Cold diode radiation testing
- Analysis and Results

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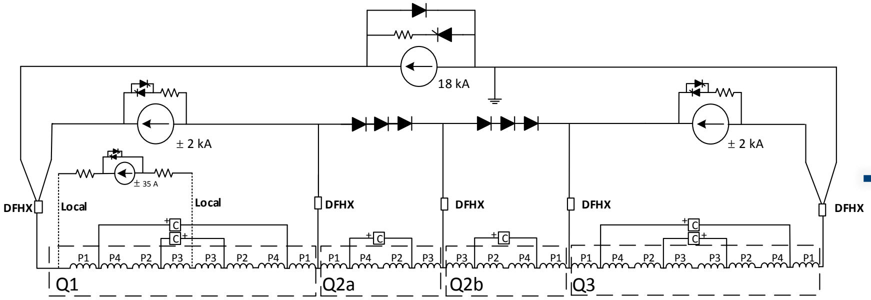
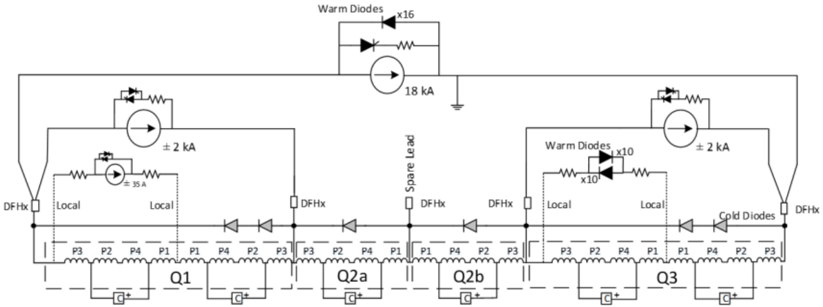
Motivation for the use of cold diodes in HL triplet

- Separate cold and warm parts of the circuit
- Reduce over currents in sc. bus bars and link
  - Sudden quench of one triplet magnet would lead up to 5 kA in the trim leads for a few 100 ms.
- Higher immunity and robustness in case of unexpected delays in quench detection and protections systems



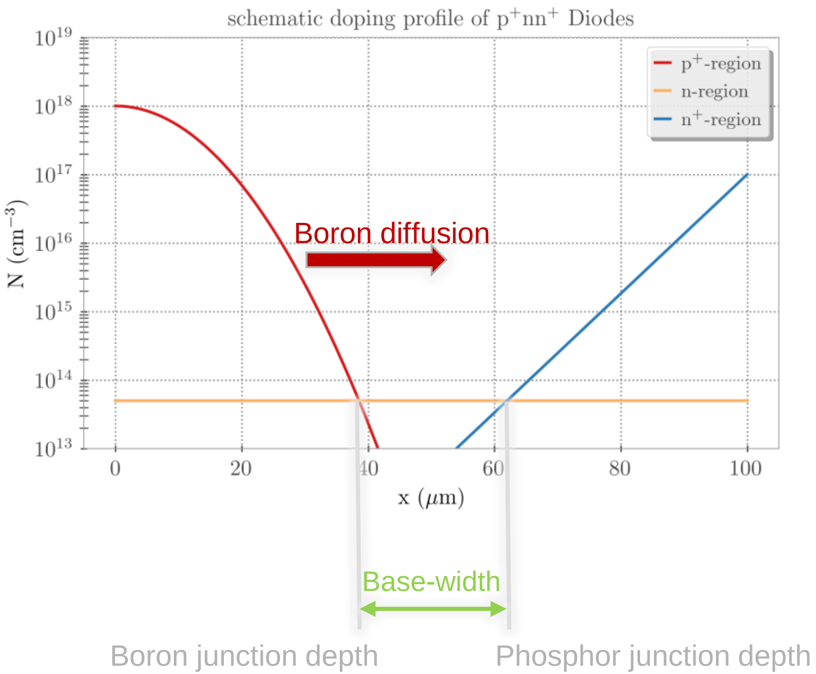


Diode - Base-width definition

- Silicon wafer has a **natural n-doping** level of ~9x10^{13}/cm^3 dopants due to impurities

- for a p^+nn^+ structure:
  - Phosphor doped nn^+ wafer
  - implant Boron
  - drive B-diffusion until desired junction depth is reached

➡ Commercial product!



