Proton and Neutron Irradiation Tests of Readout Electronics of the ATLAS Hadronic Endcap Calorimeter

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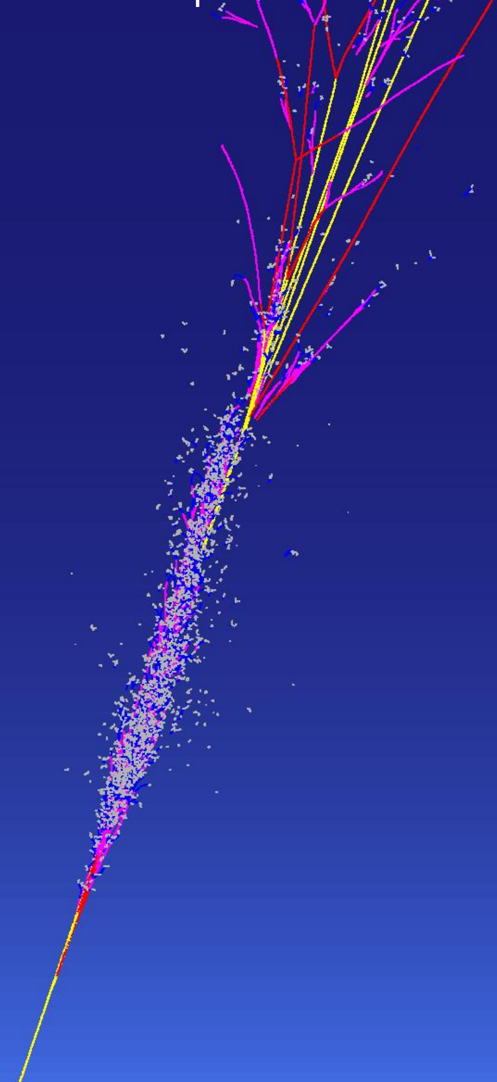
on behalf of the ATLAS Liquid Argon Calorimeter Group

- Introduction
- Proton irradiation at PSI
- Neutron irradiation in Řež
- Warm in-situ measurements
- Cold measurements after irradiation
- Conclusions



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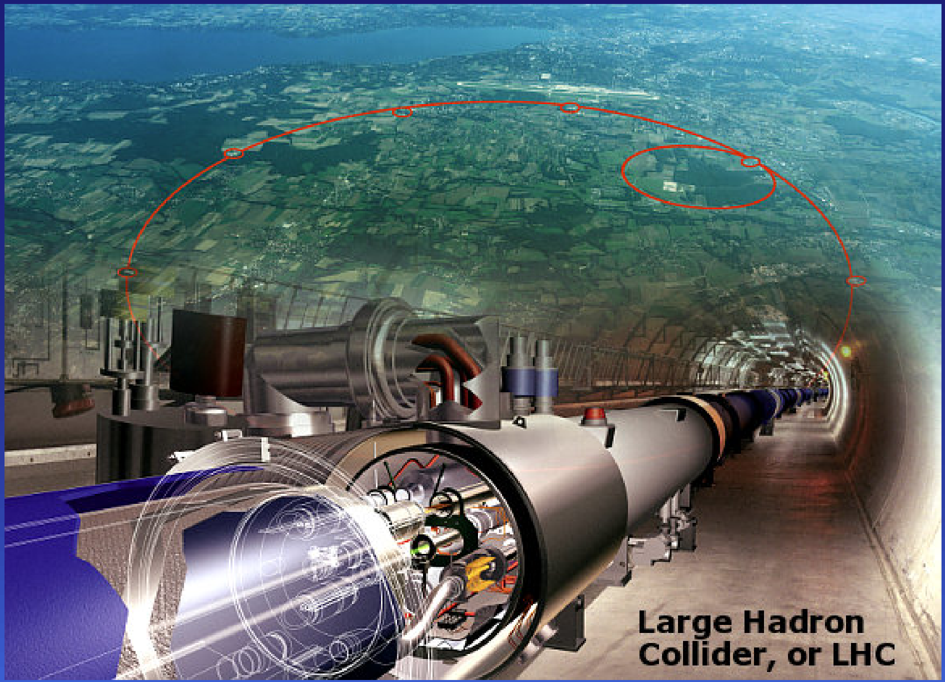
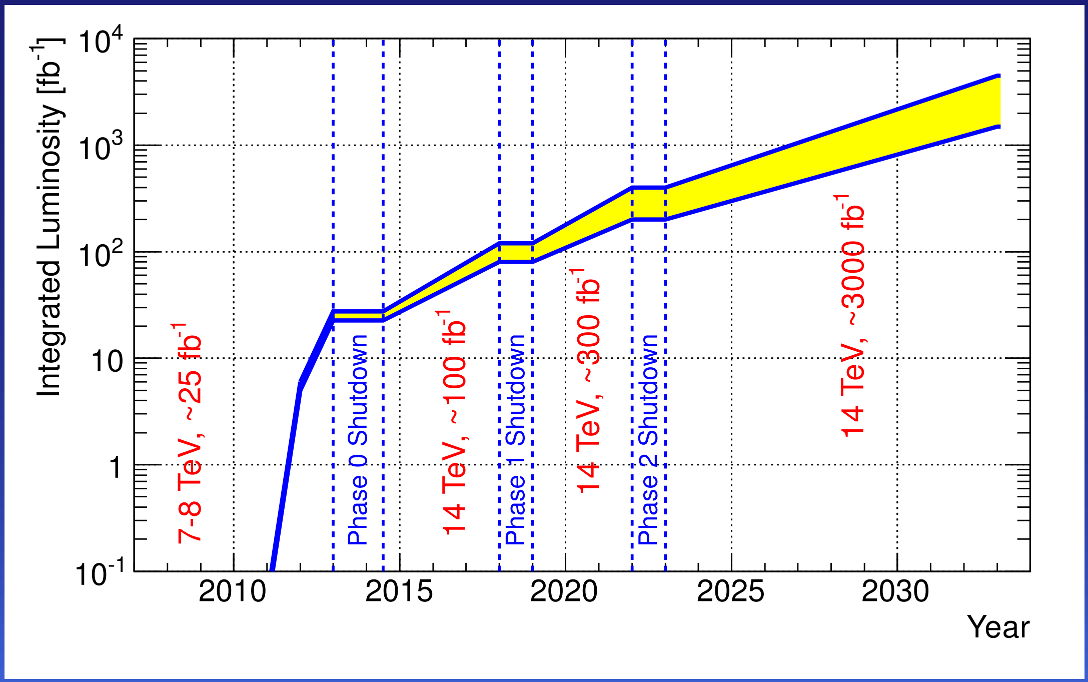
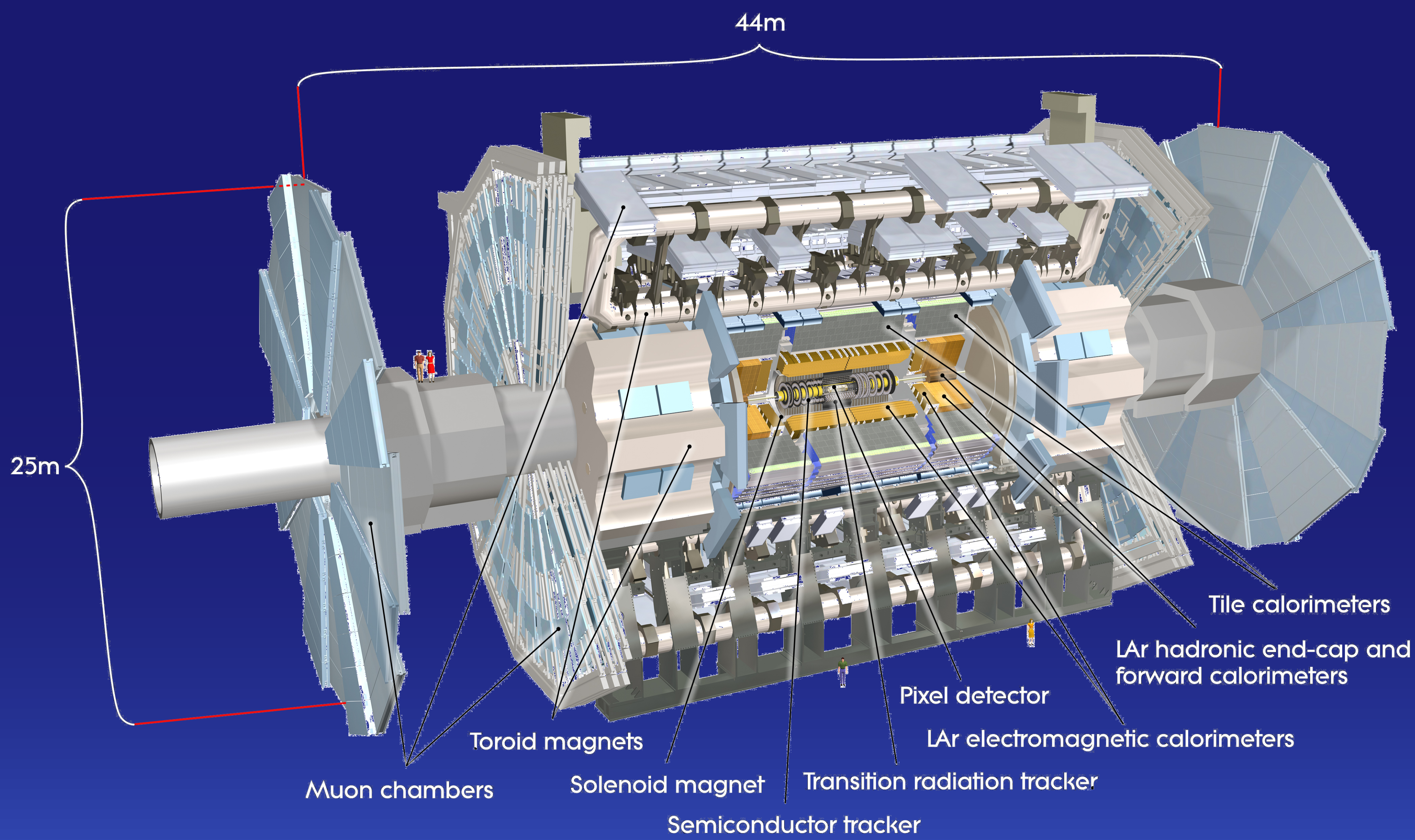
ATLAS and the HL-LHC

