Proton Irradiation of the STAR1000 Active Pixel Sensor: preliminary results of NIEL scaling

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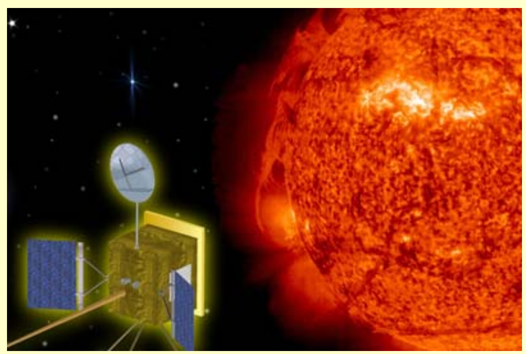
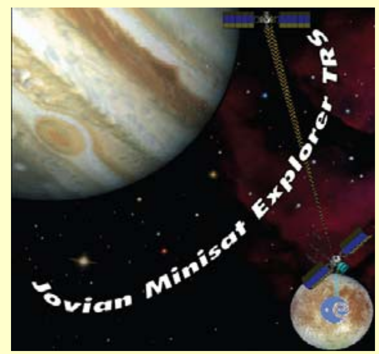
Outline

- *1- Background*
- *2- Irradiation history*
- *3- 60 MeV irradiation results overview*
- *4- Preliminary results on NIEL scaling*
- *5- Conclusion*

1- Background

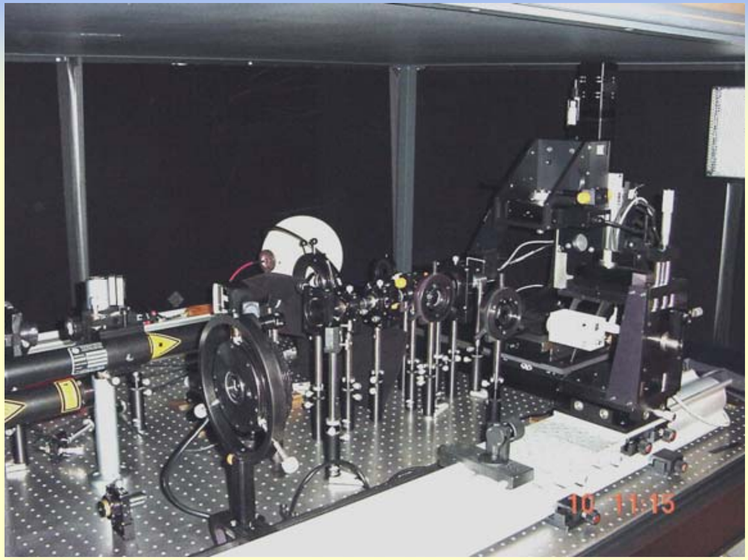
- ***CMOS APS testing in the Science Payload and Advanced Concepts Office***
  - Complement to D-TEC-QCA evaluation/qualification programs
  - APS evaluation is part of a detector technology program including compounds semi-conductor (AsGa, CdZnTe, HgCdTe…) with high and low bandgaps, scintillator materials…
    - All tests and characterizations are performed internally.
  - Short term program dedicated to the scientific payload of Bepi Colombo
    - Direct support to PI teams.
    - Support to on going industrial developments.
  - Mid-term Solar Orbiter, Xeus…
  - Build long-term expertise for even more challenging environments such as Jupiter and Europa….

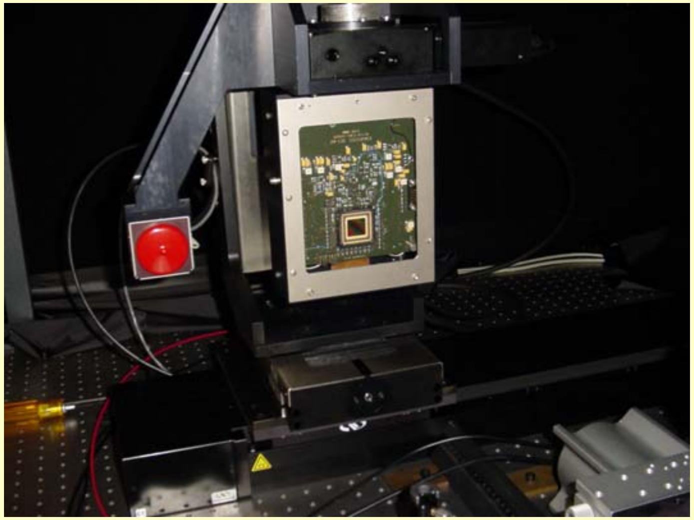




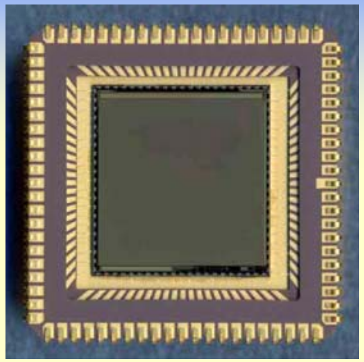
1- Background

- ***Evaluate existing APS performances…***
  - Electro optical performances:
    - Noise, dark current, spectral response, Xtalk, MTF….
  - Radiation hardness.
  - On going test activities concentrating on the STAR1000 (started end of 2005), in a few months, similar tests will be performed on the HAS (successor of STAR1000) and LUPA4000, back-illuminated chip…
- ***for the next generation…***
  - In 2008, the CMOS APS presently developed for the Bepi Colombo remote sensing payload will be available…



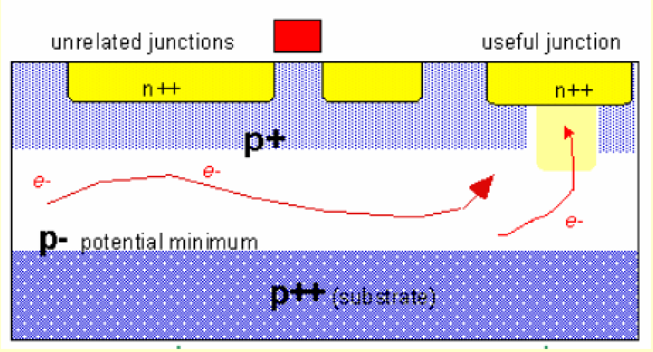


1- Background



STAR1000

- 1024 x1024
- 15 µm pitch
- Front illumination
- Rolling shutter with double sampling for Fixed Pattern Noise (FPN) correction
- High fill factor technique
- Built-in ADC
- 0.5 um AMIS CMOS techno
- Manufactured by ex Fill-factory (Belgium)
- rad-tolerant sensor (by design): still operational after 200 krad recently undergone evaluation program to join EPPL (ESA Preferred Part List)
  - Some radiation tests (Co60, protons, Heavy ions) available as well as for predecessors (STAR250).



2- Irradiation history

- **Chip1**
  - Unbiased
  - 60 MeV
  - KVI

	Cumulated Fluence (p/cm2)	Rate (p/cm2/s)	Exposure (s)	Cumulated TID (krad)	Time to next Irradiation (weeks)
Irradiation 1	$2.4\ 10^{10}$	$7.34\ 10^{7}$	327	3.3	13
Irradiation 2	$7.2\ 10^{10}$	$2.18\ 10^{8}$	220	10.0	6
Irradiation 3	$2.4\ 10^{11}$	$1.3\ 10^{8}$	1292	33.3	7
Irradiation 4	$4.8\ 10^{11}$	$1.4\ 10^{8}$	1713	66.6	25
Irradiation 5	$7.2\ 10^{11}$	$x\ 10^{8}$	x	100	TBD
Irradiation 6	Cumulated fluence of 10^{12} p/cm2				

Completed/not completed

- **Chip9**
  - Biased
  - 60 MeV
  - KVI

	Cumulated Fluence (p/cm2)	Rate (p/cm2/s)	Exposure (s)	Cumulated TID (krad)	Time to next Irradiation (weeks)
Irradiation 1	$7.2\ 10^{10}$	$7.34\ 10^{7}$	327	3.3	13
Irradiation 2	$2.4\ 10^{11}$	$1.3\ 10^{8}$	1292	33.3	6
Irradiation 3	$4.8\ 10^{11}$	$1.4\ 10^{8}$	1713	66.6	TBD
Irradiation 4	Cumulated fluence of $7.2\ 10^{11}$ p/cm2				

2- Irradiation History

- ***Chip 6,7 and 10***
  - NIEL scaling study.
  - Chip 5 as reference sample: no change at all in any parameters.
  - Chips unbiased.
  - Irradiation carried out at Louvain.