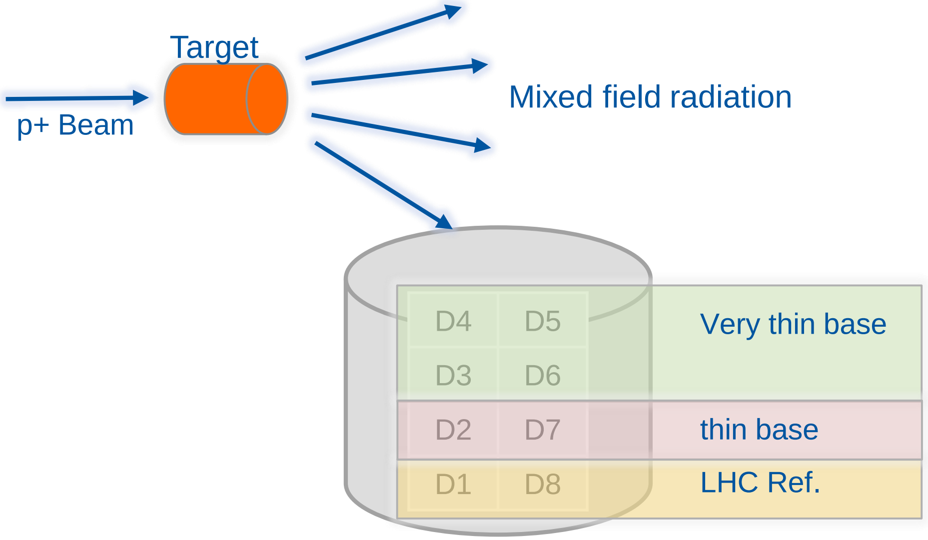
Radiation test setup in CHARM

- Cryocooler based setup with 2x four stacks of cold diodes
- Placed in dedicated position @ CHARM directly downstream of the target

HiLumi HL-LHC PROJECT

Diode labeling convention

- Irradiation campaign in CHARM, using a Cryostat with 8 Diode Prototypes at 4.2K or 77K
- 77K stack
  - D1 - LHC Reference
  - D2 - Thin base
  - D3 - Very thin base
  - D4 - Very thin base
- 4K stack
  - D5 - Very thin base
  - D6 - Very thin base
  - D7 - Thin base
  - D8 - LHC Reference



Experimental Data taken

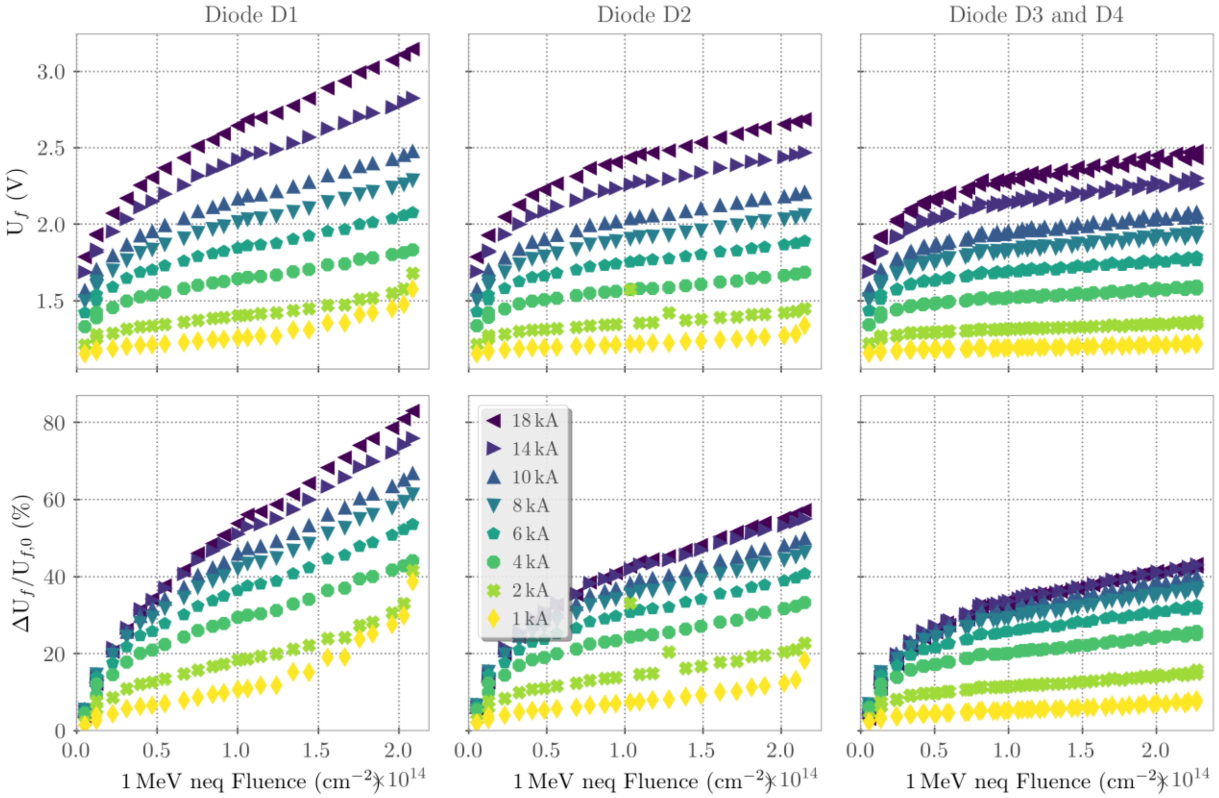
- During the irradiation campaign
  - diodes were **constantly** kept **cold**
  - <4.2K, respectively <77K
- weekly measurements yield diode properties as function of **accumulated total ionizing dose (TID)** and **1MeV Neutron equivalent (neq) Fluence**
- After the end of the run
  - **controlled warm up** and **measurement** of the Diode properties as **function of Temperature**
  - re-cooldown to measure **change of Diode properties** at cold, due to thermal cycle

