EXPERIMENTAL INVESTIGATIONS ON NON-RESONANT BEAM BREAK-UP EFFECTS IN A SUPERCONDUCTINC STRUCTURE

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Introduction and Experimental Set-up

The beam current attainable in a superconducting proton linear accelerator is theoretically limited by oscillations in longitudinal and deflecting modes excited by the beam. Considerable theoretical work on beam cavity interactions and beam break-up effects has been published]10-11]. The purpose of this paper is to report on measurements of non-resonant excitation of rf modes in a superconducting proton linear accelerator structure by an electron beam. All experimental results can be applied to protons, if the electromagnetic field strength and the beam current are increased by the proton-electron mass ratio for the considered particle velocity.

A schematic outline of the experimental arrangement [12-16] is given in fig. 1. An electron gun provides a narrowly focussed beam of variable energy in the range from 30 KeV to 130 KeV. Electron bunches of 5 degrees width in phase at a frequency of 760 MHz can be produced by a chopping system. The electron beam is injected into a 12 cell lead-plated slotted iris structure of 1.20 m length. The structure is designed for $\frac{P_b}{P_s}=0.5$ and a resonance frequency of 760 MHz. The cavity is enclosed in a cryostat which can be cooled to liquid helium temperature. The energy gain of the particles can be measured by a retarding field analyzer and the beam current in a faraday cup.

Physical picture and theoretical results

The effect of non-resonant excitation can be understood as an exchange of energy between the electron beam and the rf field of a mode of the accelerator structure. In order that an exchange of energy can take place, a small rf field must be present initally. In the case of

TM_{01}-like accelerating modes the beam gets longitudinally bunched while in the case of TM_{11} like deflecting modes a transverse modulation is produced by this field. Depending on the phase slip a of the particles with respect to the wave while passing the cavity energy will be extracted from or delivered to the beam. In the first case beam instabilities occur for sufficient high beam currents. The phase slip α is given by $\alpha = kl(1 - \beta_w/\beta_e)$ where $k = 2\pi/\beta_w \lambda_0$, β_w is the relative wave velocity and β_e the relative electron velocity. l is the length of the structure. For longitudinal modes the ratio of rf power extracted from the continuous beam and the power dissipated in the structure is given by [2, 17]

$$\frac{P_b}{P_s} = \frac{2l^2}{\pi^2 \beta_e \lambda_0} \frac{2}{\gamma(\gamma+1)} \frac{I_0 Z g(\alpha)}{V_0(1+\beta)} \quad (1)$$

Here I_0 is the beam current, eV_0 the electron injection energy, Z the shunt impedance, β the coupling coefficient, $\gamma = (1-\beta_e^2)^{-1/2}$, λ_0 the free space wavelength and $g(\alpha)$ is a function of the phase slip. Calculating $g(\alpha)$ generally at least two different space harmonics of the considered mode with nearly equal phase velocities must be taken into account simultaneously]11, 17]. In the case of π-mode or O-mode these space harmonics have equal phase velocities.

In addition theory predicts a frequency shift of the resonance frequency of the mode induced by non-resonant excitation of TM_{01}—like modes.

Non-resonant excitation of TM_{01}-like modes

We measured for a continuous beam the ratio of P_b and P_s as function of the electron injection energy for different modes in the longitudinal passband. Fig. 2 shows as an example the excitation function for the π-mode. The curve is calculated according eq. (1) with an experimentally determined effective shunt impedance. This shunt impedance has been determined from energy gain of the particles and the corresponding rf power loss in the structure.

The comparison between experimental results and theory confirms the theoretical expressions and corroborates that at least two space harmonic components must be taken into account.

We further verified experimentally the proportionality of the excitation functions with beam current below starting current and measured the starting currents. Experimentally observed and theoretically calculated frequency shifts due to the beam-rf field interaction agree with one another.

These measurements were done with currents below starting current. This is possible, if the excitation of the mode under investigation is stimulated by coupling a small amount of rf power into the cavity from an external generator. By pulsing this power source both amplitude and decay time of the stored energy can be measured with another coupling probe. The amplitude of the stored energy and the time constant are changed if exchange of energy between beam and rf field takes place and P_b/P_s can be calculated from the ratio of changed to unchanged values.

Above starting current the beam was defocussed strongly by the excited longitudinal modes.

We did also experimental investigations on the non-resonant excitation of TM_{01}-like modes with a chopped beam without accelerating field. The frequency of the particle pulses was chosen to be different from the resonance frequency of the excited mode. Our experimental results agree with the theory made for a continuous beam, if for the beam current the time average is taken. This is because in the average all phases between particle bunches and rf field occur.

