Cherenkov Flux-Flow Oscillators

A.M. Baryshev
Space Research Organization and Materials Science Center, Groningen, the Netherlands
A.V. Yulin, V.V. Kurin
Institute for Physics of Microstructures, RAS, Nizhny Novgorod, Russia
V.P. Koshelets, S.V. Shitov, P.N. Dmitriev, L.V. Filippenko
Institute of Radio Engineering and Electronics RAS, Moscow, Russia

Josephson Flux-Flow Oscillators (FFO) have been used as an on chip local oscillator at frequencies up to 650 GHz. An autonomous FFO linewidth of about 1 MHz was measured in the resonant regime at $V_b < 950$ μV for niobium - aluminum oxide - niobium tunnel junctions, while considerably larger values were reported at higher voltages. To overcome this fundamental linewidth broadening we propose an on chip Cherenkov radiation flux-flow oscillator (CRFFO). It consists of a long Josephson junction and a superconducting slow wave transmission line that modifies essentially the junction dispersion relation. Two superconductor insulator-superconductor junction detectors are connected both to the long Josephson junction and the slow wave line to determine the available microwave power. The power is measured at different CRFFO biasing conditions. Both a forward wave and a backward wave oscillation regime are observed. Samples with different slow wave line geometrical parameters are experimentally studied. The theoretical model of CRFFO is described and compared with experimental results. A FFO and a CRFFO with the same junction parameters are compared.

* The work was supported by the Russian SSP's "Superconductivity" and "Physics of microwaves", INTAS (project 97-1712) and ESA TRP contract No. 11653/95/NL/PB/SC/CCN4.
"This publication is based (partly) on the presentations made at the European Research Conference (EURESCO) on "Future Perspectives of Superconducting Josephson Devices: Euroconference on Physics and Application of Multi-Junction Superconducting Josephson Devices, Acquafredda di Maratea, Italy, 1-6 July 2000, organised by the European Science Foundation and supported by the European Commission, Research DG, Human Potential Programme, High-Level Scientific Conferences, Contract HPCFCT-1999-00135. This information is the sole responsibility of the author(s) and does not reflect the ESF or Community's opinion. The ESF and the Community are not responsible for any use that might be made of data appearing in this publication.

Latest references:

1. Baryshev, A.M., Yulin, A.V., Kurin, V.V., Koshelets, V.P., Dmitriev, P.N., Filippenko, L.V., "*Forward and backward waves in Cherenkov flux-flow oscillators*", Supercond. Sci. Technol. **12**, pp. 967-969, 1999.
2. Baryshev, A.M., Yulin, A.V., Kurin, V.V., Koshelets, V.P., Shitov, S.V., Shchukin, A.V., Dmitriev, P.N., Filippenko, L.V., "*Design and fabrication of Cherenkov flux-flow oscillators*", IEEE Trans. on Appl. Supercond., Vol. **9**, pp. 3737-3740, 1999.
3. Baryshev, A.M., Shitov, S.V., Ermakov, A.B., Fillipenko, L.V., Dmitriev, P.N., "*A wide band ring slot antenna integrated receiver*", Proc. 10th Int. Symp. on Space Terahertz Tech., Charlotteville, Virginia, USA, pp.157-167, 1999.
4. Koshelets, V.P., Shitov, S.V., Shchukin, A.V., Filippenko, L.V., Dmitriev, P.N., Vaks, V.L., Mygind, J., Baryshev, A.B., Luinge, W., Golstein, H., "*Flux flow oscillators for sub-mm wave integrated receivers*", IEEE Trans. on Appl. Supercond., Vol. **9**, pp. 4133-4136, 1999.

ABSTRACT

Josephson Flux-Flow Oscillators (FFO) have been used as an on chip local oscillator at frequencies up to 650 GHz. An autonomous FFO linewidth of about 1 MHz was measured in the resonant regime at $V_b < 950\ \mu V$ for niobium - aluminum oxide - niobium tunnel junctions, while considerably larger values were reported at higher voltages. To overcome this fundamental linewidth broadening we propose an on chip Cherenkov radiation flux-flow oscillator (CRFFO). It consists of a long Josephson junction and a superconducting slow wave transmission line that modifies essentially the junction dispersion relation. Two superconductor insulator-superconductor junction detectors are connected both to the long Josephson junction and the slow wave line to determine the available microwave power. The power is measured at different CRFFO biasing conditions. Both a forward wave and a backward wave oscillation regime are observed. Samples with different slow wave line geometrical parameters are experimentally studied. A FFO and a CRFFO with the same junction parameters are compared.

INTRODUCTION

The long Josephson junction (LJJ) is connected to the periodical stripline structure shown in Fig. 1. Radiation appears when vortices move along the junction and scatter on the all strip line ends. Let the vortex scatter on *n*-th node of the system at time $t = t_n$ and the radiation enters the strip line. The same vortex scatters on n+1-th node at a time $t_{n+1} = t+\tau$ where $\tau = d_j / v_v$ is the delay time needed for the vortex to run from *n*-th to *n+1*-th node, d_j is the junction length between nodes, v_v is vortex velocity. The waves emitted due to the vortex scattering on the different nodes should be added with proper phase. In order to get effective wave excitation the following condition must be satisfied $k\ d_l \pm \omega(k)\ \tau = 2\ pi\ l$

where *k* is wave number, $\omega(k)$ is the dispersion of waves in strip line, *l* is any integer. The frequency of the radiation of a single vortex can be found from last equation. In case of a moving vortex chain the radiation from all vortices should be added in phase. To achieve it the condition $k_v = 2\ \pi\ m$ where d_v is the distance between vortices and *m* is an integer must be satisfied. This condition could be achieved in practice by changing the distance between fluxons varying the magnetic field across the LJJ. It is possible to excite a

strong wave by a large number of vortices scattering on the strip line ends using one with small dissipation. The radiation amplitude can be controlled by adjusting the fluxons density.

