The Silicon Vertex Detector of the Belle II experiment

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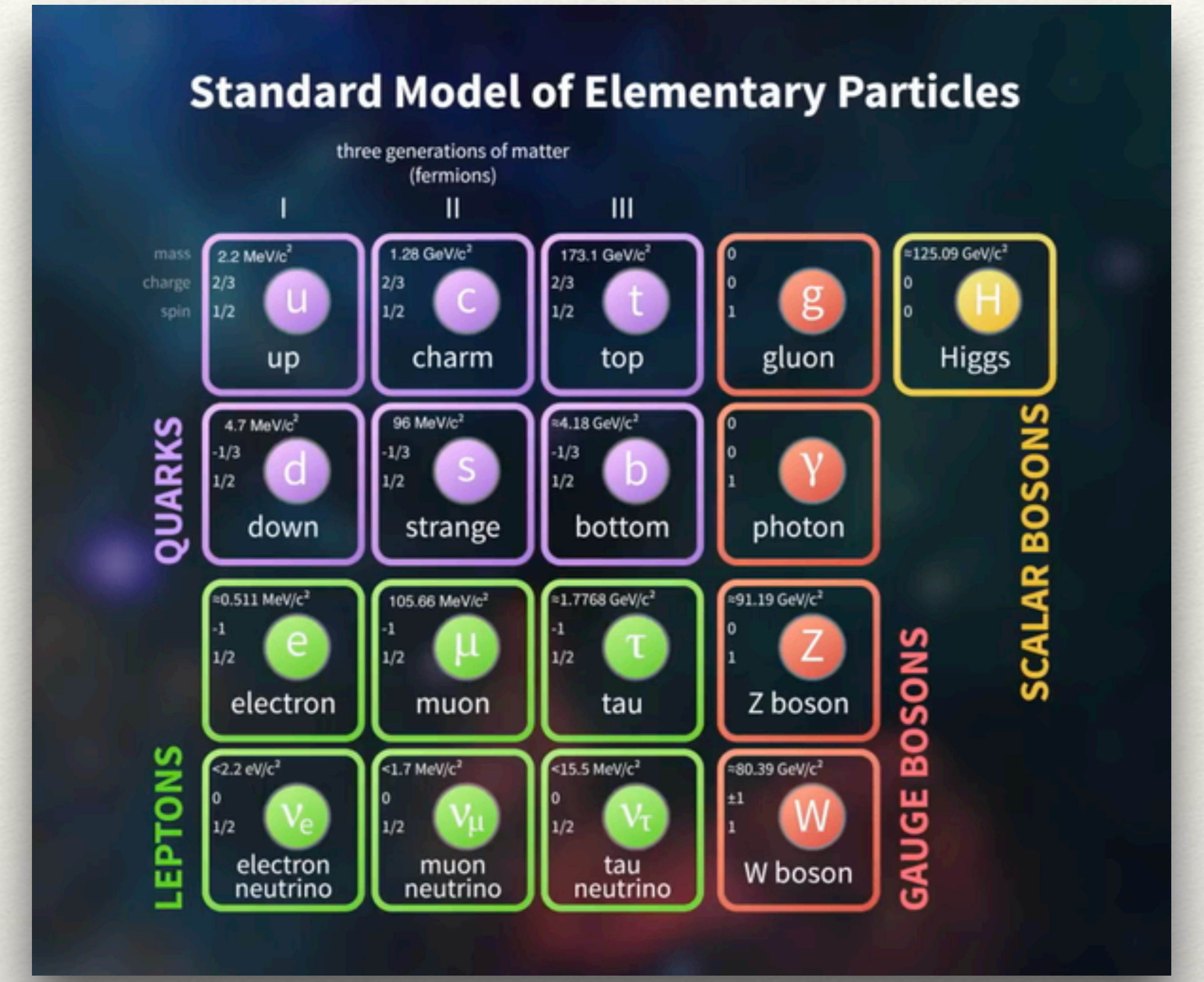
Bologna - Aperitivi Scientifici

OUTLINE

- Physics motivations for HEP experiments
- The Belle II experiment at SuperKEKB
- The Silicon Vertex Detector
  - Components
  - Assembly process
  - Commissioning - installation - operation
  - Start of data taking and performances
- Towards VXD upgrade

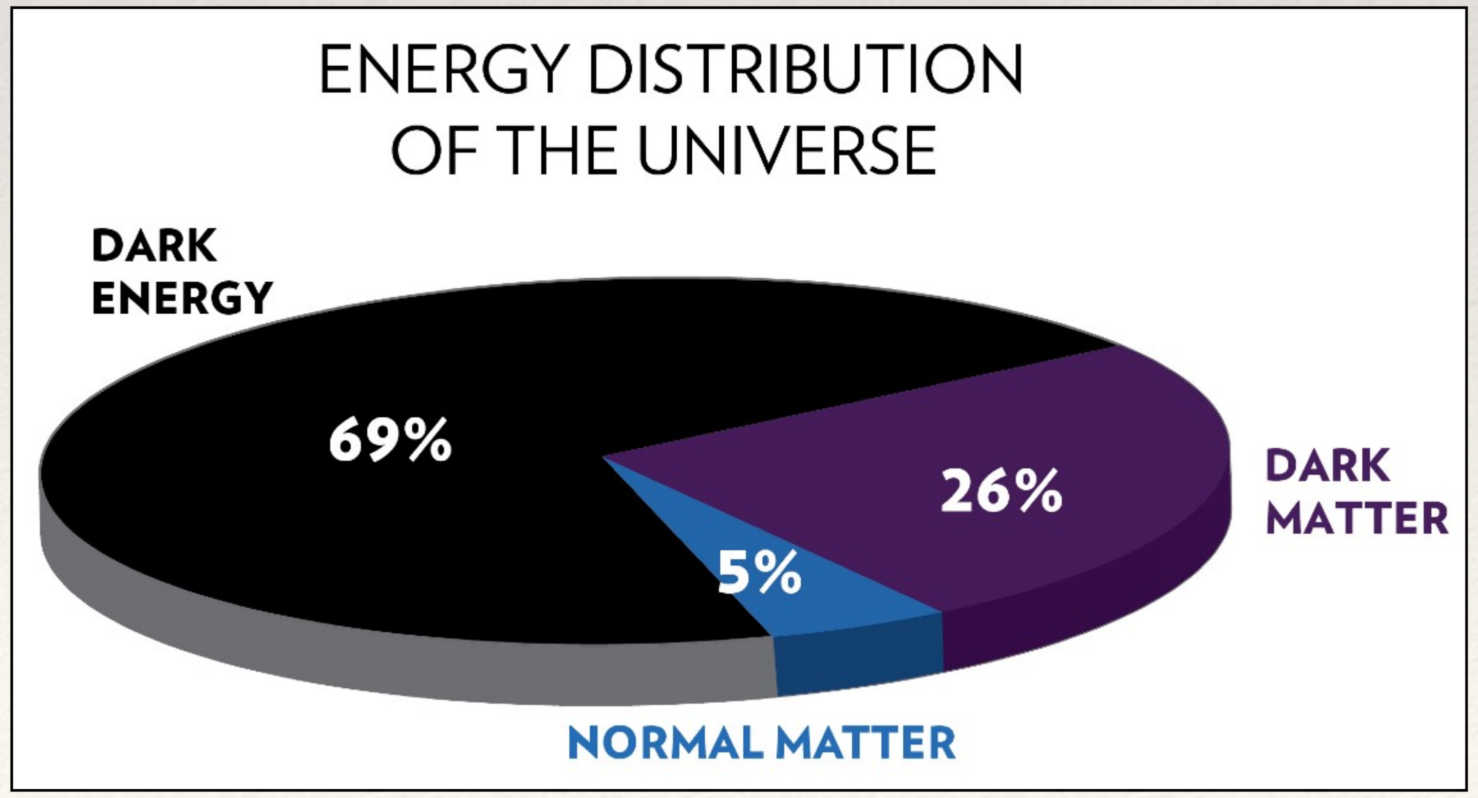
Our current understanding of the universe

The Standard Model can well explain the world as we see it…



- ✓ Elementary particles and fundamental interactions are observed and well characterised.
- ✓ Bound states, mesons and baryons are well predicted.
- ✓ Interactions between particles are well predicted.
- ✓ Branching ratios, CP violation are predicted by the model and consistent with observations.

… but … there is evidence that something is missing in the Standard Model



- Asymmetry between matter and anti-matter in the universe not explained.
- 95% of the universe is made by dark matter and dark energy.

Physics motivations for experiments

- Investigation of the discrepancies leads to the need for physics experiments.
- To find hints of New Physics, high energy Physics experiments at colliders took two different paths:

Energy frontier

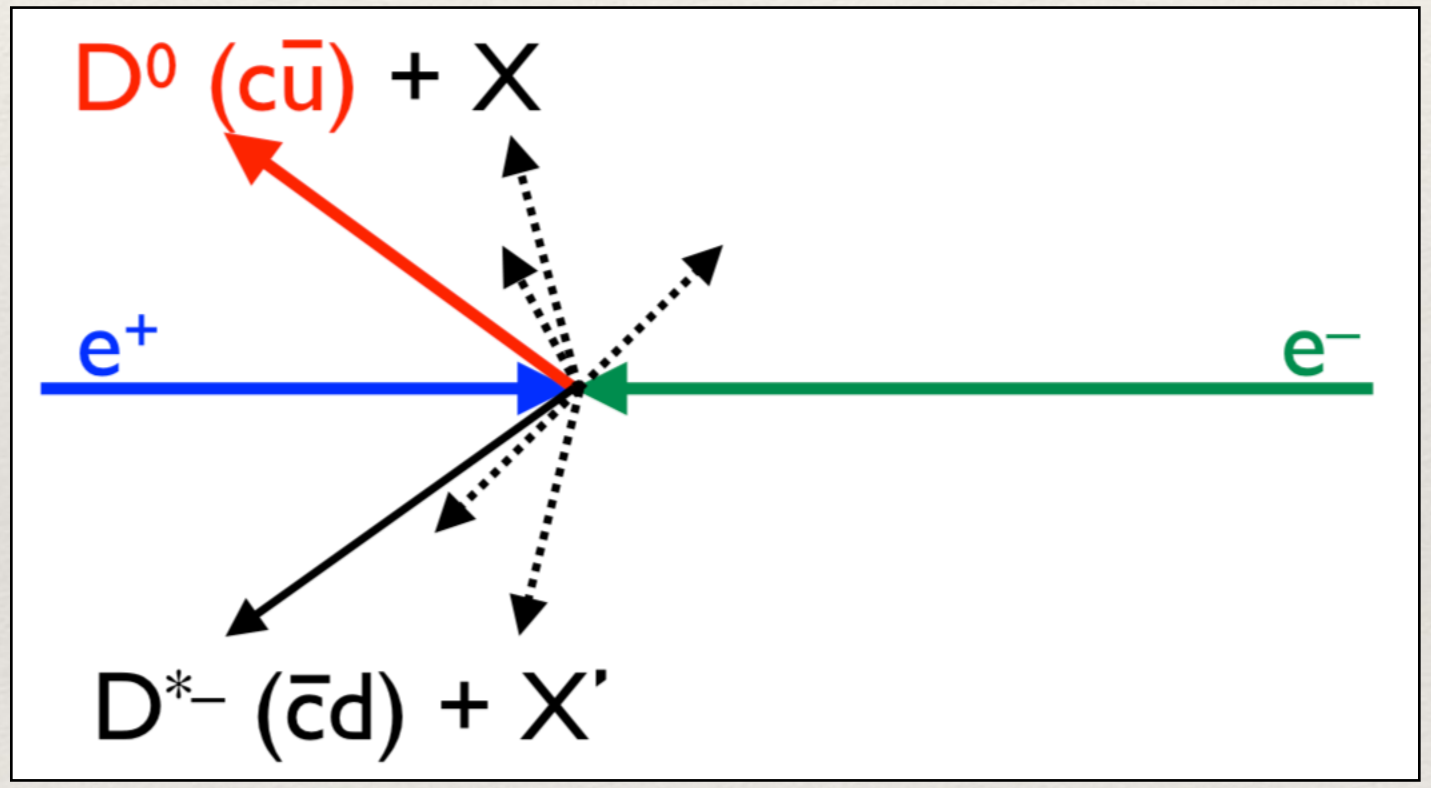
(Tevatron, LHC)

Intensity frontier

(PEP-II, KEKB)

B-factory

$e^+e^- \longrightarrow \Upsilon(4S) \longrightarrow B\overline{B}$



- Clean event environment
- High trigger efficiency
- High statistics samples
- High efficiency detection of neutrals
- Time-dependent analysis
- Smaller cross section wrt hadron colliders

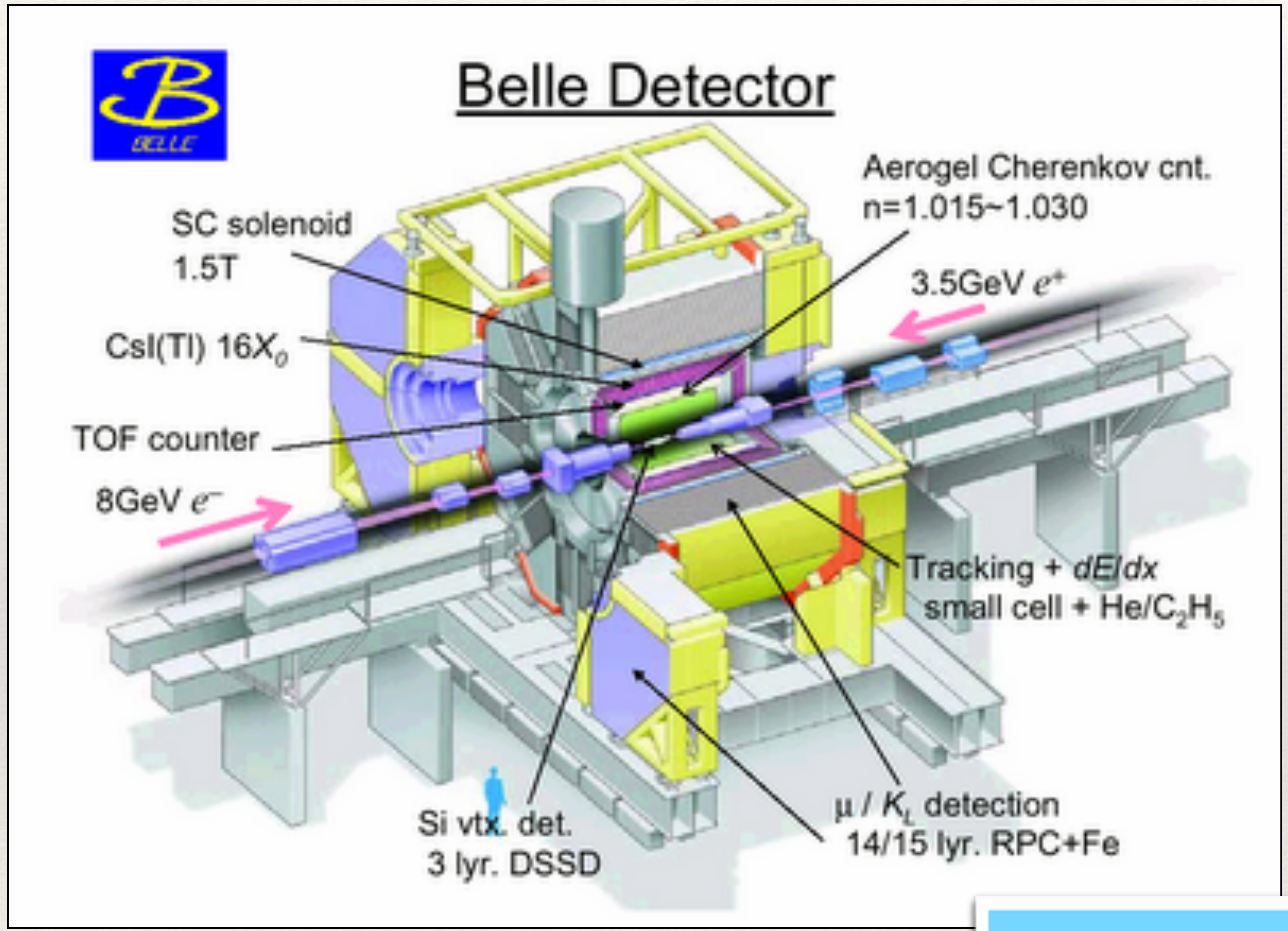
Provide a big number of events to observe extremely rare processes in the decay of B and D mesons or τ leptons, or very subtle effects in the time dependence of more abundant decays.

CP violation in B mesons decay can be studied/observed, provided a big enough data sample.

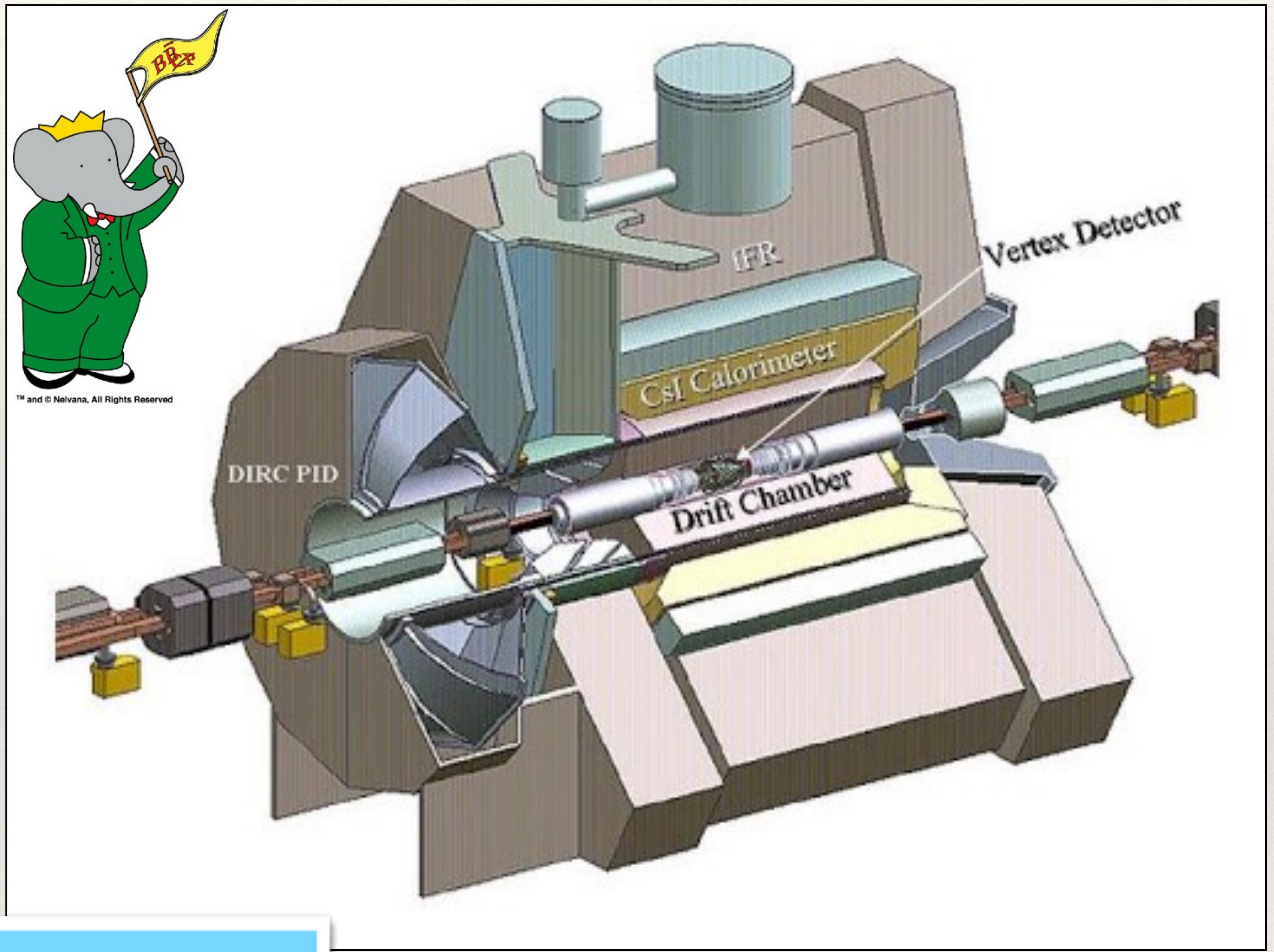
First generation of B-factories

- CKM mechanism confirmed at first B-factories, CP violation correctly predicted in the SM.

Belle - KEKB @ KEK | 1041 fb^{-1}



BaBar - PEP-II @ SLAC | 531 fb^{-1}

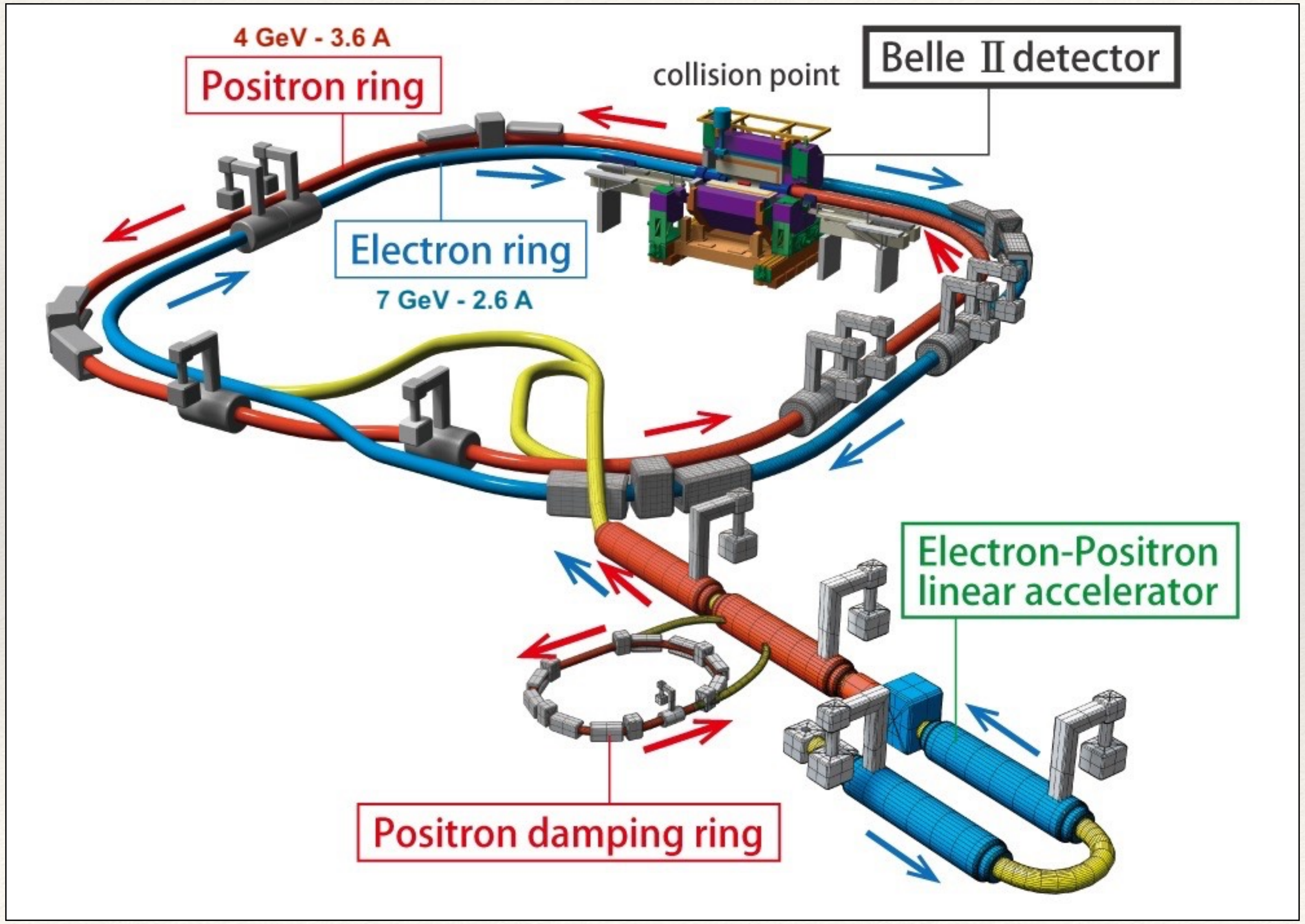


$$e^+e^- \longrightarrow \Upsilon(4S) \longrightarrow B\bar{B}$$

Measurements at Belle and BaBar limited by statistical error → Increase data sample

The SuperKEKB accelerator

- Asymmetric e^+e^- collider, aims to the unprecedented instantaneous luminosity of **8 x 10^{35} cm^{-2} s^{-1}**
- Upgrade of KEKB machine, that reached **L_{inst} = 2.1 x 10^{34} cm^{-2} s^{-1}** and a data sample of **1 ab^{-1}**
- **E_{CM}** = 10.58 GeV, **Υ**(4S) - Belle II expected integrated luminosity of about **50 ab^{-1}**

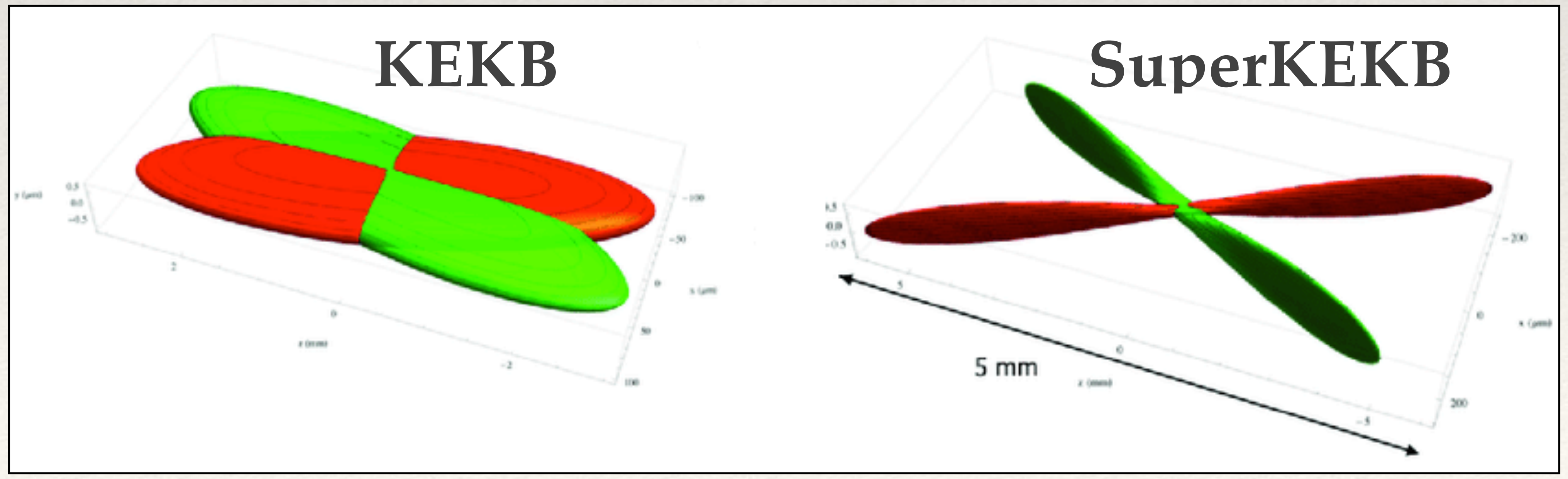


SuperKEKB luminosity 40 times higher than KEKB:
- **Reduce by factor 20 vertical betatron function at IP**
- **Increase beam currents by factor 2**

New collision scheme: **nano-beam scheme**

- Small beta function at IP
- Large Piwinski angle

$$\phi_{Piw} = \frac{\sigma_z}{\sigma_x^*} tan\theta_x$$



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	KEKB		SuperKEKB	
	LER	HER	LER	HER
E [GeV]	3.5	8.0	4.0	7.0
θ_x [mrad]	0 (11)		41.5	
ε_x [nm]	18	24	3.2	4.6
ε_y [pm]	150	150	8.64	12.9
β_x^* [mm]	1200	1200	32	25
β_y^* [mm]	5.9	5.9	0.27	0.30
σ_x^* [μm]	147	170	10.1	10.7
σ_y^* [nm]	940	940	48	62
n_b	1584		2500	
I [A]	1.64	1.19	3.6	2.6
L [cm^{-2} s^{-1}]	2.1 x 10^{34}		8.0 x 10^{35}	

