Status report on the GANIL facility

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ABSTRACT

GANIL has been fully operating for 16 months for Nuclear Physics (90%), atomic and solid state physics. More than 1600 hours of effective beam time were delivered to the experiments until April 1984. The maximum particle intensity reached in operation is 4 10^{11}pps of $^{40}Ar^{16+}$ at 44 MeV/A and 1.2 10^{12}pps of $^{16}O^{8+}$ at 94 MeV/A. Beams of Oxygen, Argon, Calcium, Neon and Krypton have been successfully tested and used for experiments. At 44 MeV/A the $^{40}Ar^{16+}$ beam is sent to the physics target with the following measured characteristics : radial emittance : ε_h = 6 πmm.mrad, ε_h = 3 πmm.mrad, energy spread (total width) : $\Delta W/W = 10^{-3}$ at 450enA , length of the RF beam pulses : ∿ 1 ns. The GANIL facility and the improvements made during the first operation year are described. The alternate injector (a small compact cyclotron identical to the first one) will be in operation in 1984 with an internal PIG source. It should be run with an ECR source and an axial injection in 1985.

1. INTRODUCTION

Detailed descriptions of GANIL (Grand Accelerateur National d'Ions Lourds) have been already given in several previous conferences[1,2,3]. Fig. 1 recalls its general layout including the present experimental area configuration where 8 caves are in use for experiments.

The accelerator complex is a combination of 2 parts :

a. Prestripper part :

- A compact cyclotron C0 as injector (K = 30) with an internal PIG source.
- A separated function beam transfer line L1 including a low energy spectrometer and a rebuncher R1.
- A 4 separated sector cyclotron SSC1 (K = 400).

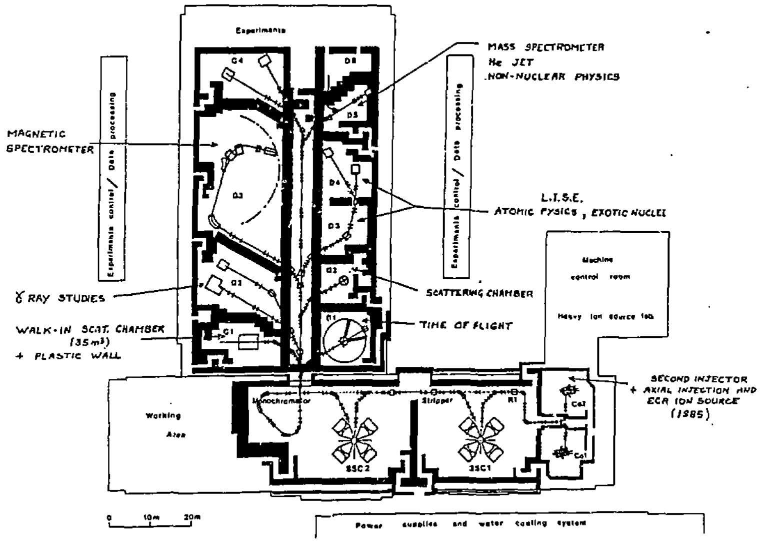


Fig. 1 General layout

b. Poststripper part

- A beam tranfer line L2 including a Carbon foil stripper.
- A 4 separated sector cyclotron SSC2 identical to SSC1.
- A beam transfer line L3 including a monochromator.

The beam is then conducted and is time shared by means of pulsed magnets to 2 physics experiments.

The first ion beam ($^{40}Ar^{4+}$) from SSC1 was obtained in June 1982. A full energy $^{40}Ar^{16+}$ beam at 44 MeV/A was accelerated in SSC2 and extracted 5 months later (in November 1982). The beam was delivered to the physicists in January 1983.

2. GANIL CHARACTERISTICS AND BEAM OPERATING RESULTS

2.1 General parameters

Fig. 2 shows the basic characteristics of the beams in the range of resonator frequencies for two combinations of acceleration harmonics. The beams already tested have been pointed.

The main GANIL measured characteristics are summarized in the following tables 1,2,3 for the 3 energy levels already tested : Argon at 27 MeV/A and 44 MeV/A, Oxygen at 94 MeV/A (max value).

