Hardness assurance tests at INFN-LNS Catania

14th Geant4 Users and Collaboration Workshop
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Radiation & Effects

- Total Ionising Dose
  - Total ionized dose degradation of semiconductor devices and different types of materials results from low and steady flux of energetic electrons and protons that exist in the natural space environment.
- Displacement Damage
  - Displacement damage in semiconductor devices are caused by exposure to a large flux of protons or neutrons. Protons or neutrons interact with the atomic structure of semiconductor device displacing them and causing electrical parametric degradation. High doses of neutron flux is generated by a nuclear detonation.
- Single Event Effects
  - Single event effects in semiconductor devices are caused be energetic cosmic ray and solar flare particles. These particles are energetic ions and protons that exist in the natural space environment. Some effects are catastrophic and others can cause functional upsets or failures.

SEE Ground Testing

- Heavy-Ion Testing (according to ESCC 25100)
  - Must be well-defined in E and specie (LET determination)
  - Uniform over DUT surface (flux values may be varied between 10^2-10^5 ions/(cm^2-s)) within 10%
  - Range in Silicon larger than 30 um
  - Tilting the DUT to allow wider range of LET values

$$\mathrm{LET}(\mathrm{MeV} \cdot cm^2/\mathrm{mg}) = \frac{dE}{dX} \cdot \frac{1}{\rho}$$

$$\mathrm{LET}_{\mathrm{eff}} = \mathrm{LET}_{\vartheta = 0} / \cos\vartheta$$

Single Event Effects Tests at Accelerators

- SEE Test: **Cyclotron at LNS-INFN** (Catania)
- LNS Beams Used for RH Qualification Tests: **Gaseous Beams at 20MeV/nucleons**
  - 20Ne
  - 40Ar
  - 84Kr
  - 129Xe

The selection of the ion species we use in SEE studies is done by taking into account the easiness of beam changing operation and at the same time the necessity to cover as large a LET interval as possible

- All events within range in Si of 40um to about 500um
- Irradiation of components in air which is used also as a degrader

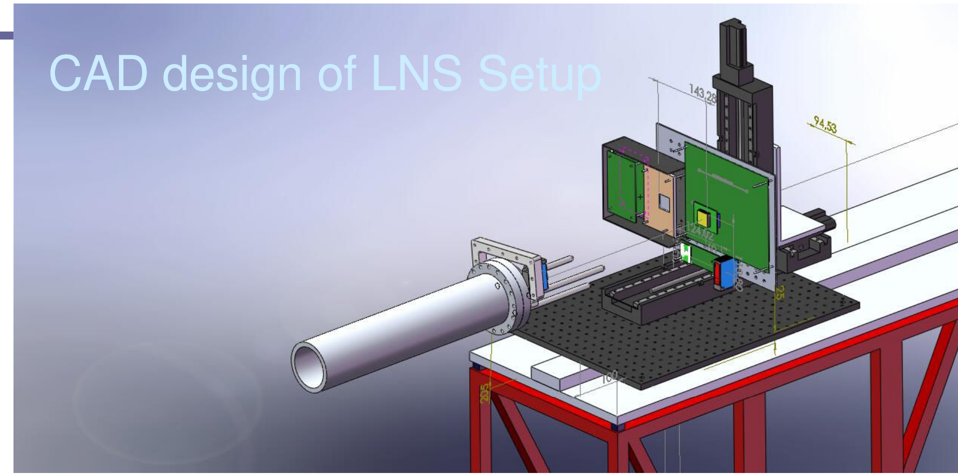
Dosimetry System Features

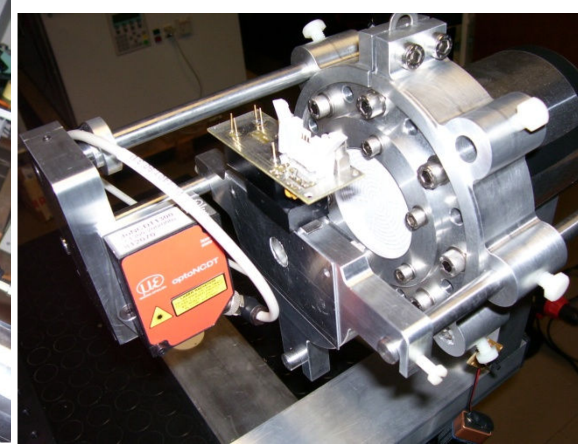
- **Thin scintillator (50 and 100 um)** for the online fluence measurement >99 % efficiency
- **Motorized stage** with submicron accuracy of position repeatability (X,Z max 30 cm and Y max 20 cm). A rotator for measurements with theta angle up 60 degrees.
- **1.5 mm thick double sided microstrip detector** with 170 um spatial resolution.
  - All the selected ions are stopping inside hence calorimetric measurements
  - To localize and measure the beam spot (profile of the beam is obtained);
    - Each event is
      - time tagged with 125 ns resolution
      - Energy tagged through dE/dX measurements in silicon
- **SELDP (Single Event Latchup Detector and Protector)**
  - Custom module to monitor and count the SEL behaviour of DUT (wide range of DUTs are covered)
- **Online Monitoring of Environmental parameters (T, RH)**

Test Procedure for SEE Studies

PERFORMING SEE MEASUREMENTS

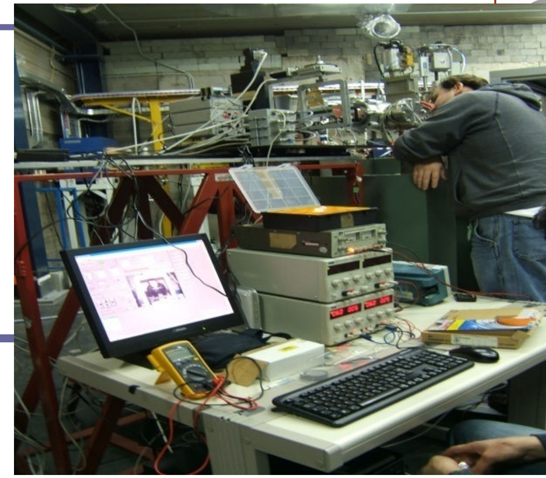
Prior to go to LNS for a test period, all dosimetry system including DUT mounting and performance is tested in MAPRAD laboratories onto a mock-up mechanical system of the beam setup which includes also a pulsed IR laser source. All mechanical parts necessary are produced and tested on this mock-up, as well as electronics parts which are tested under the pulsed laser beam to verify the behavior of the entire DAQ system.

