Development of Radiation Hard Semiconductor Sensor Devices for Tracking Detectors in Future Collider Experiments

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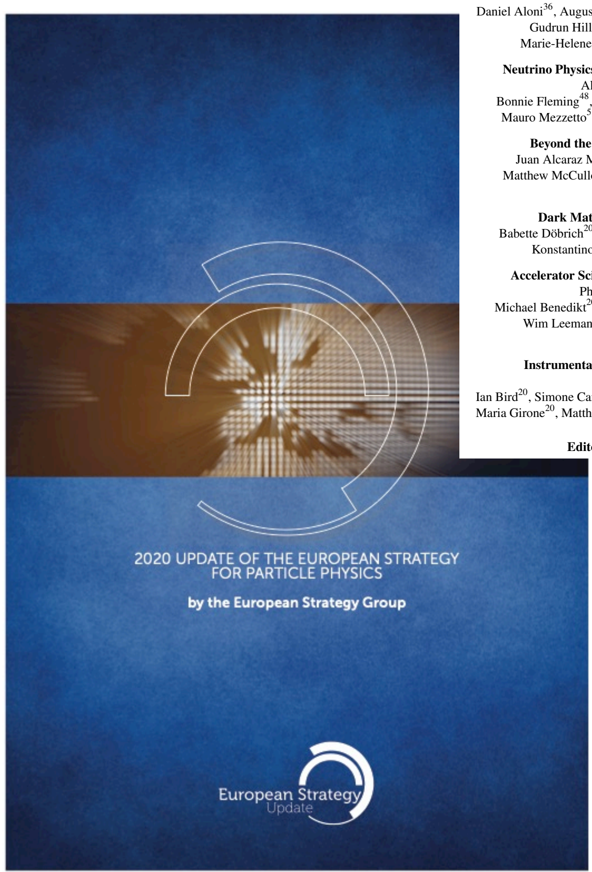
Beyond the HL-LHC: Future Colliders and Technology Challenges

- Radiation-hard semiconductor devices in the R&D forefront of sub-atomic physics community for 25 years
    - Led to construction of Si tracking detectors at the LHC and HL-LHC
- Focus shifting to meet the technology challenges for future colliders beyond the HL-LHC
    - ILC, CLIC, FCC-ee, CEPC, FCC-hh,…
- Extremely high radiation levels close to collision points
    - Will exceed 10^{17} n_{eq}/cm^2.
- Poses major challenges on semi-conductor technology
    - Material quality (defects, doping, radiation effects,…)
    - New materials beyond Si (which may reach its limitations)
    - Understand physics of radiation damage
        - And develop microscopic physics models
    - Sensor design, detector layouts, readout ASICs, data handling,…

2020 Update of European Strategy:

"Need to maintain a strong focus on detector R&D to be able to prepare and eventually realize experimental research programs."



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Physics Briefing Book

Input for the European Strategy for Particle Physics Update 2020

Electroweak Physics: Richard Keith Ellis[1], Beate Heinemann[2,3] *(Conveners)*
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R&D Aspects for Radiation-Hard Semiconductor Devices I

Theme 1: Radiation induced material defects, modelling, device characterization (Si)

- Calculate defect kinetics and the corresponding device parameters
  - Inform dedicated models for defect generation and evolution of clusters
- Assess the role of intentionally added impurities and identify optimal impurity concentrations
- Initiate and perform irradiation campaigns, short and longer-term annealing studies
  - Provide input to the models being developed
- Fabricate and test progressively more complex device structures using new defect engineered material
  - E.g., epitaxial wafers of various doping concentrations
- Develop a sustained program of macroscopic properties measurements
  - I-V characteristics, charge collection efficiencies,…
- Improve on the device characterization through the introduction of advanced experimental techniques
  - DLTS methods, Two-Photon Absorption (TPA), Edge-TCT techniques,…

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Theme 1 builds on the extensive infrastructure developed in Canada for the ATLAS-ITk project

- Leverages on the very significant CFI, NSERC and TRIUMF investment
- Ensures the continuous use of the developed infrastructure/equipment beyond the timescale of the ITk project

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Significant overlap with the ATLAS-ITk operational needs

- Detector aging, radiation damage, performance deterioration
- Detector response simulation/digitization, event reconstruction performance

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R&D Aspects for Radiation-Hard Semiconductor Devices II

