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SUPERCONDUCTING ACCELERATOR STRUCTURES FOR MEDIUM ENERGY PROTONS

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Introduction

Superconducting Alvarez structures operating at about 720 MHz could be used to accelerate protons between about 5 and 150 MeV. The energy range from about 20 to e. g. 800 MeV could be covered by 720 MHz superconducting Slotted Iris structures. We built niobium structures of each type. The Alvarez I (AI) and the Slotted Iris (SI) were designed to study high field performance only (Fig. 1). Alvarez II (AII, Fig. 2) is to be used also in the beam line of the prototype superconducting proton linear accelerator under construction at Karlsruhe [1].

Structure Design

The optimization of structure design involves several interdependent aspects [2]. Acceptances in longitudinal and transverse phase space are the larger the lower the operating frequency of the accelerator. But if the frequency is chosen too low both Alvarez- and Slotted Iris structures will have a diameter too large to enable application of the surface preparation necessary for superconducting niobium structures. A compromise is 720 MHz, at which the structure diamter is about 30 cm, and the acceptances are large enough to allow acceleration of a 100 µA beam without appreciable particle loss. Closely related is the choice of beam hole diameter: a large diameter is favored with respect to transverse acceptance and ease in chemical surface preparation; a small diameter is preferred with regard to transit-time factor T, peak fields (E_p, B_p) and shunt-impedance (Z_{eff}); a diameter of 2 cm turned out to be reasonable.

The accelerating field E_{eff} achievable in superconducting structures is limited by electron loading, or by magnetic or thermal breakdown. Experience with accelerator structures has shown that electron loading problems generally are the ones limiting the field first. Therefore in optimizing the structure geometry with the help of the LALA-program [3] most emphasis was put on minimizing E_p. The corner at the bore of the beam hole was rounded ellipticaly, the ratio of the ellipse axis in the axial direction to the one in the radial direction being 1 : 2. A similar shape was given to the corner at the outer radius of the Alvarez drift tubes. Both E_p and B_p are enhanced on the stems holding the drift tubes by a factor of two compared to a structure without stems. B_p reaches its maximum where stem and drift tube join. These theoretical predictions were confirmed by bead measurements. The stem losses were calculated by perturbation theory.

In the Slotted Iris structure B_p is maximum at the coupling slots in the discs which separate the structure cells. To ease fabrication, these slots were chosen to be circular (4.6 cm diameter, giving a passband width of 17 MHz for 4 slots per disc). By bead measurement the enhancement factor of the magnetic field at the slot was determined to be 2.

The principal parameters of the three structures discussed in this paper are summarized in Table I. Definition are: $E_{eff} = T\int E_z dz/L$; $Z_{eff} = E^2_{eff}\, L/P_s$;
$Q_o = \omega\, W/P_s = G/R_s$; L = electrical length;
R_s = surface resistance.

TABLE I

PRINCIPAL STRUCTURE PARAMETERS

	unit	AI	AII	SI
frequency	MHz	720	720	720
mode of operation	-	0	0	π
number of cells	-	2	5	2
proton design energy	MeV	5	5.86	20
electrical length	cm	8.6	23.2	8.4
Q_o (Cu, 300 K)*	10^4	2.0	3.0	0.79
G	Ω	145	209	55.2
Z_{eff}/Q_o	Ω/cm	5.66	6.39	10.6
W for E_{eff} = 1 MV/m	10^{-2} J	3.46	8.06	1.76
E_p/E_{eff}	-	7.1	6.8	3.06
B_p/E_{eff}	mT/MV/m	10.6	10.2	7.5

* for AI and AII with stem losses, for SI without slot losses.

AII was designed to cause no mechanical vibration problems. Its Q-value will be loaded to 10^7 by the rf input probe [4] resulting in a loaded bandwidth of 72 Hz. The rf feedback system [5] is capable of compensating for shifts in resonance frequency of up to ± 36 Hz. A shift of this magnitude will result from bending one end plate at the beam axis by only 26 nm. This sensitivity was the main reason for constructing the end plates double walled, allowing access for liquid helium for cooling only to the space in between the two walls. By this means the change of resonance frequency due to helium pressure change is largely reduced compared to the case of a single wall end plate, namely to about 70 Hz/Torr. The change in resonance frequency due to ambient vibrations was measured to be about ± 5 Hz without any special vibration insulation. AII can be tuned in steps as small as 1 Hz by means of a lever and gear system (Fig. 2), and a step motor operating at low temperature [6].

Fabrication and Surface Preparation

All structures were built from reactor grade niobium (Stanford specifications) by Siemens, Erlangen. The inner surfaces were machined to a surface roughness of less than 8 µm. All welds were done by electron beam from the inside of the structure, except for the ones at the circumference of the outer cylinders. Before welding these latter welds all inner surfaces were electropolished by about 100 µm. There are no flanges here, because the resulting joints would have to carry large rf currents, and for this purpose no reliable joints exist as yet.