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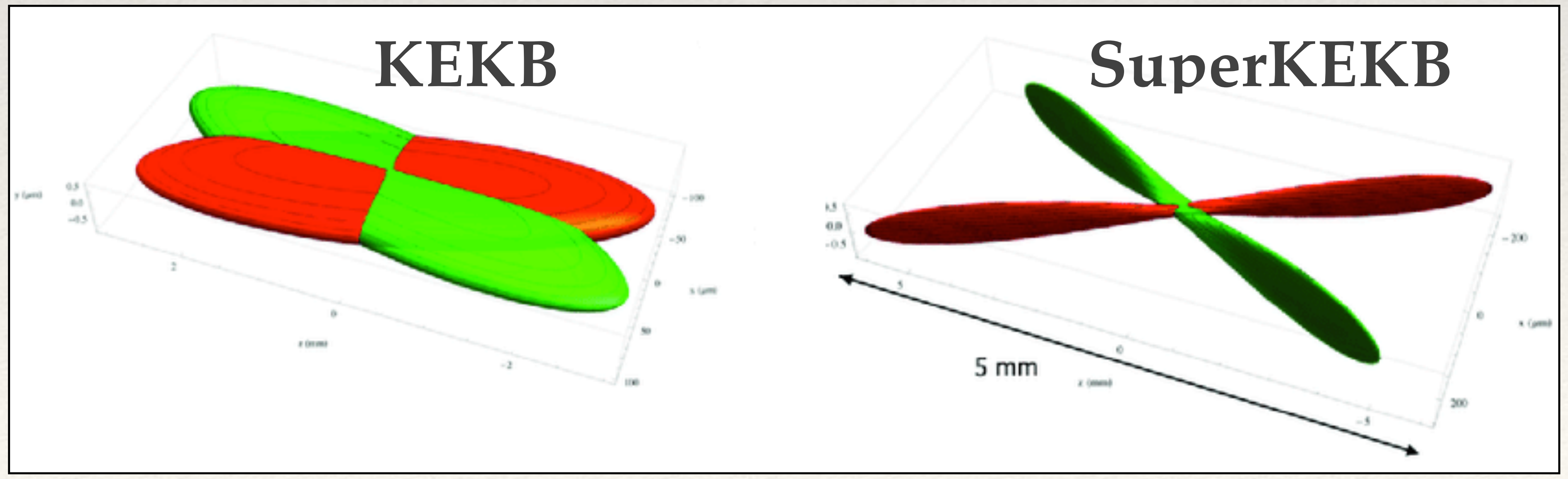
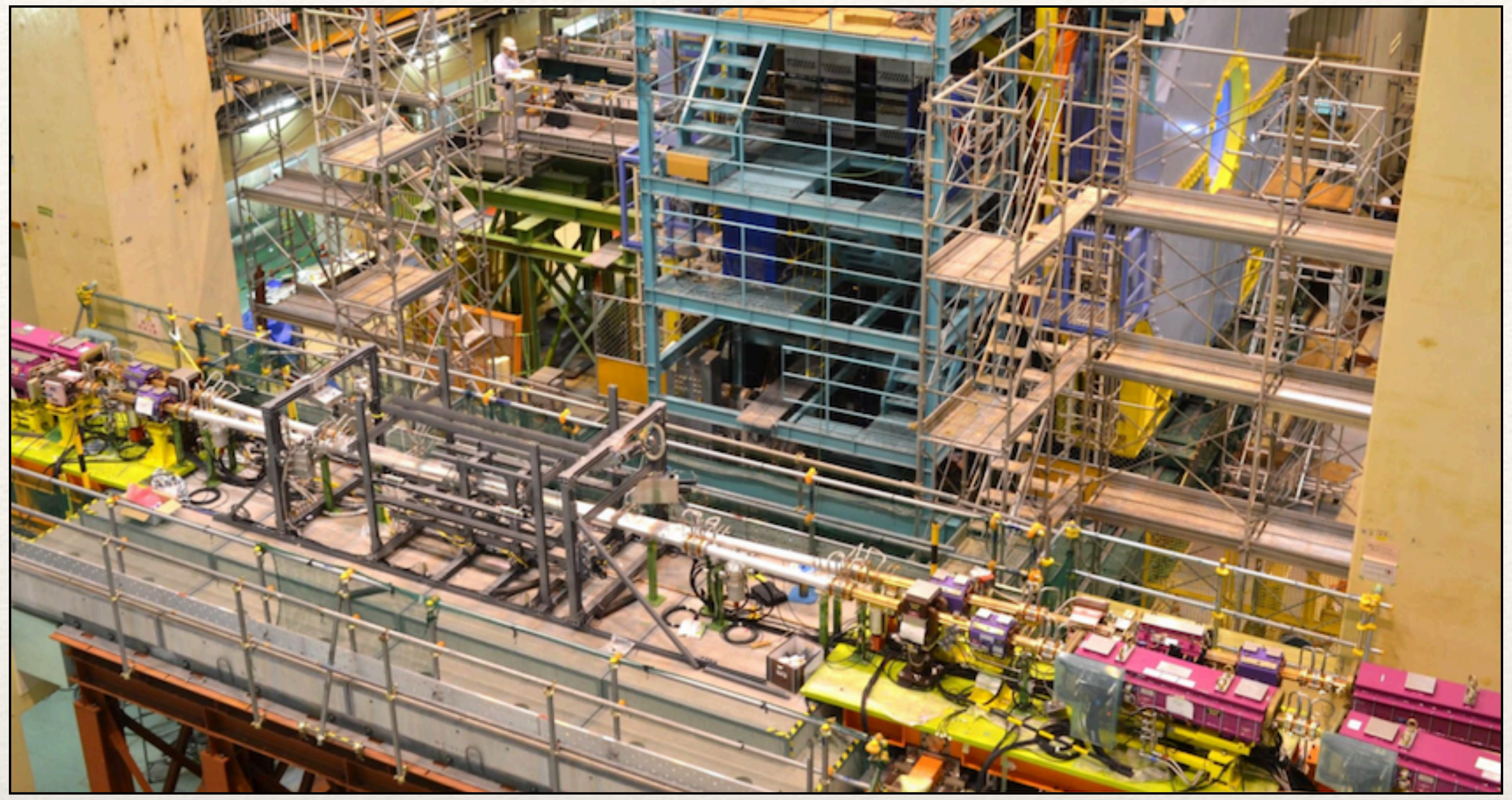
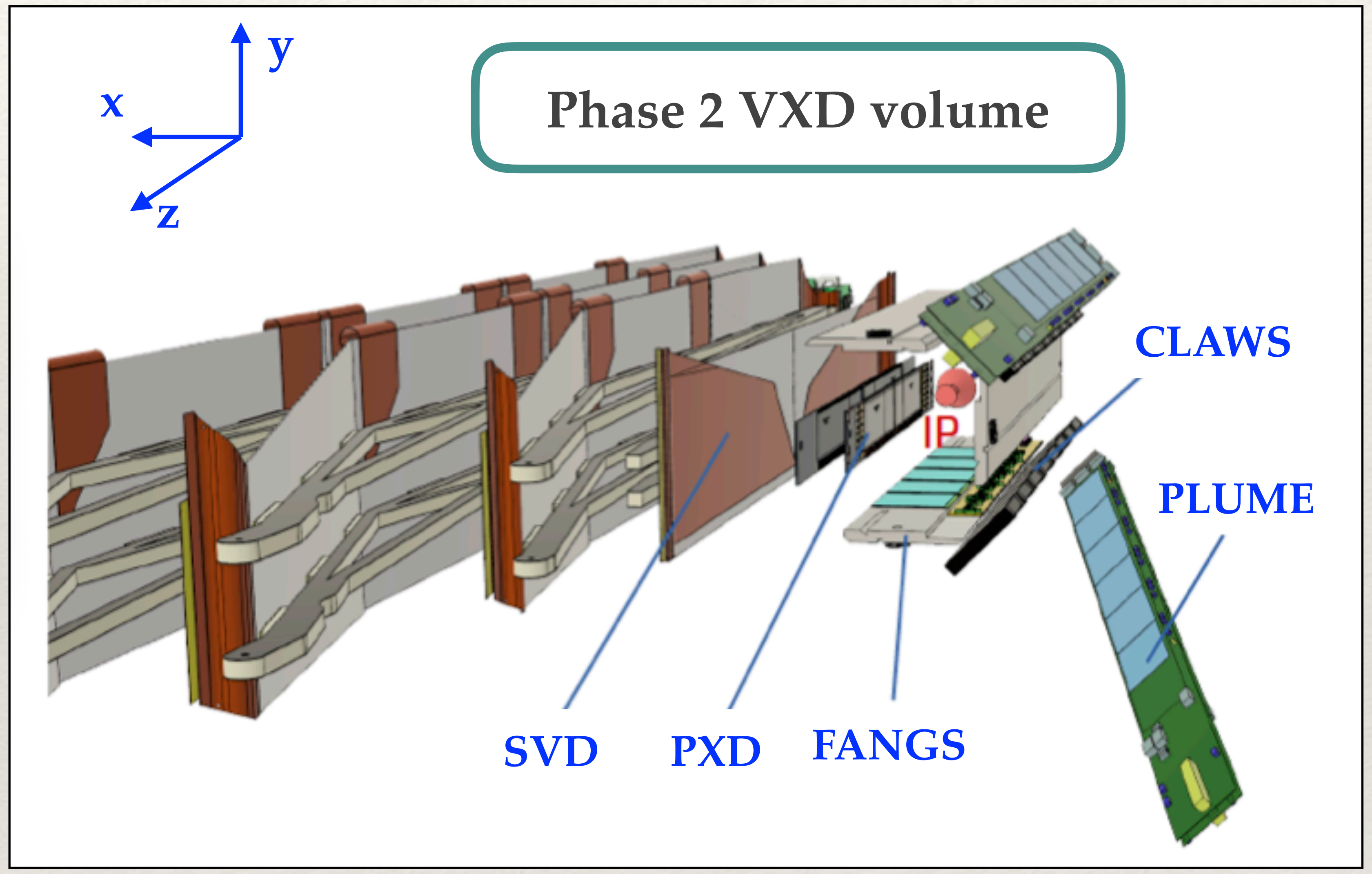


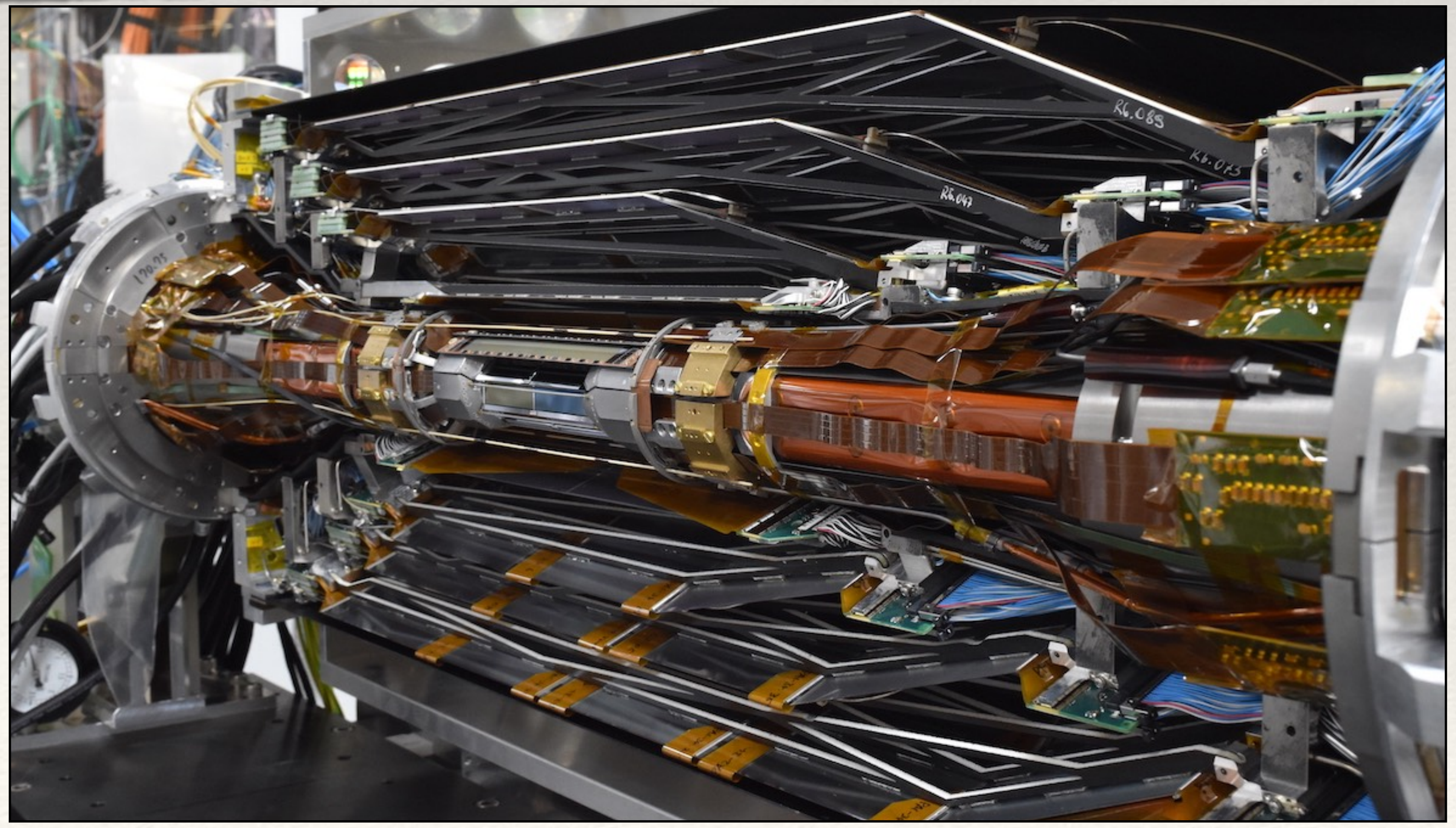
SuperKEKB commissioning



- Phase 1 - 2016: no Belle II detector, no Final Focus system, no collisions. BEAST detectors and first circulating beams.

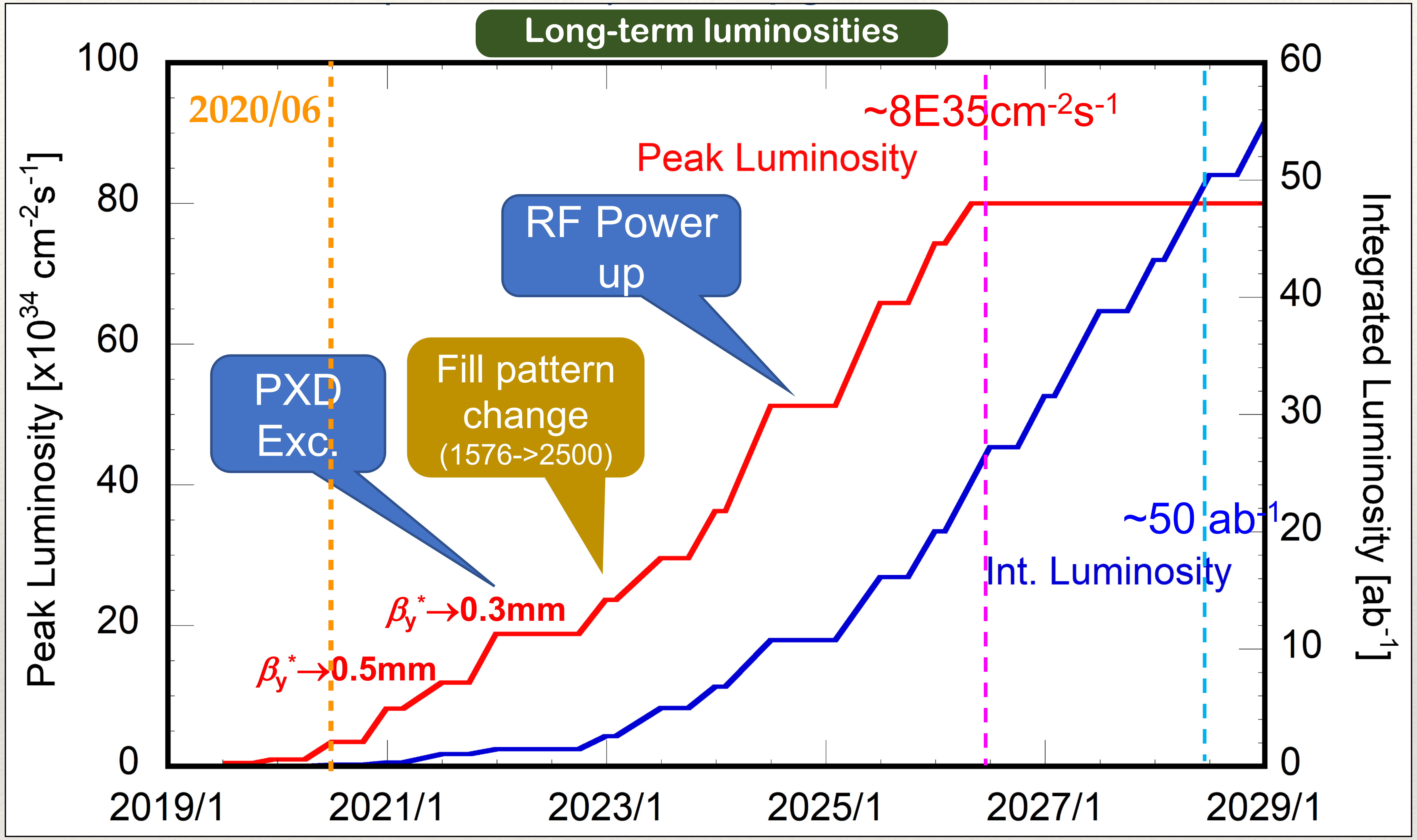


- Phase 2 - 2018: Belle II detector in its final position, BEAST VXD detectors installed, Final Focus system in place, first SuperKEKB collisions, nano beam scheme verified, background evaluation before VXD installation.



- Early Phase 3 - 2019: VXD detector installed, SuperKEKB in its final configuration, added new collimators, established continuous injection.

Operations prospects



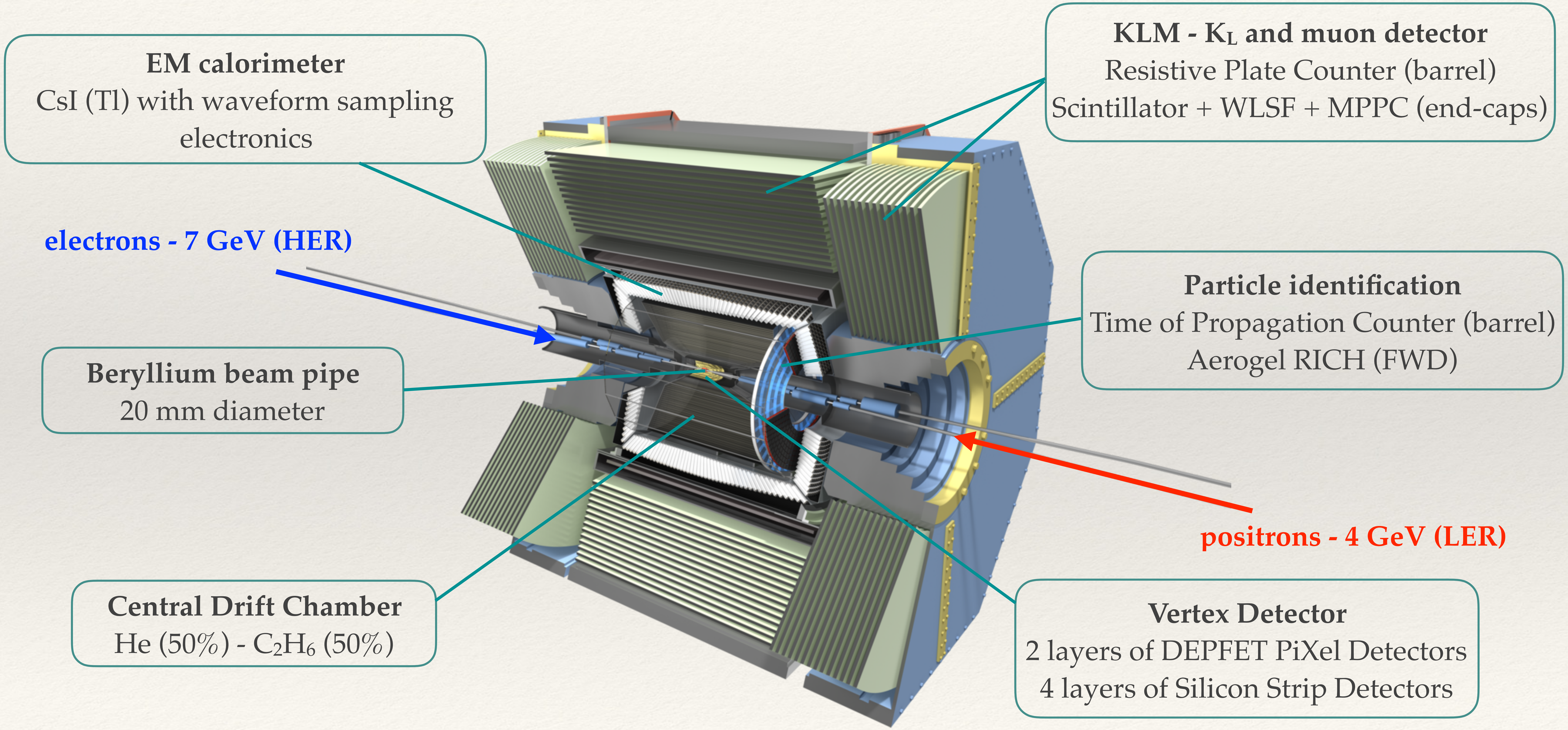
- Belle II plans to get data 8 months per year for the next 10 years.
- A possible shutdown (> 6 months) may happen in 2022, still under discussion.
- Another possible long shutdown foreseen around 2026 for a RF + IR upgrade.

- During the current run, SuperKEKB delivered a peak luminosity higher than the one achieved by KEKB, and it's aiming to deliver to Belle II the highest luminosity ever by the end of the run (July 1st).

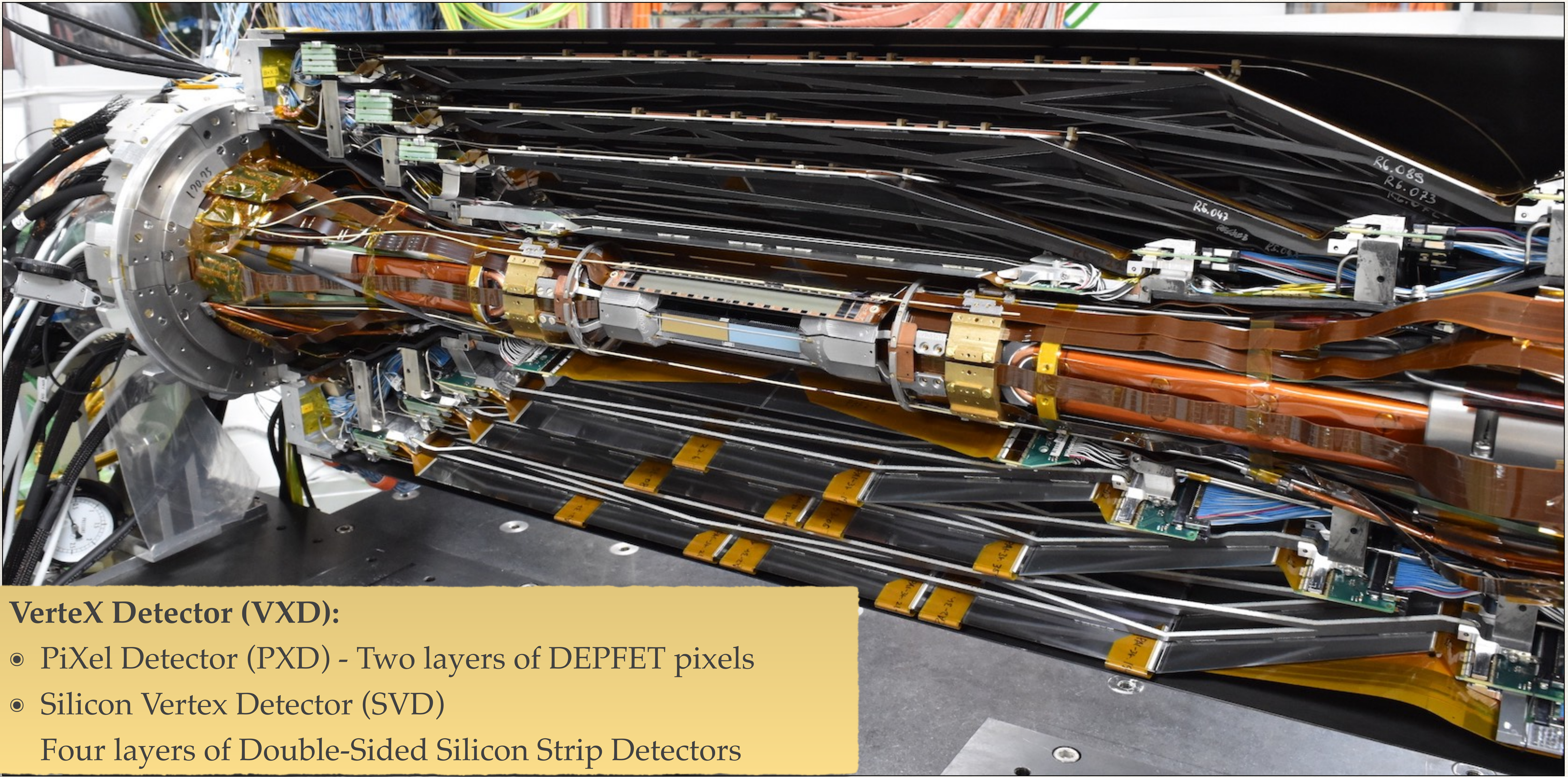
- Reached $\beta_y^* = 1$ mm (already a factor 6 better than KEKB), the smallest ever achieved
- SupreKEKB running stably at $L = 2.2 \times 10^{34}$ cm^{-2} s^{-1}
- So far Belle II recorded 67 fb^{-1}, with a data taking efficiency in the ongoing run of 90%.

The Belle II detector

- Reduced boost ($\beta\gamma = 0.28$) & high luminosity / background → thin pixel detector at small radius & silicon strip detector with fast readout electronics.

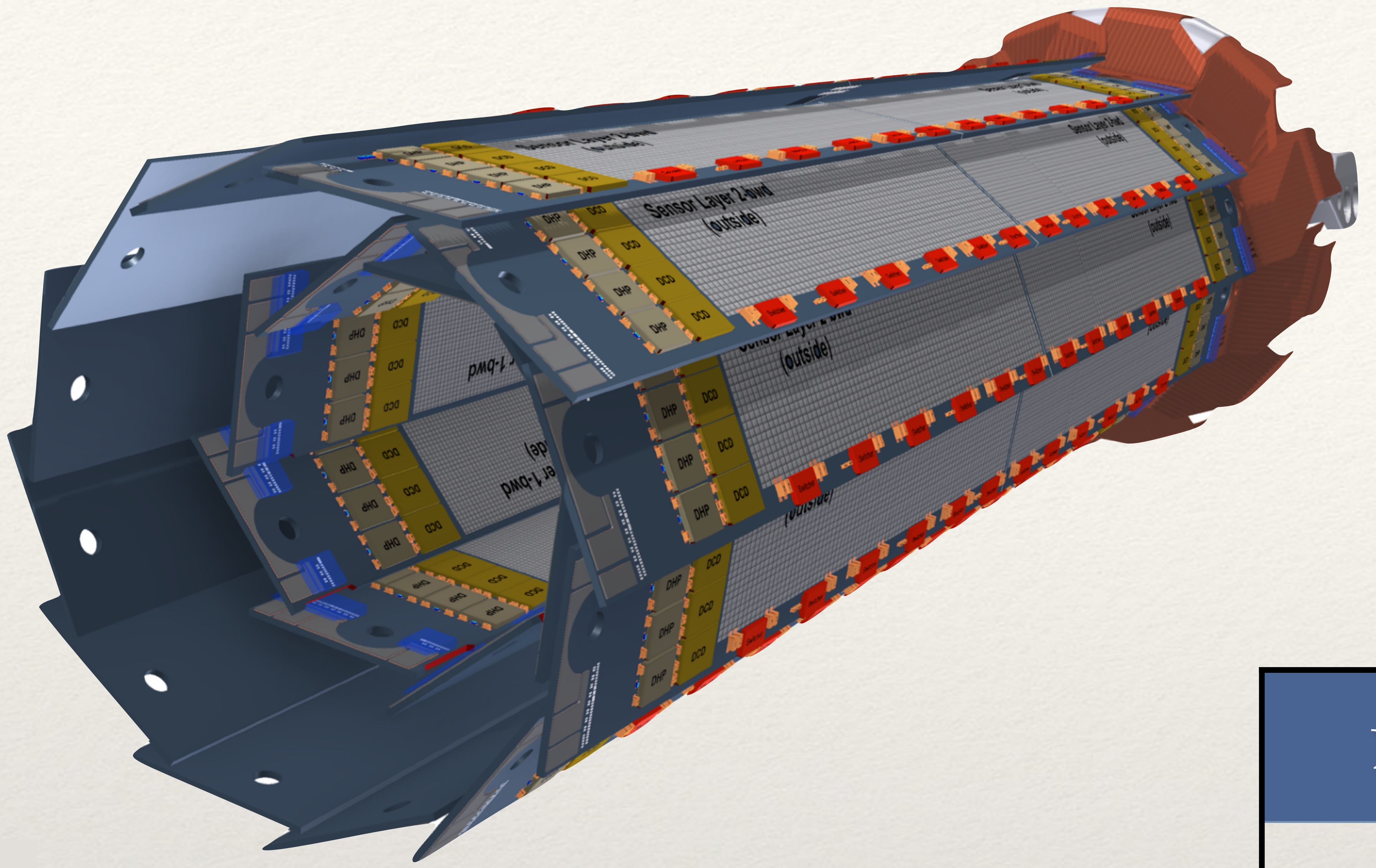


The VerteX Detector - VXD



- **VerteX Detector (VXD):**
  - PiXel Detector (PXD) - Two layers of DEPFET pixels
  - Silicon Vertex Detector (SVD)
    Four layers of Double-Sided Silicon Strip Detectors

The PiXel Detector - PXD



Belle

$\beta\gamma = 0.43$ $r_1 = 30$ mm

Belle II

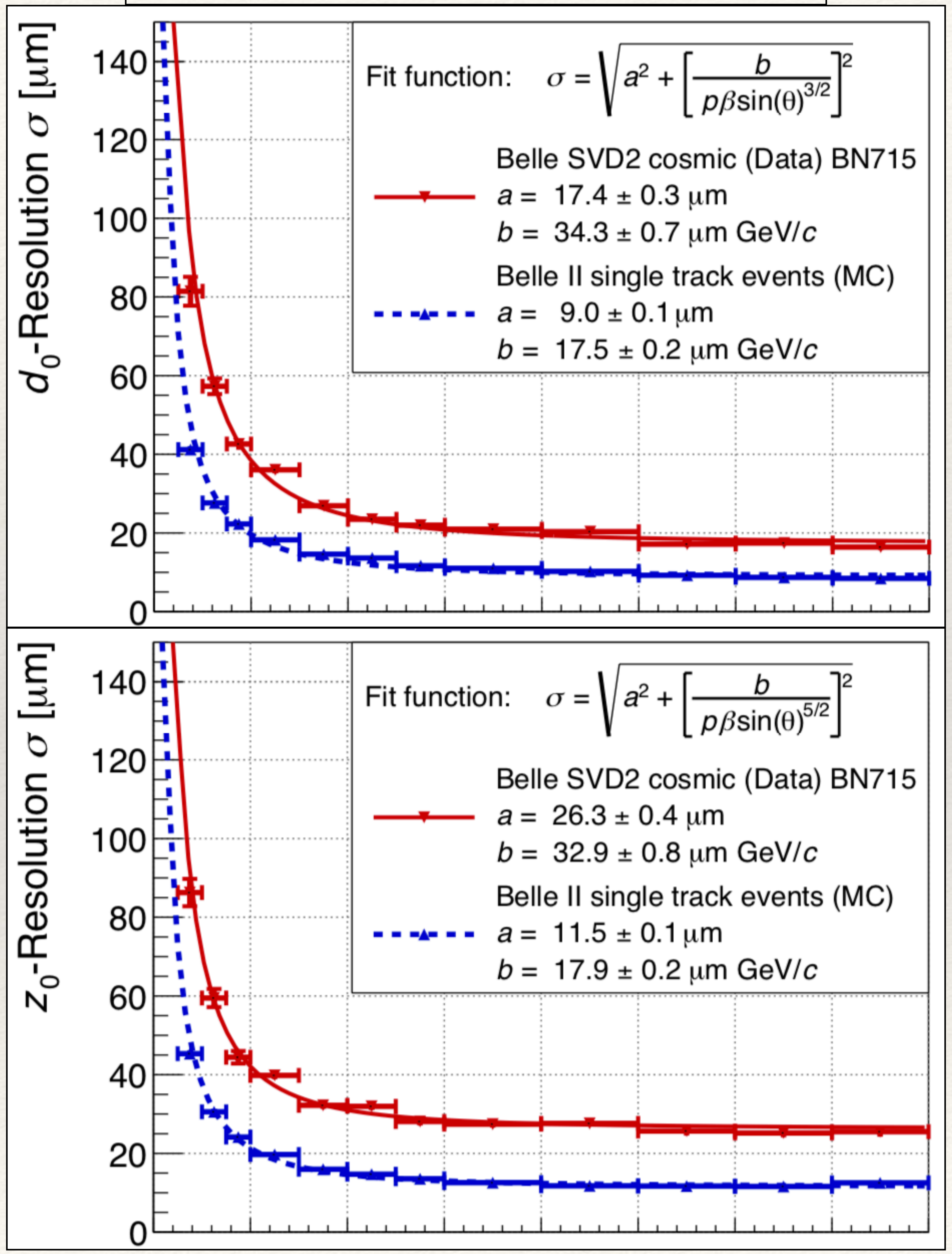
$\beta\gamma = 0.28$ $r_1 = 14$ mm

Layer	# of ladders	radius (mm)
L1	8	14
L2	12	22

- Two layers of DEPFET pixels:
  - Thickness: 75 μm
  - Pixel size: 50x55 μm^2
  - Low noise
  - Low power consumption

