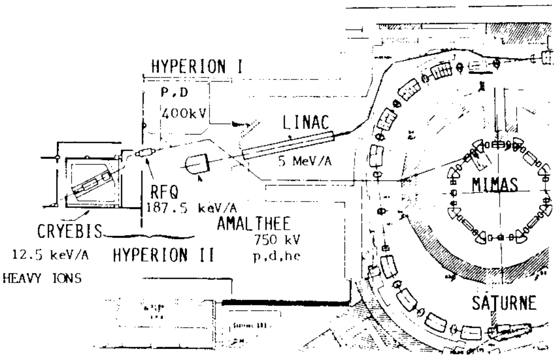
FIRST HEAVY ION ACCELERATION IN SATURNE AT 1 GEV/AMU USING THE CRYEBIS-RFQ PREINJECTOR HYPERION II

by M.OLIVIER
Saturne National Laboratory (CEA-IN2P3, Saclay France)

Since 1978 (1), the 3 GeV Synchrotron Saturne (Fig.1), has routinely operated with proton, deuteron, helium beams and since 1981 with polarized protons et deuterons (2).

On March 5th 1984, Saturne finally became a relativistic heavy ion accelerator thus joining the synchrophasotron (Dubna,USSR) and the BEVALAC (Berkeley, USA).

Presently, the terms heavy ions refers to ions from helium to Neon (plus argon in the very near future), mainly produced from gaseous mixtures by Cryebis (3)(4)(5). All these ions can be accelerated at 1 Hz up to various kinetic energies ranging from 50 MeV/Amu to 1.18 GeV/Amu giving to Saturne the necessary and complementary role of GANIL (Caen-France) expected by the nuclear Physicists in the field of intermediate energies.



- Fig.1 -

In the next 3 years, MIMAS (6) (a low energy storage ring) and DIONE(7) (a second Cryebis) will be build in order to :

- increase the intensity
- extend the variety of ion species up to xenon and higher mass.

Presently, the heavy ions are produced by a third pre-injector named HYPERION II (Fig.2) placed on the injection line in front of the 20 MeV proton Linac (5 Mev/Amu on h = 2).

HYPERION II is composed of :

- Cryebis on a 50 kV terminal (12.5 keV/amu for q/A= .25)
- Two beam lines : the LEBT at 12.5 keV/amu and HEBT at 187.5 keV/amu
- RFQ which accelerates particles of q/A = 0.25-0.5 from 12.5 keV/amu to 187.5 keV/amu, the injection energy of the Linac.

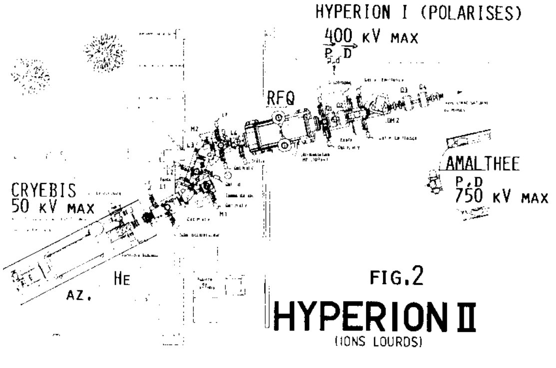


FIG.2

I - CRYEBIS -

The principle of this kind of source has already been described in numerous paper (3)(4)(5)(11). In Cryebis, in particular, detailed results and comments are also reported elsewhere in this conference(7). We recall here just some elements necessary to appreciate the parameters given in this preinjector description.

