ALICE ITS Upgrade Project

and

Contribution of NPI in Řež

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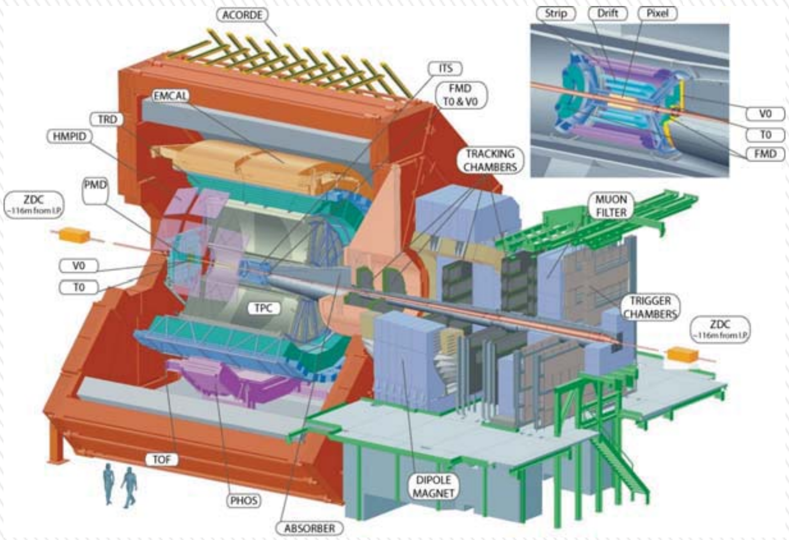
evropský sociální fond v ČR · EVROPSKÁ UNIE · MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY · OP Vzdělávání pro konkurenceschopnost

INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

Outline:

- ALICE detector with present Inner Tracker System (ITS)
- ITS upgrade
  - design goals, milestones, options, technologies, timelines
- NPI cyclotron U-120M as a test bed
  - available beams, open access mode
- Single Upset Event
  - history, design factors, critical charge
- Contribution of Nuclear Physics Institute NPI
  - measurement setup, calibration run, plans

A Large Ion Collider Experiment



Central Detectors:
Inner Tracking System (ITS)
Time Projection Chamber (TPC)
Transition Radiation Detector (TRD)
Time-of-Flight (TOF)
High Momentum PID (HMPID)
Spectrometers:
Photon Multiplicity
Forward Multiplicity
Muon Spectrometer
Calorimeters:
EM Calorimeter (EMCAL)
Photon Spectrometer (PHOS)
Zero Degree Calorimeter (ZDC)

Ultra-relativistic nucleus-nucleus collisions

- study behavior of strongly interacting matter under extreme conditions of compression and heat

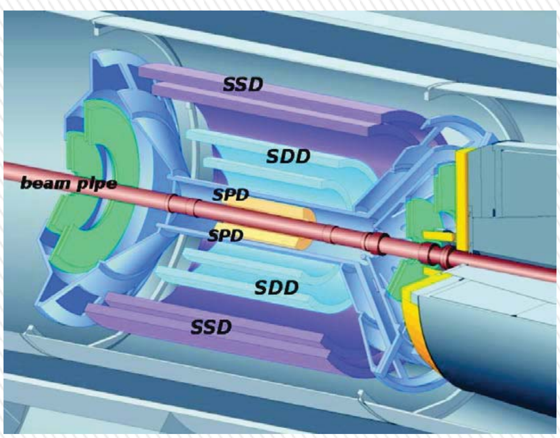
Proton-Proton collisions

- reference data for heavy-ion program
- unique physics (momentum cutoff < 100 MeV/c, excellent PID, efficient minimum bias trigger)

Detector:
Length: 26 meters
Height: 16 meters
Weight: 10,000 tons

Collaboration:
> 1000 Members
> 100 Institutes
> 30 countries

ALICE ITS (Inner Tracking System) - current detector



Current ITS consists of 6 concentric barrels of silicon detectors

3 different technologies:

- 2 layers of silicon **pixel** (SPD)
- 2 layers of silicon **drift** (SDD)
- 2 layers of silicon **strips** (SSD)

Layer/ Type	Radius [cm]	Length [cm]	Number of modules	Active area per module [mm²]	Nom. resolution rΦ x z [μm]	Material budget X/X_0 [%]
Beam pipe	2.94	-	-	-	-	0.22
1 / Pixel	3.9	28.2	80	12.8 × 70.7	12 × 100	1.14
2 / Pixel	7.6	28.2	160	12.8 × 70.7	12 × 100	1.14
Thermal Shield	11.5	-	-	-	-	0.65
3 / Drift	15.0	44.4	84	70.2 x 75.3	35 × 25	1.13
4 / Drift	23.9	59.4	176	70.2 x 75.3	35 × 25	1.26
Thermal Shield	31.0	-	-	-	-	0.65
5 / Strip	38.0	86.2	748	73.0 x40.0	30 × 830	0.83
6 / Strip	43.0	97.8	950	73.0 x40.0	20 × 830	0.83