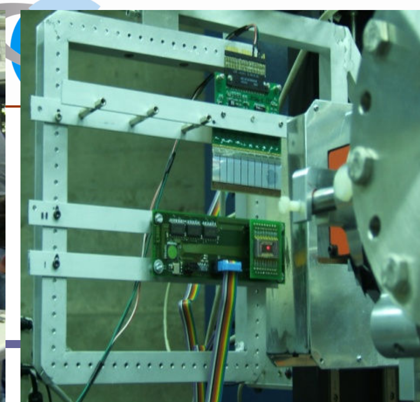




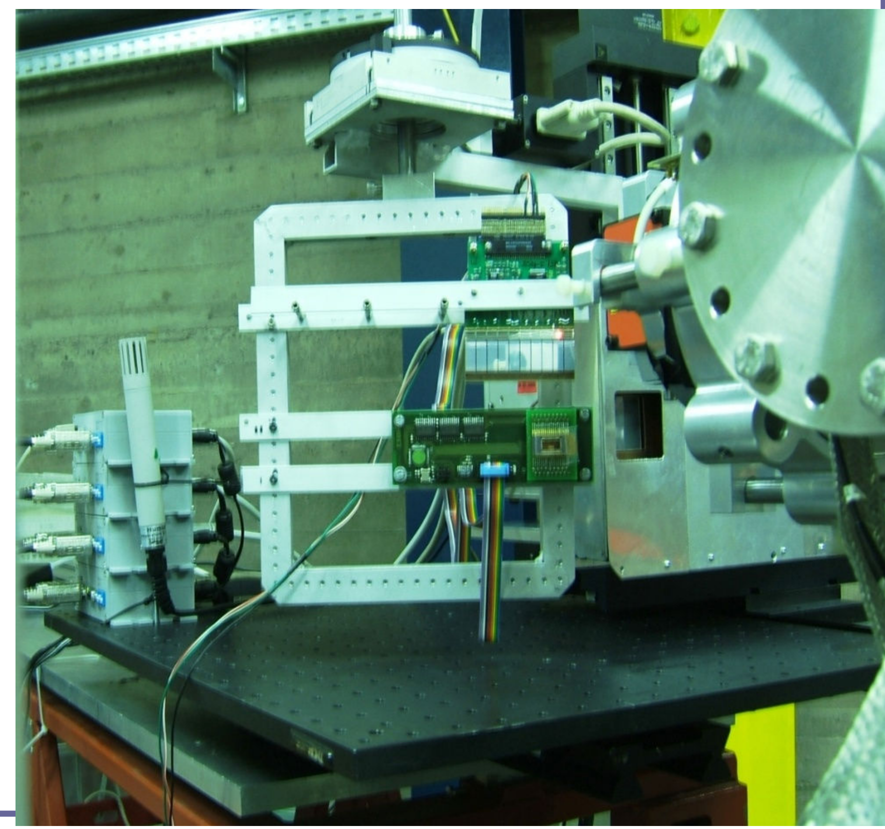
Mock-up at MAPRAD labs (March 2009)

LNS Beam SETUP (April 2009)

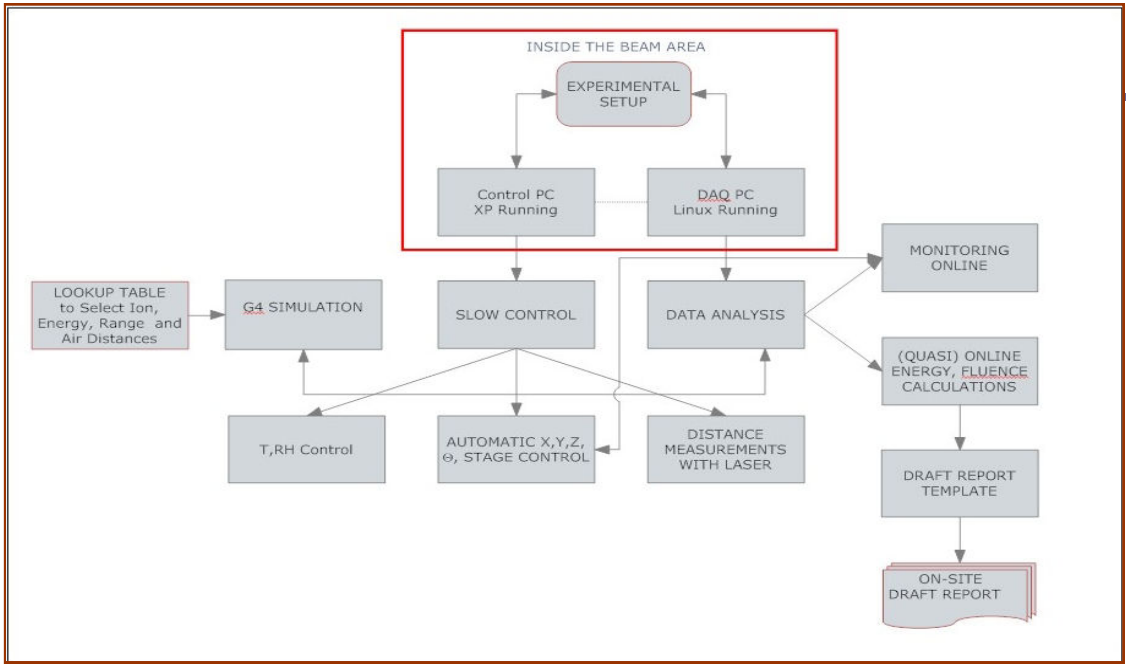


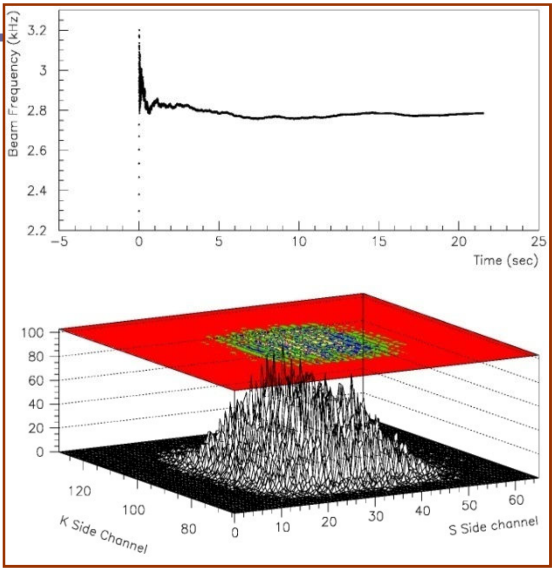


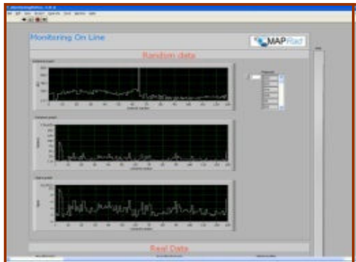
- Memorize on the control PC the data taking positions
- Start with the beam profile on the silicon detector to get the beam shape and position with respect to DUT, so that it can be automatically moved under the beam.
- Start data acquisition by monitoring; the flux measured by thin scintillator and DUT parameters. The beam parameters (energy, profile, flux, time tag) measurement is done by moving silicon detector under the beam for short periods without stopping the run. A possible alternative procedure is to keep the silicon detector off-beam close to DUT and monitor continuously the tail of the beam. A calibration run with thin scintillator "on" and silicon detector "on/off" beam will provide normalization factors to achieve the real flux.