Non-resonant Excitation of TM_{11}-like Modes

In order to allocate the plurality of higher resonance frequencies to passbands beam-rf field interactions were used in addition to rf measurements. We observed the beam spot on a screen at the downstream end of the cryostat. When rf power was fed to the structure, the beam spot became a line at each resonance frequency of a deflecting mode indicating the deflection of particles by the mode. This deflection is maximal when particle velocity and phase velocity of a space harmonic of the mode are equal and contributions of other space harmonics are negligible. Therefore the phase velocity of the space harmonic can be determined if one measures the length of this line for constant rf power as a function of particle energy. From resonance frequency and phase velocity the propagation constant of the space harmonic can be calculated.

From the extension of the deflection on the screen as function of rf power for correct chosen particle energy the transversal shunt impedance of these modes could be measured.

Further, starting currents for non-resonant excitation of deflecting modes by a continuous beam were measured for several energies by detecting the rf power coupled out of the structure on a spectrum analyzer.

Fig. 3 gives the Brillouin diagrams of the TM_{01}-like and TM_{11}-like modes for our 12 cell slotted iris structure. Modes in each passband which could be excited by the beam are indicated. The β_e-and β_w-lines are given showing clearly the non-resonant nature of the interaction. Fig. 4 gives the tabulated experimental values of starting currents and shunt impedances for the different modes discussed in this paper. The theoretical predicted values for the starting currents are given for comparison.

Conlusion

We conclude that the theory of non-resonant excitation in a accelerator structure is confirmed by experiment.

It should be mentioned that the excitation functions for the longitudinal modes have a common zero crossing for the design energy of the π-mode due to the symmetry of the TM_{01}-passband with respect to this mode. From this point of view the π-mode is favoured to use in the low energy part of a superconducting accelerator. As the starting current is proportional to $(\beta_e\gamma)^3$ for excitation of TM_{01}-like modes and proportional to $\beta_e\gamma$ for TM_{11}-like modes non-resonant excitation of these modes become most troublesome in the low energy part of a proton linear accelera'or. In a strong accelerating field, however the non-resonant excitation of modes in the longitudinal passband is not as serious due to phase focussing effects. In our special geometry with a gain in shunt impedance of the order of 10^3 at helium temperature (which is in the same order of magnitude as that of a supperconducting linear proton accelerator under the condition of heavy beam loading), the current limit for 150 MeV protons would be of the order of several milliamperes for excitation of longitudinal modes. For the deflecting modes the shunt impedances are an order of magnitude lower and hence the current limit would be an order of magnitude higher in this energy range.

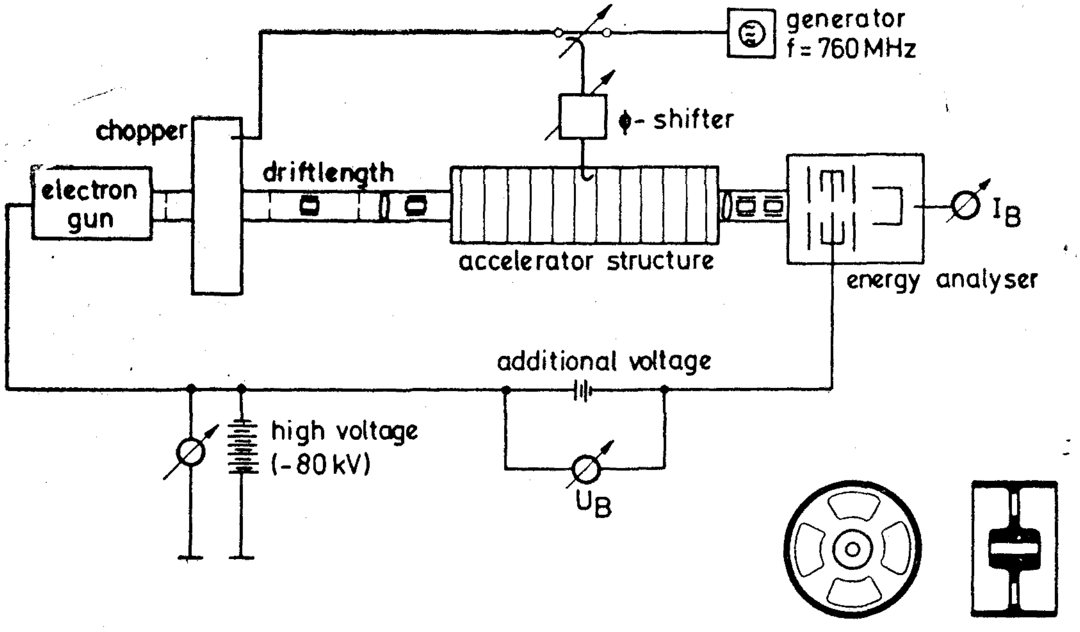

generator
f = 760 MHz
chopper
ϕ- shifter
driftlength
electron
gun
accelerator structure
energy analyser
I_B
additional voltage
high voltage
(-80 kV)
U_B

Fig. 1.

