CERN

FCC Special Technologies Workpackage

Task 11: **Radiation Hardness Assurance**

Status Report April 2017

http://indico.cern.ch/event/558539/

Previous status reports:

June 2016
https://indico.cern.ch/event/539360/

April 2017:
https://indico.cern.ch/event/632320/

Giulio Borghello, Markus Brugger, Mar Capeans, Francesco Cerutti, Salvatore Danzeca, Federico Faccio, Ruben Garcia Alia, Georgi Gorine, Angelo Infantino , Michael Moll, Federico Ravotti

FCC Special Technologies WP
Task 11 Radiation Hardness Assurance

- RHA consists of all activities undertaken to ensure that the electronics and materials developed for FCC perform to their design specifications after exposure to the FCC radiation environment.
- RHA deals with environment definition, part selection, part testing, radiation tolerant design, and FCC subsystems requirements.

  - TASK 1 Field conditions and radiation levels at FCC
  - TASK 2 FCC Qualification Protocols, evaluation of test facilities
  - TASK 3 Equipment needs for the accelerator, particle detectors and service systems; strategies for RHA taking into account maintenance, reliability and remote operation
  - TASK 4 State of the art and development efforts on radhard components for HL-LHC (assuring continuity: evaluation of HL-LHC VS FCC needs, identify common VSs specific developments).
  - TASK 5 New Technologies: developments linked to technologies: wireless communication, miniaturization, optical transmission, compactness, on-chip optical/electrical, packaging, new materials…

Tasks & Deliverables (Oct'15 – Dec'18)

FCC Task 11	Deliverables	Month	By end of	Status	WHO
TASK 1 Field conditions and radiation levels at FCC	D1-1. Evaluation of FLUKA models' needs (environment and effects)	M6	Mar'16	✓	MB, AI
	D1-2. FLUKA tuning for FCC (operational/layout options/requirements)	M12	Sep'16	✓	MB, AI
	D1-3. Agreement on FCC target radiation field/levels	M14	Nov'16	✓	MB, RG
TASK 2 FCC Qualification Protocols	D2-1. Define overall FCC qualification requirements as input to RHA	M12	Sep'16	ongoing	All
	D2-2. Evaluation of current irradiation facilities and testing infrastructure	M20	May'17	ongoing	FR, GG
TASK 3 Equipment needs for the accelerator, detectors, service systems	D3-1. Identification of technologies used at FCC with their expected radiation levels	M14	Nov'16	starting	All
	D3-2. Catalogue of critical equipment (technology, supplier, function, etc.)	M18	Mar'17	starting	All
TASK 4 Development efforts on radhard components for HL-LHC	D4.1 Evaluate HL-LHC VS FCC needs of rad hard components	M20	May'17	ongoing	All
TASK 5 New Technologies	D5.1 Prototype status and definition of developments linked to technologies	M20	May'17	ongoing	All
	D5.2 Radiation tester_of advanced components/systems	M36	Sep'18	ongoing	MB, SD
	D5.3 Radiation sensor	M40	Jan'19	ongoing	FR, GG

RHA Resources - Personnel

Funded by FCC

Category	Budget (PM)	Committed	Available
Fellow	30	24 A.Infantino EN-STI (from 1/2/16)	6
Doctoral	60	36 G.Gorine EP-DT (from 1/11/15) 24 G.Borghello EP-ESE (from 1/8/16)	0
PJAS	30	6 m (1/1/16 – 30/7/16)	23

→ 6m extension Infantino

→ Intention:
11m PJAS + R2E contribution
12m extension Borghello

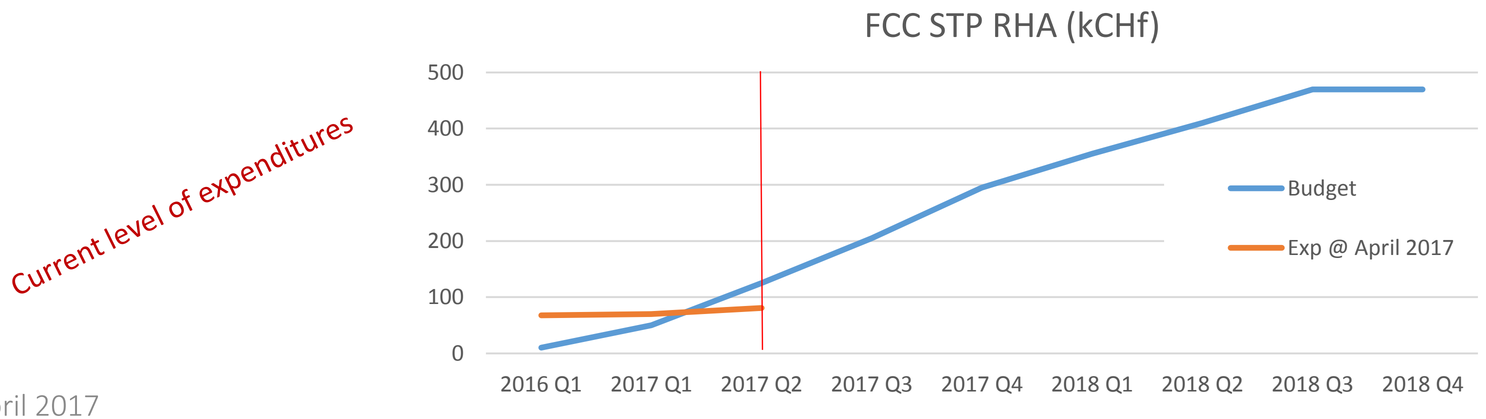
CERN personnel at 5-10% level:

- EN Dept: M.Brugger, S.Danzeca, R.Garcia Alia, F.Cerutti, A.Lechner
- EP Dept: F.Faccio, F.Ravotti, G.Pezzulo, M.Moll
- TE Dept: M.Capeans

- Many links to other FCC WPs and R2E

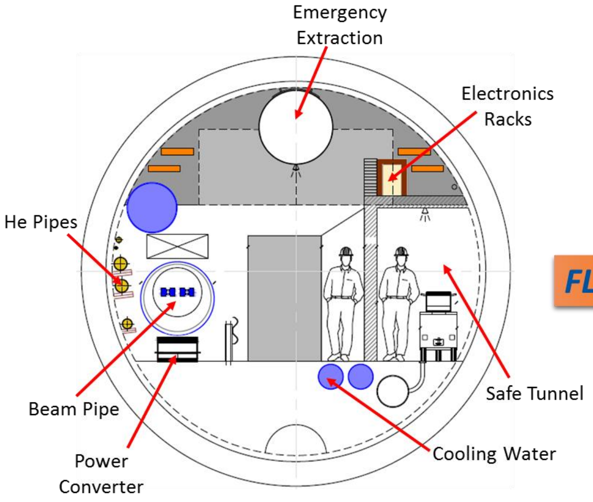
RHA Resources – Materials (B.C. 10811)

		Budget	Spending Profile									Budget
			2016	2017				2018				Apr.17
Task	Activity		Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
1	FLUKA/TCAD/Spice model development	50			25				25			50
2	Evaluation of irradiation and testing infrastructure	210		20	20	20	90	20		40		144
	Probe station (GG)		-66									
5	Development of a radiation tester	60			30				30			60
5	Development of radiation sensor, others	90	10	10		40		20		10		75.6
	Neutron Irradiation at JSI Triga Reactor (GG)				-6.3							
	Materials (GG)		-1.7	-2.4	-4							
5	R&D on materials radiation damage	60		10		20		20		10		-30
	Microelectronics test structures (FF)					-45		-45				
		470										249.6

