STRANEX:
Recent progress and perspectivesin STRANge EXotic atoms studies and related topics

ECT*

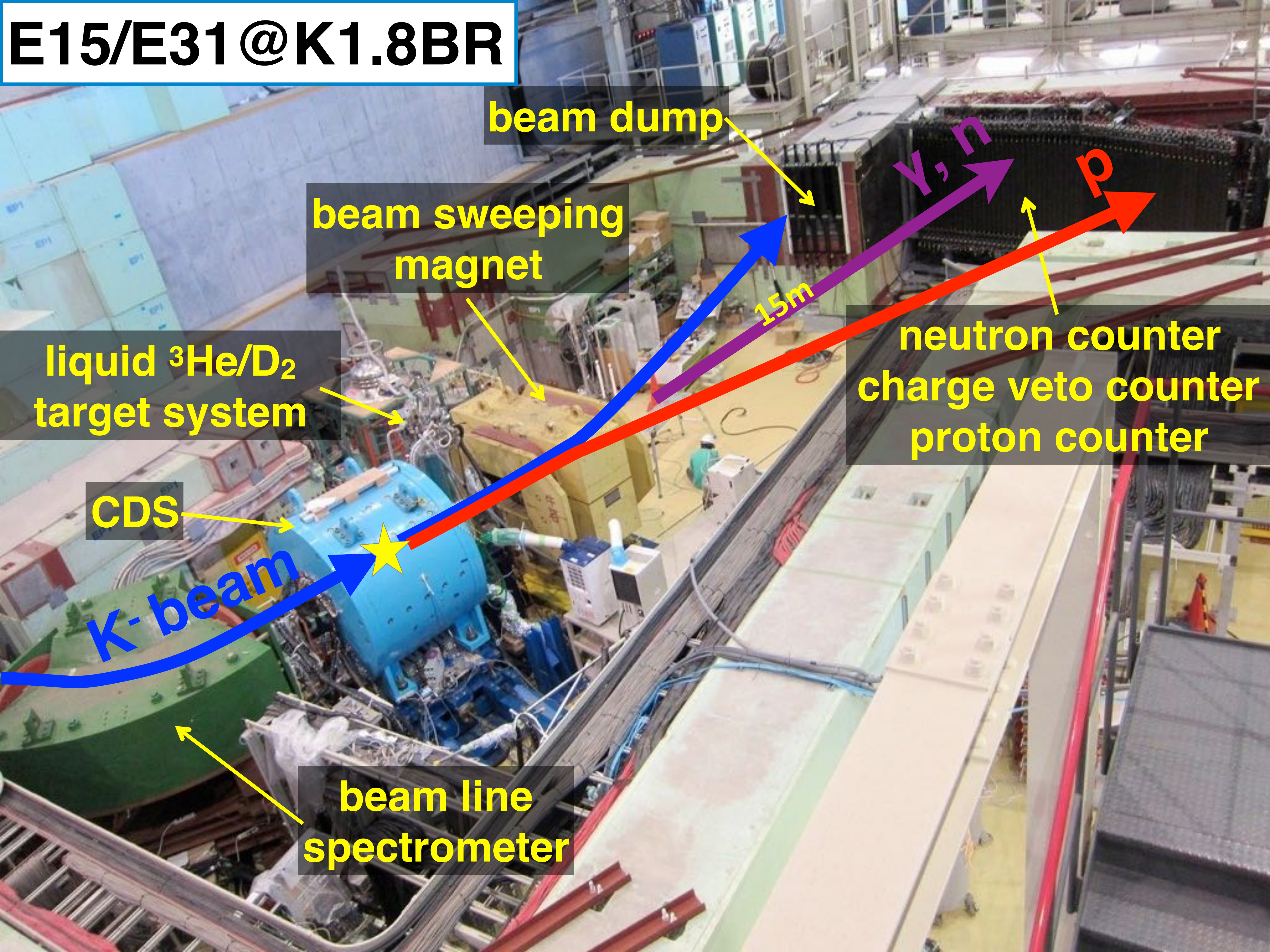
EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

TRENTO, ITALY
Institutional Member of the European Expert Committee NUPECC

Kaonic atom experiments at J-PARC

Tadashi Hashimoto (JAEA)
for the **J-PARC E57/E62** collaboration

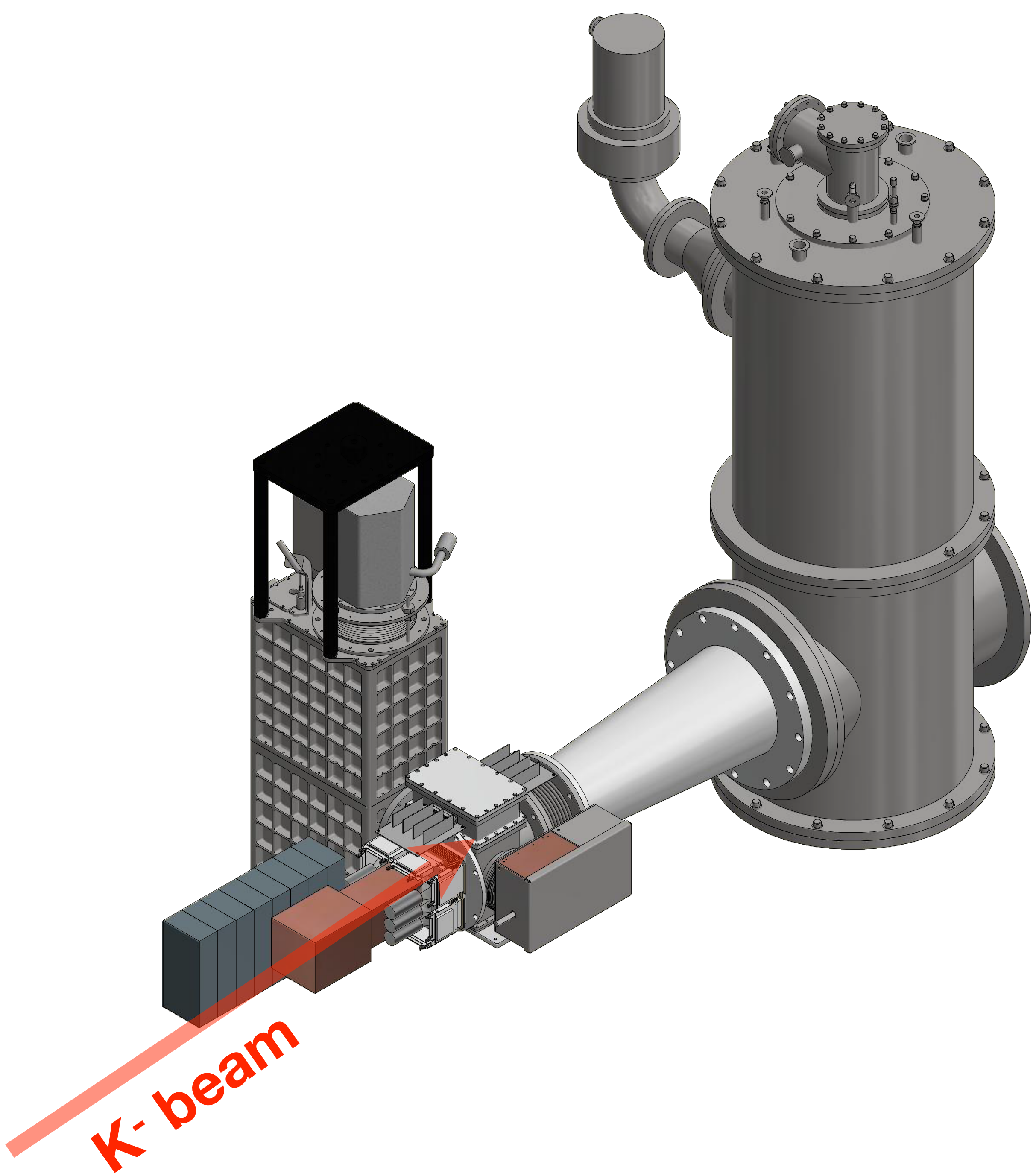
The Castle at Trento, painted by A. Dürer on his way back from Venice (1495, watercolor 19.8 x 27.7). British Museum, London


E15/E31@K1.8BR
beam dump
beam sweeping magnet
γ, n
p
15m
liquid ³He/D₂ target system
neutron counter
charge veto counter
proton counter
CDS
K- beam
beam line spectrometer

K-atom experiments @ J-PARC K1.8BR

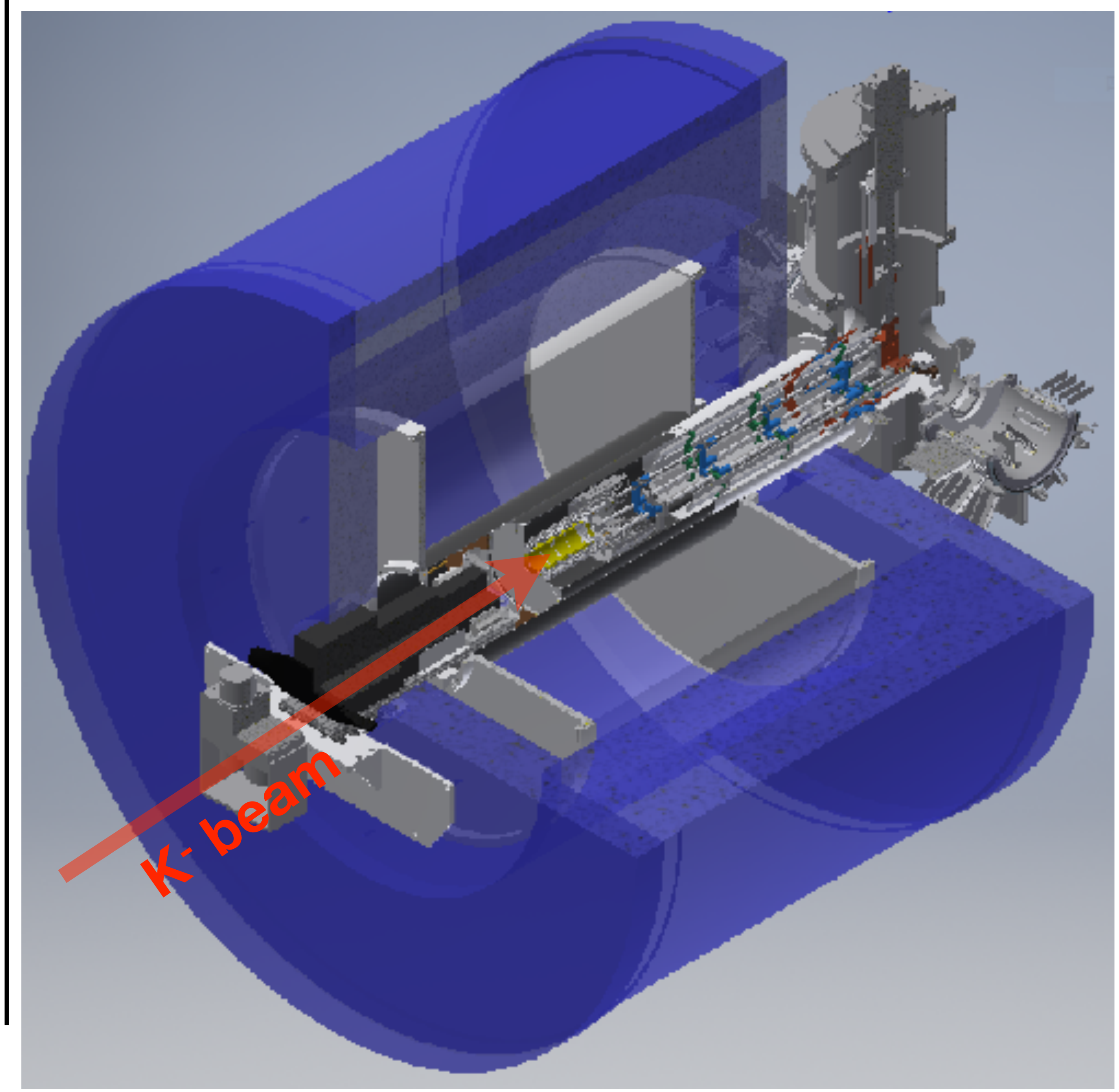
E62: K⁻He 3d-2p

sub-eV precision (ΔE_{2p})
to distinguish "deep" or "shallow" potential



E57: K⁻d 2p-1s

first measurement
to resolve isospin-dependent $K^{bar}N$ scat. length



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K-atom experiments @ J-PARC K1.8BR

	K-He (E62)	K-d (E57)
X-ray transition	3d - 2p	2p - 1s
Energy	~ 6 keV	~ 8 keV
Width	**2 ~ 5 eV**	**~ 1000 eV**
Yield (per stopped K-)	~ 7 % (Liquid He)	**~ 0.1 % (0.05% of liquid D2 density)**
X-ray detector	**TES**	**SDD**
FWHM resolution	**~ 5 eV**	~ 150 eV
Effective area	~ 0.2 cm^2	**~ 200 cm^2**
Physics	K^{bar}-nucleus potential	$K^{bar}N$ (I=1)

Ultra-high precision measurement

High sensitivity measurement

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Present status

Year	E62	E57
2006	E17 proposal (1st PAC)	
・・・		
2014	TES demonstration @ PSI	E57 proposal (18th PAC)
2015	E62 proposal (20th PAC) →**stage-2** approval	updated proposal (20th PAC) →**stage-1** approval
2016	Commissioning at K1.8BR	
2017		
2018	**K-He Physics run** (June)	SDD commissioning
2019		**K-H (+K-He) full commissioning** (Feb.—Apr.)
2020		to submit updated proposal

K^{-} $^{3/4}$He 3d-2p (E62) with TES

Physics run was completed in June. 2018

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 (NIST+) + Astro-physicists (TMU+)

71 collaborators in total

Kaonic Helium 2p shift & width

J. Yamagata-Sekihara, S. Hirenzaki :
— Strong-intaction Shift & Width calc.
E. Hiyama : (Gauss expansion method)
— Charge-density dist calc. for ^{4}He&^{3}He

Choosing the following two typical models :
[Pheno.] Mares, Friedman, Gal, NPA770(06)84
[Chiral] Ramos, Oset, NPA671(00)481

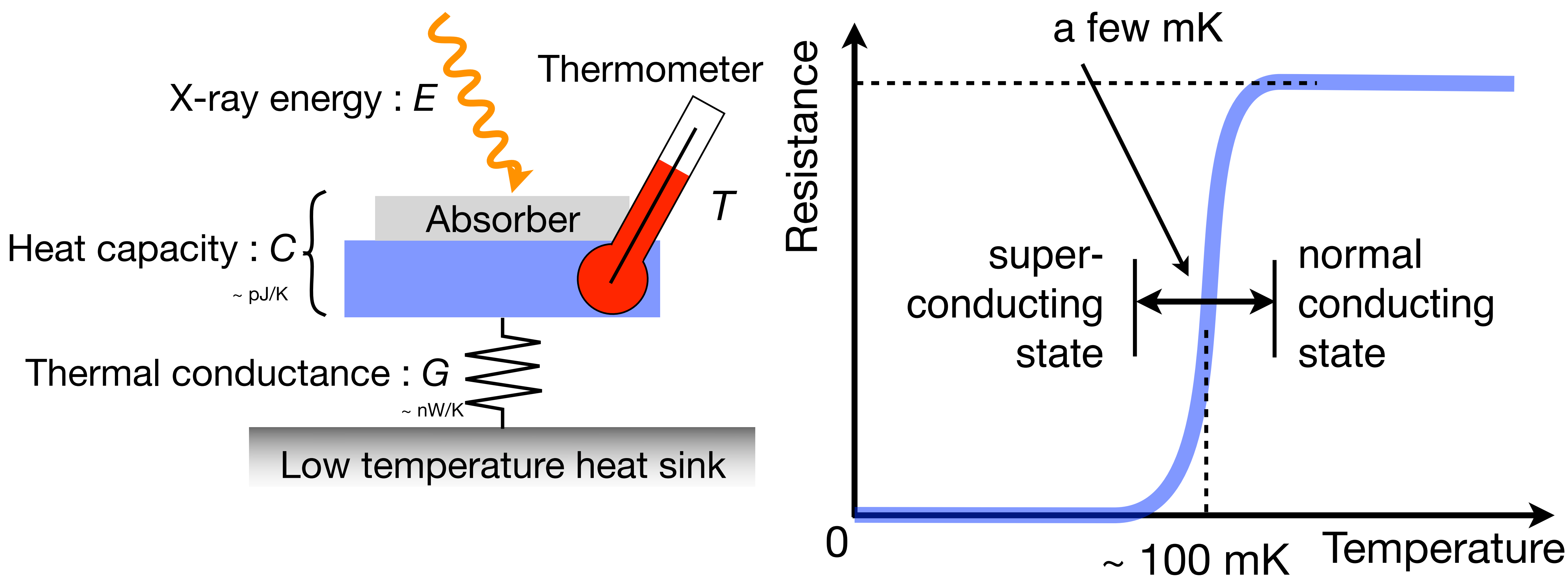
	deep	shallow
	Phenomenological $V_{opt}(r=0) \sim -(180 + 73i)$ MeV	**Chiral** $V_{opt}(r=0) \sim -(40 + 55i)$ MeV
K-^{4}He	-0.41 eV	-0.09 eV
K-^{3}He	0.23 eV	-0.10 eV
Isotope shift (K-^{4}He - K-^{3}He)	**-0.64 eV**	**0.01 eV**

preliminary

Width : 2 ~ 4 eV

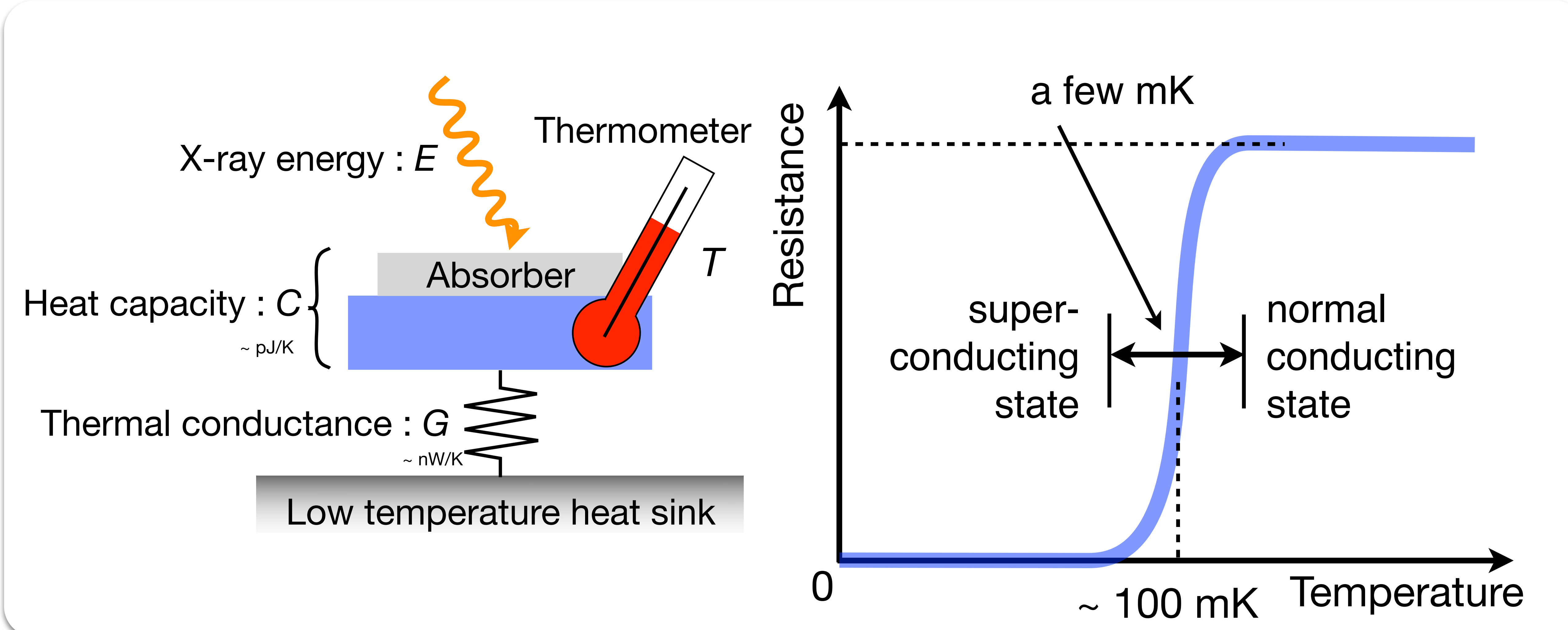
- ✓ Sub-eV precision measurement could impact on the deep/shallow potential problem
- ✓ ΔE~150 eV detector cannot control systematics < 1 eV
- ✓ Cancel out some systematics (K- mass etc.) with 2 lines.

