Novel Quantum States in Condensed Matter 2017
Yukawa Institute for Theoretical Physics, Kyoto University, Japan

Dynamics and IV-characteristics of Josephson junctions and superconductor-ferromagnet-superconductor structures

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In collaboration with:
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JINR MEMBER STATES

Armenia, Azerbaijan, Belarus, Bulgaria, Cuba, Czech Republic

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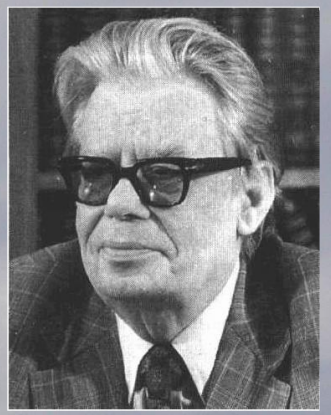
Egypt, Germany, Hungary, Italy, RSA, Serbia

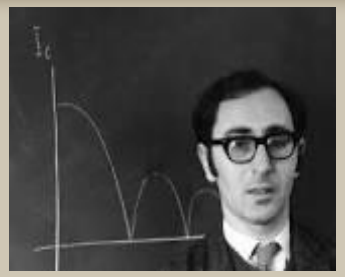
105	rutherfordium ← dubnium → seaborgium
Ta ↑ **Db** ↓ (Upp)	Db 105P 157N Periodic Table - Extended Periodic Table



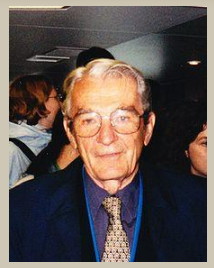
Outline

- Introduction
- Charging of S-layers in IJJ, Radiation, Shapiro steps, Shunting.
- φ_0-junction
- Magnetic moment reversal
- IV-characteristics and magnetic precession

Part 1



Brian Josephson



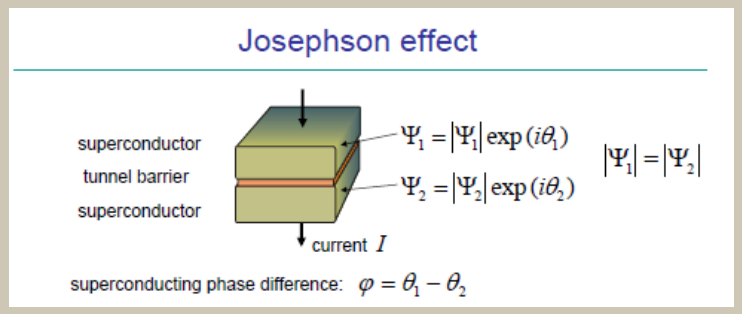
Ivar Giaever

dc Josephson effect:

$$I_s(\varphi) = I_c \sin\varphi \quad (1)$$

ac Josephson effect:

$$\frac{d\varphi}{dt} = \frac{2e}{\hbar} V \quad (2)$$



From (2) it follows that $\varphi = \frac{2e}{\hbar} Vt + \varphi_0$.

Thus, I_s oscillates with frequency

$$f = \frac{2e}{2\pi\hbar} V = \frac{1}{\Phi_0} V, \quad (3)$$

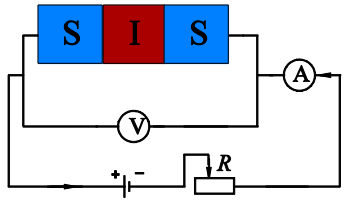
where $\Phi_0 = 2.068 \times 10^{-15}$ Wb is the magnetic flux quantum.

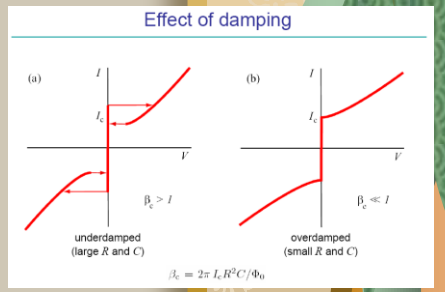
- Josephson junction is a *quantum dc voltage - to - frequency converter*
- $1\,\mu\text{V} \leftrightarrow 483.59767$ MHz

$$I = \frac{dV}{d\tau} + \beta V + \sin\varphi$$

$$V = \frac{d\varphi}{d\tau}, \quad \text{where } \tau = \omega_p t,$$

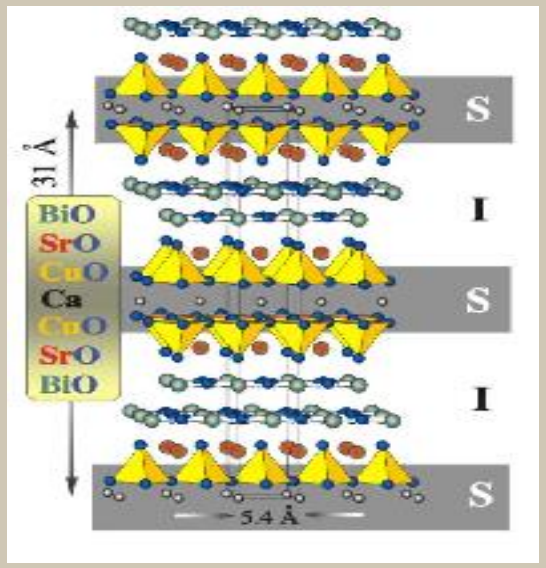
$$\omega_p = \frac{2eI_c}{\hbar C} \quad \text{and} \quad \beta = \frac{1}{\omega_p RC}$$

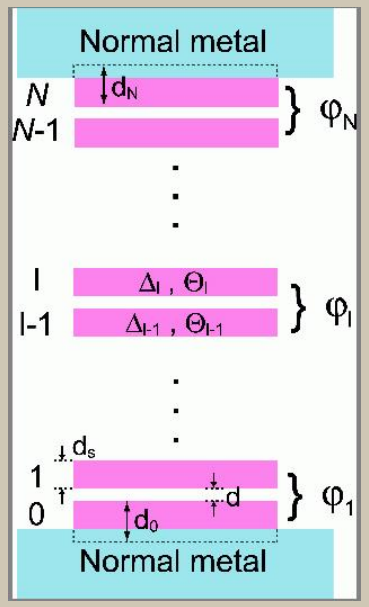


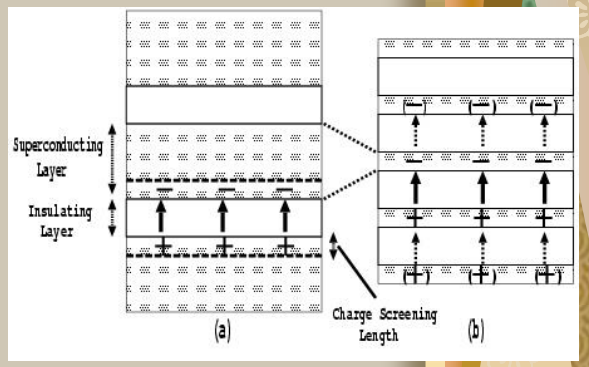


Applications in the superconducting electronics, quantum metrology, medicine.
Particularly, the system is a source of coherent electromagnetic radiation.

