Single Event Upset Characterization of Commercial Grade SRAM and FLASH-based Field Programmable Gate Array Using Proton Irradiation

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and
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european social fund in the czech republic
EUROPEAN UNION
MINISTRY OF EDUCATION, YOUTH AND SPORTS
OP Education for Competitiveness
INVESTMENTS IN EDUCATION DEVELOPMENT

Outline

- Introduction – NPI Řež cyclotron
  - Open Access
  - Parameters
  - Tools
- Motivation
  - ALICE ITS Upgrade (LHC, CERN)
  - FPGA Model Calibration
- FPGA Testing
  - Methodology
  - Results
- Conclusions and Future Work

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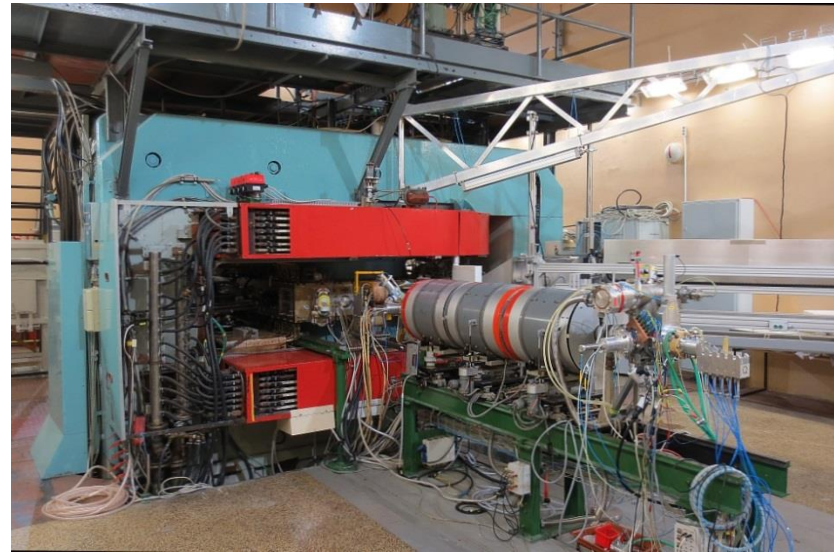
NPI Řež Cyclotron – Open Access

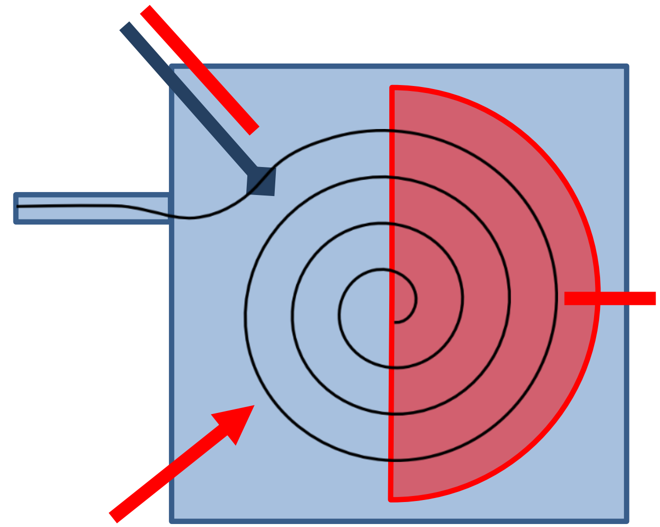


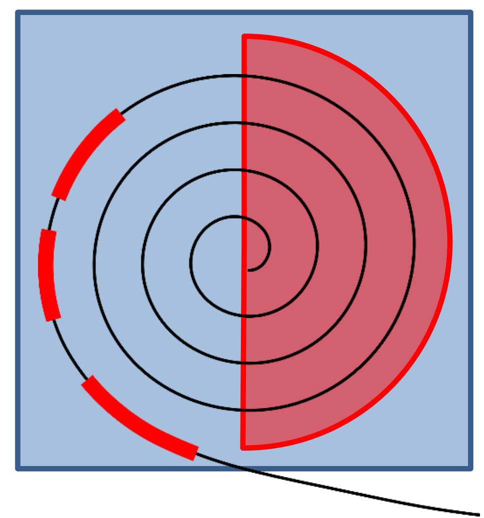
Center of Accelerators and Nuclear Analytical Methods (CANAM) offers scientists a unique experimental infrastructure in nuclear physics and neutron science: http://canam.ujf.cas.cz/

Funded by the Ministry of Education, Youth and Sports of the Czech Republic and Nuclear Physics Institute of the Academy of Sciences of the Czech Republic, experimental facilities are proffered to the users in Open Access mode.

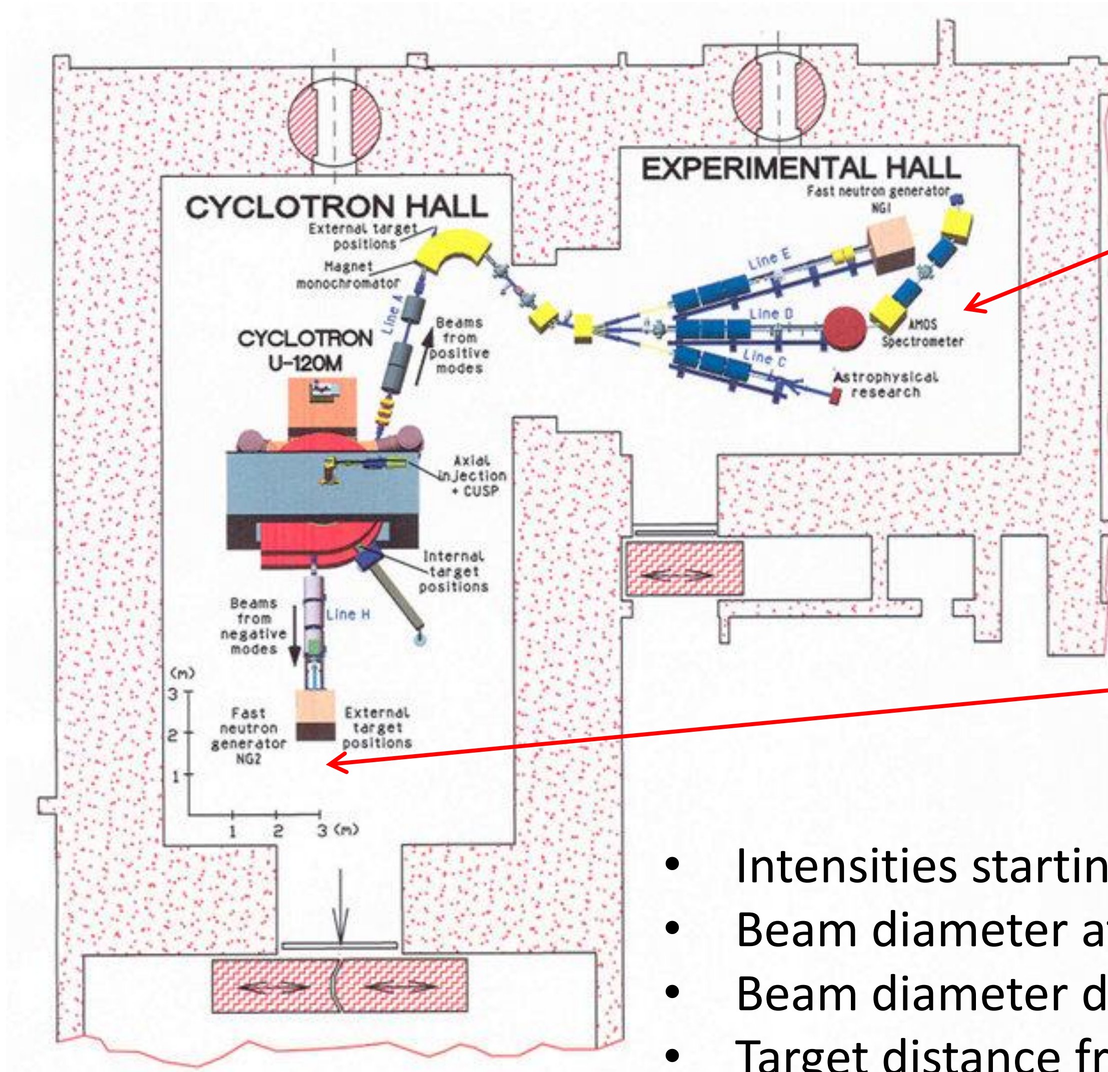
Cyclotron at Nuclear Physics Institute of the Czech Academy of Science, Řež

