Overview of Radiation Hardness Assurance studies for FCC

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Outline

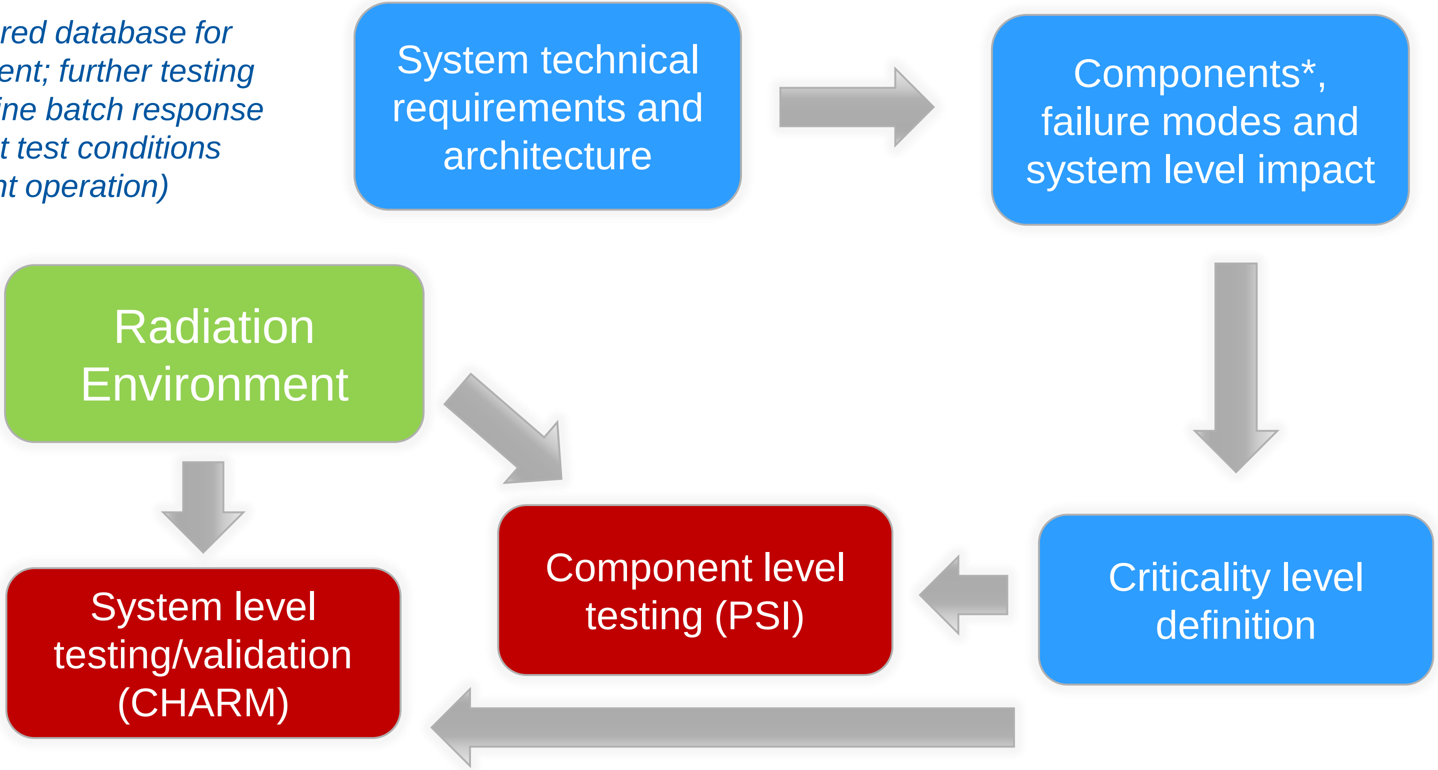
- Status of Radiation Hardness Assurance **(RHA) protocol** for LHC and HL-LHC
- **Radiation tolerant system** considerations for FCC
  - Examples: power converter controls and communication link
- FCC **radiation environment**: calculation and monitoring
- **Qualification approaches**: TID, DD and SEEs
- Synergies with **space** and **ground-level** applications

