SiPM status
and FY203 plans

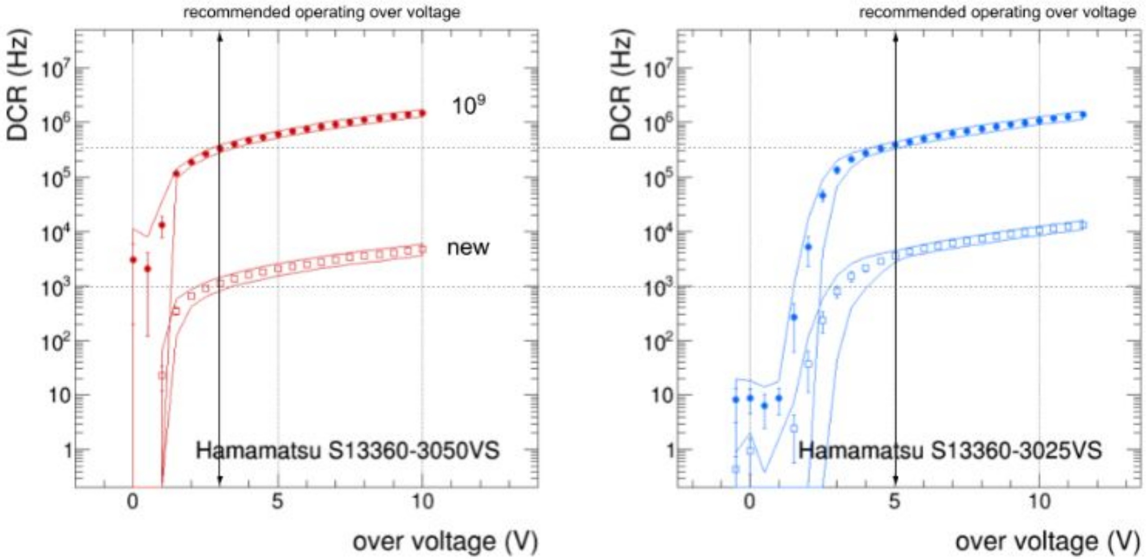
Roberto Preghenella

Outline

- highlights from 2021 and 2022 irradiation / characterisation campaigns
- highlights from 2022 beam tests
- plans for FY2023

small vs. large SPAD sensors

sensors with small SPADs have lower SNR



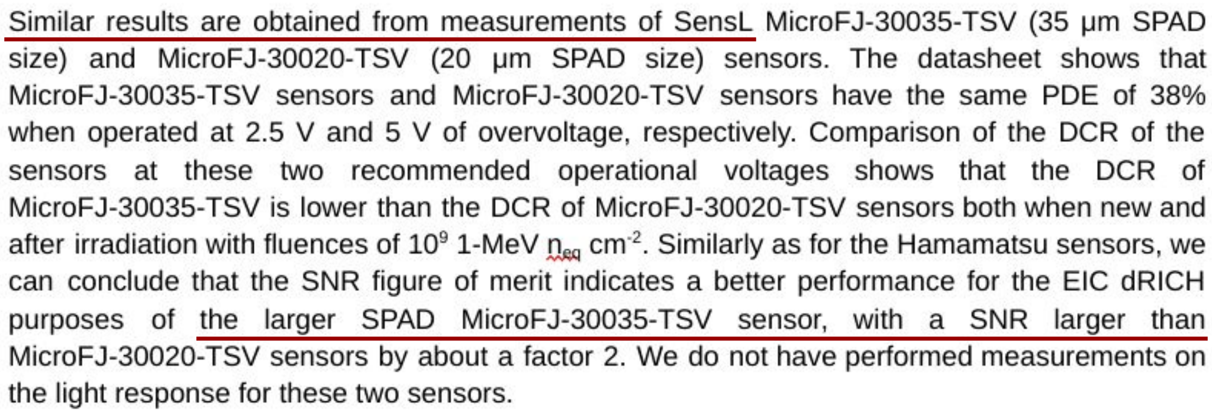
A comparison of the measured DCR shows that at the recommended operation voltages of 3 volts and 5 volts for the S13360-3050VS and S13360-3025VS sensors the DCR of S13360-3050VS is the lowest when the sensors are new. S13360-3050VS and S13360-3025VS sensors show the same DCR after irradiation of a fluence of 10^9 1-MeV n_{eq} cm^{-2}. In all cases, the performance of S13360-3050VS sensors is better than S13360-3025VS because

- the PDE is higher
- the DCR is lower or the same

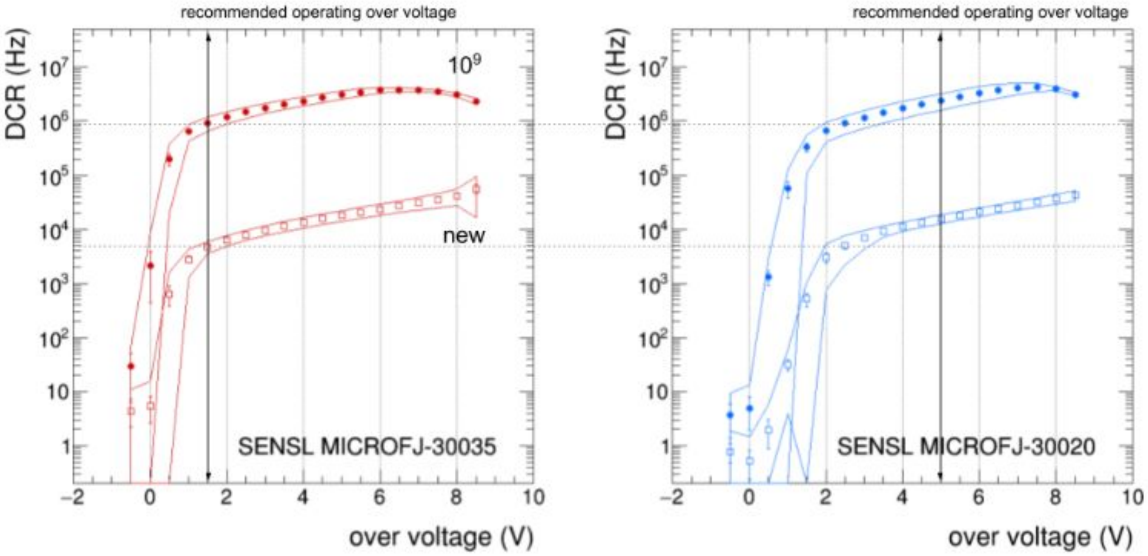
which means that at all stages the signal-to-noise ratio (SNR) figure of merit of S13360-3050VS sensors is higher than S13360-3025VS. For new sensors the SNR of S13360-3050VS is a factor ~ 5 higher than S13360-3025VS.

small vs. large SPAD sensors

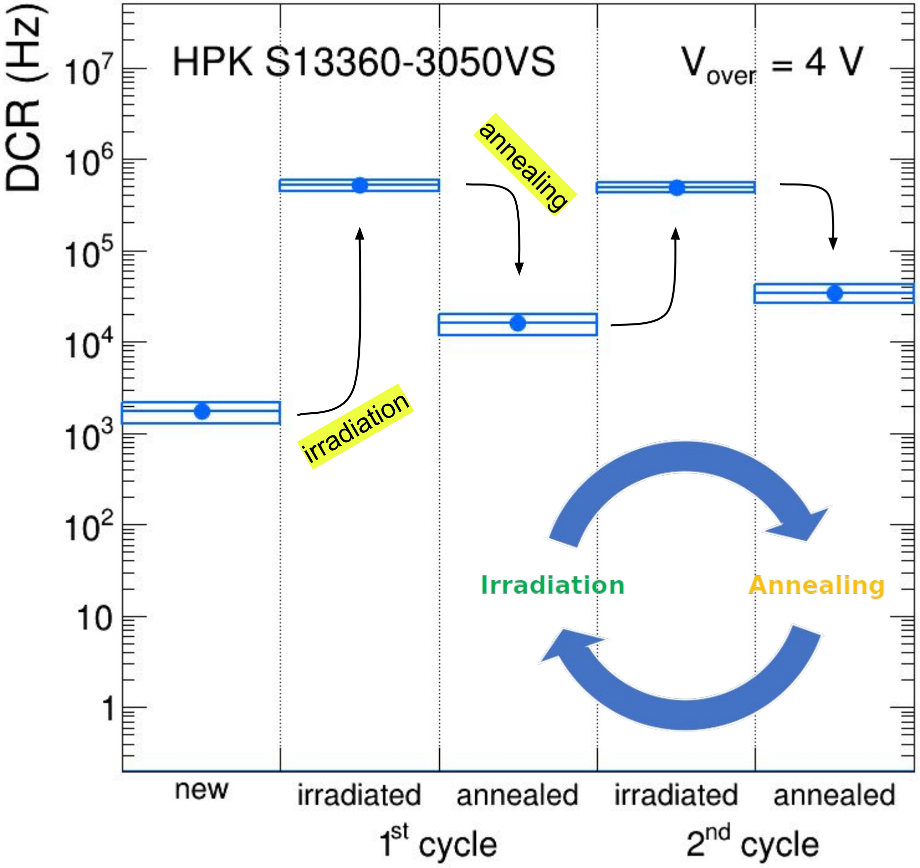
sensors with small SPADs have lower SNR



Similar results are obtained from measurements of SensL MicroFJ-30035-TSV (35 µm SPAD size) and MicroFJ-30020-TSV (20 µm SPAD size) sensors. The datasheet shows that MicroFJ-30035-TSV sensors and MicroFJ-30020-TSV sensors have the same PDE of 38% when operated at 2.5 V and 5 V of overvoltage, respectively. Comparison of the DCR of the sensors at these two recommended operational voltages shows that the DCR of MicroFJ-30035-TSV is lower than the DCR of MicroFJ-30020-TSV sensors both when new and after irradiation with fluences of 10^9 1-MeV n_{eq} cm^{-2}. Similarly as for the Hamamatsu sensors, we can conclude that the SNR figure of merit indicates a better performance for the EIC dRICH purposes of the larger SPAD MicroFJ-30035-TSV sensor, with a SNR larger than MicroFJ-30020-TSV sensors by about a factor 2. We do not have performed measurements on the light response for these two sensors.