ITS Upgrade Design Goals

1. Improve impact parameter resolution by a factor of ~3:
- Get closer to IP (position of 1-st layer): 39 mm →22 mm
- Reduce material budget: X/X_0 /layer: ~1.14% → ~ 0.3%
- Reduce pixel size (currently 50 µm x 425 µm):
  monolithic pixels → O(20 µm x 20 µm),
  hybrid pixels → state-of-the-art O(50 µm x 50 µm)

2. Improve tracking efficiency and p_T resolution at low p_T:
- Increase granularity: 6 layers → 7 layers , reduce pixel size
- Increase radial extension: 39-430 mm → 22– 430(500) mm

3. Fast readout:
  readout of *PbPb* interactions at > 50 kHz and *pp* interactions at several MHz

4. Fast insertion/removal for yearly maintenance:
  possibility to replace non functioning detector modules during yearly shutdown

ITS Upgrade Design Milestones

March 2012

Upgrade Strategy for ALICE at High Rate, CERN-LHCC–2012-005

Upgrade of the Inner Tracking System, CDR0, CERN-LHCC-2012-004

September 2012

Comprehensive Letter of Intent submitted to LHCC →

Upgrade of the ALICE Experiment, Letter of Intent, CERN–LHCC–2012 -12

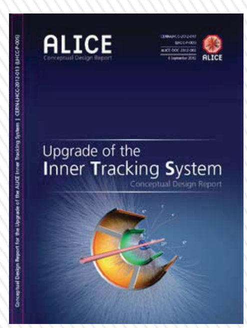
https://cdsweb.cern.ch/record/1475243/files/LHCC-I-022.pdf

together with:

Upgrade of the Inner Tracking System, CDR1, CERN-LHCC–2012-13

https://cdsweb.cern.ch/record/1475244/files/LHCC-P-005.pdf

Aim for 2013 →TDR



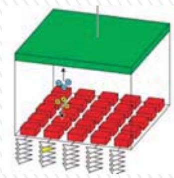
Upgrade options

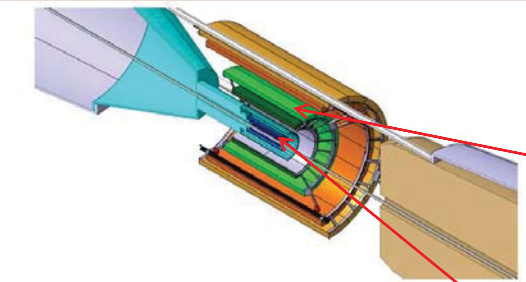
Option A: 7 layers of pixel detectors
- ❑ better standalone tracking efficiency and momentum resolution
- ❑ worse particle identification

Option B: 3 inner layers of pixel detectors and 4 outer layers of strip detectors
- ❑ worse standalone tracking efficiency and momentum resolution
- ❑ better particle identification

Option A

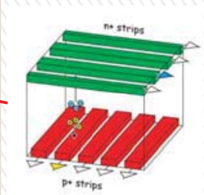
7 layers of pixels



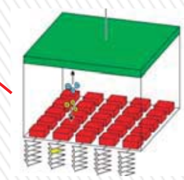


Option B

4 layers of strips



3 layers of pixels



Pixels: O(20x20µm² – 50 x 50µm²)

Pixels: O(20x20µm² – 50 x 50µm²)
Strips: 95 µm x 2 cm, double sided

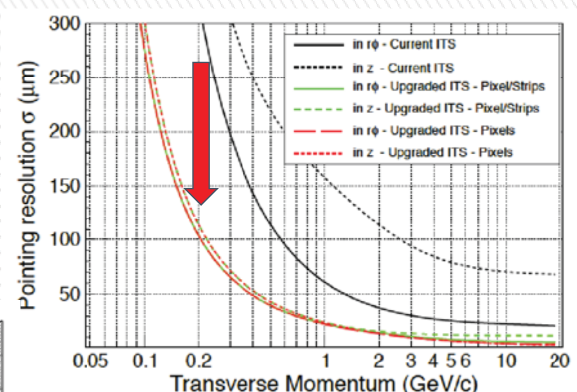
Technical specifications for the inner layers (layers 1-3) of ITS upgrade

