Detectors and electronics for neutron detection at the NMX instrument of the European Spallation Source ERIC (ESS)

M. Lupberger, P. Thuiner

on behalf of
CERN EP-DT-DD GDD and
European Spallation Source ESS ERIC, Sweden

Outline

The European Spallation Source ERIC

The NMX instrument

Detector demonstrator prototype

Detector read-out chain and electronics

Conclusions

Outlook

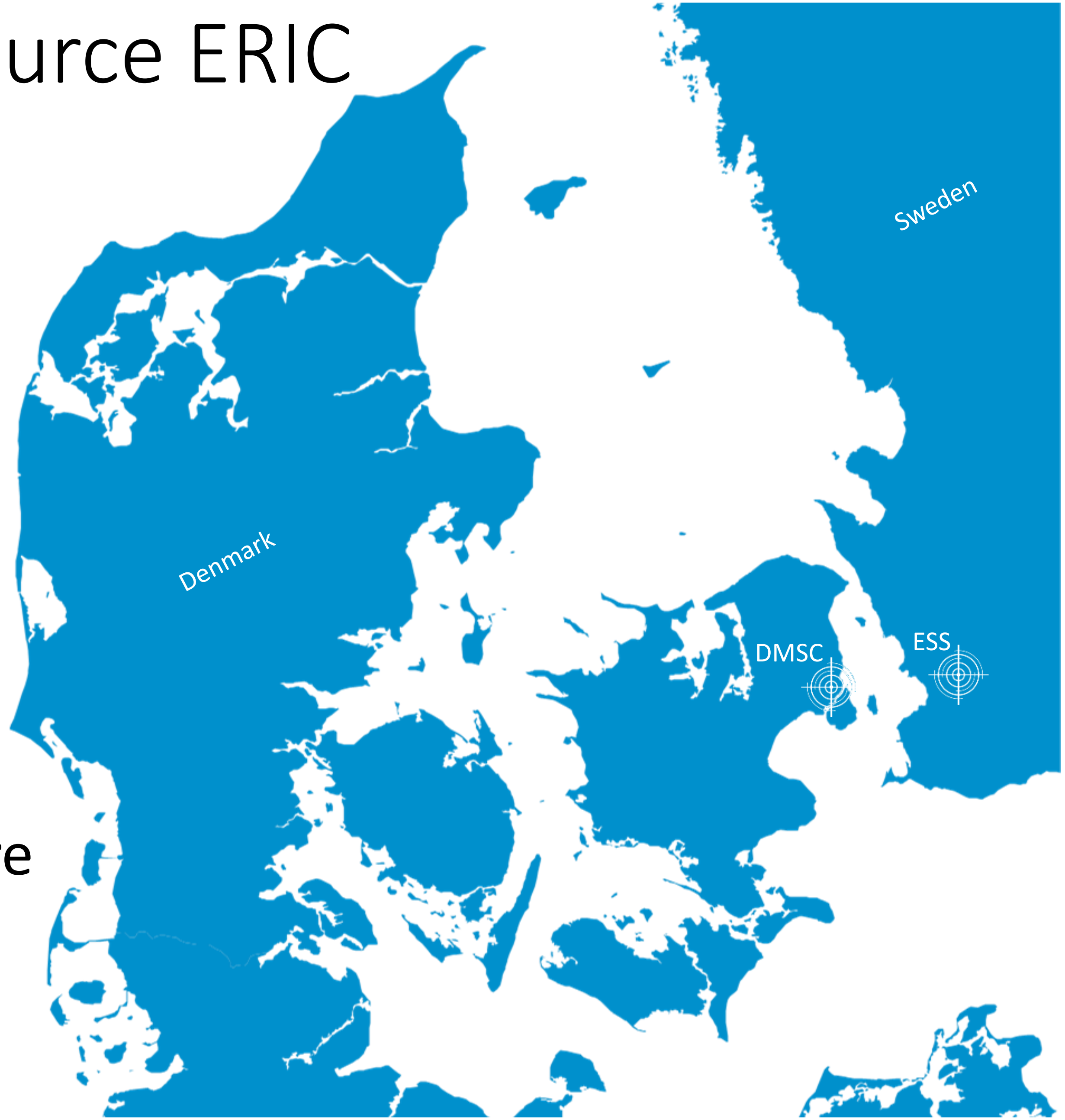
The European Spallation Source ERIC
Overview

Multi-disciplinary research centre based on world’s most powerful neutron source

Pan-European project hosted by Sweden and Denmark

Research facility currently under construction in Lund (Sweden)

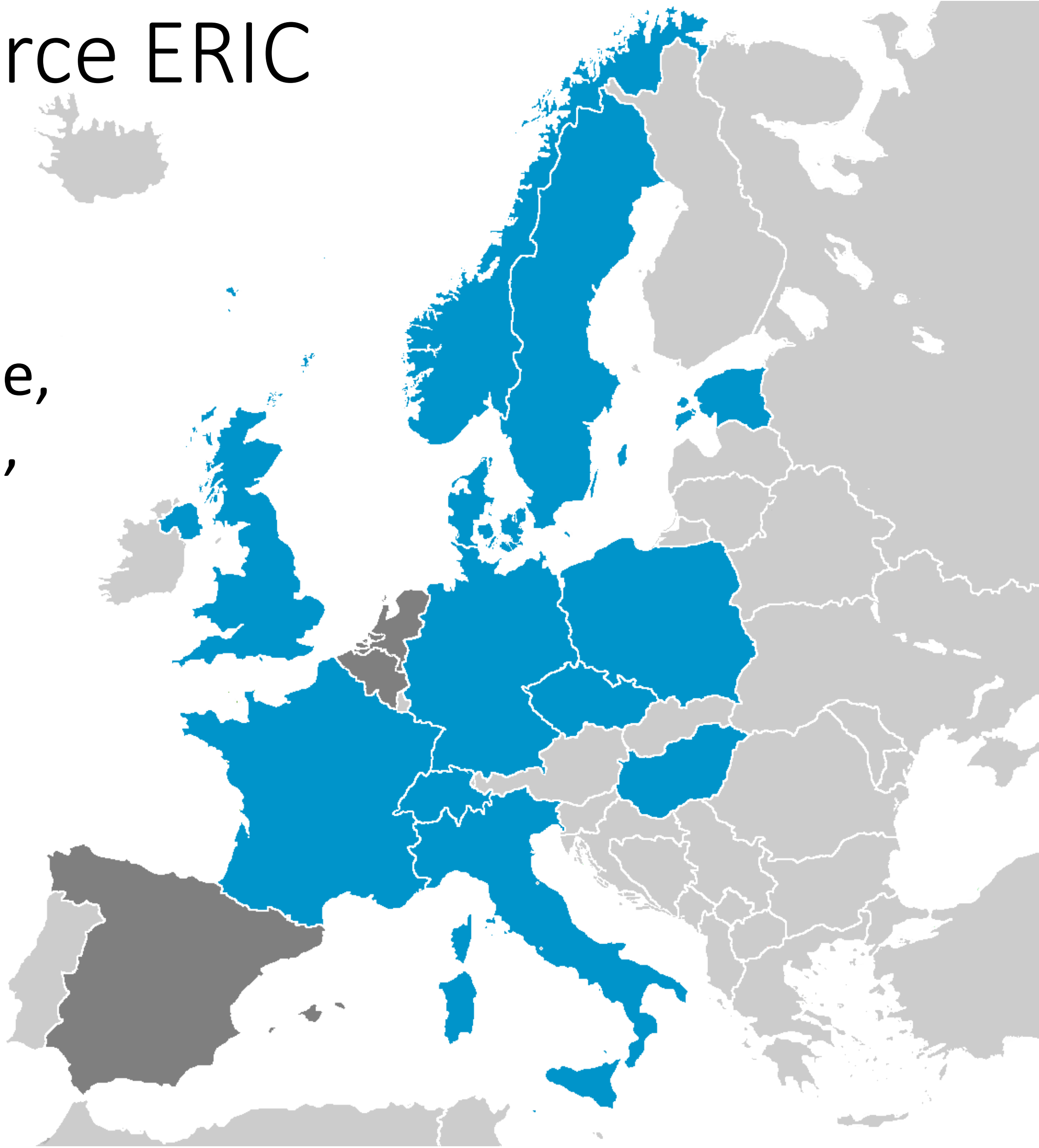
Data Management and Software Centre located in Copenhagen (Denmark)



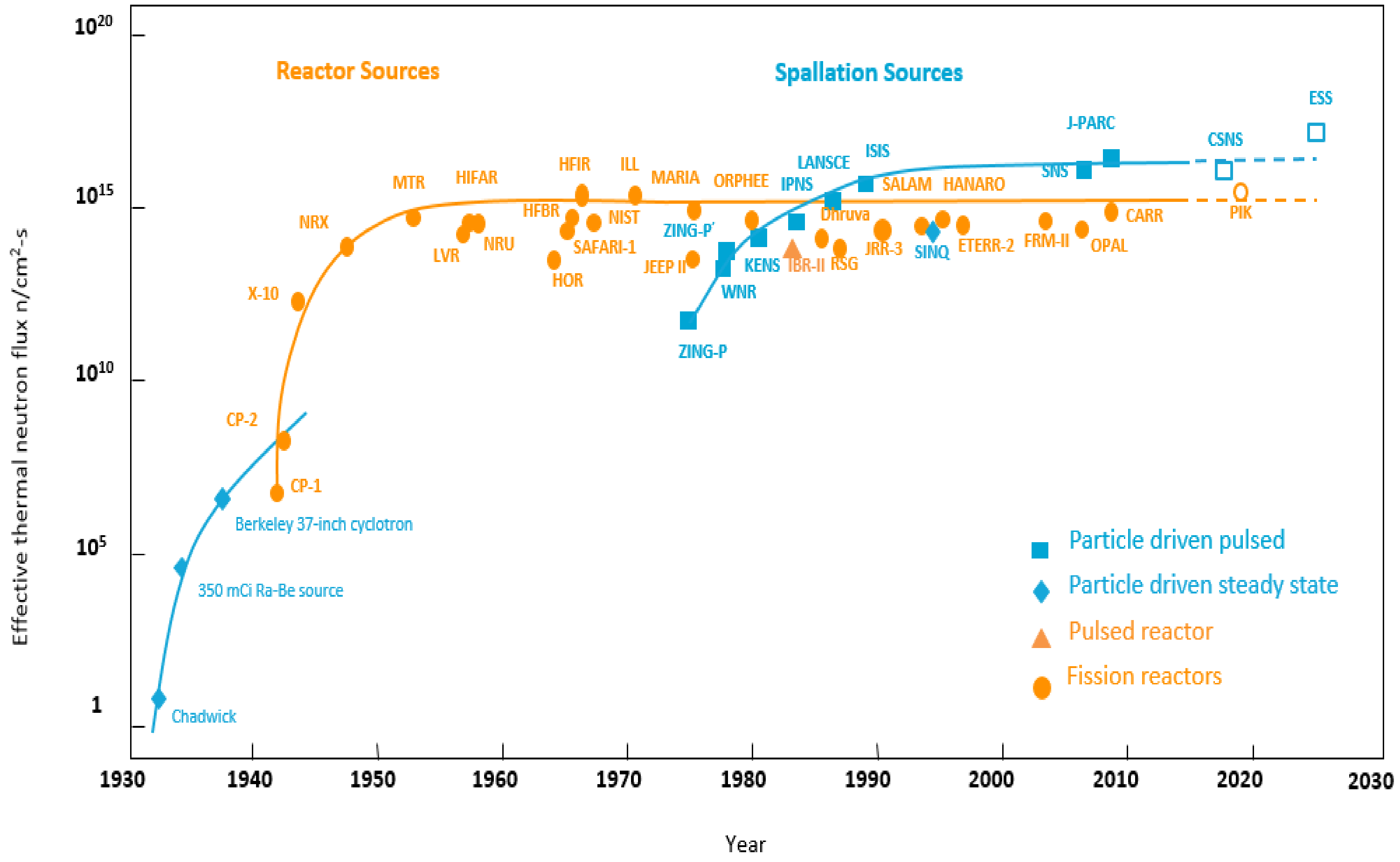
The European Spallation Source ERIC
Overview

12 founding states:
Czech Republic, Denmark, Estonia, France, Germany, Hungary, Italy, Norway, Poland, Sweden, Switzerland and the United Kingdom

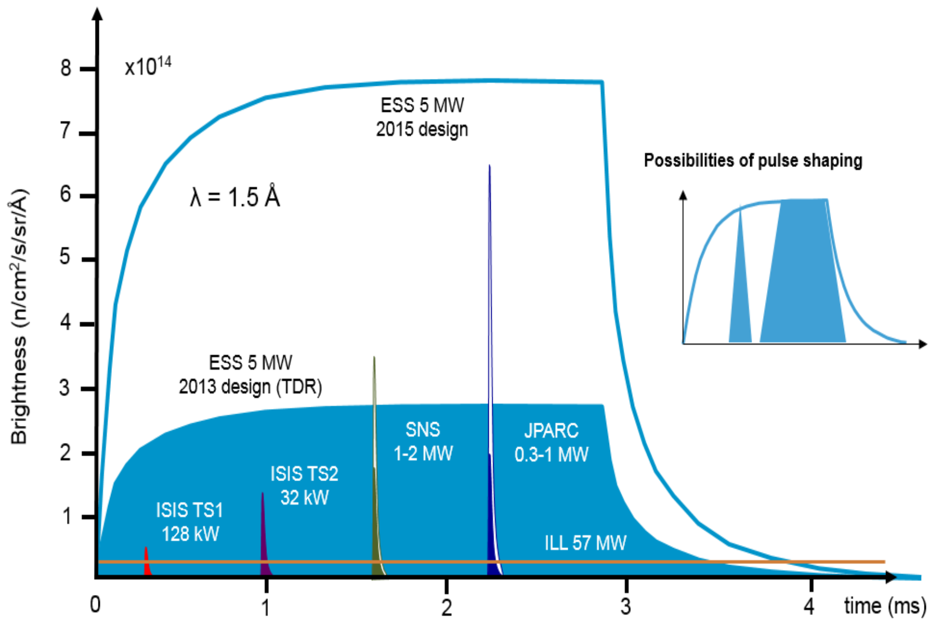
3 observer states intend to become member states in near future:
Belgium, the Netherlands and Spain



The European Spallation Source
Performance



(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)



The European Spallation Source

Campus and surroundings

The European Spallation Source

Campus

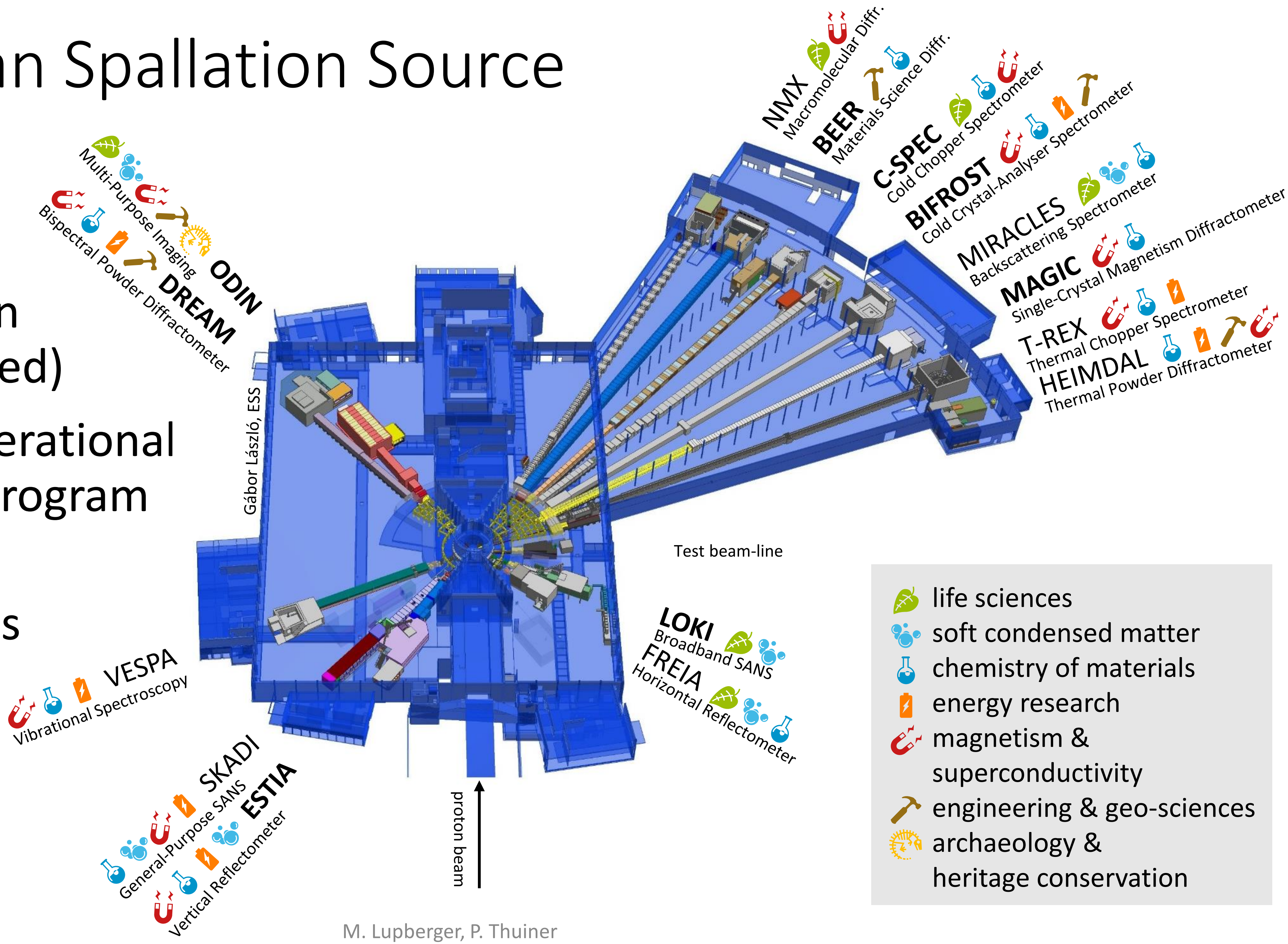
The European Spallation Source
Construction site (December 2017)

The European Spallation Source
Instruments

15 instruments currently foreseen (22 initially planned)

8 instruments operational for start of user program (August 2023)

Other instruments as possible backups in case of major delays



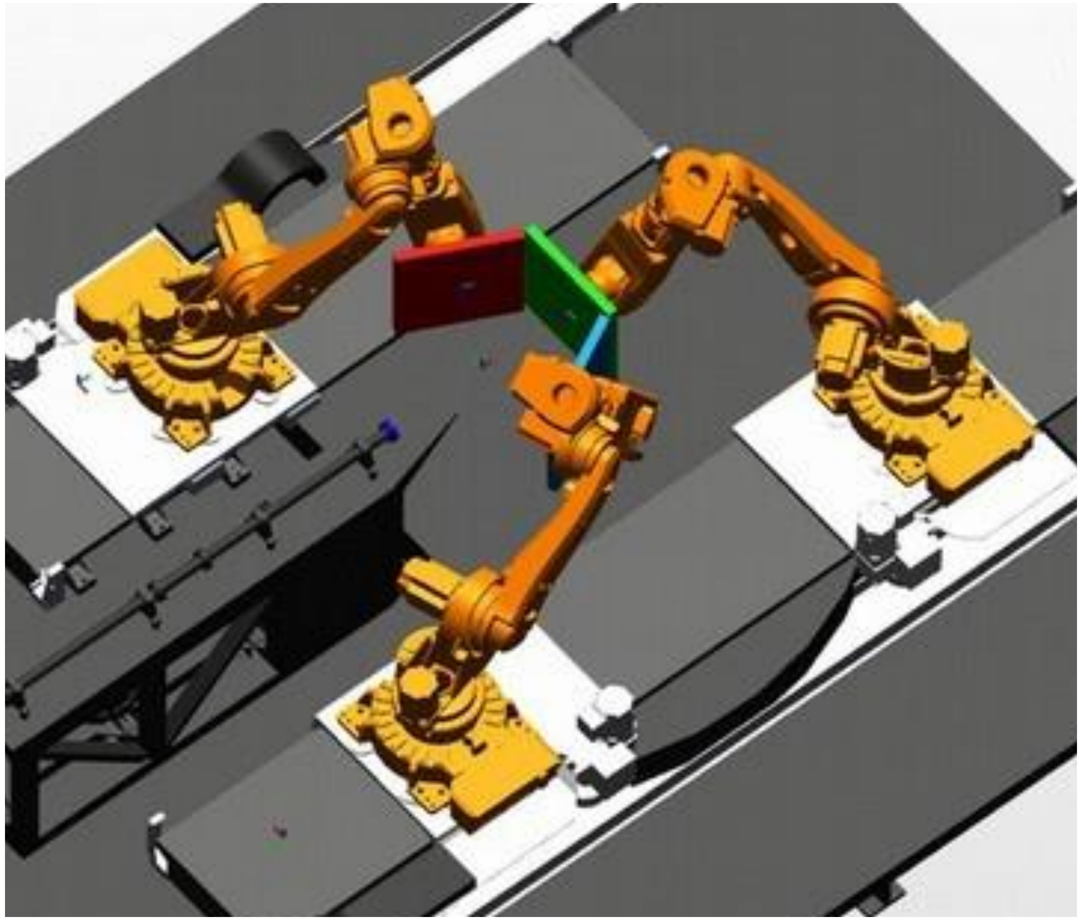
The NMX instrument
Neutron macromolecular diffractometer