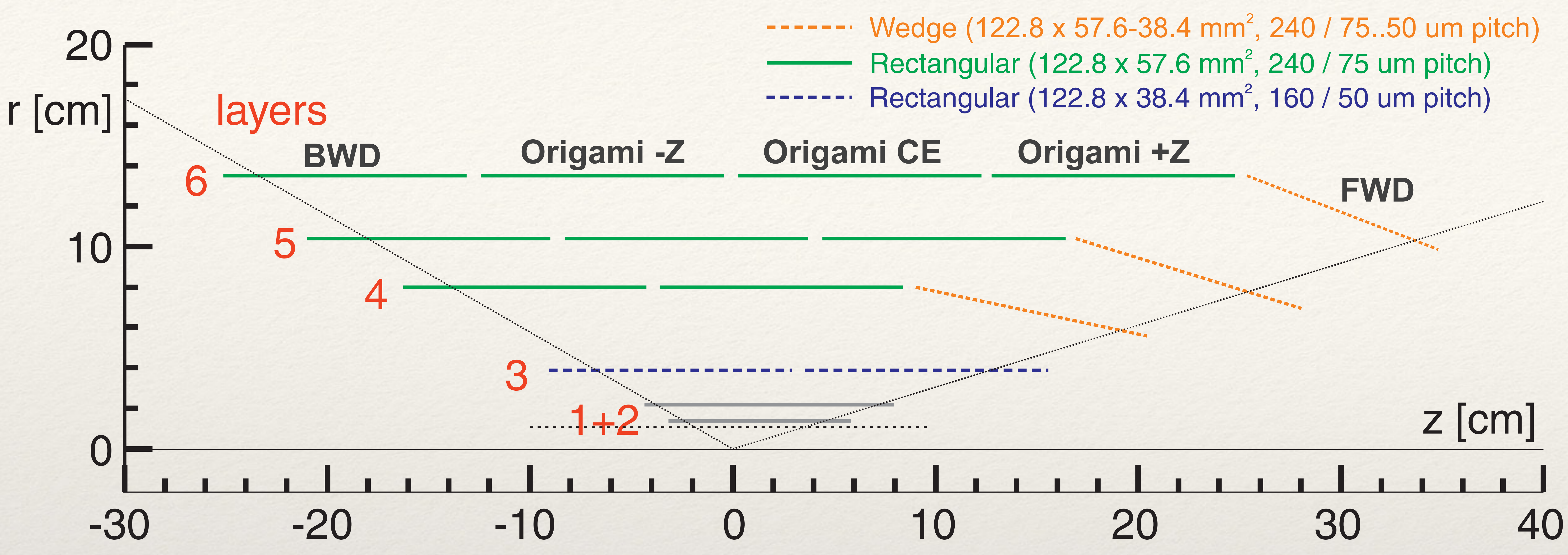
- On-line data reduction:
  - Software trigger
  - SVD track reconstruction
  - Region Of Interest definition
  - Readout of data inside ROIs

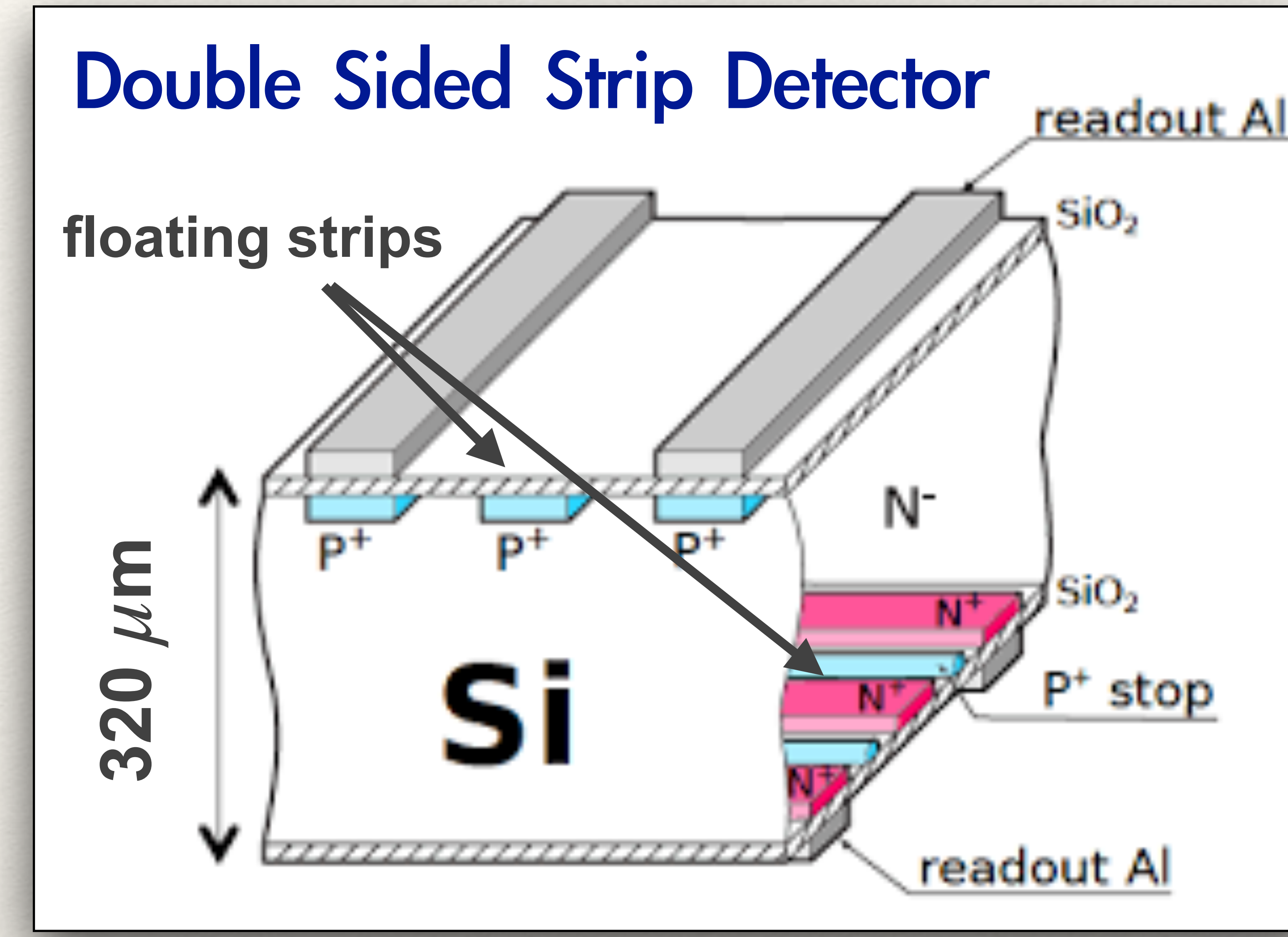
Impact parameter resolution



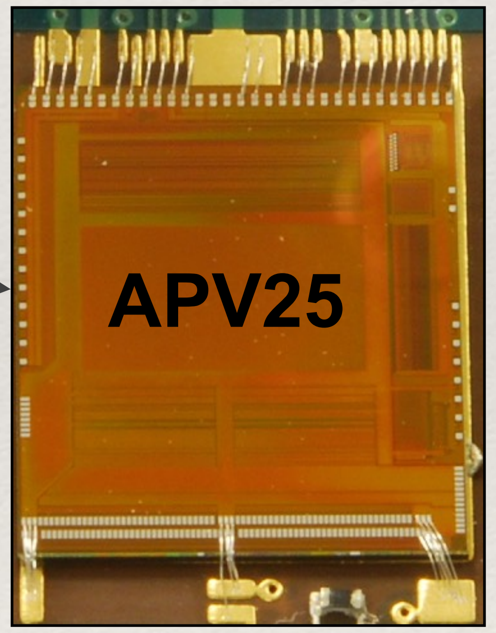
The Silicon Vertex Detector - SVD

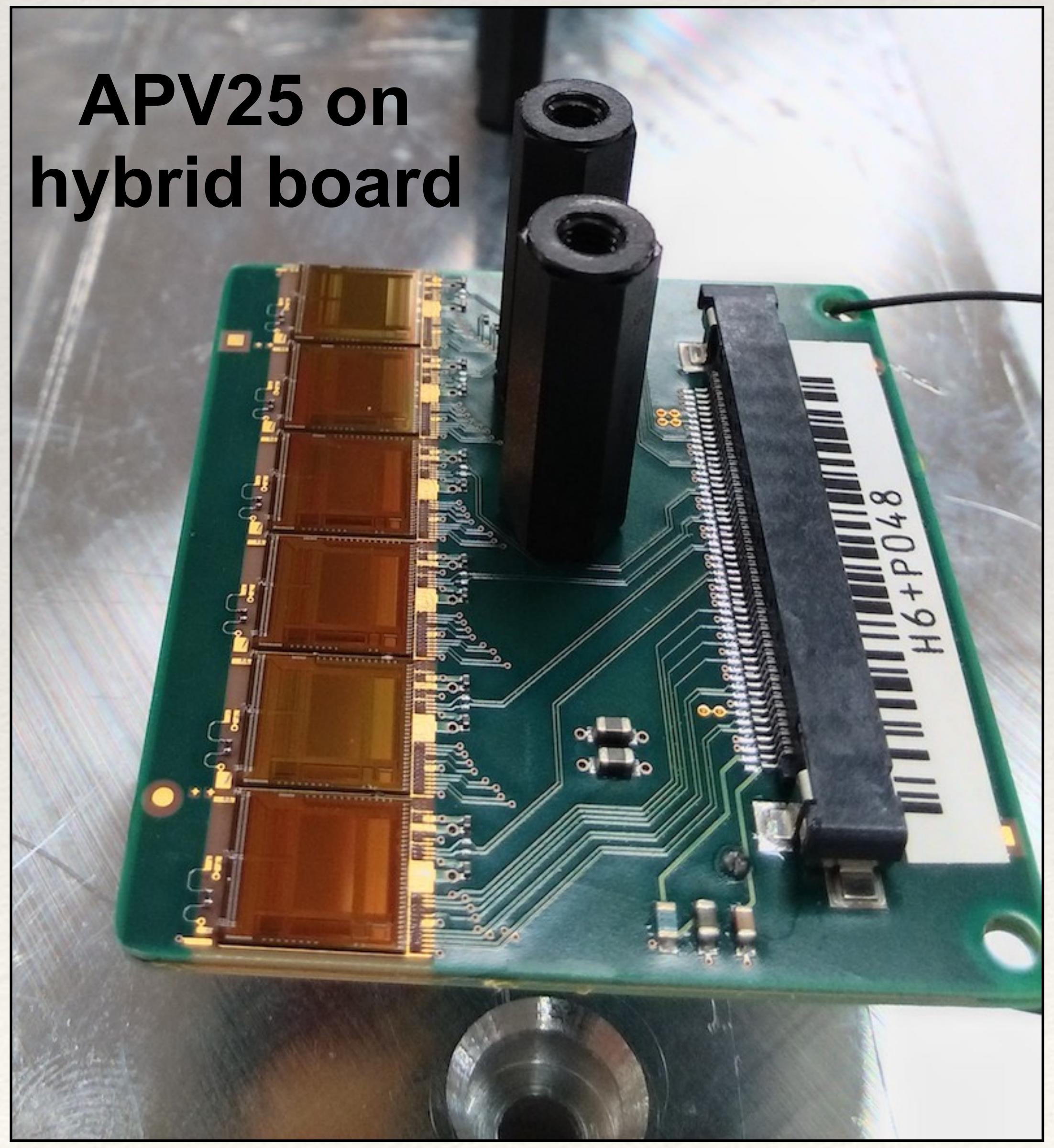
SVD main characteristics



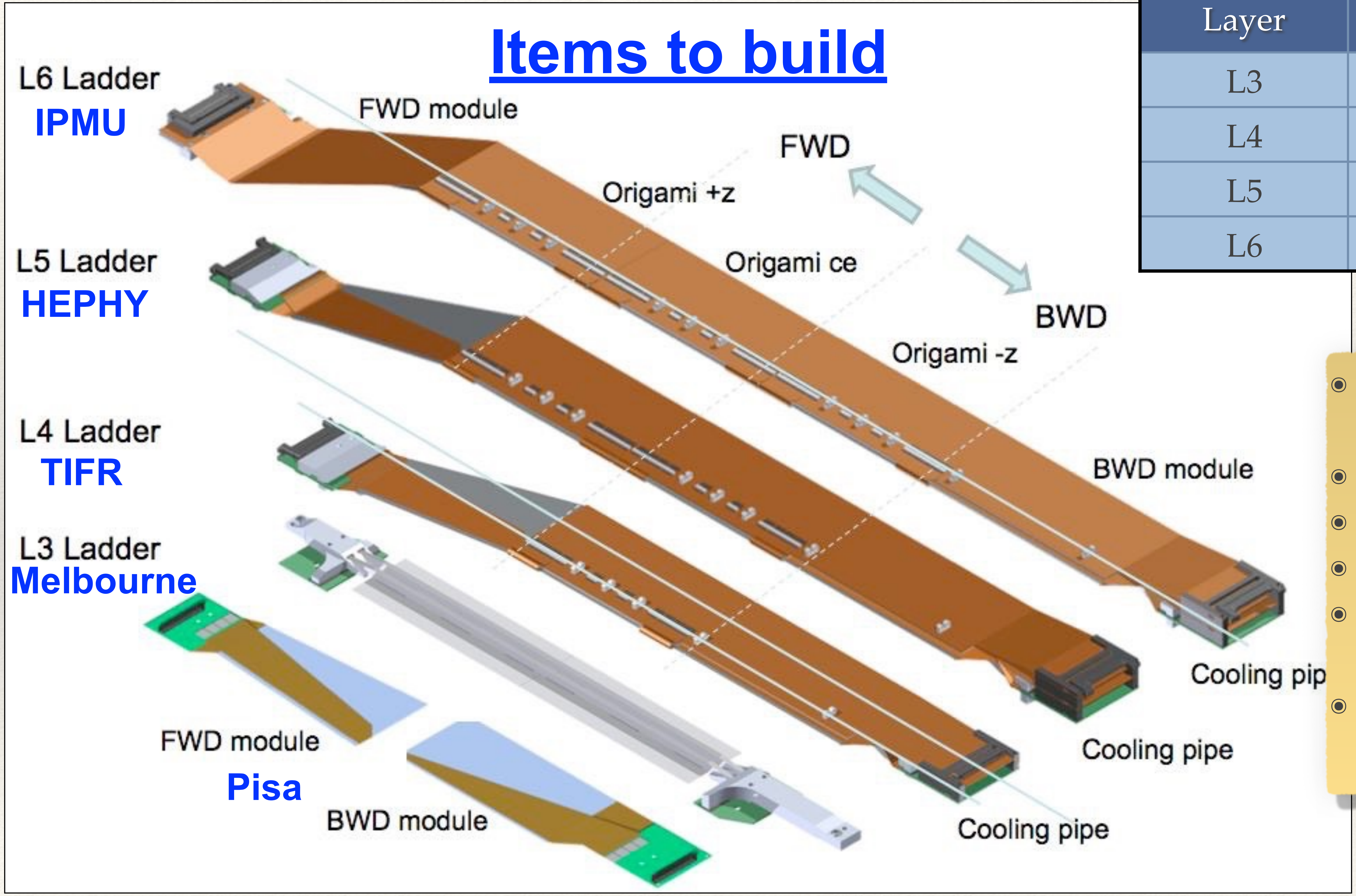


- 4 layers of DSSD on N-type silicon with AC coupled readout
- Read out chip: APV25
  - fast shaping time, radiation hardness, low material budget
- Signal readout on each sensor:
  - Origami "chip-on-sensor" concept for the inner sensors
- Slanted sensors in the forward region to reduce incident angle
  - reduced material budget
  - increase angular acceptance of the detector





SVD layers and assembly sites

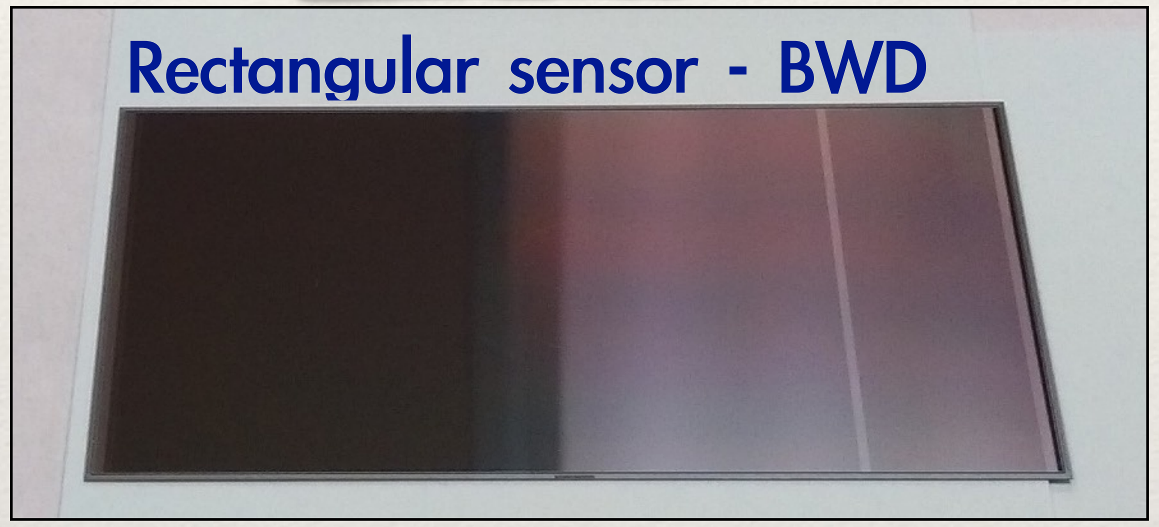


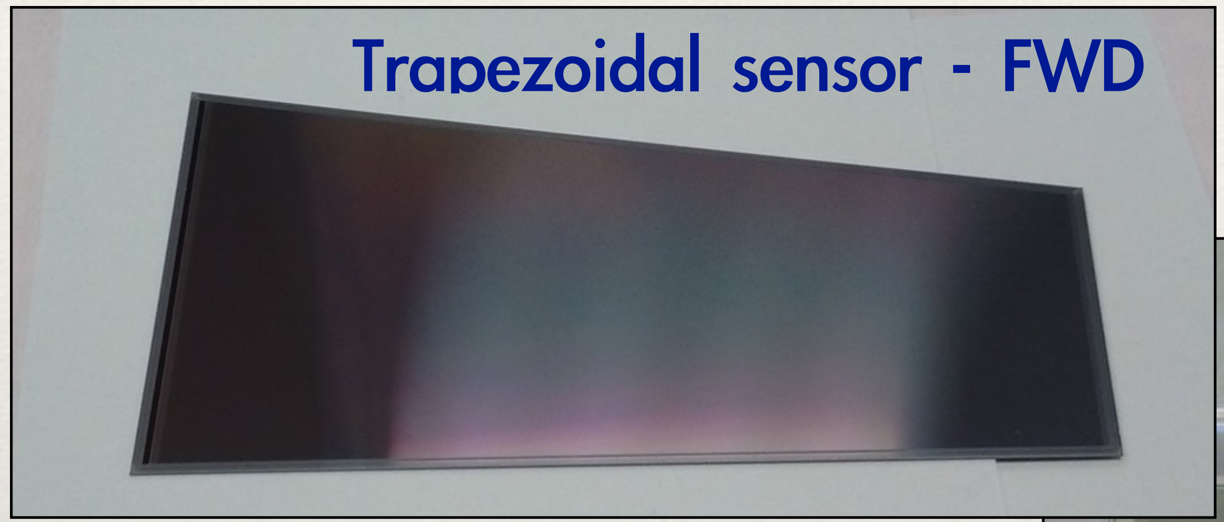
Layer	# of ladders	radius (mm)
L3	7+2	39
L4	10+2	80
L5	12+3	104
L6	16+4	135

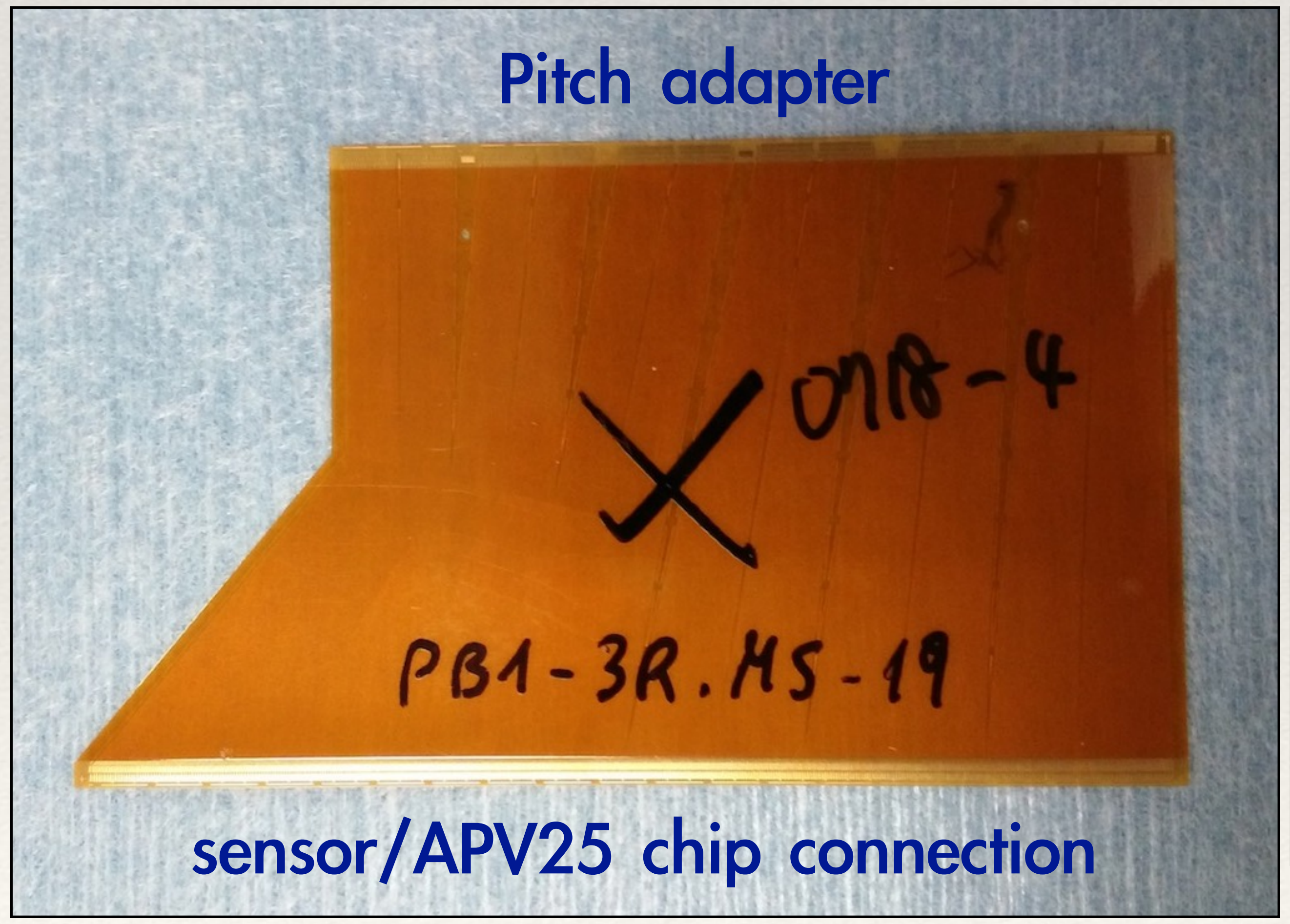
- 162 sensors used, 324 flat cables coming out from the SVD.
- pitch on r-ϕ side: 50 - 75 um
- pitch on z side: 160 - 240 um
- total silicon area: ~1.21 m^2
- 1748 readout chips, for a total of 223744 readout channels.
- power consumption: 2.31 mW/channel
  517 W for the whole SVD.

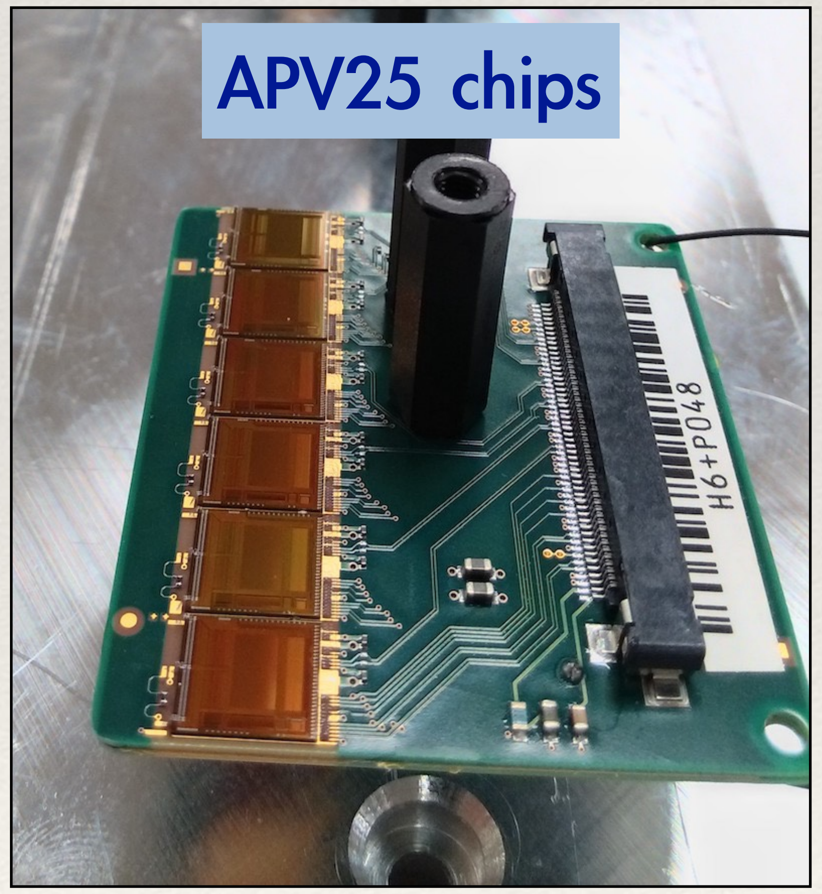
FWD-BWD sub-assemblies

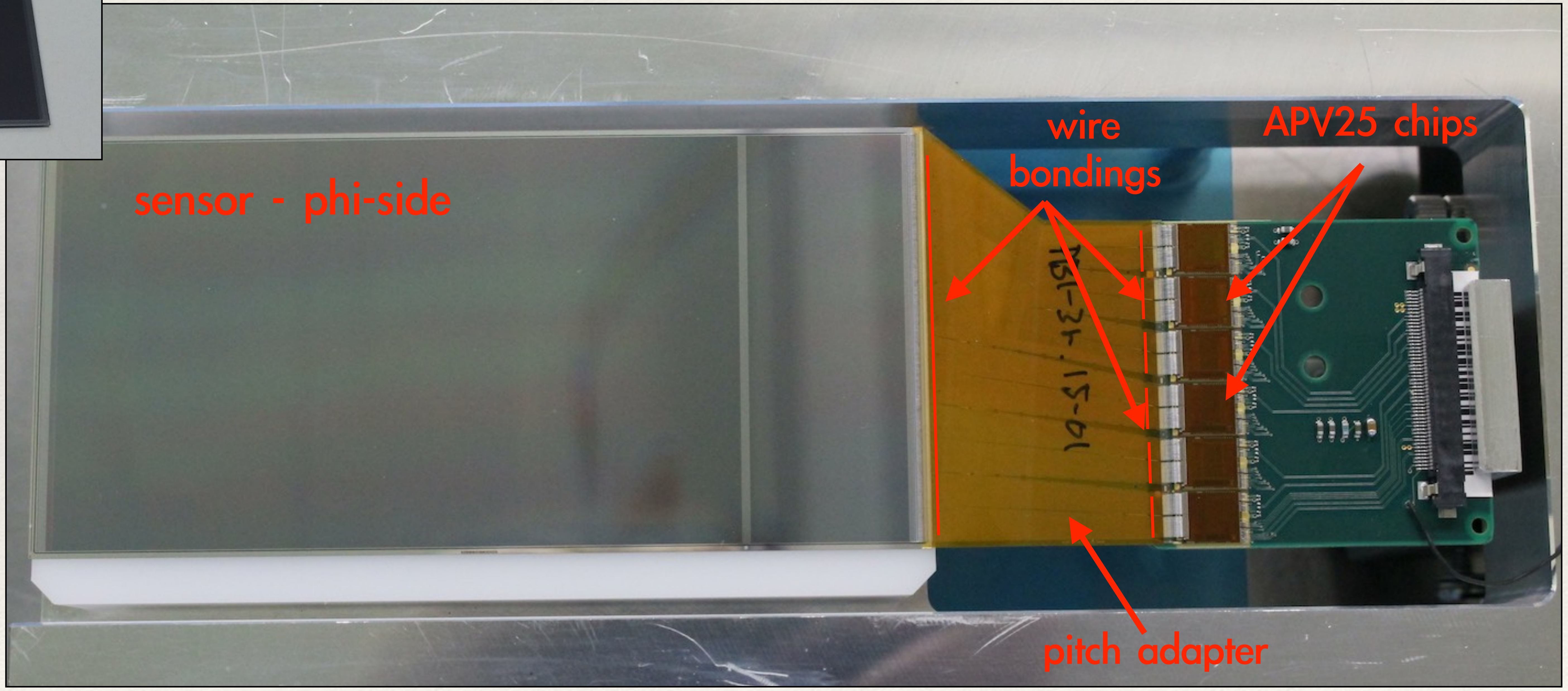
- Sub-assembly production performed entirely in the INFN Pisa clean room.
- Procedures R&D, production and testing carried out in less than three years.
- A total of 60 SBW and 63 SFW working modules have been produced and shipped to three different assembly sites, for ladder production.
- 16 people involved in the production process, including technicians, group members and students.





