Development and Construction of the TOP counter for the Belle II Experiment

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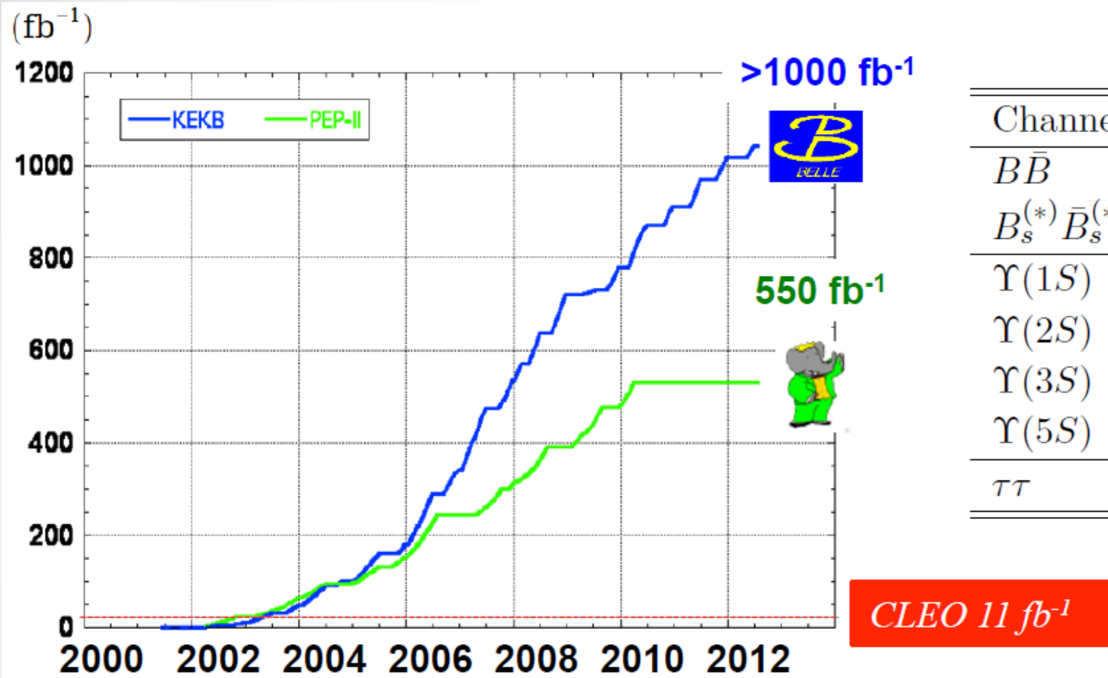
Belle ➔ Belle II

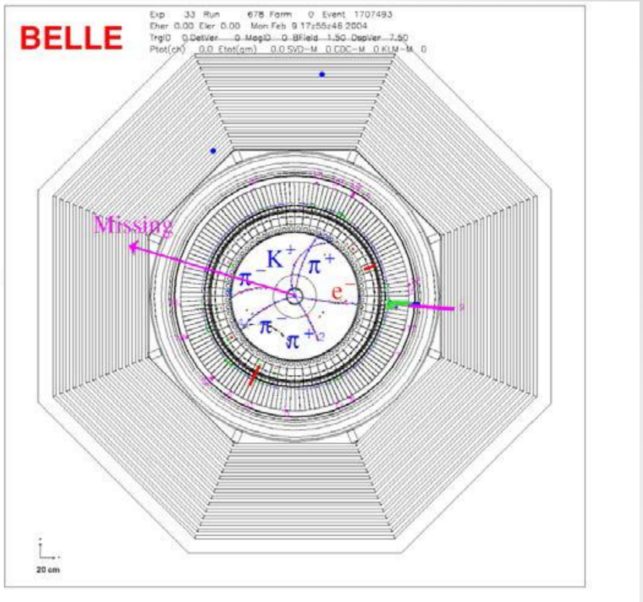


Channel	Belle	BaBar	Belle II (per year)
$B\bar{B}$	7.7×10^8	4.8×10^8	1.1×10^{10}
$B_s^{(*)}\bar{B}_s^{(*)}$	7.0×10^6	–	6.0×10^8
$\Upsilon(1S)$	1.0×10^8		1.8×10^{11}
$\Upsilon(2S)$	1.7×10^8	0.9×10^7	7.0×10^{10}
$\Upsilon(3S)$	1.0×10^7	1.0×10^8	3.7×10^{10}
$\Upsilon(5S)$	3.6×10^7	–	3.0×10^9
$\tau\tau$	1.0×10^9	0.6×10^9	1.0×10^{10}

- Belle II Goal : 40 x present = 4 x 10^{10} BB pairs
  - Accelerator upgrade (➔ SuperKEKB): Higher luminosity (x~40)
  - Detector upgrade (➔ Belle II): Precise measurement

B factories in the LHC era

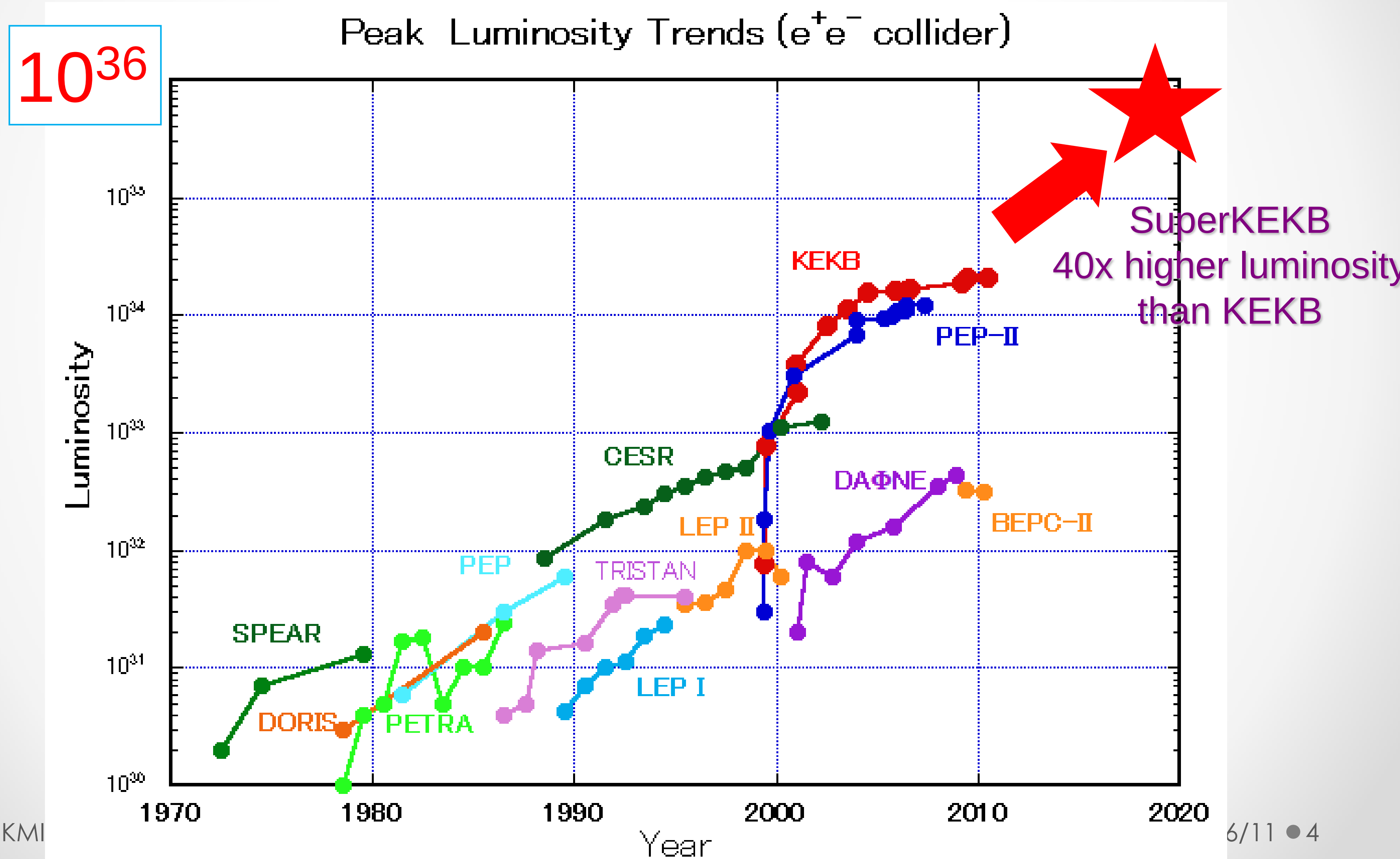
$B^+ \to D^0\pi^+$
$(\to K\pi^-\pi^+\pi^-)$
$B^- \to \tau(\to e\nu\bar{\nu})\nu$



Unique capabilities of B factories:

- Exactly two B mesons produced (at Υ(4S))
- High flavour tagging efficiency
- Detection of gammas, π^0s, K_Ls
- Very clean detector environment
  - ➔ can observe decays with several neutrinos in the final state)
- Well understood apparatus,
  with known systematics, checked on control channels

SuperKEKB
- Luminosity -



SuperKEKB
- Nano-Beam Scheme (1) -

- How to achieve L~10^{36}: "Nano-Beam" scheme
  - double the beam currents
  - squeeze vertical beta function (β^*_y) at IP (1/20)

$$L = \frac{\gamma_\pm}{2er_e}\left(\frac{I_\pm \xi_{y\pm}}{\beta^*_{y\pm}}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

Lorentz factor

Beam current

Beam-Beam parameter

Geometrical reduction factors: 0.8-1.0

Vertical beta function

	KEKB Achieved	SuperKEKB
Energy (GeV) (LER/HER)	3.5/8.0	4.0/7.0
ξ_y	0.129/0.090	0.090/0.088
β^*_y (mm)	5.9/5.9	0.27/0.41
I (A)	1.64/1.19	3.60/2.62
Luminosity ($10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	2.11	80

x ~20

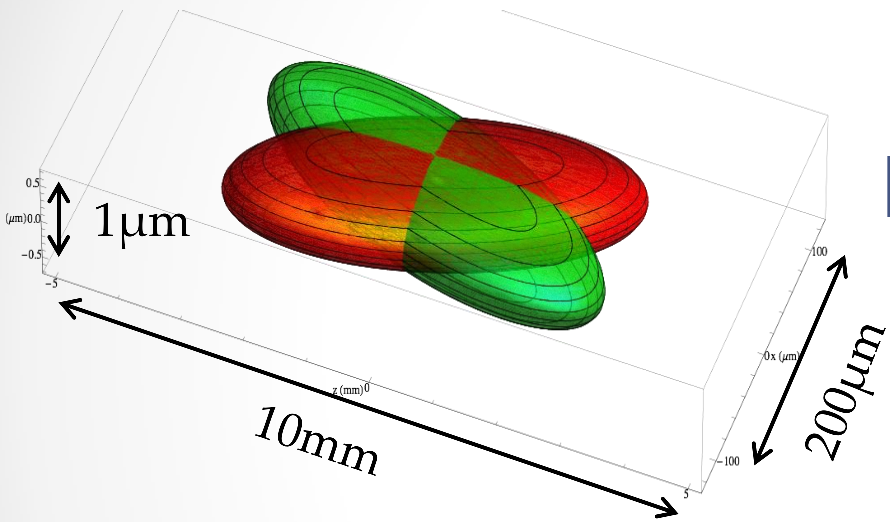
x ~2

x ~40

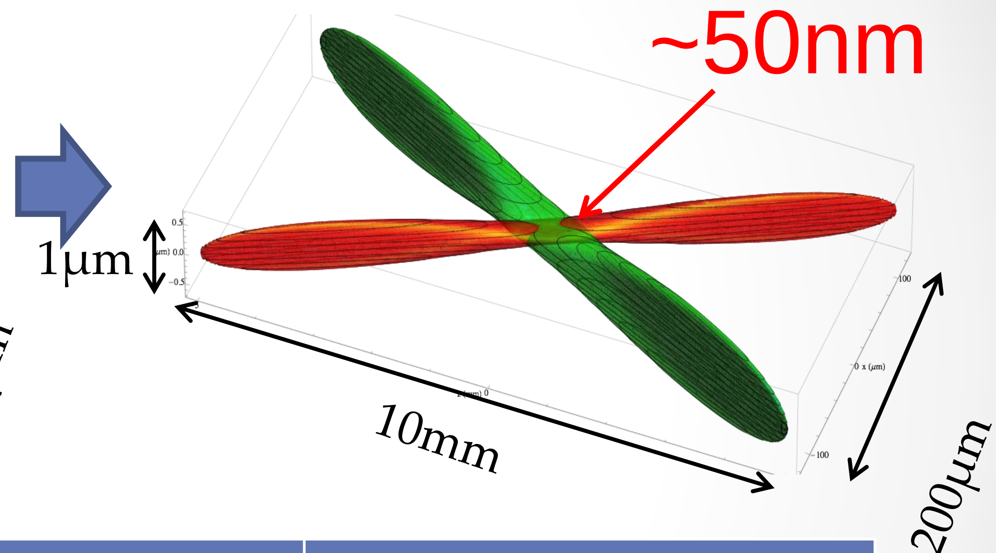
arXiv:1011.0352

SuperKEKB
- Nano-Beam Scheme (2) -

KEKB (without crab)



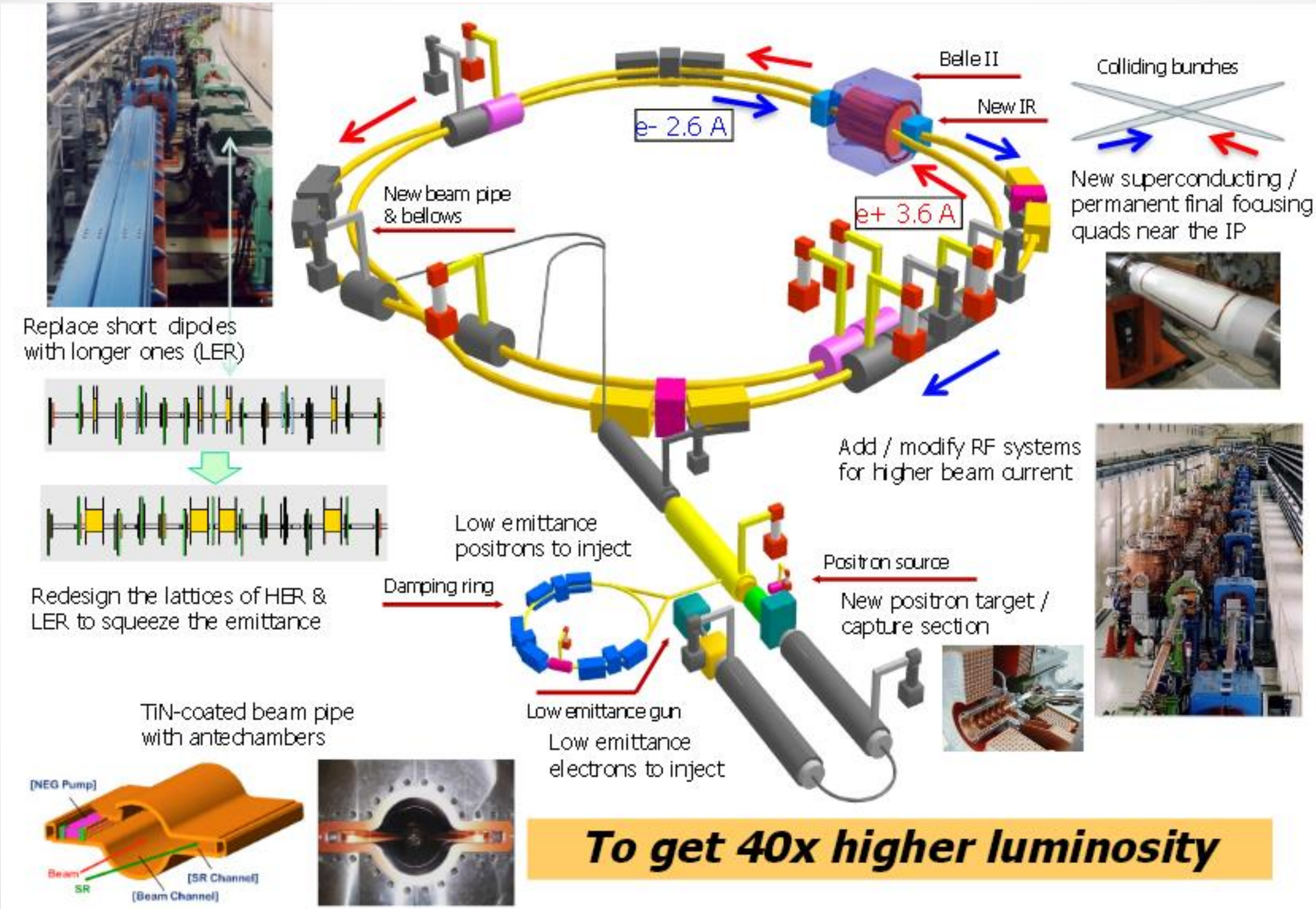
SuperKEKB



	KEKB	SuperKEKB
Beam Size @ IP	100μm(H) x 2μm (V)	10μm (H) x 59nm (V)
Crossing angle	22mrad	83mrad