Structure determination of **biological macromolecules** by crystallography

Locates **hydrogen atoms** relevant for the function of the macromolecule

Needed: high rate capabilities, good detection efficiency, position & time resolution

Physics **demonstrator** build at **CERN GDD** facilities as part of BrightnESS project within Horizon 2020

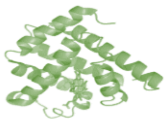


Detector Positioning System for ESS NMX, Final Design Report, J.-L. Ferrer

Diffractometry
From protein to atomic model

Diffractometry

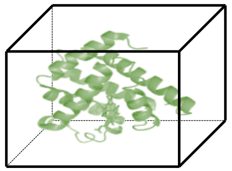
From protein to atomic model



protein

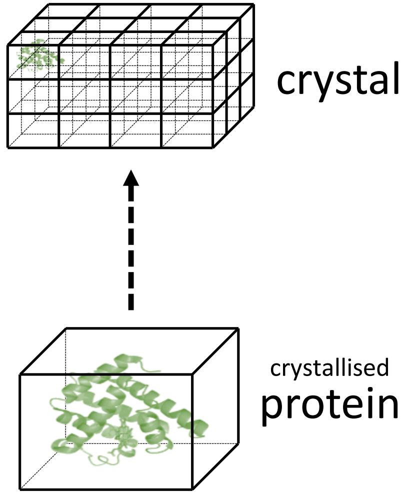
Diffractometry

From protein to atomic model



Diffractometry

From protein to atomic model



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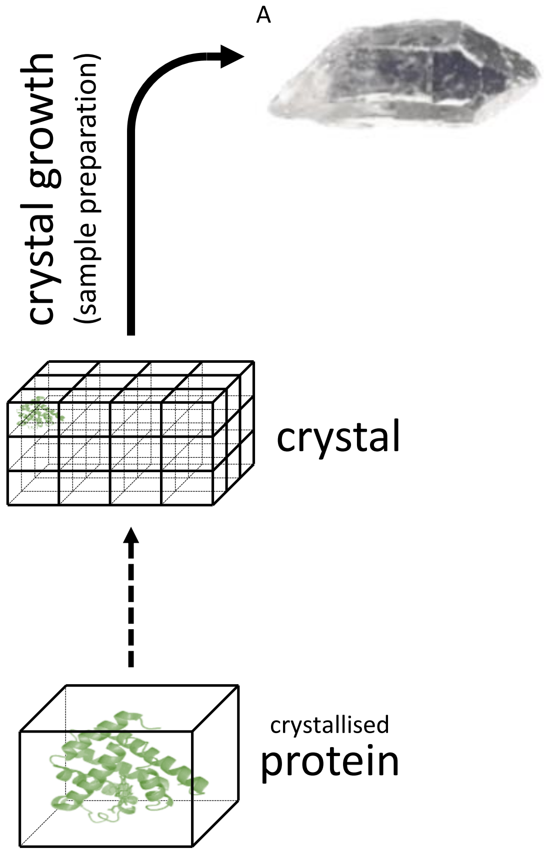

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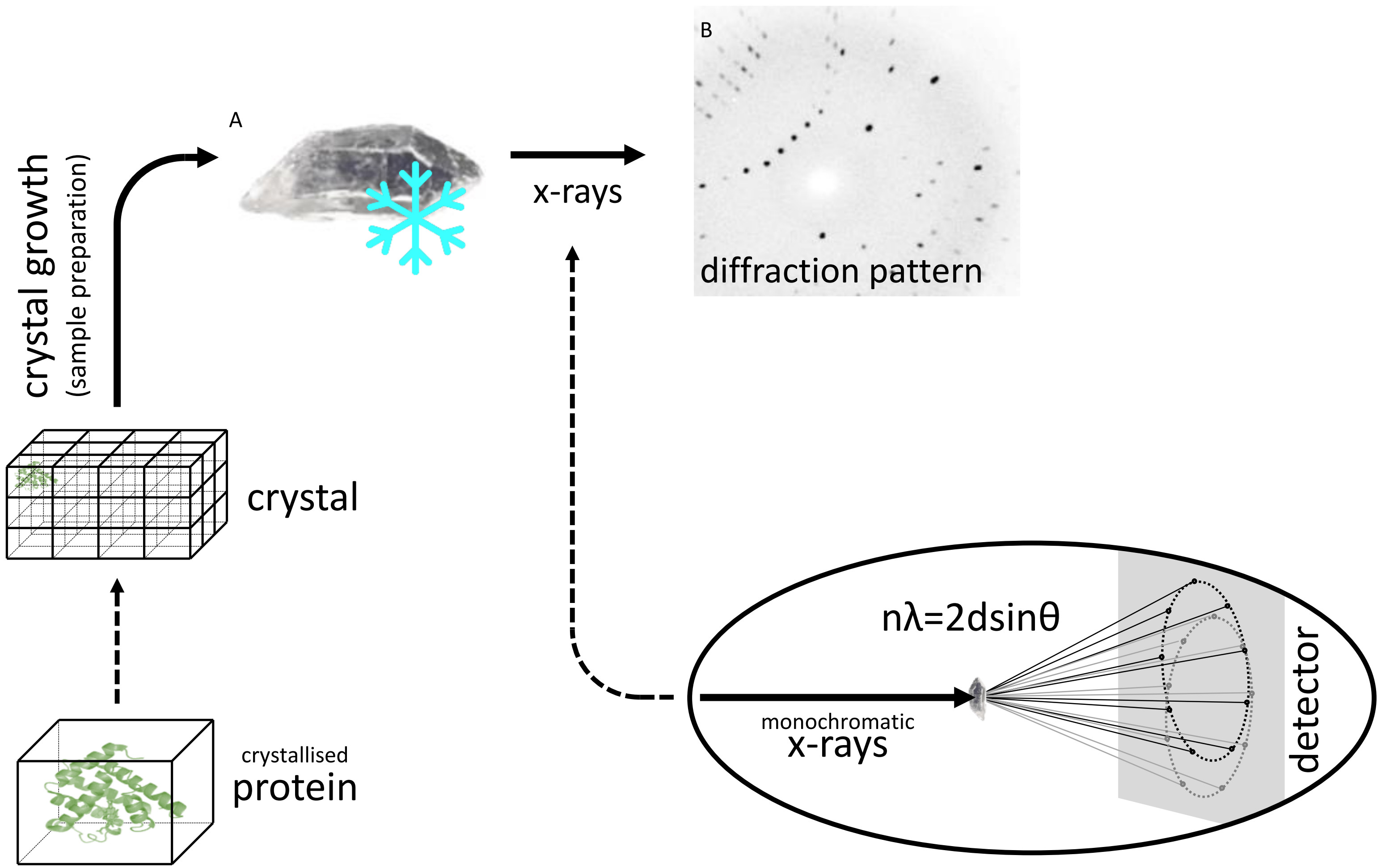

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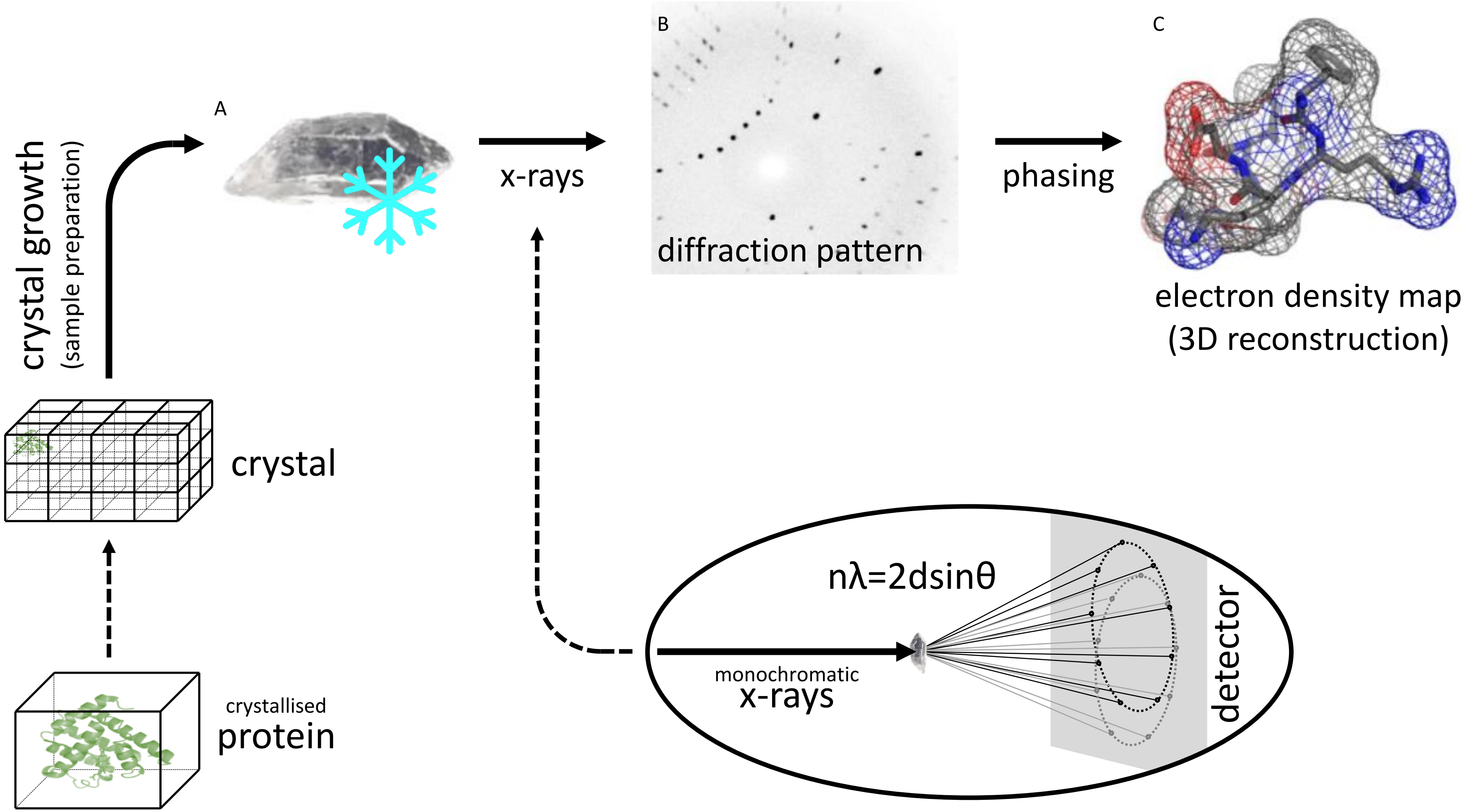
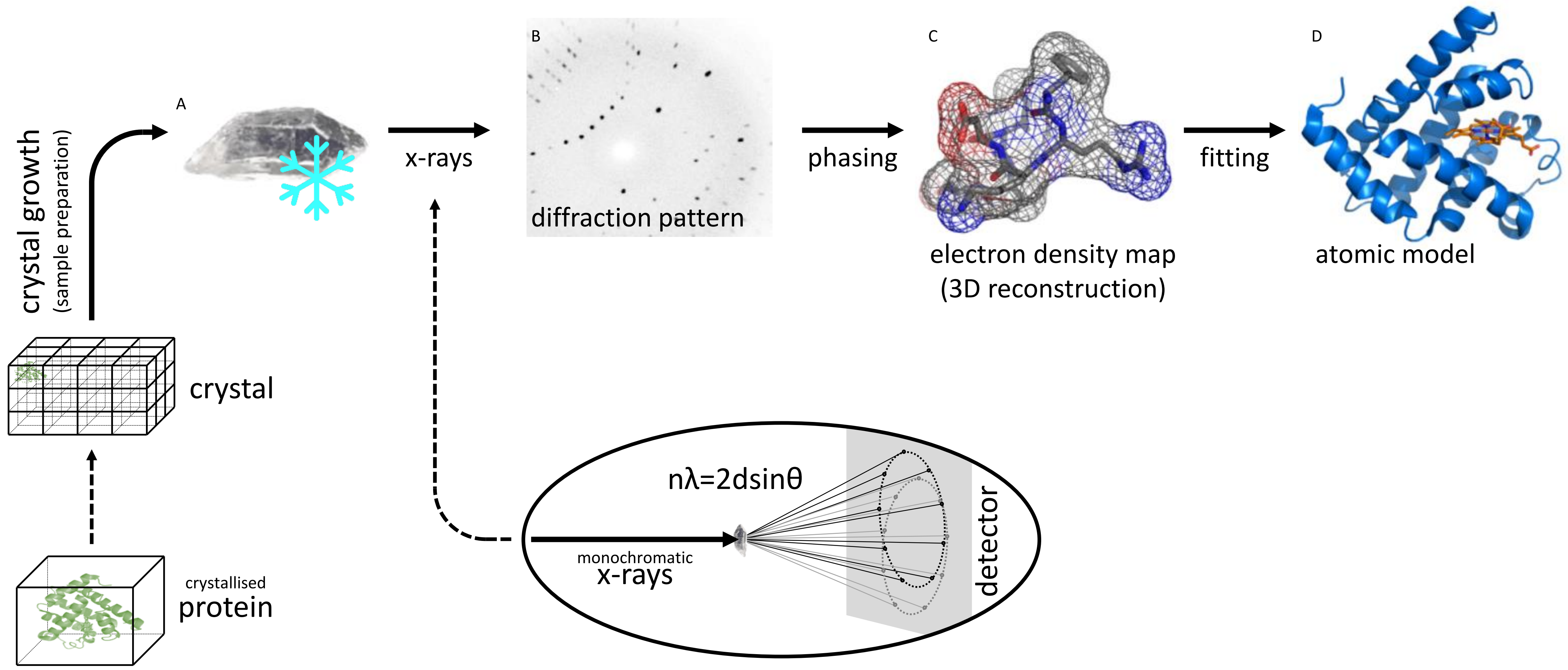


Diffractometry
From protein to atomic model

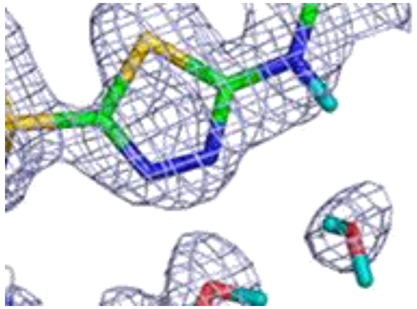


Diffractometry
Why neutrons?

Diffractometry
Why neutrons?

Diffractometry
Why neutrons?

electron density map



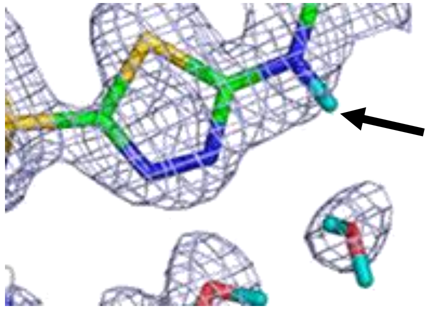
Modified from S.Z.Fisher et al.,
J. Am. Chem. Soc. **2012** *134* (36), 14726-14729

Diffractometry

Why neutrons?

x-rays

electron density map



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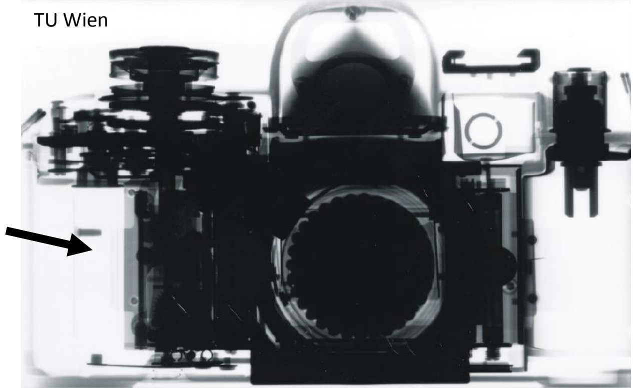
light element

TU Wien



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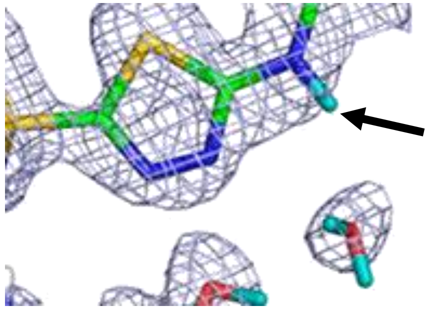

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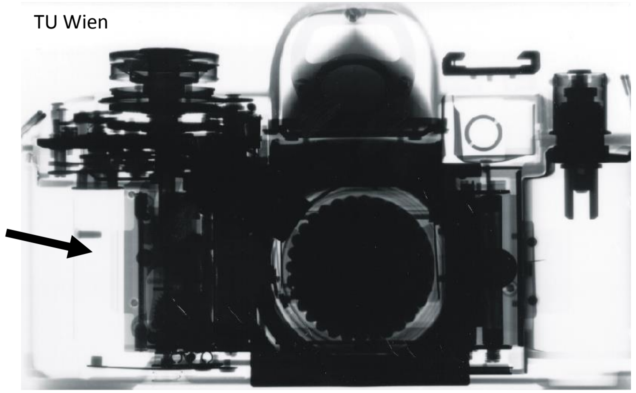
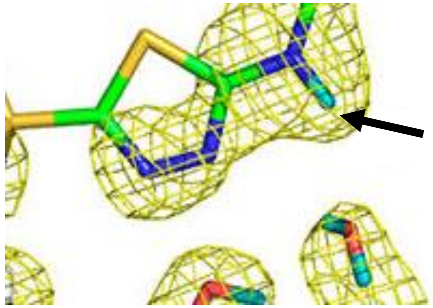


neutrons

nuclear density map



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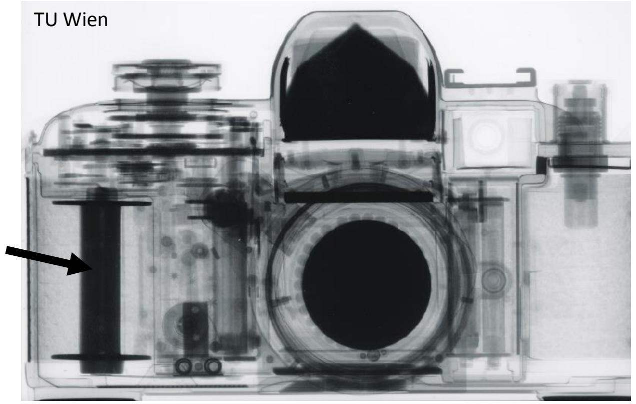
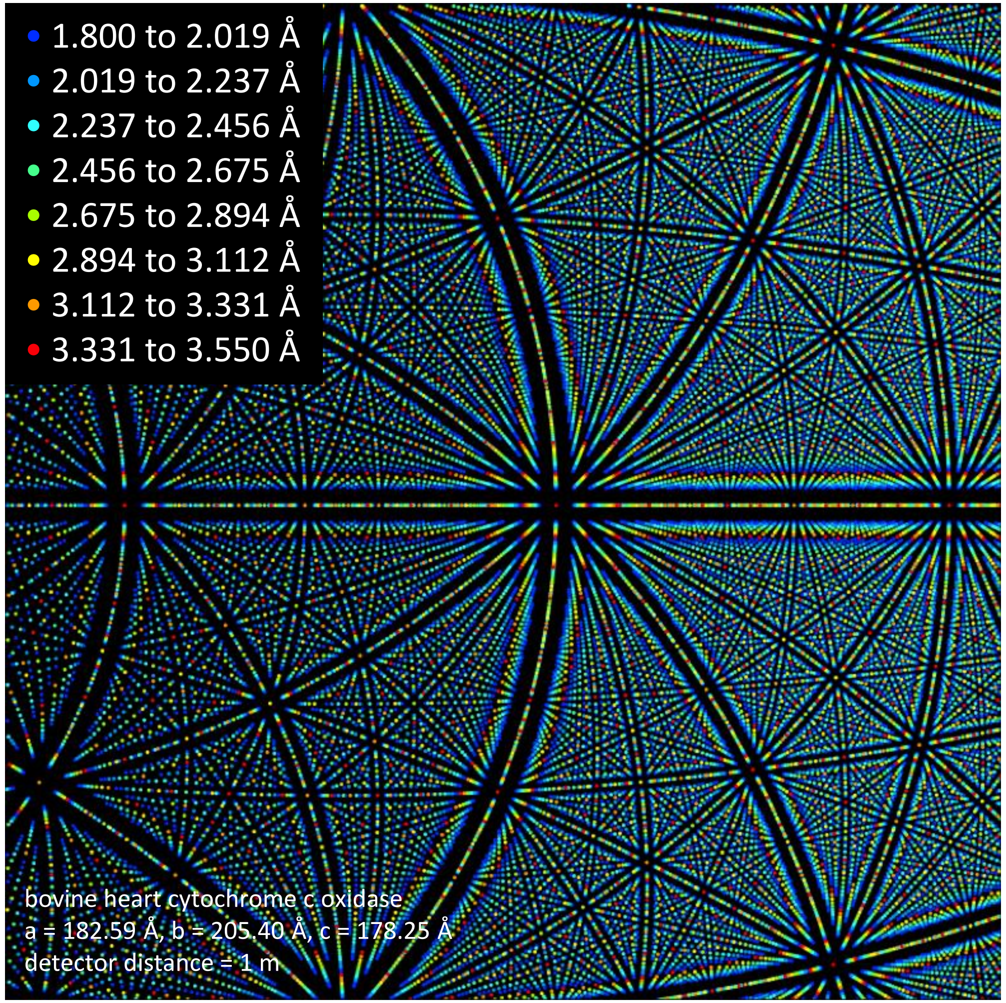
light element