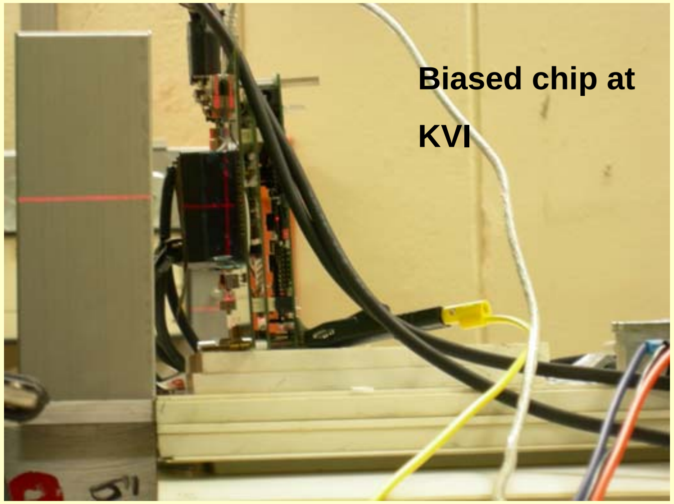
	Energie (MeV)	*Fluence (p/cm2)*	*Rate (p/cm2/s)*	*Exposure (s)*	*Dose rate (rad/s)*	*TID (krad)*
Chip 6	*10*	*$1.044\ 10^{11}$*	*1.2 e7*	*8700*	*6.4*	*55.6*
Chip 7	*33*	*$0.99\ 10^{11}$*	*2.9 e7*	*3420*	*6.9*	*23.6*
Chip 10	*51*	*$1.008\ 10^{11}$*	*4.8 e7*	*2100*	*7.9*	*16.7*

  - Second run of irradiation foreseen this year….

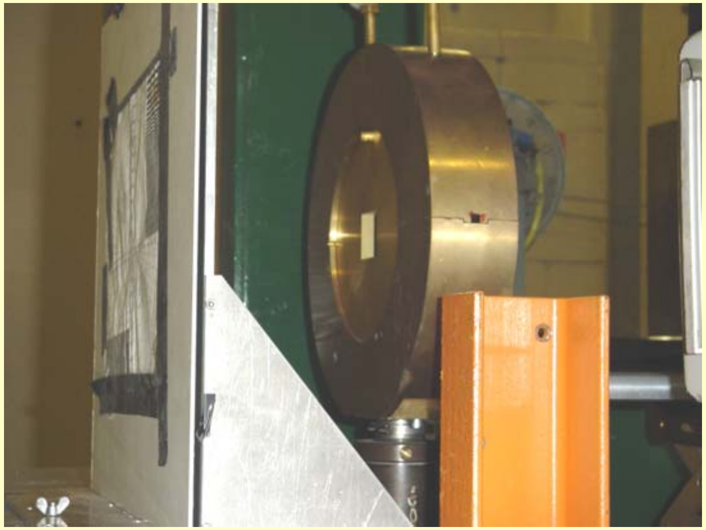
2- Irradiation History

Irradiation setup

- All irradiations performed in ambient air, with chips placed in dust protection sockets (75 um kapton foil window).
- Post calibration at KVI indicated flux error bar below 10 %
- Fluences between KVI and Louvain have been calibrated using a “Reference SEU Monitor” (R. Harboe Sorensen) but calibration factor not applied yet in this presentation.
- Electro-optical characterization was performed 1 to 2 days after each irradiation with intermediate points on dark and gain when several chips to characterize at the same time.



Accurate positioning (for beam homogeneity) of the chip thanks to the laser aligment system.



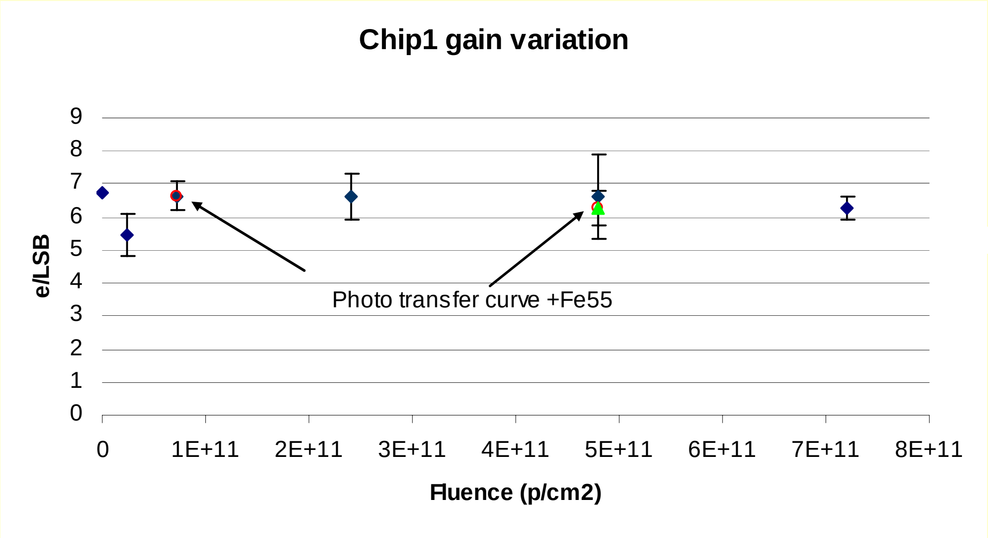
KVI degrader from 184 Mev primary energy downto 60 MeV

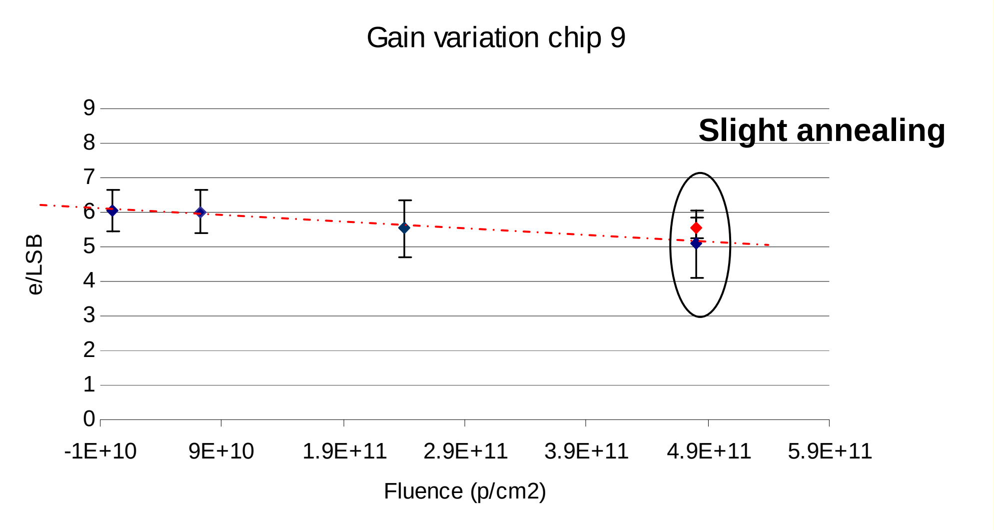
3- 60 MeV irradiation results overview

- ***Main effects:***
  - Conversion gain
    - Not altered for unbiased chip.
    - 10 % decrease (after RT annealing) at 4.8 10 ^11 p/cm2 for the biased chip.
  - Dark current:
    - Enhanced dark current generation.
    - Very good linearity with respect to fluence.
    - Hot pixels.
    - RTS like behaviour.
    - Associated mechanisms have been heavily studied and identified, especially for CCDs (very similar effects expected for CMOS APS).
  - Spectral response decrease
    - Very good linearity with respect to fluence but “saturation effect” visible eventually
    - Very few references in the literature, no definitive mechanism identified yet…
    - “Tolerant at transistor level… only”
  - Overall weak influence of biased/unbiased=> good indicator of radiation tolerance at transistor level…

3- 60 MeV irradiation results overview

- ***Conversion gain***
  - **The conversion gain was measured using the photon transfer method as well as Fe55 (not all points).**