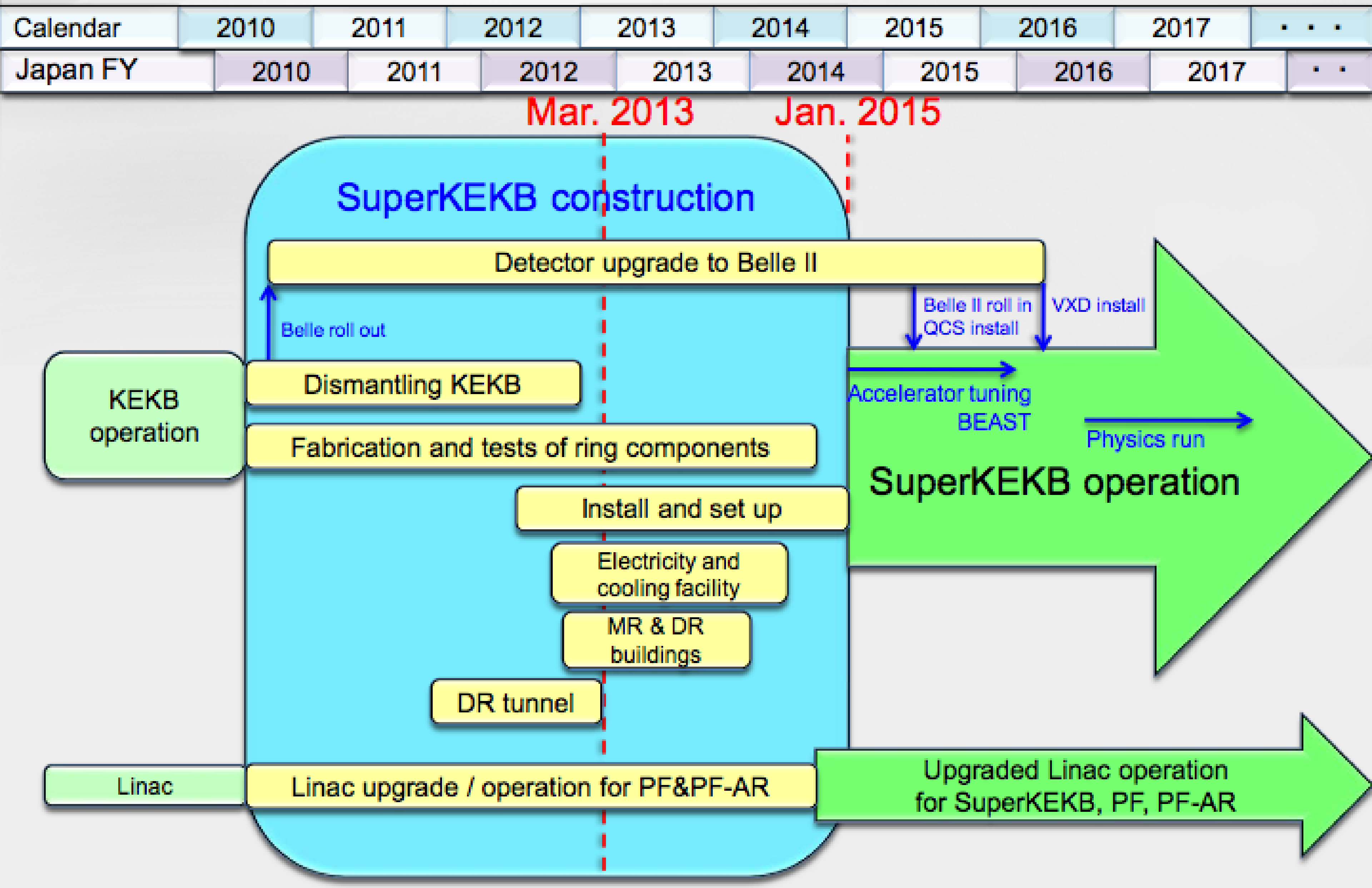
- Nano-Beam Scheme + a factor of 2 more beam current to increase luminosity
- Large crossing angle
- Change Beam energies to solve the probleam of short lift-time for the LER

SuperKEKB

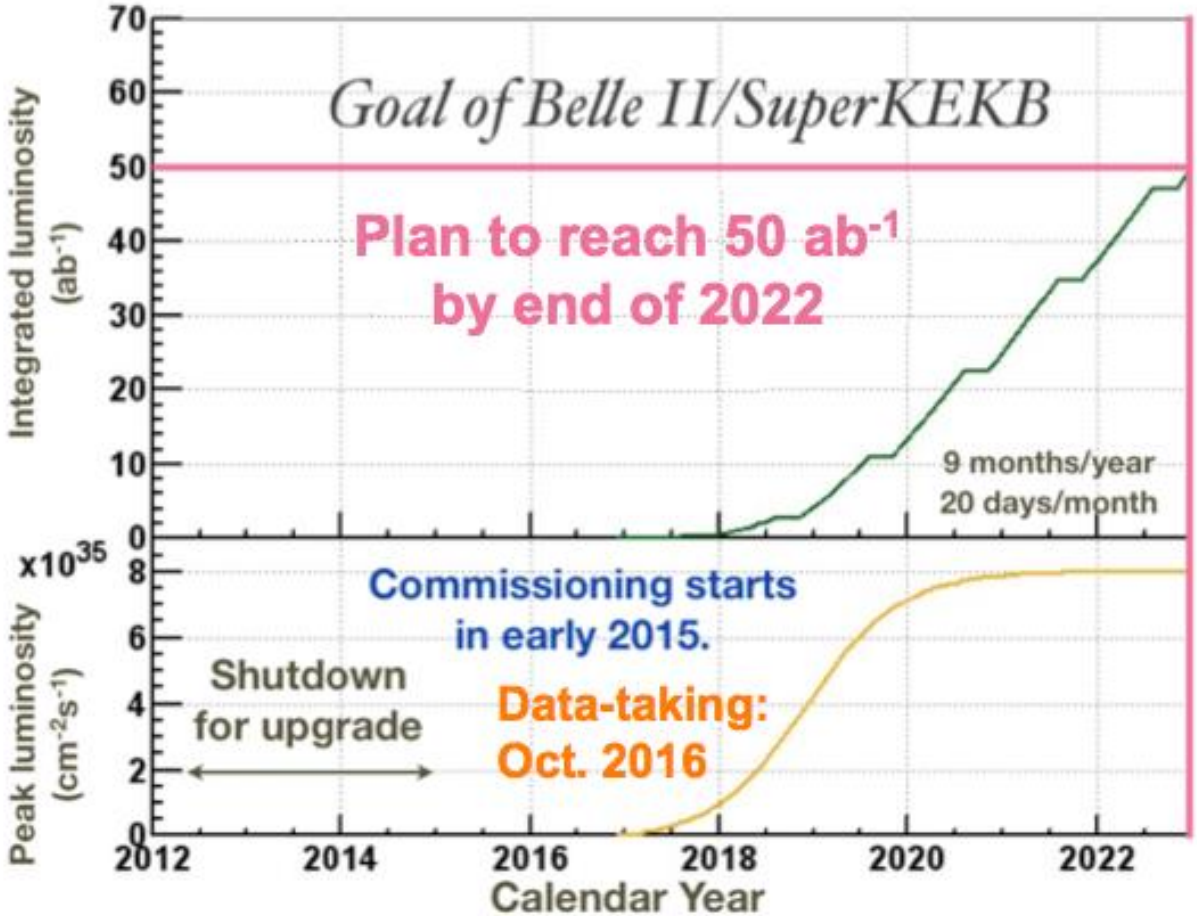


Belle II
Colliding bunches
New IR
e- 2.6 A
e+ 3.6 A
New beam pipe & bellows
New superconducting / permanent final focusing quads near the IP
Replace short dipoles with longer ones (LER)
Add / modify RF systems for higher beam current
Low emittance positrons to inject
Positron source
Damping ring
Redesign the lattices of HER & LER to squeeze the emittance
New positron target / capture section
Low emittance gun
Low emittance electrons to inject
TiN-coated beam pipe with antechambers
[NEG Pump]
Beam
SR
[SR Channel]
[Beam Channel]
To get 40x higher luminosity

SuperKEKB/Belle II schedule



Timeline & goal



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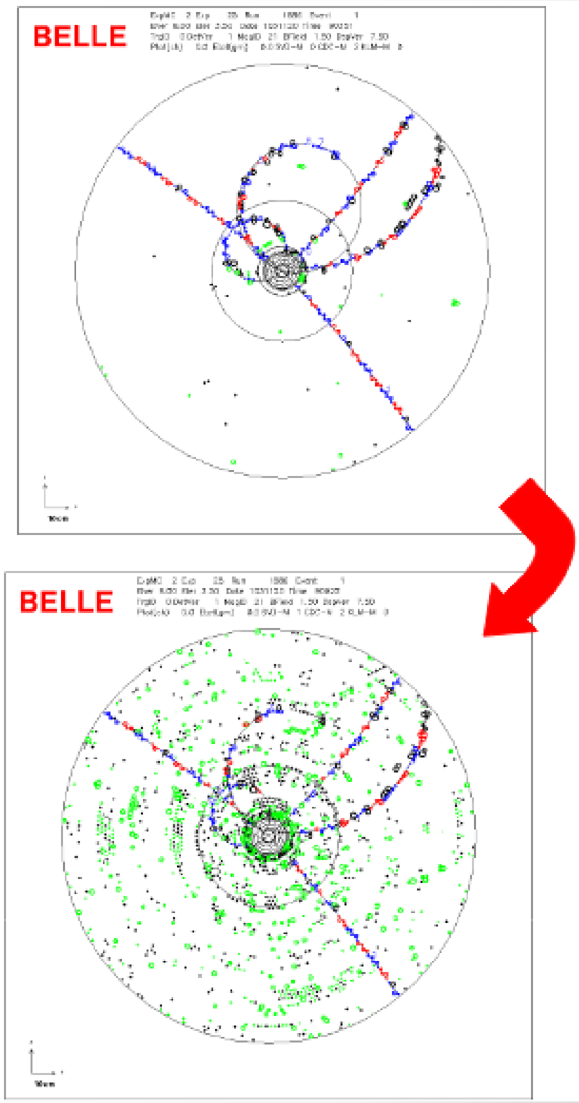
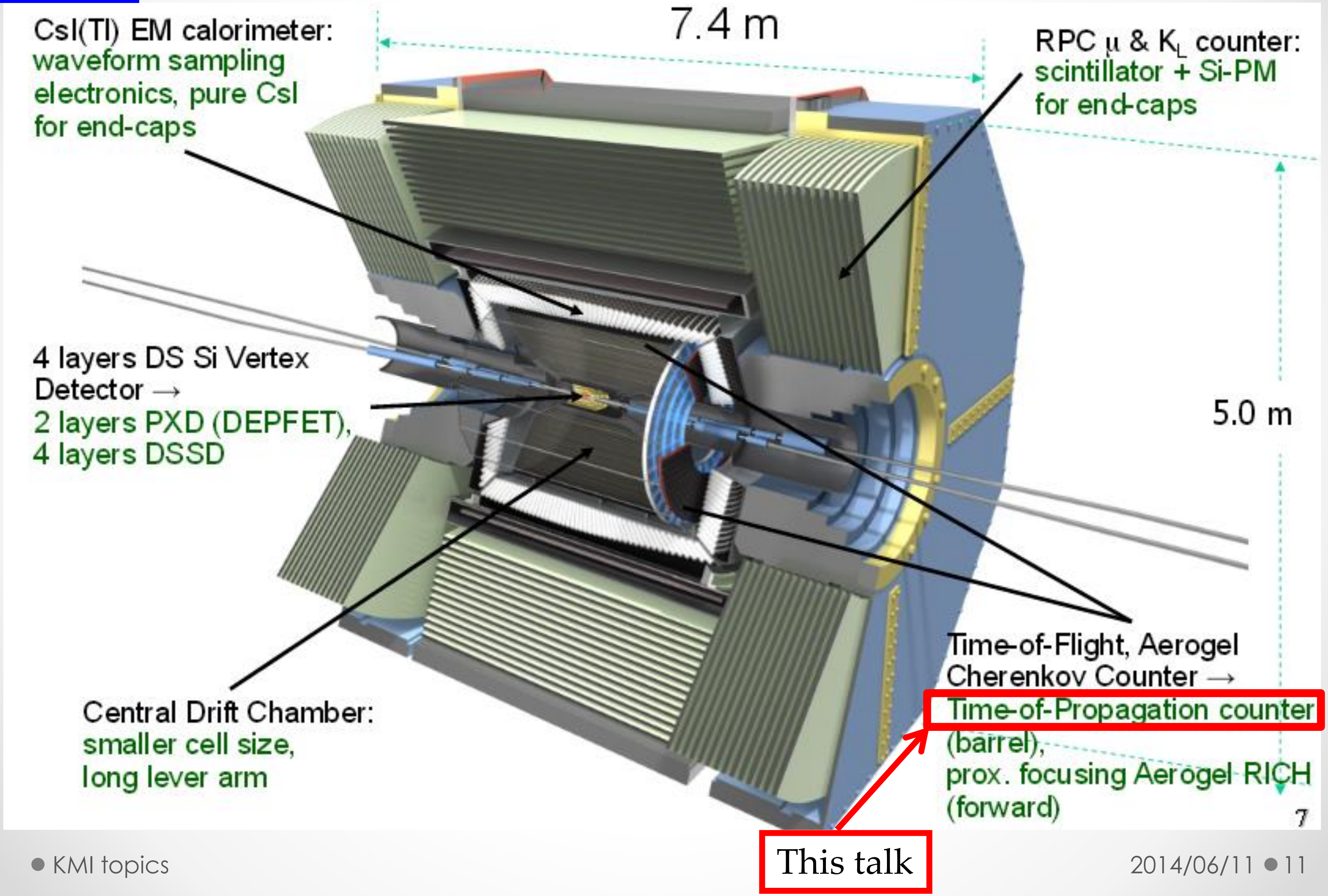
Detector upgrade

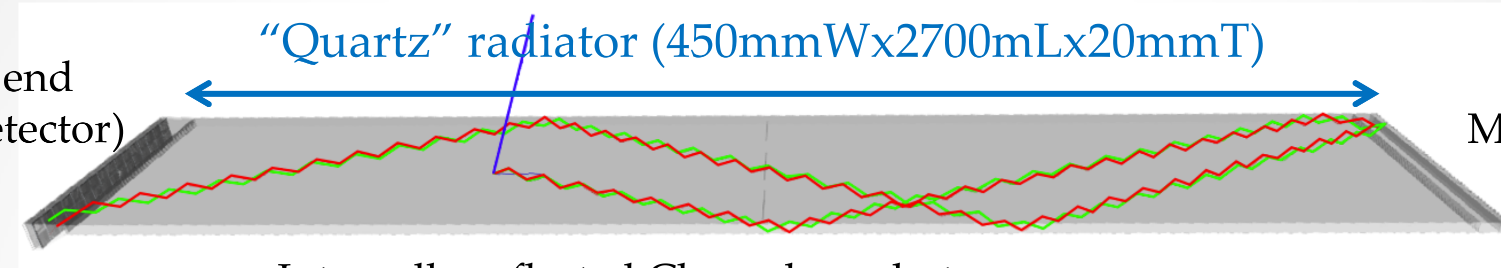
- Higher background (x20)
  - Radiation damage, occupancy
  - Fake hits and pile-up noise
- Higher event rate (x10)
  - Level1 trigger rate: 20kHz
  - High performace DAQ
- Important improvements
  - Hermiticity for full reconstruction analyses
  - IP and secondary vertex resolution
  - Ks and π^0 identification effciency
  - Improve K/π separation
- Detector components (arXiv:1011.0352)
  - SVD: 4DSSD lyrs ➔ 2 DEPFET+4 DSSS lryrs
  - CDC: small cell, long lever arm
  - ACC+TOF: TOP + Aerogel RICH
  - ECL: waveform sampling
  - KLM: RPC ➔ Scintillator + SiPM (endcaps)



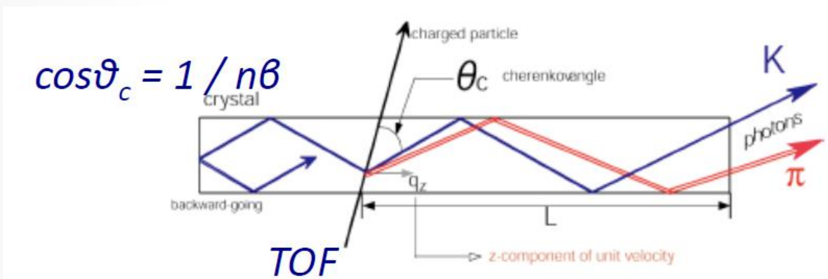
Belle II Detector

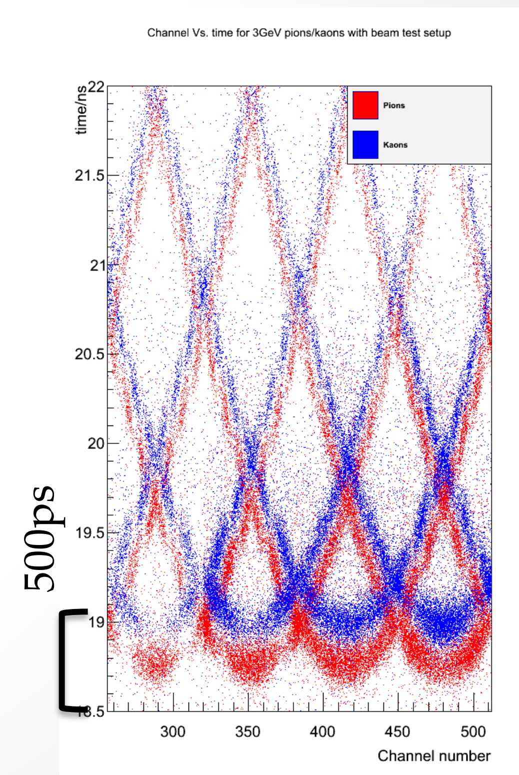


TOP counter



Internally reflected Cherenkov photons
Bounce off ≥ 100 times at thelarge faces.



