KOTO-II:
Status, prospects, and synergies with HIKE

Matthew Moulson
with slides stolen from Tadashi Nomura, Hajime Nanjo & Yu-Chen Tung

NA62 Italia
Frascati, 08 November 2024

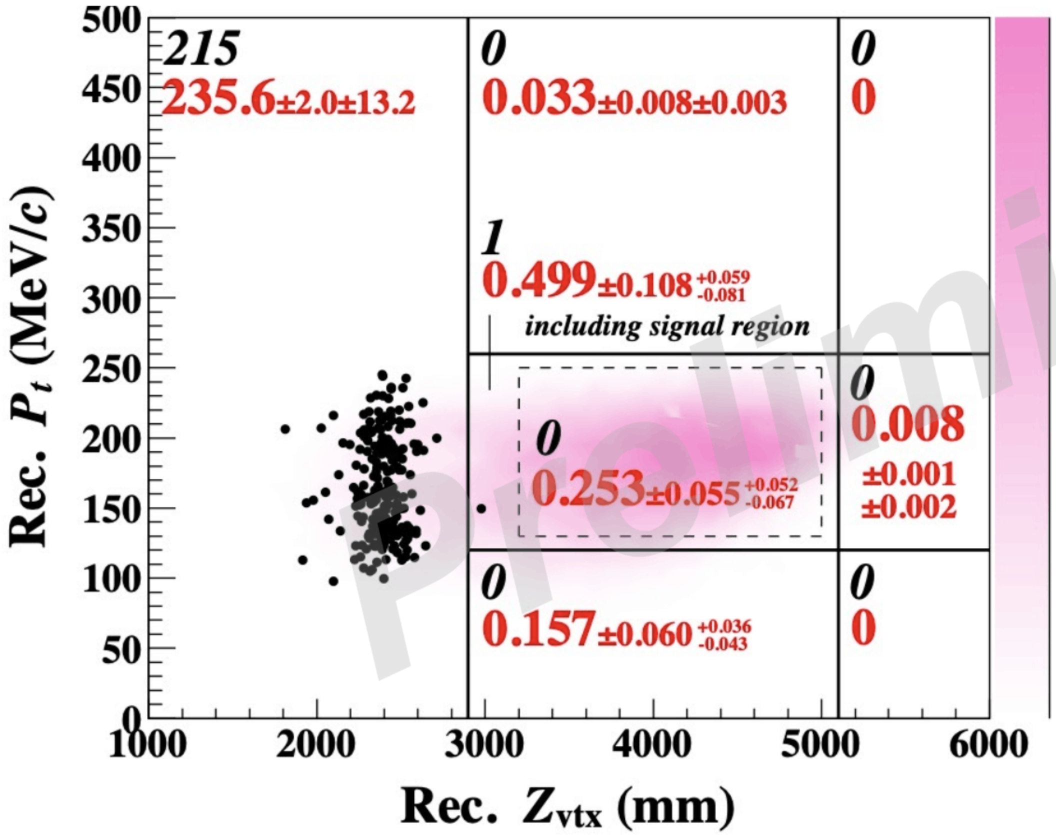
Latest results:

Results of the 2021 data analysis

Final PT vs Z plot

Black: observed
Red: expected BG
Contour: signal MC

Single Event Sensitivity = $(9.26 \pm 0.03_{stat} \pm 0.75_{syst}) \times 10^{-10}$



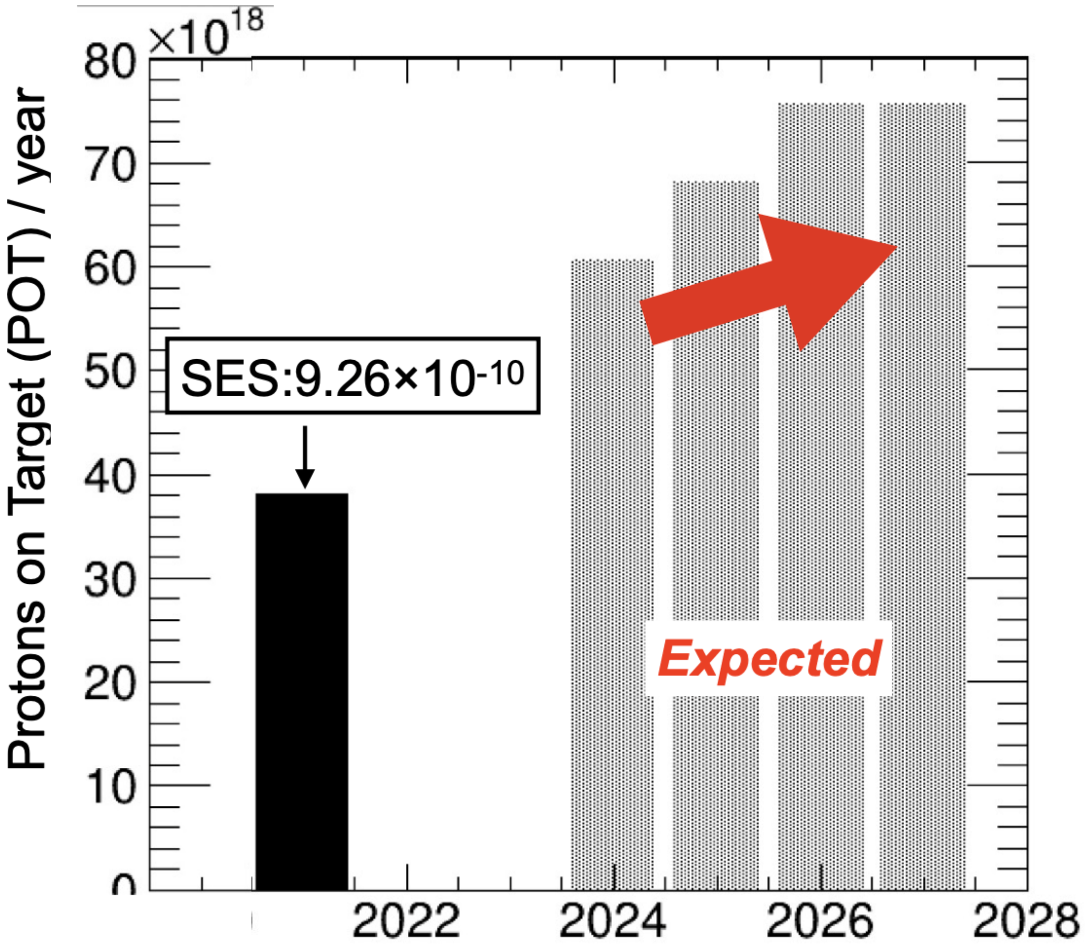
$N_{observed} = 0$

$BR(K_L \rightarrow \pi^0 \nu\bar{\nu}) < 2.1 \times 10^{-9}$ (90% C.L.)

Obtained the world best limit.

We will submit the paper on this result soon.

Consideration of sensitivity in the near future



The accumulated POT will be ×10 larger than 2021 in 4-5 years.

