MULTIPLY CHARGED ECR ION SOURCES FOR PARTICLE ACCELERATORS

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We comment on Electron Cyclotron Resonance Ion Sources (ECRIS) utilized for Atomic and Nuclear Physics. We give some details of our R and D in this field, and recall the characteristics of our sources and novel prototypes.

1. Generalities

The first double mirror ECR Ion Source (ECRIS) for Multicharged Ions, (MCI) was launched 16 years ago in our laboratory and the first high performance Bmin ECRIS worked already in 1975 [1,2]. Today ECRIS are one of the principal force vectors of MCI physics at low and high energies. An important international effort is dedicated to ECRIS Research and Development. Some 20 ECRIS are operating in different Research Centers. More than half of them were built by our group. In our ECRIS we utilize ECR above 10 GHz whereas most of the other sources work with ECR frequencies below 10 GHz. But all the ECRIS built at Grenoble as well as those built elsewhere (Table III) give very satisfying results.[3] Compared to PIG sources the improvements are dramatic (Fig. 1), this fact explains objectively the actual break through of the ECRIS. However when one compares one ECRIS to another, then the differences are more subtle and the arguments more subjective because the results look more similar. But anyhow, always better sources are demanded and ECRIS upgrading becomes now a challenging field. We show later that when the electron cyclotron resonance is shifted much above 10 GHz remarkable improvements are obtained. However these improvements are linked to more expensive and sophisticated technology. Therefore the ECRIS builders must look for the best compromise in the frame of a particular accelerator project. Whatsoever, the cost of an ECRIS is generally small with respect to the cost of an accelerator system. Of course, at the beginning, ECRIS look more expensive than PIG sources but the cost of their maintenance is much lower. In addition, their longevity and their reliability are unparalleled. Being external systems they don't introduce neither noise nor obnoxious gas flows into the accelerators. According to their utilizers, ECRIS contribute thus to better operation of the accelerators because they allow better tunings. This is attributed to the good stability, quiescence, brightness, energy dispersion etc ... of the beam, due to the absence of filaments, arcs and turbulences inside the plasma. ECRIS beams are today injected into all kinds of accelerators (RFQ, Linac, Cyclotrons, Synchrotrons). As for injection on the first cyclotron orbit, different systems are utilized, however the now famous "Belmont Inflector" seems the most popular system.[4]

For highly charged beams, ECRIS enables (Fig. 1) considerable reductions in size and cost of the new accelerator projects or considerable energy upgrade of present existing machines. But all these arguments are already very old [5]... and unfortunately during that time span, our theoretical comprehension of ECR plasma has not progressed very much. Many of our original clues and heuristic explanations are accepted. However we are not yet capable to formulate analytical solutions or scaling laws concerning stochastic ECR

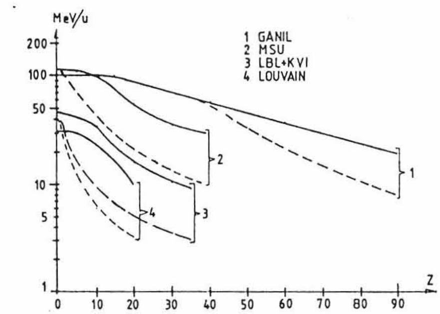


Fig. 1 : Energy upgrade achievable with existing ECRIS of typical cyclotron systems (full lines) compared to PIG operation (dashed lines).

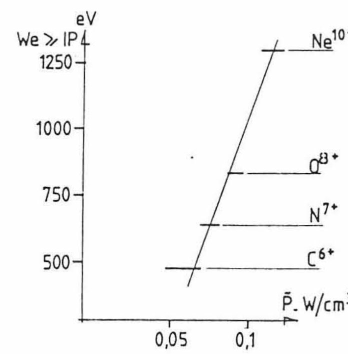


Fig. 2 : Electron energy (approximated by Ionization Potential IP) versus RF power density.

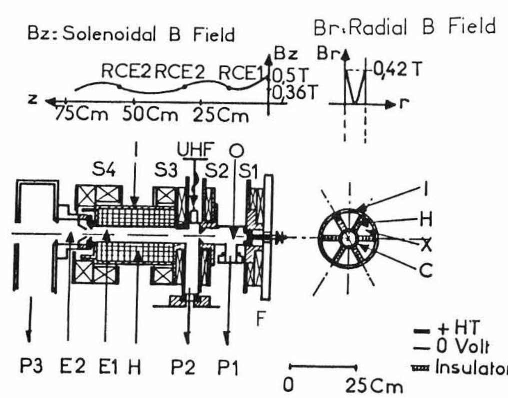


Fig. 3 : Minimafios : 10 GHz, the classical ECRIS ; stage one is on right, pumped by P_1 ; stage two is on left, extending from diaphragm O through extraction electrodes E_1, E_2, pumped by P_2 and P_3.
S_1, S_2, S_3, S_4 : Solenoïds - F : Iron shield - C : Multimode Cavity - H : Sm Co_5 hexapole - I : Insulators - X : Shield.

heating, plasma equilibrium, gas mixing, wall effects etc ... [6,7,8,9]

For instance in order to evaluate the energy gain of one electron in ECR we need among other parameters at least the value of the electromagnetic RF field $\tilde{\varepsilon}$. But even this very fundamental factor is not accessible because inside a dense plasma with ω_p close to ω_c the theoretical value of $\tilde{\varepsilon}$ vanishes. Plasma science is a victim of non linearities.

