Part 2

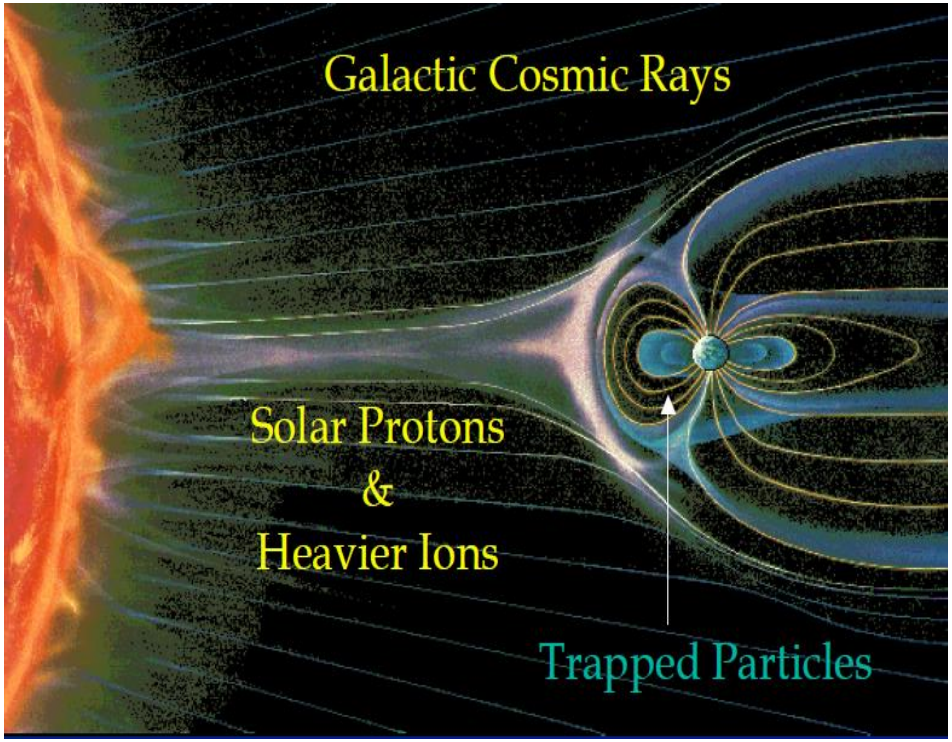
Space Radiation

CONTENTS – Radiation Studies

- Constituents of Space Radiation Environment
  - Galactic Cosmic Ray Ions
  - Solar Particle Events
  - Trapped – Van Allen Belts
  - South Atlantic Anomaly
  - Summary of Radiation Environment and Models
- Radiation Effects on Electronic Components
  - Total Ionsing Dose (TID) effect on MOS, BJTs
  - Enhanced Low Dose Rate Sensitivity (ELDRS) Effect
  - Total Non-Ionsing Dose (TNID) effect
  - Single Event Effects (SEE)
- Radiation Effects on Submicron Technology

Constituents of Space Radiation Environment

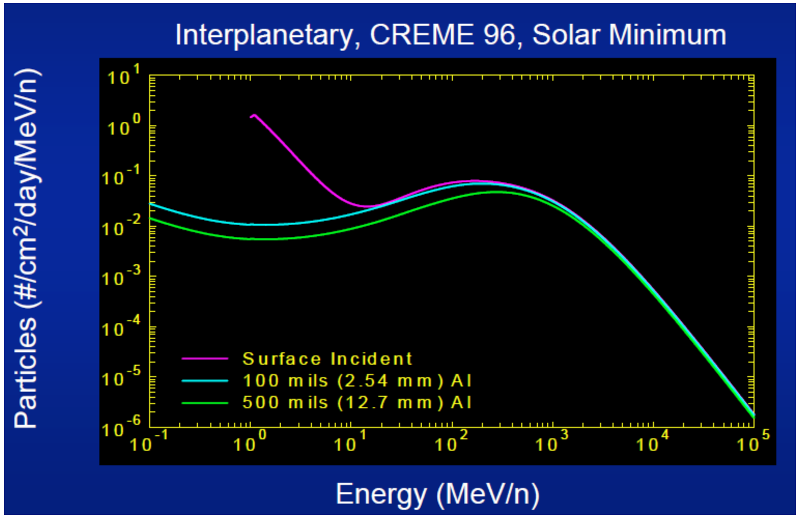
- Transient
  - Galactic Cosmic Rays
    - ✓Protons & Heavier Ions
  - Solar Particle Events
    - ✓Protons & Heavier Ions
- Trapped
  - Electrons, Protons
  - Heavier Ions



Galactic Cosmic Ray Ions

- All elements in Periodic Table -200 million years old Energies in GeV
- Found everywhere in interplanetary space
- Omnidirectional
- Mostly fully ionized -protons & bare nuclei of heavier elements
- Cyclic variation in fluence levels
  - ✓ Lowest levels in Solar Maximum peak
  - ✓ Highest levels in Lowest point in Solar Minimum
- Trajectories bent by magnetic field
- Single event effects hazard
- Model: CREME96

GCRs: Shielded Fluences-Fe



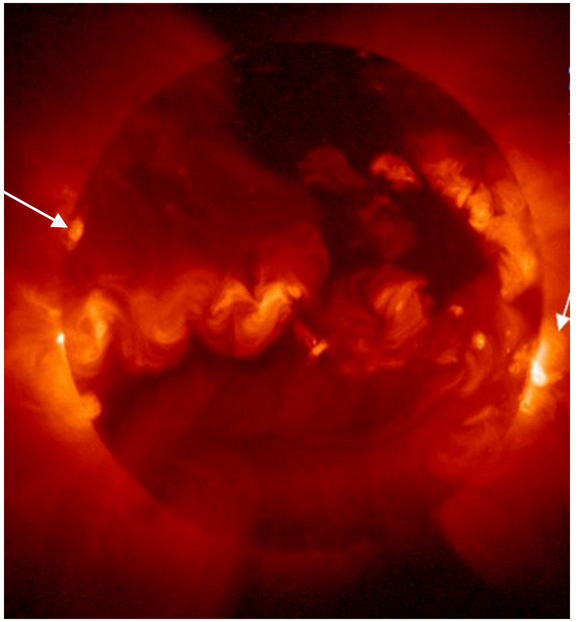
Solar Particle Events

Sun

- Dominates the Radiation Environment
  - ✓ Source & Modulator
- Structure
  - ✓ Photosphere (inner), Chromospheres (middle), Corona (outer)

Solar Wind

- Stream of Charged Particles from Sun's Corona
  - ✓ Electrons, Protons, Heavy Ions
- Magnetized Plasma
- Detected out to 10 billion km from Earth by Pioneer 10
- Velocity ~ 300 - 900 km/s
- Temperature 10^4 to 10^6 K
- Energy ~ .5 - 2.0 keV/nuc



Solar Particle Events

Coronal Mass Ejections

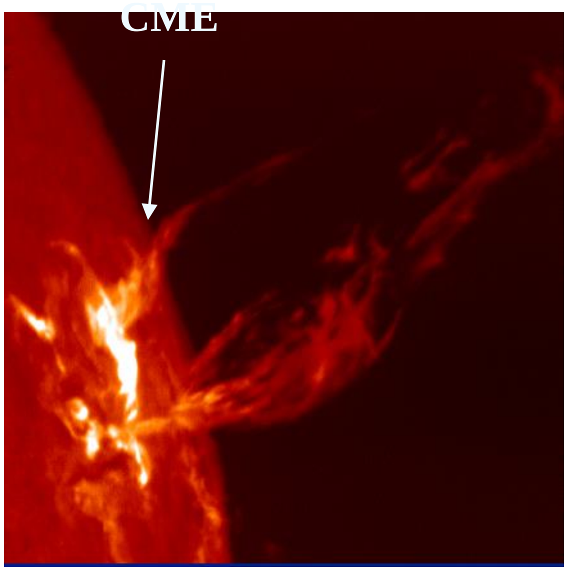
- ➢ Bubble of Gas & Magnetic Field from Chromosphere
- ➢ Ejects ~10^{17} grams of Matter
- ➢ Shock Wave Accelerates Particles to Millions of km/hr
- ➢ Associated with Magnetic Storms
- ➢ Proton Rich Solar Event

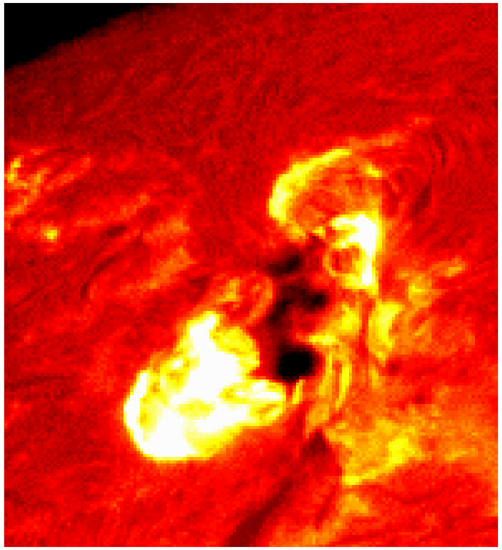
Solar Flares

- ➢ Sudden Brightening Near Sunspots
- ➢ Solar System's Largest Explosive Events
- ➢ Particles Accelerated Directly by Event
- ➢ Heavy Ion Rich Solar Events