Theme 2: New device structures and materials

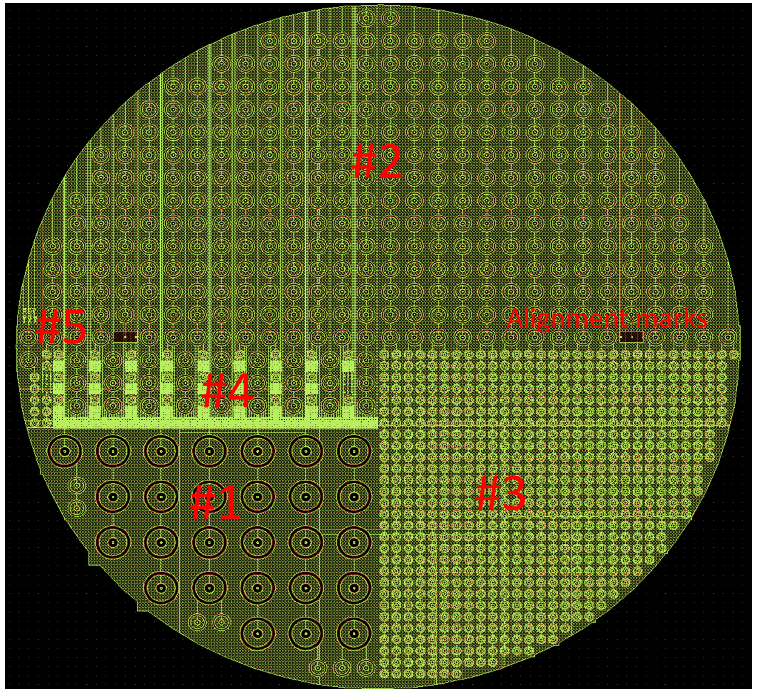
- Evaluate slim edge sensor designs for homogeneous signal readout
- Participate in the design, modelling and prototyping of sensors with intrinsic gain
  - Low Gain Avalanche Detectors (LGAD)
  - Couple spatial to temporal resolution to improve performance under high pileup conditions
- Design, modelling and fabrication of HV-CMOS monolithic large area devices
  - Evaluate performance with integrated radiation dose, high occupancy, process speed
  - Fabricate HV-CMOS monolithic large area demonstrator
- Study the feasibility of new GaN-based radiation-hard devices
- Contribute to the deployment of the Timepix-3 detector in the ATLAS experiment
  - Measure luminosity and induced radioactivity
- Contribute to the development of the Timepix-4 chips
  - Eventually to be deployed/tested in the HL-LHC

Theme 2 R&D to be pursued in parallel with that outlined in Theme 1

- Leverages on new collaboration with NRC
- Could allow for exploration of commercial/industrial applications

R&D Examples – Material Defects

Radiation Damage of Epitaxial p-type Si



RAL/ITAC

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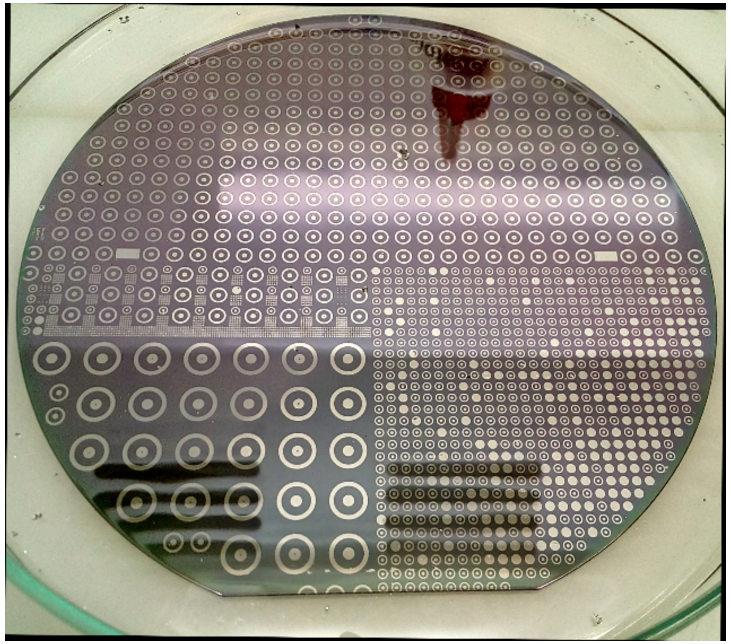
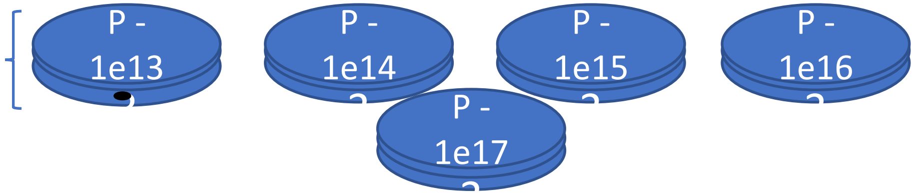
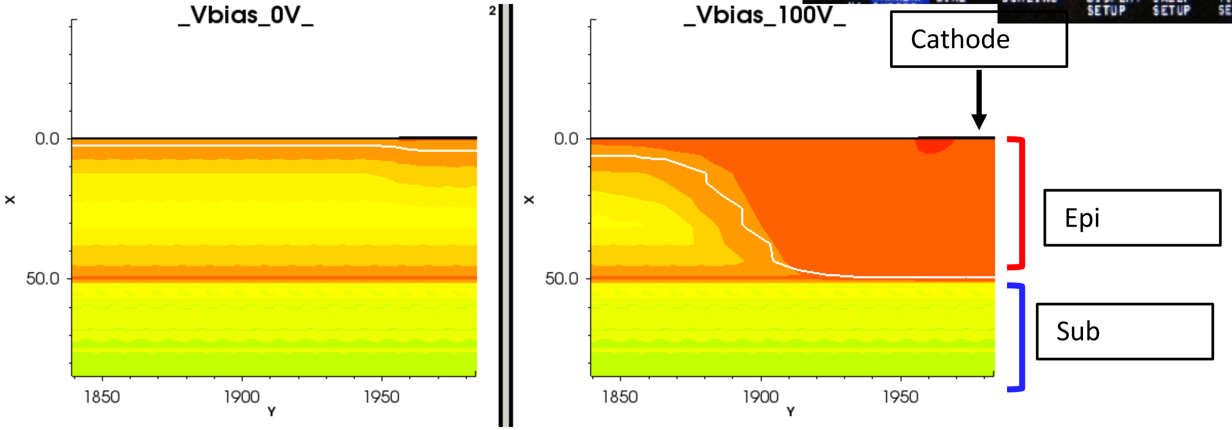






