Facilities for radiation testing and technologies for radiation monitoring

Rubén García Alía
On behalf of the R2E project

Outline

- Radiation to Electronics (R2E) project overview
- The RadMON system
- CERN Radiation test facilities
- Space application: CELESTA

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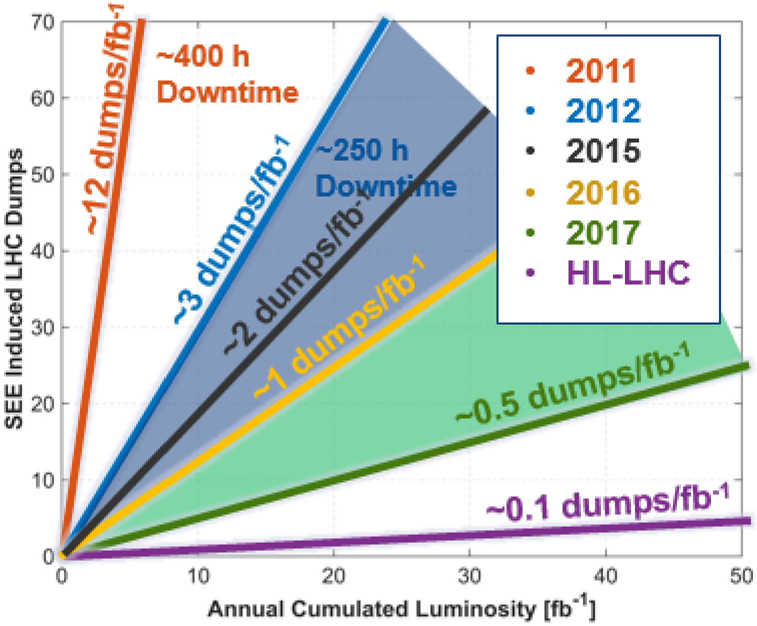
The R2E challenge



Several shielding campaigns prior 2011 + Relocations 'on the fly' + Equipment Upgrades

2011/12 xMasBreak
'Early' Relocation
+ Additional Shielding
+ Equipment Upgrades

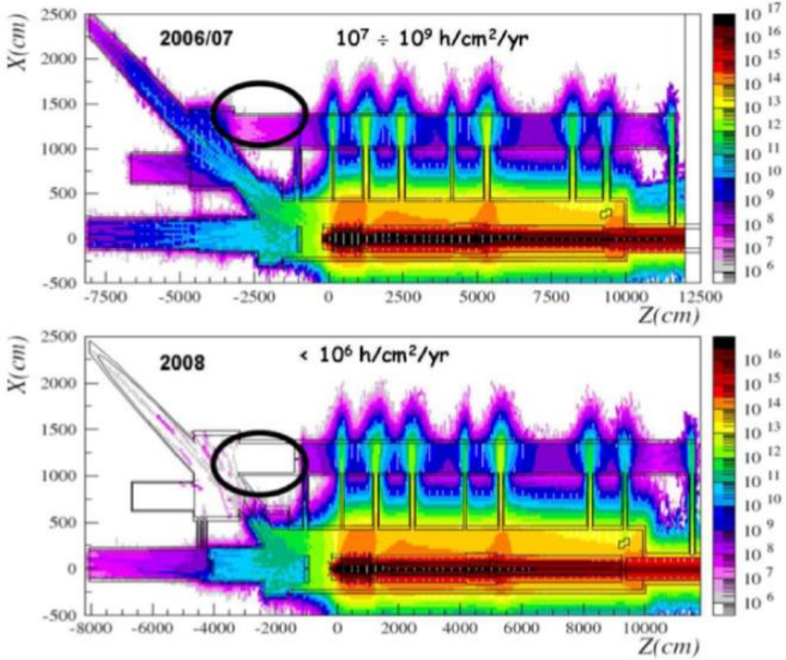
LS1 (2013/2014)
Final relocation and shielding

LS1-LS2 (2015-2018)
Tunnel equipment and power converters

LS3-HL-LHC
Tunnel Equipment (Injectors + LHC) + RRs

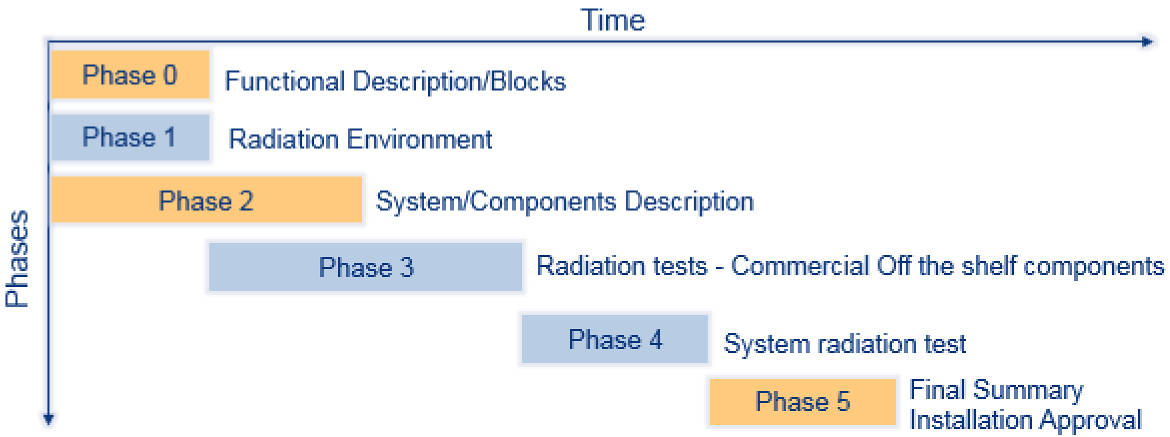
An R2E mitigation example

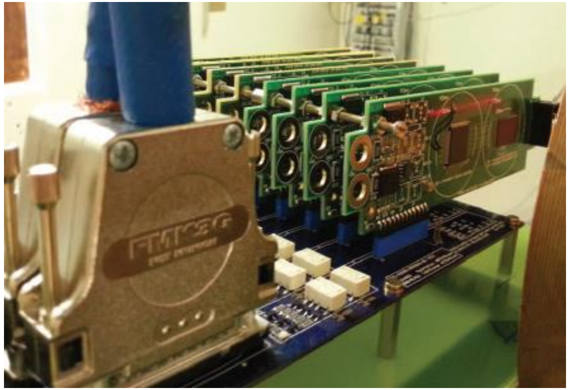
- CERN Neutrinos to Grand Sasso (CNGS) experiment
- Muon-neutrinos generated through interaction of 400 GeV protons with target
- **Shutdown** at an early stage due to successive failures in the ventilation system
- **SEEs in microcontrollers**, mitigated by reinforced shielding



