STATUS AND DEVELOPMENT OF SUPERCONDUCTING 2 GeV ACCELERATOR AT HEPL

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The superconductivity of niobium and the unique thermal properties of superfluid helium can be combined to construct a most remarkable accelerator. Normally one would have an effective shunt impedance of, say 30 MΩ/m. For fields of 10 MV/m this requires 3 MW/m. In turn, this limits the maximum duty cycle and the minimum energy spread each to a percent or so. Superconductivity however, can yield improvement factors of better than 10^6 (i. e. 3×10^7 MΩ/m). Such a conservative superconducting accelerator could operate with 3 W/m loss to the refrigerant, 1 kW/m beam loading at 100 μa CW and an energy spread of 10^{-4} or perhaps someday even 10^{-5}. The properties of superfluid helium are essential ingredients of such an accelerator to provide the stability required.

Although there are a lot of things still on the drawing board, in principle all the problems are solved. Most considerations have been analyzed in detail in a paper by Schwettman, Turneaure, Fairbank, Smith, McAshan, Wilson and Chambers[1]. The final problem to be solved was tuning. A month ago Turneaure and Nguyen[11] tuned a niobium cavity with a Q of 10^9 through 2×10^{-4} of its frequency with a superconducting niobium plunger with a degradation of the Q of only 5%. One no longer has to be an optimist to believe in the practicality of the superconducting accelerator. Table I shows the characteristics of the superconducting niobium linac now being built.

The cryogenic system has been thoroughly described by Schwettman[6] and McAshan[2]. Briefly there is a refrigerator that removes 300 watts from helium gas at 15 Torr turning the gas into superfluid helium at 1.85°K. The fluid is piped to the dewars and the gas returned to the refrigerator. The main accelerator will be in six 24-meter dewars and the capture section and preaccelerator in one 5-meter dewar. Each 24-meter dewar will consist of four 6-meter sections sharing a common vacuum. Each 6-meter dewar section will have just under 6-meters of separately powered, phased, and tuned accelerator, 600 liters of superfluid helium, a nitrogen shield, alignement adjustments, and a heat leak of 1 watt to helium and 30 watts to nitrogen. Fig. 1 is a picture of a section of helium dewar after wrapping with super insulation.

A potential problem is that of frequency detuning, which can be caused by either a change in temperature or pressure. Temperature changes cause thermal expansion and changes in skin depth, both change the effective size of the cavity. Both of these effects require temperature stability on the cavity walls of about 0.4°K. The temperature inside the cavities should be easily within a tenth of that allowed, especially with the thin wall construction being used. A change of 1 Torr around a copper structure was found to cause detuning of 1 part in 10^8, which is acceptable when compared to the loaded Q. This corresponds to a temperature change of 0.02°K in the helium. Only in superfluid helium could one design a system to carry off the waste heat from a 150 m linear accelerator with an overall temperature difference of only 0.01°K which is one of the criteria in the design.

At lower temperatures the expected improvement in Q is offset by the difficulty of refrigeration. However, both to reap the benefits of superfluidity and to stabilize the skin depth, it is essential to work below 2°K. The temperature of 1.85°K was chosen because it is below the temperature of maximum thermal conductivity thus providing a stabilizing thermal "force". At this temperature the specific heat of the superfluid is nearly that of water providing a rather large heat sink at 100 liters of the superfluid per meter of accelerator.

The niobium accelerator itself is a compromise among shunt impedance, the average energy gradient, and cost, providing that at reasonable fields there is no multipactoring nor electric nor magnetic breakdown. The structure has been developed by Schwettman, Smith[3], Jones and Turneaure[4,5]. Figure 2 shows the fundamental unit of the structure designed for 1.3 GHz. It is made up of quarter wavelength pieces which have been hydroformed, machined and electron beam welded together. The unit is heat treated in vacuum, chemically polished, and heat treated again. The units are joined together with indium. Within the unit, it is excited in the π mode, and the units with respect to each other are excited in a super $\pi/2$ mode. The overall mode provides the unexcited cavity needed at each end of each unit for the indium joint which would be too lossy in an excited cavity.

The results of the most recent experiment are shown in Table II. These results indicate that neither refrigeration nor electric field emission will be the limiting factor of the accelerating gradient. It appears that the critical magnetic field will set the limit. Among other advantages of niobium over lead, is that its critical magnetic limit is 75% above experimental observation so there is still room for improvement. Figure 3 is a picture of a test niobium unit.