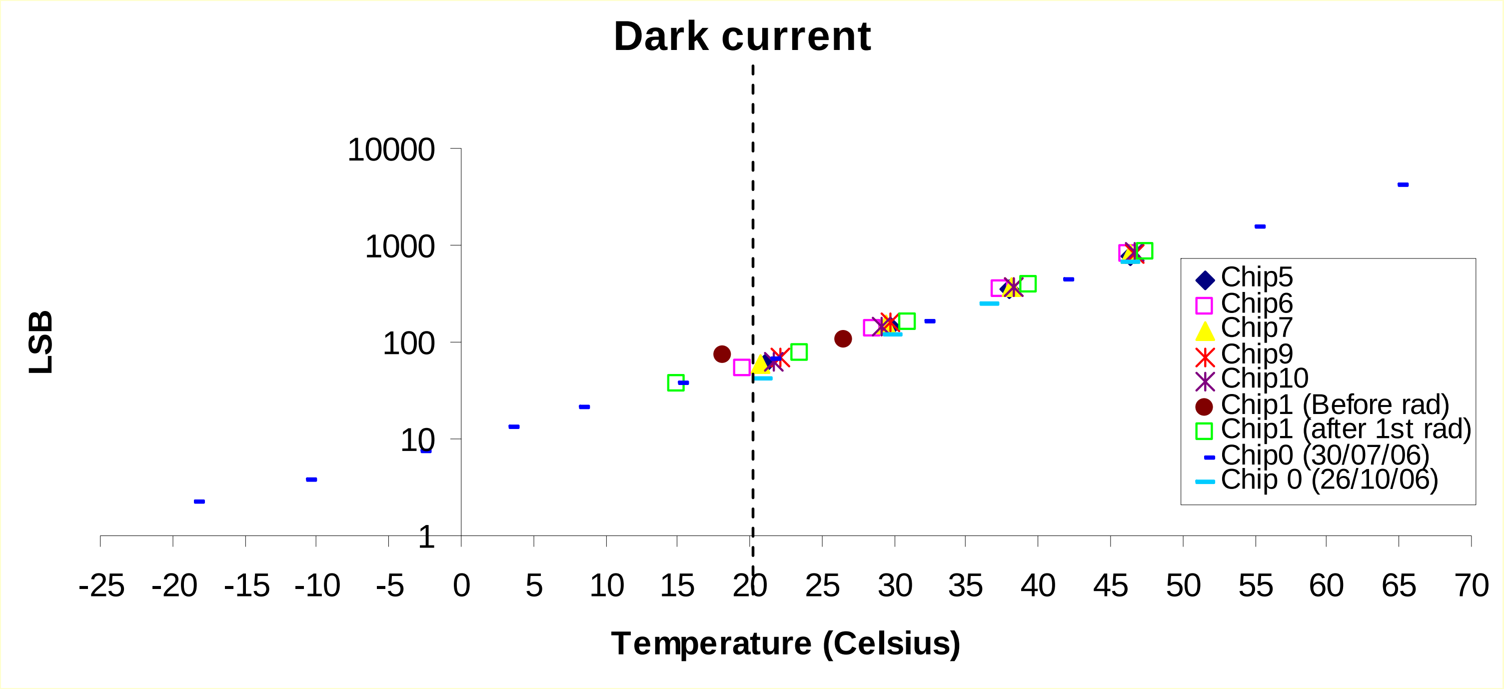




Error bars correspond to 3 sigma variations on the 7 points of measurements across the arrays.

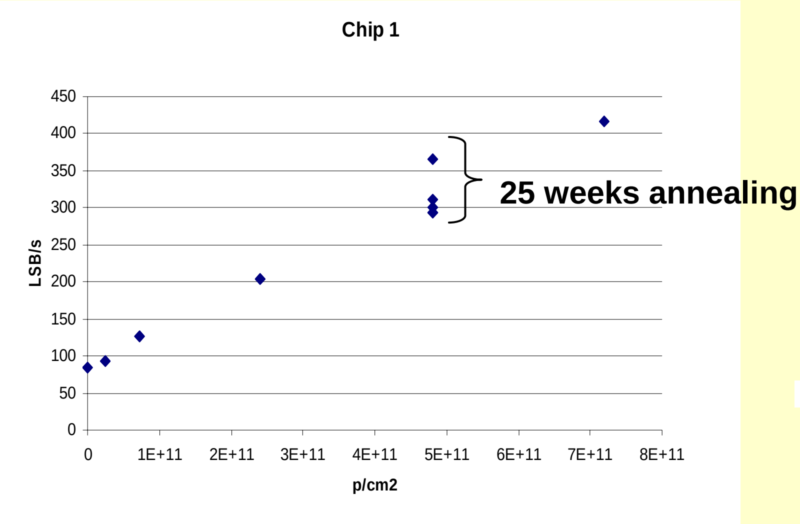
3- 60 MeV irradiation results overview

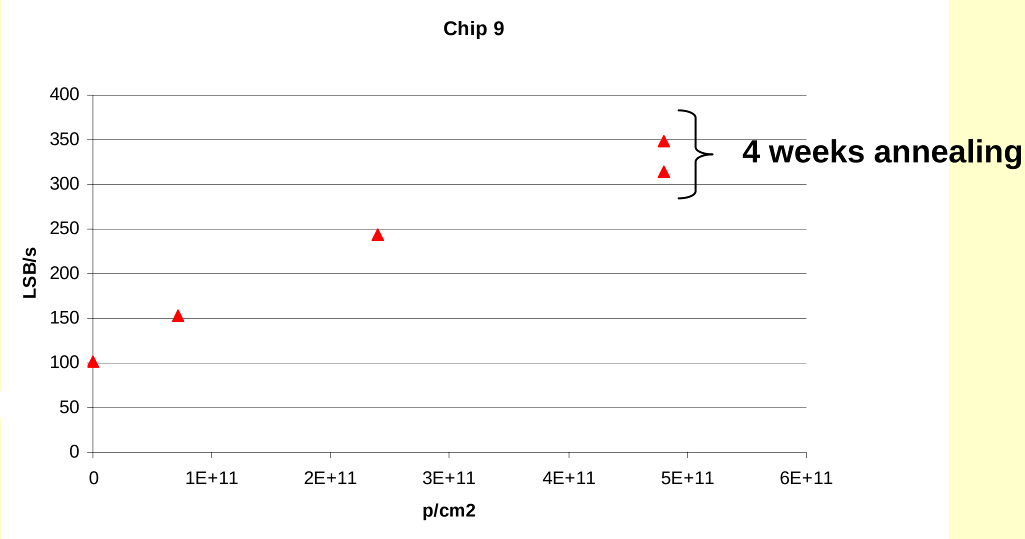
- ***Dark current***
  - Pre-irradiation dispersion is relatively low



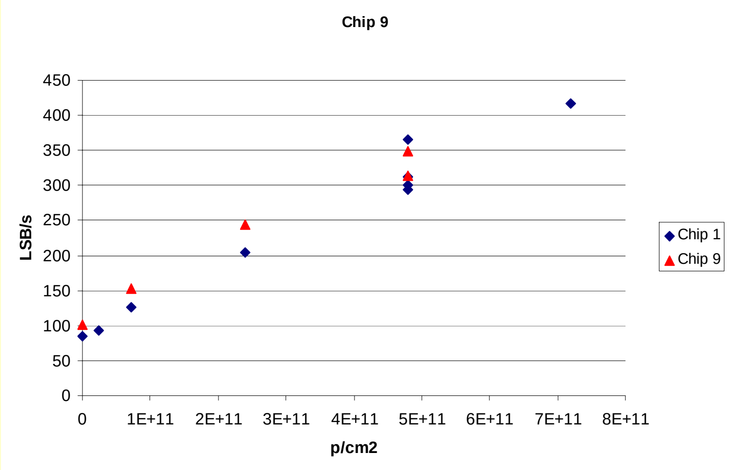
3- 60 MeV irradiation results overview

Dark current





- Very similar behaviour for both chips
- At 4.8 10^11p/cm2, after some annealing, the two chips are back on the same track



3- 60 MeV irradiation results overview

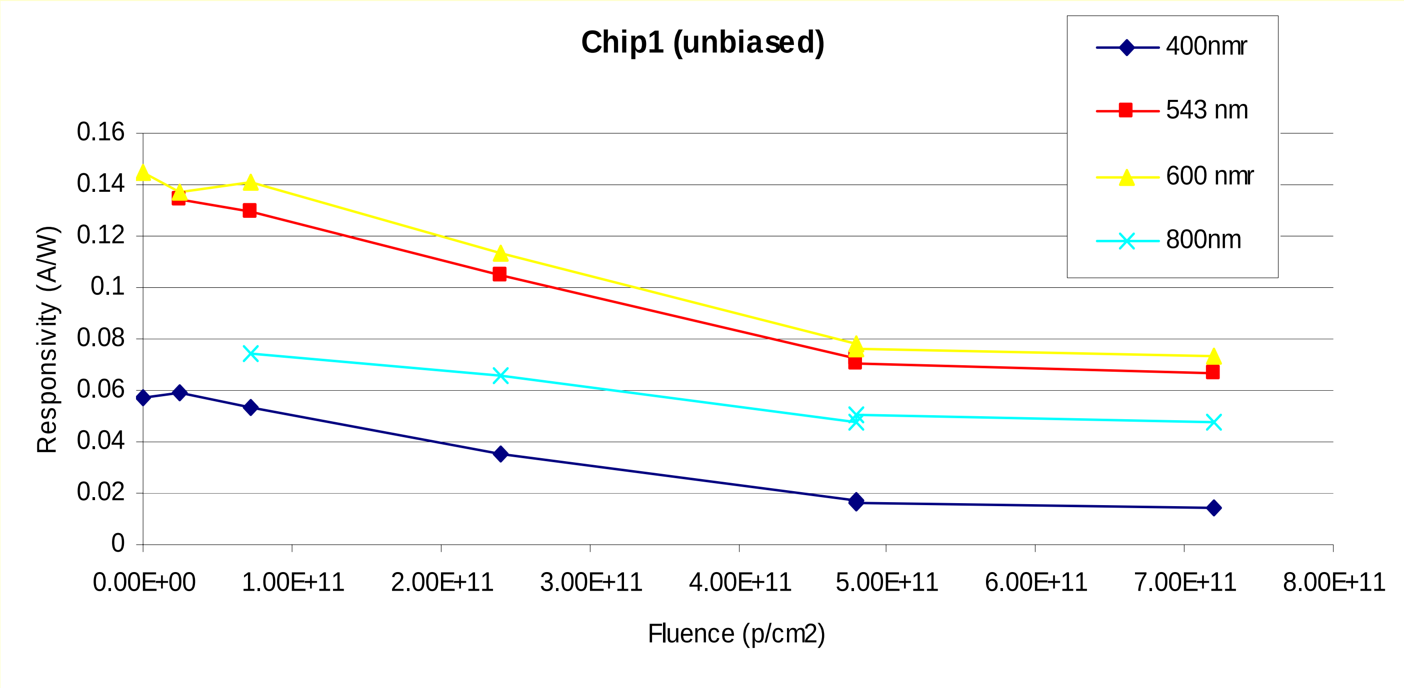
- ***Spectral Response degradation***
  - Only reported by a few authors,e.g.:
    - Radiation testing of 2-D Imaging detectors and ADCs for Attitude Sensors, G.R. Hopkinson, ESA/ESTEC contract 12227/96/NL/SB, final report, June 2000.
      - Co60 and 10 MeV protons (Non rad-tolerant design). Recovery after 14 months annealing.
    - Radiation testing of CCD and APS Imaging devices, G.R. Hopkinson, ESA/ESTEC contract 14028/99/NL/MM, final report, June 2003.
      - Co60 and 10 MeV protons (STAR250). Slight gain decrease, wavelength independent.
    - Radiation induced degradation in CMOS active pixel sensors and design of radiation tolerant image sensors, J. Bogaert, PhD thesis, Catholic Univ., Leuven, Belgium, 2002.
      - Co60 and 10 MeV protons (OISL ~STAR250). Wavelength dependence. Smoothing of spectral response.

