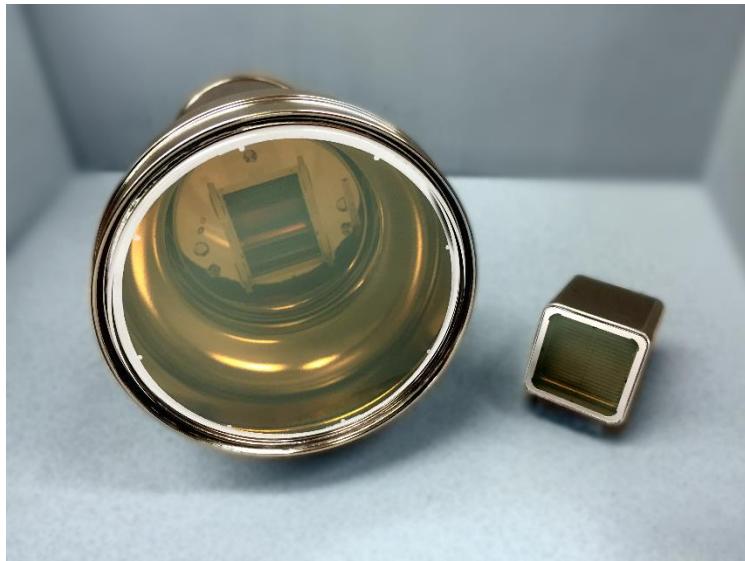


Измерение кросстоков, послеимпульсов и
темновых шумов микропиксельных лавинных
фотодиодов (SiPM) и теоретическое описание их
вклада в энергетическое разрешение детектора.

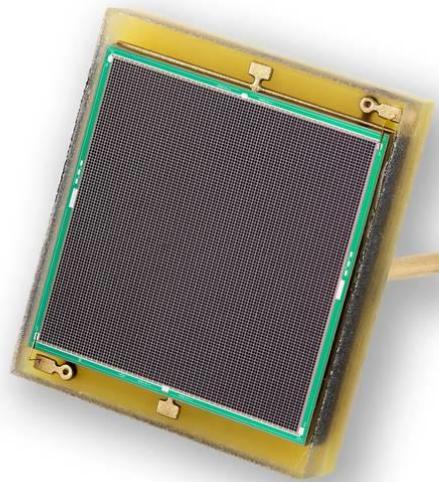
Олейников Владислав Петрович, аспирант 2-го года

Научный руководитель – Поросев Вячеслав Викторович
к.ф.-м.н., с.н.с.

Отличие от ФЭУ



VS

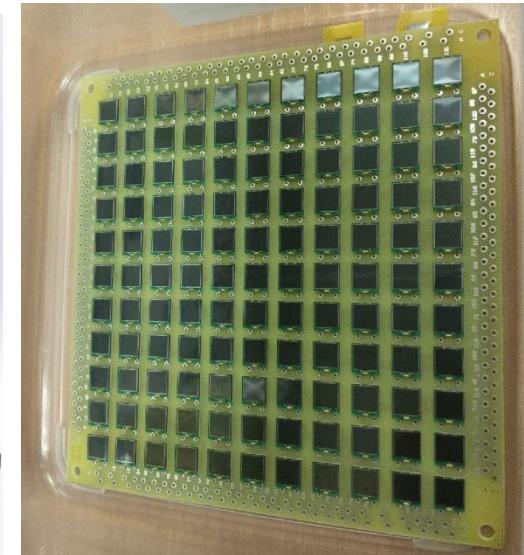
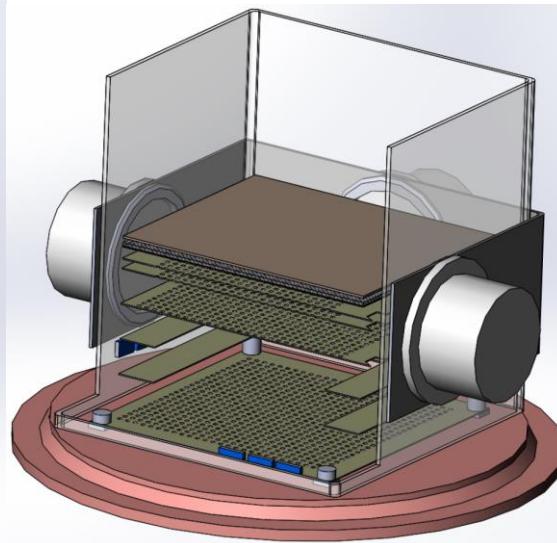
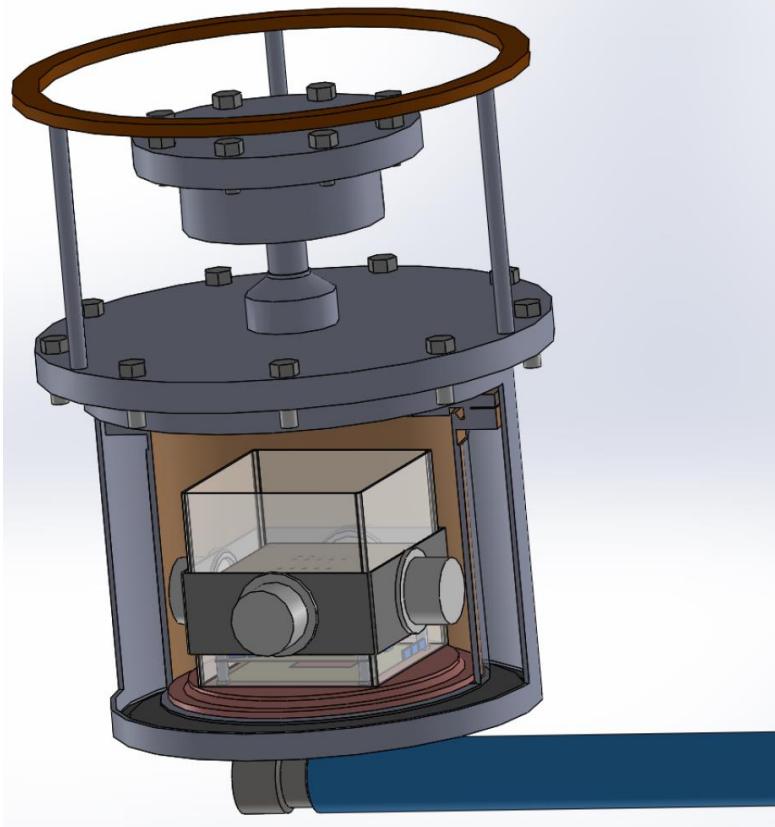


Основные:

- Координатное разрешение
- Счетный режим
- Зависимость от температуры
- Кросstalkи и послеимпульсы

Область применения

Криогенный лавинный детектор (ИЯФ)



Область применения (в будущем)

Малодозная рентгеновская установка (Толмачево)

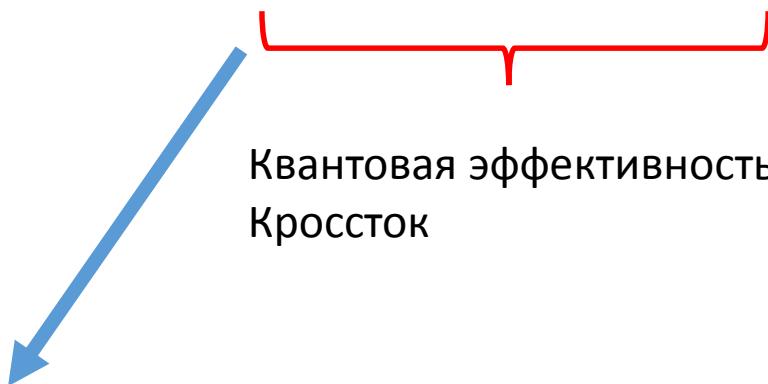


Энергетическое разрешение SiPM

$$\delta E^2 / \Delta^2 = \frac{1}{E[N_{init}]} + \frac{Var[n_{p.e.}]}{(E[n_{p.e.}])^2} \cdot \frac{1}{E[N_{init}]} + \frac{Var[G_{tot}]}{(E[G_{tot}])^2} \cdot \frac{1}{E[N_{init}] \cdot E[n_{p.e.}]}$$

Энергетическое разрешение SiPM

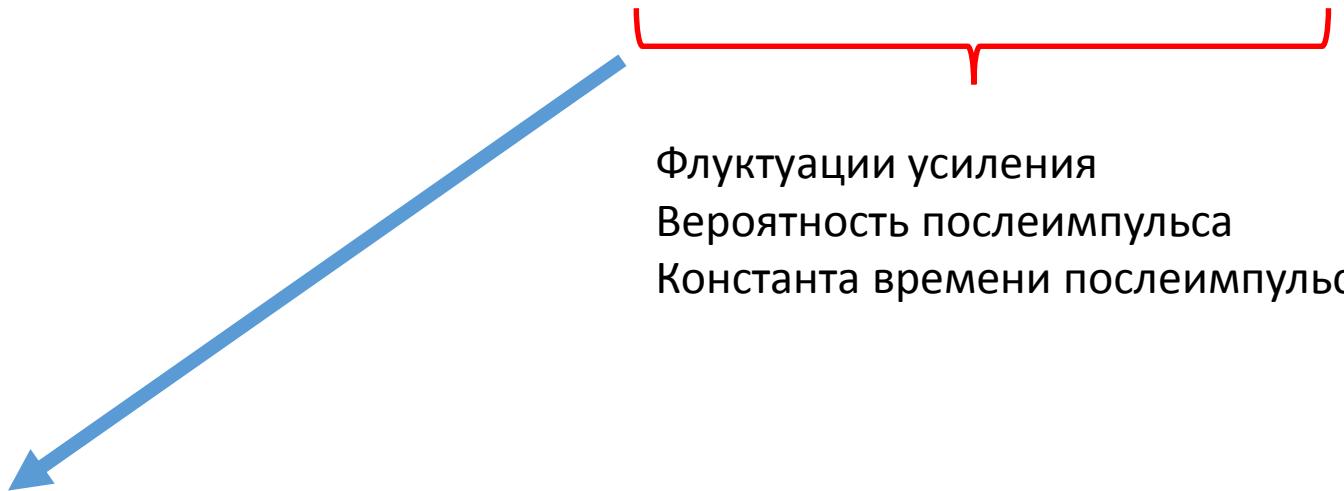
$$\delta E^2 / \Delta^2 = \frac{1}{E[N_{init}]} + \frac{Var[n_{p.e.}]}{(E[n_{p.e.}])^2} \cdot \frac{1}{E[N_{init}]} + \frac{Var[G_{tot}]}{(E[G_{tot}])^2} \cdot \frac{1}{E[N_{init}] \cdot E[n_{p.e.}]}$$



суммарное число сработавших ячеек	плотность вероятности $n_{p.e.}$
1	$\varepsilon \cdot q^4$
2	$\varepsilon \cdot 4p \cdot q^6$
3	$\varepsilon \cdot 18p^2 \cdot q^8$
4	$\varepsilon \cdot 4p^3 \cdot q^8[1 + 3q + 18q^2]$
5	$\varepsilon \cdot 5p^4 \cdot q^{10}[8 + 24q + 55q^2]$
$N > 5$	$\simeq \varepsilon \cdot P(5) \left[1 - \frac{P(5)}{1 - \sum_{k=1}^4 P(k)} \right]^{N-5}$

Энергетическое разрешение SiPM

$$\delta E^2 / \Delta^2 = \frac{1}{E[N_{init}]} + \frac{Var[n_{p.e.}]}{(E[n_{p.e.}])^2} \cdot \frac{1}{E[N_{init}]} + \frac{Var[G_{tot}]}{(E[G_{tot}])^2} \cdot \frac{1}{E[N_{init}] \cdot E[n_{p.e.}]}$$



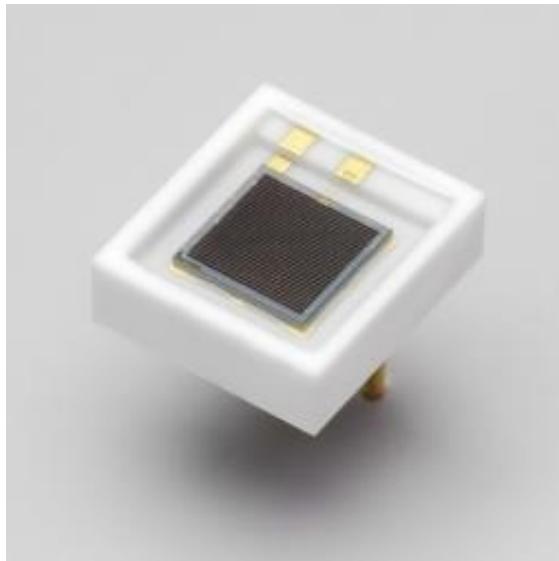
$$\frac{Var[G_{tot}]}{(E[G_{tot}])^2} = \frac{Var[\xi]}{(E[\xi])^2} = \frac{E[\xi^2] - (E[\xi])^2}{(E[\xi])^2}$$

$$E[\xi] = (1 - p_s - p_f) + \frac{p_s}{1 + \alpha_s} + \frac{p_f}{1 + \alpha_f}$$

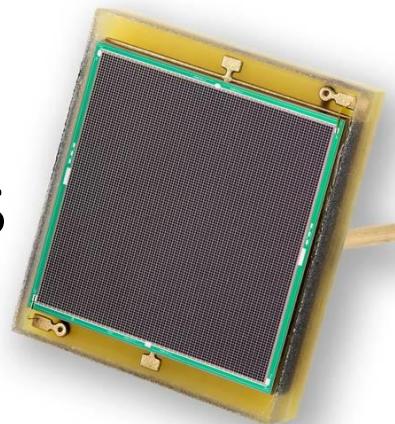
$$E[\xi^2] = (1 - p_s - p_f) + p_s \cdot \alpha_s \cdot B(3, \alpha_s) + p_f \cdot \alpha_f \cdot B(3, \alpha_f)$$

$$\alpha_s = \tau_{rec}/\tau_s, \alpha_f = \tau_{rec}/\tau_f$$

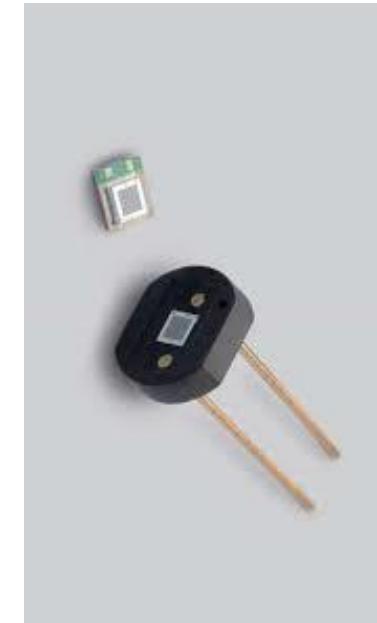
Сравнение SiPM



VS



VS

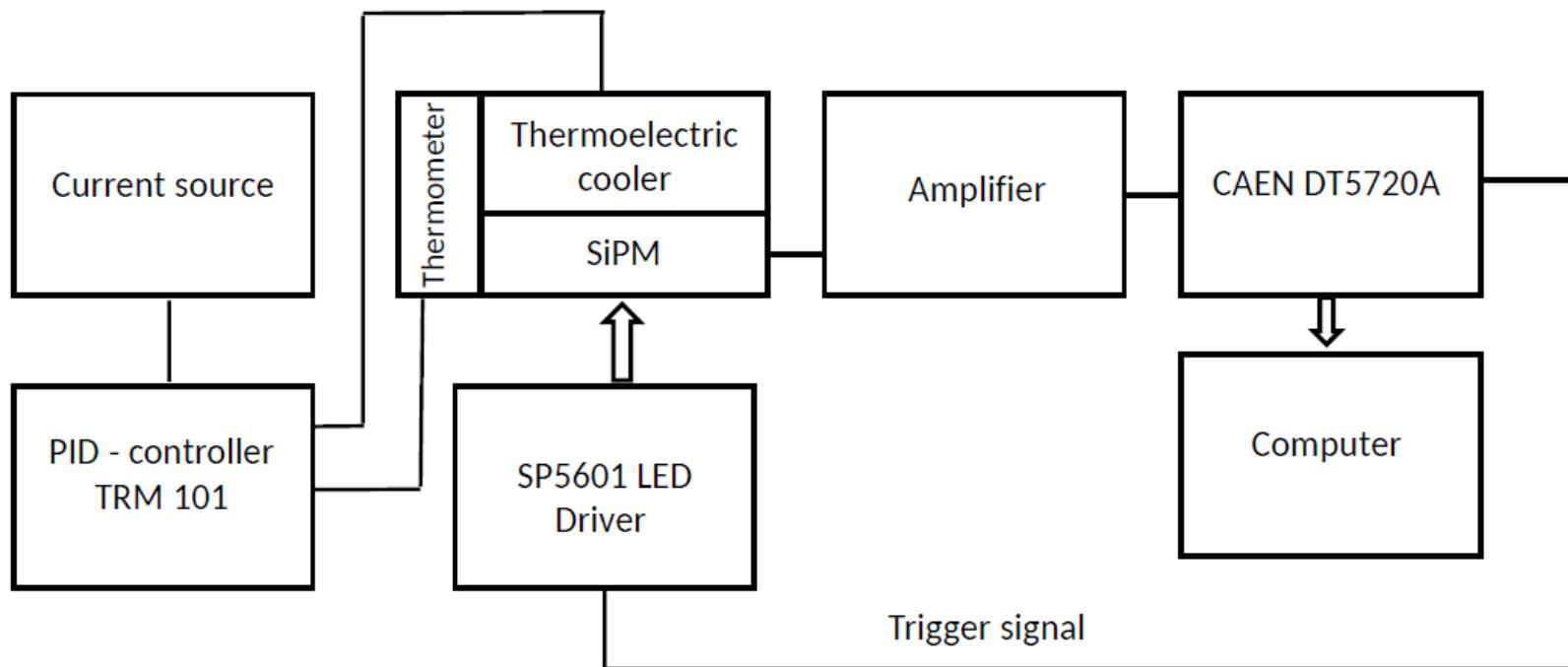


Hamamatsu S13360-3050CS

KETEK PM1125NS-SB0

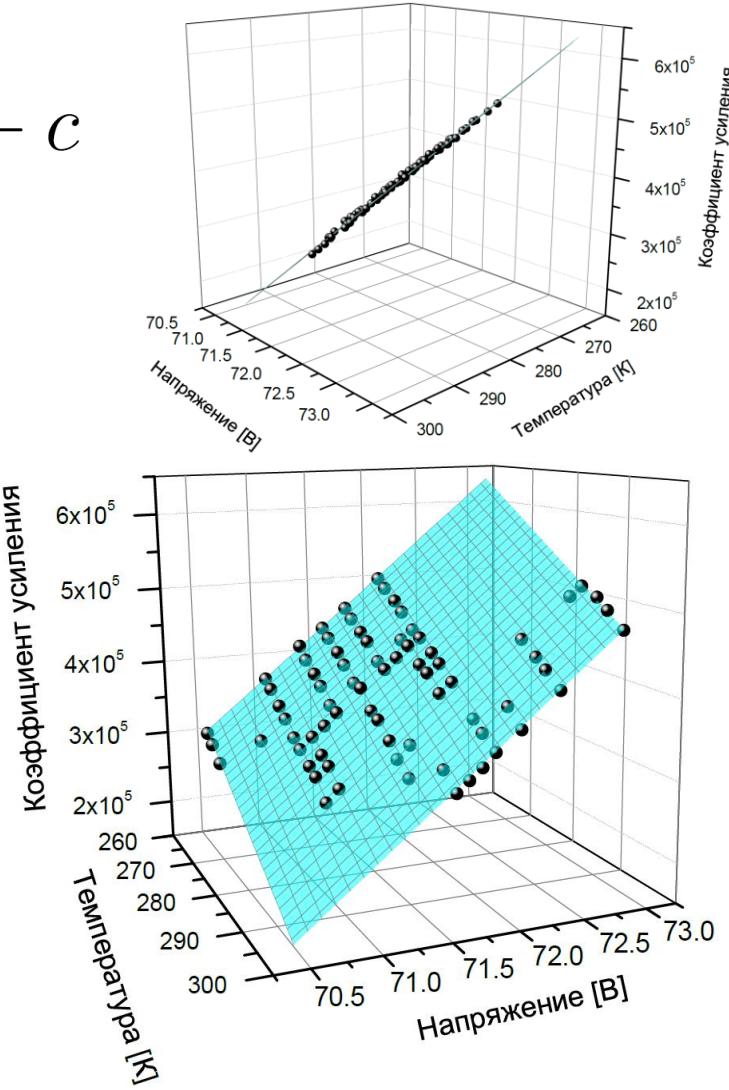
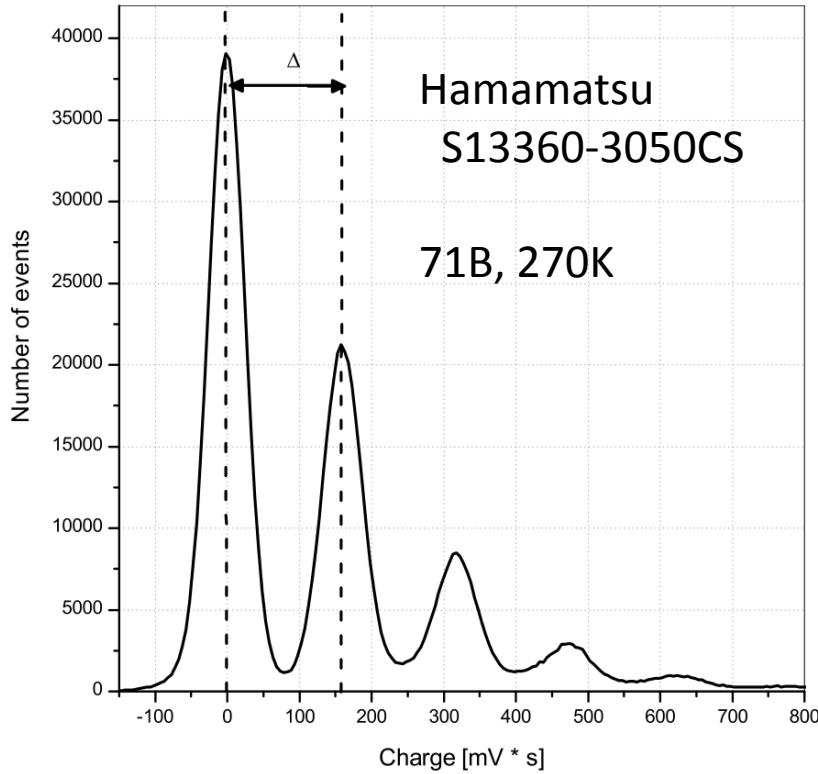
Hamamatsu S10362-11-100C

