TES-based X-ray spectroscopy of kaonic atoms

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for J-PARC E62/HEATES collaboration

July 26th, 2019

HEATES collaboration (J-PARC E62)

- **H**igh-resolution **E**xotic **A**tom x-ray spectroscopy with **TES** -

RIKEN, KEK, JAEA, RCNP, JAXA, TMU, UTokyo, TokyoTech, OsakaU, RikkyoU, TohokuU

NIST

INFN-LNF, Politecnico di Milano

Stefan Meyer Institut

KU Leuven

University of Zagreb

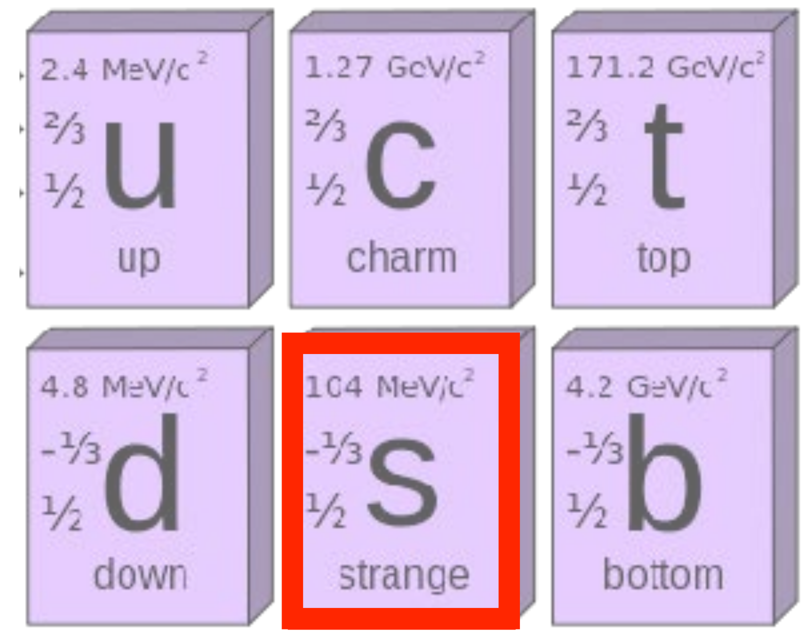
Lund University

Nuclear physicists + TES experts + Astro-physicists

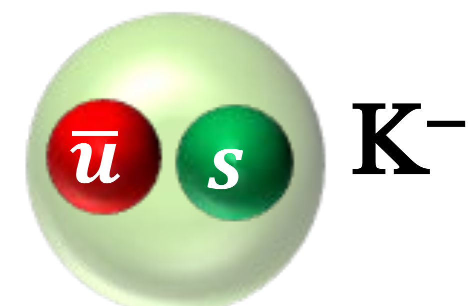
71 collaborators in total

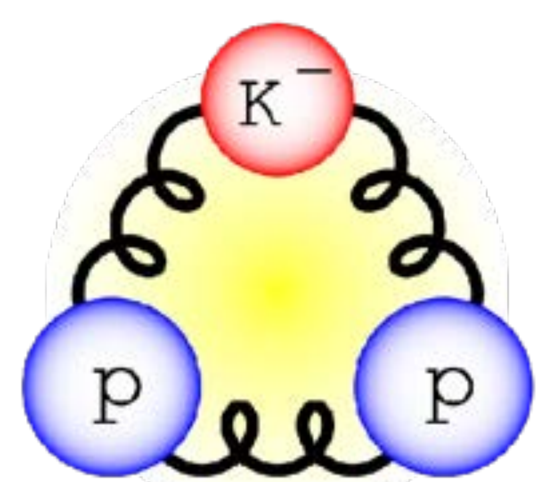
Science goal: Hadron physics with K^-

- **Hadron physics**
  - Hadron = meson(qq^{bar}) and baryon(qqq)
  - How are hadrons formed from quarks and gluons?
  - How are hadrons form nuclei?

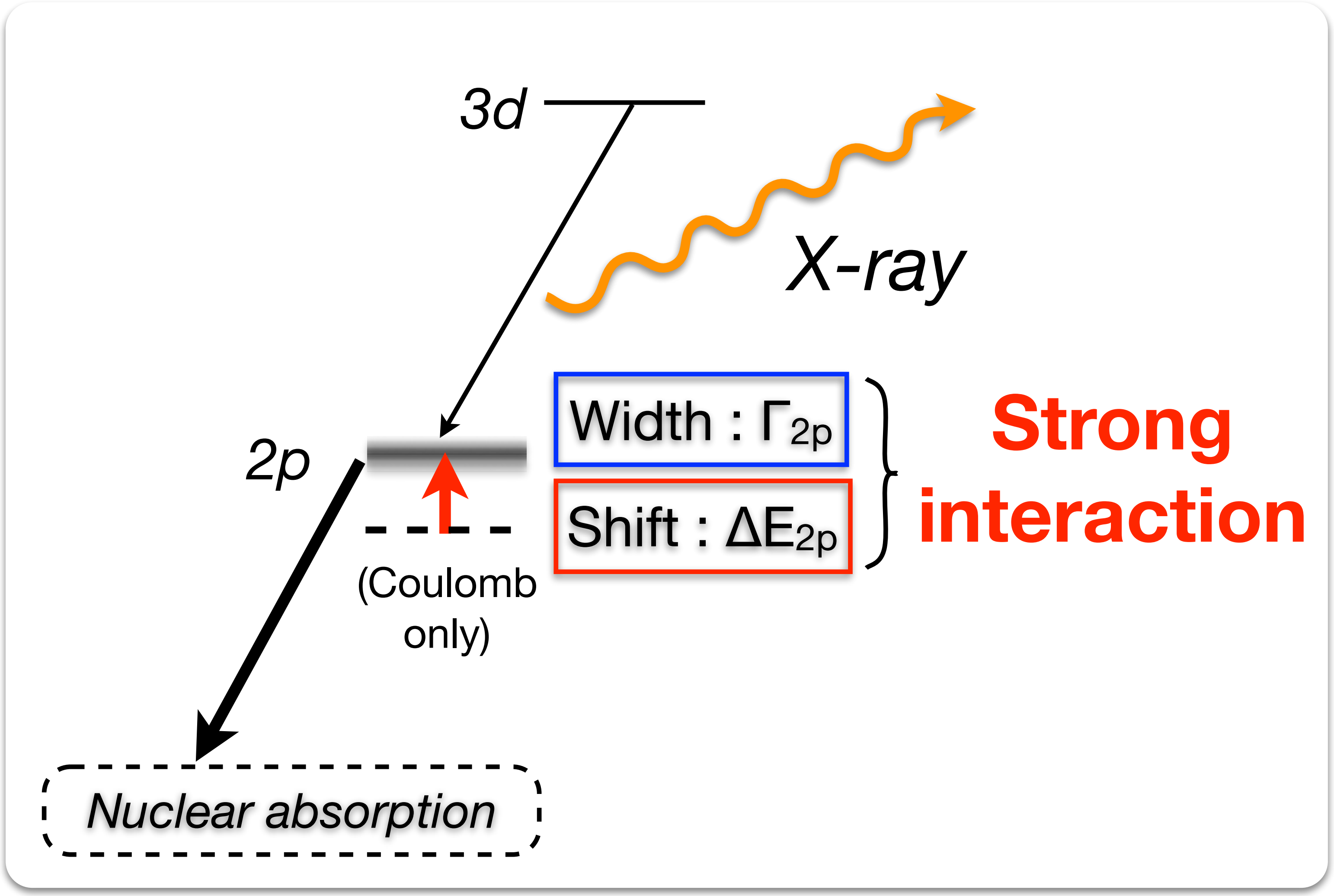


- **K^-(anti-Kaon) could be a good probe**
  - lightest particle with a *strange* quark
  - $K^{bar}N$ is strongly attractive in I=0
  - Nuclear state of a K^- and two protons could exit as a new form of matter
  - K^- might play an important role in neutron stars
  - Need more precise data for basic interactions





X-ray spectroscopy of Kaonic atom



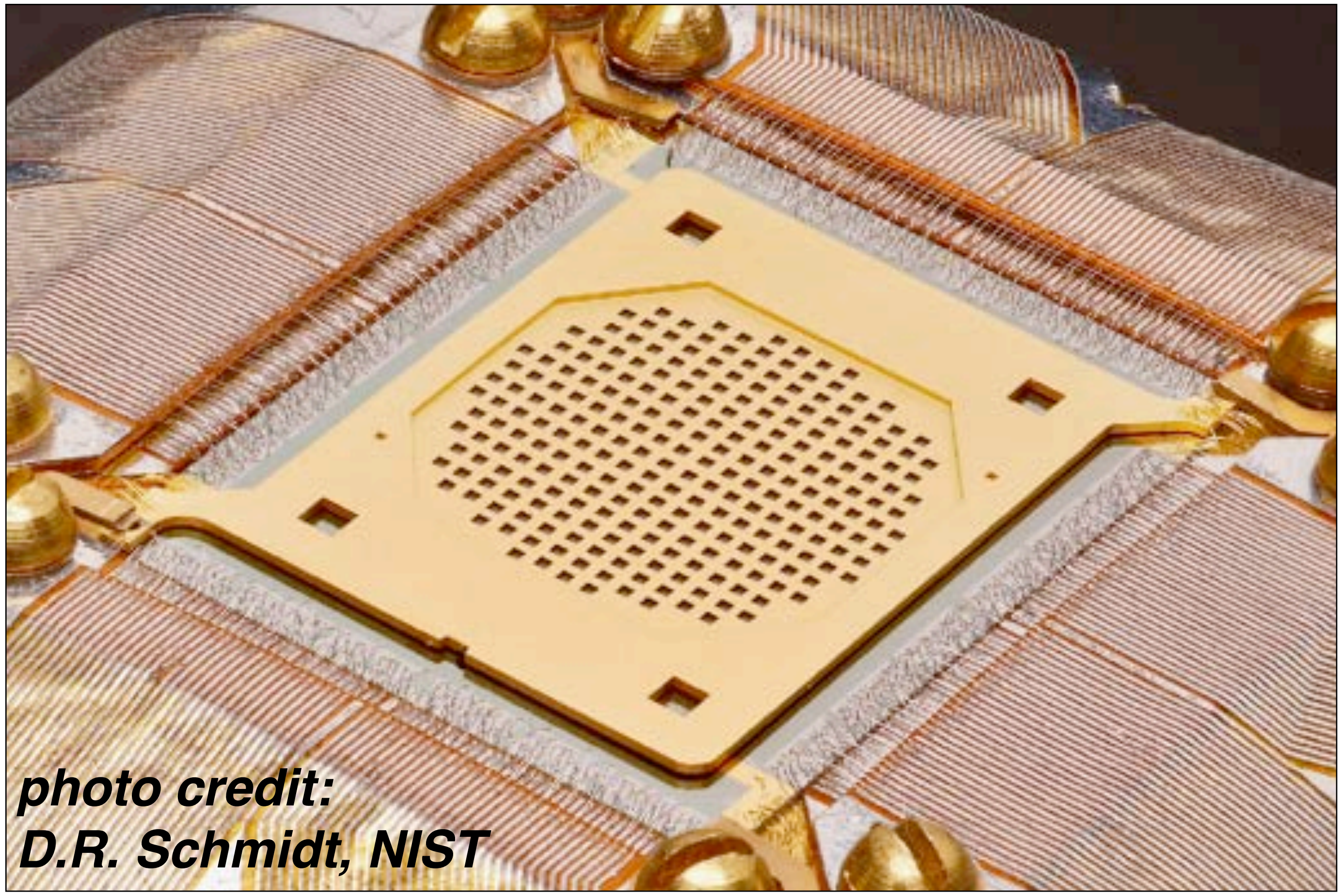
- Replace e^- with K^- →Kaonic atom
- K^- wave function overlaps with a nucleus at tightly-bound states
- Perturbation by the strong interaction
- Unique probe for K^--nucleus strong interaction