Models

- – Dose : SOLPRO, JPL, ESP/GSFC&NRL
- – Single Event Effects : CREME96 (Protons & Heavier Ions)



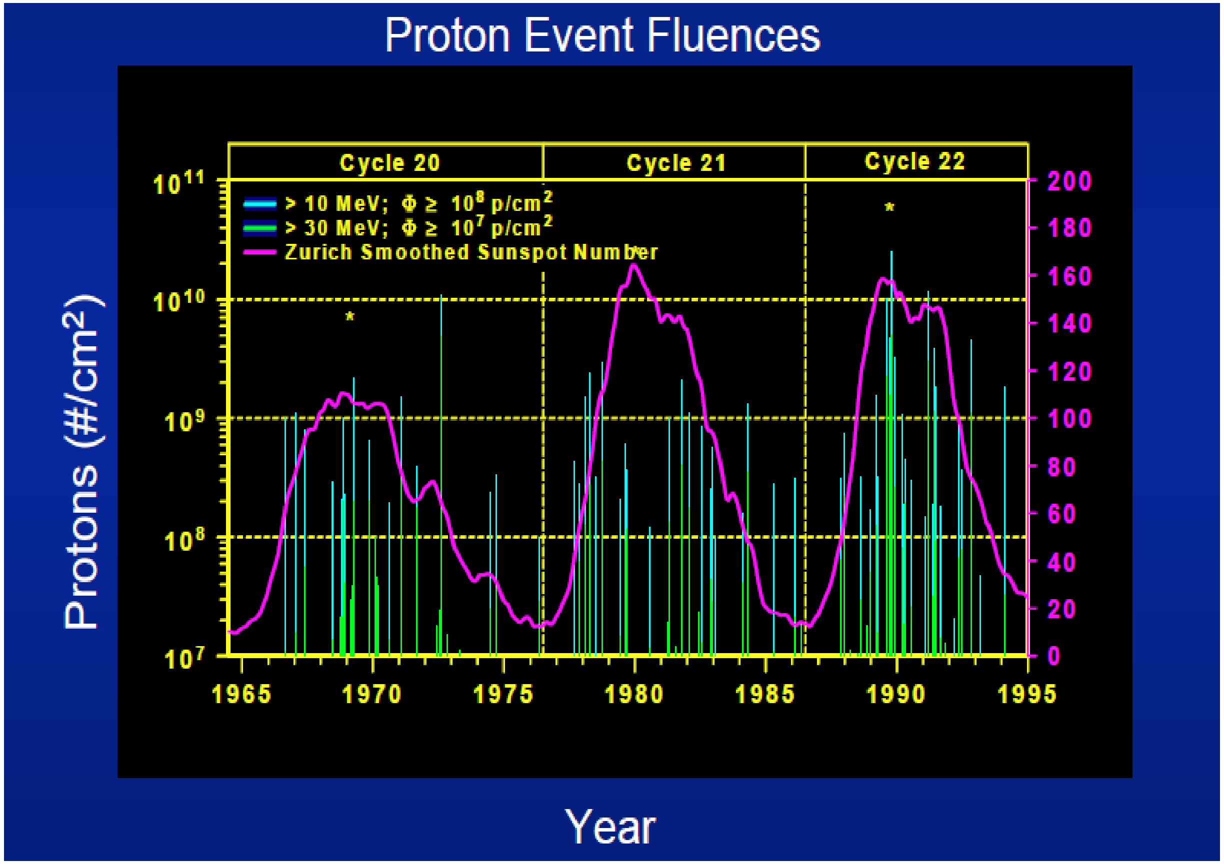


Solar Particle Events

Solar Cycle : 11 Year

Solar Maximum : 7 year

Solar minimum : 4 Year



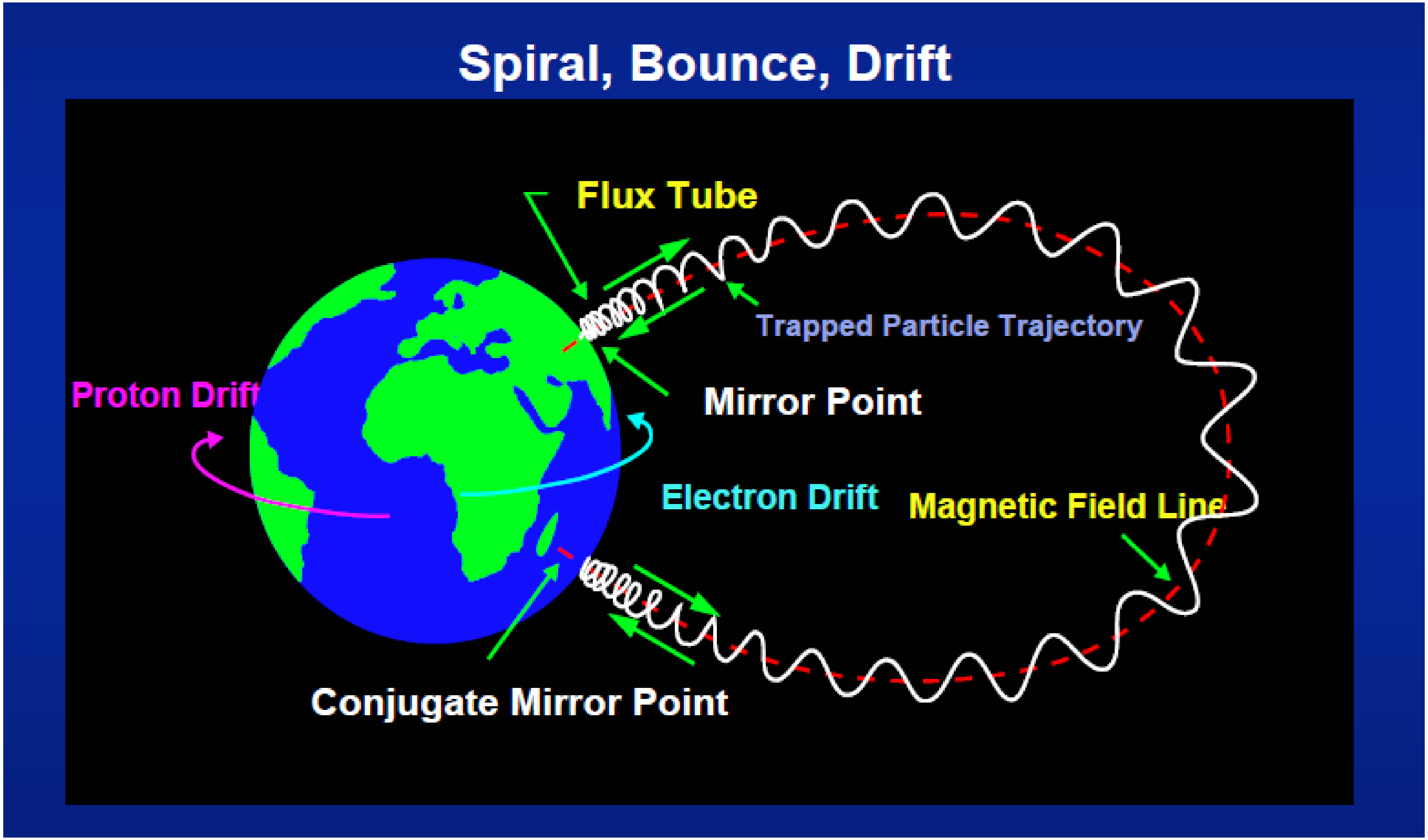
Variation in number of sunspots is representative of solar activities.

In Solar maximum of 7 year, number of transient solar event with high proton fluence are more as compared to number of event in solar minimum.