Repeated irradiation-annealing cycles

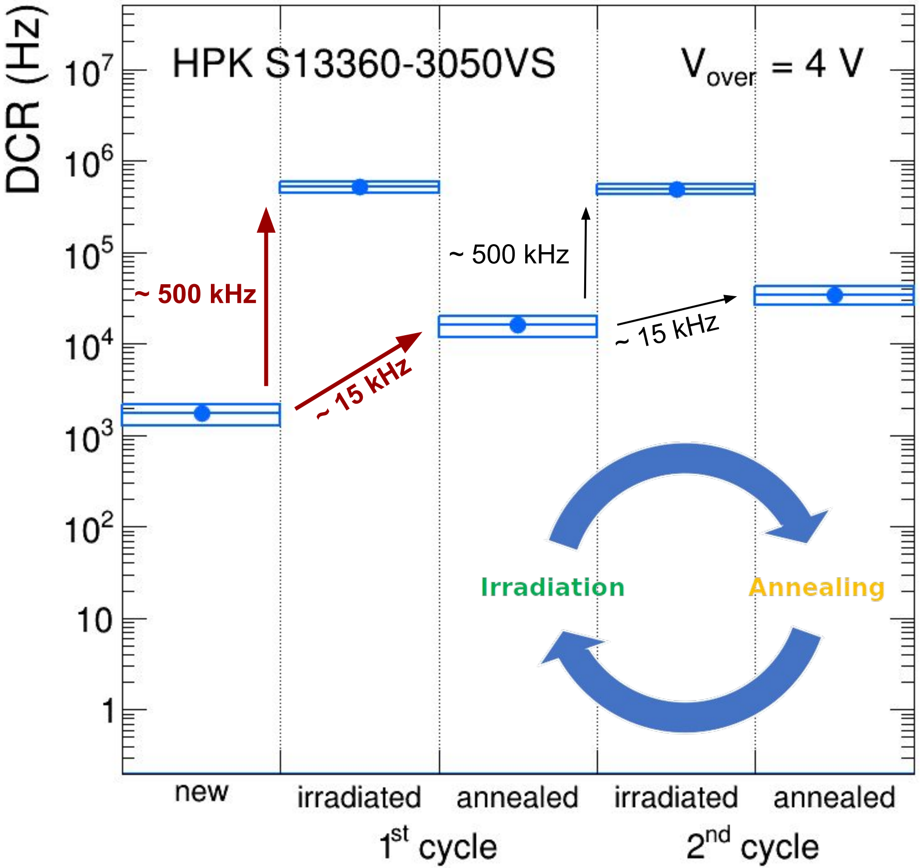


test reproducibility of repeated irradiation-annealing cycles

simulate a realistic experimental situation

- campaign is concluded
    - partial results reported here
    - all measurements in following slides
- 4 cycles performed in 2022
    - irradiation fluence/cycle of 10^9 n_{eq}
    - annealing in oven for 150 hours at 150 °C
- interleaved with full characterisation
    - new
    - after each irradiation
    - after each annealing

Repeated irradiation-annealing cycles



test reproducibility of repeated irradiation-annealing cycles

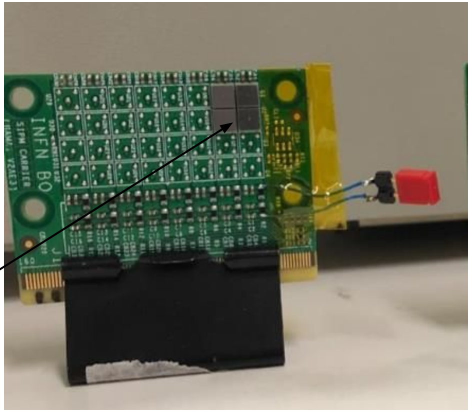
simulate a realistic experimental situation

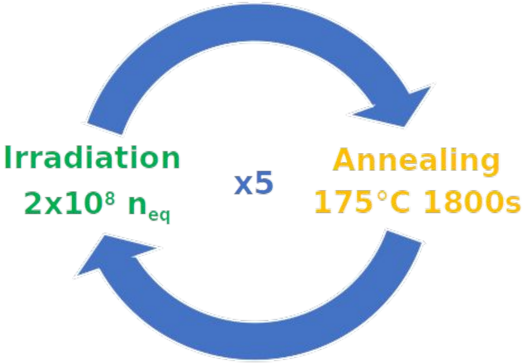
- consistent irradiation damage
  - DCR increases by ~ 500 kHz (@ Vover = 4)
  - after each shot of 10^9 n_{eq}
- consistent residual damage
  - ~ 15 kHz (@ Vover = 4) of residual DCR
  - builds up after each irradiation-annealing

annealing cures same fraction of newly-produced damage

~ 97% for HPK S13360-3050 sensors

Online annealing





Irradiation
2×10^8 n_{eq}

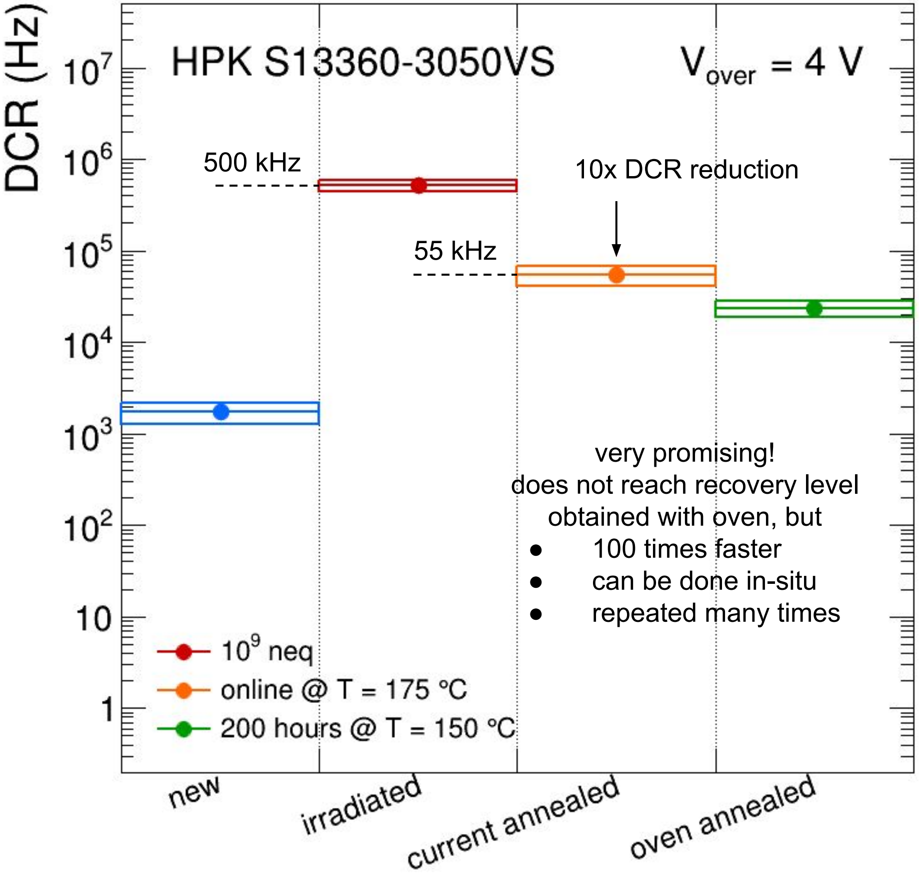
x5

Annealing
175°C 1800s

explore solutions for in-situ annealing

- total fluence of 10^9 n_{eq}
  - delivered in 5 chunks
  - each of 2 10^8 n_{eq}
- interleave by annealing
  - forward bias, ~ 1 W / sensor
  - T = 175 °C, thermal camera
  - 30 minutes
- preliminary tests
  - Hamamatsu S13360-3050