<u>Assumption</u>

- The beam power increases as 80→90→100kW.
- 60 days beam time / year. ☆
- Much smoother beam structure than 2021, expected by new MR power supplies with smaller ripples (upgraded in 2021-22).

Single event sensitivity (SES) will reach the level better than 10^{-10}.

- The achievable sensitivity will be $(5\text{-}8)\times10^{-11}$.

Acceptance recovery with a smoother beam (×1.5) is taken in account.

Consideration of backgrounds in future runs

Background level (BGL)≡N_{BG}(2021)×SES(2021)

Source	N_{BG} in 2021 analysis	BGL based on 2021 results	BGL in future runs
Upstream π^0	0.064	0.56×10^{-10}	By hardware upgrades in 2023-24 and by software developments (tighter cuts, better training of NN, …), we expect an additional factor of two reduction.
$K_L\to2\pi^0$	0.060	0.52×10^{-10}	
$K^\pm$	0.043	0.37×10^{-10}	
Scattered and halo $K_L(\to2\gamma)$	0.022	0.19×10^{-10}	
	0.018	0.16×10^{-10}	
Hadron cluster BG	0.024	0.21×10^{-10}	
η production in CV	0.023	0.20×10^{-10}	
Sum	0.255	2.21×10^{-10}	→ ~1.2×10^{-10}

Sacrificing ~10% signal acceptance

For tentative discussion only

- *We will try to develop methods to reduce backgrounds further.*
- *At least, we will take more control data for more precise background estimation.*

Summary

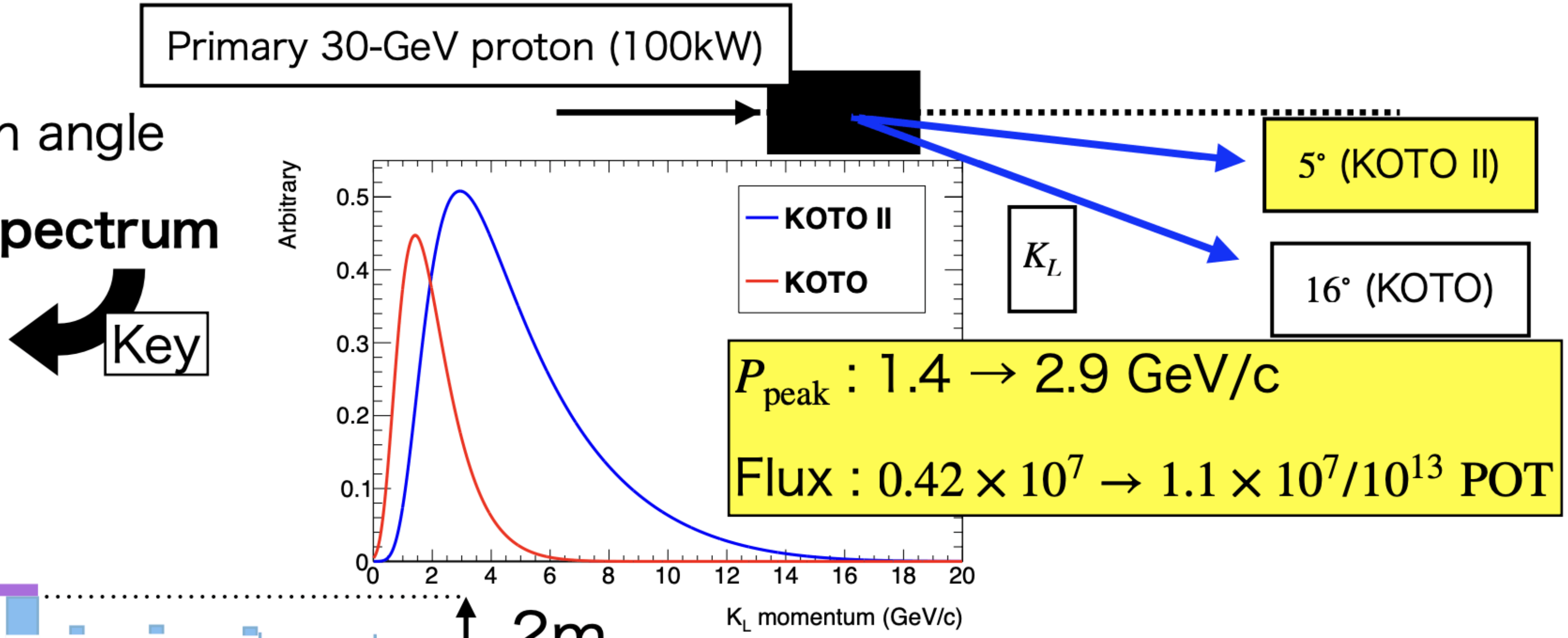
- KOTO concluded the 2021 data analysis
  - The single event sensitivity = 9.26×10^{-10},
    the expected number of backgrounds = 0.253
  - No candidate events were observed inside the signal box and set new upper limit: BR($K_L \to \pi^0 \nu\nu$)$<2.1\times10^{-9}$ (90% C.L.)

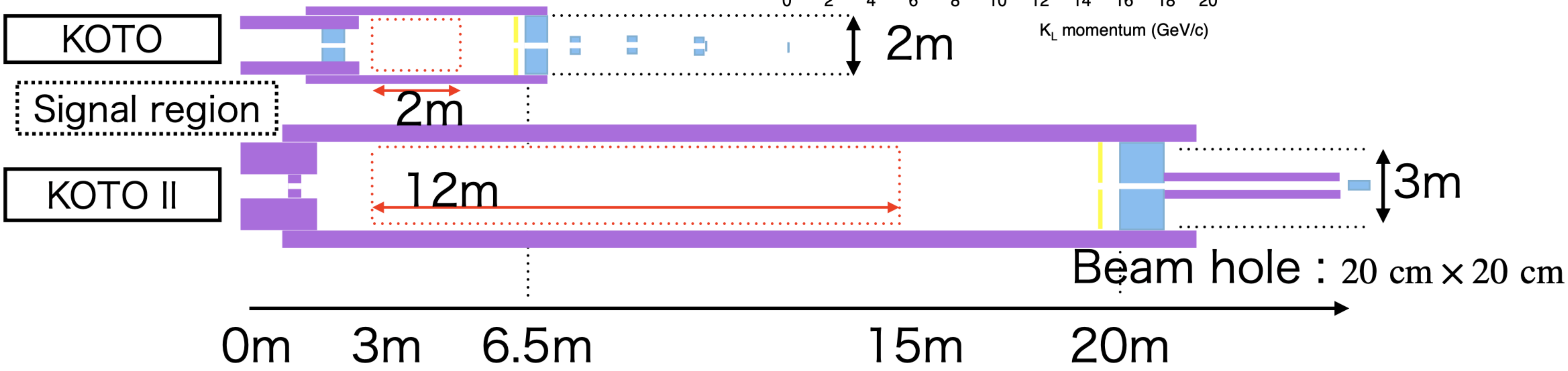
Preliminary

- KOTO is making steady efforts to reduce backgrounds further.
- KOTO plans to continue taking data and will reach the sensitivity level better than 10^{-10} in 4-5 years.
  - To discuss KOTO's reach of the $K_L \to \pi^0 \nu\nu$ search, the background level in future runs is also discussed.

