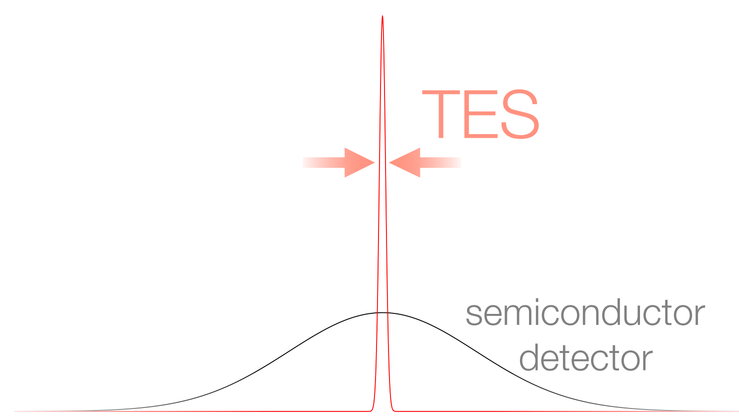
12 Sept, 2017
EXA2017 @Vienna

X-ray spectroscopy of kaonic atoms with cryogenic detectors



Shinji Okada (RIKEN)
for the HEATES collaboration

Collaboration list

HEATES = High-resolution Exotic Atom study with TES microcalorimeters

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[1] INFN-LNF, [2] NIST, [3] SMI, [4] Univ. of Zagreb, [5] Politecnico di Milano, [6] TMU,
[7] Kyoto Univ., [8] Lund Univ., [9] RIKEN, [10] UT, [11] RCNP, [12] KEK, [13] Tohoku U., [14] JAEA

(55 researchers, 14 facilities)

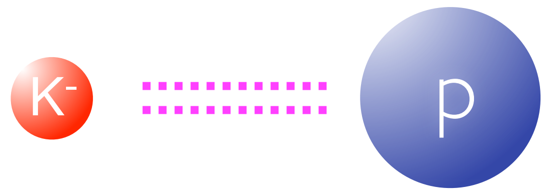
Nuclear physicists + TES experts + Astro physicists

(NIST , LundU) (TMU , TohokuU)

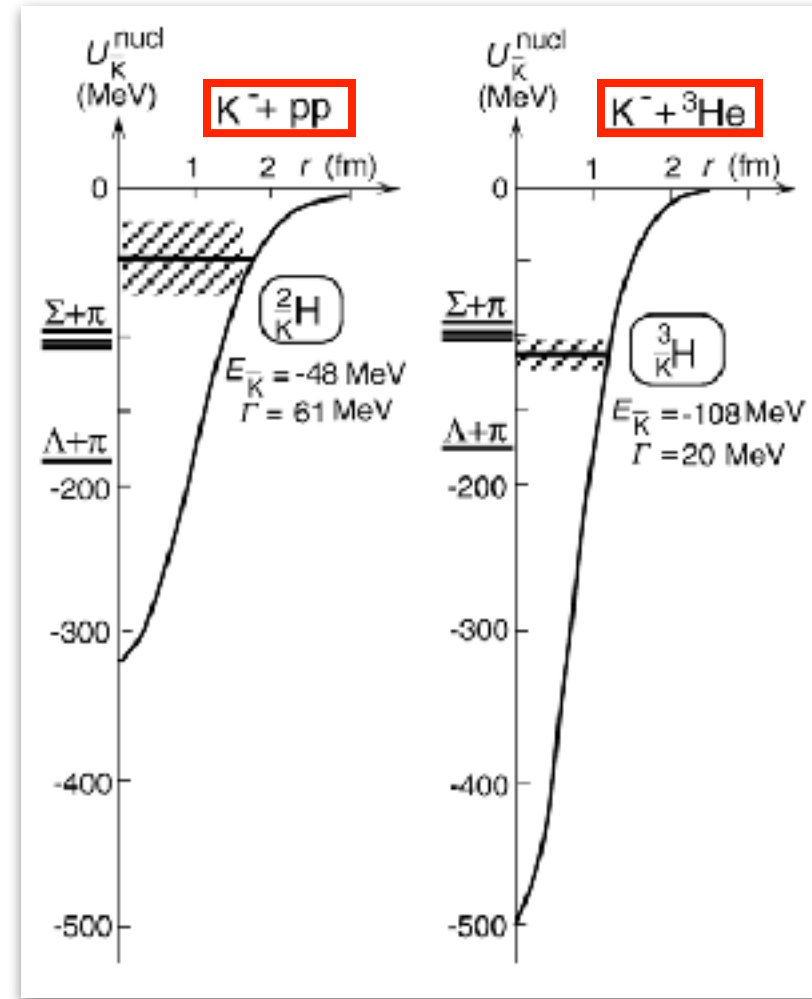
Contents

1. Introduction

$\overline{K}$ - nucleus interaction



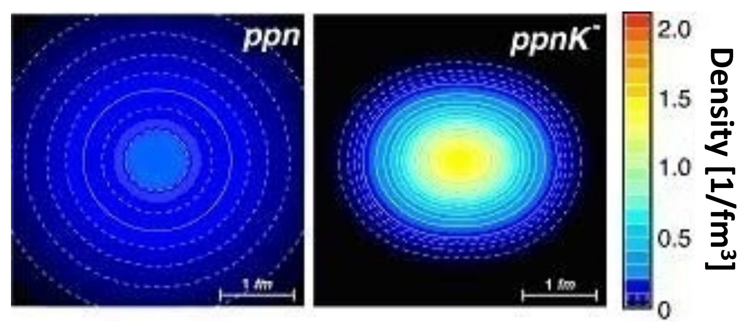
Strongly attractive!



Phys. Lett. B 535, 70 (2002)

Possible existence of deeply bound K- cluster

Phys. Lett. B587, 167 (2004)



✓ New form of a "matter"
✓ In-medium property of K

→ Depends on how much of K-nucleus potential depth

→ However the potential depth is still unknown…

discussed in today's morning session

Kaonic atom

e.g., Kaonic hydrogen

U.-G. Meißner et al, Eur Phys J C35 (2004) 349
(Deser-Type relation with isospin-braking correction)

$$\epsilon_{1s} + i\Gamma_{1s}/2 = 2\alpha^3\,\mu_r^2\,a_{K^-p}\left[1 + 2\alpha\,\mu_r\,(1-\ln\alpha)\,a_{K^-p}\right]$$

Shift **Width**

K-p Kα x-ray

K^-p scattering length

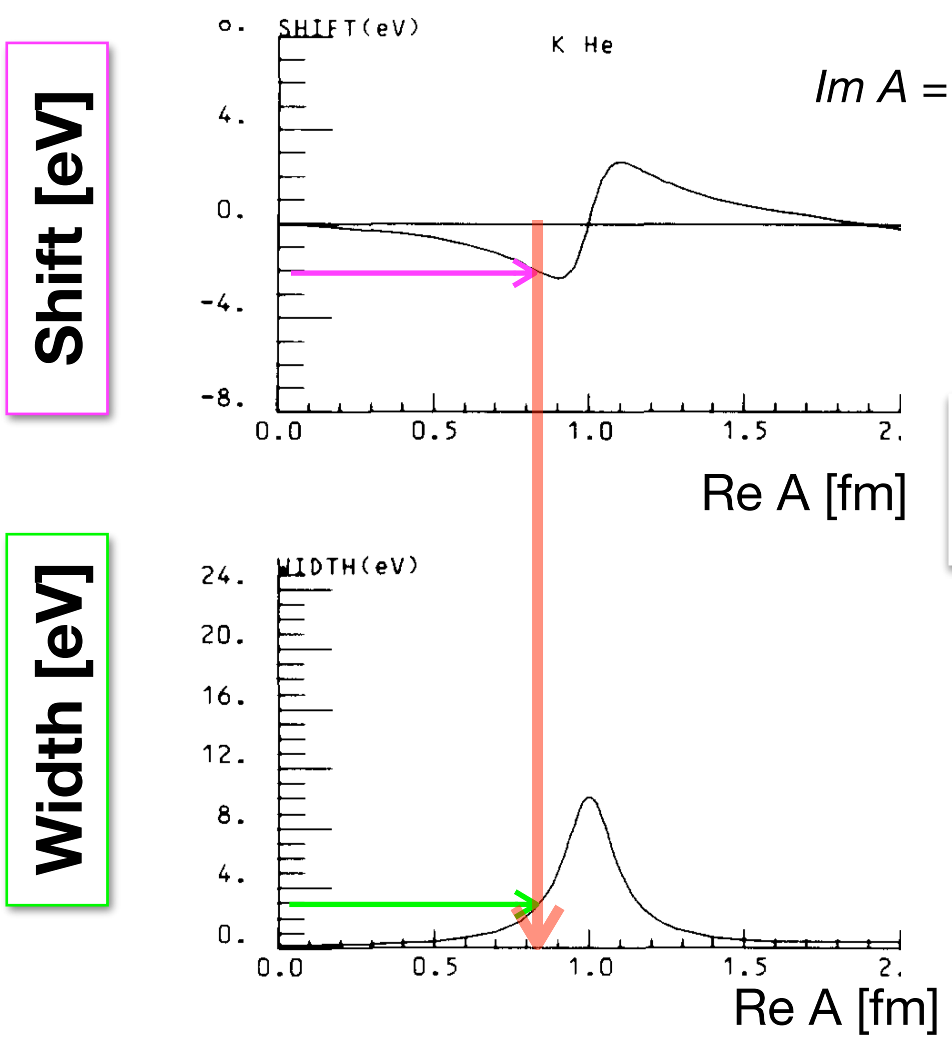
(= K^-p scattering amplitude at threshold)

K-atom data

↓

potential strength

e.g., K-He atom 2p level

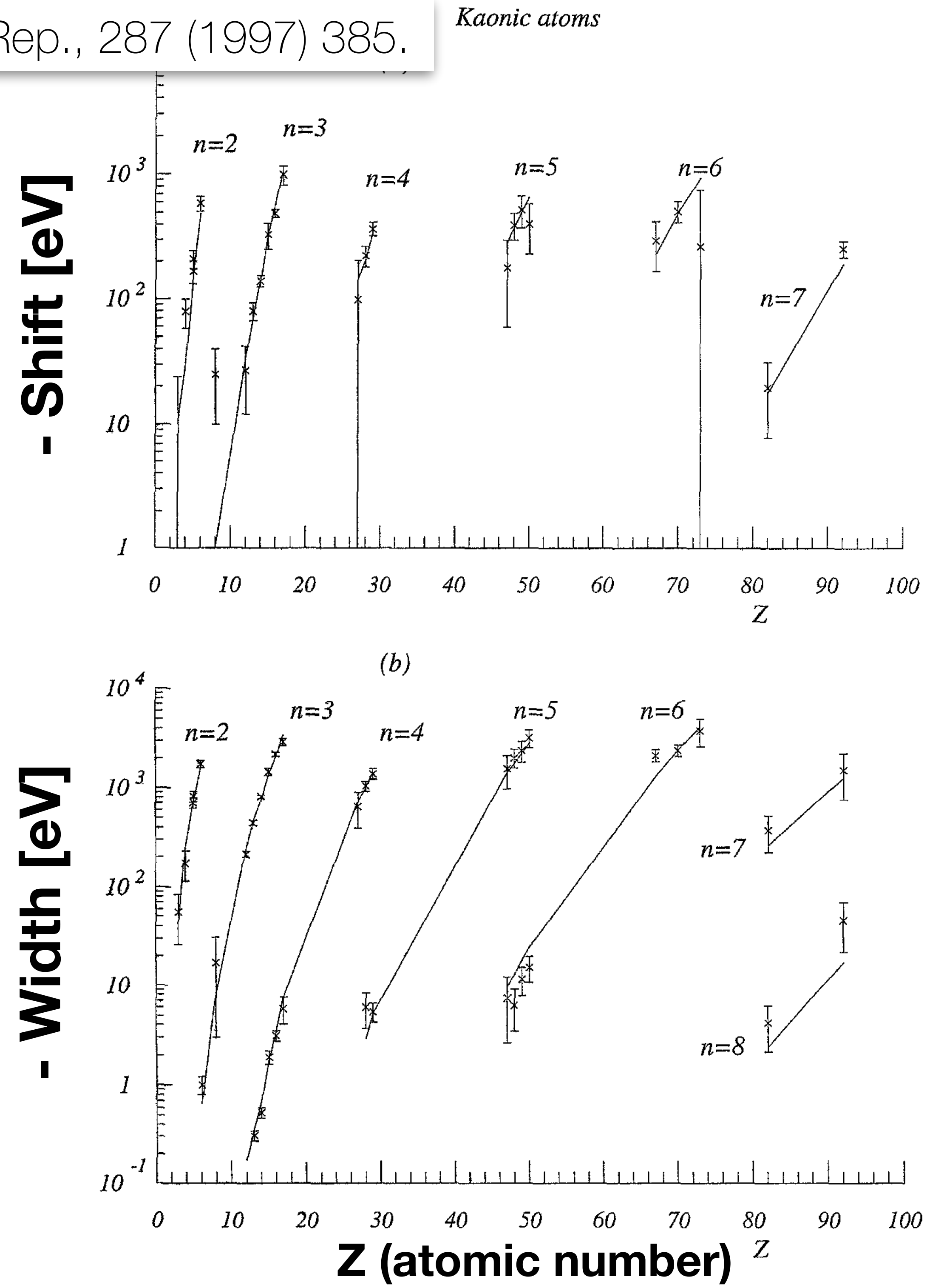


Real part of the effective scattering length [fm]

S. Baird et al.,
NPA 392 (1983) 297-310

Status of K-atom study

Phys. Rep., 287 (1997) 385.



Data :

- K-p : SIDDHARTA (2011)
- K-d : no data
- Z=2(He)~92(U) : exists, but those measurements in 70's - 80's are not so good quality.

Theories :

deep (~180 MeV) **or shallow** (~40 MeV)**?**

Global analysis prefer a deep potential ?