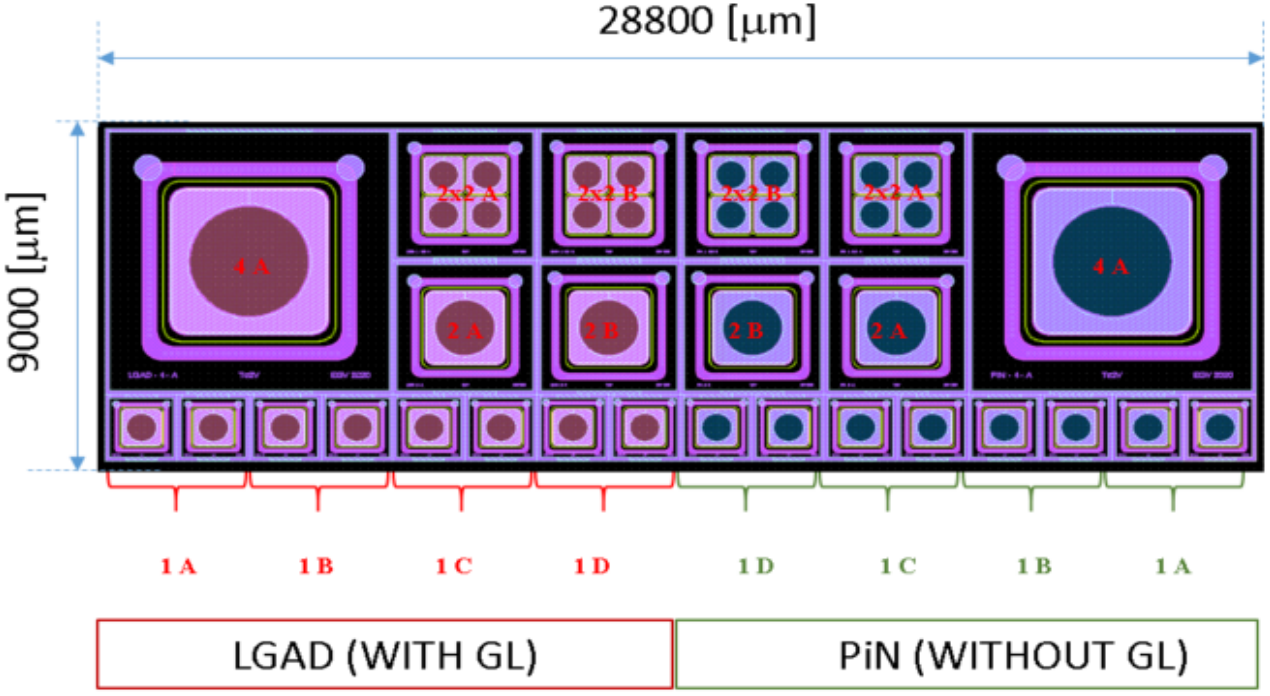
Si wafers (6 inches) of different epitaxial doping levels each

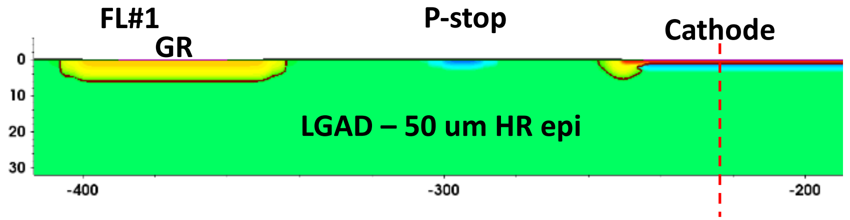
- P type doped with different **epitaxial** doping levels
- 10 Wafers /each doping type

