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Federal Ministry of Education and Research

Belle II

The Belle II Experiment

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Outline

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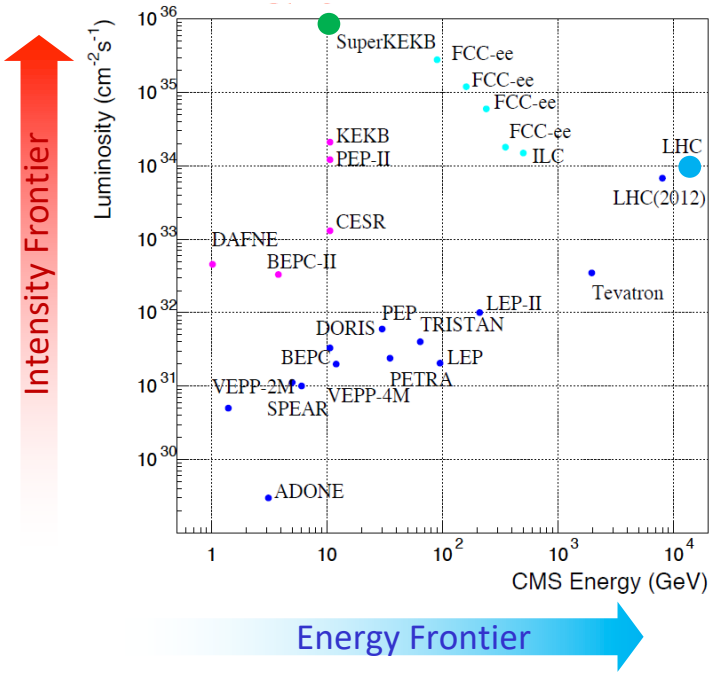
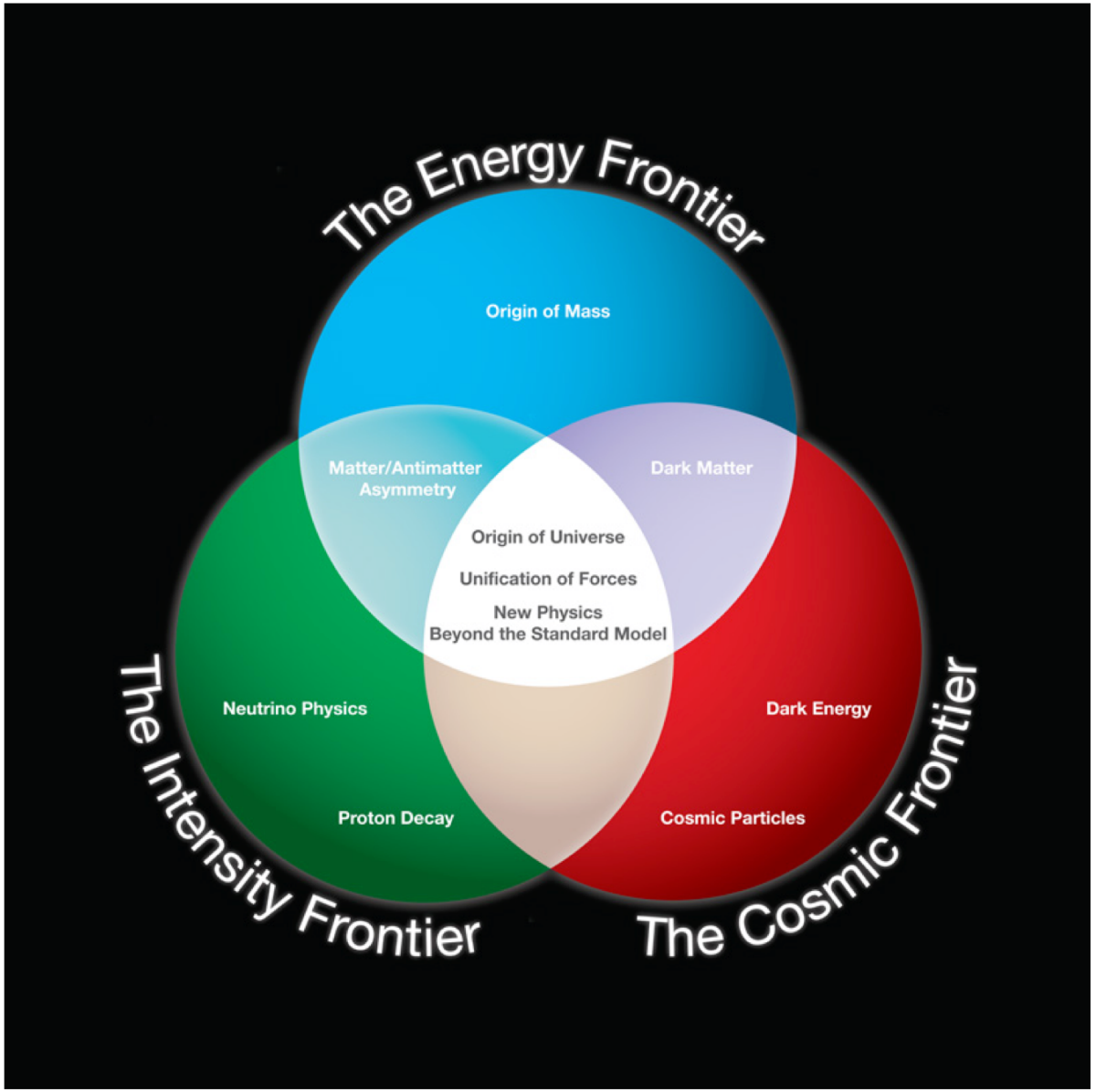
- Flavor Physics Program
- The SuperKEKB Accelerator 

- The Belle II Detector 

The Three Frontiers



- The **Intensity Frontier**: Search for rare new phenomena using *medium-energy high-luminosity* machines



The B Factories: A Success Story

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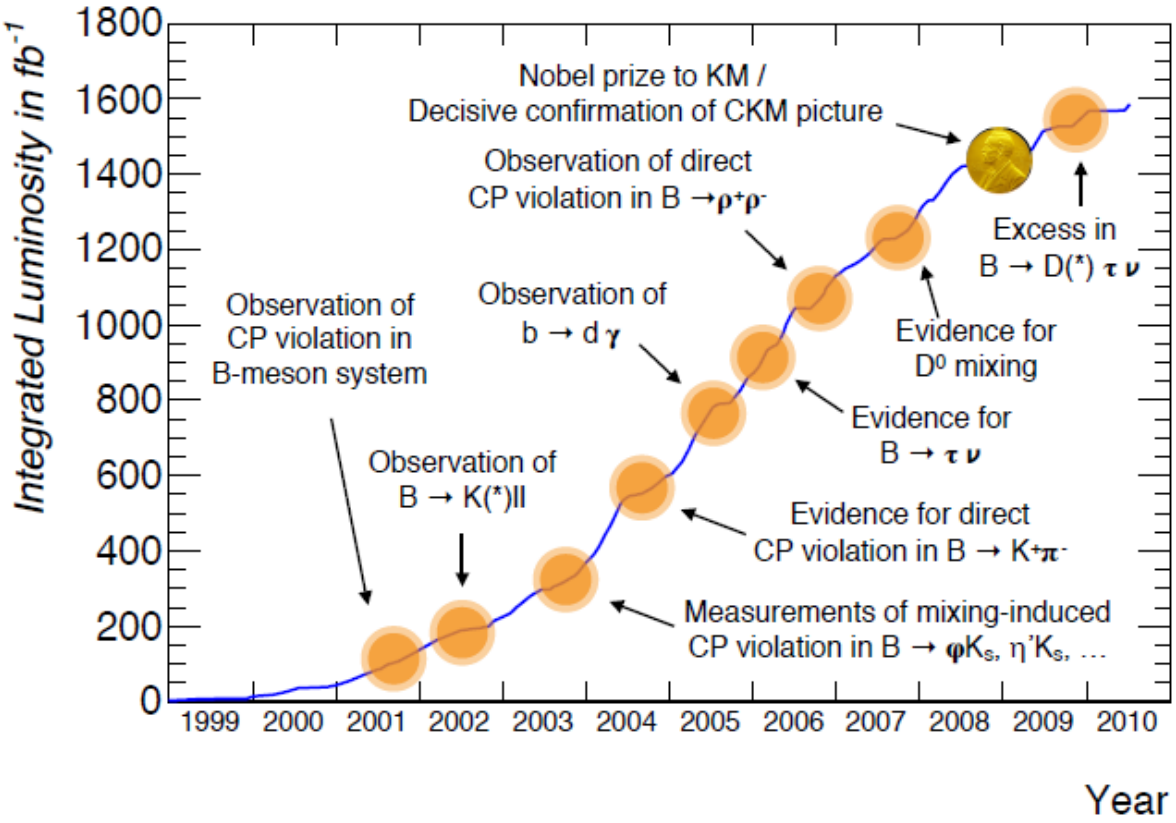
- The B factories Belle and BaBar ran from 1999 to 2010.
- They recorded over 1.5 ab^{-1} of data ($1.25 \cdot 10^9$ BB).
- Both experiments provided the experimental confirmation that led to the 2008 Nobel prize



Super Flavor Factory

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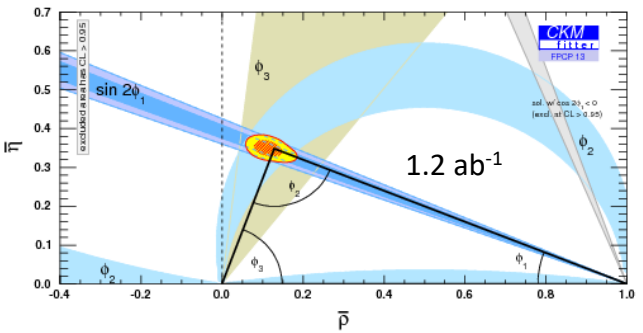
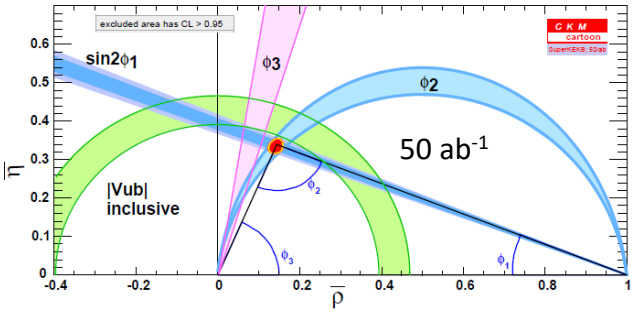
- Search for physics phenomena beyond SM in B, D and τ decays through precision measurements of the CKM sector and studies of rare or forbidden processes
- Many potential NP sources:
  - Flavor changing neutral currents
  - Lepton flavor violating decays
  - B → τ tree level new physics
  - New sources of CPV

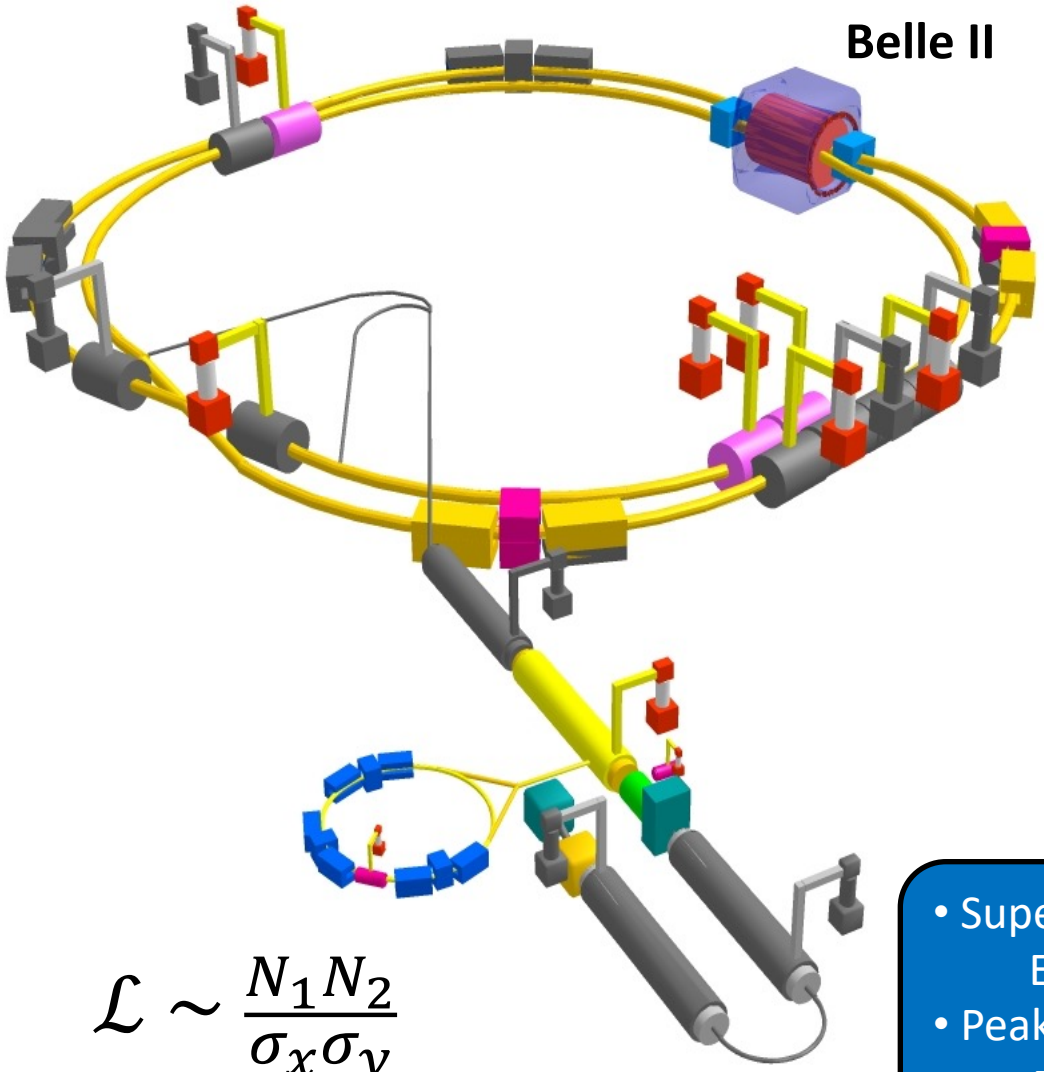
Observable	SM theory	Current measurement (early 2013)	Belle II * ($50\,\text{ab}^{-1}$)
$S(B \to \phi K^0)$	0.68	0.56 ± 0.17	± 0.018
$S(B \to \eta' K^0)$	0.68	0.59 ± 0.07	± 0.011
α from $B \to \pi\pi$, $\rho\rho$		$\pm 5.4°$	$\pm 1°$
γ from $B \to DK$		$\pm 11°$	$\pm 1.5°$
$S(B \to K_S \pi^0 \gamma)$	< 0.05	-0.15 ± 0.20	± 0.035
$S(B \to \rho\gamma)$	< 0.05	-0.83 ± 0.65	± 0.07
$A_{CP}(B \to X_{s+d}\gamma)$	< 0.005	0.06 ± 0.06	± 0.005
A_{SL}^d	-5×10^{-4}	-0.0049 ± 0.0038	± 0.001
$\mathcal{B}(B \to \tau\nu)$	1.1×10^{-4}	$(1.64 \pm 0.34) \times 10^{-4}$	$\pm 3\%$
$\mathcal{B}(B \to \mu\nu)$	4.7×10^{-7}	$< 1.0 \times 10^{-6}$	$\gg 5\sigma$
$\mathcal{B}(B \to X_s\gamma)$	3.15×10^{-4}	$(3.55 \pm 0.26) \times 10^{-4}$	$\pm 6\%$
$\mathcal{B}(B \to K^{(*)}\nu\overline{\nu})$	3.6×10^{-6}	$< 1.3 \times 10^{-5}$	$\pm 30\%$
$\mathcal{B}(B \to X_s\ell^+\ell^-)$ $(1 < q^2 < 6\,\text{GeV}^2)$	1.6×10^{-6}	$(4.5 \pm 1.0) \times 10^{-6}$	$\pm 0.10 \times 10^{-6}$
$A_{FB}(B^0 \to K^{*0}\ell^+\ell^-)$ zero crossing	7%	18%	5%
$\lvert V_{ub}\rvert$ from $B \to \pi\ell^+\nu$ $(q^2 > 16\,\text{GeV}^2)$	$9\% \to 2\%$	11%	2.1%



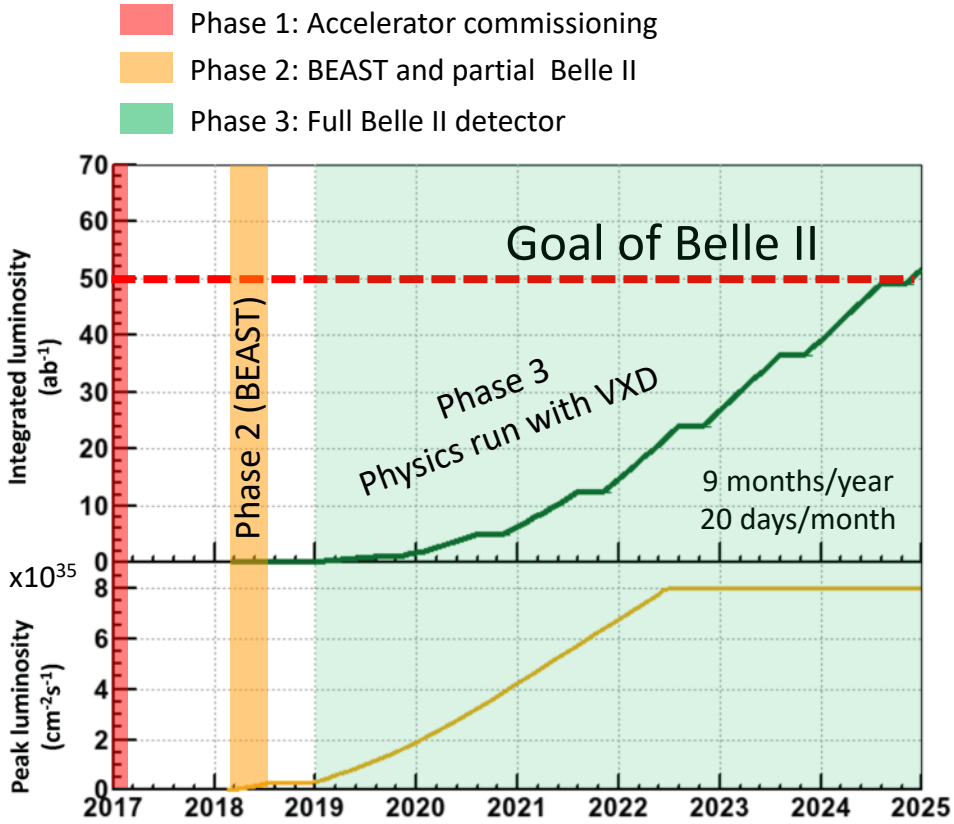


1. High luminosity accelerator (SuperKEKB)
2. High-resolution detector (Belle II)

The SuperKEKB Accelerator

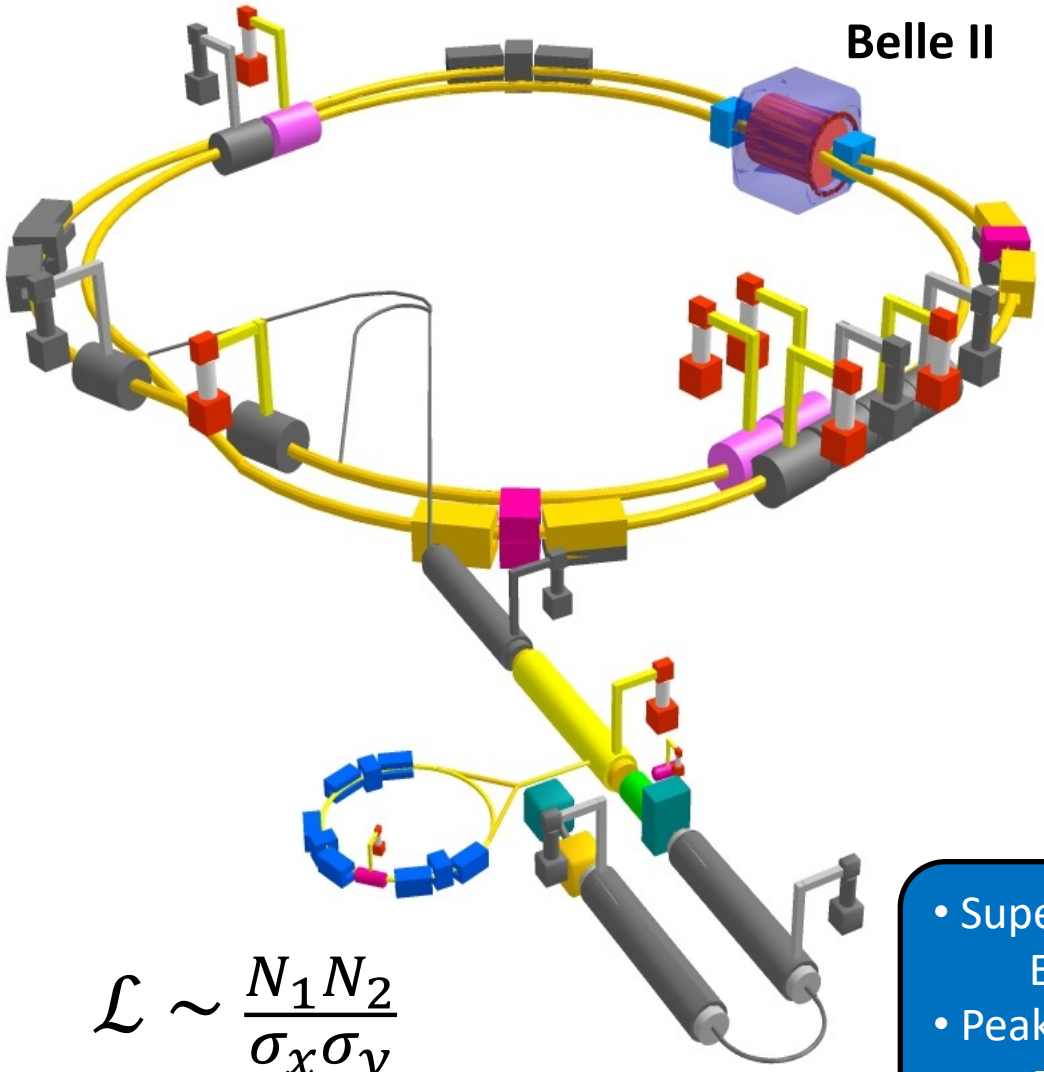


$$\mathcal{L} \sim \frac{N_1 N_2}{\sigma_x \sigma_y}$$



- SuperKEKB: Asymmetric energy e^+e^- collider
  E_{cm} = m(ϒ(4S)) = 10.58 GeV
- Peak luminosity: $\mathcal{L}$ = $8 \cdot 10^{35}$ cm^{-2} s^{-1} (x40 than KEKB)
  Beam size reduction. Higher current (x2 higher).

The SuperKEKB Accelerator



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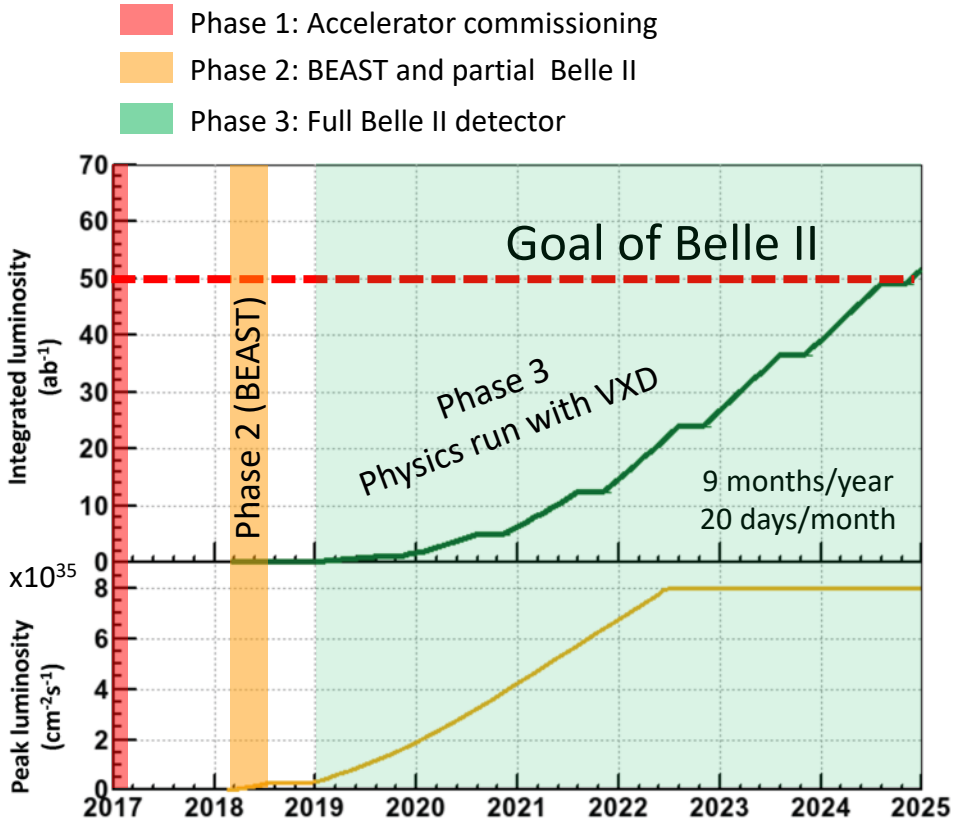

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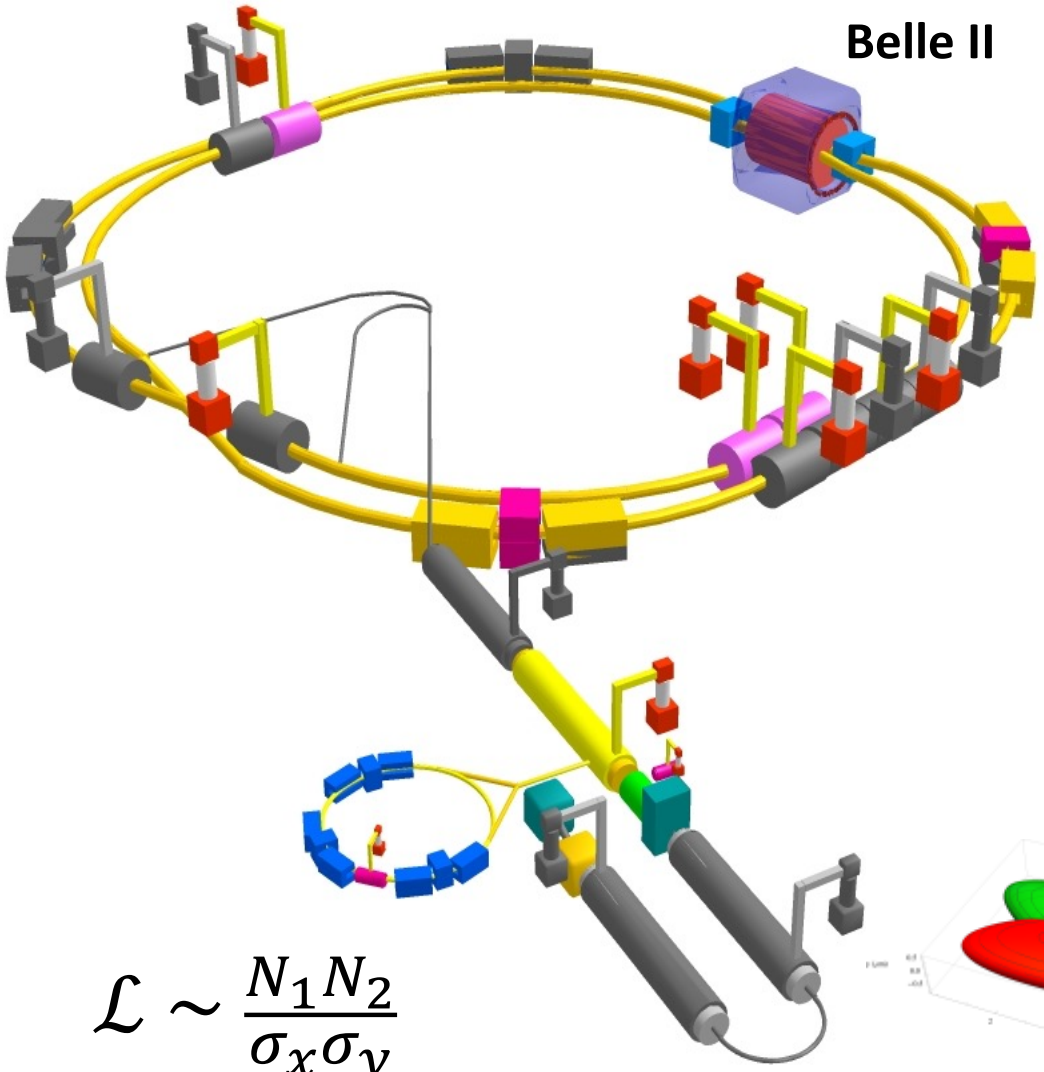

