14 Oct., 2016
計測システム研究会2016

ハドロンビーム環境下における超伝導X線検出器の性能評価

岡田 信二 (理研)
for HEATES / J-PARC E62 collaborations

Collaboration list

HEATES (J-PARC E62) collaboration

High-resolution Exotic Atom x-ray spectroscopy with TES

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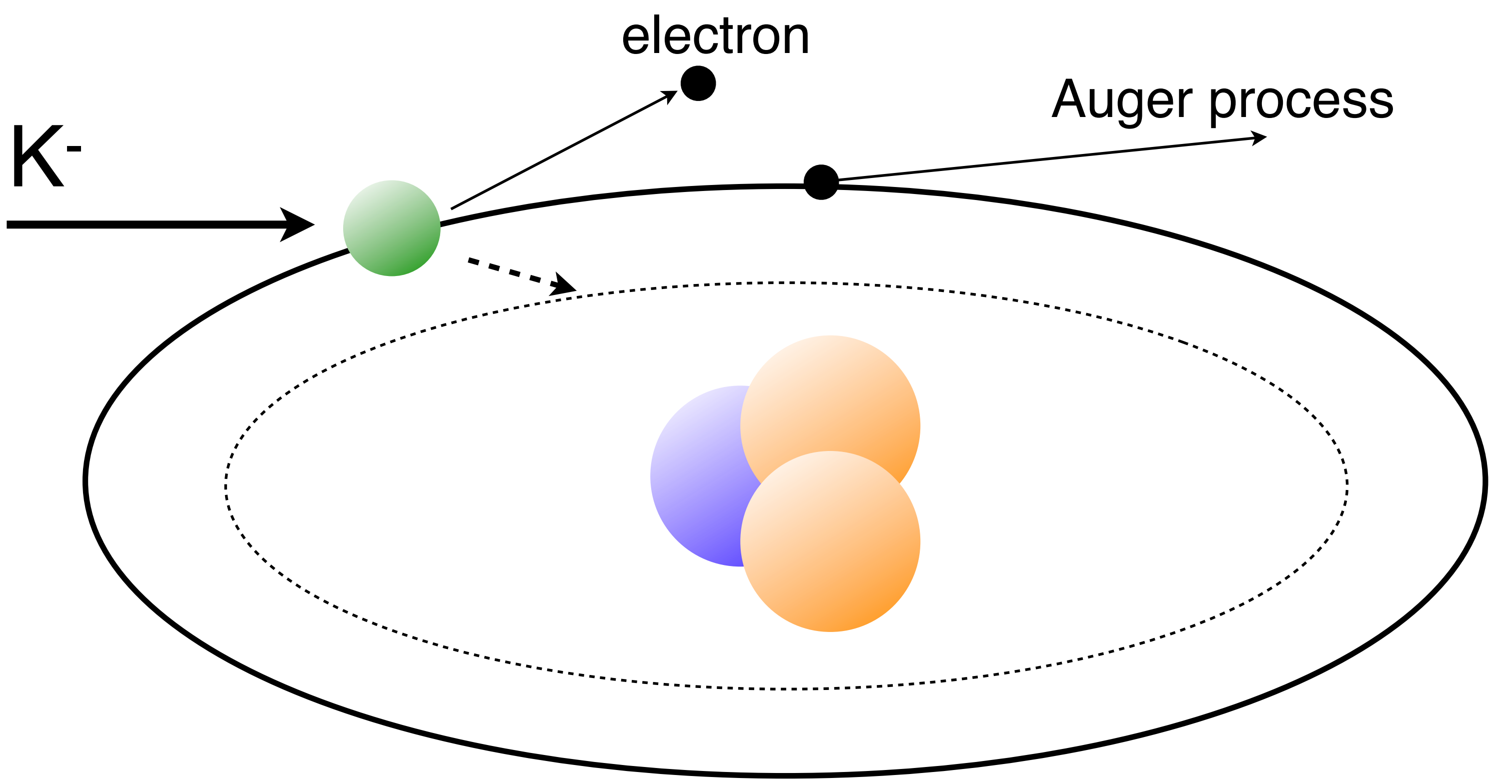
Nuclear physicists + TES experts + Astro-physicists

(NIST , LundU) (TMU , TohokuU)

Introduction

Kaonic atom

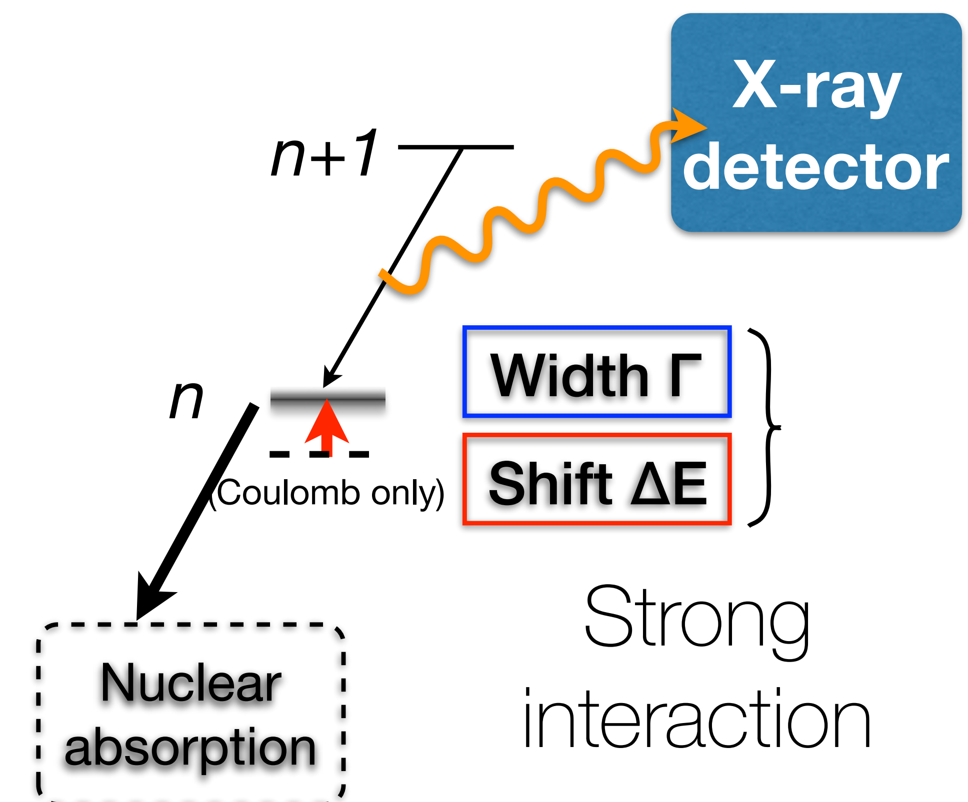


- ➡ K^- wave function largely overlaps with a nucleus at tightly-bound states
- ➡ **Perturbation by the strong interaction**
  - Energy level shift
  - Additional natural width

Initial state $\propto \sqrt{\dfrac{m^*_{K^-}}{m_e}}$ x 30

X-ray energy $\propto \dfrac{m^*_{K^-}}{m_e}$ x 1000

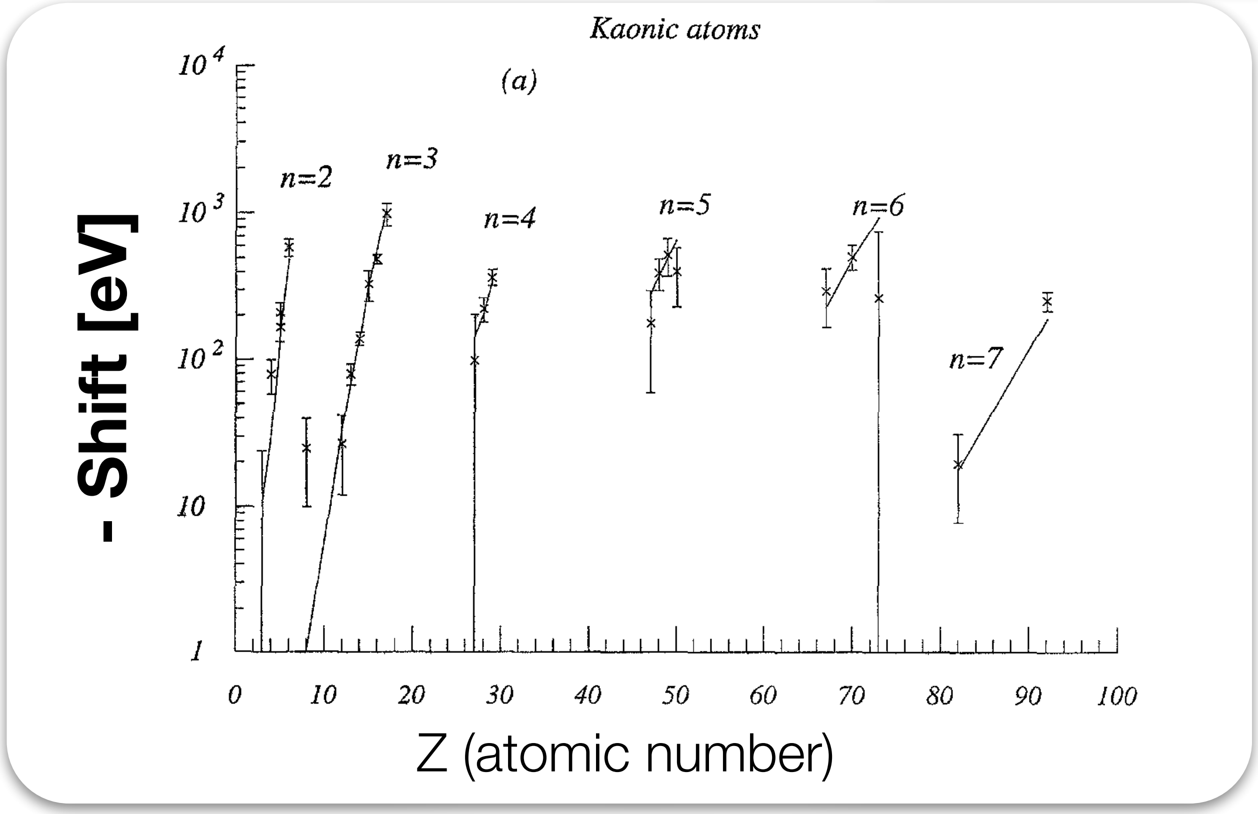
Radius $\propto \dfrac{m_e}{m^*_{K^-}}$ x 1/1000

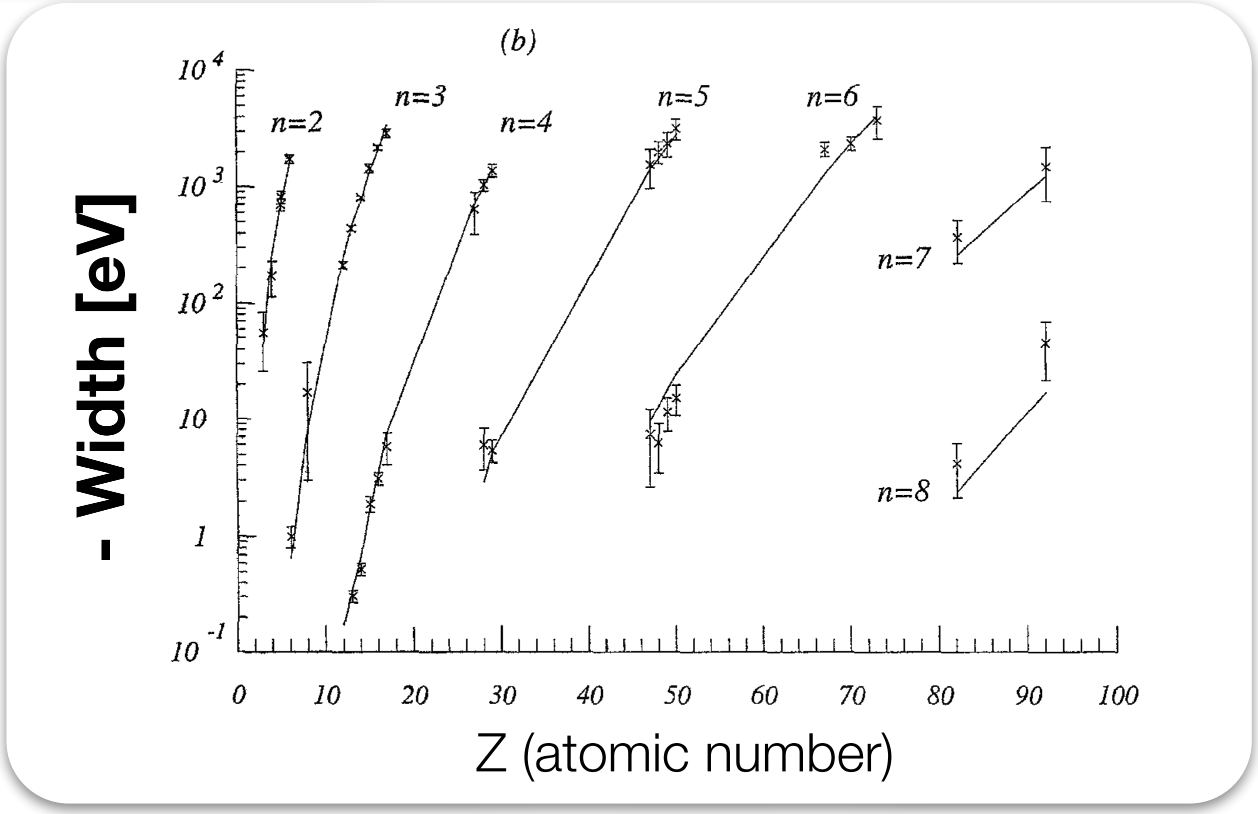


Need high-resolution

K-atom data

Phys. Rep., 287 (1997) 385.



