SEE Radiation Testing

T. Wijnands, EN Department

Abstract : Following an brief introduction on radiation effects , this presentation will focus on radiation testing for Single Event Effects (SEE). Some of the European SEE accelerators used by CERN equipment groups will be presented and simple guidelines for testing will be given.

Preliminary

- Radiation testing does not guarantee that equipment will work
- Radiation testing is really a ‘test’ so we use ‘test’ conditions
- To obtain reliable data you need :
  - A very well prepared, high performing SEE test setup
  - A very well prepared, calibrated test beam readily available
  - A test setup and a facility that fit together mechanically, electrically
- There is no such thing as ‘a single radiation test’
- There is no such thing as ‘a quick test’ before series production

Outline

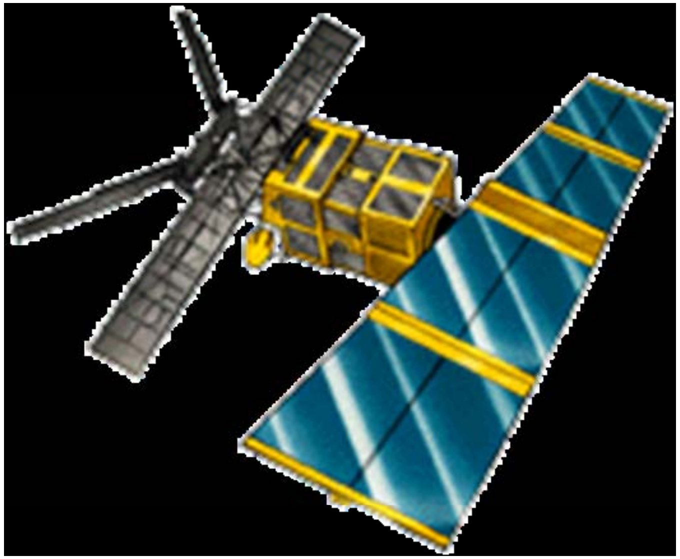
- Introduction
- Radiation Effects in the LHC
- Radiation Environments in the LHC
- SEE Test facilities
- SEE test setup and test conditions
- Experimental data collection
- Design validation

Introduction

- For decades there has been intensive research on all aspects of radiation effects in semiconductors (and other materials)
- This is a huge field
- Many different applications to medicine, nuclear power, military, aerospace and consumer electronic arenas.

1991 : ERS-1/PRARE Satellite

- July 1991 : Earth Resource Satellite ERS-1 launched into an 784 km sun-synchronous polar orbit.
- During the 5 days of operation a number of anomalies were noted inc. soft errors and a processor 'reboot'.
- After 5 days of operation the PRARE instrument shut down immediately following a transient over-current conditions and could not be restarted.
- Ground testing identified the possible cause of failure to be semiconductor related (EEPROM, SRAM).
- Proton irradiation of the engineering model confirmed the failure to be a latch-up in a 64K-bit SDRAM.



Earth Resource Satellite ERS-1

From R. Harboe Sorensen RADWG day 2005

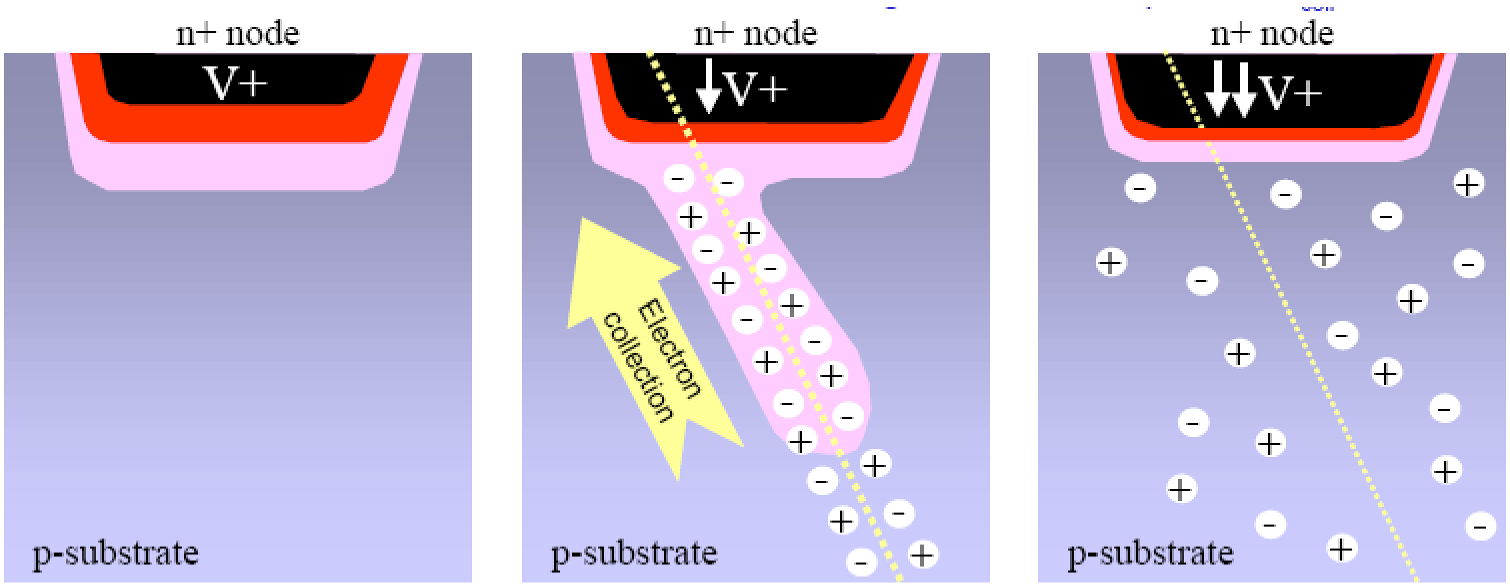
Radiation Effects

- The LHC radiation Environment :
  - Contains energetic particles capable of causing significant damage to accelerator equipment
- Resulting in :
  - Total Ionising Dose (TID) damage
  - Displacement damage
  - Single Event Effects (SEE)
- Which will cause :
  - Degraded performance
  - Temporary loss of performance
  - Catastrophic failures

Single Events

- Focus first on single event effects :
  - First concern
  - Large impact
  - Difficult subject
- Non destructive SEEs :
  - Single event upset (SEU)
  - Multiple Bit Upset (MBU)
  - Single Event Transient (SET)
  - Single Event Functional Interrupt (SEFI)
- Destructive SEEs :
  - Single Event Latch Up (SEL)
  - Single Event Gate Rupture (SEGR)
  - Single Event Burn Out (SEB)

Sensitive nodes in semi conductors



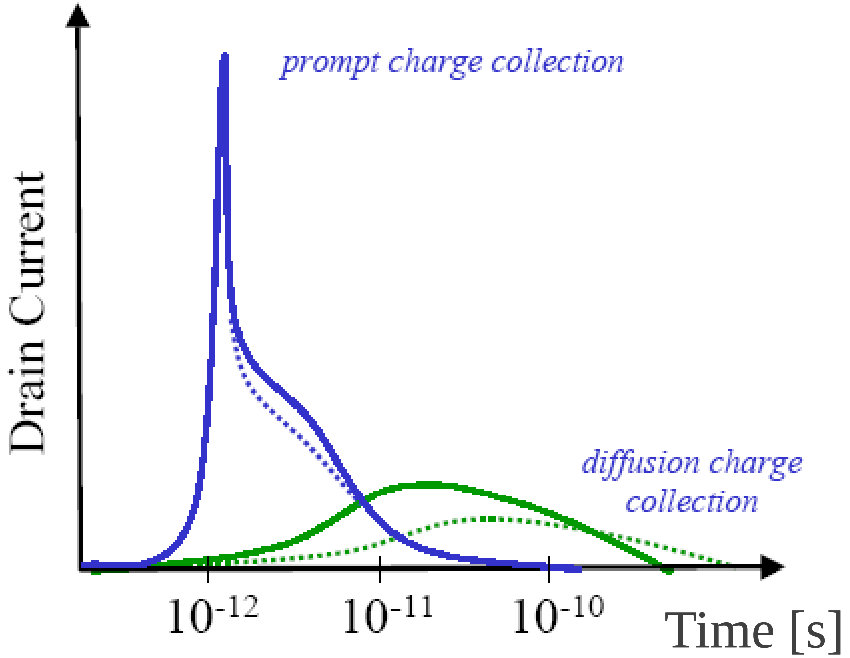
Drift Collection

Diffusion Collection

Semiconductor device structure :