Transition-Edge-Sensor microcalorimeters



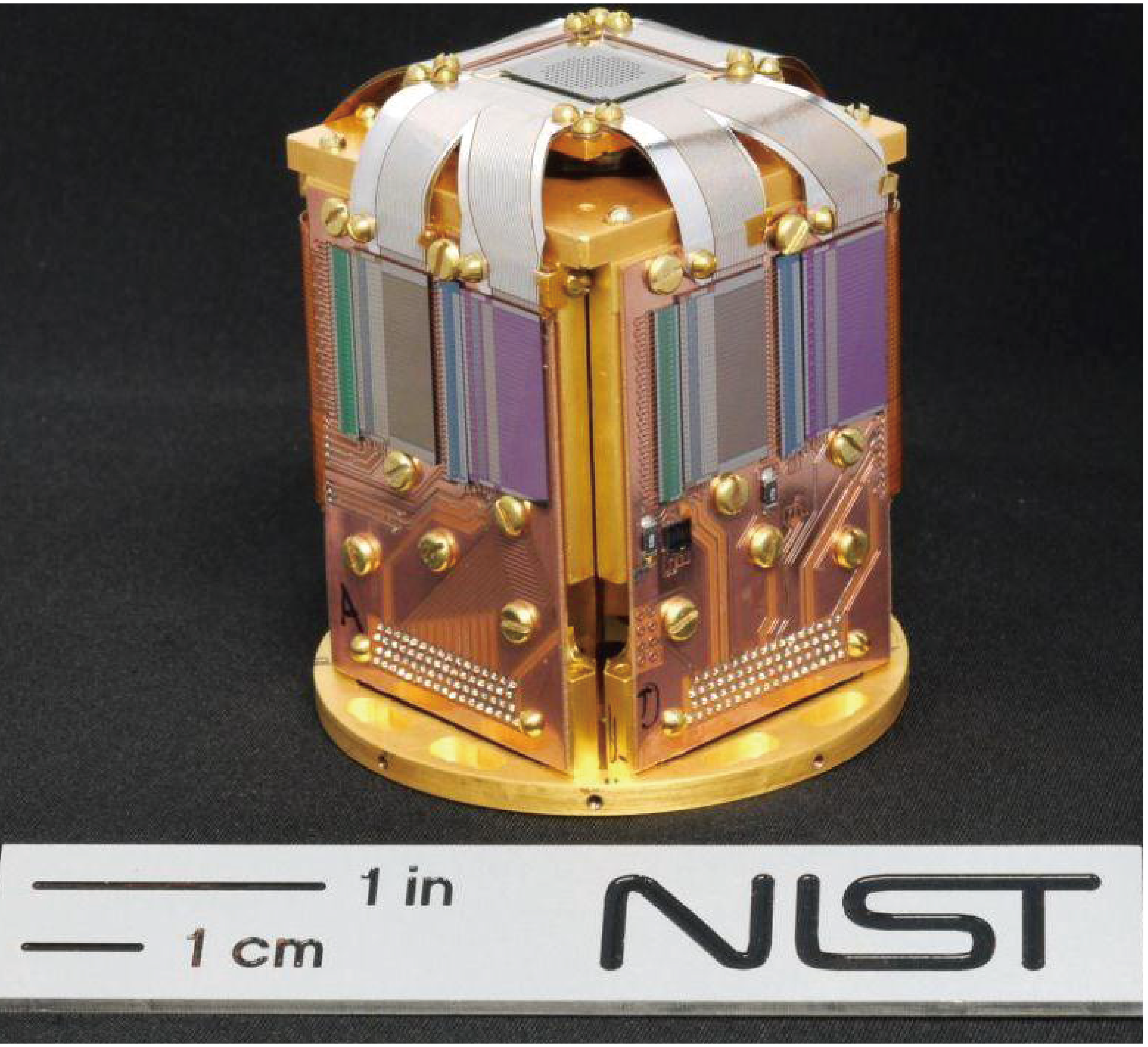
- ✓ Excellent energy resolution
- ✓ Reasonable dynamic range
- ✓ Multiplexing technique using SQUID

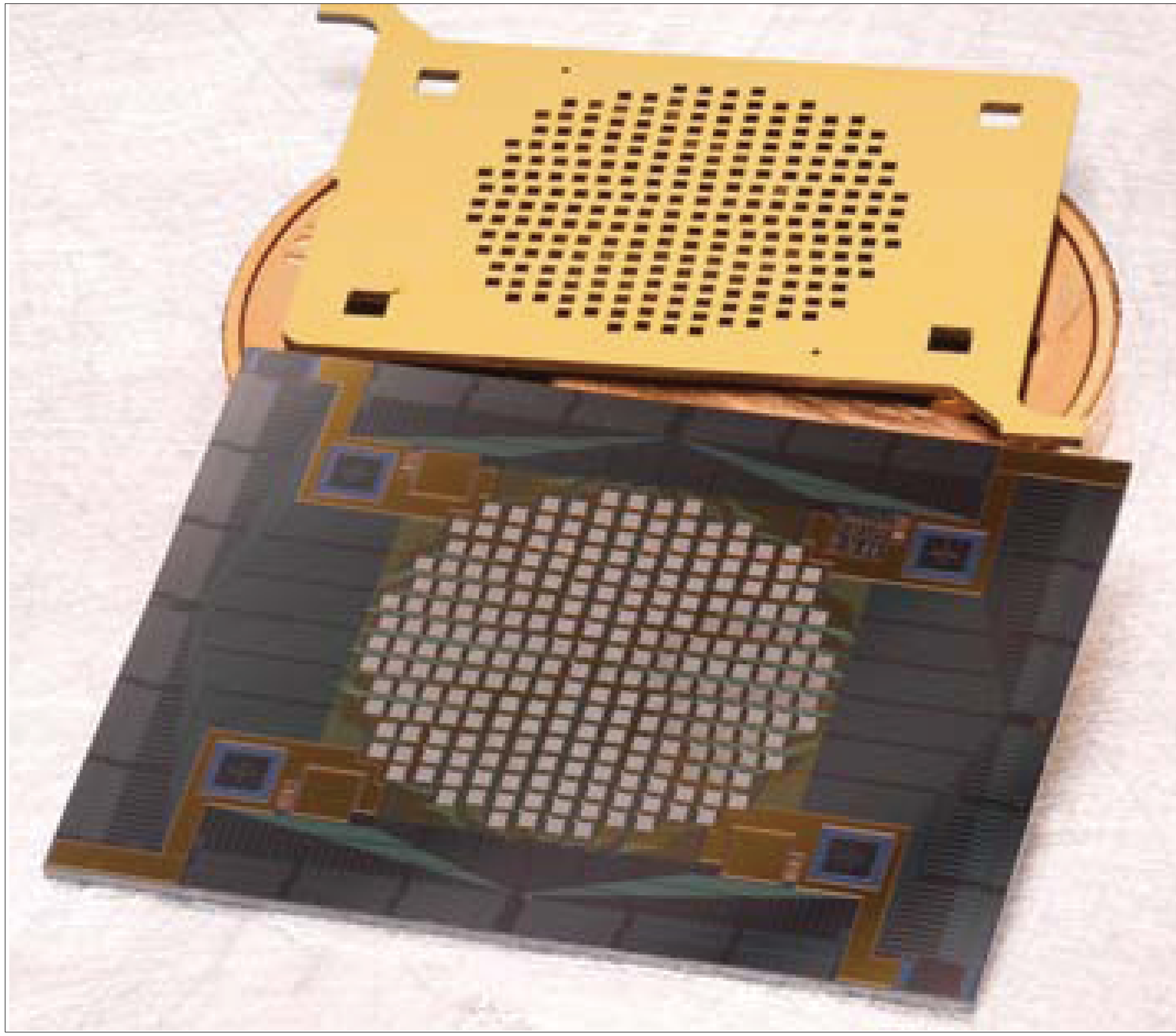
Transition-Edge-Sensor microcalorimeters



- ✓ Excellent energy resolution **~5 eV FWHM**
- ✓ Reasonable dynamic range **4-15 keV**
- ✓ Multiplexing technique using SQUID **240 pixels**

NIST(US) TES spectrometer for E62





- 240 pixel, ~23 mm², Mo/Cu + Bi 4um (85% eff.@6 keV)
- Cooled down to 70 mK with ADR & pulse tube.

Feasibility test using π beam at PSI in 2014

J Low Temp Phys (2016) 184:930–937
DOI 10.1007/s10909-016-1491-2

CrossMark

Absolute Energy Calibration of X-ray TESs with 0.04 eV Uncertainty at 6.4 keV in a Hadron-Beam Environment

H. Tatsuno[1] · W. B. Doriese[2] · D. A. Bennett[2] · C. Curceanu[3] ·

PTEP

Prog. Theor. Exp. Phys. **2016**, 091D01 (9 pages)
DOI: 10.1093/ptep/ptw130

Letter

First application of superconducting transition-edge sensor microcalorimeters to hadronic atom X-ray spectroscopy

HEATES Collaboration
S. Okada[†,1,*], D. A. Bennett[2], C. Curceanu[3], W. B. Doriese[2], J. W. Fowler[2], J. D. Gard[2],

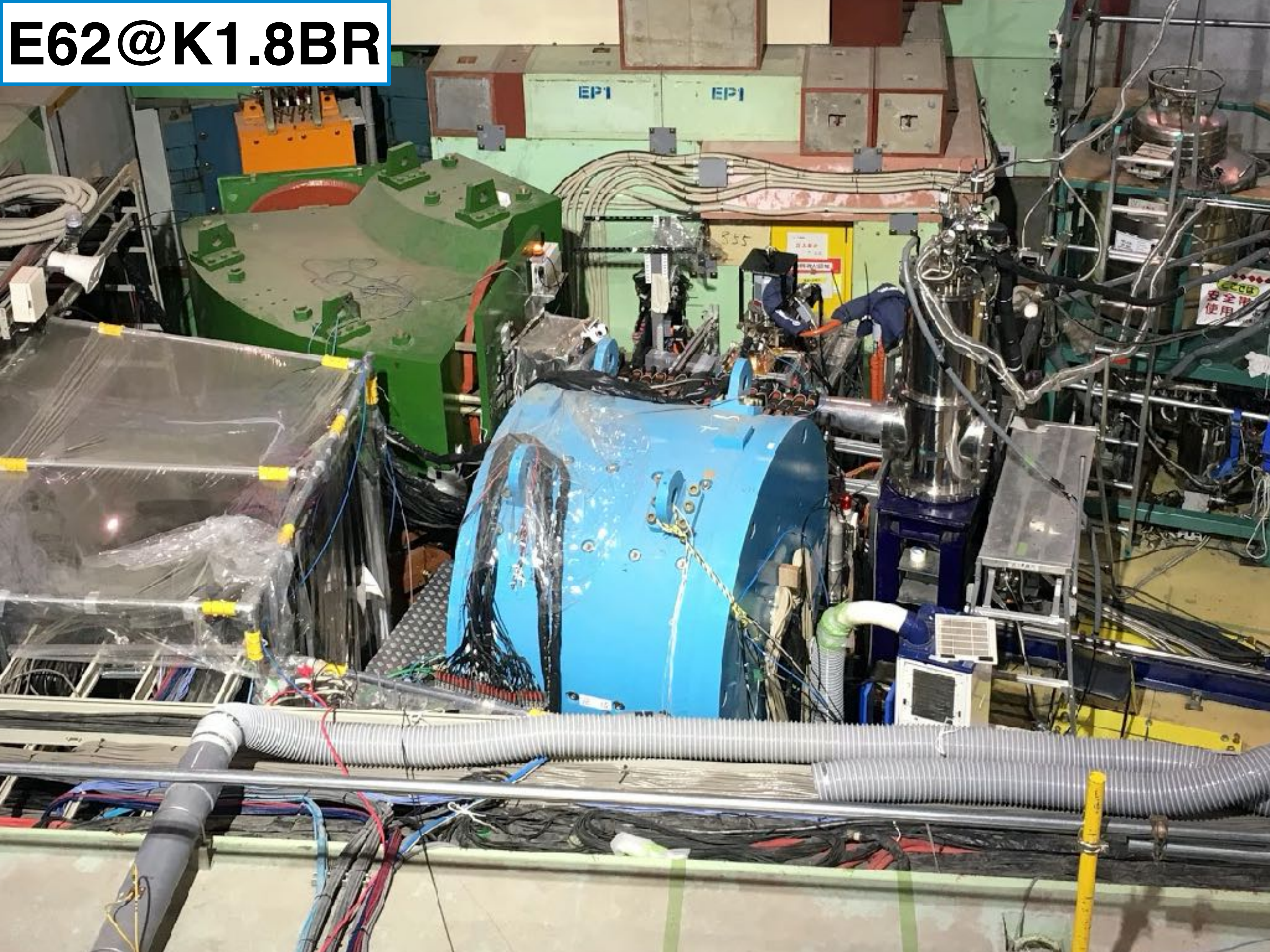
Beam commissioning at J-PARC in 2016

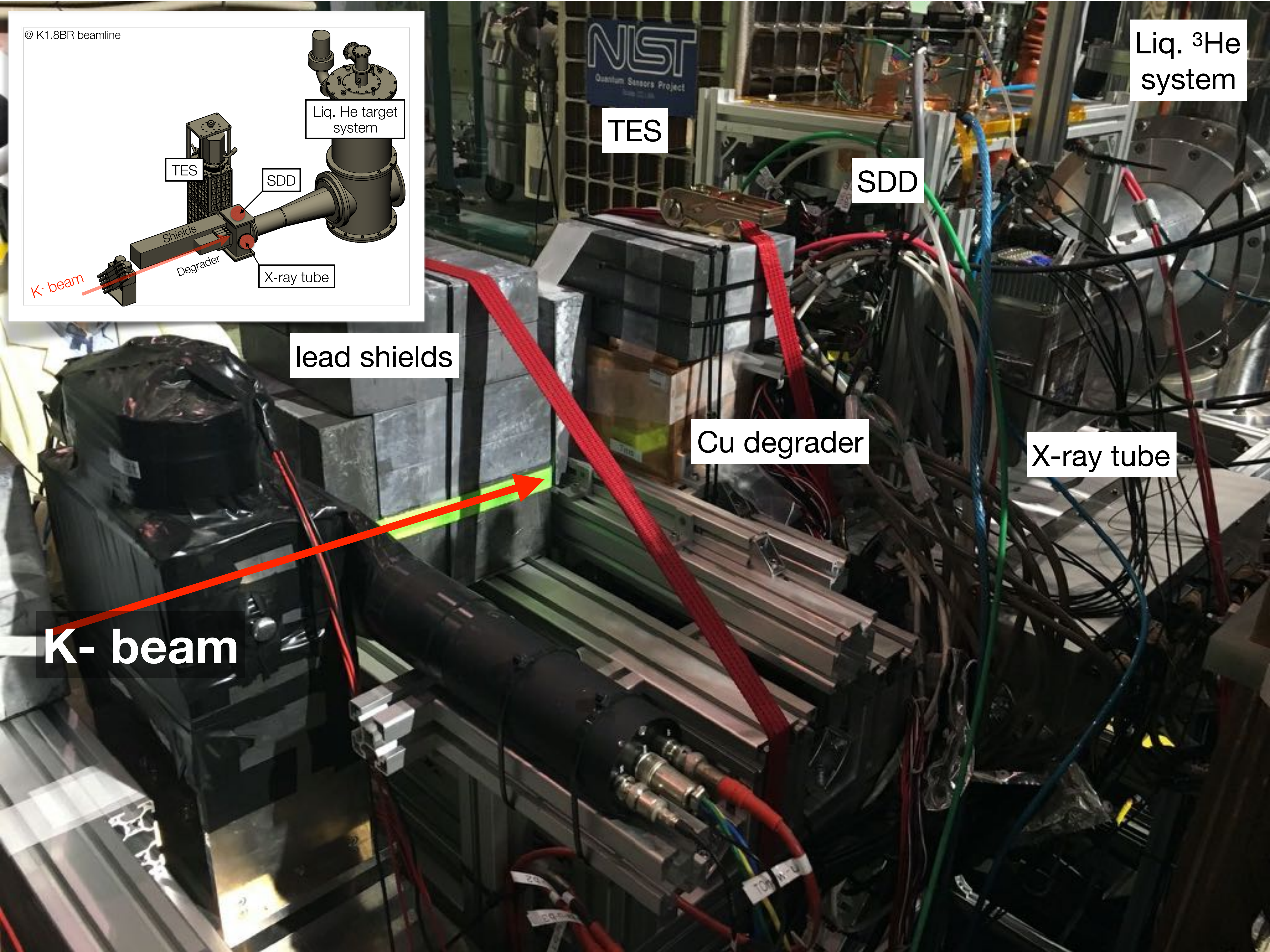
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 27, NO. 4, JUNE 2017 2100905

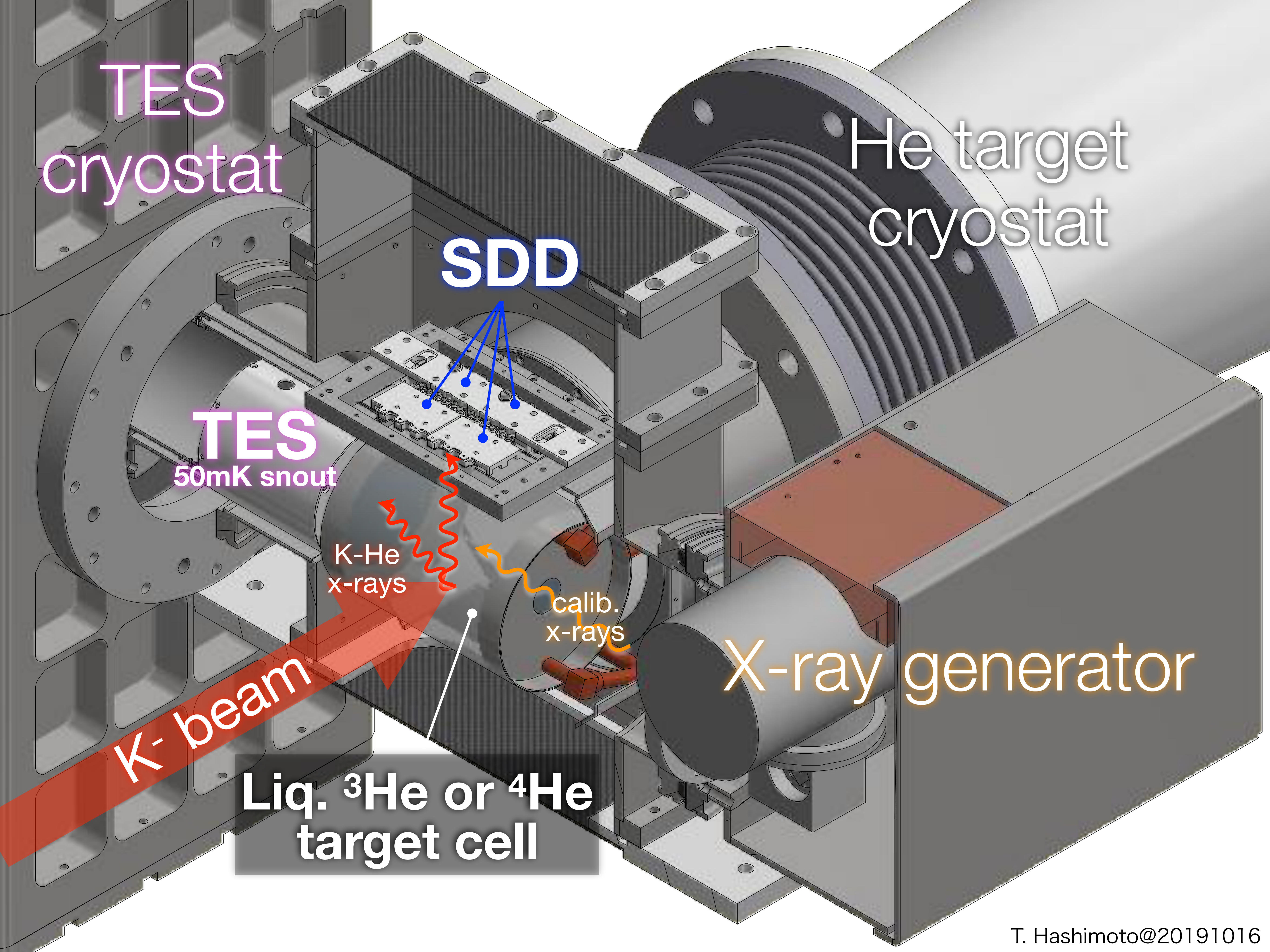
Beamline Test of a Transition-Edge-Sensor Spectrometer in Preparation for Kaonic-Atom Measurements