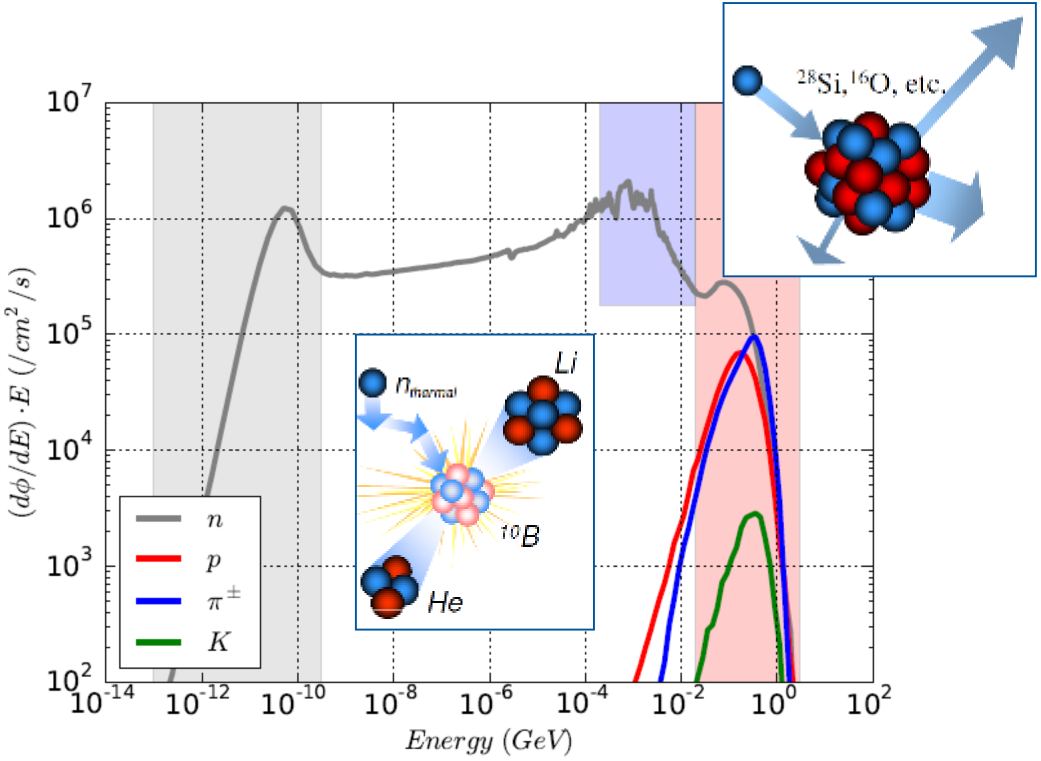
R2E: from mitigation to prevention

- In order to push radiation tolerance to levels compliant with HL-LHC requirements (~0.1 dumps/fb^{-1}) mitigation is not enough
- A **pre-emptive approach** needs to be implemented taking into account the response to radiation from a very early stage of the project



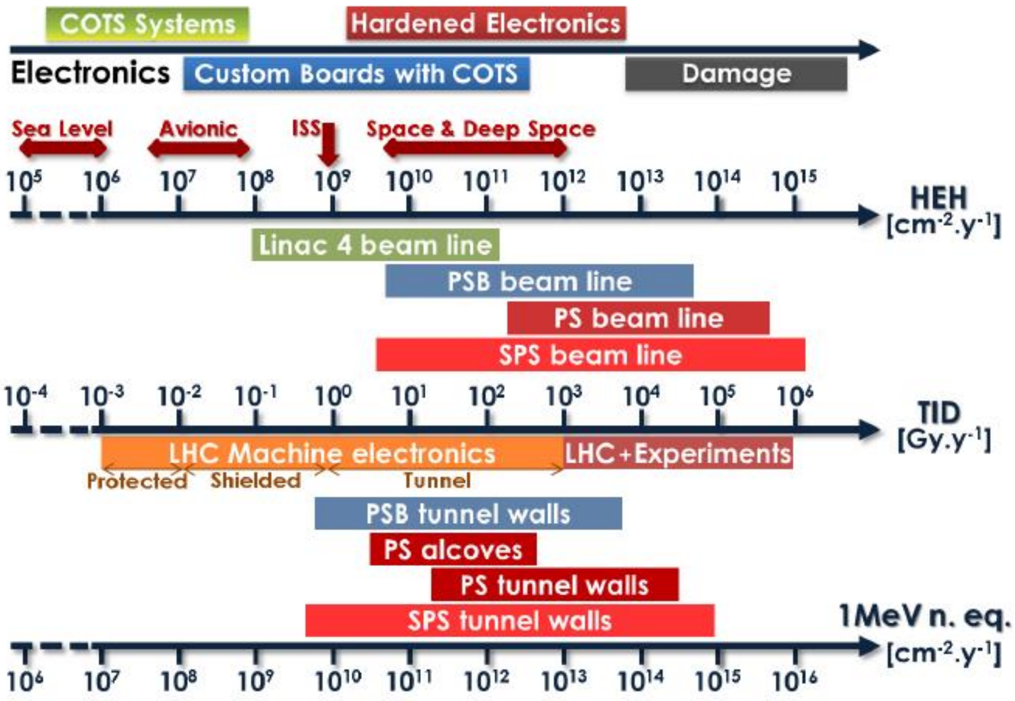


Hadronic environment at CERN



- **SEEs** are induced by indirect energy deposition (nuclear reactions) from hadrons
- Two main intervals can be distinguished: **thermal neutrons** (causing SEEs through ^{10}B capture) and **high-energy hadrons (HEH)**
- Therefore, the associated fluences need to be calculated and monitored