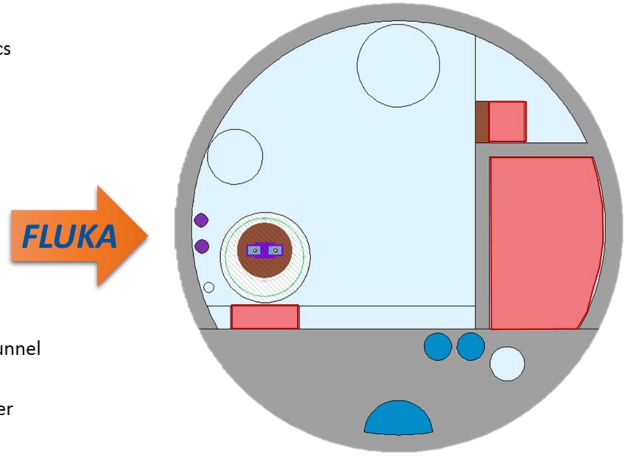


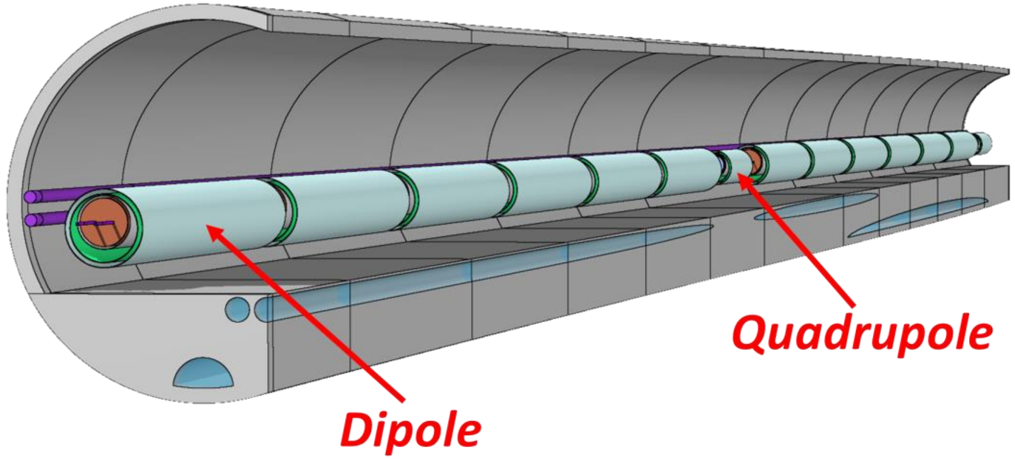
FCC FLUKA Radiation level assessment: 2016

- ✓ Considerable amount of work done in 2016 within the FLUKA team in the FCC framework
  - ❑ Scaling from LHC
  - ❑ FLUKA MC simulations of a full arc cell
- ✓ FLUKA model of the first design of the arc section
  - *ϕ_{int}=6 m single tunnel*
  - *2x* Proton beam *50 TeV/c*
  - *12 dipoles* (14.3 m) + *2 quadrupoles* (6.3m); Total length *~213 m*
  - (Tentative) *Gas-density profile (courtesy of R. Kersevan)*
- ✓ Assessment of the radiation levels in critical areas for electronics
  - *Dose* -> Cumulative Effects
  - *Fluence*: p, K, π, μ, n, High Energy Hadrons (HEH, >20 MeV) -> Single Event Effects



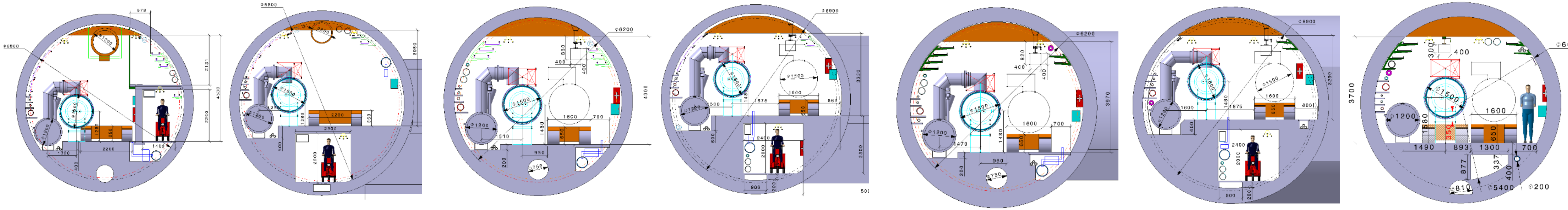
[Courtesy of V. Mertens - Civil Engineering]





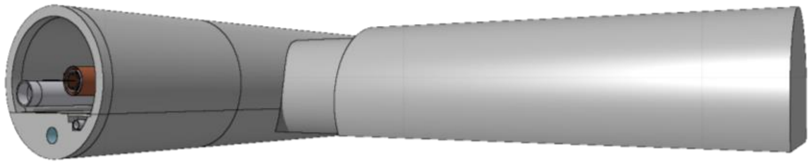
FCC FLUKA Radiation level assessment: 2017

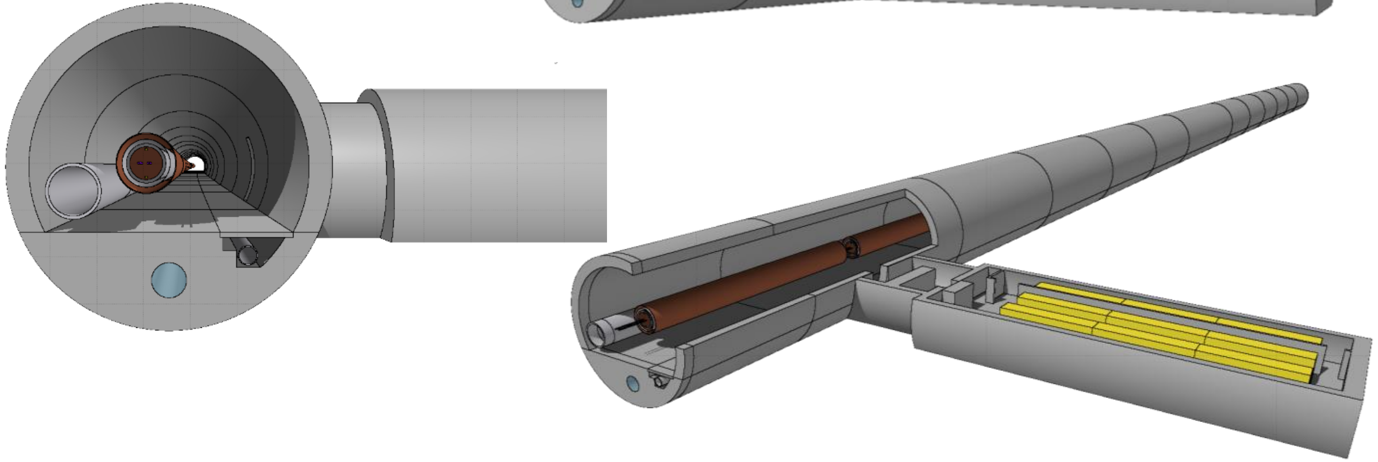
January 2017 — *February 2017* — *March 2017* — *April 2017*



[Courtesy of Fani Valchkova-Georgieva (EN/INT)]

