Test results and analyses of short samples for HT-7U conductor

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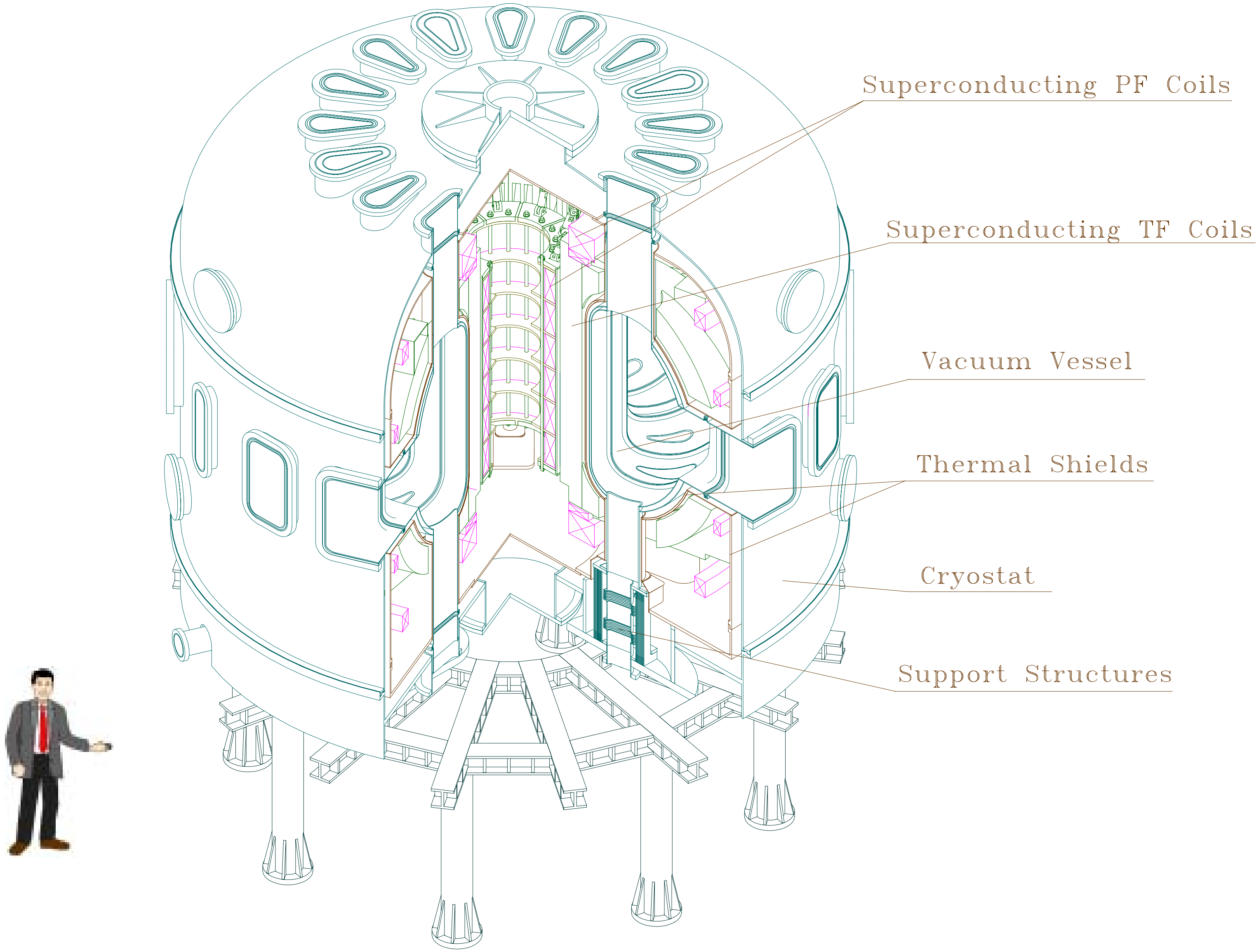
Introduction

Within the frame of the cooperation between ASIPP and CRPP, four full-size conductor samples were fabricated in ASIPP and tested in the SULTAN facility.

The results of the measurements of critical current、current sharing temperatures、AC losses and transient stability against magnet field disturbance of the conductors were presented and discussed.



The HT-7U Tokamak

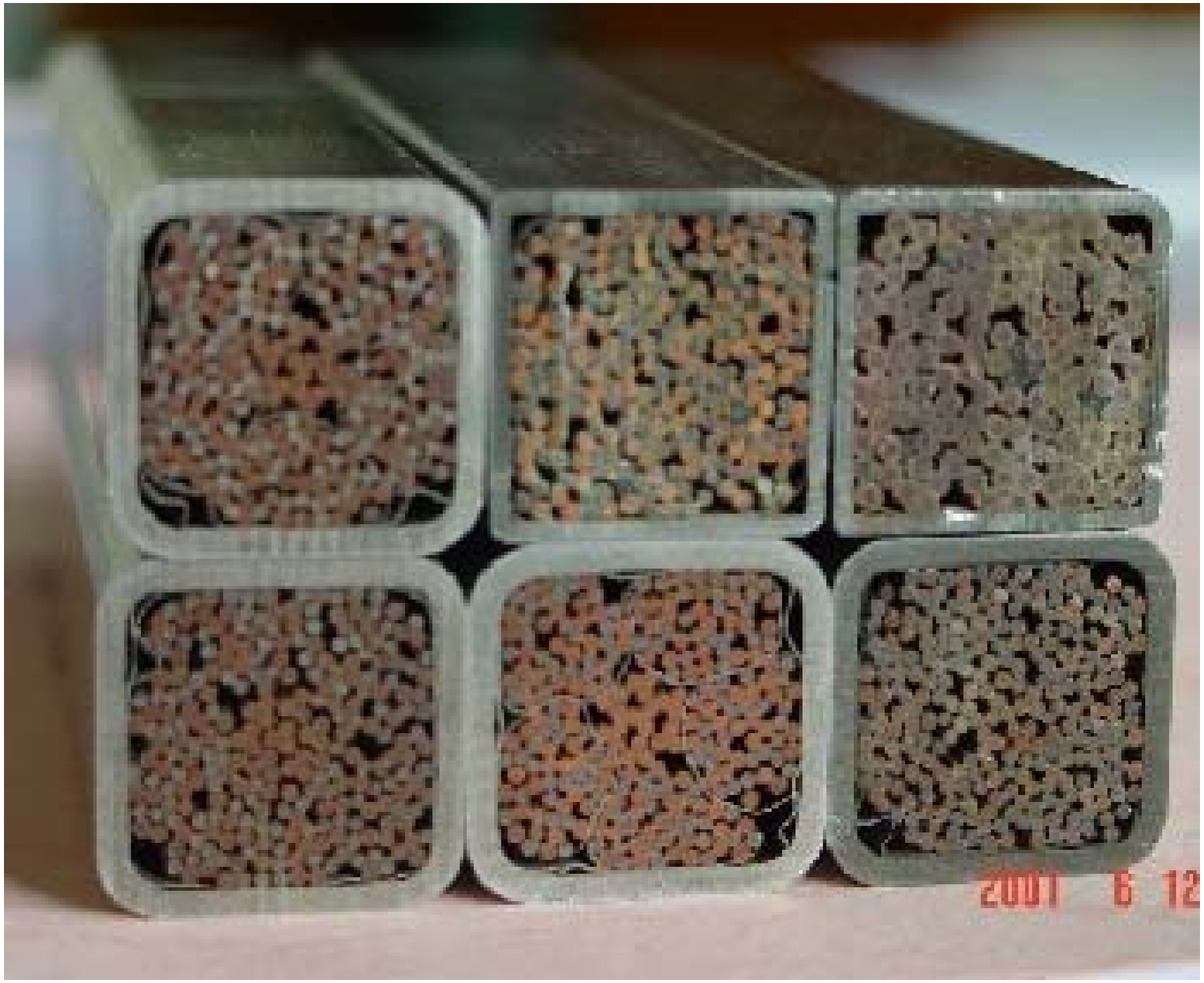
Jacketing Line and 600 meters long CICC Conductor

TF prototype coil winding

Purpose of the test

The main purpose of the test is to check the design of the conductors and to obtain the performances of the conductors, answer the questions

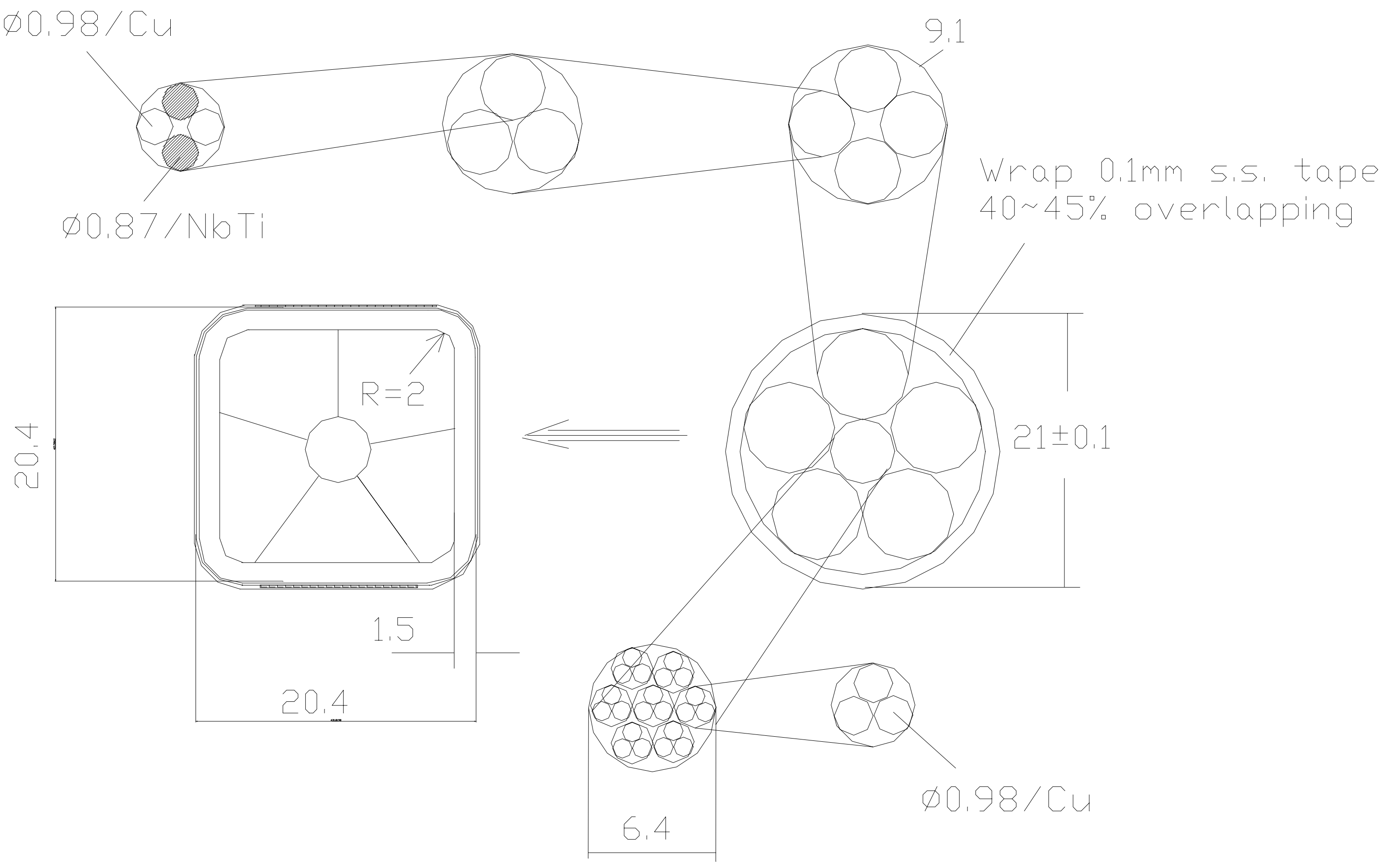
- Whether it is possible using segregated copper for both TF and PF conductor？
- How much margin do the conductor have? Is it stable enough against plasma disruption？
- Which coating is more suitable for TF and PF conductor？



Large proportion of segregated cooper in conductor (68%)
Different surface coating for TF and PF respectively

CICC for HT-7U TF & PF magnets

Conductor configuration



The parameter of the strand

Strand diameter(mm)	0.87
Cu/sc	1.38
Number of filament	8910
Filament diameter (μm)	6
Filament pitch (mm)	10
RRR	100
Thickness of Pb-30Sn-2Sb (μm)	3
Thickness of Ni (μm)	2

TF & PF conductor parameters

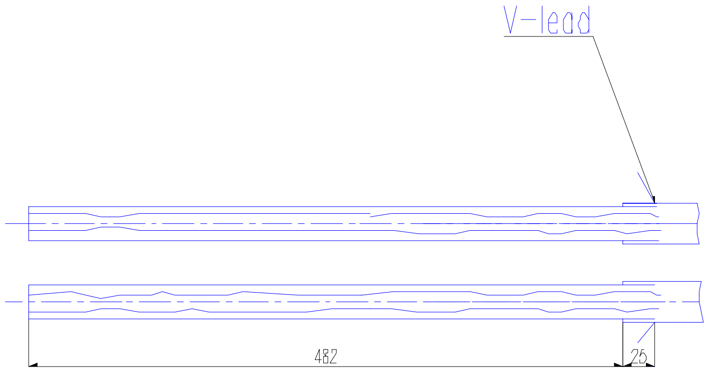
	unit	TF	PF 1-10 (3 version)		
			1	2	3
Configuration		(2S.c+2Cu)*3*4*5+1 Central Cu Cable			
Surface handling		Solder coating		Ni coating	
Wrapping on the 3rd stage of sub-cable		Without wrapping	With wrapping		Without wrapping
Conductor dimension	mm	20.4*20.4	20.8*20.8		20.47*20.47
Diameter of SC strands	mm	0.87			
Number of SC strands		120			
Diameter of Cu strands	mm	0.98			
Number of Cu strands		120+21			
Copper ration Cu/SC		4.91 (68% segregated cooper)			
Void fraction V_f		37.3	36.7	36.7	38.5
Peak filed B_m	T	5.8	4.5		
Operating current I_{op}	kA	14.3	14.5		
Operating temperature T_b	K	3.8			