Radiation levels at CERN



- For electronics in the LHC, areas with annual HEH fluxes above **10^7 cm^{-2}** are considered as SEE non-safe areas owing to the very large amount of equipment installed
- TID is typically only a concern above annual levels of **~10 Gy**, which corresponds to roughly $5 \cdot 10^9$ HEH

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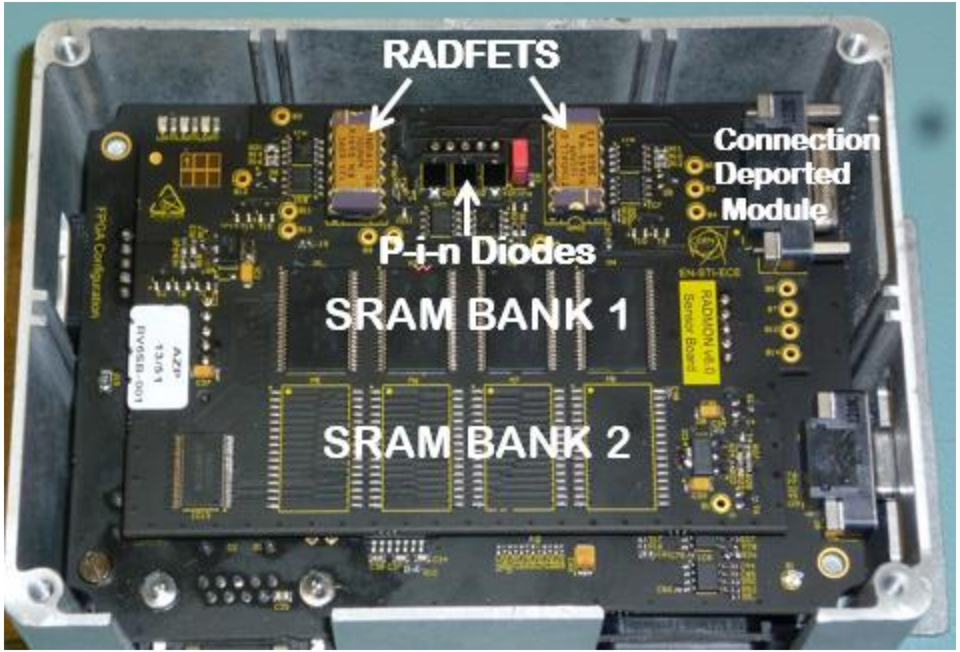
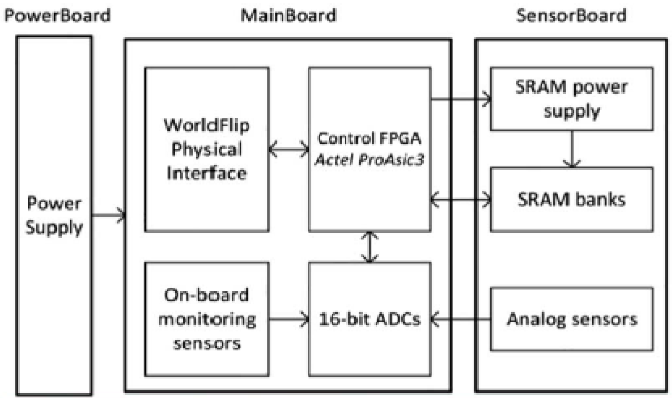
RadMON system

- Use of **commercial electronics** to monitor the radiation environment
- **HEH** and thermal neutron fluence with SRAM memories, **TID** with RadFET, **DD** with PIN diode
- Need to calibrate in relevant radiation fields



RadMON general architecture and RHA

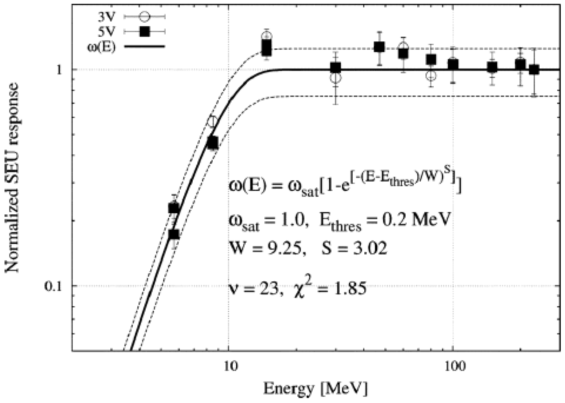


G. Spiezia et al, IEEE TNS (2014)

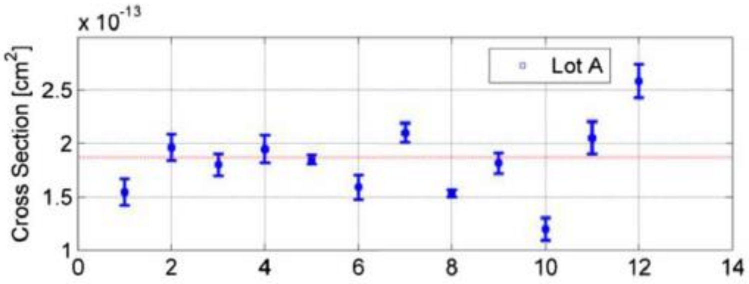
- Power board: AC transformers and linear regulators
- Main board: **ProAsic3 FPGA** with TMR both in registers and internal RAM, ADCs for dosimetry sensors
- Sensor board: TID, DD and SEU detectors. Can be connected to Deported Module for TID and DD sensors
- FPGA works correctly up to 35-40 krad. Limiting component is ADC, which fails after **25 krad**

RadMON calibration: SRAM SEU cross section

- Monoenergetic cross sections for high energy protons (30-200 MeV, PSI), intermediate energy neutrons (5-15 MeV, PTB) and thermal neutrons (nuclear reactor)
- Need to carefully evaluate the sensitivity spread