Layered $Bi_2Sr_2CaCu_2O_y$(Bi2212) single crystals represent natural stacks of atomic scale intrinsic Josephson junctions.







$$\Psi_l(t) = |\Psi_l| \exp i\theta_l(t)$$

$$\Delta_l(t) = |\Delta_l| \exp i\theta_l(t)$$

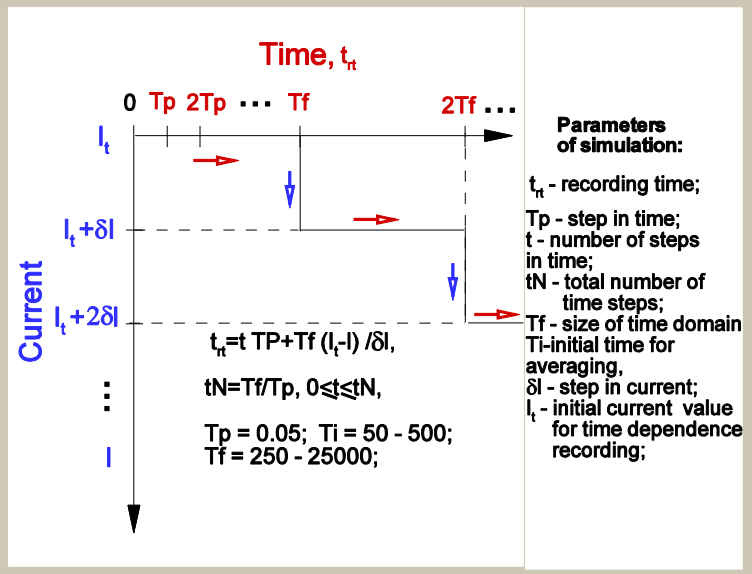
$$\rho_l = -\frac{\Phi_l}{4\pi\mu^2}; \qquad \Phi_l = \phi_l - \frac{\hbar}{2e}\frac{\partial\theta_l}{\partial t};$$

$$\frac{\hbar}{2e}\frac{\partial\varphi_{l,l+1}}{\partial t} = V_{l,l+1} + \frac{\varepsilon\mu^2}{d_s d_I}(V_{l+2,l+1} + V_{l-1,l} - 2V_{l,l+1})$$

$$\varphi_l(t) = \theta_l(t) - \theta_{l-1}(t) - \frac{2e}{\hbar}\int_{l-1}^{l} dz A_z(z,t)$$

Experimental, 5 JJ,
M. Suzuki, Kyoto University

Simulation procedure for IV-characteristics

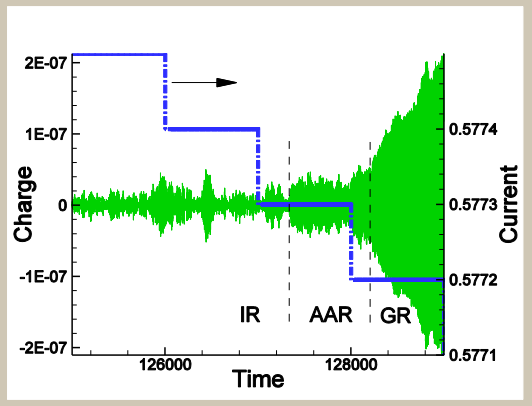


$$\operatorname{div}(\varepsilon\varepsilon_0 E) = Q$$

$$Q_l = Q_0\,\alpha\,(V_{l+1} - V_l)$$

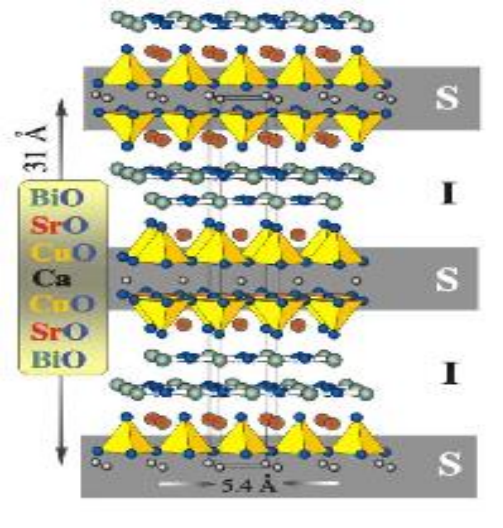
$$Q_0 = \varepsilon\,\varepsilon_0\,V_0 / r_D^2$$

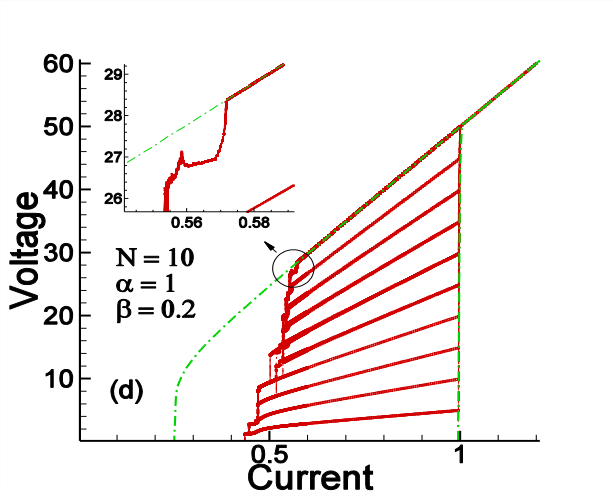
$$\begin{cases} \dfrac{d\varphi_l}{dt} = V_l - \alpha\left(V_{l+1} + V_{l-1} - 2V_l\right) \\ \dfrac{dV_l}{dt} = I - \sin\varphi_l - \beta\varphi_l + A\sin(\omega t) \end{cases}$$

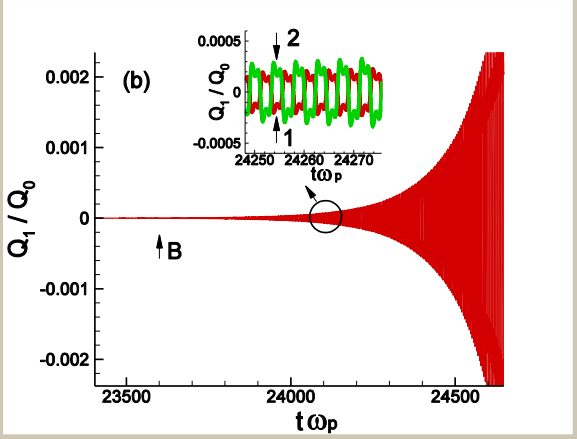


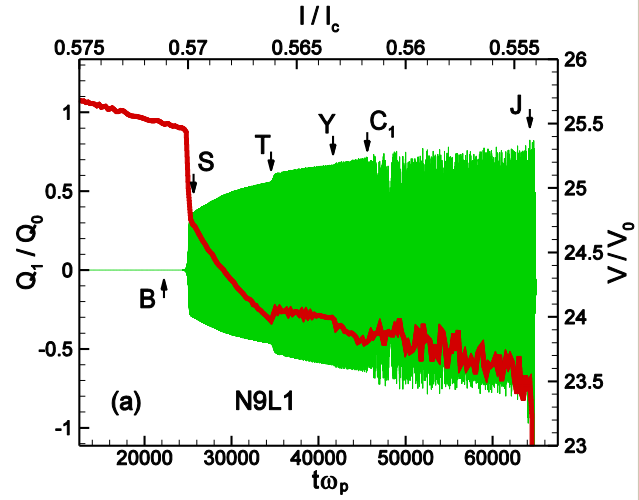
Charging of superconducting layers in HTSC

