“Резонансные свойства системы связанных джозефсоновских переходов”

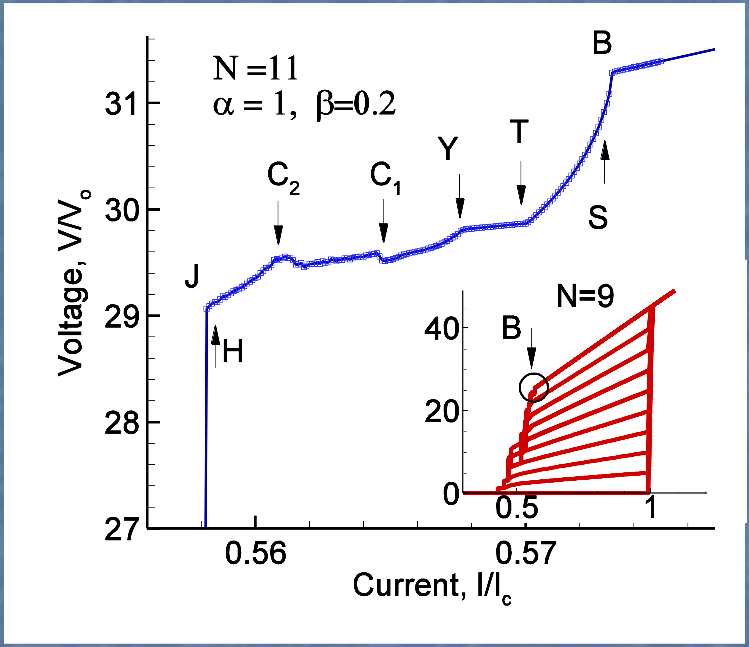
Шукринов Ю. М.   (ЛТФ, ОИЯИ)

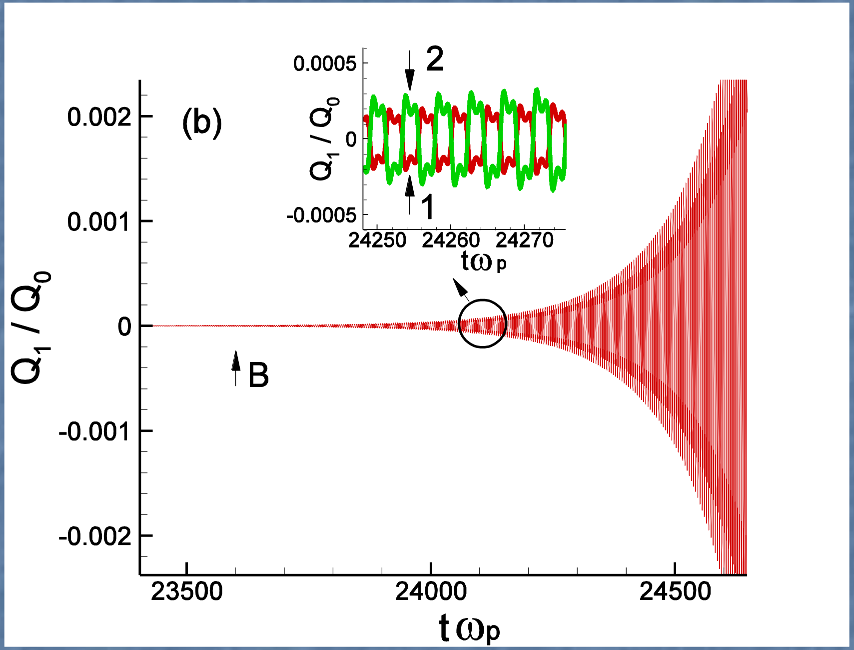
Краткое содержание

- 1. Структура ОТИ.
- 2. Корреляции в ССДП.
- 3. Нуклеация ППВ.
- 5. Диффузионный ток.
- 6. Температурная зависимость тока в ТИ.
- 7. Температурная зависимость тока возврата.
- 8. Экспериментальные свидетельства ТИ и ОТИ.

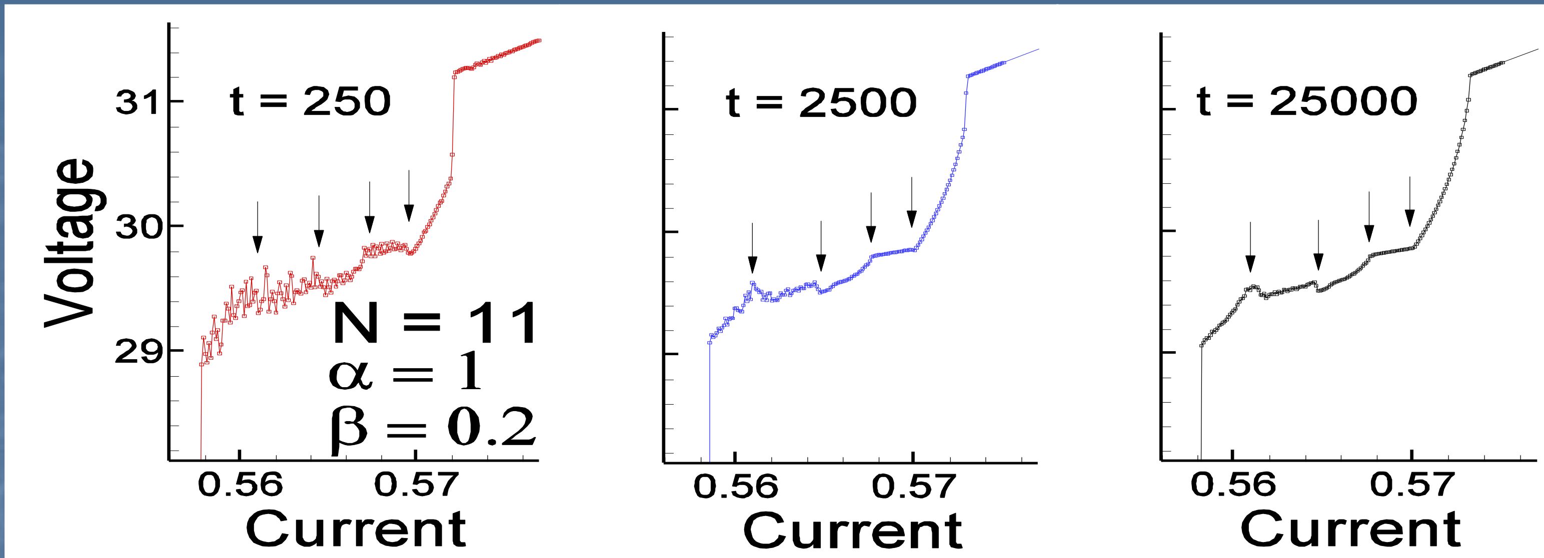
Структура ОТИ. Корреляции в ССДП.

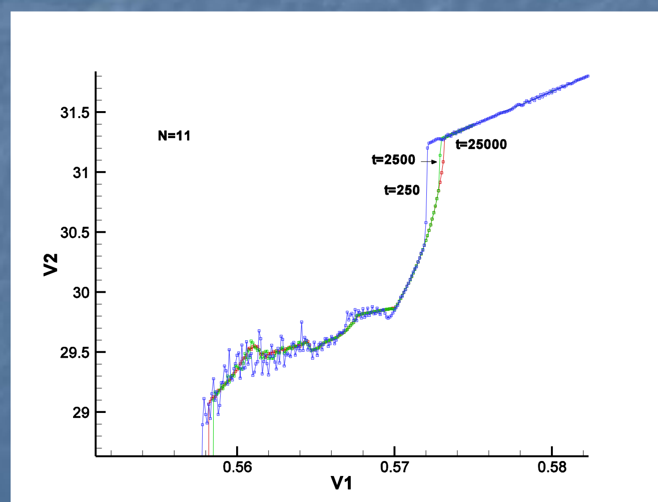
Fine structure in BPR





Yu.M.Shukrinov, F.Mahfouzi, M.Suzuki Phys.Rev.B 78, 134521 (2008).


Voltage
31
30
29
t = 250
N = 11
α = 1
β = 0.2
0.56
0.57
Current
t = 2500
0.56
0.57
Current
t = 25000
0.56
0.57
Current


N=11
t=2500
t=250
t=25000
31.5
31
30.5
30
29.5
29
V2
0.56
0.57
0.58
V1

Time dependence

- div $(\varepsilon\varepsilon_0 E) = \rho$ $\qquad Q_l = Q_0\,\alpha\,(V_{l+1} - V_l)$

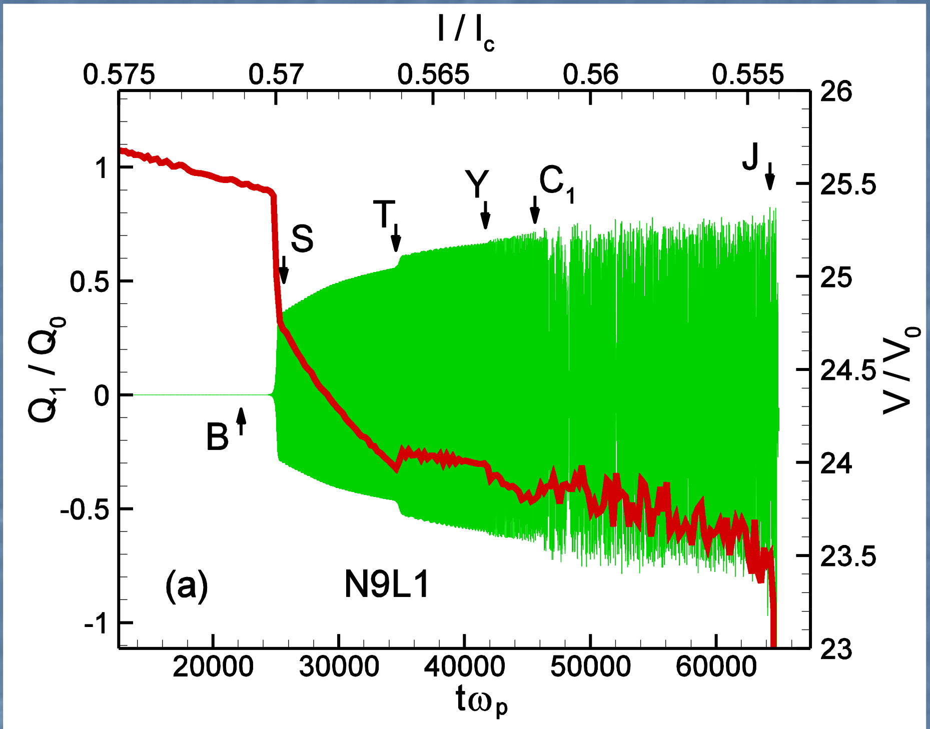
$$Q_0 = \varepsilon\,\varepsilon_0\,V_0/r_D^2$$

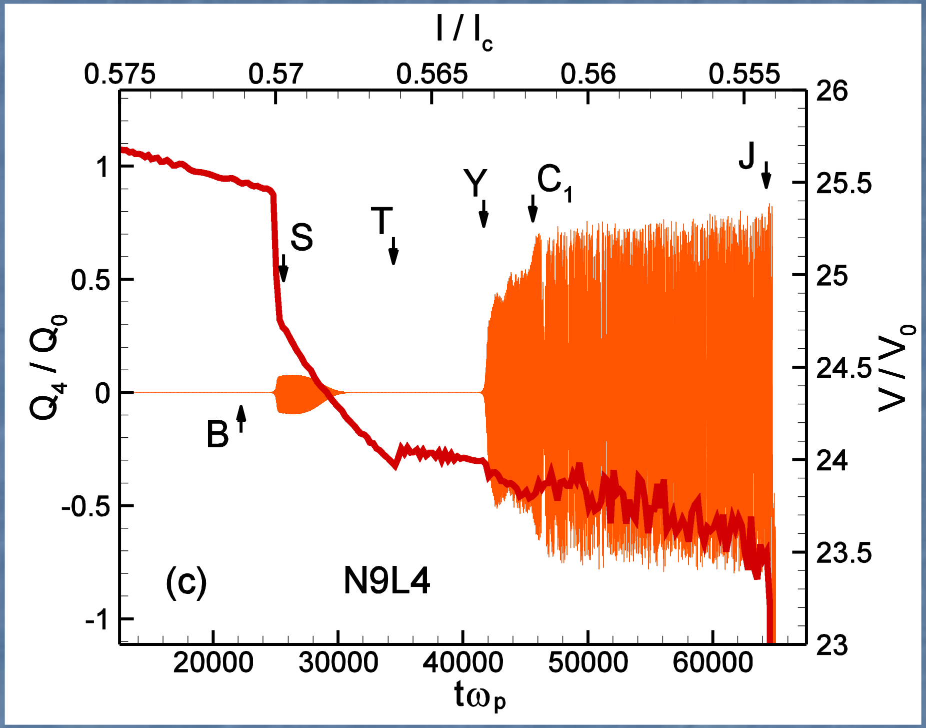
- The "time dependence" actually consists of time and bias current variation.

- We solve the system of dynamical equations for phase differences at fixed value of bias current I in some time interval $(0, T_m)$ of dimensionless time $\tau = t\omega_p$ with the time step $\delta\tau$, where t is a real time. This interval is used for time averaging procedure.

- Then we change the bias current by δI, and repeat the same procedure for the current $I+\delta I$ in new time interval $(T_m, 2T_m)$. In our simulations we put $T_m=250$, $\delta\tau=0.05$, $\delta I=0.0001$ and total recorded time was calculated as $\tau+T_m(I_0 - I)/\delta I$, where I_0 is an initial value of the bias current for time dependence recording.

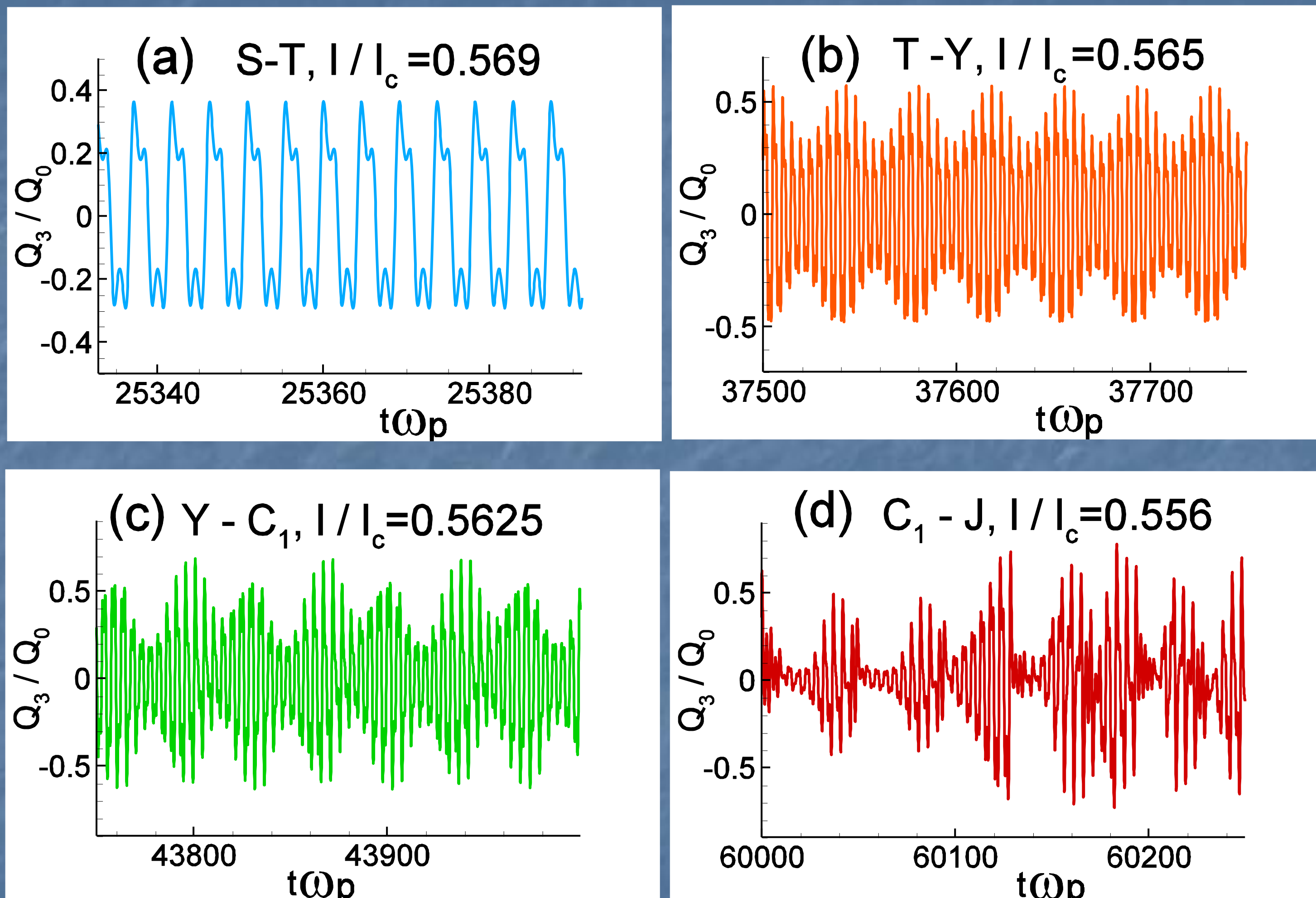
CVC and time dependence of the charge in BPR



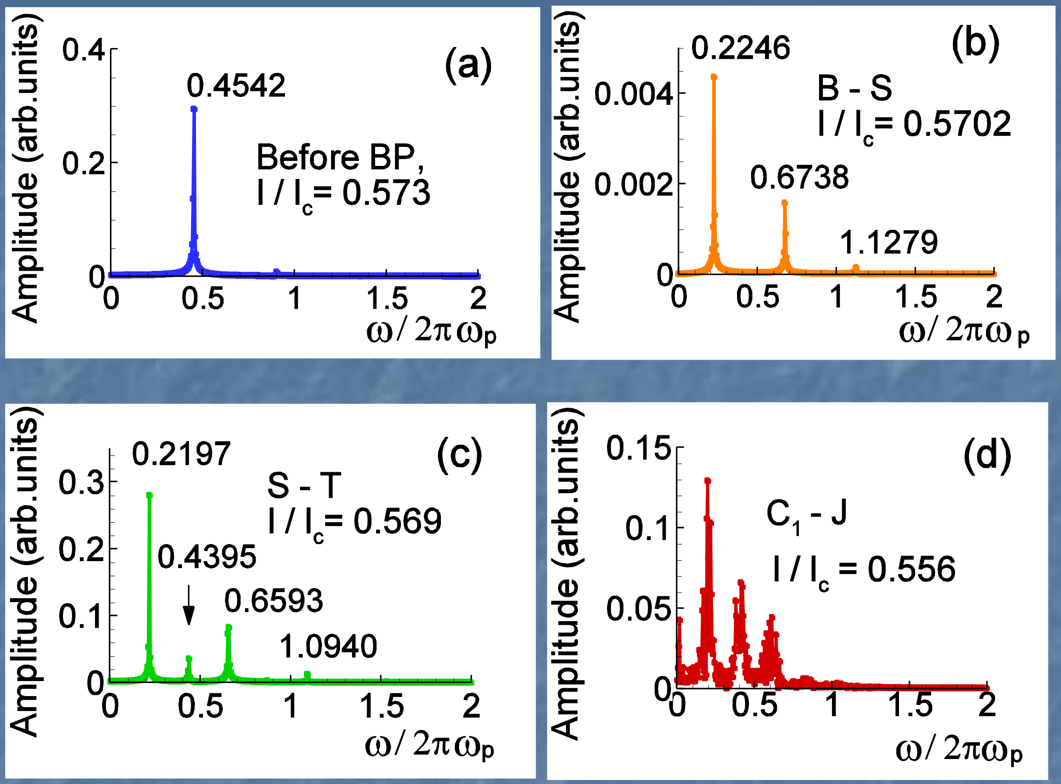


Yu.M.Shukrinov, F.Mahfouzi, M.Suzuki Phys.Rev.B 78, 134521 (2008).