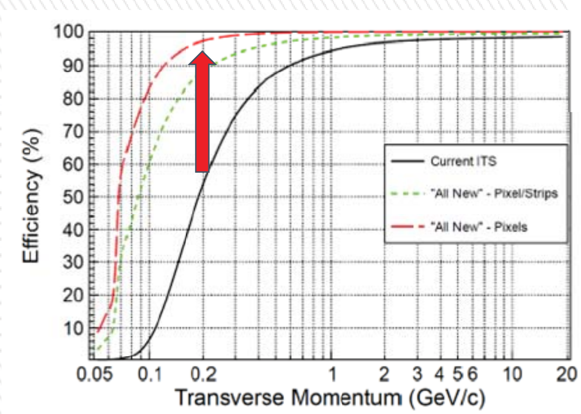
Parameter	Design Value	Comment
Material Budget per Layer	0.3% X_0	Max.: 0.5% X_0
Chip Size	15 mm x 30 mm	Target Size
Pixel Size (r-Φ)	20 µm	Max.: 30 µm
Pixel Size (z)	20 µm	Max.: 50 µm
Readout Time	≤ 30 µs	Max.: 50 µs
Power Density	0.3 W/cm²	Max.: 0.5 W/cm²
Hit Density	150 hits/cm²	Peak Value
Radiation Levels (Layer 1, r=22 mm)	700 krad (TID) 1 x 10^{13} n_{eq}/cm^2 (NIEL)	Safety-factor: 4

Technical specifications for the outer layers (layers 4-7) of ITS upgrade

Parameter	Design Value	Comment
Material Budget per Layer	0.3% X_0	Max.: 0.8% X_0
Cell Size (r-Φ)	≤ 70 μm	
Cell Size (z)	≤ 2 cm	
Readout Time	≤ 30 μs	Max.: 50 μs
Power Density	0.3 W/cm^2	Max.: 0.5 W/cm^2
Hit Density	≈ 1 hit/cm^2	Layer 4
Radiation Levels (Layer 4, r=200 mm)	10 krad (TID) 3×10^{11} n_{eq}/cm^2 (NIEL)	Safety-factor: 4

Improved impact parameter resolution and high standalone tracking efficiency





Large on-going MC simulation effort using detailed GEANT simulation within ALICE standard framework AliRoot

R&D activities

Pixel detectors

- Hybrid pixels with reduced material budget and small pitch
- Monolithic pixels rad-tolerant

Double-sided strip detectors (outer layers)

- Shorter strips and new readout electronics

Electrical bus for power and signal distribution

- Low material budget

Cooling system options

- air cooling, carbon foam, polyimide and silicon micro-channels structure, liquid vs evaporative, low material budget

For details: The ALICE Inner Tracker Upgrade presentation given by Petra Riedel on 12.10.2012 in a Joint Instrumentation Seminar of the Particle Physics and Photon Science communities at DESY, Hamburg University and XFEL:

http://instrumentationseminar.desy.de

Monolithic Pixel technology

Features:

- ❑ Made significant progress, soon to be installed in STAR
- ❑ All-in-one, detector-connection-readout
- ❑ Sensing layer included in the CMOS chip
- ❑ Charge collection mostly by diffusion (Monolithic Active Pixel Sensors - MAPS), but some development based on charge collection by drift
- ❑ Small pixel size: 20 µm x 20 µm target size
- ❑ Small material budget: 0.3% X_0 per layer

Comparison with hybrid technology:

+ material budget
+ granularity
+ low production cost
- radiation tolerance

Options under study:

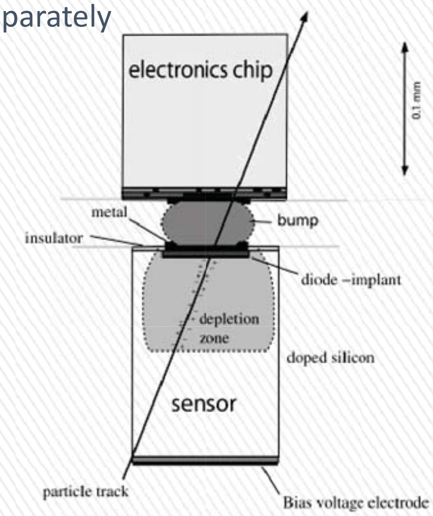
- MIMOSA (←STAR-PXL) like in 180 nm CMOS →TowerJazz
- INMAPS in 180 nm CMOS →TowerJazz
- LePix in 90 nm CMOS → IBM
- MISTRAL (←MIMOSA) prototype circuit (IPHC)

Hybrid pixel detectors

- ❑ Well known technology
- ❑ Proven radiation hardness
- ❑ Pixel size is limited due to the bump bonding
- ❑ Two Si-chips limit the minimal material budget.
- ❑ High production cost due to the bump bonding

Simplified view → Sandwich:
- Sensor
- Frontend-readout chip
- Interconnect (bump bonds)

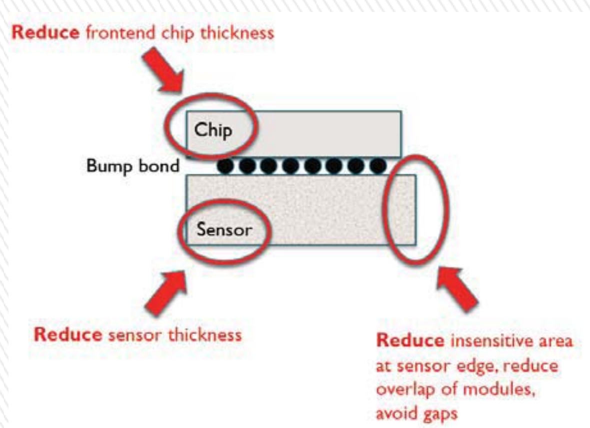
Sensor and chip can be optimized separately



Hybrid pixel detectors

R&D ongoing:
- Bump bonding with 30 µm pitch.
- Sensor and readout chip thinning: 50 µm (readout) + 100 µm (sensor) = 150 µm in 130 nm CMOS → studies in CERN.