How to improve the sensitivity?

- More K_L
  - Use forward production angle
    - $\times 2.6$ flux + **harder spectrum**
- More signal acceptance
  - Longer decay volume
  - Larger calorimeter



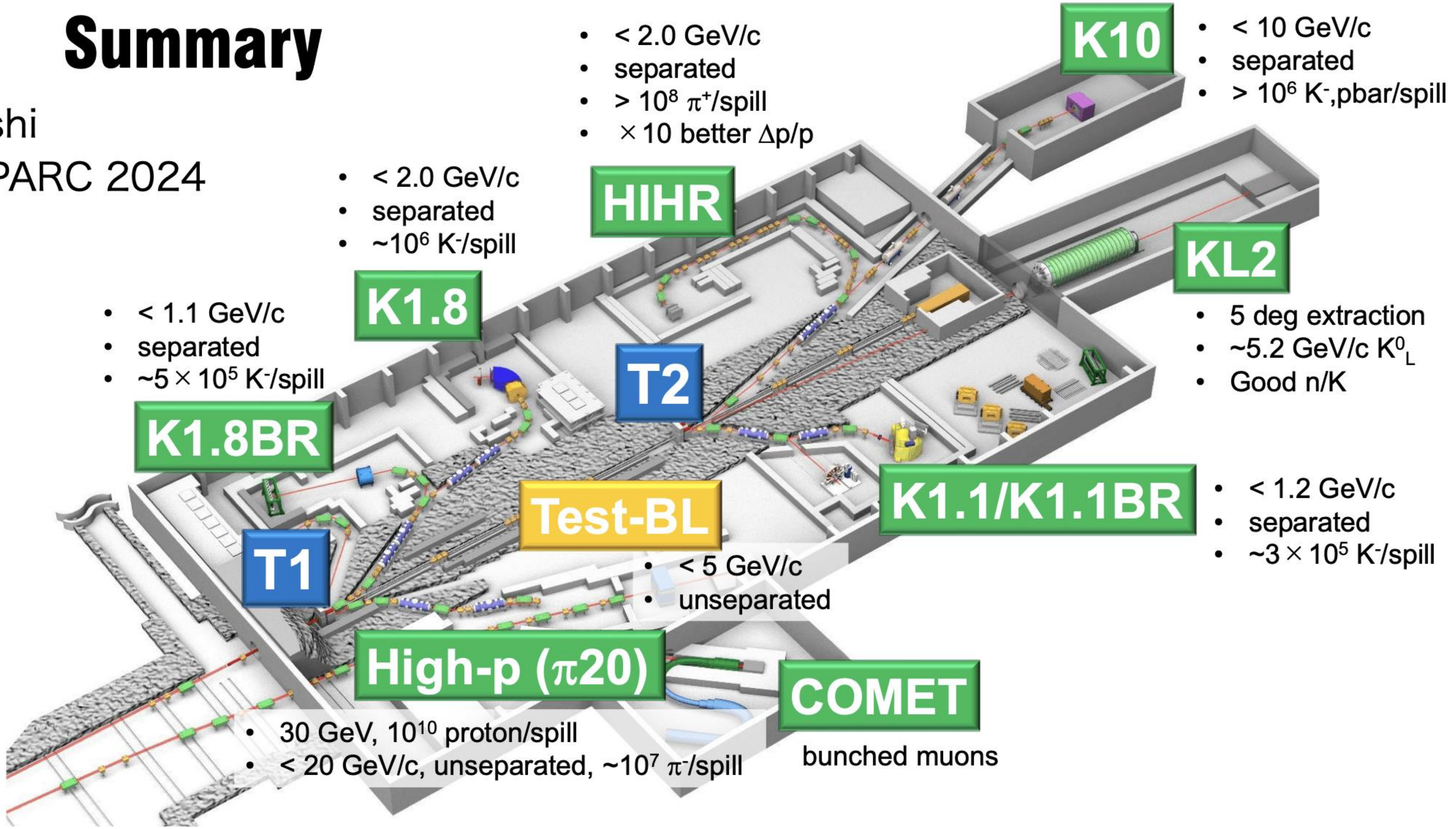


J-PARC Hadron Experimental Facility Extension

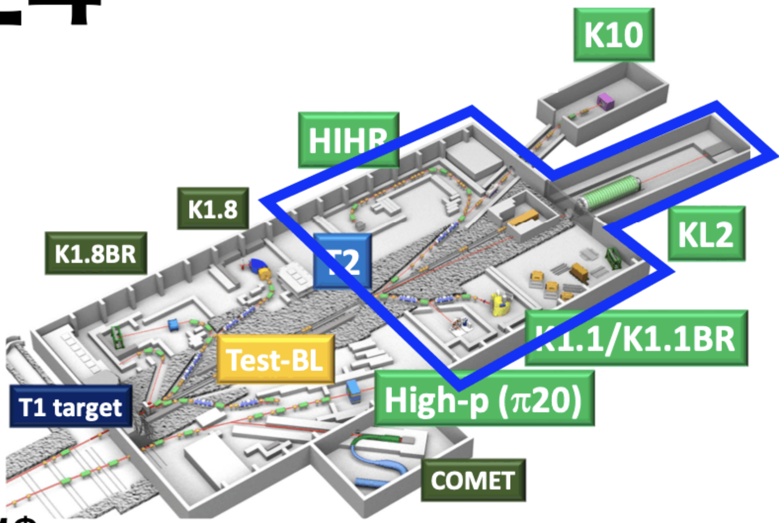
Summary

H. Takahashi

Kaons@J-PARC 2024



HEF-ex as of 2024



- Combination of Hadron physics and Particle physics

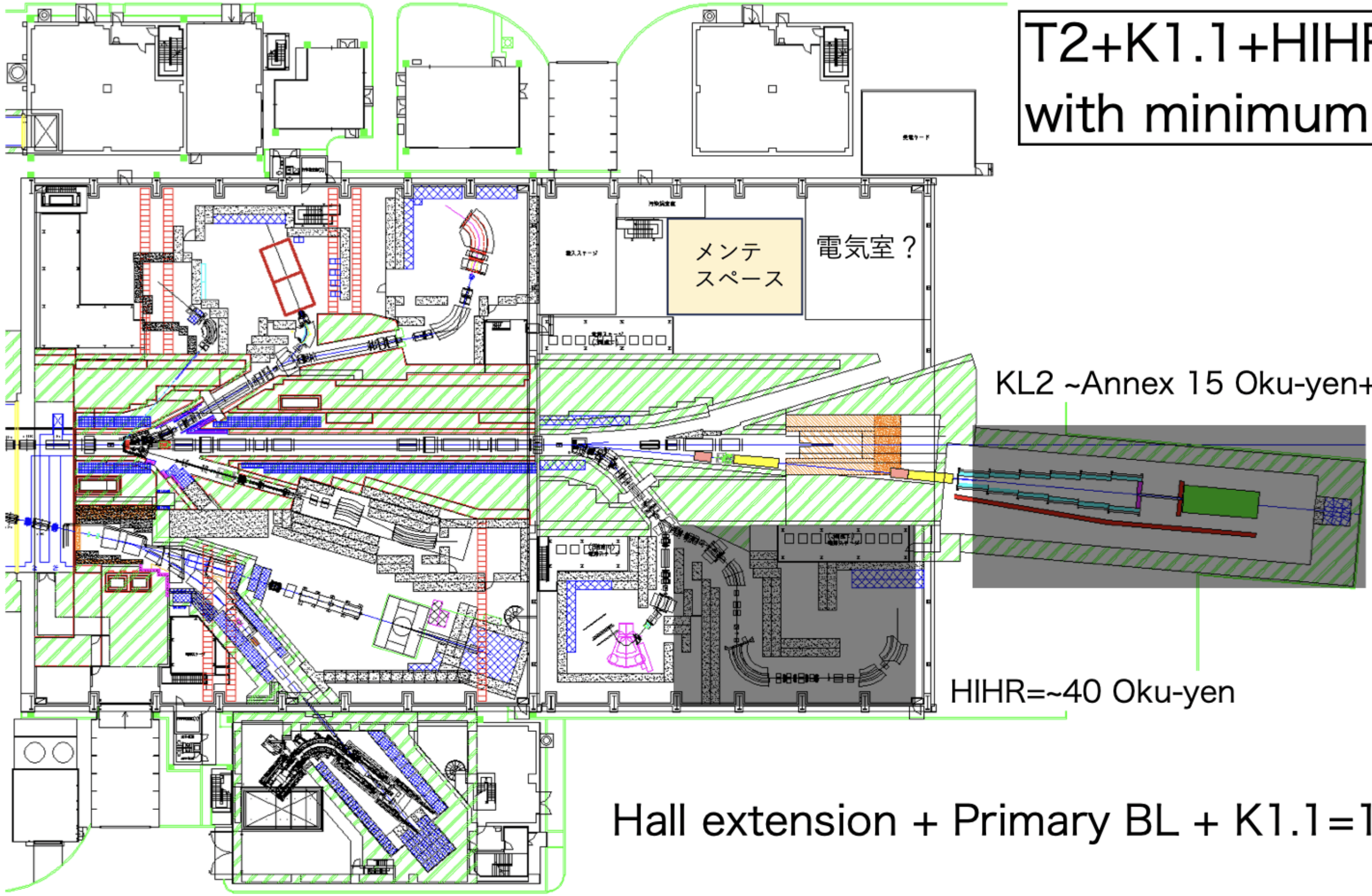
  Strangeness hadron physics
  Neutron star ↔ Hyperon puzzle (too soft)
  2 body force and 3 body force

  CP violation and high energy reach

- Cost with price rise
  - Building+Primary beamline+K1.1, HIHR KL2=196 Oku-yen ~130 M$
  - Building+Primary beamline + upstream of K1.1, HIHR, KL2 : 153 Oku-yen~100 M$