Схема установки



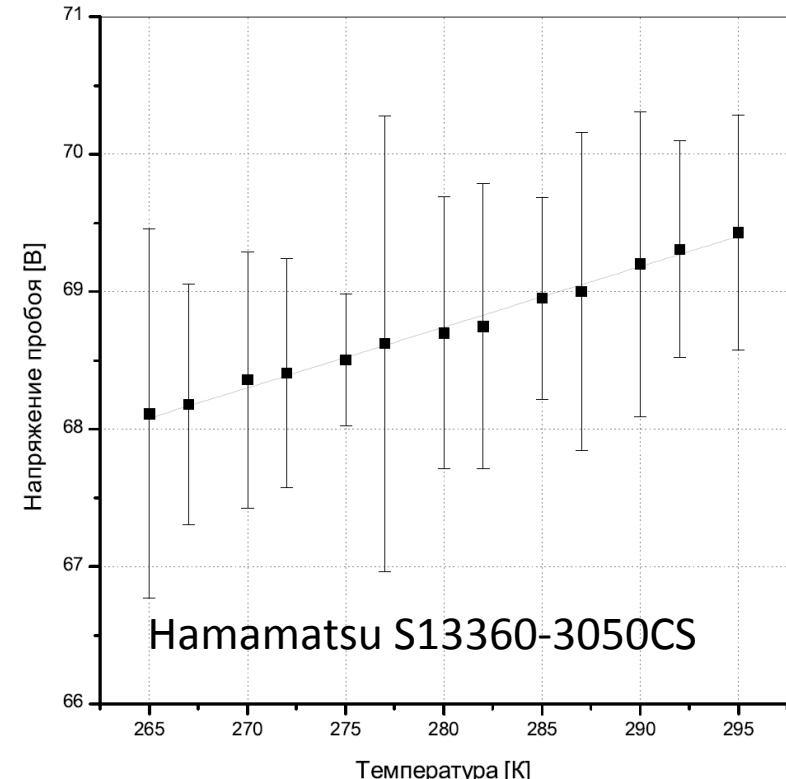
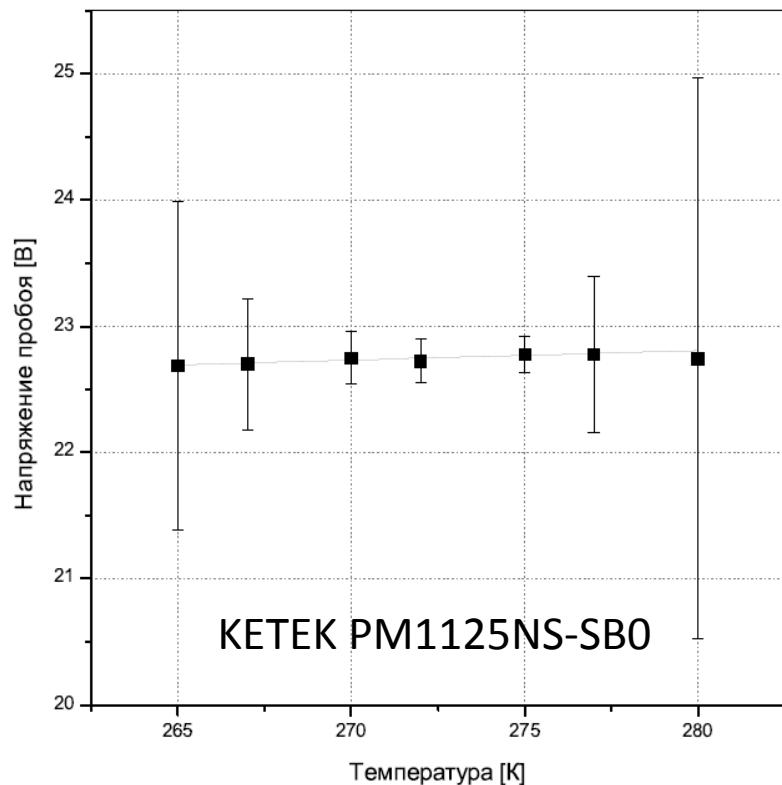
Коэффициент усиления

$$G(V, T) = a \cdot V + b \cdot T + c$$



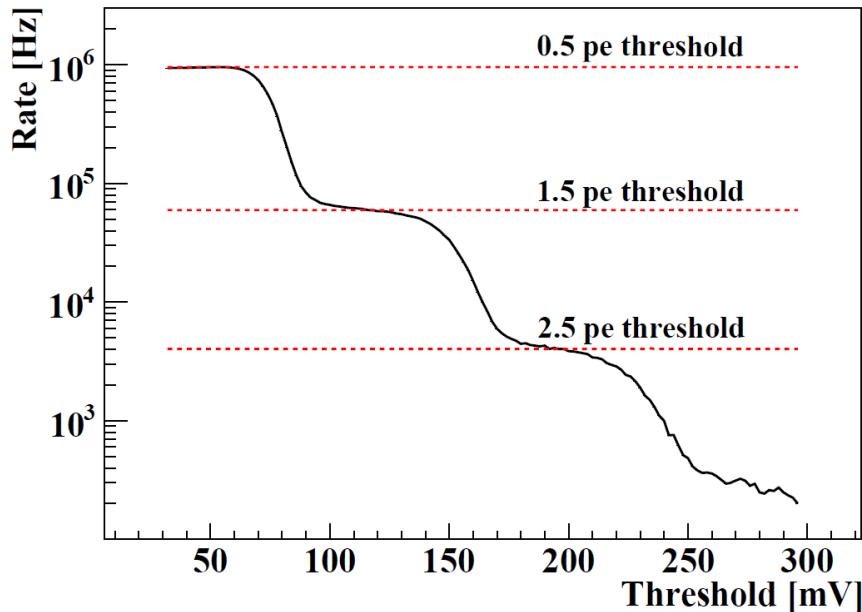
Напряжение пробоя

$$V_{BD}(T) = \frac{-(b \cdot T + c)}{a} = \frac{dV}{dT} \cdot T + const$$

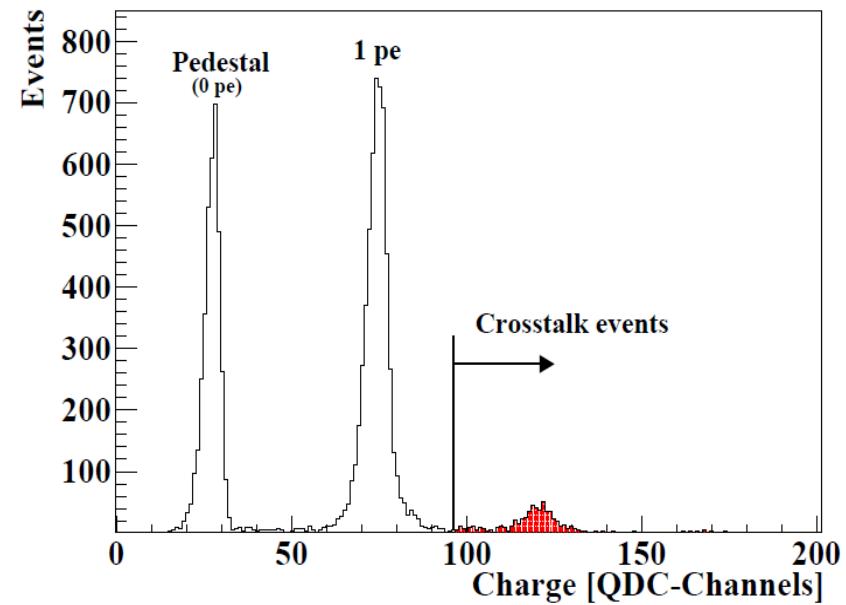


Проблема измерения кросstalkа

Метод лестницы

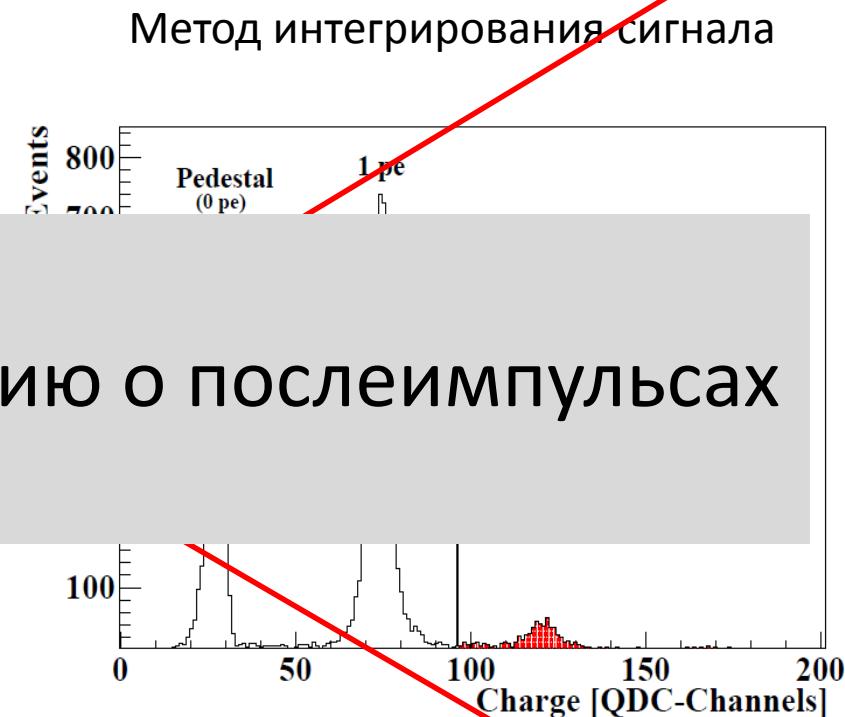
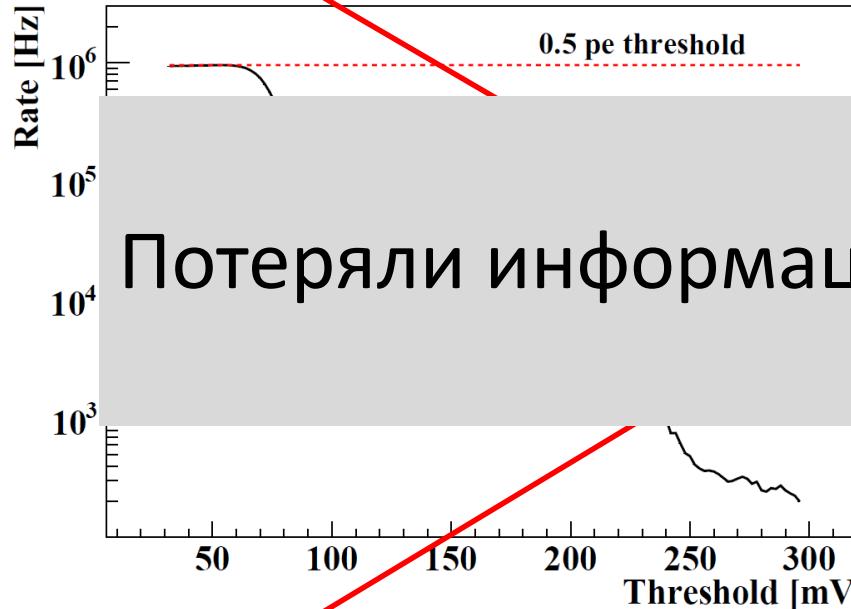


Метод интегрирования сигнала



$$P_{X-talk} = \nu_{1.5phe}/\nu_{0.5phe}$$

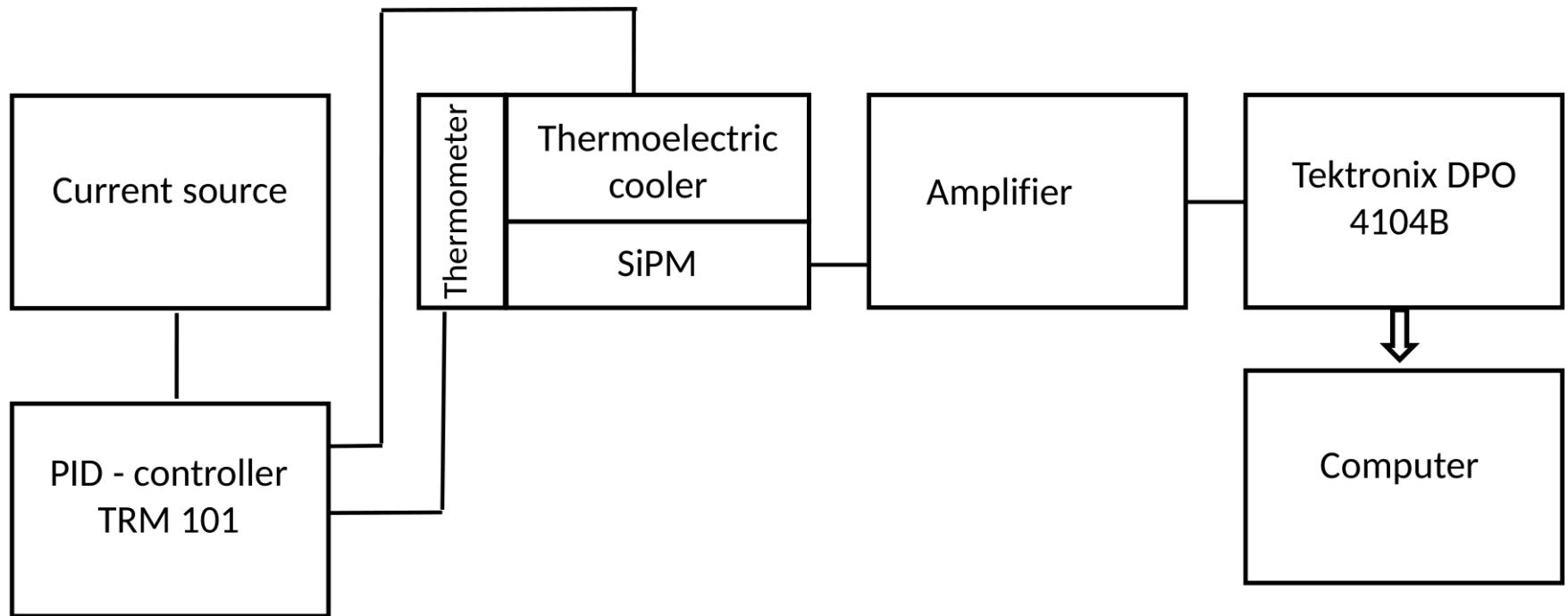
Проблема измерения кросстока



Потеряли информацию о послеимпульсах

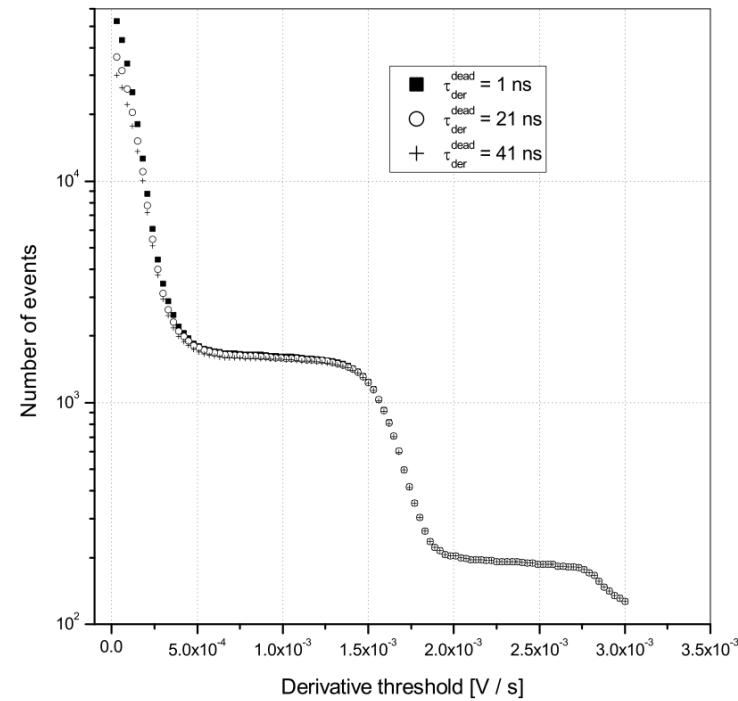
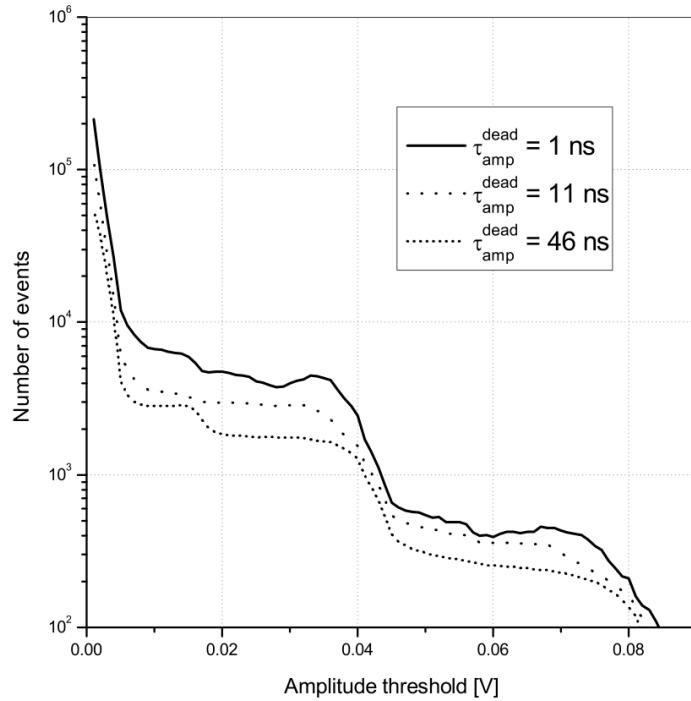
$$P_{X-talk} = \nu_{1.5phe}/\nu_{0.5phe}$$