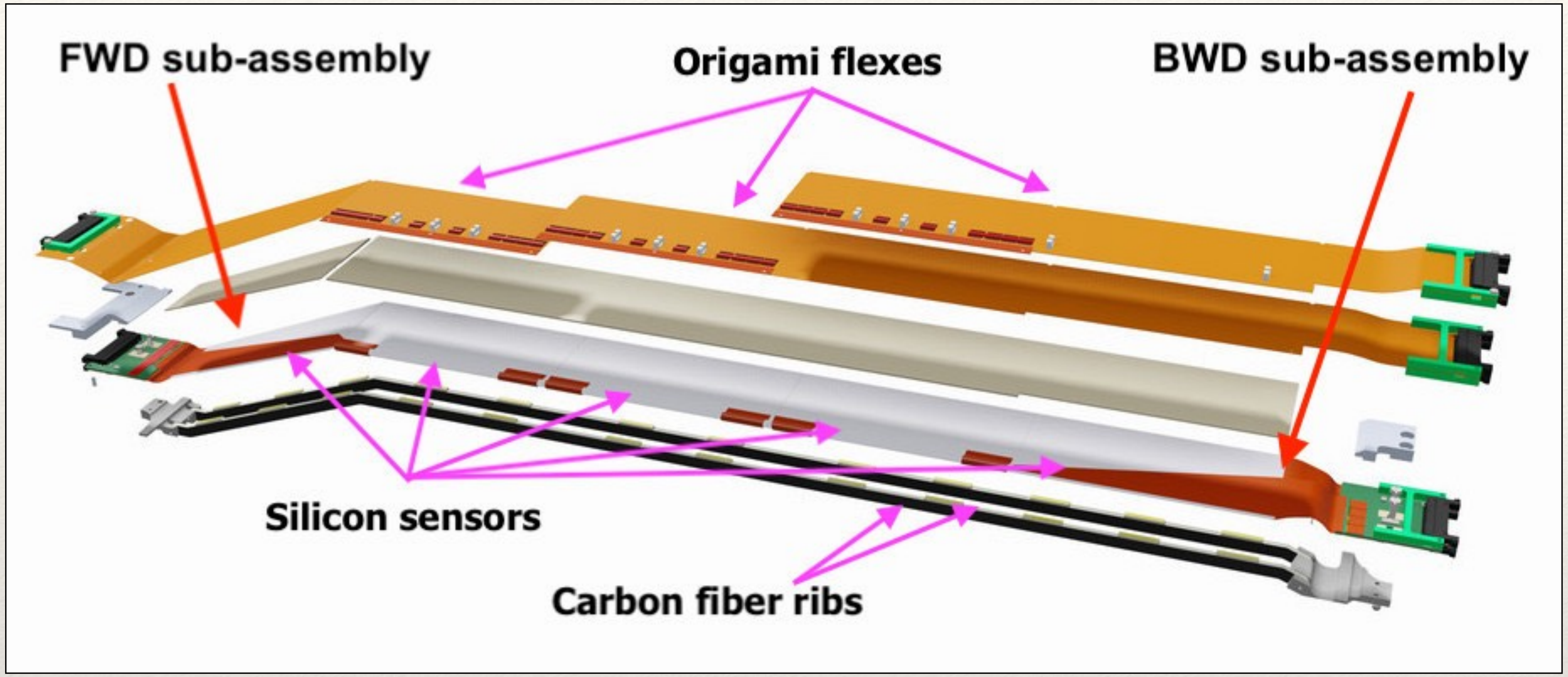


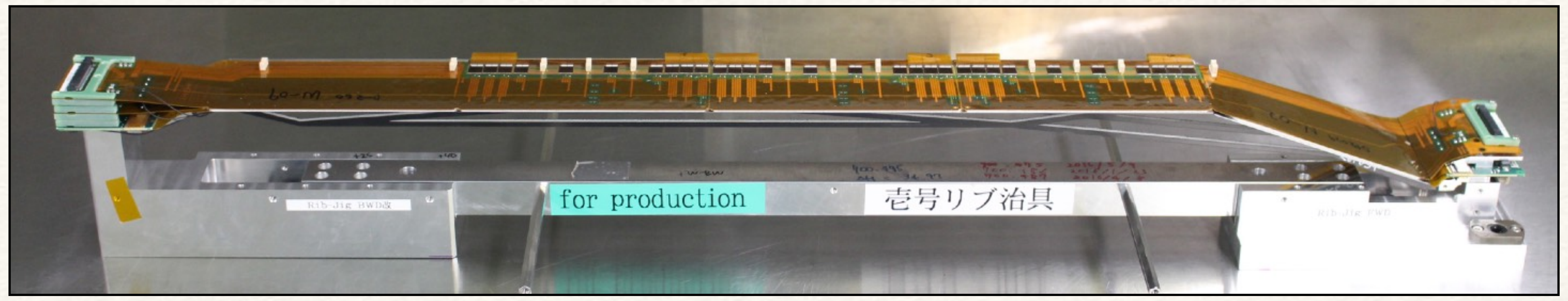


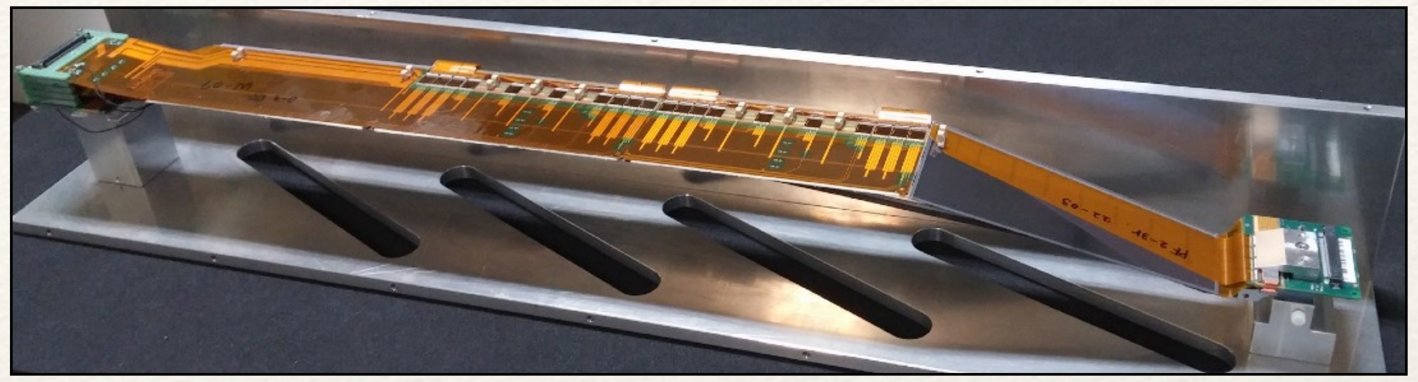


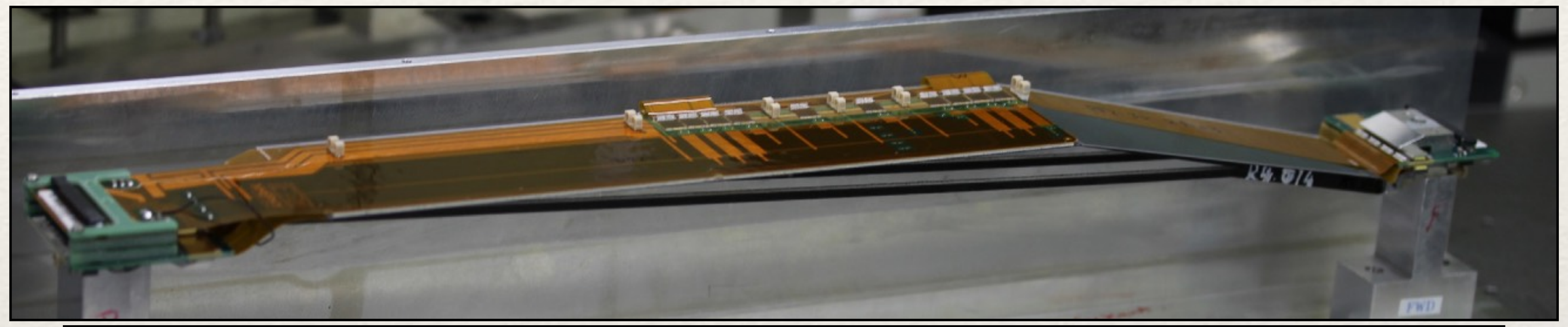
A short video of FWD/BWD sub-assemblies production is available at: https://youtu.be/Vo4tvenA4rQ

SVD Ladders



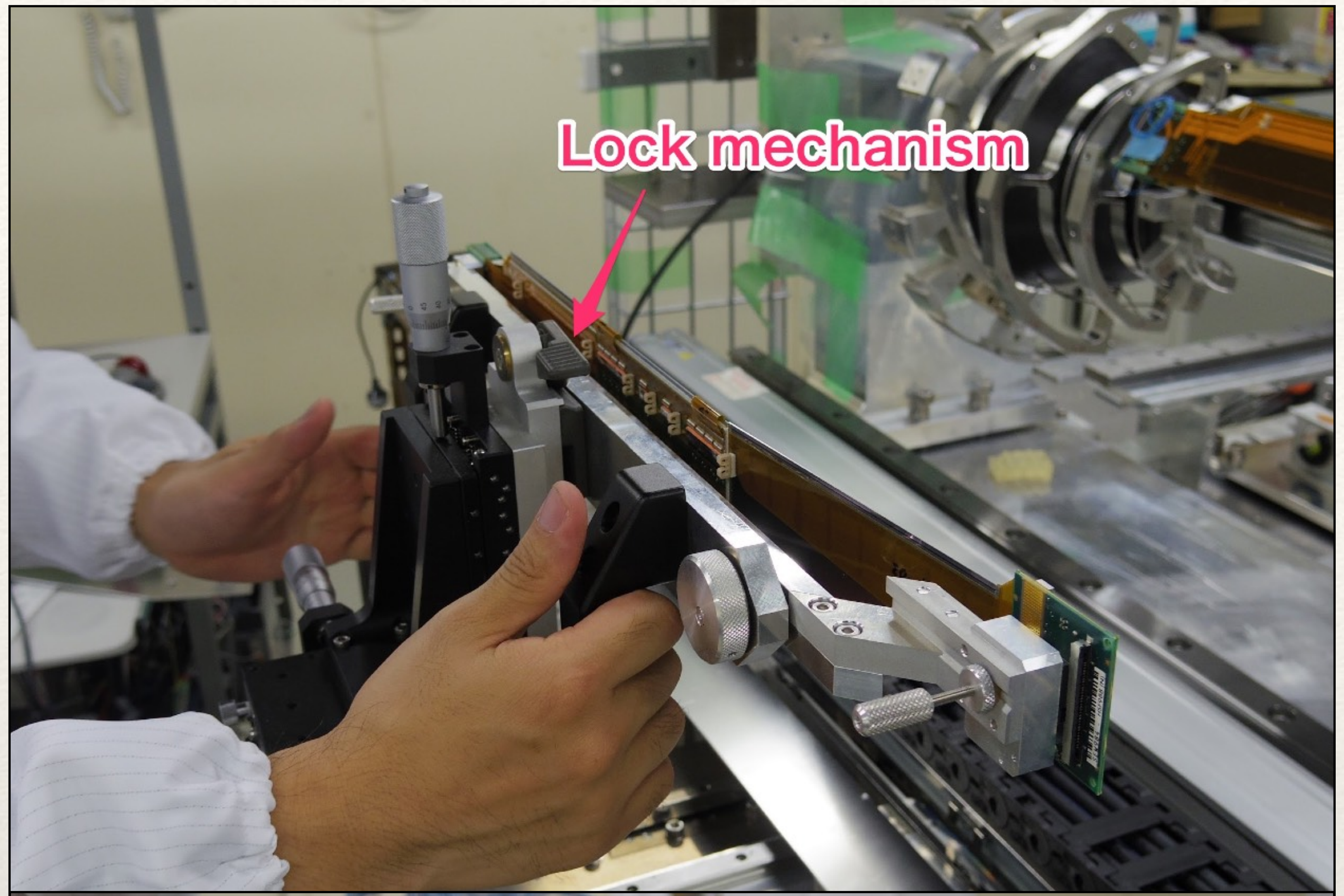






- Common procedures between L4-5-6 assembly sites.
- Internal review process to standardise quality of procedures. Quality Control Group made by SVD members to supervise activity in all assembly sites.
- Constant (weekly) communication and reports from assembly sites.
- Common ladder inspection protocol defined to assure quality of ladders before the shipment to KEK and after the arrival in KEK, to verify that no damage occurred during transportation.

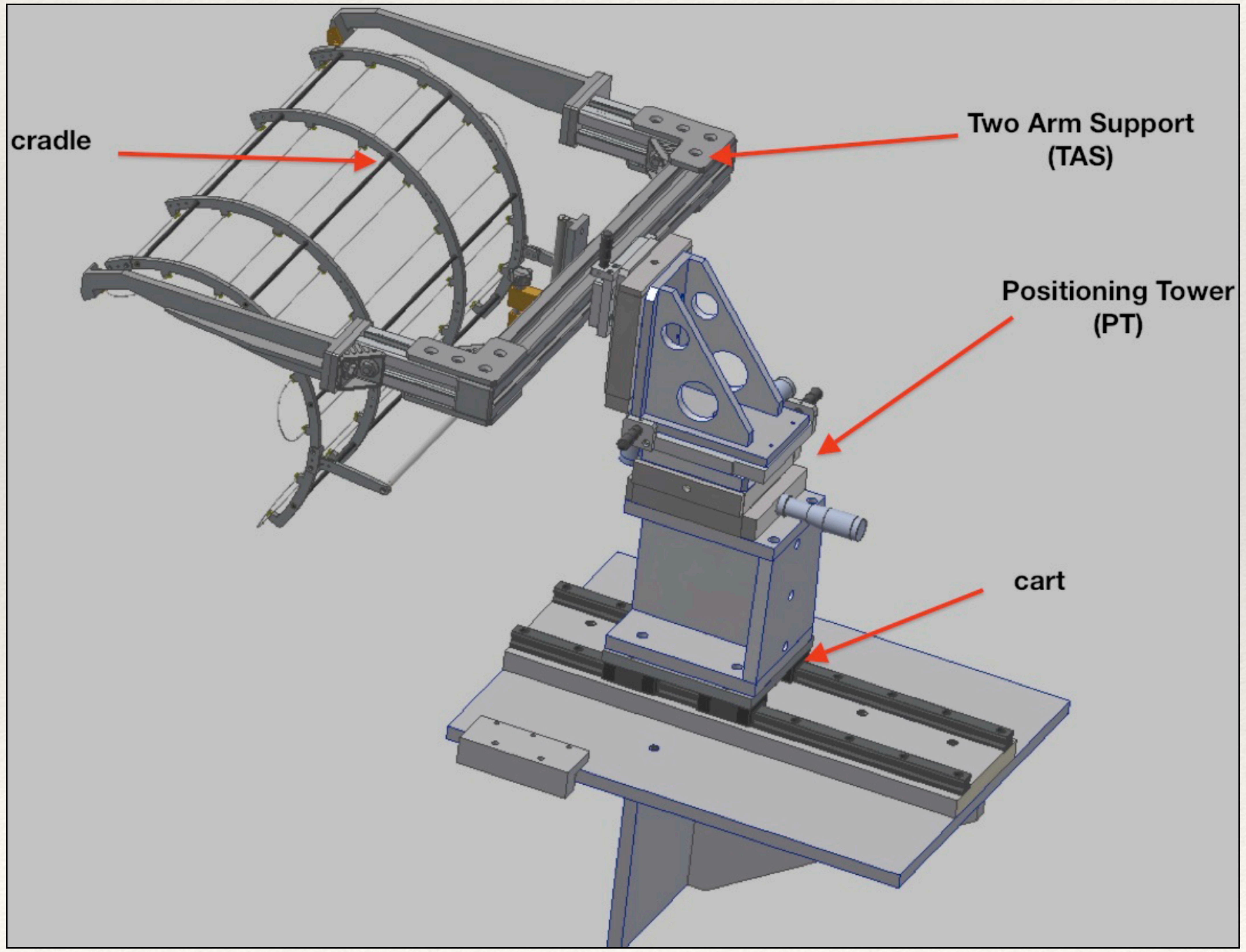
SVD assembly - Ladder mount

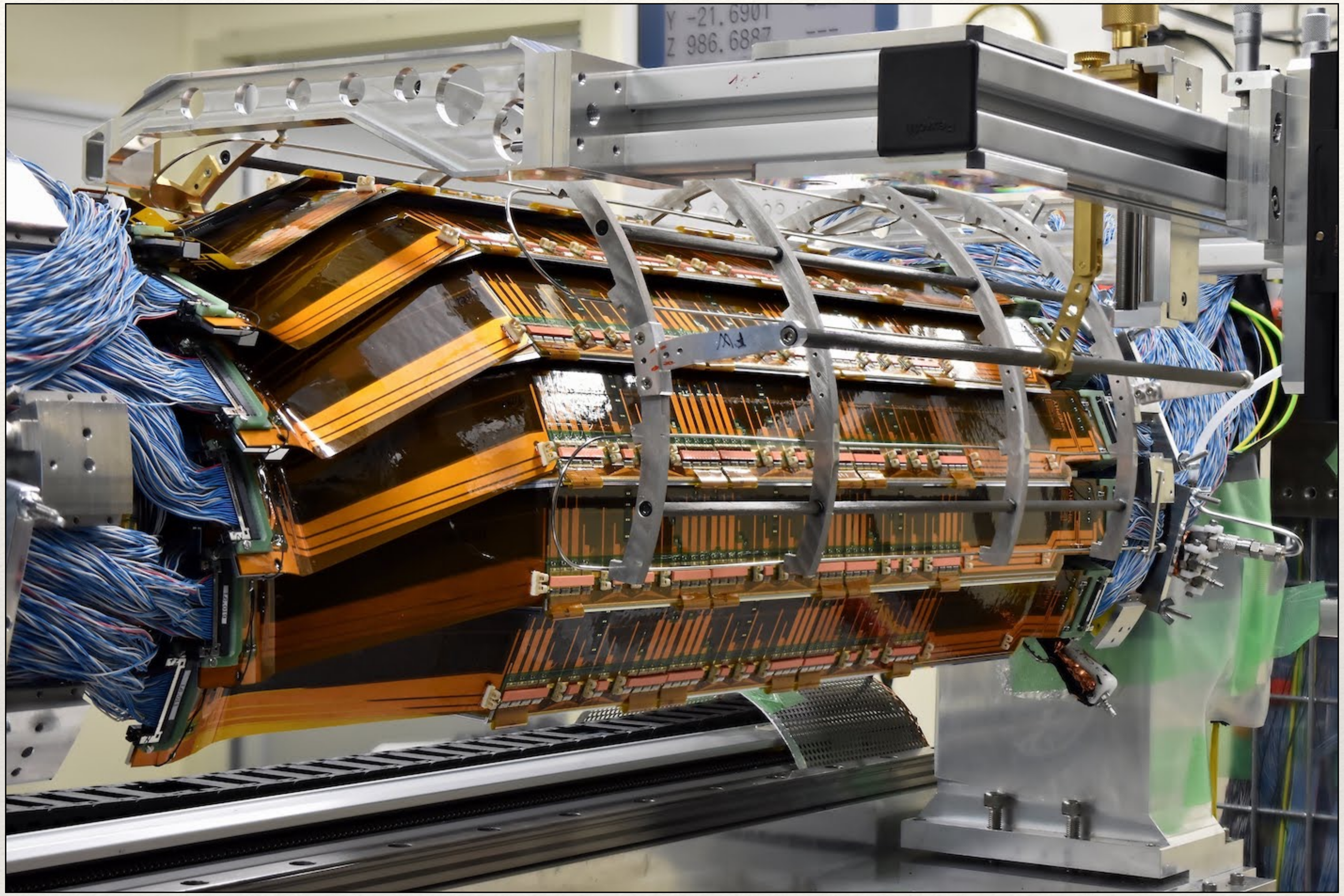


- Dedicated experts for the ladder mount helped by a representative of each assembly site.
- Review process for mounting procedures involving also mechanical experts outside the SVD group.
- Two separate half shells produced, to be coupled around the PXD.
- Each half-layer fully tested after the completion.

SVD assembly - Cooling pipe attachment

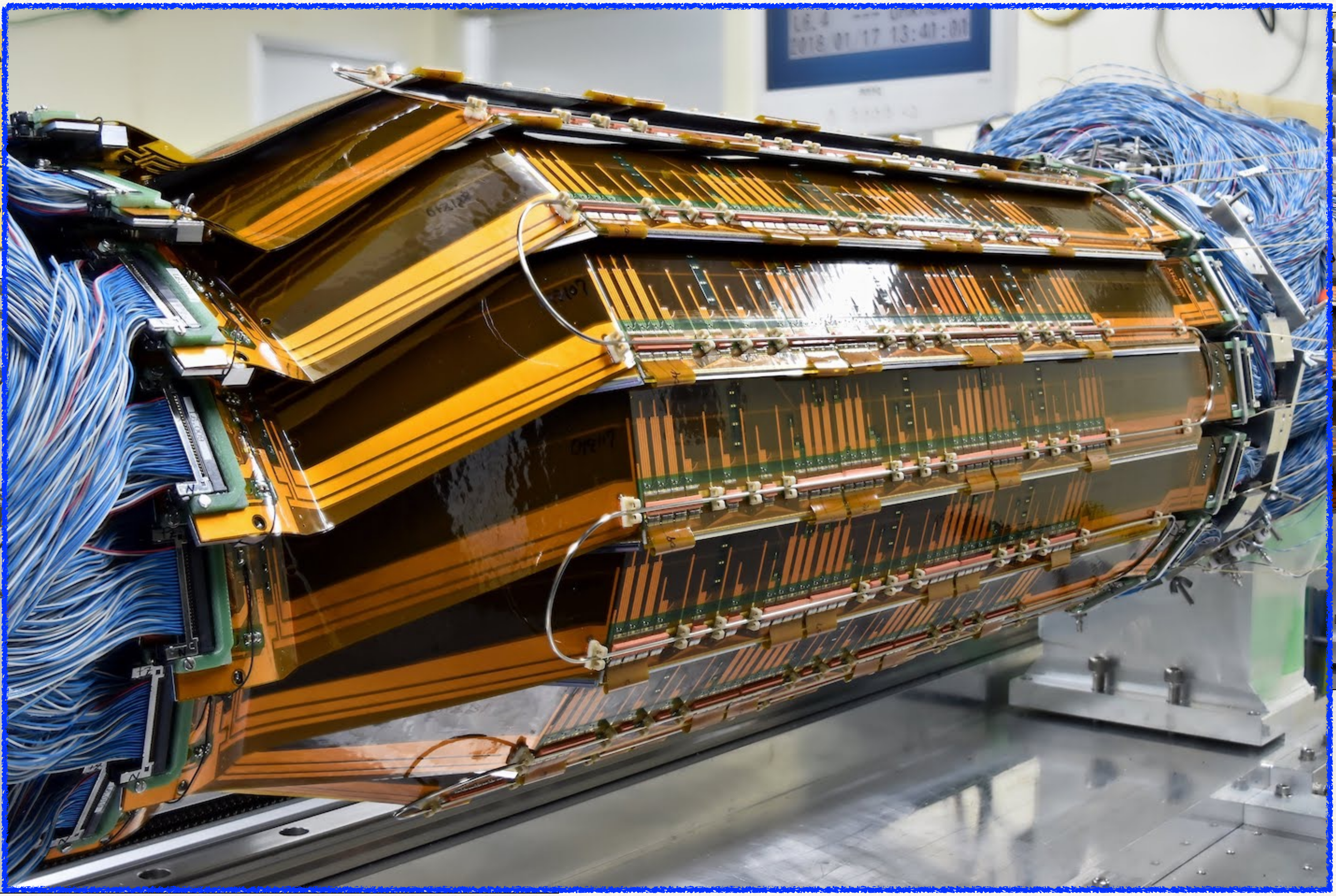
- Cooling pipe attachment tools and procedures developed in Pisa.
- Dedicated team from INFN performed six cooling pipes installations, all successful.

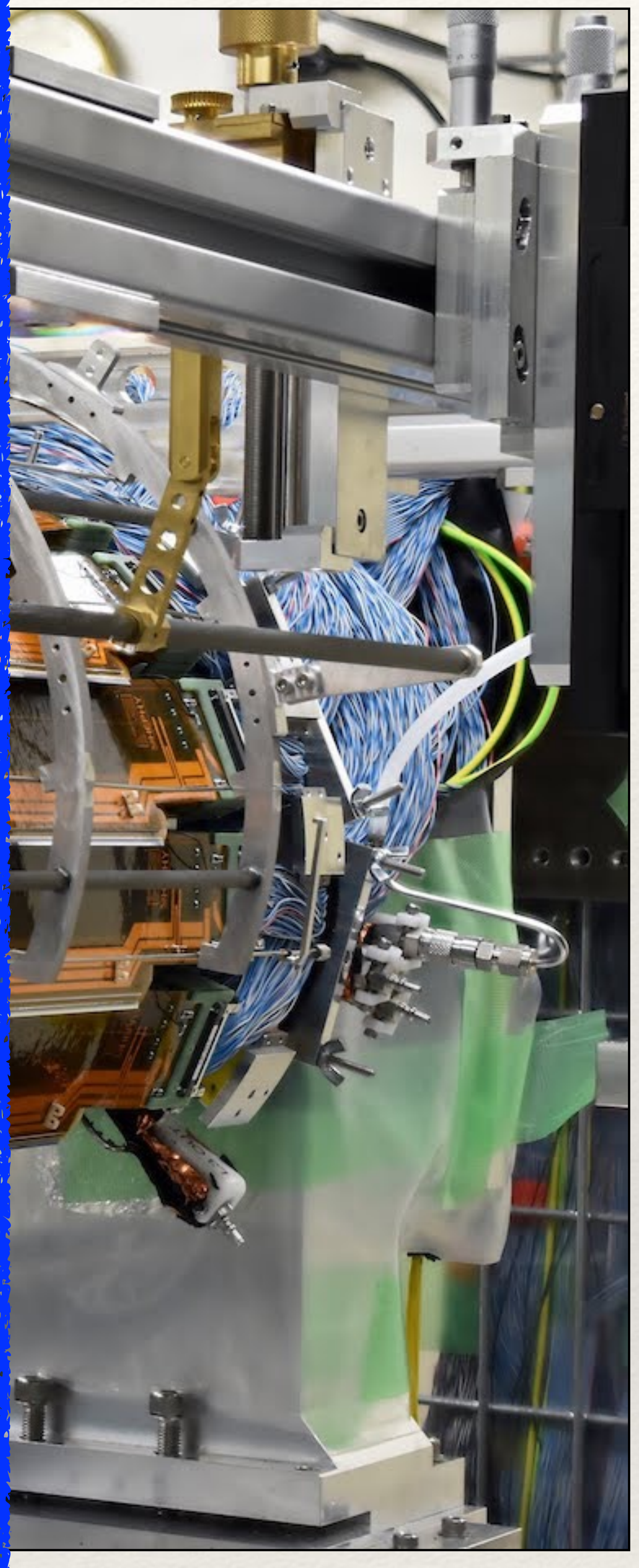




SVD assembly - Cooling pipe attachment

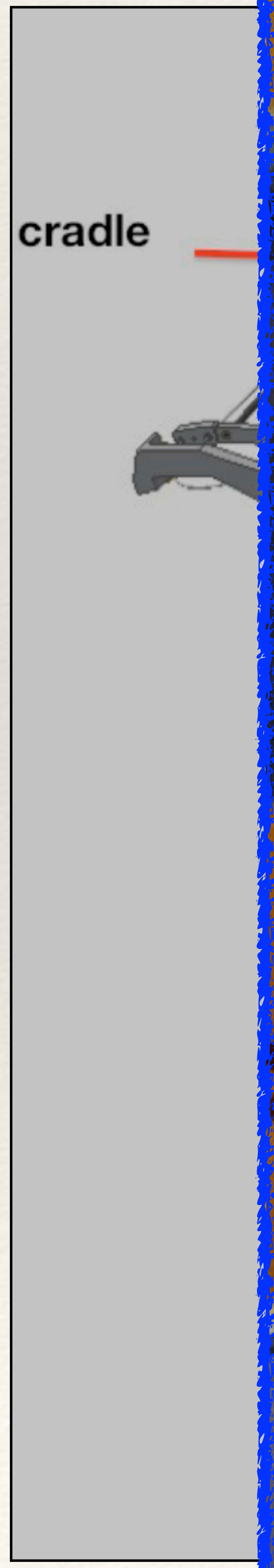
- Cooling pipe
  developed in
- Dedicated te
  cooling pipes