		$^{40}Ar^{4+}$	$^{40}Ar^{4+}$	$^{16}O^{3+}$
RF frequency (MHz)		7.6	9.52	13.37
INJECTOR				
RF harmonic number		4	4	4
RF voltage	kV	38	60	63.
Number of accele. turns		14	14	14
Magnetic field	T	1.23	1.54	1.16
Extracted beam energy	MeV/A	.15	.25	.49
Beam rigidity	T.m	.57	.72	.54
Ion source duty cycle		.25 to .5		
pulse width	ms	1 to 5		
Extracted beam intensity	10^{12}pps	6	6	10
(typical)	eµA	∿4	∿4	∿5
Energy spread $\frac{\Delta W}{W}$ (total width)	10^{-2}	1.3	1.3	1.4
Bunch length at extraction	RF°	12	12	12
Rad. emit.(full beam) ε_H	mmmrad	40π	40π	40π
Vert. emit (full beam) ε_V	mmmrad	40π	40π	40π

Table 1

		$^{40}Ar^{4+}$	$^{40}Ar^{4+}$	$^{16}O^{3+}$
SSC1				
RF harmonic number		7	7	7
RF voltage	kV	80	141	148
Number of accel. turns		80	68	68
Magnetic fields	T	1.22	1.53	1.14
Extracted beam energy	MeV/A	2.17	3.42	6.7
Beam rigidity	T.m	2.12	2.66	2.0
Energy spread $\frac{\Delta W}{W}$ (total width)			4 10^{-3}	
Bunch length (with phase compression, extracted turn)	RF°		∿3	
Rad. emittance ε_H at ej.	mmmrad		10π	
Vert. emittance ε_V at ej.	mmmrad		12π	

Table 2

		$^{40}Ar^{14+}$	$^{40}Ar^{16+}$	$^{16}O^{8+}$
SSC2				
RF harmonic number		2	2	2
RF voltage	kV	75	115	158
Number of accel. turns		>400	>400	>400
Magnetic field	T	1.24	1.37	1.58
Extracted beam energy	MeV/A	27.3	44.7	95
Beam rigidity	T.m	2.18	2.43	2.87
Energy spread $\frac{\Delta W}{W}$ (total width)	10^{-3}		7	1.7
Rad.emittance at ej. ε_H	mmmrad		6π	
Vert. emittance at ej. ε_V	mmmrad		3π	
Bunch length, extrac. turn	RF°		∿4	

Table 3

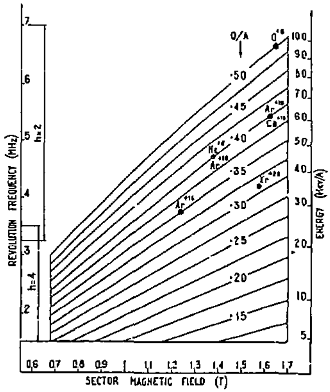


Figure 2 : Basic beam characteristics

2.2 Operating results

Injector C0

Tests on this cyclotron began on May 81[4]. The internal beam is easily tuned and the actual extracted beam characteristics are in good agreement with computations. Nevertheless the first results concerning the delivered beam intensity were lower than expected. Special studies on this problem were made . They showed that the vertical acceptance of the cyclotron and the vertical emittance of the beam extracted from the source were not well enough matched.

By changing the trim coil current configuration, cyclotron extracted beam intensity has been grown by a factor of 5.

Beam line transfer L1

- The transparency coefficients for all the GANIL beam lines and cyclotrons are given in table 4. After energy spread minimization (measured at the image point of the low energy spectrometer) tuned by fine action on injector magnetic field, the typical overall efficiency for L1 is better than 85%, slits being positionned to limit the emittance figure to 40 πmmmrad.

- The rebuncher R1 is the smallest CANIL's resonator. It works really without any problem at its nominal peak voltage (∿45 kV).

- Achromatism, correlations, and matching are still now well controlled[5].

*** SSC1**

The acceleration began on June 1982 without phase compression which was applied some weeks later.

Magnet

Maximum magnetic field configuration has been successfully tested with $^{84}Kr^{7/26+}$ at final energy 35 MeV/A needing a field value of 1.64 tesla.