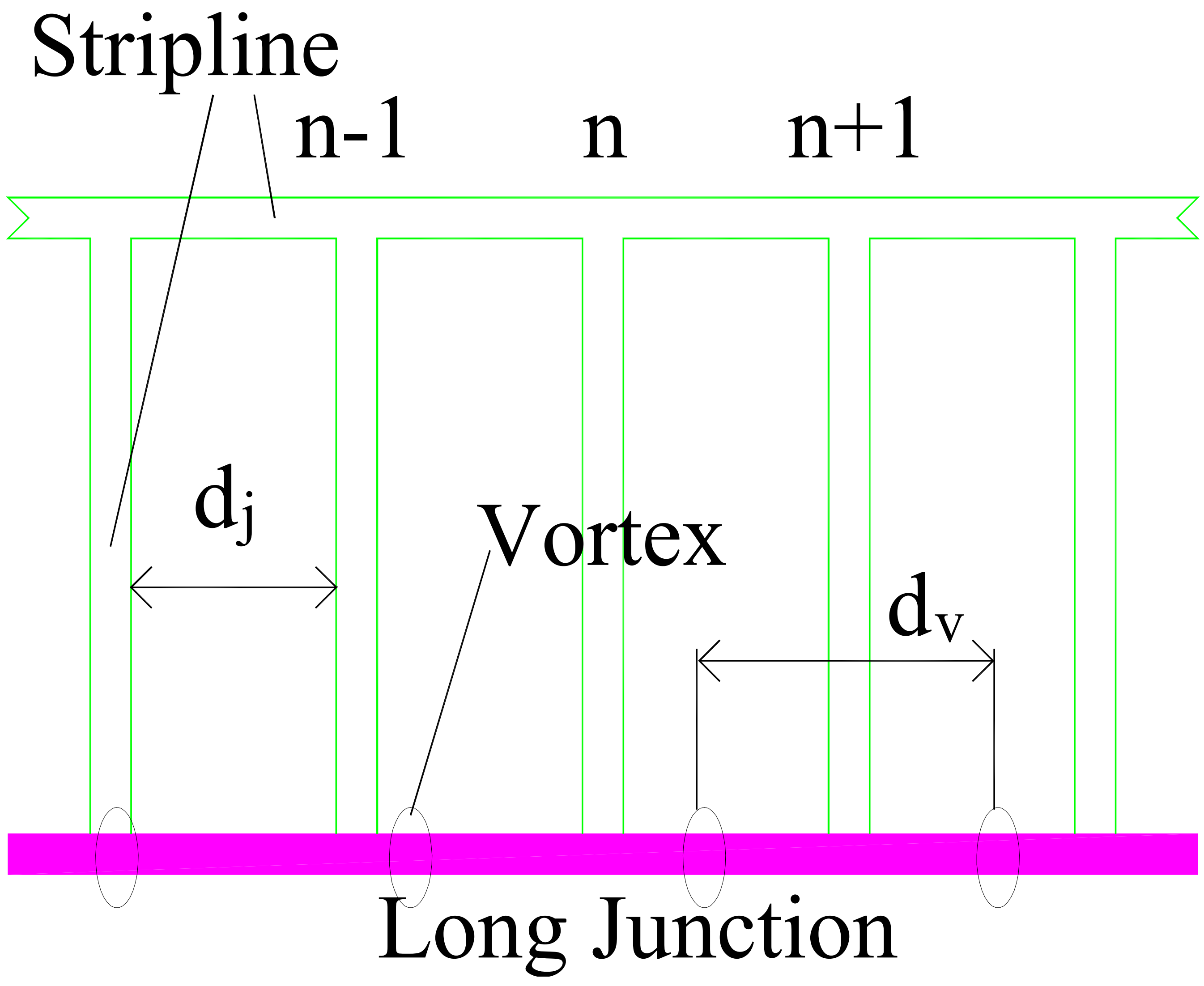


Fig. 1 **Diagram (*see introduction*)**

Backward Wave Operation

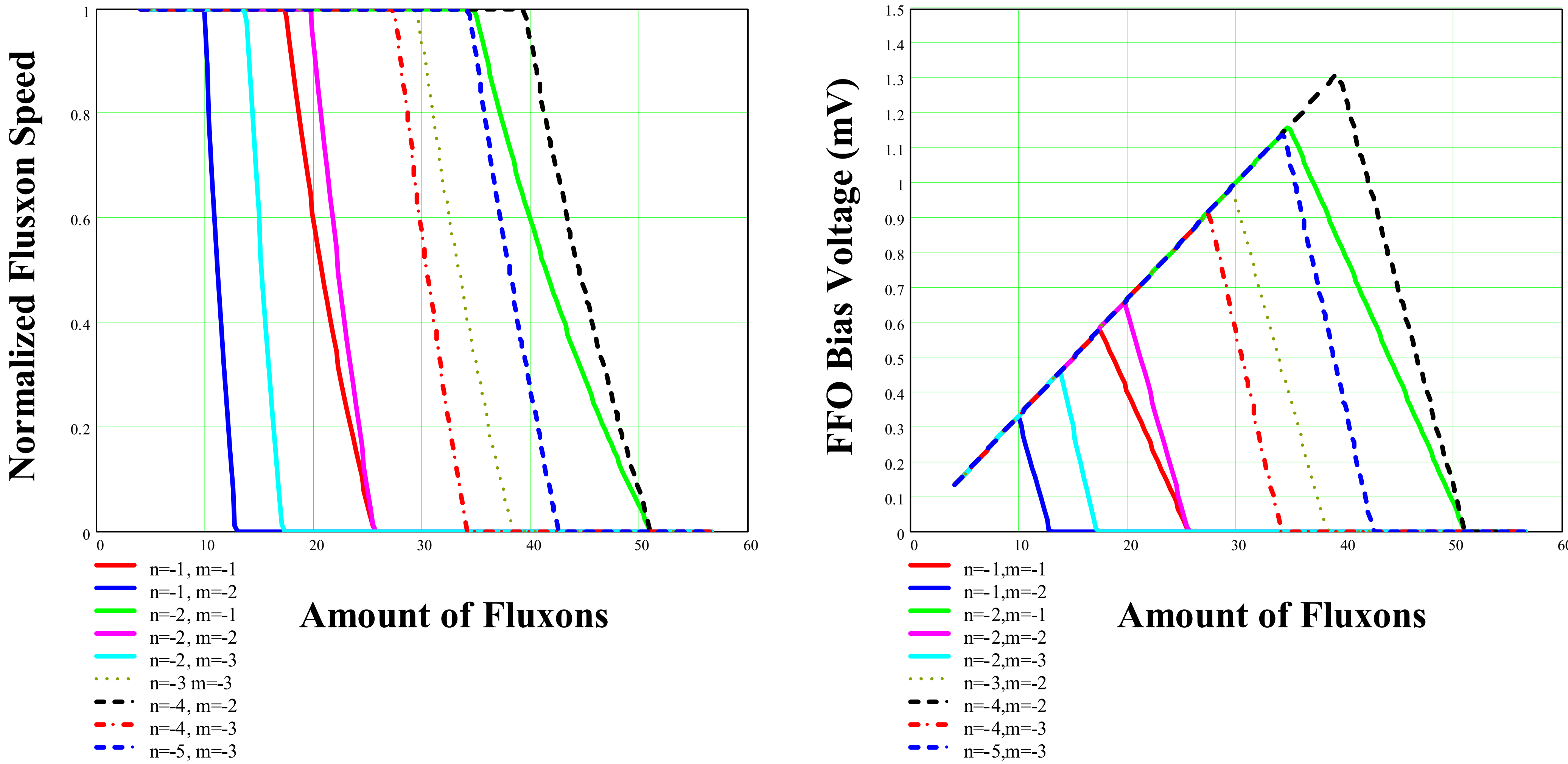
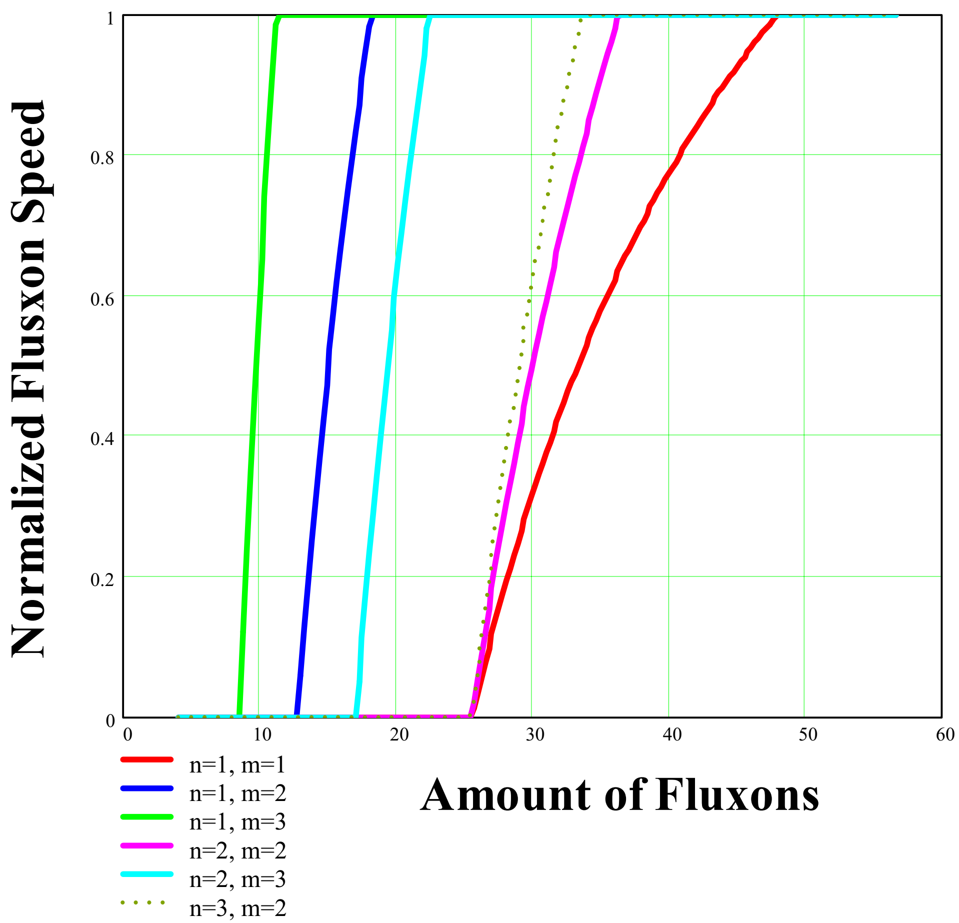


Fig. 2 Calculated resonance condition speed and bias voltage dependence on the amount of Fluxons in the LJJ.

