Proceedings of the third workshop on RF Superconductivity, Argonne, September 14-18, 1987

Fabrication, tests, and RF control of the 50 superconducting resonators of the Saclay heavy ion linac.

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Two types of niobium superconducting resonators are currently in use in the linac[1]. Outer cylinder and RF ports are identical for both designs but internal structures are different: full wave helix (λ) with three gaps behaviour or half-wave (λ/2) with two gaps behaviour (see figure below). The λ structure is based on a Karlsruhe design[1].

All cavities (34 λ and 16 λ/2) are now fabricated, tested for field, and mounted in the eight machine cryostats.

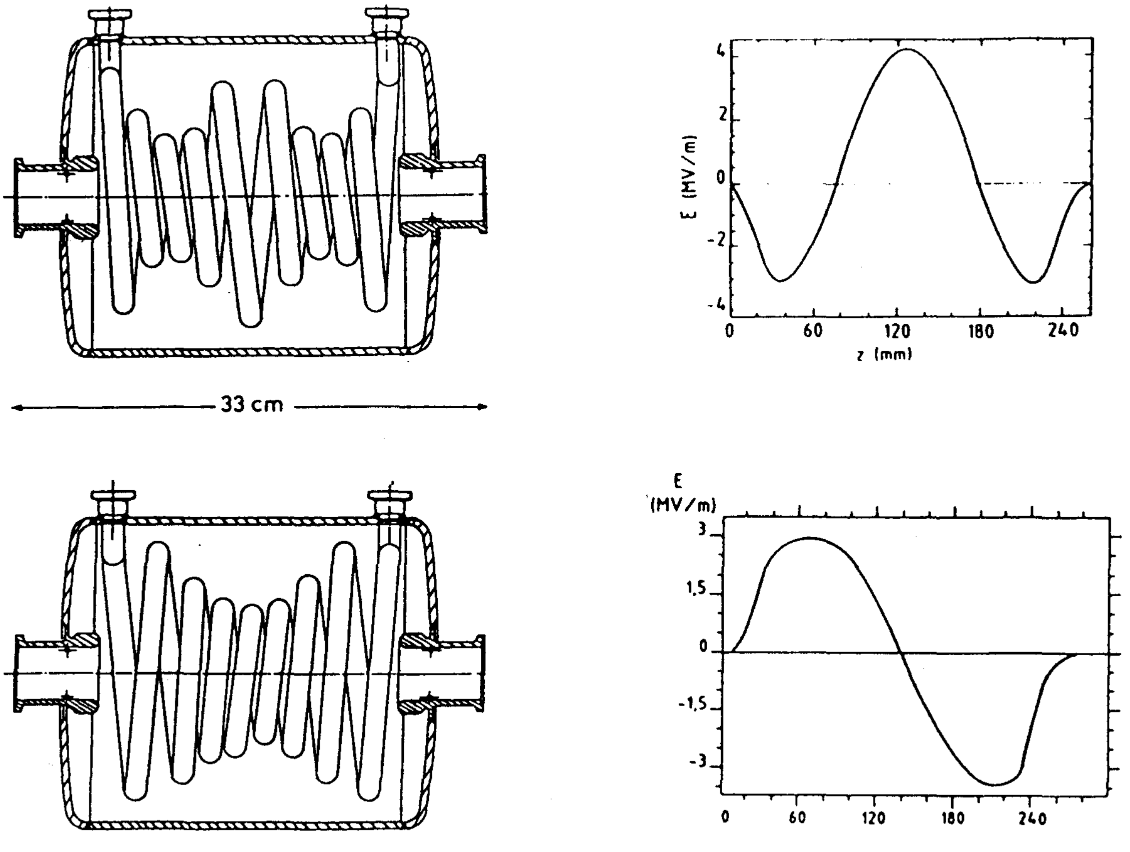

Fig. 1. Helix resonators and corresponding electric field distribution along axis

Resonator characteristics are listed in the table below. Frequencies are multiples of the low energy bunching frequency (13.5 MHz). The high magnetic fields arise at the welds joining helix to can (λ/2) or half-helices together (λ).