- IPNS director :
  - Difficult for KEK to request all budget to the government
    - Strengthen the physics impact
    - More international collaboration is also important
    - More institution to request funding or Cost reduction for realization
    - 2027 may be good target to request budget because of the gap in other large budgets

More recent status of HEF-ex

- Ideas toward more aggressive cost reduction under discussion
  - Because the IPNS director suggests <100 oku-yen = 63 M$ for Yen/$ in Aug 2024)



T2+K1.1+HIHR+KL
with minimum extension

KL2 ~Annex 15 Oku-yen+BL 7 Oku-yen

HIHR=~40 Oku-yen

Total : ~180 Oku-yen
Not so drastic…

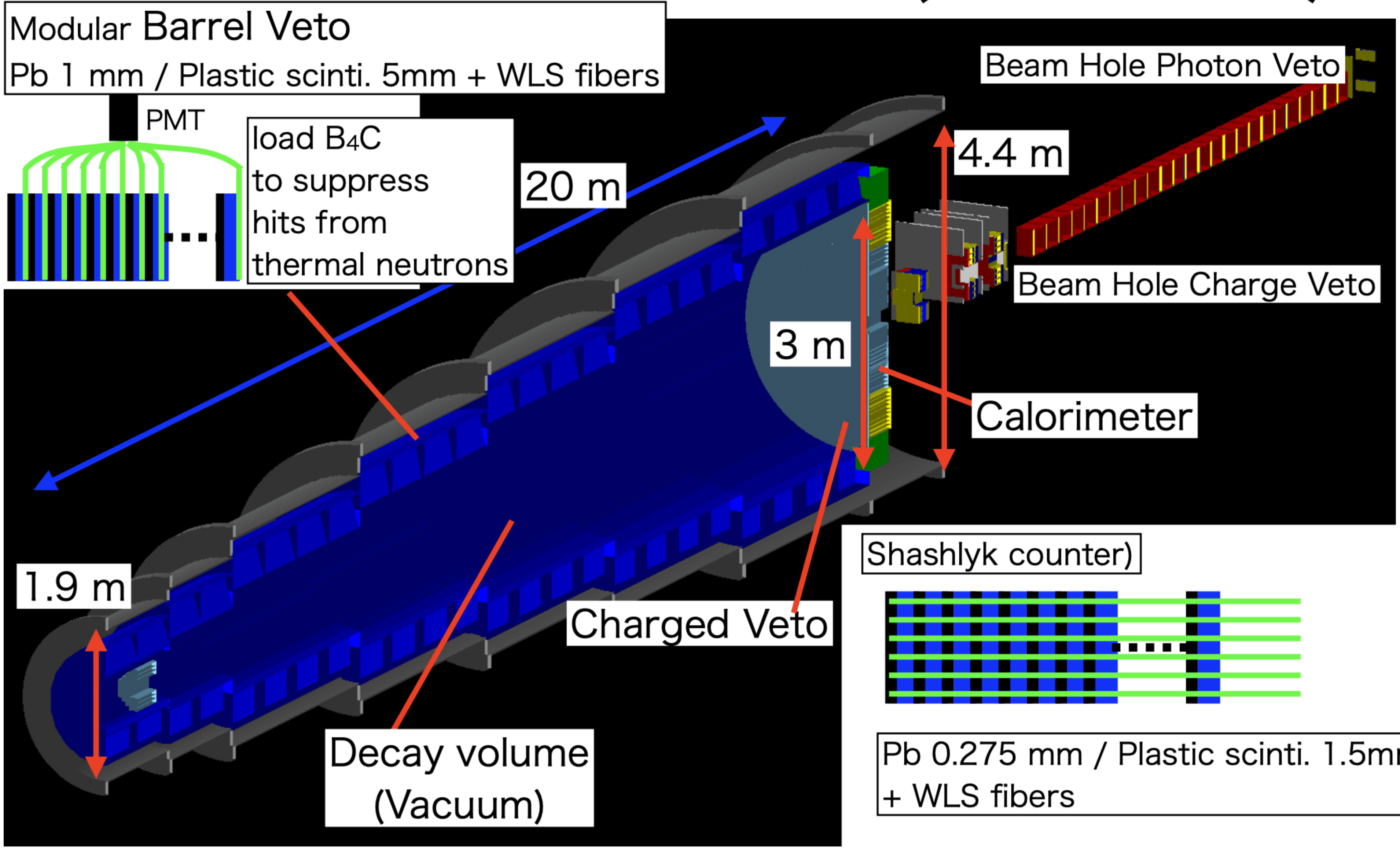
Hall extension + Primary BL + K1.1=118 Oku-yen