The NMX instrument
No fixed detector geometry



Simulation by E. Oksanen, ESS

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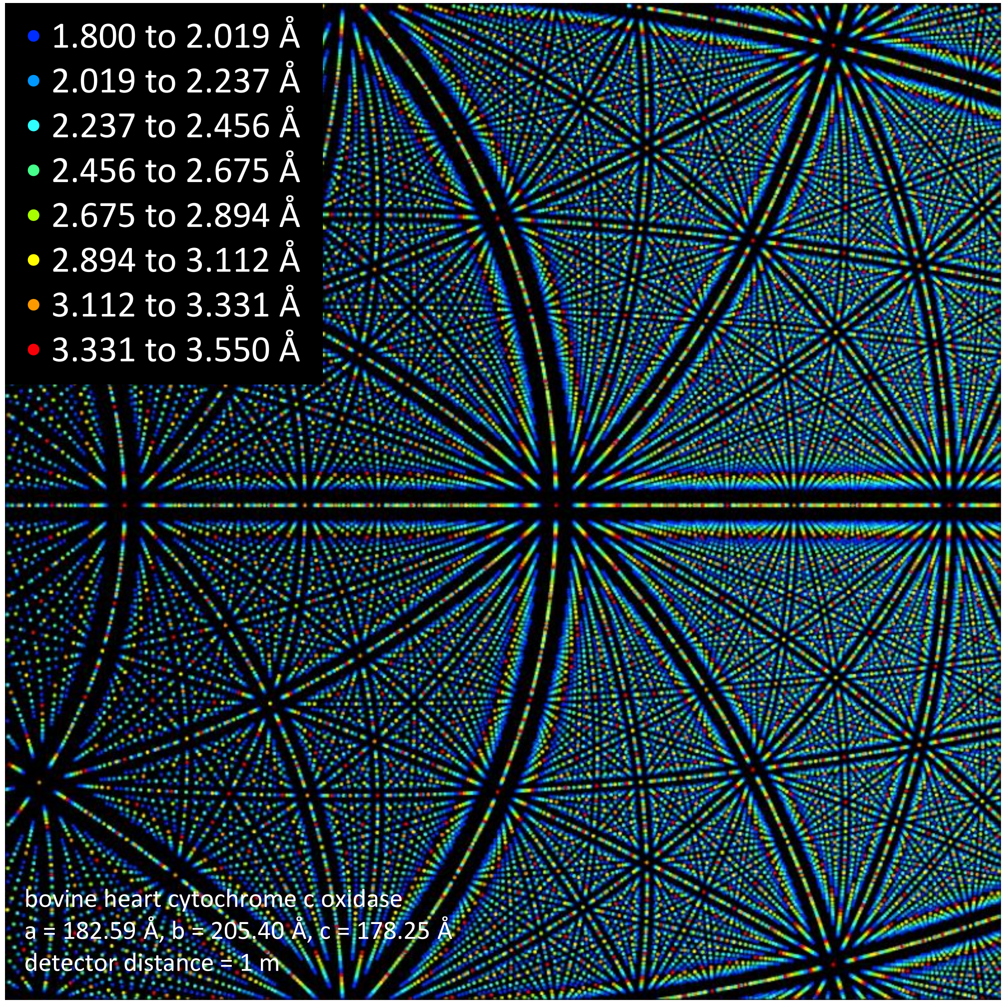

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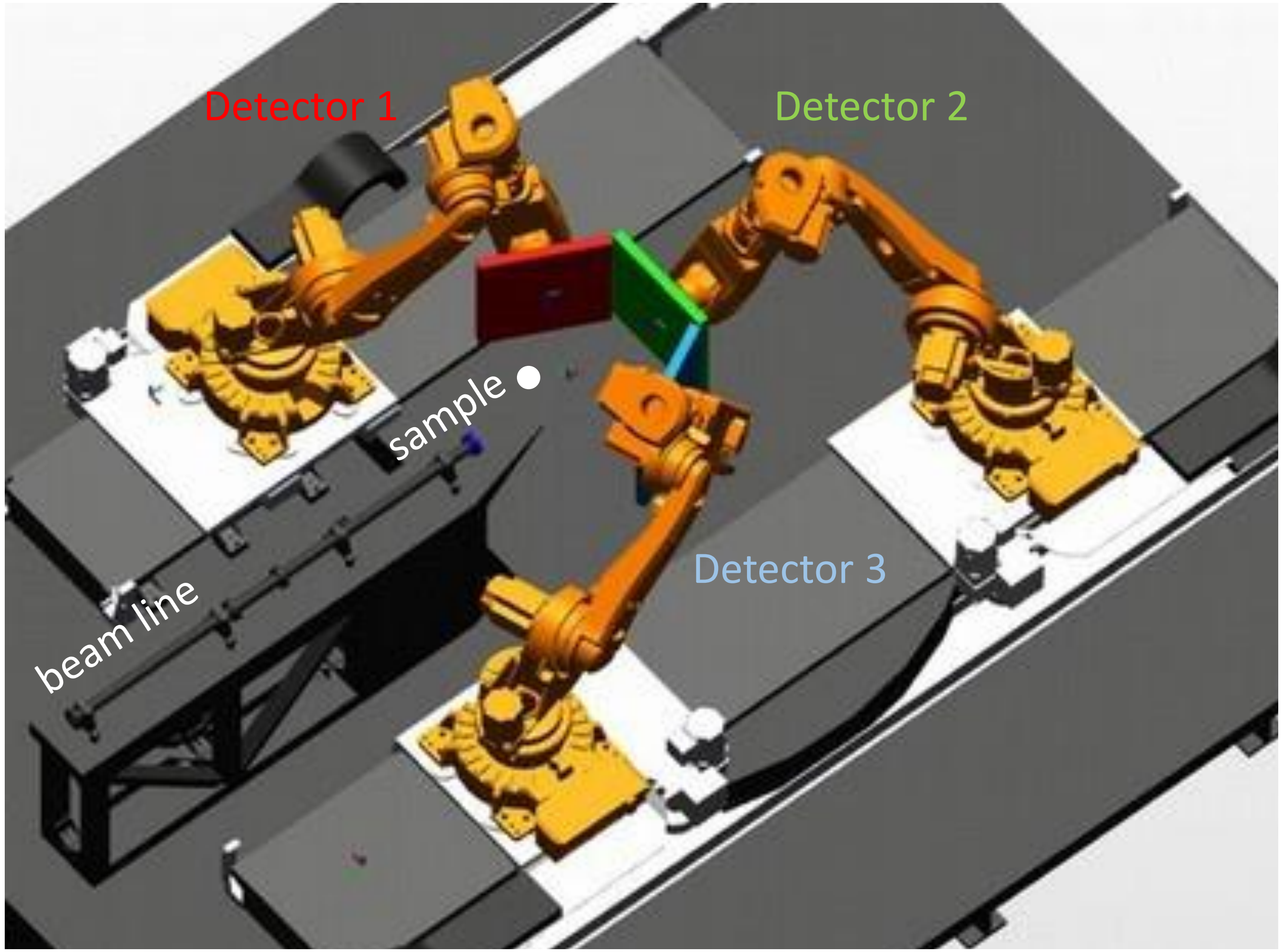

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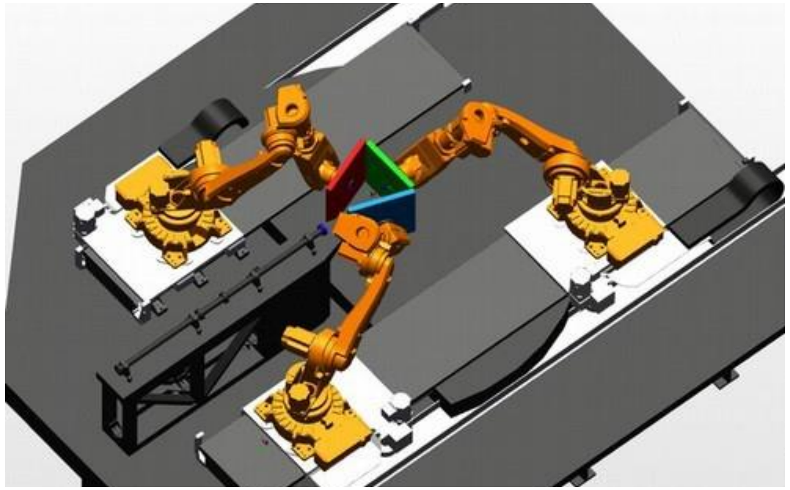
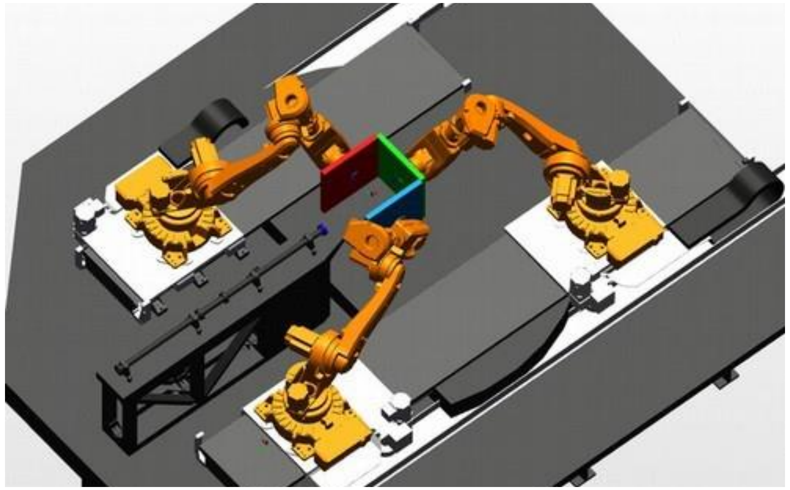
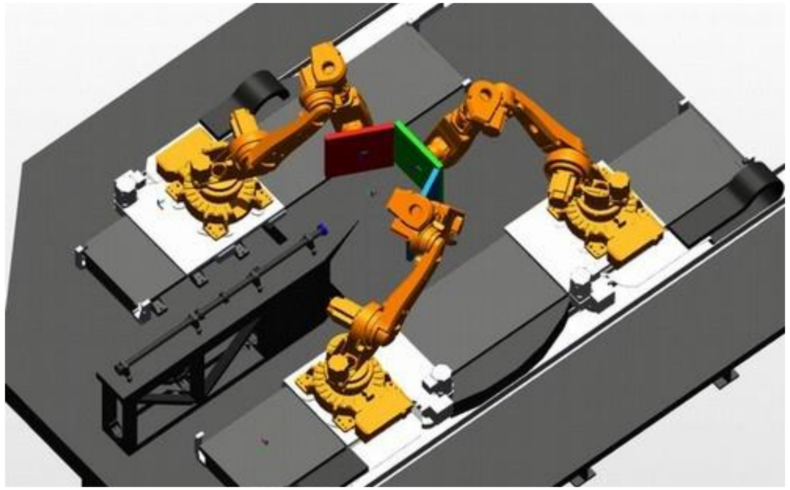
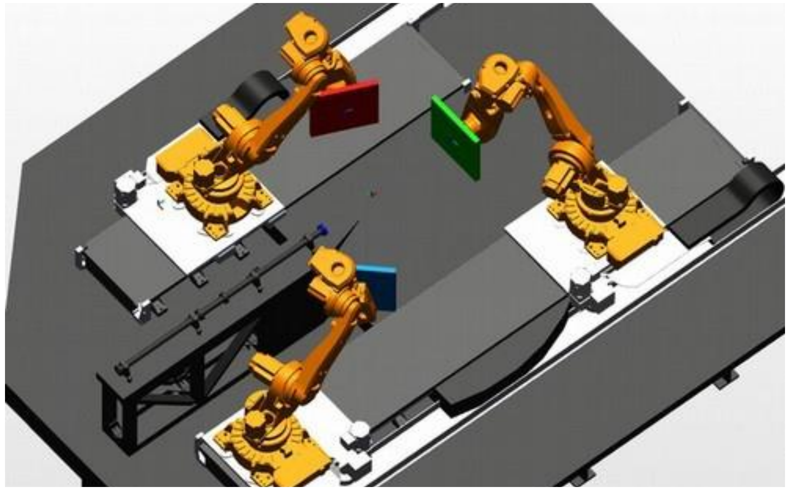
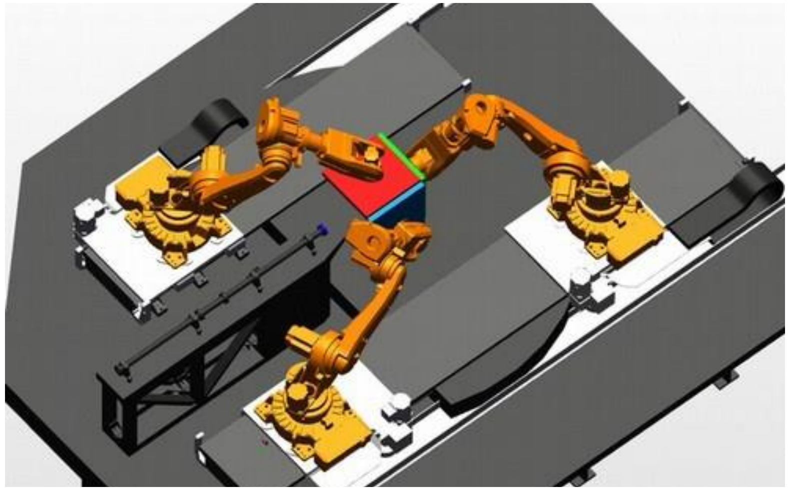
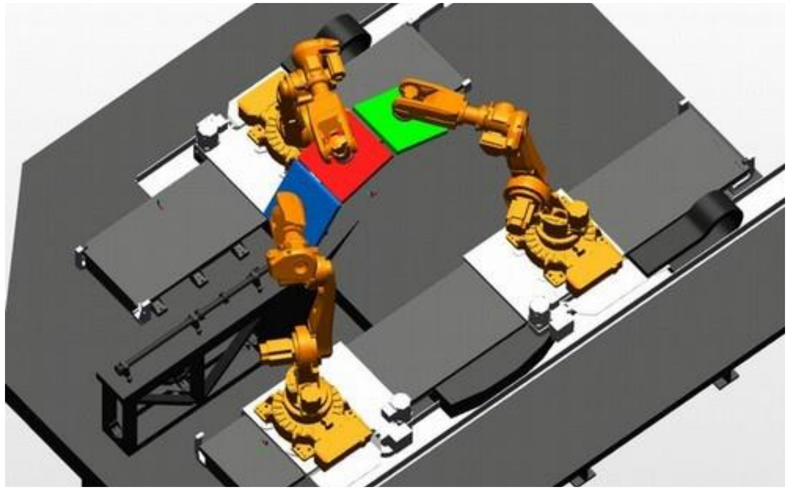

The NMX instrument
Detector baseline

Triple-GEM detector with natural gadolinium as neutron converter

Active detector area 50 x 50 cm², divided into four segments

GEM foils glued onto frames, spacers in active area to keep gap length

Minimised distance GEM – detector edge on three sides

Very low material budget readout

Cartesian 2D strip readout, 400 µm strip pitch (standard size)

5 VMM3 hybrids per coordinate per module
total of 40 hybrids read 5120 strips

µTPC method as read-out technique

The NMX instrument
Detector baseline

has been done before
TOTEM, COMPASS, …

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µTPC method as read-out technique

Michael's part

The NMX instrument

Detector technology: Gaseous Electron Multiplier (GEM)

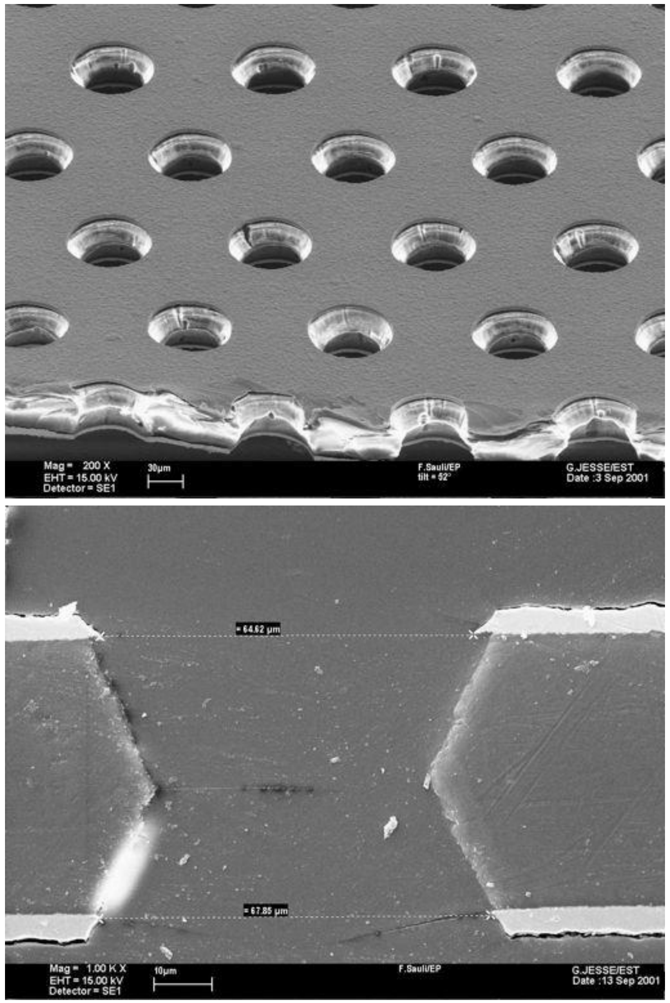
Metal-clad polyamide foil (usually 50 µm Kapton® with 5 µm Cu on both sides)

Perforated with **double-conical holes** in a honeycomb pattern (e.g. 70 µm diameter and 140 µm pitch)

Cathode on high negative potential with respect to GEM and anode

Potential difference applied between **top and bottom electrode** (typically in the order of 300-400 V)

