THE QUENCH ANALYSIS OF A 6 T S.C. WIGGLER FOR ADONE AT FRASCATI

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Introduction

A single pole 6 T s.c. wiggler with two racetracks NbTi superconducting coils, separated by a central plate and kept together by two iron yokes, has been designed and built in the Frascati INFN, LNF Laboratories in cooperation with the Ansaldo ABB Componenti, Genova, Italy.

The s.c. magnet and two low field compensating warm poles, will be installed in the near future on the straight section no.10 of the e^+, e^- storage ring Adone, to be used as wave length shifter to produce a hard X-ray flux of 2.4 10^{12} photons/s/mrad in 0.1% bandwith at a critical energy of 9 keV, six times higher than the one produced by the accelerator bending magnets.

The magnet's characteristics and the cryogenic facility dedicated have been illustrated in previous papers[1, 2]; this article will make an analysis of the typical quench during the training.

Magnet excitation and Quench detector description

Two subsequent runs of measurements have been made at the Ansaldo workshop, cooling down the s.c. magnet to 4.2 K by means of LN_2 and LHe dewars.

The Fig. 1 shows the training diagram, while the Fig. 2 shows the magnet load line and the critical field.

The magnet reached the designed field of 6 T and remained stable at such value after some quenches, all after 5.4 Tesla; the field profile measurements made confirmed the Tosca and Magnus codes calculations. The power supply of the superconducting wiggler erogates 10 V, 1000 A having an internal block of at most 400 A and a stability and ripple better than 0.01%. Different current ramps have been tested, the more convenient has been found to be of 0.5 A/sec.

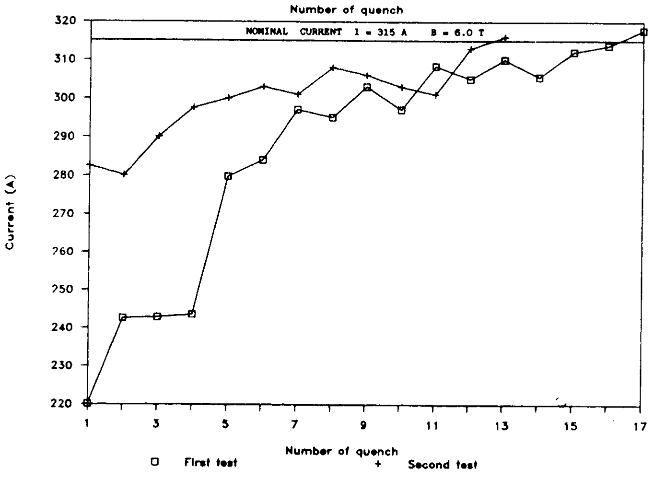

Fig. 1 - Wiggler training diagram.

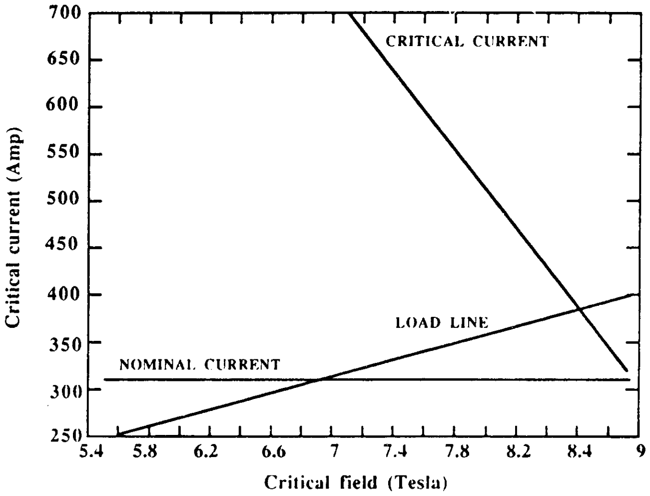

Fig. 2 - Magnet load line and critical field.

The Fig.3 illustrates the quench detection system scheme. The device is based on the differential reading of the coil voltages to detect the assymetry between the upper and the lower coil voltage if the quench occurs.

The signal is amplified, rectified, filtered and sent to a comparator having a pre-set threshold; if the signal is greater than this, an external breaker that disconnects the power supply is activated. This is the way to detect a fast quench. The external breaker is also activated by the output of an integrator, with a threshold different than the previous one, to which the signal is also sent, in order to discriminate noise from a true signal and to detect low speed transients. All the electronics components are made up by the latest semiconductor technology, the operational amplifiers have a drift of 1 μV/°C. The quench detector may be put in stand-by, by a switch before the last actuator relay, in case of calibration tests, and it provides two output signals, one going to a monitor and a second to the data acquisition system. For emergencies a "push button" commands the power supply disconnection.