Discussion with IPNS director

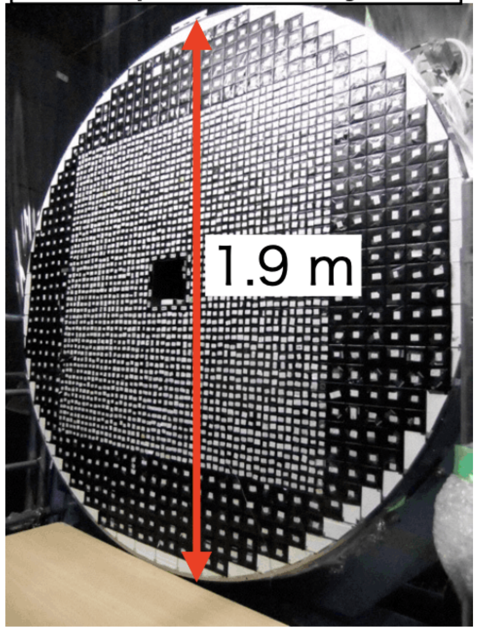
- IPNS director suggested to submit the proposal in the beginning of December.
- The official review at J-PARC PAC is important for the input of the discussion on the budget request to the government.
- Our primary goal is to obtain Stage-1 approval
  - Stage-1 status will be given by the IPNS director based on the recommendation of the PAC, if the scientific merit of the proposal is high and the experimental methods are sound.
    - (This status will help the proponents negotiate with funding agencies.)
  - → Expand our collaboration and request funding.

- **Target of submission by early December 2024**

KOTO II detector (tentative)

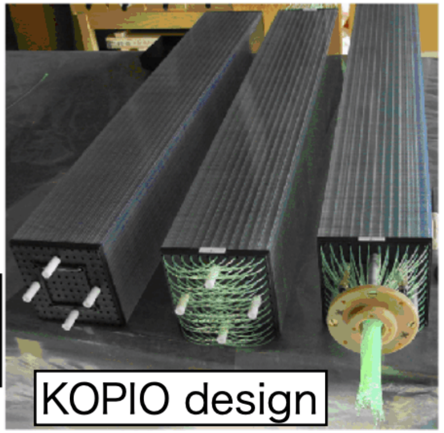


KOTO calorimeter
(undoped CsI crystal)

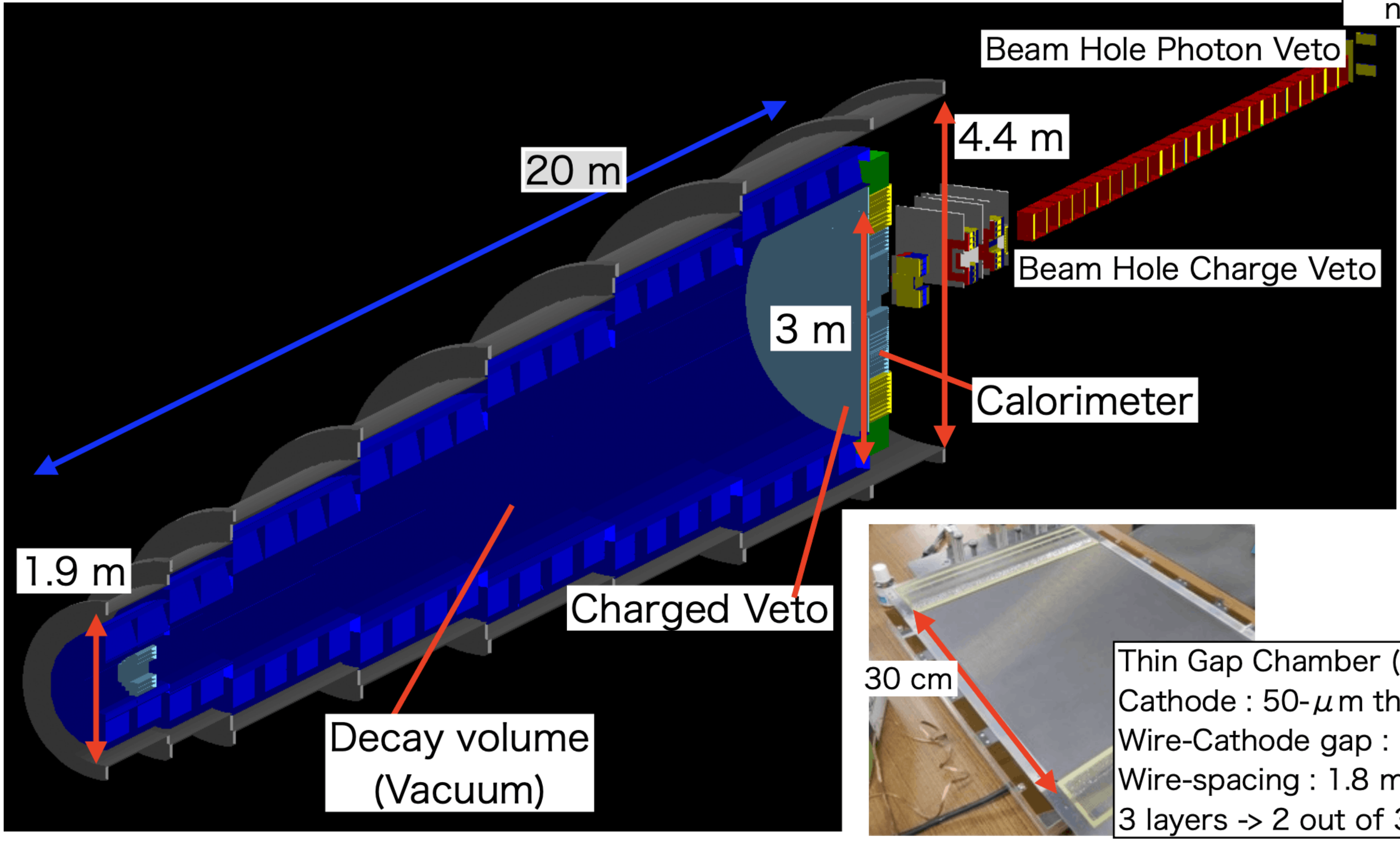


Shashlyk counter)