Схема установки – offline анализ



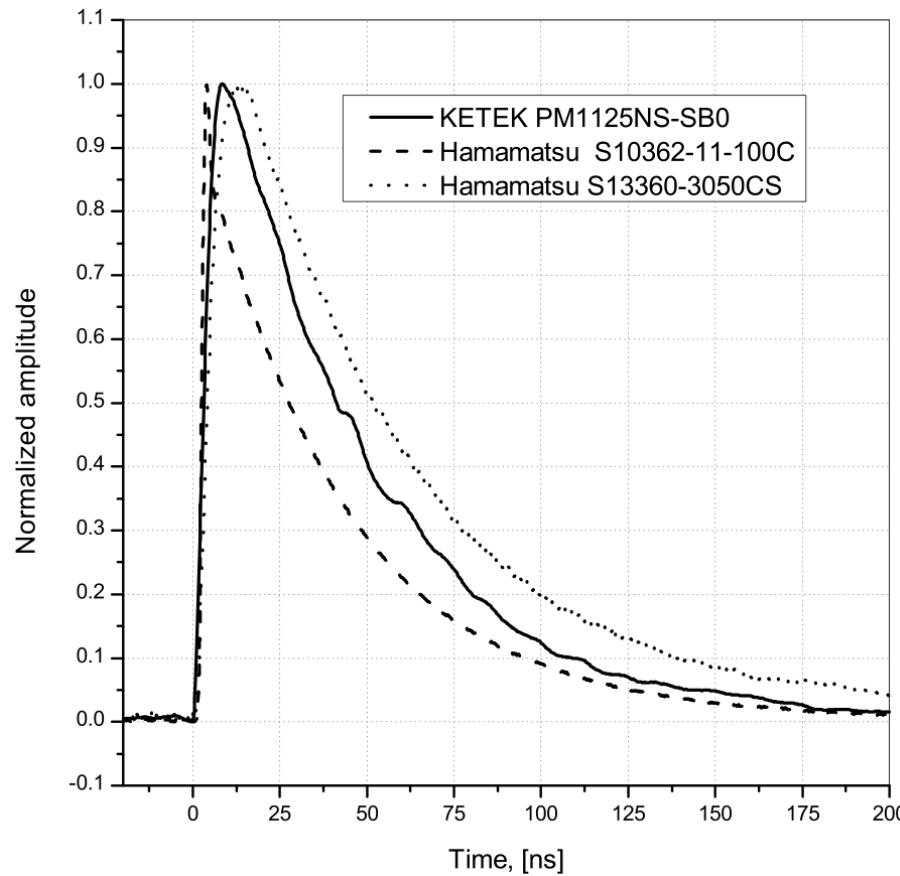
Разбиение на части

$$V(t) = \sum_{i=0}^N A_i \cdot Signal_{1e}(t - t_i) + V_0$$

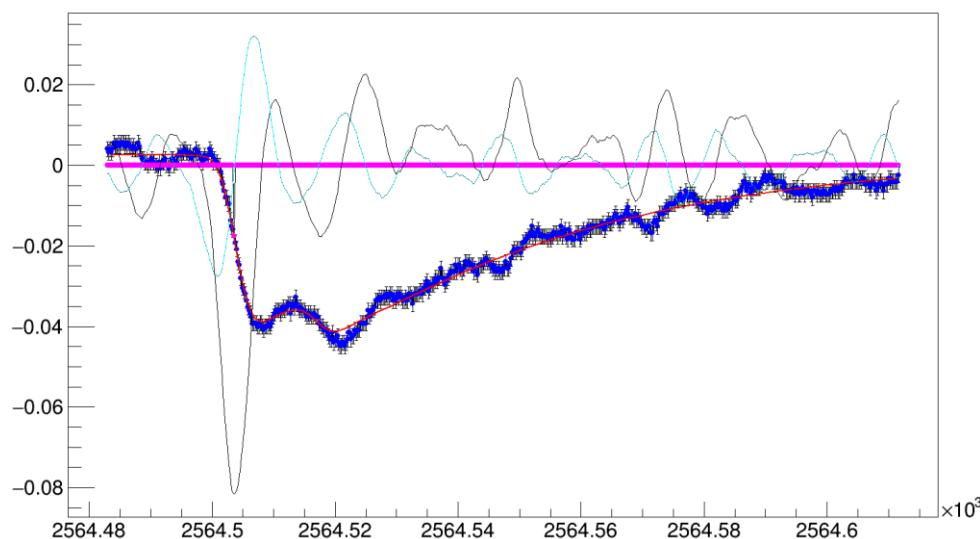
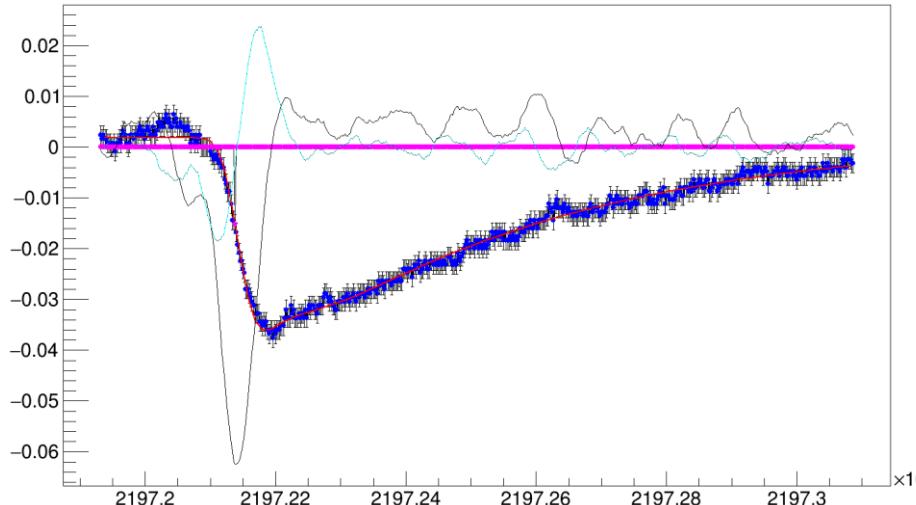
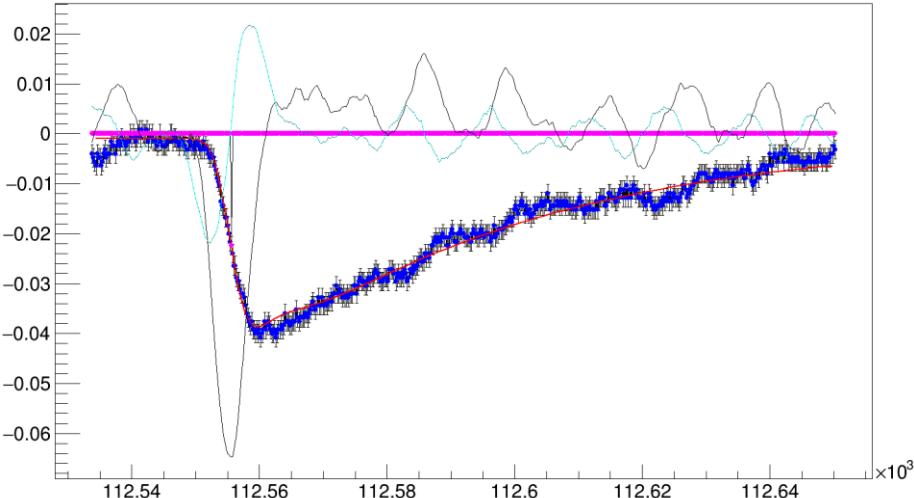


Форма сигнала

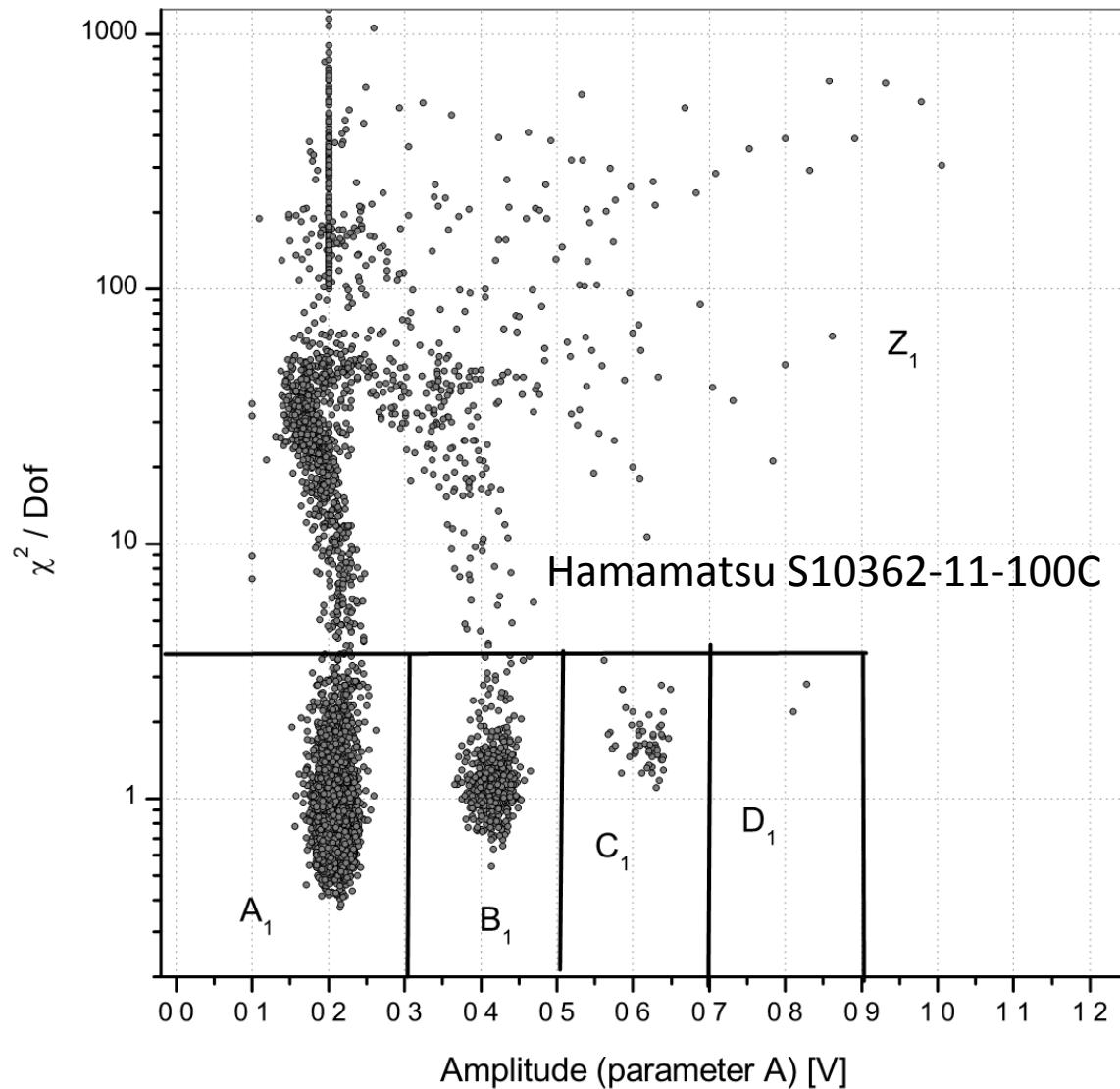
$$V(t) = A \cdot \exp \left[-\frac{t - t_0}{\tau_{rec}} \right] \cdot \left(1 - \exp \left[-\frac{t - t_0}{\tau_{rise}} \right] \right) \cdot \theta(t - t_0) + V_0$$