- Negative running mode
  - Production of radiopharmaceuticals
  - Activation & irradiation experiments
  - High energy and flux intensity
  - Neutron background
  - Neutron Generator available
- Positive running mode
  - Astrophysical and biological research
  - Spectrometry experiments
  - No neutron background
  - Lower maximal intensities
  - Need to be arranged and planned in advance (blocks radiopharmaceutical production for at least a week)





NPI Řež Cyclotron U-120M – Basic Parameters



Positive mode:
Spectrometry experiments

- protons: 6-25 MeV (<5 μA)
- deuterons: 12-20 MeV (<5 μA)
- ^{3}He-ions: 18-52 MeV (<2 μA)

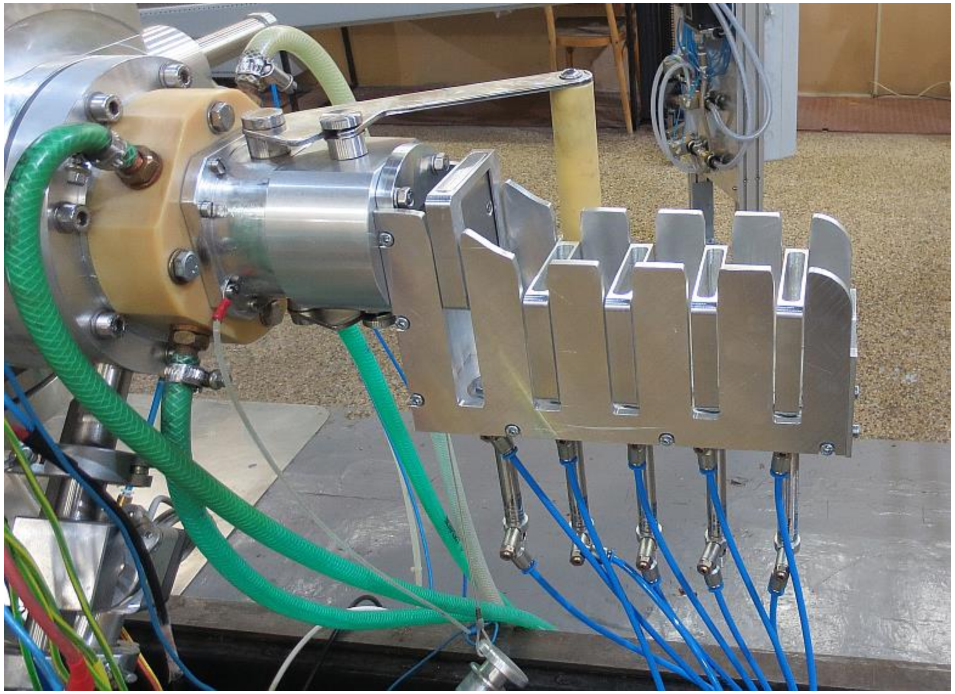
Negative mode:
Activation experiments
Irradiation experiments
Radiopharmaceutical production

- protons: 6-37 MeV (<30 μA)
- deuterons: 11-20 MeV (<20 μA)

- Intensities starting from 10^4 p/cm^2/s
- Beam diameter at the exit window: ~ 1.6 cm
- Beam diameter divergence: ~ 1 cm/m
- Target distance from the exit window: 0.5 – 4 m

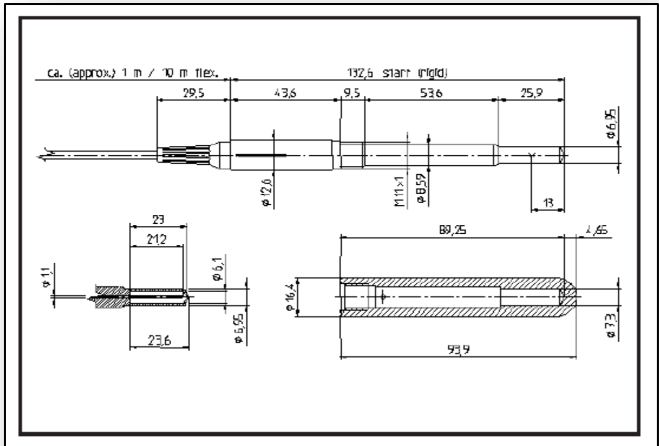
Tools:
Beam Absorber and Energy Degrader

- Instant stopping and restoring the beam without changing it’s parameters
- Lowering the beam energy without need of readjusting the cyclotron
- Integrated beam monitoring under development

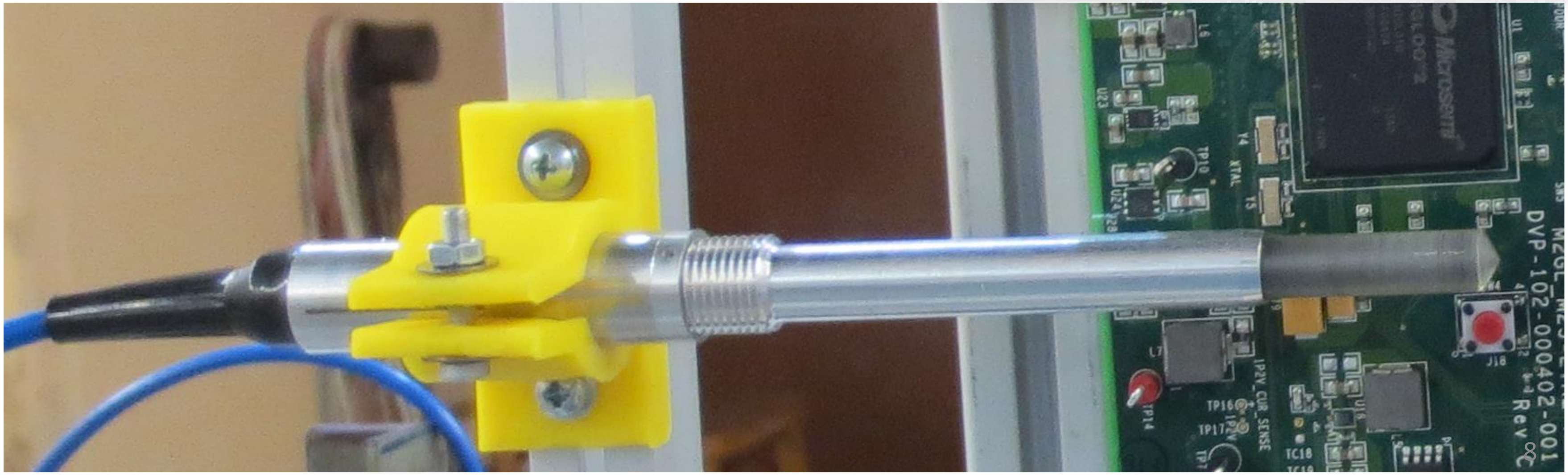


Tools:
Dosimetry – Ionization Chamber

- Commercial product from PTW Freiburg
- Placed close to the beam axis
- Calibrated by Timepix (CERN Medipix) device and cross-checked using SRIM/GEANT4 simulations

