RF Pulsed Tests on Niobium and Niobium Based 3GHz Superconducting Cavities

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Abstract:

The achievable limiting field for superconducting cavities is today an open question, not well understood. In principle, no theoretical limitation at surface fields lower than (at least) the thermodynamical critical field H_c of the material (200mT or 50 MV/m accelerating field for niobium) is foreseen. Eventually, theoretical speculations based on some measurements on indium and tin have shown that a surface magnetic field higher than H_c might be reached and that the ultimate limiting field is the superheating field H_{sh} (240mT or 60MV/m for Niobium). Despite these arguments, the maximum surface magnetic field in accelerator niobium cavities is in the range of 100mT (25MV/m), a factor two lower than the critical thermodynamical field. To assess the limiting field for niobium and niobium based superconductors, we use the NEPAL Test Facility at LAL and a vintage 83 high power test set courtesy of CEBAF with brand new niobium cavities made in INFN Genova. Pulsed measurements of the maximum achievable fields can be made. To measure the limiting field, we revisited the method developed at SLAC by I.E.Campisi and Z.D.Farkas[1]. The calculation of the fields in the cavity and the methods of the measurements will be presented together with the experimental apparatus.

Introduction:

The aim of this experiment is to measure the maximum accelerating gradient in superconducting cavities. This maximum is obtained for the maximum magnetic field. In cw mode, the higher magnetic field is the thermodynamical critical field H_c for type I and H_{c2} for type II superconductors. For RF, the maximum magnetic field[2],[3],[4],[5] is:

$$H_{sh} \approx \frac{1}{\sqrt{\kappa}} H_c \text{ if } \kappa << 1$$
$$H_{sh} \approx 1.2 H_{c1} \text{ if } \kappa = 1$$
$$H_{sh} \approx 0.75 H_{c1} \text{ if } \kappa >> 1$$

Experiments done, first by Yogi and Mercereau, then by Campisi and Farkas, and more recently by Hays and

Padamsee comfirm the existence of this limit. At Orsay, we will measure the accelerating gradient and thus the superheating field for niobium and niobium based cavities.

The fields in the cavity:

In this paragraph, we will express the cavity fields after it has been subjected to pulsed RF[6]. The amplitude P_i of the pulse is T μs long. The incident, reflected, emitted and internal fields are shown schematically in fig 1. The fields in the cavity can be calculated. We will demonstrate that they depend on the incident power, the pulse width and the decay time of the cavity.

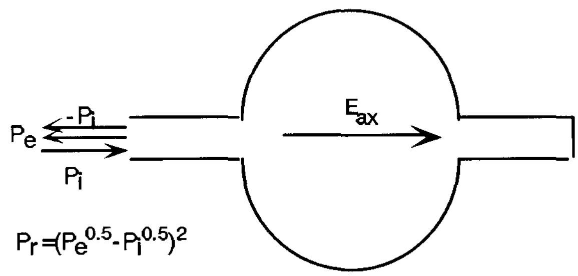

Fig. 1 - Powers and field in the cavity

The following equation is derived from the conservation of the energy. The incident power, P_i, minus the reflected power, P_r, is equal to the dissipated power plus the variation of the stored energy: $P_i - P_r = P_d + \frac{dU_S}{dt}$ (Eq. 1)

This is valid during charging of the cavity. Experimentally, we cannot rely on those signals so we choose to measure the parameters during the discharge of the cavity. In this case, there is no incident power and the reflected power is equal to the emitted one. Equation 2 describes the equilibrium between the powers: $P_e + P_d + \frac{dU_S}{dt} = 0$ (Eq.2)

From the well known relation between power and electric field, we obtain the emitted electric field from the cavity. It decays exponentially with time and its amplitude depends on the coupling factor, β_i. It is useful to know the expression for the emitted power and the stored energy in experiments. The stored energy is $U_S = \frac{Q_{ext}}{\omega} P_e$ (Eq.3) and the emitted power is:

$$P_e = \frac{4\beta_i^2}{(1+\beta_i)^2} P_i \left[1 - \exp\left(-\frac{T}{2\tau}\right)\right]^2 \exp\left(-\frac{t}{\tau}\right) \quad \text{(Eq.4)}$$

The axial electric field is: $E_{ax} = k\sqrt{P_e Q_{ext}}$. In order to have the maximum field in the cavity, we must know how the energy is transferred from the incident RF pulse to the cavity. This is given by the transfer efficiency.

Transfer efficiency:

The transfer efficiency is the ratio between the stored energy and the incident energy: $\eta = \dfrac{U_s(T) - U_s(0)}{U_i(T)}$.

One can express η as a function of the previous parameters: $\eta = \dfrac{4q\tau\left[1-\exp\left(-\dfrac{T}{2\tau}\right)\right]^2}{T}$ where $q = \dfrac{Q_0}{Q_{ext} + Q_0}$. The transfer efficiency depends on the external and unloaded quality factor, Q_{ext} and Q_0, and on the pulse length. On figure 2, one can see that, for our parameters, η reaches a maximum for Q_{ext} between 10^4 and 10^5, so there exists a Q_{ext} that maximises the transfer efficiency.

