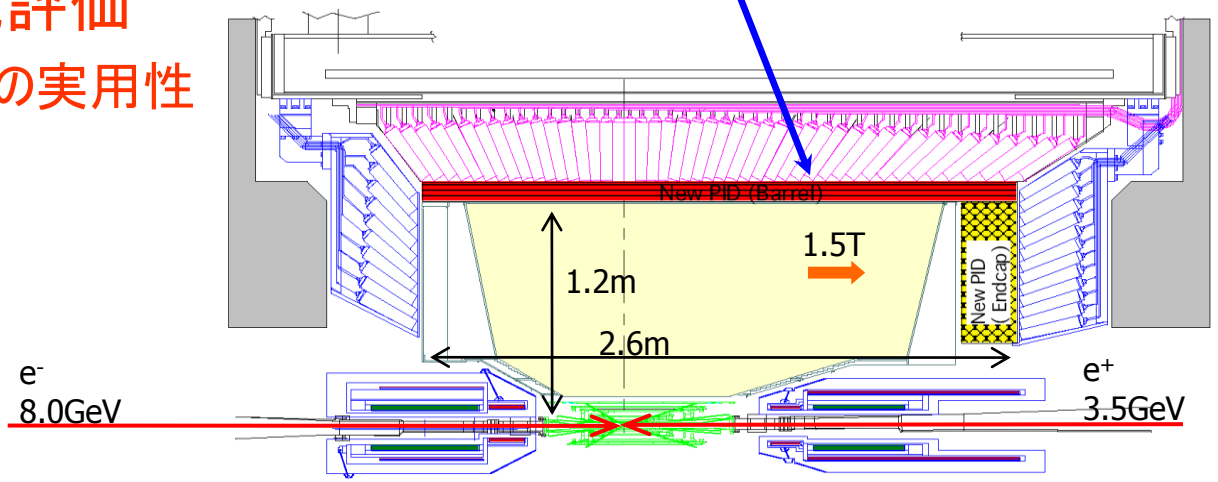
Overview of TOP detector

K.Inami

TOP detector

- TOP (Time Of Propagation) カウンター開発
  - 次世代Bファクトリー実験のための粒子識別装置
    - L_{peak}~8x10^{35}/cm^2/s, Bファクトリーと比べ、40倍の強度
  - K/π識別効率の向上
    - Physics analysis, Flavor tag, Full reconstruction

- TOPカウンターの原理検証
- 実用化のための性能評価
  - 光検出器MCP-PMTの実用性
  - 石英輻射体の性能

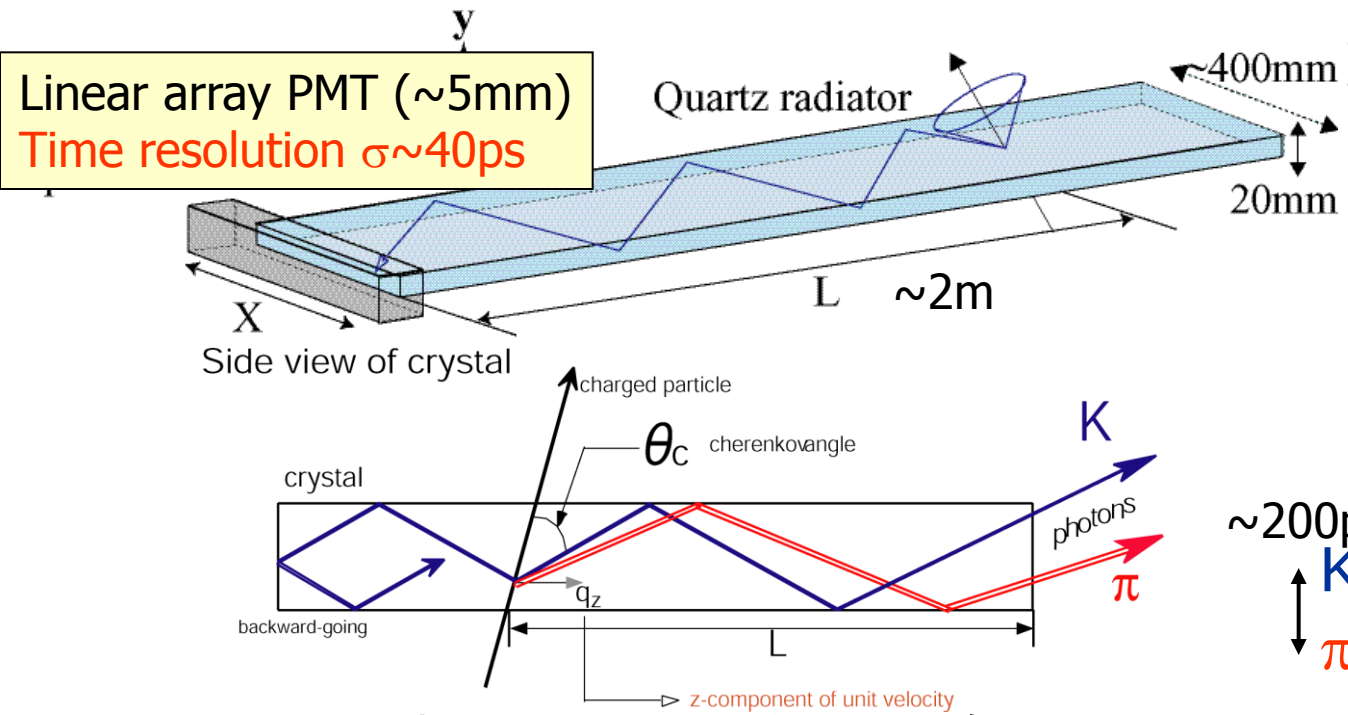


Side view of **Belle II** detector

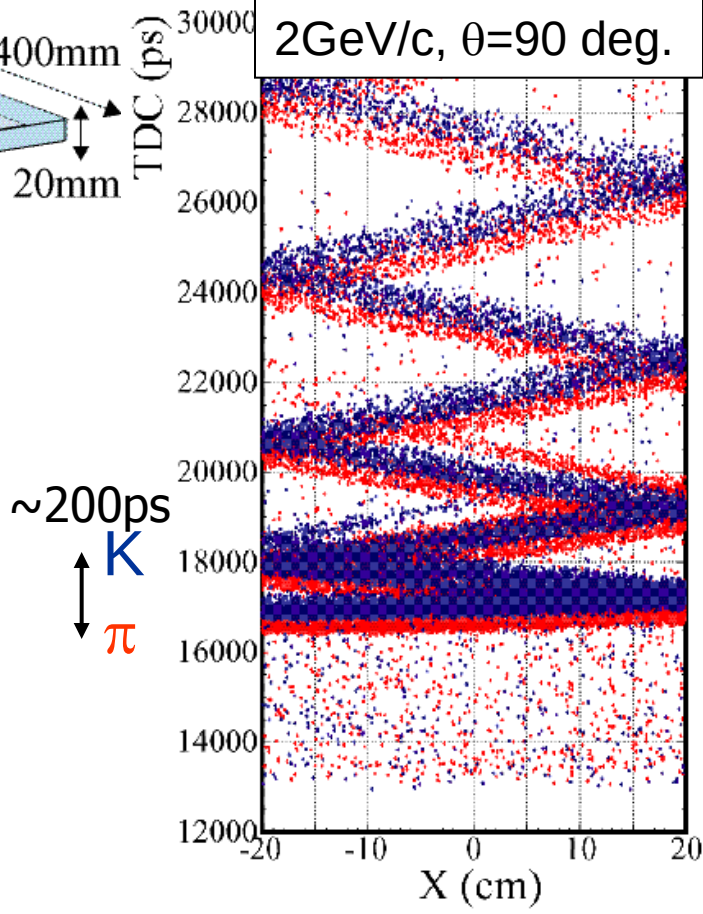
TOPカウンター原理

- チェレンコフ光の到着位置＋時間
  - コンパクト

Linear array PMT (~5mm)
Time resolution σ~40ps



Simulation
2GeV/c, θ=90 deg.



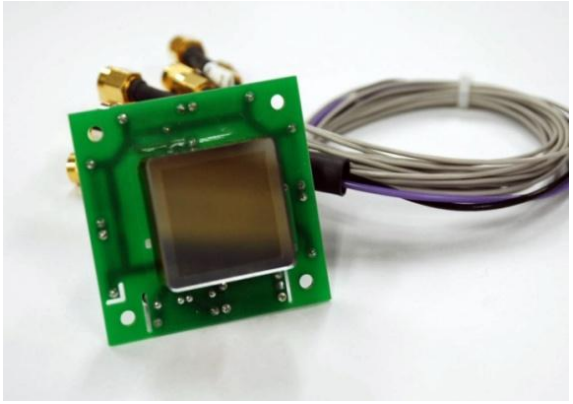
同じ運動量の粒子に対して異なる開き角
→ 異なる伝播距離 (= 伝播時間)

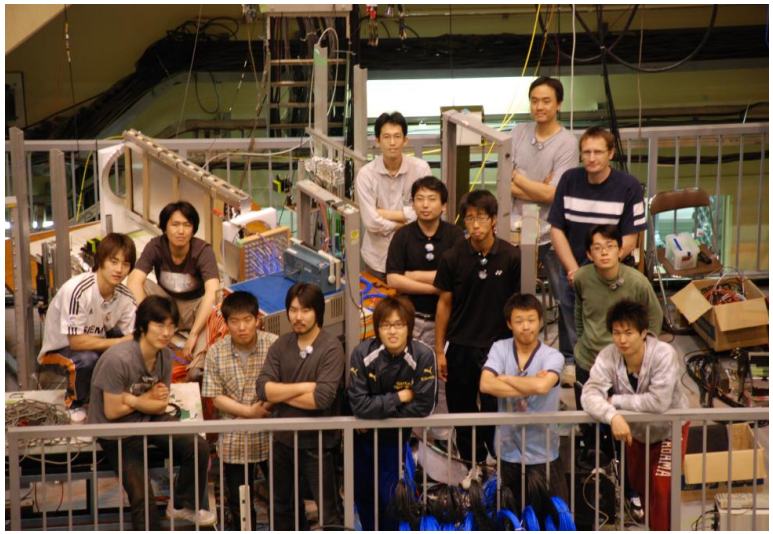
+ 衝突点からのTOFも加算的に識別に寄与

開発項目

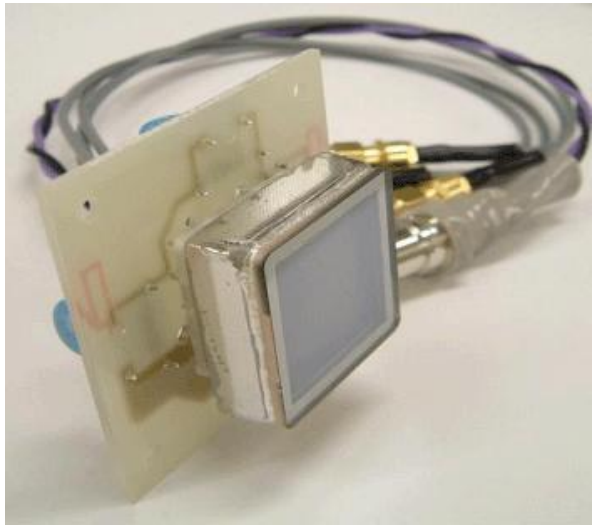
- MCP-PMT
  - 実用化に向けた寿命向上
    - 光電面の劣化メカニズムから対策案
  - 量子効率改良
    - GaAsP光電面

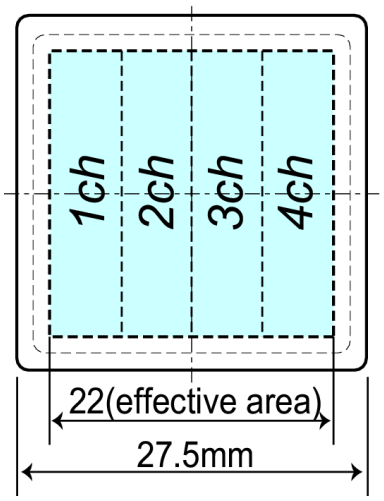
    → Super Bialkali光電面
- プロトタイプ
  - 大型石英＋MCP-PMT
  - ビームテスト
    - 色分散効果の検証(2008/6,12)
    - フォーカスミラーの動作検証(2010/11)
- 実用化に向けた開発
  - Belle-II搭載へ向けた形状最適化
  - 構造体開発
  - 放射線耐性

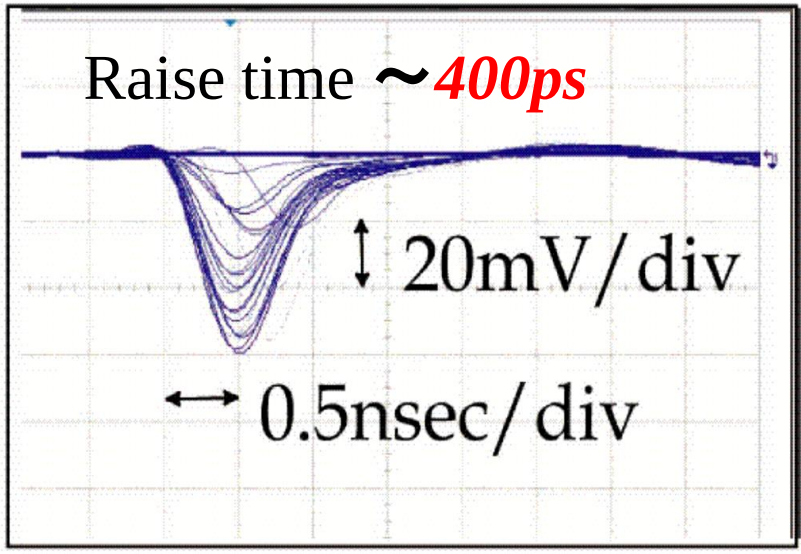




角型MCP-PMT

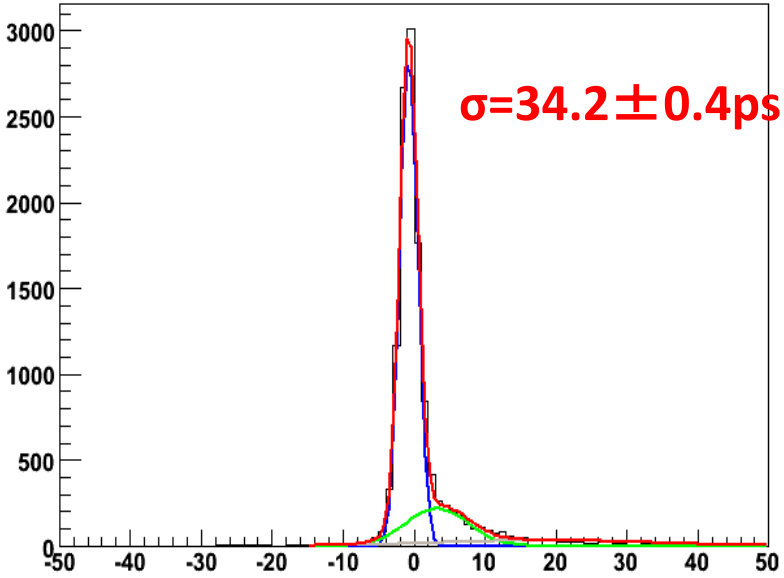






R&D with Hamamatsu

- Large effective area 64%
- Position information 4ch (5mm pitch)
- Single photon detection
- Fast raise time: ~400ps
- Gain: >1x10^6 at B=1.5T
- T.T.S.(single photon): ~35ps at B=1.5T
- Position resolution: <5mm

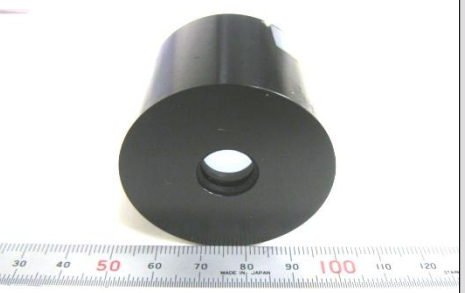


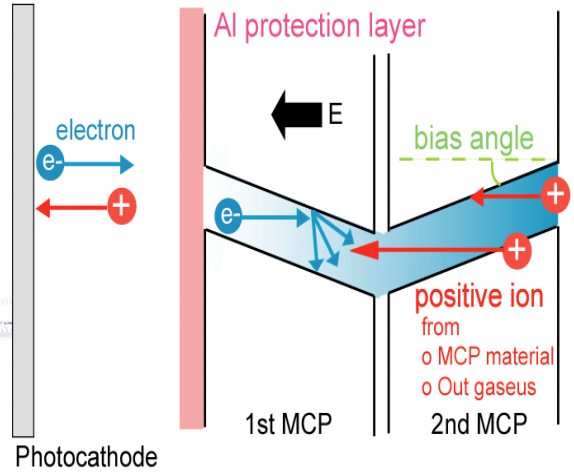
MCP-PMT寿命

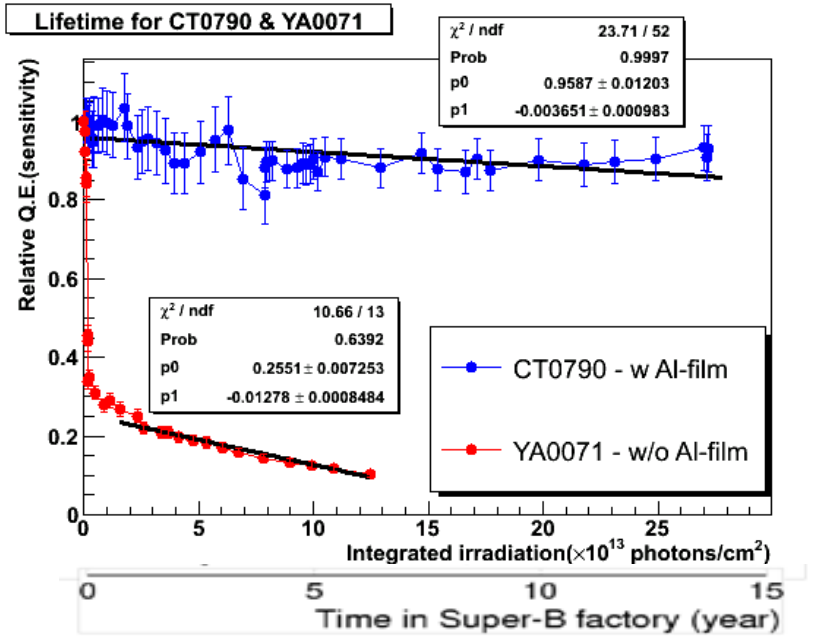
- 現在のBelle実験の20倍のバックグラウンド環境に耐えうるPMTが必要

	Belle	Belle-II
Luminosity (/cm^2/s)	1×10^{34}	8×10^{35}
Num. of detected photons (/cm^2/s)	3400	68000
Output charge (mC/cm^2/year)	~6	~120