Comparison with monolithic technology:
+ radiation tolerance
+/- granularity
- material budget



Strip Detectors

- Well known technology
- Provides ionization energy loss information that is needed for PID
- Granularity is adequate for the external layers only

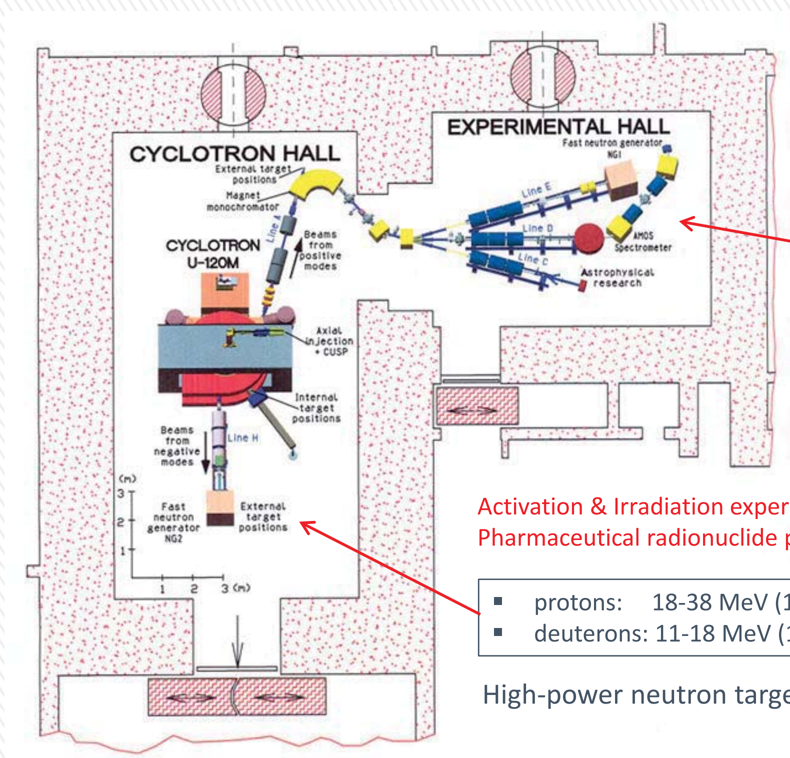
R&D Ongoing:
- Sensor is based on the old design with 2x shorter strips
- New readout ASIC will have ADC on-board

Timeline of the ITS upgrade project

2012	Finalization of specifications / first prototypes / radiation tests
2013	Selection of technologies and design of mechanics and services
2014	Final Design and validation
2015-2016	Production /construction and test of detector modules
2017	Assembly and pre-commissioning
2018	Installation in ALICE

U-120M cyclotron in Nuclear Physics Institute Řež as a test bed instrument

Cyclotron U-120M



Spectrometry experiments

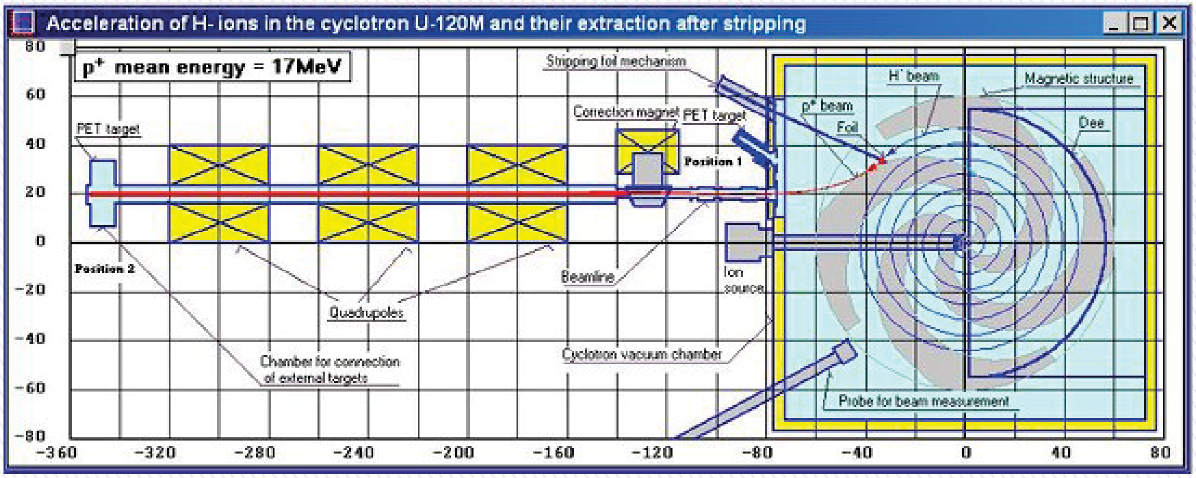
- protons: 18-24 MeV (3 μA)
- deuterons: 11-17 MeV (3 μA)
- ^{3}He-ions: 20-40 MeV (2 μA)