T. Hashimoto, M. Bazzi, D. A. Bennett, C. Berucci, D. Bosnar, C. Curceanu, W. B. Doriese, J. W. Fowler, H. Fujioka,

E62@K1.8BR

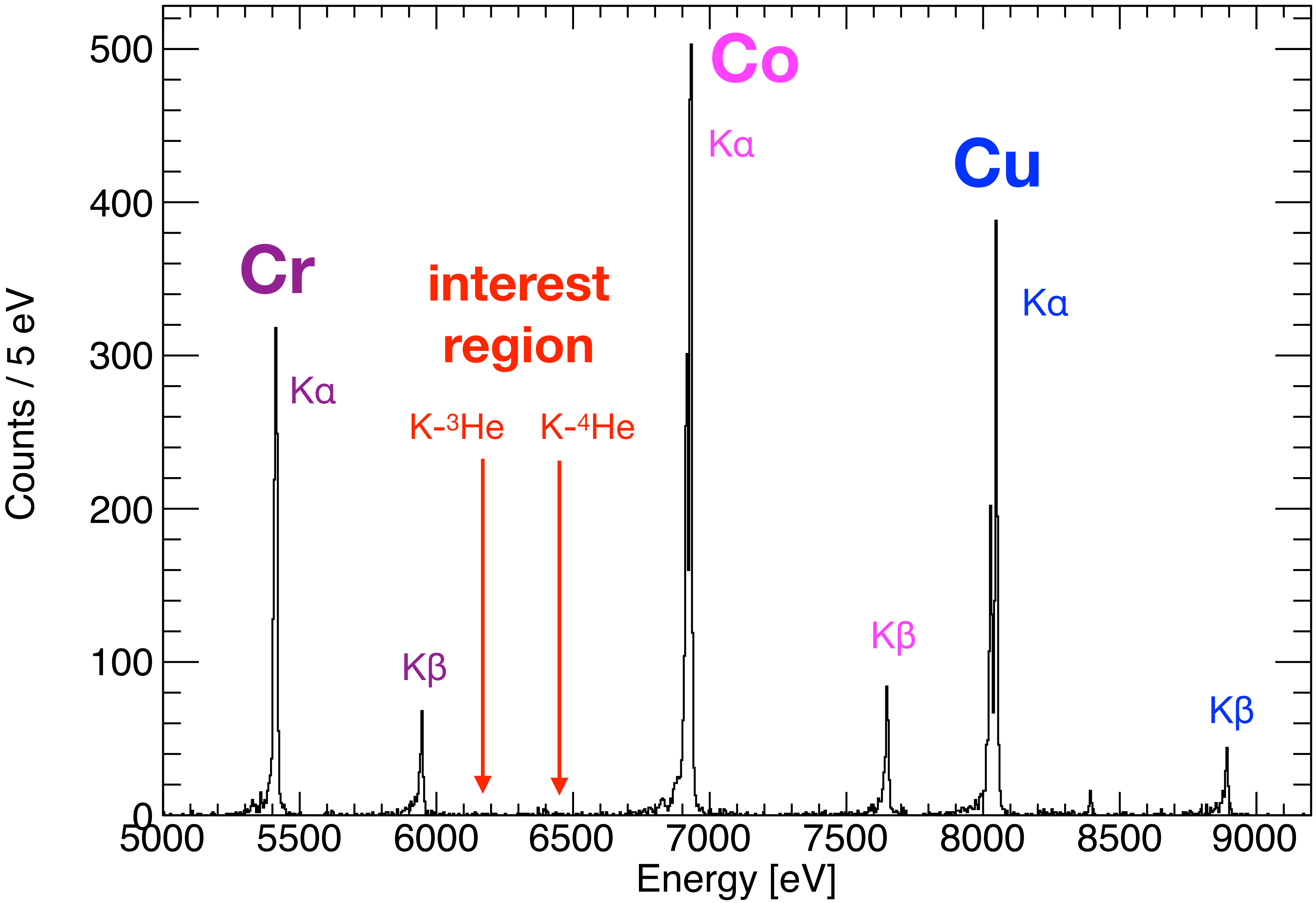



@ K1.8BR beamline
Liq. He target system
TES
SDD
Shields
Degrader
X-ray tube
K- beam
TES
SDD
Liq. ^{3}He system
lead shields
Cu degrader
X-ray tube
K- beam

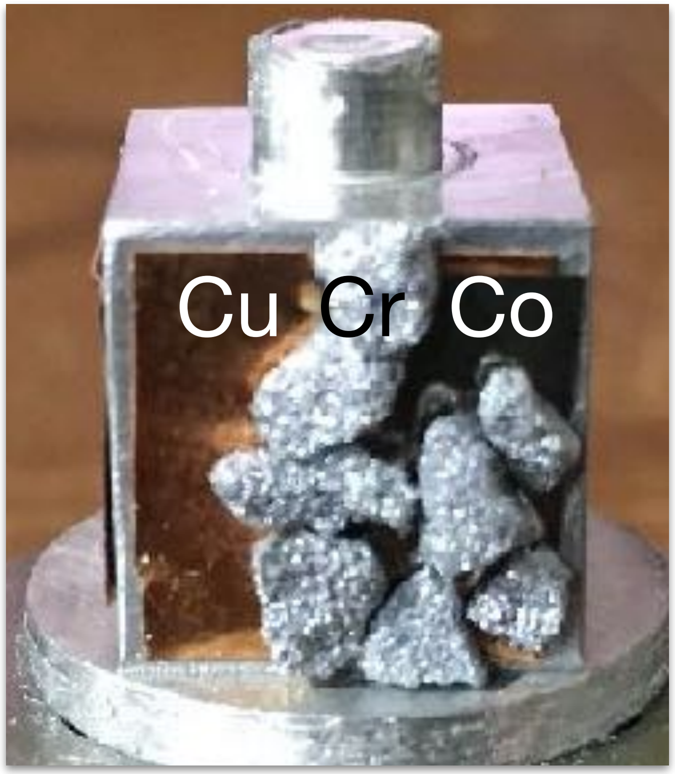

TES
cryostat
He target
cryostat
SDD
TES
50mK snout
K-He
x-rays
calib.
x-rays
X-ray generator
K- beam
Liq. ³He or ⁴He
target cell
T. Hashimoto@20191016

In-beam energy calibration

1 run, 1 pixel, ~ 2 hour exposure



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



✓ X-ray tube was always ON during the experiment

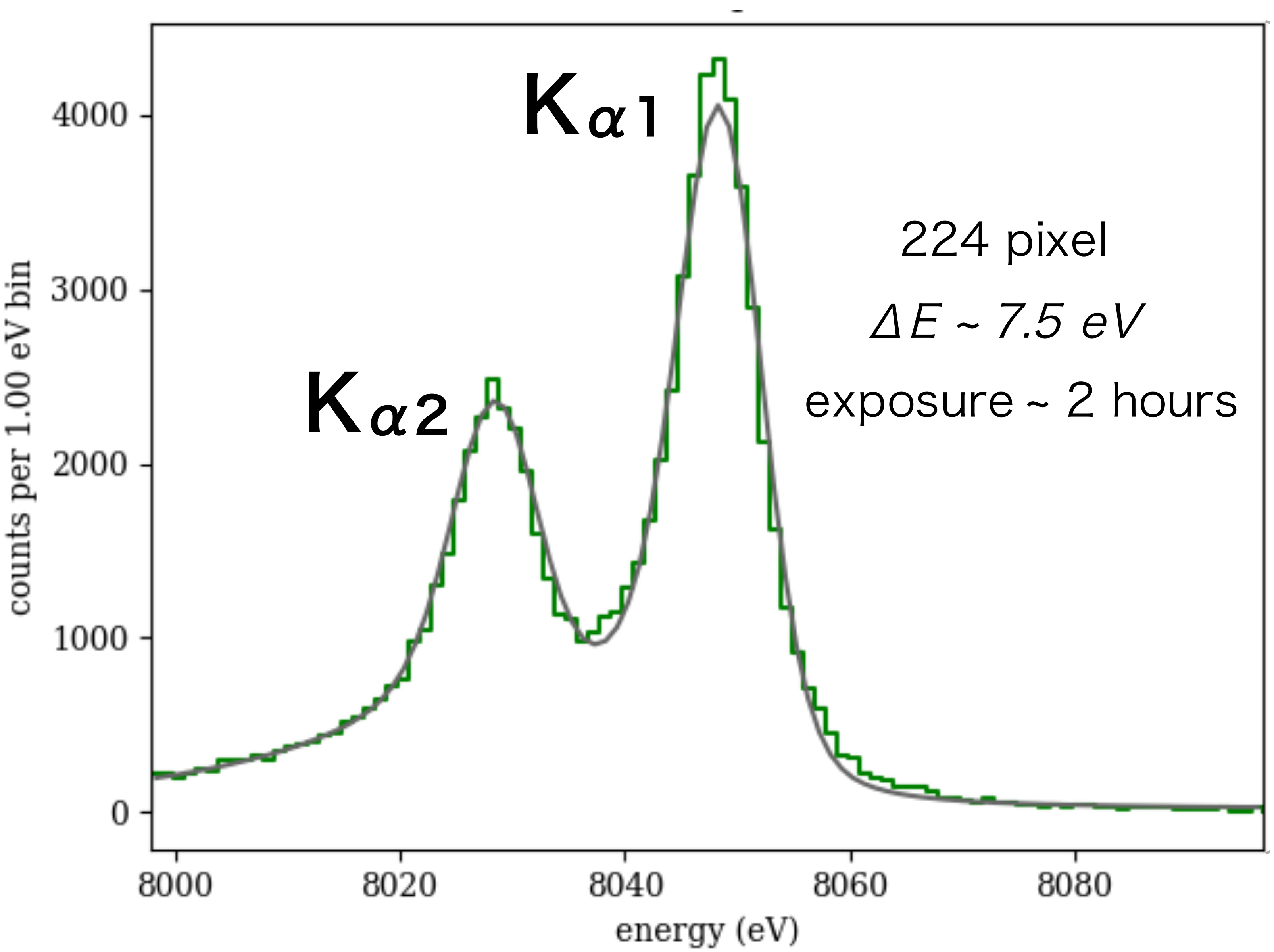
✓ Run-by-run (2 hours), pixel-by-pixel calibration

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

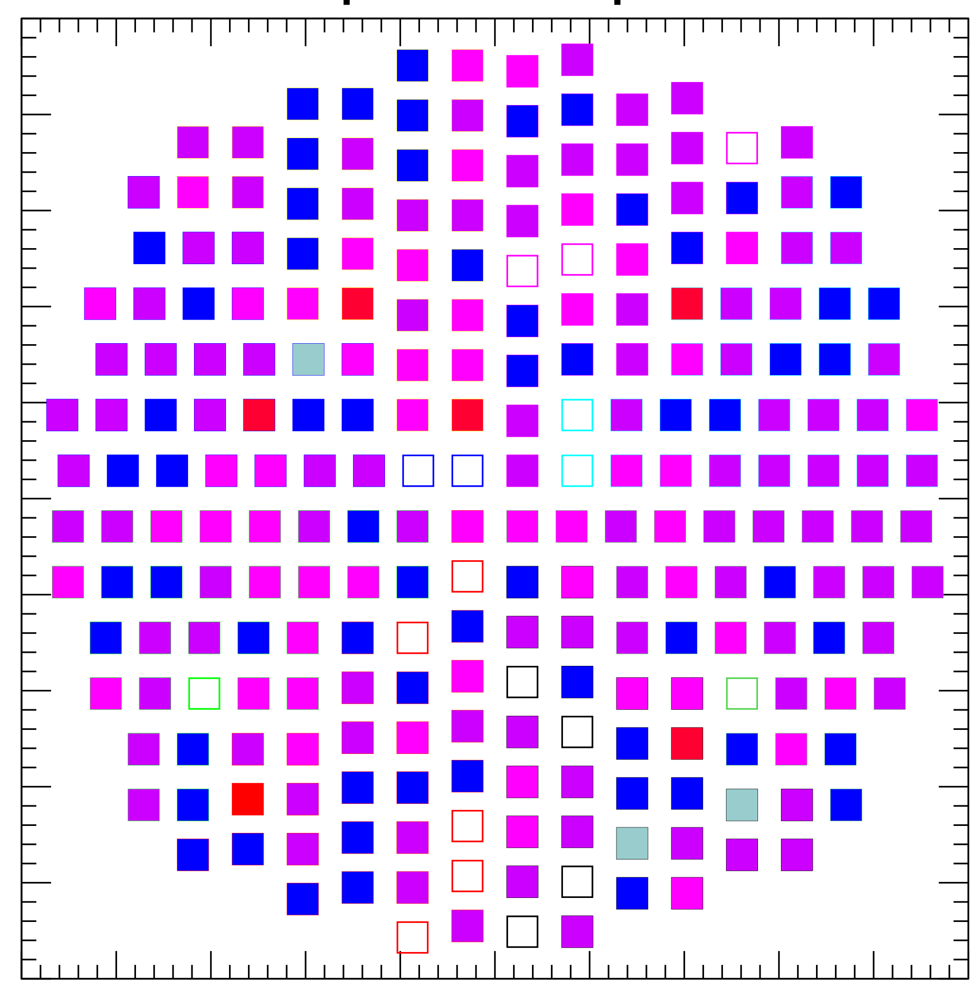
TES in-beam performance

Cu K_α spectrum from X-ray tube
in beam condition

~200 cps/array in total, 10~20 cps/array without X-ray tube

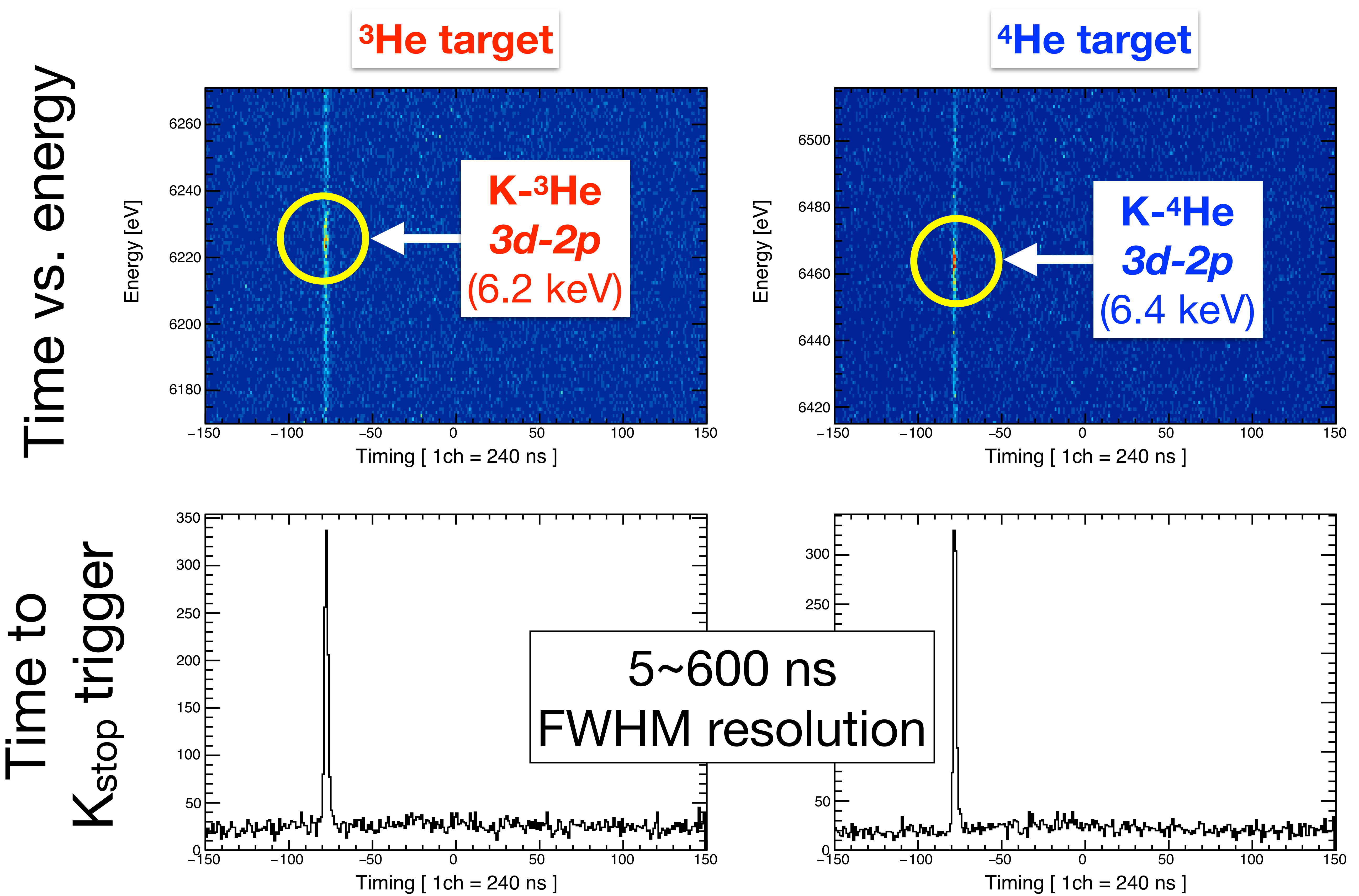


pixel map

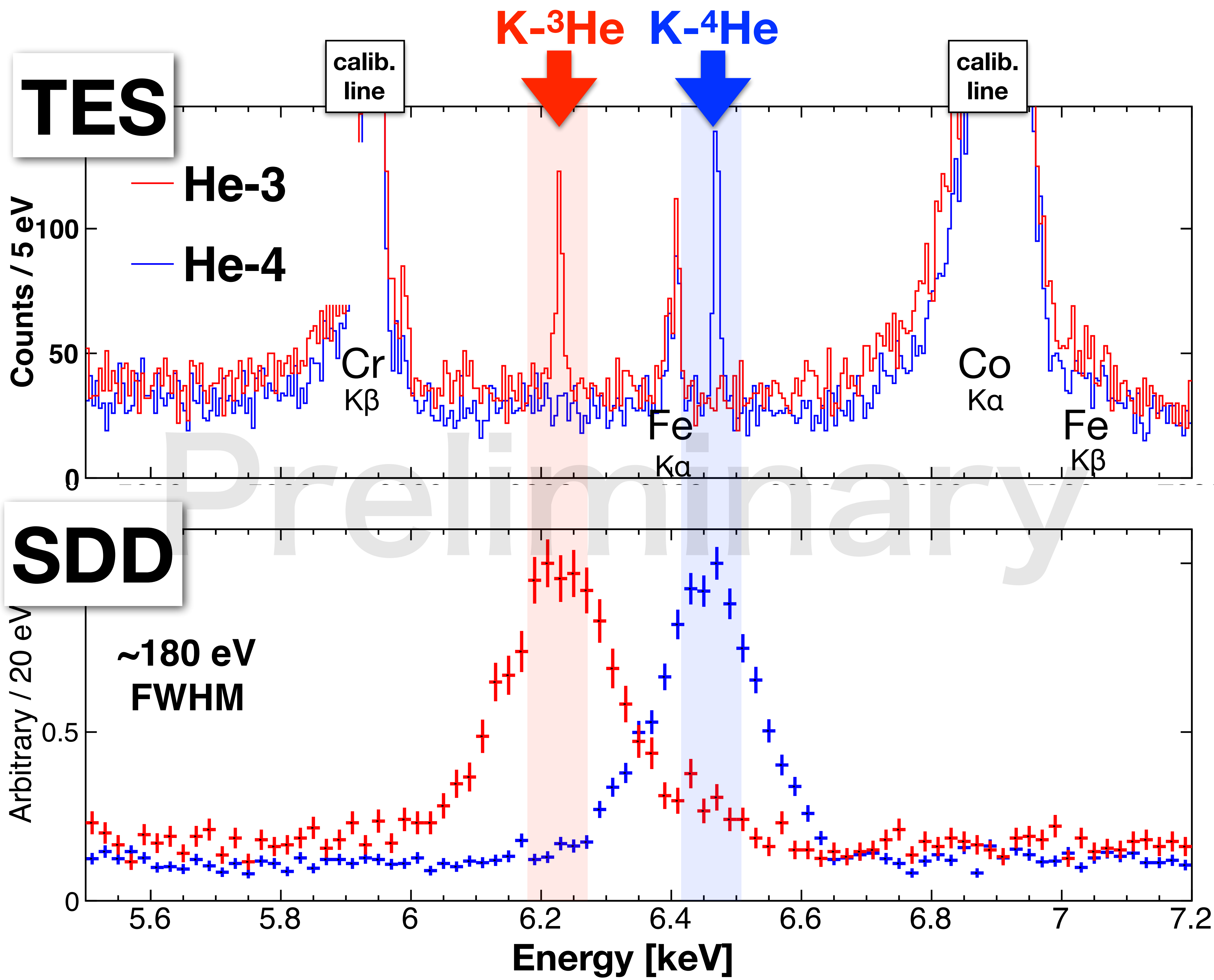


no color : doesn't work
(the colors show their resolutions)