Time dependence of the charge in BPR



Results of FFT analysis

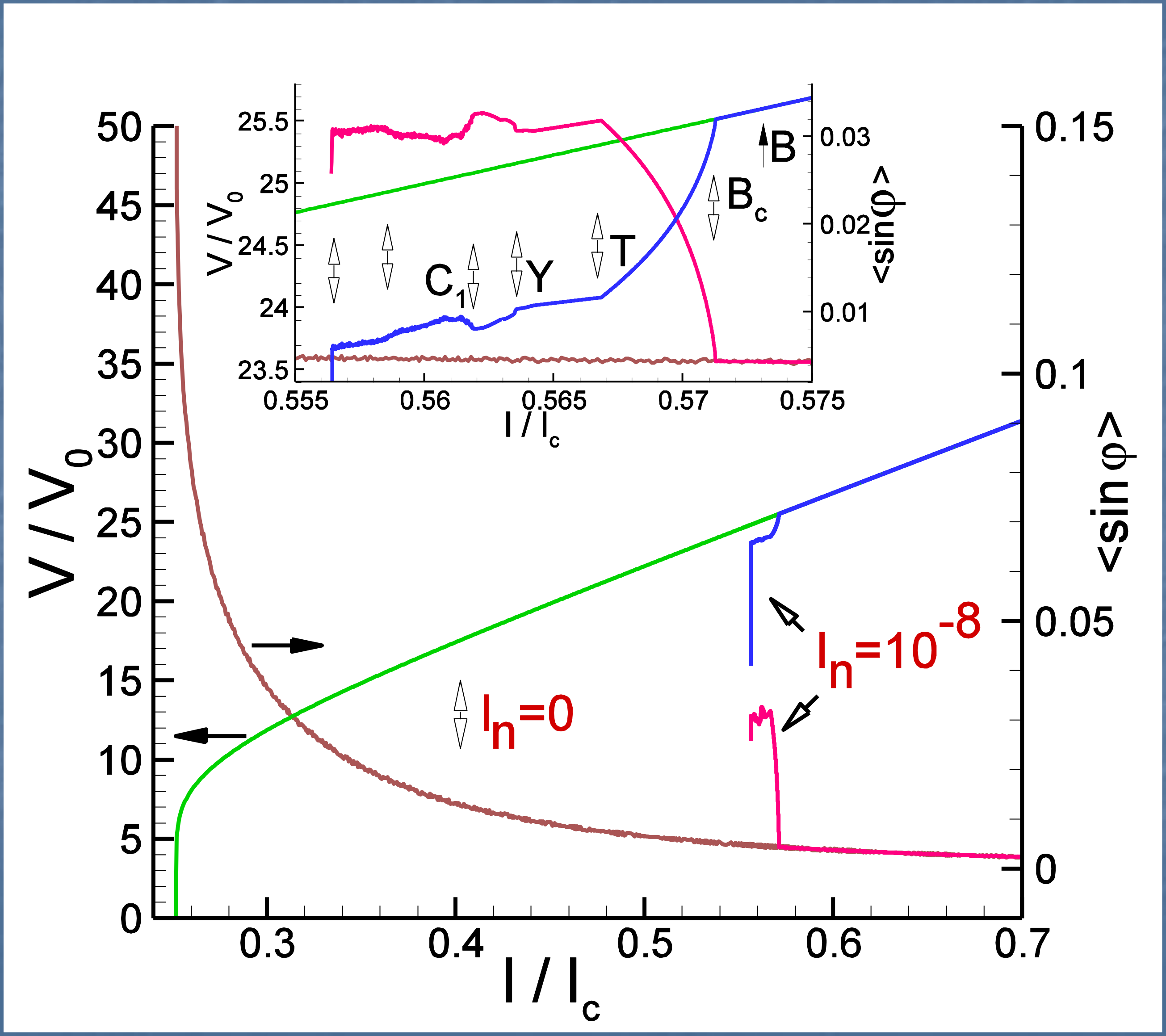


Before the BP at $I/I_c=0.573$ the Josephson frequency $\omega_J=0.4542*2\pi\omega_P$ $=2.8538\omega_p$

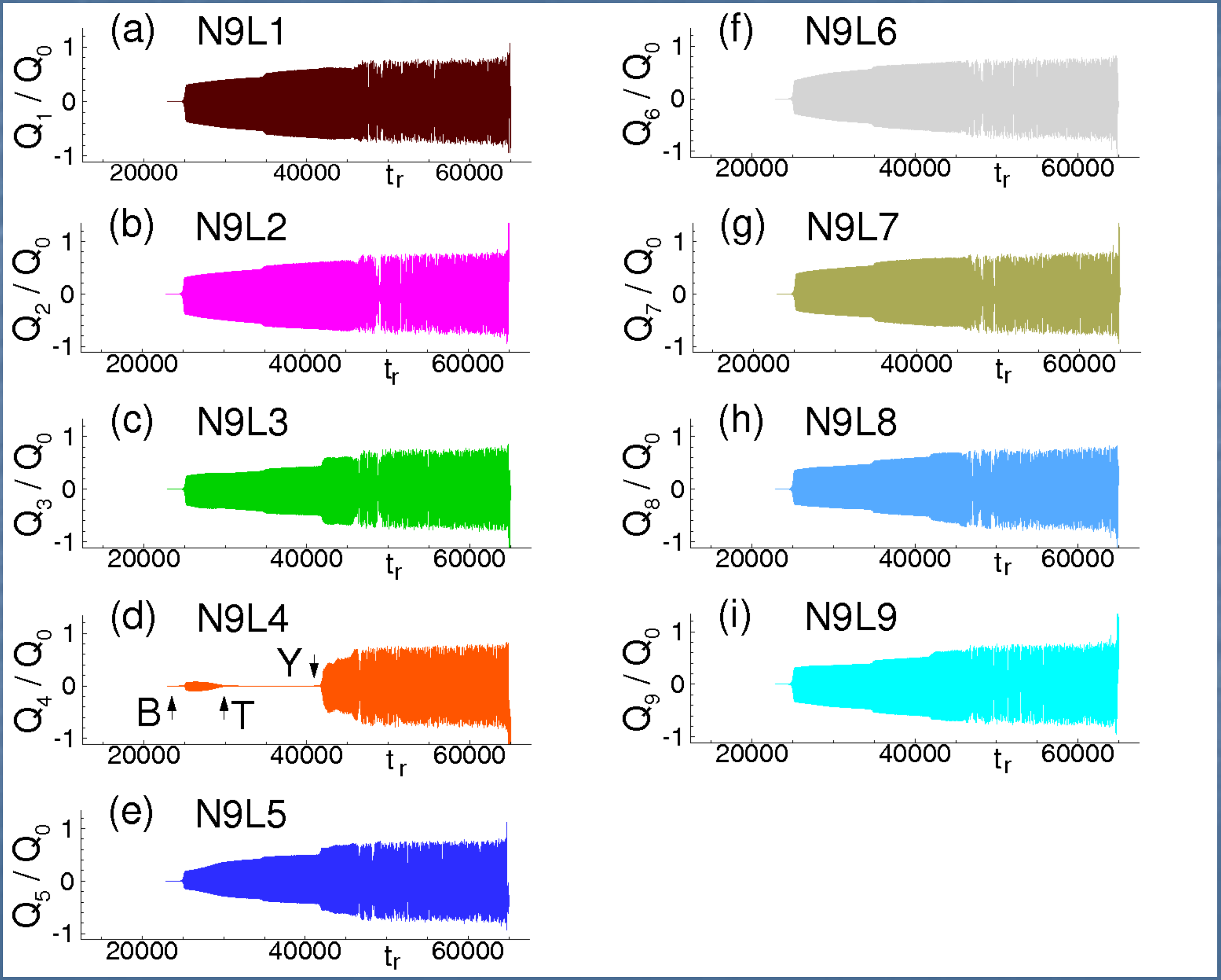
In the B-S region $\omega=0.2246*2\pi\omega_p=1.4112\omega_p$ corresponding to the LPW frequency $\omega=0.6738*2\pi\omega_p=4.2336$ corresponding to sum of the Josephson and LPW frequencies $\omega_J+\omega_{LPW}$

The S-T part shows the additional peak $0.4395*2\pi\omega_p= 2.7615\omega_p$, which value approximately equal to $2\omega_{LPW}$.

Superconducting current



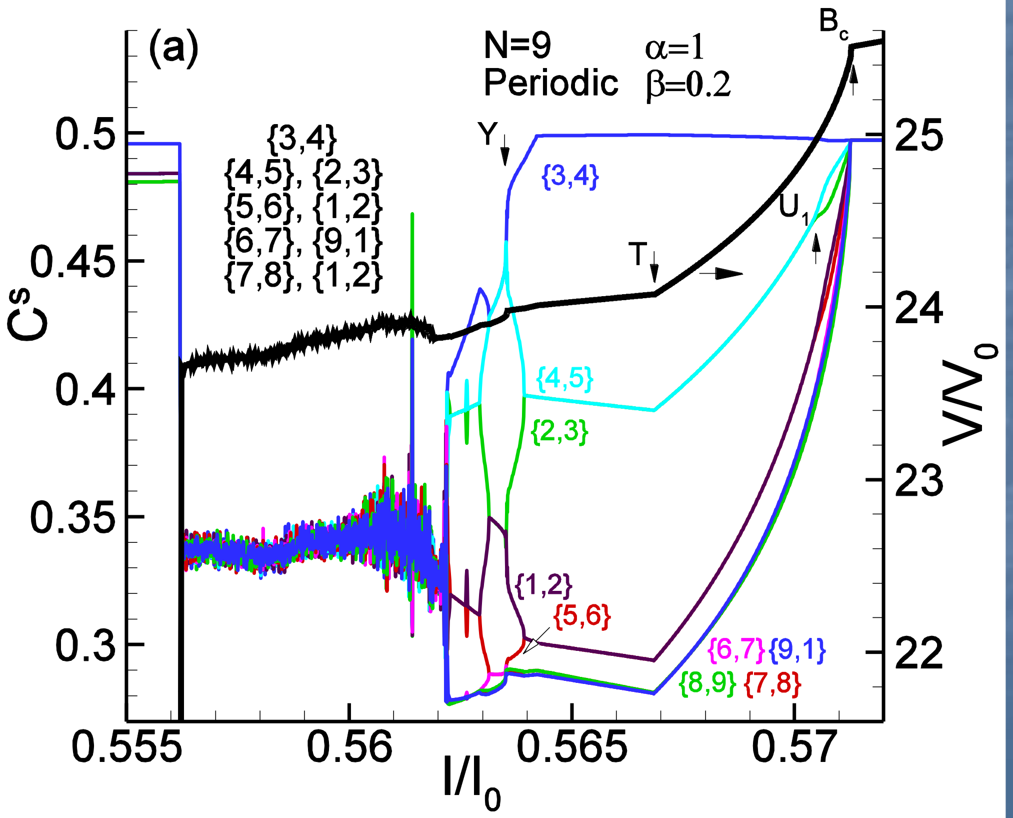
Charge on the S-layers, N=9

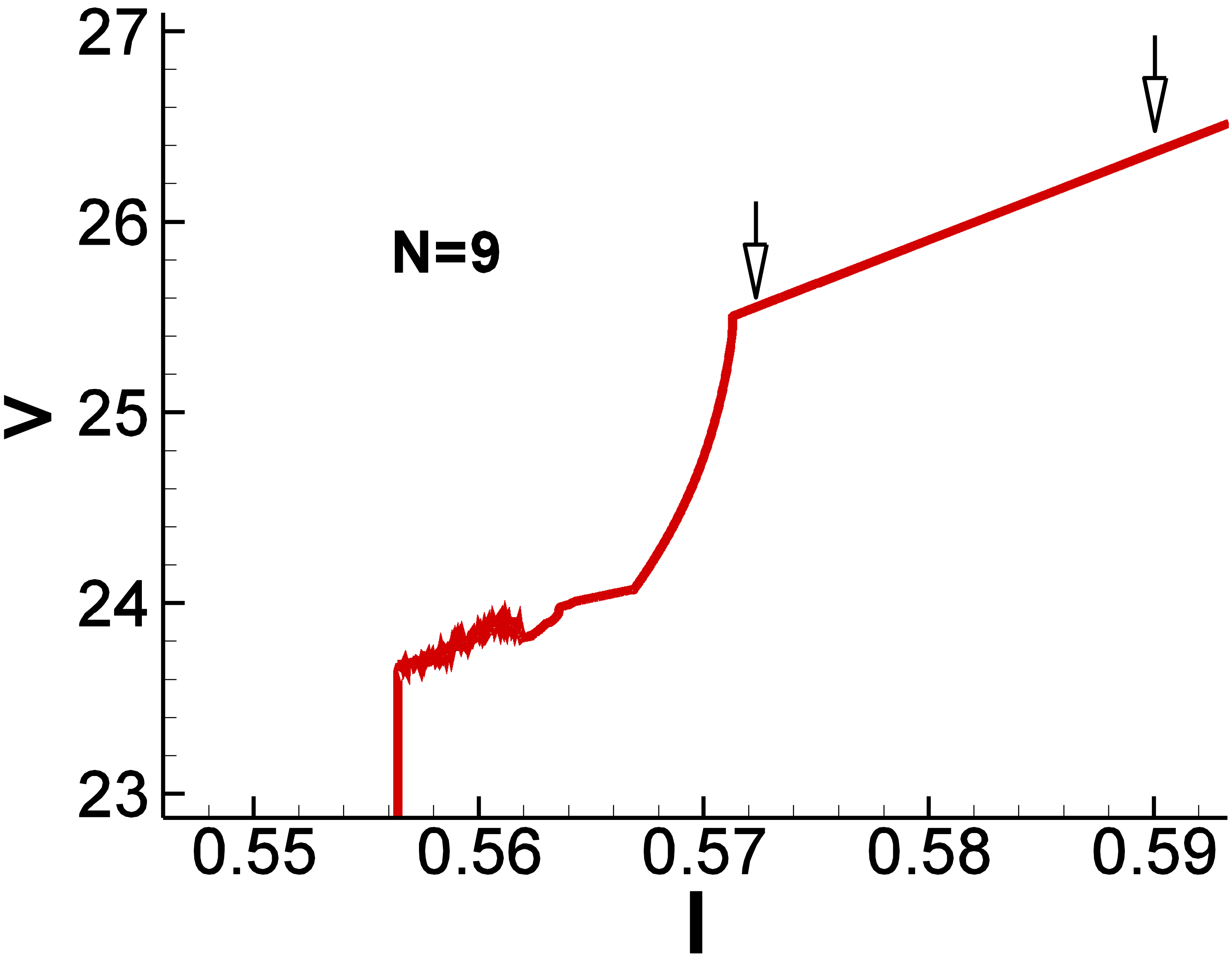


Current-current correlations

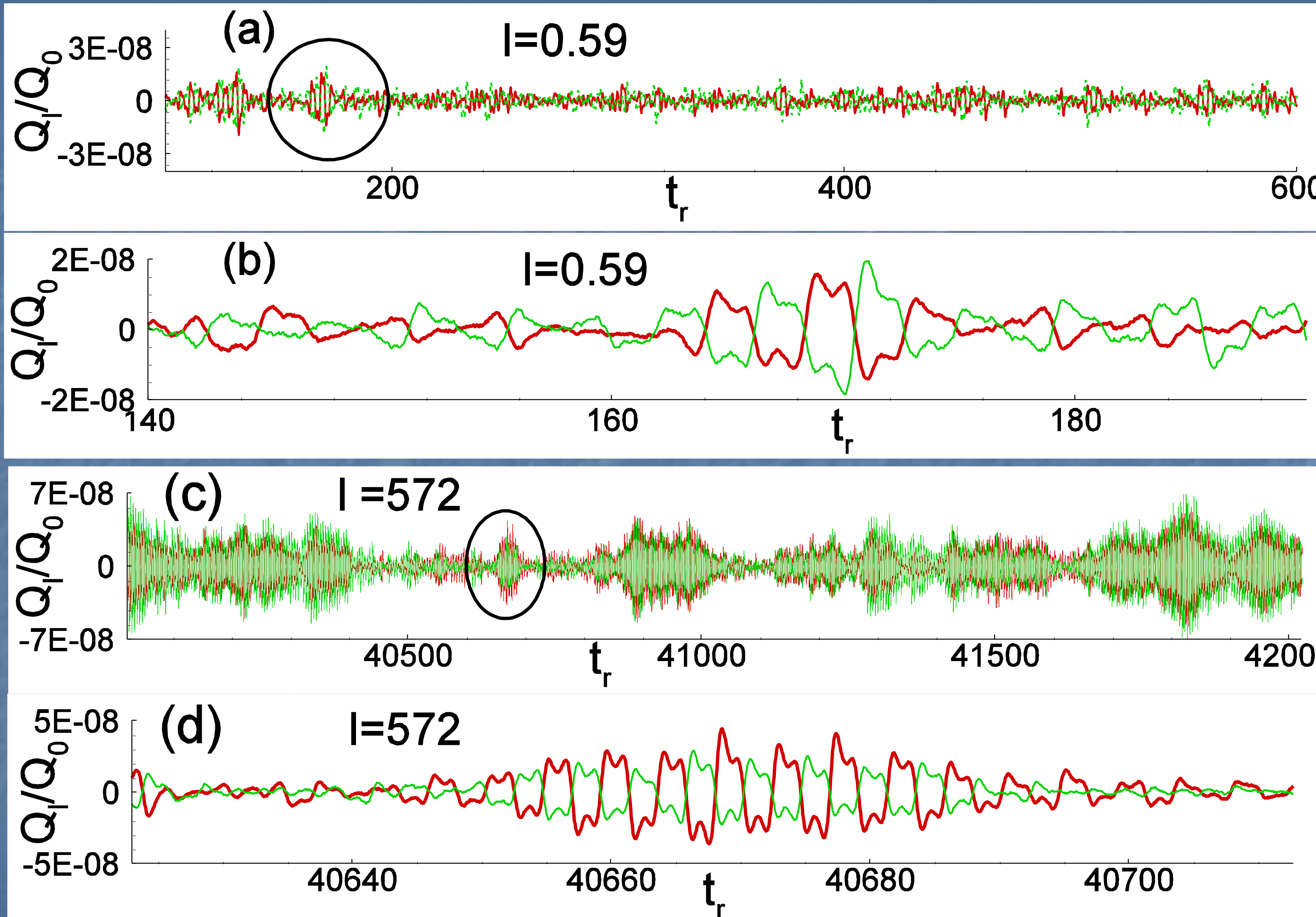
$$C^s_{j,j+1} = < \sin\varphi_j(\tau)\sin\varphi_{j+1}(\tau) > =$$

$$\lim_{(T_m - T_i)\to\infty} \frac{1}{(T_m - T_i)} \int_{T_i}^{T_m} \sin\varphi_j(\tau)\sin\varphi_{j+1}(\tau)d\tau$$