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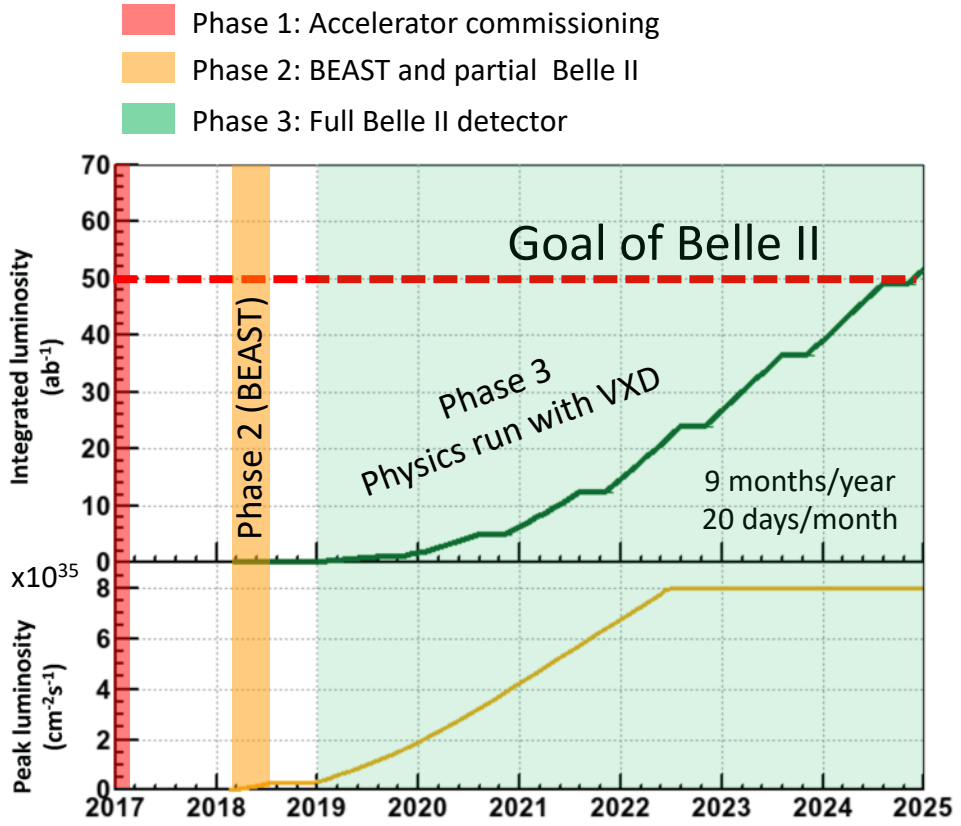
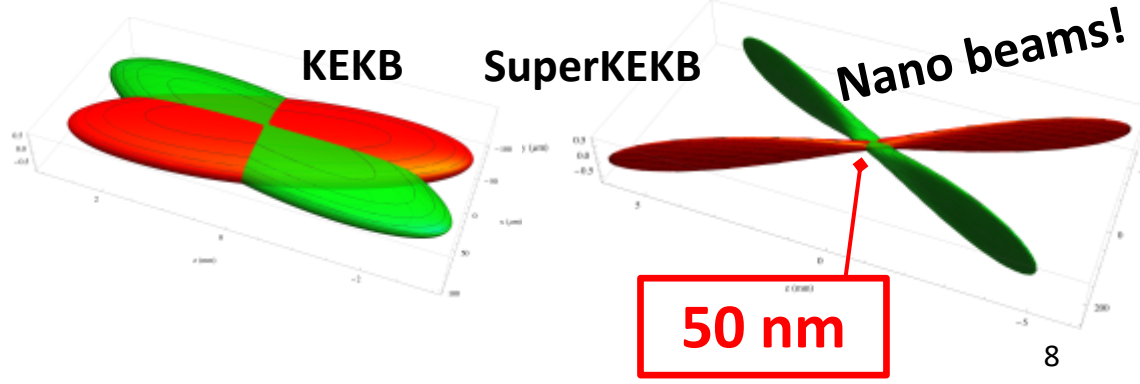
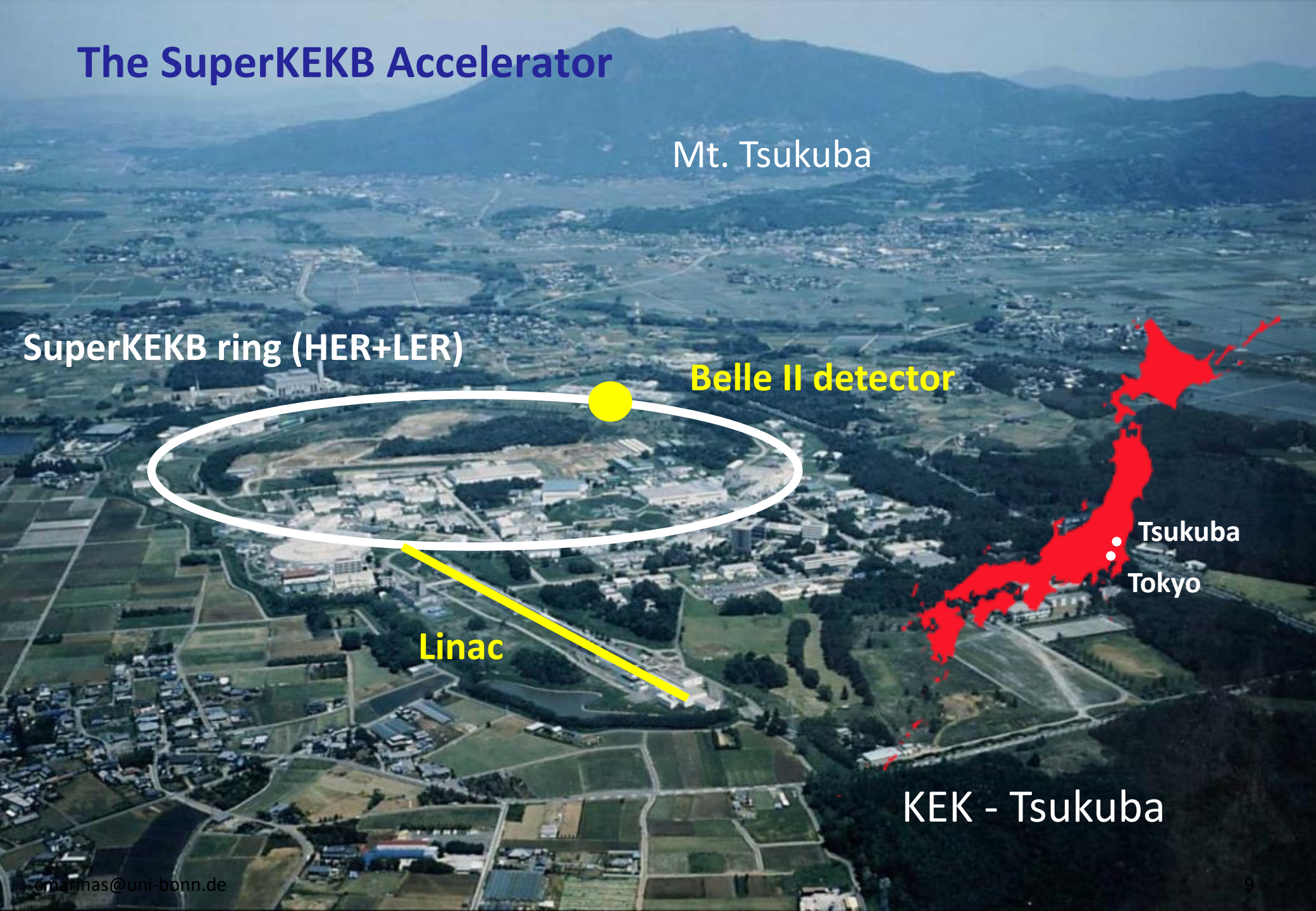


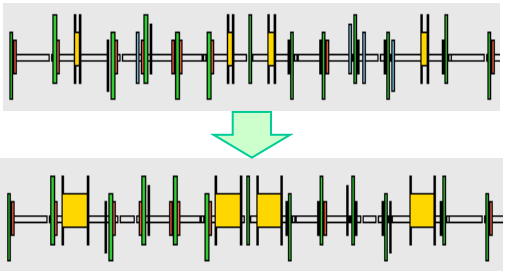


The SuperKEKB Accelerator



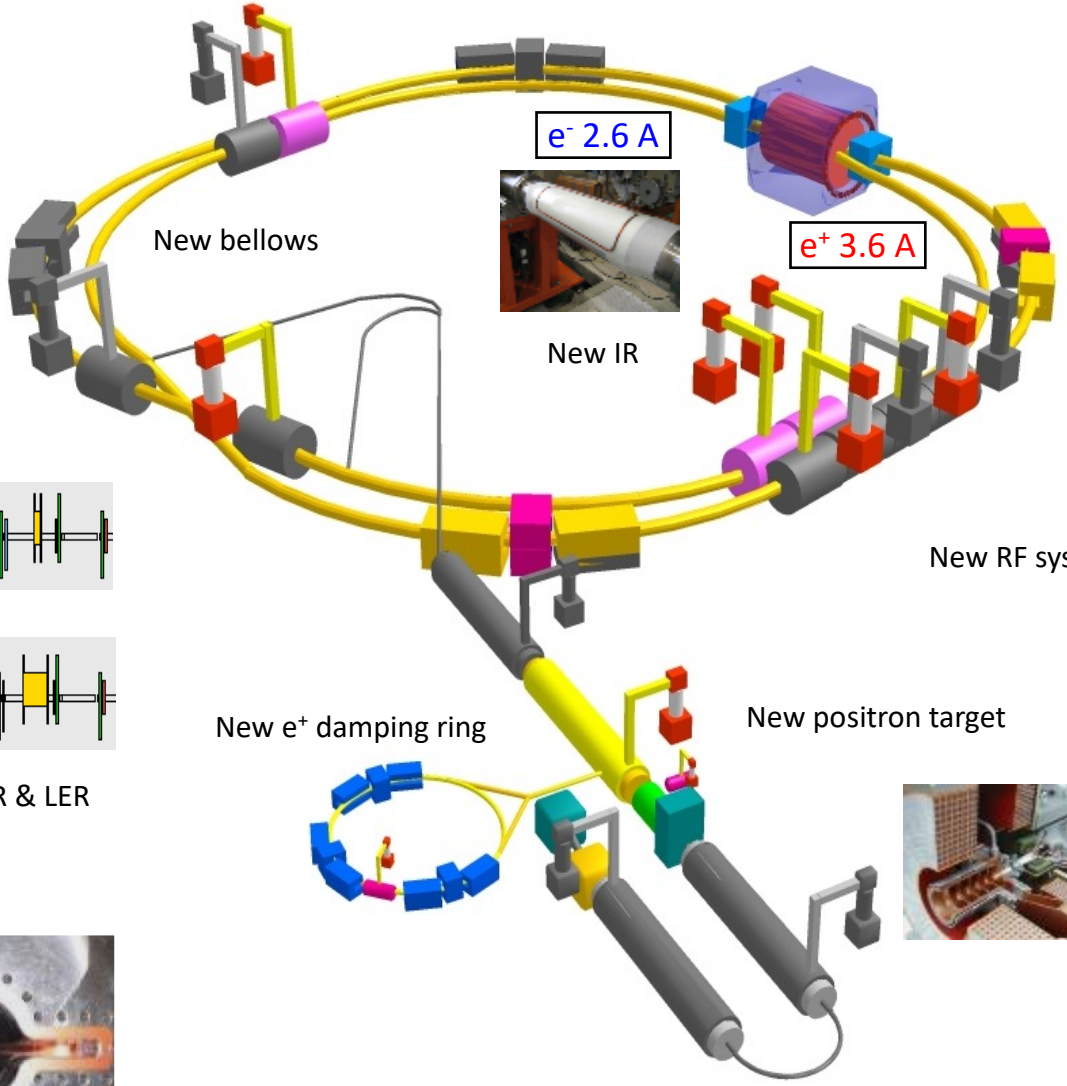
Going For a Super B-Factory: SuperKEKB

Replace short dipoles with longer ones (LER)



Redesign the lattices of HER & LER to squeeze the emittance

TiN-coated beam pipe with antechambers



New final focusing quads near the IP

Complete refurbishment to achieve x40 higher luminosity compared to KEKB

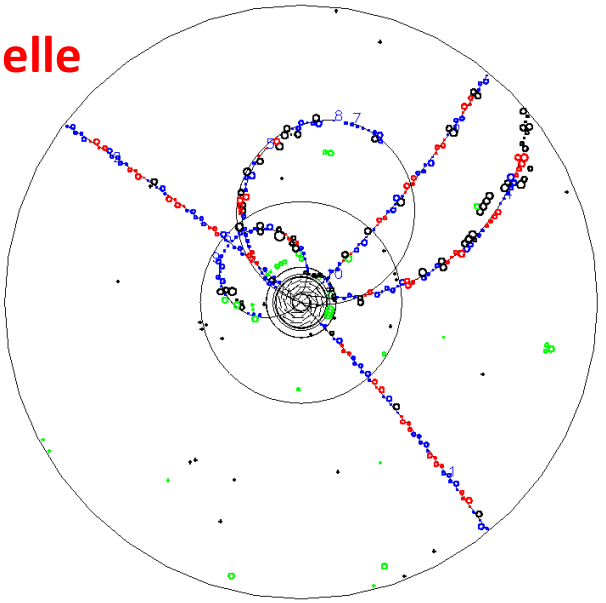
The Belle II Detector

40 times higher luminosity implies

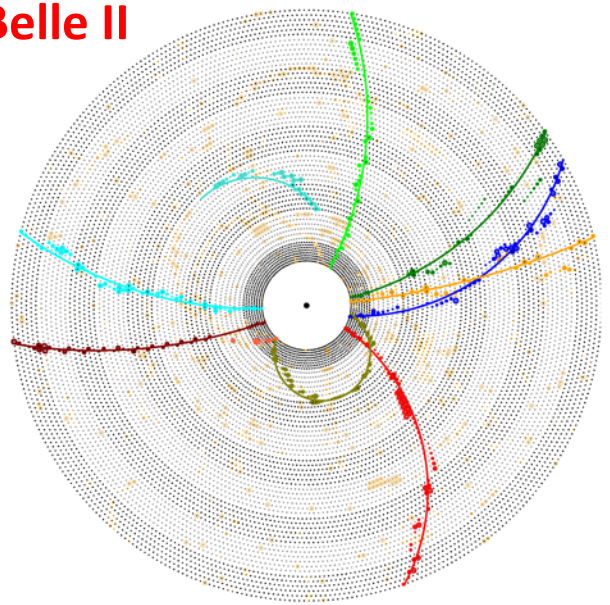
- **Higher event rate**
  - Higher trigger rate
  - Increased DAQ and computing requirements
- **Higher background**
  - Radiation damage
  - Occupancy
  - Fake hits and pile-up
- Changes in detector
  - $\beta\gamma$ reduced by factor 1.5
  - Improved vertexing needed
- Results in significant upgrade

→ Belle II

Belle



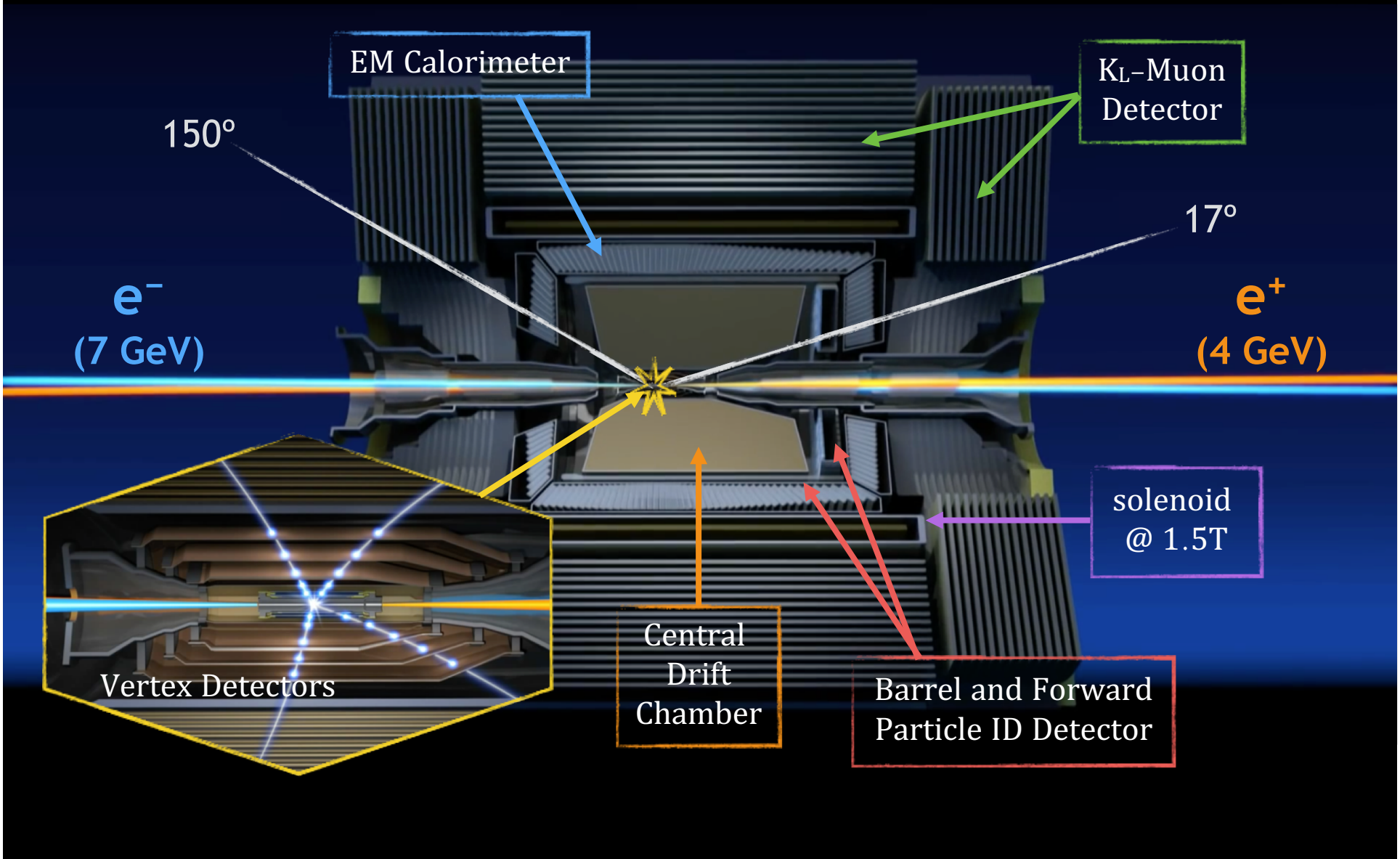
Belle II



The Belle II Collaboration

101 Institutes
750 Researchers
23 Countries
→ Germany is second largest only after Japan

The Belle II Detector



Typical Event

e^+e^- E_{cm} = 10.58 GeV

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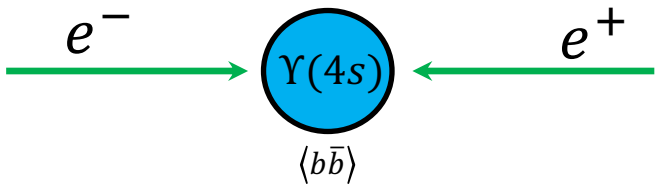
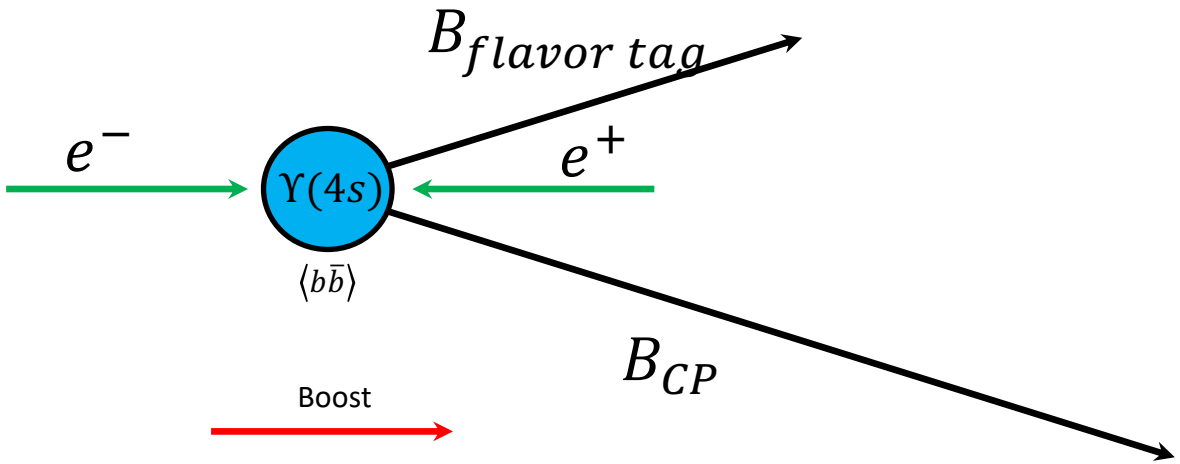
$e^+e^- \rightarrow \Upsilon(4s)$ $\quad\quad$ E_{cm} = 10.58 GeV



Typical Event

$e^+e^- \rightarrow \Upsilon(4s) \rightarrow B\bar{B}$ $\quad$ E_{cm} = 10.58 GeV



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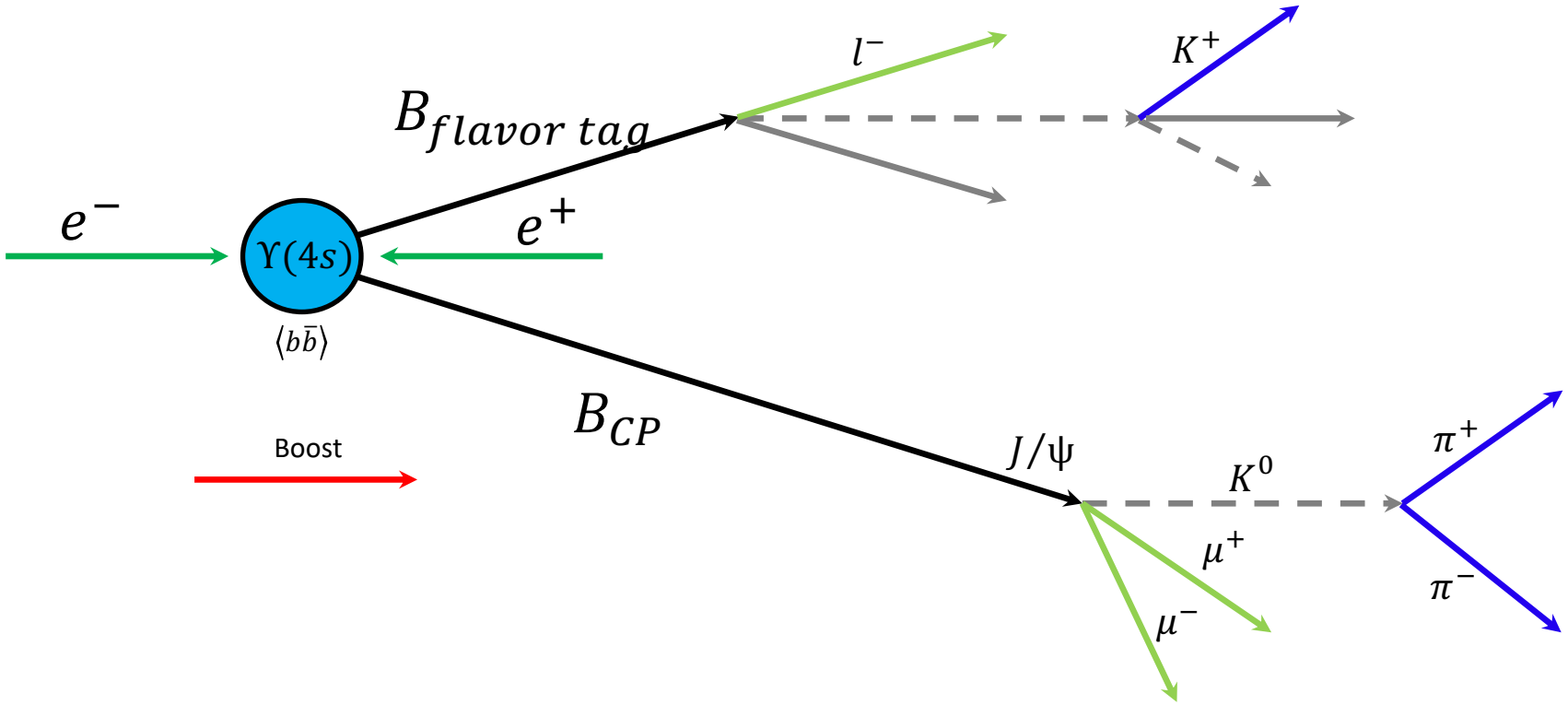
$e^+e^- \rightarrow \Upsilon(4s) \rightarrow B\bar{B}$ $\quad$ E_{cm} = 10.58 GeV