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RESONATOR DATA

Resonator	λ	λ/2	
R.F. resonance frequency	135	81	MHz
Stored energy	0.56	0.79	Joule
Geometric factor	7	9	Ω
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 (β)	0.085	0.085	v/c

The main advantage of the λ/2 helix is a much flatter variation of the accelerating potential with the ion velocity[10] giving thus a higher acceleration to the heaviest masses at the beginning of the machine (see figure 2). Another important feature of that λ/2 helix is that it can be wound from a single 3 m long tube, whereas λ helix fabrication requires a additionnal weld in a high magnetic field region at the junction between the two half-helices).

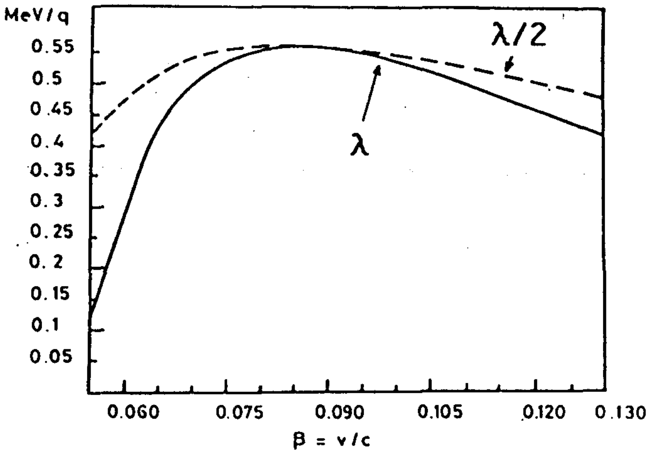


Fig.2 Energy gain per charge versus ion velocity (β=v/c).

1. Cavity fabrication.

Nb material. Standard grade niobium was used for the first cavities. Helices (where both electric and magnetic fields are the highest) were later wound from RRR 80-120 Heraeus tubes. All parts are carefully inspected under microscope. Inclusions of foreing particles (mainly iron or Nb oxides) and cracks are removed with a low velocity grinding wheel (grains of aluminium oxide imbedded in rubber).

Machining. Non critical operations (spinning, rolling) were done by local industry. One of the most critical operation is helix forming. This is done at the lab facility by winding a niobium tube (15 mm in diameter and 1 mm in thickness) on a stainless steel mandril. Prior to winding, the tube is filled with water and frozen by immersion in liquid nitrogen. Before separating the helix from the mandril, a heat treatment of 1 hour at 650 °C is applied to remove the stresses in the niobium material. After this treatment, the helix keeps the shape it was given by the mandril within a fraction of a millimeter.

Welding. Plasma and T.I.G. welding (glove box, high purity inert gas) give us consistently high fields. Unfortunately it requires skilled operators. Attempts to replace that man-dependent operation by electron beam welding at an industrial company gave lower fields and were not pursued because the shape of the structure could not be modified at this stage.

Frequency adjustment. Each resonator is tuned to the proper room temperature frequency by deforming the helix with two strong steel inserts introduced in the helix ends. A stress relieving heat treatment is later applied (650 °C) in our vacuum furnace. Slight frequency adjustments are sometimes necessary after treatment.

Surface treatments. The first cavities produced were electropolished using the Siemens process (200 microns). This time consuming treatment give mirror-like surfaces. It was replaced later by much faster hydrogen-free chemical polishing (1-1-2 buffered mixture) to remove 80 microns. The orange-peeled surface obtained with chemical polishing gives nevertheless similar Q values and fields. After chemistry, the cavity is quickly rinsed in 4 MΩ.m water to avoid formation of unsoluble phosphates. Final rinsing (shower + circulation) is done with filtered high purity water (17 MΩ.m) in dust free (class 100 laminar air flow) environment. If mounting in cryostat is delayed, the resonator is stored with a mild over pressure of clean argon gas.