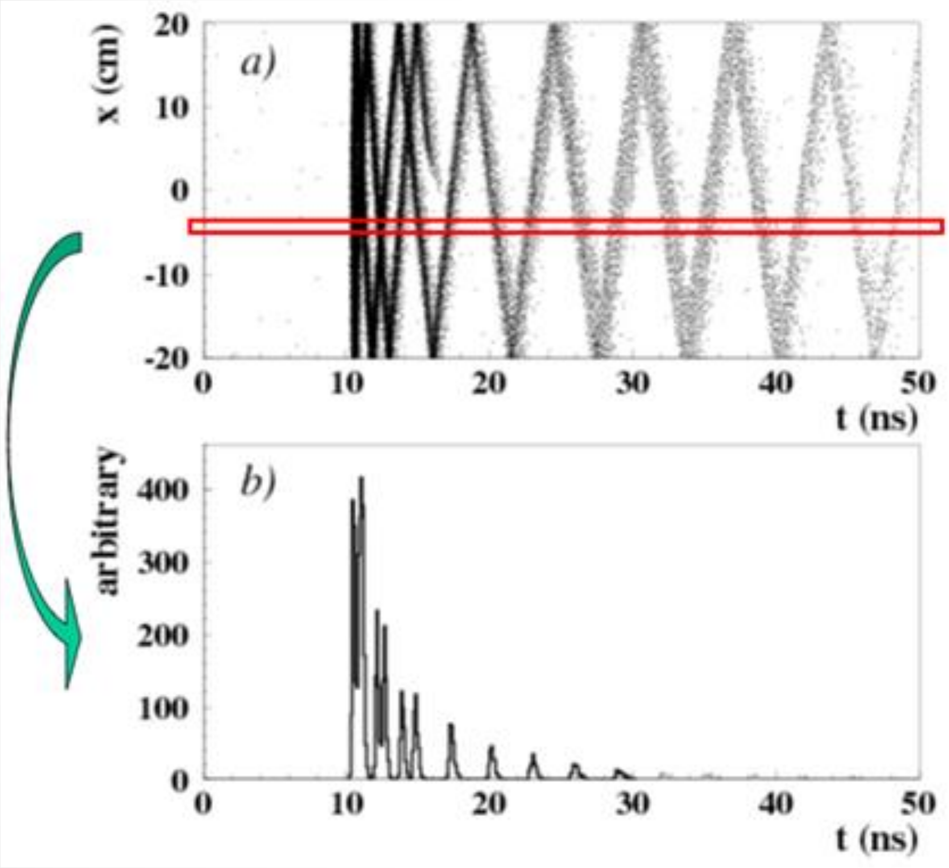


- Separation power (S)

$$S = \frac{\Delta TOF + \Delta TOP}{\sigma_{TOP}} \sqrt{N_{det}} \qquad \sigma_{TOP} = \sqrt{\sigma_{PD}^2 + \sigma_{opt}^2}$$

- Ndet: Number of photons detected (~20)
- σ_{PD}: time resolution (photo-detector + elec.) (~50ps)
- σ_{opt}: chromatic dispersion (>~50ps)

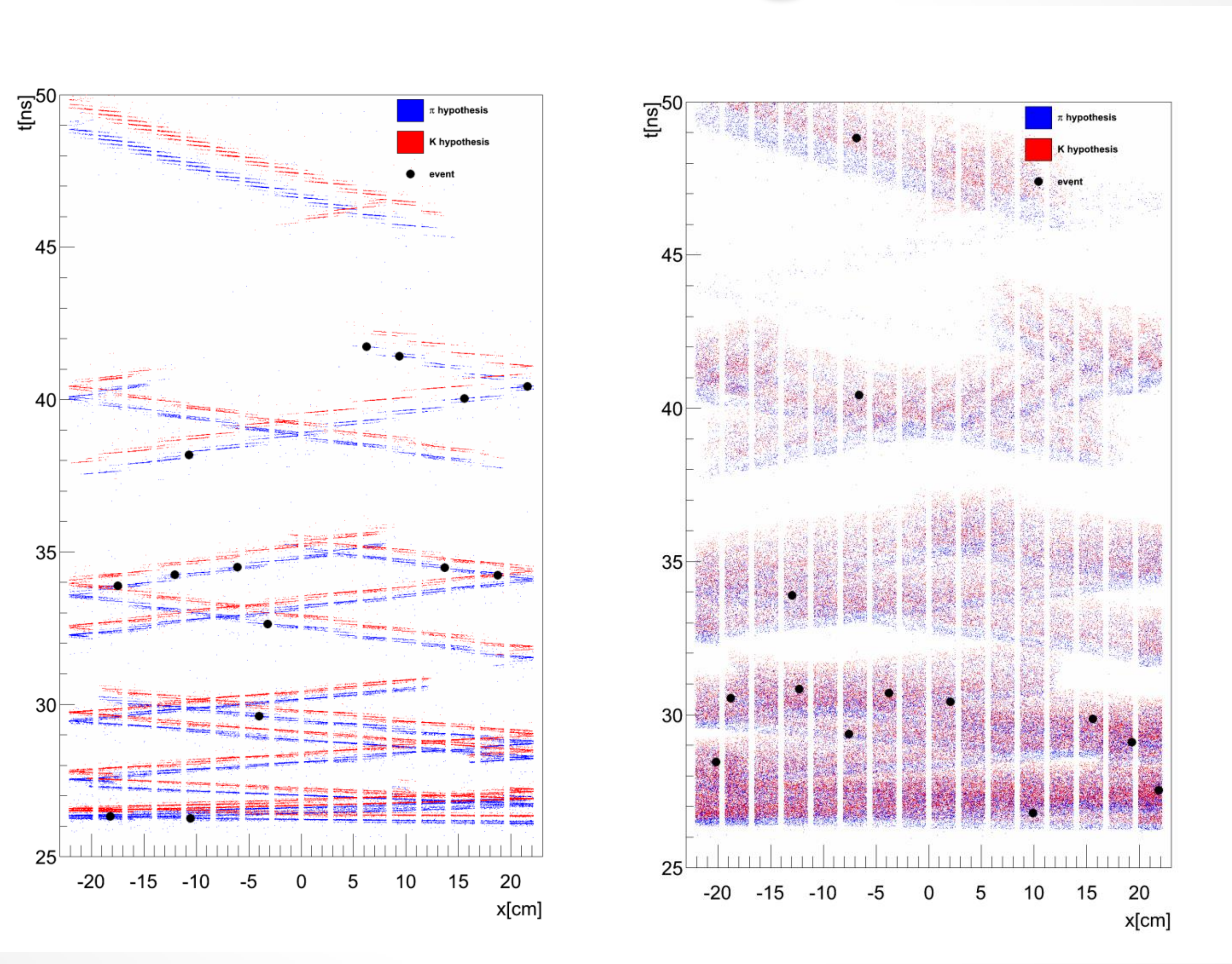
“Ring” image (1)



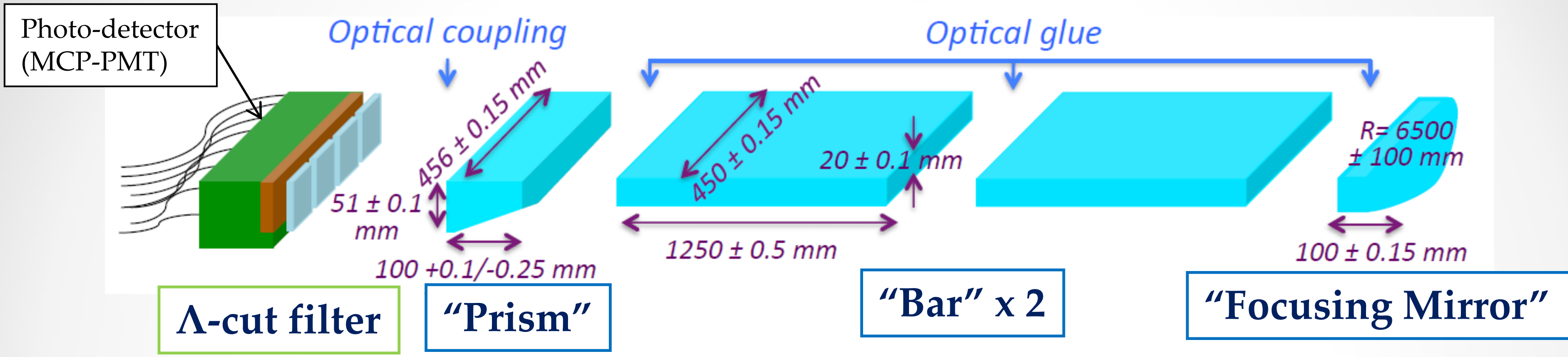
- Pattern in the coordinate-time space (‘ring’) of a pion hitting a quartz bar.

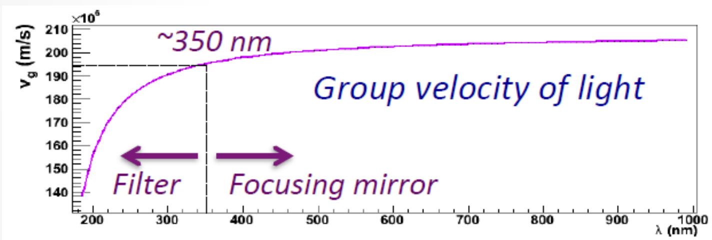
- Time distribution of singals recorded by one of the PMT channels:
  ➔ Different for π and K (~shifted in time)

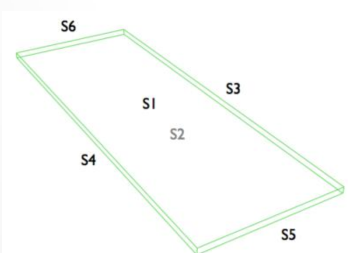
"Ring" image (2)


t[ns]
50
45
40
35
30
25
-20
-15
-10
-5
0
5
10
15
20
x[cm]
π hypothesis
K hypothesis
event

Optical components







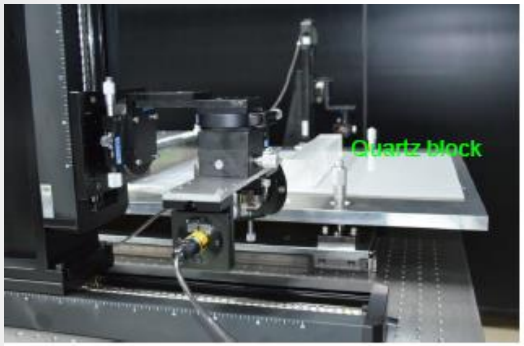
Tolerance	Specification	Comments
S1 ⏥ (Datum A)	≤6.3 μm	Equal to 10 waves over full aperture of surface
S2 ⏥	≤6.3 μm	Equal to 10 waves over full aperture of surface
S3 ⏥ (Datum B)	≤6.3 μm	Equal to 10 waves over full aperture of surface
S4 ⏥	≤6.3 μm	Equal to 10 waves over full aperture of surface
S5 ⏥ (Datum C)	≤25 μm	Equal to 40 waves over full aperture of surface
S6 ⏥	≤25 μm	Equal to 40 waves over full aperture of surface
S1 // S2	≤4 arcsec	4 arcsec = 24 micron runout over 1.25 m
S1 ⊥ S3	≤20 arcsec	20 arcsec = 2 micron runout over 20 mm
S1 ⊥ S4	≤20 arcsec	20 arcsec = 2 micron runout over 20 mm
S1 ⊥ S5	≤1 arcmin	1 arcmin = 6 micron runout over 20 mm
S1 ⊥ S6	≤1 arcmin	1 arcmin = 6 micron runout over 20 mm
S3 // S4	≤60 μm	60 microns = 10 arcsec over 1.25 m as projected on datum A; note that an angular specification would over-constrain perpendicularity relative to S1
S3 ⊥ S5	≤20 arcsec	20 arcsec = 44 micron runout over 0.450 m; note that this tolerance is comparable to the flatness of the surface S5
S3 ⊥ S6	≤20 arcsec	20 arcsec = 44 micron runout over 0.450 m; note that this tolerance is comparable to the flatness of the surface S6
S5 // S6	≤20 arcsec	20 arcsec = 44 micron runout over 0.450 m

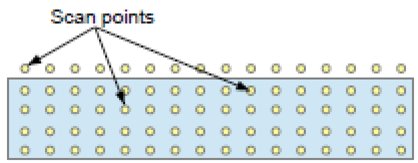
- Very tight requirements on material quality and dimensional tolerances.
- Quality Control & Precise Assembly (to be established)

QA: quartz bar (1)

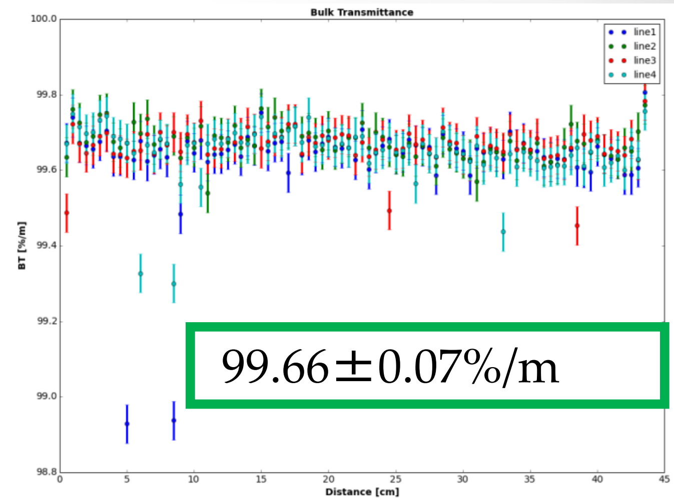
- Automatic scan system (Laser + PD)

Bulk transmittance (spec. >98.5%/m)



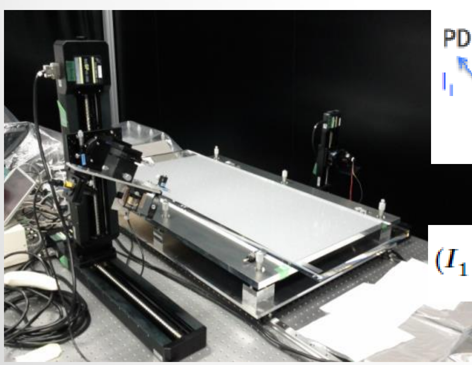


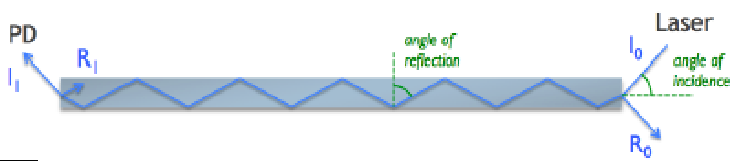
$$I_0(1-R_0)\tau(1-R_1)=I_1$$



99.66±0.07%/m

Internal reflectance (spec. >99.90%)