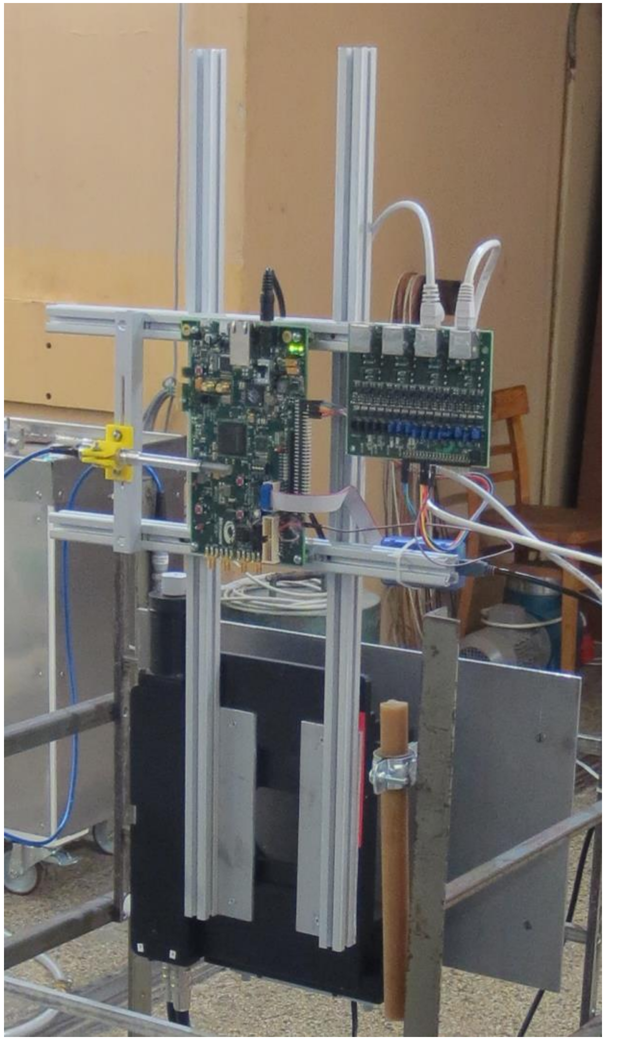


Farmer Chamber 30010



Tools:
Positioning system

- Remotely controlled
- Positioning in X and Y axis
- +/- 5 cm in both axes
- 1 µm accuracy possible
  (now using 1 mm accuracy)



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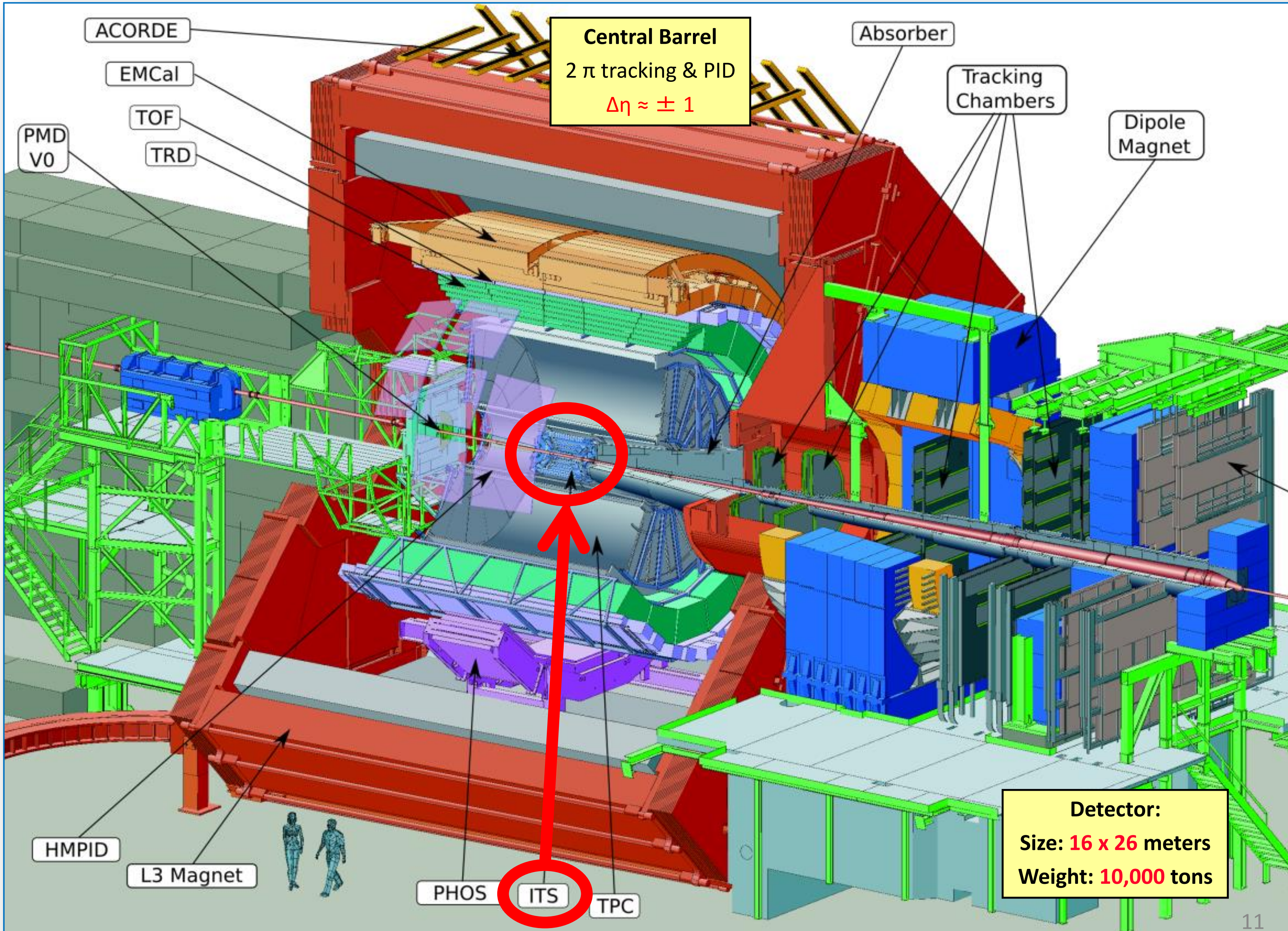
ALICE detector at LHC in CERN



ITS Upgrade – Technical Design Report

ALICE

ALICE-TDR-017

CERN-LHCC-2013-024
07 November 2010

http://cds.cern.ch/record/1625842

Technical Design Report

for the

Upgrade of the
ALICE Inner Tracking System

The ALICE Collaboration

116th LHCC Meeting - DRAFT Agenda OPEN Session

chaired by Eckhard Elsen (Deutsches Elektronen-Synchrotron (DE))

from Wednesday, 4 December 2013 at **09:00** to Thursday, 5 December 2013 at **17:30**
at **CERN (500-1-001 - Main Auditorium)**

Table 9.2: Institutes participating in the ITS Upgrade Project.

Country	City	Institute
CERN	Geneva	European Organization for Nuclear Research
China	Wuhan	Central China Normal University (CCNU)
Czech Republic	Prague	Faculty of Nuclear Science and Physical Engineering, Czech Technical University
Czech Republic	Řež u Prahy	Nuclear Physics Institute of the ASCR

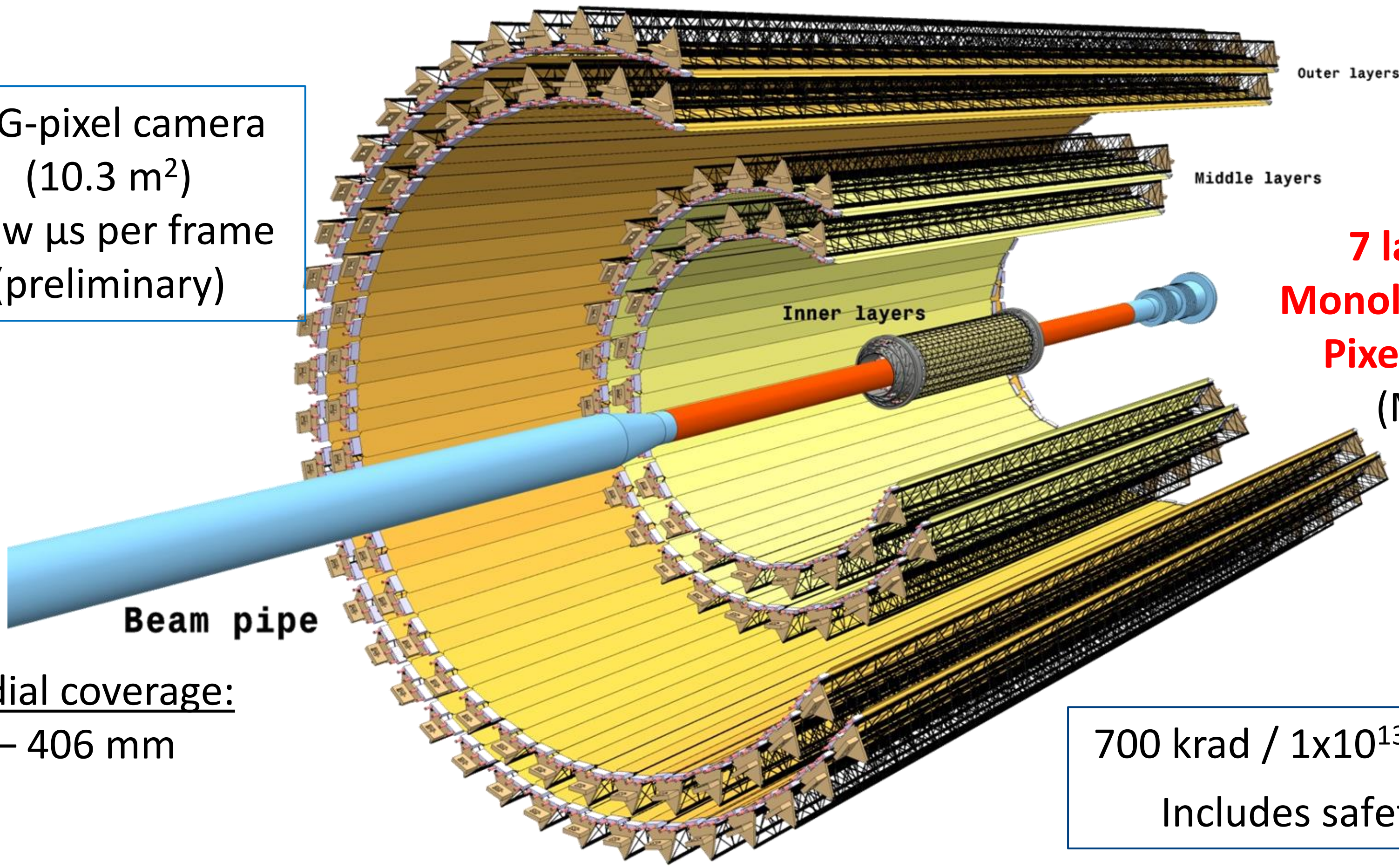
+ 32 other institutes from 14 countries
Total cost = 12 MCHF