- LHC: pp collisions at $\sqrt{s} = 7\,\text{TeV}$ 2010 - 2011 and at $\sqrt{s} = 8\,\text{TeV}$ since March 2012
- several upgrade phases (energy and luminosity) are foreseen until 2023:
  - end of 2012: $\sim 25\,\text{fb}^{-1}$ pp collisions at 7-8 TeV
  - Phase 0 (until 2019): $\sim 100\,\text{fb}^{-1}$ pp collisions at 14 TeV
  - Phase 1 (until 2022): $\sim 300\,\text{fb}^{-1}$ pp collisions at 14 TeV
  - Phase 2 (beyond 2023): $\sim 3000\,\text{fb}^{-1}$ pp collisions at 14 TeV



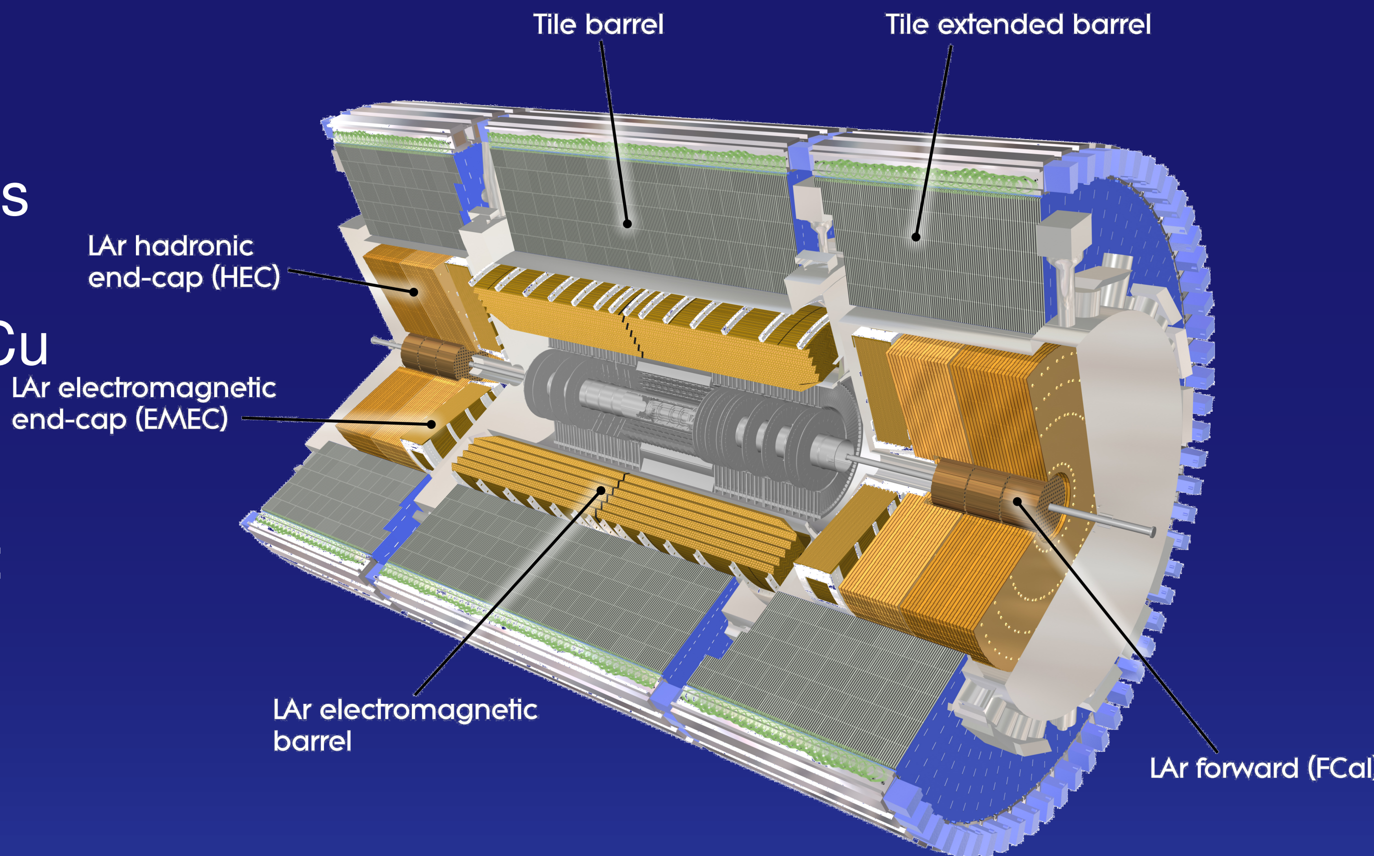


The ATLAS Detector



A Torodial **L**HC **A**pparatu**S**: 25 m high; 44 m long; 7000 t heavy

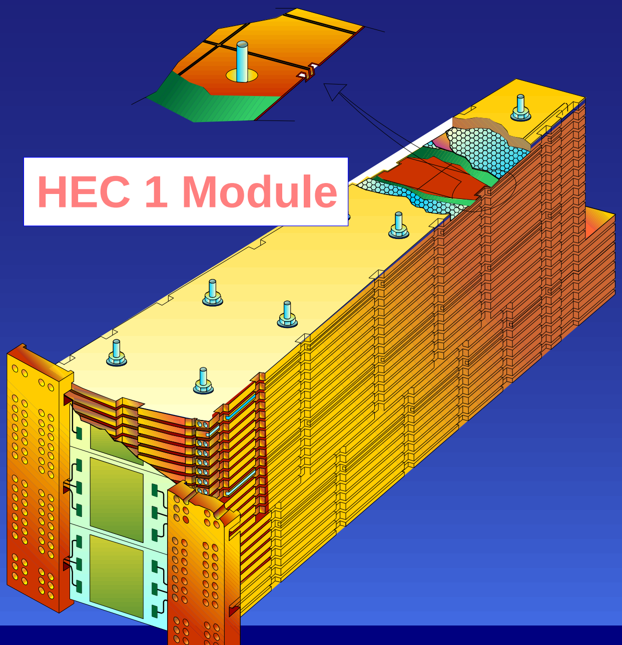
- Calorimeter coverage up to $|\eta| < 4.9$
- EM Barrel/Endcap: LAr/Pb Accordion $|\eta| < 1.4/1.375 < |\eta| < 3.2$
- Had Barrel: iron/scintillating tiles $|\eta| \lesssim 1.7$
- Had Endcap: LAr/Cu parallel plates $1.7 \lesssim |\eta| \lesssim 3.2$
- EM(HAD) Forward: LAr/Cu(W) tubular electrodes $3.2 \lesssim |\eta| \lesssim 4.9$



- typical cell sizes $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ (EM) and 0.1×0.1 (HAD); 3 to 7 samplings; at least $24\,X_0$ (EM) and $10\,\lambda$ (EM+HAD)
- e/γ: $\sigma_E/E \simeq 10\%/\sqrt{E}$
- jets: $\sigma_E/E \simeq 50\%/\sqrt{E} \oplus 3\%$

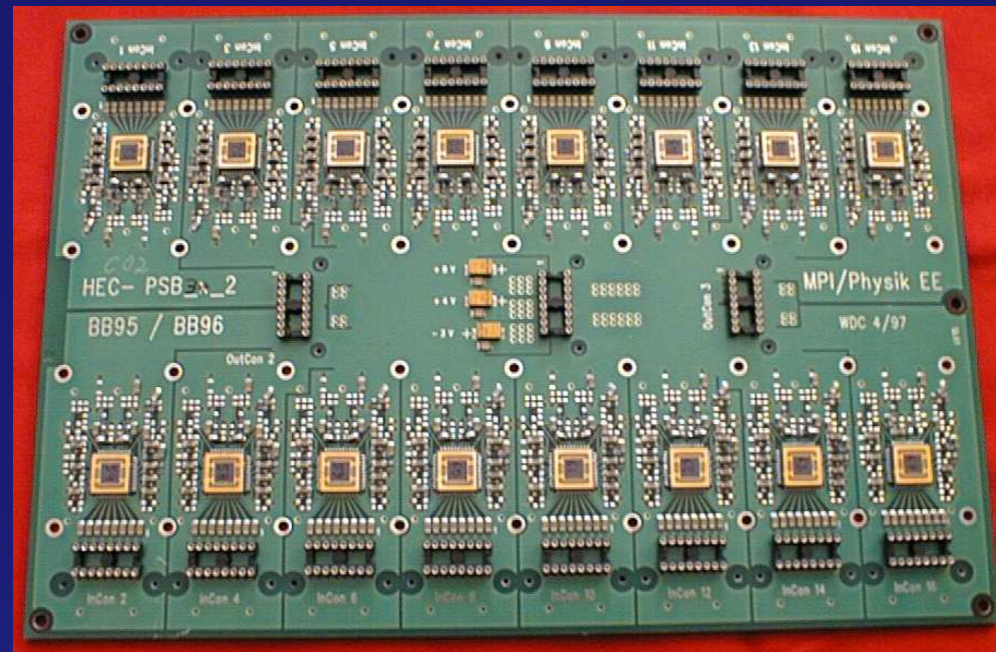
The Hadronic Endcap Calorimeter of ATLAS (HEC)