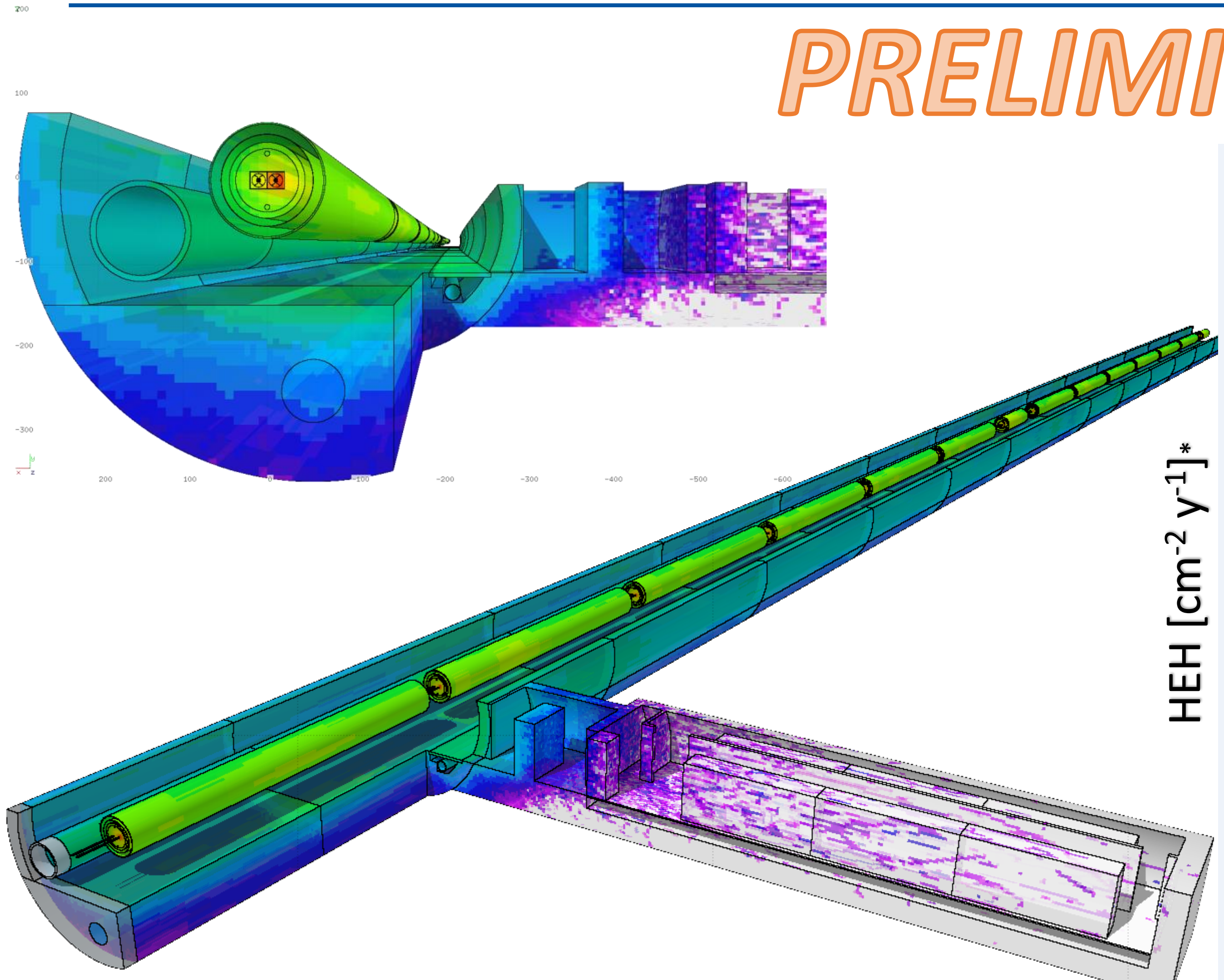
- New layout of the *tunnel*
- First tentative layout of the *alcove* (maze + sliding door)
- Latest design of the *main dipole*
- Up-to-date tentative *gas-density profile*
- *DPMJET* development: *[Courtesy of Francesco Cerutti]*
  - Nuclear reaction at FCC energies

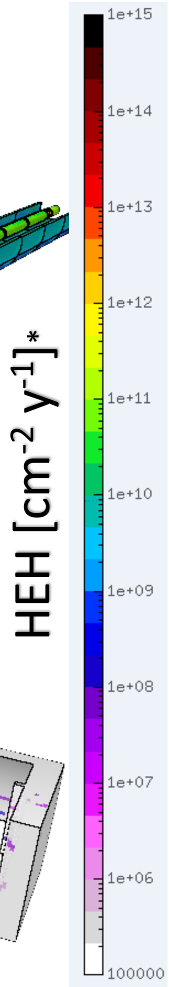


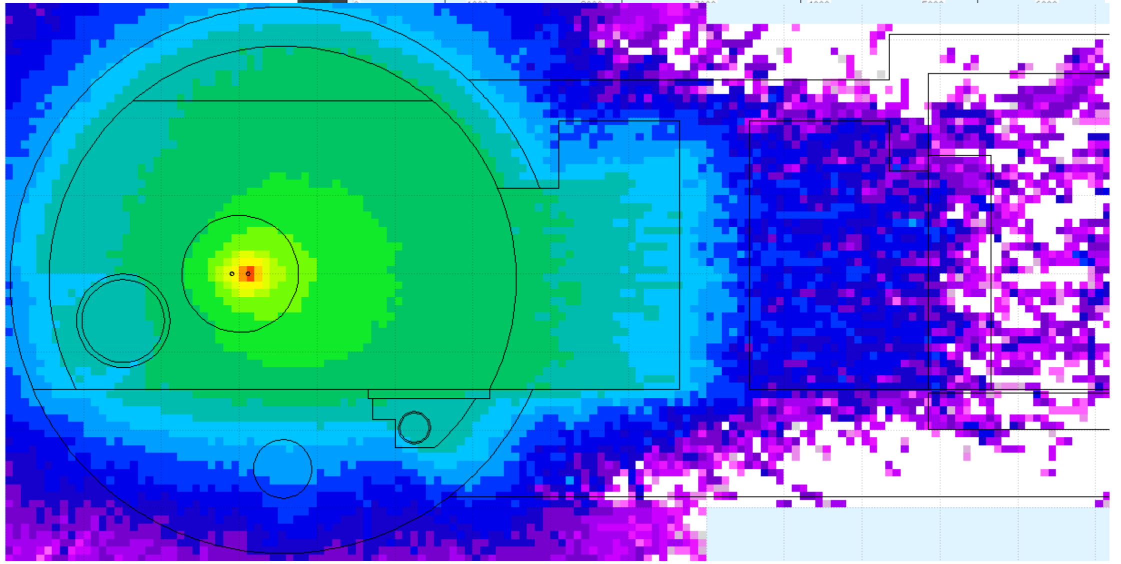


FCC FLUKA Radiation level assessment: 2017

PRELIMINARY







All the plots share the same scale
** Normalized to 10^7 seconds of operation*

Tasks 2 & 3: Qualification & Protocols & Equipment needs

Defining first rough qualification levels

- **Tunnel** (FCC as compared to HL-LHC): close to beamline and adjacent, missing: high-loss locations (e.g, collimators, etc.) -> scaling most likely similar as for the tunnel
- **Equipment availability**: impact on the qualification requirements of components/systems

  Starting from a general 'maximum' and 'relative' unavailability possibly to be tolerated by R2E

  maximum: 10% of unavailability -> thus defining test/qualification constraints

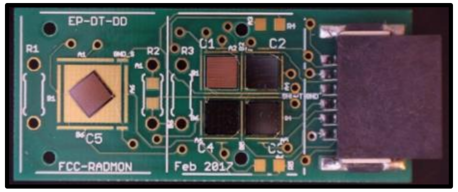
Defining RHA strategy for new developments and known equipment/system changes (R.Garcia Alia):

- 'Frozen' tunnel design - first radiation level 'matrix' for typical tunnel section (in very good agreement with original estimate based on 'first principles')
- The approach is that we'll face a LHC-like situation with similar equipment groups
- Knowledge on existing 'inventories' from the LHC and discuss what will most likely have to remain in radiation areas or relocated into safe places: critical equipment inventory and availability implications
- Showing that for a COTS-based design we hit a boundary with the current qualification procedure and available testing facilities

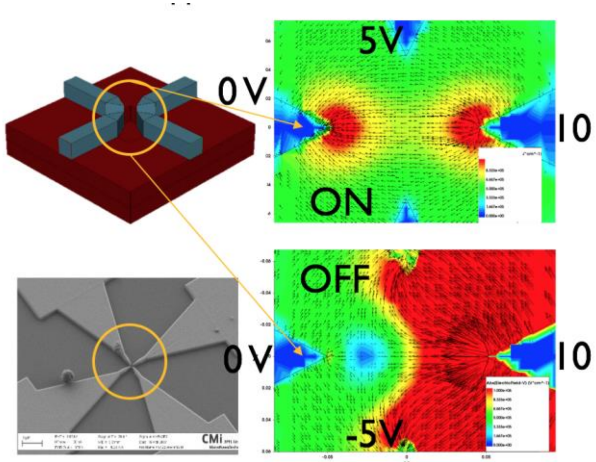
Tasks 2 & 3: Qualification & Protocols & Equipment needs

