4EP2-23: Critical current scattering in series arrays of HTS SQUIDs based on ion-damaged barrier Josephson junctions

Denis Crété[1], Eliana Recoba Pawlowski[1], Julien Kermorvant[2], Yves Lemaître[1], Bruno Marcilhac[1], Christian Ulysse[3]

[1]Unité Mixte de Physique CNRS-THALES, Univ. Paris-Sud, Univ. Paris-Saclay, Palaiseau, France
[2]THALES Com. and Security, France,
[3]Labo. Photonique & Nanostructures, CNRS, Marcoussis, France

Abstract

Characterization of scattering for an HTS Josephson junction (JJ) technology is usually based on critical current I_C (and normal resistance R_n) defined by the Resistively Shunted Junction (RSJ) model. Accounting for thermal noise e.g. using Ambegaokar and Halperin (AH) model [1] is necessary but time consuming and not always sufficient.

We propose the thermal noise voltage (TNV) criterion for the determination of critical current, using AH model. At $I=I_C$, $<V>$ is related to the junction parameters I_C, R_n and $\gamma = hI_C/2\pi k_B T$ where T is the physical temperature. An empirical analytical function has been found to fit the normalized thermal-noise/voltage relation given by AH.
We present the results of the TNV criterion on JJ based on the ion damage barrier technology described in [2] and compare it to the usual "predefined voltage threshold" (PVT) method.

[1] Ambegaokar V. and Halperin B.J.,Phys. Rev. Lett., 22,1364-1366 (1969)
[2] App. Phys. Lett. 87, 102502 (2005) ; 89, 112515 (2006) ; 91, 142506 (2007) ; 91 262508 (2007).