3- 60 MeV irradiation results overview

- ***Spectral Response degradation***
  - Potential origins:
    - Ionizing dose effects:
      - Carrier build-up in the oxides causing additional depletion areas at the surface.
      - Charge trapping at the interface that influences generation-recombination rates at the surface.
      - In pixel transistor gain variation.
      - Modifications of the electric field distribution.
    - Non Ionizing dose effects:
      - Increase the number of generation-recombination centers in the bulk of the device, decreasing minority carrier lifetime.
    - Surface layers optical degradation: radiation induced colour centers (as in common optical glass).

3- 60 MeV irradiation results overview

Spectral Response degradation



20 nm bandwidth filter

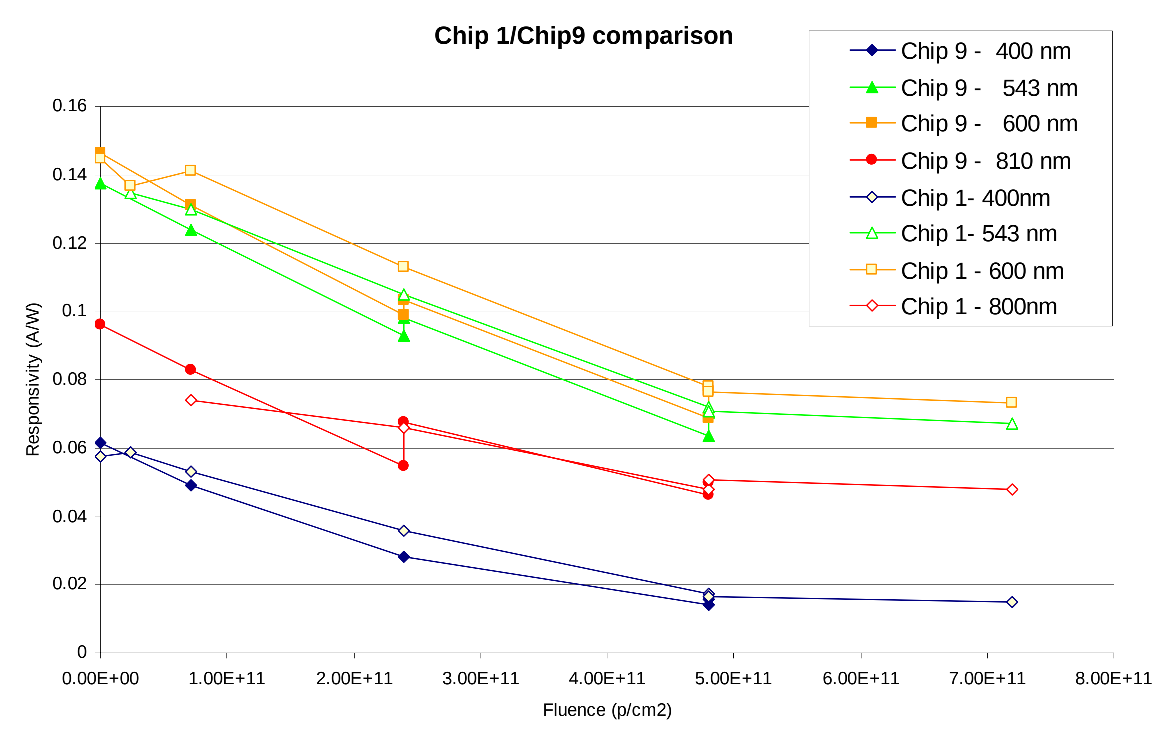
Good linearity with fluence up to 4.8 10^11 p/cm2 (TID66 krad)

3- 60 MeV irradiation results overview

Spectral response degradation

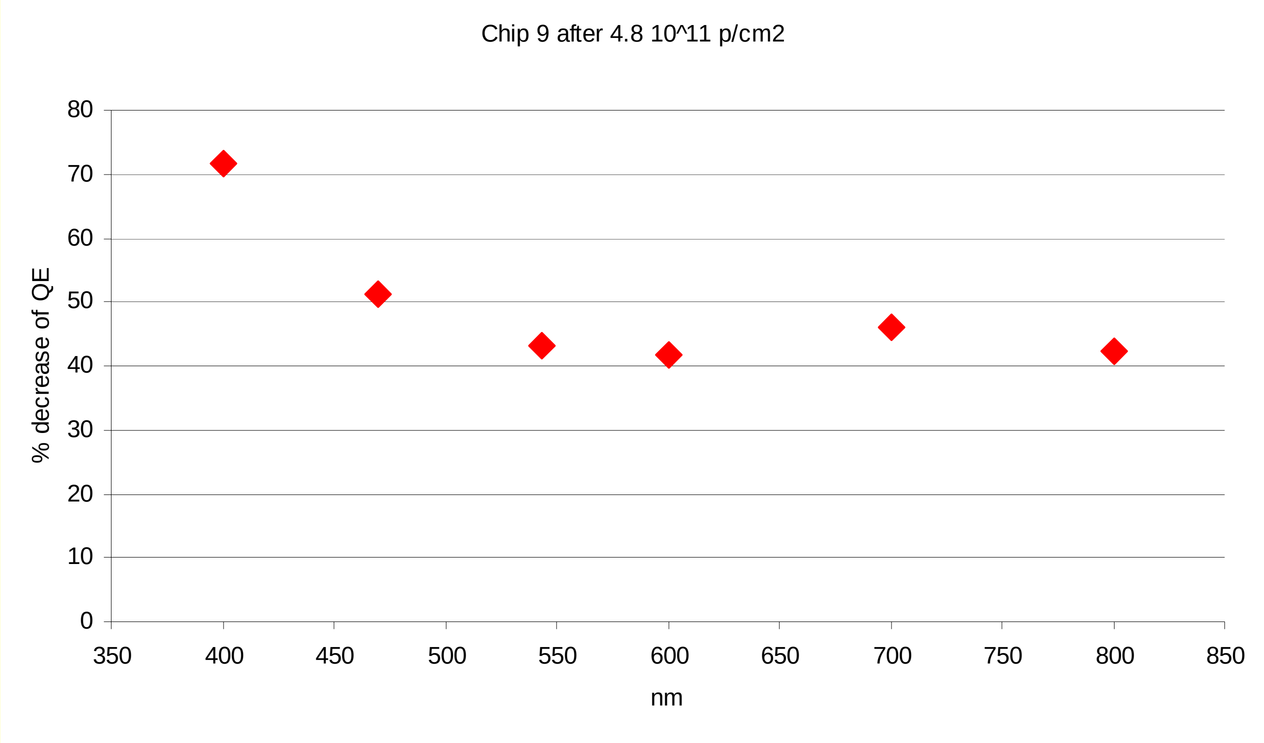
- Decrease per unit of fluence is very similar for both chips.

- Annealing stronger for biased chip and for longer wavelength.