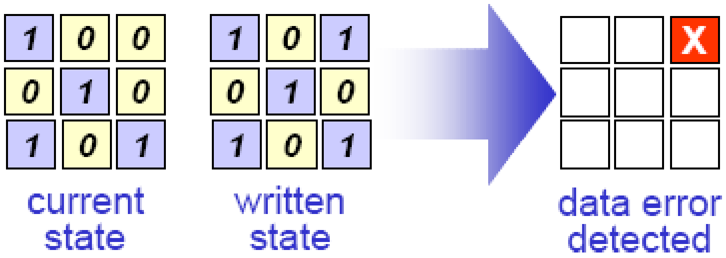
- Sensitive structure is reverse biased junction
- Charge collection following impact of <u>*a single*</u> ionizing particle

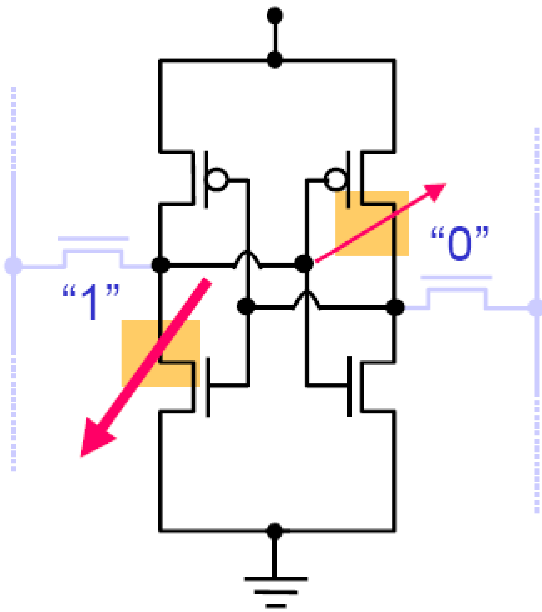
Charge collection



$$Q_{crit} = C_{node} V_{node} + I_{restore}/\tau$$

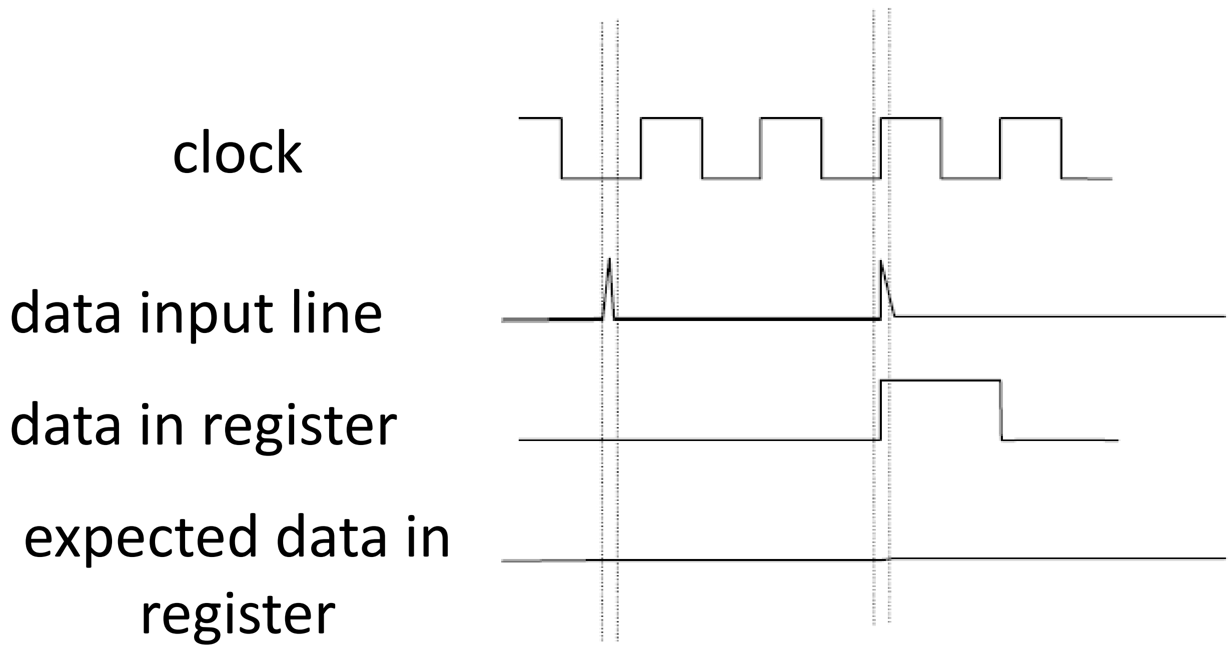
Single Event Upset



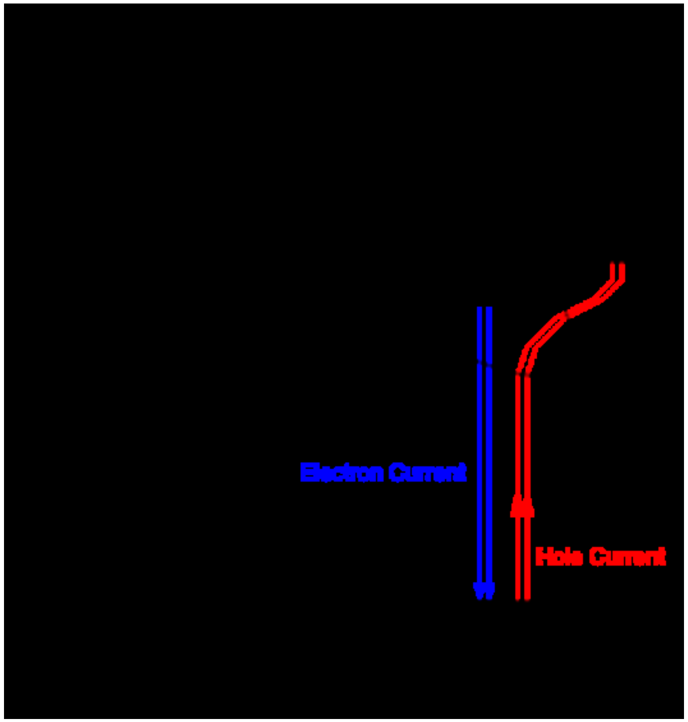


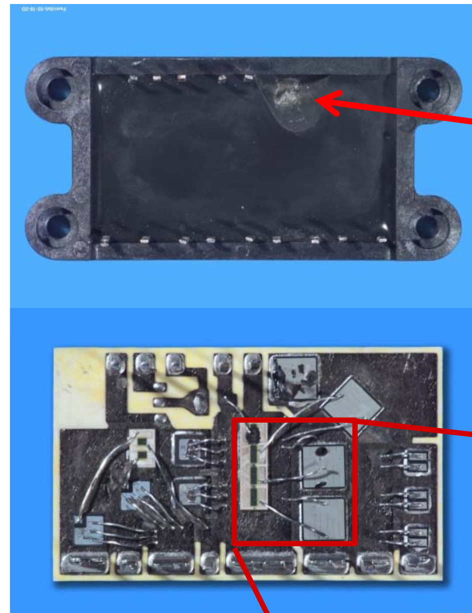
SRAM memory cell (1 bit)

Single Event Transient

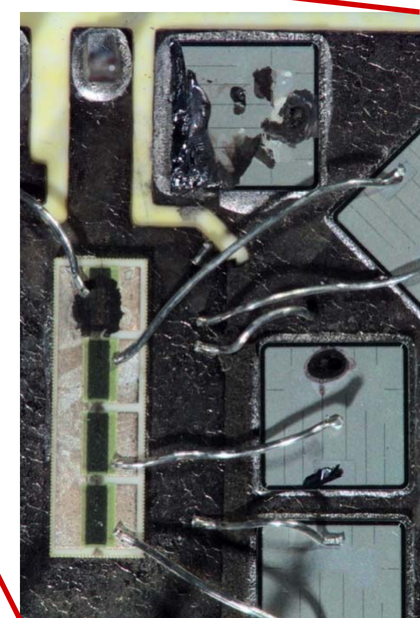


Single Event Burn Out





epoxy covering fractured



silicon in MOSFET sublimated during discharge through single component

From R. Tesarek, Workshop on radiation effects in Power Converters, CERN 30 November 2004