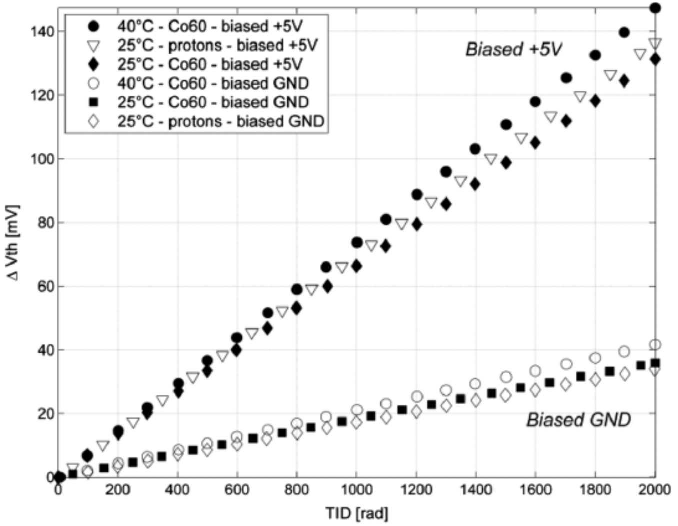


K. Roed et al, IEEE TNS (2012)



S. Danzeca et al, IEEE TNS (2014)

RadMON calibration: RadFET

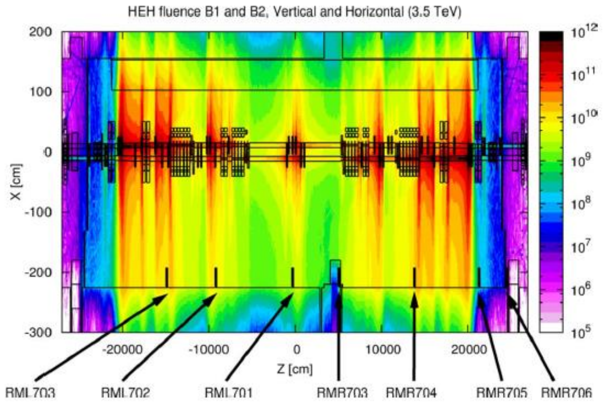


G. Spiezia et al, IEEE TNS (2014)

- Performed mainly using ^{60}Co but also other particles such as protons
- Different oxide thicknesses available, but 100 nm typically used (larger measurement range, better response in mixed field)
- Sensitivity can be increased significantly by applying 5V bias

RadMON benchmarking

- RadMON is regularly benchmarked against FLUKA Monte Carlo simulations both in radiation test facilities (e.g. CHARM) or in actual operation
- Example: RadMONs installed in LHC IR7 for 2010 run



RadMon	Measured (Err [%])	FLUKA (Err [%])	F/M (Err [%])
RML703	13246 (± 1)	13800 (±19)	1.0 (±19)
RML702	4601 (± 2)	7650 (±20)	1.7 (±21)
RML701	2406 (± 2)	3590 (±20)	1.5 (±20)
RMR703	878 (± 3)	641 (±20)	0.7 (±21)
RMR704	17903 (± 1)	17600 (±20)	1.0 (±20)
RMR705	264 (± 6)	731 (±18)	2.8 (±19)
RMR706	13 (±30)	7 (±28)	0.6 (±40)

K. Roed et al, IEEE TNS (2012)

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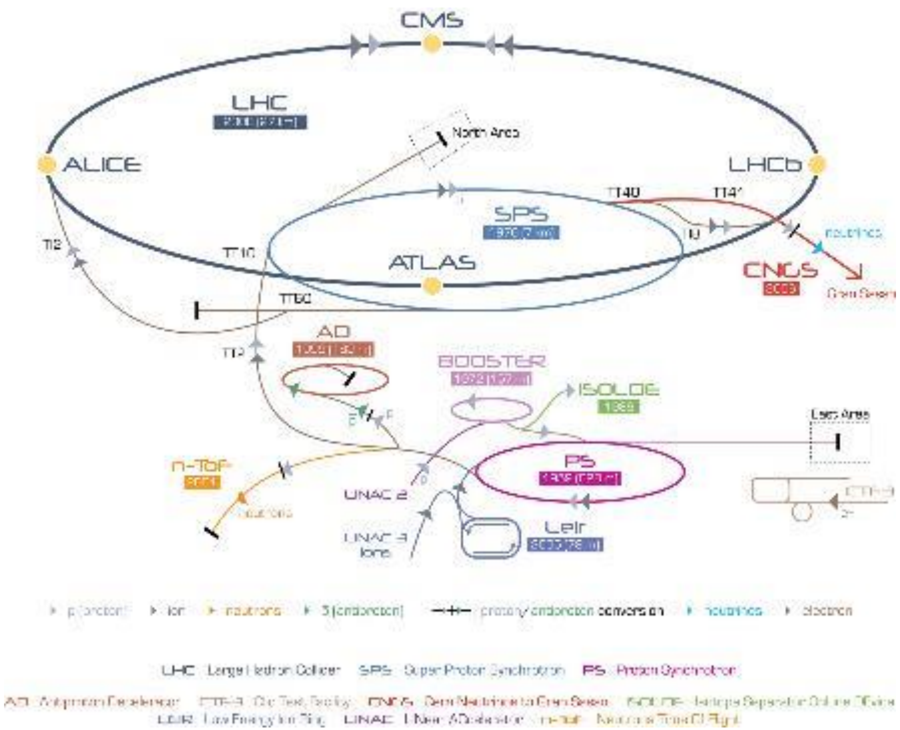
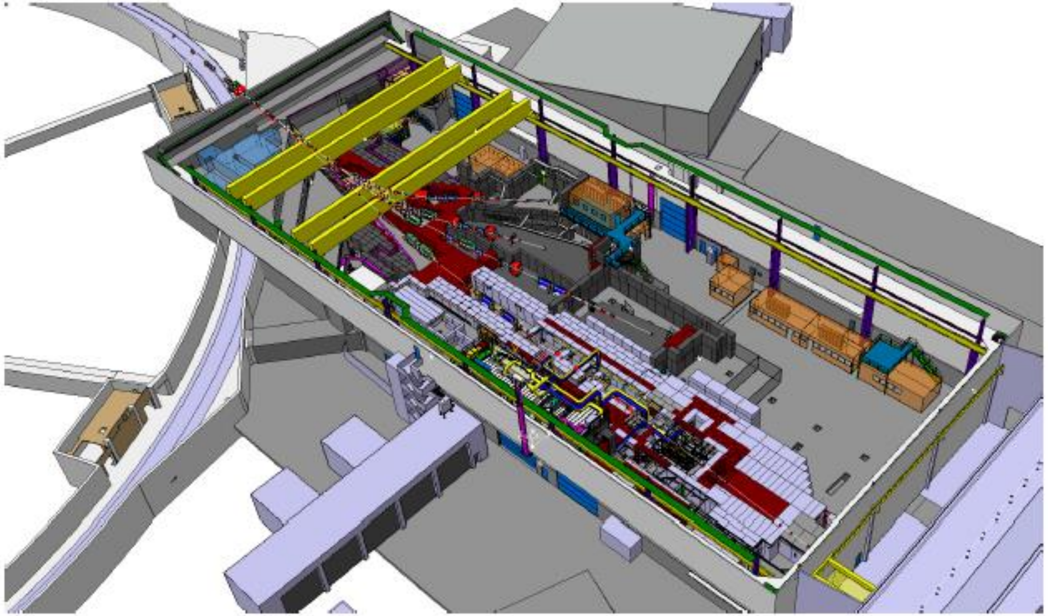
CHARM in the CERN accelerator complex