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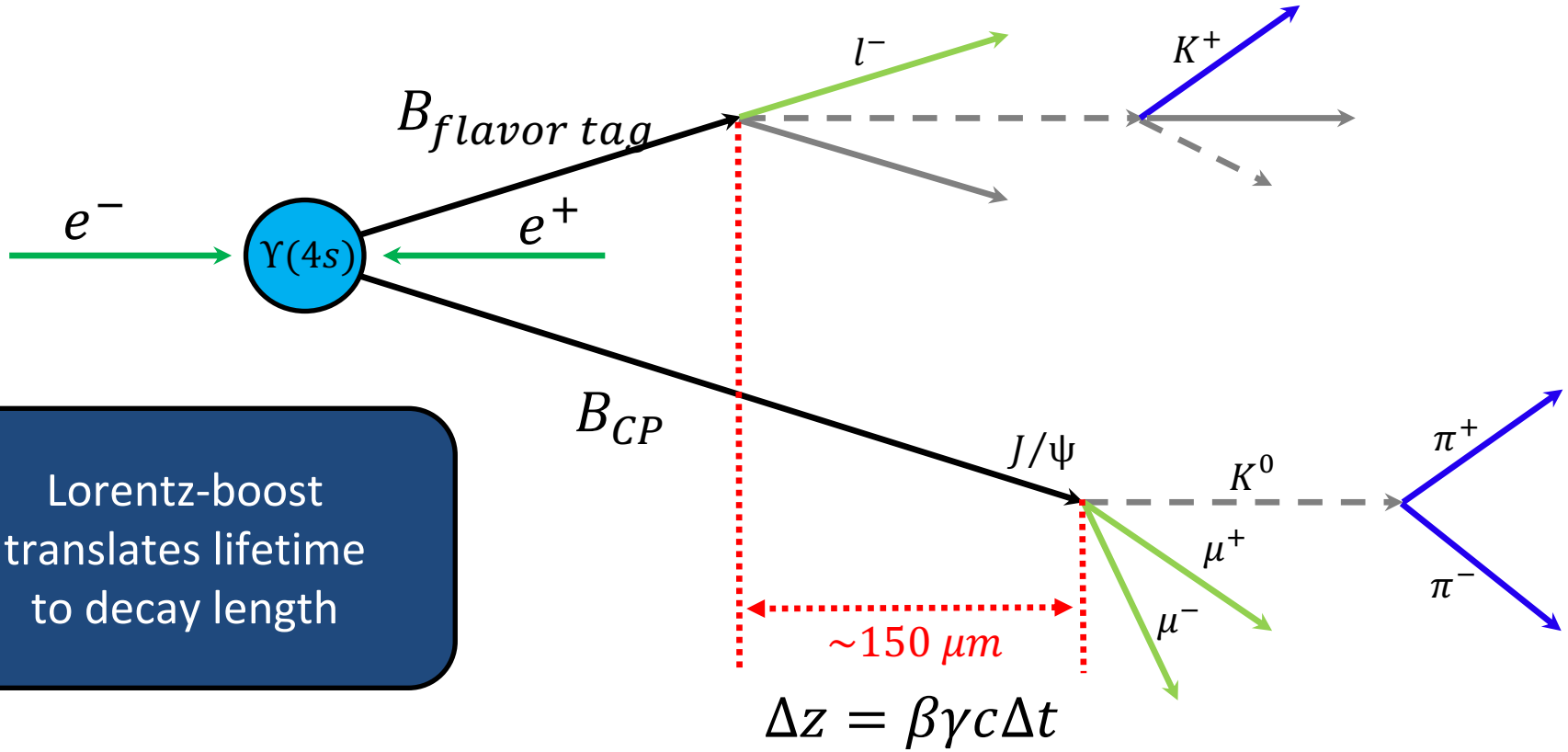
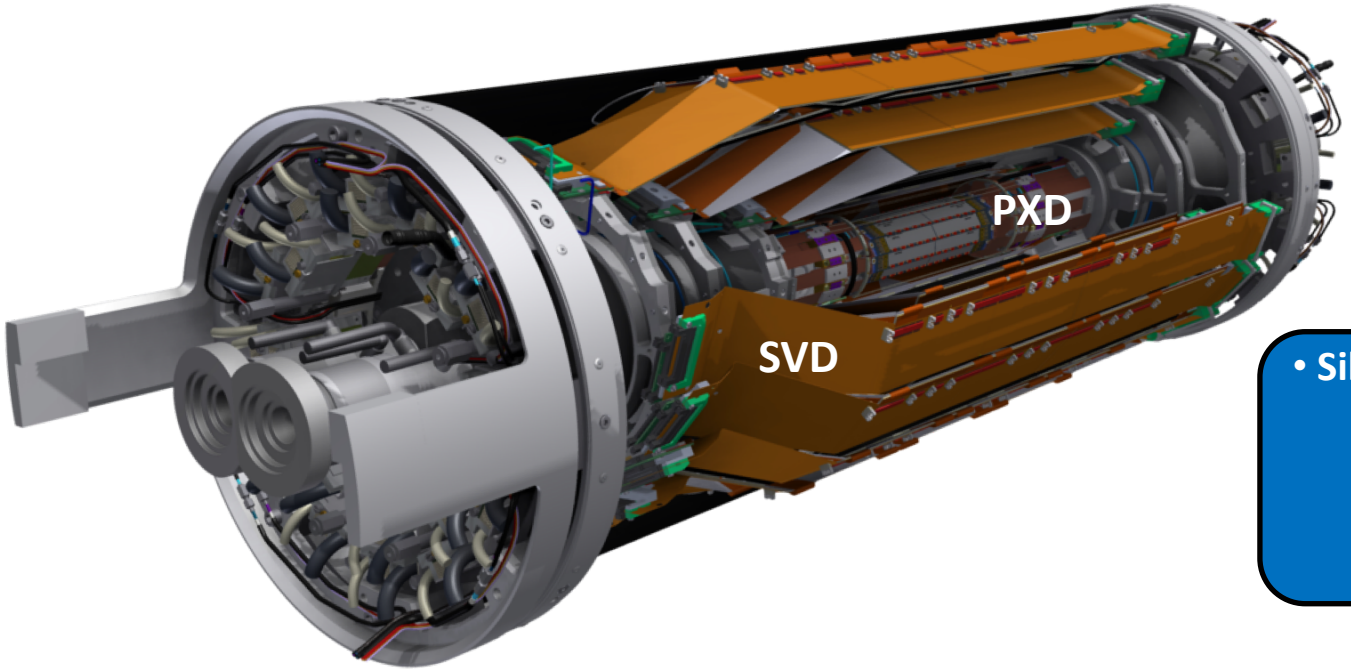


Lorentz-boost translates lifetime to decay length

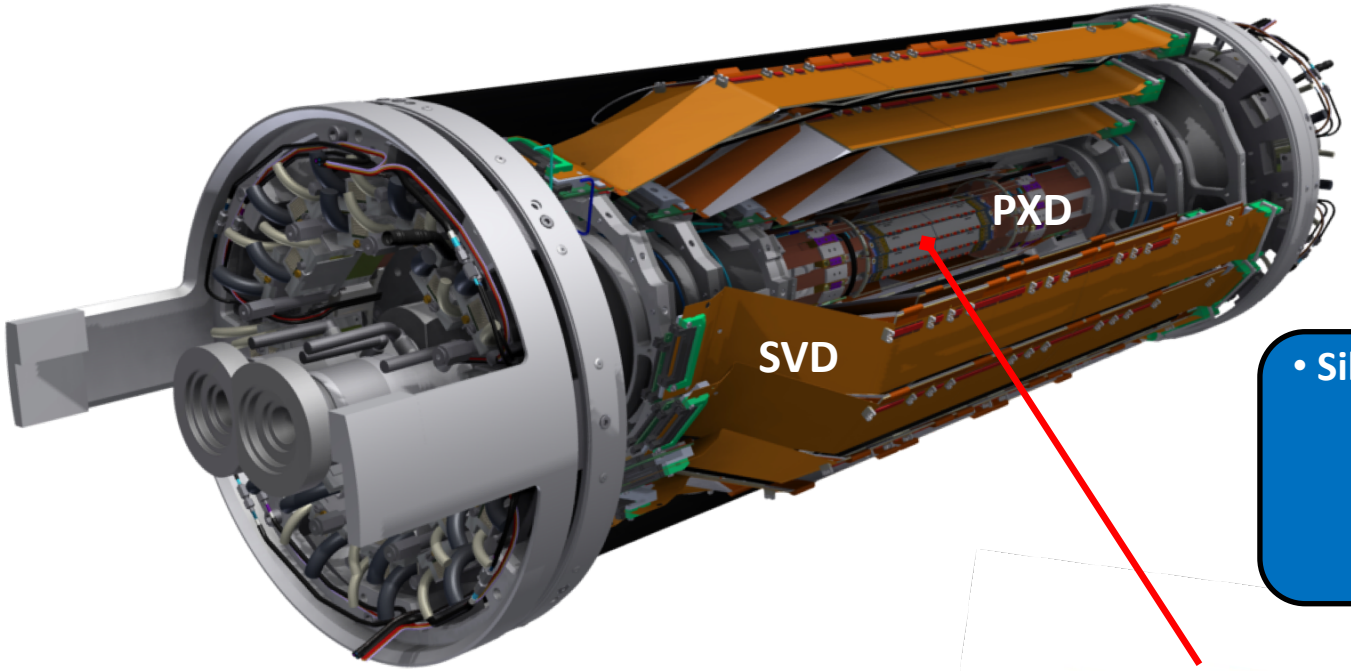
Precise vertexing → High resolution and light inner detector

Vertex Detector: PXD and SVD



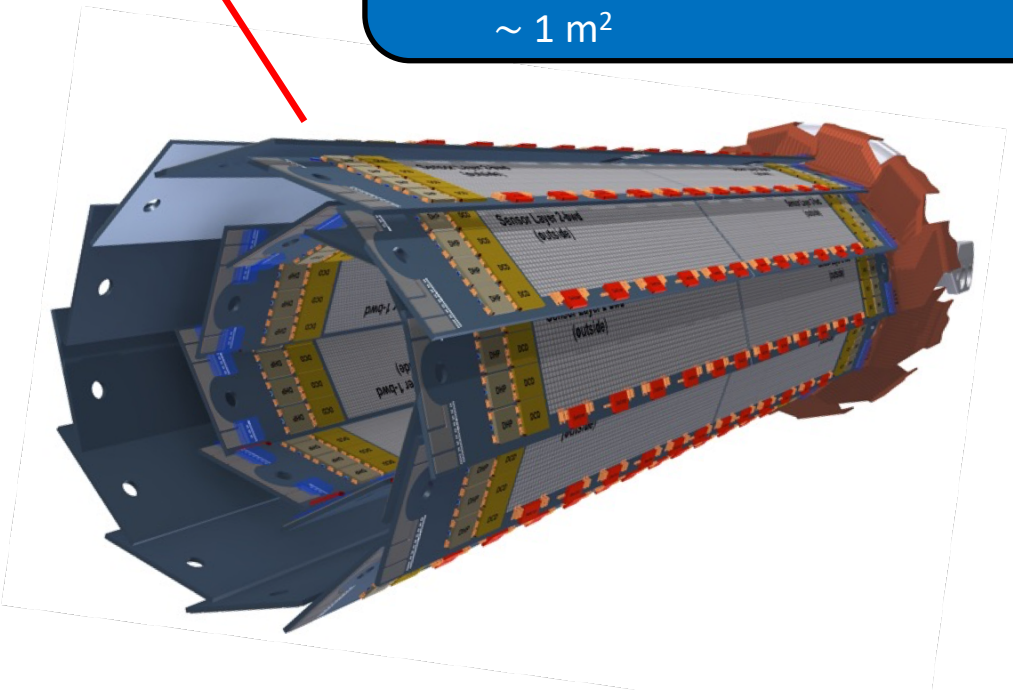
- **Silicon Vertex Detector (SVD)**
  - 4 layers of DSSD
  - r = 3.8 cm, 8.0 cm, 11.5 cm, 14 cm
  - L = 60 cm
  - ~ 1 m^2

Vertex Detector: PXD and SVD



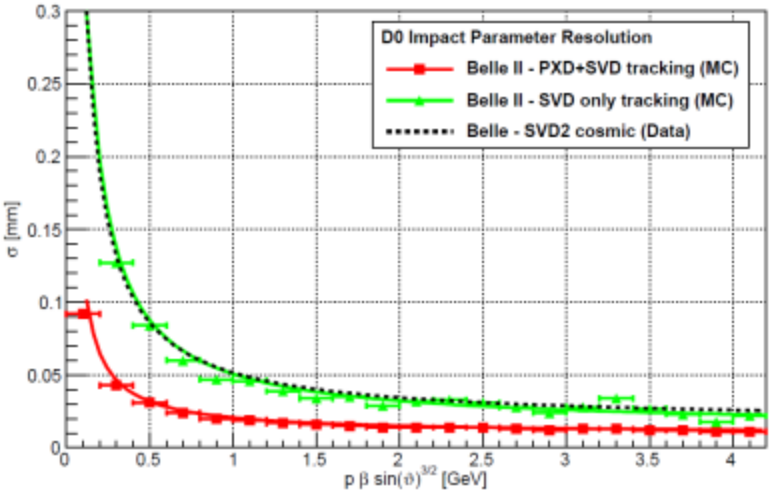
- **Silicon Vertex Detector (SVD)**
  - 4 layers of DSSD
  - r = 3.8 cm, 8.0 cm, 11.5 cm, 14 cm
  - L = 60 cm
  - ~ 1 m^2

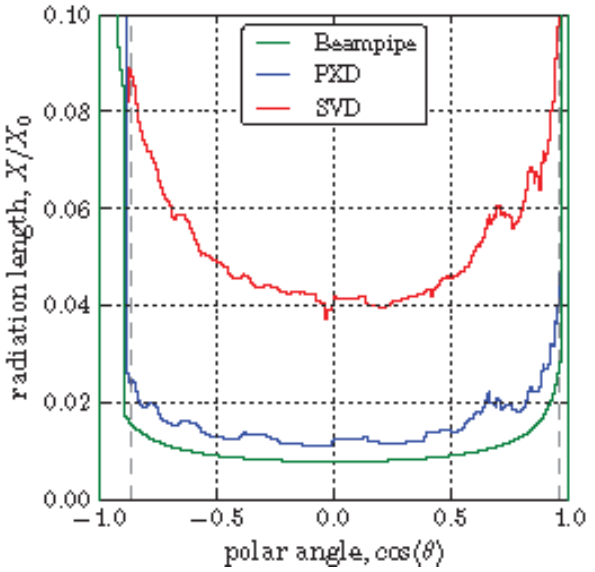
- **Pixel Detector (PXD)**
  - 2 layers of DEPFET pixels
  - r = 1.4 cm, 2.2 cm
  - L = 12 cm
  - ~ 0.027 m^2



Belle II VXD Requirements and Parameters

	Belle II PXD
Occupancy	0.4 hits/μm²/s (3% max)
Radiation	2 Mrad/year
	$2 \cdot 10^{12}$ 1 MeV n_{eq} per year
Integration time	20 μs
Momentum range	Low p (50 MeV - 3 GeV)
Acceptance	17°-155°
Material budget	0.21% X_0 per layer
Resolution	15 μm (50x75 μm²)





- Impact parameter resolution (15 μm), dominated by multiple scattering mainly in BP → Pixel size (50 x 75 μm²)
- Lowest possible material budget (0.21% X_0/layer)
  - Ultra-transparent detectors
  - Lightweight mechanics and minimal services in physics acceptance

The DEPFET Ladder

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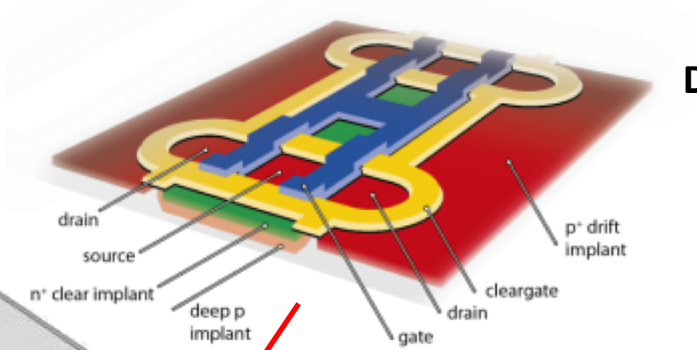
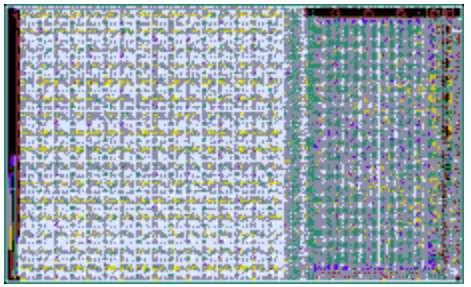
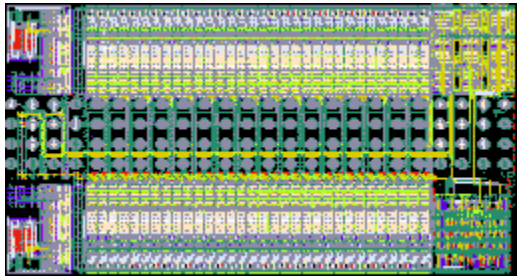


DCDB (Drain Current Digitizer)
Analog frontend



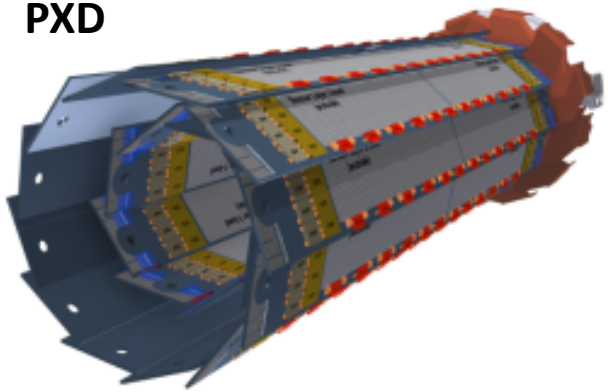
UMC 180 nm
Size 5.0 × 3.2 mm^2
TIA and 8-bit ADC
92 ns sampling time
Pedestal compensation

SwitcherB
Row control

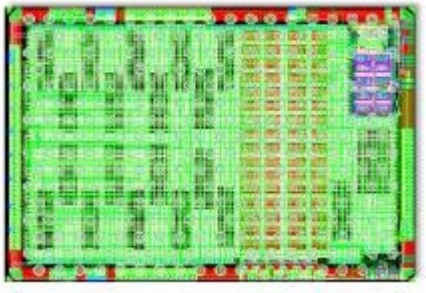


AMS/IBM HVCMOS 180 nm
Size 3.6 × 1.5 mm^2
Gate and Clear signal
Fast HV ramp for Clear

PXD



DHP (Data Handling Processor)
First data compression



TSMC 65 nm
Size 4.0 × 3.2 mm^2
Stores raw data and pedestals
Common mode and pedestal correction
Data reduction (zero suppression)
Timing and trigger control

Belle II PXD Ladder

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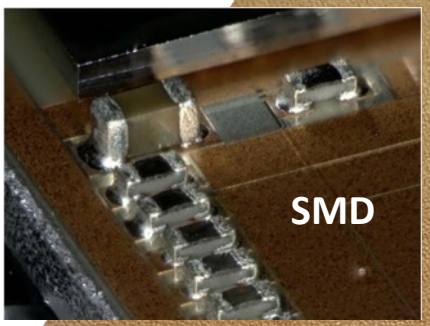
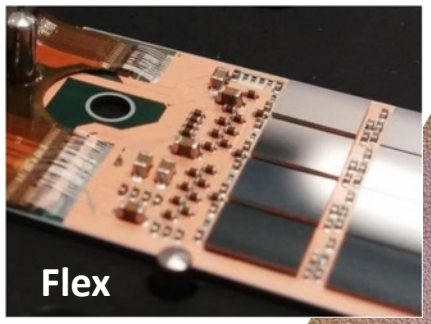
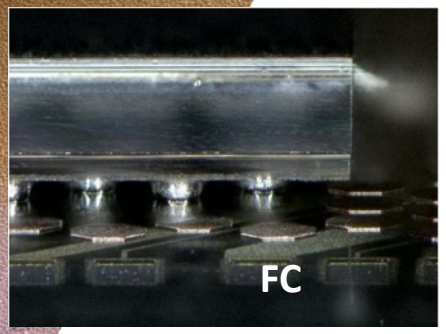


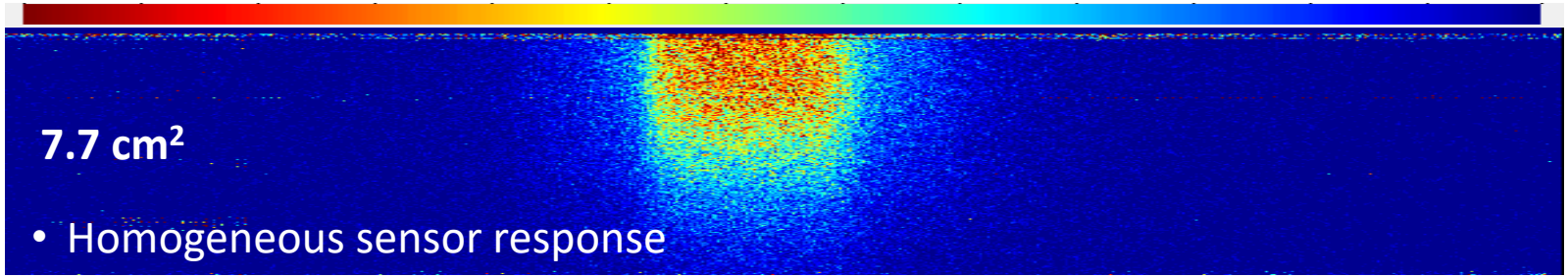




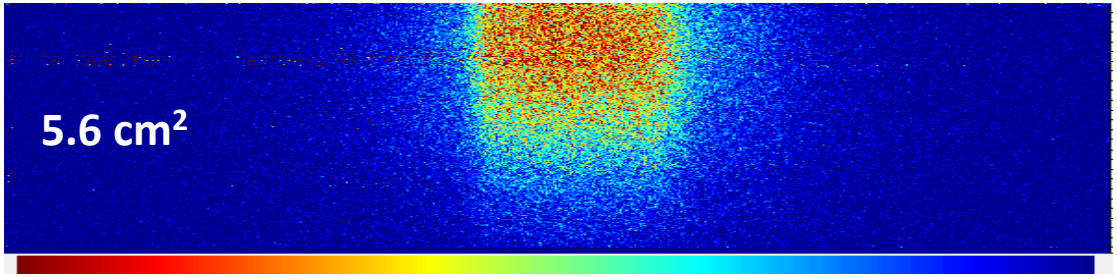
- ~400000 DEPFET Pixels
- 50x75 µm^2 pixel pitch
- 75 µm thickness

See L. Andricek's talk

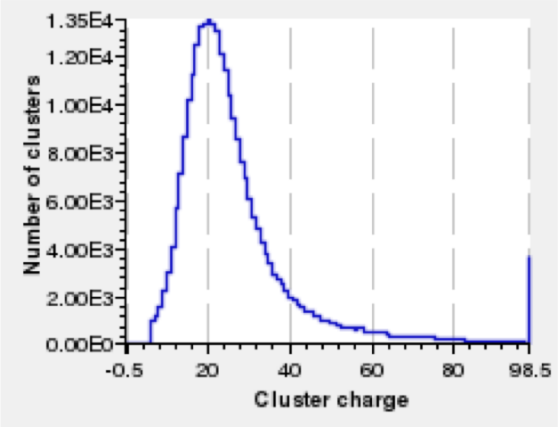
PXD Module Performance: Test Beam



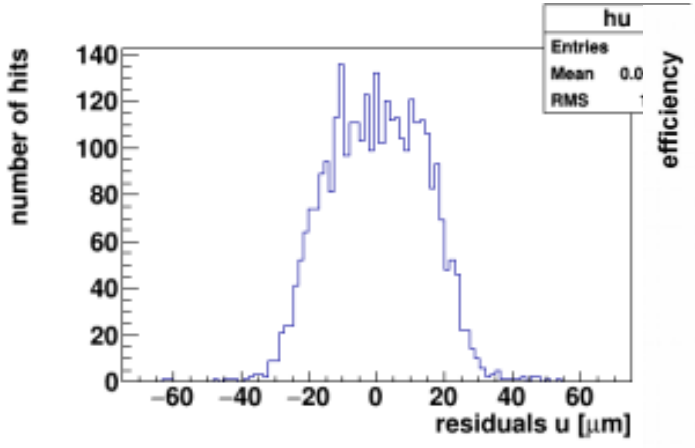
- Homogeneous sensor response



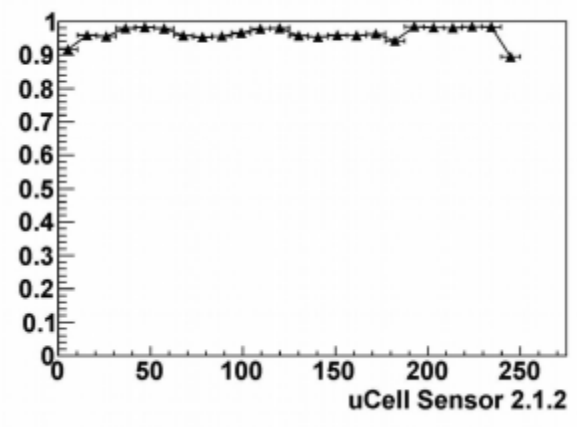
Threshold ~ 1200 electrons



- SNR ~ 30



- 14 µm resolution (50 µm)

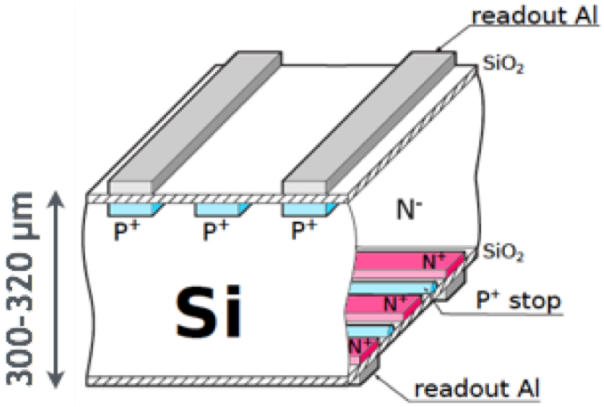


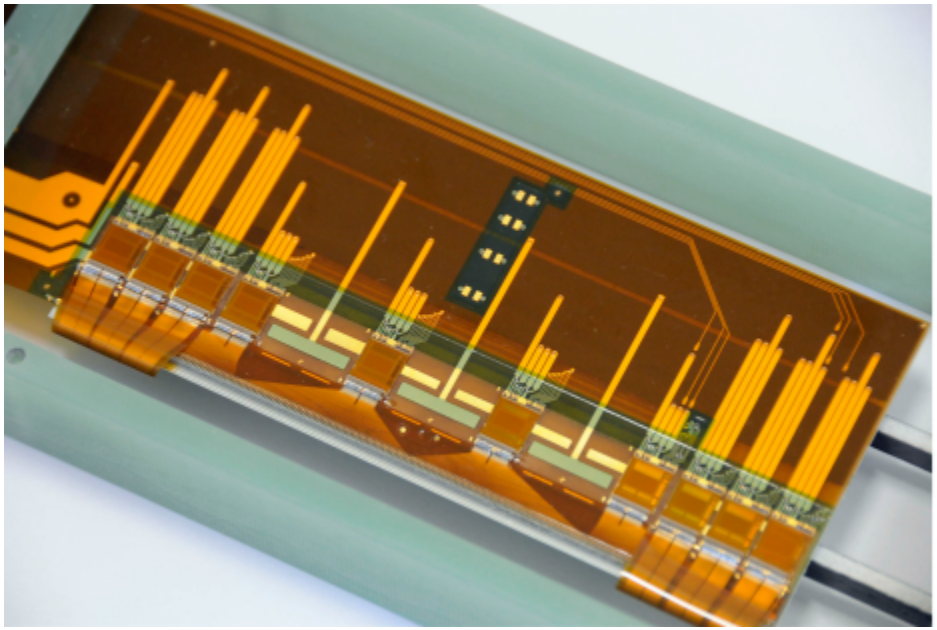
- ε > 99%

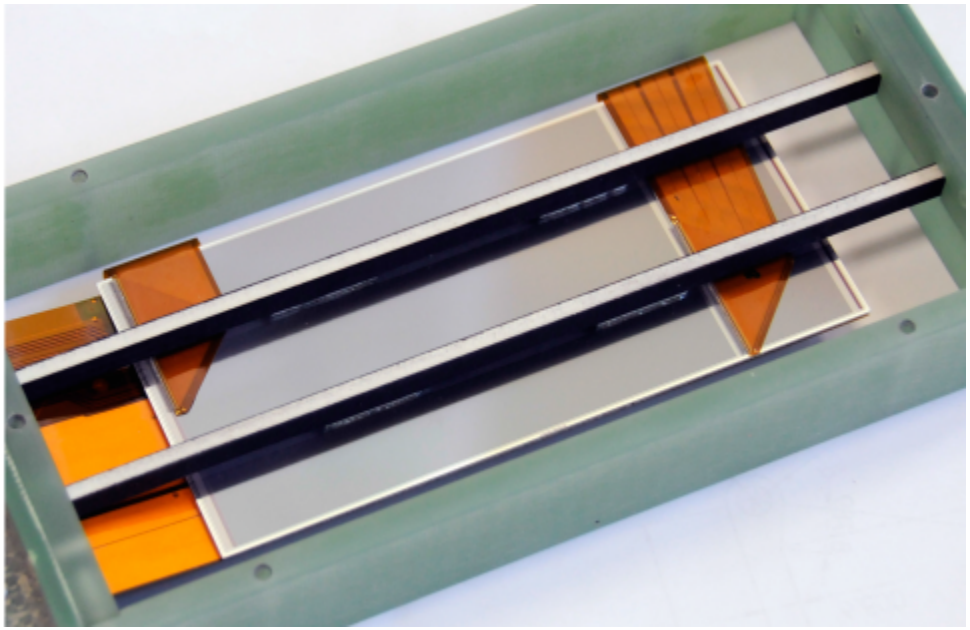
Belle II SVD Module

- Double Sided Silicon strip Detector
  Low material budget ~0.7 X_0 per layer
  "Chip-on-sensor" design for central modules

- APV25 readout chip
  - Fast shaping time, radiation hard, thinned to 100µm
  - Heat dissipation up to 700W
    → CO_2 cooling