thermal cycle

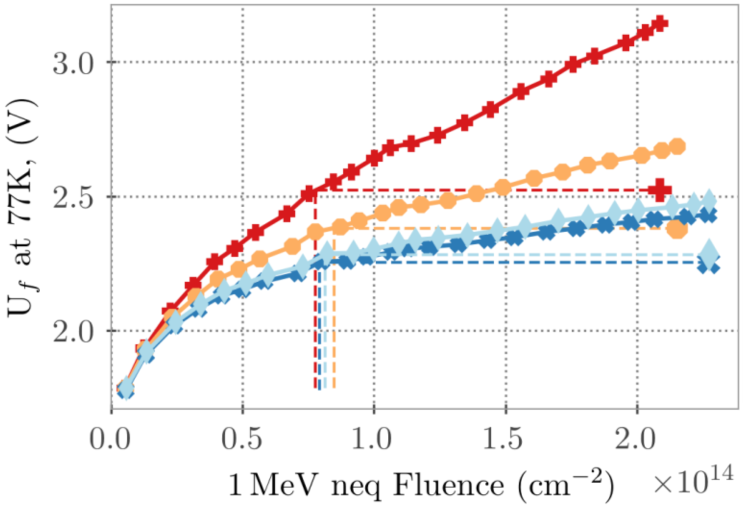
Forward voltage

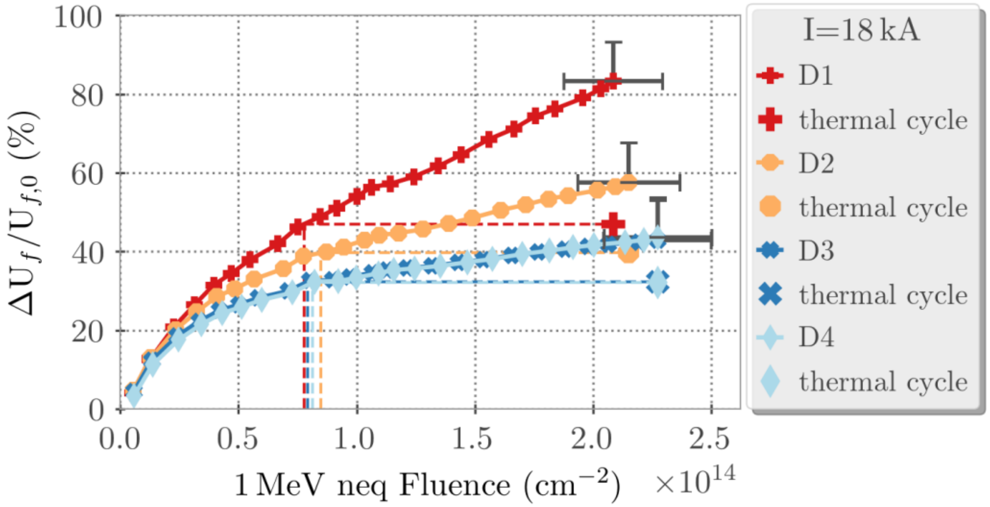
D1 - LHC Reference
D2 - Thin base
D3 - Very thin base
D4 - Very thin base

- Very thin base diodes (D3/D4) show degradation of U_f(18kA)~40%
- LHC type diode (D1) shows degradation of Uf(18kA)~80%
- Stronger relative (all) degradation for higher currents



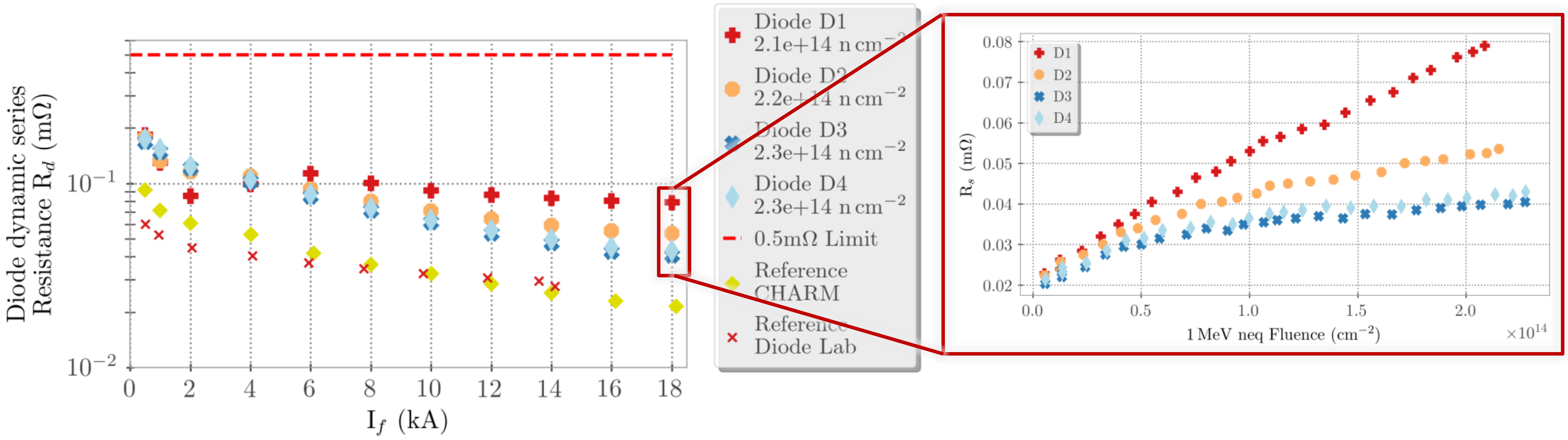
Forward voltage at 18kA – all diode types