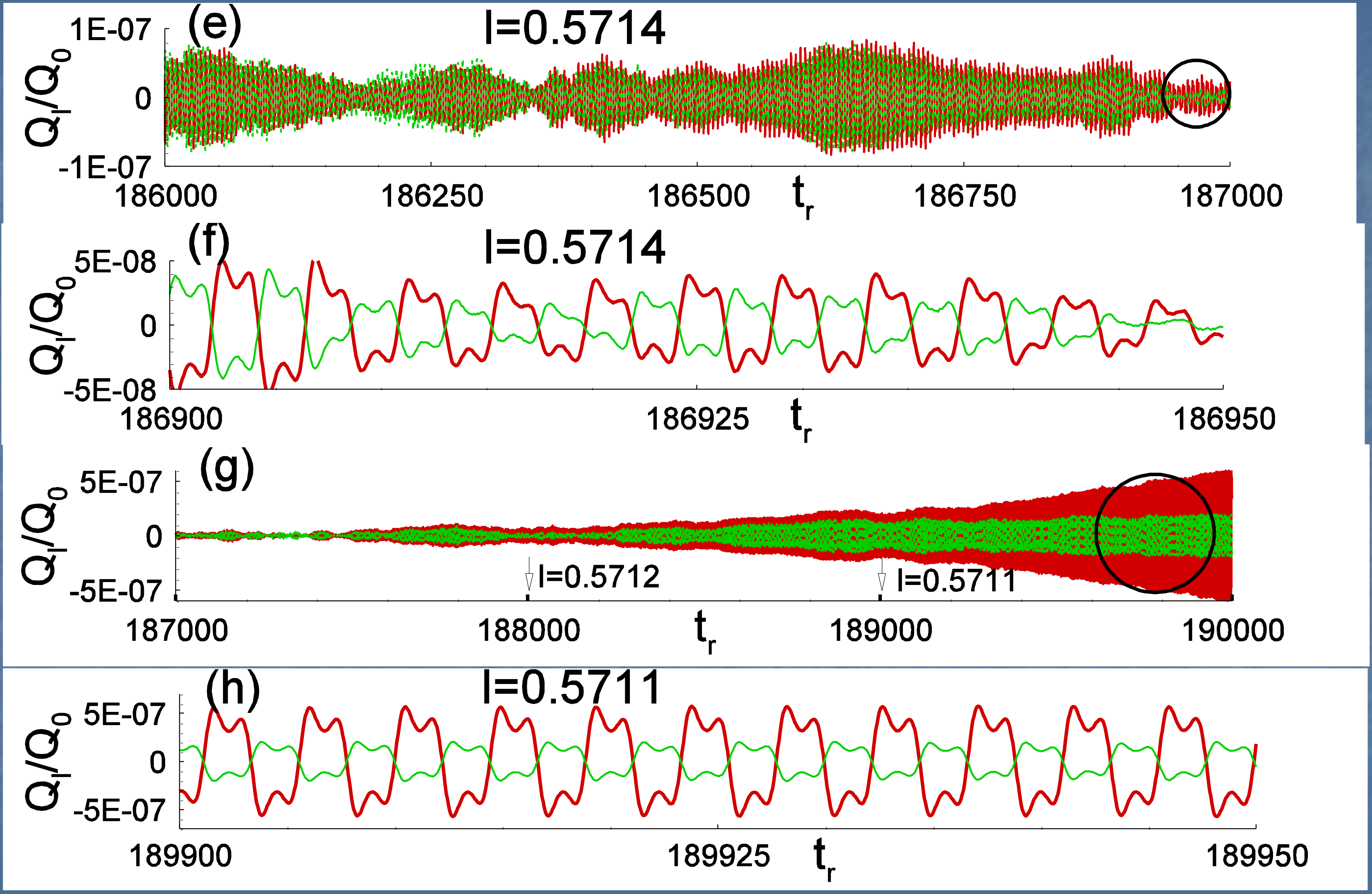




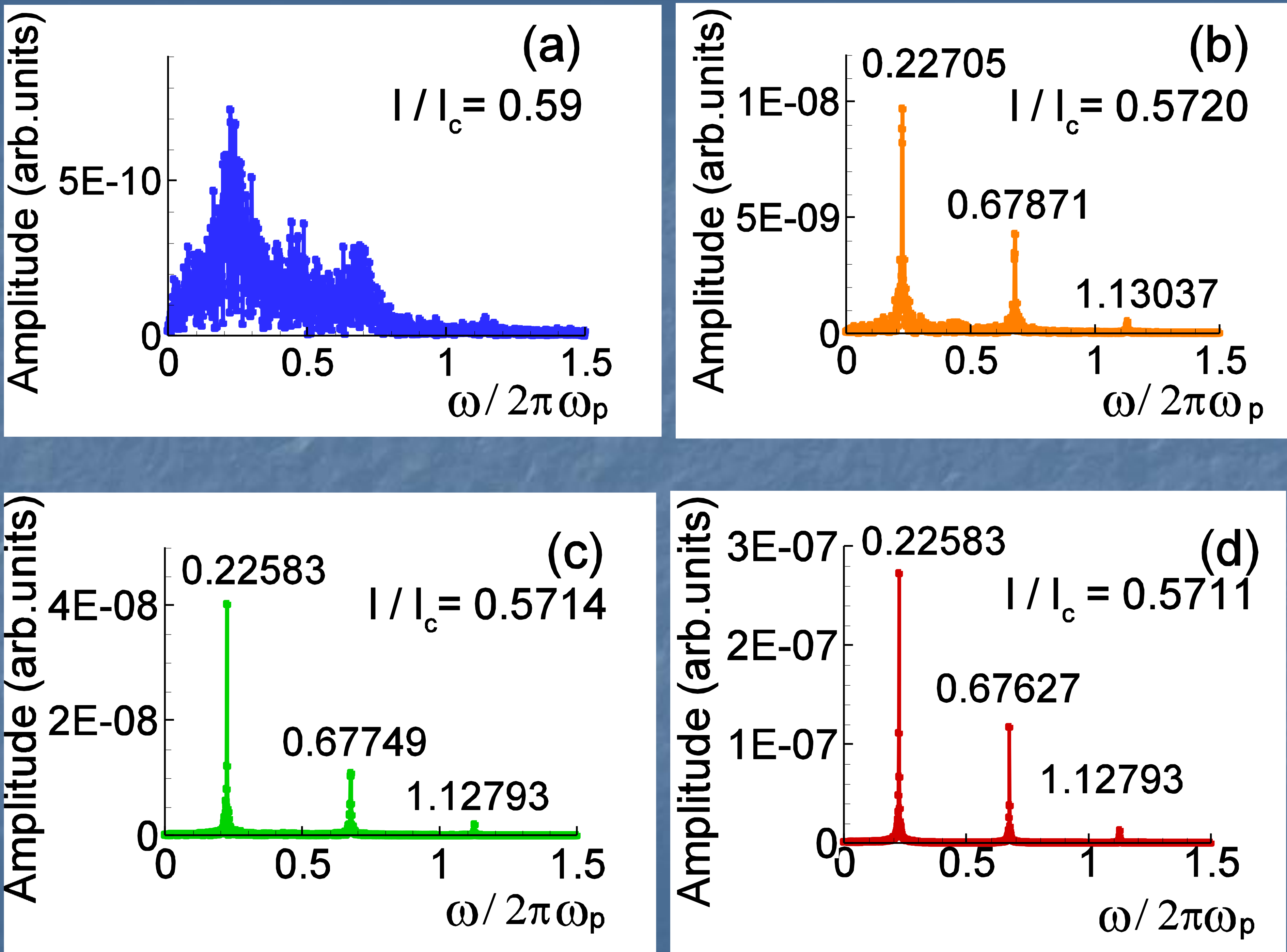
27
26
25
24
23
V
N=9
0.55
0.56
0.57
0.58
0.59
I

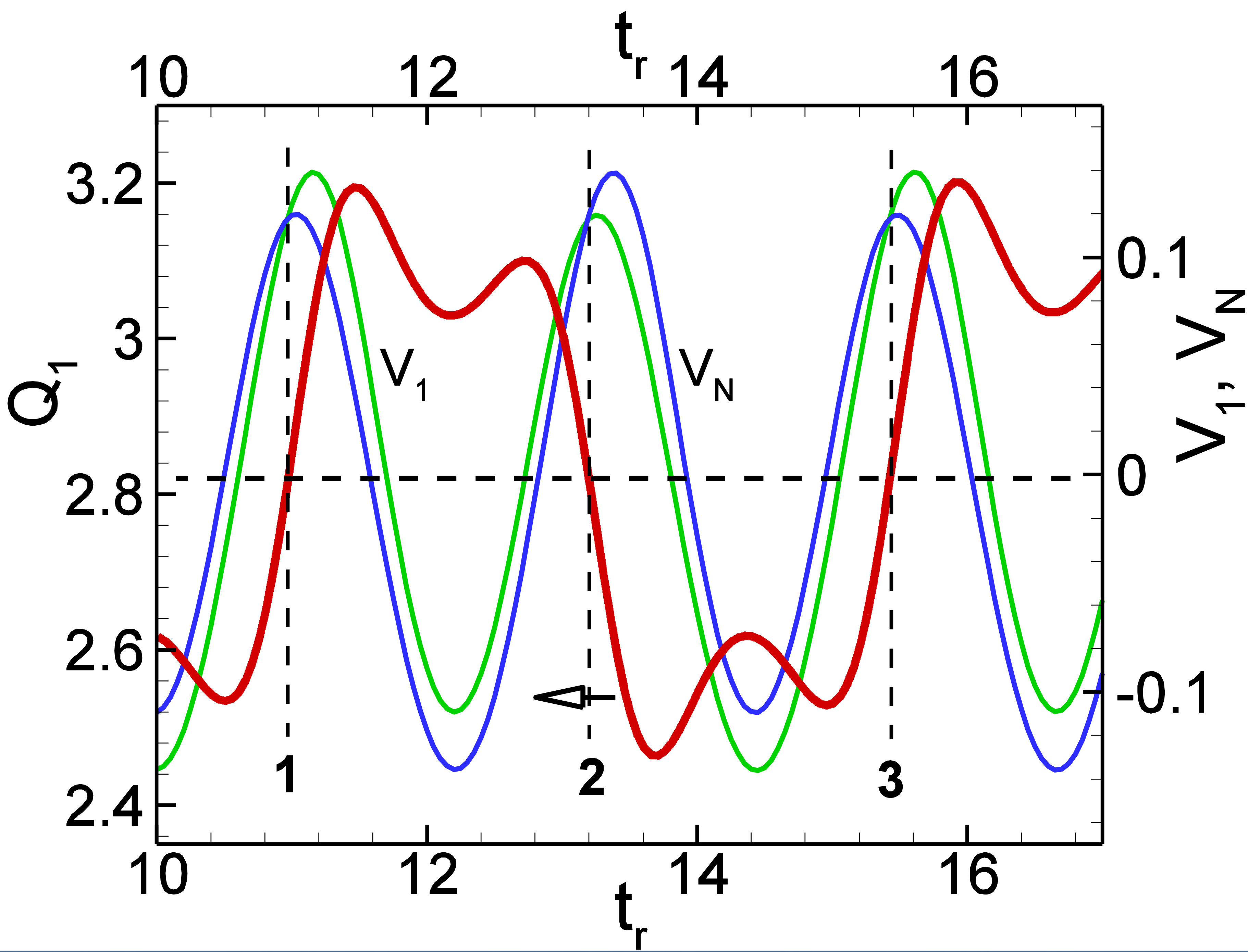


(a)
I=0.59
Q_I/Q_0
3E-08
0
-3E-08
200
400
600
t_r
(b)
I=0.59
Q_I/Q_0
2E-08
0
-2E-08
140
160
180
t_r
(c)
I =572
Q_I/Q_0
7E-08
0
-7E-08
40500
41000
41500
42000
t_r
(d)
I=572
Q_I/Q_0
5E-08
0
-5E-08
40640
40660
40680
40700
t_r

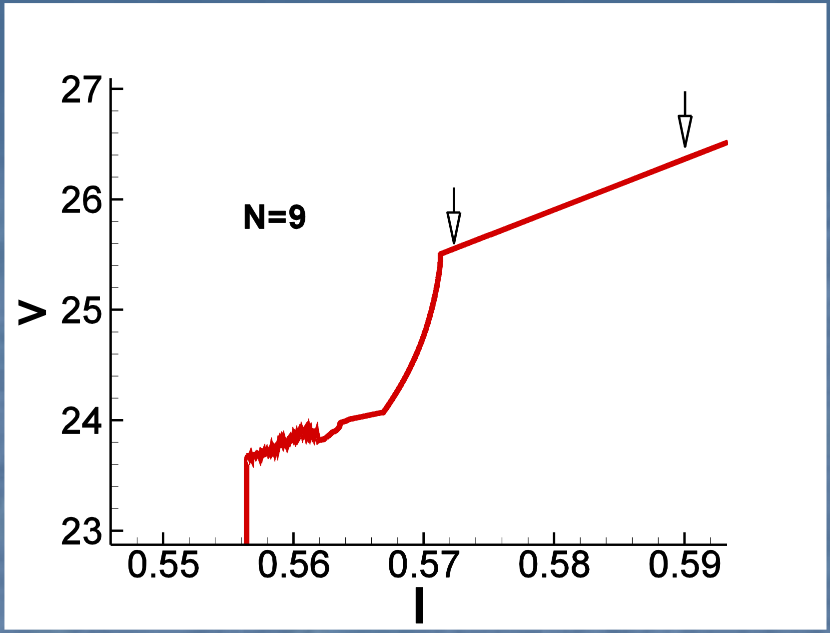


(e)
I=0.5714
1E-07
0
-1E-07
Q_I/Q_0
186000
186250
186500
186750
187000
t_r
(f)
I=0.5714
5E-08
0
-5E-08
Q_I/Q_0
186900
186925
186950
t_r
(g)
5E-07
0
-5E-07
Q_I/Q_0
I=0.5712
I=0.5711
187000
188000
189000
190000
t_r
(h)
I=0.5711
5E-07
0
-5E-07
Q_I/Q_0
189900
189925
189950
t_r

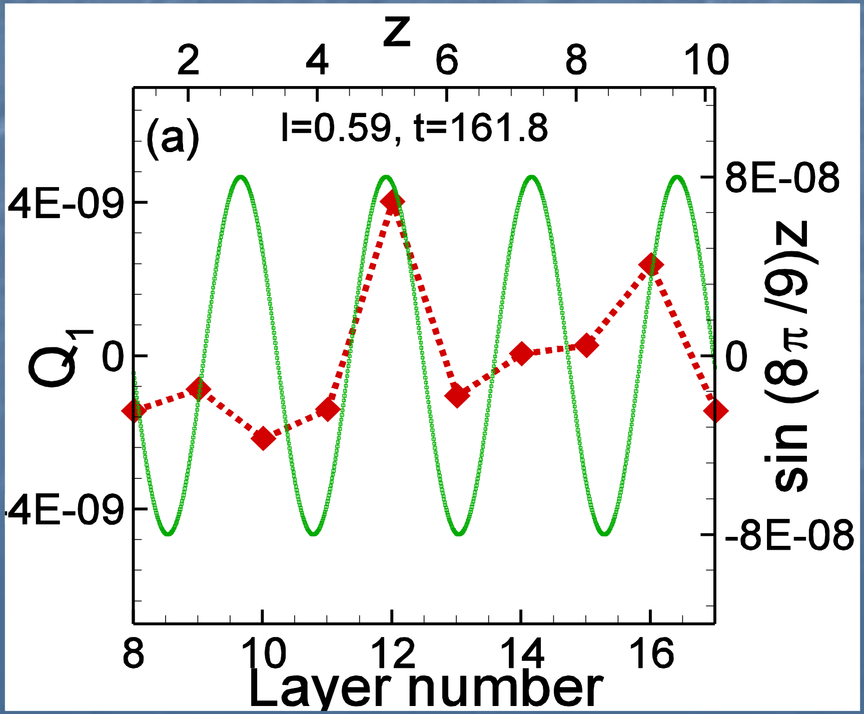

(a)
I / I$_c$= 0.59
Amplitude (arb.units)
5E-10
0
0
0.5
1
1.5
ω / 2πω$_p$
(b)
0.22705
I / I$_c$= 0.5720
1E-08
5E-09
0.67871
1.13037
0
0
0.5
1
1.5
Amplitude (arb.units)
ω / 2πω$_p$
(c)
0.22583
I / I$_c$= 0.5714
4E-08
2E-08
0.67749
1.12793
0
0
0.5
1
1.5
Amplitude (arb.units)
ω / 2πω$_p$
(d)
0.22583
I / I$_c$ = 0.5711
3E-07
2E-07
1E-07
0.67627
1.12793
0
0
0.5
1
1.5
Amplitude (arb.units)
ω / 2πω$_p$