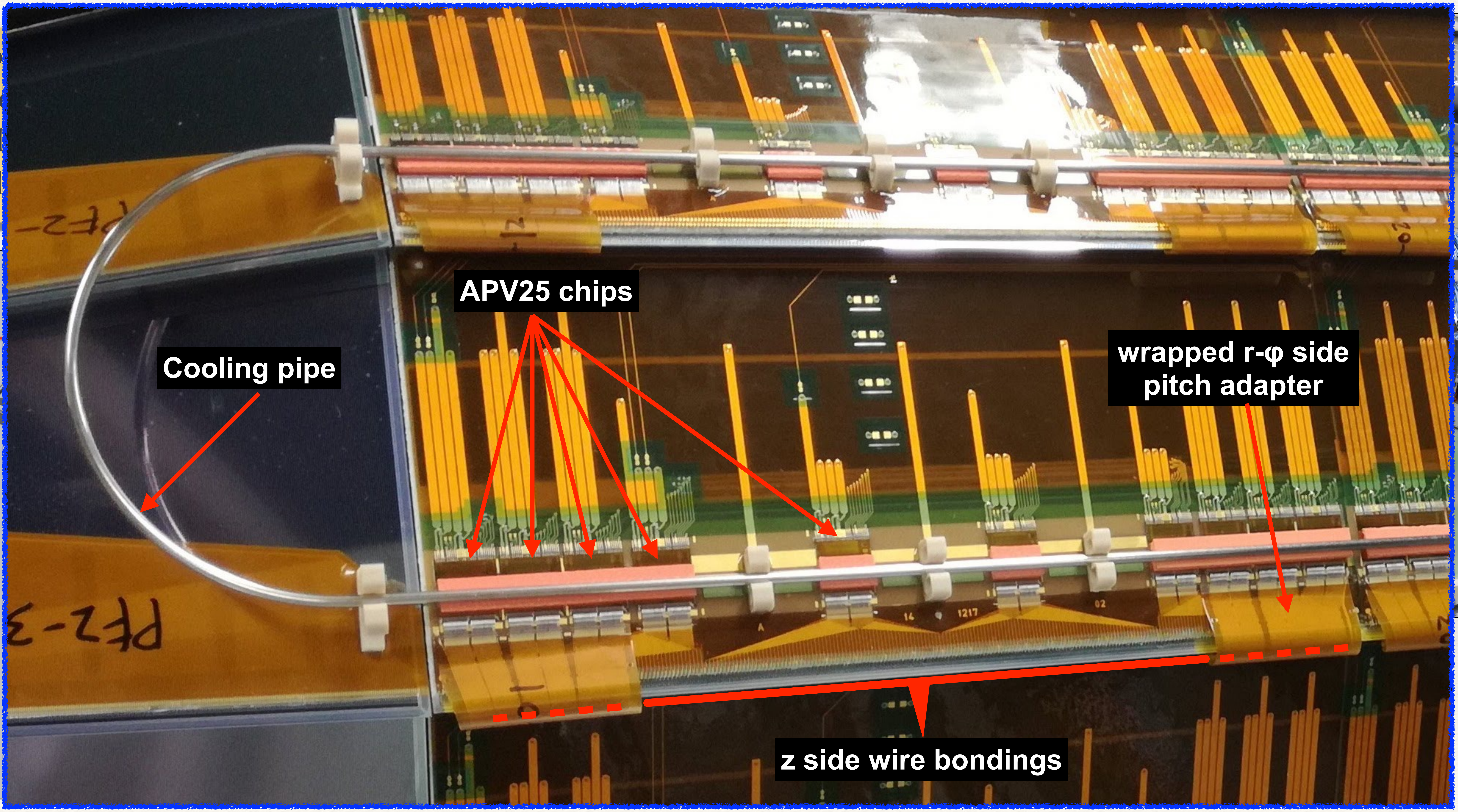


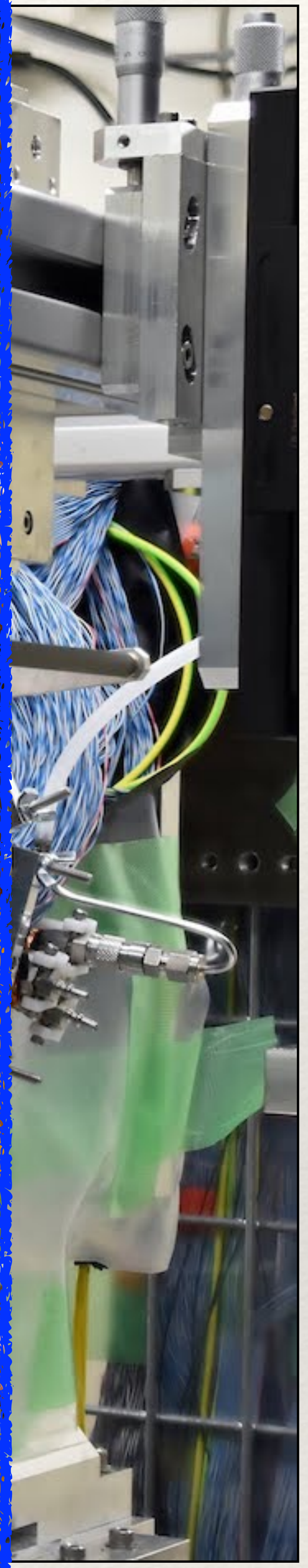


SVD assembly - Cooling pipe attachment

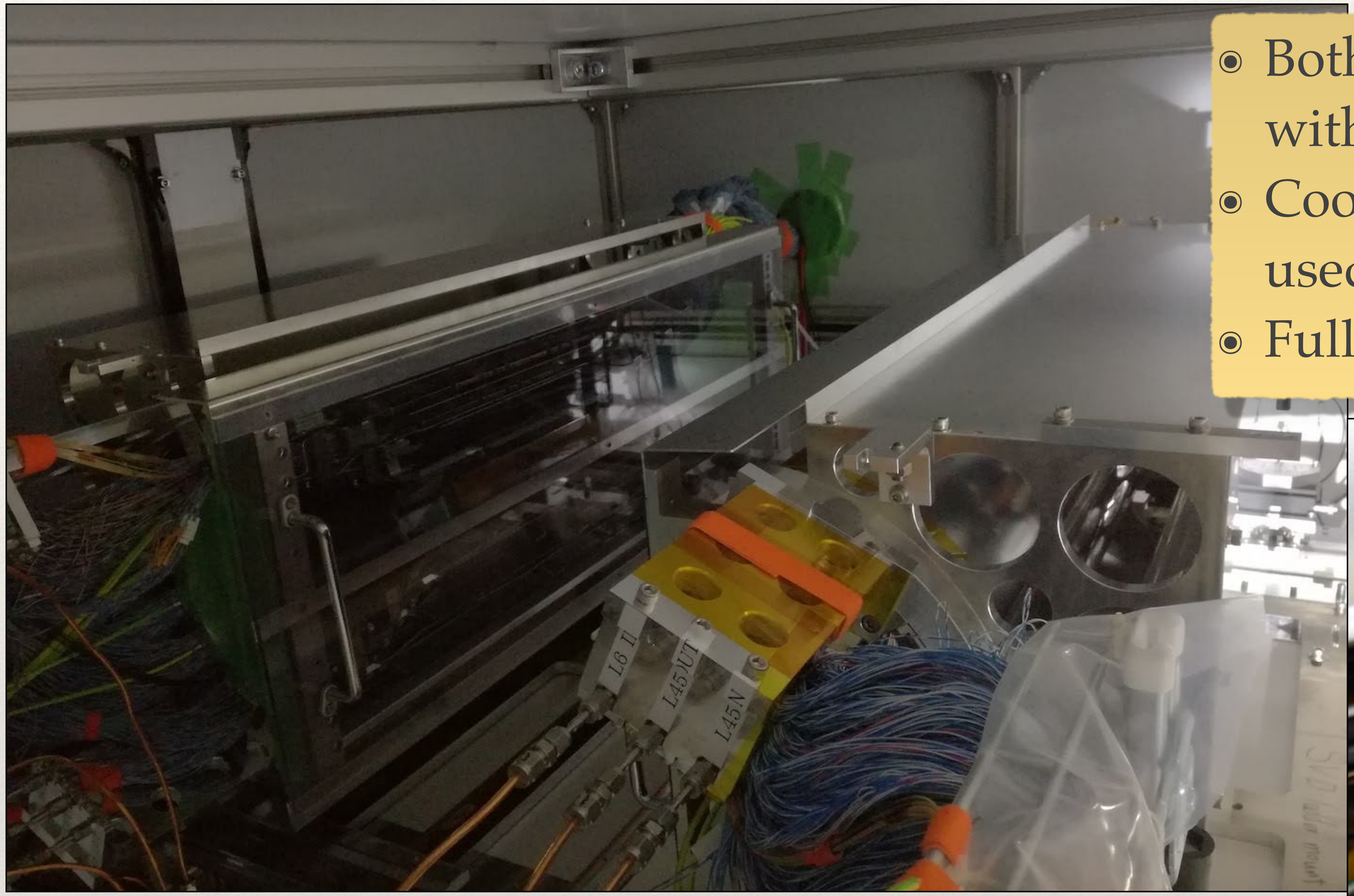
- Coo
dev
- Ded
cool



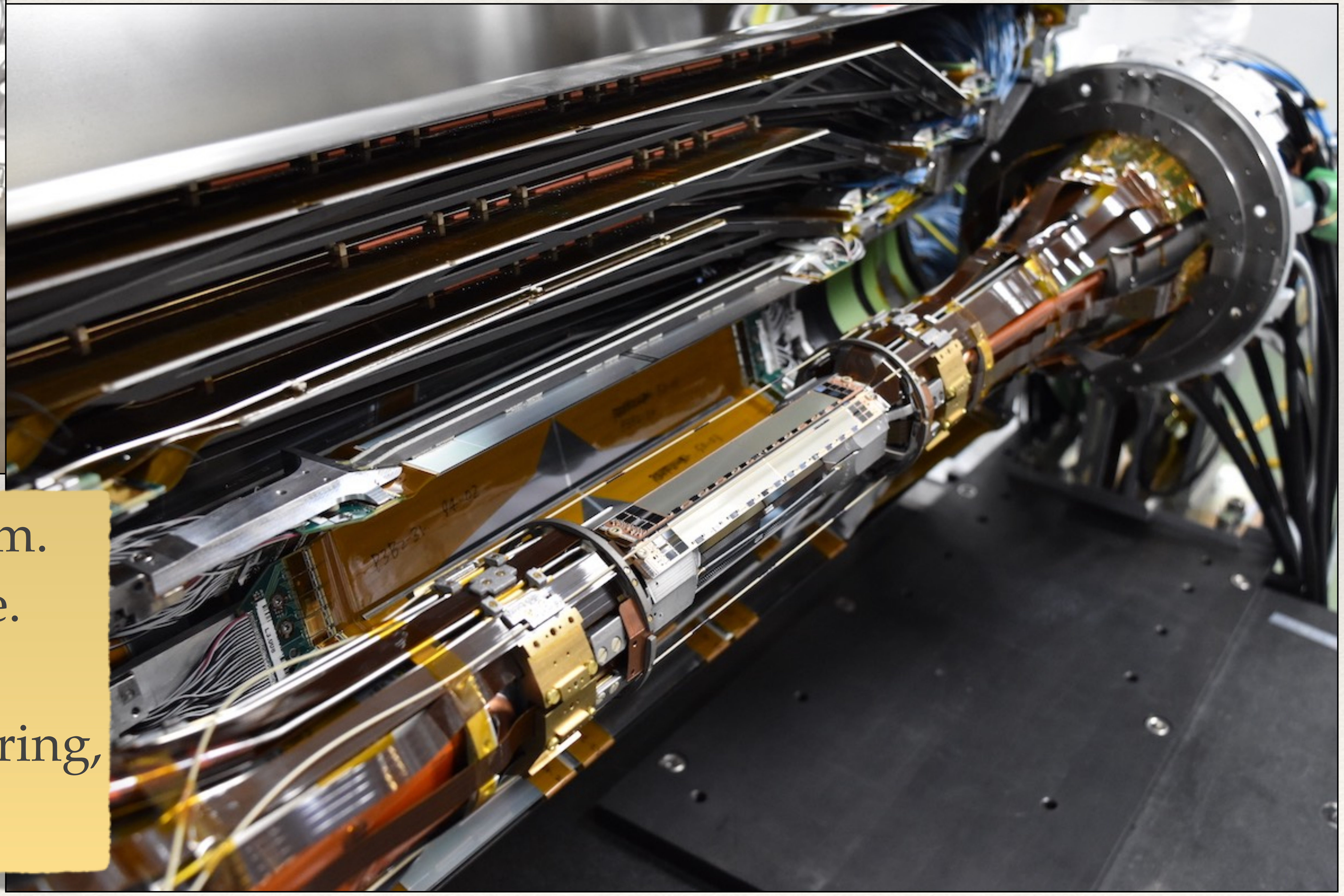




SVD commissioning …



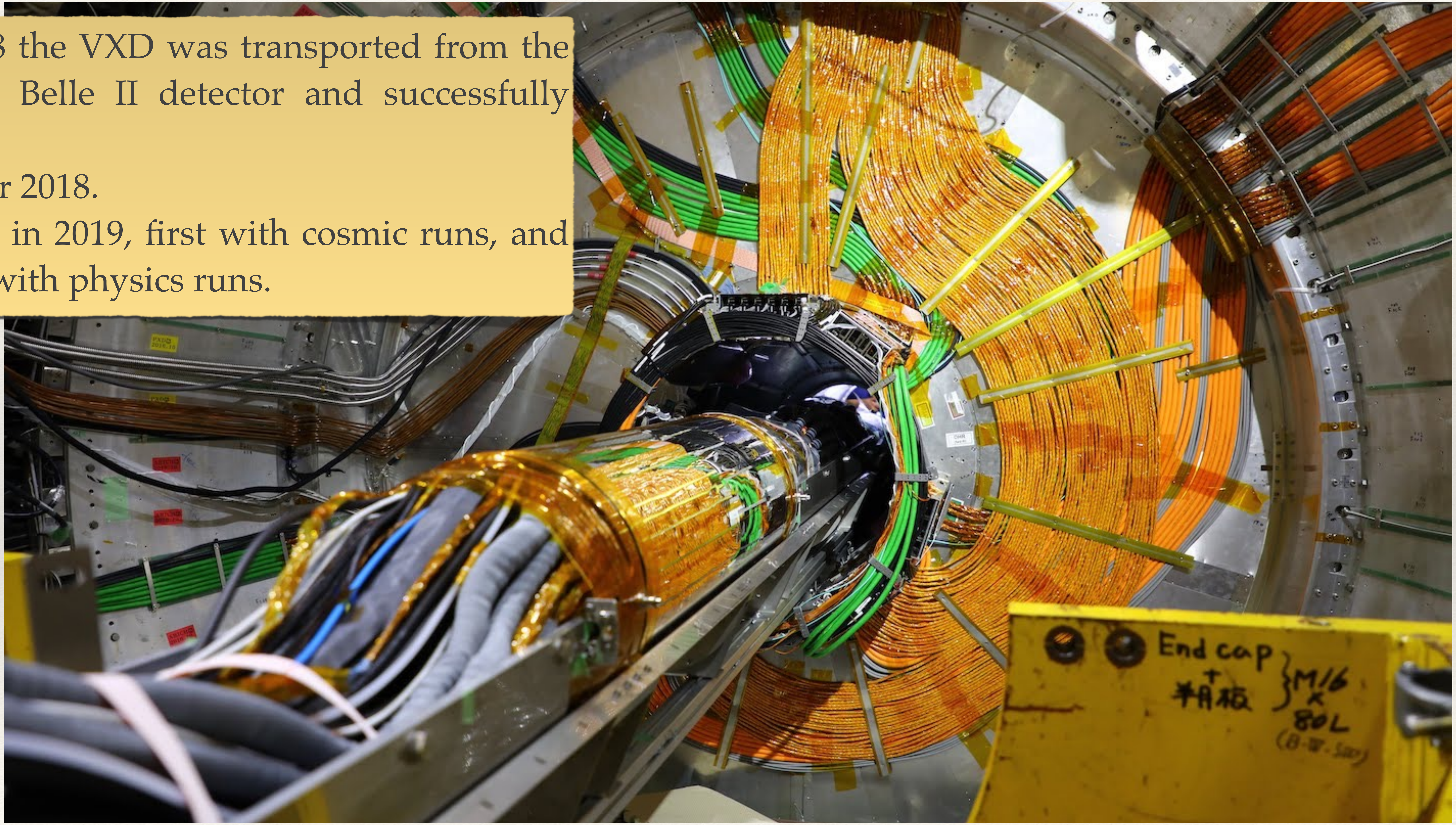
- Both SVD halves were stored on two tables, in a dark box with dry air flushed.
- Cooling circuit connected to a provisional cooling system used only for commissioning.
- Full DAQ system tested before installation.



- “Marriage” with PXD done in a dedicated clean room.
  - L1 fully installed, only two ladders of L2 available.
- Commissioning of the full VXD with cosmic rays.
- Commissioning also of environmental monitoring, interlocks, slow control.

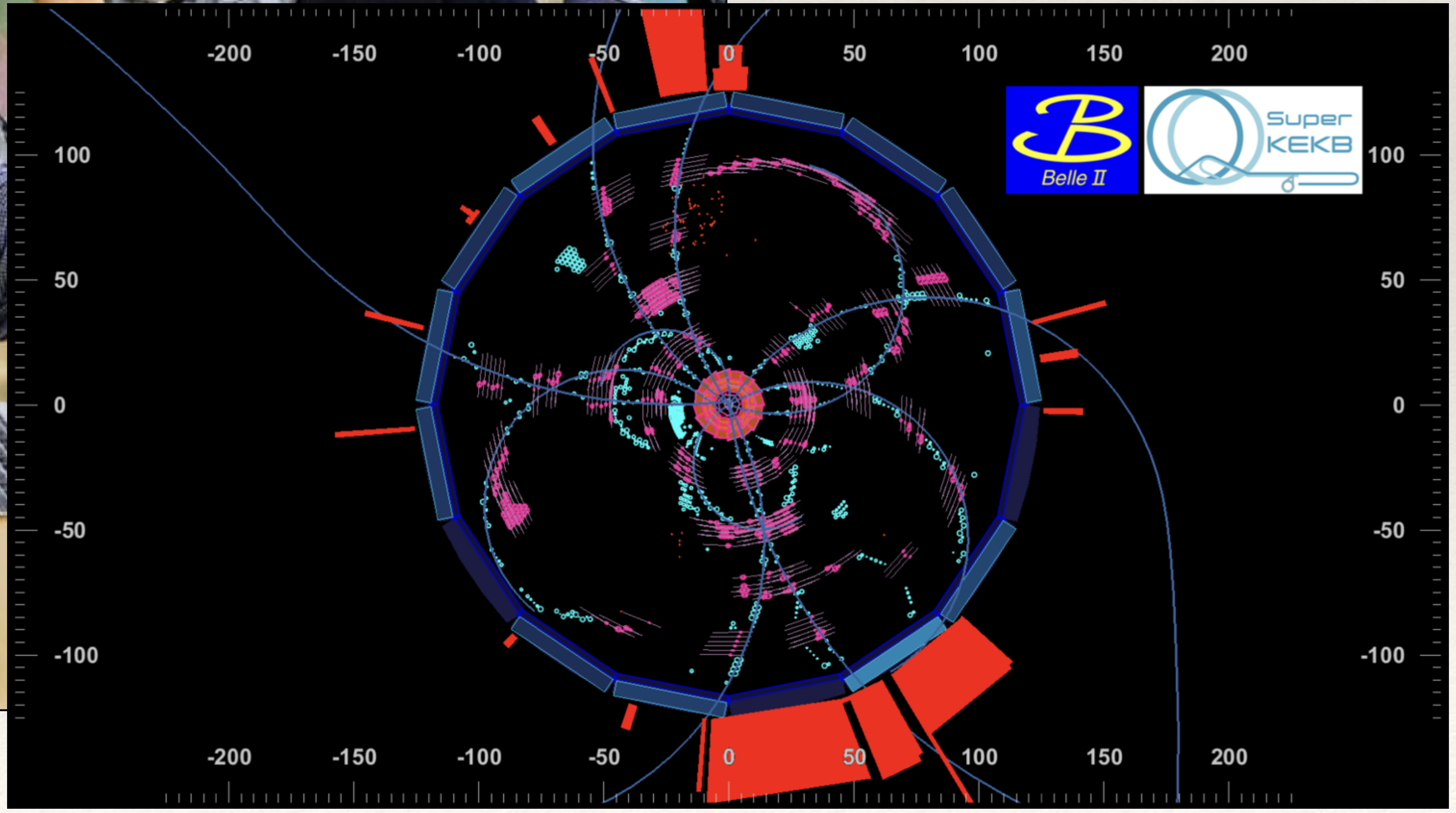
… and installation

- On November 2018 the VXD was transported from the clean room to the Belle II detector and successfully installed.
- Tested on December 2018.
- Started data taking in 2019, first with cosmic runs, and then, since March, with physics runs.



First Phase 3 collisions

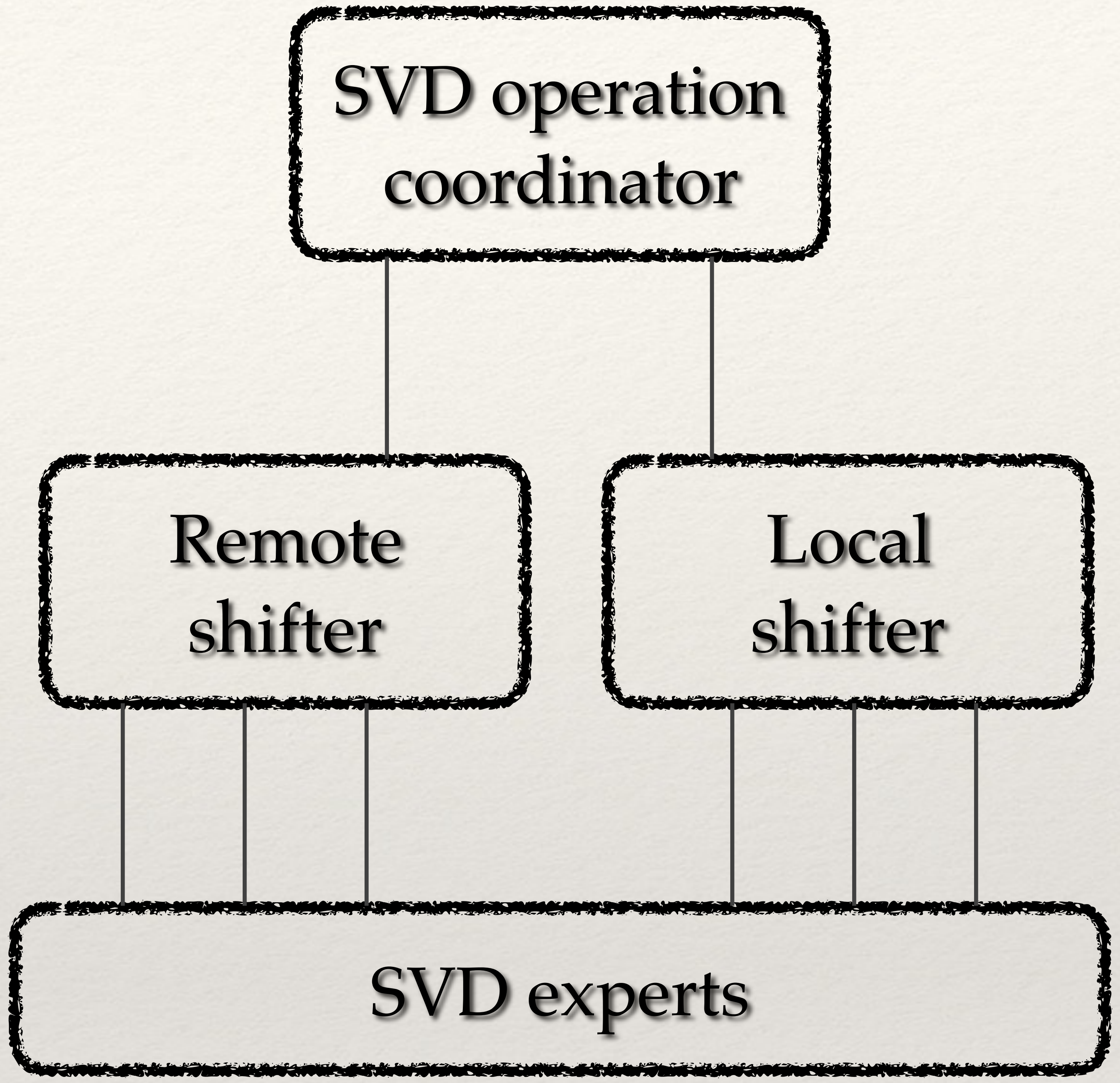
- First collisions in Phase 3 recorded on 2019/03/25
- First collisions for SuperKEKB happened during Phase 2, on 2018/04/26.



SVD operation

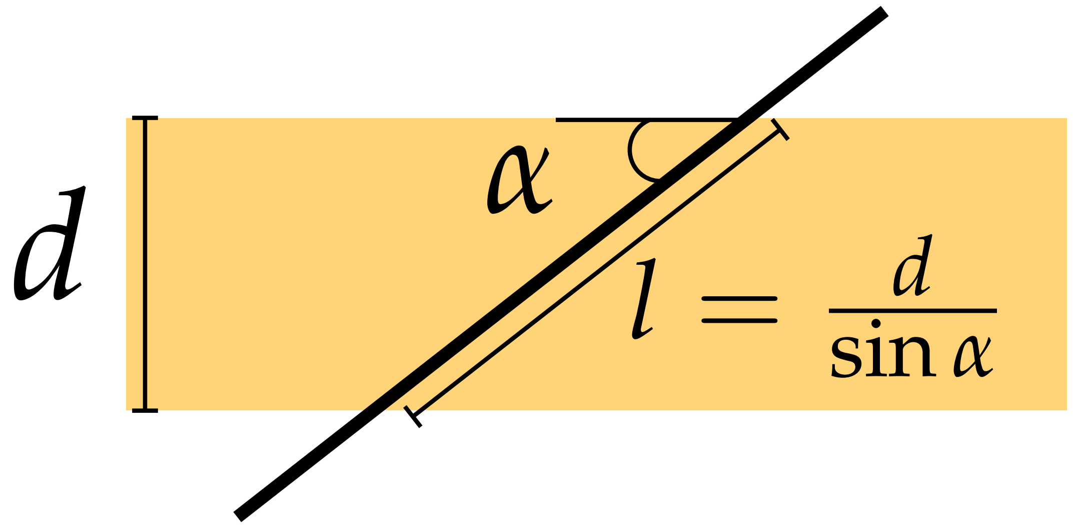
- SVD operations started on January 2019.
- Shift system with 1 local shifter and 1 remote shifter:
  - Periodic monitoring of environment variables and data, local expert on-call 24/7.
  - Safety of the detector assured by software and interlock systems.
- All relevant procedures for monitoring and operations well documented and available for shifters.

- Since March 2019, shift system revised due to the COVID-19 emergency:
  - SVD operated mainly remotely, with experts on-call and local people available for hardware operations.



- Overall, SVD has been quite stable during operations, with just minor issues that barely affected Belle II data taking.