- **Phenomenological density dependent optical potential**
  Batty, Friedman, Gal, Phys. Rep., 287 (1997) 385.
- **Chiral potential (~50 MeV)** Ramos, Oset, NPA671(00)481
  + Phen. multi nucleon terms.
  A. Cieply´, et al., Phys. Rev. C 84 (2011) 045206.
  Friedman, Gal, NPA 899 (2013) 60.

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Data :

- K-p : SIDDHARTA (2011)
- K-d : no data
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Current data quality is not good enough to determine K-nucl. potential strength

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  Friedman, Gal, NPA 899 (2013) 60.

K-He atom 2p level shift

a recent theoretical calculation

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

	deep	shallow
Choosing the following two typical models : *[Pheno.] Mares, Friedman, Gal, NPA770(06)84* *[Chiral] Ramos, Oset, NPA671(00)481*	**Phenomenological** $V_{opt}(r=0)$ ~ - (180 + 73i) MeV	**Chiral** $V_{opt}(r=0)$ ~ - (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**

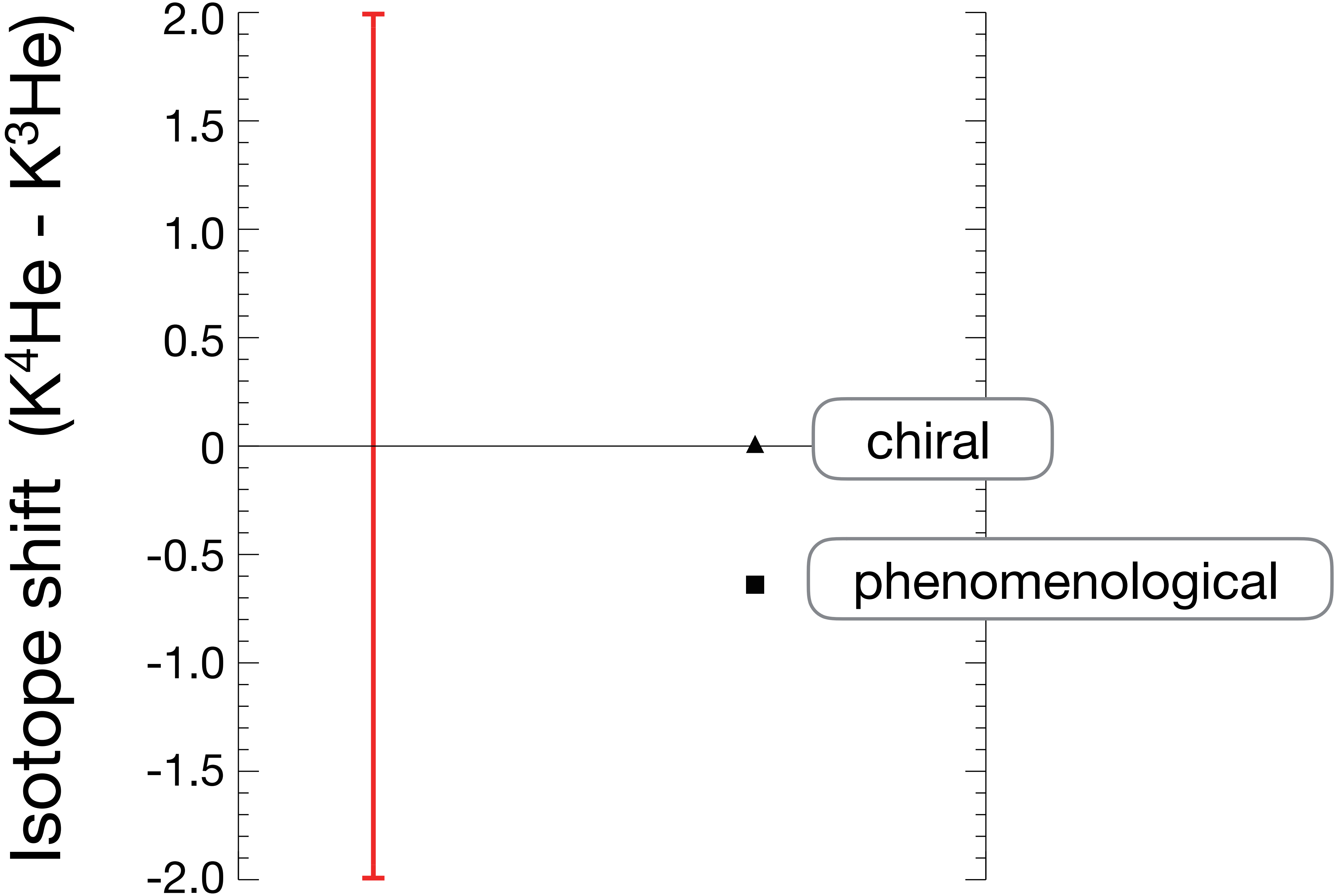
preliminary

Dominant systematic error (~0.15 eV)
due to kaon-mass uncertainty will be cancelled.

Width : 2 ~ 4 eV

Experimental accuracy

Past experiments : ± 2 eV



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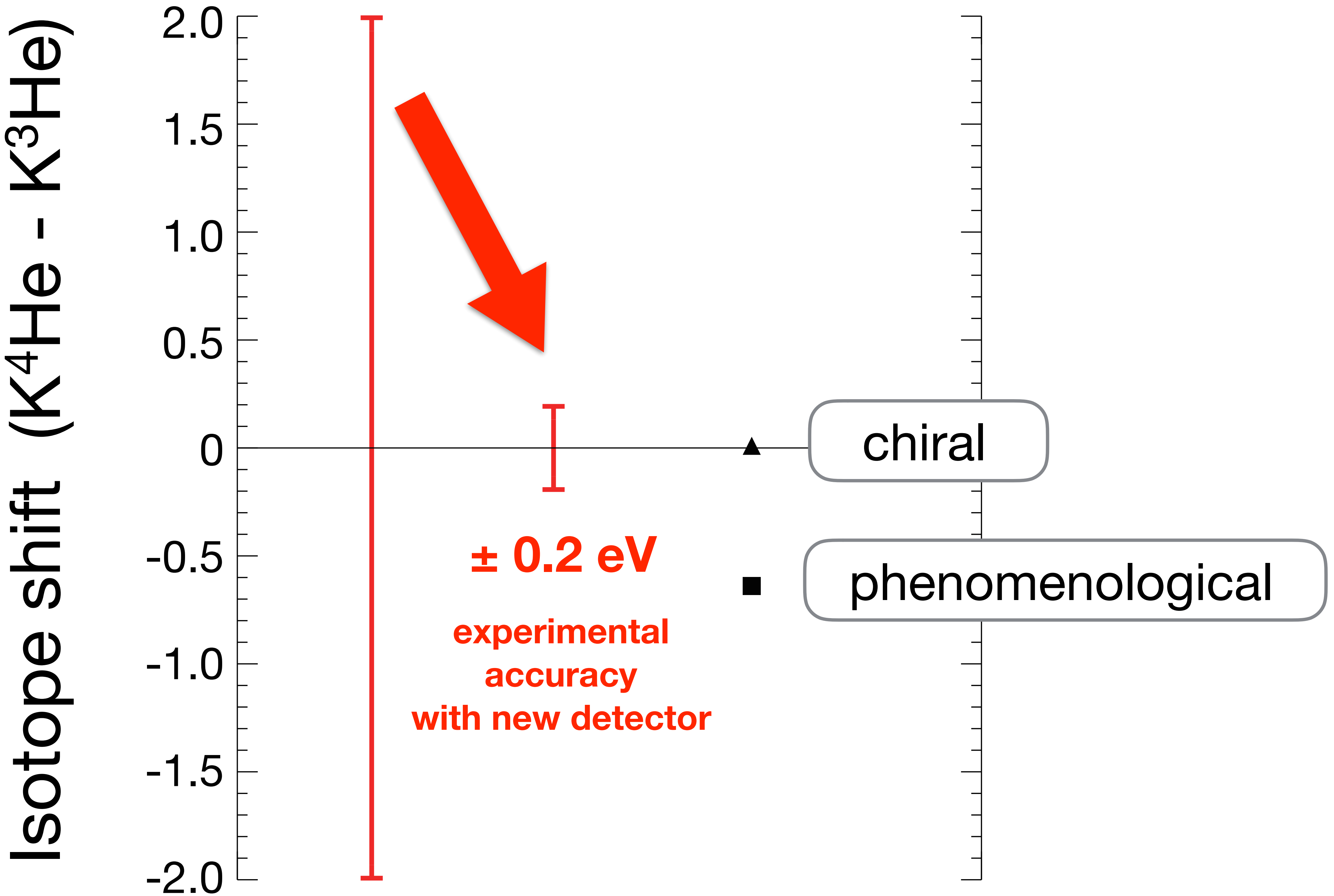
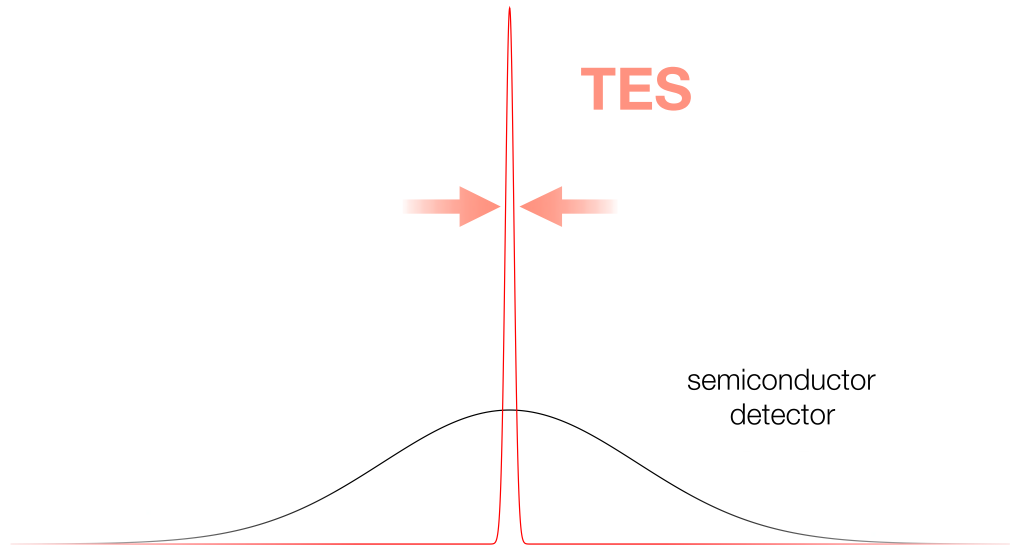
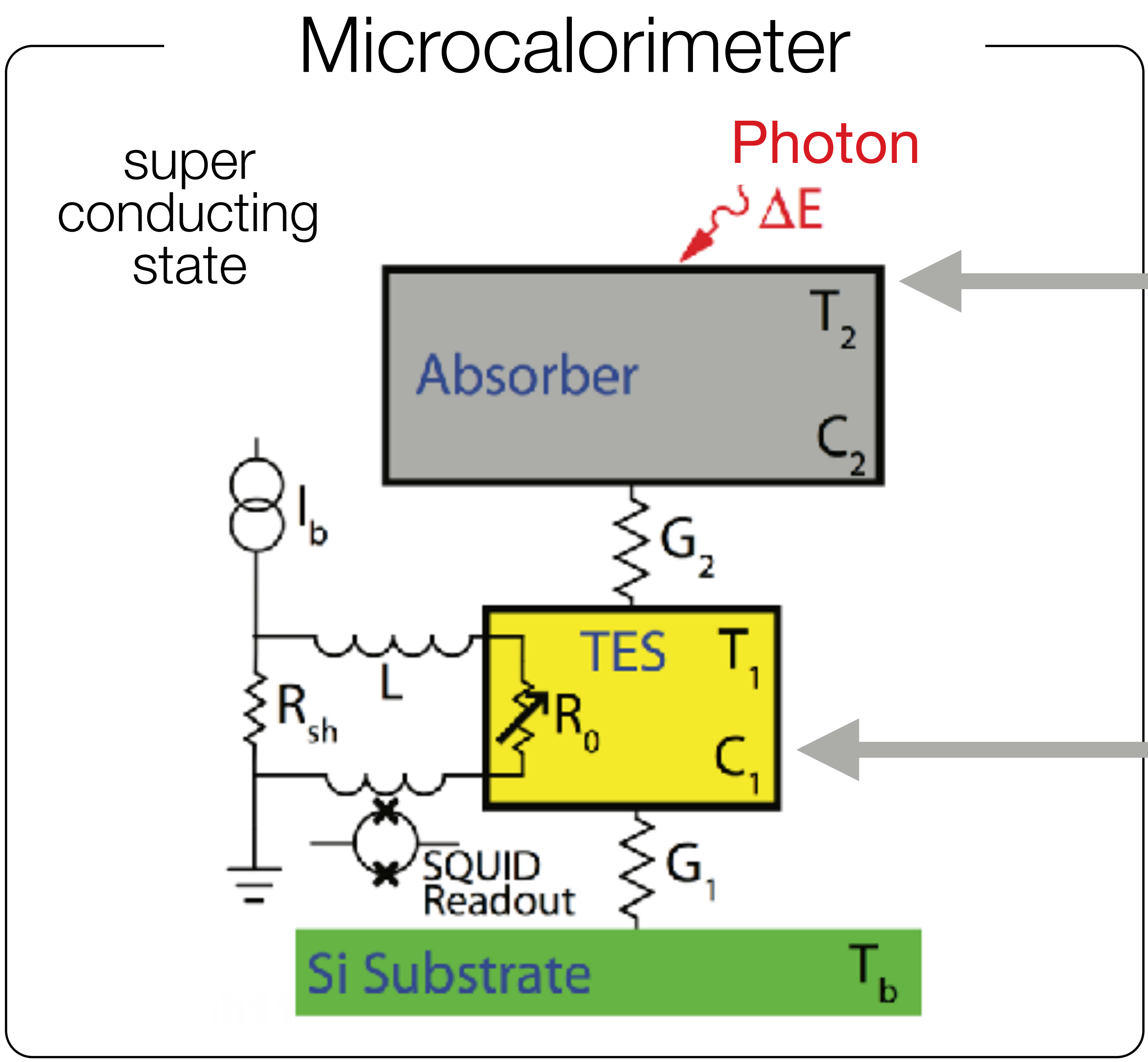