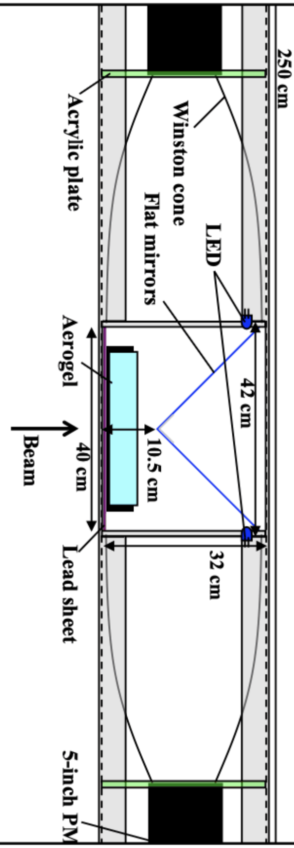
Pb 0.275 mm / Plastic scinti. 1.5mm
+ WLS fibers



KOTO II detector (tentative)

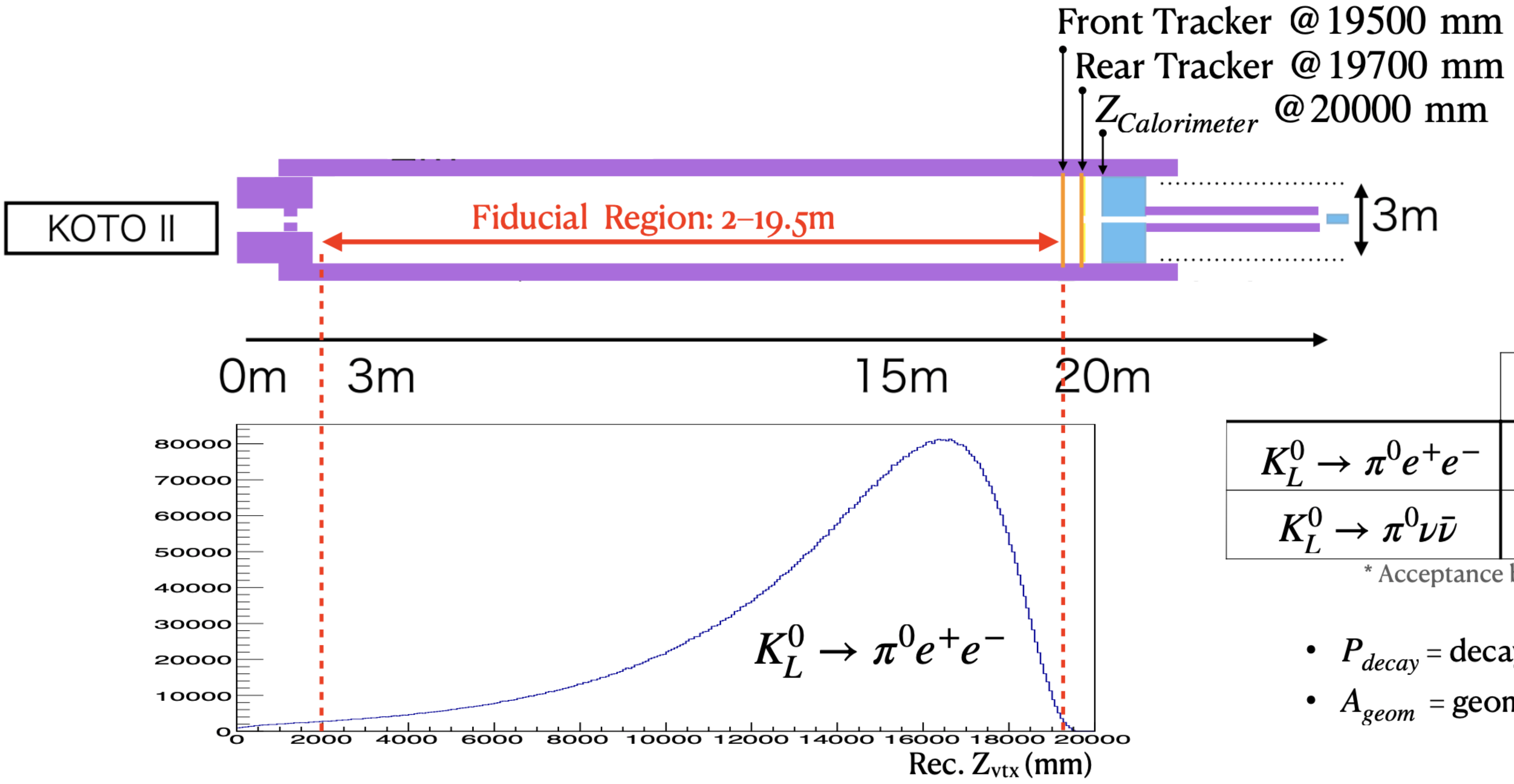


BHPV module (used in KOTO)
Pb converter+Aerogel
$\gamma \rightarrow e^+e^- \rightarrow$ Cherenkov photon
neutron insensitive



Thin Gap Chamber (used in KOTO)
Cathode : 50-μm thick carbon-coated kapton
Wire-Cathode gap : 1.4 mm
Wire-spacing : 1.8 mm
3 layers -> 2 out of 3 logic -> 99.5% efficiency