- thermal cycle can anneal a significant amount of the displacement damage (details later in this talk)
- Amount of defects annealed is independent of the prototype (thermal process)
- resulting in a reduction of the forward voltage

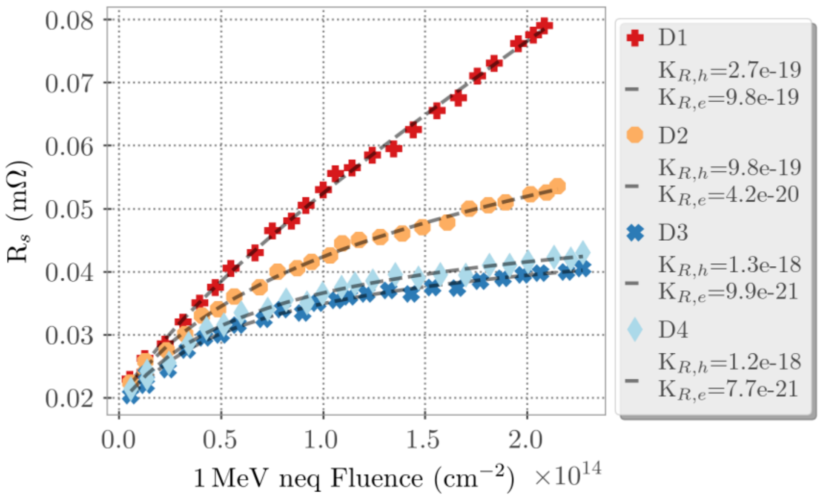
Series resistance of the diodes



- Dynamic series resistance calculated numerically from measurements $\Delta U/\Delta I$
- Series resistance is well below the HL-LHC circuit design limit of 0.5 mΩ

Resistance and carrier lifetimes

D1 - LHC Reference
D2 - Thin base
D3 - Very thin base
D4 - Very thin base



- resisitivity of n-base depends on two lifetimes for e/h

$$\rho = \frac{1}{\frac{e^2}{m_e} n \tau_e + \frac{e^2}{m_h} p \tau_h}$$

- each lifetime should degrade linearly with fluence

$$\frac{1}{\tau_{e/h}} = \frac{1}{\tau_{0,e/h}} + K_\tau \Phi_{neq}$$

- different degradation for e/h lifetimes results to non-linear growth of measured base-resistance

$$R = \frac{1}{(R_{0,e} + K_{R,e}\Phi_{neq})^{-1} + (R_{0,h} + K_{R,h}\Phi_{neq})^{-1}}$$

Schockley Equation

$$U = IR_s + \frac{2k_BT}{e}\ln\left(I/I_s + 1\right)$$

Power diode voltage characteristics described by Schockley Equation

$$\rho = \frac{1}{\frac{e^2}{m_e}n\tau_e + \frac{e^2}{m_h}p\tau_h}$$

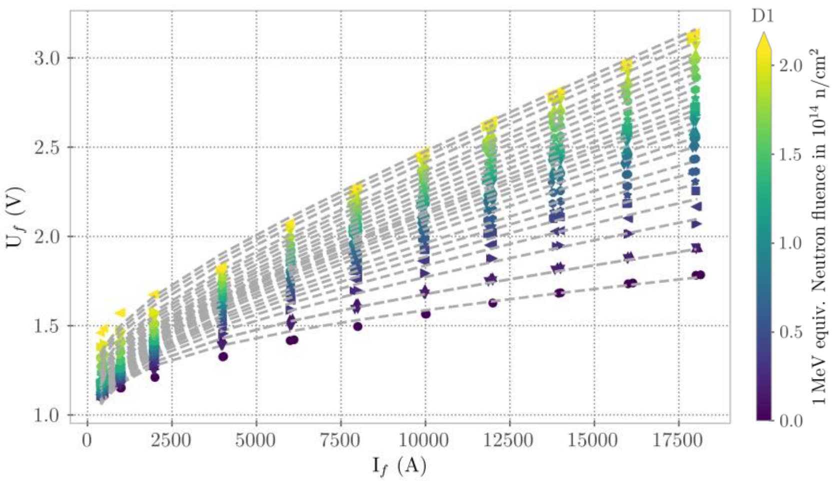
- Series resistance R_s
- I_s (diffusion- and recombination current)