R2E RHA protocol for LHC and HL-LHC

- So far only based on “best-practice” through interaction of equipment groups with R2E and RADWG
- Now formalized through light-weight protocol
- Takes input from radiation qualification **standards** (mainly space), but tailored to high-energy accelerator environment and requirements
- In continuous development, also related to other applications (e.g. COTS in space, automotive…) mainly in the context of the **RADSAGA** Marie Curie training network

R2E RHA protocol for LHC and HL-LHC

**importance of structured database for tested COTS component; further testing still needed to determine batch response and if applicable adapt test conditions (radiation + component operation)*



System technical requirements and architecture

Components*, failure modes and system level impact

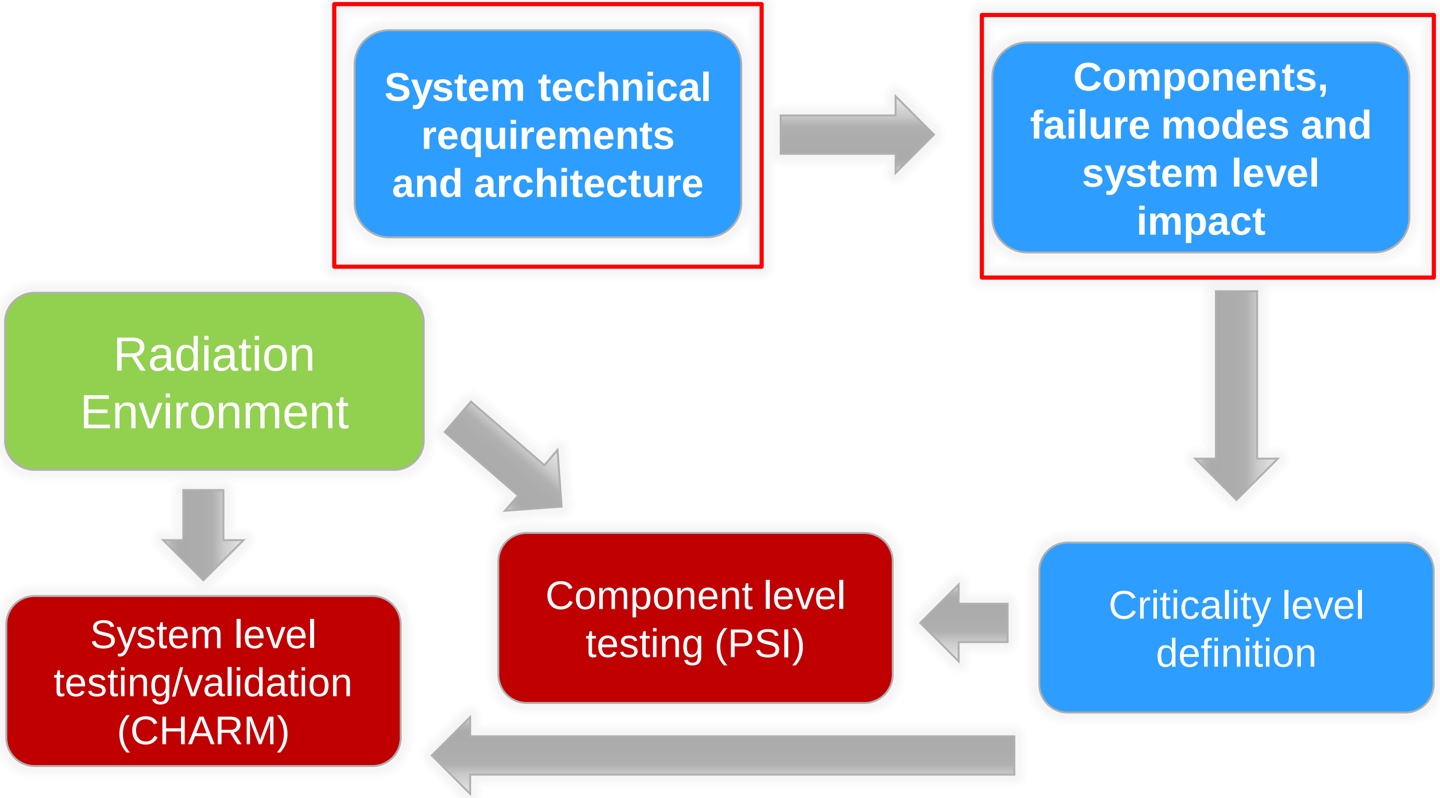
Criticality level definition

Component level testing (PSI)