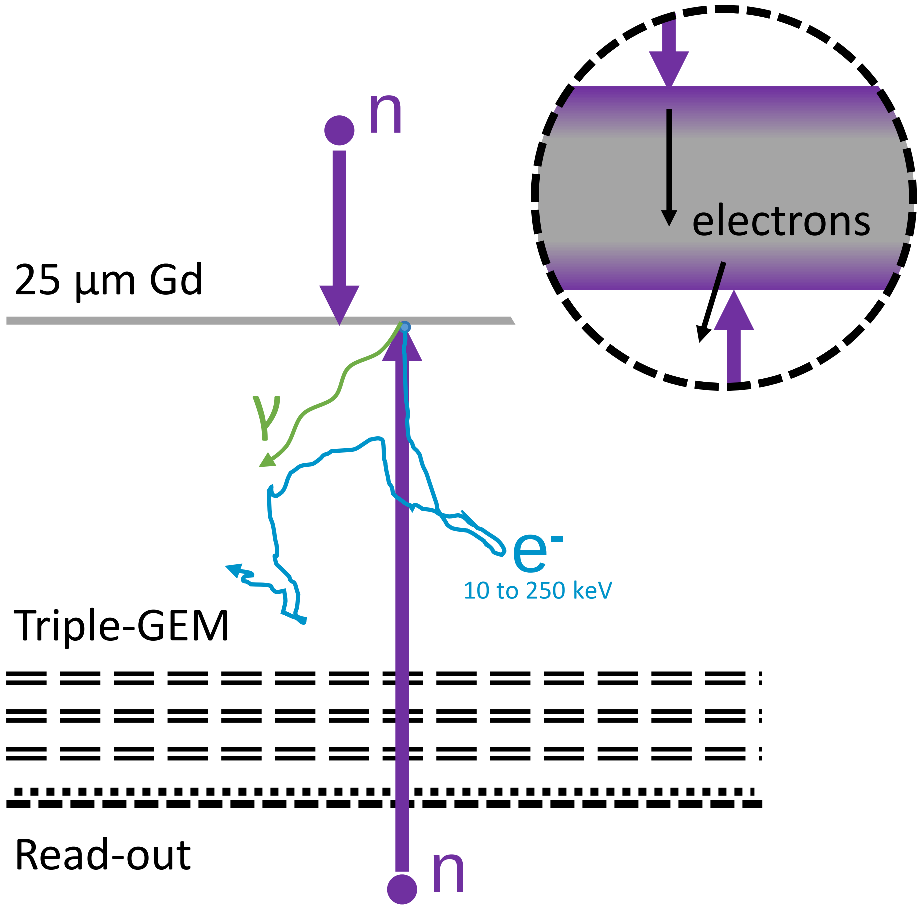
Usually **more than one GEM used in series** to achieve stable operation at increased amplification

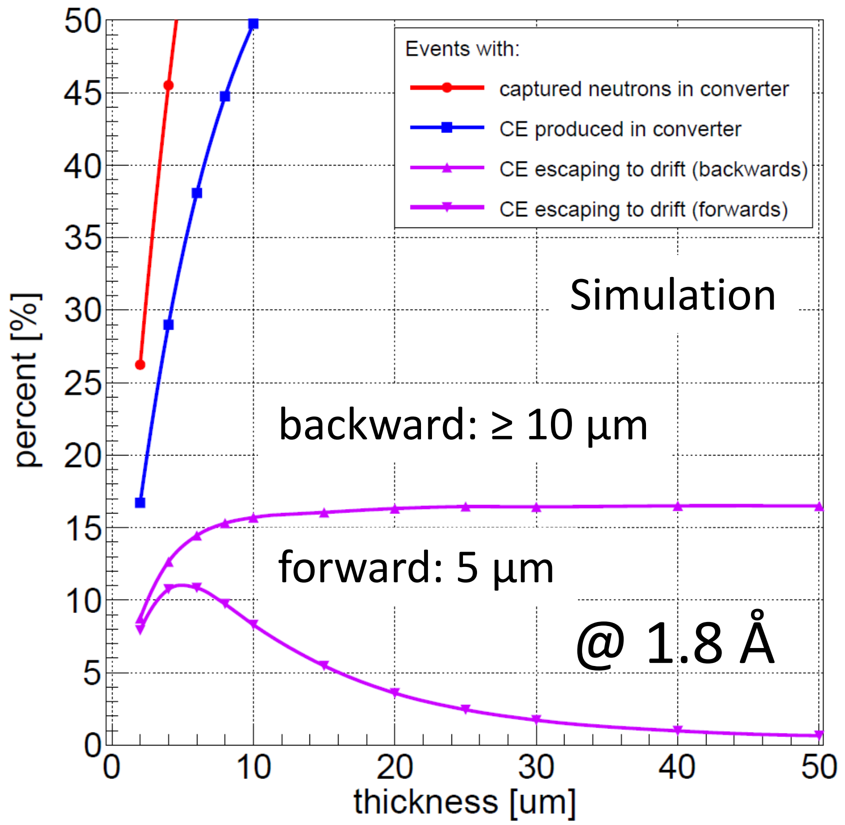


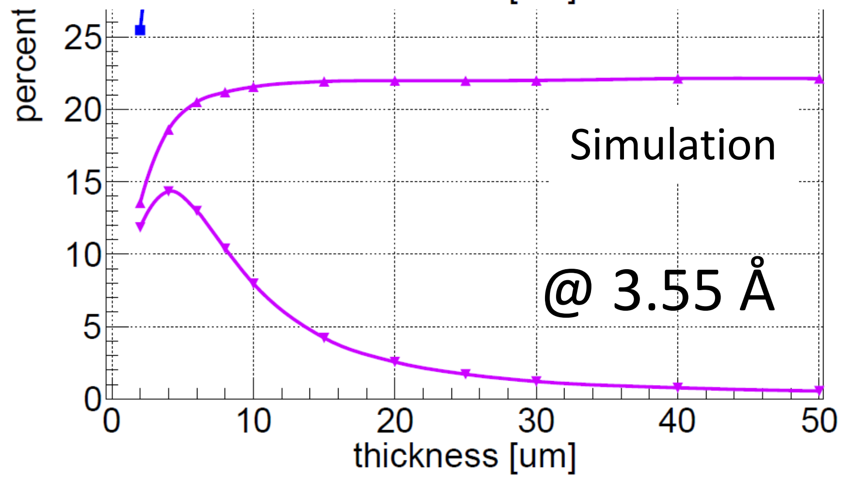
F. Sauli, *The gas electron multiplier (GEM): Operating principles and applications*, Nucl. Instr. Meth. A 805 (2016) 2-24

The NMX instrument

Neutron converter: Gadolinium

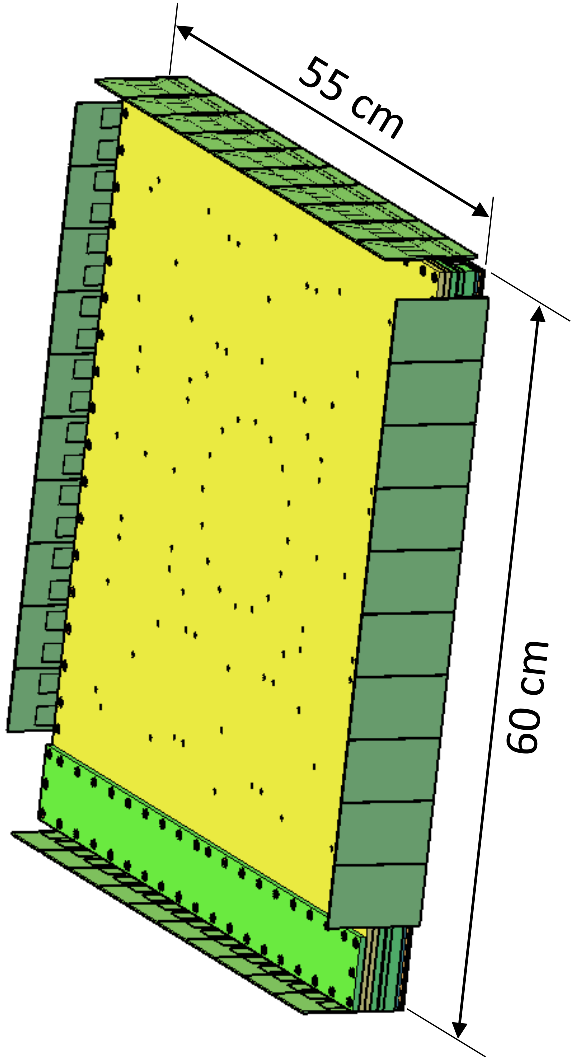






NMX demonstrator prototype v0 “Zita”

900+ pieces of fun



shielding and cables not shown

NMX demonstrator prototype v0 "Zita"

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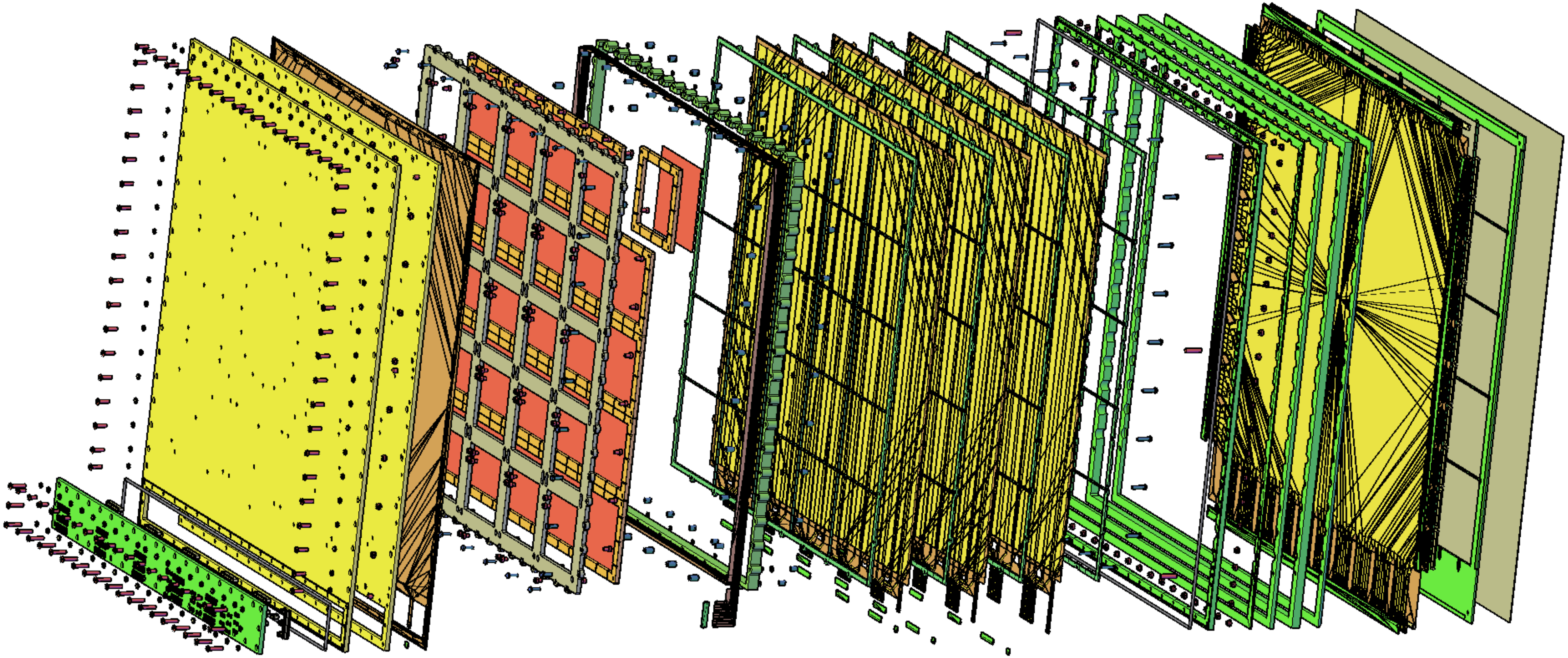
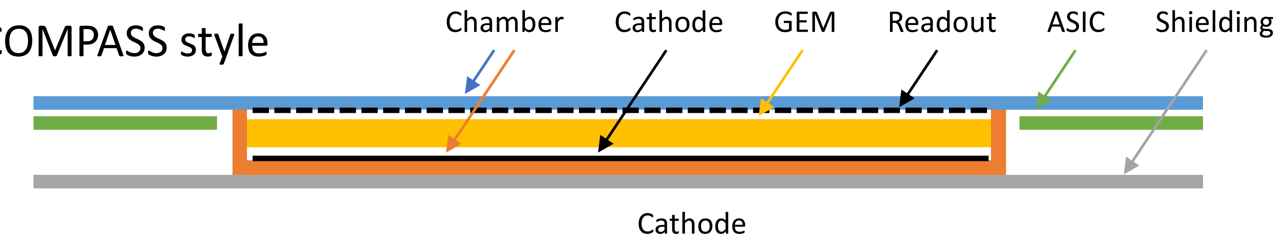


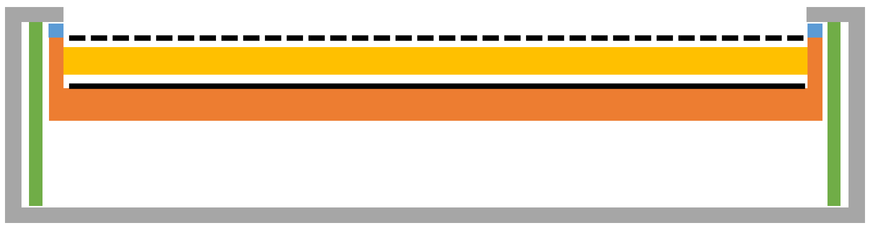
NMX demonstrator prototype v0 “Zita”
Design challenges

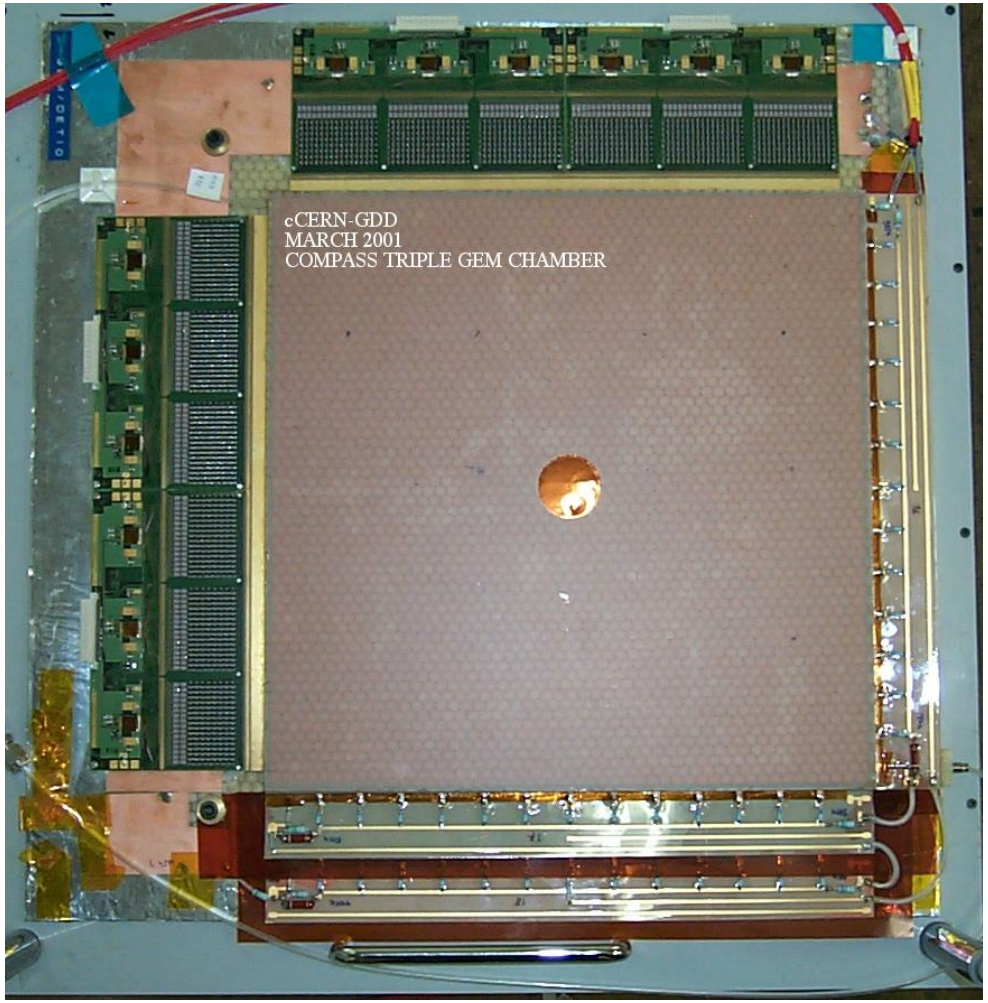
COMPASS style



CMS style

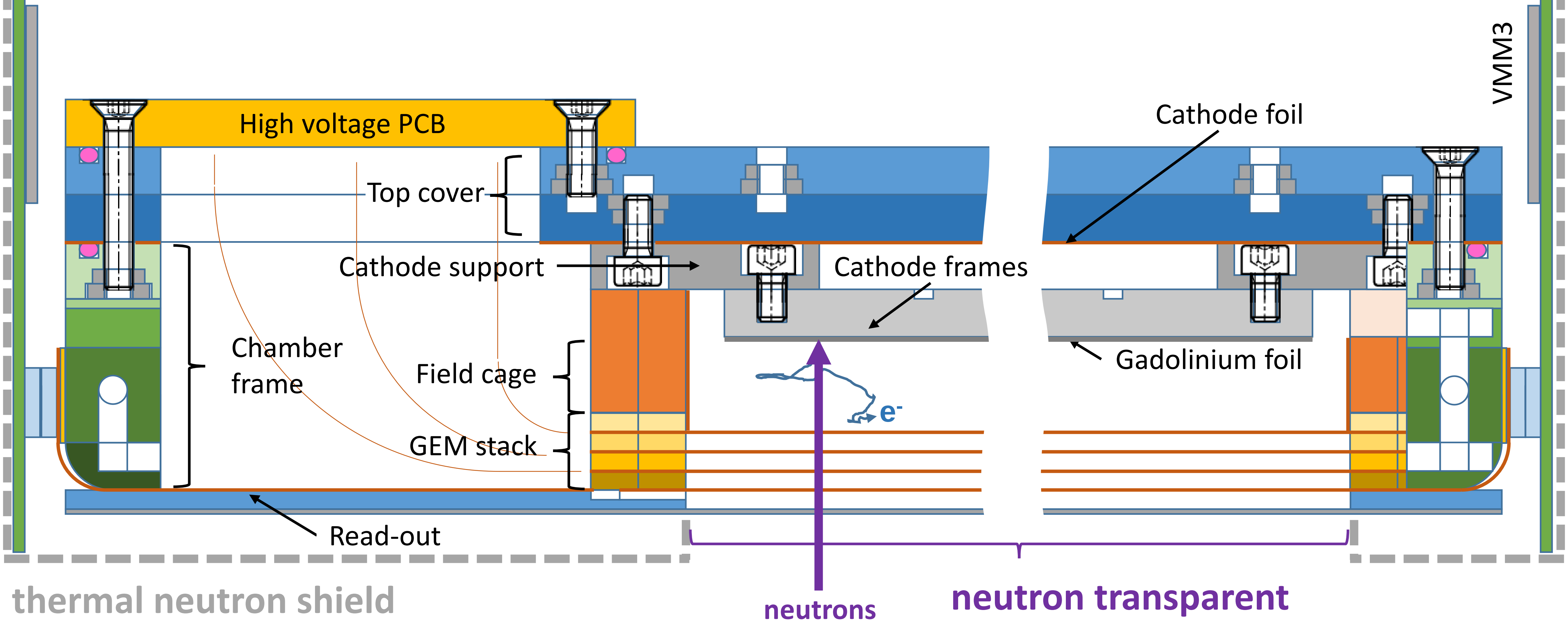
NXM style





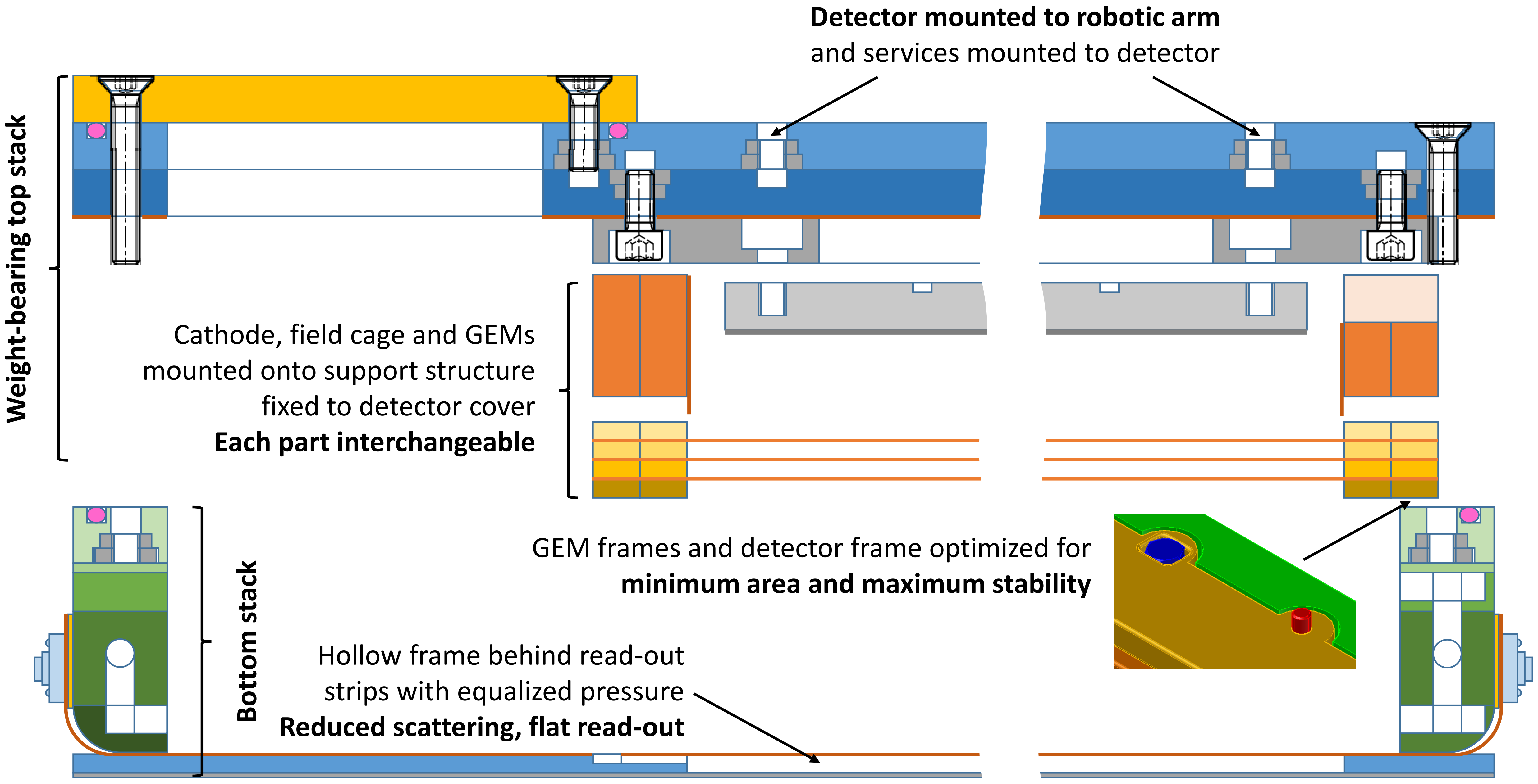
NMX demonstrator prototype v0 “Zita”

