World irradiation facilities for silicon detectors

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Several irradiation facilities are used for studies of radiation hardness of silicon detectors. Variety of particles and energies allow better understanding of damage mechanism. Future upgrades of experiments will demand even an order of magnitude higher fluences in irradiation tests. An overview of most suitable and accessible irradiation facilities is given in this paper.

The 23rd International Workshop on Vertex Detectors
15-19 September 2014
Macha Lake, The Czech Republic

1. Introduction

The development of radiation hard semiconductor detectors is a wide spread task in which many groups from all over the world joined their effort to contribute to the common goal: to build experiments with detectors components that will survive a harsh radiation environment over the lifetime of experiment. The upgrade scenario of the LHC to a luminosity of 10^{35} cm^{-2} represents a challenge for developing sensors as well as for their tests after irradiations under realistic conditions. Fluences of fast hadrons above 10^{16} cm^{-2} are expected in the most exposed regions of detectors. Spectra of particles cover a wide range with energies up to tens of GeV [1]. Radiation damage will be mainly caused by hadrons, therefore irradiation facilities providing these particles are playing important role in the studies of damage effects. Irradiation facilities cannot exactly reproduce the spectra of particles at high energy experiments therefore it is important to make irradiations with different particles and energies to understand the damage mechanism in detectors.

2. Radiation damage

Atomic displacement and ionization are caused by energy transfer from radiation to material and serious degradation effects can thereby be caused. Increase of leakage current [2], change of effective dopant concentration [3] and increased trapping of drifting charge carriers [4] are the mostly recognized effects of atomic displacement, also called bulk damage. Trapped charge on deep traps in insulator and single event phenomena can be caused by ionization. Non Ionizing Energy Loss (NIEL) scaling to the energy loss of 1 MeV neutrons is common concept used to compare the bulk damage of various particles with different energies. However this hypothesis has proved to be valid only for leakage current caused by hadrons [2], but it is not valid for trapping and the effective dopant concentration. For example, the trapping damage constant is higher for neutrons than for protons after the same NIEL [3], while higher oxygen concentration in silicon helps to reduce the change of the effective dopant concentration in float zone material after proton radiation, while it has little or no effect after neutron irradiation [5]. Even more dramatic are differences between neutron and proton induced damage in n type magnetic Chocralski material [6]. Difference can be explained by the different distribution of interstitials and vacancies after charged or neutron hadron irradiation.

The relative composition of the irradiating particles will also vary across detectors, with pions, protons and neutrons being responsible for most of the bulk damage in material. Therefore it is of vital importance to understand the damage mechanism and perform irradiations with different kinds of particles having different energies.

3. CERN Irradiation facility

The CERN Proton Synchrotron (PS) [7,8] accelerates protons to a momentum of 24 GeVc^{-1}. It has been a valuable source of high intensity proton beams for many irradiations in recent years. The complete reconstruction of the proton irradiation facility in the PS East Area (IRRAD) was completed in autumn 2014. In this new facility (Fig.1), located on the T8 beamline, higher beam intensities than in the past will become possible. Moreover, in the new facility, the beam spot can be varied from 5x5 mm^2 to 20x20 mm^2 (FWHM) with a maximum of 6 spills per PS super cycle, each spill containing about 5 10^{11} protons [9]. A cooling system can cool samples down to -20°C, while remotely controlled moving tables allow irradiation of larger samples. Setup for irradiations at cryogenic conditions, beam profile monitoring and dosimetry with foils and 10% accuracy are also available. The damage has been measured as 0.62 for 24 GeVc^{-1} protons [10]. With twice as frequent spills foreseen in the future, irradiations at 10^{17} pcm^{-2} with a focused beam (5mm FWHM) will be possible in about 4 days.

The mixed field CHARM Facility [11] is located behind the IRRAD facility. The goal of this complex project is to provide irradiations with different hadron types having broad spectra in the MeV to several GeV region simulating the environment in the LHC tunnel and for space applications. In CHARM, the PS proton beam will hit various targets and movable shielding absorbers can be applied. The maximum flux of high energy hadrons will be about 10^{10} cm^{-2}h^{-2}.