Let us now consider more pragmatic approaches (for instance measurements of $\tilde{\varepsilon}$, of electron temperature Te and electron distributions inside the plasma with the usual diagnostics). With probes, only measurements inside cold plasmas are possible. For our ECR plasmas, probes are not imaginable because :

1. When they are inside the plasma they perturb totally the confinement and the plasma has no longer the characteristics of normal operation.
2. They are immediately destroyed by the incident energetic electron flux.

Other well known plasma diagnostics like Thomson scattering and microwave interferometry are marginal. X-ray analysis remains possible provided that the electron distribution functions is maxwellian or is at least well known, which is not the general case.

Thus, plasma in situ measurements, are difficult. Fortunately some valuable answers are given by the analysis of the extracted ion beam. For instance the threshold of appearance of a given ion specie proves that inside an even badly defined electron population, there exists electrons with an energy superior to the ionization potential of the given specie [10] (Fig. 2).

The energy dispersion and the emittance of the beam provide informations on the upper limit of the ion temperature inside the ECR plasma ($T_i \leq 3$ eV).[11] The production of the different ions vs RF power density gives a global check of electromagnetic power absorption of the plasma and its lifetime (Fig. 2).

The quiescence of the ion beam is a powerful diagnostic of the plasma stability. The degree of turbulence (measured by analogical signals or by frequency analysis) is also interesting : low frequency waves or relaxations are often harmless. They are detected when $\omega_p \sim n^{1/2}$ approaches ω_{RF} giving us an idea of the electron density n (when these relaxations are correlated to microwave power reflexions, then the waves feel a cut off and n is then well approximated). Very High Frequency turbulence is difficult to interpret even by specialists. Sometimes beam/plasma instabilities, drift instabilities and all kinds of anomalous plasma/wall diffusion processes lead to this turbulence . Finally in most cases they can be cancelled by a different tuning of the gas pressure, microwave power and the current in the magnetic coils ... Therefore let us avoid to write equations because when they are not directly applicable they are misleading.

Practically all ECRIS have two plasma stages with differential pumping and have at least one multimode cavity inside a B minimum structure in the second stage for plasma confinement, electron heating and stabilization. Before 1980 we utilized two independent microwave generators for the two ECR stages and most of the ECRIS builders do still like that. But the coupling of the two plasmas creates some extra tunings problems. We avoid these additional and sometimes delicate tunings by utilizing one single microwave generator feeding simultaneously the two resonances. The RF power divider is an experimentally optimized internal microwave iris (Fig. 3).

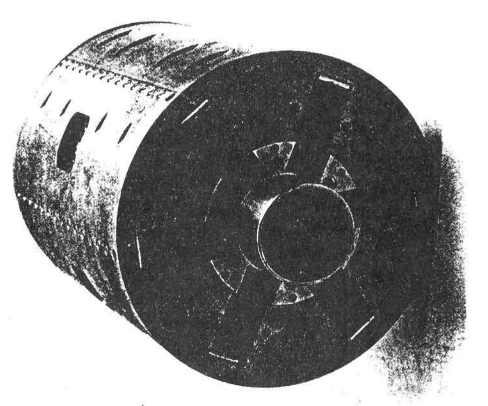


Fig. 4 : Pauthenet's first hexapole inside the X-ray shield and vacuum cavity.

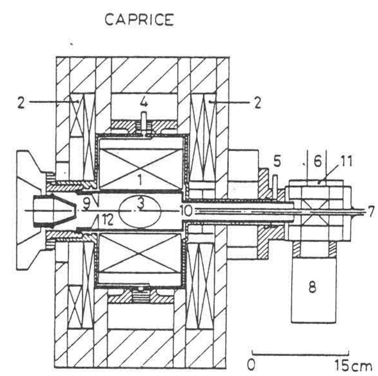


Fig. 5 : Caprice Source : (1) Magnets - (2) Solenoïd coils - (3) Closed ECR surface - (4) Water cooling inlet - (5) Water cooling outlet - (6) R.F. power inlet - (7) Gas inlet - (8) Turbo molecular pumps - (9) Ions extraction - (10) Gas inlet tube - (11) R.F. window - (12) Removable vacuum chamber.

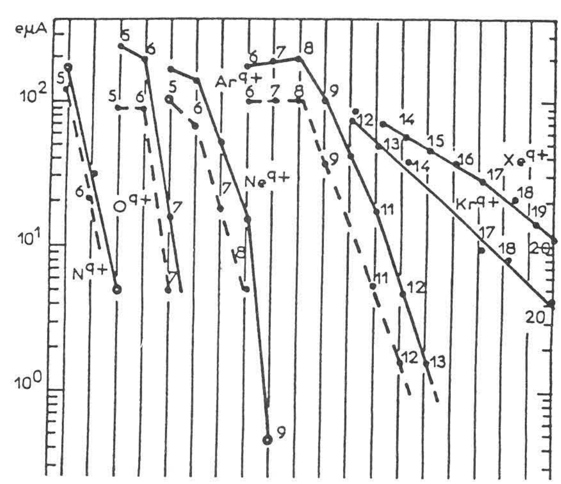


Fig. 6 : Gaseous ion yields of 10 GHz Caprice. Comparison between the two regimes. Hexapole 0.4 Tesla Ø 6 , 100 % continu.

a. 2 resonances : $\omega_{ce} = \omega_{HF}$, $\omega_{ce} = 2\omega_{HF}$ | P_{RF} = 500 W ——

b. 1 resonance : $\omega_{ce} = \omega_{HF}$ | P_{RF} = 250 W ---

• : measured point - ⊖ : extrapoled point

V_{ex} : 15 kVolts.