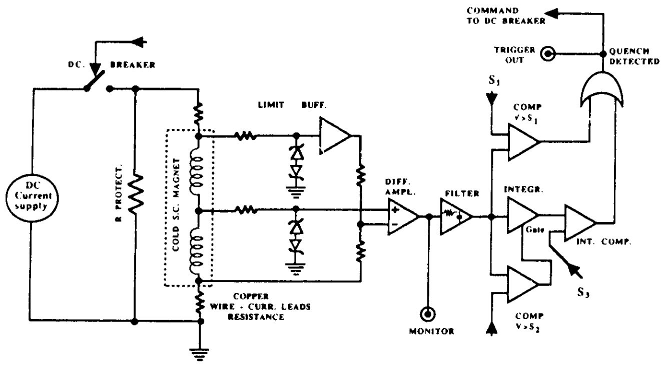

Fig. 3 - Quench detection system scheme.

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Quench Analysis

As soon as a resistive area appears, the magnet quenches; then the whole stored energy is dissipated in the zone of the quench's initiation point and an enormous heating take place creating a serious danger for the magnet's integrity. The helium vessel may be submitted to high pressure due to the rapid vaporization of LHe. By making an adiabatic approximation around the initiating point and integrating over the quench's duration it is possible to calculate the temperature of the hottest point θ_{max} using the equation:

$$\int_0^\infty J^2(t)\,dt = \int_{\theta_0}^{\theta_{max}} \frac{m \cdot c(\theta)}{\rho(\theta)}\,d\theta$$

where:
J = current density in copper;
m = average density;
$c(\theta)$ = specific heat;
$\rho(\theta)$ = resistivity.

Since for a given material m, c, ρ are fixed, the only way to decrease θ_{max} is by removing as much as possible of the stored energy by a fast current decay on an external resistance. As soon as the power supply is switched off a voltage appears across the magnet and the risk of voltage break down should balance the risk of overheating the magnet.

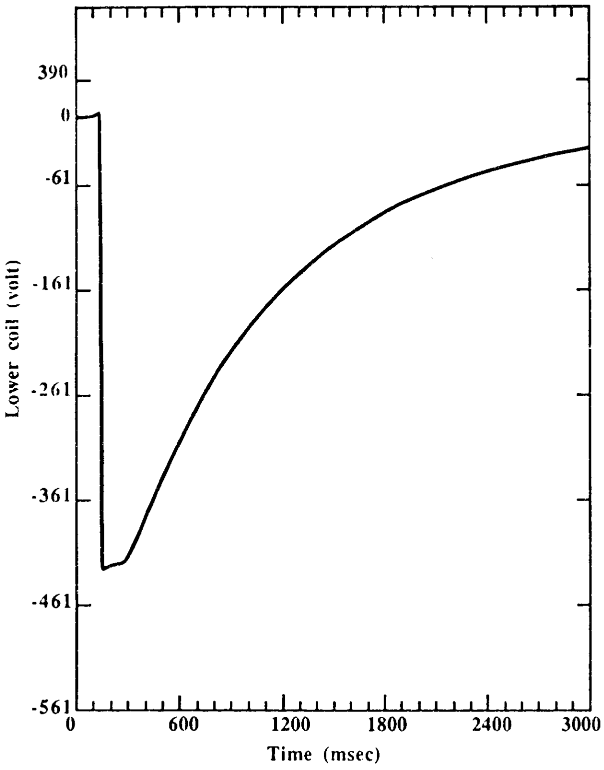


Fig. 4 - Lower coil voltage behaviour during the quench.