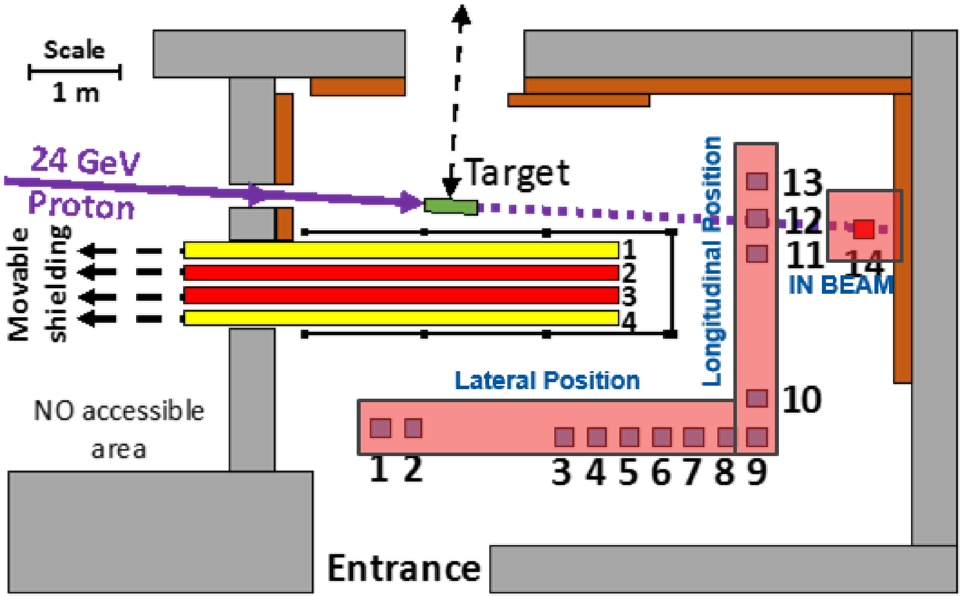
- CERN injector chain to LHC (7 GeV), from SPS (450 GeV) and PS (24 GeV)
- PS first accelerated protons in 1959, being CERN's first synchrotron
- It has a circumference of 628 meters

CHARM in the PS East Area



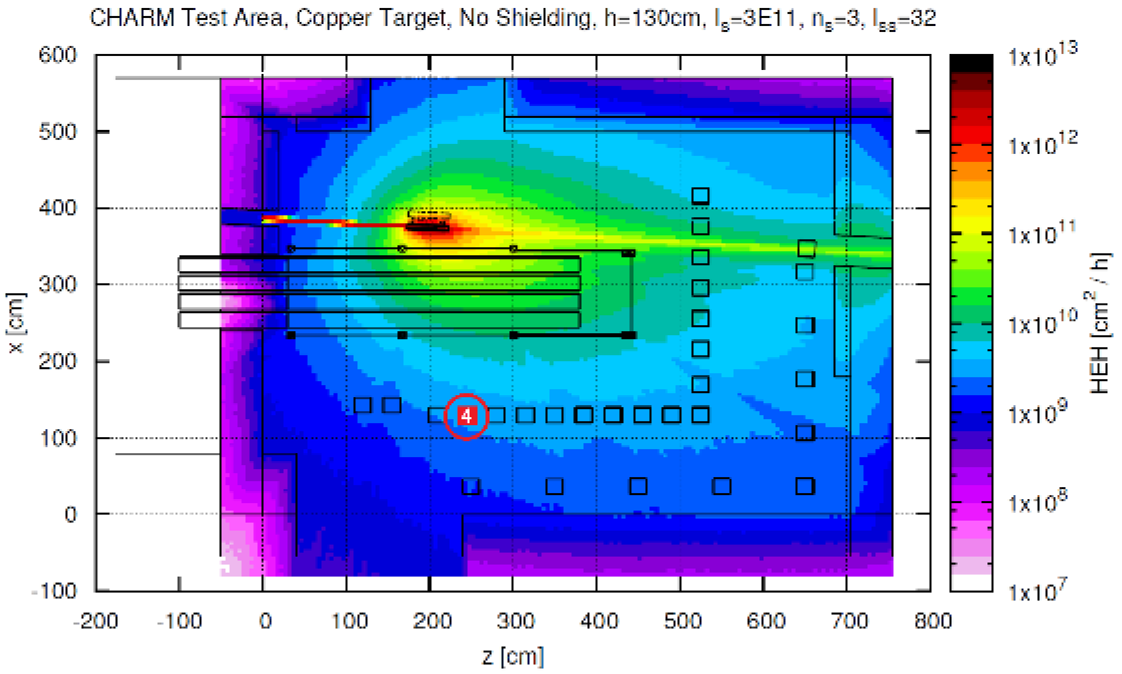
- Located in the PS East Area T8 beamline
- Typically extracts **24 GeV protons**, however heavy ion extraction (Pb, Xe) is foreseen in the near future
- Proton arrive in spills of ~350 ms every 10 seconds