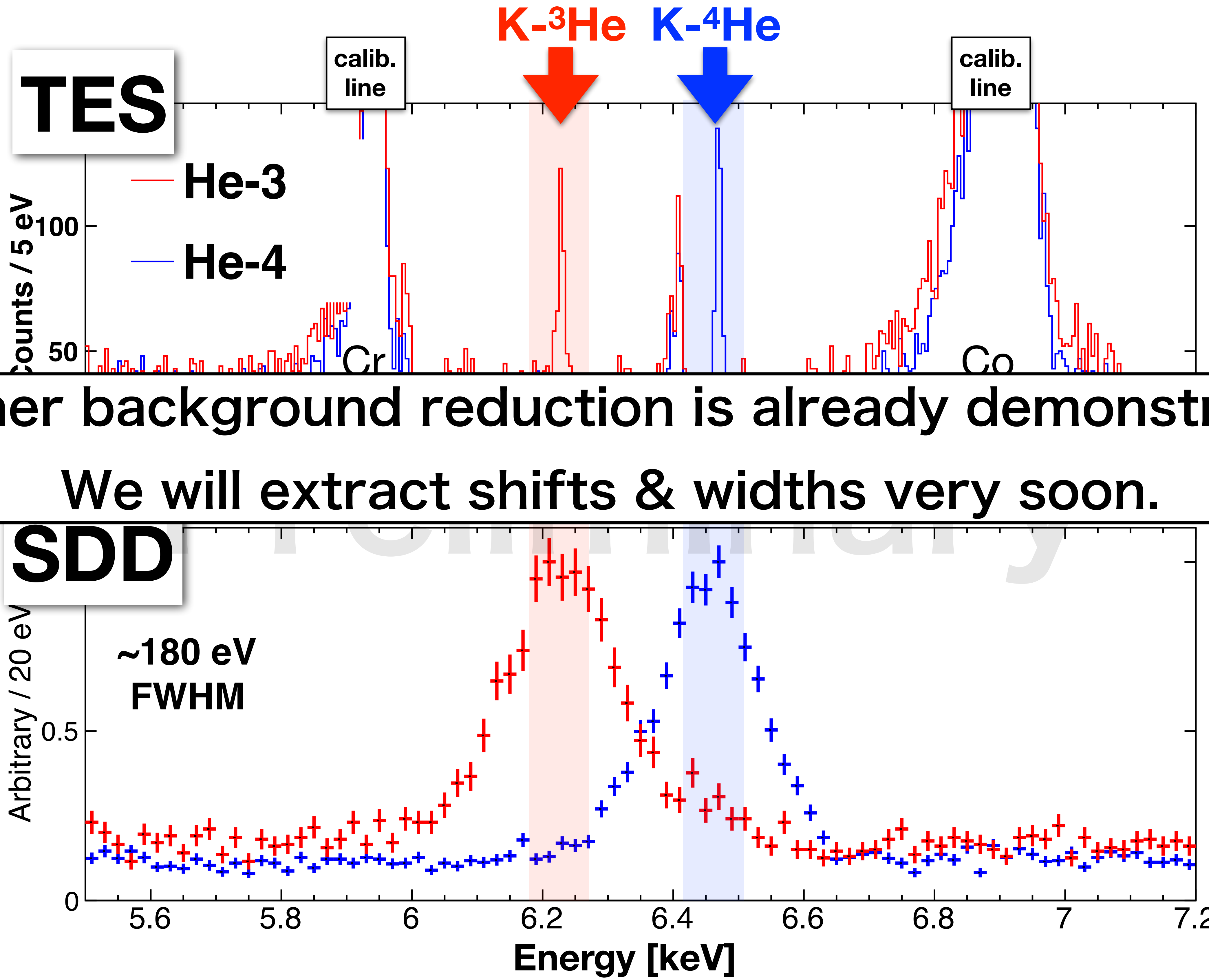
Preliminary result : time vs. energy



Preliminary result : K-He X-rays

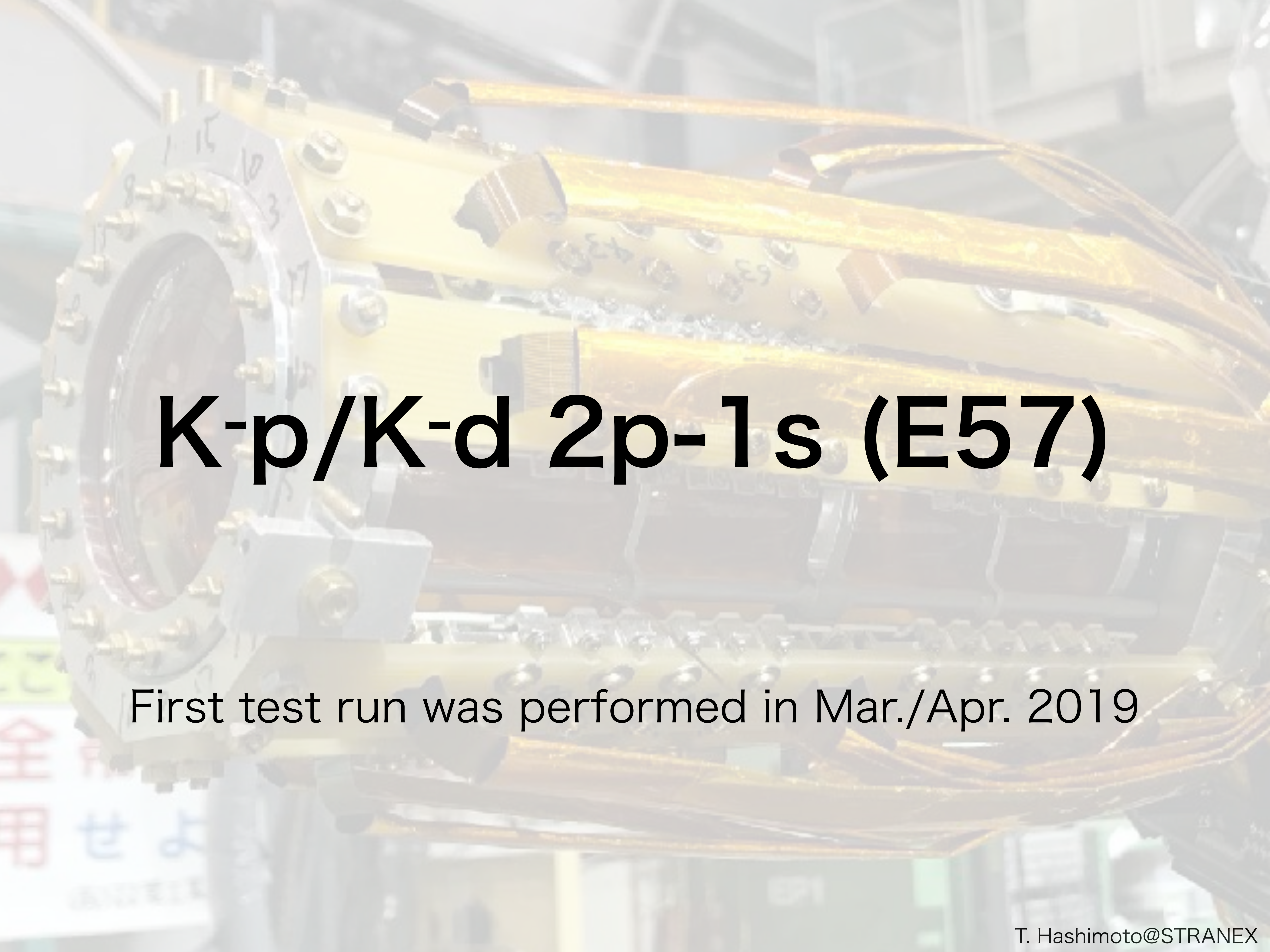


Preliminary result : K-He X-rays



Further background reduction is already demonstrated.

We will extract shifts & widths very soon.



K^-p/K^-d 2p-1s (E57)

First test run was performed in Mar./Apr. 2019

K–d collaboration

LNF- INFN, Frascati, Italy
SMI- ÖAW, Vienna, Austria
IFIN – HH, Bucharest, Romania
Politecnico, Milano, Italy
RIKEN, Japan
Tokyo Univ., Japan
Victoria Univ., Canada
KEK, Tsukuba, Japan
RCNP, Osaka, Japan
Seoul Univ., South Korea
Zagreb Univ., Croatia
INFN, Torino, Italy
Osaka Univ., Japan
TUM, Garching, Germany
Kyoto Univ., Japan
Jagiellonian Univ., Poland
RCJ, Juelich, Germany
Santiago de Compostela Univ., Spain
Tohoku Univ., Japan
KIRAMS, Seoul, South Korea

20 institutes / 10 Countries

K^bar N scattering length

Deser-Type relation

U.-G. Meißner, U.Raha, A.Rusetsky, Eur. phys. J. C35 (2004) 349
next-to-leading order, including isospin breaking

$$\varepsilon_{1s} - \frac{i}{2}\Gamma_{1s} = -2\alpha^3\mu_c^2 \boxed{a_{K^-p}} \left(1 - 2\alpha\mu_c(\ln\alpha - 1)a_{K^-p}\right)$$

Shift **Width** **Scattering length**

Kaonic hydrogen (K-p)

$$a_{K^-p} = \frac{1}{2}\left[a_0 + a_1\right]$$

$$a_{K^-n} = a_1$$

no atom

Kaonic deuterium (K-d)

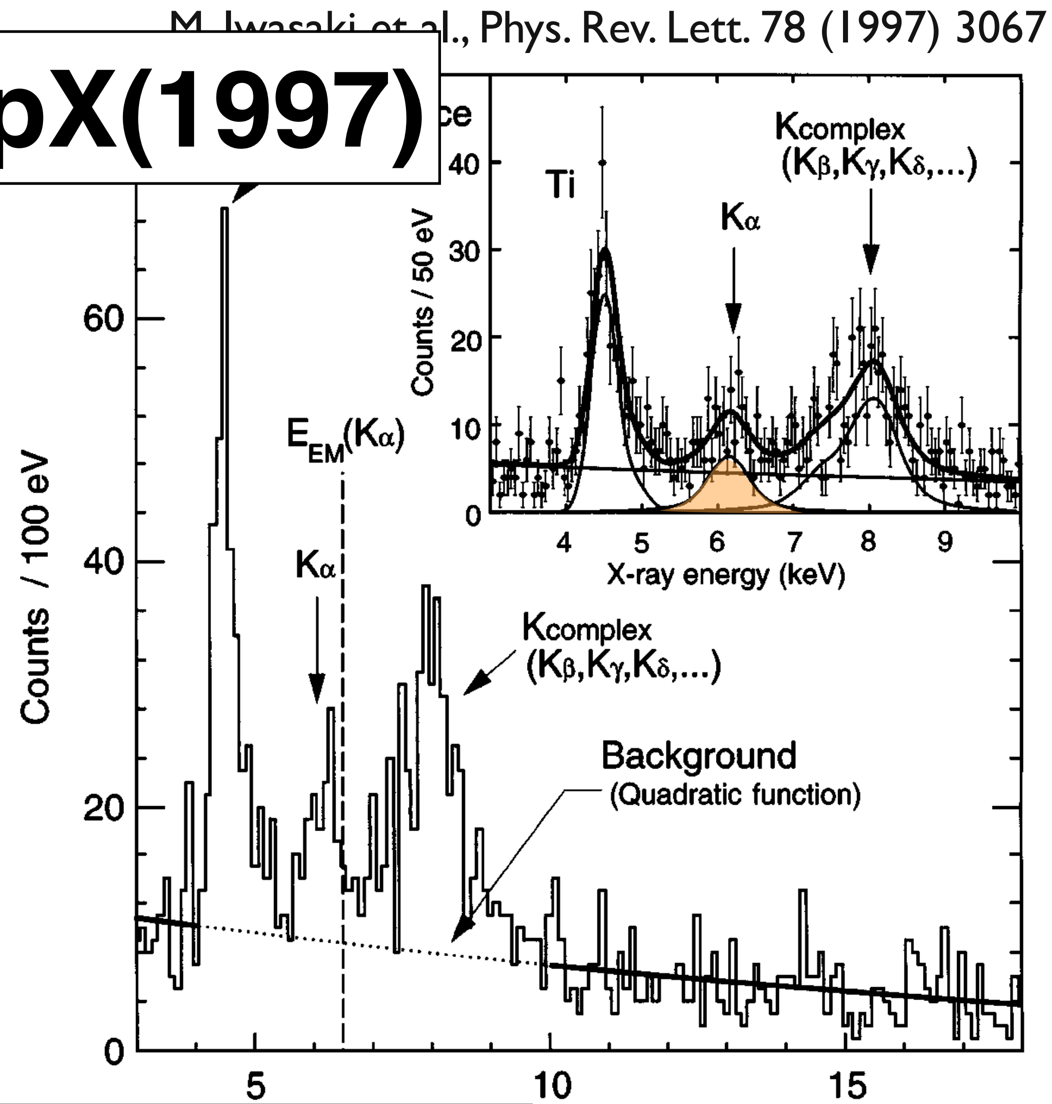
$$a_{K^-d} = \frac{k}{2}\left[a_{K^-p} + a_{K^-n}\right] + C = \frac{k}{4}\left[a_0 + 3a_1\right] + C$$

$$k = \frac{4\left[m_n + m_K\right]}{\left[2m_n + m_K\right]}$$

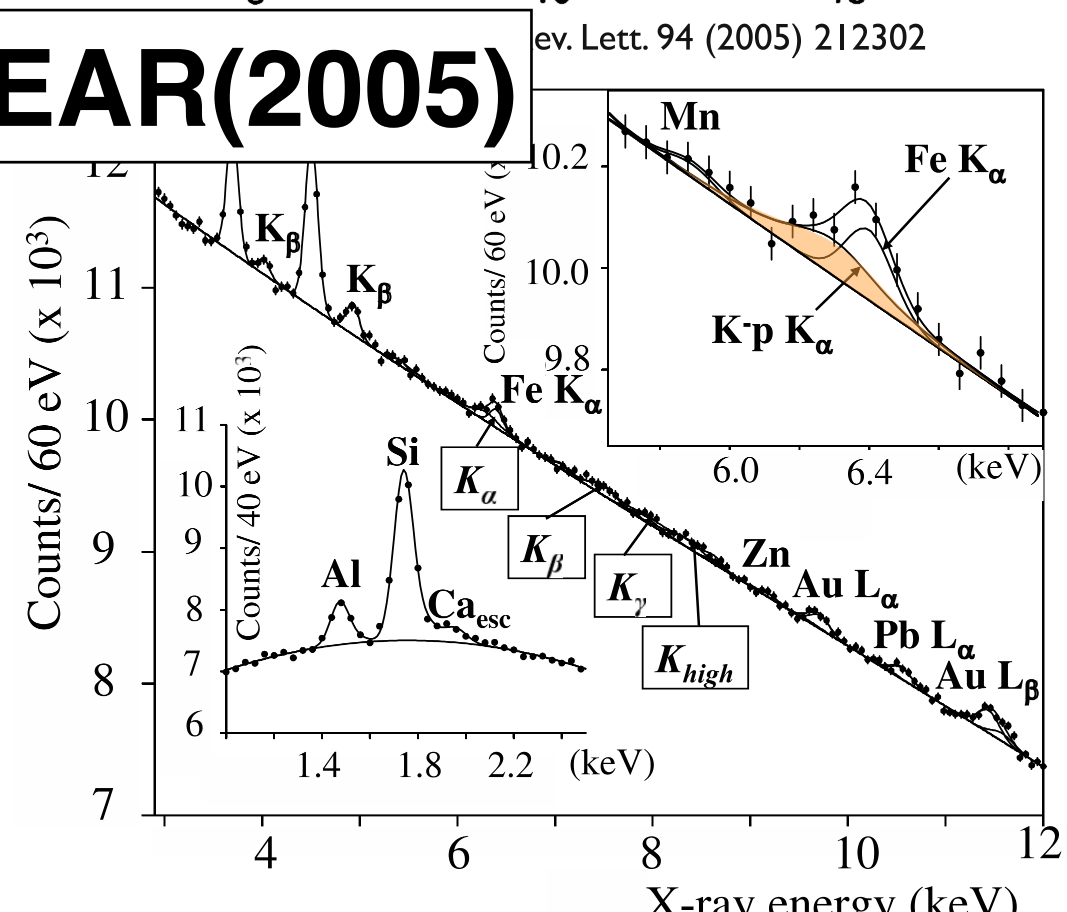
Theoretical calc.

✓ **X-ray spectroscopy of K-p and K-d resolve the isospin-dependent K^bar N scattering length**

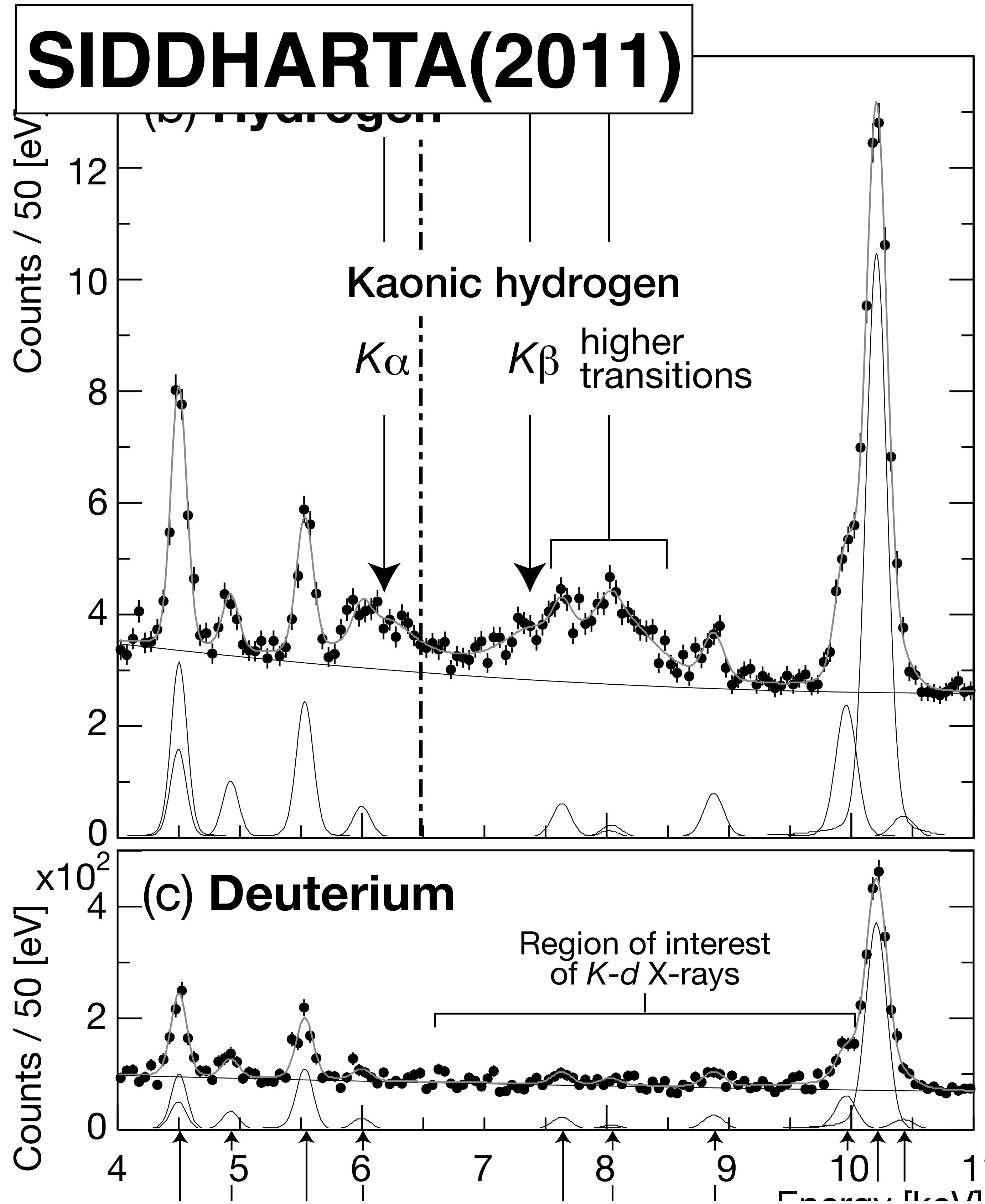
KpX(1997)



DEAR(2005)