Radiation in the LHC

- Beam On :
  - Some accelerated particles (protons) will be lost
  - Particles will strike nuclei of matter will create secondary particle radiation
  - Various types of particles at a wide range of energies are produced

  main concern : equipment exposed

Radiation Monitoring via BLM, RadMon

- Beam Off :
  - Some of the struck nuclei are radioactive
  - The fragments of the nuclei will decay
  - Type of radiation is mainly β and γ radiation

  main concern : personnel exposed (radioprotection)

Radiation Monitoring via RAMSES

Radiation Environment LHC

	FROM IP		NON-IP		TOTAL	
	<N>	<E> (GeV)	<N>	<E> (GeV)	<N>	<E> (GeV)
p	7.8106E-06	1.3928E+03	7.3854E-02	1.5650E+02	7.3862E-02	1.5663E+02
n	1.8278E-01	2.9556E+03	3.0651E-01	1.0426E+02	4.8929E-01	1.1694E+03
$\pi+$	3.9053E-05	1.4448E+03	1.8044E-01	2.6252E+01	1.8048E-01	2.6559E+01
$\pi-$	1.2583E-03	2.5358E+03	2.0158E-01	3.3929E+01	2.0284E-01	4.9450E+01
K+	3.9053E-05	1.5920E+03	1.3593E-02	1.8641E+01	1.3632E-02	2.3149E+01
K-	1.8779E-04	2.6675E+03	1.1495E-02	1.4602E+01	1.1683E-02	5.7245E+01
$\mu+$	0.0000E+00	0.0000E+00	3.3441E-04	6.3382E+00	3.3441E-04	6.3382E+00
$\mu-$	0.0000E+00	0.0000E+00	7.6302E-04	9.9281E+00	7.6302E-04	9.9281E+00
γ	6.4190E+00	7.9219E+01	8.9348E+01	1.9997E-01	9.5767E+01	5.4964E+00
e+	2.3936E-01	3.3844E-01	5.9039E+00	1.5220E-01	6.1432E+00	1.5946E-01
e-	9.6830E-02	1.2591E+00	5.7887E+00	1.6300E-01	5.8856E+00	1.8103E-01
pbar	1.4059E-04	2.8715E+03	5.1247E-03	9.8705E+01	5.2652E-03	1.7274E+02
K^0_L	3.6506E-02	1.2308E+03	1.2349E-02	2.6881E+01	4.8855E-02	9.2650E+02
K^0_S	4.8158E-03	2.2434E+03	2.1740E-04	4.7451E+01	5.0332E-03	2.1485E+03
Λ	2.2313E-02	3.5788E+03	0.0000E+00	0.0000E+00	2.2313E-02	3.5788E+03
Λbar	6.3297E-04	1.8356E+03	0.0000E+00	0.0000E+00	6.3297E-04	1.8356E+03
$\Sigma-$	1.5640E-05	2.3074E+03	0.0000E+00	0.0000E+00	1.5640E-05	2.3074E+03
nbar	1.2447E-02	1.1503E+03	6.2474E-03	1.7173E+02	1.8694E-02	8.2330E+02

N. Mokhov, TAN workshop 2006

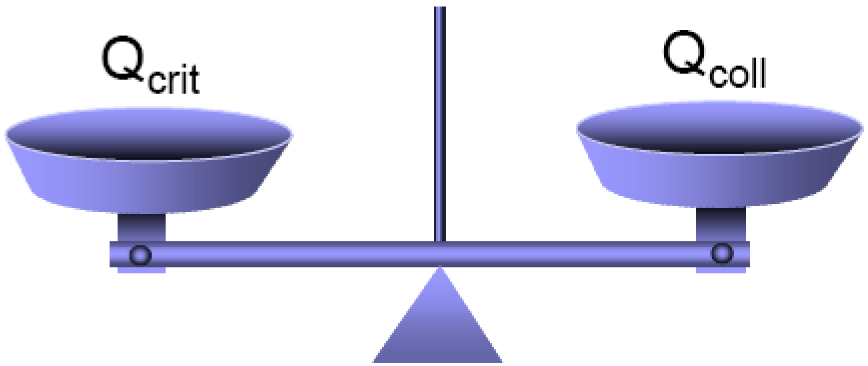
How to test electronics ?

- Imagine testing :
  - With all types of particles LHC will generate
  - With all energies that we can find in LHC
  - Under various conditions (angle, temperature, bias, ..)
  - At a yield comparable to that in the LHC

This would be impossible, hence we use :

- parameterization of the particle radiation field
- scaling laws
- accelerated testing at high radiation yields

Charge collection



- This is a key issue to model and understand SEEs in a component
- Circuit robustness vs. magnitude of the disturbance
- Q_{crit} = charge needed to create a SEE
- Q_{coll} = charge collected via an radiation event
- Error if $Q_{coll} > Q_{crit}$

Charge deposition

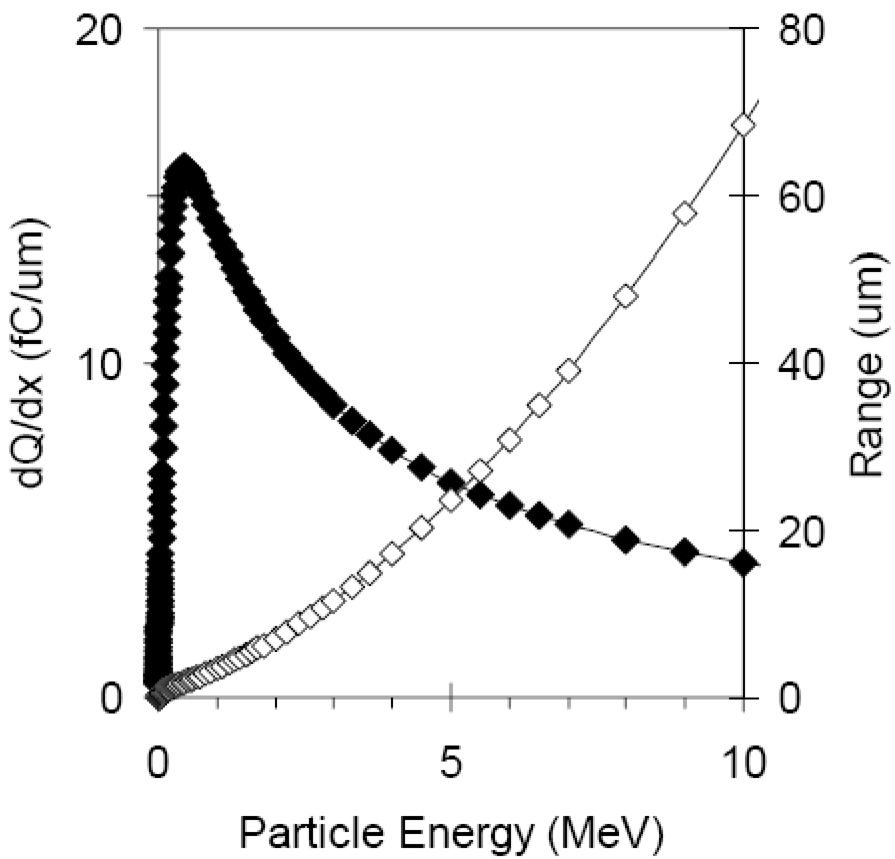
- To create a SEE, we need to :
  - Generate sufficient charge
  - Generate it in a dedicated volume
- How to achieve this :
  - direct ionisation (heavy ion beam)
  - Inelastic interaction with Si (p,n,π beam)

Direct ionization

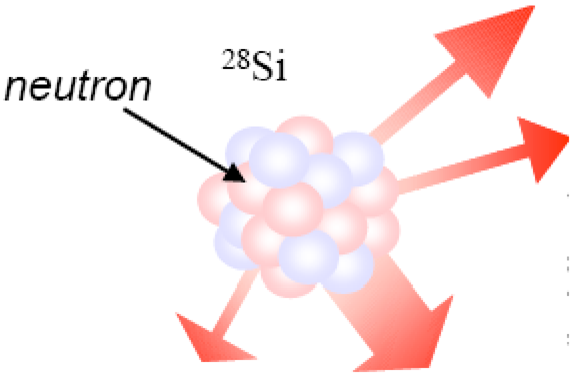
Example :

- Distance a heavy element can travel in silicon (open diamonds)
- Charge created per micron travelled in silicon (closed diamonds)
- Integration gives amount of charge deposited.