3- 60 MeV irradiation results overview

Spectral response degradation



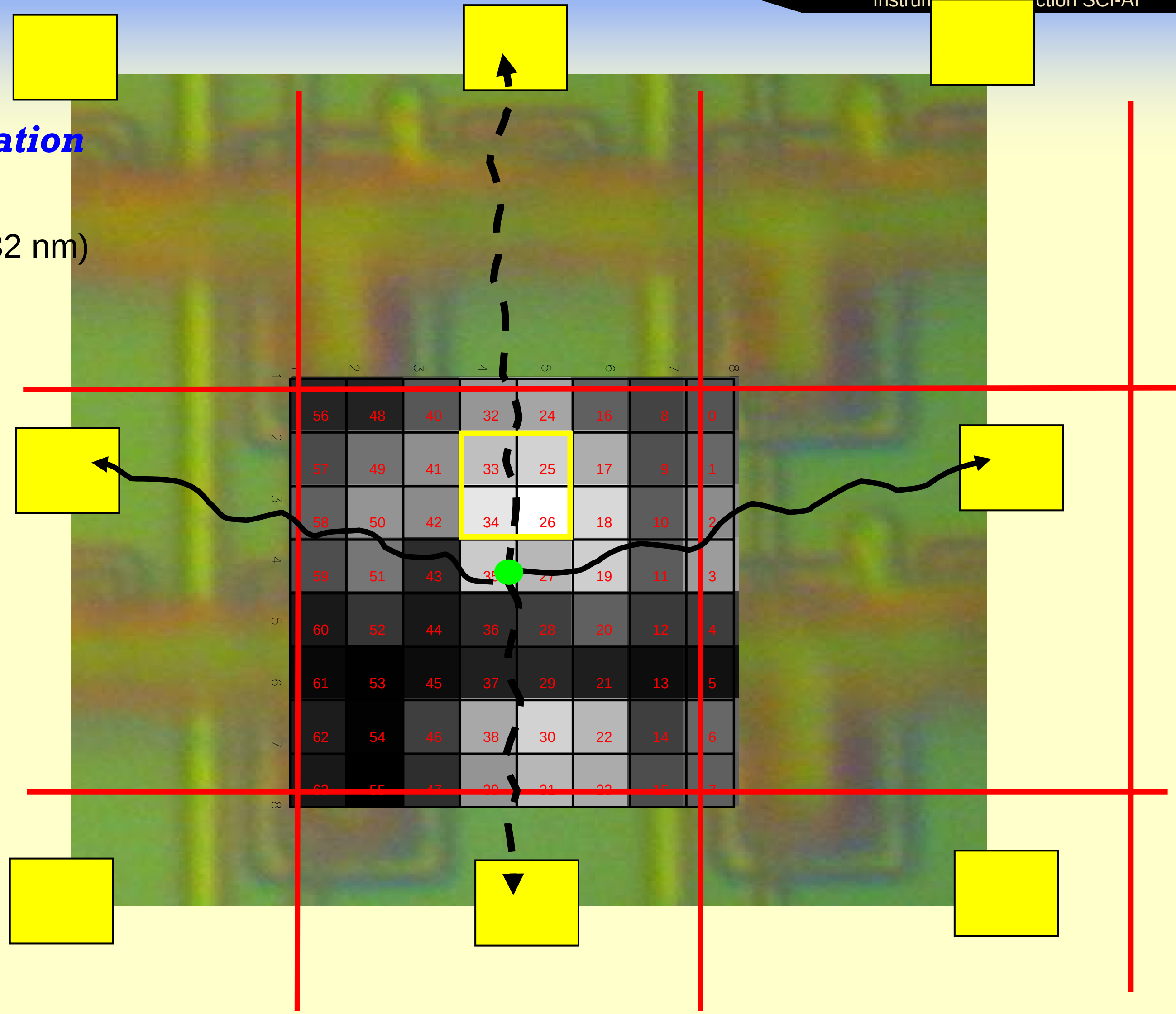
Proportionally, the decrease is stronger for the blue

=> Surface effect > bulk effect?

(Similar result for chip 1)

3- 60 MeV irradiation results overview

- ***Spectral response degradation***
  - Spot scanning:
    - ~2um spot (543, 632 nm)
    - Subpixel response
    - Xtalk



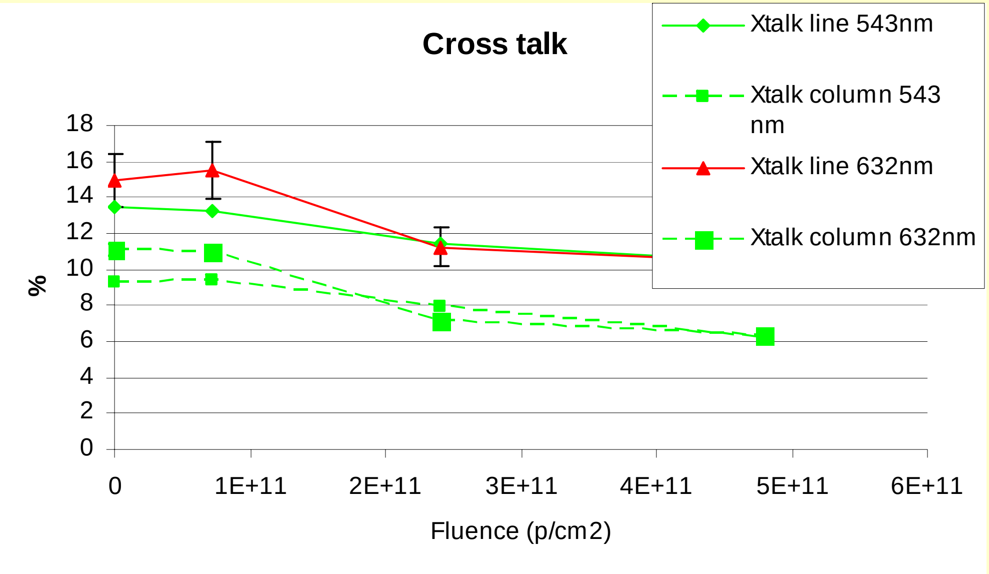
Xtalk column

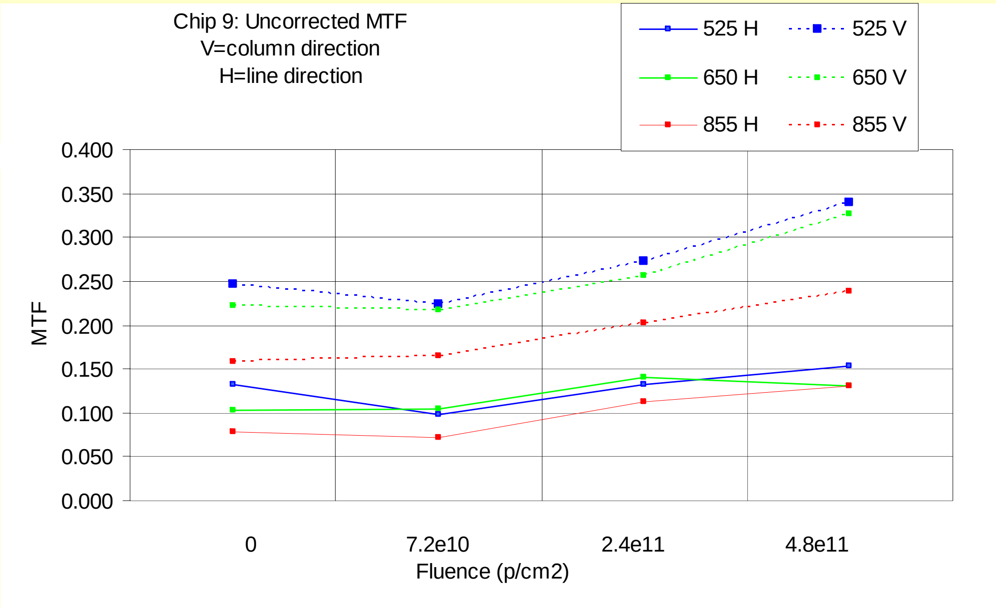
Xtalk line

3- 60 MeV irradiation results overview

- ***Spectral response degradation***
  - Xtalk is slightly decreasing with successive irradiation
  - Coherent with increasing MTF ("slanted edge method")
  - Weak wavelength dependence

Diffusion length decrease (bulk effect due to displacement damage)



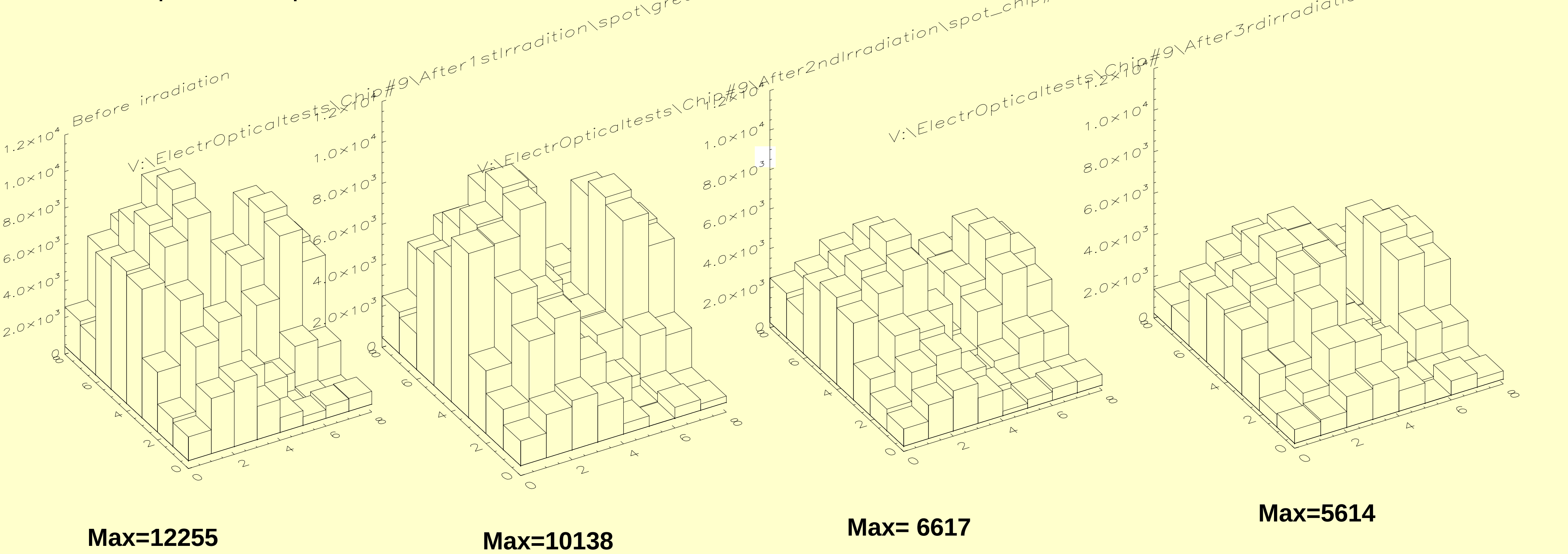


Error bar corresponds to ~10 % (rms variation on all pre-irradiated measurements)