Evaluating specs of irradiation facilities for FCC and test infrastructure:

- **Irradiation Facilities DB: http://irradiation-facilities.web.cern.ch**



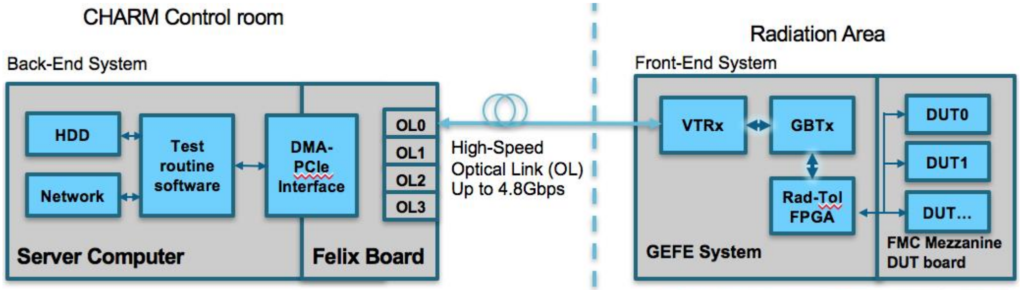
FCC-RADMON



Vacuum Transistor (VFET)

- **MGy dosimetry** (F.Ravotti, G.Gorine)
  - Analysis of state-of-the-art technologies for radiation measurement
  - Study of existent RADMON sensors at LHC, development for FCC
  - Design, realization, and testing of an innovative dosimetry solution for ultra-high fluences

- **High-speed Readout for mixed-field irradiations** (S.Danzeca)
  - Collaboration between EN-STI, BE-BI, EP-DT
  - First test this year in CHARM



Tasks 4&5: Technologies

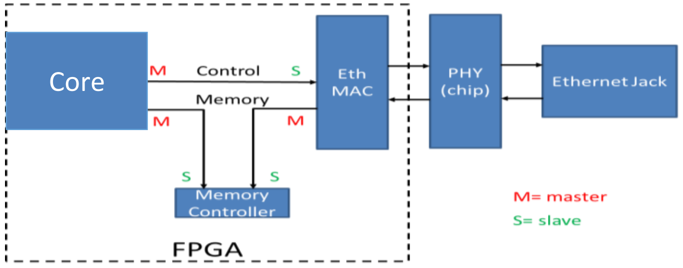
Strategy

- Impossible to know technology in 20+ years, but we can study concepts relevant for future strategies as redundancy/qualification can likely be ported to future technologies, facilitating design choices.
- We study and develop building blocks of multiple high-end solutions.

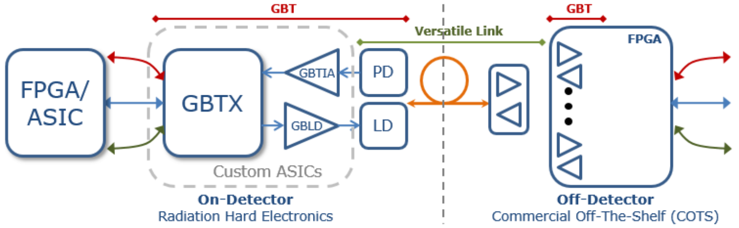
Technology Demonstrators

- **Communication links** (S.Danzeca)
  - Ethernet- based FPGA/PHY solution similar for the fibre based solution (GBTX and VTTx) combined with FPGA/ASIC design
  - Fiber-optic based: Basic building blocks taking as an example the GBTx CERN development
  - Wireless solutions, 'early R&D’: gathering necessary requirements for a wireless network structure and specifications, focus on assessing possible induced failures due to the radiation

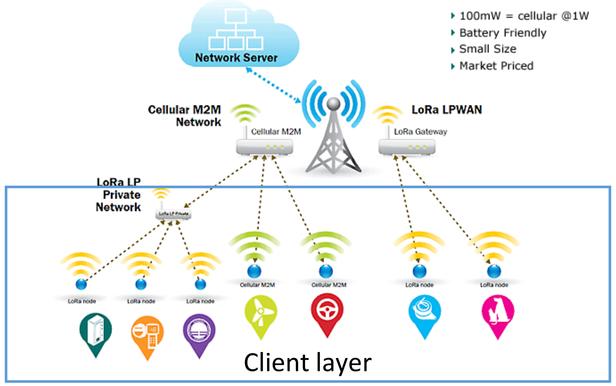
Speed 10-100Mbit/s up to 1Gbit/s



Speed 5-10Gb/s (>10Gb/s)

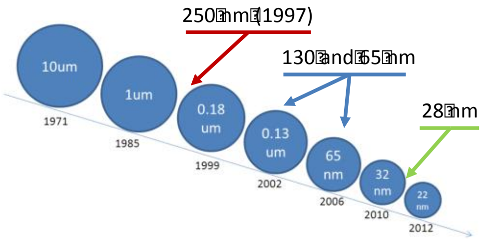


Speed (Wifi) ~1Gb/s



Technology Demonstrators

- **Deep submicron CMOS technologies** (F.Faccio, G.Borghello)



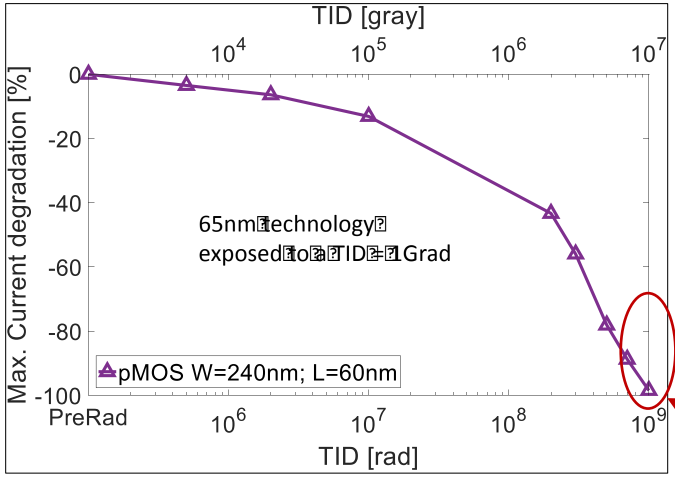
❑ The technology node is defined by the minimum channel length (L).

❑ The technology currently used in the LHC experiments is the 250nm.

❑ LHC upgrades will increase the Total Radiation Dose that detectors and devices have to withstand.

❑ We are mainly studying the 65nm technology, that has been proposed for the new pixel detectors used in the HL-HLC and we started to investigate the radiation response of 28nm MOS technology.

❑ Irradiation strongly affect CMOS 65nm performances.



❑ In HL-LHC pixels of inner layer will be exposed at TID = 1Grad in 10 years.

❑ At 1Grad the 65nm technology shows an extreme degradation of its main parameters.