Cross-section



thermal neutron shield

(not part of BrightnESS project)



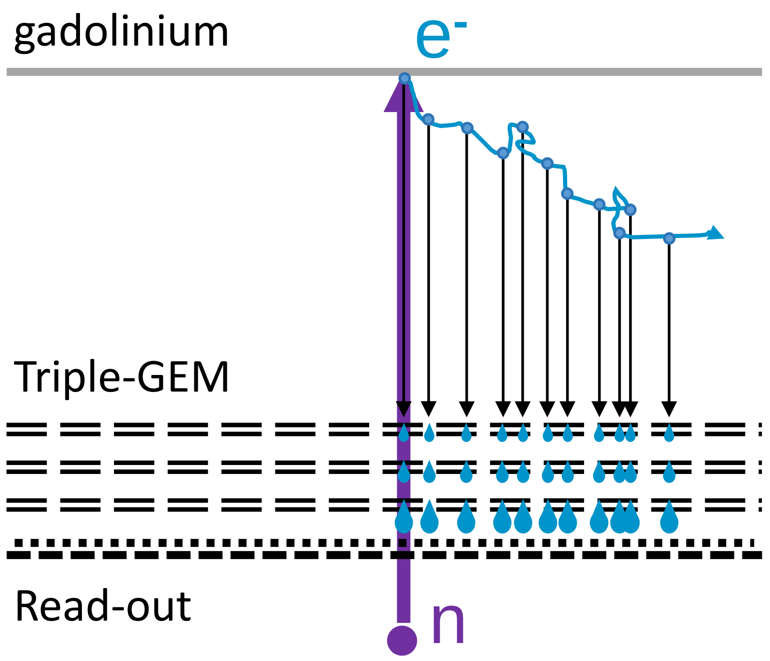
Weight-bearing top stack
Detector mounted to robotic arm
and services mounted to detector
Cathode, field cage and GEMs
mounted onto support structure
fixed to detector cover
Each part interchangeable
Bottom stack
GEM frames and detector frame optimized for
minimum area and maximum stability
Hollow frame behind read-out
strips with equalized pressure
Reduced scattering, flat read-out

Detector read-out chain and electronics

The NMX instrument

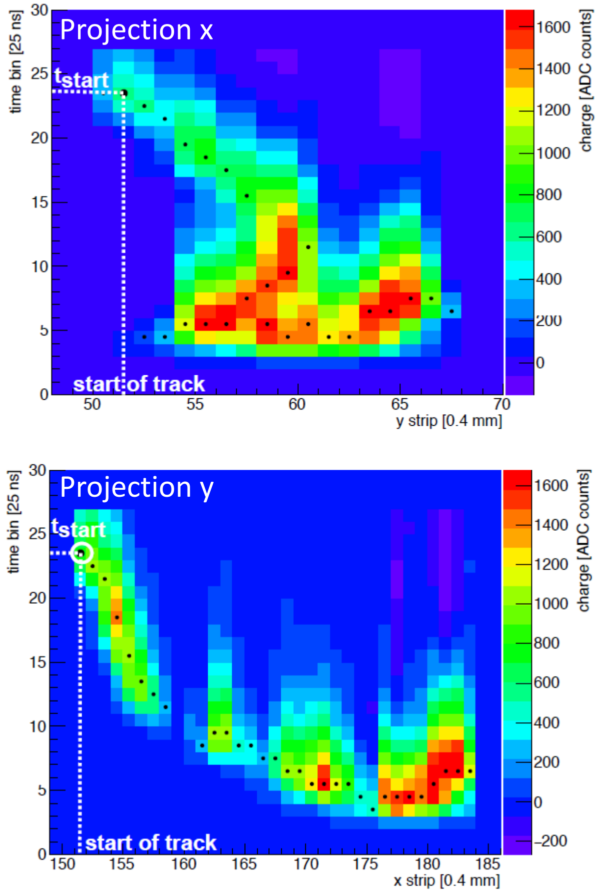
Read-out technique: Micro Time Projection Chamber (µTPC)

Already **working read-out technique**
demonstrated for 10B† and Gd‡ neutron converters



Requirements:

- **position resolution** of ***O*****(200µm)** (strongly depending on read-out but generally improved by µTPC)
- **time resolution *O*(ns)**



† D. Pfeiffer et al., JINST 10 (2015) 04, P04004 ‡ D. Pfeiffer et al, 2016 JINST 11 P05011 BrightnESS D4.3

The NMX instrument
Read-out technique: Micro Time Projection Chamber (µTPC)

Anode strip **pitch**: 400 µm ⇨ position resolution

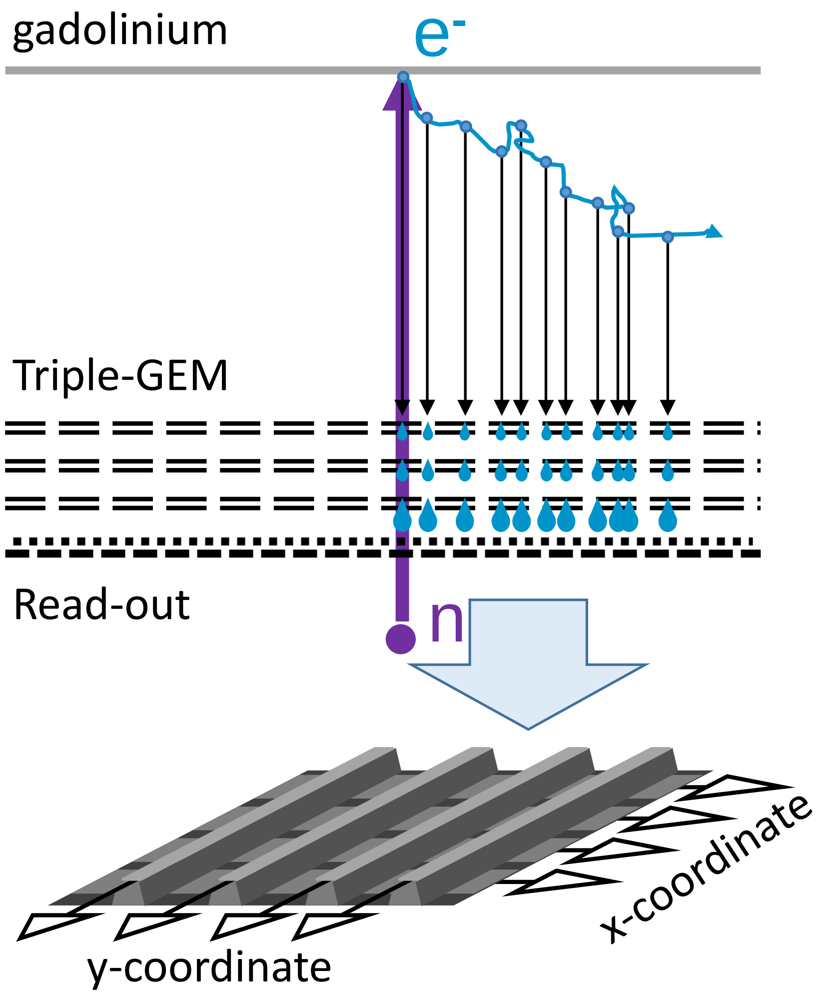
NMX prototype: 5120 strips w/ 4 kHz hits per strip
→ fast dense electronics needed to process charge signal: **integrated circuit**

µTPC requires time resolution *O*(ns)
→ high **time resolution** required

Robotic arms restrict number of cables from detector to back-end

→ **digitise data** on detector

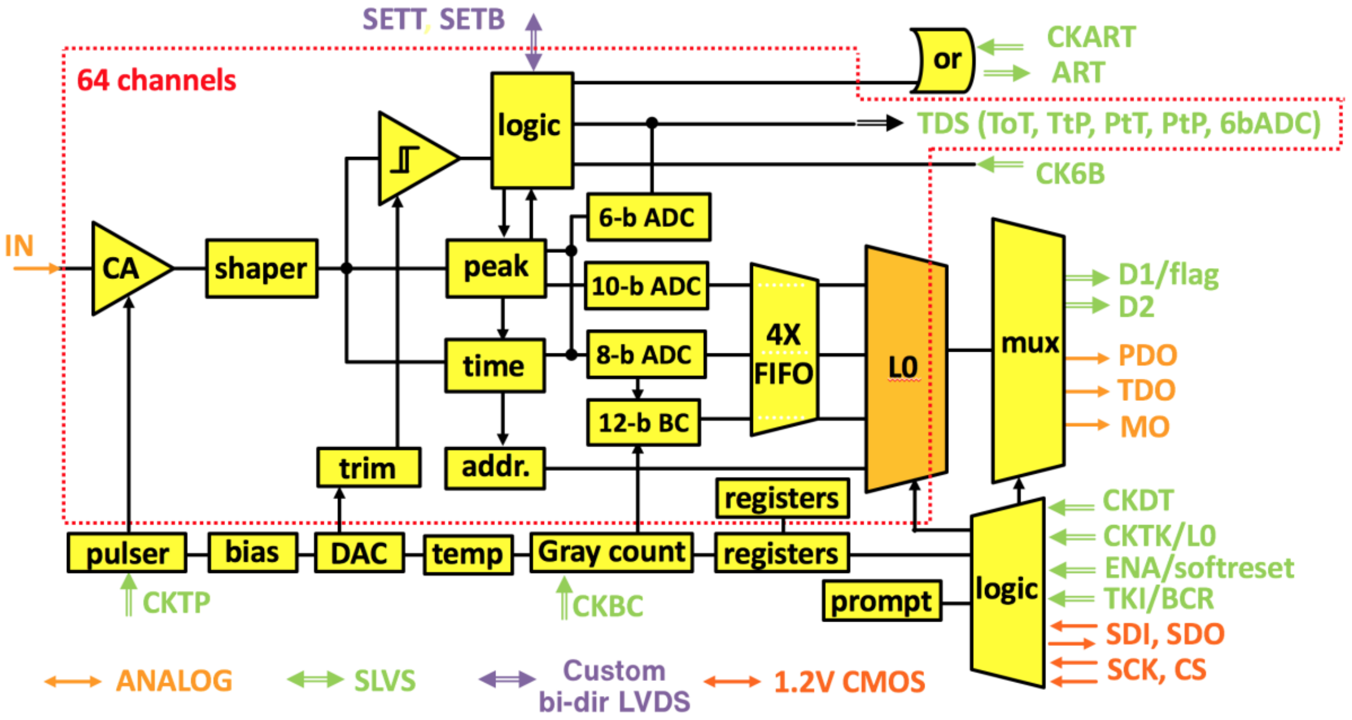
⇨ Use high rate **front-end ASIC** with digitisation



Electronics

The VMM ASIC – Features

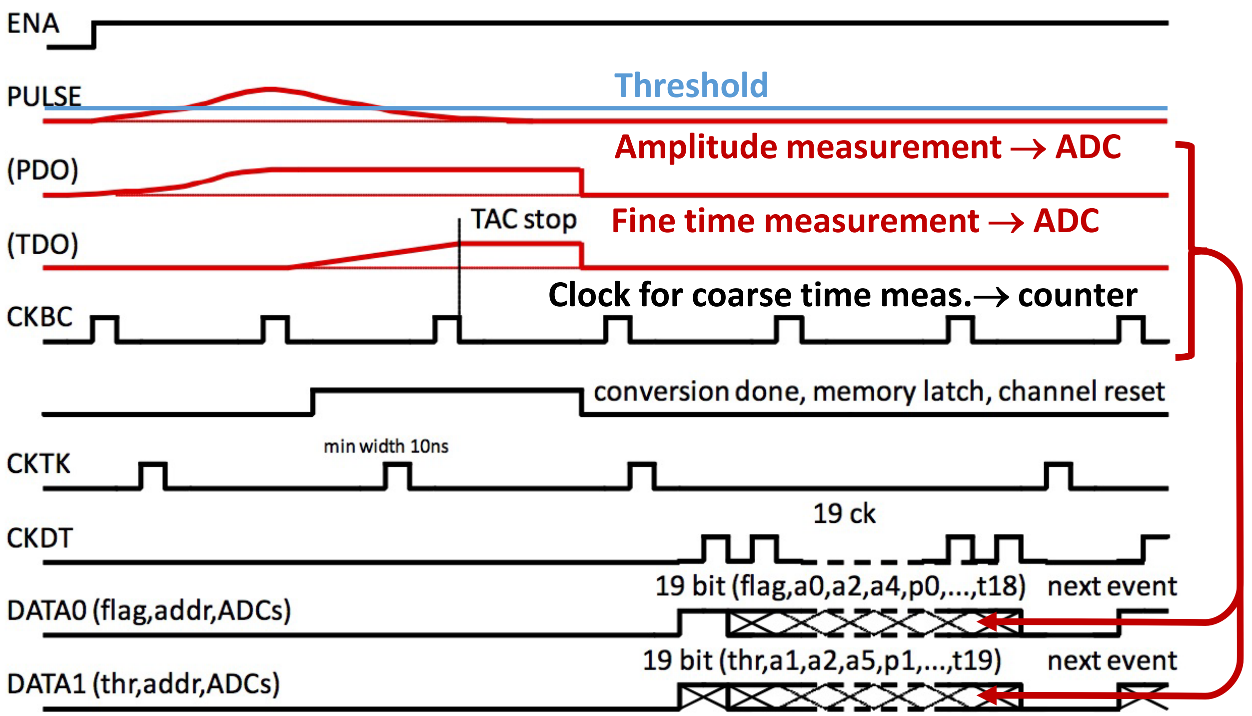
- 130 nm CMOS technology
- **64 input channels**, each w/ preamplifier, shaper, peak detector, several ADCs
- Pos. & neg. polarity sensitive
- **Digital** block w/ neighbouring logic, FIFO, multiplexer
- Adjustable **gain** 0.5 – 16 mV/fC
- Adjustable **shaping time** from 25 ns – 200 ns
- **Input capacitance** from few pF – 1 nF



Electronics

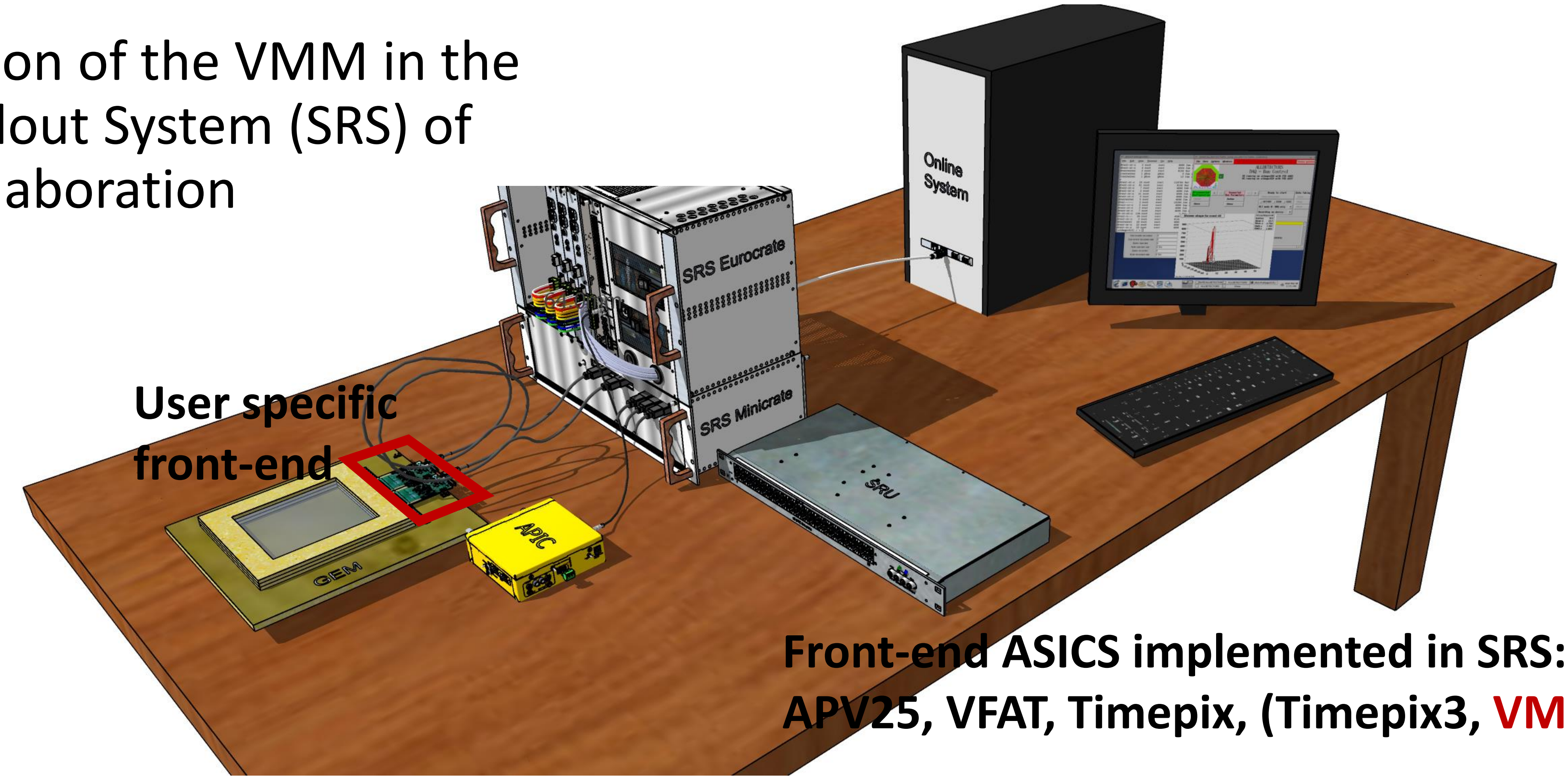
The VMM ASIC – Features (continued)