VXD Online Data Reduction

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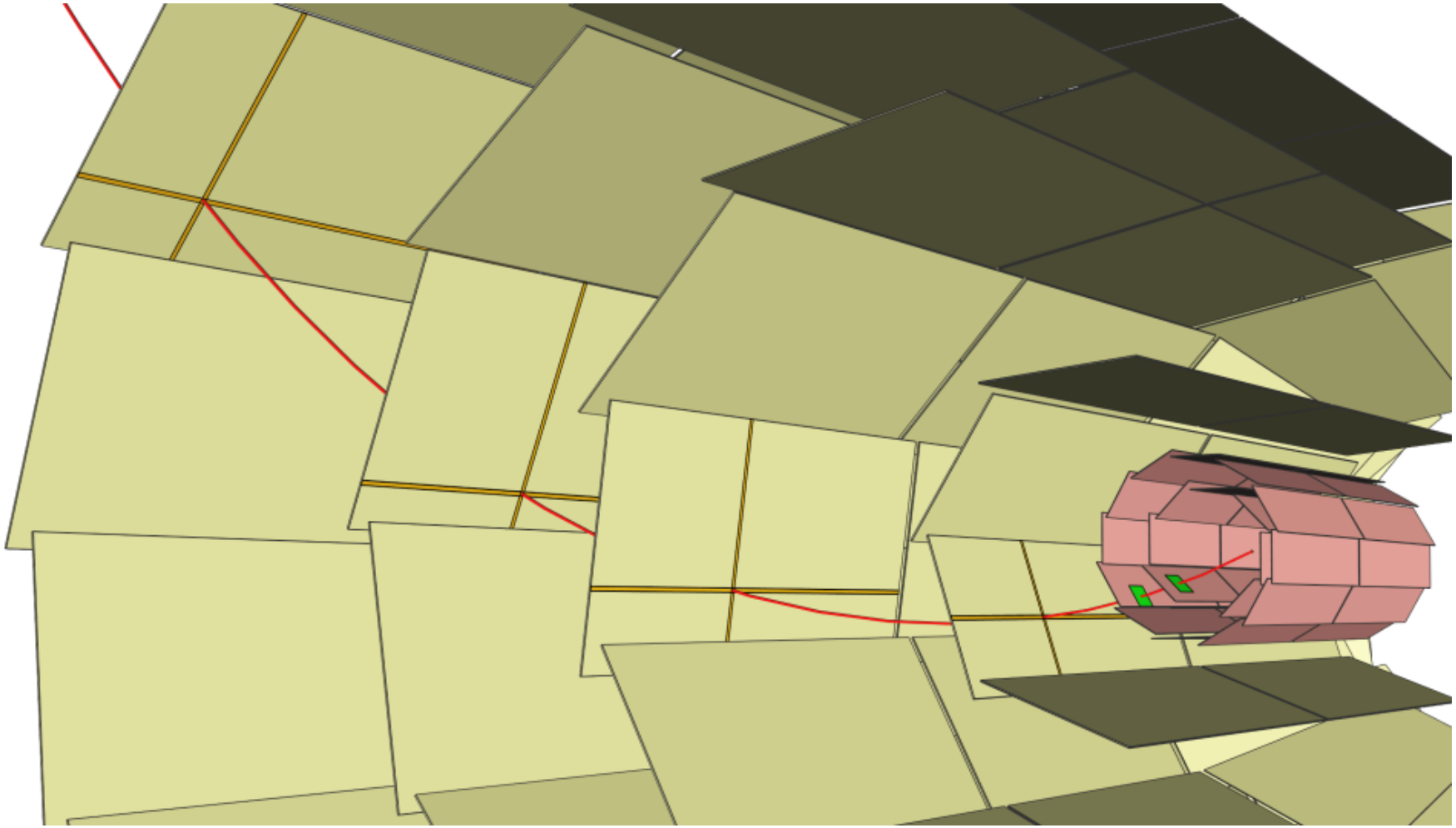
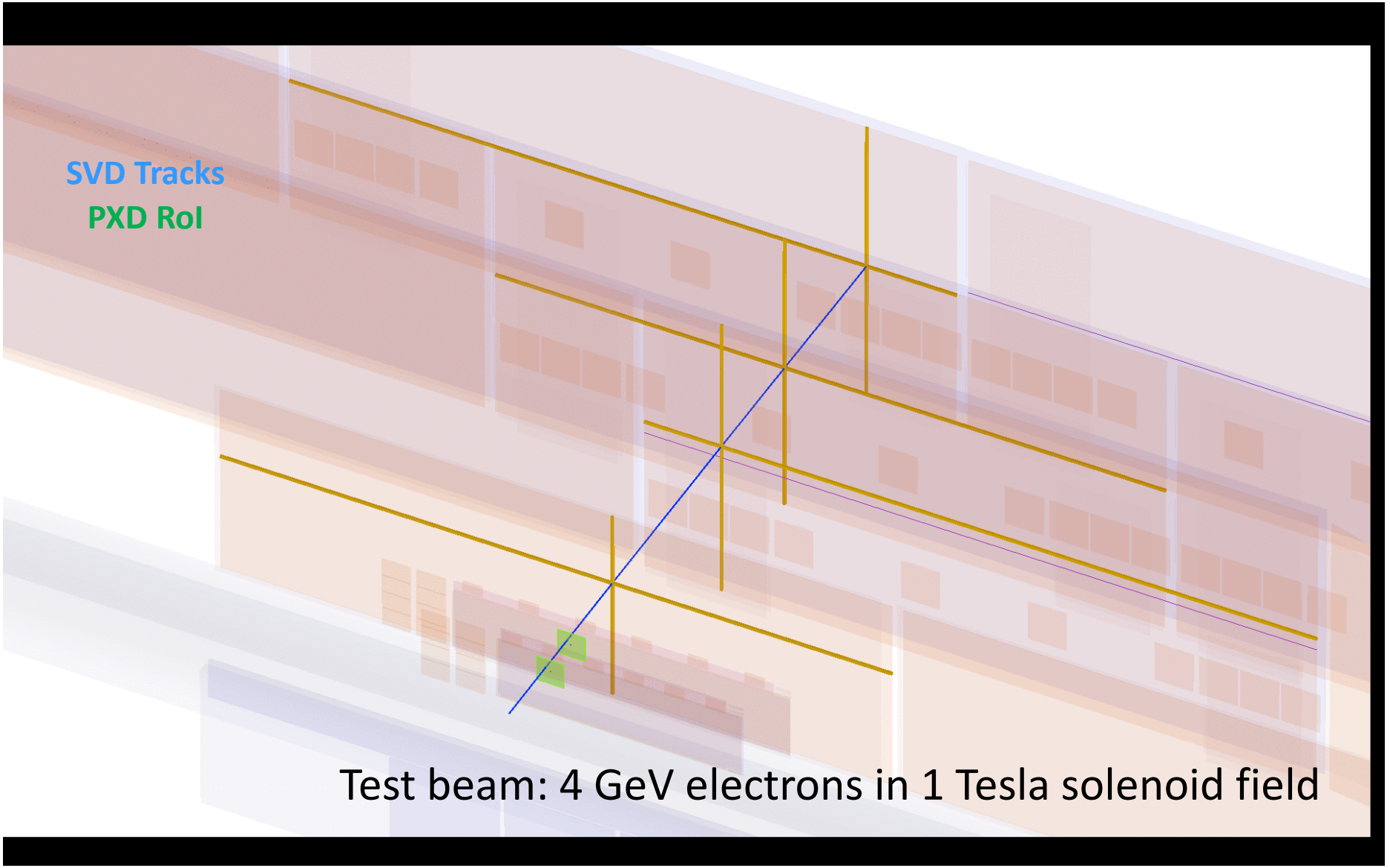
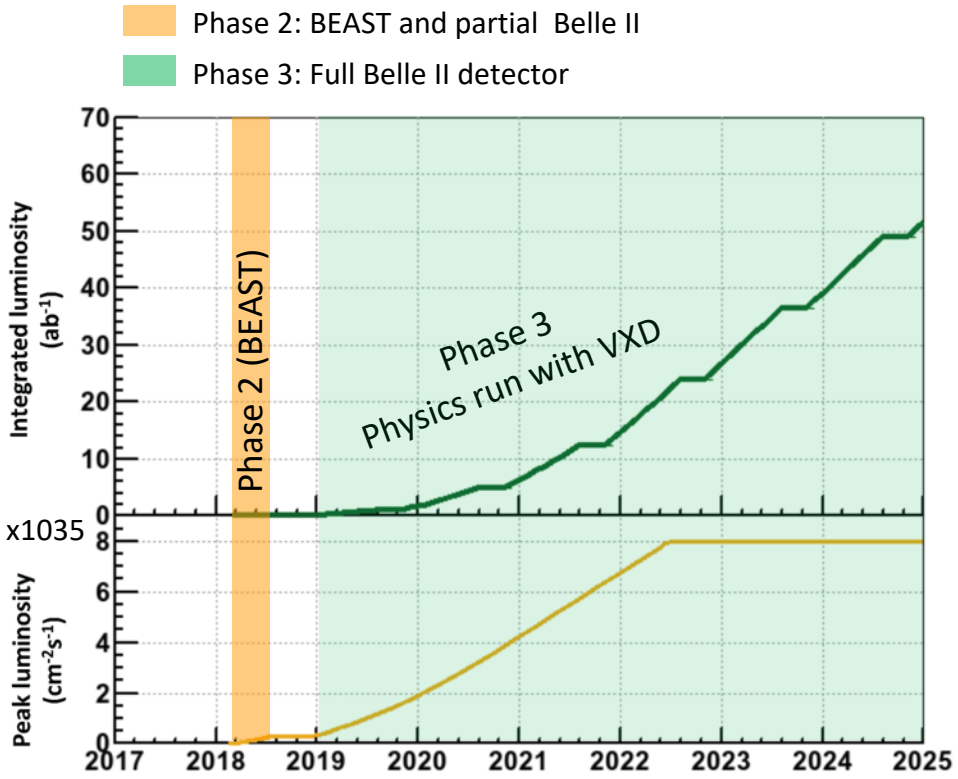


- Amount of data created by PXD is larger than the data generated by all other subdetectors
- Only reduced PXD data is written to tape
- Use tracks in SVD (and CDC) to find PXD regions of interest

VXD Online Data Reduction



Phase 2



- The SuperKEKB accelerator will be operating, for the first time, with QCS magnets
  - First operation with focused beams
  - First beam collisions
- The Belle II detector, minus the vertex detector (VXD), rolled into the beam line

Phase 3 VXD Volume

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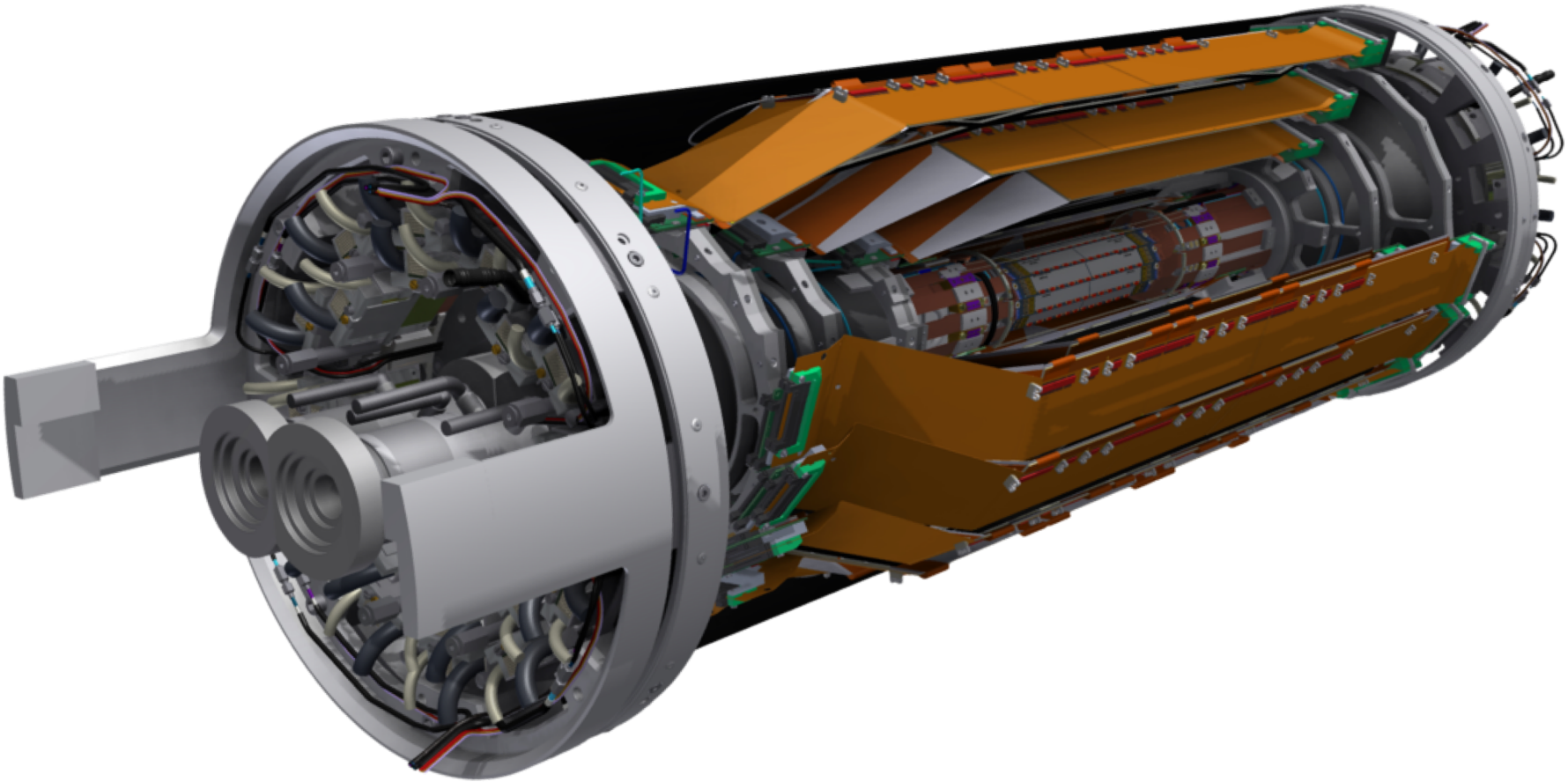
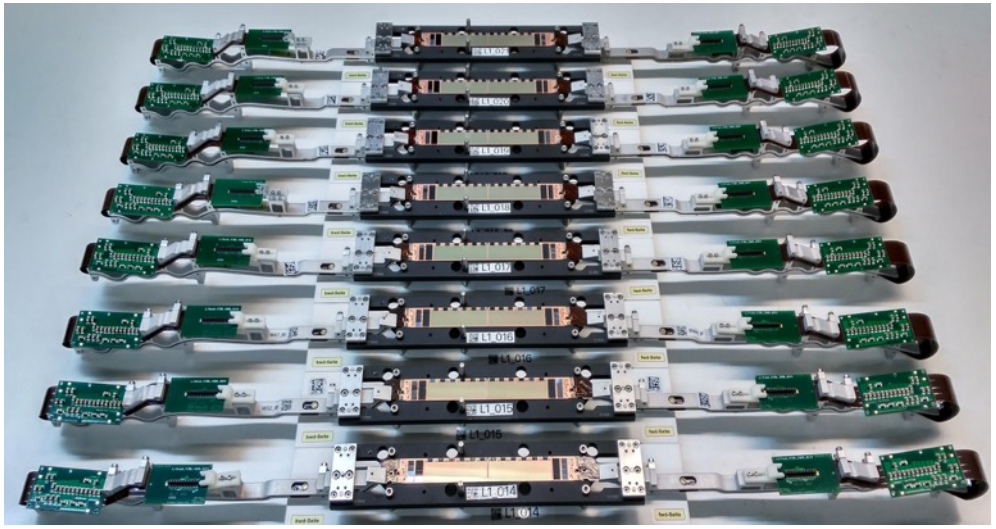


Phase 3 VXD Volume



PXD and SVD will marry mid August 2018…

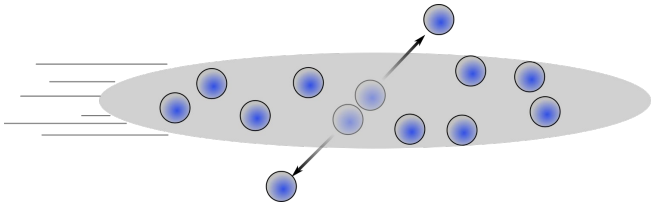
… but before that: Understanding the backgrounds

Beam Backgrounds

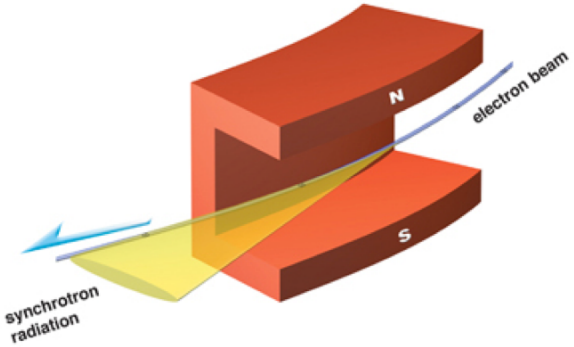
Beam backgrounds studied during SuperKEKB commissioning phases with dedicated radiation monitors

→ **BEAST**

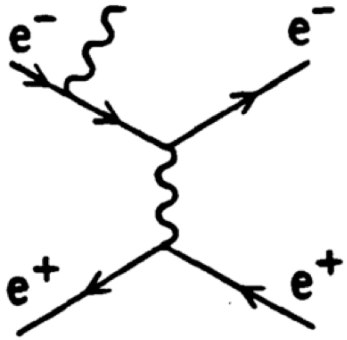
Touschek Scattering



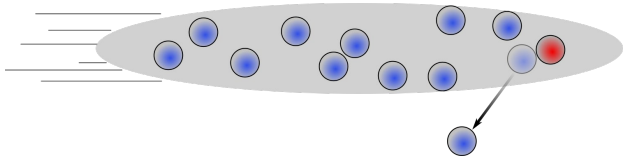
Synchrotron Radiation



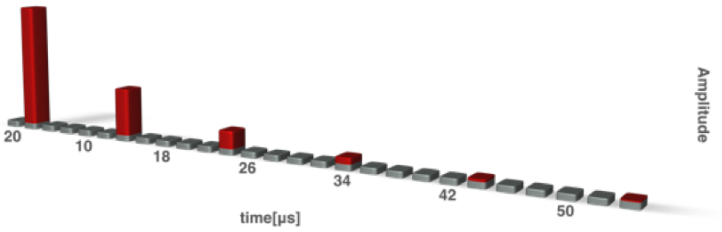
Radiative Bhabha



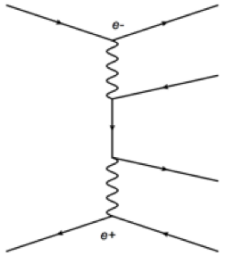
Beam-gas



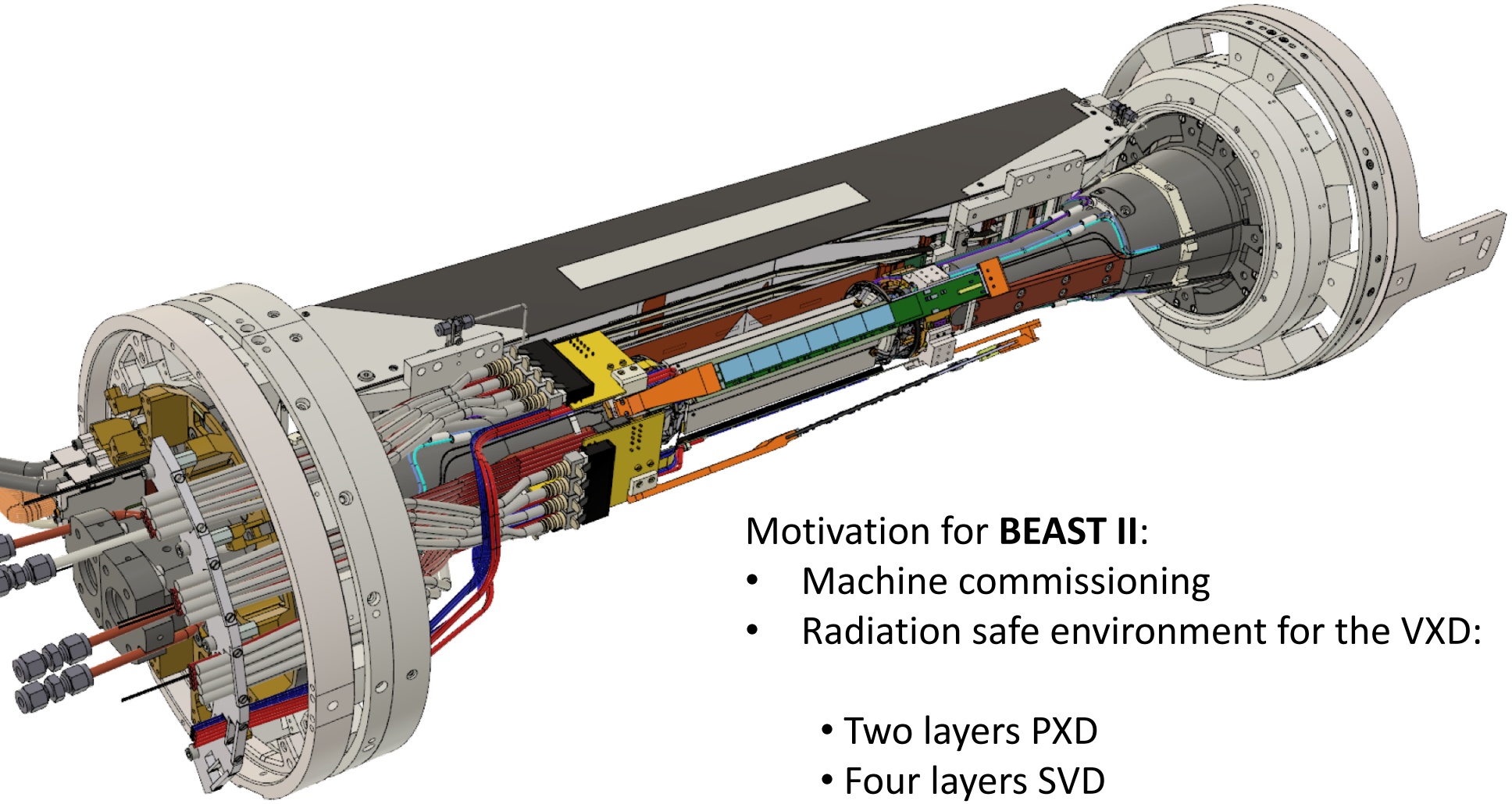
Injection Background



Two photon process



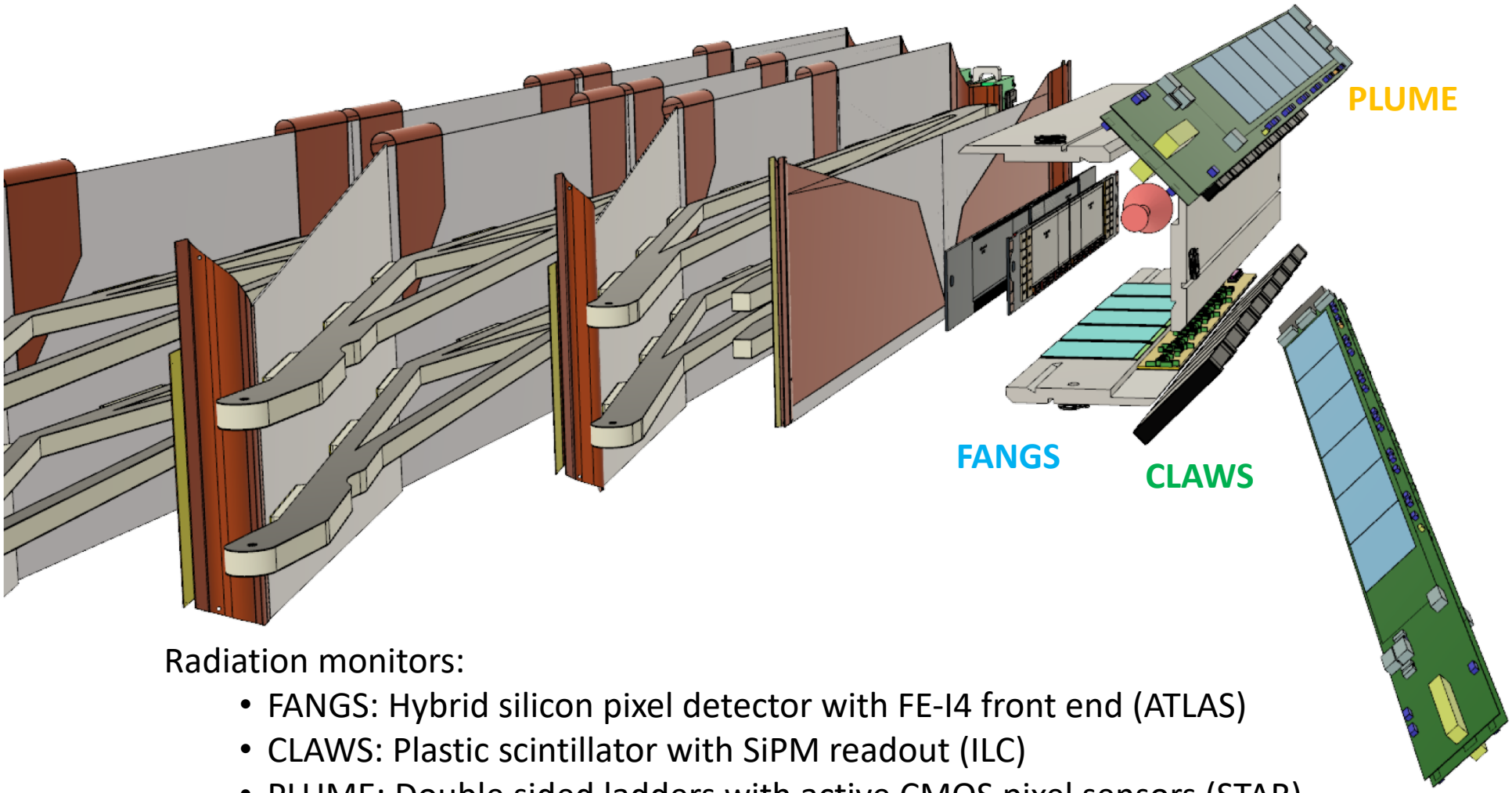
BEAST Commissioning Phase



Motivation for **BEAST II**:

- Machine commissioning
- Radiation safe environment for the VXD:
  - Two layers PXD
  - Four layers SVD
  - Dedicated radiation monitors
    FANGS, CLAWS, PLUME

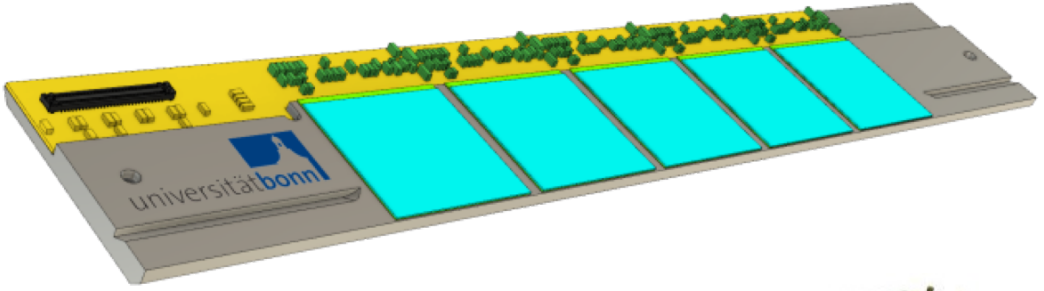
BEAST Commissioning Phase

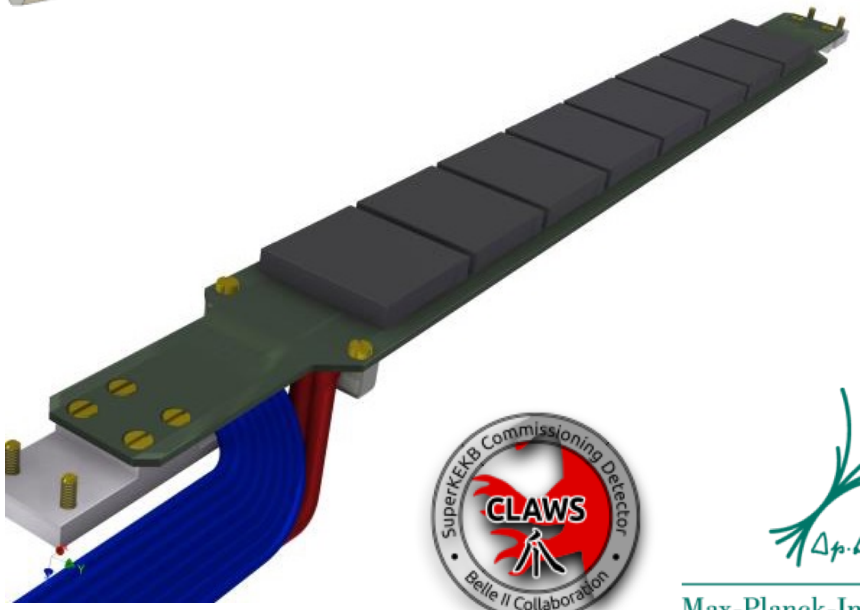


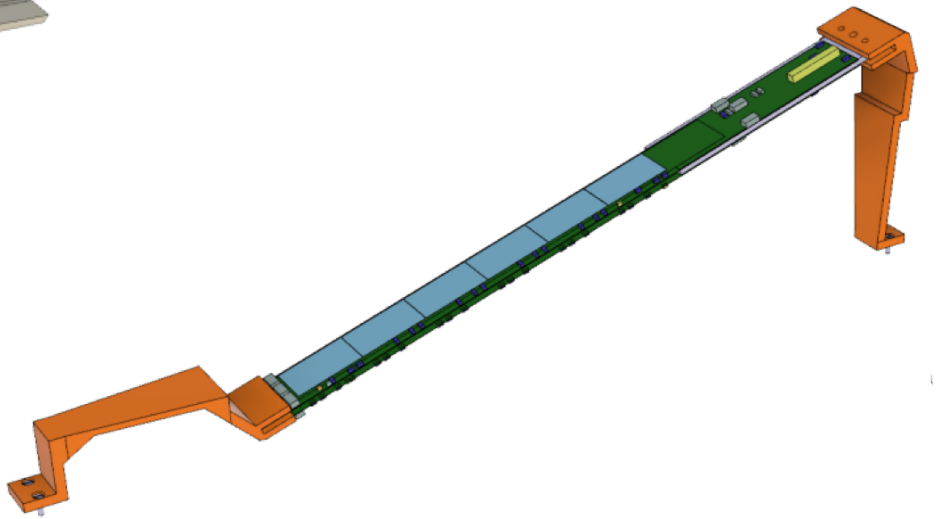
Radiation monitors:

- FANGS: Hybrid silicon pixel detector with FE-I4 front end (ATLAS)
- CLAWS: Plastic scintillator with SiPM readout (ILC)
- PLUME: Double sided ladders with active CMOS pixel sensors (STAR)

BEAST Commissioning Phase







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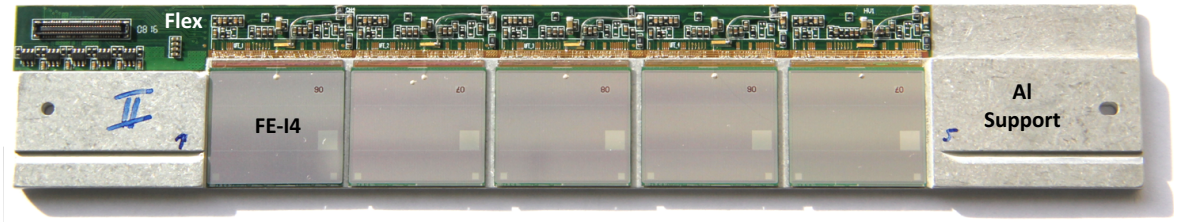
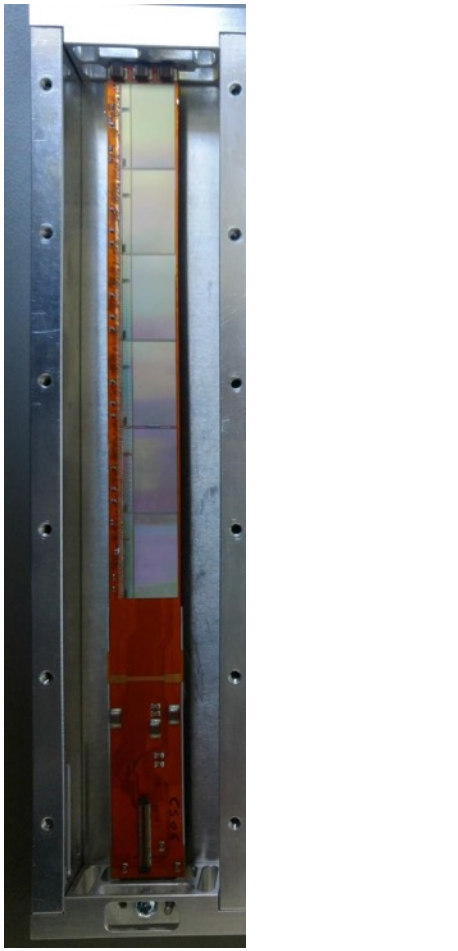
(Werner-Heisenberg-Institut)

BEAST Commissioning Phase





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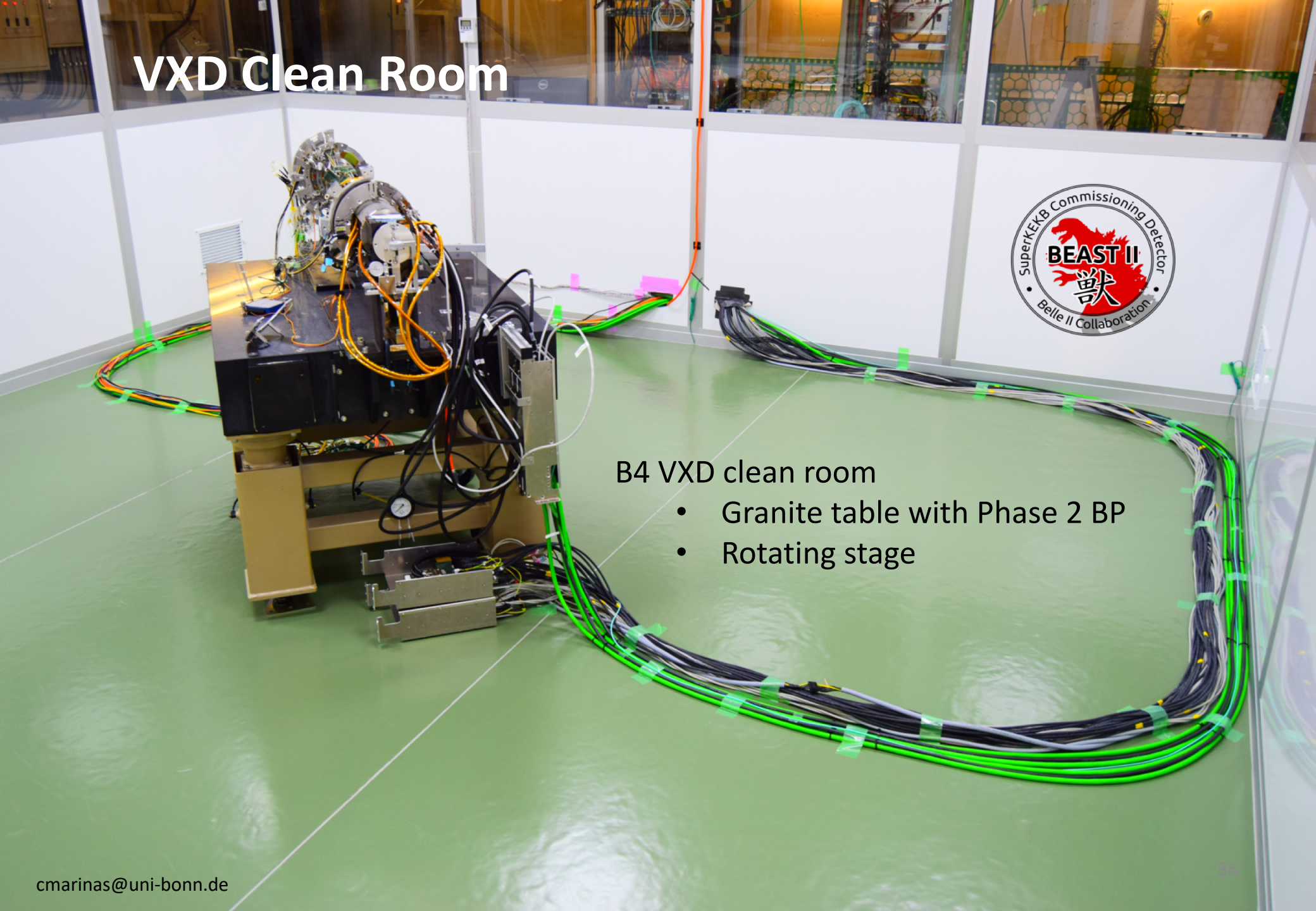
(Werner-Heisenberg-Institut)

VXD Clean Room



B4 VXD clean room

- Granite table with Phase 2 BP
- Rotating stage

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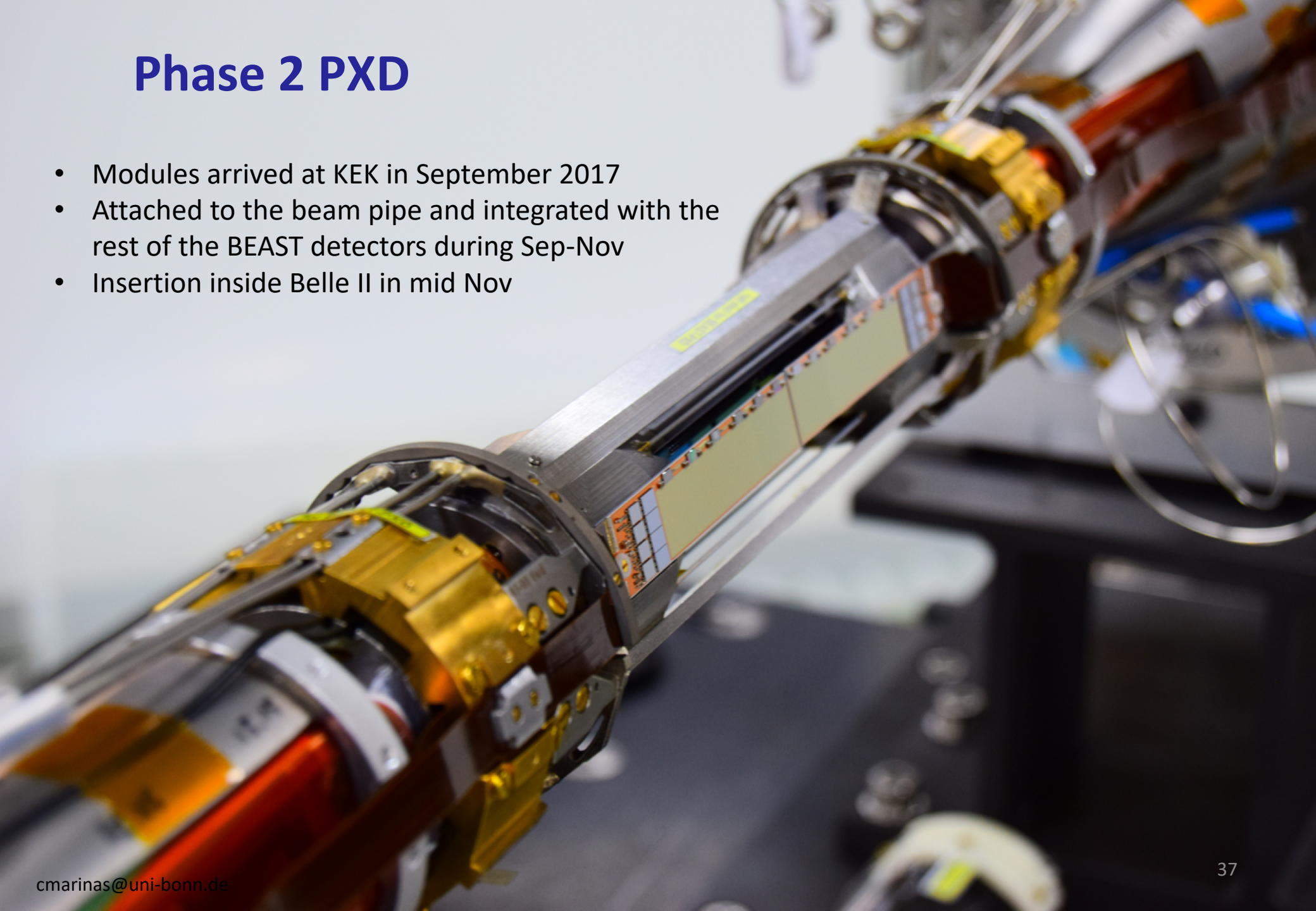
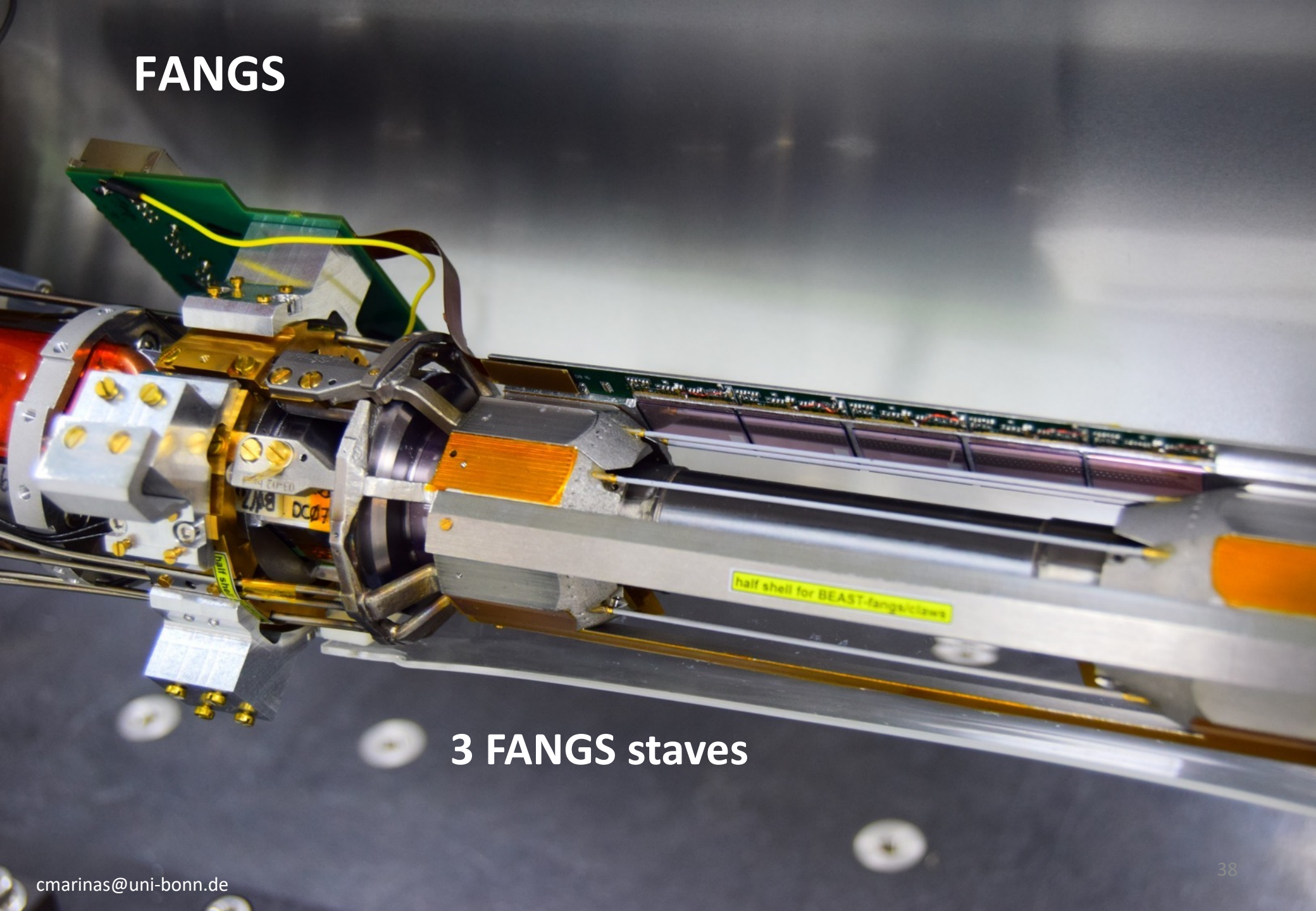
Phase 2 PXD

- Modules arrived at KEK in September 2017
- Attached to the beam pipe and integrated with the rest of the BEAST detectors during Sep-Nov
- Insertion inside Belle II in mid Nov

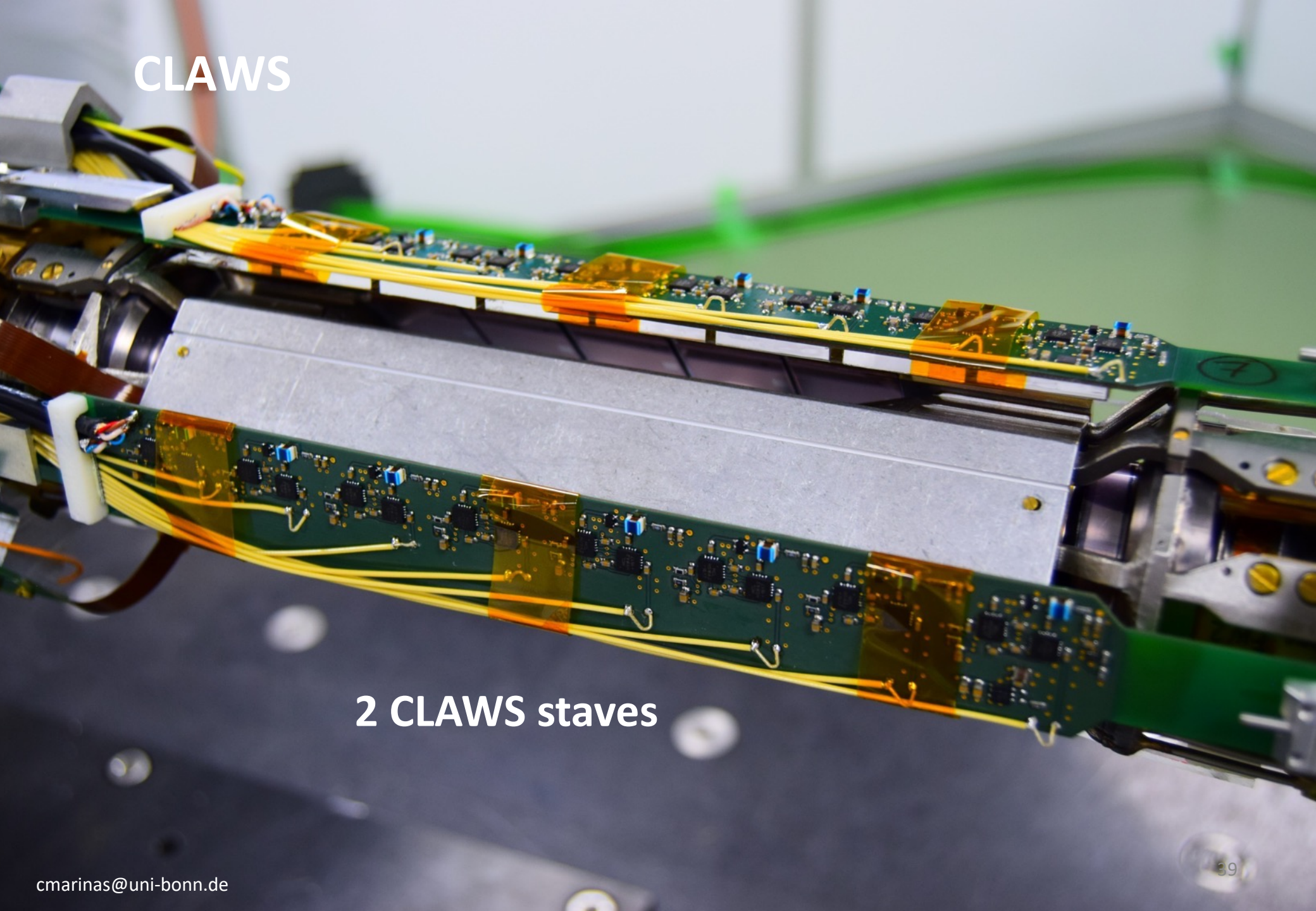


FANGS



3 FANGS staves

CLAWS



2 CLAWS staves

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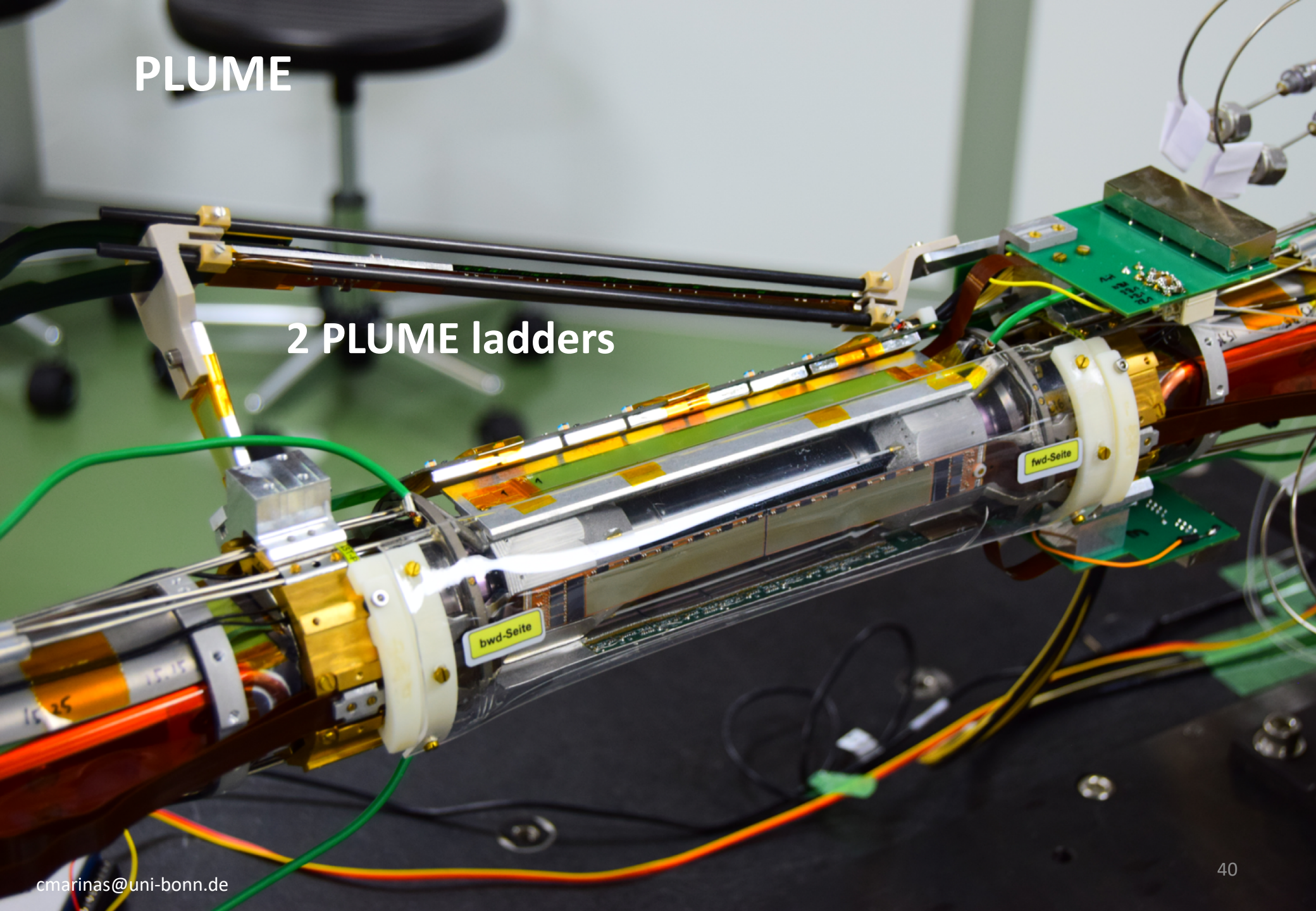
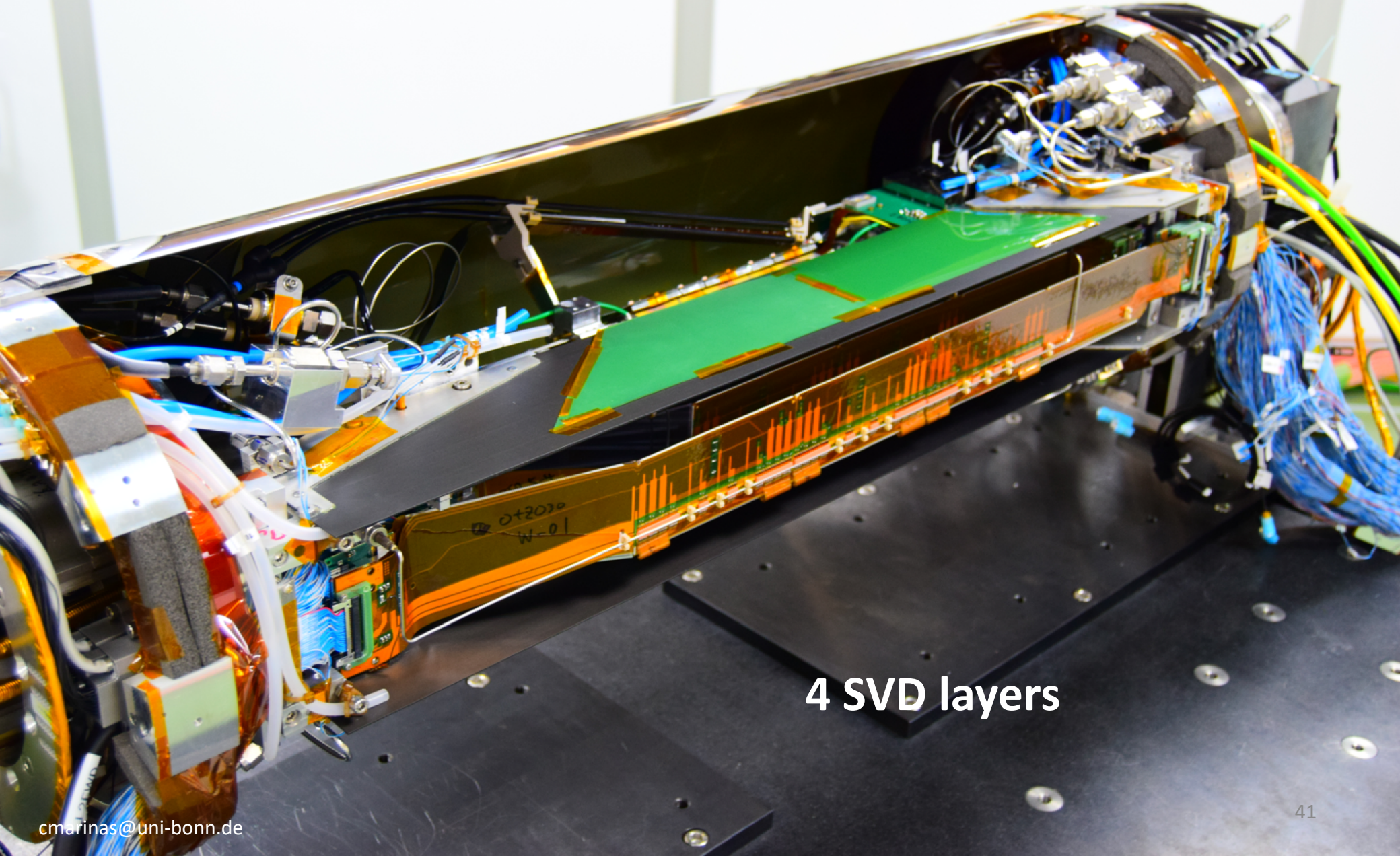
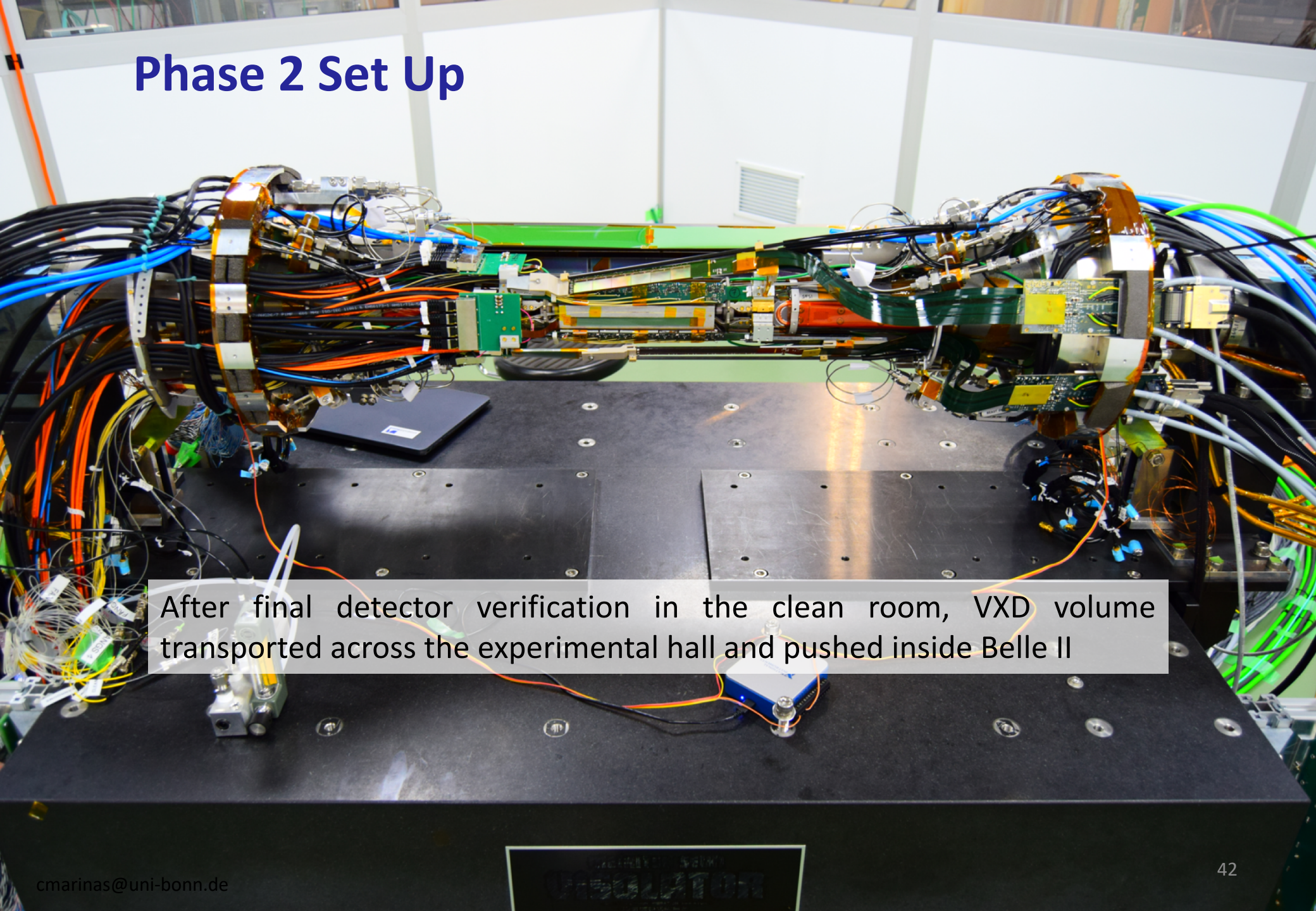
PLUME