- The Hadronic Endcap Calorimeter of ATLAS consists of 2 calorimeters (one per endcap) and each of those of 2 wheels (front and back)
- It's a sampling calorimeter with copper plates as absorbers and liquid argon as sensitive material
- The wheels are segmented in φ into 32 modules and in z in 4 layers
- Each module has for each layer one or two Preamplifier and Summing Boards (PSB) attached directly on the outer perimeter – i.e. the electronics sits inside the liquid argon cryostat and is exposed to severe radiation
- HEC absorber structure
  - Absorbers plates parallel to beam axis
  - 2.5 cm thick Cu plates in HEC 1
  - 5.0 cm thick Cu plates in HEC 2

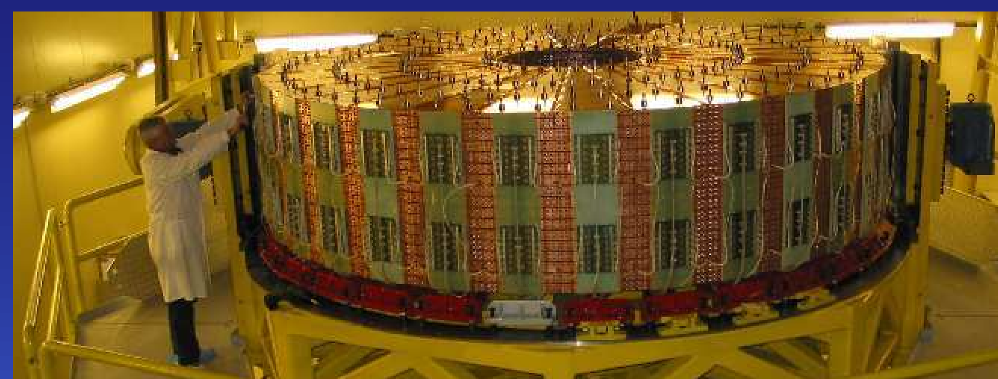


HEC Cold Electronics

- The heart of the PSBs are ~ 2600 GaAs ASICs with 8 input channels and 2 output channels

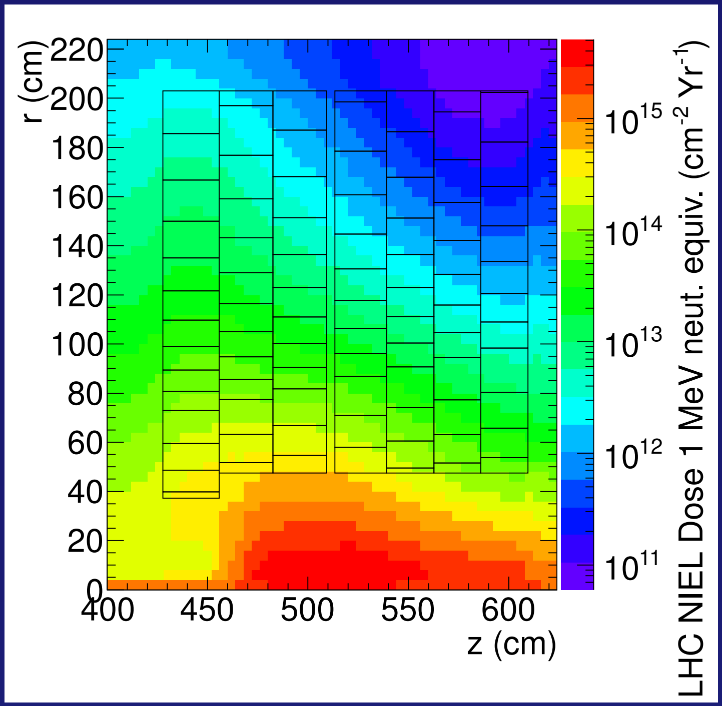


- Design principles for the ASICs:
  - 2 stage design consisting of 8 Pre-Amplifiers (PA) and 2 summing-amplifiers or drivers
  - large PA input transistor for low noise
  - input impedance of $50\,\Omega$ and large output impedance to allow summing of signals after the PAs
  - good high-frequency performance (up to $\sim 20\,\mathrm{MHz}$)
  - adjustable gain and timing by external components
  - radiation hardness for $(\text{Safety Factor} = 10) \times 12\,\text{years}$ of LHC running
  - low power consumption to avoid LAr boiling

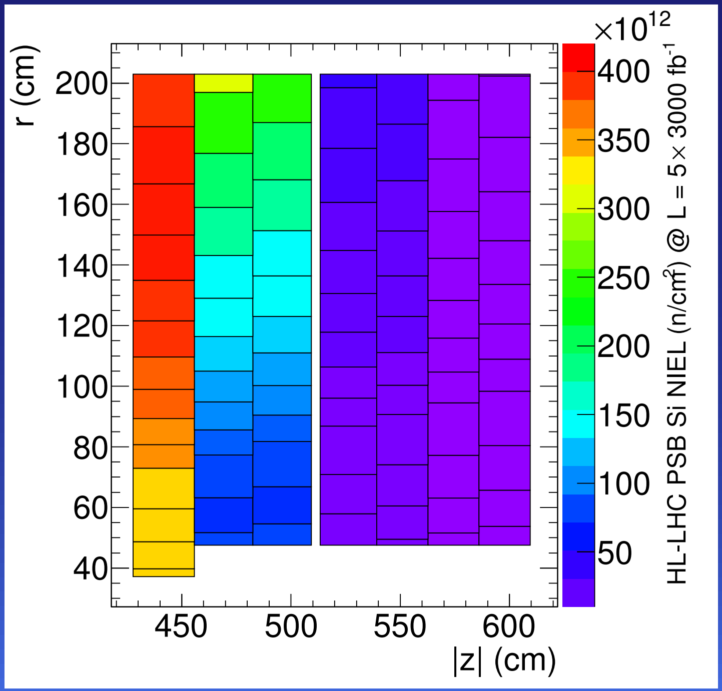


- upper picture shows one PSB
- lower picture shows one HEC wheel with PSBs mounted on the outer perimeter

Radiation Levels in ATLAS

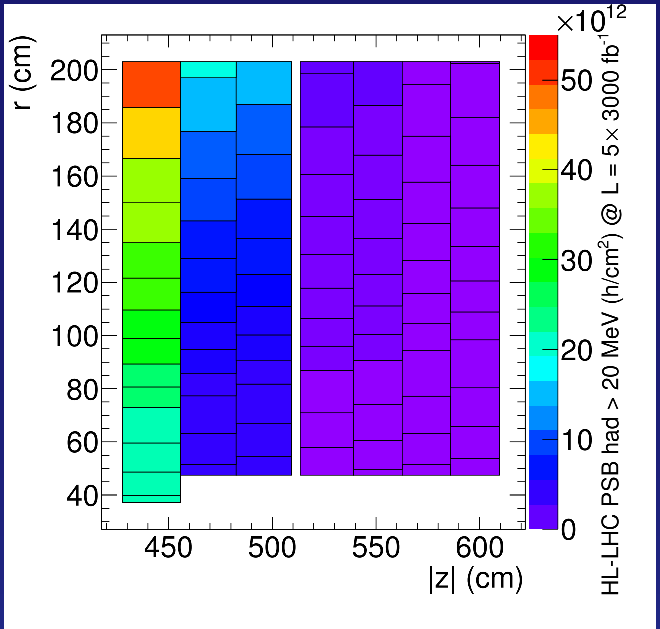


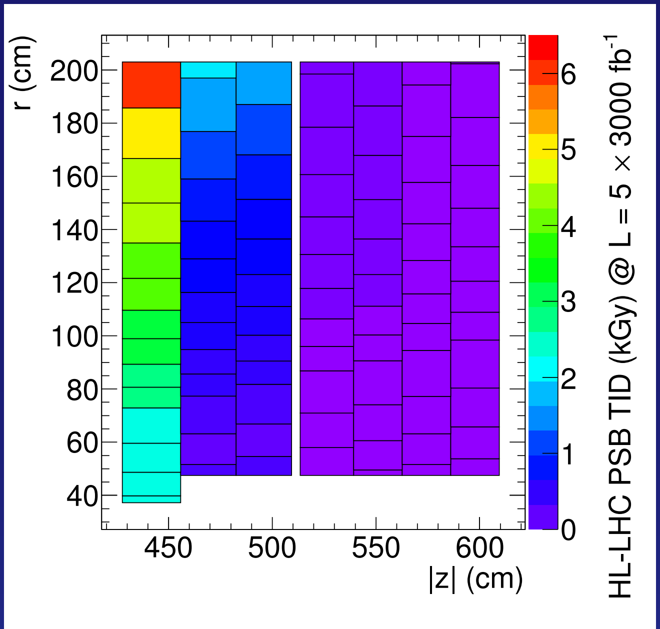
- look at simulations of neutrons (NIEL), hadrons ($E > 20$ MeV), and total ionization dose (TID) for ATLAS from 2003
- the numbers correspond to
  - 14 TeV pp collisions with $\sigma_{\text{inel}} = 79.3$ mb
  - Nominal luminosity of $\mathcal{L} = 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$
  - A standard running year of 10^7 s or 100 fb^{-1} per year
  - plot to the left shows NIEL for 1 LHC year in the HEC region
- ASICs are located at $r = 204$ cm and $429\,\text{cm} < |z| < 597\,\text{cm}$
- assumptions for HL-LHC:
  - 14 TeV pp collisions with $\sigma_{\text{inel}} = 79.3$ mb
  - Nominal (average) luminosity of $\mathcal{L} = 3 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$
  - A standard running year of 10^7 s or 300 fb^{-1} per year
  - A running time of 10 years
  - A safety factor of 5 for the simulation
  - plot to the right shows NIEL dose in PSBs at the location of the corresponding calorimeter segment