Online annealing



500 kHz

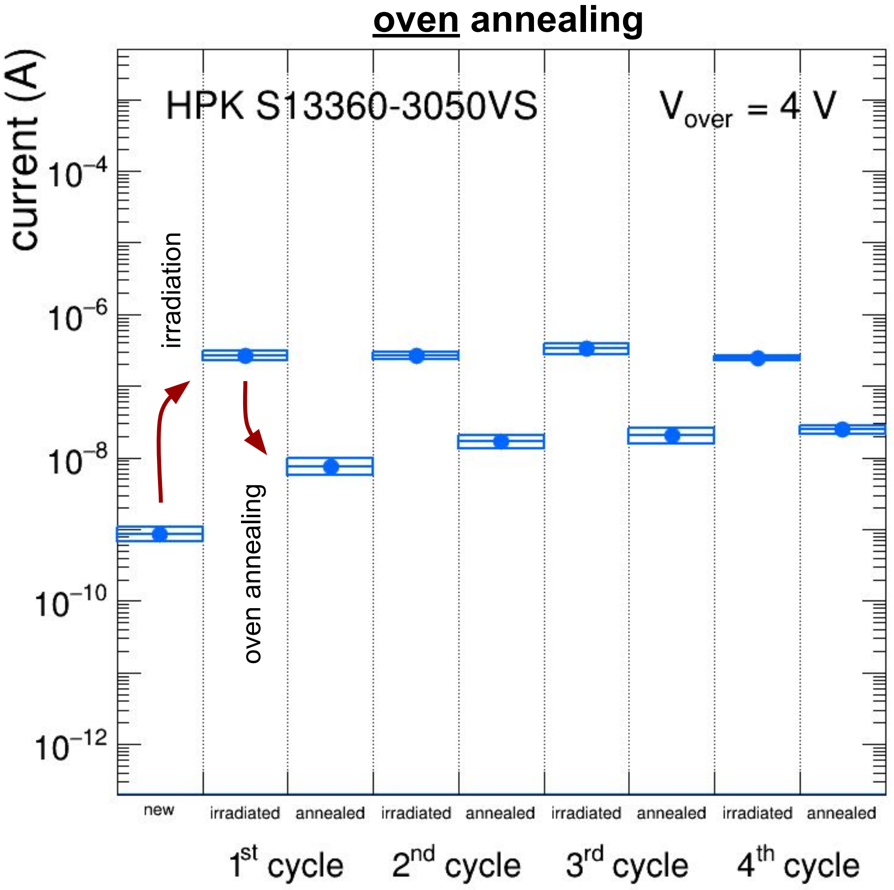
55 kHz

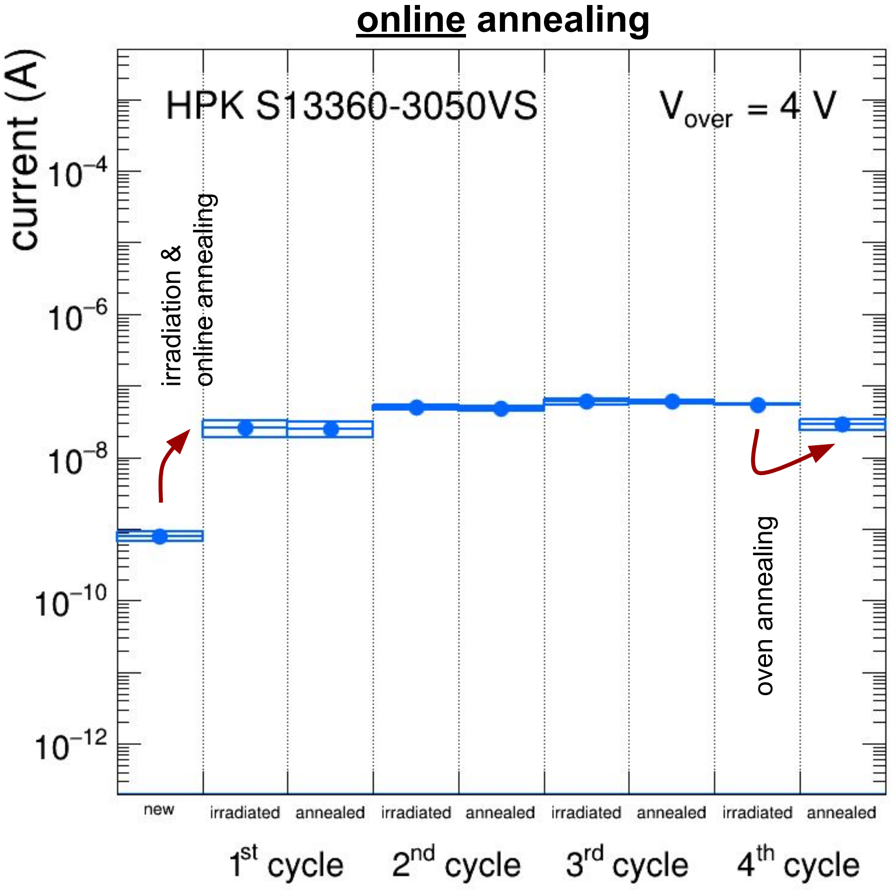
10x DCR reduction

very promising!
does not reach recovery level
obtained with oven, but

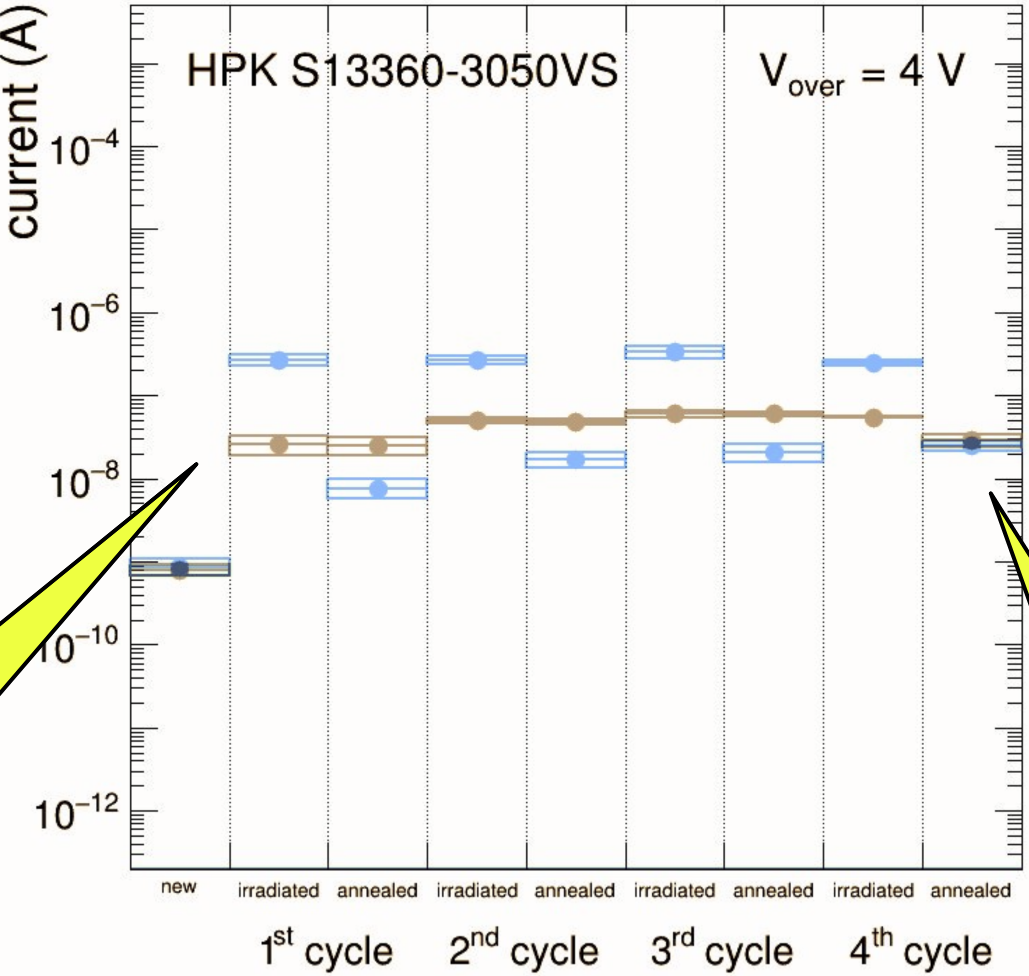
- 100 times faster
- can be done in-situ
- repeated many times

