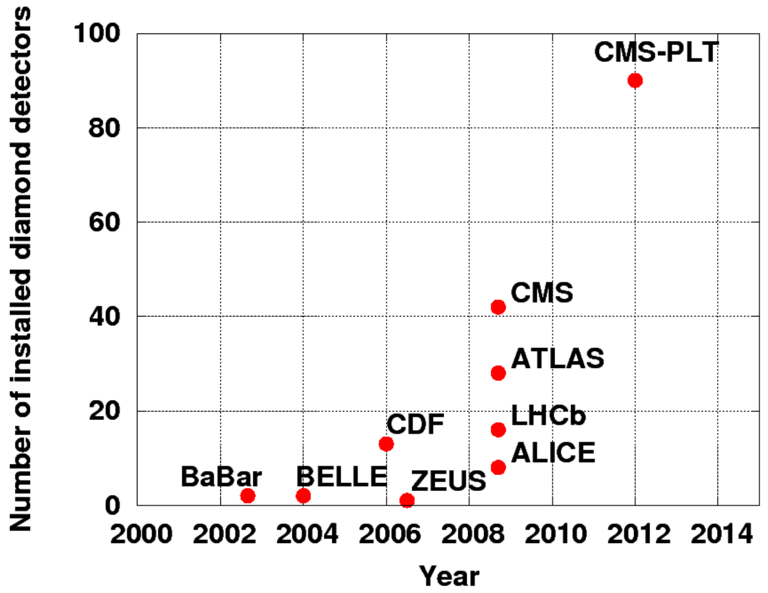
NIEL studies with FLUKA in comparison to data.

S. Mueller (CERN / KIT)

References:
-W. deBoer, ‘Radiation Hardness of Diamond and Silicon sensors compared’, Phys. Stat. Sol. 204(2007) 3004
-S.Mueller: ‘The Beam Condition Monitor 2 and the Radiation Environment of the CMS detector at the LHC” (Thesis, in preparation)

Motivation

- Modern High Energy Physics experiments use CVD-diamond for beam monitoring applications:



- Key argument for using diamond is often the radiation hardness of the material (amongst others: no cooling, inert to temperature drift…)
  - Diamond detectors are possible candidates, for the inner detector upgrade of CMS and Atlas.
- This necessitates a method to predict radiation damage in mixed field environments.
- With a scaling hyposthesis (NIEL/DPA-scaling) one can scale monoenergetic test beam results to a mixed field scenario (A widely used method in Si-community).

NIEL scaling

- The NIEL hypothesis states that the detector efficiency degrades proportional to the Non Ionising Energy Loss (NIEL).
- NIEL is widely used in silicon community to scale the damage potential of different particle types.
- However, NIEL is just an indication how much detector material is damaged, it is not necessarily a measure of detector efficiency:
  - Especially for modern silicon detector devices it is not true anymore that detector efficiency scales with NIEL (cryogenic-, 3d-detectors, see RD50 reports).
  - For diamond devices it still needs to be proven experimentally how well the NIEL scaling works in terms of detector efficiency.

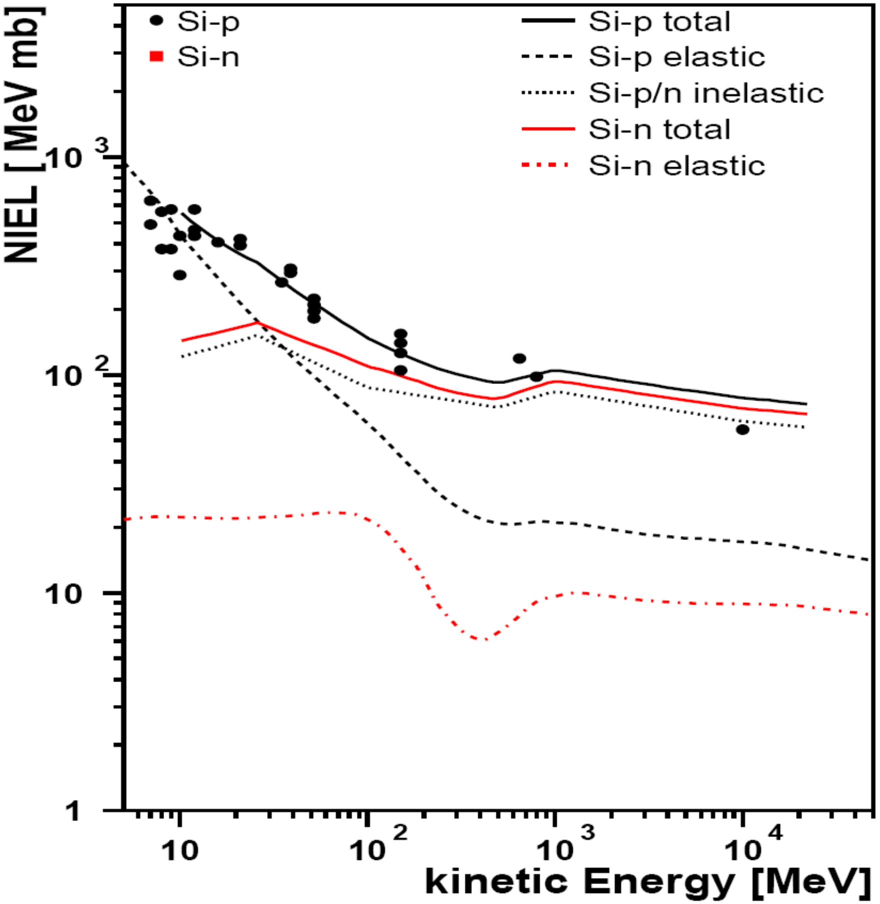
Previous NIEL study

- NIEL was calculated using the SRIM package.
- However: SRIM can only handle elastic interactions, therefore simulations were done in a twofold way:
  - Calculate all inelastic fragments with FLUKA
  - Use fragments to feed into SRIM to calculate NIEL
- Tuning necessary to combine both simulation packages.