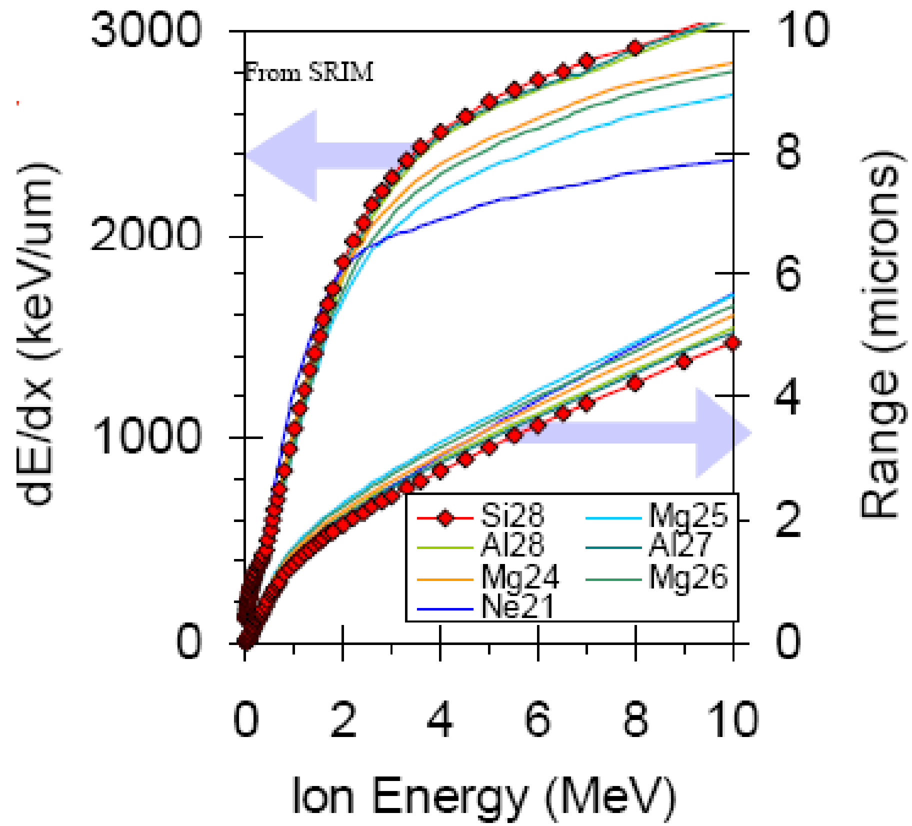
Note : most of the energy of the incident particle is deposited when the particle is almost stopped



Inelastic interaction



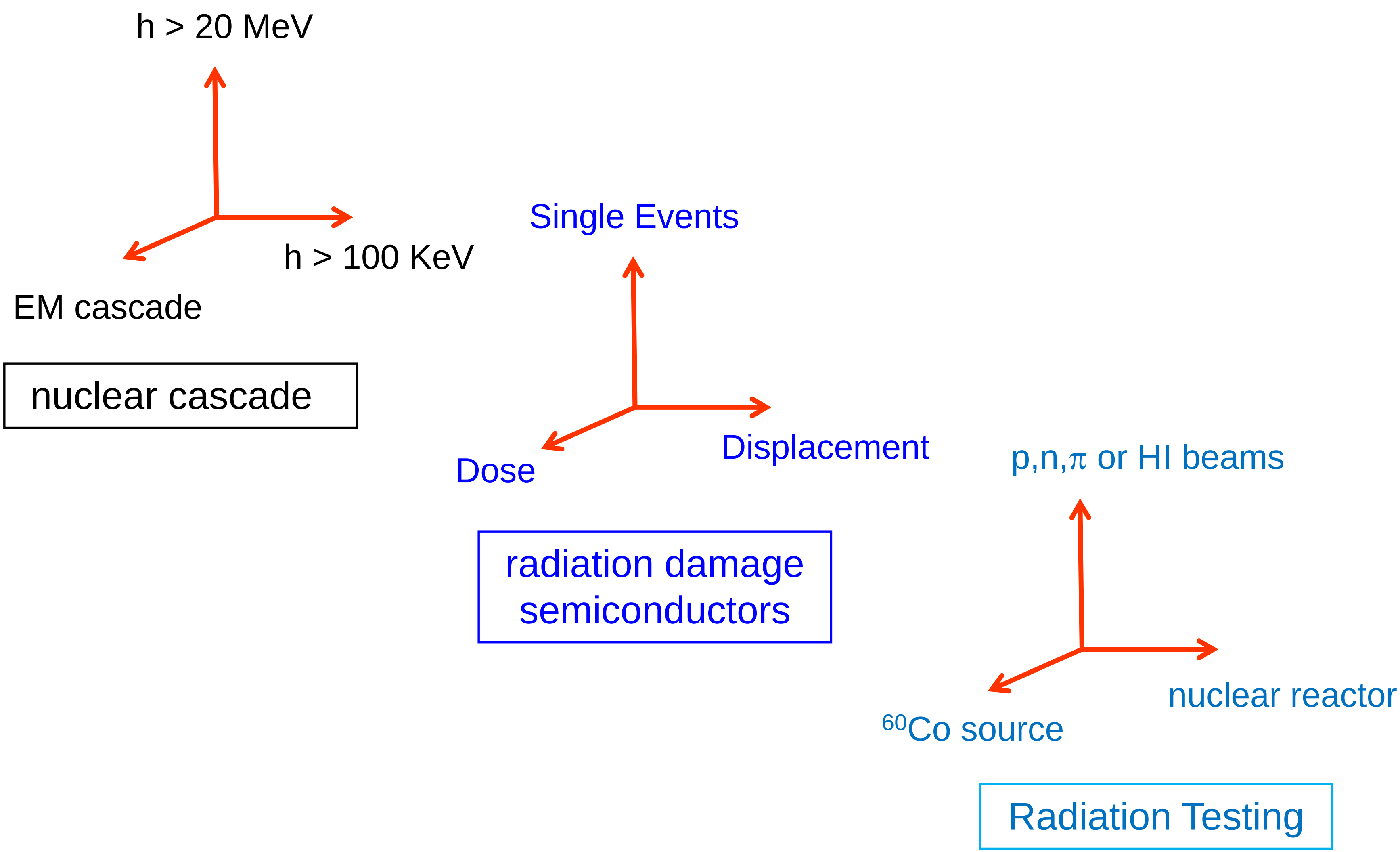
$^{25}Mg + \alpha$	2.75 MeV
$^{28}Al + p$	4.00 MeV
$^{27}Al + d$	9.70 MeV
$^{24}Mg + n + \alpha$	10.34 MeV
$^{27}Al + n + p$	12.00 MeV
$^{26}Mg + {}^{3}He$	12.58 MeV
$^{21}Ne + 2a$	12.99 MeV



What does this all mean ?

- In the LHC we do not have direct heavy ion radiation
- SEE will be mainly caused by the fragments resulting from elastic, inelastic interactions of p, n, π with Si
- Simulations have shown that the maximum LET in the LHC via these mechanisms is approximately 15 $MeV.cm^2/mg$
- So we can choose a parameterization of the LHC radiation field for SEE studies in terms of hadrons h>20 MeV
- So we can perform SEE tests with :
  - Heavy ions
  - p,n,π beams

Radiation Engineering



ARCs and DS

Hadrons > 20 MeV

- Dispersion Suppressors
  - Neutrons 66%
  - Protons 9%
  - Pions (+/-) 24 %
- ARC alongside dipole
  - Neutrons 86%
  - Protons 4%
  - Pions (+/-) 9 %

Heavy Ion Testing at UCL

Ion Cocktail M/Q=4.94	Energy MeV	Range µm Si	LET MeV(mg/cm²)
$^{10}B^{2+}$	41	80	1.7
$^{15}N^{3+}$	62	64	2.97
$^{20}Ne^{4+}$	78	45	5.85
$^{40}Ar^{8+}$	150	42	14.1
$^{84}Kr^{17+}$	316	43	34.0
$^{132}Xe^{26+}$	459	43	55.9
UCL – Ion Cocktail #1 produced for ESA			