Parametric resonance in coupled Josephson junctions









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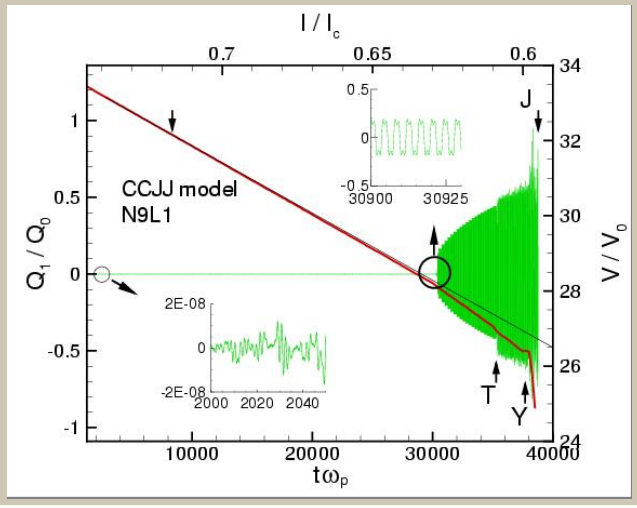
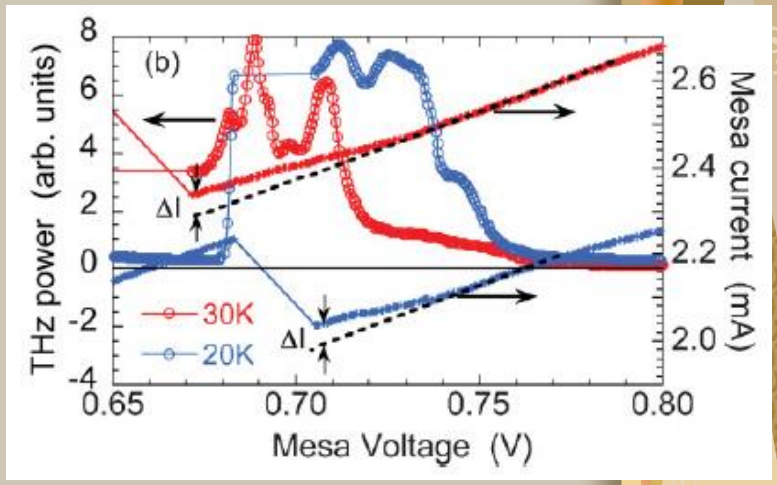
Phys.Rev.Lett, 98, 157001 (2007)

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

CVC and charge-time dependence in CCJJ model





The 7th International Symposium on Intrinsic Josephson Effects and Plasma Oscillations in High-T_c Superconductors (PLASMA 2010)
Hirosaki Univ., Hirosaki, Japan, April 25-28, 2010

Phase Dynamics in IJJ: Comparative Study in Different Models

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[c] *ECTP, Modern University, Mokattum, Cairo, Egypt*

A.Irie et al, Apl.Phys.Lett., 2008

PHYSICAL REVIEW B **84**, 064523 (2011)

Tunable terahertz emission from $Bi_2Sr_2CaCu_2O_{8+\delta}$ mesa devices

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(Received 24 June 2011; revised manuscript received 29 July 2011; published 24 August 2011)

The International Conference on Theoretical Physics 'Dubna-Nano2008' — IOP Publishing
Journal of Physics: Conference Series 129 (2008) 012029 — doi:10.1088/1742-6596/129/1/012029

Experimental observation of the longitudinal plasma excitation in intrinsic Josephson junctions

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[2] Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna, Moscow Region, 141980, Russia

Breakpoint region

Charging of superconducting layers

The electric charge density in the superconducting layers is determined by the difference between the voltages V_l and V_{l+1} across the neighboring insulating layers, i.e.

$Q_l=Q_0\alpha(V_{l+1}-V_l)$, where $Q_0 = \varepsilon_r\varepsilon_0 V_0/r_D^2$,

ε_r is the relative permittivity

ε_0 is the permittivity of free space.

For typical values:

$r_D = 3 \times 10^{-10}$ m,

$\varepsilon_r = 25$,

$\omega_p = 10^{12}$ s^{-1},

we find $V_0 = 3 \times 10^{-4}$ V and $Q_0 = 8 \times 10^5$ C m^{-3}.

Thus, for a superconducting layer with area $S = 1$ μm^2 and thickness $d_s = 3 \times 10^{-10}$ m, at $\alpha=0.1$ and $(V_{l+1}-V_l)=1$, the charge value is about

$Q_l=10^{-17}$ C.

This value of charge is sufficiently high to play a significant role in the physical processes in the stack of intrinsic Josephson junctions in high temperature superconductors.

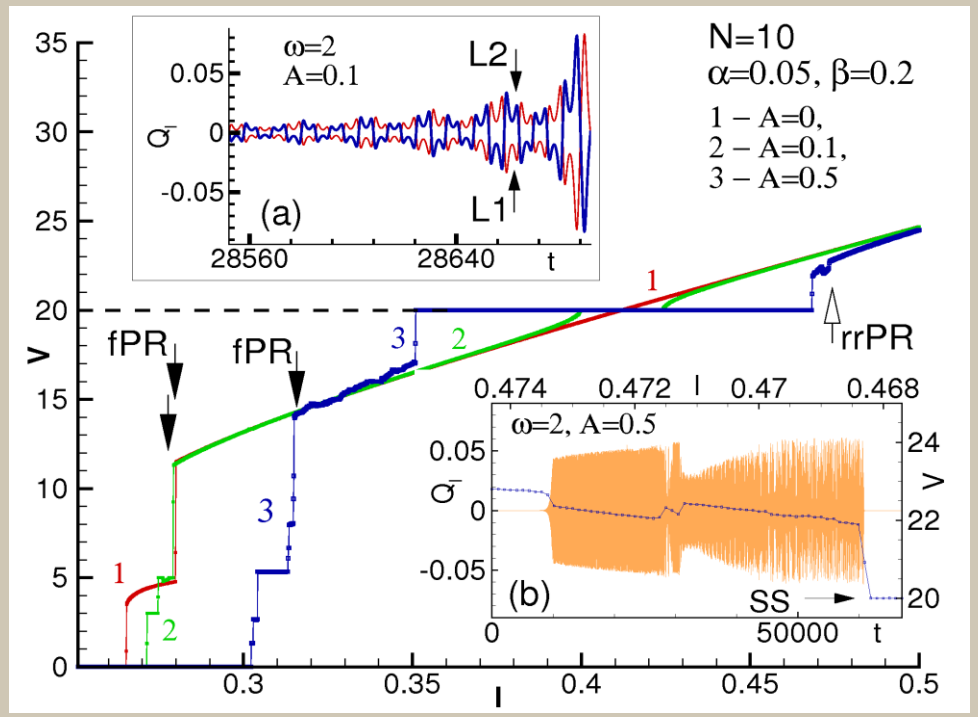
Variation of Longitudinal Plasma Wavelength under External Electromagnetic Radiation

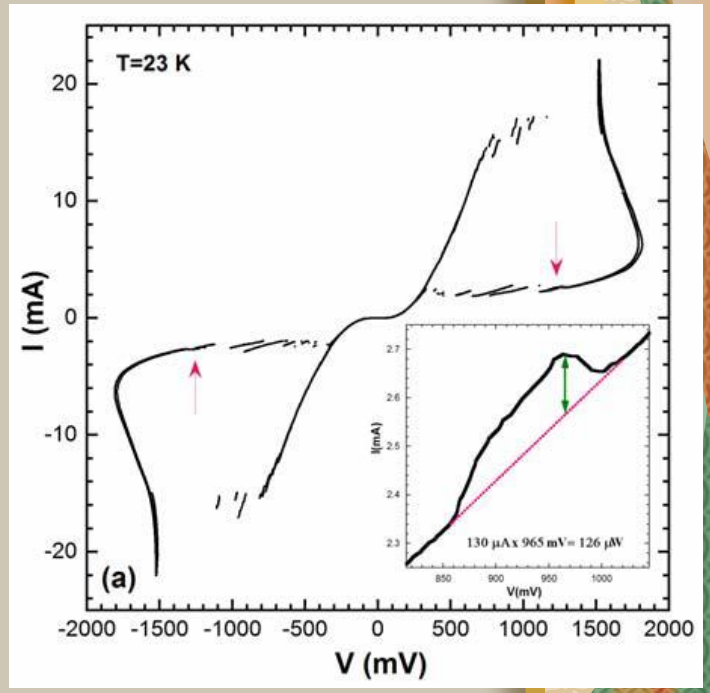
IV-characteristics

without irradiation (curve 1)

under radiation with *A = 0.1 (curve 2)*

A = 0.5 (curve 3).