Repeated annealing results





online annealing in 2022 was playground (only two sensors) and must be seriously tested (250 mA over TSV)



online-annealed sensors reach same DCR as oven annealed

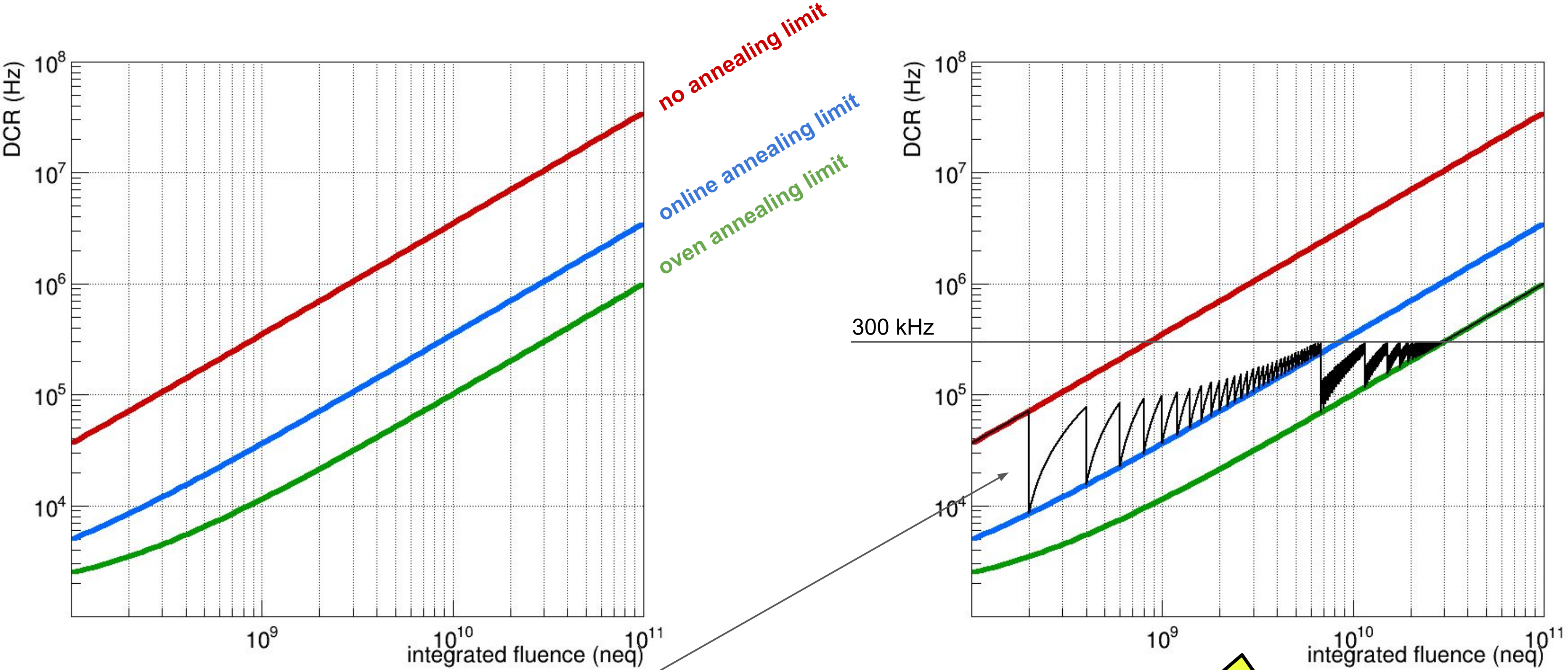
online annealing an effective operational way to mitigate DCR increase in the experiment

oven annealing does better job online-annealed sensors can be oven-annealed after some time to gain further reduction

Radiation damage model (HPK S13360-3050 @ Vover = 3 V)

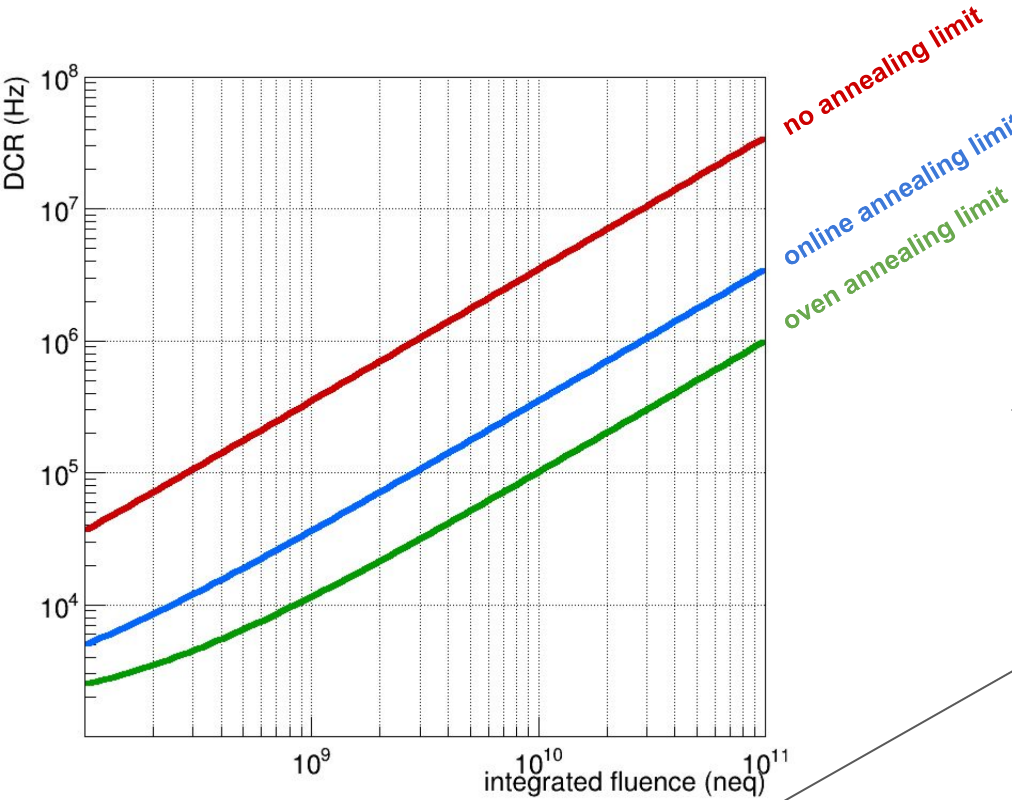
- **reasonable assumptions**
    - radiation damage is additive
    - does not know and care of the past damage
    - annealing heals up to a certain fraction of damage, not more than that
- **numbers**
    - DCR when new = 1.5 kHz
    - DCR increase with radiation damage = 350 kHz / 10^9 neq
    - DCR increase with online annealing = 35 kHz / 10^9 neq
    - DCR residual after oven annealing = 3%
- **how it works?**
    - start with DCR as new → NEW
    - add DCR with increasing radiation → NEW + NIEL1
    - heal with annealing → NEW + x NIEL1
    - add DCR with increasing radiation → NEW + x NIEL1 + NIEL2
    - heal with annealing → NEW + x (NIEL1 + NIEL2)

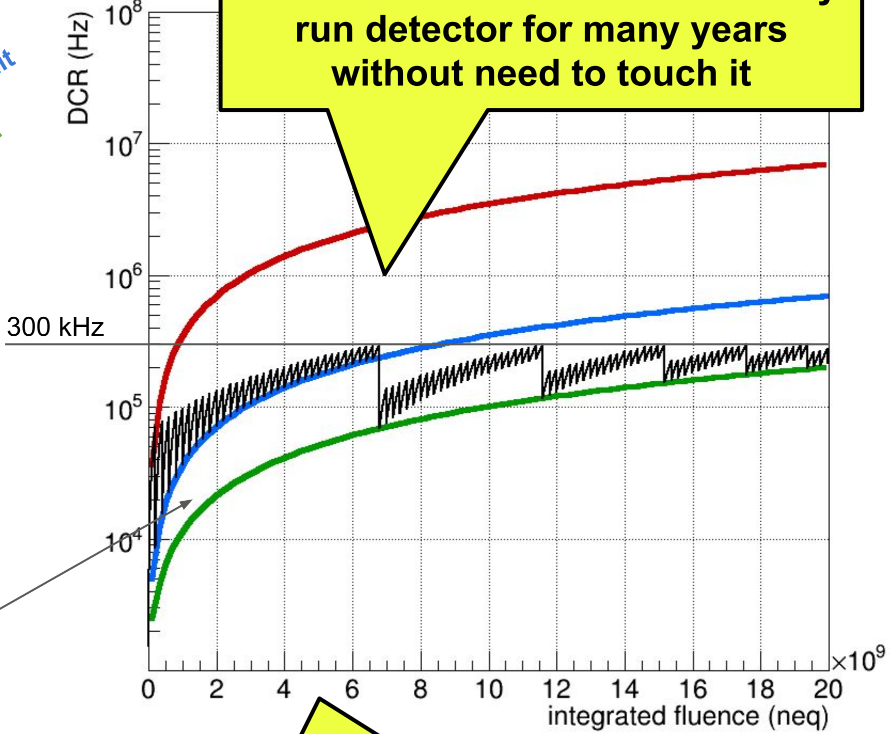
this is an old set of slides, these reasonable assumptions have been verified



online annealing every 2 10^8 neq (many times)
oven annealing when DCR > 300 kHz (few times)