This type of source is intended to provide ions fully stripped by means of an electron beam ionizing longitudinally and radially trapping low charged ions. This process lasts a time Tc (confinement time) which in fact fixes the repetition rate. The final charge state, k, depends on, Tc, the flux, Φ, of the electron beam and the stripping cross sections, σ by :

$$Tc = 1.6\ 10^{-19}\ \frac{\sum_{1}^{K} \frac{1}{\sigma_i}}{\Phi} \qquad \sigma\ cm^2 \quad \Phi A/cm^2$$

The total number of ions obtainable depends on the trapping capacity. Longitudinally, the particles are reflected by electrostatic mirrors. Radially, they are attracted towards the propagation axis by the electronic space charge forces generated by the electron beam itself. In this view, an order of magnitude for the limitation of the ionic intensity is given by the rule of full space charge compensation :

$$Q+ = Q- = 10^{13}.I.L.V^{1/2} \text{ per pulse.}$$

I Electron Intensity
V Electron Energy
L Confinement Length

Unfortunately, this rule is not often respected and only a few percent of Q- is generally obtained in ions per pulse (15% max in Cryebis). Other parameters like emittance and momentum dispersion are found generally smaller than in any other kind of source.
In the case of Cryebis, the measured emittance ($\pi \beta \gamma c$) (100% of the beam) was :
En = 7.10^{-7} rad.m and dp/p = ± 3.10^{-3} for a pulse duration of 50 μs.

Table I gives the intensities and confinement times for the acceleration through the RFQ to SATURNE (March 1984) :

IONS	C	N	Ne	Ar*
Charges States	6(.72) 5(.23) 4(.05)	7(.61) 6(.31) 5(.08)	10(.26) 9(.34) 8(.31) 7(.09)	18(8.10^{-3}) 17(.04) 16(.44) 15(.24) 14(.16) 13(.06)
Total Intensity charge/Π $\bar{I}$	3.810^9 12 μA	5.10^9 16 μA	3.710^9 11 μA	3.10^9 10 μA
Confinement Time **	150 ms	150 ms	180 ms	180 ms

*Ar has not yet been accelerated in Saturne.
**Technically limited to 200 ms

The reproduceability and the long term stability (>24 h 00) are remarkable. The change of ion specie is easy (15 m) and clean.
All the advantages above are due to the auxiliary source (10), a new way of injecting the exact amount of 1+ ions into the confinement volume instead of the previous DC gas injection still in use in others EBIS.

II - BEAM OPTICS (Fig.3)

Briefly described, the line between Cryebis and the RFQ is composed (9) of 3 parts :

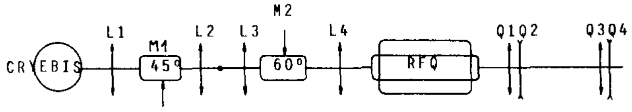


Fig.3

L1,L2 are used as matching electrostatic Einzel lenses.
M1,L2,L3,M2 is an achromatic optics assembly which recombines emittances scattered by dp/p (L2,L3 Einzel lenses, M1,M2 magnets).

The same section is also operated as a charge selector by using slits placed in front of L2. Two 200 l/s ion pumps provide a vacuum of 5.10^{-9} Torr necessary to transport fully stripped ions at 12.5 keV/amu.

Profile monitors, Faraday cups and emittance measurement units are placed along the beam trajectory in order to obtain matching and alignment as the beam enter the RFQ.

After the RFQ, two pairs of quadrupoles transport the beam to the junction with the presnet polarized beam line coming from the 400 kV terminal $(\vec{p}, \vec{d})$ Hyperion I.

The measured transmission of the LEBT is 100% when considering the necessary charge selection after M1. The transmission between RFQ and linac, eventhough suffering from a lack of diagnostics, is also 100% demonstrating once more the excellence of the optical properties of the beam delivered by Cryebis and accelerated by the RFQ.

III CONSTRUCTION

The Saclay RFQ study for beam dynamics and RF parameters was first carried out in close collaboration with Los Alamos Laboratory (12).
Later, the final design (13), the vane machining and the construction were executed by the different services of Saturne National Laboratory. The RF tuning took largely benefit from the CERN model and information from Los Alamos.

The copper plating of the 4 vanes and of the two cavities (RFQ and manifold) was performed by GSI Darmstadt.