65nm pMOS
$\Delta_{ON} \cong 100\%$

- The study of 65nm radiation-hardness is at an advanced stage. Confirmed strong dependency on irradiation, and unexpected dose rate dependence (lower dose ~ larger degradation) and understood the physical processes
- The firsts experiment at 28nm MOS show also large parameters degradation

Detailed Reports

24/4/2017 Meeting FCC Special Technologies Workpackage: Task 11 progress reports

https://indico.cern.ch/event/632320/

FCC Special Technologies Workpackage: Task 11 progress reports

Monday 24 Apr 2017, 15:00 → 16:30 Europe/Zurich

30-6-019 (CERN)

Mar Capeans Garrido (CERN)

Description Meeting to review the FCC RHA task status

- Overview of current resources (P&M)
- Reminder of milestones and deliverables
- Review of technical progress in the different areas, each presentation includes current status, planned work and view on resources for 2017 and 2018
- Discussion of work ahead, and plans for FCC CDR
- Reminder of presentations at the FCC week in Berlin

LINK TO PREVIOUS MEETING & REPORT: https://indico.cern.ch/event/539360/

15:00 → 15:10 **Task goals, status of resources, upcoming deliverables** 10m

Speaker: Mar Capeans Garrido (CERN)

WP11_April17.pdf WP11_April17.pptx

15:10 → 15:20 **Status R2E-related studies on FCC** 10m

FCC radiation environment:
o FLUKA geometry model update (focus CE layout) and first target levels
o in agreement with Francesco/Ruben to comment on the FLUKA model needs and on-going efforts in terms of the nuclear models/updates

Speaker: Angelo Infantino (CERN - EN/EA)

20170424_FCC_R... 20170424_FCC_R...

15:20 → 15:30 **Communication link strategies/ingredients** 10m

Speaker: Salvatore Danzeca (CERN)

FCC meeting April ... FCC meeting April ...

15:30 → 15:40 **Status studies on deep submicron CMOS technology** 10m

Speaker: Giulio Borghello (Universita degli Studi di Udine (IT))

2017_04_24 - FCC ... 2017_04_24 - FCC ...

15:40 → 15:55 **Status MGry dosimetry sensor and Irradiation Facilities Evaluation** 15m

Speakers: Federico Ravotti (CERN) , Georgi Gorine (Ecole Polytechnique Federale de Lausanne (CH))

20170424_FCCme... 20170424_FCCme...

15:55 → 16:10 **Missing efforts wrt initial program** 15m

- Critical equipment: knowledge on existing 'inventories' from the LHC and discuss what will most likely have to remain in radiation areas and what could possibly be relocated into safe places. Some words on critical equipment inventory and availability implications
- FCC radiation qualification requirements: view on the recently drafted qualification procedure (Salvatore) and evaluate if this can be presented as FCC baseline approach
- Radiation tester; report on the results of combined component/batch and system tests performed at CHARM, as well as options for more complex tester developments.

16:10 → 16:20 **Recap and organisation of work ahead** 10m

From FCC Week 2017 to the CDR

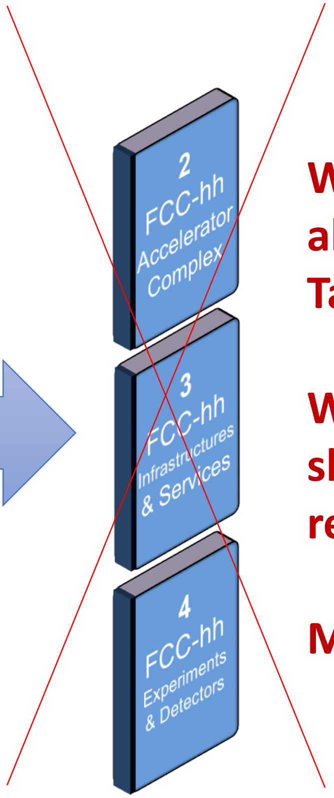
2 oral
1 poster

Special Technologies sessions

- ✓ Status overview of the radiation hardness assurance studies for FCC (Wed 31/05)
- ✓ FLUKA Monte Carlo modelling of the FCC arccell: radiation environment and energy deposition due to beam-gas interactions (Thu 01/06)
- ✓ Radiation Monitoring Technologies and Irradiation Test Facilities for FCC

12 CDR volumes (9 + 3 annexes)

From M. Benedikt's presentation in FCC CGM #39 7.10.2016
https://indico.cern.ch/event/547867/



We favor a unique chapter summarizing all RHA aspects being tackled in FCC STP Task 11

We will include a summary for identified showstoppers and clear long-term R&D requirements (beyond CDR)

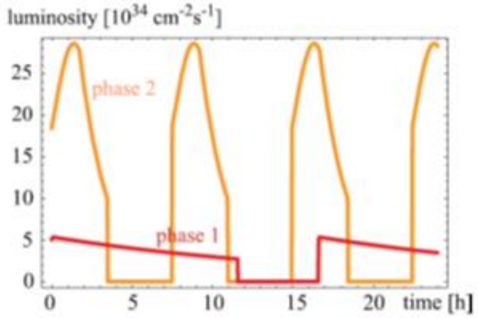
Min 25 pages, Max 40 pages

SPARES

General R2E/availability considerations

[Courtesy of Ruben Garcia Alia]

- *Integrated luminosity target*: 20 ab^{-1} in 3.5 yr periods of 5 ab^{-1} (1.5 yr long shutdown)
- *Burn-off* is expected to be extreme, with stable beams lasting ~3h
- Therefore, turnaround time needs to be very small: best reasonably achievable is ~3h (~50% maximum efficiency), thus need to minimize *R2E downtime*
  - *Injector availability* will therefore be crucial (LHC or superconducting SPS)



"Availability studies for FCC", Arto Niemi

- Availability working group: *accelerator unavailability* (failure rate times recovery time) budget will be given *by system*
- A part of this unavailability will be allocated to *R2E* (roughly *10%* but to be studied per system)
  - to then be translated to target failures per unit luminosity and respective *target system cross sections* through *radiation levels*
  - Critical points: *system-level testing approach*, no guidelines/standards available (link with *RADSAGA* training network), redundancy

Integration of R2E with the different WG

- ✓ Work fully integrated in the *FLUKA team* of EN/STI where additional resources (Ilaria Besana, Fellow) are specifically dedicated to different FCC studies, in particular concerning *lifetime assessment for detector components*.

- ✓ Strong presence in the *Infrastructure & Operation* and *Integration* WG

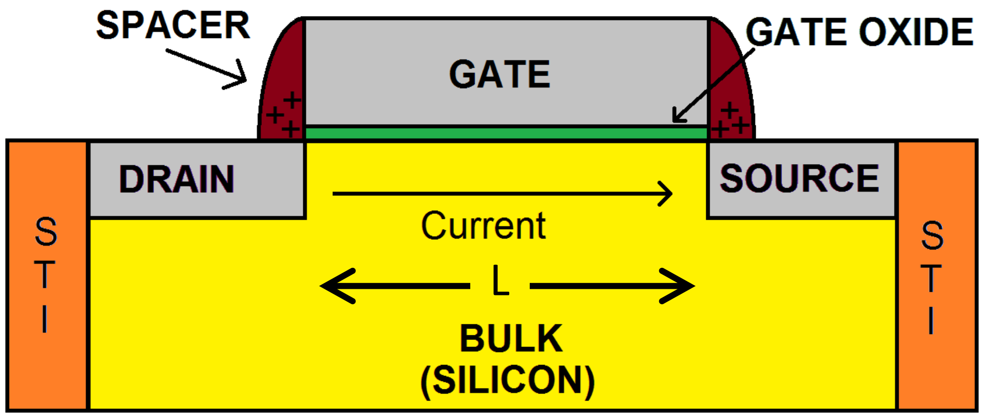
- ✓ Collaborations across many different groups
  - Daniel Schoerling (TE-MSC), Barbara Caiffi (INFN) -> *Magnets*
  - Volker Mertens (TE), Fani Valchkova-Georgieva (EN-ACE-INT) -> *Civil Engineering Design, Integration*
  - Valentina Venturi (TE-MSC-CMI) -> *Cryostat design*
  - Roberto Kersevan (TE-VSC-VSM), Ignasi Bellafont (TE-VSC-VSM) -> *Gas-density profile, beam screen design*
  - Davide Bozzini (EN-EL-DDO), Maria Mylona (EN-EL-DDO) -> *Electrical requirements*
  - Andrea Apollonio (TE-MPE-PE) -> *Availability*
  - Ahmed Bannour (IT-CS-TR) -> *Data transmission requirements*
  - Cedric Garion (TE-VSC-DLM) -> *Beam screen design*
  - Barbara Dalena (BE-ABP-HSS) -> *Beam optics*
  - Markus Widorski (HSE-RP-AS) -> *RP-related*

"The total number of instrumented channels is about 80 million, each containing approximately 1,000 transistors".