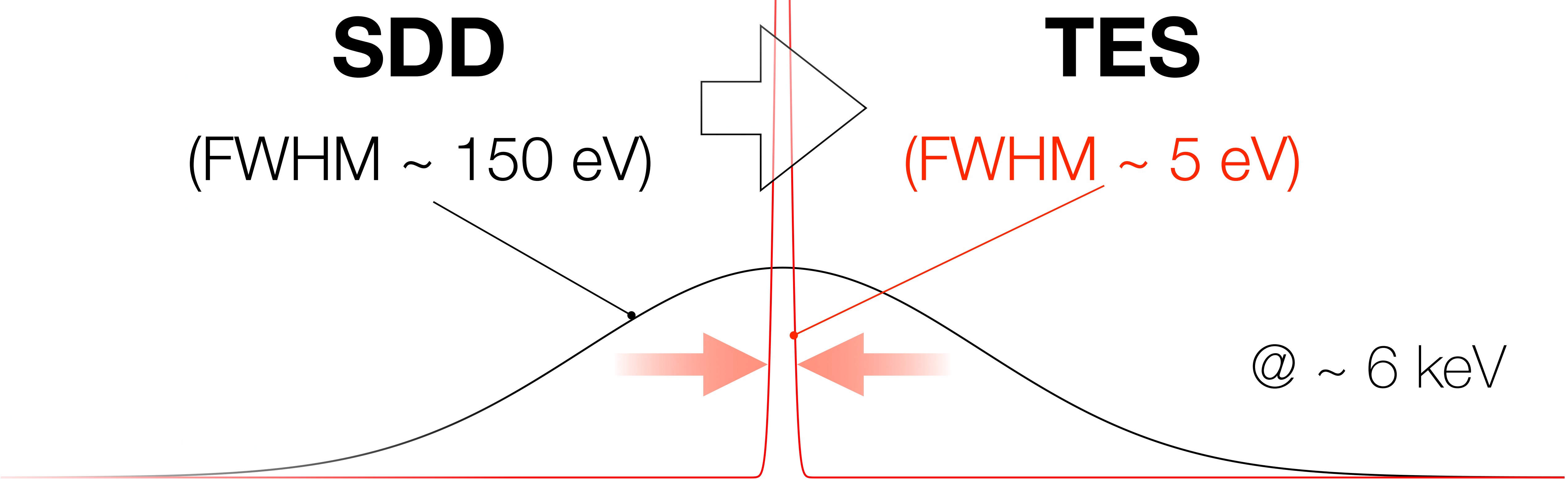


K⁻ - nucleus strong interaction is attractive & absorptive.
but unknown **how much attractive ?**
due to insufficient precision of K-atom data

⇒ Kaonic nuclei might exist! (Hot topic in hadron physics)

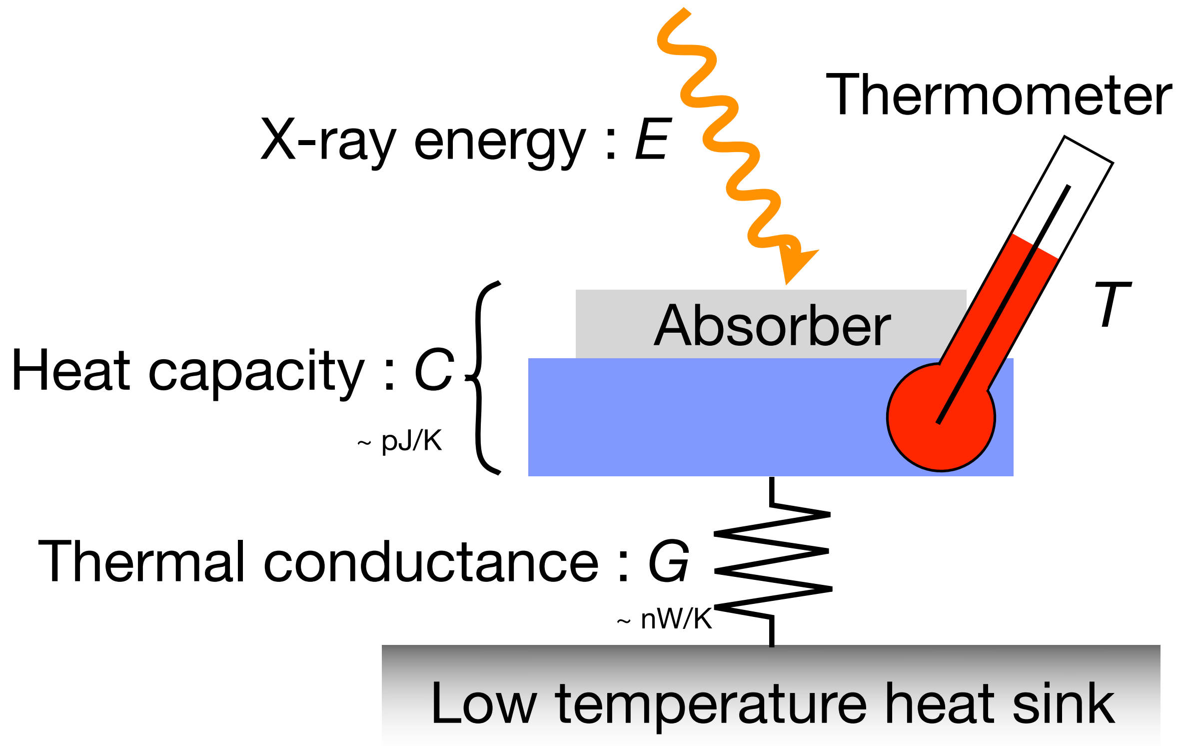
Drastic improvement in resolution

- ✓ Shift : precision goal “2eV → 0.2 eV”
- ✓ Width : sensitive for Γ_{2p} > ~2eV

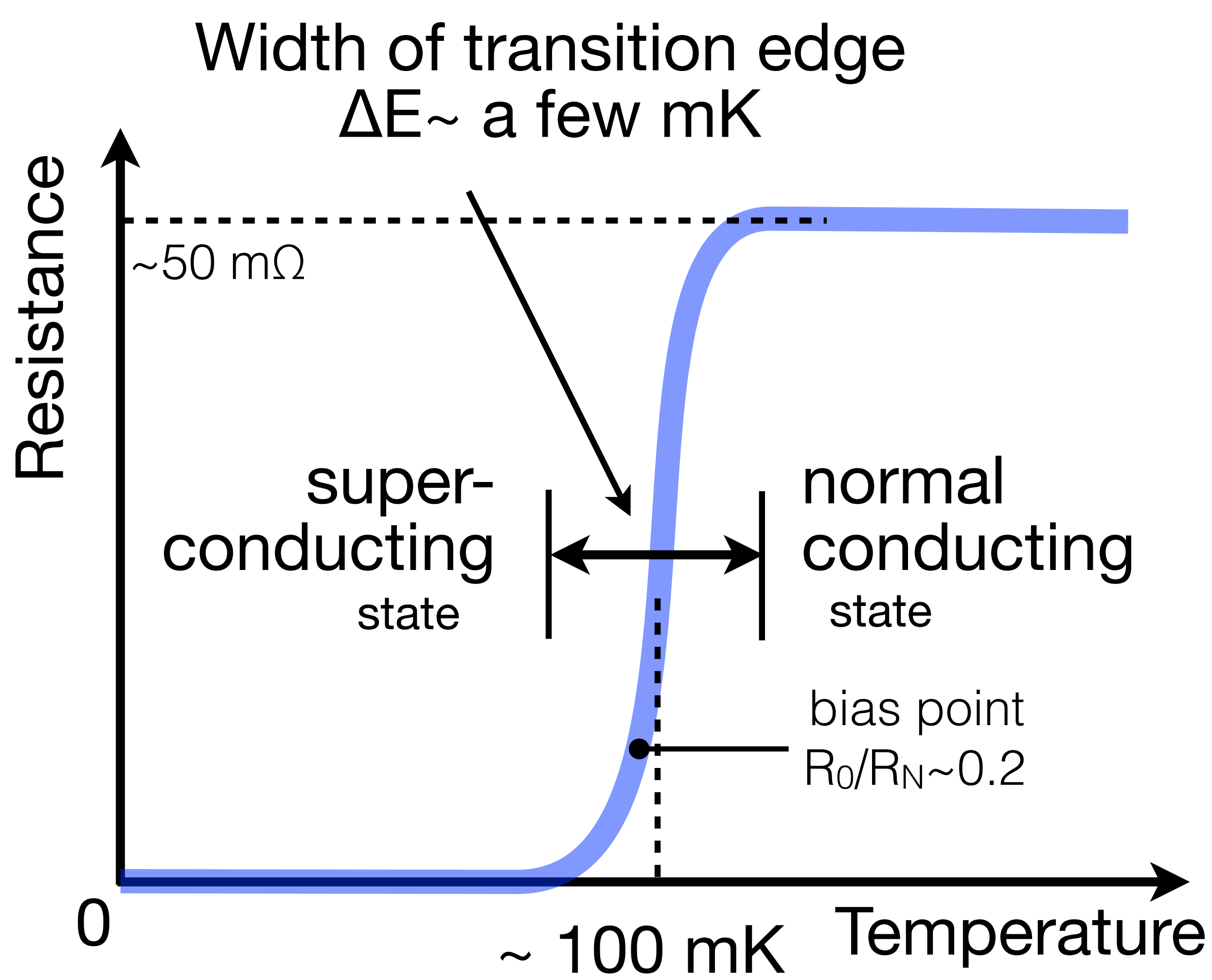


Transition-Edge-Sensor microcalorimeter

Microcalorimeter



Transition Edge Sensor (TES)



- ✓ High energy resolution :~2 eV FWHM @ 6 keV
- ✓ Wide dynamic range possible

$$\alpha \equiv \frac{d \ \ln R}{d \ \ln T} \qquad \Delta E = \sqrt{\frac{k_B T^2 C}{\alpha}} \qquad E_{max} \sim C T_C / \alpha$$

NIST's TES array system

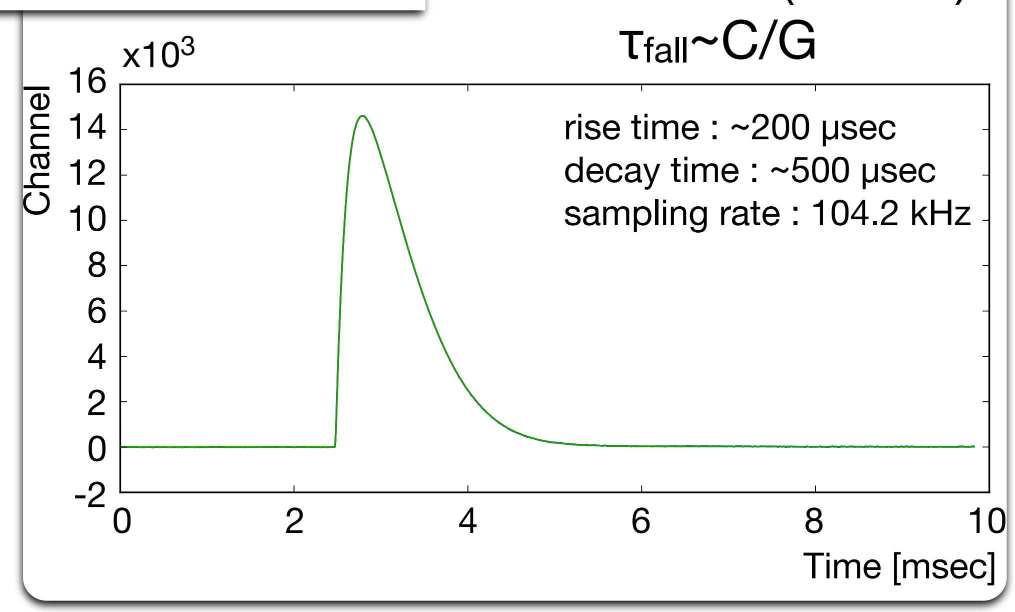
✓ Compact and portable

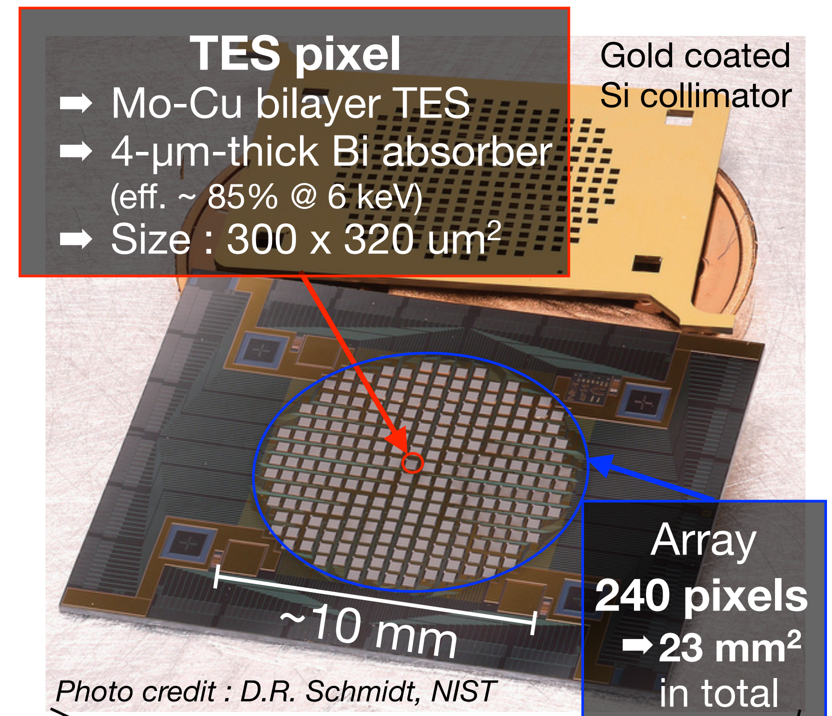
✓ Large effective area w/multiplexing tech.