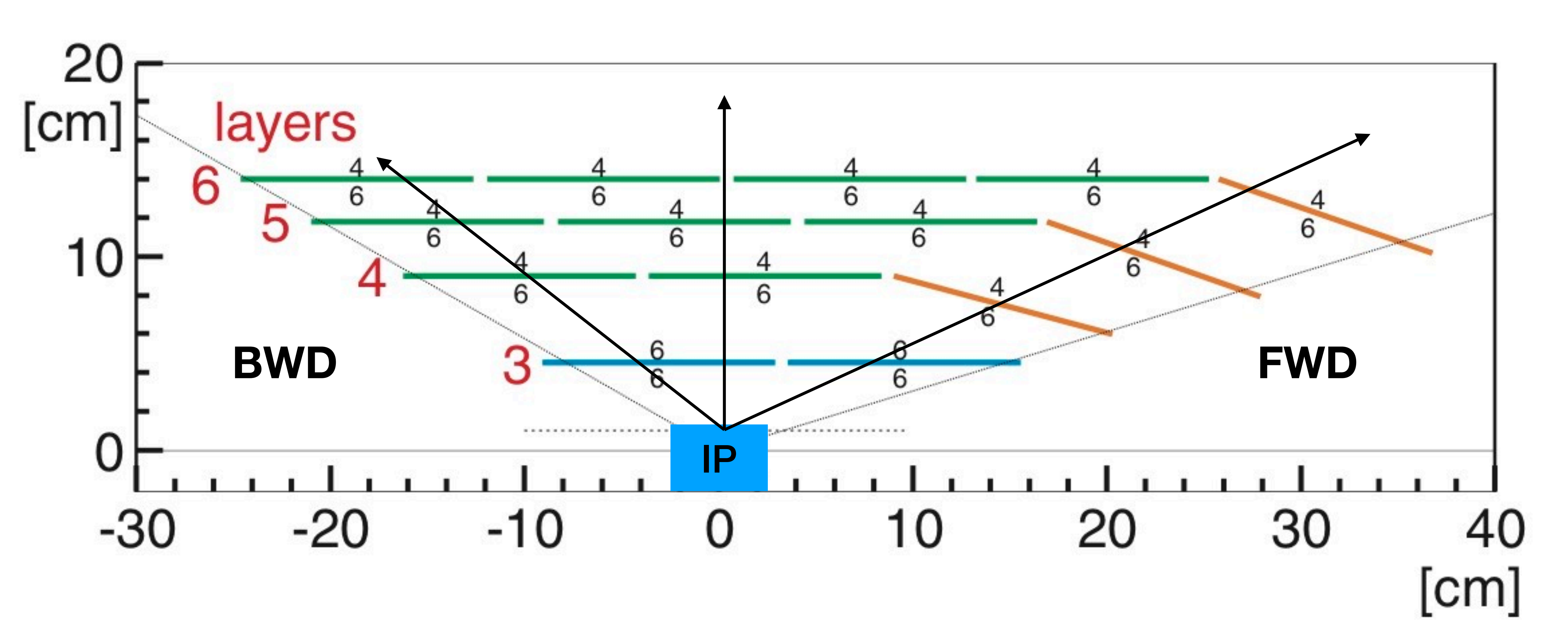
SVD Performance - Signal-to-noise Ratio



$$d = 300\mu m$$

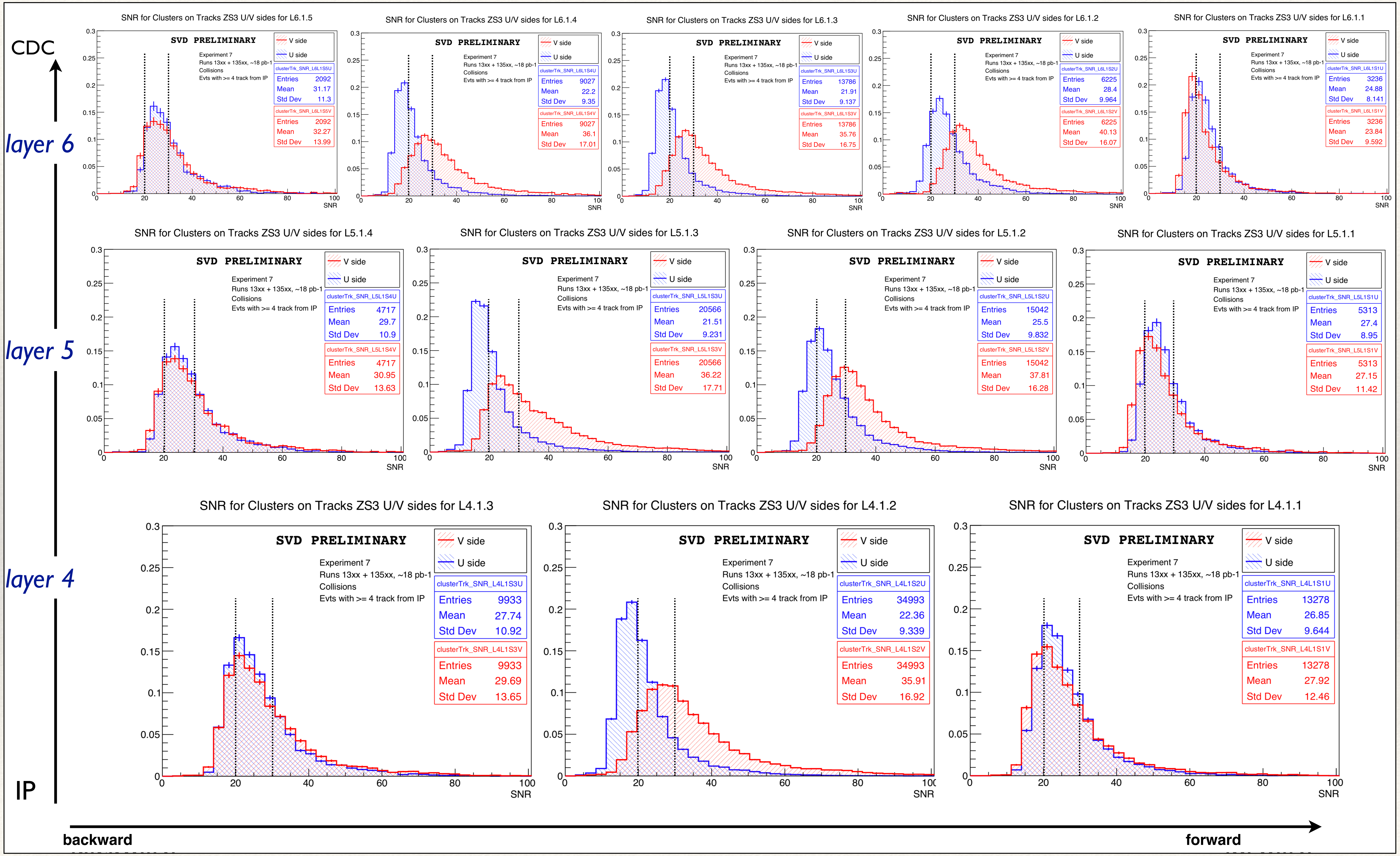
$$E \simeq \frac{d}{\sin\alpha} \cdot 80\frac{e^-}{\mu m}$$

$$SNR_{cls} = \frac{\sum_{strips} S_i}{\sqrt{\sum_{strips} N_i^2}}$$



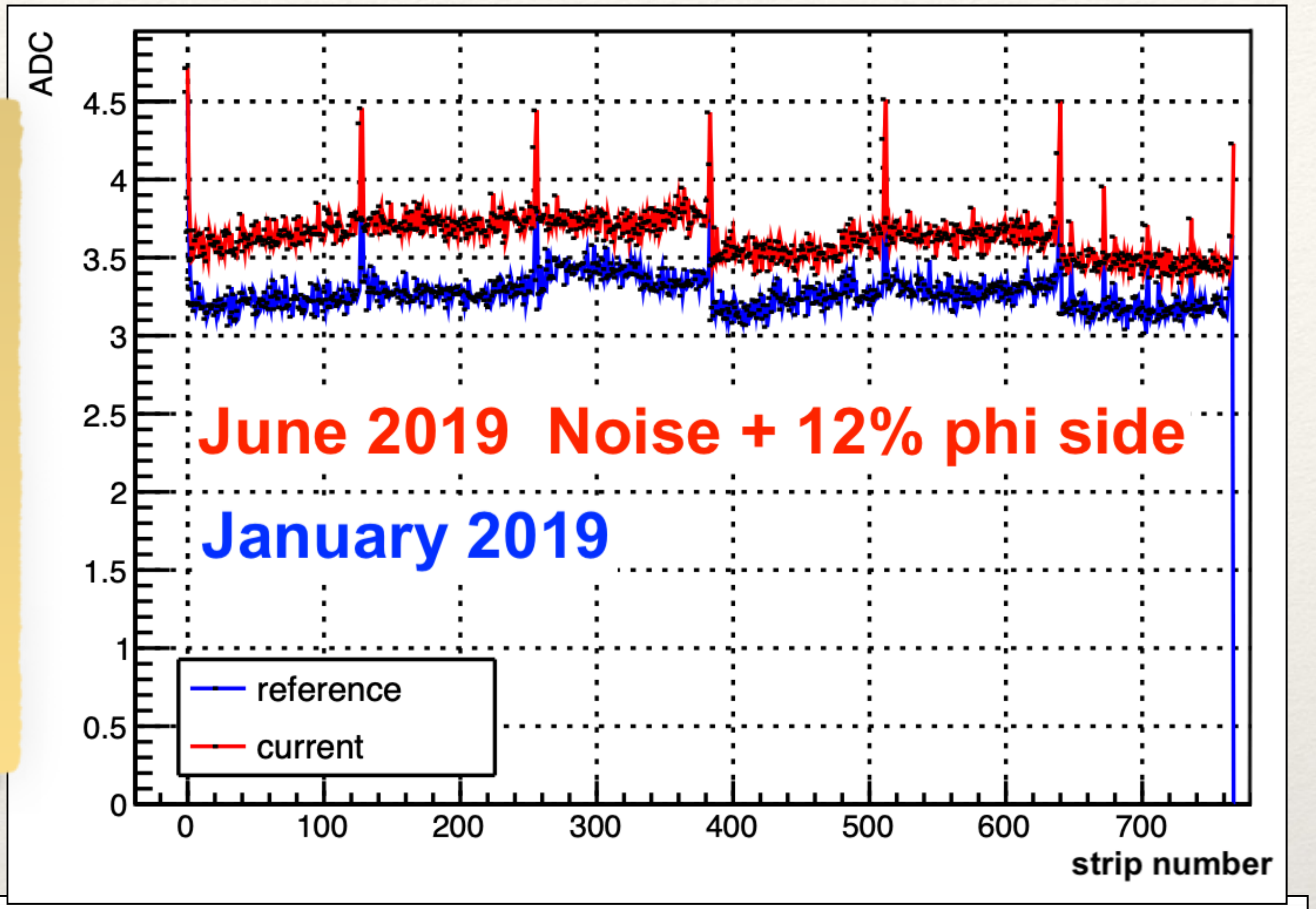
- SNR depends on channel noise and on collected charge:
  - noise is higher in r-ϕ side, that has longer strips.
  - signal depends on sensor position due to the track incident angle.
  - signal is slightly lower on the z side: charge loss due to the floating strips and the larger pitch.
  - In the end the noise difference is dominant and SNR is higher on the z side.
- Measured SNR MPV in all sensors is between 15 and 25 for r-ϕ side, 18 and 30 for z side.

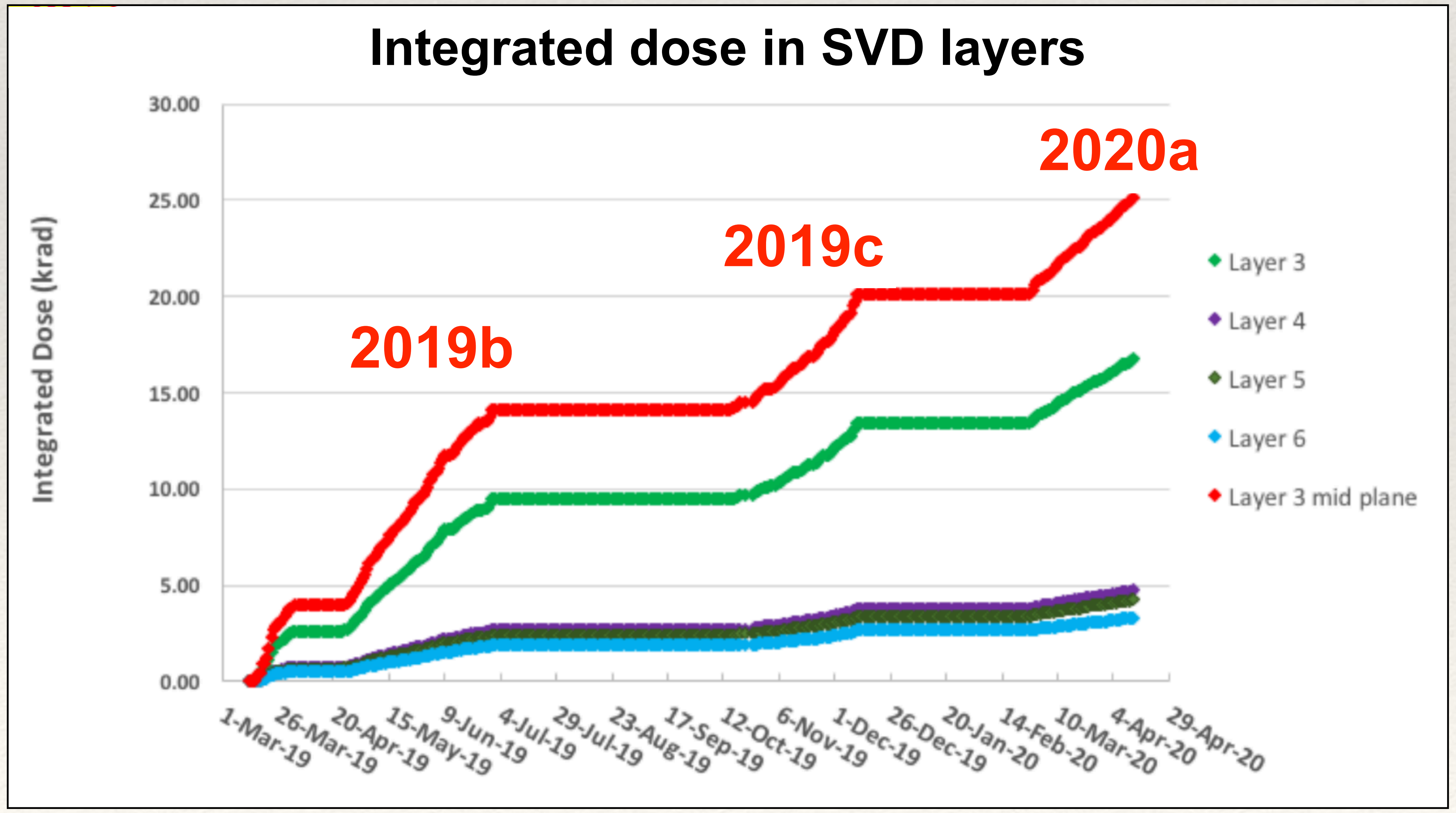
SVD Performance - Signal-to-noise Ratio

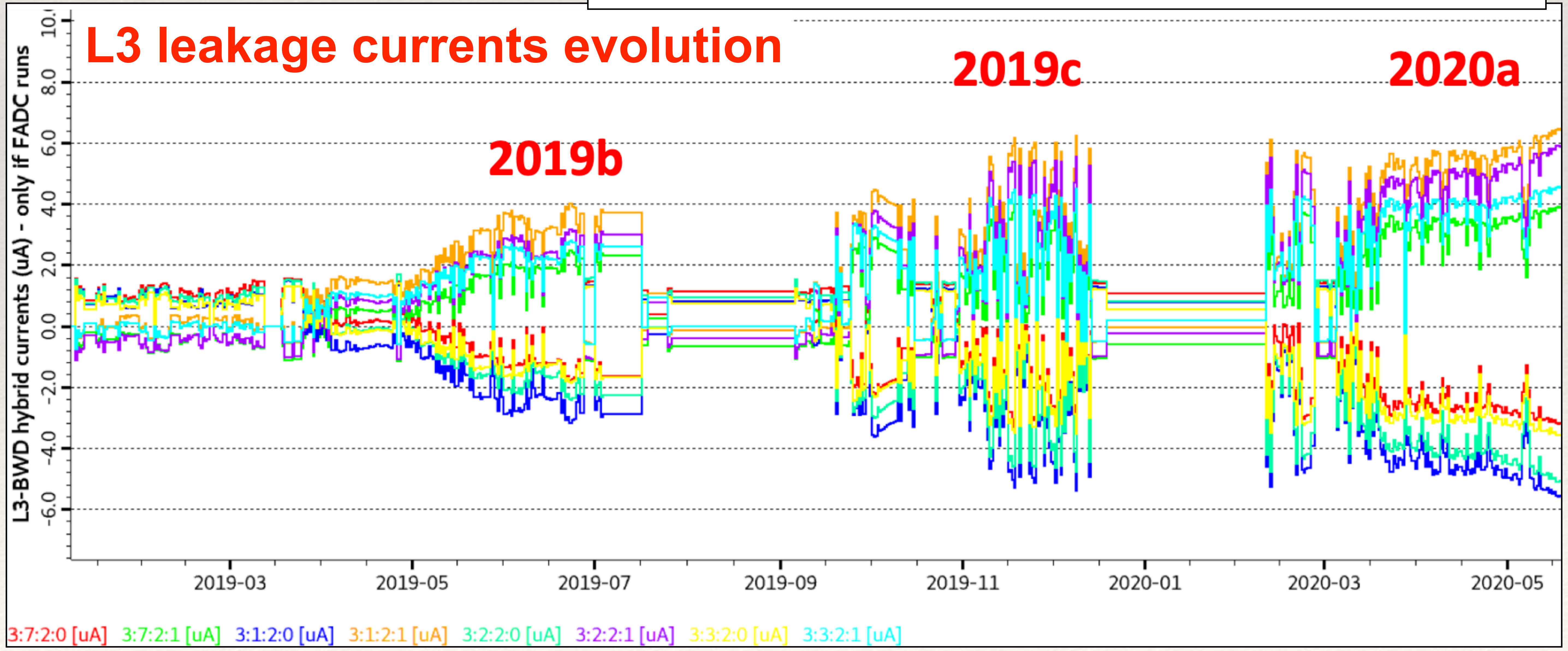


Radiation effects after one year

- Integrated dose in SVD estimated using data from diamond sensors.
  - Higher dose absorbed by the outer part of Layer 3
- Irradiation effects observed in all sensors:
  - SNR reduction in Layer 3 by 5-10% due to noise increase.
  - Noise increased on average by ~15-20% since operations have started.
  - Leakage currents increased with time, especially on Layer 3.
- Overall, none of these changes affect the performance of SVD.



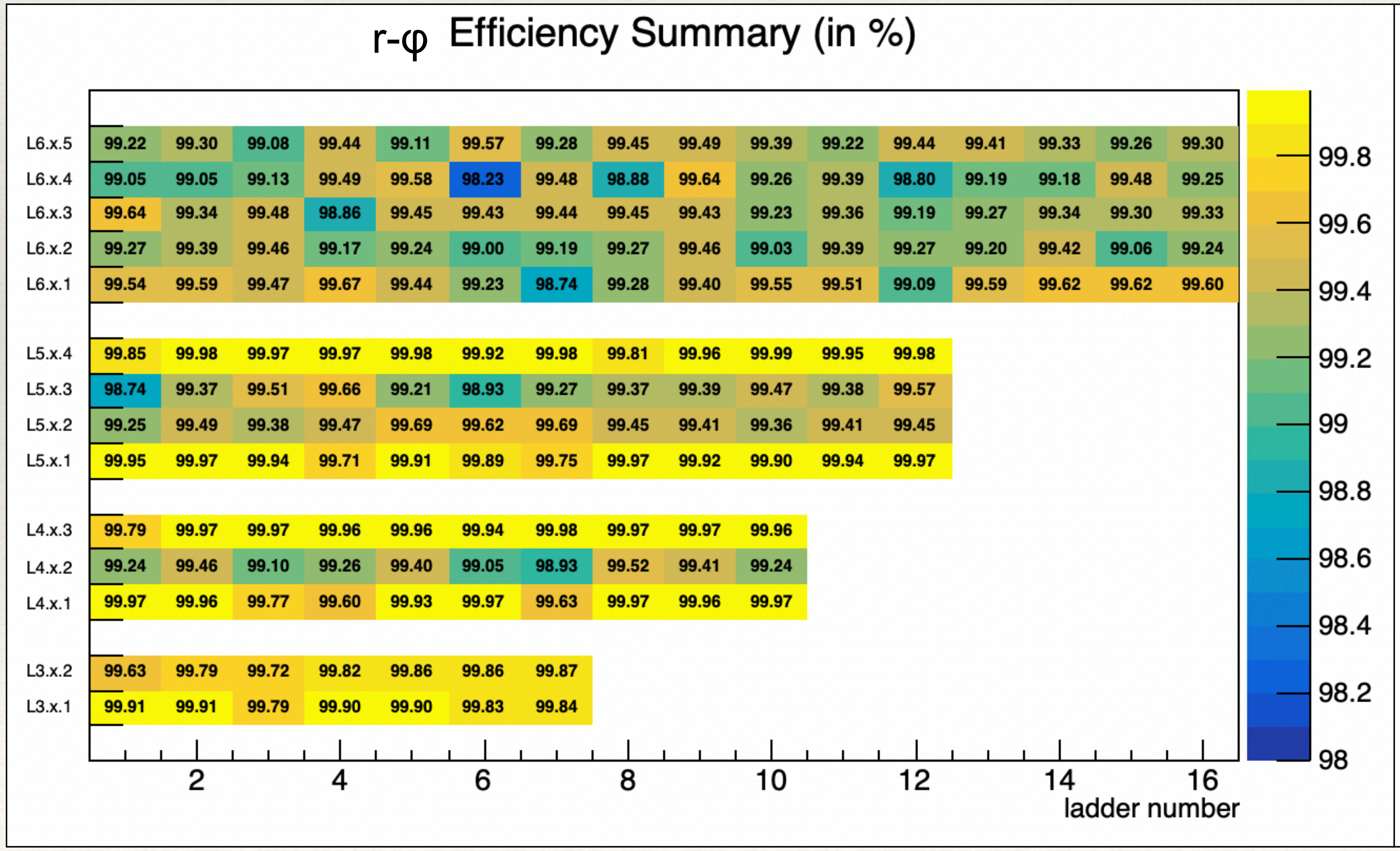


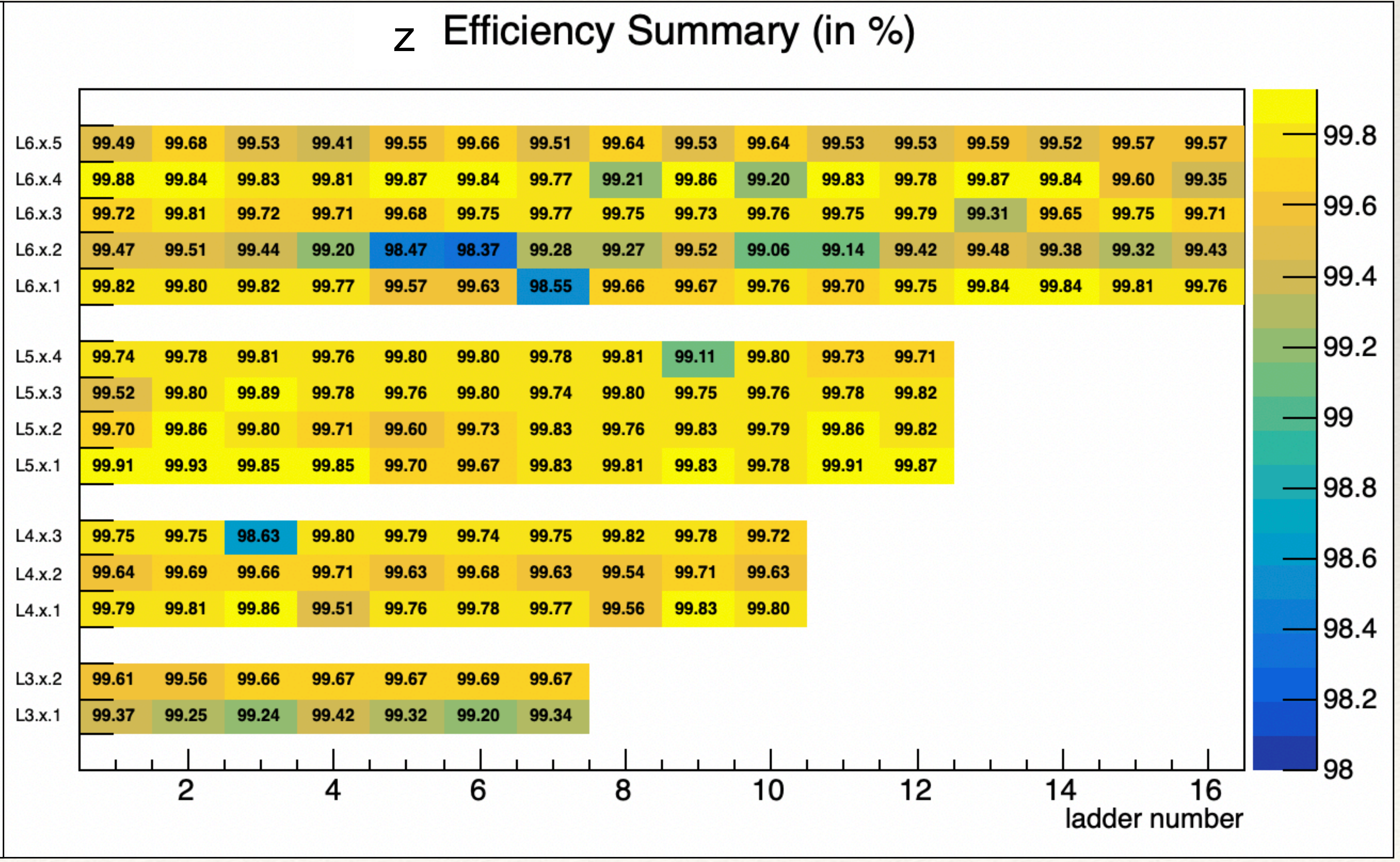


SVD Performance - Efficiency

- Tracks selection:
  - tracks from the Interaction Point, |d0|<0.1 cm and |z0|<0.2 cm
  - tracks with at least 1 SVD hit and 20 CDC hits
  - tracks with transverse momentum at least 1 GeV/c
- Very few noisy strips masked for data taking.
- Negligible additional defects during the assembly process.

efficiency	r-φ	z
Layer 3	(99.83±0.01)%	(99.48±0.03)%
Layer 4	(99.69±0.03)%	(99.68±0.03)%
Layer 5	(99.66±0.04)%	(99.77±0.03)%
Layer 6	(99.31±0.08)%	(99.58±0.06)%

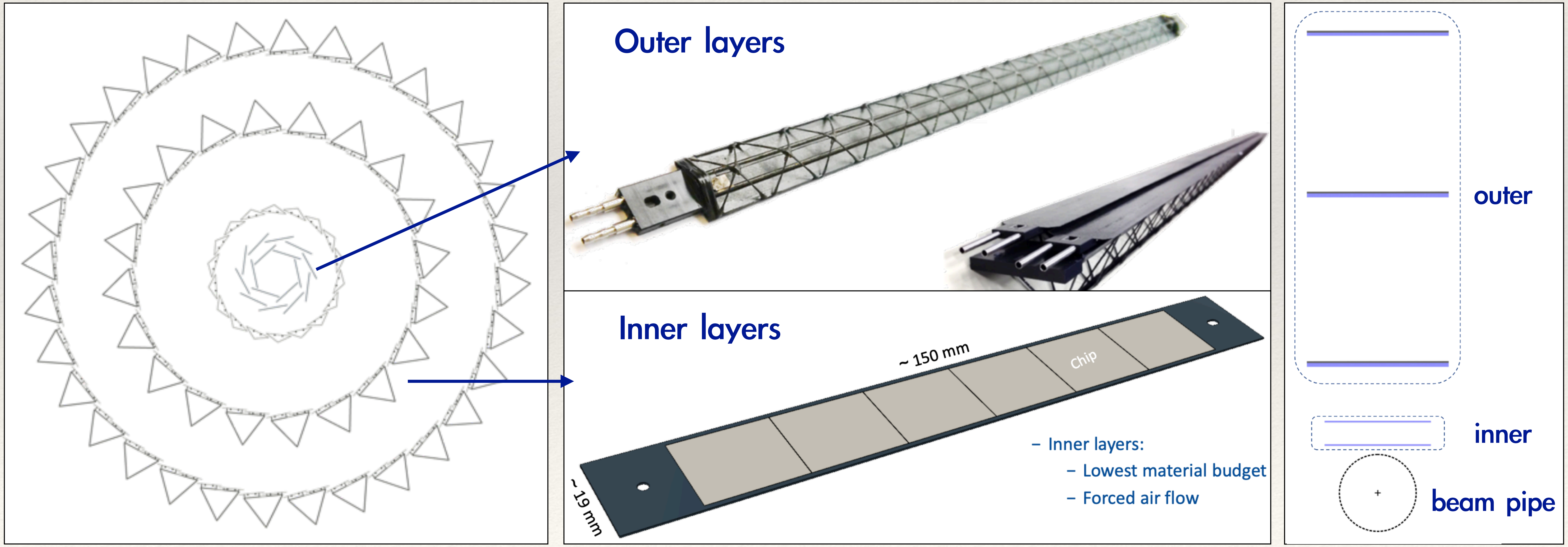




Towards VXD upgrade

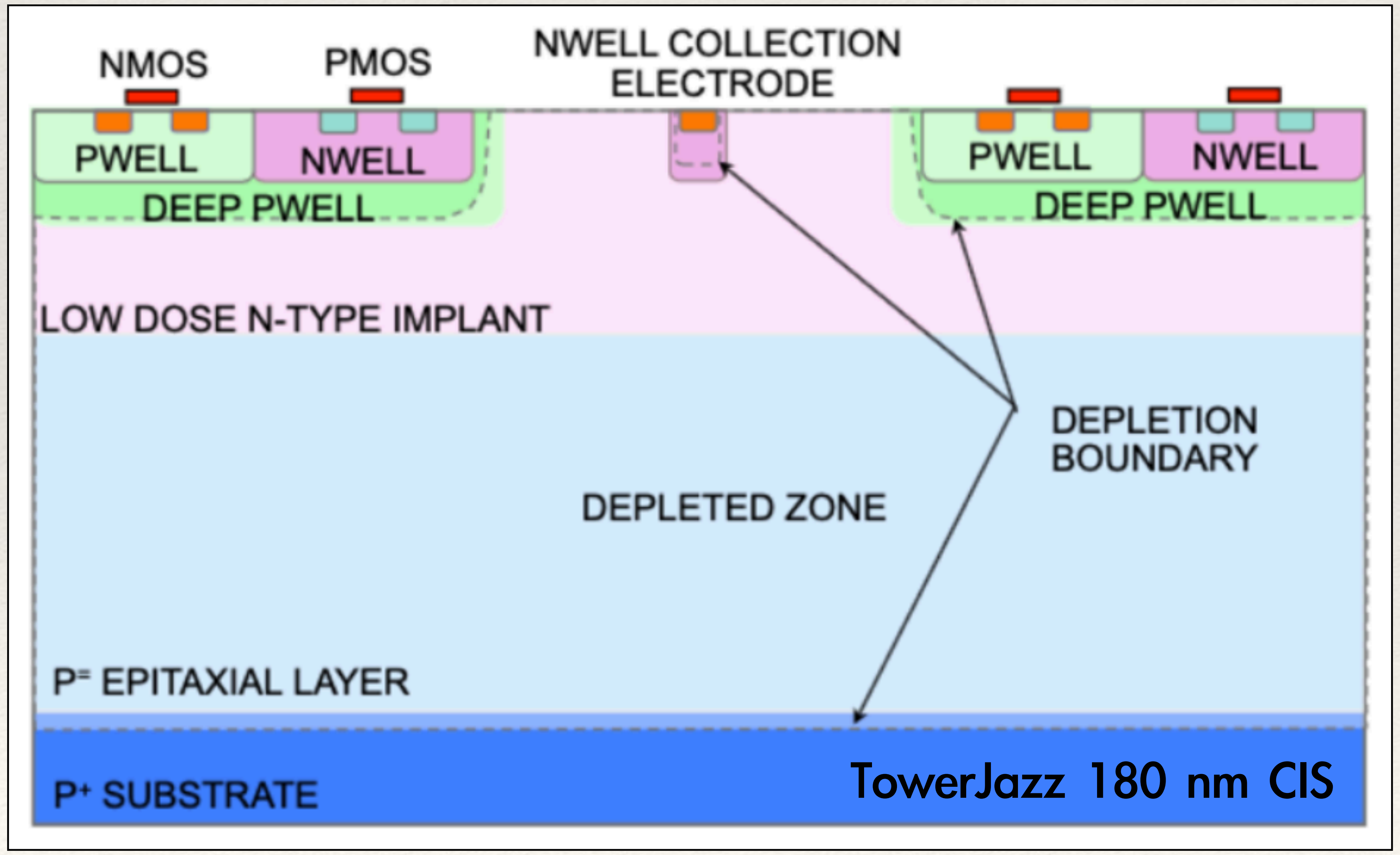
- SuperKEKB/Belle II is currently supposed to continue until we accumulate $50ab^{-1}$.
- The feasibility of a further luminosity increase is being considered. A factor 5 higher luminosity seems a reasonable goal, if technology evolution provides suitable solutions.
- Two options for the vertex detector upgrade:
  1. Replacement of the actual VXD with an upgraded pixel vertex detector keeping boundary conditions.
  2. Longer term option, towards Belle III, with upgraded technologies, after 2030.
- Workshops started in 2019 to explore the options, in particular using CMOS technology.