[1] AAD, G., et al. ATLAS pixel detector electronics and sensors. *Journal of Instrumentation*, 2008

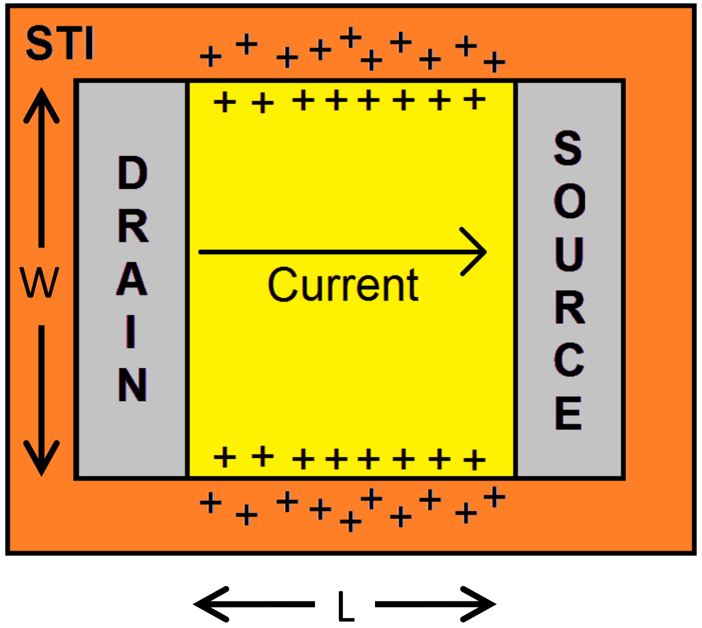
The most rad-sensitive part of the CMOS technology are the oxides.

- Gate oxide
- Shallow trench Isolation (STI)
- Spacers



MOS Cross Section

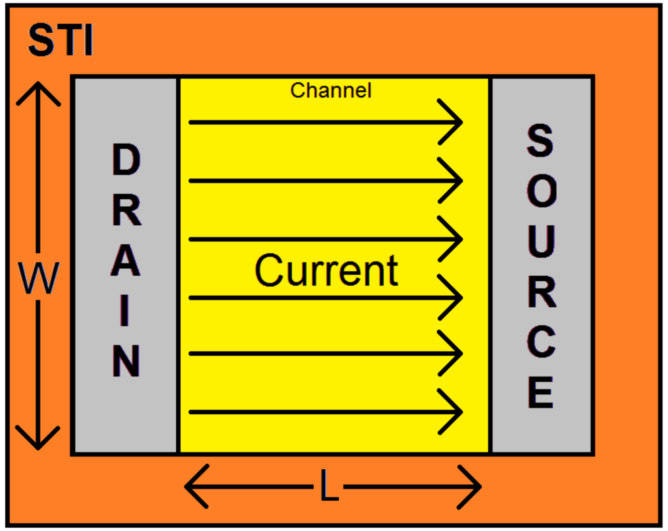
MOS Top View

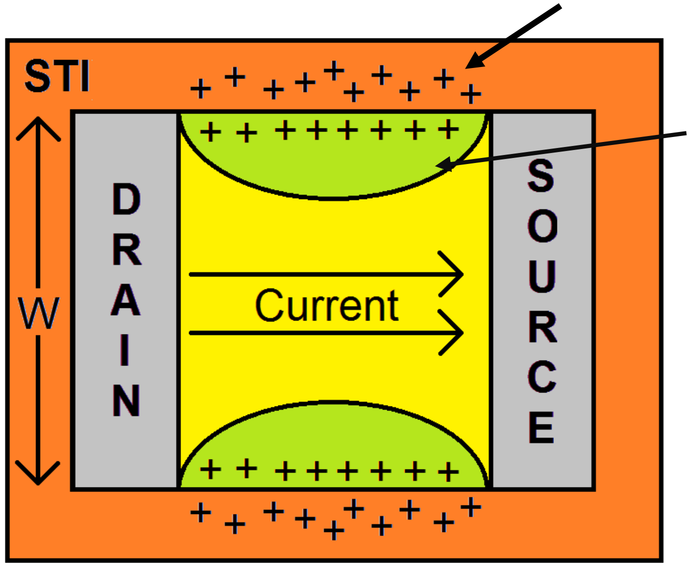


Radiation-induced charge may be trapped in the oxides and in the interface between silicon and oxides. If located near the channel, the charge can perturb the current.

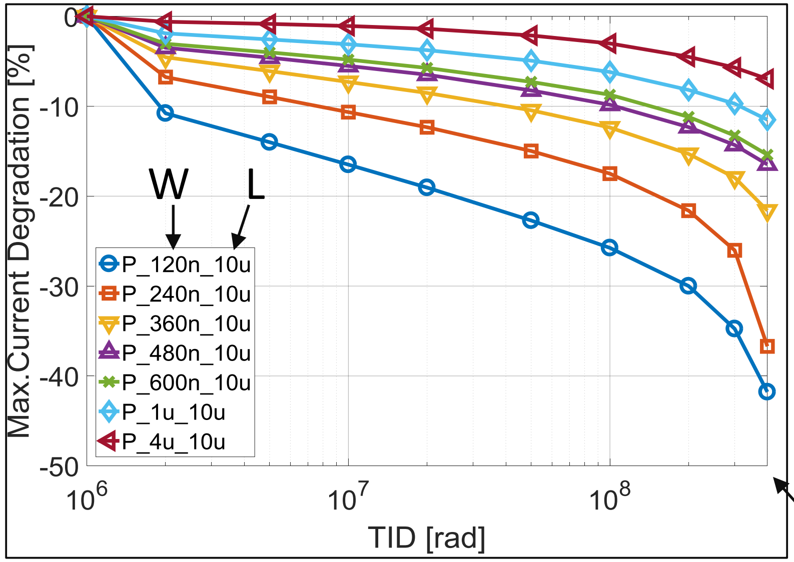
- W-dependent radiation effects:

Charge trapped in the STI reduce the effective W and the current.





Charge-induced electric field.

