



# Detector Integration

Dirk Wiedner on behalf of Mu3e

February 2018

# Introduction

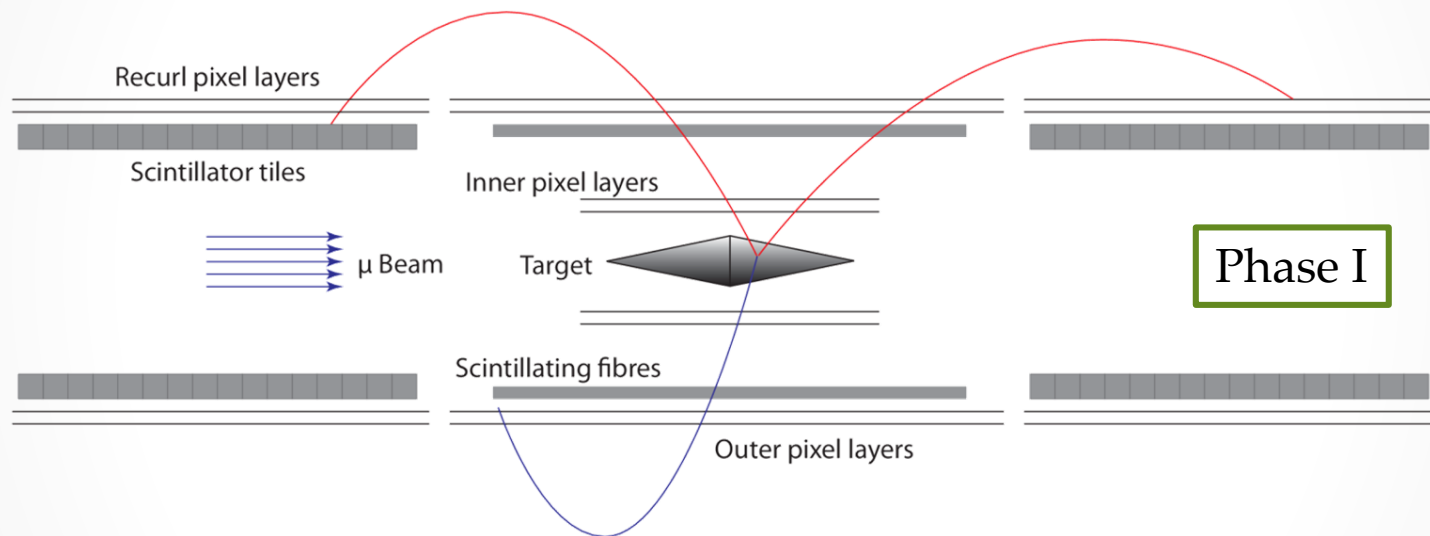
- Mu3e experiment
  - Pixel detector
  - Scintillating fibre detector
  - Tile detector
  - Target
- But also:
  - Solenoid magnet
  - Mechanics
  - Cooling
  - Cabling
  - Electronics...



Technical design of the Phase I  
**Mu3e Experiment**



# Phase I Experiment



- Muon beam  $O(10^8/s)$
- Helium atmosphere
- 1 T B-field

- Target double hollow cone
- Silicon pixel tracker
- Scintillating Fiber detector
- Tile detector

# Integration Challenges

## Subsystem

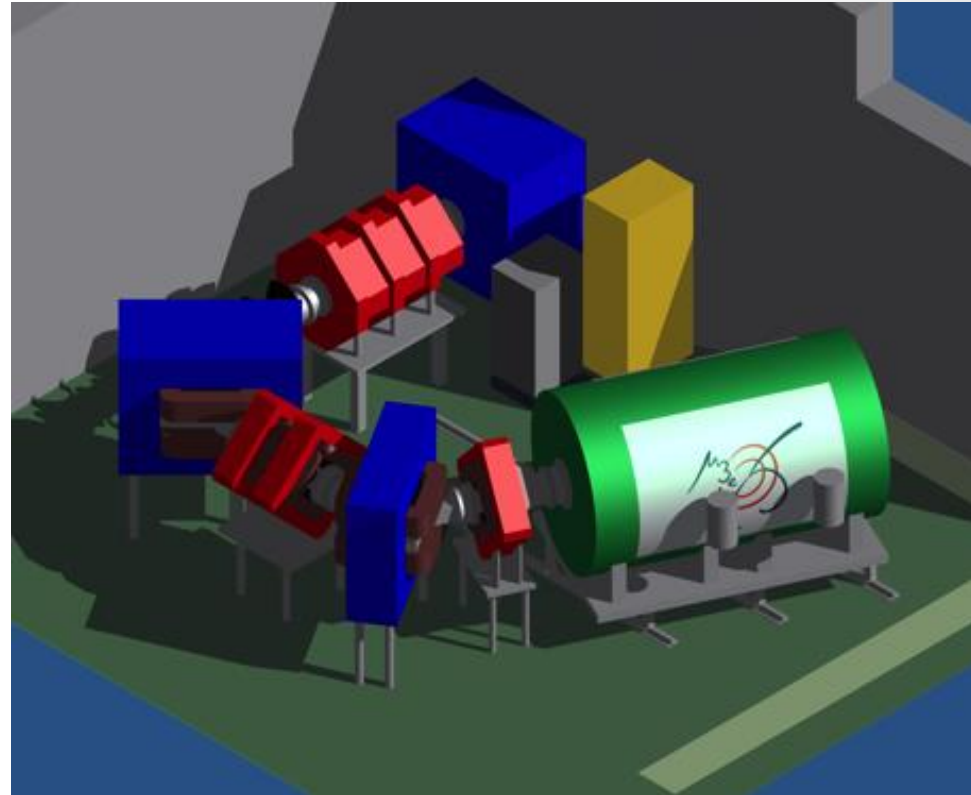
- 1 T Solenoid
- Power and cabling
- Readout

## Challenges

- piE5 limited space
- >5kW overall power
  - Tight space
- Trigger less system
  - High bandwidth >Tbit/s
  - Three sub-detectors
  - Two different front end chips

# Mu3e Solenoid

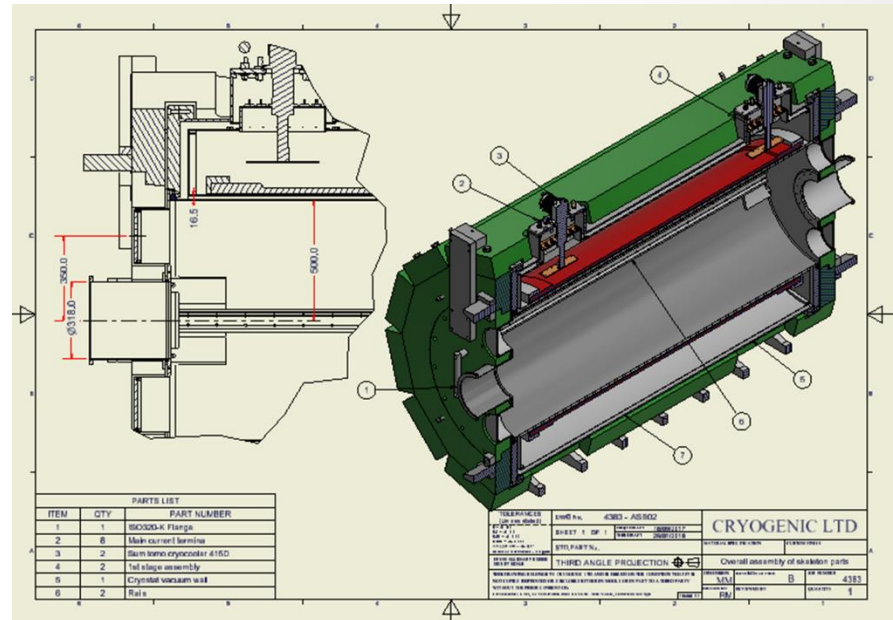
- Very limited space in piE5
- Solenoid under balcony
- Procedure for detector access lengthy- but well thought trough



Mu3e magnet

# Mu3e Solenoid

- Very limited space in piE5
- Solenoid under balcony
- Procedure for detector access lengthy- but well thought trough
- Magnet does not run in persistent mode

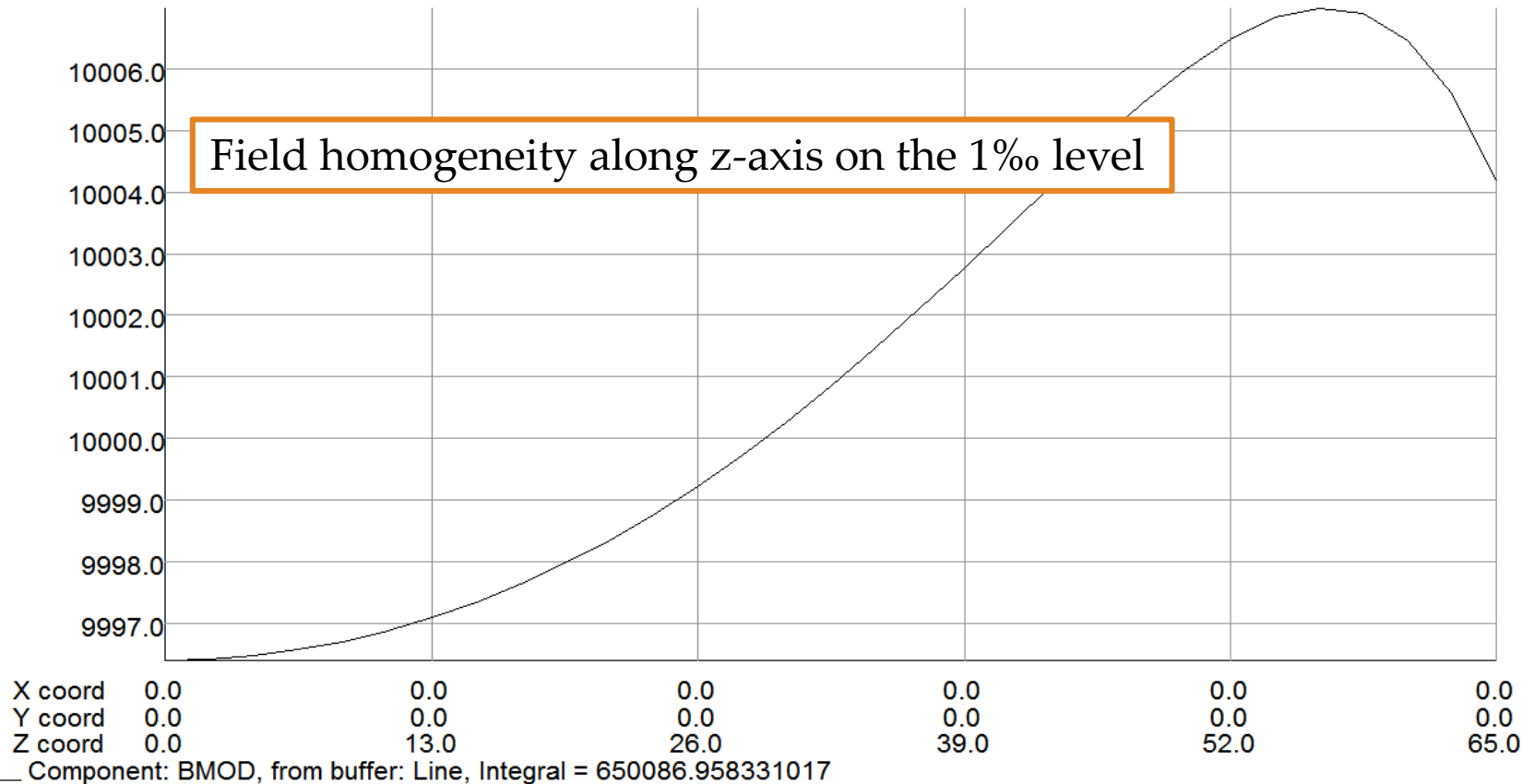


Mu3e magnet

# Mu3e Solenoid

Field modulus along axis over 65cm (at 1T) ; +0.105%, -0%

30/Jan/2018 11:21:27

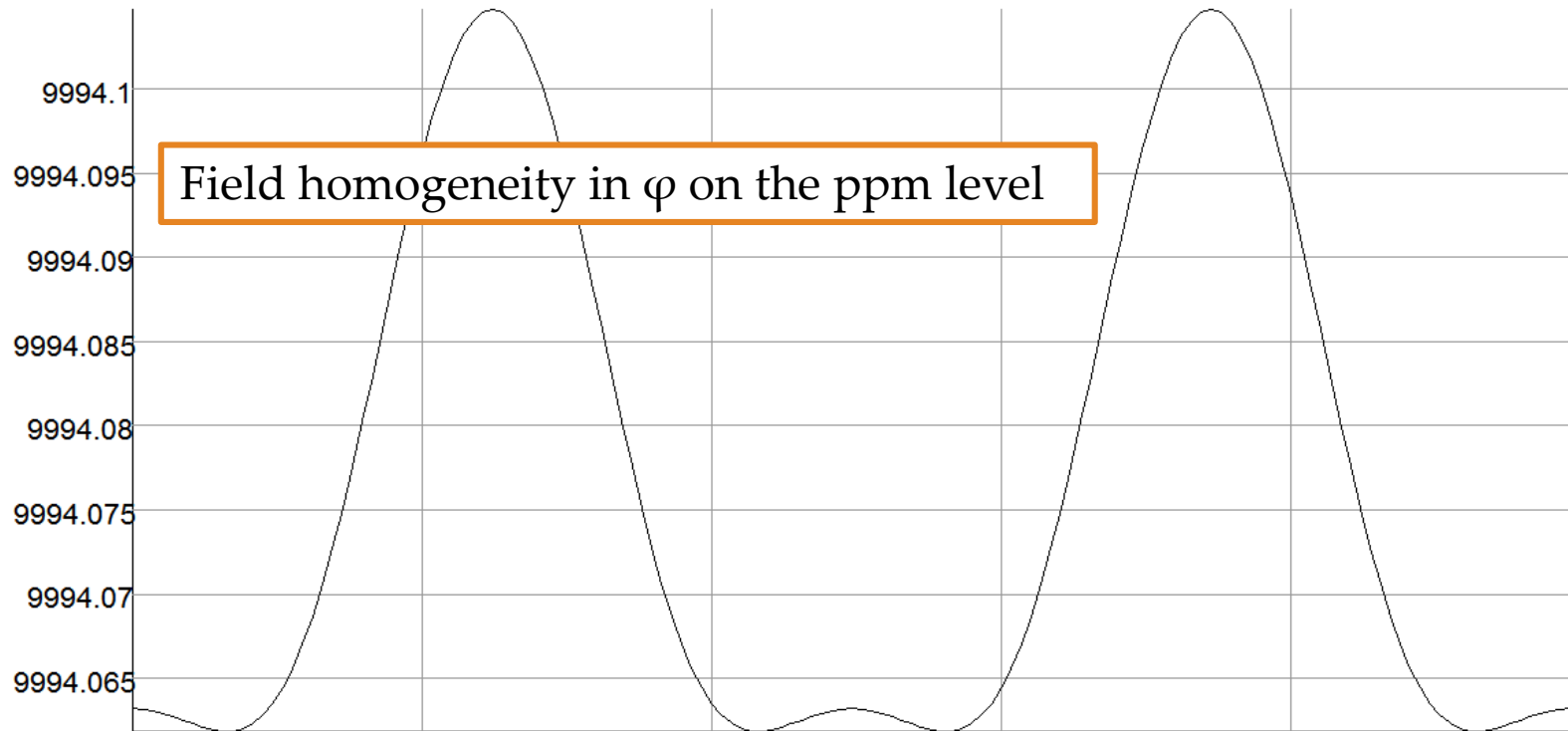


Opera

# Mu3e Solenoid

Modulus field around a R35cm circle centred at Z=0 (Variation ~ 0.0003%)

30/Jan/2018 12:04:06



X coord	35.0	10.524703	-28.670322	-27.767367	11.970705
Y coord	0.0	33.3800933	20.0751753	-21.30665	-32.889242
Z coord	0.0	0.0	0.0	0.0	0.0

Component: BMOD, from buffer: Circle, Integral = 2.19763785399395E+06

Opera



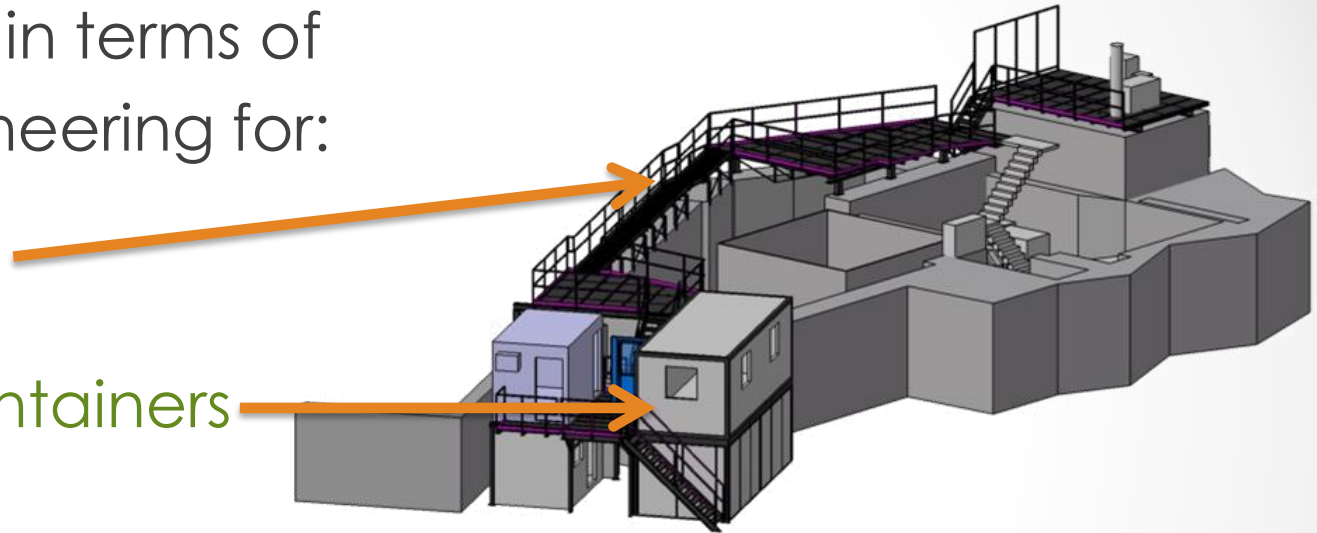
# Area Planning

Good progress in terms of  
CAD, civil engineering for:

- ✓ Platforms
- ✓ Access ways
- ✓ Counting containers
- ✓ Power
- Cooling

Remark:

- Space in area  
**extremely** limited



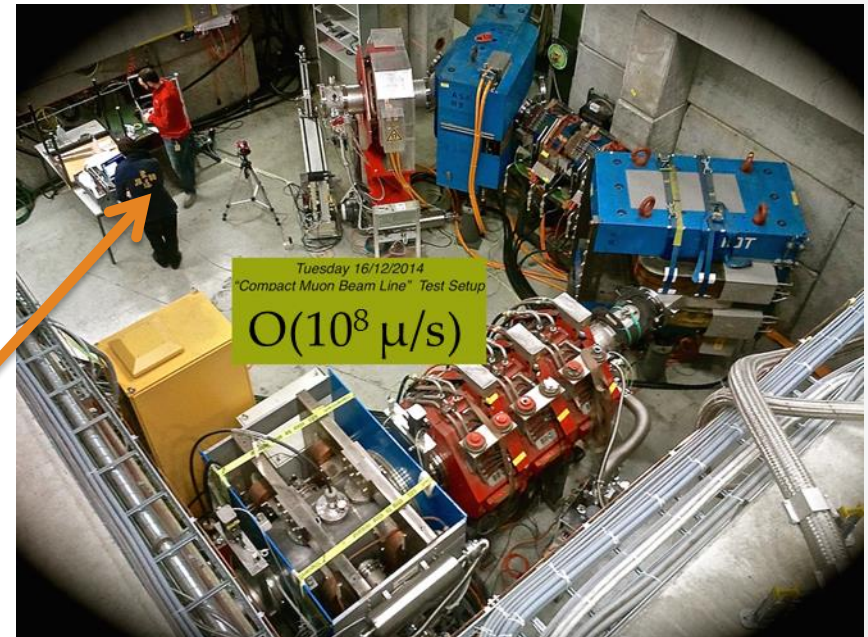
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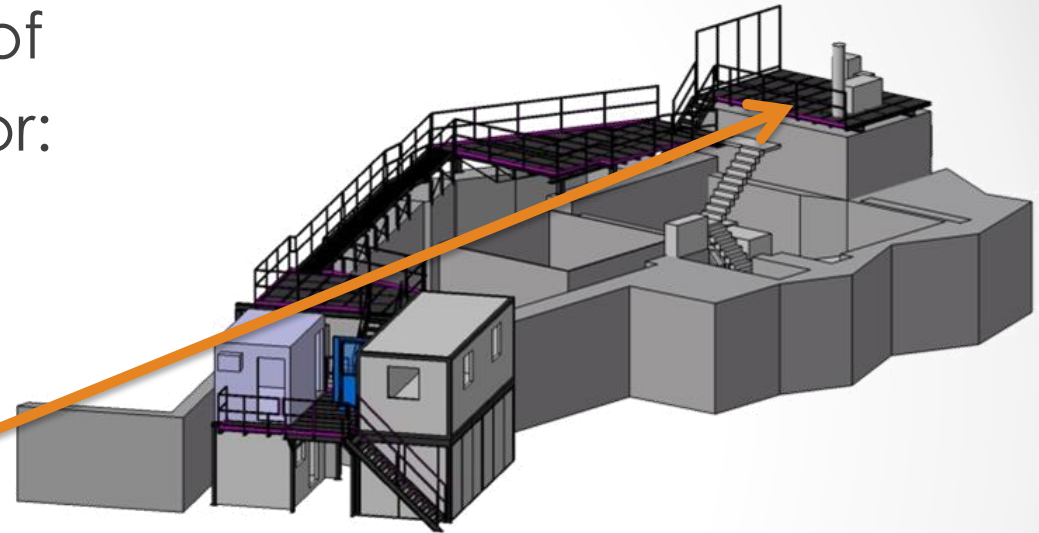
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# Racks

- piE5
  - Low Voltage rack
  - Commissioning rack
- Skywalk platforms
  - Magnet power rack
  - Magnet compressor rack
  - Magnet control rack
  - Helium cooling rack
- Counting house
  - Filter farm racks
  - Clock and pixel slow control rack
  - Midas slow control rack

Sufficient rack space on skywalk platforms  
and in counting house

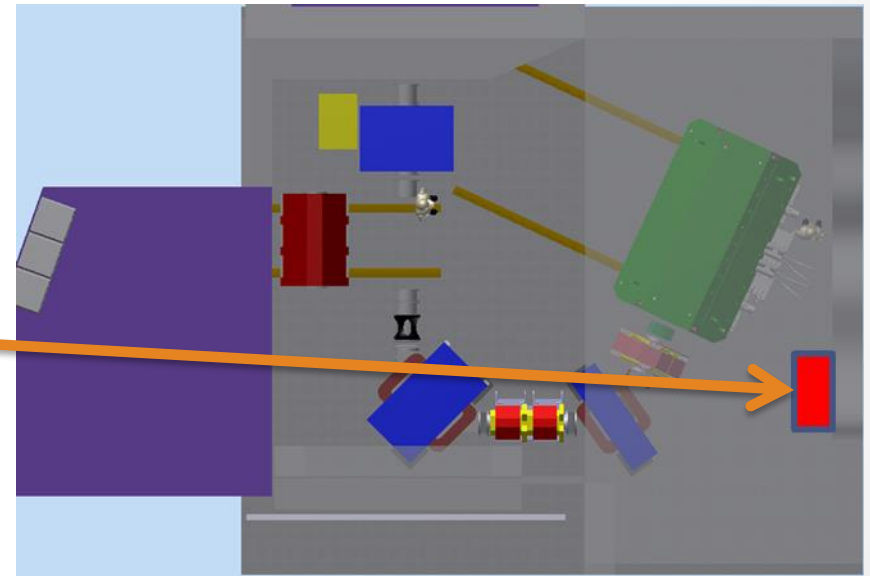
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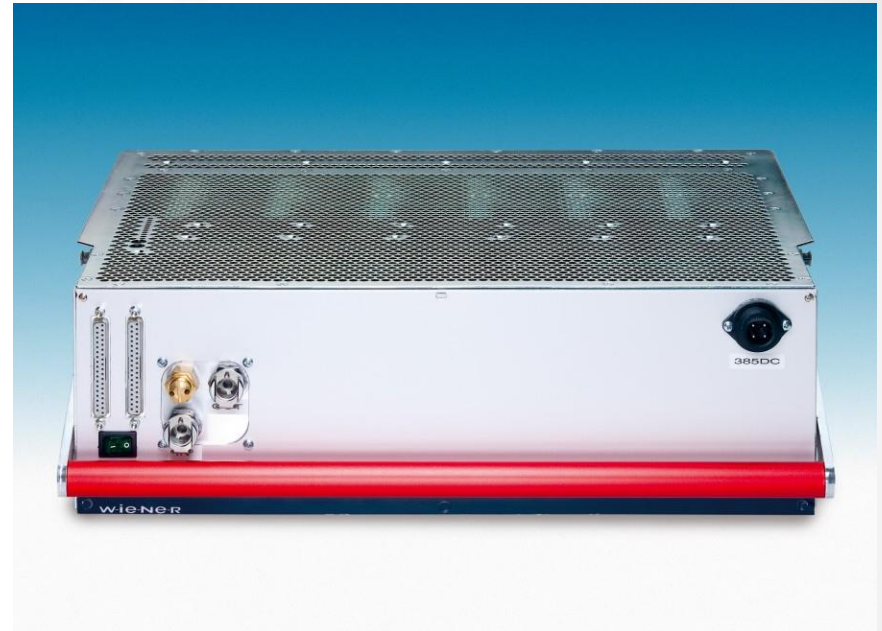
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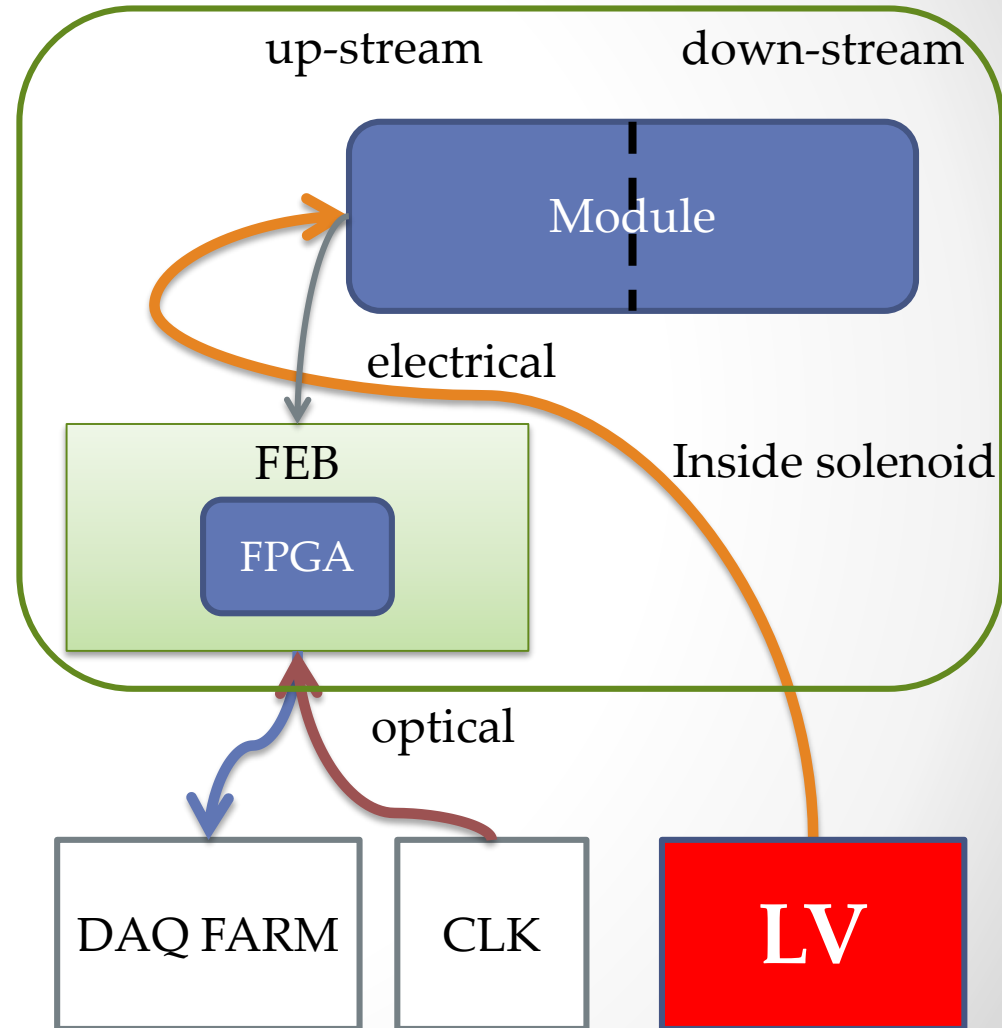
# Power Supplies

- Wiener Maraton
- 10 crates
- 12 channels each
- Each channel:
  - 230W
  - 20V
  - 11.5A
  - Other versions available



# Detector Partitions

- Half module corresponds to partition
- Modules read-out on both ends
- One front end board (FEB) per partition
- One low voltage per partition
- One high voltage per partition
- 112 partitions in total
  - +8 spares