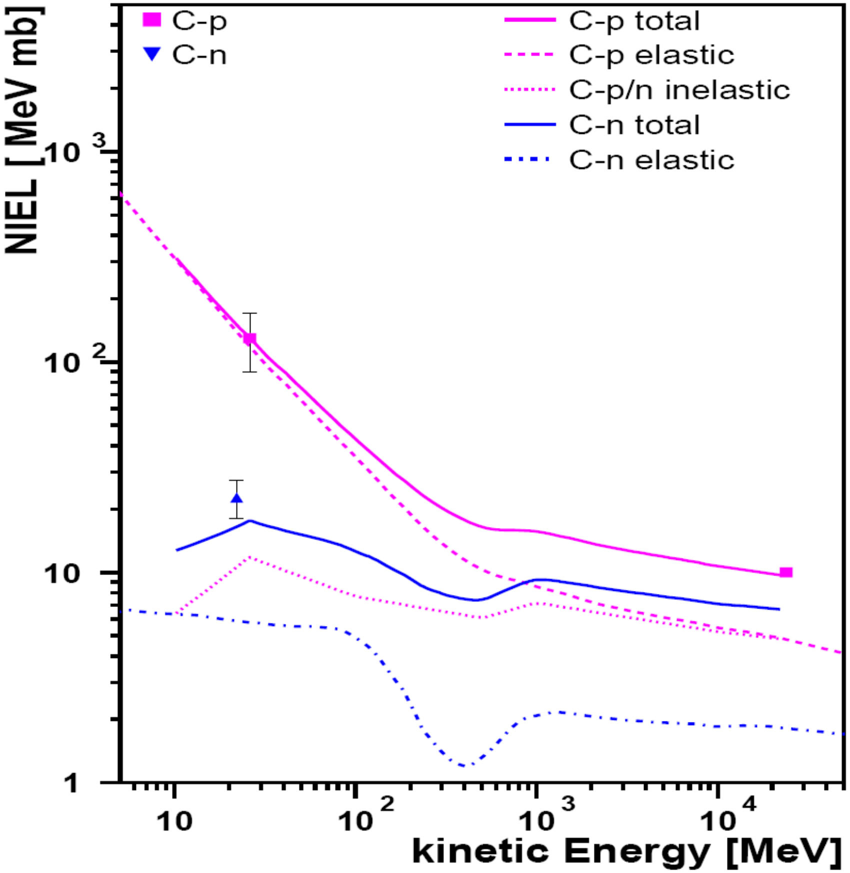
References:
SRIM: Stopping and Range of Ions in Matter, www. Srim.org
"FLUKA: a multi-particle transport code",
A. Fasso`, A. Ferrari, J. Ranft, and P.R. Sala, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773
"The physics models of FLUKA: status and recent developments",
A. Fasso`, A. Ferrari, S. Roesler, P.R. Sala, G. Battistoni, F. Cerutti, E. Gadioli, M.V. Garzelli, F. Ballarini, A. Ottolenghi, A. Empl and J. Ranft, Computing in High Energy and Nuclear Physics 2003 Conference (CHEP2003), La Jolla, CA, USA, March 24-28, 2003, (paper MOMT005), eConf C0303241 (2003), arXiv:hep-ph/0306267

Previous results

Silicon



Diamond



New NIEL study

- Latest FLUKA development version, has an implementation to calculate displacements per atom.
- All quantities of interest can be calculated using only one simulation package, so no tuning within different simulation packages is needed.
- New FLUKA code is believed to be stable and final, but no extensive benchmarking campaigns with real data took place yet (to my knowledge).

Therefore all results preliminary.

Displacements per Atom (DPA)

- DPA is a measure of the amount of radiation damage in irradiated materials.
  - 3DPA means that each atom in the material has been displaced from its site within the structural lattice of the material an average of 3 times.
  - DPA is a better quantity to calculate radiation damage, compared to NIEL (NIEL also contains non damaging energy transfer like Phonon interactions).