	K^- ^{3}He	K^- ^{4}He
X-ray energy	6.22 keV	6.46 keV
Shift	< 1 eV (expected)	
Width	2~5 eV (expected)	

$$e^- \text{ mass } : m_e = 0.511 \text{ MeV}/c^2$$
$$K^- \text{ mass } : m_{K^-} = 493.7 \text{ MeV}/c^2$$

x1000 mass→x1000 X-ray energy

NIST TES for kaonic atom experiment



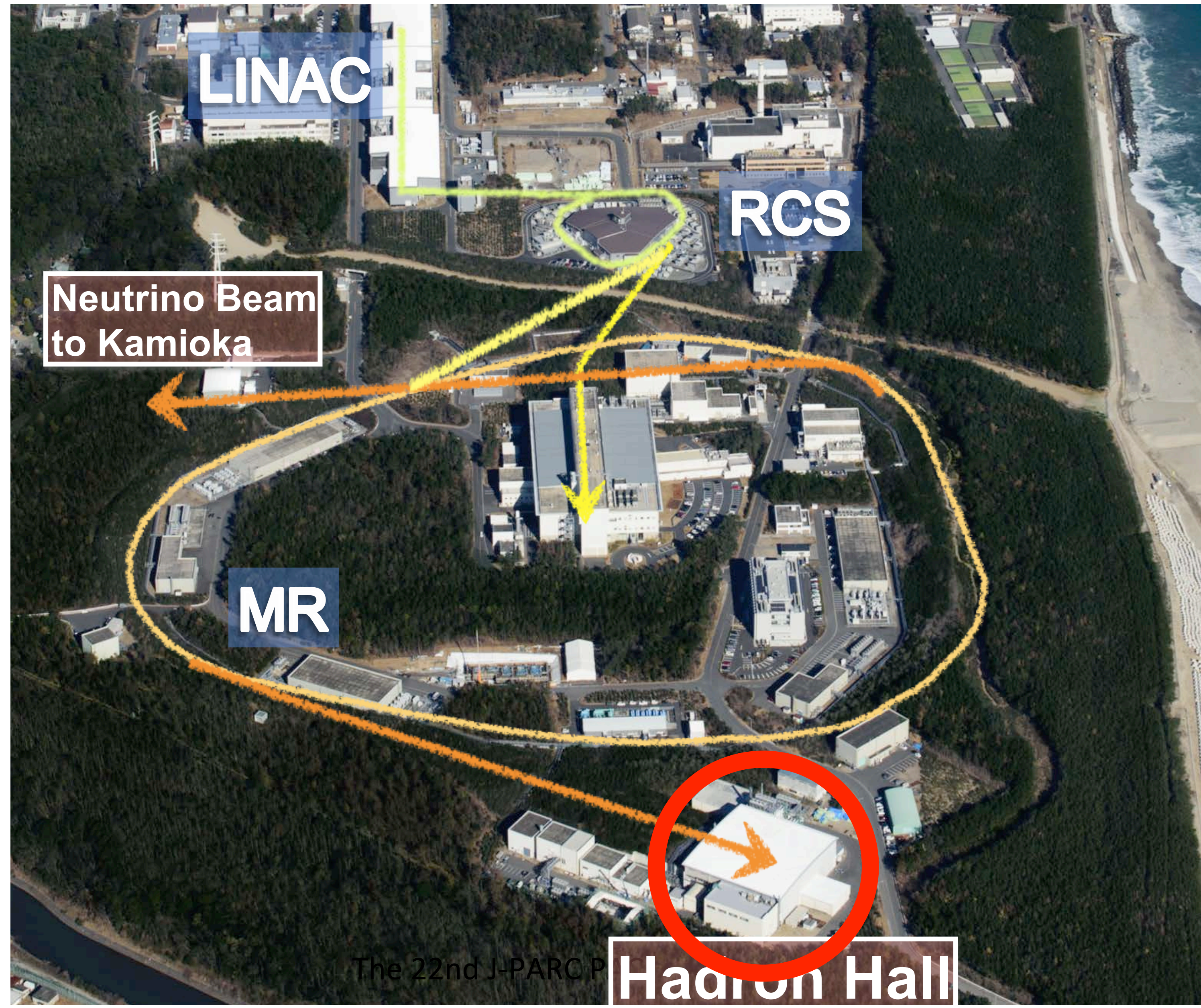
- ◉ Mo/Cu + Bi 4um (85% eff.@6 keV)
- ◉ 240 pixels, 23 mm^2
- ◉ 30 x 8 TDM readout
- ◉ HPD102 cryostat

- ☐ Integrate with a cryogenic target system
- ☐ In a charged-particle rich environment
- ☐ Low science X-ray rate (~200/week=~1/hour)
- ☐ Absolute energy calibration to 0.1 eV precision

HEATES project

2013	Start collaboration with NIST *LTD15: S. Okada*
2014	**Demonstration experiment @ PSI, Switzerland (pionic atom)** *H. Tatsuno et al., Jour. Low Temp. Phys., 184(3), 930-937, 2016.* *S. Okada et al., Prog. Theor. Exp. Phys.* ***2016****, 091D01, 2016.*
2015	*LTD16: H. Tatsuno*
2016	**Commissioning with K^- beam @ J-PARC, Japan** *T. Hashimoto et al., IEEE Trans. Appl. Supercond. 27(4), 1-5, 2017.*
2017	*LTD17: T. Hashimoto*
2018	**Physics data taking for K^- atom @ J-PARC**
2019	*LTD18: This talk* *Poster#61 S. Yamada* *Poster#203 H. Tatsuno* *Poster#243 R. Hayakawa*

J-PARC: Japan Proton Accelerator Research Complex



J-PARC provides high-intensity proton beam

MR: 30 GeV, ~55Tppp, 1.6 km ring (cf. 7 TeV, 27km@LHC)

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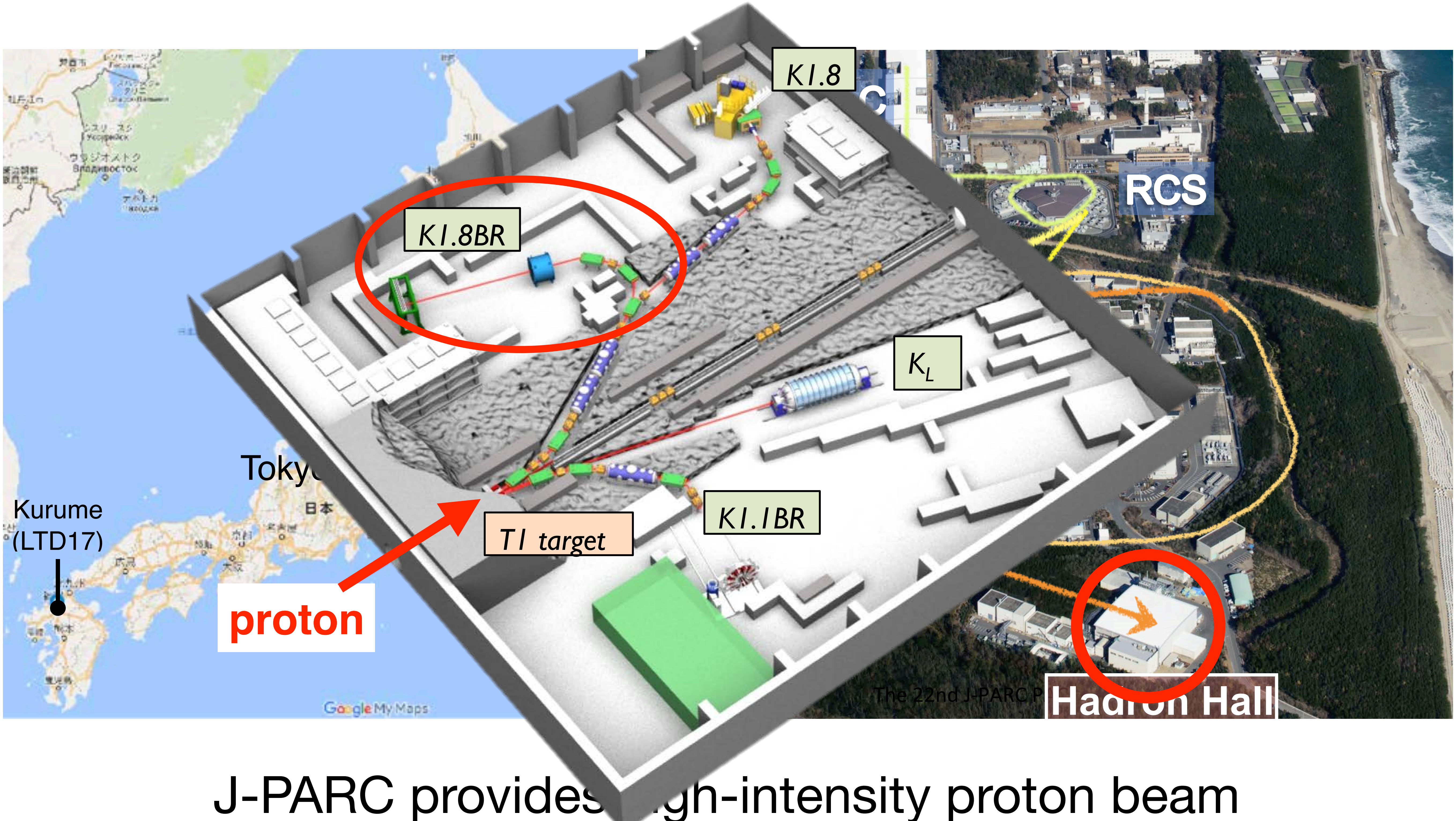