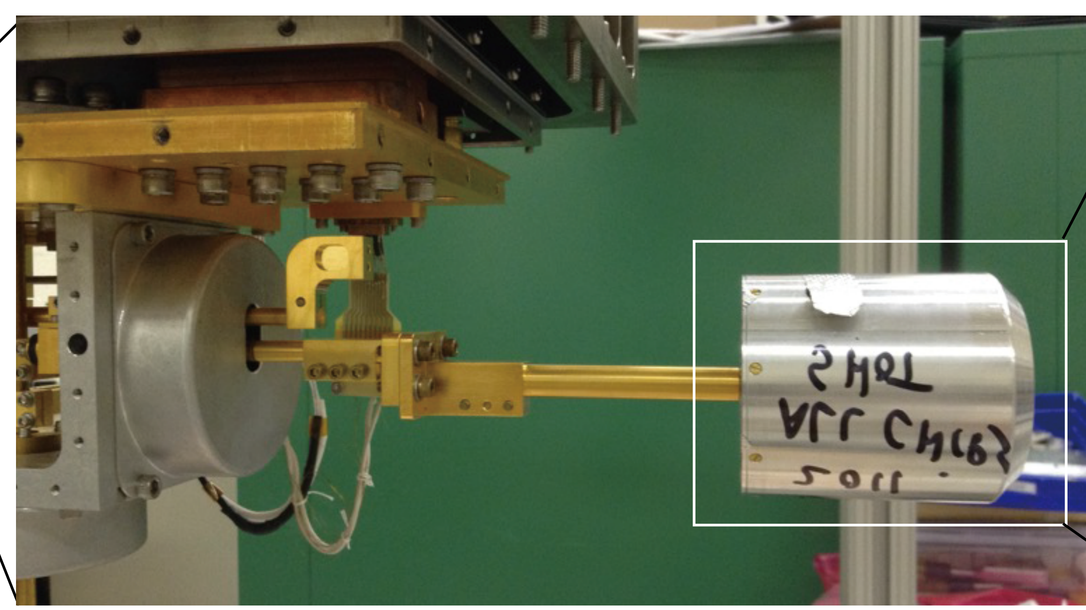
Pulse signal

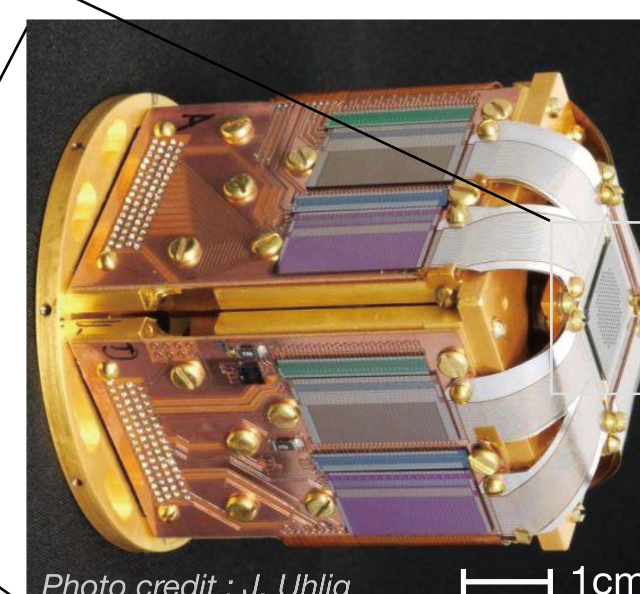
$\tau_{rise} \sim L/(R_{sh}+R_0)$

$\tau_{fall} \sim C/G$









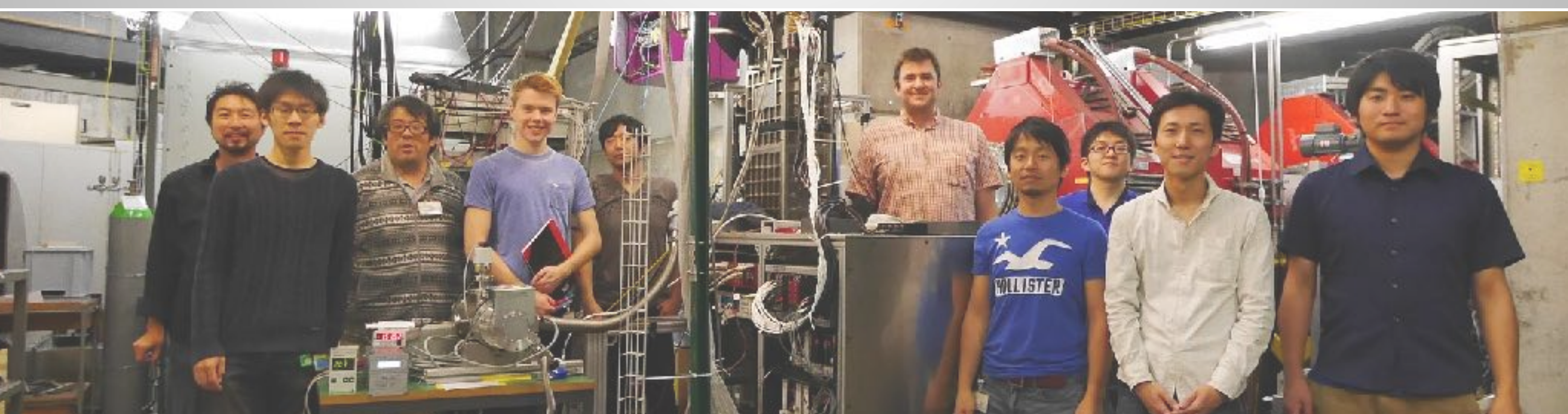
Status of HEATES project

2012	Collaborate with astro-physics guys developing TES
2013	get started the collaboration with NIST
2014	**Demonstration study (π beam) @ PSI** ①
2015	stage-2 approval by J-PARC PAC
2016	**Commissioning run (K beam) @ J-PARC** ②
2017	J-PARC E62 physics run ?

Two performance evaluations

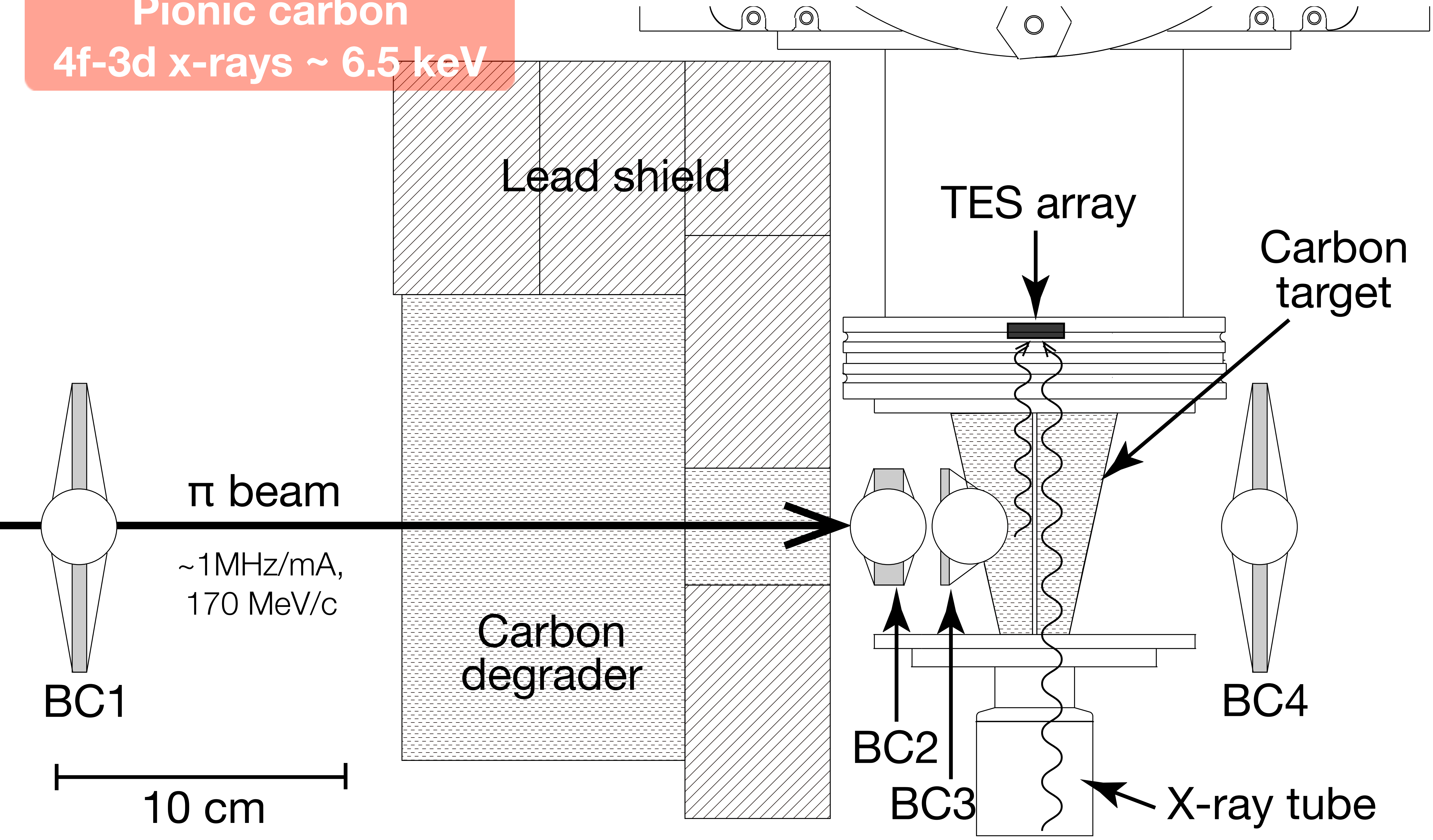
	①	②
location	PSI (Switzerland)	J-PARC (Japan)
beam line	πM1	K1.8BR
particle	π-	K-
purity	~ 0.4	~ 0.3
momentum	170 MeV/c	900 MeV/c
intensity (sum of all particles)	1.4 ~ 2.8 x 10^6 cps	8 x 10^5 / spill
hadronic atom x-rays	π ^{12}C 4-3 (6.4 keV)	K-^{3}He 3-2 (6.2 keV) K-^{4}He 3-2 (6.4 keV) to be measured
science X-ray rate	~ 200 **/ hour**	~ 200 **/ week**