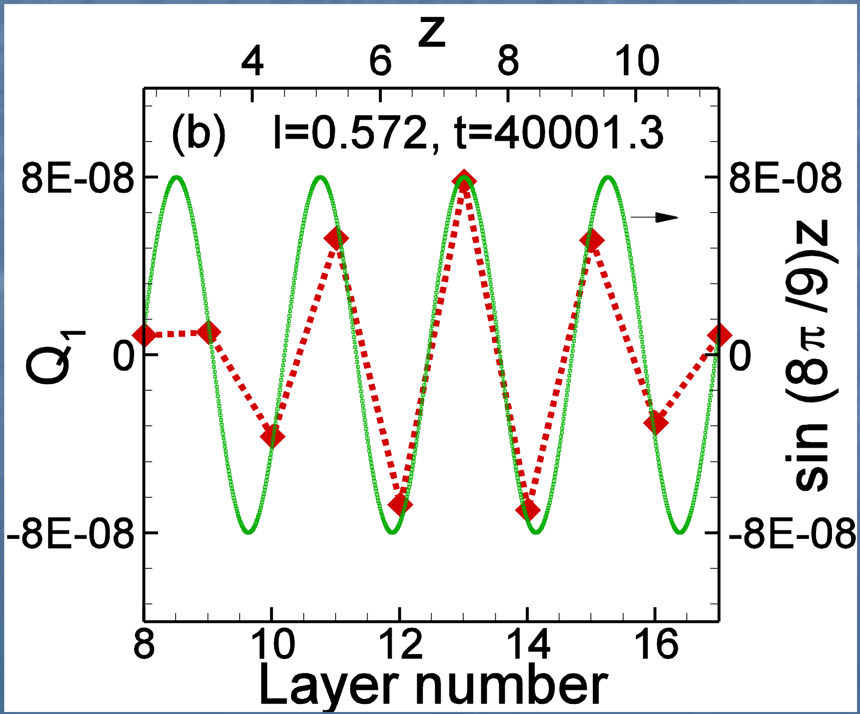
t_r
10
12
14
16
3.2
3
2.8
2.6
2.4
Q_1
0.1
0
-0.1
V_1, V_N
V_1
V_N
Δ
1
2
3



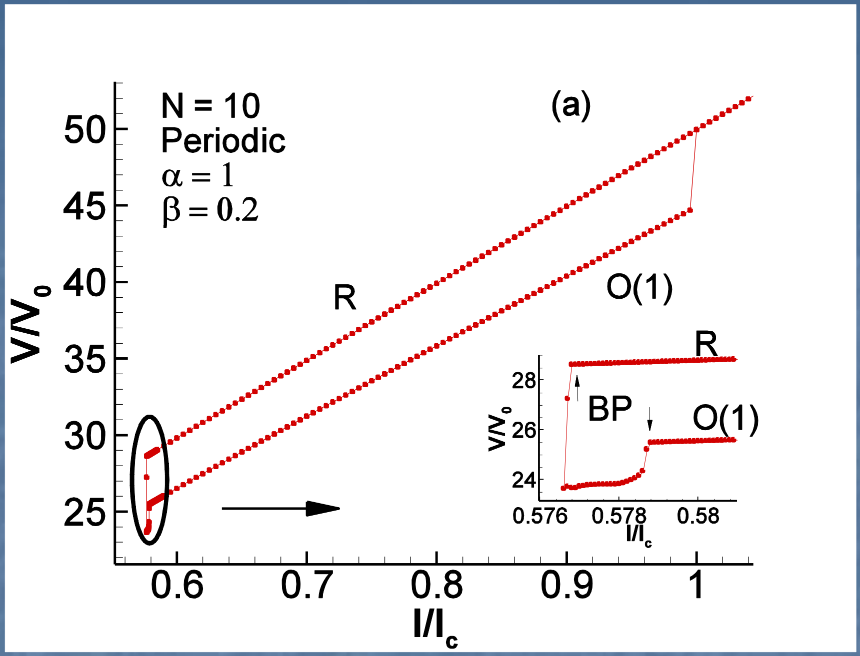
N=9
V
I
27
26
25
24
23
0.55
0.56
0.57
0.58
0.59



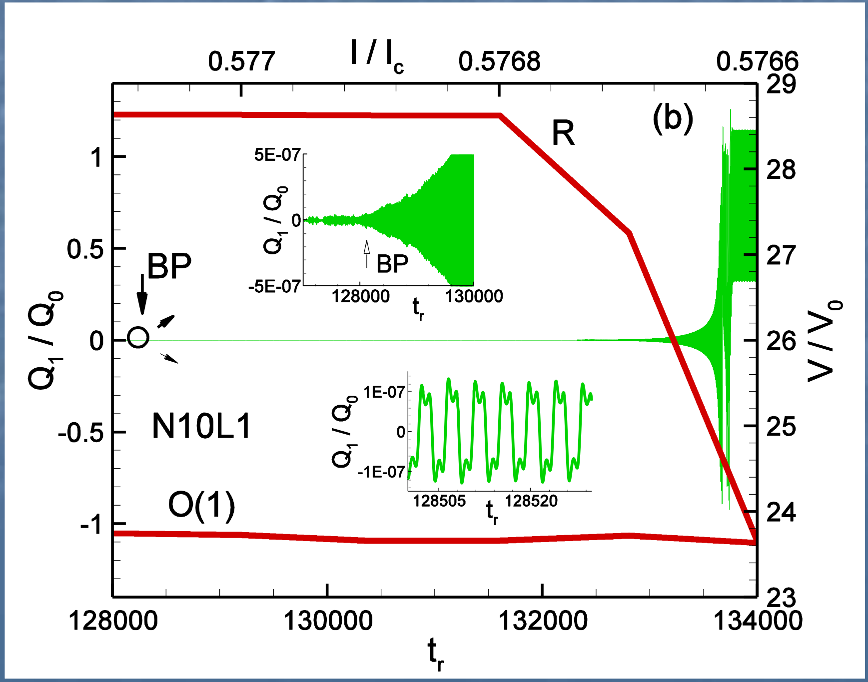
z
(a)
I=0.59, t=161.8
Q1
sin (8π/9)z
4E-09
0
-4E-09
8E-08
-8E-08
Layer number
8
10
12
14
16
2
4
6
8
10



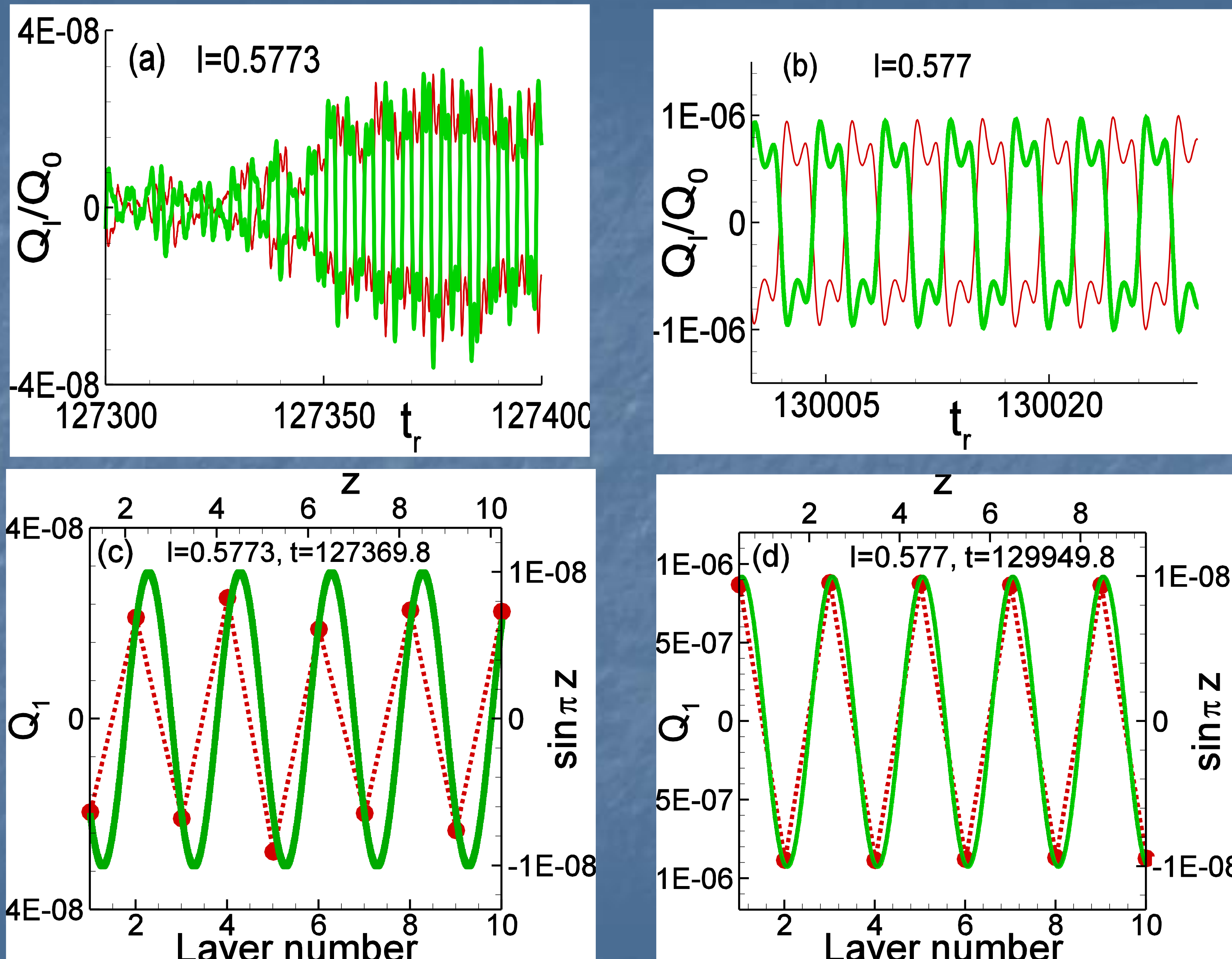
z
(b)
I=0.572, t=40001.3
Q1
sin (8π/9)z
8E-08
0
-8E-08
Layer number
8
10
12
14
16
4
6
8
10



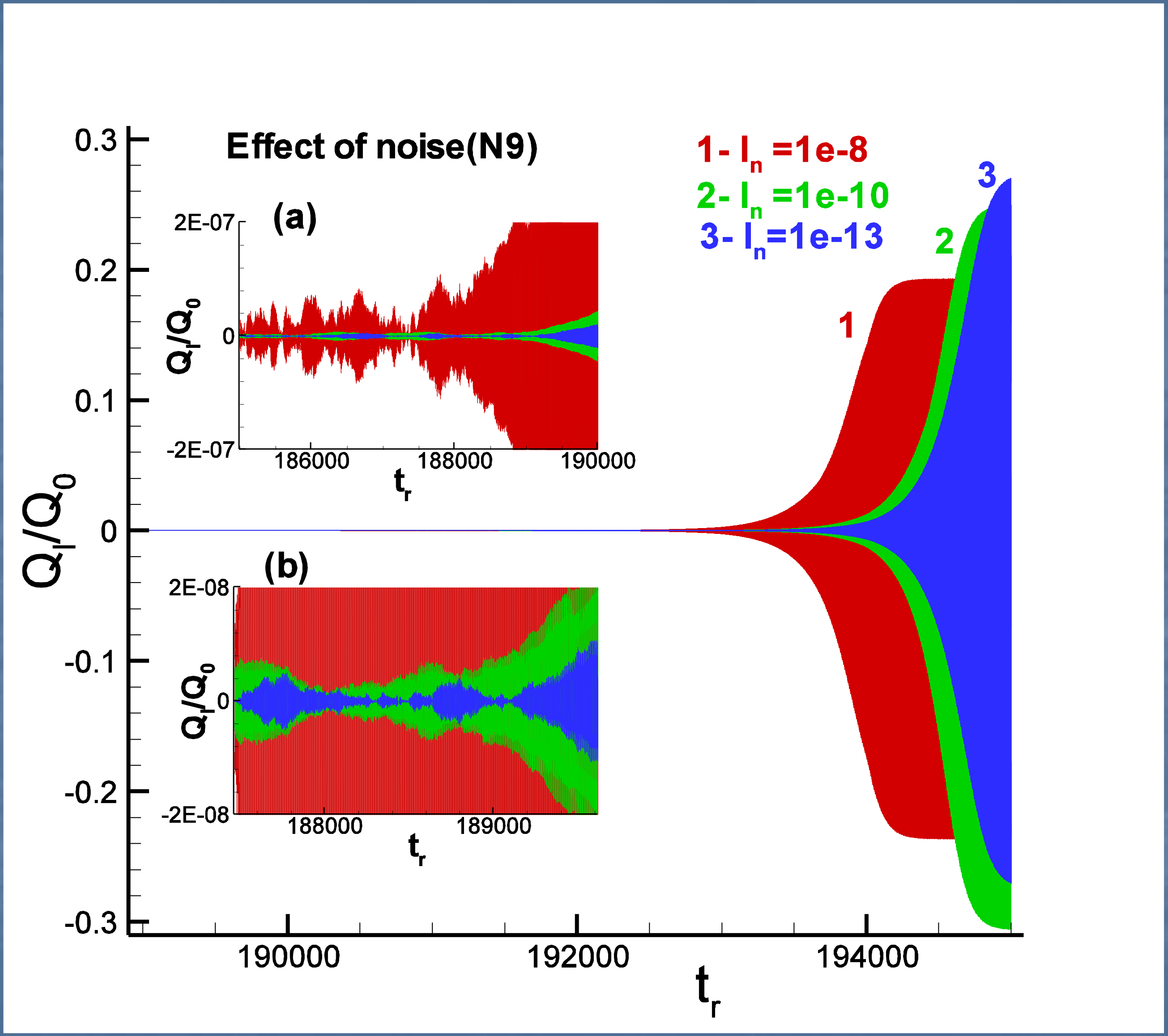
N = 10
Periodic
$\alpha = 1$
$\beta = 0.2$
(a)
R
O(1)
BP
V/V_0
I/I_c



I / I_c
(b)
R
BP
N10L1
O(1)
Q_1 / Q_0
V / V_0
t_r

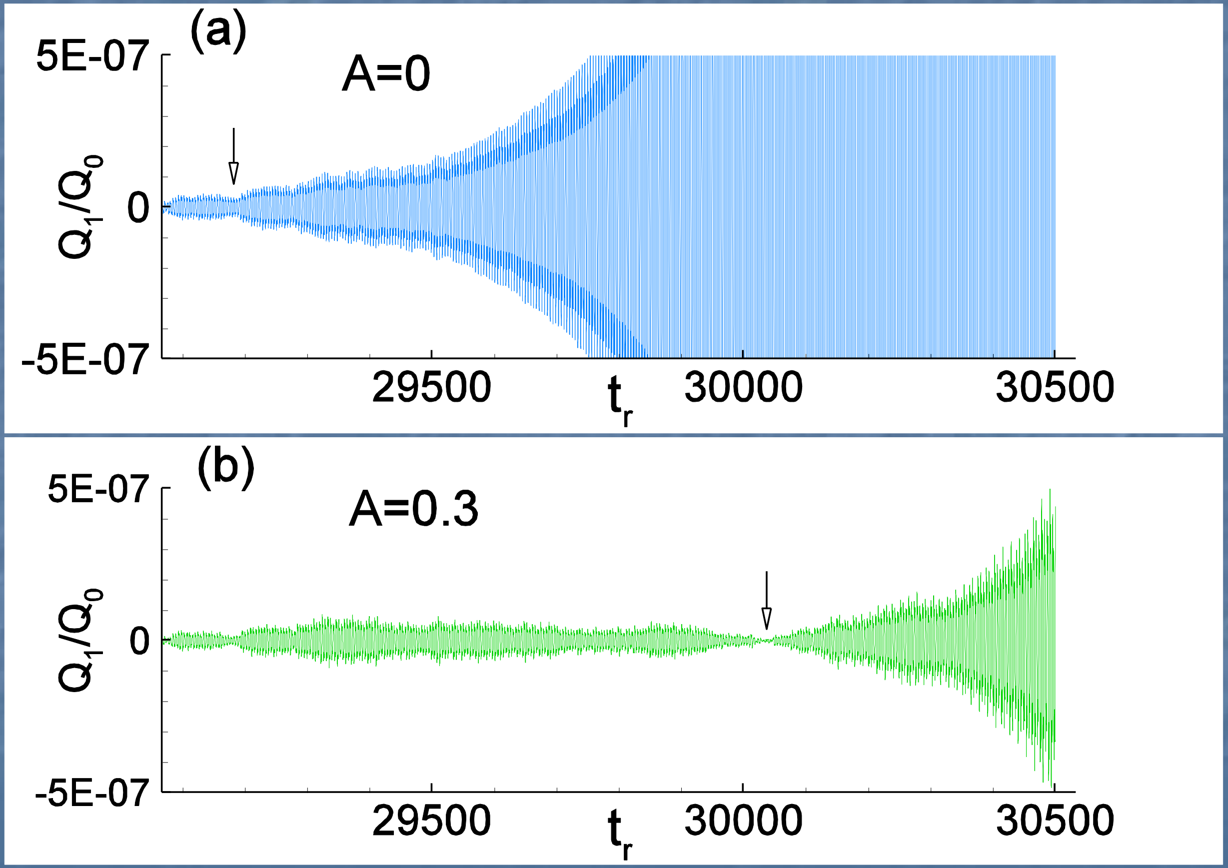


(a) l=0.5773
4E-08
0
-4E-08
Q_l/Q_0
127300
127350
127400
t_r
(b) l=0.577
1E-06
0
-1E-06
Q_l/Q_0
130005
130020
t_r
z
2
4
6
8
10
4E-08
(c) l=0.5773, t=127369.8
1E-08
Q_1
0
sin π z
-1E-08
4E-08
Layer number
z
2
4
6
8
1E-06
(d) l=0.577, t=129949.8
1E-08
5E-07
Q_1
0
sin π z
5E-07
1E-06
-1E-08
10
Layer number