1) - Beam dynamics and technical requirements

This project had to face many specific requirements (14) :

1 - Because of the number of pre-injectors, it was not possible to place an RFQ close to the linac. It is located 10 m away from it.

2 - Its length was kept as short as possible because of the available space and to ease its fabrication(< 3m).

3 - The frequency of operation is fixed at 200 MHz to fit exactly our RF power generator. This had to be realized in a band-width of 500 kHz.

4 - The output energy of 182,7 keV/A was imposed by the linac within 4%

5 - The ion species vary from N^7 to Xe^{33}_{131} (q/A = 0.5; 0.25) with an RF field in the cavity never more than twice Kilpatrick's criterium (15 MV/m).

6 - Peak power consumption≤150 kW.

Obviously, the usual parameters such as emittances (radial and longitudinal) and transmission efficiency have also been considered but are not very specific to this problem.

All the above constraints were studied carefully and an optimized solution was found, which resulted in :

1 - A fixed radius of curvature of the pole tips in order to reduce the peak surface field and to facilitate the numerical machining (estimation of the field reduction is 10%). The advantages of this geometry were already demonstrated at ITEP (Moscow).

2 - An additional section in the RFQ, called the debunching section, to reduce the momentum spread. This manipulation begins at cell 110 and stops at cell 144. The following table gives the initial and final $\Delta\Phi$ and dp/p with and without this section.

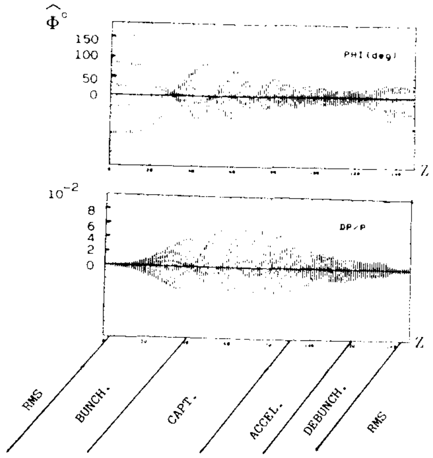
R F Q	Input	Output	Without debunching
$\widehat{\Delta\Phi}$ Deg.	± 180	± 90	± 20
$\widehat{\Delta p}/p$	± 3,4 10^{-3}	±4.10^{-3}	± 1.5 %

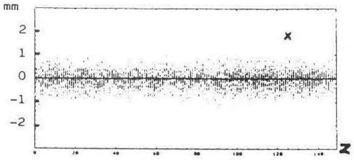
3 - Consequently, a radial matching section was also added at the output of the RFQ to transform the time-dependant focusing beam into a DC beam, i.e.acting exactly opposite to the entrance section.

The next tables give the final RFQ design parameters :

Frequency..................	199.99 MHz
Length......................	2.30 m
Number of cells.............	299
Average radius, ro..........	0.0033 m
Transverse curvature radius..	0.0033 m
Minimum radius, a...........	0.00279 m
Maximum modulation factor, m.	1.349
Initial energy..............	12.5 keV/a.m.u.
Final energy................	182.7 keV/a.m.u.
Inner diameter of the cavity.	0.336 m

Ions q/A	0.5	0.25
Intervane voltage (kV)	36.4	72.8
Peak surf.field (MV/m)	15	30
Peak Power (KW)	22.5	90
Stored energy (J) RFQ	0.22	0.88





2) - Mechanical features

Numerous problems had to be solved before powering the cavities :

a) - Vane tip machining : the 2.3 m long vane were machined in two operations.

First, the iron block is machined to final size less 1 mm in 3 cuts with 2 thermal stabilizations (650°C, 8h).

Secondly, the NC machine, using a spherical ended cutter of 10 mm diameter at 1500 rev/mm, machines the final profile in 80 hours in 2 cuts. The tolerances imposed on the machining and alignment were ± 5/100 mm over the full length (2.3 m). The maximum size of an elementary step is 6/10 mm, it can be less when the modulation is larger (Fig.4).