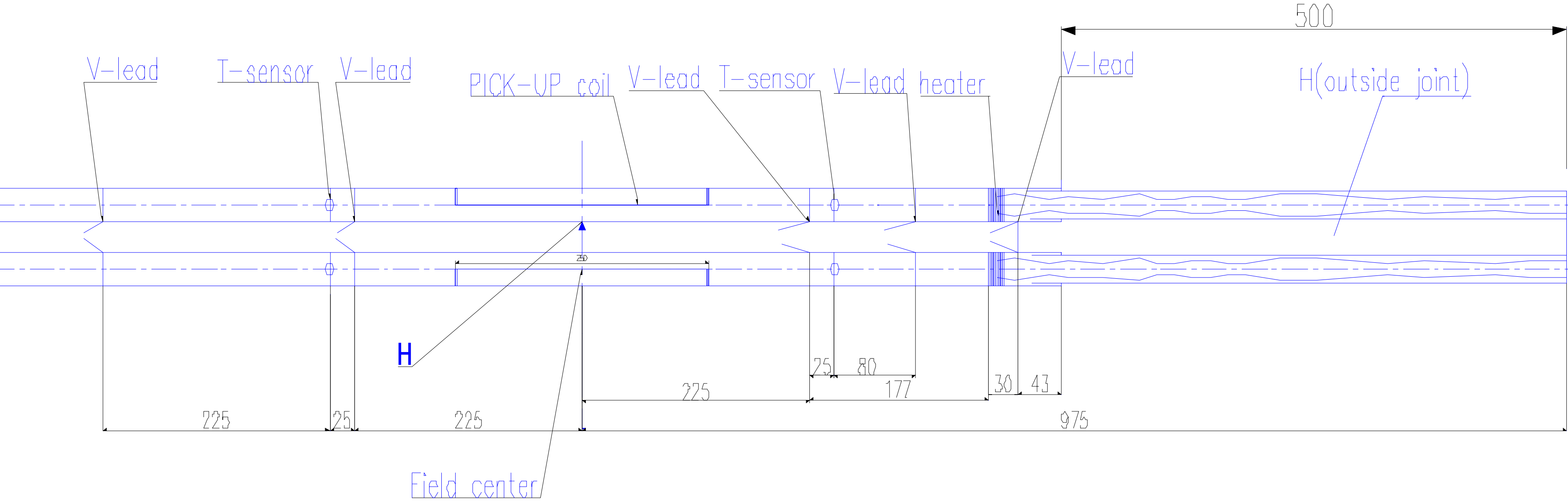
Sample check in CRPP

Joints of the short samples

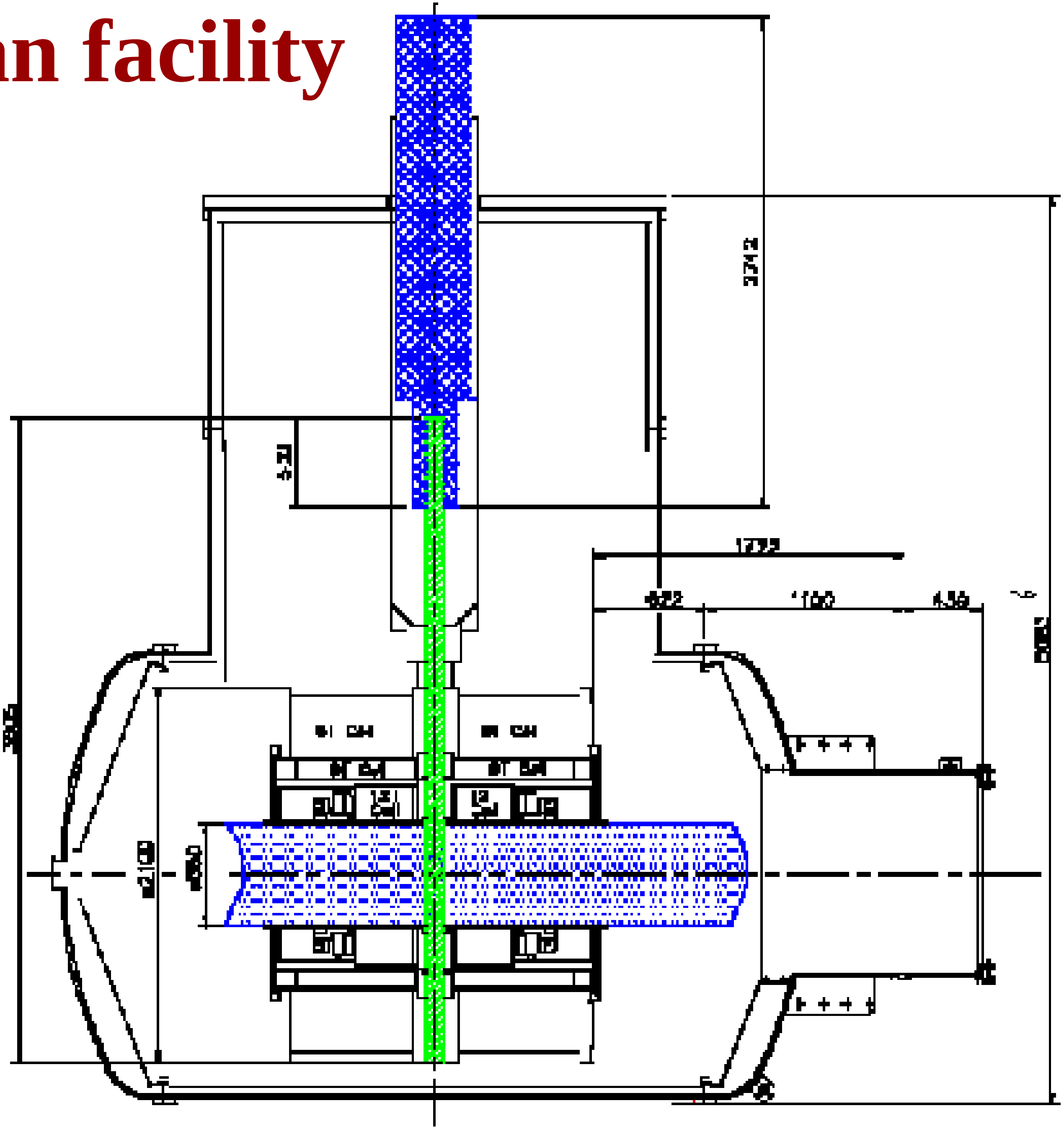
full size short samples assembling

Instrumentation





Sultan facility



Test program

- **DC performance**

  Ic

  Tcs

- **AC losses**

  Calorimeter

  magnetization

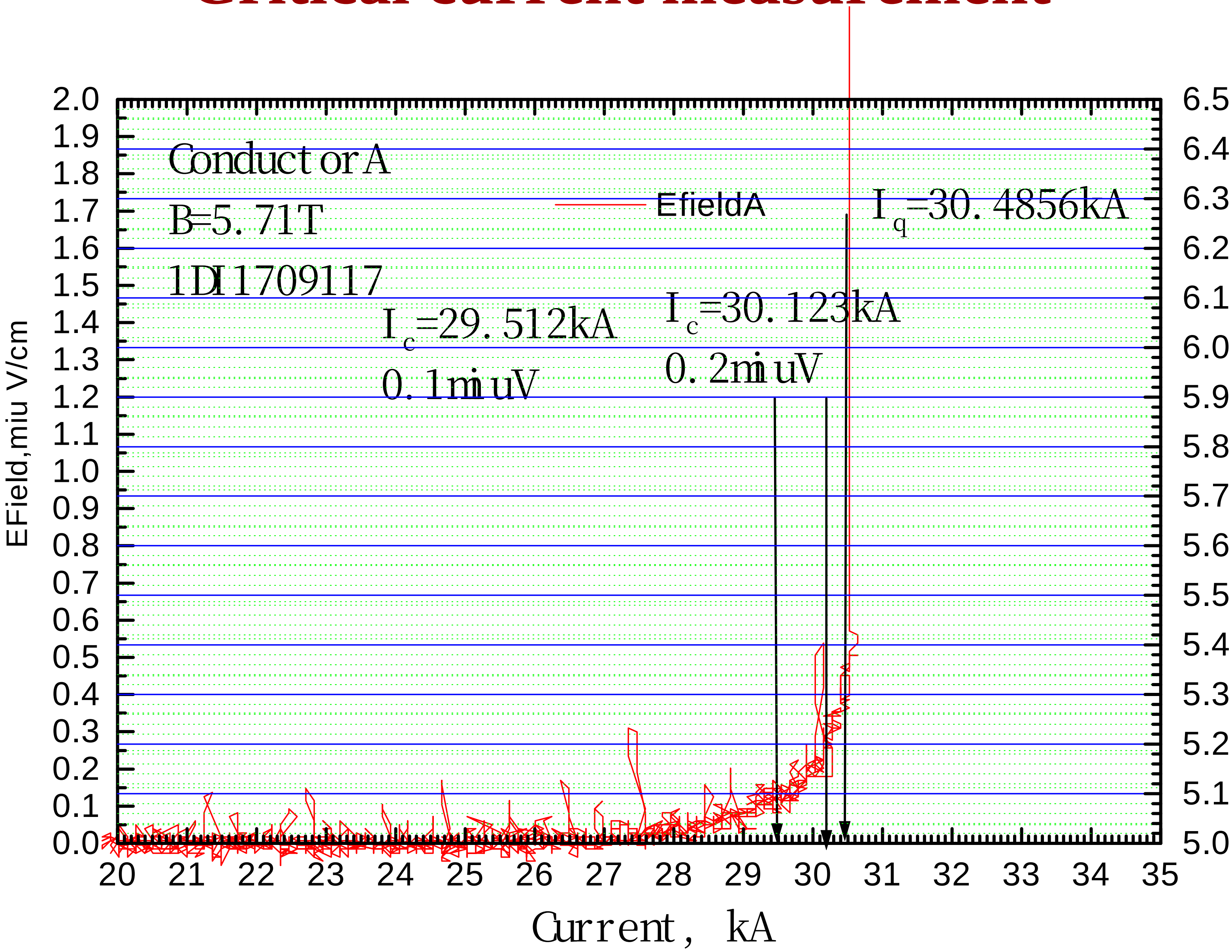
- **Transient Stability**

  Temperature margin VS stability

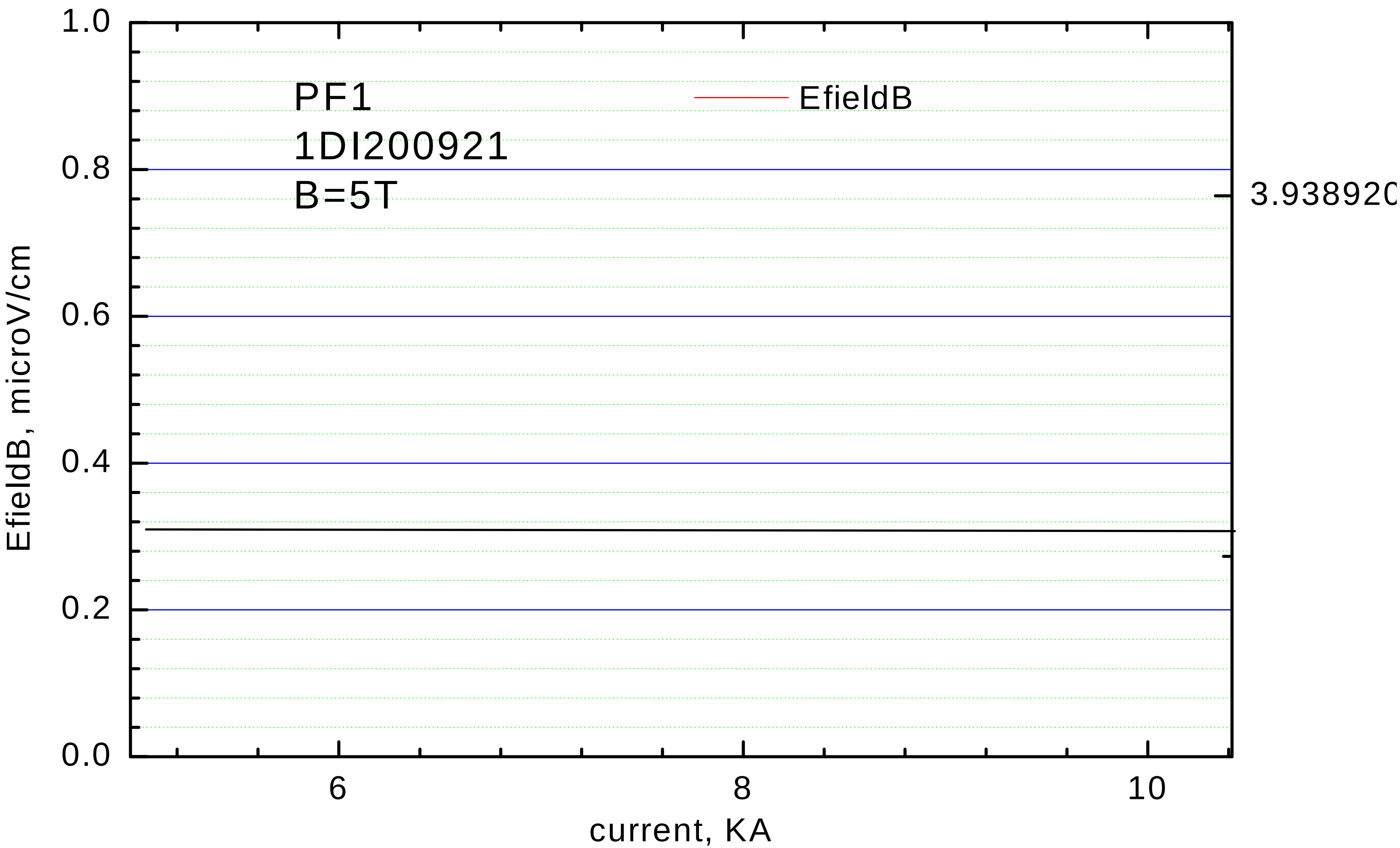
  I_{op}/I_c VS stability

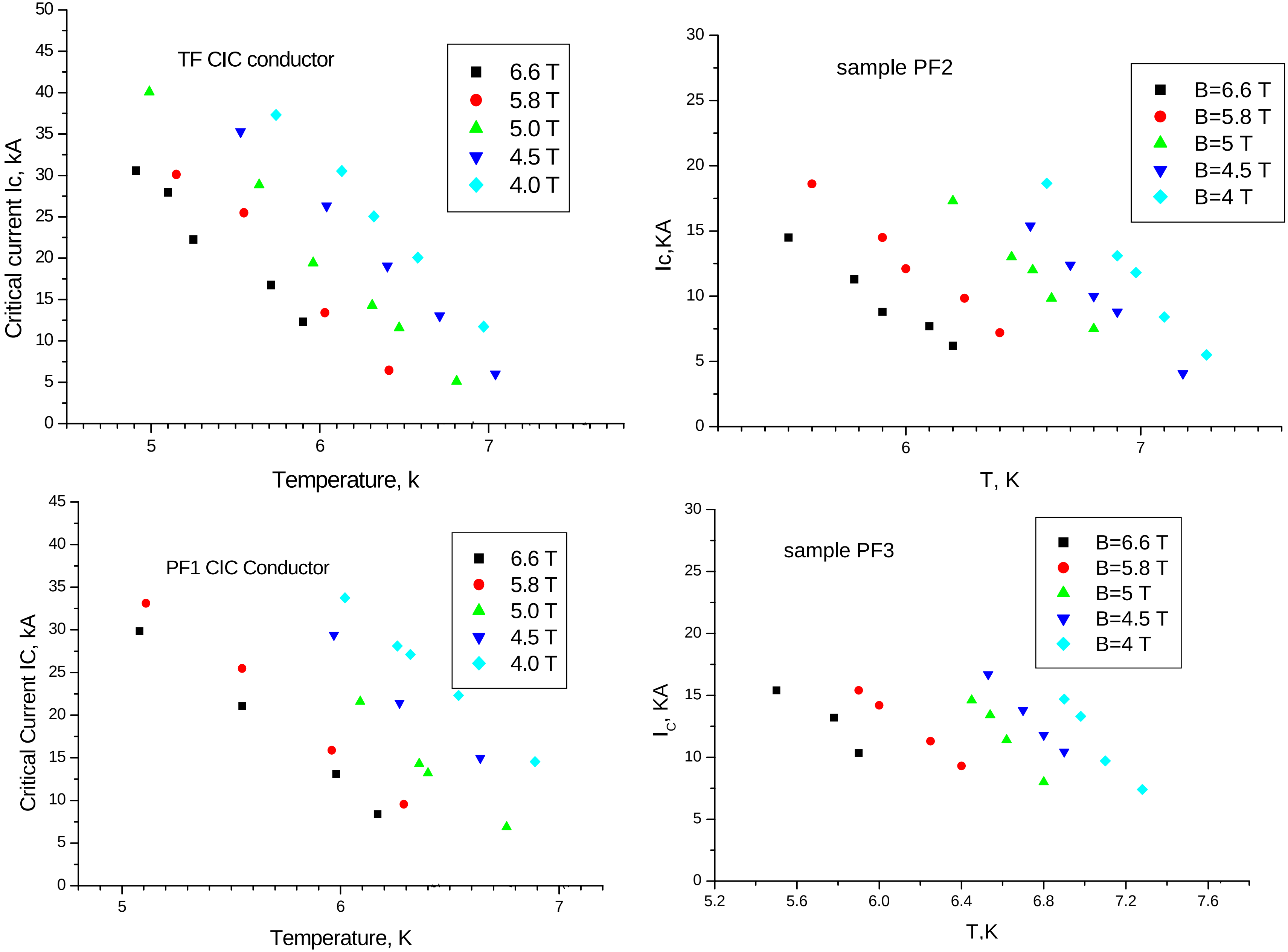
  dm/dt VS stability

Critical current measurement

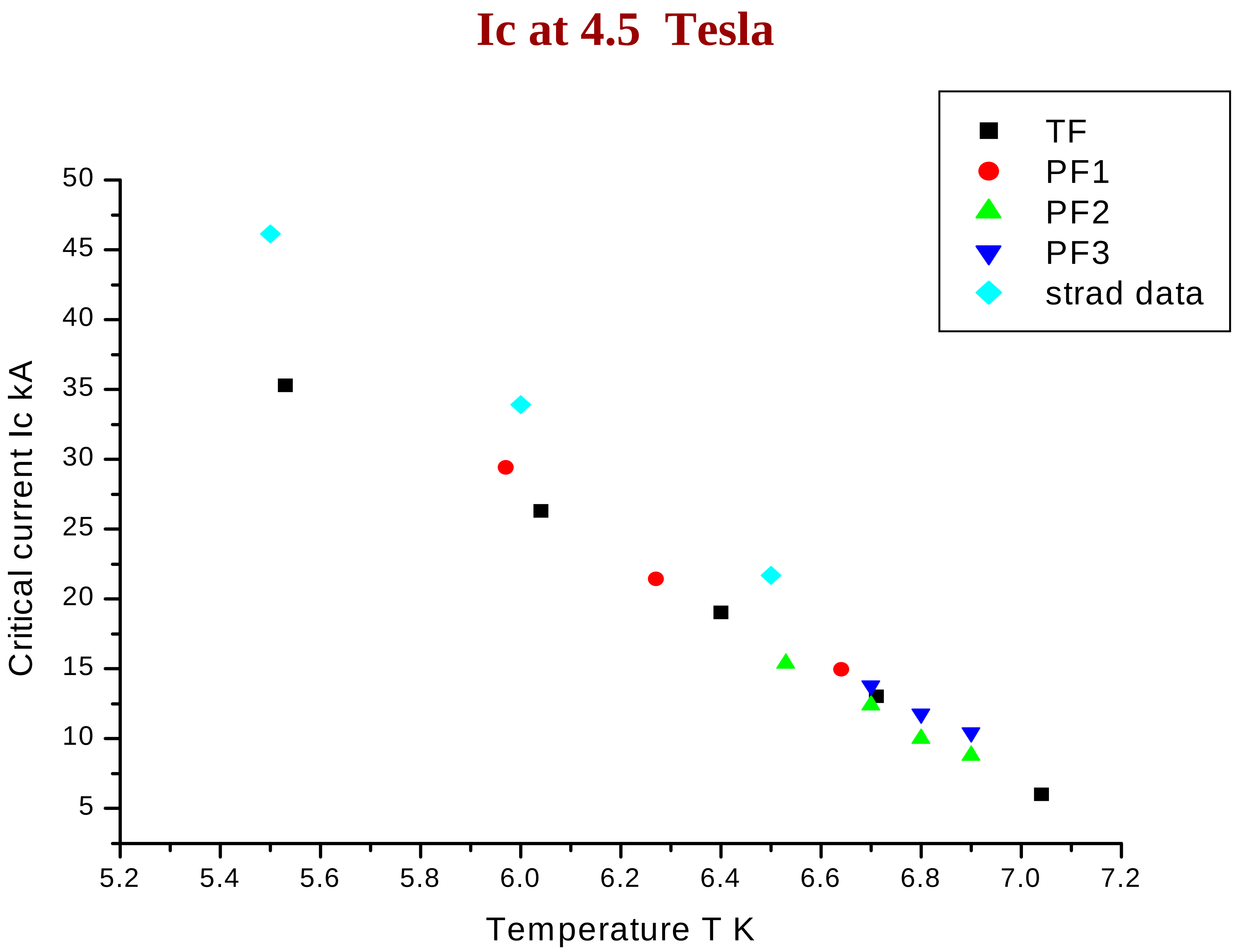


Current redistribution likely voltage signal



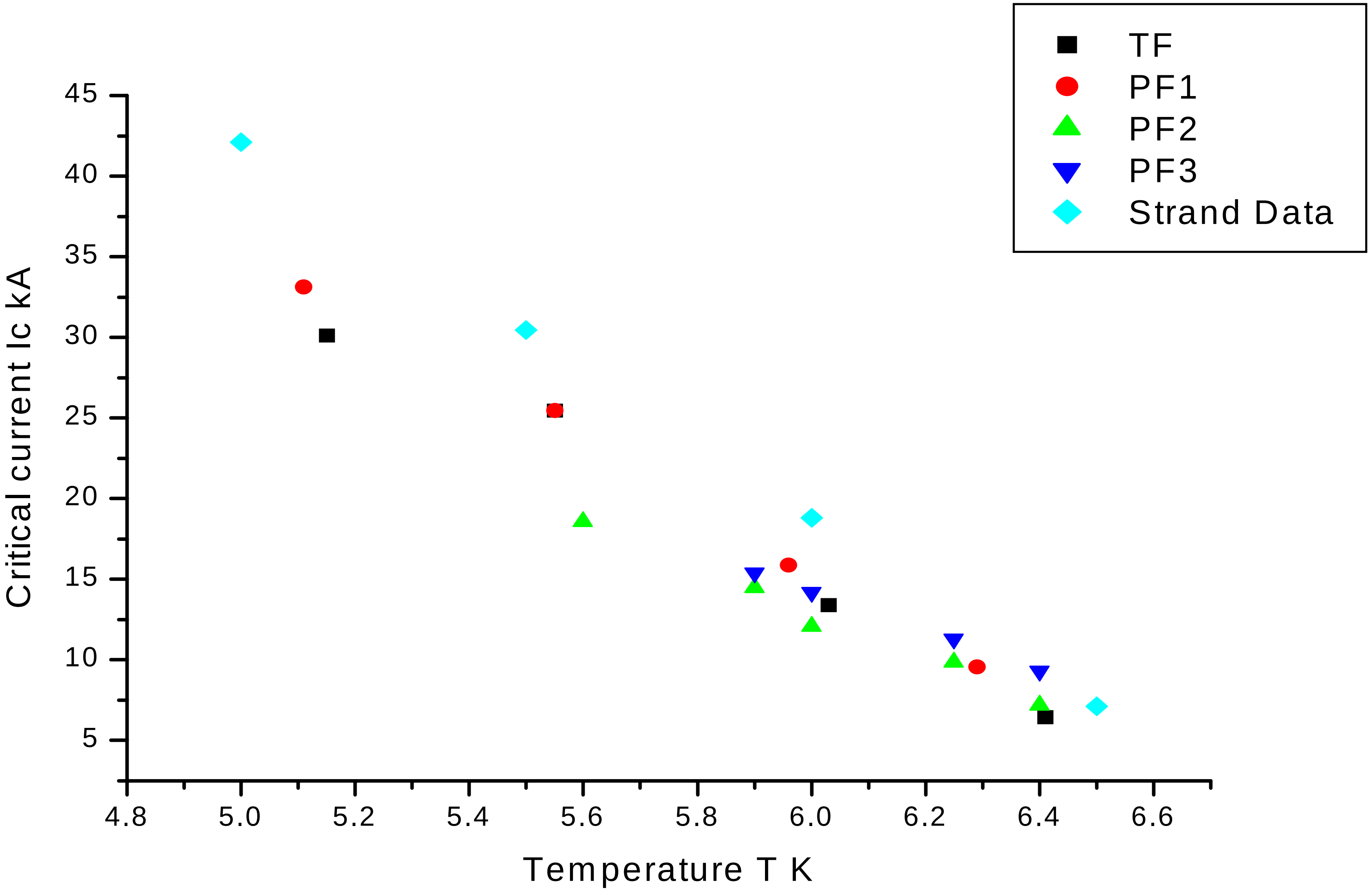


Ic measurement