online annealing extends detector lifetime by 10x



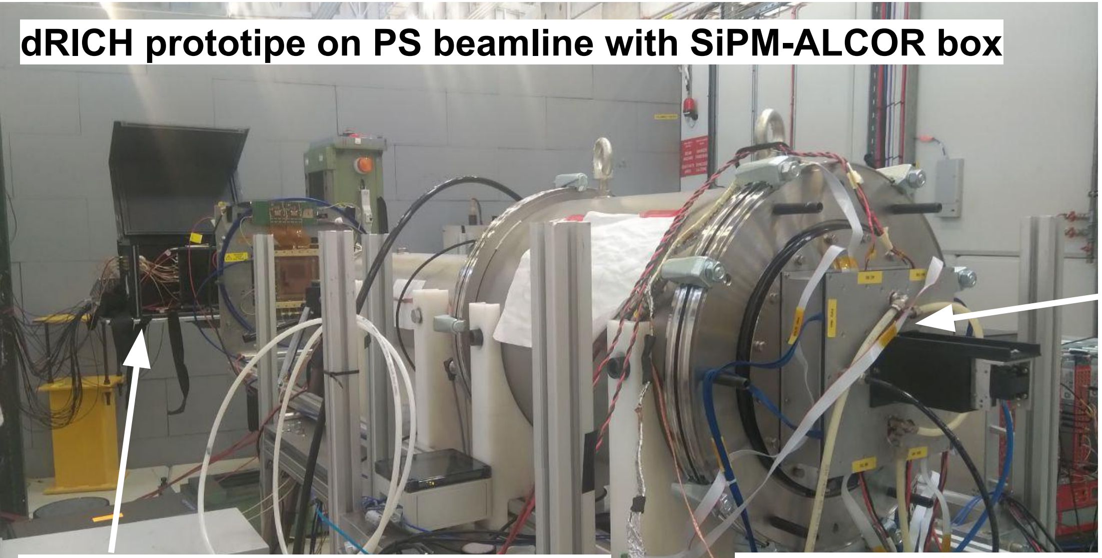


> 6x 10^9 it should be ok to initially run detector for many years without need to touch it

online annealing every 2 10^8 neq (many times)
oven annealing when DCR > 300 kHz (few times)

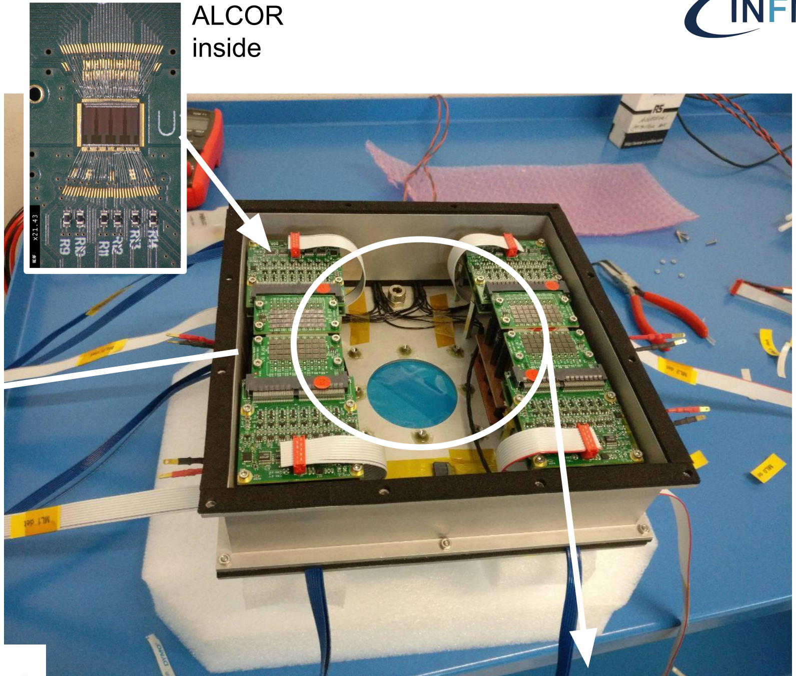
this is an old estimate, numbers as ballpark there are more ways to stay < 300 kHz (lower T, …)

2022 test beam at CERN-PS



dRICH prototipe on PS beamline with SiPM-ALCOR box

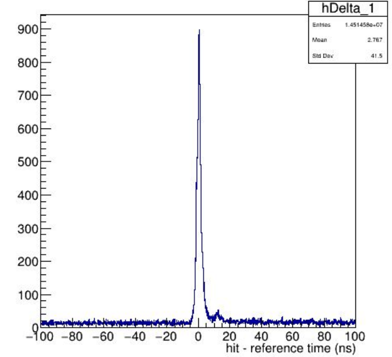
beamline shared with LAPPD test



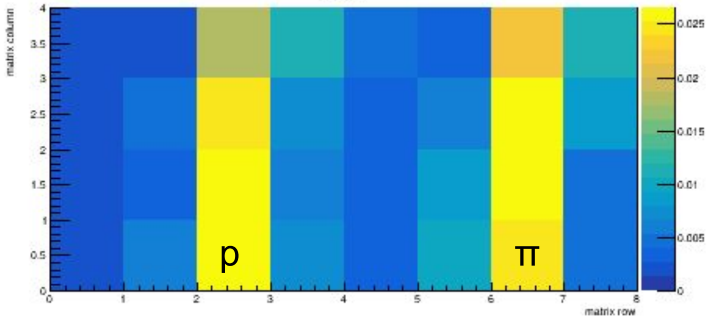
ALCOR
inside

successful operation of SiPM
irradiated (with protons up to 10^{10})
and annealed (in oven at 150 C)