For more information, contact:
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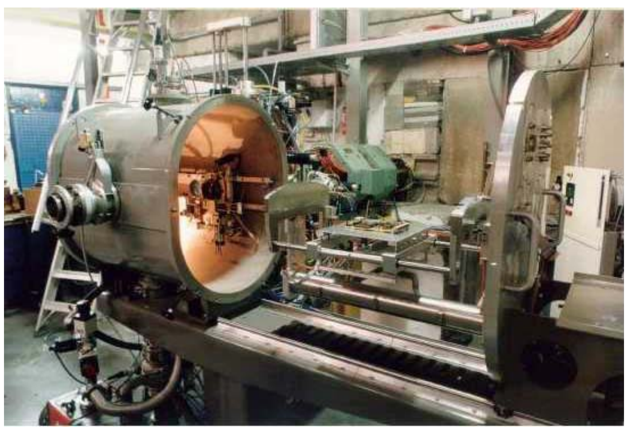
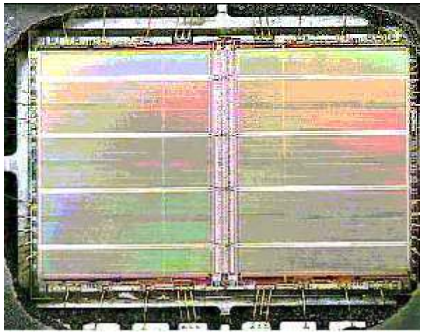


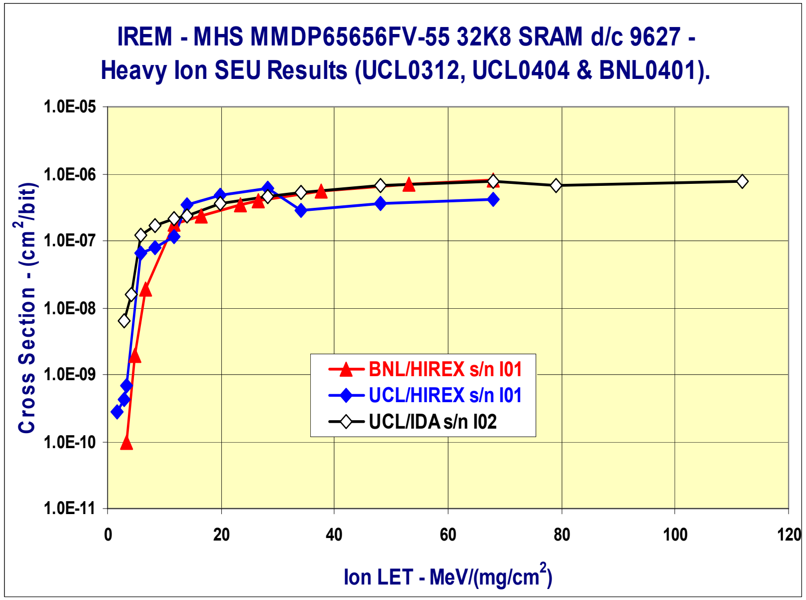
Ion Cocktail M/Q=3.3	Energy MeV	Range µm Si	LET MeV(mg/cm²)
$^{13}C^{4+}$	131	266	1.2
$^{22}Ne^{7+}$	235	199	3.3
$^{28}Si^{8+}$	236	106	6.8
$^{40}Ar^{12+}$	372	119	10.1
$^{58}Ni^{18+}$	567	98	20.6
$^{83}Kr^{25+}$	756	92	32.4
UCL – Ion Cocktail #2 produced for ESA 2004			

European Component Irradiation Facilities – HIF
Heavy-ion IrHeavy Ion testing at UCLradiation Facility – UCL, Belgium.

Heavy Ion Testing

- Only for component testing
- Components have to be prepared
- Setup is in vacuum so automation required
- Complete characterization of a component





Proton Testing at PSI (1)

Low Energy PIF

- Initial Energies: 6 to 71 MeV
- Maximum Proton flux : 5E8 p/cm2/sec
- Beam spot ~50 mm diameter
- Beam uniformity > 90 %

For more information, contact:
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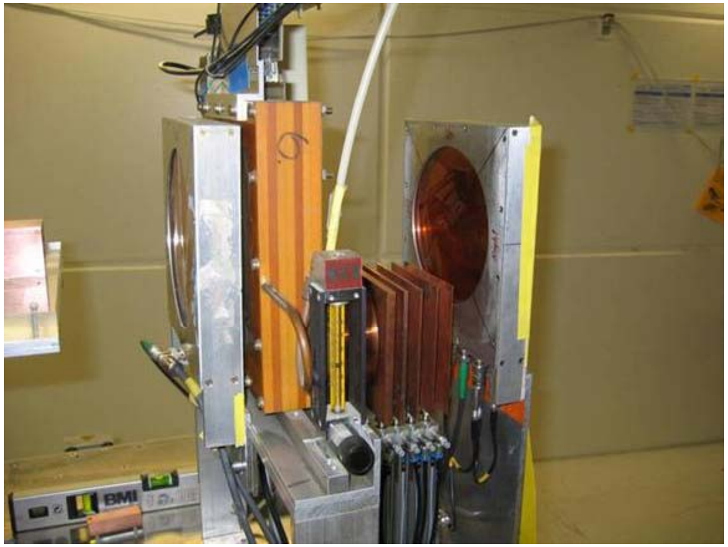
Proton Irradiation at PSI (2)

High Energy PIF

- Energy range: 30 to 254 MeV
- Initial Energies: 235, 200, 150, 100 and 70 MeV .
- Maximum Proton flux (254 MeV): 2.5E8 p/cm2/sec
- Beam spot ~90 mm diameter
- Beam uniformity > 90 %



Neutron Irradiation at TSL

- Neutron production: $^{7}Li(p,n)$, enriched to 99.99%, 1-24 mm thick
- Peak neutron energy: 11-174 MeV
- Characterized neutron fields: 11*, 22, 47, 94, 143, 174* MeV
- Peak neutron flux: $1 \cdot 10^{4}$ - $5 \cdot 10^{5}$ neutron/(cm^{2}/s)
- Area available for users at the beam line: 15 m long, 3 m wide