2. The ≧ 10 GHz ECRIS : Research Development and Construction

The 10 GHz MINIMAFIOS [12,13,14]

As mentioned, a classical ECRIS source has two stages. In the first which is at ≦ 10^{-3} torr pressure, a cold plasma is ignited by ECR which then diffuses towards the second stage at low gas pressure with hot electrons inside a minimum B configuration. The pressure gradient is obtained by vacuum conductances and differential pumping. The "in situ" ion pumping due to ECR and the effects of wall recycling play a capital role in the source behaviour. Figure 3 shows the main components of a typical 10 GHz MINIMAFIOS source and also its axial and radial magnetic fields whose importance was emphasized in all the previous papers. Ionic and turbomolecular pumping provide ~ 10^{-7} torr in the second stage where 10 GHz microwave is injected through a tight BeO window. Generally 70 to 90 % of the power is absorbed in the cavity. The multimode cavity C (which we consider as the most convenient microwave receptacle for our purpose) is made of a box of stainless steel. Ionic extraction is beyond the axial magnetic mirror. Its optimum position has been experimentally determined. The whole ion source is isolated up to 25 kV and connected to the high voltage except the solenoïds which are grounded. All the Grenoble built ECRIS exhibit similarities : they are very easy handling ECRIS. They have only one microwave generator for the two stages and three remote control buttons for the adjustable parameters which are : the gas flux handled by a needle valve, microwave power and extraction voltage. Among our ECRIS models, MINIMAFIOS is still the most employed because such sources can work for years without any internal failure. The figure 4 hexapole is made of Sm Co_5 permanent magnets with 4000 Gauss on the poles (hexapoles only are utilized in our sources).

The beam intensities shown in table I can by individual peak tuning, gas mixing and some patience be strongly improved. For instance we show exceptionally 140 µA of O^{6+}. Such an optimum could be reached with a carefully titrated Helium mixture after one week of operation. The other currents in Table I are routine performances rapidly tuned and directly collected by Faraday cages, with a signal to noise ratio of at least ten. Typically emittances at 15 kV are ≦ π 50 mm.mrad. When a minimum energy dispersion is needed, small apertures in the extraction system help and energy dispersion of < 1 eV/charge have been measured with O^{8+} ion beams.

Somewhat better performances might be expected by increasing the number of tuning possibilities (but this advantage is balanced by longer and more complex adjustments for routine operation).

Let us recall that the Groningen KVI facility and SARA at Grenoble work now for years with a MINIMAFIOS source. In the two last years the SARA source was operating 100 % of the demanded time. Its reliability is legendary and no maintenance problem exists. GANIL, CERN and several atomic physics facilities are equiped with a 10 GHz MINIMAFIOS. A MINIMAFIOS for NAC is under construction... However its power consumption (100 kW) is sometimes inconvenient. Therefore we launched more compact sources.

The need of new 10 GHz prototypes

The new MINIMAFIOS sources are mainly demanded for cyclotron and synchrotron injection. In this case their high electrical power consumption is not considered as a big drawback because power is not a problem when the supplies are grounded and reliability is a more important factor. However for LINAC injection one needs the source on a high voltage platform (up to

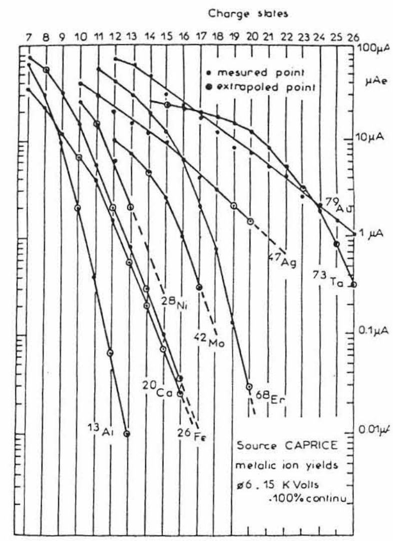


Fig. 7 : Metallic ion yields of 10 GHz Caprice - P_{RF} = 600 Watts.

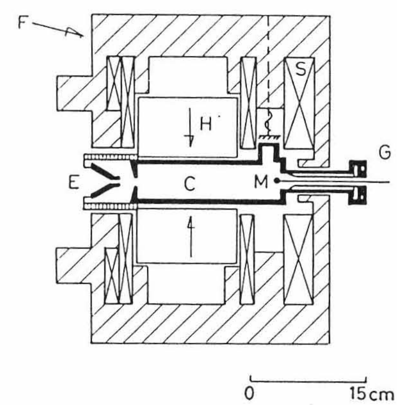


Fig. 8 : Ferromafios Source - (S) Solenoïds - (H) Hexapole - (F) Iron yoke - (C) Multimode Cavity - (G) Gas inlets - (M) Metal evaporator - (E) Extractor.

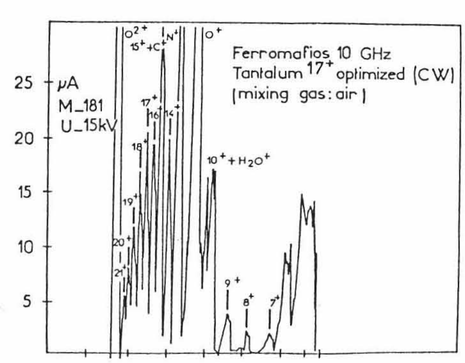


Fig. 9 : Ferromafios 10 GHz : Tantalum^{17+} optimized (CW).