A drift of main magnetic field (∿5 gauss) is observed during the first 2 days after starting, in spite of very good power supply current stability (better than 10^{-5}). This effect is a cause of difficulties for an easy beam tuning in the second SSC at the beginning of every run.

RF system

Due to the sparking limit of the SSC's resonators the RF dee voltage initially expected cannot be reached except for the upper part of the frequency range (above ∿11 MHz). Consequently, for the heavier ions (>100 Amu) we have to reduce the radial turn separation at injection to the lowest acceptable value, (especially in SSC2 where the number of turns is greater than 400). The turn number inside both SSC's is then depending, for a given frequency, on the maximum possible value of the RF dee voltage.

Injection-ejection

Beam injection and ejection are performed routinely. A small vertical motion has been observed which can be corrected satisfactorily. Correlations are easily checked at injection.

Acceleration

The first and last 10 turns are pertubed by injection and ejection magnets. The compensation of these defects is now achieved with the aid of TROPIC code[2] and associated beam current measurements made by means of the 4 sector yoke probes. The sector balancing has been then verified : residual beam off-centering is of the order of ± 5 mm corresponding to a balancing error less than ± 2 gauss.

The use of phase compression in SSC1 leads to have a rather small energy dispersion for the extracted beam ($\Delta W/W \sim 10^{-3}$).

*** Beam transfer line L2**

The achromatism is now in good agreement with the theoretical conditions.

Optimum charge ratio at the stripper is 3.5 corresponding to the ratio of ejection to injection radii and to the ratio of accelerating frequency harmonic numbers of both SSCs.

The thickness of Carbon stripper foils has been optimized in order to get better efficiency[5] not only regarding the stripper itself but with respect to the emittance figures before injection to SSC2. The growth of the energy spread for a beam crossing the stripper is order of 1.1 to 1.5 depending on the ion its energy, and of the foil thickness.

*** SSC2**

First tests of acceleration began in November 1982.

The maximum magnetic field configuration (1.6 tesla) has been tested with the acceleration of Argon at 60 MeV/A.

Single turn extraction is achieved on SSC2 by the combined effects of a precession of the beam created at injection and a first order field perturbation localized near the extraction radius.

The same precession in SSC2 will also be well suited to the phase compression configuration. The reduction of the radial turn spacing at injection which is a corollary of phase compression would result in a substantial beam loss without the help of precession.

*** Beam transfer line L3**

Not enough time was devoted for fine tuning of L3 line, the achromatism conditions are actually not fully controlled and matching has to be frequently retuned depending on the characteristics of the SSC2 extracted beam.

2.3 Beam efficiency

The overall efficiency of GANIL is depending on tuning conditions and of the type of particle. Of course the efficiency is generally better, when measurements are made just after machine retuning, than observed in average during a long time period. Table 4 shows the practical case of Oxygen measured after beam tuning optimization on November 1983.

	line L1	SSC1	line L2	SSC2	line L3
Local (part.) %	83	71	72[b]	60	95
Overall(part.)100	83	59	42	25	24[a]

a-measured from the ejected beam of the injector C0 to monochromator image point.
b-including stripping efficiency

Table 4

With the precessional ejection in SSC2 and after a control of correlations in L1, the transparency is now better in SSC1 and SSC2 : around 80% in good accelerating conditions.

2.4 Accelerated beams

The table 5 presents the listing for all ions and energies already fully tested and available with the maximum corresponding intensity on targets.

The maximum beam currents have been measured the machine being perfectly tuned, the ion source and the puller far of their life time limits.

	ENERGY MeV/A	MAXIMUM CURRENT	
		pps	enA
$^{16}O^{3}/^{8+}$	93.7*	$11.7\ 10^{11}$	1500
$^{20}Ne^{2}/^{8+}$	44	$1.1\ 10^{11}$	150
$^{40}Ar^{4}/^{14+}$	27	$0.36\ 10^{11}$	80
$^{40}Ar^{4}/^{16+}$	44	$3.9\ 10^{11}$	1000
$^{40}Ar^{5}/^{16+}$	60	$2.3\ 10^{11}$	600
$^{84}Kr^{7}/^{26+}$	34.7	$0.23\ 10^{11}$	100
$^{40}Ca^{5}/^{16+}$	60	$0.2\ 10^{11}$	∿ 50

* max. GANIL energy

Table 5 : Accelerated beams

3. GANIL OPERATION

During the first few months of operation, most equipments were individually set up and tuned by means of the 16 pseudo-knobs associated with 4 touch panels. Moreover numerous basic equip ments such as RF systems, *RF phase adjustement system and a certain number* of steering power supplies were not connected to the main computer.