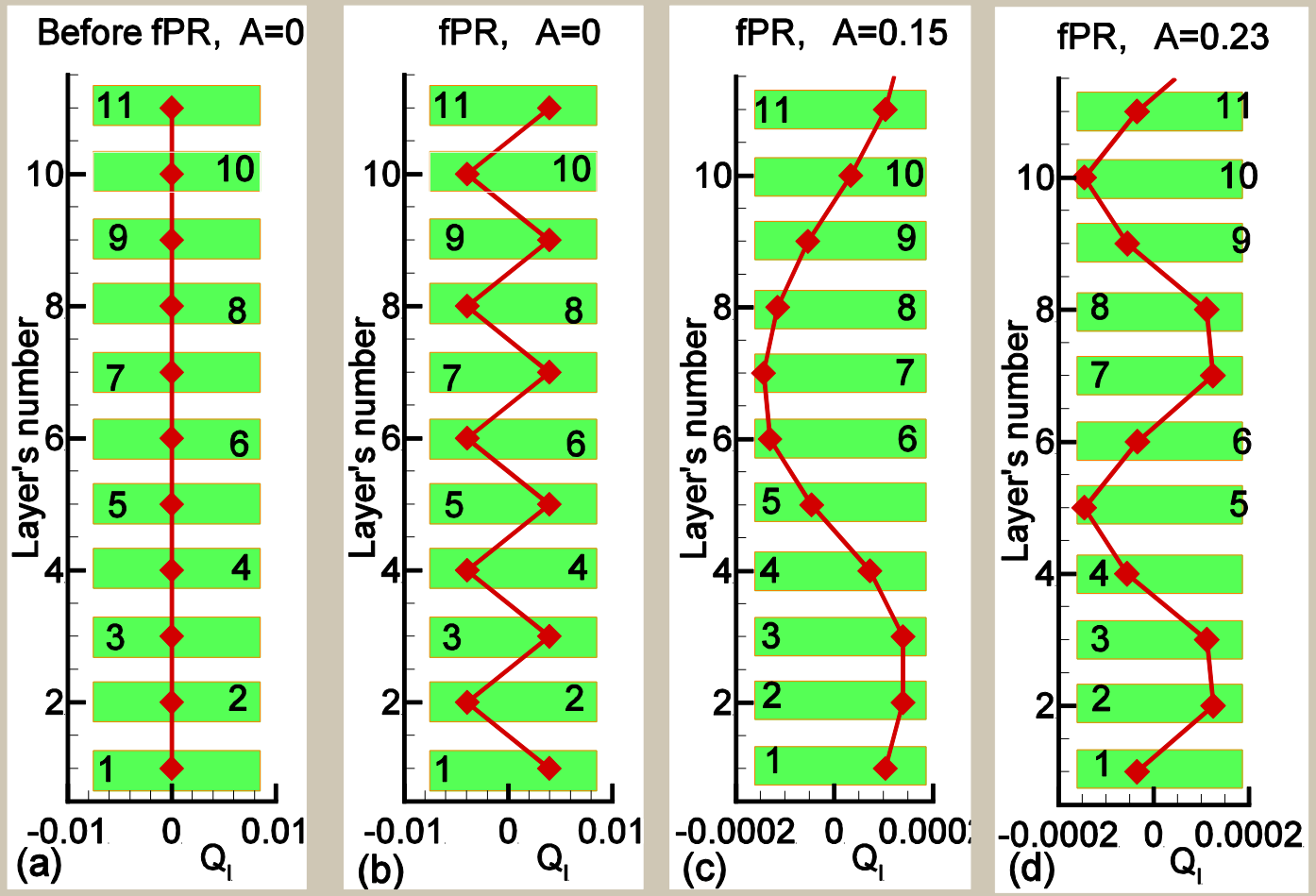




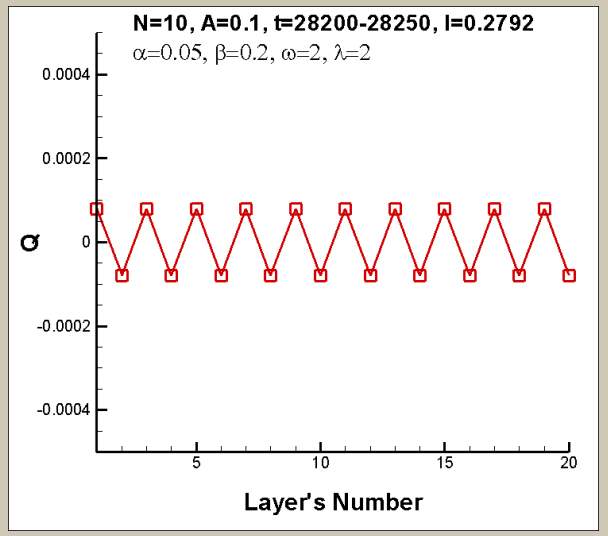
Yu.M.Shukrinov, I.Rahmonov, M. Gaafar, Phys.Rev.B, 86, 184502 (2012)

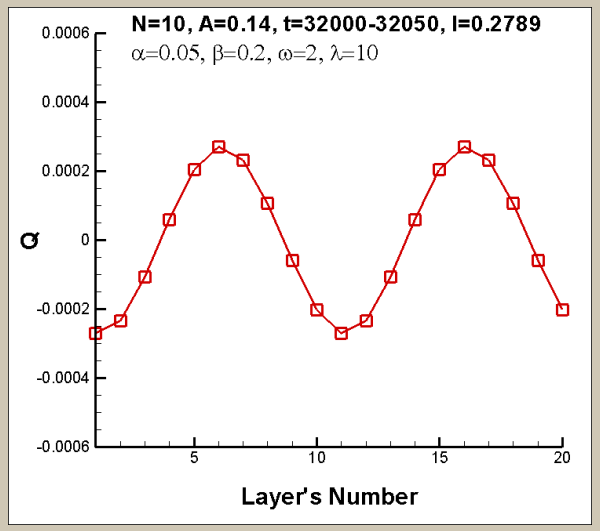
F Turkoglu, H Koseoglu, Y Demirhan, L Ozyuzer, S Preu, S Malzer, Y Simsek, P Müller, T Yamamoto and K Kadowaki 2012 *Supercond. Sci. Technol.* **25** 125004

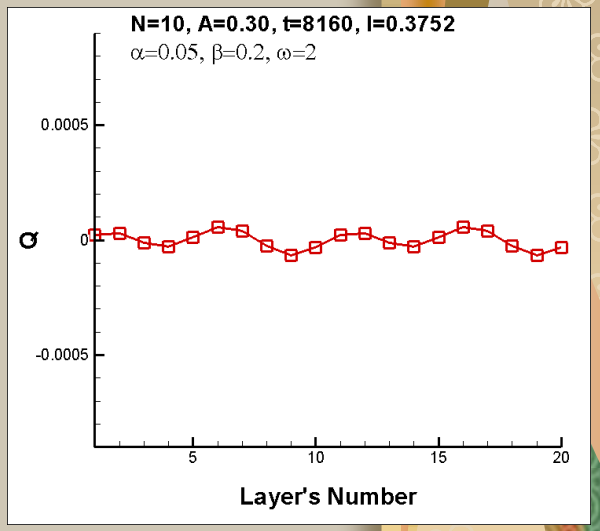
Demonstration of changing of LPW wavelength with an increase of the amplitude of radiation.