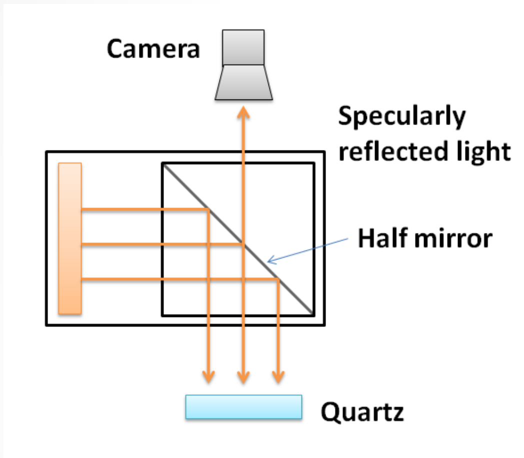
$$(I_1 - R_1) = (I_0 - R_0)\cdot\alpha^N\cdot\exp\left(-\frac{L}{\Lambda}\cdot\sqrt{1+(Nh/L)^2}\right)$$

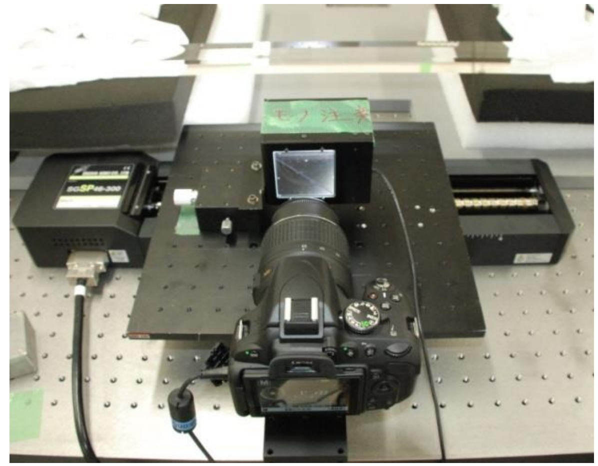
99.971±0.013%

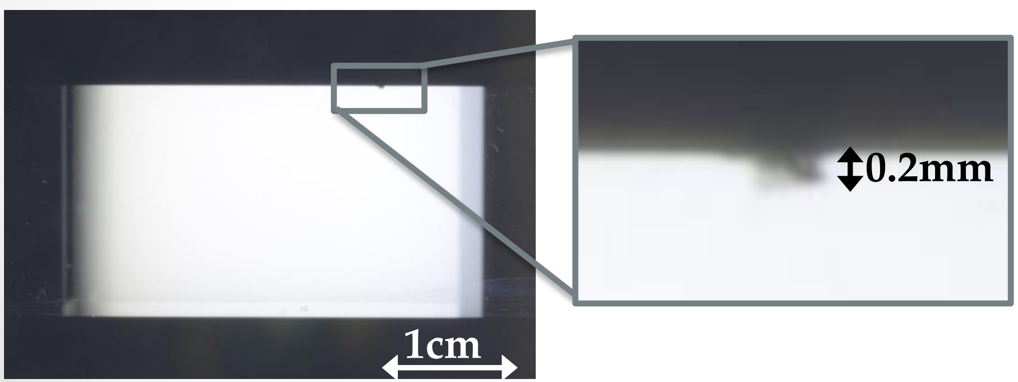
QA: quartz bar (2)

Chip/scratch inspection system

- To check for damage during transportation/handling



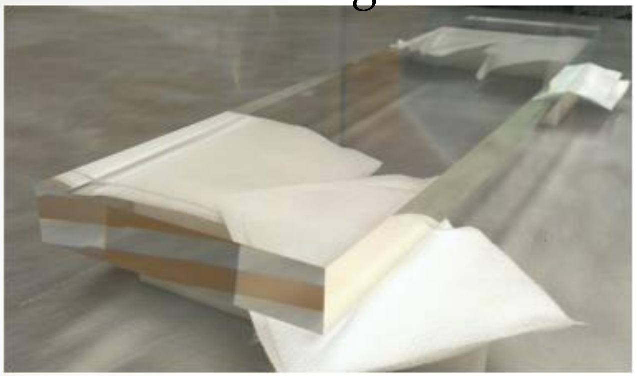


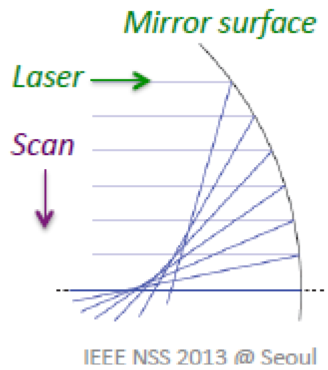


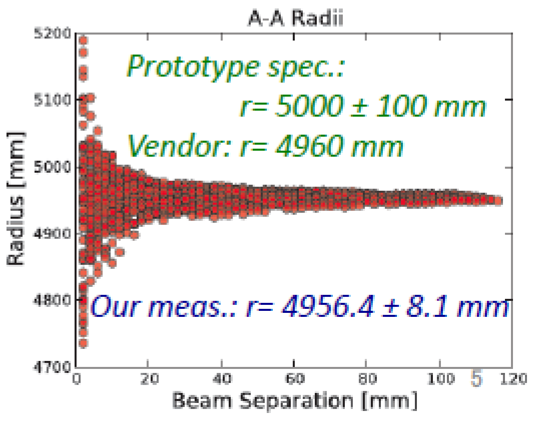
- Semi-automatic scan system
  - Coaxial episcopic illumination
  - High-contrast chip images
  - Chip size analyzed with OpenCV-based softwares

QA: prism / mirror

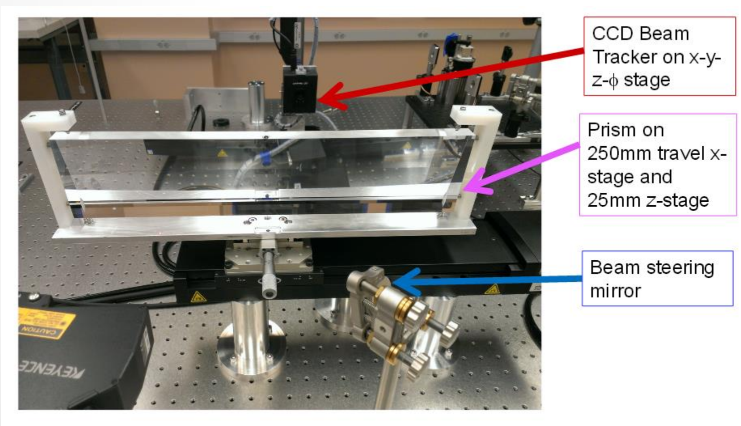
- Mirror focal length

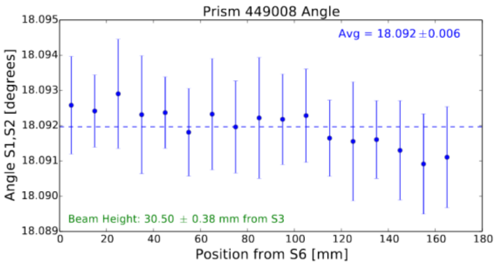


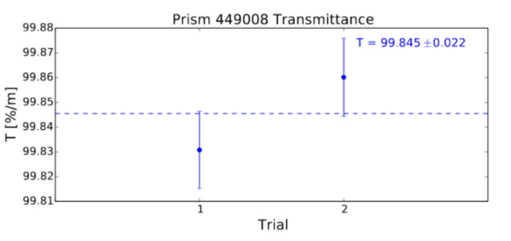




- Prism shape / bulk transmittance

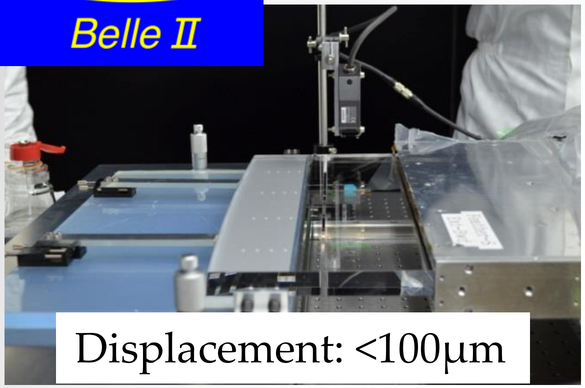


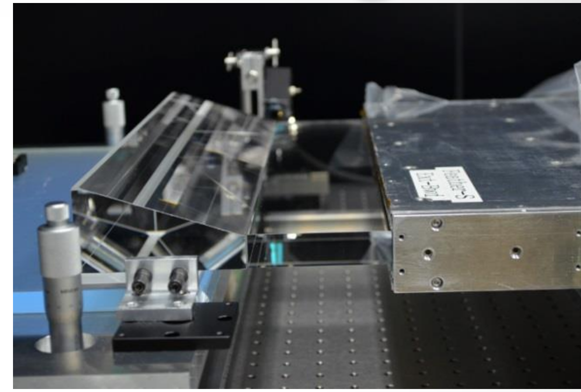




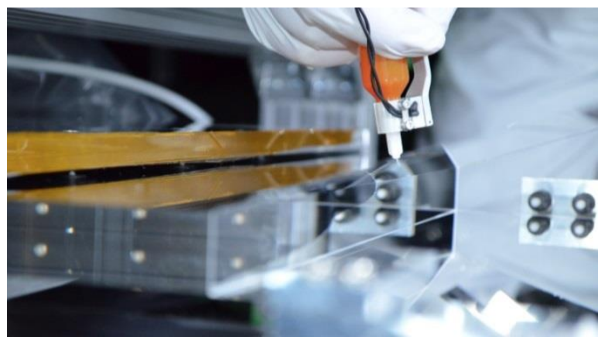
- Acceptance test system @ UC: working well

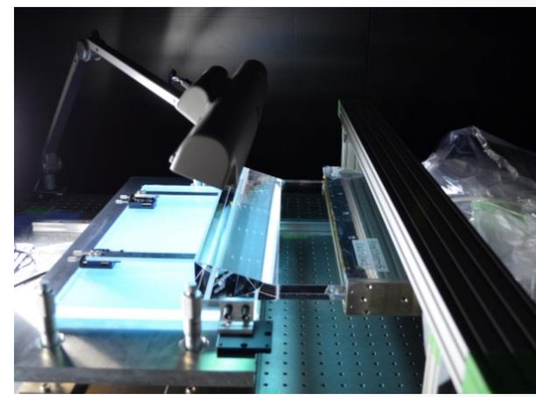
Quartz assembly (Gluing)



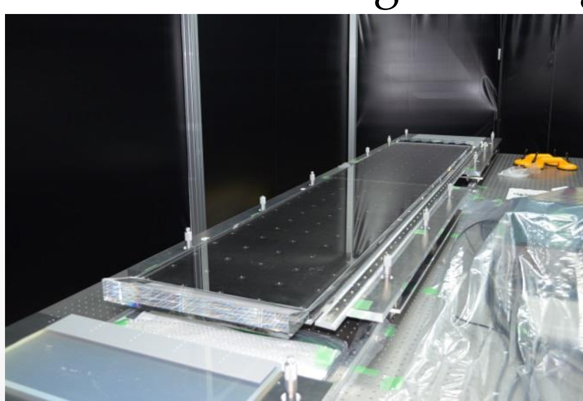


(1) Alignment (using the laser displacement sensor, autocollimator)





(2) Put glue on the surfaces & UV Light Curing



Gluing succeeded
under clean-room conditions
(class 100-1000)

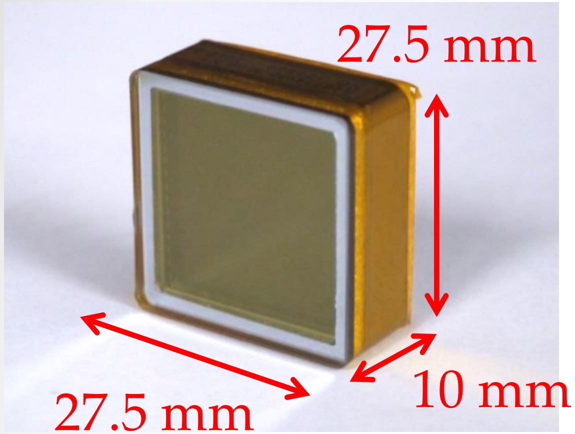
Quartz procurement

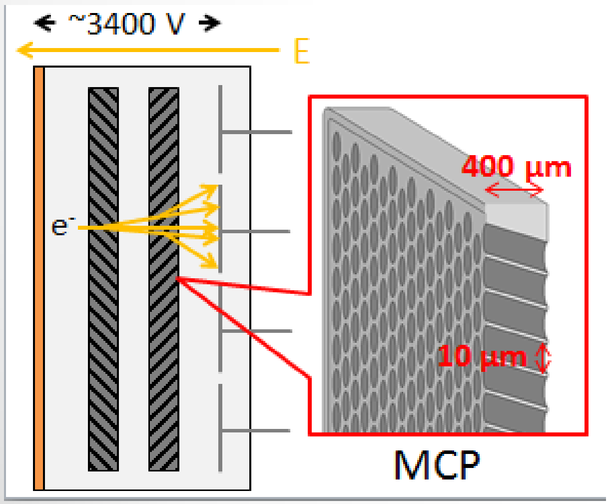
- 16 + 2(spare) sets of the components to be produced
  - The first set has been delivered & tested
  - No problem on packing and transportation
  - 2 bars, 4 prims and 1 mirror pass acceptance tests.
  - ➔ All quartz optics for the first TOP module: Ready for assembly

	Bar 1	Bar 2	Prism	Mirror
Delivered	2	1	4	4
Tested	1	1	4	2

  - 4 bars will be delivered & tested in June.
  - ➔ 4 sets of quartz optics will be ready for assembly this summer.
- The delivery schedule has been significantly delayed.
  - Delayed 3-8 months.
  - Grinding process didn't go well…
- Module assembly procedure has been revised to catch up the original schedule.
  - Multi vendor production
  - Two TOP assembly lines

Photodetectors (MCP-PMT)





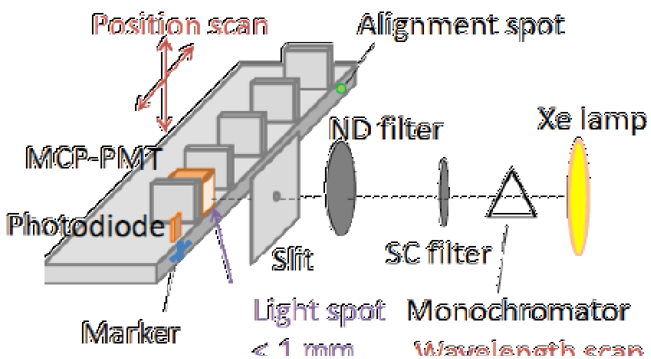
- MCP-PMT
  - Square-shape to minimize the dead space
  - High-gain for single photon detection
    - ➔ 2×10^6 at nominal HV
  - Fast time response
    - ➔ Transit Time Spread (TTS) <50ps
  - High quantum efficiency (QE)
    - ➔ QE > 24% (a.v. 28%) @ λ=380nm
  - Low dark noise rate
    - ➔ < 100kHz
  - Operative in 1.5 T

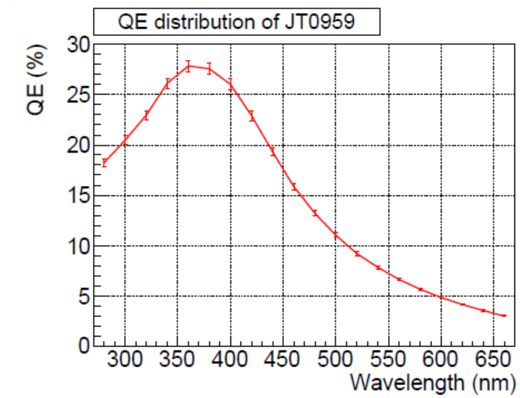
SL-10 specification	
Photo-cathode	NaKSbCs
Anode	4 x 4
Collection efficiency	50-55%
Nominal HV	~3.4kV

MCP-PMT measurement (1)

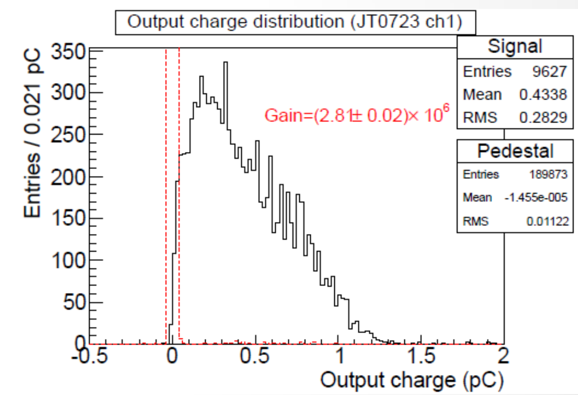
- Quantum efficiency (QE)
  - Photocathode currenet measurement