Radiation Levels in ATLAS

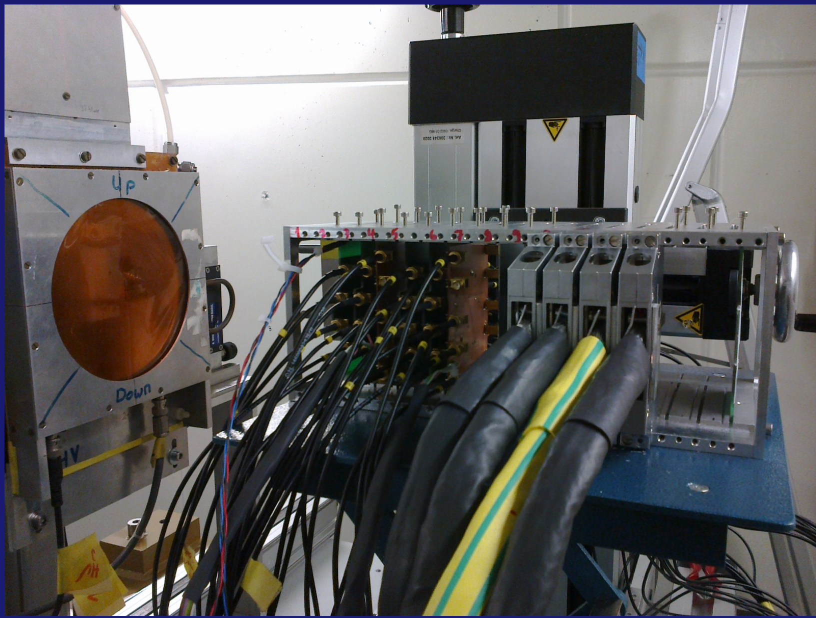
- similar plots below for the HL-LHC expected values at the ASIC locations (plotted at the corresponding HEC cell) for hadrons ($E > 20$ MeV), and total ionization dose (TID)
- the limiting numbers for all are reached in the first and most important section of the HEC at the lowest $|\eta|$ values
  - NIEL: 4.1×10^{14} n/cm^2
  - hadrons ($E > 20$ MeV): 5.1×10^{13} h/cm^2
  - TID: 6.2 kGy

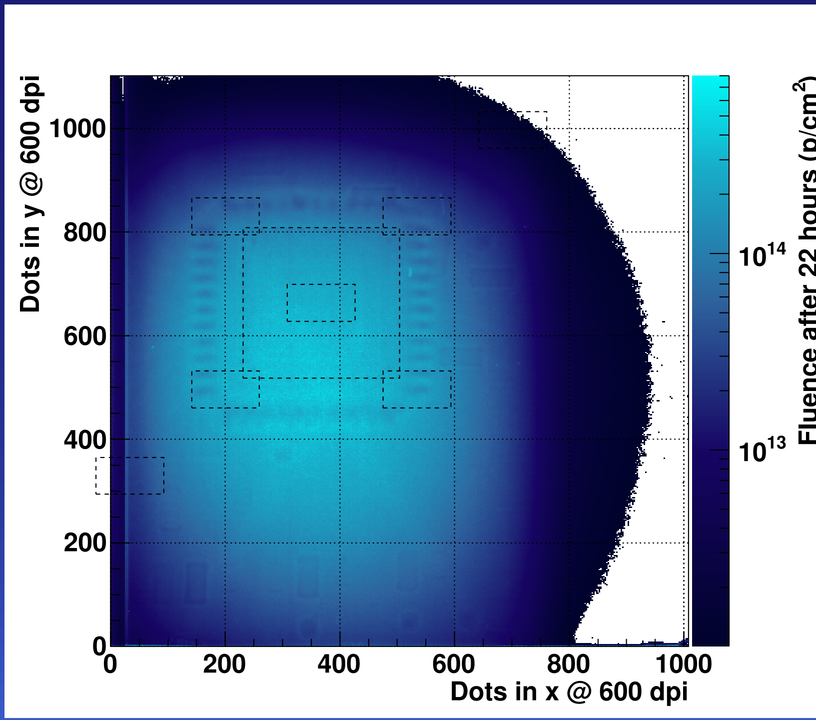




- use 200 MeV protons from the Proton Irradiation Facility (PIF) at the PSI to test hadrons $E > 20$ MeV
- use neutrons from (p, n) reaction of 36 MeV protons on D_2O target at Řež to test NIEL

Proton Test May 2011@PSI

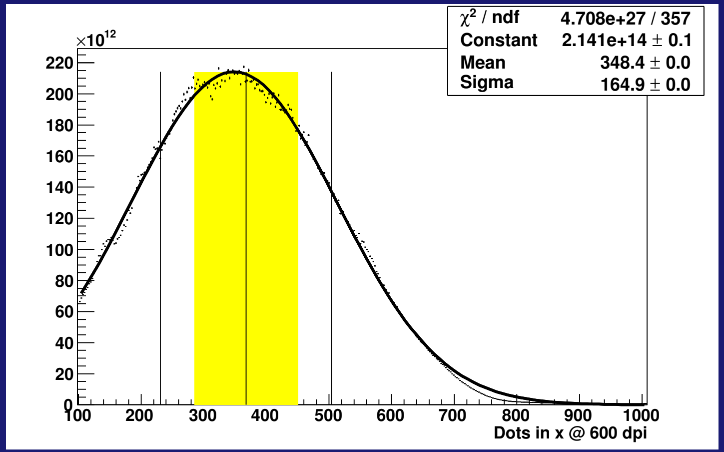


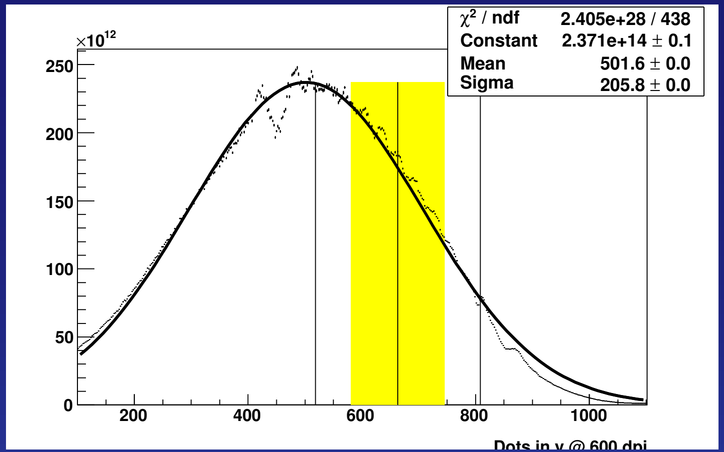


- proton beam from cyclotron with 198.9 MeV and $\sim$ 2.7 nA for $\sim$ 22 h and $\sim 7 \times 8.5\,\mathrm{mm}^2$ width (6.5 mm offset in y)
- beam comes from the left
- aluminum frame with up to 16 slots and 17 mm spacing
- final alignment was done closer to the collimator (5 cm)
- Slots 3 and 6 present HEC ASICs (BB96)
- For 5 minutes radiation films in Slots 2-6, 10 (not on picture)

Proton Fluence May 2011 at PSI

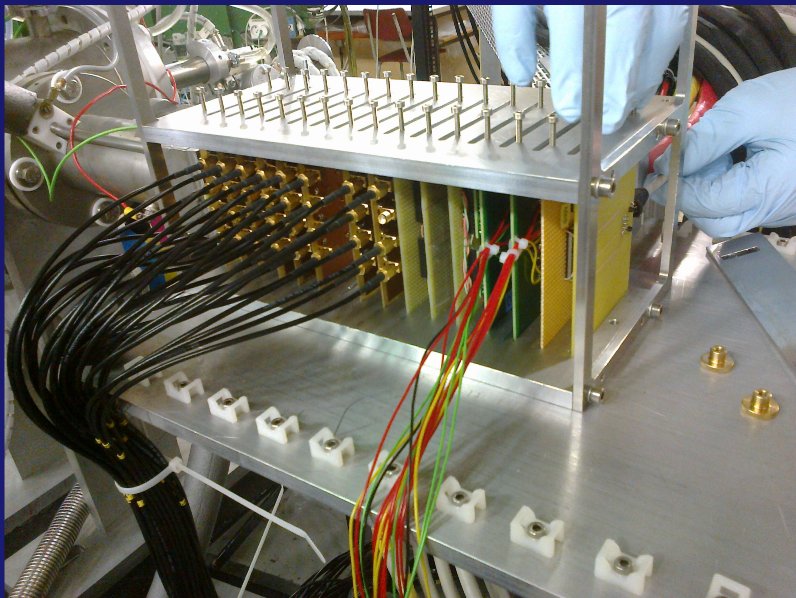
- Proton Beam at PSI was normalized with Ionization Chamber (IC) measurement: $255\,\mathrm{nA} \equiv 3\,\mathrm{nA}$ proton beam
- radiation films revealed displaced beam spot and confirmed small beam width:
  - $\Delta_x = (0 \pm 1)\,\mathrm{mm}$
  - $\Delta_y = (-6.5 \pm 0.1)\,\mathrm{mm}$
  - $\sigma_x = (7.1 \pm 0.2 - (0.08 \pm 0.03)\#_{\mathrm{slot}})\mathrm{mm}$
  - $\sigma_y = (8.5 \pm 0.2 + (0.11 \pm 0.03)\#_{\mathrm{slot}})\mathrm{mm}$
- The total fluence in the relevant areas of all slots is found to be constant and after $22.05\,\mathrm{h}$ of beam time at an average current of $2.714\,\mathrm{nA}$ is found to be $(2.6 \pm 0.4) \times 10^{14}\,\mathrm{p/cm^2}$