DPA in FLUKA

NRT model (Norgert, Robinson and Torrens) implemented in FLUKA for quantifying the number of atomic displacements in irradiated materials:

$$N_F = \kappa(T)\frac{\xi(T)T}{2E_{th}}$$

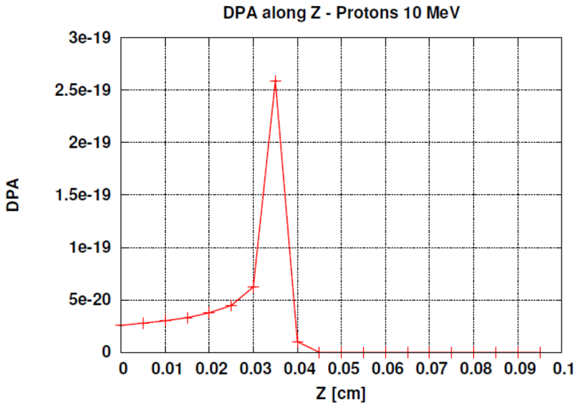
PKA kin. Energy
Displacement energy
Lindhard partition function
Displacement efficiency
Frenkel pairs

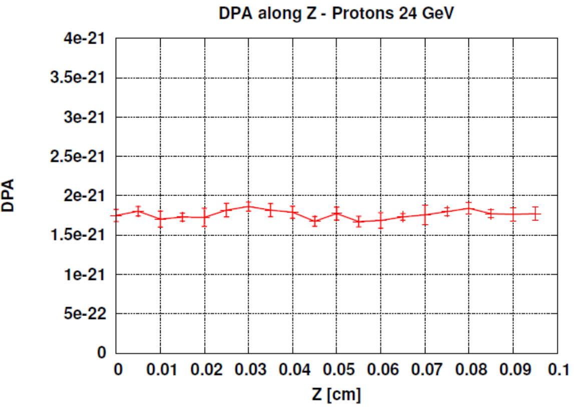
Displacement energies:

- **Silicon ~25eV**
- **Diamond ~42eV**

More detailed information about the implementation in FLUKA can be found in this talk: "DPA for FLUKA", Vasilis Vlachoudis, FLUKA Users Meeting 27.11.2008

Results simulated DPA

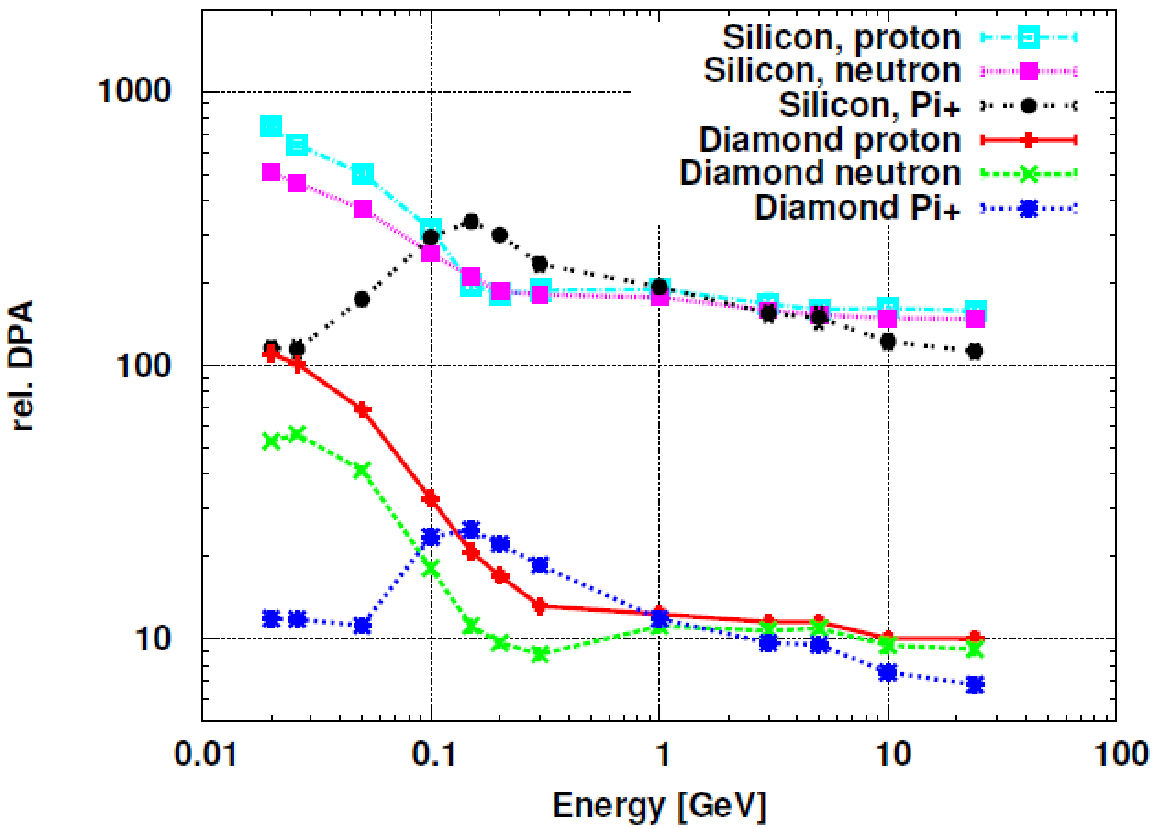




Simulated DPA along beam axis for two different proton energies. Low energetic particles lose a large fraction of energy resulting in a 'Bragg-peak' with high number of lattice displacements (left).

High energetic particles show a constant behaviour over a large path length (right).

Results of DPA simulations for Si and Diamond



DPA simulation result for Silicon and Diamond. Shown are the simulations for Protons, Neutrons and Pions at energies between 20MeV and 24GeV.

Diamond is generally more radiation hard than silicon. At high impact energies Silicon shows a factor of 10 higher DPA. At low energies however, this factor decreases to about 5-6 for protons.