Published in:
B. Abelev et al. (The ALICE Collaboration) 2014 J. Phys. G: Nucl. Part. Phys. 41 087002

Time schedule (*LHC Large Shutdown 2: start = July 2018 for 18 months*) :
selection of design: beginning 2015, production: fall 2015 → beginning 2017, global assembly: beginning 2018, commissioning: end 2018 → beginning 2019

New ITS Layout

25 G-pixel camera
($10.3\ m^2$)
A few µs per frame
(preliminary)



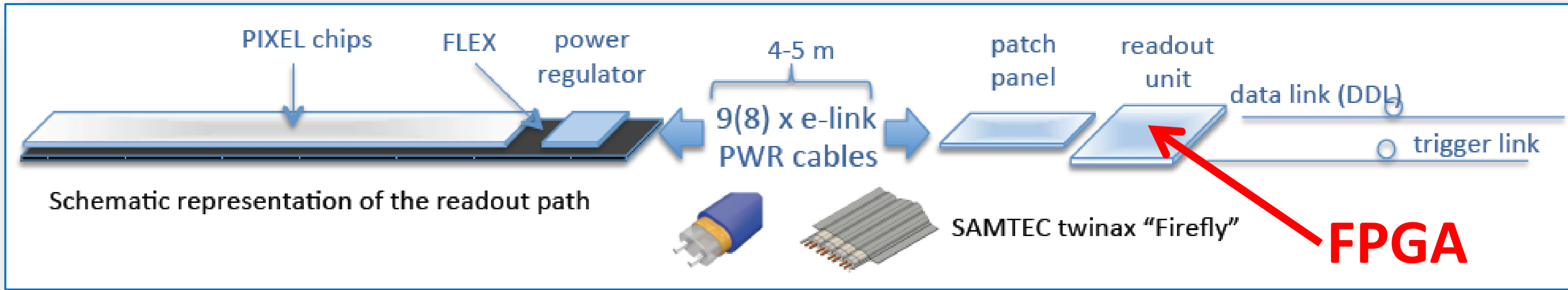
7 layers of Monolithic Active Pixel Sensors (MAPS)

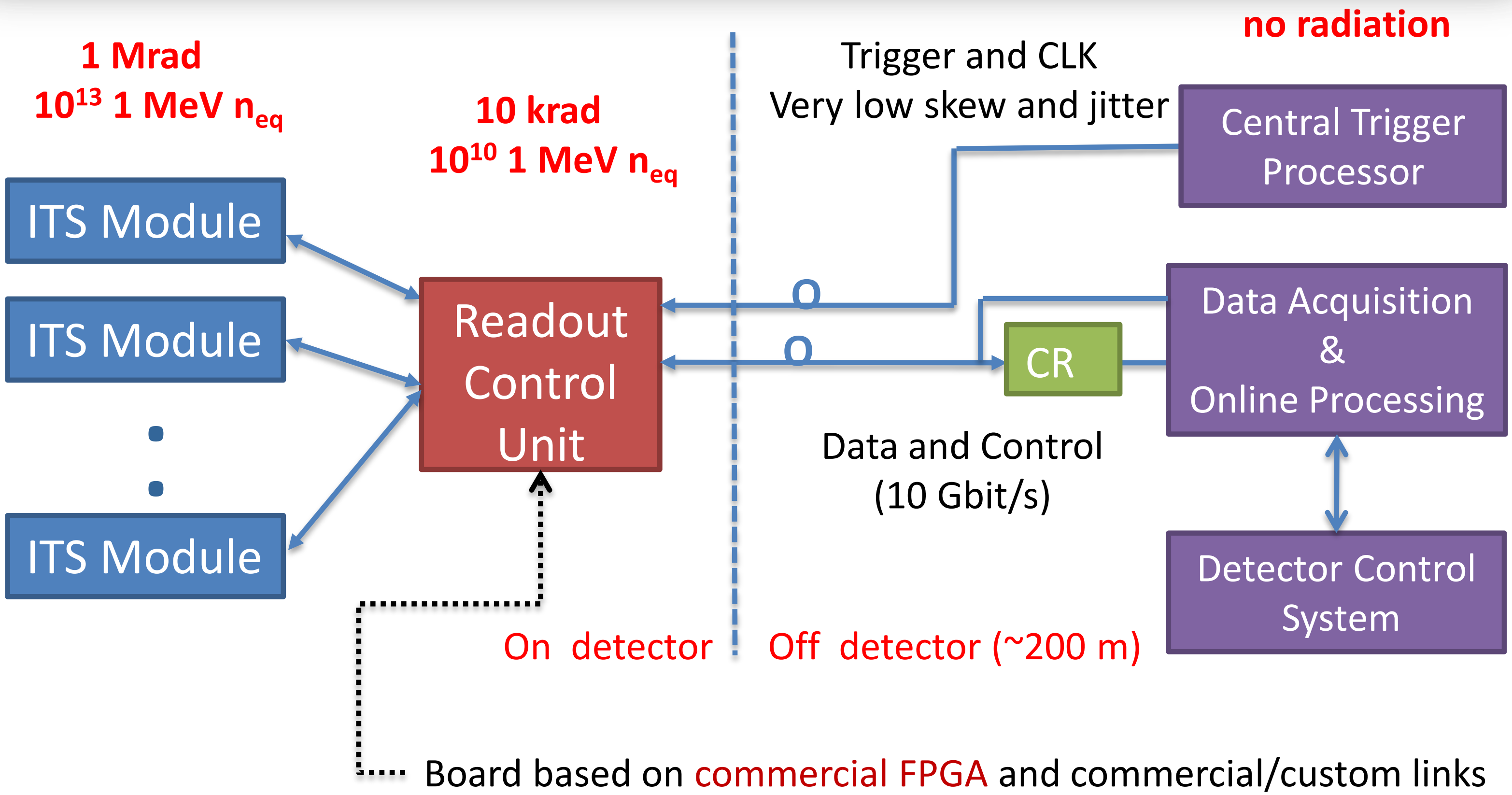
Radial coverage:
22 – 406 mm

700 krad / $1\text{x}10^{13}$ 1 MeV n_{eq}
Includes safety factor 10

	Layer 0	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
Radial position (minimum (mm)	22.1	28.9	37.5	175.3	210.0	387.0	423.0
Length (mm) sensitive area		270		843		1475	
Nr. pixel chips	108	144	180	2688	2912	9408	9996
Pixel size (μm^2)		20×20		20×20		20×20	