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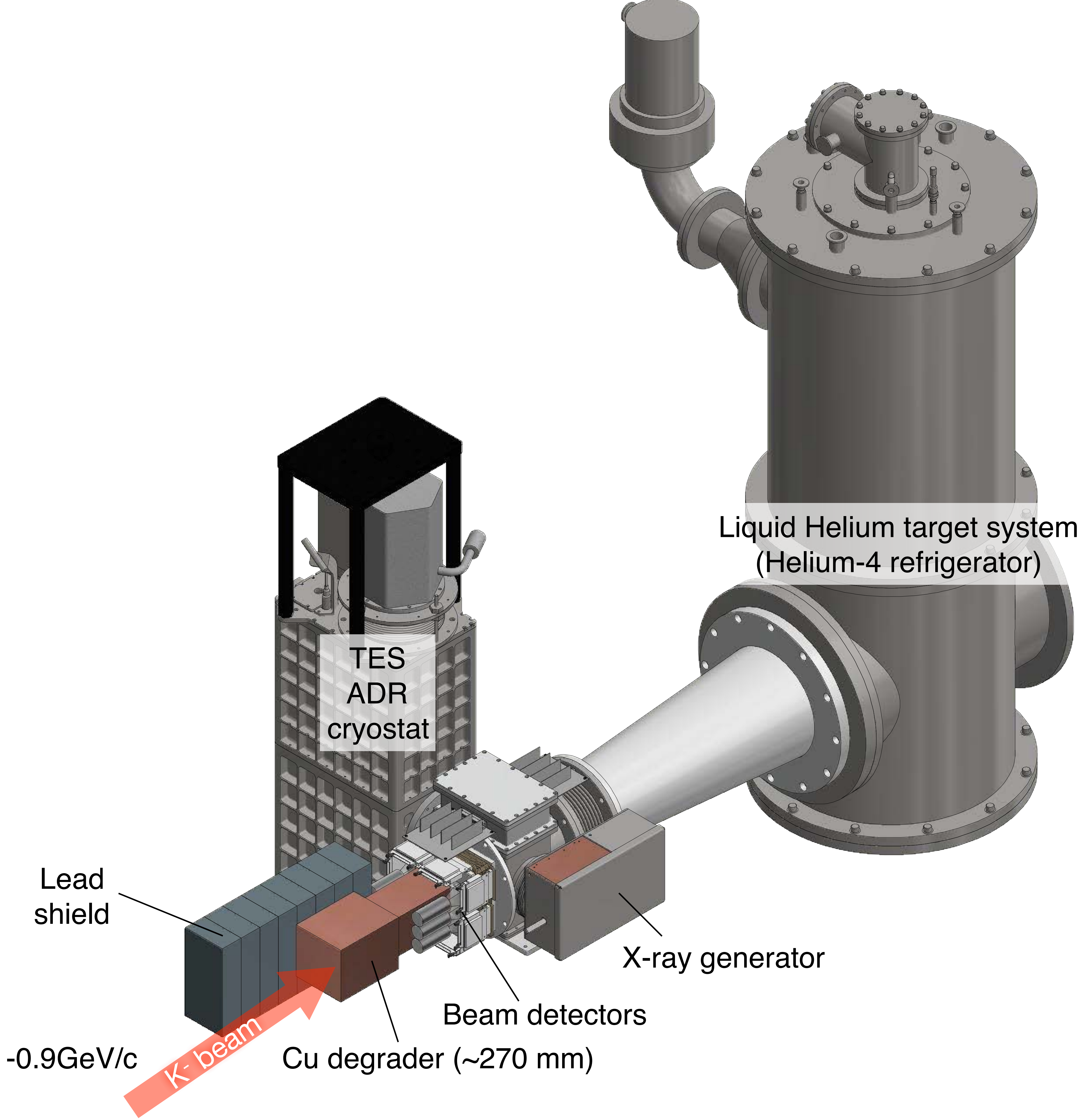
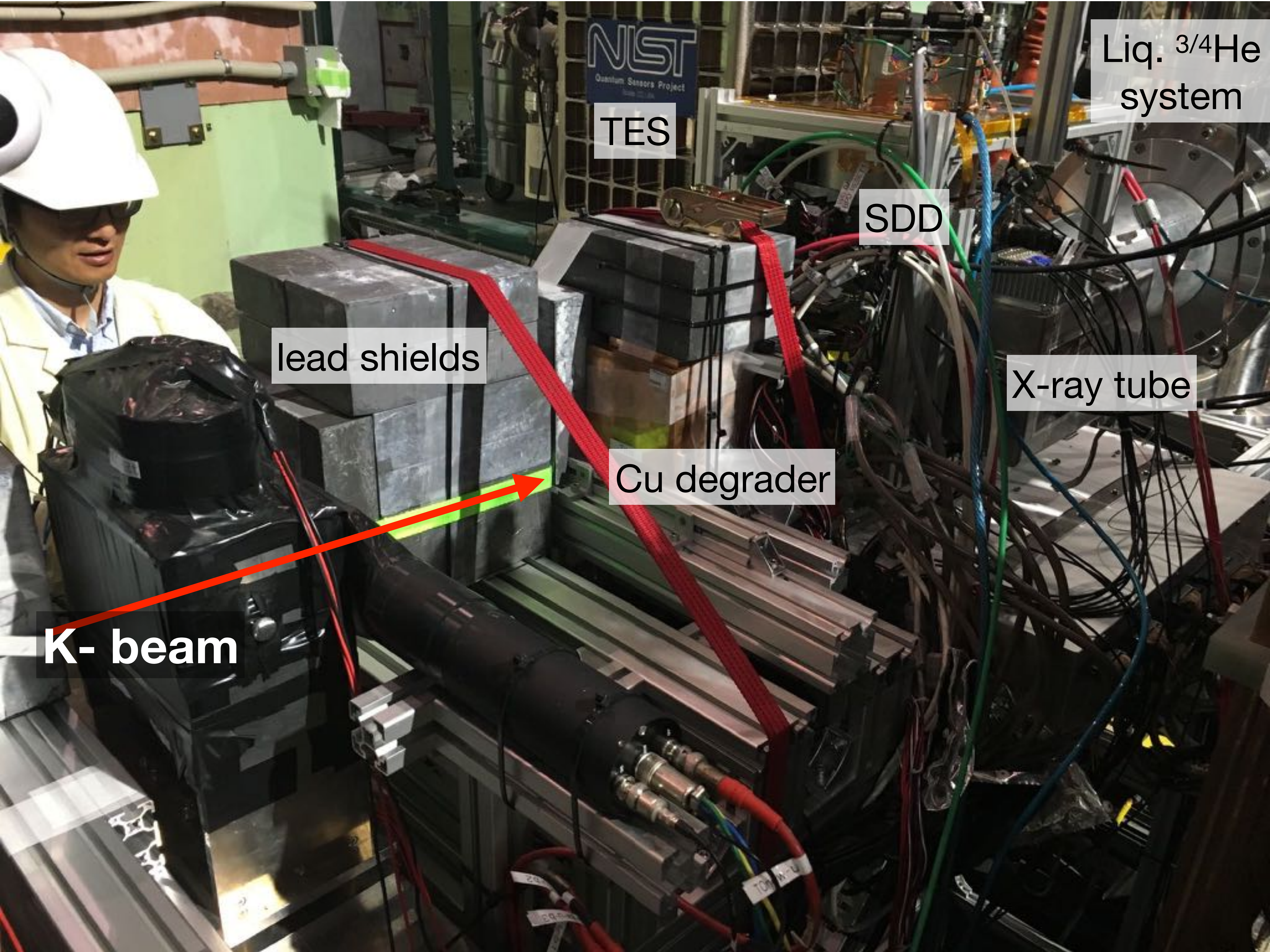
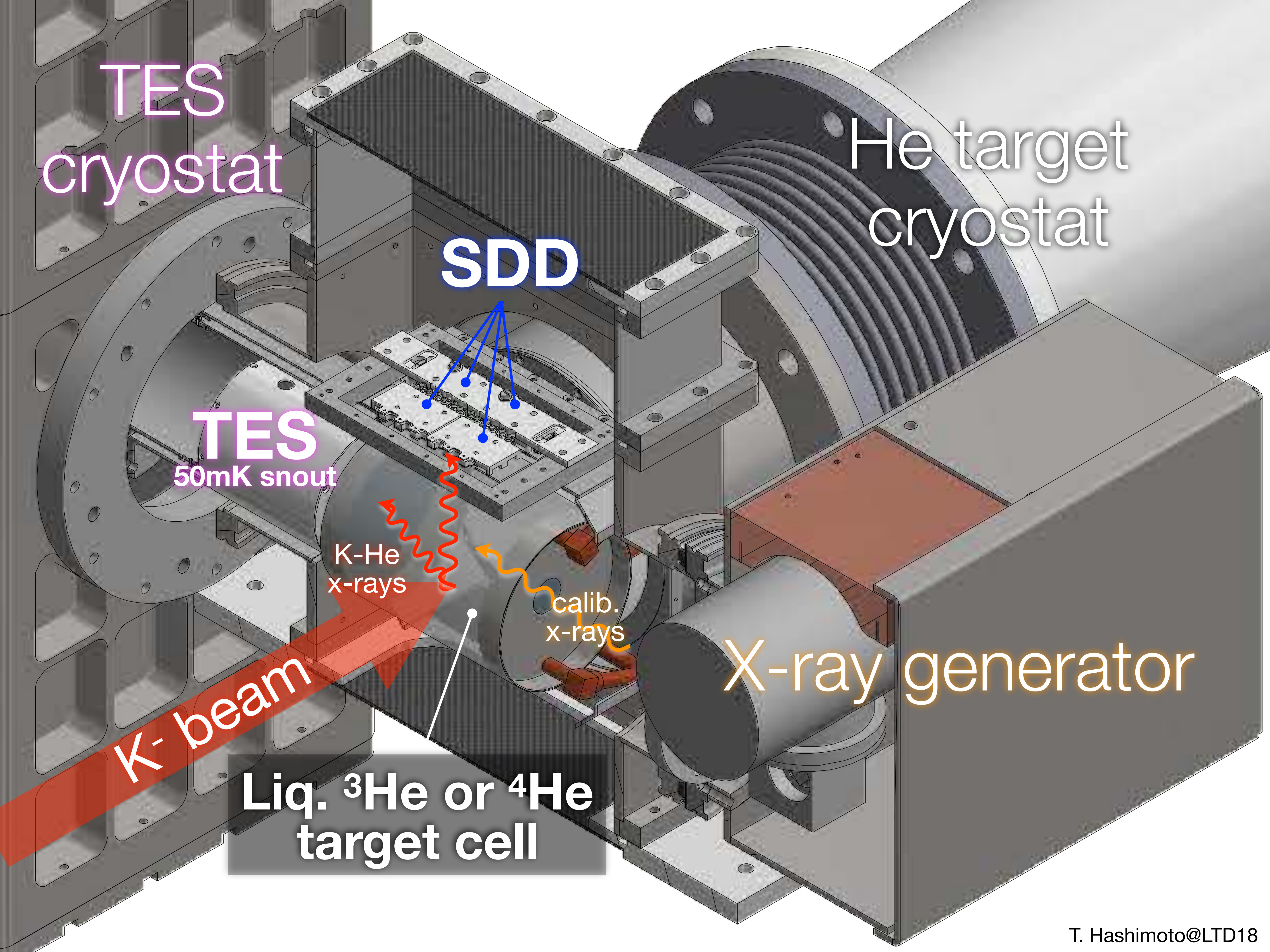
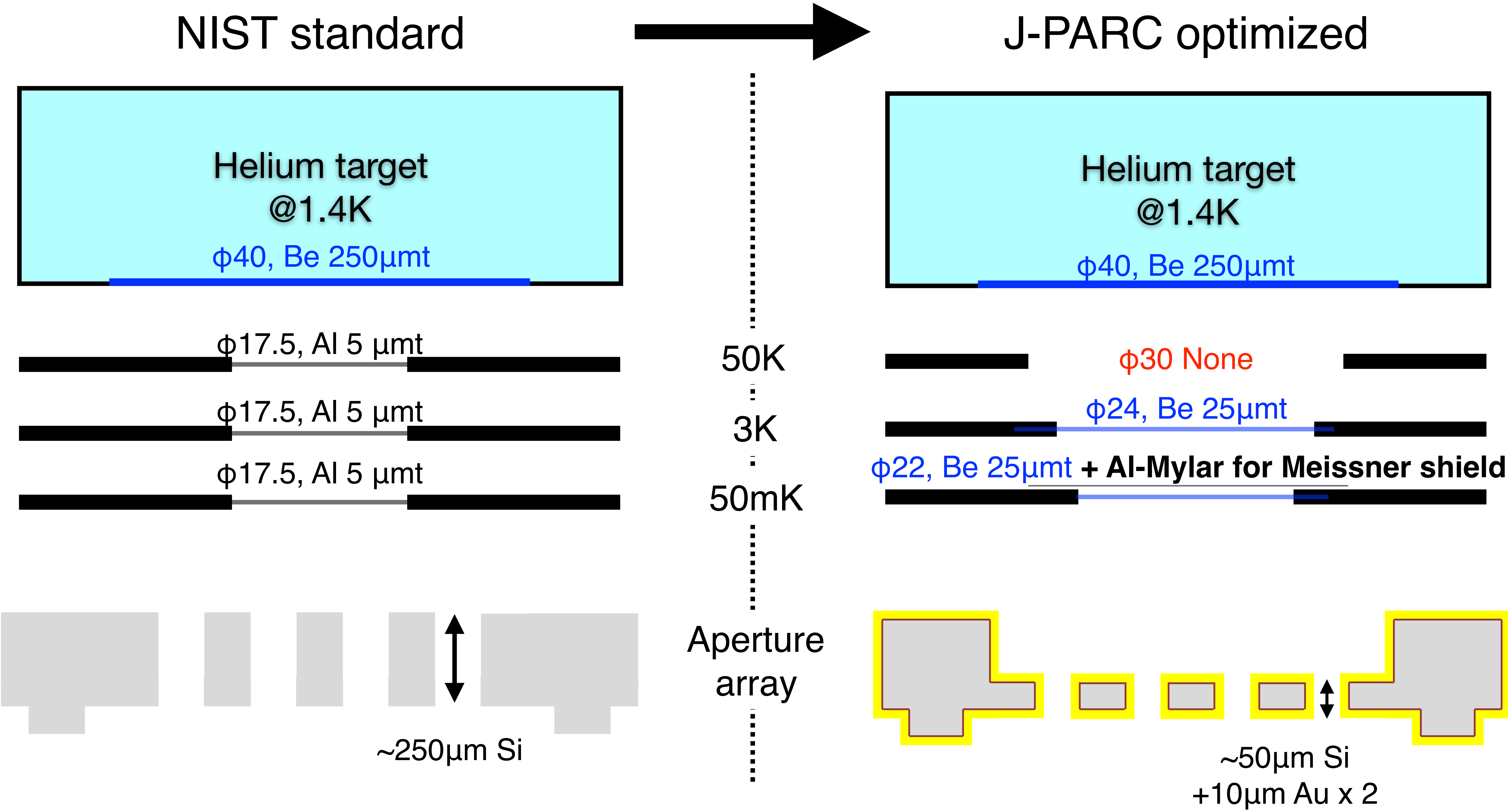