Radiation Environment

System level testing/validation (CHARM)

Outline



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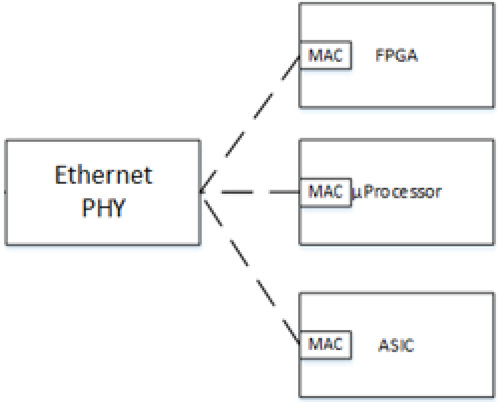
R2E considerations for FCC system: power converter controls

- Consolidated experience in radiation-tolerant COTS based system design, notably through **FGClite** (HL-LHC availability and radiation tolerance requirements)
- The use of COTS components in FCC tunnel is highly challenging due to radiation levels, and could require the (partial or total) combination with rad-hard components
  - Present R2E qualification approach not directly applicable to FCC tunnel environment, whereas still valid for FCC shielded areas
- *Centralised* versus *Embedded/Distributed* approach, exploiting evolution of **communication networks** (i.e. processing higher in network as opposed to closer to the equipment under control)
- New system level reliability design approach: **“total availability”**, based on: (i) degraded mode operation, (ii) failure self-diagnose, (iii) online hot-swap and (iv) remote handling capability

Communication link

- **Rad-tol, high-bandwidth communication link** will be fundamental part of FCC centralised processing approach
- Strategy for FCC: development of multiple high-end solutions (e.g. Ethernet-based) which will constitute the common building blocks for future modular systems
- Main components: Ethernet PHY, transceiver, FPGA/micro-processor/ASIC
- Preliminary studies carried out on **FPGA solution** using hard/soft processor to be able to conduct additional operations → preferred solution for SEU tolerance: flash-based FPGA with radiation mitigated soft core
- Strong link to BE/CO + HL-LHC WP18



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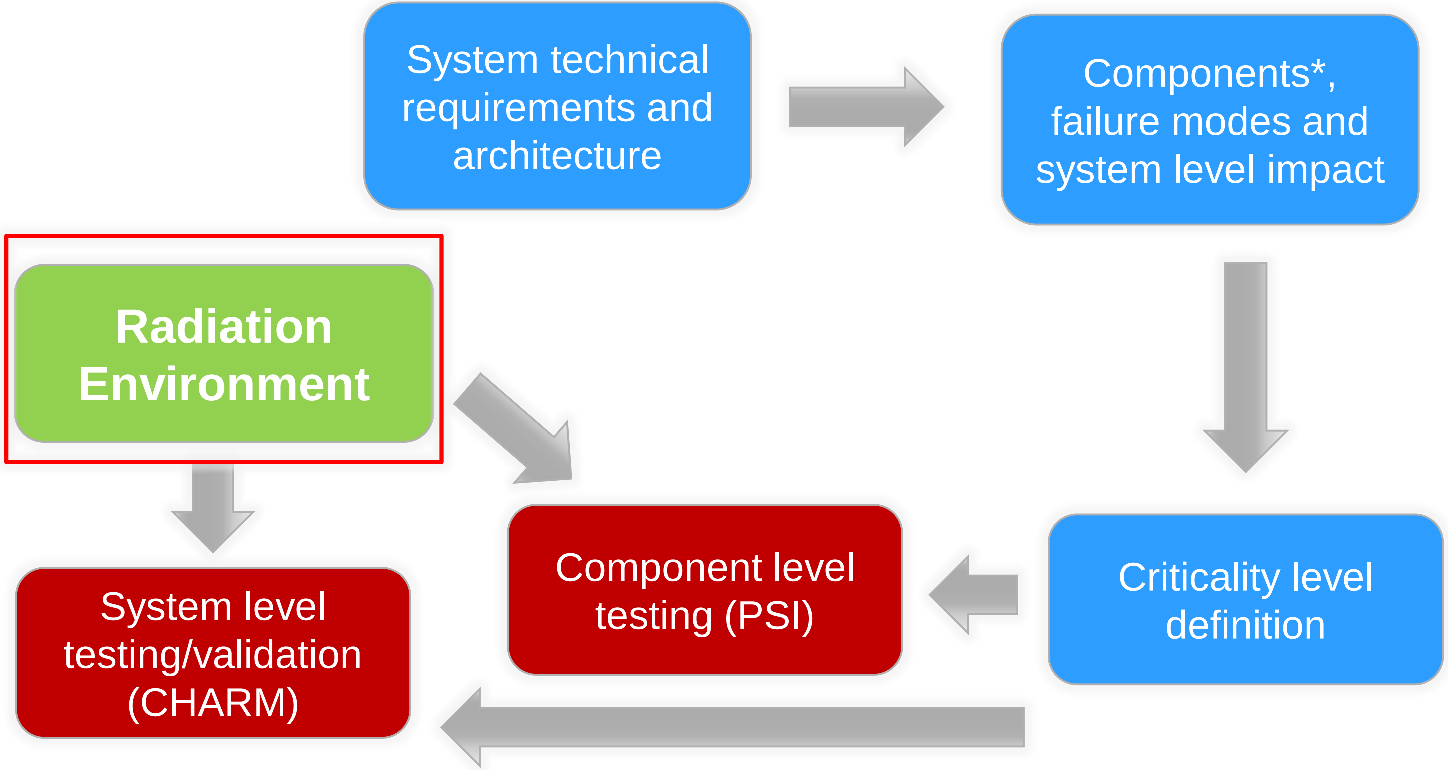