SVD

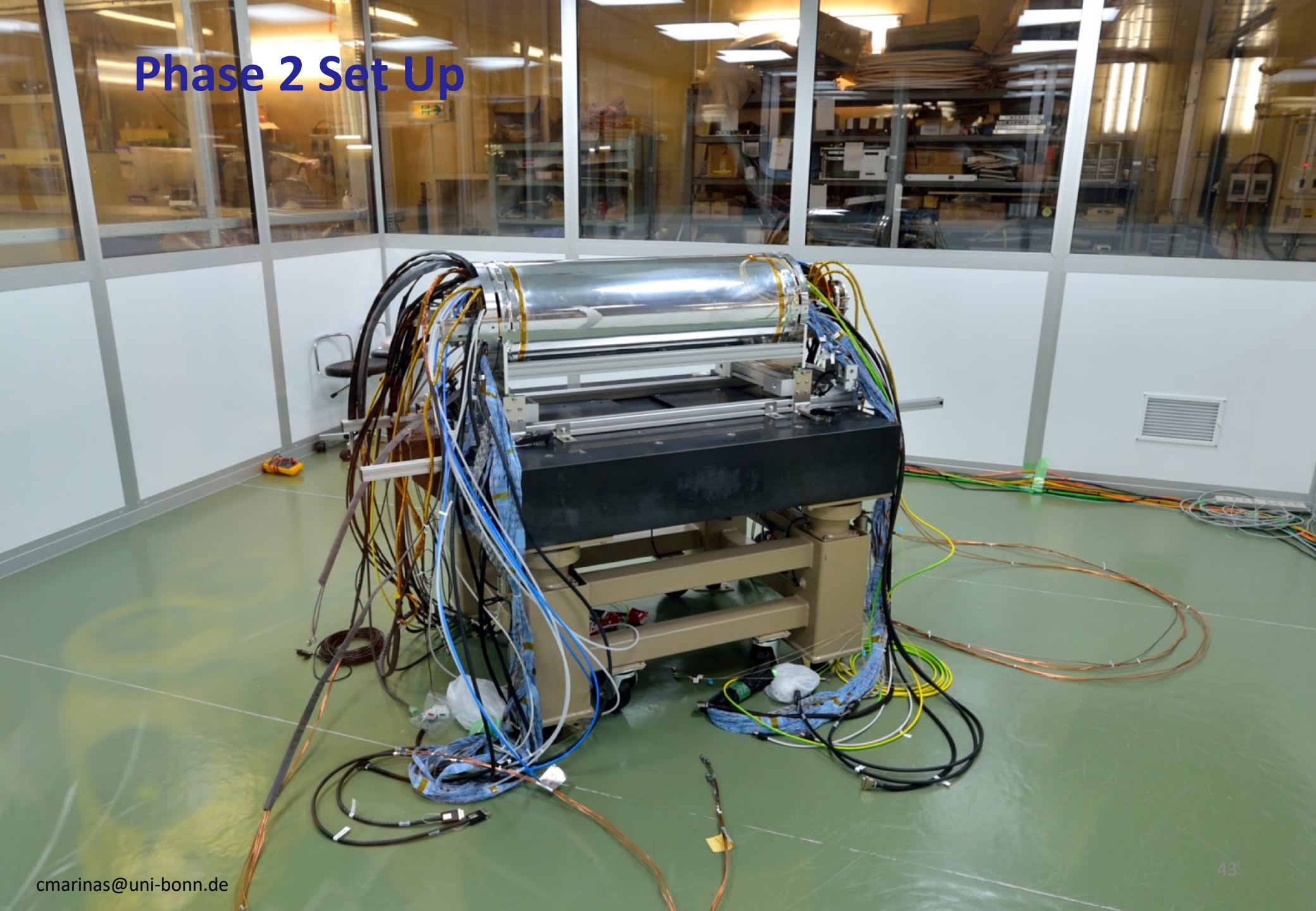


Phase 2 Set Up



After final detector verification in the clean room, VXD volume transported across the experimental hall and pushed inside Belle II

Phase 2 Set Up



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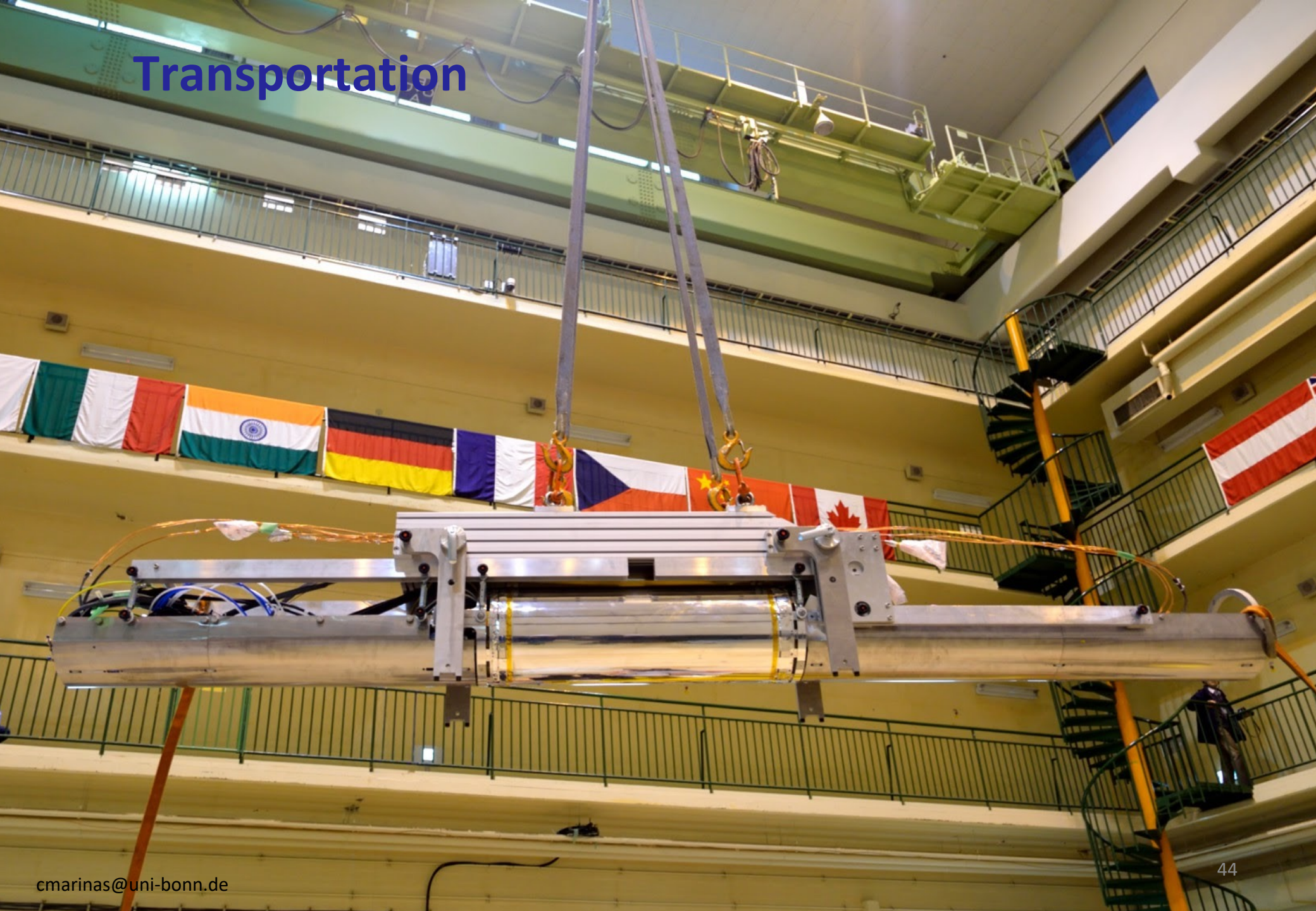
Transportation



Belle II Roll-in

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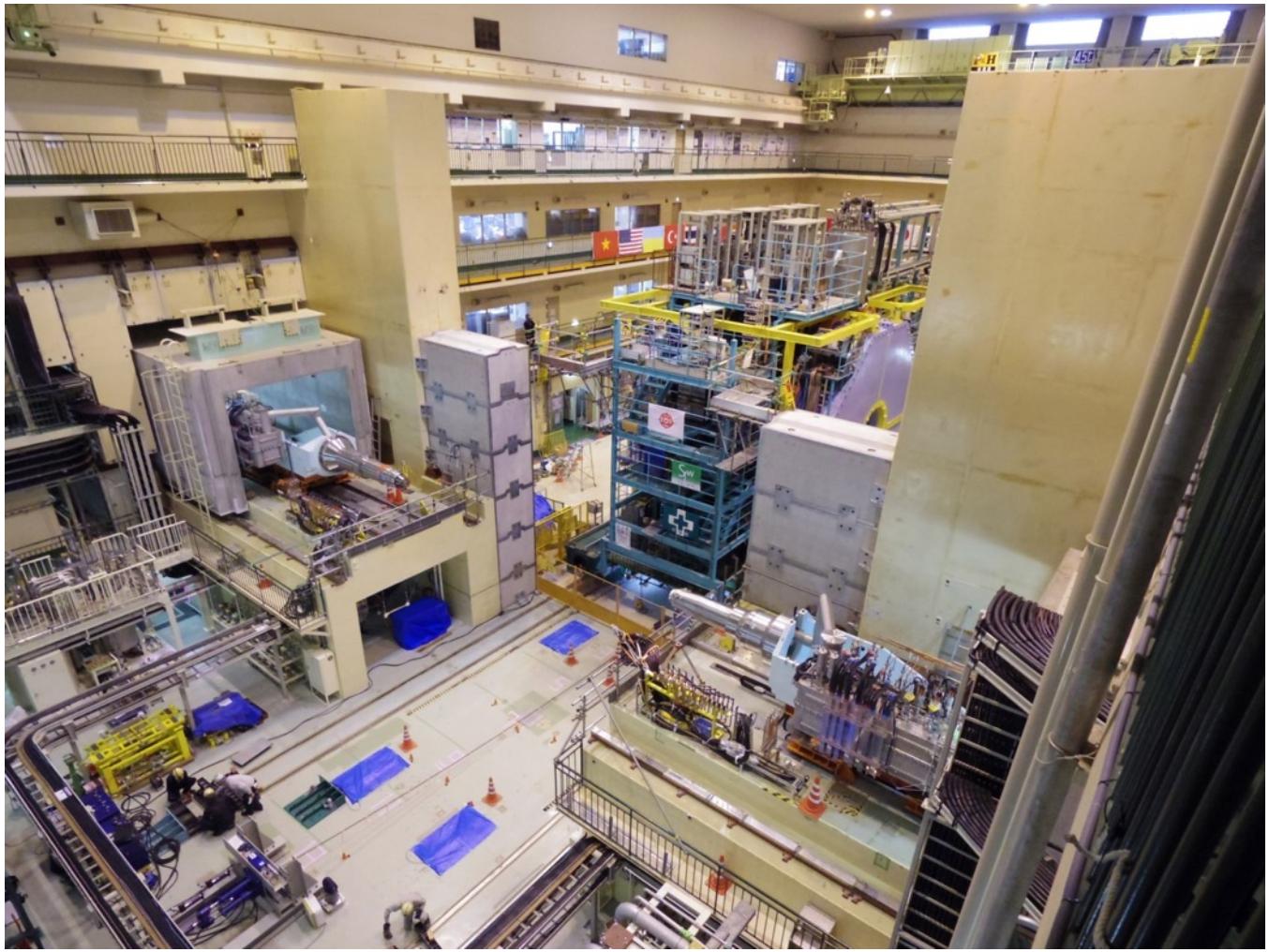

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Open Endcaps and QCS Insertion

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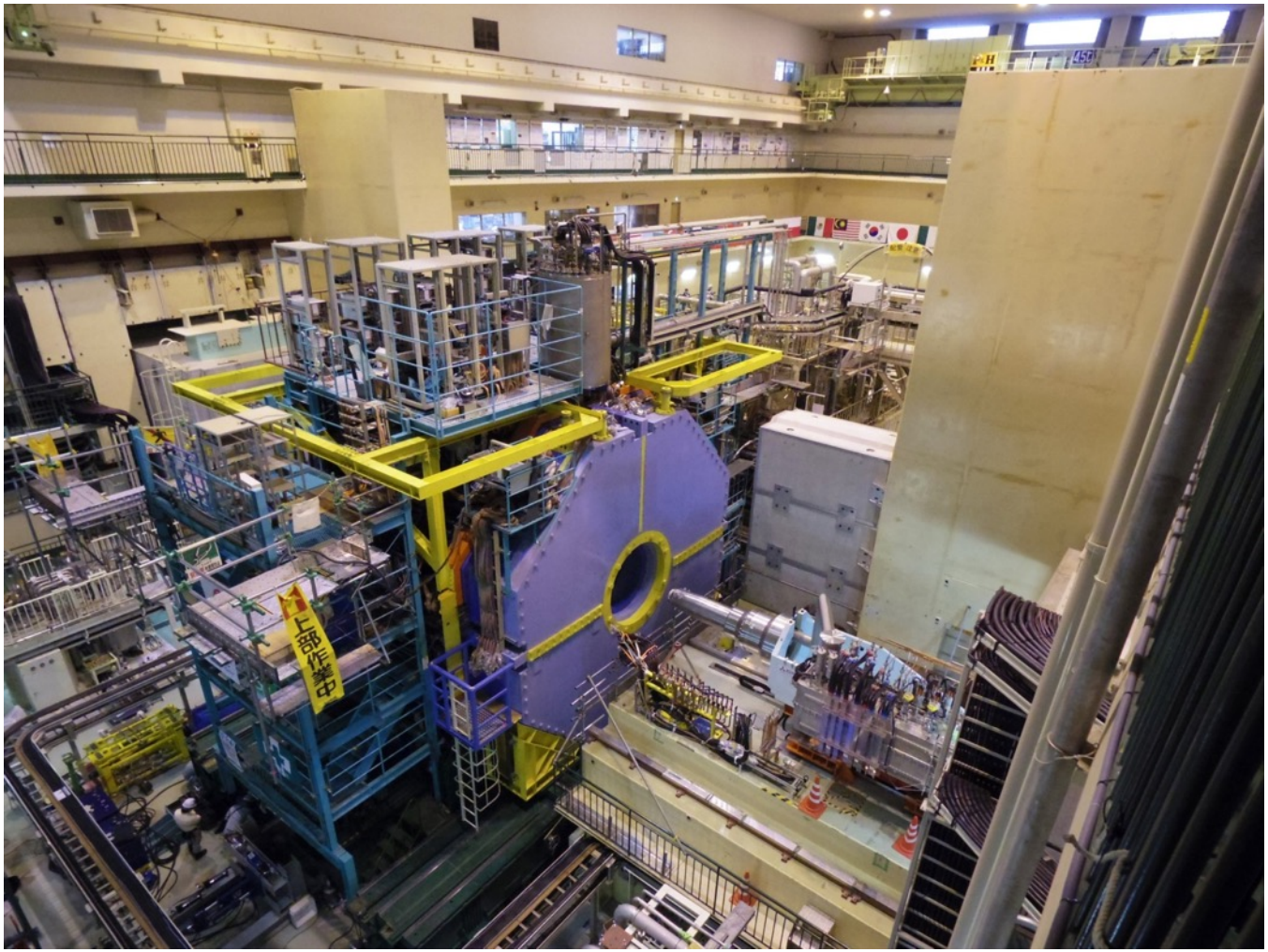

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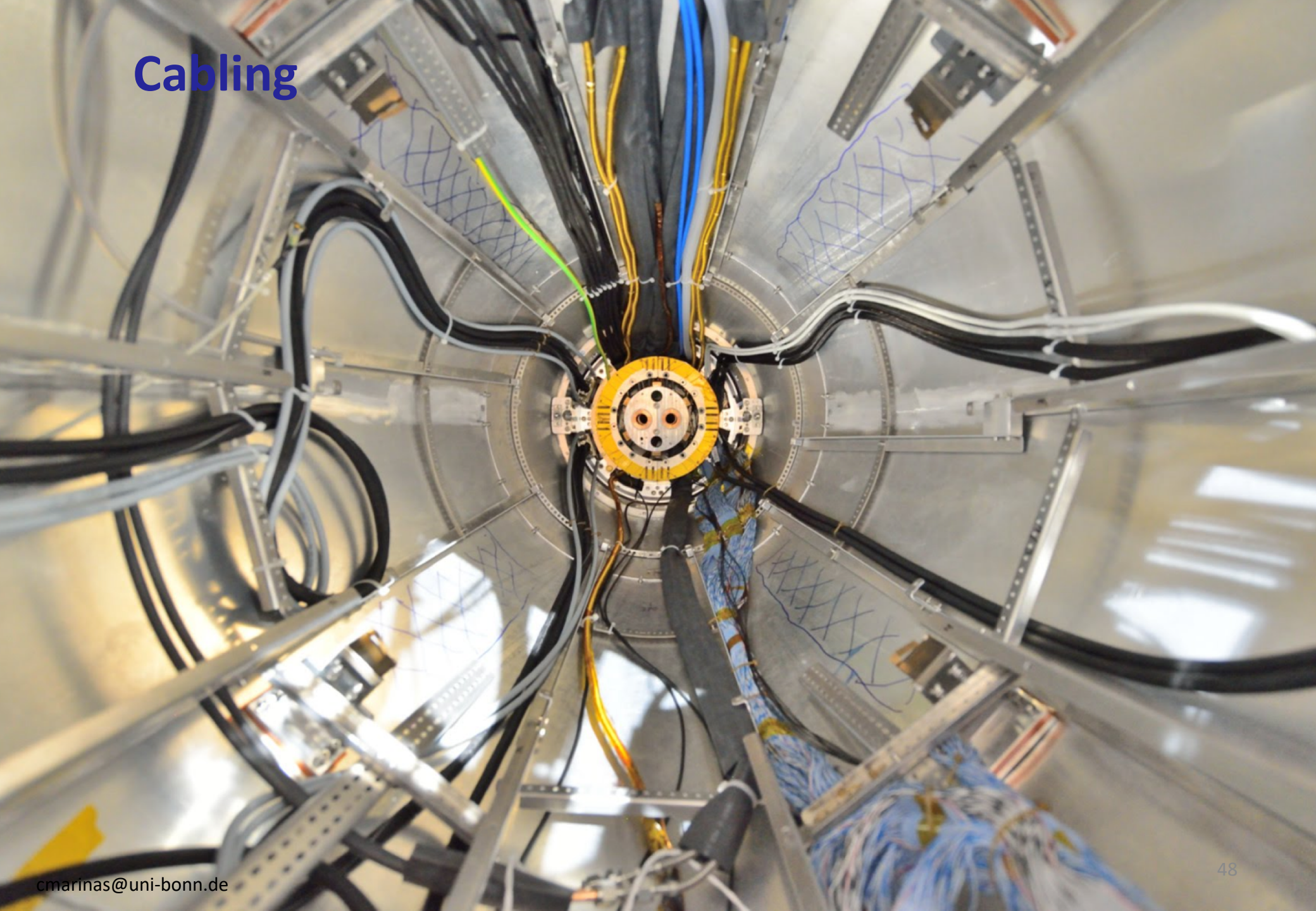
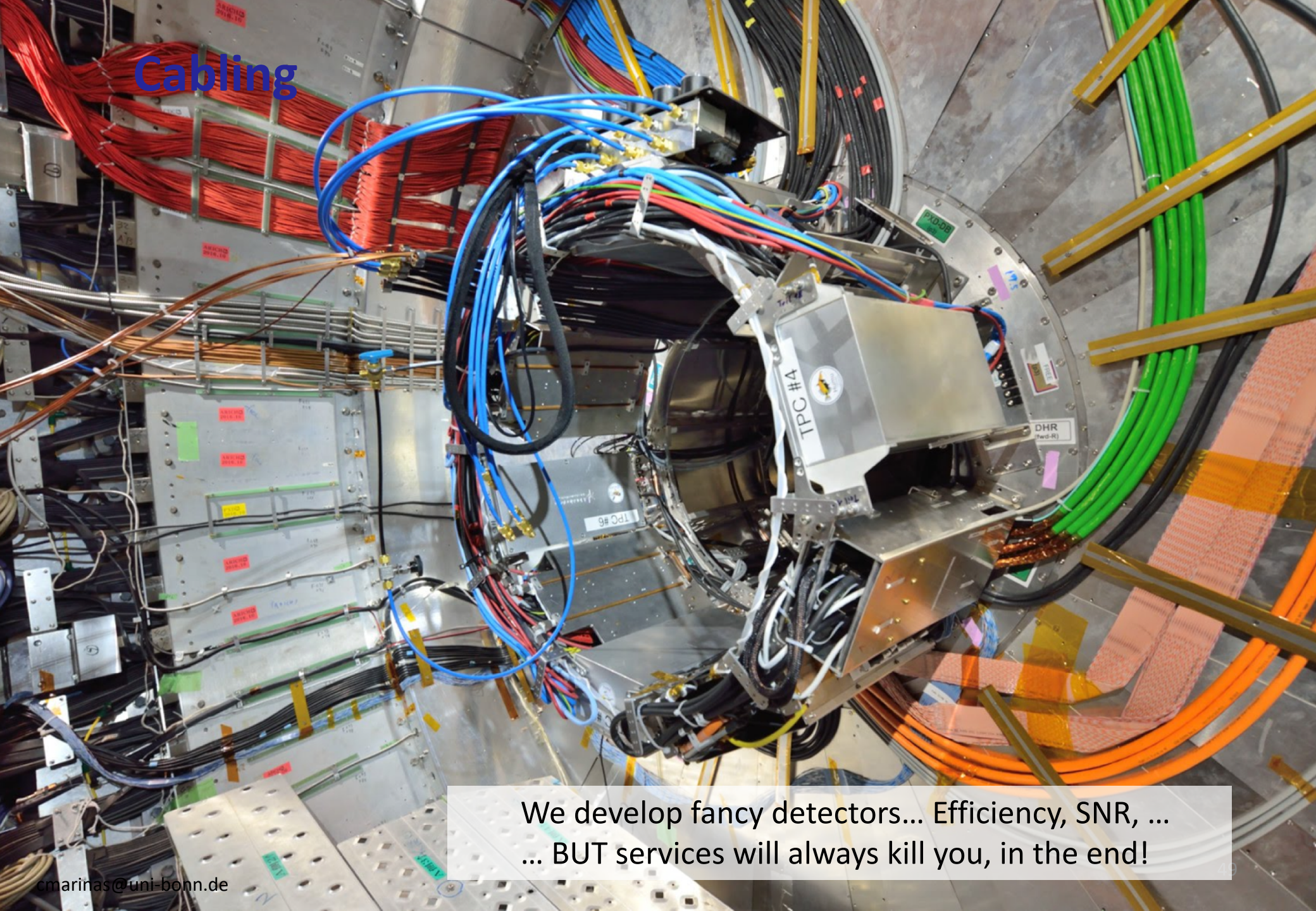
Cabling



Cabling



We develop fancy detectors… Efficiency, SNR, …
… BUT services will always kill you, in the end!

First Cosmic Through VXD

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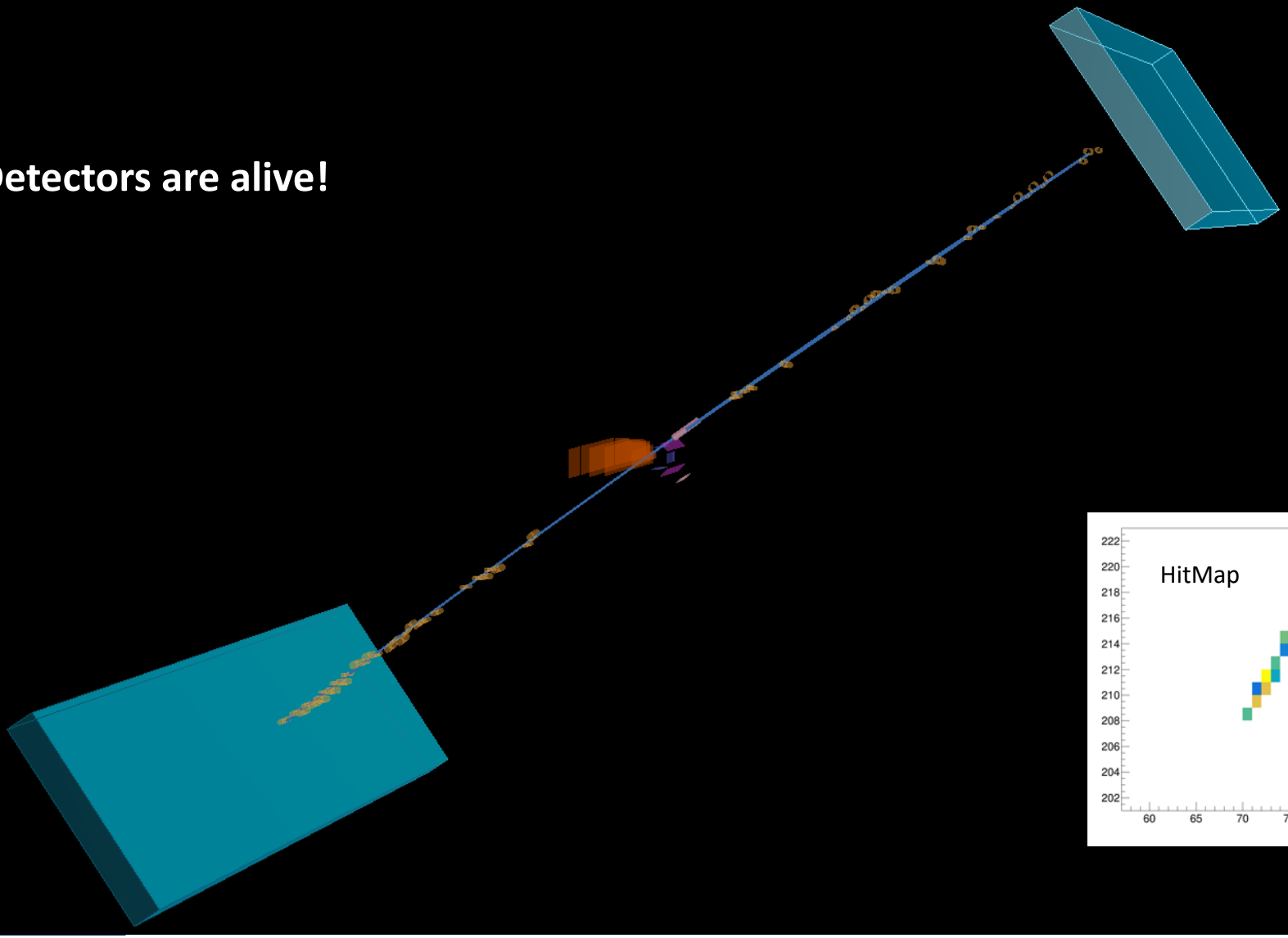
Detectors are alive!