- Internal **test pulser** with adjustable amplitude
- Global **threshold** & adjustment per channel
- **Self-triggered**, **zero suppressed**
- **38 bit** per hit
  (if input charge goes over threshold)
  1. Event flag (1 bit)
  2. Over threshold flag (1 bit)
  3. Channel number (6 bit)
  4. Signal amplitude (10 bit)
  5. Arrival time (20 bit)



Electronics
The Scalable Readout System

Implementation of the VMM in the Scalable Readout System (SRS) of the RD51 Collaboration

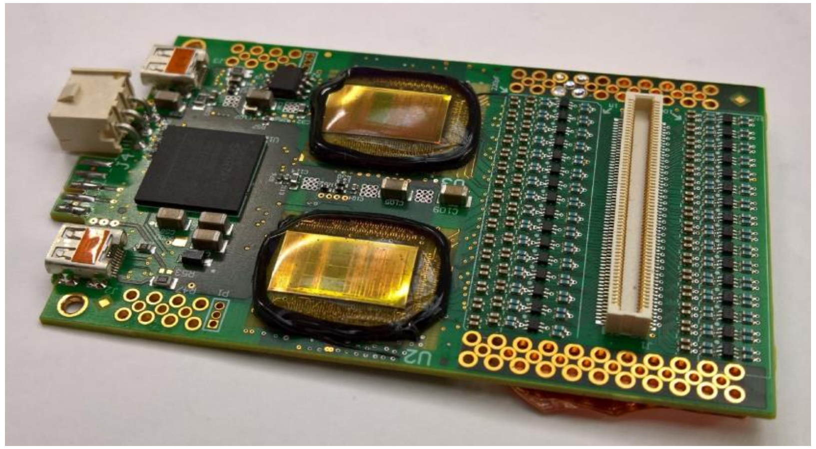


User specific front-end

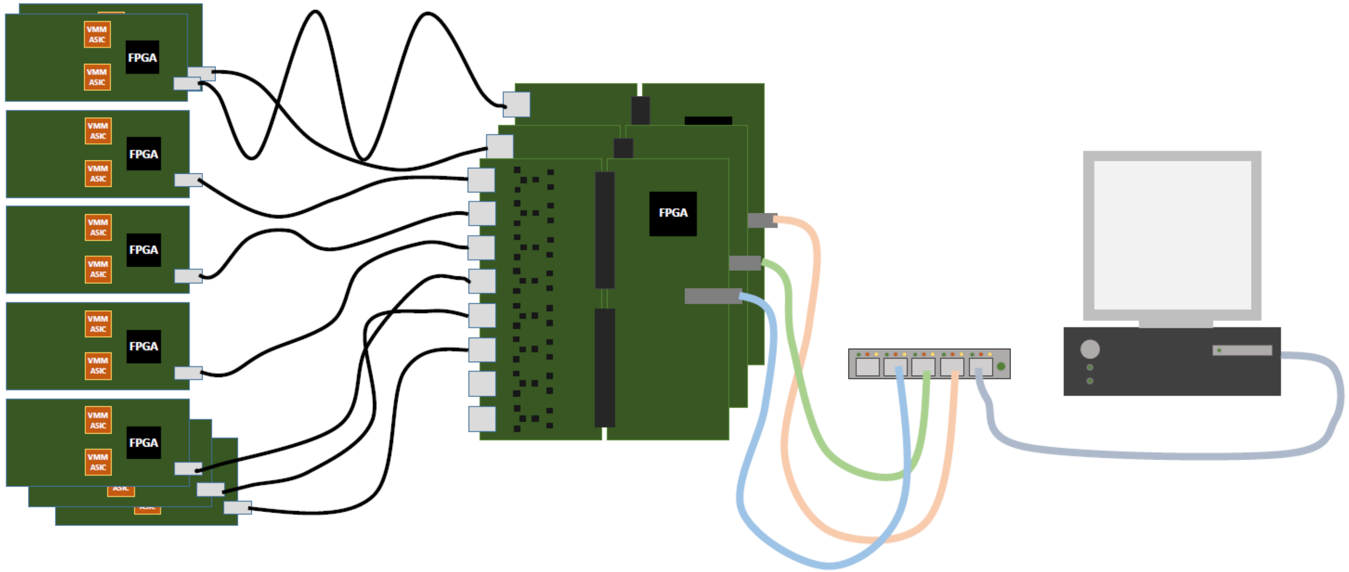
Front-end ASICS implemented in SRS: APV25, VFAT, Timepix, (Timepix3, VMM)

Electronics
Readout chain and components

New hybrid and adapter card, FPGA firmware, and PC software has been designed to implement VMM in SRS



VMM hybrid



VMM Hybrid → HDMI cable → Adapter card + FEC → Ethernet → Switch →Ethernet → PC

SRS FEC and adapter card for VMMs

Scalability: up to 8 VMM hybrids/FEC, many FECs/PC
→ system scalable from one to 64 hybrids and more

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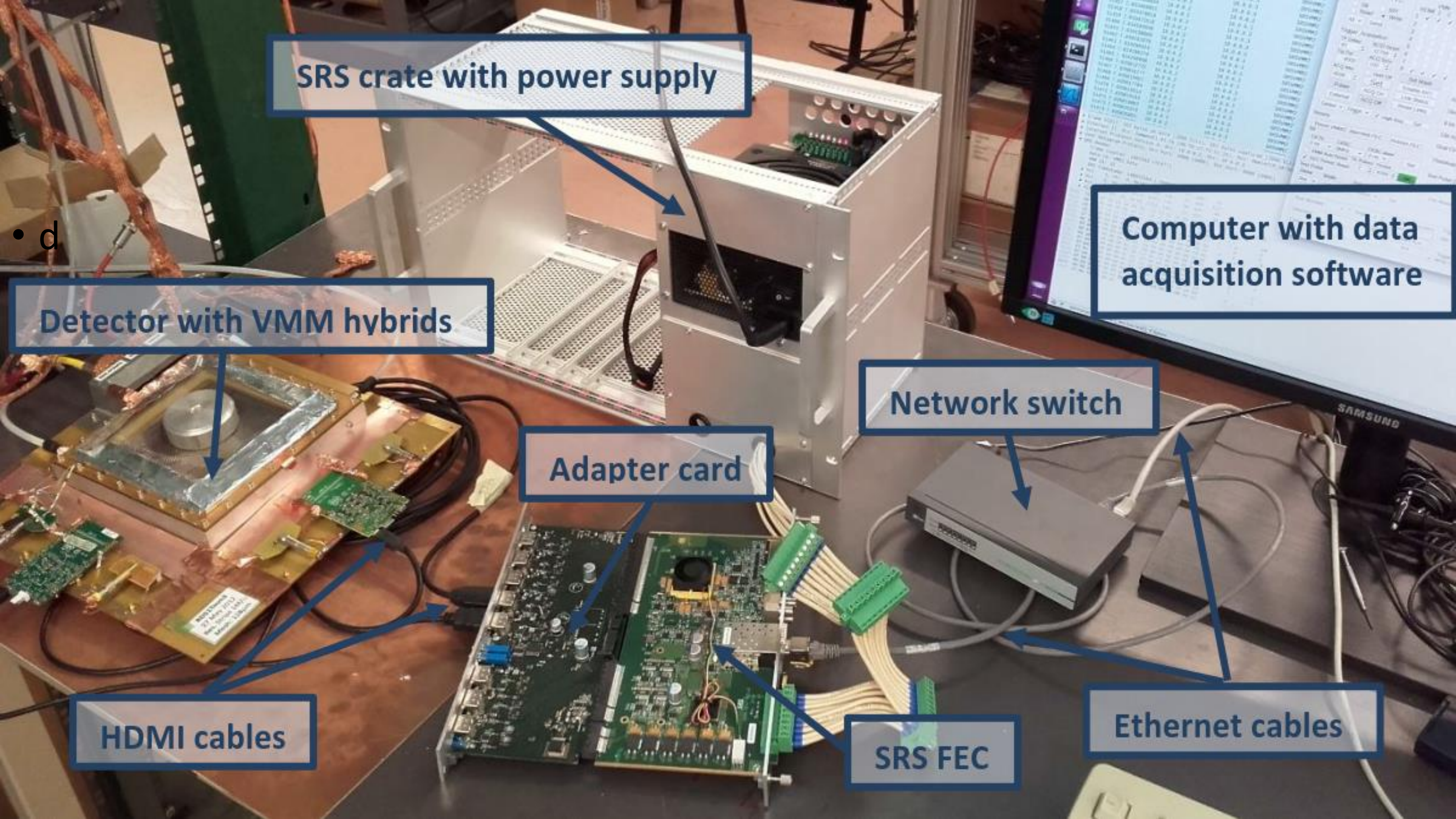
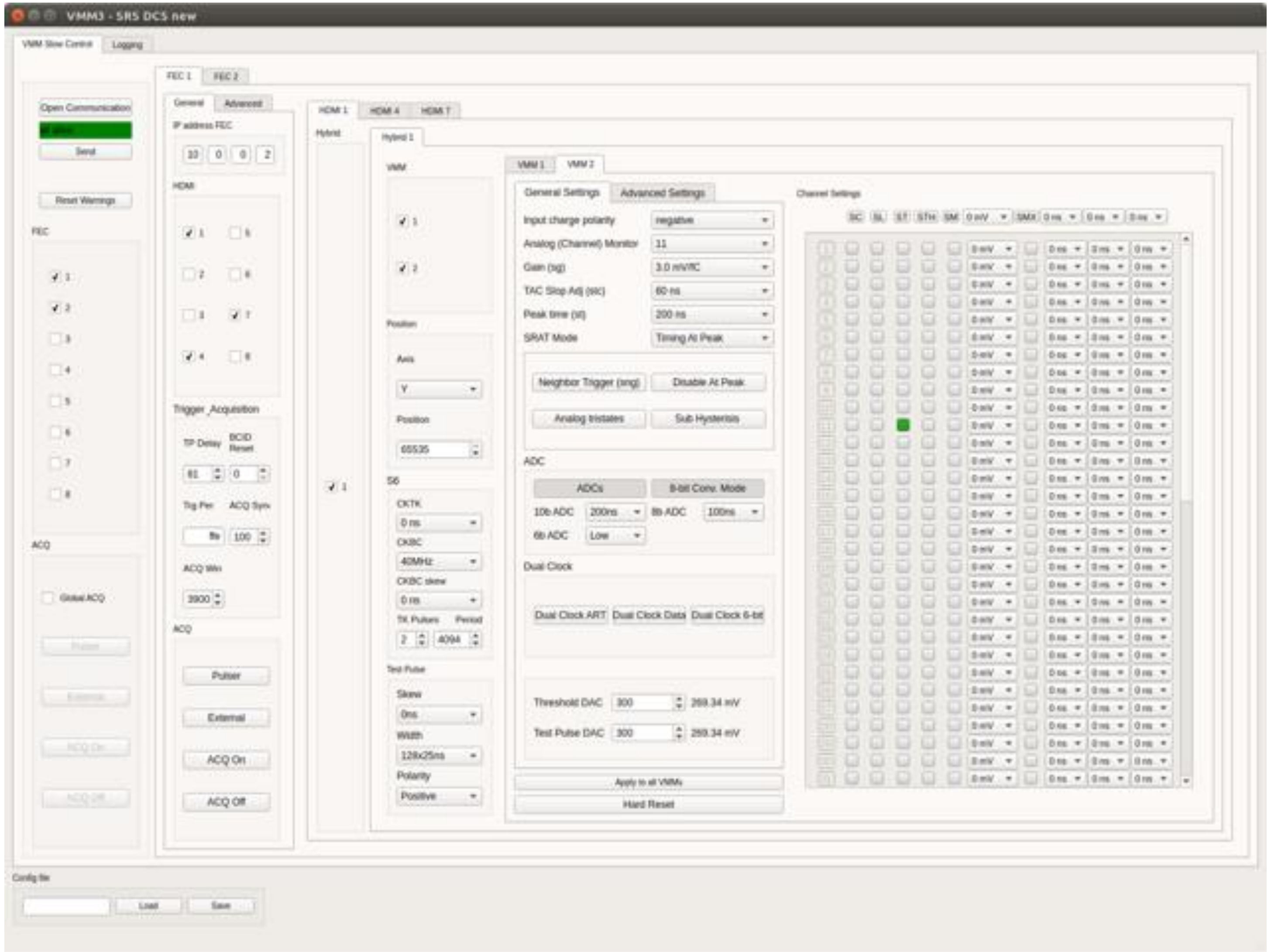

SRS crate with power supply
Computer with data acquisition software
Detector with VMM hybrids
Network switch
Adapter card
HDMI cables
Ethernet cables
SRS FEC

Electronics
Slow control for the readout system

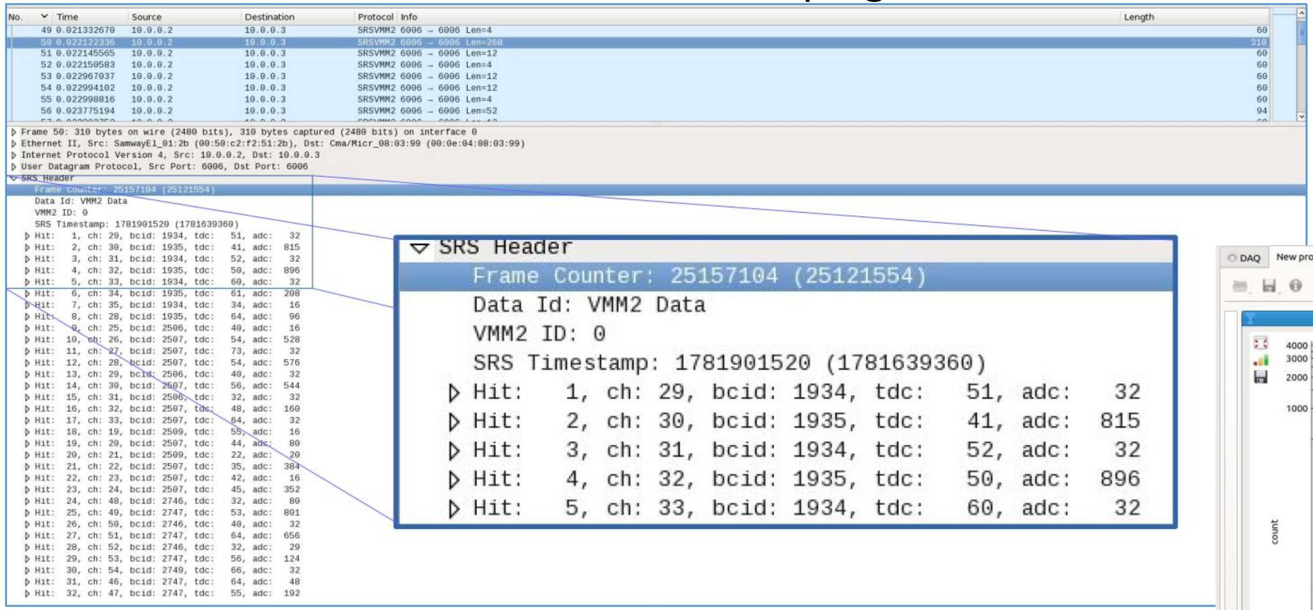


CERN Summer student project of Manuel Guth

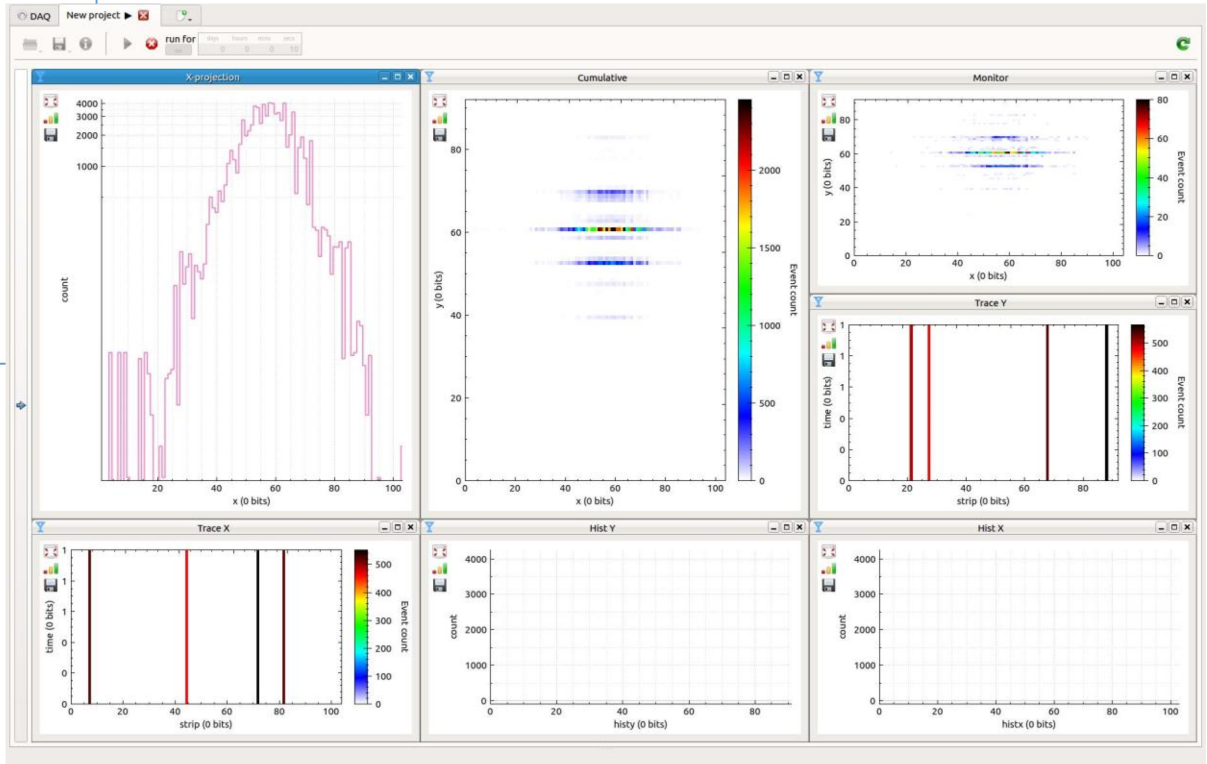
Electronics

Data from SRS

Wireshark & plugin for first data check



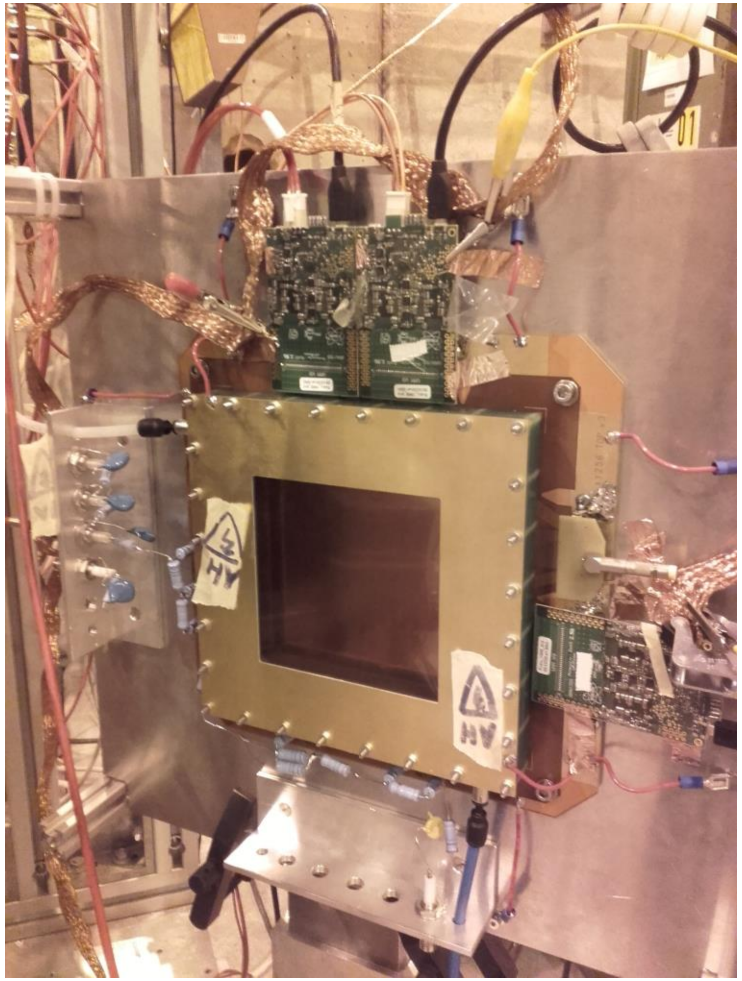
Online monitoring



Help from BrightnESS WP5.1, DMSC for online data monitoring and fast data acquisition