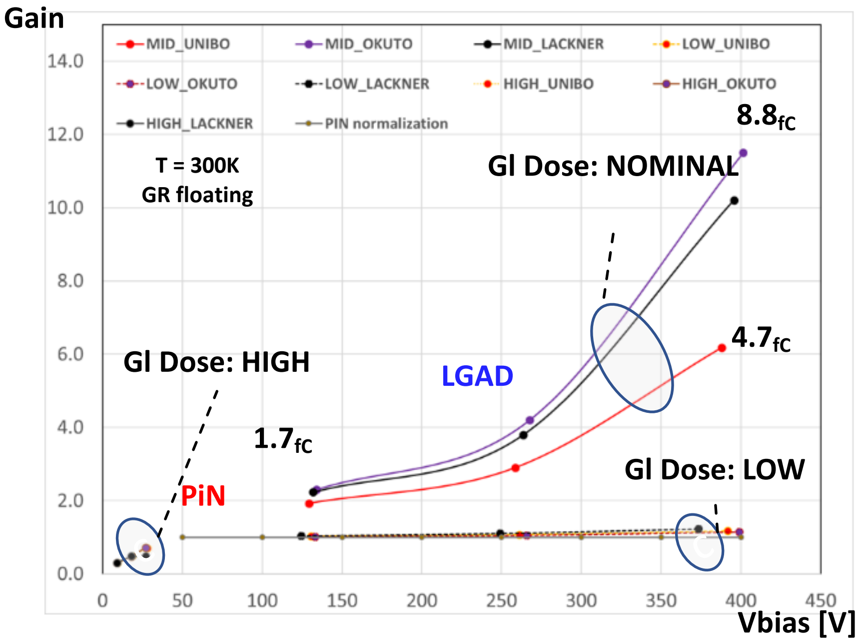
R&D Examples – New Structures

LGAD Project, study radiation effect on Gail Layer (GL) charge amplification

- LGAD and PiN diodes share the same layouts on each split
- Three different gain layer doses and energy
- Fabrication expected July 2020





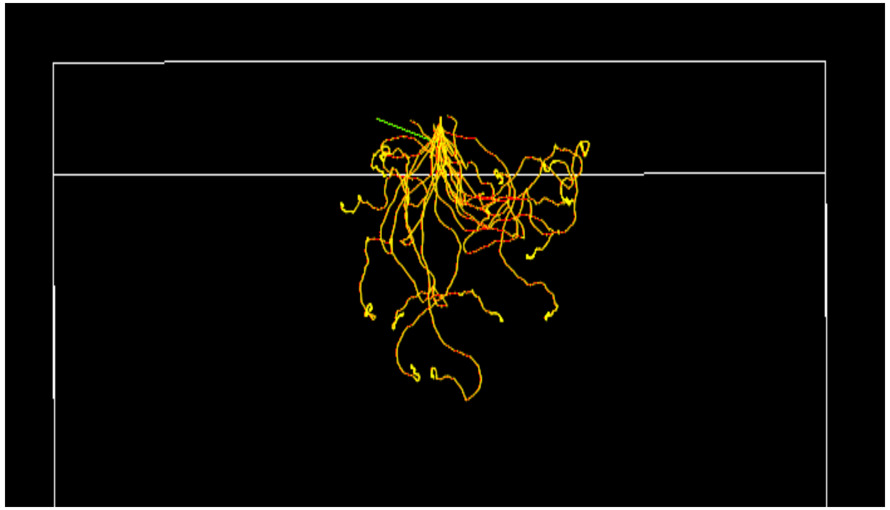


R&D Examples – New Materials

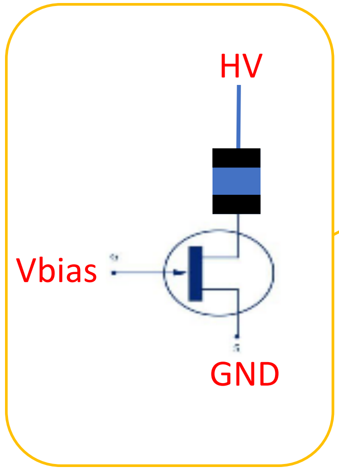
NRC GaN Fabrication Process Radiation Hardness