After fabrication, electropolishing of the inner surfaces is no longer possible because the ratio of beam hole to structure diameter is too small. Possible surface preparations are UHV-firing, anodizing, oxypolishing, and chemical polishing. The latter involves acids which rapidly etch the niobium surface, once only a thin acid film is left on it. Therefore the structures were chemically polished in a device that allowed precooling of both the acid and the structure to -20°C and 0°C respectively. Then the acid was pumped into the structure, and out again quickly after about one minute. It was flushed with distilled water immediately afterwards. Thus the film etching time was less than 30 sec.

Structure Performance

After each surface preparation the Q_o-value was measured as a function of E_p. The cryogenic set-ups for these tests were designed such that no warm gases could be cryopumped into the structures during measurements. Generally the cool-down was such that the UHV-system connecting the structures to the pump was cooled to about 80 K before cool-down of the structures began. The results of these experiments are now presented.

Influence of DC Magnet Field

At the location of the structures the earth's magnetic field was shielded by µ-metal to less than 0.1 µT for AI and SI. To determine the surface resistance R_B due to frozen-in dc magnetic flux a homogeneous dc magnetic field could be turned on inside the shielding. When cooling below the transition temperature, the magnetic flux will be frozen in mainly at surfaces perpendicular to field lines. This enhances the rf losses compared to the case without field applied. R_B was evaluated from this difference, taking into account the partial geometry factor of the surfaces perpendicular to field lines by means of LALA-calculations:

$R_B(720\ \mathrm{MHz},\ B=0.1\ \mathrm{mT},\ T=1.5\ \mathrm{K}) = 6.2 \times 10^{-7}$

R_B scales linear with B [7].

Surface Resistance at Low Field

Small surface resistances could be obtained only after heating the structures to 1200° C at 5×10^{-6}Torr. Apparently, recrystallization of the electron beam welds is necessary. Chemical polishing afterwards resulted in further improvement. An explanation could be that during cool-down in the furnace the niobium acts as a getter, so that the surface layer responsible for the superconducting properties contains many impurities afterwards. This layer is then removed by a chemical treatment, which will furnish a purer surface layer than the one obtained directly after vacuum firing, if the chemicals are rinsed off carefully by distilled water.

Even better results were obtained after heating to 1200° C at 10^{-8} Torr, though also only after additional chemical polishing. Heating to 1700° C at 10^{-8} Torr gave no further improvement for AI, whereas for SI the gain was considerable, even without further chemical treatment. The results were about equal for AI and SI:

$R_s(4.2\ \mathrm{K}) = 1.6\times10^{-7}\Omega$ and $R_s(1.8\ \mathrm{K}) = 7\times10^{-9}\Omega$.

The value at 4.2 K is in agreement with the BCS-theory[8]. At 1.8 K the measured value is a factor of 7 higher than the theoretical one, but still a factor of 10^6 lower than the surface resistance of copper at room temperature.

Electron Loading

Multipacting in the structures under discussion is complicated for two reasons. First the geometry is different from the case of two parallel plates, especially so for the Alvarez (Fig. 1, 2). Second, the electric field is fairly homogeneous only in the gap close to the beam hole. It decreases in the radial direction, where it becomes superimposed by an increasing magnetic field. Therefore it is not surprising that no distinct multipacting levels could be observed, but rather extendend regions of field strength over which electron barriers occurred.

The two point multipacting levels for the gap close to the beam hole were scaled from the results of reference [9]: the first order levels should be between electric peak fields of 0.4 to 1.1 MV/m for both structure types; the impact energy of the electrons should be of the order of 7 keV; levels of higher order would occur at lower fields. Most of the observed multipacting levels below 1 MV/m could be correlated with these predictions (see e. g. curve a in Fig. 3).

Generally these low field levels could be overcome easily within at most a few minutes of processing. Only if the surface of the structure was anodized before the measurements had the processing time to be extended to a few hours. In one experiment with SI - anodized at 20 V, corresponding to an oxide layer of about 50 nm - third order multipavting could not be overcome at all. We conclude that electron secondary emission is more enhanced for thick, anodized Nb_2O_5 oxide layers than for thin ones obtained after vacuum firing or after chemical polishing.

However, we observed also multipacting-like barriers at much higher field levels, e. g. for AI between about 12 and 18 MV/m (curve a in Fig. 3). This high field multipacting was accompanied by high intensity bremsstrahlung originating from of the order of 100 keV electrons, and could not be overcome in many experiments. He-processing generally gave improvements only of the order of 10% in fields, if applied, after operating the structure under heavy electron loading.

A possible explanation for the high field multipacting observed is electron multiplication in the off-beam hole region of the structure. This will no longer be of the two point multipacting type. For, due to the influence of the magnetic field the electron trajectories will be bent. Therefore they hit the surface in a different field region from where they originated. Computer studies on other structures support the existence of this effect [10]. As the secondary emission coefficient for 100 keV electrons is less than 0.5, some kind of field enhancement must exist at the surface to allow electron multiplication, possibly the Malter effect in the metal - oxide surface layer [11].