TABLE I

Minimafios yields (in electric microamperes) at 15 kV extraction for gaseous ions (cw). Extraction hole ⌀ : 6 mm

Z	1	2	3	4	5	6	7	8	9	10	11	12	13	16	19	22	27
$^{6}_{12}C$	300	300	300	70	15	0.9											
$^{7}_{15}N$	300	300	300	300	100	6	0.9										
$^{8}_{16}O$		300	300	300	125	140	15	0.4									
$^{10}_{20}Ne$		300	230	130	80	50	20	5	0.4	0.01							
$^{18}_{40}A$			130	130	100	100	90	60	21	7	1..8	0.7	0.005				
$^{36}_{84}Kr$						25	25	26	28	30	32	36	28	0.005	1.2	0.05	
$^{54}_{129}Xe$						25	30	30	30	25w	20	18	17	12	9	0.05	0.03

500 kV unless an intermediate RFQ is provided).

For these facilities as well for small University Laboratories, ECRIS with much less electrical power drain are desirable. Therefore we studied and devellopped new prototypes for different particular utilizers. Different novel sources work now. Each of these sources has a particular aim.

Among these aims let us quote :

1. Maximum duration runs with metallic ions
2. Maximum reproducibility of beams
3. Minimum gas or metal consumption (when expensive isotopes are utilized)
4. Minimum electrical power drain
5. Minimum maintenance problems
6. Minimum parameter tunings during operation
7. Optimized performances for one given ion specie ...

CAPRICE prototype [15,16] (Fig. 5)

The 10 GHz CAPRICE prototype remains until now a tool for Research and Development of ECRIS ; elaborated by B. JACQUOT, it was launched in 1982. The performances of this first compact prototype are always improving. Note that in addition to its compact structure completely enclosed by a return yoke, the wave plasma coupling system differs from all other ECRIS. The coupling is achieved with an original axial 10 GHz microwave accessibility. This allows a very compact two stages source in an entirely removable vacuum chamber.

Thus CAPRICE is well fitted to produce metallic ions in long runs by working without any insulator inside the removable plasma chamber. The metal evaporator is constituted as usually in our other ECRIS by a metal sample approaching more or less the ECR surface. It is automatically driven and feedback controlled. In the last CAPRICE two different working modes are possible :

1. A classical mode : with in average ~ 300 W RF power and 20 kW electrical power for the coils gives performances similar to the other 10 GHz ECRIS
2. A harmonic mode : with an additional resonance surface at ω_{RF} = 2 ω_{RF} which needs in average 600 W RF and 33 kW for the coils but in this mode the ion currents on high charge states are generally increased by a factor of 3.

In Figure 6 we see the two modes for some gases and notice the improvements due to the harmonic mode for Nitrogen, Oxygen, Neon and Argon.

In Figure 7 we see charge states for different metal ions in the harmonic mode. Note that all kinds of metal ions are produced and many are interesting for cyclotrons.

FERROMAFIOS prototype (Fig. 8)

The other compact source is the 10 GHz FERROMAFIOS prototype which needs roughly 50 kW. FERROMAFIOS is

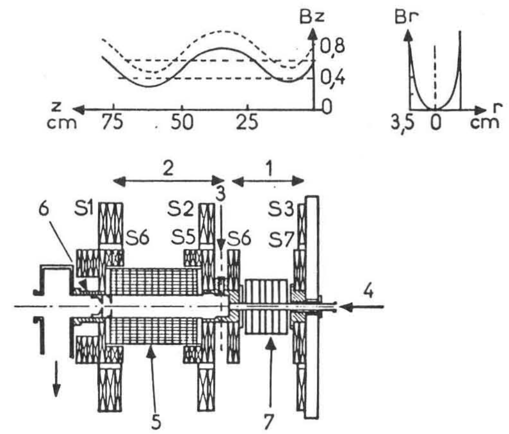


Fig. 10 : The novel Minimafios - General view - Note the absence of pumping, the new magnetic configurations, the compact first stage with the same overall size. On the top of the figure, the axial B field profile : full line represents : for 10 GHz operation and dashed line B : for 16.6 GHz. The 10 and 16.6 GHz microwave power are successively injected into the cavity C.
$S_{1...7}$: Solenoïds - 1 : 1st stage - 2 : 2nd stage - 3 : H.F. injection - 4 : gas - 5 : Hexapole - 6 : Extraction - 7 : Heat radiator.

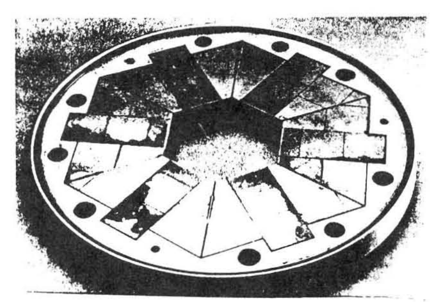


Fig. 11 : A slice of Pauthenet's second hexapole inside the X-ray shield.

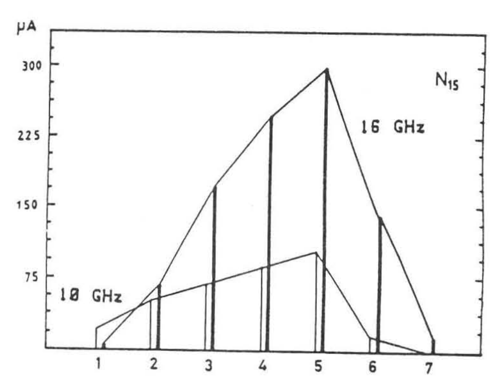


Fig. 12 : Comparative CSD distributions for ^{15}N.

characterized by its minimized tunings. Its performances are well reproducible. The source has already worked for months without troubles. Its size is larger than CAPRICE, but smaller than the 10 GHz MINIMAFIOS. Here only internal ion pumping is provided and gas feeding is minimized. In addition, for simplicity, only one supply for all the solenoïds is used. The microwave coupling system is the same as for the MINIMAFIOS. Whereas the hexapole, the iron yoke and endplates are directly inspired by the CAPRICE magnetic configuration.