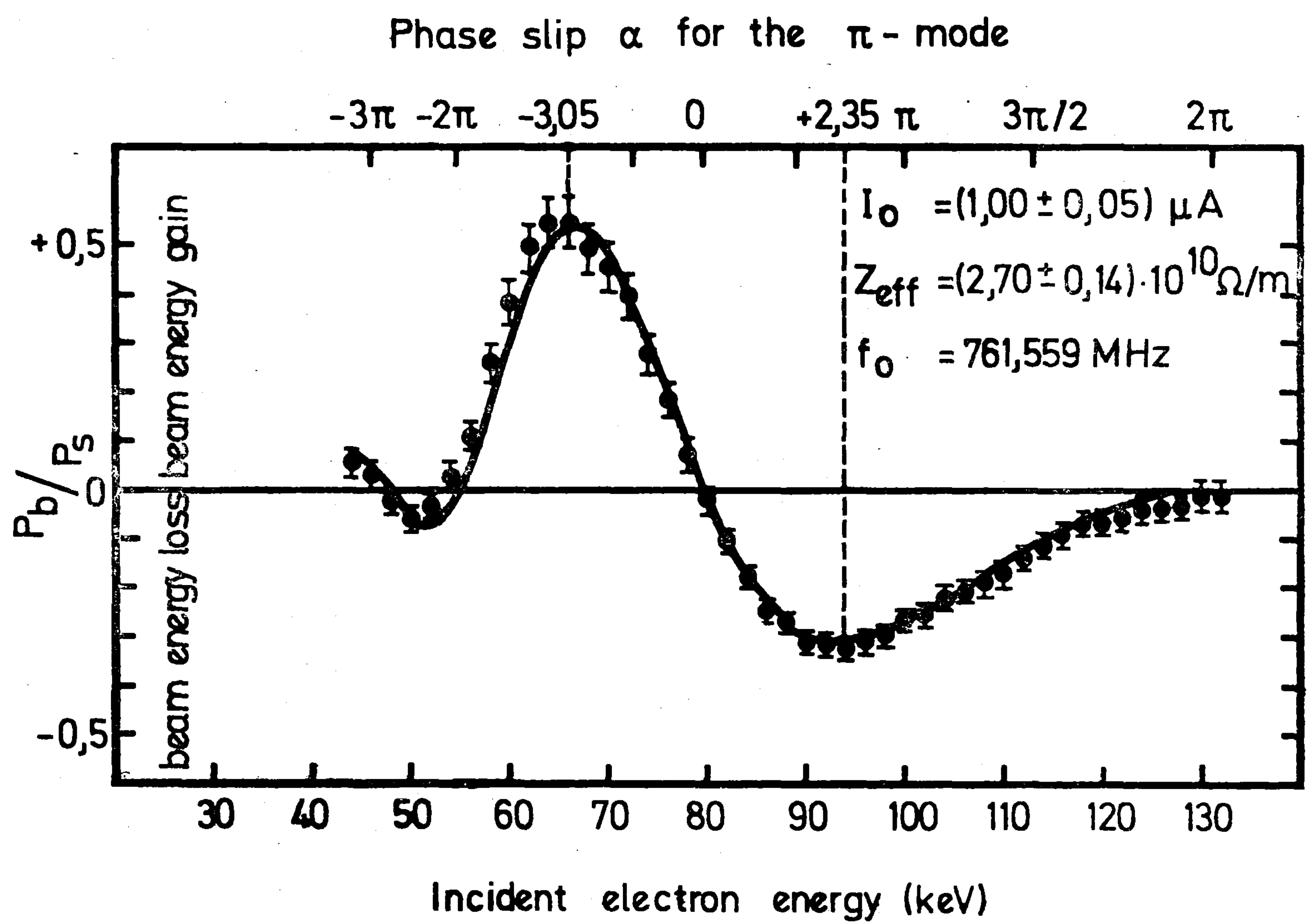
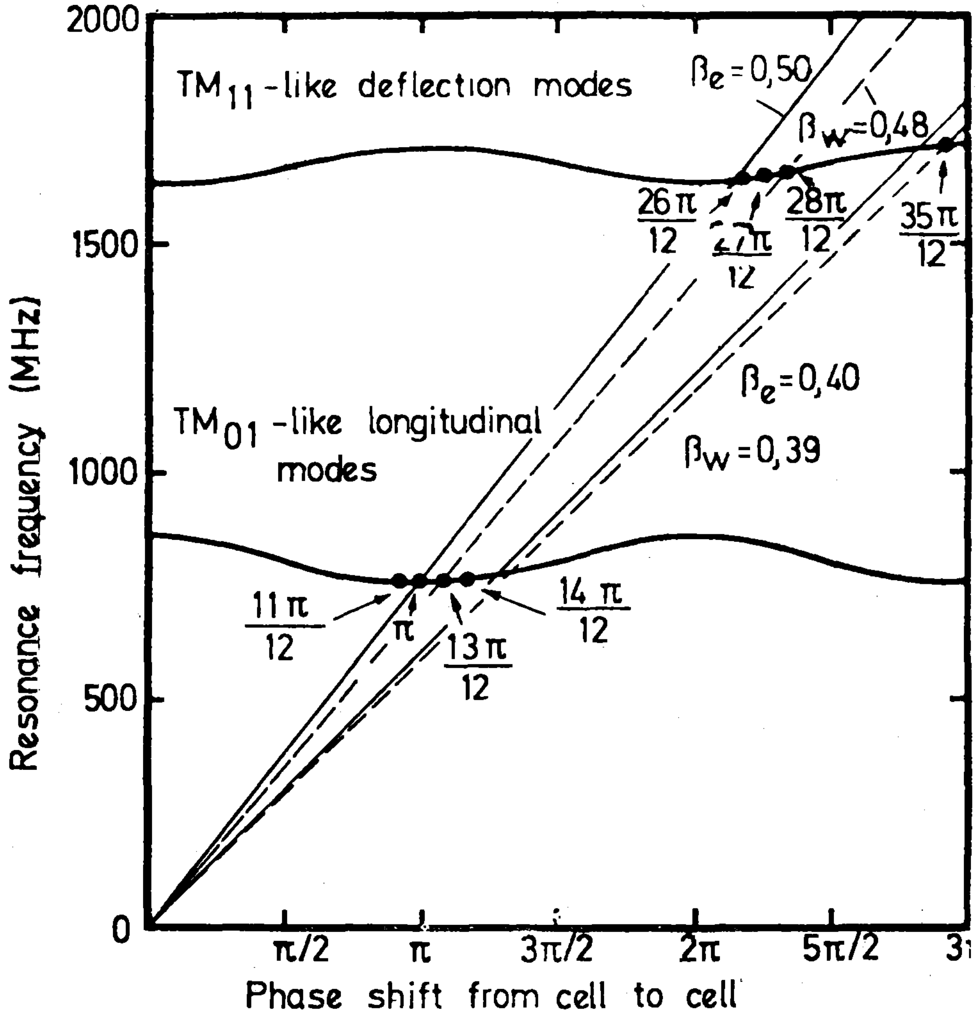