① π^- beam

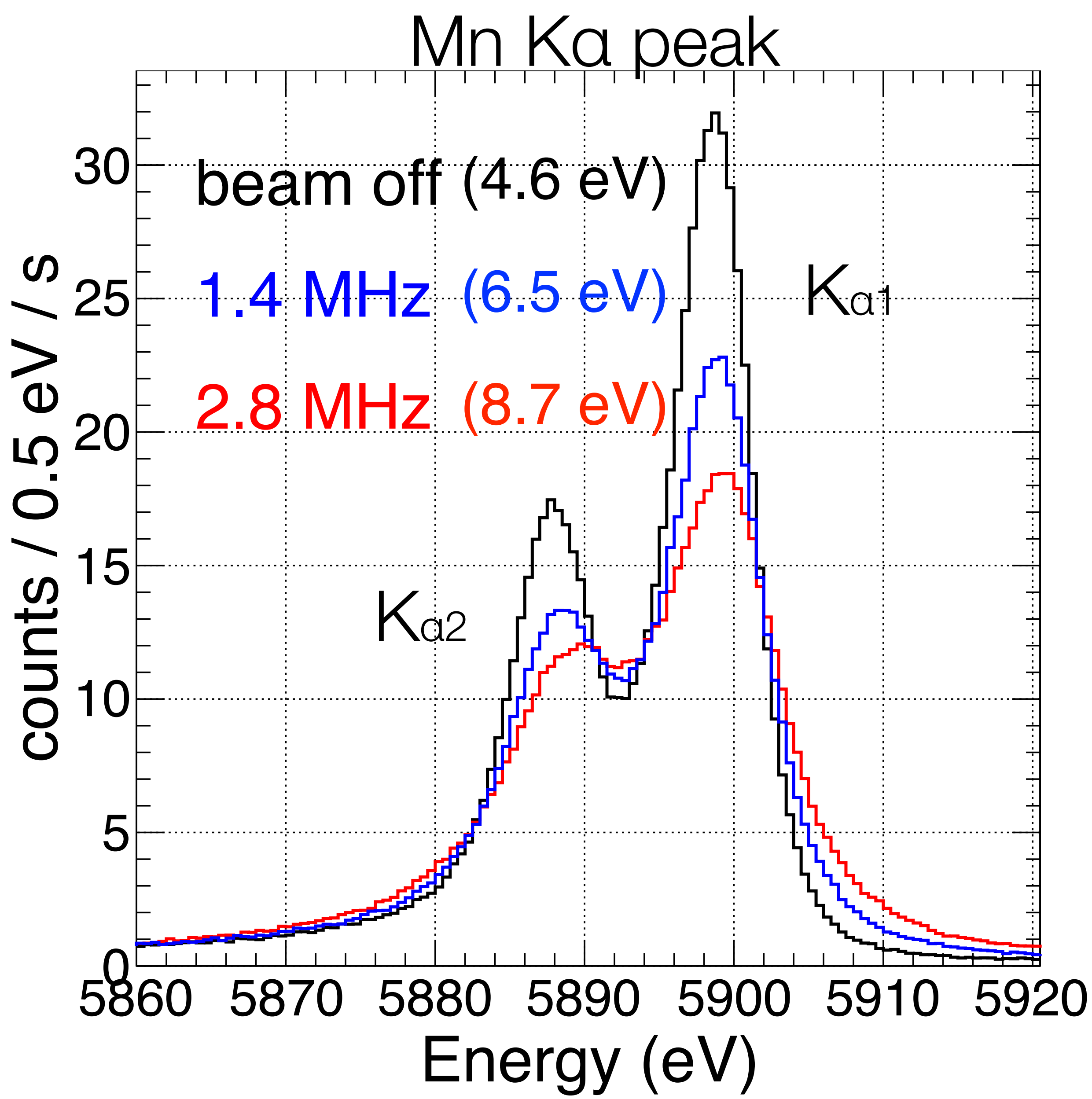


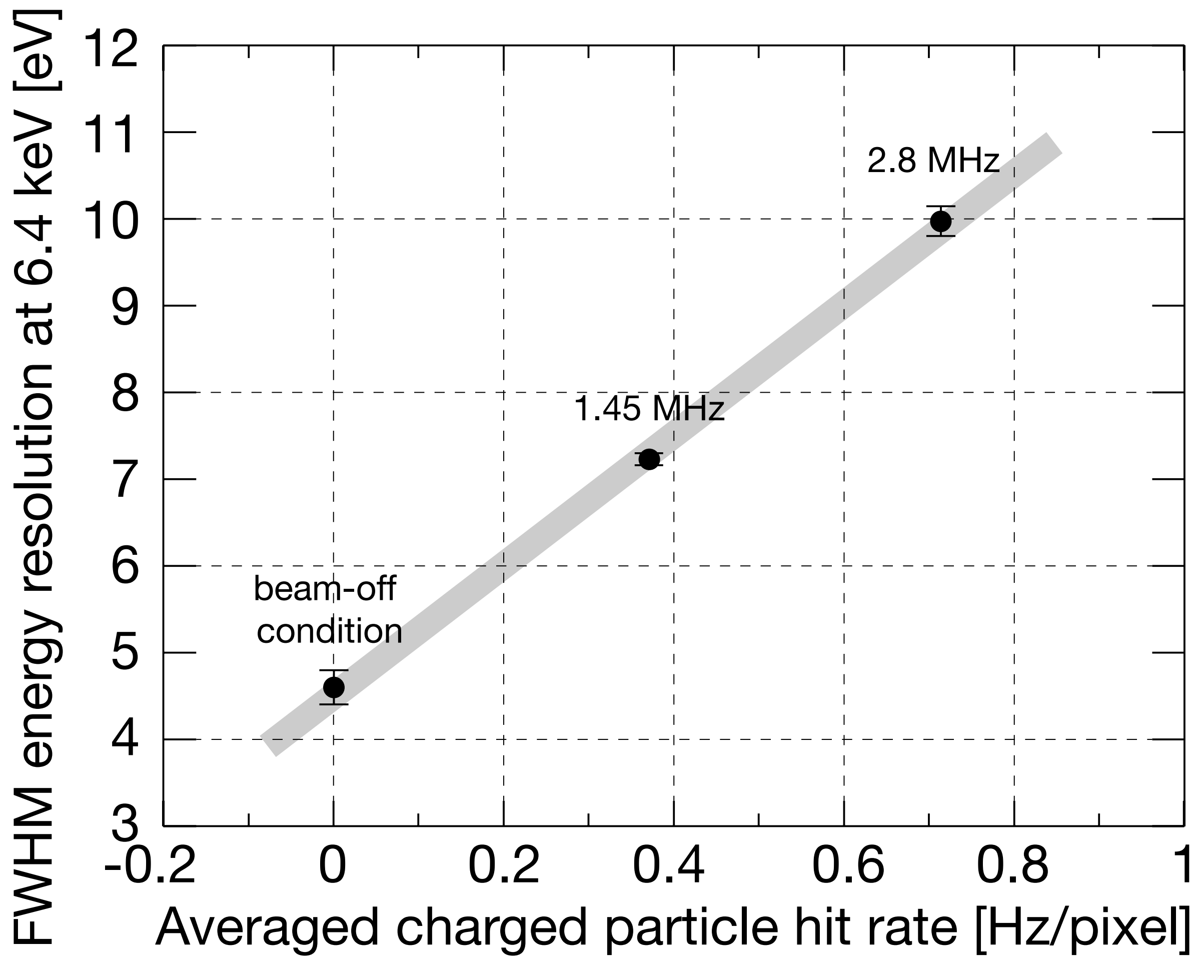
π atom expt @ PSI πM1 beamline

Pionic carbon
4f-3d x-rays ~ 6.5 keV



In-beam performance



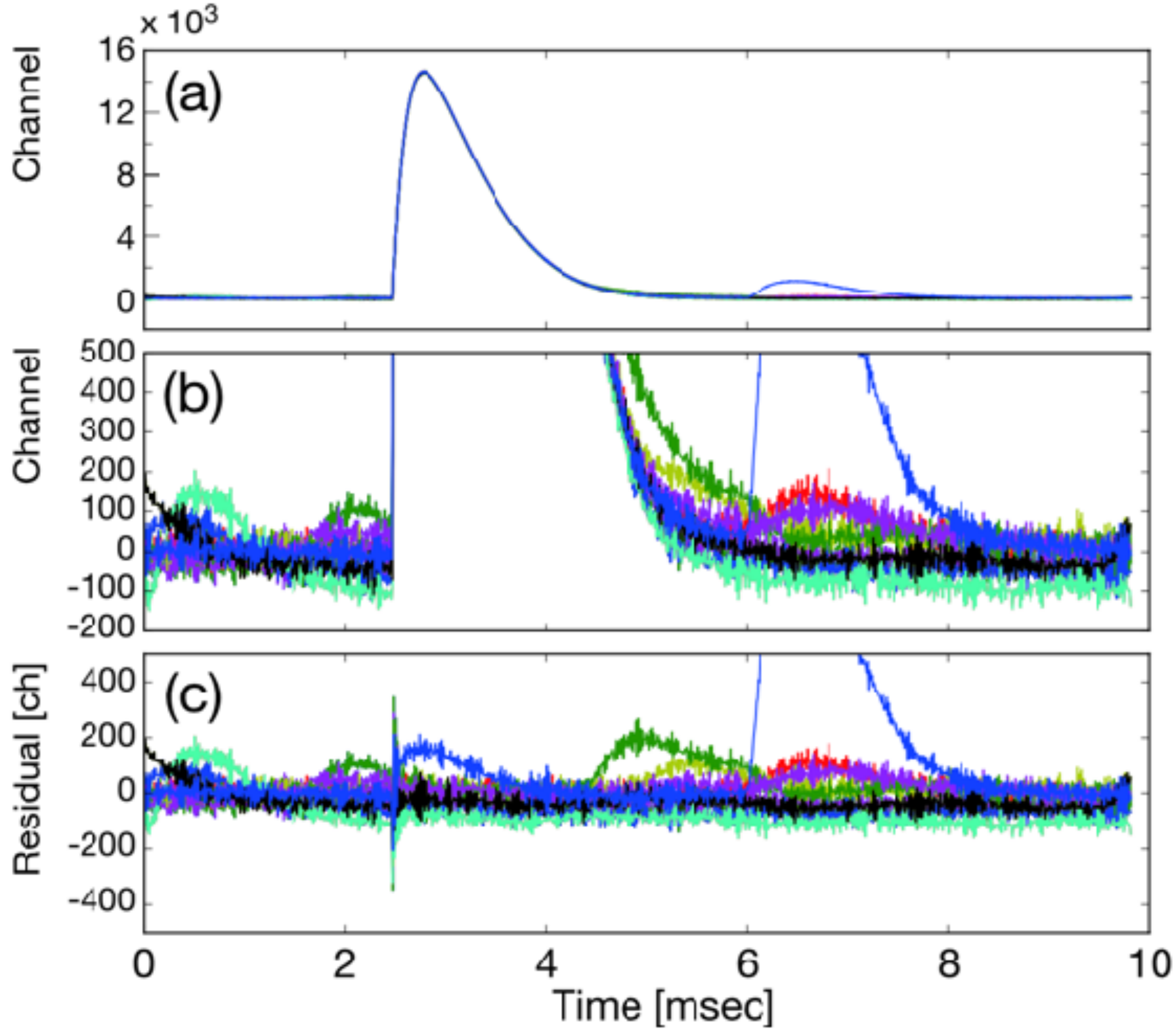


Hit-rate difference between beam-on and off conditions

High energy particle beam degrades resolution
(Hit rate ∝ incident beam intensity)

NOTE : Energy scale is well controlled by in-situ calibration.

A typical thermal crosstalk event



Enlarged view

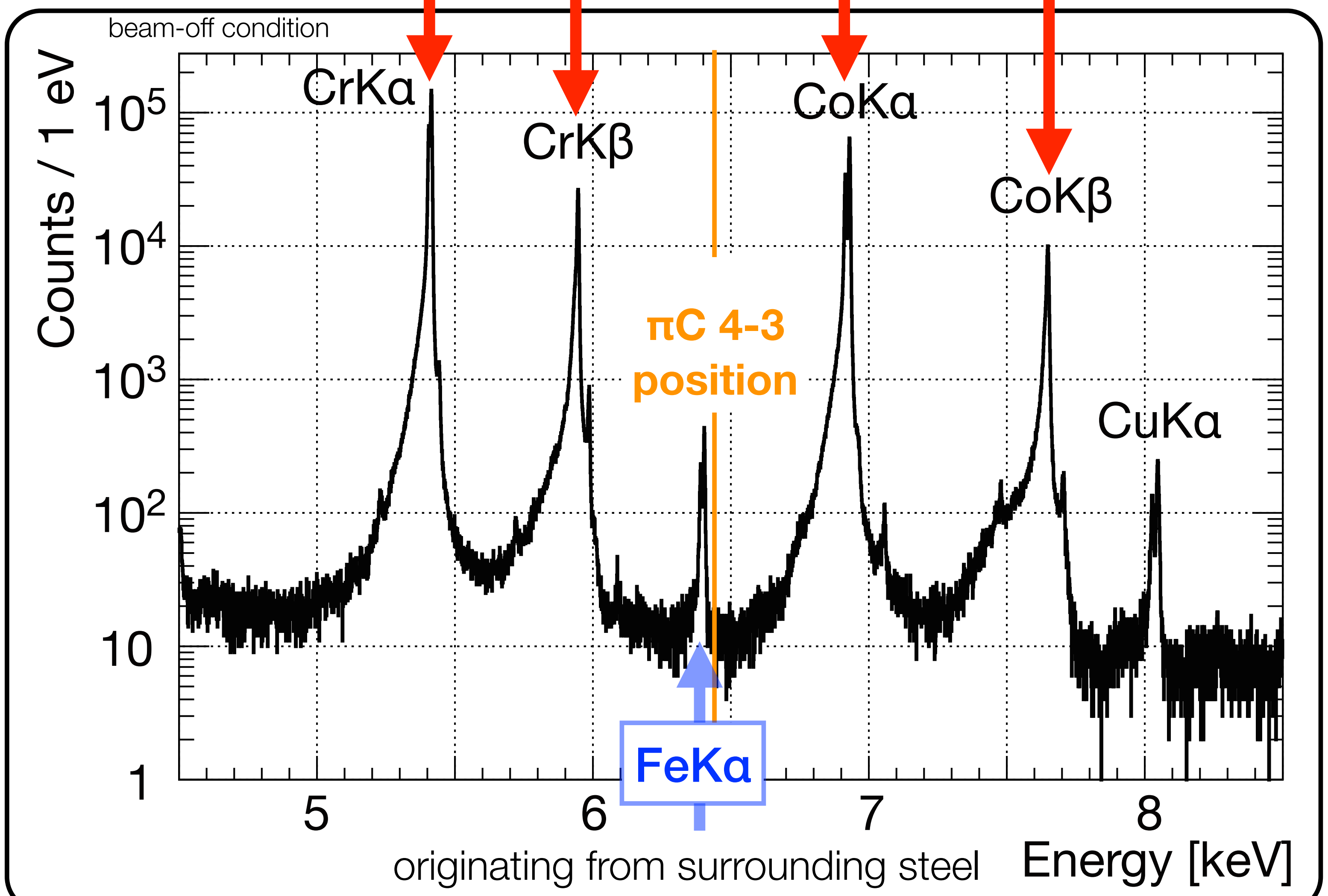
Residuals from the averaged pulse

- *High-energy charged particles deposit energy in Si frame of TES chip*
- *Resulting thermal-crosstalk pulses degrade the energy resolution*

In-situ energy calibration with x-ray tube

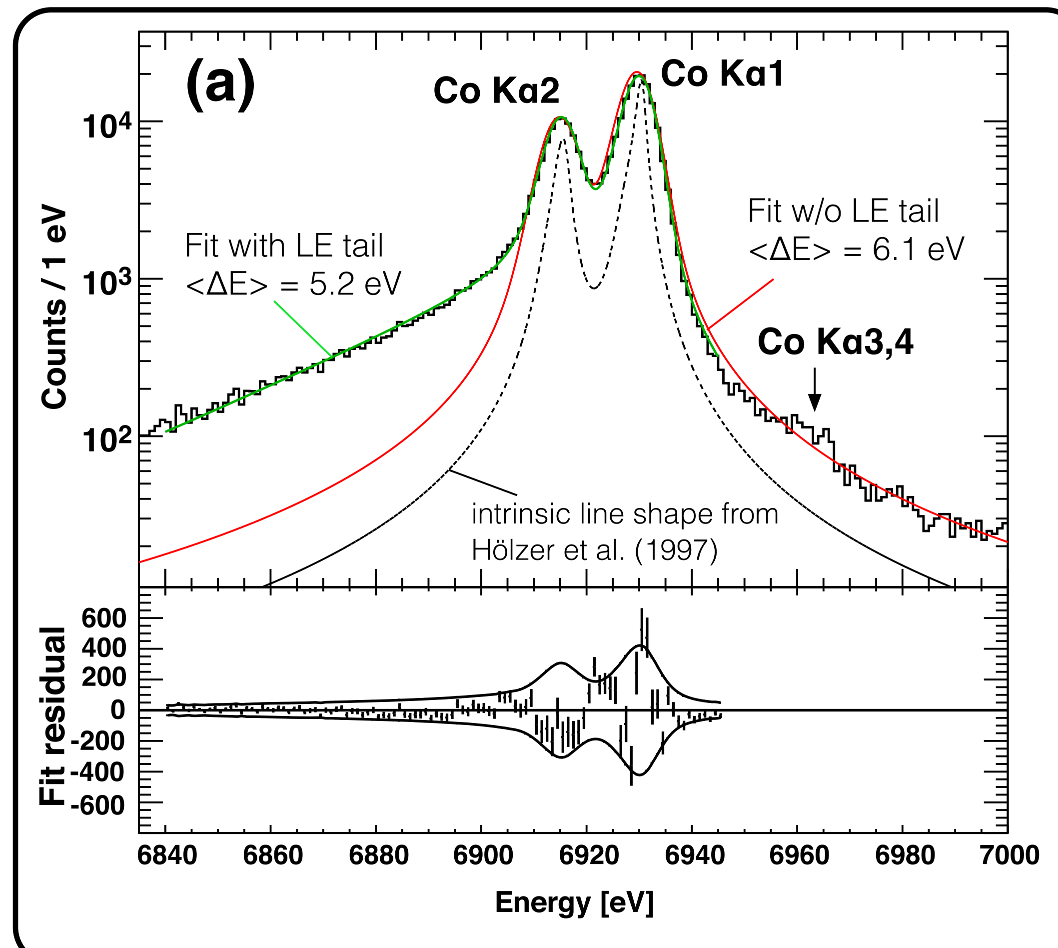
- ✓ each 240 pixels calibrated individually
- ✓ every 2 hours
- ✓ natural cubic spline using 4 lines

