STATUS REPORT ON THE SACLAY HEAVY ION SUPERCONDUCTING LINAC.

B. CAUVIN , J. P. FOUAN.

Institut de Recherche Fondamentale, DPhN/TP
C.E.N.- SACLAY, 91191 Gif sur Yvette CEDEX , FRANCE

The Saclay Heavy Ion Superconducting Linac is now in full operation with all 50 resonators and delivers routinely beams to Nuclear and Solid State Pysics experiments since March 1989. After describing the LINAC, we give informations on the upgrading of the cryogenic system and summarize our experience of resonator behaviour on the accelerating line. Cooldown, multipactor barrier conditioning, and field raising procedures are also discussed*.

1. Introduction

After the pioneering applications of R.F. superconductivity to heavy ion acceleration by the Argonne and Stony-Brook laboratories, many other superconducting accelerators are now under construction and some are in operation. The Saclay Superconducting Heavy Ion Linac is the first European machine of this type.

The construction of the accelerator was finished early in 1988. Lack of cryogenic power has prevented us at this time to operate all the resonators simultaneously. The first half of the machine (24 resonators) was nevertheless used for Nuclear and Solid State Physics experiments for more than a year. With the cryogenic power of 500 watts now available at 4 K, the second half is now fully operationnal and beams are routinely used for Nuclear and Solid State Physics experiments.

The resonators of the linac have been described in detail in refs.[1,2,3]. Ref.[1] gives more details on their fabrication and also on the associated electronics. The velocity matching device of the resonators consists either of a halfwave ($\lambda/2$) or of a full wave(λ) helix. The sketch of the λ helix resonator is given in Fig. 1. See refs.[2,3] for specific information on the $\lambda/2$ helix resonator. Resonators characteristics are listed in table. 1. Frequencies are multiples of the low energy bunching frequency (13.5 MHz). The high magnetic fields arise at the welds joining helix to can ($\lambda/2$) or half-helices together (λ). See figure 5 for actual values of electric and magnetic fields of the resonators in the linac.

2. Accelerator layout (figure 2).

The injector of the linac is a standard 9MV FN Tandem with a 200 kV platform and a Cesium sputtering source. At the output of the Tandem, the beam goes through an achromatic S bend and is injected in the first leg of the linac, after beeing bunched by a λ resonator. It is then first accelerated by 24 resonators housed in 3 cryostats along with superconducting focussing solenoids.

The U turn at the end of the first leg is achromatic but the beam is wide in time because of the 20 meters long drift before entering the second leg of the accelerator. A second rebuncher is used to time focus again the beam at the beginning of the second leg of the machine. It is then accelerated by the remaining of the resonators (24). A 90° magnet at the end of the machine directs it to the experimental areas.

The $\lambda/2$ helix accelerating potential velocity dependence is similar to that of a two gap structure. The potential varies much less with ion velocity than in the case of the λ helix [1,2]. It gives thus higher acceleration both to slow and fast particles. This property is particularly important for the heaviest ions delivered by the Tandem.(β=0.06 for ^{58}Ni at the linac input) This is the reason why $\lambda/2$ resonators have been mounted in the first and last accelerating cryostat of the linac. The other 6 cryostats are equipped with earlier designed λ resonators.

The experimental facilities consists of a QDDD spectrometer, scattering chambers of various types (one of them is 2 meters in diameter), and Solid State Physics irradiation systems.

Up to now, four ion species have been accelerated (^{12}C, ^{16}O, ^{24}Mg, ^{58}Ni). With 48 resonators running (46 in the case of oxygen), the energies obtained were 160 MeV for the oxygen and 360 MeV for the nickel beams. The accelerator is easy to set for light ions. Nickel beams are more difficult, mainly because of the time spread induced by the stripper located at the terminal.of the tandem.

3. Cryogenics

3.a Refrigerator.

The refrigerator wich maintains the cryostats at 4.2 K is an upgrade of the standard R2TN refrigerator from L'AIR LIQUIDE. This machine has liquid nitrogen precooling and two tubines expansion at 40 K and 13 K.

As shipped from the factory, the refrigerator produced about 180 Watts of cryogenic power.at 4 K. In addition 1000W of power at 55 K can be extracted (15 bar helium gas) to cool the thermal shields of the cryostats. The 4 K power was enough to compensate for the static losses of the transfer line and of the cryostats (total static loss: 140W), and for the RF operation of the first half of the machine at moderate fields. To be able to withstand the full power dissipation of the accelerator, with the resonators running at high field, we made several modifications to the refrigerator:

1-Increasing the helium flow in the cold box. This was done by adding an other screw compressor, increasing this flow from 48g/s to 72 g/s. Fortunately the turbines are able to withstand the increased speed in the refrigerator mode of operation. This is not the case in the liquefactor mode because the reduced cold gas backflow, characteristic of this mode, requires more work from the turbines to maintain adequate cooling at the level of the last heat exchanger before the Joule-Thomson expansion valve (JT).