- 丸型MCP-PMT
  - アルミ保護膜を導入することで、十分な寿命を達成

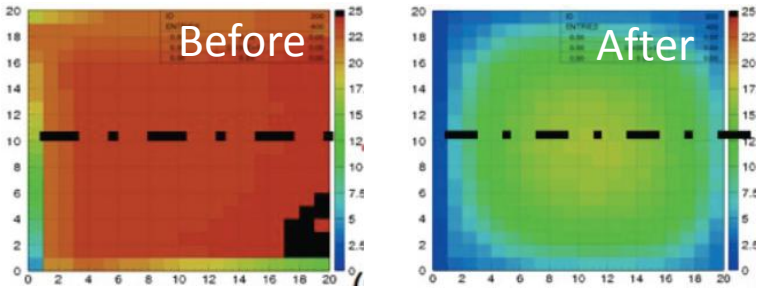


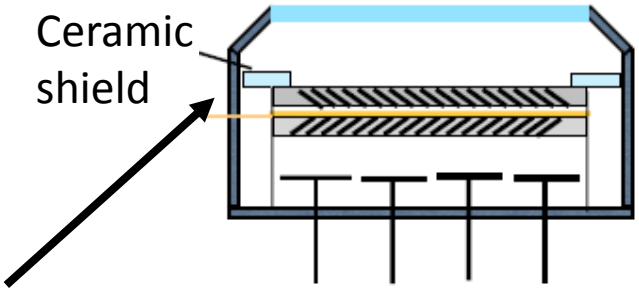




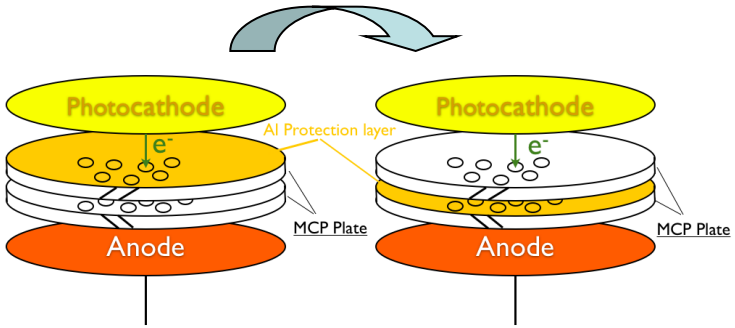
MCP-PMT寿命

- 角型MCP-PMTの寿命測定
  - アルミ保護膜があっても短寿命であることが判明
  - 量子効率の面一様性から内部構造の違いについて考察
    - MCPと側管の間から中性ガスが光電面へ到達し得る



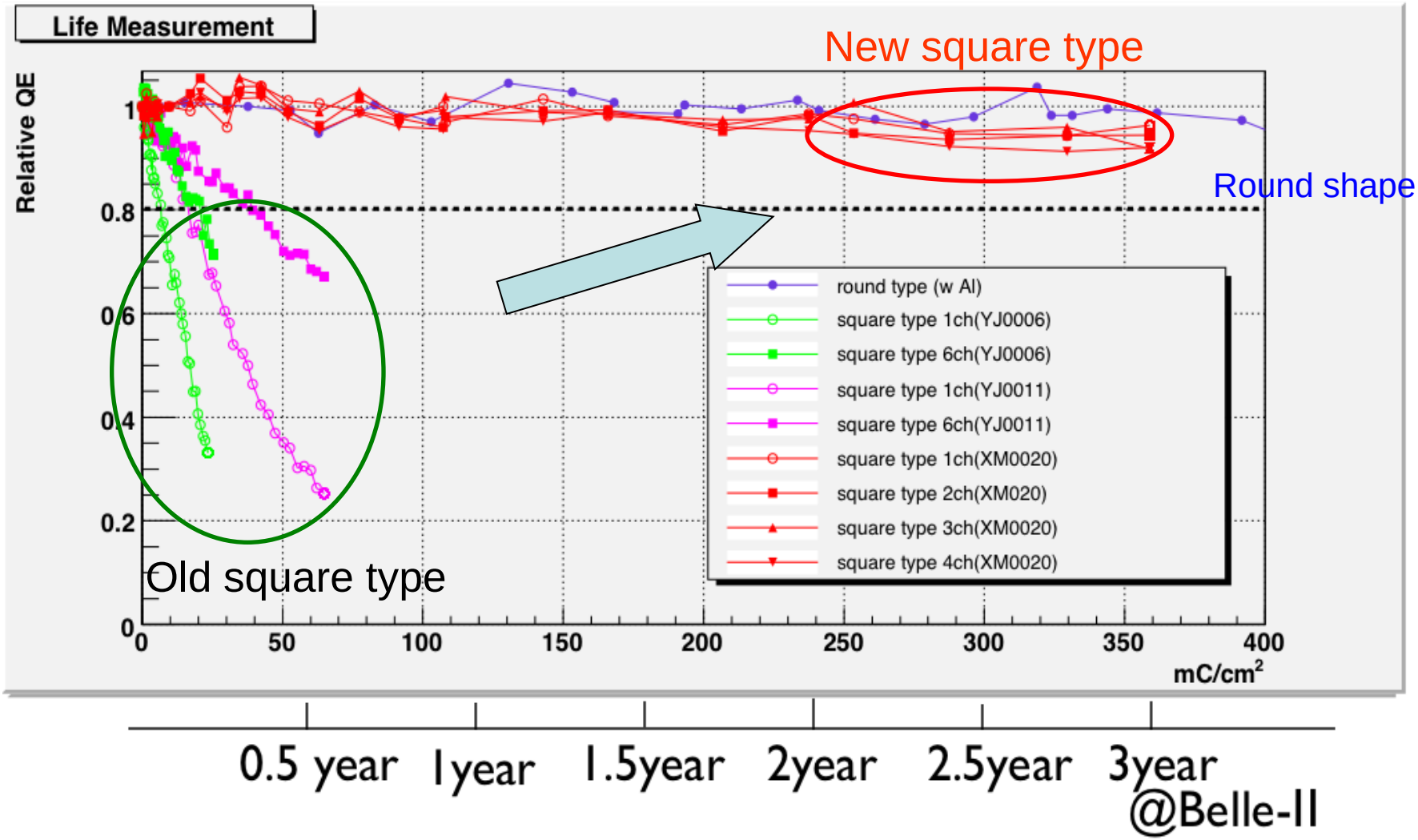


- 改良版MCP-PMTの試作
  - セラミックシールドを導入し、中性ガスを遮断
  - 中性ガスが発生しにくいMCPの処理
  - アルミ保護膜をMCP2枚目へ導入
    - 収集効率の向上(35%→60%)



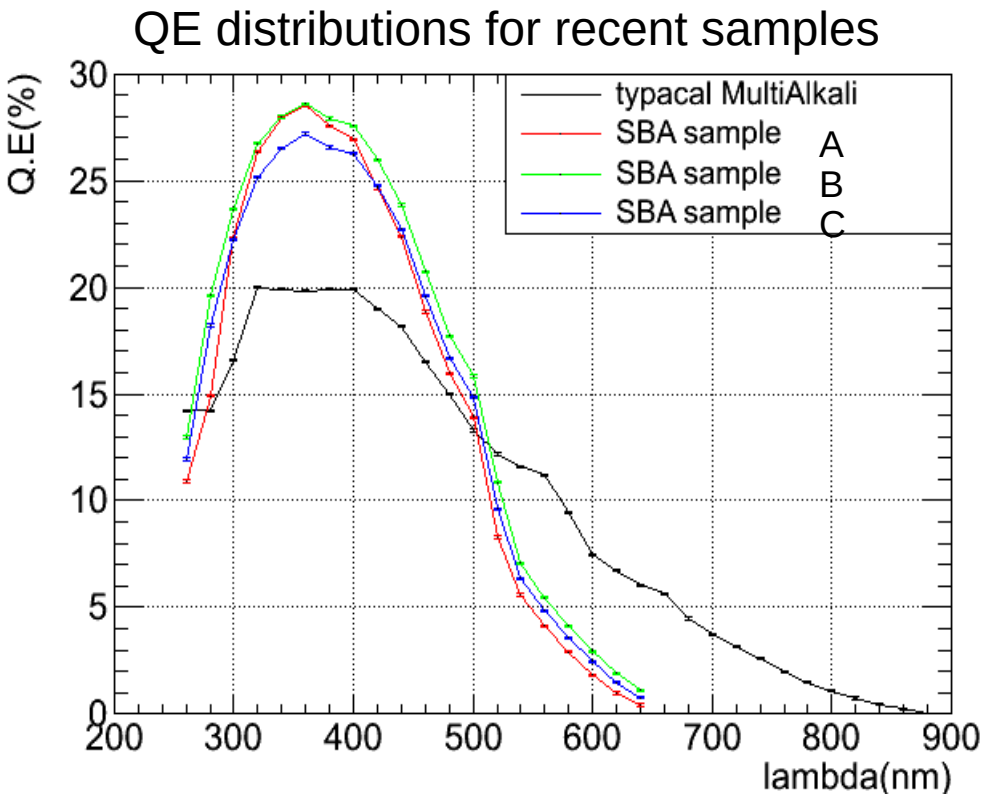
MCP-PMT寿命結果

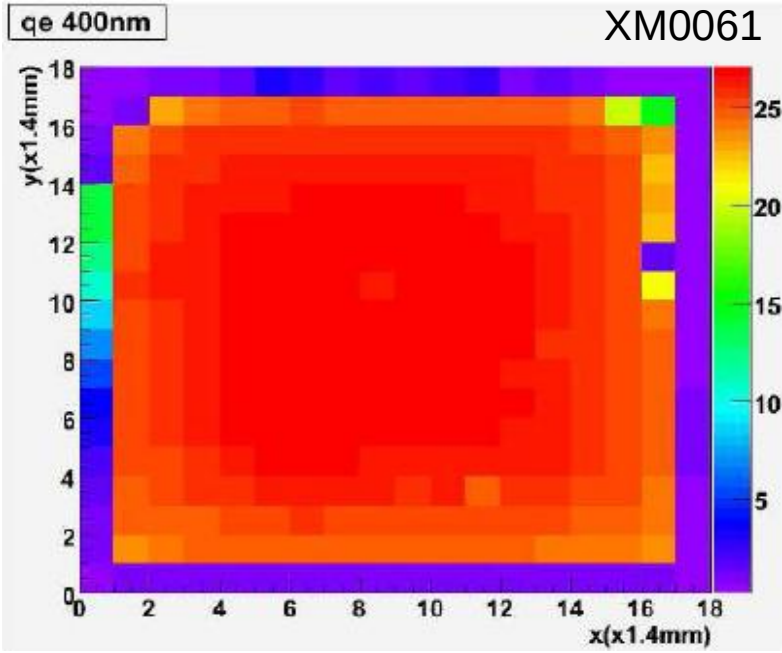
- 大幅に向上させることに成功し、十分な寿命を達成



光電面の改良

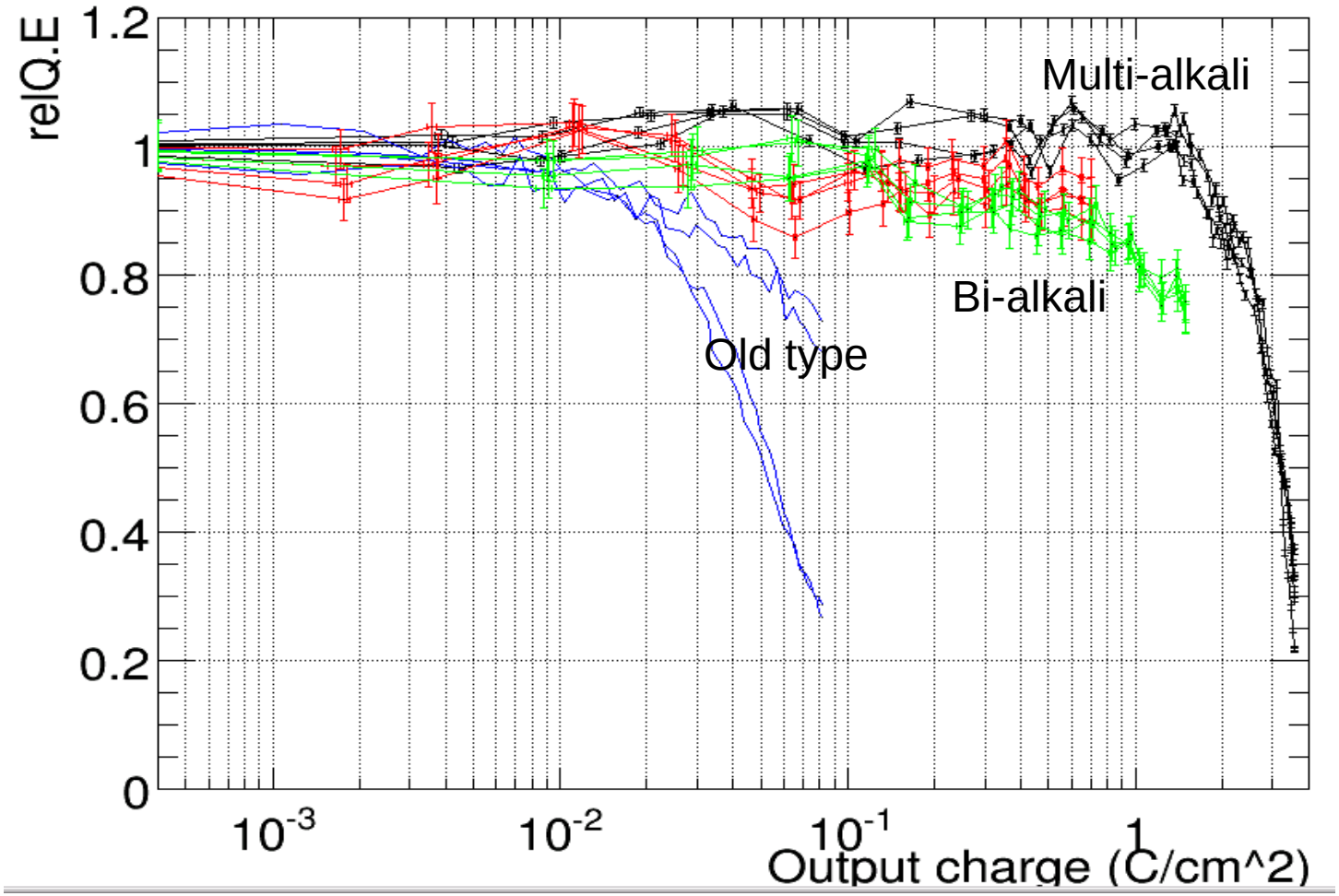
- GaAsP光電面は歩留まりが向上せず、実用化が困難
- Super bialkali 光電面技術の適用
  - 検出光子数20%の向上が見込める



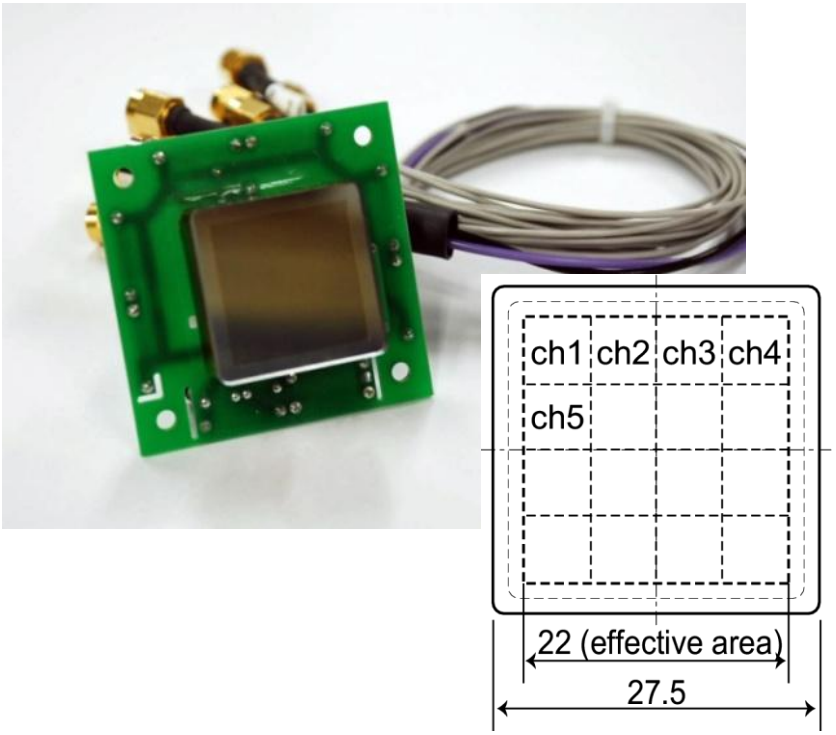


MCP-PMT寿命結果

- 新しい光電面MCP-PMTにおいても1~2 C/cm^{2}の寿命を達成



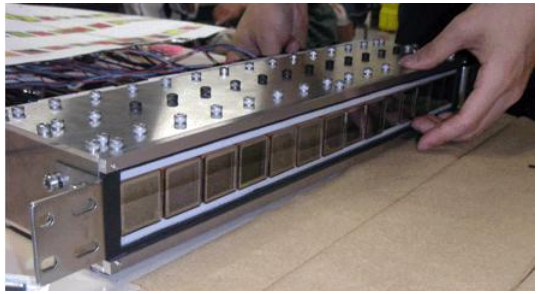
角型MCP-PMT for TOP

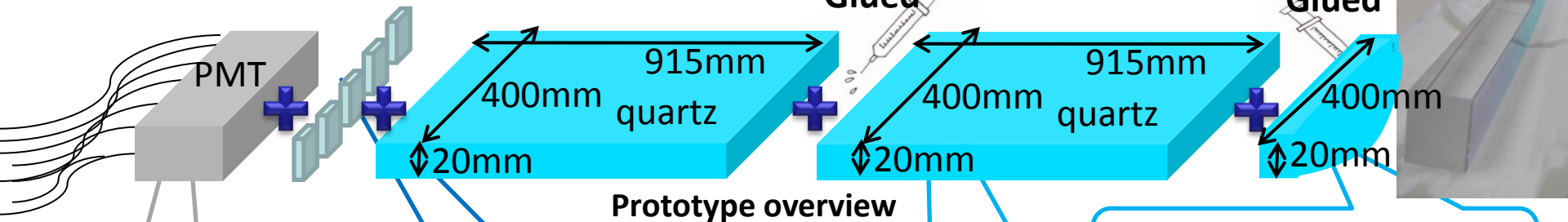


Size	27.5 x 27.5 x 14.8 mm
Effective area	22 x 22 mm(64%)
Photo cathode	Enhanced Multialkali
Q.E.	~28%(λ=400nm)
MCP Channel diameter	10 μm
Number of MCP stage	2
Collection efficiency	~60%
Anode	4 x 4
Anode size (1ch)	5.3 x 5.3 mm
Anode gaps	0.3 mm

- High time resolution — σ<40ps
- Large effective area — 64% by square shape
- Position information — 4x4ch matrix anode (5mm pitch)
- Sufficient lifetime — >1C/cm^2

プロトタイプ製作





Prototype overview

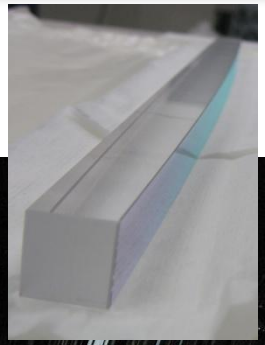
Photon detector
- Time resolution
- Efficiency

Filter (λ>400nm)
- Suppression of chromatic dispersion

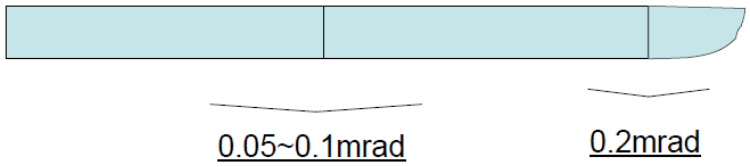
Quartz radiator (Fused silica)
- Flatness:<1.2μm/m
- Roughness:0.5nm