ITS Readout Scheme





Criteria for FPGA Candidate

- **Price**: ~1000 data channels → the price of the readout unit must not dominate the price of the total project

- **Speed:** up to 1.5 Gbit/s per data channel

- **Radiation:** 4-5 meters from the ITS detector, 1 m from the beampipe, still in the radiation environment of the LHC accelerator
→ 10 krad TID

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FPGA Model – Motivation

- SEU vulnerability depends on actual design
- New design need to be SEU-characterized
- Basic approaches known:
  - Simulation

    too complex, unknown structure of FPGAs
  - Accelerated Life Testing (ALT) in radiation fields

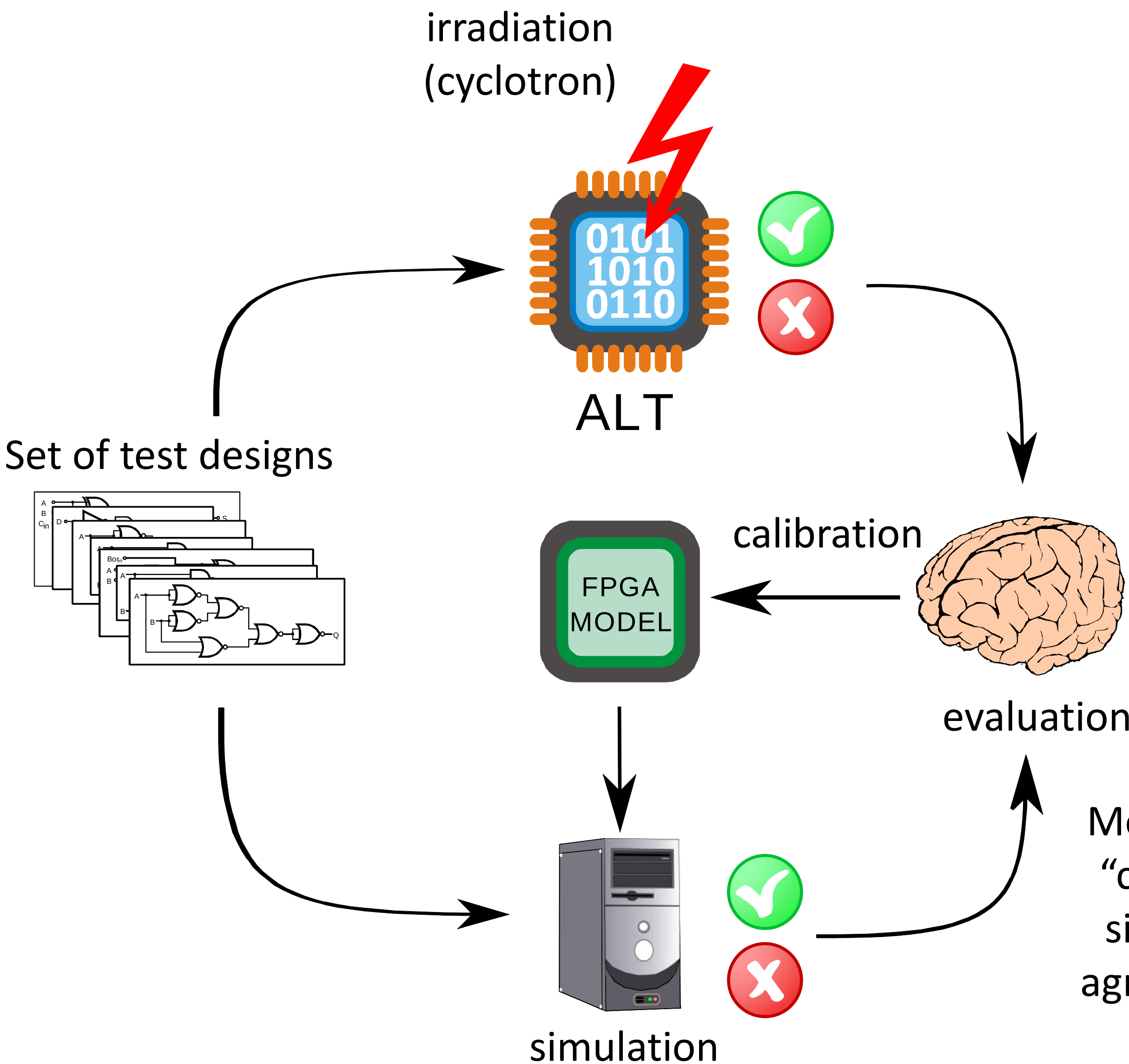
    too specific, too expensive

    only for specific device–design pair

FPGA Model – Approach

- Create a model of FPGA
  - Fault models library
- Create a framework to test the circuit implemented in the FPGA based on the given FPGA model
- Calibrate model through ALT (Accelerated Life Testing) on cyclotron

FPGA Model – Approach



Model modified (by "calibration") until simulation results agree with observed reality

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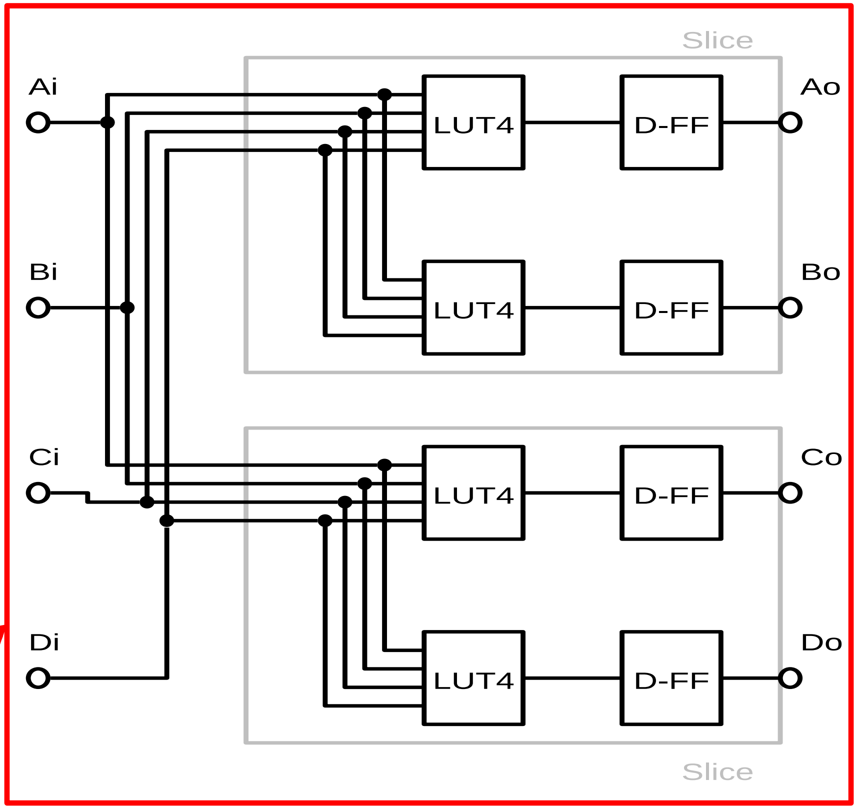
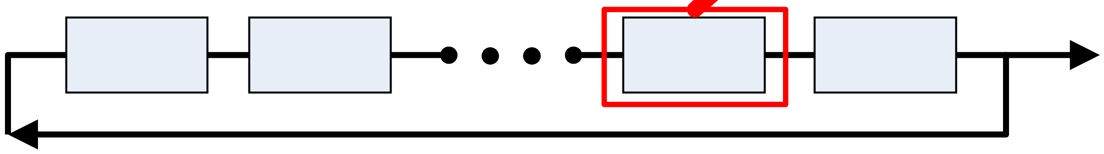
Test Design Example

- Tests all LUTs and flip-flops
- Propagates any error to output
- Forms a long pipeline
- Is preloaded with data upon flip-flops reset
- Detects fault rate on the particular device under particular conditions