2-Adding in parallel with the JT a two cylinders wet expander from KOCH. The JT valve is not completely closed in normal operation but acts as a trimmer.and is used temporarily in case of maintenance (greasing) of the expander.

The benefits of these modifications are seen on figure 3 where the power availaible at 4k is plotted for different modes of operation as a function of the temperature of the cold turbine outlet.

The power increase brought by the wet expander is of the order of 180 W when the two compressors are running, bringing the total power up to 500 W
The wet expander has proved its reliability since we installed it in February 1989, totalizing now more than 2000 hours of operation.

3.b Transfer line.

A 2000 liter helium Dewar is used for intermediate storage. It is also very helpful in decoupling the cryostats from the wobble in pressure due to the reciprocating machine of the wet expander.

A double transfer line is used to supply with liquid helium the two legs of the machine.It also recovers the evaporated gas from the cryostats. The thermal shield is cooled by 55 K helium gas. Cryostat feeding is done in parrallel to permit heating up a particular cryostat while keeping the others at 4 K. The heat loss of this line is about 25 W.

3.c Cryostats.

Each 4 meter long accelerating cryostat houses 8 resonators and two superconducting solenoids (figure 4). The helium vessel is filled up to the top, cooling thus the solenoids, the external envelope of the resonators and the superconducting part of the RF feed-throughs. The helices, where most of the RF dissipation takes place, are cooled in series with intermediate heat exchangers between resonators. These heat exchangers, sitting in the helium bath, help to recondense the vapor produced by the RF power. The flow in the helices is automatically adjusted to maintain the helium level in the vessel at a given setting (95% of maximum level). It is generally sufficient for high field operation of the resonators. It can sometimes be increased (essentially for RF processing) by adding electrical power in the bath (costly in cryogenic power) or by letting the cryostats overflow slightly, because the coaxial transfer line structure (good thermal contact between incoming liquid and outgoing gas) makes it a good heat exchanger.

4. Cooldown and multipactor conditioning procedures.

As our cold vacuum seals are made of indium, we cannot heat very much the resonator body during pumping. We do however heat the helix, wich is the most critical part of the cavity, with R.F. pulsed power. The room temperature quality factor is very low and the corresponding R.F. coupling very weak. The external Q is of the order of $3\ 10^{5}$ for both types of resonators (this is strong coupling for a superconducting resonator of $Q_0 \approx 5\ 10^8$ but unfortunately weak coupling at room temperature when $Q_0 \approx 2000$). Direct injection of R.F. power would be very ineffective. We enhance artificially this coupling by making the

R.F. coupling line resonate as a quarter wave (actually 3λ/4) resonator, the hot tip being at the entrance port of the cavity. To do this we use a removable short and an auxiliary coupling. The quarter wave acts then as a voltage raising transformer and about 30-50 % of the R.F. amplifier power is actually fed to the resonator. This outgassing procedure is only necessary when a cryostat was opened to air. If it is kept under vacuum, cooling down can proceed without it.

The cryostat is then cooled to liquid nitrogen temperature. The cooldown speed is computer controlled to prevent unequal contractions around the indium joints. This is particularly important for the 4 meter long gasket between the helium vessel body and its top flange. Pulsed R.F. power is then switched on and the cryostat is filled with liquid helium, controlling again the cooldown speed.

Even at room temperature, a strong multipactor barrier appears at very low field (E_{acc} / 100). Conditioning away this barrier at 4 K can take several hours. Maintaining R.F. power at liquid nitrogen temperatures and during cooldown to 4 K seems to reduce this time somehow. It has also the very important effect of maintaining the helix at a higher temperature that the external body of the cavity wich acts as a cryo-pump.

5. Accelerating fields

The absolute maximum accelerating potentials (labelled breakdown on Fig. 6) depend very much on the cleanliness of all the cryostat mounting operations, and on the thoroughness of RF conditioning. When clean mounting is performed , and clean vacuum is maintained, these potentials attain, on the average, the design values (540 -560 kV).

The cryostats are kept at liquid helium temperature for 2 months periods followed by shutdown periods during which they are generally kept at liquid nitrogen temperature, although maintenance sometimes requires heating up a particular cryostat to room temperature. This happens also for long time shutdowns. When cooling again the resonators, the breakdown fields are found different from those of the last cold run but the mean value is about the same. This is even true for runs separated in time by more than a year as can be seen on figure 5. Between these two runs the resonators of cryostats #3 and #4 have been left untouched, but the resonators of cryostat #2 (λ at this time) and cryostat #7 (λ/2) have been interchanged The only treatment applied before mounting was high purity water rinsing in our clean room.

Cryostat assembly (mounting of resonators, connecting their ports to RF feed-throughs, to beam pipes and to the superconducting solenoids) is done very carefully under class 100 laminar air flow. A single mistake, like putting for an instant clothing or hair in the clean flow, may result in dust contamination of one or several resonators. One such mistake may explain the lower fields shown on Fig. 5 by resonators #23, #25, #28 (although resonator #24 is much better now that it was before). Indeed field emission is high in this cryostat as it exhibits unusual X ray radiation. X ray radiation levels are generally less than 10 mrem/h on the external envelope of the cryostats at full field, but some resonators show occasionally more than 100 mrem/h. This was the case of the abovementioned resonators when the data of figures 5 and 6 were taken in april 1989. One should note however (figure 6) that resonator #88 shows a reasonably high accelerating field despite an X ray radiation level in excess of 500 mrem/h.