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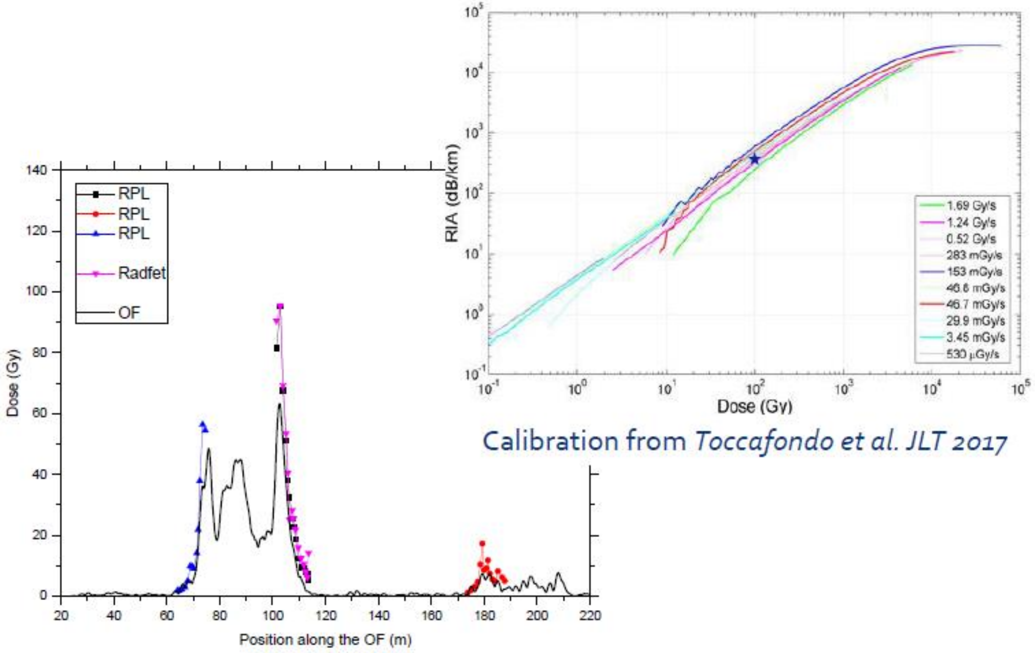
Radiation environment: monitoring and calculation

- Based on FLUKA calculations (for FCC, A. Infantino) and measurements
- Main progress in LHC and injector chain radiation level monitoring:
  - **RadMON** v6 deployment, R&D activities (e.g. floating gate, 65 nm SRAM) for v7
  - **Distributed Optical Fibre system**: already deployed in PSB and PS; in LS2: installation in SPS and (parts of) LHC; cost driven by interrogation units, which therefore scales very favourably for large machines (e.g. FCC)