Operating under heavy electron loading lowered the initial Q_o-value at low field irreversibly within a few minutes, typically form curve a) to b) in Fig. 3. At high fields the intensity of the bremsstrahlung increased, and the attainable maximum field reduced typically to $E_p \approx 15$ MV/m for AI, after having operated close to the break down field for a while. Most probably the electron bombardement causes defects in the metal-oxide surface layer which lead to enhanced electron field emission and higher surface resistance [11]. This damage does not anneal at room temperature. However, a new chemical surface treatment removes the damaged layer, and the previous performance of the structure can be restored. Hence the bulk material had not been damaged.

Summary of experiments

The best results obtained as yet are summarized in Table II. The surface preparations leading to them were not quite the same for the Alvarez and the Slotted-Iris structures. AI was heated to 1800° C at 10^{-8} Torr for 2 hours, followed by chemical polishing, and starting 6 hours of He-processing immediately after the first appearance of electrons at $E_p = 11$ MV/m. This structure was then operated for 40 hours at 22 MV/m (curves b, c in Fig. 3). However, running it for an additional 10 minutes at 24 MV/m caused damage due to heavy electron field emission loading leading to a breakdown at 19 MV/m. AII was treated similarly to AI, and was operated at 15 MV/m with only small electron loading. SI was heated to 1700° C at 10^{-8} Torr for 2 hours. It was then operated at 15 MV/m with little electron loading. However, breakdown occurred at 17.5 MV/m caused by heavy electron loading.

To summarize, high Q_o-values and both high electric and magnetic peak fields were reached. The limitation in field was due to electron loading problems, which could not be solved as yet.

TABLE II

STRUCTURE PERFORMANCE AT 1.8 K

	$Q_o(E_p \approx 0)$	E_p	B_p	$Q_o(E_p)$	E_{eff}
	10^9	MV/m	mT	10^9	MV/m
Alvarez	20	22	33	1	3
Alvarez II	3	15	23	2	2.2
Slotted Iris	8	15	37	5	5

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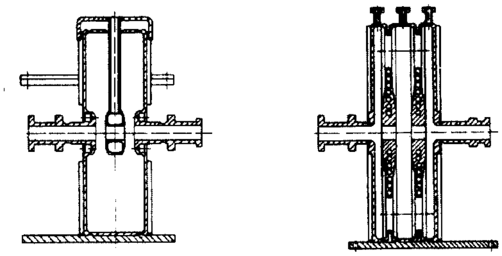

Fig. 1: 720 MHz Alvarez and Slotted Iris structures

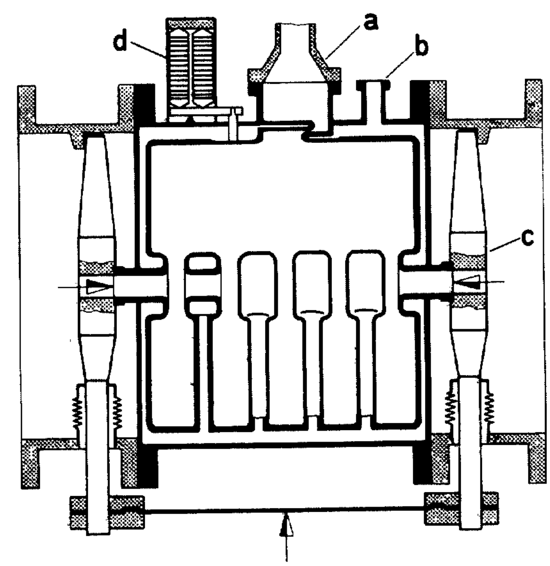

Fig. 2: 720 MHz Alvarez for 5.8 MeV protons to be used in prototype accelerator, showing also rf input (a), helium input (b), mechanical tuner (c), piezo-tuner (d)

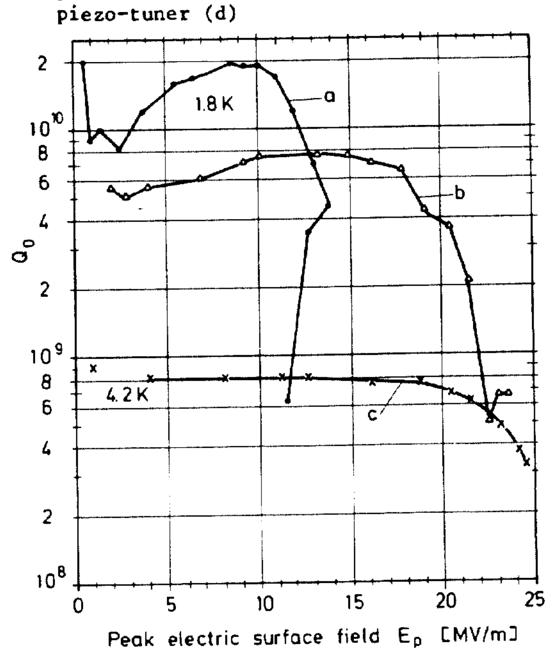

Fig. 3: Typical performance of two cell Alvarez structure, showing low field and high field multipacting (a), Q_o-value at small field lowered by electron radiation damage (b), and high field limitation due to field emission (b,c), probably enhanced by building up of charges in the metal-oxide surface layer