Annealing effects and DPA

- Spatial distribution of defects:

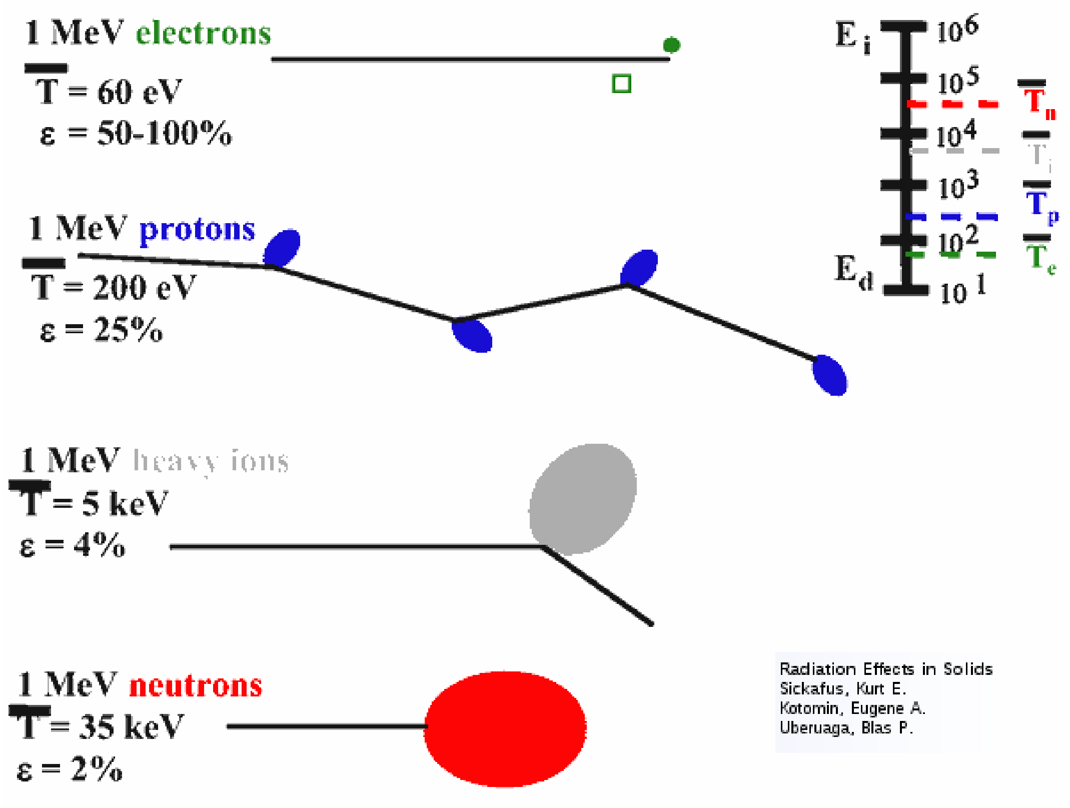


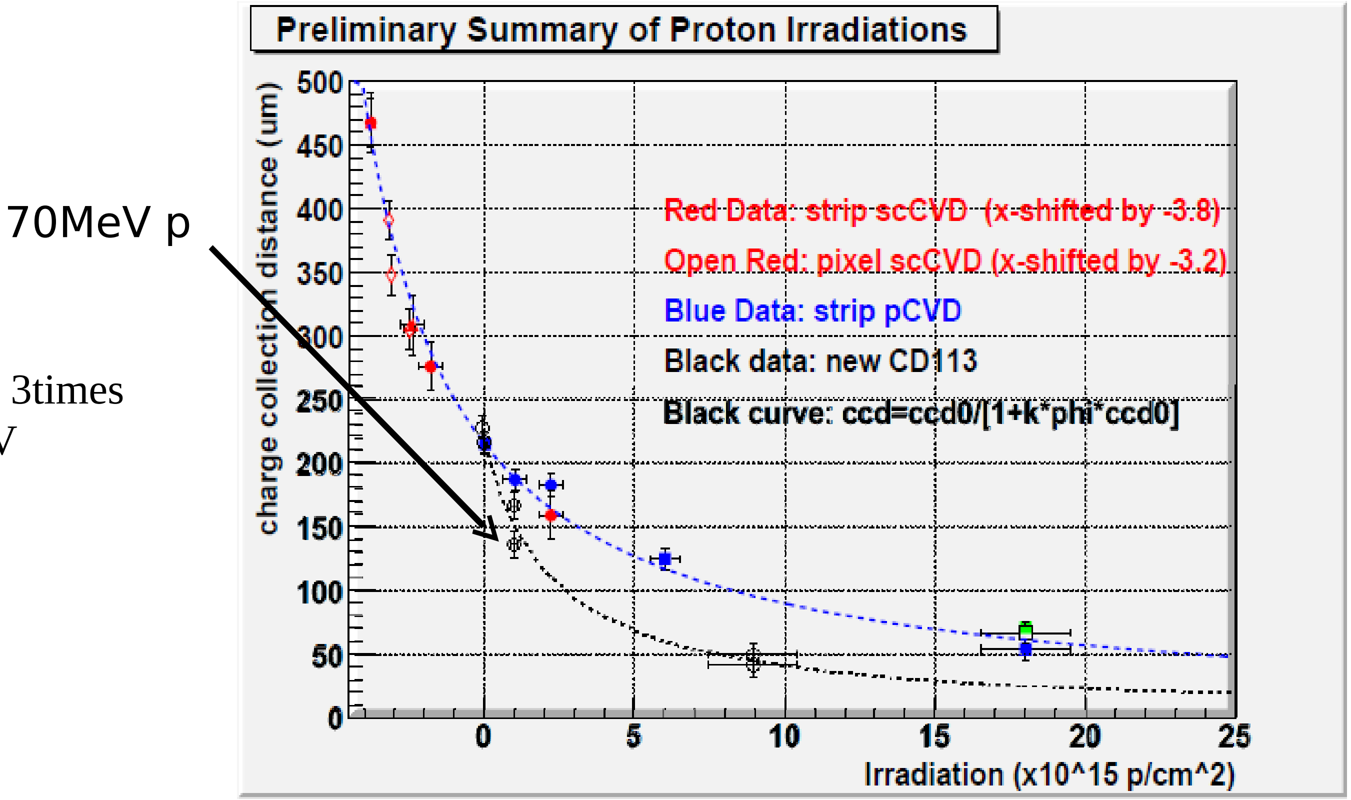
Figure 4. Difference in damage morphology, displacement efficiency and average recoil energy for 1 MeV particles of different type incident on nickel.