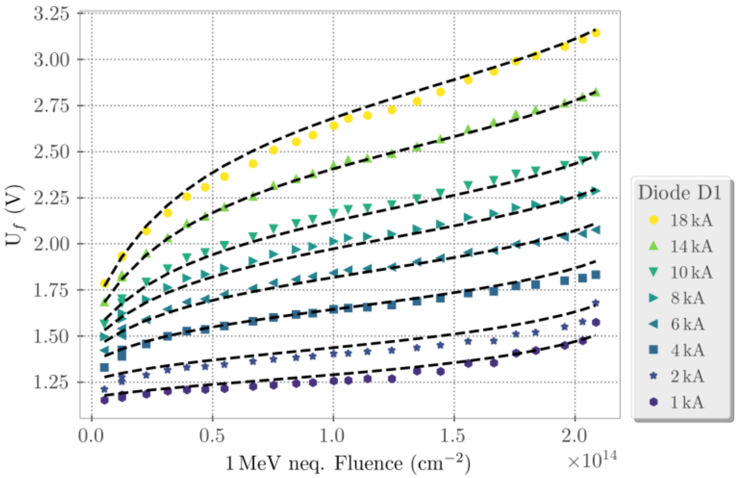
still valid?

$$I_s = I_{s0} + K_I \cdot \Phi_{neq}$$

Fit - Linear I_s model

2D input data over full measurement campaign is fitted on the model Uf(I,Φ,T=77K), assuming linear model for I_s





Fit - Linear I_s model

- **I_s approaches zero** in this model, (regime of high damage), for Diode D1
  - this is reflected in the more-than-linear growth of U_f for smaller currents, in accordance to Schockley equation.
- BUT negative current is not physically meaningful
- linear model can only be an approximation, close to zero should flatten out

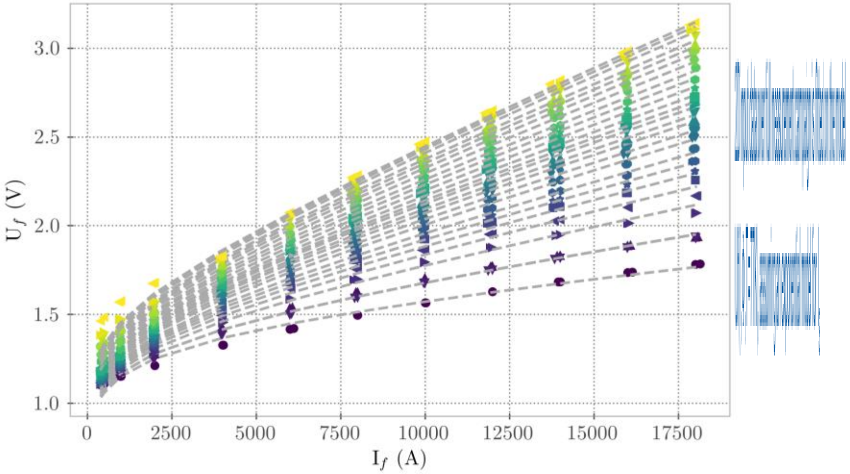
- Exponential model, where first order approximation is the linear model

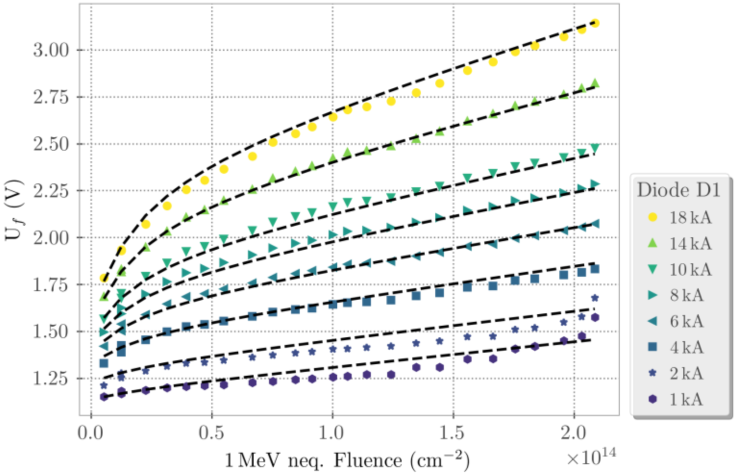
$$I_s(\Phi_{neq}) = I_{s,0} \cdot \exp\left(-K_I \Phi_{neq}\right)$$

$$\approx I_{s,0} - K_I \Phi_{neq} + \mathcal{O}(K_I \Phi_{neq})^2$$

Fit - exponential I_s model

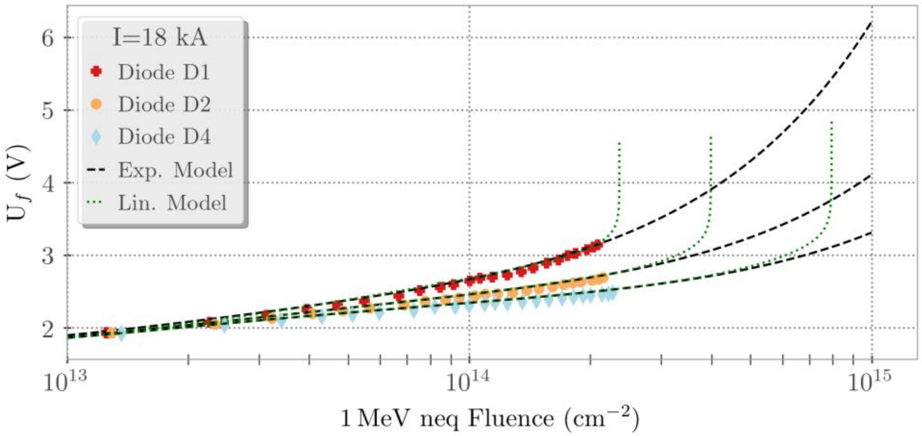
2D input data over full measurement campaign is fitted on the model $U_f(I, \Phi, T=77K)$, assuming an exponential model for I_s