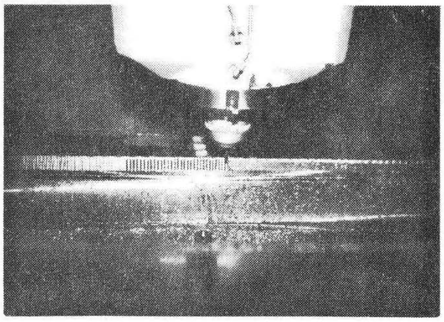


Fig.4 - Vane Machining

b) - Laser welding : to allow possible rocking of the vane during the positioning a flexible element between the RF contact on the cavity wall and the vane itself was inserted. This 0.5 mm thick copper flexible junction was first brazed on the adjacent bar (pressing the RF contact) and then laser welded on the vane (Fig.5). The laser was a YAG type of 30 J at $\lambda = 1,06$ μm providing a beam pulse of 10 ms at 100 p/mm. The laser, moving along the bench at 2 cm/m, completed a vane (both side) in 4 hours.

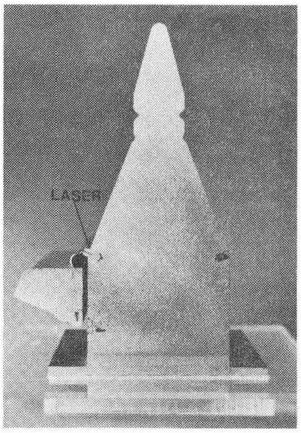
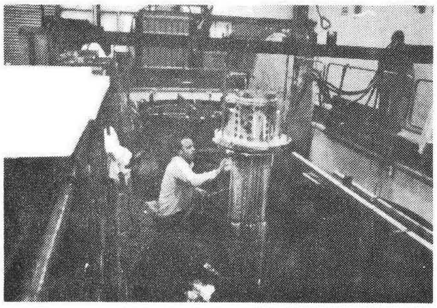


Fig.5

Laser Welding

c) - Copper-plating : carried out at GSI after numerous experimental tests were used to find the right position and the right size of the counter-electrode assuring a uniformity of ± 6% of the copper deposit. The copper-plating of 1/10 mm including a 10 - 15 μm layer of nickel was completed in half a day per-vane excluding time for the mounting and shielding (Fig.6).



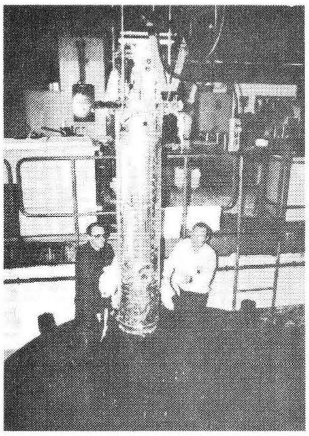


Fig.6

Copper-plating

at G S I

Remark : Effort to find a vane material avoiding copper plating led to the discovery of a copper-chromium alloy described in Ref.15. Good thermal and electrical conductivity combined with good hardness and yield strength can be found in ELMEDURX. This material therefore presents the advantages of :
- elimination of copper-plating
- high machining precision
- good thermal transfer from the vanes to the cooling pipes.

Discovering this material too late in our schedule we could not use it for the final construction. However we still test it for possible future uses.

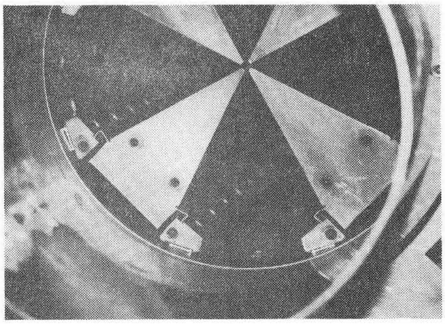


Fig.7 - Cavity-vane RF contact while tested in a 375 MHZ cavity

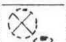
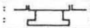
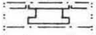
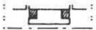
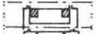
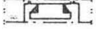
d)-RF contacts : as often as possible we refused double gaskets (vaccum and RF) and used helicoflex joints for both purposes.
The joint between the vanes and the cavity wall was of aluminium similar to that used for ion pumps. Metex was prefered on uncertain surfaces like the moving end wall of the manifold, pick up loops, inductive termination, different caps... (Fig.7).