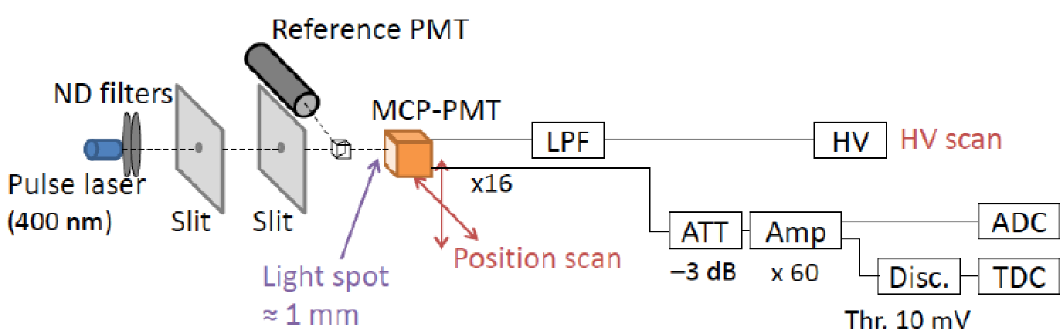
$$QE_{MCP} = I_{MCP} / I_{PD} \times QE_{PD}$$

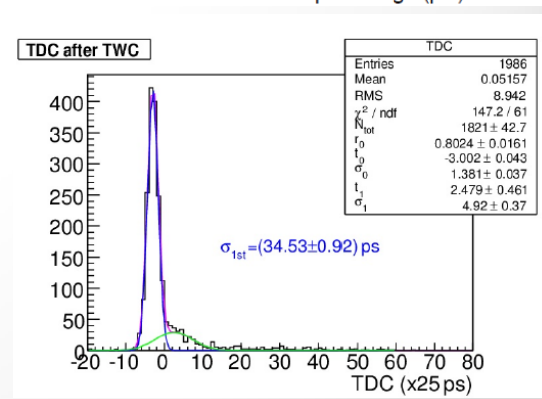




- Gain and Timie Transit Spread (TTS)
  - Single photon measurement





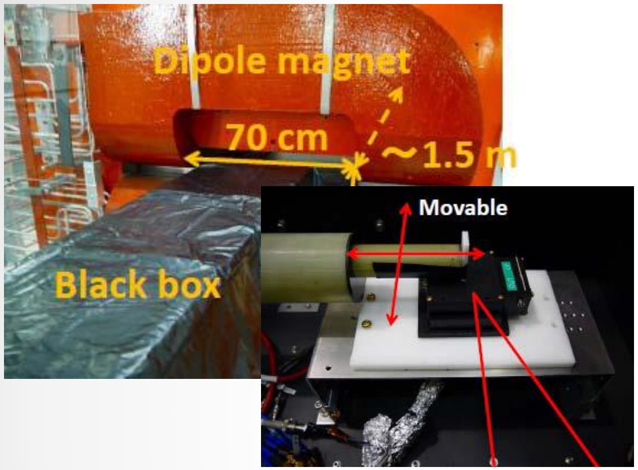


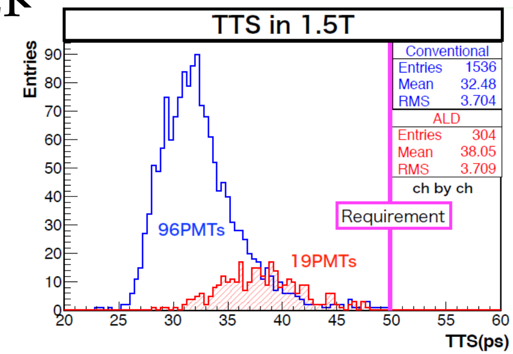
- KMI topics

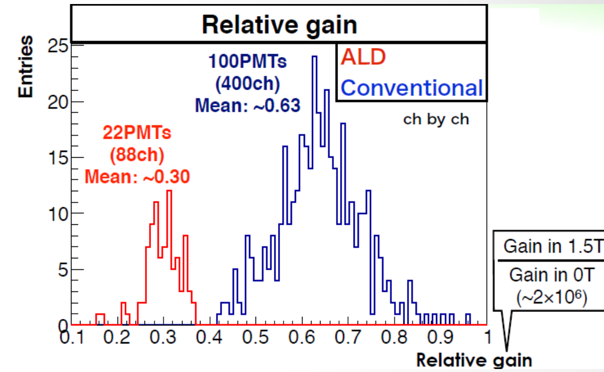
MCP-PMT measurement(2)

T. Yonekura, TIPP2014

➢ Test in magnetic field @ KEK

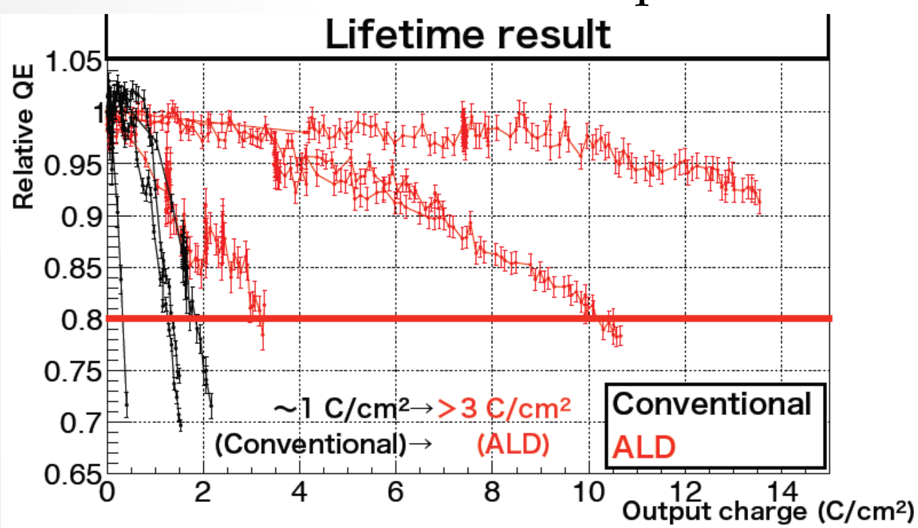






- TTS in 1.5T: ~40ps
- Gain in 1.5T: enough to detect single photon
- Measurement underway

➢ Photocathode lifetime improvement



- Lifetime depends on output charge
- Conventional PMT: ~0.5-2C/cm^2
- ALD-PMT: > 3C/cm^2

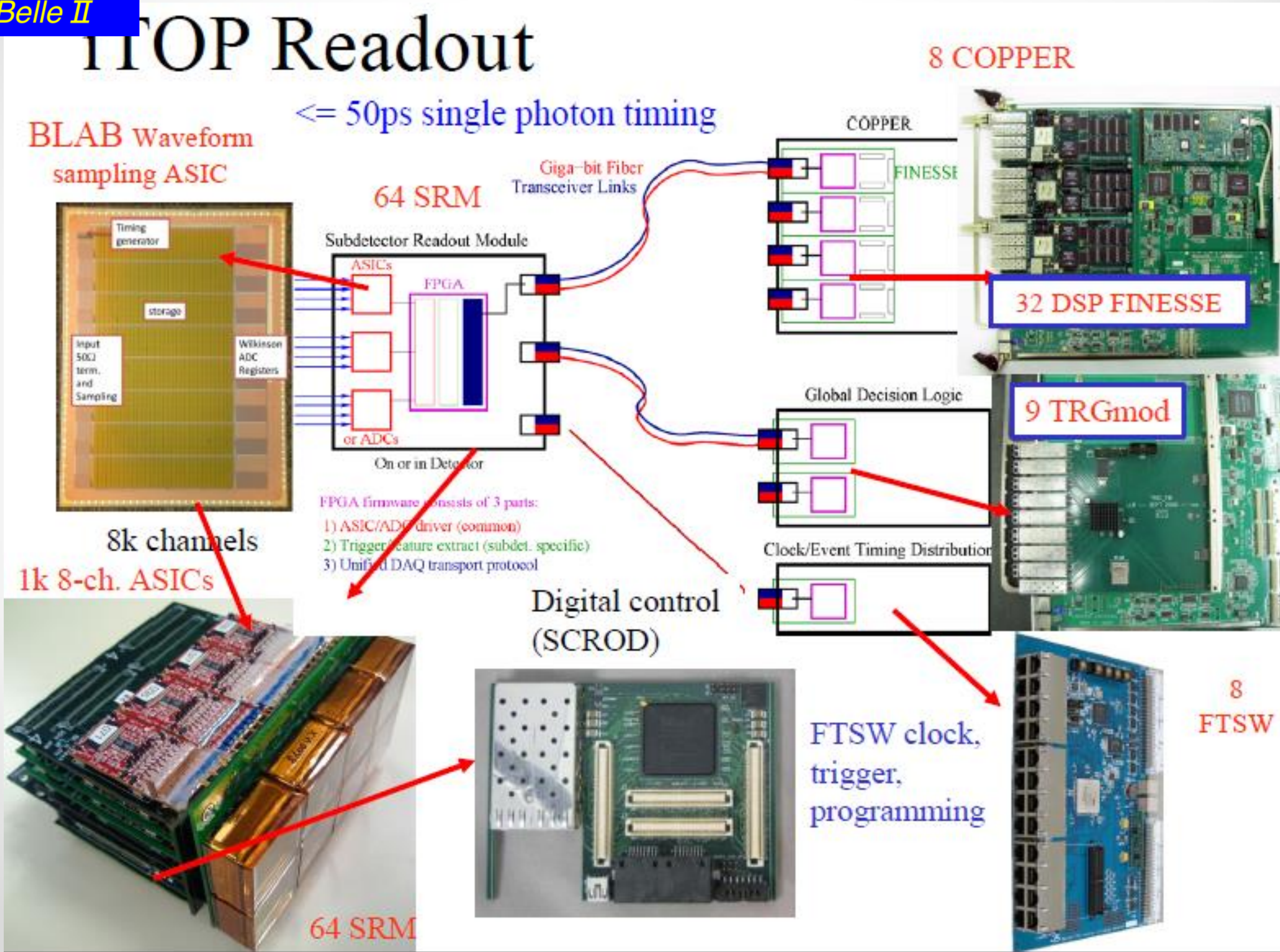
(c.f.) 2-4C/cm^2/50ab^{-1} at 5x10^5 gain

➔ The lifetime to be improved further

MCP-PMT mass production

- 32PMTs/ module ➔ 512PMTs / 16 TOP modules
- About 50% of the PMTs will be ALD-MCP-PMTs
- Conventinal MCP-PMTs will be used in half-gain operation
  - The lifetime is expected be ~2 C/cm2.
  - Still need PMT replacement procedure.
- PMT measurements / inspections are in progress.
  - QE measurement: 474
  - Gain, TTS measurement: 324 (ALD: 80)
  - Gain measurement in 1.5T: 122 (ALD: 22)
  - TTS measurement in 1.5T: 117 (ALD: 19)

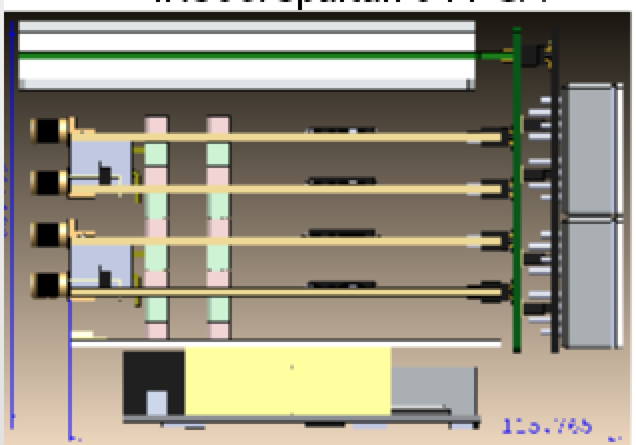
Front-end Electronics (1)



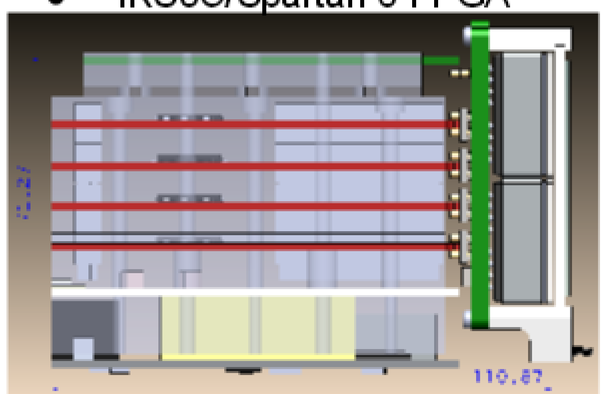
Front-end Electronics (2)

- High-speed waveform sampling ASICs ("IRS")
  - Developed by Univ. of Hawaii.
  - Targeting the timing jitter $\sigma < 50$ps
  - Hardware/firmware/Mechanics development
    - ➔ $\sigma \sim 60$ps with the intermediate board stack
    - ➔ Various calibrations and updates are necessary.

LEPs Beam Test Electronics:
- IRS3C/Spartan 6 FPGA

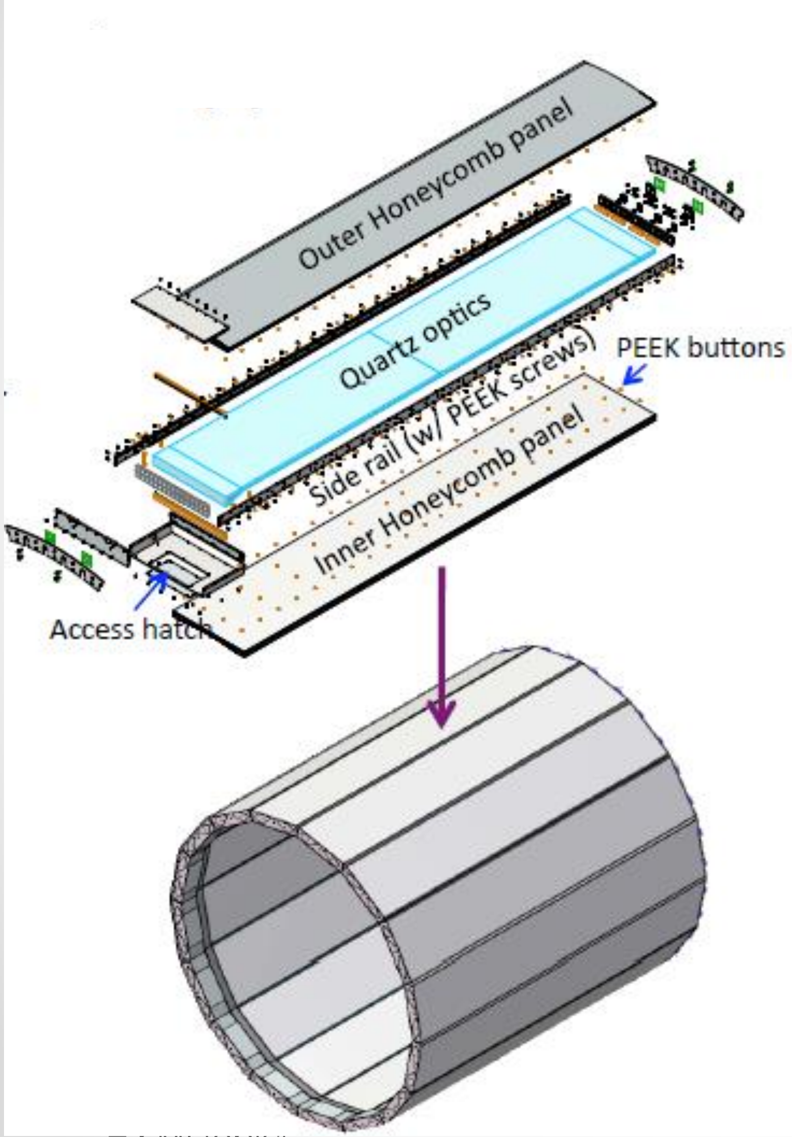


Intermediate:
- POGO pins
- IRS3C/Spartan 6 FPGA

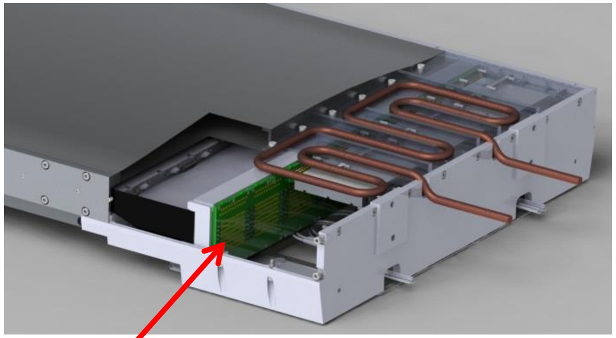


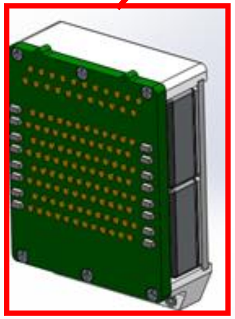
Final Electronics
- POGO pins
- IRSX/Zynq SOC