Morphology of defects changes probability of annealing/healing. Effect is more pronounced in Silicon than in diamond.

Comparison to test beam data (RD42)

24GeV Proton Irradiation Summary 2009:

70MeV Protons about 3times as damaging as 24GeV protons (k-value fit).



pCVD and scCVD diamond follow the same damage curve:

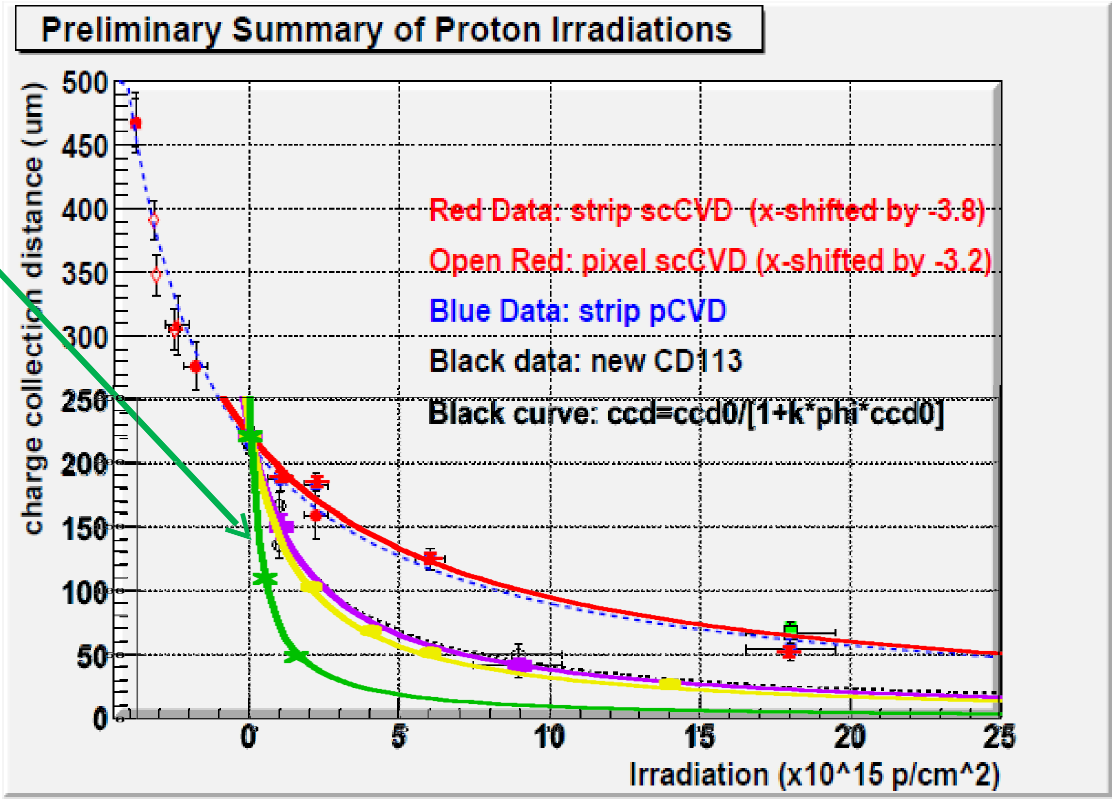
$$\mathrm{CCD}(\phi) = \frac{\mathrm{CCD}_0}{1 + k\phi\mathrm{CCD}_0}$$

Testbeam data (Karlsruhe 26MeV)

24GeV Proton Irradiation Summary 2009:

26MeV p

26MeV Protons about 16 times as damaging as 24GeV protons (k-value fit).