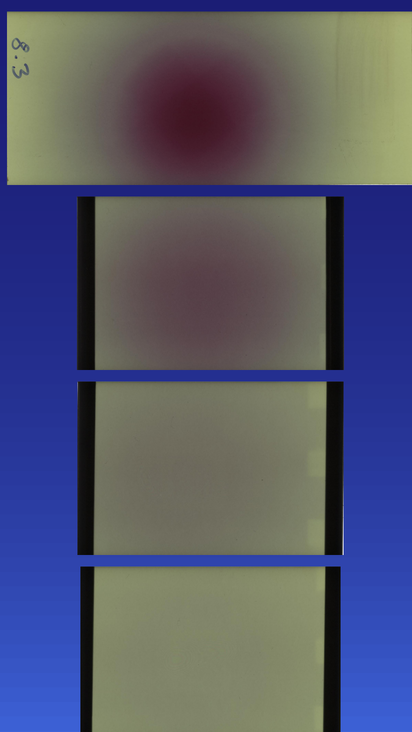




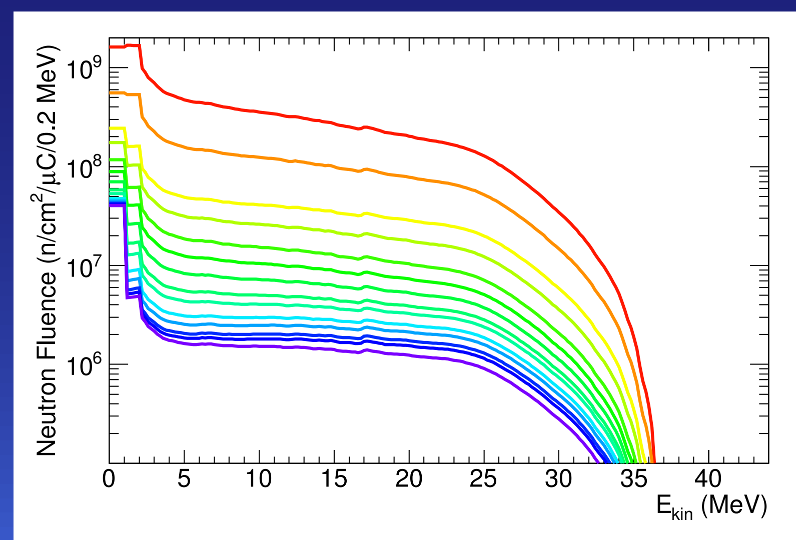
- The biggest contribution to the 15% error stems from the displaced beam spot in y which causes a large variation of the total intensity (12% for $\pm 2.5\,\mathrm{mm}$)

Neutron Test February 2012@Řež





- neutron irradiation at the 36 MeV proton cyclotron in Řež from 17.2.-19.2.2012
- beam comes from the left and enters D_2O target to produce neutrons
- similar aluminum frame with 16 slots and 17 mm spacing as at PSI
  - in slots 1-6,8,9: BB96 (the HEC chip) with 4 channels (3 for slot 9) each
  - in front of slot 1: radiation films at $\sim$ 1.2 μA for 60, 120, and 300 s.
  - behind slots 2-6,8,9,12-15: films in the 300 s 1.2 μA run

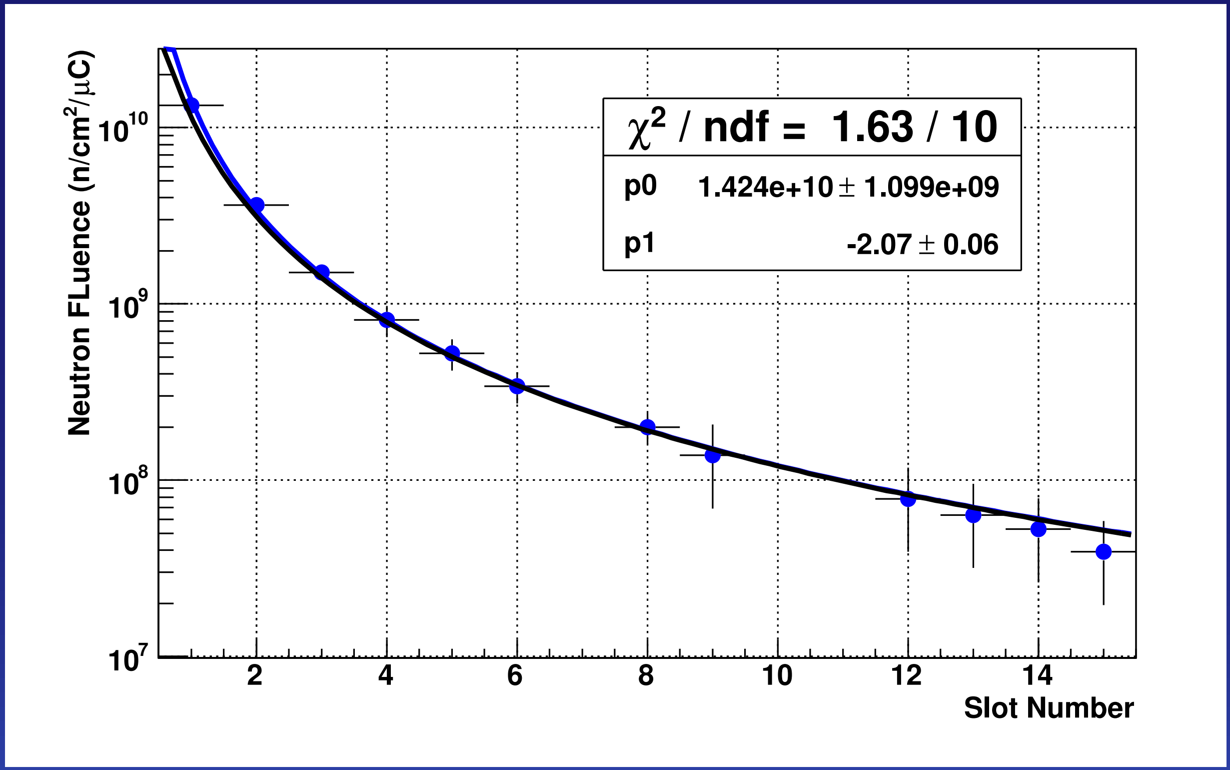


Neutron Fluence

- compare relative dose of films to results from 2010 run with radmons in each slot and account for additional 3 mm distance
- total fluence per slot for $2.0 \times 10^6\ \mu C$:

  $$\text{fluence} = 3.22 \times 10^{16} \times \left(\text{slot} + \frac{3}{17}\right)^{-2.11} \frac{n}{cm^2}$$

- estimated error from distance uncertainty ± 2 mm
  - $\sim 25\%$ in slot 1
  - $\sim 3\%$ in slot 8
- estimated error from current measurement $\pm 5\%$
  - total $\sim 25\%$ in slot 1
  - total $\sim 6\%$ in slot 8

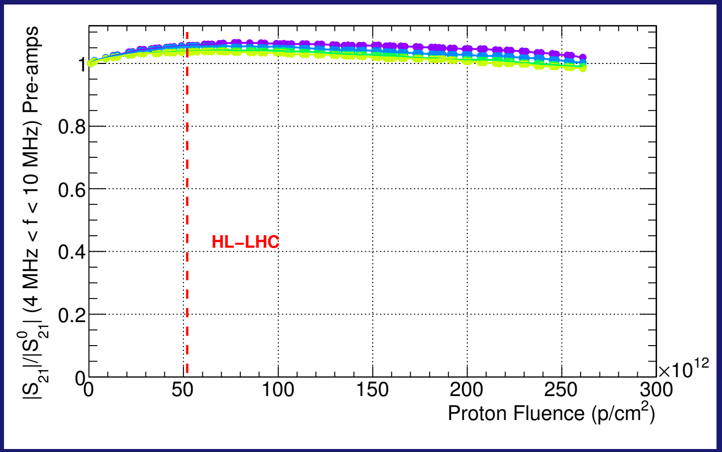


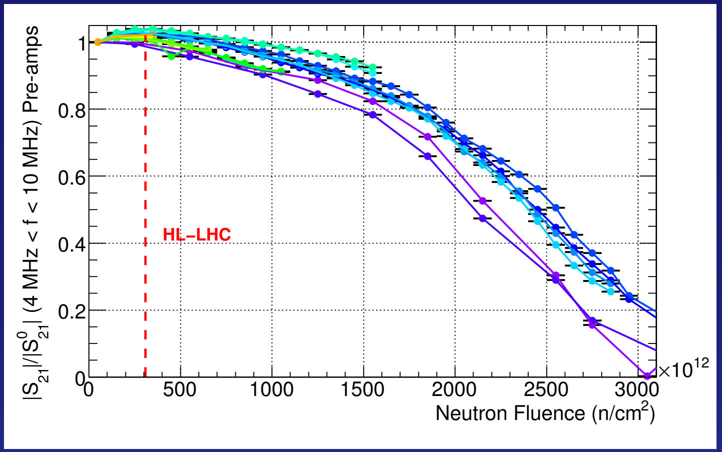
Measurements

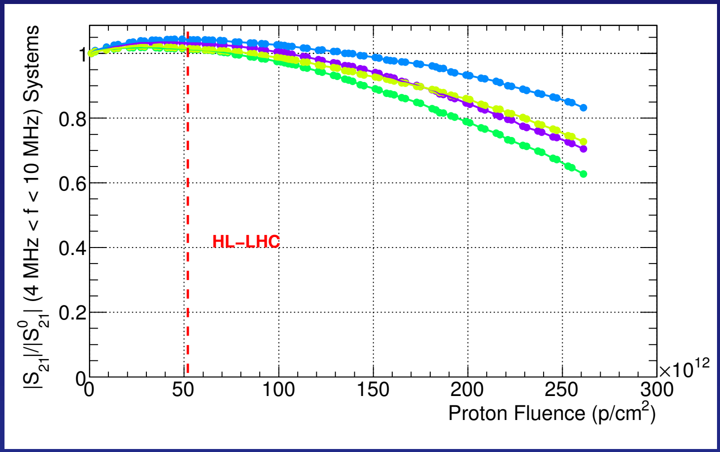
- Warm in-situ measurements for the HEC Chips:
  - Monitoring of DC values
  - Calibrated S-parameters over $2 \times 40\,\mathrm{m}$ cables in the frequency range $300\,\mathrm{kHz}$ to $100\,\mathrm{MHz}$ at $-55\,\mathrm{dBm}$ ($-35\,\mathrm{dBm}$ at PSI) cable input level
  - Oscilloscope linearity scan with $500\,\mathrm{ns}$ triangular voltage pulses corresponding to $10\,\mu\mathrm{A}$ – $1000\,\mu\mathrm{A}$ at BB96 input for 10 logarithmically distributed points (Řež only)
- Cold measurements of the n-irradiated HEC Chips:
  - about 3 months after the neutron irradiation the boards were shippable
  - we re-measured the S-parameters and pulse response in the Lab under cold (LN_2) conditions
  - in a small cryostat ($\sim 3\,\ell$) with 2 boards at a time
  - We measure continuously like in Řež all S-parameters, DC values and pulse response and temperature