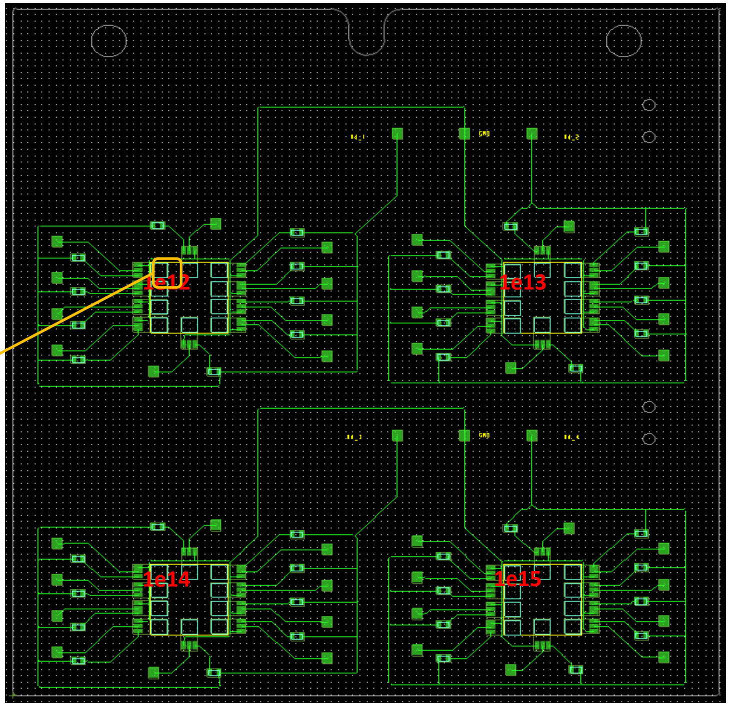
Modified GaN HEMT structure as rad-hard sensor for ionizing radiation

- GEANT4 simulations of 500 keV normally incident β-particles on a GaN slab demonstrate sufficient energy deposition for detection

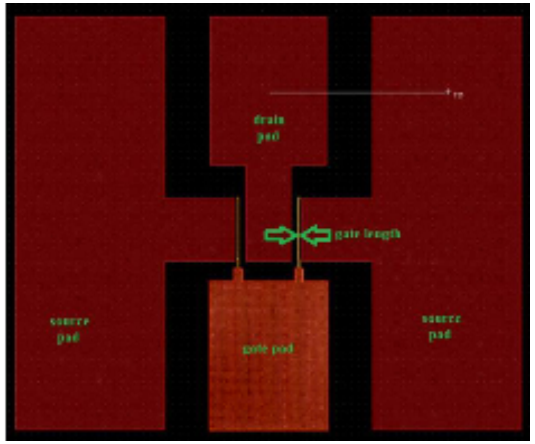


- TCAD simulations being performed on the modified GaN HEMT to investigate if gain can be achieved in a similar manner to that of LGADs
- Aim to irradiate some GaN HEMTs fabricated by NRC with 26MeV p up to fluences of 10^{15} [cm^2] (TID around 230Mrad [GaN]) to compare with previously irradiated Panasonic GanFETs used in Strips ITK





PCB holding up to 40 NRC 1x2 mm2 GaN devices, divided into 4 blocks. Each block of 10 devices receives a different p fluence, up to 1e15 [cm-2]



NRC 1x2 mm2 GaN HEMT layout
Each 1x2 mm2 chip contains 4 HEMTs, differing in gate length

R&D Framework – CERN Collaborations

The RD50 Collaboration

An international collaboration that aims to provide radiation-hard semiconductor devices for future colliders

New!

- ***63 institutes, 370 members***
  - 50 European institutes
  - 8 North American institutes
  - 2 Asian institutes
  - 1 Middle East institute