Liquid Helium target system
(Helium-4 refrigerator)
TES
ADR
cryostat
Lead
shield
X-ray generator
Beam detectors
-0.9GeV/c
K- beam
Cu degrader (~270 mm)


TES
Liq. $^{3/4}$He system
SDD
lead shields
X-ray tube
Cu degrader
K- beam


TES
cryostat
He target
cryostat
SDD
TES
50mK snout
K-He
x-rays
calib.
x-rays
X-ray generator
K- beam
Liq. ³He or ⁴He
target cell
T. Hashimoto@LTD18

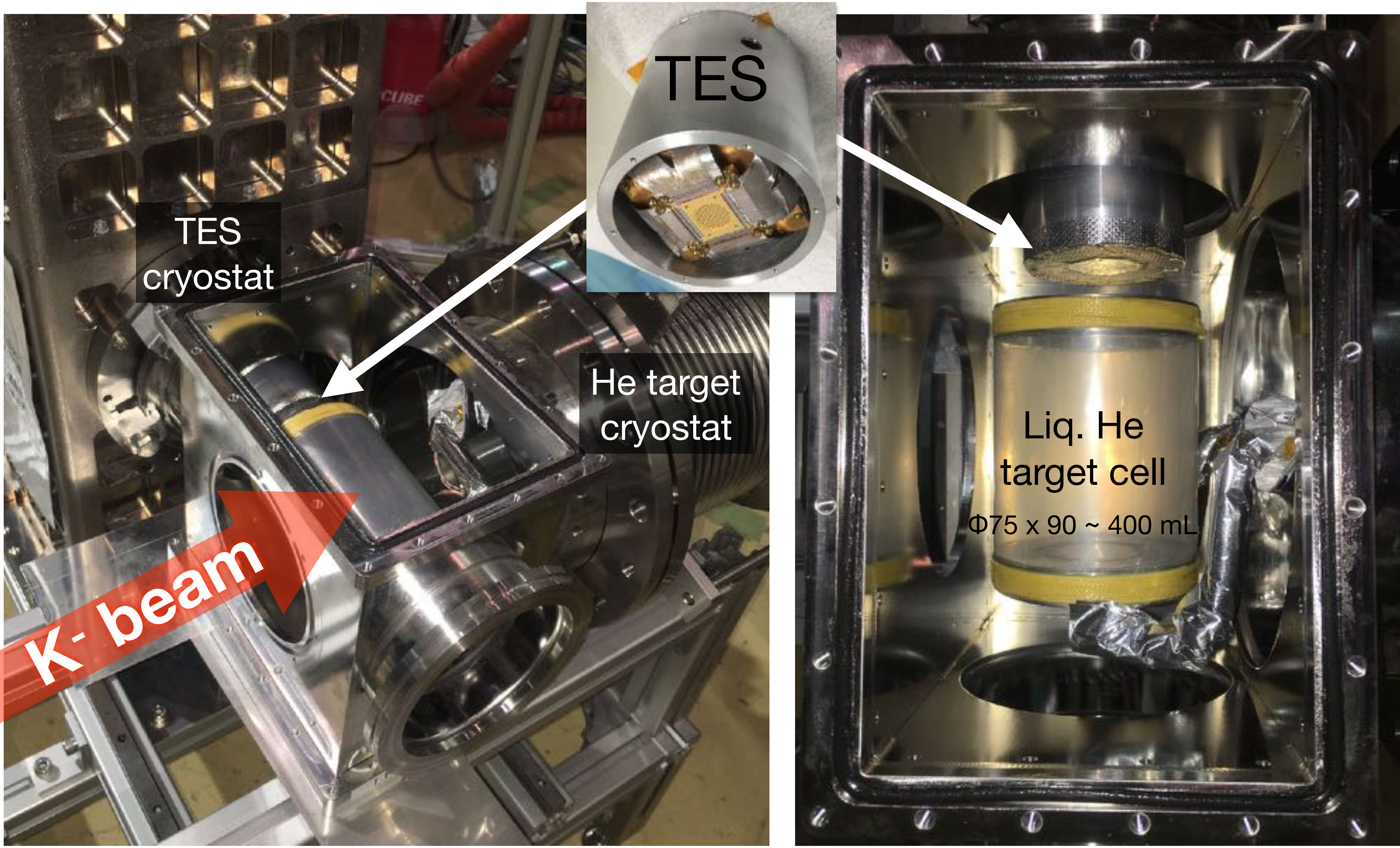