Used high-intensity **4 lines**



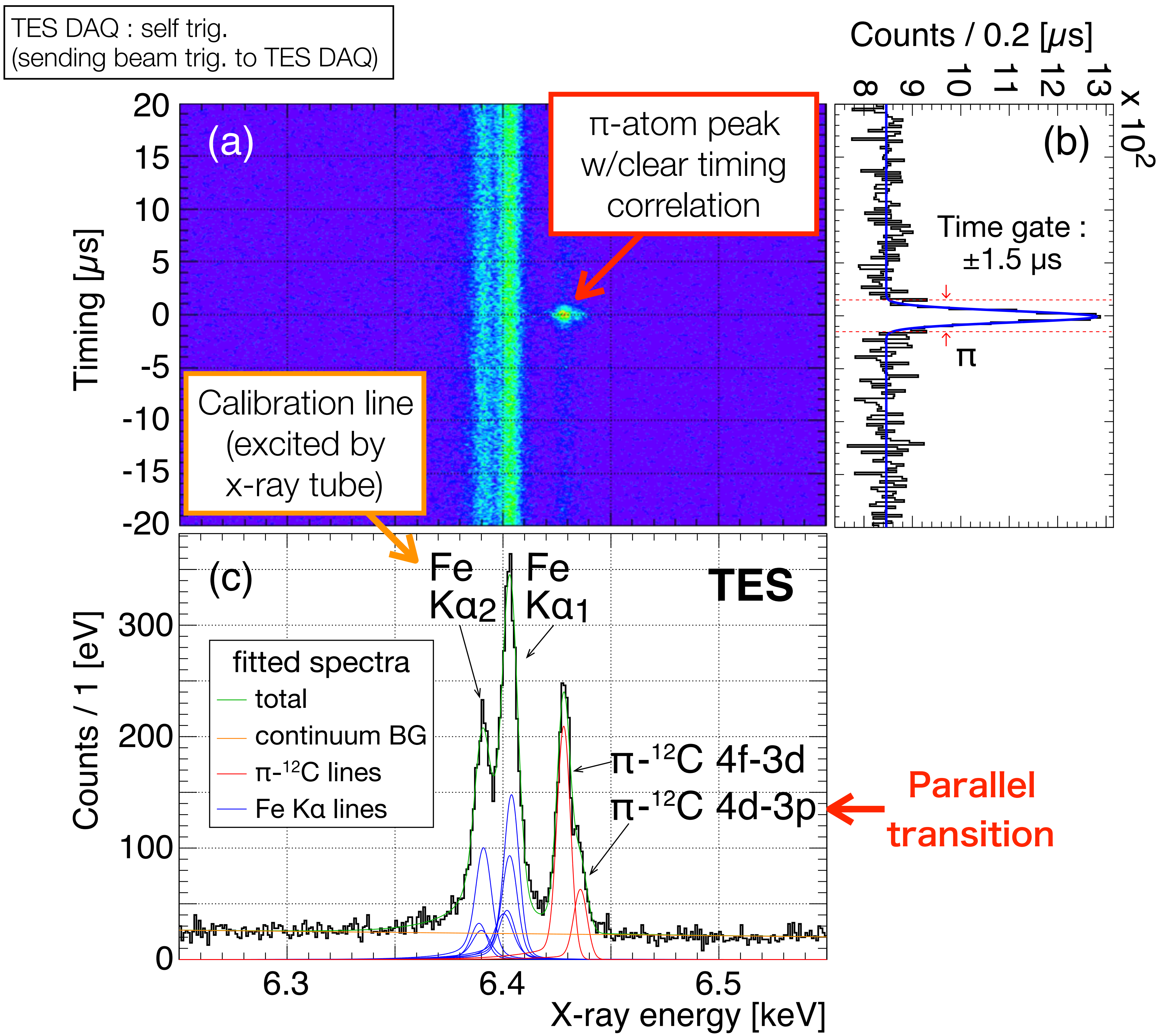
useful to **estimate the accuracy** of energy calibration

Fit example

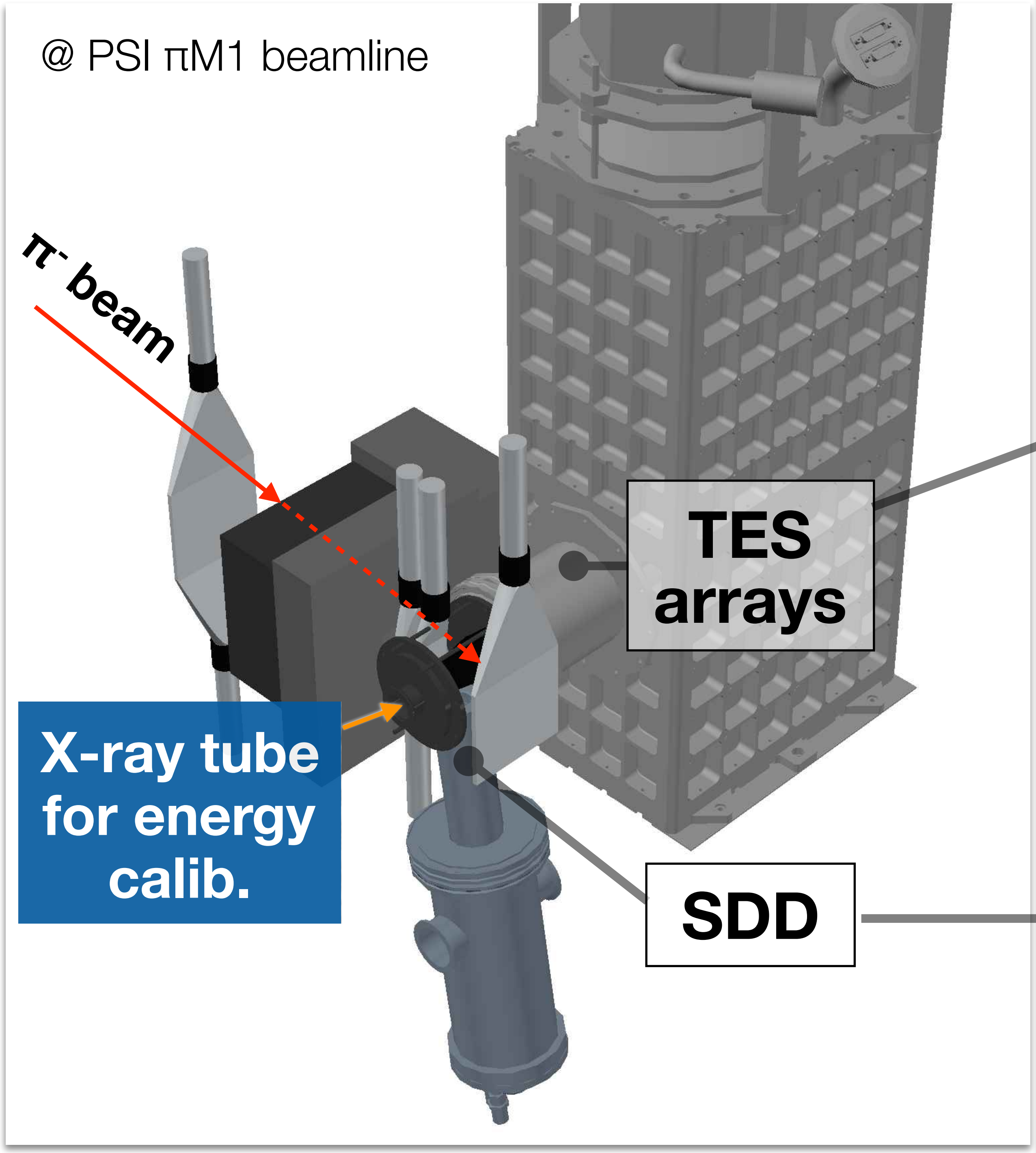


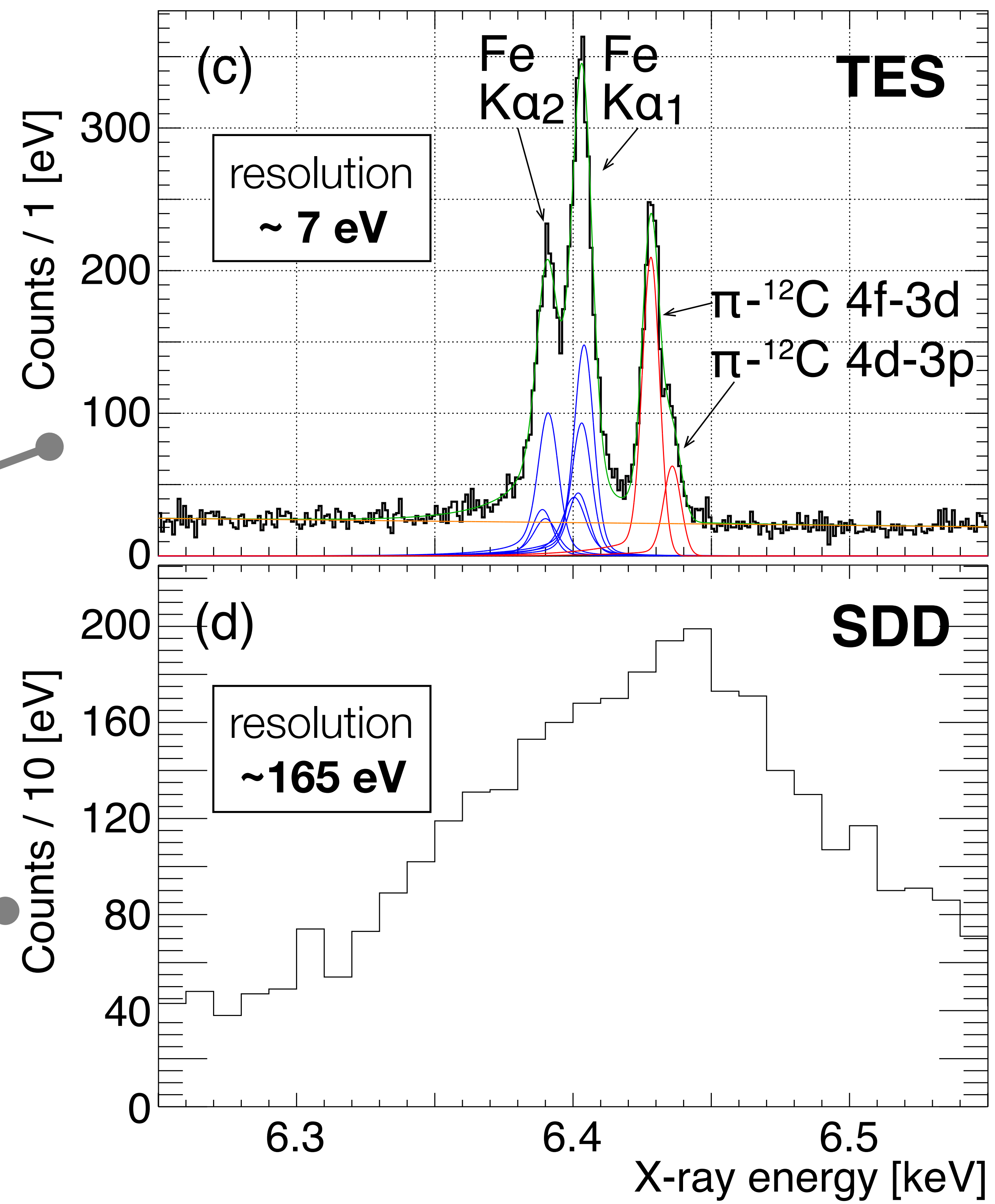
H. Tatsuno et al.,
J Low Temp Phys 184 (2016) 930-937

Successful demonstration w/ π- atom



Comparison with SDD spectrum





published very recently

on 30 Sept, 2016

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
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Fit results

Fe $K_{\alpha 11}$ line (confirmation of energy calib.):

$$6404.07 \pm 0.10(\mathrm{stat.})^{+0.06}_{-0.04}(\mathrm{syst.})\ \mathrm{eV}$$

⇒ **good agreement** with the reference value :

6464.148(2) eV [G. Holzer et al., PRA56(1997)4554]

Pionic atom lines :

$$\begin{aligned} E(4f \rightarrow 3d) &= 6428.39 \pm 0.13(\mathrm{stat.}) \pm 0.09(\mathrm{syst.})\ \mathrm{eV} \\ E(4d \rightarrow 3p) &= 6435.76 \pm 0.30(\mathrm{stat.})^{+0.11}_{-0.07}(\mathrm{syst.})\ \mathrm{eV} \\ I(4d \rightarrow 3p)/I(4f \rightarrow 3d) &= 0.30 \pm 0.03(\mathrm{stat.}) \pm 0.02(\mathrm{syst.}) \end{aligned}$$

⇒ comparison with EM calc?

EM values & strong-int calc.