The control and stabilization of the accelerator is accomplished by a feedback system designed by Suelzle[7] Early this year a lead plated copper capture section was operated for six weeks and could have run indefinitely. The experiment is described in detail by Jones, McAshan. and Suelzle[9,10]. The experiment demonstrated, besides the general workability of the idea, that field levels could be controlled to better than 10^{-4} and phase to much better than the necessary $0.1°$, that two superconducting RF cavities can be tuned to the same frequency, that electron orbits were as predicted and bunching easily accomplished (Chambers[8]), and that an appropriate injector has been built.

At the top of Fig. 4 there are two curves superimposed. The one with the greater ordinate is the field level in the cavity, the other is the input power level. As the cycle begins the power is fed in at a high rate and the field level builds up to the predetermined level of 3 MV/m in 0.01 seconds. At this time the input power level reduces to near zero and remains there for about 0.025 seconds when the beam is turned on. Power is increased to compensate for the beam loading without noticeably affecting the field level. The middle section of Fig. 4 is the field level trace highly magnified on the oscilloscope. One vertical unit is 1.2×10^{-3}. The pip at 0.035 seconds is the beam coming on and to the right of that the field is clearly stable to 10^{-4}.

In addition to the capture section there was a superconducting RF separator. It provided the test of tuning two cavities to the same frequency and it was used to separate electrons of different phase. The bottom of Fig. 4 is a double exposure. The wide spot on the left is with the RF separator off. After the camera was moved horizontally and the separator turned on, the vertically-spread spot on the right was photographed. The phase spread appears to be no greater than 2°. By quantitative measurements with a movable collector FWHH was measured to be 2.0° which was the valve predicted by calculations.

The 180m$\times$4m diameter tunnel is complete and utilities are being installed. The refrigerator is installed and tests have begun. The end station is being built and will be completed next year. Another tunnel 2m$\times$2m and 22 meters from the first is soon to be started to provide 180 meters of electron photon interaction area and a return path for recirculation.

In the visionary stage now are a superconducting proton linac that harnesses the alternating gradient focussing principle for both longitudinal and radial focussing with RF fields only, and the next generation of refrigerator with low temperature recompression of the helium.

A superconducting accelerator is not cheap, but it is a bargain. The refrigerator operates on 7 doll. worth of electricity (700 KW), and 4 doll. worth of liquid nitrogen (110 l/hr) per hour. The nitrogen for the radiation shield in the dewar costs another doll. 1/hour. The power for the RF supply is directly proportional to the beam power and taking efficiency and overdrive into consideration should cost 0.03 doll. per KW/hr of beam. The direct costs for a superconducting accelerator are relatively small compared to the total cost of the modernization of the High Energy Physics Laboratory at Stanford. Table III shows the costs.

Table I

Electron beam characteristics

Gun	80 kV±10 V	$\pi \times 5$ mm-mr
Chopper-Buncher	± 5°	±1.0 kV
SC capture section	±0.5°	2 MV±18 kV
SC preaccelerator	±0.5°	30 MV±20 kV
150 meter accelerator		100 μa CW
2 GV ±0.01%		0.1 mm-mr

Table II

RF Cavity experiment

Date	June 1, 1969
Material	EB welded Nb
Frequency	8,7 GHz
Temperature	1,25°K
Average field on axis	8,4 MV/ft.=27 MV/m
B_{max} at surface	1060 Gauss
E_{max} at surface	70 MV/m(!)
Q	8×10^9
Duty cycle	100%
Duration	90 minutes
Reason for termination	Experimenter tired
Higher field limit	Low Q, probably magnetic
Lower field Q	10^{11}
Improvement factor	10^7
Experimenter	J. P. Turneaure

Table 3

Costs, installed

	K doll.
Refrigerator	500
Dewars 8 c He Manifold	600
Niobium cavities	900
Vacuum furnace	200
RF supply and control	900
S. C. Accelerator	3100