3- 60 MeV irradiation results overview

Spectral response degradation

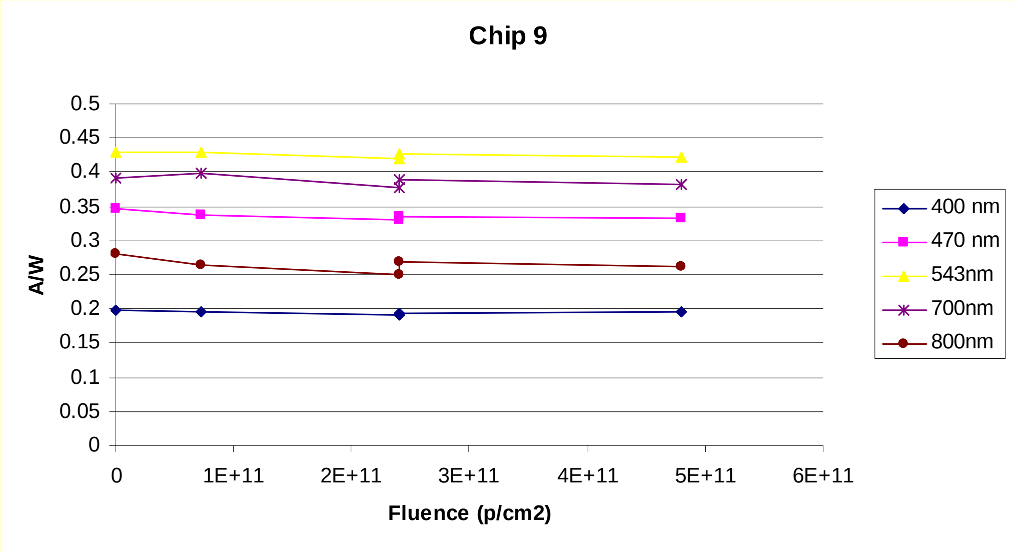
- Subpixel responsivity MAP scales roughly with QE decrease, no dramatic change in distribution
- Si diffusion length is > 10 um for doping < 3.10^19 cm^-3 (100 um at ~10^19 cm^-3)
- Diffusion length decrease (see previous slide) but not enough to explain the overall loss of spectral response



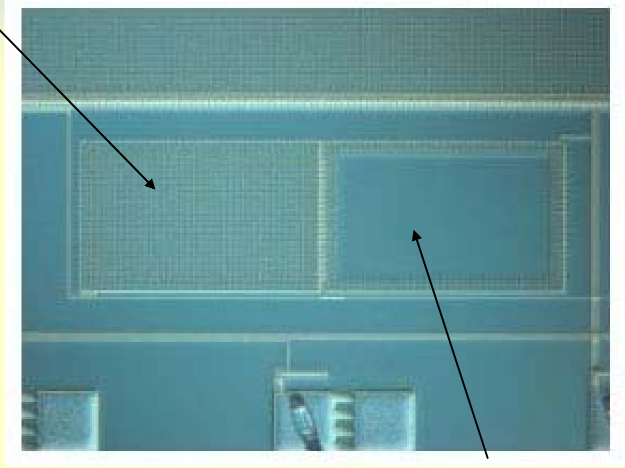
3- 60 MeV irradiation results overview

Spectral response degradation

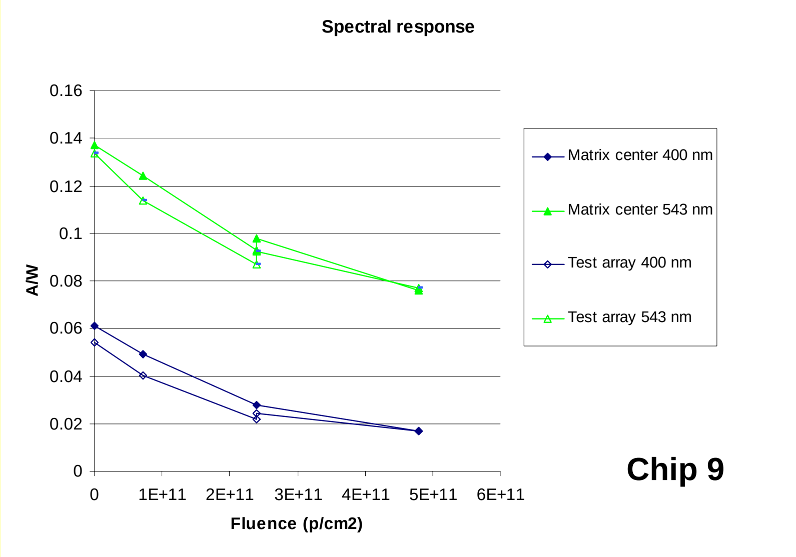
- Extremely low on “plain photodiodes”



Pixels with photodiodes connected in parallel: “Test array”



Plain photodiodes with 100 % fill factor



Chip 9

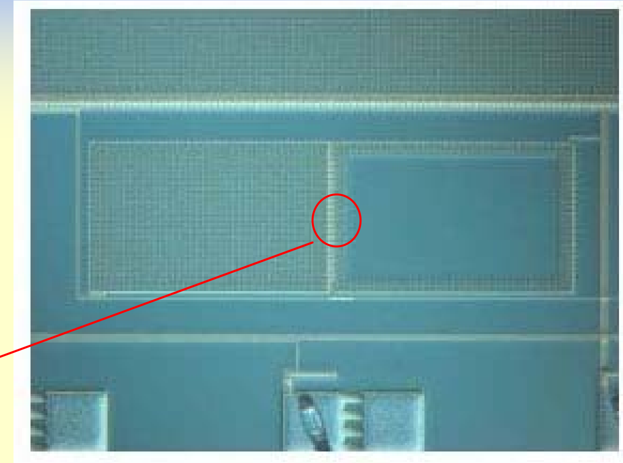
In plain photodiodes, metallizations and associated oxides are not present:

-> minimize dose effect?

-> optical alteration of the different oxide layers in the case of the array?

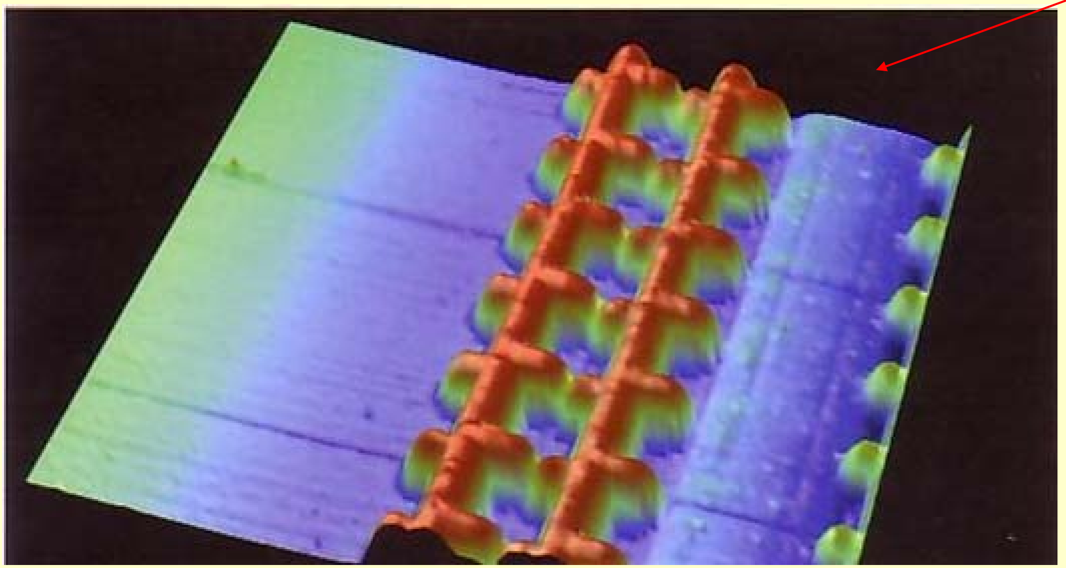
-> since “test diodes” have 100 % fill factor, limited lateral diffusion so difficult to conclude on bulk effect….

3- 60 MeV irradiation results overview



- ***Spectral response degradation***
  - Degradation of the optical properties of the top layers?