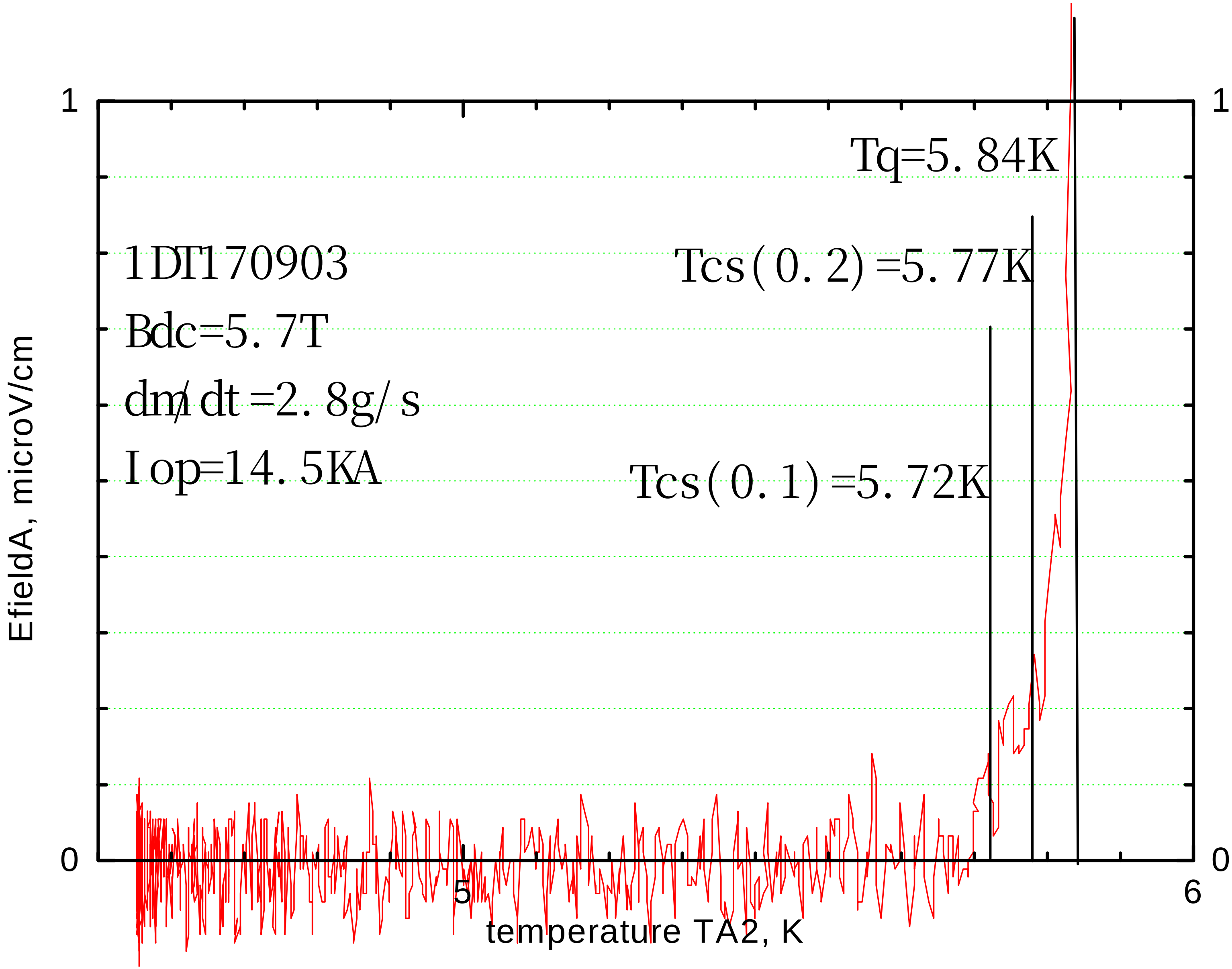


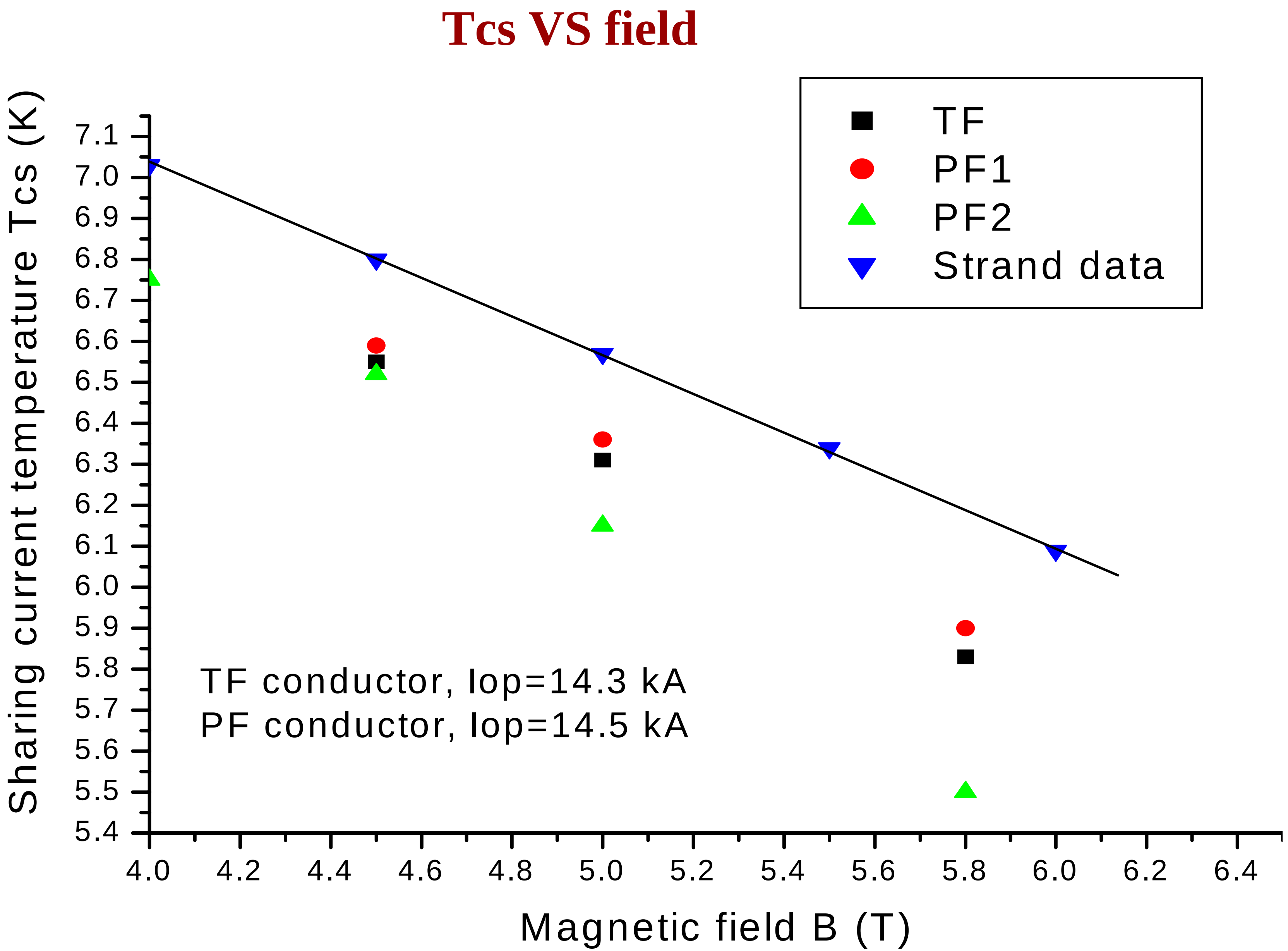
Ic at 4.5 Tesla
TF
PF1
PF2
PF3
strad data
50
45
40
35
30
25
20
15
10
5
Critical current Ic kA
5.2
5.4
5.6
5.8
6.0
6.2
6.4
6.6
6.8
7.0
7.2
Temperature T K

Ic at 5.8 Tesla



Measurement T_{cs} of TF




Tcs VS field
TF
PF1
PF2
Strand data
Sharing current temperature Tcs (K)
7.1
7.0
6.9
6.8
6.7
6.6
6.5
6.4
6.3
6.2
6.1
6.0
5.9
5.8
5.7
5.6
5.5
5.4
4.0
4.2
4.4
4.6
4.8
5.0
5.2
5.4
5.6
5.8
6.0
6.2
6.4
Magnetic field B (T)
TF conductor, Iop=14.3 kA
PF conductor, Iop=14.5 kA

Summary of the DC performance

- Ic of all of the conductors are about 10-12 % lower than strand data, the degradation is due to poor performance uniformity along strands length and suggest filament broken in the strand.