For more information, contact:
Dr. Alexander Prokofiev,
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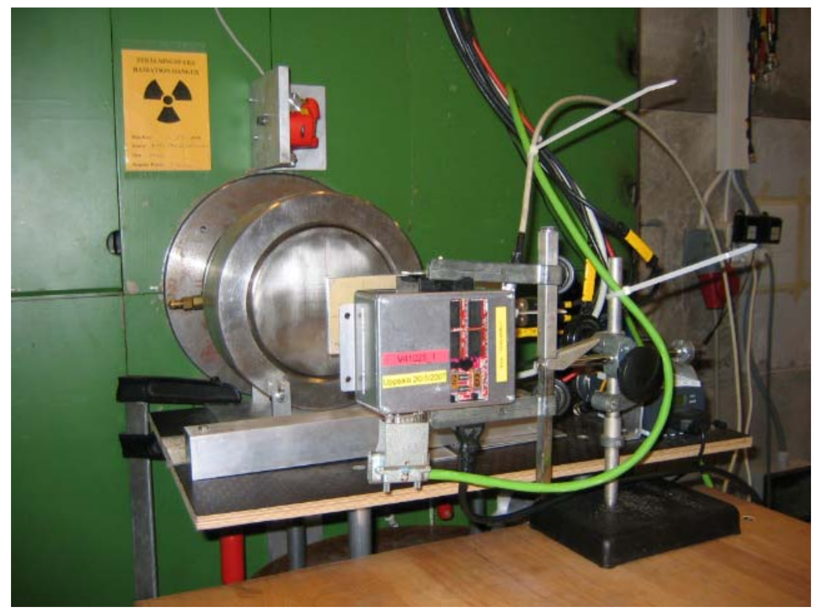
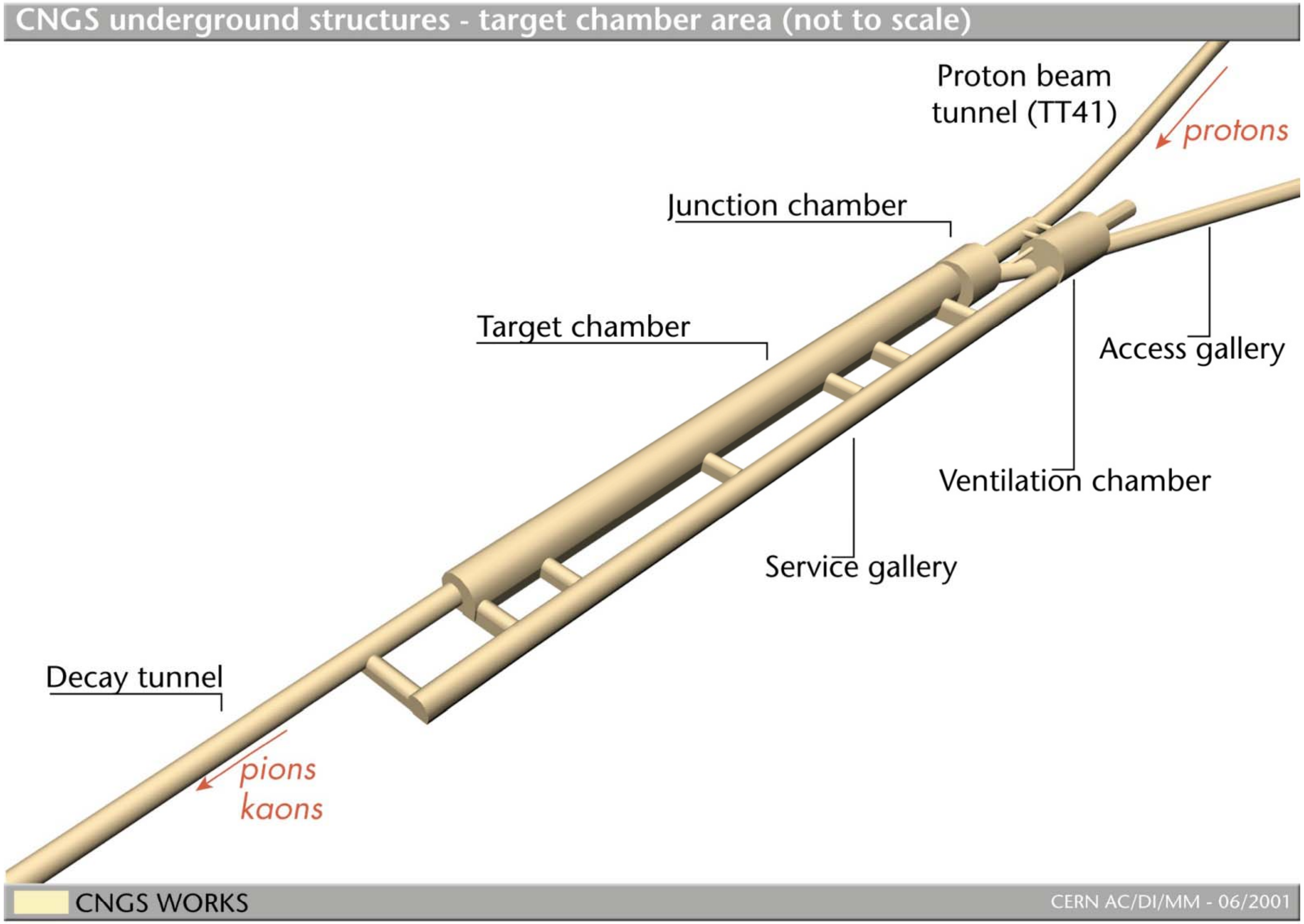
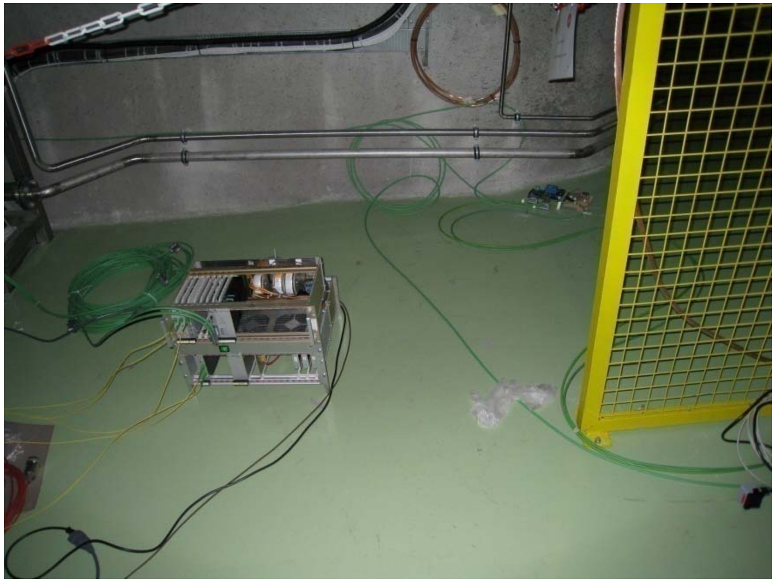


CNGS TSG4 area



CNGS facility in 2009



General considerations

Where to test ?

- Accelerator selection criteria as a service provider
- Technical: beam characteristics
- Facility approved for SEE testing
- Overall beam acquisition cost for full characterization of a device
  - beam cost
  - travel cost
  - overall test time (user manpower)
- SEE Test slots availability

Lessons Learned

- Preparation has to be impeccable :
  - Dedicated team of at least 2 persons/device
  - Complete test setup prepared
  - Irradiation plan
  - Sufficient spares
  - Dry run before leaving CERN
- Data validation: back to home, it is too late
  - To have the beam data in real time
  - to perform a data analysis (first check) upon completion of each run
- Set-up installation: trouble issues
  - Cables and connectors:
  - inversion, pin integrity,cables blocked or damaged during a tilt, etc
  - Electrical noise
  - Parasitic light

SEE Data taking

- In addition to error detection, the following parameters should be monitored and recorded all along the run and within the same time system

  - Beam count versus time from the **accelerator**
  - DUT U/Is versus time
  - DUT temperature versus time
  - Number of errors versus time

- This gives a way to check data consistency and find anomalies, to correlate between events occurrence and parameters (DUT current variations, beam instability,…)

- Check of beam calibration (Use of a reference)

Test set up

Some issues to consider :

- Beam count signal to the user test equipment
- User control of a beam shutter (heavy ions, DUT initialization phase, integrity)
- Reliable cables and connectors (savers, electrical check)
- cables in place between beam test area and user room (long distance)
- clean power network
- protection parasitic light (heavy ion)
- Friendly beam user interface (PSI is a good example)
- beam data log in real time

Radiation Tolerant Equipment

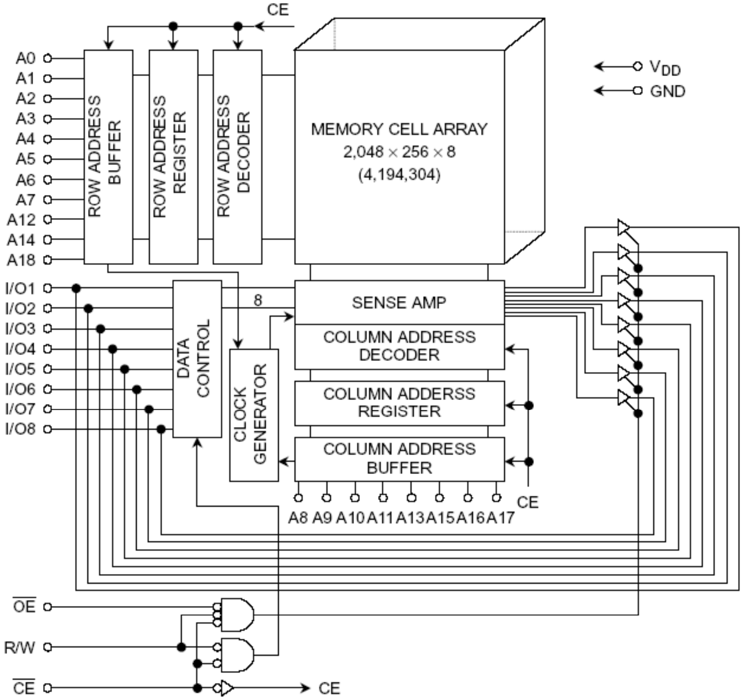
Standard Procedure :