Focus mirror
- Chromaticity correction

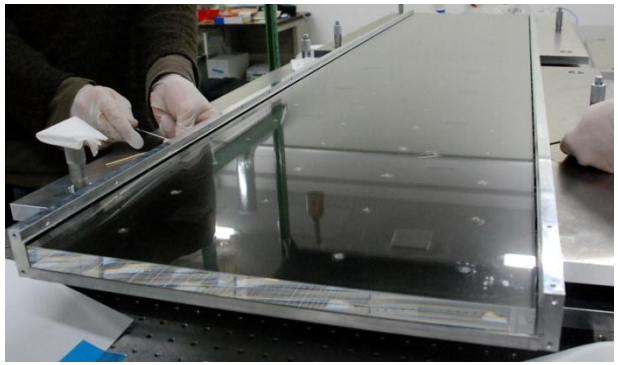
石英輻射体

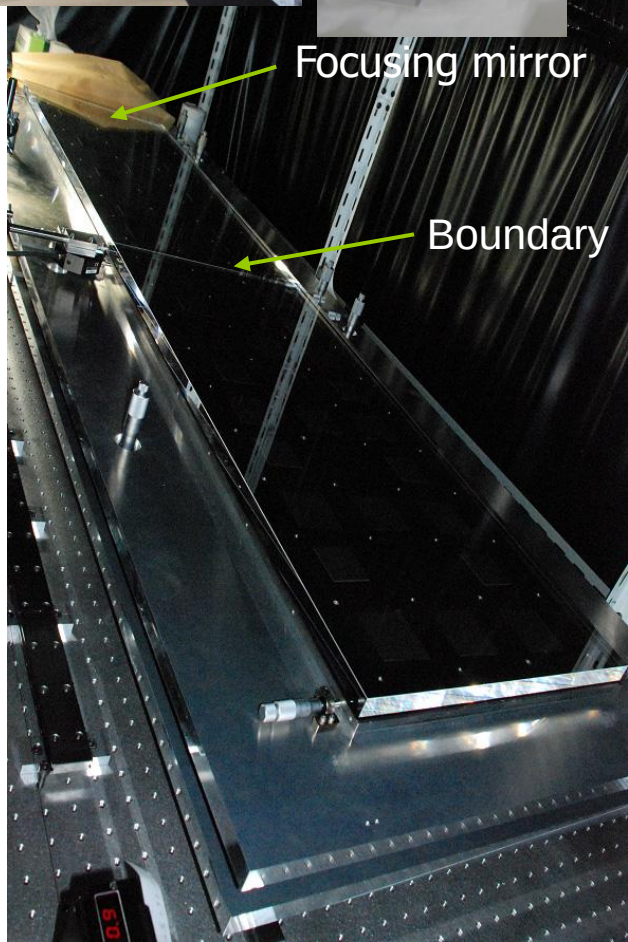


- 高精度研磨石英板2枚
  - 91.5 x 40 x 2 cm^3, 岡本光学
  - 平面性: <1.2μm/m
  - 面粗度: <0.5nm
- フォーカスミラー (R=5m)
- 接合
  - 平面度; ~0.2mrad



- アルミハニカム支持体を製作

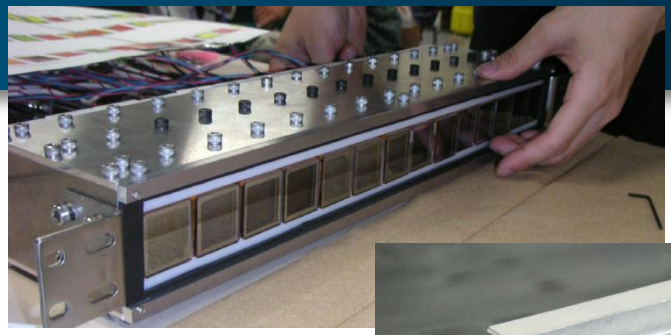


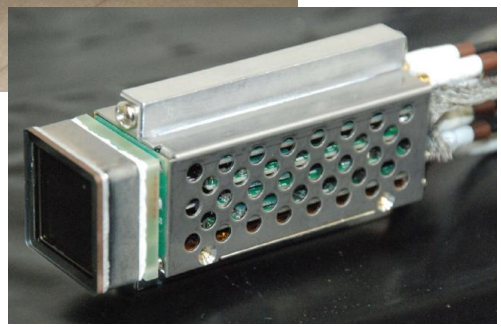


光検出器

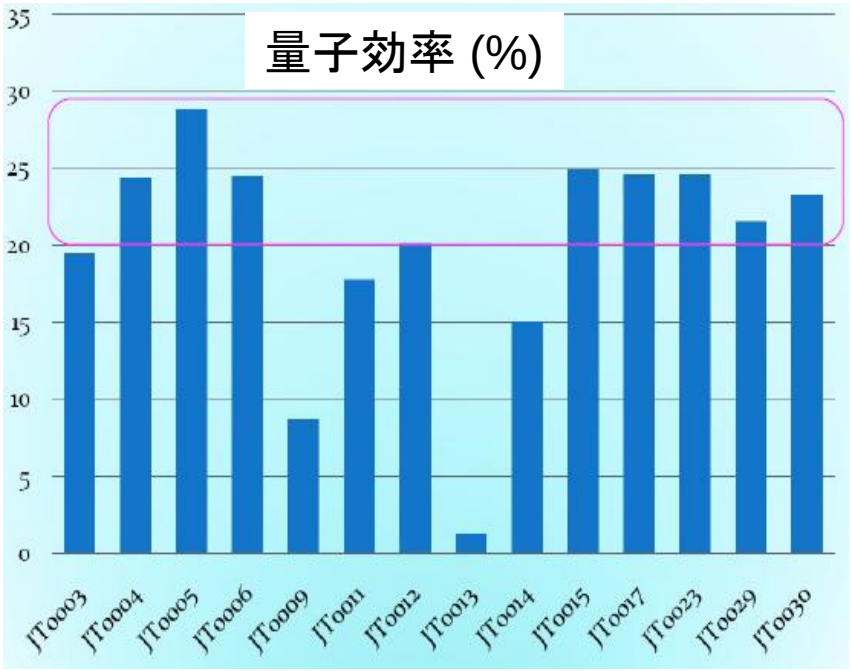
- MCP-PMT１４個試作・検査
  - TOPプロトタイプ用
  - 製作での安定性を評価

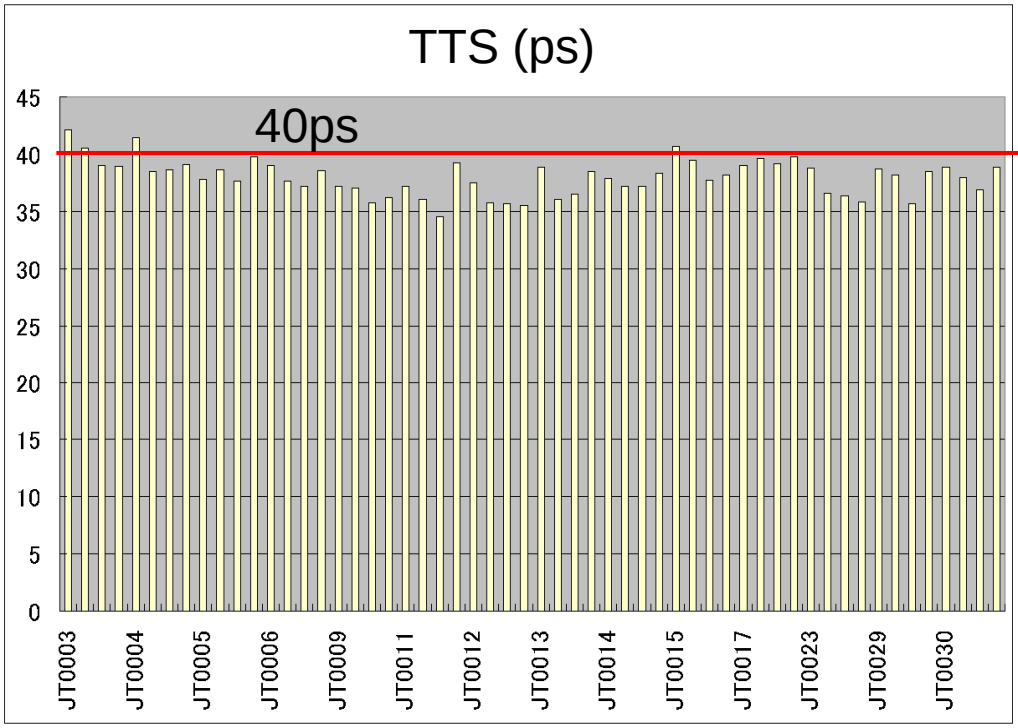
  - TTS, Gainは安定的
  - 量子効率は開発の必要性有り



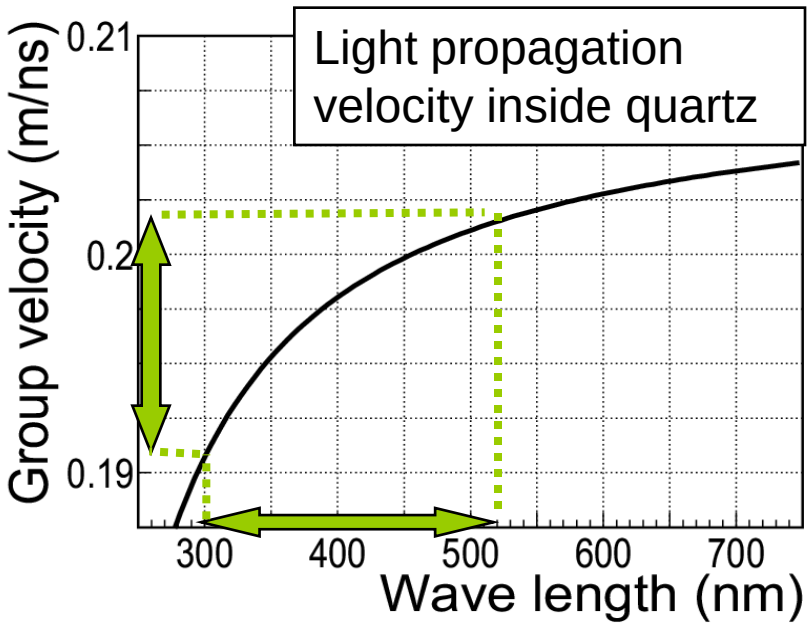


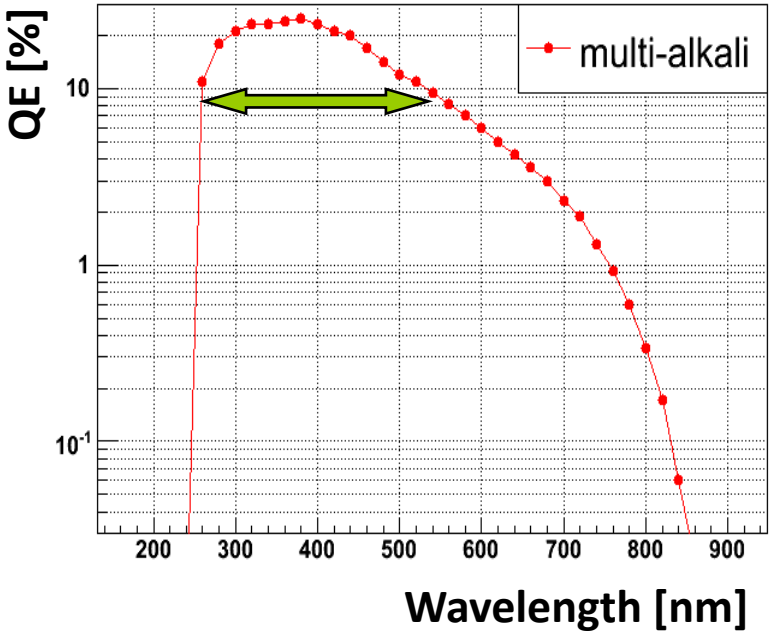
MCP-PMT出力に対応した
読み出し回路の開発





色分散効果

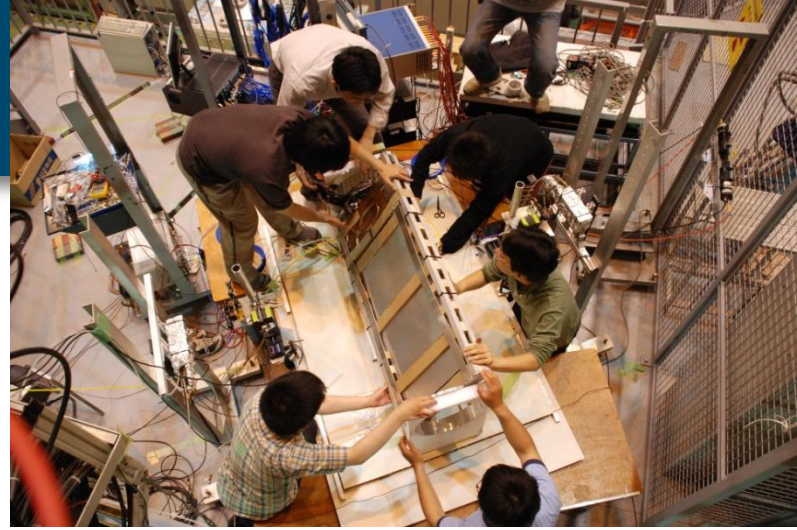




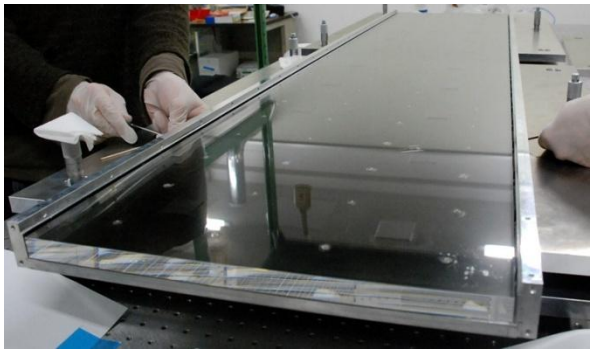
- 輻射体内での伝播速度依存性 + チェレンコフ光の検出波長範囲
  → リングイメージの時間ふらつきを生み出す
    → 伝播距離に依存した時間分解能の変化

ビームテスト(2008)

- KEK Fuji test beam line, 電子ビーム



Quartz + support jig

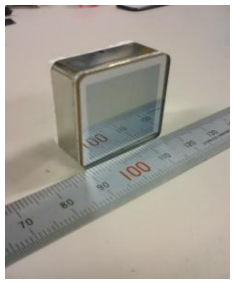


TOP counter
Quartz bar
(1850 x 400 x 20mm)

Timing counter
10mm$^{\phi}$ quartz + MCP-PMT
σ_{t0} < 15ps

MWPC 1

MWPC 2



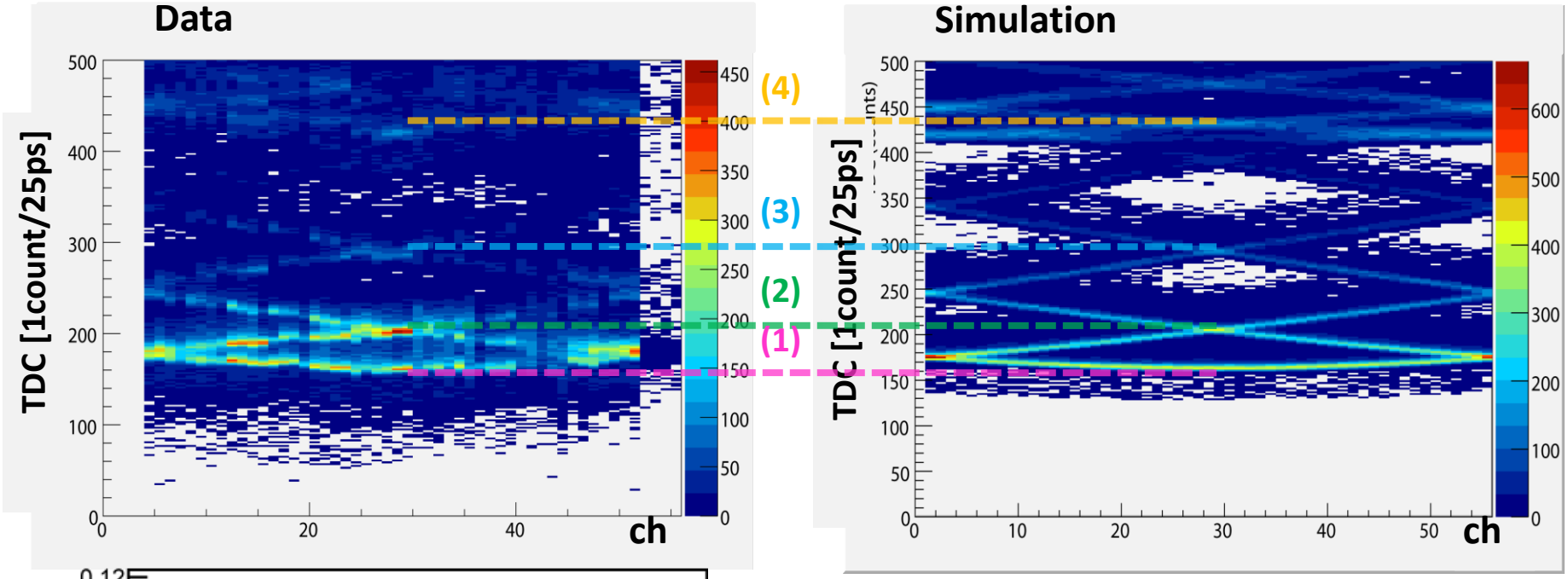
Trigger counter

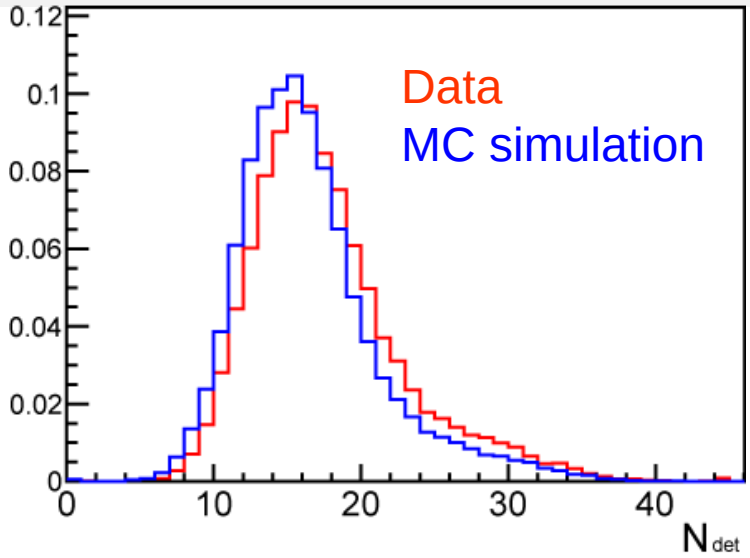
Lead glass +
Finemesh PMT

MCP-PMT (10 PMT)