Modification for a larger solid angle



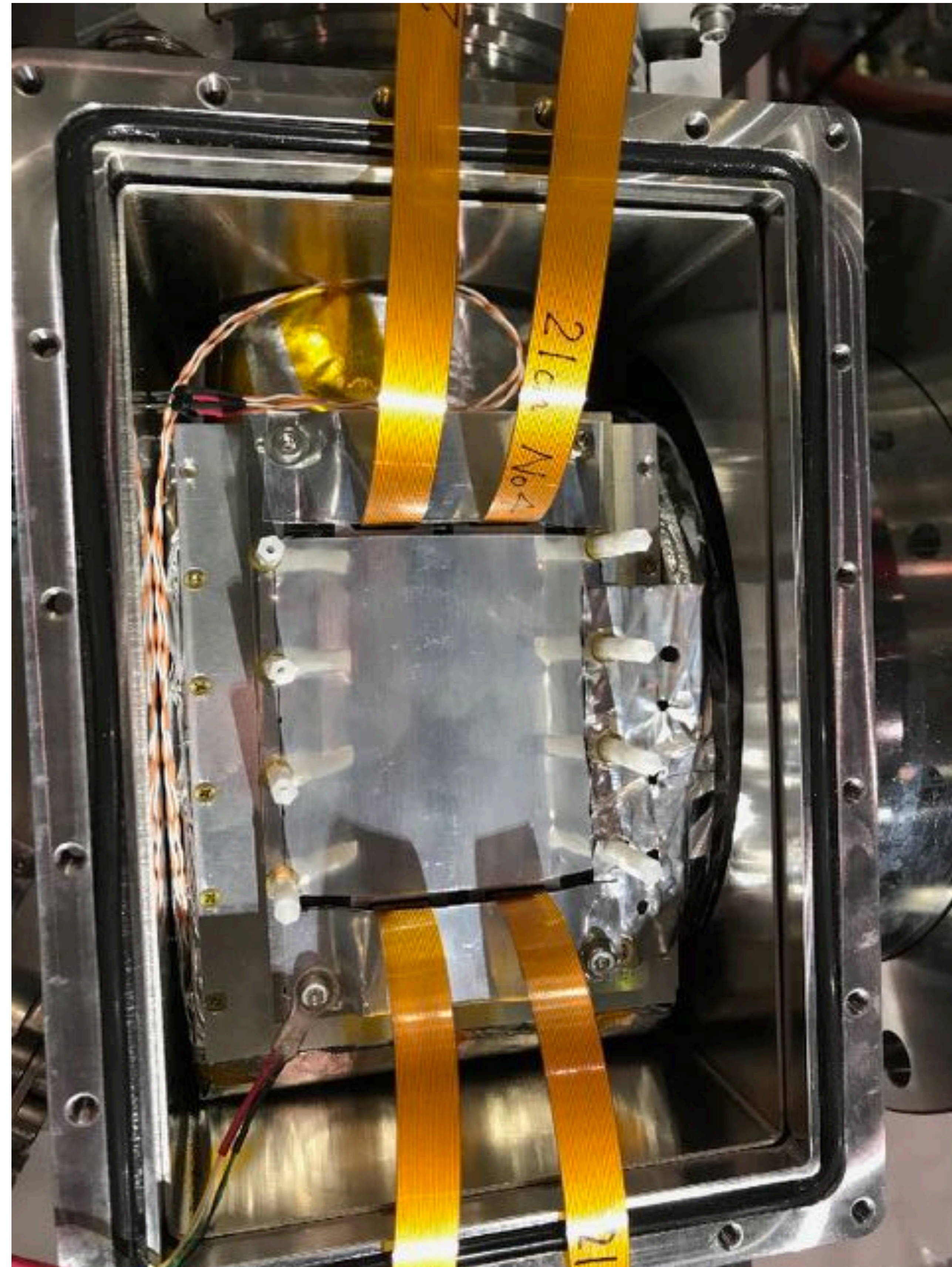
✓ Solid coverage: x1.5

✓ X-ray transmittance at 6 keV: 64%→95%

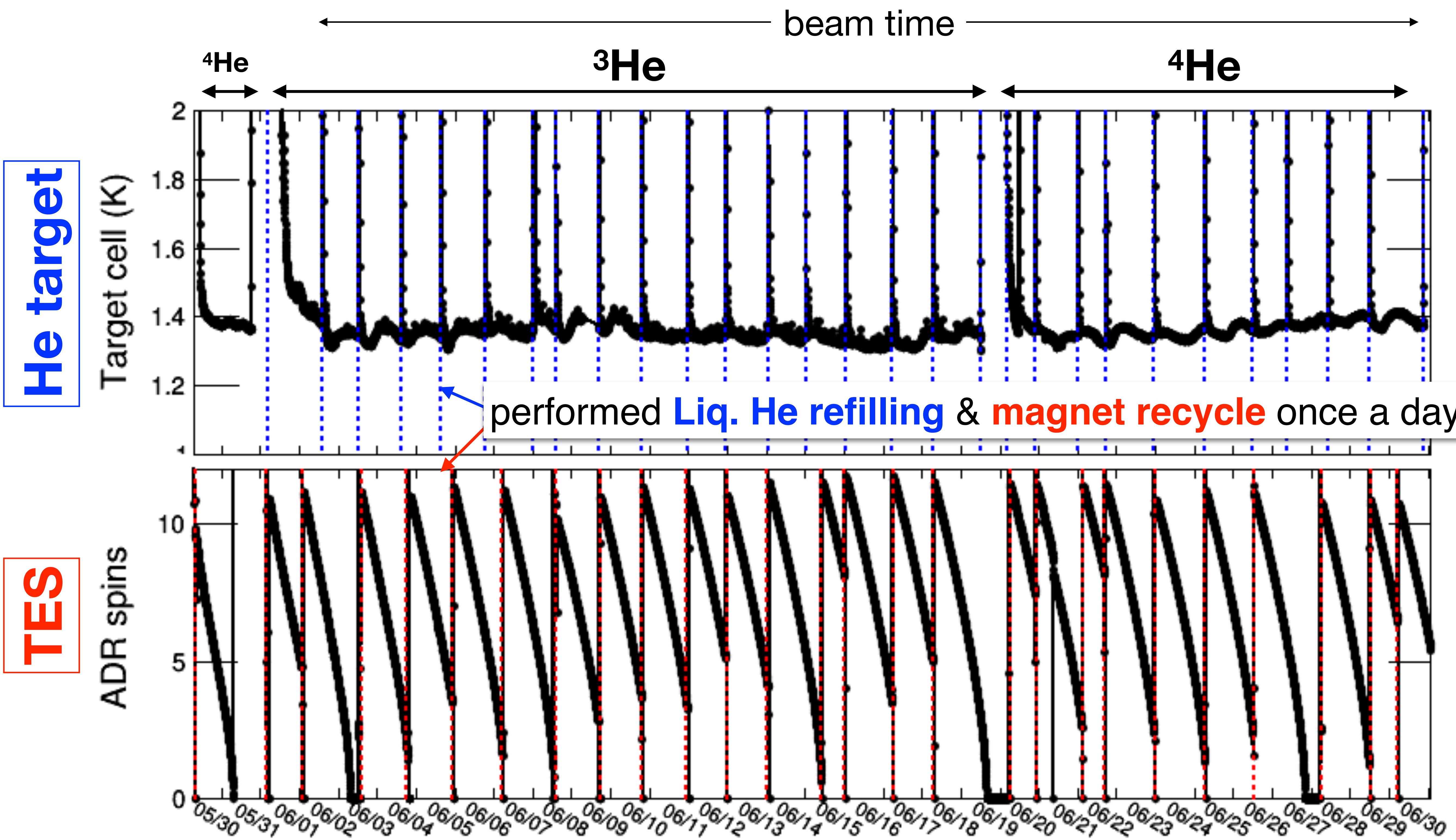
TES & He target cell



Target region with shield, MLI, SDDs



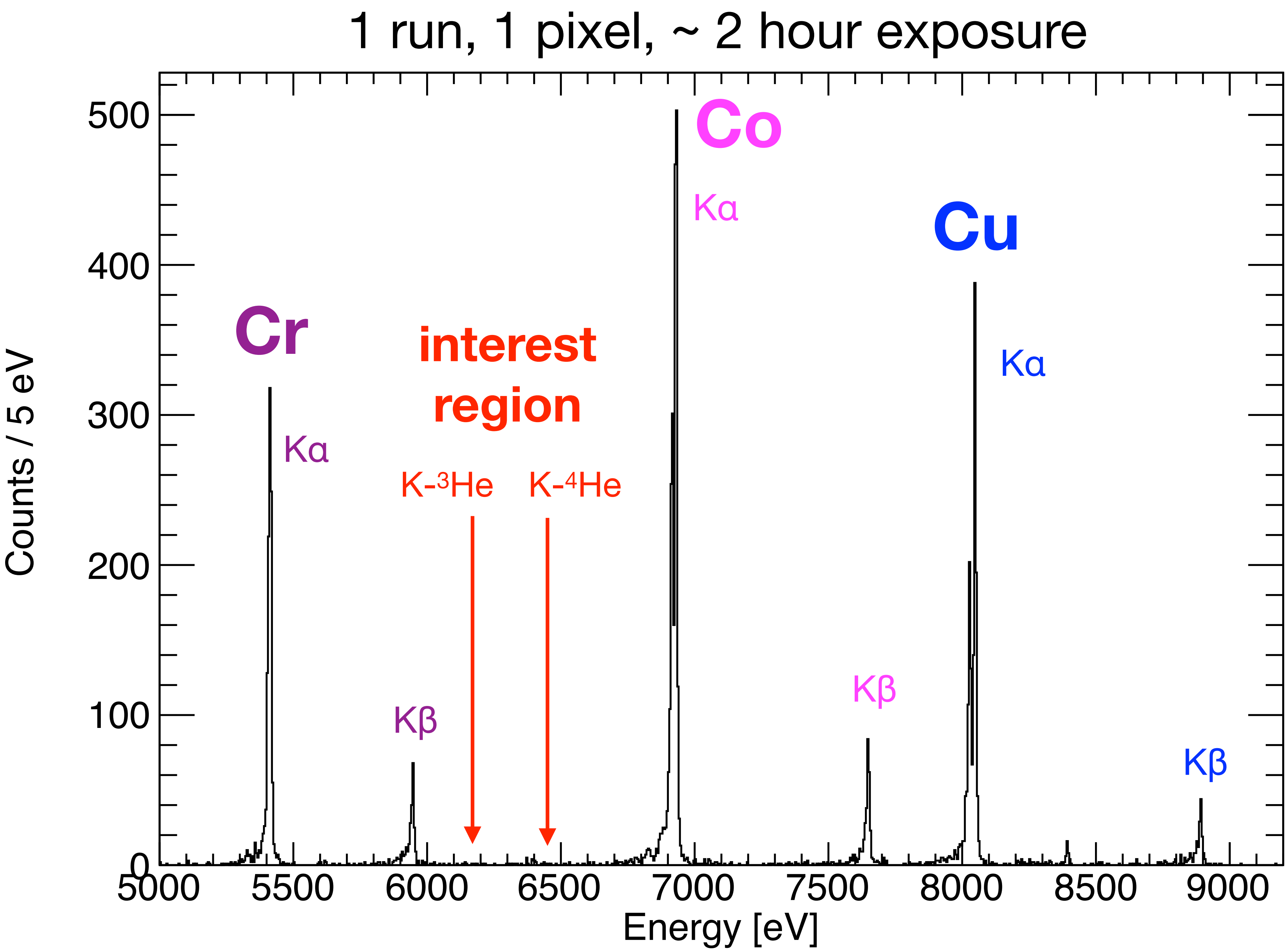
Long-term operation of cryogenic systems



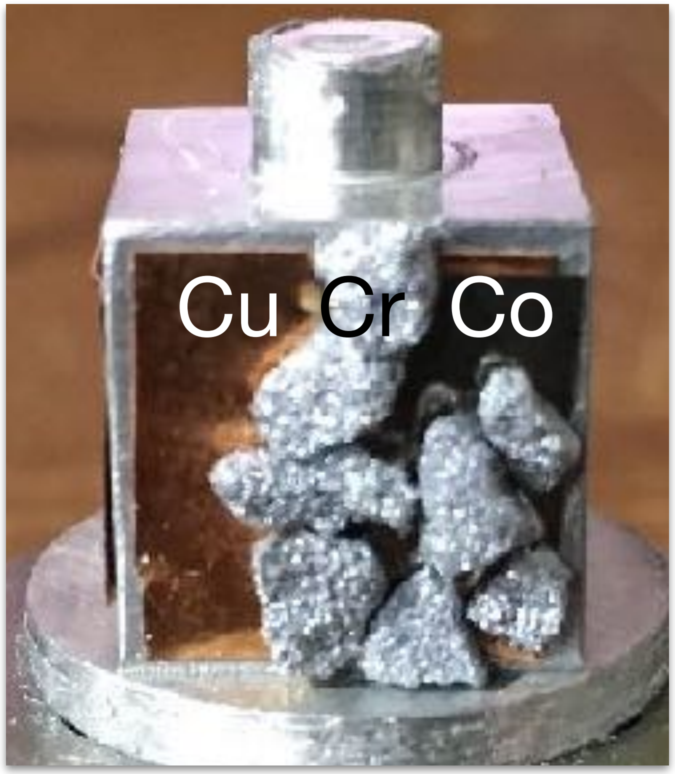
Stable operation for one month

(28 He refills & 27 mag cycles)