One pipeline stage



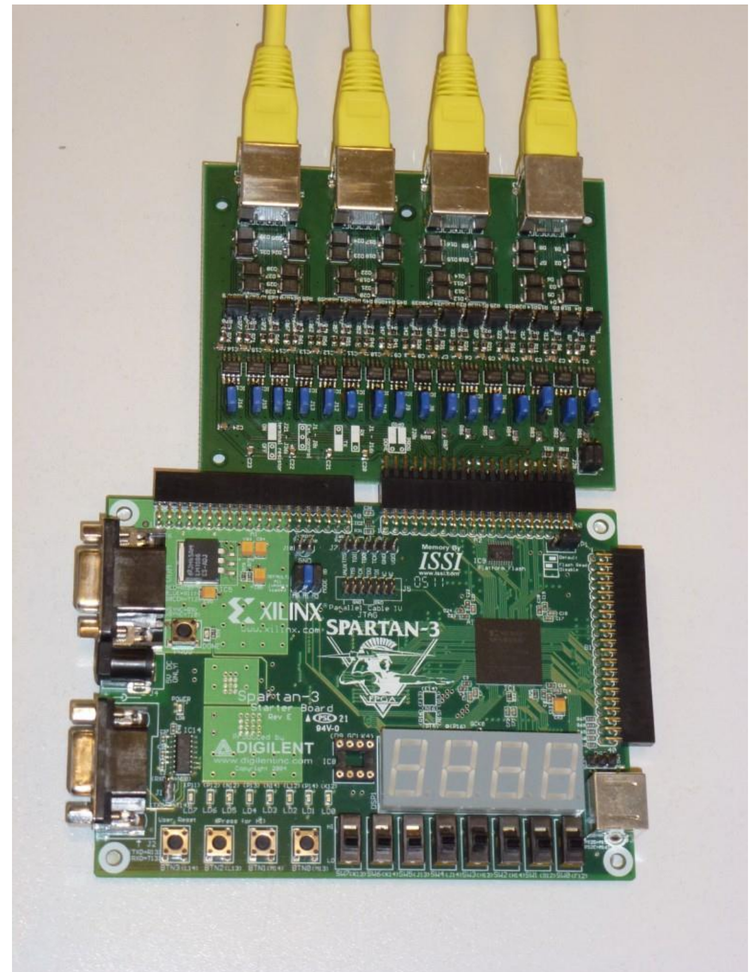
Pipeline

Entire Test System

- Based on Spartan 3 Starter Kit
- Two parts
  - One under radiation
  - One away from radiation

- Connected trough 16 differential lines

- Radiated part is controlled from the shielded one
  - Remote monitoring, reset, reload



Irradiation Setup

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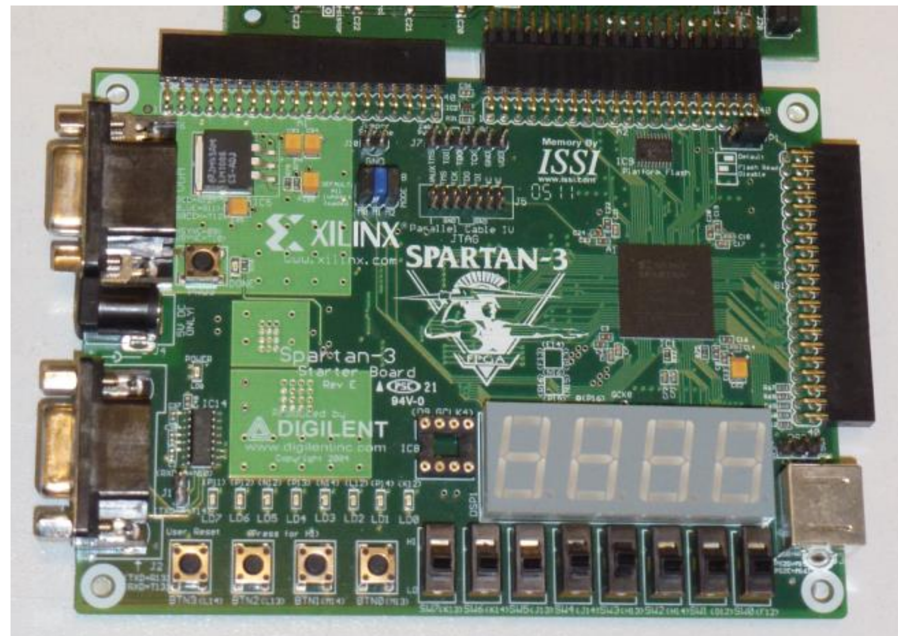
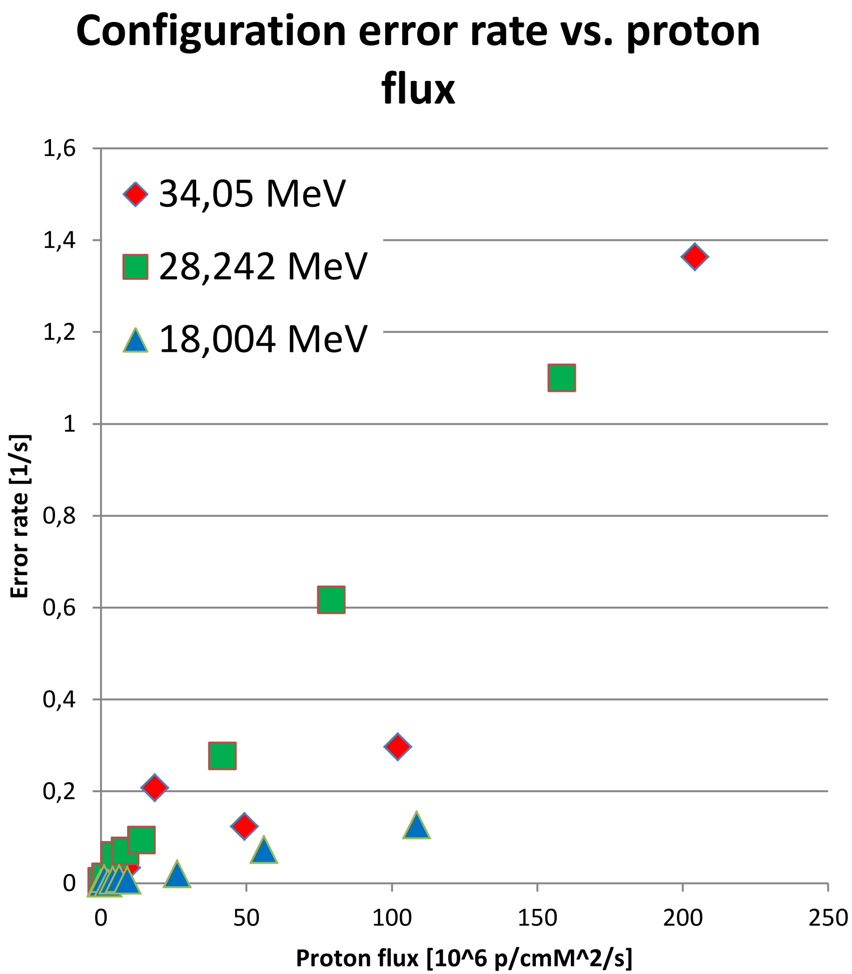
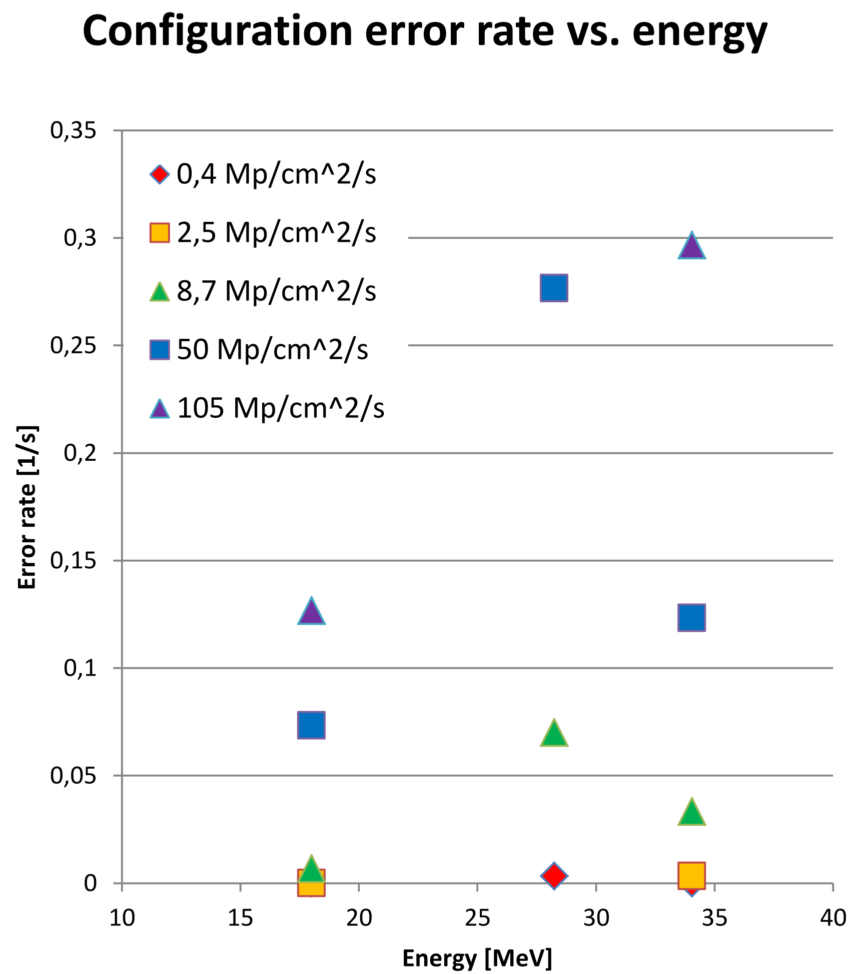
Spartan 3 Irradiation