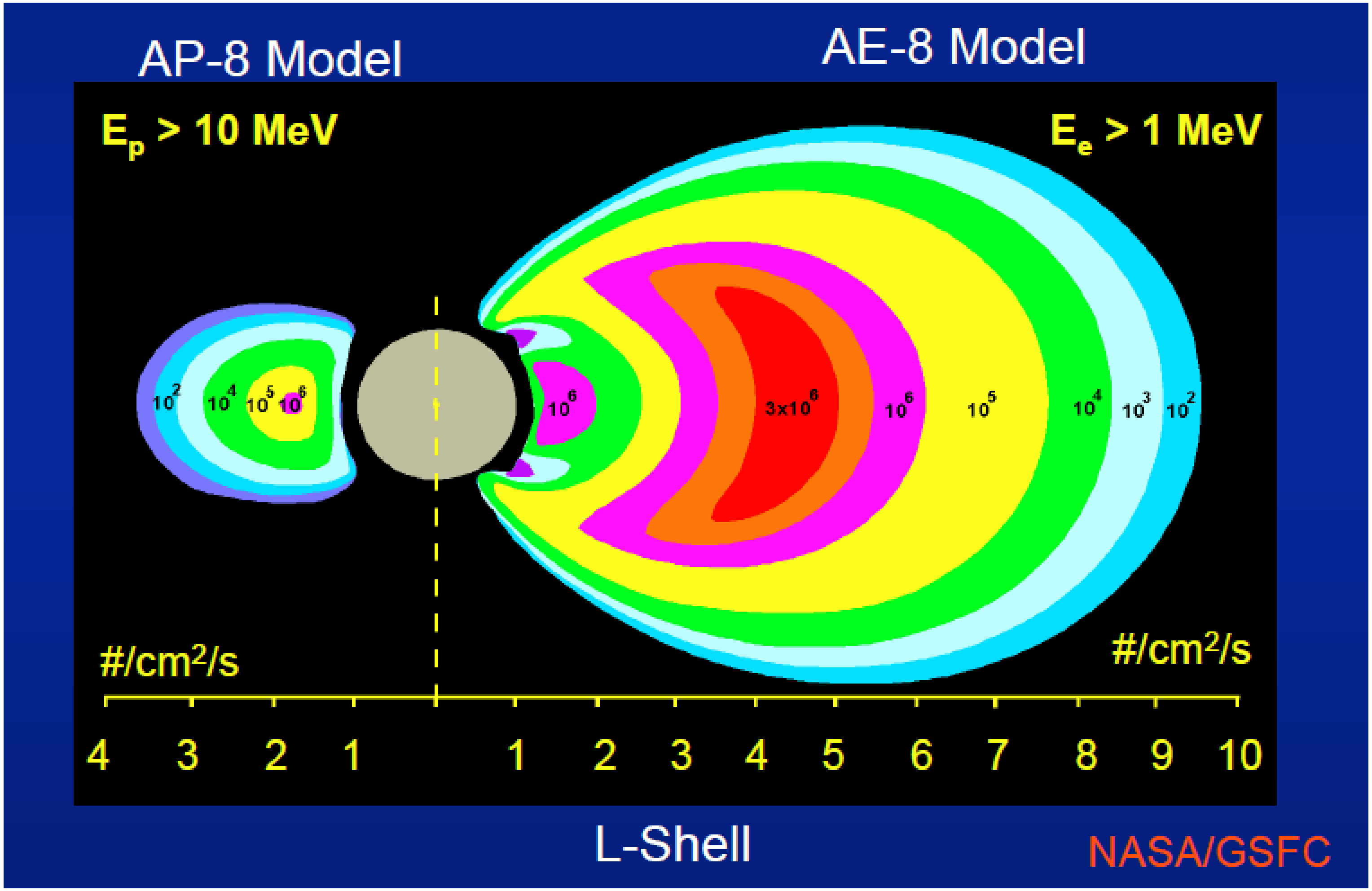
Trapped – Van Allen Belts

- **Omnidirectional**
- **Contains**
  - **Protons:E ~ .04 -500 MeV**
  - **Electrons:E ~ .04 -7 MeV**
  - **Heavier Ions: Low E -non-problem for electronics**
- **Density of particle levels vary by location**
  - **Orders of magnitude**
  - **Steep gradients in some locations**
- **Location of peak levels depends on energy**
- **Average counts vary slowly with the solar cycle**
- **Models –AP-8, AE-8, NOAA-PRO, CRRESPRO, CRRESELE**

Trapped Particle Motions in Van Allen Belts



Proton & Electron Intensities in Van Allen Belts

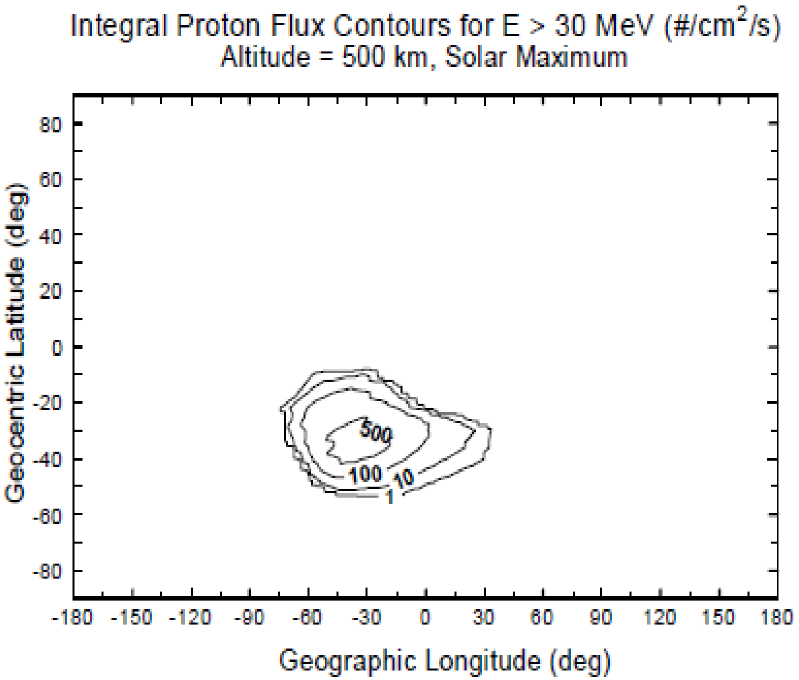


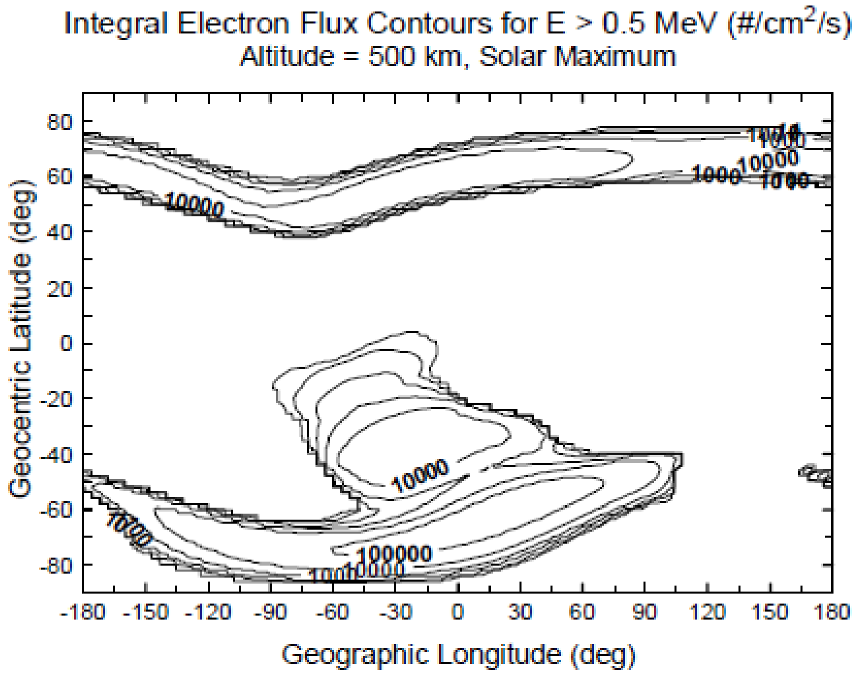
L = Distance at Equatorial Crossing in Earth Radii

South Atlantic Anomaly

Depression in the magnetic field in the South Atlantic is caused by the 11° angle between the magnetic and geographic axes.

This magnetic field sink causes charged particles to be trapped at low altitudes (<1000 km) forming the South Atlantic Anomaly (SAA).