In-beam energy calibration



X-ray tube w/ Cr, Co, Cu foils

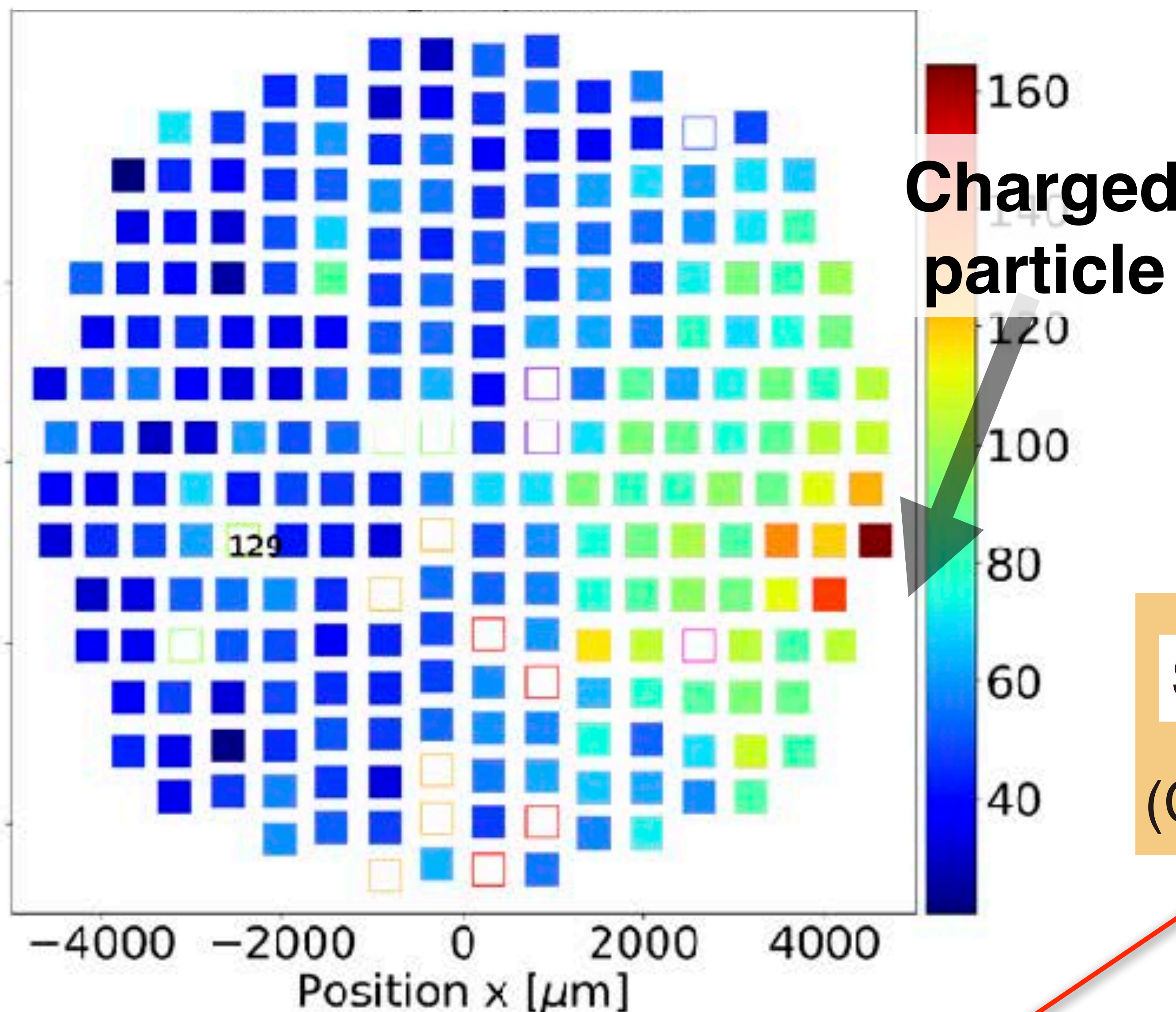


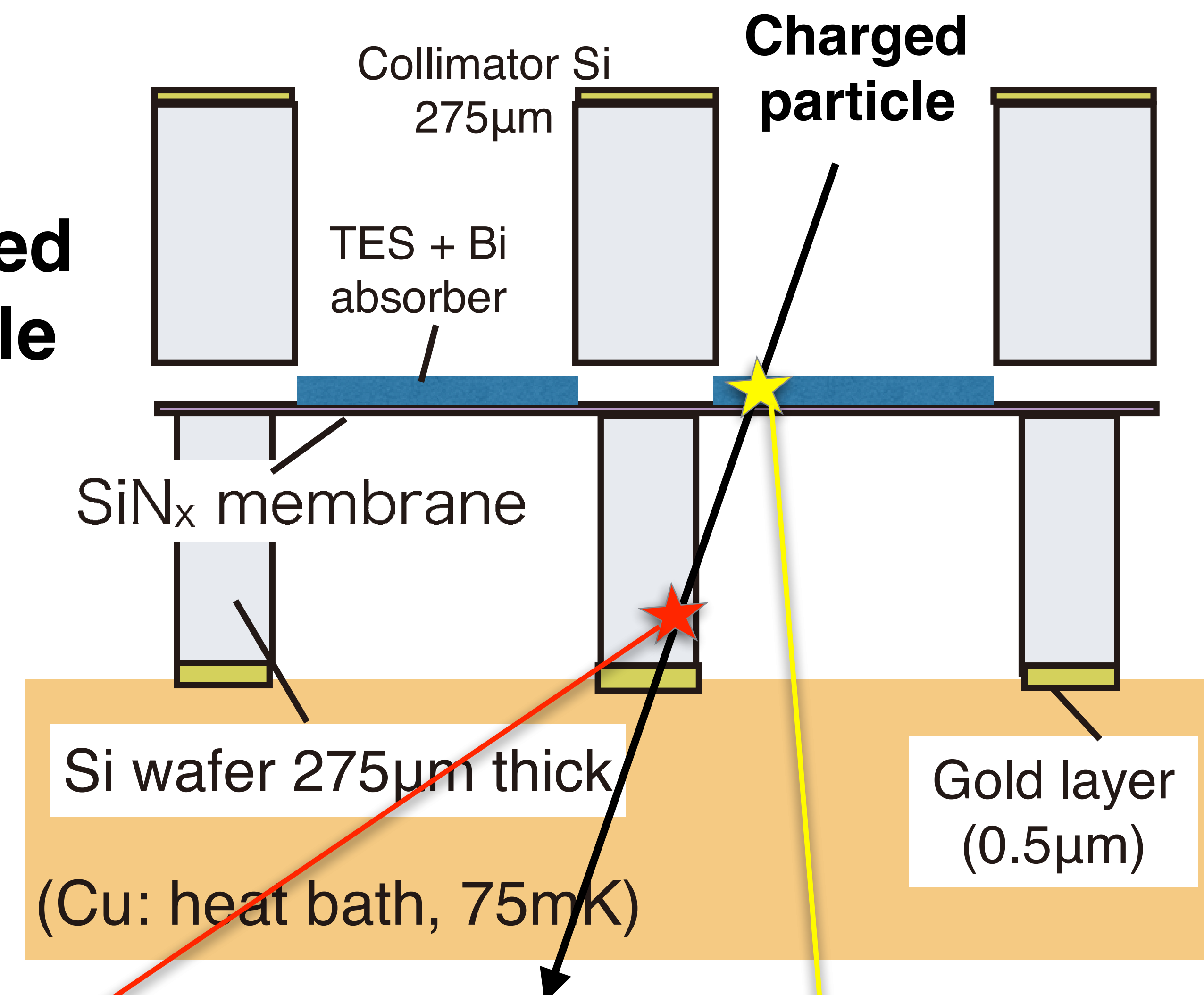
- ✓ X-ray tube was always ON during the experiment
- ✓ Run-by-run (2 hours), pixel-by-pixel calibration