Electronics

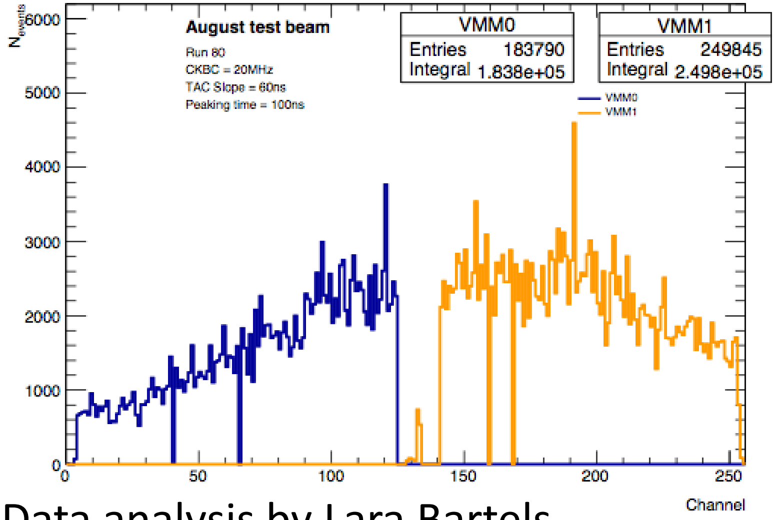
Latest test beam at CERN North area with beam from SPS

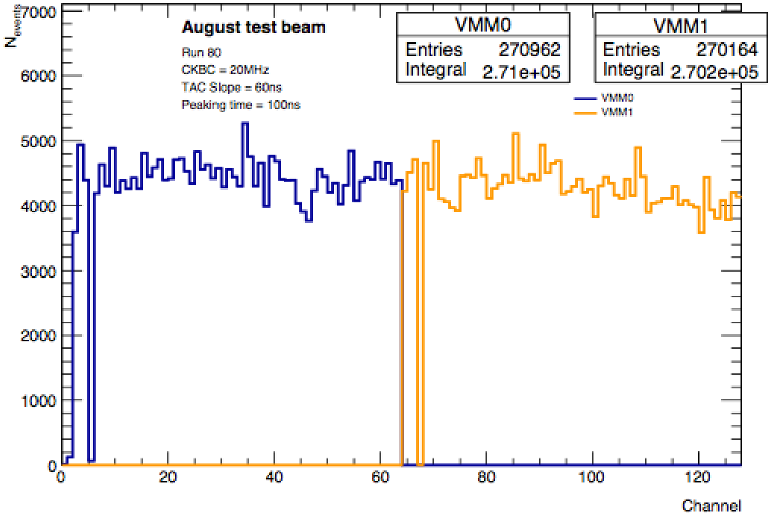


Triple-GEM detector with copper cathode (no gadolinium for muons and pions)

Three VMM3 hybrids (2 on x-axis, 1 on y-axis)

- Continuous data in self-triggered mode at 5kHz readout frequency
- Goal of test: operate electronics and test different settings

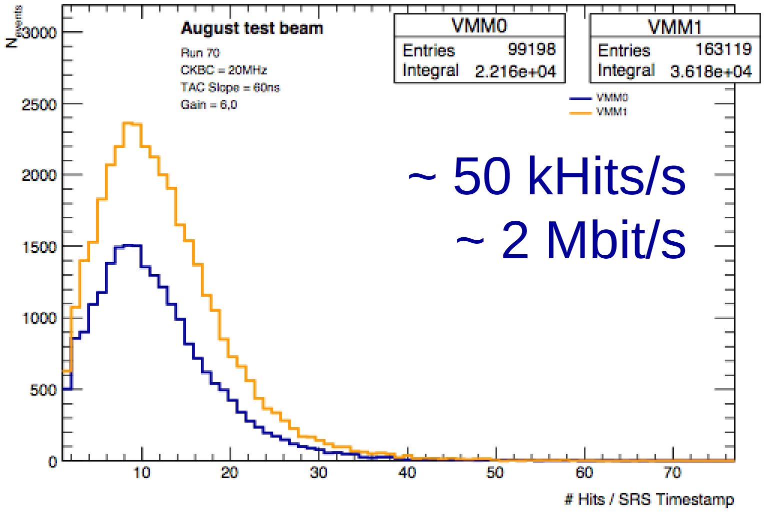


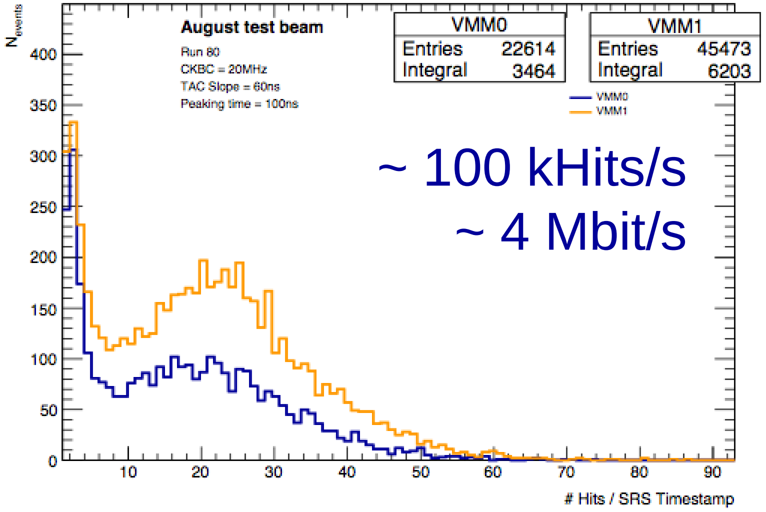


Data analysis by Lara Bartels

Electronics

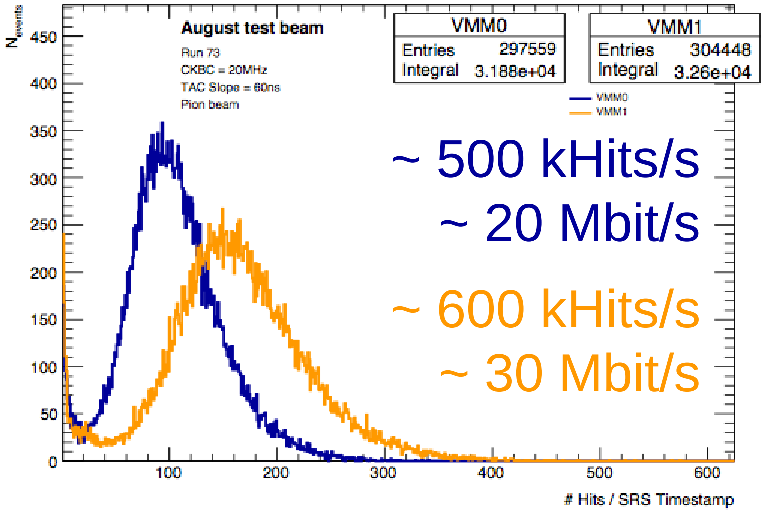
Latest test beam SPS beam

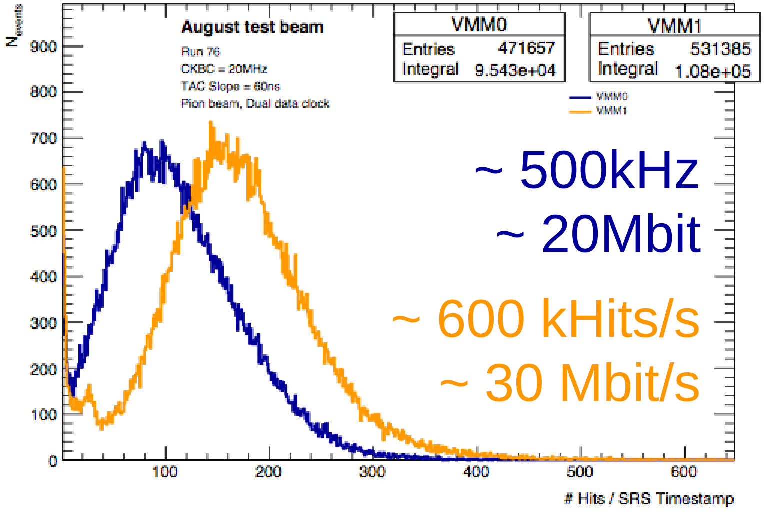




muon beam

pion beam



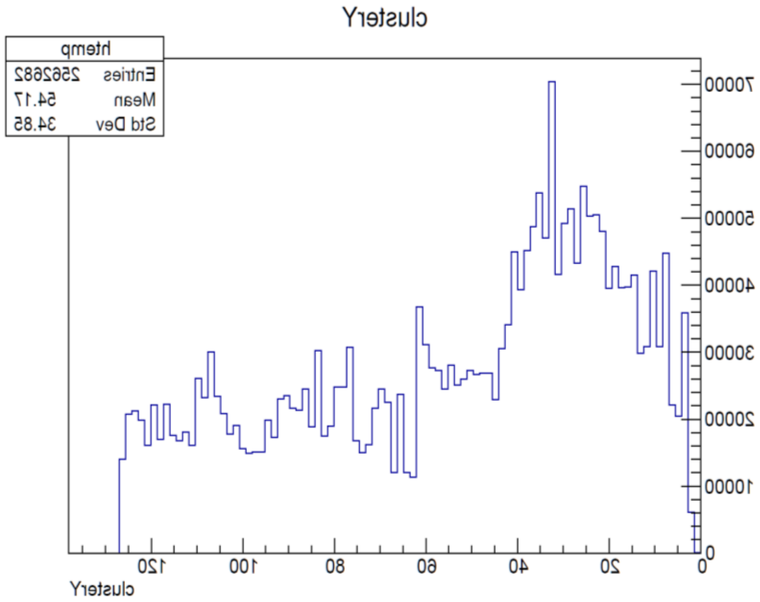


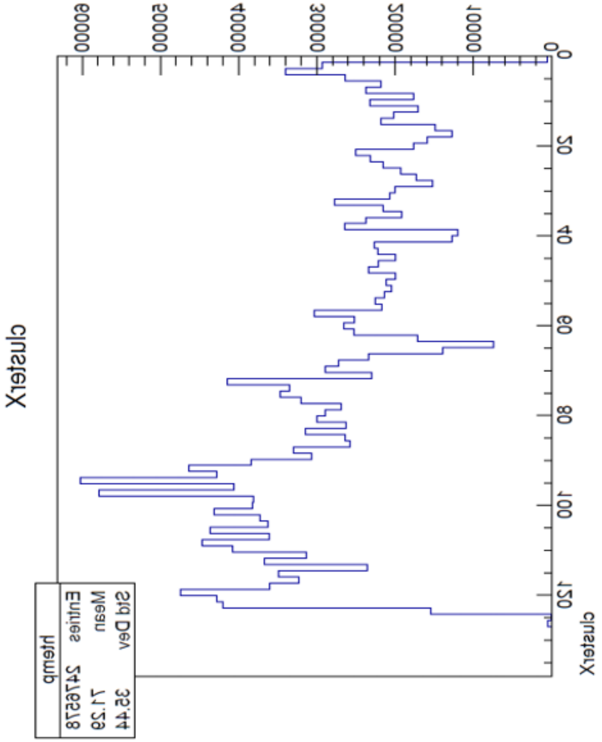
Electronics

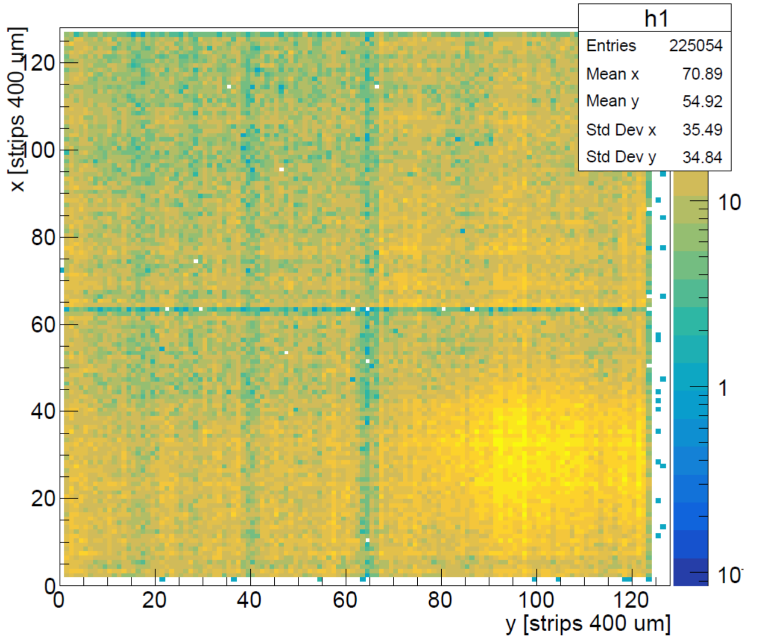
Latest test beam SPS beam

Clustered data from pion beam

VMM3 is working with SRS
and will also work with
all diffraction patterns!



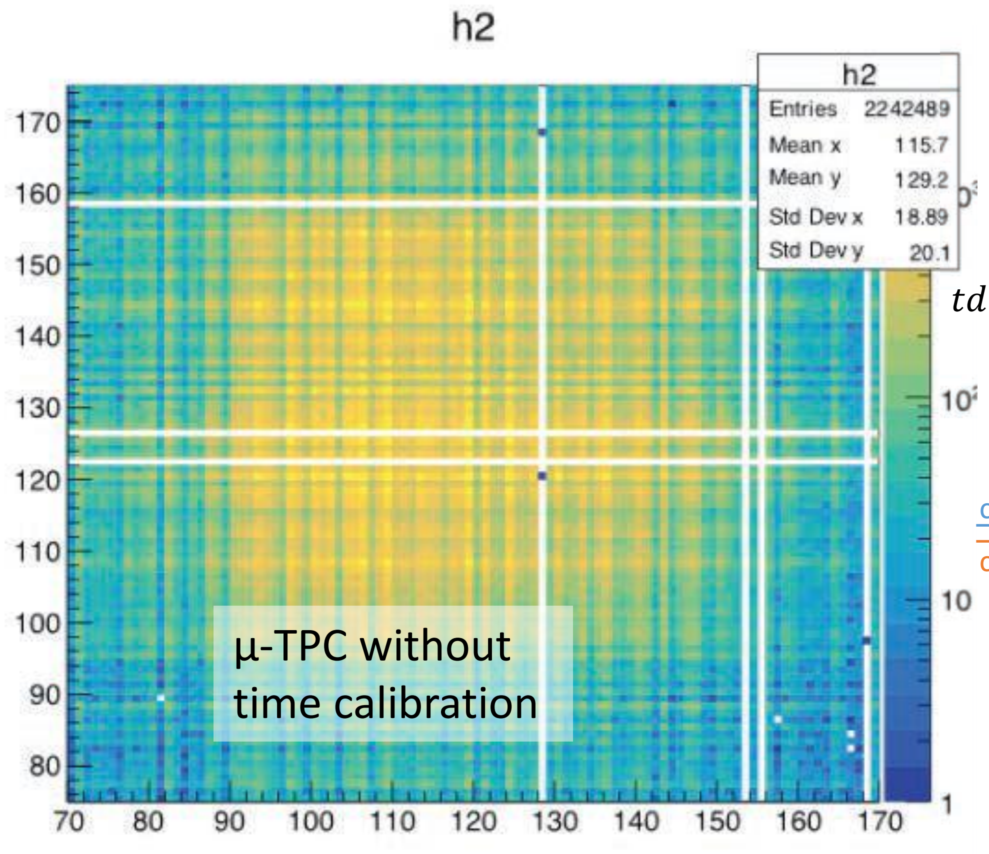




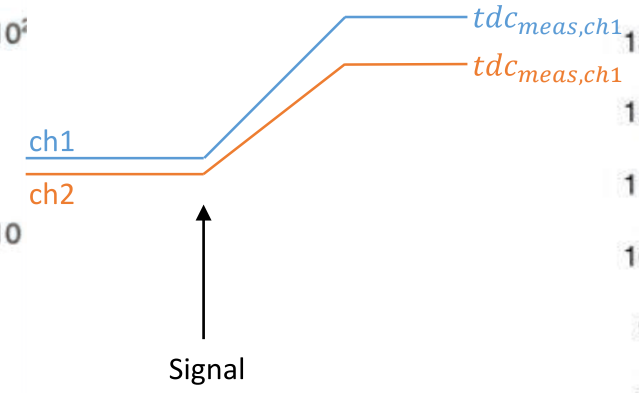
Electronics

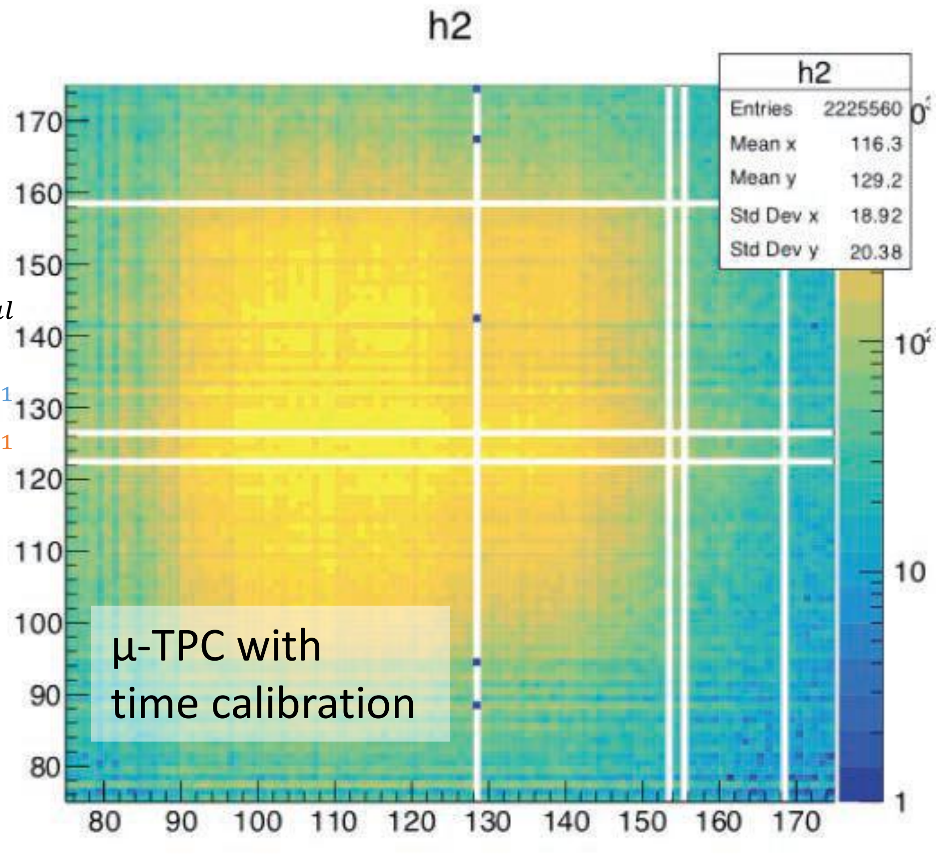
Latest test beam at JEEP II reactor, IFE, Olso

Clustered data from neutron beam with improved analysis



$$tdc_{cal} = tdc_{meas} \cdot slope_{cal} + offset_{cal}$$





Electronics
Next steps

VMM3a will be available end February

- **New hybrids** with additional functionality
  - For **automated calibration** (ADCs on BCP to measure pedestal and threshold levels)
  - For **higher amount of readout channels** per FEC (two hybrids per HDMI input)

Electronics
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  - For more stable **power supply** of multiple hybrids
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Electronics
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- **More ASICs** will allow further testing and readout of the large detector
- Three SPS **test beams** and least two test beams at neutron facilities foreseen
- SRS + VMM will become available for **more users**!