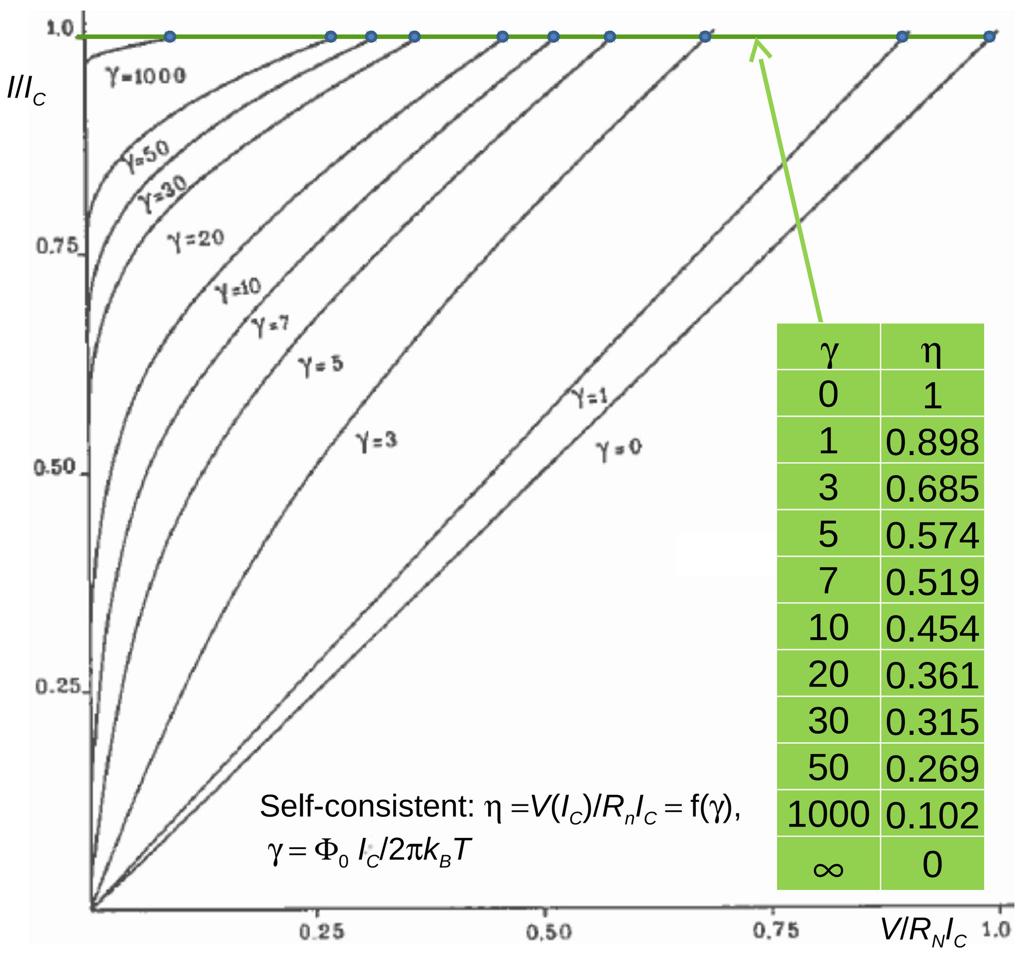
Classical I_c determination methods

Fixed Voltage Threshold (FV): $I_C=I(V=V_{thres})$
+ Simple (typ. V_{thres}= 1µV)
+ For N JJ series array $I_C=I(N.\ V_{thres})$
+ widely used (easy comparison)
- The extracted value of I_C is lowered by thermal noise
- In case of I_C scattering, TM essentially probes the JJ with the smallest critical current.

Ambegaokar & Halperin (AH):
Adjust the full $V(I)$ curve $V(I,I_C,R_n,T)$
+ No hypothesis made on any of the parameter ($T=T_{noise}$)
+ In principle, applicable to JJ arrays, but …
- Very sensitive to deviation from RSJ model (and scattering)
- Computation time is longer (and convergence is not guaranteed)

Ambegaokar & Halperin (limited to very small I_C):
I_C = f(T,R_{d0}/R_n) where R_{d0} is the dynamic resistance at I=0
+ Simple
- Not applicable when Josephson energy > k_BT