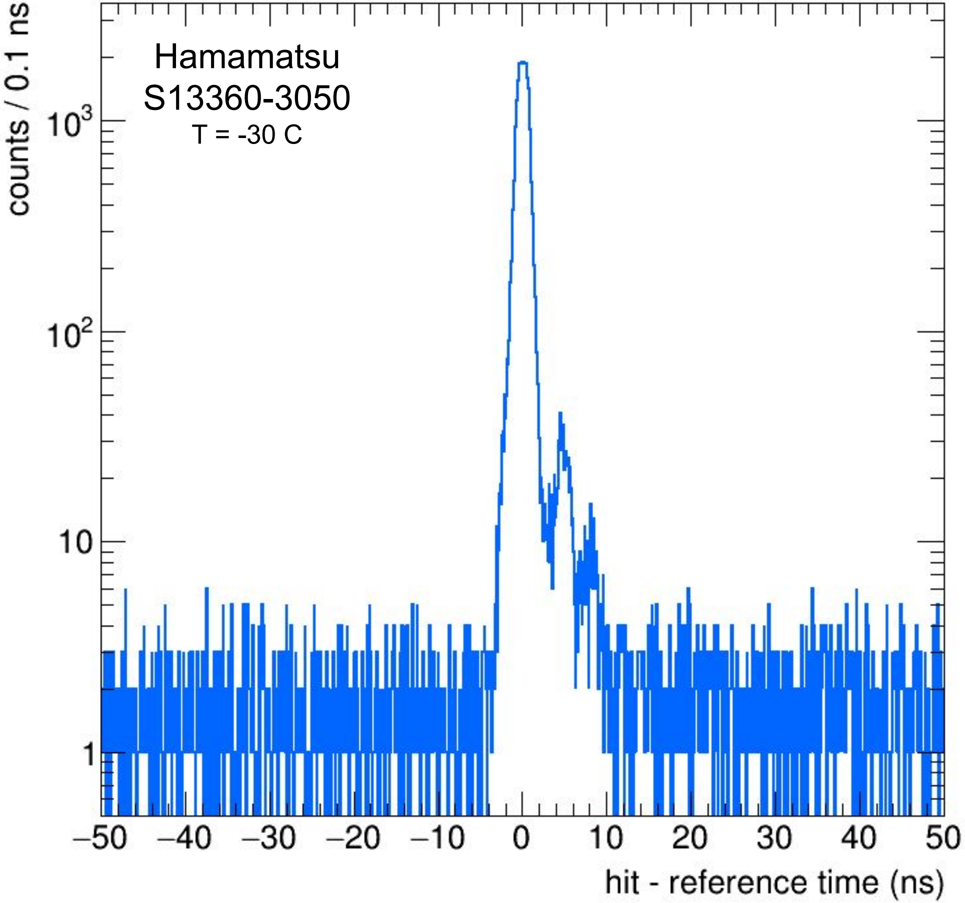
time coincidences

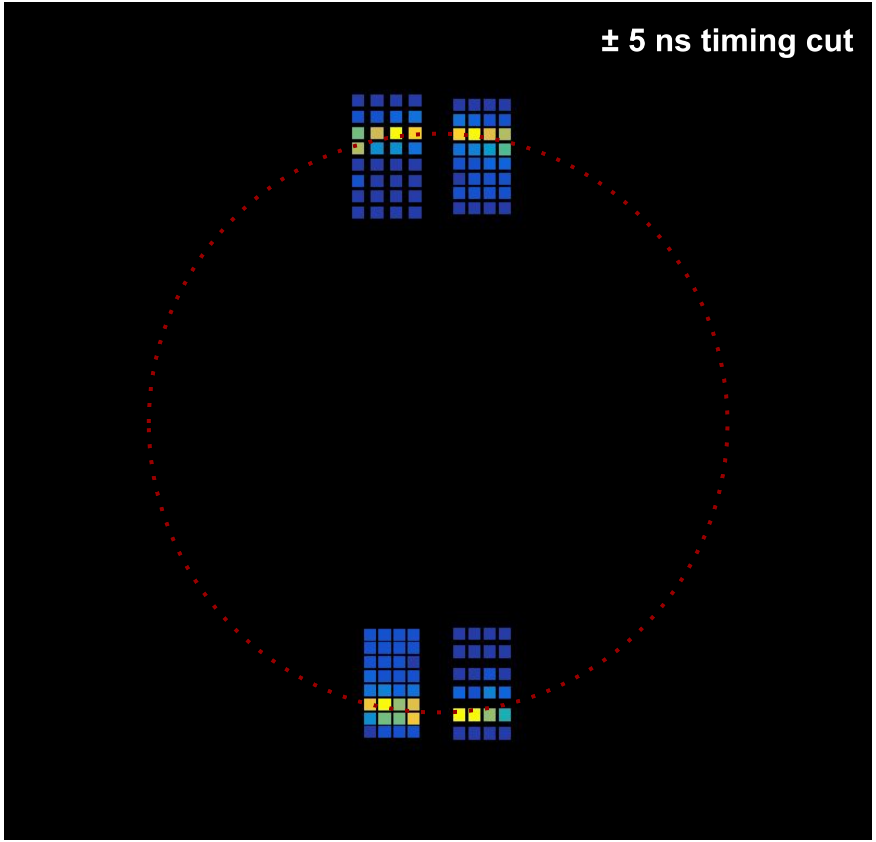


8 GeV positive beam (aerogel rings)



after irradiation with $2\cdot10^9$ n_{eq}/cm^2 fluence (protons)
and oven annealing at T = 150 C for 150 hours





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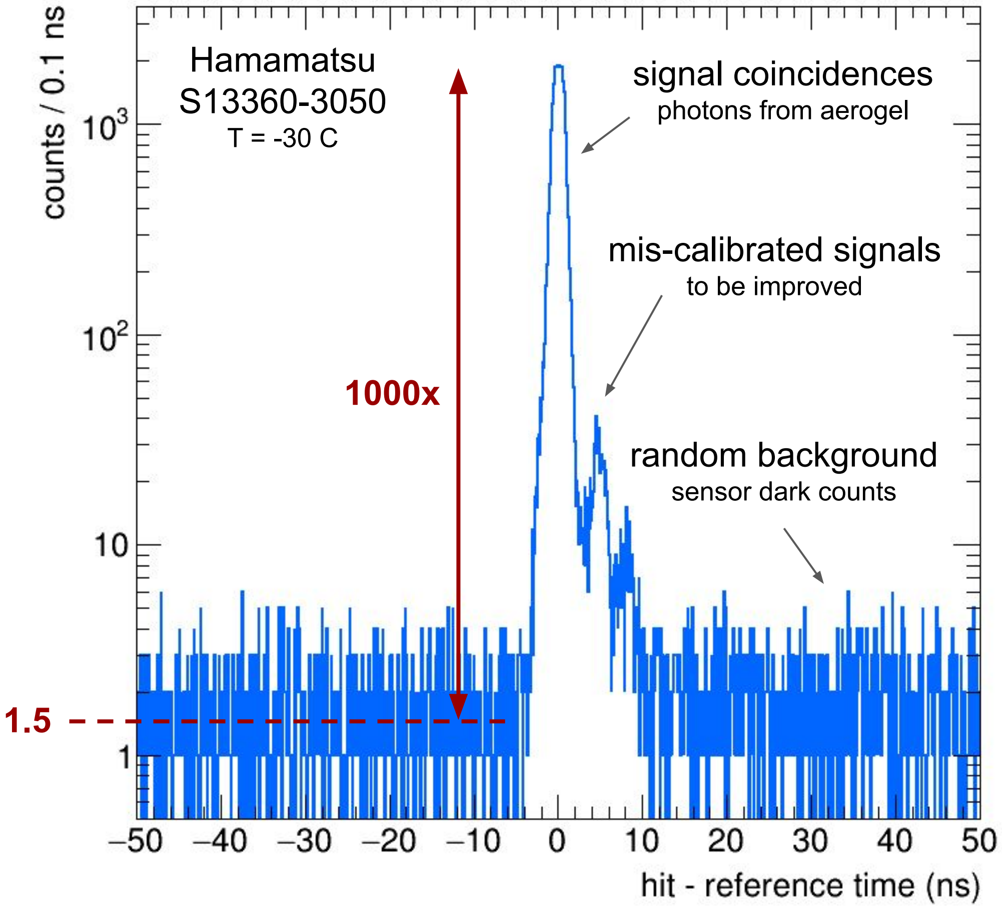
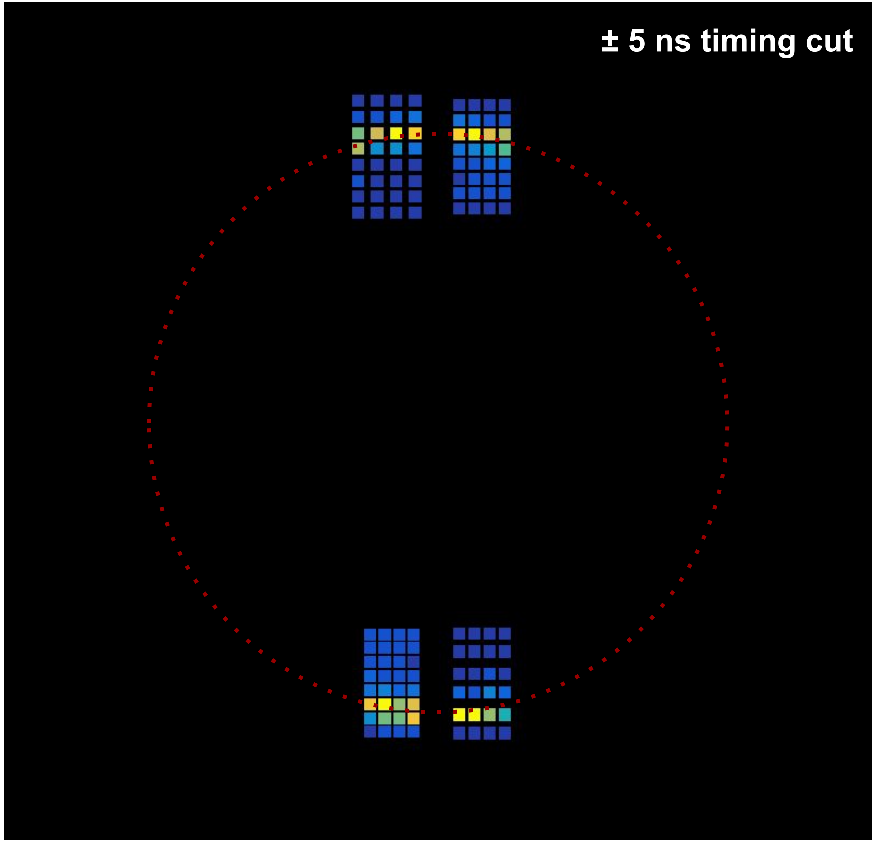


Hamamatsu
S13360-3050
T = -30 C

signal coincidences
photons from aerogel

mis-calibrated signals
to be improved

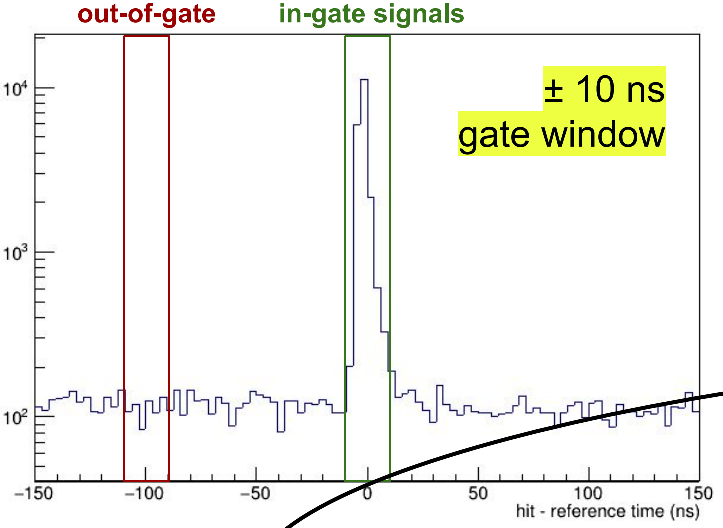
random background
sensor dark counts



± 5 ns timing cut

sensor DCR ~ 15 kHz

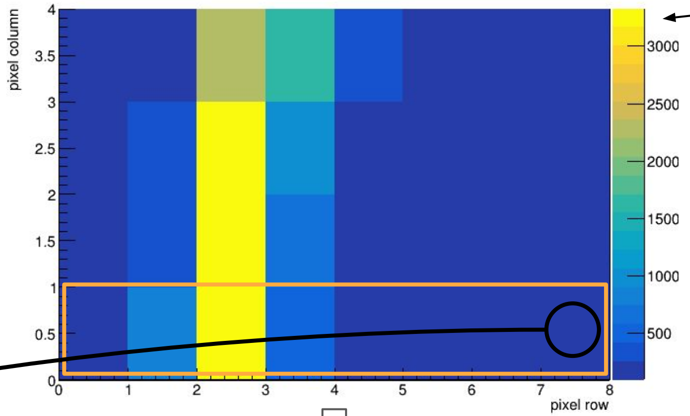
reference time is the particle time measured by the timing scintillators
an time offset of ~10 ns is removed to correct for distance of ~ 2 m between Cherenkov radiator and timing scintillators