- 評価項目
  - リングイメージ
  - 検出光子数
  - 時間分解能

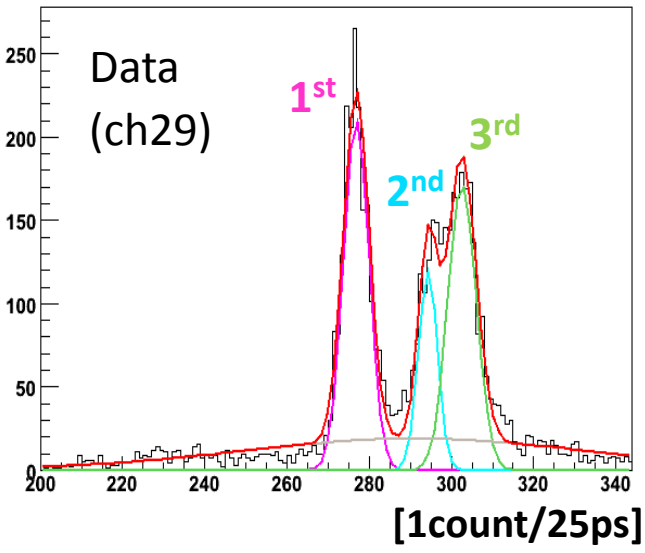
リングイメージ・検出光子数



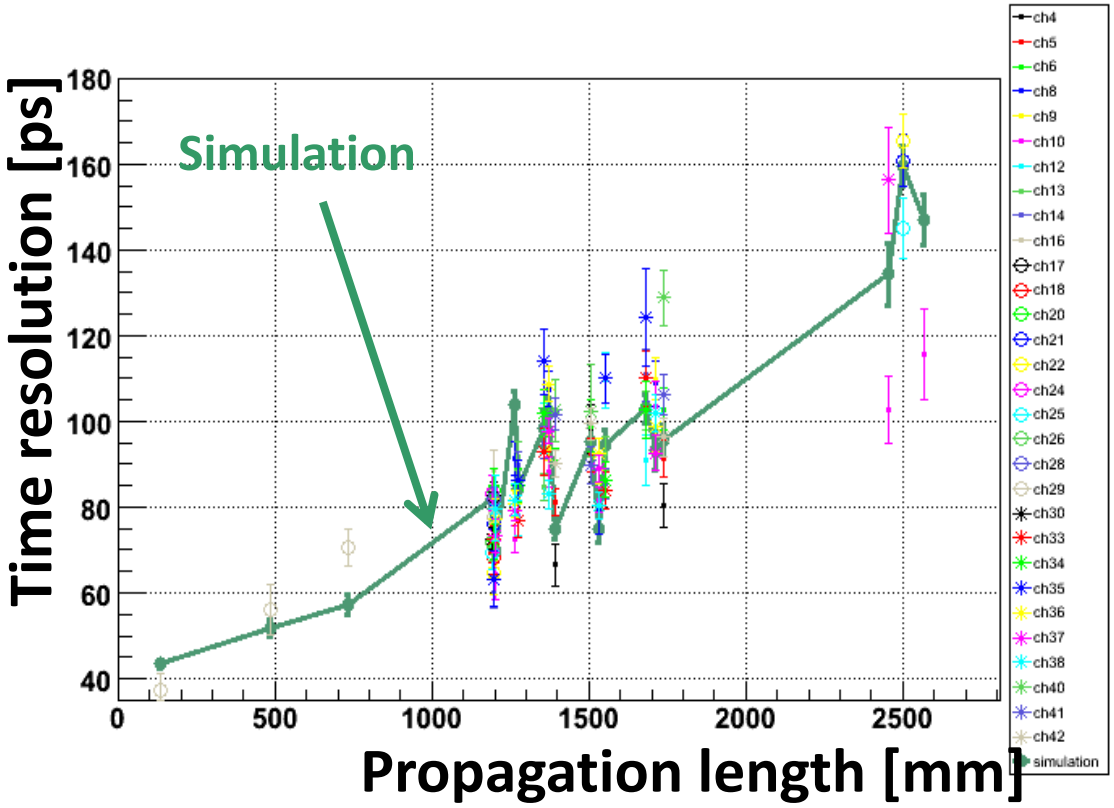


- 期待されるリングイメージ・検出光子数を取得

時間分解能



ch.29	Resolution(1st peak)
Data	76.0±2.0 [ps]
Simulation	77.7±2.3 [ps]



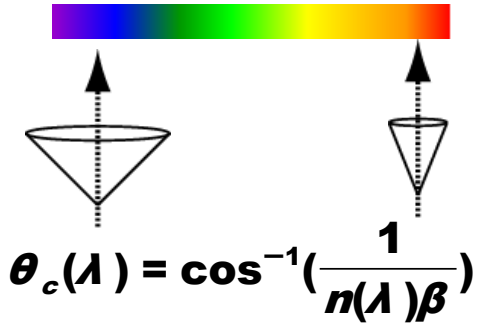
- 期待される時間分解能
- 伝播距離依存性を再現
  - 色分散効果による時間分解能の悪化

Focusing TOP

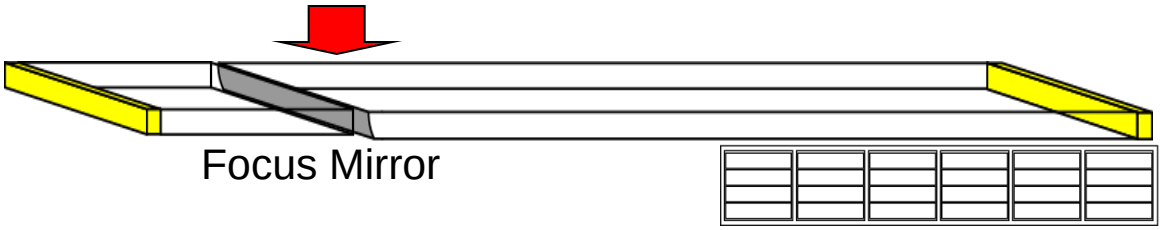
- フォーカスミラー導入により色分散を抑制
  - 色収差補正のために、チェレンコフ角の波長依存性を利用

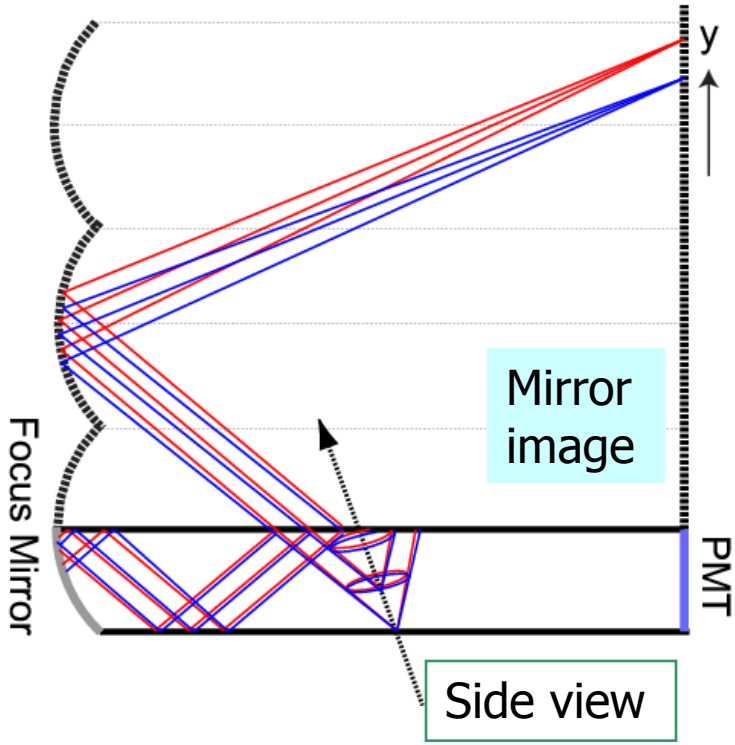
➔ $\lambda \leftarrow \theta_c \leftarrow$ y位置

  - 2次元位置と時間の3次元情報を用いたリングイメージの再構成
  - 長距離焦点ミラーの導入により、コンパクトな測定器を実現　＋　5mmの位置分解能で波長分解が可能



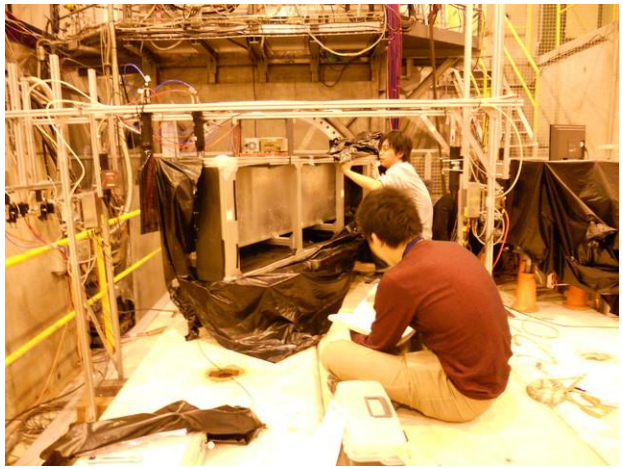
$$\theta_c(\lambda) = \cos^{-1}\left(\frac{1}{n(\lambda)\beta}\right)$$

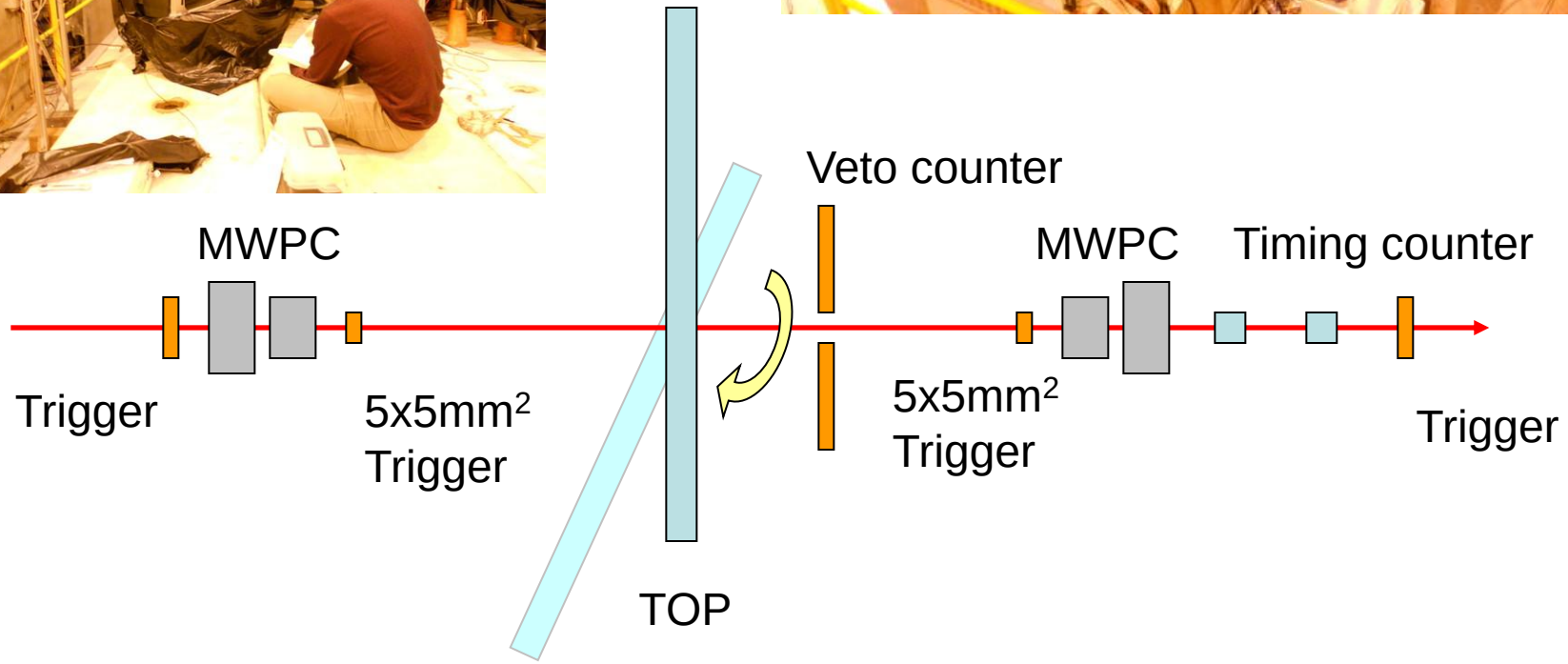




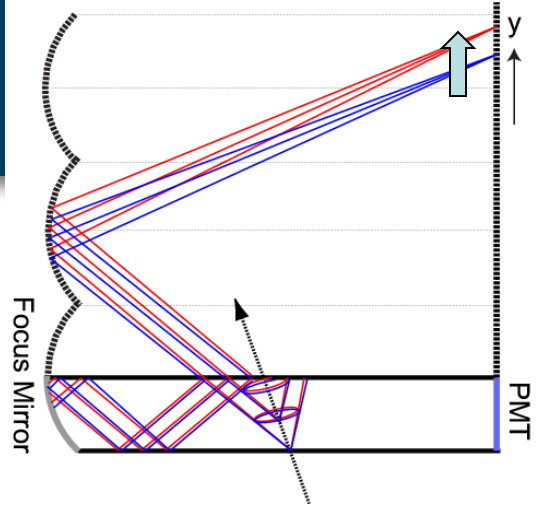
ビームテスト(2010)

- CERN SPS T4-H6B
  - pion; +120GeV
  - 11月8-15日

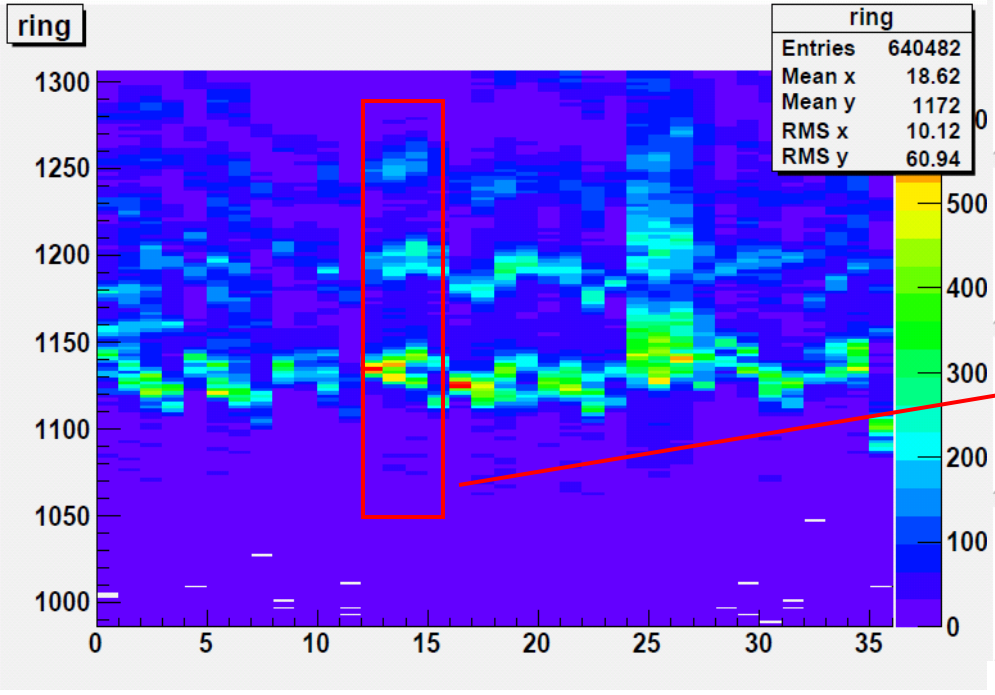


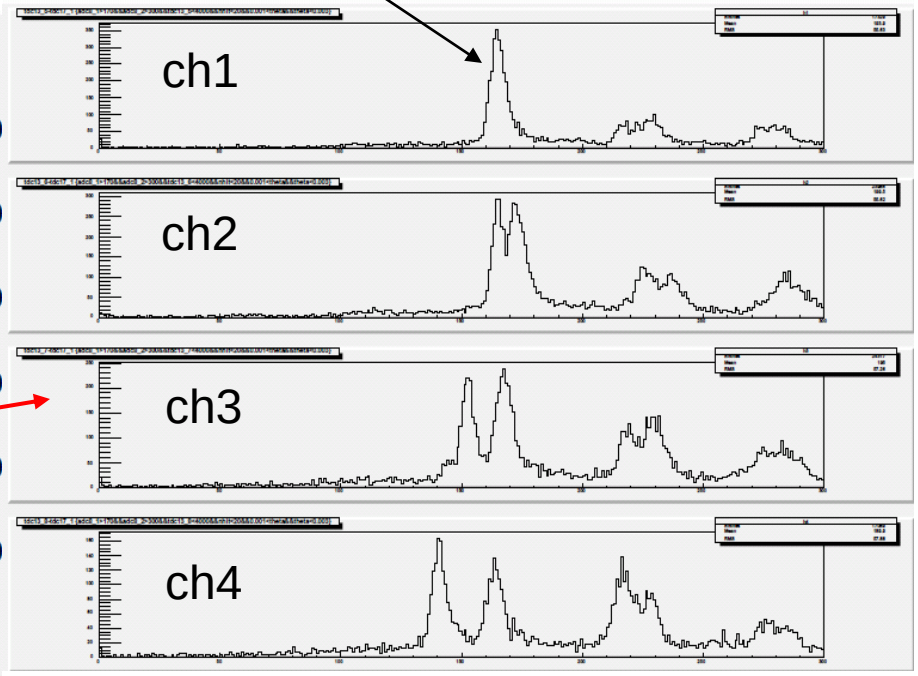


測定結果



- 角度付き入射(cosθ=0.3に対応)
- 期待される振る舞いを持つリングイメージを取得
- 時間分解能の向上を確認 : ~95ps
  - シミュレーション: ~103ps
  - 色分解なしでは、2900mmの伝播に対応し、~170psの分解能
  - 詳細な解析は現在進行中