After a year of completion, the computer control system is now linked to 1500 equipments or parameters and offers the expected facilities.

With the fast development of specific user[6] software (or tasks) for the machine operation, it became the powerful and efficient tool for people in charge of beam tuning and surveying.

* Initial settings

Approximately 6 hours are now necessary for this operation. The power supplies (about 220 regulated current power supplies, those of the experimental areas not still included) are automatically switched on and set to the expected value with different user tasks, taking the values in the computer disk-file.

SSC's magnetic fields are precisely cycled, their power supplies being under a dedicated microprocessor, while the others dipoles, such as bending magnets in beam lines, are cycled directly by the main computer.

Balancing of the SSC's sector field is done by means of a combined action of the main computer and of a local automatic gaussmeter using for each SSC 4 NMR probes at the centers of the sectors.

The RF parameters are controlled by 5 local microprocessors (one per cyclotron, one for the buncher and one for RF phase adjustment) which are under the main computer dependence[7,8].

* Injector CO + L1

The PIG source being switched on the injector cyclotron is easily tuned. Attention must be paid to have a good beam matching in the transfer line L1 : the energy spread of the CO beam must be carefully minimized by means of small corrections on the main magnetic field.

However, reduction of the energy spread is made to the detriment of the beam current : a good compromise has to be found by the operator.

The beam along all the transfer beam lines is driven looking at beam profiles (∿100 for the whole machine). These diagnostics can be moved in or out and measurements displayed on screens.

Steering corrections being achieved the buncher is switched on. Its RF voltage value is not critical (∿ 45 kV) but its RF phase has to be carefully tuned watching the beam central phase at the end of L1. The right RF phase is obtained when the beam central phase does not change with or without buncher on.

* SSC1

All the previous magnetic and RF parameters being put on, a preliminary RF phase value for the RF resonators is computed, using central beam phase probes (absolute measurement method)[14].

Then the operator uses several other tasks to tune readily the beam following the normal procedure :

- to align the beam on to the injection channel axis,
- to find the optimal radial phase law,
- to determine the best injection phase looking at the separation of the last 4 accelerated turns and tuning the RF phase,
- to adjust RF dee voltage in order to have exactly 68 accelerated turns,
- to put the beam in the center of the first ejection electrostatic septum.

All these operations are now made with the very convenient aid of numerous specific codes or tasks on wich detailed informations are given in other papers (this conference)[6,9].

If the above mentionned procedure is carefully followed then the single turn extraction is straight forward with a good efficiency (∿90%).

* Transfer line L2

The focusing parameters are known better than in L1 and the theorical conditions (particularly achromatism and matching) are rather well controlled.

Then the tuning only consists in steering or bending adjustments.

* SSC2 and L3

The procedure in use is exactly the same as for SSC1. However it is not possible to assume a fixed number of turns like in SSC1 , turns being not separated at ejection. Consequently the tuning of the line L3 strongly depends on the characteristics of the extracted beam : the orientation and the shape of transverse emittance may change with a change in the tuning of SSC2.

From this, it results a practical difficulty when the machine is working for physics : complete retuning of L3 and experiments beam line is a necessity if failures or breakdowns occur, changing the accelerating condition in SSC2.

3.2 Operation statistics and experiences

In normal operation 18 days run (trio mode) are followed by a maintenance week.(54 shift run).

The run is usually divided in starting time (36 hours), machine studies (48 hours), new beam tests (72 hours) and physics (276 hours).

During the first year of operation (1983), the beam time devoted to physicists has been 62% of GANIL's facility running time. Table 6 gives the distribution of the running time (1983).