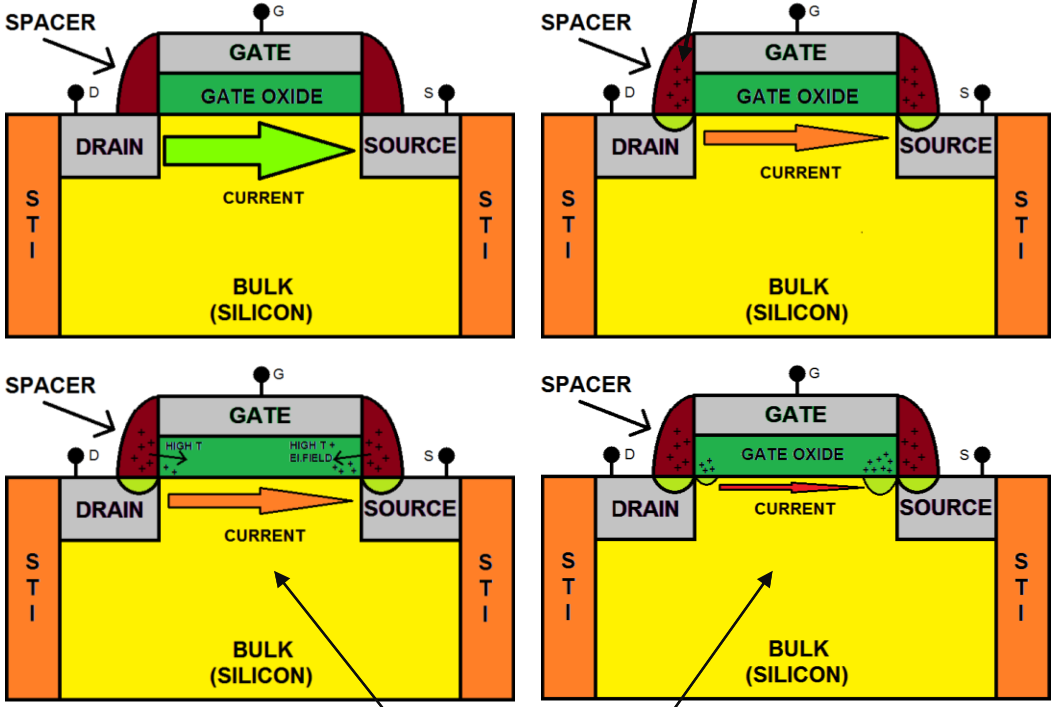


TID=400Mrad

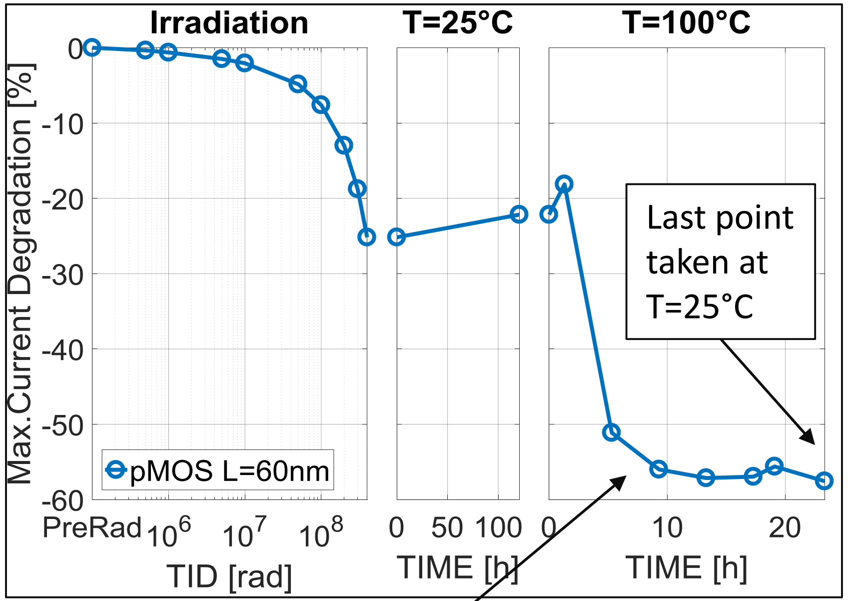
- Narrower channel show larger degradation
- We called this effects Radiation Induced Narrow Channel Effects (RINCE)

- L-dependent radiation effects (not trivial):
- The degradation of the current strongly depend on temperature and on applied electric field.

Charge trapped in the spacers during irradiation.

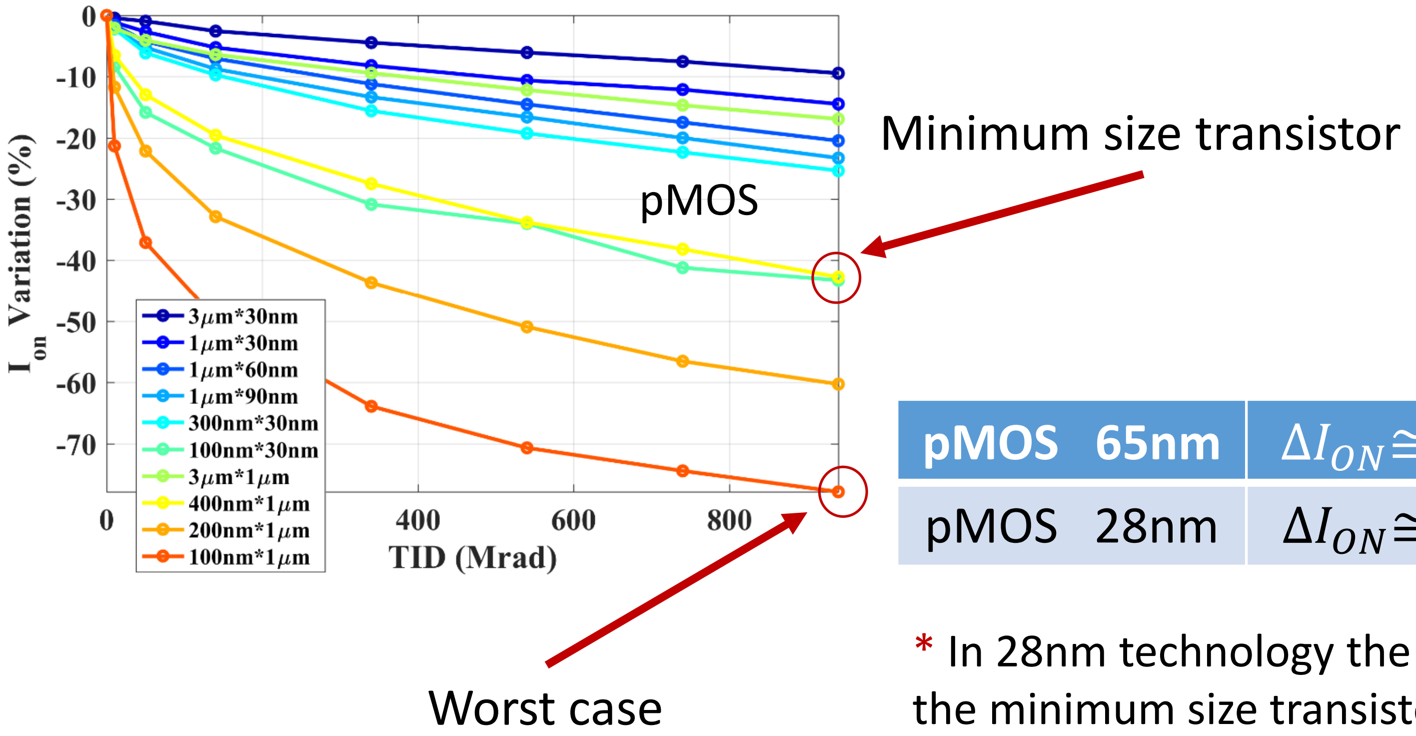


Trapped charges move into the gate oxide, interfering with the current flowing in the channel.



- Large and unexpected further degradation when high temperature and polarization are applied to an irradiated device.
- During irradiation:
  - The charge trapped in the spacers increase the series resistance.
- During annealing:
  - Charge moves into the gate oxides, increasing the threshold voltage.

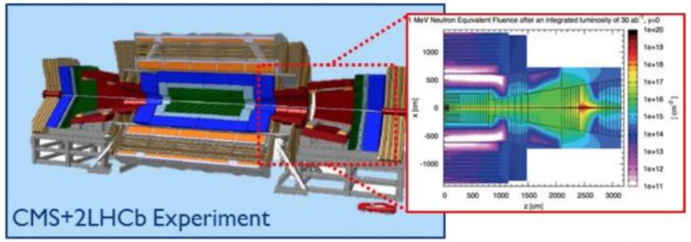
❑ We started to study the 28nm technology, in collaboration with EPFL (ICLAB) and INFN.