Summary of Radiation Environment and Models

Particle Origin	Particle Type	Solar Cycle Effects	Variations	Orbit Configurations Affected	Models
Trapped	Protons	Solar Min-Higher Solar Max-Lower	Geomagnetic Field, Geomagnetic Storms	LEO, MEO, HEO, GTO, Transfer Orbits	AP-8 CRRESPRO Watts Pfitzer Huston et al.
	Electrons at L < 2.8	Solar Min-Lower Solar Max-Higher	Geomagnetic Field, Geomagnetic Storms	LEO, MEO, HEO, GTO, Transfer Orbits	AE-8 CRRESELE ESA/SEE1
	Electrons at L > 2.8	Masked by other effects	Local Time, Solar Rotation, Geomagnetic Storms	Polar LEO, MEO, HEO, GEO, GTO, Transfer Orbits	AE-8 CRRESELE ESA/SEE1
	Heavy Ions	Unknown	Unknown	LEO, MEO, HEO, GTO, Transfer Orbits	None
Transient	Galactic Cosmic Rays	Solar Min-Higher Solar Max-Lower	Ionization State, Orbit Attenuation, Geomagnetic Storms	Polar LEO, MEO, GEO, HEO, Interplanetary	CREME96 CHIME MACREE Badhwar & O'Neill
	Solar Protons	Solar Max- Large # of Events Solar Min- Very Few Events	Distance from Sun, Orbit Attenuation, Solar Longitude, Ionization State	LEO (I> 45°), MEO, GEO, HEO, Interplanetary	CREME96 SOLPRO JPL92 Xapsos
	Solar Heavy Ions	Solar Max- Large # of Events Solar Min- Very Few Events	Distance from Sun, Orbit Attenuation, Solar Longitude, Ionization State	Polar LEO, MEO, GEO, GTO, Interplanetary	CREME96 JPL92 CHIME

Model used in ISAC are marked with red color box

Radiation Effects on Electronic Components

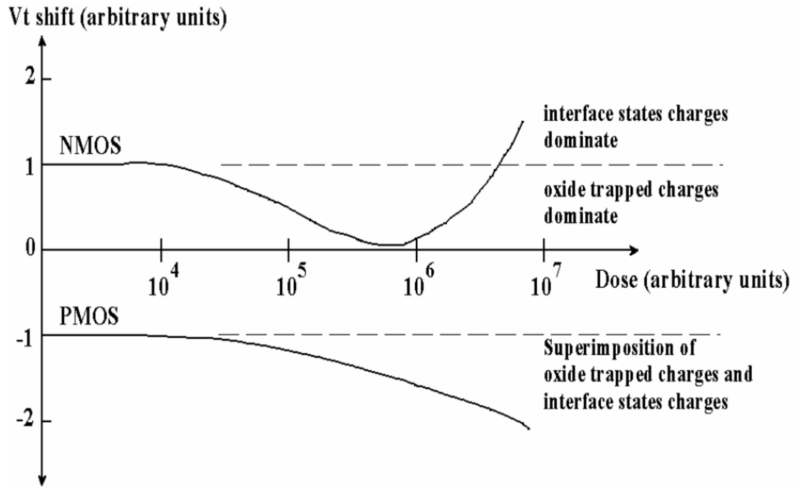
Radiation Effect	Mechanism	Due to	Main Effects
TID	Charge generation, trapping and build-up in insulating layers	Electrons, Protons	Parameter drift. Increased leakage currents, Loss of noise immunity, Eventual functional failure
DD/TNID	Disruption of crystal lattice	Protons	Reduced gain, increased ‘ON’ resistance, reduced LED output, reduced charge transfer efficiency in CCDs.
SEE	Dense path of localised ionization from a single particle ‘hit’	Cosmic rays, high energy protons	Transient current pulses, variety of transient and permanent ‘Single Event Effects’

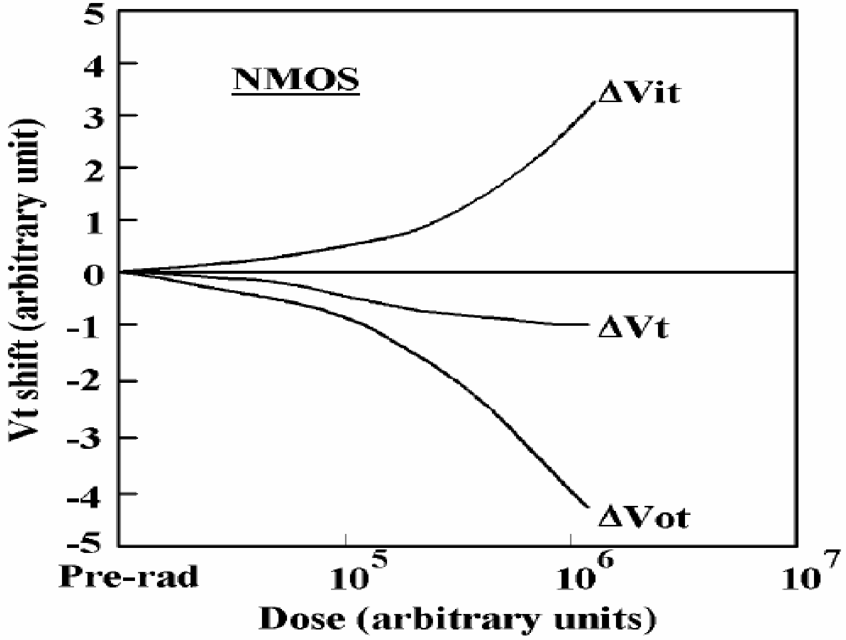
Radiation Effects on Electronic Components

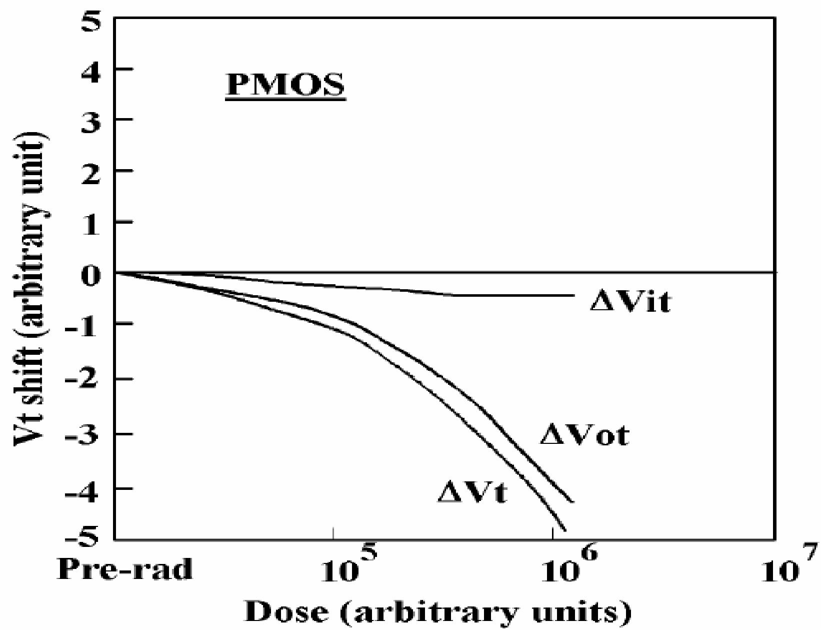
- **Total Ionizing Dose(TID) –Degradation**
  - **Linear ICs, CMOS ICs, BJT, MOSFET etc**
- **Total Non-ionizing Dose(TNID) –Degradation**
  - **Solar Cells**
  - **Detectors –e.g., CCDs, APS**
  - **Opto couplers**
  - **Optical lens**
- **Single Event Effects(SEE) –Single particle strikes**
  - **Destructive –SEL, SEGR, SEB**
  - **Non-destructive –SEU, SET, SEFI, MBU**
  - **Loss of data to loss of mission**
  - **Memories, Power MOSFETs, ADC,DAC etc..**

TOTAL IONIZING DOSE (TID) EFFECTS on MOS

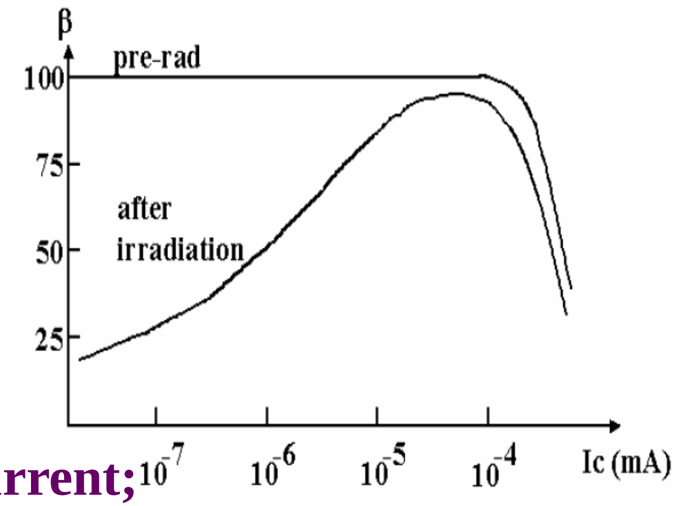
- Threshold voltage shift (ΔVt);
- Leakage currents;
- Transconductance (Gm) decrease;
- Weak inversion slope (Swi) decrease;







Total Ionizing Dose (TID) Effects on BJT



Before irradiation:

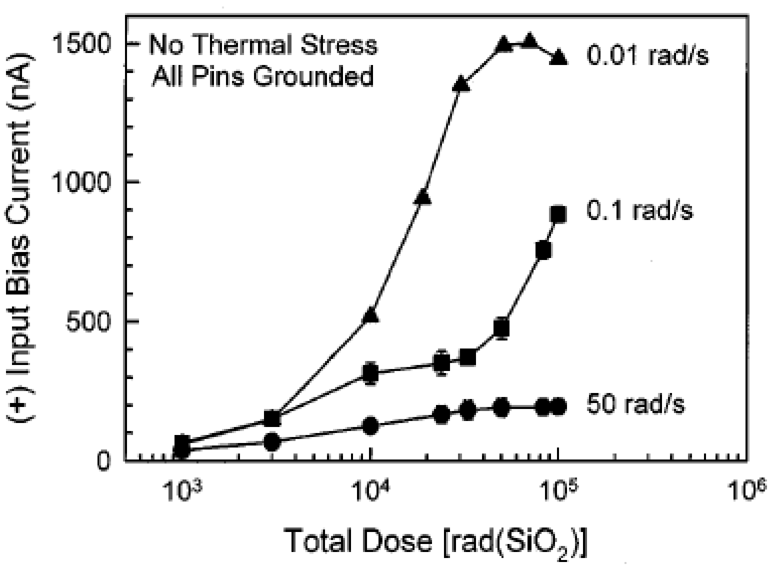
- **β(Ic) is almost flat**

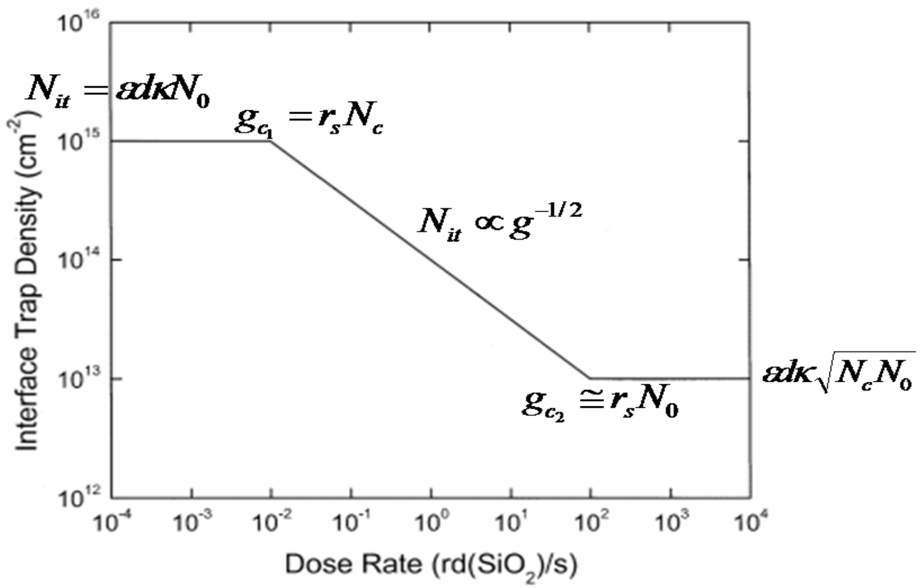
After irradiation:

- **In strong injection (high Ic):**
  - ✓ **saturation on the interface states;**
  - ✓ **saturation of the surface recombination current;**
  - ✓ **β degradation decreases slowly when Ic increases.**
- **In weak injection (low Ic):**
  - ✓ **no saturation on the interface states;**
  - ✓ **no saturation of the recombination current;**
  - ✓ **β degradation increases rapidly when Ic decreases.**

Remark : β degradation also depends on the dose-rate

Enhanced Low Dose Rate Sensitivity (ELDRS)





Ionising radiation degrades performance of bipolar devices by creating interface traps and oxide traps.

At Low dose rate density of interface traps is more for same accumulated total dose. Hence more degradation.

Summary of main TID effects on silicon devices

MOS Transistors:

- Threshold voltage shift (ΔVt);
- Leakage currents between source and drain, and between adjacent MOS;
- Transconductance (Gm) decreases;
- Weak inversion slope (Swi) decreases.

Bipolar Transistors: + ELDRS

- Gain (β) decreases

JFET Transistors:

- **P-JFET transistors** Transconductance (Gm) decreases; Pinch off voltage decreases.
- No TID effect on N-JEFT

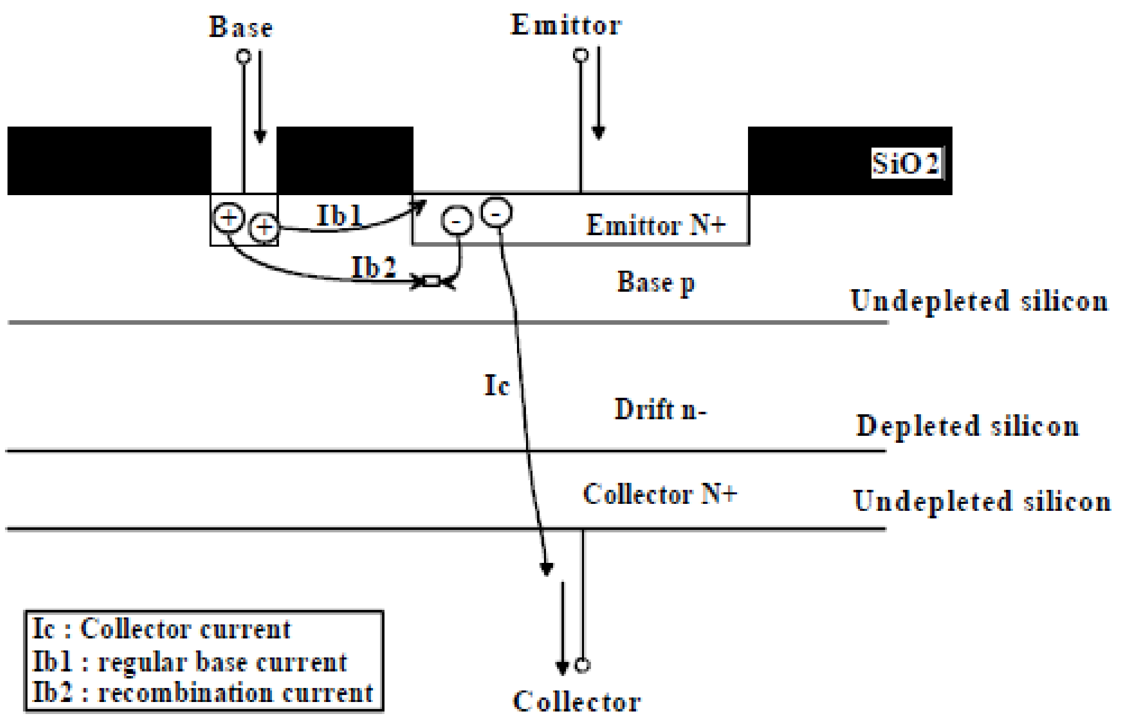
Silicon Resistors:

- **P-silicon resistors** Resistance increases;
- No effect on N-silicon resistors

MOS Capacitors:

- No TID effect.

TNID- Displacement damage effects on NPN Bipolar transistor



Emitter - base junction is forward biased.

Before irradiation:

- Ib1 = holes current injected from the base into the emitter.
- $\beta o = Ic / Ib1$

After irradiation:

- Ib1 = holes current injected from the base into the emitter.
- creation of recombination centers in the base.
- Ib2 = recombination current of a fraction of the electrons injected by the emitter into the base.
- $\beta = Ic / (Ib1 + Ib2) < \beta o$

Summary of Displacement Damage Effects on Si devices

MOS transistors:

- No effects

Bipolar transistors:

- Gain (β) decreases
- Vce saturation decreases
- Diodes breakdown voltage increases

JFET transistors (both N-type and P-type):

- Pinch-off voltage (Vp) decreases
- Drain-source saturation current (Idss) decreases
- Transconductance (Gm) decreases;

Silicon resistors (high resistivity material): Resistance increase;

MOS capacitors: No effects.

Optocouplers: Overall gain decreases.

LEDs: Efficiency decreases.

Single Event Effects – SEE, SEU, SEL, SEB, SEGR

BASIC MECHANISMS

A "Instantaneous" charge injection in a node, enhanced by funneling:

- **Single highly ionizing particle;**
- **High electron-hole pairs density along its track;**
- **The track cross a space charge region from a reverse-biased junction;**
- **The electrical field of the junction propagates along a portion of the track;**
- **Charges along this portion of the track are quickly swept onto the junction by the electrical field (funneling);**
- **Fast collection of a very high quantity of charges on a unique node (or on several nodes in the case of very integrated technologies).**

B "Instantaneous" short circuit along a conductive plasma string:

- **Single highly ionizing particle;**
- **High electron-hole pairs density along its track;**
- **High conductivity string along the track;**
- **Instantaneous short circuit across a reverse biased junction, or across a gate oxide, etc. This short circuit can be non-destructive or destructive.**

Memories are sensitive to SEE (Single Event Effects):

Bit storage = electrical charge => SEE sensitive via charge deposition.