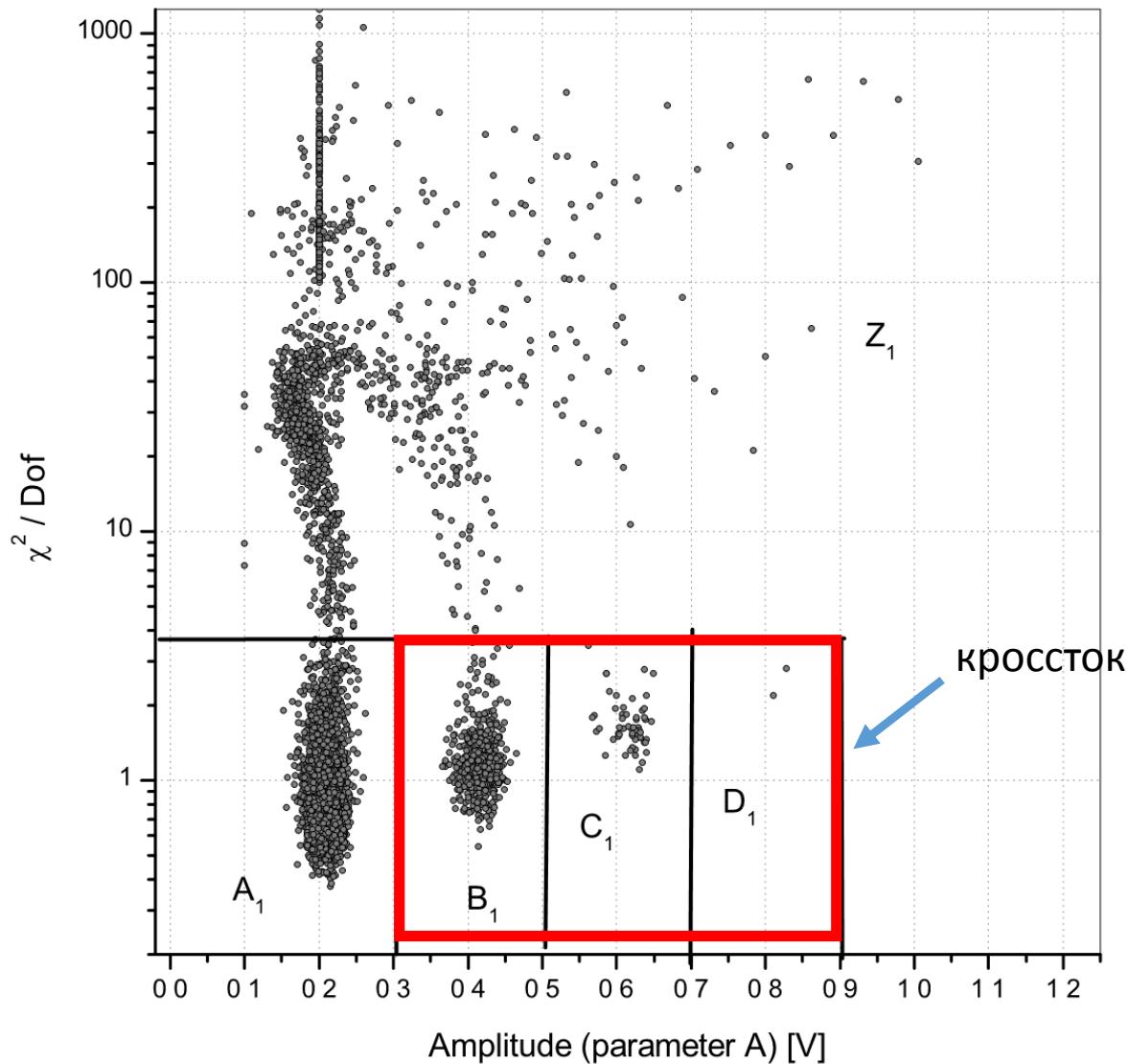
Характерные сигналы



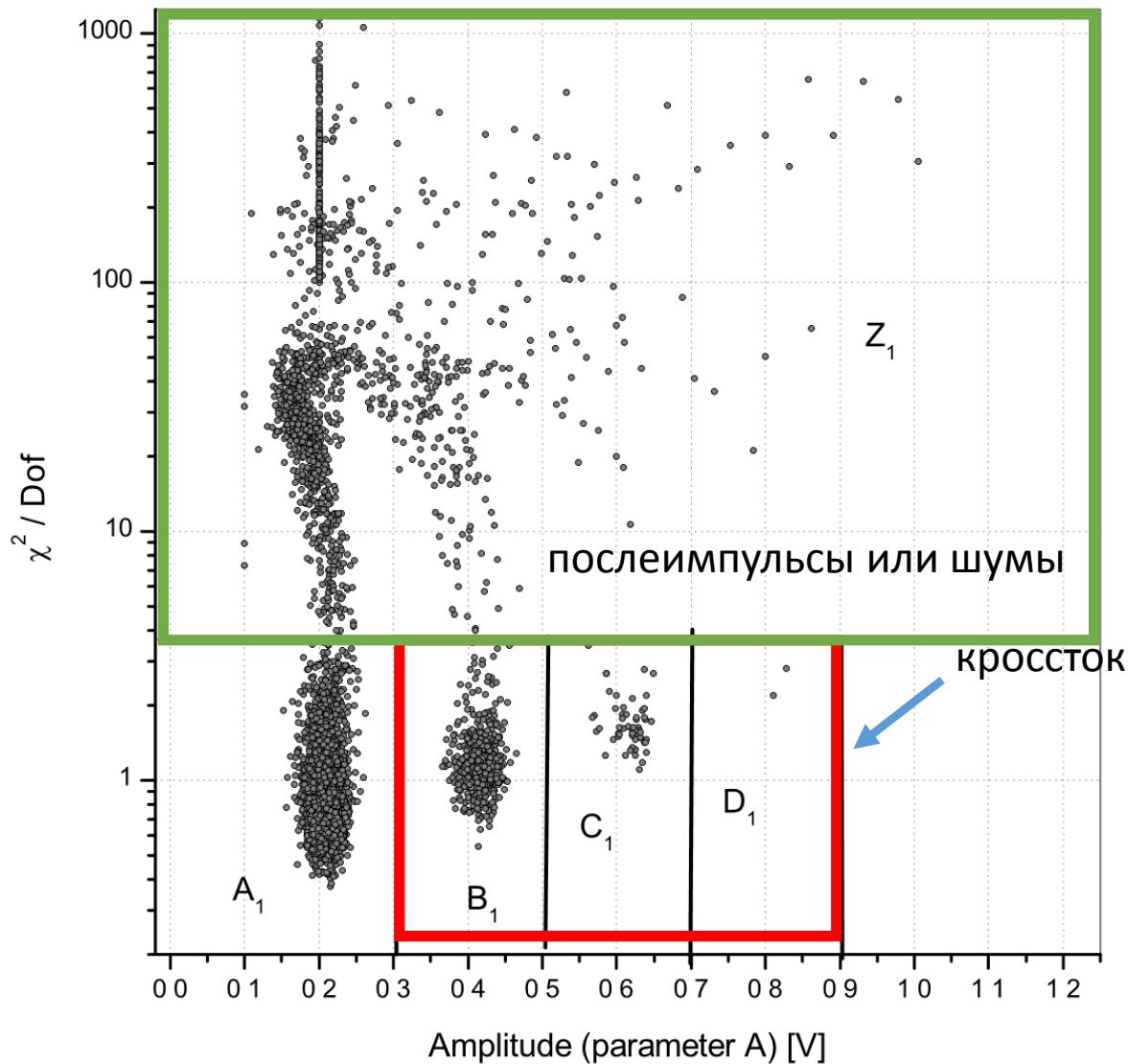
Однокомпонентная аппроксимация



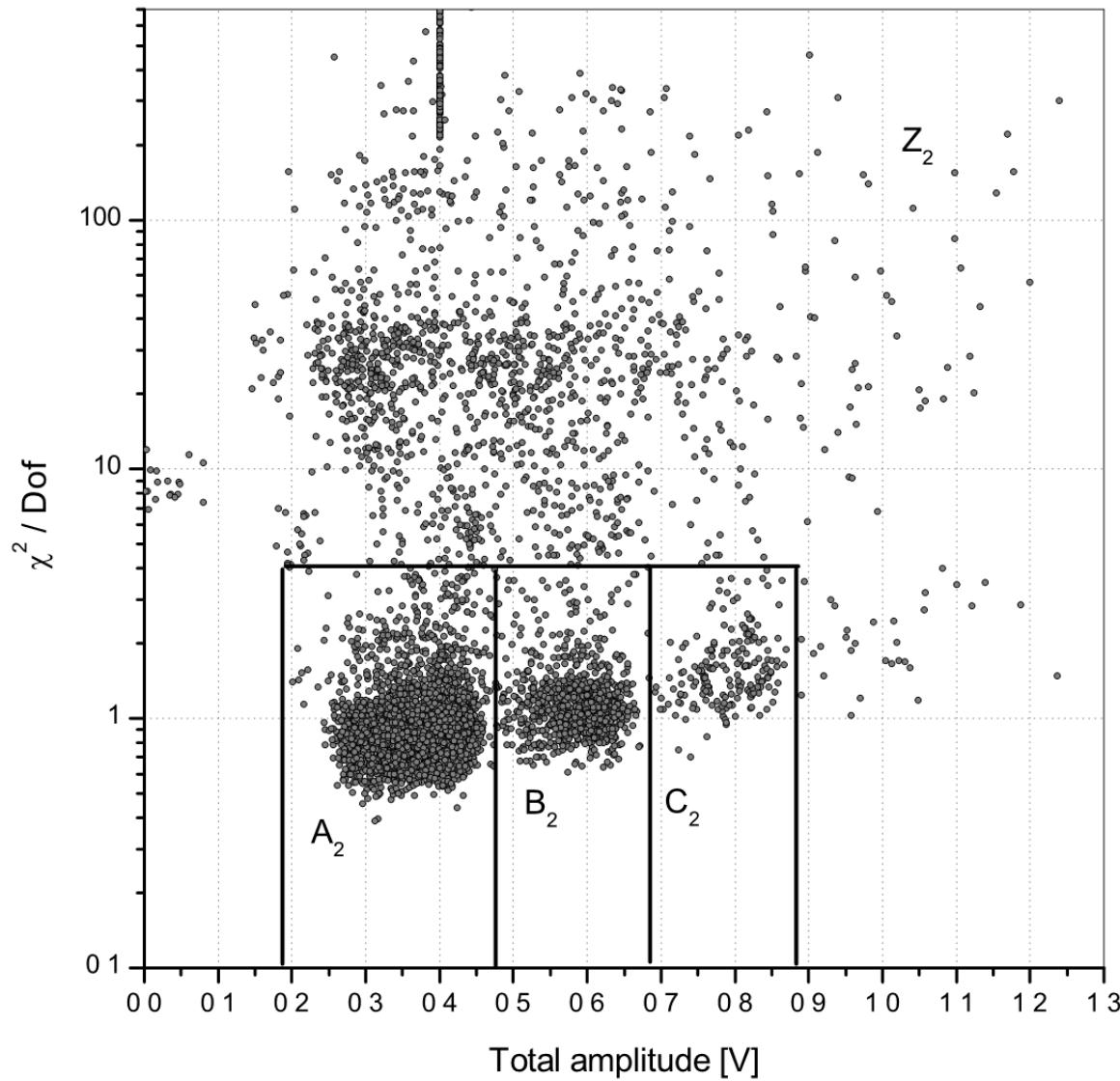
Однокомпонентная аппроксимация



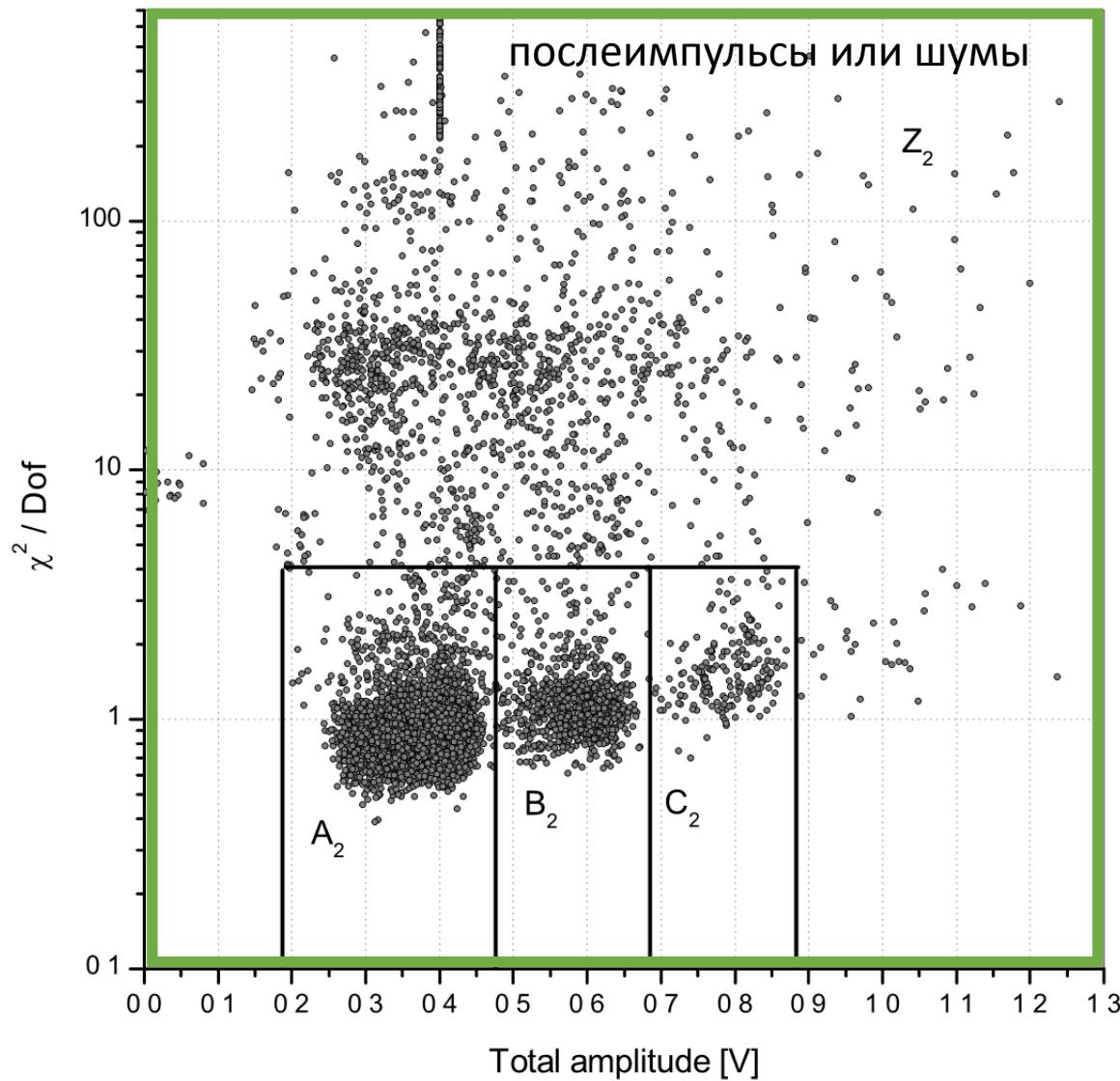
Однокомпонентная аппроксимация



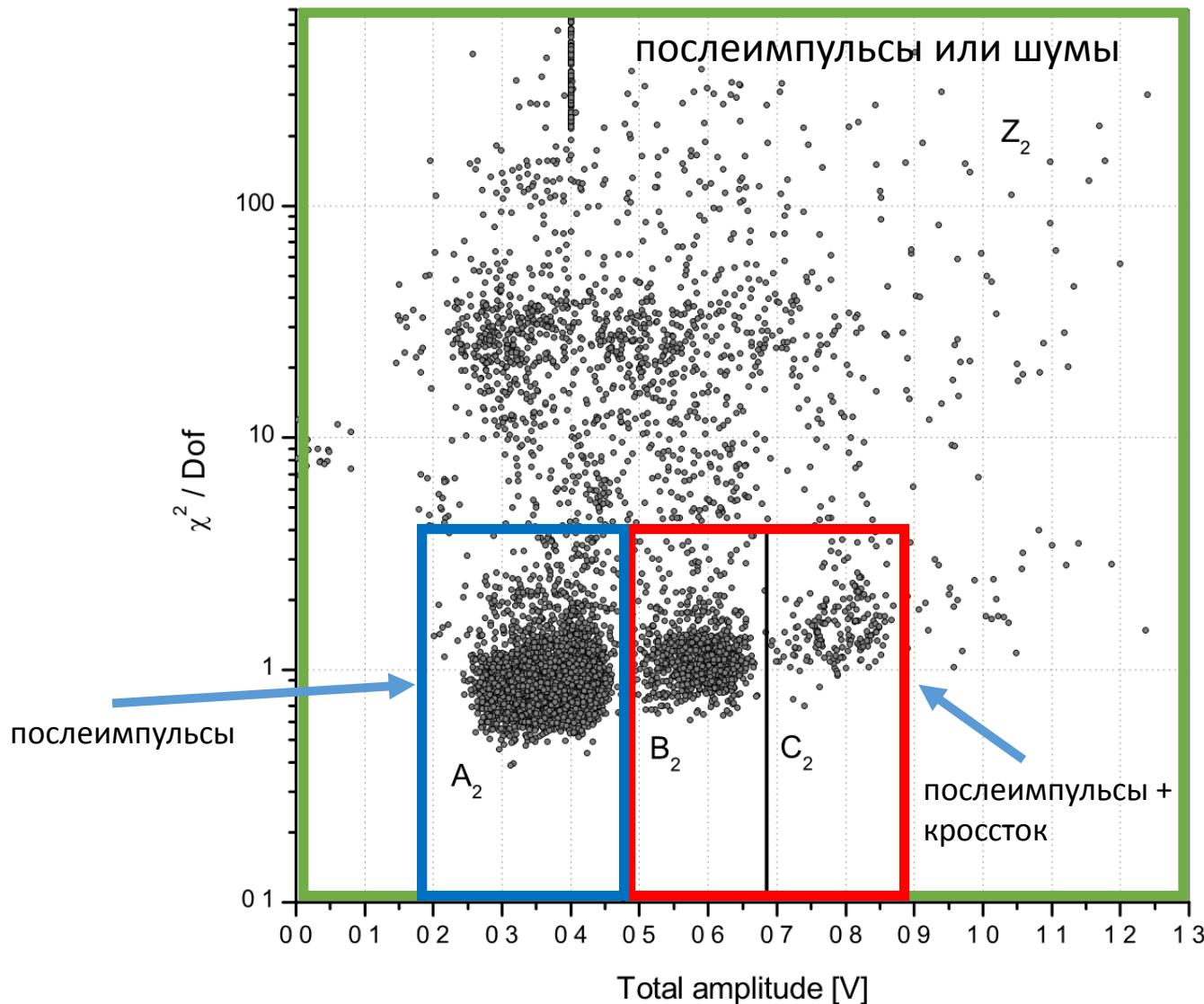
Двухкомпонентная аппроксимация



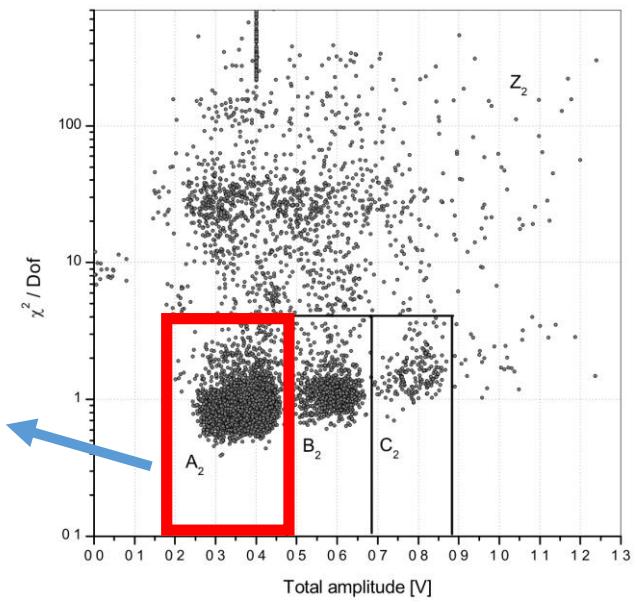
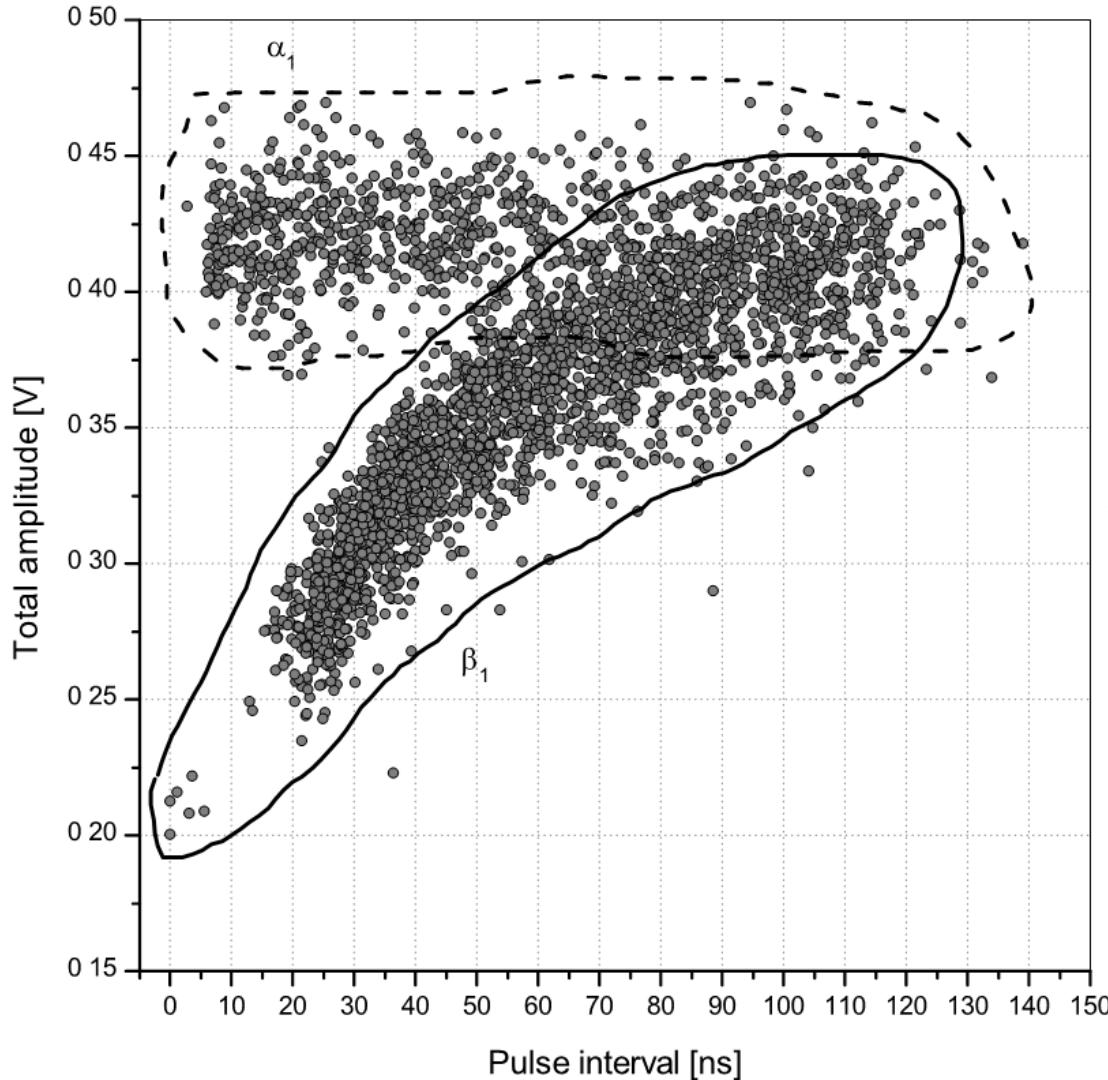
Двухкомпонентная аппроксимация



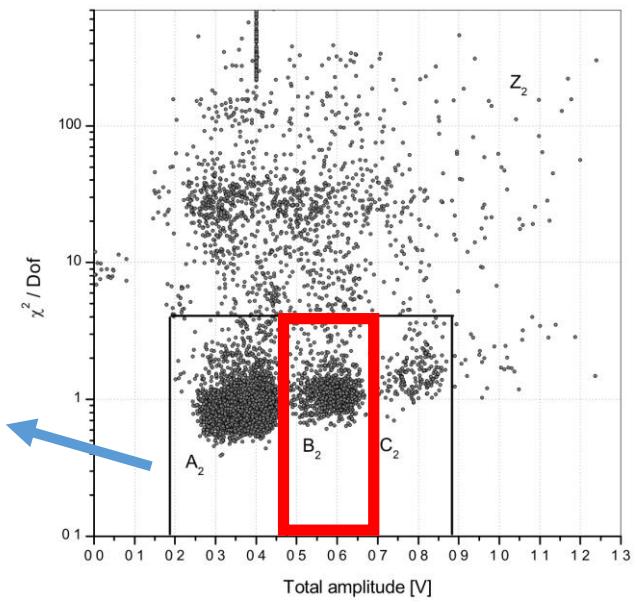
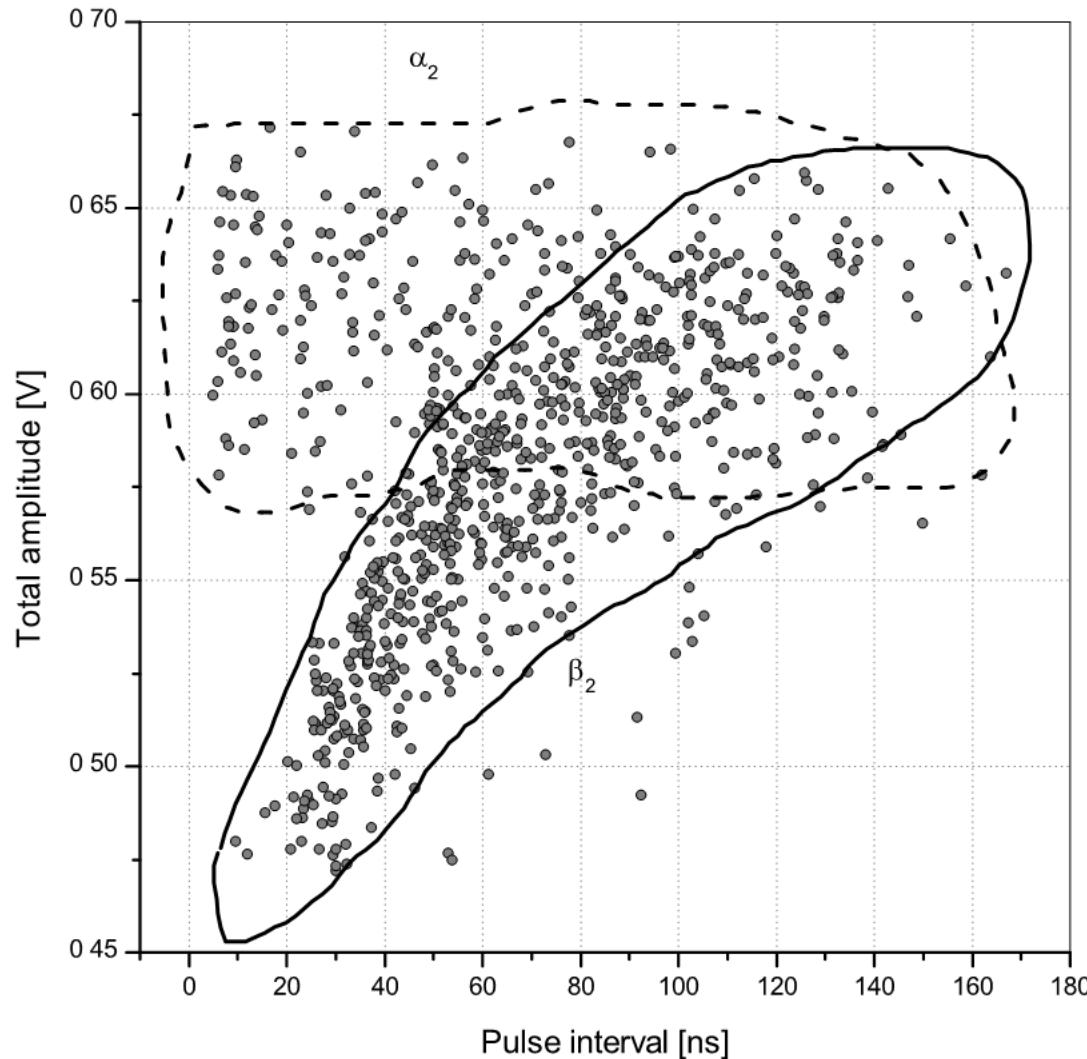
Двухкомпонентная аппроксимация



Двухкомпонентная аппроксимация

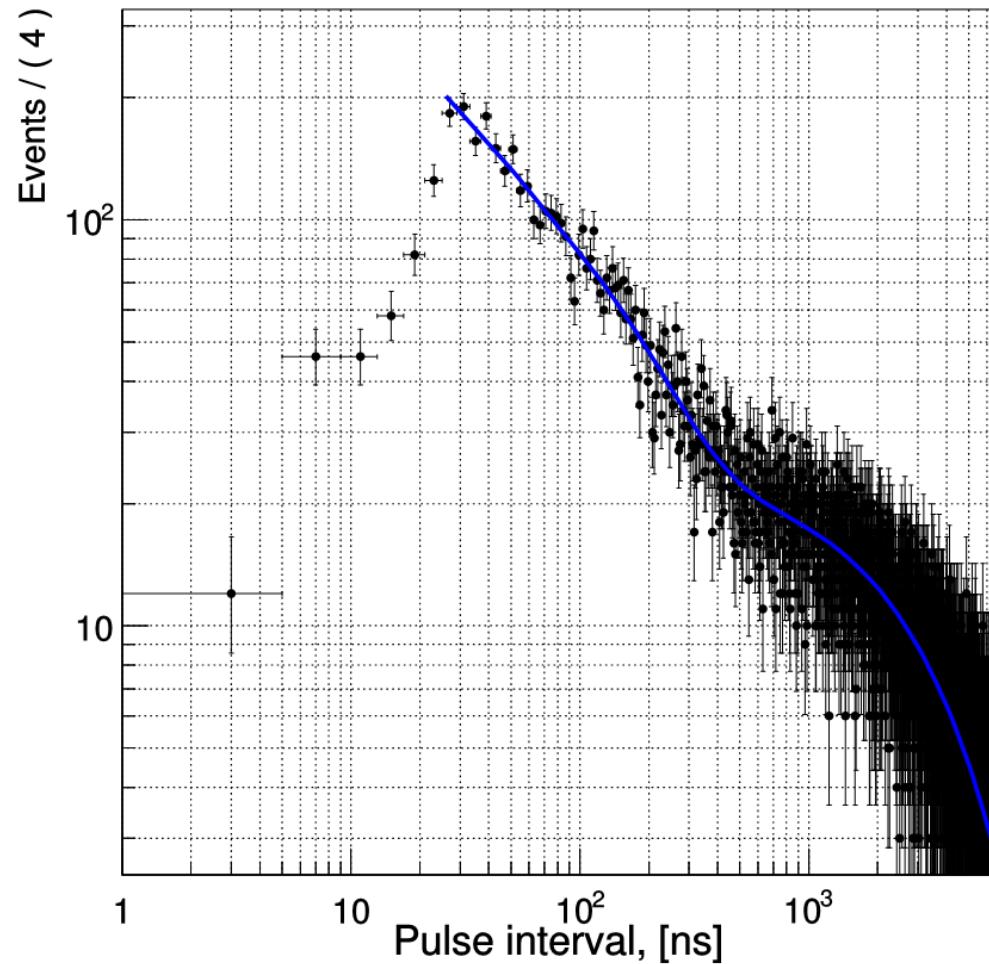
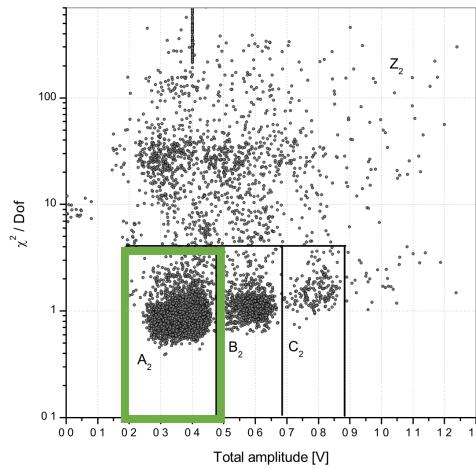
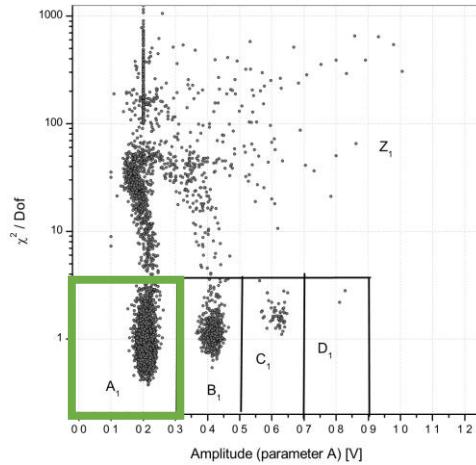