2. Cavity performance.

Tests. Each cavity is mounted, under laminar air flow, in our test cryostat and checked for field, Q value, frequency, and defect location. Defect location is obtained by lowering the temperature of the helium bath well under the l point of liquid helium so that the very sharp heat pulses induced by the quench propagate with second sound velocity (20 m/s) in the superfluid helium inside the helix. The quench position on the helix is determined by the time difference between pulses observed with two fast heat detectors (Allen Bradley carbon resistors thinned to 0.5 mm) mounted at each end of the helix. Since high RRR material is used and cleanliness is improved, quenches no longer originate from helix surface defects. They are now located at welds joining helix to can (λ and $\lambda/2$) or half helices together (λ) . At these points the magnetic field is as high as 600-800 Gauss at E_{acc}=2.2 MV/m . Likely candidates for defects are metallic inclusions from the T.I.G. welding electrode (as observed by X ray radiography in sample welds) or impurities in the inert gas.

Q values are greater than 3.10^8 (see figure 3 for a typical accelerating field dependence of the quality factor) and the average field is now around 2 MV/m. One can see also clearly on this figure the paramount importance of mounting the cavity under laminar air flow to prevent dust contamination. Without this precaution, heavy electron emission appears at moderate field (1.5 MV/m in the example given). The higher low field Q value observed in the second test of the same cavity must be attributed to the light chemistry done between the two tests. Note that in the last test the quality factor stays above 3.10^8 up to 2.2 MV/m accelerating field.

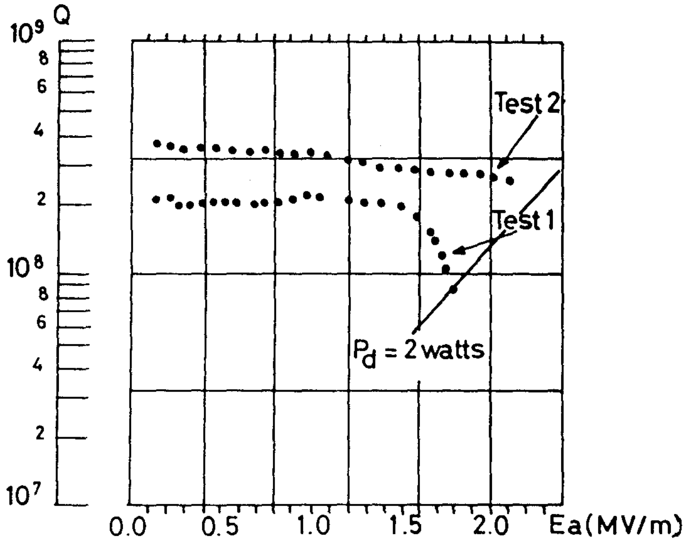


Fig.3. Q value vs accelerating field
1. First test without dust-free mounting
2. Second test with light chemistry and dust-free mounting

Cavity selection. Minimum accelerating field of 1.8 MV/m (450 keV energy gain per charge) is requested for mounting in the machine cryostats. This field was not attained for some resonators after several 20-40 microns etchings (due to the compactness of the structure close inspection is difficult and mechanical repair impossible). These resonators were then discarded. This is made possible by the relatively low rejection cost ($4000 per resonator, excluding lab personnel expenses).

On beam performance. Two operations were found essential to attain high fields with low electron activity in the beam line cryostats.
1.High purity water rinsing and dust-free mounting.
2.Thorough outgassing of cavities at room temperature and during cooldown. Outgassing of helix (and conditioning) is done with pulsed RF power (100-200 W peak and 10-20 W average) and strong coupling.
With these provisos, the fields attained in the machine cryostats are similar to those measured at our test facility (best beam measured accelerating field: 2.7 MV/m). An other point worth mentioning is the adequate cooling by the 4 K helium forced flow through helices.