Figure 9 shows a tantalum spectrum in C.W. regime obtained during a one week run, the average tantalum consumption was ~ 1 mg/hour. A FERROMAFIOS producing mainly metal ions, will be mounted in 1987 on a new injector line of GANIL and another is built for SARA.

3. Upgraded Sources

The 16.6 GHz MINIMAFIOS prototype [9,17,18,19] (Fig. 10)

For upgrading the MINIMAFIOS we always recommended to increase $n\tau$. This can be done by increasing the magnetic field B and the frequency ω_{RF} (because the plasma density n is expected to increase like ω^2_{RF} and the ion lifetime τ should be improved by a better magnetic confinement due to a lower plasma diffusion through the higher magnetic field

In 1984, we built a special 16.6 GHz MINIMAFIOS in order to prove this effect. This new ECRIS is built in such a way that it can work both at 10 and 16.6 GHz. So direct comparison of the main performances became possible. Other innovations are :

1. The total suppression of vacuum pumps inside the ECRIS.
2. The utilization of a new hexapole of Sm Co_5 which gives 0.8 T on the poles (Fig. 11).
3. The different arrangement of the coils and a compact first stage.

The dashed line gives Bz when operating with the 16.6 GHz (in this case, the total power drain exceeds 150 kW). The microwave generator can give up to 15 kW RF power.

For optimum 16 GHz operation, we noticed that the gas pressure must be increased by a factor ~ 3 with respect to 10 GHz operation and the microwave power must be considerably increased in order to see the upgrade of the high Z ions. Then, as shown in Table II the currents of Ne^{8+} + Ne^{9+} and Ne^{10+} jump by an important factor, much bigger as $(\frac{16.6}{10})^2$ suggesting a longer ion confinement.

Other gases were studied under the same conditions. Figures 12, 13, 14 show the results respectively for ^{15}N ^{16}O ^{40}Ar . In all these experiments, the shift from 10 GHz to 16.6 GHz exhibits a shift of the charge state distribution towards the higher Z and an unparalleled increase of the available ion currents for the highest charge states.

With this ECRIS completely stripped Sulfur and Argon beams were obtained for investigations in Atomic Physics. The currents were in the Nano Amp. range. Neither gas mixing in the source nor beam optics were optimized for these experiments.

The source worked in a pulsed regime with a duty cycle of ≤ 0.5 . Until now gaseous ions were tested. The heaviest gas was Argon. In 1987 heavier gases and metal ions will also be produced.

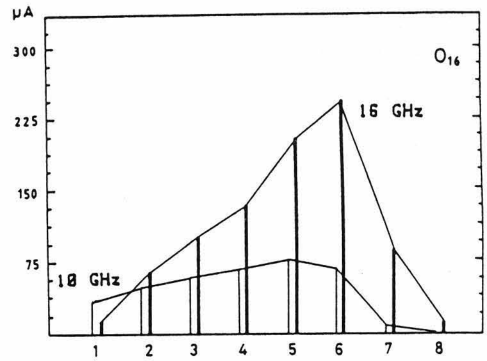


Fig. 13 : Comparative CSD distributions for ^{16}O.

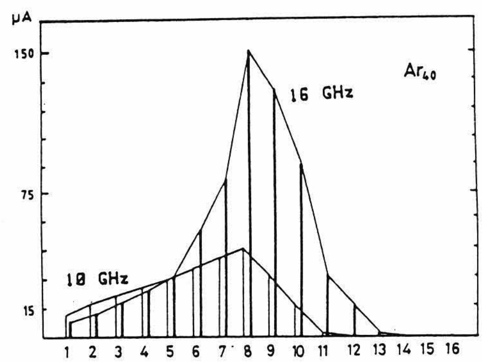


Fig. 14 : Comparative CSD distributions for ^{40}A.

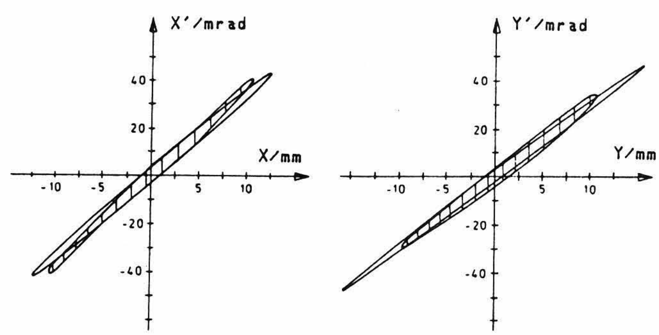


Fig. 15 : Measured (hatched) and calculated emittances 32 cm after RFQ. I^{6+}= 80 μA.