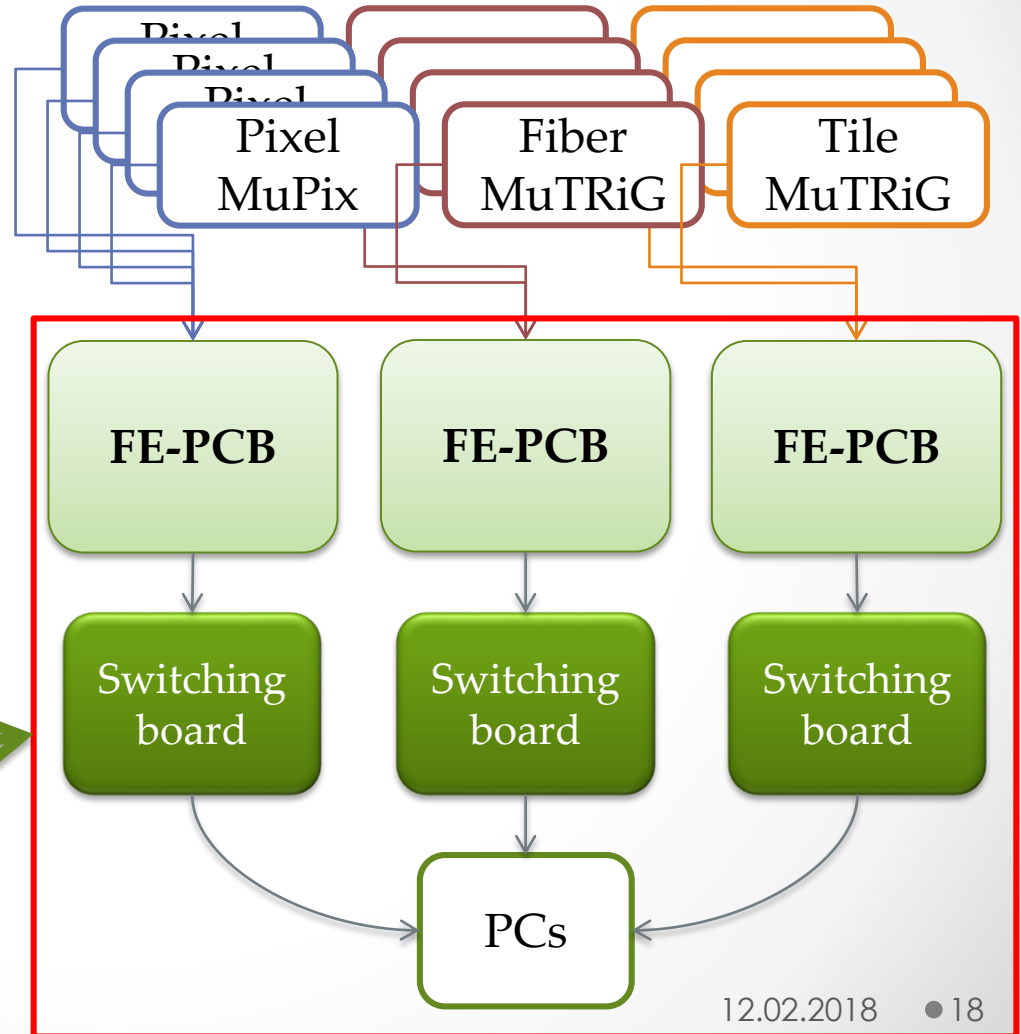


# Detector Power

Detector	ASIC	#partitions	#ASICS/ partition	Power ASICs [W]	Power others [W]	Sum [W]	DC-DC [W]	Total power [W]
Pixel Layer 1	MuPix	<b>4</b>	<b>12</b>	<b>19.2</b>	<b>20.9</b>	<b>40.1</b>	<b>69</b>	<b>229</b>
Pixel Layer 2	MuPix	<b>4</b>	<b>15</b>	<b>24</b>	<b>22.7</b>	<b>46.7</b>	<b>80.1</b>	<b>267</b>
Pixel Layer 3	MuPix	<b>3x12</b>	<b>32, 36</b>	<b>51.2, 57.6</b>	<b>20.9</b>	<b>72.1, 78.5</b>	<b>1162</b>	<b>3873</b>
Pixel Layer 4	MuPix	<b>3x14</b>	<b>36</b>	<b>57.6</b>	<b>20.9</b>	<b>78.5</b>	<b>1413</b>	<b>4710</b>
Fibre	MuTRiG	<b>12</b>	<b>16</b>	<b>17.6</b>	<b>17.9</b>	<b>35.5</b>	<b>182.6</b>	<b>609</b>
Tile	MuTRiG	<b>14</b>	<b>14</b>	<b>15.4</b>	<b>17.9</b>	<b>33.3</b>	<b>199.8</b>	<b>666</b>
Total		<b>112</b>						<b>10354</b>

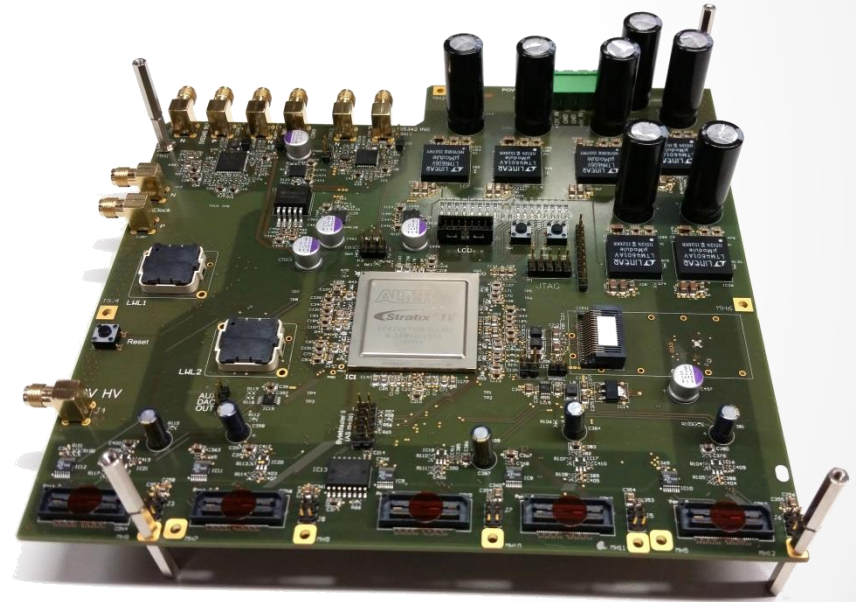
# Readout System

- Pixel detector
  - HV-MAPS (MuPix)
    - ✓ Pixel detector system on one chip
    - ✓ Zero-suppressed serialized data
- Timing detectors
  - SiPMs plus MuTRiG
    - ✓ TDC system
    - ✓ Zero-suppressed serialized data
- **Common read-out system**

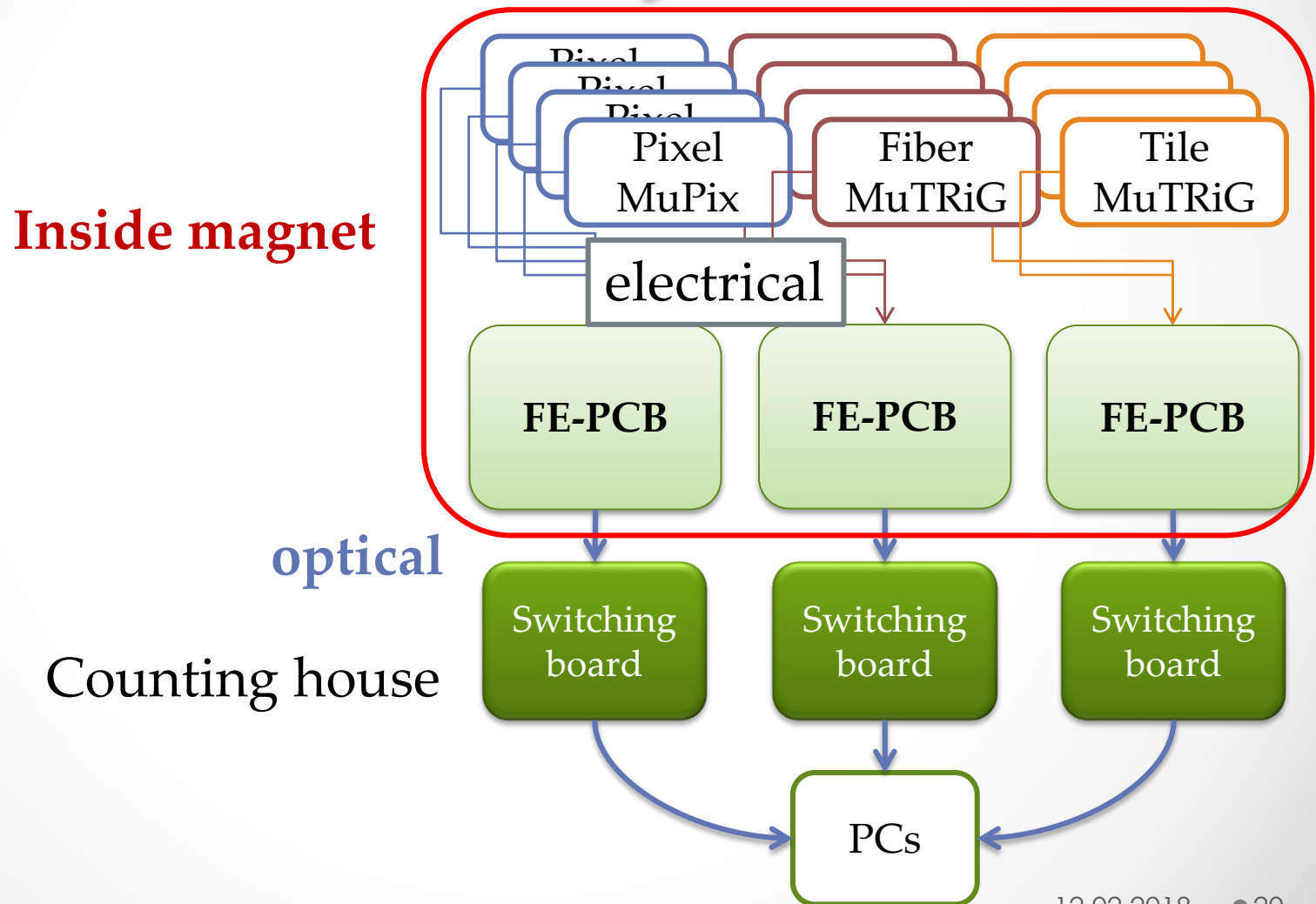


# Common Read-out PCB

- ✓ **Front-end PCB**
  - Common for pixel, fibre and tile detector
  - ✓ Data acquisition
  - ✓ Clock distribution
  - ✓ Slow control distribution
- ✓ Prototype **functional**

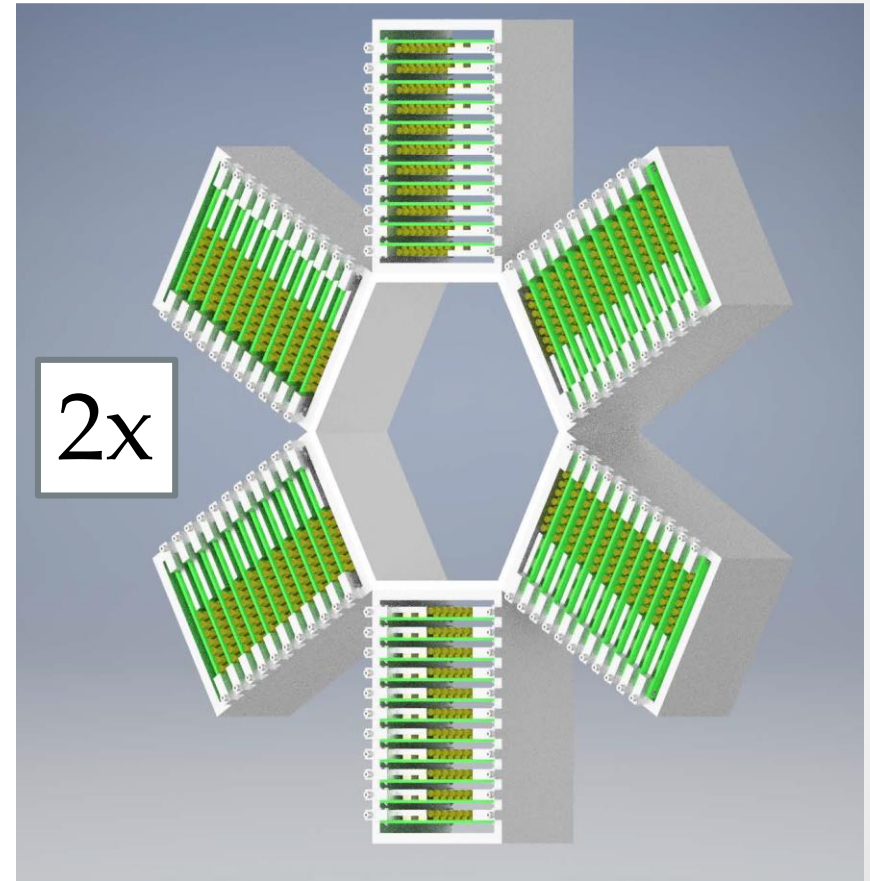


# Readout System



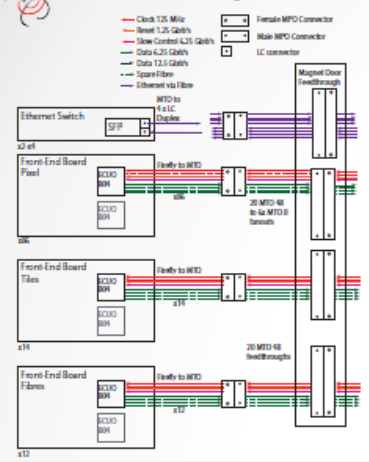
# FEB Crates

- Front end boards inside magnet
- 120 FEBs in total
- Mounted in mini crates
- Star of crates
  - Upstream +
  - Downstream

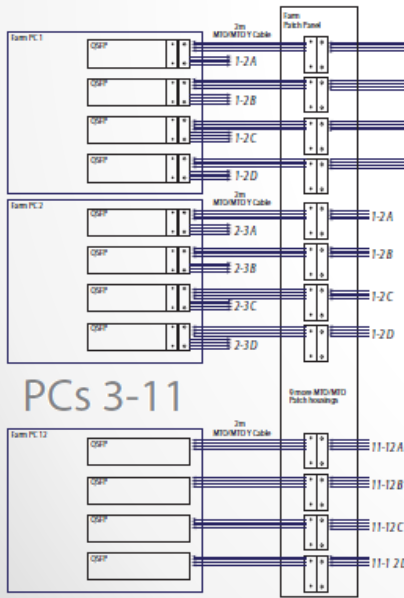


# Optical cabling scheme

Mu3e Phase I fibre cabling scheme

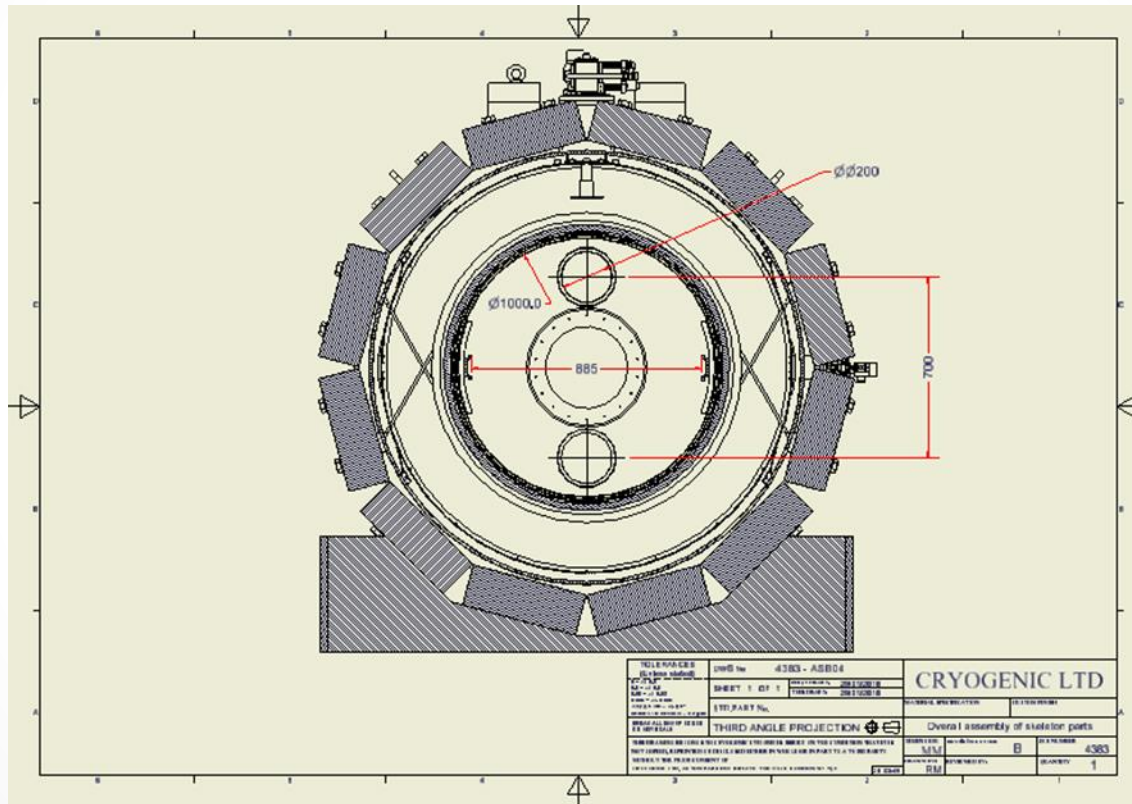


## Counting House



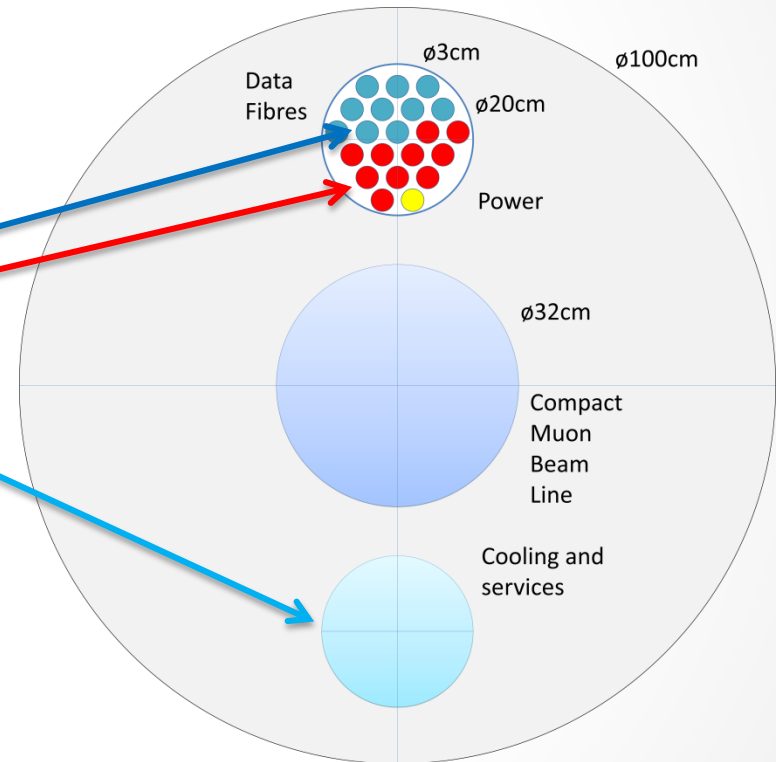
Version History		
v0.1	24.6.2017	Niklaus Berger
v0.2	6.7.2017	Niklaus Berger
v0.3	21.11.2017	Niklaus Berger

# Magnet End Plate Feed-through



# Magnet End Plate Feed-through

- He Atmosphere inside magnet
- Endplate feed troughs:
  - Optical data connectors
  - Power connectors
  - Cooling and services

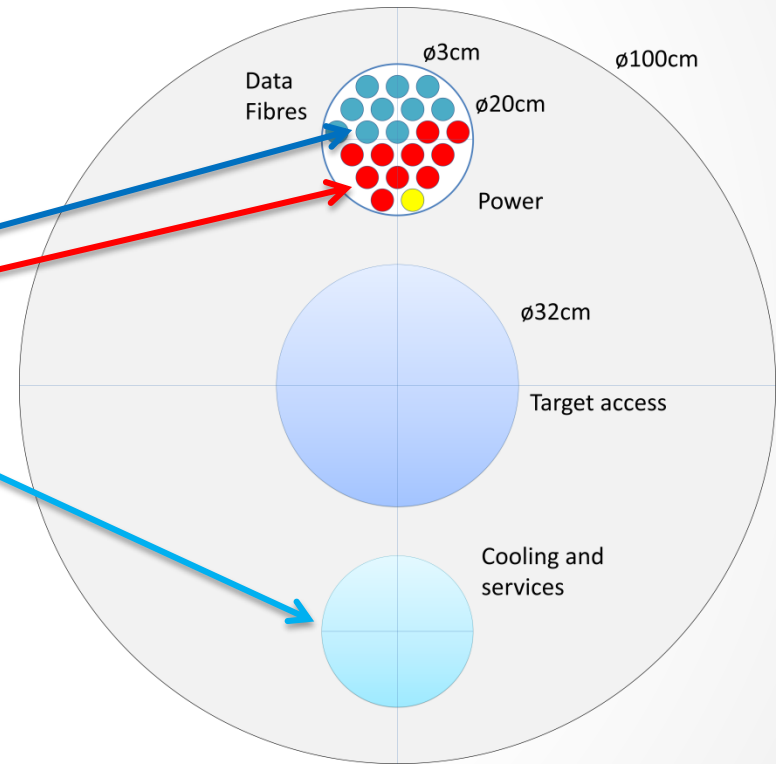


Upstream



# Magnet End Plate Feed-through

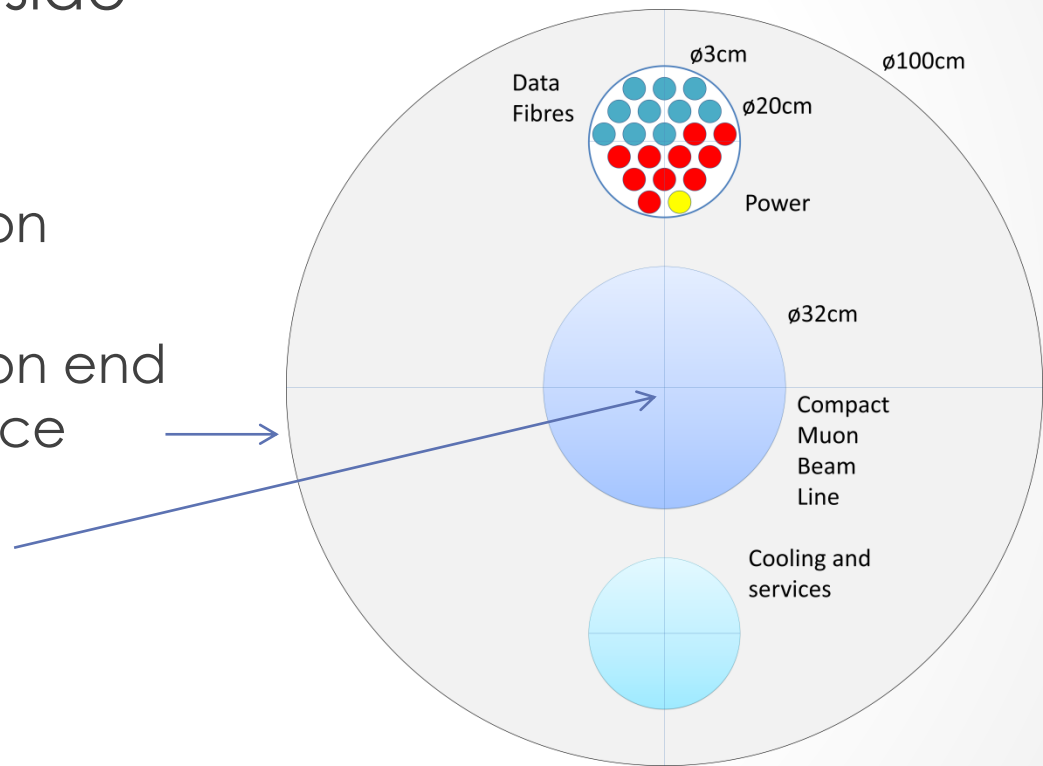
- He Atmosphere inside magnet
- Endplate feed troughs:
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  - Cooling and services



Downstream

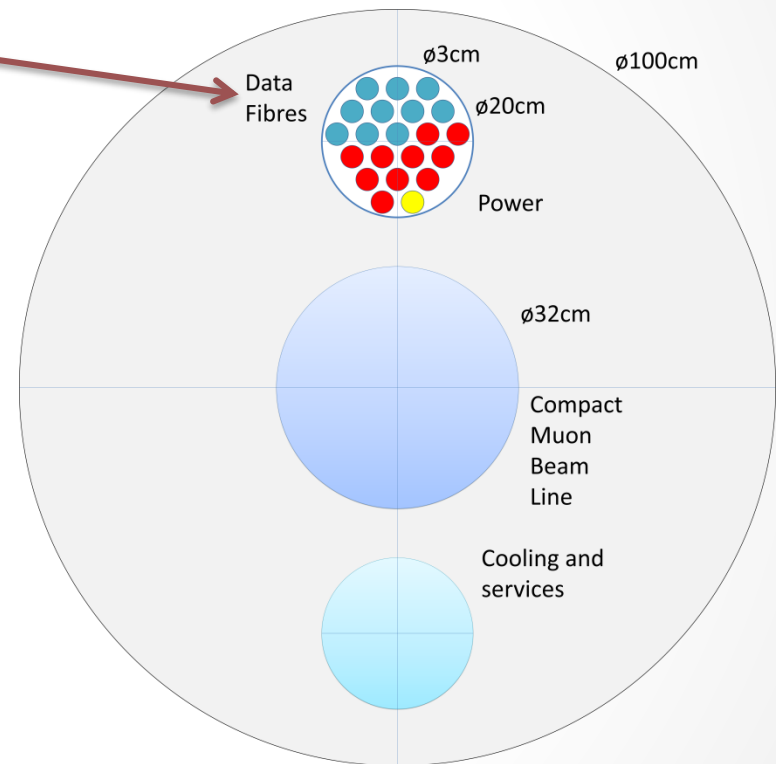
# End plate design

- He Atmosphere inside magnet:
  - He tight design
  - Precision surface on magnet end rings
  - Precision surface on end plate circumference
- Beam pipe under vacuum
- Data and power connectors
  - Gas tight



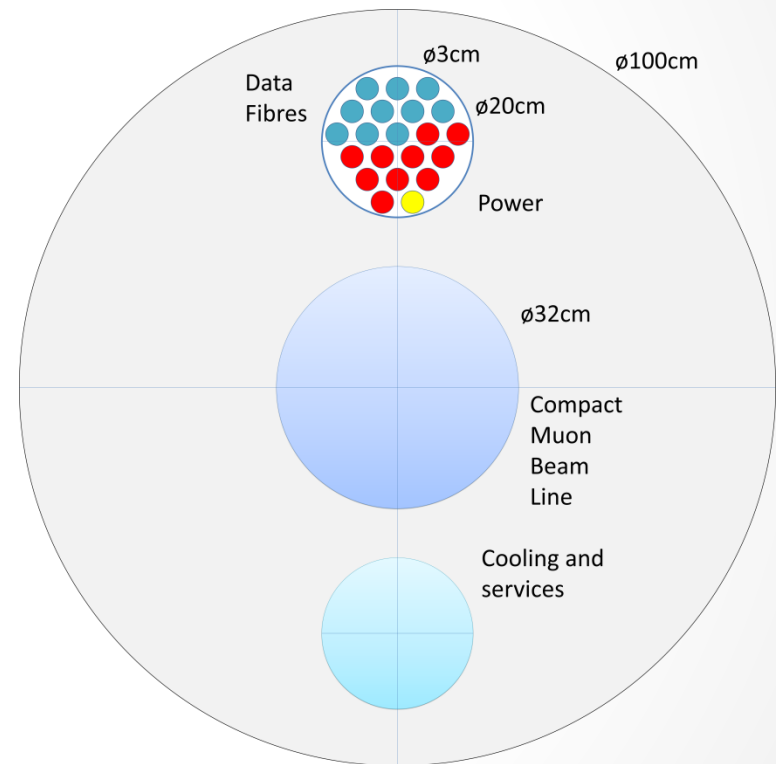
# End plate design

- Data and power connectors
  - Gas tight
  - 120 detector partitions
  - One connector per 6 partitions
  - Each connector 3 cm diameter



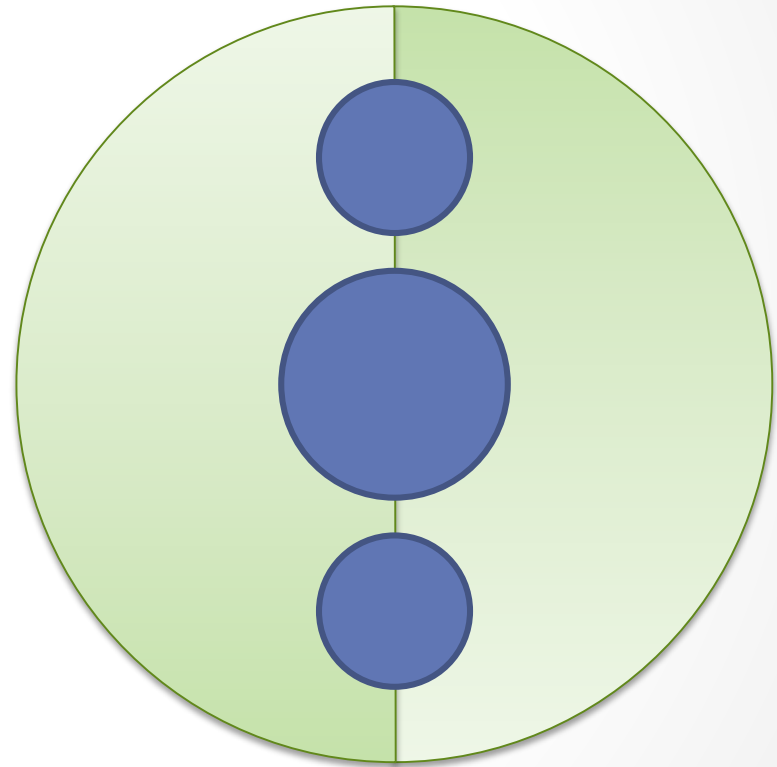
# End plate design

- Data and power connectors
  - Gas tight
  - 120 detector partitions
  - 20 connectors of each type
  - Each connector 3 cm diameter
  - Requires 2 x 20 cm  $\varnothing$
  - On plates