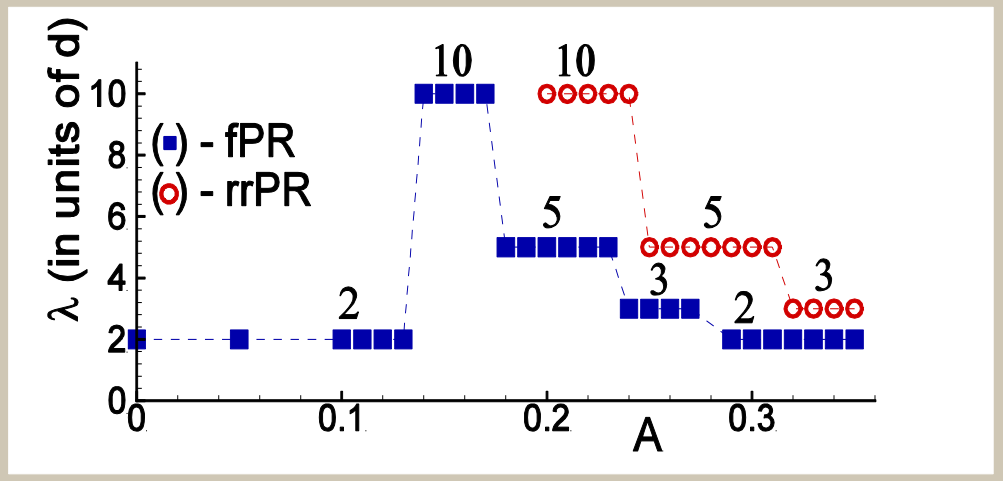


Waves in the stack of coupled JJ





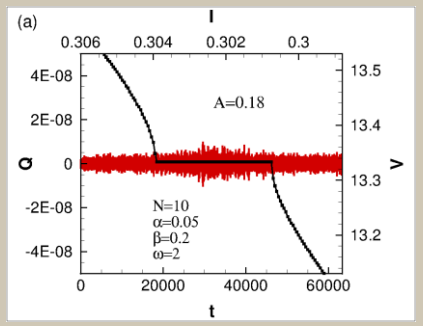


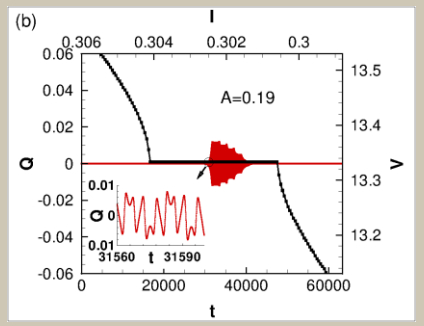


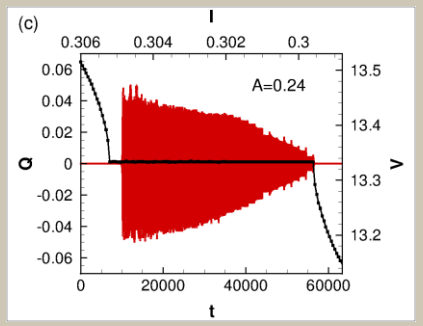
LPW wavelengths at *w = 2*
Filled squares - fundamental PR
Circles - radiation related PR

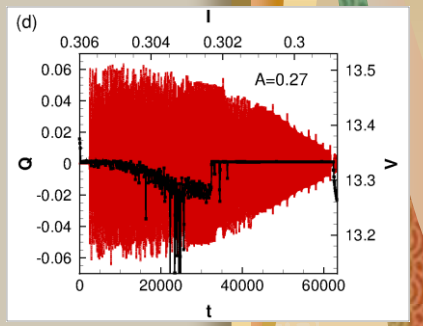
Yu.M.Shukrinov, I.Rahmonov, M. Gaafar, Phys.Rev.B, 86, 184502 (2012)

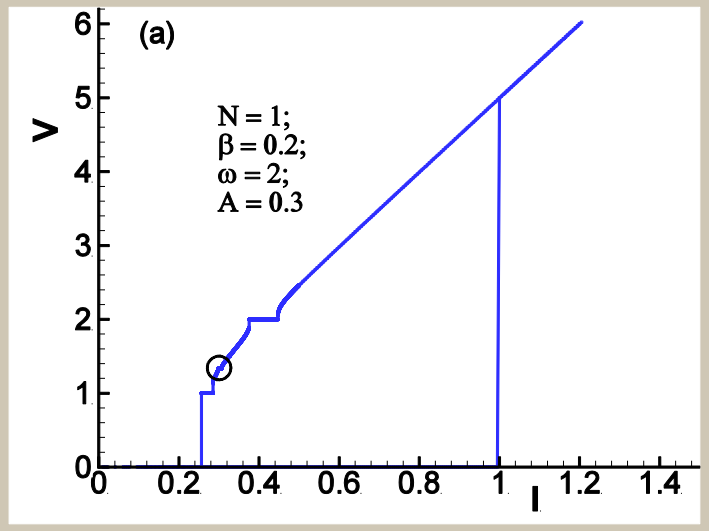
Charging of superconducting layers in current interval corresponded to SS subharmonics and chaos