EM calc. (T. Koike)

State	K.G. energy (eV)	Vacuum polarization $\alpha(Z\alpha)$ (eV)	Vacuum polarization $\alpha^2(Z\alpha)$ (eV)	Nuclear finite size effect (eV)	Relativistic recoil effect (eV)	Strong interaction effect (eV)	Total energy (eV)
$3p$	-14685.15	-11.56	-0.08	$+0.01$	-0.02	-0.78	-14697.58
$3d$	-14682.65	-5.39	-0.04	$+0.0005$	-0.02	$< 10^{-4}$	-14688.10
$4d$	-8259.04	-2.10	-0.02	$+0.0003$	-0.01	$< 10^{-4}$	-8261.17
$4f$	-8258.59	-0.72	-0.004	$+0.0003$	-0.01	$< 10^{-4}$	-8259.32

Strong int calc. via Seki-Matsutani potential
(N. Ikeno, J. Yamagata-Sekihara, S. Hirenzaki)

$\Rightarrow$ Non-negligible contribution from 3p level

Electron screening effects

calc. by T. Koike

one e- in K-shell → $1s^1\ 2s^2\ 2p^1$
two e- in K-shell → $1s^2\ 2s^2\ 2p^1$

Transitions	Electron screening effect (eV) Configuration	K-shell contribution	L-shell contribution	Transition energy (eV)
$4f \rightarrow 3d$	no electron	-	-	6428.78
	$1s^1\ 2s^2\ 2p^1$	-0.19	-0.02	6428.57
	$1s^2\ 2s^2\ 2p^1$	-0.31	-0.01	6428.46
	Experimental result (this work) :			$6428.39 \pm 0.13 \pm 0.09$
$4d \rightarrow 3p$	no electron	-	-	6436.41
	$1s^1\ 2s^2\ 2p^1$	-0.25	-0.02	6436.14
	$1s^2\ 2s^2\ 2p^1$	-0.42	-0.01	6435.98
	Experimental result (this work) :			$6435.76 \pm 0.30\ ^{+0.11}_{-0.07}$

good agreement within error

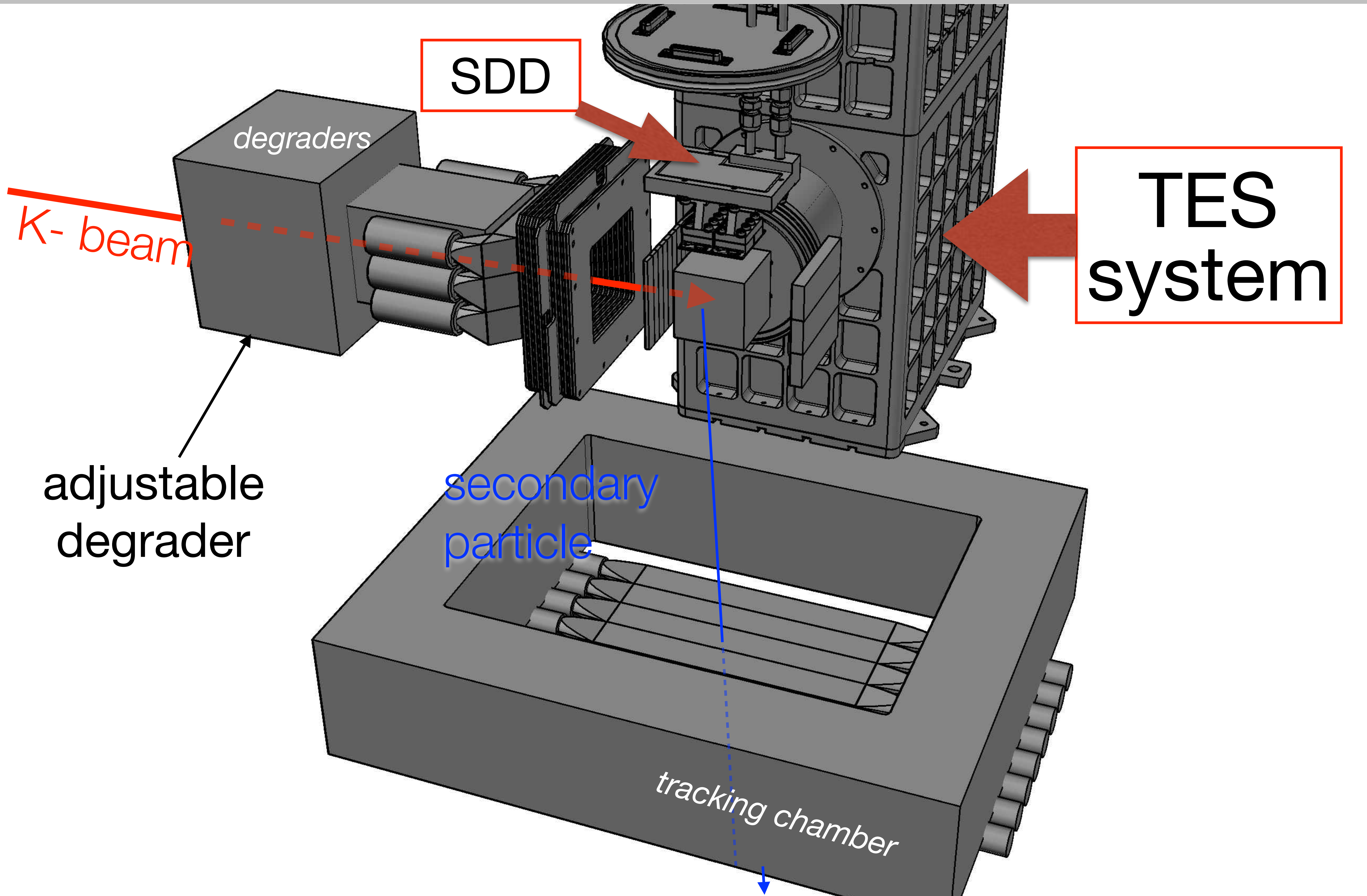
Conclusion :

- ✓ **favor two 1s electrons** in the K-shell
- ✓ energy shift of measured parallel-transition is **consistent** with strong-int effect assessed via **Seki-Matsutani potential**

② K^- beam

4-days beamtime
on June, 2016

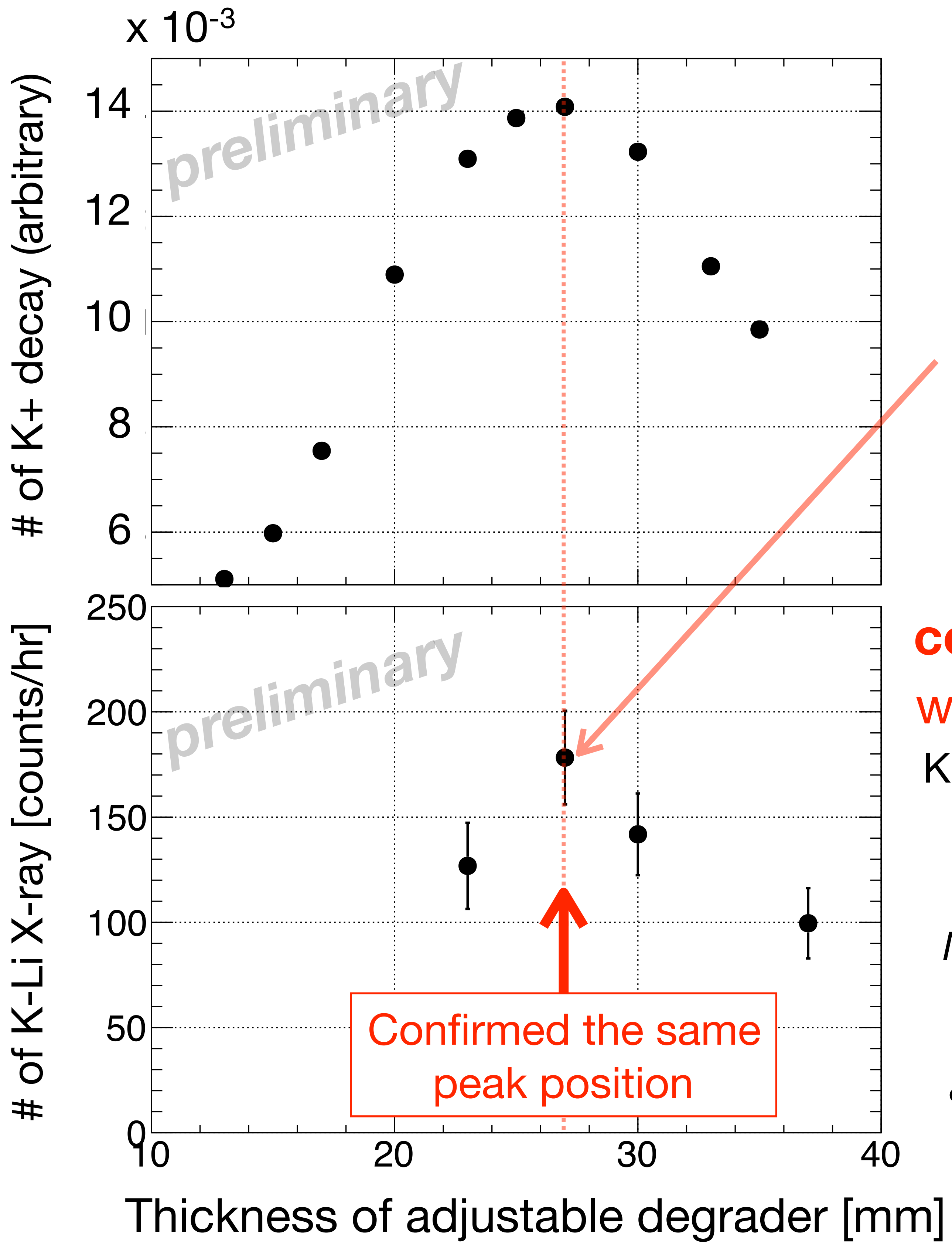
Kaon-stop tuning setup



K- stop tuning

with tracking chamber system for **0.9 GeV/c K+**

with SDDs for **0.9 GeV/c K-**



K-Li x-ray yield :
~180 counts / hr
(with 24 good SDDs)

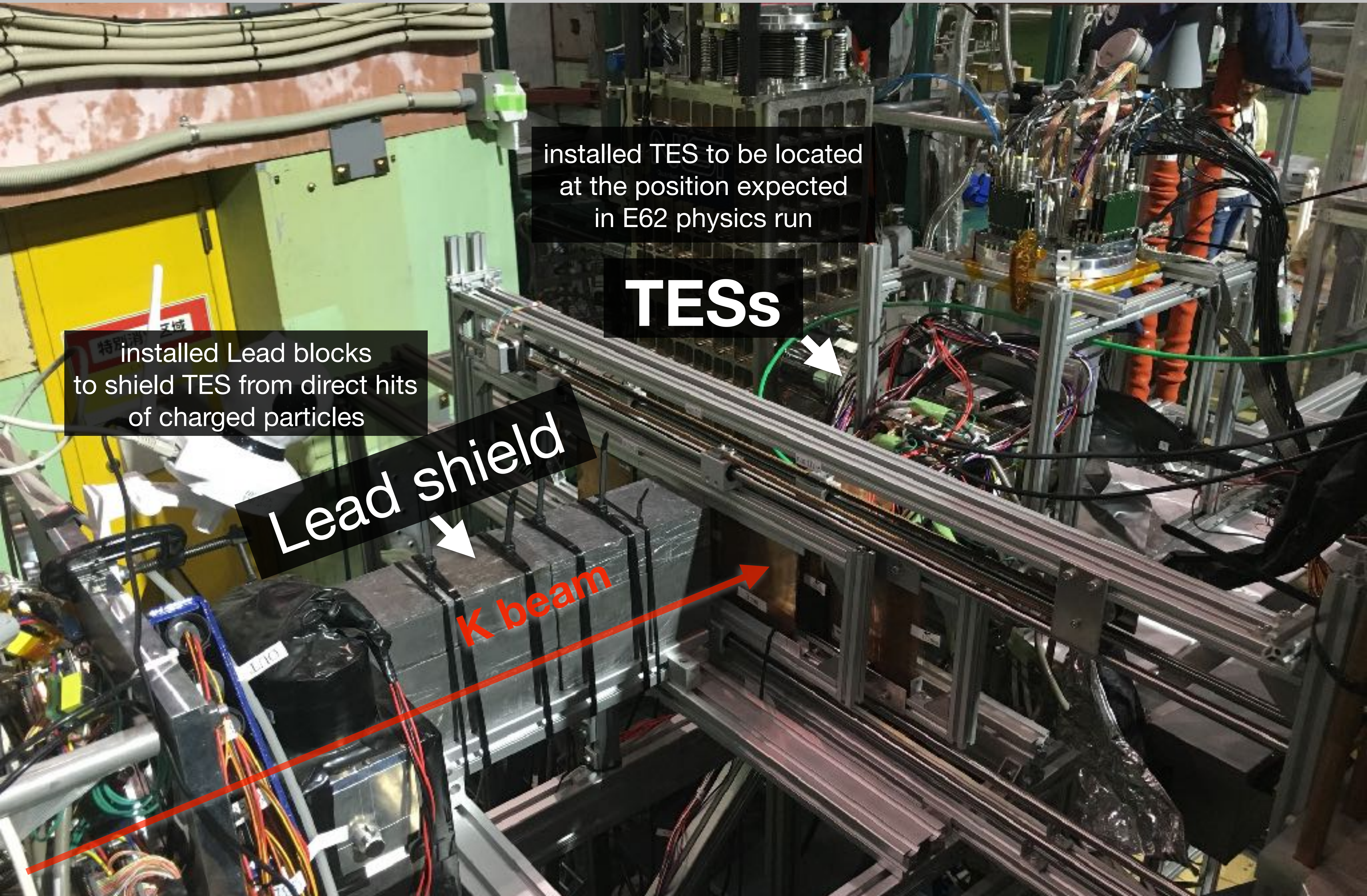
consistent with G4 sim

within error of ref. value:

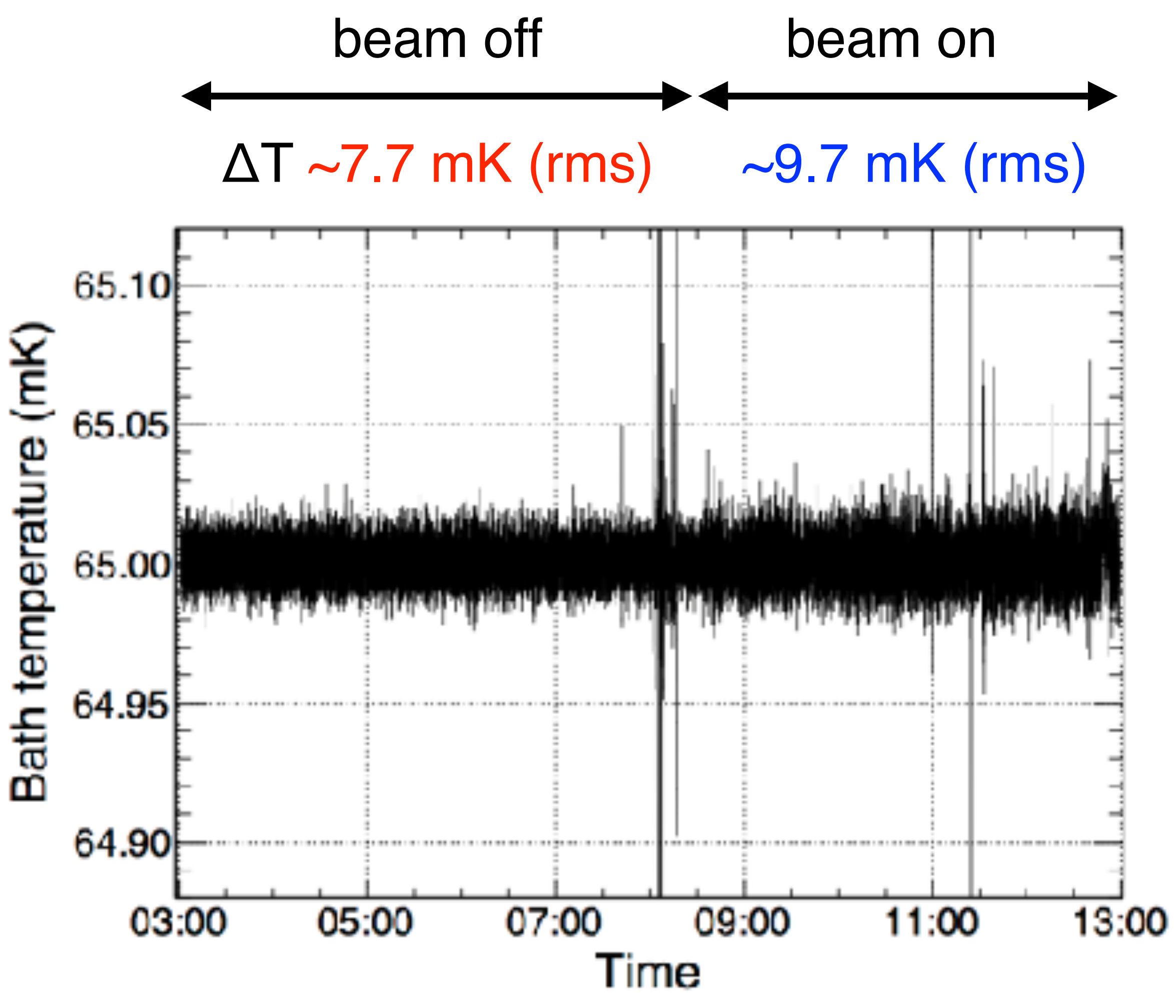
K-Li yield = 15 ± 3 % / stop K
[PRA 9 (1974) 2282]