technology

Knowledge Transfer
Accelerating Innovation

CERN Technology Portfolio

TIMEPIX 3/4

Partners

International

Jožef Stefan Institute Ljubljana, Slovenia

Science & Technology Facilities Council

UK Research and Innovation

SCIPP SANTA CRUZ INSTITUTE for PARTICLE PHYSICS UC SANTA CRUZ

University of Glasgow

UNI FREIBURG

University of Oxford

CNM Centro Nacional de Microelectrónica IMB

UNIVERSITY OF BIRMINGHAM

CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

Canadian

UBC

TRIUMF

YORK UNIVERSITÉ UNIVERSITY

SFU SIMON FRASER UNIVERSITY

Université de Montréal

UNIVERSITY OF TORONTO

Carleton UNIVERSITY

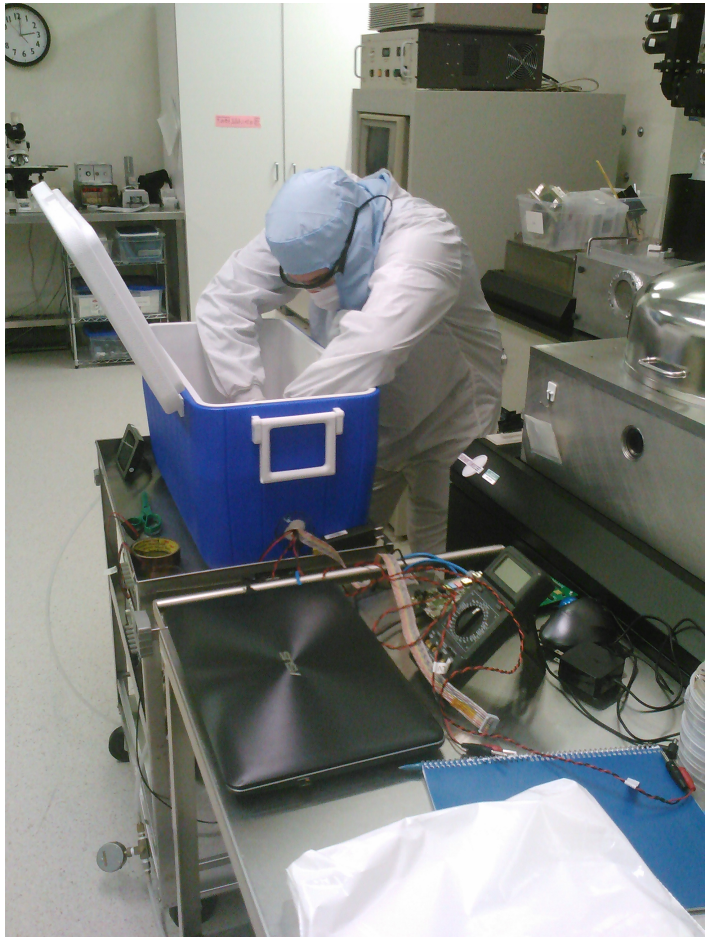
Canada NRC·CNRC

Researchers

Name	Institution	FTE
Nigel Hessey	TRIUMF	0.5
Fabrice Retiere	TRIUMF	0.05
Bernd Stelzer	SFU	0.1
Matthias Danninger	SFU	0.1
Alison Lister	UBC	0.05
Claude Leroy	UdeM	0.25
Richard Teuscher	UoT /IPP	0.1
Nikolina Ilic	UoT/IPP	0.2
Claire David	York	0.1
Thomas Koffas	Carleton	0.35
Razvan Gornea	Carleton	0.1
Dag Gillberg	Carleton	0.05
Ryan Griffin	Carleton/NRC	0.1
Garry Tarr	Carleton	0.1

- 14 researchers from 8 institutes, 2.15 FTE
- Strong overlap with the ATLAS-Canada ITk research teams
  - Inherit/share ITk infrastructure
  - Build on ITk expertise in Canada
- Strong research ties with ITk-Canada effort
  - Research also beneficial to ITk operations/performance
  - Large fraction of FTE shared with ITk-Canada effort
- Large number of younger physicists
  - Half of the people listed hired in the last 5 years
  - Not surprising given scope of proposed R&D
- Large number of physicists attracted from abroad
  - Some with strong ties to international partners
  - Enhanced ability to attract international HQP

HQP



Expected HQP training:
- 2 RA/post-doc FTEs
- 4-5 graduate students
  - Potentially shared projects with ATLAS-ITk
- MRS-funded technical personnel
- TRIUMF Science/Technology Dept. personnel

HQP (being) trained on radiation-hard technologies:
- 9 Ph.D. students; 7 M.Sc. students
- 7 RAs

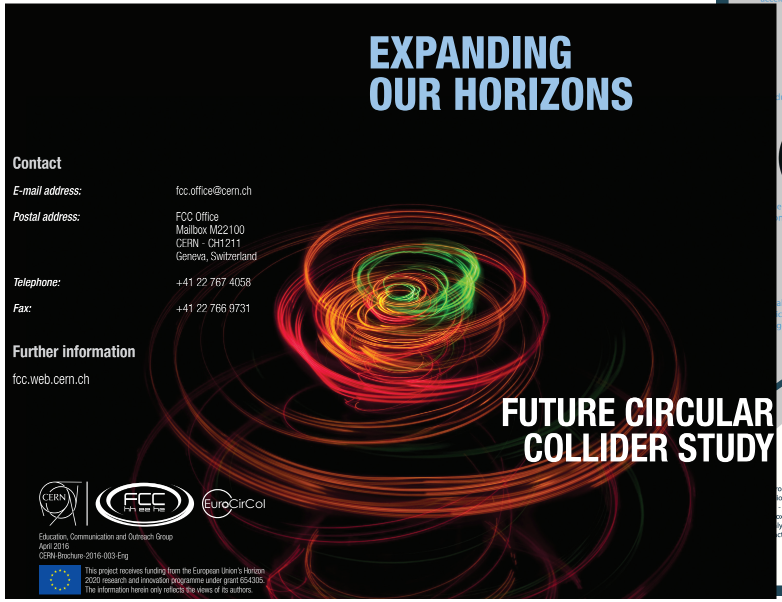
Long list of valuable training skills:
- Semi-conductor device physics; material science
- Semi-conductor device layout design; TCAD modelling
- Semi-conductor device fabrication processes
- FPGA programming; DAQ techniques; ASIC logic verification/simulation