- Xilinx SRAM FPGA
- Starter Kit used
  - XC3S200 device
- 90 nm CMOS technology
- Only SEU in configuration memory measured



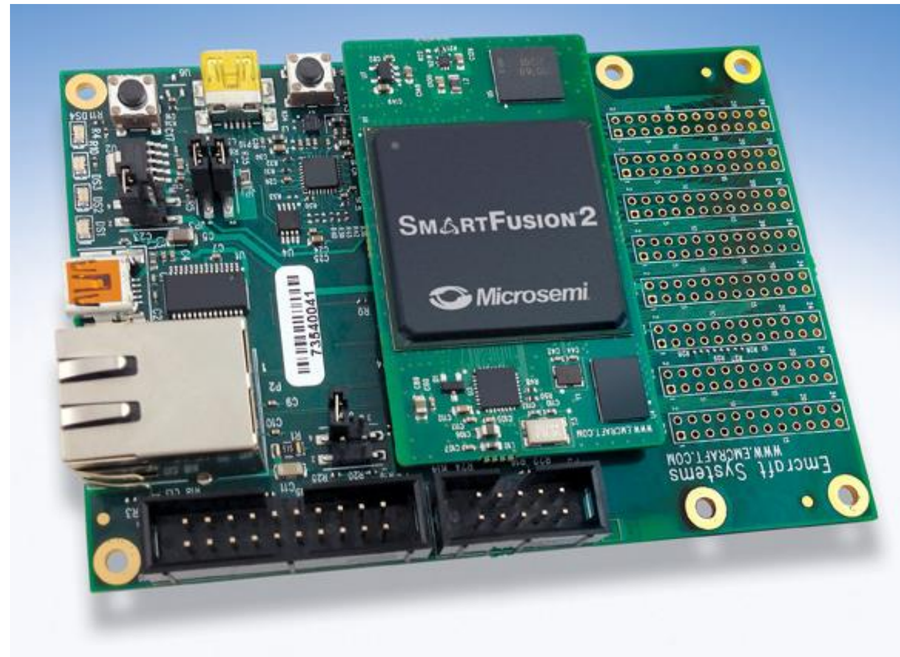
Spartan 3 Irradiation – Results





SmartFusion2 Irradiation

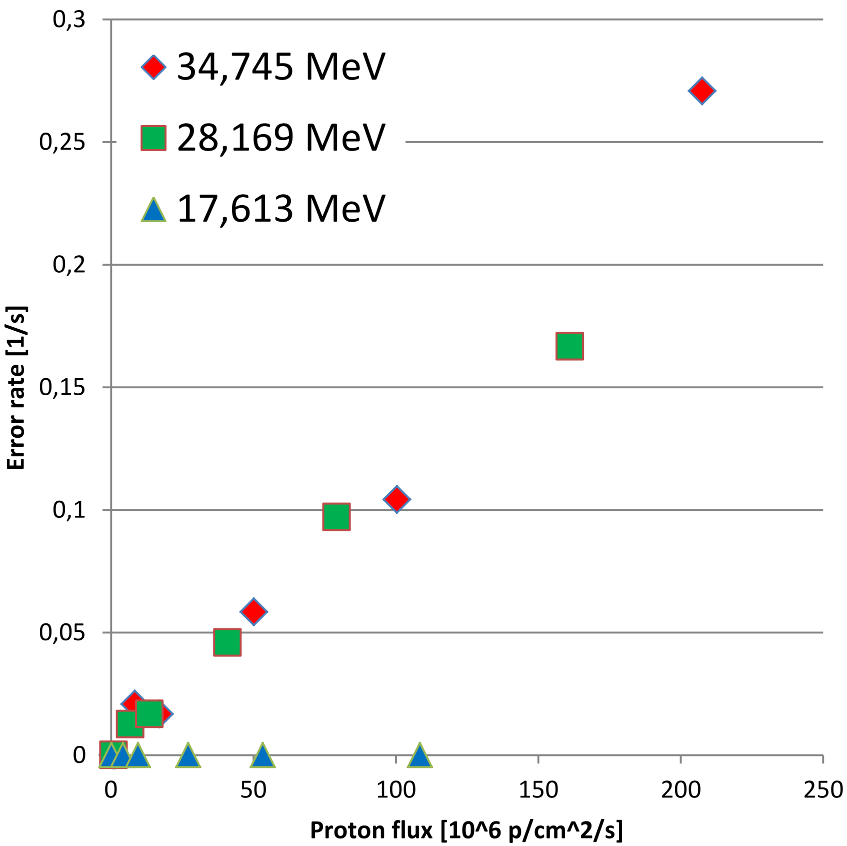
- Microsemi FLASH SoC
  - Only the FPGA part tested
- Starter Kit used
  - M2S050-FGG484 device
- 65 nm CMOS technology
- No SEU in configuration memory (as expected)
- Some SEU in "data" flip-flops (D-FFs)



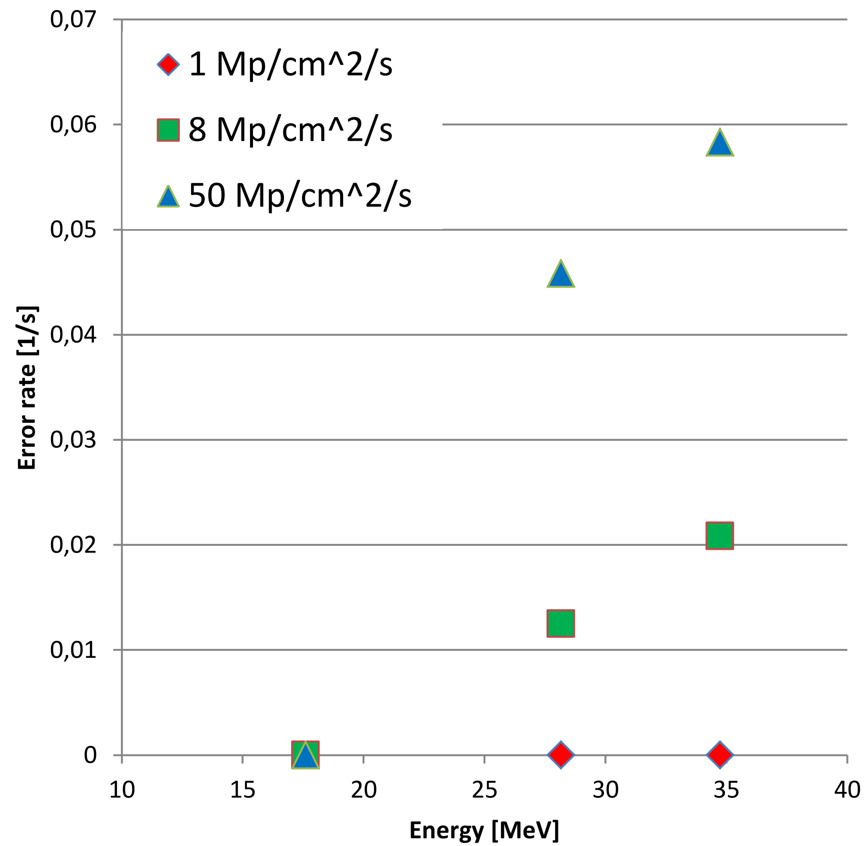
- Programming SEFI after approx. 10-70 krads)
  - results confirmed and refined to 4 krads by Ketil Røed et al. (RCU for ALICE TPC)