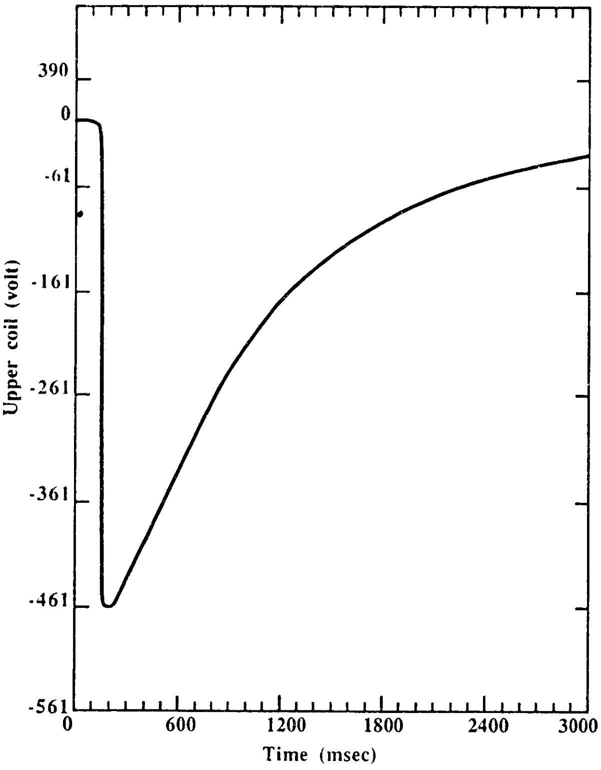


Fig. 5 - Upper coil voltage behaviour during the quench.

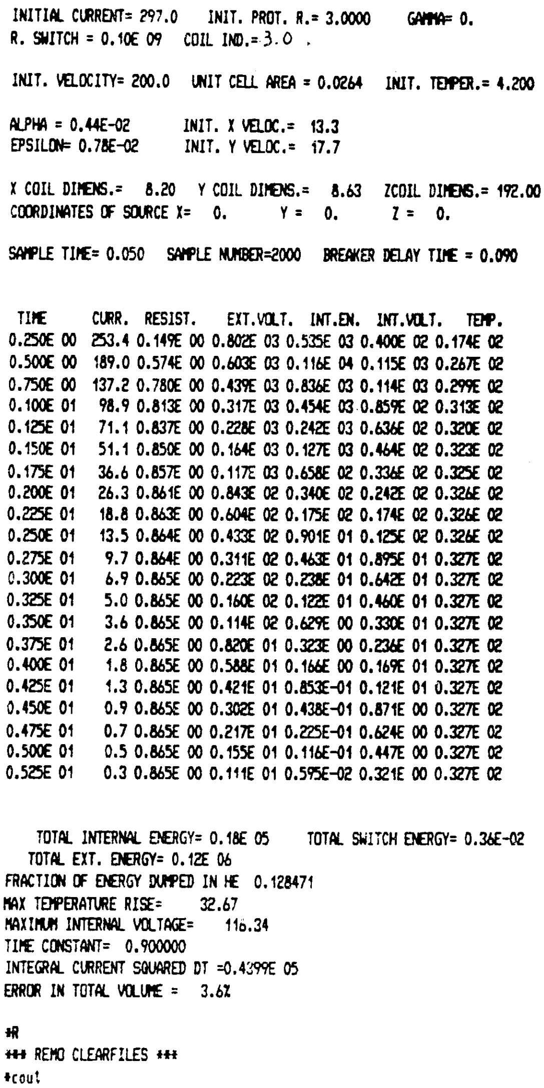
In our case an external stainless steel resistance of 3 Ohm, 120 KJ, 20÷120°C is connected in parallel between the two outputs bars of the p.s. to extract a significant fraction of the stored energy.

The magnet's inductance L has been measured taking into account that V = L dI/dt, fixing dI/dt by selecting a current ramp speed and reading the voltage appearing to the coil ends. After the iron saturation for I = 120, the inductance has been found equal to 3 H. In case of quench at 6 T and 315 A, the extraction efficiency is 80% and the rupture disk broke at an overpressure of 0.3 bar; the maximum pressure allowed on the bath being 1.7 bar.

All the relevant data were monitored, in particular the time, the current, the upper and lower coil voltages as well as the total voltage, its derivative and the resistance were recorded on-line by an HP2240 while the off line analysis was made with the Quench[3] program. The quench detector thresholds were fixed (in case of fast quench) to 200 mV and 800 mV (in case of slow quench).

The Figs. 4 and 5 show the coil voltage versus the time for a quench occurred during the first test at I = 293 A. As we can see both coils quenched symmetrically and that was due to cracks into the epoxy resin, to mechanical settlements of the coils and the yoke, to mechanical stress in a weak zone because the racetrack coils are supported by the magnetic yoke over a short length of the long side and not at the curved heads. We proved also that the transitions were not at all due to the conductor current limit by increasing the bath temperature from 4.2 K to that corresponding to a bath pressure of 1.41 bar (4.6 K) and finding no difference in the current values.