Forward Wave Operation



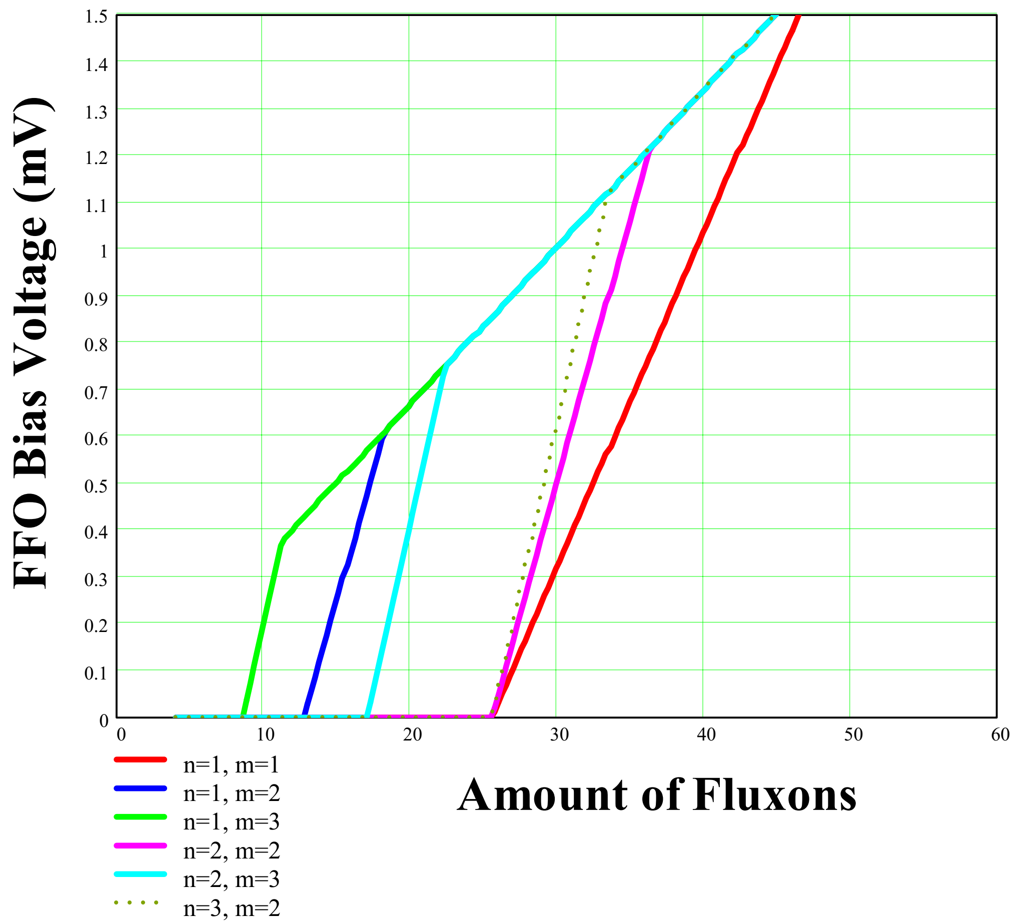


Fig. 3 **Calculated resonance condition speed and bias voltage dependence on the amount of Fluxons in the LJJ.**

LAYOUT DESCRIPTION

The layout of the experimental chip is shown in Fig. 4-6. The CRFFO consists of a 510 μm long and 3.5 μm wide LJJ and the periodical slow wave line. The period of the line along the LJJ is 20 μm. The λ/4 length of the parts of the slow wave system, perpendicular to the LJJ, has been chosen in order to provide a good impedance match between the 20 Ω impedance line and the low impedance (~ 0.5 Ω) of the LJJ at around 450 GHz. The needed delay in the line is realized by additional sections along the LJJ. The external magnetic field has been applied to the LJJ by means of the integrated magnetic field control line in the top electrode of the LJJ. Most of the *dc* control line current follows

the low-inductance part on top of the LJJ. The LJJ critical current density was ~8 kA/cm^2. A normal metal stripline load is connected to the end of the slow wave line to prevent possible reflection.

Two detector chains are attached to the experimental structure as shown in Fig. 4-6. Detector 2 is connected to the slow wave line and Detector 1 is connected directly to the LJJ. Each detector has a band pass filter and *dc*-breaks. A twin SIS junction circuit is used as the wide band microwave

detector. The operating range of this circuit is 300-650 GHz. LLJ of the same size and with the same detector 1 chain has also been made for comparison.

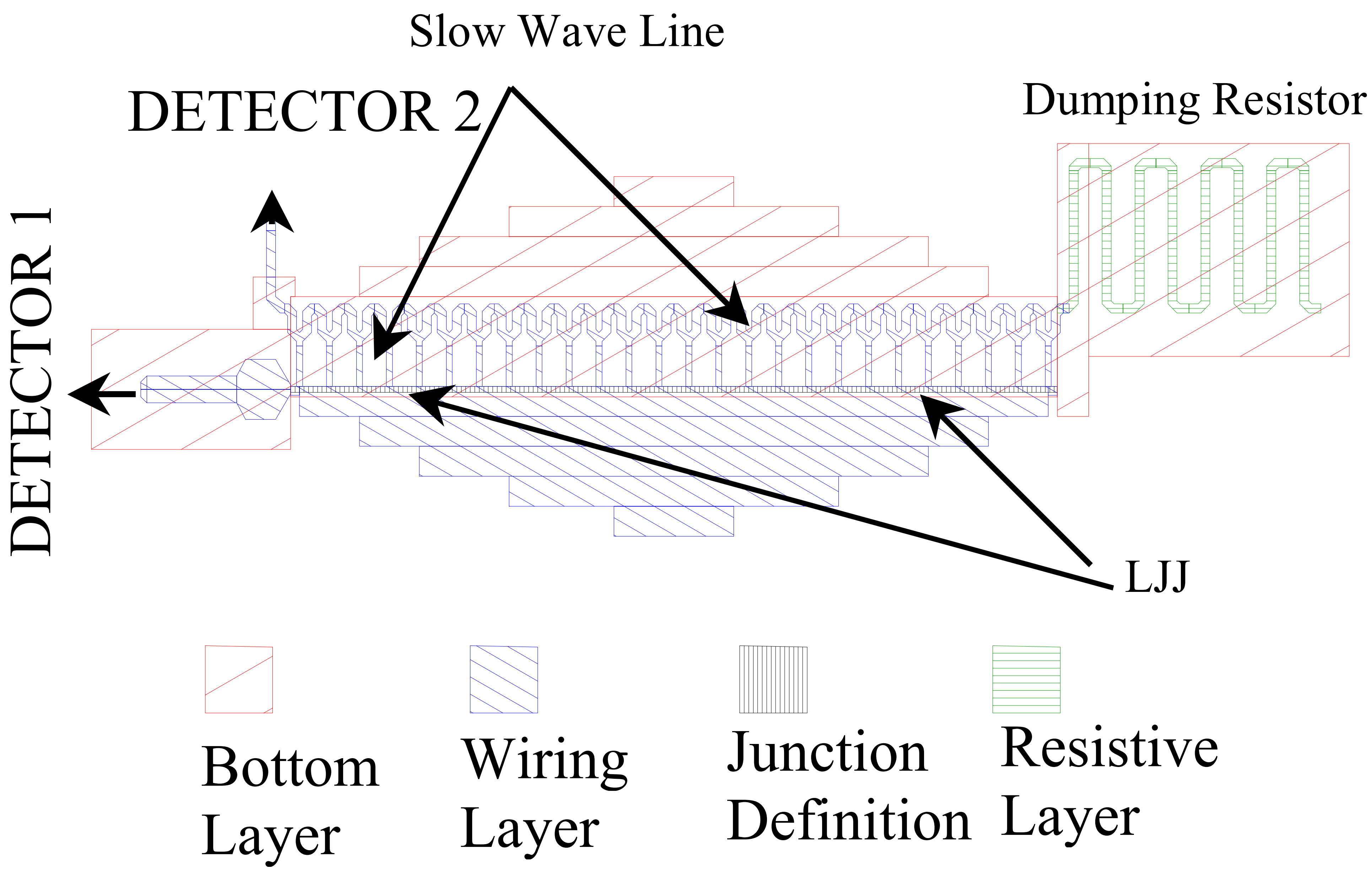


Fig. 4 Layout of CRFFO with layer diagram.