Profilometer (



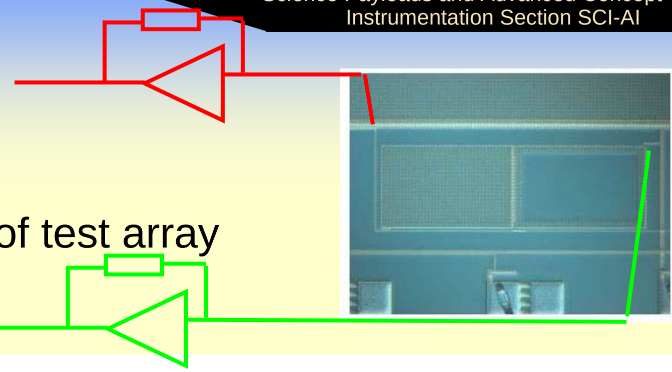
-**Thickness difference between plain photodiodes and test array is less than 1.5 um**

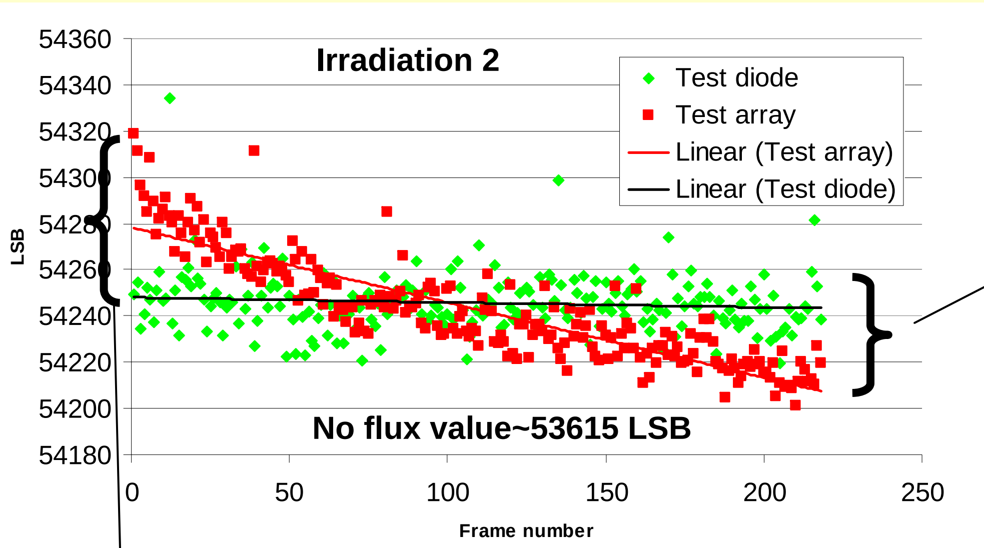
-**The exact characteristics (dielectric material, doping profile…) of the these tests structure is not known from us (difficult to get info from manufacturer).**

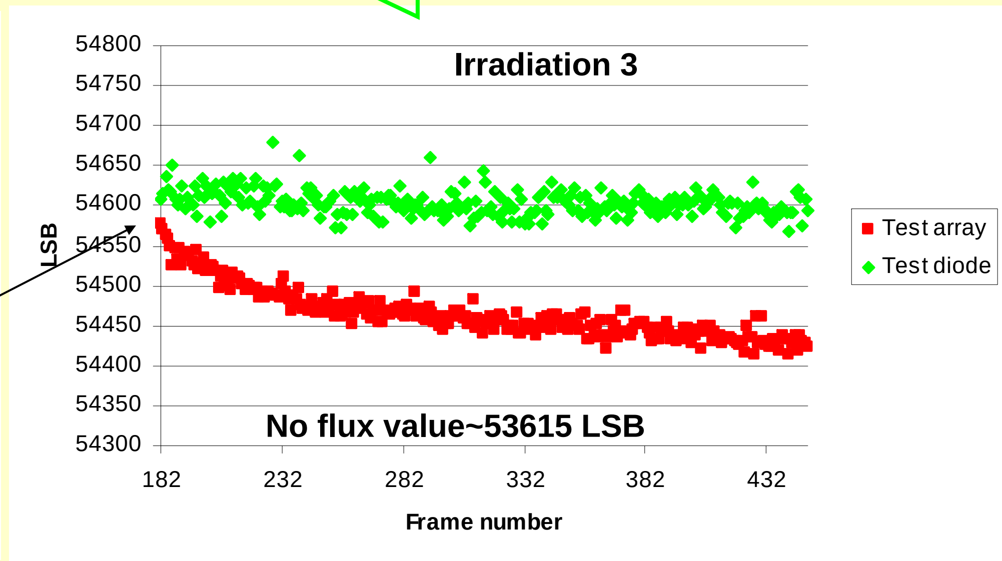
3- 60 MeV irradiation results overview

Spectral response degradation

- Charge collection decrease during irradiation (measure of test array currents)







Current measurement calibration artefact.

15 % decrease of the collected charge to compare to more than 25 % decrease in QE for the visible =>proton induced carriers are generated all along the track and deeper than for photons so minority carrier lifetime decrease should play a more important part for them….

3- 60 MeV irradiation results overview

- ***Spectral response degradation***
  - Decrease of diffusion length is observed but not enough…
  - Conversion gain is constant.
  - Stronger in blue.
  - Carrier build up in the oxide and/or interface trap can explain only partially the measurements, especially the fact that the intra-pixel response scales quite well with fluences.
  - Test structures based on plain photodiodes are almost not affected.
    - Top layers different from test array/main array?
  - Could the main effect due to optical alteration of some of the top surface layers?

Do the observed degradations scale linearly with NIEL?

4- Preliminary results on NIEL scaling

- ***NIEL scaling is extremely important in damage prediction for a given mission but can also help in understanding the processes involved.***
  - We want to see if the degradations observed mainly dark current increase and spectral response decrease are proportional to NIEL.
  - For dark current, NIEL scaling has been shown for many devices, especially CCDs, very few publications on CMOS APS.

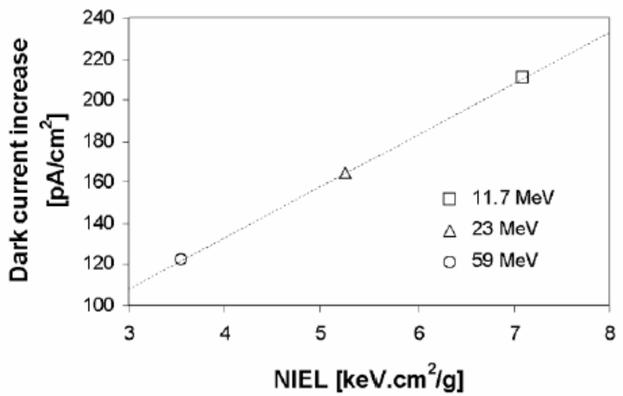


Fig. 6. Mean dark current increase versus the NIEL value at the different proton energies and after a fluence of 1×10^{11} protons/cm^2 at (27 °C).

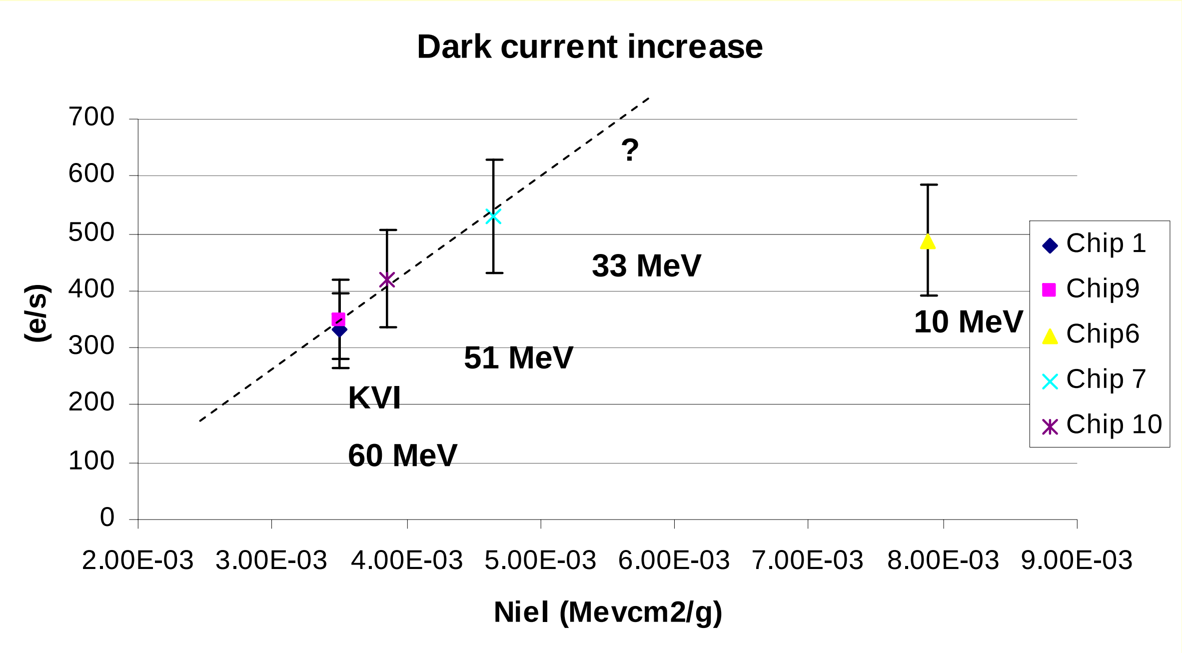
STAR250, Bogaert et al. (Jan.2003)

  - For the spectral response degradation, no known (?) study…

4- Preliminary results on NIEL scaling

Dark current

- For chips irradiated at 10, 33 and 51 MeV, gain variation is within the error bar of the measurement.