TABLE II

The new source performances for ^{22}Ne. Ø extr.: 6 mm, V_{HT} = 10 kV, collected ion currents in μA, duty cycle θ ~ 0.15 (each peak optimized)

Z neon	1	2	3	4	5	6	7	8	9	10
10 GHz operation	> 100	> 100	> 100	100	100	50	20	2	0.2	5×10^{-3}
16.6 GHz operation	> 300	~ 300	> 300	> 300	> 300	200	80	30	8	1
Improvement factor	3	3	3	3	3	4	4	15	40	200

MINIMAFIOS for CERN

The successful operation of the 16.6 GHz MINIMAFIOS encouraged us to consider this ECRIS as fitted for synchrotrons. In a first joint cooperation for employing heavy ions inside the PS and SPS synchrotrons of CERN, we built a 10 GHz pulsed MINIMAFIOS ordered by GSI (Darmstadt). This first source did deliver a beam of >80 μA of O^{6+}_{16} during a few milliseconds at 1 Hz repetition rate inside an emittance of ~ 150 mm.mrad (Fig. 15 - 16a - 16b).

This beam, after passing through an RFQ built by LBL and a modified CERN LINAC, is completely ionized by a foil stripper and then injected through a booster (PSB) into the Proton Synchrotron (PS) delivering oxygen particles of ≦ 12.6 GeV/nucleon. The PS is followed by the Super Proton Synchrotron (SPS) delivering oxygen particles up to 226 GeV/nucleon. This complete heavy ions system is working fine and new results were obtained.[20,21,22,23] It delivers ~ $10^8/\Pi$ O^{8+} particles at ~ 200 GeV/nucleon (Fig. 18 photo). A new project was decided using exactly the same accelerator system delivering the same particle energies but requesting another beam from the source : 25 μA of sulfur ions S^{12+}_{32} and thus extending the CERN operation to heavier elements. Such a beam performances was already achieved by the 16.6 GHz MINIMAFIOS in 1985. However the very expensive 16.6 GHz 15 kW microwave generator creates technical and financial problems. We therefore decided to try out another generator at 18.2 GHz whose microwave power is only 1.5 kW CW but utilized under special pulsed conditions it can deliver enough power for our purpose. The 10 % increase in frequency from 16.6 GHz to 18.2 GHz should anyhow be beneficial. It needed however a corresponding increase of the magnetic field and the general arrangement of the coils was changed, which in turn led to some other structural changes mainly in the first stage.

In June 1986 we reached the demanded performance for S^{12+}_{32} (Fig. 17) and the 18.2 GHz MINIMAFIOS will be installed at CERN in Spring 1987 and replace there the 10 GHz MINIMAFIOS.

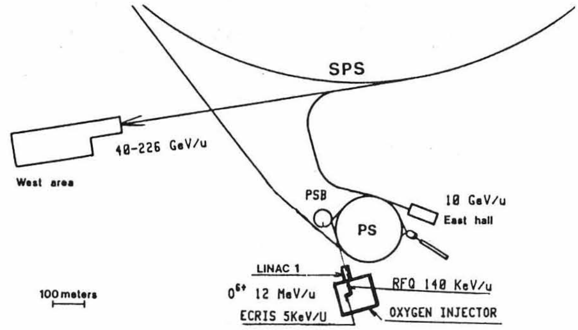
The 14.5 GHz FERROMAFIOS - Prototype

The new GANIL 2.5 project asks for heavy metallic ions with relatively high charges and substantial beam intensities. Even located on a 100 kV platform the data of the novel 10 GHz prototypes look marginal and a new 14.5 GHz FERROMAFIOS is presently under development. Its expected performances are between the 10 GHz FERROMAFIOS and the 18.2 GHz MINIMAFIOS.

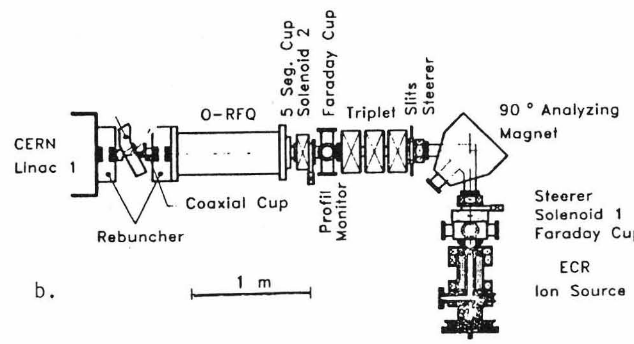
Other ECRIS prototypes - Table III

Many of them are described in this issue[3a-3g] In short Karlsruhe launched the HISKA family after 1980 and Louvain-la-Neuve ECREVETTE and ECREVIS. These sources work with 14 GHz in the first stage and ~ 7 GHz in the second stage which is partly or completely made of super-conductors. In 1983 at Oakridge a 10 GHz frequency MINIMAFIOS type Source was built for Atomic Physics. In 1984 Y. JONGEN and C. LYNEIS came also back to permanent magnets in the second stage but featuring an octopole instead the hexapole (ECR_1 9 GHz - ECR_2 7 GHz). A somewhat similar ECRIS was built in 1985 by Y. JONGEN at Louvain. Then in 1986 a 2 x 6.4 GHz source was built by T. ANTAYA at M.S.U. featuring Bmin structures in the first and second stage. Whereas Julich built a 5 GHz single stage ECRIS and now operates ISIS II, a superconducting 14 GHz and 14 GHz double stage ECRIS.

In spite of the fact that these diversified sources work with different gas pressures, different microwave frequencies and powers, different aspects ratios and other technologies, all of them gave earlier or later very satisfying results. However none of these sources



a. C.E.R.N. accelerator complex for O^+ beams



b.

Fig. 16 :

a. The CERN Accelerator system for heavy ions

b. Oxygen Injector enlarged.