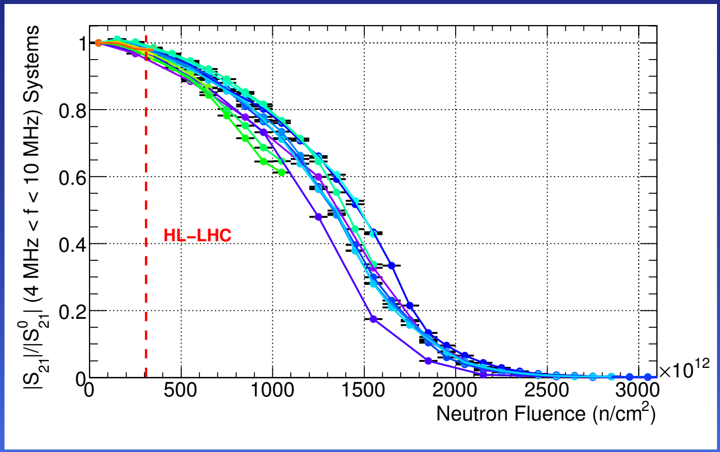
Proton and Neutron in-situ Measurements (Warm)

- evaluate gain of pre-amps (right) at frequencies relevant for shaper ($4\,\mathrm{MHz} < f < 10\,\mathrm{MHz}$)
- normalize to values before irradiation
- for protons (top) and neutrons (bottom)





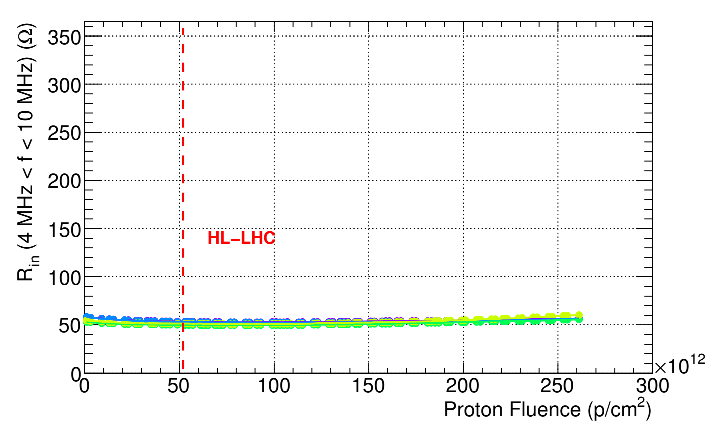


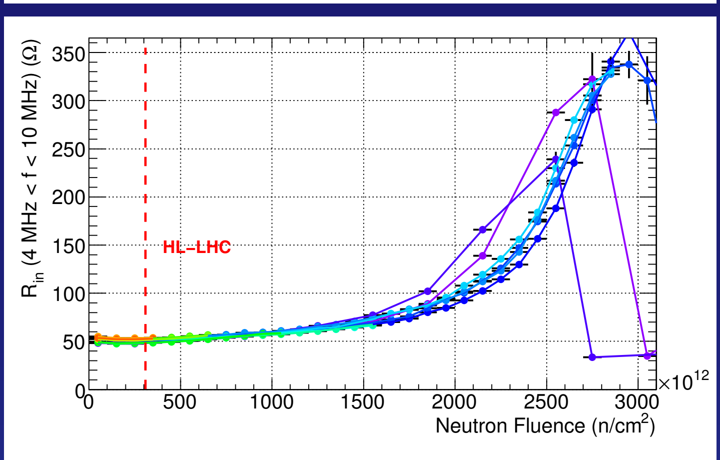


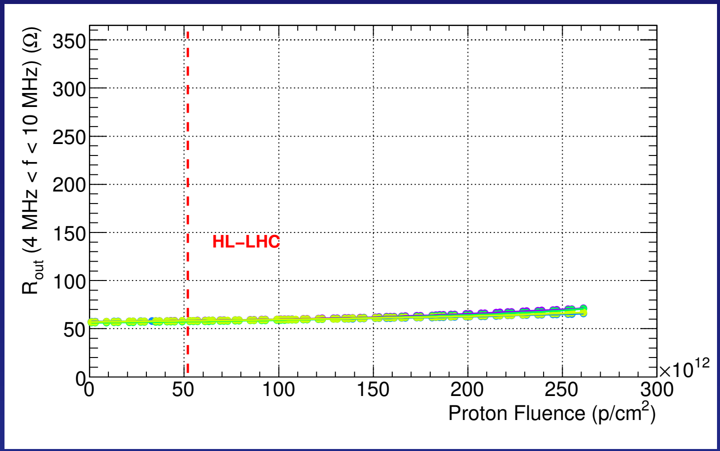
- and for the systems (left)
- protons have $\sim 4 - 5\times$ larger effect at the same fluence value
  - but neutron rates are $\sim 10\times$ that of hadrons ($E > 20\,\mathrm{MeV}$)
- red dashed lines indicate HL-LHC levels (adjusted for GaAs NIEL in case of neutrons)

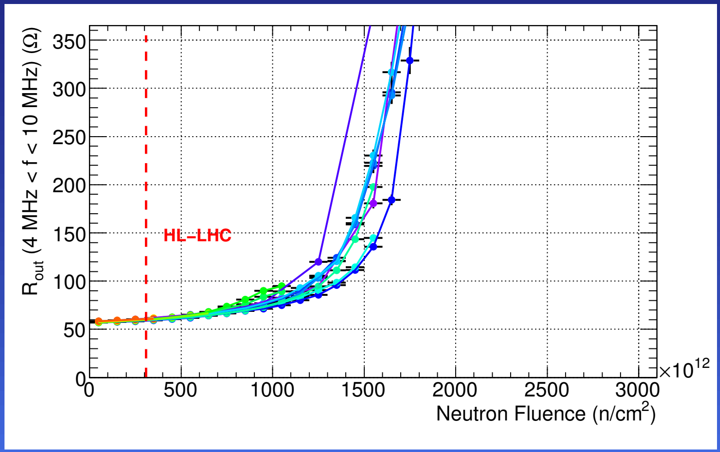
Proton and Neutron in-situ Measurements (Warm)

- input impedance for the pre-amps (right) at frequencies relevant for shaper ($4\,\mathrm{MHz} < f < 10\,\mathrm{MHz}$)
- for protons (top) and neutrons (bottom)





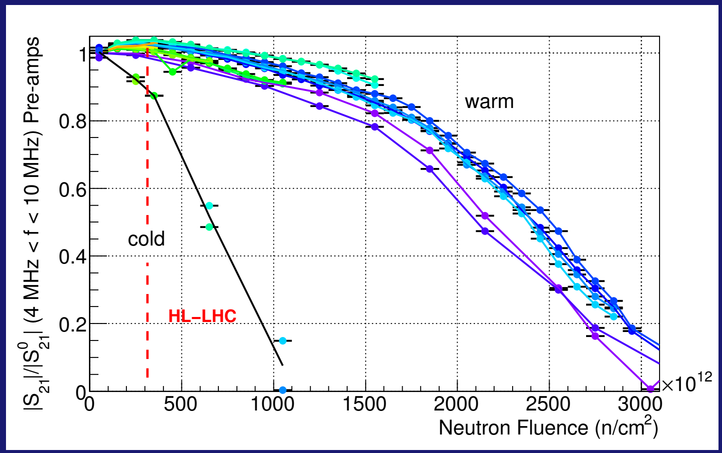


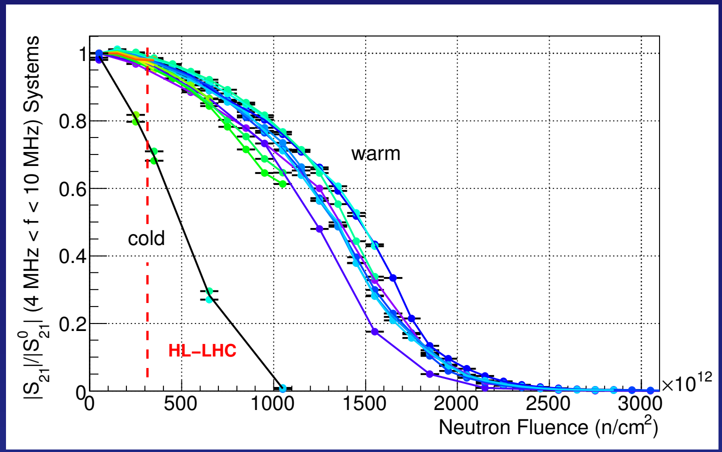


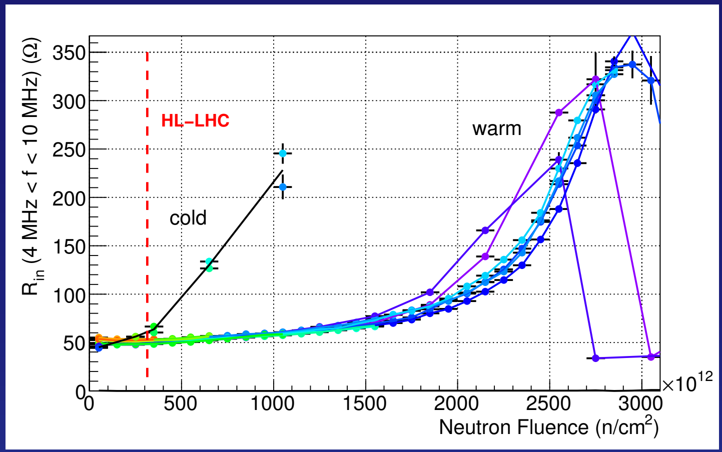
- and output impedance for the systems (left)
- for protons (top) and neutrons (bottom)
- R_{out} rises quickly beyond $\sim 10^{15}\,\mathrm{n/cm^2}$