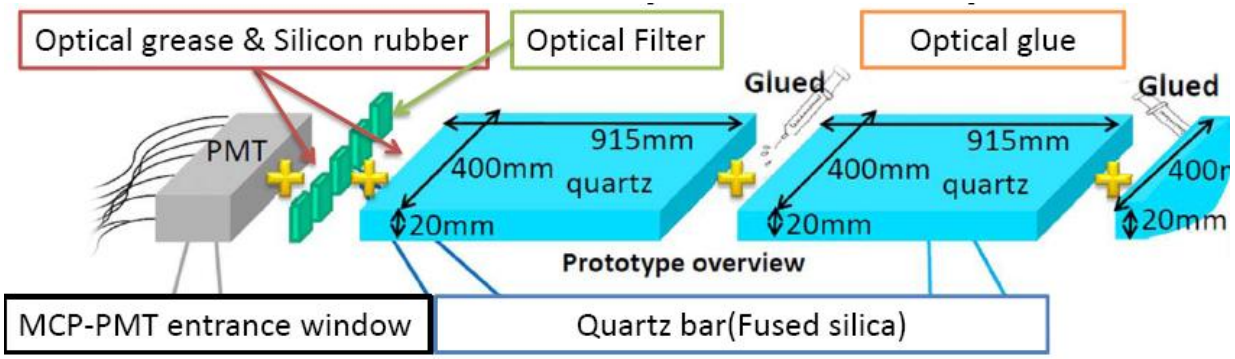


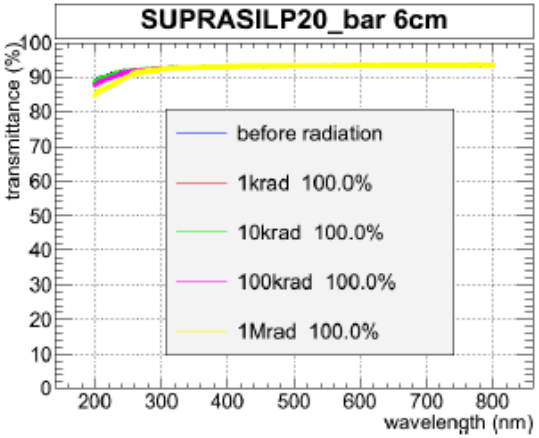


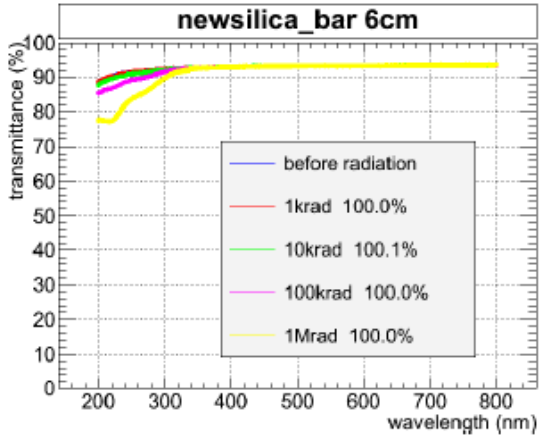
実用化に向けた開発研究

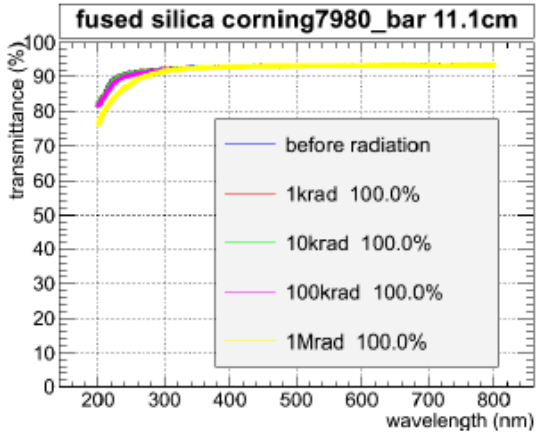
- 放射線耐性試験
  - γ線・中性子線
  - 光学素子の透過率、MCP-PMTの量子効率
  - γ線1Mrad, 中性子10^{12}n/cm^{2}まで問題なし

名古屋大学Co60照射室



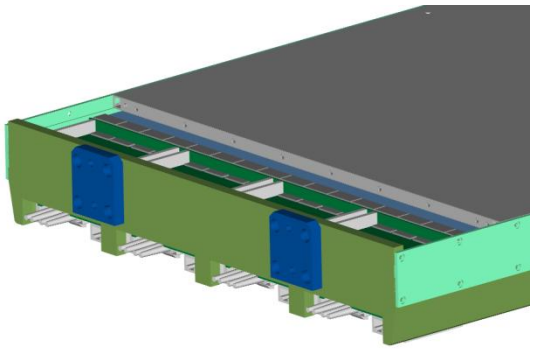


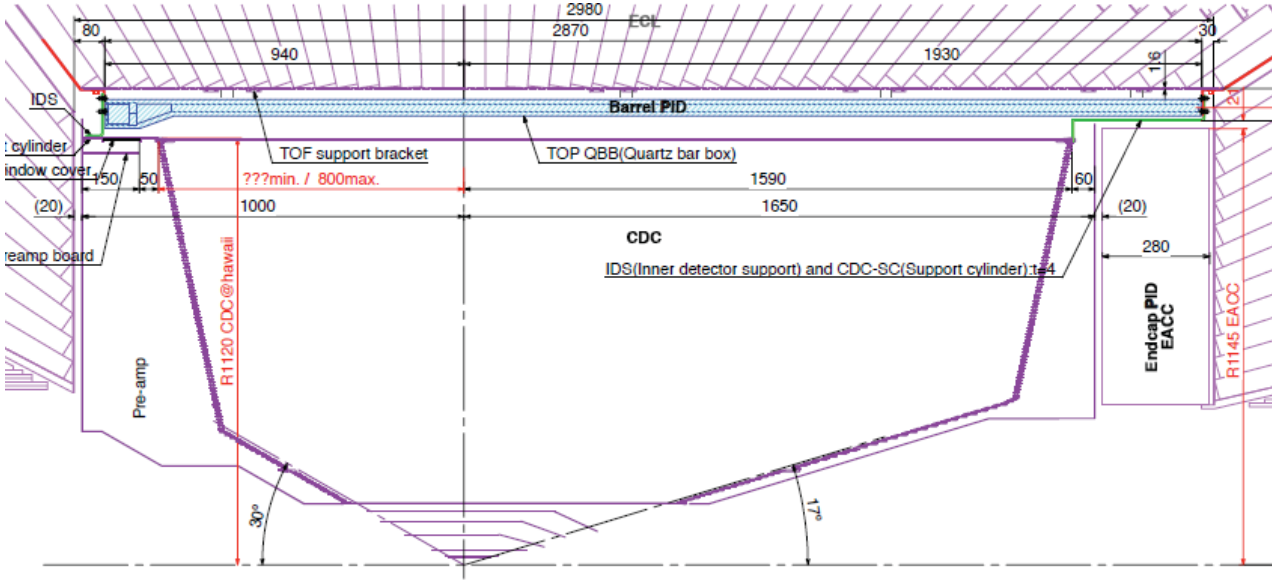




実用化に向けた開発研究

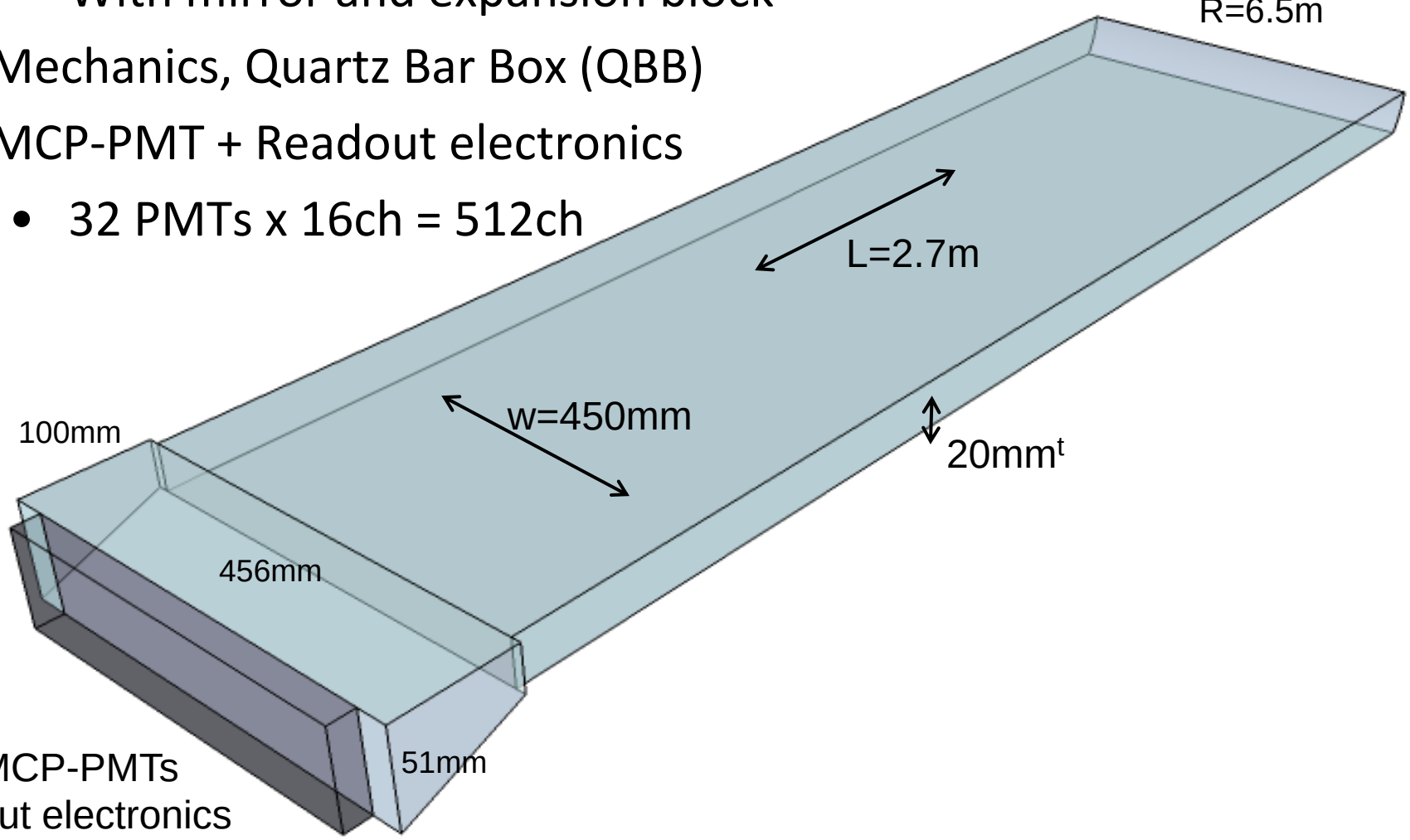
- Belle-II搭載に向けた形状最適化・構造体開発
  - ハワイ大学、リュブリアナ研究所等との共同開発研究
  - 物理過程(B→ππ, ργなど)に対する性能比較による測定器形状の選択
  - 設置可能な範囲で測定器形状を最適化
    - 既存のBelle構造体に設置できる支持体のデザイン



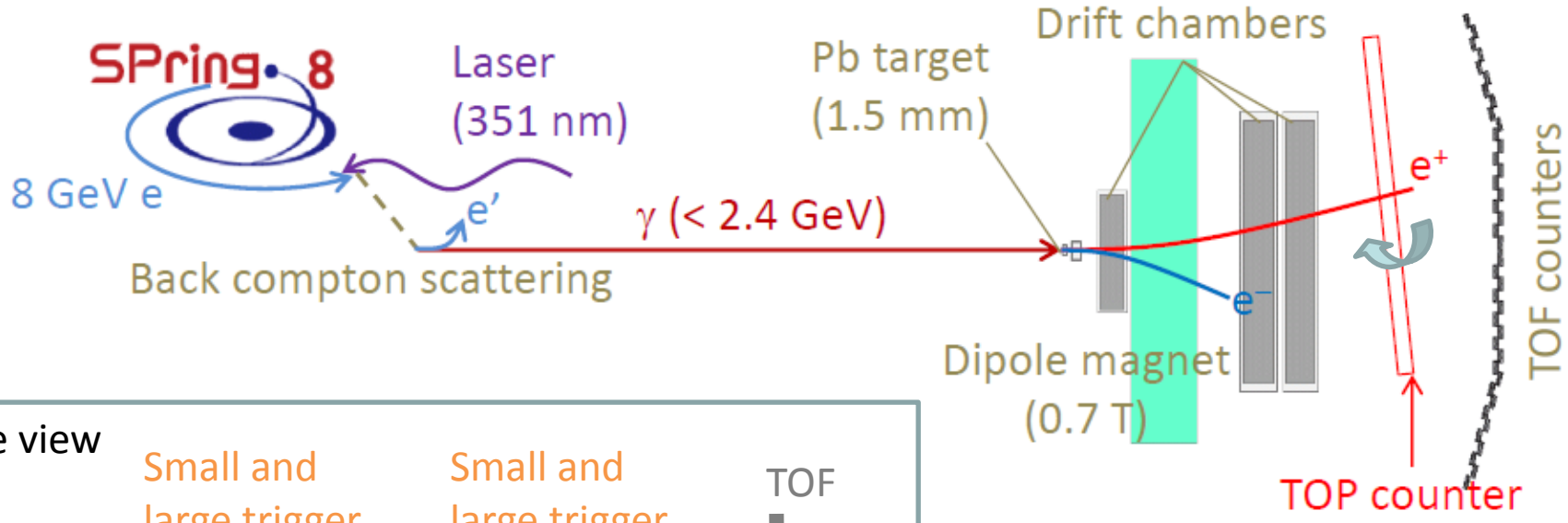


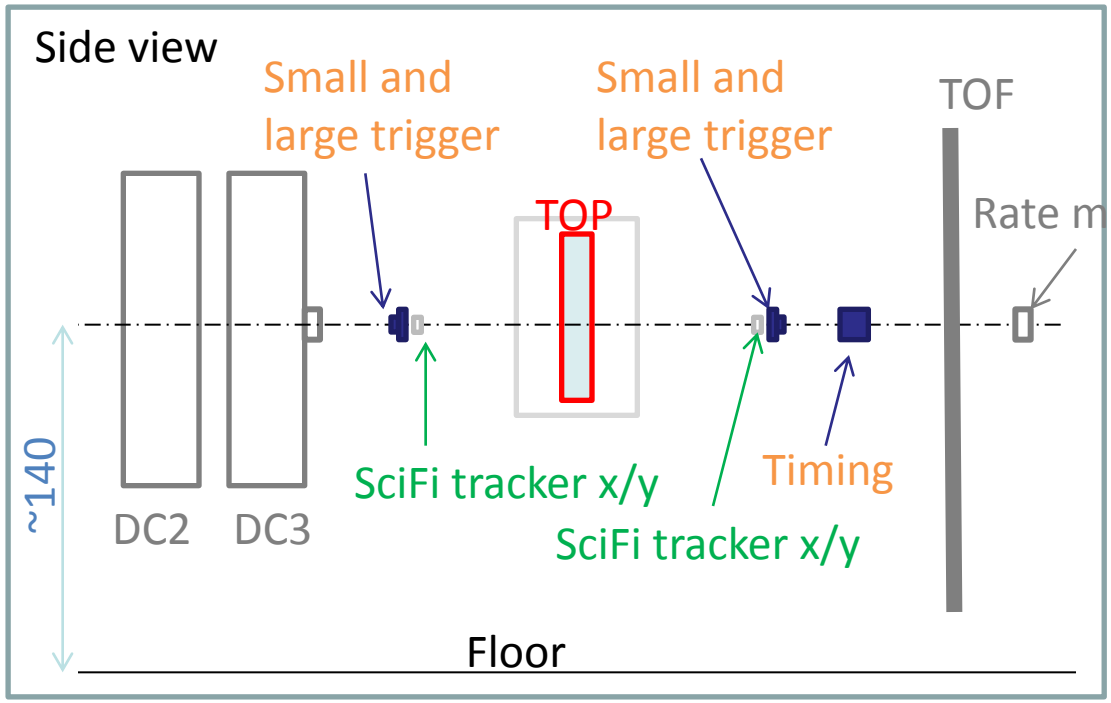
TOP counter for Belle II

- Quartz radiator
  - With mirror and expansion block
- Mechanics, Quartz Bar Box (QBB)
- MCP-PMT + Readout electronics
  - 32 PMTs x 16ch = 512ch



Beam test at Spring-8 LEPS





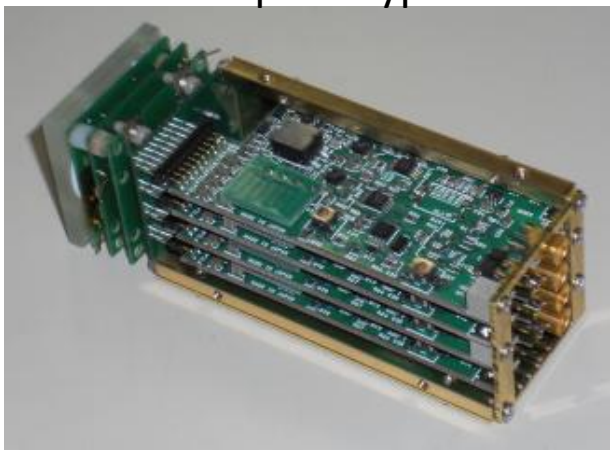
Triggered the 2 GeV/c e^+ beam with the four trigger counters (two 40 x 40 mm^2 and two 5 x 5 mm^2)

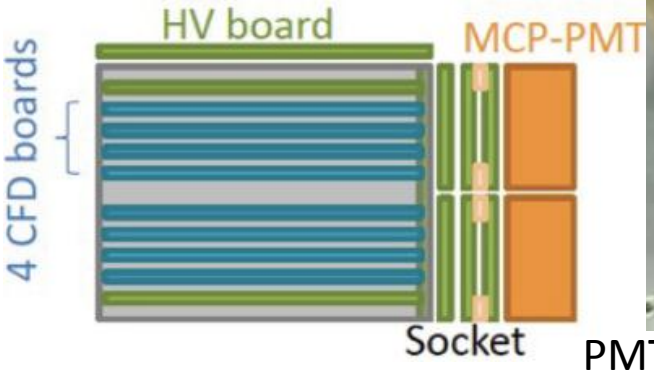
- γ rate: ~300 kHz
- Trigger rate: ~10 Hz
- DAQ rate: ~5 Hz (IRS run)
  ~10 Hz (CFD run)

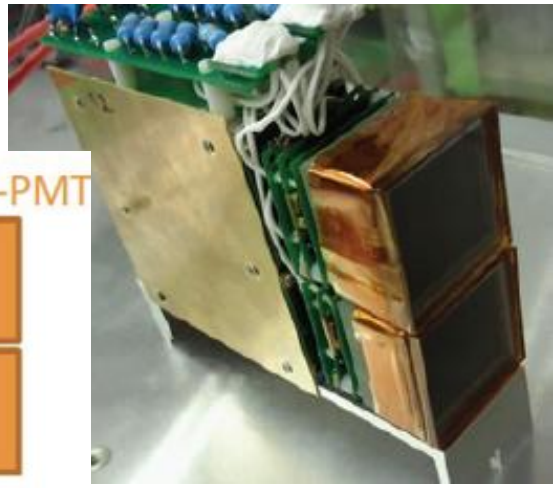
CFD readout for beam test

- CFD readout
  - Used already at previous beam tests
  - 1x4 readout.
    - 4-channels are combined (128ch/module).
  - Suitable back-up for beam tests.
- Good resolution (~40ps for single photon)
  - With MCP-PMT and CAEN VME TDC (V1290A)
  - Confirmed by laser