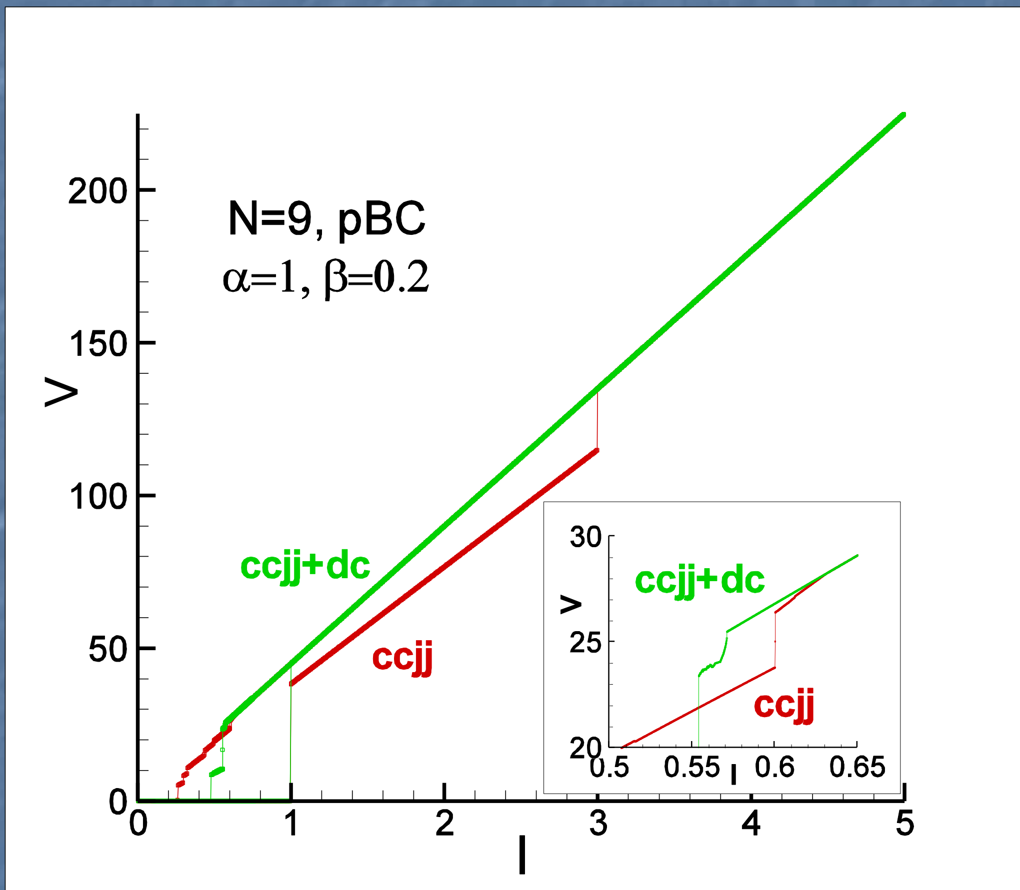


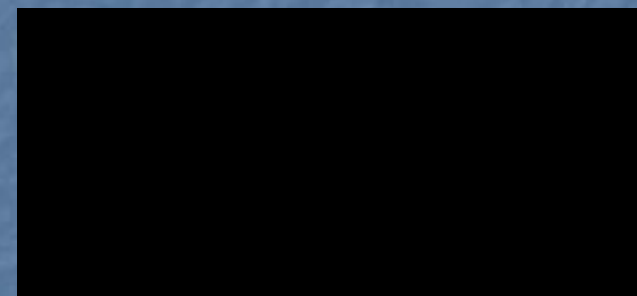
Effect of noise(N9)
1- I_n =1e-8
2- I_n =1e-10
3- I_n=1e-13
(a)
(b)
Q_I/Q_0
t_r
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
190000
192000
194000
2E-07
-2E-07
186000
188000
2E-08
-2E-08
189000
1
2
3

Влияние амплитуды излучения



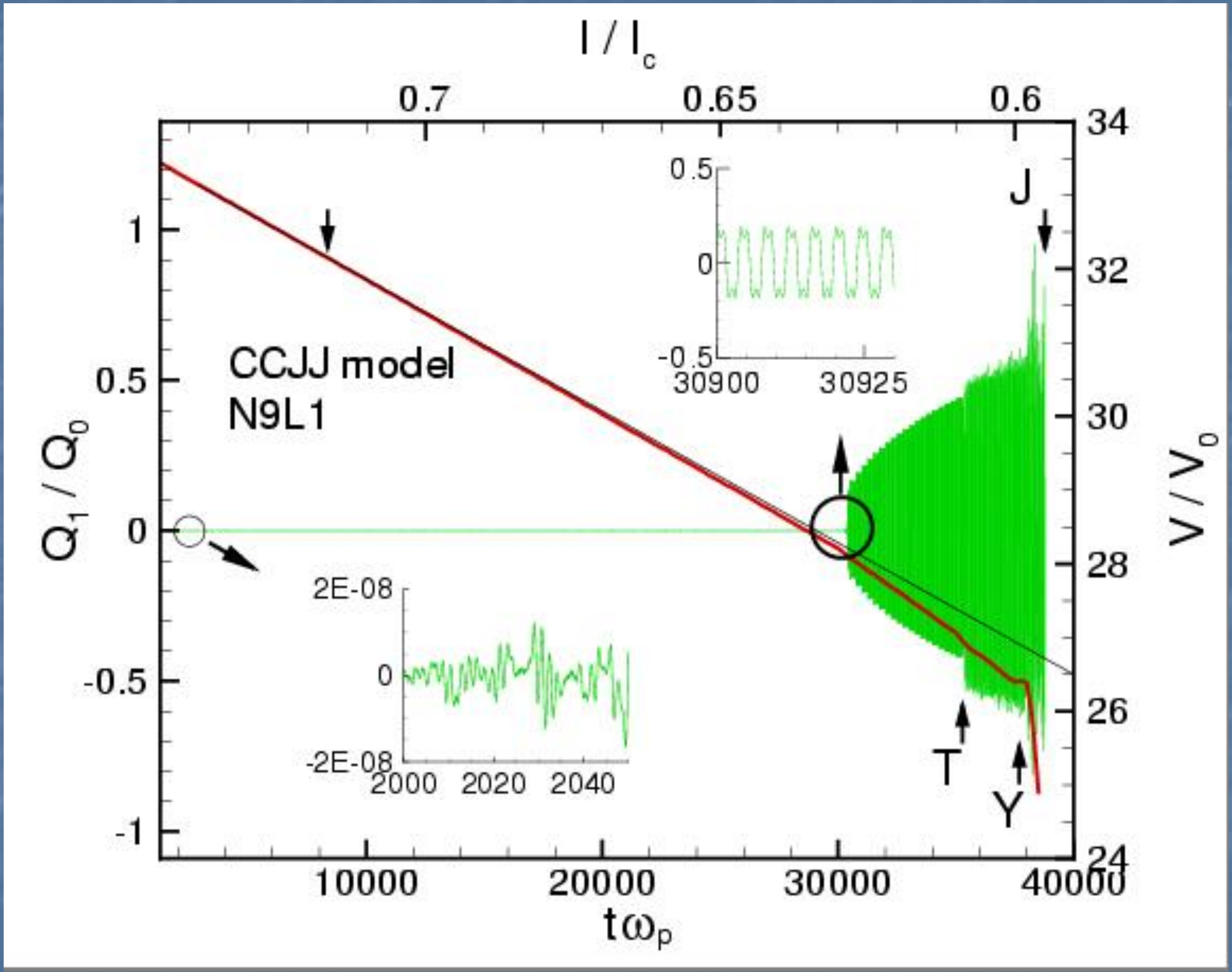
CVC in CCJJ and CCJJ+DC models.





M. Machida, T. Koyama, and M. Tachiki, Phys Rev. Lett. 83, 4816 (1999).

CVC and charge-time dependence in CCJJ model



Comparison with the experimental results

8 IJJ, $Bi_2Sr_2CaCu_2O_y$, T=77 K, $I_c = 240\ \mu$**A.**

$\Delta V = 39.1$ **mV,** $N = 8 -> R_n =$ **20.4** Ω.

$S = 25\mu m^2$, $d_t = 12$**Å**, $\varepsilon_r = 10 -> C = \varepsilon S/d_t =$ **1.84 pF.**

Using these data, we can estimate McCumber parameter:

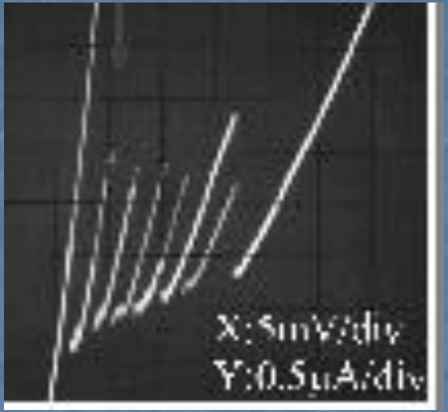
$\beta_c(77\ \mathrm{K}) \approx 560$.

In Zappe model, based on $I_r/I_c = 4/(\pi\beta_c^{-1/2})$ **at** $\beta_c >> 1$ **we get**

$I_r \simeq 13\ \mu$**A (or** $I_r/I_c = 0.054$**).**

This value is essentially different from the experimental one $I_r = 45\ \mu$***A (or*** $I_r/I_c = 0.188$***)***

A.Irie, Yu.Shukrinov, G.I.Oya, Appl.Phys.Lett, 93, 152510 (2008)



CCJJ+DC model

$$J = C\partial V/\partial t + V/R + J_C \sin\varphi$$

$$J_D^l = -\frac{\Phi_l - \Phi_{l+1}}{R}$$

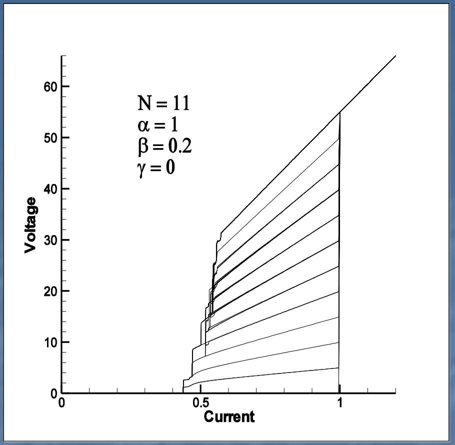
$$J = C\frac{dV_l}{dt} + J_c^l \sin(\varphi_l) + \frac{\hbar}{2eR}\dot{\varphi}_l$$

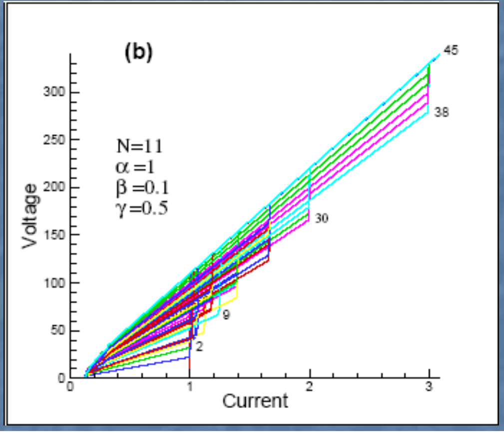
$$\ddot{\varphi}_l = \sum_{l'=1}^{n} A_{ll'}[\frac{J}{J_c} - \sin(\varphi_{l'}) - \beta\dot{\varphi}_{l'}]$$

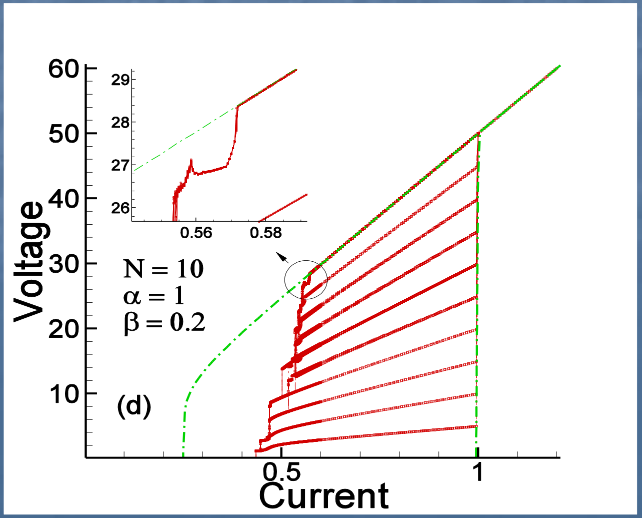
$$A = \begin{pmatrix} 1+\alpha G & -\alpha & 0 & \dots & & & \\ -\alpha & 1+2\alpha & -\alpha & 0 & \dots & & \\ 0 & -\alpha & 1+2\alpha & -\alpha & 0 & \dots & \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ & & & \dots & 0 & -\alpha & 1+\alpha G \end{pmatrix}$$

$$A = \begin{pmatrix} 1+2\alpha & -\alpha & 0 & \dots & & & -\alpha \\ -\alpha & 1+2\alpha & -\alpha & 0 & \dots & & \\ 0 & -\alpha & 1+2\alpha & -\alpha & 0 & \dots & \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ -\alpha & & & \dots & 0 & -\alpha & 1+2\alpha \end{pmatrix}$$

$$\frac{d^2}{dt^2}\varphi_l = (I - \sin\varphi_l - \beta\frac{d\varphi_l}{dt}) + \alpha(\sin\varphi_{l+1} + \sin\varphi_{l-1} - 2\sin\varphi_l) + \alpha\beta(\frac{d\varphi_{l+1}}{dt} + \frac{d\varphi_{l-1}}{dt} - 2\frac{d\varphi_l}{dt})$$

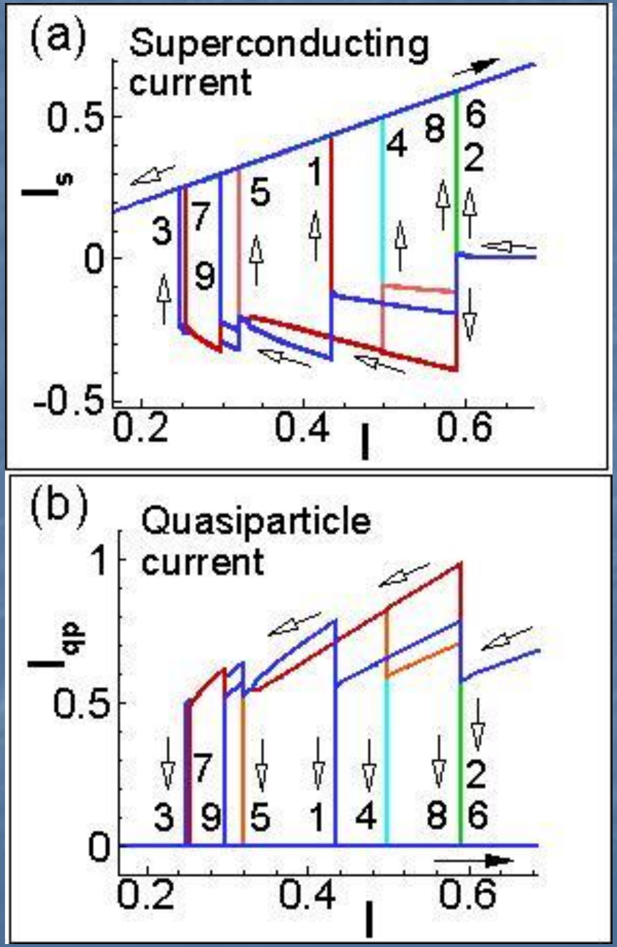






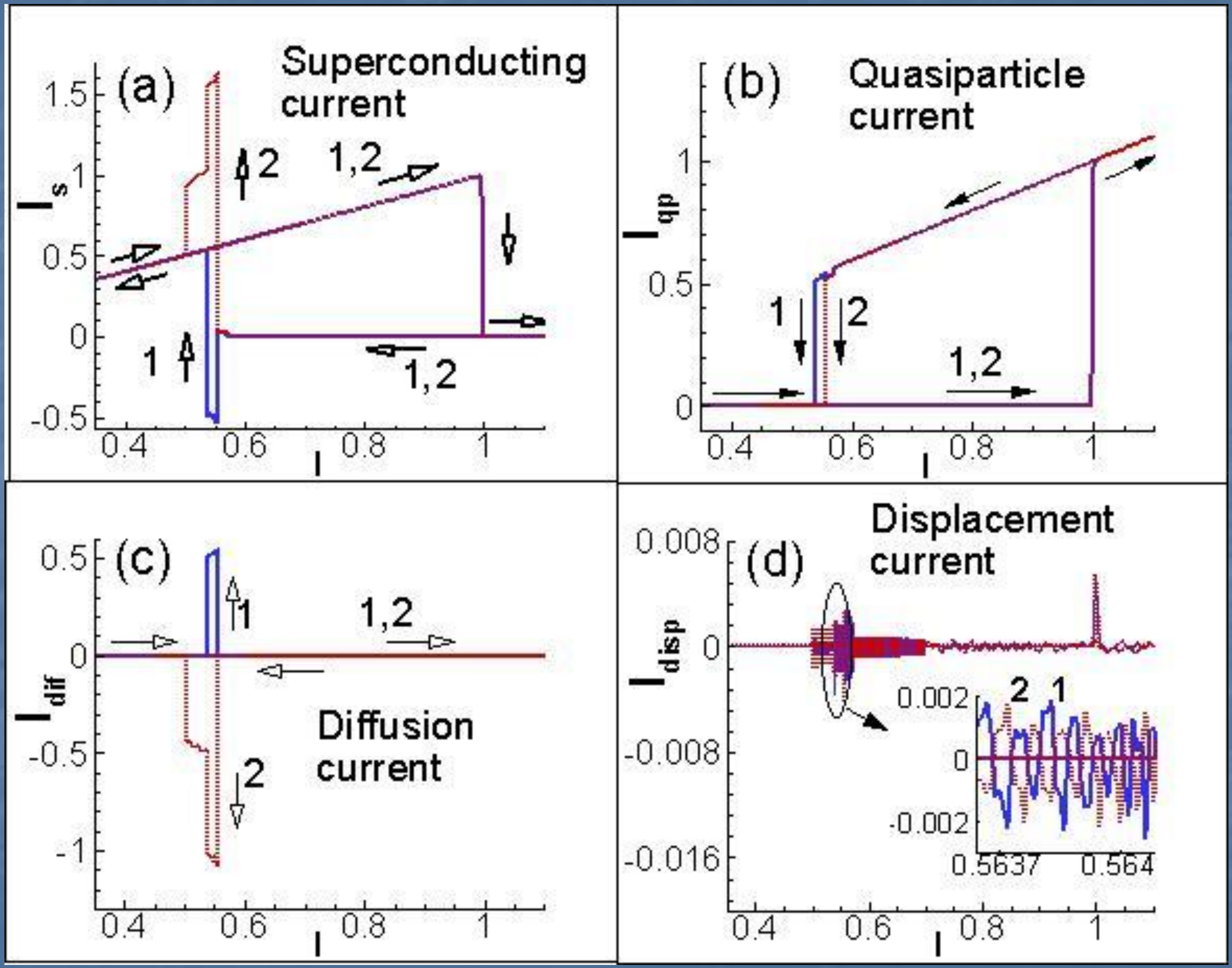
Yu. M. Shukrinov, F. Mahfouzi and P. Seidel,
Physica C 449, 62-66 (2006)

Currents in hysteretic region in CCJJ model



Yu.M.Shukrinov, I.Rahmonov JETP Letters (2010).