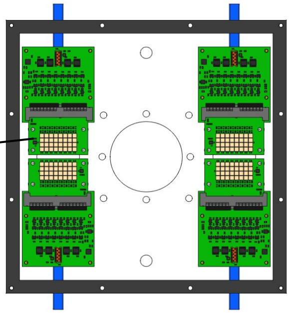


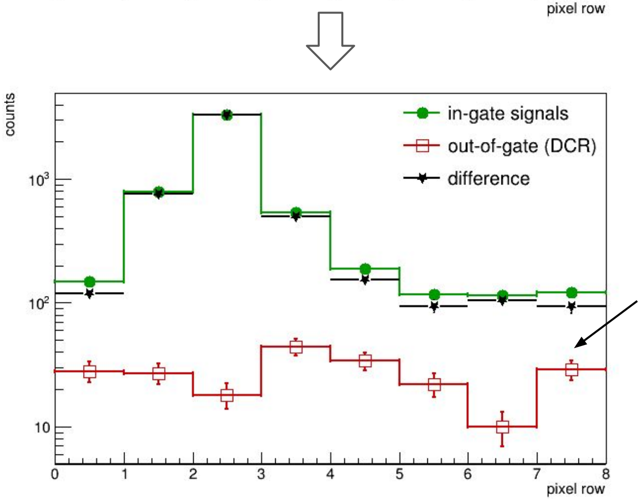
± 10 ns
gate window

out of topic from test beam
but nice and important to share

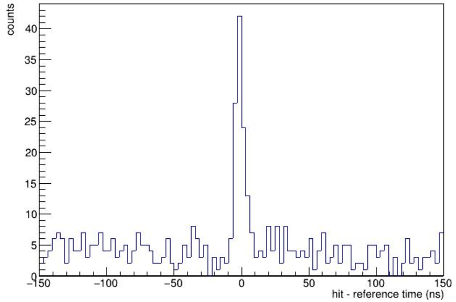
HAMA1 - 8 GeV negative beam







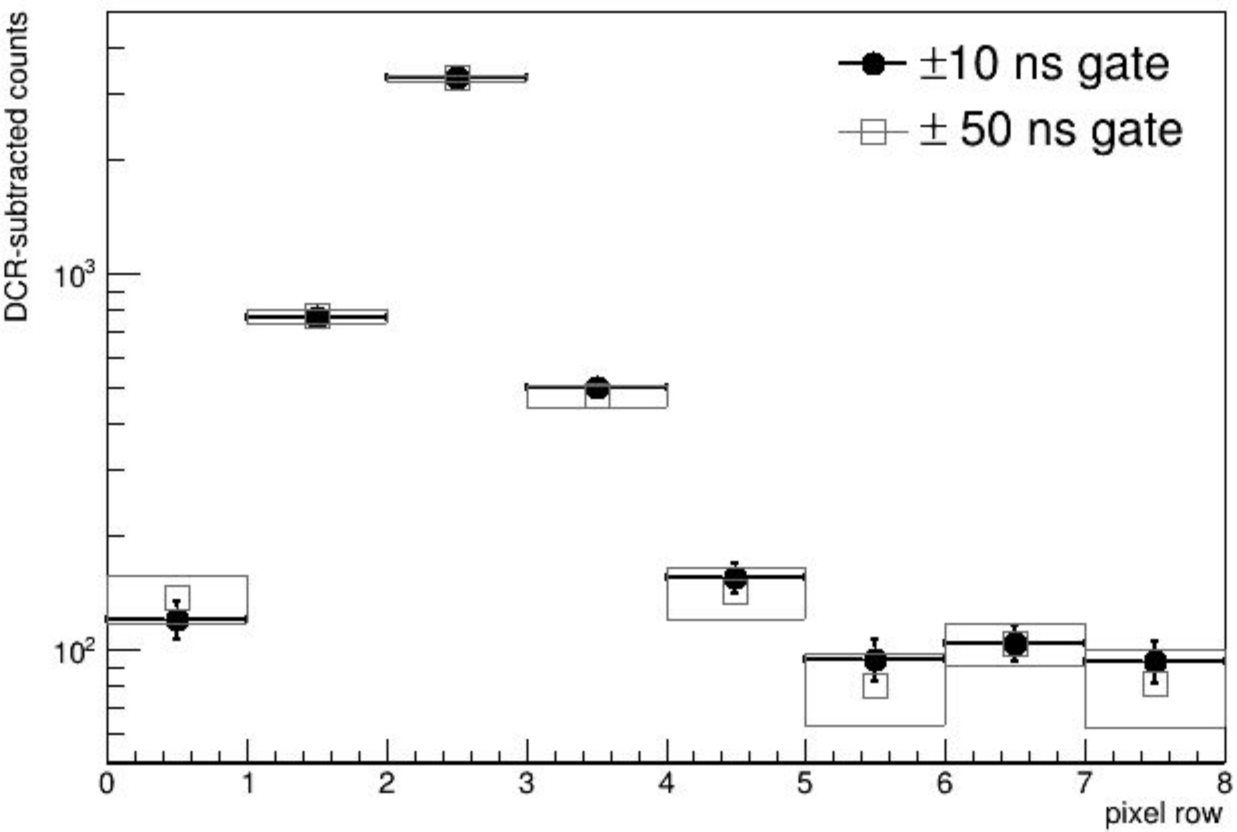
amount of signals outside of coincidence gate (due to SiPM DCR) is negligible wrt. physical background coincidences (likely due to Rayleigh scattering of Cherenkov light in aerogel)



this SiPM sensor also sees signals correlated with passage of particle

Rayleigh scattered photons in aerogel?

try with larger coincidence gate
smaller gate needs timing calibration
(not yet ready)



DCR-background subtracted signal unaffected by width of coincidence gate

Plans for FY 2023

Milestones FY 2023

critical results for pre-TDR

- Timing measurement of irradiated (and annealed) sensors (6/2023)
- Comparison of the results achieved with proton and neutron irradiation sources (8/2023)
- Study of annealing in-situ technique with a proposed model selected as baseline for the pre-TDR (9/2023)

- **single-photon time resolution**
    - of full SiPM-ALCOR readout chain
        - no capacity to measure it so far
    - critical to set performance simulation
- **alternative annealing solutions**
    - so far done with industrial oven (days)
    - address ideas for faster / in-situ recovery
        - exploration started, promising
        - critical to become structured R&D
- **irradiation campaigns**
    - so far only with 150 MeV protons
    - critical to test neutron damage
        - might be topologically different
        - effectiveness of annealing
        - test NIEL damage hypothesis
    - irradiation needed to test new annealings
- **operation at low temperature**
    - so far characterisation in climatic chamber
        - compare results with TEC (Peltier) cooling
    - explore alternative solution to TEC
        - liquid, hybrid (liquid + TEC) approaches
- **development of new sensors**
    - within INFN-FBK collaboration agreement
        - critical for procurement risk mitigation
    - reduction of DCR
        - field / thickness optimisation
        - exploration of advanced microlensing
    - development of “monolithic” SiPM sensor array
        - wire bonded, cost reduction

Financial requests for FY2023

- **SiPM R&D program benefits from significant INFN in-kind contribution**
  - infrastructures
  - access to irradiation facilities (TIFPA proton, LENA reactor)
  - laboratory equipment (power supplies, climatic chamber, …)
  - procurement of new sensors and electronics
  - engineering run with FBK
- **complementary characterisation setup in Cosenza**
  - most of the equipment funded by INFN
  - request eRD110 support for FPGA eval. board (ALCOR readout) [7.5 k$]
- **other financial requests**
  - partial support for irradiation costs [14 k$]
  - laser equipment for time resolution measurements [20 k$]
  - partial support to cover the cost of the FBK engineering run [20 k$]
- **manpower**
  - 6 researcher and several technicians available
    - one post-doc ending contract in early 2023
  - request eRD110 support for co-funding of two post-docs [40 k$]
    - critically required given the extent of the R&D program