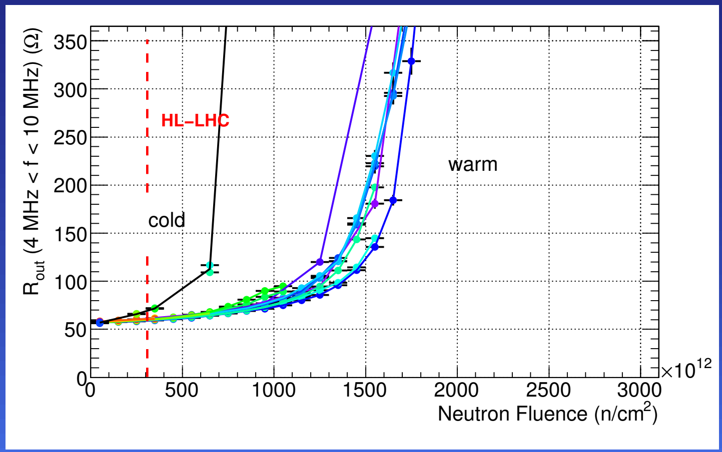
Gain and Impedances in Warm and Cold

- evaluate gain at frequencies relevant for shaper ($4\,\text{MHz} < f < 10\,\text{MHz}$)
- normalize to values before irradiation
- right top (bottom) plot shows pre-amps (systems)





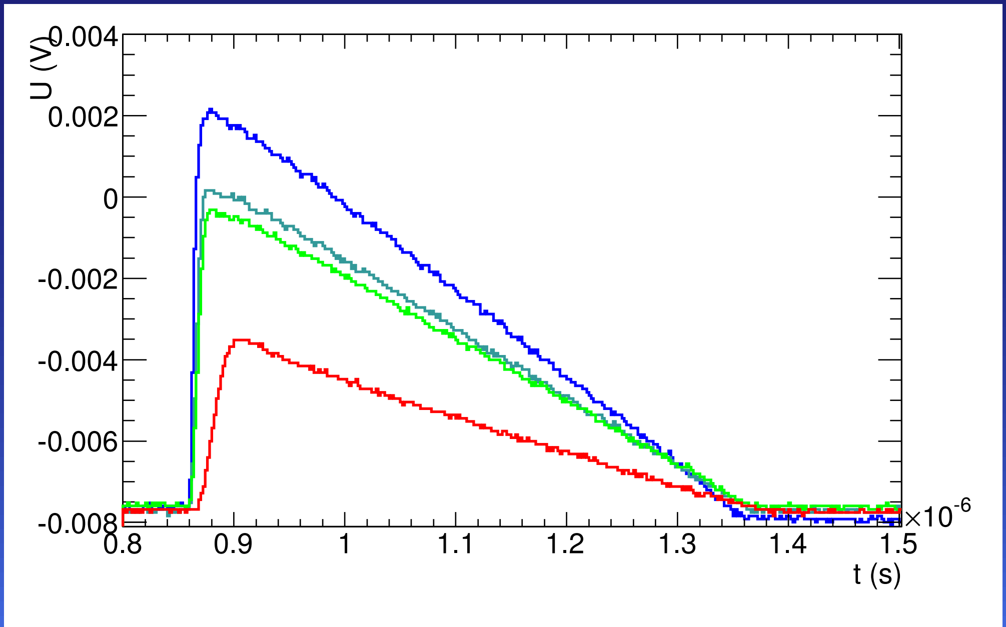


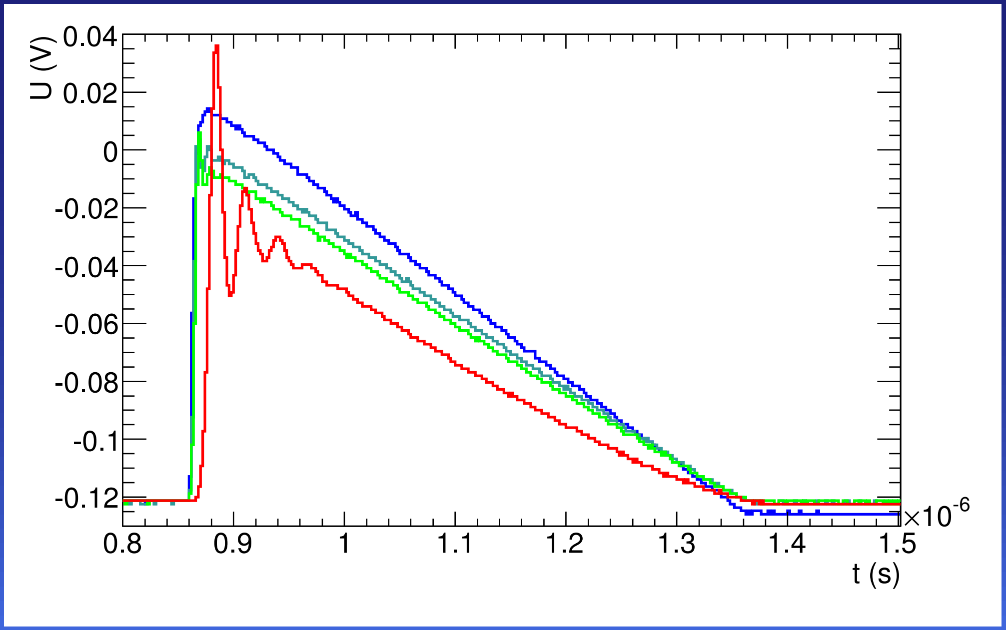


- in cold the gain of the pre-amps is much worse after irradiation
- also the input (left top) and output (left bottom) impedances rise quickly
  - non-matched circuits

Cold Oscilloscope Measurements

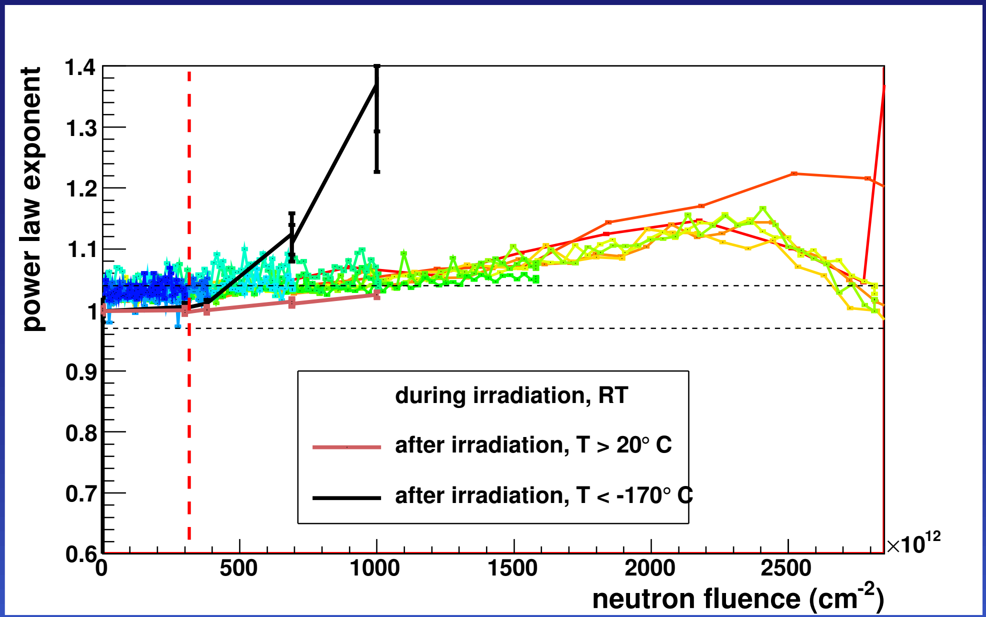
- blue: non-irradiated
- cyan: slot 9 (Si NIEL = $3.0 \times 10^{14}\ \mathrm{n/cm^2}$)
- green: slot 8 (Si NIEL = $3.8 \times 10^{14}\ \mathrm{n/cm^2}$)
- red: slot 6 (Si NIEL = $6.9 \times 10^{14}\ \mathrm{n/cm^2}$)
- left a small input pulse; right a $13.5\times$ larger input pulse
- relative to the blue pulse the other pulses should have the same height on the left and the right for a linear system
- non-linearities and oscillations are getting severe already for the green pulses ...