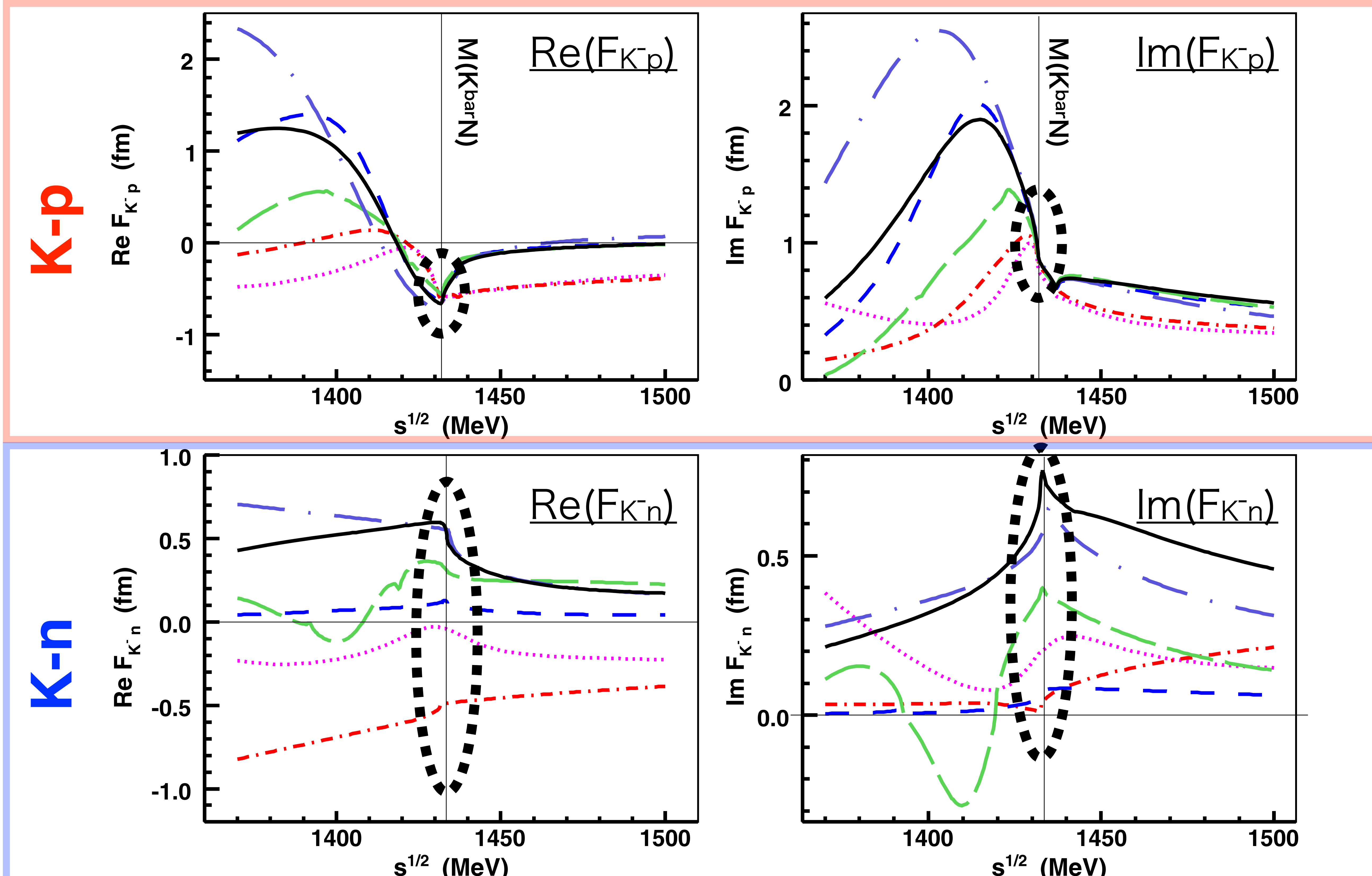
SIDDHARTA(2011)



Good K⁻p data
no K⁻d data ← low yield, large width

Theoretical calculation

A. Cieplý et al. NPA 954 (2016) 17–40



Need K$^-$d data to constrain isospin 1 component

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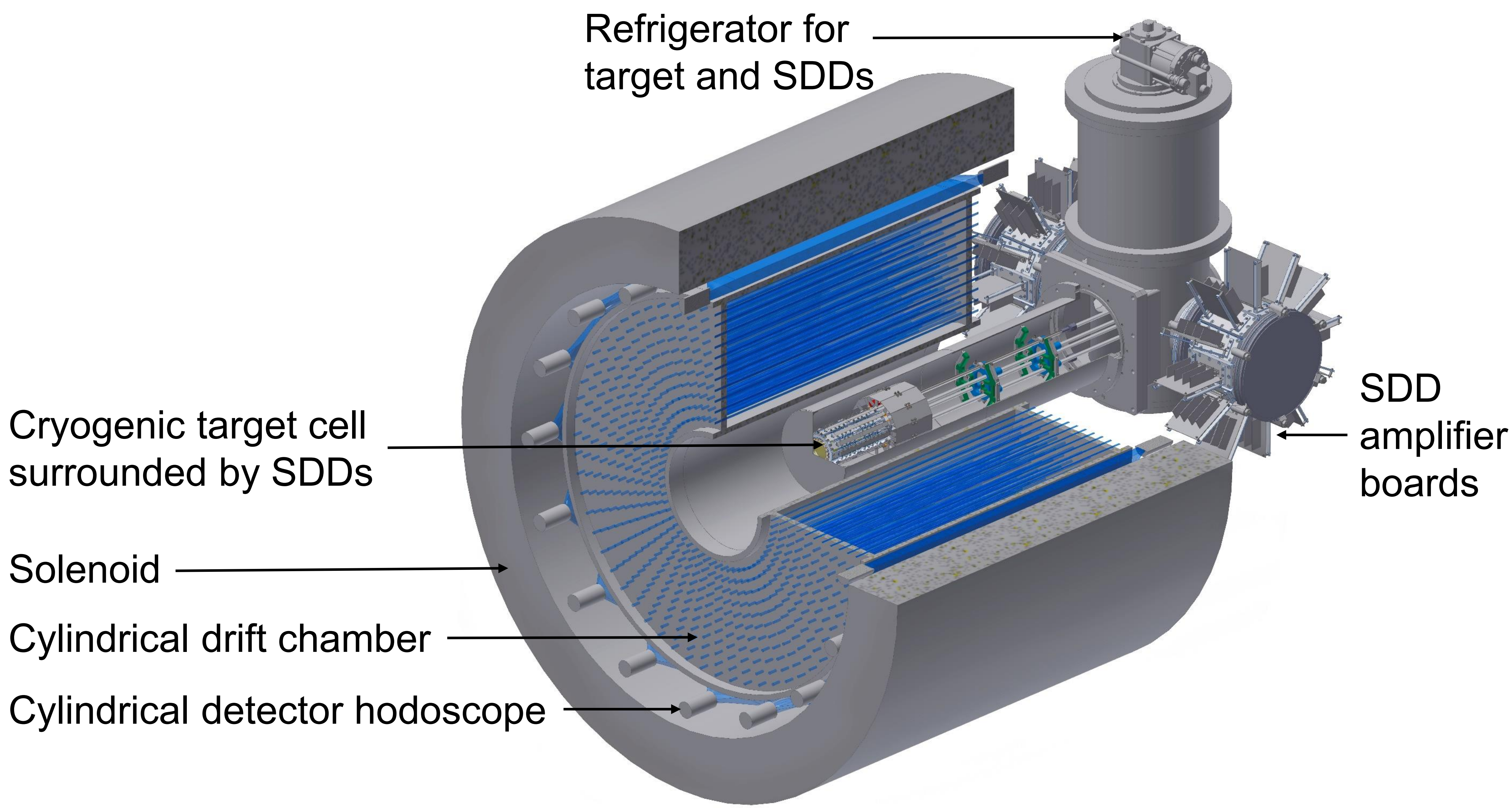
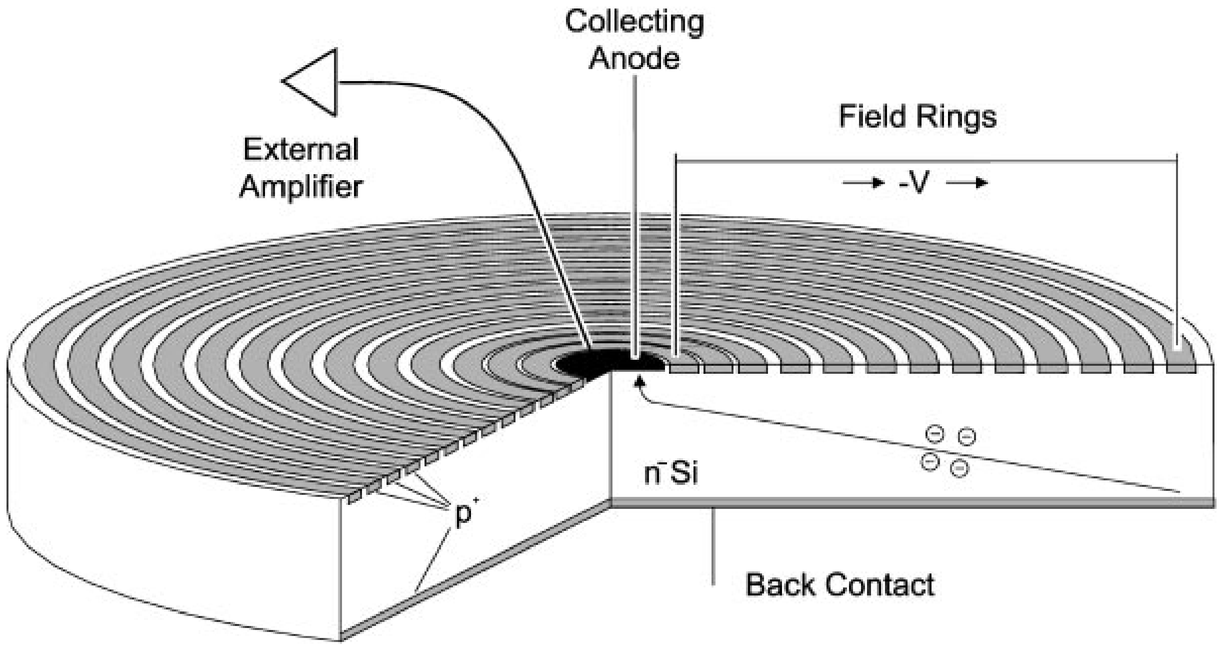
J- PARC E57 Setup

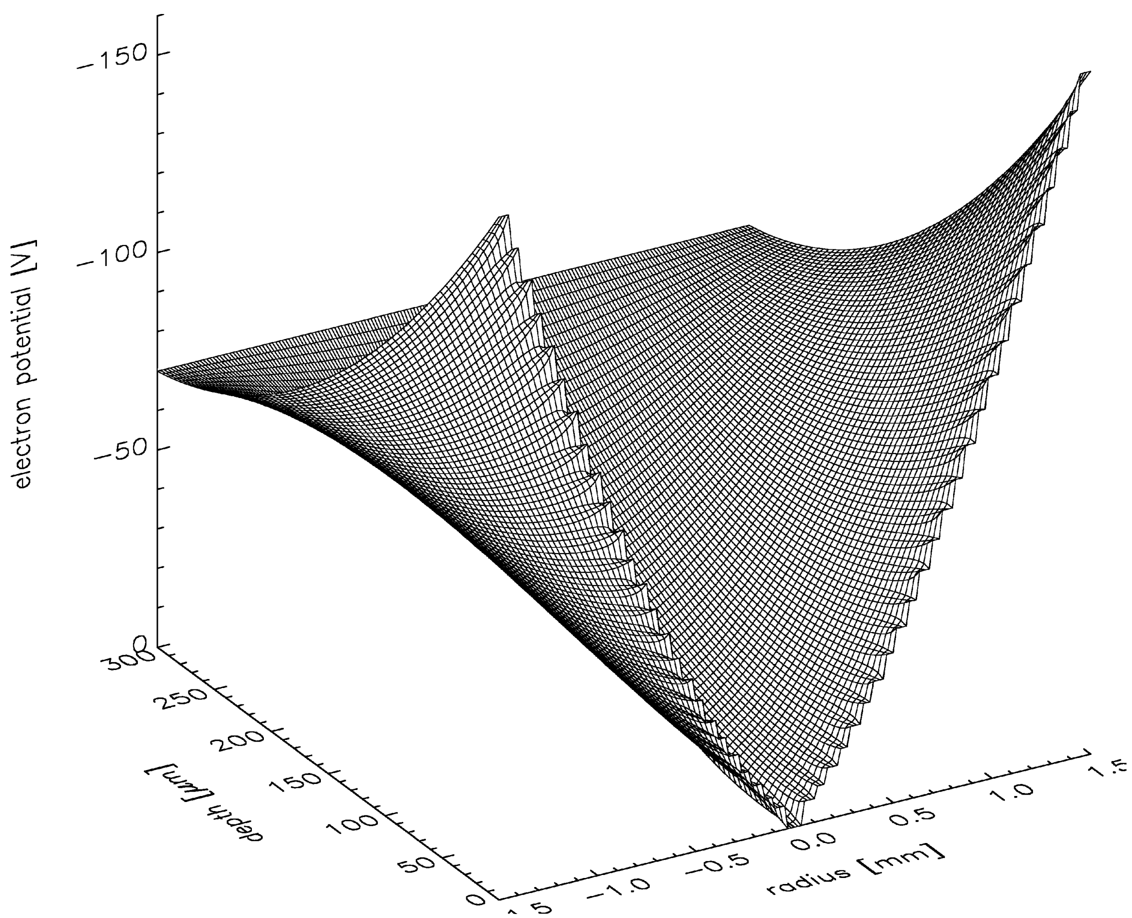


- ✓ Large area Silicon Drift Detector arrays
- ✓ Target at 30K & 0.3 MPa to optimize stopping power & X-ray yield
- ✓ Vertex cut & charged particle veto by using CDC ←**unique in J-PARC**

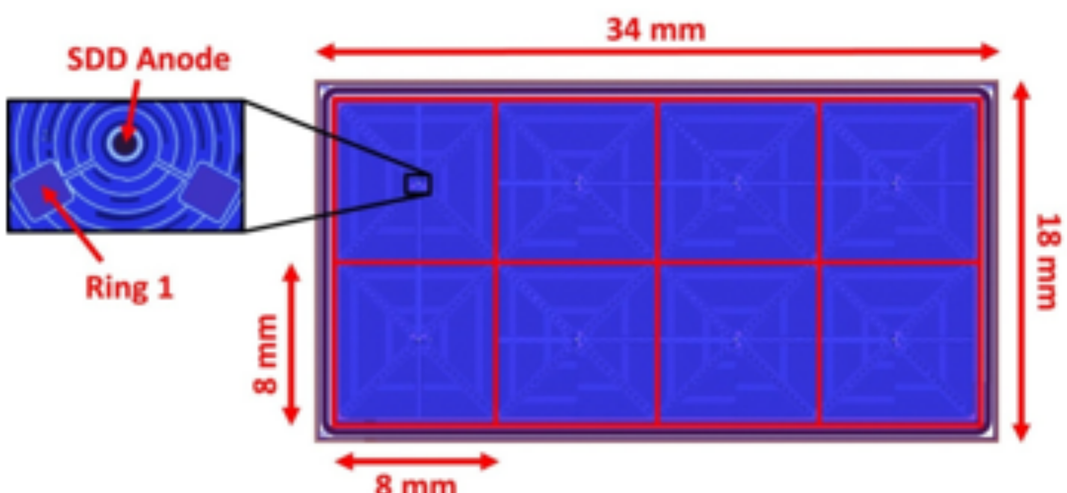
Silicon Drift Detectors

Reasonable Energy&Timing resolution. Large collecting area.