NEW ENTRY

R&D plan was initially NOT FUNDED eventually funded with 50 k$ of PED

we will not be able to deliver full FY23 plans, but honour milestones

fruitful collaboration with FBK

- since the inception
- prototype sensors

great perspective for joint R&D

Plans for FY 2023

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will do

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will do

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  - irradiation needed to test new annealings

maybe within eRD102

- **operation at low temperature**
  - so far characterisation in climatic chamber
    - compare results with TEC (Peltier) cooling
  - explore alternative solution to TEC
    - liquid, hybrid (liquid + TEC) approaches

no support, will suffer

- **development of new sensors**
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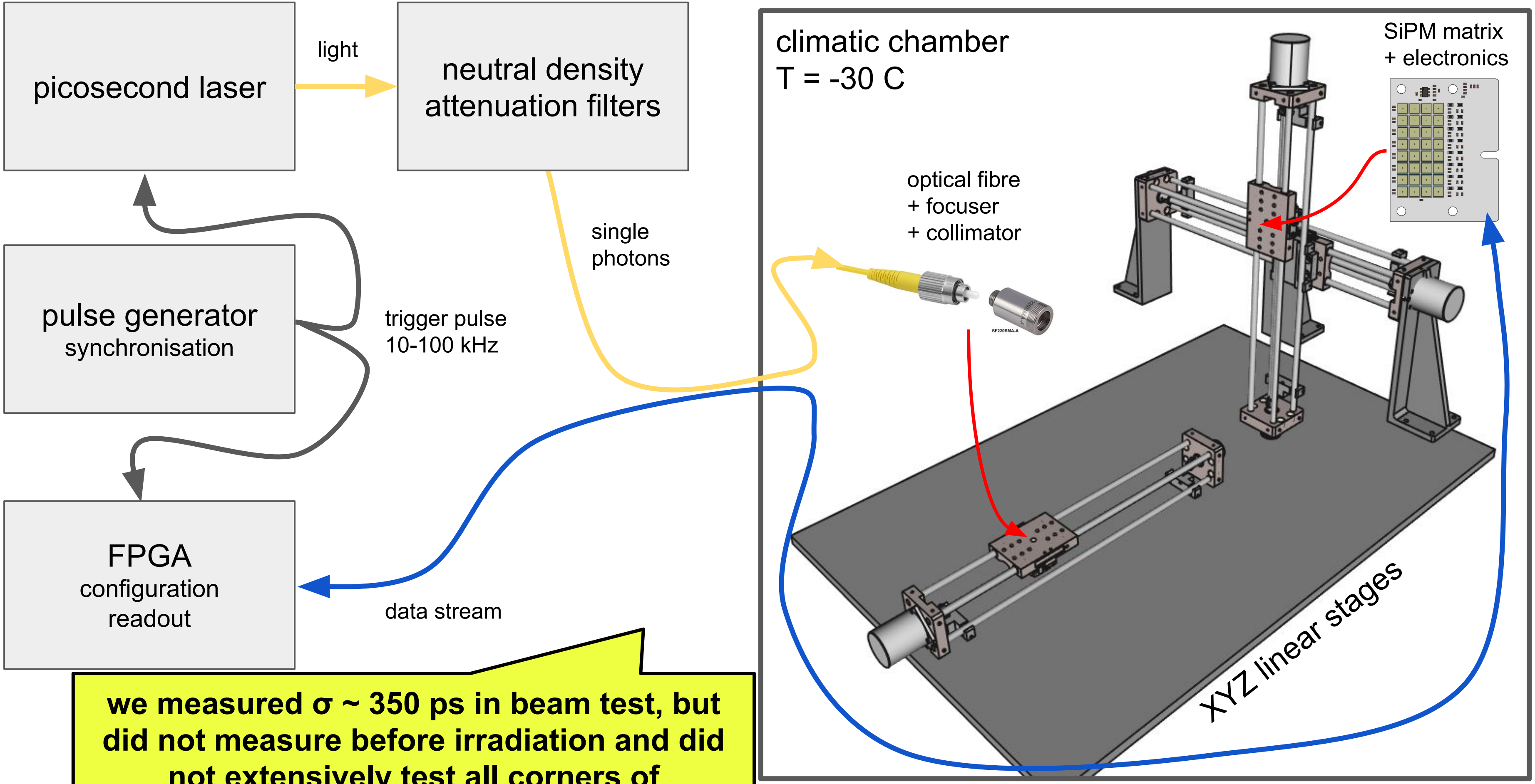
new laser setup for detailed characterisation of SiPM before/after irradiation/annealing



picosecond laser

light

neutral density attenuation filters

single photons

pulse generator
synchronisation

trigger pulse
10-100 kHz

FPGA
configuration
readout

data stream

climatic chamber
T = -30 C

optical fibre
+ focuser
+ collimator

SiPM matrix
+ electronics

XYZ linear stages

we measured σ ~ 350 ps in beam test, but did not measure before irradiation and did not extensively test all corners of SiPM+electronics phase-space, do it in lab

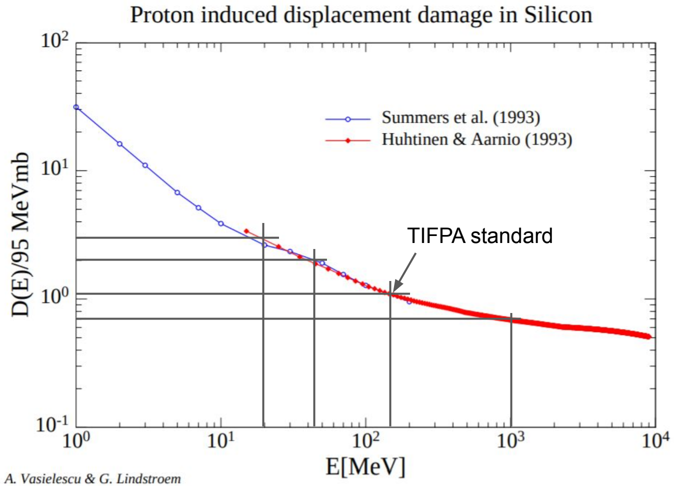
New LIGHT SiPM carriers

our results point towards large SPADs for RICH applications must test 75 um

- **1x4 LIGHT carrier**
  - keep same boards designed in 2020
  - populate 2 / 3 rows
    - 4 sensors / row
  - sensors from Hamamatsu
    - 4x S13360-3050
    - 4x S14160-3050
    - 4x S13360-3075
- **perform different type of irradiation/annealing studies**
  - one LIGHT carrier for each study
- **keep a minimal statistical sample for each study**
  - 4 sensors / type

Irradiation studies

- **with protons at different energies**
  - test NIEL scaling hypothesis of radiation damage with energy
  - test annealing cure has same effectiveness
  - need data for radiation damage model
  - 2 or possibly three energies
    - 150 MeV, 40 MeV, 20 MeV
    - would be nice also 1 GeV
- **with beam and reactor neutrons**
  - test NIEL scaling hypothesis and annealing effectiveness is same as for protons
  - need data for radiation damage model
  - central reactor flux has both fast and slow neutron component
    - possibly different damage
    - irradiate in central reactor channel
      - both fast and slow
    - irradiate in peripheral channel
      - fast component suppressed
- **at different levels of fluence**
  - 10^9, 10^{10}, 10^{11} neq in one shot
  - 10^9 repeated irradiation/annealing cycles



A. Vasielescu & G. Lindstroem

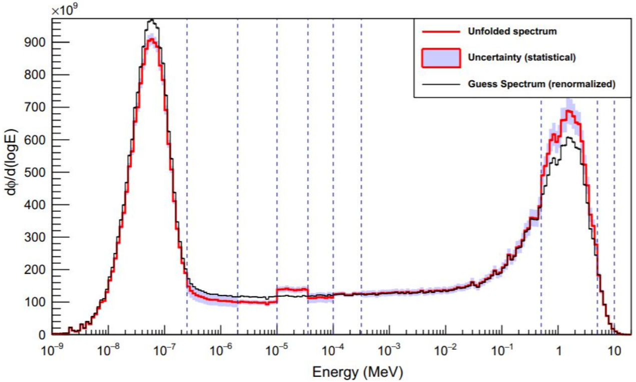


Fig. 12 Unfolded neutron flux spectrum in Central Channel at 100 kW power (same plot description as Fig. 10)

Boards and sensors needed

Fluence	10^9	x	x	x	x	x
	10^{10}	x				
	10^{11}	x				

Irradiation		Annealing					N boards	N SiPM
Particle	Energy	Oven	Online	Forward	Inverse	Else		
Neutrons	central	3	1	1	1	1	14	56
	peripheral	3	1	1	1	1		
Protons	150 MeV	3	1	1	1	1	16	64
	40 MeV	3						
	20 MeV	3						
	1 GeV	3						

	N boards	N SiPM
Needed	30	120
Spares	5	30
Total	35	150

for each type

comparison across different radiation field types
performed for three levels of fluence

Boards and sensors needed

Fluence		Oven	Online	Forward	Inverse	Else
	10^9	x	x	x	x	x
	10^{10}	x				
	10^{11}	x				

Irradiation		Annealing					N boards	N SiPM
Particle	Energy	Oven	Online	Forward	Inverse	Else		
Neutrons	central	3	1	1	1	1	14	56
	peripheral	3	1	1	1	1		
Protons	150 MeV	3	1	1	1	1	16	64
	40 MeV	3						
	20 MeV	3						
	1 GeV	3						

	N boards	N SiPM
Needed	30	120
Spares	5	30
Total	35	150

for each type

comparison of different annealing methods performed only for 10^9 fluence levels

developing mechanical layout, readout electronics for SiPM-ALCOR-based dRICH prototype