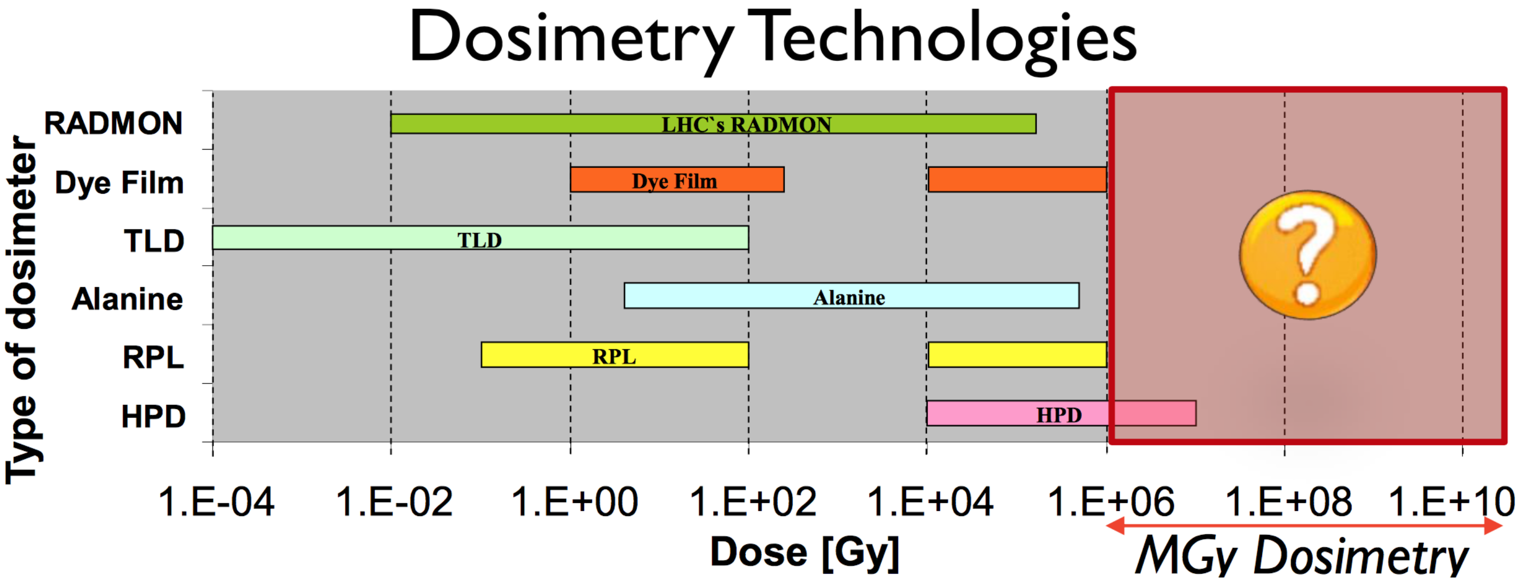
pMOS 65nm	$\Delta I_{ON} \cong 100\%$ (1Grad)
pMOS 28nm	$\Delta I_{ON} \cong 75\%$ (1Grad) *

* In 28nm technology the worst case is not the minimum size transistor, but the one with smaller W (100nm) and larger L (1μm)

Dosimetry

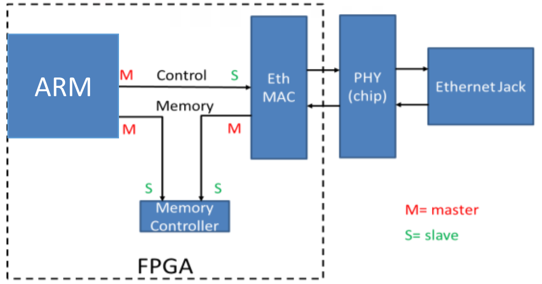


- **HL-LHC 3ab^{-1}** (Target for current IRRAD)
  - Fluence = 1.5×10^{16} cm^{-2} , Dose = 4.8MGy
- **FCC 3ab^{-1}**
  - Fluence = 2.8×10^{16} cm^{-2} , Dose = 9 MGy
- **FCC 30ab^{-1}**
  - Fluence = 2.8×10^{17} cm^{-2} , Dose = 90 MGy



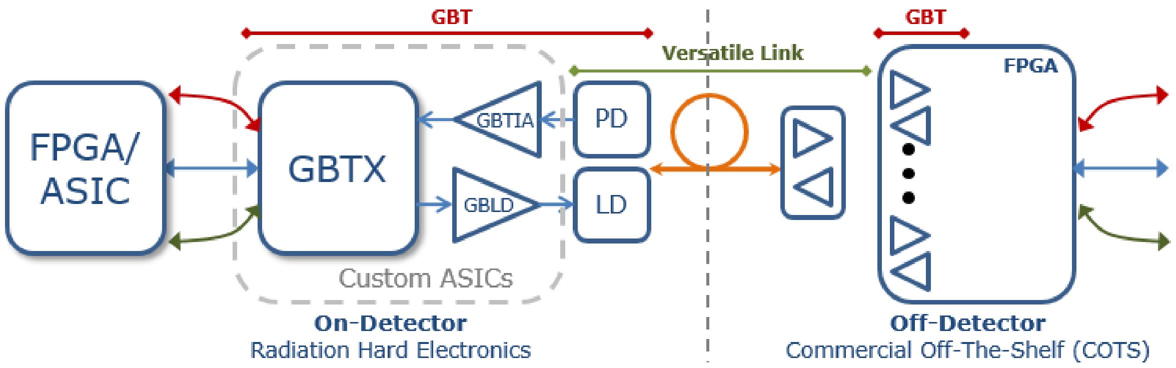
Ethernet based solutions

- Current status FPGA:
  - Several FPGAs/Microcontroller can be suitable for 10-100Mbit/s link.
  - 10-100 Mbit MAC can be implemented
  - Artix SRAM based FPGA and Flash based SmartFusion2 are under investigation for their tolerance and failure rate in radiation environment
  - Artix FPGA is Latchup free but several mitigation schemes should be applied for making the link robust. This solution could work in low radiation areas. The SRAM solution is not dependent on the Artix but the development methodology and mitigation techniques can be ported to any tolerant SRAM FPGA.
  - Flash based FPGA SmartFusion 2 has very low cross section for Latchup event. It can be used as an easy development tool for assessing the feasibility of the Ethernet link without applying complex mitigation scheme. It has the advantage of having hard-coded a ARM processor which can reduce the development time. Possible test of a very simple solution this year.
  - No solutions yet for the 1Gb/s link due to the necessity to have a radiation tolerant SERDES for the MAC implemented in the FPGA
- Current status Ethernet PHY:
  - On the track to join as partner a consortium for the development of a radiation hard PHY. The project name is Space Ethernet Physical Layer Transceiver (SEPHY) and it is an European project already started and leaded by TTECH and Arquimea. NDA signed, waiting for the inkind contribution. First tape out of the chip during this year.
  - In parallel we tested a 1Gb/s PHY under irradiation and we plan to make a radiation test on a 10/100Mbit during this year.
- On going path:
  - At the moment all the FPGA developments are based on a soft or hard core microprocessor which helped in verifying the functionalities of the link. But the soft,hard core are more prone to single events and the migration strategies are primitive.
  - The need is to develop a more robust structure on the FPGA which can be more easily mitigated
  - This solution can be ported to any FPGA also in the future.
  - **Resources needed**



Fiber Optic based solutions

- Fiber optic solution advantages:
  - Speed 5-10Gb/s (>10Gb/s)
  - Possible to cover very long distances (km)
  - Slow control signalling possible
  - Audio/video communication possible
- The topology of the network can be only point to point. The daisy chain is possible but two links should be implemented on the same card
- Basic building blocks taking as an example the GBTx CERN development



Ethernet based solutions

- Current status Transceiver:
  - GBTX 4.8 Gb/s Transceiver developed by EP is implemented in several boards and can be used as a baseline for all the developments. Long term support. RadHard by design
  - New version of GBTX for HL currently under development
- Current status Small Form Factor (SFP) Transceiver:
  - VTTx is a RadHard by design physical layer developed by EP
  - Current version provided by EP is multimode but a single mode is being developed for the accelerator sector thanks to a collaboration between EP and BE.
- Current status FPGA/ASIC:
  - Scalable Sensor Data Processor (SSDP) is a mixed-signal ASIC DSP processor
    - The design and development of the SSDP is an activity stemming from the European Space Agency and is supported by a consortium lead by Thales Alenia Space.
    - We are including in the SSDP the e-link interface with which we will be able to talk with the GBTX and have a RadHard by design DSP processor
- On going path:
  - At the moment the SSDP need a followup with the activities that Thales is going to do on the prototype.
  - First it will be necessary a verification of the inclusion of the elink in the design.
  - Then the SSDP should be tested in our environment with in mind some intense computing application
  - **Resource needed**