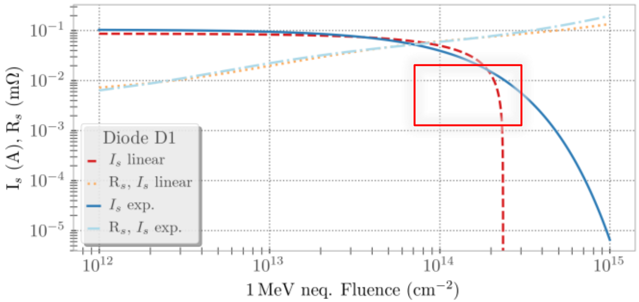


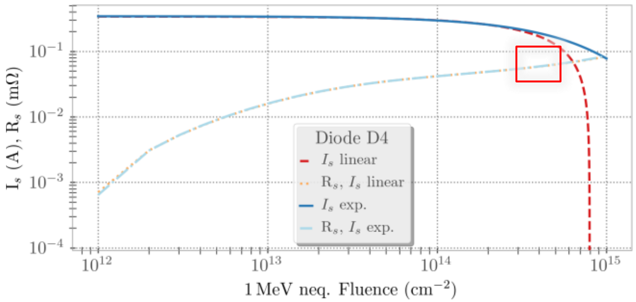
Fits: Comparison and Extrapolation

- Difference in the models becomes clear when extrapolating
- Divergence in the linear model is not physical and cancelled out in the exp. model.
- **Series resistance** part is **barely affected, fit is very good, separating the two effects** (see Schockley equation)