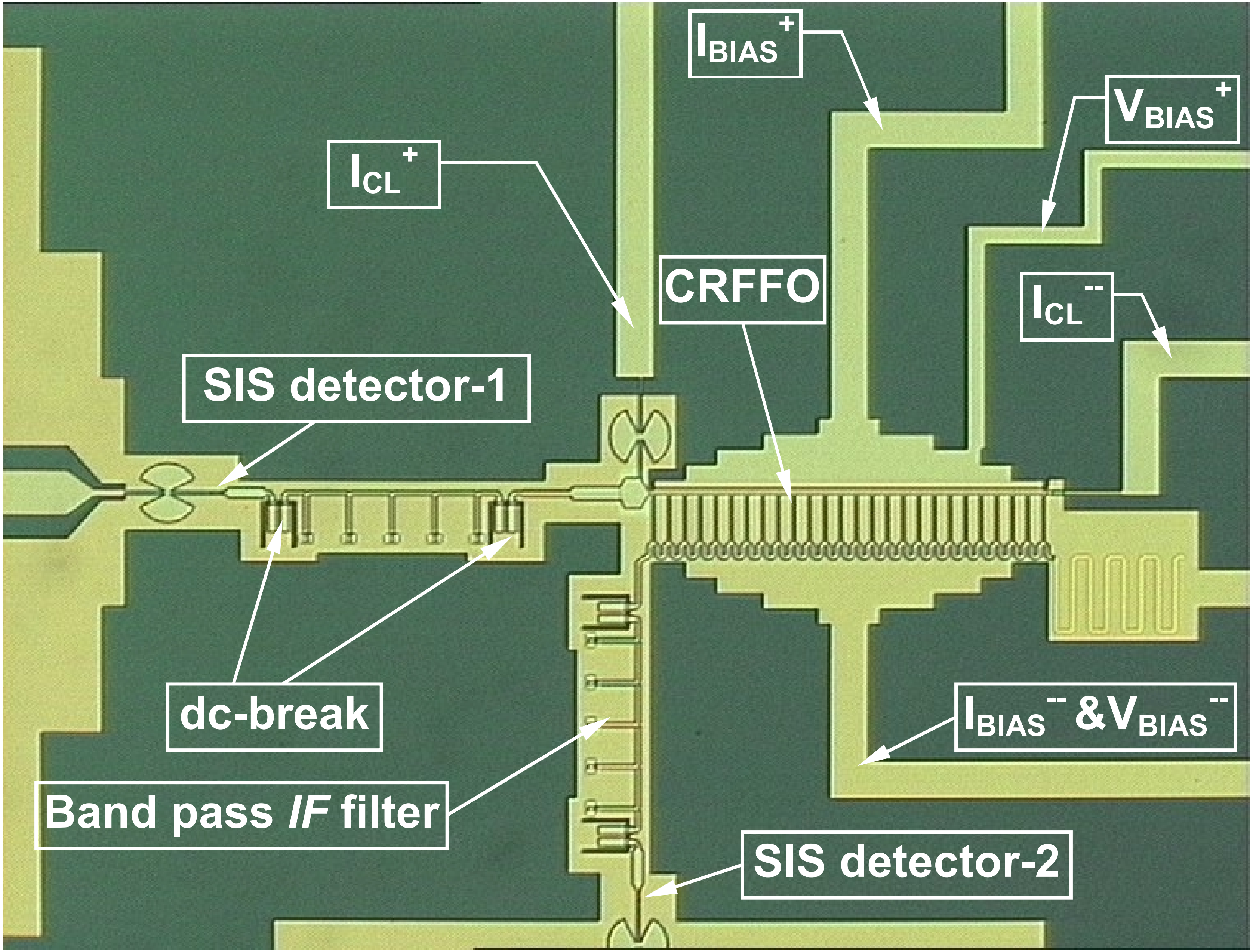


Fig. 5 **Layout of CRFFO. Photograph of the chip.**

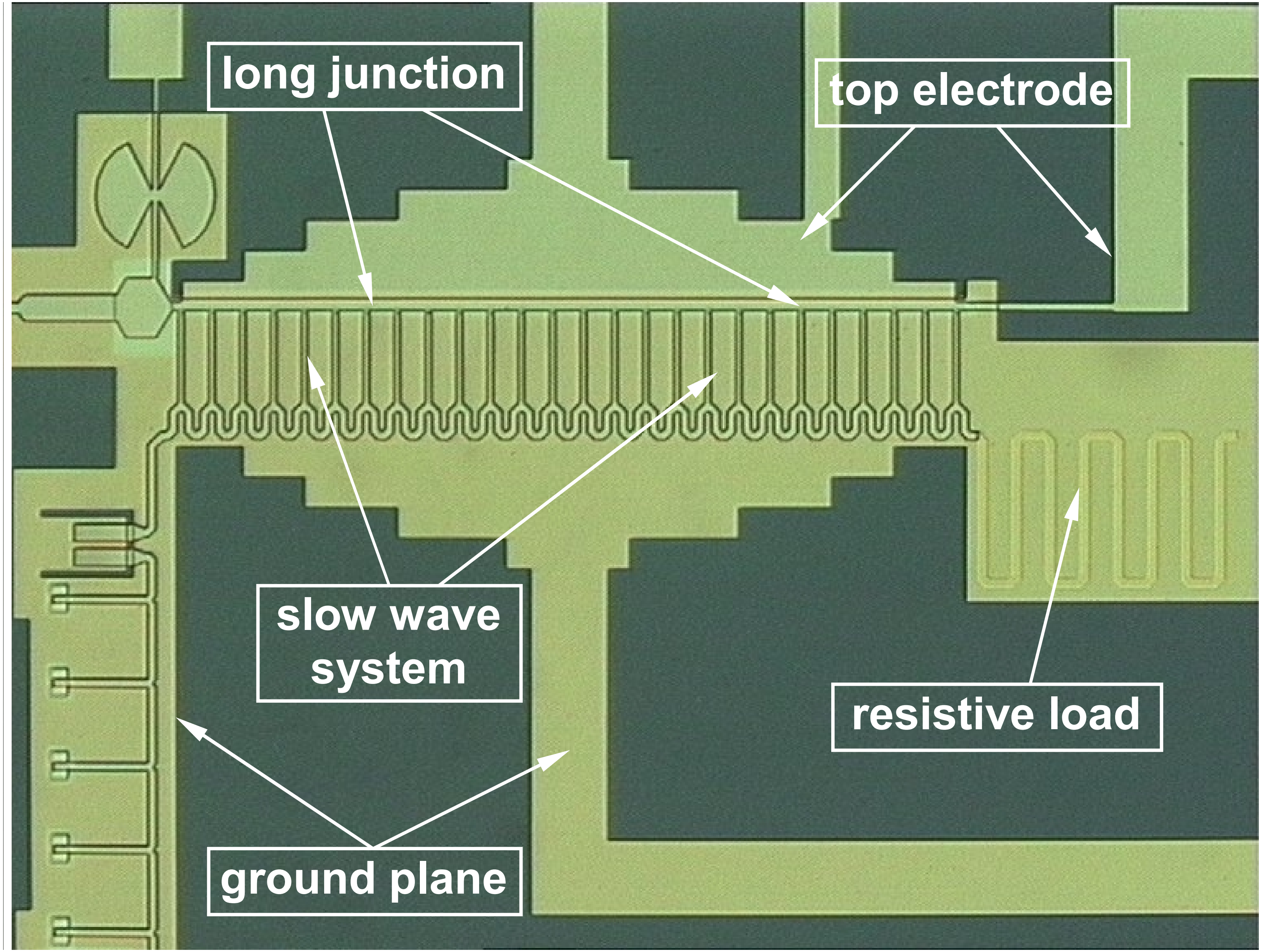


Fig. 6 **Layout of CRFFO. Photograph of the chip.**

EXPERIMENT DESCRIPTION

The experiment has been carried out on a dipstick at 4.2 K physical temperature. The power from both detectors has been measured simultaneously with the I-V characteristics of the LLJ. Each detector junction has a normal resistance of about 10 Ω. The microwave power is estimated by measuring the increase of the SIS junction bias current at a fixed bias voltage in the first photon step. This current is proportional to the absorbed *rf* power in the range of experimental parameters. The measured I-V characteristics of SIS detector are presented in Fig. 7.
The measured I-V characteristics of LLJ without slow wave structure is presented in Fig. 8. Fiske steps are clearly visible at voltages below 0.95 mV.
The measured I-V characteristics of the CRFFO are presented in Fig. 9-14. It shows the set of resonances around 0.8 mV bias voltage at different bias currents and magnetic fields. These resonances correspond to the different modes of operation of the CRFFO and confirms that R_d of the LJJ can be reduced by the slow wave line. It is possible to tune the voltage of the resonances by adjusting the external magnetic field, while the position of Fiske steps in Fig. 8 is fixed.