H. Tatsuno et al., Jour. Low Temp. Phys., 184(3), 930-937, 2016.

Effect of charged particle hits

Pulse height distribution in the array

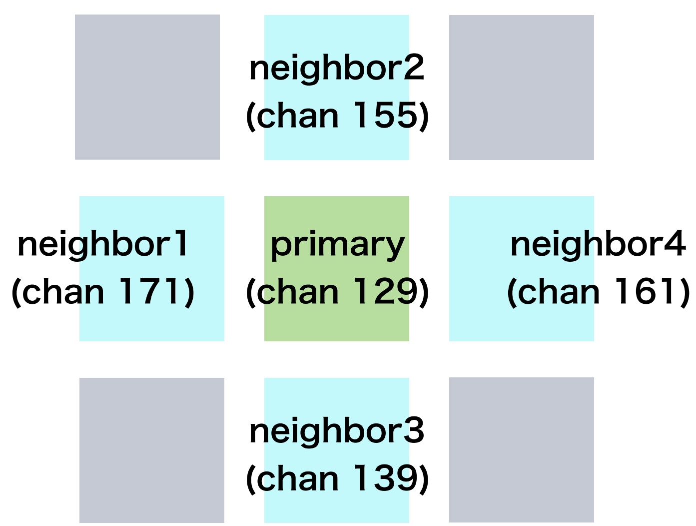


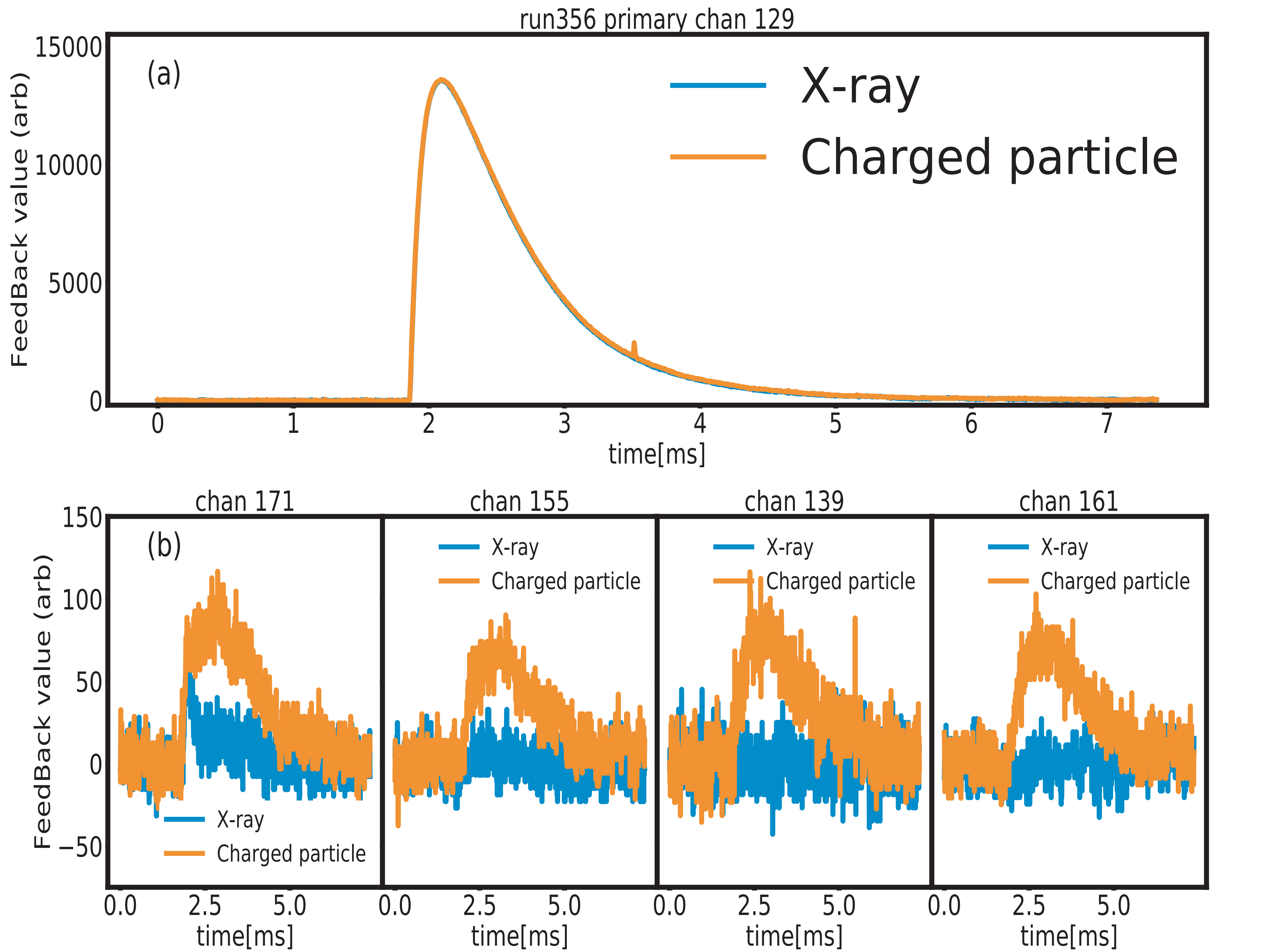


If charged particle hit on the Si substrate, heat will spread out throughout the array, making small bump signals in many pixels

If charged particle hit on the detector pixel, it deposits ~10 keV energy (Bi 4um), which become severe background in the spectrum

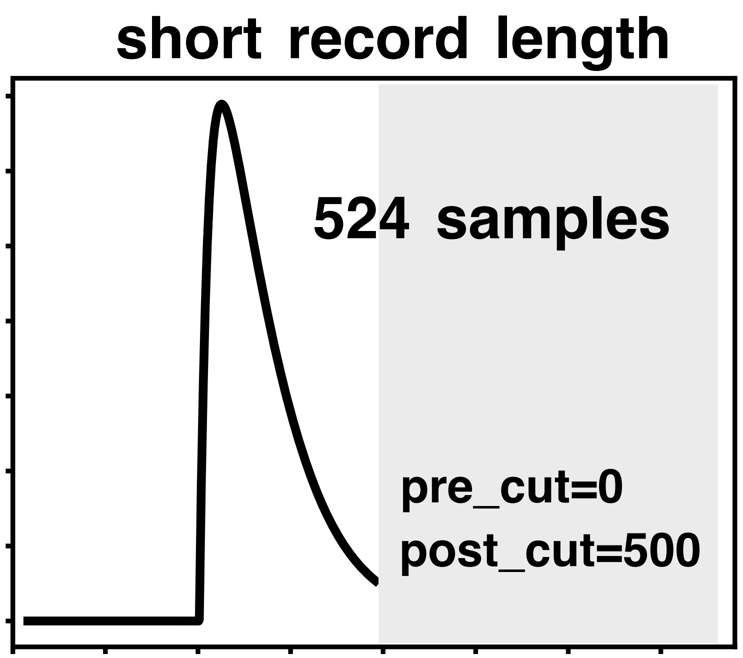
Charged particle identification

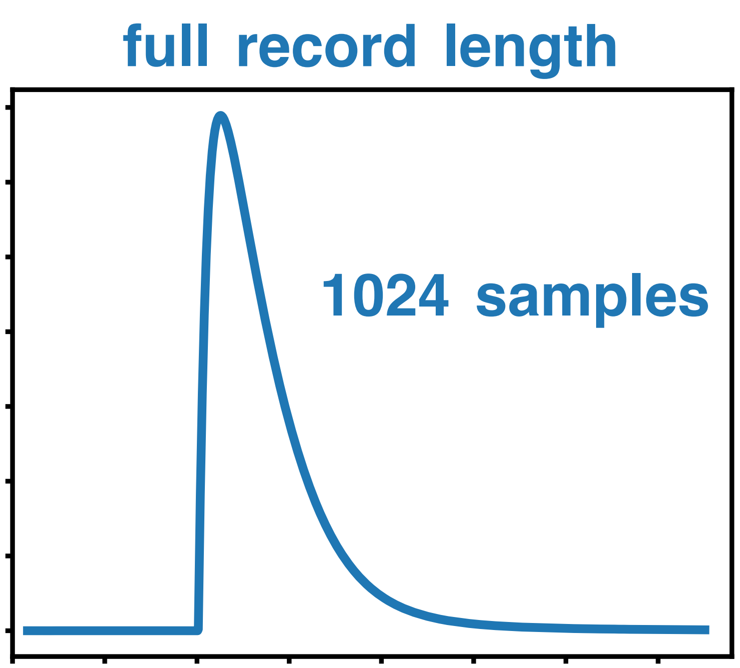


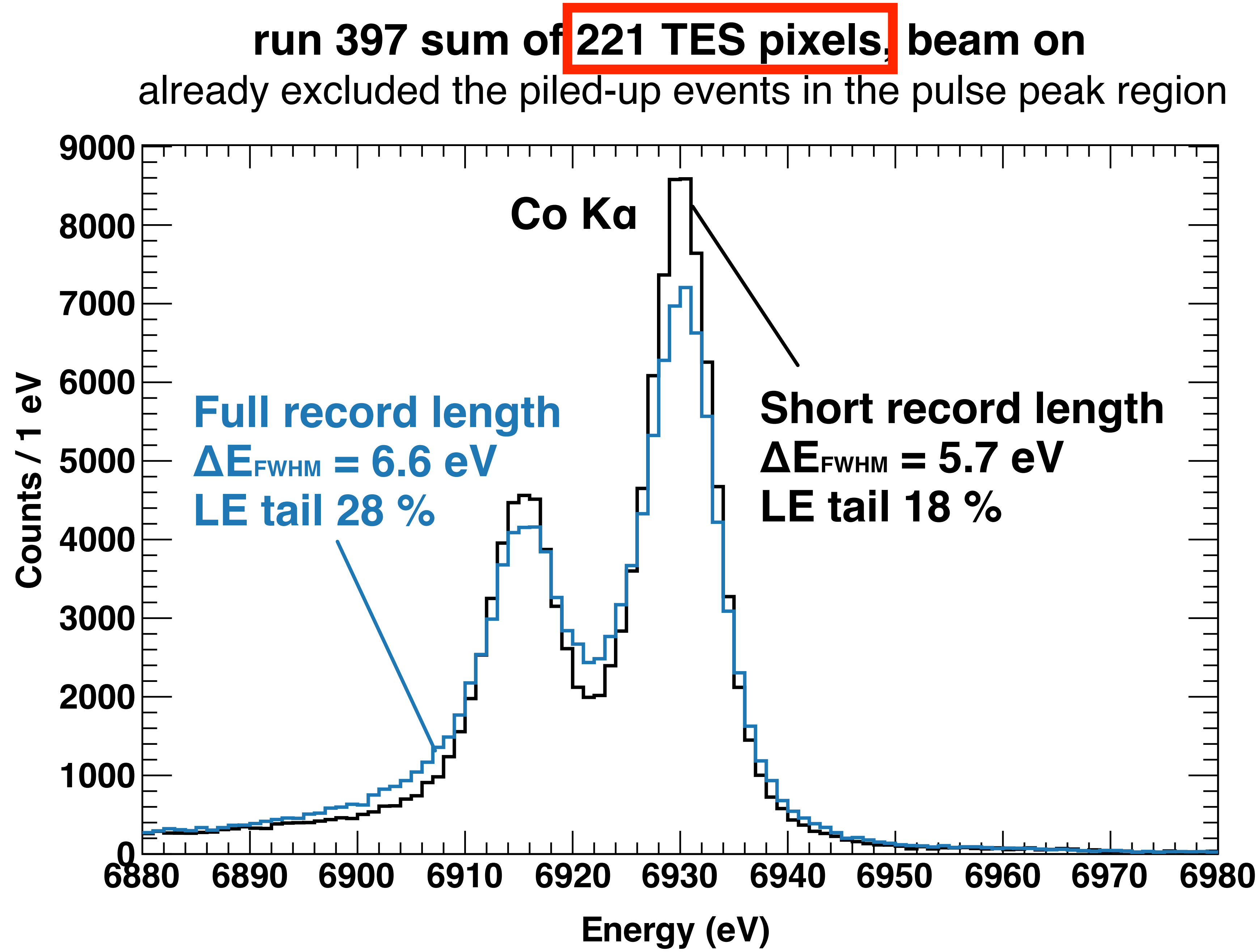


- No difference in the primary pulses between X-rays and charged particles
- If we look at neighboring pixels, we can reject half of the charged particles