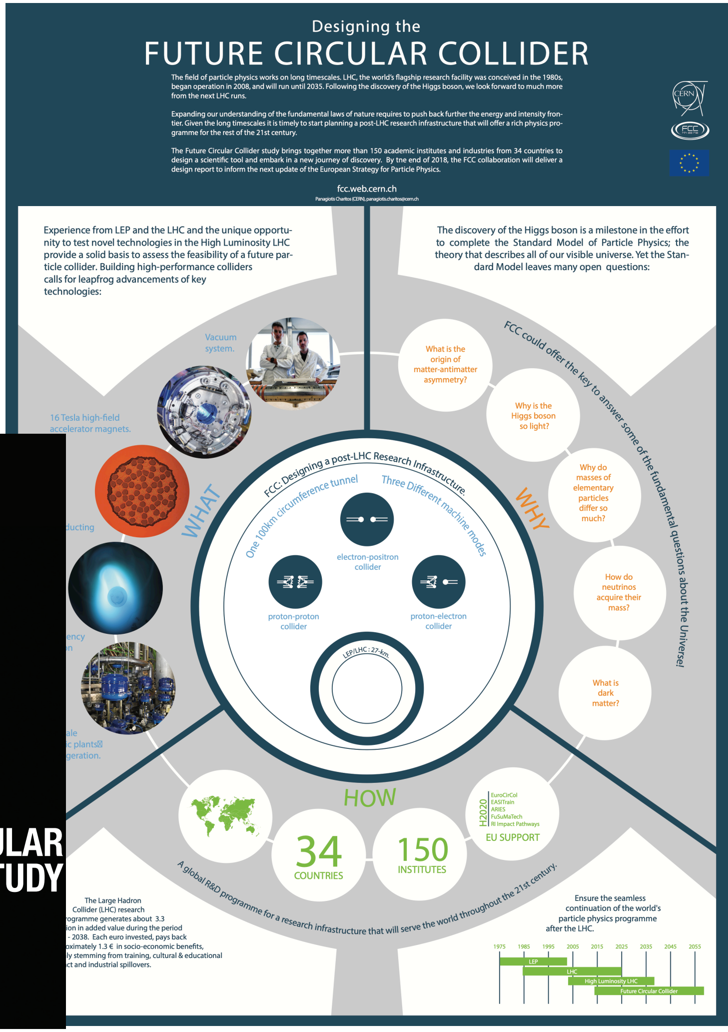
HQP will acquire high value-added skills valued by industry offering career options beyond the academia

Outlook: FCC-ee/hh Program

- Particle physics community gradually shifting focus towards the post-LHC era
- Ample physics motivation:
  - Uniquely map properties of Higgs and EW gauge bosons
  - Improve discovery reach of new particles at highest mass
  - Improve sensitivity to elusive phenomena at low mass
  - Facilitate search for Dark Matter
  - Probe energy scales beyond direct kinematic reach
- Physics program implementation requires development of new technologies
  - Transition of radiation-hard R&D to new tracking detector development
- Focus R&D to specific experimental challenges:
  - Tracking detector layout
  - Sensor design, granularity, material budget
  - Optimize detector sensitive area
  - Optimize detector coverage
  - DAQ architecture to cope with high data rates
  - On-detector readout electronics
  - Performance tailored to physics program needs

Normal development/construction cycle of an approved particle physics experiment





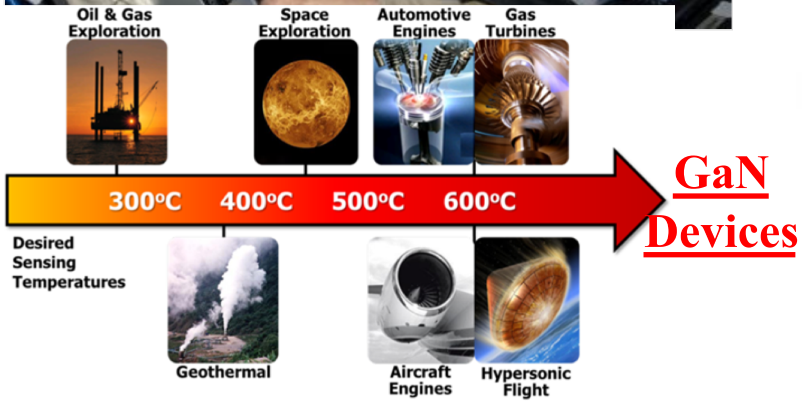
Societal and Economic Impact

Numerous applications with potentially significant economic impact:

- Material fabrication technology, optoelectronics, deep space exploration, nuclear technology, medicine
- Established connection with Timepix/Medipix efforts, one of CERN’s technology transfer vehicles