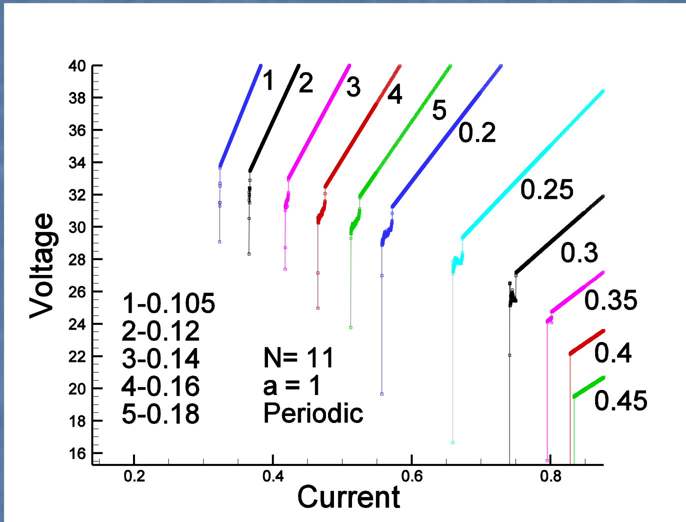
Averaged currents in CCJJ+DC model

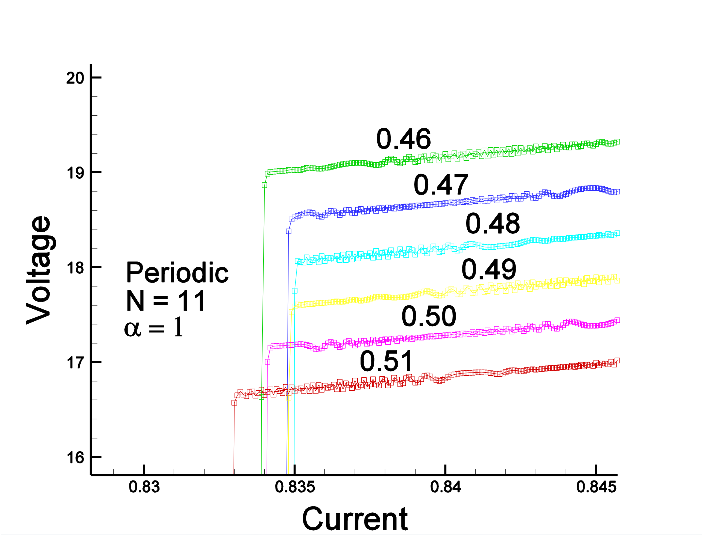


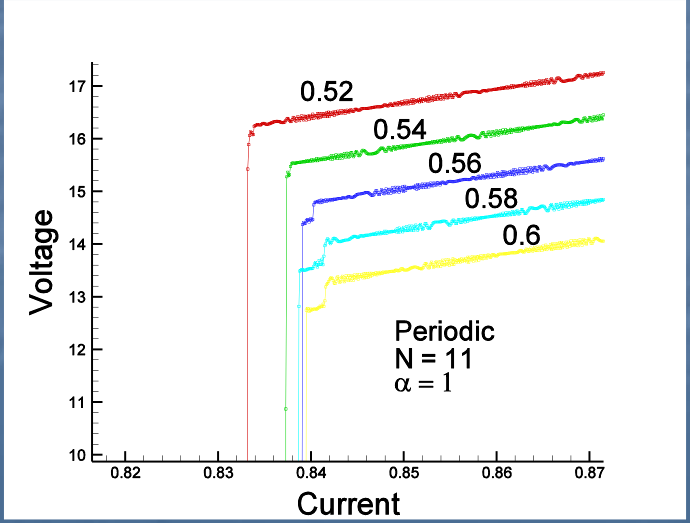
Yu.M.Shukrinov, I.Rahmonov JETP Letters (2010).

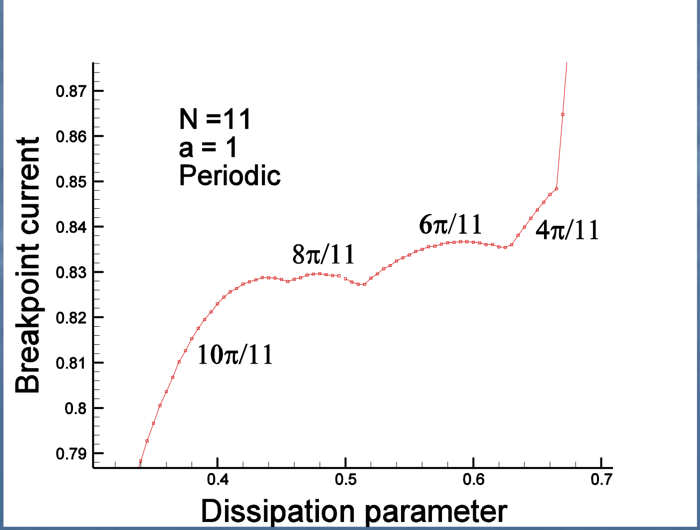
- **Temperature dependence of the breakpoint current**

IVC of the stack of 11 IJJ and beta dependence of the BPC









Temperature dependence 1

- In the simple parallel resistance model a single junction resistivity $\rho_J(T)$ at subgap voltage region is given by
- $\rho_J^{-1}(T)=\rho_{sg}^{-1}+\rho_C^{-1}(T)$
- where ρ_{sg} is the temperature independent tunnel resistivity of the junction, and
- $\rho_C(T)= a \exp(b/T)+cT+d$ is the empirical Heine formula of the c-axis resistivity with a,b,c,d as fitting parameters.

Temperature dependence 2

Estimating the tunnel resistivity by $\rho_{sg} = \Delta(0)S/eDI_c(0)$, the energy gap Δ from the expression $2\Delta(0)/kT_c = 6$

$$R_J = \frac{\rho_{sg}\rho_c}{(\rho_{sg}+\rho_c)}\frac{D}{S}$$

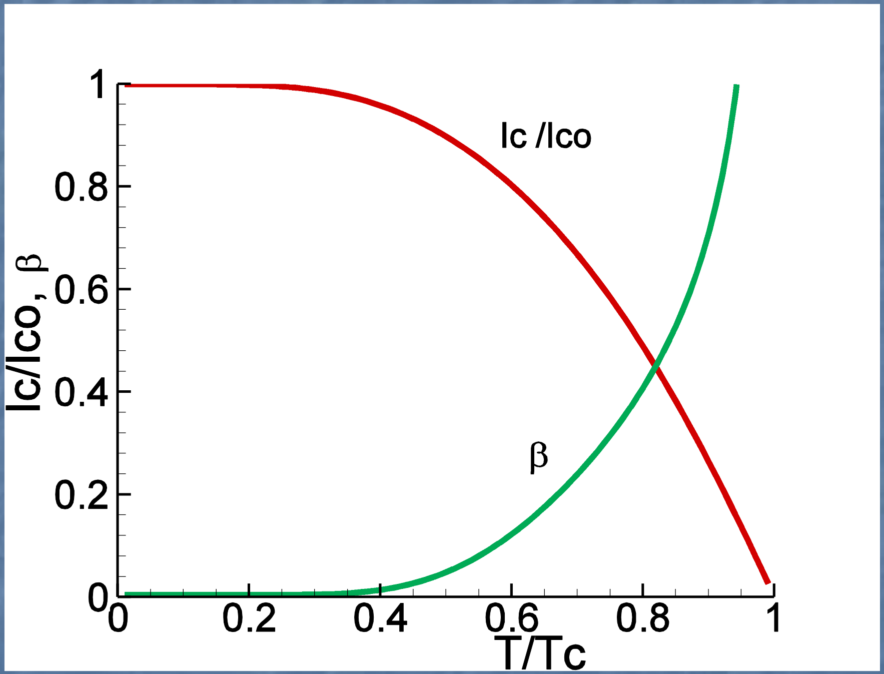
$$I_C = \frac{\pi\Delta(T)}{2eR(T)} tanh\frac{\Delta(T)}{2T}$$

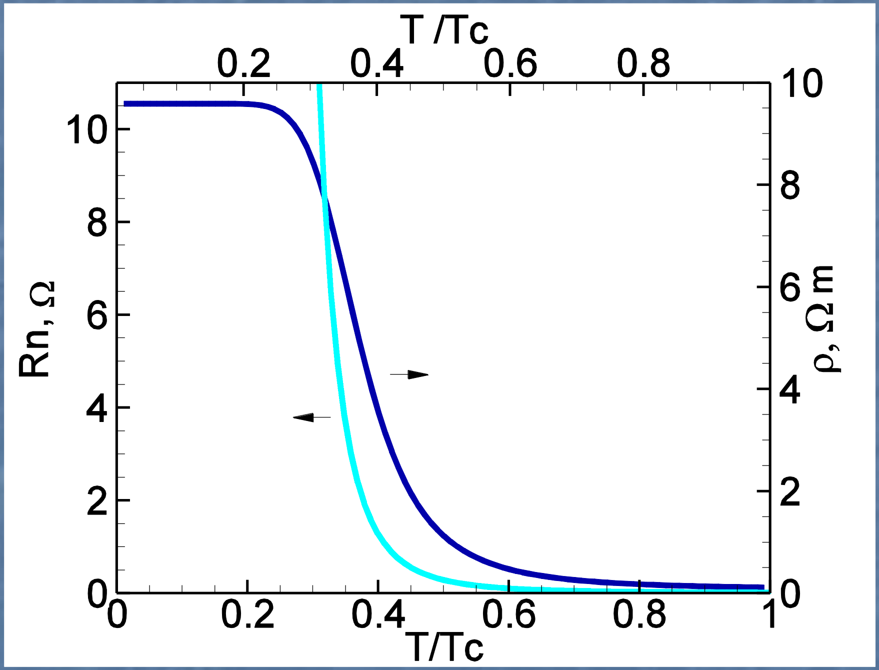
$$I_c(T) = I_c(0)\sqrt{\cos\frac{\pi}{2}(\frac{T}{T_c})^2}\tanh(0.88\sqrt{\cos\frac{\pi}{2}(\frac{T}{T_c})^2}\frac{T_c}{T})$$

$$C_J = \varepsilon_r\varepsilon_0 S/D$$

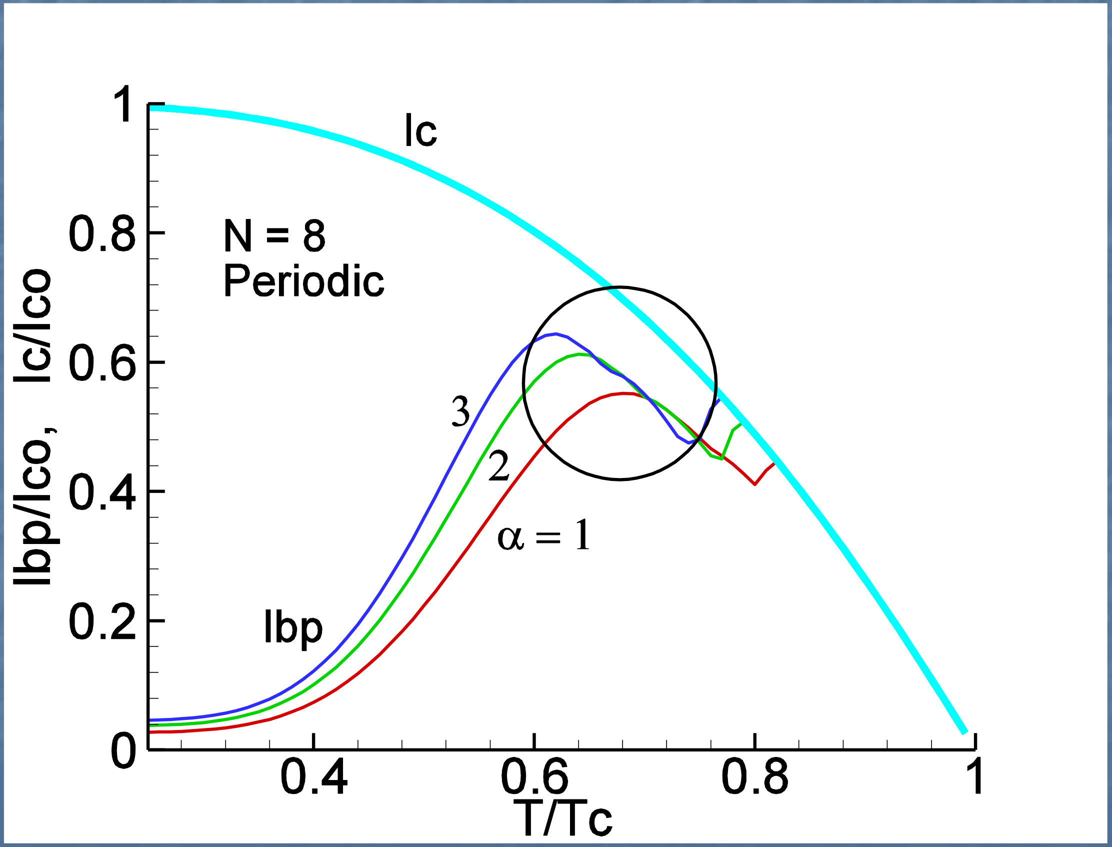
$$\beta^2 = 1/\beta_c = \hbar/2eC_J R_N^2 I_C$$

- In our simulations we chose $S=2.32*10^{-10}$m for the area, T_c=90K for the critical temperature, $j_c(0)=9*10^6$ A/m^2 for the density of critical current at T=0.
- The fitting parameters were chosen as $a=6*10^{-4}\Omega$ m, b=273K, $c=24*10^{-6}\Omega$ m/K, $d=1.23*10^{-2}\Omega$ m.