- Express required tolerance in terms of TID, SEE cross section, NIEL
- Decide : COTS or custom design ?
- Carefully select electronic parts/systems
- Radiation test prototypes
  - Single Event Errors
  - Total Dose (not discussed here)
  - 1 MeV neutrons (not discussed here)
- Test pre-series in HEP radiation field (CNGS)
- Produce series with components from same production batch as protos and pre-series

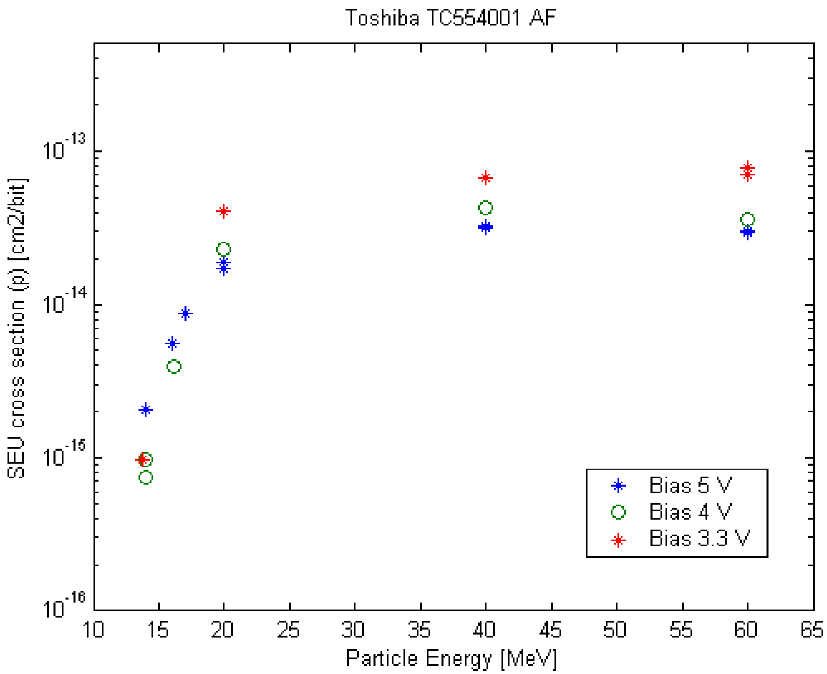
Component testing

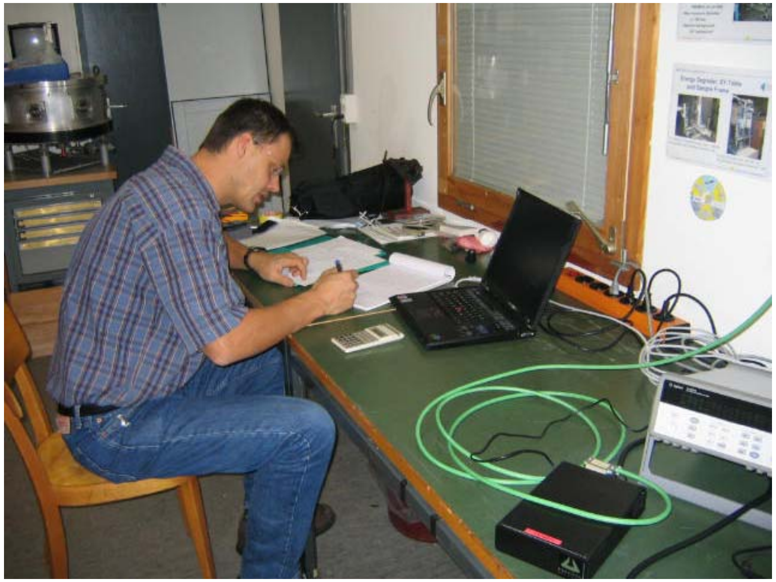
Toshiba TC554001AF-70L

- 0.4 µm technology
- 3 – 5 V operation
- 4 Mbit (524288 words x 8 bits)
- grid arrangement 8192 x 512
- min cycle time 70 ns