SmartFusion2 Irradiation – Results

D-FF error rate vs. proton flux

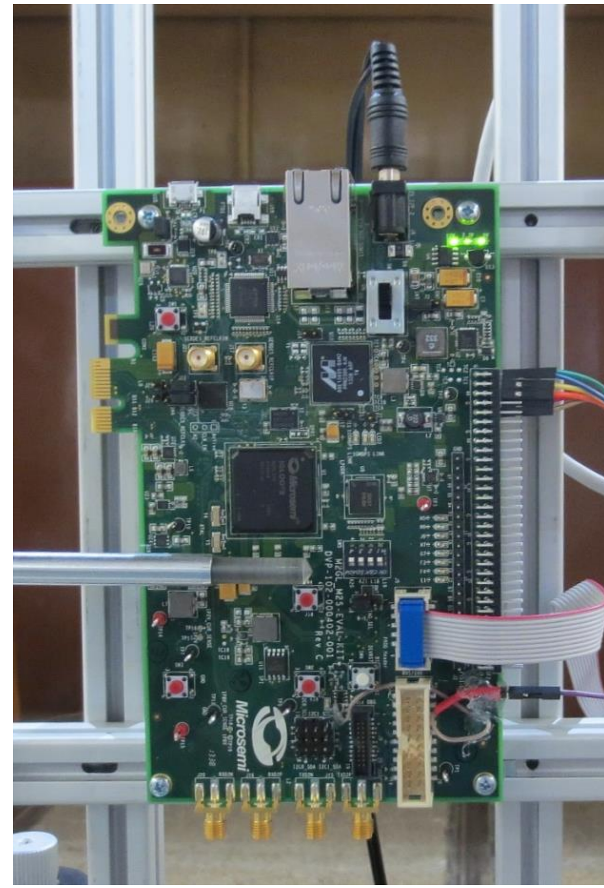


D-FF error rate vs. energy



IGLOO2 Irradiation

- Microsemi FLASH FPGA
- Same FPGA fabric as SF2
- Starter Kit used
  - M2GL010T device
- 65 nm CMOS technology
- No SEU in configuration memory
- SEU rate in “data” flip-flops (D-FFs) comparable to SF2 device
- Only one short (6 min) irradiation performed till now.
- Programming SEFI after approx. 1 krad



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Conclusions I

- Cyclotron in NPI Řež is a suitable instrument for a radiation testing of FPGAs and other components
- Within the Open Access project the cyclotron is available for a broad community
- ALICE ITS Upgrade project requires to identify the radiation hardness of (commercial grade) FPGAs, suitable for use in the Readout Control Unit
- We have proposed a method for predicting the quantitative characteristics of SEU sensitivity of digital circuits implemented in the FPGA
- This method can be used for verifying dependability and security parameters of various designs implemented in FPGA
- We have completed the first runs of ALT for different FPGAs

Conclusions II

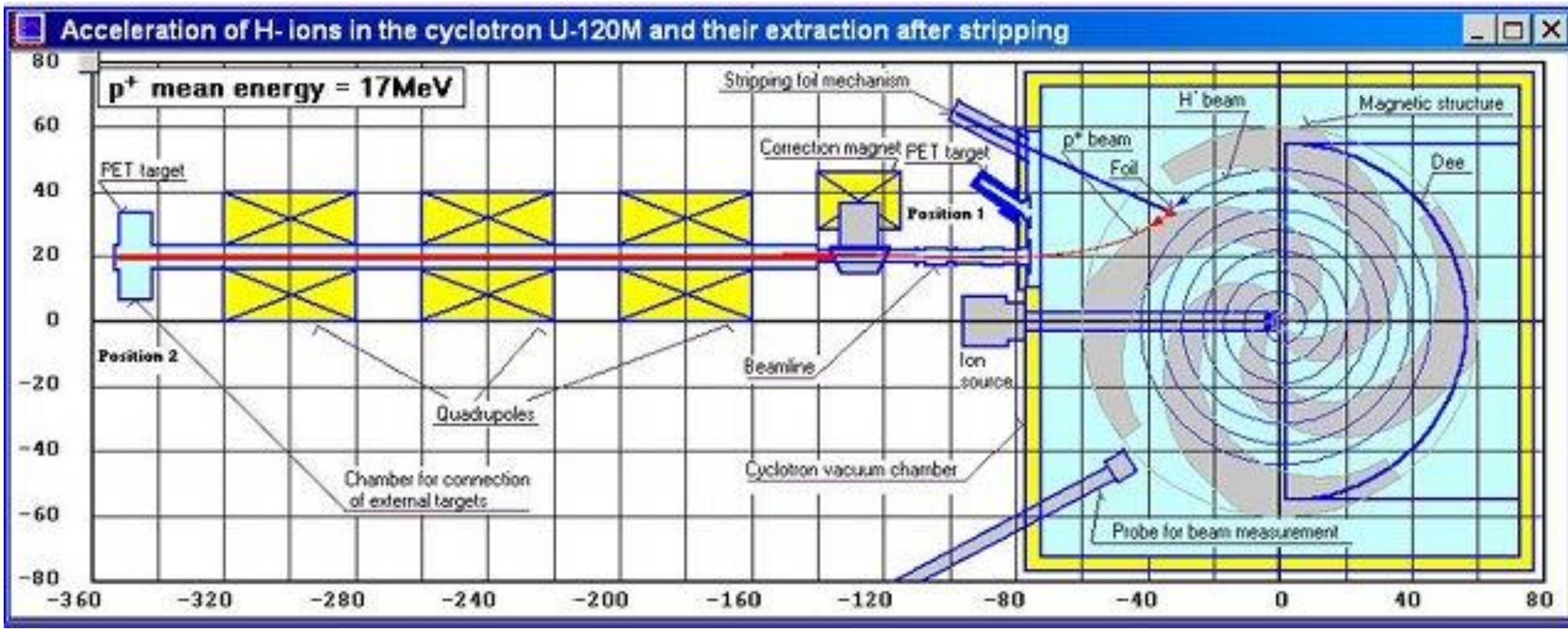
- FLASH based SmartFusion2 and IGLOO2 (65 nm) has better resistance to Single Event Effects in comparison with Spartan 3 (90 nm)
  - Configuration memory is completely safe
  - D flip-flops are less vulnerable, although it is a smaller technology
- On the other side, the SmartFusion2 and IGLOO2 FLASH programming controller is very sensitive to total ionizing dose. It is permanently destroyed at:
  - ~4 krads for SF2
  - ~1 krad for IGLOO2
  - Spartan 3 already survived several hundreds of krads without permanent error noticed
- SF2 and IGLOO2 are not suitable for the ALICE ITS Upgrade at the moment because of programming SEFI

Outlook and Future Work

- Improving the monitoring of the total ionizing dose
- Upgrade the communication module of DUT for higher data transfer rate
- Synchronization of the FPGAs clock with cyclotron frequency to study Single Transient Events
- Improving the FPGA model, collect a set of data to calibrate the model
- Select and test another candidate for ALICE ITS Upgrade project

Spare Slides

Acceleration of H$^-$ ions and extraction using the stripping foil



Negative mode:

Acceleration of H with loosely bounded additional electron → H$^-$

Carbon stripping foil: H$^-$ → protons

Carbon foil source of additional neutron background

Transmission efficiency (source to extracted beam) typical: 52% for H$^-$

Test Design Example – Code

- Symmetric
- After odd number of conversions, the output is same as input
- Any bit flip in any LUT appears as a change in the sequence

Code 1	Code 2
0000	1001
0001	1010
0010	1111
0011	0110
0100	0011
0101	0111
0110	1100
0111	0101

Code 1	Code 2
1000	1011
1001	0000
1010	0001
1011	1000
1100	0110
1101	1110
1110	1101
1111	0010