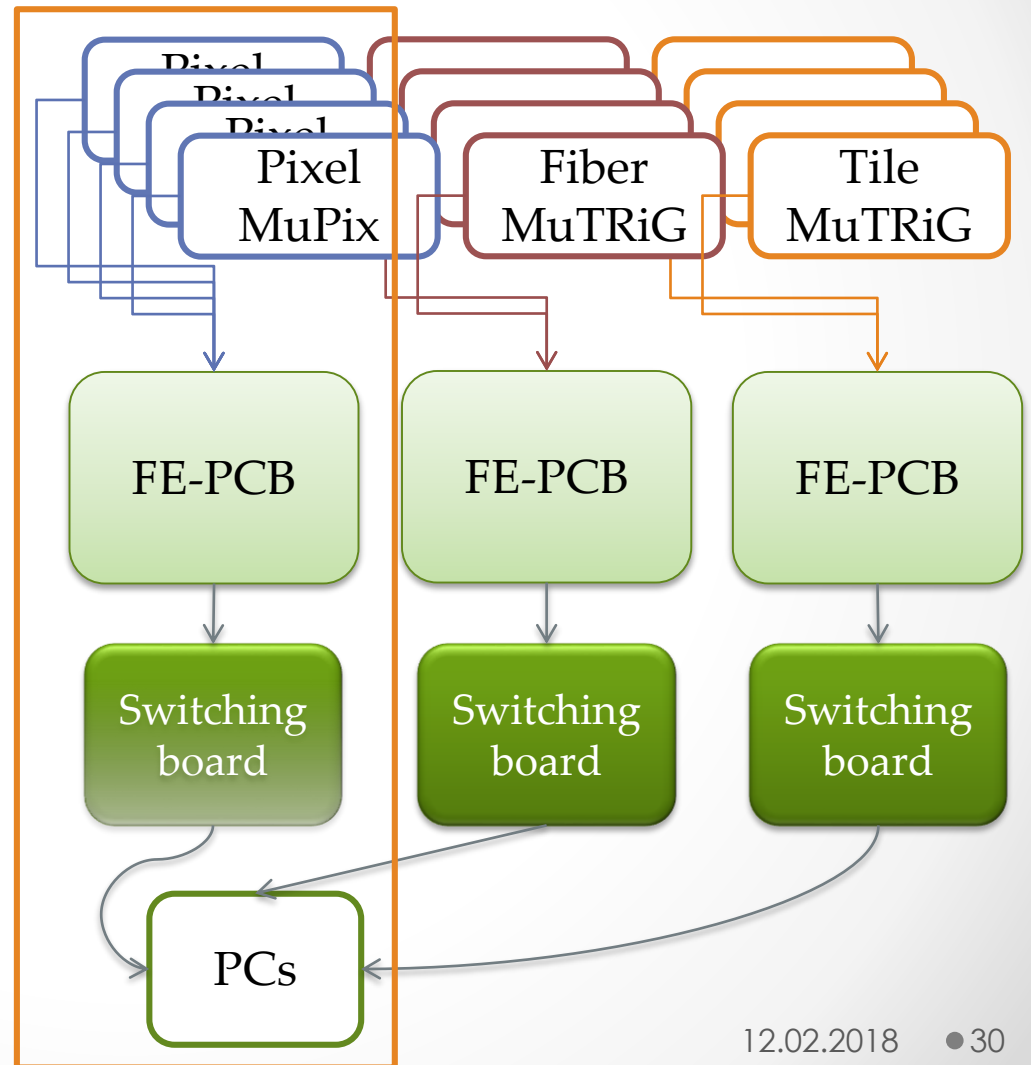
# Magnetic shield doors

- Magnetic shield doors
  - Ca. 32 cm  $\varnothing$  cutout for beam
  - 2x 20 cm  $\varnothing$  cutout for signal/power/cooling
- Symmetrical upstream and downstream



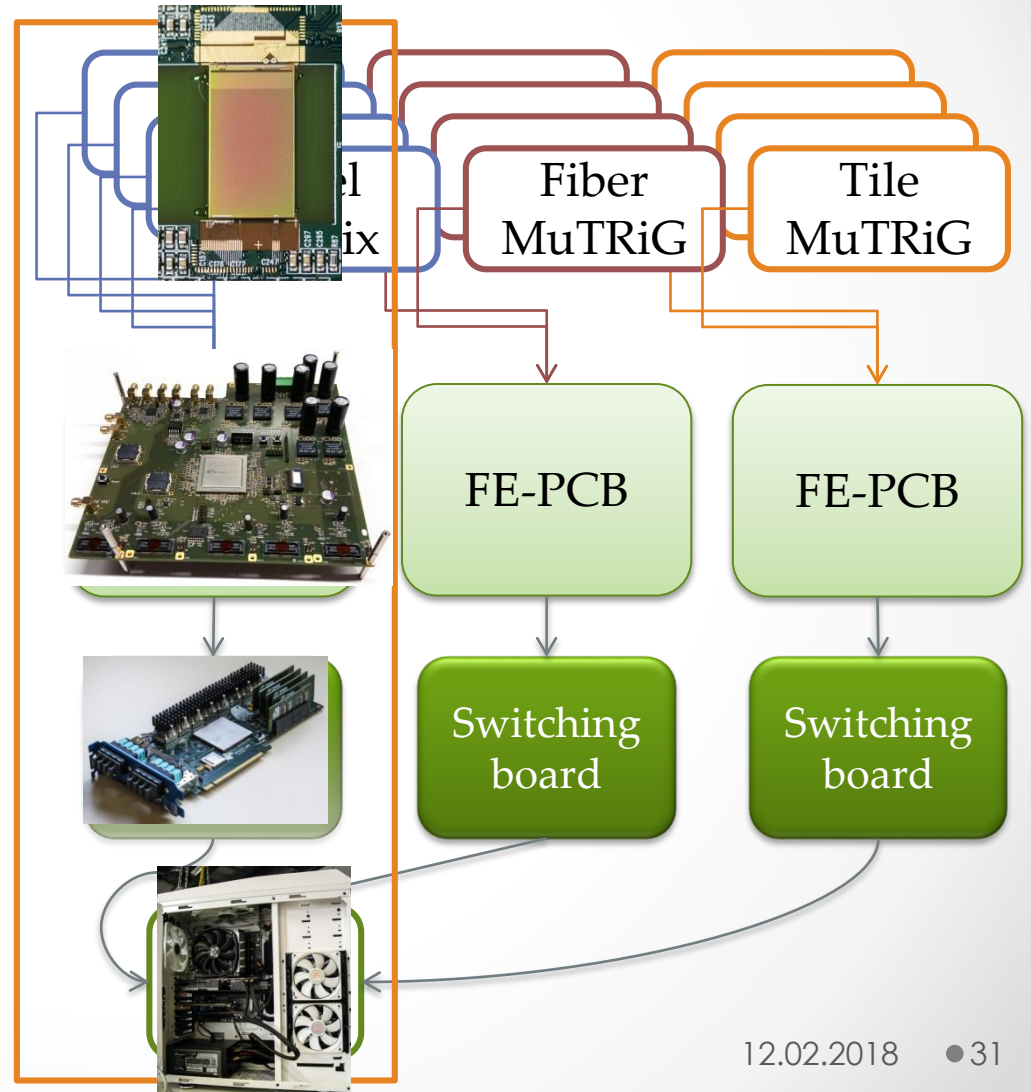
# Readout Vertical Slice Test

- Pixel detector
  - HV-MAPS (MuPix8)
    - ✓ Large prototype
- Front end board
- Switching board
  - PCIe40
  - Delivery 2018
- PC



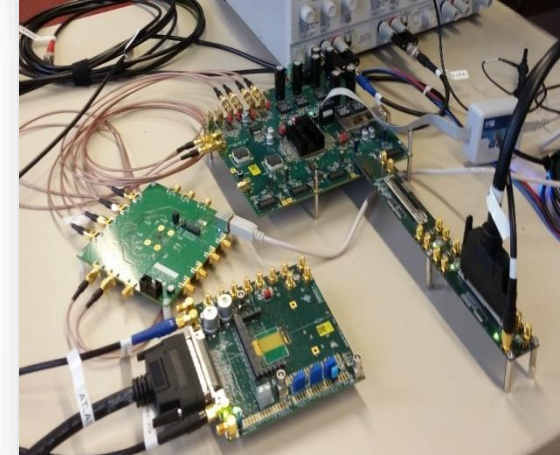
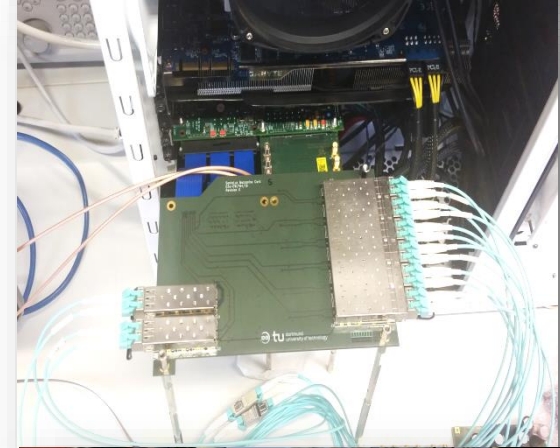
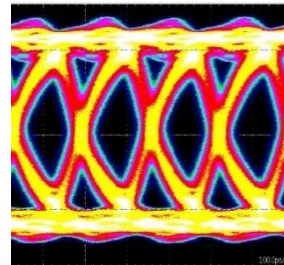
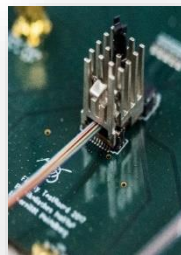
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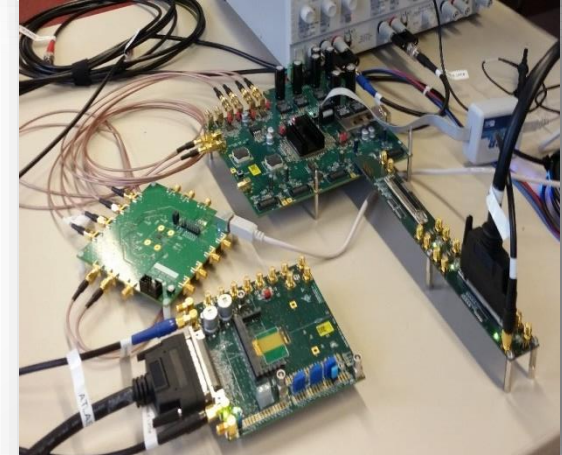
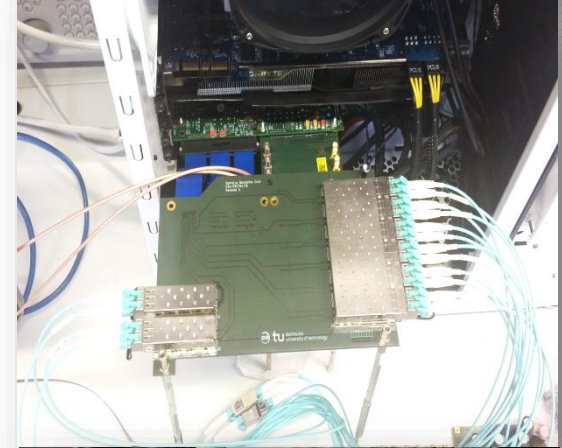
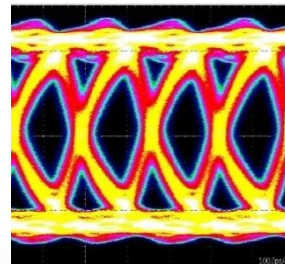
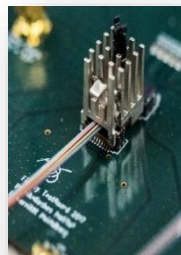
- ✓ Control and readout firmware of MuPix sensors
- ✓ Optical links tested intensively: MiniPods, QSFP and Samtec Firefly
- ✓ Front end board to PC communication
- ✓ **Front end board MuPix8 readout**  
**NEW!**
- ✓ Optical clock distribution





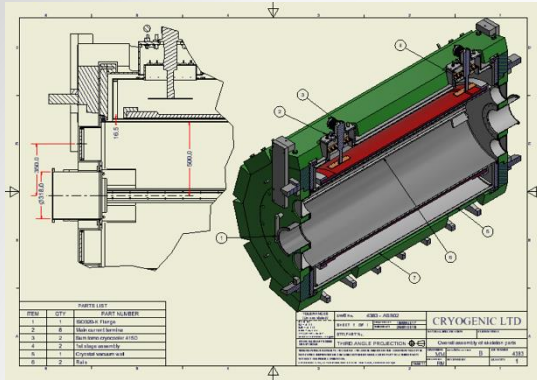
# Readout Vertical Slice Test

- Test the system fully in the lab
  - Up to 8 MuPix8
- Use the vertical slice test system in DESY test-beam
- Include the tile detector readout prototype
- Include the SciFi readout

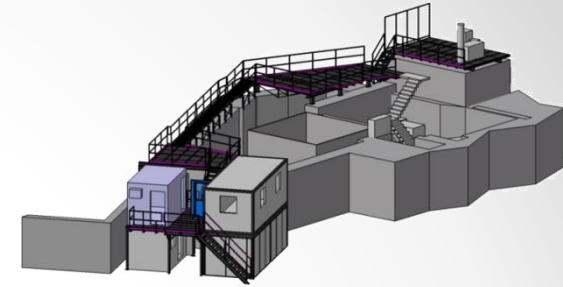


# Milestones

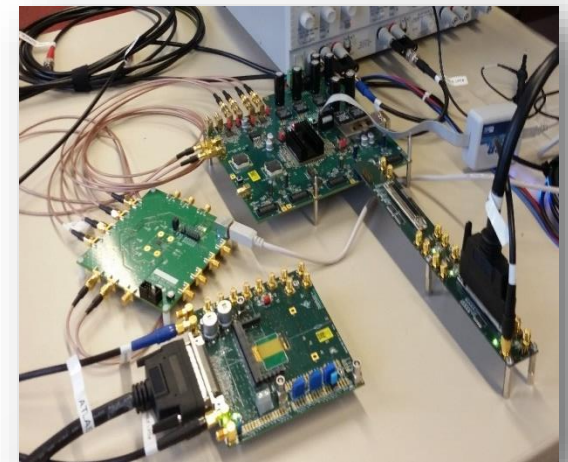
Milestone	
Vertical slice MuPix readout	Q1 2018
Magnet TDR	Q1 2018
Vertical slice Pixel + Tile detector	Q3 2018
Vertical slice Pixel + Tile + Fiber detector	Q1 2019



# Summary



- Magnet technical design back on track
- Advanced area preparation
- Partitioning scheme for readout and power
- Vertical readout slice for pixel detector advanced



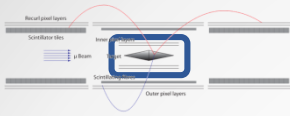
# Outlook

- Magnet production this year
- Vertical slice tests for readout of all sub-detectors



# Backup Slides

...

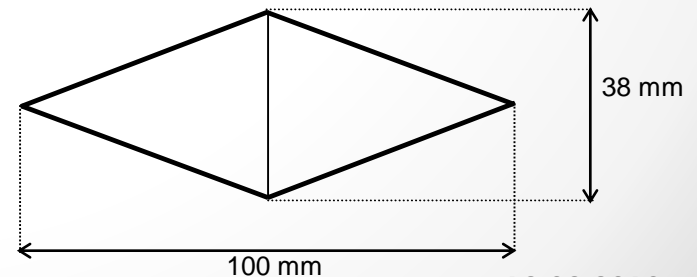
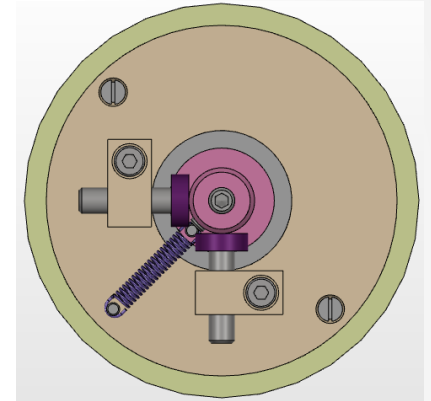


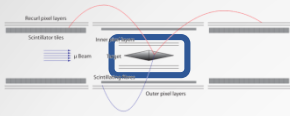
# Muon Stopping Target

- Hollow double cone
- Mylar "sandwich" structure
- two/three rolled up foils glued with epoxy:

Upstream:  $75\ \mu\text{m}$

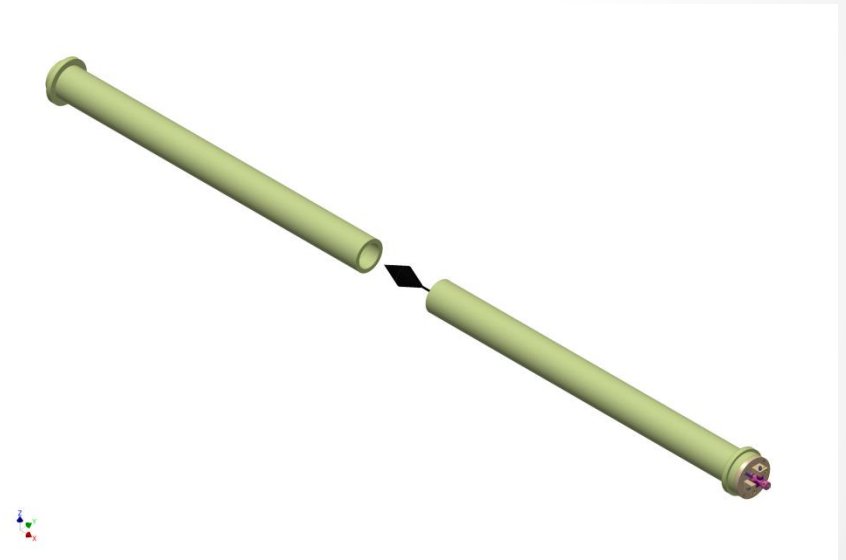
Downstream:  $85\ \mu\text{m}$

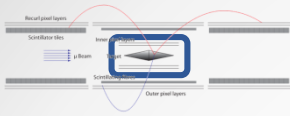




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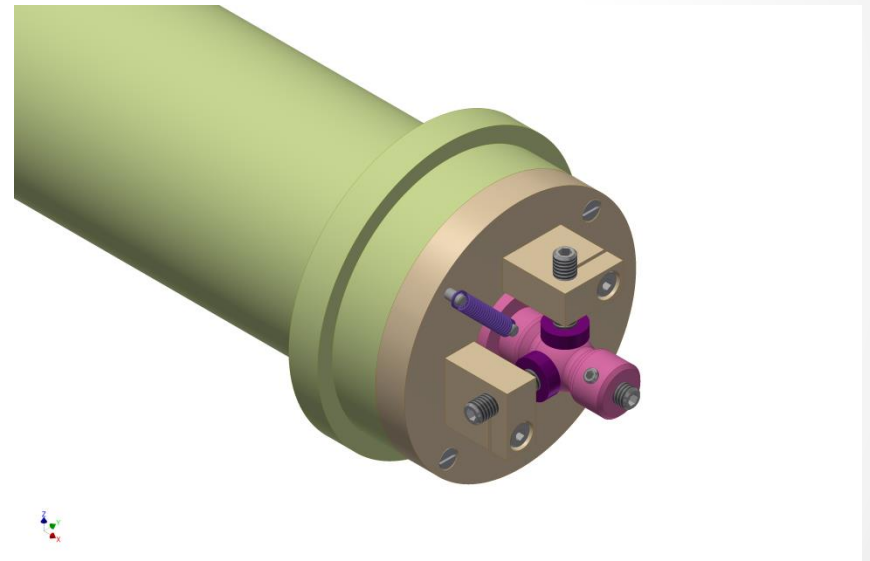
- Target position can be adjusted from the outside
- Target can be exchanged
- Pixel detector can stay during target exchange



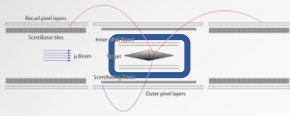


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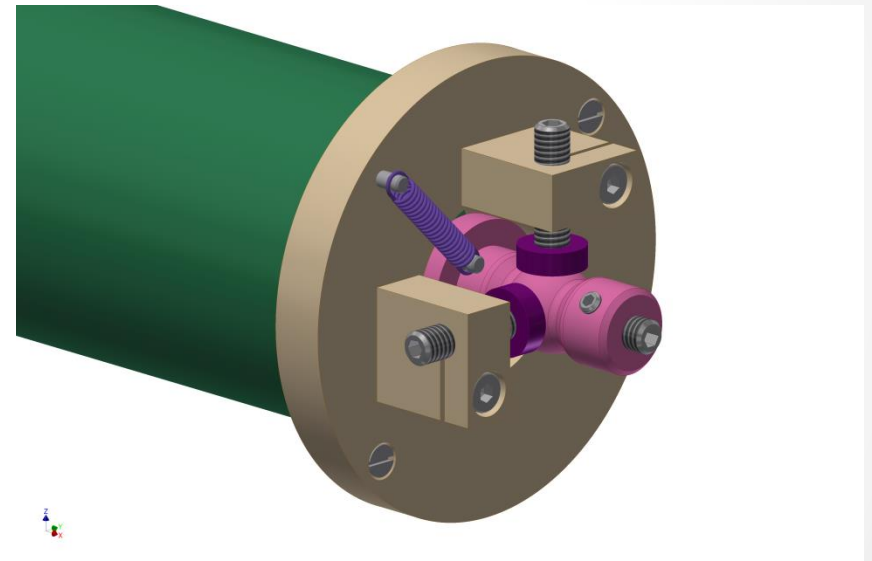


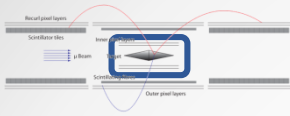




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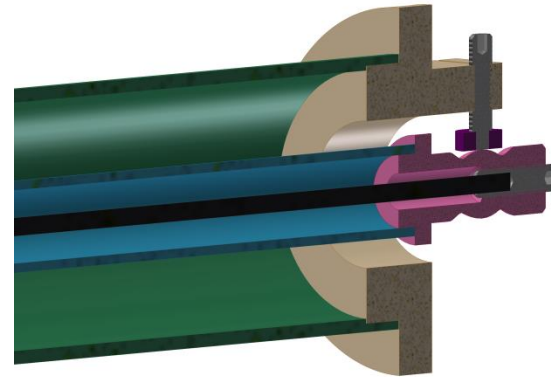
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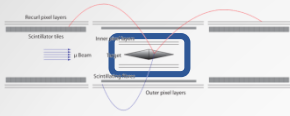




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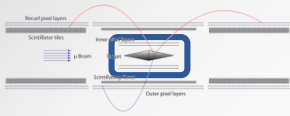




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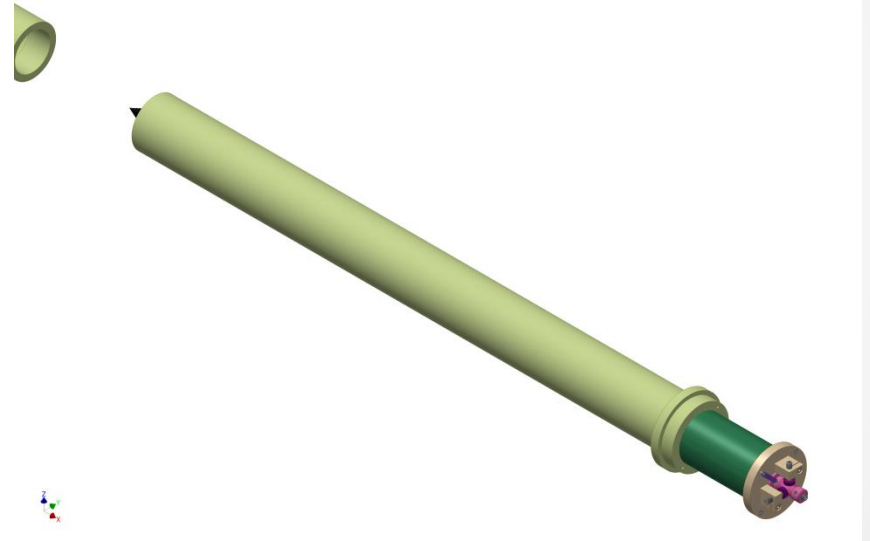
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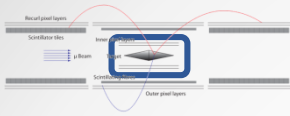




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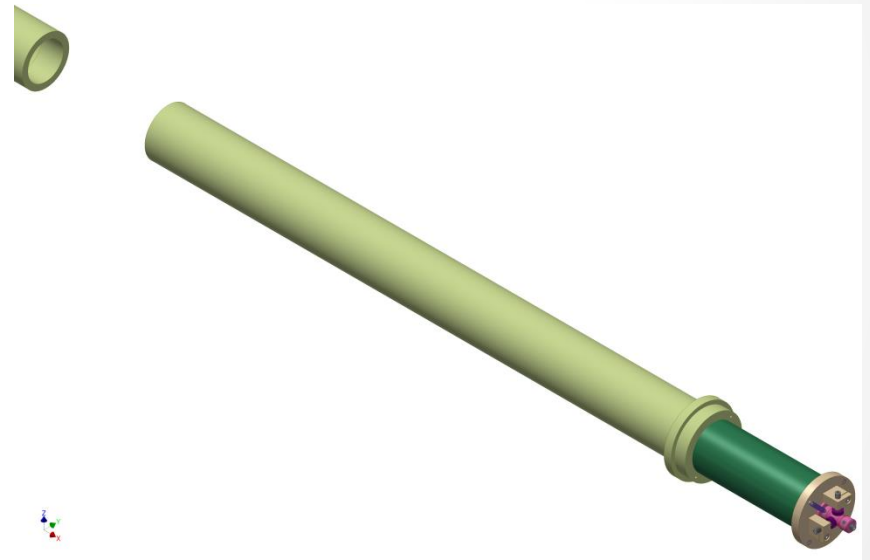
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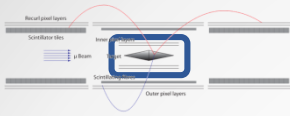




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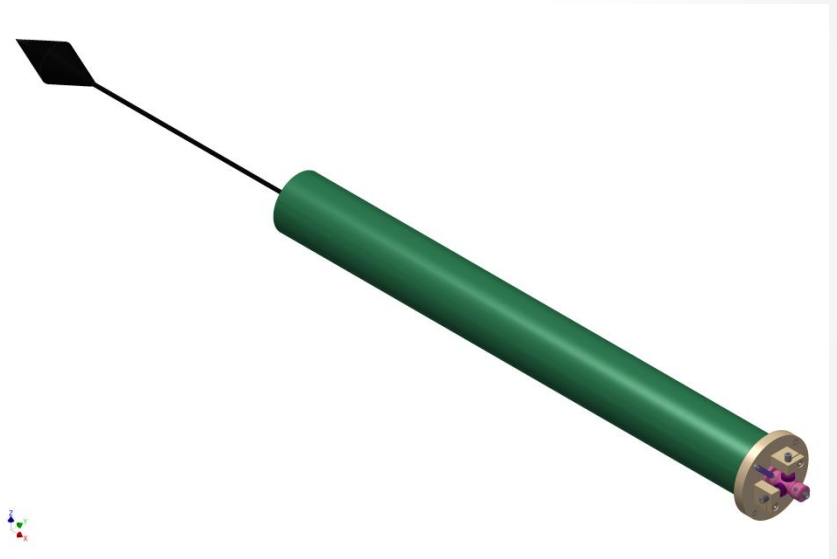
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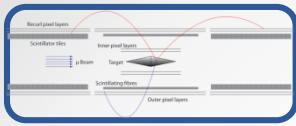




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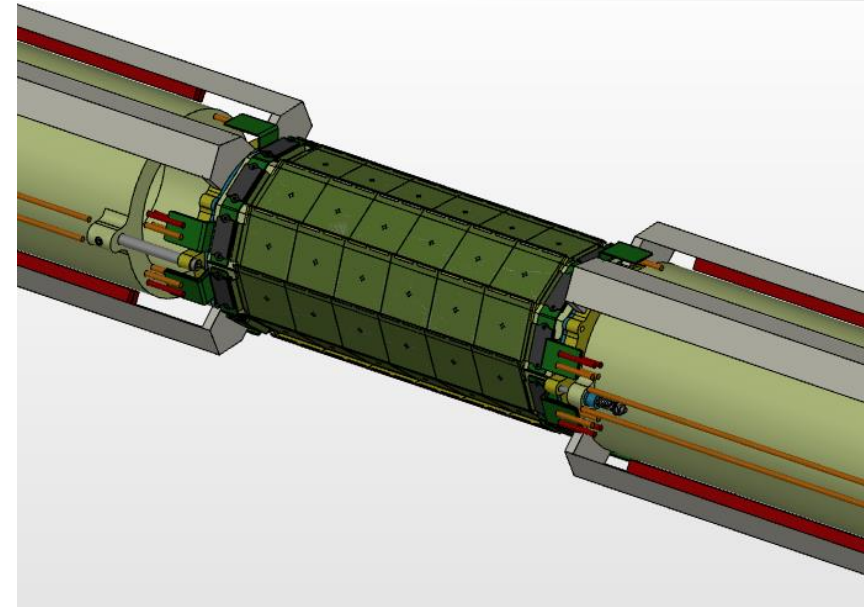


# Pixel Tracker

- ✓ Successful **feasibility** studies for:
  - ✓ Module mechanics
  - ✓ He-cooling with low vibration
  - ✓ Ultrathin Flexible circuit boards
  - ✓ HV-CMOS large prototype
  - ✓ Readout board prototypes
- ✓ Ongoing re-design of pixel detector services
  - ✓ He distribution
  - ✓ Power and cabling
  - Effects all surrounding systems

To be done:

- **1<sup>st</sup> operational detector module**
- Qualification of optimized module design



Pixel Tracker  
Rendering of CAD study  
Re-optimized pixel tracker

*See talk:*  
*Pixel Detector*  
Frank Meier Aeschbacher



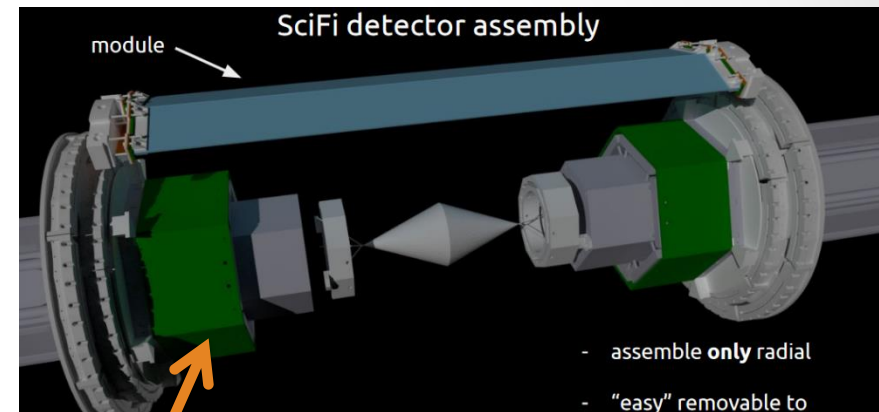
# Fibre Detector

Accomplished:

- ✓ Characterization of fibres
- ✓ **Proof of concept** including
  - ✓ Simulation of fibre response
  - ✓ Identification of working point

To be done:

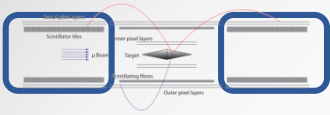
- Choice of fibre type
- 1<sup>st</sup> operational detector module
- **Ultra compact front end electronics**
  - **critical**
  - **Integrate** new MuTRiG TDC chip



Fibre Detector  
Rendering of CAD study

*See talk:*  
*SciFi*  
Antoaneta Damyanova





# Tile Detector

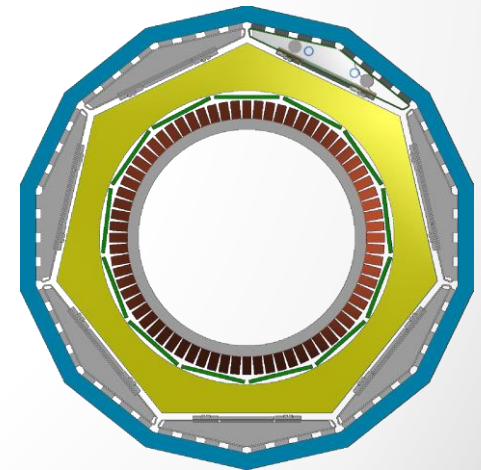
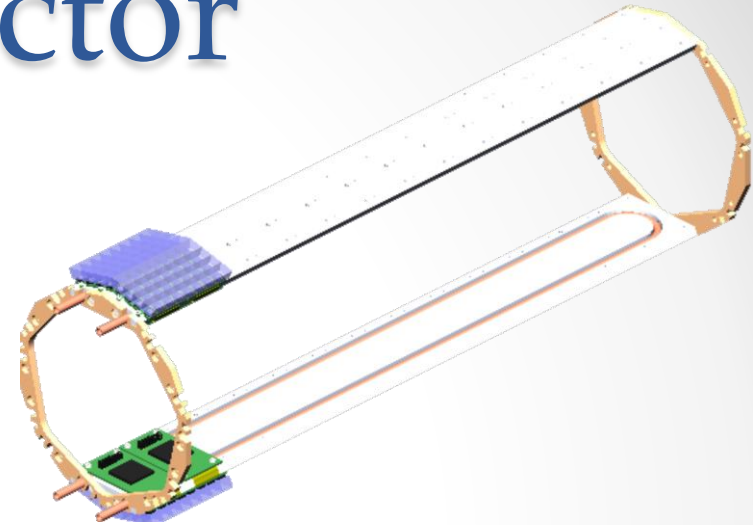
Accomplished:

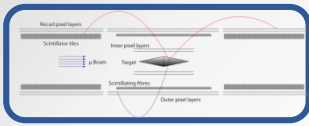
- ✓ Characterization of submodule
- ✓ **Proof of concept** including
  - ✓ Production of similar system
- ✓ Development of TDC ASIC  
MuTRiG

To be done:

- 1<sup>st</sup> operational detector module
  - Prototypes in production
- **Share space with He lines and cables**

*See talk:  
Timing Detectors  
Yonathan Munwes*





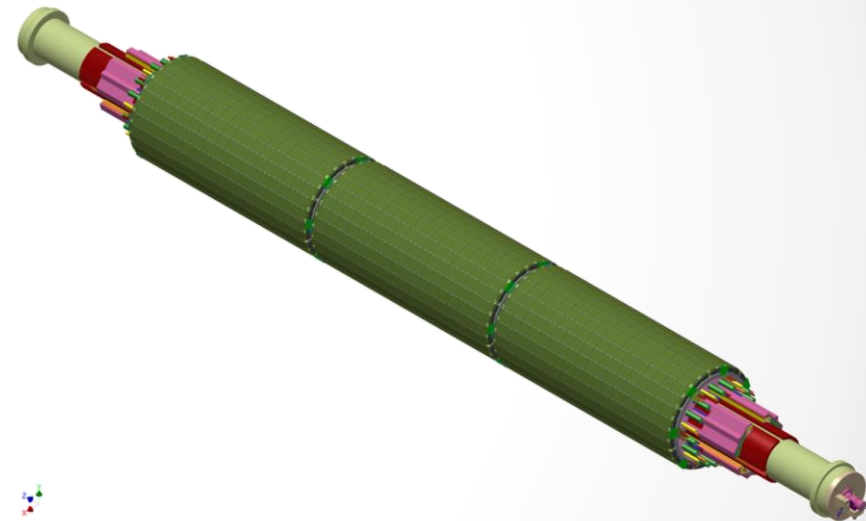
# Mechanical Integration

Accomplished:

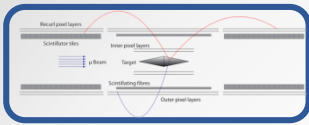
- ✓ CAD of modules
- ✓ Mechanical prototypes

To be done:

- Integration of cooling and cables
  - **advancing well**
- Re-distribution of space
- **Remark:**
- **Space inside detector extremely limited**
- **Extreme power and cooling requirements (pixel detector)**



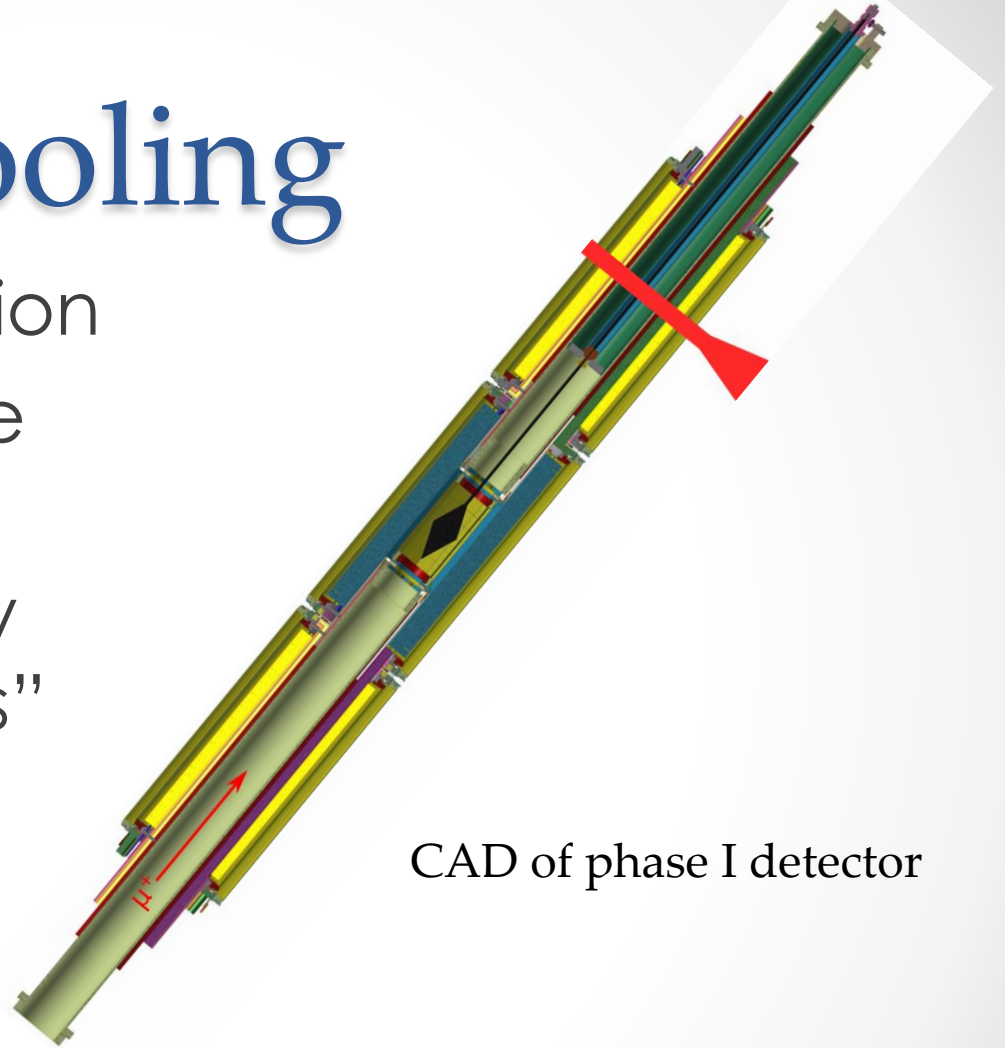
CAD of phase I detector



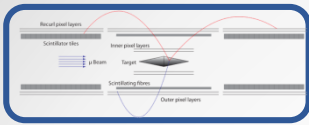
# Cooling

**5 + 5KW** heat dissipation

- He cooling in active area
- Inside detector only few “classical pipes”
- **He distribution**
  - ✓ integrated in mechanical structures of pixel detector



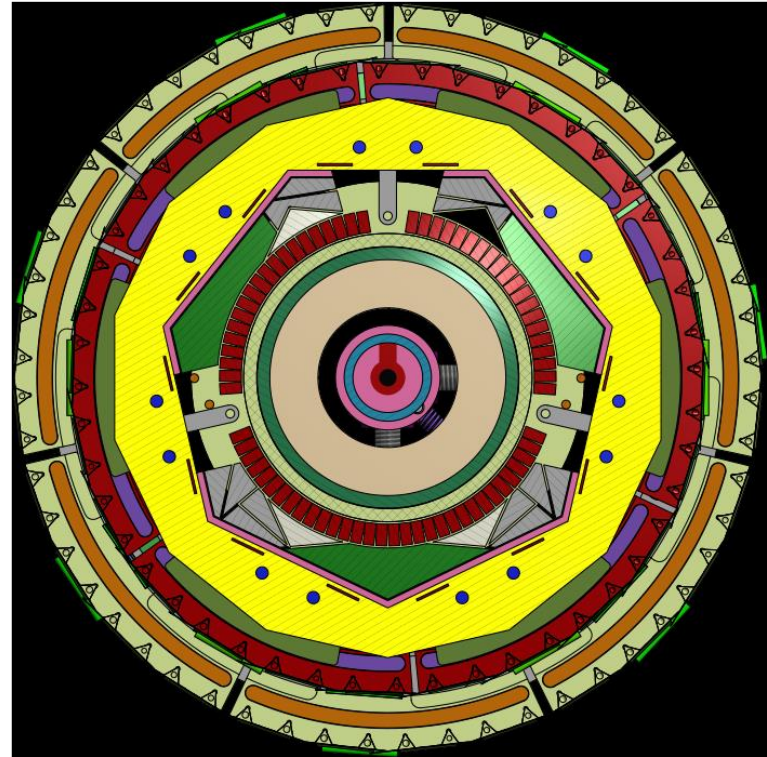
CAD of phase I detector



# Cooling pipes

**5 + 5KW** heat dissipation

- He cooling in active area
- Inside detector only few “classical pipes”
- **He distribution**
  - ✓ integrated in mechanical structures of pixel detector

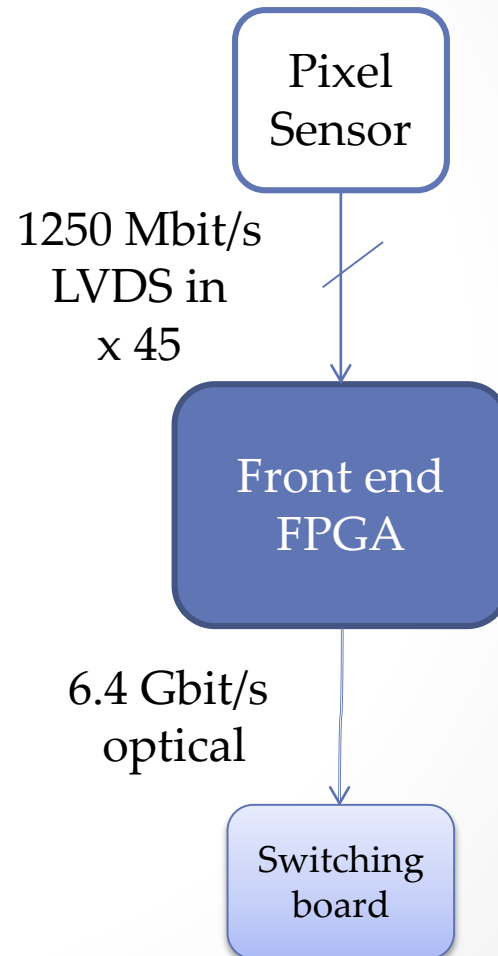


CAD of phase I detector

# DAQ Backup ...

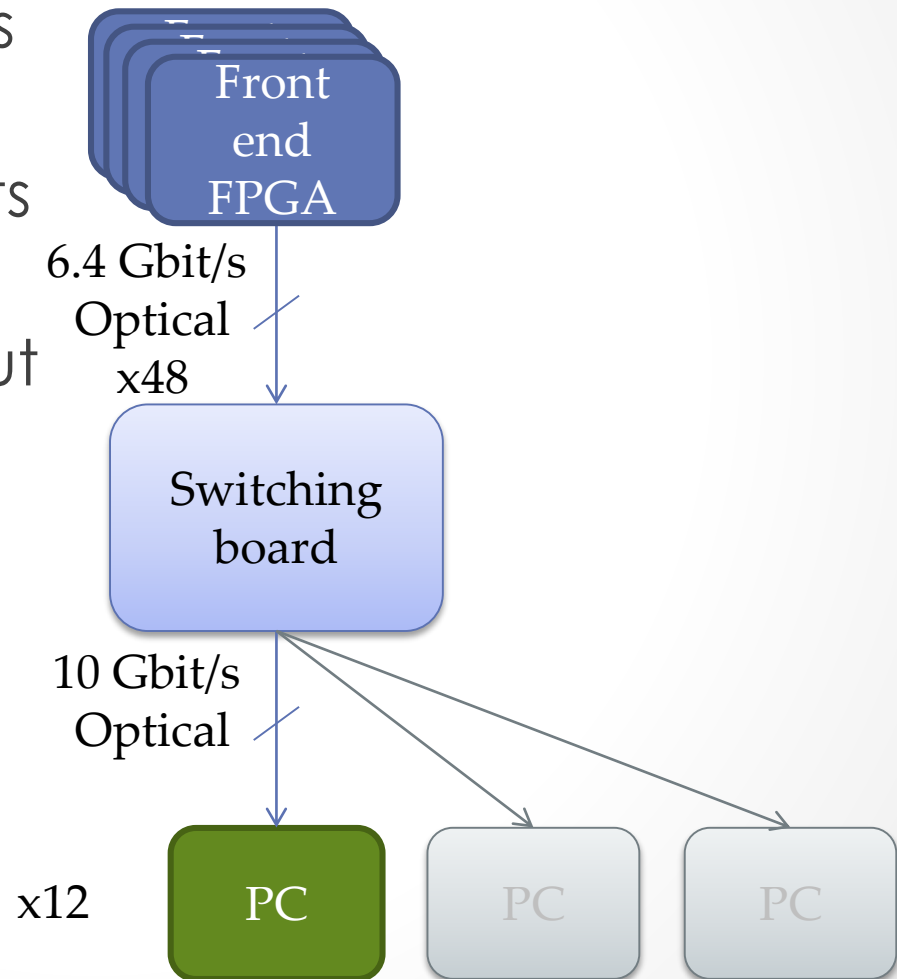
# Front End FPGAs

- FPGAs in magnet volume
  - 112 pieces
- Receive sensor data
  - 36-45 LVDS inputs
- 6.4 Gbit/s outputs
  - 8 optical links
  - ... to counting house



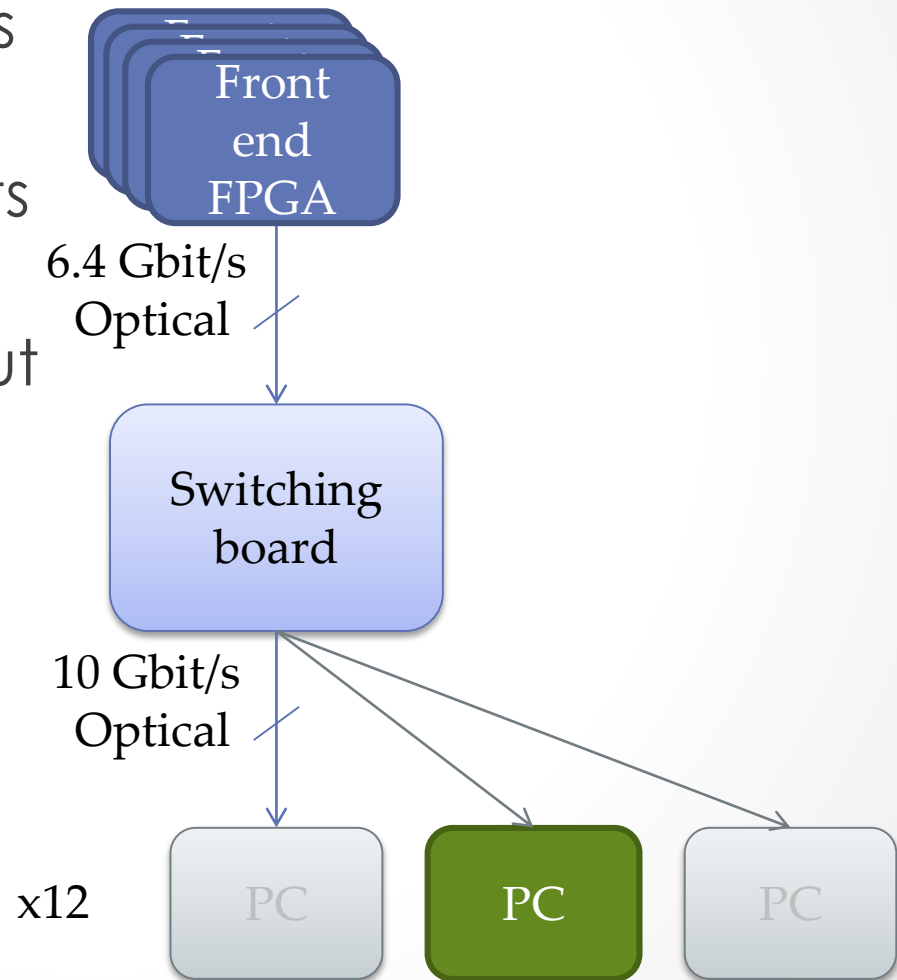
# Switching Board

- FPGA switching boards
  - per sub-detector
- 6.4 Gbit/s optical inputs
  - 16-48 inputs
- 10 Gbit/s optical output
  - 12 outputs to PCs
- Switching network
  - One output per PC



# Switching Board

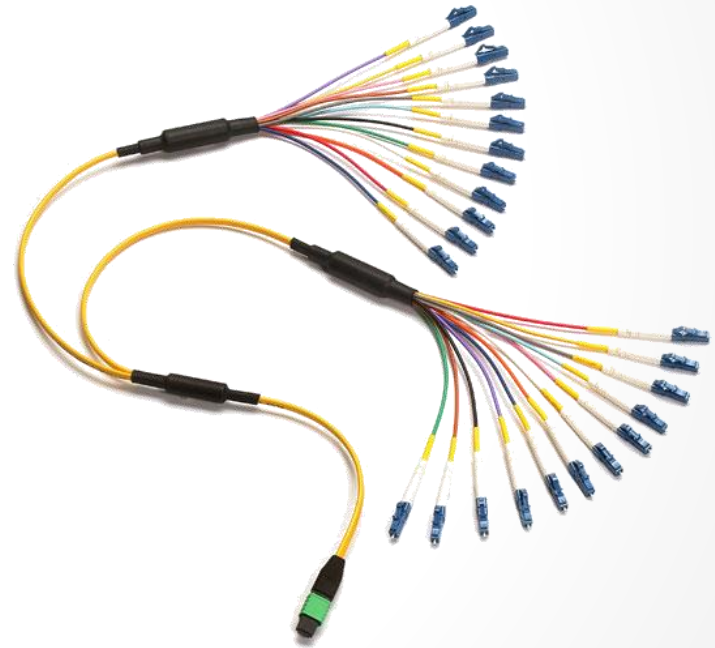
- FPGA switching boards
  - 4 per sub-detector
- 6.4 Gbit/s optical inputs
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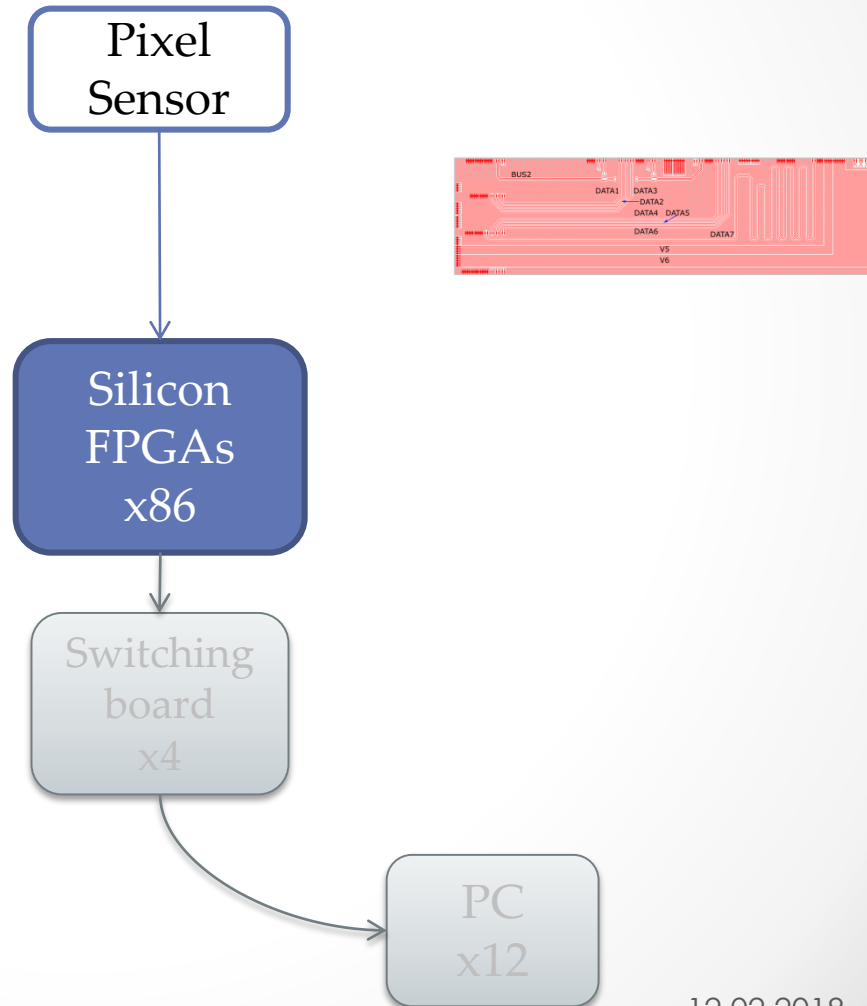
# Trigger-less DAQ

- Front end links
  - Pixel sensor to on-detector FPGA
    - 1250 Mbit/s
    - LVDS
  - Timing detector readout
- Optical links from detector
  - Front end FPGAs
  - ... to switching boards
  - 6.4 Gbit/s
- Optical links in counting room
  - Off-detector read out boards
  - ...to PC Farm



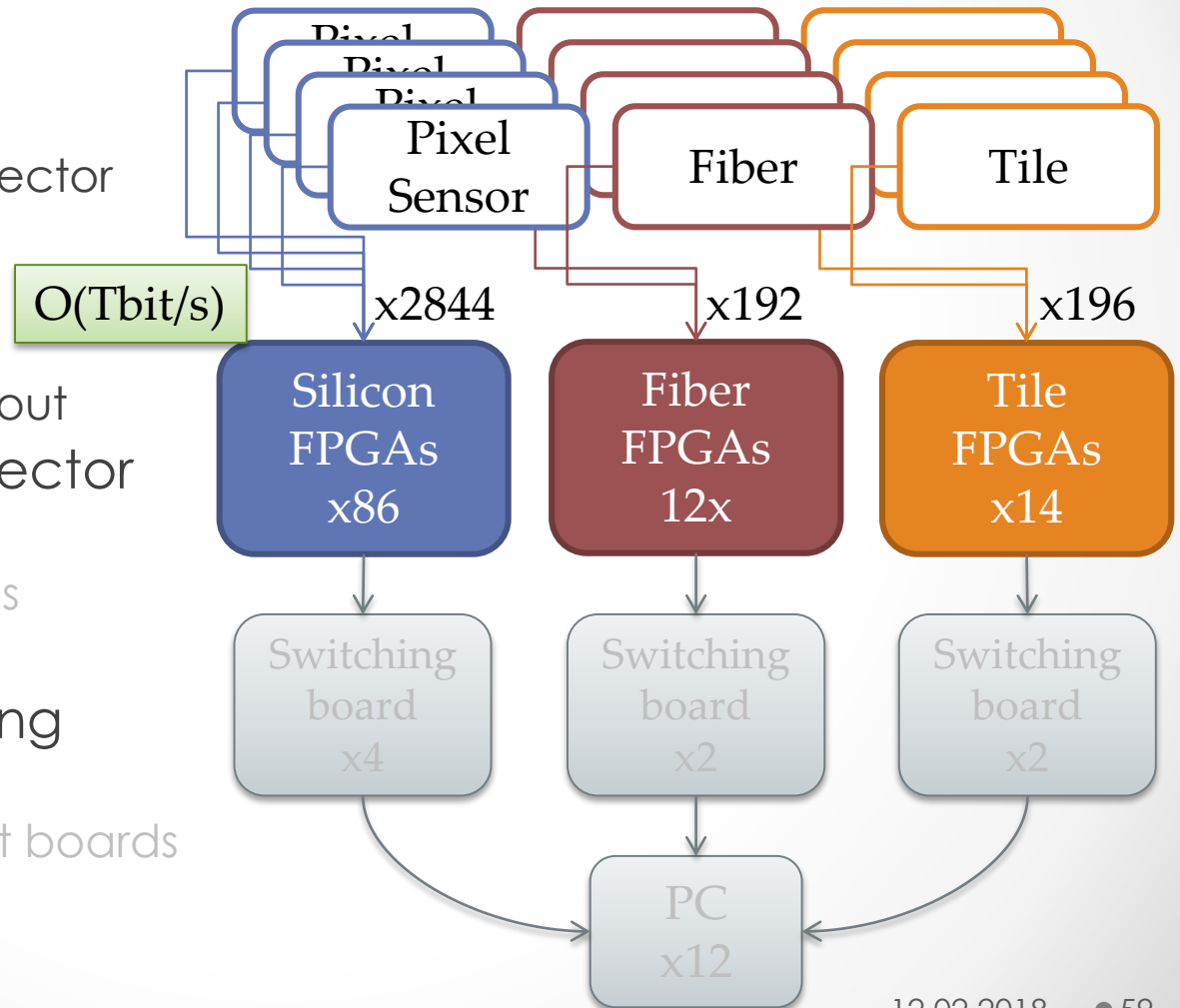
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- Optical links from detector
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  - ... to switching boards
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- Optical links in counting room
  - Off-detector read out boards
  - ...to PC Farm



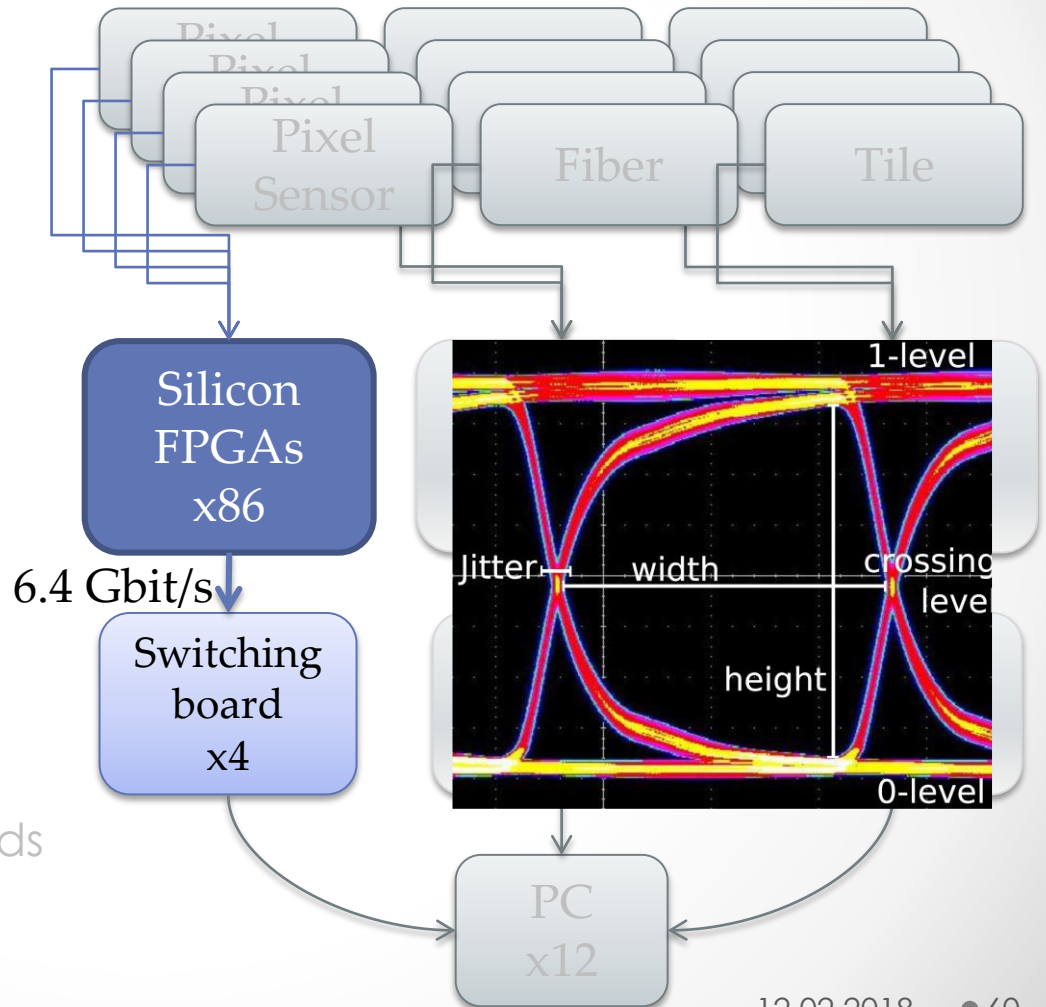
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  - ...to PC Farm