Acceptance of $K_L^0 \to \pi^0 e^+ e^-$



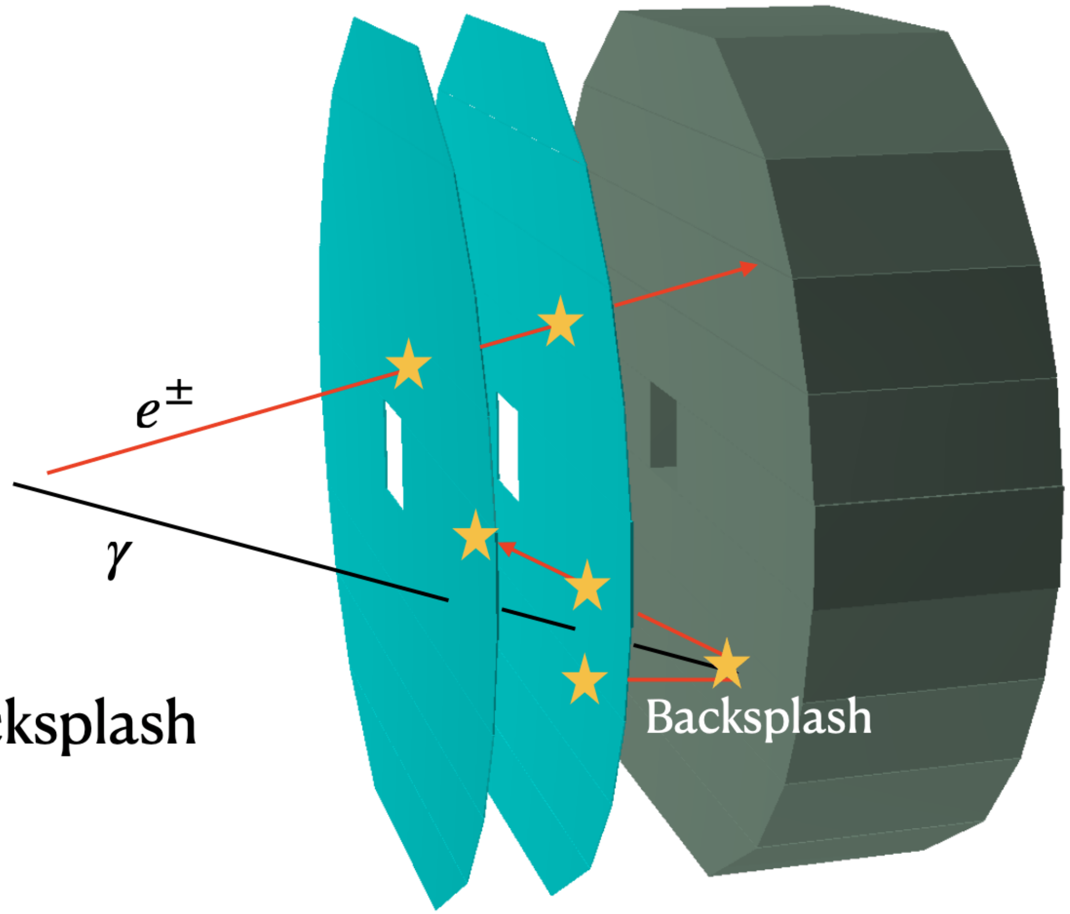
	$P_{decay} \times A_{geom}$
$K_L^0 \to \pi^0 e^+ e^-$	0.82%
$K_L^0 \to \pi^0 \nu \bar{\nu}$	2.4%

* Acceptance before other selection cuts

- P_{decay} = decay probability
- A_{geom} = geometric accept.

Charged Particle Tracker

- Two layers of charged tacker at
  - Z_{CsI} - 30 cm, Z_{CsI} - 50 cm
- Design requirements:
  - Spatial resolution: ~100 μm
    - to provide better $\sigma(M_{\pi^0})$, $\sigma(M_{K_L})$
  - Timing resolution: ~300 ps
    - to separate charged hits from the backsplash
- Detector candidates:
  - Straw tracker, Scintillating fiber, or ?



Summary

- The measurement of $K_L \to \pi^0 e^+ e^-$ can be a potential by-product at KOTO II
- Assuming $\mathscr{B}(K_L \to \pi^0 e^+ e^-)$ aligns with the SM prediction,
  - expect to collect S/N~15/17 in parallel with the $K_L \to \pi^0 \nu \bar{\nu}$ data-taking.
  - S/N = 0.88 $\to$ 3.6σ observation
  - $\delta\mathscr{B}/\mathscr{B} = 38\,\%$
- The design for charged particle detector has not yet been finalized:
  - charged particle tracker before the calorimeter
  - $\mu^\pm/\pi^\pm$ identification beyond the calorimeter

Full Simulation for the calorimeter

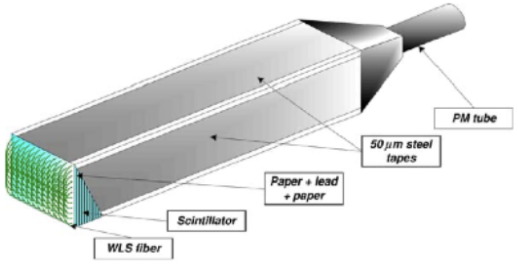
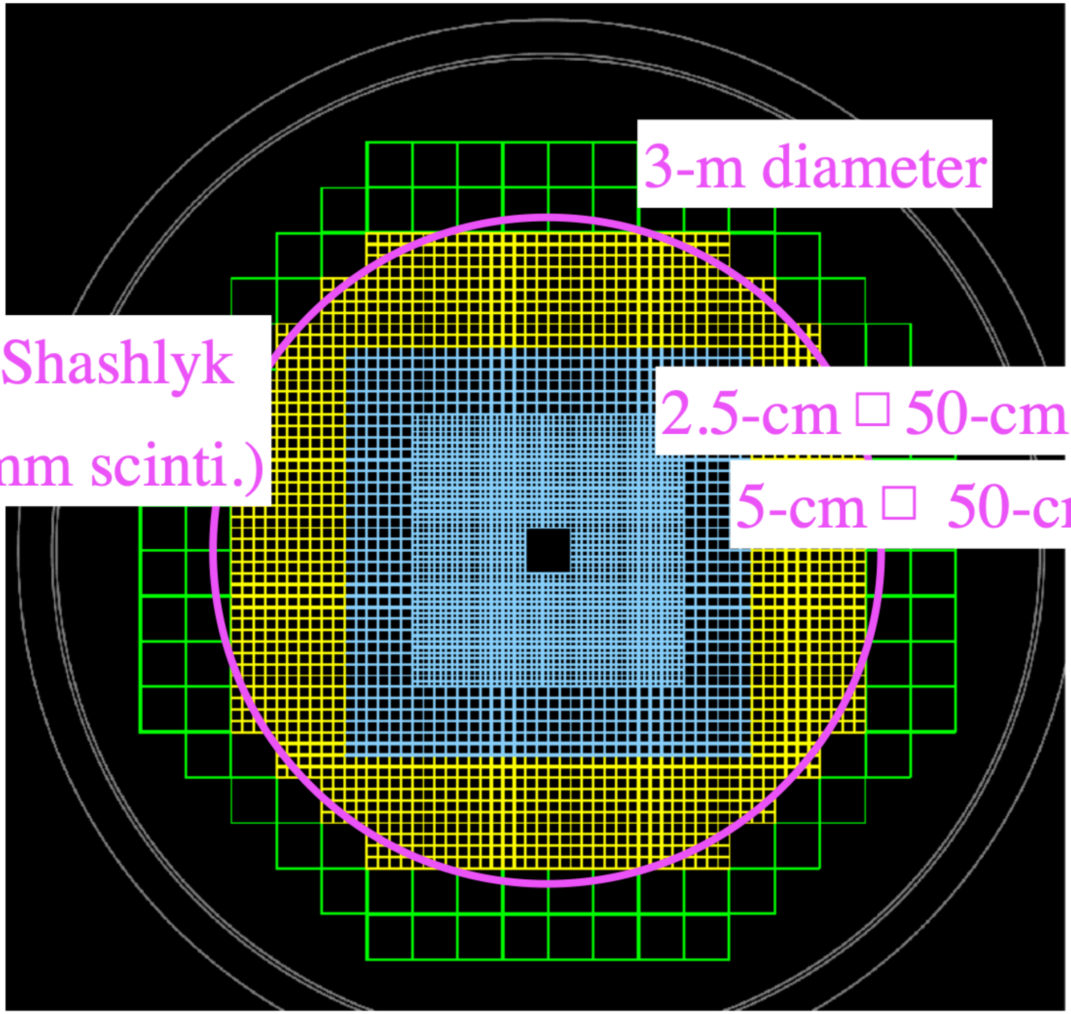


Fig. 1. Shashlyk module design.