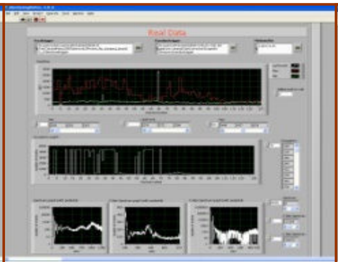


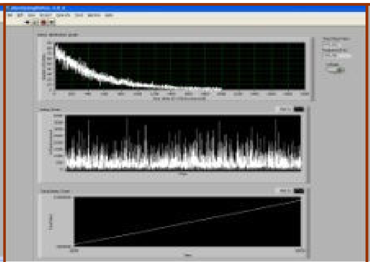
Configuration of beam setup

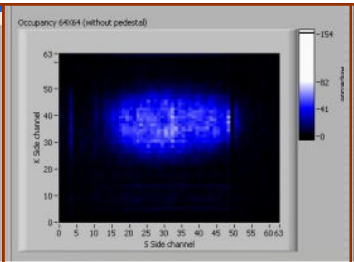


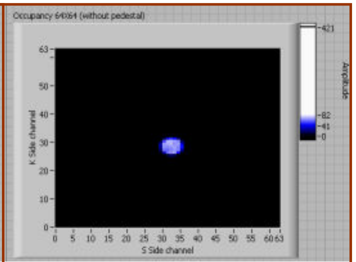



Random Data


Real Data


Timing

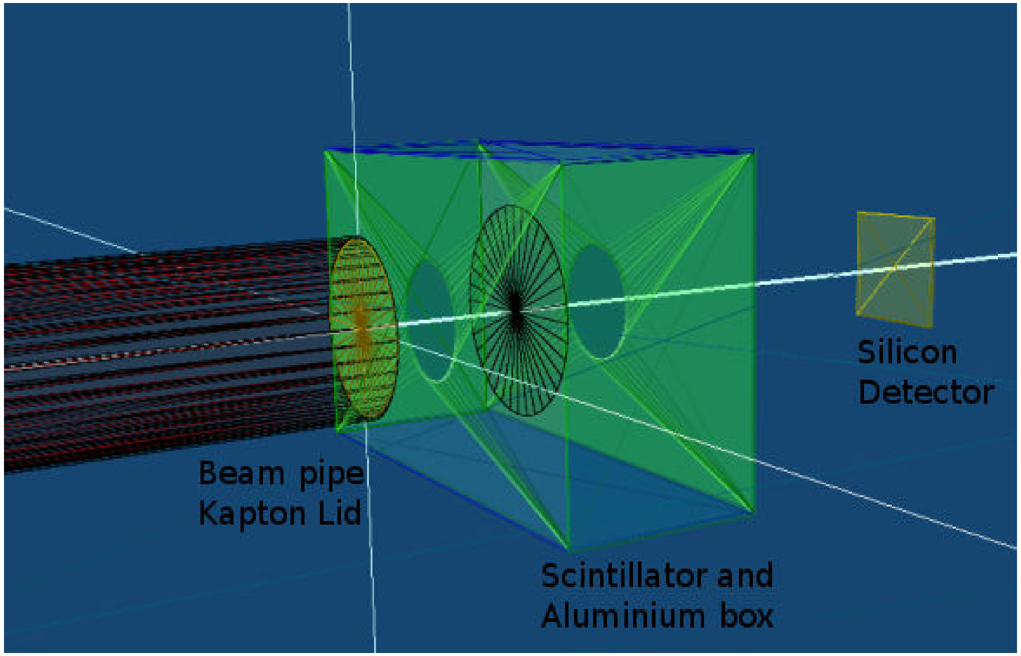

Beam Profile protons


Beam Profile Cm244

Geant4 Simulation Features

- Goal: A full Geant4 Monte Carlo description of the setup to prepare a detailed look-up table for the four different ion species in use
- Description of simulation
  - Geometry
  - Physics
- Results

Geant4 Geometry



Simulated set-up

Air1 is the distance between the end of kapton's window and the centre of scintillator's box.

Air2 is the distance between the centre of scintillator/s box and silicon surface.

- Configuration parameters in ASCII file: easy reconfiguration without recompile
  - Air1
  - Air2
  - Thickness of Scintillator
  - Box of Scintillator
  - Detector dimensions
- Material parameters taken from NIST database
- Mono-energetic 20MeV/n Beam
  - 20Ne
  - 40Ar
  - 84Kr
  - 129Xe
- World material is air

Geant4 Physics

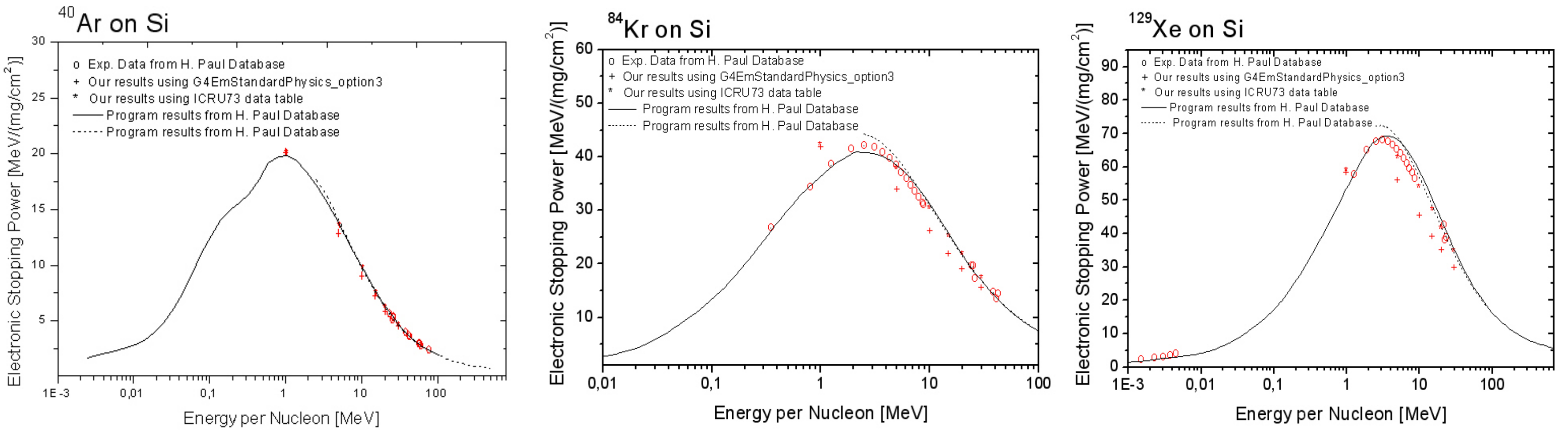
In the first phase, only electromagnetic process were taken into account, later on we decided to review the physics list to evaluate the contribution of fragmentation due to air and to try the new electromagnetic models developed and/or included in Geant4.

