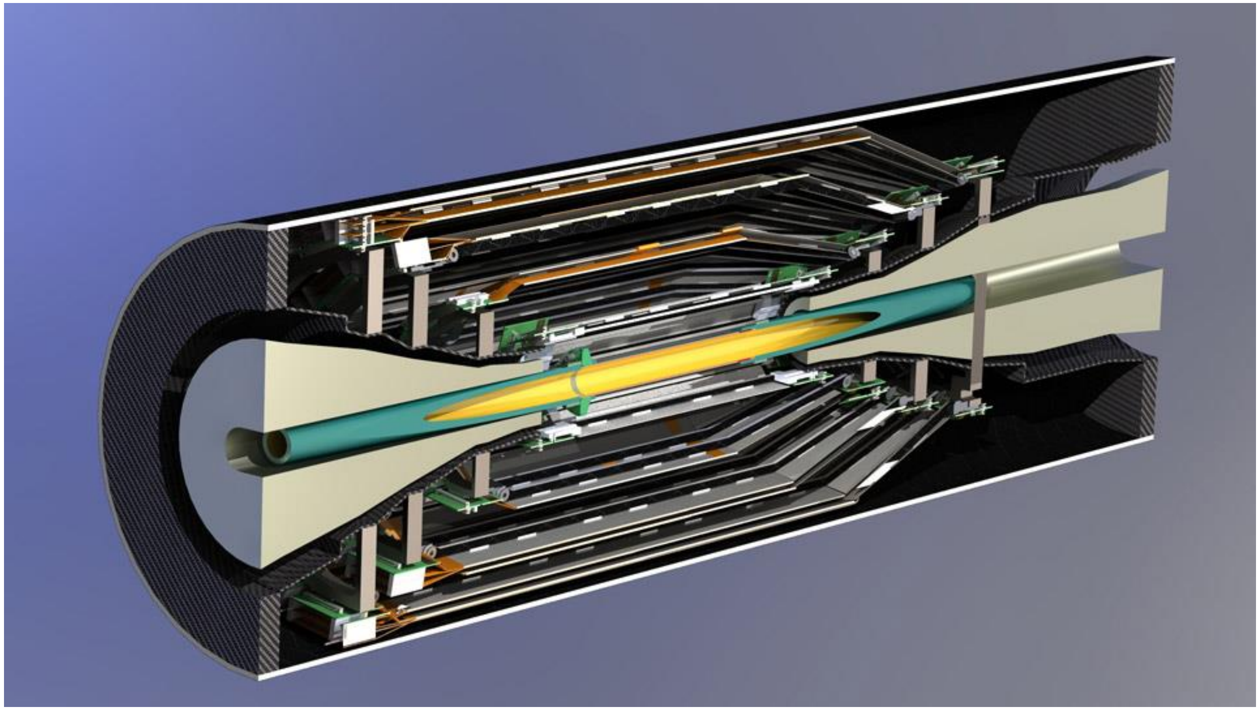


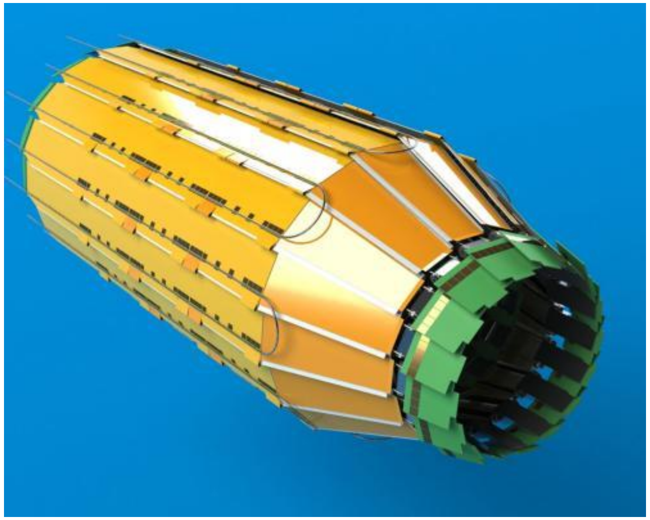
Belle II

Status of the Silicon Strip Vertex Detector of the Belle II Experiment

Thomas Bergauer (HEPHY Vienna)

Vertex 2013 Lake Starnberg

16 September 2013



Belle and Belle II

- Components
  - Sensors
  - Electronics
  - Mechanics and Cooling
  - Ladder assembly
  - Mockups
- Summary

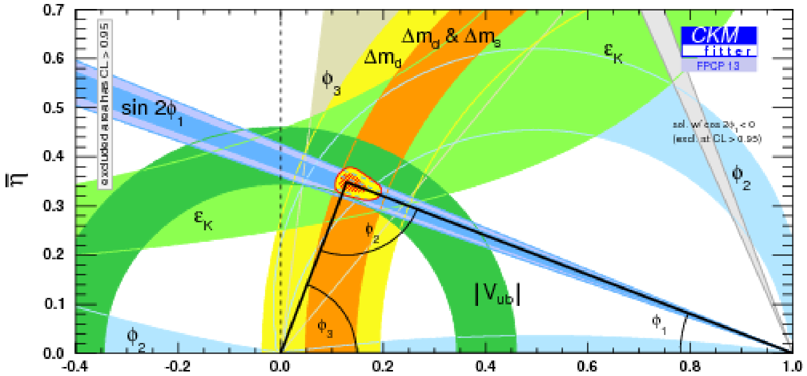
Belle I at the KEKB accelerator (1999-2010)

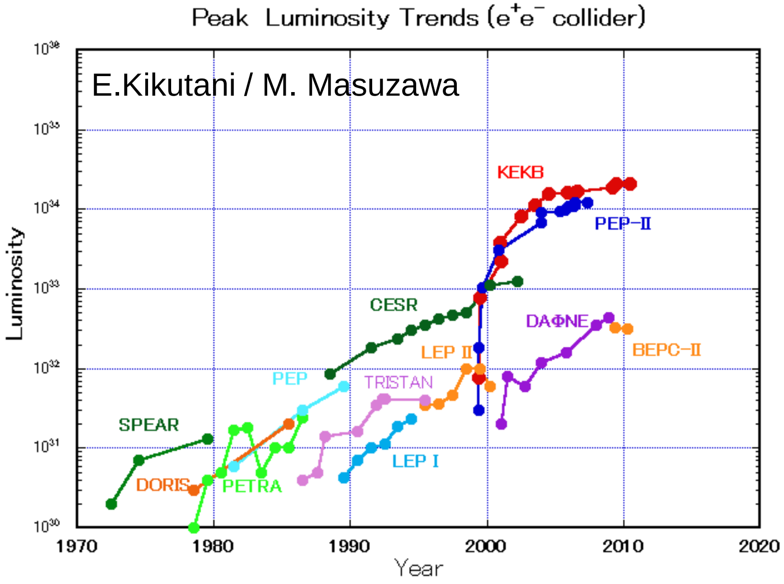
Belle I:

- Measurements of CKM matrix elements and angles of the unitary triangle
- CP & T & CPT test
- Observation of direct CP violation in B decays
- probe for new sources of CPV

KEKB accelerator:

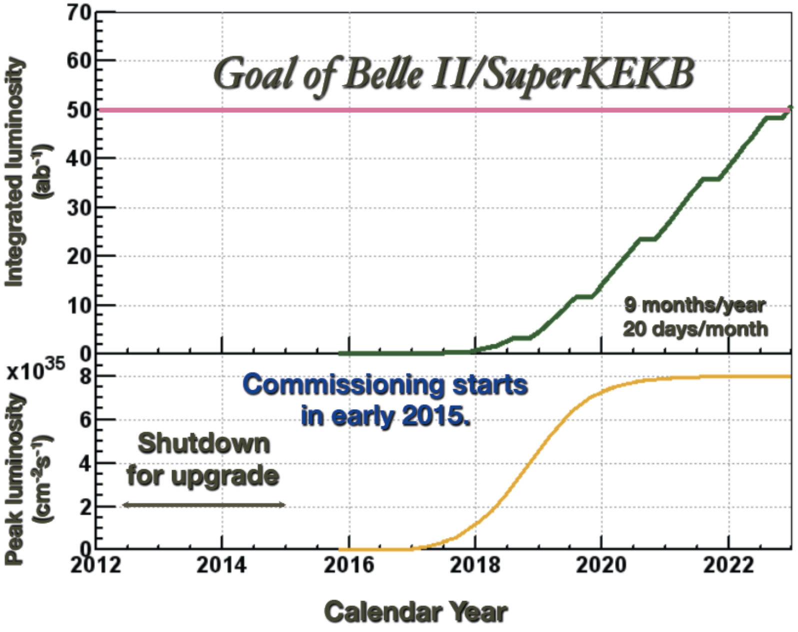
- Center of mass **energy**: Y(4S) resonance (10.58 GeV)
- **High intensity** beams (1.6 A & 1.3 A)
- Integrated luminosity of **1 ab^{-1} recorded** in total

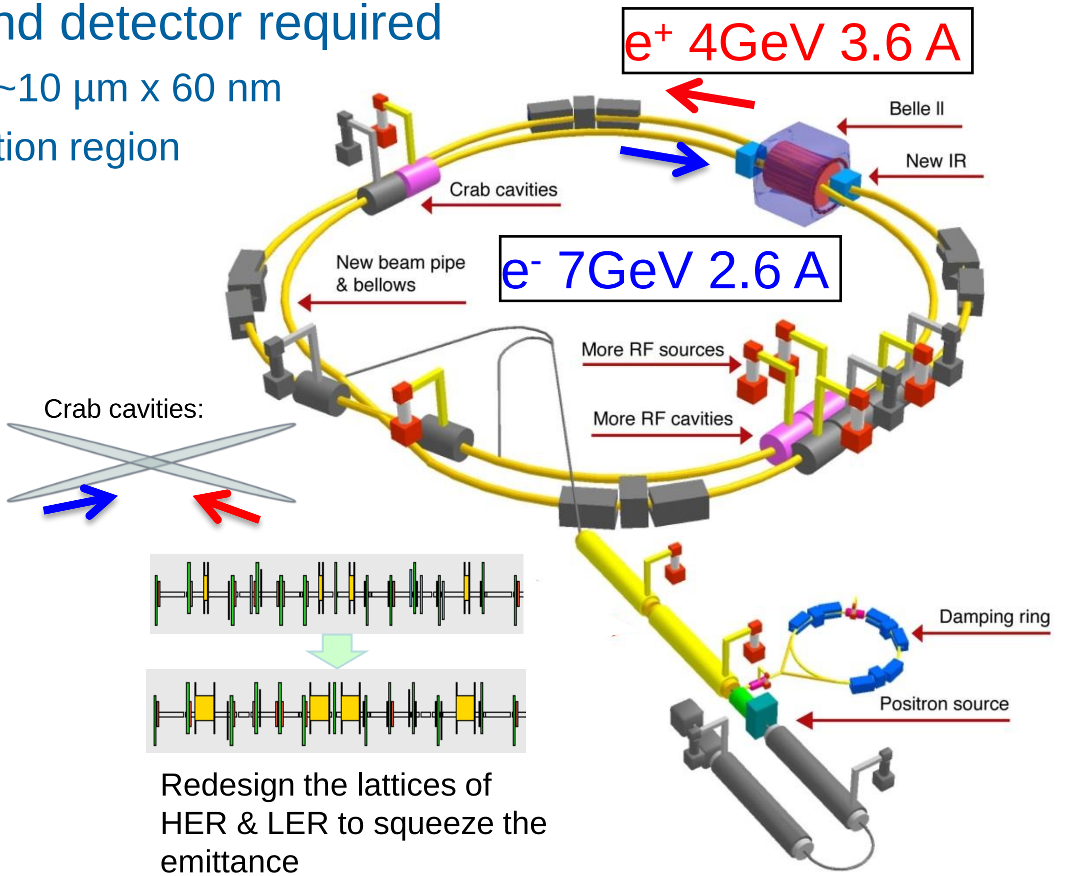




SuperKEKB/Belle II Upgrade: 2010–2015

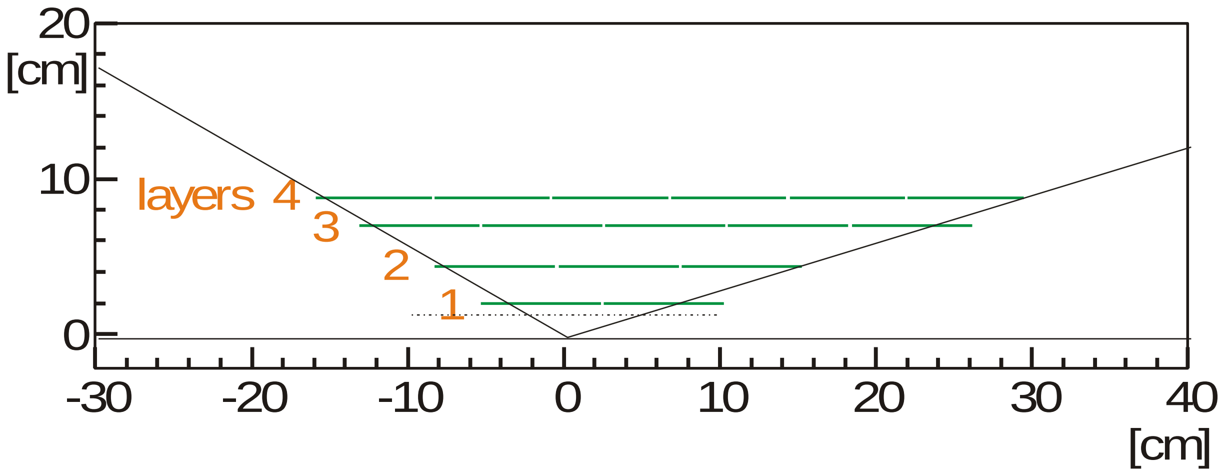
- 40-fold increase in peak luminosity to $8\times10^{35}\,\mathrm{cm^{-2}s^{-1}} \rightarrow 1\times10^{10}\, B\bar{B}$ / year
- 50-fold increase in integrated luminosity until 2023 w.r.t. Belle I
- Refurbishment of accelerator and detector required
  - nano-beams with cross-sections of ~10 µm x 60 nm
  - 2 cm diameter beam pipe at interaction region





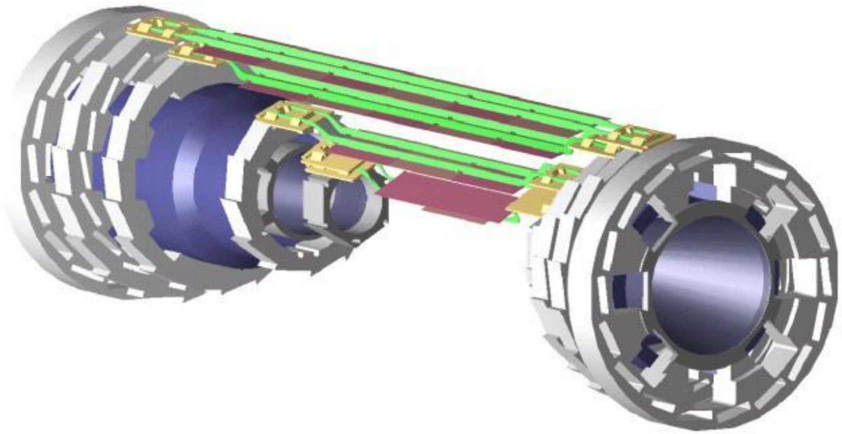
Redesign the lattices of HER & LER to squeeze the emittance

Belle Silicon Vertex Detector (SVD) until 2010



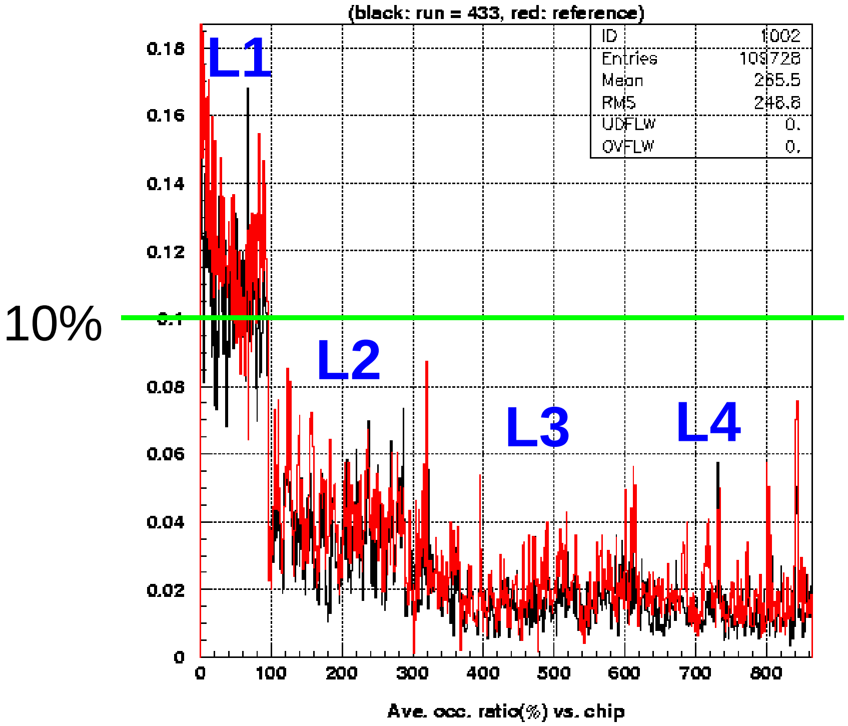
- **4 straight layers** of **4" double-sided silicon detectors** (DSSDs)
- Outer radius of r~8.8 cm
- Acceptance angle 17° …150°

- **Up to three 4" sensors were daisy-chained** and read out by one hybrid located outside of acceptance region (VA1 chip)



Belle SVD limitations

- Previous SVD limitations were
  - **occupancy** (10%-18% in innermost layer) → need faster shaping or smaller detector elements
  - **dead time** → need faster readout and pipeline
- Belle II needs detector with
  - high **background tolerance**
  - **pipelined** readout
  - **robust tracking**
  - **low material budget** in active volume



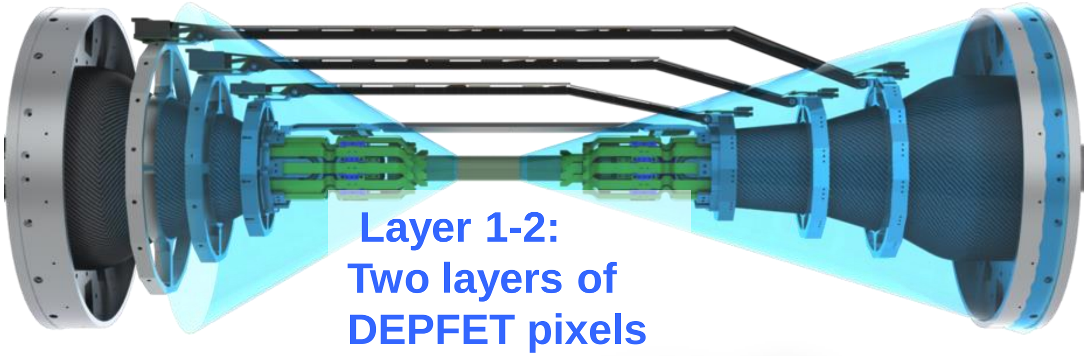
Previous SVD is not suitable for Belle II !