e)- Vacuum : Two 200 l/s ion pumps of 200 l/sec were expected to be enough to obtain 10^{-7} Torr in the cavity. However, less than 10^{-6} Torr was never measured before RF power was introduced. Neither the cavity nor the manifold were outgassed after copper-plating.

f)- Vane positioning in the cavity : the vane were placed within ± 5/100 mm at 3 different positions along the axis by using a telescope and a movable target. The principle,which consists of rocking the vanes by two opposite pushing screws,turned out to be correct and would have been better if we had kept the target station on the same locations and added two additional stations along the vane (for example closer to the ends).

g)- RFQ tuning : the RFQ tuning was carried out by using the perturbation method (ΔF = 5 kHZ) controlled by a computer. Six perturbations in each quadrant could be introduced in holes distributed along the cavity. Each perturbation was followed by a $\Delta\phi$ ($\Delta\phi \sim H_z^2$) datataking. When a sequence, either azimuthal distribution at a given location along the axis,or longitudinal in a given quadrant was completed a graph was plotted together with the characteristic parameters (tuning bars, balancing bars, inductive tuners, capacitive tuners, frequency...).

The different steps of our tuning can be summed up by the table :

Situation	Frequency	Fieldshape	Geometry Azimuthal	Geometry Longitudinal	Q_0
After positioning	196.738	◡			5700
After balancing	197.507	◡			"
Cut-backs (filled up)	201. 54	◠	//		"
End caps	202.458	◠	//		"
Shaped cut-backs	200.	—	//		"
Final equipments (loops, caps...)	200.045	—	//	//	"
Closed slots	200.093	—	//	//	"
Vaccum (- 56 KHZ)	200.048	—	//	//	5000

At the final tuning the situation was (before vaccum) :

Fq = 200.093 Fd1 = 197.910 Fd2 = 197.012

and $\widehat{\frac{dH_z}{H_z}}$ max = ± 3% (Fig.8, 9).

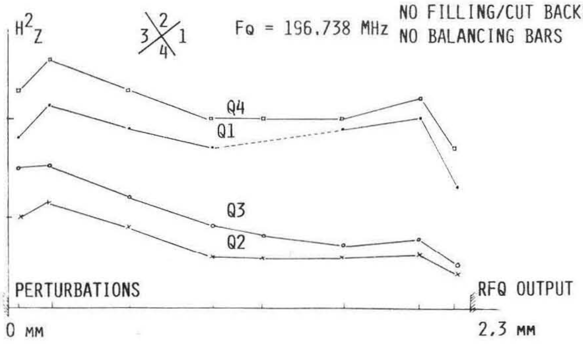


FIG.8 - H^2_Z FIELD AFTER VANE POSITIONING

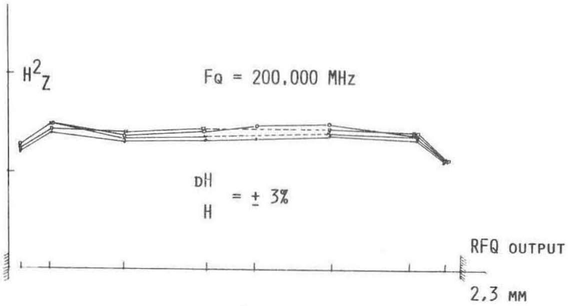


FIG.9 - H^2_Z FIELD AFTER TUNING

h)- Manifold tuning : the RFQ with closed slots was placed in the manifold and the sliding RF end wall was adjusted to get 200 MHz ($L = 2\frac{\lambda}{2}$) Fig.10).
The slots were then opened and the entire system was pumped down with the end wall at the same previous position. The zero mode (correct ratio of stored energies in RFQ and Manifold) had to be adjusted to 200 MHz again by the 8 slugs (2 x 4) located in the 2 Emax field planes. In our case, the process appeared difficult because of losses in the bellows of the slugs which caused dramatic Q decreases. The final frequency was obtained by moving the RF end wall step by step and correcting the RFQ frequency (end turners). The result is that our power consumption is 80 kW (for q/A = 0.5) instead of 50 kW. The overall Q value on the RFQ - manifold in transmission was found to be 4800 and the frequency of the π mode as close as 199.7 MHz.