NbN tests. The main field limitation of our resonators arise from welding defects. They may be due to heavy metallic inclusions (tungsten). In that case eddy currents heat up the normal conducting particles above the critical temperature of the surrounding superconducting niobium, inducing a field breakdown. Higher Tc material would then be very favourable for increasing the accelerating field. NbN has a Tc of 17 K and can be formed at the Nb surface by a simple diffusion process at moderately high temperature. Our procedure is the following:

-Outgassing of resonator at 1000 °C under vacuum of a few 10^{-7} mbar.

-NbN film forming (25 min at 650 °C) with 10^{-3} mbar of filtered nitrogen evaporated from a dewar.

-Fast cooling by introduction of 1 bar of nitrogen in the furnace. This operation is supposedly beneficial to film stability[2].

Two resonators were treated and 10 nm NbN layers were formed on the Nb surface. Tc around 13 K were measured on test samples. As can be seen on figure 4 the low field Q value measured after nitridation is 40% higher . The breakdown field level is unfortunately the same as that of the untreated cavity. It is probably due to an insufficient thickness of the NbN film. Thicker film formation is currently under development.

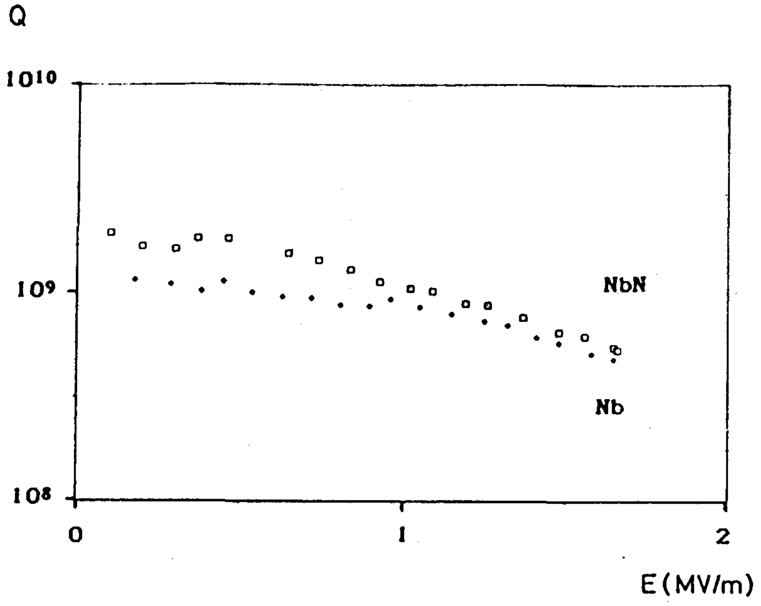


Fig.4. Q values vs accelerating field before and after NbN layer formation.

Magnetic field shielding. Magnetic field vortices are created in the superconducting Nb when cooling is done under external magnetic fields (mainly the natural earth field). In these vortices the magnetic field is close to B_c and Nb is normal conducting, with the result of increased RF losses[3]. Simple flux conservation arguments indicate that the total surface occupied at 4 K by these vortices should be proportionnal to the external magnetic field B before cooldown. The increase ΔR_s in the surface resistance is then expected to be proportionnal to B.

The data given in fig 5, obtained for a $\lambda/2$ resonator, are indeed in good agreement with a linear dependence of ΔR_s with B. To obtain these data, the resonator was placed inside a long solenoid and a mumetal shield to eliminate the earth field. Cycles of cooldown with different B values and reheating above T_c were applied before each Q measurement. The results given in fig 5 were obtained at low field (0.25 MV/m).

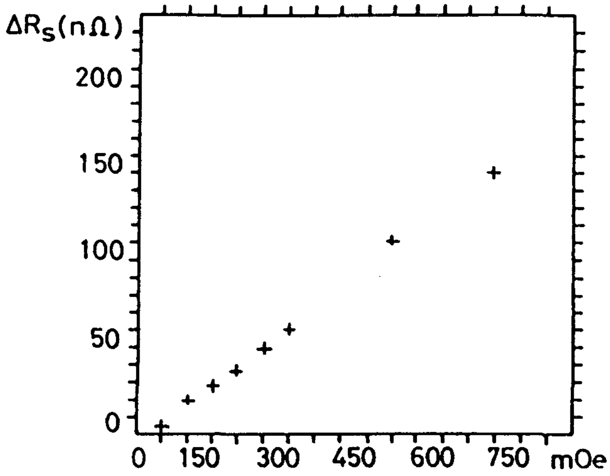


Fig.5. Additional surface resistance ΔR_s induced by cooldown under external magnetic field. R_s value at B=0 is around 45 nΩ.