New Layout for Belle II SVD (2015-)

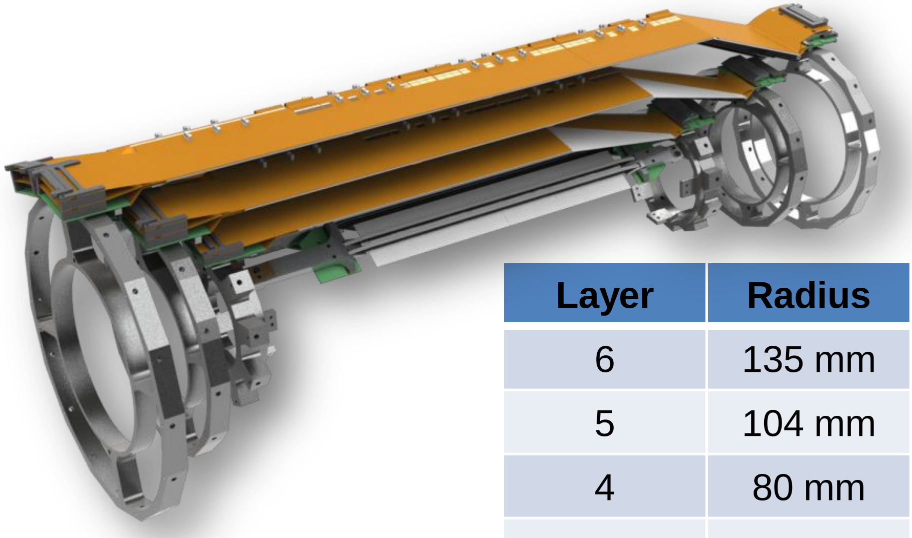
Four layers with 6” **double-sided strip detectors at larger radii** and **forward part**

- Large, individually read out sensors
- FE readout electronics inside acceptance region
- Maintain low material budget
  - Lightweight mechanics
  - Thin cooling pipes (CO_2)
- Fast readout

Layer 3 to 6: 4 layers of double-sided strip sensors



Layer 1-2: Two layers of DEPFET pixels

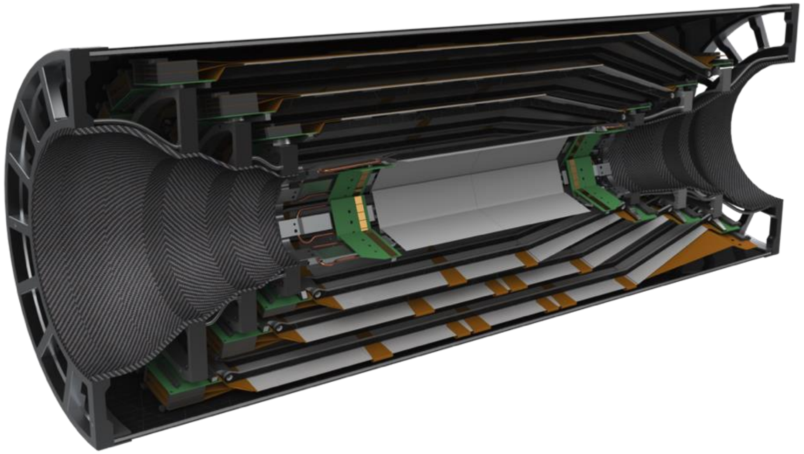


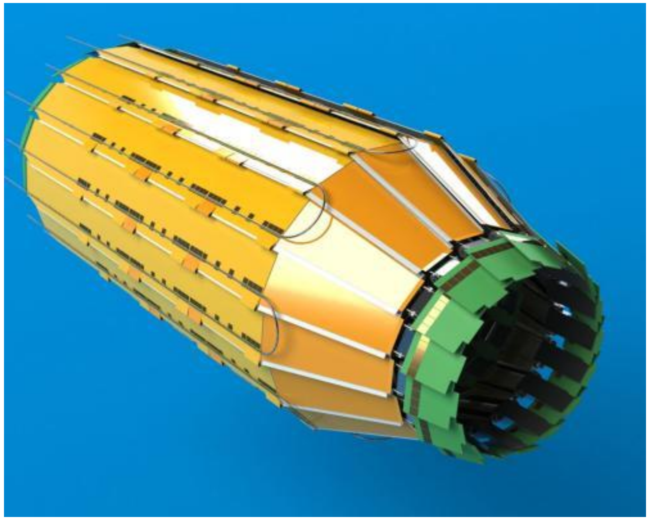
Layer	Radius	Ladders
6	135 mm	16
5	104 mm	12
4	80 mm	10
3	38 mm	7

Current Status

- **Transition from R&D to production phase**
- Milestones defined by Belle II schedule
  - SVD ladder assembly Nov. 2013 – Sept. 2014
  - Ladder mount: Sept. 2014 – August 2015
  - **SVD ready by August 2015**
  - VXD (PXD+SVD) ready by January 2016
  - VXD installation June 2016

- **Components**
  - Sensors
  - Front-end and backend electronics
  - Mechanics design
  - CO_2 cooling
  - Ladder assembly and lab infrastructure
  - Mockups



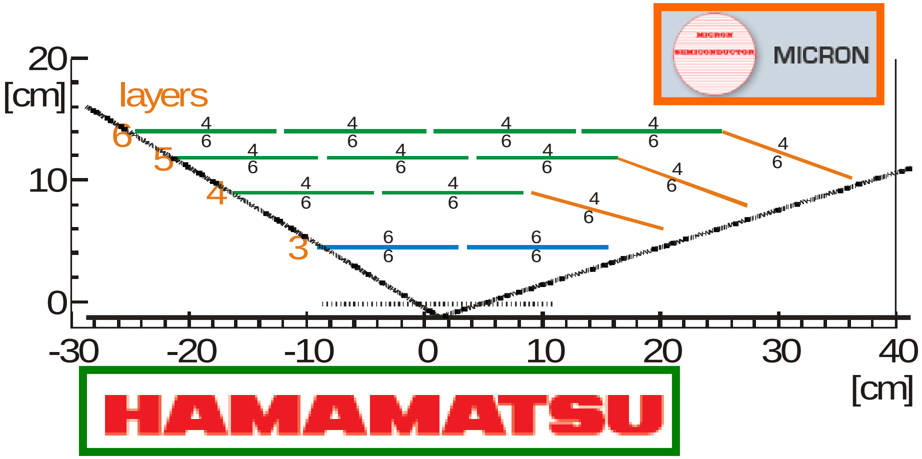


- Belle and Belle II
- **Components**
  - **Sensors**
  - Electronics
  - Mechanics and Cooling
  - Ladder assembly
  - Mockups
- Summary

Double-sided strip sensors from 6” wafers

Sensor Properties:

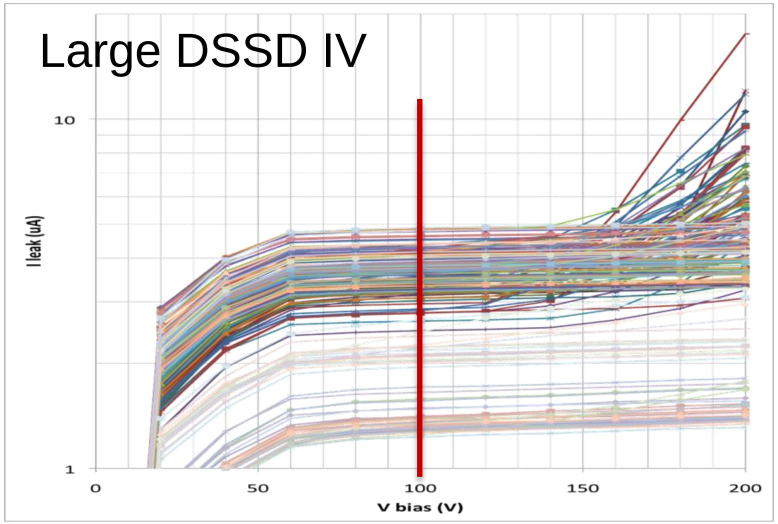
- Double-sided with perpendicular strips
- AC-coupled readout with poly-silicon resistor
- N-bulk, 300/320 micron thickness
- Three layouts only:
  - Rectangular small for layer 3 (HPK)
  - Rectangular large for layers 4-6 (HPK)
  - Trapezoidal for forward layers 4-6 (Micron)

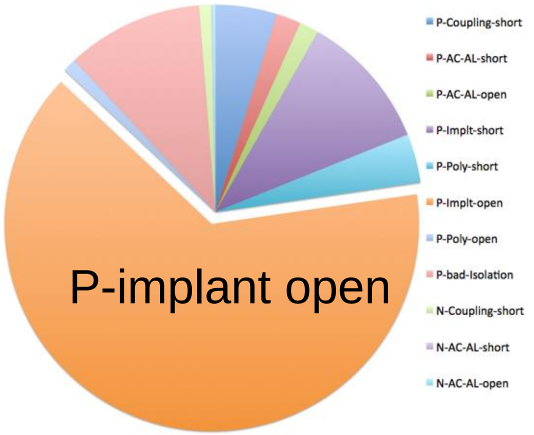


	Readout strips(p/Rϕ)	Readout strips(n/z)	Readout pitch (p/Rϕ)	Readout pitch(n/z)	Sensors # (+ spares)	Active area (mm²)
Large	768	512	75 µm	240 µm	120+18	122.90x57.72 =7029.88
Trapezoidal	768	512	50-75 µm	240 µm	38+6	122.76x(57.59+38.42) /2=5893.09
Small	768	768	50 µm	160 µm	14+4	122.90x38.55 =4737.80

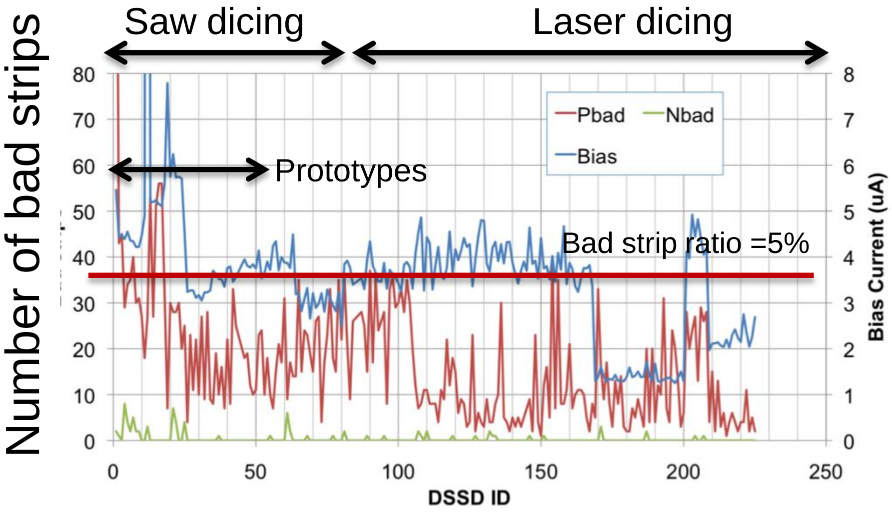
Rectangular sensors (HPK)

- Small DSSDs
  - Delivery of 24 pcs. scheduled for end of September
  - Two mechanical samples available
- Large DSSDs:
  - Production finished
  - 150 pcs in hand





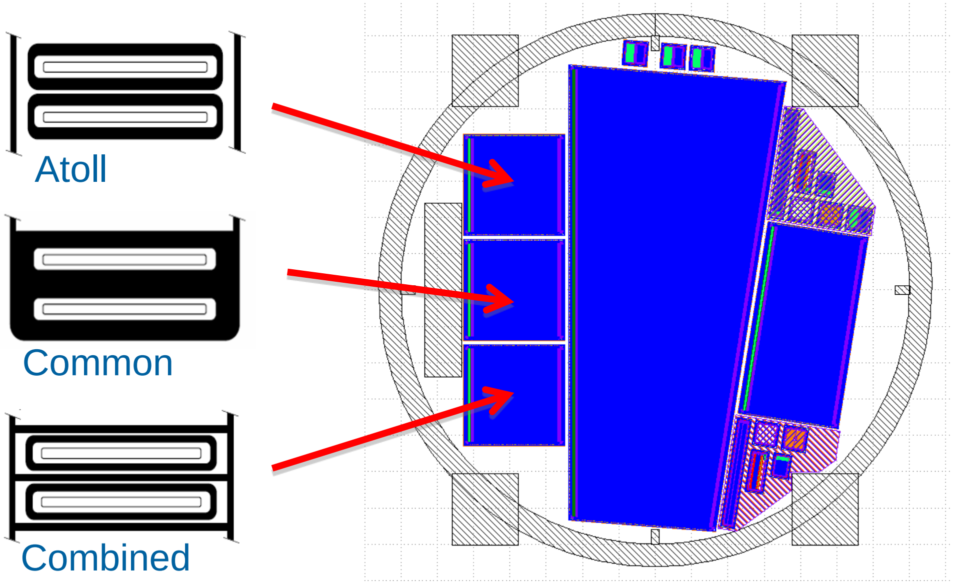
Classification of bad strips (ID>26)

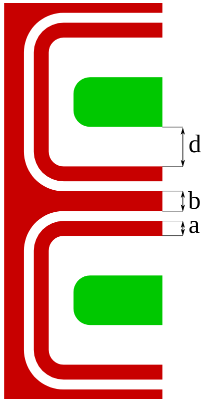


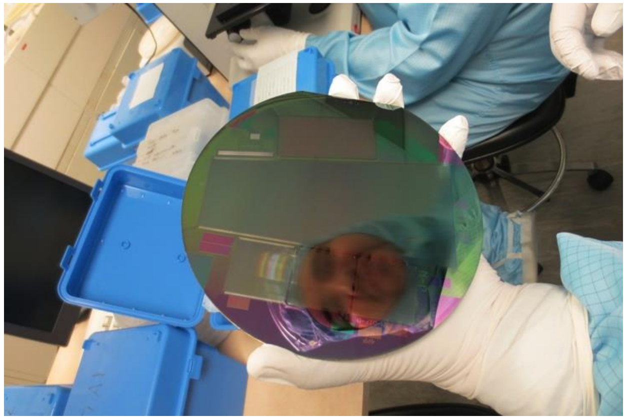
Trapezoidal Sensors for Forward Region

MICRON SEMICONDUCTOR ltd

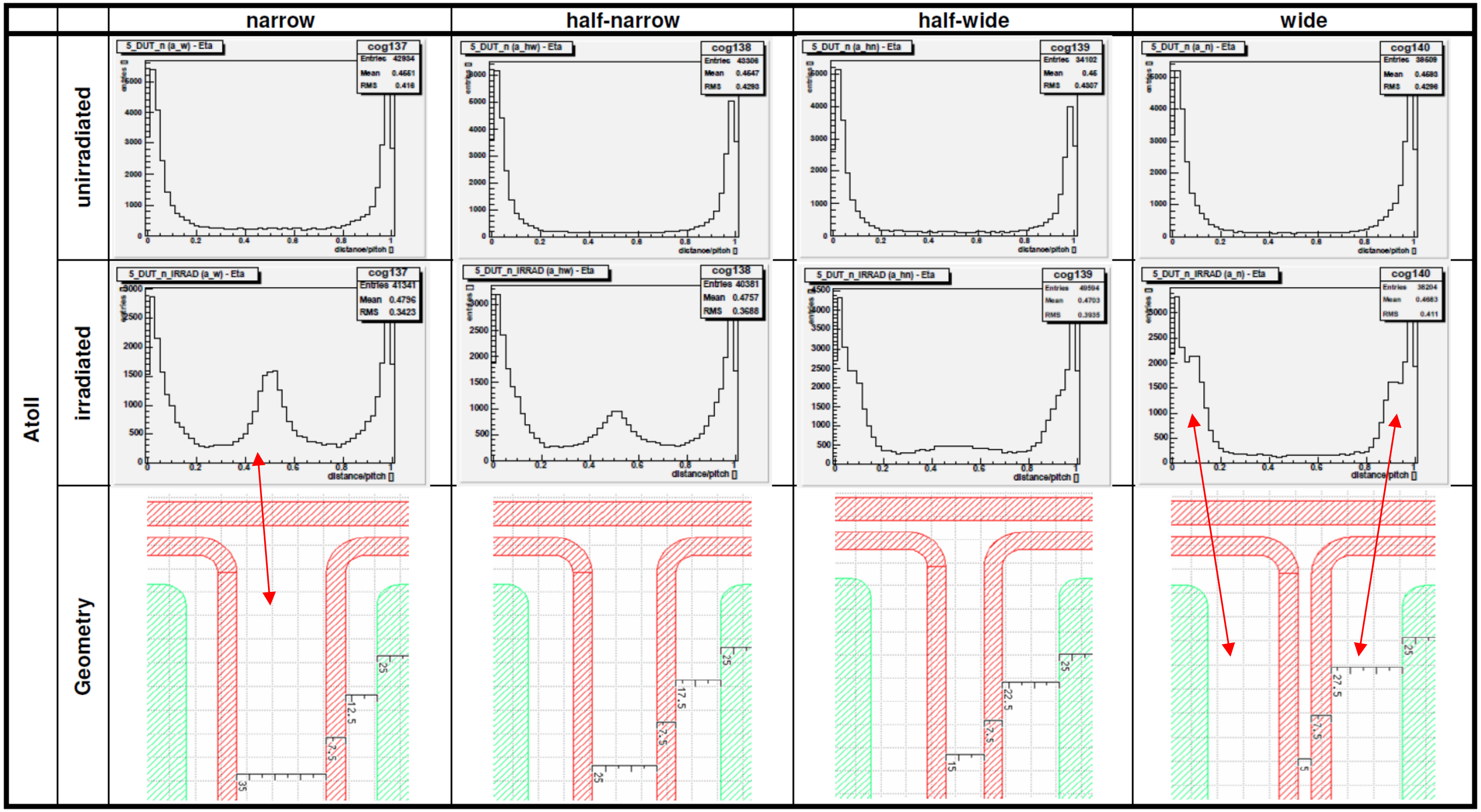
- Trapezoidal sensor for forward region
- Different p-stop layouts on test sensors
- Each layout type with four variants (narrow/half narrow/ wide / half wide)
  - Testbeam and irradiation study to determine best structure







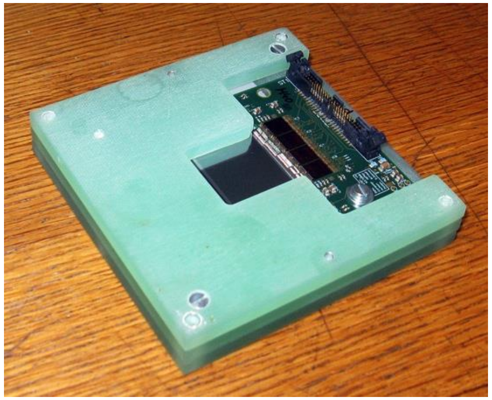
eta distribution for atoll p-stop

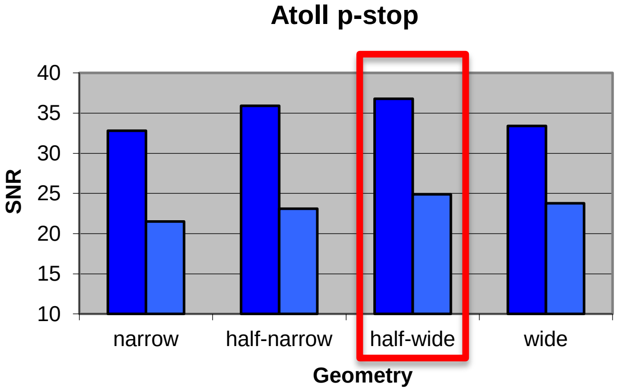


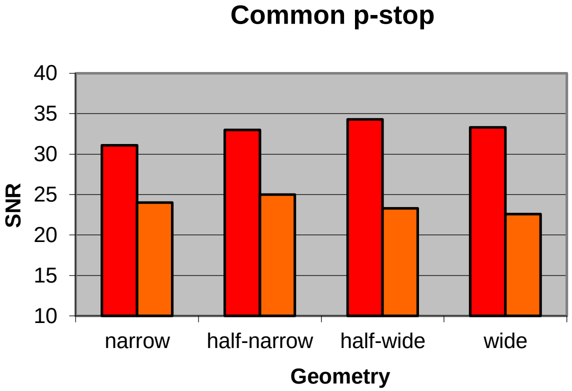
Charge accumulation in unimplanted region

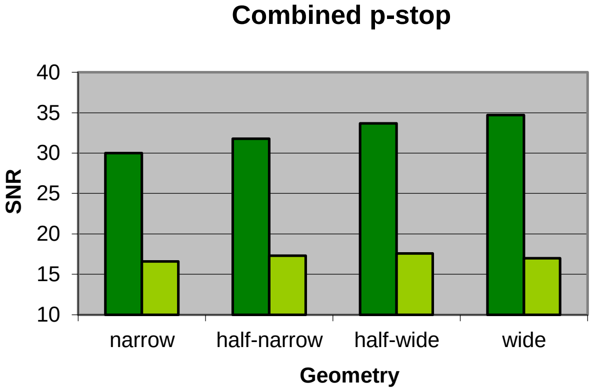
Signal-to-noise-ratios

- Test sensors have been Gamma-irradiated with Co-60 (70 Mrad) in Mol (Belgium)
- Tested before and after at CERN beam test (H6A 120 GeV hadrons)





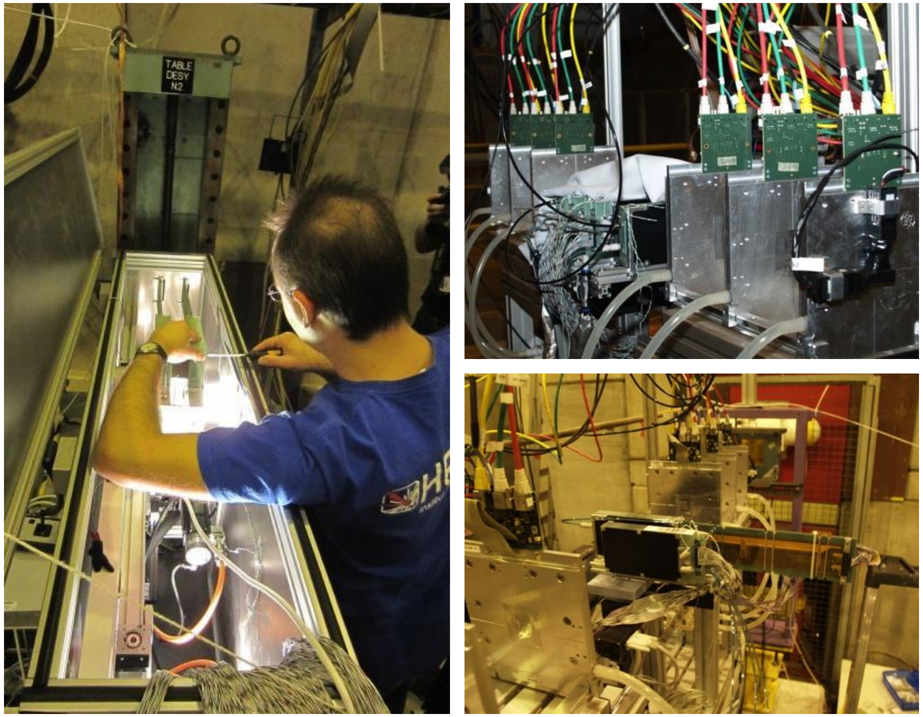


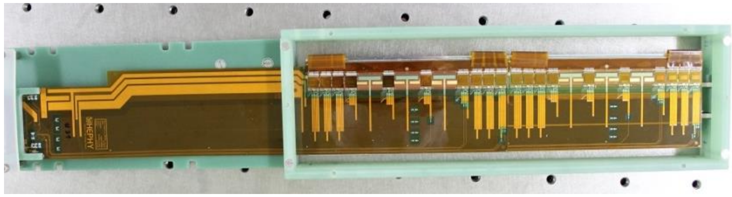


- Dark colors: non-irradiated, Light colors: irradiated
- Atoll pattern (half-wide) performs best, both irradiated and non-irradiated
  - Chosen for final sensor, 100 wafers currently being processed by Micron

Beam test results

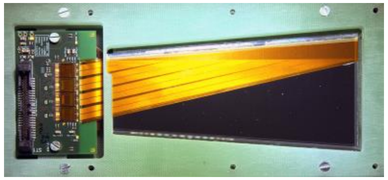
- Performance of full modules verified in several beam tests at CERN (2008-2012)
  - Including CO_2 cooling
  - Using EUDET and own beam telescope