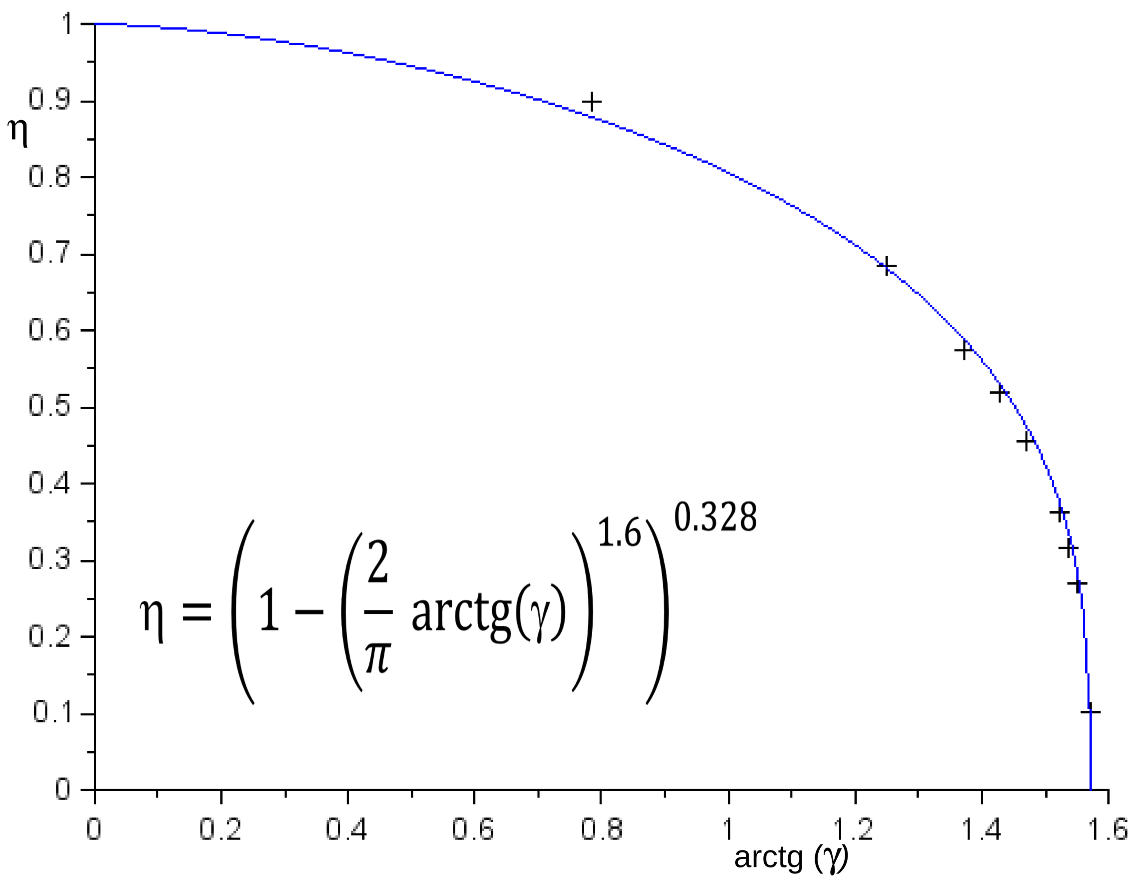
« Thermal noise voltage » (TNV) method



γ	η
0	1
1	0.898
3	0.685
5	0.574
7	0.519
10	0.454
20	0.361
30	0.315
50	0.269
1000	0.102
∞	0

$V(I)$ curves of RSJ model in reduced coordinates for different values of γ (Ambegaokar & Halperin). For each γ, only the point at $I=I_C$ is used

Analytical approximation of f(γ)



Variation of the reduced « thermal noise voltage » η versus atan(γ). Crosses represent tabulated values, and the blue curve is the analytical approximation.

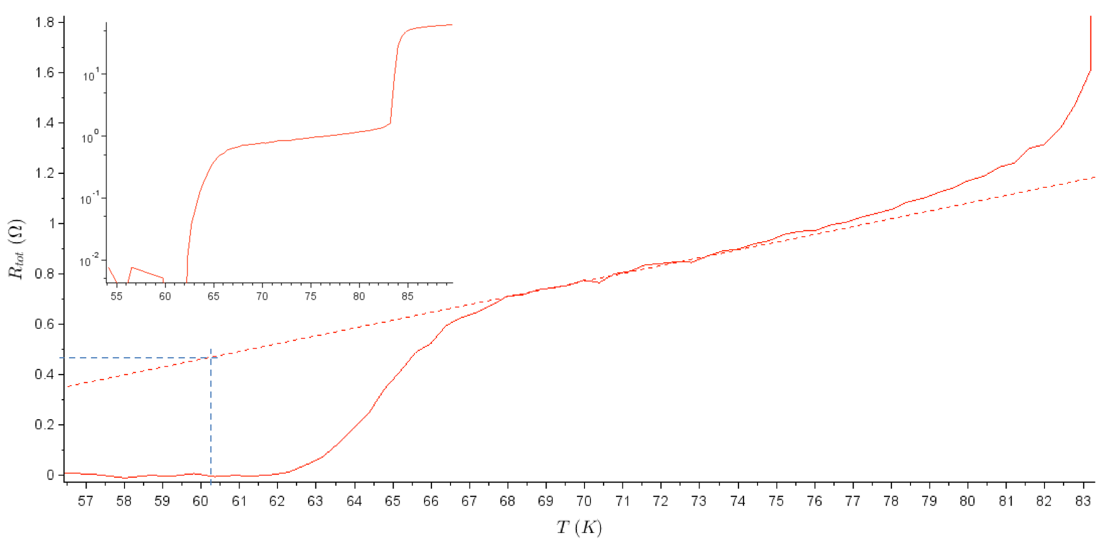
Asymptotic behaviour

$$arctg\left(\frac{\Phi_0 I_C}{2\pi k_B T}\right) = \frac{\pi}{2}\left(1-\left(\frac{V(I_C)}{R_N I_C}\right)^{3,08}\right)^{0,63}$$