Outlook

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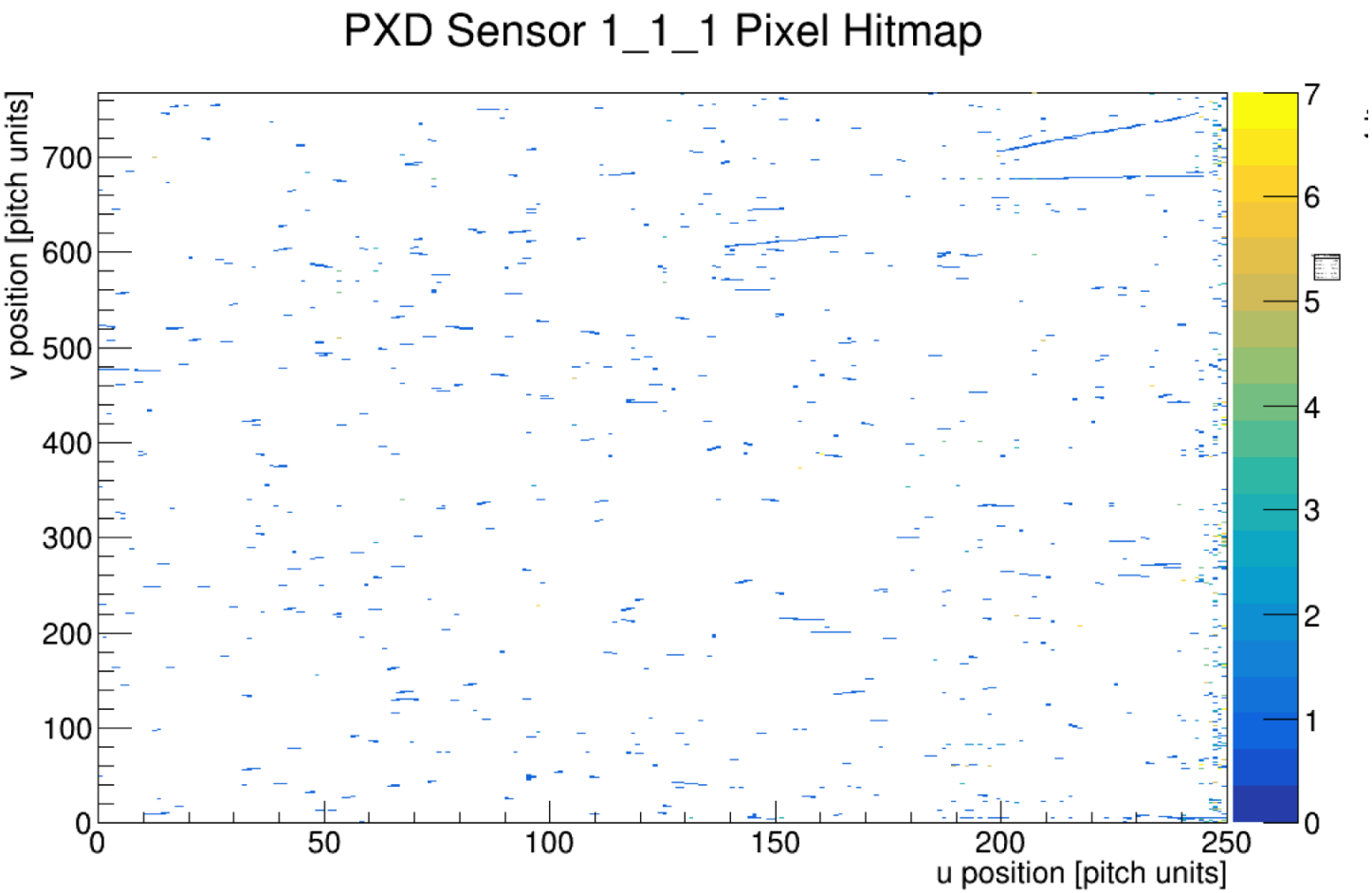
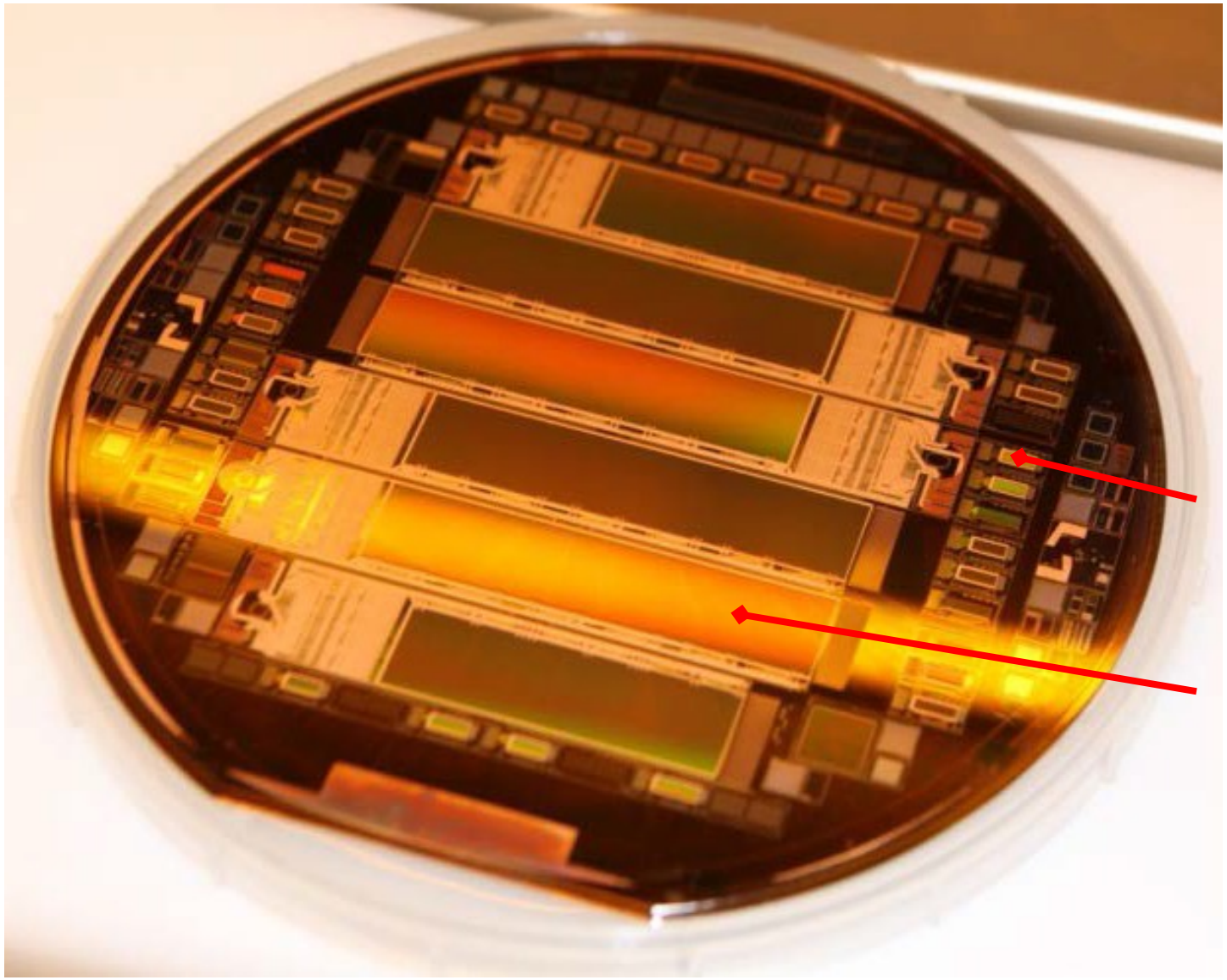
- Belle II will search for New Physics at the intensity frontier with a target integrated luminosity of 50 ab^{-1}
- Belle II detector is now complete for Phase 2
  - Global Cosmic Ray run ongoing right now
- Accelerator to start **operation in March 2018** (Phase 2) and start taking **physics data beginning 2019** (Phase 3)
- Stay tuned!

Thank you

VXD Global Cosmic Ray



PXD9 DEPFET Sensors

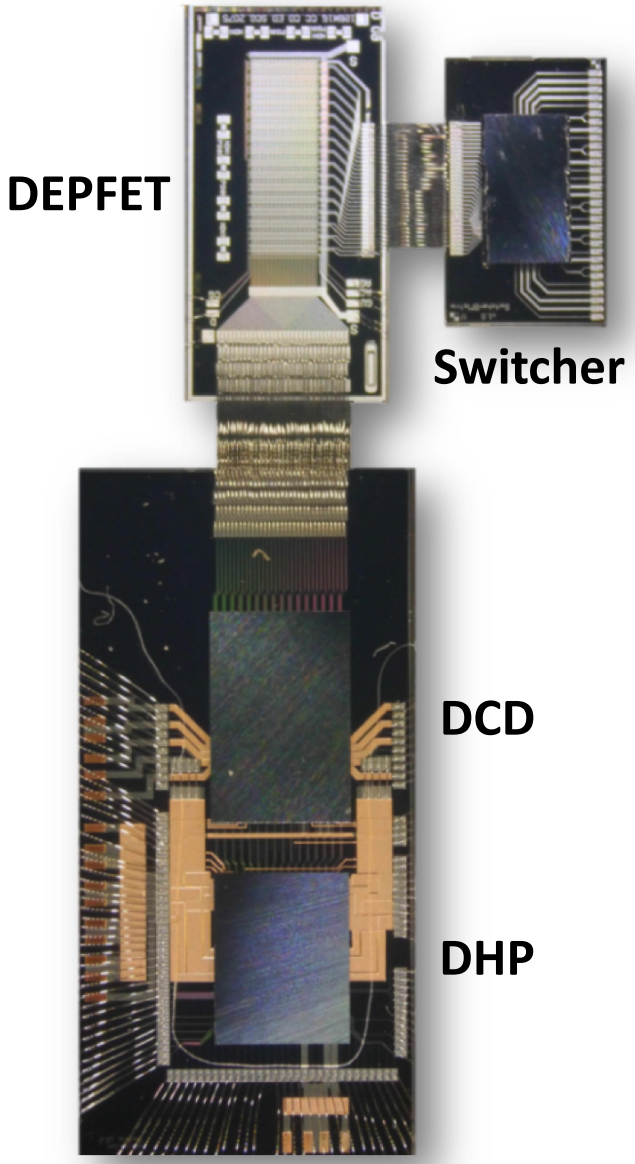


- Small matrices
  - 80x32 pixels
  - Test systems
- Full modules (large matrices)
  - 768x250 pixels
  - VXD combined test beams
  - BEAST Phase 2
  - Full Belle II PXD

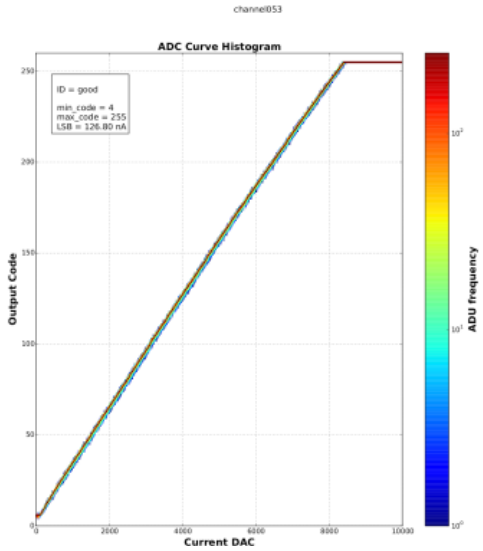
Hybrid 5 – Full System Demonstrator

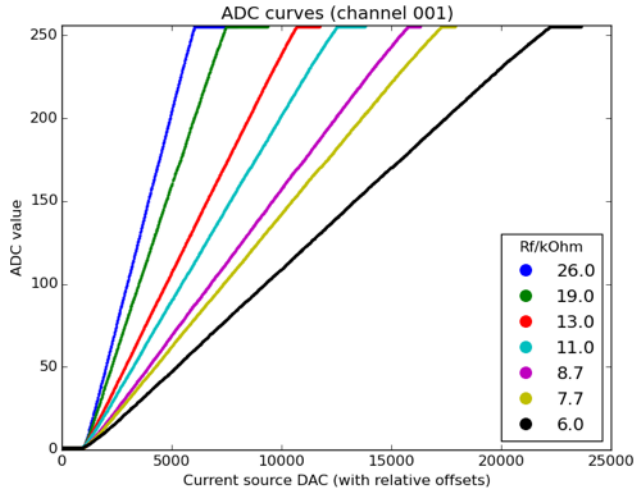
- PXD9 small Belle II type matrix
  - Pixel pitch: 50x55 μm^2
  - Thinned to 75 µm
  - Gate length: 5 µm
  - Thin gate oxide
  - 32x64 pixels readout
- Final readout chain
  - SwitcherB
  - DCDB
  - DHPT
  - DHPT → DHH

All measurements, at nominal speed



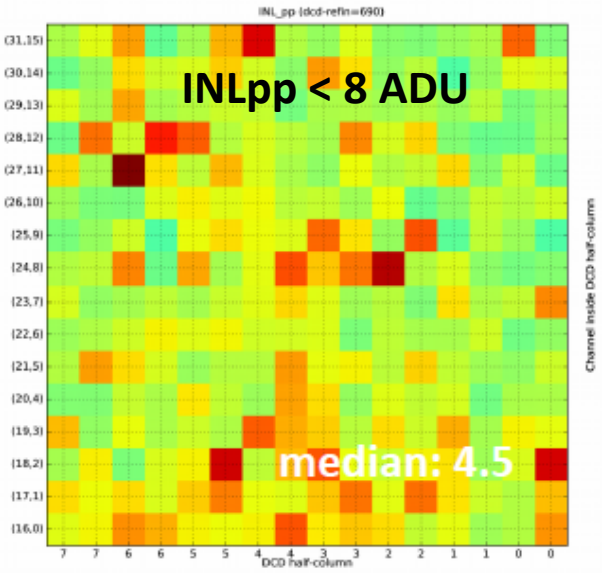
DCD Characterization

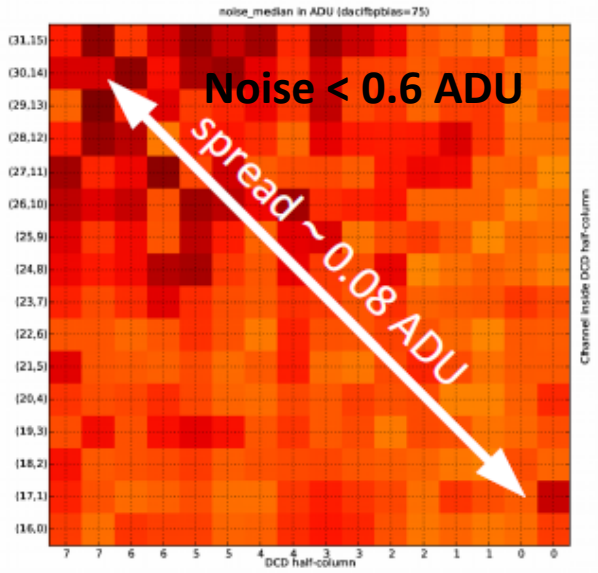


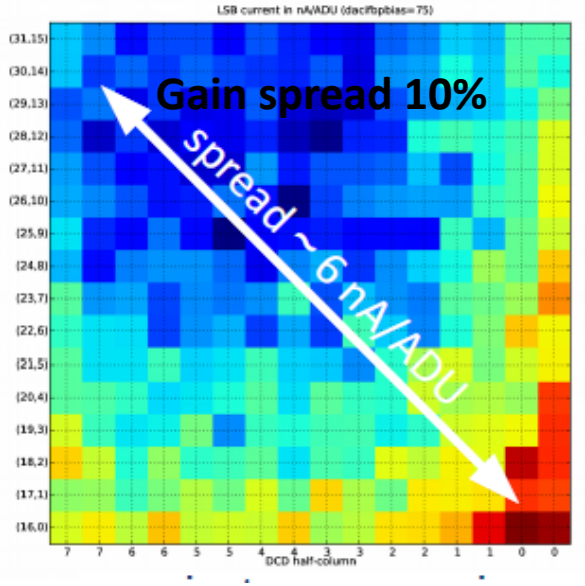


Performance according to specs

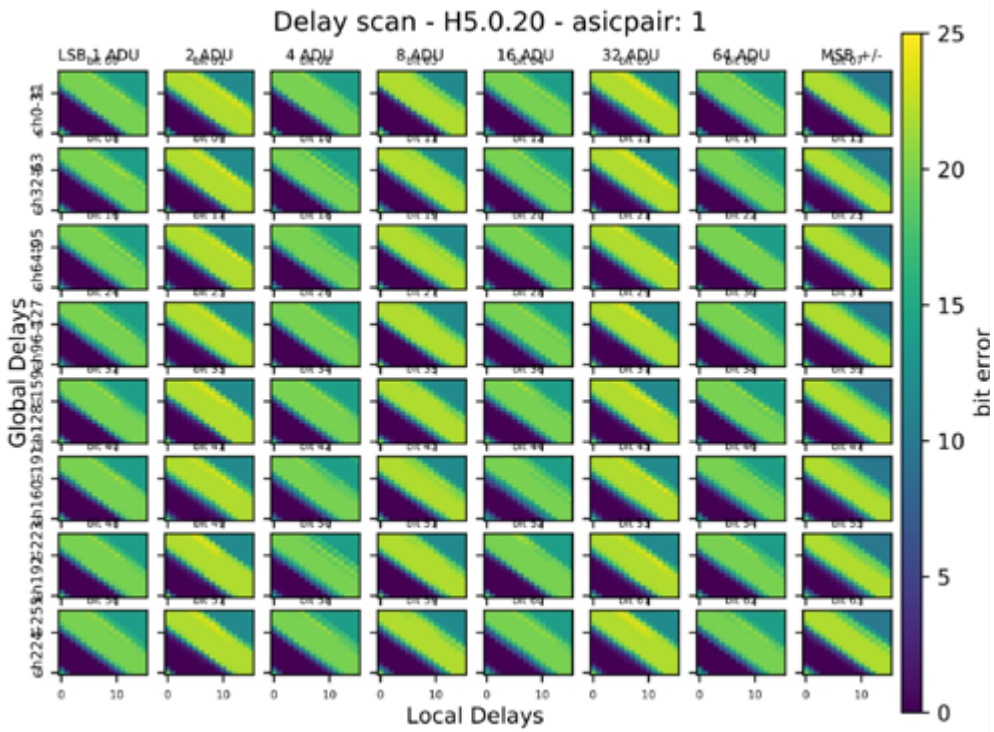
- Linearity
- Noise
- Gain



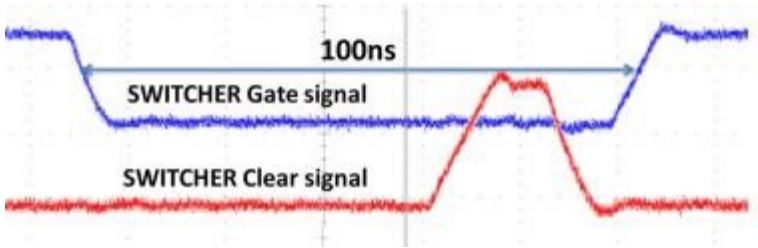




DHP Characterization

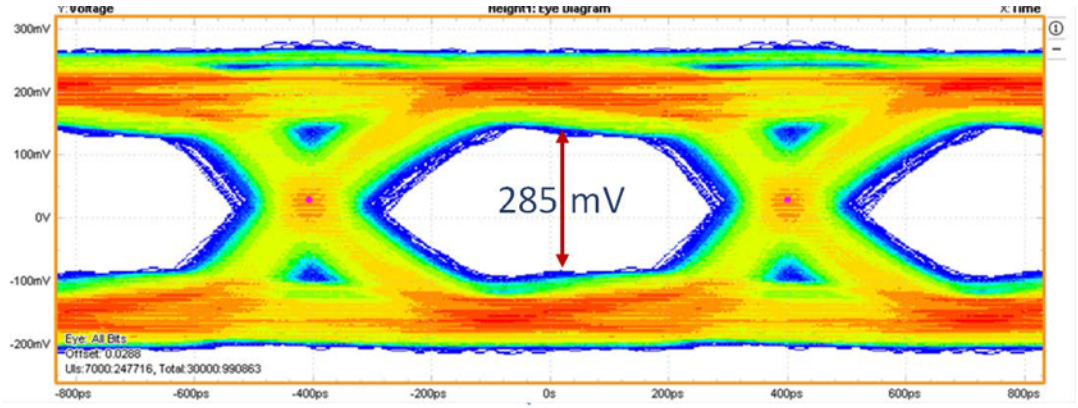


Error free DCD-DHP communication



Performance according to specs

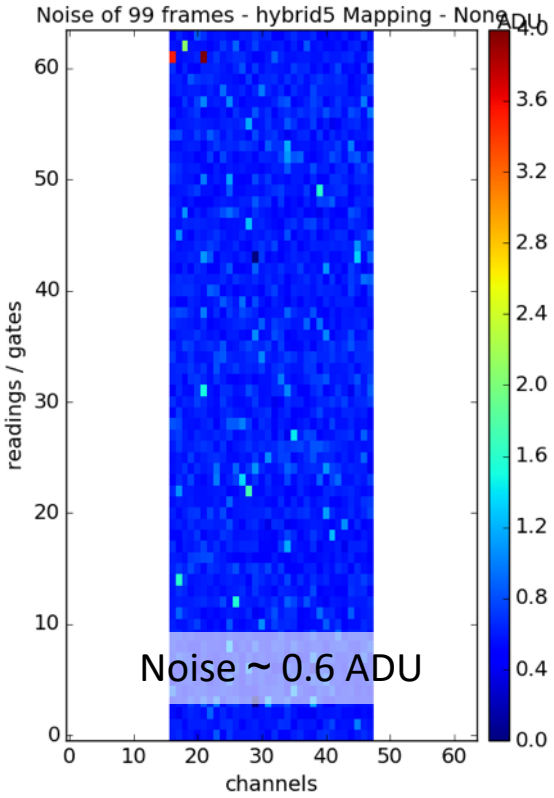
- High speed link
- Configuration and communication with DCD
- Data processing
- Switcher output sequences

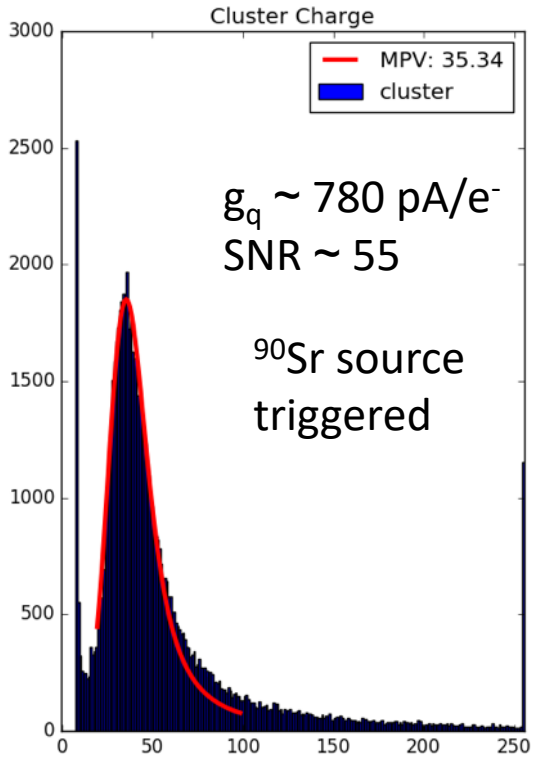


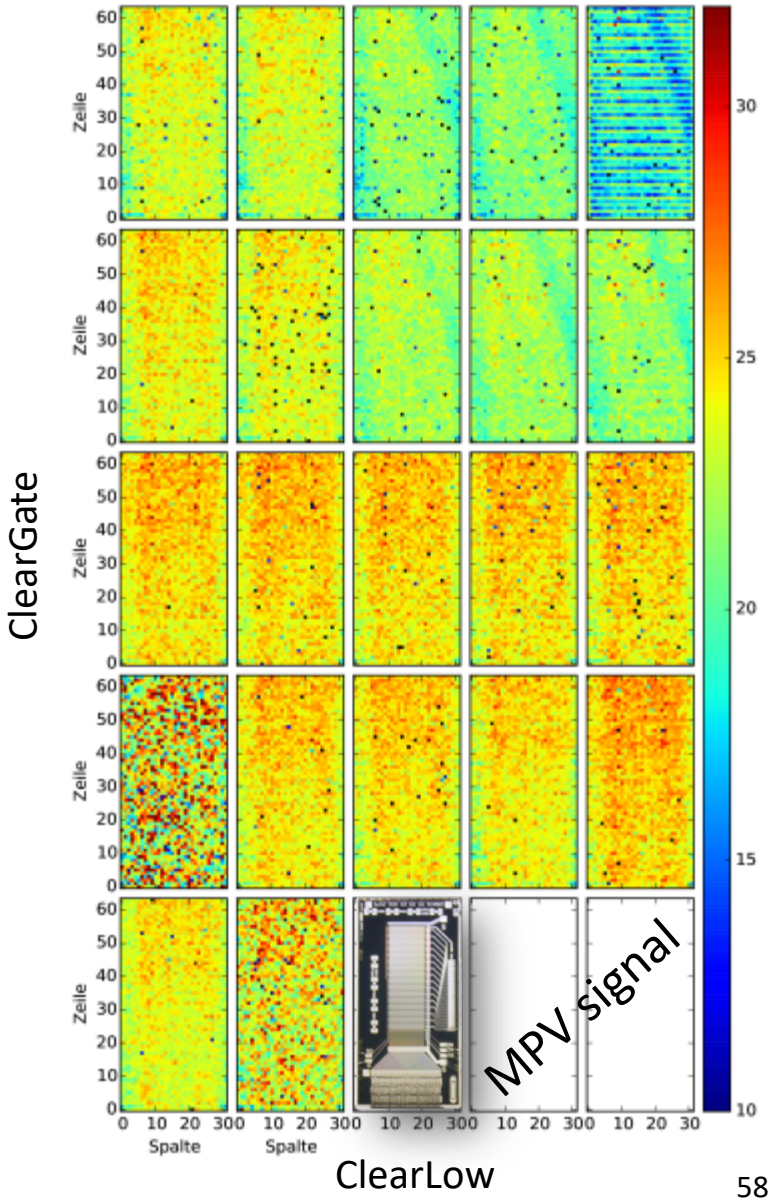
10 m Infiniband

DEPFET Characterization

- Optimization of DEPFET voltages
  - Source measurements

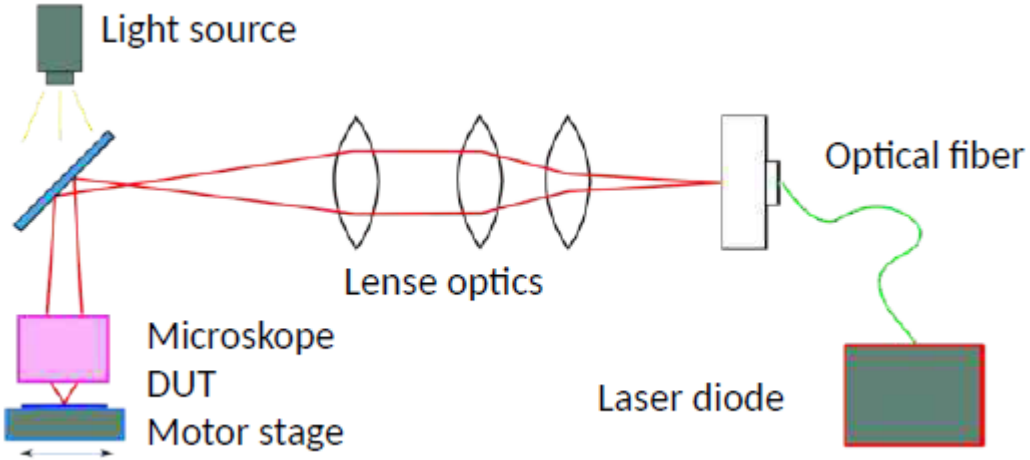


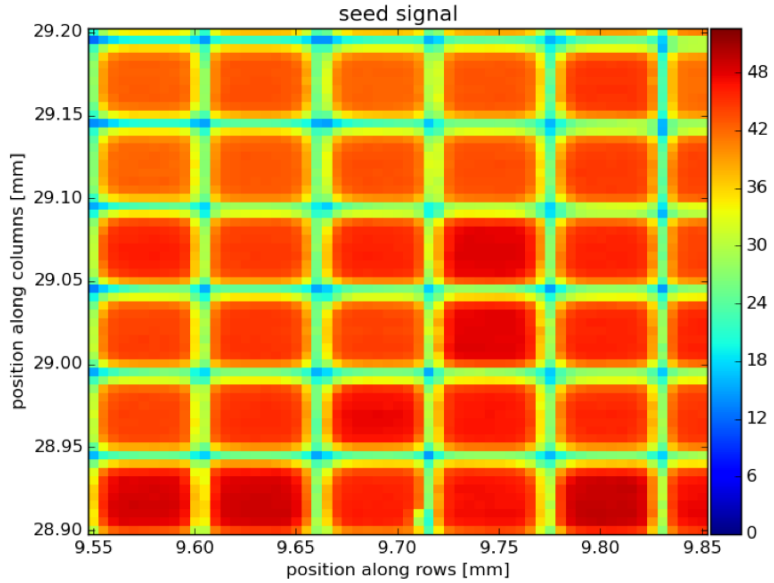


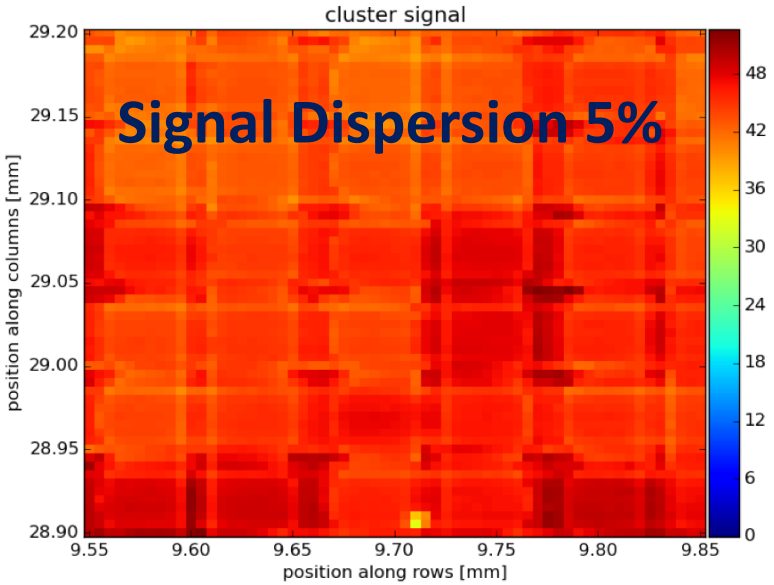


DEPFET Characterization

- Optimization of DEPFET voltages
  - Source measurements
  - Laser scans







- Laser focused through microscope
- ~3 µm spot size
- Laser moves over matrix – position resolution