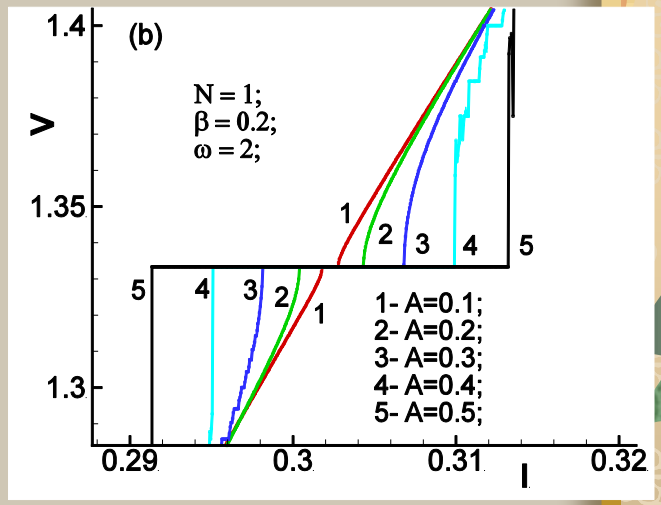






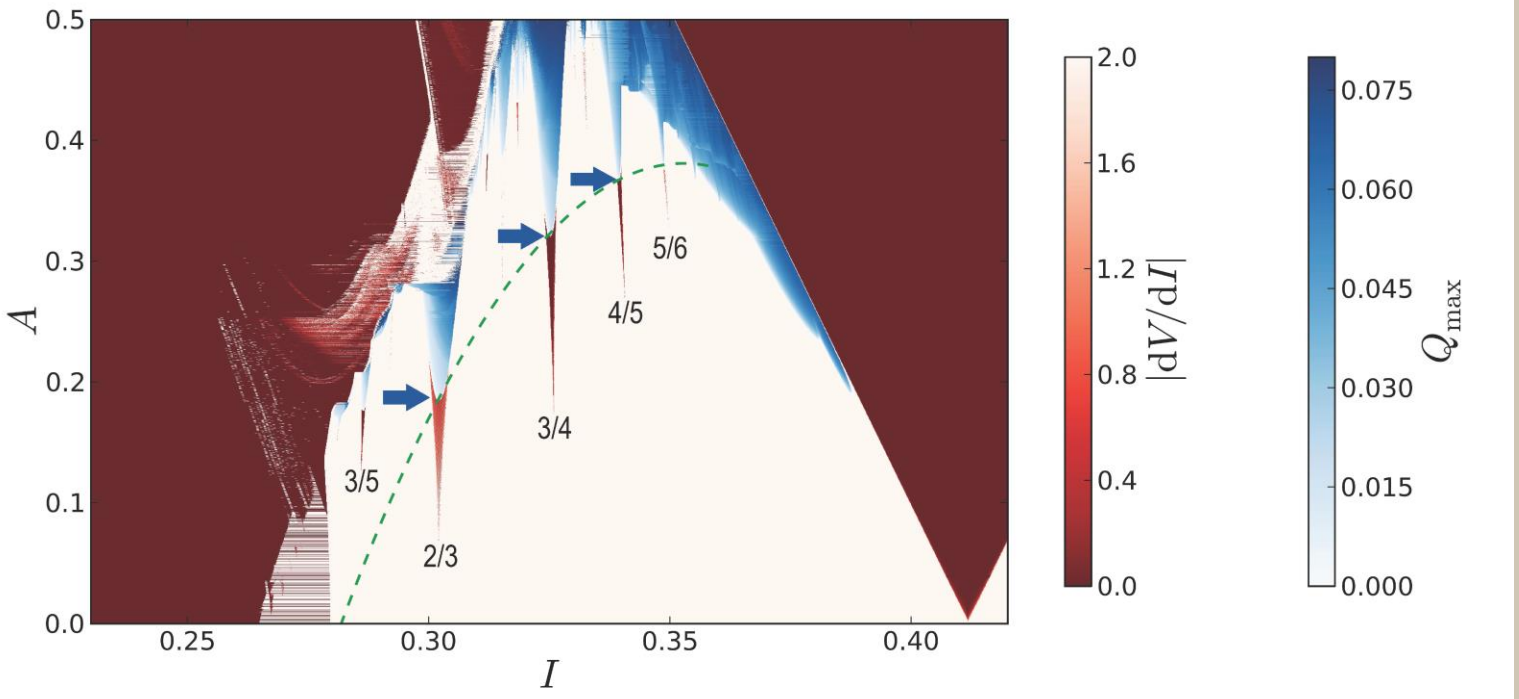






Yu.M. Shukrinov, H.Azemtsa-Donfack, À.E.Botha.
JETP Letters, 101, 251--257 (2015)

Charging of superconducting layers in current interval corresponded to SS subharmonics



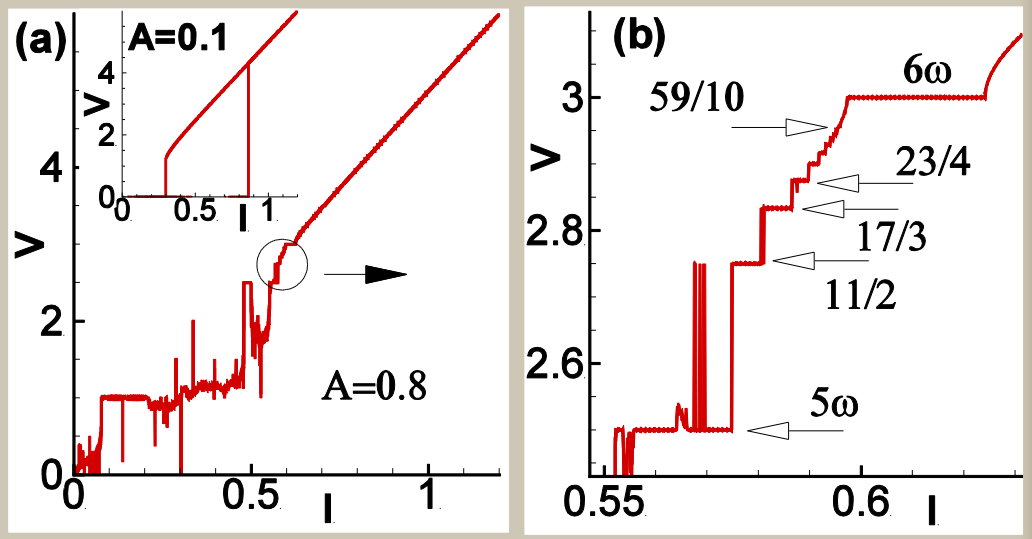
In general, the Shapiro and subharmonic steps follow the continued fractions formula given by,

$$V = \left(N \pm \frac{1}{n \pm \frac{1}{m \pm \frac{1}{p \pm \ddots}}} \right) \omega, \qquad (1)$$

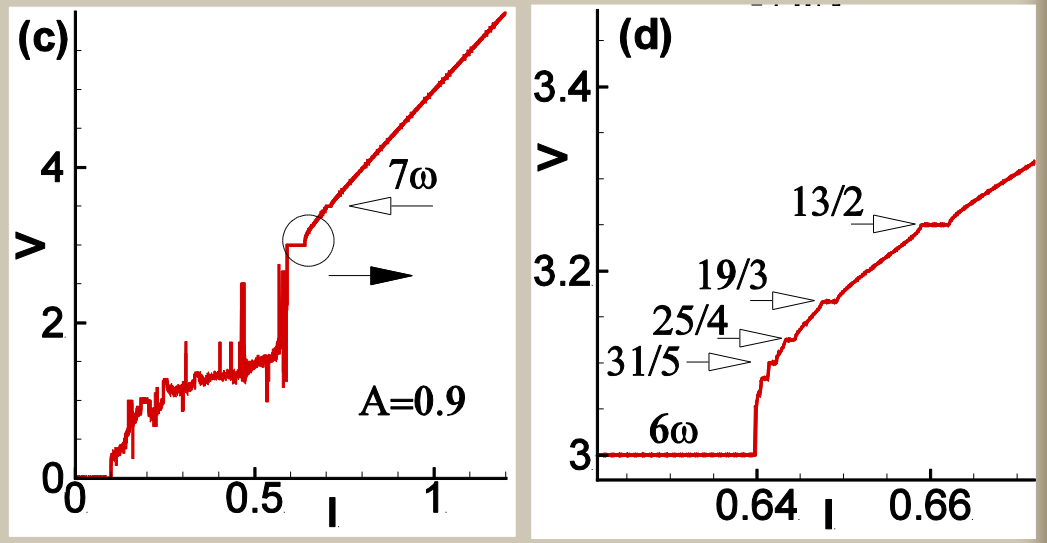
Yu.M. Shukrinov, H. Azemtsa-Donfack, I.R. Rahmonov, and A.E. Botha, Low Temperature Physics, 42, 573, 2016

Devil's Staircases and Continued Fractions in Josephson Junctions.