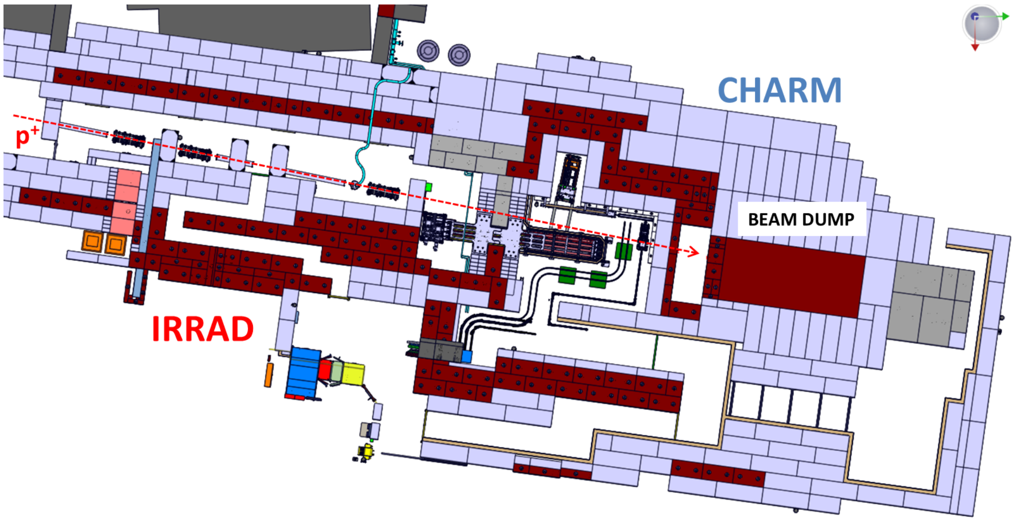

Fig. 1: New CERN irradiation facility (from[8])

4. The Karlsruhe Proton Cyclotron

The compact Cyclotron operated by ZAG Zyklotron AG on the Campus north of Karlsruhe Institute of Technology (KIT) accelerates protons up to 25 MeV [12]. A proton beam with a typical current of 1.5 µA is extracted to the target area with a beamspot size of 7 mm (FWHM). The total flux of protons at the target is 2.3 10^{13} $ps^{-1}cm^{-2}$. With a scanning procedure objects having a size up to 40 cm x 60 cm can be irradiated. Special care is devoted to cooling with nitrogen which can reduce the temperature in the insulated irradiation box down to -40°C. Cooling is particularly important at irradiation facilities with lower energies of charged particles, since the large ionization and thus stopping power can cause heating of the target sample and uncontrolled annealing of defects. Another consequence of the high stopping power is the non-negligible energy loss of protons in the beam. Since the damage factor depends on the proton energy, only thin targets (less than 1 mm) can be irradiated or/and energy losses have to be taken into account. Dosimetry with nickel foil has an error of 12 %. The damage factor is 2.0 and the measurement of the equivalent fluence has an error of 20 % [13].

5. Cyclotron Research Centre (CRC) at Louvain

The variable energy cyclotron at CRC is capable of accelerating protons up to 65 MeV [14]. There are several areas with beams of protons, neutrons and heavy ions. The neutron Irradiation facility produces neutrons from a 50 MeV deuteron beam impinging on a Be target. The neutrons have a continuous spectrum up to 50 MeV with a mean energy of 20 MeV. The beam with diameter of approximately 4 cm can have a flux of 7.3 10^{10} $nscm^{-2}$. A cryogenic box capable of cooling the device under test (DUT) down to -20°C with dry air during the whole process of irradiation and deactivation is available [15]. The light ion irradiation facility provides beam of protons with energies between 20 and 65 MeV. The beam is extracted through a 0.2 mm thin copper window which serves also as a diffuser. Samples are placed behind collimators. The uniformity of the beam with a maximum flux of 5 10^{8} $ps^{-1}cm^{-2}$ and approx. 8 cm diameter, is better than 10 %.

6. Birmingham MC40 Cyclotron

The cyclotron accelerates beams of protons (3-40 MeV), deuterons (5.5-20 MeV), 3He (9-53 MeV) and 4He (11-40 MeV). Beam currents up to 50 µA (hydrogen) or 20 µA (helium) are routinely available [16]. A new irradiation facility with 27 MeV protons has been commissioned recently. For irradiation purposes the beam is collimated to 1 cm^2 with vertical and horizontal plates. At this size a 10^{15} ncm^{-2} 1 MeV neutron equivalent fluence can be reached in 80 s. The scanning area is limited to the window of 80 mm x 140 mm with 10 % uniformity. First irradiations of silicon sensors using an air cooling system and a glycol heat exchanger (-10°C) showed evidence of overheating of samples and annealing of damage during irradiation. Therefore a new system with evaporative cooling by dripping a controlled quantity of liquid N_2 on a metal box was developed and the first results were successful. The temperature of samples heated with 1 µA beam was kept below -5°C, low enough to prevent annealing during the irradiation.

7. Triga Nucler Reactor at Jožef Stefan Institute.

Irradiations at Triga Mark II [17,18] are done by insertion of samples directly into the reactor core (Fig. 2). The spectrum of neutrons covers energies from thermal to several MeV. Only fast neutrons with energies larger than 100 keV contribute significantly to the NIEL in silicon, the contribution of slower (thermal, epithermal) is only about 1 %. The damage constant for fast neutrons was measured to be 0.90±0.05 [2] which is in excellent agreement with the value of 0.88±0.05 [19] calculated from theoretical predictions of neutron NIEL [20]. The size of samples is limited by the size of tubes which lead to the core. A small tube allows irradiations of samples with a maximum diameter of 25 mm while an elliptic tube has inner diameter of 7 cm and 5 cm. The length of samples is limited by the size of the core to 15 cm. The flux of fast neutrons (3.3 10^{12} ncm^{-2}s^{-1} at full power of 250 kW) can be tuned by reducing the power to the one Watt scale. The environmental temperature inside the core is 20°C. The temperature of samples increases to 45°C during irradiation which keeps annealing low since irradiation times are short compared to annealing times of defects in silicon. A fluence of 10^{16} ncm^{-2} can be reached in less than one hour.