2. X-ray detector : TES



TES microcalorimeter



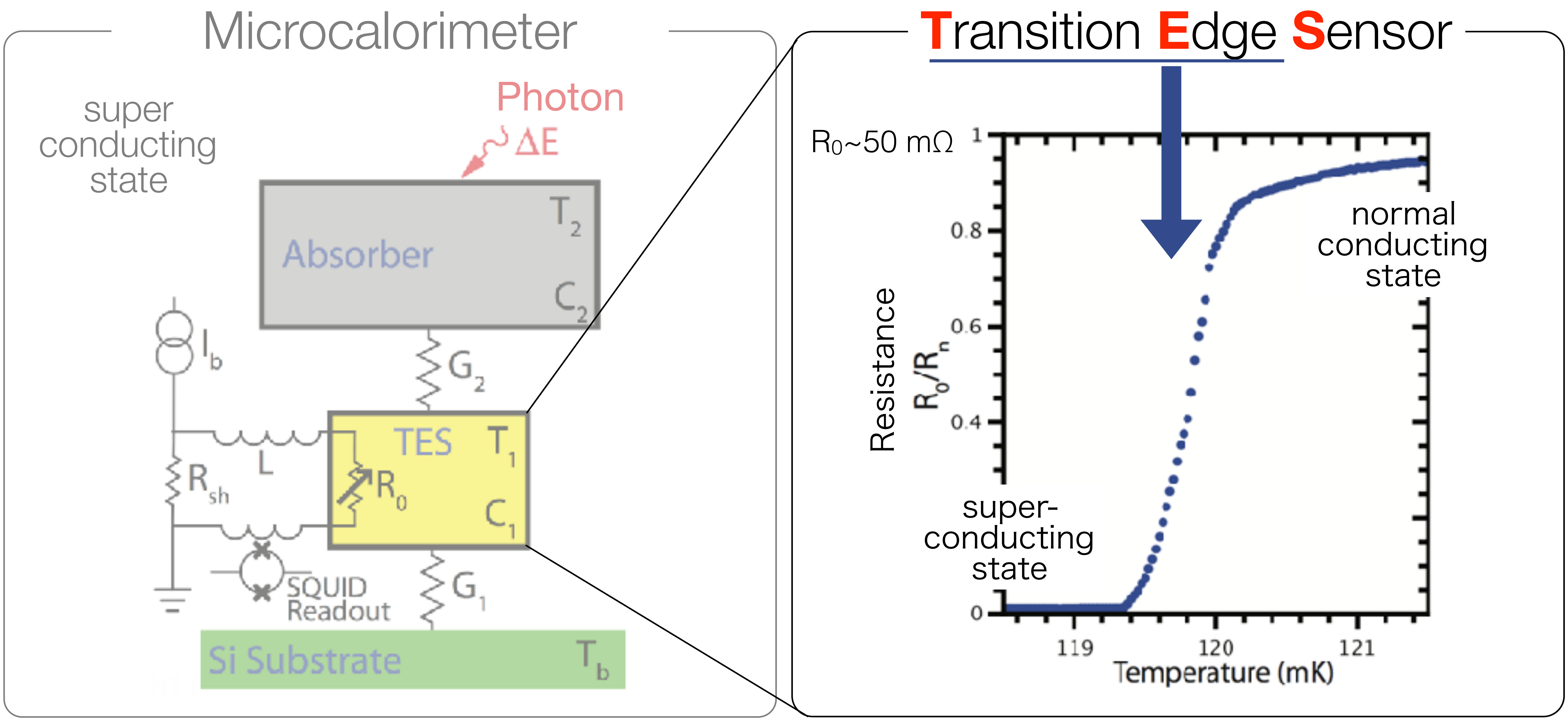
1. Photon absorbed

2. Energy ΔE -> Phonon

3. Tiny temperature rise is measured by a highly sensitive temperature sensor **TES**

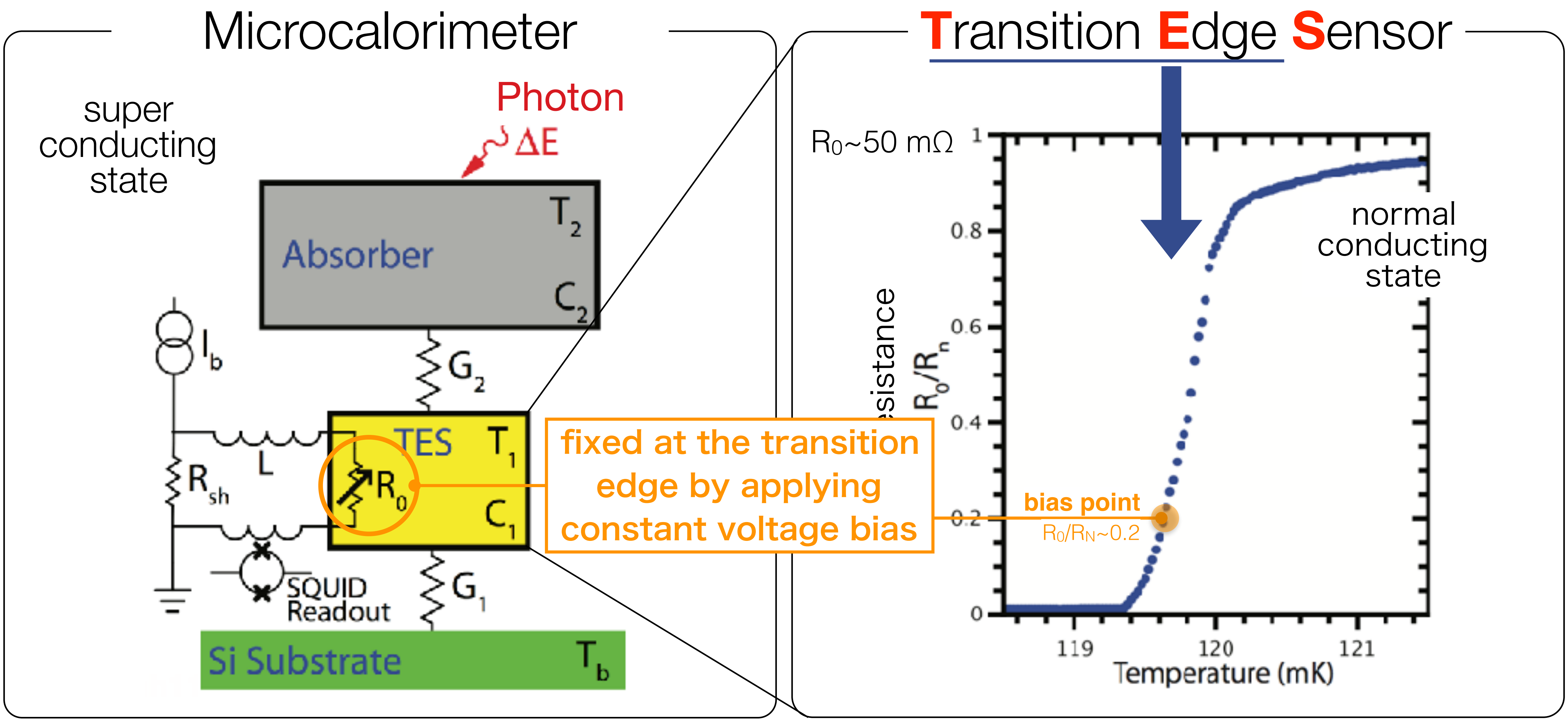
Reference : Bennet et al., Rev. Sci. Instrum. 83, 093113 (2012)

TES microcalorimeter



Reference : Bennet et al., Rev. Sci. Instrum. 83, 093113 (2012)

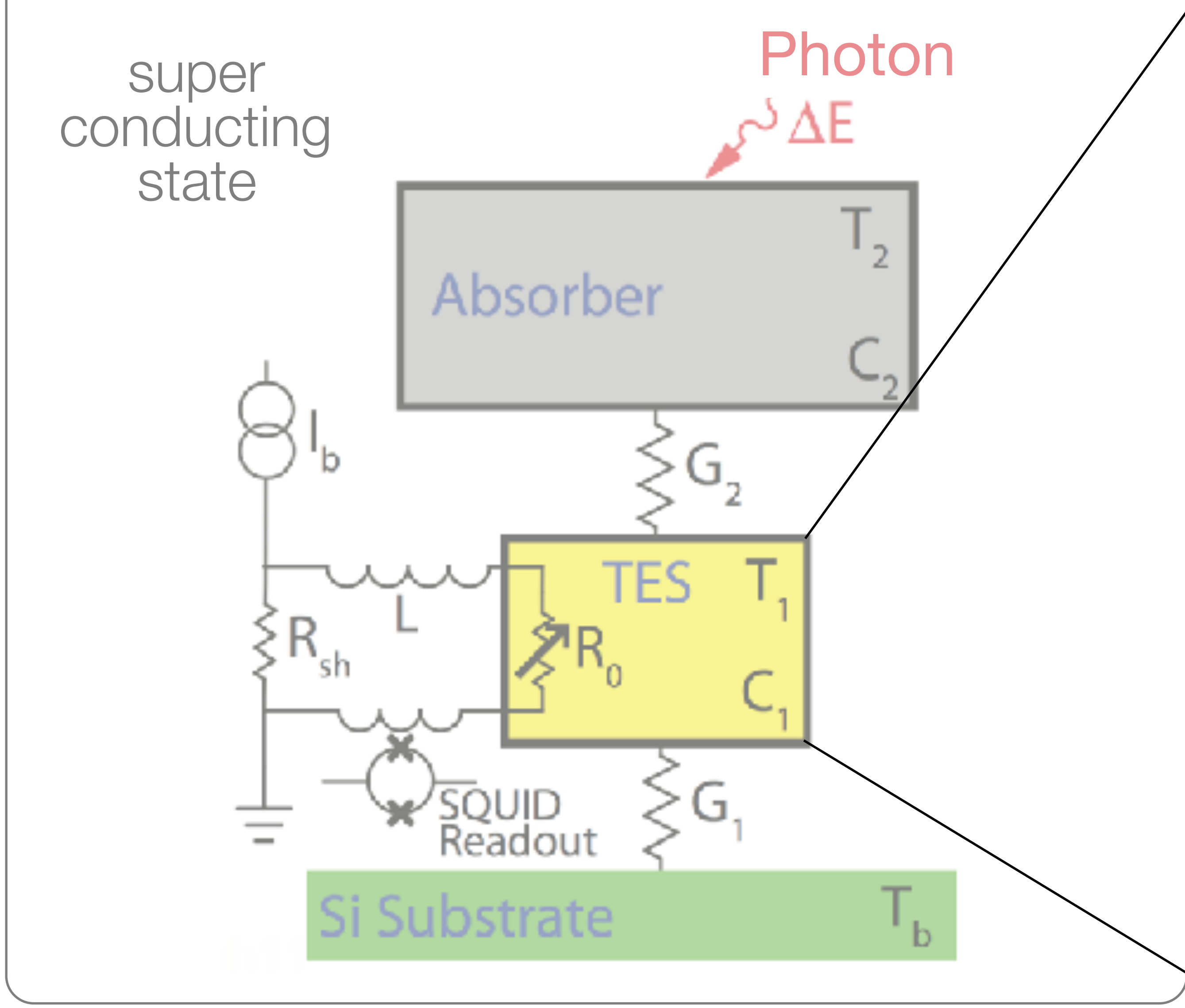
TES microcalorimeter



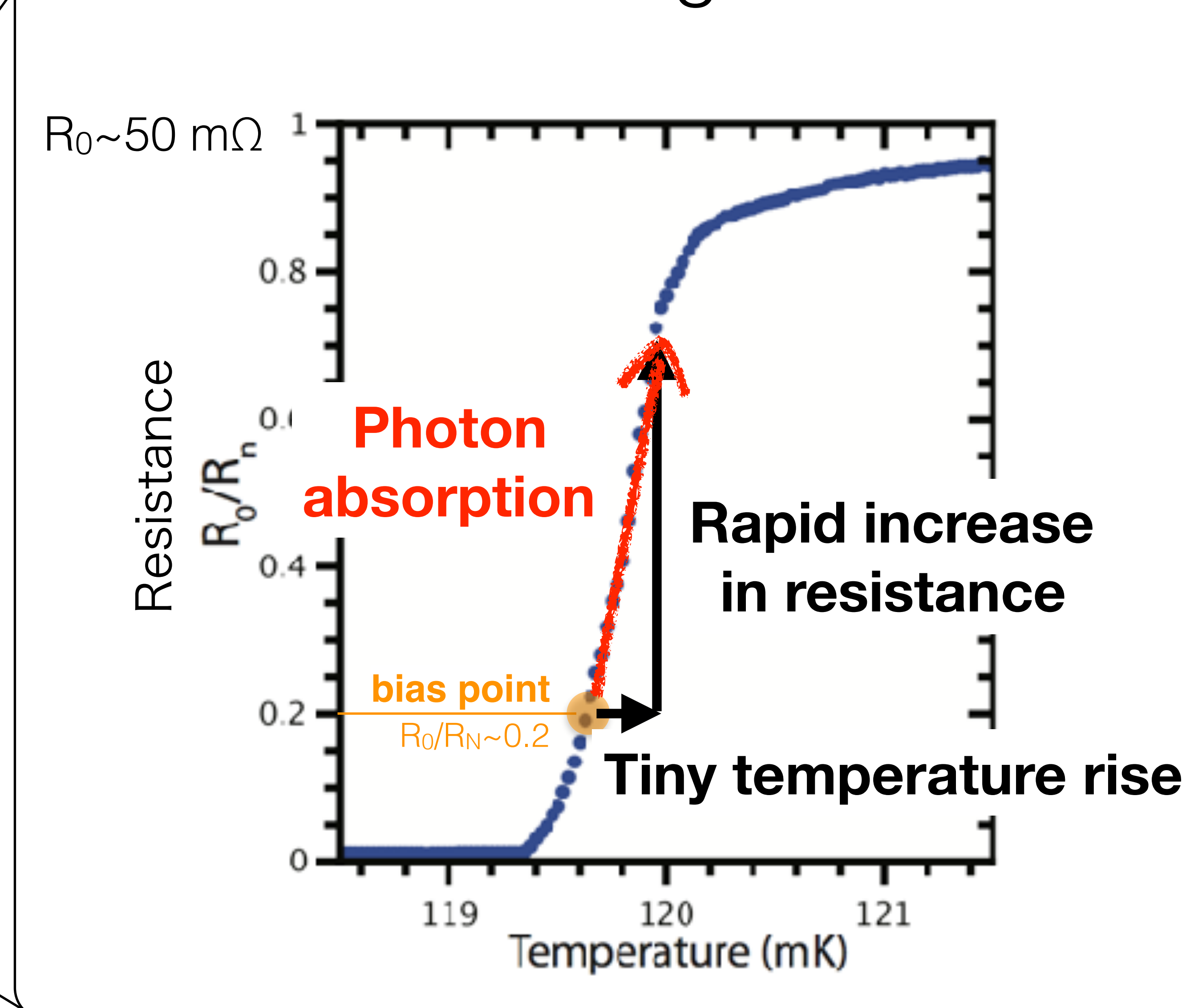
Reference : Bennet et al., Rev. Sci. Instrum. 83, 093113 (2012)