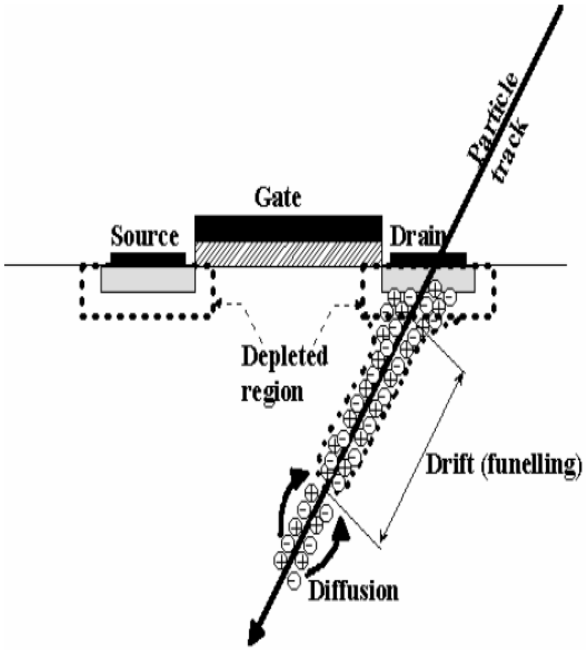
Bit storage = latch logic state => SEE sensitive via current pulse.

Single Event Effects

Conditions for Single Event Upset (SEU):

- A “large enough” quantity of charges must be deposited in a “short enough” time in a “sensitive” node of the circuit.
- Quantity of deposited charges > Critical Charge
- LET (Linear Energy Transfer) > T*hreshold LET*.
- The cross section of the sensitive node depends on the incident angle: **S = U / (Φ cos** θ) **(cm²)**

  (U = Upset number; Φ = fluence; θ = incident angle)



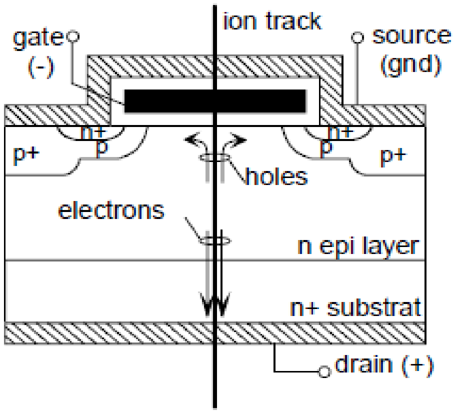
Single Event Burnout (SEB) in power MOS and power BJTs:

- device “OFF”
  - ✓ **high voltage drop across the reverse biased junction; (BJT base-collector junction, or DMOS drain – channel junction)**
  - ✓ **high electrical field;**
- *a single* highly ionizing particle crosses the junction
  - ✓ high electron-hole pairs density along its track;
  - ✓ Multiplication by avalanche (owing to the high electrical field);
  - ✓ high instantaneous current, amplified by the gain of the bipolar;
  - ✓ junction breakdown;
  - ✓ **short circuit** (permanent effect).

Single Event Effects

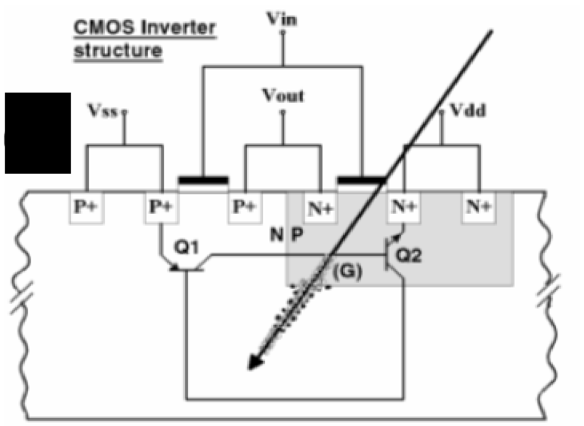
Single Event Gate Rupture (SEGR) in MOS devices:

- *single* highly ionizing particle;
- high e+e- pair density along its track across the gate oxide
- bias across the oxide;
- high instantaneous current;
- oxide breakdown.
- gate-to-channel short circuit: ***permanent effect.***



SINGLE EVENT LATCH-UP (SEL)

- A single highly ionizing particle trigger the parasitic thyristor contained in bulk CMOS inverter. => Vdd to Vss short circuit.
- Destructive mechanism if no current limitation
- Possible recovery by bias switch off if the circuit is protected by a current limiter



Summary of SEE

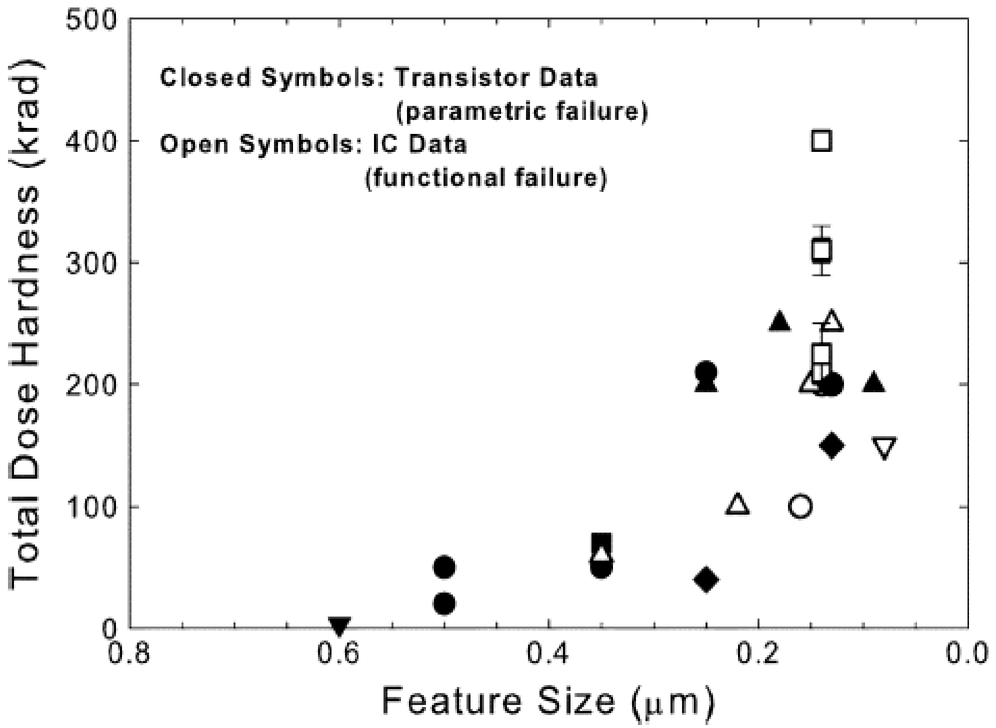
Effects on elementary device		
Permanent effect: • Leakage current • Parameters degradation	**Destructive effect:** • Single Event Gate Rupture • Single Event Burnout • Single Event Latch- up	**Non destructive effect:** • Single Event Upset
Effects on circuit:		
Permanent effect: • Power consumption • Features degradation • Lose of functionality • Stuck bits in memory	**Destructive effect:** • Single Event Gate Rupture • Single Event Burnout • Single Event Latch-up	**Non destructive effect:** • Memories : bit errors, memory erasing • Logic circuits : bit errors • Analog memory : errors

Radiation Effects on Submicron Technology

TID Hardness Trend (CMOS)