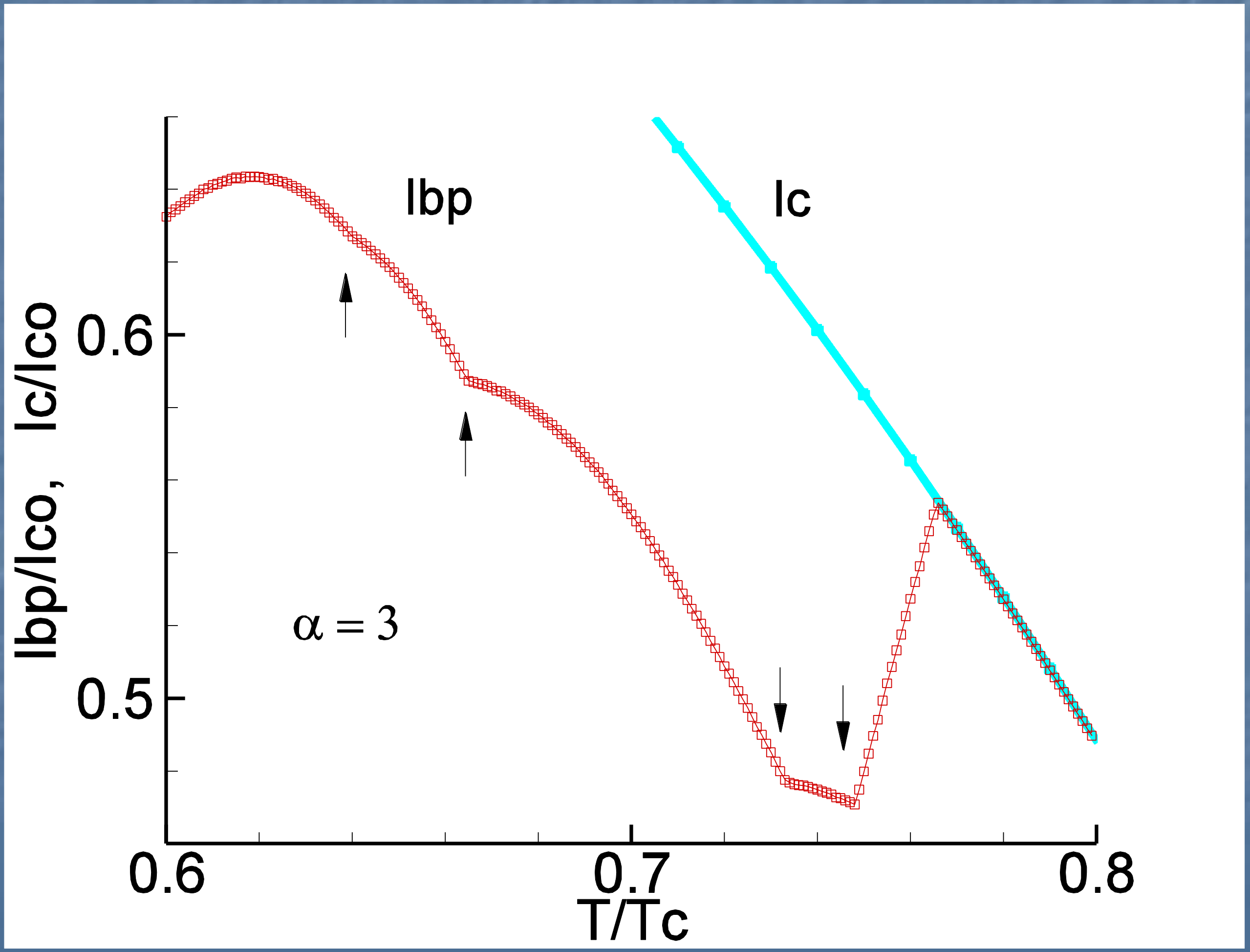

Ic/Ico, β
Ic /Ico
β
T/Tc
0
0.2
0.4
0.6
0.8
1


T /Tc
0.2
0.4
0.6
0.8
Rn, Ω
ρ, Ω m
T/Tc
0
2
4
6
8
10

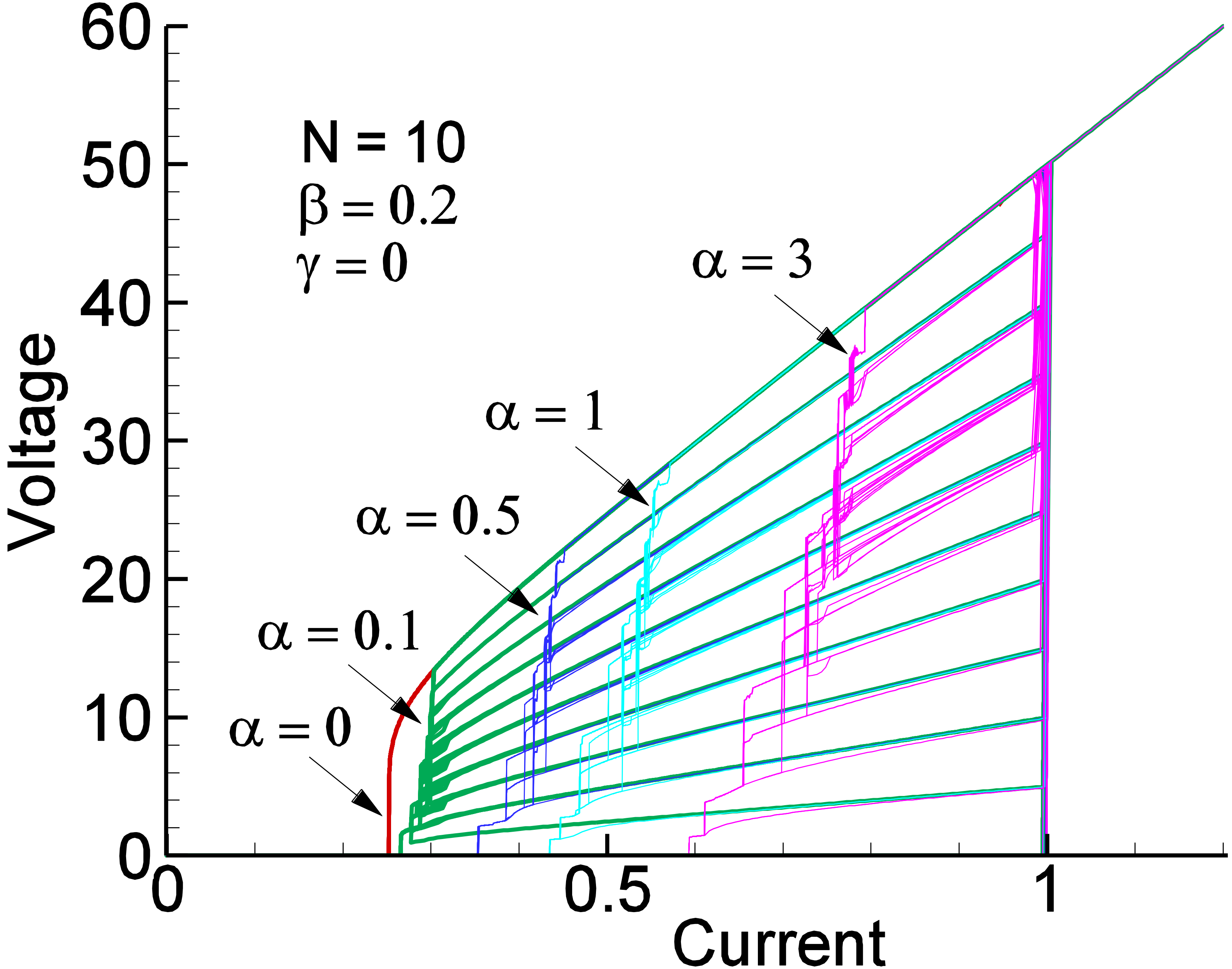
Temperature dependence of the breakpoint current



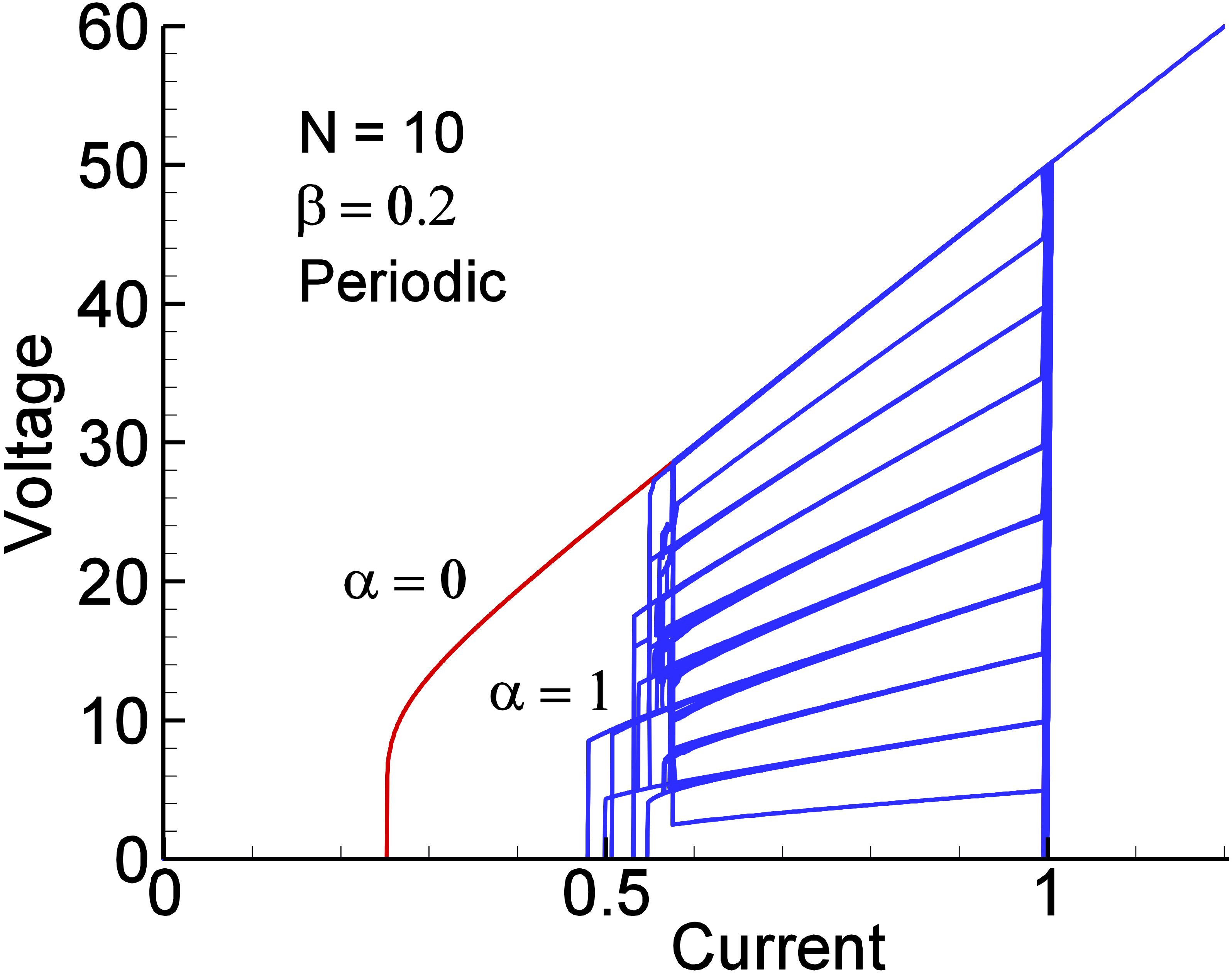
Temperature dependence of the breakpoint current



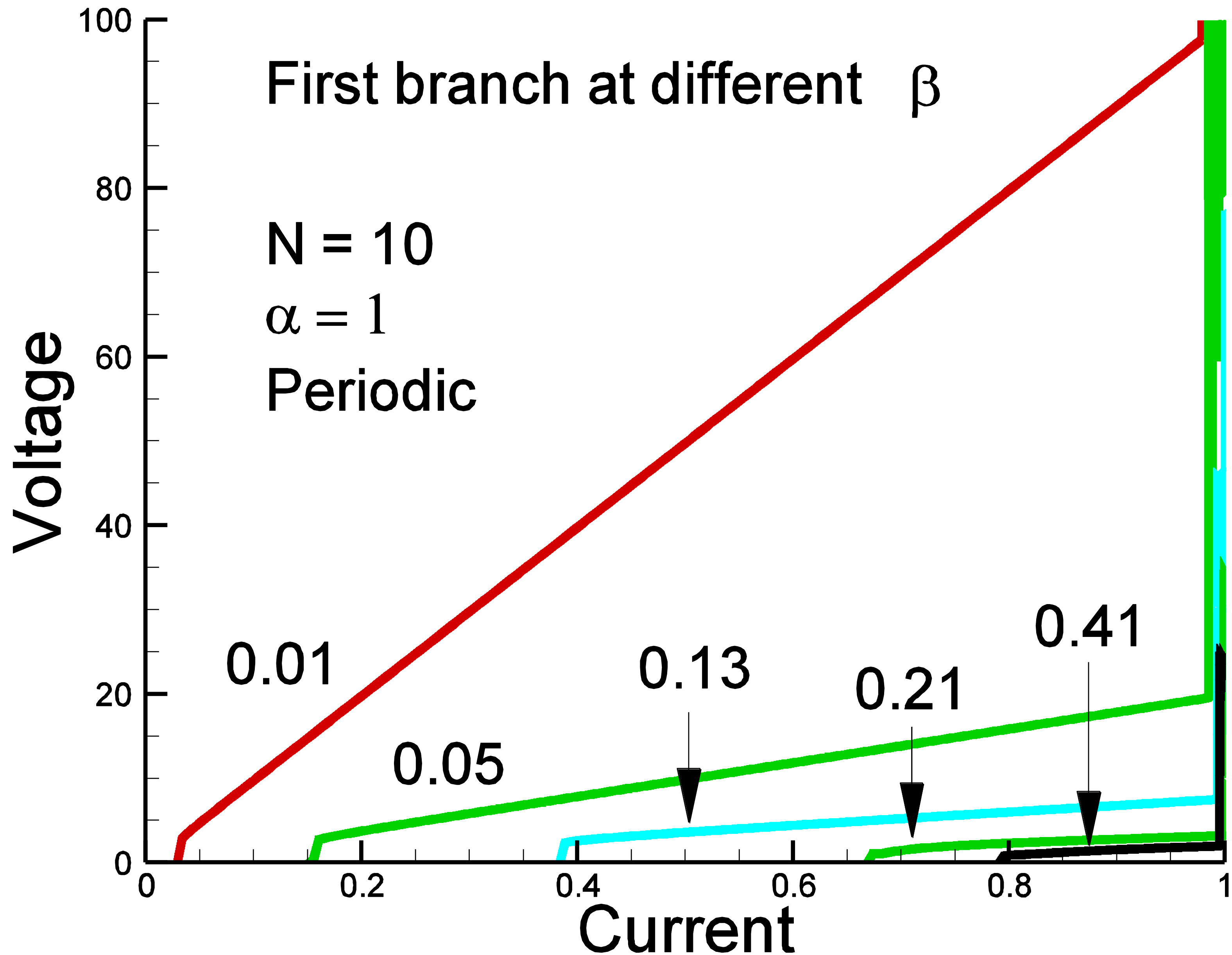
Return current



N = 10
β = 0.2
γ = 0
α = 3
α = 1
α = 0.5
α = 0.1
α = 0
Voltage
Current
60
50
40
30
20
10
0
0
0.5
1



N = 10
β = 0.2
Periodic
α = 0
α = 1
Voltage
Current
0
10
20
30
40
50
60
0
0.5
1


First branch at different β
N = 10
α = 1
Periodic
Voltage
Current
0.01
0.05
0.13
0.21
0.41
100
80
60
40
20
0
0
0.2
0.4
0.6
0.8
1

$$\beta_c = 2eC_J R_N^2 I_C/\hbar$$

$$\beta^2 = 1/\beta_c$$

$$\rho_J^{-1}(T) = \rho_{sg}^{-1} + \rho_C^{-1}(T)$$

$$\rho_C(T) = a\exp(b/T) + cT + d$$

$$R_J = \frac{\rho_{sg}\rho_c}{(\rho_{sg}+\rho_c)}\frac{D}{S}$$

$a = 6*10^{-4}\Omega m$, $b = 273K$, $c = 24*10^{-6}\Omega m/K$, $d = 1.23*10^{-2}\Omega m$ (Okanoue06)

$$I_c(T) = I_c(0)\sqrt{\cos\frac{\pi}{2}(\frac{T}{T_c})^2}\tanh\left(0.88\sqrt{\cos\frac{\pi}{2}(\frac{T}{T_c})^2}\frac{T_c}{T}\right)$$

$$C_J = \varepsilon_r\varepsilon_0 S/D$$

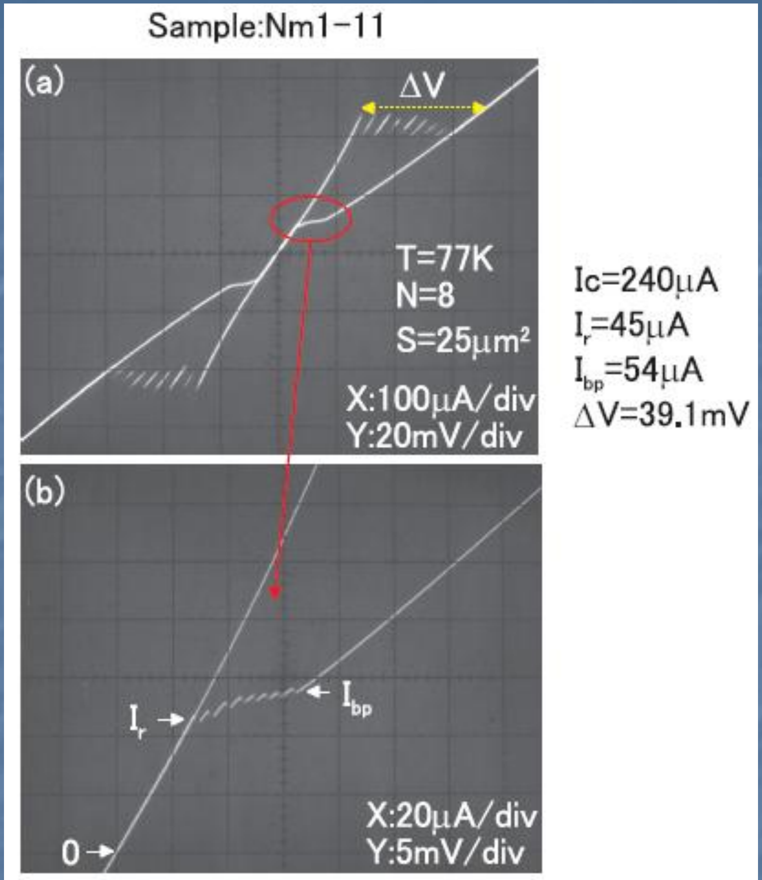
$$I_r(T) = I_c(T)\frac{-(\pi-2)+\sqrt{(\pi-2)^2+8\beta_c}}{2\beta_c}$$

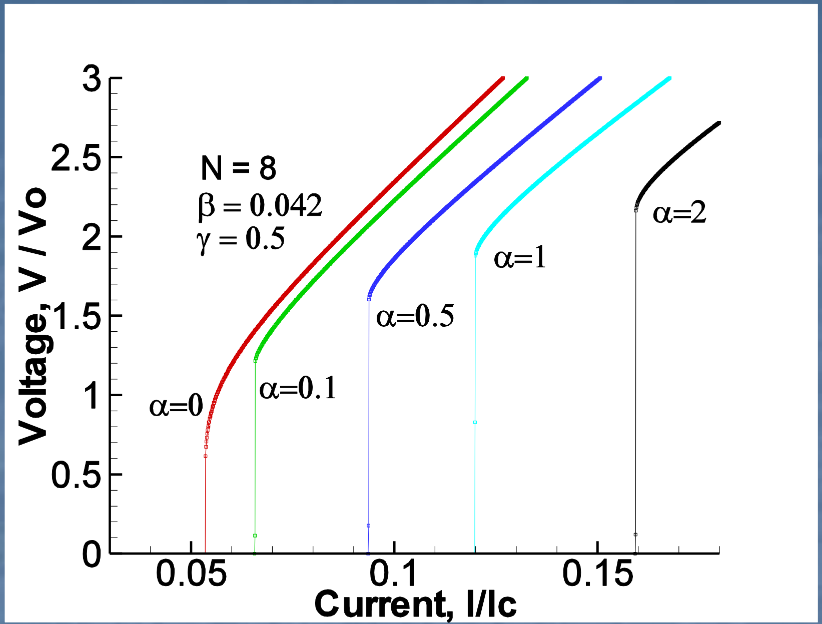
$$\frac{d}{dt}V_l = I - \sin\varphi_l - \beta\frac{d\varphi_l}{dt}$$
$$\frac{d}{dt}\varphi_l = V_l - \alpha(V_{l+1}+V_{l-1}-2V_l)$$

$$\frac{d}{dt}V_l = I - J_c\sin\varphi_l - \tilde{\beta}\frac{d\varphi_l}{dt}$$
$$\frac{d}{dt}\varphi_l = V_l - \alpha(V_{l+1}+V_{l-1}-2V_l)$$

Fitted β: $\beta = c0 + c1 * exp(T/c2)$ with $c0 = 0.01861, c1 = 5.10414*10^{-5}, c2 = 0.09989$

$\tilde{\beta} = \beta * (I_c/I_{c0})^{1/2}$ with a fitted β.