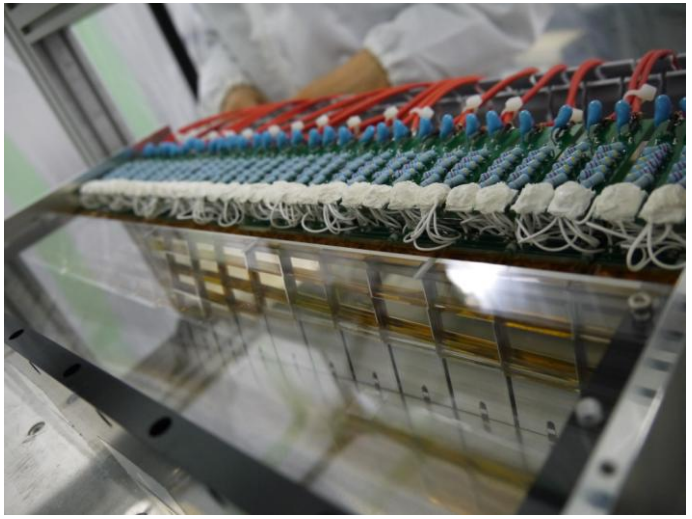
CFD module prototype





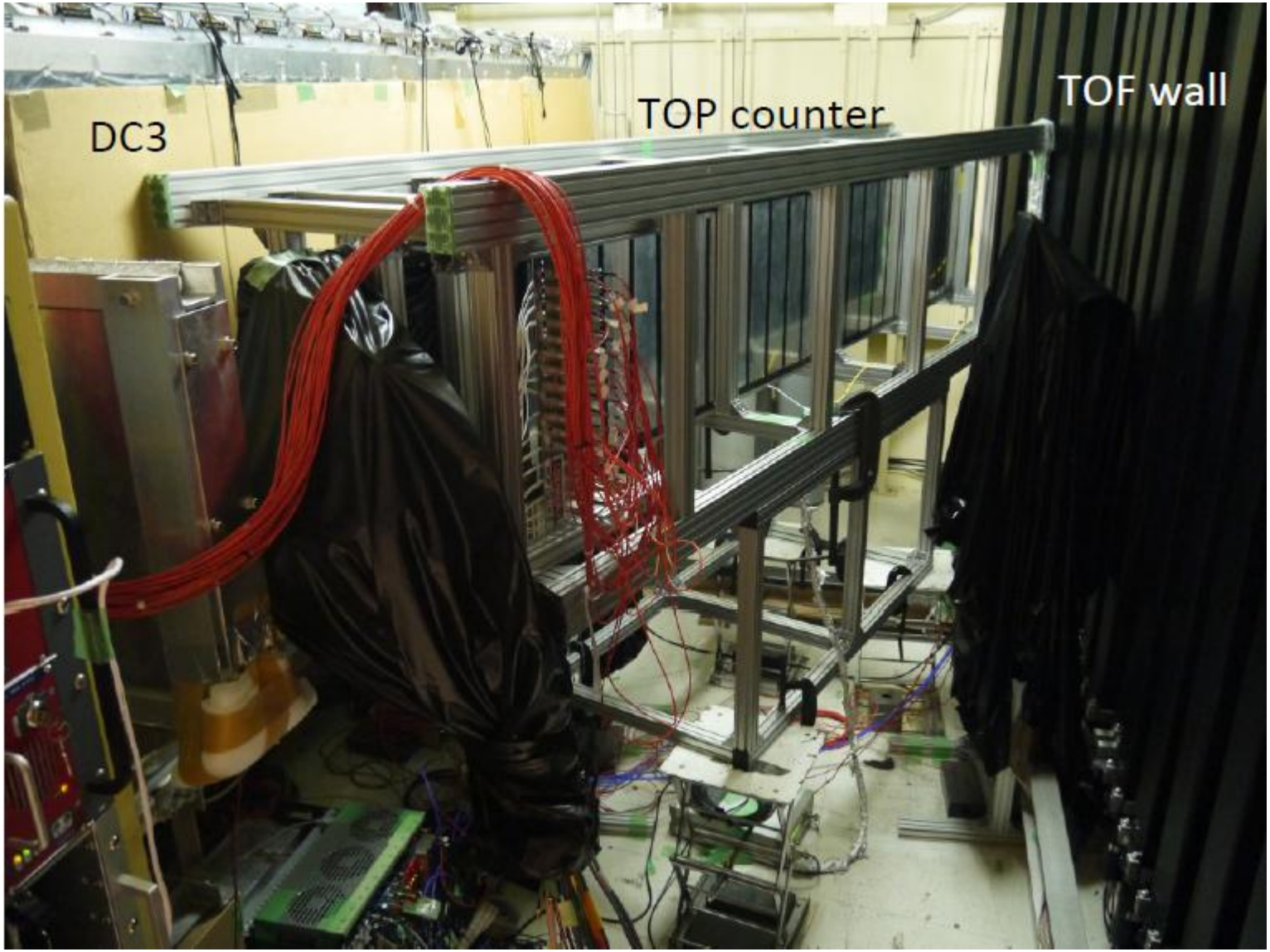


PMT module for beam test

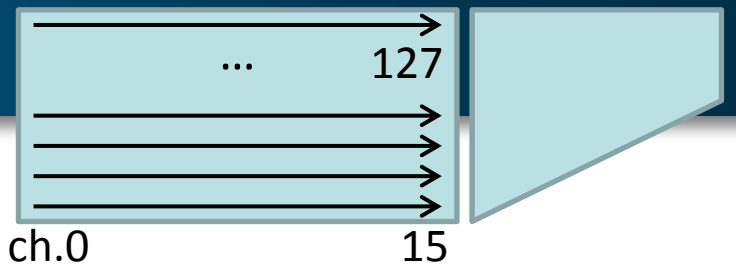


PMT modules mounted

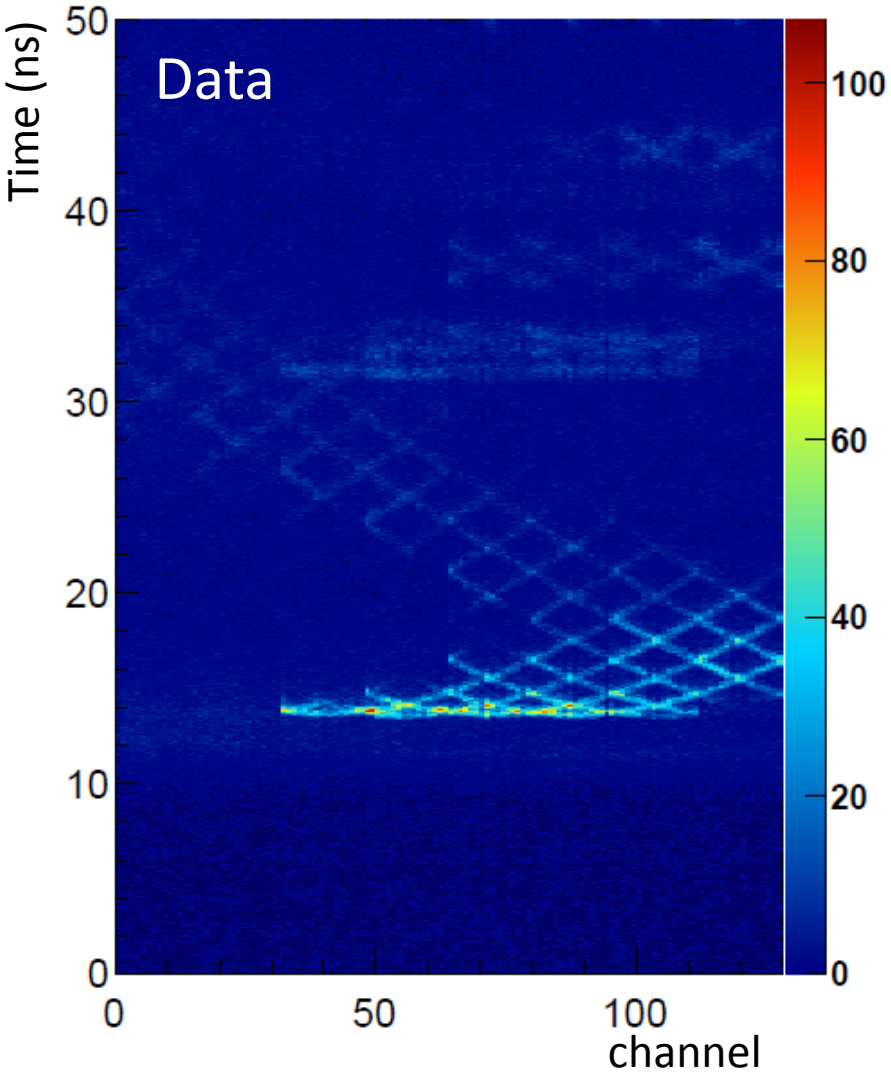
TOP counter in LEPS beam line

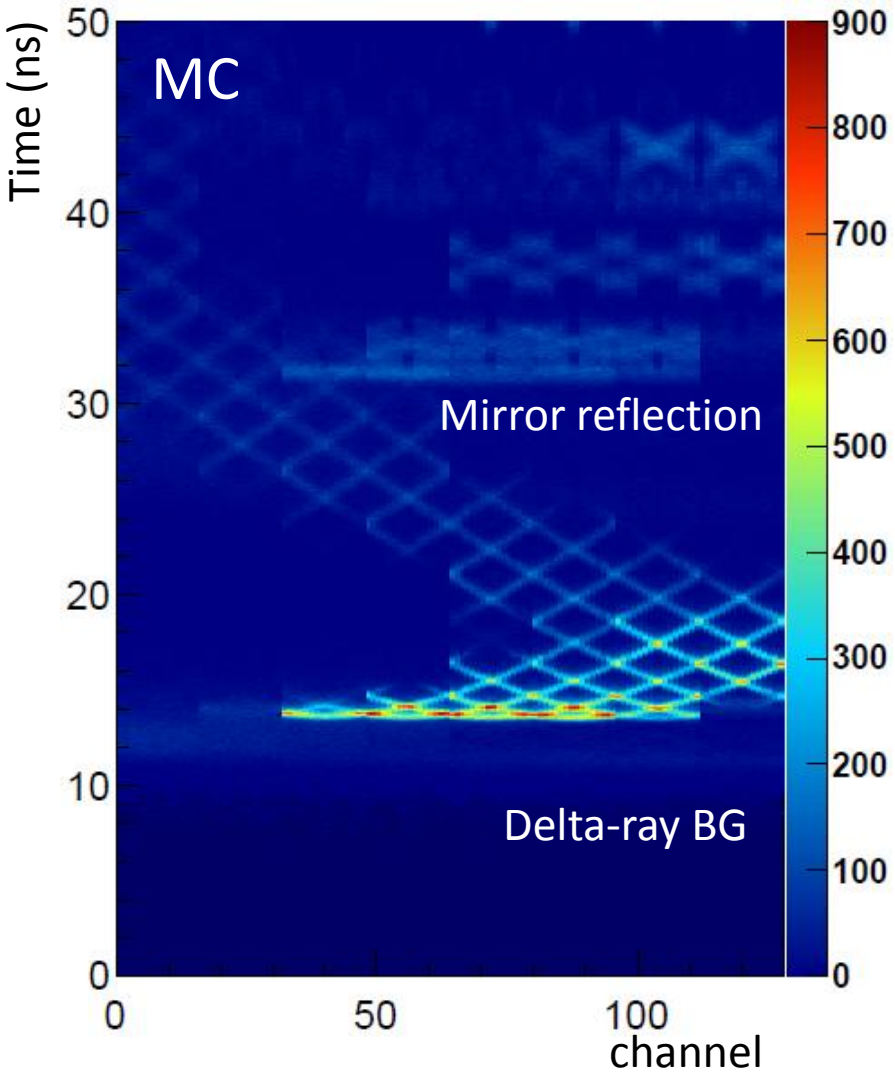


Ring image



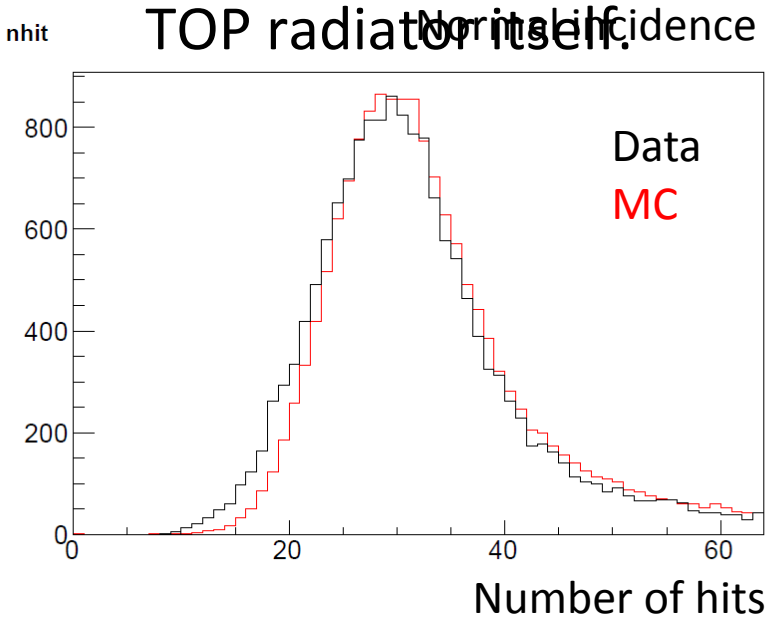
- Normal incidence, CFD readout

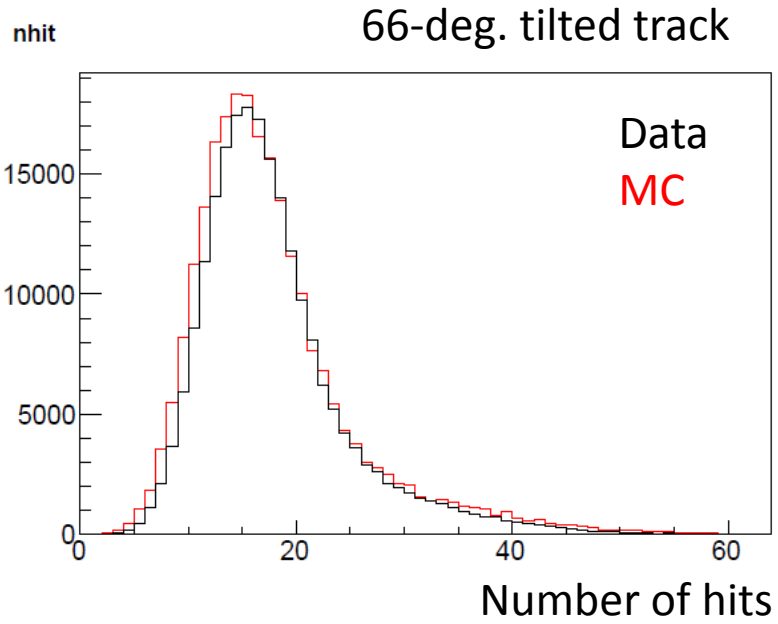




Number of detected photons per event

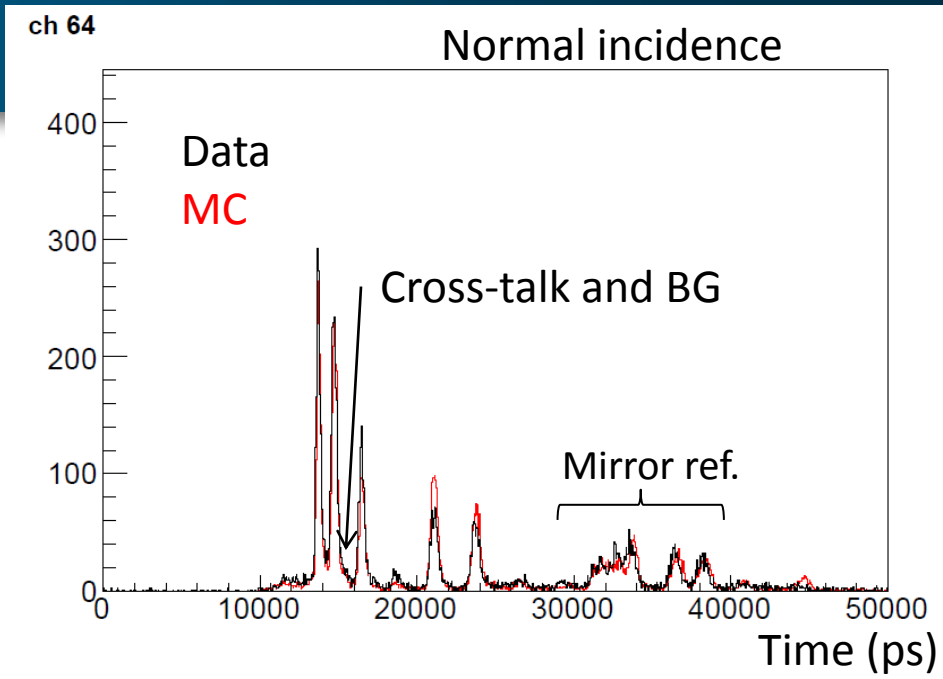
- Number of hits was obtained as expected.
  - Peak: 25 hits for normal incidence, 15 hits for tilted track
  - Considering path length, photon acceptance, QE (av. 29% at peak), cross-talk/charge sharing (~13%), etc.
  - Tail component is due to the delta-ray and shower tracks in the front of TOP counter (trigger and Scifi tracker) and TOP radiator itself.

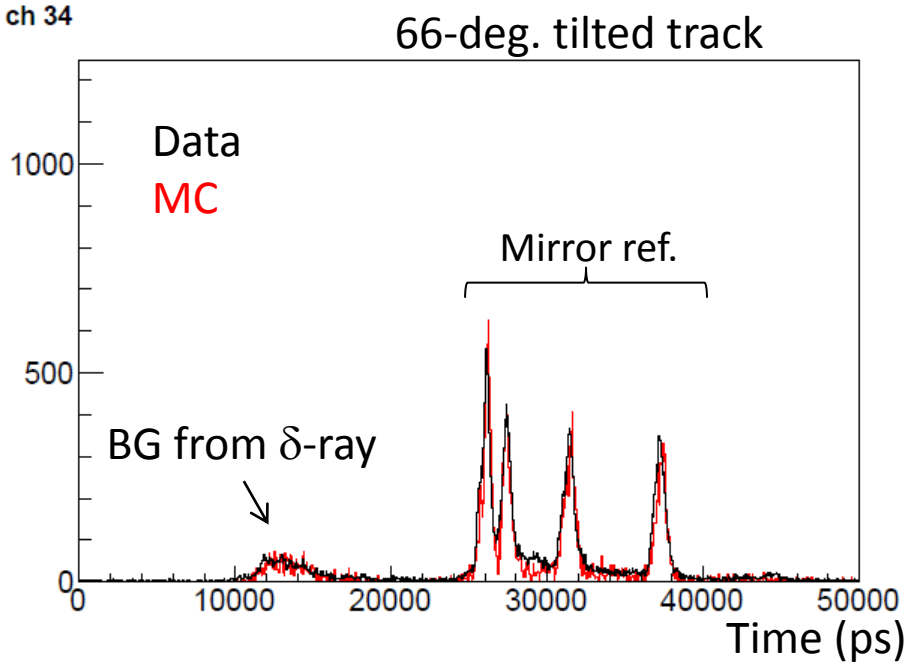




TDC distribution

- Good agreement between data and MC expectation.
  - Background component (especially for the data before first peak)
    - Due to delta-ray/showering tracks by the electron beam interaction with the material in front of detector.
  - Tail component
    - Reproduced by cross-talk hits and background





まとめ

- TOPカウンターの原理的な動作検証と実用化に向けた開発

- MCP-PMT
  - 安定的に良いTTS(<40ps)、十分なゲインが得られることを確認
  - 内部構造の改良により寿命を向上させた
  - Super Bialkali光電面技術の適用
    - 検出光子数の向上、十分な寿命の実現

- プロトタイプの開発・ビームによる性能評価
  - リングイメージ、検出光子数が期待どおり得られた
  - 時間分解能の伝播距離依存性
    → 色分散効果の大きさを検証
  - フォーカシングミラーを用いた光学系で時間分解能が向上することを確認