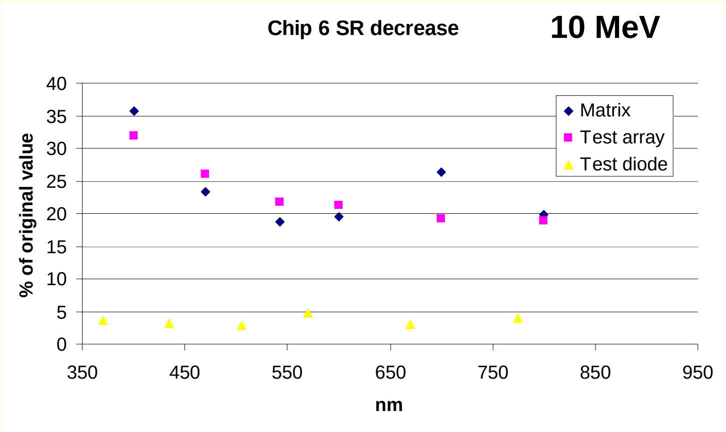
-Points at 60, 51 and 33 seem to follow a trend

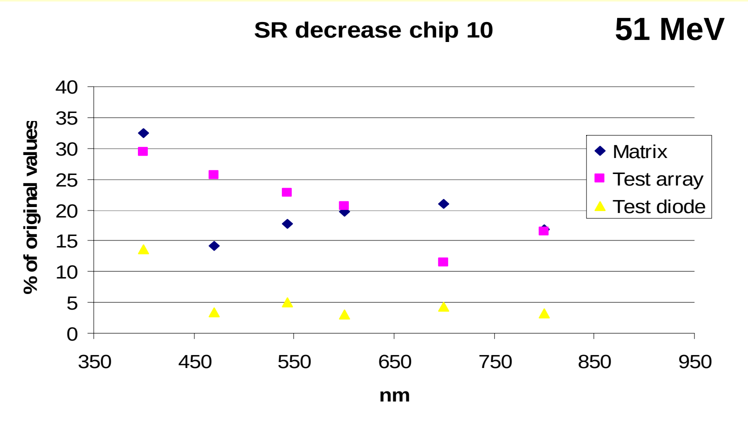
-Problem with point at 10 MeV?

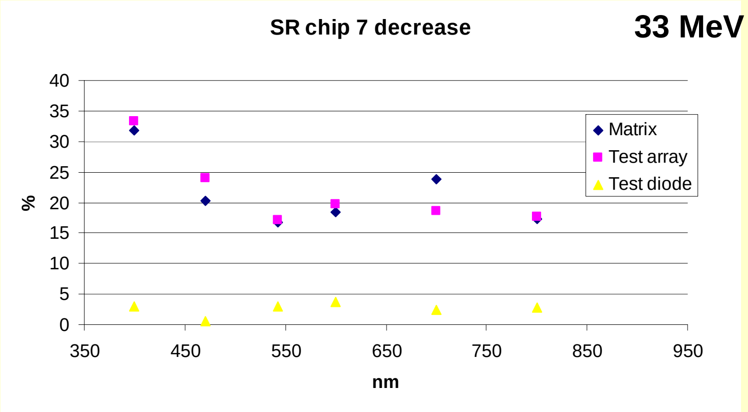
20% error bar: uncertainty on fluences (TBC)

4- Preliminary results on NIEL scaling

Spectral Response decrease

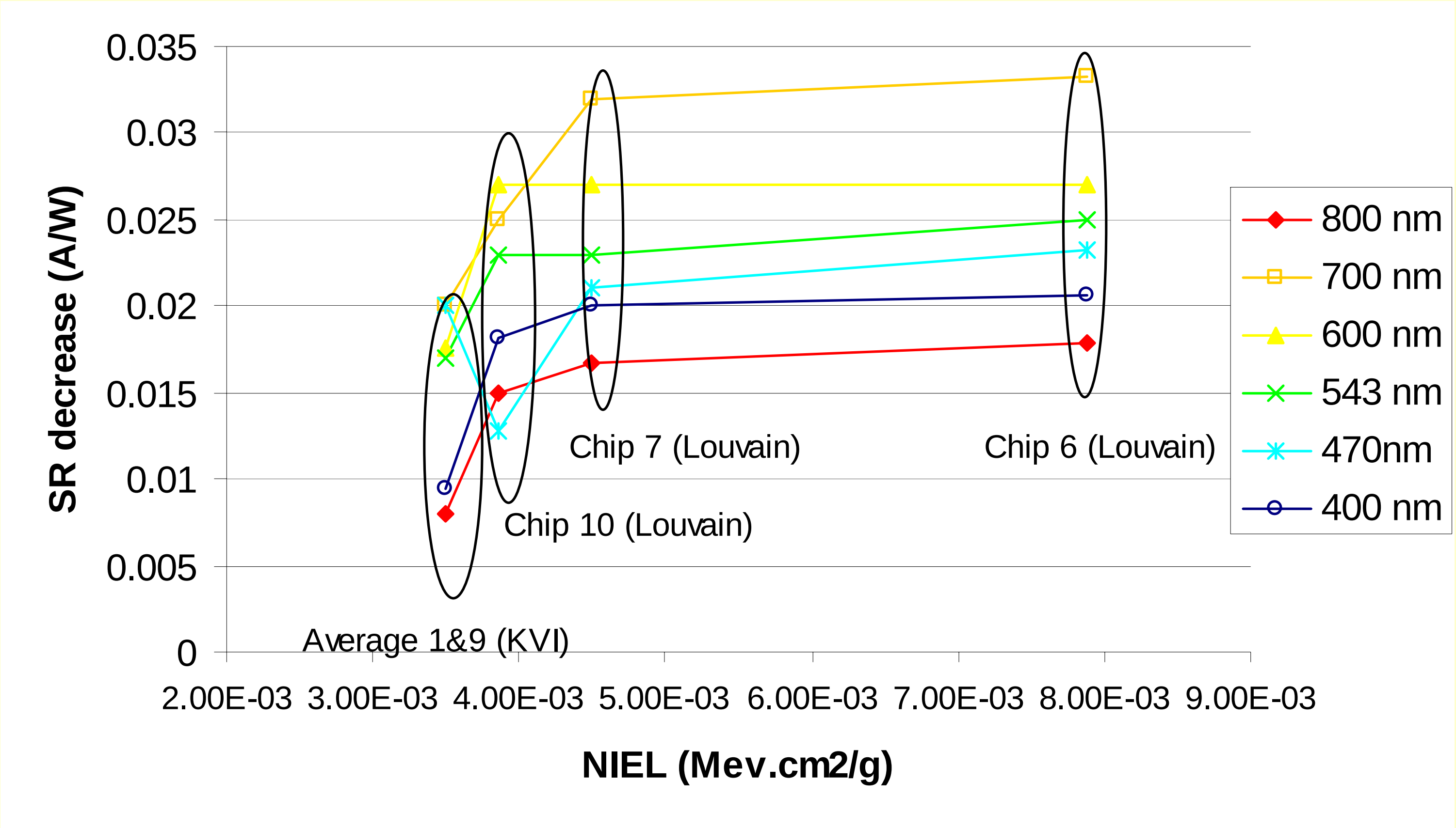






4- Preliminary results on NIEL scaling

Spectral Response decrease



1e11 p/cm2

- Same "overall" shape as for dark current increase but linear scaling seems even less probable at this stage…

4- Preliminary results on NIEL scaling

- ***At this stage no conclusion is really possible***
  - For chip at 60 MeV (biased and unbiased), linearity with proton fluences is good up to high TID (66 krad)=> TID received by chips at 10, 33 and 51 MeV is lower so one could assume that “displacement damage” shall be the dominating effect.
  - Need a second run on chip 6,7 and 10 to derive a “slope” and not a single point
  - Need to apply KVI/Louvain calibration factor.
  - Linear scaling only valid for high energy?
  - Need an extra point at ~ 15 MeV to bridge the gap in NIEL values and a point at higher energy.

5- Conclusion

- ***Preliminary results on the STAR1000 irradiation by protons have been shown***
  - Main effects are:
    - Dark current increase as expected.
    - Spectral response decrease => overall effect would lead typically to a loss of ~20 % for Bepi Colombo.
  - Definitive explanations for SR decrease has not been found yet, however minority carrier life time decrease in the bulk is very unlikely to be the main process.
  - NIEL scaling of damages is not confirmed at this stage
    - Additional points needed
  - Annealing behaviour should bring additional info.
  - Comparison with other sensors HAS (front illuminated) and back illuminated sensors (Earth Observation development) will also bring extra clue.

Thanks for Your Attention

- Many thanks to:
  - T. Beaufort (ESA/ESTEC)
  - R. Harboe-Sorensen (ESA/ESTEC)
  - R. Osteindorf (KVI)
  - G. Berger (Louvain)