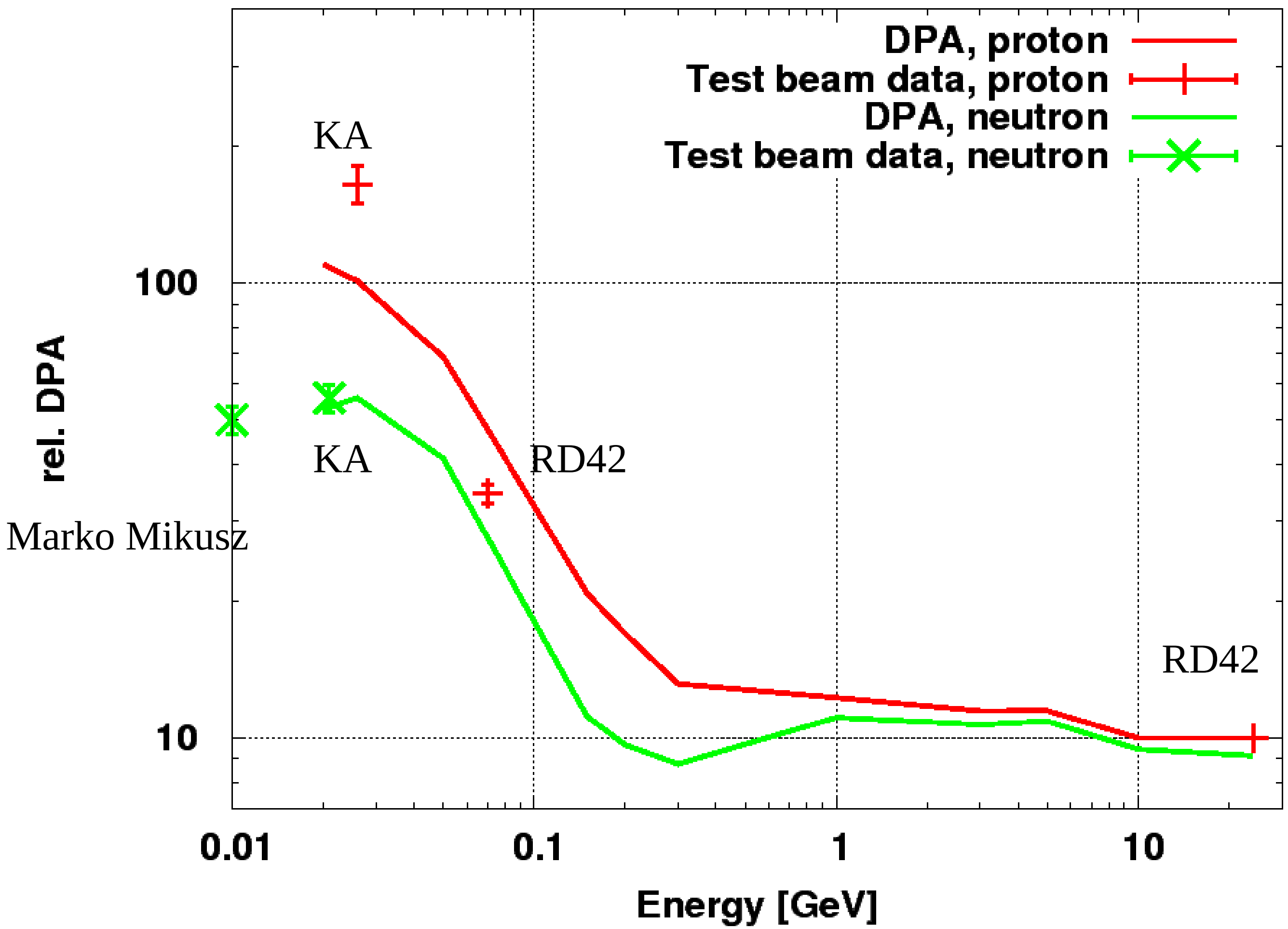


pCVD and scCVD diamond follow the same damage curve:

$$1/ccd = 1/ccd_0 + k\,\phi.$$

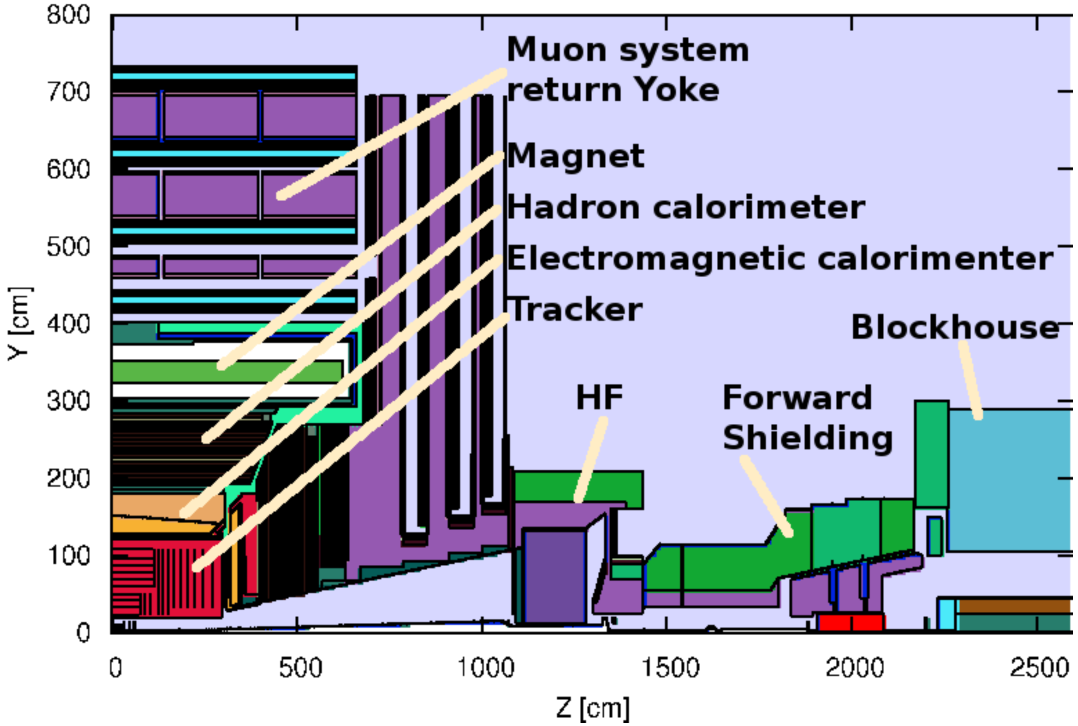
From Data: Clear that lower energy particles damage significantly more.