- The voltage developed very quickly.
- Part of plot voltage Vs current shows some signal looks like current redistribution when current is low.

Summary of the DC performance

- the current sharing temperatures of three conductors are below the calculated curves, larger drop was seen under high magnetic field, especially for PF2.
  This suggests poor current sharing due to high inter-strand transverse resistance plus stainless steel wrapping on the third stage of sub-cable probably.

AC Losses measurement

Iop=0 and 14.5kA separately , B=4.5T,

ΔB=±0.1T for sample 1# (TF and PF1),

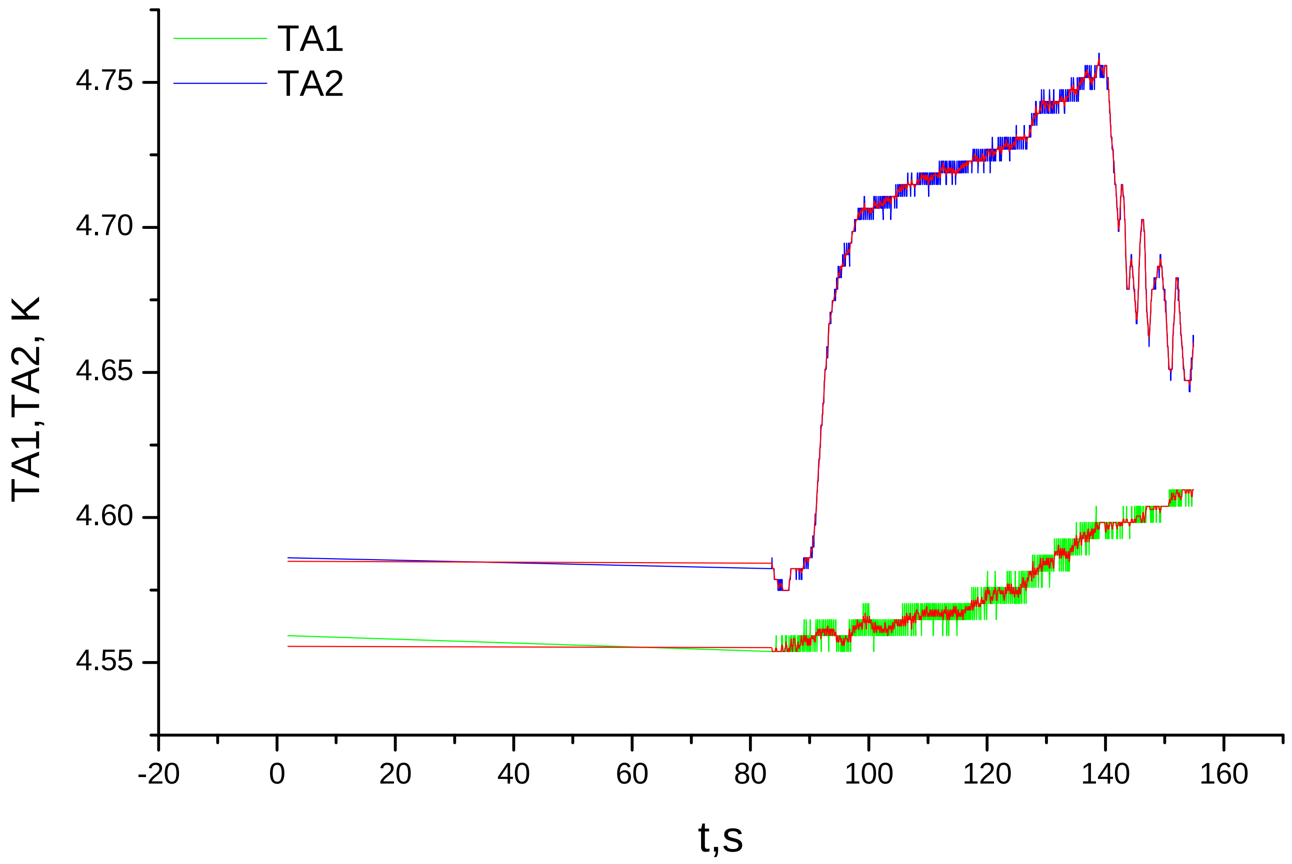
ΔB=±0.2T for sample 2# (PF2 and PF3)