An other way of monitoring electron activity is based on the D.C. electron current which we measure on the R.F. pick-up probe of each resonator. This information is accessible at any time from the main console of the machine. It is normally less than 10^{-10} A, but can reach a few 10^{-9} A in some cases. During the low level multipactor barrier conditioning, the current is of course much higher (a few µA).

Dust contamination is not the only phenomenon which can induce field emission in superconducting resonators. Frozen air on the RF surface and particularly on the helix in our case, even in minute amounts, can induce high X ray radiations and strong D.C. electron current in the pick-up probe. This effect was observed on the last resonators of cryostat #4 in Dec 1987. These resonators had very high X ray activity (more than 200 mrem/h radiation level) and low breakdown fields at first cooldown. Warming up to room temperature (during which strong (?) outgassing at the 10^5 mbar level was observed in the beam vacuum) followed by cooldown has restored fields and X ray activity to normal.

Vacuum accidents can be much more severe than the example quoted above, and can degrade dramatically resonator performance. One such accident, during which two cold cryostats were opened suddenly to the atmosphere, has forced us to dismantle them completely for resonator cleaning. No chemistry was done, only high purity water rinsing.

6. Operating fields

With so many resonators running, one cannot expect them to operate reliably if their operating field is set very close to the absolute maximum limit. Instability in the helium flow, switching-on of electron emitting dust particles, or other phenomena, induce occasional breakdowns at lower fields. Some safety margin has to be taken to set the actual accelerating fields. This margin depends on the number of breakdowns per hour which can be considered as tolerable, which in turn depends on the time taken by the field raising procedure and on the overall down time. At the present time, raising the field of a resonator to its working level, and putting (manually from the console) into action all the regulation loops takes about 30 seconds. This time can increase somehow if unfrequent ponderomotive instabilities develop wich require some action from the operator. This procedure is not yet fully automatized and we would like to limit ourselves to a maximum of one breakdown every 10 mn, on the average, for the 50 resonators.

The actual accelerating potentials used in April 1989 with O^{16} and Ni^{58} beams are given in Fig. 6 along with the corresponding breakdown levels. The safety margin was rather large for many resonators and, indeed, some of them never experienced any breakdown whereas others would ask for frequent interventions from the operators. We are trying to improve this situation by acting at three levels:

1. *Increase the breakdown fields* with helium processing. The so called helium processing technique is used by many R.F. superconductivity laboratories, including ours. The principle is to introduce clean helium gas in the beam vacuum up to a pressure of a few 10^{-4} mbar (opinions differ on the right pressure to use). The ions produced by the electrons emitted by a dust particle or a bad spot will then bombard back the niobium surface and "clean" it at the right spot. We have applied this method regularly in our test cryostats, yielding often field improvements, but sometimes unexpected degradations which do not seem to depend on the processing time. An alternative to helium processing is pulsed R.F. conditionning: very high power (in the kilowatt range) is applied to the resonator during a pulse short enough so that the niobium temperature around a bad electron emitting spot does not have time to raise considerably. It is then possible to attain very high fields and the cleaning process is very effective. This procedure is applied with success at Argonne on the ATLAS resonators. We plan to use either one or both of these techniques.on the machine resonators.

2. *Increase the speed and fully automatize* the field raising procedure. Since the resonator is shut off immediately when its associated microprocessor detects a breadown by a sudden increase in the R.F. power delivered by the 200 W amplifier, the extension of the normal conducting spot created on the niobium surface by the breakdown is small, its temperature is low, and it cools again quickly. Also the vapor generated in the helium flow through the helix is in small quantity (only the stored R. F. energy of 0.5 Joule is dumped into the helium). It is then possible to put a resonator back in operation in a very short time. With an improved automatized field raising procedure, we hope to reduce the overall downtime to less than 8 seconds.

3. *Improve the phase adjusment procedure*. Correct beam acceleration requires a proper setting of the phase of each resonator in relation to the beam. This setting has to be changed for the full machine downward of a particular resonator if too frequent breakdowns require to lower its accelerating field to a safe value. The phases can be either precomputed or determined experimentally with the beam by switching on in turn each resonator, locate the maximum acceleration phase, and set it backwards to the desired value. We do not precompute the phases at present and use only manually the second time consuming method. Speed will be improved considerably by using a computer to do these operations.

All these improvements will permit to increase substancially the accelerating fields of the resonators.

7.Vibrations.

Because of their very high Q values, and thus of their very narrow bandwidths, all superconducting resonators are sensitive to the R.F. resonance frequency variations induced by mechanical vibrations. The mechanical weakness of our helix makes it, of course, particularly sensitive to them.