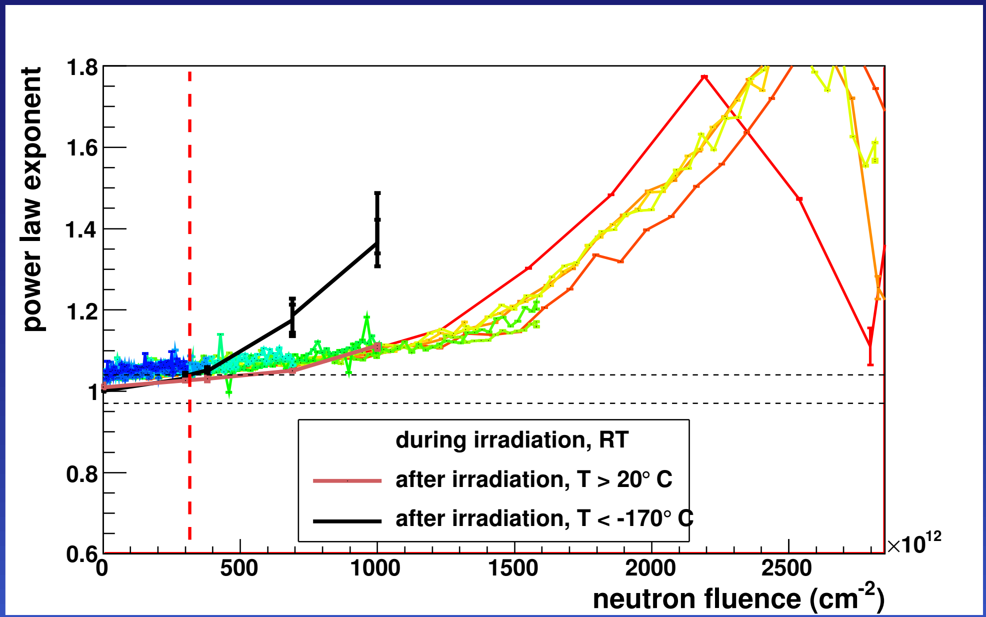




Comparison of warm and cold non-linearities

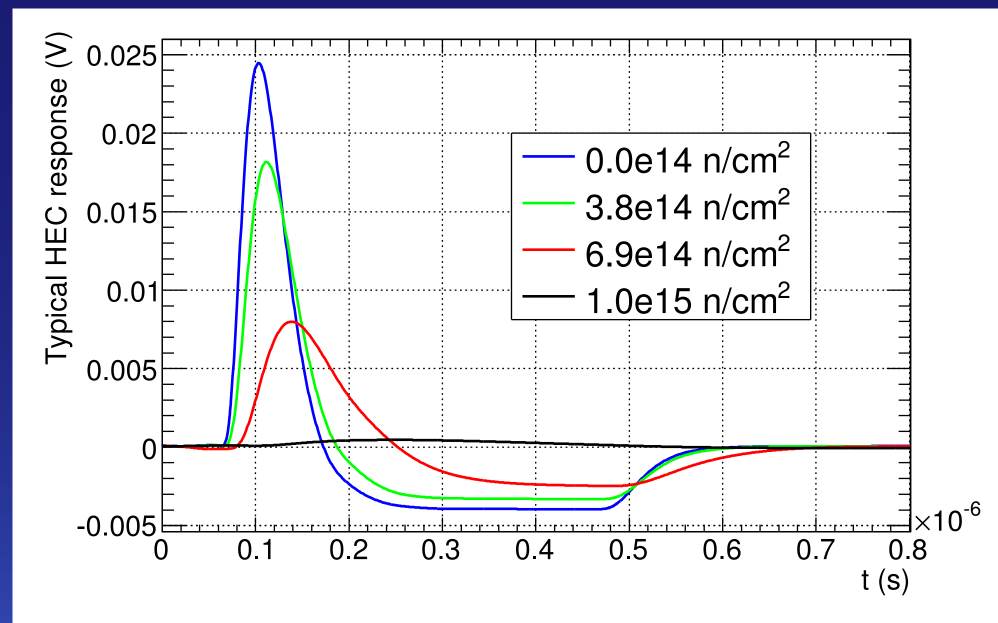
- Shown are the exponents of a power-law-fit of the form $\text{out} = a \times \text{in}^x$
- as measured in Řež (warm) in-situ as many colored points/lines
- re-measured for 4 irradiated boards at MPI (warm) in brown
- re-measured for same 4 irradiated boards at MPI (cold) in black
- horizontal lines indicate $\Delta_{\text{max}} = 1\%$ limits, where Δ_{max} is the deviation from a linear fit ($x = 1$) relative to the maximum output
- non-irradiated BB96 are better in the cold
- severe increase of non-linearity ~ 3 times earlier in cold than in warm





Summary of cold measurements

- Cold measurements show:
  - BB96 rapidly degrades beyond $3 - 4 \times 10^{14}\,\mathrm{n/cm^2}$ Si-NIEL (Řež)
  - input and output impedance not longer matching $50\,\Omega$ system
  - signals start to oscillate
  - gain, bandwidth and dynamic range get limited
  - pulses get broader
- This translates to $4.0 - 5.4 \times 10^{14}\,\mathrm{n/cm^2}$ Si-NIEL (ATLAS) (see Appendix)
  - non-linearities (in the Δ_{max}-sense) rise above 3%
  - simulations of the full electronics readout chain with all measured S-parameters (right) show that the degradation in $|S_{21}|$ describes the degradation in transimpedance gain



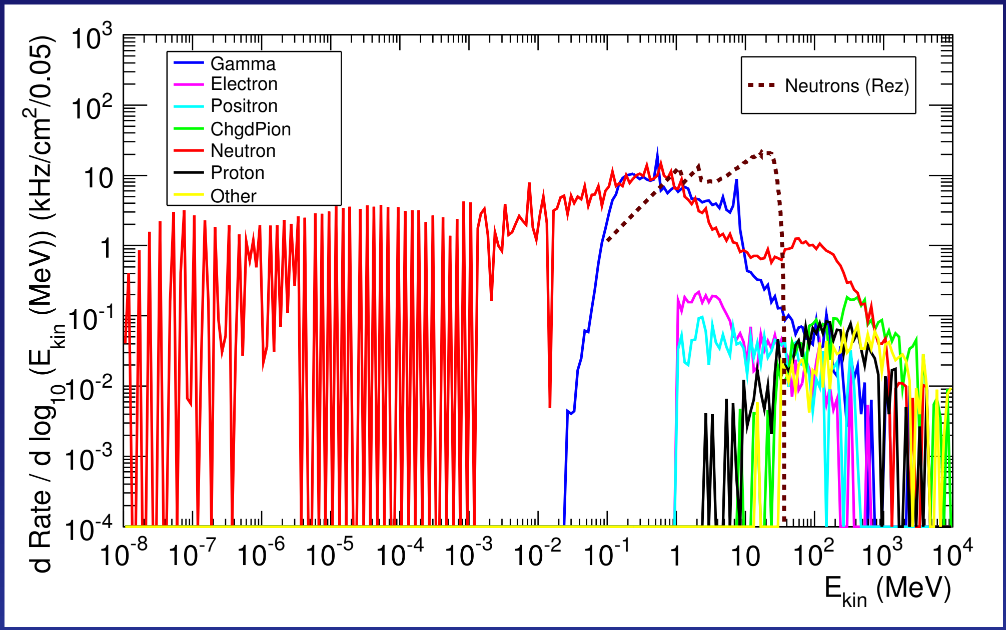
► the rising input impedance does not compensate the voltage gain loss

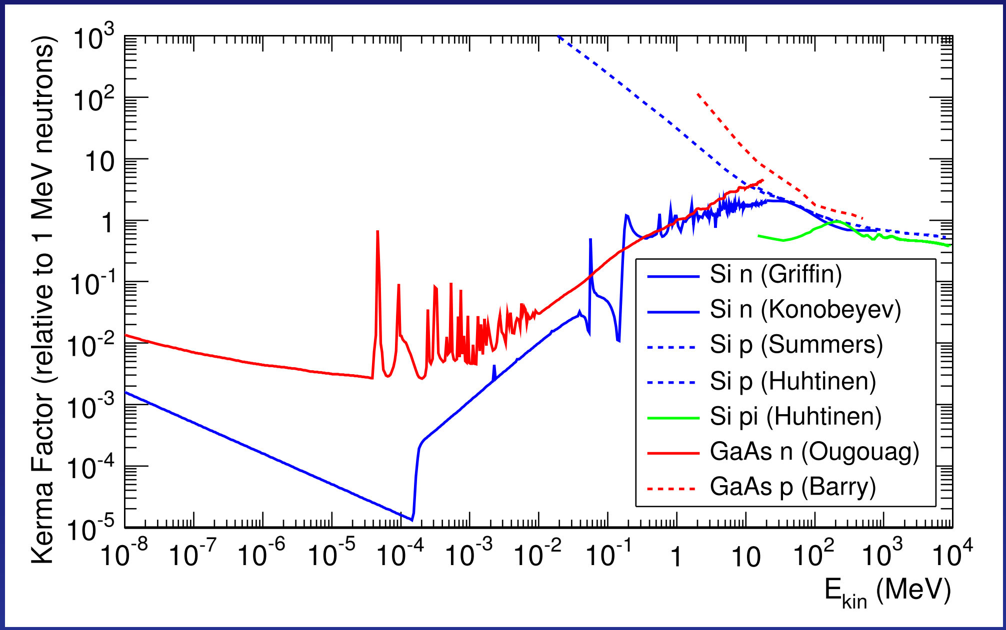
Conclusions

- How to combine the proton and neutron results?
  - proton irradiated chips measured only in warm
  - compared to the neutron measurements in warm the protons produced a $4-5$ times larger damage at the same fluence values
  - translate the proton flux to non-ionizing dose (NIEL) plus ionizing dose (TID) and assume similar effects for cold vs. warm
    - we expect additional TID degradation on the level of $\sim 10\%$ of the NIEL degradation
- NIEL measurements from neutrons set the most stringent limits on the present readout electronics of HEC
- the values expected for HL-LHC including simulation safety factors of 5 are at the working limit for the BB96 ASICs
- the impact on physics analyses at HL-LHC with degraded electronics is under investigation

Appendix: NIEL Calculations

- to compare Si-NIEL for GaAs devices one has to convert to GaAs NIEL at one site (test facility) and back to Si NIEL at the other site (ATLAS)
- this requires the knowledge of the particle spectra
- For Řež we have a MCNP based simulation
  - the Řež ratio GaAs NIEL/Si NIEL is ~ 1.82
- The spectra for ATLAS are taken from FLUKA simulations in the HEC PSB region
  - for ATLAS in the HEC PSB region the ratio GaAs NIEL/Si NIEL is ~ 1.35





- Thus to translate from Řež to ATLAS it is best to stick to Si-Numbers and multiply by $1.82/1.35$
- $3.8 \times 10^{14}\ \mathrm{n/cm^2}$ Si-NIEL in Řež corresponds to $5.1 \times 10^{14}\ \mathrm{n/cm^2}$ Si-NIEL in ATLAS for GaAs devices in the PSB HEC region