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:
- PhotonMultiplicity
- Forward Multiplicity
- Muon Spectrometer

Calorimeters:
- EM Calorimeter (EMCAL)
- Photon Spectrometer (PHOS)
- Zero Degree Calorimeter (ZDC)

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

Collaboration:
- > 1000 Members
- > 100 Institutes
- > 30 countries

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)

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)

<table>
<thead>
<tr>
<th>Layer/ Type</th>
<th>Radius [cm]</th>
<th>Length [cm]</th>
<th>Number of modules</th>
<th>Active area per module [mm²]</th>
<th>Nom. resolution rΦ x z [μm]</th>
<th>Material budget X/X₀ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam pipe</td>
<td>2.94</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.22</td>
</tr>
<tr>
<td>1 / Pixel</td>
<td>3.9</td>
<td>28.2</td>
<td>80</td>
<td>12.8 x 70.7</td>
<td>12 x 100</td>
<td>1.14</td>
</tr>
<tr>
<td>2 / Pixel</td>
<td>7.6</td>
<td>28.2</td>
<td>160</td>
<td>12.8 x 70.7</td>
<td>12 x 100</td>
<td>1.14</td>
</tr>
<tr>
<td>Thermal Shield</td>
<td>11.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.65</td>
</tr>
<tr>
<td>3 / Drift</td>
<td>15.0</td>
<td>44.4</td>
<td>84</td>
<td>70.2 x 75.3</td>
<td>35 x 25</td>
<td>1.13</td>
</tr>
<tr>
<td>4 / Drift</td>
<td>23.9</td>
<td>59.4</td>
<td>176</td>
<td>70.2 x 75.3</td>
<td>35 x 25</td>
<td>1.26</td>
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<tr>
<td>Thermal Shield</td>
<td>31.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.65</td>
</tr>
<tr>
<td>5 / Strip</td>
<td>38.0</td>
<td>86.2</td>
<td>748</td>
<td>73.0 x 40.0</td>
<td>30 x 830</td>
<td>0.83</td>
</tr>
<tr>
<td>6 / Strip</td>
<td>43.0</td>
<td>97.8</td>
<td>950</td>
<td>73.0 x 40.0</td>
<td>20 x 830</td>
<td>0.83</td>
</tr>
</tbody>
</table>
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 $\rightarrow$ 22 mm
   - Reduce material budget: $X/X_0$ /layer: $\sim 1.14\% \rightarrow \sim 0.3\%$
   - Reduce pixel size (currently 50 $\mu m \times 425 \mu m$):
     - monolithic pixels $\rightarrow$ O(20 $\mu m \times 20 \mu m$),
     - hybrid pixels $\rightarrow$ state-of-the-art O(50 $\mu m \times 50 \mu m$)

2. **Improve tracking efficiency and $p_T$ resolution at low $p_T$:**
   - Increase granularity: 6 layers $\rightarrow$ 7 layers, reduce pixel size
   - Increase radial extension: 39-430 mm $\rightarrow$ 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 $\rightarrow$
Upgrade of the ALICE Experiment, Letter of Intent, CERN–LHCC–2012 -12
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 $\rightarrow$ 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

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Budget per Layer</td>
<td>0.3% $X_0$</td>
<td>Max.: 0.5% $X_0$</td>
</tr>
<tr>
<td>Chip Size</td>
<td>15 mm x 30 mm</td>
<td>Target Size</td>
</tr>
<tr>
<td>Pixel Size (r-ƿ)</td>
<td>20 μm</td>
<td>Max.: 30 μm</td>
</tr>
<tr>
<td>Pixel Size (z)</td>
<td>20 μm</td>
<td>Max.: 50 μm</td>
</tr>
<tr>
<td>Readout Time</td>
<td>≤ 30 μs</td>
<td>Max.: 50 μs</td>
</tr>
<tr>
<td>Power Density</td>
<td>0.3 W/cm²</td>
<td>Max.: 0.5 W/cm²</td>
</tr>
<tr>
<td>Hit Density</td>
<td>150 hits/cm²</td>
<td>Peak Value</td>
</tr>
<tr>
<td>Radiation Levels (Layer 1, ρ=22 mm)</td>
<td>700 krad (TID)</td>
<td>Safety-factor: 4</td>
</tr>
<tr>
<td></td>
<td>$1 \times 10^{13}$ n_{eq}/cm² (NIEL)</td>
<td></td>
</tr>
</tbody>
</table>
Technical specifications for the outer layers (layers 4-7) of ITS upgrade