The resonator Q is degraded by a factor of 2 by the earth field. B field was reduced to 50 mOe in our beam line cryostats with two 0.1 mm sheets of high µ alloy (CONETIC-AA), surrounding respectively the He vessel and the LN_2 thermal shield.

3. Vibrations

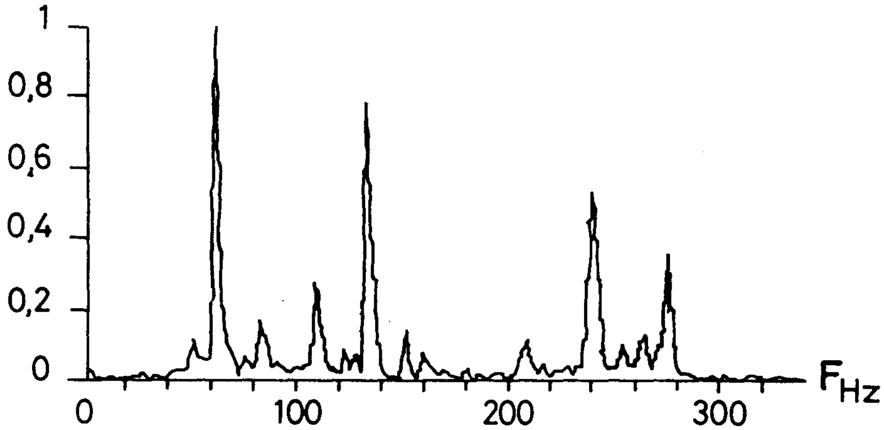
Vibration induced frequency excursions well outside the very narrow bandwith of superconducting cavities are particularly severe for heavy ion structures. In this respect the mechanical weakness of the helix which is the velocity matching device of our resonators renders this problem more acute. These frequency excursions make it impossible to lock the phase of the accelerating field to that of the master oscillator (M.O.) of the machine without strong coupling to the cavity and thus considerable RF reactive power exchange between the cavity and the outside (5 kVA max in our case). With direct coupling (as for example in the Stony Brook design[7]) this very expensive power would be requested from the driving RF amplifier and lost in the dump load of the amplifier isolator.

An elegant way out of this difficulty is to connect to the cavity an external voltage controlled reactance (V.C.X.) dynamically adjusted as to compensate the variations of the cavity eigenfrequency. The RF power needed is then lowered to an acceptable value (130 W).

This technique has been originally developped at Argonne[4] on the split-ring structure and at Karlsruhe[5,6] on helical cavities. Our V.C.X. design is very similar to that of the Karlsruhe group and is now used on all linac resonators.

At the very beginning of our project, we were aware of the great sensitivity of our helices to mechanical disturbances. The first step we took was to identify the main vibration sources and to decouple them from the building and from the cryostats. For example the primary vacuum pumps and the helium compressor of the refrigerator were isolated from the floor by massive vibration filters, and bellows or flexible connections were inserted on tubing where possible. Great care was also taken in the cryostat design to include protection against external vibrations.

Frequency spectra. In order to identify the main vibration modes, a free running λ cavity was phase locked on an external synthetizer. The frequency error signal was then analyzed by fast Fourier transform (see figure below).