	Scheduled (hours)	Actual (hours)
Physics time	2296	2446
Particle changes	56	68
New beam developments	370	385
Machine studies	569	336
Starting time	765	765
Total running time	4056	4056

Table 6

Table 7 and Fig. 3 represent the physics time distribution

	hours	%
Beam on target time	1260	52
Down time (tuning+breakdown)	1000	41
Running maintenance	185	7
Total physics time	2446	100

Table 7 : Physics time distribution on 1983

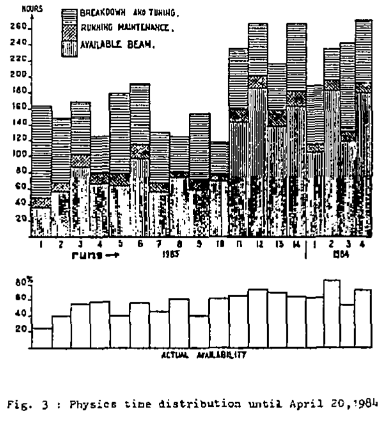


Fig. 3 : Physics time distribution until April 20, 1984

Short instabilities of the 50 Hz mains frequently lead us to a full re-setting up the machine parameters and represent an important unavailable beam time. Consequently, a program of implementing changes to the existing power supplies has been realised and a 120 kVA inverter installed to save computers and electronics.

At the beginning the long term drift of a few parameters resulted in hours of retuning but with experience and improvements like beam feedback controls, the lost time has been reduced by a factor two, while the time failures ratio decreased to about 8% of the total experiment time.

3.3 Operation staff

The three cyclotrons and the beam lines are routinely driven by 3 operators, partially backed up by one operation engineer (2 shifts a day).

3.4 Ion source maintenance

Life of PIG sources depends on the kind of accelerated particle and on expected beam intensity. Mean values are summarized in table 8.

	hours		hours		hours
Ar^{4+}	21	Kr^{7+}	14	Ne^{2+}	24
Ar^{5+}	16	Kr^{8+}	11	O^{3+}	30

Table 8

4. MACHINE STUDIES

Machine studies performed on GANIL have included studies on SSC's and on beam transport lines. Beam transport lines are treated in a separated paper where are described the problems of betatron and chromatic matching from lines to SSC's and from SSC's to lines. SSC's studies can be put into two classes, ignoring the actual chronological order in which they were made :

4.1 Transverse motion in SSC's

The four probes method previously described in [1,2] allows not only the observation of betatron oscillations but also the measurement of closed orbit off-centering. Field unequalities in the four sectors can be detected and corrected. The effect of residual field local imperfections can be compared to orbit computations[9]. Fig. 4 shows an example on SSC2 first 80 turns. Such a good result encouraged an extensive use of computer simulation to study a precessional extraction with bump. After about 460 turns a precession of 15 to 20 mm (35 mm peak to peak) and a small amount of bump, good in simulation, gave experimentally an excellent turn separation, Fig. 5 allowing a practically lossless extraction.

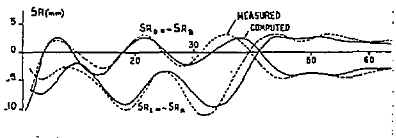


Fig. 4

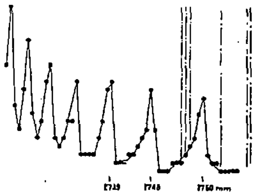


Fig. 5a : SSC2 last turns (Bump pencil beam)

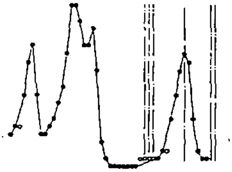


Fig. 5b : SSC2 last turns (Bump + precession)

4.2 Longitudinal motion in SSC's

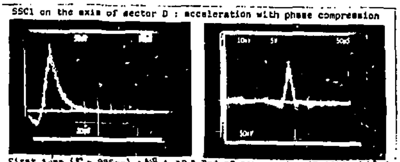
On this complex problem, studies mainly concerned the adjustment (or effect of misadjustments) of rf voltage, rf phase and magnetic field of SSC1.

A change in rf voltage V_{rf} practically only changes the final energy ; it provides an excellent method for adjusting the chromatic matching of a SSC into its output transport line[5].