Conclusions & outlook
NMX @ CERN

NMX instrument will be first diffractometer without fixed geometry
Three **fully integrated and moveable detector units**

Concept for **detector** works & **close to requirements**

Testing and **assembly** of demonstrator **ongoing** with CERN GDD

VMM has been **implemented** in SRS for detector readout

Test-beam at ILL D16 diffractometer in **late spring**

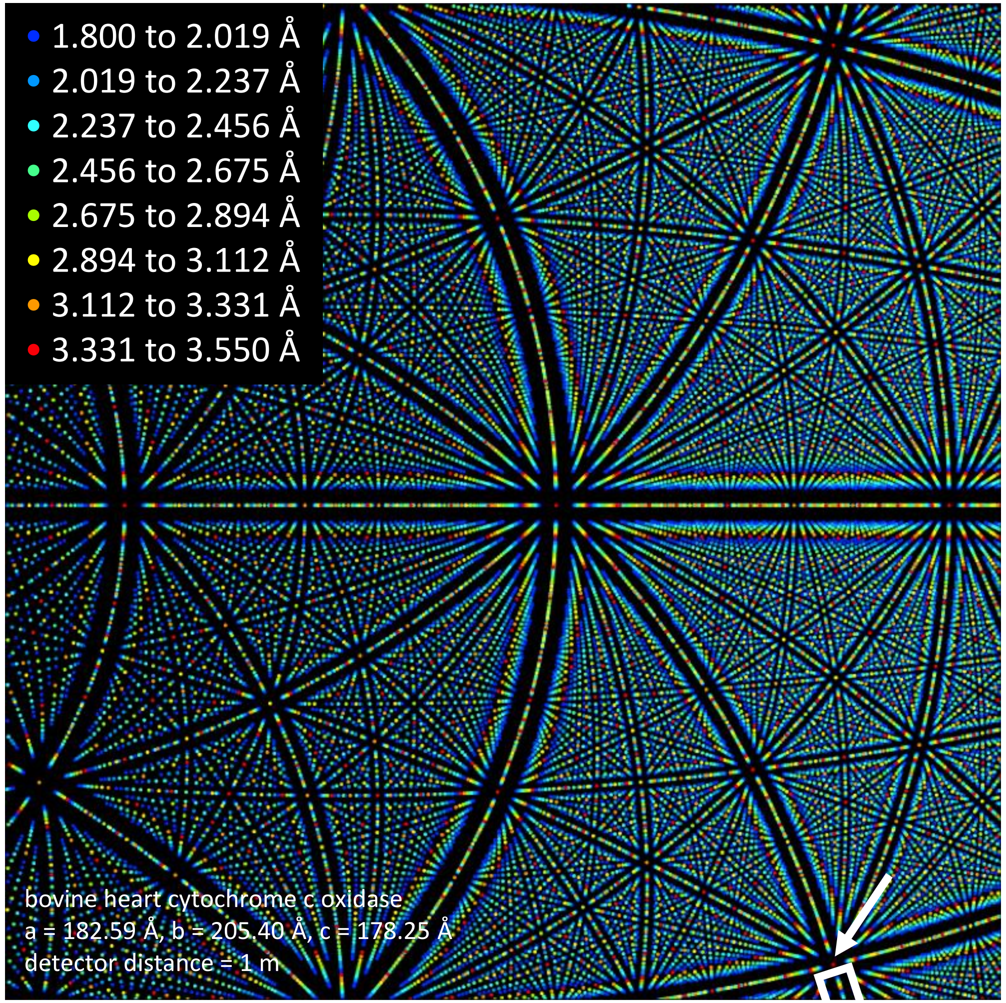
BrightnESS project will successfully finish in **August 2018**

Thank you!
for letting us use your facilities at CERN

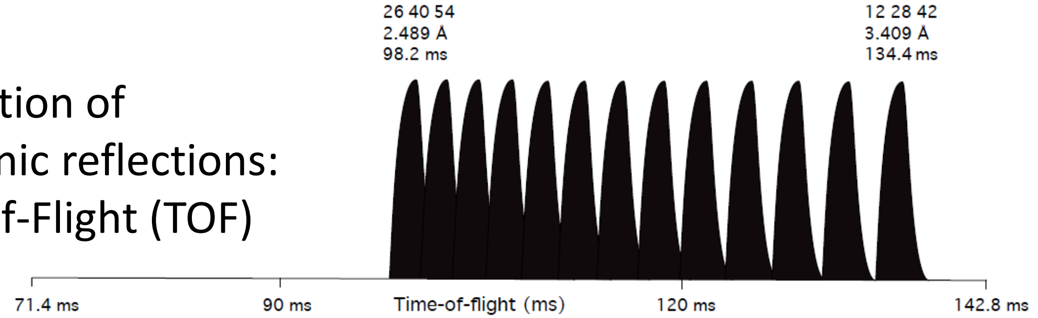
Backup slides

Quasi-Laue Time-Of-Flight Diffractometry

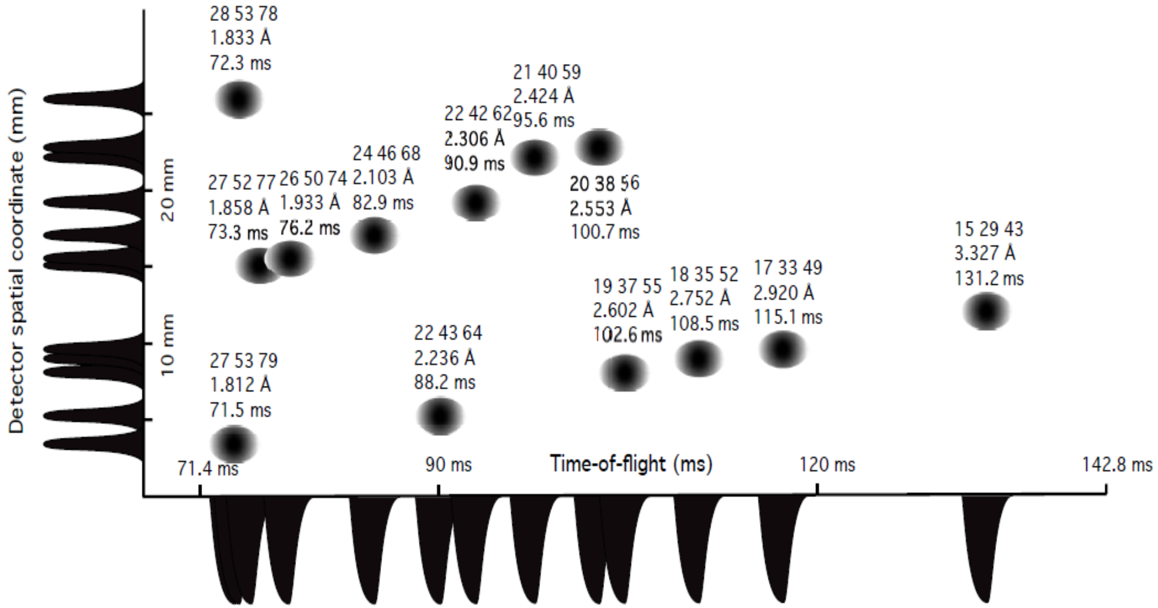
Example diffraction pattern



Separation of harmonic reflections: Time-of-Flight (TOF)



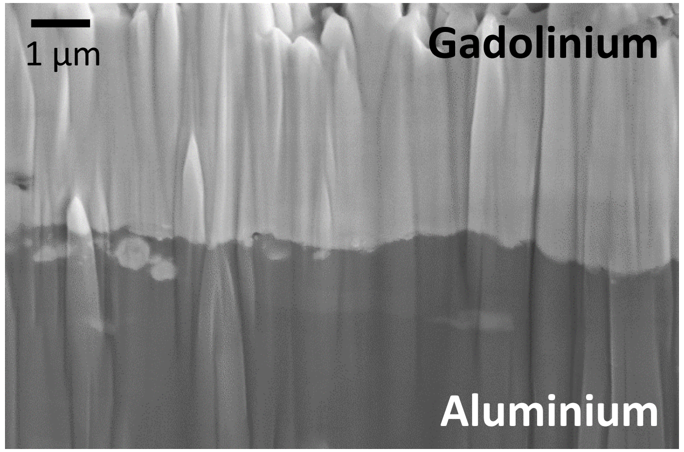
Separation of spatial reflections: TOF and superior position resolution

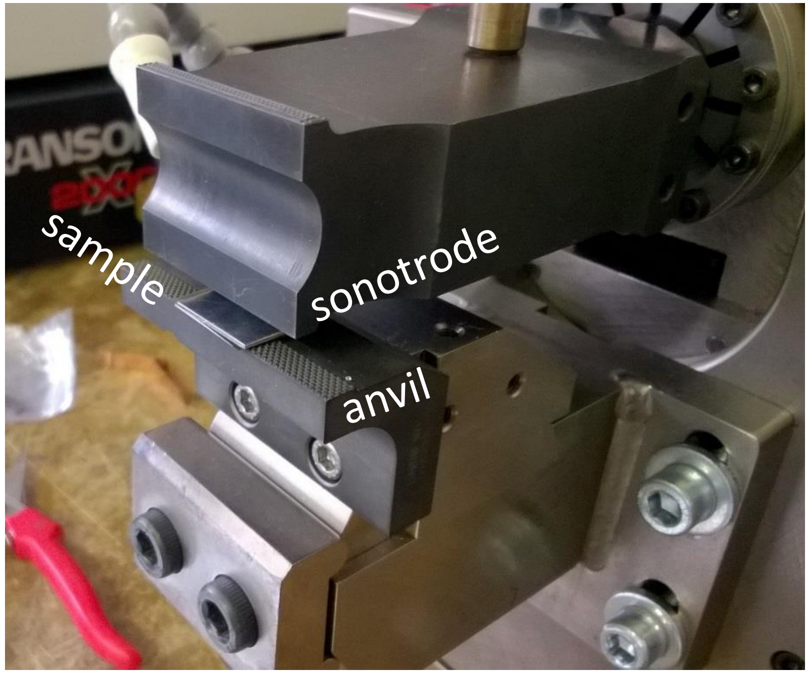


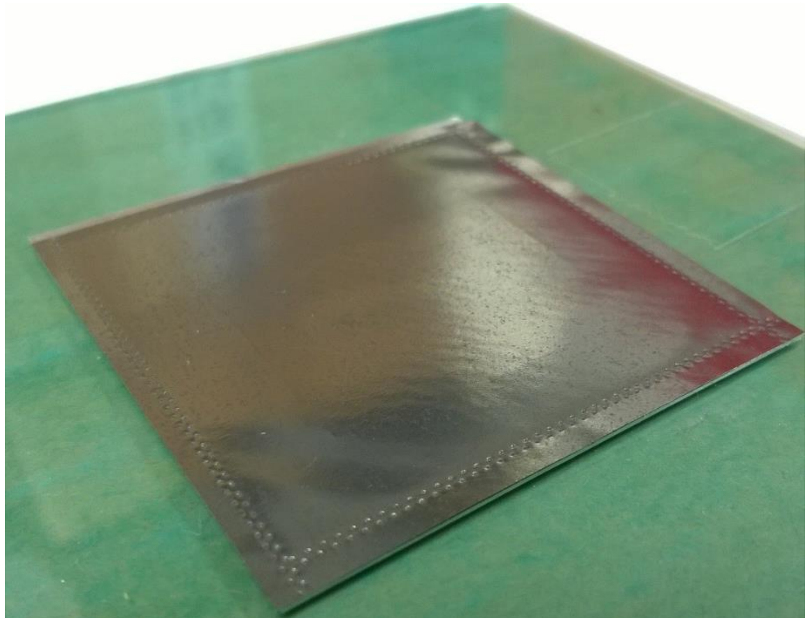
Cathode assembly due to maximum foil size

Ultrasonic welding for mechanical and electrical connection with

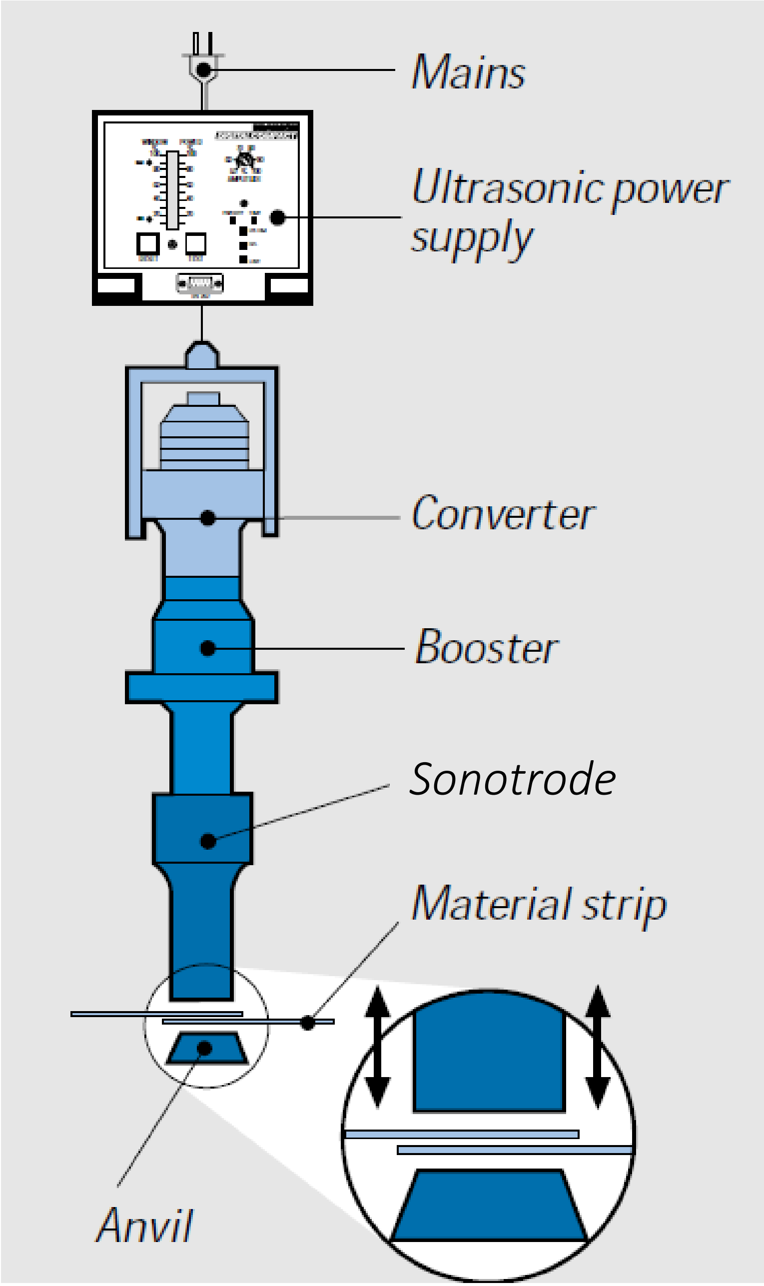
No dead area







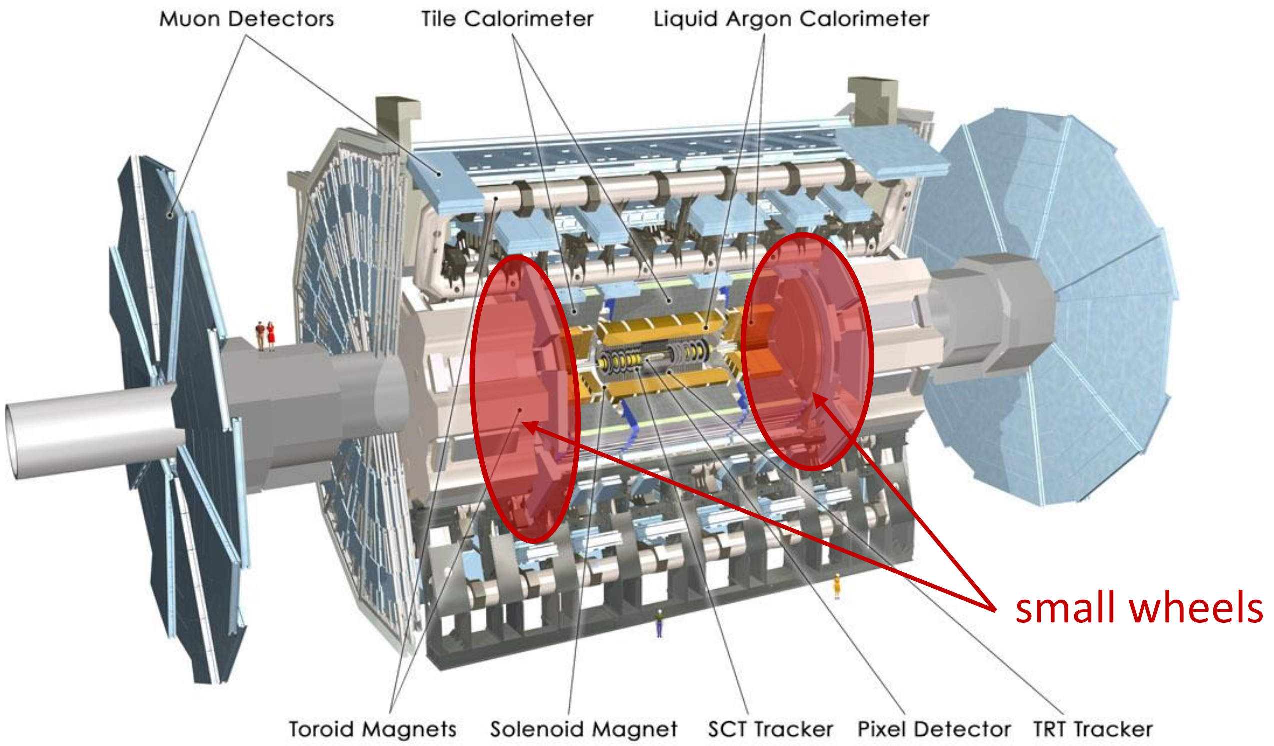
25 µm gadolinium on 1 mm aluminium, 5 x 5 cm²



Electronics

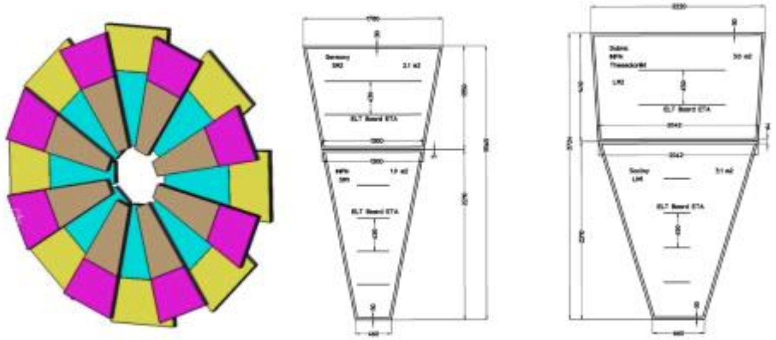
The ATLAS New Small Wheel Upgrade

In the scope of the high luminosity upgrade of the LHC at CERN, the ATLAS experiment replaces parts of its muon detectors

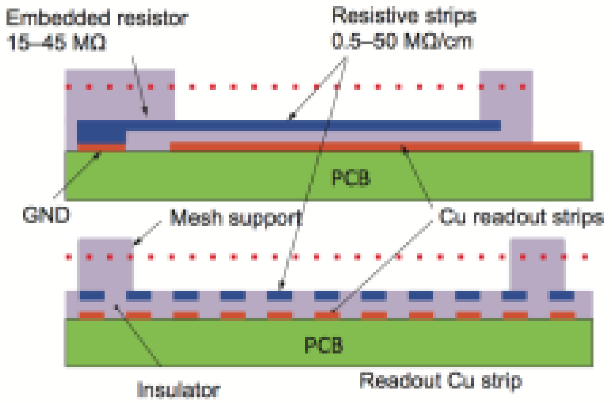


http://www.atlasexperiment.org

New fronted ASIC developed by Brookhaven National Lab.



One of the new detector types are Micromegas



Anode strips read-out similar to our GEM detector

Iakovidis, Georgios. "The Micromegas project for the ATLAS upgrade." *Journal of Instrumentation* 8.12 (2013): C12007.

Electronics
Current status

SRS + VMM readout still in prototype status with development ongoing

CERN and IFE test beams have shown that:

- Prototype system is operational and can read out signals from detector
- All hardware components work
- Software for slow control, online monitoring and data acquisition is available and allows for smooth operation of the system
- System can handle data rates up to about 50 Mbit/s/VMM for 6 VMMs (NMX prototype: 80 VMMs at equal data rates)
- Data analysis software available (Lara's Summer Student project)