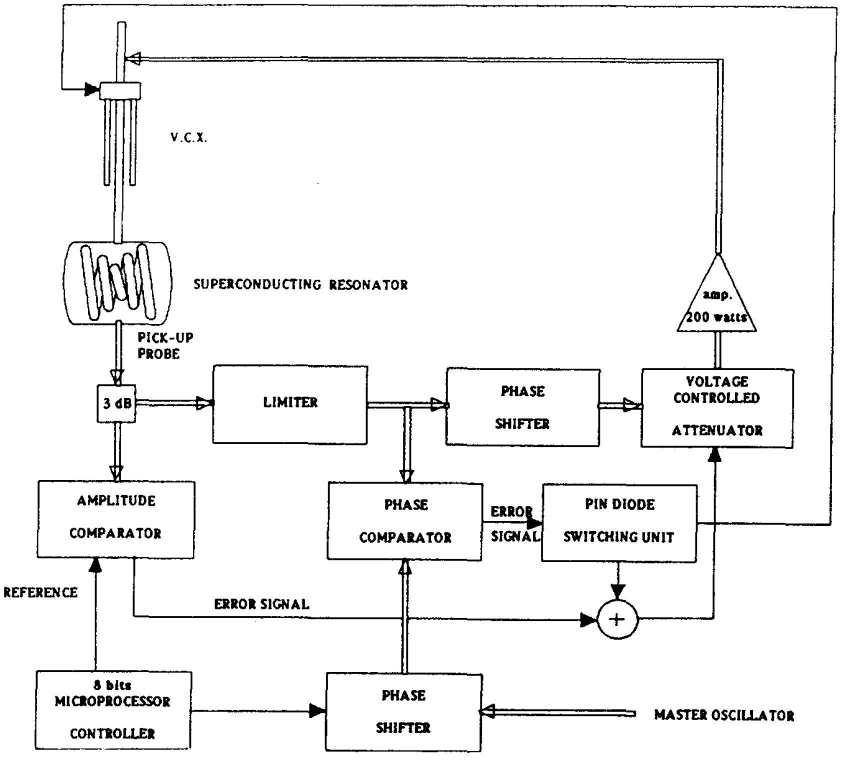


The main mechanical vibration mode is around 60 Hz. The 240 Hz mode, weak when the

above spectrum was taken, is sometimes excited to such a extent that phase lock within the VCX window is not possible without strong electronic damping (see further).
The width of the frequency spectrum of the cavity varies between 100 Hz and 300 Hz FWHM depending on vibration level and electronic damping. This is much more than the values measured at Argonne[4] (100 Hz base width) or at Stony-Brook[7] (50 Hz FWHM for the split ring and less than 10 Hz for the quarter wave resonator). It is nevertheless well within the frequency window of our V.C.X (800-1000 Hz).

4. RF control.

Each resonator is individually controlled by a Motorola 6800 microprocessor giving to the operator full access, via a CAMAC link, to the many parameters necessary for cavity operation. The various phase and amplitude reference values are also given to the regulation electronics by this microprocessor. Like for all the other microprocessor units of the machine, driving for example the magnets and the vacuum pumps, CPU and interface boards were designed and partially fabricated in the lab.
The RF control electronics is sketched in the diagram below:



Oscillating loop. RF oscillation of the cavity is maintained through a self excited loop as in other designs[4]. The pick up signal (P.U.) travels through a limiter, a phase shifter, an amplitude modulator, and is sent back to the cavity after power amplification. Phase shifter and power coupling to the V.C.X. are so adjusted as to reduce to a very small value the power reflected back by the cavity. Note that a single power coupling is used for cavity and V.C.X.

Amplitude regulation. The P.U. amplitude is compared, after detection, with the reference value, and the error signal, after amplification and filtering, is used to drive the amplitude modulator, closing thus the amplitude regulating loop.

Mechanical tuner. Resonator slow frequency tuning is done by elastic deformation of the helix with two stainless steel tubes introduced in the helix ends and activated by a variable reluctance stepping motor in the helium bath. This motor has **no permanent magnet** which is indeed a very important property in the vicinity of a superconducting cavity. Roll bearings were replaced by thoroughly degreased stainless steel models. The tuning range is around ±150 kHz for a λ helix

Phase regulation. The phase error signal is obtained at the output of a balanced mixer comparing master oscillator and P.U. signal phases. The error signal is digitized to control the 6 PIN diodes of the V.C.X.