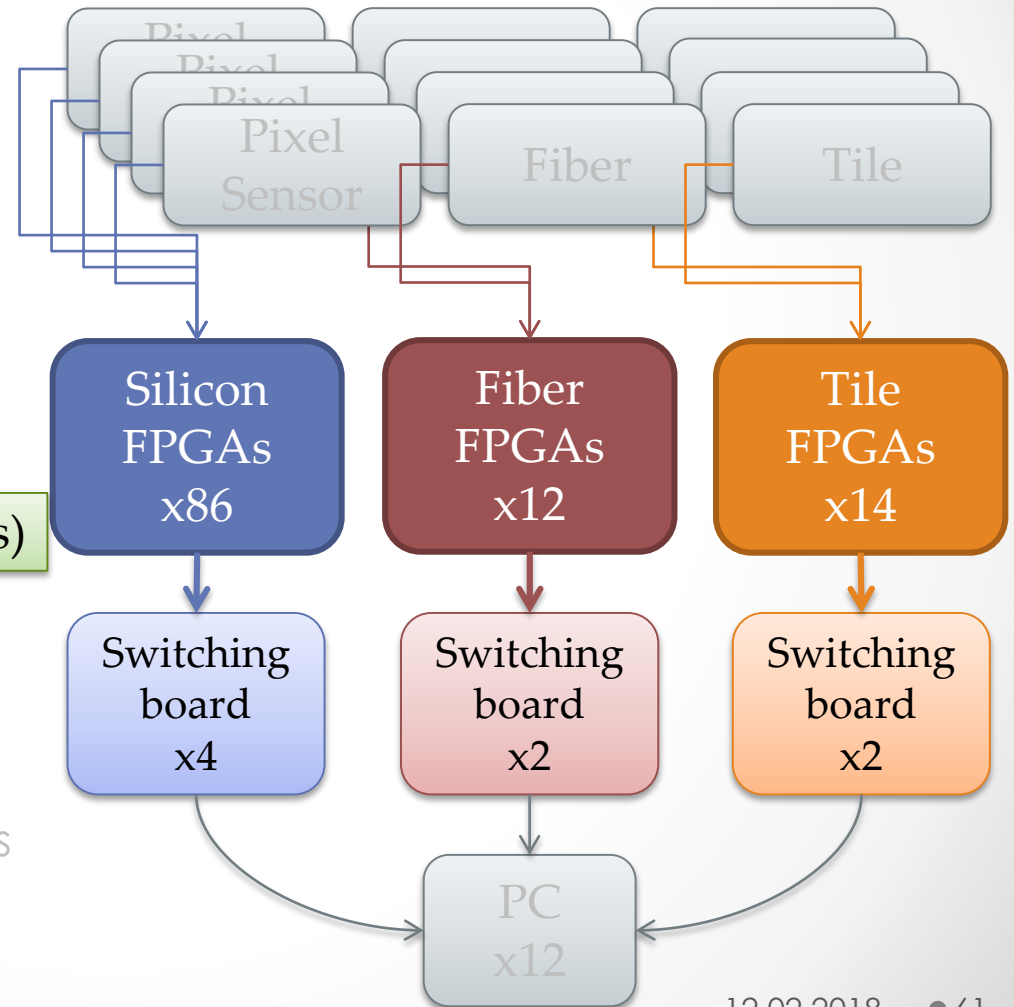
# Trigger-less DAQ

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  - ... to switching boards
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- Optical links in counting room
  - Off-detector read out boards
  - ...to PC Farm



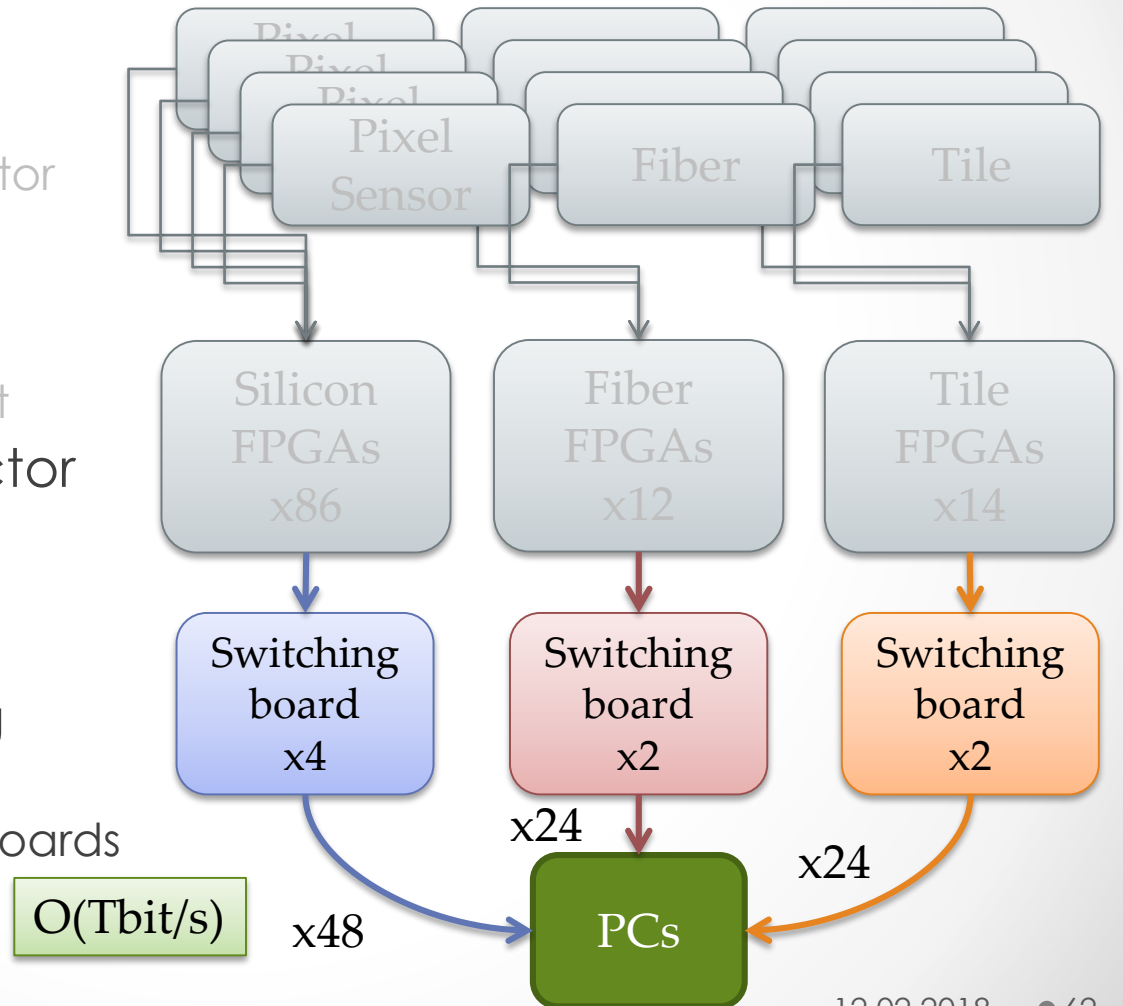
# Trigger-less DAQ

- Front end links
  - Pixel sensor to on-detector FPGA
    - 1250 Mbit/s
    - LVDS
  - Timing detector readout
- Optical links from detector
  - Front end FPGAs  $O(\text{Tbit/s})$
  - ... to readout boards
  - 6.4 Gbit/s
- Optical links in counting room
  - Off-detector read out boards
  - ...to PC Farm



# Trigger-less DAQ

- Front end links
  - Pixel sensor to on-detector FPGA
    - 1250 Mbit/s
    - LVDS
  - Timing detector readout
- Optical links from detector
  - Front end FPGAs
  - ... to readout boards
  - 6.4 Gbit/s
- Optical links in counting room
  - Off-detector read out boards
  - ...to PC Farm



# GPU-PC

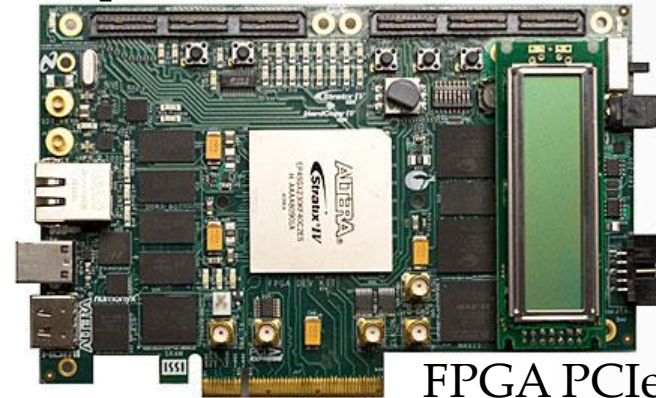
- PC with GPU
- 10 Gbit/s Fiber input
  - 8 inputs from sub-detectors
- Data filtering
  - Timing Filter on FPGA
  - Track filter on GPU
  - Data to tape < 100 MB/s



# GPU-PC

- PC with GPU
- 10 Gbit/s Fiber input
  - 8 inputs from sub-detectors
- Data filtering
  - Timing Filter on FPGA
  - Track filter on GPU
  - Data to tape < 100 MB/s

Optical mezzanine connectors



FPGA PCIe board



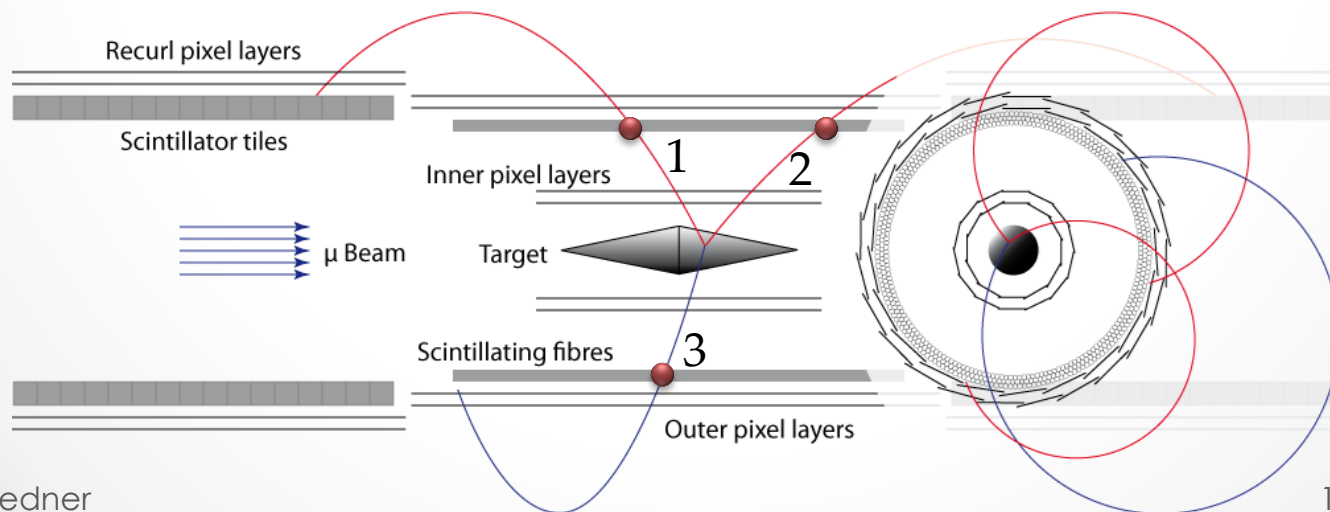
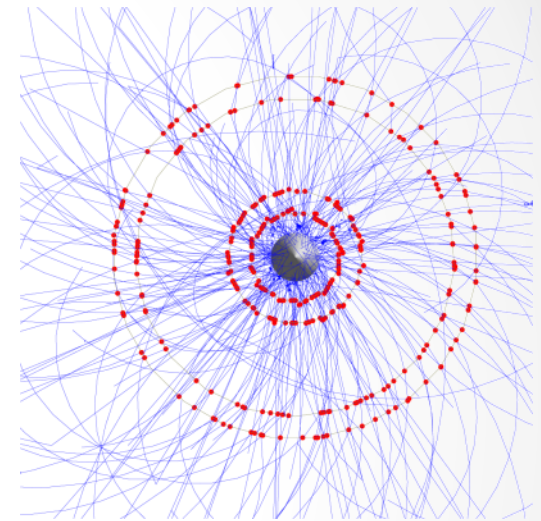
GPU computer



# Timing Filter

Under discussion

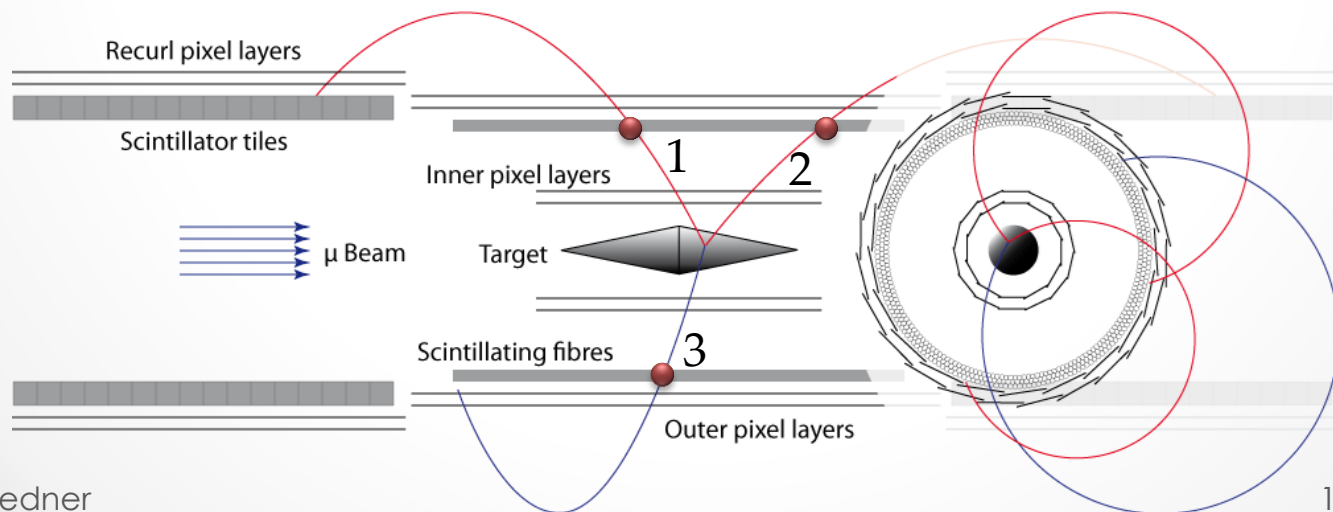
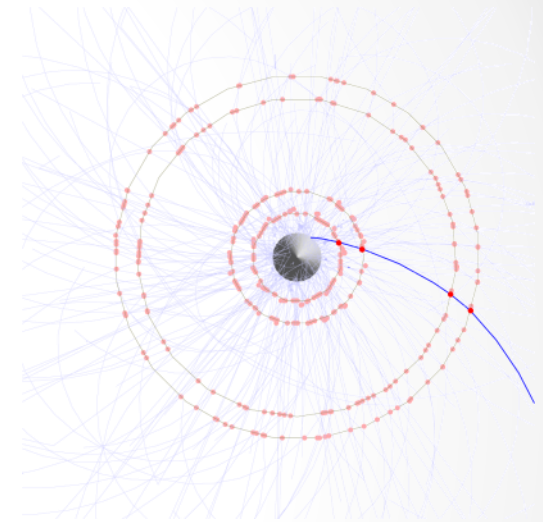
- Entire event on PCIe FPGA
- Tile and Fiber data
  - Easy to match
  - Look for three tracks
- Reject data without three hits
  - ... inside time interval



# Timing Filter

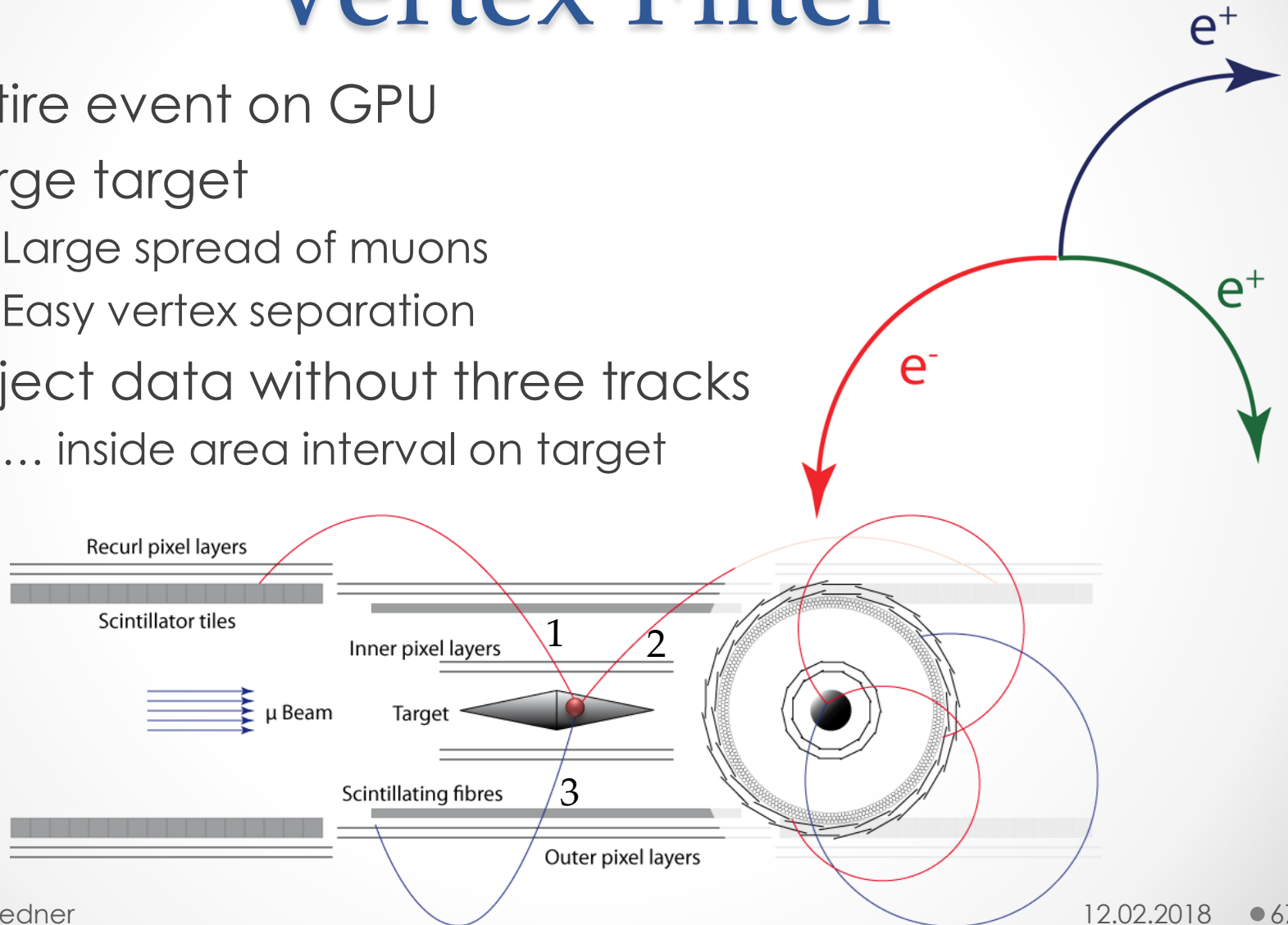
Under discussion

- Entire event on PCIe FPGA
- Tile and Fiber data
  - Easy to match
  - Look for three tracks
- Reject data without three hits
  - ... inside time interval



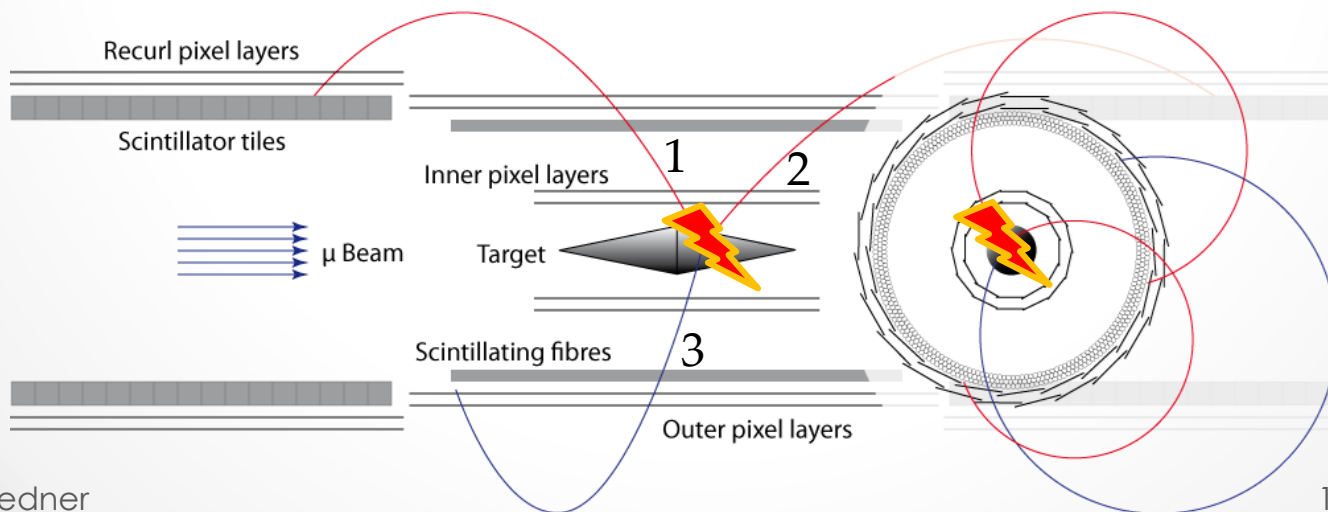
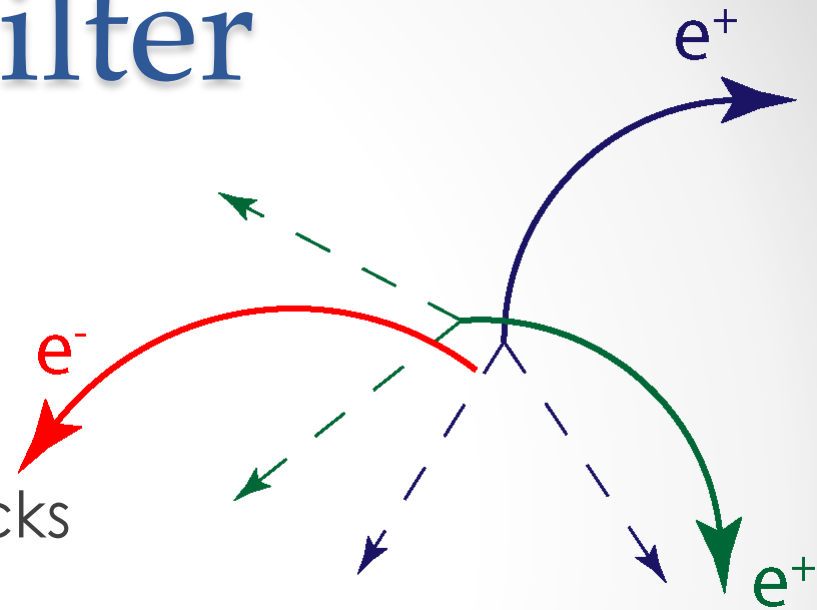
# Vertex Filter

- Entire event on GPU
- Large target
  - Large spread of muons
  - Easy vertex separation
- Reject data without three tracks
  - ... inside area interval on target



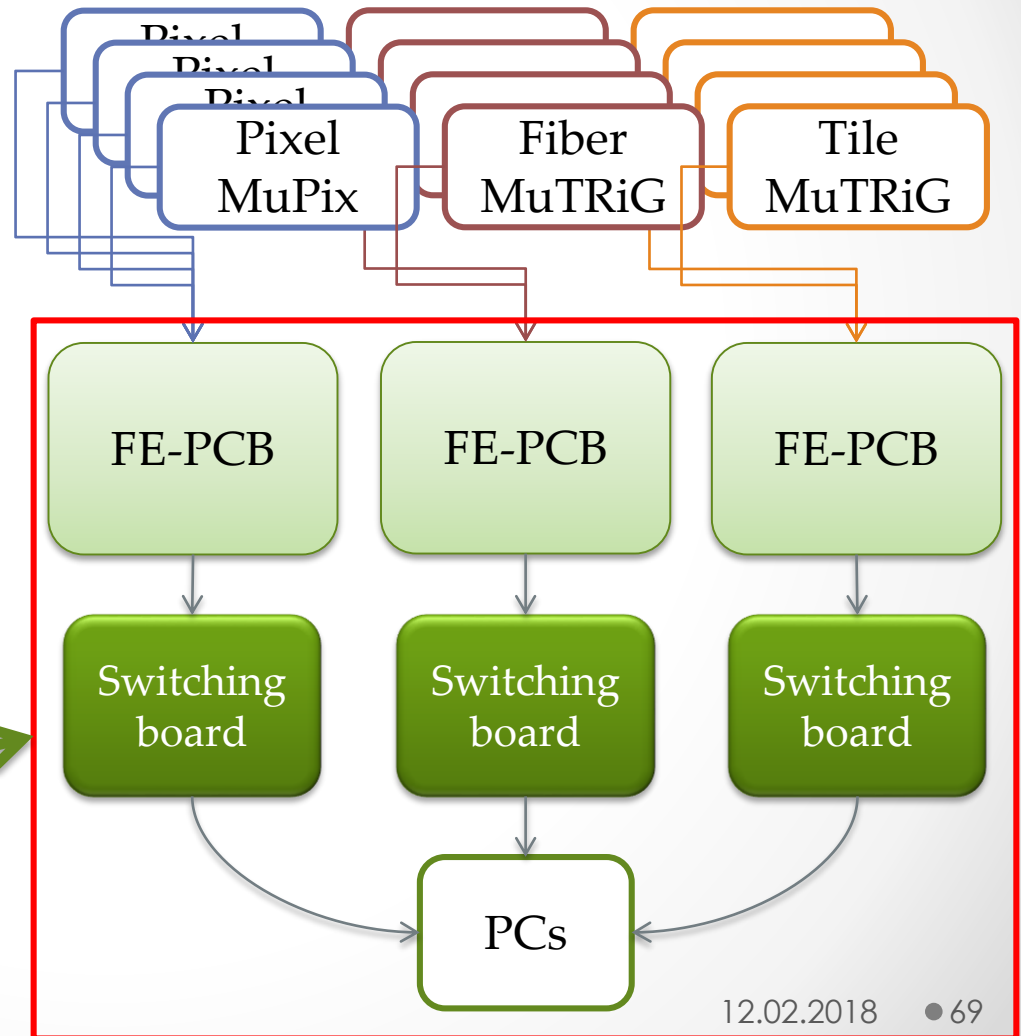
# Vertex Filter

- Entire event on GPU
- Large target
  - Large spread of muons
  - Easy vertex separation
- Reject data without three tracks
  - ... inside area interval on target



# Readout system

- Pixel detector
  - HV-MAPS (MuPix)
    - ✓ Sensor and read-out chip in one
    - ✓ Deliver zero-suppressed serialized data
- Timing detectors
  - SiPMs plus MuTRiG TDC
  - Deliver zero-suppressed serialized data
- **Common read-out system** →



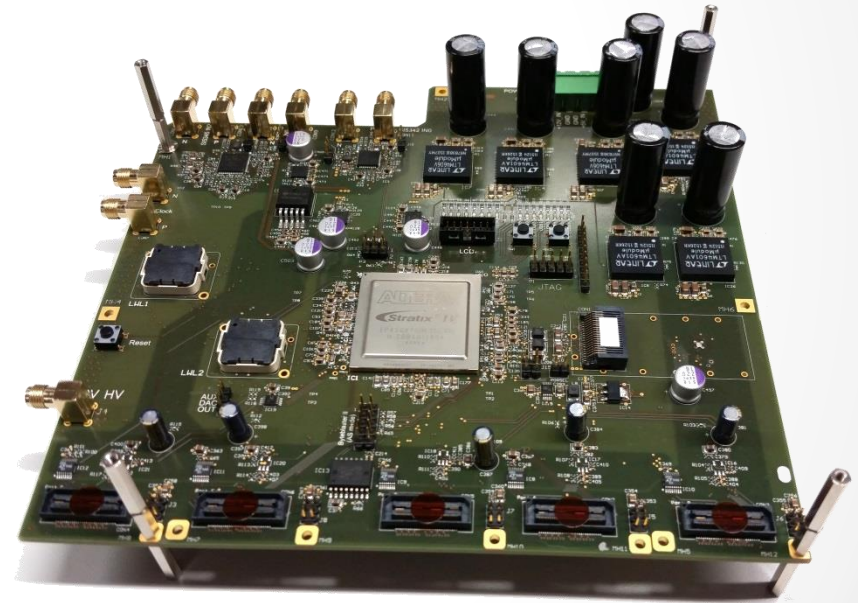
# Common read-out PCB

## ✓ Front-end PCB

- Common for pixel, fibre and tile detector
- ✓ Data acquisition
- ✓ Clock distribution
- ✓ Slow control distribution

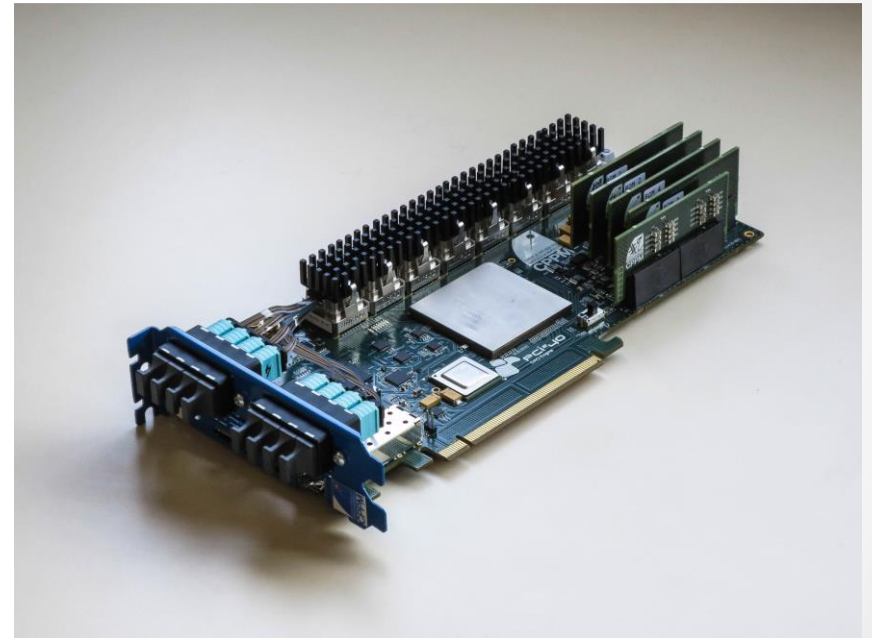
## ✓ Prototype **functional**

- Improved version for Q3/2017
- Next: Vertical slice test:
  - All electronics from (pixel) module to PC