f=6, 5, 4, 3, 2 . Pulse 50 Sec. (Calorimeter)。

f=3，2，1, 0.8, 0.5, 0.1, 0.05, Pulse 20~60 Sec（magnetization）

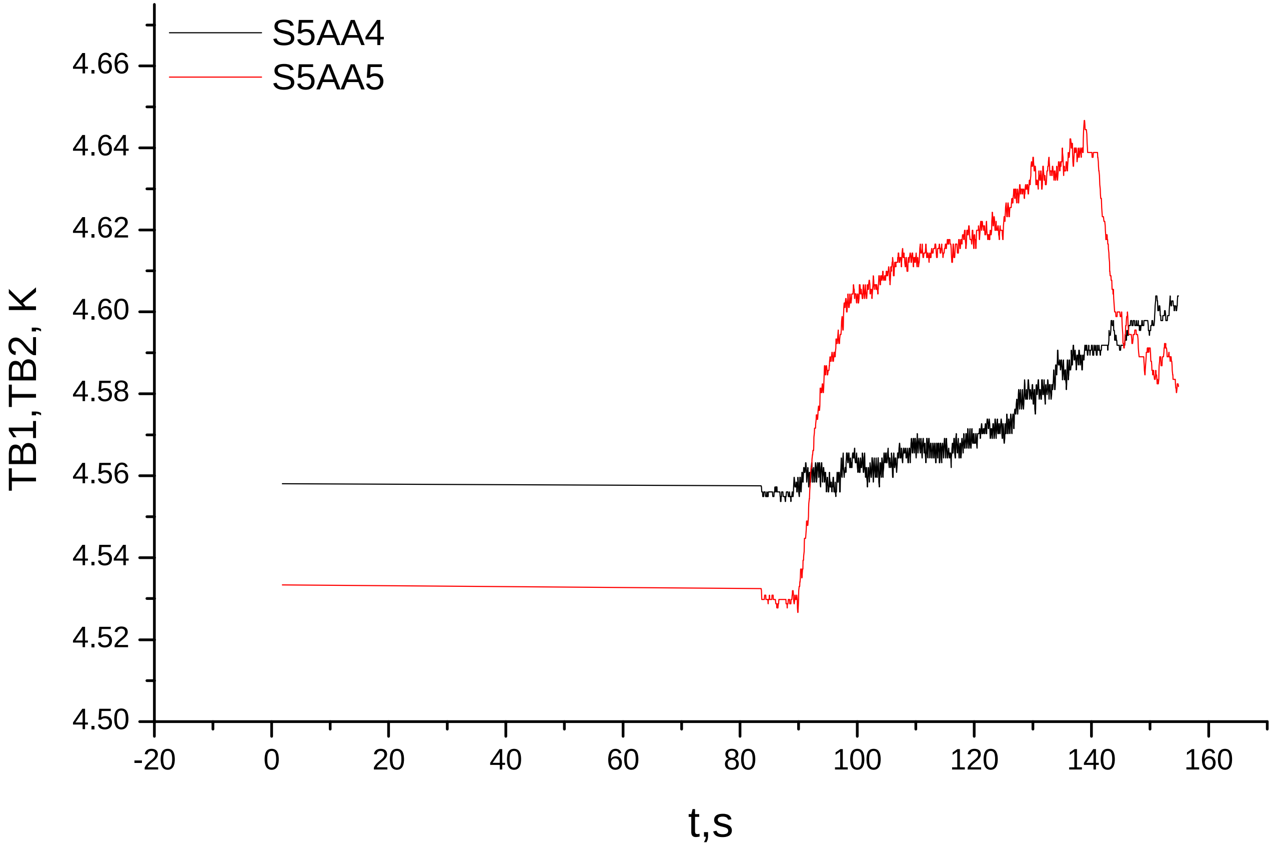
TF sample AC loss measurement

Inlet and outlet temperature of the heating area



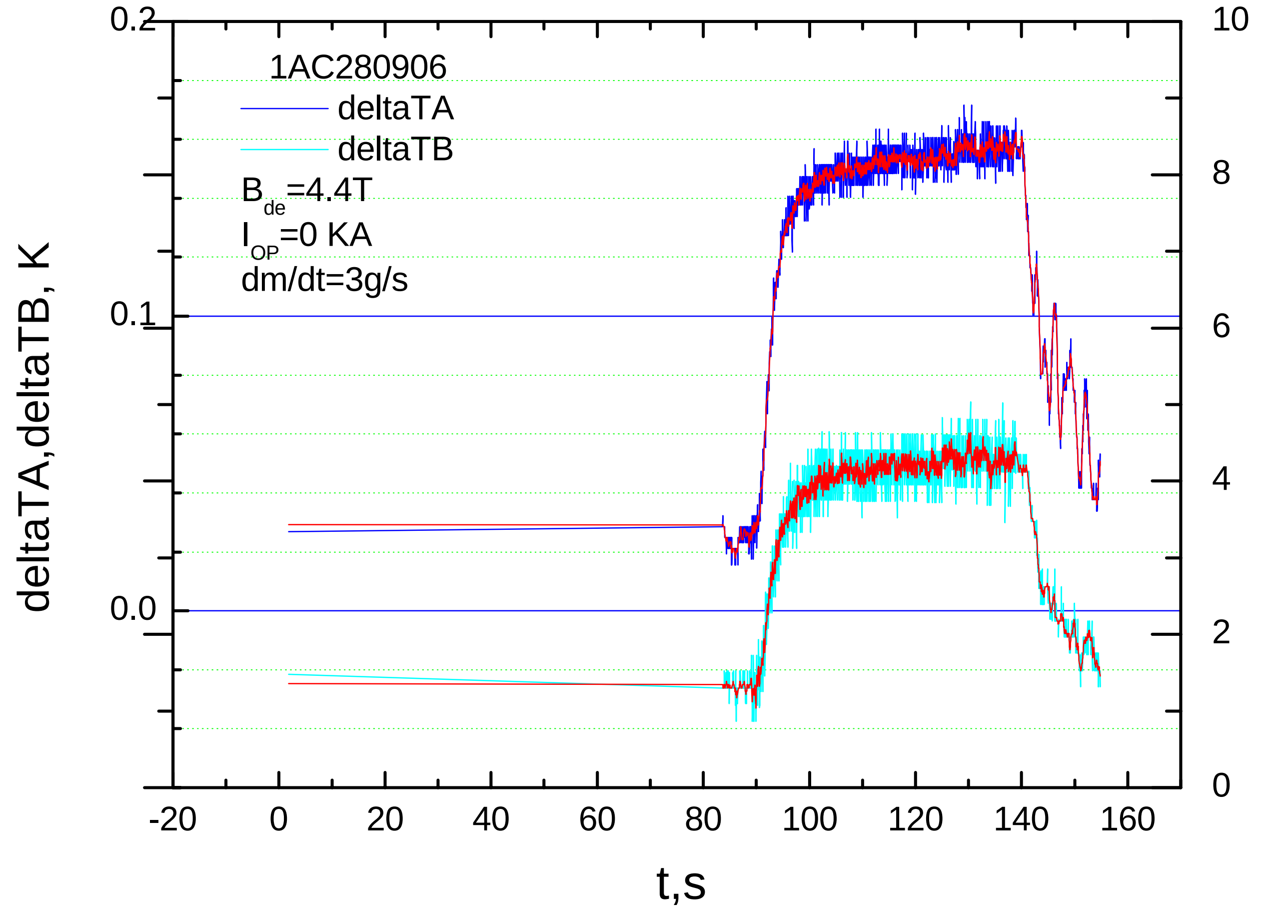
PF1 sample AC loss measurement

Inlet and outlet temperature of the heating area

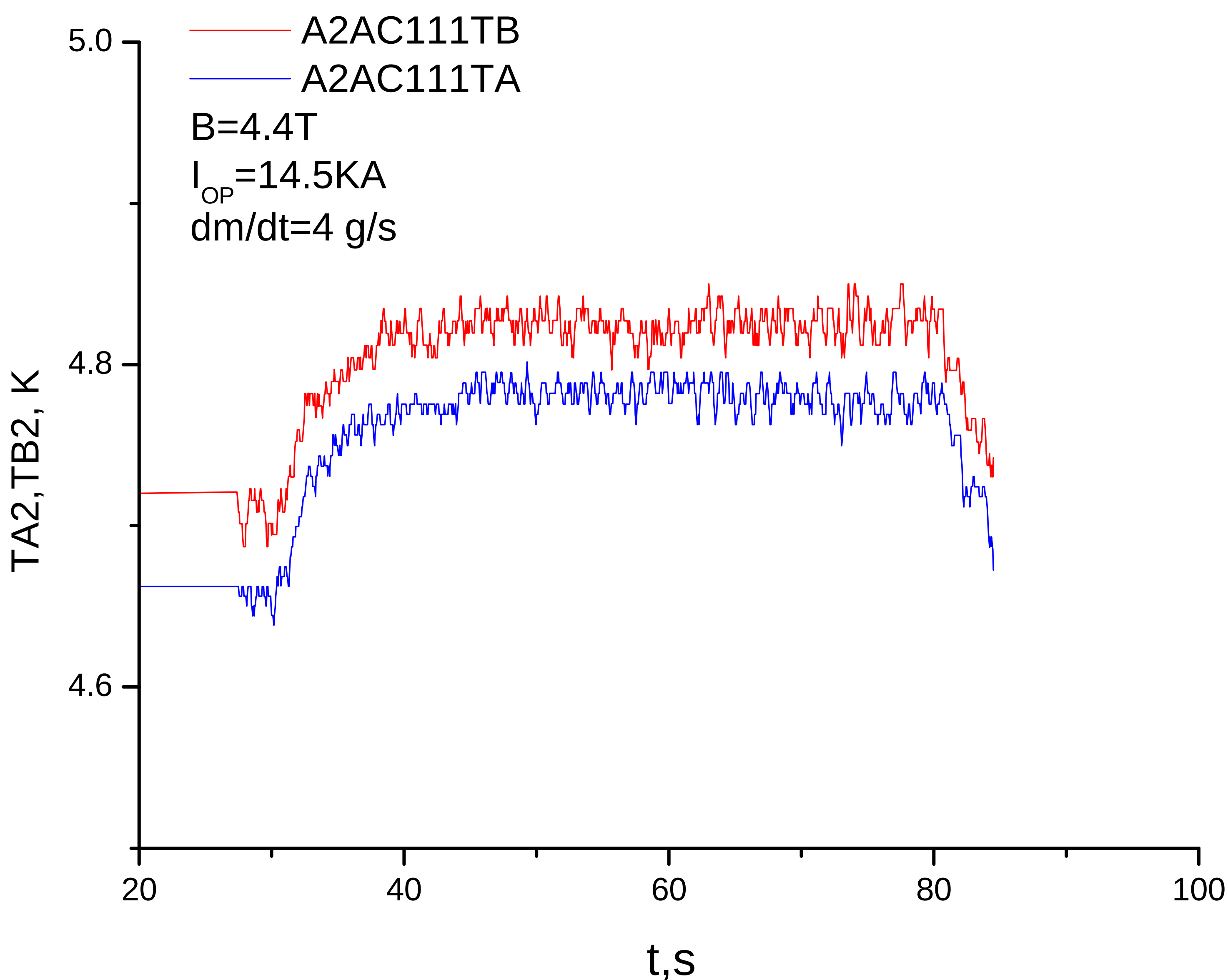


TF and PF1 AC loss measurement

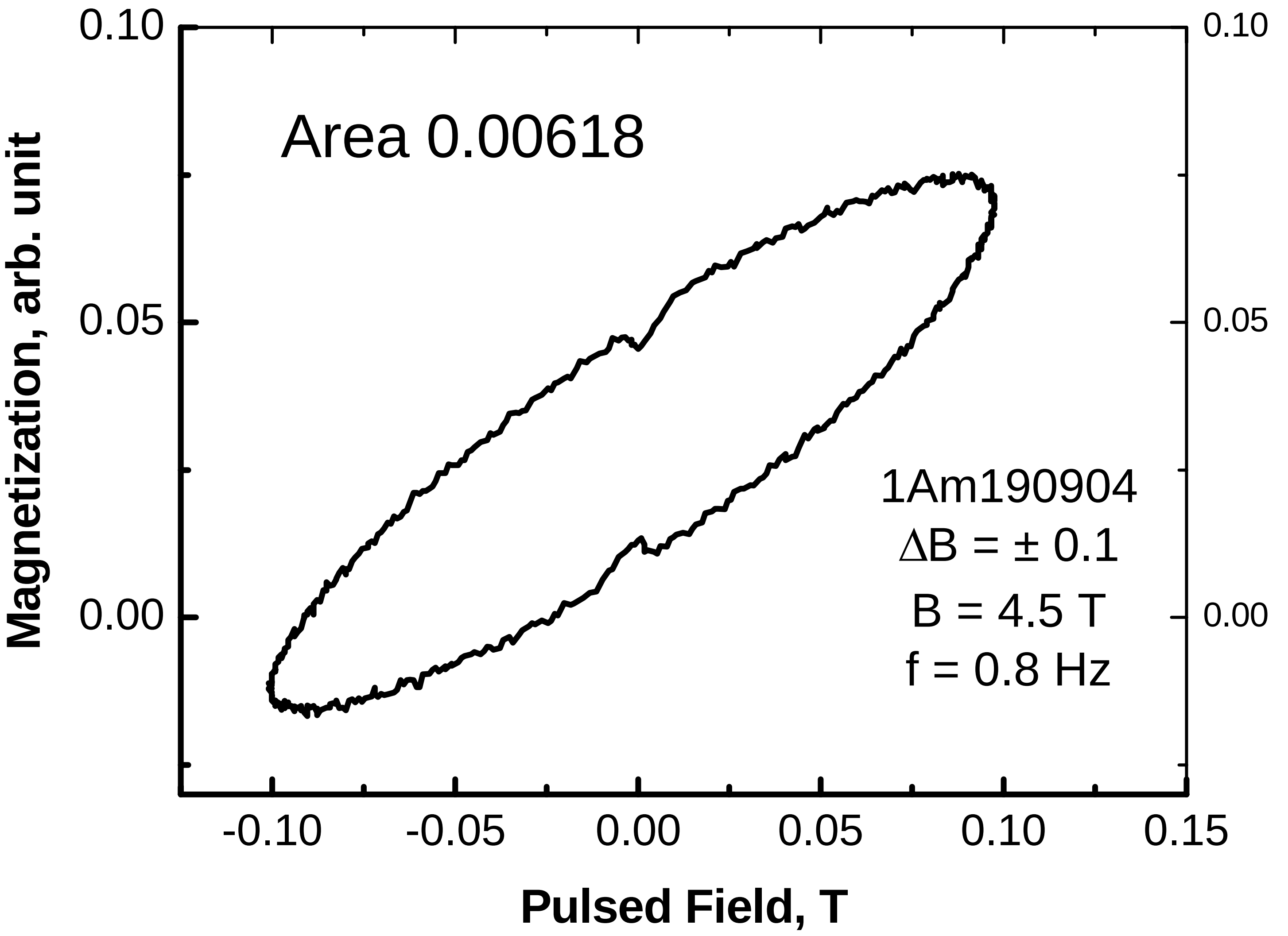
temperature increasing (T_{in}-T_{out})

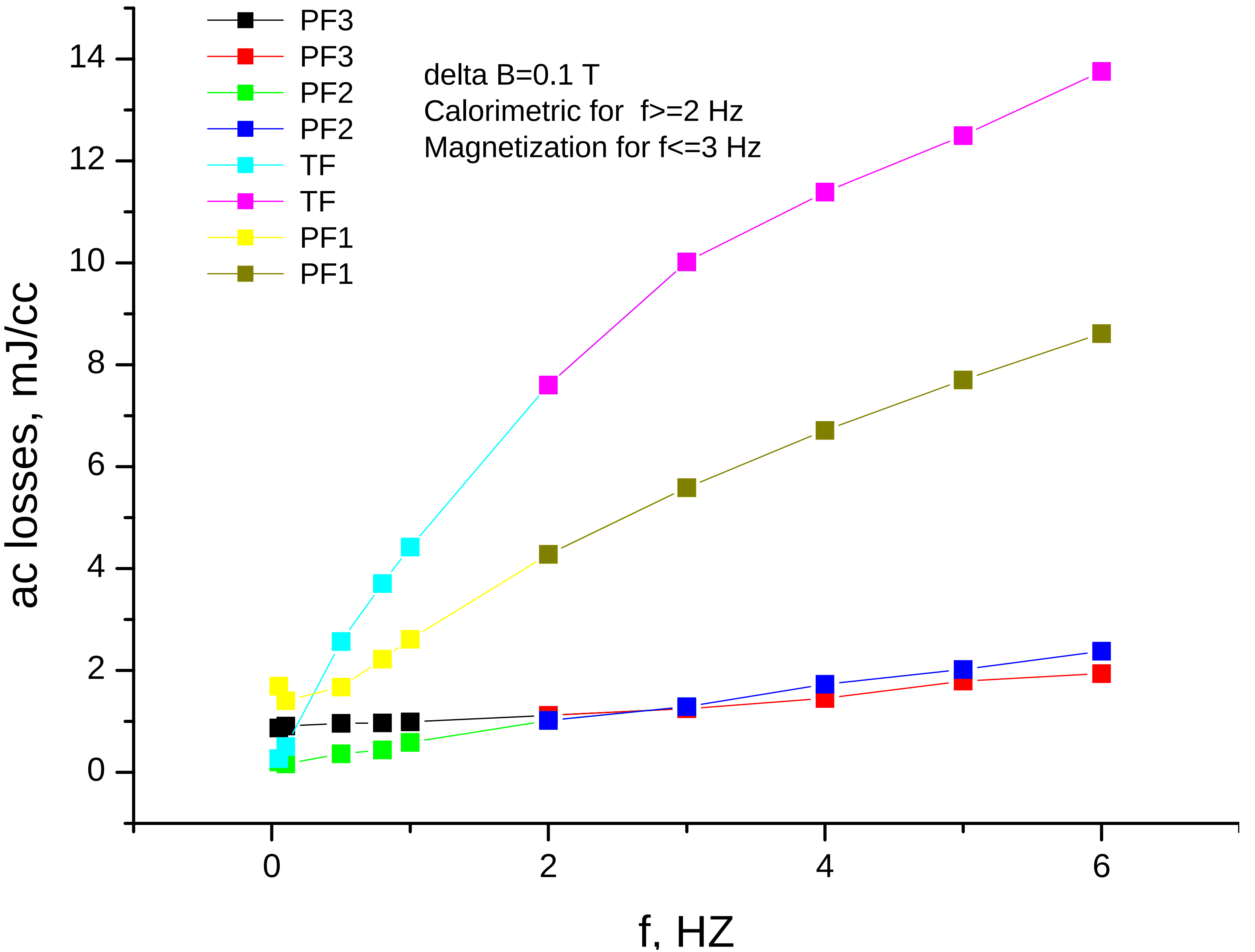


PF2 and PF3AC loss measurement
temperature increasing (outlet)