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Budget per Layer</td>
<td>0.3% $X_0$</td>
<td>Max.: 0.8% $X_0$</td>
</tr>
<tr>
<td>Cell Size (r-Φ)</td>
<td>≤ 70 μm</td>
<td></td>
</tr>
<tr>
<td>Cell Size (z)</td>
<td>≤ 2 cm</td>
<td></td>
</tr>
<tr>
<td>Readout Time</td>
<td>≤ 30 μs</td>
<td>Max.: 50 μs</td>
</tr>
<tr>
<td>Power Density</td>
<td>0.3 W/cm²</td>
<td>Max.: 0.5 W/cm²</td>
</tr>
<tr>
<td>Hit Density</td>
<td>≈ 1 hit/cm²</td>
<td>Layer 4</td>
</tr>
<tr>
<td>Radiation Levels (Layer 4, r=200 mm)</td>
<td>10 krad (TID)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$3 \times 10^{11}$ n$_{eq}$/cm$^2$ (NIEL)</td>
<td>Safety-factor: 4</td>
</tr>
</tbody>
</table>

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% X₀ 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

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**

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>Finalization of specifications / first prototypes / radiation tests</td>
</tr>
<tr>
<td>2013</td>
<td>Selection of technologies and design of mechanics and services</td>
</tr>
<tr>
<td>2014</td>
<td>Final Design and validation</td>
</tr>
<tr>
<td>2015-16</td>
<td>Production /construction and test of detector modules</td>
</tr>
<tr>
<td>2017</td>
<td>Assembly and pre-commissioning</td>
</tr>
<tr>
<td>2018</td>
<td>Installation in ALICE</td>
</tr>
</tbody>
</table>
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 \(\rightarrow H^-\)
Carbon stripping foil: \(H^- \rightarrow\) 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/](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](http://canam.ujf.cas.cz/).
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

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

- Critical charge $Q_{\text{crit}} = (0.0023 \text{ pC/μm}^2) L^2$ ← empirical law
  
  $L =$ feature size (SEU chip: $L=0.18 \text{ μm}$)

- Energy deposition $E_{\text{dep}} = \text{LET} \cdot \rho \cdot s$
  
  LET = linear energy transfer (energy deposited per unit path length as an energetic particle travels through a material)
  
  $\rho =$ density (Si: $\rho = 2.33 \text{ g/cm}^3$);
  
  $s_{\text{max}} =$ path length ($s_{\text{max}}^2 = 2L^2 + c^2$, for $a=b=L$, $c =$ device depth)

  $s_{\text{min}} =$ 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 $1/\cos(\Theta)$ longer than the path at normal incidence → cosine law.
Single Event Upset

- Charge deposition \( Q_{\text{dep}} = E_{\text{dep}} \frac{q}{w_{\text{ehp}}} \)
  \( q = 1.6022 \times 10^{-19} \text{Coulombs/e} \)
  \( w_{\text{ehp}} = \text{electron-hole pair creation energy (Si: } w_{\text{ehp}} = 3.6 \text{ eV)} \)

- Minimum LET to cause an upset:
  \( \text{LET}_{\text{threshold}} = \frac{Q_{\text{crit}} w_{\text{ehp}}}{(q s_{\text{max}})} \)

- \( \text{LET}_{\text{threshold}} \) (APEX FPGA) \( \approx 100 \text{ keV/mg/cm}^2 \)

- LET (30 MeV proton in Si) = 15 keV/mg/cm²

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
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:

\[
\sigma_{\text{seu}} = \frac{\# \text{ failures}}{\# \text{ bits} \cdot \text{flux} \cdot \Delta t}
\]

Estimated SEU cross section per bit: \( \approx 10^{-13} \text{ cm}^2 \text{ bit}^{-1} \)

SEU chip bonding in DESY Zeuthen

Many thanks to Wolfgang Lange and Jürgen Pieper

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

- **Ionization chamber**
- **Pt100 thermometer**
- **2 x AL + 1 x Au activation analysis foils**
- **X & Y 1μm step motors**
- **5x5 mm² (= SEU chip) hole**

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

$\sigma_x = 19.4$ mm and $\sigma_y = 20.9$ mm

Low intensity scan:

$\sigma_x = 16.8$ mm and $\sigma_y = 19.3$ 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!