Phase slip α for the π - mode
-3π -2π -3,05 0 +2,35 π 3π/2 2π
I₀ =(1,00 ± 0,05) μA
Z_eff =(2,70 ± 0,14)·10^10 Ω/m
f₀ = 761,559 MHz
+0,5
0
-0,5
P_b/P_s
beam energy loss
beam energy gain
30 40 50 60 70 80 90 100 110 120 130
Incident electron energy (keV)

Fig. 2.



2000
1500
1000
500
0
Resonance frequency (MHz)
TM11 -like deflection modes
TM01 -like longitudinal modes
βe = 0,50
βw = 0,48
βe = 0,40
βw = 0,39
26π/12
27π/12
28π/12
35π/12
11π/12
π
13π/12
14π/12
π/2
π
3π/2
2π
5π/2
3π
Phase shift from cell to cell

Fig. 3.

Table 1

Starting currents for $Q_0 = 15 \cdot 10^6$ calculated with experimental shuntimpedances

pass-band	kl	V_0(keV)	I_{Start}^{exp} (μA)	I_{Start}^{calc} (μA)	Z_{eff} (Ω/m)
TM_{01}	12 π	94	3,22 ± 0,15	3,23	$(2,7 \pm 0,14) \cdot 10^{10}$
~760MHz	11 π	128	8,2 ± 0,8	7,69	$(1,7 \pm 0,2) \cdot 10^{10}$
	13 π	69	2,2 ± 0,3	2.2	$(1,4 \pm 0,2) \cdot 10^{10}$
	14 π	58	2,8 ± 0,3	2.7	$(1,3 \pm 0,2) \cdot 10^{10}$
TM_{11}	26 π	79	21 ± 10	48	$(0,18 \pm 0,03) \cdot 10^{10}$
~1640MHz	27 π	79	42 ± 10	70	$(0,11 \pm 0,03) \cdot 10^{10}$
	34 π	47	100 ± 20	60	$(0,10 \pm 0,03) \cdot 10^{10}$

Fig. 4.

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