- $I_C/T \sim \left(\frac{V(I_C)}{R_N I_C}\right)^{-3,08}$ when η → 0
- But $I_C \sim (1-\eta)^{0.63}$ when η → 1 instead of $I_C \sim 1-\eta$. It only impacts at high temperatures when the V(I) curves are nearly linear.

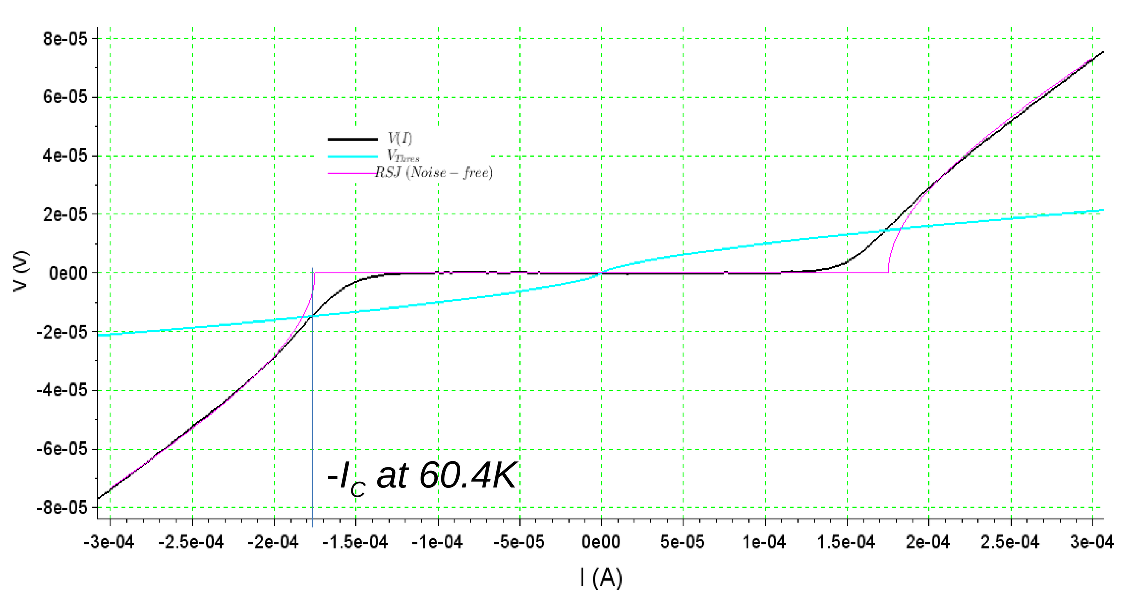
Application of TNV method: determination of R_n

- Requires R_n : usually determined by the slope of $V(I)$. However, a few JJ types do not allow this method, e.g. ion-damaged barriers → Extrapolation of $I(T)$ from above the Josephson coupling range (and of course below T_C).