$$\beta_c = \frac{2\pi I_c R^2 C}{\Phi_0} = 558 \quad (\text{for} \quad \varepsilon_r = 10)$$

$$\beta_c = \left(\frac{4}{\pi}\frac{I_c}{I_r}\right)^2 \quad (\text{for} \quad \beta_c >> 1)$$

$$\frac{I_r}{I_c} = 0.054$$

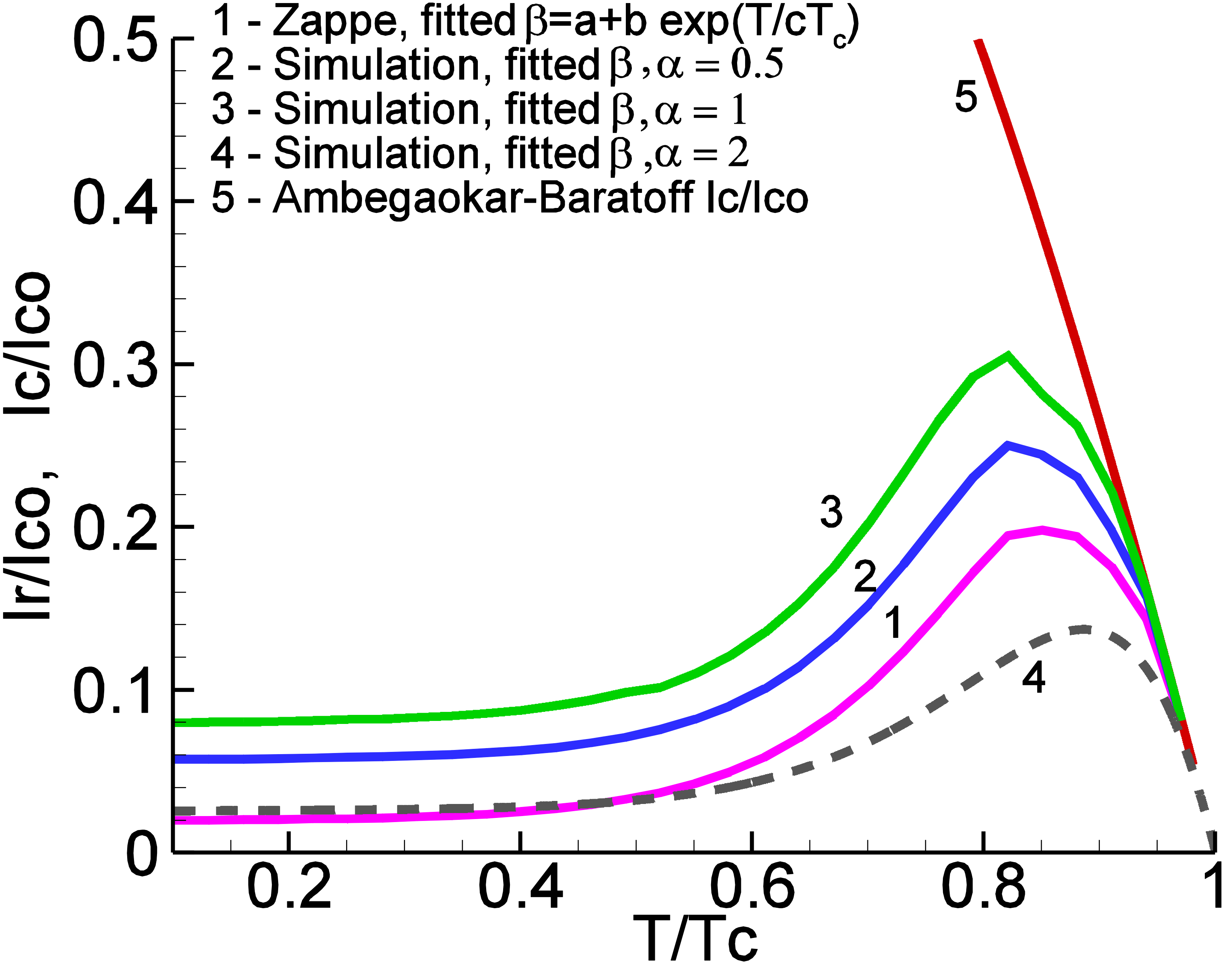
$$\frac{I_r}{I_c}(exp) = 0.188$$

Vbp - from numerical simulations, Ibp=0.576 Ic0, β - calculated by formula

$$\beta = N \frac{I_{bp}}{V_{bp}}$$

$\alpha = 1$

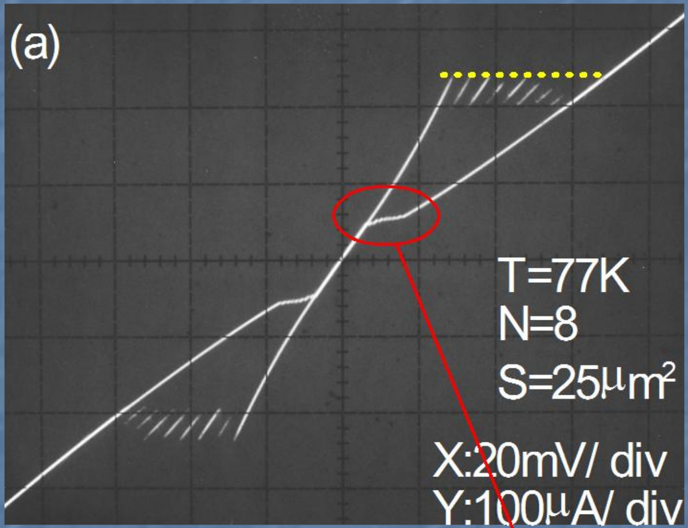
N	V_{bp}	β
4	11.352	0.2029
6	17.158	0.2014
8	22.667	0.2033
10	28.595	0.2014
12	34.300	0.2015
14	39.870	0.2022
16	45.684	0.2017
18	51.474	0.2014



1 - Zappe, fitted β=a+b exp(T/cT_c)
2 - Simulation, fitted β, α = 0.5
3 - Simulation, fitted β, α = 1
4 - Simulation, fitted β, α = 2
5 - Ambegaokar-Baratoff Ic/Ico
Ir/Ico, Ic/Ico
T/Tc
0.5
0.4
0.3
0.2
0.1
0
0.2
0.4
0.6
0.8
1
5
3
2
1
4

Breakpoint current I_{bp}

Sample:Nm1- 11

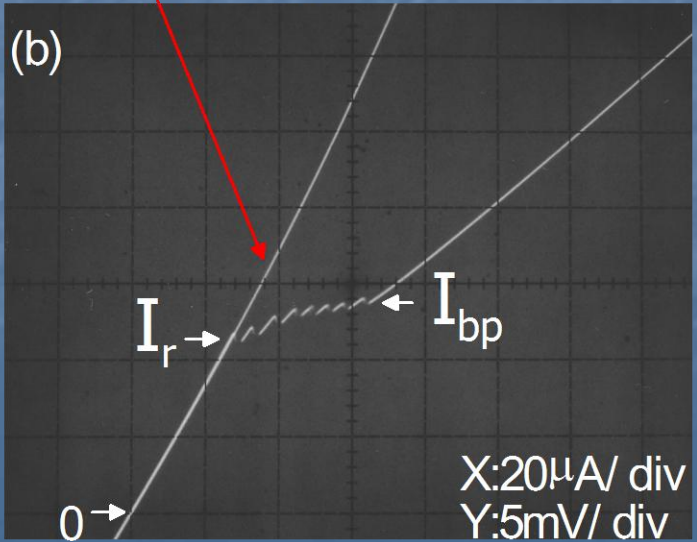


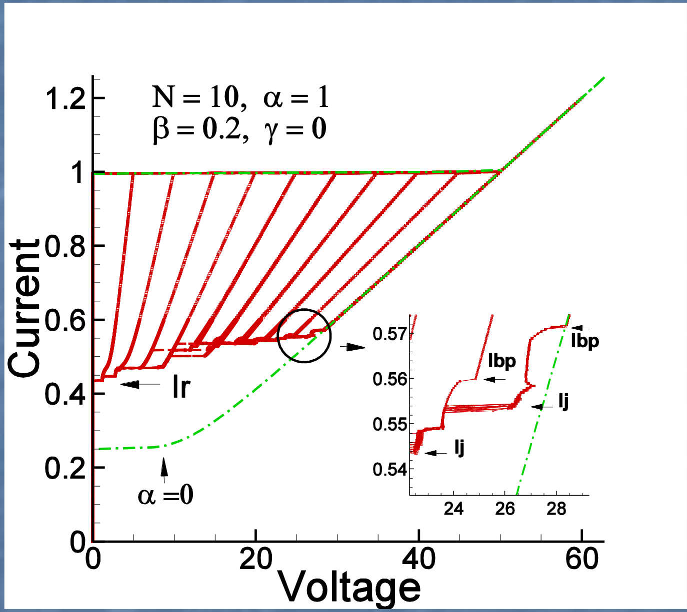
I_c=240μA

I_r=45μA

I_{bp}=54μA

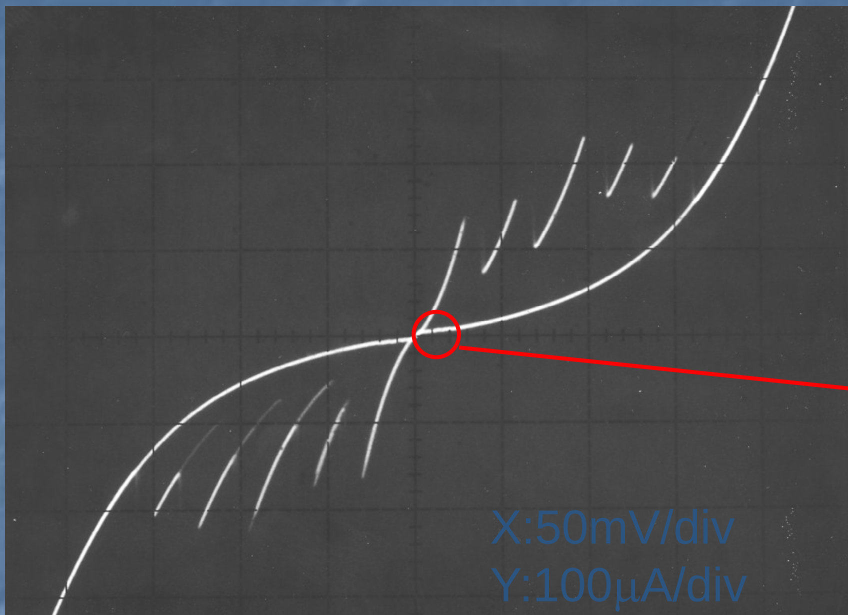
ΔV=39.1mV

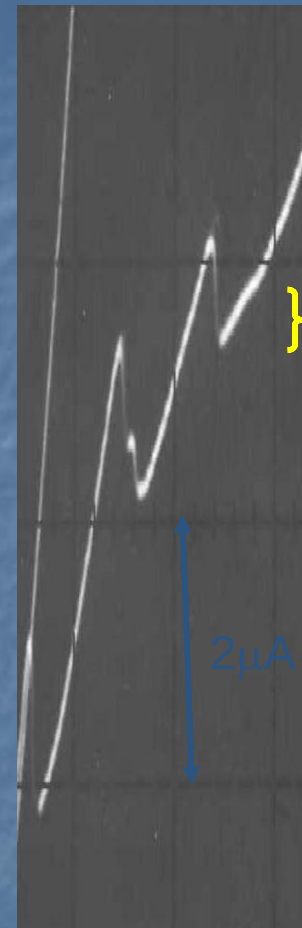




Experimental results: Utsunomiya university

Breakpoint region





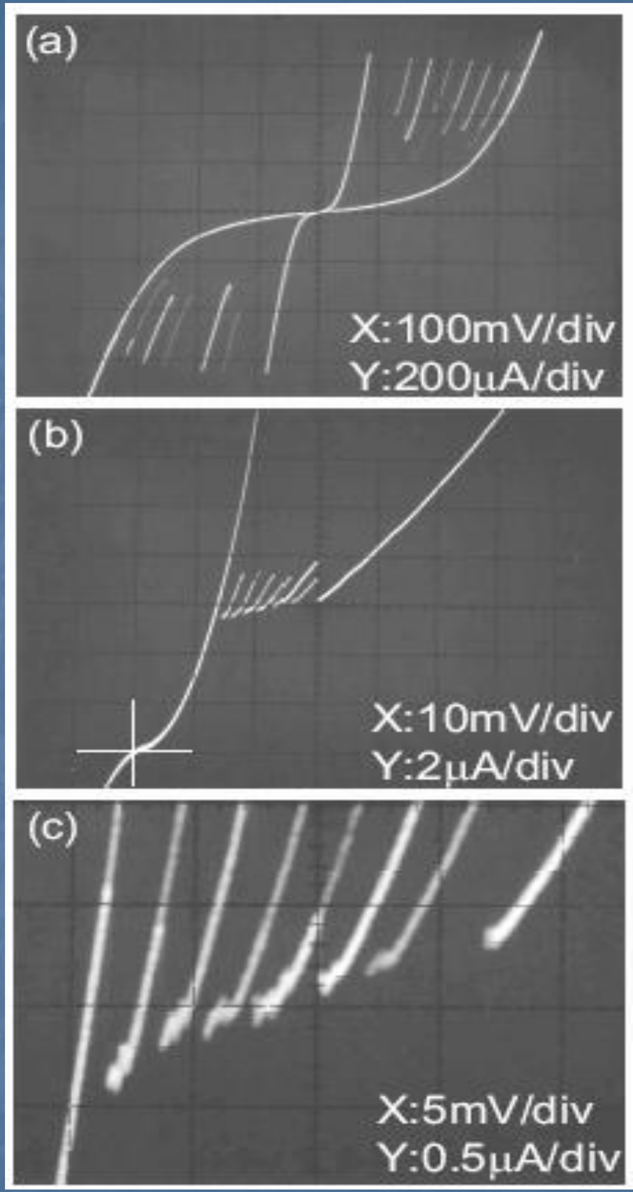
Breakpoint region

$\Delta I = \sim 0.5 \mu A$

The observation of the breakpoint region suggests the excitation of the longitudinal plasma wave in the mesa.

$\omega_J = 2\omega_p$ ⇒ $f_p = 1.97$ THz

Experimental results: Utsunomiya university



Experimental IVC of BSCCO-2212 (Sample #1) K.Okanoue, K.Hamasaki, APL, 87,222506, (2005)

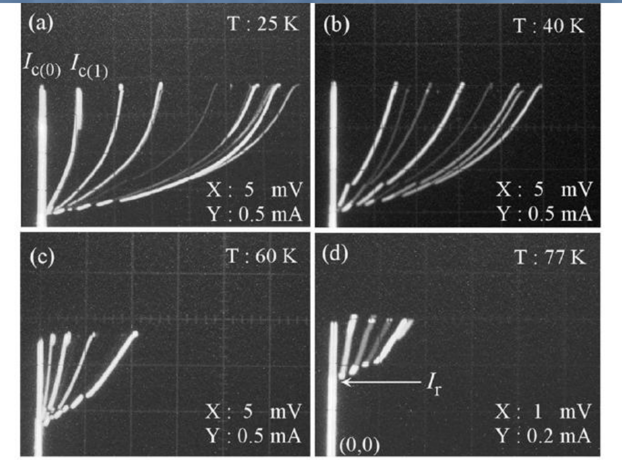


FIG. 2. *I-V* characteristics of a self-planarized stack (Sample No. 1) at 25, 40, 60, and 77 K.

Experimental results: Utsunomiya university

Bogoliubov Laboratory of Theoretical Physics

Institute for Advanced Studies in Basic Sciences
Gava Zang, Zanjan, Iran

Investigation of Breakpoint region in the stacked Josephson junctions

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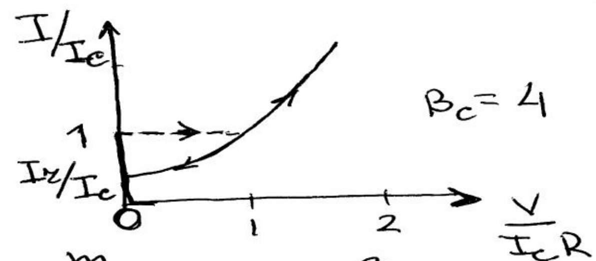
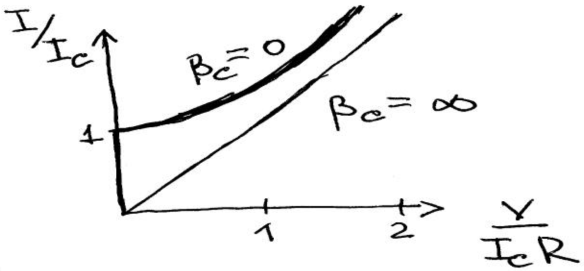
IX Winter School on Theoretical Physics
NONLINEAR PHENOMENA IN CONDENSED MATTER
Dubna, Russia

- Спасибо за внимание

Один контакт



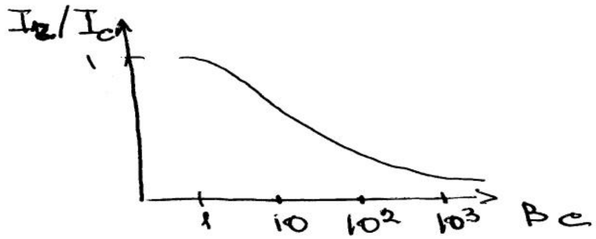


$$\underbrace{\left(\frac{\hbar}{2e}\right)^2 C}_{m}\ddot{\varphi} + \underbrace{\left(\frac{\hbar}{2e}\right)^2 R^{-1}}_{\eta}\dot{\varphi} + \underbrace{E_J}_{E_J(1-\cos\varphi)}\sin\varphi = \underbrace{E_J \frac{I}{I_c}}_{F} \qquad \frac{mv^2}{2} = \frac{CV^2}{2}$$

J – момент инерции; η – вязкость; mgl – мах. грав. момент; вращ. момент

$$\omega_p = \left(\frac{E_J}{J}\right)^{1/2}$$ – плазм. частота

$$E = E_J(1-\cos\varphi) - \frac{\Phi_0}{2\pi} I\varphi$$



$$\beta_c = \left(\frac{2e}{\hbar}\right) I_c C R^2$$

$$\beta^2 = \frac{1}{\beta_c}$$