Point of start: geant4/examples/hadrontherapy…

- Electromagnetic model
- Hadronic elastic model (*G4HadronElasticPhysics()*)
- Hadronic inelastic model for proton and neutron (*G4HadronInelasticQBBC()*) …and for ions?

Electromagnetic interactions: *G4IonParametrisedLossModel*

Beam particles generated in front of silicon detector and the world's material is vacuum.



- BraggIon : Emin = 0eV Emax = 2MeV ← *G4EmStandardPhysics_option3()*
  BetheBloch : Emin = 2MeV Emax = 10TeV
- ParamICRU73 : Emin = 0eV Emax = 100TeV ← *G4EmStandard+G4IonParametrisedLossModel +G4IonFluctuations*

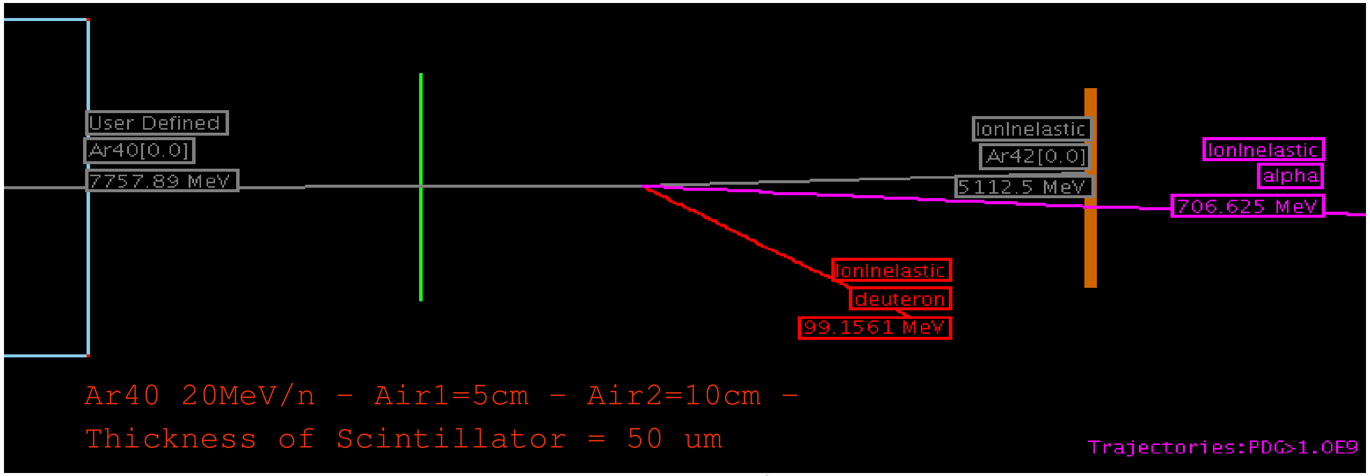
Geant4 Physics

- Hadronic inelastic interactions : which model?

  - ☑ Binary Cascade Light Ions
  - ☑ QMD

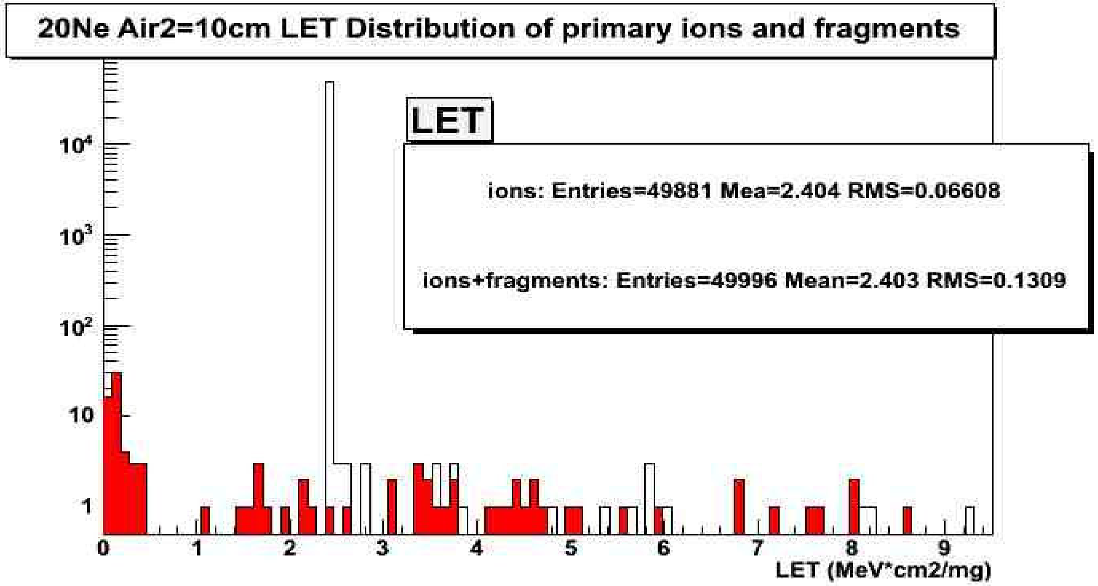
At the moment we are just interested to see how many fragmentations are produced in air and hit the silicon detector.

Results: Fragmentations



Plot created using HepRep browser, produced fragments are visible.

The fragments produced by nuclear reactions in air not change significantly the LET distribution.