Calibration from *Toccafondo et al. JLT 2017*

FCC radiation environment & test targets

- Radiation levels
  - in FCC ARC tunnel (i.e. area where most tunnel equipment will be hosted) correspond to:
    - **10^{11} HEH/cm^2/yr** (for SEE cross section levels)
    - **4 kGy** and **$2 \cdot 10^{13}$ n$_{eq}$/cm^2** (for TID and DD cumulative effects)
  - In FCC “RE-like” shielded alcoves
    - **<10^7 HEH/cm^2/yr** (for SEE cross section levels)
    - TID and DD levels not a concern for electronics

“FLUKA Monte Carlo modelling of the FCC arc cell: radiation environment and energy deposition due to beam-gas interactions” A. Infantino, FCC week 2017

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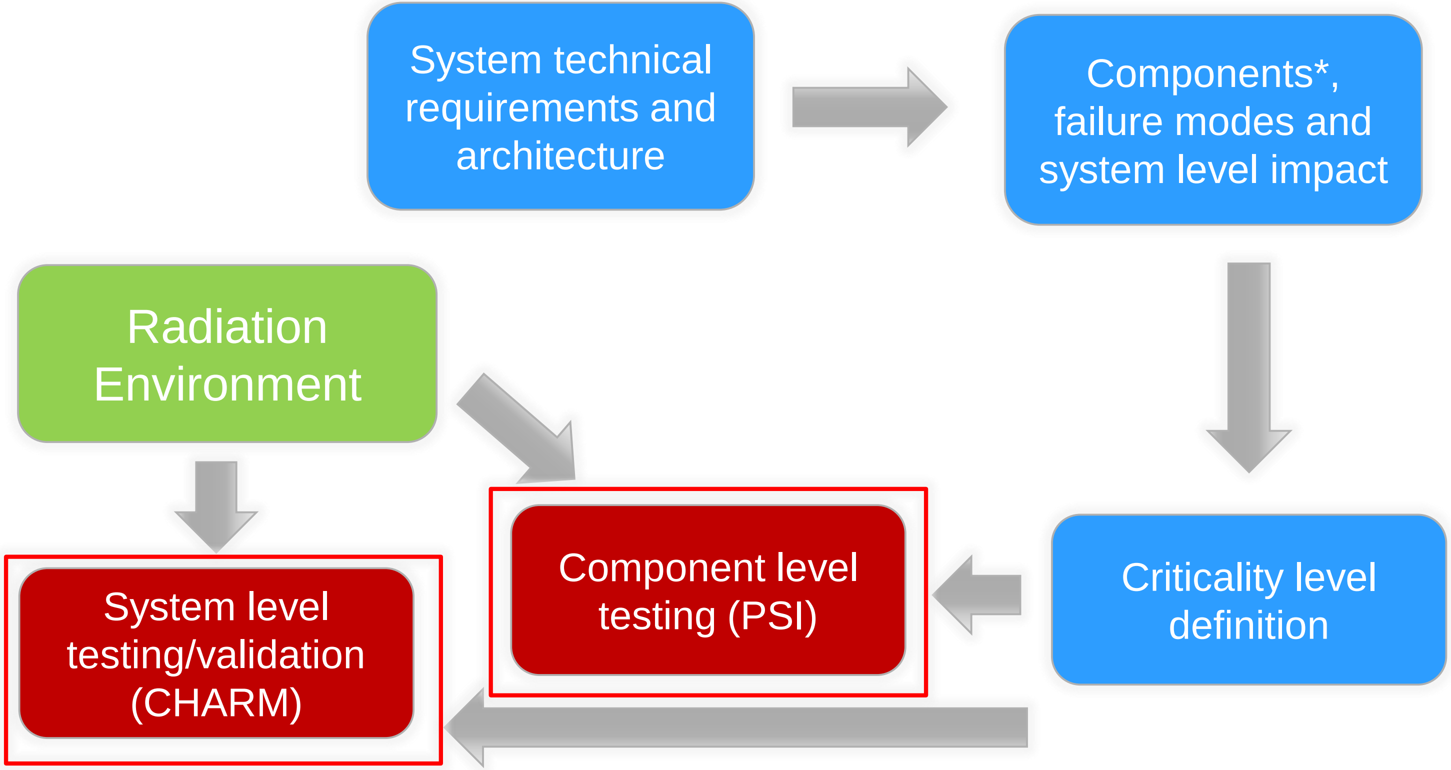