The CRFFO I-V characteristics with power received by the detector 2 and detector 1 are presented in Fig. 9-14. In Fig. 9-11 fluxons are moving towards detector 2. The peak of output power in this figure represents a forward wave mode of operation.

In Fig. 12-14 fluxons are moving from detector 2 and a backward wave mode of operation is shown. Both modes can be continuously tuned by changing the bias current and the external magnetic field across the structure. The power scale for both figures is the same.

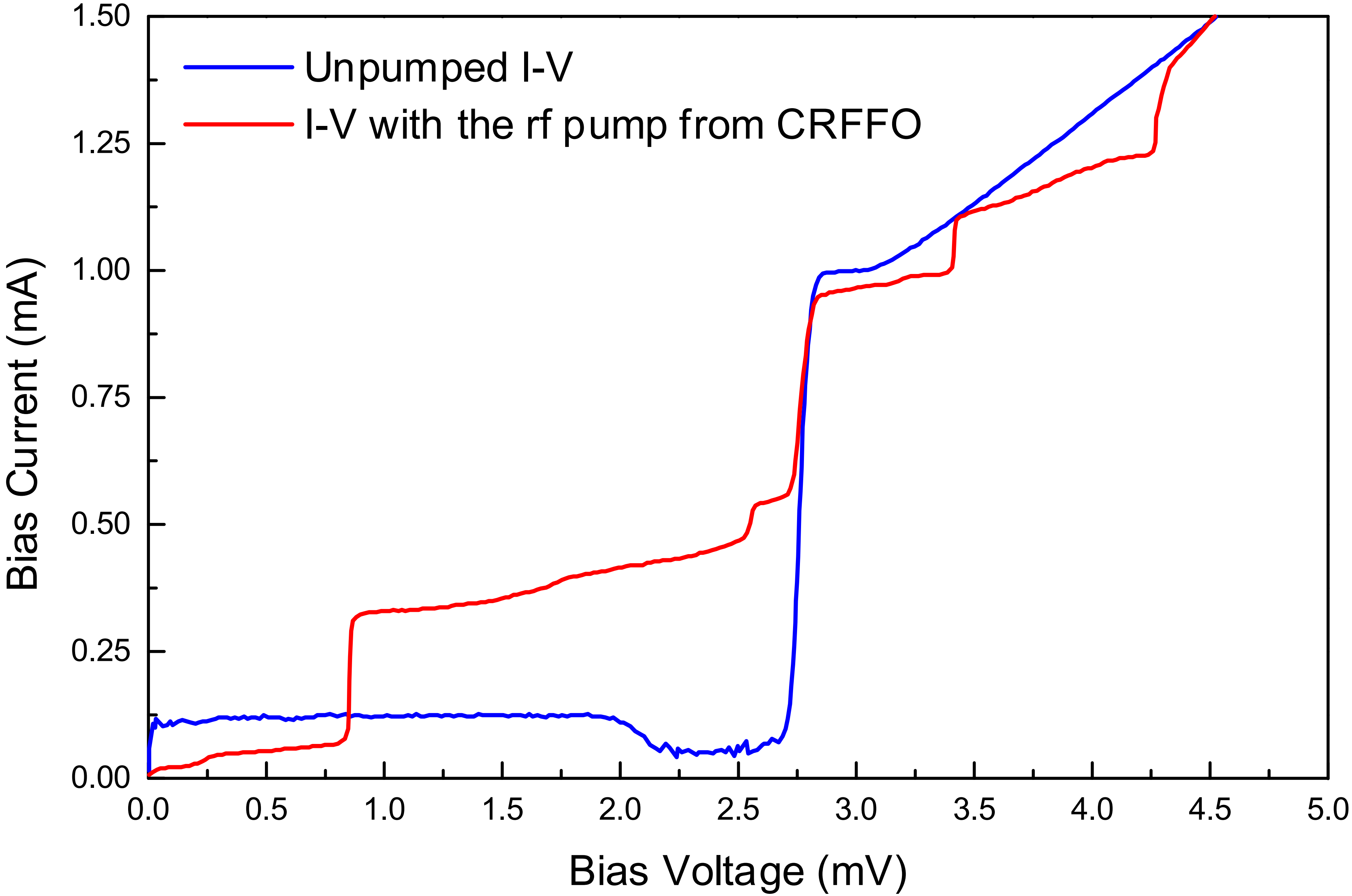


Fig. 7 Measured I-V characteristics of the SIS detector.

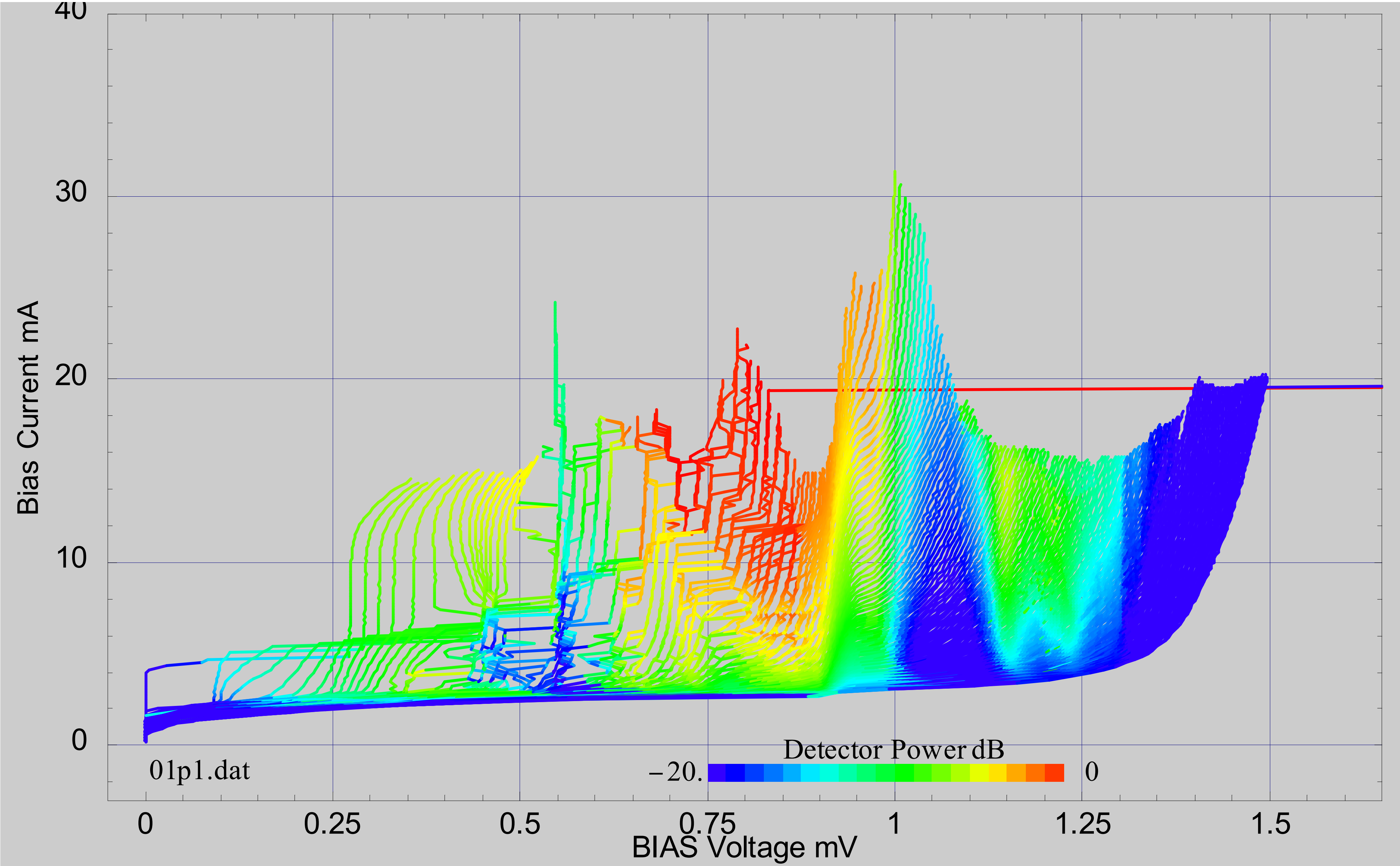


Fig. 8 **Set of I-V characteristics of LLJ without Slow Wave Structure with detector power plotted in color. Magnetic field is parameter.**