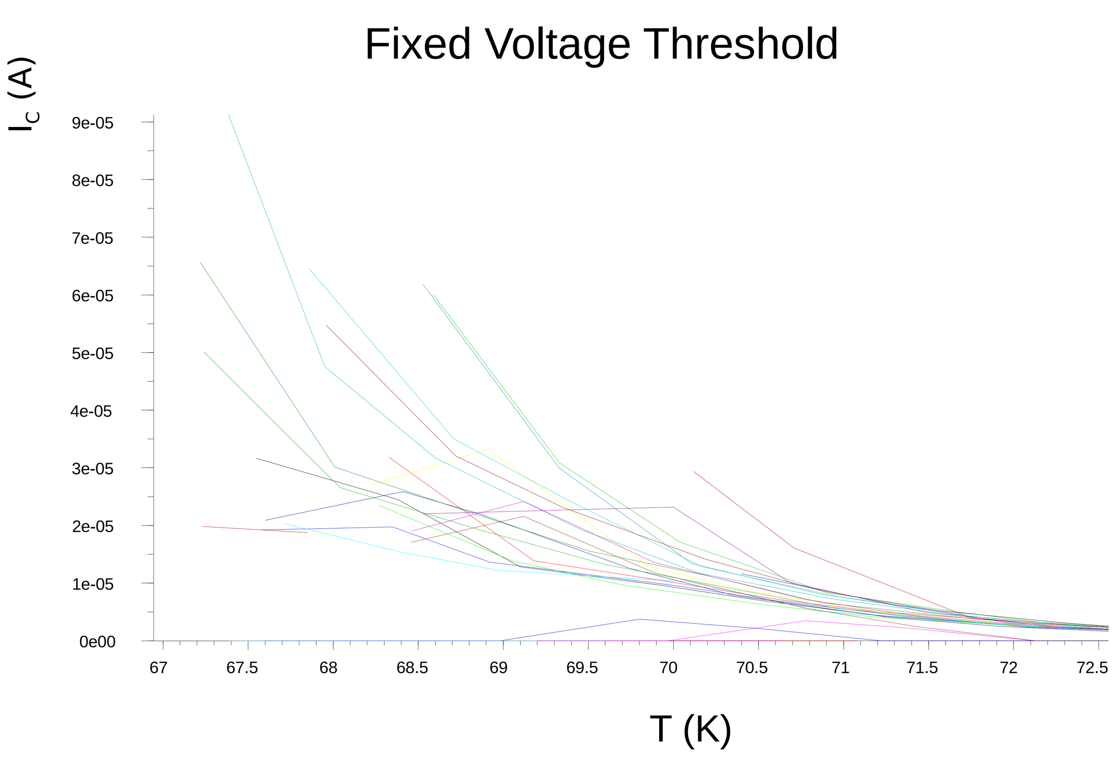


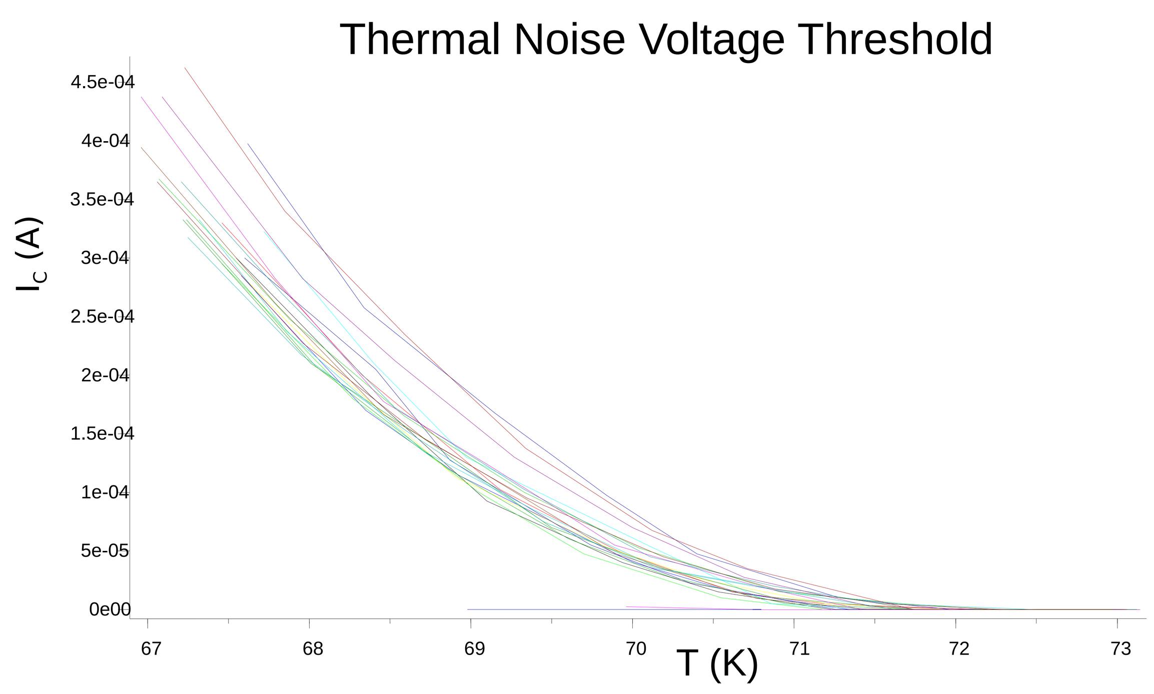
Application of TNV method

$g_i=\Phi_0/(2k_BT_{noise})$; // with $T_{noise}=T_{physical}$
$V_{Thres}=R_n*I.*(1-\ (2/\pi*atan(g_i*|I|)).\hat{}(1/0.63)\ ).\hat{}(1/3.08)$