Mechanics – QBB-

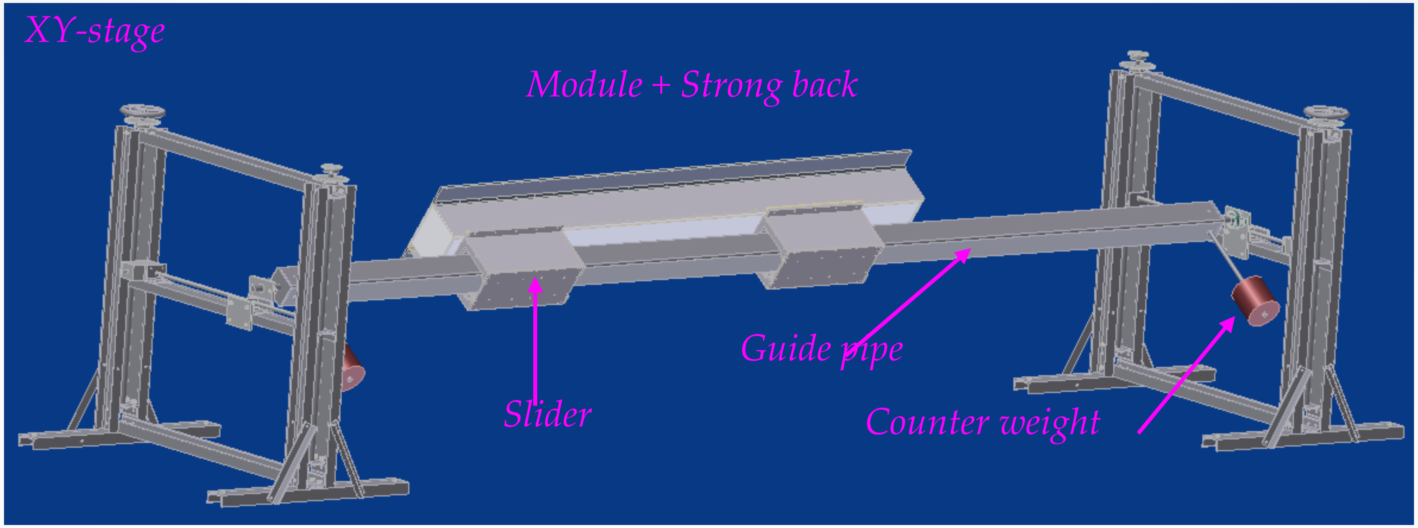


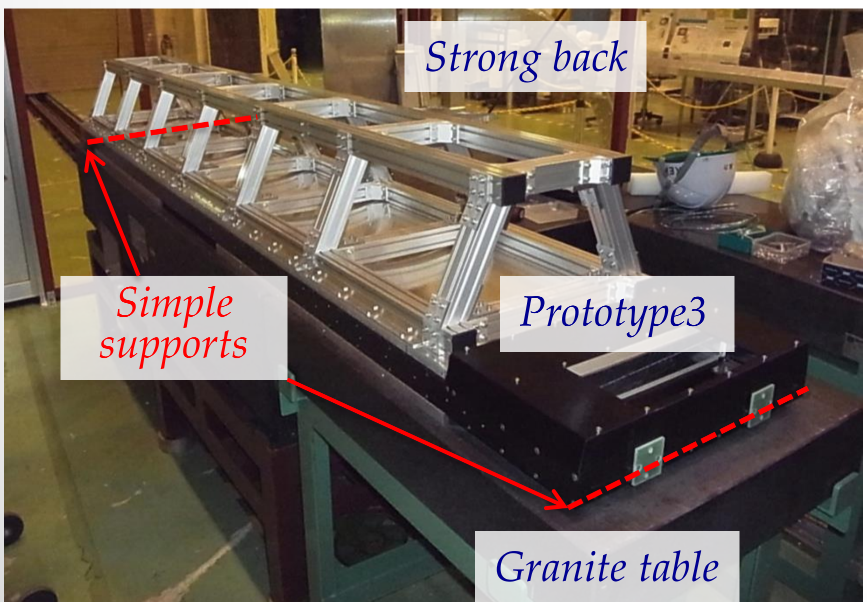
- Quaartz Bar Box (QBB)
- Module container
  - Aluminum Honeycomb panels
  - PEEK material to support the quartz optics
- Final prototyping / producting: on-going
  - Prism/front-end closure
  - Optical coupling
  - Gas sealing



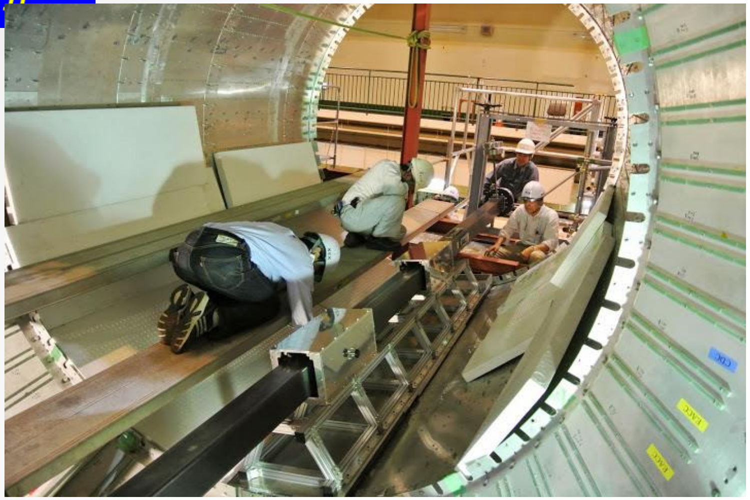


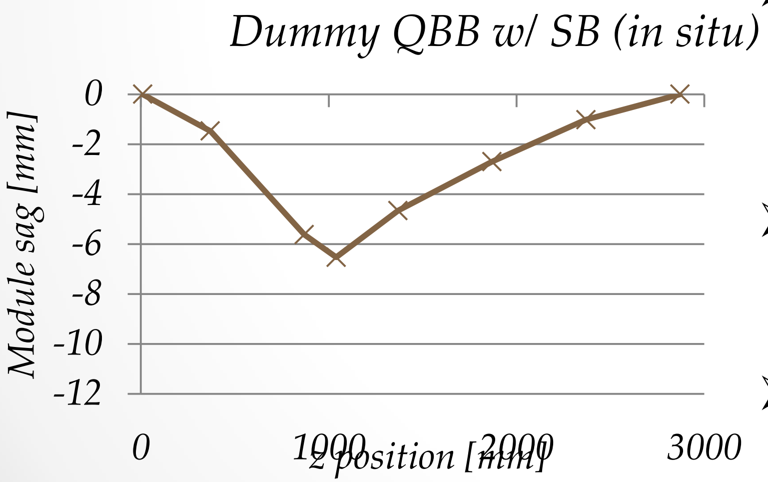
TOP installation jig





TOP installation test (in-situ)

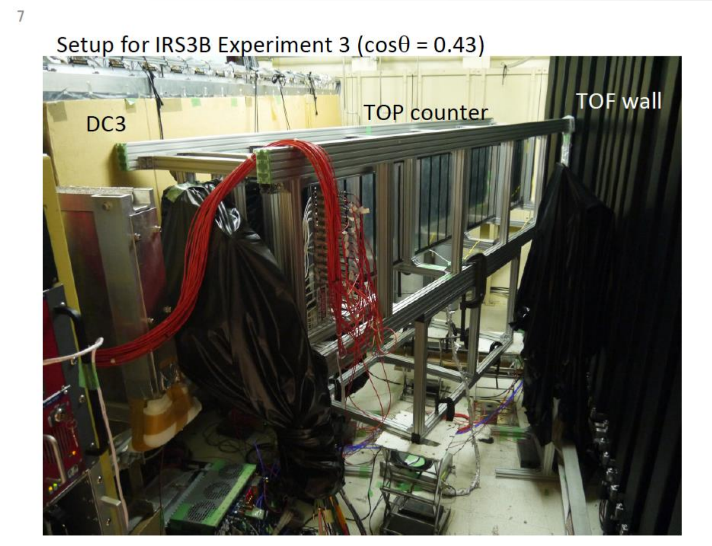


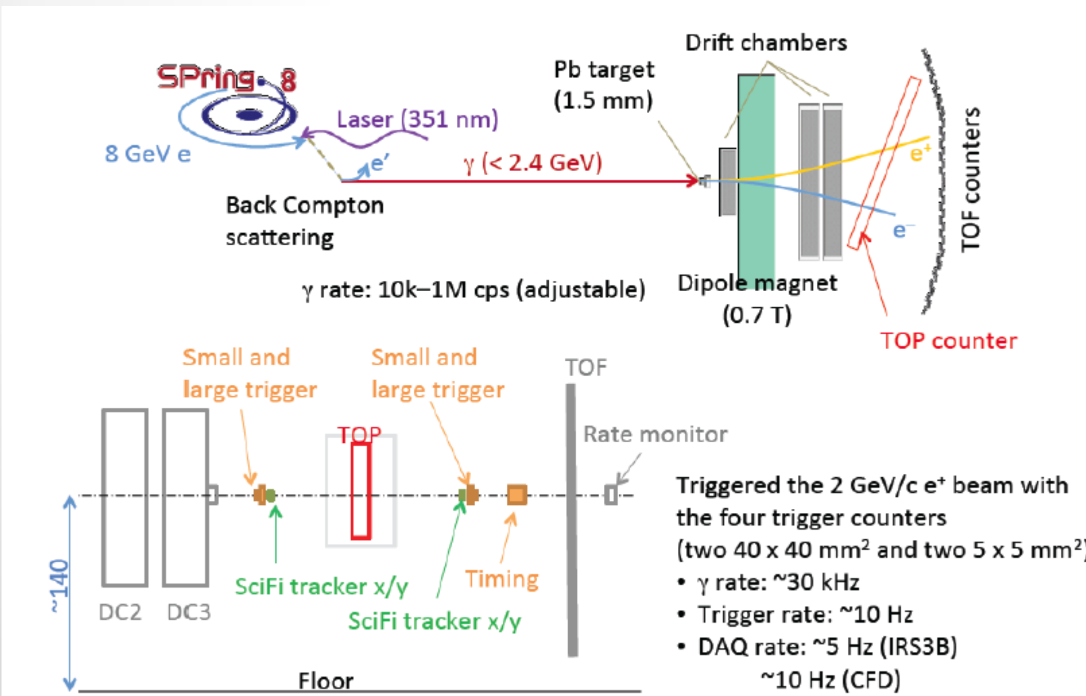


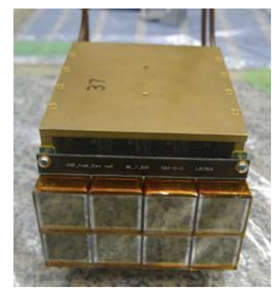
- Guide pipe deflection coupled to strong back and QBB because of rigid coupling of sliders on guide pipe during this test
- Design modified to provide clearance so angle of sliders is not transferred to QBB
- New SB ➔ Maximum deflection (simple support at ends) <0.8 mm
- Sliders also modified to minimize the sag.

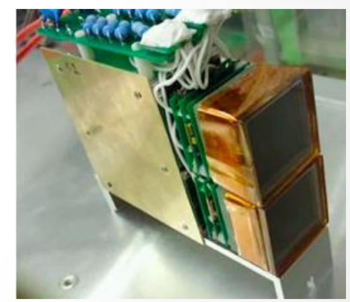
Beam Test @ SPring-8/LEPS (1)

- Performace studies using 2GeV/c e+
- Full-scale prototype
  - almost the final optics
  - 32PMTs for full photo-coverrage
  - Two types of front-end electronics
    - IRS3 (baseline)
    - (conventional) “CFD” modules