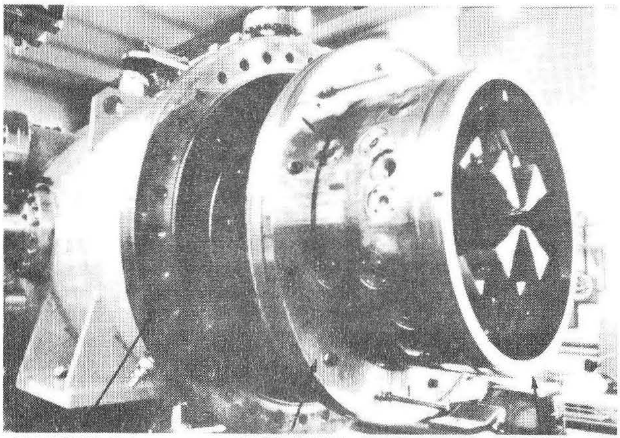


FIg.10 - SLIDING END WALL OF THE MANIFOLD

IV - RFQ - FIRST OPERATION (Fig.11)

The conditioning of the RFQ + Manifold lasted about 3 weeks during which we had to face :

- very strong outgassing which led us to an in-situ warm up of the manifold with heating wires up to 60°C for 12 hours. Several hundred watts caused pressure bumps up to 10^{-5} Torr despite the two 200 l/s turbo pumps.

- strong multipactor effects in the same range of power. The two spectra of multipactor of the cavities do not coincide necessarily and create an complicated situation. The baking of the manifold was found sufficient to cure the first step of the multipactor

On the other hand, the frequency stability versus the temperature was measured and found quite remarkable : ± 5 kHz over 24 h within ± 2°C. This was adjusted by using one of the slugs of the manifold.

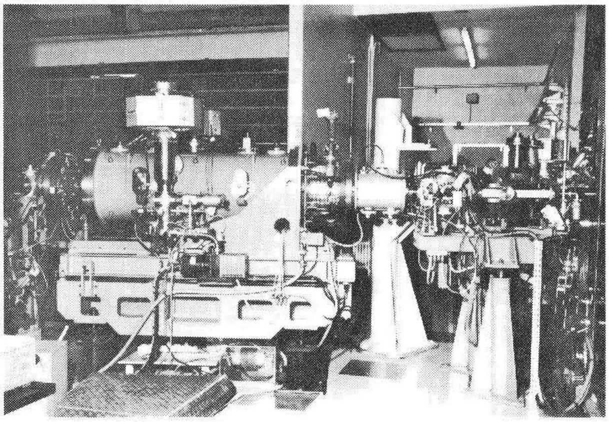


Fig.11 - The RFQ on the site

No breakdown under the usual conditions of pressure ($P \leq 5.10^{-7}$ Torr) was observed up to 100 kW, which corresponds to 1.2 K with a 25 μA heavy ion beam. However, after the accidental switch off of an ion pump, one breakdown was observed with beam (pressure went up to 5.10^{-6} Torr).

Finally, on the 22nd of February 1984, after careful tuning of Cryebis and the LEBT on N7+ (q/A =0.5) the first beam was accelerated by the RFQ. The curve I out = f(E_{RF}) shows the correct value of the E_{RF} field to accelerate the incoming beam (Fig.12).