Shorter record length to avoid pileup



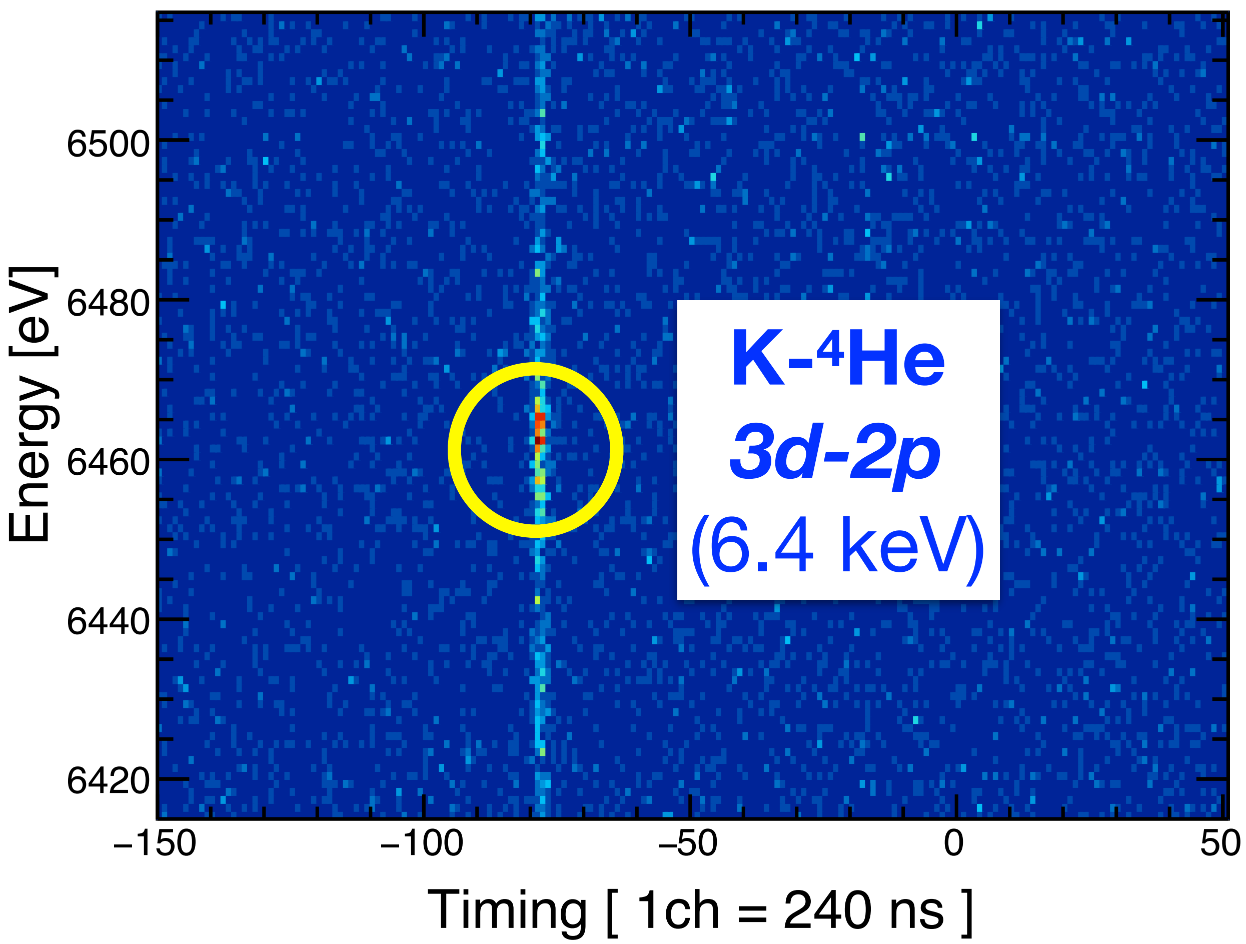


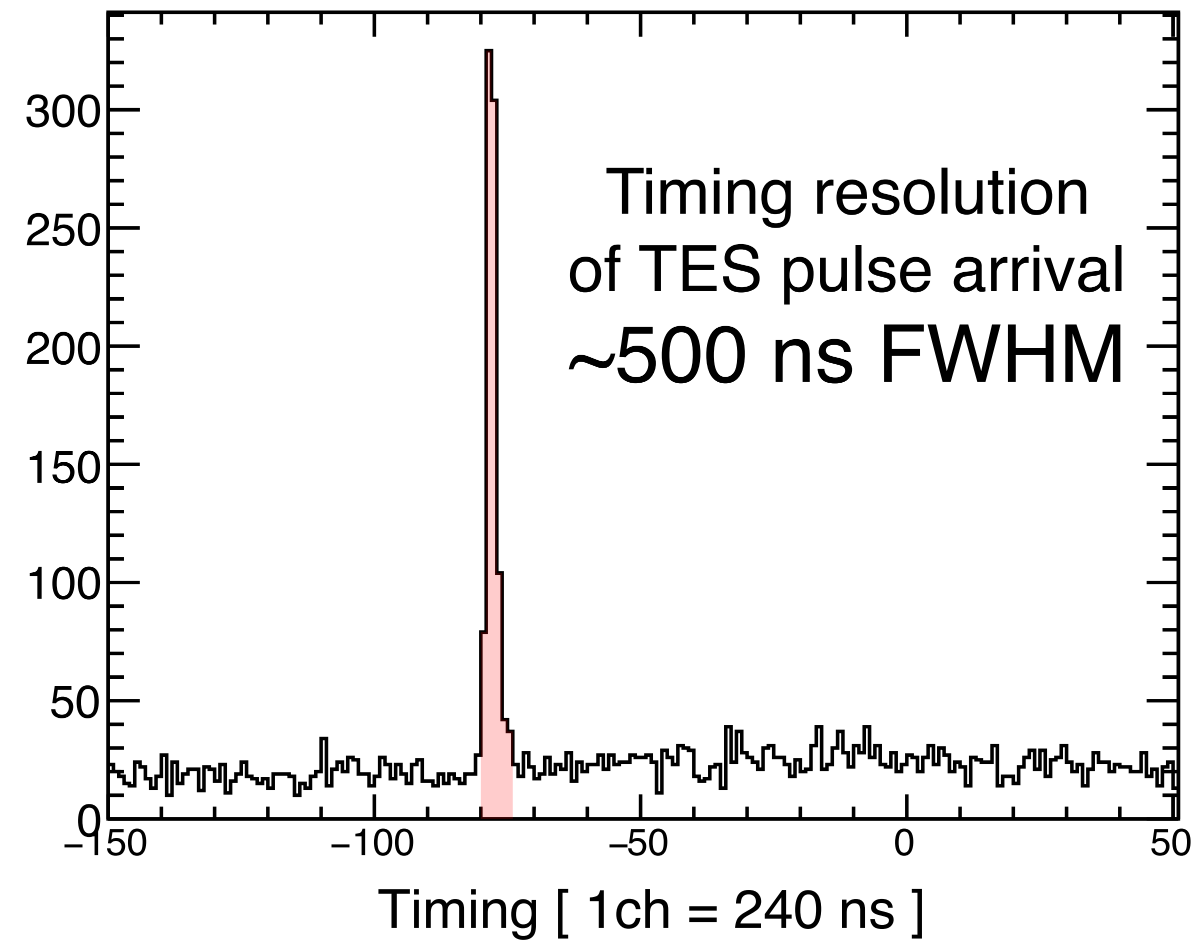


* ~5eV FWHM @ beam off

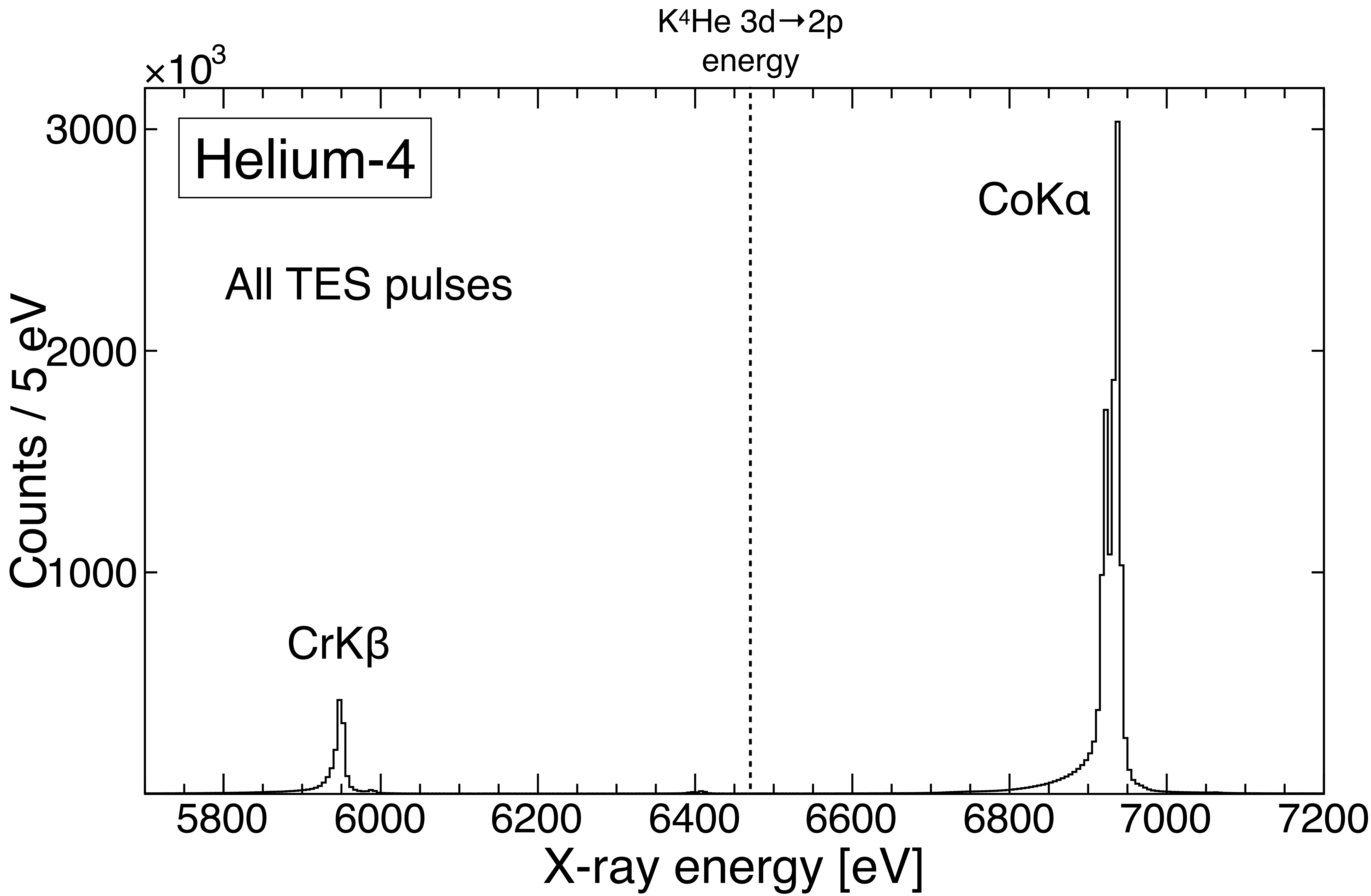
- ✓ Thermal cross talk bumps deteriorate resolution
- ✓ Minimize chance to have pileup bumps

Combine with beam-line information





- ✓ Every kaon beam timings are implemented into the TES data stream in the row time unit. (t_{row}=240 ns)
- ✓ Full information of the beam line detectors (~1000 readout channels) for each kaon beam is available by offline synchronization based on the timestamp.


K⁴He 3d→2p
energy
×10^3
Helium-4
CoKα
All TES pulses
CrKβ
Counts / 5 eV
3000
2000
1000
5800
6000
6200
6400
6600
6800
7000
7200
X-ray energy [eV]

Kaonic Helium-3/4 X-ray spectrum

We will carefully extract the peak positions and widths

Summary

- **TES-based X-ray spectrometer was applied to Kaonic atom experiment at J-PARC, Japan.**
  - Contribute to determine the K^{bar}-nucl. potential depth.

- **Successfully obtained nice spectra by using various analysis techniques**
  - In-beam energy calibration
  - Charged particle ID with neighboring pixels: “group trigger”
  - Shorter record length
  - Combine with beam line detector data: “external trigger”

- **Next: Kaonic atom at DAΦNE in Frascati**