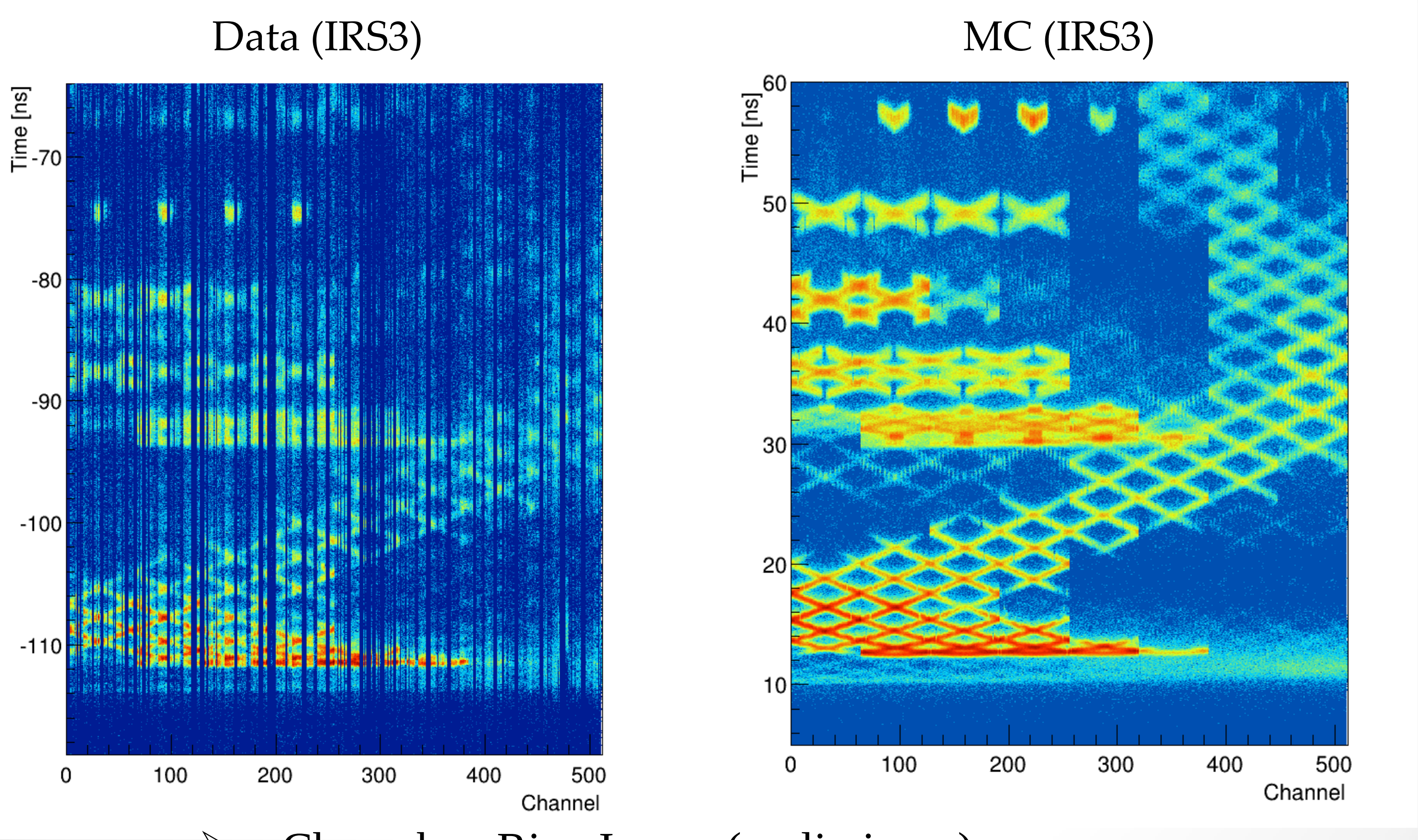






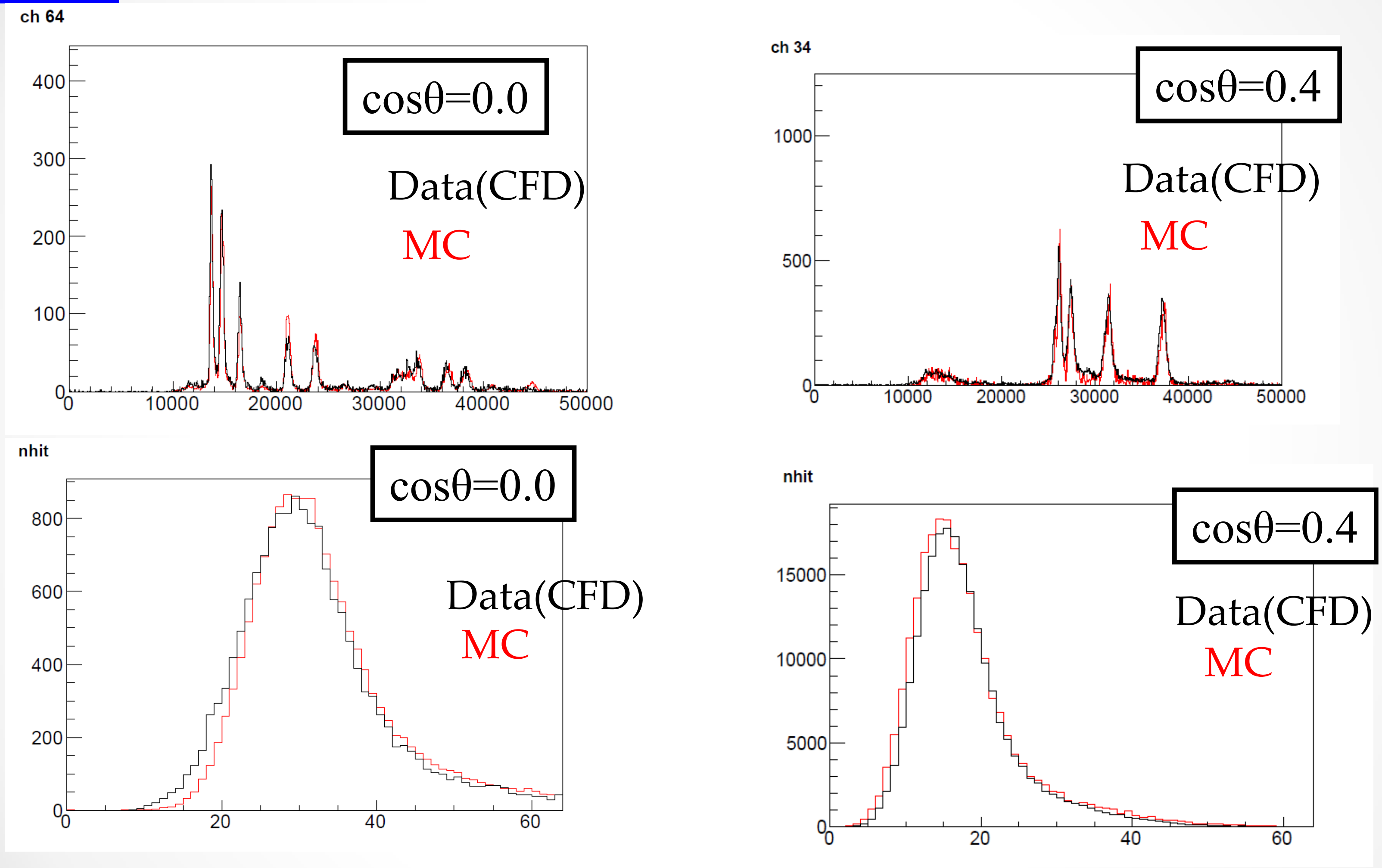
- “IRS3B”: Based on a waveform-sampling ASIC 4×10^9 samples /sec.
- “CFD”: Based on constant fraction discriminator MCP-PMT 16 channels are merged into 4 at the MCP-PMT socket (σ ~ 50psec.)

Beam Test @ SPring-8/LEPS (2)



- ➢ Cherenkov Ring Image (preliminary)
- Beam conditions: cosθ = 0, x = 0
- Time resolution: 156ps (Time jitter (IRS3B) ~ 100ps)

Beam Test @ SPring-8/LEPS (3)



- Data taken with CFD modules
- Time resolution: 110-120ps
- Good agreement between data and MC

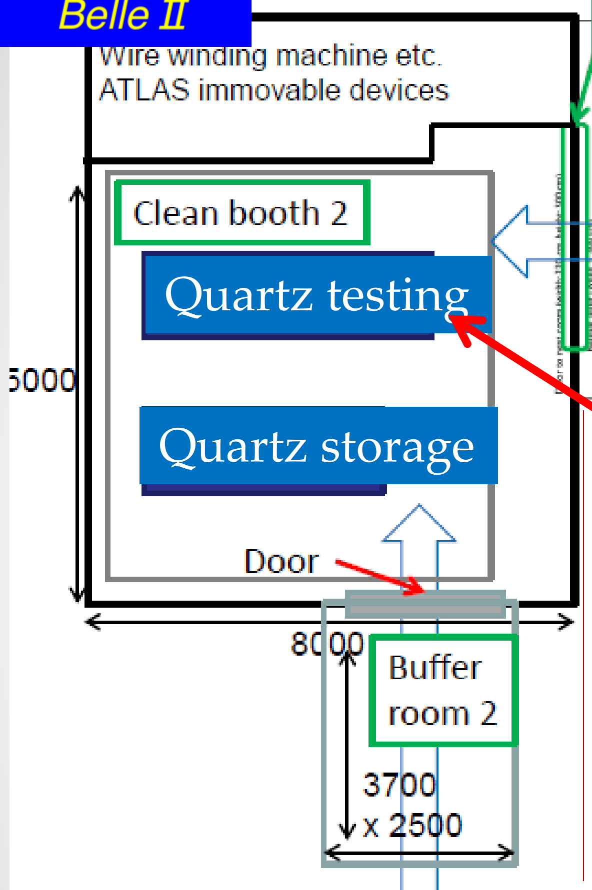
Physics Performance

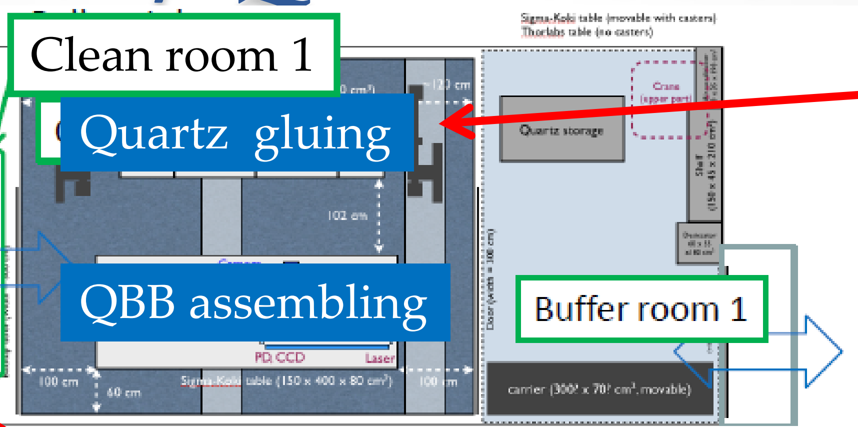
Decay mode	π efficiency with 2% K fakes π rate 100ps electronics jitter	π efficiency with 4% K fakes π rate 100ps electronics jitter	π efficiency with 4% K fakes π rate 50ps electronics jitter
$B \to \pi\eta\gamma$ vs $K\eta\gamma$	84.28 +/- 0.91	94.13 +/- 0.57	93.22 +/- 0.52
$B^+ \to \rho\gamma$ vs $K^*\gamma$	80.71+/-1.07	93.19+/-0.67	92.55 +/- 0.62
$B^0 \to \rho\gamma$ vs $K^*\gamma$	81.50+/- 0.78	92.63+/-0.49	92.13 +/- 0.46
$B^+ \to \pi\pi\pi^0\gamma$ vs $K\pi\pi^0\gamma$	83.55+/-0.76	94.03+/-0.46	93.47 +/- 0.43
$B^0 \to \pi\pi\gamma$ vs $K\pi\gamma$	79.50 +/- 0.67	91.48+/-0.45	92.56 +/- 0.38
$B^+ \to \pi\pi\pi\pi^0\gamma$ vs $K\pi\pi\pi^0\gamma$	75.00+/-0.72	90.50 +/-0.44	91.01 +/- 0.38
$B^0 \to \pi\pi\pi\gamma$ vs $K\pi\pi\gamma$	76.33+/-0.37	90.00+/-0.33	92.20 +/- 0.31

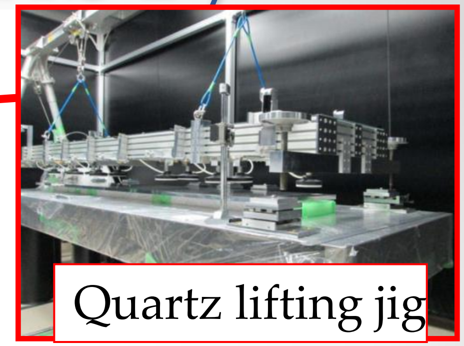
- TOP Beam Test performance implemented in BASF2 for Belle II Physics Studies

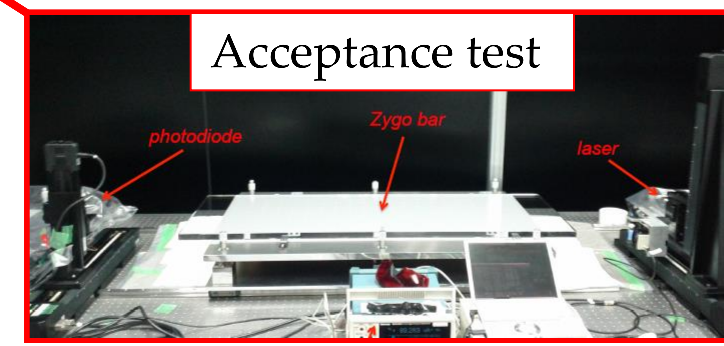
➔ Negligible improvement from electronic resolution 100ps ➔ 50ps
(Beam test performance adequate to do 1-2% measurement of $|V_{td}|/|V_{ts}|$)

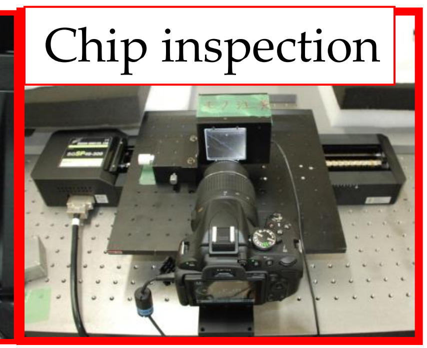
Quartz/QBB assembly







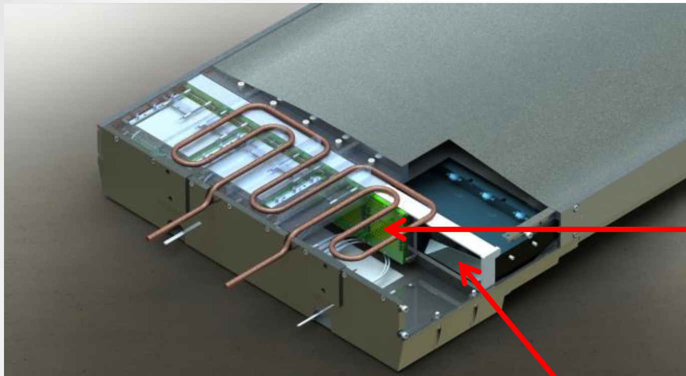


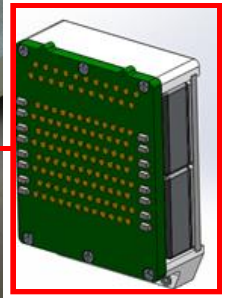


- Belle II TOP fabrication line constructed @ KEK-Fuji
  - Class 100-1,000 large cleanrooms
  - Quartz testing / handling / assembly procedures: well established
  - Quartz Bar Box assembly under preparation

PMT module assembly

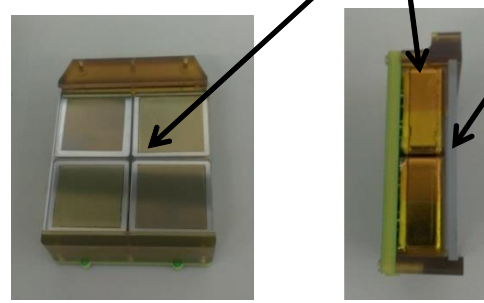
- PMT module



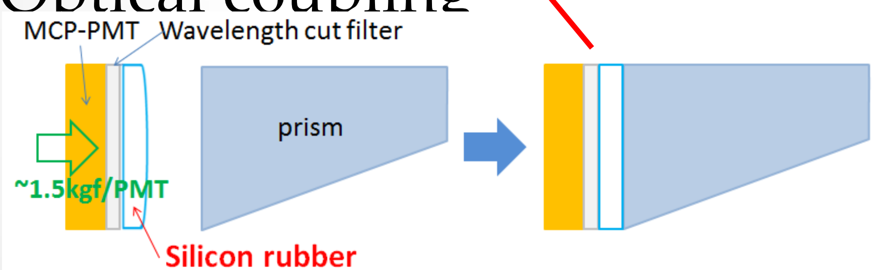


4 MCP-PMTs

λ-cut filter



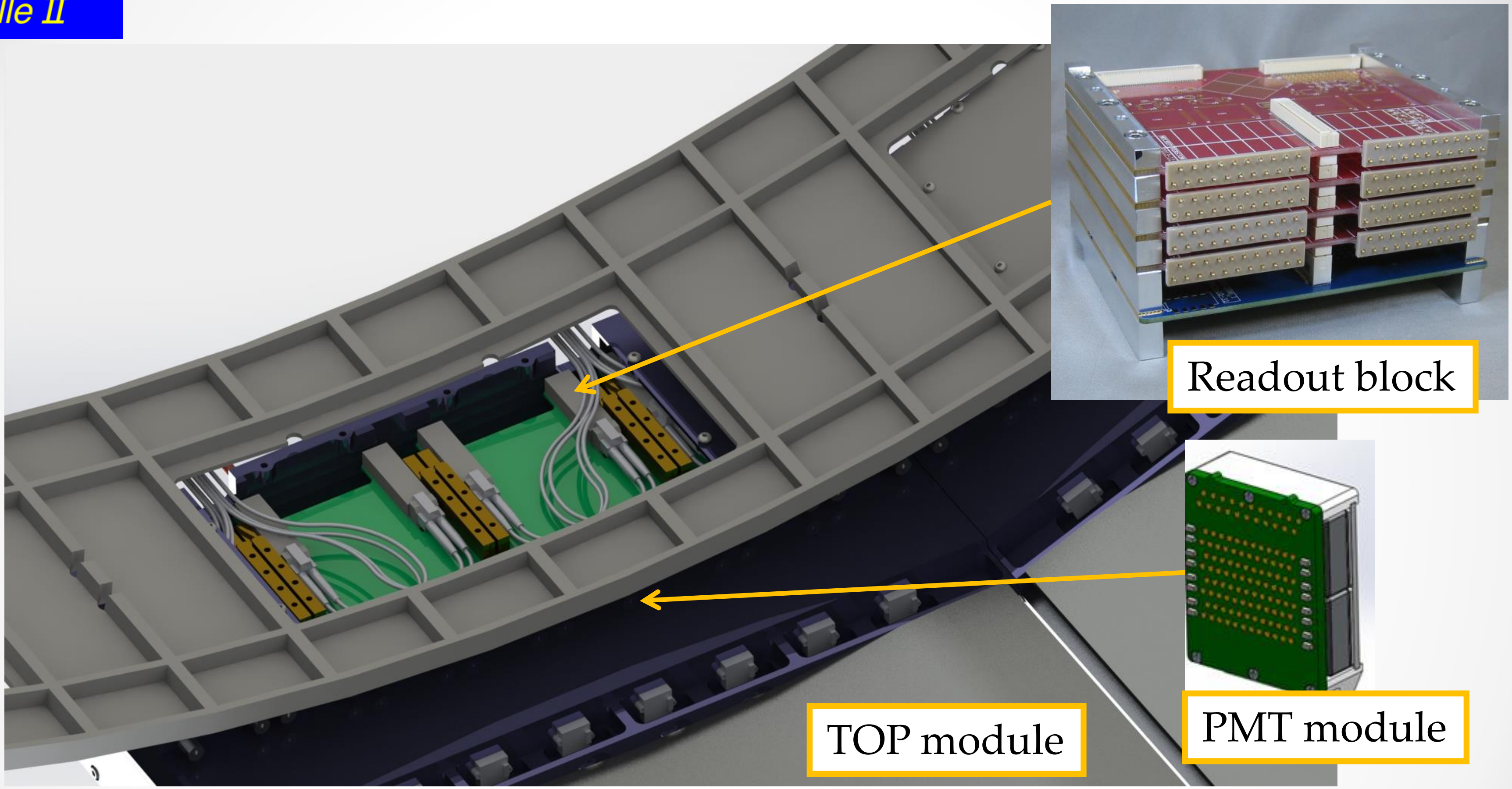
- Optical coupling



Clean bench for optical cookie & PMT module @ KEK

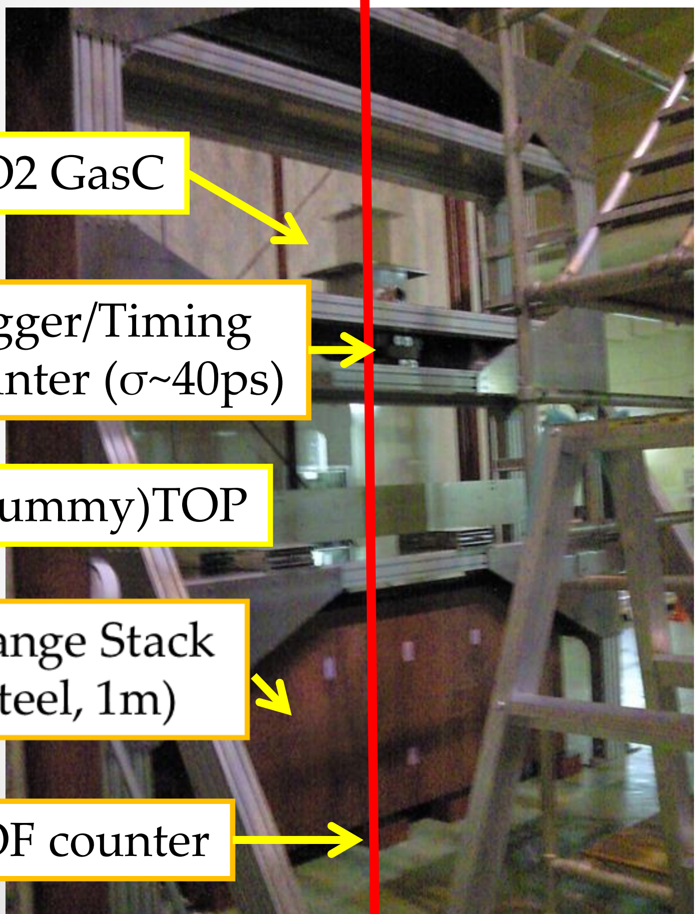
- TSE3032 silicon rubber: optical cookie
  - Easy to remove MCP-PMTs from quartz prism
- Procedures for optical coupling are being finalized.