DATA/Simulation comparison



FLUKA CMS calculation with DPA

- With FLUKA it is also possible to calculate DPA per LHC pp-event.
- For this, all diamond based BRM systems were implemented into the FLUKA CMS-Framework.
- Goal: Find hardness factor of average pp-event normalised to 24GeV protons.

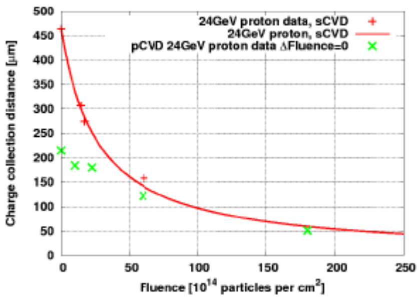


Results CMS

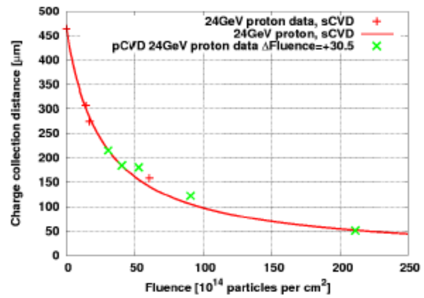
- Results are presented in CMS years to reach 50% detector efficiency (based on 24GeV proton irradiation).

	BCM2I	BCM2O	BCM1F	BCM1L
DPA per pp	8.02×10^{-24}	6.24×10^{-24}	3.18×10^{-24}	4.15×10^{-24}
Error	6.27×10^{-25}	2.45×10^{-25}	7.19×10^{-25}	6.29×10^{-25}
Error %	7.82	3.92	22.62	15.16
Hardness factor	0.1054	0.0820	0.0418	0.0546
Seconds at nominal luminosity to reach 50% efficiency	8.37×10^{7}	1.08×10^{8}	2.11×10^{8}	1.62×10^{8}
in CMS years (1×10^{7} s/a)	8.4	10.8	21.1	16.2

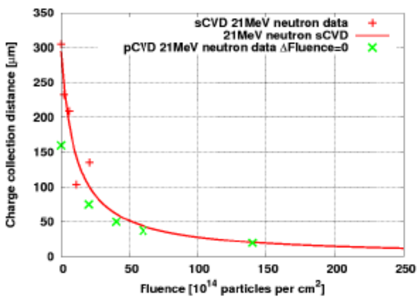
sCVD/pCVD scaling



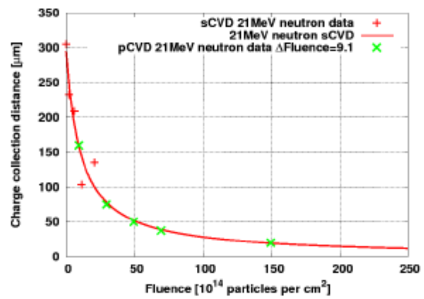
(a) 24 GeV protons, no shift.



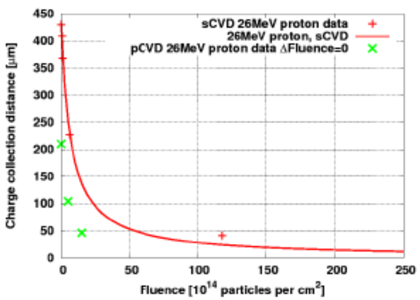
(b) 24 GeV protons, shift of 30.5 $\times 10^{14}$ $\frac{p}{cm^2}$.



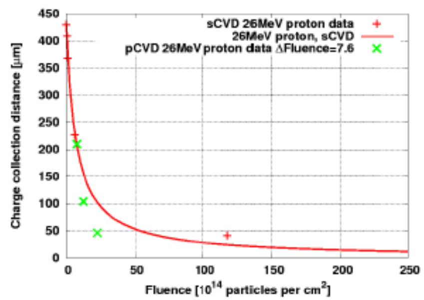
(c) 21 MeV neutrons, no shift.



(d) 21 MeV neutrons, shift of 9.1 $\times 10^{14}$ $\frac{p}{cm^2}$.



(e) 26 MeV protons, no shift



(f) 26 MeV protons, shift of 7.6 $\times 10^{14}$ $\frac{p}{cm^2}$.

Do pCVD diamonds behave like irradiated sCVD diamonds?