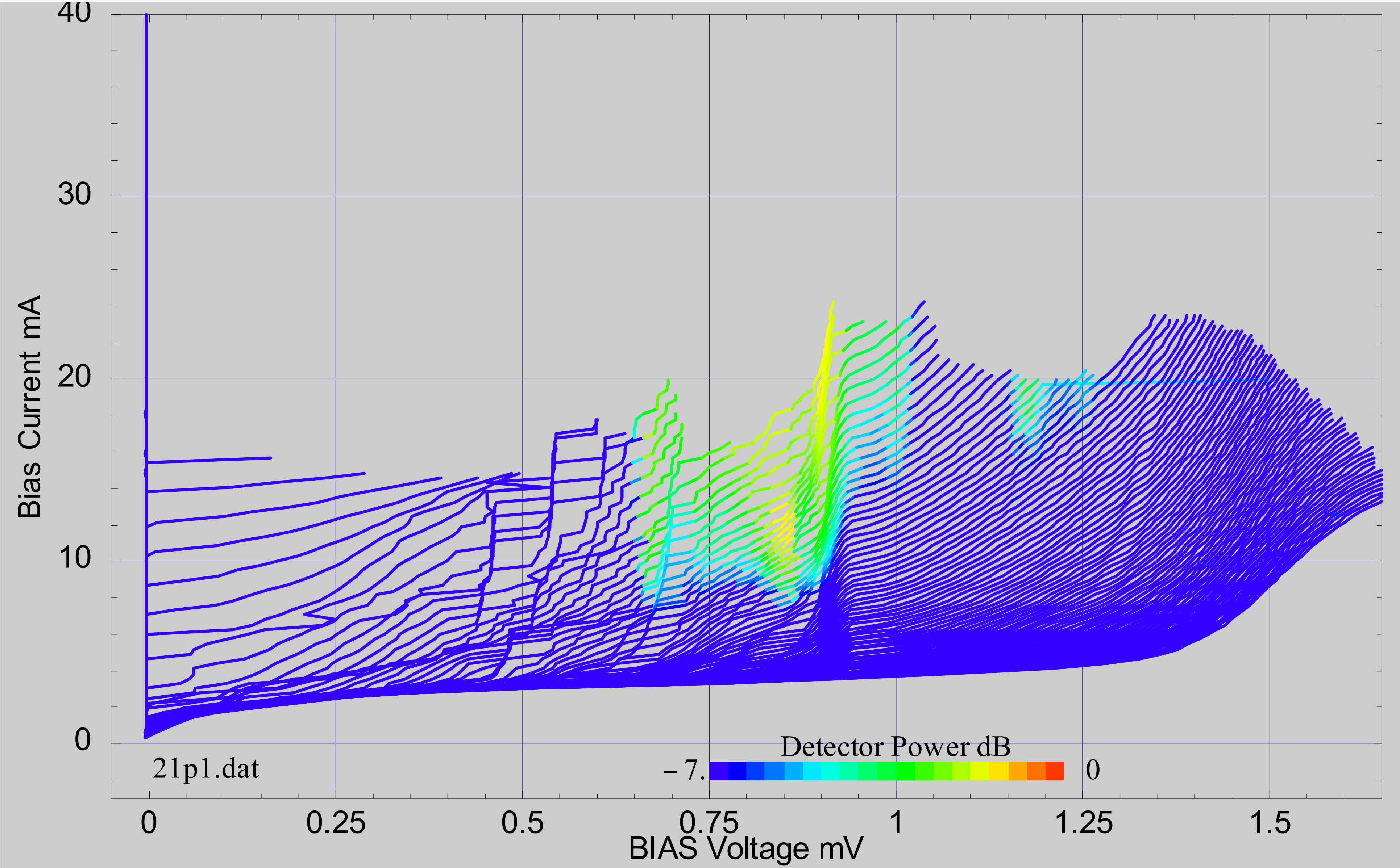


Fig. 9 Set of I-V characteristics of CRFFO with detector 1 power plotted in color. Magnetic field is parameter. Fluxons move towards detector

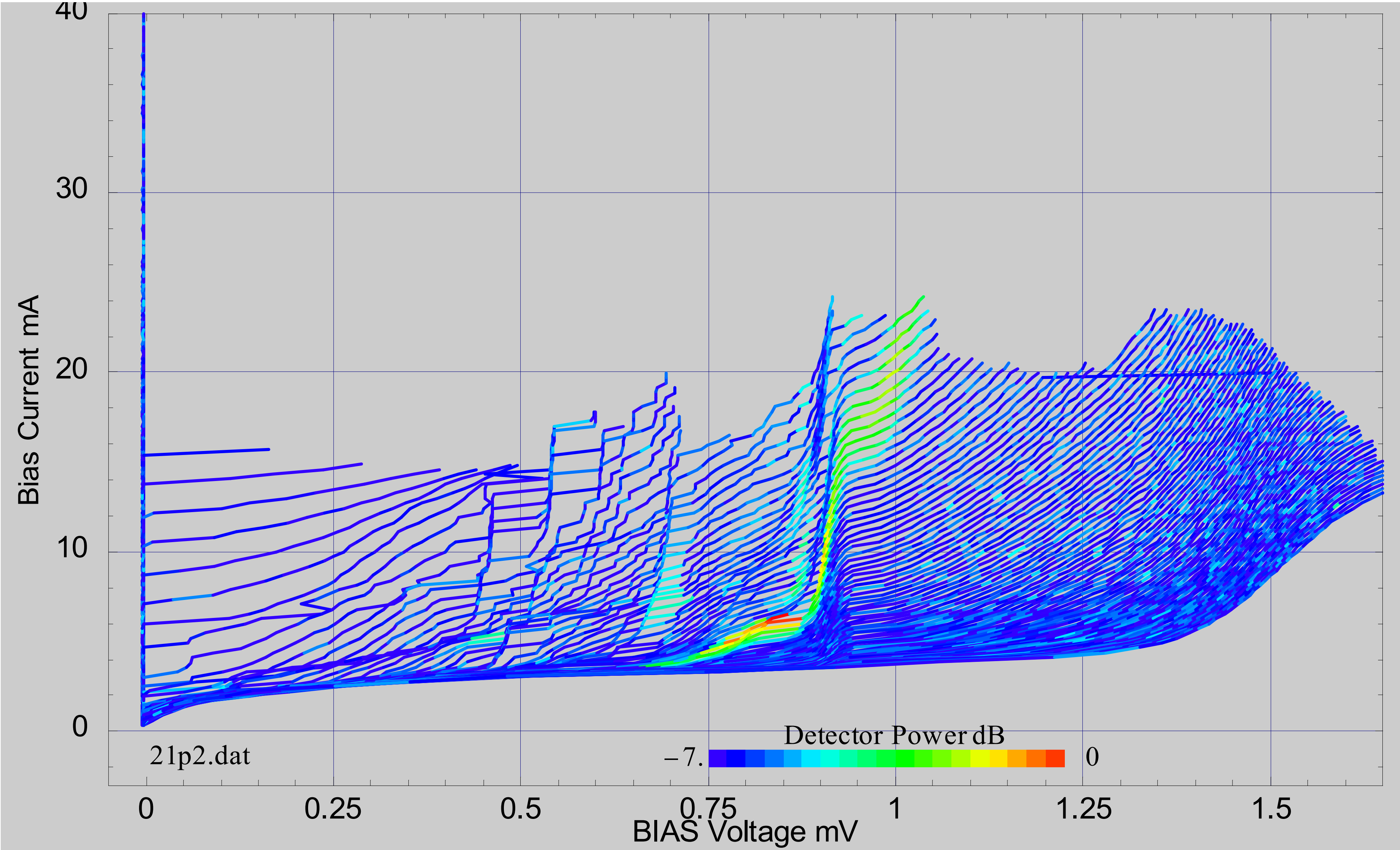


Fig. 10 **Set of I-V characteristics of CRFFO with detector 2 power plotted in color. Magnetic field is parameter. Fluxons move towards detector**