Back up

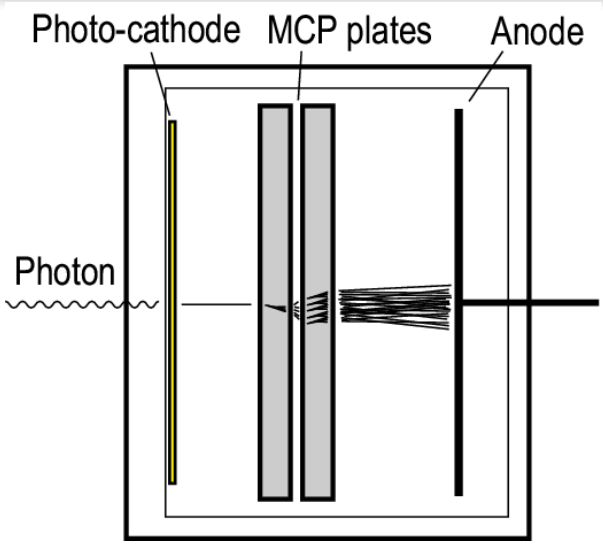
MCP-PMT

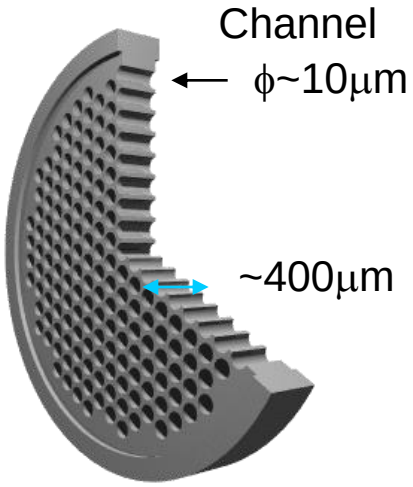
- Micro-Channel-Plate
  - Tiny electron multipliers
    - Diameter ~10μm, length ~400μm
  - High gain
    - ~10^6 for two-stage type

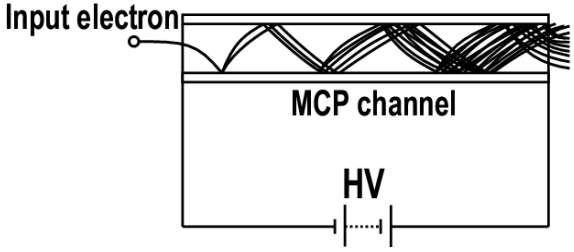
→ Fast time response

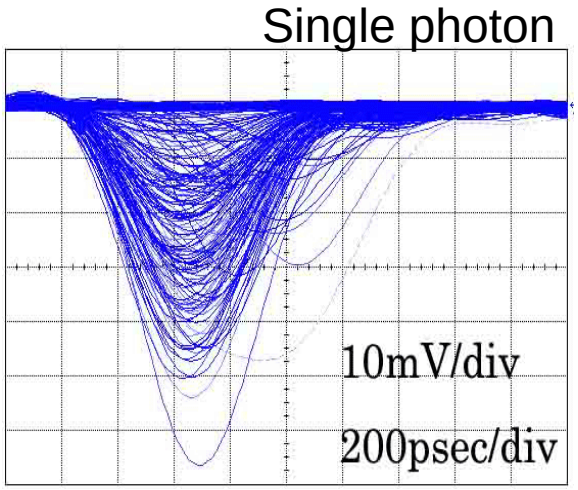
Pulse raise time ~500ps, TTS < 50ps

- can operate under high magnetic field (~1T)



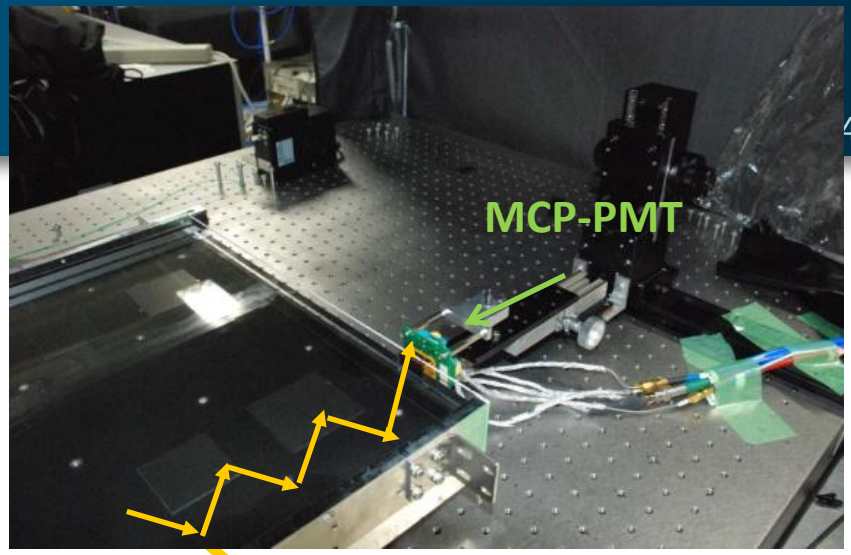


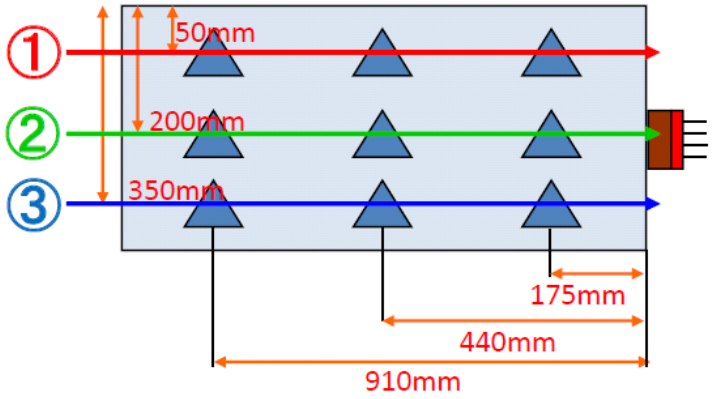


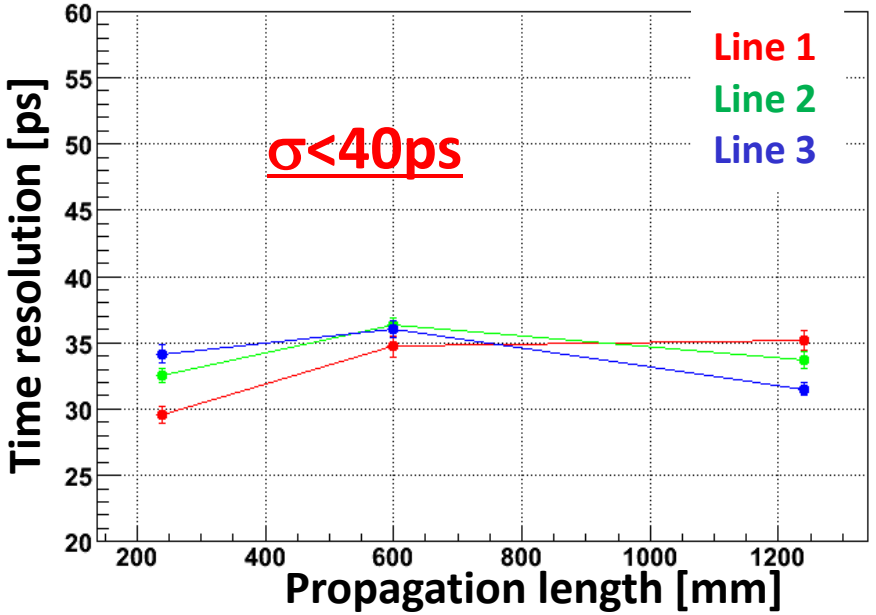


Quartz radiator

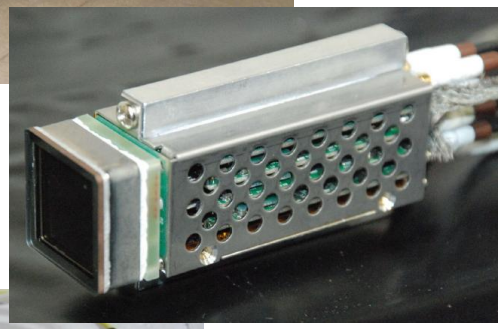
- Made by Okamoto optics
  - Size; 91.5 x 40 x 2 cm^3
  - Flatness: <1.2μm/m
  - Roughness: <0.5nm
- Check the quality for time resolution
  - Single photon pulse laser
    - λ=407nm
  - MCP-PMT
  - Several incident position
- → No degradation of time resolution
  - Enough quartz quality



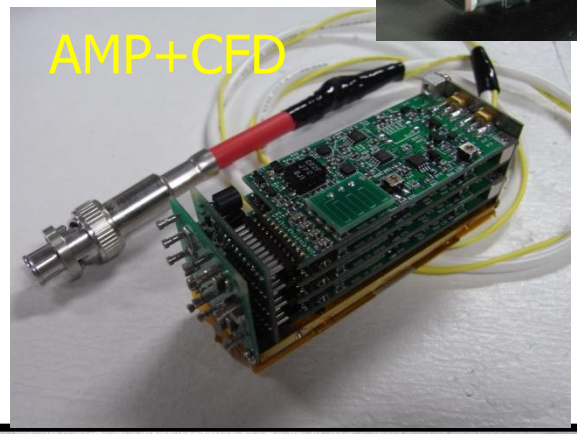




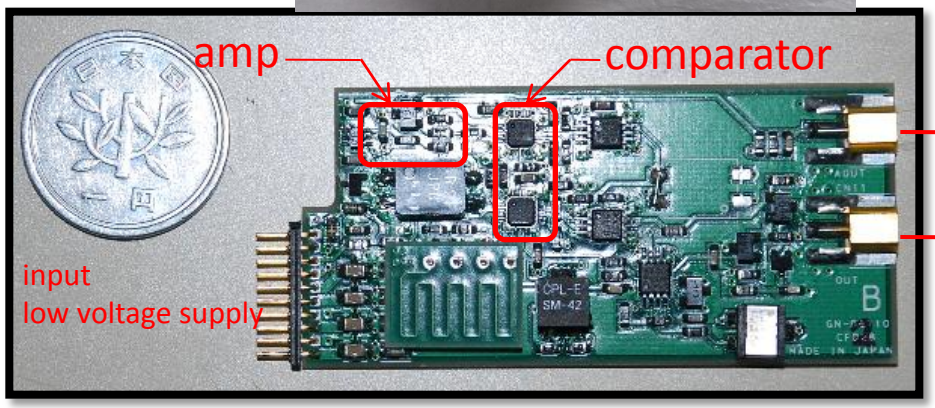
PMTモジュール



- HV divider + AMP + Discriminator
- 小型 (28mm^{W})
- 試作機
  - 高速アンプ(MMIC, 1GHz, x20)
  - 高速コンパレータ (180ps propagation)
  - CFD with pattern delay

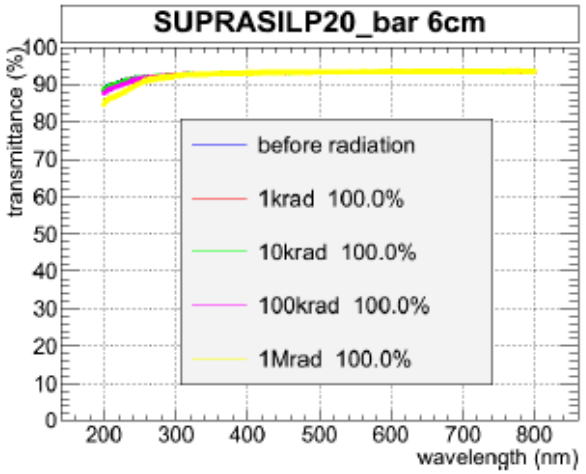


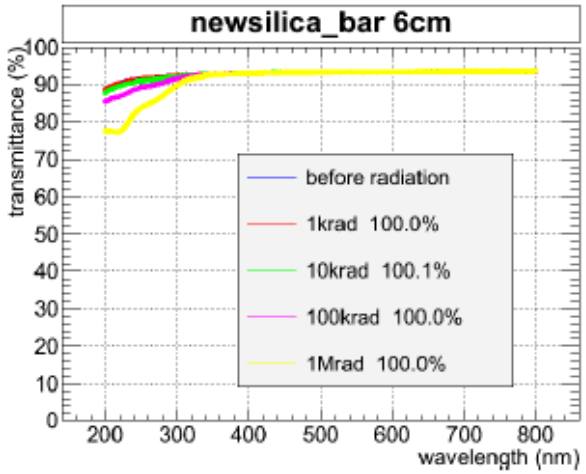
- 性能
  - Test pulse
    - ~5ps resolution
  - MCP-PMT
    - σ<40ps

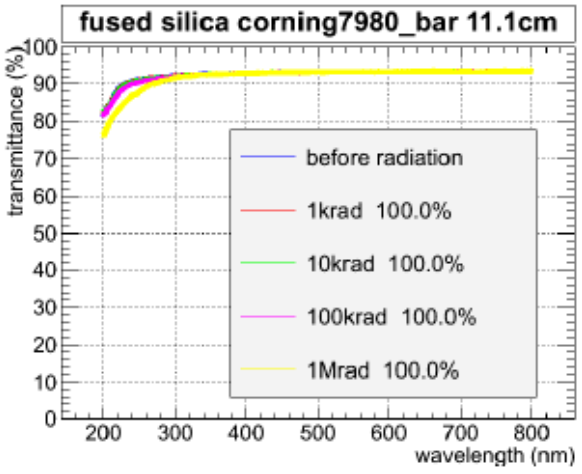


放射線照射後の透過率変化

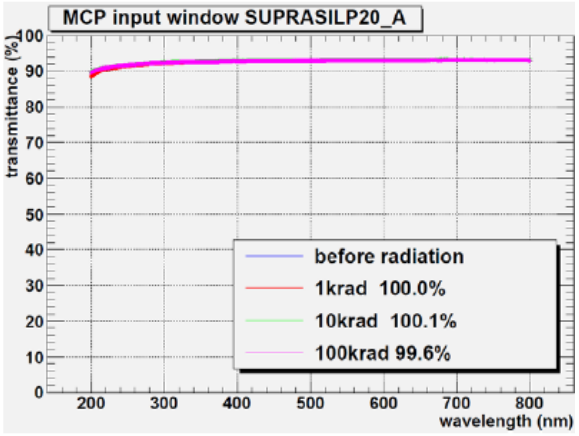
- Quartz

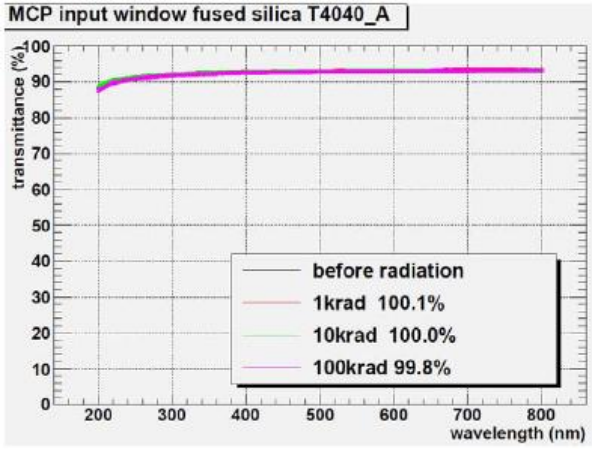


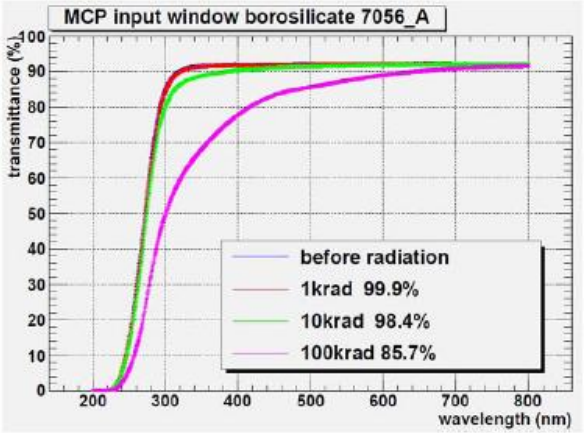




- MCP-PMT window



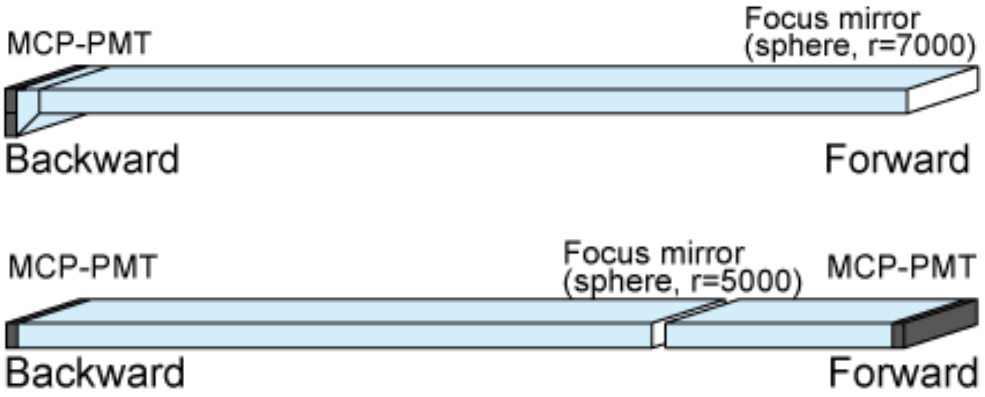




- Belle-IIで期待される放射線量に対して変化なし

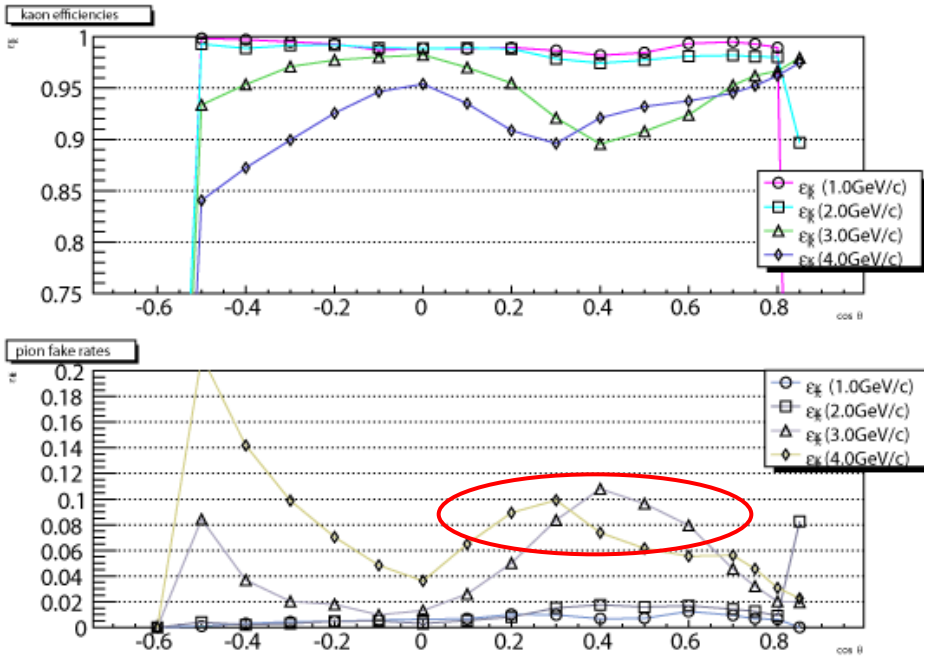
Configuration study

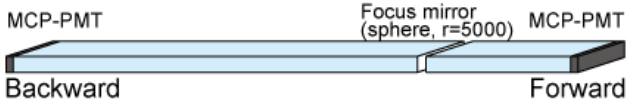
- Two options
  - 1-bar/2-bar configurations
    - Use the similar detector components and technologies.
      - Same quartz radiator size, same MCP-PMT, same mirror shape
  - By simulation studies and prototype operations, we have confirmed the robustness against the timing jitter, tracking resolution, production readiness etc.