Optimization of rf accelerating phase ϕ_{rf} can be made according to several criteria : maximum energy, minimum energy spread, minimum bunch length at some given point. Even if the last method is probably going to be preferred in the future the first two have so far been more examined, either by looking at the last turns inside the SSC or by using the monochromator.

GANIL SSC's rf cavities are delta shaped and each gap, in addition to acceleration, produces a transverse kick. For peak acceleration phase, the two kicks of a delta cancel each other ; not for other phases. With two cavities per turn the effect of such kicks is reduced, but not completely ; in particular this is true for the first turn where the injection orbit crosses the first cavity with a different phase. As observed experimentally the result is the excitation of a betatron oscillation with an amplitude proportional to input phase displacement : according to the turn and the azimuth on which the radius is observed for phase optimization, several degrees error may result from this effect. A way to avoid such an error is to choose for the observation a node of this betatron oscillation. If, similarly, the extraction electrostatic septum is put at such a node, just a small change in voltage, when close to optimum phase, is enough to keep the beam trajectory fixed in the output transport channel when the injection phase is being adjusted.

Bunch length compression from field perturbation is used in GANIL SSC1[10,11]. The most evident observation of the effectiveness of the method has been obtained from direct bunch measurement (Fig. 6) on the beam probe.



First turn (r = 885mm) : Δφ ≤ 12° End of compression (r=1310mm): Δφ ≤ 6

Fig. 6

If compression is easily achieved, field adjustment and phase law may however require some care and a special choice. In particular a change in average field is then changing linearly the energy : only about one gauss increase is enough to increase the energy by several per cent and change the extraction turn. A study of this phenomenon[12] has shown that one way to avoid this effect is to increase the average field and adopt a phase law as indicated on Fig. 7b (such a law would in fact avoid in the same time the risk of radial emittance increase in case of relativistic operation[13]). Experimentally, the field level producing this phase law can easily be found with the help of the monochromator by progressively increasing and reajusting continuously V_{rf} and ϕ_{rf} in order to keep the same extracted turn and optimize the energy spread (with a proper number of turns-see above-a slight correction of electrostatic extractor voltage is sufficient to keep the beam perfectly aligned in the transport line). For a proper B field level one has $\partial W_{out}/\partial B = 0$ for the optimum phase and voltage adjustment.

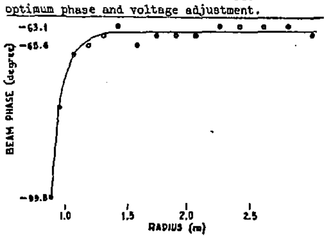


Fig. 7a : Normal phase law

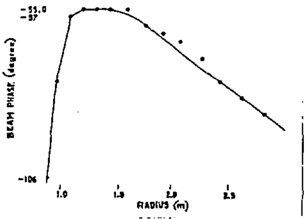


Fig 7b : Phase law with $\partial W/\partial B = 0$

5. IMPROVEMENTS

5.1 Beam switching

The time sharing between two experiments is already operational., but the beam intensity should also be controlled according to the user's demand. This will be possible in the next future by the means of a slit of special design which will be synchronized with the beam commutation.

5.2 On-line beam stabilisation

Owing to the great sensitivity of the beam phase to the various parameters, several feedback control systems have been designed[14] using on-line beam measurements as shown in Fig. 8. The basic principle is to keep constant the beam central phase all along the machine by adjusting the injector RF voltage, the main magnetic field of SSC1, the polarization of the stripper and the main magnetic field of SSC2.

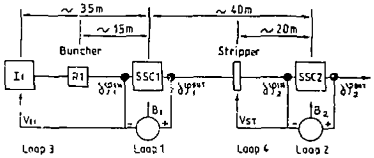


Fig. 8

5.3 SSC's magnetic field adjustment

The field level and the balance of the four magnet sectors of each SSC are adjusted using four Hall probes movable along the sector axis. At the beginning the accuracy of the Hall gaussmeter system was about ± 1 gauss, but during a year of experience we have observed drifts in the absolute calibration of Hall probes.

As the recalibration is a critical operation due to the tightness of the system involved in the SSC design and that we would like a better accuracy on field level measurement we have decided to install NMR probes close to Hall probes. When the isochronism field gradient is sufficiently smooth we can use directly NMR probes to adjust the field within $\pm 1.10^{-5}$ otherwise recalibration of Hall probes is done just before putting in field gradient.