Двухкомпонентная аппроксимация



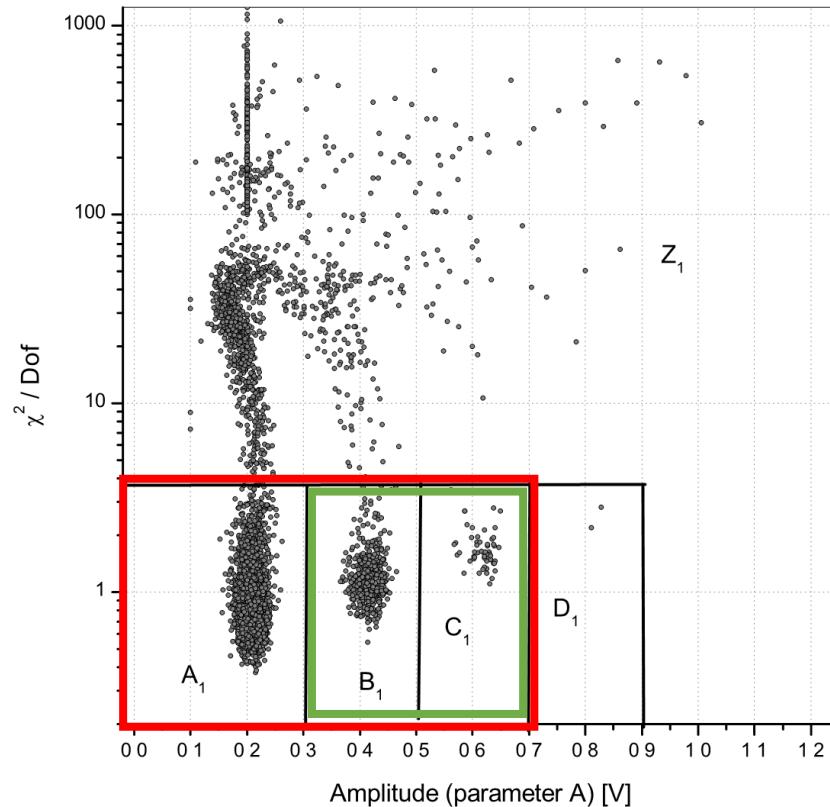
Спектр временных интервалов

$$f(t) = p \cdot (\nu + \nu_{dc}) \cdot e^{-(\nu + \nu_{dc}) \cdot t} + (1 - p) \cdot \nu_{dc} \cdot e^{-\nu_{dc} \cdot t}$$



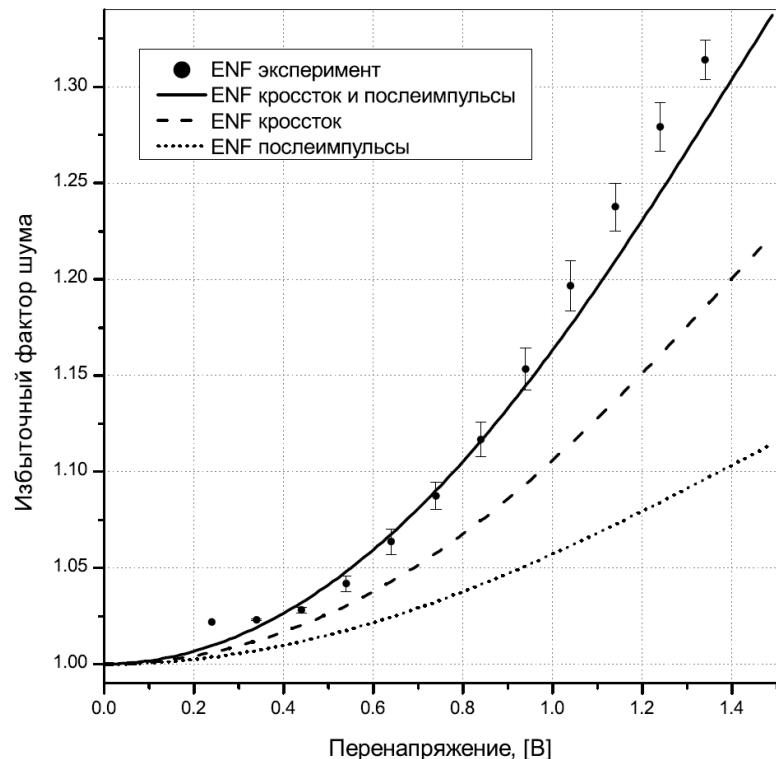
Кроссток

$$P_{X-talk} = \frac{(N_{B_1} + N_{C_1})}{(N_{A_1} + N_{B_1} + N_{C_1})}$$



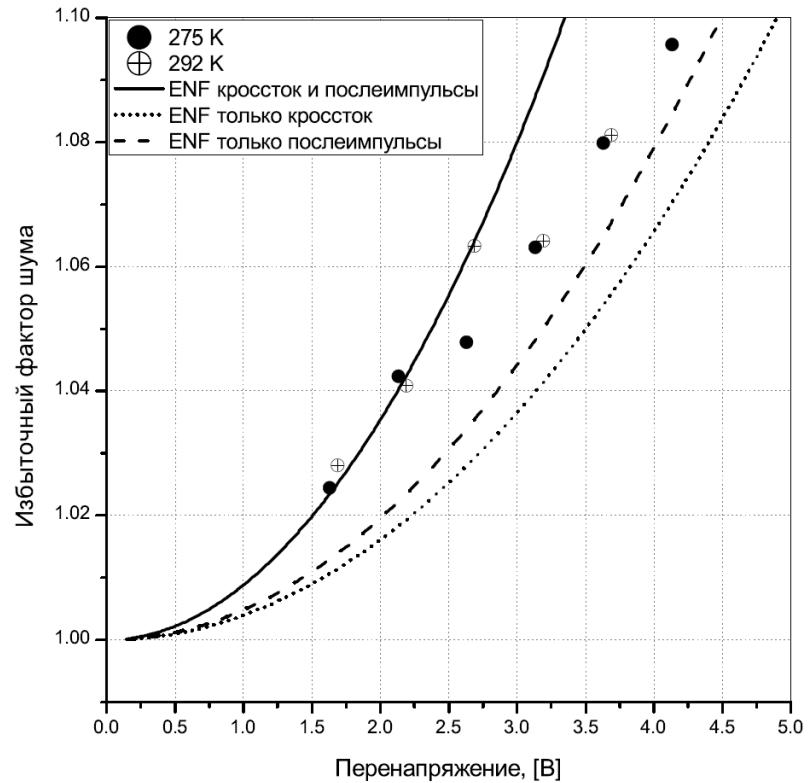
ENF - избыточный фактор шума

$$ENF = SNR_{in}^2 / SNR_{out}^2$$



Hamamatsu S10362-11-100C

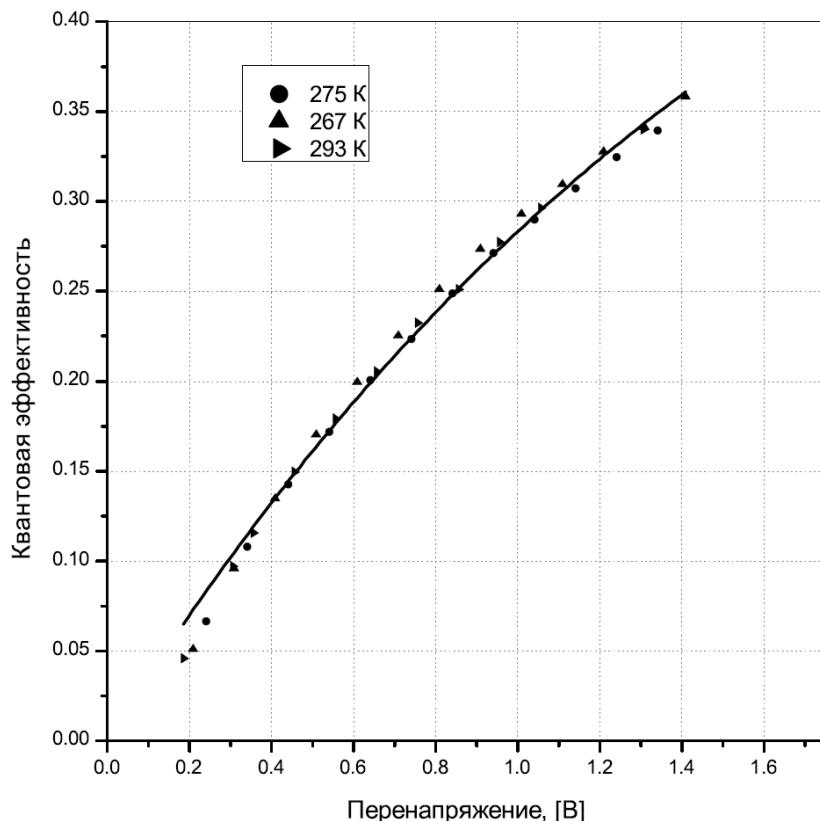
$$ENF = \frac{\delta E^2}{\Delta^2} \cdot E[N_{p.e}^{noX-talk}]$$



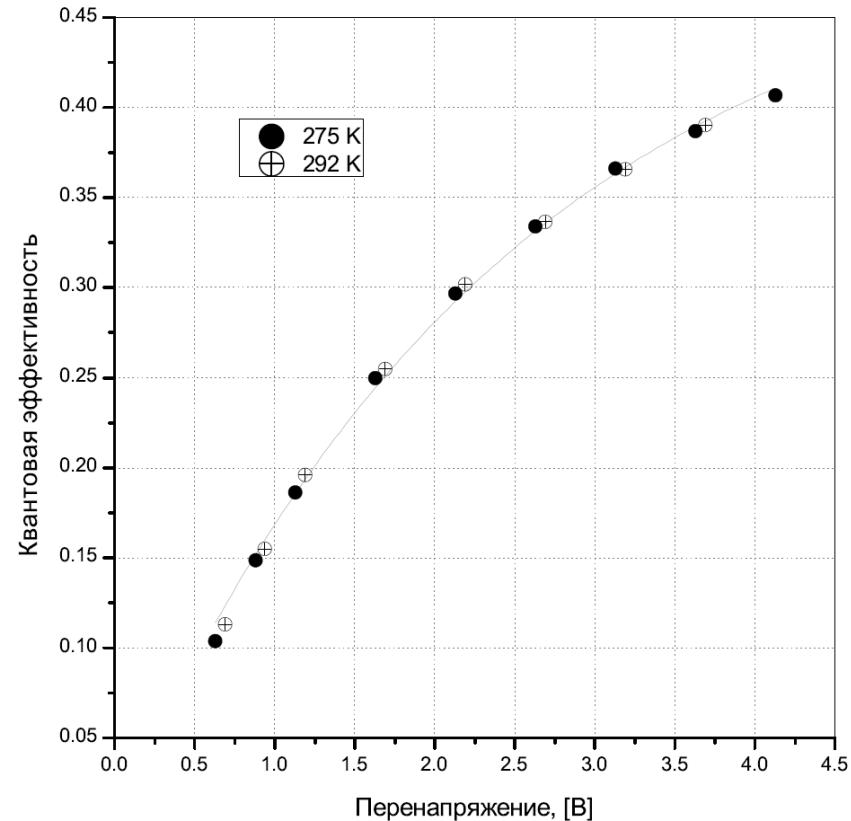
Hamamatsu S13360-3050CS

Квантовая эффективность

$$\varepsilon_{Geiger}^{electron} = \varepsilon_{max} \cdot (1 - e^{-k_{QE} \cdot \Delta V})$$

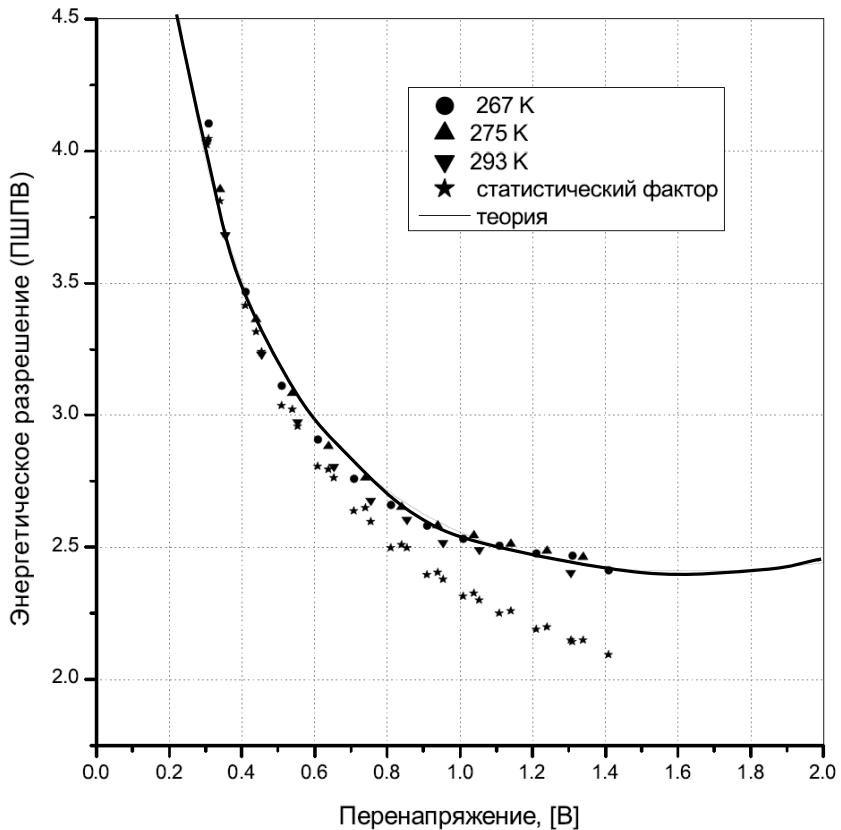


Hamamatsu S10362-11-100C

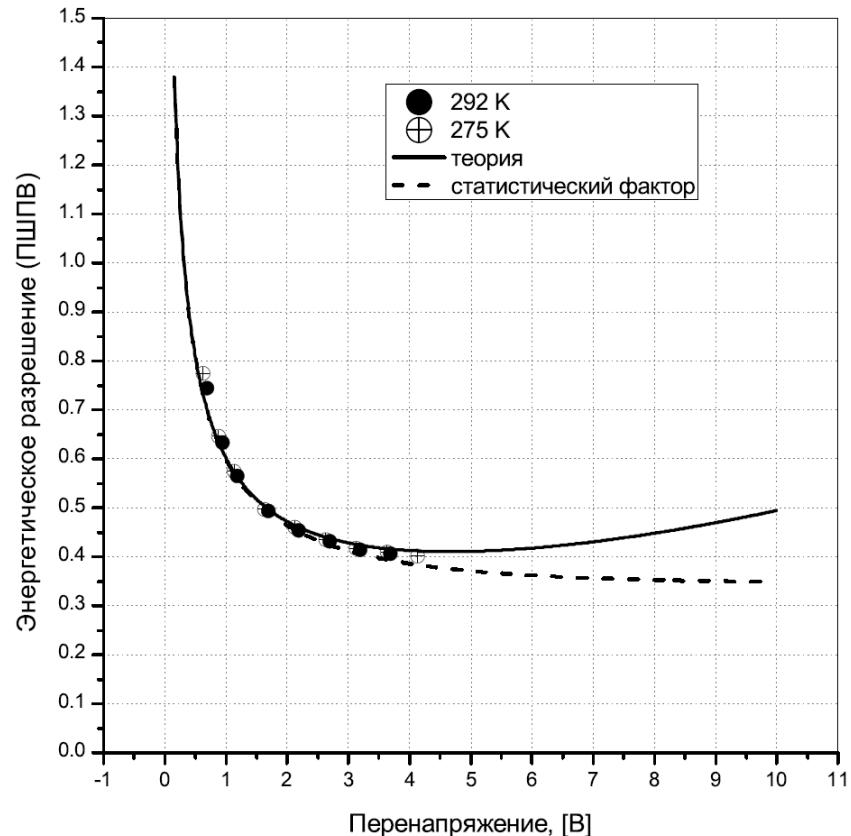


Hamamatsu S13360-3050CS

Энергетическое разрешение

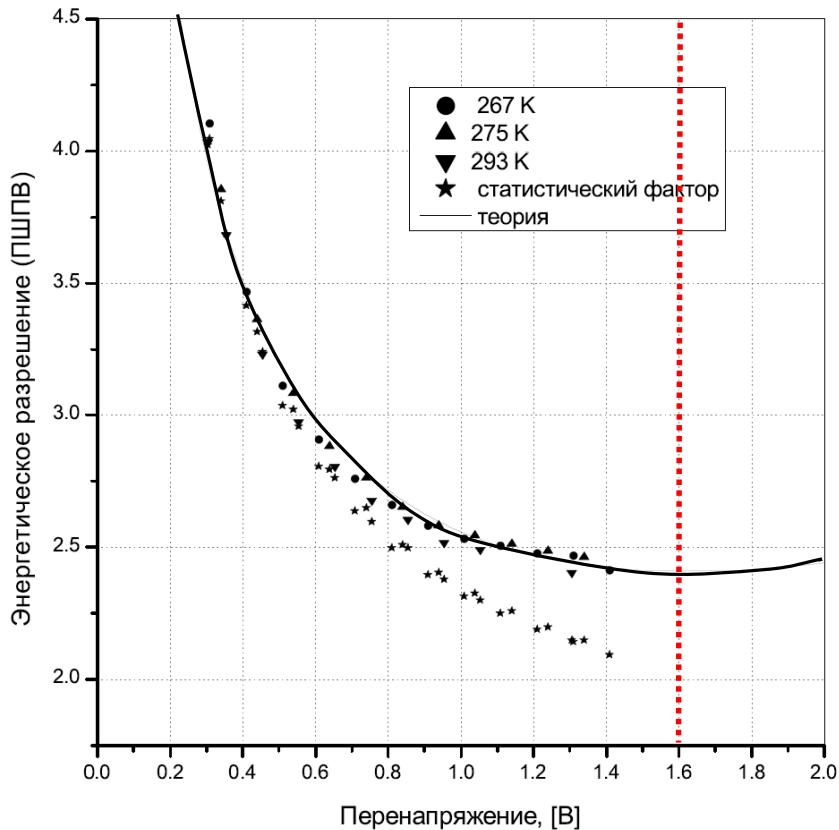


Hamamatsu S10362-11-100C

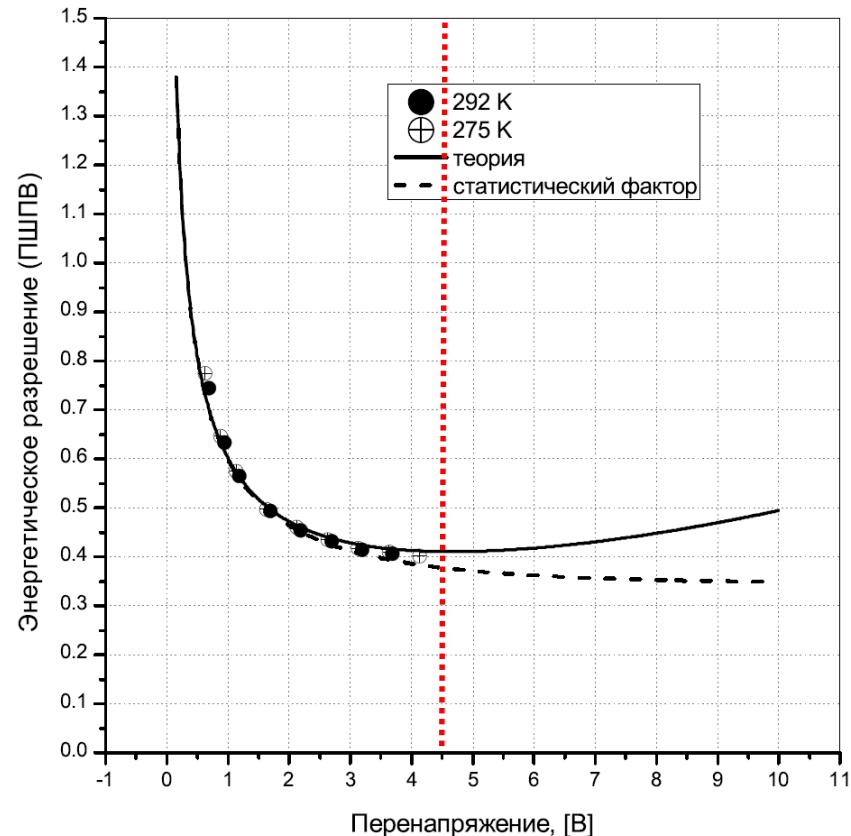


Hamamatsu S13360-3050CS

Энергетическое разрешение



Hamamatsu S10362-11-100C



Hamamatsu S13360-3050CS

Результаты:

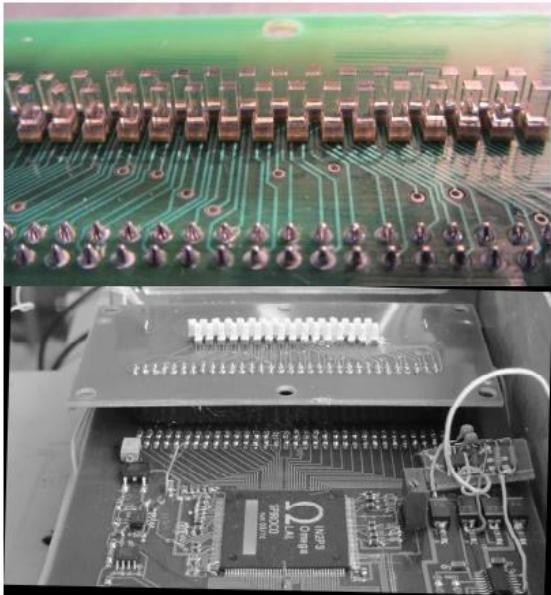
	Hamamatsu S13360-3050CS	KETEK PM1125NS-SB0	Hamamatsu S10362-11-100C
Темновой шум [кГц / мм ²]	30	80	300
Кросstalk	6%	6%	12%
Вероятность послеимпульса	10%	9%	10% (быстрая) 15% (медленная)
Константа времени послеимпульса [нс]	9	28	35 (быстрая) 170 (медленная)
ENF	1.1	1.1	1.3

Результаты:

	Hamamatsu S13360-3050CS	KETEK PM1125NS-SB0	Hamamatsu S10362-11-100C
Темновой шум [кГц / мм ²]	30	80	300
Кросstalk	6%	6%	12%
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ENF	1.1	1.1	1.3

Сборка детектора

Малодозная рентгеновская установка (ИЯФ)

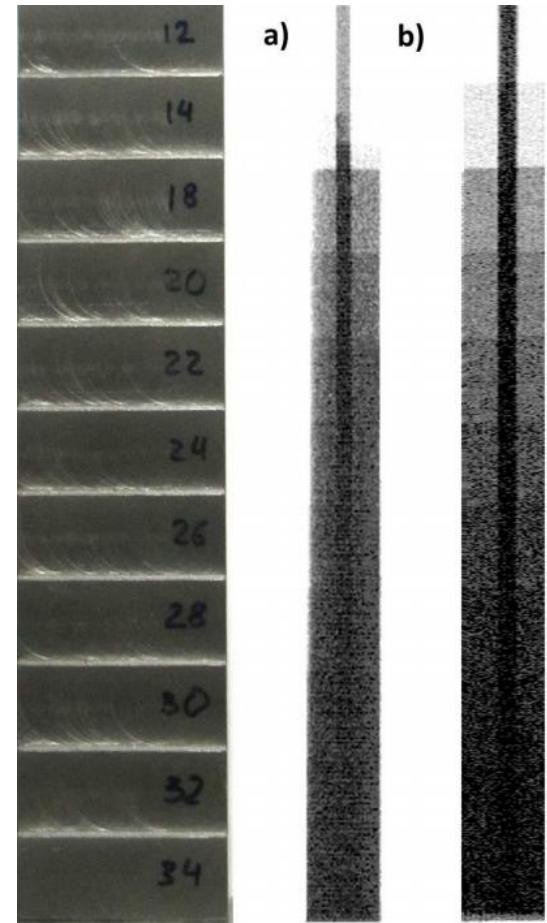


Detector assembly



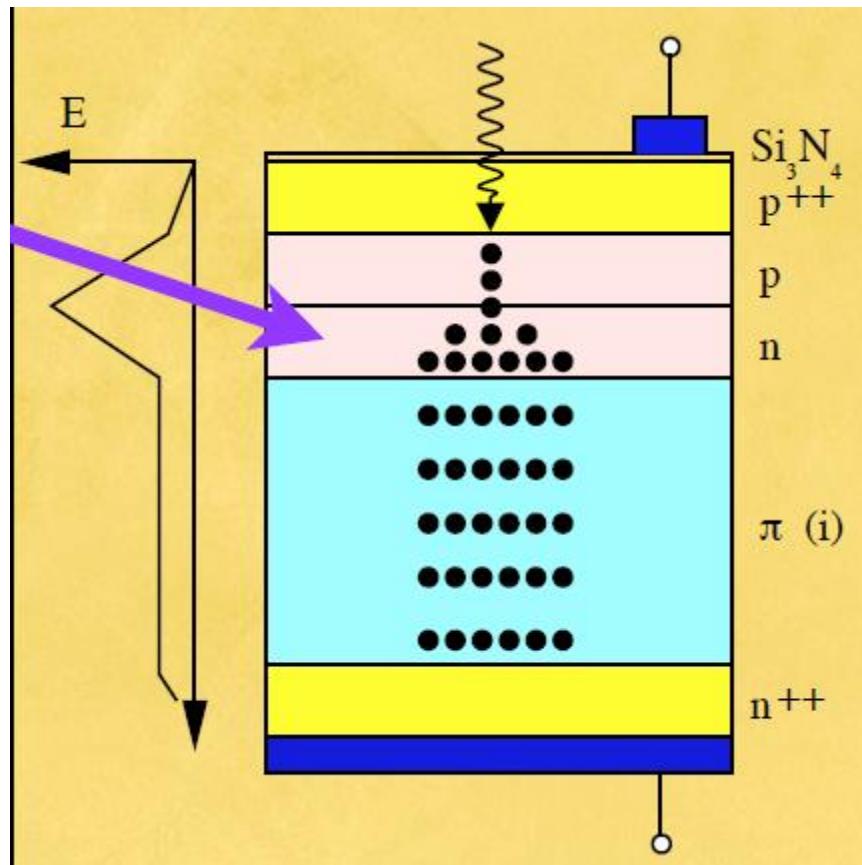
Scanning system with the detector

KETEK PM1125NS-SB0



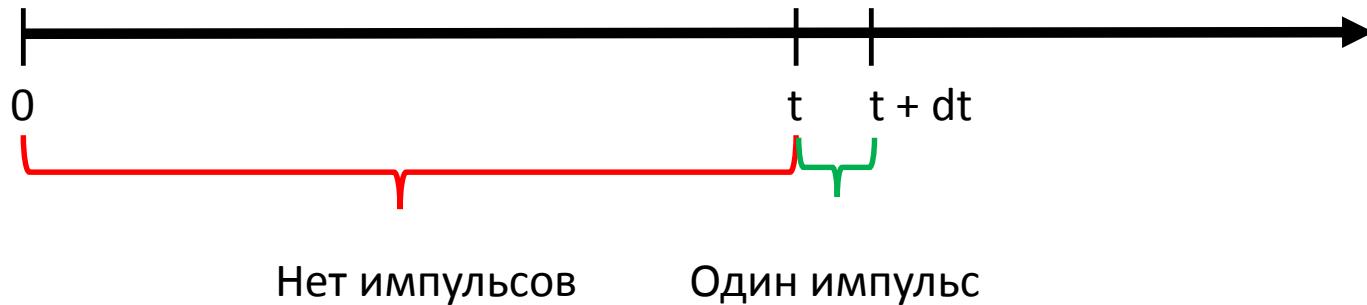
Спасибо за внимание!

Устройство SiPM



Спектр временных интервалов

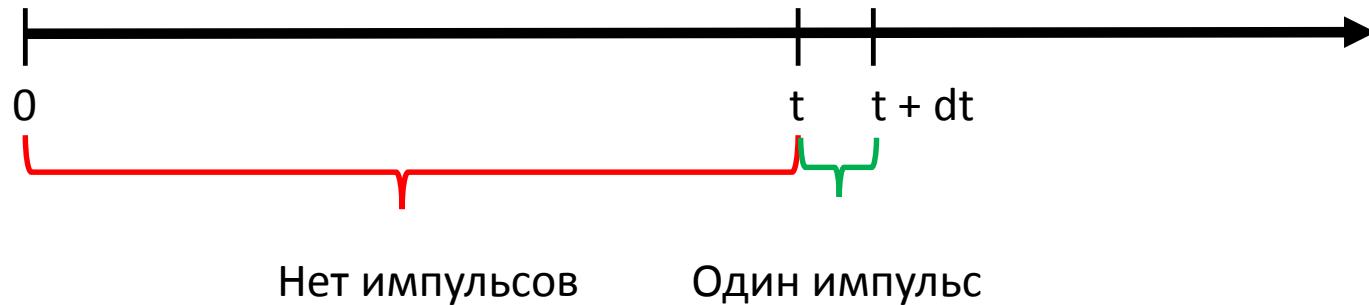
Один процесс – темновой шум



$$f(\Delta t) = \frac{1}{\tau} \cdot \exp(-\Delta t/\tau)$$

Спектр временных интервалов

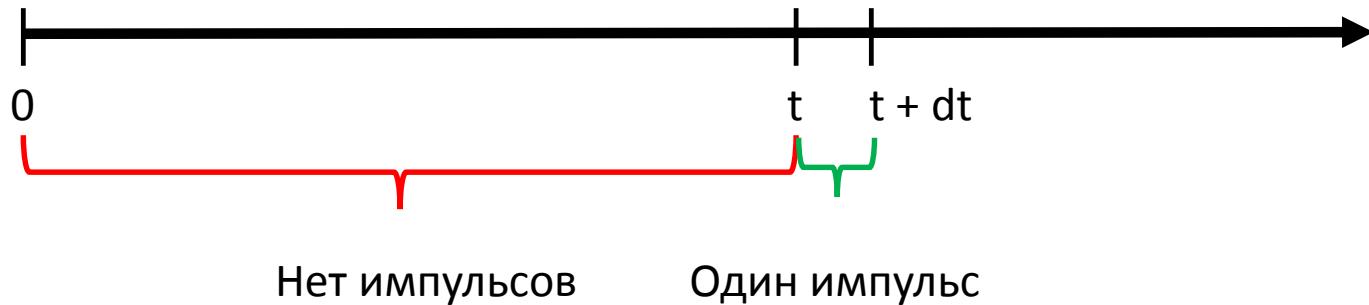
Два процесса – темновой шум и послеимпульсы



$$f(t) = p \cdot (\nu + \nu_{dc}) \cdot e^{-(\nu + \nu_{dc}) \cdot t} + (1 - p) \cdot \nu_{dc} \cdot e^{-\nu_{dc} \cdot t}$$

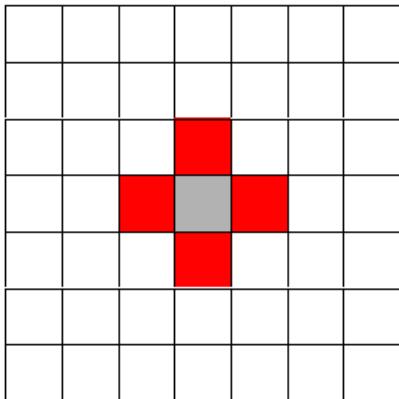
Спектр временных интервалов

Три процесса – темновой шум, послеимпульсы (быстрые и медленные)

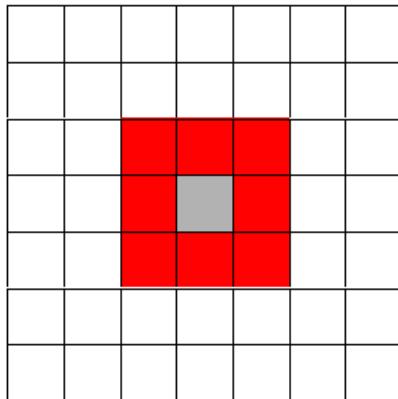


$$\begin{aligned} f(t) = & p_s \cdot p_f \cdot (\nu_s + \nu_f + \nu_{dc}) \cdot e^{-(\nu_s + \nu_f + \nu_{dc}) \cdot t} + \\ & p_s \cdot (1 - p_f) \cdot (\nu_s + \nu_{dc}) \cdot e^{-(\nu_s + \nu_{dc}) \cdot t} + \\ & p_f \cdot (1 - p_s) \cdot (\nu_f + \nu_{dc}) \cdot e^{-(\nu_f + \nu_{dc}) \cdot t} + \\ & (1 - p_s) \cdot (1 - p_f) \cdot \nu_{dc} \cdot e^{-\nu_{dc} \cdot t} \end{aligned}$$

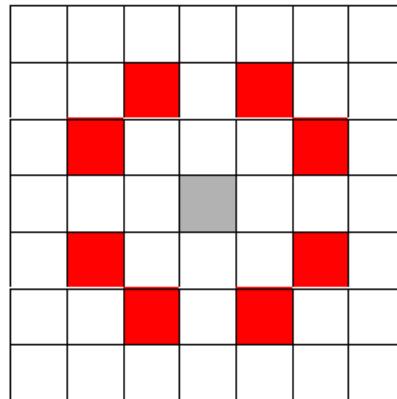
Модель распространения света



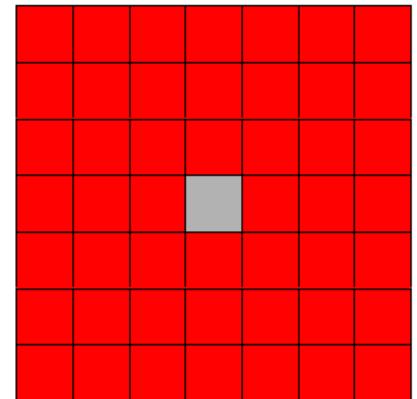
4 nearest neighbors



8 nearest neighbors



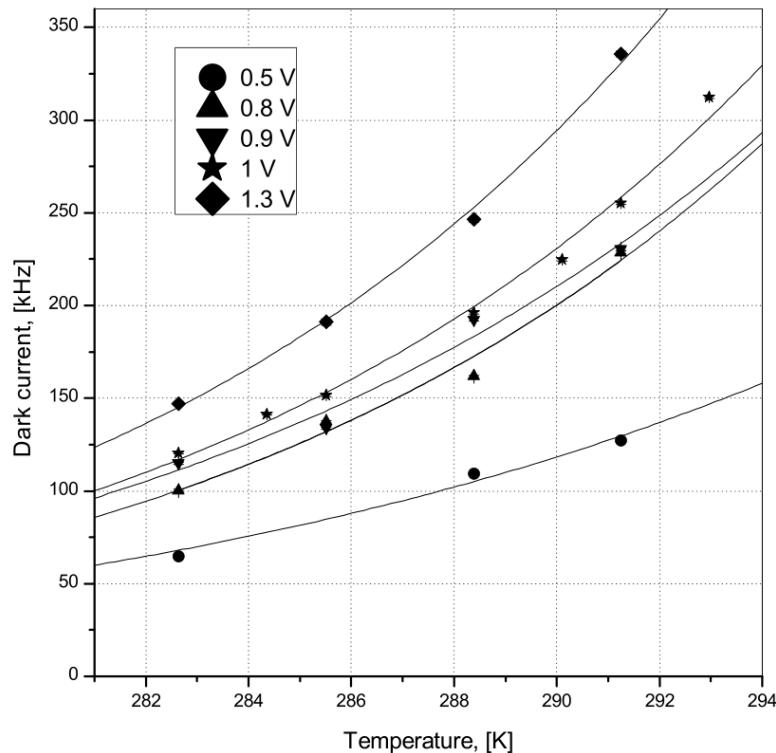
8 L-connected
neighbors



all neighbors

Темновой шум

$$\nu(\Delta V = \text{const}, T) = A \cdot T^{3/2} \cdot \exp\left[-\frac{E_g}{2k_B \cdot T}\right]$$

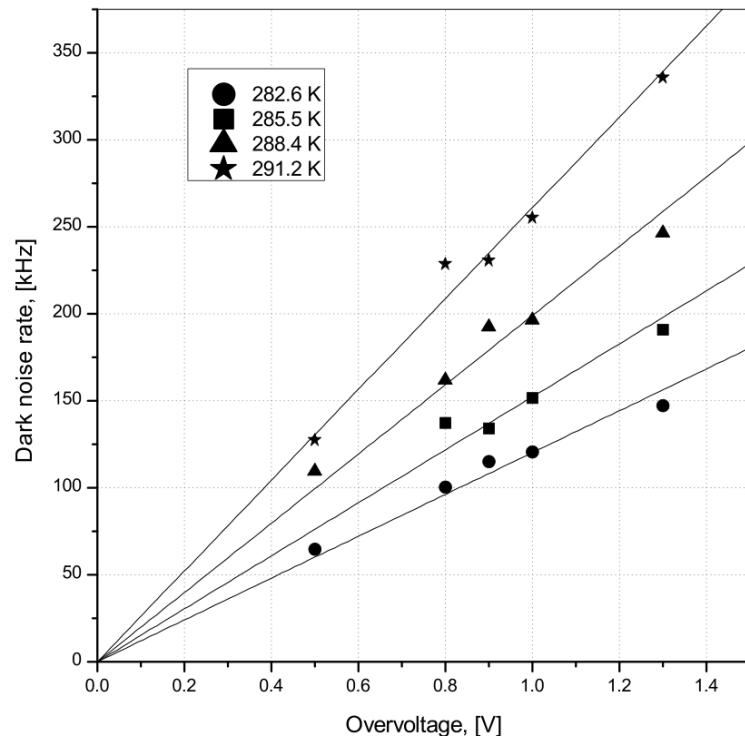
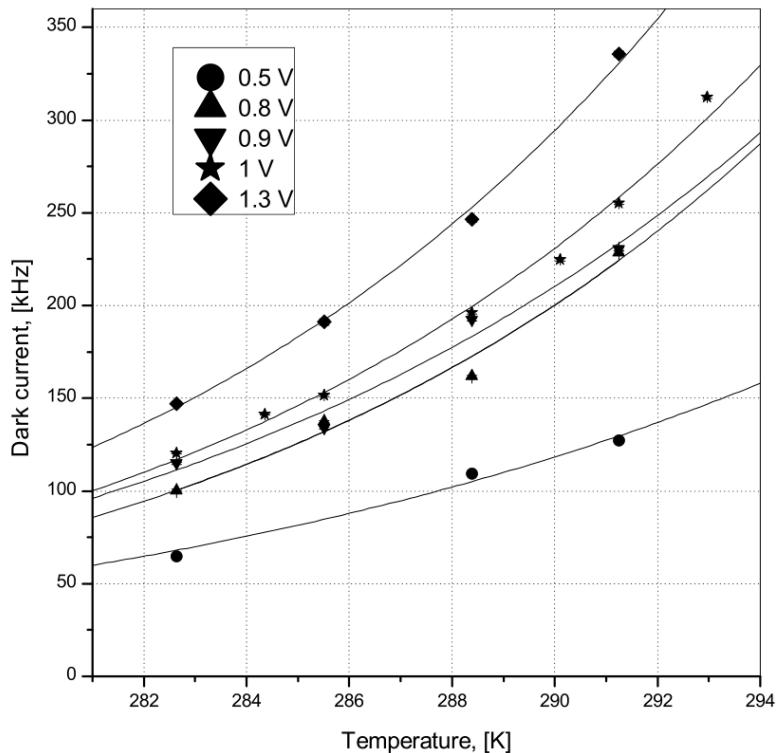


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Темновой шум

$$\nu(\Delta V = \text{const}, T) = A \cdot T^{3/2} \cdot \exp\left[-\frac{E_g}{2k_B \cdot T}\right]$$