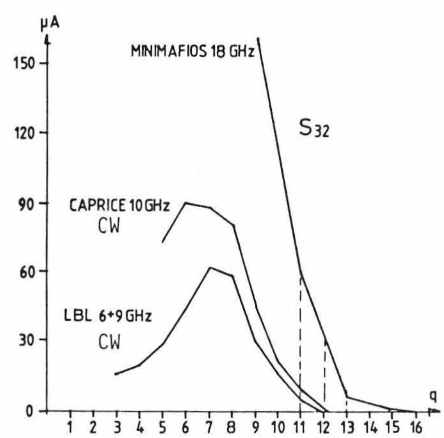


Fig. 17 : The Sulfur ions delivered by the 18.2 GHz Minimafios compared to Caprice and Octogun (LBL).

TABLE III

OVERALL VIEW OF MULTIPLY CHARGED ECRIS

ECRIS TYPE	MICROWAVE FREQUENCY AND POWER	B_{min}	CONSTRUCTED SITE AND YEAR OF 1st OPERATION	UNDER CONCTRUCTION SITE AND YEAR OF DELIVERY	UTILIZERS	OBSERVATIONS
I. Grenoble-built ECRIS						
1. MAFIA ^{W}	10 GHz - 300 W	EM	Saclay 1969		Fusion Res.	Simple mirror single stage ECRIS
2. SUPERMAFIOS ^{O}	8 GHz - 20 kW +16 GHz - 15 kW	EM	Grenoble 1975		ECRIS Res. & Dev.	Giant Bmin double stage - 4 MW Tot. power.
3. MICROMAFIOS ^{O}	10 GHz - 300 W +10 GHz - 2.5 K	PM	AGRIPPA Grenoble 1979		Atomic Physics	1st miniaturized Bmin prototype.
4. MINIMAFIOS ^{W}	10 GHz - 2.5 kW	PM	AGRIPPA Gr. 1980		Atomic Physics	Extremely reliable Series :
5. MINIMAFIOS ^{W}	10 GHz - 2.5 kW	PM	KVI Groningen 1982		Atomic Physics + Cyclotron K160	. No critical tunings . 100 kW Tot. power
6. MINIMAFIOS ^{W}	10 GHz - 2.5 kW	PM	SARA Gren. 1983		K150 Cyclotrons	. CW and pulsed regimes
7. MINIMAFIOS ^{W}	10 GHz - 2.5 kW	PM	GANIL1 Caen 1984		K400 Cyclotrons	. Lateral μW coupling
8. MINIMAFIOS ^{W}	10 GHz - 2.5 kW	PM	GSI/CERN 1985		LINAC+Synchrotrons	. 2 years guarantee
9. MINIMAFIOS ^{P}	10 GHz - 2.5 kW	PM		NAC South Afr. 1987	Cyclotrons	
10. MINIMAFIOS ^{P}	10 GHz - 2.5 kW	PM		IMP Pop. China 1988	Cyclotrons	
11. CAPRICE ^{W}	10 GHz - 2.5 kW	PM	PADSI Grenoble 1984		ECRIS - Res. and Development	Most performant 10 GHz - Prototype Gas & Metal Ions - Smallest power drain - CW coaxial μwave coupling - Iron yoke.
12. FERROMAFIOS ^{W}	10 GHz - <2.5kW	PM	PADSI Grenoble 1986		Surface Physics	Minimized Gas Flow - Gas & Metal Ions - Tot. power < 50 kW.
13. FERROMAFIOS ^{W}	10 GHz - <2.5kW	PM		GANIL II Caen 1986	K400 - Cyclotrons	No pumps - CW lateral μwave coupling.
14. MINIMAFIOS ^{W}	16.6GHz- <15 kW	PM	PADSI Grenoble 1985		Atomic Physics + ECRIS - Res. & Dev.	CW & pulsed ECRIS - Highest currents & charge-states most expensive - delicate μwave generator - No pumping Tot. power 150 kW.
15. MINIMAFIOS ^{W}	18 GHz pulsed P ≈ 3 kW	PM		GSI/CERN II 1987	LINAC+Synchrotrons	Only pulsed ECRIS - 1 Hz 300 ms - Objective : 30 μA S^{12+} & Ca^{15+} - Tot. power ≈ 150 kW.
16. FERROMAFIOS ^{P}	14 GHz	PM		SARA II Grenoble 1987	Cyclotrons	For medium heavy ions - no pumpings - CW regime - Lateral μwave coupling.
17. FERROMAFIOS ^{P}	CW 2.5 kW	PM		GANIL 2.5 Caen 1988	Cyclotrons	
18. MINIMAFIOS ^{P} High Current Prototype	30 GHz	?		GANIL Caen 1989		Aims : 2 mA of Ar^{6+} and Kr^{12+}
II. Louvain-la-Neuve-built ECRIS [3a]						
19. ECREVETTE ^{O}	14 GHz - 2 kW + 8 GHz - 3 kW	SC	CYCLONE Louvain 1981		ECRIS Res. & Dev.	Small volume superconducting - 2nd stage.
20. ECREVIS ^{O}	14 GHz - 2 kW + 8 GHz - 3 kW	SC	CYCLONE Louvain 1983		Atomic + Nucl. Phys. Cyclotron K = 110	Big volume superconducting - 2nd stage.
21. OCTOPUS ^{W}	14 GHz 2 kW +10 GHz 2 kW	PM	CYCLONE Louvain 1985			Permanent magnet octupole.
III. Karlsruhe-built ECRIS [3e]						Super-conducting Solenoïds
22. HISKA	14 GHz + 7 GHz	SC	KFZK 1981		Cyclotron K ~ 100	$\frac{q}{m} = \frac{1}{2}$ Beam - Premiere
23. Pico HISKA	14 GHz + 7 GHz	PM	Karlsruhe 1982			Cyclotron Injection -
24. LISKA	7 GHz	PM	1984			Lithium Li^{3+}.
IV. Julich-built ECRIS [3b]						
25. PREISIS ^{O}	5 GHz - 2 kW	PM	KFAJ 1983		Cyclotron	Perm. Magnet Multipole
26. ISIS ^{W}	14 GHz - 3 kW +14 GHz - 3 kW	SC	Julich 1985			Superconducting ECRIS
V. Oakridge-built ECRIS [3h]						
27. MINIMAFIOS ^{W} LIKE	10 GHz - 2 kW	PM	ORNL 1984		Atomic Physics	External RF power divider
VI. Berkeley-built ECRIS [3f]						
28. OCTOGUN ^{W}	10 GHz +6.4 GHz	PM	LBL 1984		Cyclotron K150	Hexapole or Octupole Perm. magn.
VII. East Lansing-built ECRIS [3c]						
29. MSU I ^{W}	6.4 GHz - 3 kW +6.4 GHz - 3 kW	PM	MSU 1985		Superconducting Cyclotron K500	Iron yoke - Premiere Injection into supercon. cyclotron Bmin for both stages.
30. MSU II ^{P}	Gyrotron 30 GHz - 100 kW	SC		NSCL 198?	Superconducting Cyclotron K800	Superconducting ECRIS Highest Q/M and ion currents.
VIII. Argonne-built ECRIS [3h]						
31. PIIECR	10 GHz - 2.5 kW	PM		ATLAS ANL 1988	Supercond. LINAC	High Voltage platform ECRIS $\frac{q}{m}$ > 0.1 heavy ions < 1 μA. currents.