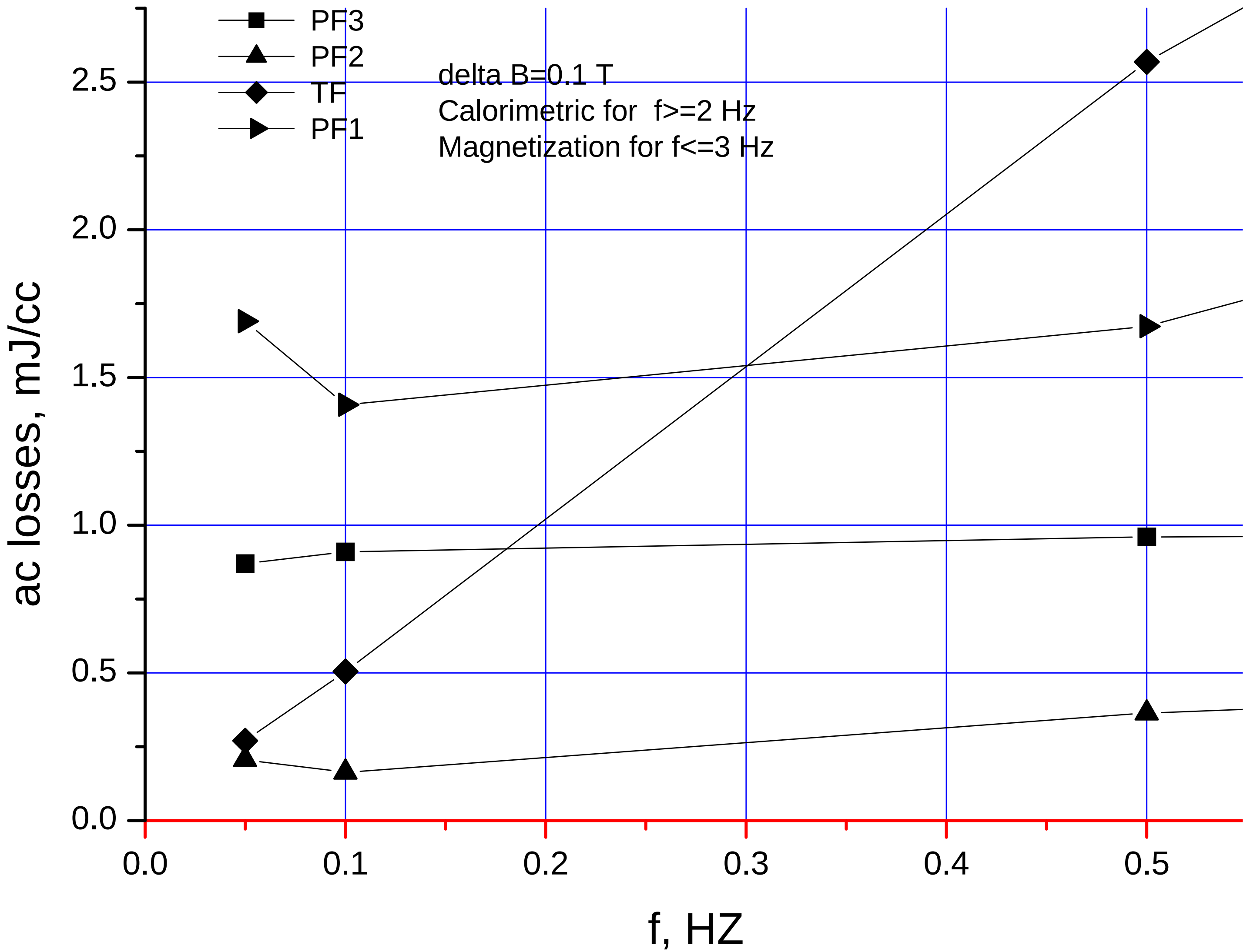


TF magnetization measurement

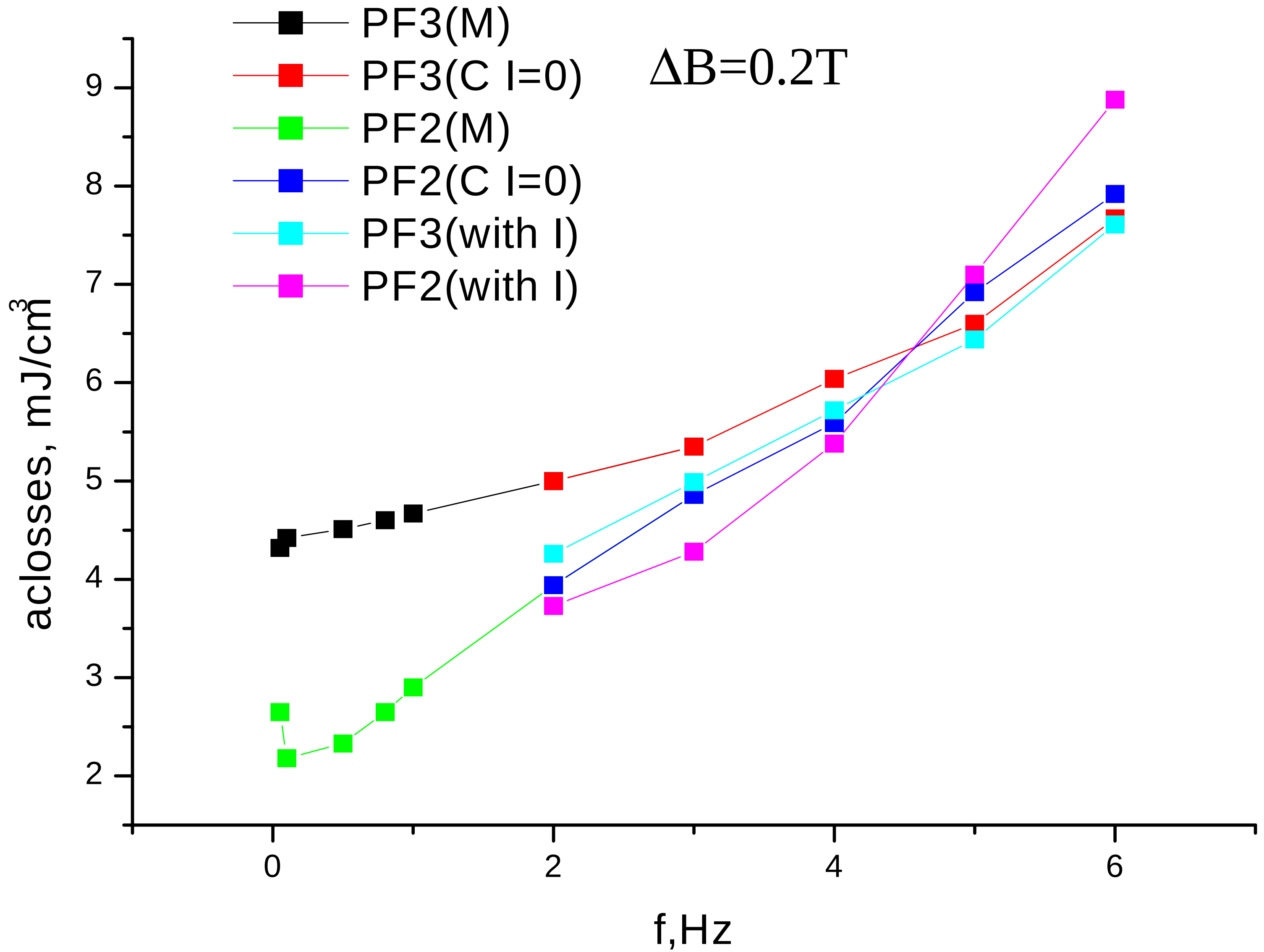




AC loss results without transport current



AC loss results without transport current



AC loss results of PF2 and PF3

AC losses results

- The four conductor have nonlinear behavior, it shows the conductor have more than one time constant
- Time constant are much lower than expected

The soldered TF and PF1 (with a 70% wrapping on the third stage sub-cables) have the values about 37-13 ms, the of PF1 is half of the TF only, it confirm the role played by the steel spacers in the loss reduction.

AC losses results

- The Ni coated PF2 (with a 70% wrapping on the third stage sub-cables) and PF3 have the values 2.3-5 ms, which reach nearly the strand value.
- The conductors have different loss behaviors at f≈0, the conductors, which has wrapping on the sub-cable, (PF1 and PF2) has higher AC loss at f=0.05 than the loss at f =0.1.

Time constant evaluation

conductor	TF	PF1	PF2	PF3
$n\tau$ (f=0.05-0.5)	36.8ms	13.5ms	2.3ms	5.1ms
$n\tau$ (f=2-6)	12.4ms	7.8ms	2.37ms	1.43ms

Transient Stability

Pulse 142 ms

- Temperature margin VS stability：

  B= 4.0 ~ 4.5 T, I=14.3 ~ 14.5 kA.

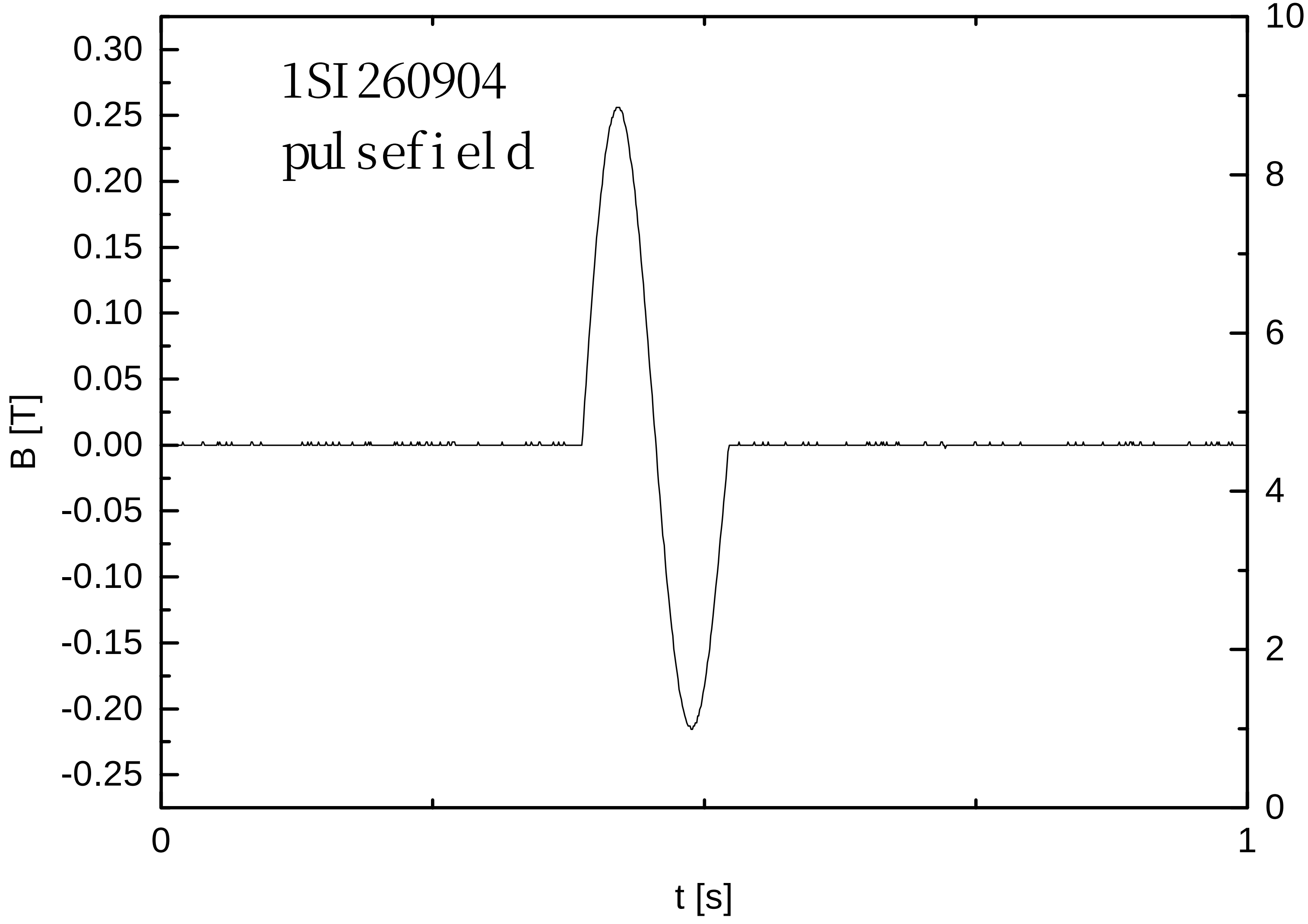
- I_{op}/I_c VS stability：

  B=4.5 and 5.8 T separately.