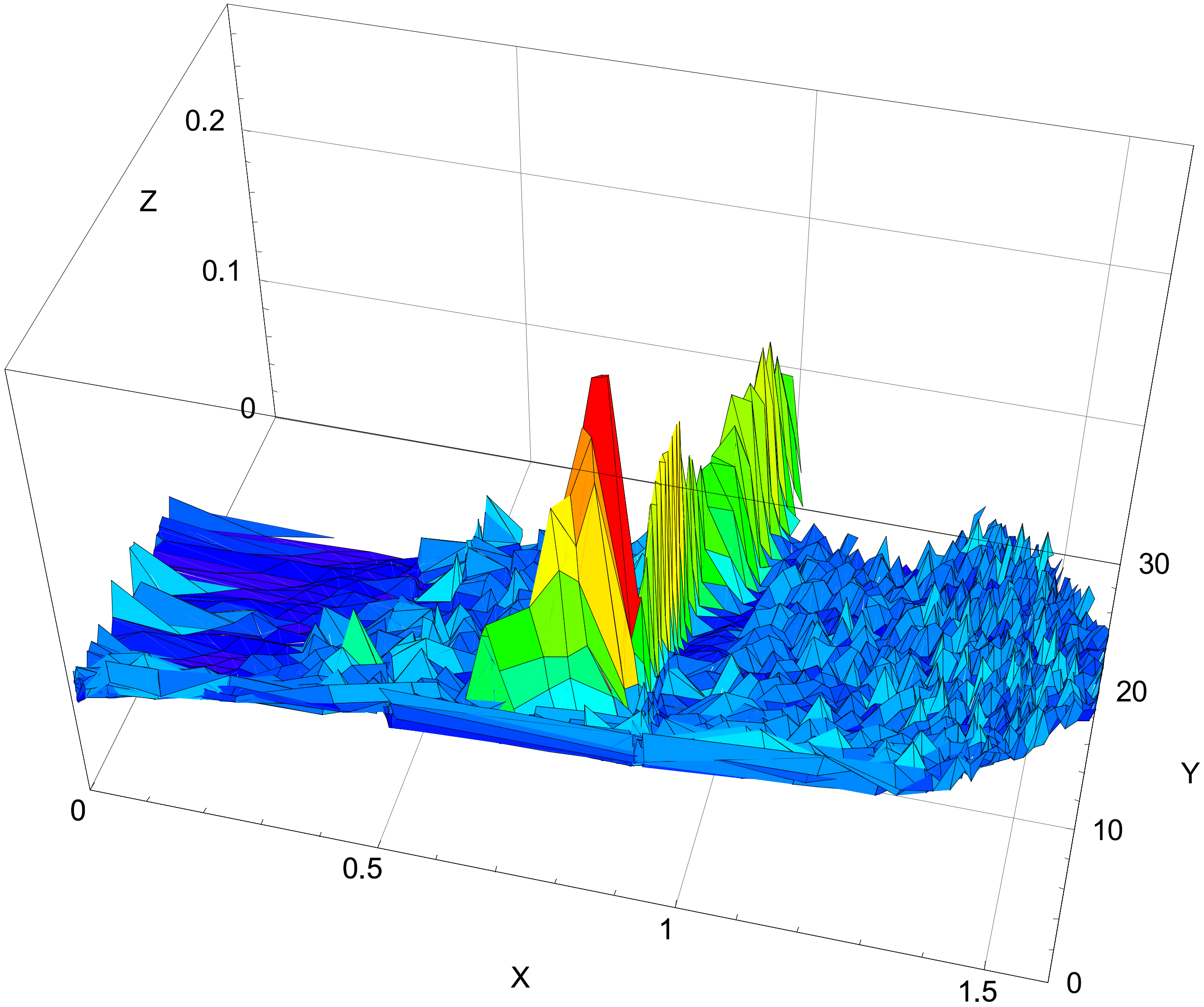


Fig. 11 **Set of I-V characteristics of CRFFO with detector 2 power plotted Z axis. Magnetic field is parameter. Fluxons move towards detector. X-Bias Voltage (mV), Y-Bias Current (mA), Z –power (a.u.)**

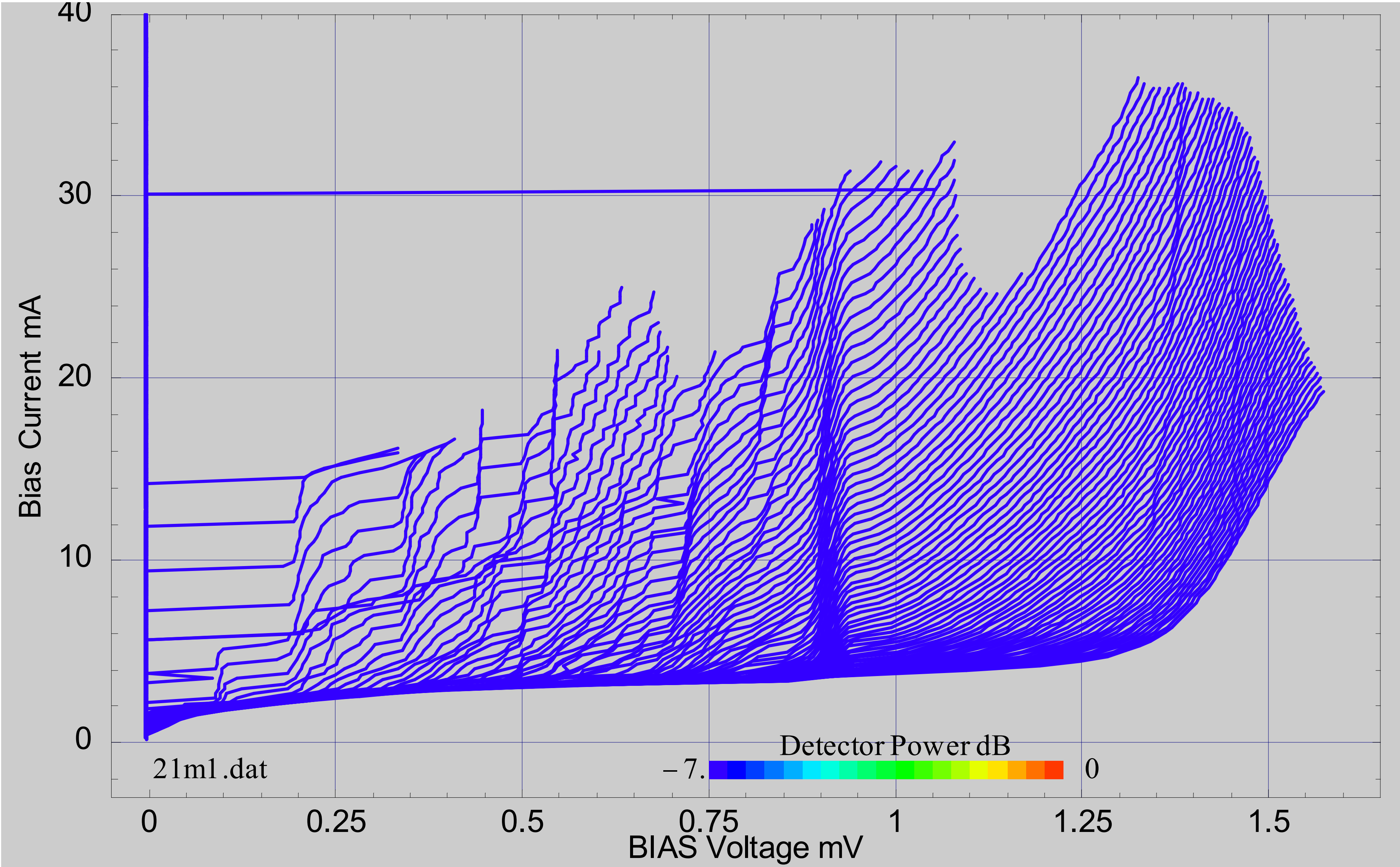


Fig. 12 Set of I-V characteristics of CRFFO with detector 1 power plotted in color. Magnetic field is parameter. Fluxons move from detector