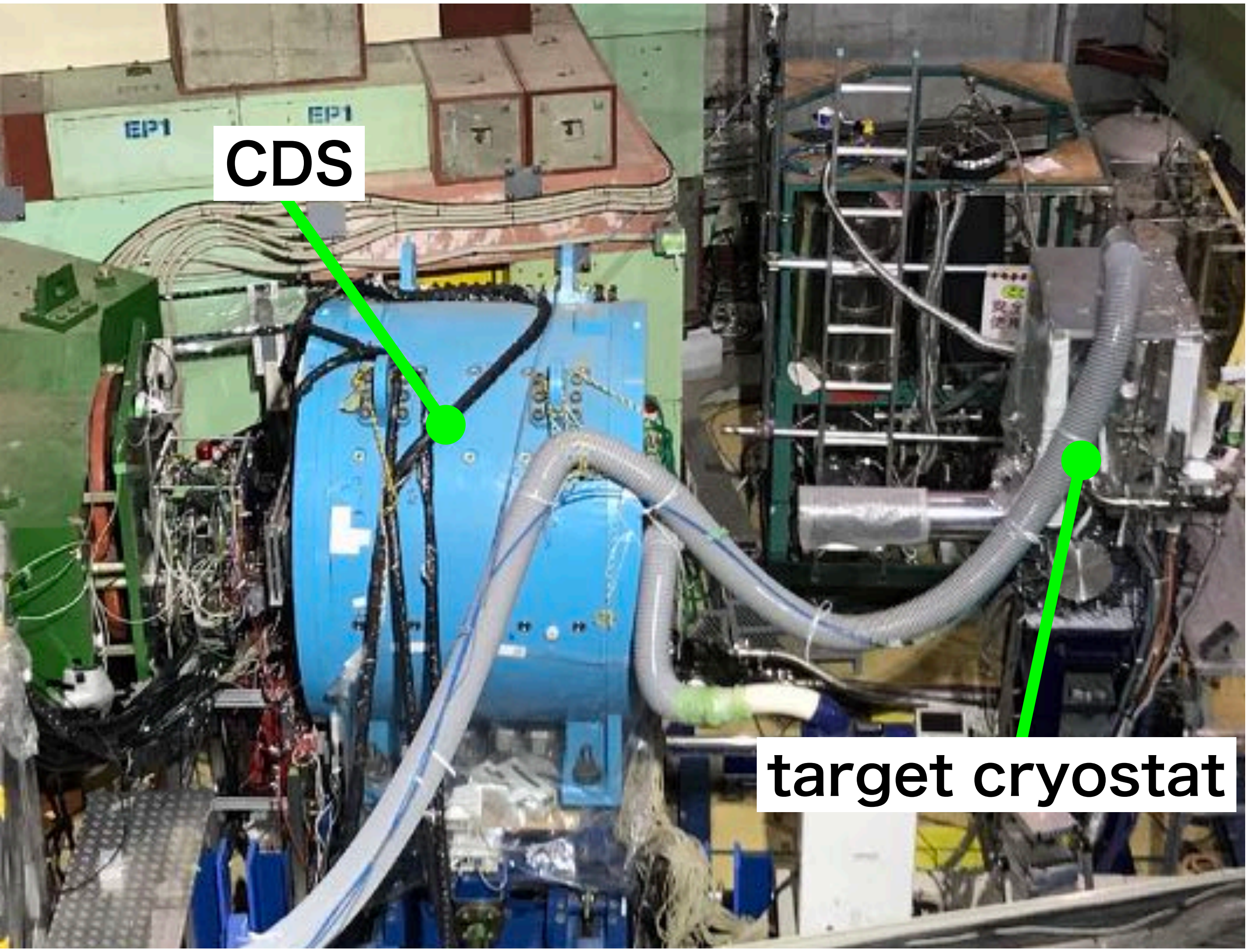
P. Lechner et al. NIMA 458 (2001) 281

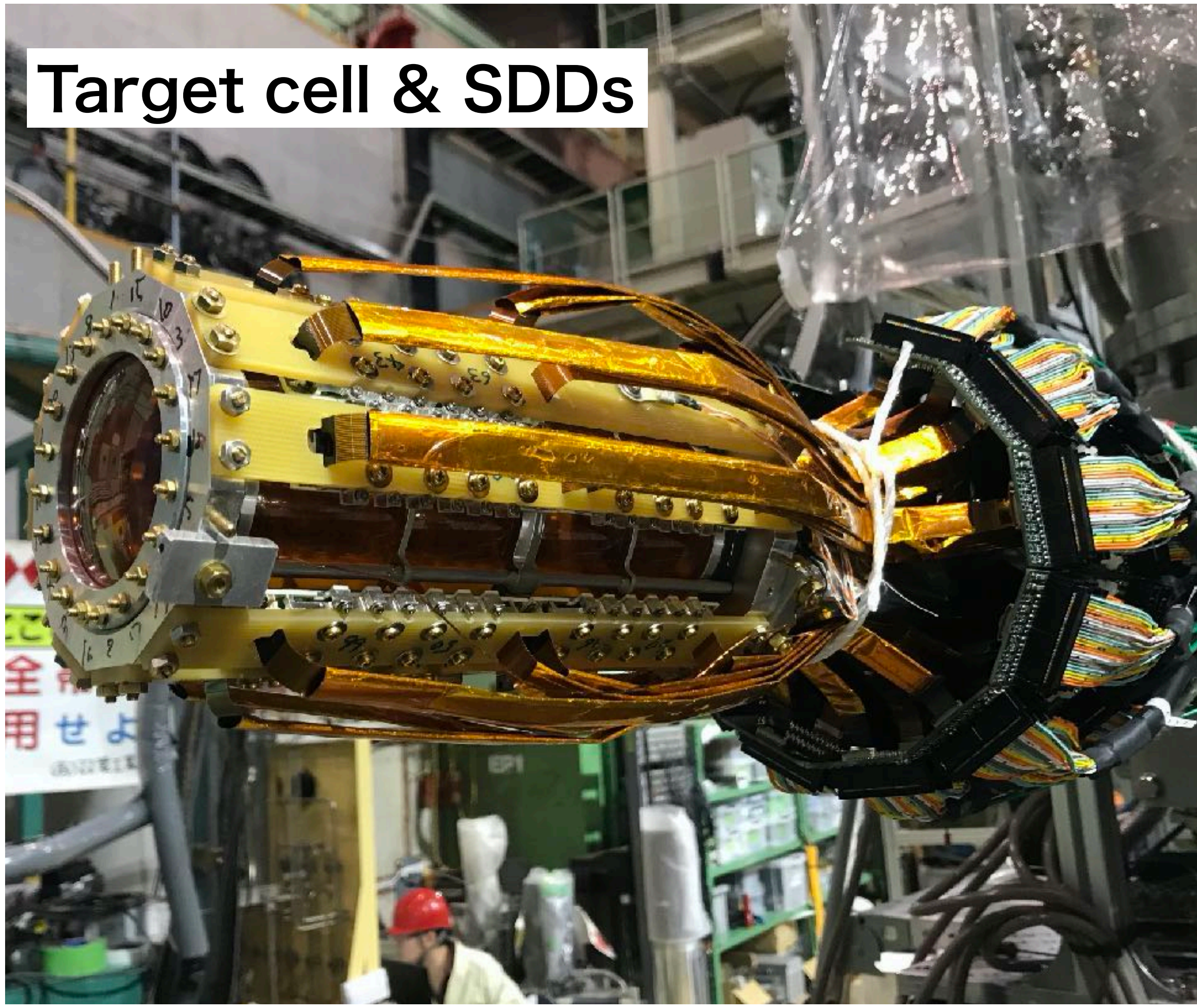


1unit := 8 pixels, 8 x 8 mm²/pixel
compact package

Details by
Marco Miliucci & Barbara Reingruber

E57 setup as of Feb. 2019

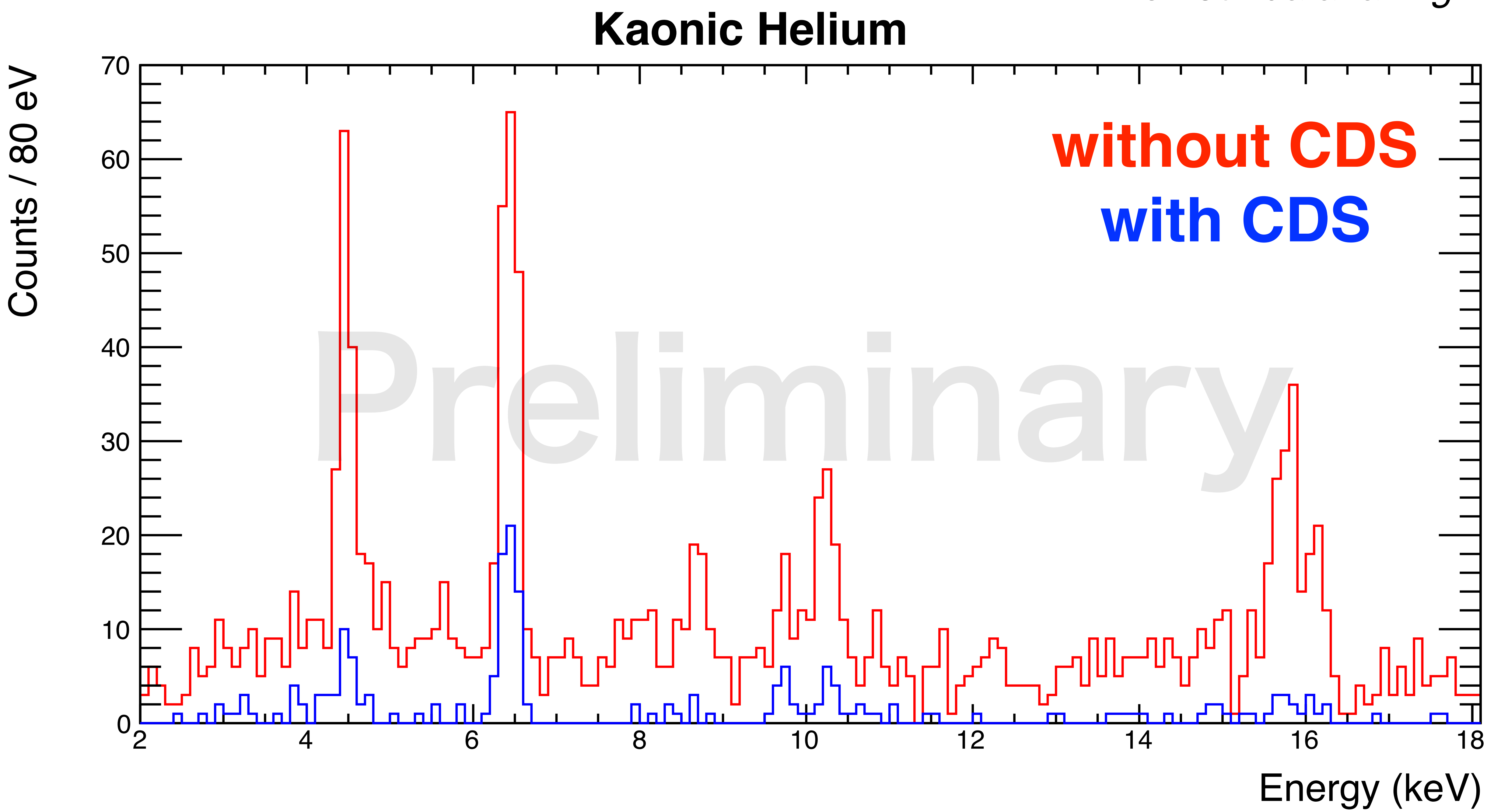




- ✓ ~ 6-day beam time in Feb./Mar./Apr. 2019
- ✓ ~145 ch in 26 units worked. (145/208 ~ 70%, 48 units in K-d run)
- ✓ Target gas (He/H2) at 30K, 3.5bar, SDDs at 190K

Helium data in E57

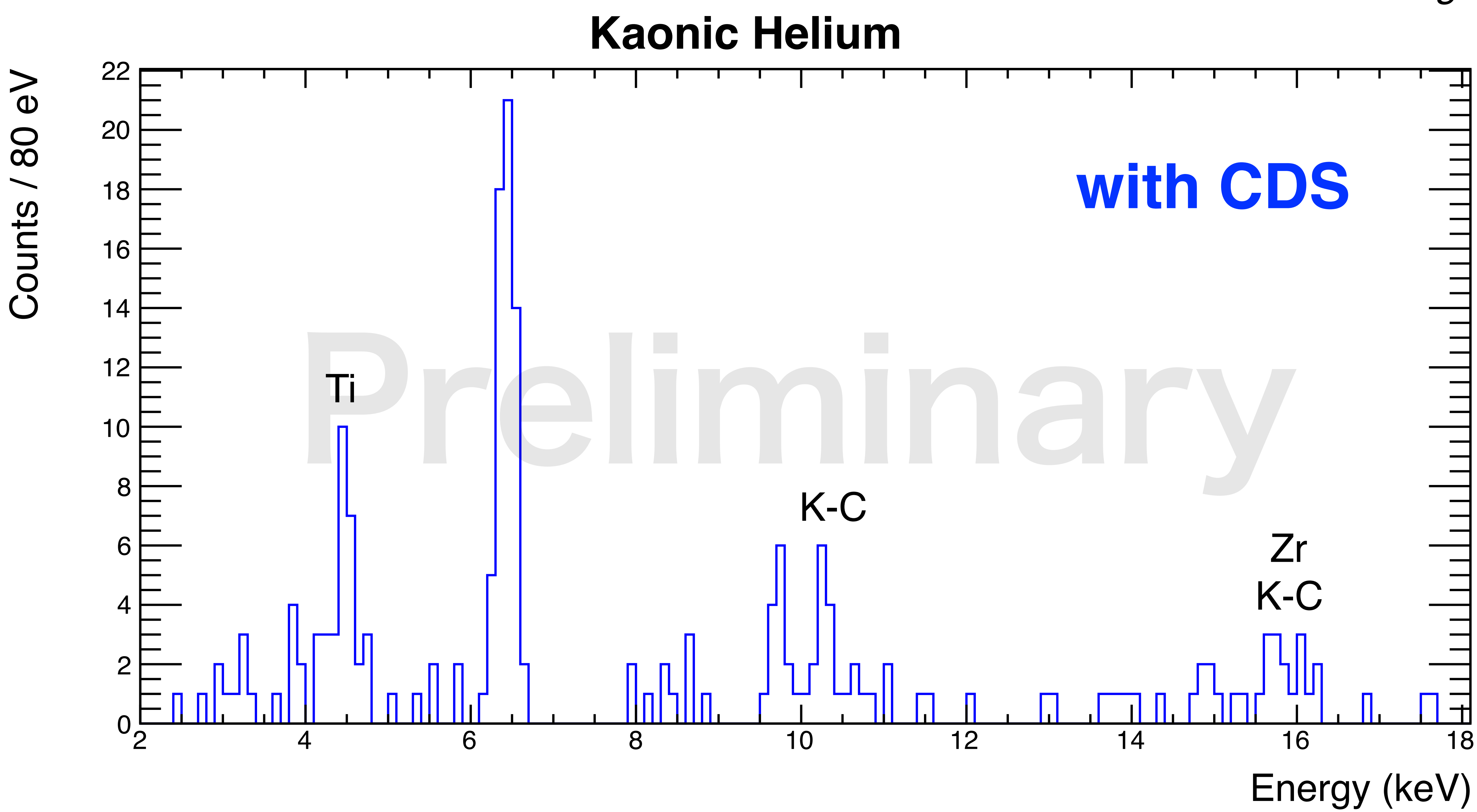
~6 hour data taking



- Background reduction with CDS worked well !
  (reasonable signal loss ~1/3)

Helium data in E57

~6 hour data taking



✓ 80 counts KHeLa

✓ almost background free as designed

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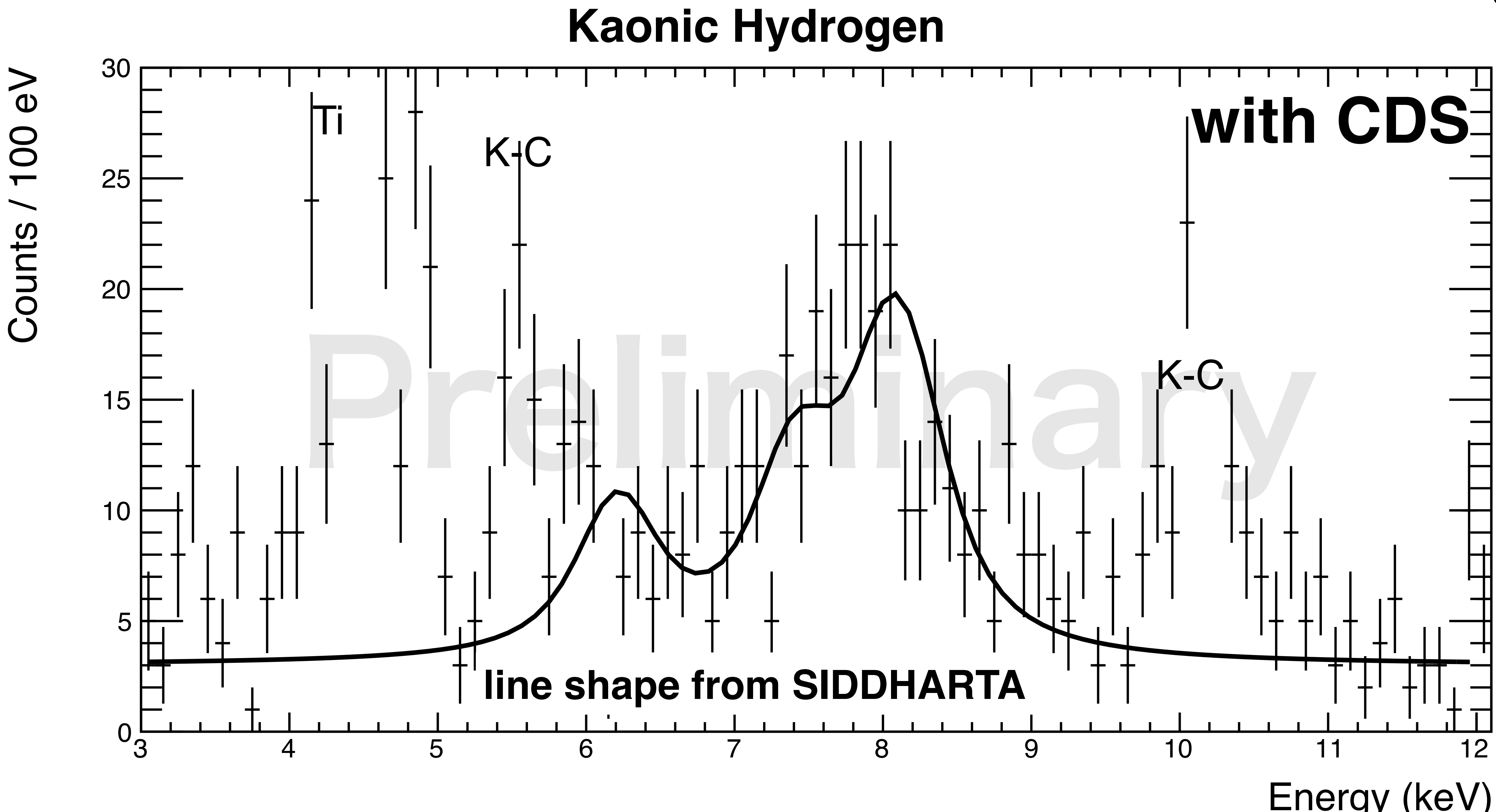
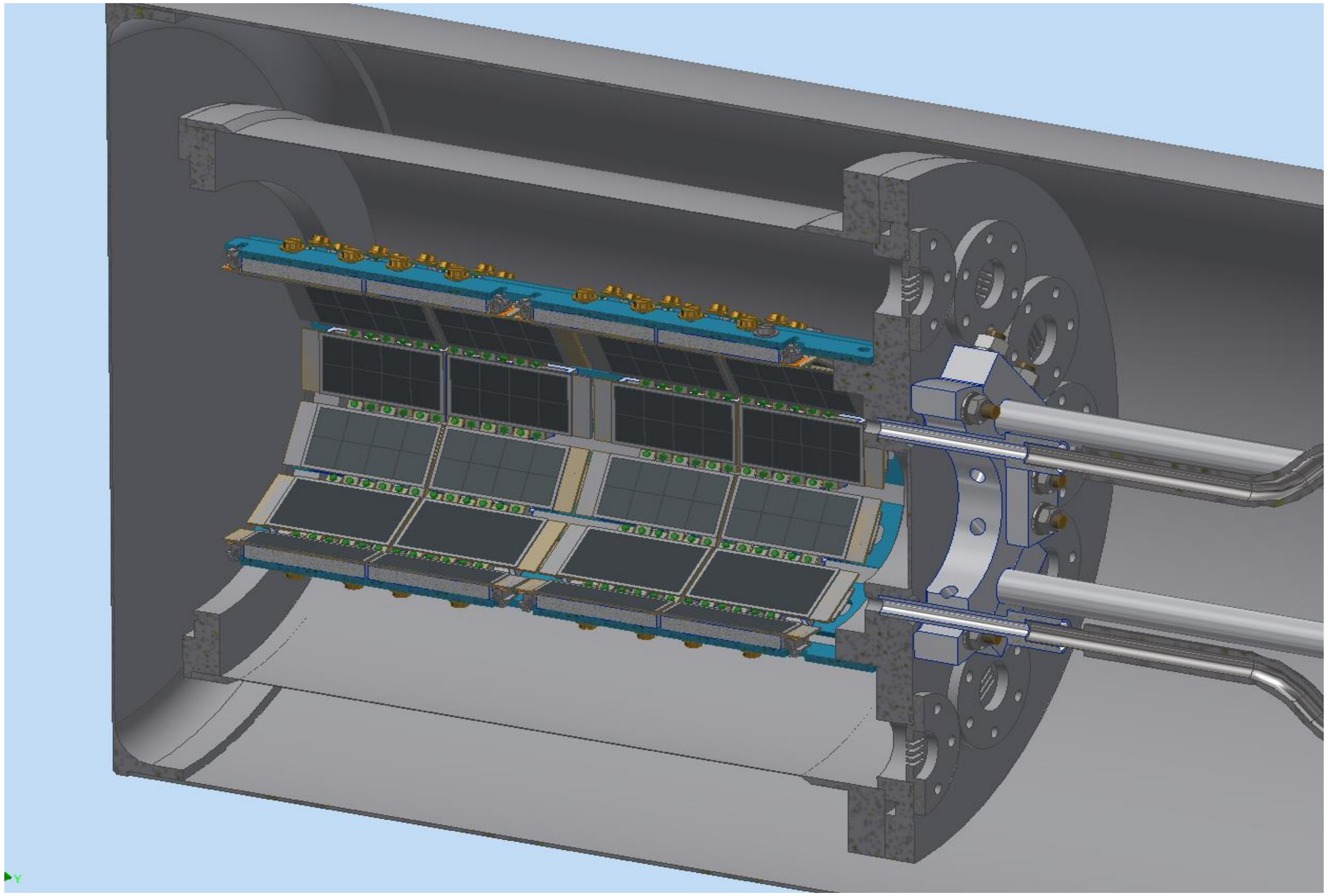
Hydrogen data

~90 hour data taking



- Higher transitions are observed
- at most 50 counts Ka X-rays. We expected more…
- Kaonic Kapton lines cannot be completely removed with the CDS.

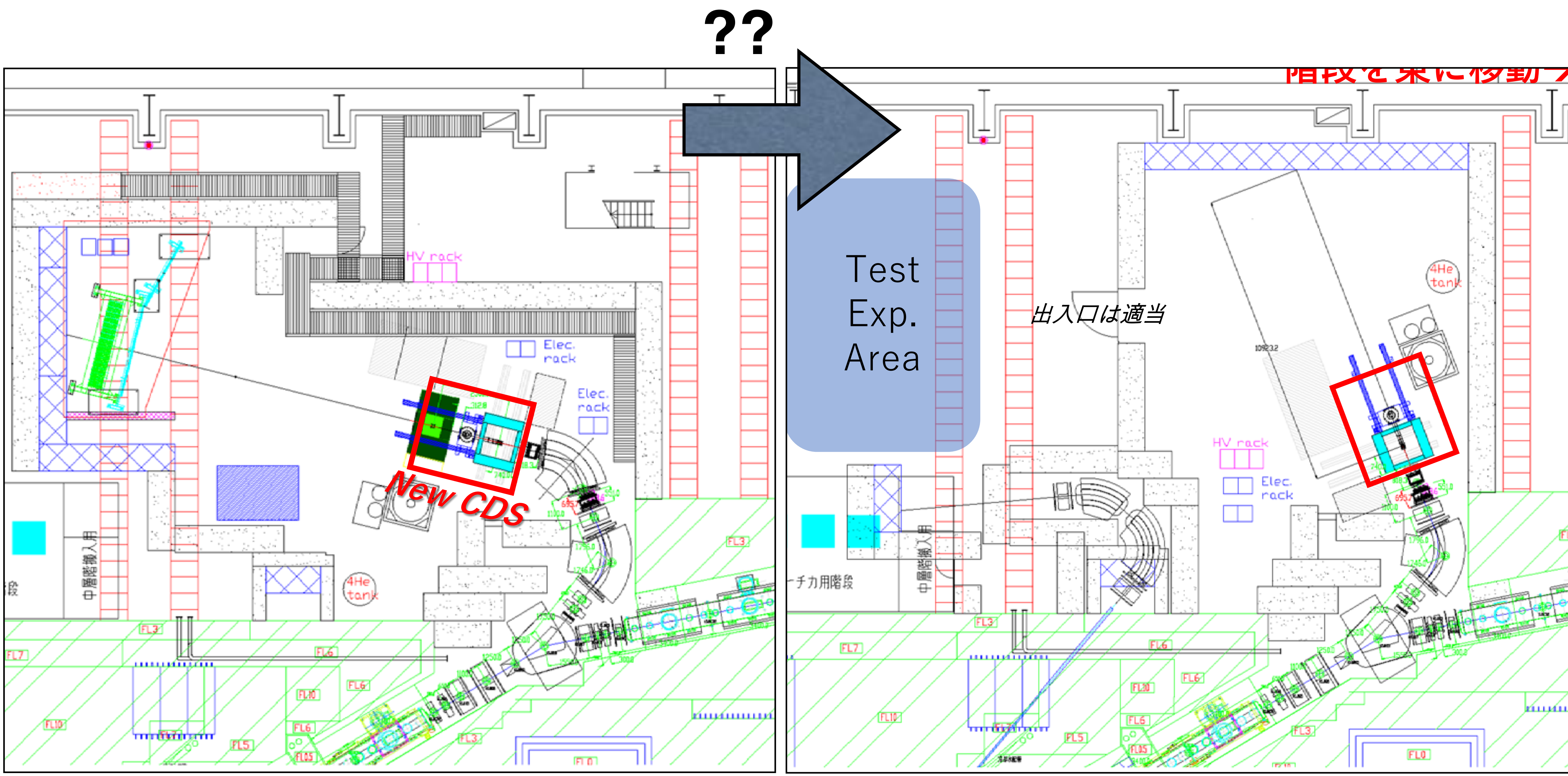
SDDs in a hydrogen atmosphere



- ✓ no Kaonic Kapton lines
- ✓ no attenuation at the window
- ✓ Larger hydrogen volume
- ✓ Chance to detect lines to 2p state

We have already succeeded to operate SDDs in a hydrogen (<10bar, 135K) in Vienna!