One of he first thing twe did before starting the machine construction was to search for the main vibration sources and to try to minimize their effects. For example, the primary vacuum pumps and the helium compressors of the refrigerator are isolated from the floor by massive vibration filters, and bellows or flexible connections are inserted on tubing, where possible. Great care was also taken in the cryostat design to include protection against external vibrations.

The next step was to design, pursuing the early studies of the Karlsruhe group described in ref[4], a Voltage Controlled Reactance (V.C.X) to insure proper lock of the RF field to the master oscillator. This V.C.X is now used on every resonator of the machine. We have , of course, two different versions because the frequencies of the λ and λ/2 cavities are very different. The V.C.X consists of 6 coaxial lines connected in parallel to the main resonator coupling·line. P.I.N. diodes are used to change dynamically the electrical length of these coaxial lines. Switching on or off one diode changes the frequency of the resonator by 100-150 Hz. The total tuning width of the V.C.X is then 600-900 Hz. This bandwidth is wide enough to encompass easily the spectrum of the frequency variations of any resonator (100-200 Hz FWHM). As a result the overall out-of-lock time of the full machine is well below 1 per cent.

Although submitted to high RF currents (6 A rms) and voltages (300 V peak), the failure rate of the P.I.N. diodes (300 for the 50 resonators) is generally low (one failure per month). A recent accident should be quoted however, during wich a dozen of them were destroyed. The probable cause is that the operator in charge of setting to their working fields the resonators of cryostat #4 did not notice that the reverse voltage polarisation of the PIN diodes of the VCX was low (we keep it low during shutdown periods), and, apparently, the hardware protection failed. A reverse voltage of 200 to 250 V is necessary so that the 1 kV diodes from UNITRODE have their intrisic region fully depleted. Of course the maximum RF voltage (300 V peak) requires a higher polarisation (350 V), although there is some tolerance on this last figure.

8. Conclusions.

The accelerator has now delivered beams for more than 3000 hours, in running periods of several weeks, including week-ends. It is our experience that starting the machine after a week end , during which the cryostats are kept at 4 K but the RF is shutdown, takes a long time to get it back in operation.

Also we found that the resonators are very reliable if they are kept permanently with RF at high field. In fact, occasionnal resonator breakdowns diminish significantly in number after several weeks of uninterrupted operation.

Despite the complexity of the RF control of the resonators, the machine operators can easily raise them to their working fields and correct minor instabilities. They are helped by software procedures handled by the local microprocessor associated with every resonator.

9. References

[1] B. Cauvin et al, Proceedings of the third workshop on RF Superconductivity, Argonne, September 14-18, 1987

[2] B. Cauvin et al, Proceedings of the 1989 Particle Accelerator Conference, Chicago, 20-23 March 1989. To be published in IEEE Transactions on Nuclear Science.

[3] G.Ramstein, thesis. Note C.E.A. N-2531 (1987)

[4] G. Hochshild, Karlsruhe internal report KFK 2094

[5] B. Cauvin et al, proceedings of the 5^{th} International Conference on Electrostatic Accelerators and Associated Boosters, May 24-30 1989,.to be published in N I.M.

* **Note:** parts of this paper were already presented in May at the joint STRASBOURG (France) and HEIDELBERG (Germany) meeting on Electrostatic Accelerators and Associated Boosters (see ref [5]).

Resonator type	λ	λ/2	
RF resonance frequency	135	81	MHz
Maximum surface electric field	19	16	MV/m
Maximum surface magnetic field	60	80	mT
Accelerating field	2.25	2.15	MV/m
Optimum ion velocity ($\beta=\frac{v}{c}$)	0.085	0.085	
Low field Q value	$3\ 10^8$	$3\ 10^8$	
Power in helium at design field	3.5	3.5	W
Maximum VCX reactive power	5	5.5	KVAR.

Table 1. Resonator data. Accelerating field is defined here by the ratio of the energy gain per charge (at the optimum phase) to the "effective field length". This length is equal to 25 cm for both resonator types. Values of the fields are design values. Actual fields attained in the machine cryostats (see fig [5]), and 4 K power dissipations, are widely scattered, depending of RF surface conditions.