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TID qualification

- Commercial-Off-The-Shelf (**COTS**) components offer key advantages such as cost, availability and performance
- Radiation tolerance is not a design driver, and parts can start failing after a **few tens of Gy**, with many types having lifetimes in the **few hundreds of Gy** interval
- Special attention required to **lot variability** (i.e. spread in sensitivity) and Enhanced Low Dose Rate Sensitivity (**ELDRS**)
- TID limit for **FCC ARC tunnel** presently set to **~4 kGy**, therefore an order of magnitude larger than typical limit values for present technology

Family	Failure Level [Gy(SiO_2)]
Linear ICs	20-300
Mixed-signal ICs	20-250
Flash memories	50-150
DRAMs	150-500
Microprocessors	150-700

Typical TID limits for COTS components currently used in space

TID qualification

- R2E TID qualification approach mainly based on in-house **Cobalt-60** source (10 TBq, maximum dose rate for component and system level qualification of ~12 Gy/h [50 cm] and ~1 Gy/h [2m]) and/or mixed-field in CHARM (~200 Gy/week)
- Not practical for reaching **kGy levels required for FCC**, therefore alternatives are being studied:
  - Upgrade of CERN Cobalt-60 source by factor ~10 (main constraint: shielding for radiation protection)
  - At component level: use of in-house, high-energy electron beam (main constraint: possible impact of dose rate and synergy with displacement damage)
  - Use of external facilities (main constraint: need to find good balance between dose rate, field homogeneity and possibility of performing active, biased tests)

DD qualification

- Mainly affecting **optoelectronics** and **bipolar transistors**
- In principle, not dependent on bias and dose rate
- Presently tested at CHARM (~$2\cdot10^{12}$ n_{eq}/cm^2 per week in standard locations, factor ~100 larger in T0 passive location) or with mono-energetic protons/neutrons
- Synergy effects between TID and DD in mixed-field environment under analysis

SEE qualification

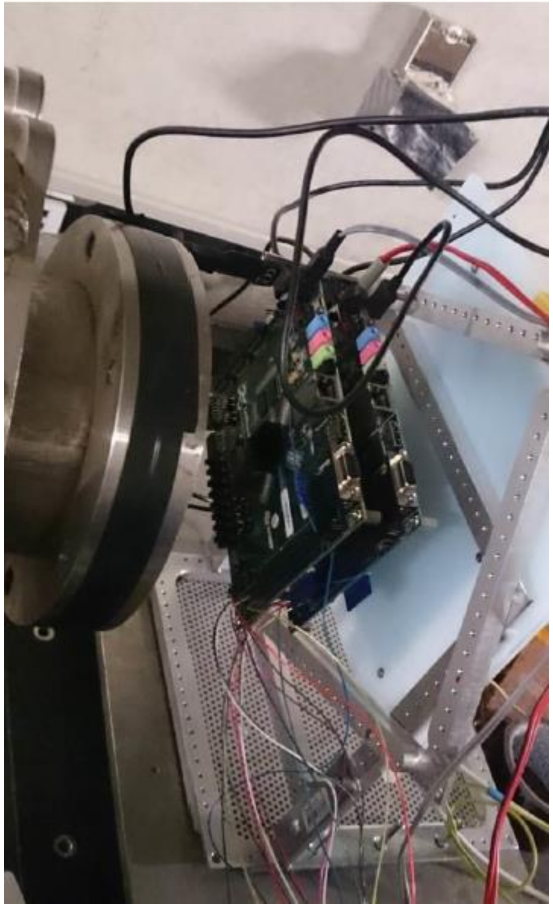
- Important difference between **soft errors** (can be corrected via remote reset while system continues to operate in degraded mode) and **hard errors** (online hot-swap needed, as well as replacement of faulty board)
- Soft/Hard error criticality needs to be evaluated at **system level**, including redundancy considerations, in order to establish target SEE cross section at component/sub-system/system level
- Example: system with 4000 units in FCC ARC and upper failure limit of one dump per year would require SEE cross section upper limit 10^{-14} cm^2 (~2 orders of magnitude below LHC and HL-LHC limits, i.e. virtually **SEE-free**)
- Main constraints of qualifying components & systems to such low SEE cross section limits in proton and/or mixed-field environment: very large beam time required, and TID/DD levels potentially above required values