The information recorded during all the quenches have been used as data base and input for the Quench program to compute the velocity propagation of the transition and the increasing of the temperature of coils.



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INITIAL CURRENT= 297.0    INIT. PROT. R.= 3.0000    GAMMA= 0.
R. SWITCH = 0.10E 09   COIL IND.= 3.0  .

INIT. VELOCITY= 200.0   UNIT CELL AREA = 0.0264   INIT. TEMPER.= 4.200

ALPHA = 0.44E-02        INIT. X VELOC.=  13.3
EPSILON= 0.78E-02       INIT. Y VELOC.=  17.7

X COIL DIMENS.=   8.20   Y COIL DIMENS.=   8.63   ZCOIL DIMENS.= 192.00
COORDINATES OF SOURCE X=   0.       Y =   0.       Z =   0.

SAMPLE TIME= 0.050   SAMPLE NUMBER=2000   BREAKER DELAY TIME = 0.090


 TIME       CURR.  RESIST.    EXT.VOLT.  INT.EN.  INT.VOLT.   TEMP.
0.250E 00  253.4 0.149E 00 0.802E 03 0.535E 03 0.400E 02 0.174E 02
0.500E 00  189.0 0.574E 00 0.603E 03 0.116E 04 0.115E 03 0.267E 02
0.750E 00  137.2 0.780E 00 0.439E 03 0.836E 03 0.114E 03 0.299E 02
0.100E 01   98.9 0.813E 00 0.317E 03 0.454E 03 0.859E 02 0.313E 02
0.125E 01   71.1 0.837E 00 0.228E 03 0.242E 03 0.636E 02 0.320E 02
0.150E 01   51.1 0.850E 00 0.164E 03 0.127E 03 0.464E 02 0.323E 02
0.175E 01   36.6 0.857E 00 0.117E 03 0.658E 02 0.336E 02 0.325E 02
0.200E 01   26.3 0.861E 00 0.843E 02 0.340E 02 0.242E 02 0.326E 02
0.225E 01   18.8 0.863E 00 0.604E 02 0.175E 02 0.174E 02 0.326E 02
0.250E 01   13.5 0.864E 00 0.433E 02 0.901E 01 0.125E 02 0.326E 02
0.275E 01    9.7 0.864E 00 0.311E 02 0.463E 01 0.895E 01 0.327E 02
0.300E 01    6.9 0.865E 00 0.223E 02 0.238E 01 0.642E 01 0.327E 02
0.325E 01    5.0 0.865E 00 0.160E 02 0.122E 01 0.460E 01 0.327E 02
0.350E 01    3.6 0.865E 00 0.114E 02 0.629E 00 0.330E 01 0.327E 02
0.375E 01    2.6 0.865E 00 0.820E 01 0.323E 00 0.236E 01 0.327E 02
0.400E 01    1.8 0.865E 00 0.588E 01 0.166E 00 0.169E 01 0.327E 02
0.425E 01    1.3 0.865E 00 0.421E 01 0.853E-01 0.121E 01 0.327E 02
0.450E 01    0.9 0.865E 00 0.302E 01 0.438E-01 0.871E 00 0.327E 02
0.475E 01    0.7 0.865E 00 0.217E 01 0.225E-01 0.624E 00 0.327E 02
0.500E 01    0.5 0.865E 00 0.155E 01 0.116E-01 0.447E 00 0.327E 02
0.525E 01    0.3 0.865E 00 0.111E 01 0.595E-02 0.321E 00 0.327E 02


    TOTAL INTERNAL ENERGY= 0.18E 05    TOTAL SWITCH ENERGY= 0.36E-02
   TOTAL EXT. ENERGY= 0.12E 06
FRACTION OF ENERGY DUMPED IN HE  0.128471
MAX TEMPERATURE RISE=     32.67
MAXIMUM INTERNAL VOLTAGE=    116.34
TIME CONSTANT=  0.900000
INTEGRAL CURRENT SQUARED DT =0.4399E 05
ERROR IN TOTAL VOLUME =   3.6%