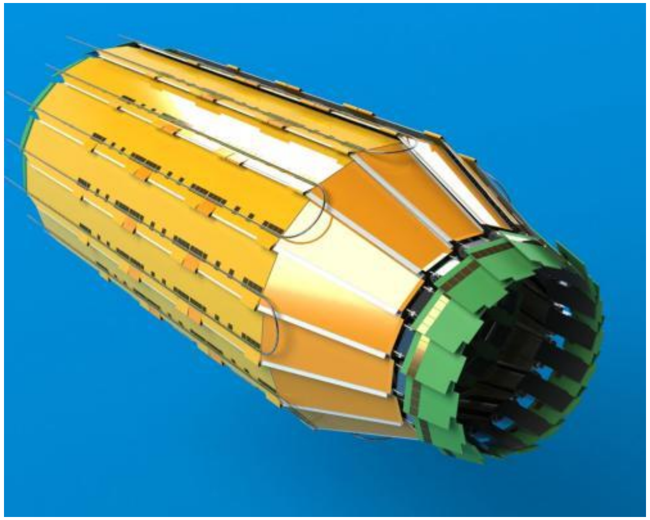


Double Origami module

FW wedge module

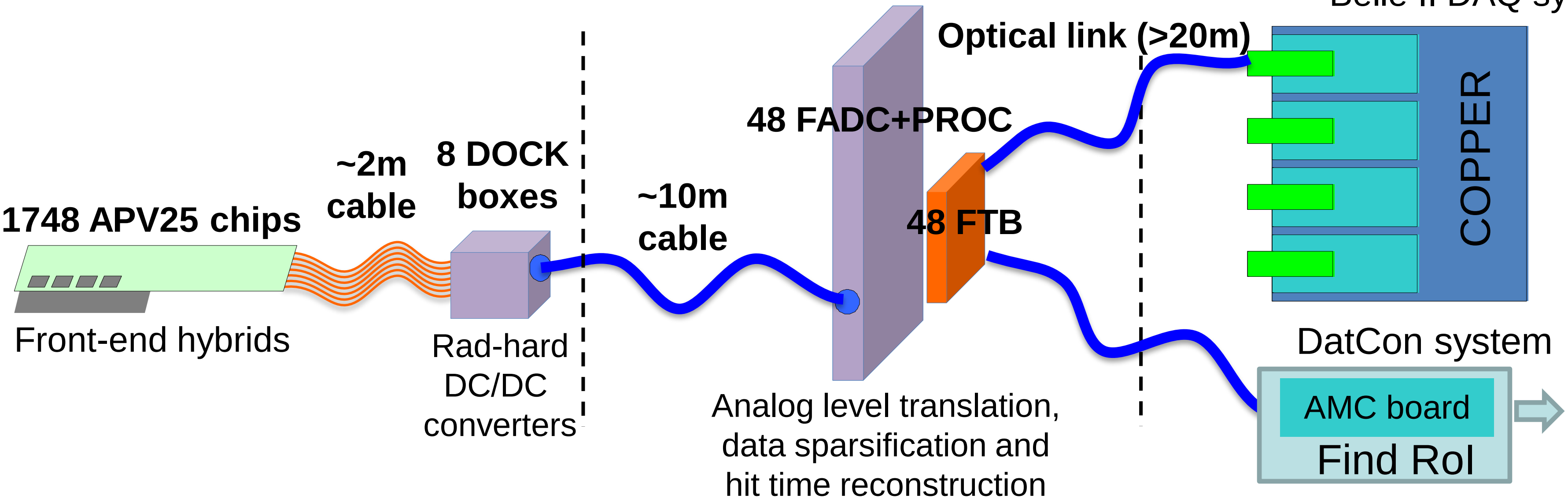


Irrad	Origami #4		Origami #3		Wedge #1	
	p	n	p	n	p	n
Before	12.2	22.7	12.0	23.4	14.9	13.0
After	11.9	16.0	12.6	23.4	12.6	12.0



- Belle and Belle II
- Components
  - Sensors
  - **Electronics**
  - Mechanics and Cooling
  - Ladder assembly
  - Mockups
- Summary

Readout System Concept



Inside of SVD

Crates on top of Belle II

Electronics Hut
Belle II DAQ system

Optical link (>20m)

1748 APV25 chips

~2m cable

8 DOCK boxes

~10m cable

48 FADC+PROC

48 FTB

COPPER

Front-end hybrids

Rad-hard DC/DC converters

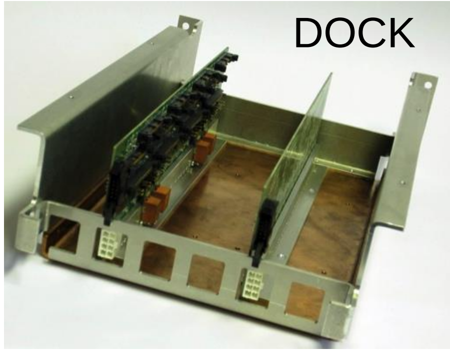
Analog level translation, data sparsification and hit time reconstruction

DatCon system

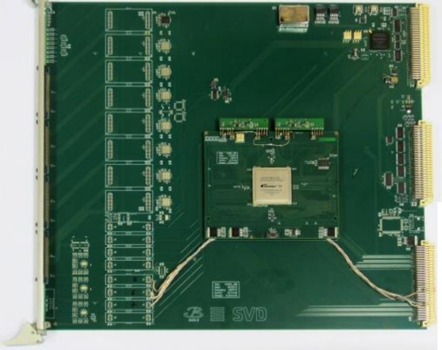
AMC board

Find RoI

PXD



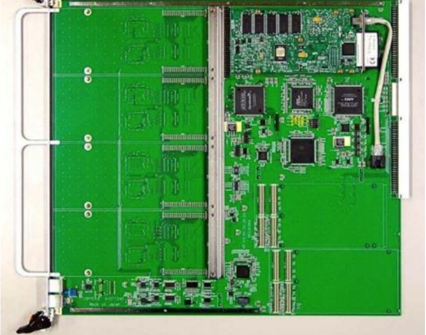
DOCK



FADC+PROC

FTB

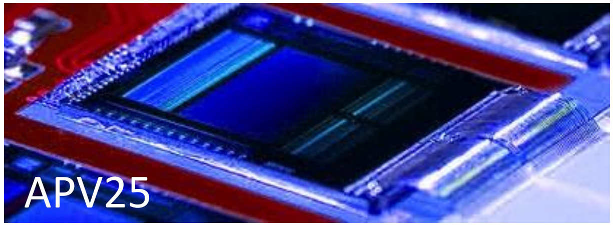
AMC board

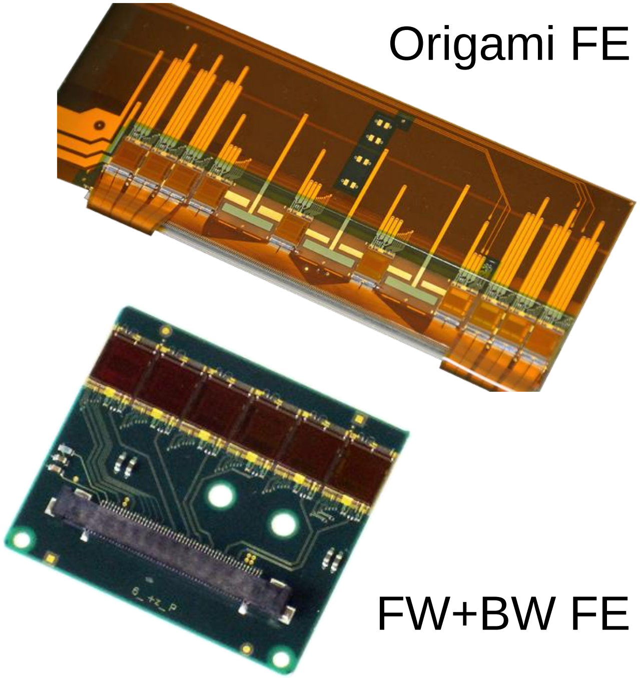


COPPER

Readout Chip: APV25

- Developed for **CMS** (LHC) by *Imperial College London* and *Rutherford Appleton Lab*
  - 70.000 chips installed
- 0.25 µm CMOS process (**>100 MRad tolerant**)
- 128 channels
- **192 cell analog pipeline**
  → almost no dead time
- **50 ns shaping time** → low occupancy
- **Multi-peak mode** (read out several samples along shaping curve)
- **Noise:** 250 e + 36 e/pF
  → must minimize capacitive load!!!
- **Thinning** to 100µm successful

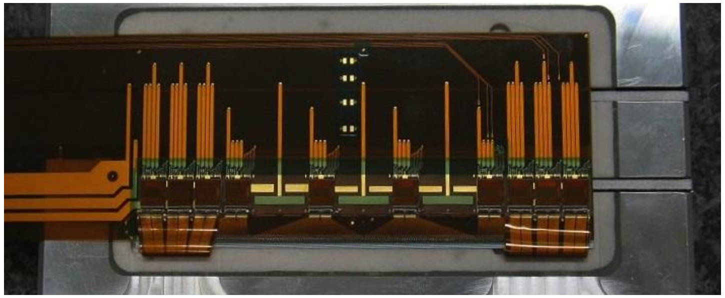


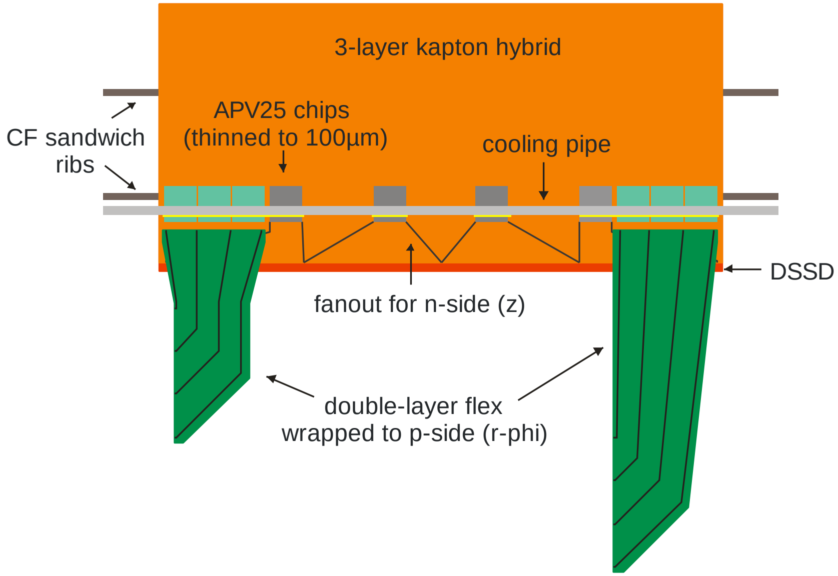

Origami FE

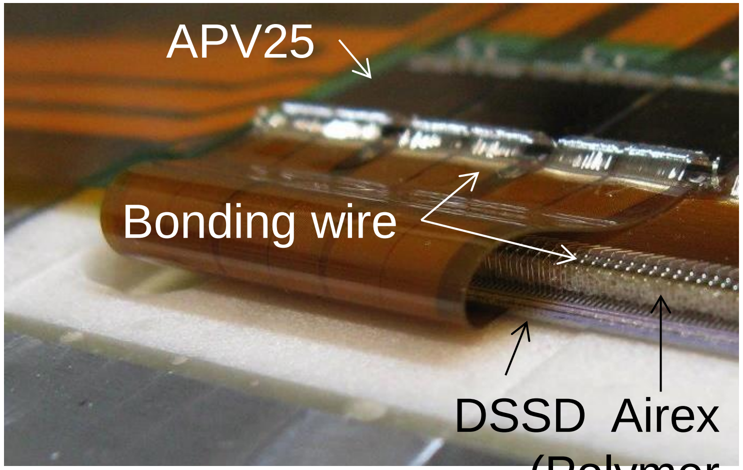
FW+BW FE

Origami Chip-on-Sensor Concept

- **Chip-on-sensor** concept for **double-sided readout**
- **Flex fan-out** pieces **wrapped** to opposite side (hence “Origami“)
- All chips aligned on one side → **single cooling pipe**





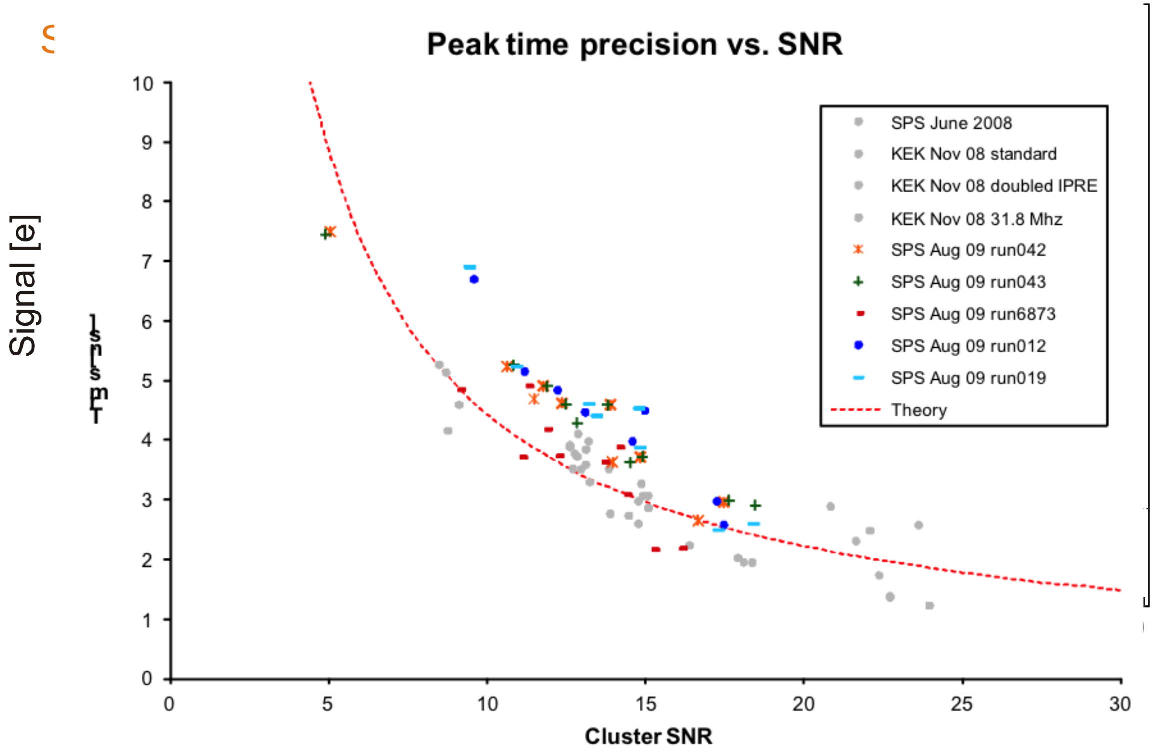


APV25 – Hit Time Reconstruction

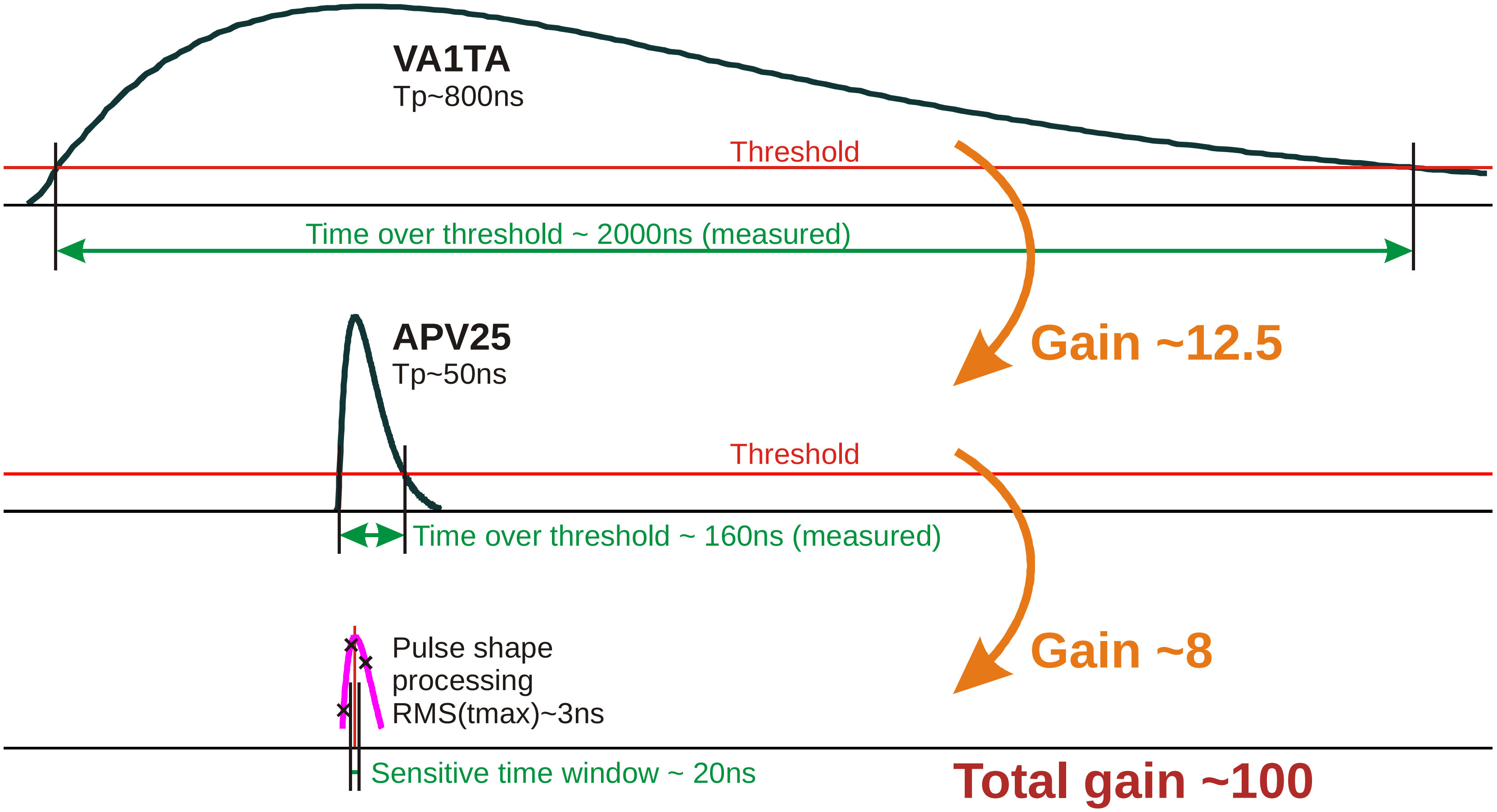
- Possibility of recording **multiple samples** (**x**) along shaped waveform (feature of APV25)

Measurement

- Reconstruction of **peak time** (and amplitude) by waveform fit
  - Using LUT in FPGA
- Is used to **remove off-time background** hits
- **2...3 ns RMS** accuracy at typical S/N



Occupancy Reduction Belle -> Belle II



VA1TA
Tp~800ns

Threshold

Time over threshold ~ 2000ns (measured)

APV25
Tp~50ns

Threshold

Time over threshold ~ 160ns (measured)