# Switching Board

- PCIe40
- Developed for LHCb and ALICE upgrade by CPPM (Marseille)
- 48 optical I/Os
- Optical network switch for Mu3e filter farm
- Mu3e will receive samples from the current production



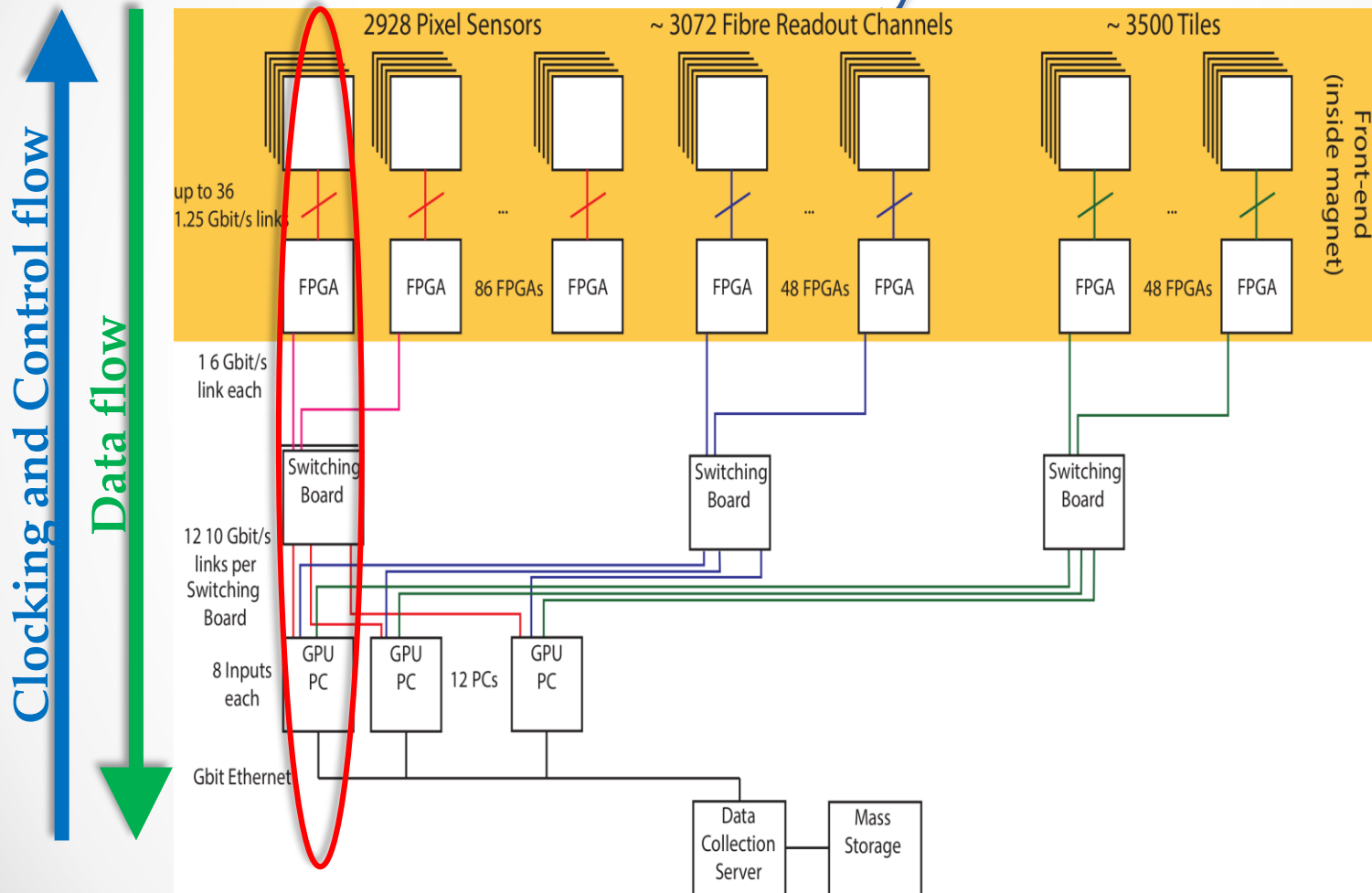
# Receiving FPGA board PC side

- De5a-NET boards from Terasic
- Successfully tested at Mainz
- 8 out of 12 boards already acquired





# Vertical slice of the Mu3e readout system

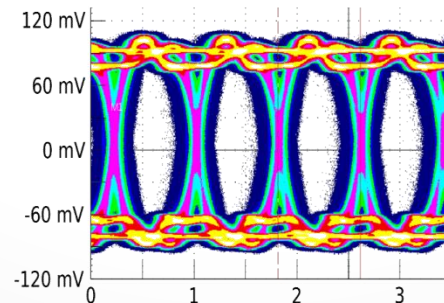
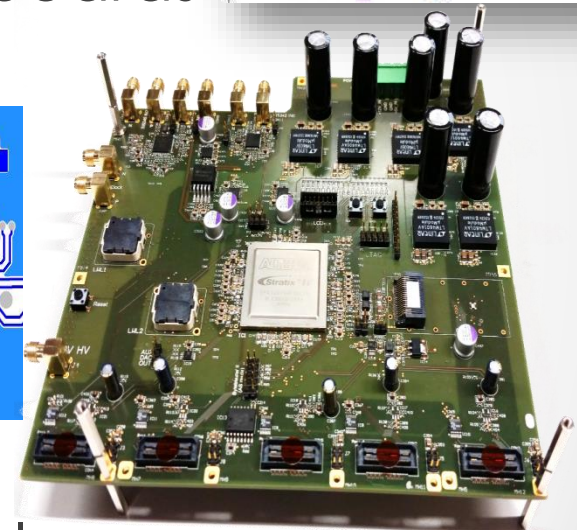
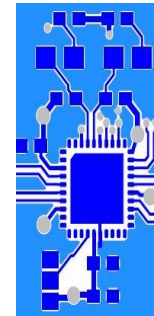


# Tasks, problems, challenges

- Hard-, firm- and software developments
- Testing custom designed front-end boards and bringing them to operation
- Data transmission studies
  - Electrical links
  - Optical links
- **Data reduction at front-end:**  
Up to  $45 \times 1.25$  Gbps  $\rightarrow$   $1 \times 6$  Gbps with as little logic utilization as possible

```
write_process : process(clkin, reset_n)
begin
  if(reset_n = '0')then
    syncfifo_wmem(0) <= '0';
```

```
void MudadqDevice::zero_wmem()
{
  uint32_t temp;
```



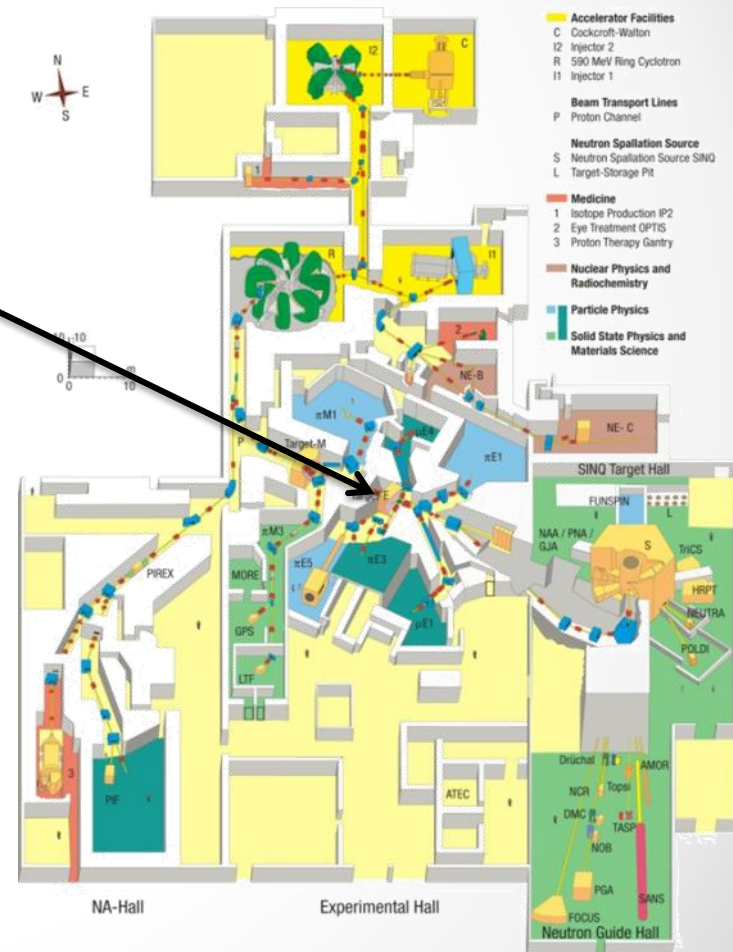
# Backup Area Planning

...

# PSI $\mu$ -Beam

Paul Scherrer Institute Switzerland:

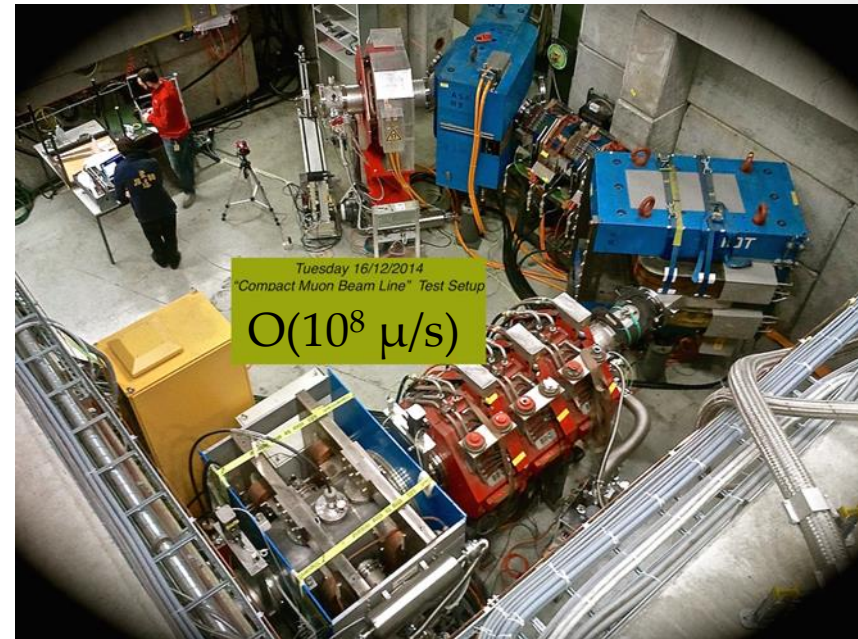
- 2.2 mA of 590 MeV/c protons
- Surface muons from target E
- Up to  $\sim 10^8 \mu/s$
- $> 10^{15}$  muon decays per year



# PSI $\mu$ -Beam

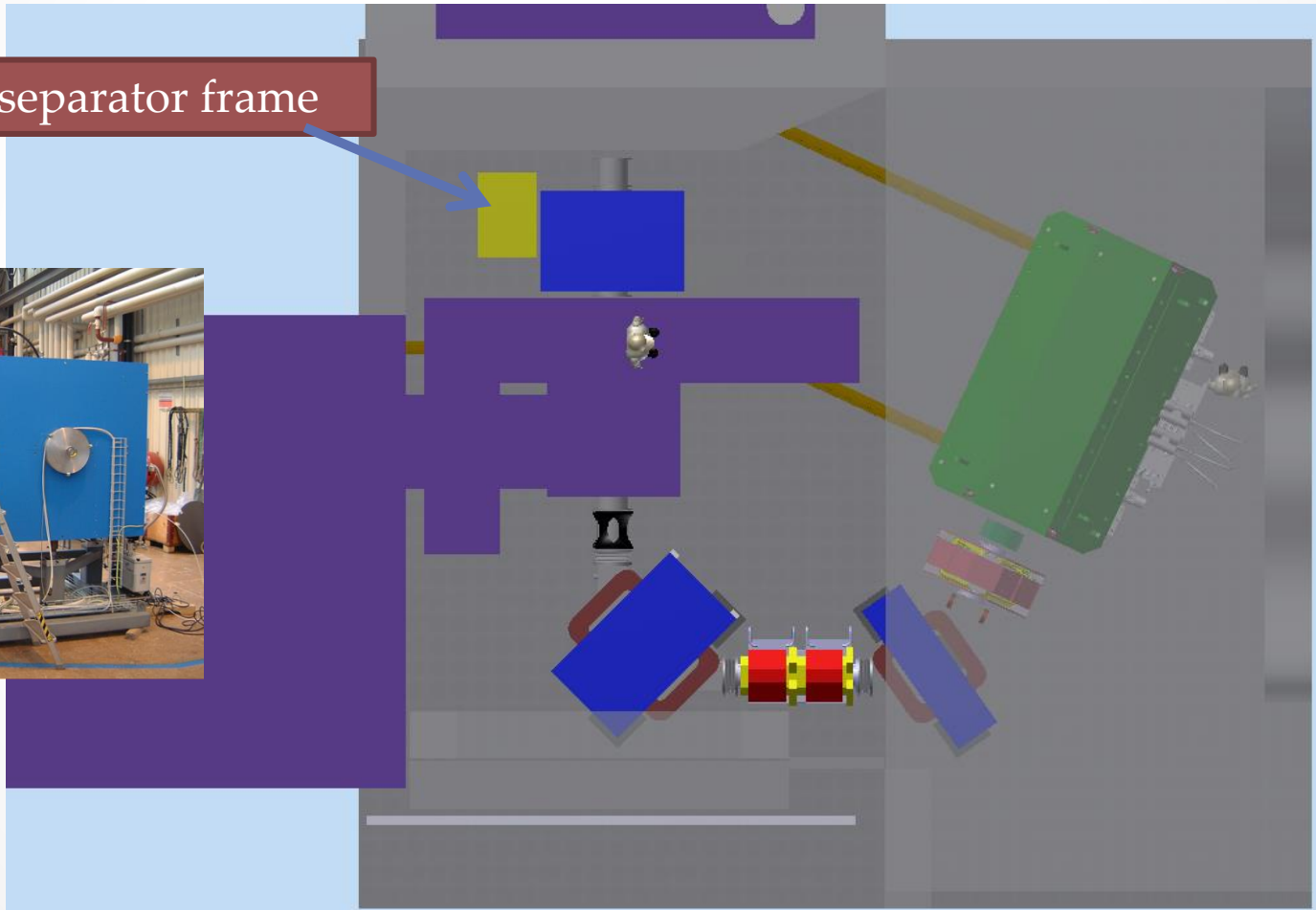
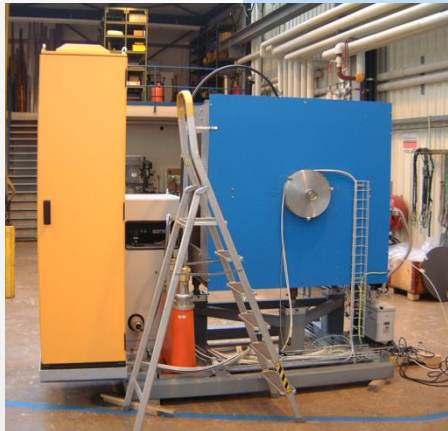
Paul Scherrer Institute Switzerland:

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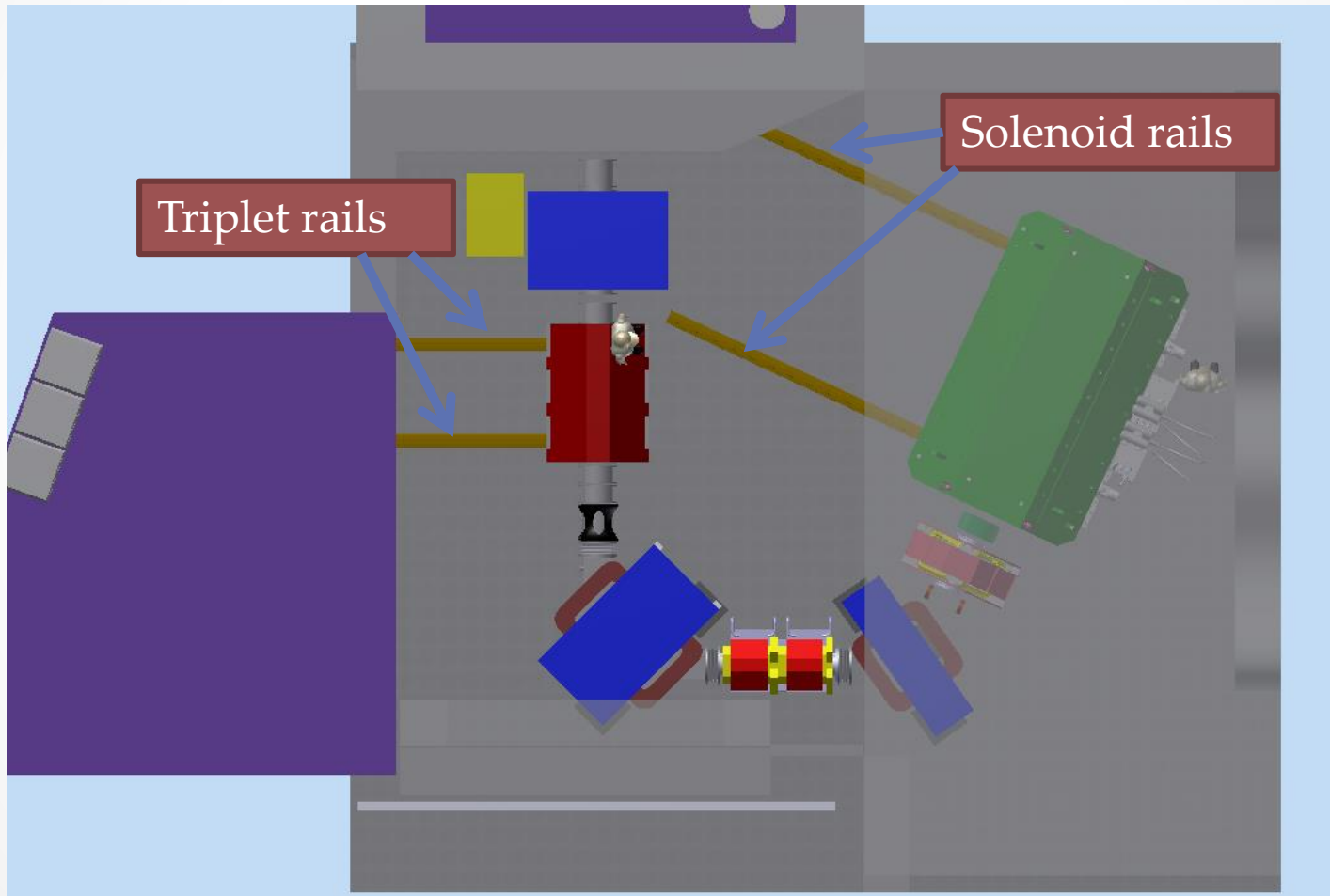


# Area Layout

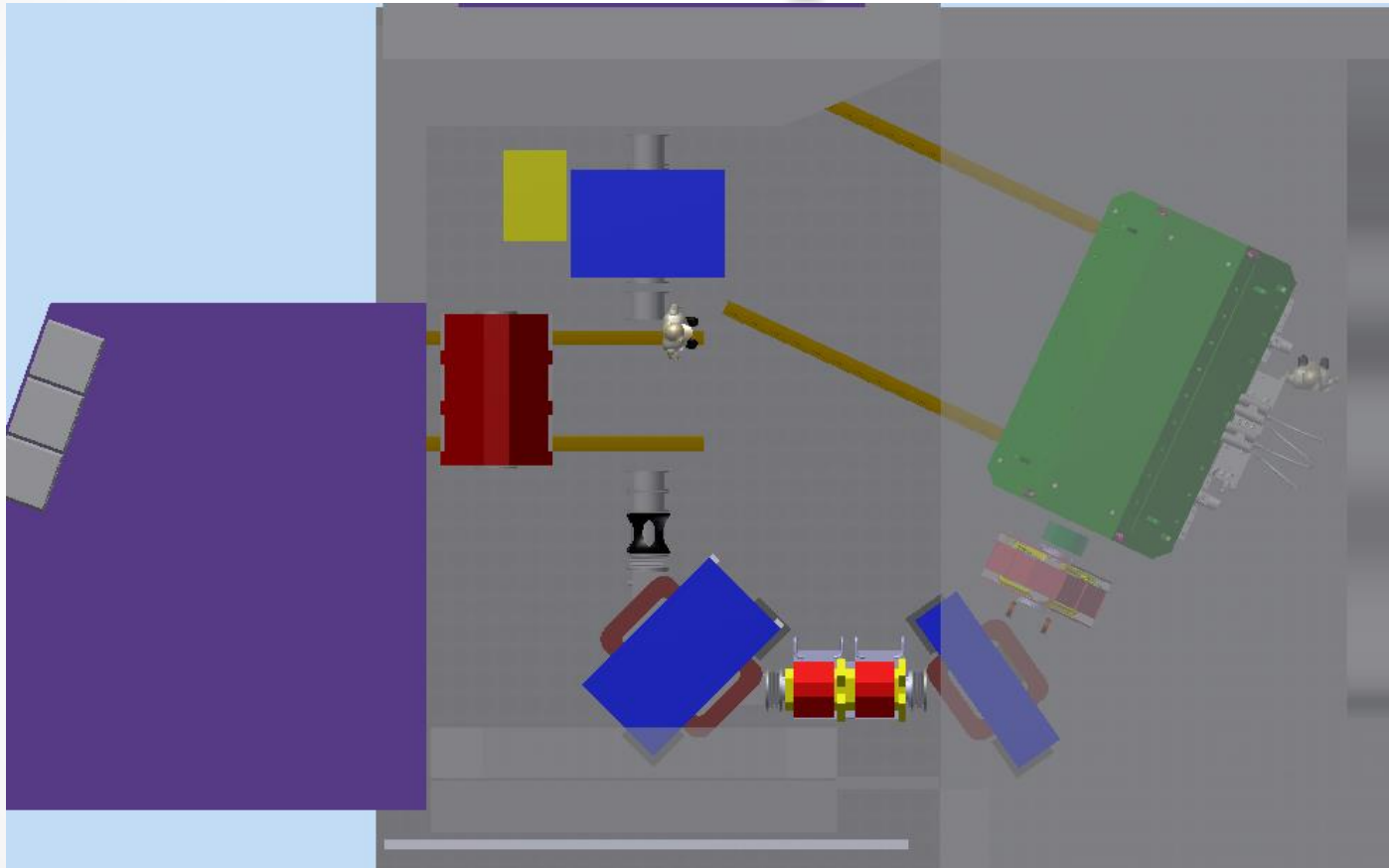
Modified separator frame



# Remove Triplet platform and stairs



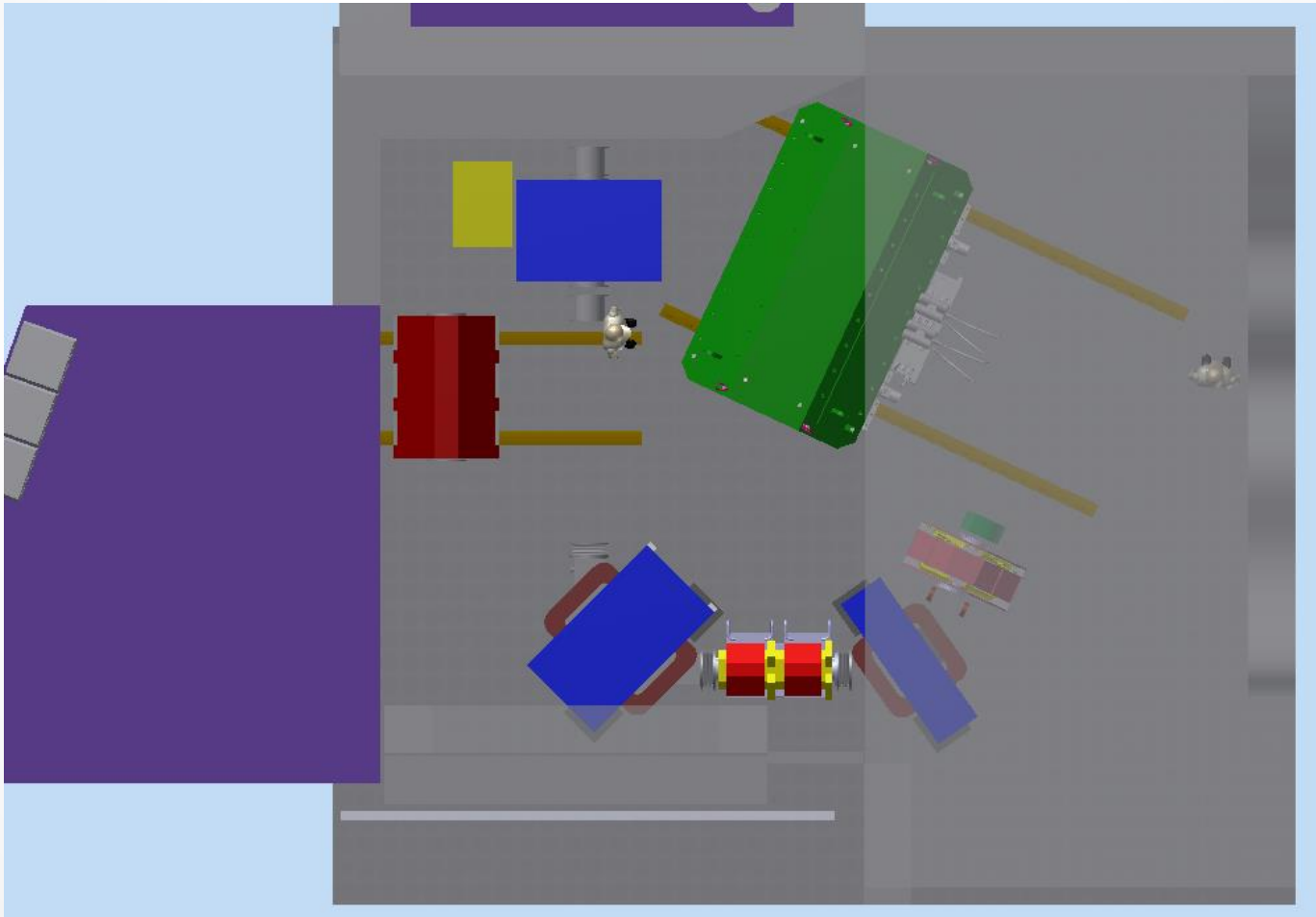
# Move triplet II



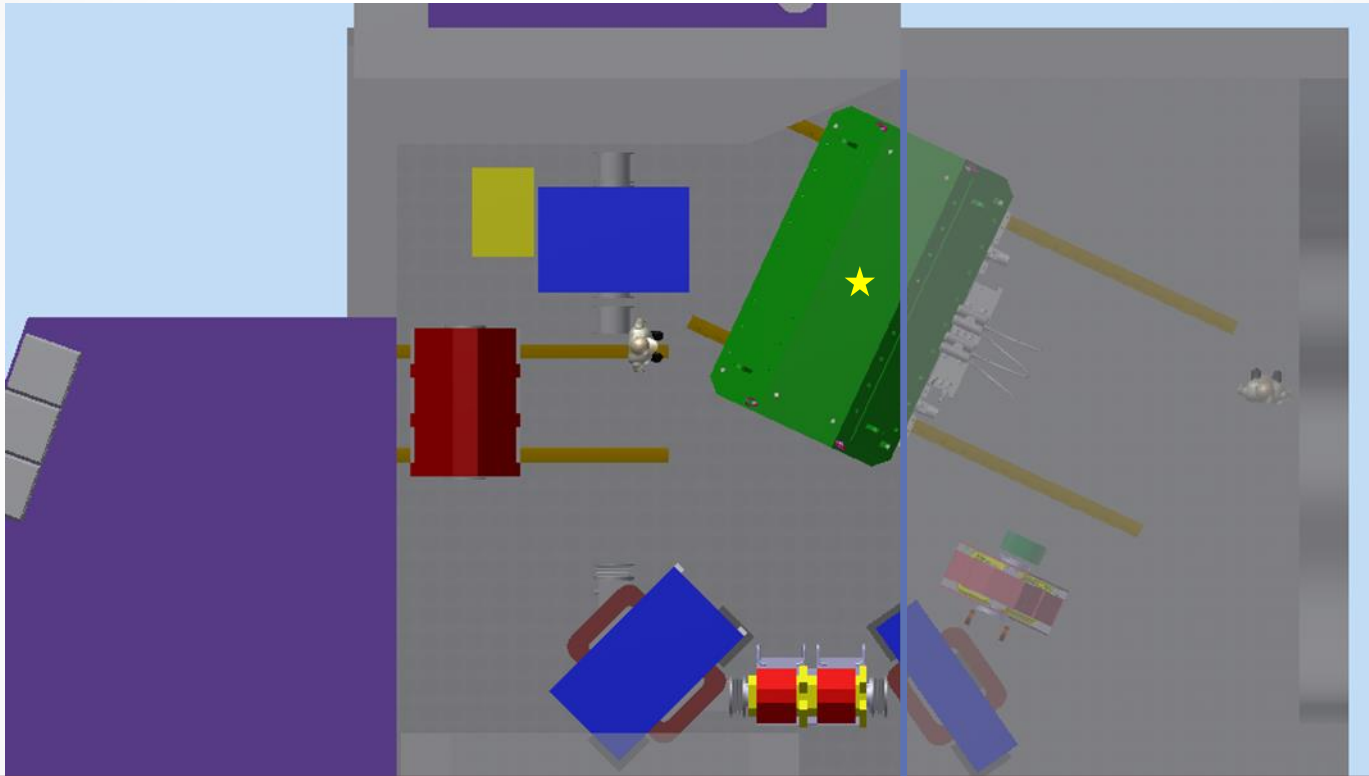
Optionally the beam pipe and collimator DS triplet II could be attached to triplet II frame and could be moved at once. Otherwise remove beam pipes and collimator.