- 5 layers design
- L1 + L2 full silicon
- L3 based on ALICE inner space frame
- L4-5 based on ALICE outer space frame

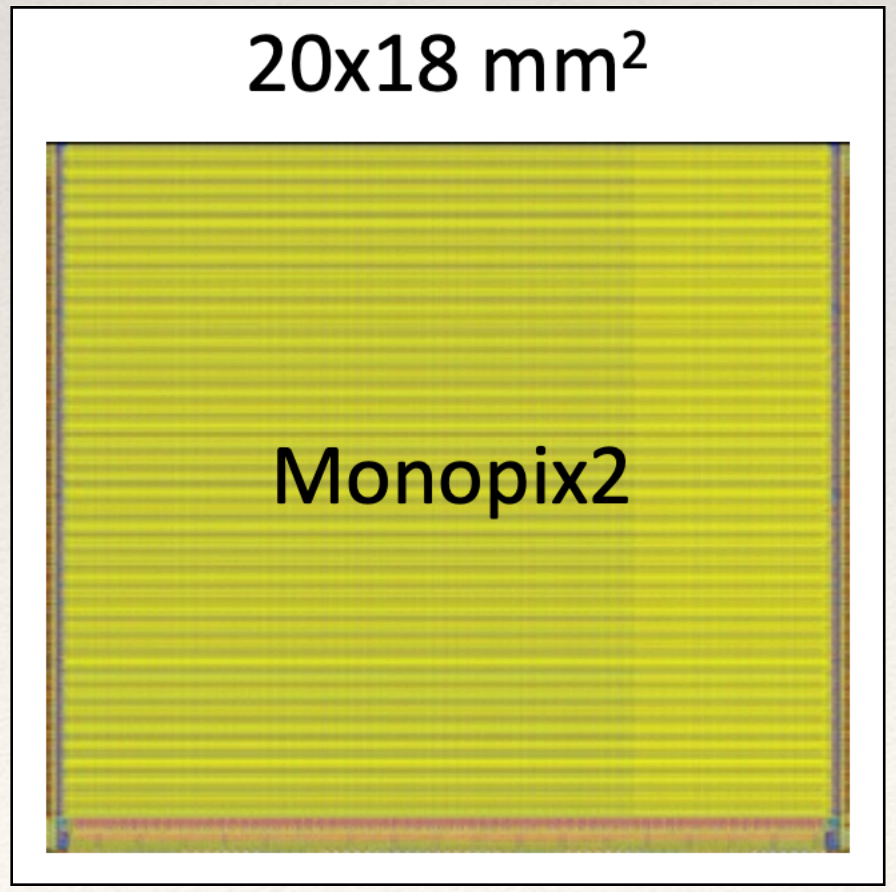


CMOS pixel sensors option

- A few guidelines established for the upgrade:
  - Light. Thin DMAPS: 0.1% X_0 (inner) - 0.3%-0.5% X_0 (outer).
  - Precise. Small pixel pitch: 30-40 μm.
  - Fast. Full electronics circuitry per pixel: 25-100 ns, sparsified readout.
  - Simplified services: Warm operation and fewer cables.
  - Reduced costs and production time. Easy to assemble, test and replace.



- Monolithic detector: sensor and readout on the same wafer
- n-well working as charge collection electrode
- in-pixel electronics with CMOS technology
- small capacitance, low noise and power
- Demonstrator built on 20×18 mm^2
  - 80 Mrad and 10^{15} neq/cm^2
  - 25 ns response time
  - 33x33 μm^2 pitch
  - 200 MHz/cm^2 hit rate



Conclusions

- The Silicon Vertex Detector of the Belle II experiment was built, tested and developed between 2015 and November 2018.
- Belle II started data taking in March 2019. Up to May 2020, it recorded 67 fb^{-1} of data.
- SVD has been running very stably since the start of data taking.
- SVD parameters are evolving as expected and do not affect performance.
- Machine induced background levels are under control at the moment, must be mitigated approaching design luminosity, to avoid degradation of tracking performance.
- The possibility of an upgrade of the vertex detector is already under development.

A few references

- **Belle II Silicon Vertex Detector (SVD)**
  - *"Construction and test of the first Belle II SVD ladder implementing the origami chip-on-sensor design"*, JINST 11 (2016) 01, C01087, DOI: 10.1088/1748-0221/11/01/C01087
  - *"The Belle II silicon vertex detector: Assembly and initial results"*, Nucl.Instrum.Meth.A 936 (2019) 712-714, DOI: 10.1016/j.nima.2018.08.066
  - *"Performance of the Belle II Silicon Vertex Detector"*, Nucl.Instrum.Meth.A 972 (2020) 164129, DOI: 10.1016/j.nima.2020.164129
- **Belle II VerteX Detector (VXD)**
  - *"Operational experience and commissioning of the Belle II vertex detector"*, *PoS* VERTEX2018 (2019) 006, DOI: 10.22323/1.348.0006
- **Belle II publications:**
  1. *"Measurement of the integrated luminosity of the Phase 2 data of the Belle II experiment"*, Belle II collaboration, Chin.Phys.C 44 (2020) 2, 021001, DOI: 10.1088/1674-1137/44/2/021001
  2. *"Search for an invisibly decaying Z′ boson at Belle II in $e^+e^- \rightarrow \mu^+\mu^-(e^{\pm}\mu^{\mp})$ plus missing energy final states"*, Belle II collaboration, Phys.Rev.Lett. 124 (2020) 14, 141801, DOI: 10.1103/PhysRevLett.124.141801
- **SuperKEKB:**
  - *"SuperKEKB Collider"*, K. Akai, K. Furukawa, H. Koiso, Nuclear Instruments and Methods in Physics Research Section A, vol. 479, pp. 188-199, 2018, DOI:10.1016/j.nima.2018.08.017
- **Belle II:**
  - T. Abe et al., Belle II Collaboration, *"Belle II Technical Design Report"*, ArXiv e-prints (2010) , arXiv:1011.0352.

Thank you for your attention

BACKUP

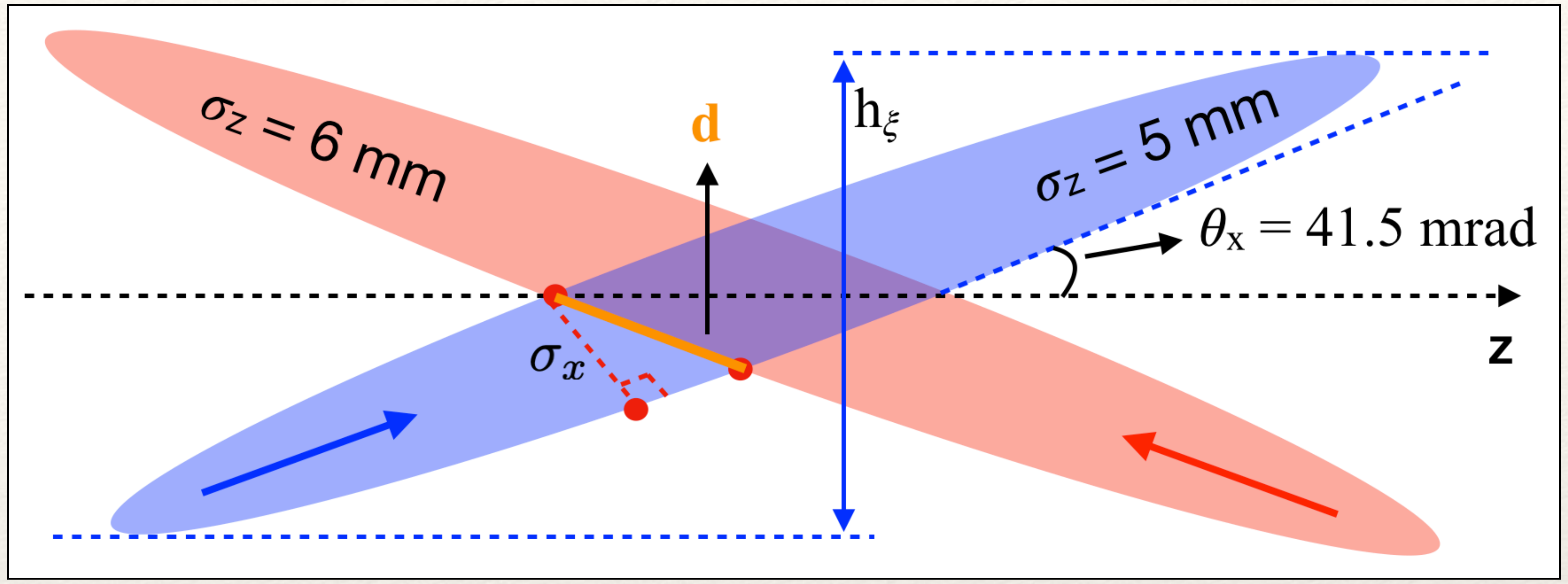
KEKB - SuperKEKB parameters

$$L = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y}$$

$$\phi_{Piw} = \frac{\sigma_z}{\sigma_x^*}tan\theta_x$$

Hourglass effect condition:

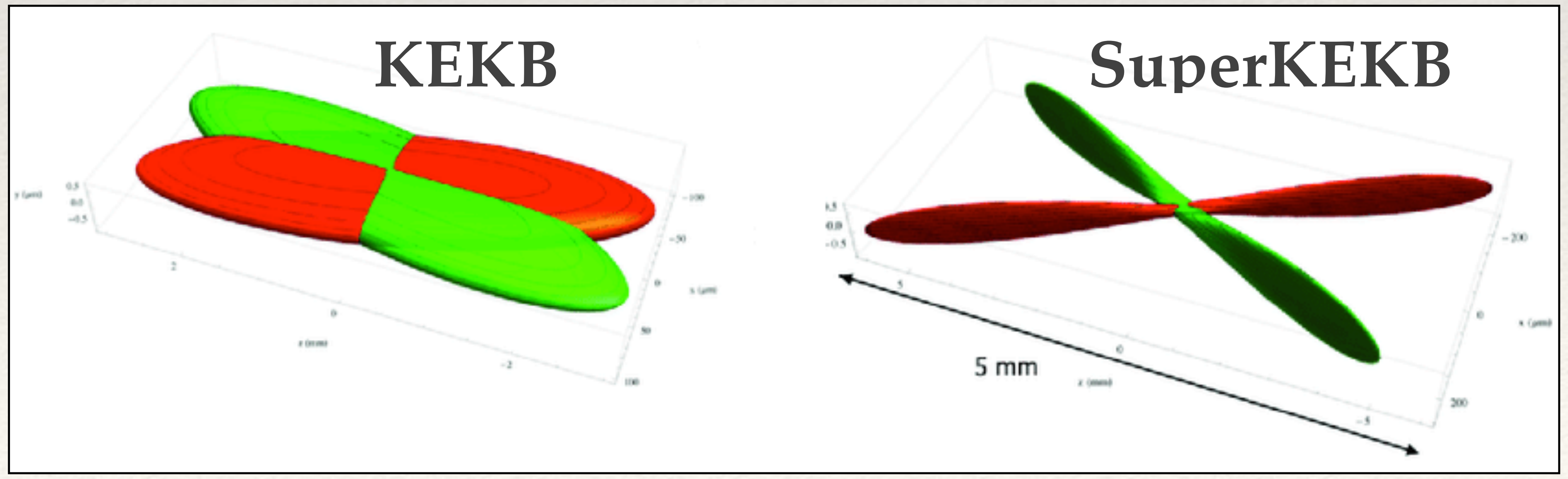
$$\beta_y^* \geq d = \frac{\sigma_x^*}{sin(2\theta_x)}$$



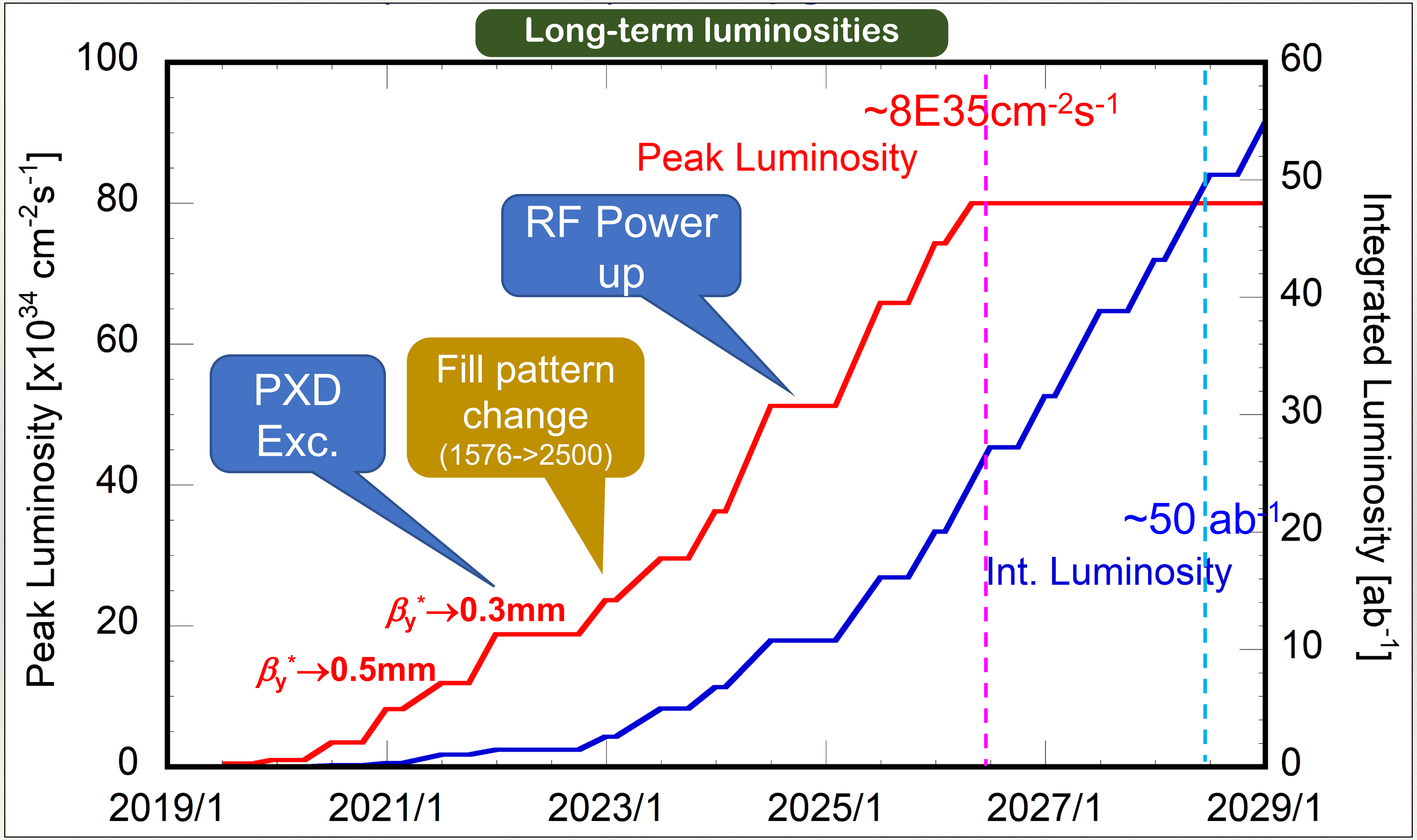
	KEKB		SuperKEKB	
	LER	HER	LER	HER
E [GeV]	3.5	8.0	4.0	7.0
θ_x [mrad]	0 (11)		41.5	
ε_x [nm]	18	24	3.2	4.6
ε_y [pm]	150	150	8.64	12.9
β_x^* [mm]	1200	1200	32	25
β_y^* [mm]	5.9	5.9	0.27	0.30
σ_x^* [μm]	147	170	10.1	10.7
σ_y^* [nm]	940	940	48	62
n_b	1584		2500	
I [A]	1.64	1.19	3.6	2.6
L [cm^{-2} s^{-1}]	2.1 x 10^{34}		8.0 x 10^{35}	

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm\xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_{y\pm}}}\right)$$

$$\xi_{y\pm} = \frac{r_e}{2\pi\gamma_\pm}\frac{N_\mp\beta_y^*}{\sigma_y^*(\sigma_x^*+\sigma_y^*)}R_{\xi_{y\pm}} \propto \frac{N_\mp}{\sigma_x^*}\sqrt{\frac{\beta_y^*}{\varepsilon_y}}$$

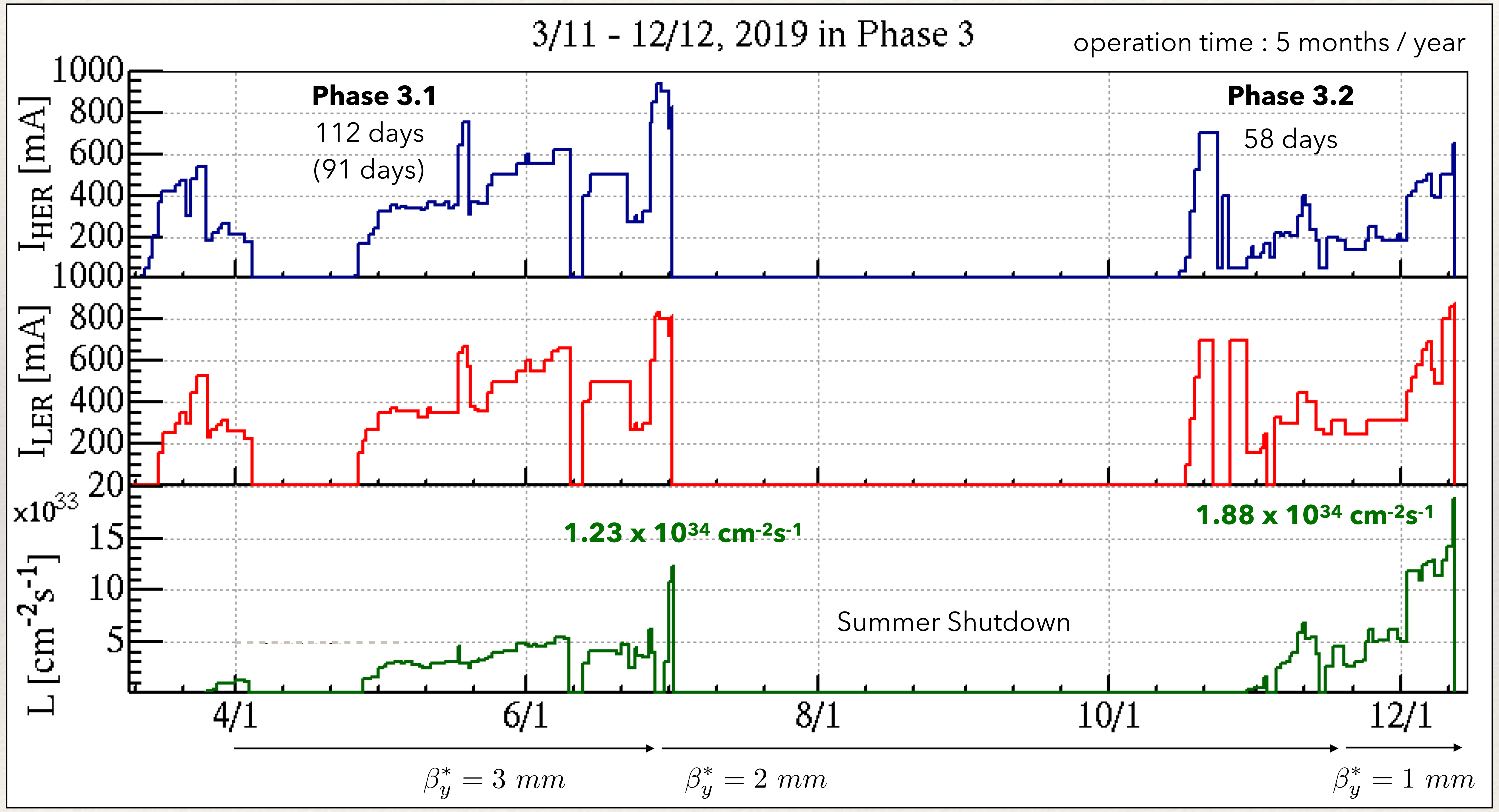


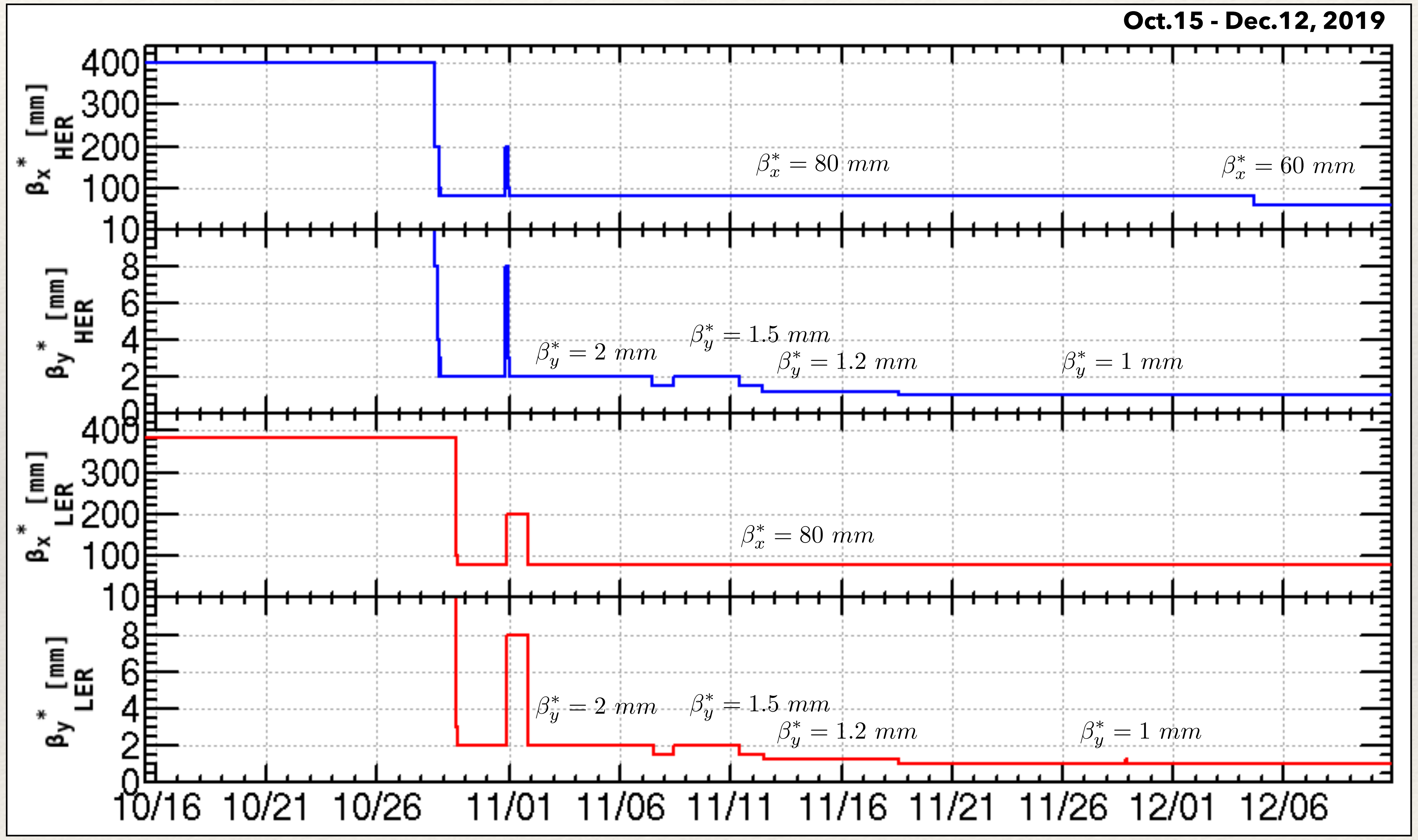
SuperKEKB - luminosity projection



Beta function evolution in 2019

- Reached $\beta_y^* = 3$ mm (factor 2 better than KEKB) already in Phase 2
- In Phase 3 squeezed from $\beta_y^* = 3$ mm to $\beta_y^* = 1$ mm
- Actually the smallest β_y^* ever achieved, still a factor 3 to improve.





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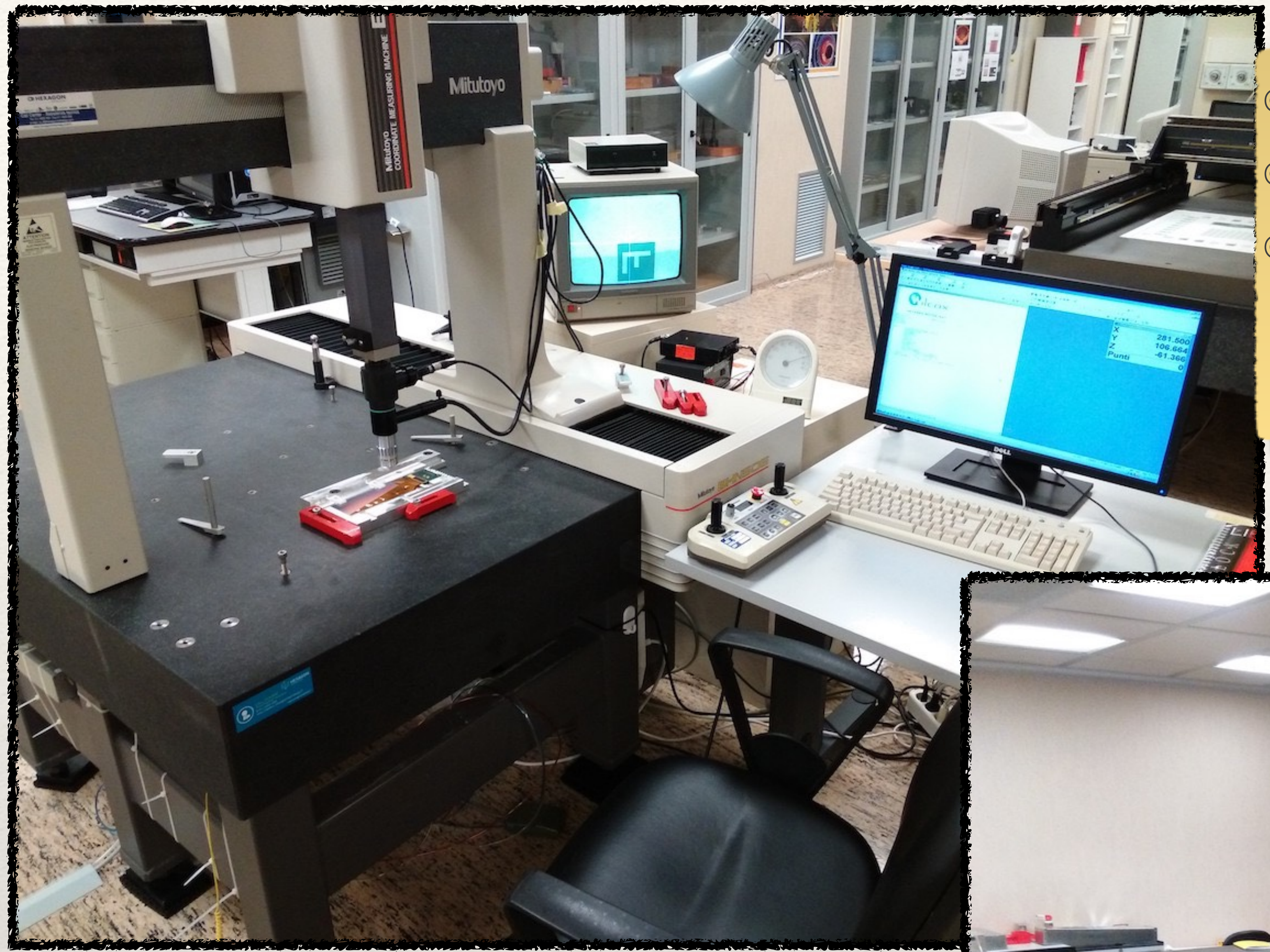
Clean room in Pisa



- Dedicated vacuum and air pressure facilities.
- Dry air, due point at -40˚ C
- Thermo-hygrometric conditions monitored
  - Temperature: 21 ± 1°C
  - Humidity: 50% ± 5%

- 600 m² divided into 3 closed environments + a common space with CMMs and other common tools/machines.
- Clean Room Cleaness Class: 100.000 - 10.000

Machine induced background

Modern e^+e^- colliders are subject to many sources of background, that can be divided in single beam backgrounds and luminosity backgrounds. The challenging machine parameters that should be used to achieve SuperKEKB design luminosity will make background conditions particularly harsh.

Systematic strong efforts were done by Belle II and SuperKEKB groups to study the effects of backgrounds induced by the machine on the detector, already from Phase I, with dedicated studies that have the goal of disentangling the different background contributions.