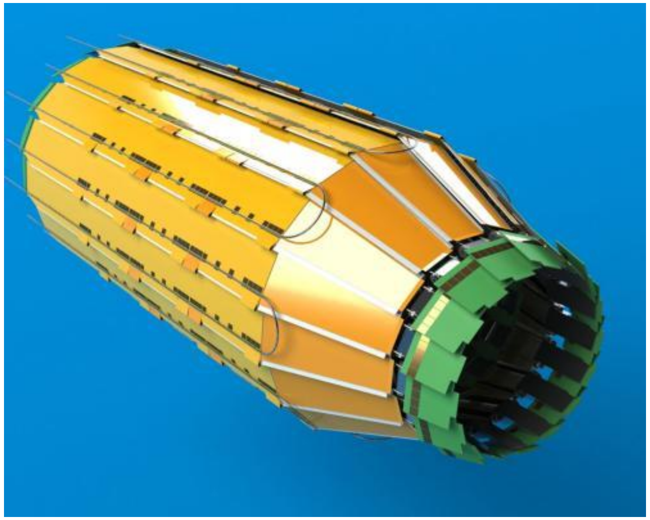
Gain ~12.5

Pulse shape
processing
RMS(tmax)~3ns

Sensitive time window ~ 20ns

Gain ~8

Total gain ~100



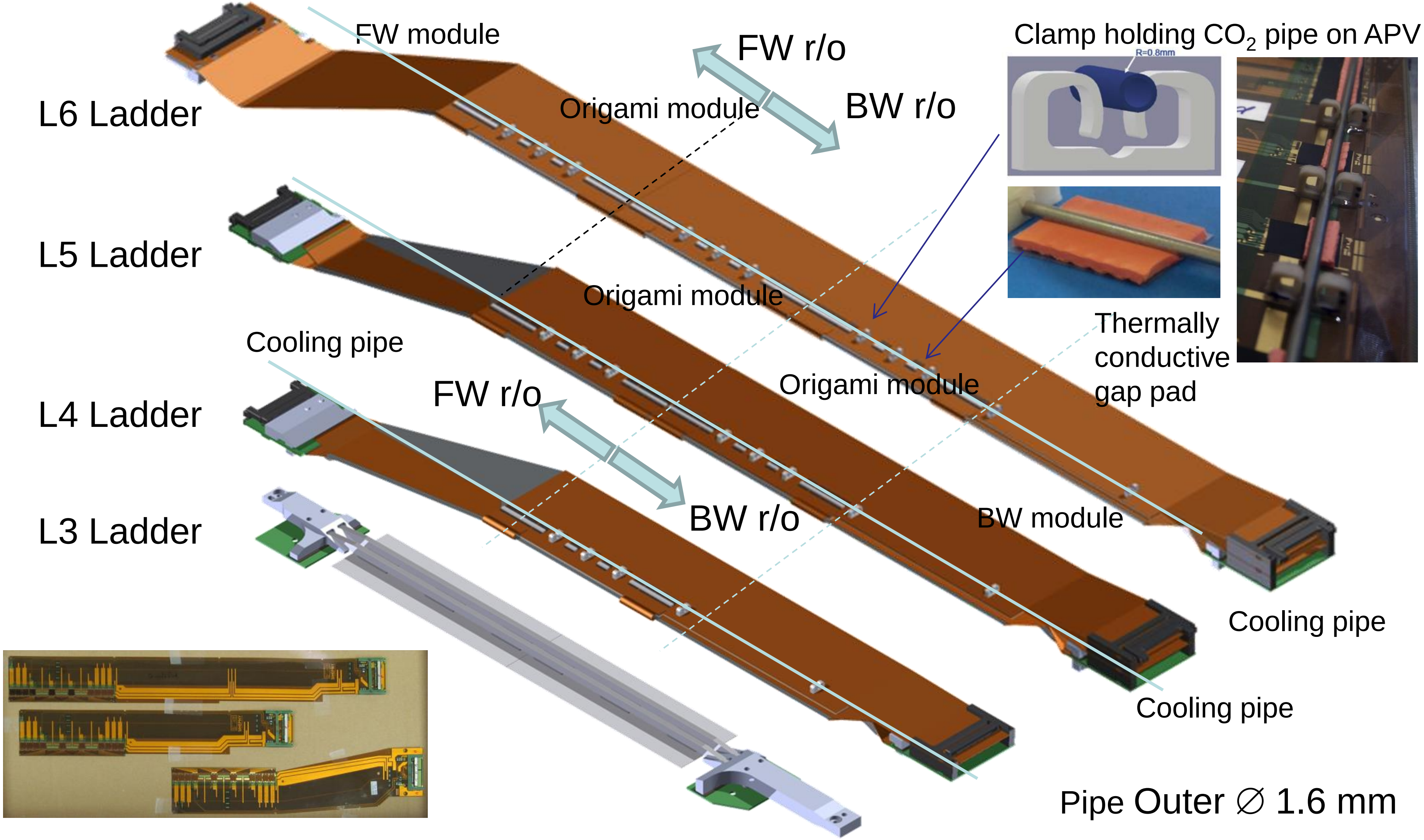
Belle and Belle II

Components

- Sensors
- Electronics
- **Mechanics and Cooling**
- Ladder assembly
- Mockups

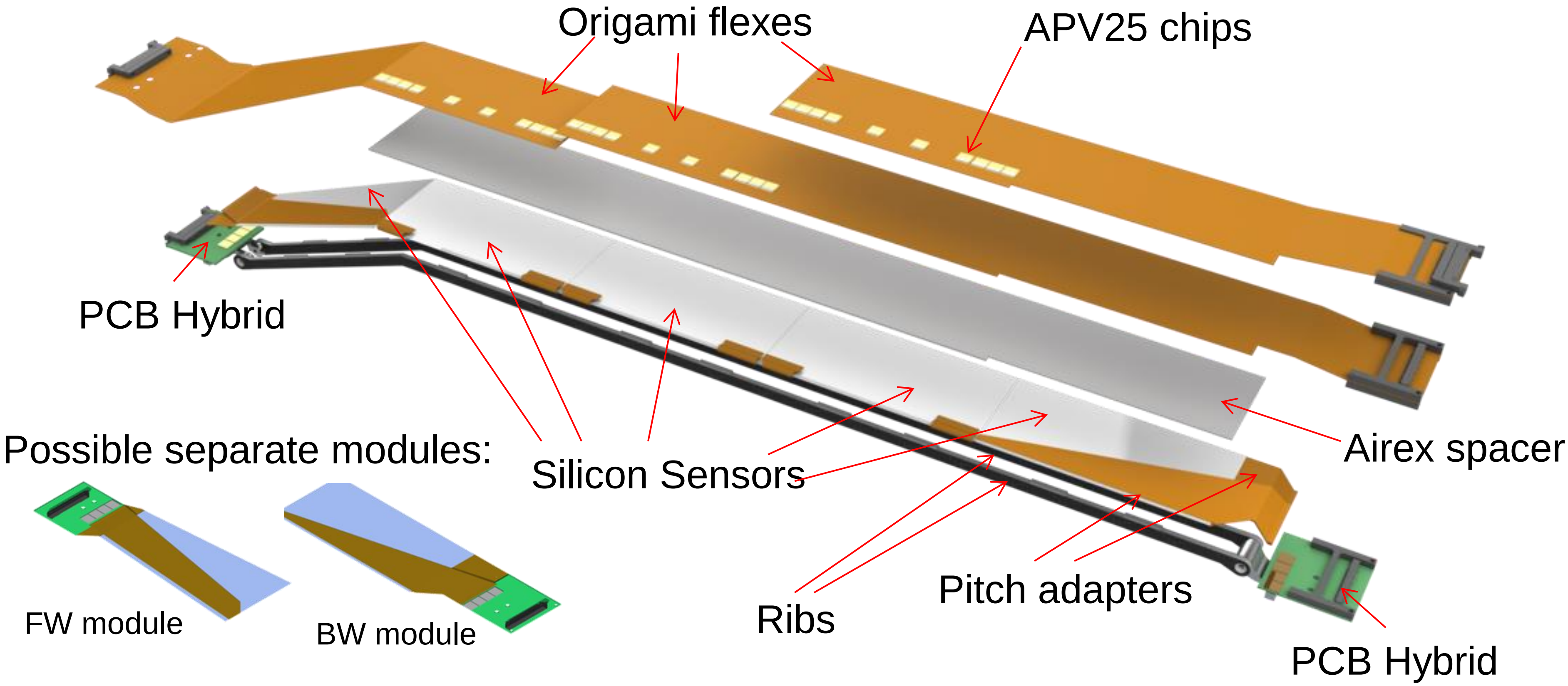
Summary

SVD Ladders



Pipe Outer ∅ 1.6 mm

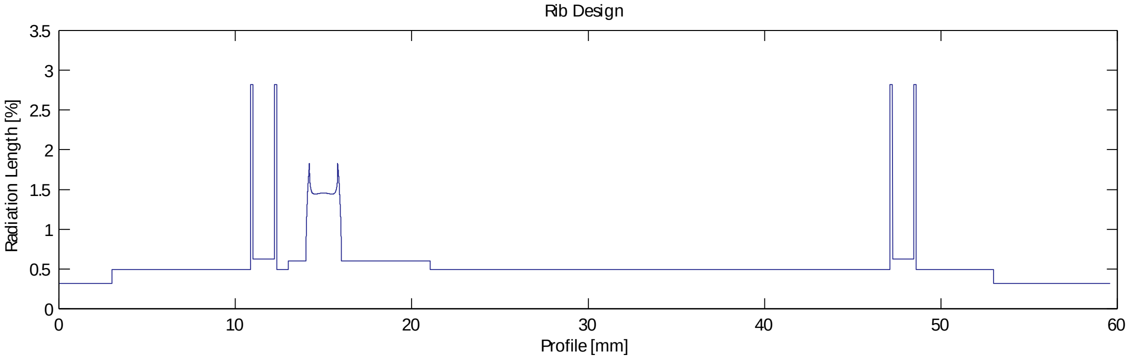
Ladder of Layer 6

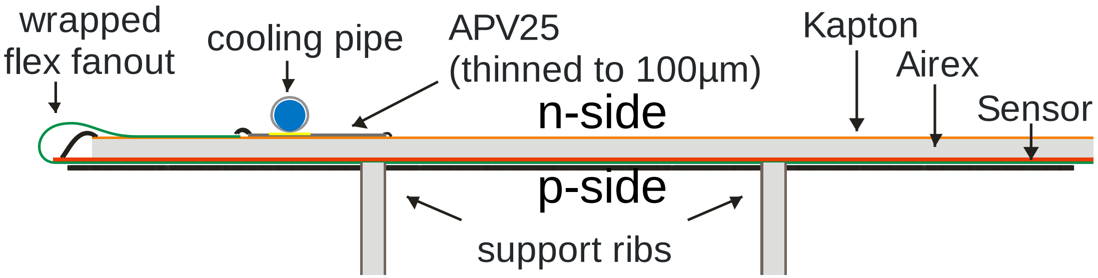


- Basic element “atomic unit” is one ladder
- Only FW and BW module can be assembled independently
- No single Origami module with one sensor possible

Material Budget of a ladder

- Largest peak contribution by
    - Cooling pipe
    - Support ribs



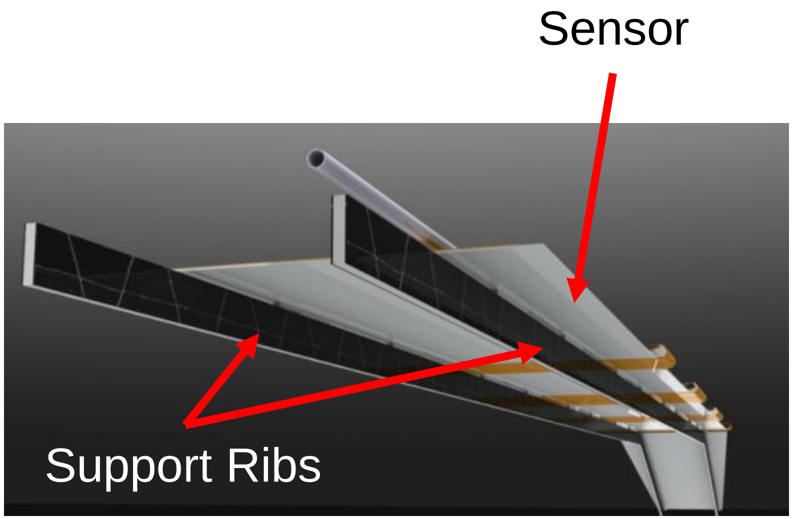


Components:

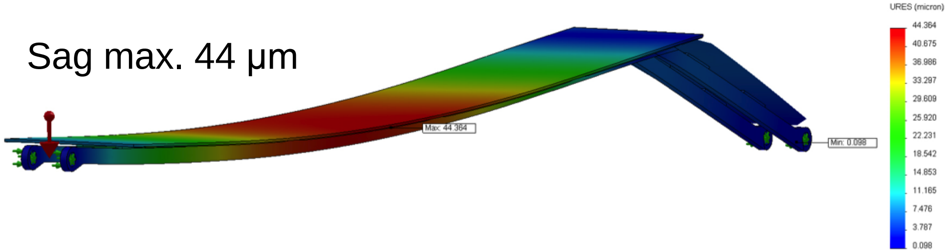
- Single cooling pipe
- Thinned APV25 (100µm)
- 3-layer flex circuit
- Connection to Strips:
    - PA on top side
    - wrapped PA for bottom
- 1mm Airex sheet
- 6” DSSD
- CF support ribs

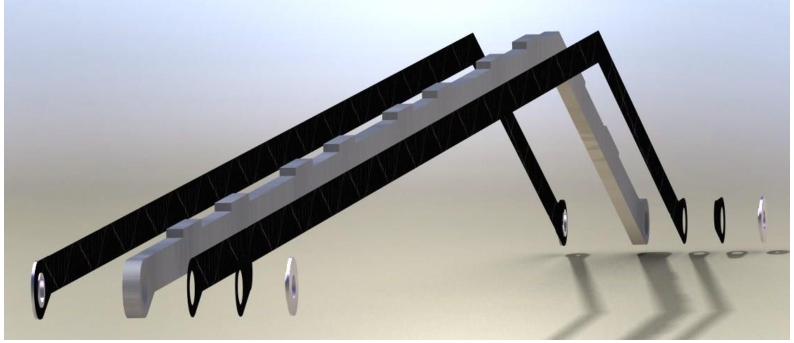
- Average Material Budget: 0.59%X_0

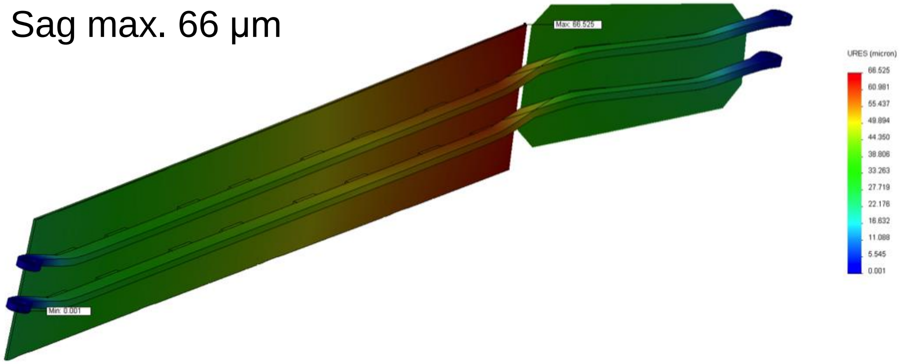
Support Ribs



- 3mm Airex core with laminated 0.15mm CF sheets
- Very stiff, yet lightweight thanks to the sandwich construction

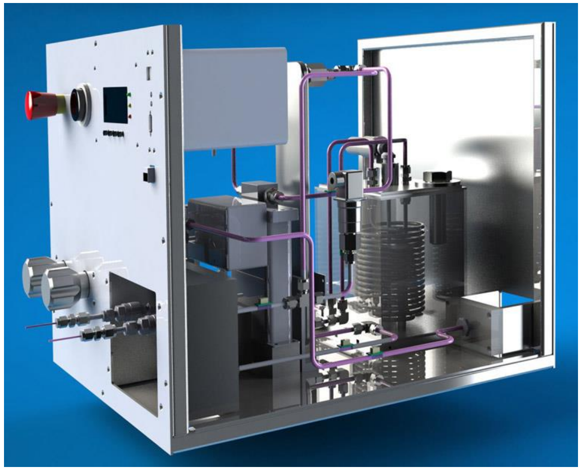

Sag max. 44 µm



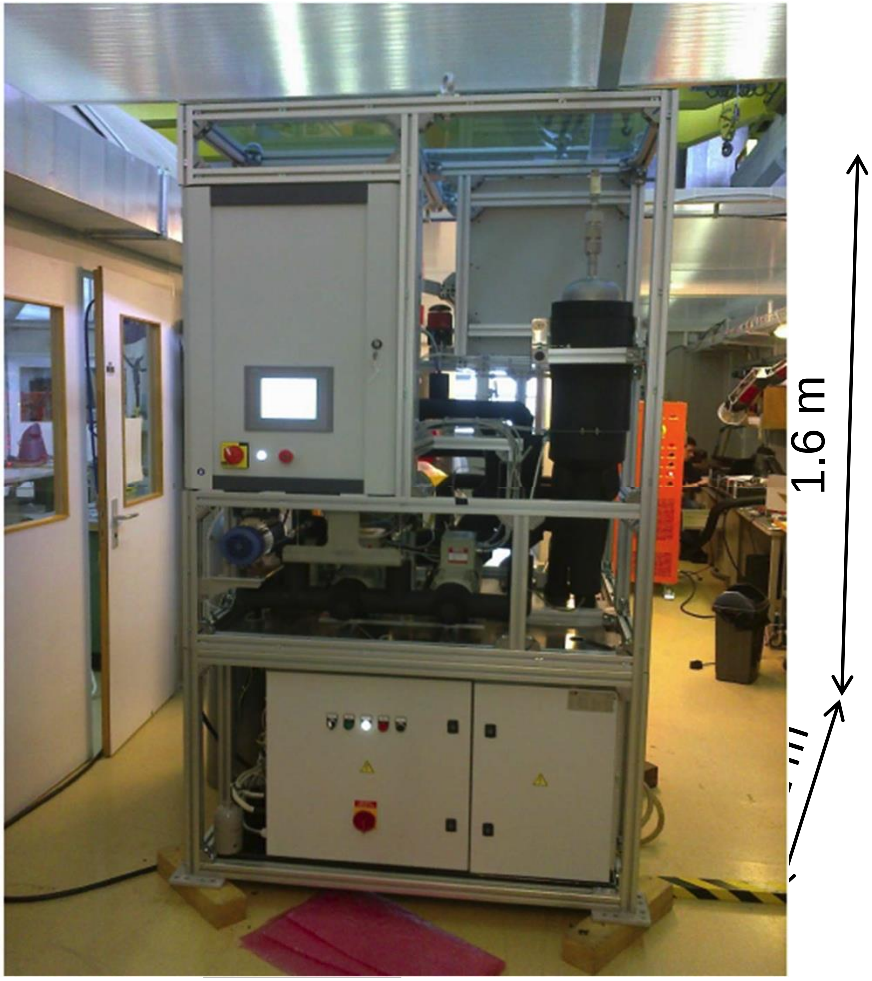

Sag max. 66 µm

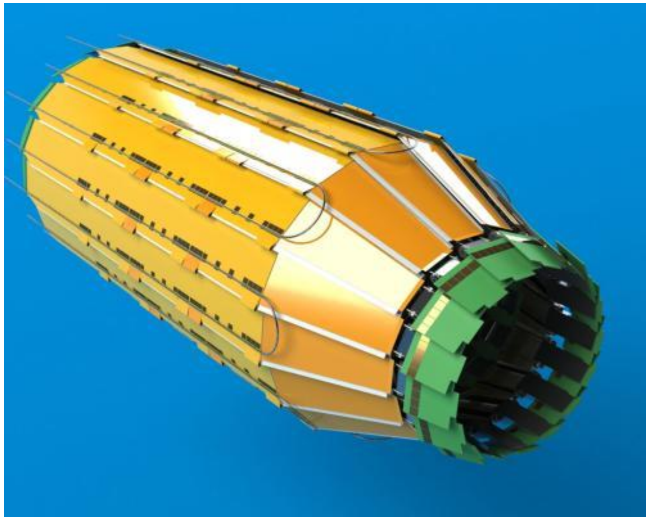
CO_2 cooling system

- IBBelle Prototype “MARCO” (**M**ulti-Purpose **A**pparatus for **R**esearch in **CO**$_2$)
  - Power ~ 1 kW
- Based on concept by NIKHEF (B. Verlaat)
- CO_2 plant shared with PXD
- Development in collaboration between PXD group (MPI), CERN and NIKHEF
- Ladder production sites uses small open (blow) CO_2 system



Vienna open CO_2 system



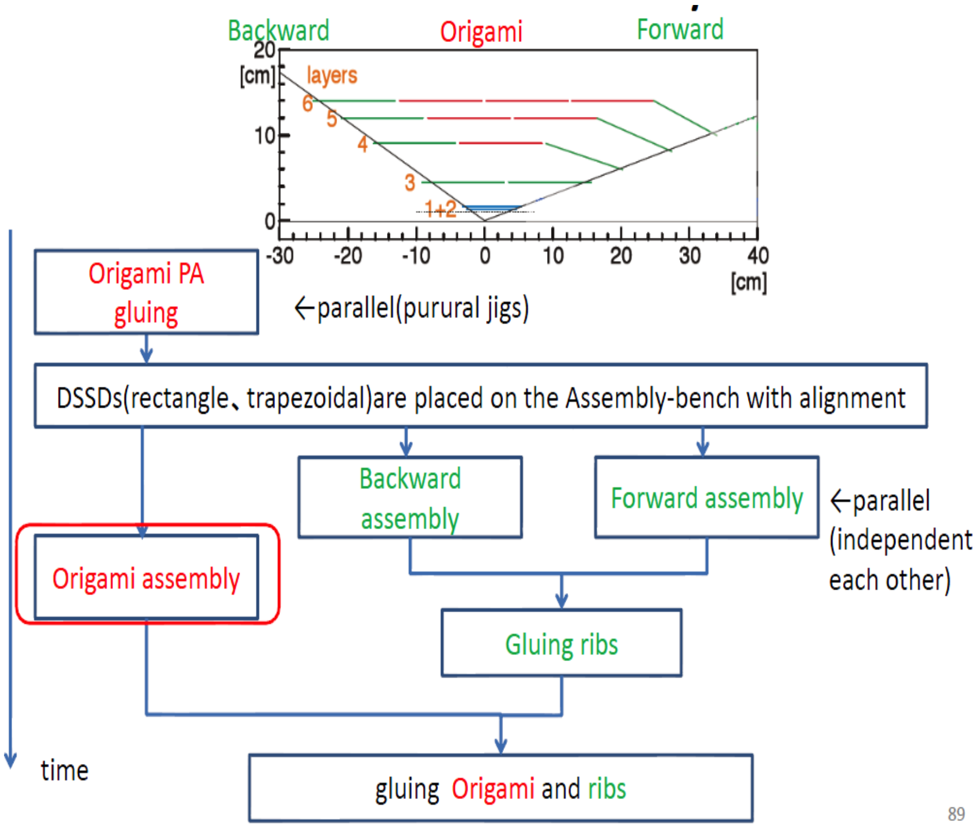


- Belle and Belle II
- Components
  - Sensors
  - Electronics
  - Mechanics and Cooling
  - **Ladder assembly**
  - Mockups
- Summary

SVD ladder assembly flow

- Three modules types:
  - Forward (FW)
  - Backward (BW)
  - Origami
- Ladder assembly sites:

Layer	Institute
3	Melbourne (AUS)
4	TIFR India @ IPMU
5	HEPHY Vienna (AT)
6	Kavli IPMU (Japan)
FW & BW	INFN Pisa (possibly)



Origami PA gluing

←parallel(purural jigs)

DSSDs(rectangle、trapezoidal)are placed on the Assembly-bench with alignment

Backward assembly

Forward assembly

←parallel (independent each other)