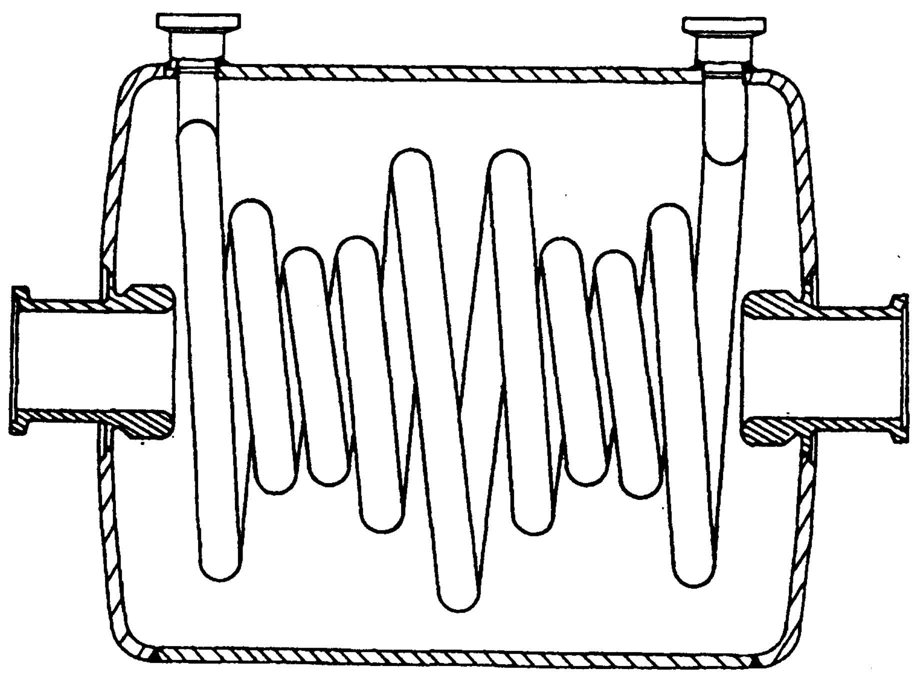

Figure 1 Sketch of the λ resonator. The overall length is 33 cm. The RF magnetic field on the helix surface is maximum at the welds joining helix to can and also at the middle of the helix.