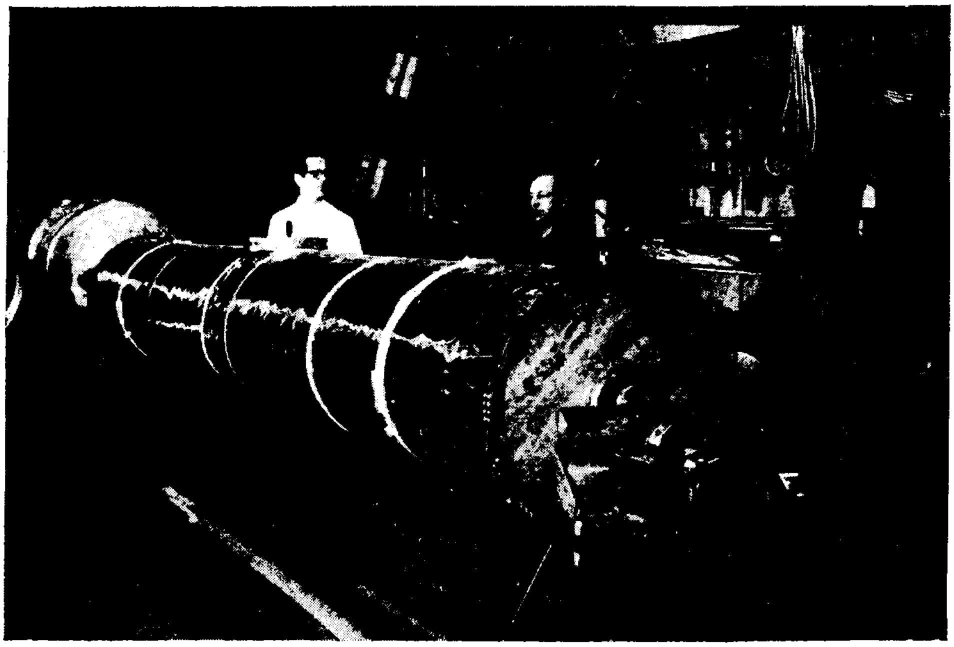

Fig. 1 Six Meter Section of Helium Dewar

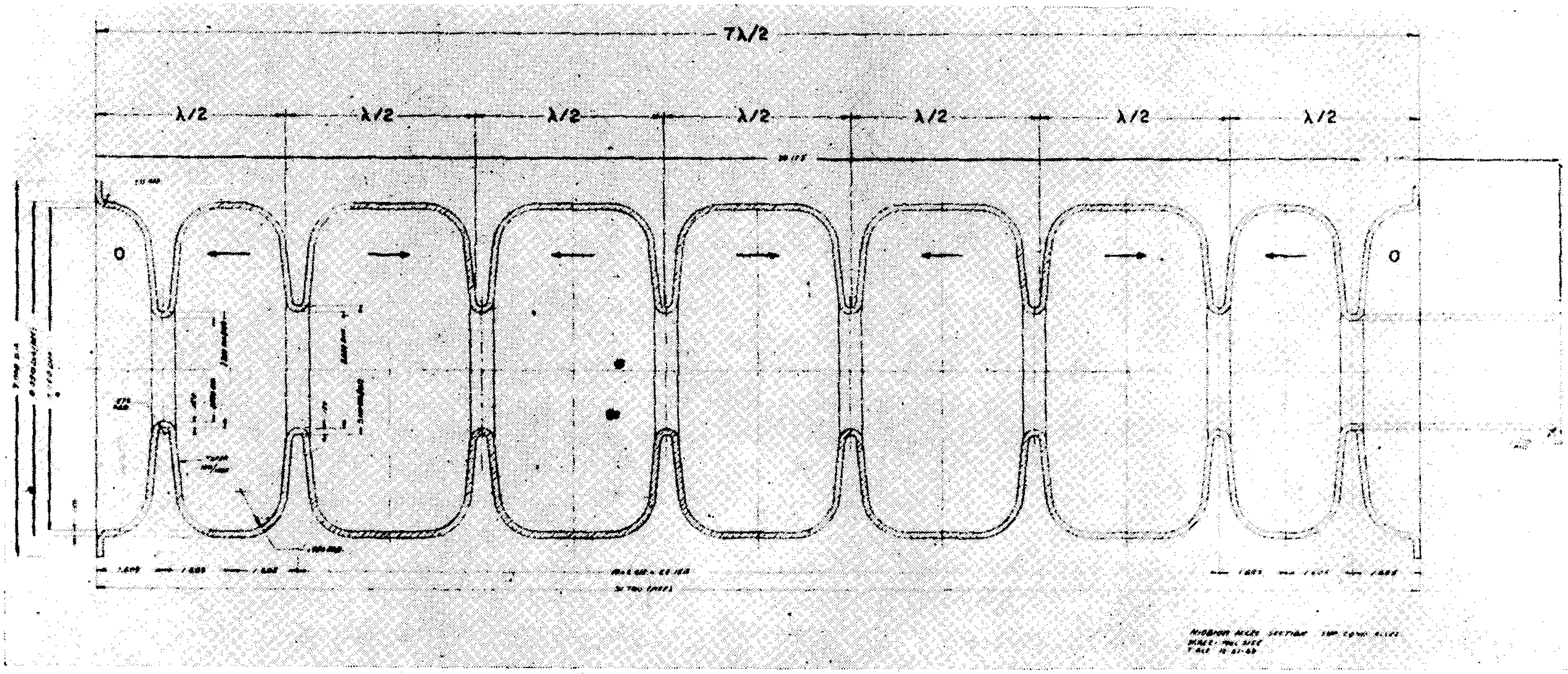

Fig. 2 Unit of Accelerator

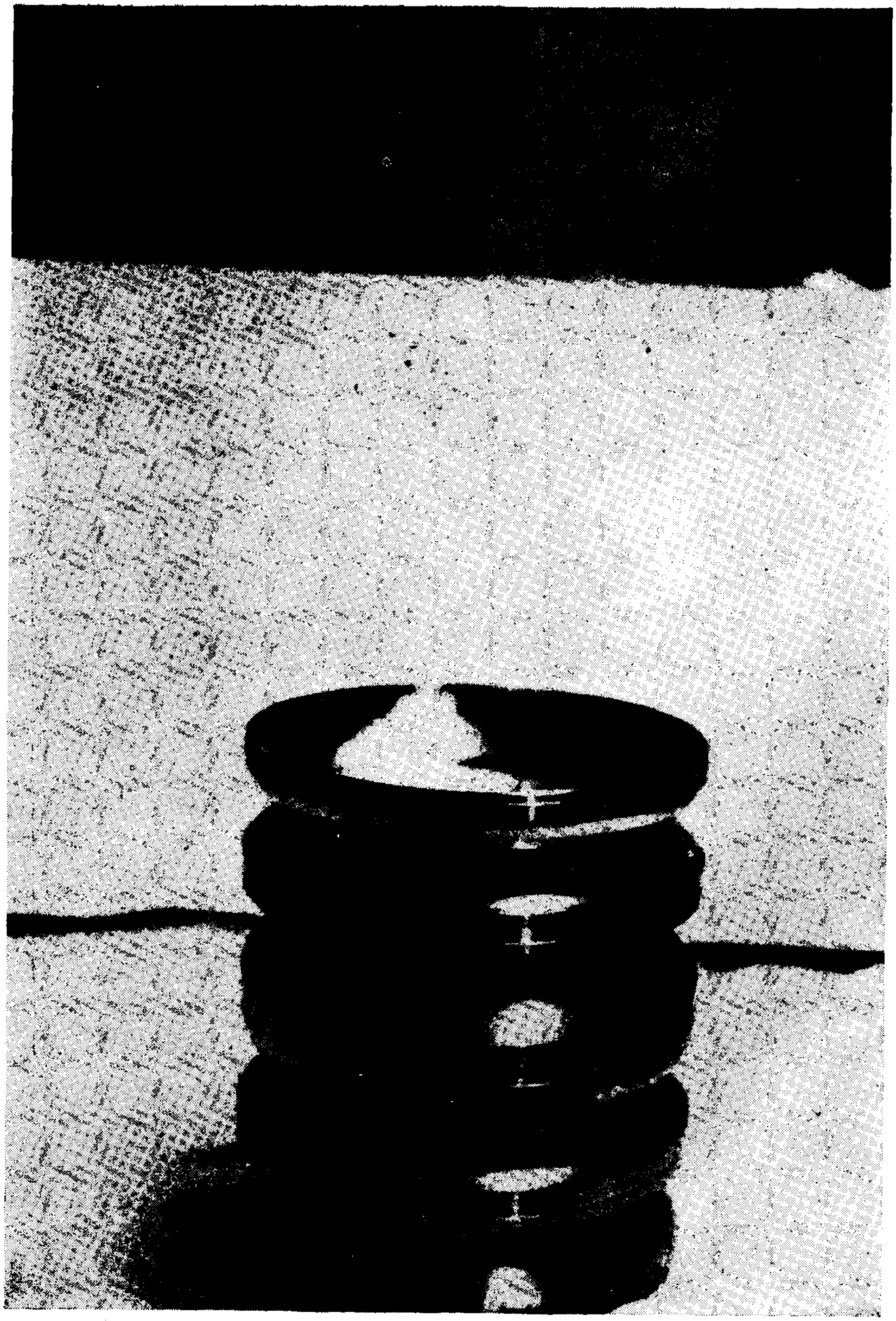

Fig. 3 Test Unit

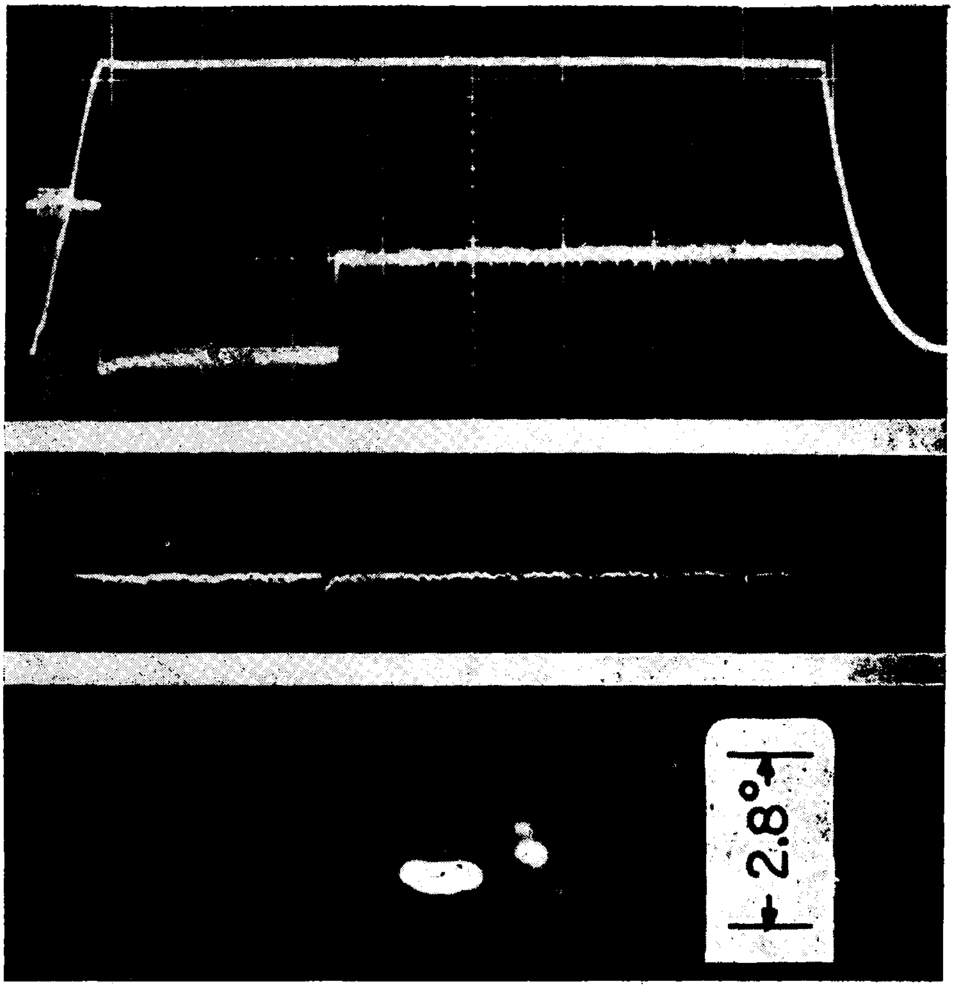

Fig. 4 (a) Field Level and Power In
(b) Field Level Amplified
(c) Beam Spot and Phase Separated Beam

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ДИСКУССИЯ

Citron: As I understand the tuning problem has been solved. Could you reveal how it has been solved?

Chambers: A superconducting niobium Planger is inserted into the R. F. cavity. The details will not be in reference II but may be obtained by writing directly to Dr. Turneaure et help, Stanford.

Bruck: When are you going to complete the construction?

Chambers: The first section consisting of the capture section and preaccelerator is scheduled for test in March, 1970. Certainly a significant piece of the accelerator will be completed by the end of 1970, or as much sooner as we can make it.

Зыков: Какова чистота ниобия в %?

Chambers: The best commercial grades available (Wah-Chang Corp, New York, N. Y.) were used, 99,9% pure is typical, I refer you to reference 11 for a discussion of the subject.

Коломенский: Нельзя ли подробнее сказать о технологии покрытия?

Chambers: Before electron beam welding it is etched about 2. Afterward it is brought up to 1900 C in 4 hoursm held there for 10 hours (ultimate vacuum 10^{-9} or 10^{-10} Torr) and brought back to room temperature in 8 hours, it is etched another 10 in HNO_3 and HF. it is then given a similar heat treatment and there after kept under dry nitrogen. This will be discussed in reference II.