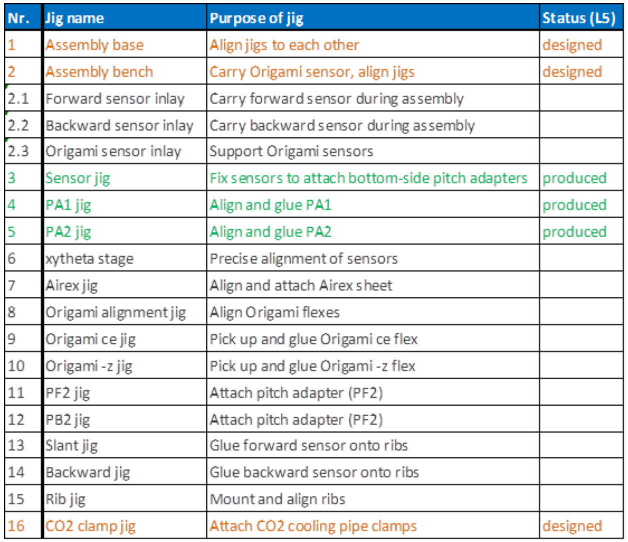
Origami assembly

Gluing ribs

gluing Origami and ribs

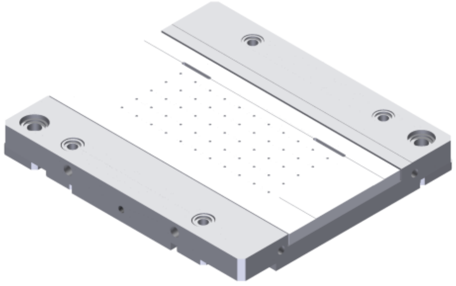
Assembly Jigs

Huge number of different jigs (up to 17) necessary:

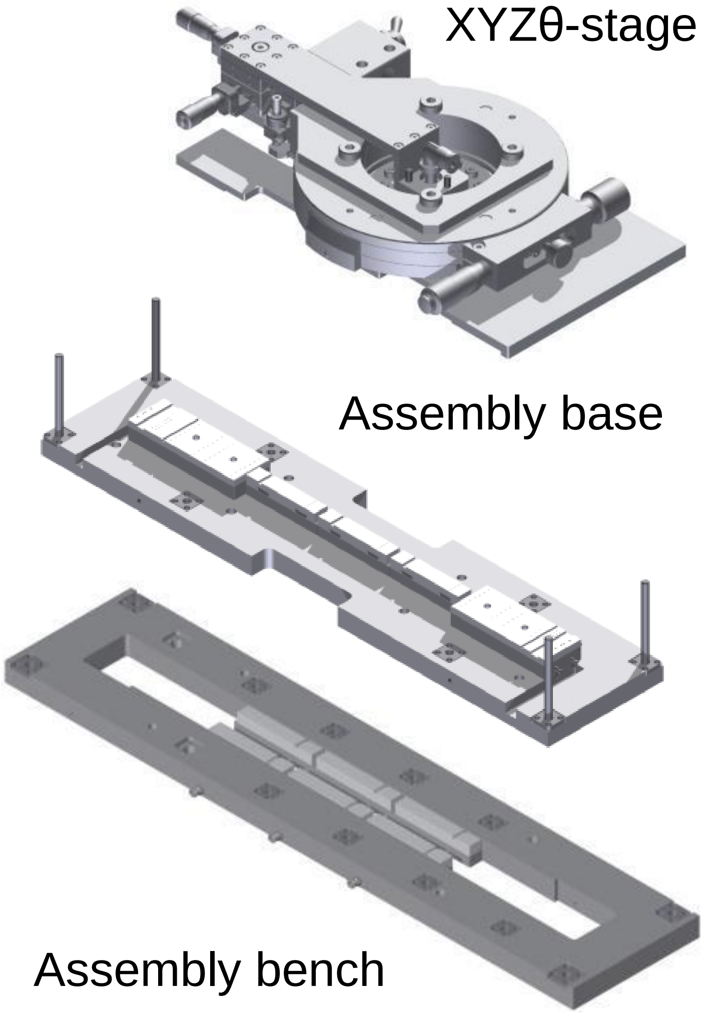


Nr.	Jig name	Purpose of jig	Status (L5)
1	Assembly base	Align jigs to each other	designed
2	Assembly bench	Carry Origami sensor, align jigs	designed
2.1	Forward sensor inlay	Carry forward sensor during assembly	
2.2	Backward sensor inlay	Carry backward sensor during assembly	
2.3	Origami sensor inlay	Support Origami sensors	
3	Sensor jig	Fix sensors to attach bottom-side pitch adapters	produced
4	PA1 jig	Align and glue PA1	produced
5	PA2 jig	Align and glue PA2	produced
6	xytheta stage	Precise alignment of sensors	
7	Airex jig	Align and attach Airex sheet	
8	Origami alignment jig	Align Origami flexes	
9	Origami ce jig	Pick up and glue Origami ce flex	
10	Origami -z jig	Pick up and glue Origami -z flex	
11	PF2 jig	Attach pitch adapter (PF2)	
12	PB2 jig	Attach pitch adapter (PF2)	
13	Slant jig	Glue forward sensor onto ribs	
14	Backward jig	Glue backward sensor onto ribs	
15	Rib jig	Mount and align ribs	
16	CO2 clamp jig	Attach CO2 cooling pipe clamps	designed

	CMM	XYZθ–stg	bench	base	Sensor-jig	Status
Melbourne	Mitsutoyo QV-PRO302	KIPMUdesign+ 1comp	✓	Draft design	Draft design	
TIFR	Sharing with KIPMU	Sharing	manufacturing	✓	✓	
HEPHY	Mitsutoyo Euro-C776	In progress	designed	designed	✓	
KIPMU	Mitsutoyo QV-606	✓	✓	✓	✓	Finalizing?
INFN	Mitsutoyo F604	designing	-	-	designing	



Sensor jig



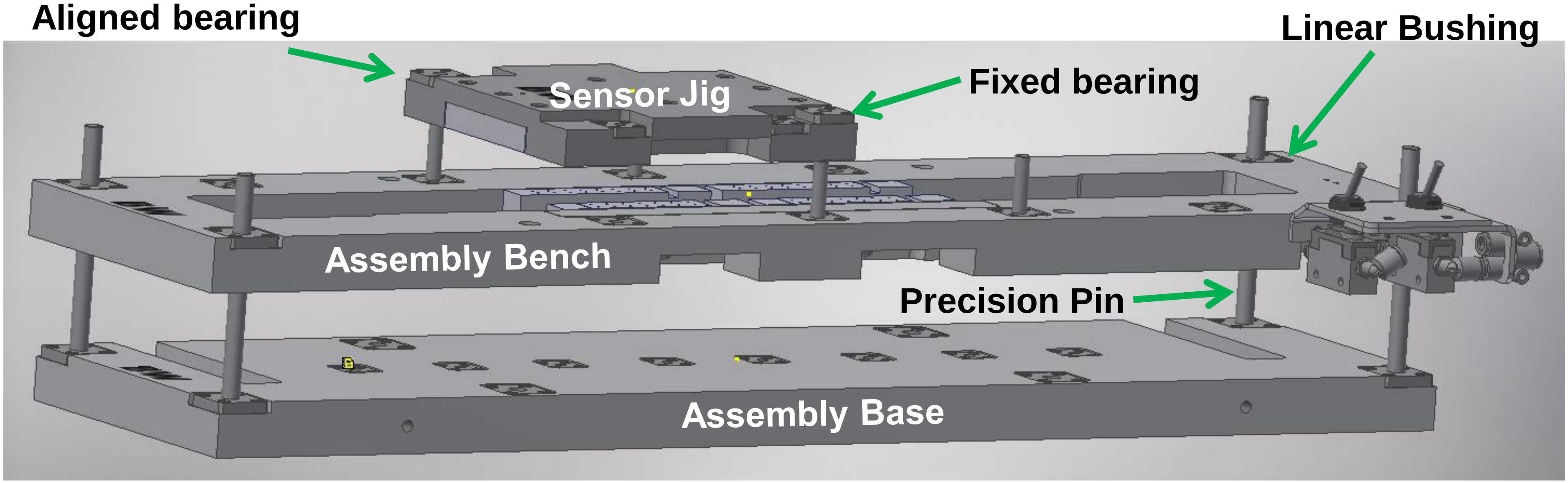
XYZθ-stage

Assembly base

Assembly bench

Alignment of Jigs

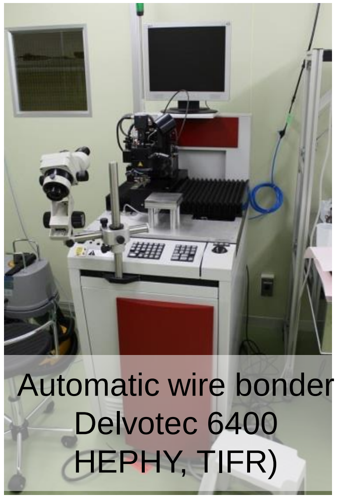
- Using linear bushings (+0/-13µm) & precision pins (g6)
- Assembly base & bench are reference
  - All linear bushings are fixed bearings → high precision holes (H7)
- All other jigs are aligned to them, e.g. Sensor jig



Ladder assembly equipment

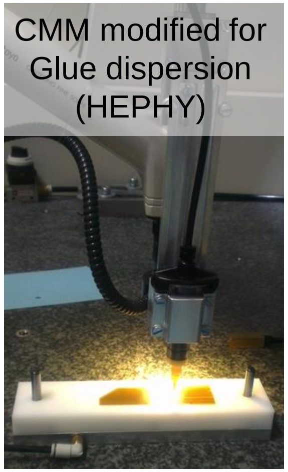
- Coordinate Measurement machines (Mitutoyo)
- Glue dispensing robots
  - CMM used as glue robot in Vienna
- Fully-automatic wire bonders
- (lot of) manpower and ideas


Automatic wire bonder
Choonpa Co. REBO-7W
IPMU(borrowed KEK)


Automatic wire bonder
Delvotec 6400
HEPHY, TIFR)


Travelling trolley
for vacuum tube

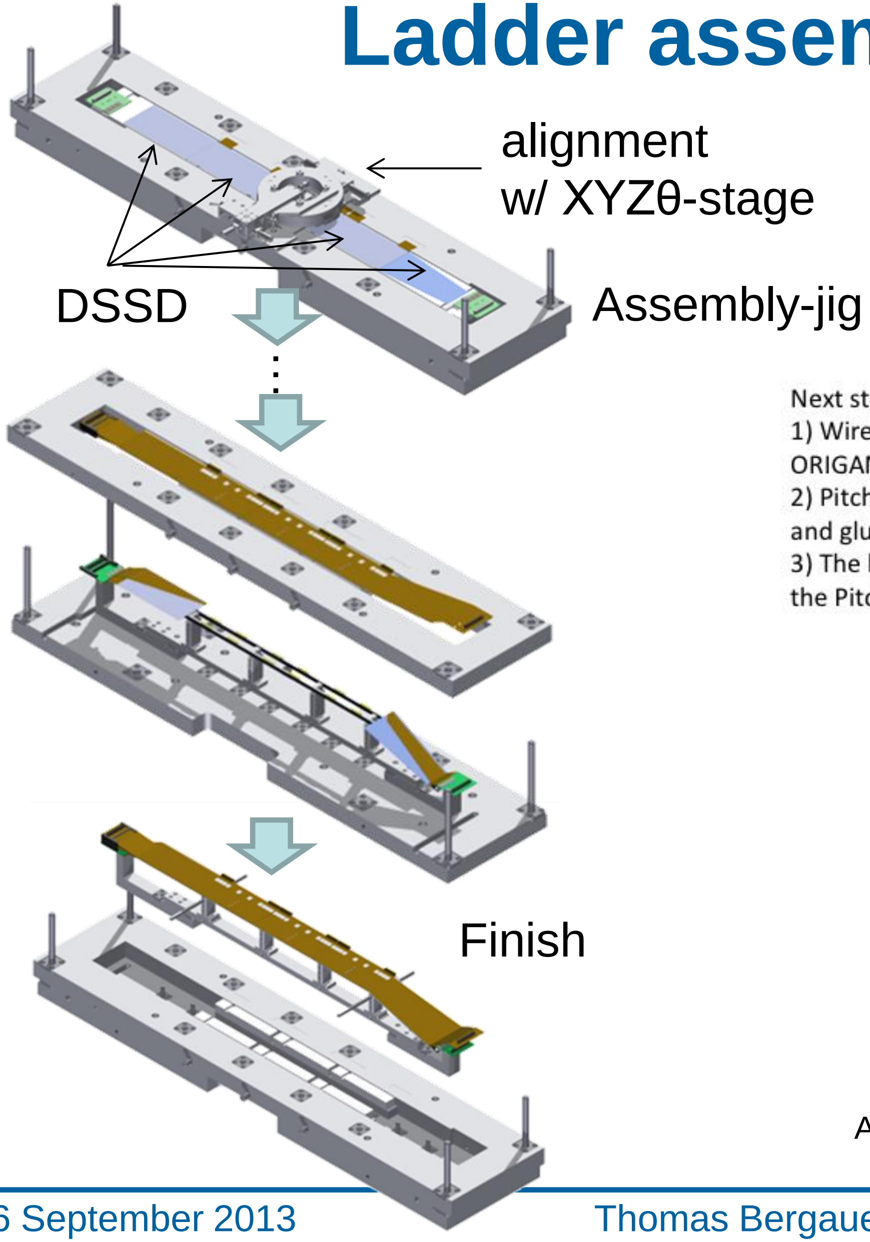
CMM modified for
Glue dispersion
(HEPHY)



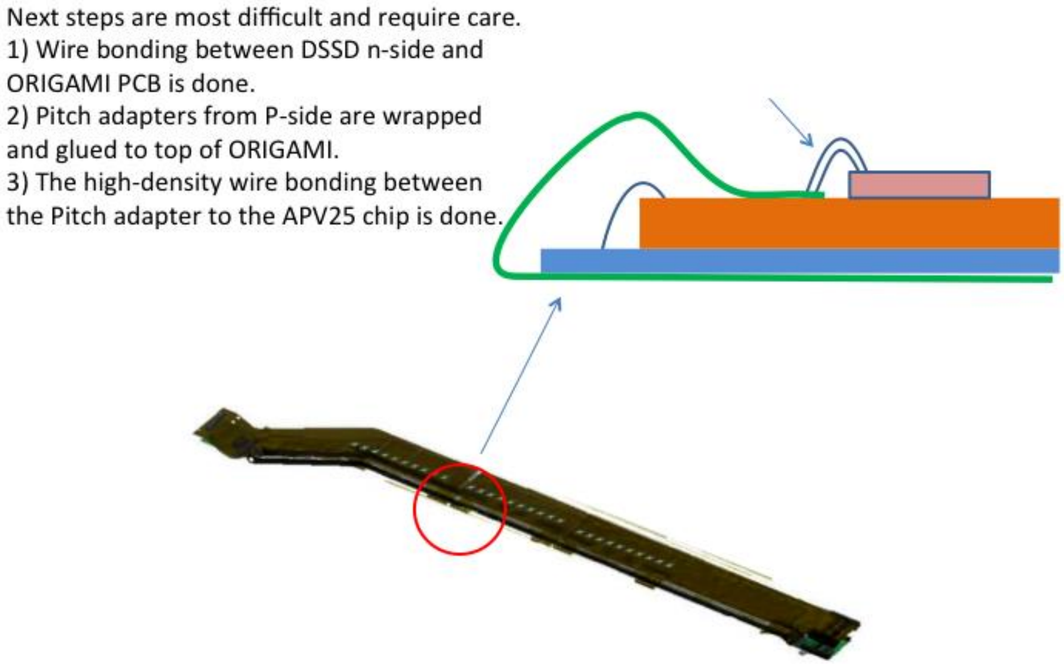

CMM
Mitutoyo QV606
(IPMU)


CMM
Mitutoyo Euro-C776
(HEPHY)

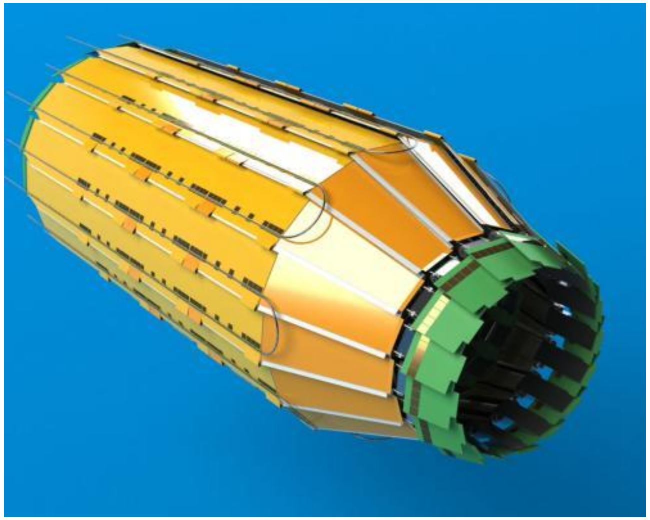
Ladder assembly procedure



- Two weeks per ladder expected
- Bonding/glue-curing interlaced


Next steps are most difficult and require care.
1) Wire bonding between DSSD n-side and ORIGAMI PCB is done.
2) Pitch adapters from P-side are wrapped and glued to top of ORIGAMI.
3) The high-density wire bonding between the Pitch adapter to the APV25 chip is done.

Animation of (simplified) procedure



- Belle and Belle II
- Components
  - Sensors
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  - Ladder assembly
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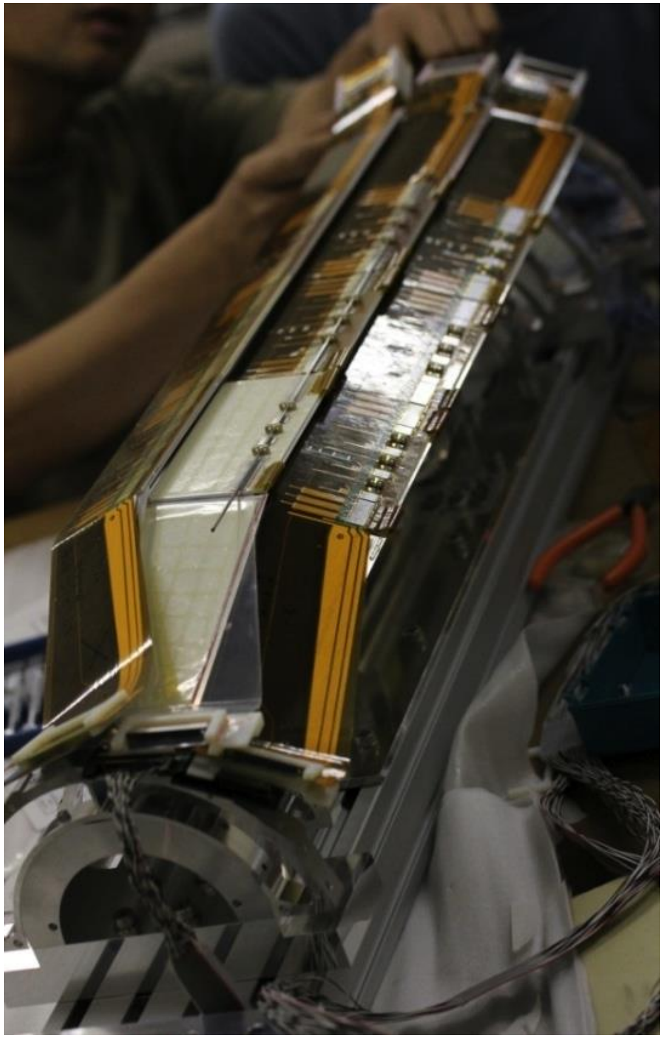
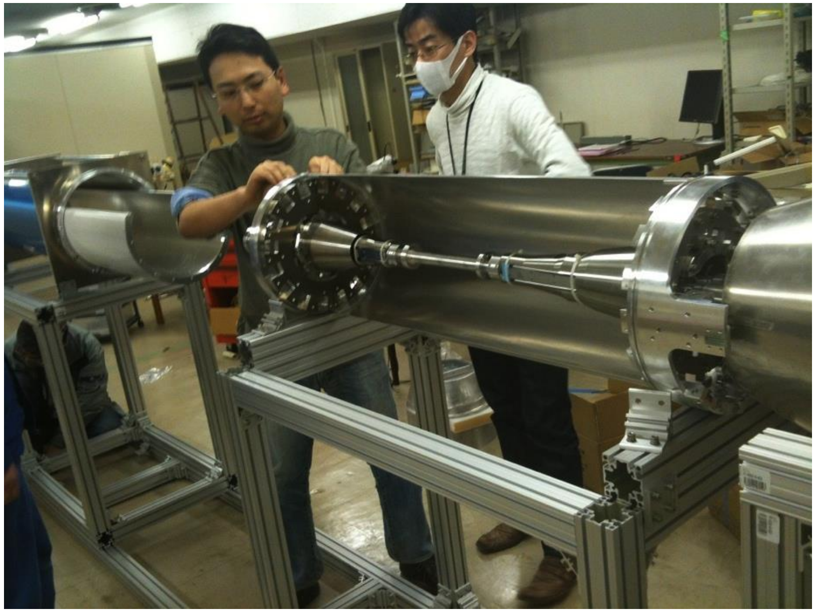
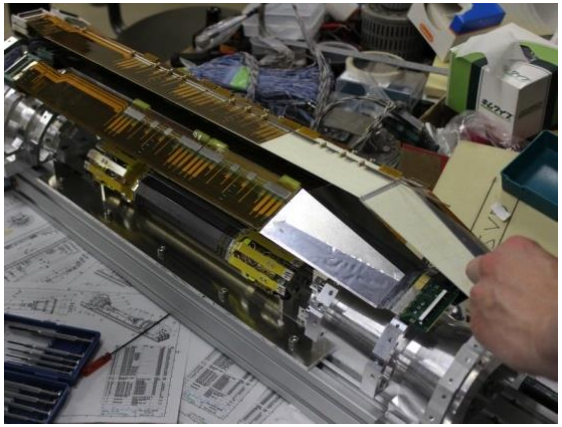
- Summary