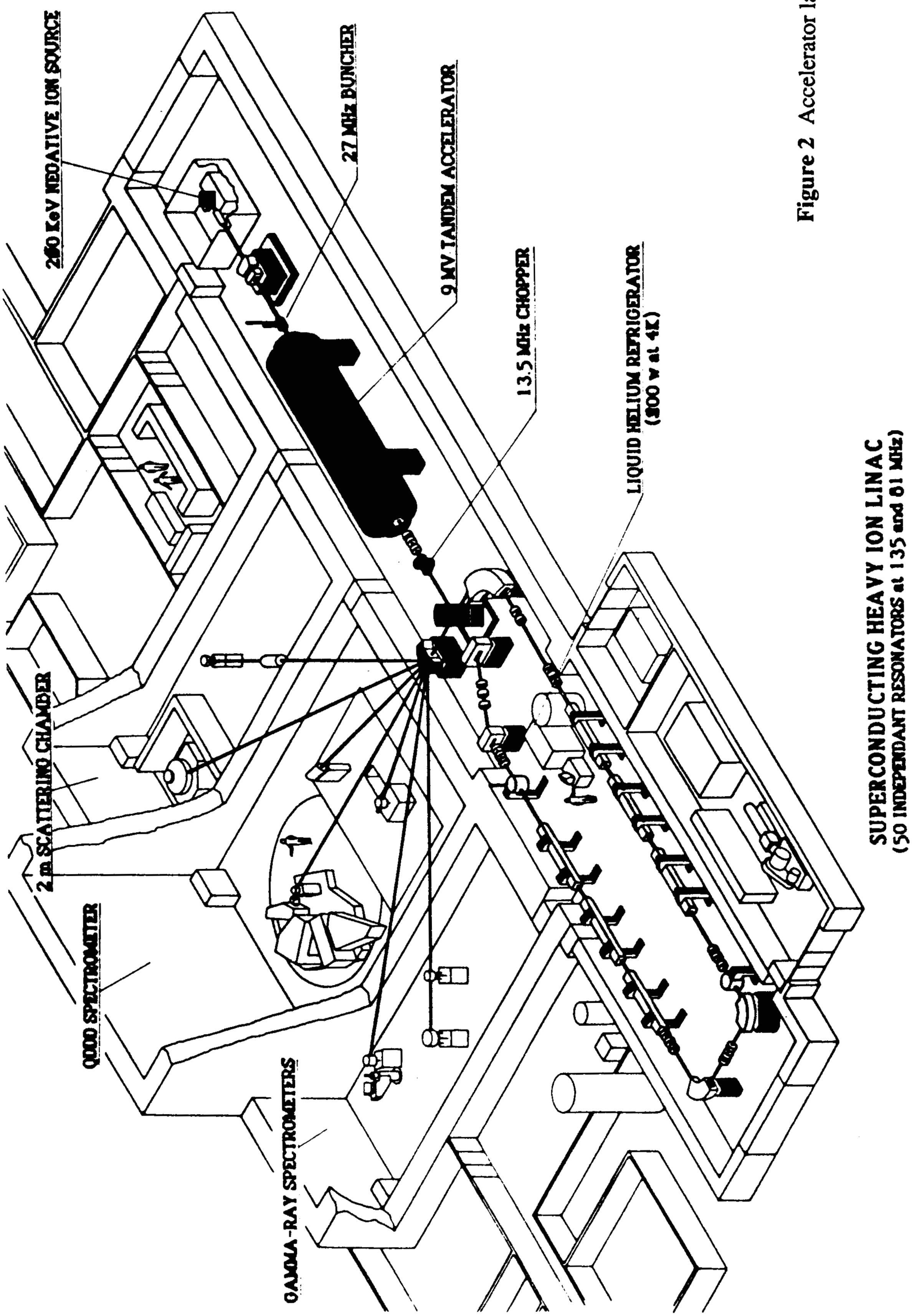

Figure 2 Accelerator layout

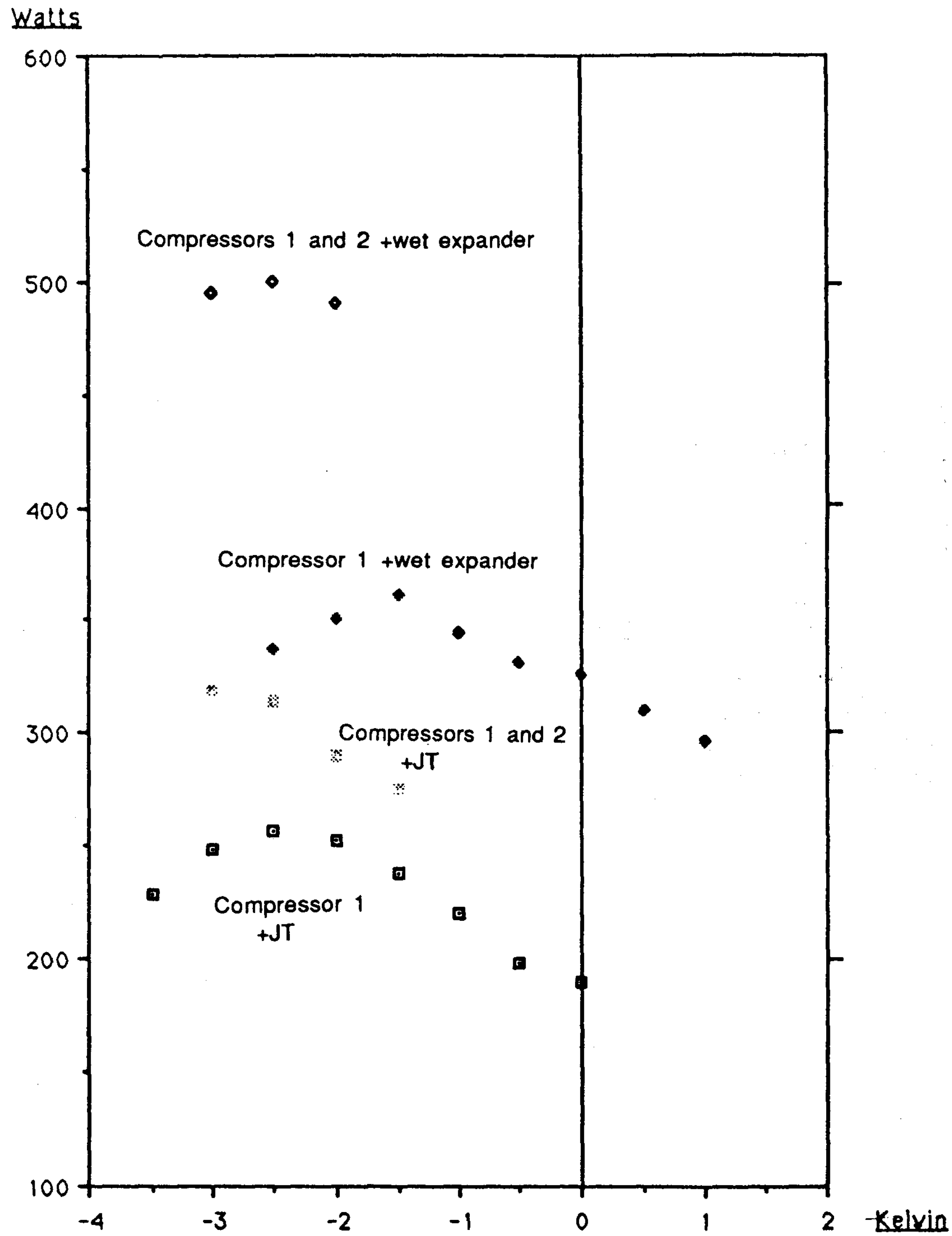

Figure 3 Power at 4 K delivered by the refrigerator. The abcissa represent the temperature of the cold turbine outlet (0 is the initial setting). Absolute values of the temperatures are unknown.

- The two bottom curves were measured with the JT expansion valve using the 48 g/s main compressor (lower curve) and the full flow (72 g/s) given by the two compressors (upper curve).

-The two upper curves were measured as above with the wet expander.