The CHARM irradiation facility



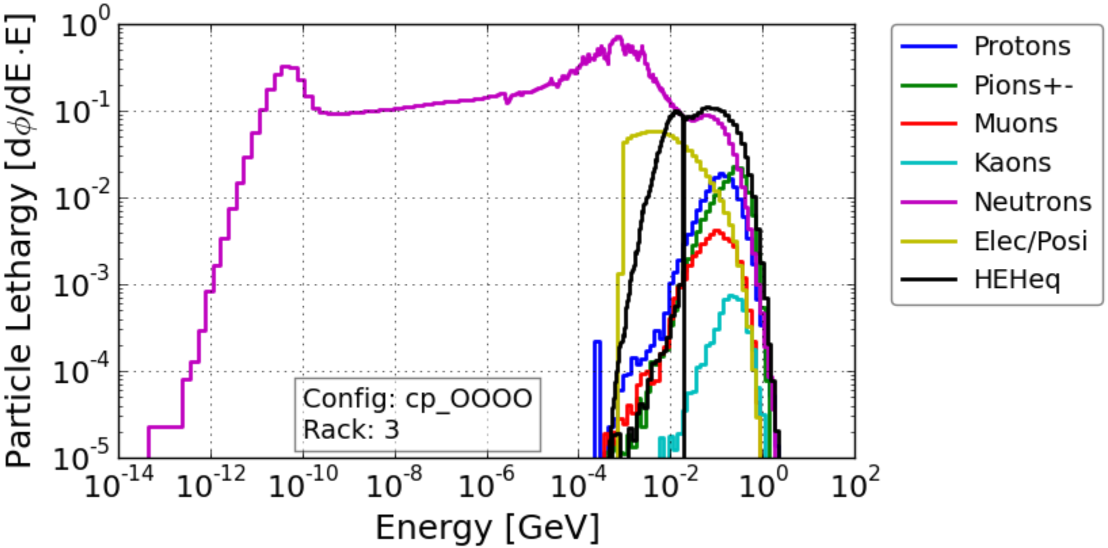
- A broad range of **test configurations** are available in the CHARM irradiation area
- Different particle energy spectra and intensities can be obtained by varying the target material, movable shielding and test location
- Full internal area is subject to large radiation levels (local shielding is not possible) and cable length to control room is ~40m
- Provided the large volume in the irradiation area, **full system tests** are possible

Radiation levels at CHARM



- The CHARM radiation levels are simulated using FLUKA and benchmarked against measurements (e.g. RadMON)
- HEH fluence levels of 10^{10} cm^{-2} (e.g. **worst-case annual LHC tunnel conditions**) can be reached in **one hour**

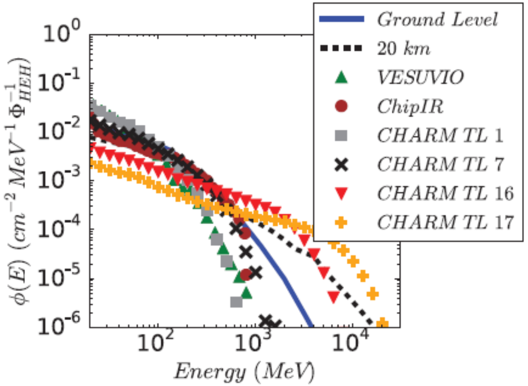
Particle energy spectra

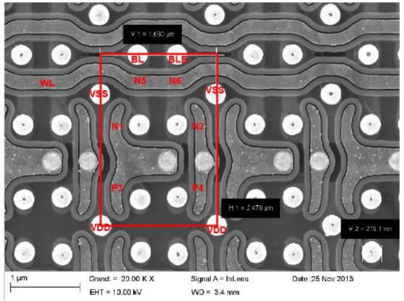


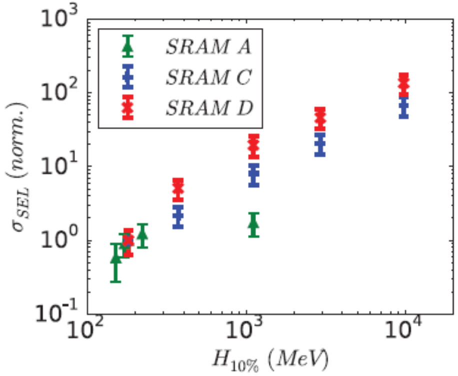
- Mixed-field in which the contribution to **TID** is roughly equally divided between charged hadrons, photons and electrons/positrons
- The **HEH** contribution varies from ~40% pions, ~35% neutrons and ~25% protons for near in-beam positions, to >95% neutrons for shielded lateral locations

Importance of HEH spectrum hardness

- Components with high LET-thresholds and **high-Z materials** (e.g. tungsten) near their SVs are known to have a strong hadron cross section energy dependence with energy up to the GeV range
- Therefore, testing in an environment which is softer than the operational one can lead to a **significant underestimation** of the associated SEE rate

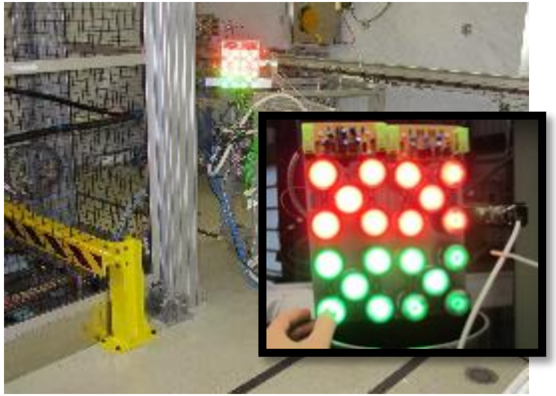






R. G. Alia et al, IEEE TNS (2015)

CHARM tests in 2015

Cryogenic crate:
- Temperature
- Pressure
- Liquid He level gauges
- Cold Mass Heaters
- Beam Screen Heaters
- Mechanical Switches

Red and Green LED array:
- Current consumption
- LED luminosity

CELESTA 1U CubeSat testBoard:
- SEL detection
- Current Consumption
- Accumulated dose
- HEH monitoring
- FPGA functionality