$I_C=-I(find(V>=V_{Thres},1))$; // « floor » value with sampling resolution

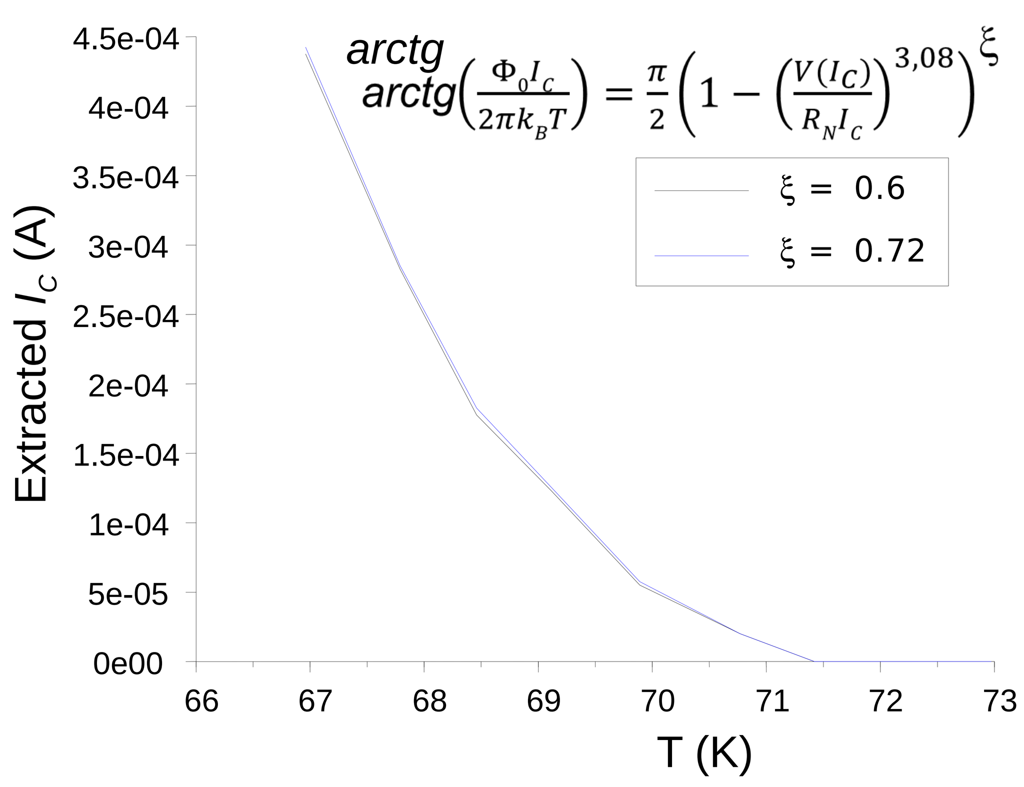


Comparison of FV and TNV methods (on a collection of SQUIDs within same chip)