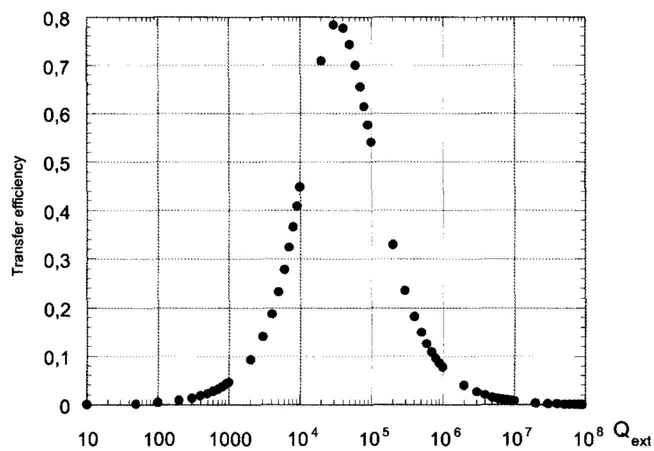

Fig. 2 - Transfer efficiency versus external quality factor for out pulse length (4.5µs)

We can demonstrate that for $Q_0 >> Q_{ext}$, thus for Q_0 tending to infinity, such a Q_{ext} is equal to 2.5fT. If Q_0 is finite but $Q_0 >> Q_{ext}$, then η_{max} is:

$$\eta_{max} = 1.59q^2\left[1-\exp\left(\frac{-1.26}{q}\right)\right]^2 \text{ where } q = \frac{Q_0}{Q_0 + 2.5fT}.$$

The variations of η_{max} are very low (~3%) if Q_0 varies between 10^6 and 10^9, these values of the Q_0 correspond to our experimental expectations. In our case, the pulse width is 4.5µs long, the Q_0 is 10^9 and the calculated external Q_{ext} is 33750. The transfer efficiency is then 81%. In order to have the maximum efficiency, we have designed a variable coupler built at Genova.

Methods of measurement:

The first method[6] :

The fundamental mode is excited with an antenna or a wave guide. From the expression for the stored energy (Eq.4), we can determine the relation between U_S and the average emitted power $\overline{P_e}$: $U_S = \left(1+\frac{Q_{ext}}{Q_0}\right)\overline{P_e}$.

On the other hand, as we have demonstrated that the stored energy is a function of the incident energy; $U_S = \eta U_i = \eta \overline{P_i}$ where $\overline{P_i}$ is the average incident power.

We deduce from these two last equations that the ratio between the two powers is: $\frac{\overline{P_e}}{\overline{P_i}} = \eta\left(1+\frac{Q_{ext}}{Q_0}\right)$

$\overline{P_e}$ and $\overline{P_i}$ are determined experimentally. The accelerating gradient E_{acc} is given by: $E_{acc} = k\sqrt{P_e Q_{ext}}$. k is determined by simulation.

The second method[7] :

This is mostly used for low power measurements. However, it seems to work with high power also. In any case, it will be used to cross check measurements. The emitted power decays exponentially with a time constant τ. We evaluate $P_e(t=0)$ and we denote it P_e^{max}. Then we estimate the time t between P_e^{max} and $\frac{P_e^{max}}{2}$. This time is equal to $\frac{\ln(2)}{2}\tau$. From this, we determine t and deduce Q_L. P_e is determined and Q_{ext} is known, we can deduce the accelerating gradient.

Experimental apparatus[8]

In order to create high gradients in the cavity, we use a 3GHz-35MW klystron with a 4.5μs long pulse width. The cavity is decoupled from the klystron via a 7dB coupler. The incident and the reflected powers are sampled using a 60dB bidirectional guide coupler and two identical measurement lines. If we use the first method of measurements described above, we measure the average power so we use a peak power meter and an integrator triggered by synchronisation signal. Average emitted power, $\overline{P_e}$, and incident power, $\overline{P_i}$, will be measured. If we wish to evaluate the decay time (using the second method), the integrator can be dismounted.

The control of the system and the data acquisition is done using labview. Figure 3 is a schematic outlook of the experimental apparatus

Remark: Losses in the cavity wall will be evaluated. In fact, the plot of $\overline{P_e}$ *versus* $\overline{P_i}$ *should be linear. If losses are present,* $\overline{P_e}$ *versus* $\overline{P_i}$ *will be non-linear.*

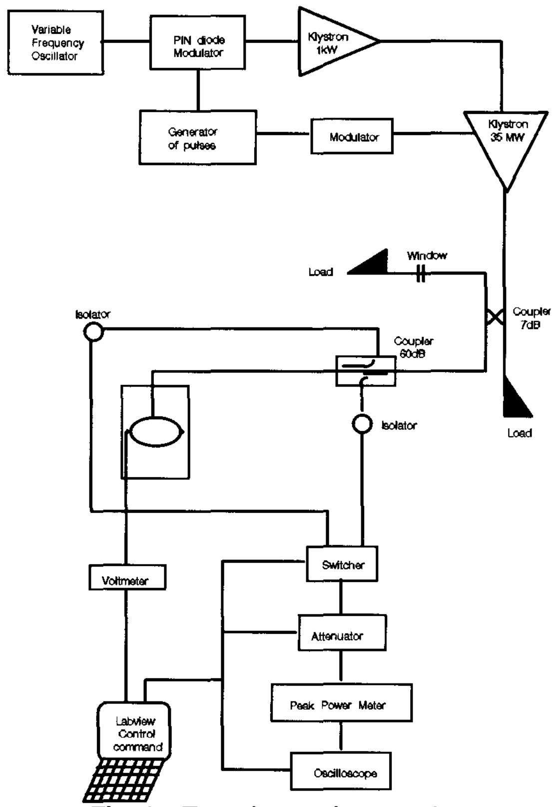

Fig. 3 - Experimental apparatus

Persepectives:

The experiments will start end of November and we hope to have the first results in December.

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