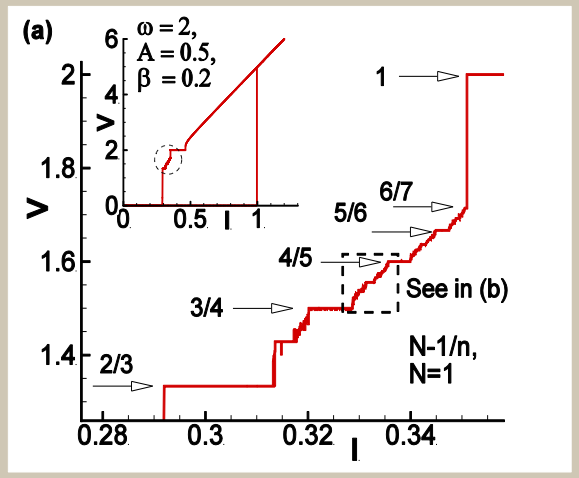
DS structure, A=0.8

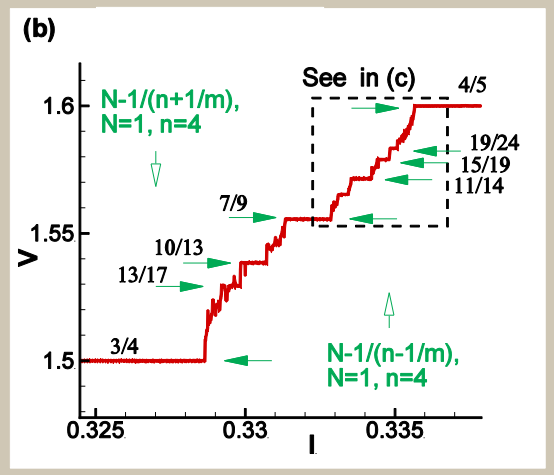


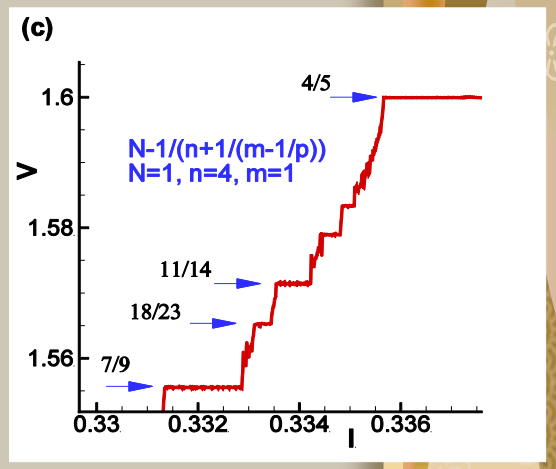
DS structure, A=0.9



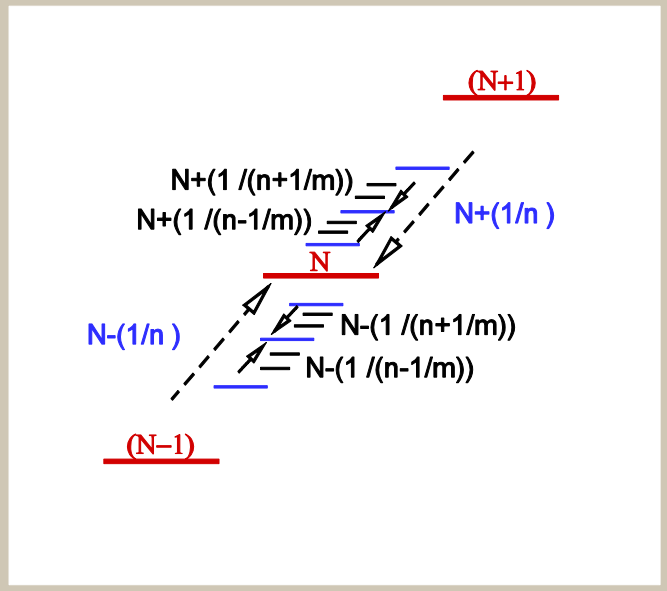
Fractal structure







$$V = \left(N \pm \frac{1}{n \pm \frac{1}{m \pm \frac{1}{p \pm \ddots}}} \right) \omega$$



Yu. M. S., S. Yu. Medvedeva, A. E. Botha, M. R. Kolahchi, and A. Irie.,
- Phys. Rev. B, 88, 214515 (2013)

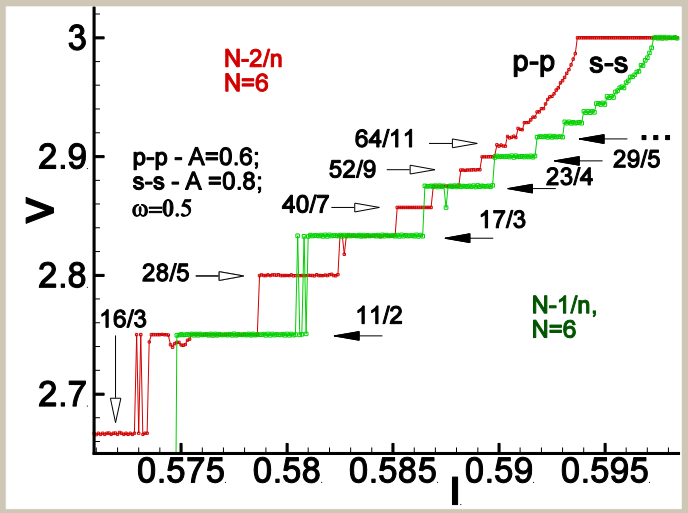
Why appearance of Shapiro step subharmonics followed the continued fractions algorithm?

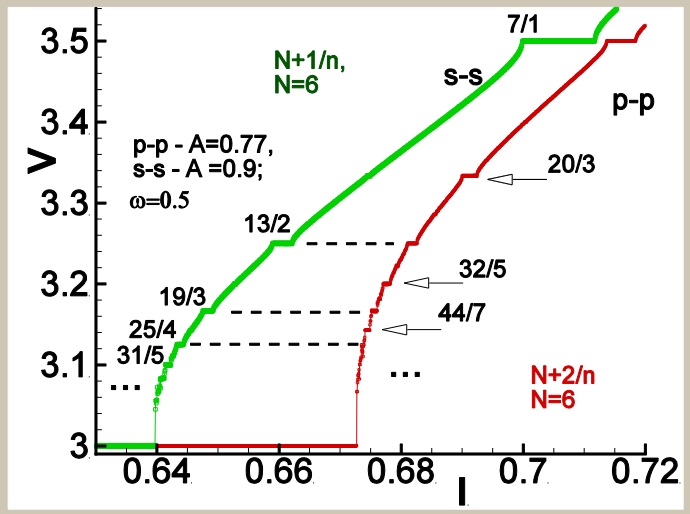
JJ

as Majorana fermions detector

Josephson junctions detectors for Majorana fermions

We demonstrate that the current-voltage (I-V) characteristics of resistively and capacitively shunted Josephson junctions (RCSJs) hosting localized subgap Majorana states provide a phase-sensitive method for their detection.
In addition, the RCSJs hosting Majorana bound states also display an additional sequence of steps in the devil's staircase structure seen in their I-V characteristics; such a sequence of steps makes their I-V characteristics qualitatively distinct from that of their conventional counterparts.



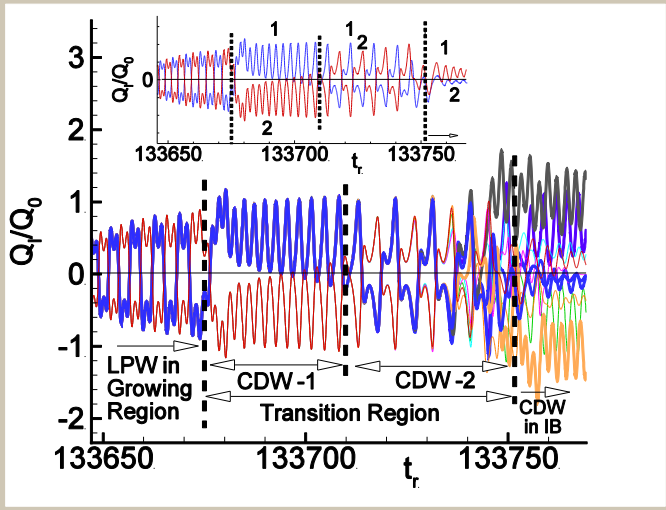


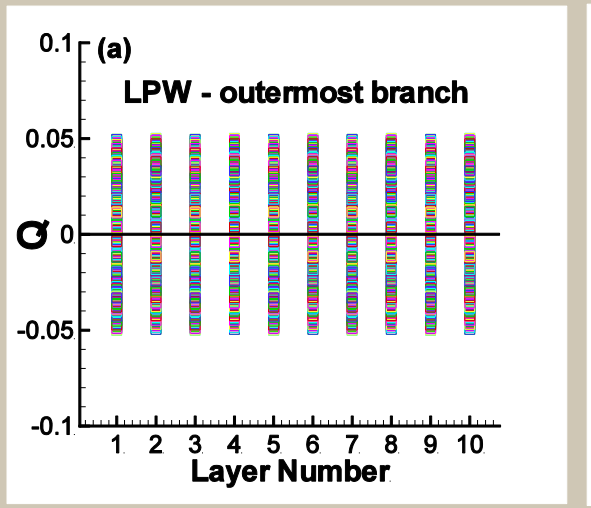
M. Maiti, K. M. Kulikov, K. Sengupta, and Y. M. Shukrinov,