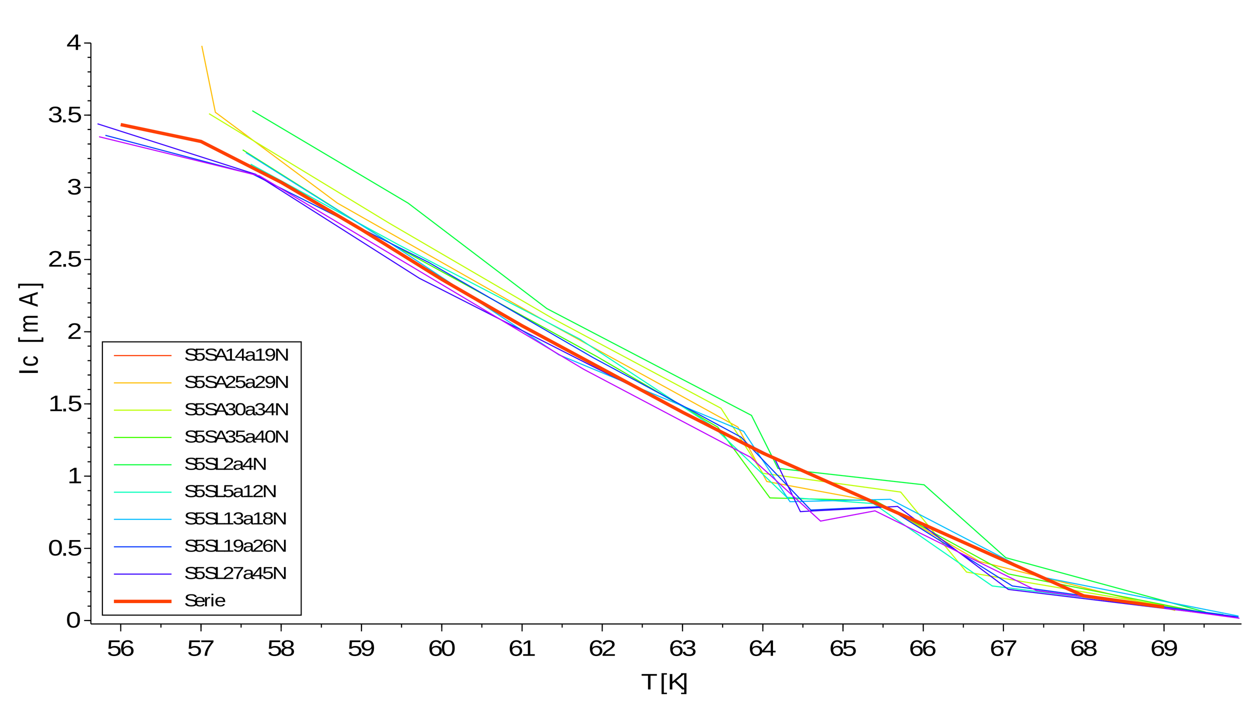




Moderate dependance of extracted I_C values on ξ



TNV method and scattering



The extracted I_C value for a series array is an average lying in the lower range of the I_Cs of its constituants (but larger than the minimum I_C, due to the larger voltage threshold).

Conclusion

The expression we propose for the voltage measured at the terminals of an RSJ device biased at its critical current (TNV) is:
- analytical (fast),
- accurate (to within ~1% for a purely RSJ device),
- « tunable » with 2 parameters,
- useful for critical current determination from experimental results (provided R_n and T are known),
- basically robust against noise,
- applicable when either I_C=0 or when the noise is very small.

It can be applied to series, parallel and 2D arrays of JJ.

Scattering in JJ parameters results in a weighted average of the critical current. This « average » is useful for choosing the bias point for operation of an array.