Activation & Irradiation experiments
Pharmaceutical radionuclide production

- protons: 18-38 MeV (15 μA)
- deuterons: 11-18 MeV (10 μA)

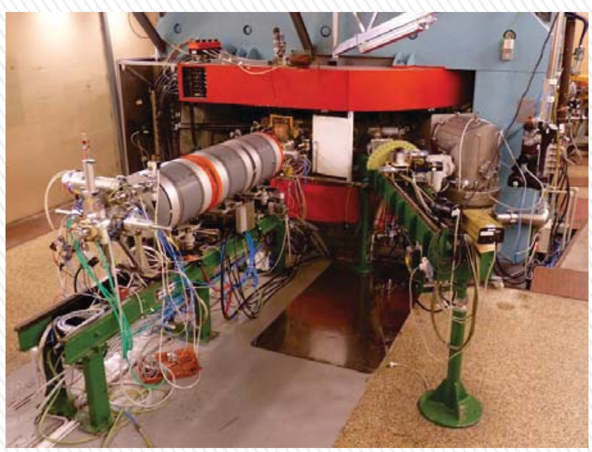
High-power neutron target station

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^-

Open Access mode



Center of Accelerators and Nuclear Analytical Methods (CANAM infrastructure) 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 ASCR, experimental facilities are proffered to the users in Open Access mode. The proposals should be submitted via User Portal

Radiation Hardness

-

Single Upset Event

Single Event Upset

Wikipedia: Change of state in memory cells or registers caused by ionizing particles. The state change is a result of the free charge created by ionization in a sensitive node of the circuit. The SEU itself is not permanently damaging to the transistor's or circuits' functionality.

Specific design factors which impact error rates:

- Increased complexity raises the error rate.
- Higher-density (higher-capacity) chips are more likely to have errors.
- Lower-voltage devices are more likely to have errors.
- Higher speeds (lower latencies) contribute to higher error rates.
- Lower cell capacitance (less stored charge) causes higher error rates.
- Shorter bit-lines result in fewer errors.
- Wafer thinning improves error tolerance (especially with backside contacts).
- "Radiation hardening" can decrease error rates by several orders of magnitude , but these techniques cost more, reduce performance, use more power, and/or increase area.

For some of your infamous Windows blue screen you should blame not only MicroSoft

Soft Error Rates as a Function of IC Process Technology

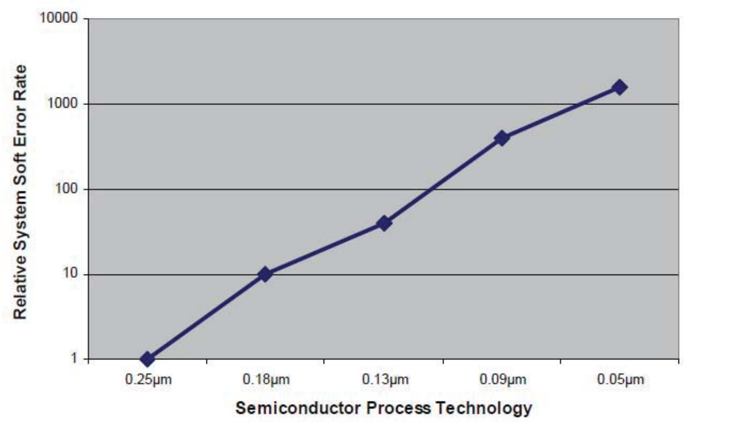


Chart (*) includes α particle effects as well as neutron effects.
At ground level, cosmic radiation is about 95% neutrons and 5% protons.