5-cm □ ~50-cm long Shashlyk
(0.275-mm lead / 1.5-mm scinti.)

- 300 layers=15.8X0
  - (CsI 50cm: 27X0, 1X0=1.87cm)



3-m diameter

2.5-cm □ 50-cm long CsI

5-cm □ 50-cm long CsI

Small : 2240
Large : 720
Shashlik : 1456
Current Large: 476
Extra Large : 92

Outer Veto : 20-cm □ ~50-cm long Shashlyk (1-mm lead / 5-mm scinti.)

Additional questions on KOTO-II calorimeter

1. What calorimeter performance is required in terms of:
   - Energy resolution?
   - Time resolution?
   - Radiation robustness? Has the radiation dose (ionizing and hadronic) been estimated?
2. Is the digitization frequency for the calorimeter readout sufficient to deliver the required time resolution? What are the implications for DAQ performance?
3. Would increasing the transverse segmentation of the calorimeter help in terms of
   - shower shape discrimination/angle of impact determination for photons?
   - n/γ separation?
4. What would be gained by longitudinal segmentation of the calorimeter? What segmentation would be needed for
   - decay π^0 identification by reconstructing shower direction?
   - n/γ separation?
5. Which aspects of scintillator performance are most critical for the KOTO-II calorimeter?
   - e.g., high light yield, fast emission time, radiation hardness…
6. Did you develop a simulation of the shashlyk design with optical transportation included? Have you thought about ways to reduce the computation time when dealing with scintillation photons transportation?

Table 4. Expected particle yields estimated by the simulations.

Particle	Energy range	Yield (per 2×10^{13} POT)	On-spill rate (MHz)
K_L		1.1×10^7	24
Photon	>10 MeV	5.3×10^7	110
	>100 MeV	1.2×10^7	24
Neutron	>0.1 GeV	3.1×10^8	660
	>1 GeV	2.1×10^8	450

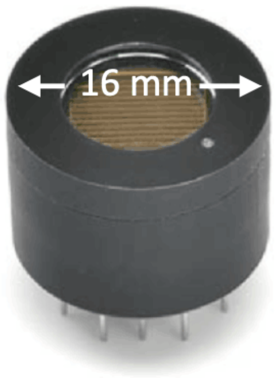
Table 5. Detector rate, veto width, and accidental loss.

Detector	Rate(MHz)	Veto width (ns)	Loss (%)
Central barrel	2.2	40	8.5
Calorimeter + Charged veto	3.5	20	6.7
Beam-hole charged-veto	2.9	30	8.3
Beam-hole photon-veto	35	6	19

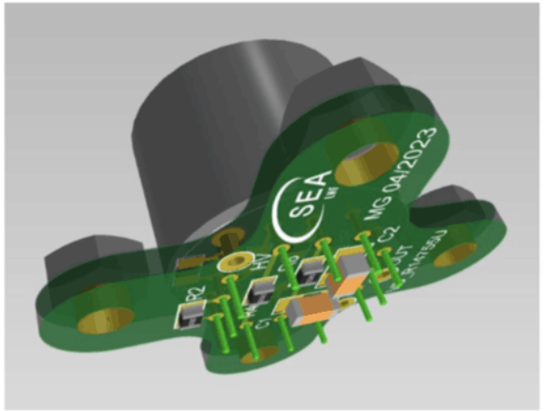
BHPV: The BHPV alone accounts for half of the accidental losses. An alternate technology for the BHPV, such as highly compact, ultra-fast calorimeter, for example, based on fast high-Z crystals, or a fine-sampling tungsten/silicon design, might be studied. It is important to accurately parameterize the required photon detection efficiency as a function of energy in order to evaluate these solutions. This will also help to understand what time resolution vs. energy would be required to reduce accidental BHPV losses by a factor of 3–4.

From CRILIN to the (ex HIKE) SAC

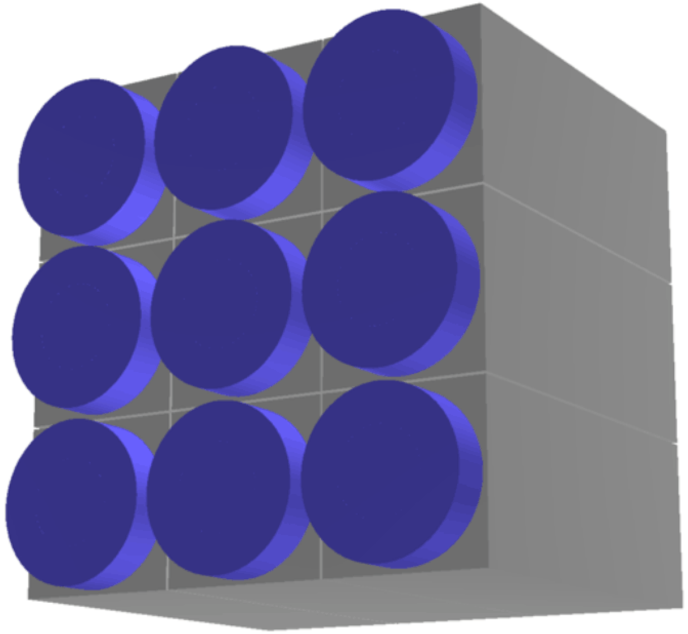
R14755 PMT



Custom divider:



1-layer prototype with 3x3 PWO-UF crystals of bigger size: 18 x 18 x 40 mm^3
Alignable mechanics and single-board **PMT readout**



- Stackable planes, like CRILIN, with PCB photosensor plane
- Layer mechanics to allow alignment of crystal plane
- Crystals pre-aligned à la OREO
- From SiPM to PMT readout: Hamamatsu R14755 PMTs under test
- Custom divider implemented on sensor board
- PMT-crystal coupling will be tested with and without Winston cones

Beam request at CERN T9 for 2025 to test this new prototype

Summary and outlook

Meeting at J-PARC 27-29 July:

- Cristina, Evgueni, MM, Mattia, Ilaria, Rainer, Rado, Augusto, Hans

Biweekly meetings since August (Wed 14:00)

- Strong participation from Birmingham, Frascati
- Preparation of KOTO-II proposal for end of year

Strong interest from HIKE UK:

- Birmingham, Lancaster, Edinburgh. Liverpool, Manchester, Warwick
- BHCV and possibly Charged Veto/tracking system
- Significant interest in $K_L \to \pi^0 \ell^+ \ell^-$

Possible involvement for NA62 Italia:

- Shashlyk (main calorimeter)
- SAC as high-performance, fast BHPV