TES microcalorimeter

Microcalorimeter



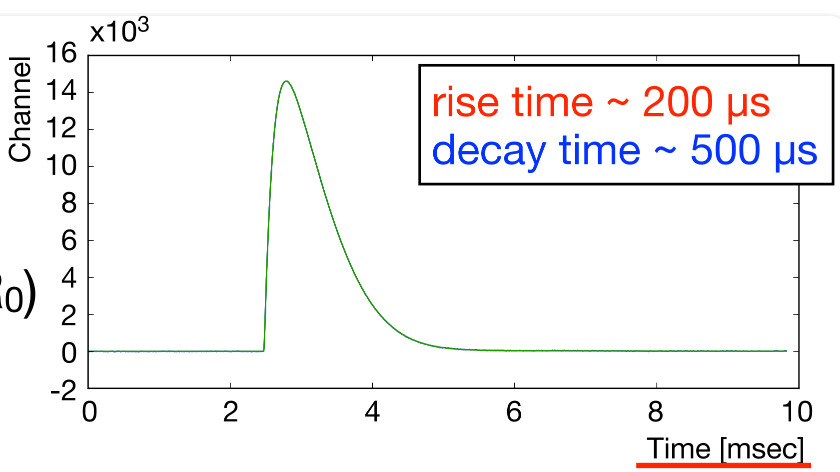
Transition Edge Sensor



Typical pulse

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

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



high energy resolution (ΔE / E ~ 10^{-3})

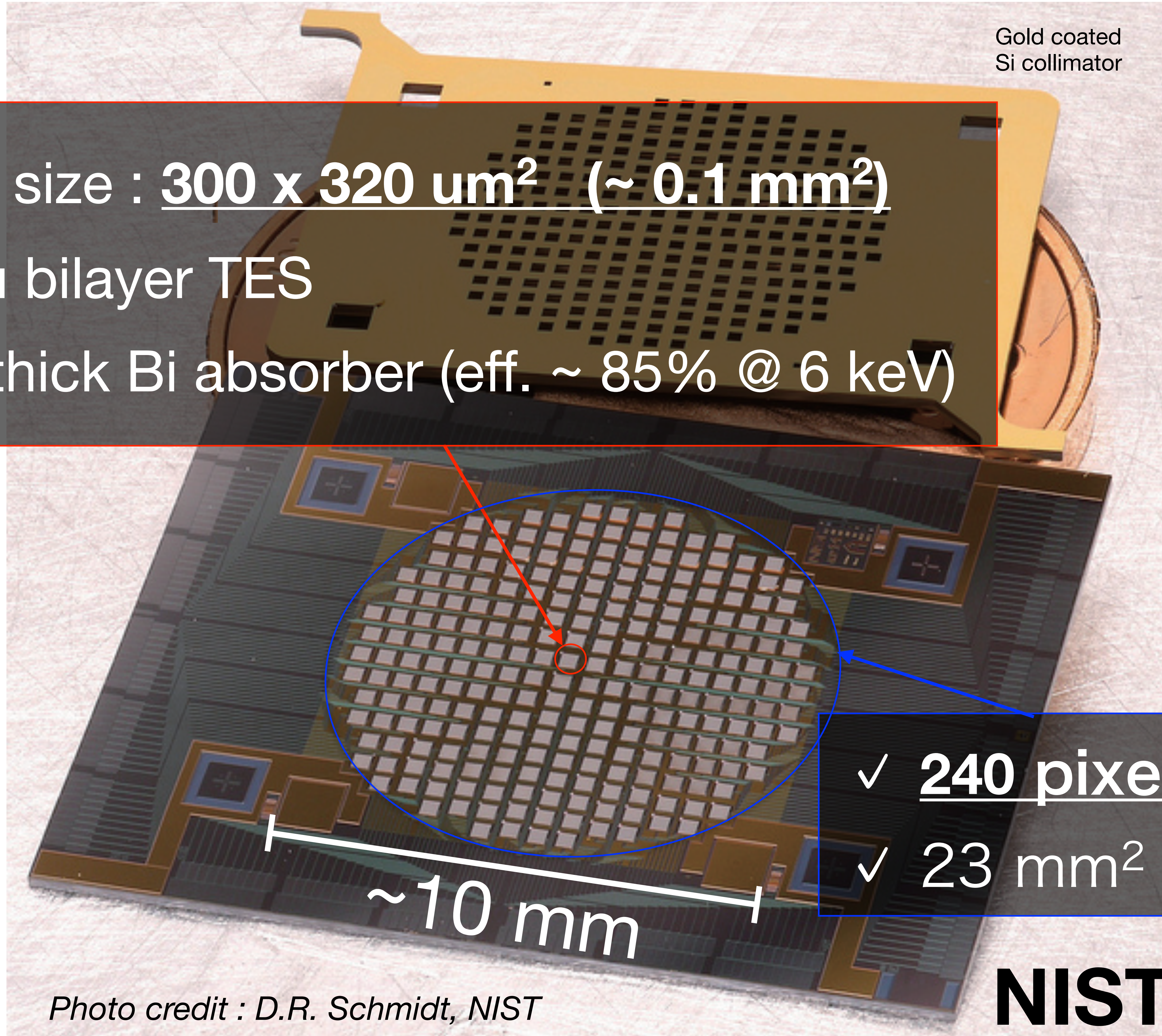
TES : ΔE (FWHM) ~ 5 eV @ 6 keV X-ray

(ref. SDD : ΔE (FWHM) ~ 150 eV @ 6 keV)

Reference : Bennet et al., Rev. Sci. Instrum. 83, 093113 (2012)

multi-pixel TES

- ✓1 pixel size : **300 x 320 um^2 (~ 0.1 mm^2)**
- ✓Mo-Cu bilayer TES
- ✓4-μm-thick Bi absorber (eff. ~ 85% @ 6 keV)



- ✓ **240 pixels**
- ✓ 23 mm^2 eff. area

Photo credit : D.R. Schmidt, NIST

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**
2015	stage-2 approval by J-PARC PAC as "E62 experiment"
2016	**Commissioning run (K- beam) @ J-PARC**
2017	ready for J-PARC E62 physics run

EXA2014
just before PSI

Now in EXA2017

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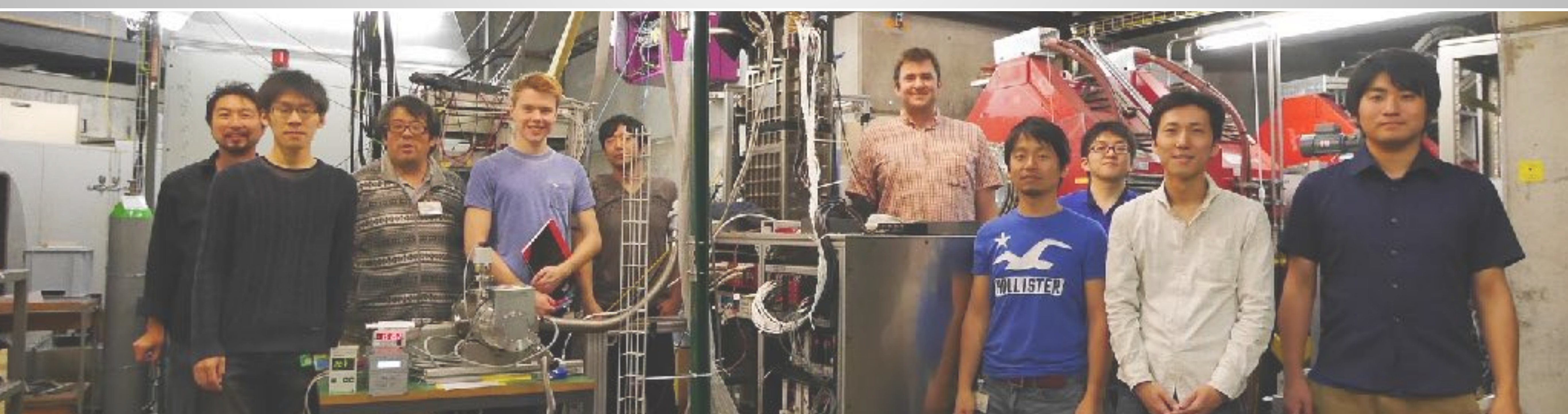
EXA2014 just before PSI

Now in EXA2017

Two performance evaluations

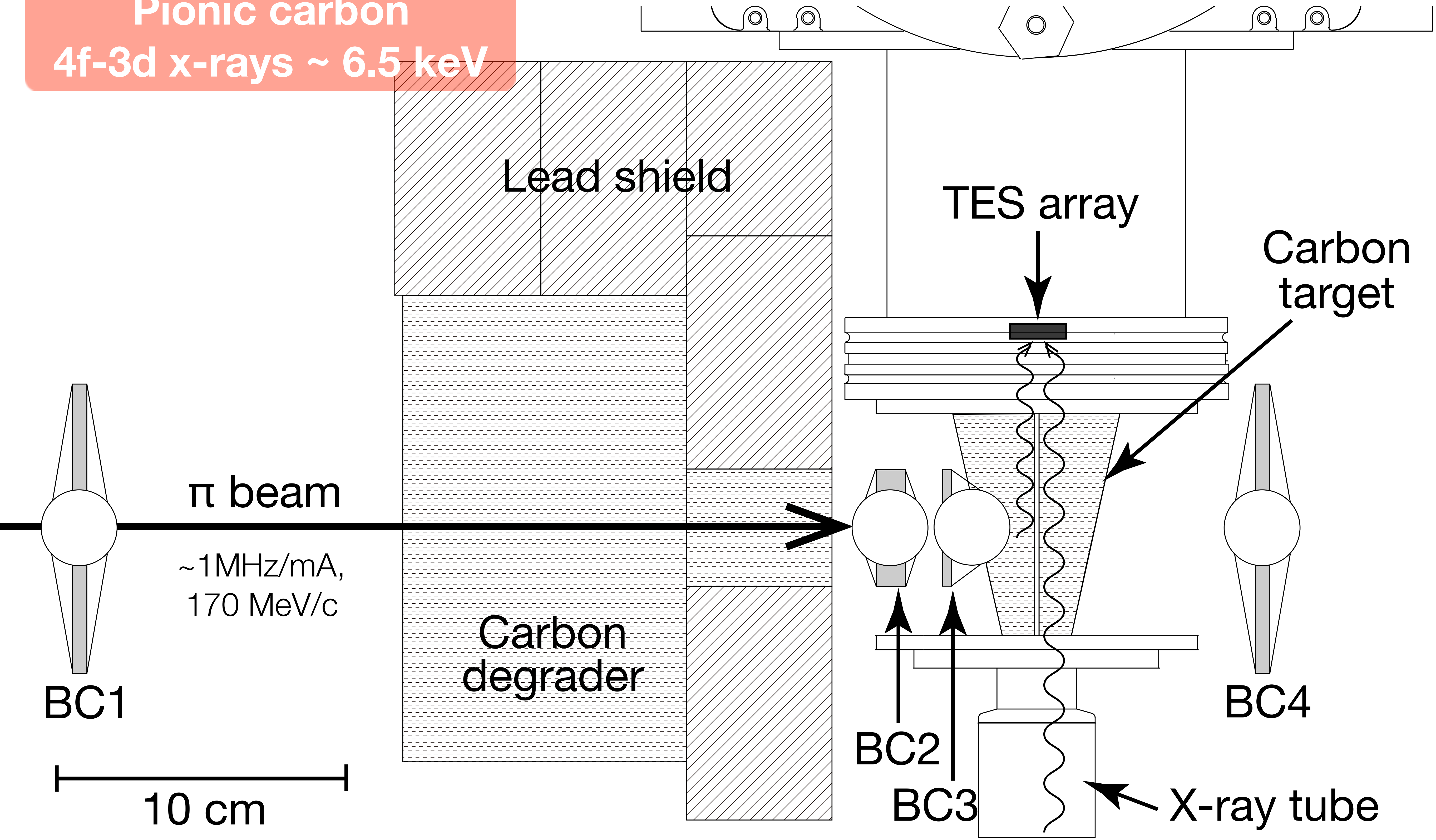
	①	②	
location	PSI (Switzerland)	J-PARC (Japan)	
beam line	πM1	K1.8BR	
particle	π-	K-	
purity	~ 0.4	~ 0.3	
momentum	170 MeV/c	900 MeV/c	
intensity (sum of all particles)	1.4 ~ 2.8 x 10^6 cps	8 x 10^5 / spill	
hadronic atom x-rays	π ^{12}C 4-3 (6.4 keV)	K-^3He 3-2 (6.2 keV) K-^4He 3-2 (6.4 keV)	to be measured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