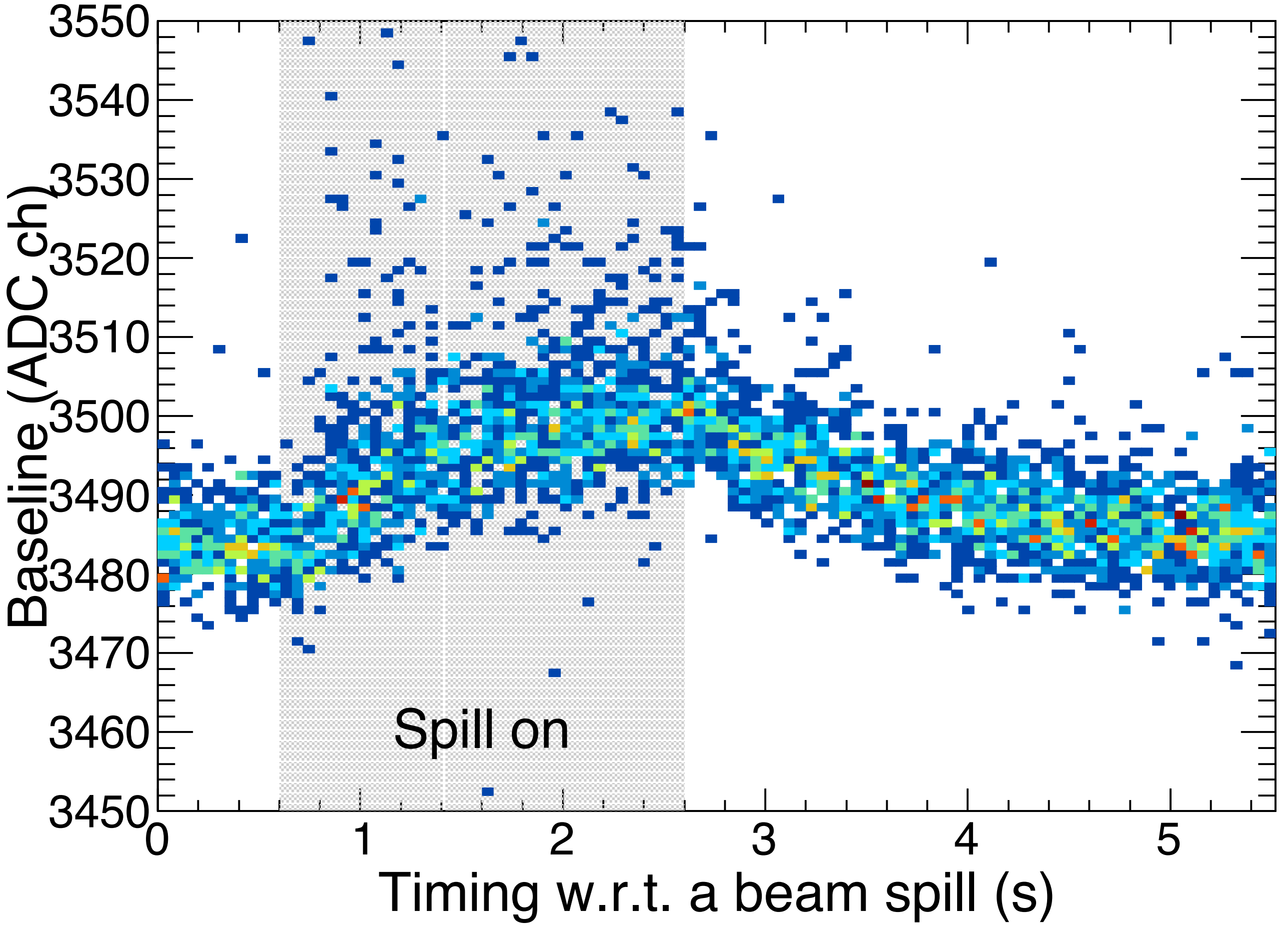
Note that the simulation was performed again with obtained beam profile & actual geometrical inputs.

Setup from upstream



Beam structure

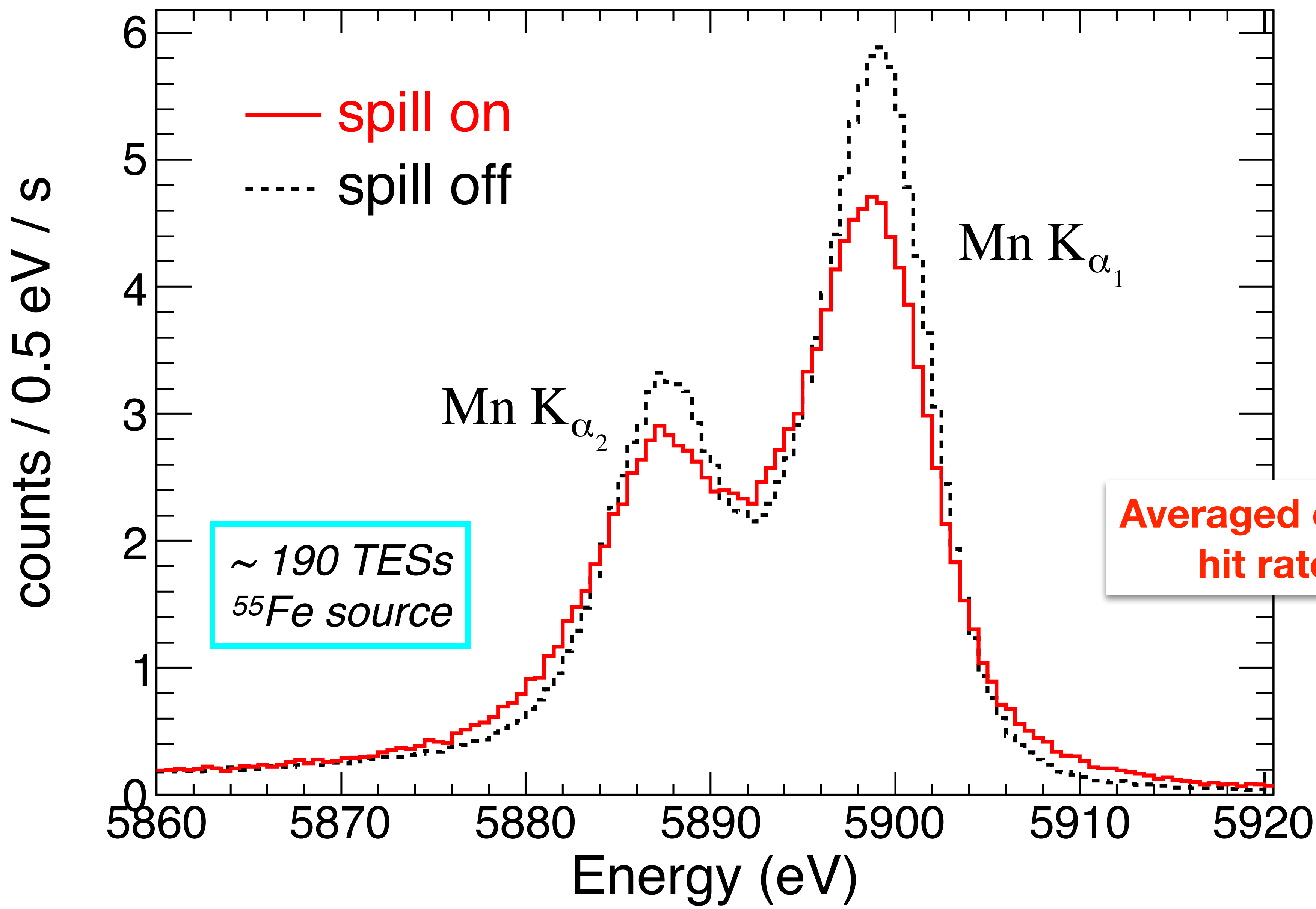




- Temperature regulation holds in the pulsed beam
- TES temperature clearly increases during a beam spill

⇒ this effect can be compensated in the standard analysis procedure

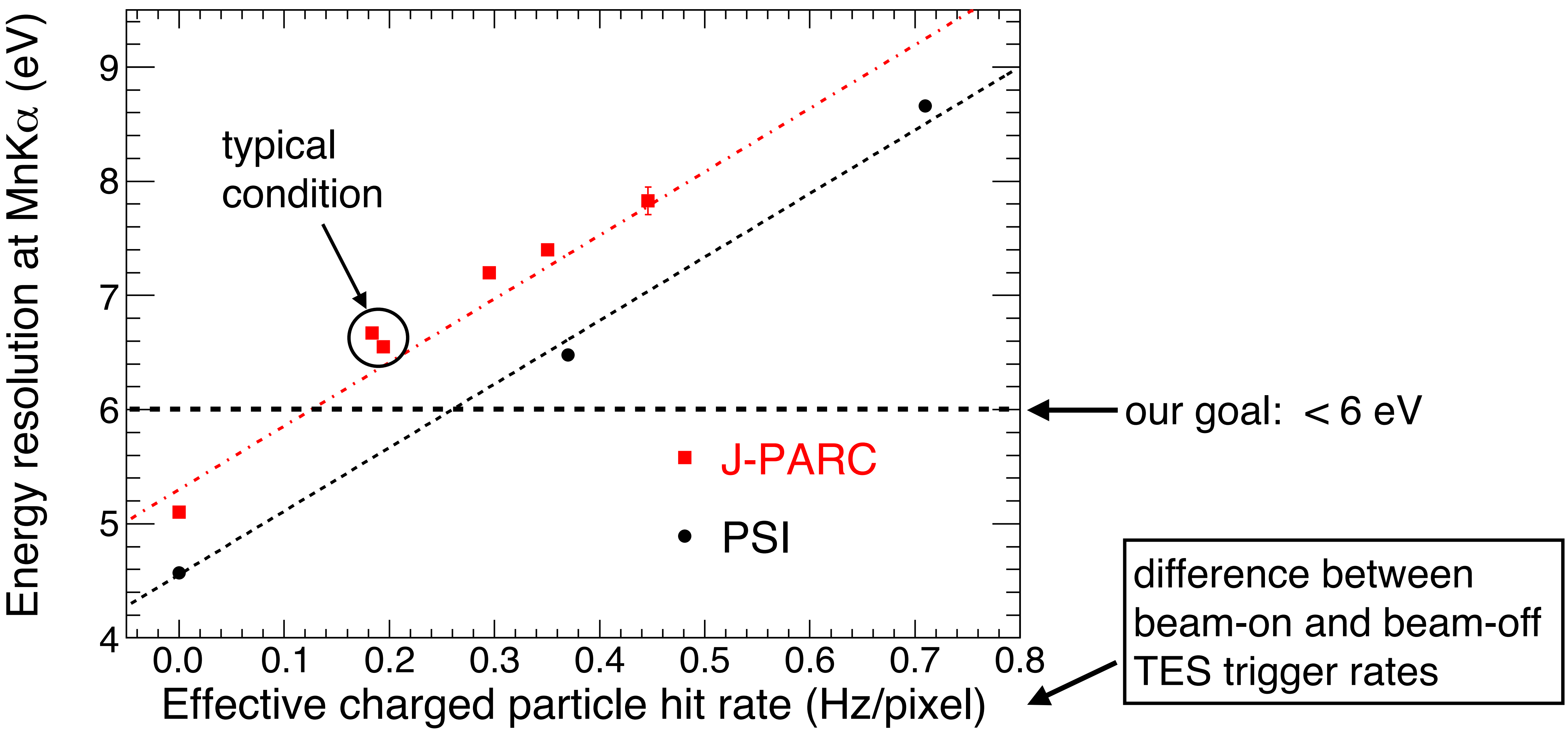
Mn Kα spectrum



Averaged charged-particle hit rate : ~0.1 [cps]

- Clear gap between Kα1 & Kα2 -> excellent resolution
- High-energy particle beam degrades resolution a bit.
- If no lead shield, $\Delta E > 10$ eV. ⇒ Lead shield was quite effective.