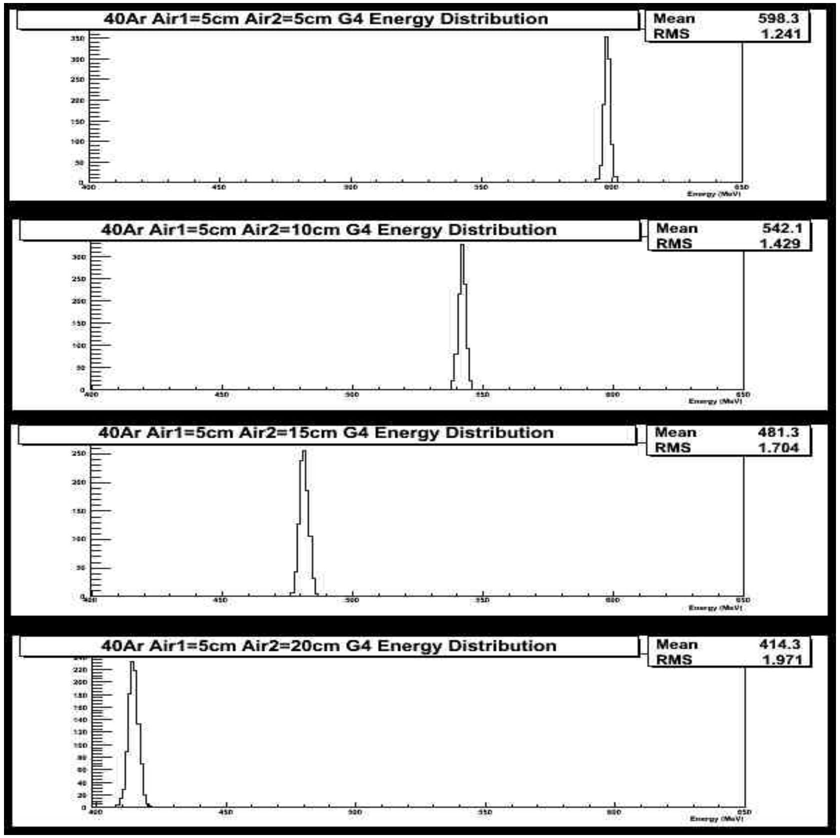


Results: Fragmentations

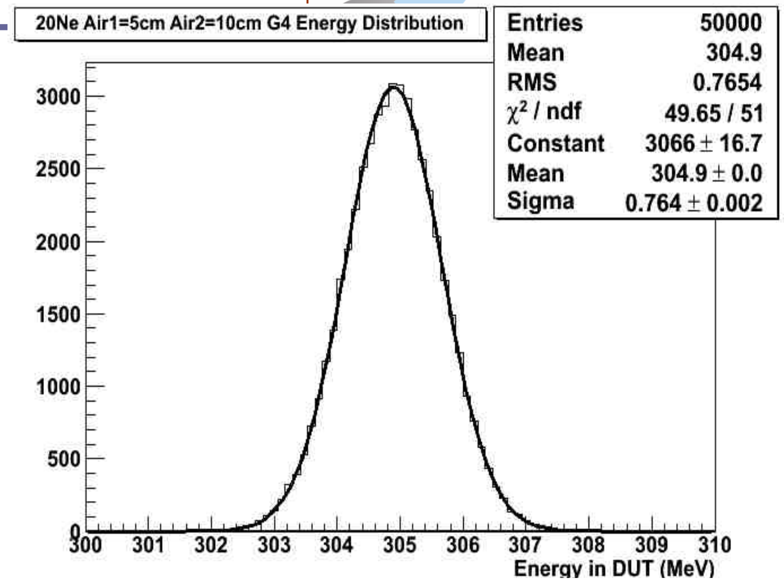
Hadronic Inelastic model for ions:					Binary		QMD	
Beam ion	Energy (MeV)	Air1 (cm)	Air2 (cm)	Scint (um)	Number of primary particles @ Silicon entrance (per event)	Number of secondary ions @ Silicon entrance (per event)	Number of primary particles @ Silicon entrance (per event)	Number of secondary ions @ Silicon entrance (per event)
Ne20	400	5	5	100	0,998	0,002	0,999	0,001
Ne20	400	5	10	100	0,997	0,002	0,996	0,002
Ne20	400	5	15	100	0,997	0,000	0,998	0,005
Ne20	400	5	20	100	0,997	0,000	0,996	0,002
Ar40	800	5	5	50	0,999	0,001	0,998	0,002
Ar40	800	5	10	50	0,997	0,007	0,998	0,003
Ar40	800	5	15	50	0,993	0,008	0,994	0,006
Ar40	800	5	20	50	0,995	0,008	0,996	0,002
Ar40	800	5	25	50	0,994	0,001	0,991	0,004
Kr84	1680	5	5	100	0,994	0,007	0,994	0,006
Kr84	1680	5	10	100	0,996	0,002	0,993	0,002
Kr84	1680	5	15	100	0,994	0,001	0,994	0,002
Kr84	1680	5	20	100	0,479	0,000	0,492	0,001
Xe129	2580	5	3	50	0,996	0,006	0,999	0,001
Xe129	2580	5	5	50	0,998	0,002	0,999	0,001
Xe129	2580	5	10	50	0,997	0,004	0,995	0,004

Results: G4-to-Data

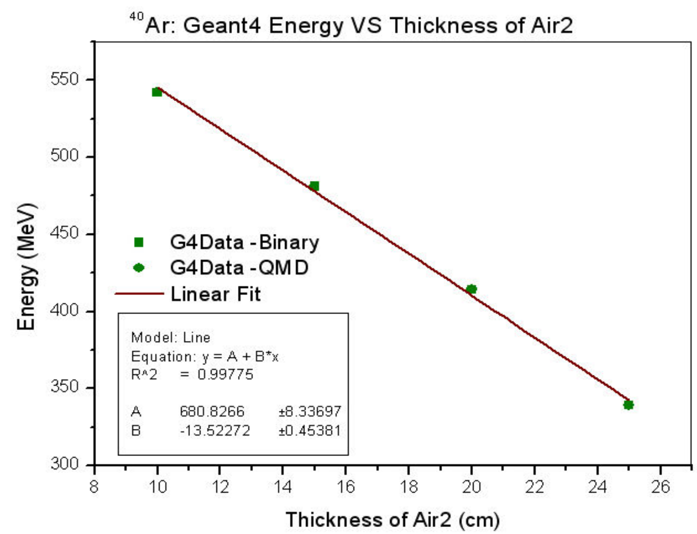
The determination of energy deposited in DUT by Geant4 simulation