# Move Solenoid

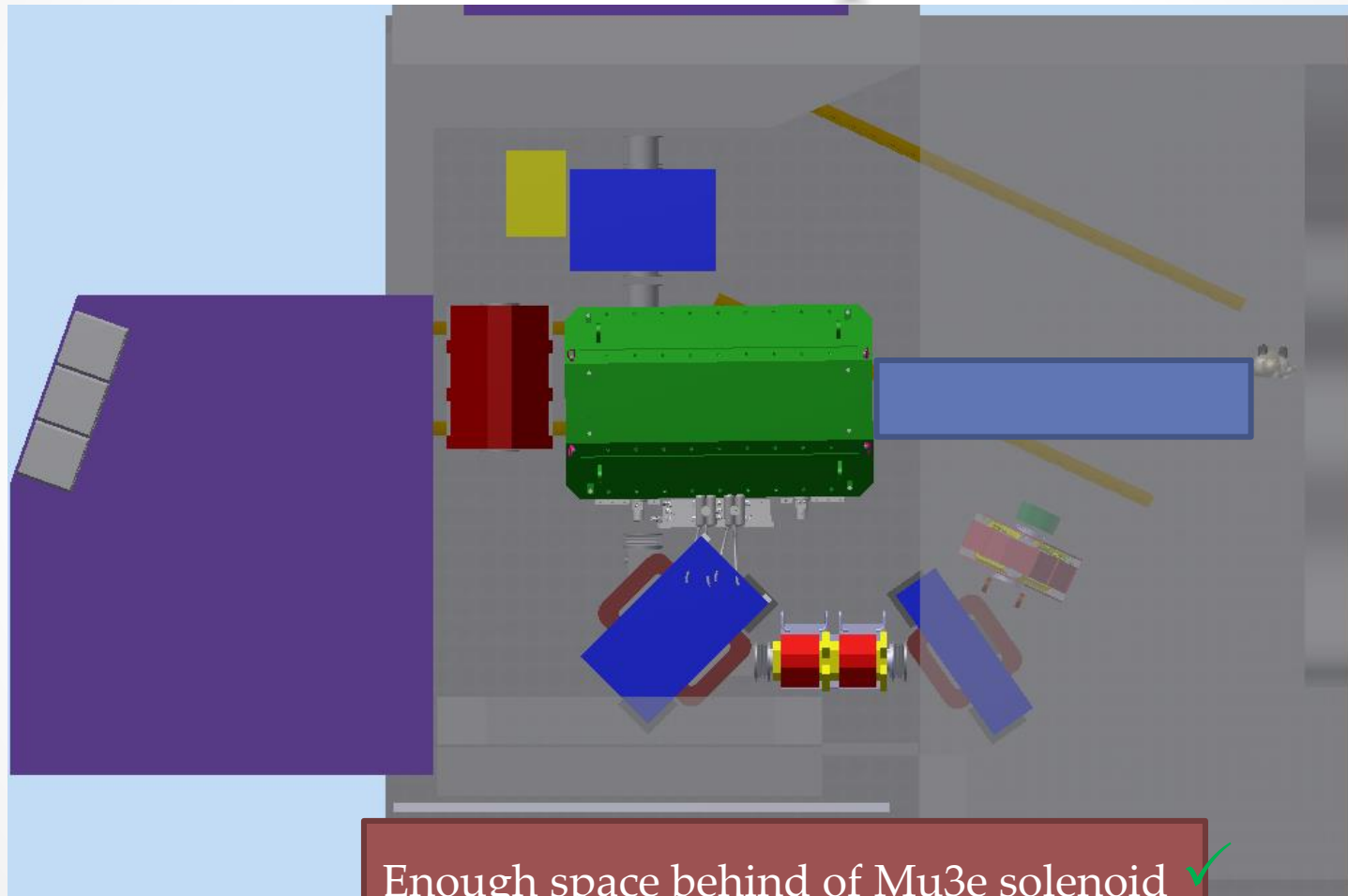


# Access with crane



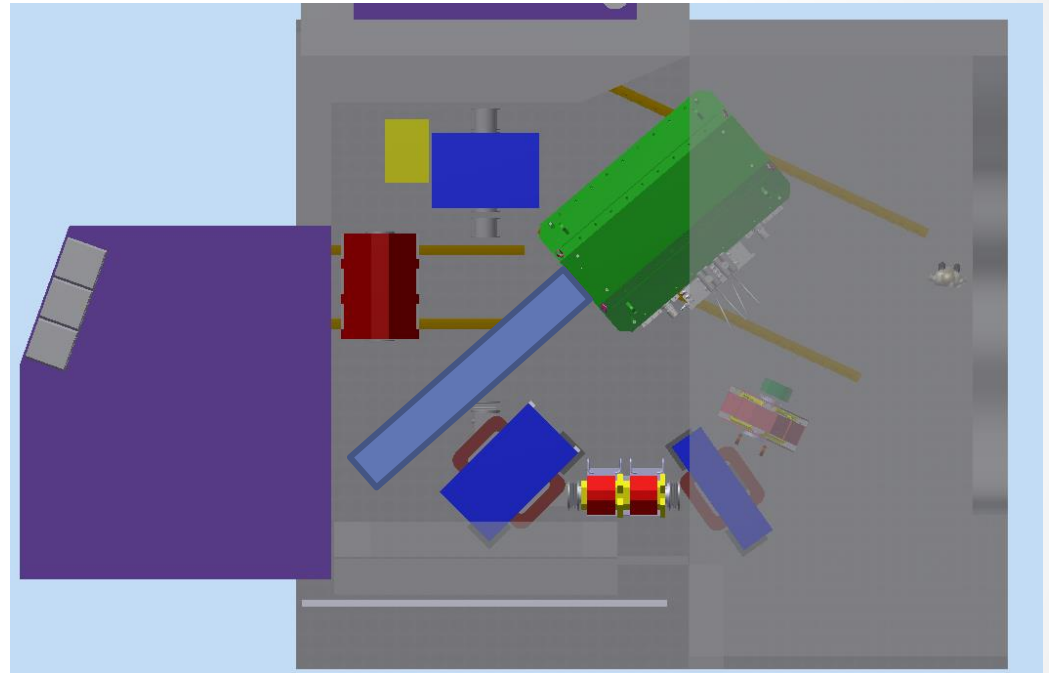
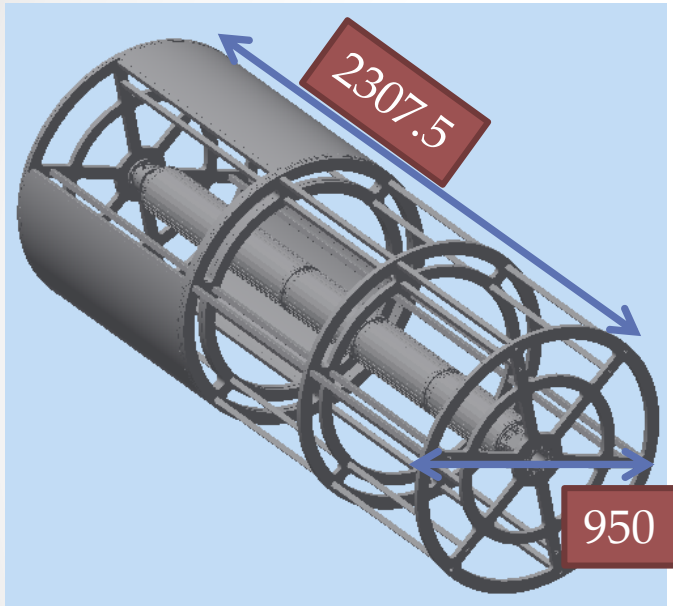
Center of solenoid is now not covered by ceiling anymore. Therefore the solenoid can now be moved with the crane (allows translation and rotation. Need frame of max 1m height on top of solenoid if frame stays attached to solenoid lifting eyes)

# Crane in/out position



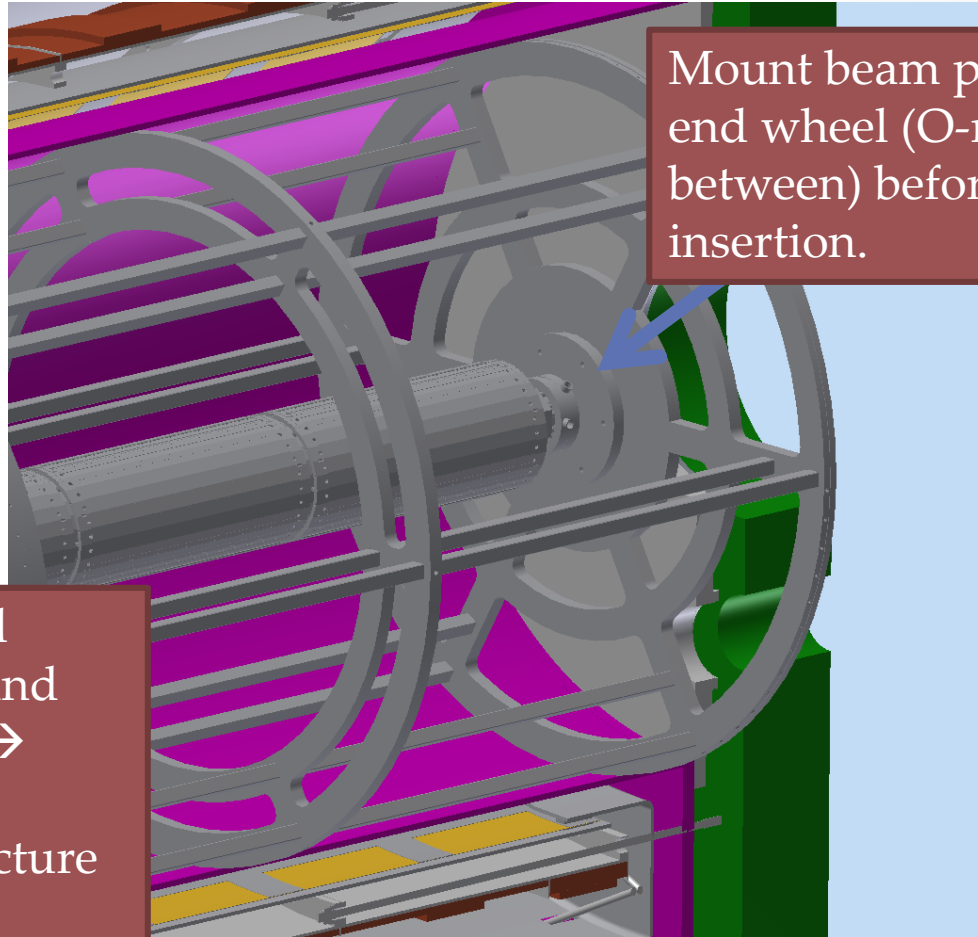
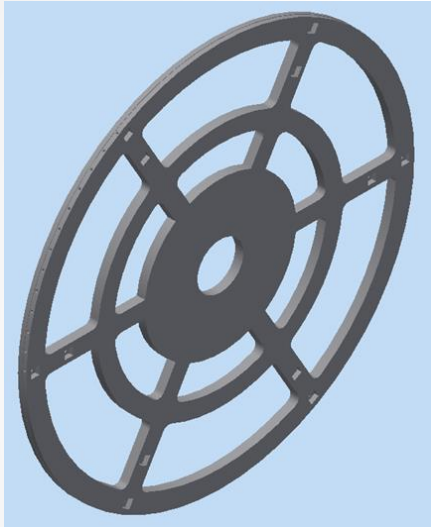
Enough space behind of Mu3e solenoid ✓

# Insert / Extract Detector on railsystem



Enough space in front of Mu3e solenoid ✓

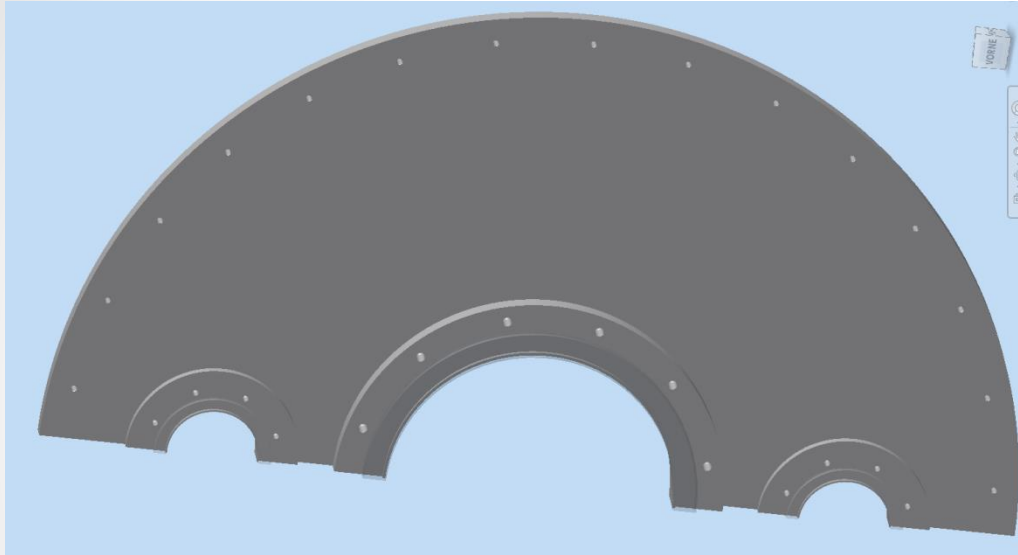
# Inner Beam Pipe and End wheel modified



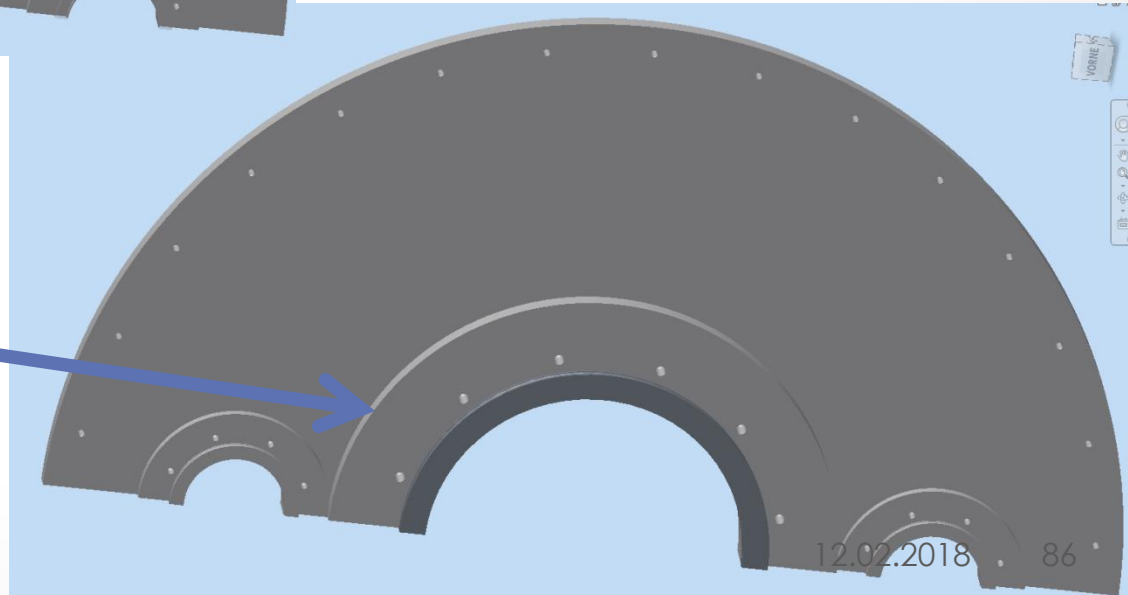
Mount beam pipe to end wheel (O-ring in-between) before insertion.

End wheel has a bigger radial surface with sealing surface and blind holes from both sides. → Mount beam pipe before implementation of inner structure to end wheel sealing surface

# Helium lid modified (only half of the lid is shown)

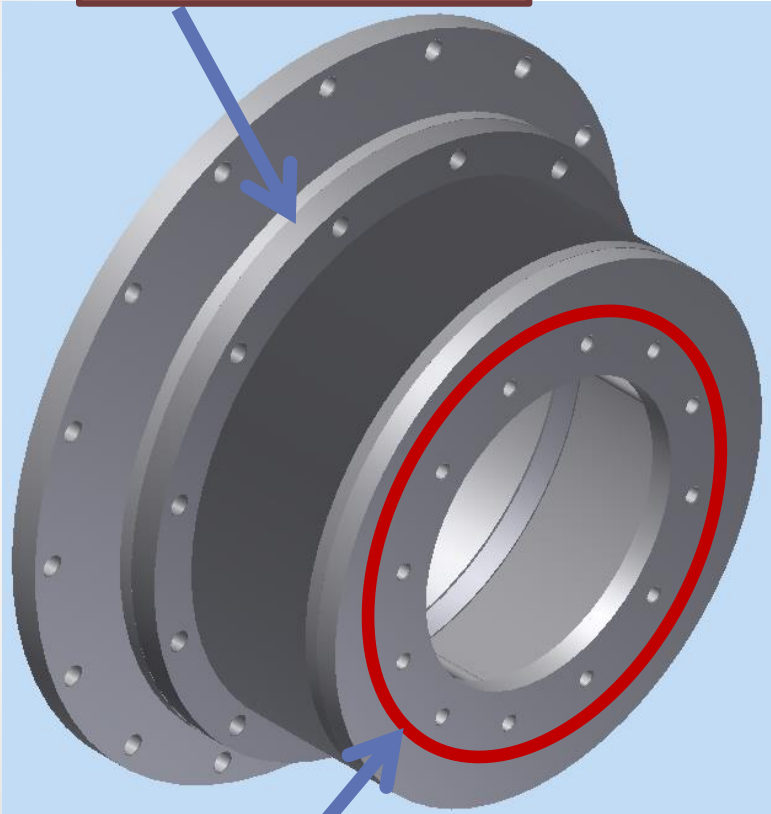


Need more material here  
to have blind holes from  
detector side

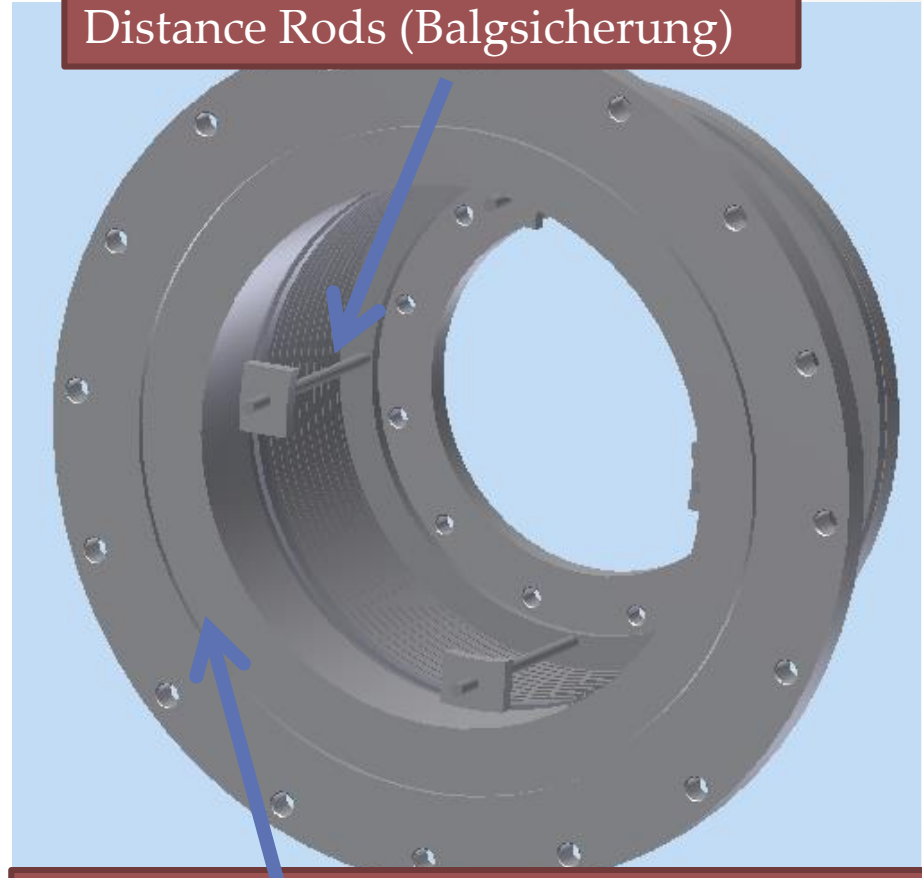


# Inner Coupling Tube (Nose)

Welded connection



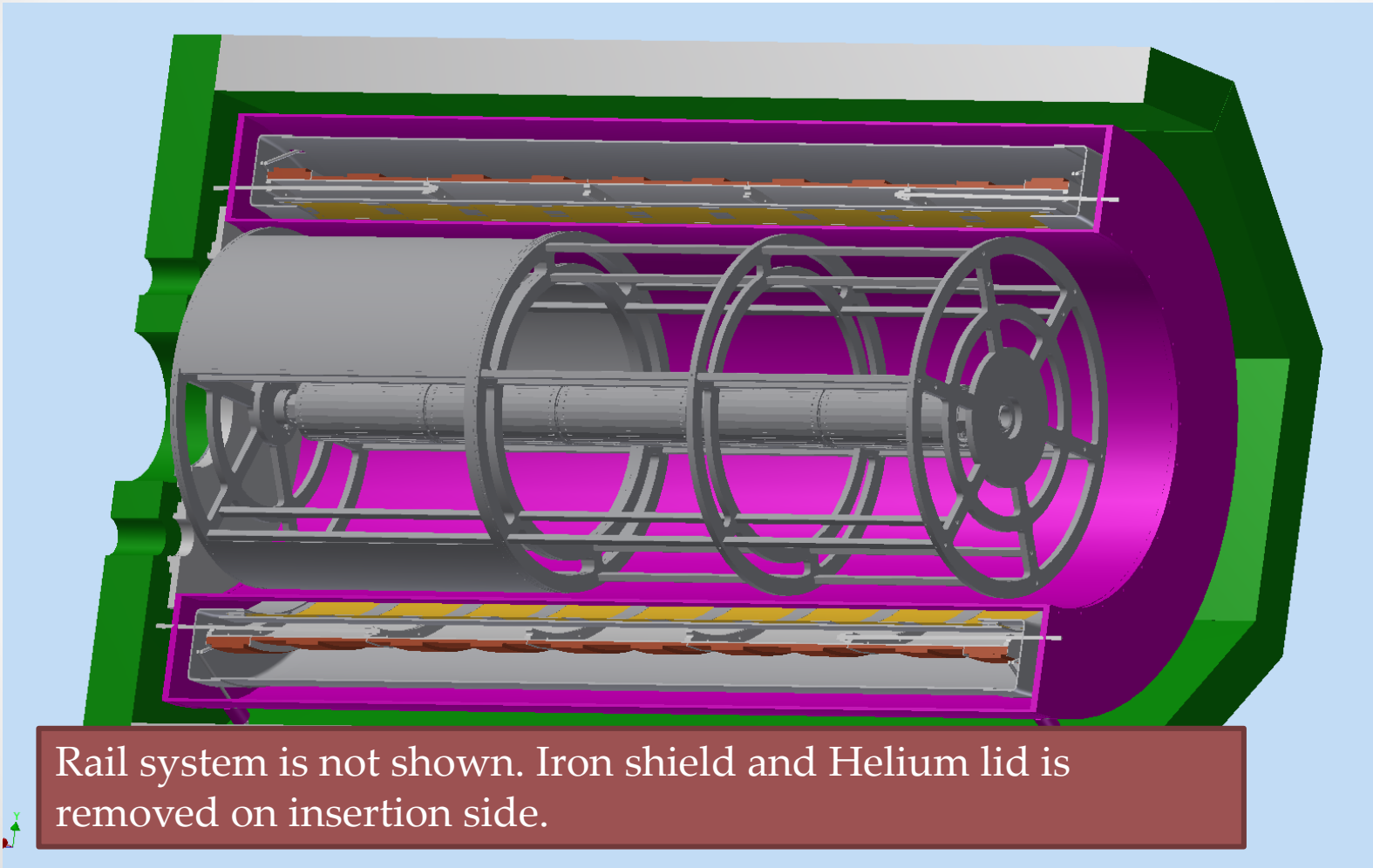
Distance Rods (Balgssicherung)



Sealing surface inside screws on area side

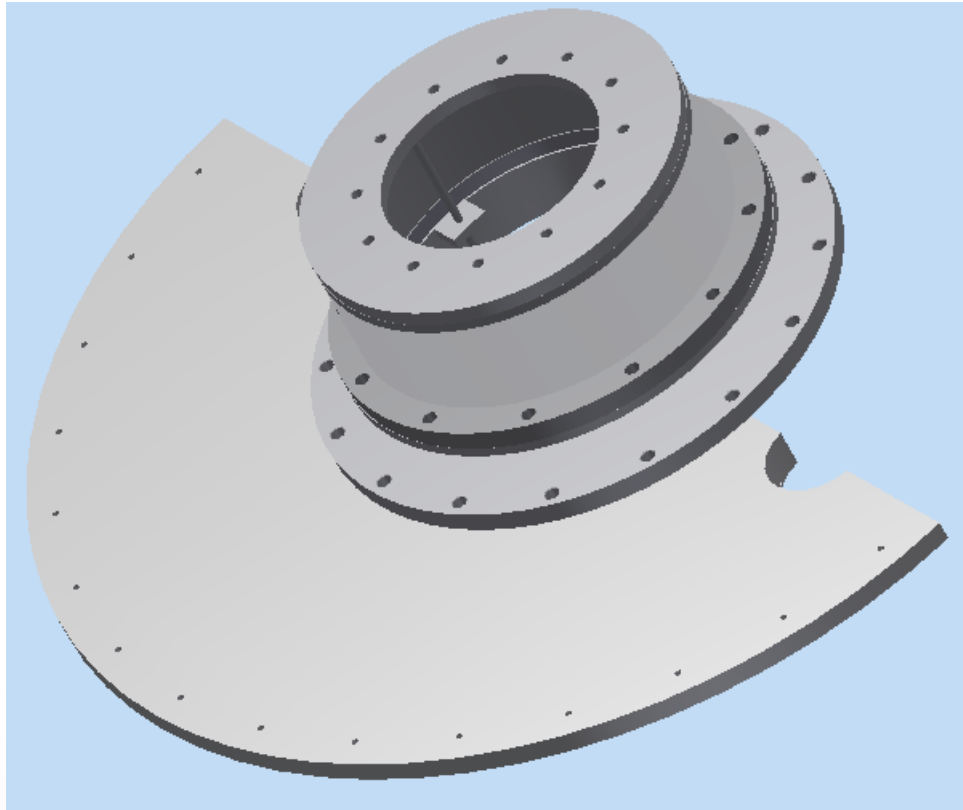
Sealing surface outside screws on detector side