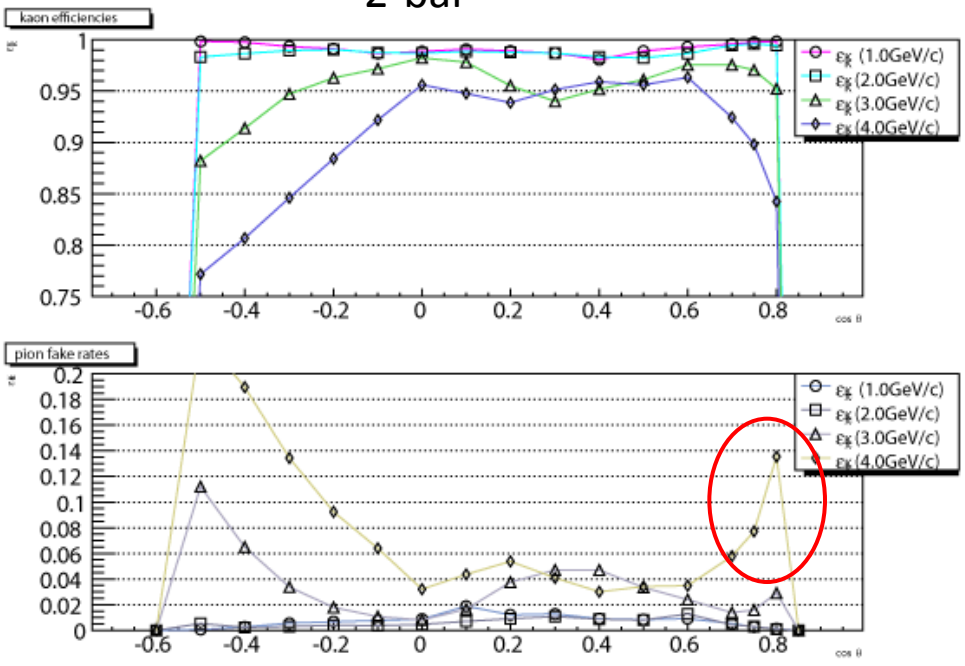
Performance

1-bar





2-bar



Incident angle fluctuation (1mrad)

Timing fluctuation (25ps)

<u>Performance similar (weighted) for physics case studies</u>

Performance check

- For physics cases

From TDR

- Check by three simulation program

Table 7.8: Efficiencies and fake rates obtained from simulation for $B \to \pi\pi$, under the set of assumptions described in the text.

		K efficiency (%)			π fake rate (%)		
Geometry	Photocathode	GSIM	Geant4	stand-alone	GSIM	Geant4	stand-alone
2-bar	MA	95.8	97.3	96.2	2.6	2.4	3.7
1-bar	MA	93.4	95.5	96.7	5.2	3.9	3.1
2-bar	SBA	96.7	98.1	97.5	1.4	1.5	2.4
1-bar	SBA	95.4	97.2	98.5	3.3	1.9	1.4

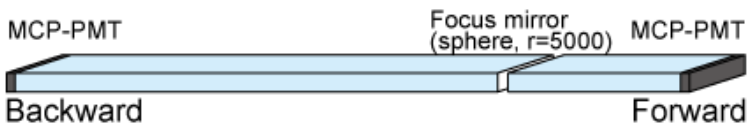
Table 7.9: Efficiencies and fake rates obtained from simulation for $B \to \rho\gamma$, under the set of assumptions described in the text.

		K efficiency (%)			π fake rate (%)		
Geometry	Photocathode	GSIM	Geant4	stand-alone	GSIM	Geant4	stand-alone
2-bar	MA	97.4	99.5	99.1	0.9	0.3	0.9
1-bar	MA	96.8	99.1	98.6	1.0	0.5	2.1
2-bar	SBA	97.7	99.8	99.6	0.8	0.1	0.4
1-bar	SBA	97.4	99.6	99.5	0.7	0.1	1.0

Nagoya **Hawaii** **Ljubljana**

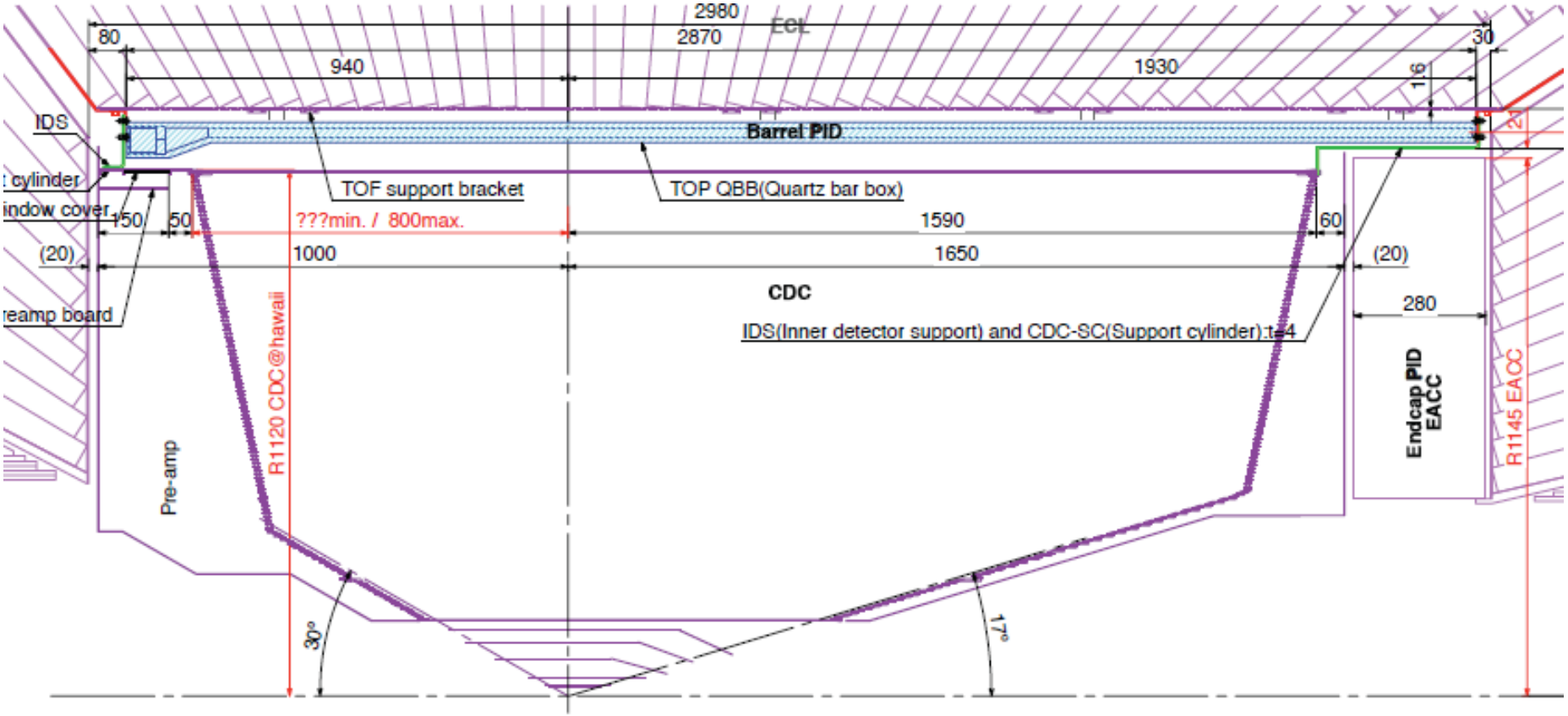
- Chose 1-bar configuration due to practical considerations

Comparison



	1-bar	2-bar
Structure / configuration	Needs expansion block	Need forward PMTs + readout Strong bar box (between 2-bars)
TOP-CDC gap	Somewhat larger (~25mm)	Minimum
Acceptance	Larger in forward region (better overlap with endcap PID)	There is a small polar angle gap between the 2-bars
Readout	Backward	At both ends
Construction	Needs test of prototype	2m prototype
Performance	Better in the most forward acceptance	Better for mid-forward polar angles Slightly better overall
Note	Track extrapolation resolution (<2mrad)	Timing determination (<30ps) for forward (Need precise calib. of 25ps)

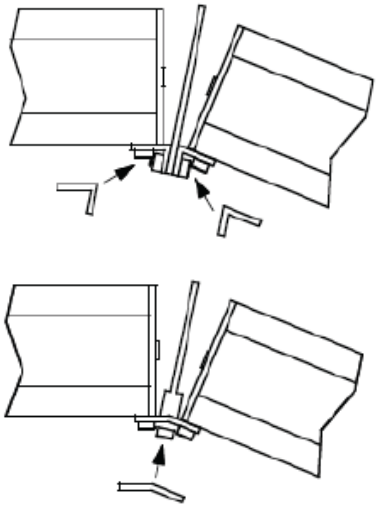
Structure

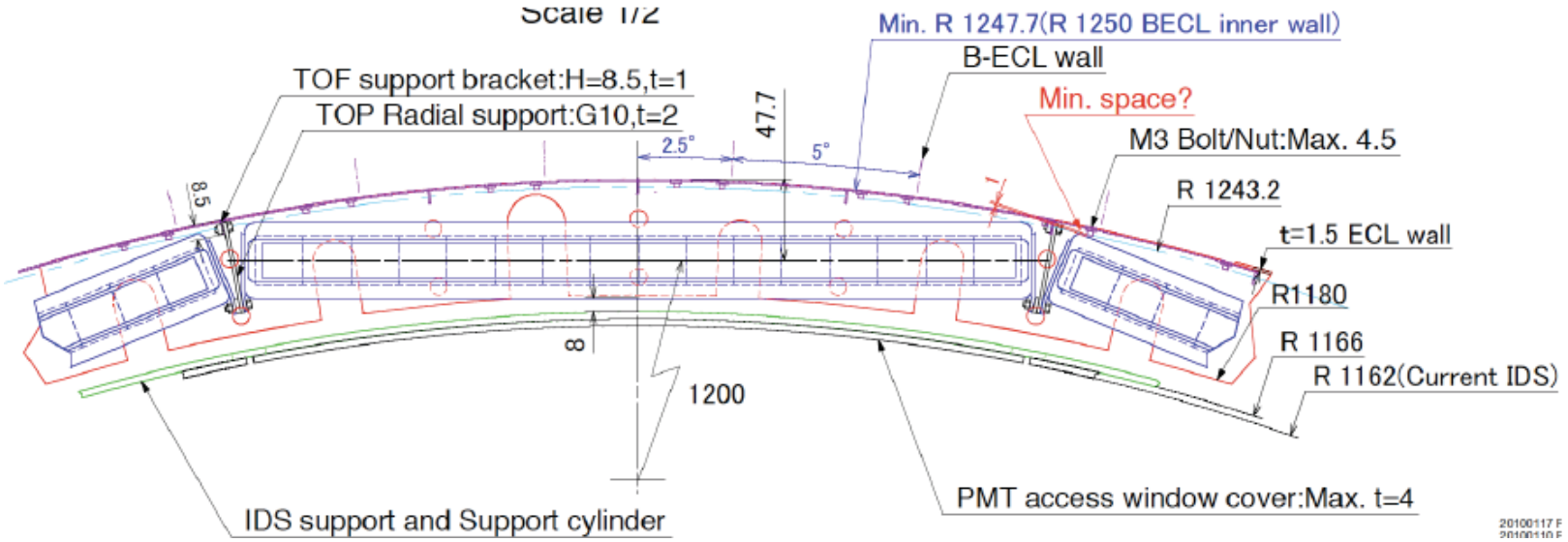


- Check possible detector size and support
  - Quartz length, width, thickness
  - Minimize dead space and material

Structure design

- Maximize the single module performance under the following constraints.
  - Reuse the existing ECL container.
  - Quartz bar dimension
    - W:400 - 500 mm x T:~20 mm
    - 16 azimuthal segments (ϕ = 22.5 deg.)
    - Maximize the azimuthal coverage (η_ϕ = 95 %)

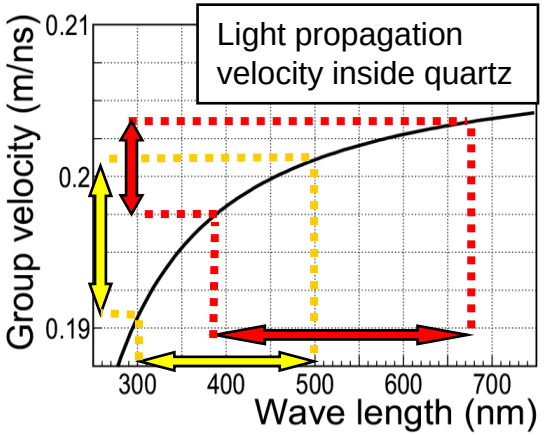


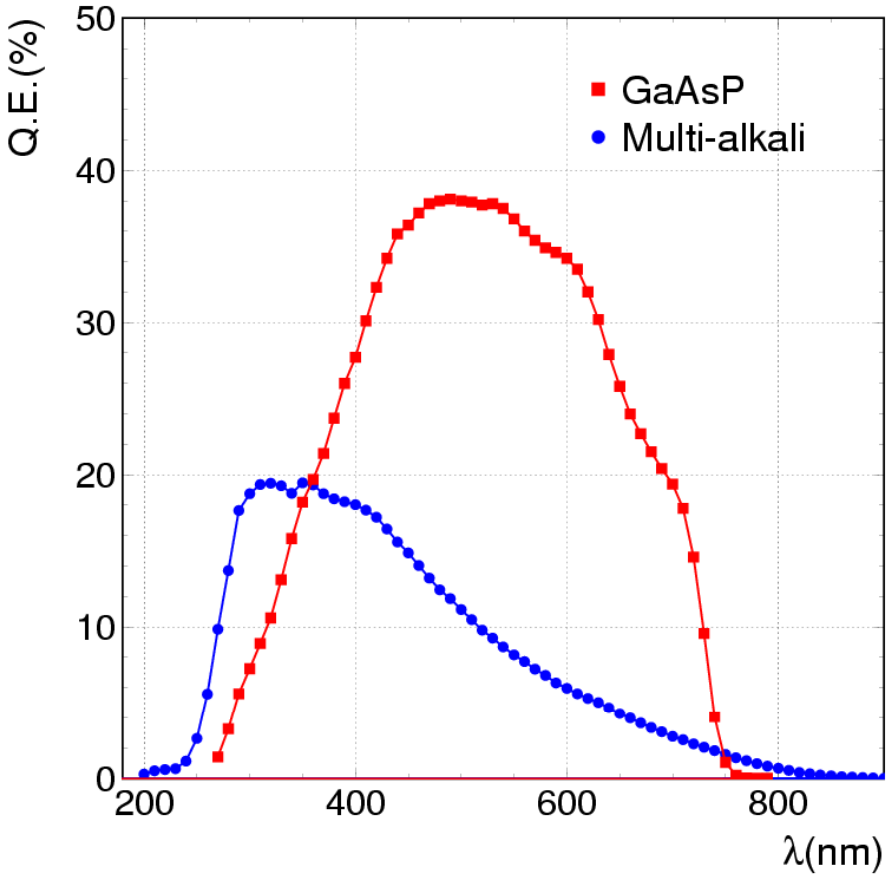


GaAsP MCP-PMT; Q.E. 分布

- プロトタイプ

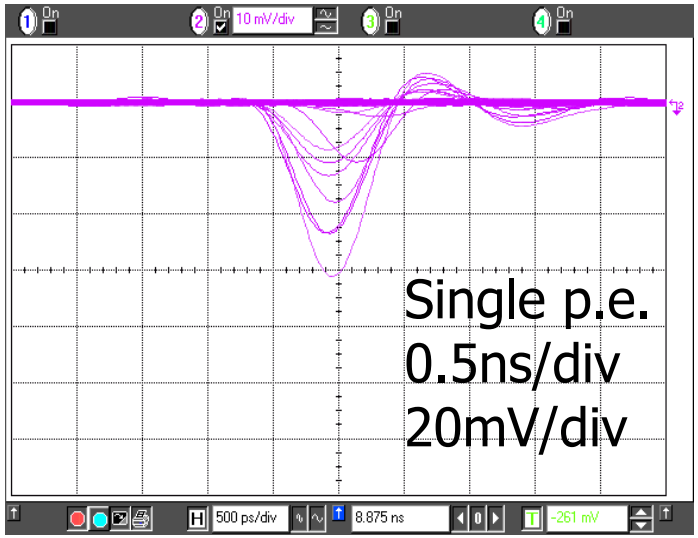
- マルチアルカリ光電面と比較して
- 良い量子効率
  - >35% at 500nm
- 長波長に感度

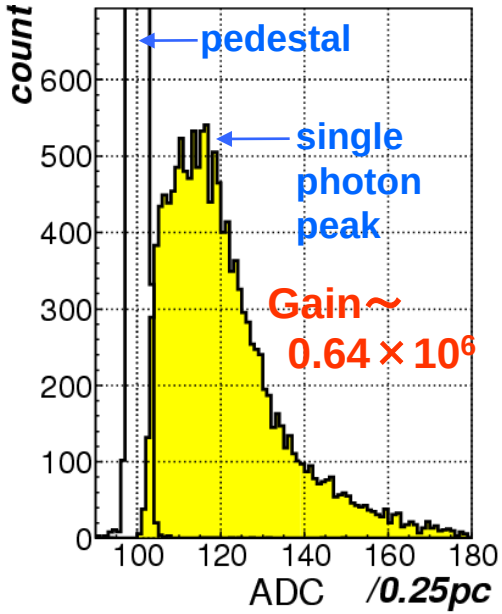


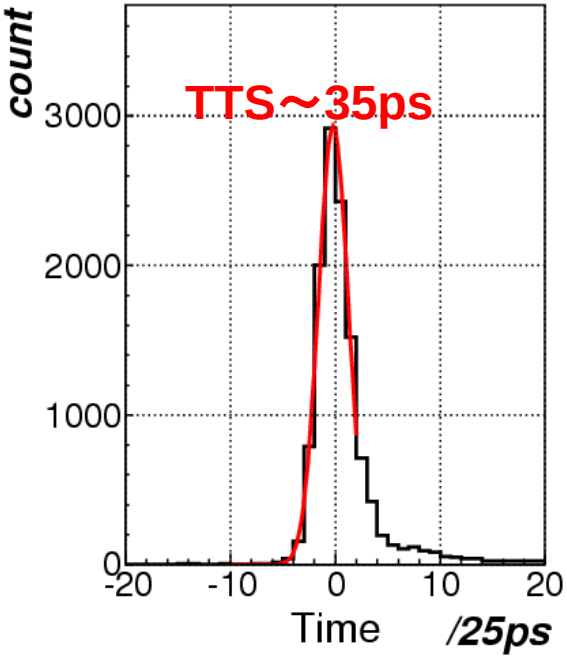


GaAsP MCP-PMT 基本性能

- 一光子照射時の出力波形, ADC, TDC分布







- 一光子を検出するために十分なゲイン
- 35psの十分良い時間分解能
- ダークカウント: 数kHz
  - MCP増幅部は正常に動作
  - 光電面の時間分解能に対する影響は少ない