From G4 Montecarlo,40Ar Energy Distribution for different air2 values

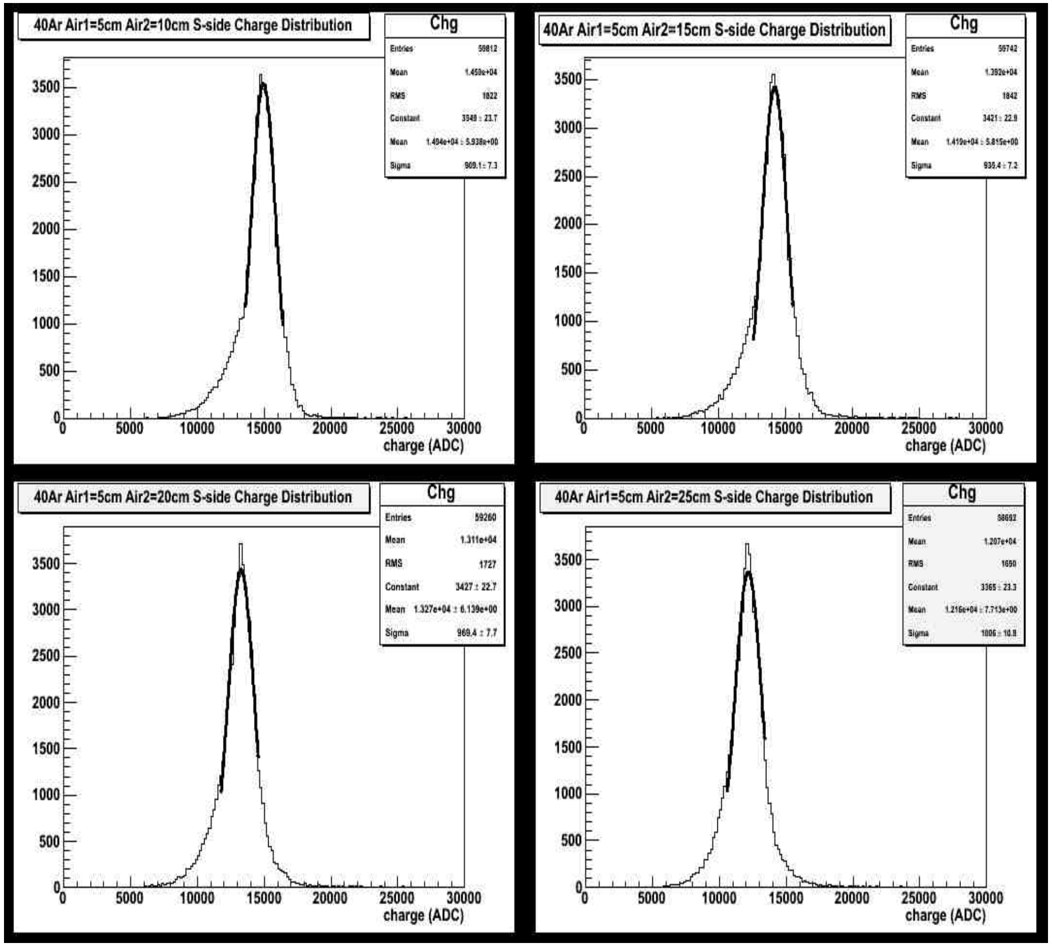


From G4 Montecarlo, Energy Distribution for 20Ne air2=10cm

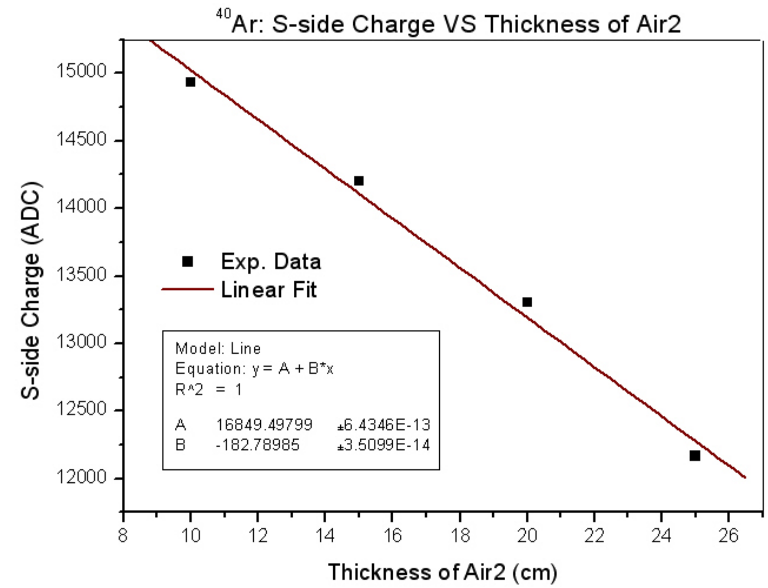


From G4 Montecarlo, Energy Distribution for 40Ar versus air2=10,15,20,25 cm

Results: G4-to-Data



From LNS dataset, Charge Distributions for 40Ar for different air2 values



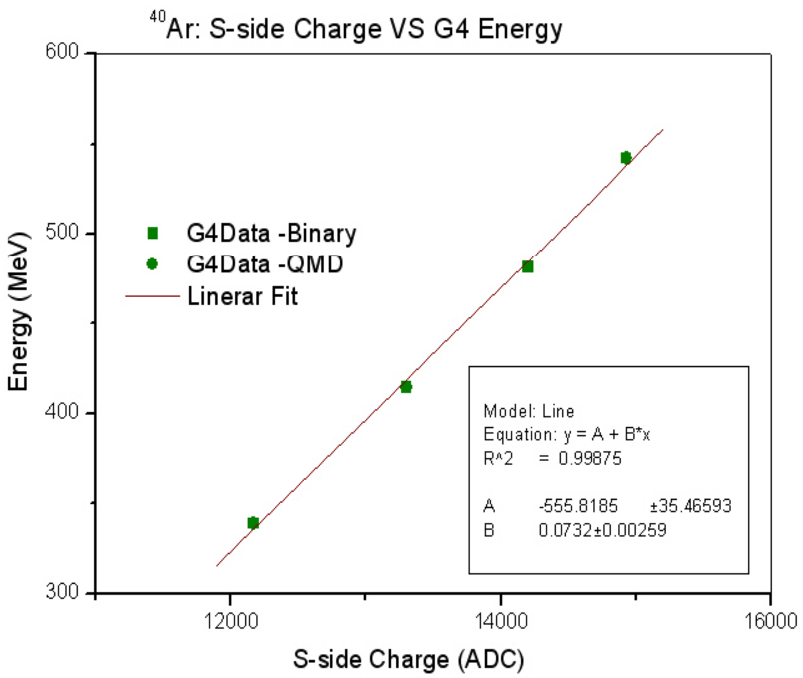
From LNS dataset, Charge Distributions for 40Ar versus air2=10,15,20,25 cm

In the right the charge distributions on S-side are not correlated to K-side charge distributions, just basic cuts are used.