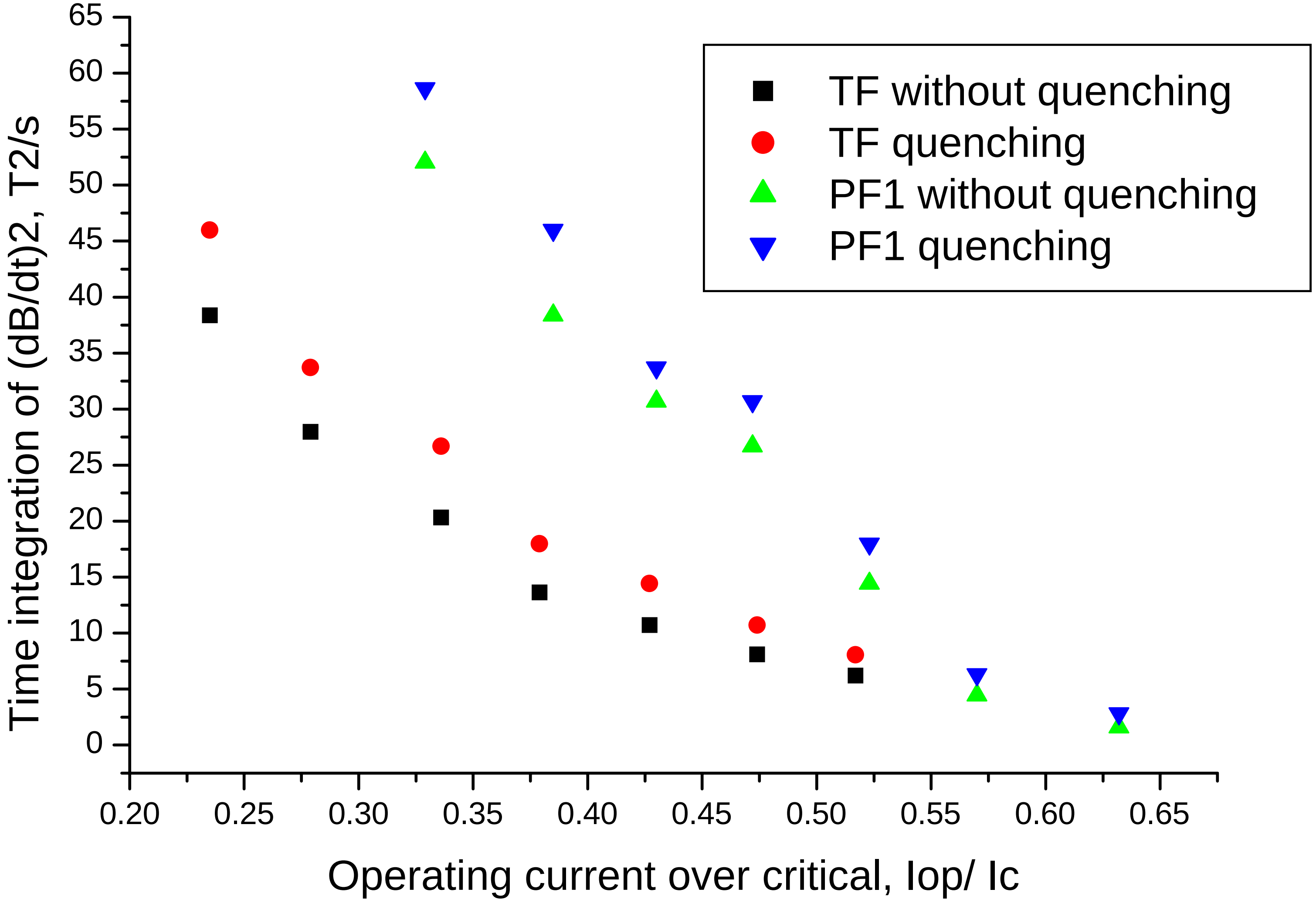
- dm/dt VS stability

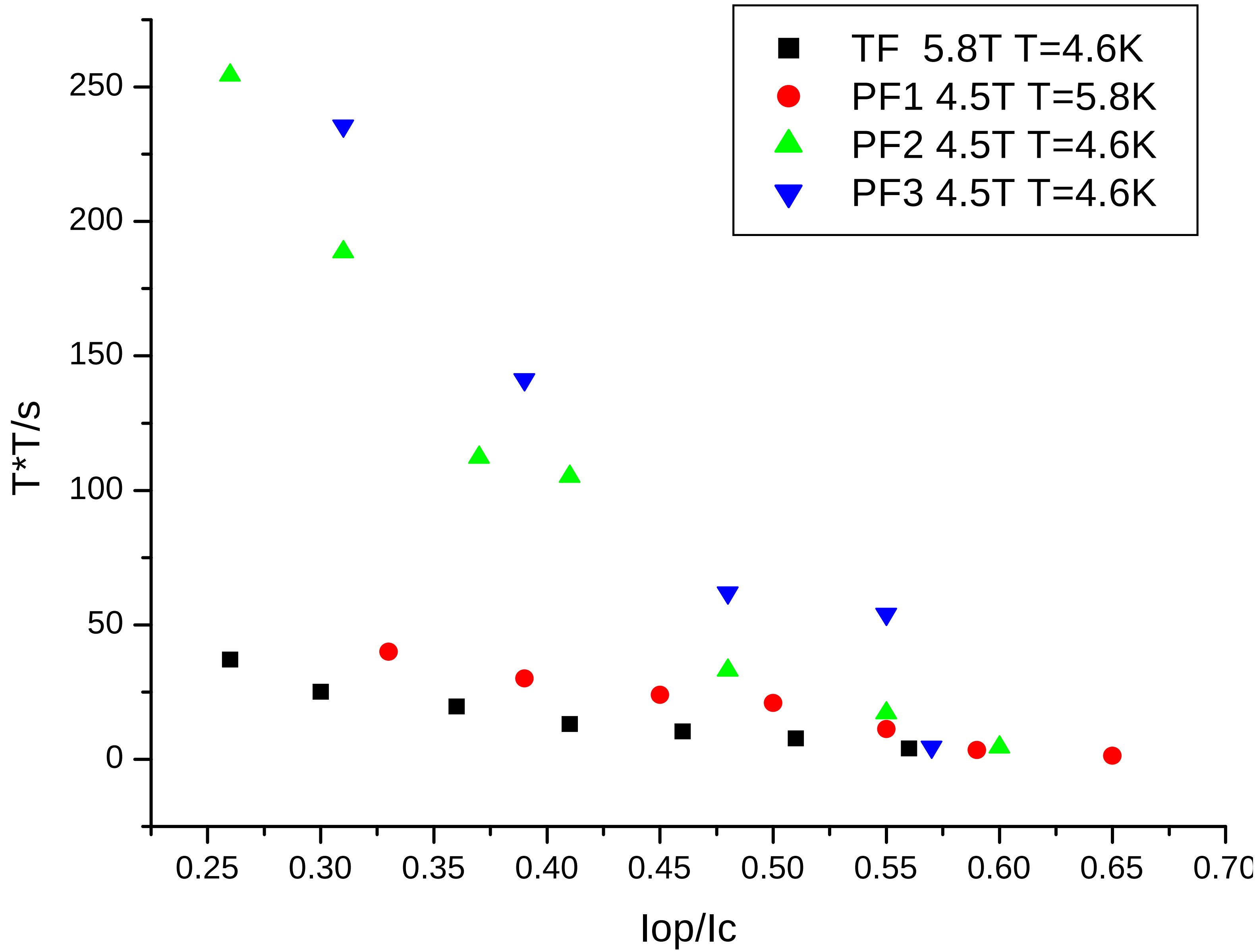
  B=4.5 and 5.8 T separately，I=14.5kA.

Pulse field applied on the sample



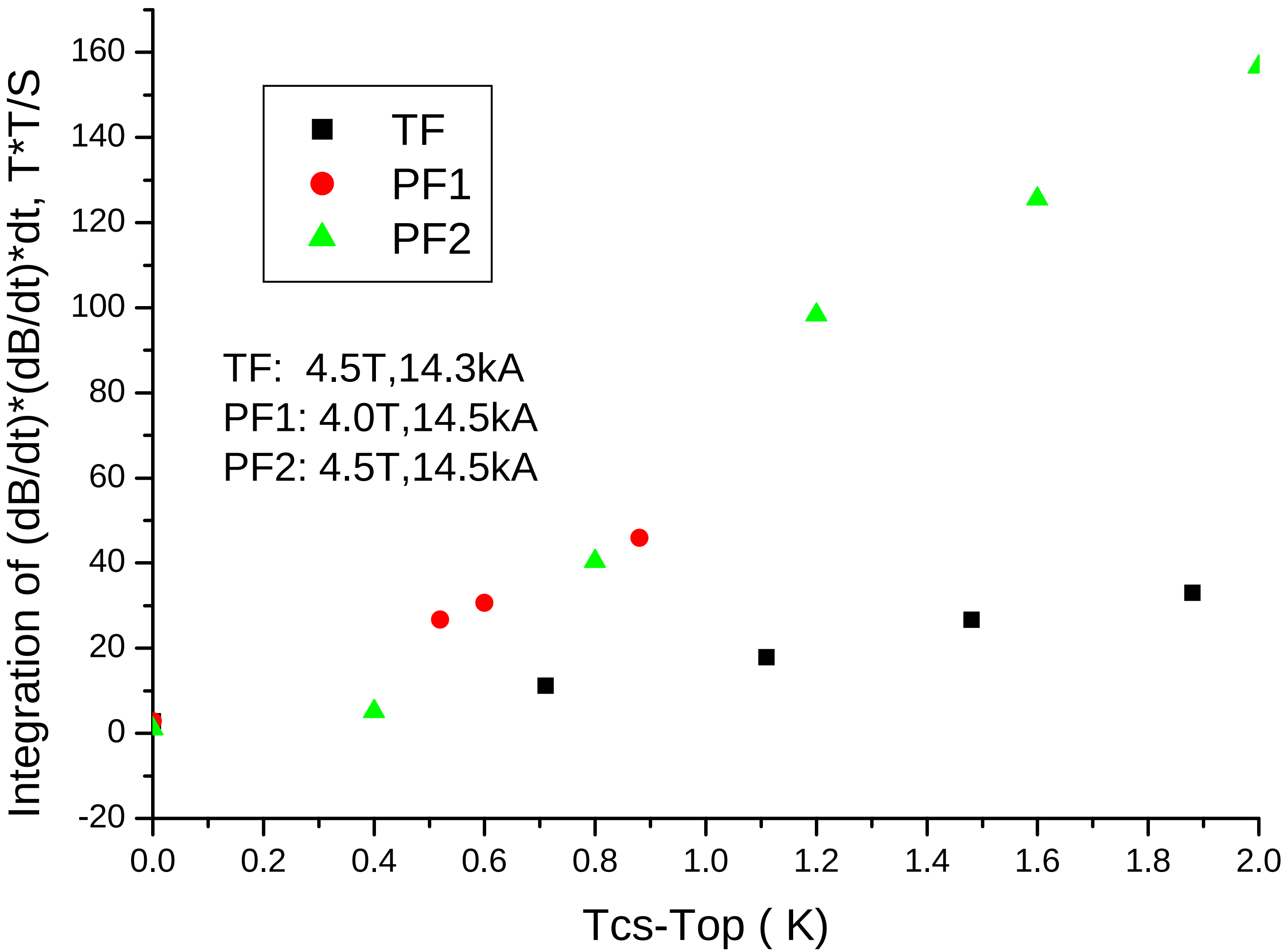
Transient stability of TF&PF1 VS Iop / Ic