(*) Semico Research Corporations, "Gate Arrays Wane while Standard Cells Soar: ASIC Market Evolution Continues"

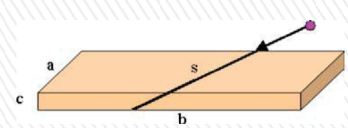
History: ground nuclear testing (1954-1957), space electronics (during the 1960s), first evidence of soft errors from α particles in packaging materials (1979) and from sea level cosmics rays. Many resources, e.g.:

http://radhome.gsfc.nasa.gov/radhome/see.htm
http://www.altera.com/support/devices/reliability/seu/seu-index.html

Single Event Upset

Charge deposition by ionizing particle can lead to a change in state of a transistor:

- Critical charge $Q_{crit} = (0.0023\ pC/\mu m^2)\ L^2$ ← *empirical law*
  L = feature size (SEU chip: L=0.18 µm)
- Energy deposition $E_{dep} = LET\ \rho\ s$
  LET = linear energy transfer (energy deposited per unit path length as an energetic particle travels through a material)
  ρ = density (Si: ρ = 2.33 g/cm^3);
  s_{max}= path length ($s_{max}^2 = 2L^2 + c^2$, for a=b=L, c = device depth)



  s_{min} = minimum distance particle of given LET must travel before being able to deposit sufficient energy to cause an SEU.

  Particles incident at an angle have a path that is 1/cos(Θ) longer than the path at normal incidence → cosine law.

Single Event Upset

- Charge deposition $Q_{dep} = E_{dep}\ q / w_{ehp}$

  $q = 1.6022 \times 10^{-19}$ Coulombs/e

  w_{ehp} = electron-hole pair creation energy (Si: w_{ehp} = 3.6 eV)
- Minimum LET to cause an upset:

  $LET_{threshold} = Q_{crit}\ w_{ehp} / (q\ s_{max})$
- $LET_{threshold}$ (APEX FPGA) ≈ 100 keV/mg/cm^2
- LET (30 MeV proton in Si) = 15 keV/mg/cm^2

Even using a relatively conservative error rate a system with 1 GByte of RAM can expect an error every two weeks due to cosmics rays. A hypothetical Terabyte system would experience a soft error every few minutes.

The most commonly used system of error recovery (Error Checking and Correction - ECC), adds extra bits (check bits) to each data item. These bits are re-computed and compared whenever the data item is accessed. Most ECC algorithms can correct single-bit errors and detect, but not correct, double-bit errors.

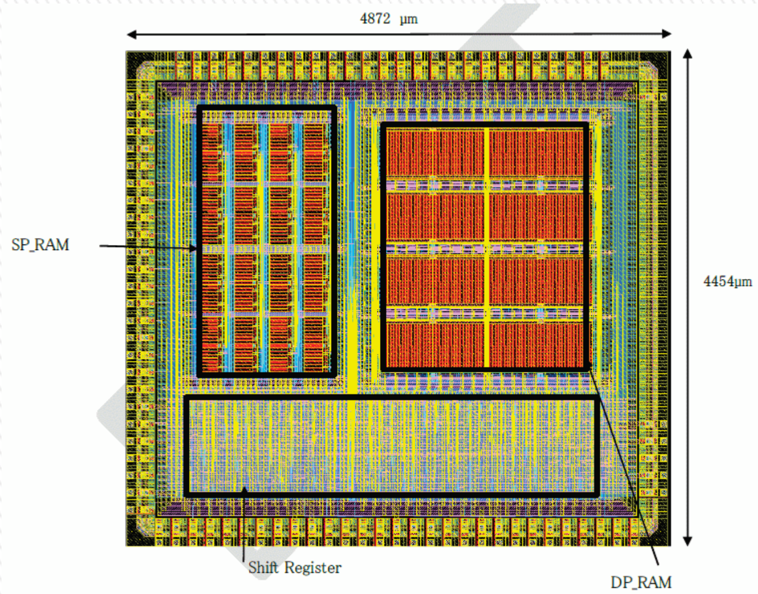
Contribution into ITS upgrade project of NPI CAS Řež and IEP SAS Košice

Group consisting of

NPI CAS: V.Kushpil, S.Kushpil, V.Mikhaylov, J.F.

IEP SAS: J.Špalek

SEU chip



Contribution of our group: to measure the SEU sensitivity / cross section for:

- single port RAMs (16 x 1024x16bits)
- dual port RAMs (8 x 2048x16bits)
- 16 bit 32K stages shift register

Circuits designed in CERN using a commercial 180 nm low power CMOS technology:
- TowerJazz 0.18 mm
- 1.8 V
- 4 Metal Layers
- Max. frequency 10MHz

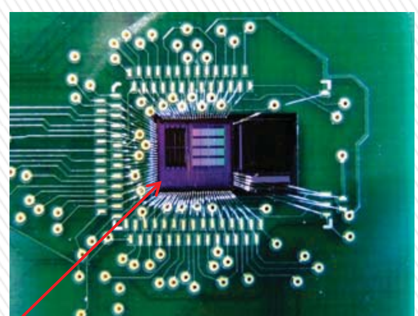
SEU cross section per bit:

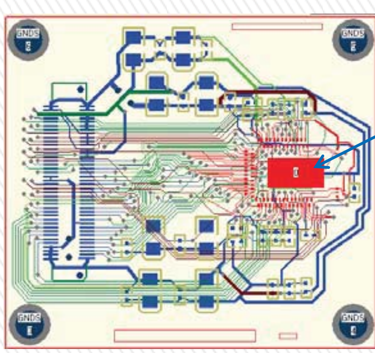
$$\sigma_{seu} = \frac{\#\,\text{failures}}{\#\,\text{bits}\,.\,flux\,.\,\Delta t}$$

Estimated SEU cross section per bit: ≈ 10^{-13} cm^2 bit^{-1}

SEU chip bonding in DESY Zeuthen

Many thanks to Wolfgang Lange and Jürgen Pieper





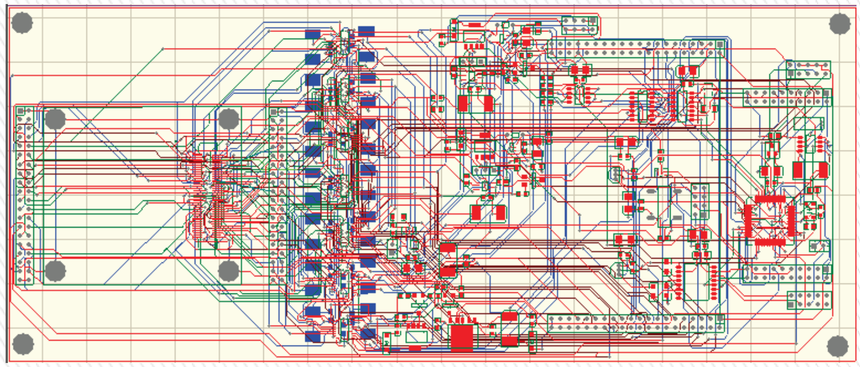
SEU chip

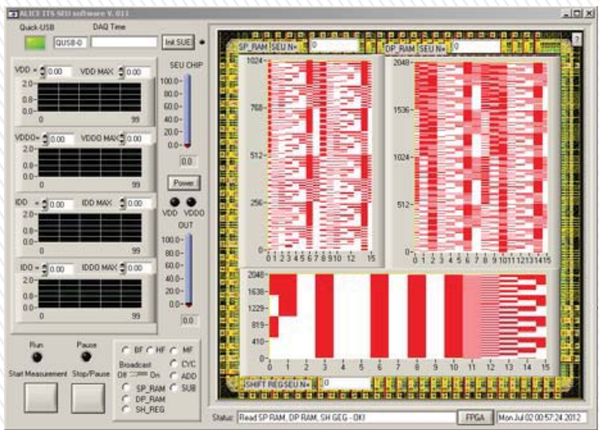
Custom SEU chip board by V.Kushpil

Measurement setup

Custom analog signals DAQ Board
SEU chip readout via FPGA with clock speed or USB (slower)

V. Kushpil



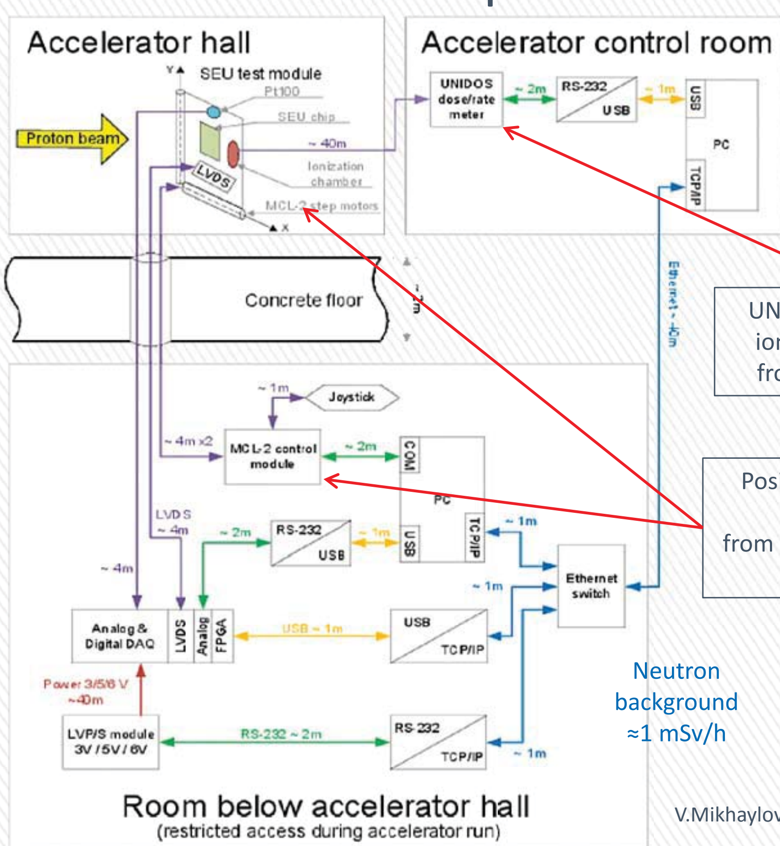


Graphical User Interface (LabView)