Results: G4-to-Data/Charge-to-Energy Conversions

There is a good correlation with the charge measured by the silicon detector, which provides the possibility to convert the charge values to deposited energy.

The correlation between charge collected in silicon and simulated energy for different air thicknesses for 40Ar is given in Figure, where the values are the means of Gaussian fits.



Results: G4 Table LET

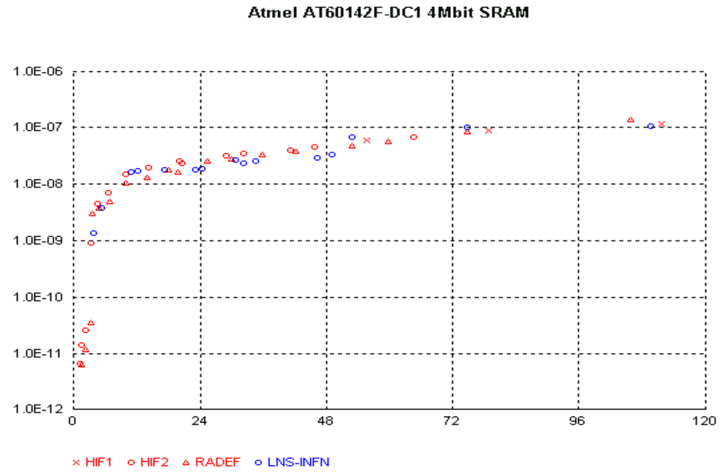
Setup parameteres					Kinetic Energy @ Silicon entrance (MeV)				LET [MeV/(mg/cm2)]			
Beam	Energy	Air1	Air2	Scint	G4Code	G4Code	TRIM	Gras	G4Code	G4Code	SRIM	Gras
ion	MeV	cm	cm	um	Binary	QMD			Binary	QMD		
Ne20	400	5	5	100	321,91	321,94	323,79	323,9	2,31	2,31	2,37	2,46
Ne20	400	5	10	100	304,42	304,91	323,30	307,6	2,41	2,40	2,37	2,56
Ne20	400	5	15	100	287,07	287,07	306,88	290,5	2,52	2,52	2,48	2,67
Ne20	400	5	20	100	268,07	268,36	289,80	272,5	2,64	2,64	2,59	2,79
Ar40	800	5	5	50	598,33	598,26	603,16	609,901	7,39	7,39	7,58	7,58
Ar40	800	5	10	50	541,75	542,05	550,05	560,382	7,88	7,87	8,04	8,03
Ar40	800	5	15	50	481,30	481,26	493,60	506,218	8,52	8,52	8,60	8,47
Ar40	800	5	20	50	414,22	414,31	432,51	447,943	9,32	9,32	9,32	9,17
Kr84	1680	5	5	100	702,88	702,83	749,15	879,5	31,50	31,50	32,72	27,77
Kr84	1680	5	10	100	436,47	436,40	512,16	686,2	36,52	36,52	36,84	30,54
Kr84	1680	5	15	100	121,76	121,52	251,39	472,2	42,17	42,16	40,71	34,91
Xe129	2580	5	3	50	1299,78	1299,61	1256,29	1568	52,56	52,56	59,22	46,29
Xe129	2580	5	5	50	1131,21	1131,09	1090,23	1444	54,68	54,68	61,74	47,50
Xe129	2580	5	10	50	672,56	672,70	648,27	1123	60,98	60,97	68,20	51,48

Results: G4 Table Range

Setup parameteres					Kinetic Energy @ Silicon entrance (MeV)				ProjectedRange [micrometer]			
Beam	Energy	Air1	Air2	Scint	G4Code	G4Code	TRIM	Gras	G4Code	G4Code	SRIM	Gras
ion	MeV	cm	cm	um	Binary	QMD			Binary	QMD		
Ne20	400	5	5	100	321,91	321,94	323,79	323,9	498,30	498,38	352,96	361,40
Ne20	400	5	10	100	304,42	304,91	323,30	307,6	451,28	452,19	352,07	331,67
Ne20	400	5	15	100	287,07	287,07	306,88	290,5	406,08	406,08	322,86	299,79
Ne20	400	5	20	100	268,07	268,36	289,80	272,5	359,92	360,32	293,77	263,76
Ar40	800	5	5	50	598,33	598,26	603,16	609,901	288,71	288,65	232,85	222,36
Ar40	800	5	10	50	541,75	542,05	550,05	560,382	244,21	244,37	203,52	197,03
Ar40	800	5	15	50	481,30	481,26	493,60	506,218	200,53	200,50	174,24	169,13
Ar40	800	5	20	50	414,22	414,31	432,51	447,943	156,91	156,95	144,80	139,96
Kr84	1680	5	5	100	702,88	702,83	749,15	879,5	78,14	78,13	91,58	75,19
Kr84	1680	5	10	100	436,47	436,40	512,16	686,2	40,92	40,91	62,16	53,76
Kr84	1680	5	15	100	121,76	121,52	251,39	472,2	9,07	9,05	33,33	33,30
Xe129	2580	5	3	50	1299,78	1299,61	1256,29	1568	87,23	87,22	91,68	77,95
Xe129	2580	5	5	50	1131,21	1131,09	1090,23	1444	72,57	72,56	79,85	69,95
Xe129	2580	5	10	50	672,56	672,70	648,27	1123	37,78	37,79	50,58	50,82

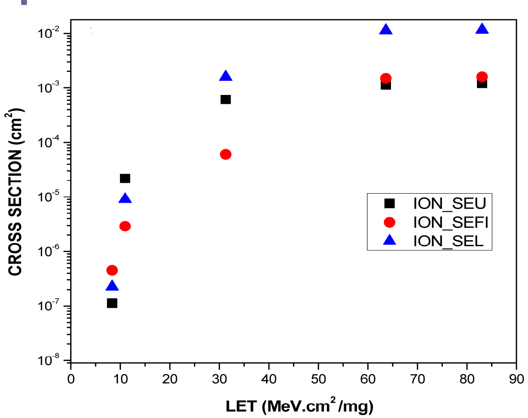
Some examples

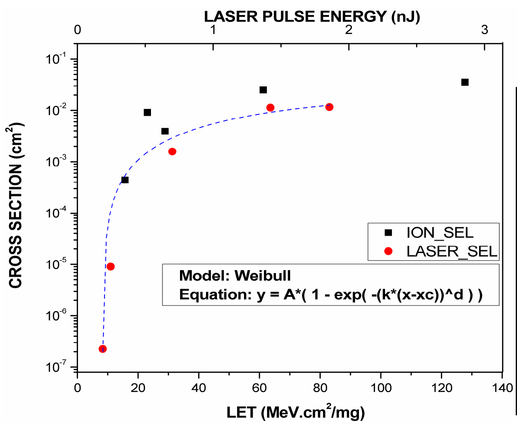
In order to measure the consistency of our measurements with other measurements done in other beams we used a benchmark setup developed by ESA/ESTEC named SEU monitor. This setup measures the number of SEU events on a Atmel AT60142F-DC1 SRAM which is a component that has a well known SEU cross section versus LET curve (measured in several facilities) and is Latchup immune. The Figure shows our results compared with these values measured in other facilities. As shown our results are in good agreement with the previous measurements.