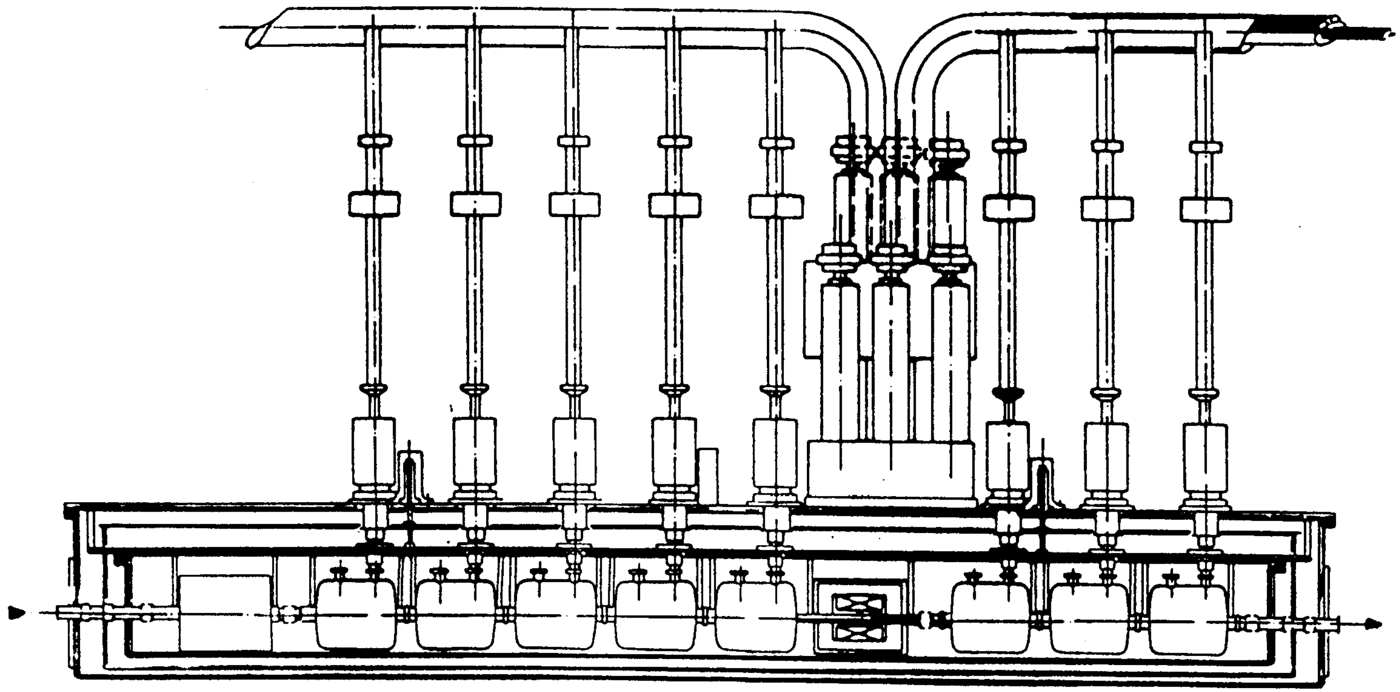

Figure 4 Cryostat housing 8 accelerating resonators and two focussing solenoids. On top of each resonator is sketched (very roughly: the actual design is somehow different but the symmetry is correct) the RF coupling line and the VCX used to control the vibrations of the helix. The helium coaxial transfer line can be seen in the upper part of this figure. The 'empty' port on the resonators is used for the RF field phase and amplitude pickup probe. The location of this port was later changed to another place on the resonator body. One can see also the two superconducting solenoids. The helium vessel, the 55 K thermal screen and the external envelope are also seen on this figure. Beam is going from left to right.