# Detector in solenoid



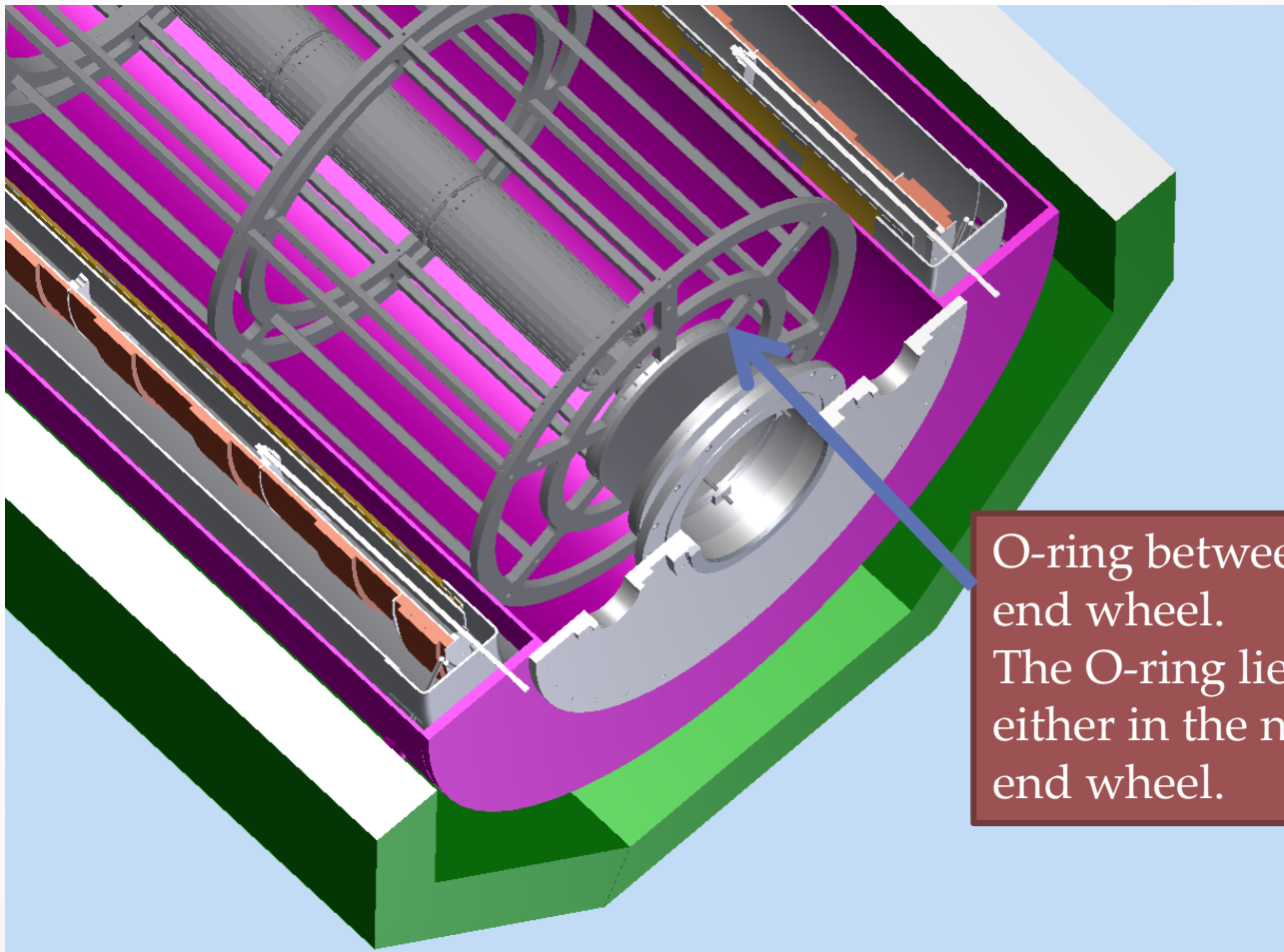


# Premount nose on Helium lid (outside)



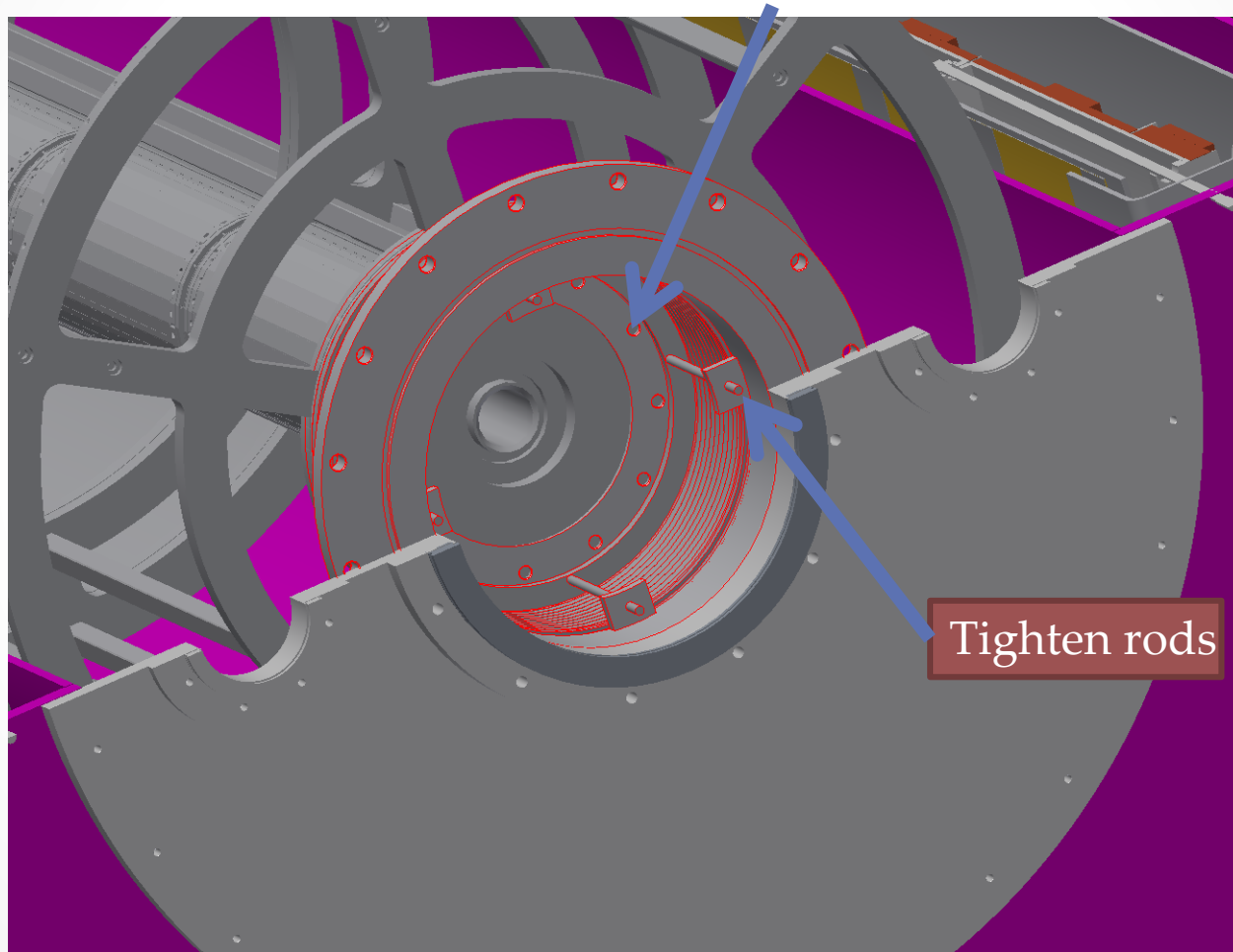
Before attaching the He lid inside attach cables to feedthroughs on the DN100's

# Mount helium lid with attached nose

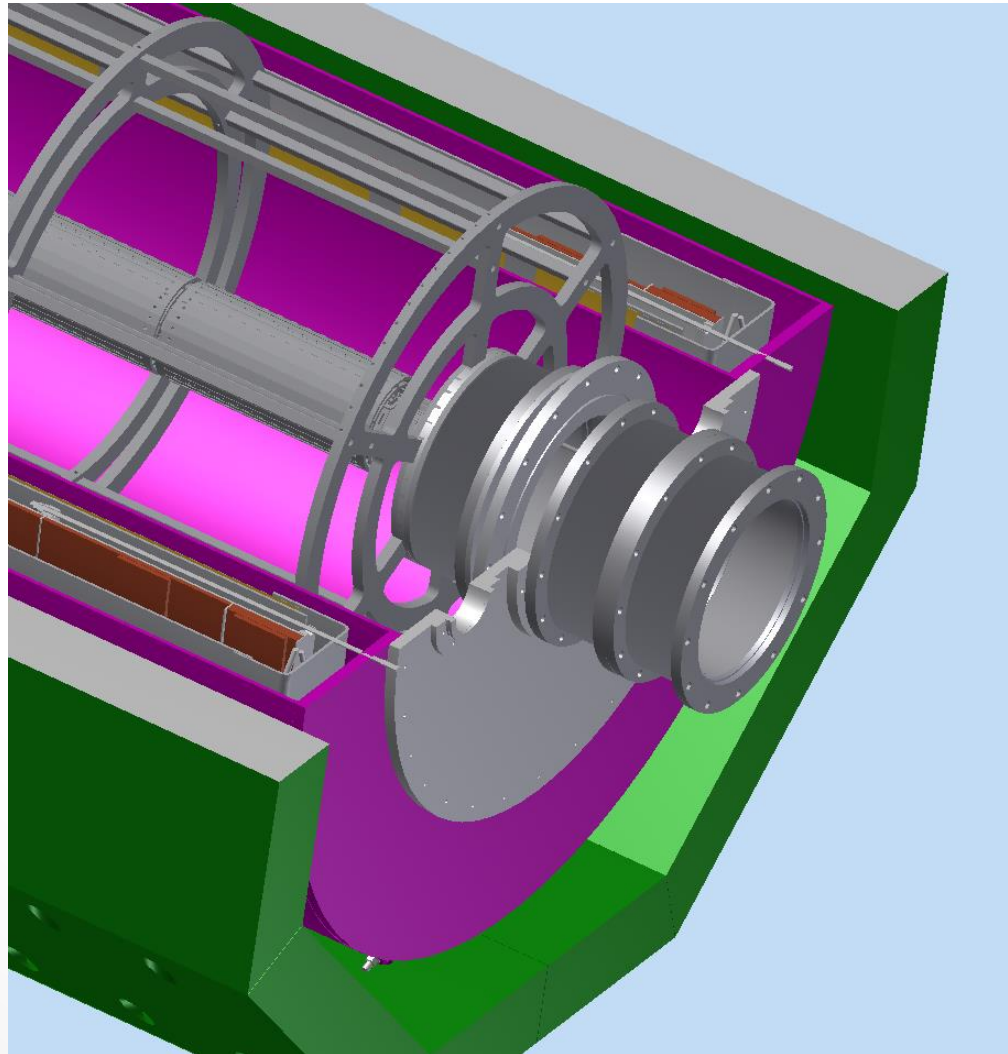


O-ring between nose and end wheel.  
The O-ring lies in a groove either in the nose or the end wheel.

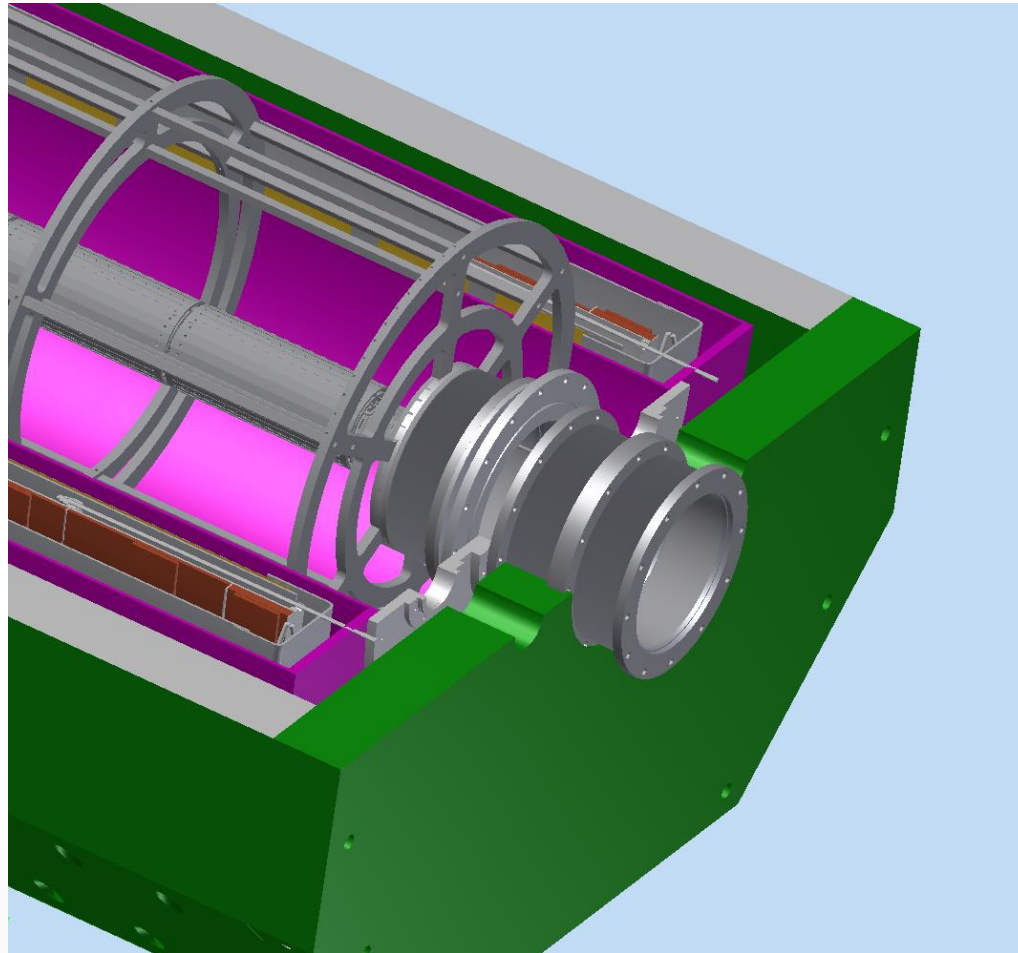
# Tighten screws (nose to blind holes in end wheel)



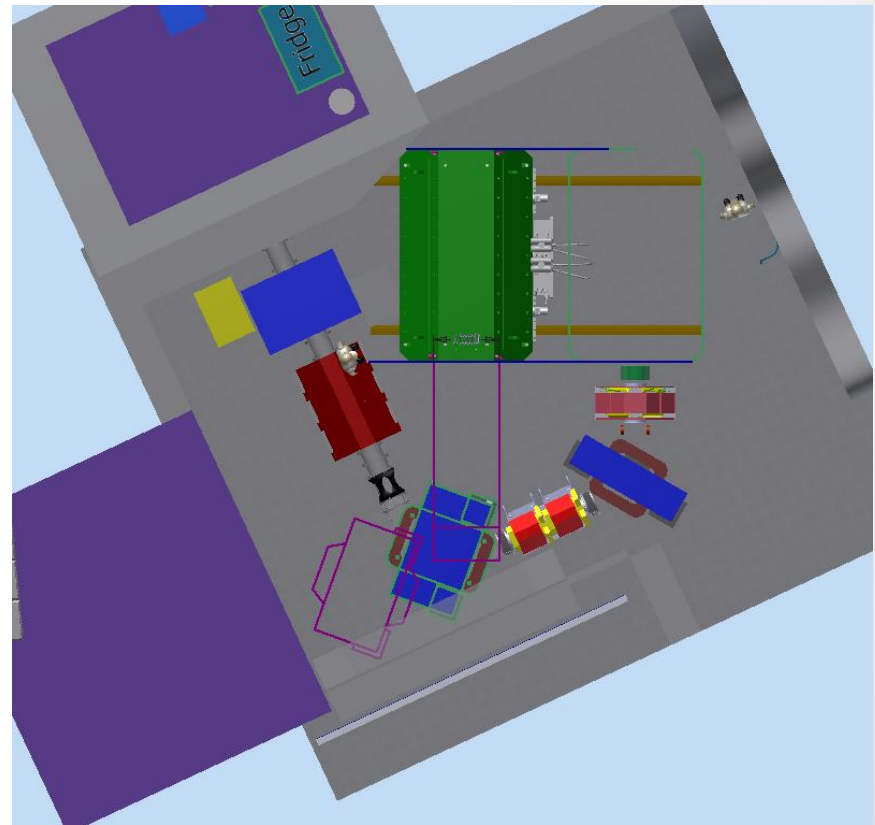
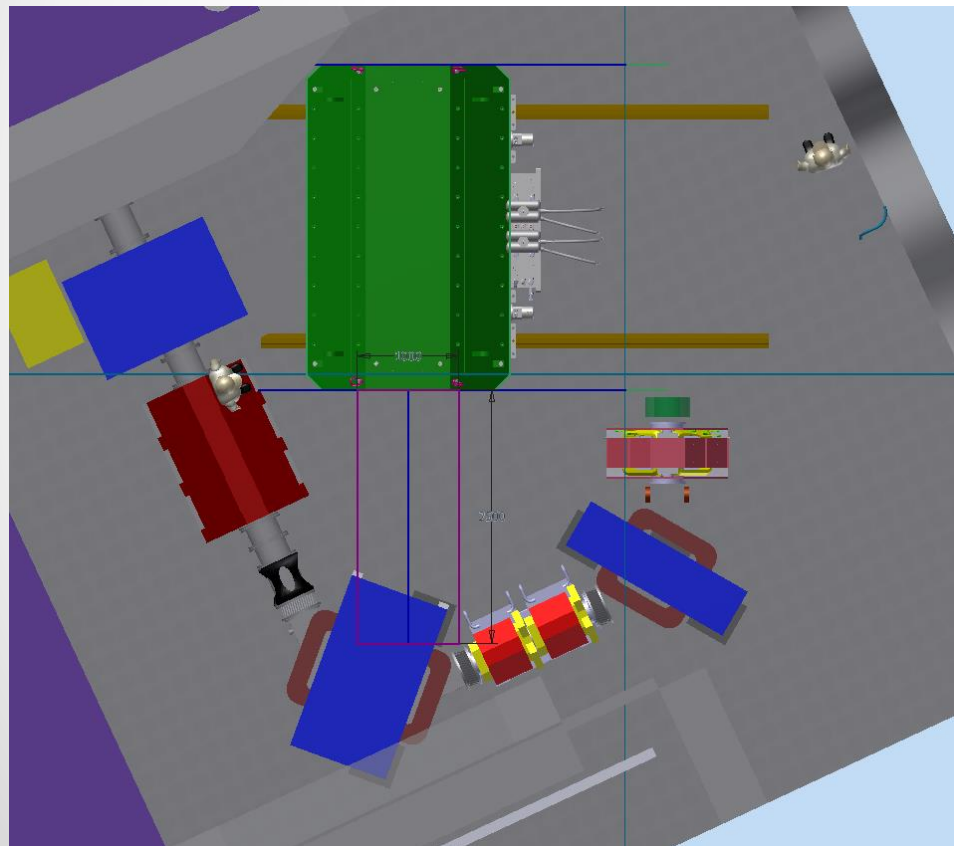
# Mount connection to outside (tube/bellow)



# Mount iron shielding

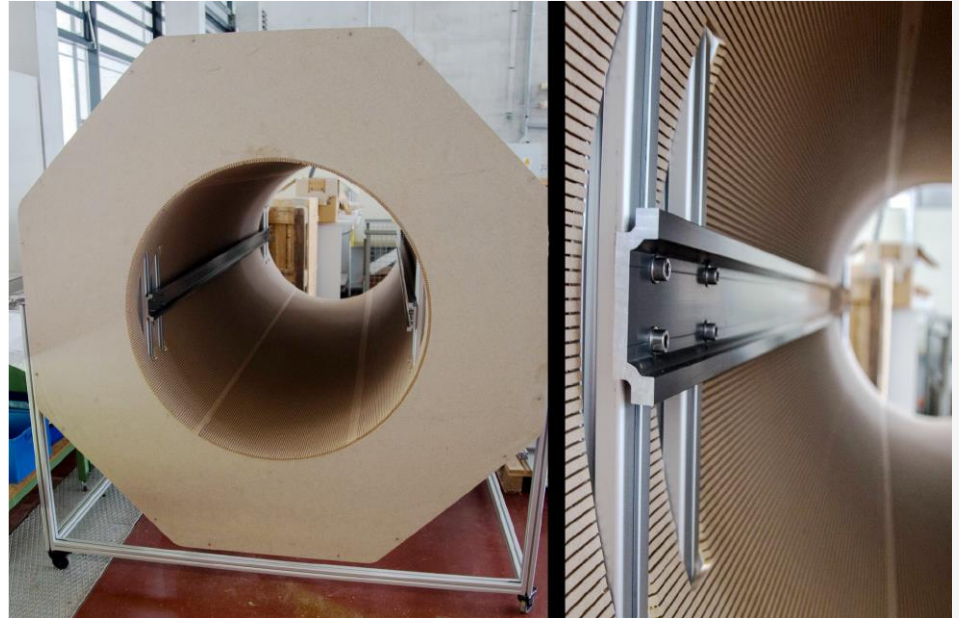


# Move ASL → access one side w/o craning



# Cage and rails in Magnet

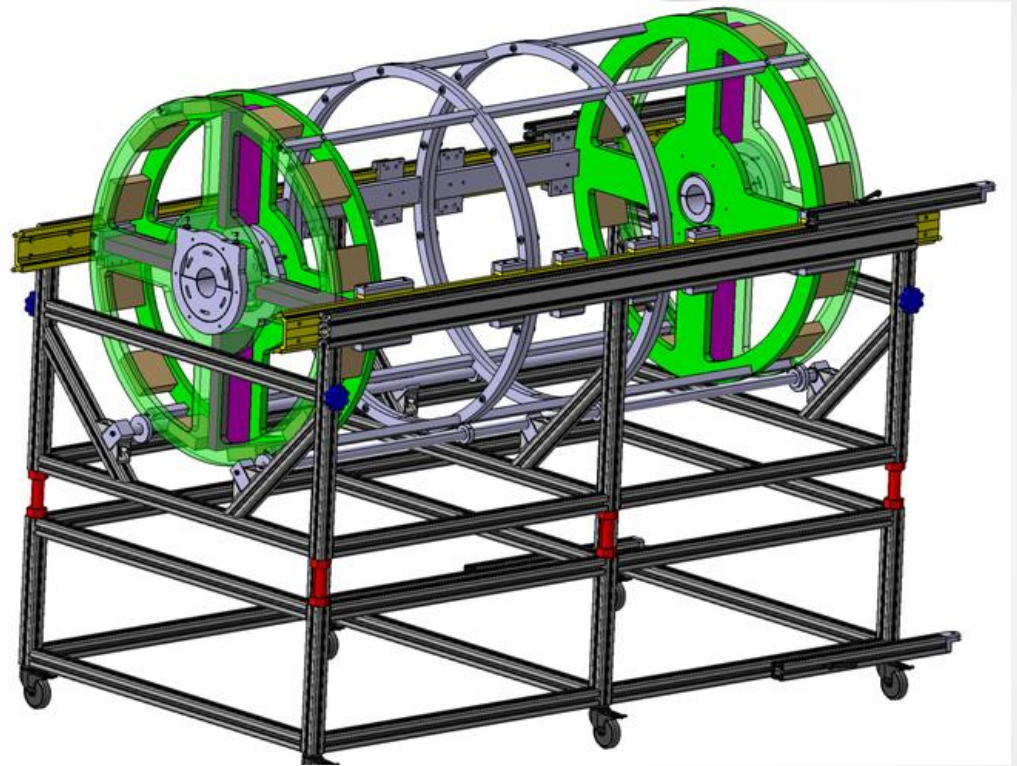
- ✓ Full-size mockup
  - ✓ Magnet
  - ✓ Rail system
  - ✓ Cage
  - ✓ Cart
    - Rotatable



Mockup of **magnet** and rail system

# Cage and rails in Magnet

- ✓ Full-size mockup
  - ✓ Magnet
  - ✓ Rail system
  - ✓ Cage
  - ✓ Cart
    - Rotatable

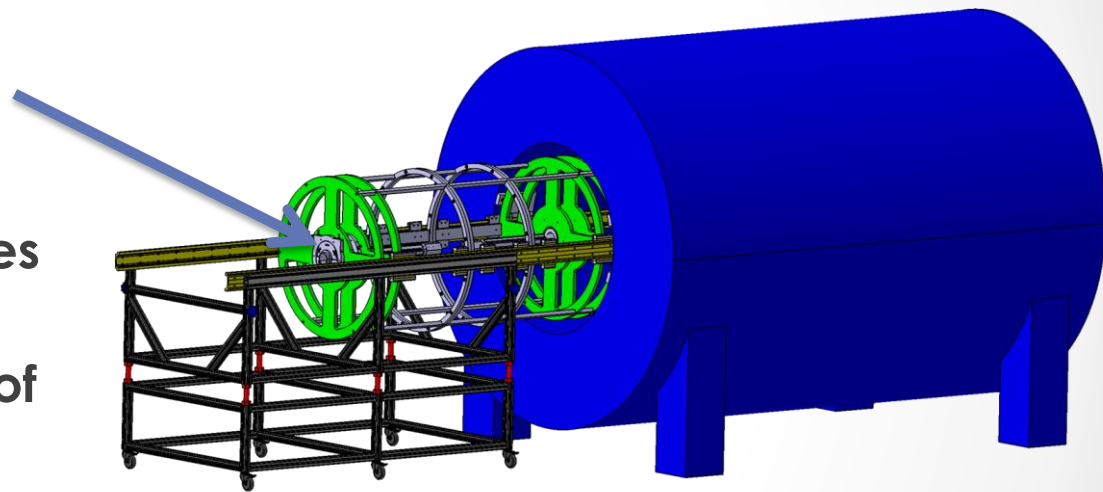


Rotatable detector cart



# Mu3e detector support

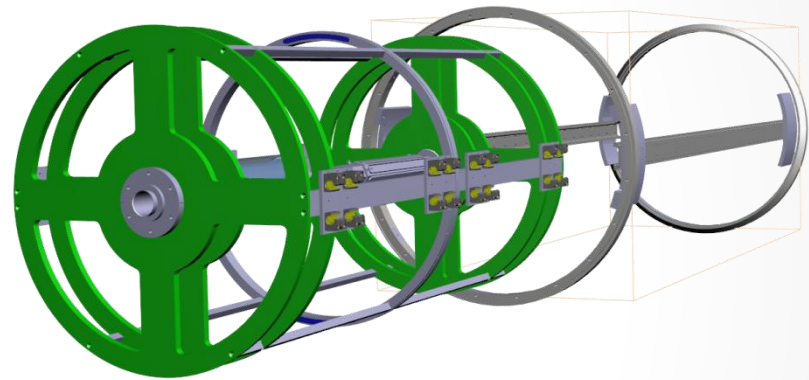
- Detector mounted in cage
  - Cage supports beam pipes
    - **Mechanical reinforcement studies ongoing**
    - **Simulation studies of beam pipe sag ongoing**
  - Cage is inserted on rails
- Rail system inside magnet
  - Mounted only to the magnet far ends



(Old) CAD of phase I detector

# Mu3e rail system

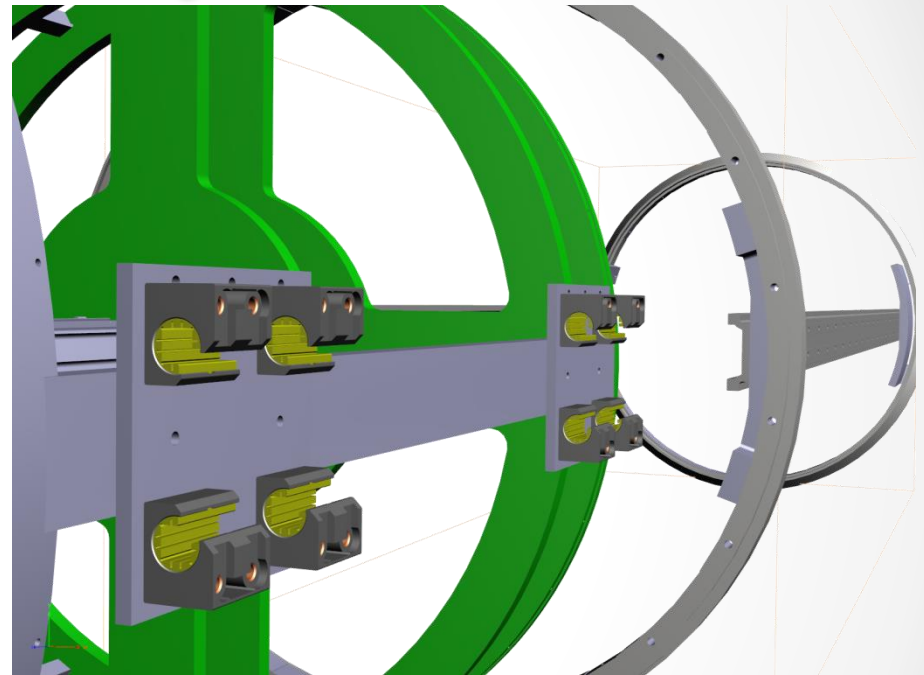
- Detector mounted in cage
  - Cage supports beam pipes
  - Cage is inserted on rails
- Rail system inside magnet
  - Mounted only to the magnet far ends
  - ...to avoid influence of thermal expansion etc.



(Old) CAD of rails inside magnet

# Mu3e rail system

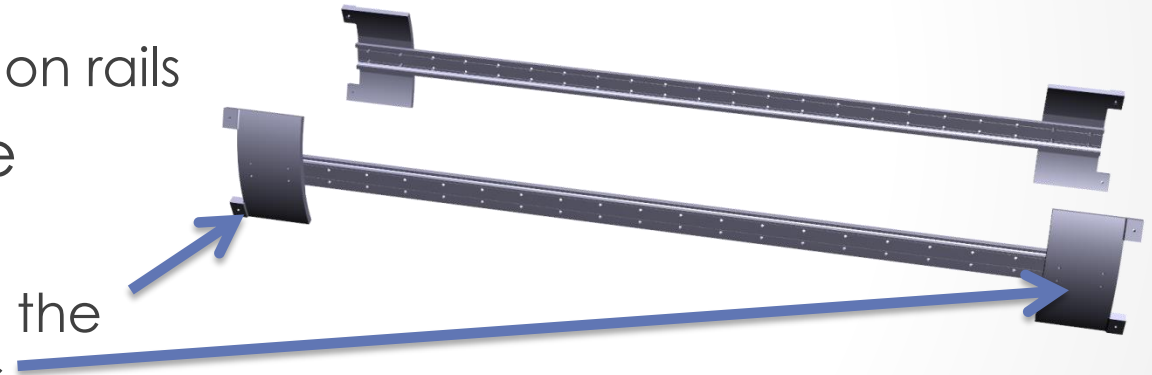
- Detector mounted in cage
  - Cage supports beam pipes
  - Cage is inserted on rails
- Rail system inside magnet
  - Mounted only to the magnet far ends
  - ...to avoid influence of thermal expansion etc.



(Old) CAD of rails inside magnet

# Mu3e rail system

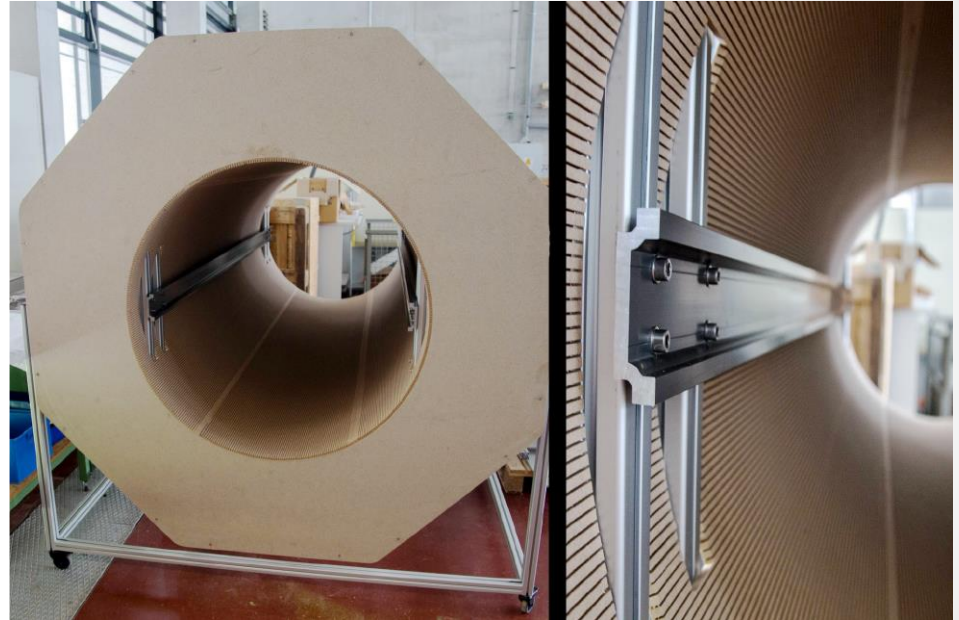
- Detector mounted in cage
  - Cage supports beam pipes
  - Cage is inserted on rails
- Rail system inside magnet
  - Mounted only to the magnet far ends
  - ...to avoid influence of thermal expansion etc.



(Old) CAD of rails inside magnet

# Mu3e rail system

- Detector mounted in cage
  - Cage supports beam pipes
  - Cage is inserted on rails
- Rail system inside magnet
  - Mounted only to the magnet far ends
  - ...to avoid influence of thermal expansion etc.



Mockup of **magnet** and rail system

# Summary

- Rail system
  - Healthy design
  - Prototype tested
- End plates
  - He enclosure
  - Beam pipe feedthrough
  - Signal and power feedthrough
- Magnet shield
  - Doors must respect feedthroughs