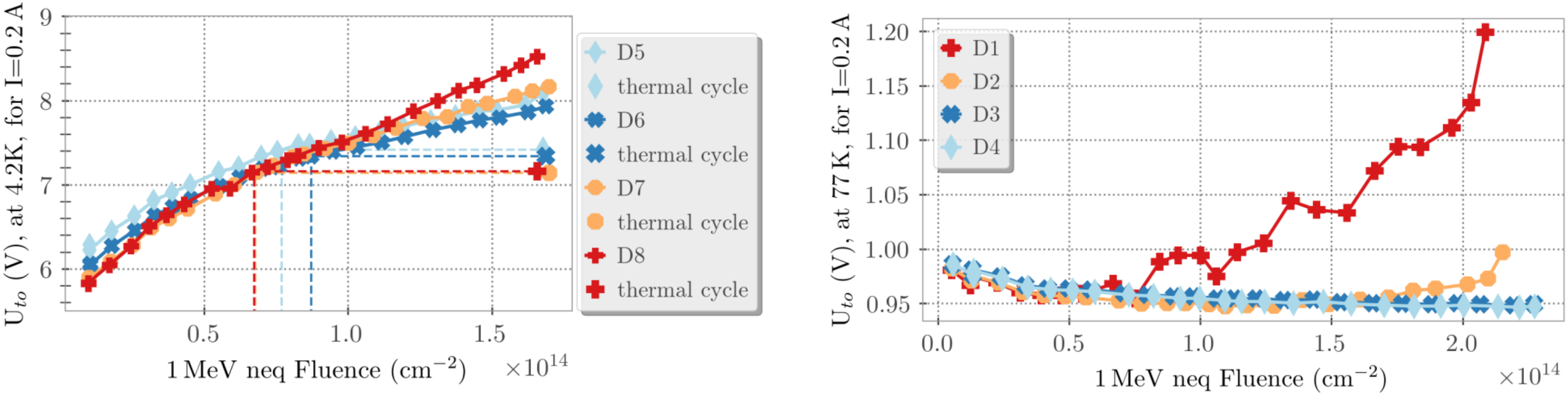


First order model no longer valid





Turn-on voltage – all prototypes

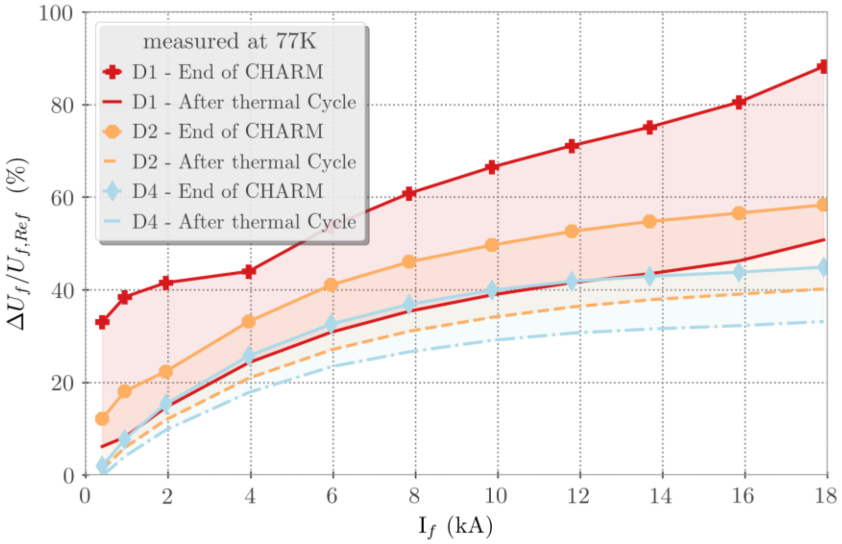


- At 77K only the LHC reference shows unusual increase of U_{to}

Thermal annealing – Forward voltage at 77K

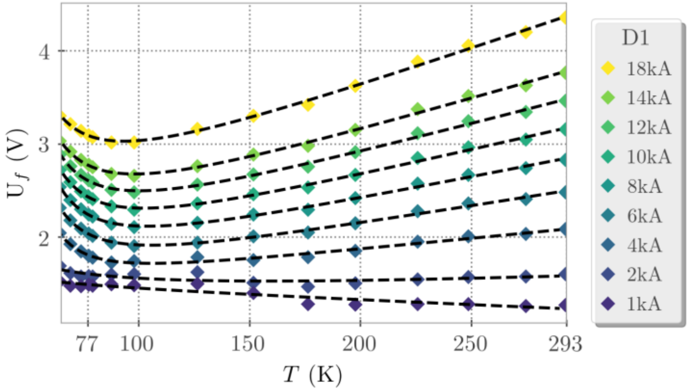
D1 - LHC Reference
D2 - Thin base
D3 - Very thin base
D4 - Very thin base

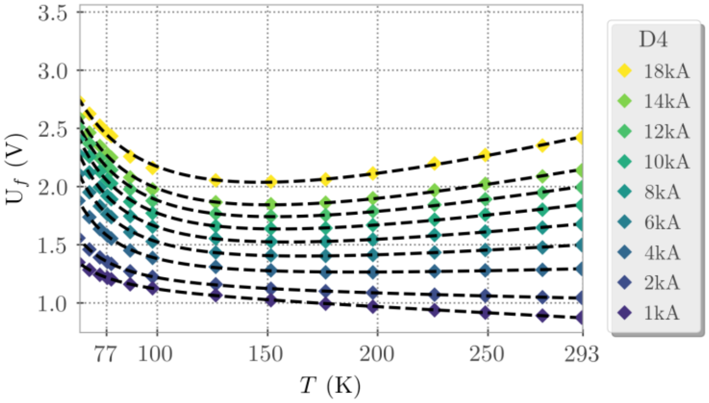
- Comparison of thermal annealing for all diode prototypes
- Annealing for all current levels
- Unusual bump in the LHC-reference Diode curve, as observed before, was annealed



Fit on $U_f(T)$

$$U = IR_s + \frac{2k_BT}{e}\ln\left(I/I_s+1\right)$$





$$U_f(T) = C1 \cdot exp(T_0/T) + C2 \cdot T + C3$$

- Only one warm up at the end
  - Therefore, only two values in time for Fluence

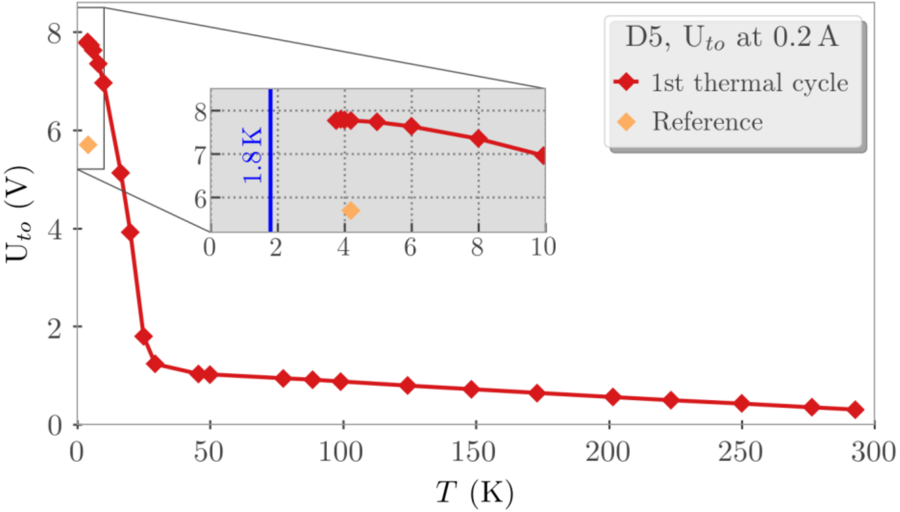
  -> difficult to benchmark model.

- Fit works very well and can be used for thermal modelling of diodes, when analytical formulation is needed over interpolation.