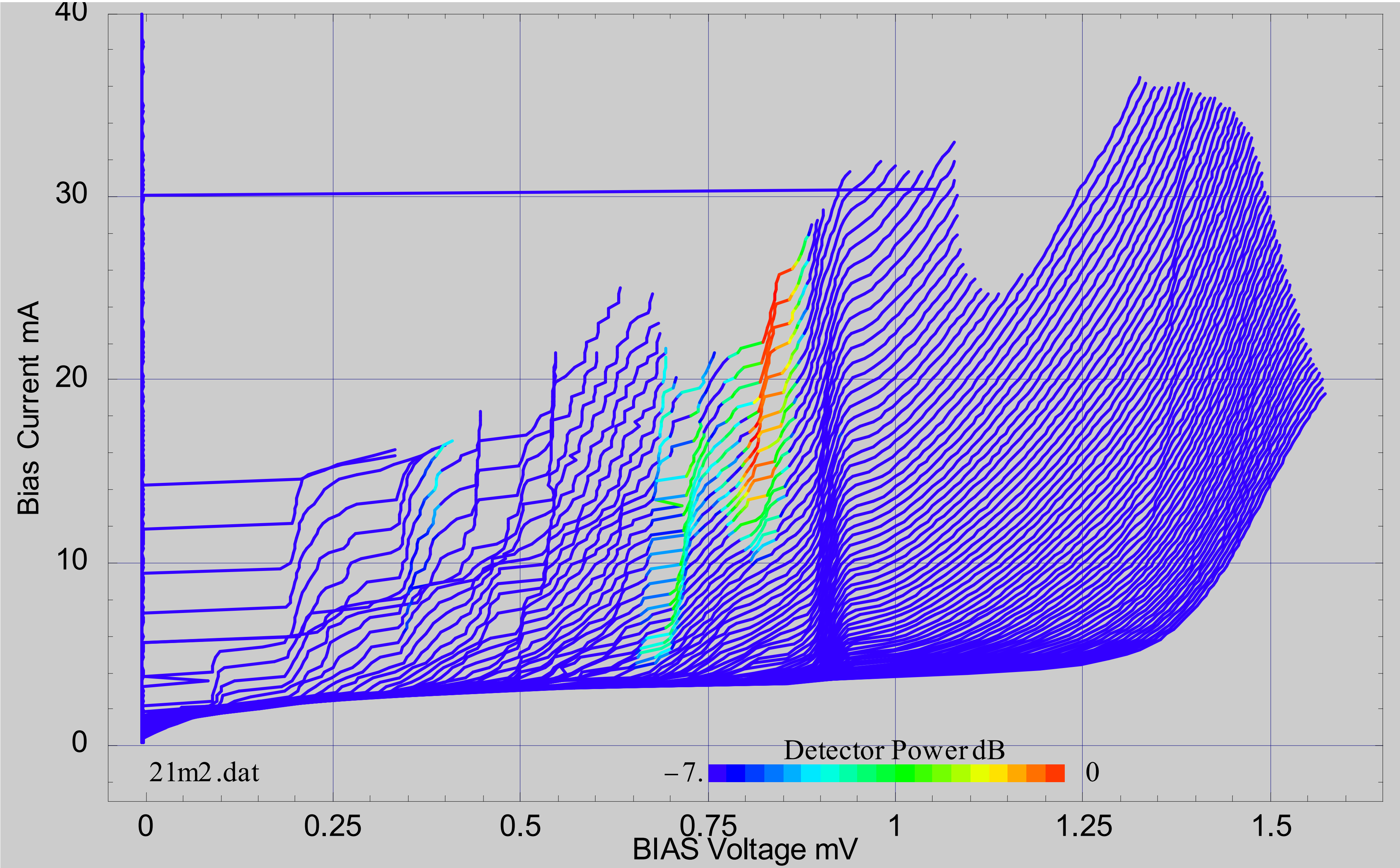


Fig. 13 **Set of I-V characteristics of CRFFO with detector 2 power plotted in color. Magnetic field is parameter. Fluxons move from detector**

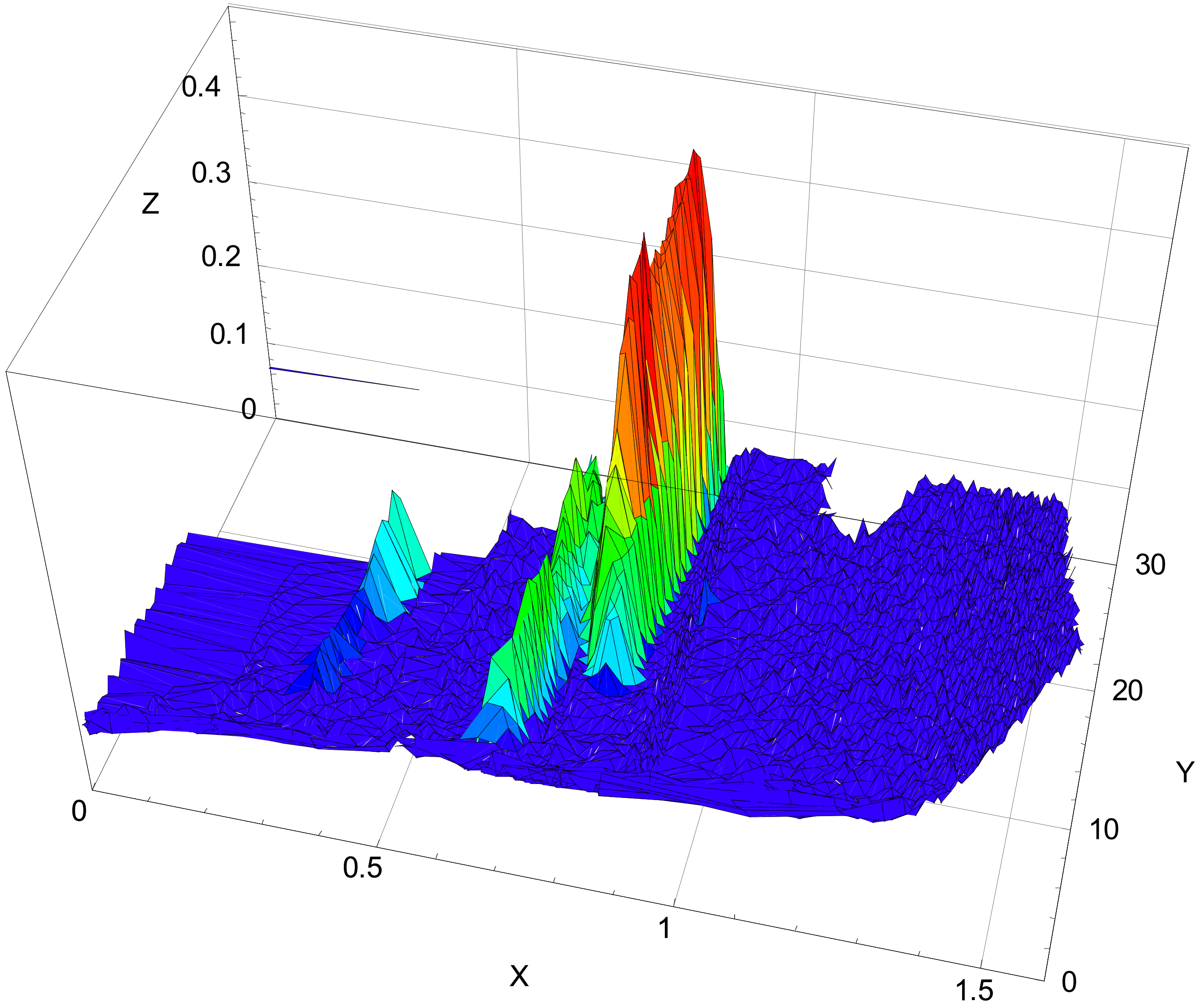


Fig. 14 **Set of I-V characteristics of CRFFO with detector 2 power plotted Z axis. Magnetic field is parameter. Fluxons move from detector. X-Bias Voltage (mV), Y-Bias Current (mA), Z –power (a.u.)**

CONCLUSION

We conclude that the Cherenkov Flux-Flow Oscillator with microstrip loops type slow wave system has been designed fabricated and measured. The measurement shows induced resonances on the CRFFOs I-V curves with tunable frequency. The positions of resonances and it's magnetic field dependence confirm the Cherenkov mode of interaction between vortices and electromagnetic waves in the system. Both forward and backward wave types of resonances have been observed by changing the direction of flux-flow. The microwave power of order 0.8 μW has been measured both in the LJJ and in the slow wave system.

ACKNOWLEGEMENT

Authors would like to thank Willem Luinge, Nick Whyborn, Teun Klapwijk and Sergey Shitov for useful comments and stimulating discussions.