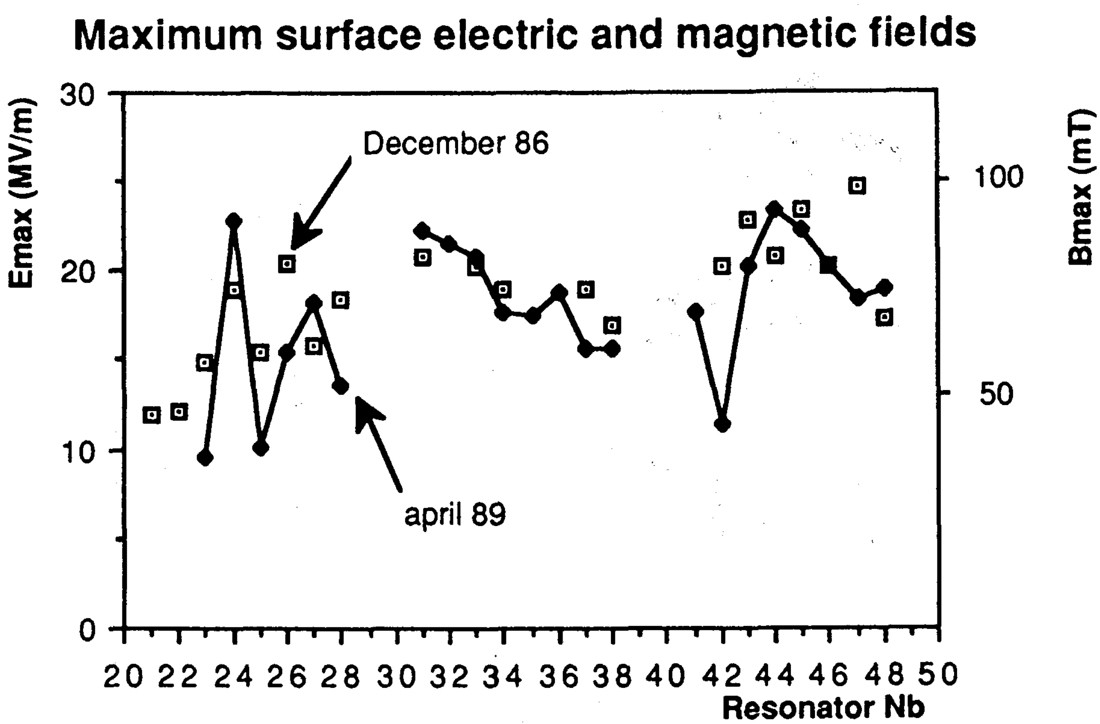

Figure 5 Comparison of the maximum electric and magnetic surface fields measured with a $^{12}C^{6+}$ beam in december 1986 (squares) and with an $^{16}O^{8+}$ beam in april 1989 (solid line) for the resonators of the first leg of the machine. Resonators are identified on the horizontal axis according to their position (in december 1986) in the N^{th} cryostat (from N1 to N8). Data for the first high energy rebuncher (resonator #11) are not given.

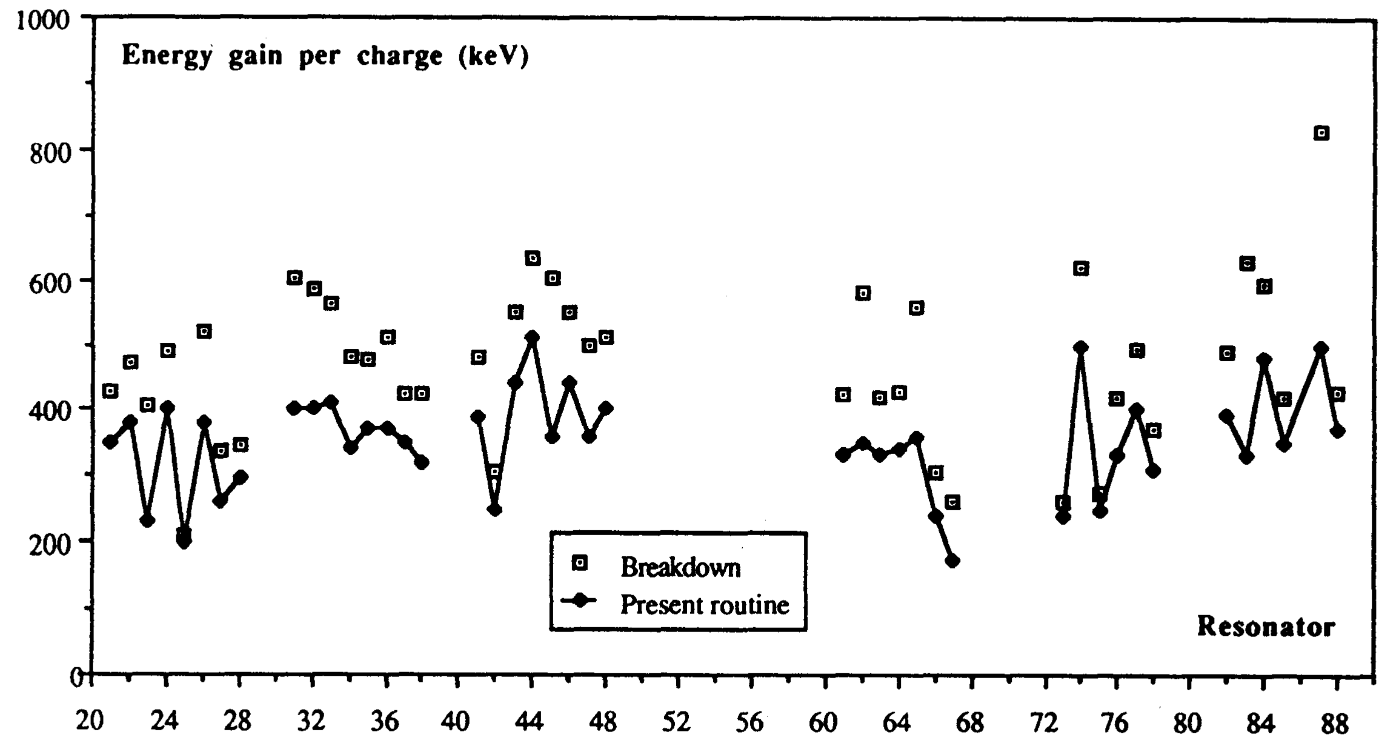

Figure 6 Maximum (squares) and routine (solid line) accelerating voltage gain per charge of the resonators of the full machine. The fields of the two high energy rebunchers were not measured. Resonators are identified as in figure 5. The energy gains were measured with an $^{16}O^{8+}$ beam selected at the output of the second stripper (the first being at the Tandem terminal) and corrected for the phase of the accelerating field and for the transit time factor. Four resonators were down at the time of the measurements.

The final energy of the $^{16}O^{8+}$ beam was 157 MeV. A $^{58}Ni^{20+}$ beam was later accelerated (with only two resonators missing from the accelerating line) up to an energy of 357 MeV.