and after 9 of the 70 accelerating turns. Compression is done by a factor of about 2, pulse length going from 10 to 12° down to 4 or 5°. The result is a reduction in energy spread ; no very accurate and detailed measurement of it has been terminated yet but compression is clearly seen. This beautiful result has however to be paid : turn to turn separation is reduced at injection and in addition beam energy, if no special care is taken, becomes very sensitive to magnetic field but good stabilization of that field is anyway necessary (10^{-5}) to keep a small energy spread.

GANIL SSC1 was tested first in June 1982 and SSC2 in November. Since mid-January 1983, GANIL delivers beam for physics and so far 9 experiments have been performed. Due to the very tight schedule of construction all the very flexible possibilities the computer control system will give are not yet available and experience on machine operation is very limited.

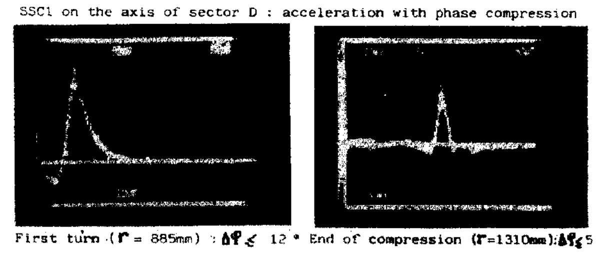

Fig. 4 - Bunch length compression at GANIL SSC1 (1st and 9th turns).

Beam transparency of each SSC including injection and extraction can be close to 75 % ; even if some loss may also occur in transfer lines, the overall efficiency is very good. Only one beam has been accelerated yet : $^{40}Ar^{16+}$ of 44 MeV/A with an intensity so far limited to 150 enA (transparency through each SSC about 70 %). As soon as physics demand points to other beams they will be studied.

Despite the lack of much experience, GANIL appears as a powerful heavy ion accelerator which has been recognized as a very good tool for physics.

Apart from GANIL, two big similar SSC's are now under construction, one at the Heavy Ion Research Facility in Lanzhou (HIRFL) in China[16] and one at RIKEN in Japan[17]. The first one will use as an injector a rebuilt SF cyclotron and the second the variable RILAC (for a second stage an SFC will extend the capability towards lighter ions). Their K's are respectively 450 and 540. RIKEN SSC is planned to be finished in 1986.

THE BEGINNING OF THE FUTURE - SUPERCONDUCTING MACHINES

The advent of superconducting magnets had led to the development of several projects of SFC with reduced size and very small power consumption. One of them is now in operation at Michigan State University (MSU)[18].

This superconducting cyclotron of K = 500 has an internal source and is planned as an injector for another cyclotron of K = 800 now under construction. In order to profit of this injector now and do physics experiments with it, it is pushed to maximum charge state and field operation. Some trouble have resulted from this situation : with the amount of gas going out of the source, the vacuum is not good enough in the machine ; ions being stripped at already high energy may be deflected back into the cathode and activate it. Furthermore, electrostatic extraction septa, having to compete with large magnetic bending strength require large electric fields ; present upgraded conditions lead to field values which are difficult to hold.

Despite these difficulties which are partly accidental, the machine runs quite smoothly. A list of beams is given in Table VIII. Reduction of size leads to extremely tight tolerances (extraction for instance) ; on the other hand beam quality becomes a necessity and the performance of the machine is certainly very good. The main advantage of such cyclotrons is probably however their very nice field stability. Adjustments may be difficult to make but, when done, they are probably very stable.

The last development of superconductivity for heavy ion machines concerns the use of r.f. superconducting cavities as booster for tandems.

The upgrading of tandems with the help of external r.f. cavities was made in various places like Munich in 1976[19] and on a larger scale at Heidelberg in 1979[20].

Table VIII

Short list of beams at MSU (extracted)

Ion	Charge state	Energy MeV/A
C	4	35
N	4	30
0	3	17.3
Ne	5	25

In constrast to the reentrant cavities boosting the UNILAC, Heidelberg is using spiral resonators at room temperature. Superconducting cavities are of a new design ; the double electrode split ring and split loop resonators are commonly used. Two boosters of this type are now in operation ; the ATLAS prototype[21], in Argonne and the SUNYLAC[22], at Stony Brook. Others are under construction at Florida State and Saclay (helix resonators made at Karlsruhe), on order or development at Oxford, Canberra, Weizmann Inst.(Quarter wave resonators) and Tata Inst., others under discussion.

It must be recognized that such boosters (except Munich) behave on a different mode compared to conventional linacs. Short cavities can be adjusted individually in phase to produce maximum acceleration ; a slight displacement allows to keep bunch length at an optimum value (like in the bunch compression process of GANIL). Cavities have an optimized velocity for acceleration but their transit time factor only falls off by 30 % inside an energy range of almost a factor of 5 around the optimum (and even more for some types).

Another way of presenting the operation is to say that such boosters really constitute a prolongation, with limited distorsion, of the acceleration length (at least for the proper range of velocity, i.e. of masses) with the possibility of bunching, of stripping where appropriate. Not least is also the facility of extension (Fig. 5).

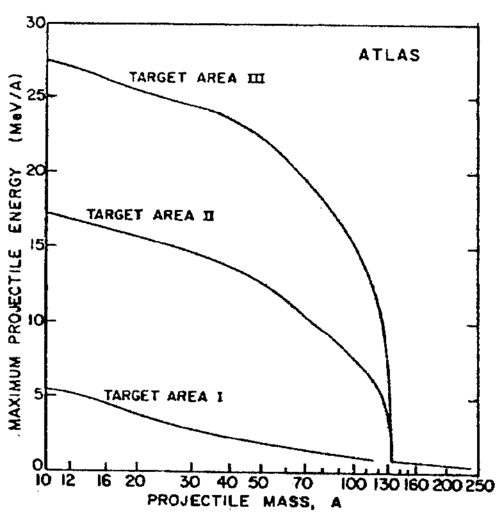

Fig. 5 - Energy from ATLAS : I without booster ; II with present prototype booster ; III with the full booster.

Operational experience seems extremely good. Typical emittances are 1πmm mrad, bunch length 150 psec (at about 100 MHz), energy spread better than $0.5.10^{-3}$ for an intensity of 100 enA (on ATLAS prototype). Apart from fast and easy adjustment (computer control can change the energy in about one minute) the main advantage is probably the stability. As for superconducting cyclotrons, this may be a non expected but very essential feature.

CONCLUSION

In the last few years, many new or upgraded heavy ion machines have come into service. ES machines probably deliver beams of the best quality but with reduced energy, linacs and cyclotrons differ by their mass-energy curves but give better and better beam quality. Computer control systems have introduced, except for cyclotrons an extremely fast flexibility of operation (adjustment times of the order of minutes for the BEVALAC). One of the main results the advent of superconductivity has introduced is an extremely good stability of operation: the development of tandem boosters may really extend to higher energies the advantages of ES machines at least for a chosen range of masses. They may even become serious competitors for cyclotrons.

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