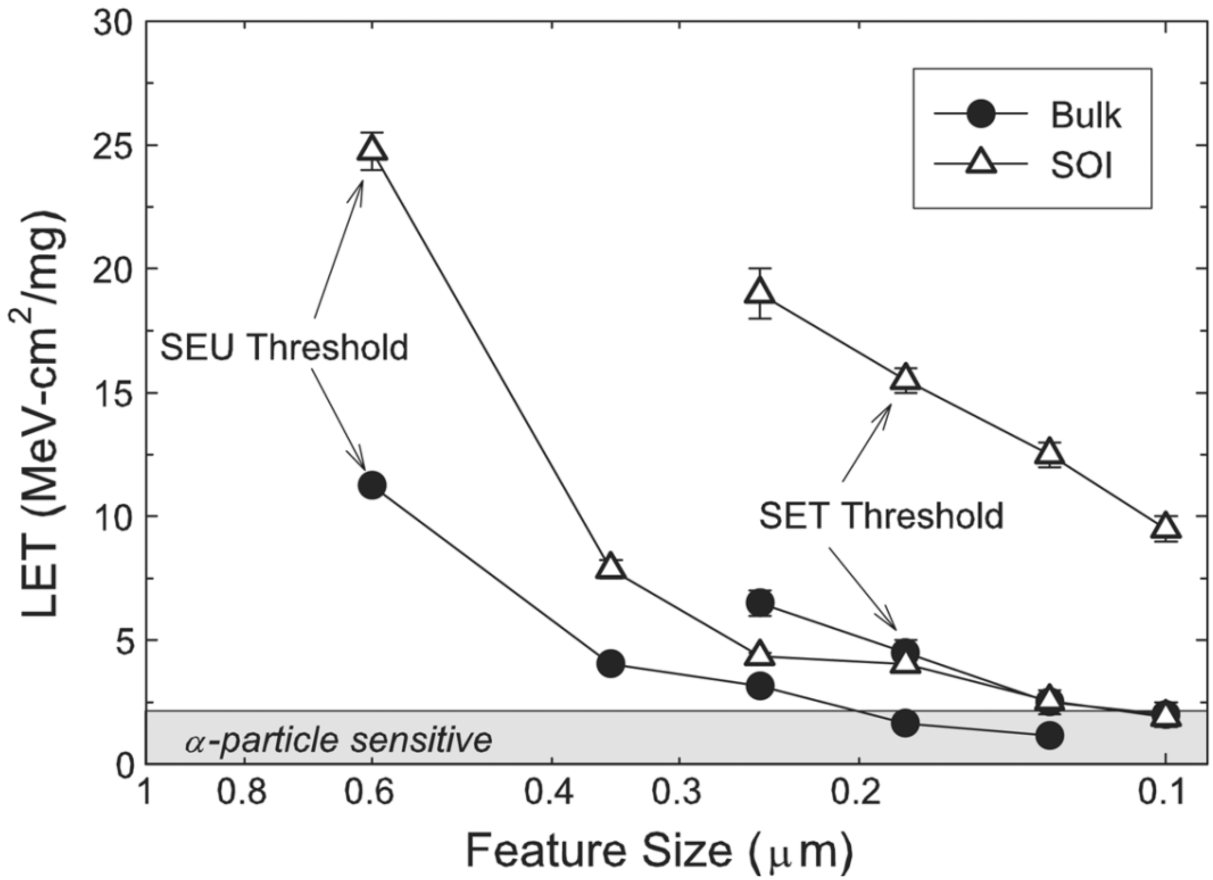
Few years ago total dose failure levels of a few tens of krad (SiO_2) were common.

Today's advanced digital CMOS ICs can in some cases approach failure levels of 500 krad (SiO_2)



Radiation Hardness of device for same feature size from different manufacturer is different.

SEE LET Threshold Trend



As the amount of charge that represents stored information has dropped lower and lower, so the sensitivity of CMOS devices to single-particle charge collection transients has increased.

Radiation Hardness Assurance(RHA) for ISRO Satellite Program

RHA For ISRO Satellite Program

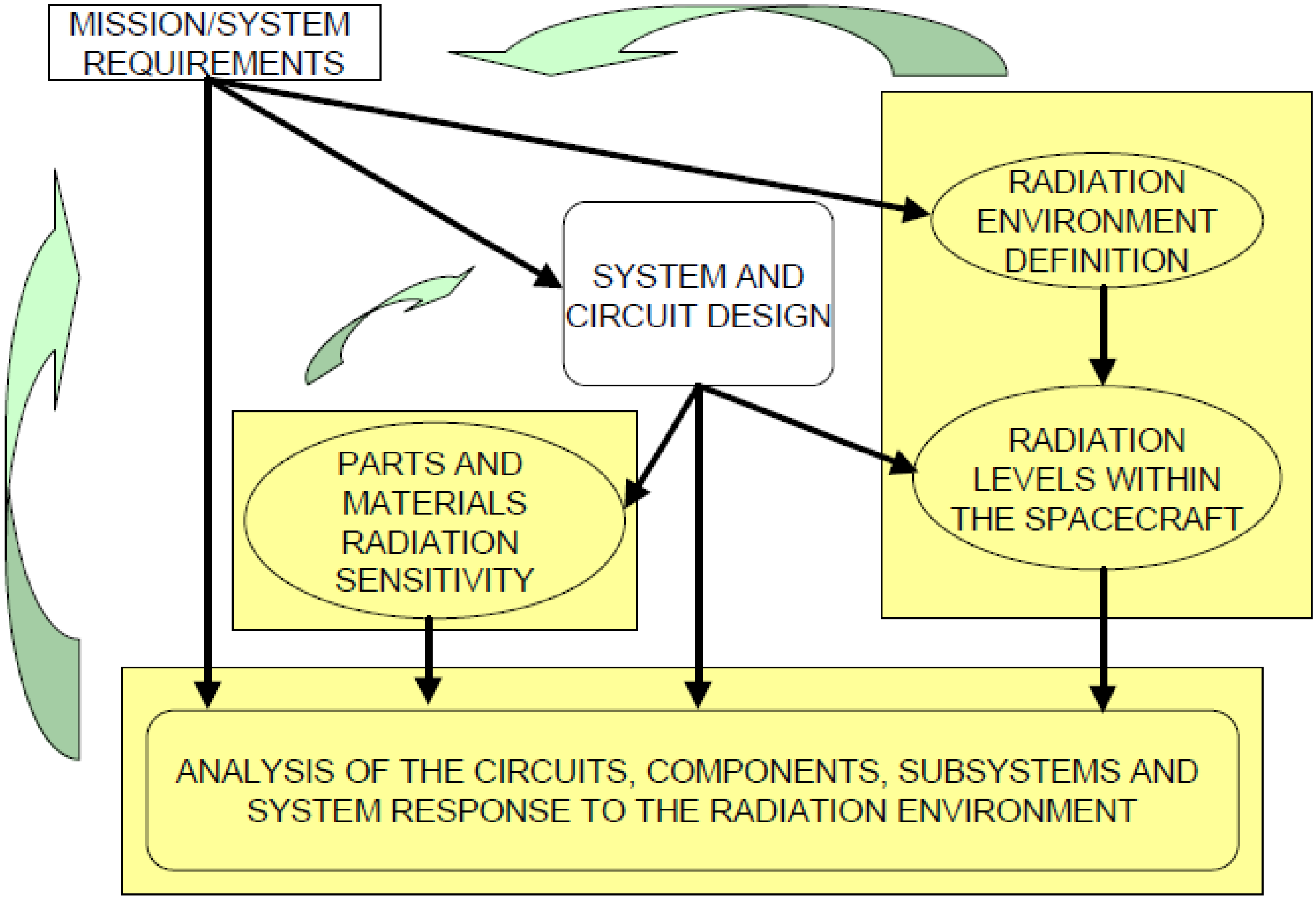
Definition

- RHA consists of all activities undertaken to ensure that the electronics and materials of a space system perform to their design specifications after exposure to the space environment.

- Deals with mission/system/subsystems requirements, environmental definitions, part selection, part testing, shielding, and radiation tolerant design

- Radiation Hardness Assurance goes beyond the Component level

RHA Overview



Radiation Environment Specification

- **TID specification**
  - **Dose-depth curves**
  - **Spacecraft specific dose levels (TID level on chip)**
- **TNID specification**
  - **Energy spectra (Trapped Electron, Trapped protons, Solar protons)**
- **SEE specification**
  - **Heavy ions -linear energy transfer (LET) Spectrum**
  - **Protons -energy spectra**

Requirements for Radiation Shielding calculation

- Spacecraft structure details (Required from Project or subsystem)
  - Main cuboids, load cylinder, fuel tanks, shear web etc dimensions , thickness and density
  - Electronics package dimensions, thickness and density.
  - Number of PCBs and PCB dimensions, thickness and density.
- Dose vs Depth data (From SPENVIS)
  - Mission duration, mission start date, orbit altitude and inclination, transfer orbit details (Inputs required for SPENVIS)
  - Model for trapped particles (AP8 & AE8), solar particles (JPL 91) radiation environment (Available in SPENVIS)
  - Radiation transport data (Available in SPENVIS)
- Software tool for ray tracing (DOSEMAP in-house developed software)