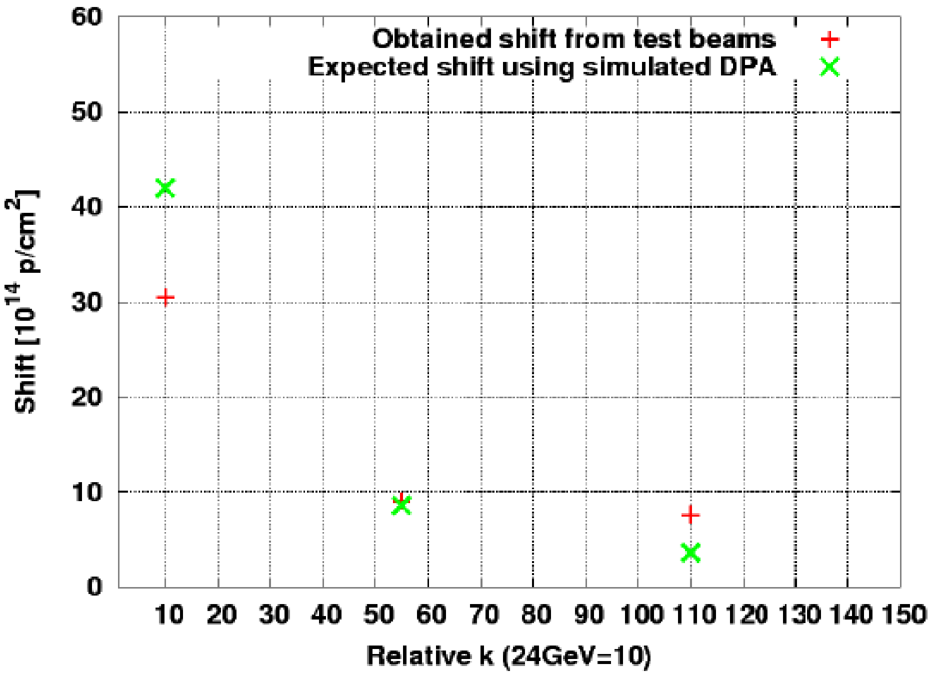
RD42 hypothesis:

- pCVD diamond behave like sCVD diamonds.
- Hypothesis tested with available data
  - Shift pCVD data on top of sCVD data
  - Shift is determined by particle type

- Hypothesis works for 24GeV protons and 21MeV neutrons, 26MeV proton data is not compatible with hypothesis.

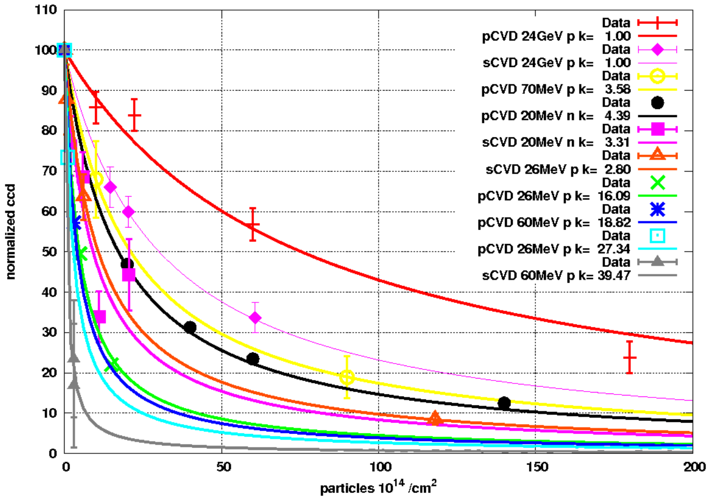
- Shift can be also predicted by simulation results. Comparison shown next slide.

Comparison expected/measured shift



Comparison of expected shift from simulations
and obtained shift from data.

Some thoughts about sCVD / pCVD



- Large amount of diamond irradiation data available.
- Plot shows only a part of available data.
- Large spread in data.
- But difficult to get a consistent picture explaining the data.

- The CCD is a robust characterisation number for pCVD diamonds, as it is mostly independent from diamond geometry. (CCD << thickness)
  - pCVD CCD can be measured by using beam signal and 36MIPs/um relation.
- CCD for sCVD need to be treated differently
  - CCD >> thickness
  - Same measurement as for pCVD would result in a CCD of sCVD thickness, which is wrong.
  - Possible to calculate sCVD CCD via charge carrier lifetime and mobility.
  - sCVD CCD values between 500um and few cm. Large spread in sCVD quality (from junk to very good).
  - No real definition of what sCVD is.

Conclusion

- CMS has a large set of diamonds installed
  - 9 x sCVD, 32 x pCVD, 1 x unpolished pCVD.
  - In addition:
    - 72 sCVD diamonds for PLT and
    - further 10 sCVD and 4 pCVD for upgrad studies.
  - Many regions with different particle energy spectra.
  - Unique possibility to check radiation hardness of different diamonds in a real experiment environment.
  - Motivation to study radiation hardness of diamond.
- Latest FLUKA offers a very convenient way to calculate irradiation induced lattice displacements.
- DPA is only a measure for lattice defects, but other diamond detector features (metallisation, grain boundaries, impurities) might have an effect on detector efficiency as well.
  - Data available so far confirms DPA-scaling, however:
  - More consistent experimental data would be useful to validate DPA scaling theory.
- Hypothesis that pCVD diamonds are damaged sCVD diamonds tested and partially describes data.
- DPA simulation for CMS:
  - Lifetime expectation for all installed diamonds sufficient for 10y LHC.
  - Ongoing LHC-data taking will be used to test prediction.