SEE qualification

- Alternative to proton/mixed-field SEE testing for very low upper cross section limits: **heavy ion testing** with LET > 15 MeVcm^2/mg (> 40 MeVcm^2/mg if impact of high-Z materials is considered)
- Main constraint: standard heavy ion test facilities use energies of ~10 MeV/n, with **limited ion ranges** of ~90-200 µm, which require part opening/thinning and testing in vacuum
  - Test of complex packages (e.g. flip-chip) and at board level might therefore not be feasible
- High-energy ion beams (~1 GeV/n at GSI [Germany] or NSRL [USA])
  - 2017: first evaluation of ultra-high energy (UHE) ion beams at CERN

SEE qualification

- Evaluation of SEEs induced by **Xe beam** from **PS** at CHARM and **SPS** at H8 North Area
  - Highly penetrating beam, allowing for testing of multiple boards in air, without need of opening parts
  - Provided a large enough LET (e.g. Pb) parts could be qualified as SEE-free* in similar conditions as with protons (e.g. in air, no need of opening parts, possibility to test at board level) but in significantly **shorter beam times** and exposed to significantly **lower TID and activation levels**
  - Evaluation will continue in 2018 with Pb beam



**when considering silicon fragments, with LETs up to ~15 MeVcm^2/mg*

Importance of external facilities

- CHARM mixed-field facility and the Cobalt-60 source at CERN cover a broad range of qualification needs for accelerator systems
- However, external facilities are needed as complement the CERN facilities in order to:
    - Cover **dose rates/fluxes** that are not accessible in the CERN facilities
    - Evaluate the sensitivity to a specific particle and/or energy (e.g. thermal neutrons, low energy protons)
    - Perform tests during CERN accelerator complex **shutdown** (e.g. LS2)
- Main external facilities used: blanket contracts with **PSI** for high-energy protons and **Fraunhofer** for larger Cobalt-60 doses
- Continuous evaluation of other external facilities for high-energy accelerator RHA

External facility evaluation

- **LPSC:**
  - 14 MeV neutrons representative of soft-error induction for high-energy accelerator mixed-field → can be used as a more accessible beam, lower cost; not applicable to hard failures
- **ILL:**
  - High-flux (~10^8 n/cm^2/s) thermal neutron beam; useful for thermal neutron SRAM detector calibration (large lot-to-lot variability) and evaluation of sensitivity of deep sub-micron CMOS technologies
- **ChipIr:**
  - Neutron spallation source for atmospheric-like spectrum; fluxes similar to CHARM (~$3 \cdot 10^6$ $n_{>10MeV}$/cm^2/s) and large beam (up to ~25 x 25 cm), therefore potentially suitable for board level testing

Synergies with space applications

- Radiation effects on electronics are not specific to the high-energy accelerator applications, but impact other domains, notably **space**
- The large space agencies (ESA, NASA…) have recently acknowledged the need of **harmonizing** use and qualification of **COTS** for space
- Possible points of **collaboration**:
  - Sharing beam time and test facilities
  - Common identification of COTS of interest and respective qualification & reports
  - Development of qualification guidelines (e.g. through **RADSAGA** Marie Curie project)

Conclusions

- Existing LHC and HL-LHC RHA protocol is a first step for FCC qualification
- Protocol to evolve to specific FCC requirements related to radiation environment and system performance
  - Expected TID levels in FCC tunnel are clearly a threat for use of COTS components
  - SEE requirements for distributed systems (both COTS and rad-hard based) will pose serious constraints on qualification through protons/mixed-field, therefore heavy ion qualification needs to be explored
- Collaborations and synergies with other applications (e.g. space, automotive) identified as key point to guarantee successful development & qualification of rad-tol systems for FCC