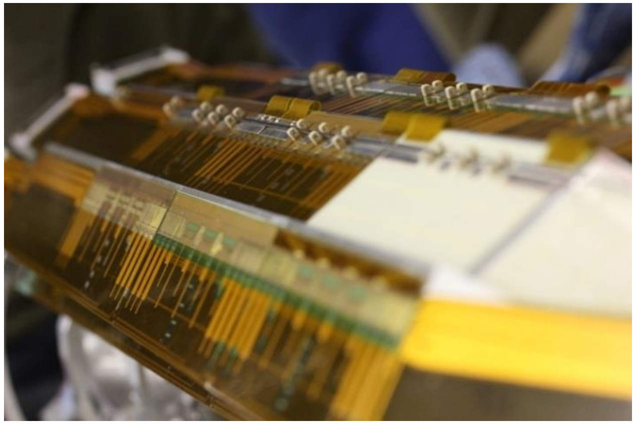
Mockup IR-PXD-SVD



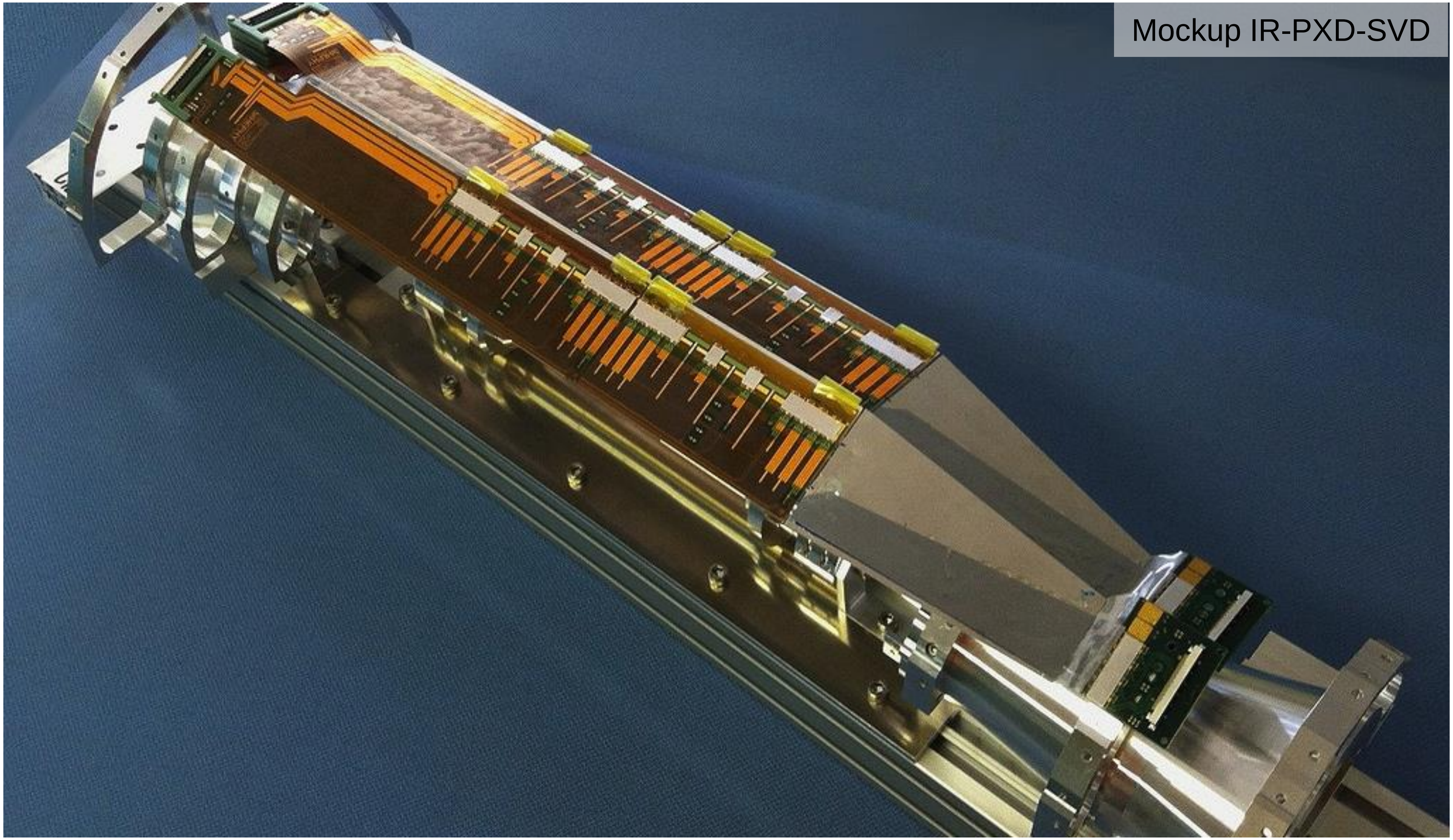


mockup study
@ KEK



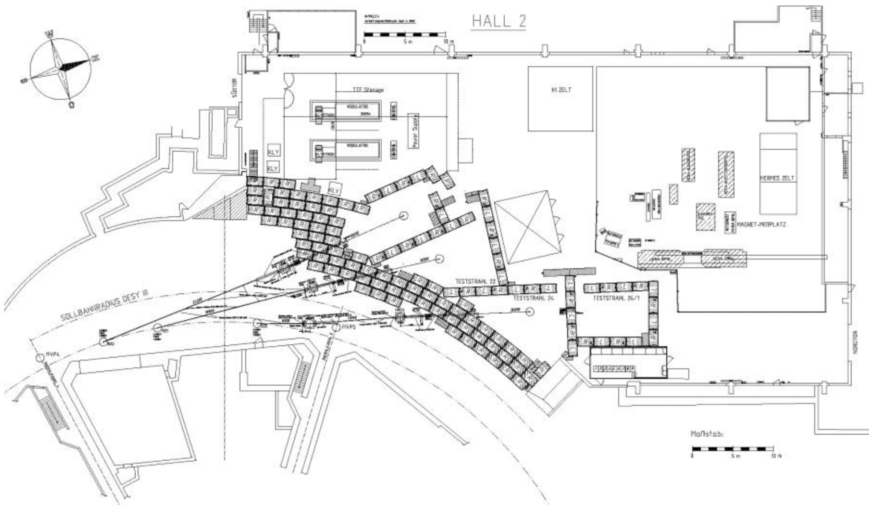


Going real!

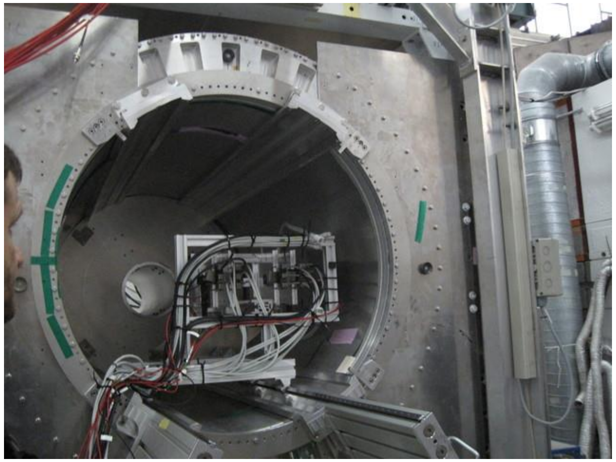


PXD+SVD Testbeam @ DESY

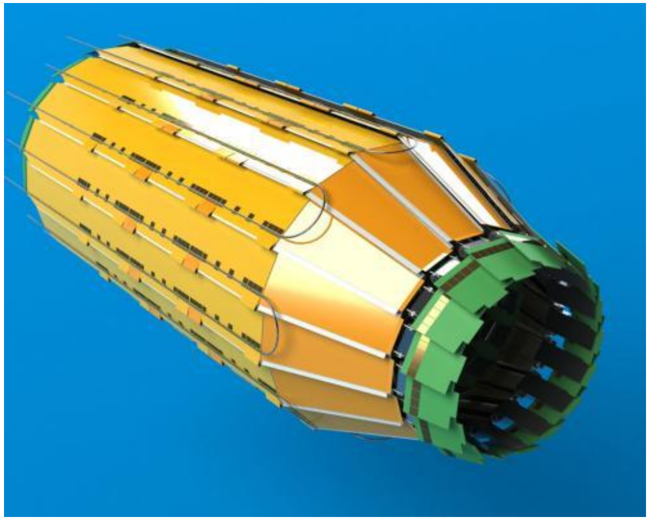
- Test of “full” VXD
  - 2 Layers DEPFET
  - All 4 layers of SVD (one sensor per layer only)
  - Inside PCMAG superconducting magnet
  - MARCO CO_2 cooling plant
  - Full readout chain



- 4 weeks beamtime at DESY TB24 in January 2014
  - Connectivity test end of June in Vienna to test connection between SVD FADC, FTB, DataCon
  - Installation in zone starting end of November 2013



Belle II



- Belle and Belle II
- Components
  - Sensors
  - Electronics
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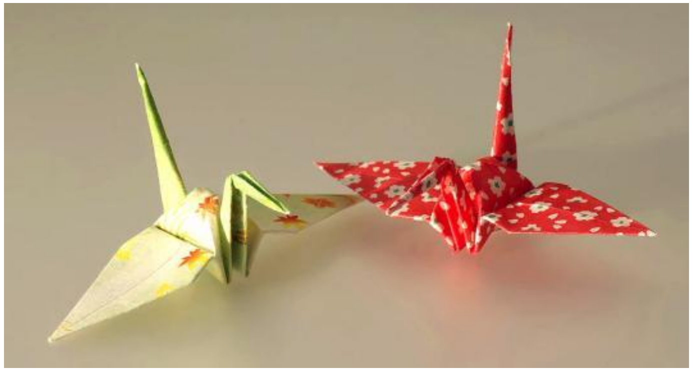
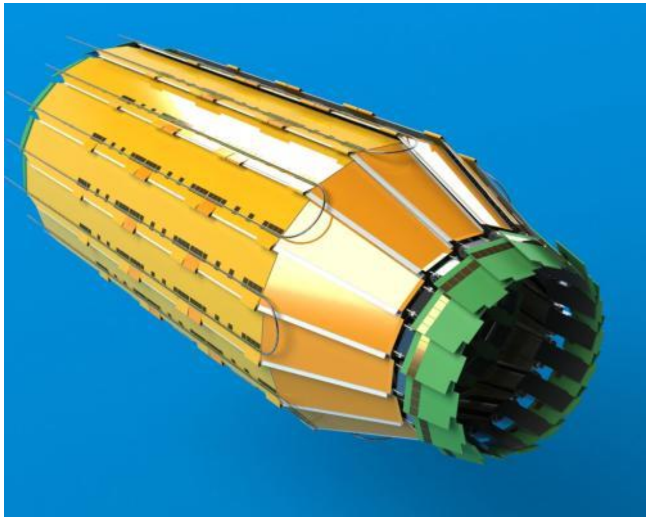
- **Summary**

Summary

- **SuperKEKB** will be the **highest luminosity** machine in the world
- **Belle II** detector will consist of new, enlarged **Silicon Vertex Detector**
  - 2 layers DEPFET Pixels (PXD) and
  - 4 **double-sided strip** layers (SVD)



- **Strip Detector (SVD)**
  - **Double Sided Strip Detectors**
    - Optimal p-stop geometry identified by SNR measurements before and after irradiation
  - **Chip-on-sensor readout scheme**, named Origami, for outermost three layers for low material budget, using CF ribs and CO_2 cooling
  - Readout with **hit time reconstruction** for improved background tolerance
  - **Mass production** of ~50 ladders starts **this fall, SVD ready by 2015**



The End.

Backup Slides follow

Belle Detector (1999–2010)

ter

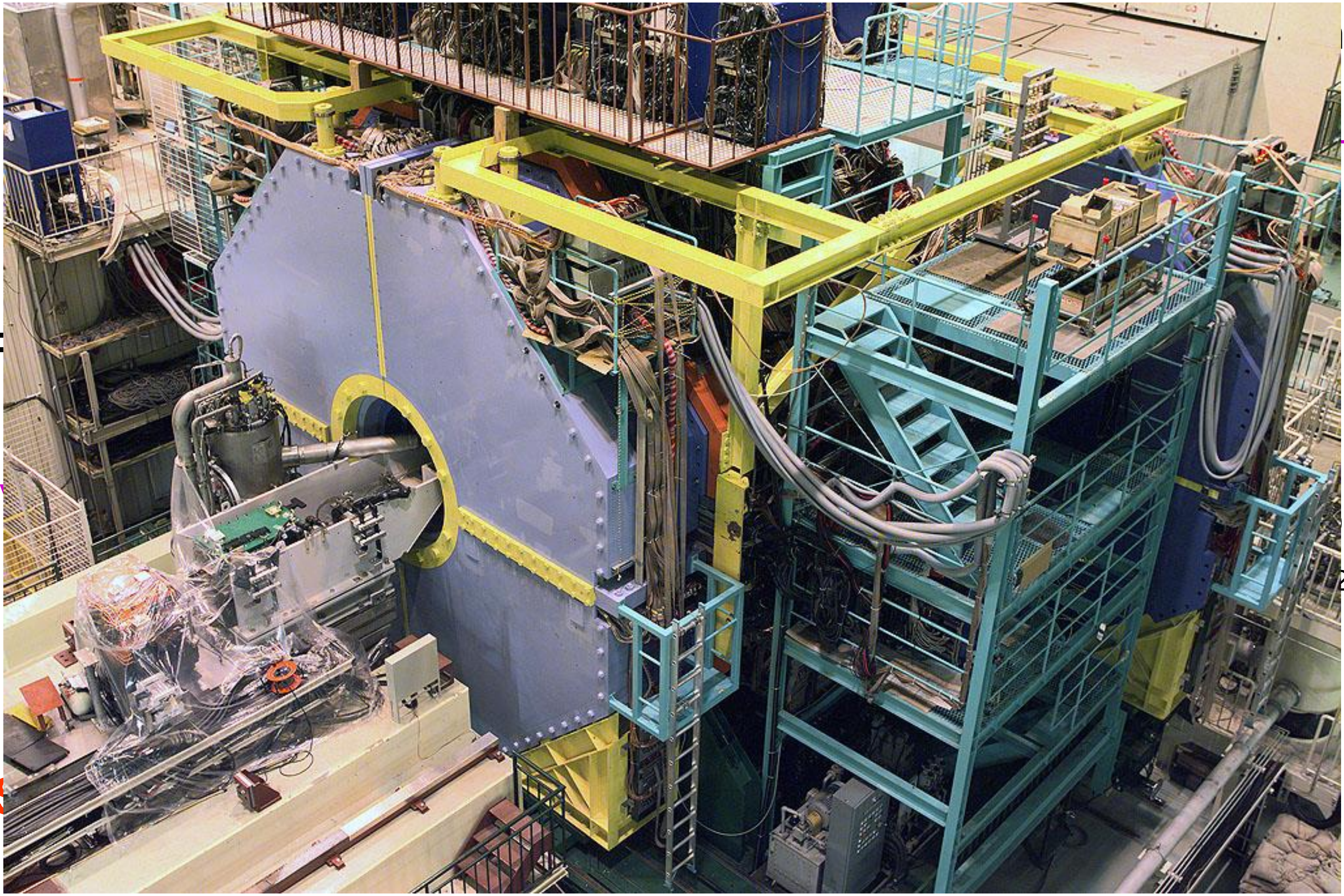
TOF

8 Ge

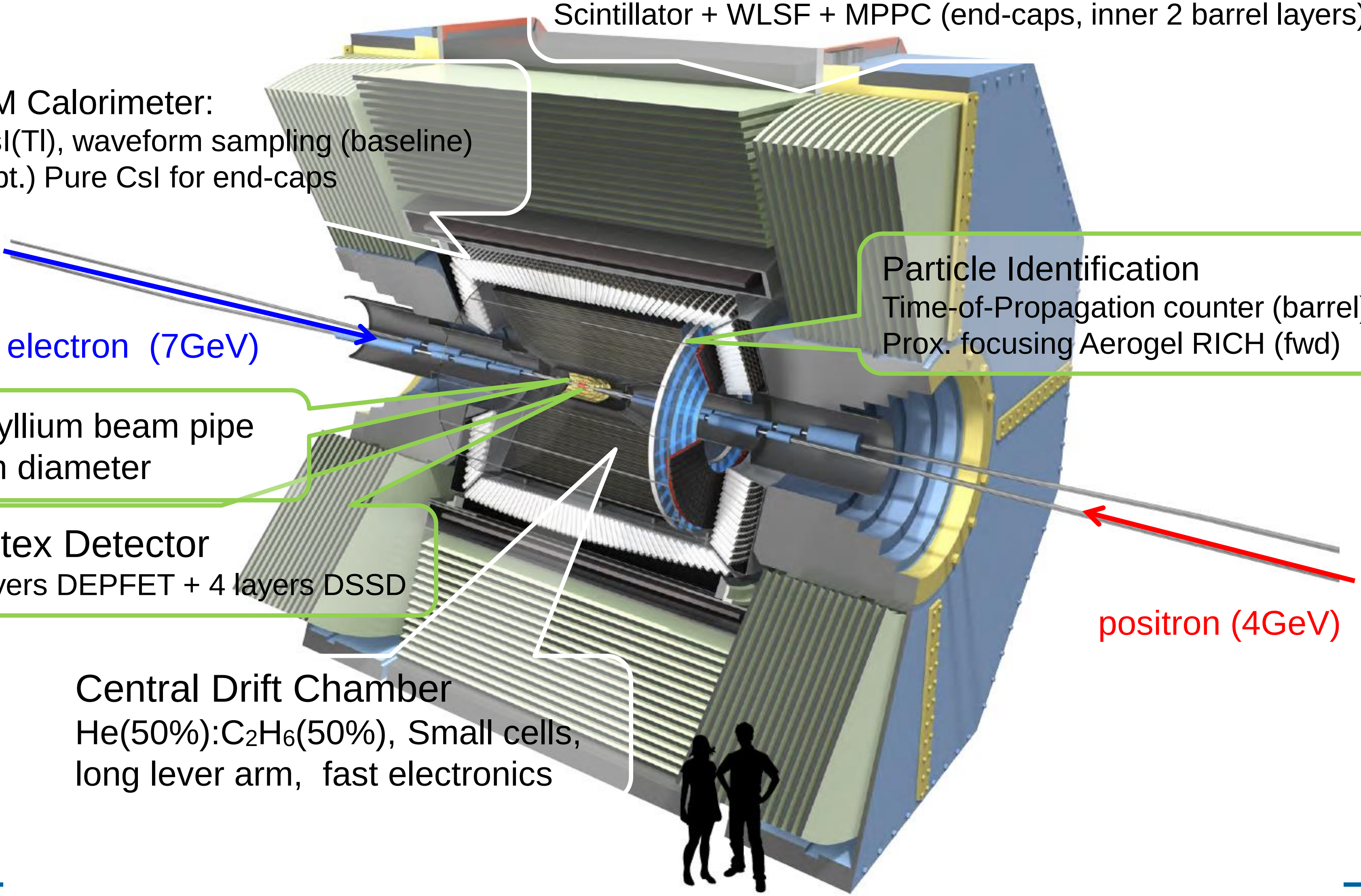
er

$_2H_5$

S



Belle II Detector



K_L and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

EM Calorimeter:
CsI(Tl), waveform sampling (baseline)
(opt.) Pure CsI for end-caps

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

electron (7GeV)

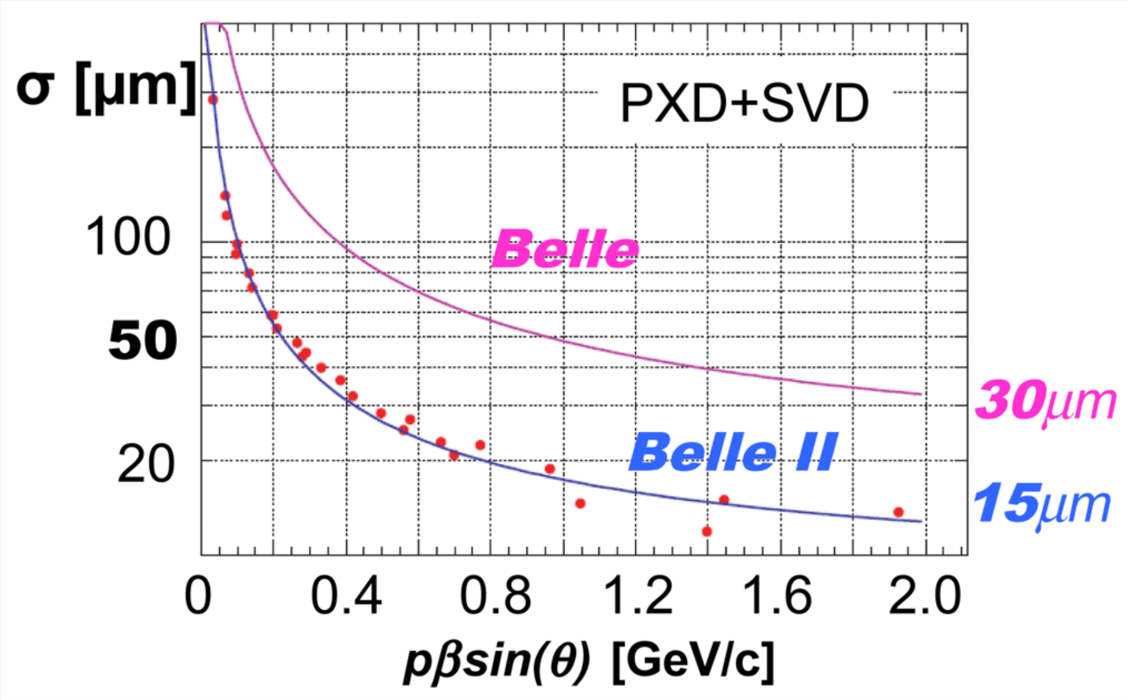
Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD

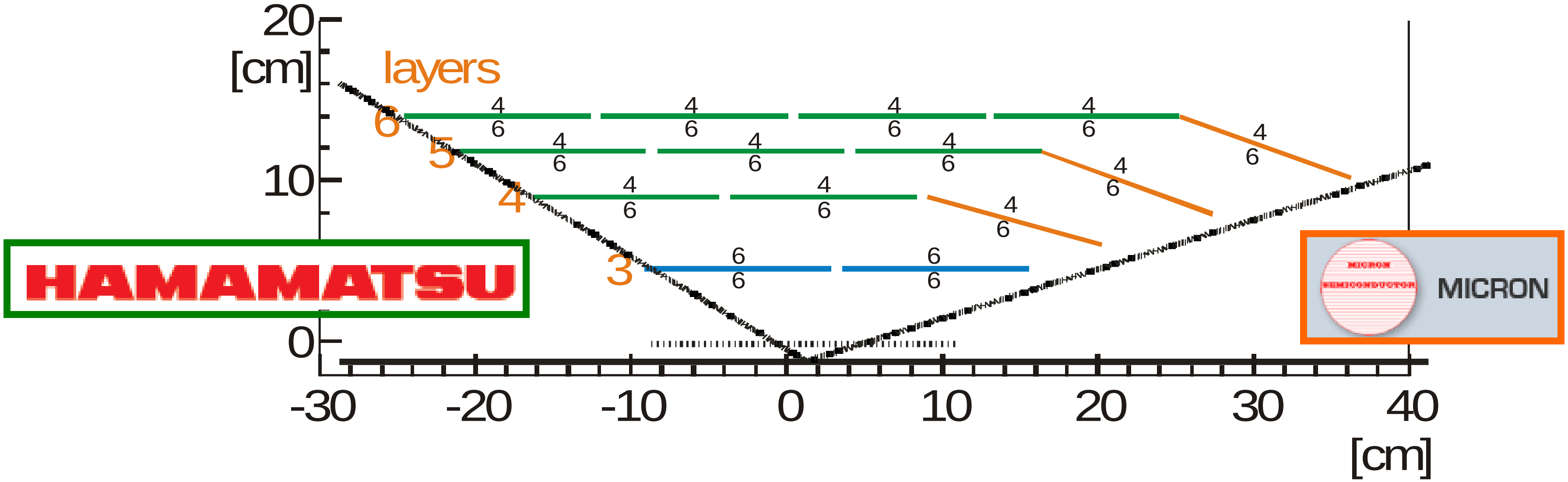
positron (4GeV)

Central Drift Chamber
He(50%):C_2H_6(50%), Small cells,
long lever arm, fast electronics

Spatial Resolution of the Belle II Detector

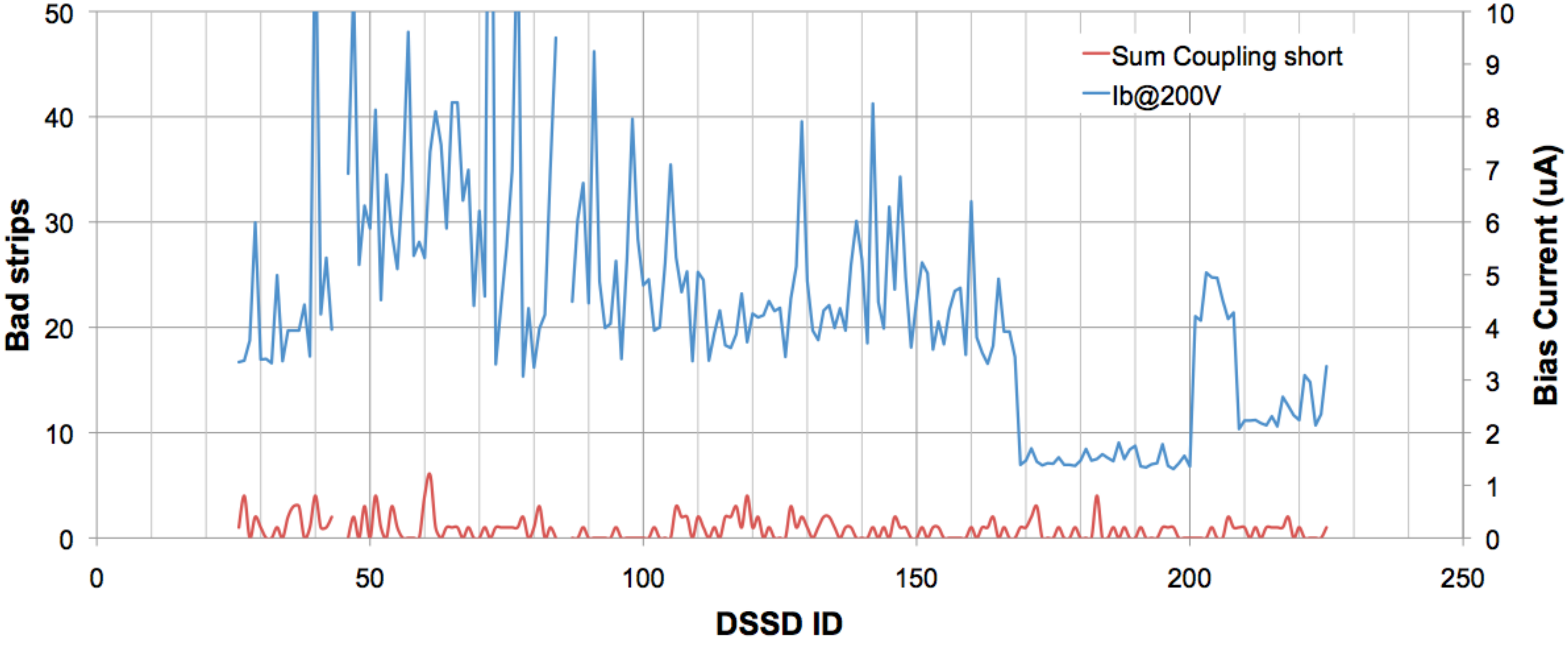


Sensor Types and Vendors



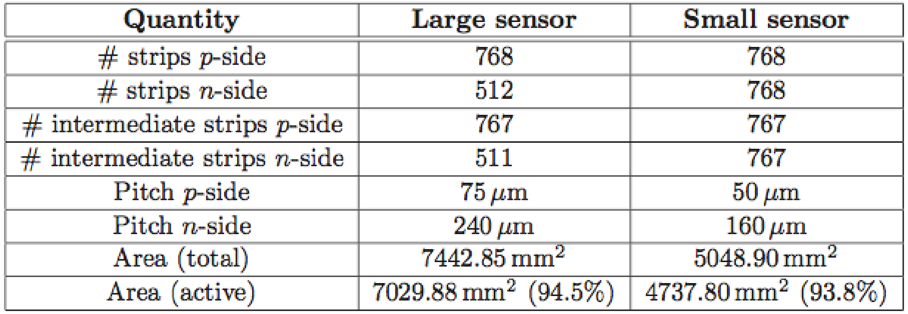
Layer	# of Ladders	Rect. Sensors [narrow]	Rect. Sensors [wide]	Wedge Sensors	APVs
6	16	0	64	16	800
5	12	0	36	12	480
4	10	0	20	10	300
3	7	14	0	0	168
Sum:	**45**	**14**	**120**	**38**	**1748**

HPK Pinholes

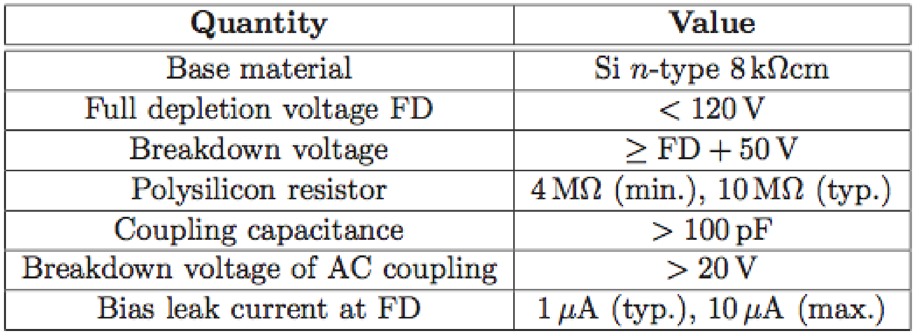


Sensor Parameters

Rectangular Sensors

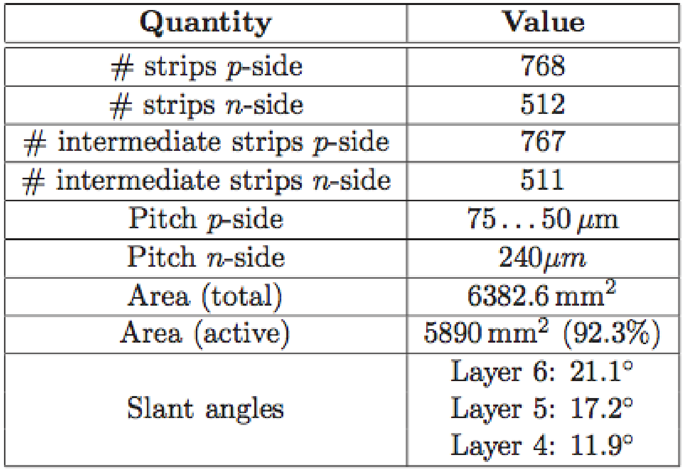


Quantity	Large sensor	Small sensor
# strips p-side	768	768
# strips n-side	512	768
# intermediate strips p-side	767	767
# intermediate strips n-side	511	767
Pitch p-side	$75\,\mu m$	$50\,\mu m$
Pitch n-side	$240\,\mu m$	$160\,\mu m$
Area (total)	$7442.85\,mm^2$	$5048.90\,mm^2$
Area (active)	$7029.88\,mm^2$ (94.5%)	$4737.80\,mm^2$ (93.8%)

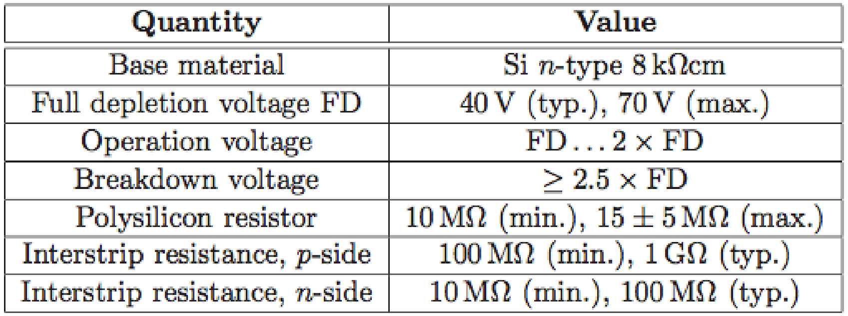


Quantity	Value
Base material	Si n-type $8\,k\Omega cm$
Full depletion voltage FD	$< 120\,V$
Breakdown voltage	$\geq FD + 50\,V$
Polysilicon resistor	$4\,M\Omega$ (min.), $10\,M\Omega$ (typ.)
Coupling capacitance	$> 100\,pF$
Breakdown voltage of AC coupling	$> 20\,V$
Bias leak current at FD	$1\,\mu A$ (typ.), $10\,\mu A$ (max.)

Trapezoidal Sensors



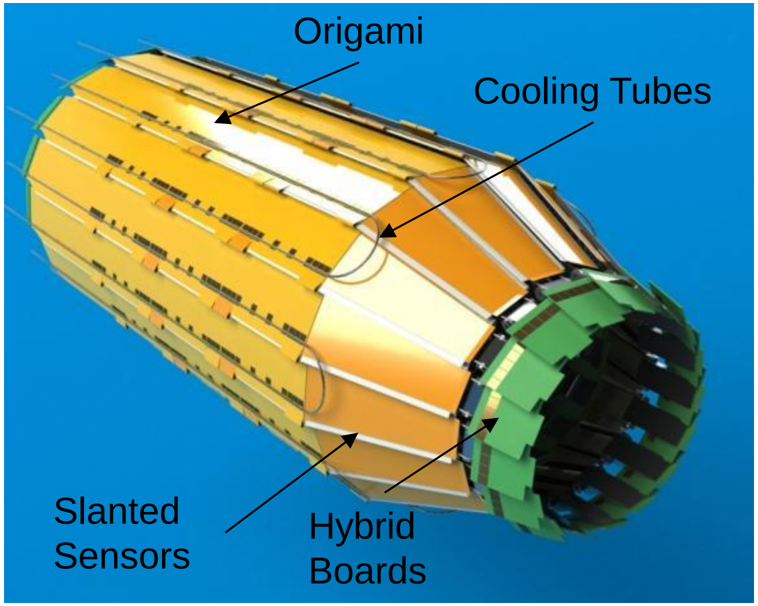
Quantity	Value
# strips p-side	768
# strips n-side	512
# intermediate strips p-side	767
# intermediate strips n-side	511
Pitch p-side	$75 \ldots 50\,\mu m$
Pitch n-side	$240 \mu m$
Area (total)	$6382.6\,mm^2$
Area (active)	$5890\,mm^2$ (92.3%)
Slant angles	Layer 6: 21.1° Layer 5: 17.2° Layer 4: 11.9°

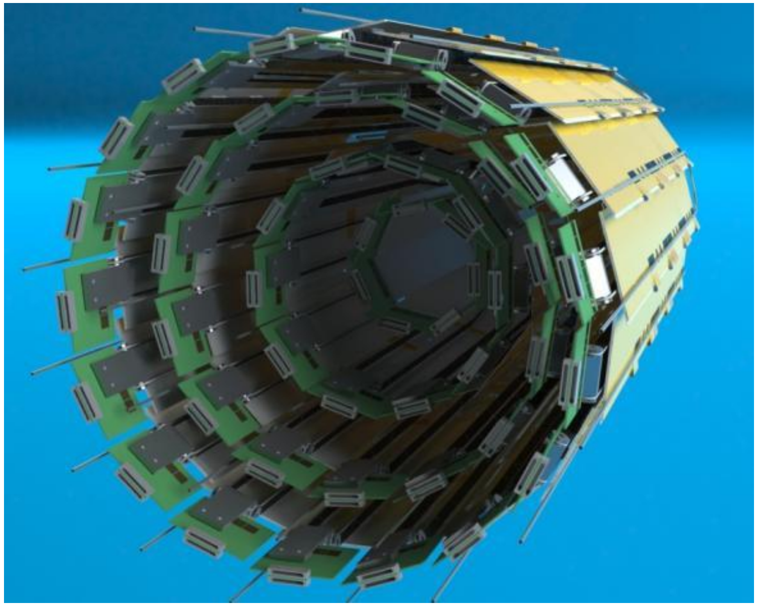


Quantity	Value
Base material	Si n-type $8\,k\Omega cm$
Full depletion voltage FD	$40\,V$ (typ.), $70\,V$ (max.)
Operation voltage	$FD \ldots 2 \times FD$
Breakdown voltage	$\geq 2.5 \times FD$
Polysilicon resistor	$10\,M\Omega$ (min.), $15 \pm 5\,M\Omega$ (max.)
Interstrip resistance, p-side	$100\,M\Omega$ (min.), $1\,G\Omega$ (typ.)
Interstrip resistance, n-side	$10\,M\Omega$ (min.), $100\,M\Omega$ (typ.)

Current Barrel Layout

Layer	Sensors/ Ladder	Origamis/ Ladder	Ladders	Length [mm]	Radius [mm]	Slant Angle [°]
3	2	0	7	262	38	0
4	3	1	10	390	80	11.9
5	4	2	12	515	104	16
6	5	3	16	645	135	21.1

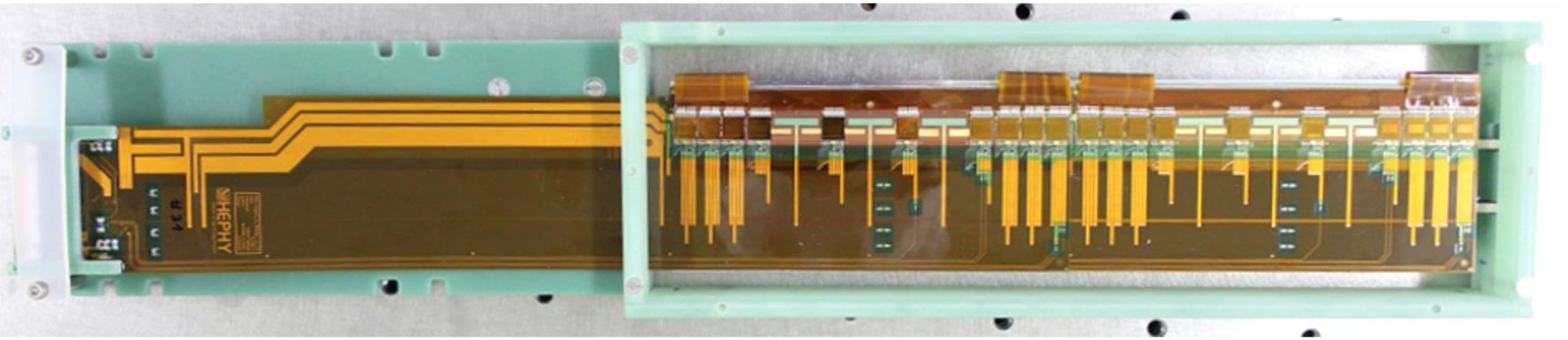




Origami Prototype Modules

- Single Origami module (layer 4)

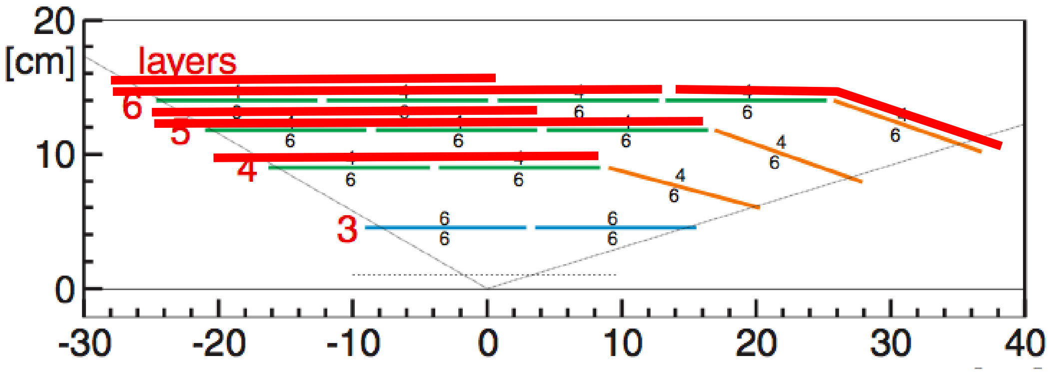
- Double Origami module (layer 5)



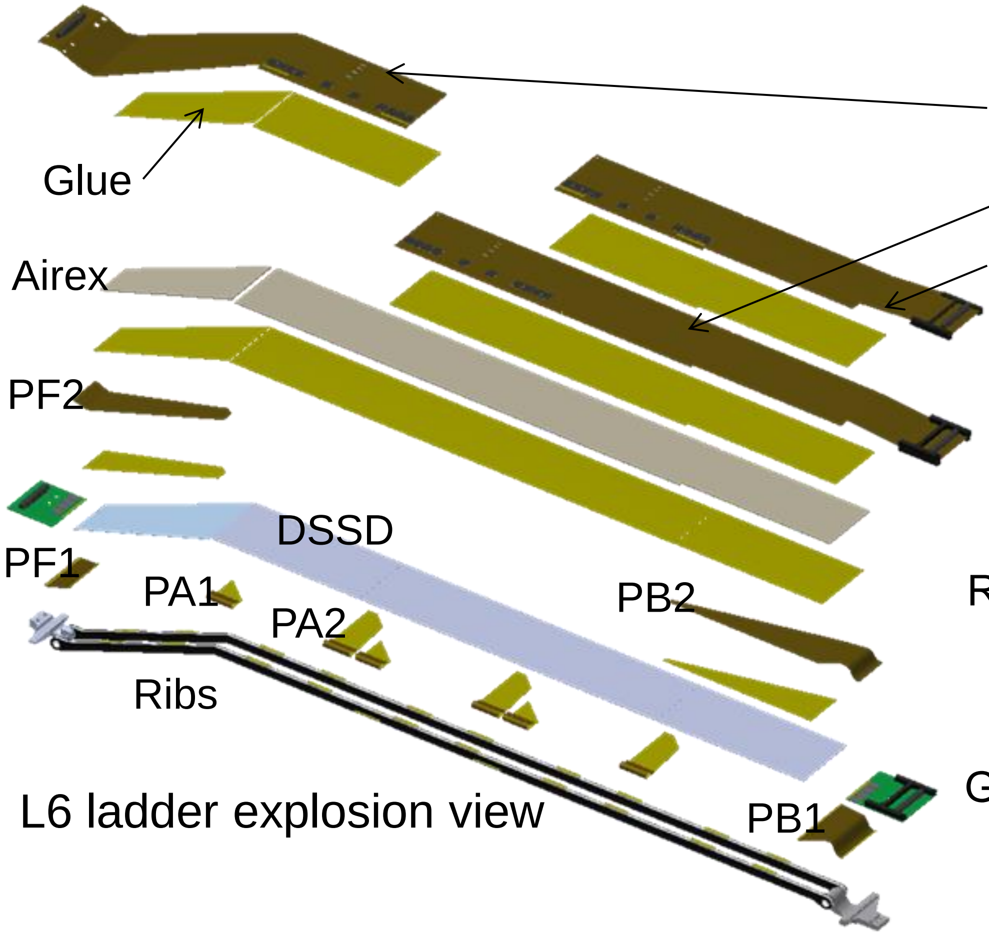
Material budget

DSSD+ Origami	Rib	DSSD	Airex sheet	Origami	CO2 Cooling	100 μm Glue	Total
HPK+1ORIGAMI	0.035	0.340	0.055	0.133	0.037	0.033	0.593
HPK+2ORIGAMI	0.035	0.340	0.055	0.266	0.037	0.033	0.733
Micron	0.035	0.320	0.055	0	0	0.011	0.421
Micron+ORIGAMI	0.035	0.320	0.000	0.133	0	0.033	0.576

- PA/PE/PB/SMD/ are neglected.
- Thickness of epoxy glue in ladder assembly is assumed to be 100 μm, or, 0.033 % X_0.