RadMON upgrades:
- Test new sensors.
- Monitor functionality
- Validate new firmware

Heavy ions at CHARM

- **GCR heavy ion spectra** typically peak at **several hundred MeV/n**, whereas ground tests at **standard facilities** are carried out at **~10 MeV/n** (e.g. ranges limited to ~100 um in Si)
- At CHARM, heavy ion tests at GeV/n energies are possible, providing mid-LET ion with very **large penetration** (in the mm range) and therefore enabling access to sensitive region of complex components (e.g. flip chips)
- Currently collecting declarations of interest from space community (ESA, CNES…) and a first run might be possible in 2017

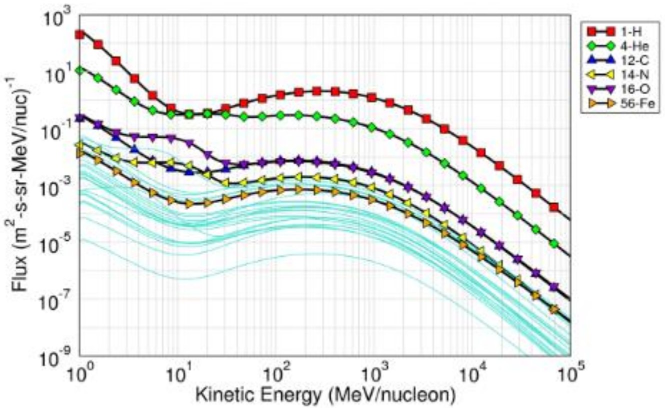
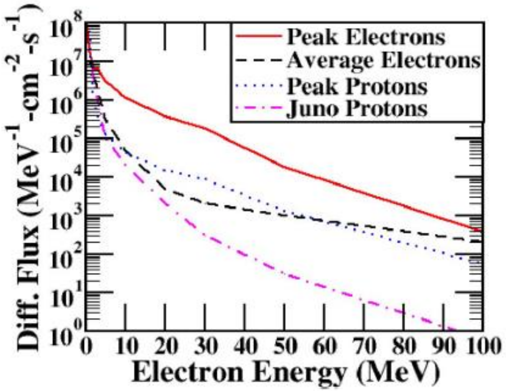


Table 1. 9.3 MeV/amu cocktails (M/Q≈3.7, ‡M/Q≈3.3).

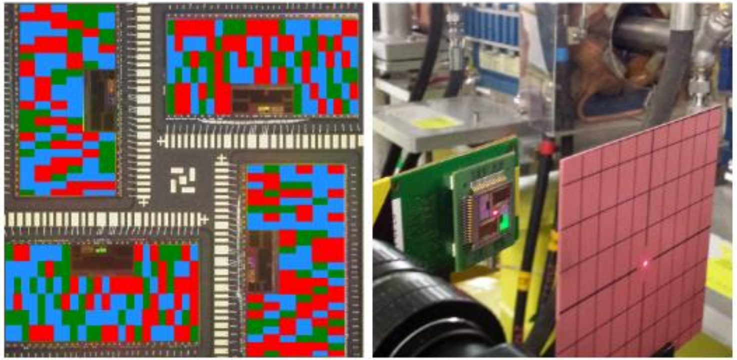
Ion	Energy [MeV]	LET^{MEAS} @surface [MeV/mg/cm^2]	LET^{MEAS} @Bragg peak [MeV/mg/cm^2]	*LET^{SRIM} @surface [MeV/mg/cm^2]*	*Range^{SRIM} [microns]*	*LET^{SRIM} @Bragg peak [MeV/mg/cm^2]*
$^{15}N^{+4}$	139	1.87	5.92 (@191 um)	*1.83*	*202*	*5.9 (@198 um)*
$^{20}Ne^{+6‡}$	186	3.59	9.41 (@138 um)	*3.63*	*146*	*9.0 (@139 um)*
$^{30}Si^{+8}$	278	6.53	13.7 (@114 um)	*6.40*	*130*	*14.0 (@120 um)*
$^{40}Ar^{+12‡}$	372	10.07	18.9 (@100 um)	*10.2*	*118*	*19.6 (@105 um)*
$^{56}Fe^{+15}$	523	18.59	29.7 (@75 um)	*18.5*	*97*	*29.3 (@77 um)*
$^{82}Kr^{+22}$	768	31.21	41.7 (@68 um)	*32.2*	*94*	*41.0 (@69 um)*
$^{131}Xe^{+35}$	1217	57.36	67.9 (@57 um)	*60.0**	*89**	*69.2 (@48 um)*

VESPER: 200 MeV electrons for radiation testing

- High intensity **200 MeV electron** linac, mainly motivated for **Jovian environment** application (e.g. JUICE)
- Facility currently under calibration for radiation effects test purposes
- Preliminary results: SEUs observed in 0.25 um SRAM technology (~3 $MeVcm^2/mg$ LET threshold) and are attributed to electro-nuclear events
- Open to external users! (contact: ruben.garcia.alia@cern.ch)



J. M. Trippe et al, IEEE TNS (2016)



M. Tali et al, submitted to RADECS 2016

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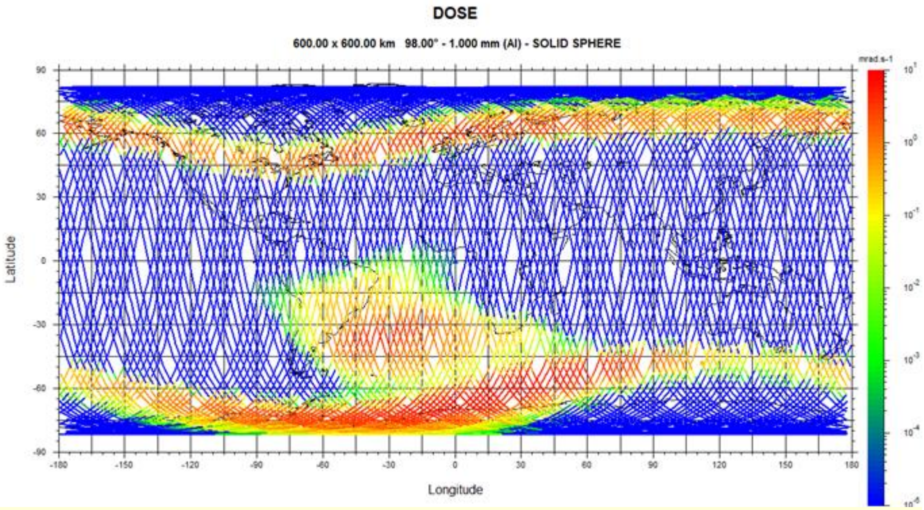
CHARM space applications: CELESTA