Few samples DUTs tested at LNS and the cross section versus LET for PIC18F8680 (ions/laser)

Device	Manufacturer	Application	Technology	Power Supply	Data Rate	Data Storage
CC1020	CHIPCON	Transceiver RF 400-940 MHz	CMOS 0.35um	3.3V	153.6kbit	-
AT45DB321CTI	ATMEL	Flash RAM	-	3.3V	40Mbit	4.3MB
EX128TQ100	ACTEL	FPGA	CMOS 0.22um	3.3-5V	-	10k gates
FM20L08	RAMTRON	Ferroelectric RAM	-	3.3V	33MHz	1Mbit
PIC 18F8680	MICROCHIP	Microcontroller	-	5V	40MHz	64kb





Conclusions

- About dosimetry system:
  - An automatic dosimetry system for beam parameters monitoring for SEE and DD test (ESCC 25100) in LNS has been realised and used successfully, a critical part of test procedure relies on Geant4.
  - Results are cross-checked with ESA based “Reference SEU monitor” system.
  - With four gaseous ions of 20 A·MeV it is possible to fulfil ESCC 25100 requirements.
  - Beam changing time is relatively short (few hours) and flux and beam size are stable in time.
  - LET values can be “fine-tuned” by using air as degrader.
  - Great ease of use is provided by operating the system in air.

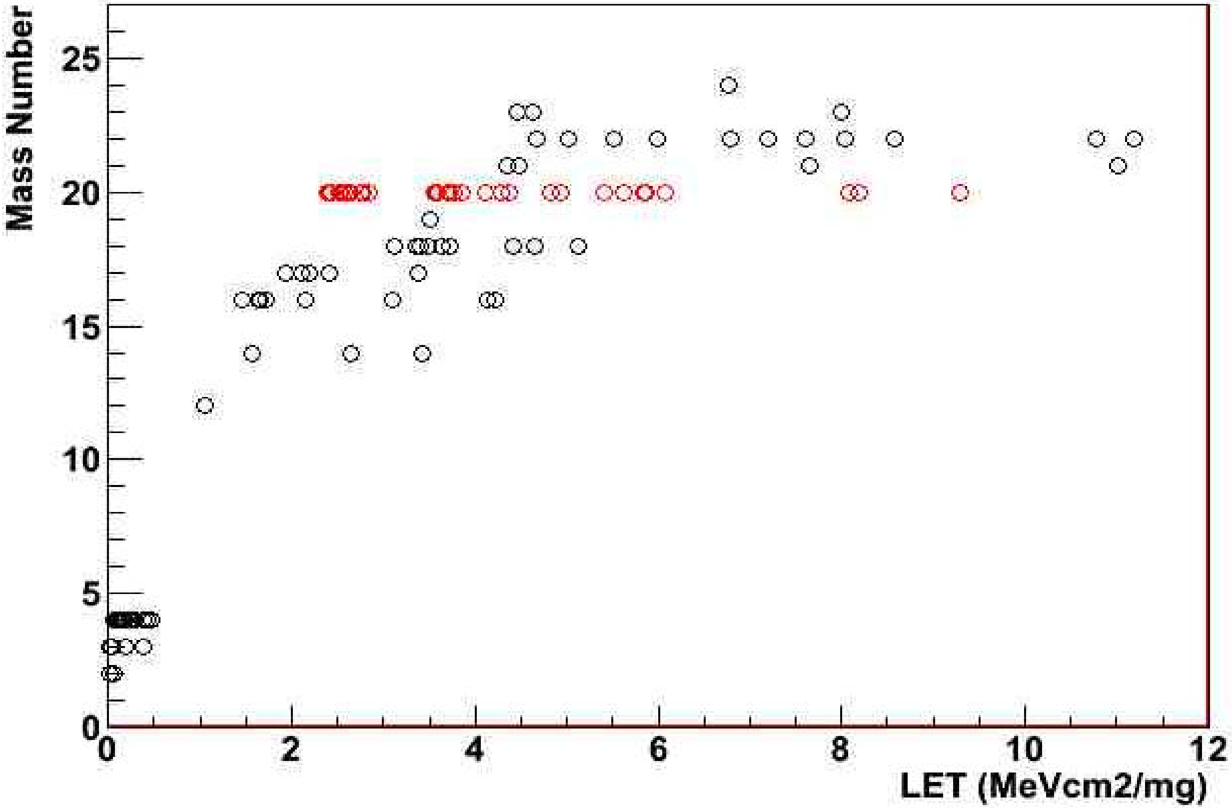
Overall Error Estimation on LET values

With average trigger efficiency of ~88 %

Ion/LET (MeV/mg/cm2)	**Error on LET (MeV/mg/cm2)**
Neon-20/3.7	0.1
Argon-40/13.13	0.2
Krypton-84/30.6	0.7
Xenon-129/52.9	0.8

Fragmentations versus Mass Number A

20Ne Air1 = 5cm - Air2 = 10cm - thickness of scintillator = 100um



Results: Error Evaluation

- The systematic errors contributing to the overall error on LET are;
  - **Error on LET Value**
    - Distance measurements (air thickness).
      - This is done with 200 um accuracy laser system only once during the initial calibration phase. All other positions are relative to that point with submicron precision 4-D stage (X,Y,Z, Theta)
    - Fragmentation (i.e. $<10^{-3}$ per all set-up)
    - Determination of energy deposited and Range in DUT
      - Deposited charge in silicon; from data
      - Deposited energy and range in silicon; from G4 simulation
      - Charge-to-Energy Conversion
- Cross section errors are calculted taking in to account
  - **Error on Fluence Value**
    - Positioning of beam spot center to the center of DUT
      - This is done through positioning of beam spot first on double sided thick silicon with 170 um spatial resolution. Then it is shifted on to DUT centre (the DUT reference crosses wrt to Silicon reference crosses are measured once during the initial calibration phase)
    - Fluence measurement from thin scintillator and from silicon detector

$$\sigma(\#/cm^2) = \frac{N_{SEE}}{Fluence \cdot \cos\vartheta}$$