For on-line corrections, NMR compensated gradient probes has been installed at the rear of the pole gap (one per SSC). This main magnetic field measurement will allow permanent monitoring and on-line feedback correction of the starting drift.

5.4 Second injector and ECR source

In addition to the internal source, an ECR source MINIMAFIOS, actually in test at GRENOBLE (R. Geller) will be incorporated in the 2nd injector. An injection system has been designed and it is under construction. The axial injection operation is expected in June 85[15].

5.5 Ion sources

The design of GANIL has been based upon the characteristics of the PIG ion source. New types of ion sources are interesting as far as they yield beams of similar charge states in sufficient abundance.

This is the case of the ECR source, as far as gaseous ions are concerned. The production of metallic ions is to be developped in the next future for this type of source whose main advantage is an almost continuous operation.

5.7 Time structure

Various demands have been formulated by the users concerning time structure of the beam. The most difficult requirement is relative to the production of very short pulses , in the order of .2 nanosecond.. At the present time, with special care, pulses a little smaller than one nanosecond can be produced. More machine studies have still to be made so as to find the most convenient solution.

6. PHYSICS EXPERIMENTS AND FUTURE BEAMS

During the first 15 months of operation, physics at GANIL was carried out essentially along 2 directions.

- Reaction mechanism
- Production of exotic nuclei

The main points of interest which have shown up during these studies are :

* Elastic scattering (27 and 44 MeV/A ^{40}Ar + Ni, Sn and Pb).

The roles of the real and the imaginary parts of the optical potential can clearly be disentangled. A Coulomb rainbow and a 40% reduction of the depth of the real potential are observed. There results are consistent with the 86 MeV/A, ^{12}C, CERN data.

* High energy structures in energy spectra (44 MeV/A ^{40}Ar + ^{208}Pb) : are still present at such an higher incident energy.

* Neutral pion production (44 MeV/A ^{40}Ar + Ca, Sn, U) : cross-sections between 1 and 3 pb have been measured, with the same $A^{2/3}$ dependence, well below the threshold.

* Quasi-fusion events are observed (27 MeV/A ^{40}Ar + ^{12}C, ^{27}Al and Ag) with 35 MeV/A ^{35}Kr ions, a good evidence for fission events and very strongly relaxed products is obtained from the same targets.

* Transfer of linear momentum (27 and 44 MeV/A ^{40}Ar or ^{137}Ar, ^{232}Th and ^{238}U) : a large amount of mass appears to be transferred to the target. Excitation energies as large as 900 MeV could be deposited in a quasi compound nucleus system. A large degree of relaxations is reached. However, the qualitative patterns are strongly different at 27 and 44 MeV/A.

As for the production of exotic nuclei, 3 main experimental set-up are used.

* Mass spectrometer : alcaline (Rb) and halogeneous (Br, I) distribution have been obtained with 100 MeV/A ^{16}O and 44 MeV/A ^{40}Ar.

* An He-jet transport system is now under operation.

* The super-stripped ion line L.I.S.E, including 2 magnetic dipoles is ready for operation.

Hopefully, physical results are to be expected during the second half of 1984.

Future beams

The future new ions having to be tested are summarized in table 9

Particle	Energy MeV/A	
^{12}C ^{14}N ^{20}Ne ^{28}Si ^{32}S	95	Not still scheduled
^{40}Ar ^{48}Ti	∿82	
^{58}Ni	55	Tested in injector + L1
^{84}Kr	45	Not still scheduled
$^{132}Xe^{9/32+}$	23	Will be tested on May 84

Table 9

CONCLUSION

- After a first year of completion, the beam characteristics have been appreciably improved : the beam intensity from the injector has been grown by a factor of 5 and the overall machine transparency by roughly a factor 3. The beam optical quality, stability and reproduc ibility are now better controlled. In the same time the availability of beams for physics reached in average 70% of the scheduled time.

- These encouraging results are the consequence of the time alloted for machine studies, but would have not been possible without the enthusiasm of GANIL peoples

- With the next installation of the ECR ion source, we hope for new appreciable improvements in the beam stability and availability.

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