Larger samples (few dm^2) can be irradiated outside the reactor core, where fluxes up to 10^7 ncm^{-2}s^{-1} can be used.

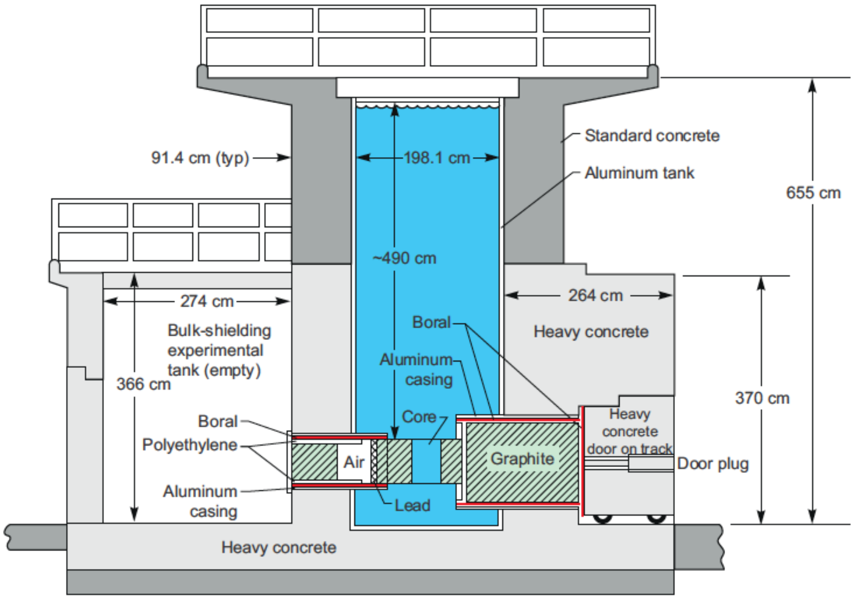

Fig. 2: TRIGA reactor at JSI, side view (from [17])

8. Cyclotron on PSI Villigen

300 MeVc^{-1} pions having an energy of 191.3 MeV are available in the irradiation beam at the Paul Scherrer Institute Cyclotron [21]. They are produced with a beam of 590 MeV protons impinging on secondary target. The flux and beam size depend on the position along beam line an are listed in Table I. The damage factor was measured to be 1.5 ± 0.3 [22].

Position along the beam line	Beam size	Beam size	
z	x	y	Flux
(mm)	FWHM (mm)	FWHM (mm)	(10^{14} cm^{-2}day^{-1})
50	16	13	1.5
100	17	16	1
150	18	23	0.5
200	21	30	0.4
250	24	38	0.25

Table I. Pion beam characteristics at PSI

PoS(Vertex2014)026

9. Summary

There are other facilities around the word that are used for irradiations, for example the Los Alamos National Laboratory [23] provides 800 MeV protons with a flux up to 5 10^{11} pcm^2s^{-1} and CYRIC in Japan provides a beam of 70 MeV protons [24]. An overview of facilities is given in Table II. Access to these facilities is particularly important for the future development of radiation hard detectors. Therefore the European commission co-funded the transnational access to several facilities within Framework Programme 7 Capacities, Grant Agreement 262025 (AIDA).

Institution	Facility	Source	Particles	Energy (MeV)	Max. Flux $cm^{-2}s^{-1}$	AIDA 2011-2015
CERN	IRRAD	PS	p	24000	$2\ 10^{11}$	✔
KIT	Compact Cyclotron	Cyclotron	p	25	$2\ 10^{13}$	✔
UCL	NIF	Cyclotron	n	<50	$7\ 10^{10}$	✔
UCL	LIF	Cyclotron	p	20-65	$5\ 10^{8}$	✔
UoB	MC40	Cyclotron	p	26	$1.5\ 10^{13}$	
JSI	TRIGA MARK III	Reactor	n	< 15	$4\ 10^{12}$	✔
PSI	PIF	Cyclotron	pions	191	10^{10}	
LANL	LANSC Linac	Linac	p	800	$5\ 10^{11}$	
CYRIC	CYRIC	Cyclotron	p	70		

Table II: List of irradiation facilities

10. Acknowledgements

The author would like to thank the many people that helped to collect the information summarized in this paper: M. Moll and F. Ravotti for the CERN irradiation facility, A. Dierlamm for Karlsruhe Proton Synchrotron, E. Cortina for CRC at Louvain and J. Wilson for Birmingham MC40 Cyclotron.

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