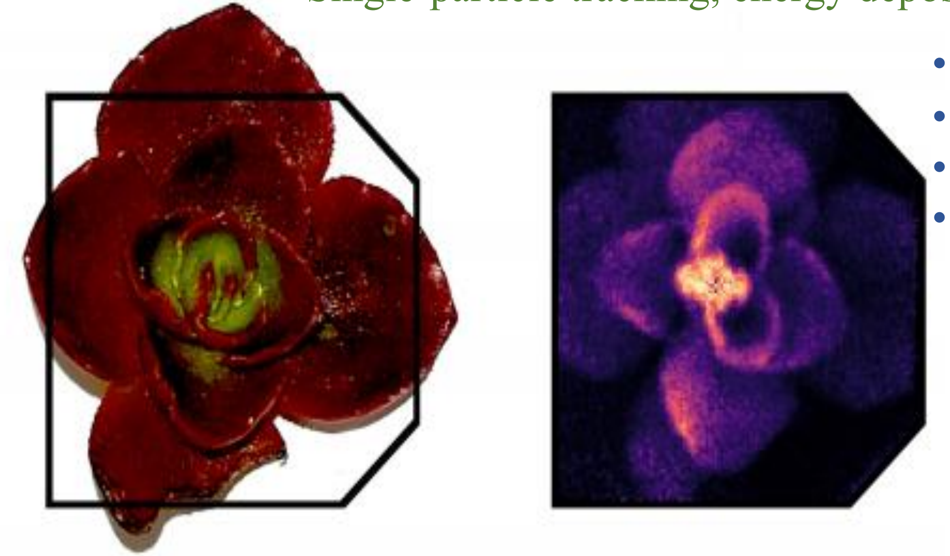
EXAMPLE: International Space Station

- Monitor radiation environment of space station
- **5 Timepix** sensors into laptop USB ports!



EXAMPLE: Ion Beam Radiotherapy Imaging

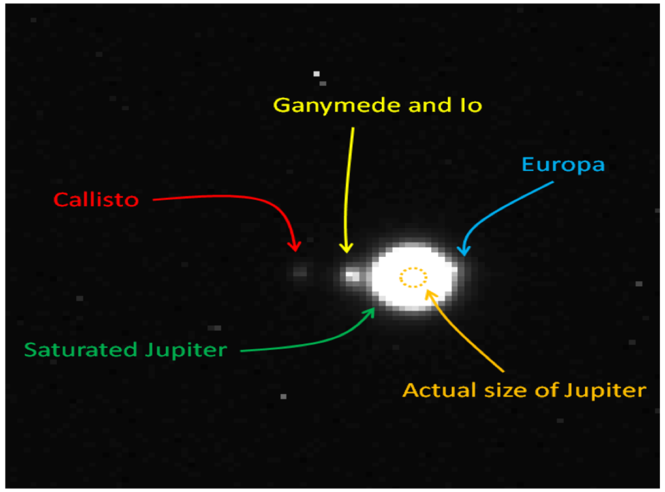
- Requires new methods of radiation dose measurement
  - Single-particle tracking, energy deposition, particle type sensitivity



- System of Timepix detectors put together
- Assembly very similar to ATLAS-ITk
- Measure deposition of single ion energy
- Allows for high-contrast images

EXAMPLE: NavCam System, JUICE

- Harsh radiation environment to survive for 11 years
- Fluences within 2 orders of magnitude of LHC!
- Total integrated dose could exceed 1MRad
- **Knowledge transfer between CERN-ESA**



Credit: Airbus Industries

Summary

- International physics community gradually shifting its focus to the post-LHC era
  - Excellent opportunity for Canadian sub-atomic physics to join international detector R&D efforts from early on
  - **Builds on infrastructure and knowledge gained during the ATLAS-ITk project**
    - **Ensures continuous use of >$24M investment by Canadian funding agencies, universities and TRIUMF**
- Ample scope to develop robust R&D efforts on radiation-hard semi-conductor devices
  - Theme 1 focuses on Si pushing its capabilities and understanding its limitations
    - Of major importance on ITk operations and for predicting its long-term performance
  - Theme 2 investigates new materials and device structures to overcome challenges of future colliders
    - Aim to reach fluences at 10^{17} n_{eq}/cm^2 where Si may actually fail
- Enhance Canadian presence at CERN in international collaborations other than ATLAS
  - By participating in the RD50 collaboration and the Medipix/Timepix collaborations
- Allows for Canadian participation in major future CERN collider projects
  - **FCC-ee and FCC-hh whose combined program will cover the next seven decades**
- Provides for HQP to participate in R&D on cutting-edge technologies
  - **New knowledge creation with wide range of economic and industrial applications**
  - **Skill development of immediate use in modern knowledge-based economy**
- Unique example of basic science research with wider societal and economic impact