Shorter beam line for more kaons



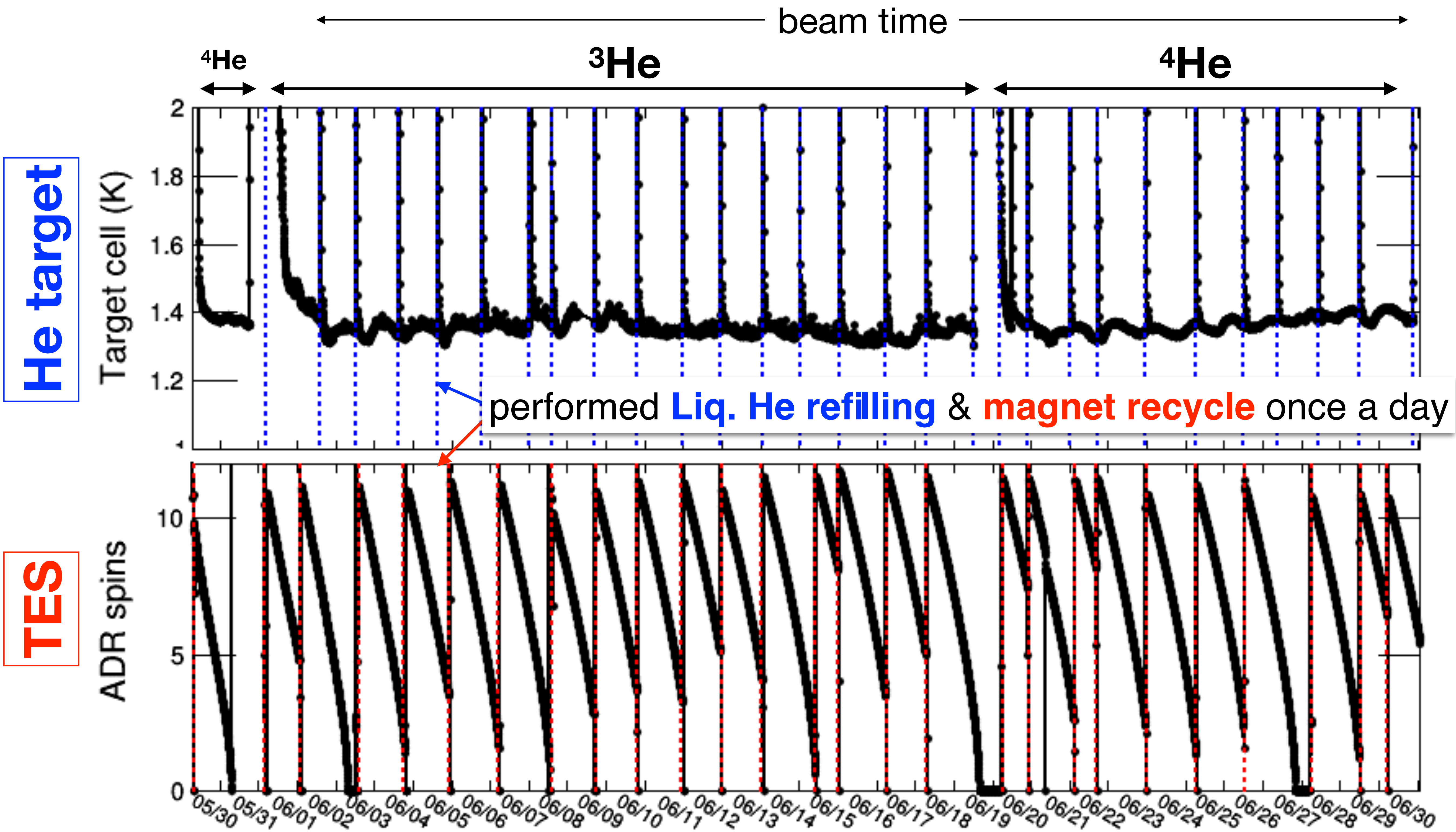
- ✓ ~3m shorter, ~x2 K^- @ 0.7 GeV/c
- ✓ Better beam focusing

Summary

- **Kaonic Helium 3d -> 2p**
  - Sub-eV precision by using a cryogenic detector **TES**
  - could impact on K^--nucleus potential
  - Physics data taking was completed in June, 2018
  - Publication to come soon…

- **Kaonic hydrogen/deuterium 2p -> 1s**
  - to resolve isospin-dependent $K^{bar}N$ interaction
  - High sensitivity measurement with **SDDs & CDS**
  - Excellent background capability was demonstrated.
  - next run in 2022? after the setup upgrade

Operation of cryogenic systems



Stable operation for one month

(28 He refills & 27 mag cycles)

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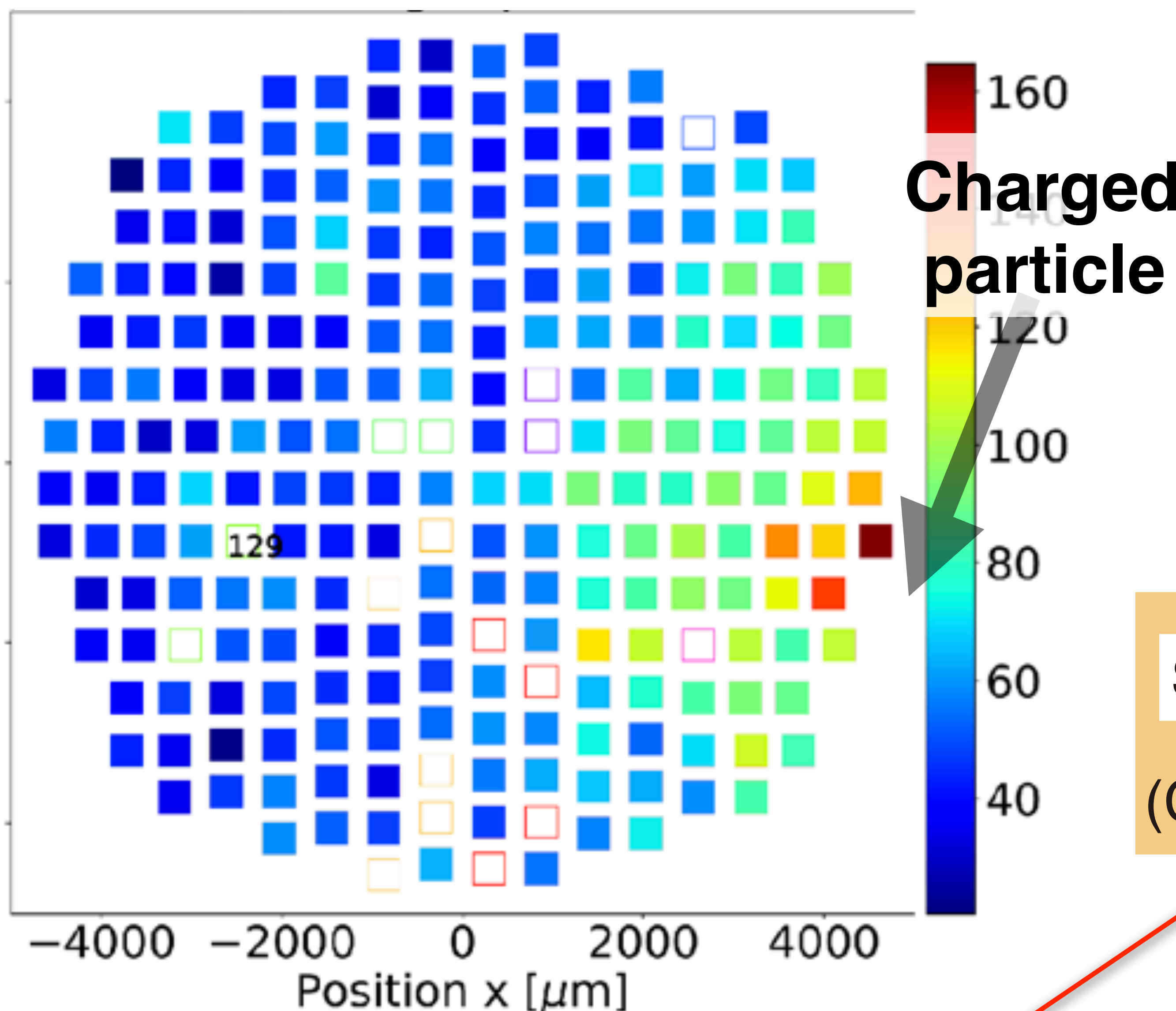
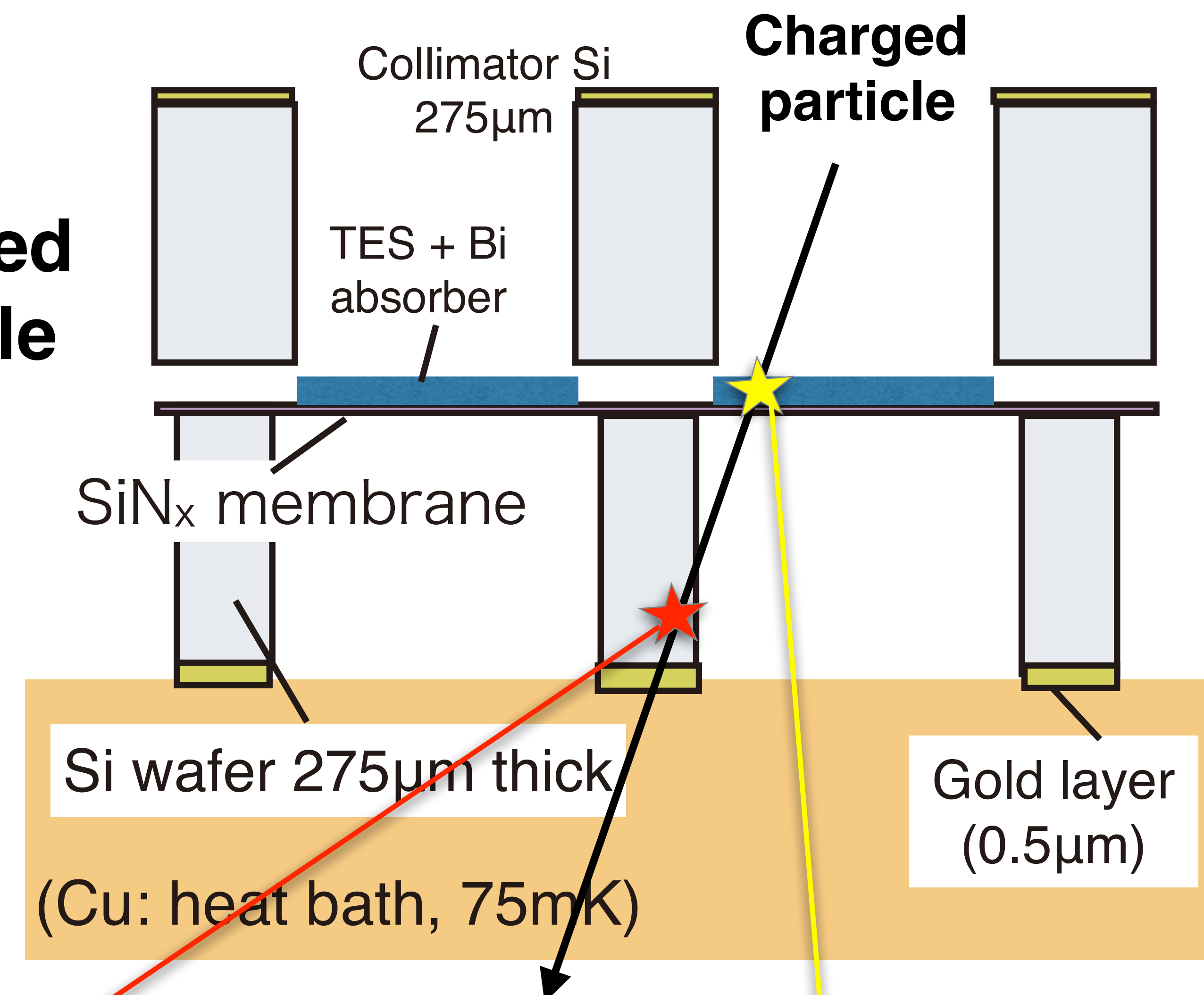
Effect of charged particle hits

Pulse height distribution in the array





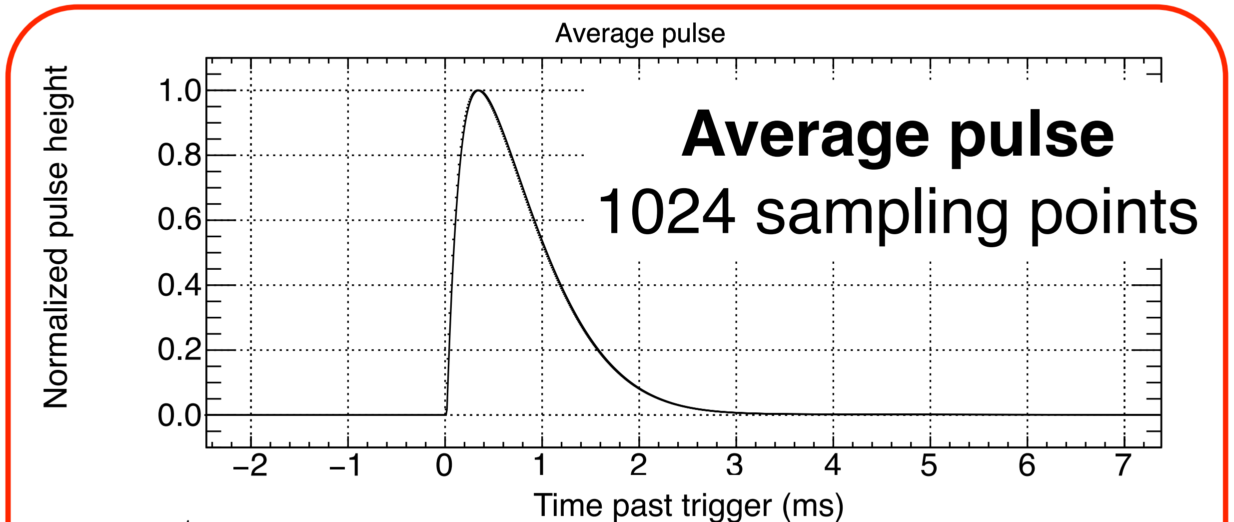
If charged particle hit on the Si substrate, heat will spread out throughout the array, making small bump signals in many pixels

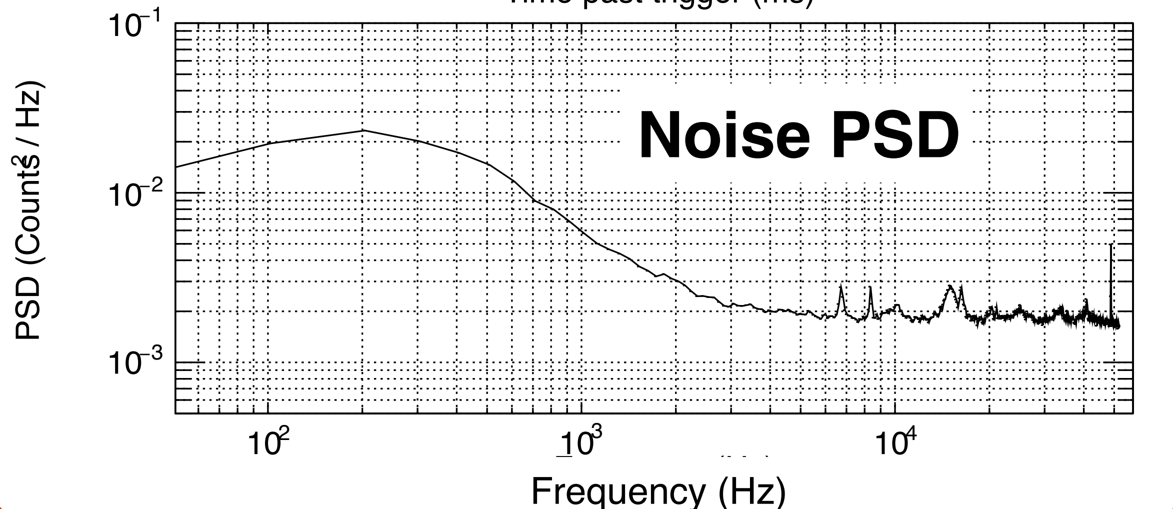
If charged particle hit on the detector pixel, it deposits ~10 keV energy (Bi 4um), which become severe background in the spectrum

- **Detailed waveform analysis is must to minimize these effects**

Pulse analysis

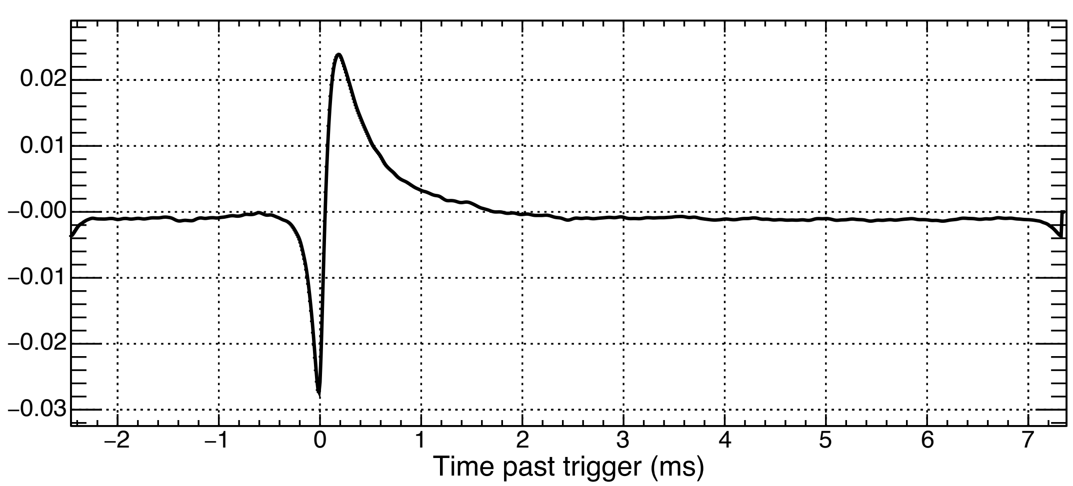
"Optimal filtering"