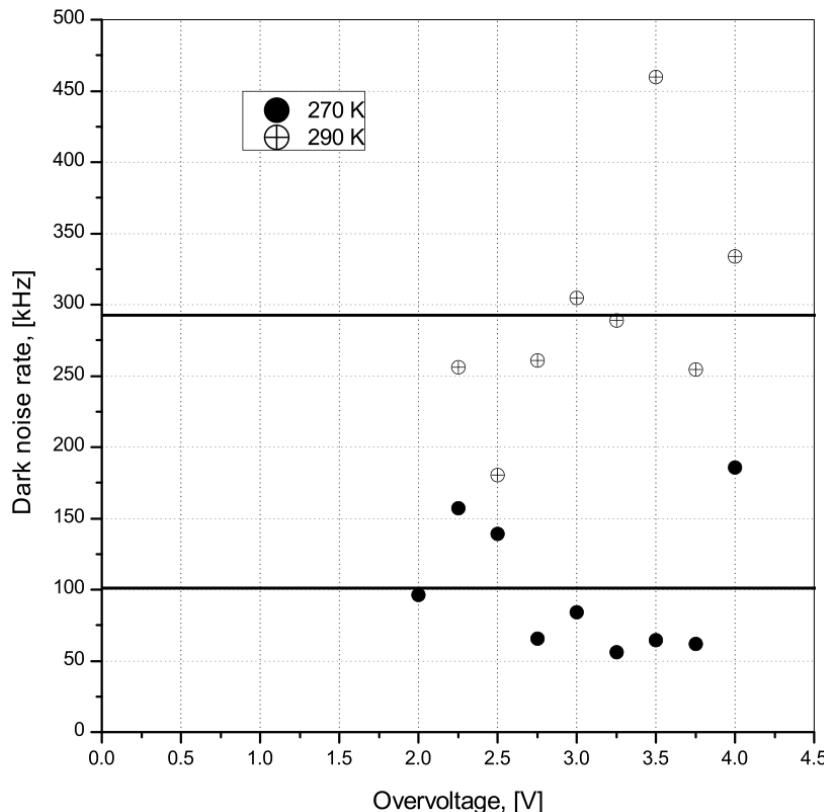
$$\nu(\Delta V, T = \text{const}) = k \cdot \Delta V$$



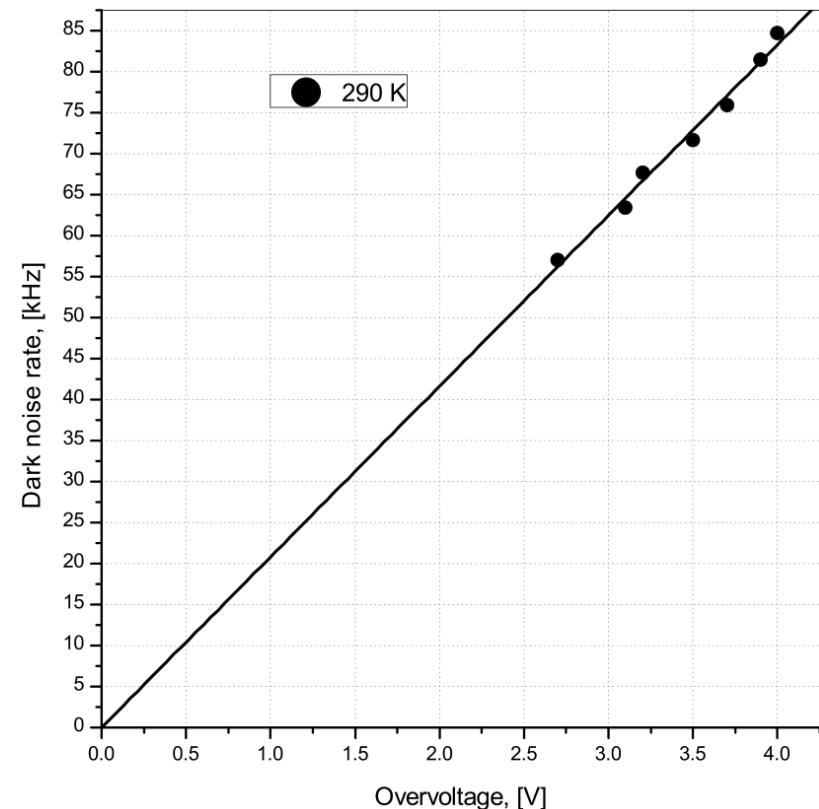
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Темновой шум

$$\nu(\Delta V, T = \text{const}) = k \cdot \Delta V$$

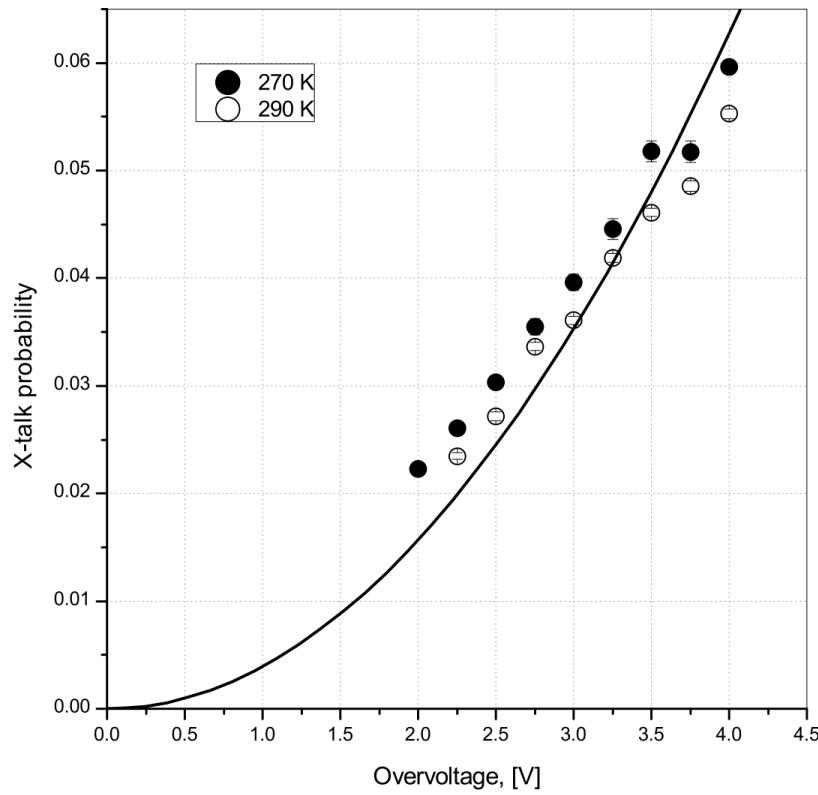


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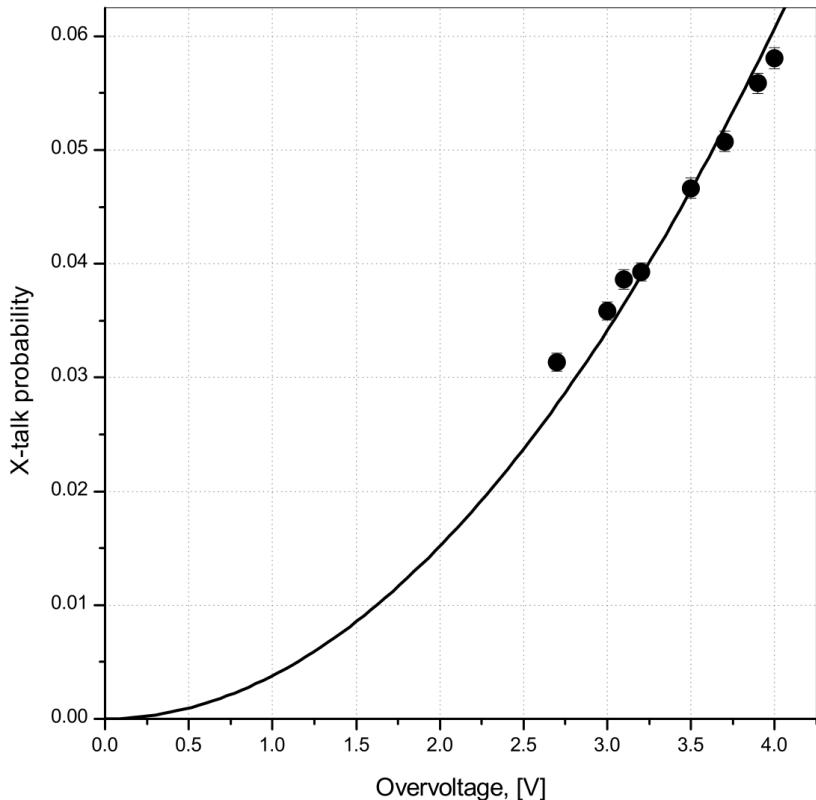


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Кросстоки



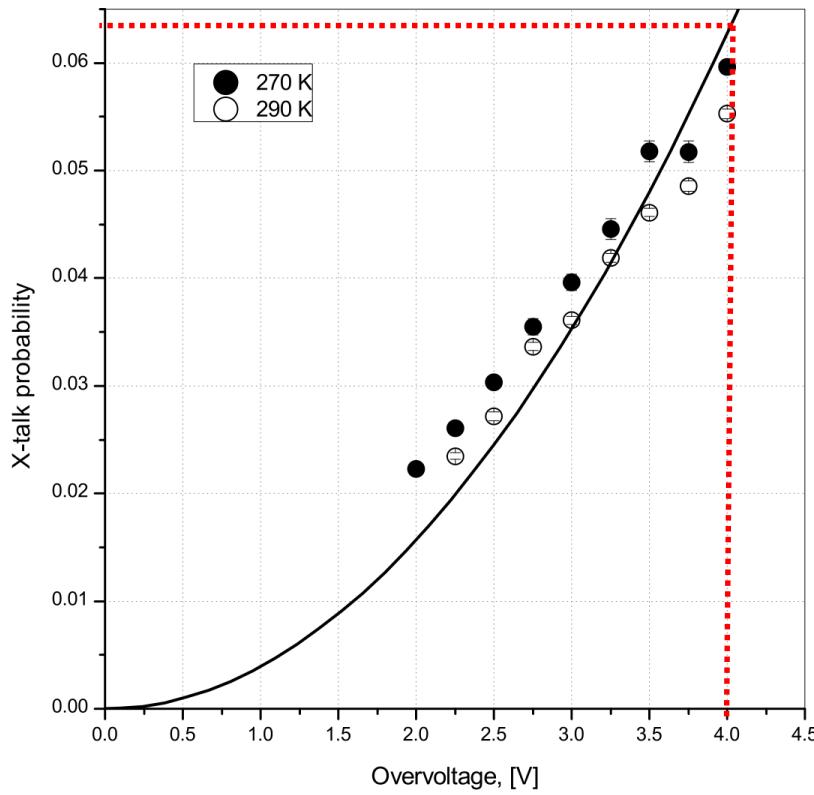
Hamamatsu S13360-3050CS



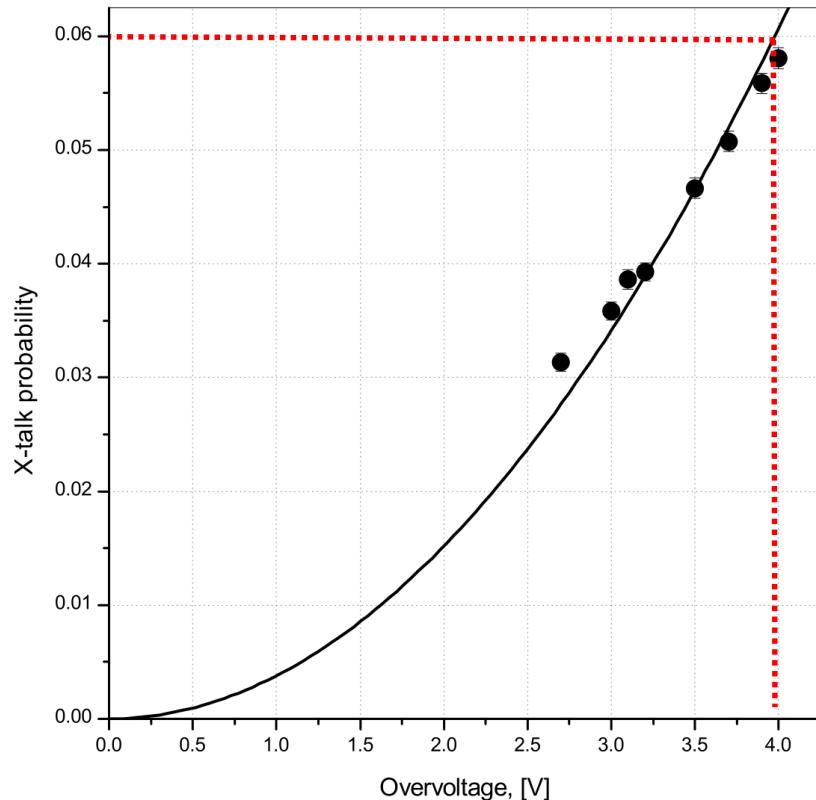
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Кросстоки

Практически идентичны!

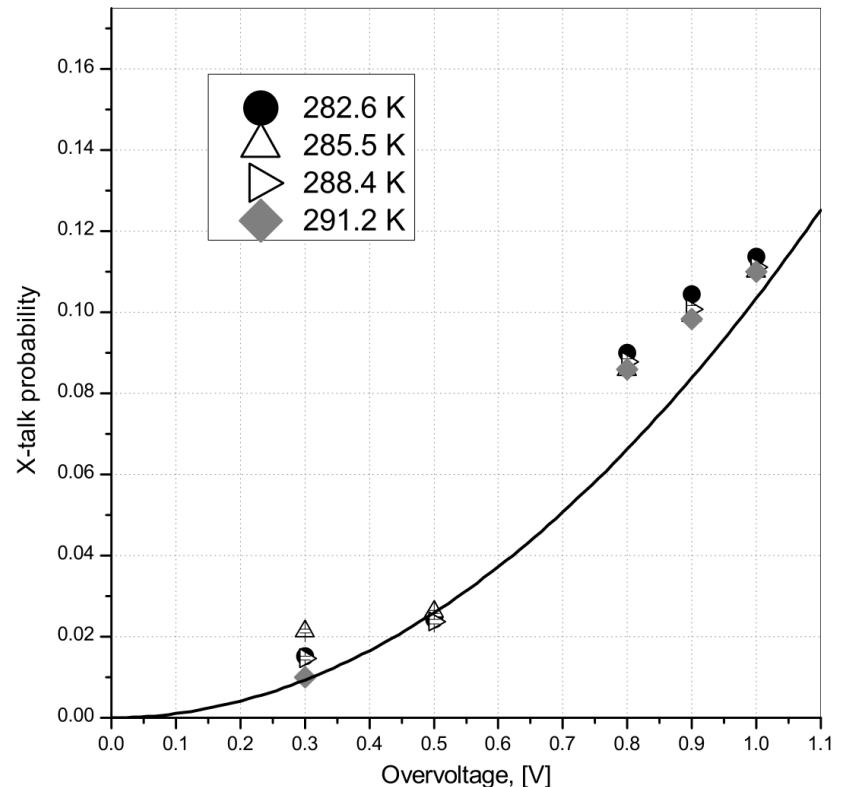
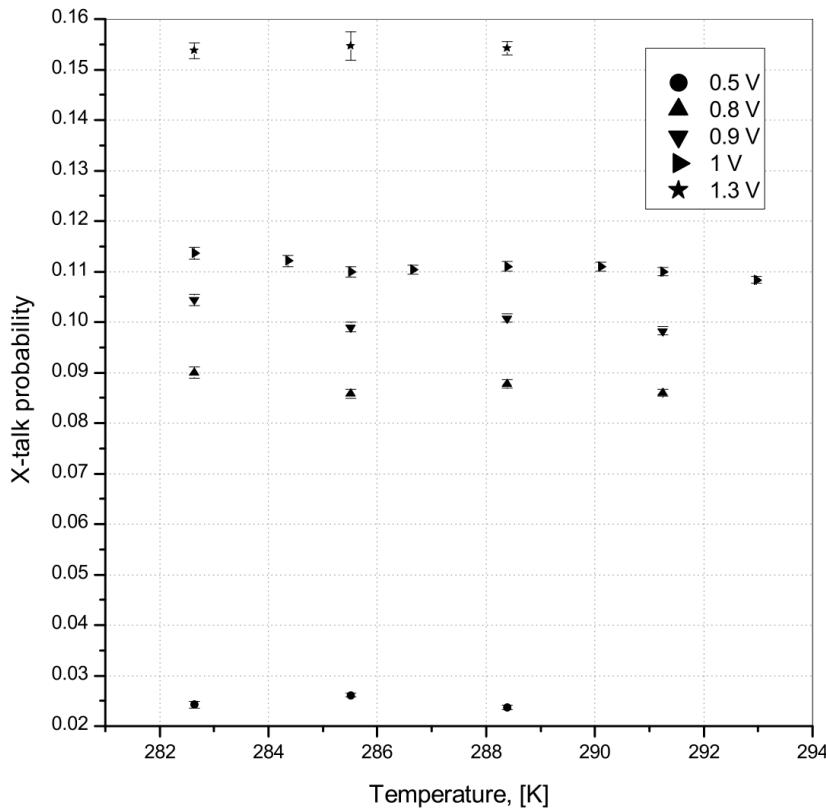


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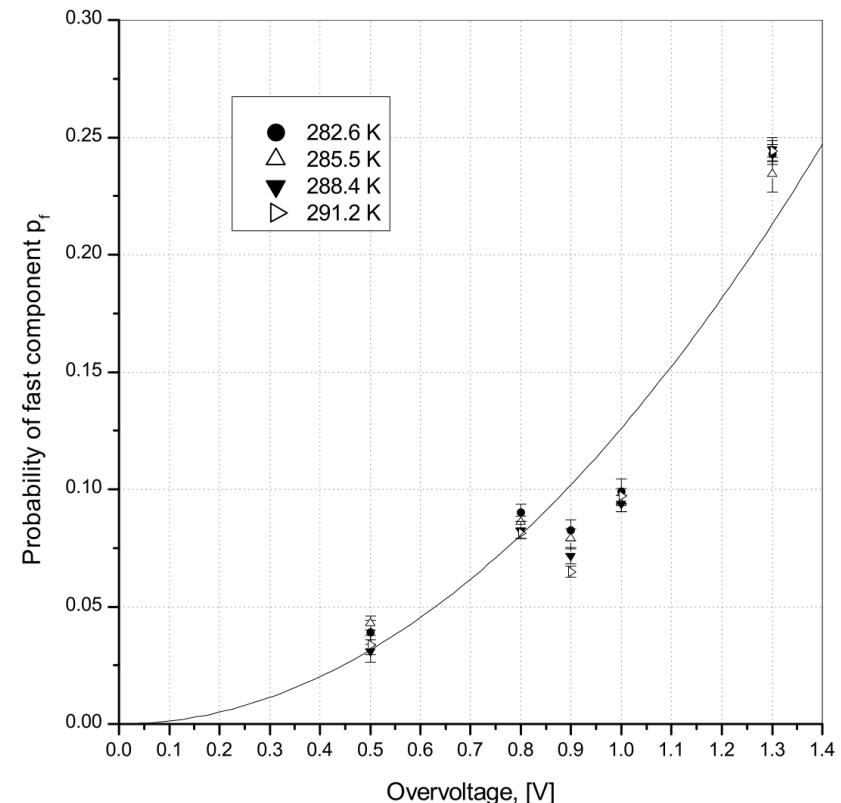
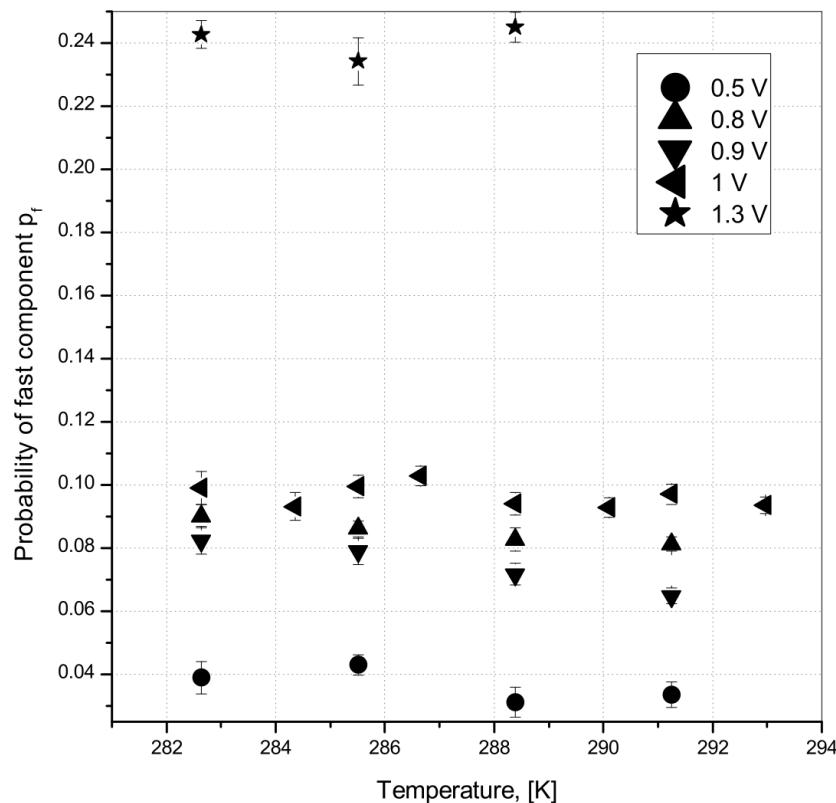
Кросстоки