- CELESTA (CErn Latch-up Experiment STudent sAtellite) is a fully approved 1U CubeSat project
- Issued by a collaboration between CERN (providing the payload) and the Montpellier University space Center (CSU) providing the platform based on the ROBUSTA heritage
- Main objectives:
  - Technical: develop and validate a **cubesat** radiation monitor based on CERN's **RadMON**
  - Scientific: determine **proton and HI induced SELs** through geographical correlation and compare with predictions from **CHARM tests**

CSU Montpellier - Nîmes

CELESTA orbit



	Dose		Proton flux [p/cm-2/h-1]	#SEL over 2 years			#SEU over 2 years
	Dose rate [Gy/h]	TID [Gy]		HI	Protons	Total	
Circular	9.06	160	1.93E5	425	470	895	2500
Elliptical	16.55	290	2.41E6	430	2700	3130	14000

A. Merlenghi et al, 4S conference (2016)

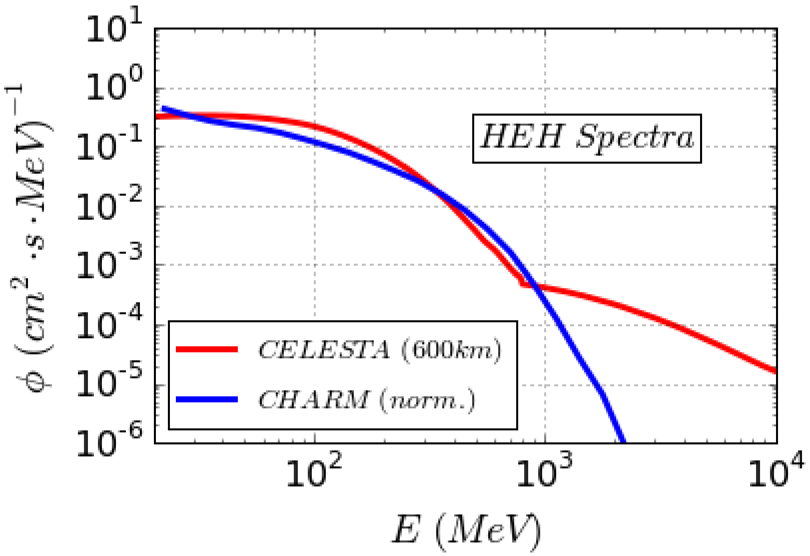
- Two baseline orbit scenarios: circular (600 km, 98º) and highly elliptical (300 x 1400 km, 99º)
- In both cases, the expected number of SELs for the candidate SRAM memories are statistically meaningful

SEL detection and protection system for CubeSats

- **COTS based, low-cost, low-power and radiation tolerant**
- Use of an ADC for continuous power consumption monitoring results in a power consumption for affordable for cubesat power budget
- Analog circuit (difference amplifier + voltage reference) + counter on FPGA can be used instead
- **Tested at CHARM**, yielding SEL cross section measurements compatible with previous results using “standard” SEL detection approach
- TID tolerant for CELESTA mission

R. Secondo et al, submitted to RADECS 2016

Correlating CHARM with space

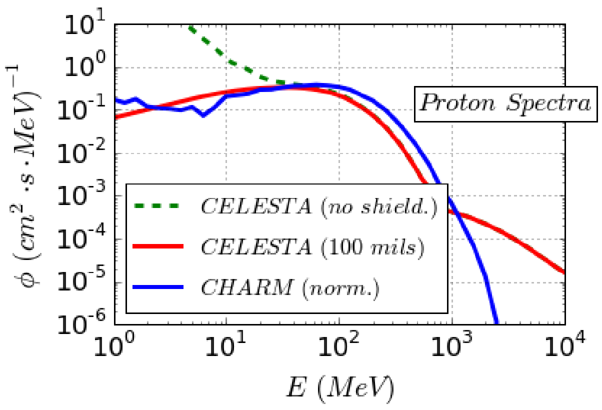


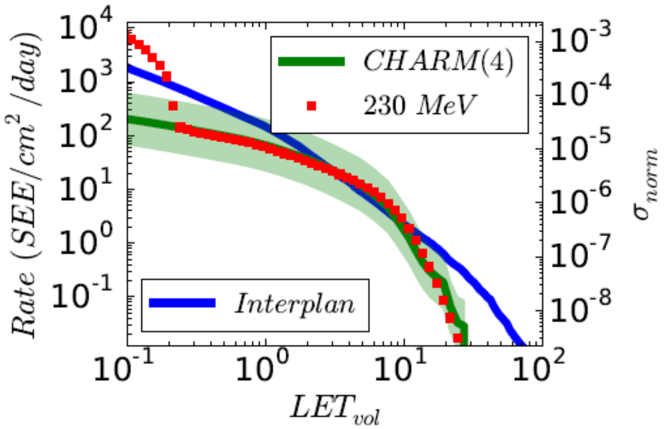
Acceleration factor at CHARM: $2 \cdot 10^4$

- The **HEH spectrum** at CHARM (protons, neutrons, pions) closely resembles that of the trapped proton belt
- Under the assumption of SEEs induced by indirect energy deposition, hadrons can (in first approximation) be considered as identical particles, therefore CHARM HEH cross sections can be used to obtain **in-flight trapped proton SEE rates**

Correlating CHARM with space (II)

- Possible applications for **direct ionization form singly charged particles** (left) or **heavy ion effects** pre-screening (right) but different metrics (as opposed to HEH approach) are required!





RADECS 2017 at CERN

Looking forward to seeing you there!

Many thanks for your attention, and questions are welcomed!

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