Energy resolution vs. charged-particle hit rate



✓ Similar correlation in the two different beams

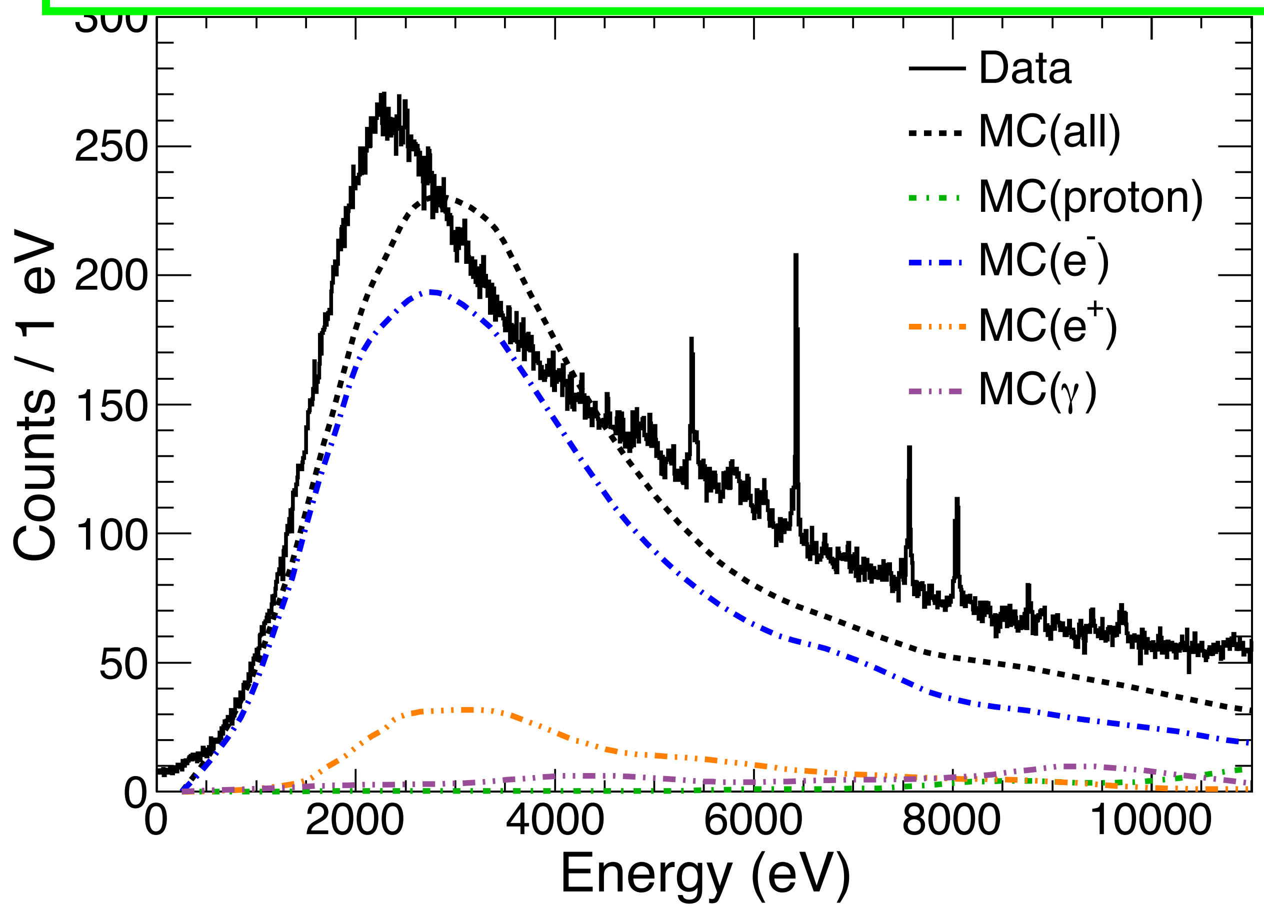
✓ Promising to achieve our goal at J-PARC

1. Room to improve the base resolution
2. More optimal setup (shielding, etc.): further suppress changed-particle hit rate

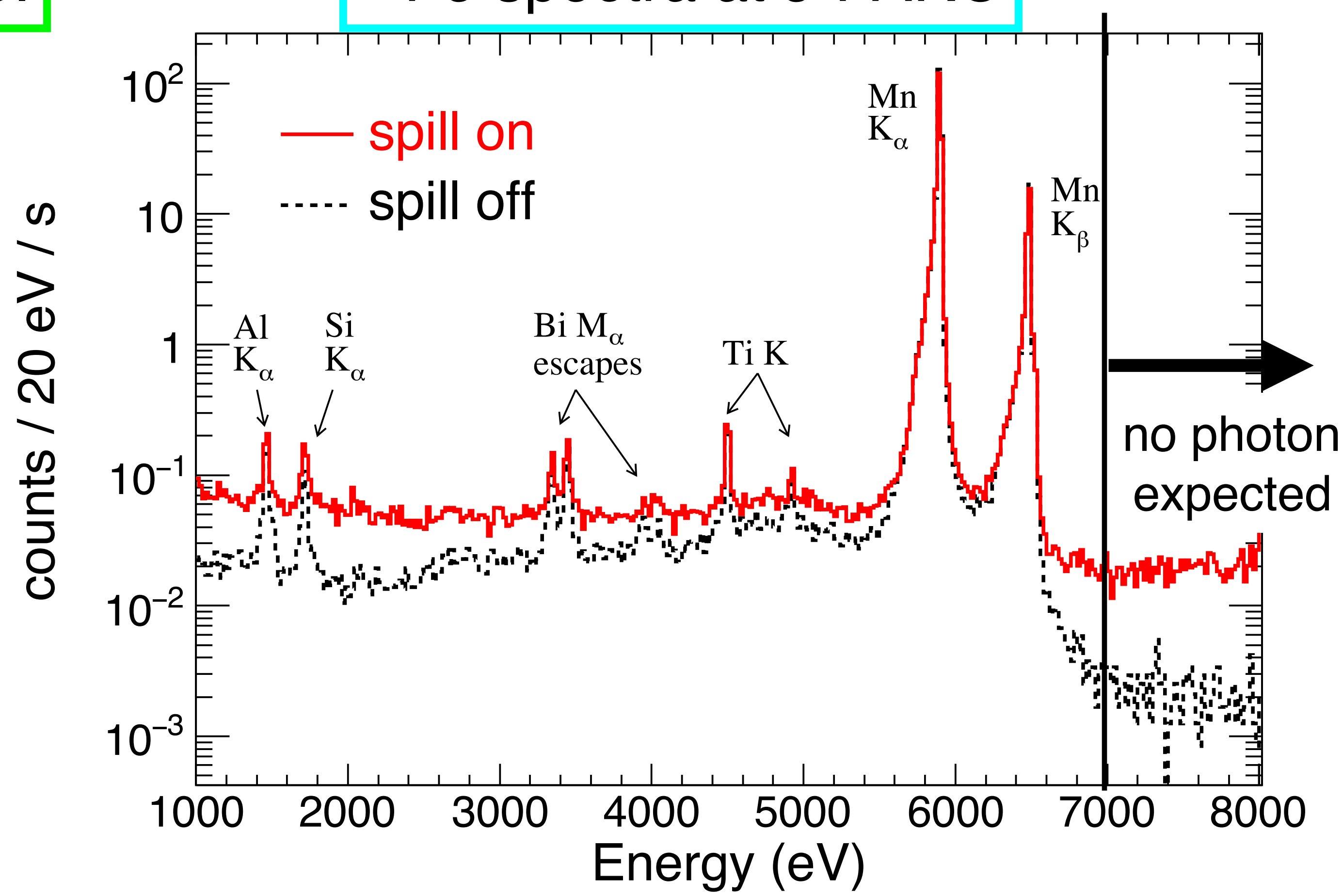
Charged particle background

Energetic charged particle deposits several keV energy on 4 um thick Bi absorber

In-beam spectrum w/o photon source at PSI



^{55}Fe spectra at J-PARC



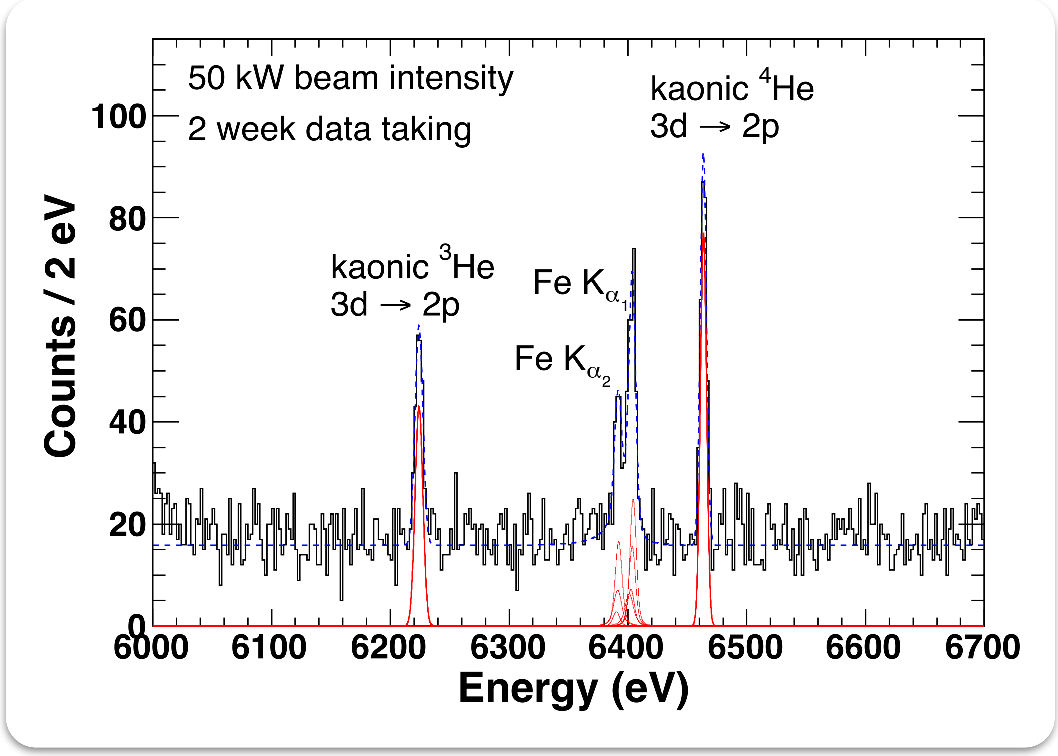
We understand the beam-induced background

✓ explained PSI spectrum well by simulation including its intensity

✓ J-PARC background level is consistent with the MC

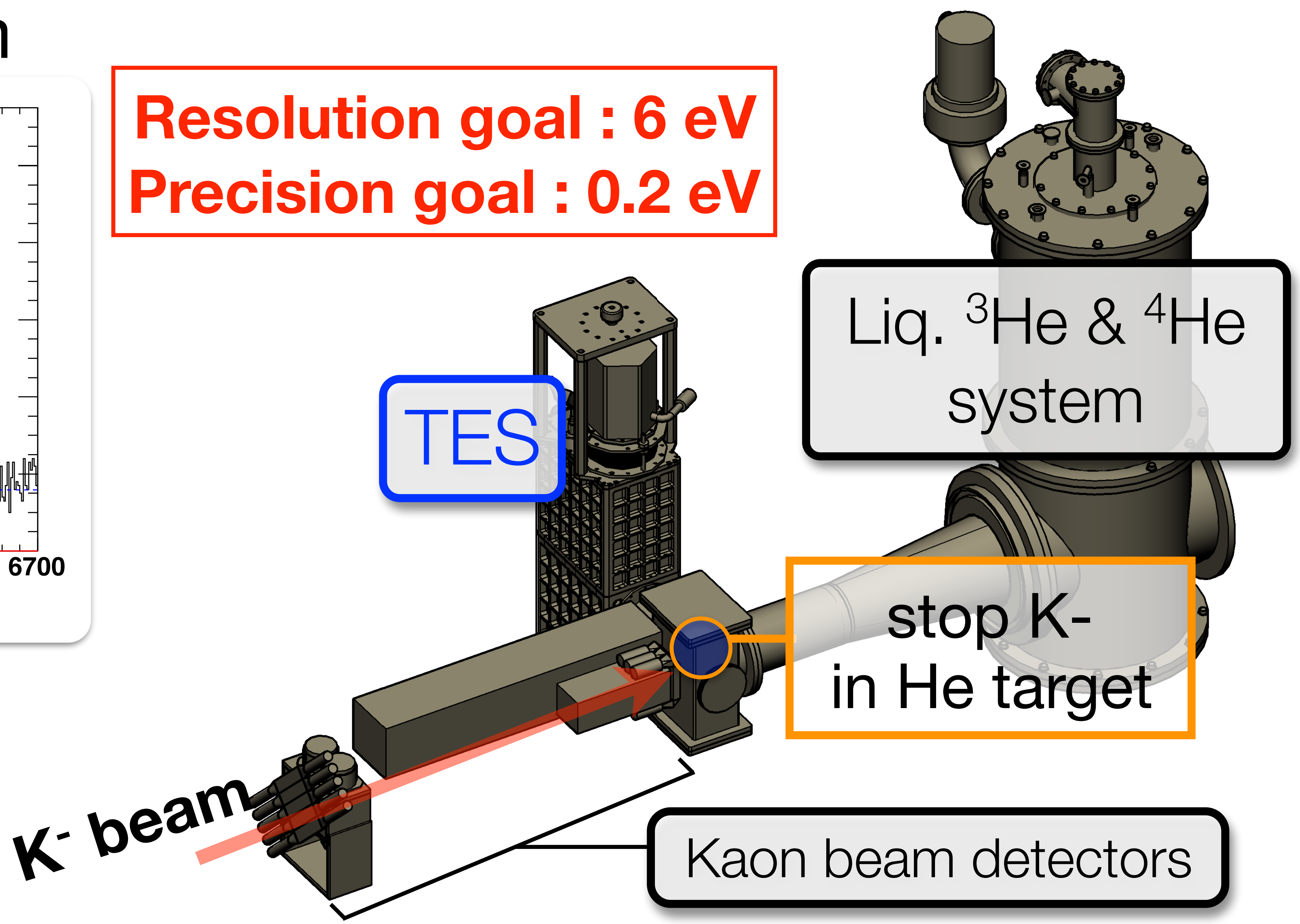
J-PARC E62 : K-He atom exp.

Expected spectrum



Asynchronous bg. : 1.5 counts /eV
Synchronous bg. : 6 counts /eV

Resolution goal : 6 eV
Precision goal : 0.2 eV



To do :

- Increase the number of working pixels (now ~190/240)
- Detailed study with an X-ray tube and radioactive sources
- Combine the TES spectrometer with the liquid helium target

6. Summary

Summary

◉ TES performance evaluation with hadron beams

① **π^- beam** : successfully demonstrated π atom expt.

- energy resolution ~ 6 eV (FWHM @ 6 keV)
- timing resolution ~ 1 μs (FWHM)
- accurate energy calibration : less than 0.1 eV

② **K^- beam** : good performance at actual beamline as well

◉ J-PARC E62 (K-He atom x-ray) physics run in 2017 (?)