3. π^- beam @ PSI



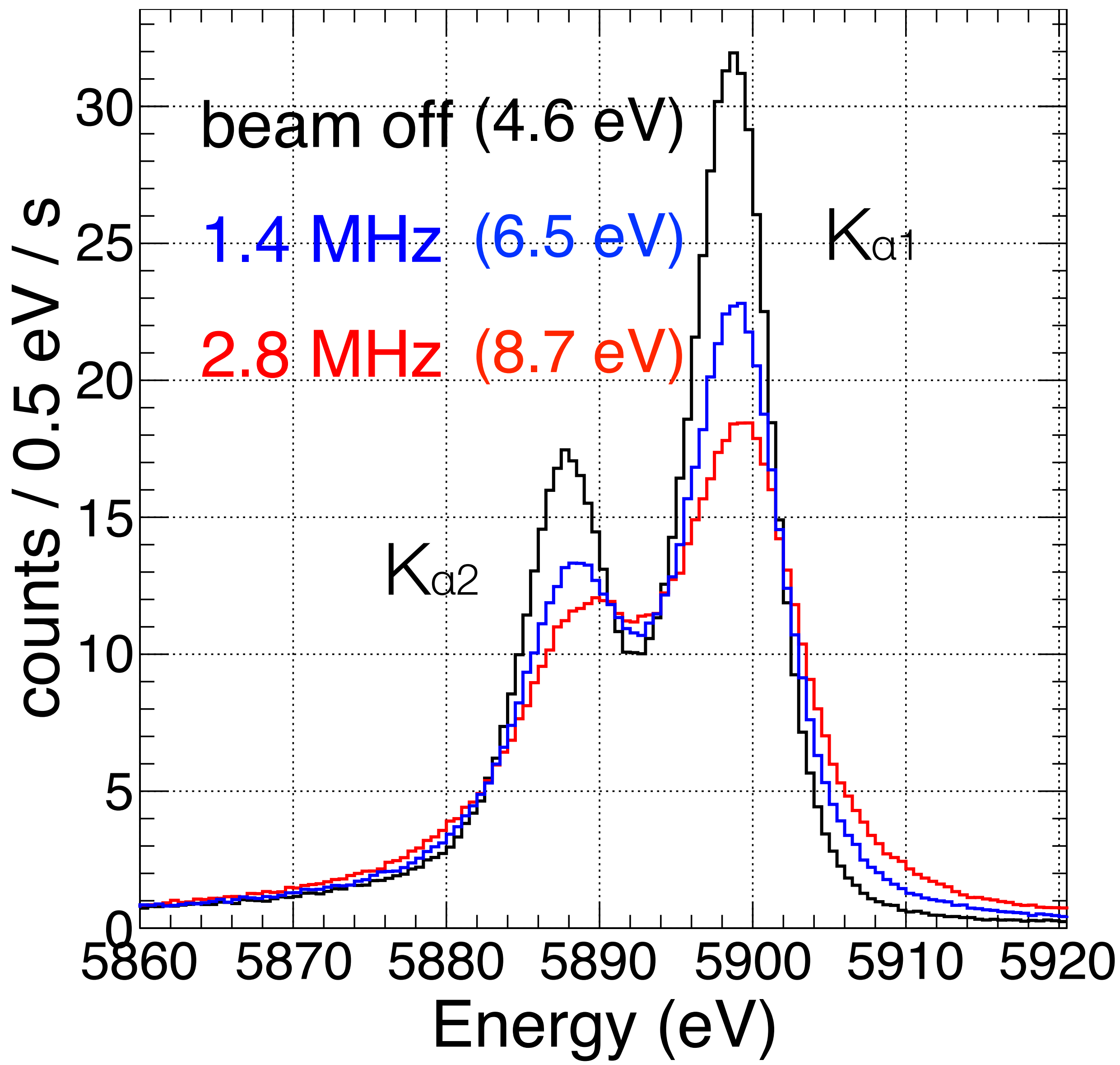
π atom expt @ PSI πM1 beamline

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



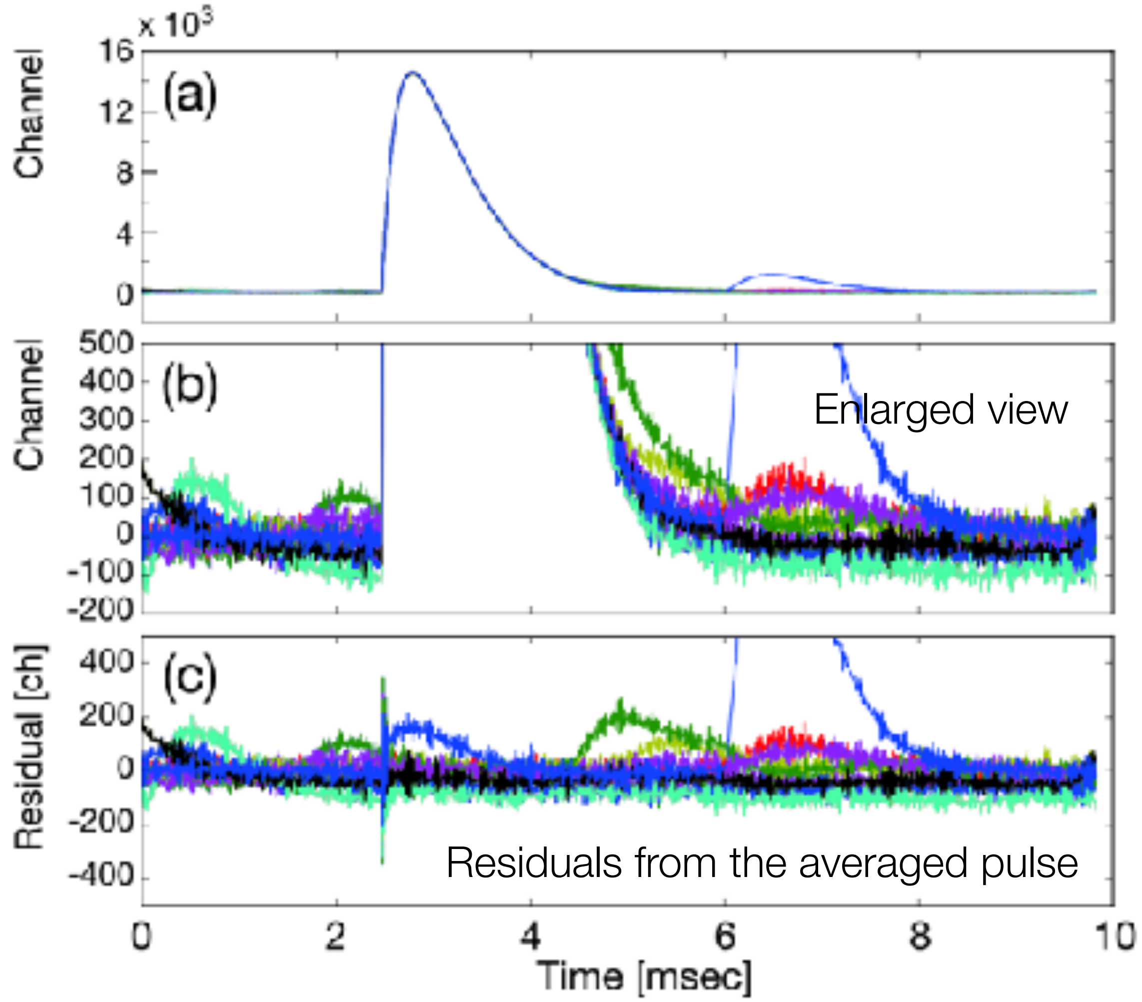
In-beam performance

Mn Kα peak



energy resolution getting worse
with higher beam rate

A typical thermal crosstalk event

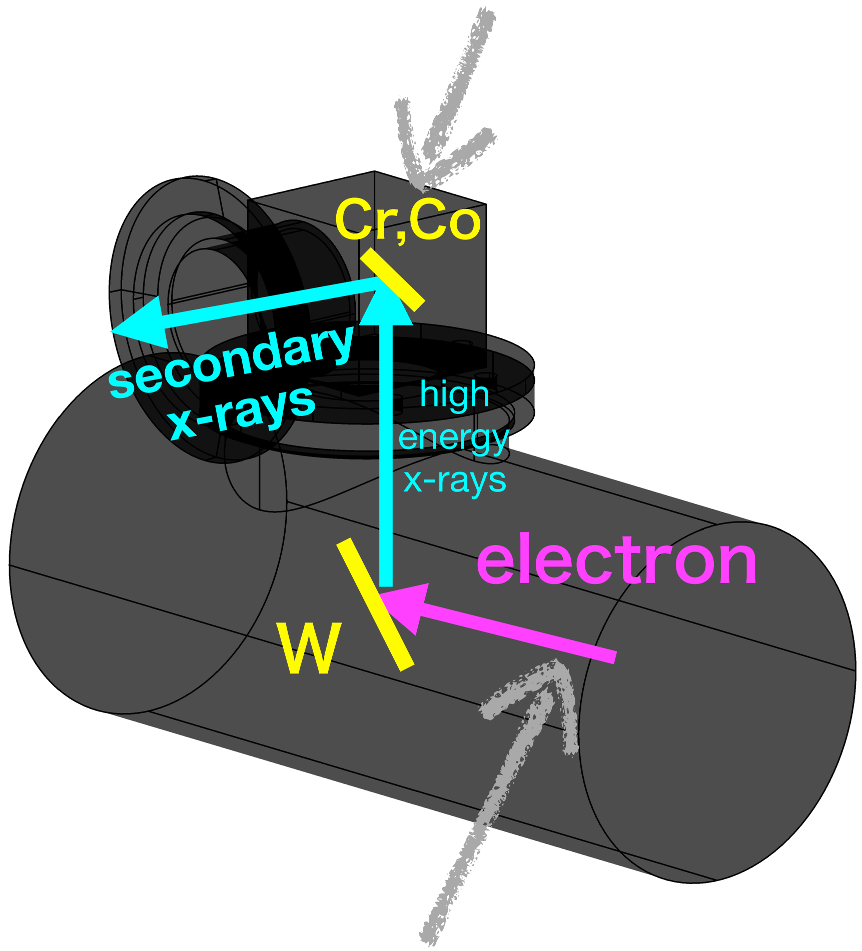


Energy deposit of charged particles
in Si frame of TES chip
results in thermal-crosstalk pulses
which deteriorates the energy resolution