*P : Planned - *W : Working - *O : Obsolete.

*SC : Super-Conductors - *PM : Permanent Magnet. - *EM : Electro-Magnet.

in spite of valuable innovations,gave an evidence of a specific ECRIS improvement with respect to the older Grenoble Sources (and this remains true for the cost, reliability, simplicity, maintenance and of course performances).

4. Conclusions

For an external observer the relatively rapid breakthrough of ECRIS can at a first glance be attributed to its basic simplicity : "An empty box, just filled with adequate gas pressure, microwave power and magnetic confinement fields ..."

In fact the simplicity is not basic but is the final phase of a long and difficult effort of a team of specialists each of them accomplishing some new technological or scientific achievement. At first in the field of permanent magnet hexapoles without the assistance of the Laboratoire Louis Neel at Grenoble headed by Prof. R. PAUTHENET, nothing serious would have been done. On the other hand, numerous innovations of advanced microwave techniques were realized by F. BOURG, P. BRIAND and B. JACQUOT who fully involved in the SUPERMAFIOS as well as in the 10 GHz MINIMAFIOS. CAPRICE and FERROMAFIOS is in addition the author and coauthor of many basic ECRIS ideas and patents since 1975.[24]

As for the 14.5 - 16.6 and 18.2 GHz ECRIS their new confinement geometries and plasma conditions were theoretically and experimentally elaborated during three years by P. SORTAIS. An ECRIS is a cocktail of many complex ingredients including also plasma heating and quiescence. Those people who believe that they can rapidly conceive and build a high performance ECRIS without an experienced team are wrong ... and it is my duty to inform them. Only quasi duplications or minor extrapolations of existing and well working ECRIS have a chance of rapid success. Taking a 10 GHz ECRIS as a pivot, we think that frequency decreasing makes the technology easier but did never improve the performances, whereas, no doubts, increasing of ω and B leads to higher performances of the ECRIS but the technology becomes more fragile , expensive and sophisticated. Super-conducting magnetic structures and gyrotron microwave generators will enter in the next generation of ECRIS and ask for new technical efforts. Nevertheless many experiments can and will be done in the next decade with the presently available ECRIS sources improving the present particle accelerator systems. But I am convinced that all new heavy ion accelerator, small or big, from now on, will and must consider ECRIS as an ingredient of capital importance in the general economy of a project. Therefore the difficult race towards higher frequencies (for instance a 30 GHz ECRIS) seems already unavoidable.

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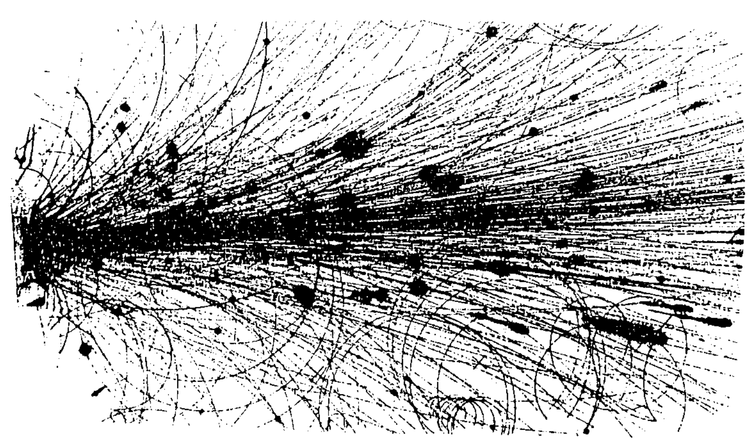

Fig. 18 : One out of hundreds of ultra relativistic heavy ion collisions observed in the streamer chamber. Incident a 3.2 TeV oxygen nucleus hitting a Pb nucleus. Neither target transparency nor fragments are observed, but an outstanding multiplicity ... issuing from the overheated and compressed nuclear matter (from R. STOCK, CERN NA 35).