Breakdown of material budget



L6 ladder explosion view

Origami +Z flex

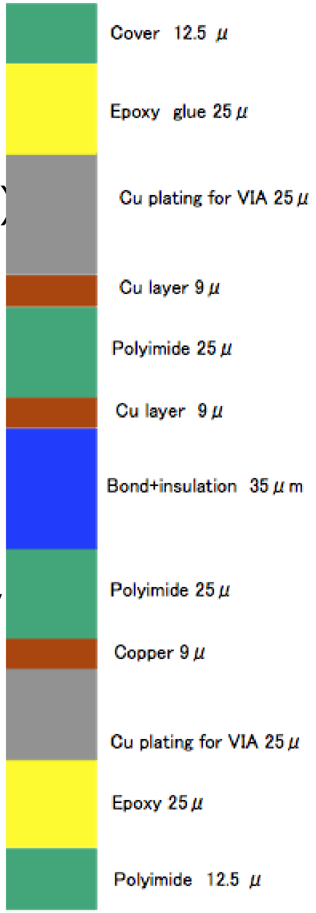
Origami CE flex(length 450mm)

Origami −Z flex

…Three Cu layer FLEX (Taiyo Co.)

Ribs…Airex foam sandwiched by Carbon fiber ribs

Glue…Araldite 2011



🟩	Cover 12.5 μ
🟨	Epoxy glue 25 μ
⬜	Cu plating for VIA 25 μ
🟫	Cu layer 9 μ
🟩	Polyimide 25 μ
🟫	Cu layer 9 μ
🟦	Bond+insulation 35 μm
🟩	Polyimide 25 μ
🟫	Copper 9 μ
⬜	Cu plating for VIA 25 μ
🟨	Epoxy 25 μ
🟩	Polyimide 12.5 μ

Total 237 μ

Comparison VA1TA – APV25

VA1TA (SVD)

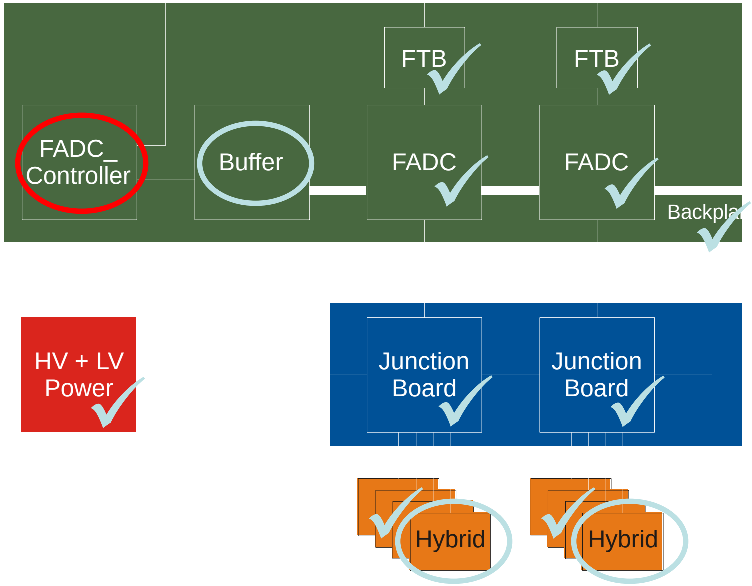
- Commercial product (IDEAS)
- Tp = 800ns (300 ns – 1000 ns)
- no pipeline
- <10 MHz readout
- 20 Mrad radiation tolerance
- noise: ENC = 180 e + 7.5 e/pF
- time over threshold: ~2000 ns
- single sample per trigger

APV25 (Belle-II SVD)

- Developed for CMS by IC London and RAL
- Tp = 50 ns (30 ns – 200 ns)
- 192 cells analog pipeline
- 40 MHz readout
- >100 Mrad radiation tolerance
- noise: ENC = 250 e + 36 e/pF
- time over threshold: ~160 ns
- multiple samples per trigger possible (Multi-Peak-Mode)

Status of Belle II Readout Electronics

- Pre-production is driven by DESY beam test (January 2014)
  - first version of all boards to be used there
- Design is done; most parts of hardware exist already



✓ Ready and tested

○ PCBs ordered, expected soon

○ PCB being designed

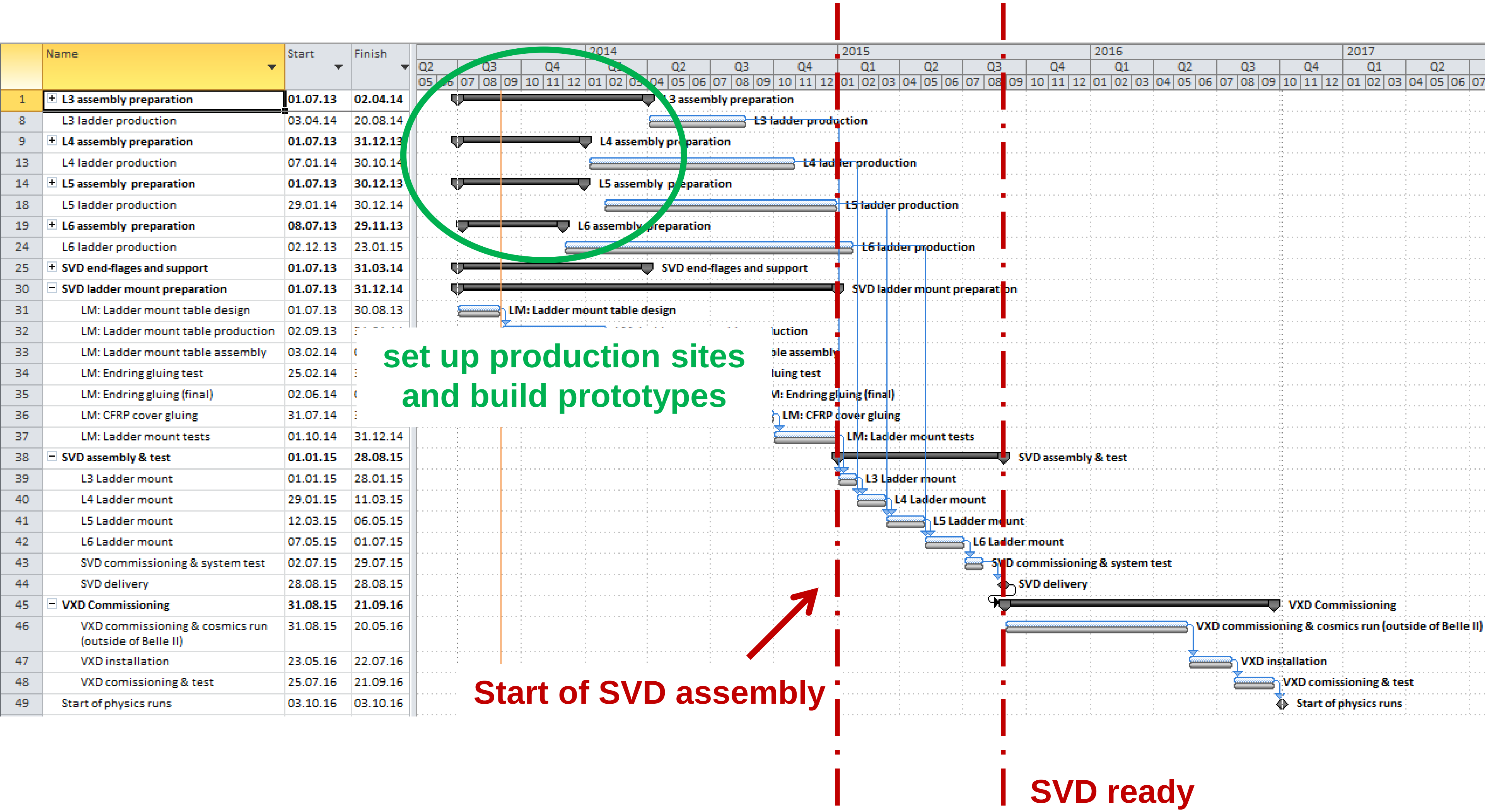
Cooling Boundary Conditions

- Power dissipation per APV: 0.40 W
- 1 Origami sensor features 10 APVs

heat amount [W]	APV	pipe	end-ring	cone (L3/4)	cone (L5+6)	cable	Origami	hybrid	total
end-ring (FWD)	92.8	20.0	7.0	18.9	13.8	29.2		13.3	195.0
end-ring (BWD)	92.8	15.0	9.1	32.2	6.8	29.2		13.3	198.4
Origami (L6)	94.0	19.6					7.4		121.0
Origami (L5+4)	68.0	20.0					5.2		93.2
total	347.6	74.6	16.1	51.1	20.6	58.4	12.6	26.6	607.6

- Total SVD power dissipation: 607 W

Baseline Schedule



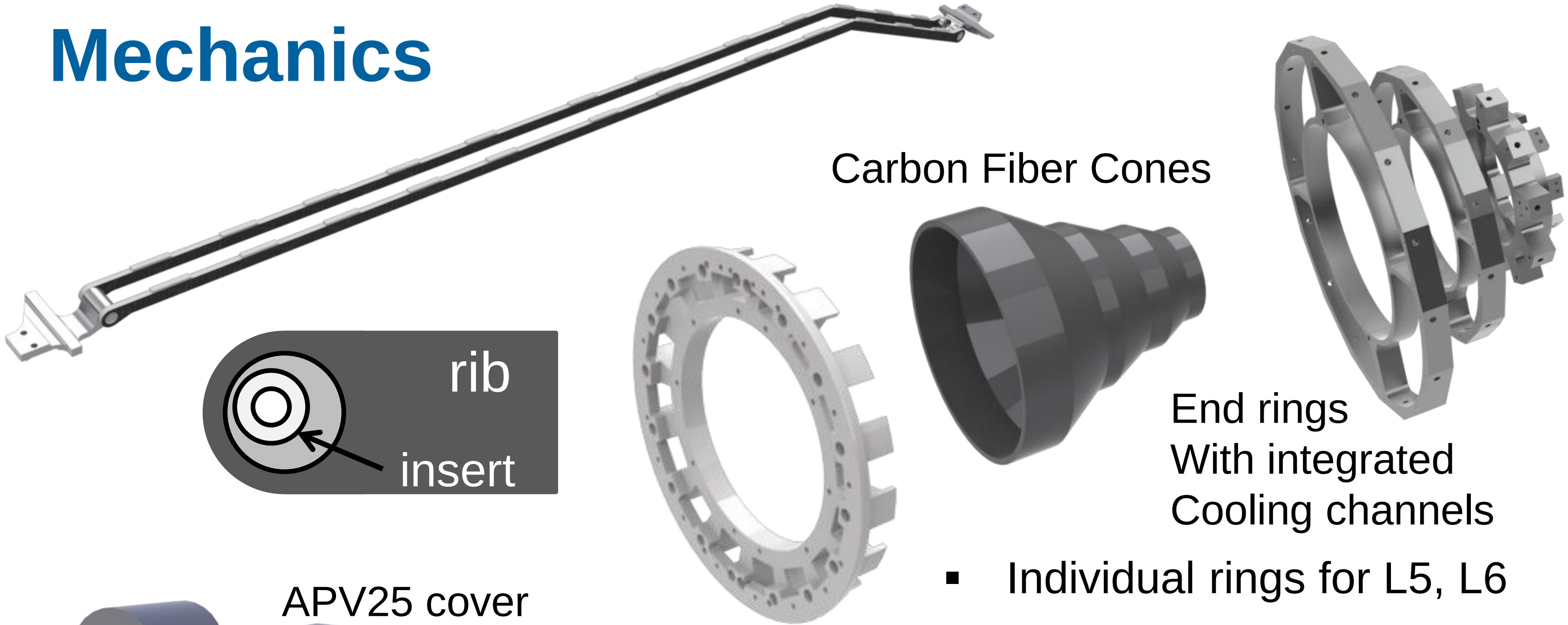
	Name	Start	Finish
1	⊞ **L3 assembly preparation**	**01.07.13**	**02.04.14**
8	L3 ladder production	03.04.14	20.08.14
9	⊞ **L4 assembly preparation**	**01.07.13**	**31.12.13**
13	L4 ladder production	07.01.14	30.10.14
14	⊞ **L5 assembly preparation**	**01.07.13**	**30.12.13**
18	L5 ladder production	29.01.14	30.12.14
19	⊞ **L6 assembly preparation**	**08.07.13**	**29.11.13**
24	L6 ladder production	02.12.13	23.01.15
25	⊞ **SVD end-flages and support**	**01.07.13**	**31.03.14**
30	⊟ **SVD ladder mount preparation**	**01.07.13**	**31.12.14**
31	LM: Ladder mount table design	01.07.13	30.08.13
32	LM: Ladder mount table production	02.09.13	
33	LM: Ladder mount table assembly	03.02.14	
34	LM: Endring gluing test	25.02.14	
35	LM: Endring gluing (final)	02.06.14	
36	LM: CFRP cover gluing	31.07.14	
37	LM: Ladder mount tests	01.10.14	31.12.14
38	⊟ **SVD assembly & test**	**01.01.15**	**28.08.15**
39	L3 Ladder mount	01.01.15	28.01.15
40	L4 Ladder mount	29.01.15	11.03.15
41	L5 Ladder mount	12.03.15	06.05.15
42	L6 Ladder mount	07.05.15	01.07.15
43	SVD commissioning & system test	02.07.15	29.07.15
44	SVD delivery	28.08.15	28.08.15
45	⊟ **VXD Commissioning**	**31.08.15**	**21.09.16**
46	VXD commissioning & cosmics run (outside of Belle II)	31.08.15	20.05.16
47	VXD installation	23.05.16	22.07.16
48	VXD comissioning & test	25.07.16	21.09.16
49	Start of physics runs	03.10.16	03.10.16

set up production sites and build prototypes

Start of SVD assembly

SVD ready

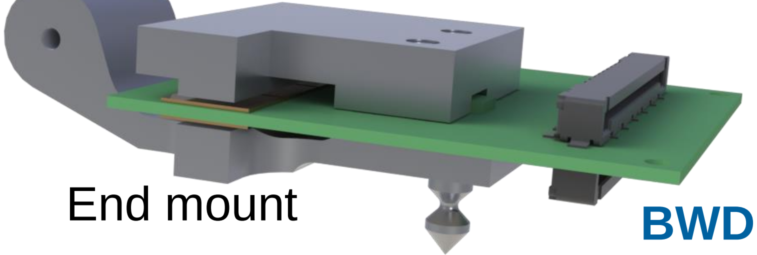
Mechanics



Carbon Fiber Cones

End rings
With integrated
Cooling channels

- Individual rings for L5, L6
- Combined L3+4 end rings



APV25 cover

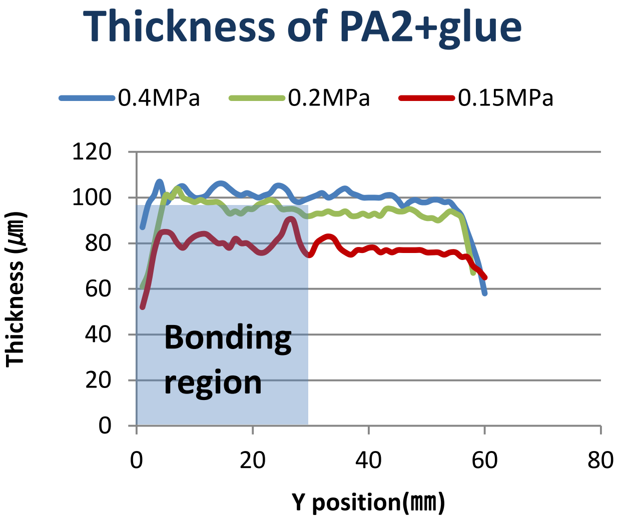
End mount

BWD

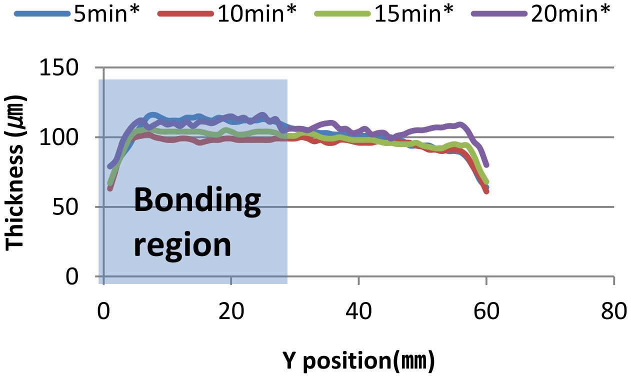
Kokeshi pin
= origin of ladder

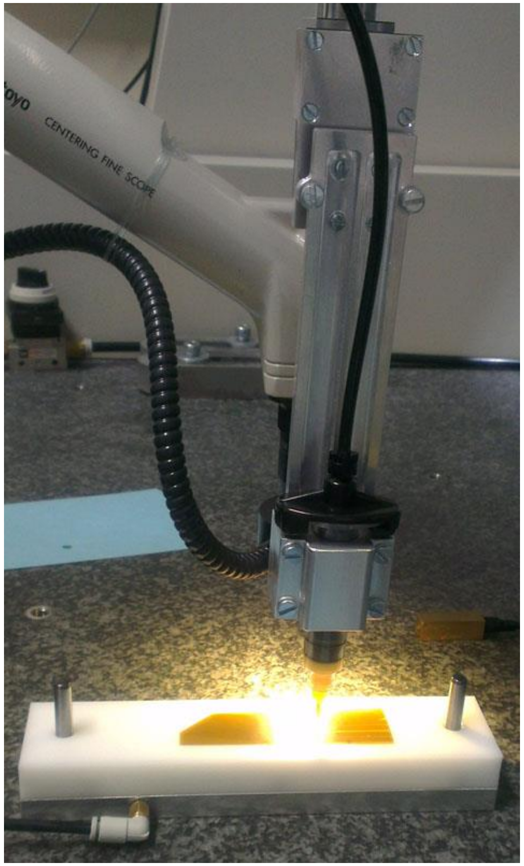
Glue Dispension

Varying pressure

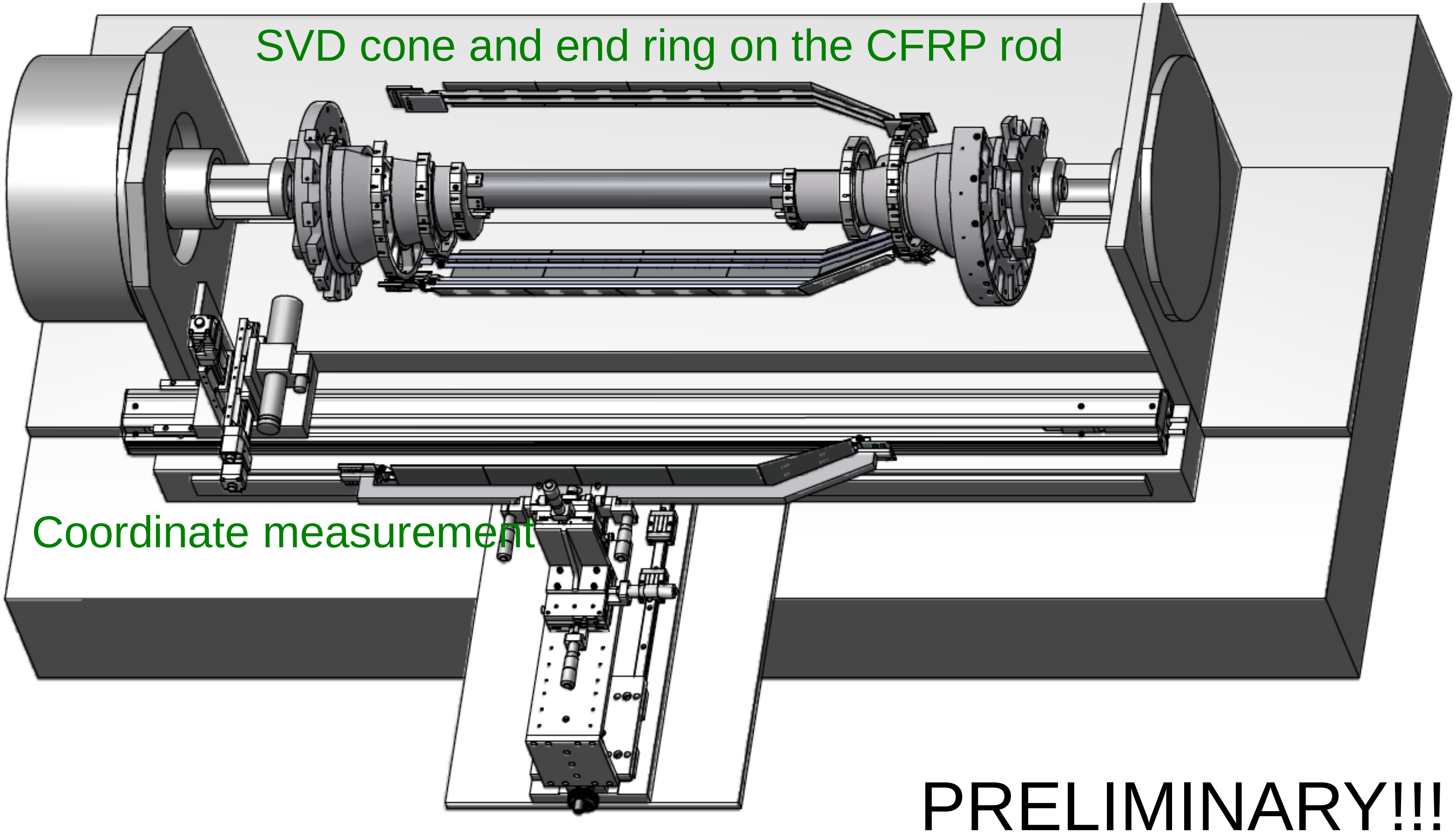


Varying curing time





Idea of Ladder Mount Stage



Rotation axis with encoder

SVD cone and end ring on the CFRP rod

Coordinate measurement

Ladder mount arm

PRELIMINARY!!!