S. Kushpil, V.Mikhaylov

Measurement setup schematics

Neutron background ≈10 mSv/h



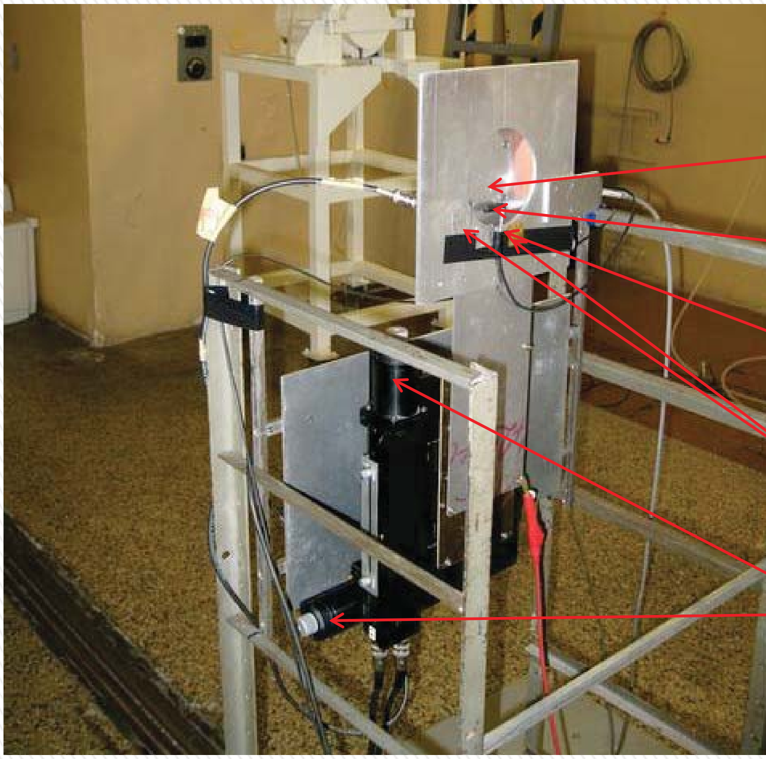
UNIDOS system with ionization chamber from PTW Freiburg

Position Control System MCL-2 from LANG GmbH & Co. KG Hüttenberg

Neutron background ≈1 mSv/h

V.Mikhaylov

Measurement setup in cyclotron



5x5 mm² (= SEU chip) hole

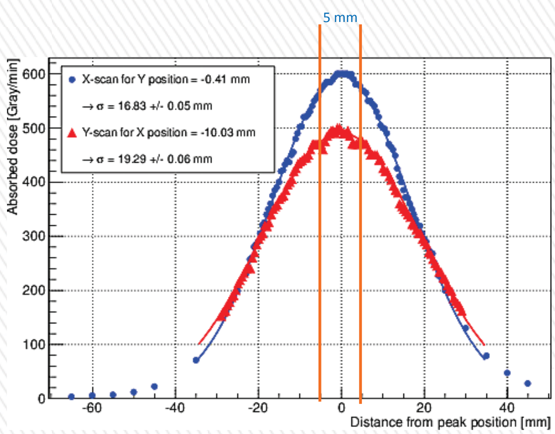
Ionization chamber

Pt100 thermometer

2 x AL + 1 x Au activation analysis foils

X & Y 1µm step motors

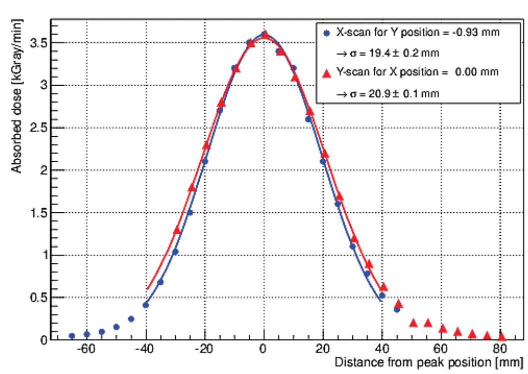
Proton beam profile scan in negative mode



Low intensity (~*0.4 µA*):
with collimator slit 1 mm
High intensity (~*2.1 µA*):
with collimator fully open

Extracted E_p = 27.845 MeV

High intensity scan
σ_x = 19.4 mm and σ_y = 20.9 mm



Low intensity scan:
σ_x = 16.8 mm and σ_y = 19.3 mm

Irradiation homogeneity required better than 10% → beam alignment at the level of few mm for SEU chip 5 x 5 mm²

→ Radiation doses ~ 1 Mrad (10 kGray) can be accumulated within short time

Immediate plans:

- finish & test the electronics setup
- determine SEU proton energy dependence as a function of accumulated doses
- verify SEU proton angular dependence
- especially look for multiple bit errors
- the same above also for neutrons

Thank you for your attention !