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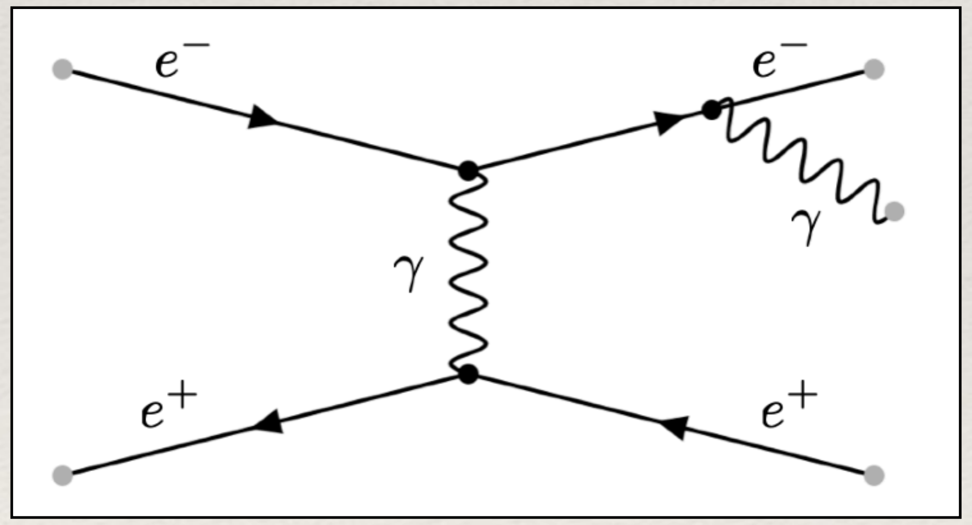
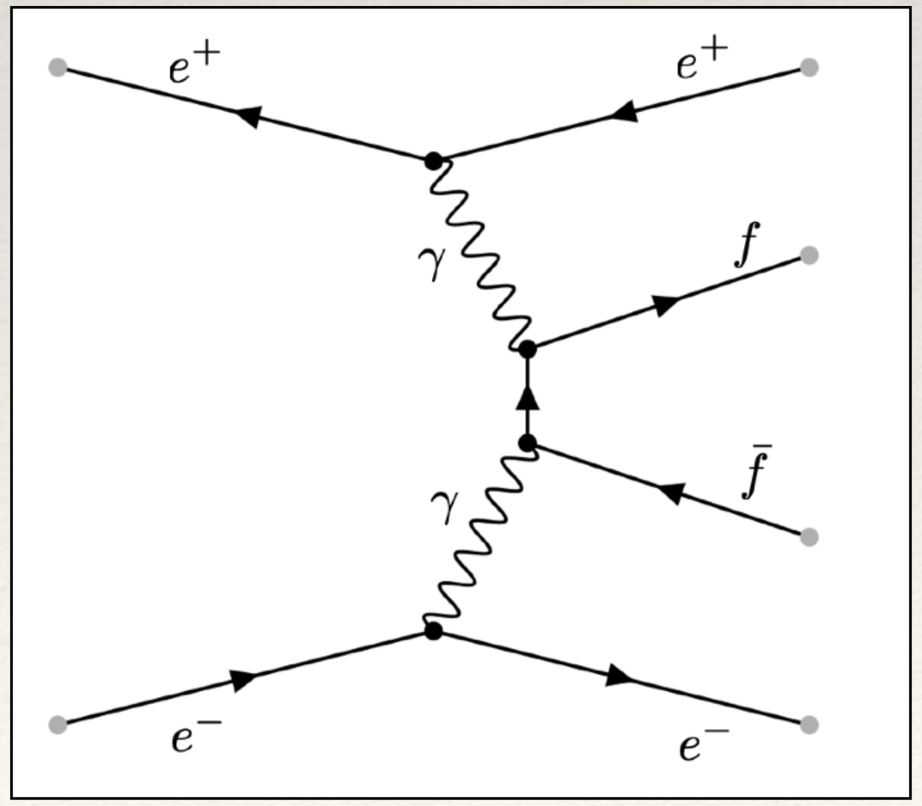
beam-beam background sources



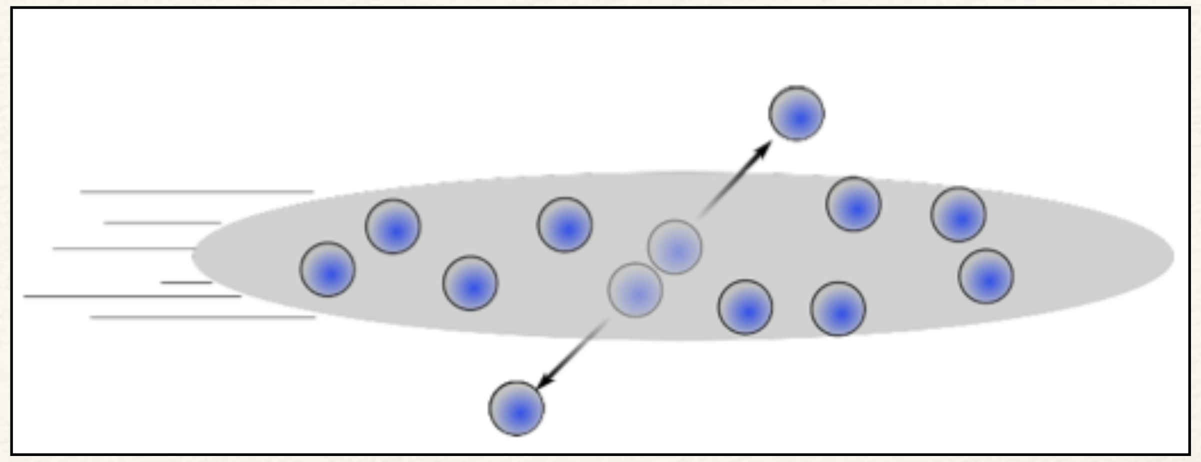
Radiative Bhabha: neutron production from emitted photons (shields used for mitigation); off-energy primary particles lost in final focus magnets.

Two photons process: low momentum electron-positron pairs that can generate multiple hit in the VerteX Detector.



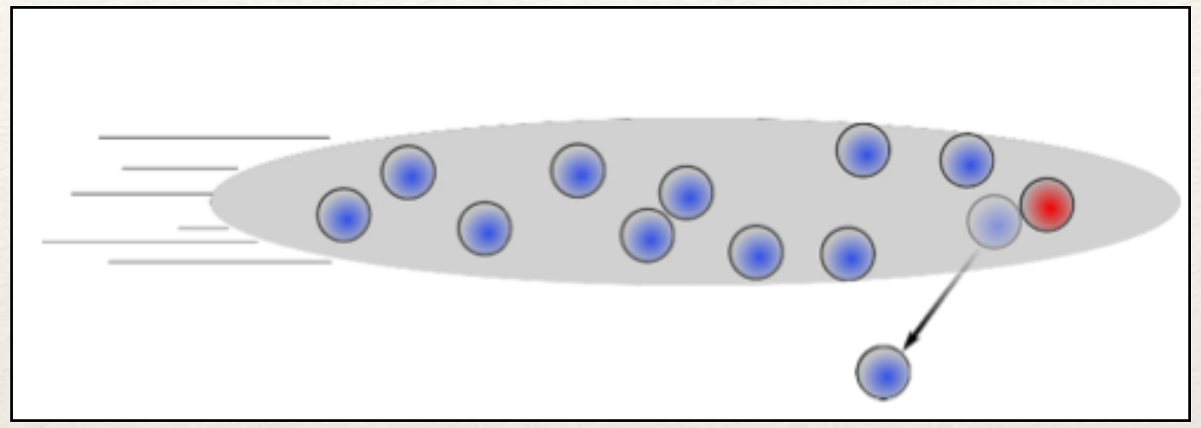
Single beam background sources

Touschek scattering: single Coulomb scattering event between two particles of the same bunch, that are lost.



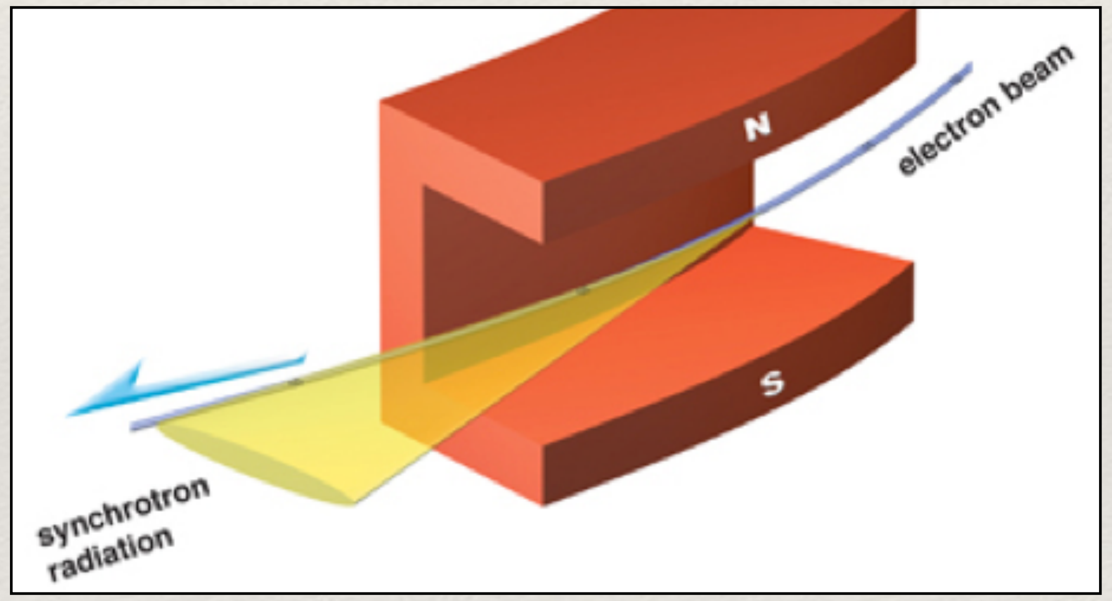
$$R_{Tou} \propto \frac{1}{\sigma E^3 n_b} I^2_{beam}$$

Beam-gas scattering: Coulomb elastic scattering or bremsstrahlung with residual gas atoms.



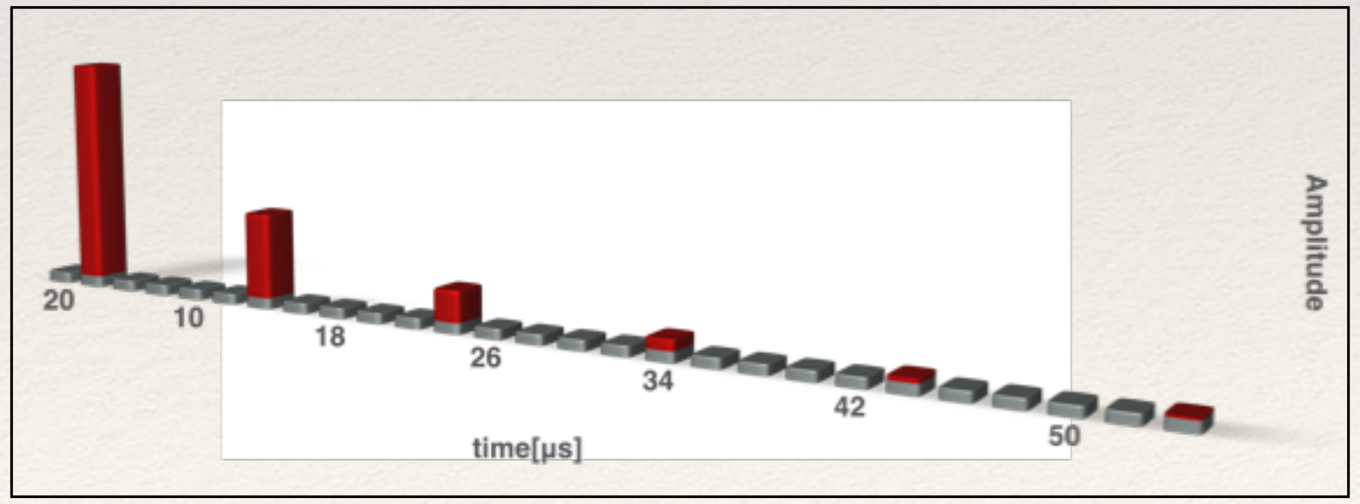
$$R_{bg} \propto I_{beam} P$$

Synchrotron Radiation (SR): photon emission from beam particles when subject to acceleration.



$$W_{SR} \propto \frac{E^4 I_{beam}}{\rho^2}$$

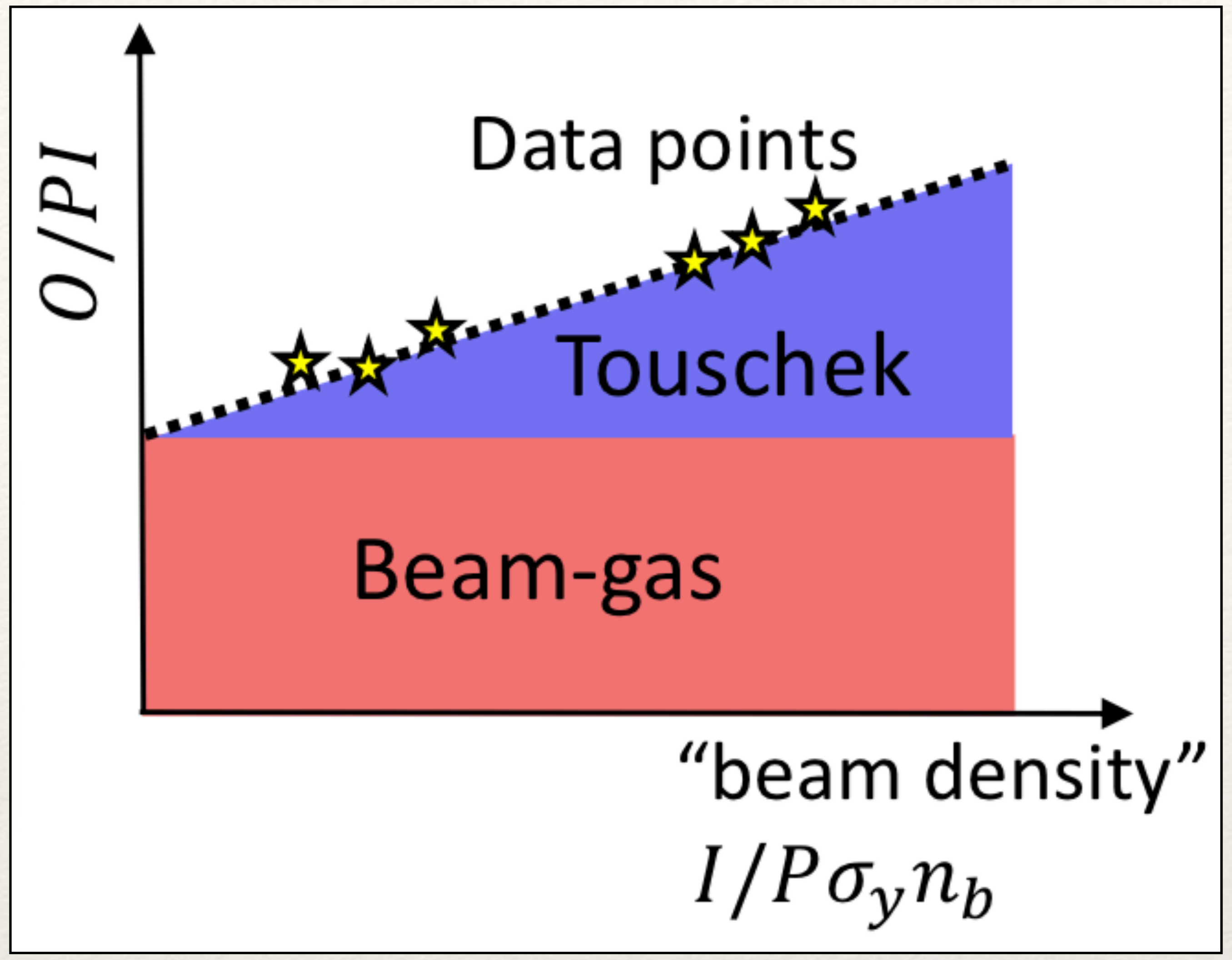
Injection background: injected bunch performing betatron oscillation around the stored bunch, resulting in particle losses especially in the interaction region.



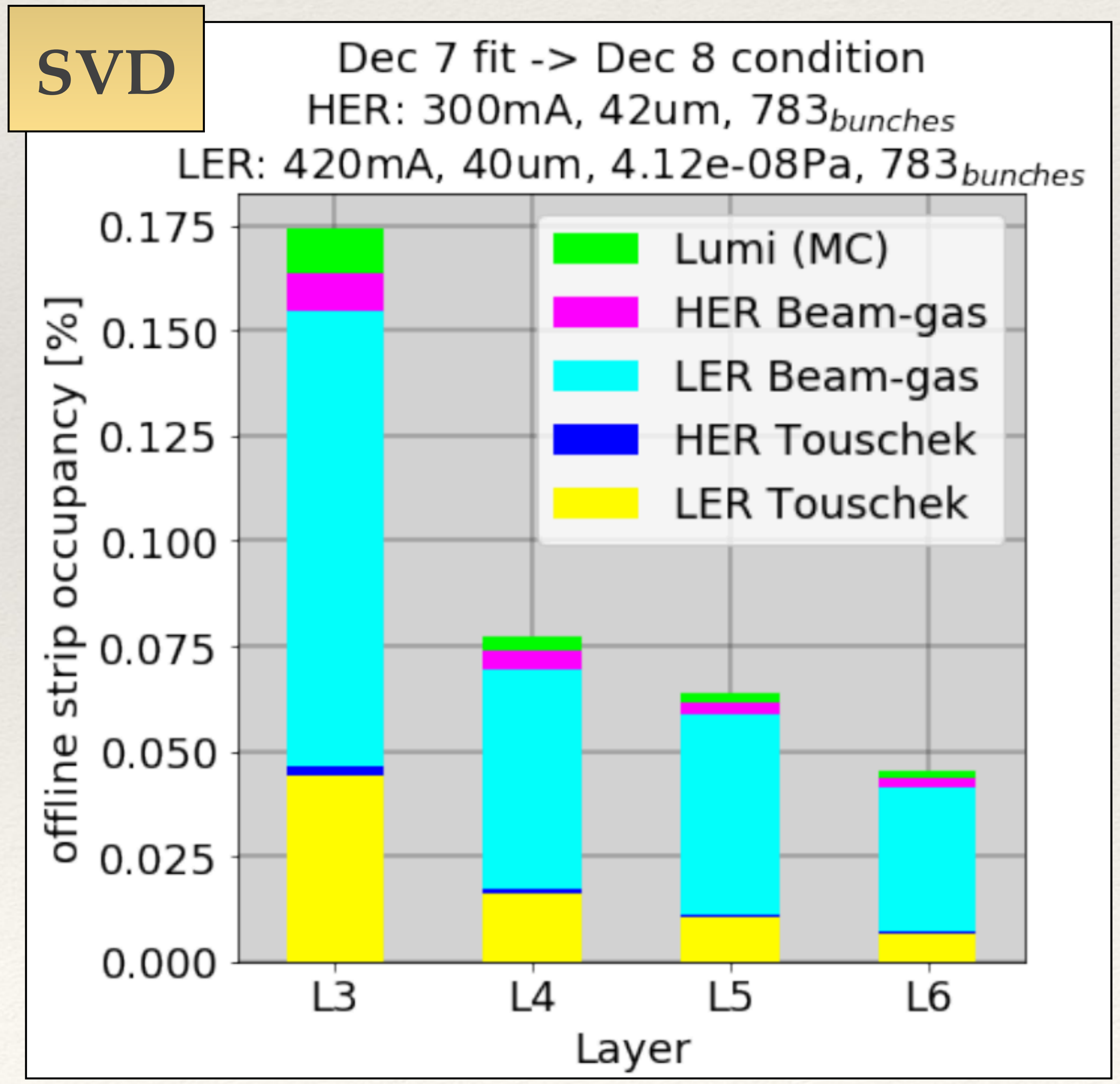
$$R_I \propto R_{inj}$$

Single beam background studies

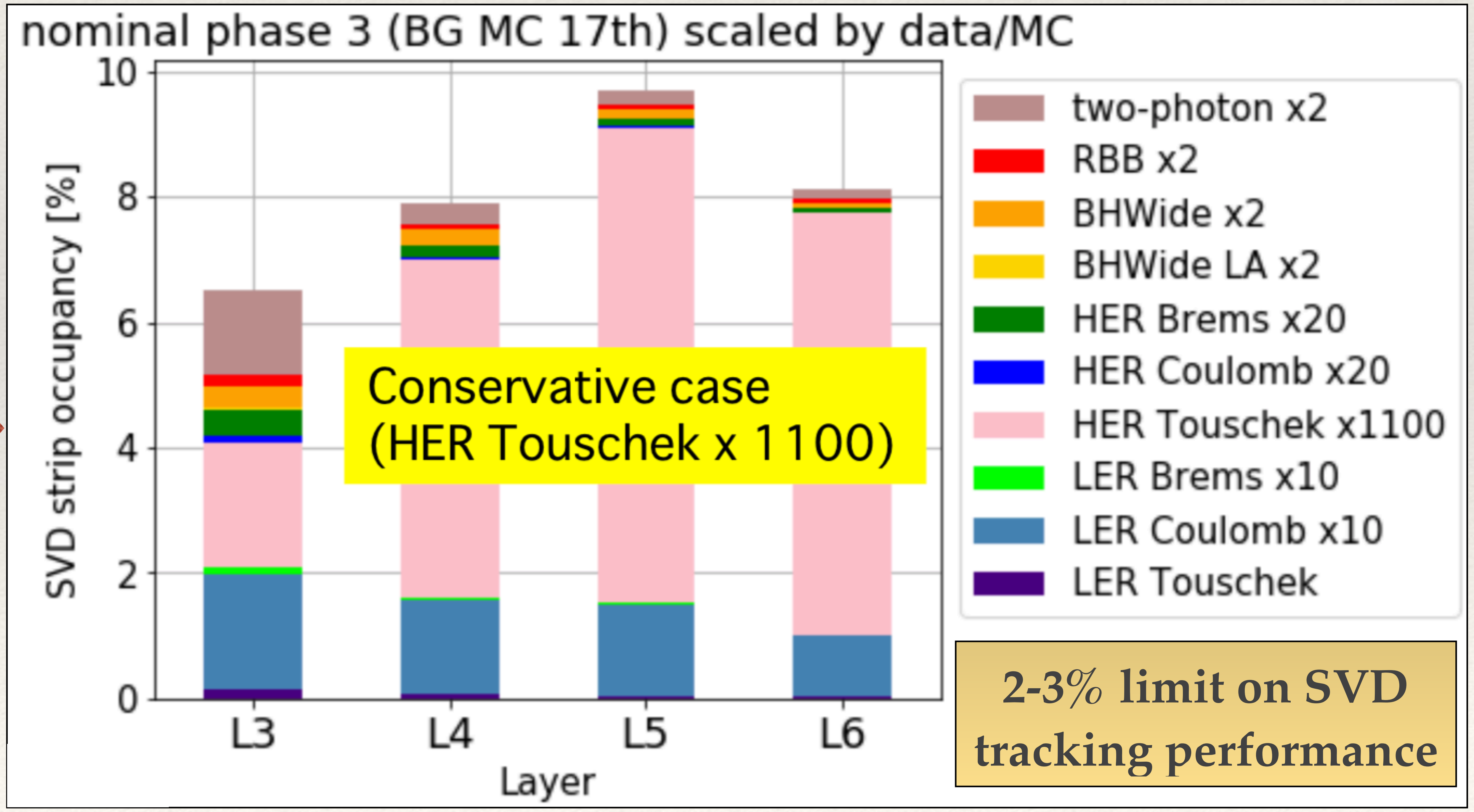
$$Obs. = T \cdot \frac{I^2}{\sigma_y n_b} + B \cdot IPZ_{eff}^2 \quad \longrightarrow \quad \frac{Obs.}{IPZ_{eff}^2} = T \cdot \frac{I}{PZ_{eff}^2 \sigma_y n_b} + B$$



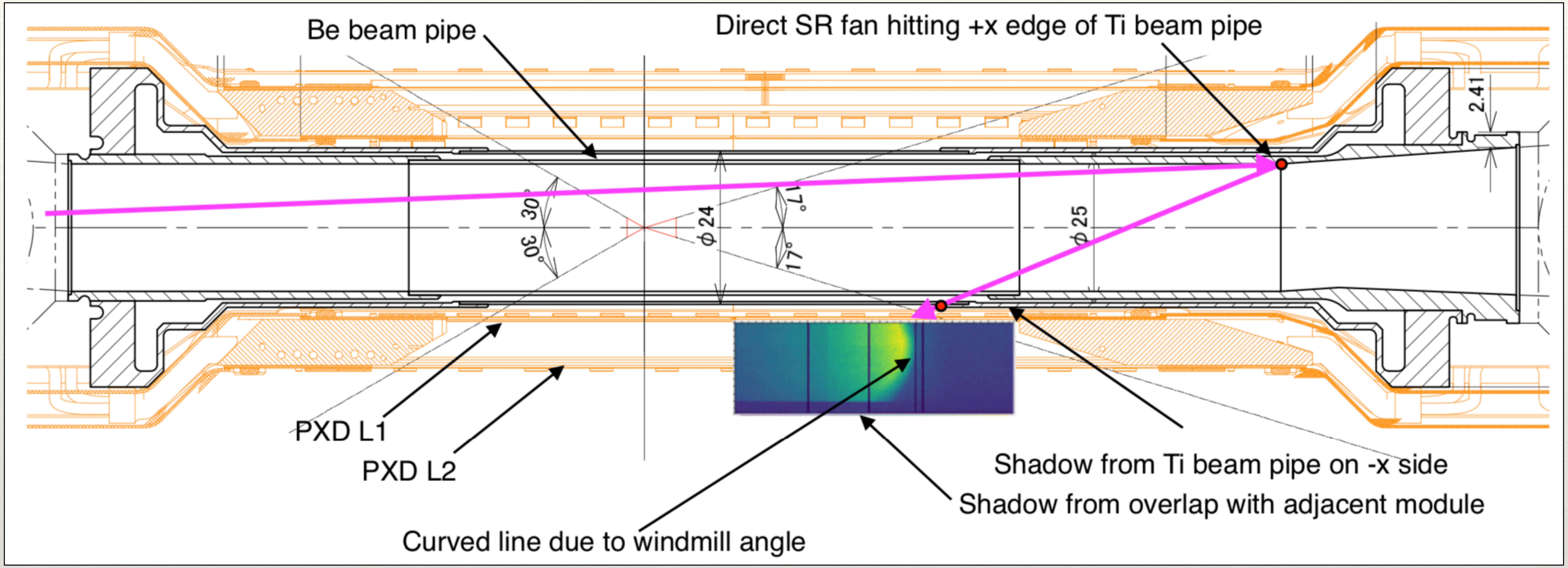
- Change n. of bunches or beam size. Data points will sit (in principle) on a straight line.
- Fit the model to get T and B parameters, and compare with MC predictions.
- Estrapolate background levels to final machine parameters using data/MC ratios.



extrapolating to design parameters



Synchrotron radiation on PXD

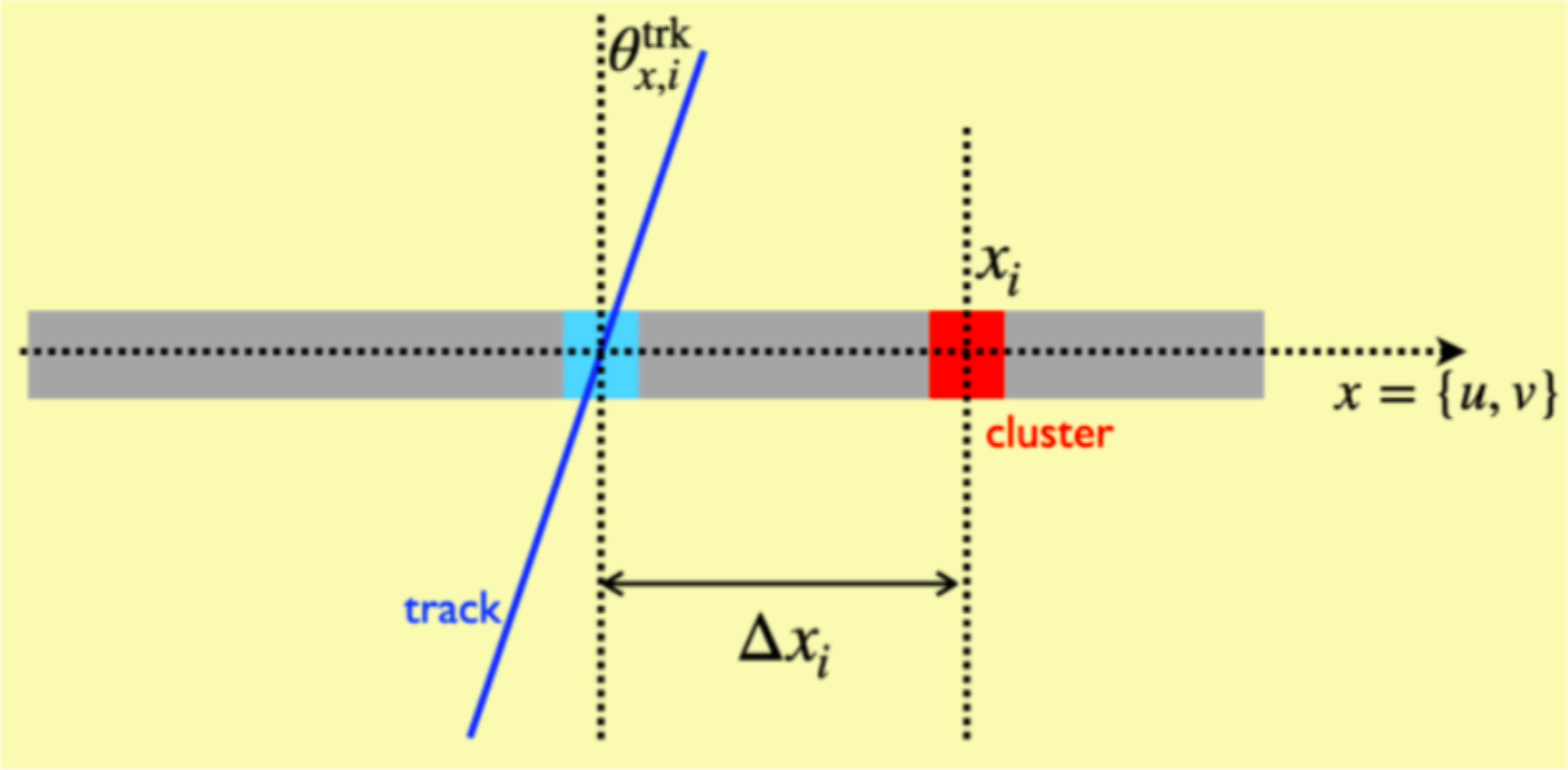


- Synchrotron radiation observed on PXD after squeezing betatron function.
- SR photons of injected bunches are backscattered from the edge of Ti beam pipe.
- Can be reduced by changing the beam orbit angle.
- Not fully eliminated, storage component still observed, caused by increased horizontal dispersion.
- New beam pipe design under discussion to protect against back scattered SR photons.

Cluster position resolution

- First estimation of cluster position resolution estimated with di-muon events of the spring run.
- Resolution estimated from the residual between the cluster position and the unbiased track position.

- Preliminary result: 20 μm in Layer 3
    - Possible improvement of the algorithm
    - Worse than the most optimistic MC prediction. SVD simulation to be tuned.



$$\sigma_x = \sqrt{\left\langle (\Delta x_i)^2 - \left(\sigma_{x,i}^{trk}\right)^2 \right\rangle}$$

$\sigma_{x,i}^{trk}$ = unbiased track position error