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Послеимпульсы: вероятность

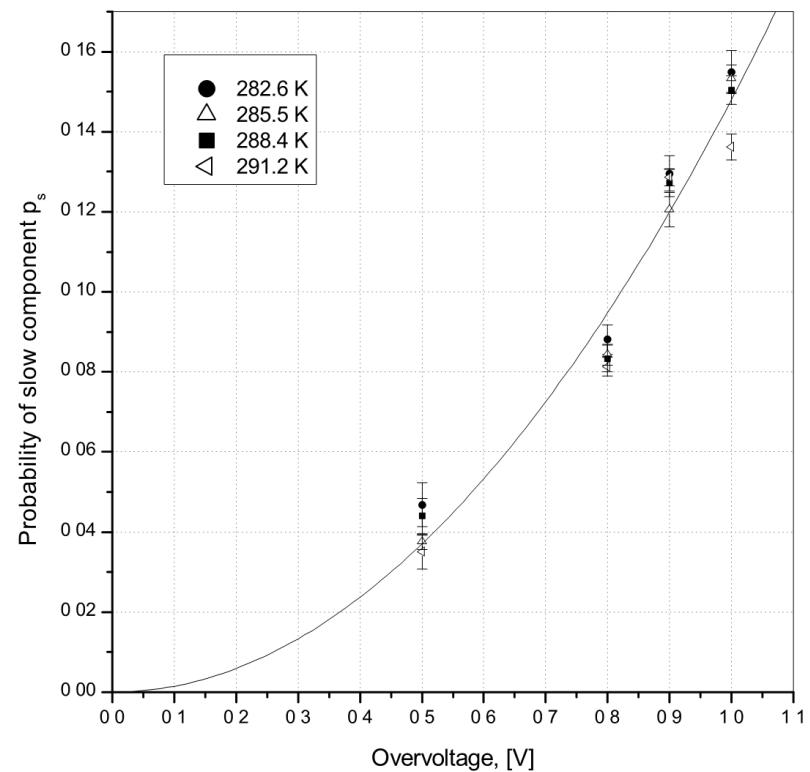
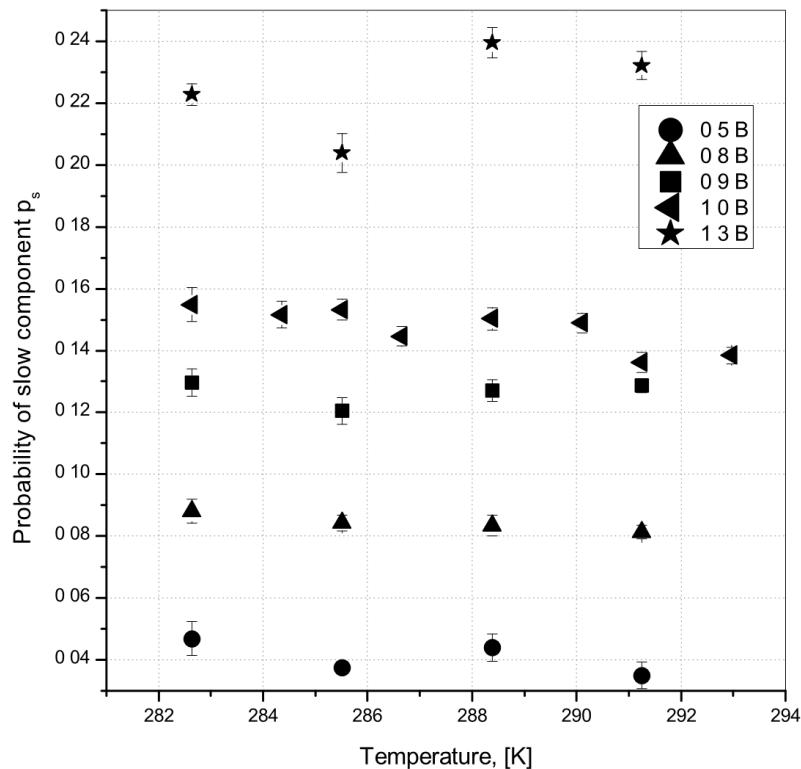
Быстрая компонента



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Послеимпульсы: вероятность

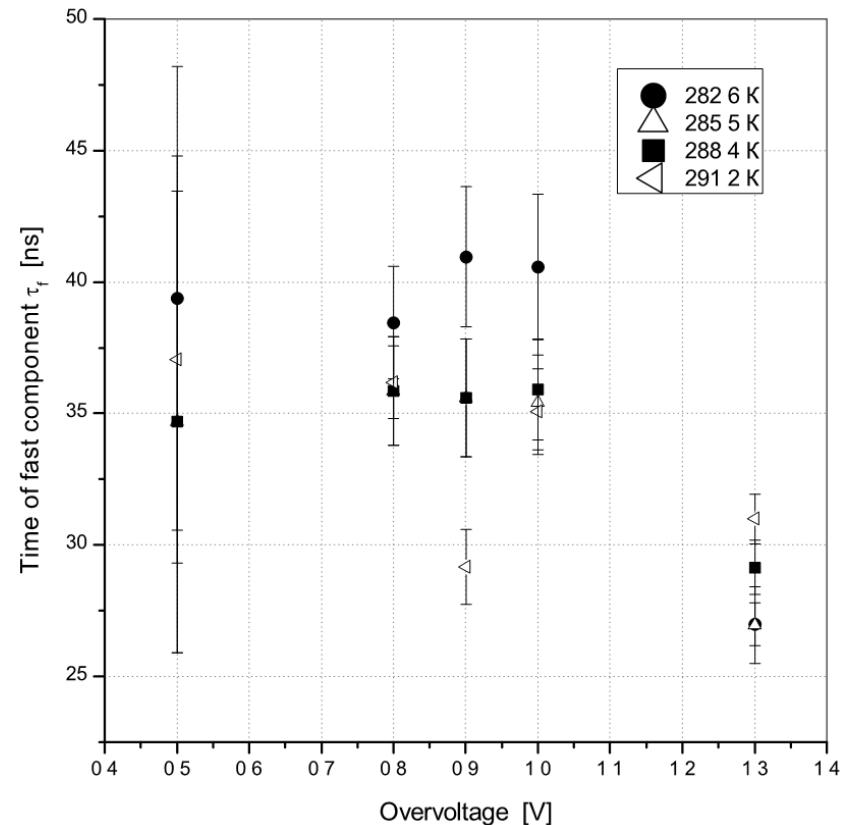
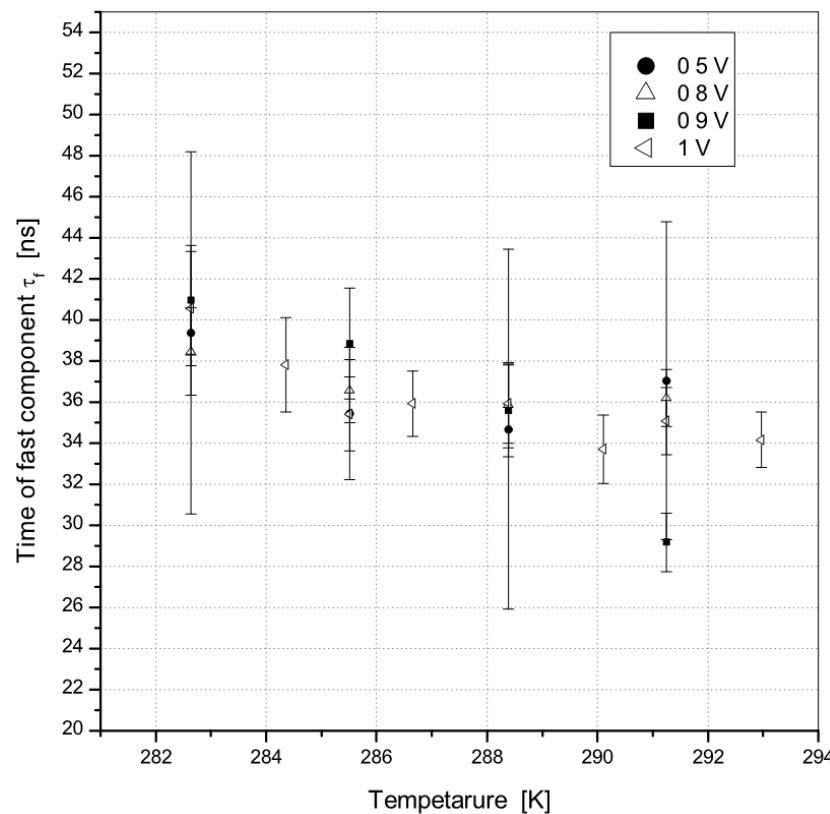
Медленная компонента



Namamatsu S10362-11-100C

Послеимпульсы: постоянная времени

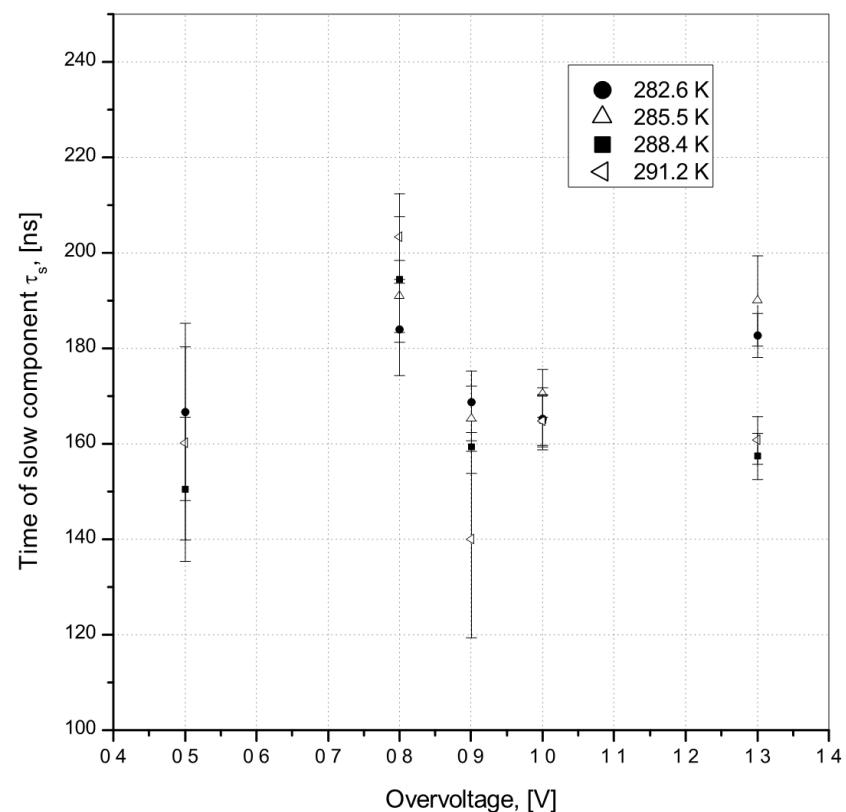
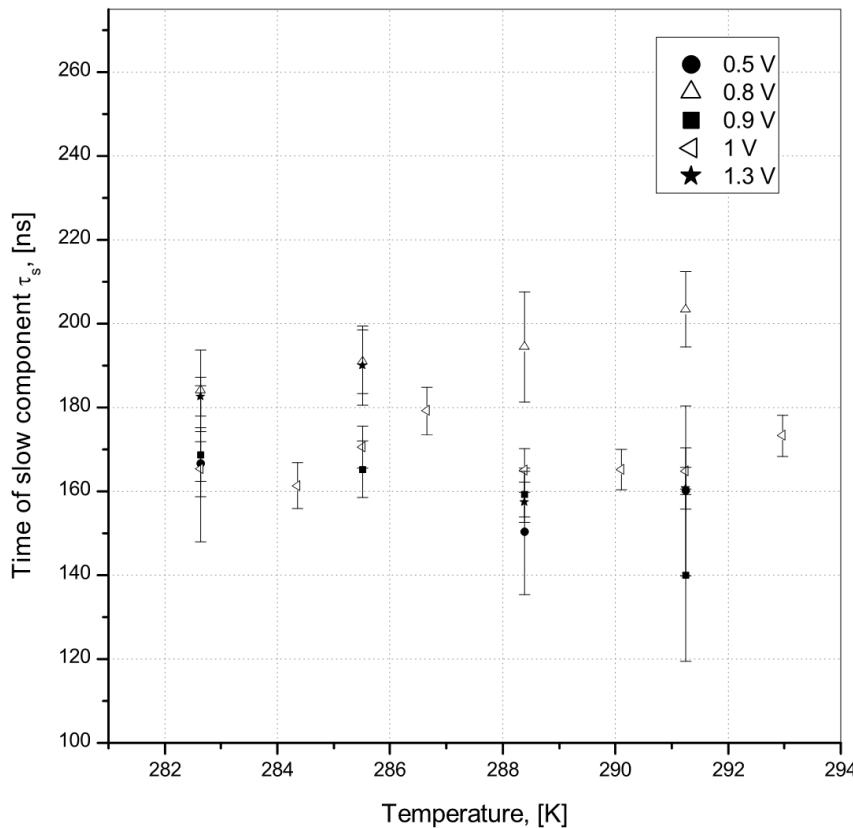
Быстрая компонента



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Послеимпульсы: постоянная времени

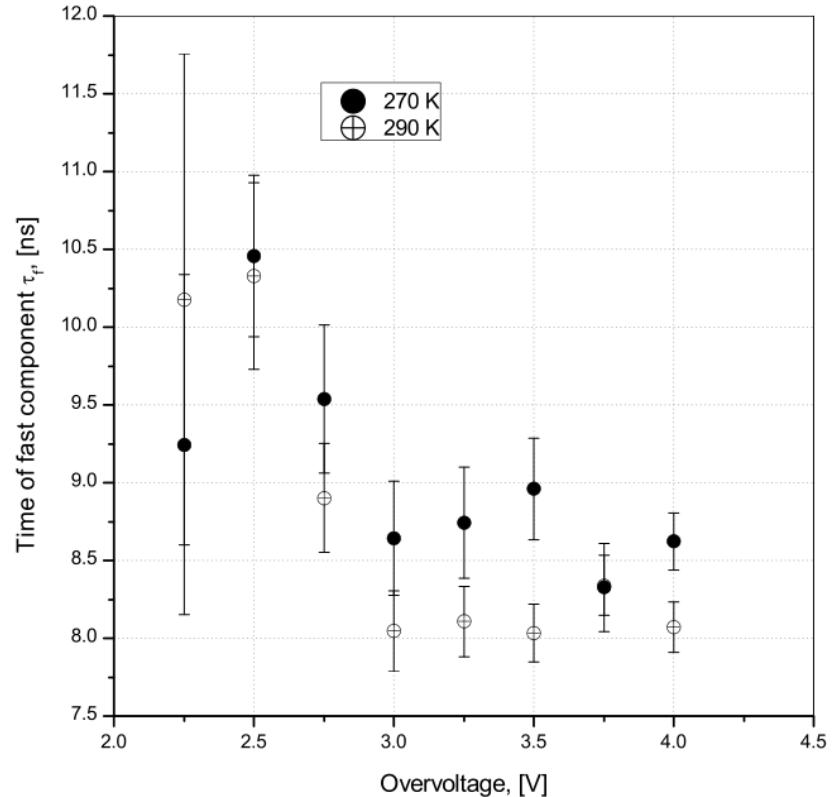
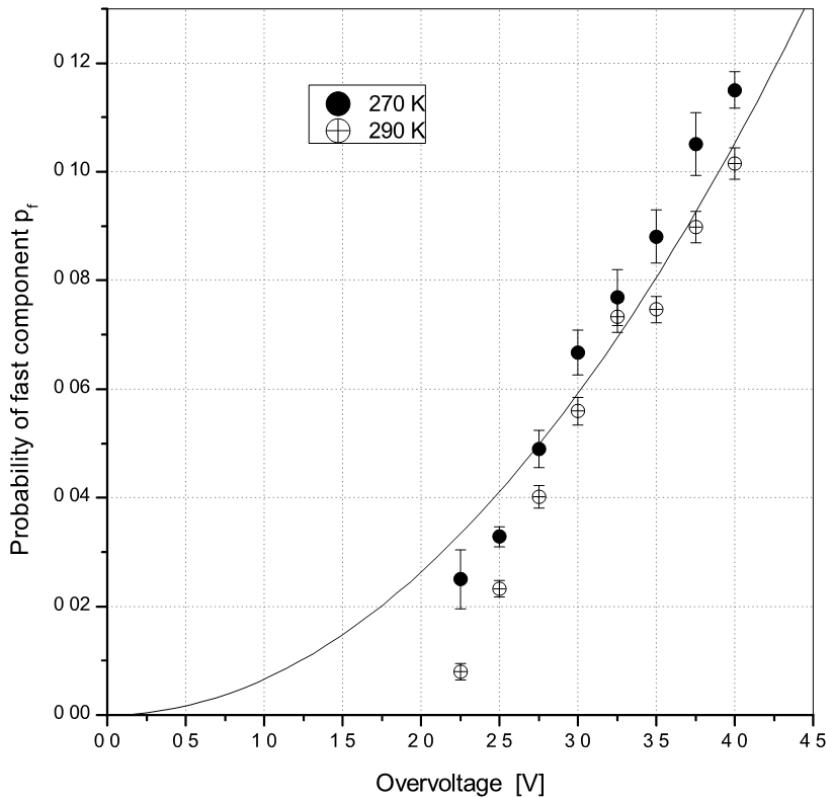
Медленная компонента



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Послеимпульсы

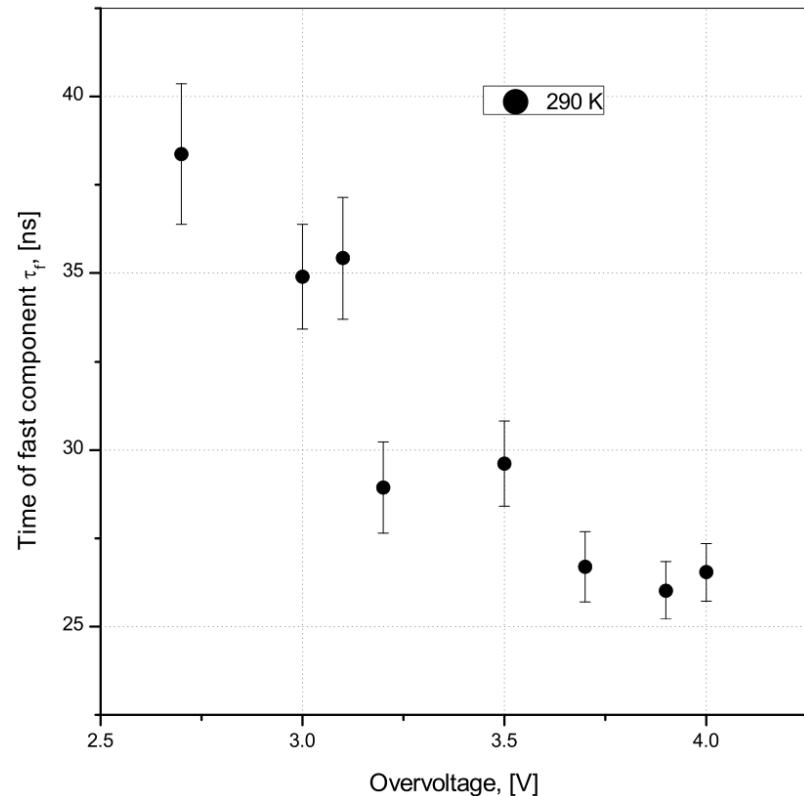
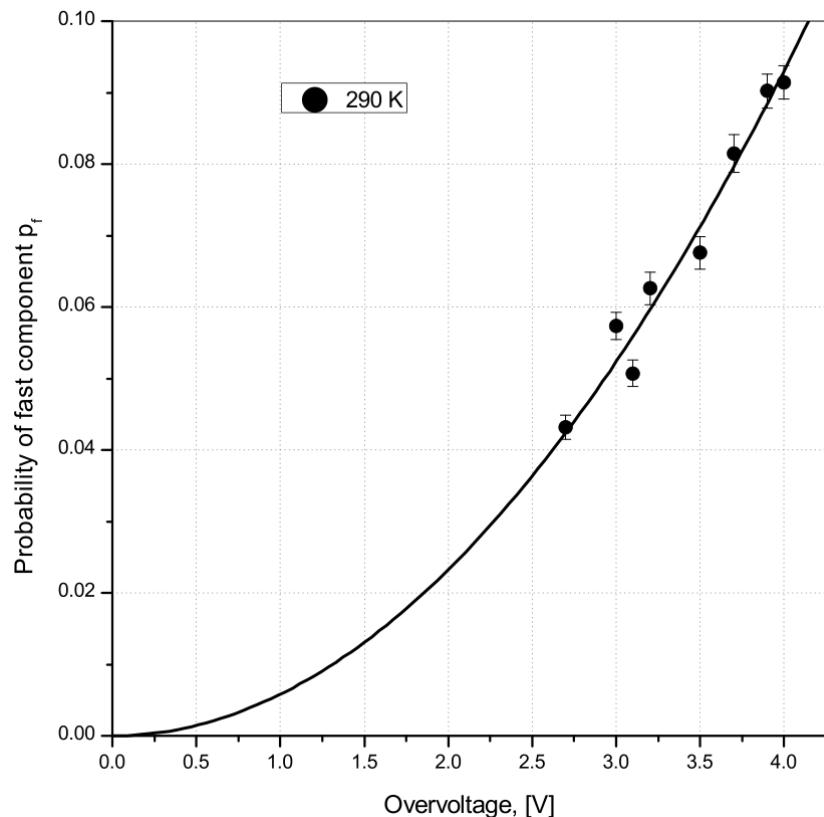
Быстрая компонента



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Послеимпульсы

Быстрая компонента



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