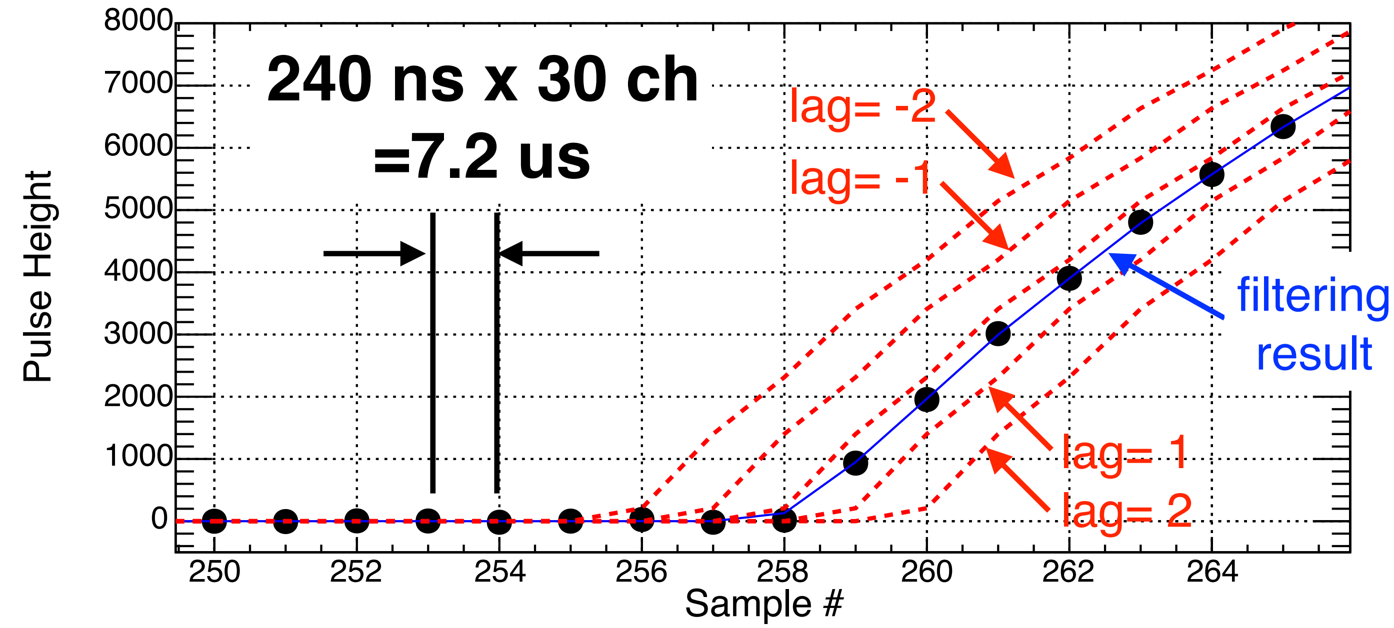


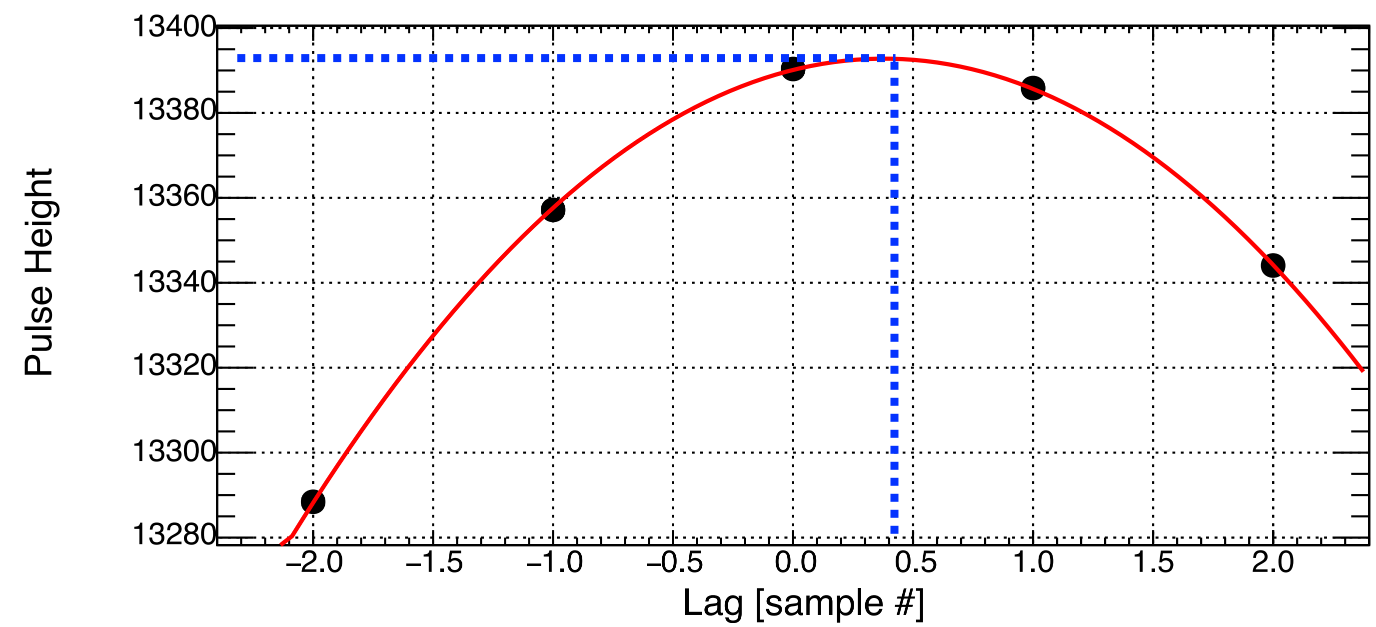


+ autocorrelation

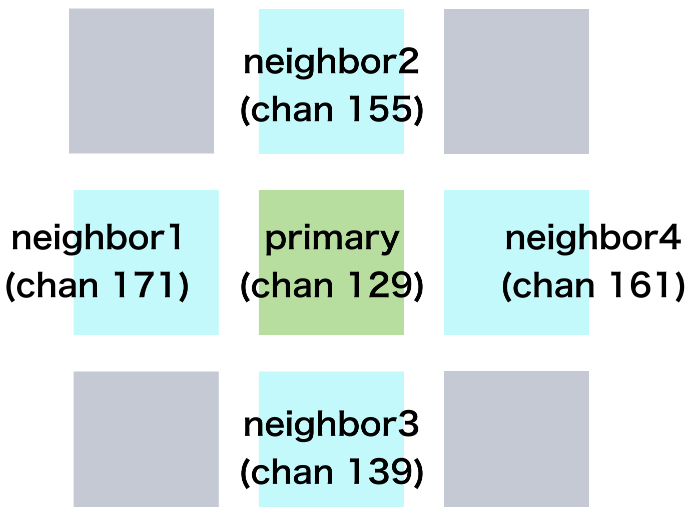
Filter to convolve with data

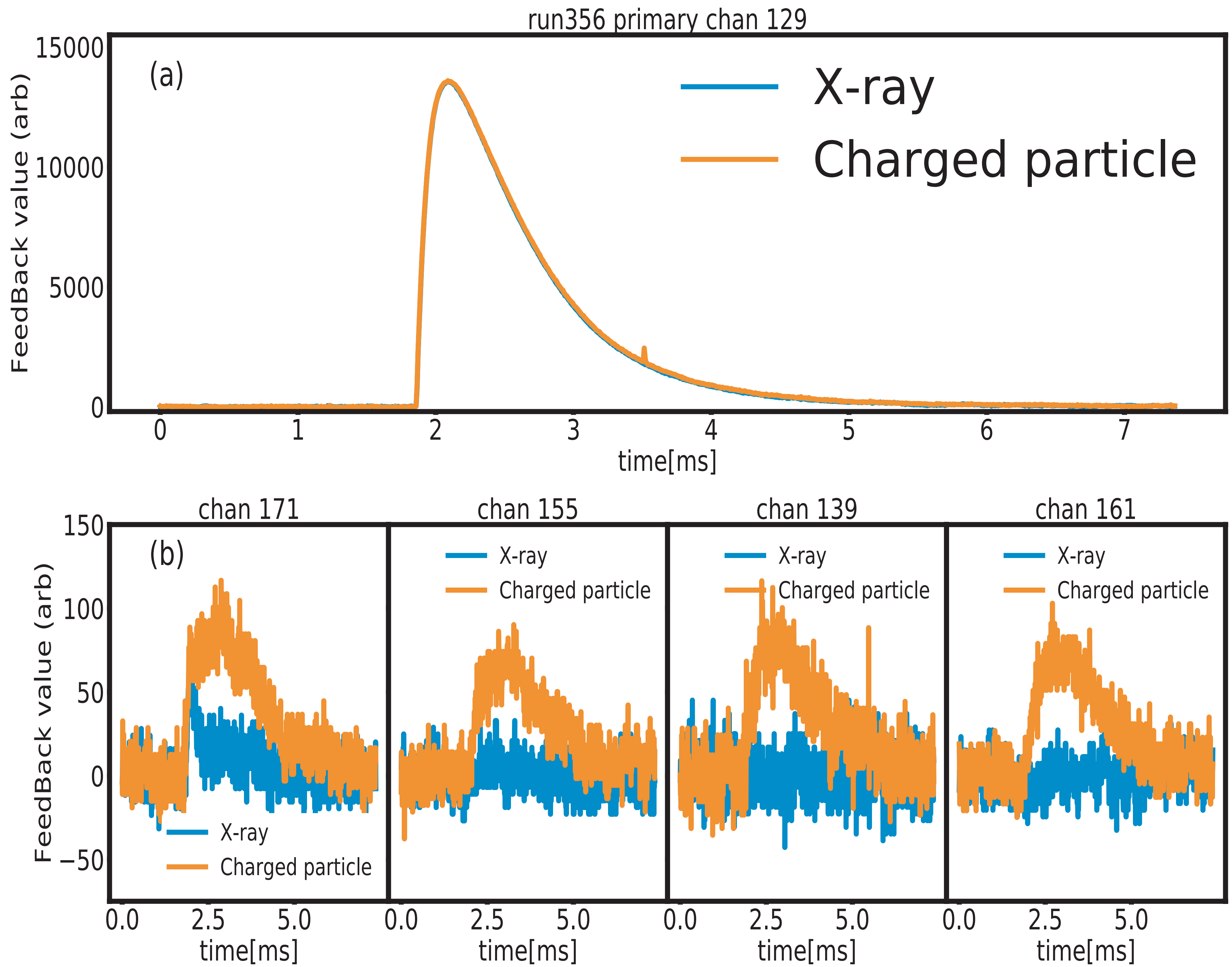






Charged particle identification

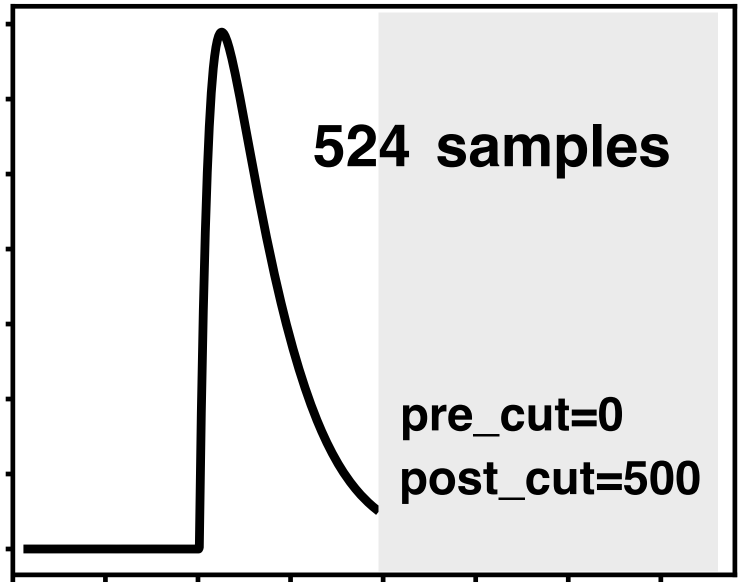




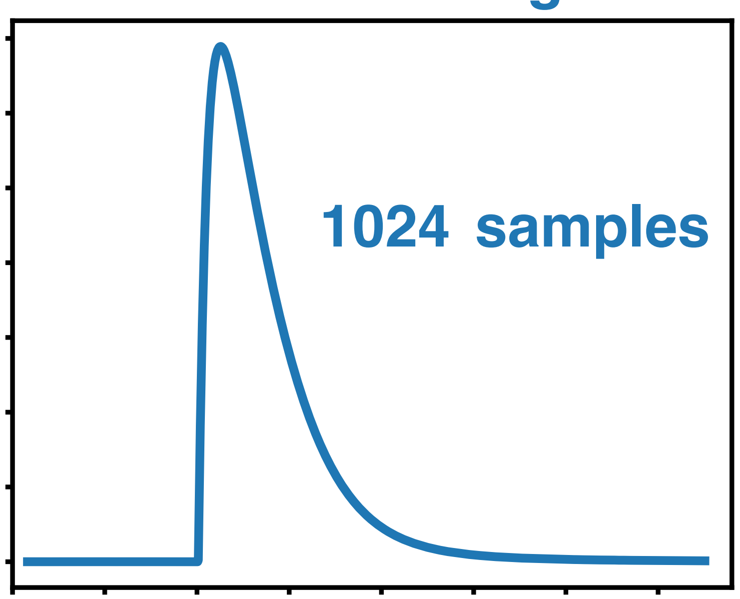
- No difference in the primary pulses between X-rays and charged particles
- If we look at neighboring pixels, we can reject half of the charged particles

Shorter record length to avoid pileup

short record length

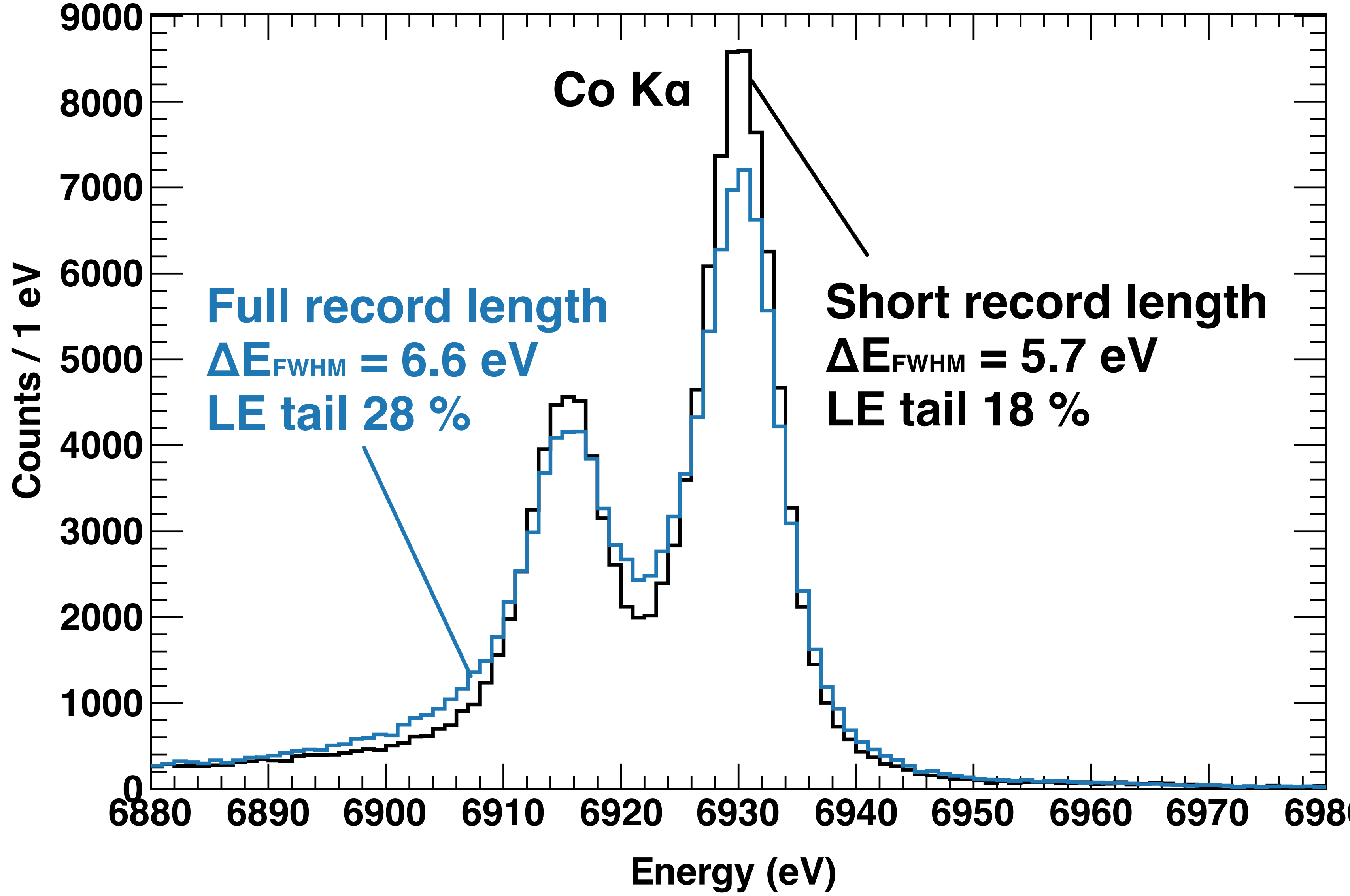


full record length



run 397 sum of 221 TES pixels, beam on

already excluded the piled-up events in the pulse peak region



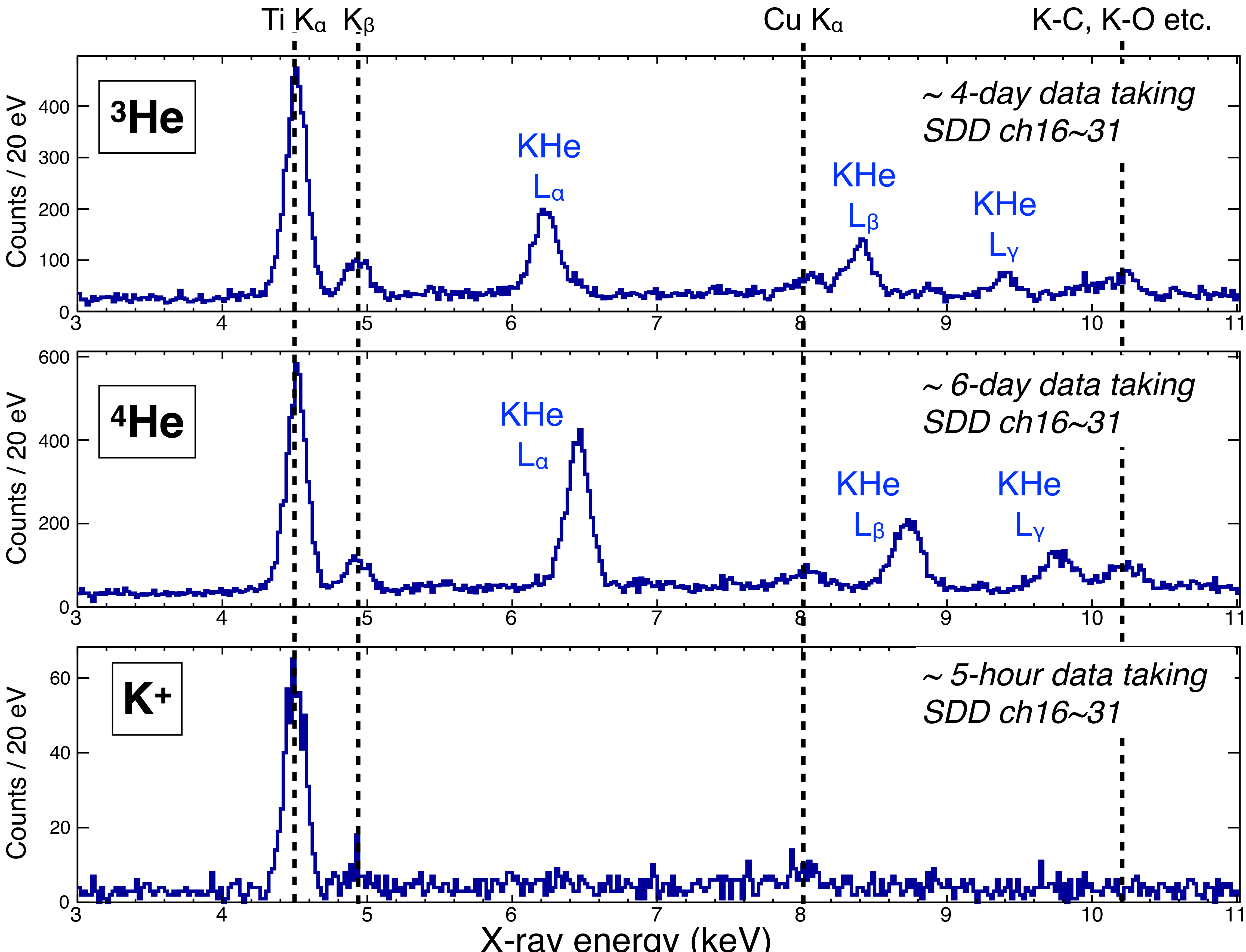
* ~5eV FWHM @ beam off

✓ Thermal cross talk bumps deteriorate resolution

✓ Minimize chance to have pileup bumps

SDD spectra

< 200 eV FWHM @ 6 keV



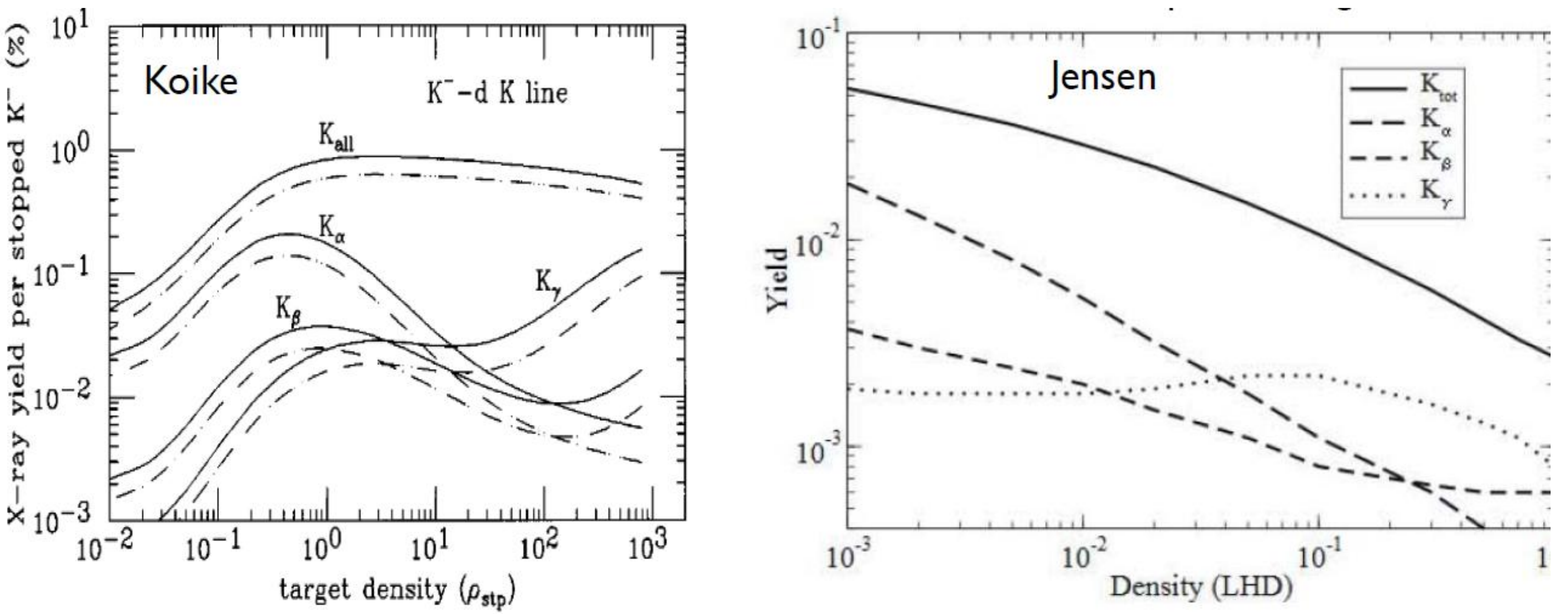


Figure 14: Kaonic deuterium cascade calculations, for the X-ray yield of K_α, K_β, K_γ and K_{tot}; figure from reference [33] (left) and from [34] (right).