Access Window/Hatch

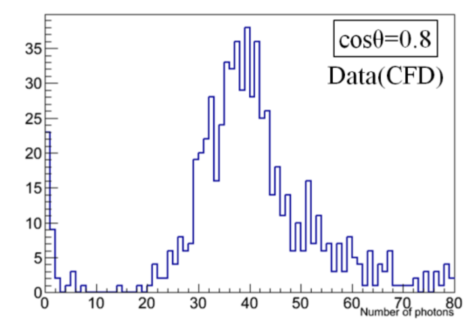


- PMT modules/Readout blocks to be assembled from Access Window
  - Clean env. (~class 1,000) needed to install PMT modules (contacting to prism).
    ➔ Class 1,000 clean booth prepared.
- Access Hatch to replace/(re)install PMT modules / readout blocks (in-situ).
  - The details of the procedures to be tested.

Cosmic Ray Test (CRT)



- Cosmic Ray Test stand for the Belle II TOP counters
  - ✓ Muon filter (β~0.999)
    - ➔ GasChe, Range Stack
  - ✓ Timing/trigger counter
    - ➔ Belle TOF (custom)
  - ✓ Stand
    - ➔ ~2-4 TOP module s



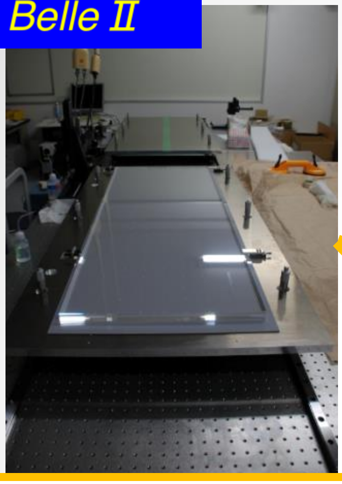
Number of photon hit

- Upgrade: on-going
  - Muon Tracker
    - ➔ ATLAS Drift Tube
  - Stand, module handling
  - Slow control/monitoring
    - Quartz
    - Gas
    - Cleanliness

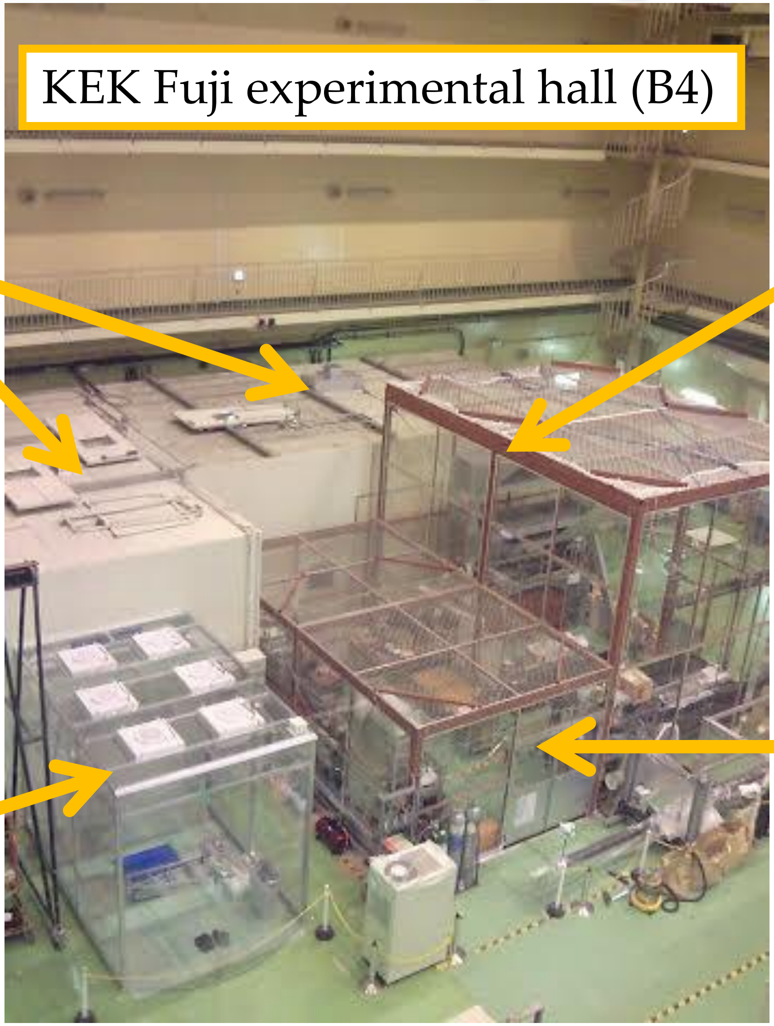
ATLAS Drift Tube

- CRT w/ "IRS" readout will start shortly.

TOP assembly space @ KEK



(1) Class 100-1000 clean room for Quartz



KEK Fuji experimental hall (B4)

(2) PMT assembly Space

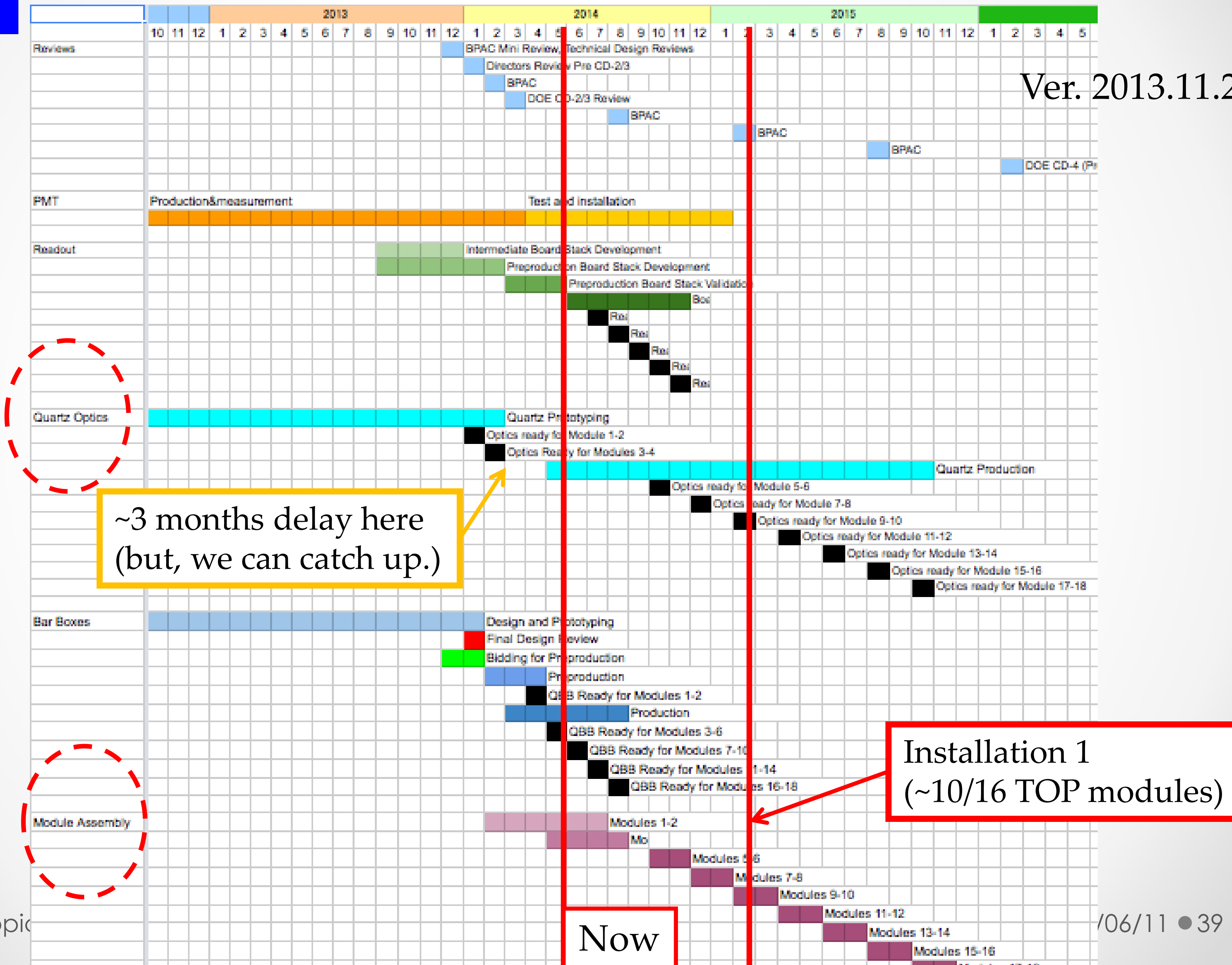
(4) Cosmic Ray Test Setup

(3) Mechanics / Readout Electronics

1st TOP module assembly is scheduled to start this summer

TOP Construction Schedule

Ver. 2013.11.27



Summary

- 1st full scale prototype of the Belle II TOP counter successfully assembled @ KEK-Fuji.
- Performance of the prototype counter tested using 2GeV/c e+ beam at LEPS and cosmic muons at KEK.
  - Several feed-backs have been obtained to the front-end electronics and the opto-mechanical components.
- Production of the MCP-PMTs is going well.
  - Inspection procedure is mostly established.
- Mass production of the quartz optics in progress
  - Acceptance testing: on-going @ KEK and Cincinnati.
  - Procurement schedule still notional.
- Detecotr development / assembly procedures are being finalized.
  - Turning into the construction phase targeting the installation in Feb./Mar. 2015.

backup

…

Complementary to LHCb

Observable	Expected th. accuracy	Expected exp. uncertainty	Facility
CKM matrix			
$\lvert V_{us}\rvert$ [$K \to \pi \ell \nu$]	**	0.1%	K-factory
$\lvert V_{cb}\rvert$ [$B \to X_c \ell \nu$]	**	1%	Belle II
$\lvert V_{ub}\rvert$ [$B_d \to \pi \ell \nu$]	*	4%	Belle II
$\sin(2\phi_1)$ [$c\bar{c}K_S^0$]	***	$8 \cdot 10^{-3}$	Belle II/LHCb
ϕ_2		$1.5°$	Belle II
ϕ_3	***	$3°$	LHCb
CPV			
$S(B_s \to \psi\phi)$	**	0.01	LHCb
$S(B_s \to \phi\phi)$	**	0.05	LHCb
$S(B_d \to \phi K)$	***	0.05	Belle II/LHCb
$S(B_d \to \eta' K)$	***	0.02	Belle II
$S(B_d \to K^*(\to K_S^0\pi^0)\gamma))$	***	0.03	Belle II
$S(B_s \to \phi\gamma))$	***	0.05	LHCb
$S(B_d \to \rho\gamma))$		0.15	Belle II
A^d_{SL}	***	0.001	LHCb
A^s_{SL}	***	0.001	LHCb
$A_{CP}(B_d \to s\gamma)$	*	0.005	Belle II
rare decays			
$\mathcal{B}(B \to \tau\nu)$	**	3%	Belle II
$\mathcal{B}(B \to D\tau\nu)$		3%	Belle II
$\mathcal{B}(B_d \to \mu\nu)$	**	6%	Belle II
$\mathcal{B}(B_s \to \mu\mu)$	***	10%	LHCb
zero of $A_{FB}(B \to K^*\mu\mu)$	**	0.05	LHCb
$\mathcal{B}(B \to K^{(*)}\nu\nu)$	***	30%	Belle II
$\mathcal{B}(B \to s\gamma)$		4%	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$		$0.25 \cdot 10^{-6}$	Belle II (with 5 ab^{-1})
$\mathcal{B}(K \to \pi\nu\nu)$	**	10%	K-factory
$\mathcal{B}(K \to e\pi\nu)/\mathcal{B}(K \to \mu\pi\nu)$	***	0.1%	K-factory
charm and τ			
$\mathcal{B}(\tau \to \mu\gamma)$	***	$3 \cdot 10^{-9}$	Belle II
$\lvert q/p\rvert_D$	***	0.03	Belle II
$\arg(q/p)_D$	***	$1.5°$	Belle II

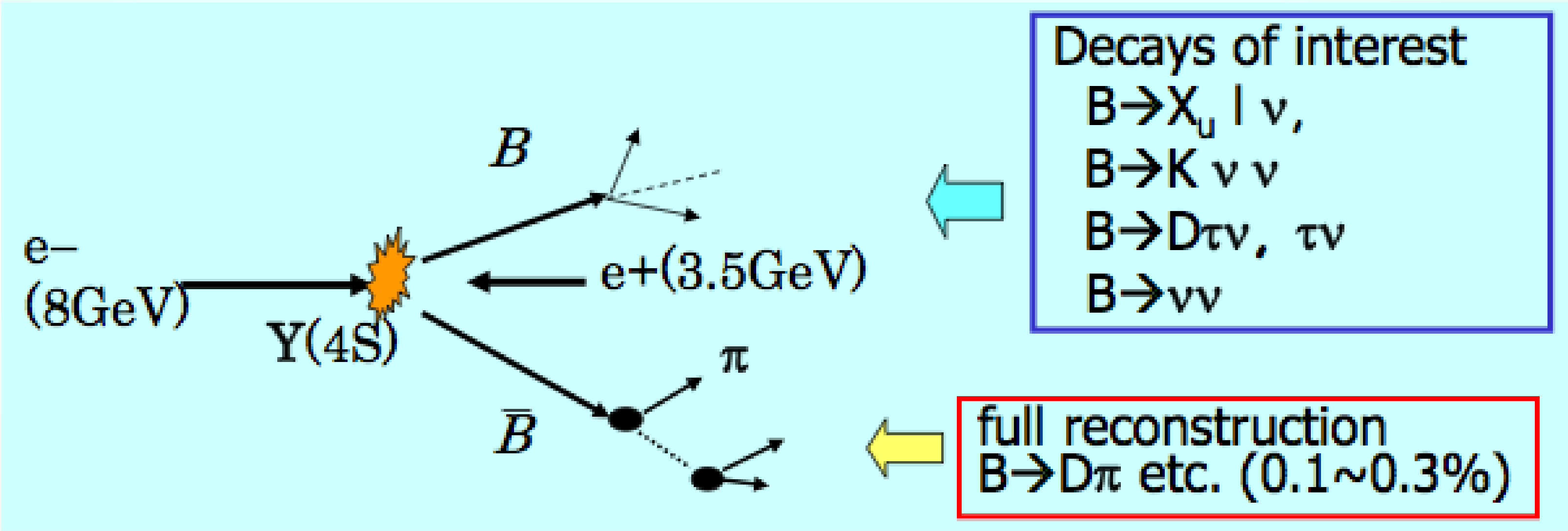
→Need both LHCb and super B factories to cover all aspects of precision flavour physics

adapted from G. Isidori et al., Ann. Rev. Nucl. Part. Sci. 60, 355 (2010)

B. Golob, KEK FF Workshop, Feb. 2012

Power of e^+e^-, example: Full Reconstruction Method

- Fully reconstruct one of the B mesons to
  - Tag B flavor/charge
  - Determine B momentum
  - Exclude decay products of one B from further analysis



→ Offline B meson beam!

Powerful tool for B decays with neutrinos