Energy calibration with X-ray tube

X-ray tube

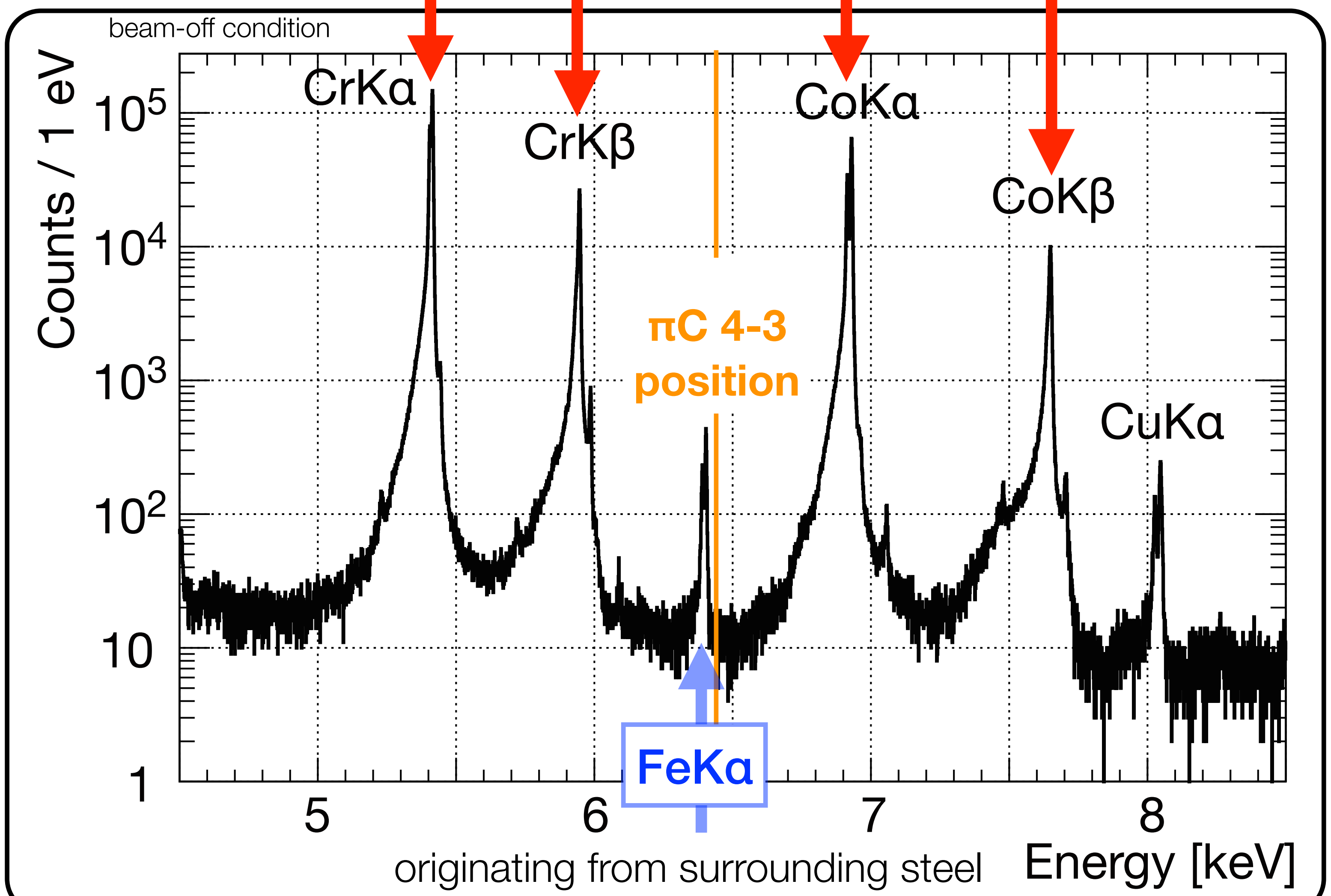
pure metals
as secondary target



electron gun

need high intensity to calibrate 240 pixels individually for every 2 hours

Used high-intensity **4 lines**

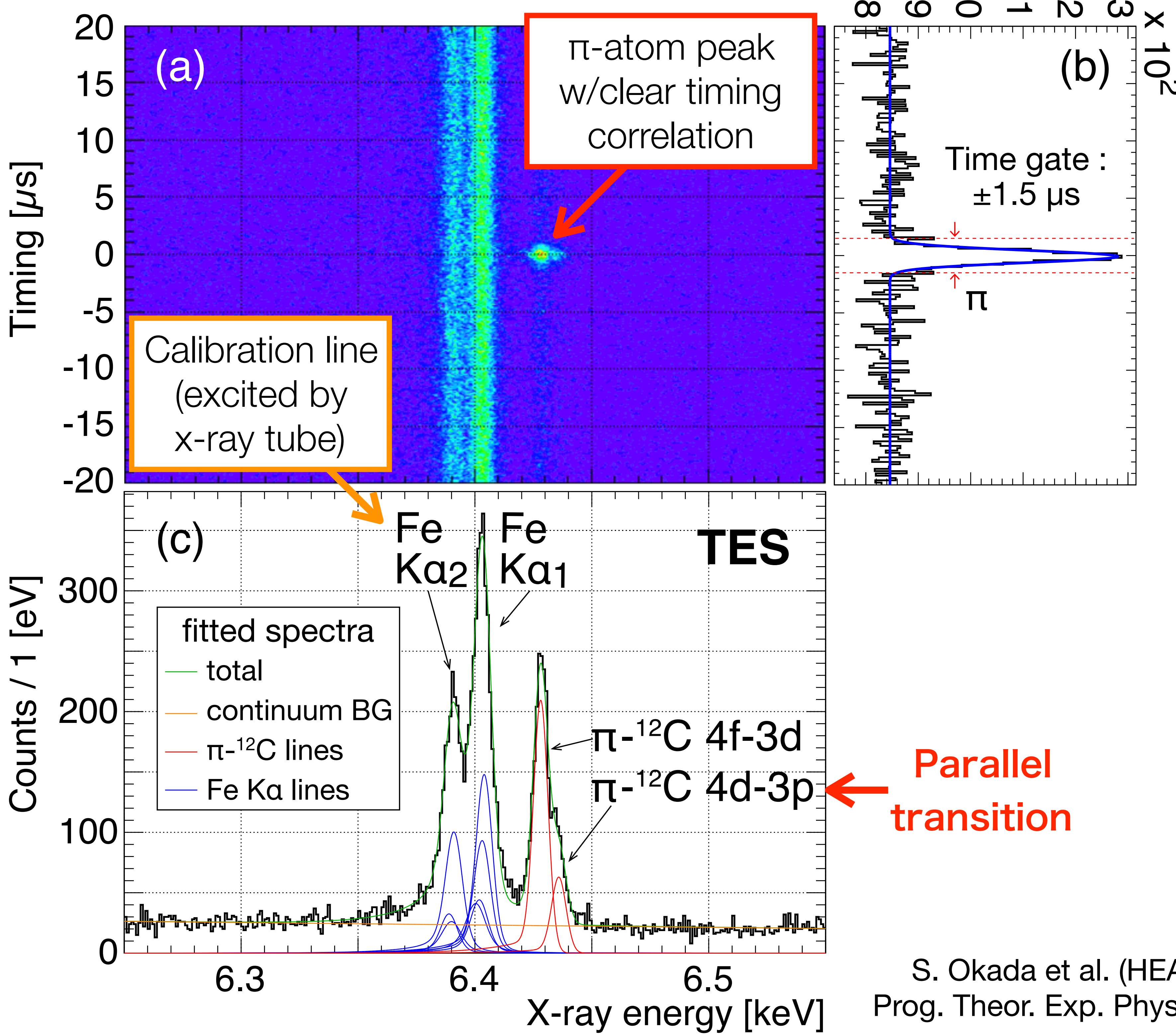


originating from surrounding steel

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

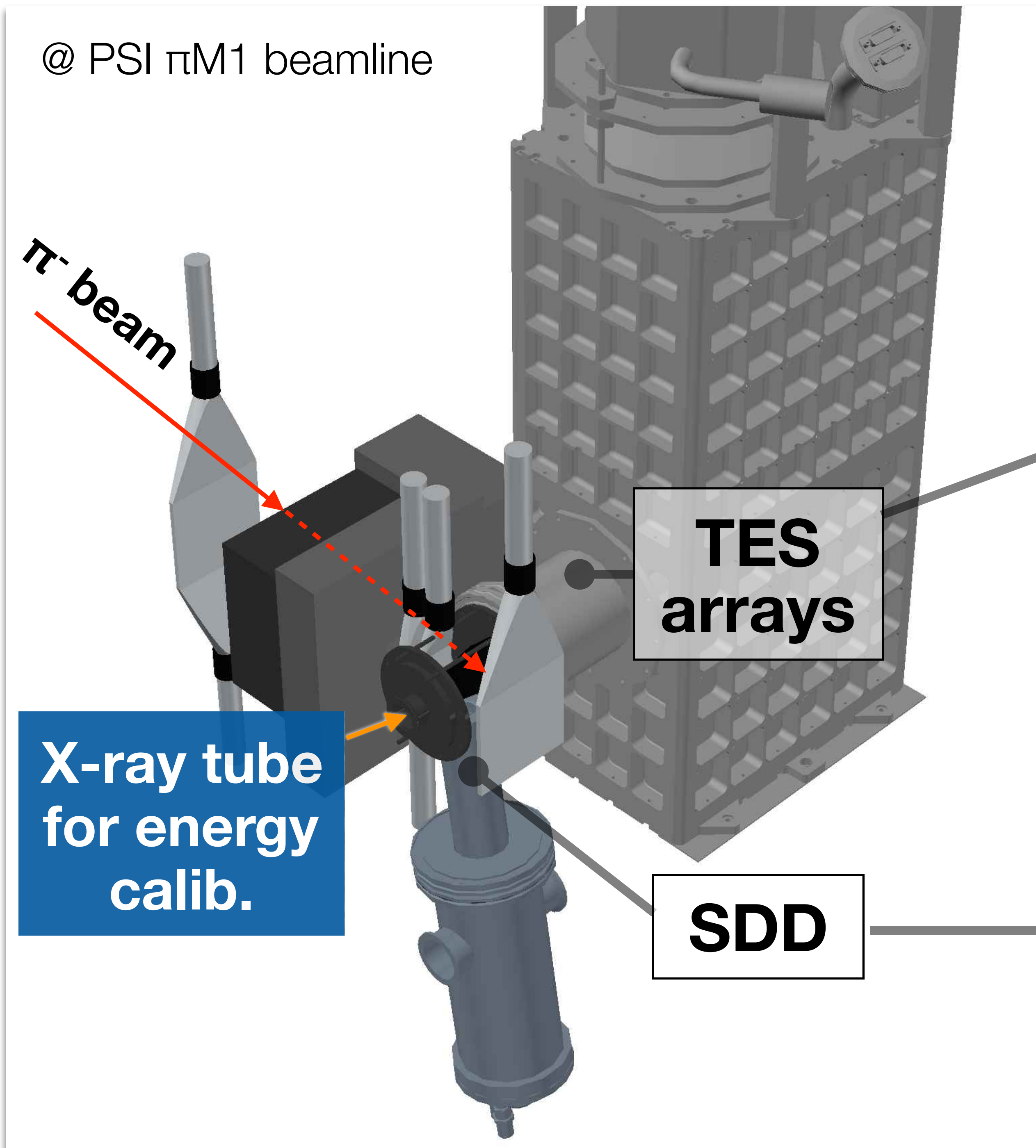
Result

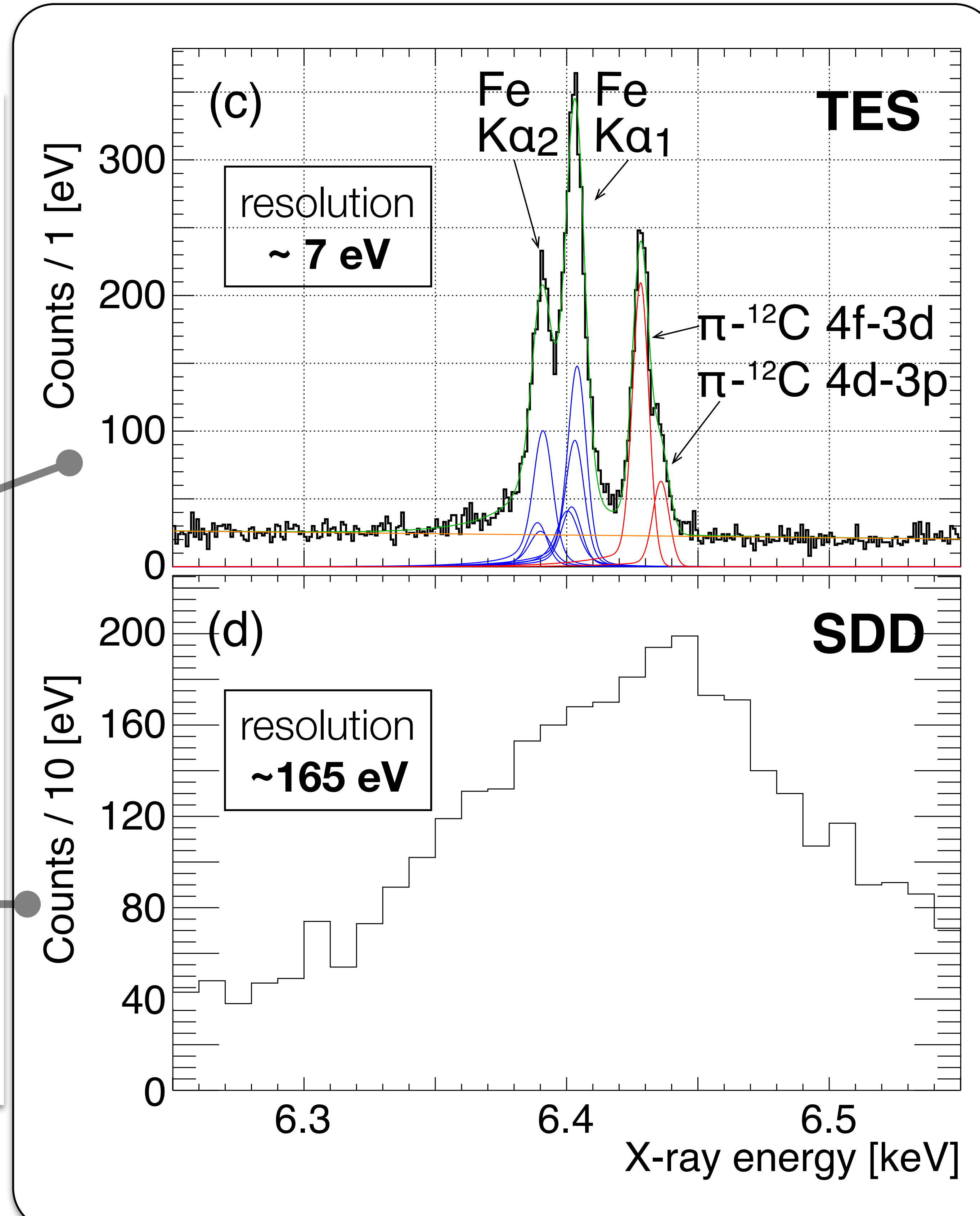
TES DAQ : self trig.
(sending beam trig. to TES DAQ)



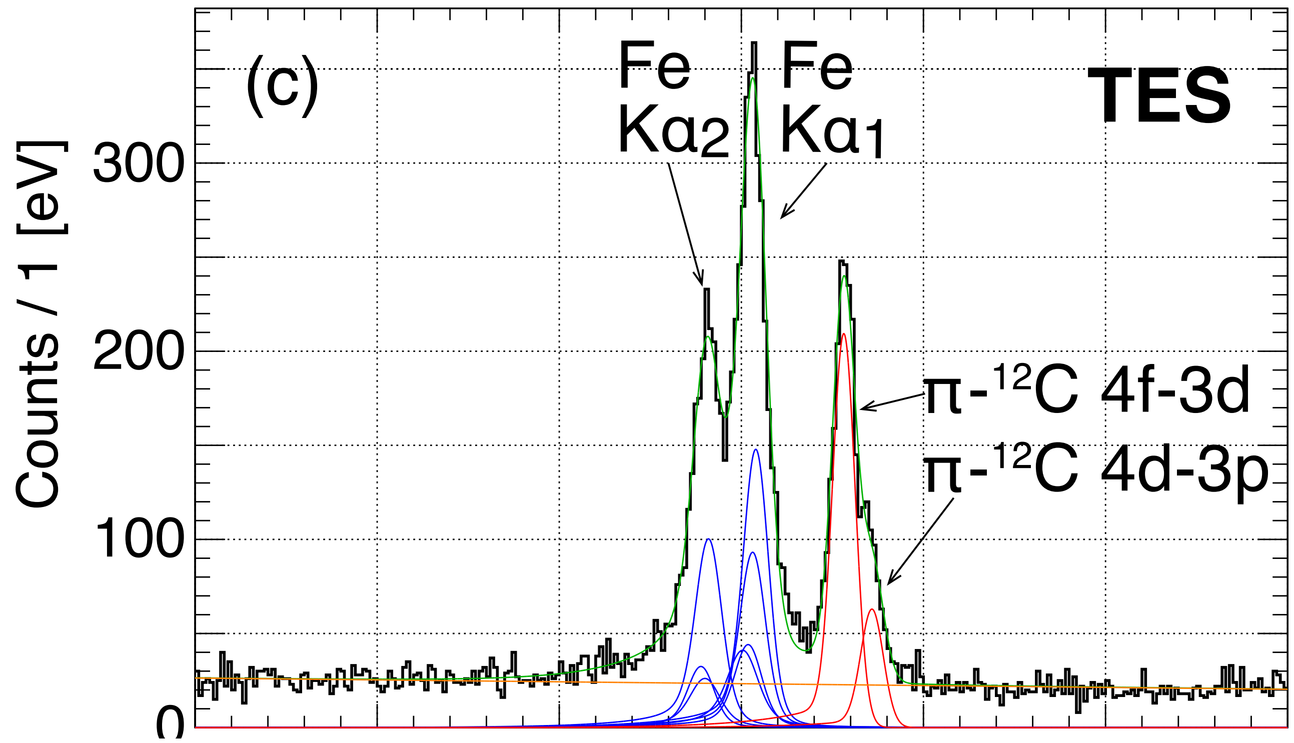
S. Okada et al. (HEATES collaboration), Prog. Theor. Exp. Phys. 2016, 091D01 (2016)

Comparison with SDD spectrum





Fit results



Fe $K_{\alpha 11}$ line

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

⇒ good agreement with reference val.