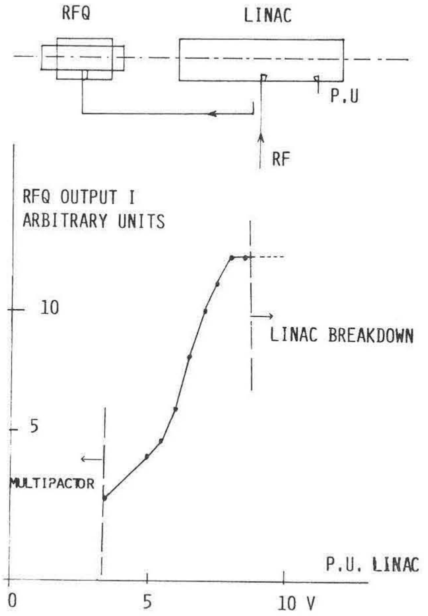


FIG. 12

The correct value of the RF field was also checked by Ne 10+, 9+, 8+ acceleration. Later, after tuning the linac, the 27 m injection line and Saturne with a He beam delivered by the first pre-injector, Saturne accelerated the first beam of N7+ up to about 1 GeV/amu without problem (Fig.13).

Other ions like neon and carbon were also accelerated after changing the Cryebis parameters (1/4 h) and gaseous material. The carbon produced from CH4 caused some trouble after a few hours because of a thick carbon deposit in the auxiliary source. We are now looking for a different solution to avoid this difficulty.

Fig.13 a) - First Beam/RFQ - Nitrogen

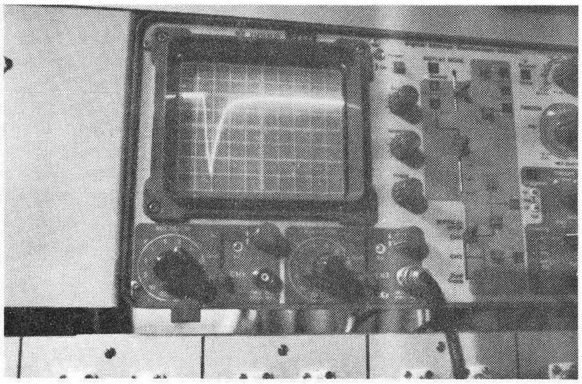
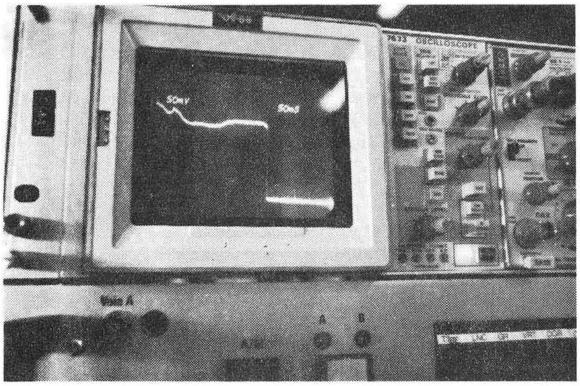


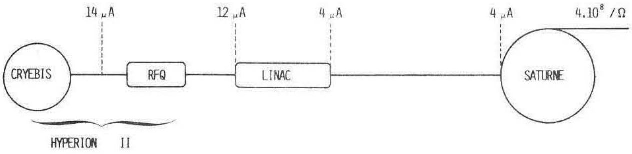
Fig.13 b) - First Beam/saturne - Nitrogen



The following results were initially obtained in a rough optimization :

	Cryebis out	RFQ in	RFQ out	Sat.1GEV/amu user's target
C	6+ 5+ $\hat{I}$ 25 μA 4+	15(6+)	12(80%)	4.10^8 ch/Π
N	7+ 6+ $\hat{I}$ 25 μA 5+	14(7+)	12(85%)	4.10^8
Ne	10+ 9+ $\hat{I}$ 25 μA 8+ 7+	5(10+)	3,5(70%	10^8

Further optimization on the RFQ gave more than 95% transmission with nitrogen. The overall efficiency for nitrogen is shown in the following sketch.