As in "Expected Lifetime of By-pass diodes for the LHC magnet protection subjected to LIQUID helium temperatures and irradiation" -** *R.Denz, D. Hagedorn*

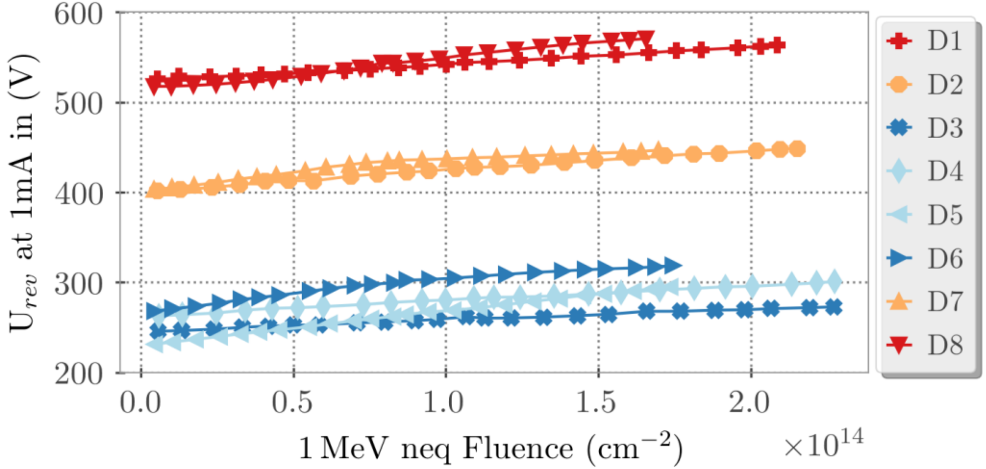
Thermal annealing – Turn-on voltage

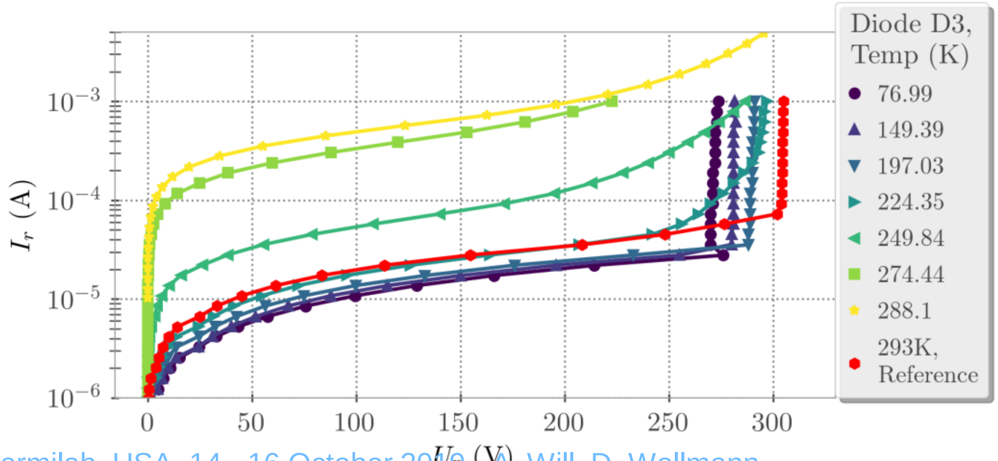
- Little annealing observed (~0.5V)
- in LHC dipoles: ELQA-team has measured U_{to} at 1.8K, no steep increase compared to measured values at 4.2K has been seen.
  - projection to 1.8K feasible from temperature dependent measurements, performed down to 3.5K



Reverse bias voltage

- slight increase of reverse voltage at -1mA observed with increasing 1MeV neq Fluence
- Prototypes of same kind behave similarly
  - very thin base prototypes have larger spread in U_r by manufacturing design
- thermal cycle revealed large increase in leakage current at elevated temperatures (as expected for p^+nn^+ diodes)
  - largely suppressed at cryogenic temperatures
  - not an issue for HL-LHC anyways





Passivation layer - radiation hardness

- ‘Durimide 10/32’ is used
- Poly**i**mide/Poly**a**mide

up to MGy

dependent on specific Material,
from 10s of kGy to MGy ...

- For HL-LHC dose levels, both materials should be suitable, however, polyimide provides far more margin in terms of dose resistance
- At a gamma source: Insulation strength of samples could be tested up to MGy levels

Conclusion

- Three different types of power diodes have been successfully tested in charm up to ~2.2 x 10^{14} 1MeV equiv. n cm^{-2} and 12 kGy → equivalent to the expected levels in future position close to D1
- All diodes full-fill the electrical requirements after irradiation
  - LHC reference type diode worst during the test
  - Very thin base width type best as least sensitive to radiation
- Exponential model proposed to describe the degradation of the diffusion and recombination current I_s as function of neutron fluence → avoids divergence issue of linear model and allows extrapolations until 10^{15} 1MeV equiv. n cm^{-2}.
- Radiation resistance of passivation layer should be measured
- Cold diodes are now baseline for HL inner triplet circuit

Thanks for the attention!

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