V.C.X. This crucial component is made of 6 coaxial lines shorted to ground at an end (length>λ/4) and connected in parrallel at a common point (star point) to the main coupling line to the cavity. A PIN diode is mounted on each coaxial line at an intermediate position. When switched on by the fast V.C.X electronics the PIN diode acts as an effective RF short, changing the length of the coaxial line to a value <λ/4 and thus the total admittance seen at the star point. The variation of the cavity eigenfrequency will then be corrected by one step.

The nominal tuning width (800 Hz) can be changed by ± 40% by moving dielectric blocks inside the room temperature part of the main coupling line.

The RF amplifier output power varies with the number of PIN diodes in the "on" state. Maximum power is around 130 W, 60% of which is dissipated in the PIN diodes and the remainder as ohmic losses in the coaxial and main coupling lines. Each PIN diode housing is water cooled.

Because of high RF currents (18 A peak) and as low RF and thermal losses are mandatory for 4 K operation, the design of the cold part of the main coupling line was very difficult[8]. In a first model the coupling was made adjustable by moving the antenna in and out of the cavity. This mechanical adjustment was implemented because strong coupling is necessary at room or liquid nitrogen temperature for RF conditioning of the cavity. This first design was rejected in reason of bad RF losses and poor cleanliness due to common vacuum between cavity and coupling line. Our new and cheaper design is much simpler and much better for cavity cleanliness: the geometry of the line is fixed permitting vacuum separation by an aluminum oxide window at the input RF port of the cavity. Strong coupling is achieved nevertheless for conditioning by transforming the line into a quarter wave resonator by means of a removable short. This resonator acts as a voltage raising transformer. Power is fed to the resonator with a removable auxiliary coupling.

Damping loop .When the V.C.X was put to use for the first time at moderate or low field level, it performed well and vibrations were easily compensated. When tried at higher fields, ponderomotive instabilities developed, increasing dramatically the out of lock time. This problem was beautifully cured by the method already in use at Argonne[9] and Karlsruhe[6]. The idea is to superimpose to the amplitude error signal, and thus to the field of the cavity, a component proportionnal to the frequency error signal with the right 90° phase. This will change dynamically the frequency of the resonator and will generate a differential ponderomotive force in the right direction to counteract instabilities. As a bonus the overall width of the frequency spectrum can be reduced, with full damping, by a factor of almost 3. The obvious drawback of this procedure is to lower the amplitude resolution of the accelerating field. Since damping is needed only when external vibrations increase or ponderomotive instabilities develop, the 6800 microprocessor sets automatically the right amount of damping necessary at a given time for proper phase lock.

Performances. Amplitude and phase stabilities were measured for a typical beam line resonator: phase error was 0.2 degree FWHM and relative amplitude resolution was 10^{-3} FWHM without damping and $5.\ 10^{-3}$ with strong damping.
During the Christmas 1986 beam experiment with the first half of the machine (4 cryostats and

21 cavities at high field), the total out-of-lock time percentage was less than 0.05 %. The measured frequency spectrum widths were less than 100 Hz FWHM with moderate damping.

Conclusion. Helix resonators were considered by several laboratories (Argonne, Caltech, Karlsruhe) in the past as interesting accelerating structures because of their simplicity. Vibration problems were of course encountered in the early designs and their development was stopped at the benefit of intrinsically more stable (but also more expensive) structures. We feel that this rejection was not really justified because helix vibrations can be fully mastered with appropriate counter-measures. The very low out of lock time percentage that we measured in our first acceleration test with 21 cavities is a strong proof of the above statement. The full machine is scheduled to give its first beam to experimental areas at the end of 1987.

Acknowledgements. Thanks are due to a number of people of the S.T.I.P.E. cryogenics group involved in resonator machining, welding and cryostat design, fabrication, and mounting. This accelerator could never have been built without the very precious help we received from the group of Pr Citron at Karlsruhe in communicating to us their RF superconductivity experience. Help is particularly acknowledged for cavity and V.C.X design.

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