The excellent quality of the beam delivered by the 3rd pre-injector is confirmed by :

1) - The ease of transporting the beam in the beam line before the linac where we have severe geometric constraints.

2) - The excellent injection-capture-acceleration efficiency (60%). The overall efficiency between the RFQ and the users' target being about 15% instead of the 3 to 4 % seen for the other two pre-injectors.

3) - An emittance measurement behind the RFQ of 7.10^{-7} rad.m ($\pi \beta \gamma$ c).

This work was performed under the auspices of the French A.E.C. and CNRS (IN2P3) at Saturne National Laboratory. The author wishes to underline particularly the role played by J.M.LEFEBVRE (Mech. and Technology), J.L.LACLARE (Theory), R.VIENET (Saturne operation) and J.FAURE (Cryebis), during all the steps of the construction of our 3rd pre-injector. Mention should be made of the nice work carried out by Mrs.M.TKATCHENKO in designing the computer controlled RFQ tunings.
The RFQ construction benefitted also from discussions with W.PIRKL (CERN) and R.GOUGH and J.STAPLES (LBL). The LNS is very grateful to K.BLASCHE and H.GEISER (GSI) for the copper-plating of the two cavities.

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REFERENCES -

(1) Status Report in Rejuvenating Saturne and Future Aspects, R.VIENET et al., IEEE Trans.NS-26,No3, (1979)

(2) Status Report on Acceleration of Polarized Protons and Deuterons of the Saturne Linac, J.L.LEMAIRE LINAC 84, GSI, Darmstadt

(3) Numerous papers by E.D. DONETZ from 1968 to 1980. JINR Dubna (USSR) and a Review of the JINR Electron Beam Ion Sources, IEEE Trans.NS-23 No2, April 1976.

(4) First EBIS Workshop, Darmstadt (W.G) 1977 edited by B.H. WOLF and H. KLEIN - GSI - P3 - 77 - Oct. 1977 (W.G).

(5) Second EBIS Workshop, Saclay-Orsay May 1981 edited by J. ARIANER and M. OLIVIER - LNS/SD - CEN-Saclay France.

(6) Mimas Project of Low Energy Storage and Booster Ring for Saturne, J.FAURE, J.L.LACLARE, G.LELEUX, M. OLIVIER, A.ROPERT, IEEE Trans. NS- 26,No3, June 1979.

(7) Heavy Ion Sources at Saturne - J. FAURE, LINAC 84.

(8) Hyperion II : A Heavy Ion Pre-Injector for Saturne M. OLIVIER and al - Journées d'Etude Saturne. Fontevraud 1983 - LNS/SD - CEN Saclay - France.

(9) Internal Reports, A. TKATCHENKO - LNS/GT - CEN Saclay - France.

(10) External Ion Injection into Cryebis, J. FAURE, B. FEINBERG - NIM - 219 (1984) 449-455.

(11) Status Report on Cryebis, J. FAURE - 12th Int. Conf. on High Energy Accelerators 1983, Chicago

(12) Final Design for the Saclay RFQ, K.R. CRANDALL, J.L. LACLARE, R.S. MILLS, A. ROPERT, R.H. STOKES, T.P. WRANGLER - June 1982 - Memorandum AT 1 - 82 - 120 - LASL (NM) USA.

(13) The Saclay RFQ, J.L. LACLARE, A. ROPERT - LNS Getis 063 - LNS - CEN Saclay - France.

(14) The EBIS - RFQ Couple : A Fully Matched Heavy Ion 3rd Pre-Injector for Saturne, M. OLIVIER, J. FAURE J.L. LACLARE, J.M. LEFEBVRE, G. LELEUX, A. ROPERT, A. TKATCHENKO, M. TKATCHENKO - LNS - Saclay - France.

(15) Use of a Copper-Chronium Alloy for the Construction of RFQ Electrodes, J.M. LEFEBVRE - LNS-SSG 84-11/ME 79 - Laboratoire National Saturne - CEN Saclay - France.