Beam tests

- **DEPFET PXD extensively tested over several campaigns**
  120 GeV pions at CERN-SPS
  1-5 GeV electrons at DESY
  1T Magnetic field

- **Sensor properties**
  Charge collection homogeneity, operating points, efficiency, angular scans

- **System related aspects**
  Back end electronics

Here, just an appetizer

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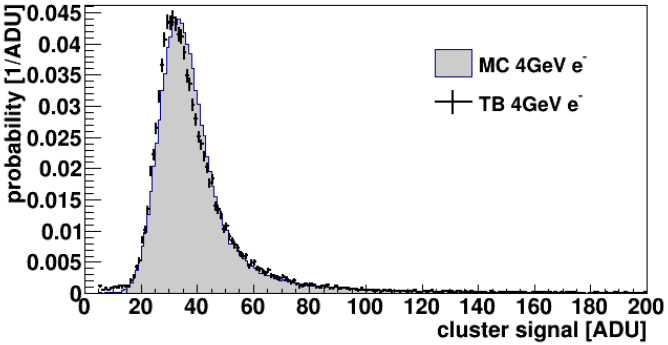
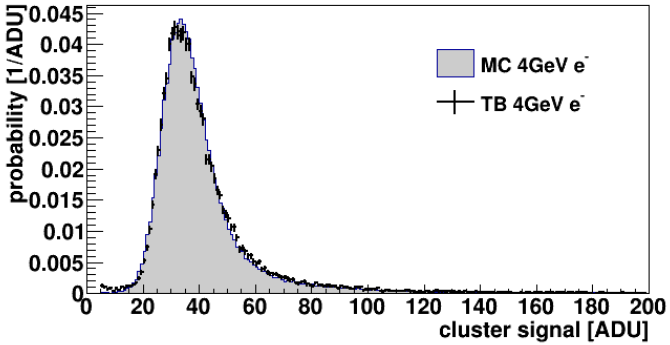
Belle II PXD MIP Signal

- Measured 4 GeV electrons at different incidence angles
- Checked against Geant4 simulation with DEPFET digitizer
- $g_q = 740 \pm 50$ pA/e$^-$ measured

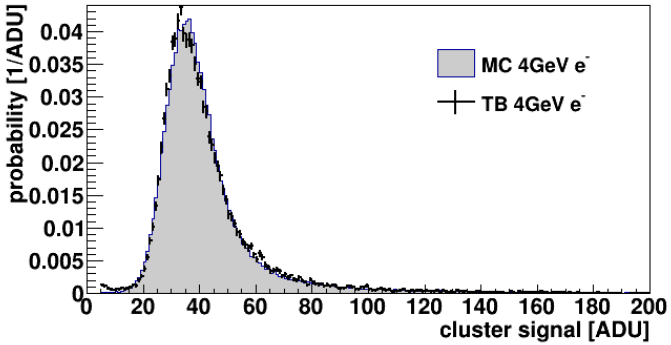
0 degree



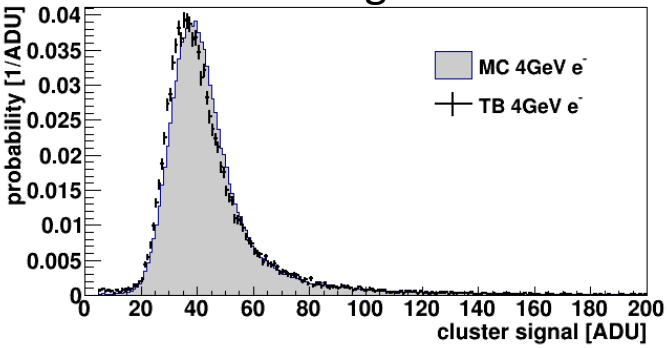
10 degree



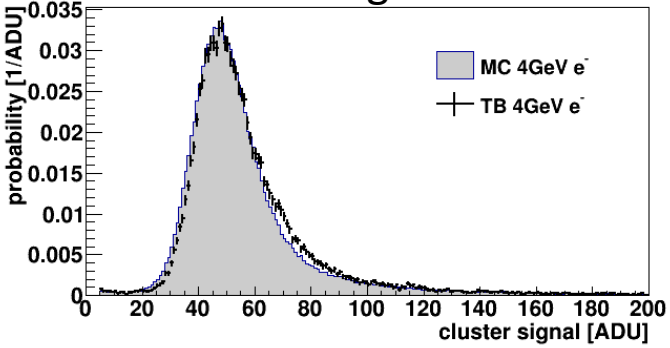
20 degree



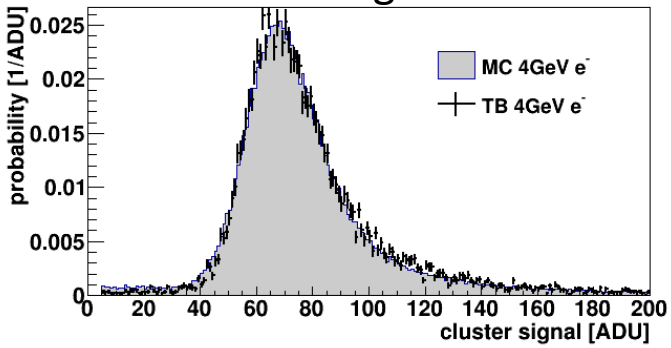
30 degree



45 degree



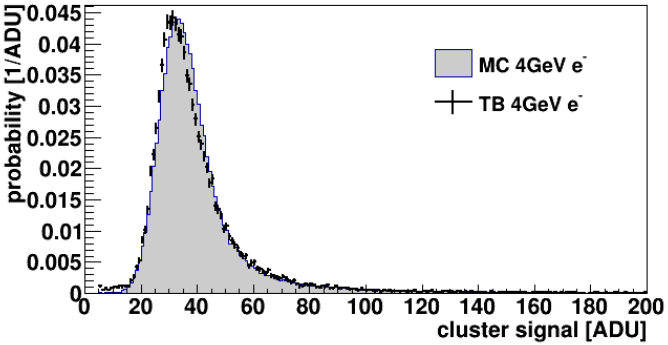
60 degree



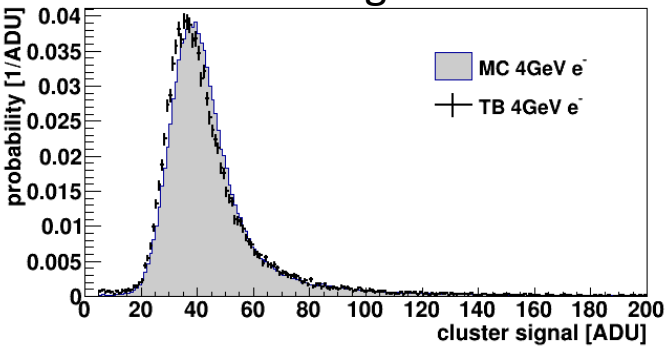
Belle II PXD MIP Signal

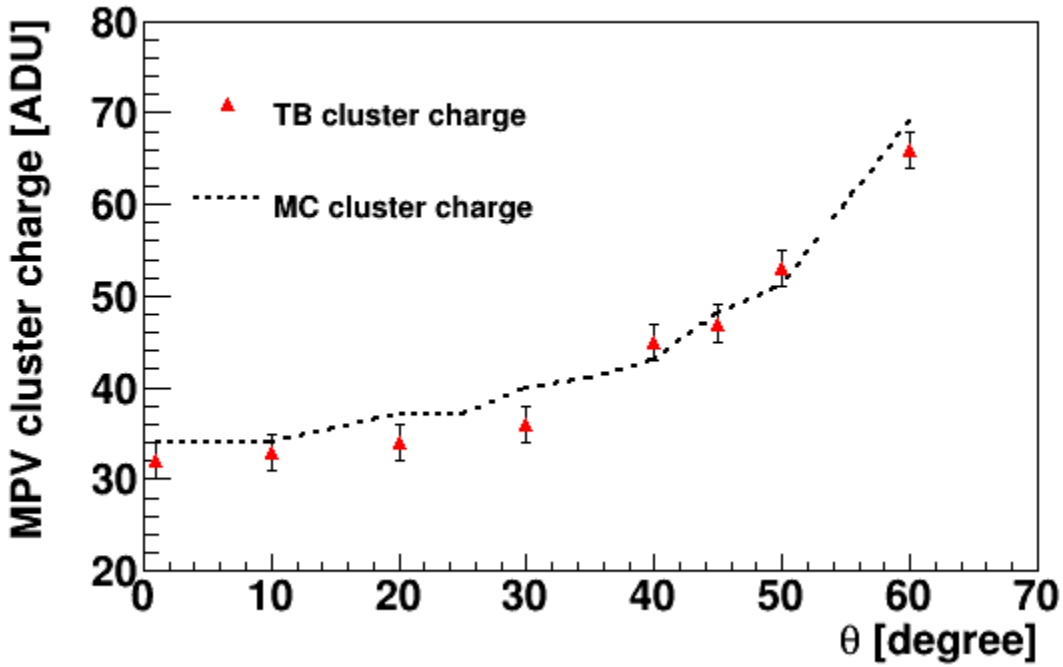
- Measured 4 GeV electrons at different incidence angles
- Checked against Geant4 simulation with DEPFET digitizer
- $g_q = 740 \pm 50$ pA/e$^-$ measured

0 degree



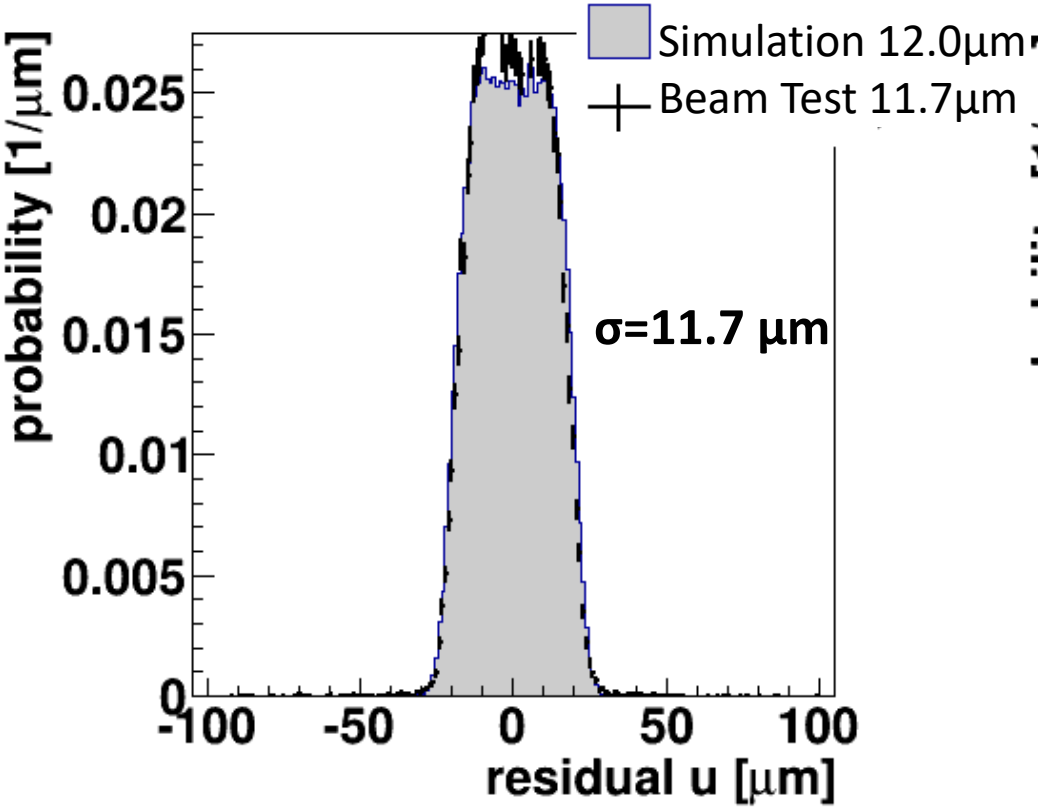
30 degree



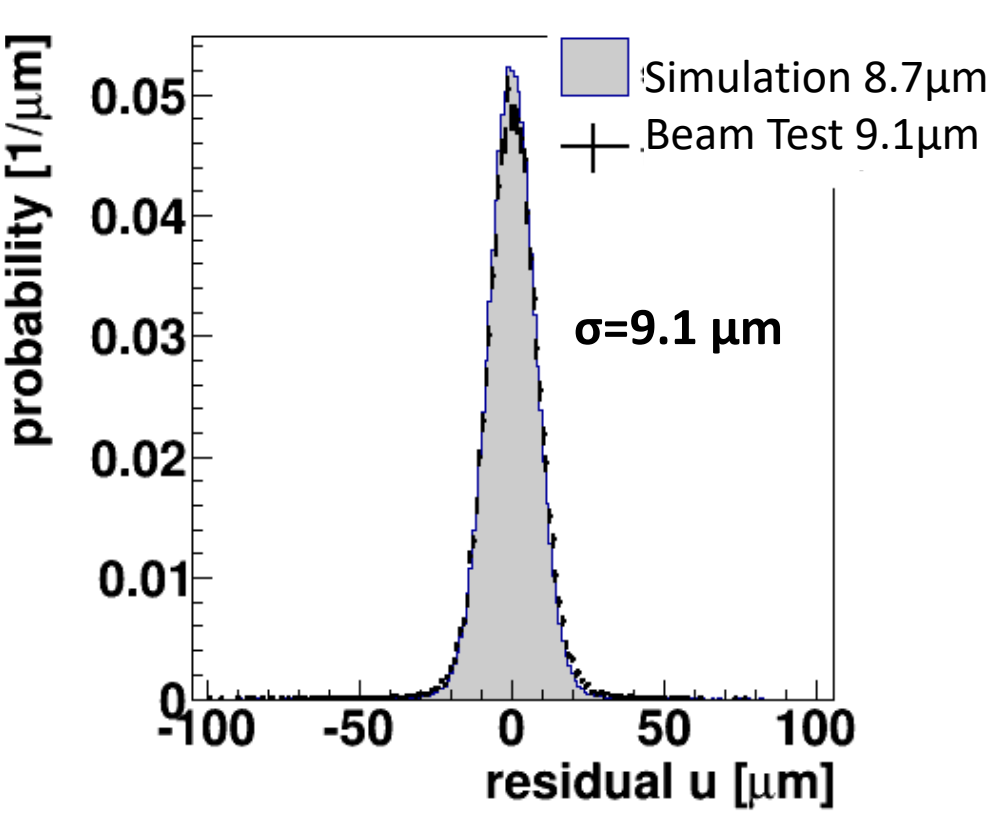


Belle II PXD Residuals

0° tilt: perp. incidence



30° tilt: many 2 pixel clusters

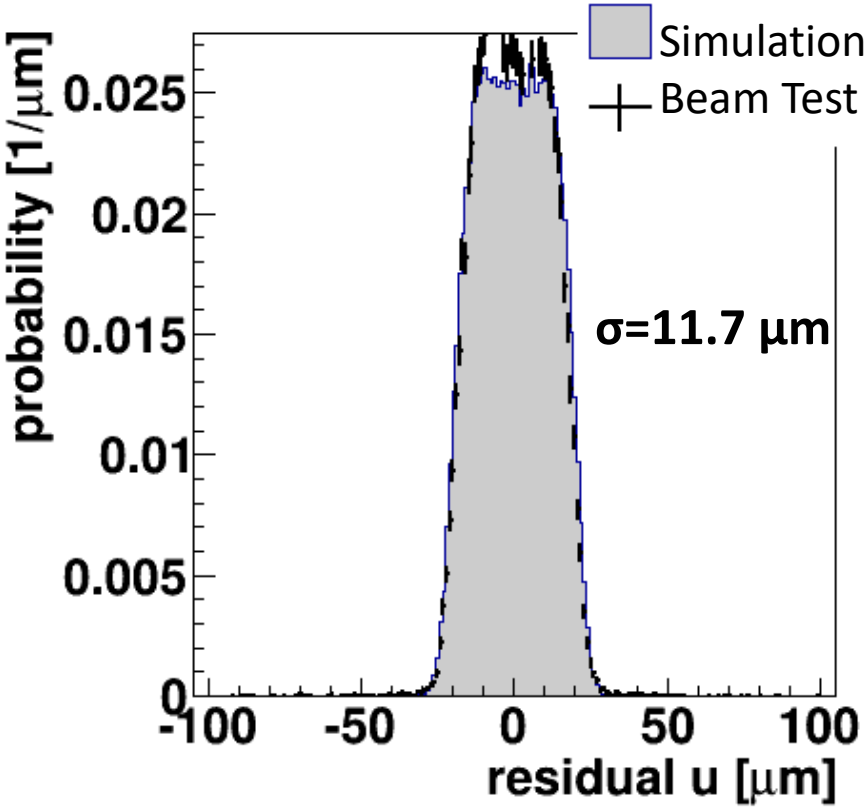


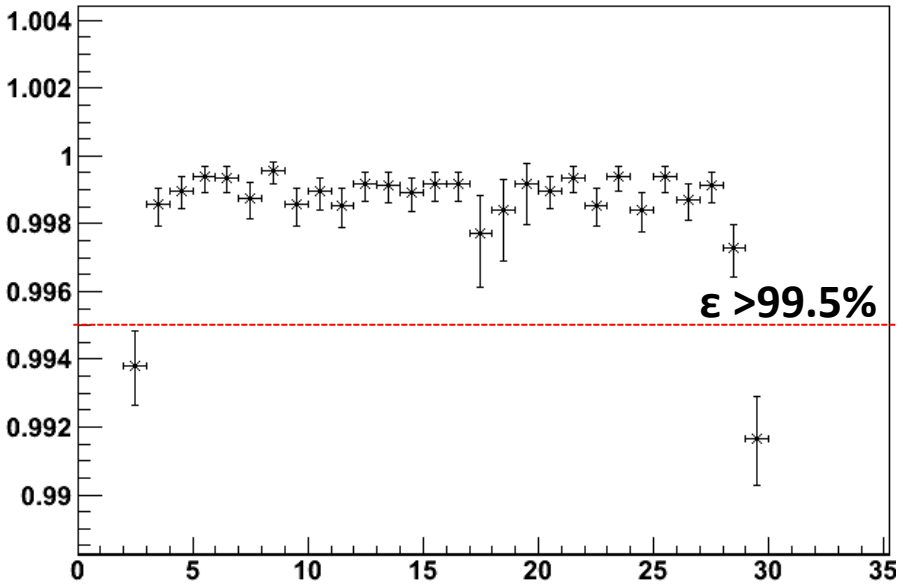
- Matrix tilted along column: multi-column clusters
- Expectation for single pixel readout: $\mathrm{RMS} = 50\,\mu\mathrm{m}/\sqrt{12} \approx 14.5\,\mu\mathrm{m}$

Belle II PXD Efficiency

universitätbonn

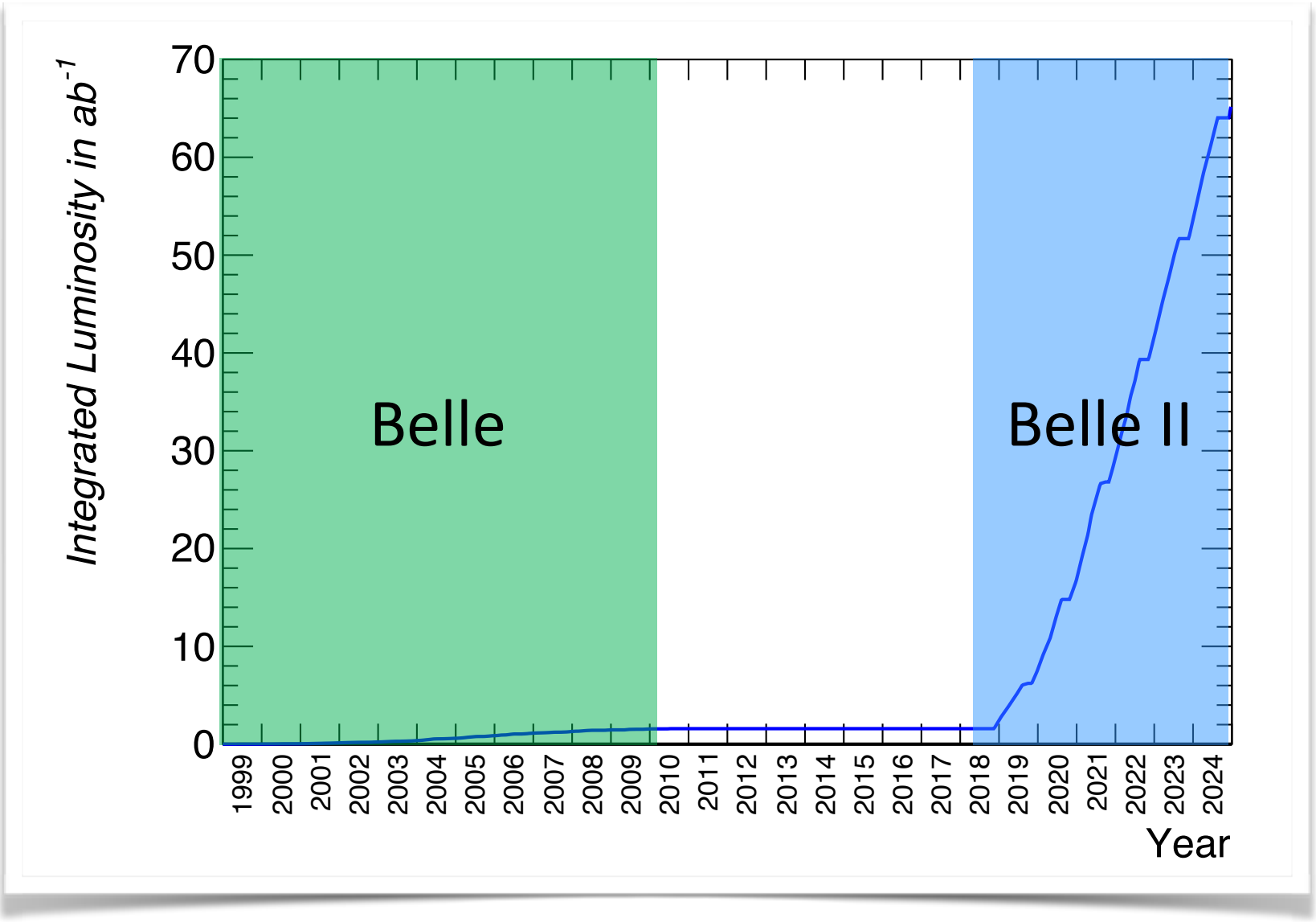
0° tilt: perp. incidence



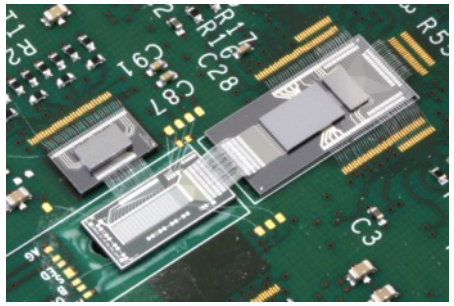


- Matrix tilted along column: multi-column clusters
- Expectation for single pixel readout: $\mathrm{RMS} = 50\,\mu\mathrm{m}/\sqrt{12} \approx 14.5\mu\mathrm{m}$

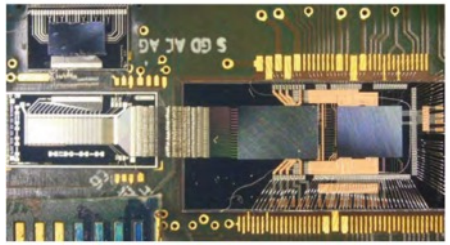
Belle vs Belle II



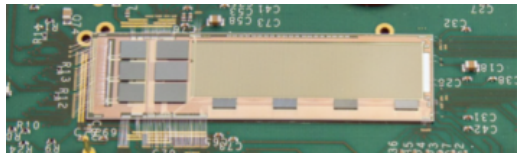
Several Test Vehicles



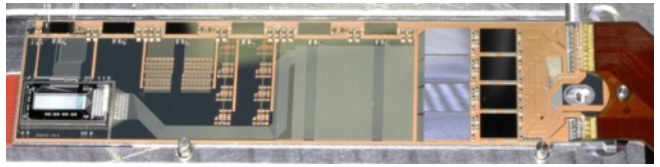
Hybrid4: DCD stand-alone tests (/w small DEPFET matrix)
DCDB2, DCDB4
DCDr/o as interface to FPGA System
Different versions of SWB, Switcher-B18 v2.0 (gated mode)



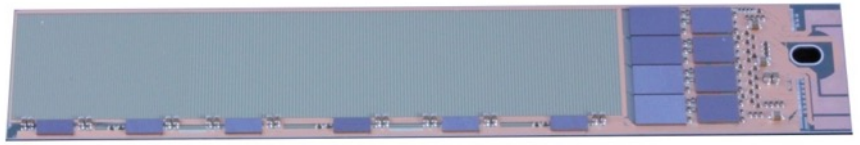
Hybrid5: single ASIC system (/w small DEPFET matrix)
DCDB4
DHPT 1.0
Switcher-B18 v2.0



Hybrid6: first multi-chip system with large proto. matrix
DCDB2, DHP0.2, Switcher-B18 v2.0



EMCM: main test vehicle for multi-chip systems (/w matrix)
Different versions of ASICs…
DCDB2, DCDB4, DHP0.2, DHPTv1.0, Switcher-B18 v1.0 & v2.0



PXD9 Pilot Modules:
DCDB4, DHPT1.0 (&DHPT1.1), Switcher-B18 v2.0