Methodology for radiation shielding calculation

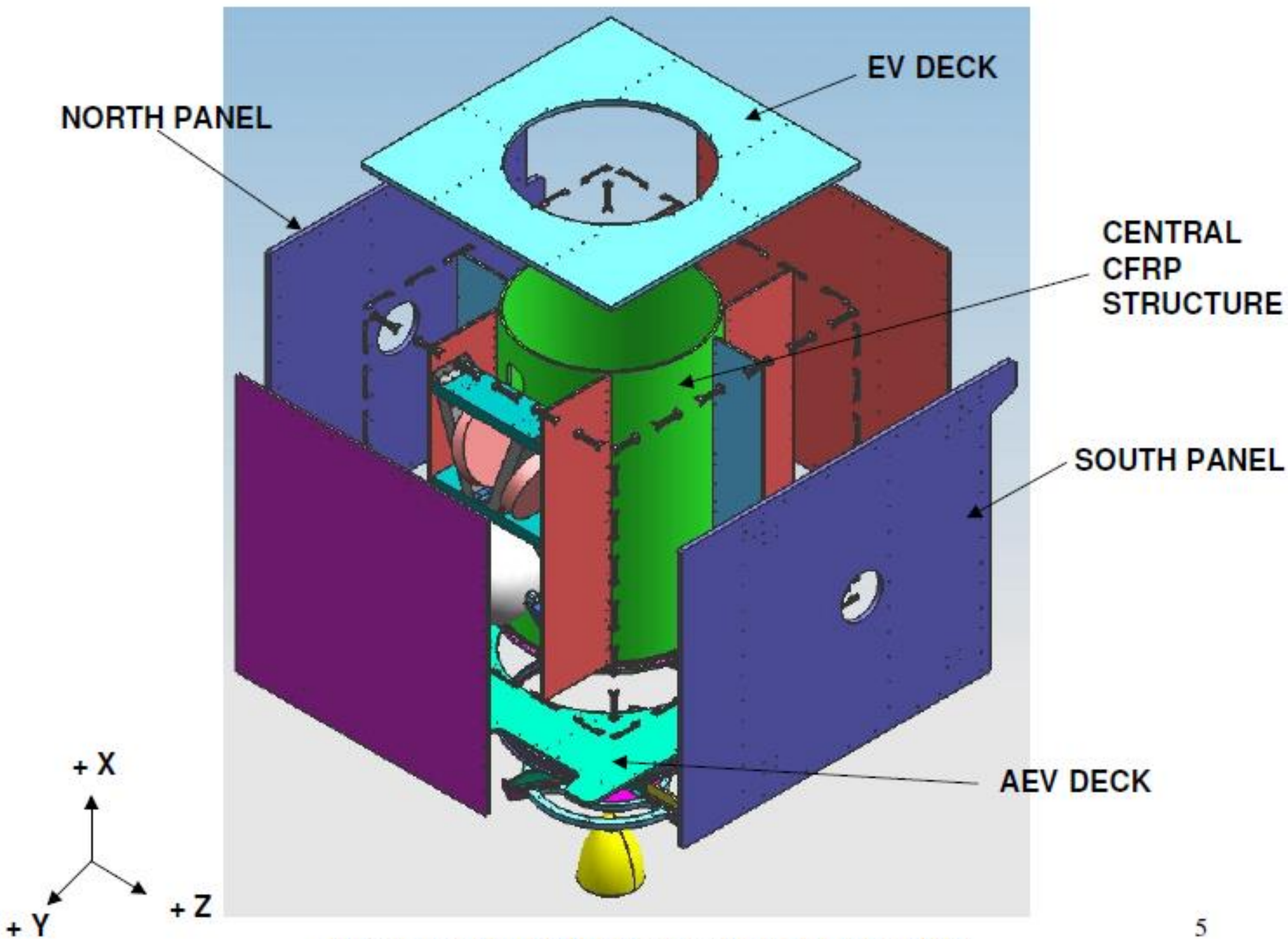
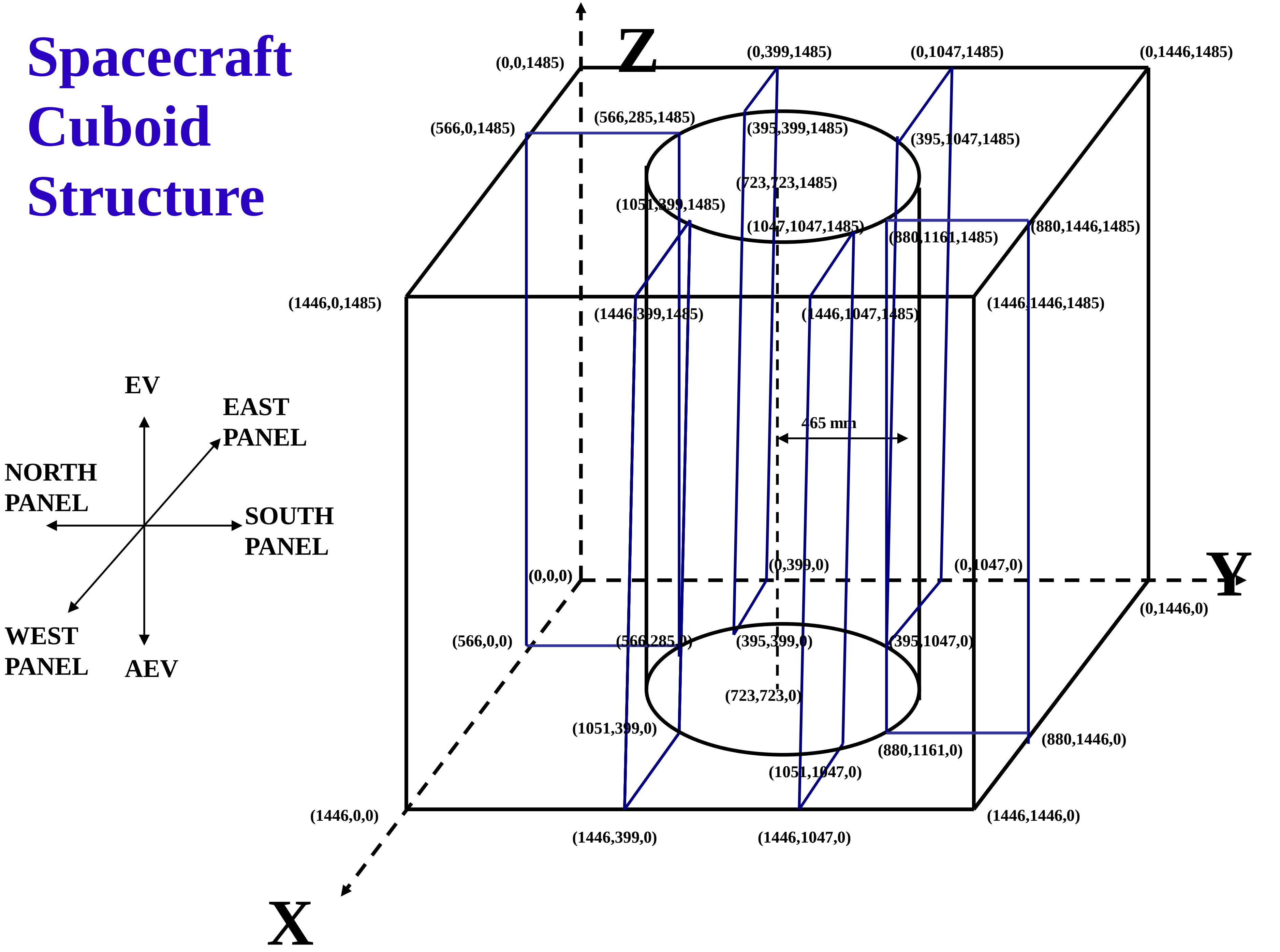


FIG 1.2 EXPLODED VIEW OF GSAT-12 STRUCTURE

Spacecraft Cuboid Structure



Policy for Total dose Hardness of Components

Period	CMOS Krads(Si)	Linear Krads(Si)	Discrete Krads(Si)	Zener Krads(Si)	Minimum RDM	GEO Design Mission Life (years)	Remarks*
Before W2M	100	20	100	100	1	7/10/12/15	Mission life based on requirement
W2M and Hylas	100	20	20*	100	1.2	15	Due to Contractual requirement with ELDRS effects
Post W2M GSAT 5,8	100	20	100*	100	1 or 1.2	15	ELDRS effects not considered
GSAT 10	100	20	100*	100	1.1	15	ELDRS effects not considered
Production 15 years	100	20	50*	100	1.2	15	Based on ELDRS test data,

ELDRS is batch, manufacturer and technology dependent.
Now ELDRS test data for 20 date codes is available and for remaining devices ELDRS testing will be carried out.

Standardisation Documents

Considerations

–I1K spacecraft structure (GSAT12)

–15 year mission life with 20 % design margin

–Package and components details provided by subsystem

–Radiation hardness considered as per presented table.

–Estimation is based upon worst case spacecraft structure, location of package and location of device.

Conclusions

- Space radiation environment is presented
- Defining the space radiation environment is an essential input to cope with radiation effects in EEE components during space missions.
- Standardisation of radiation carried out for GEOSAT and IRNSS missions of 15 years.
- Estimation is based upon worst case spacecraft structure, location of package and location of device.
- All estimations are with 20% radiation design margin for GEOSAT.
- These estimations are applicable for all GEO missions with 15 year or less life.
- Document also provided details of the package considered for shielding estimation.
- Re-estimation is required, If there is a change in package thickness, number of PCBs or components list provided by subsystem.
- RHA is matured and stabilised

Thanks For your

Attention