*R
*** REMO CLEARFILES ***
*cout
```

Fig. 6 - Typical print output of the Program Quench.

The Fig. 6 shows the output for the quench at I = 297 A, giving 18 KJ as the total internal energy dissipated into the bath corresponding to 7 l, in agreement to the 7.7 measured.

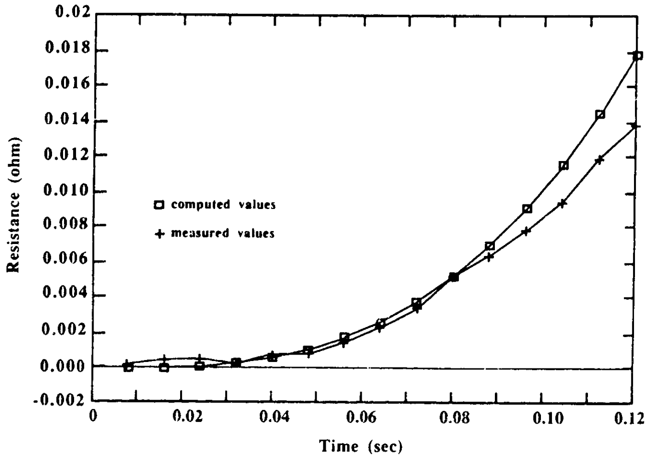

Fig. 7 - Computed coil resistance during the quench and fitted value.

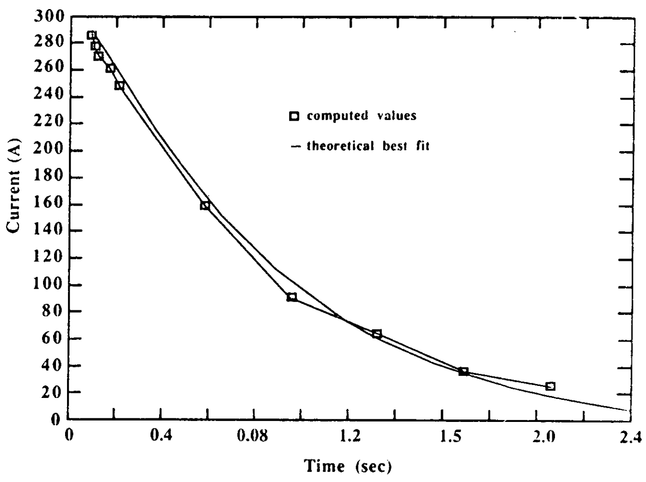

Fig. 8 - Current change after opening switch.

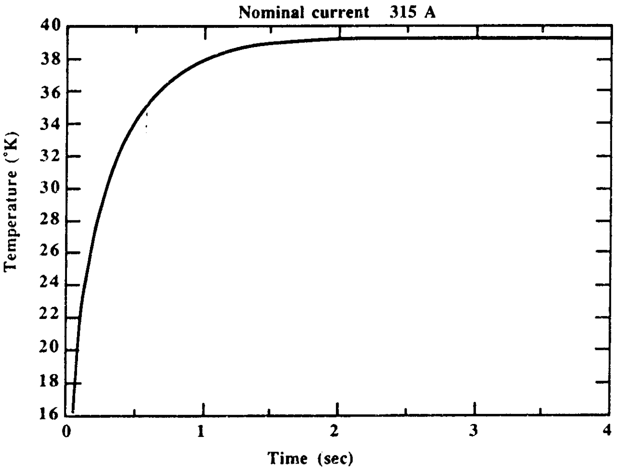

Fig. 9 - Maximum temperature (theoretical behaviour).

In order to calculate the quench propagation velocity, the coil resistance, before the switch was open, has been computed by measuring the voltage at the coil terminals plotting its evolution against time, and fitting this to the theoretical curve made by Quench (assuming a velocity of 2 m/s).

The Fig. 7 shows such behaviour while the Fig. 8 proves that it is good, because the theoretical current evolution after the switch is open, fits well the experimental values. Finally the Fig. 9 shows the maximum adiabatically computed temperature reached by the coils during the quench period.

References

[1] M.Barone, A.Cattoni, C.Sanelli: "Successful test of a superconducting wiggler for the storage ring Adone", Proceedings of MT-11 Conference, Tsukuba 1989, Vol. 1, p.331, edited by Elsevier Applied Science London, and New York, 1990.

[2] M. Barone, A. Cattoni, G. Modestino, M. Perrella, C. Sanelli: "Design, manufacturing, and test of a s.c. wiggler facility for Adone in Frascati", Presented to 2nd European Conference on progress in X-ray synchrotron radiation, Rome, 1989.

[3] M.N. Wilson: "Computer simulation of the quenching of a superconducting magnet", Rutherford Lab. Report RHEL/M151.