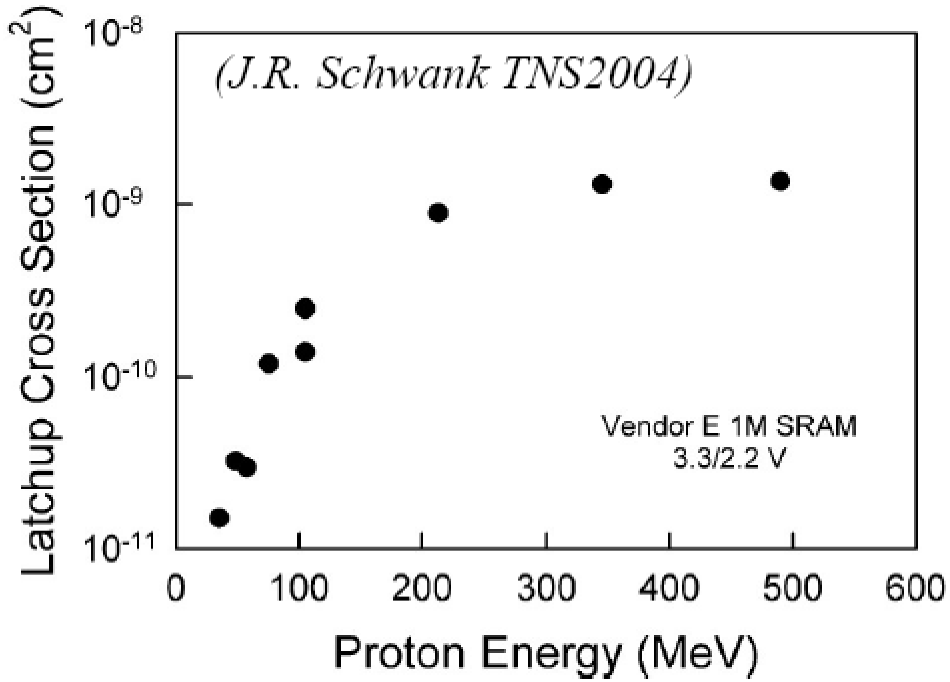


Proton Irradiation

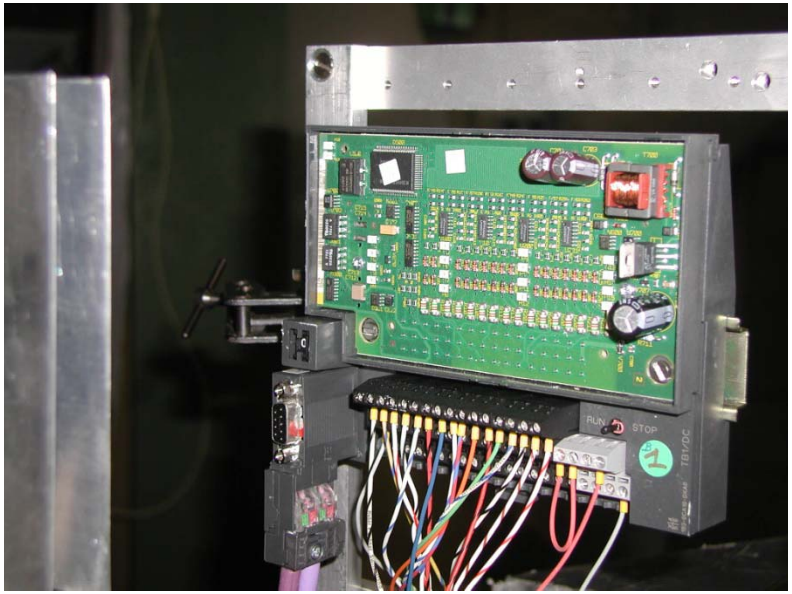


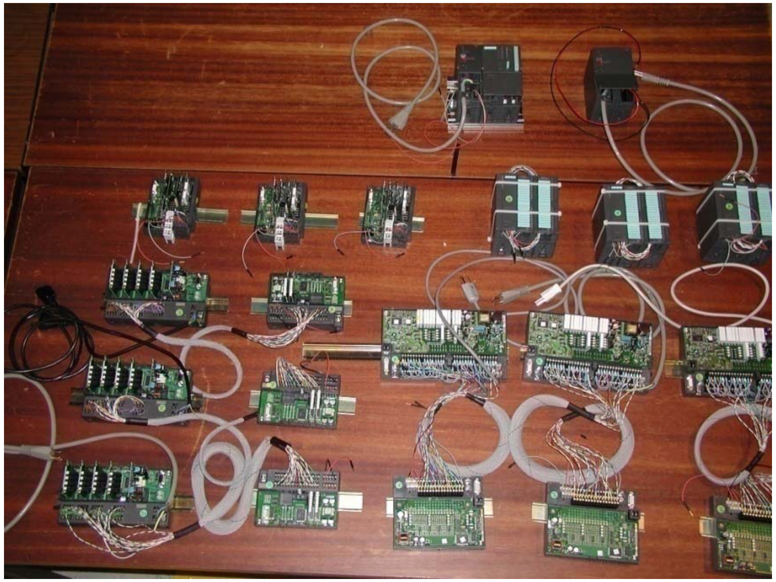


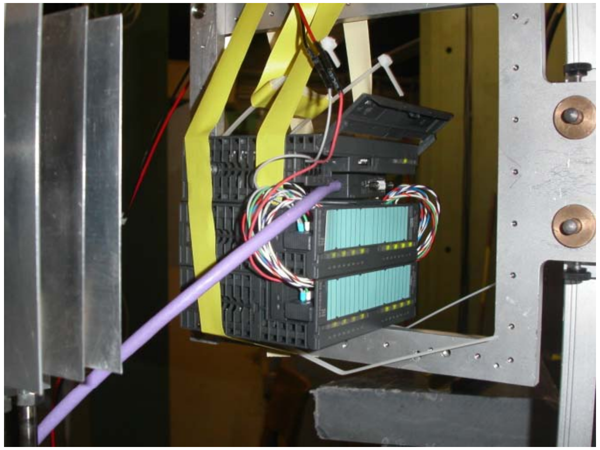
Saturation of cross section

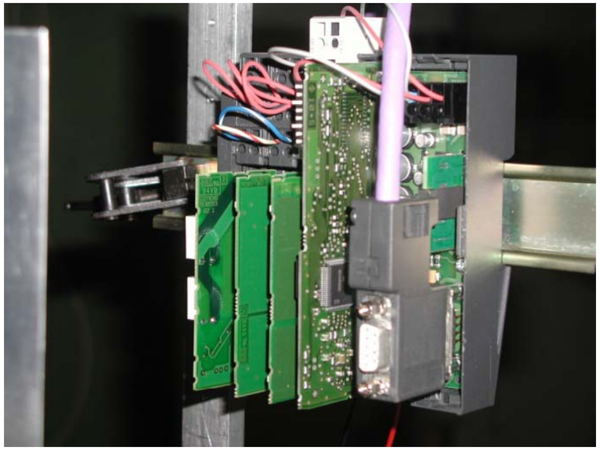


SEE test SIEMENS automation equipment

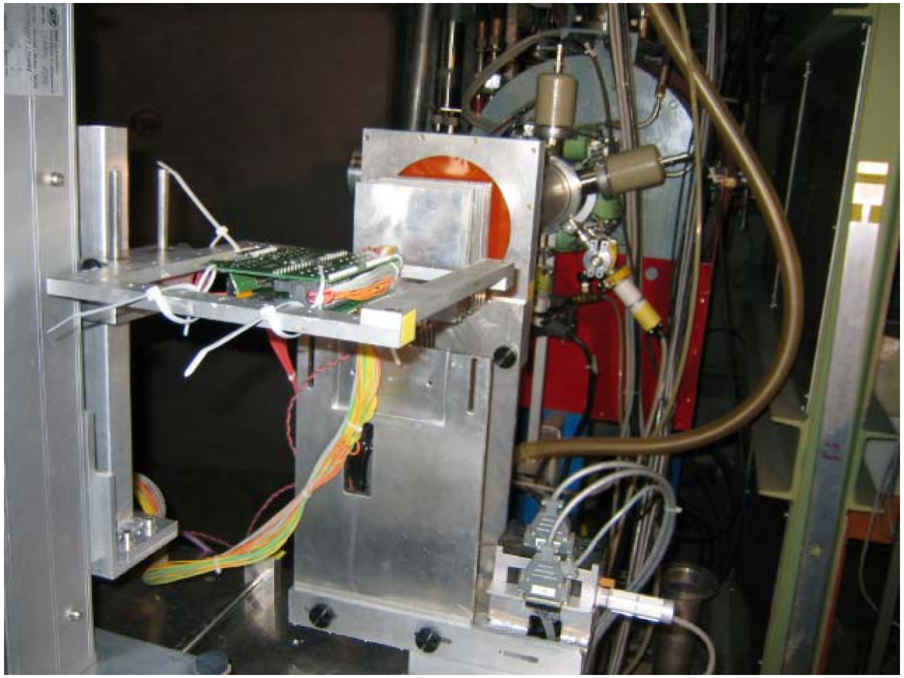


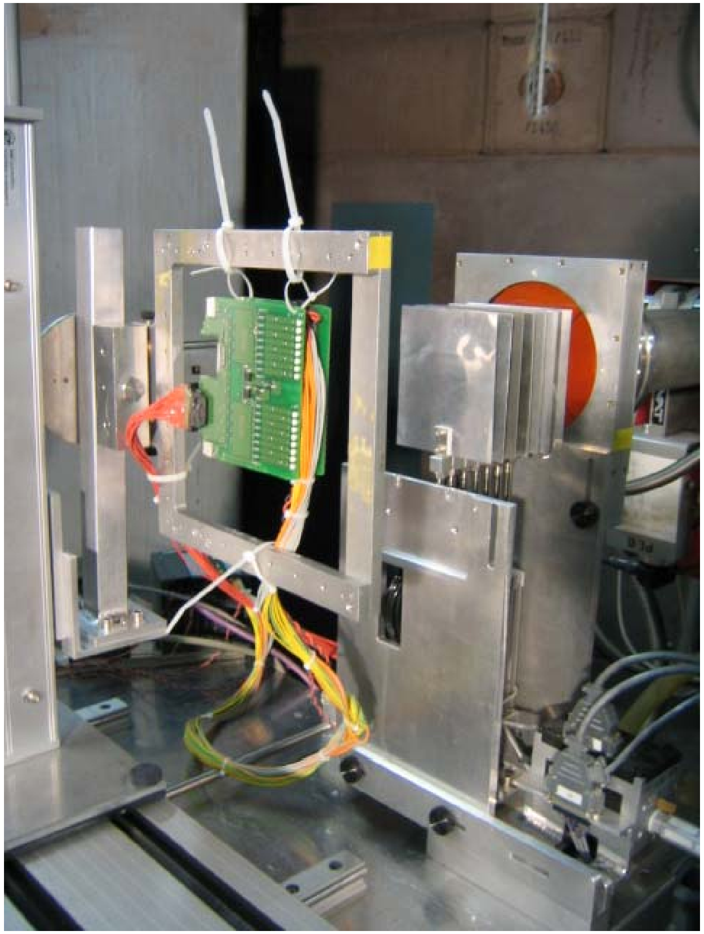






SEE- Proton beam testing





Interaction with Industry

Data from P. Dahlen

SIEMENS PS 07 2A (Automation)

- Standard Module 24 V – 2A
- Module with Optocoupler CNY17-F3 Temic
- Module with Optocoupler CNY65 – Vishay Telefunken
- Module with Primary coils IC (N3) in copper foil
- Module with Volt. Reg. Replaced by Zener Diode
- Module with MOSFET 25K1358 - Toshiba

Irradiation in mixed field in LHC Test facility :

2 kRad [Si]

1.5×10^{12} 1 MeV eq. neutrons per cm^2

4×10^{10} hadrons (E>20 MeV) per cm^2

ONLY Modified Module with MOSFET 25K1358 – Toshiba **STILL OPERATIONAL**

Data collection

Run	Part number	Fluence	Nb event	Sigma
1	1	$3\ 10^{11}$	1	$3.4\ 10^{-12}$
2	2	$3\ 10^{11}$	1	
3	3	$3\ 10^{11}$	1	
4	4	10^{11}	7	$7\ 10^{-11}$
5	4	10^{11}	1	10^{-11}
	mean	$1.1\ 10^{12}$	11	10^{-11}

Output of a SEE campaign

- Having a SEE test result is good…but not sufficient…
- Update specification/requirements for SEE test report validation
  - To define the mandatory information to be placed in a SEE test report according to state of the art
  - To provide with guide lines regarding test consistency determination
  - To specify the applicability domain of the SEE test results
- To state about the usage of SEE rate prediction tools

  combine experimental data with simulations