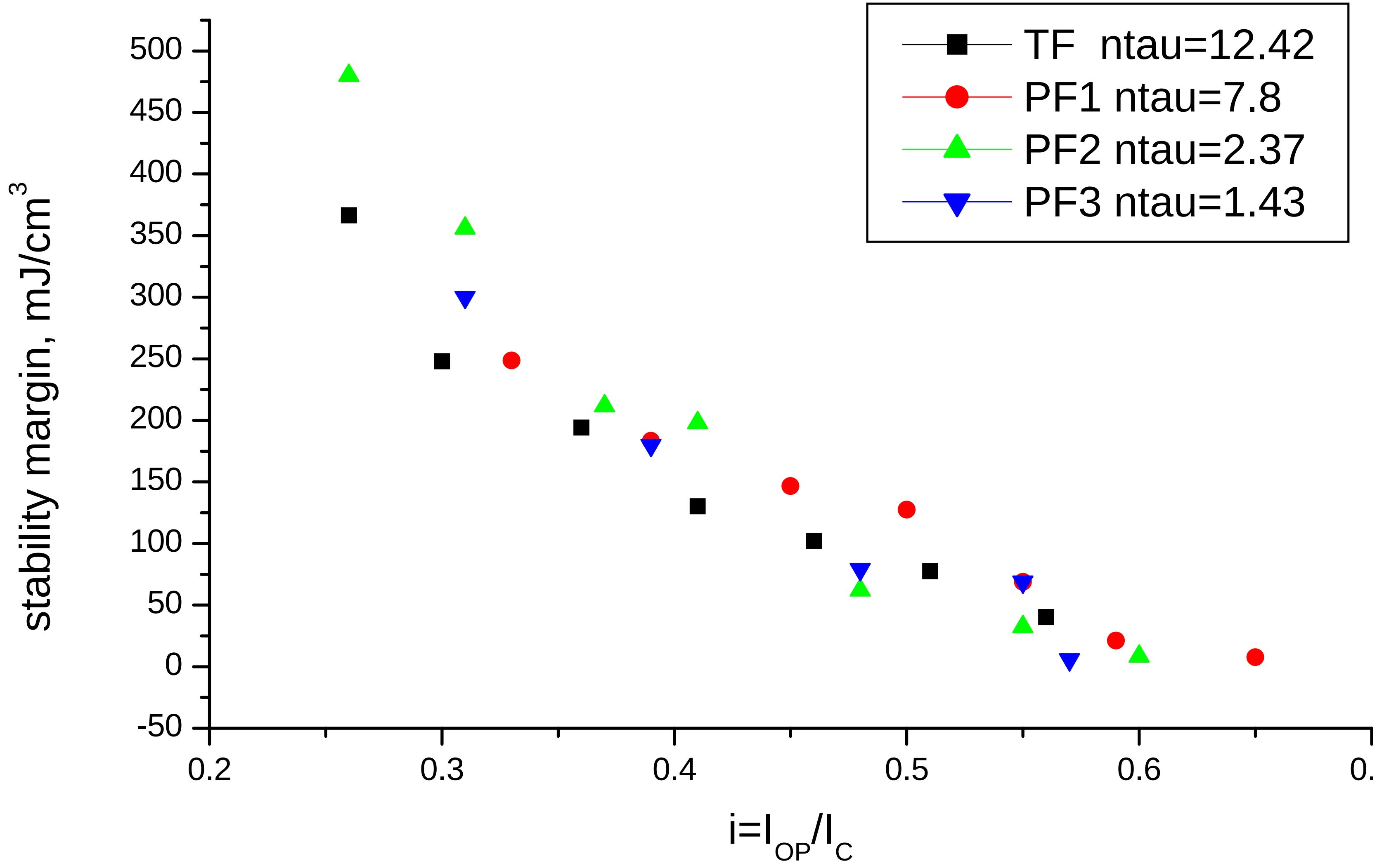




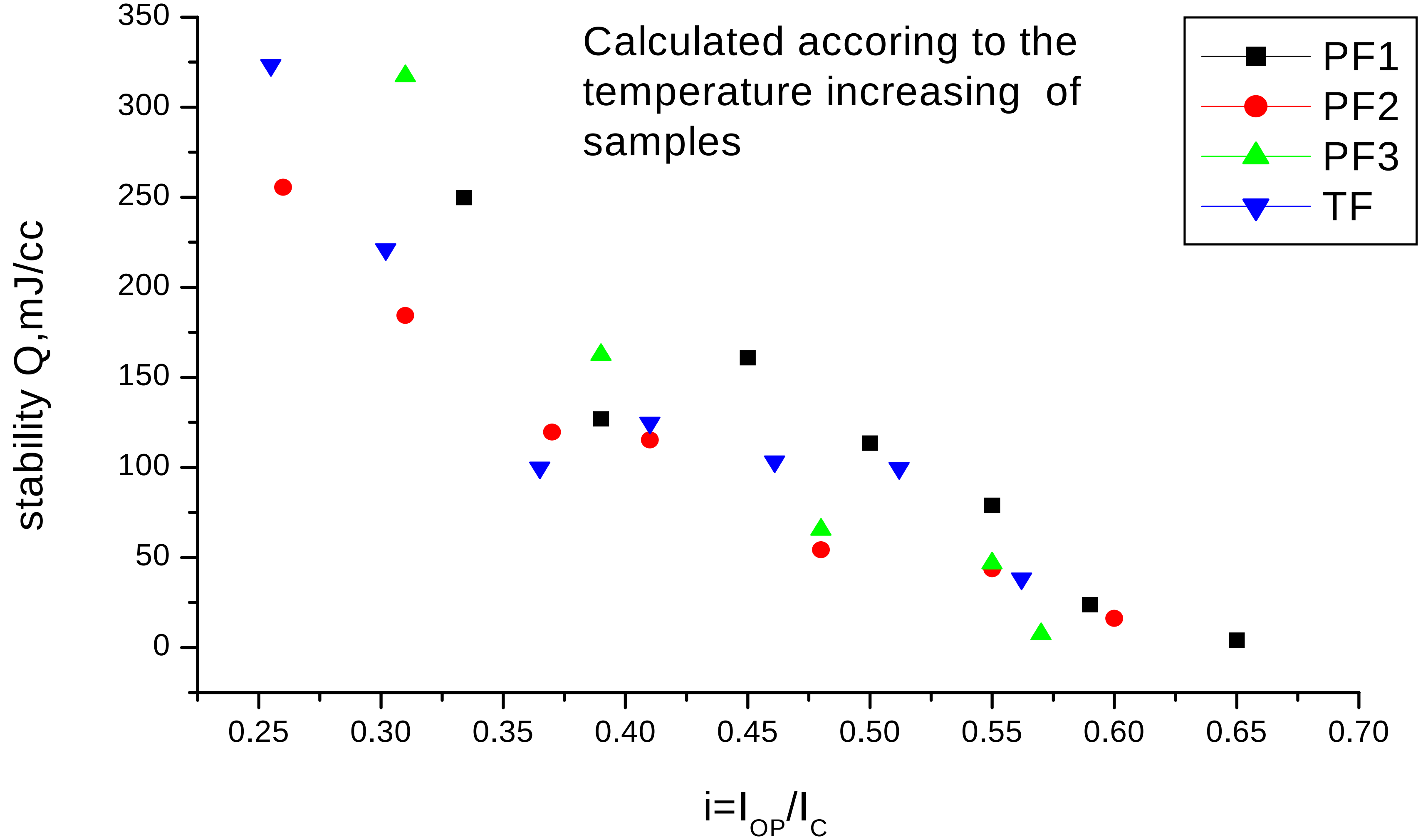
Transient stability VS Iop/Ic

Transient stability VS ΔT

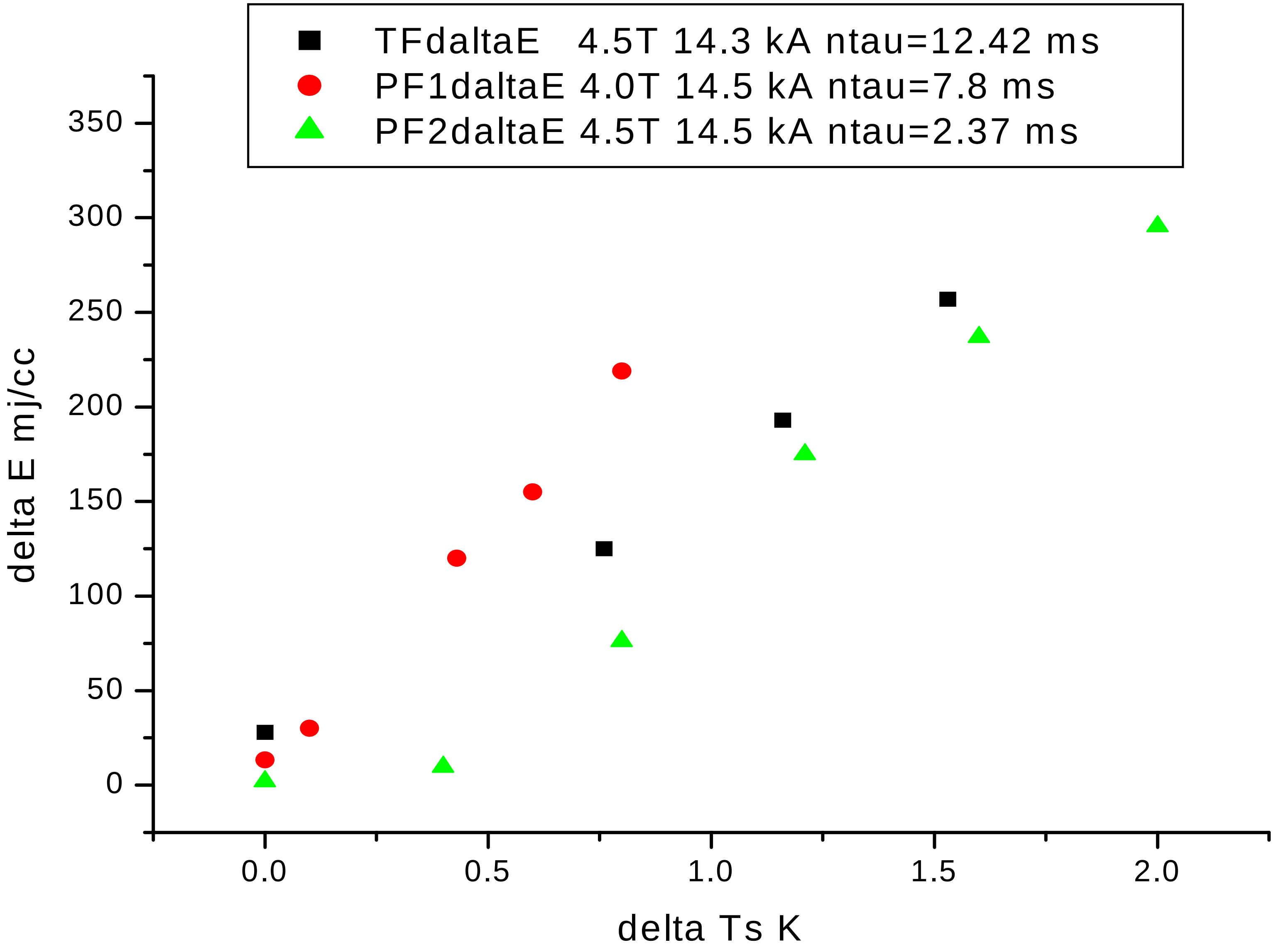




Stability margin VS Iop/Ic evaluated according to nτ (f=2-6)

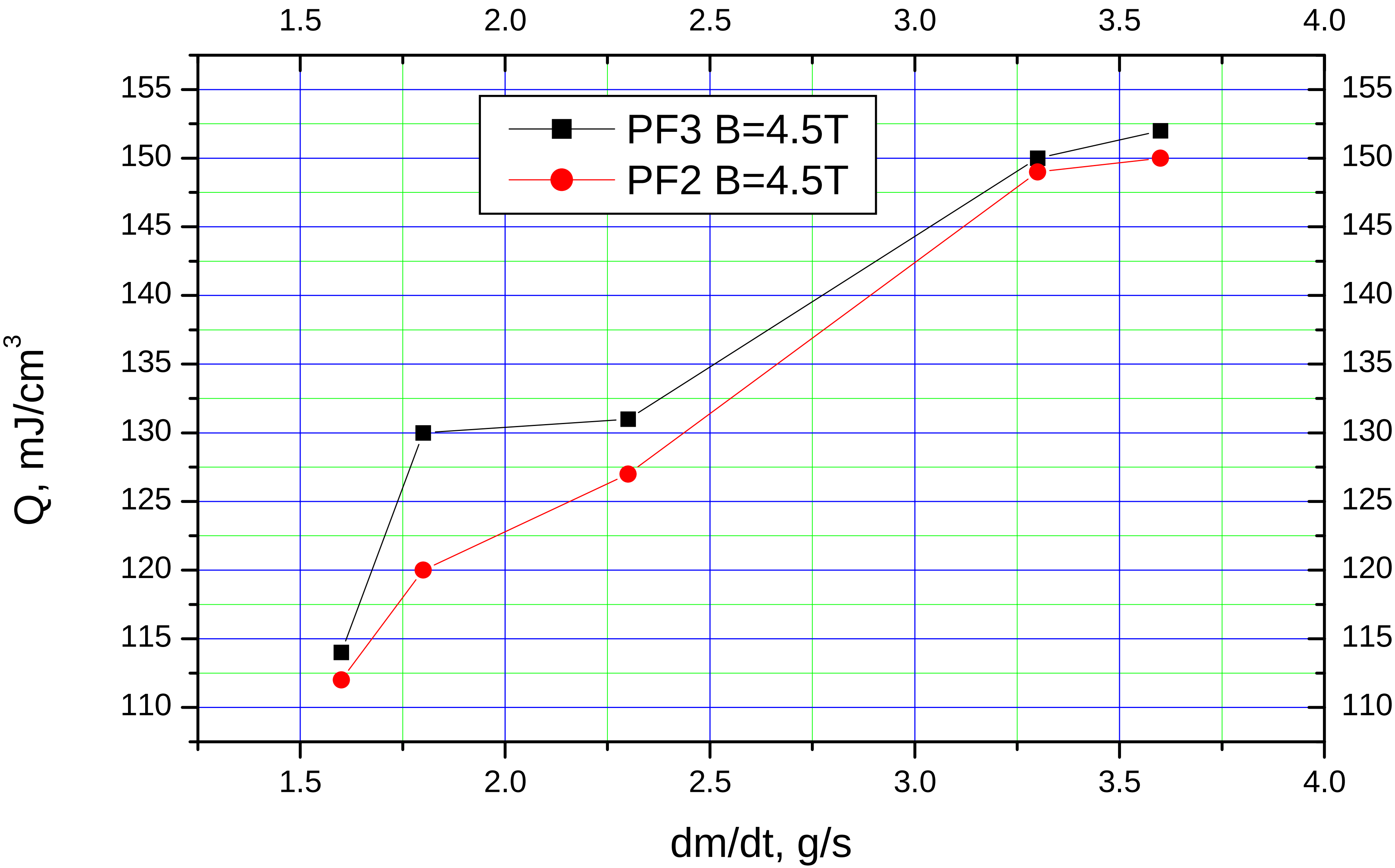


Stability margin VS Iop/Ic evaluated according to temperature measurement



Stability margin VS ΔT evaluated according to nτ (f=2-6)

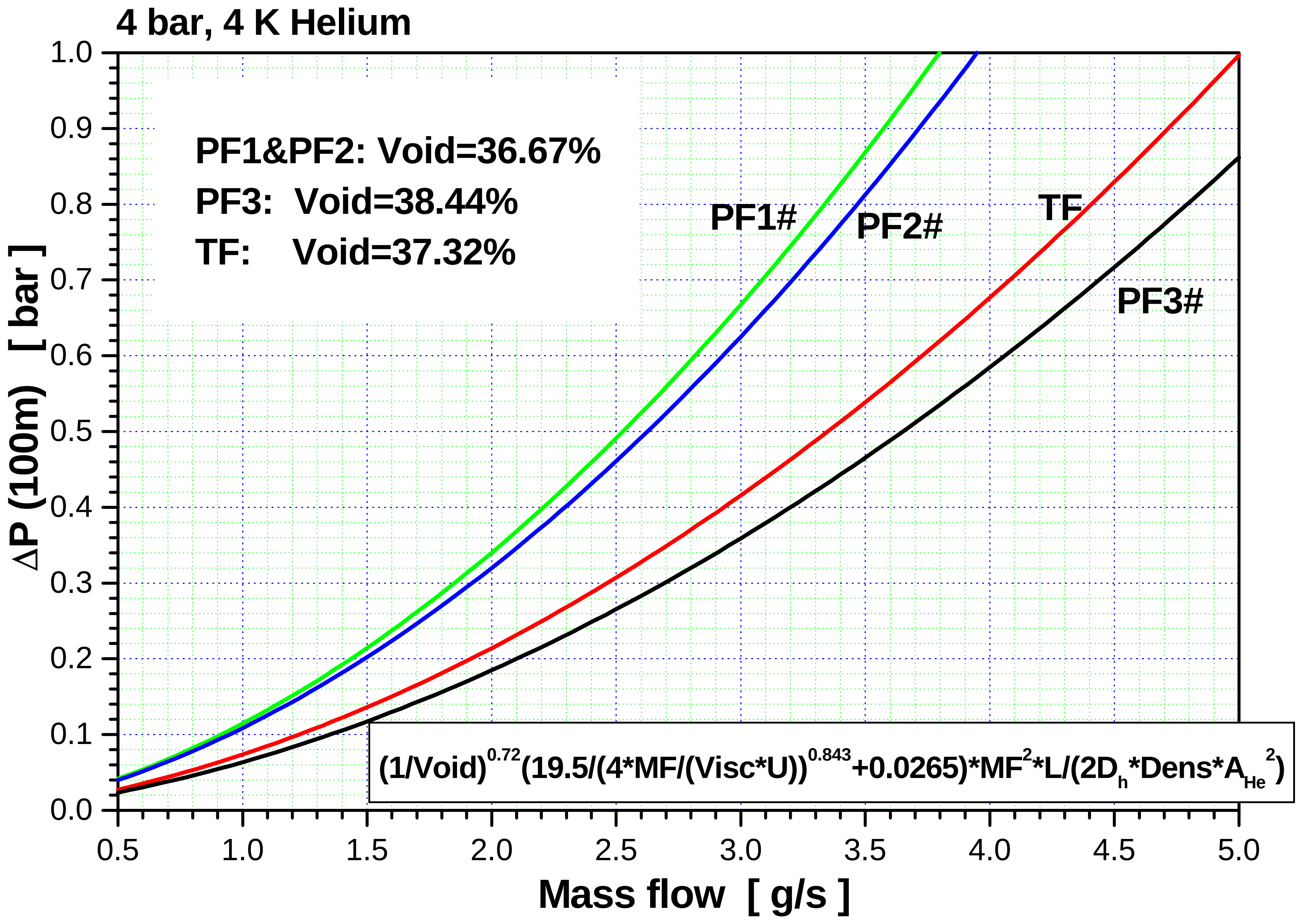
ΔE Vs dm/dt



1.5
2.0
2.5
3.0
3.5
4.0
155
150
145
140
135
130
125
120
115
110
PF3 B=4.5T
PF2 B=4.5T
Q, mJ/cm3
dm/dt, g/s

Results of transient stability test

- All of the conductors have enough ability against transient disturbance due to plasma disruption at the nominal operating condition.
- The conductor, which has smaller AC losses, have higher ability against transient disturbance.
- Increase of mass flow rate can increase transient stability
- The energy margin of the 4 conductors is almost same according to our preliminary estimation.



4 bar, 4 K Helium
PF1&PF2: Void=36.67%
PF3: Void=38.44%
TF: Void=37.32%
PF1#
PF2#
TF
PF3#
(1/Void)^0.72(19.5/(4*MF/(Visc*U))^0.843+0.0265)*MF^2*L/(2D_h*Dens*A_He^2)
ΔP (100m) [bar]
Mass flow [g/s]
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

Conductor selection

• TF magnet will be operated in steady state and at relative high magnet field (B_{max} = 5.8 T). Therefore, the stability is more important than AC losses for TF conductor. From this point, **the conductor with solder coating and without rapping on sub-cable is chosen for TF magnet.**

• PF3 or PF2 with Ni coated has lower AC losses and high transient stability against dB/dt, and seems a good candidate for PF magnet, both conductor have very high transverse resistance and likely to bring current sharing problem. The drop of current sharing temperature for PF2 conductor at high magnet field suggested this problem.

Conductor selection

• **we chose Nickel as coating material for PF**. In order to decrease the transverse resistant, the coating **thickness will be reduced from 2μm to 1.5μm, sulfuric-chloride electrolyte will be used to instead of Acetic-electrolyte and the void fraction will be reduced from 38 % to 35% as well.**

$n\Omega \cdot m$

• It is no doubt that **the rapping on the third sub-cable should leave out. The design of PF3 with above modification is chosen for HT-7U PF magnet.**

• **The prototype PF(CS) coil is in fabrication. We will test it and to check the conductor design.**

Summary (1)

- **The NbTI samples with very high proportion (68.6%) of segregated copper have been properly tested in Sultan facility.**

- **The Critical currents of the four conductors are lower than the strand data 10-12% and the current sharing temperatures of PF1 and TF are lower than the calculated value 0.2 K. It is noticed that the drop of PF2T_{cs} is increased while the magnet field increasing suggests there is a current sharing problem probably.**

Summary (2)

- The AC losses of four conductors are much lower than expected and have a non-linear behavior. The value of time constant of solder coated TF and PF1 are close to the results of virgin state of SeCRETS measured by University of Twente. The Nickel coated PF2 and PF3 have very low time constant reach the strand level. It is clear that the inclusion of segregated pure copper strands in the conductor will decrease the coupling loss and consequently increase the transverse resistance greatly.

Summary(3)

· The solder coating results lower inter-strand resistance can ensure adequate current sharing and therefore ensure the effect of segregated copper as stabilizer, however, it bring high coupling loss too, we will use it for HT-7U TF magnet.

·The Nickel coating has relative higher inter-strand resistance and can reduce the coupling loss effectively shows high transient stability against magnet field disturbance, we choose it for PF magnet.

· A prototype central solenoid coil using Ni coated conductor is in fabrication now. It is planning to be tested this year. The design of PF conductor will be fixed according to the test results.

Diameter available 3.1 m

Height available 4.7 m

Vacuum 1×10^{-5} τ

Maximal current 30 kA

Refrigerator 500W/4.5 k

The prototype of TF and PF magnet will be tested in the facility this year

Superconducting magnet test facility

Thank you !