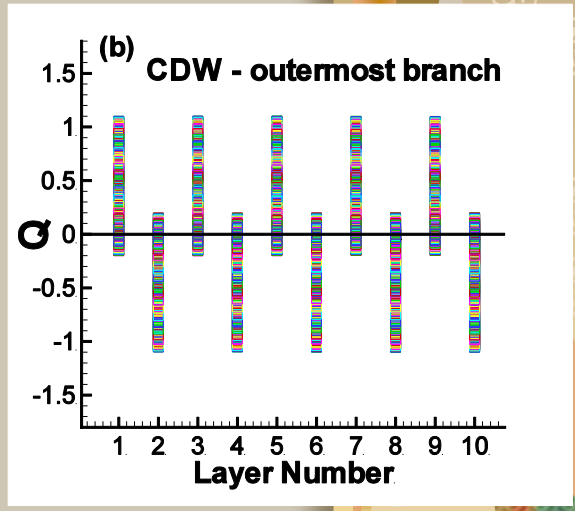
(Physical Review B 92, 224501 (2015))

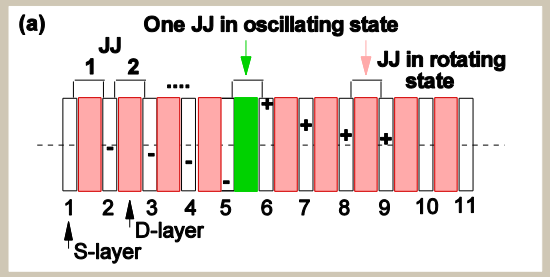
Charge density waves in intrinsic Josephson junctions

Charge Density Waves

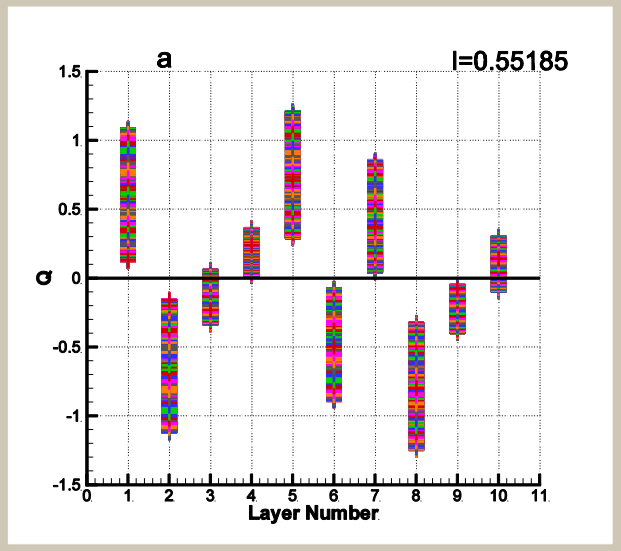


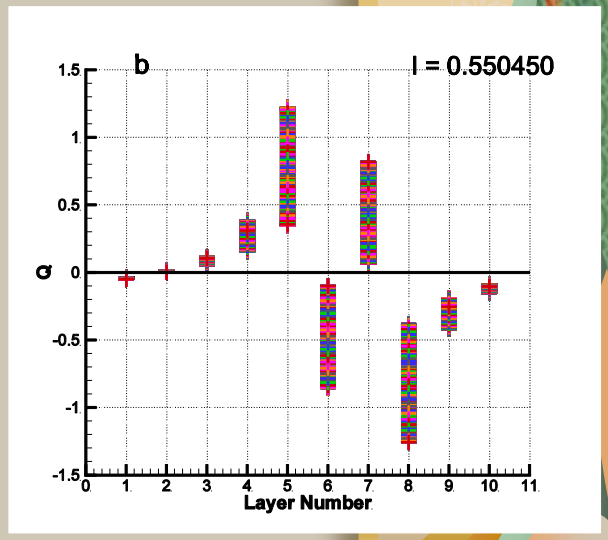






LPW→ CDW, CDW → CDW





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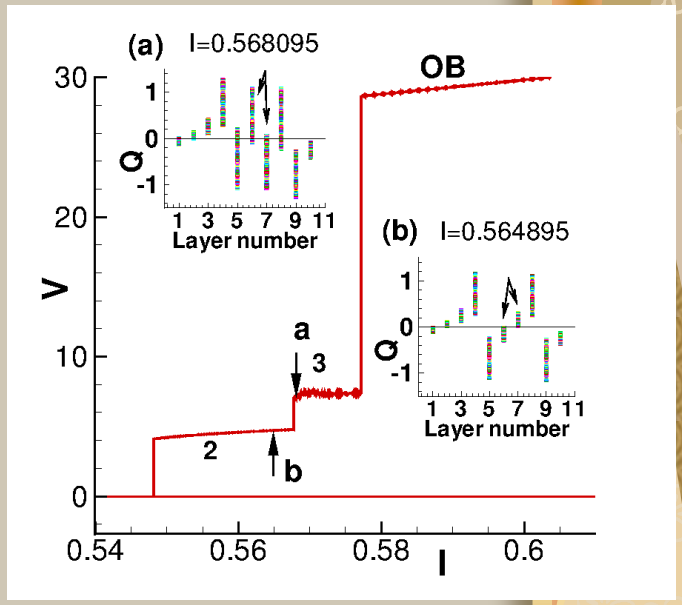
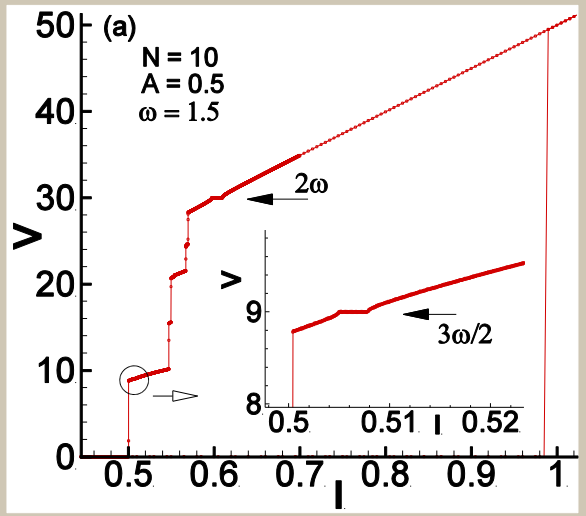
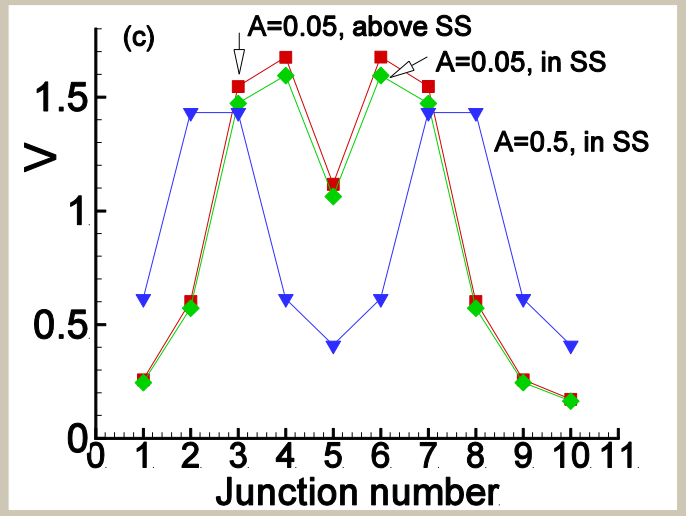
Breathing Charge Density Waves in Intrinsic Josephson Junctions

The effect of external electromagnetic radiation on the system of coupled Josephson junctions in the CDW state is completely different from the case of single JJ. It causes the appearance of the set of the Shapiro steps in the IV-characteristics of JJ of the stack related to the voltage distribution among JJs. However, usual harmonics and subharmonics of radiation frequency are observed in the total IV-characteristics of the stack.







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