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

Confirmation of energy calib.

Pionic atom lines

$$E(4f \to 3d) = 6428.39 \pm 0.13(\text{stat.}) \pm 0.09(\text{syst.})\ \text{eV}$$

$$E(4d \to 3p) = 6435.76 \pm 0.30(\text{stat.})^{+0.11}_{-0.07}(\text{syst.})\ \text{eV}$$

$$I(4d \to 3p)/I(4f \to 3d) = 0.30 \pm 0.03(\text{stat.}) \pm 0.02(\text{syst.})$$

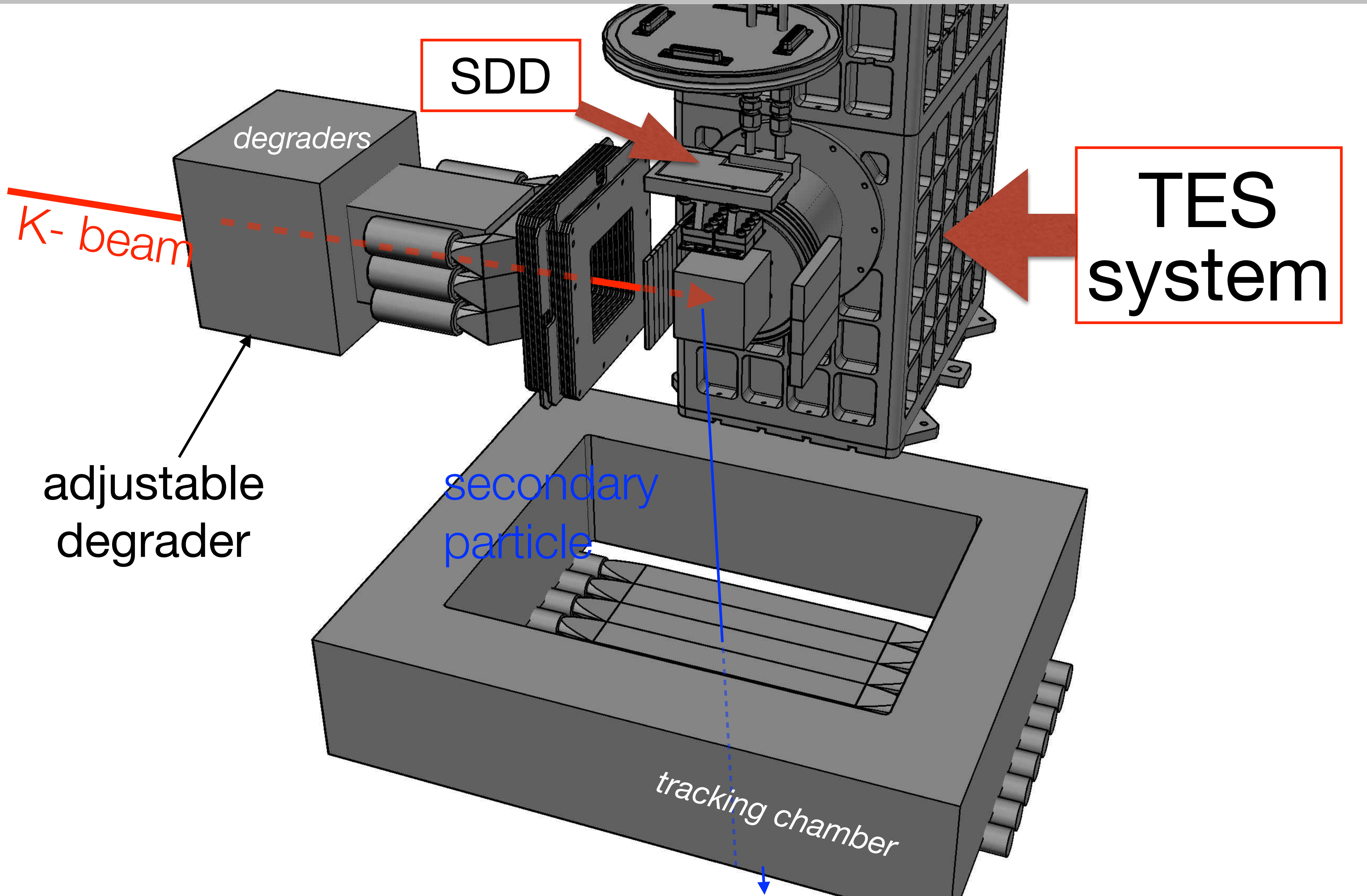
⇒ comparison with EM calc.

- ✓ e^- population : **favor two 1s e^-** in K-shell — comparing e^- screening calc. (T. Koike)
- ✓ Energy shift of measured parallel-transition is **consistent** with strong-int effect assessed via **Seki-Matsutani potential**

4. K^- beam @ J-PARC

4-days beamtime
in June 2016

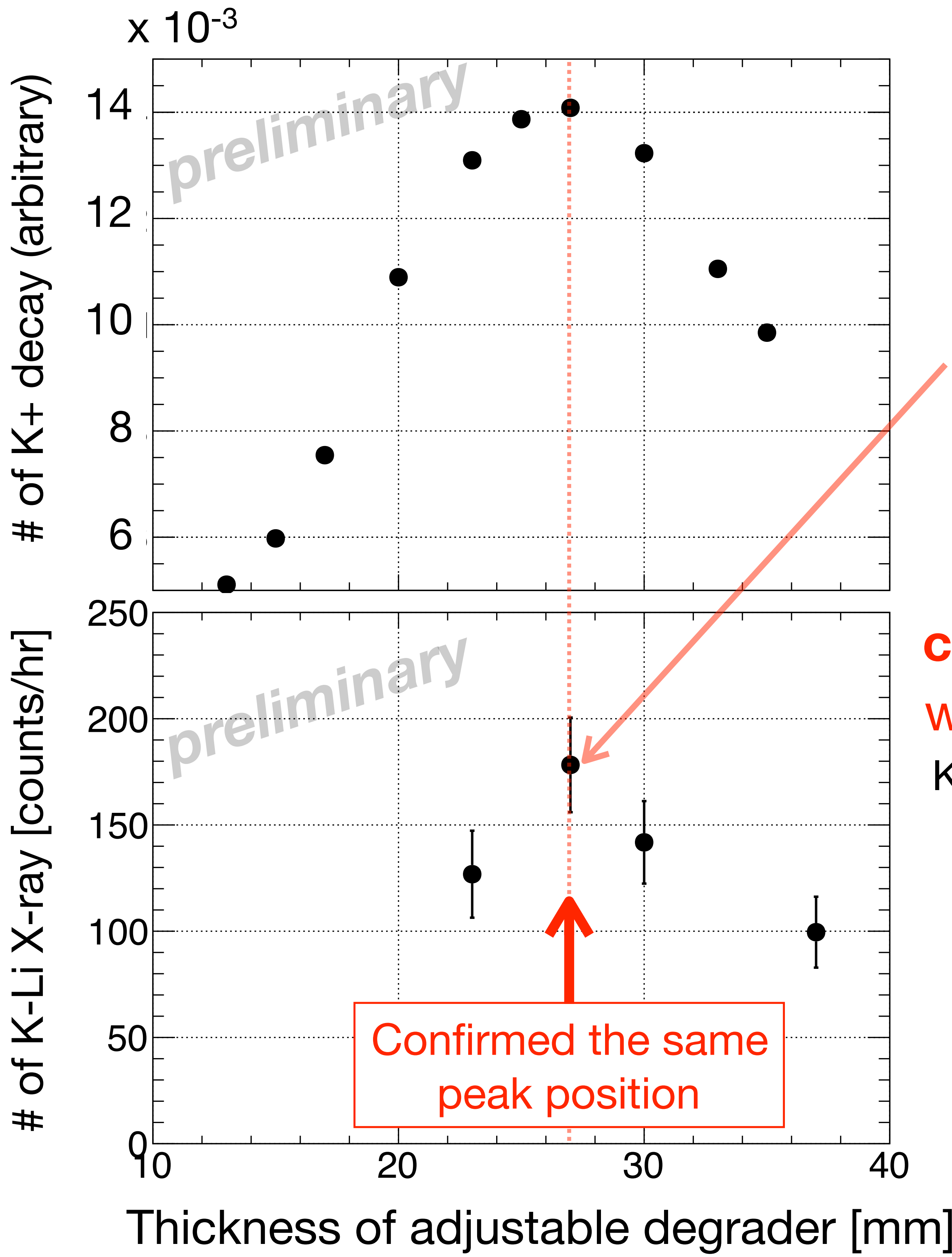
Kaon-stop tuning setup



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)

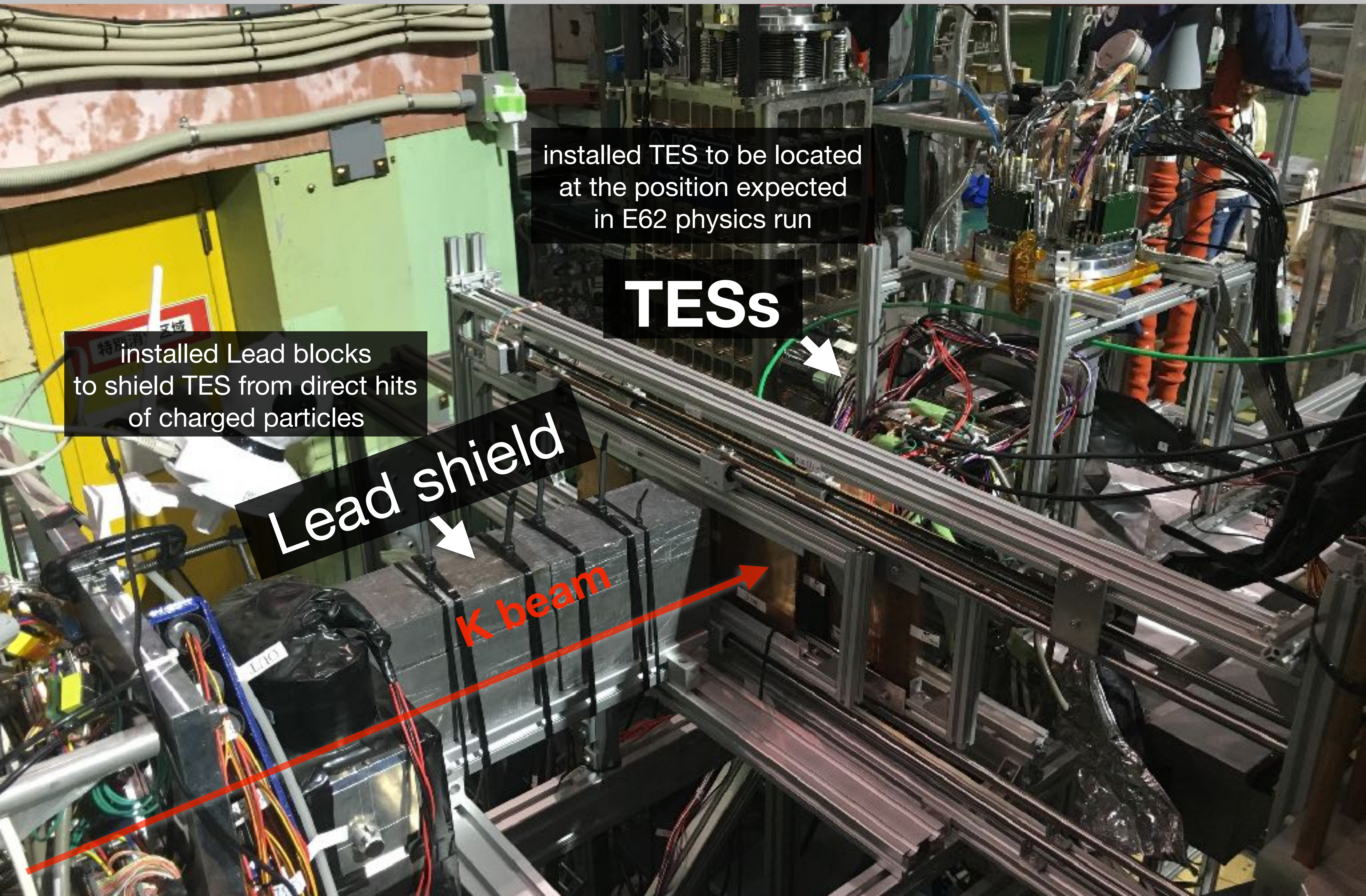
consistent with G4 sim

within error of ref. value:

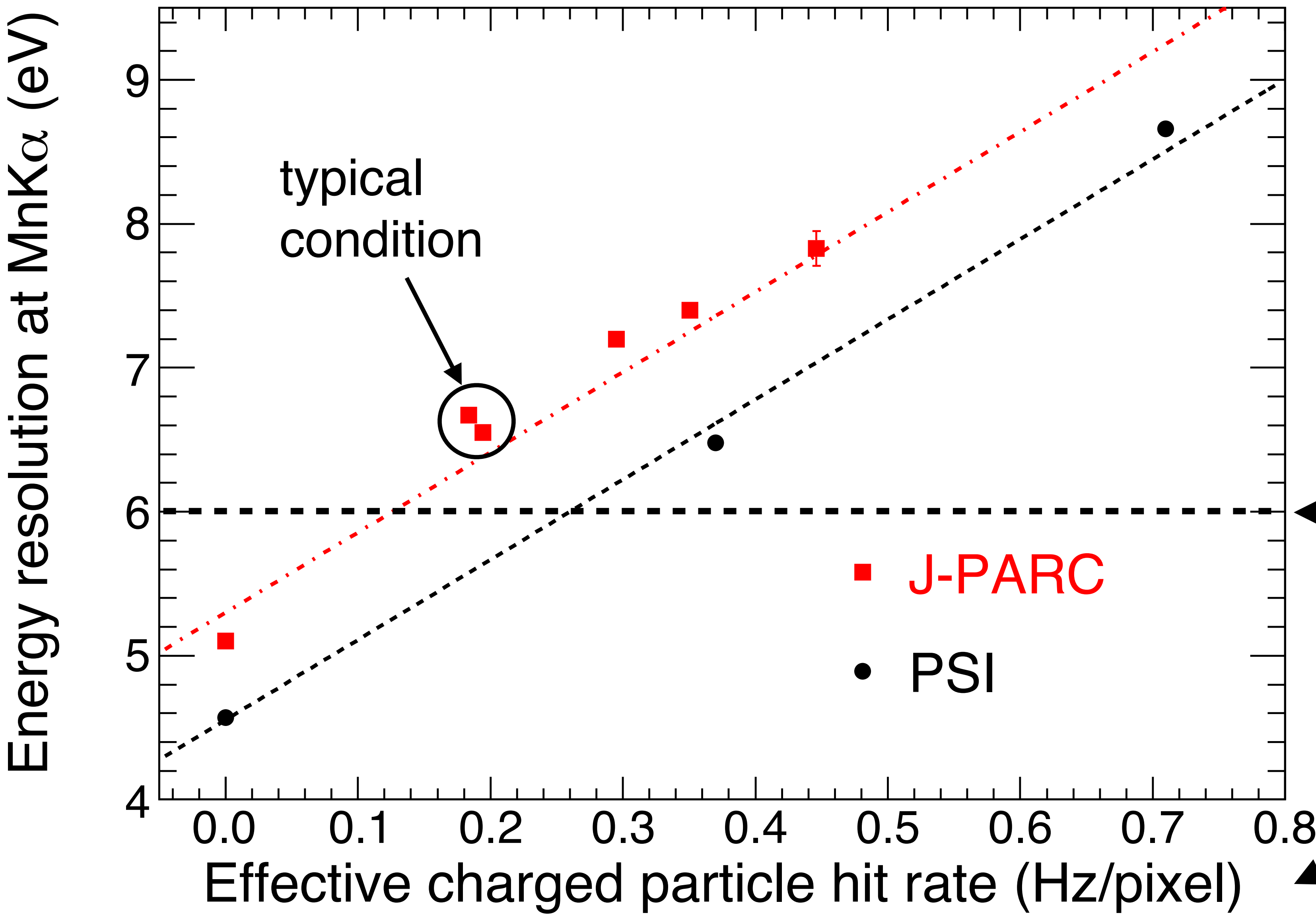
K-Li yield = 15 ± 3 % / stop K [PRA 9 (1974) 2282]

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

Setup from upstream



Energy resolution vs. charged-particle hit rate



resolution proportional to particle hit rate

our goal: < 6 eV

difference between beam-on and beam-off TES trigger rates

✓ Similar correlation in the two different beams

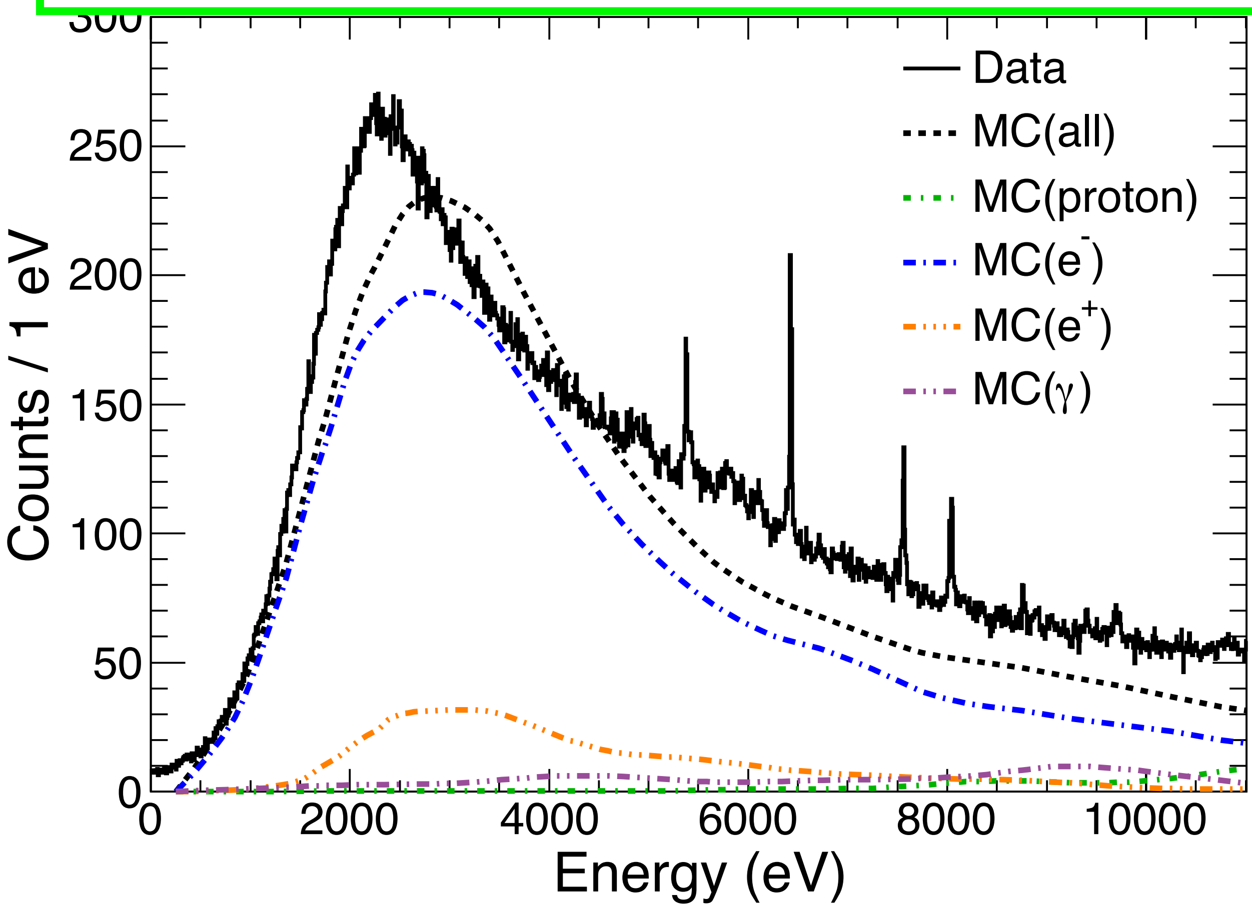
✓ **Promising to achieve our goal at J-PARC**

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

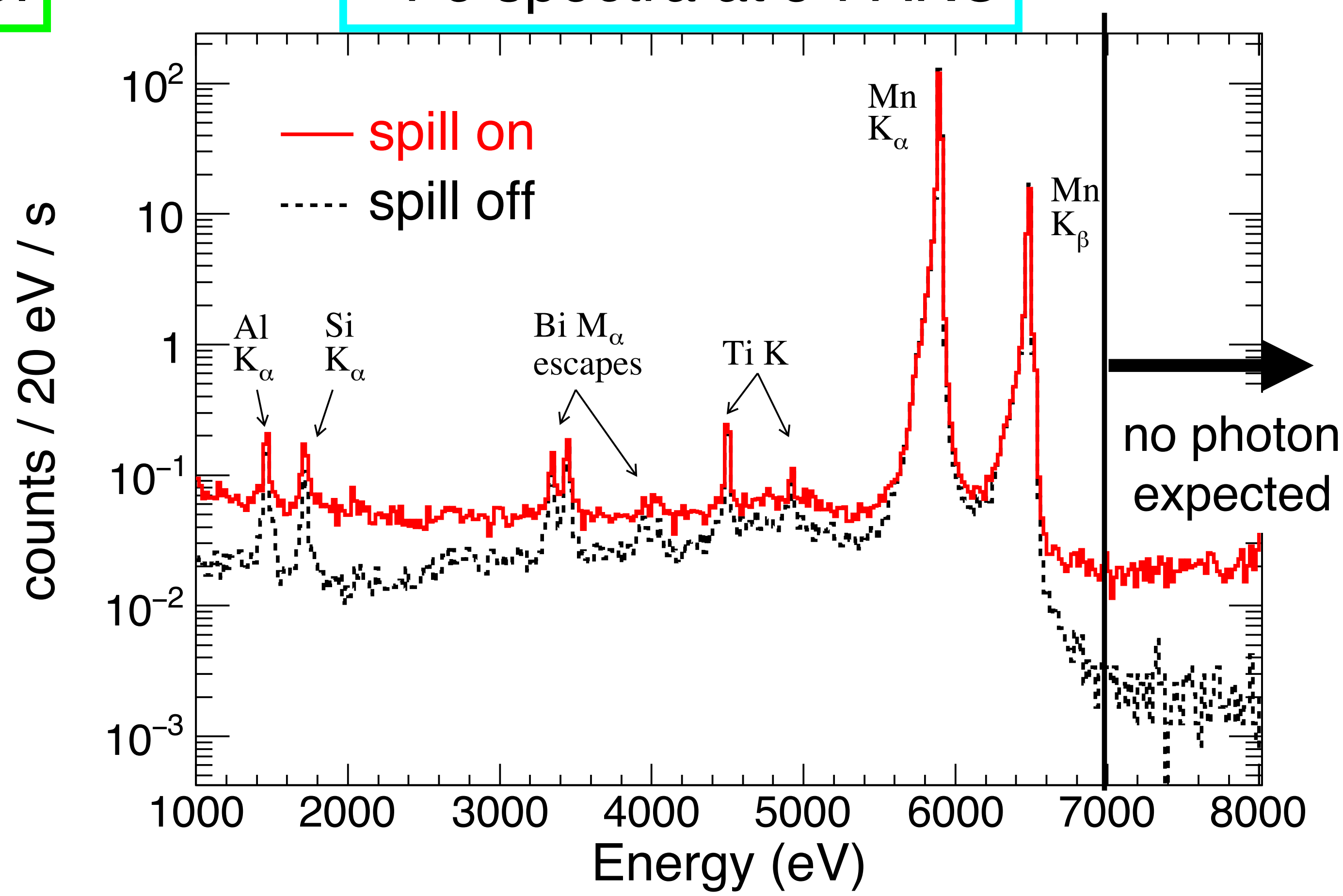
Charged particle background

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



understood the beam-induced background

✓ explained PSI spectrum well by simulation including its intensity

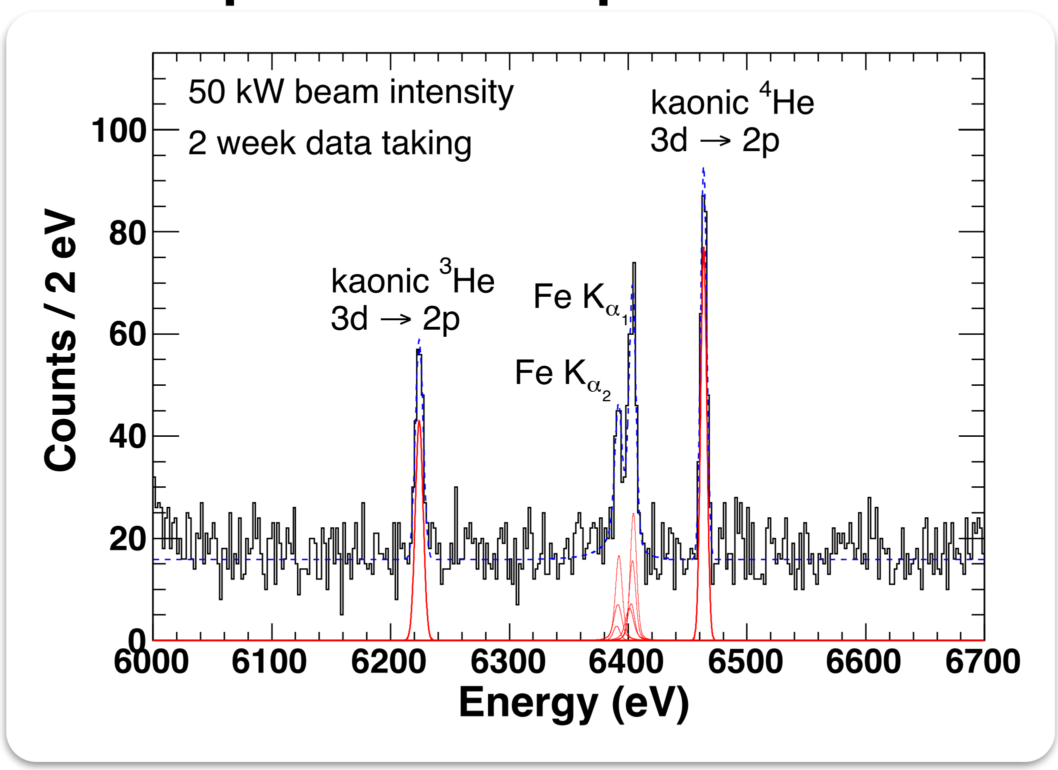
✓ J-PARC background level is consistent with the MC

5. J-PARC E62 status

J-PARC E62 setup

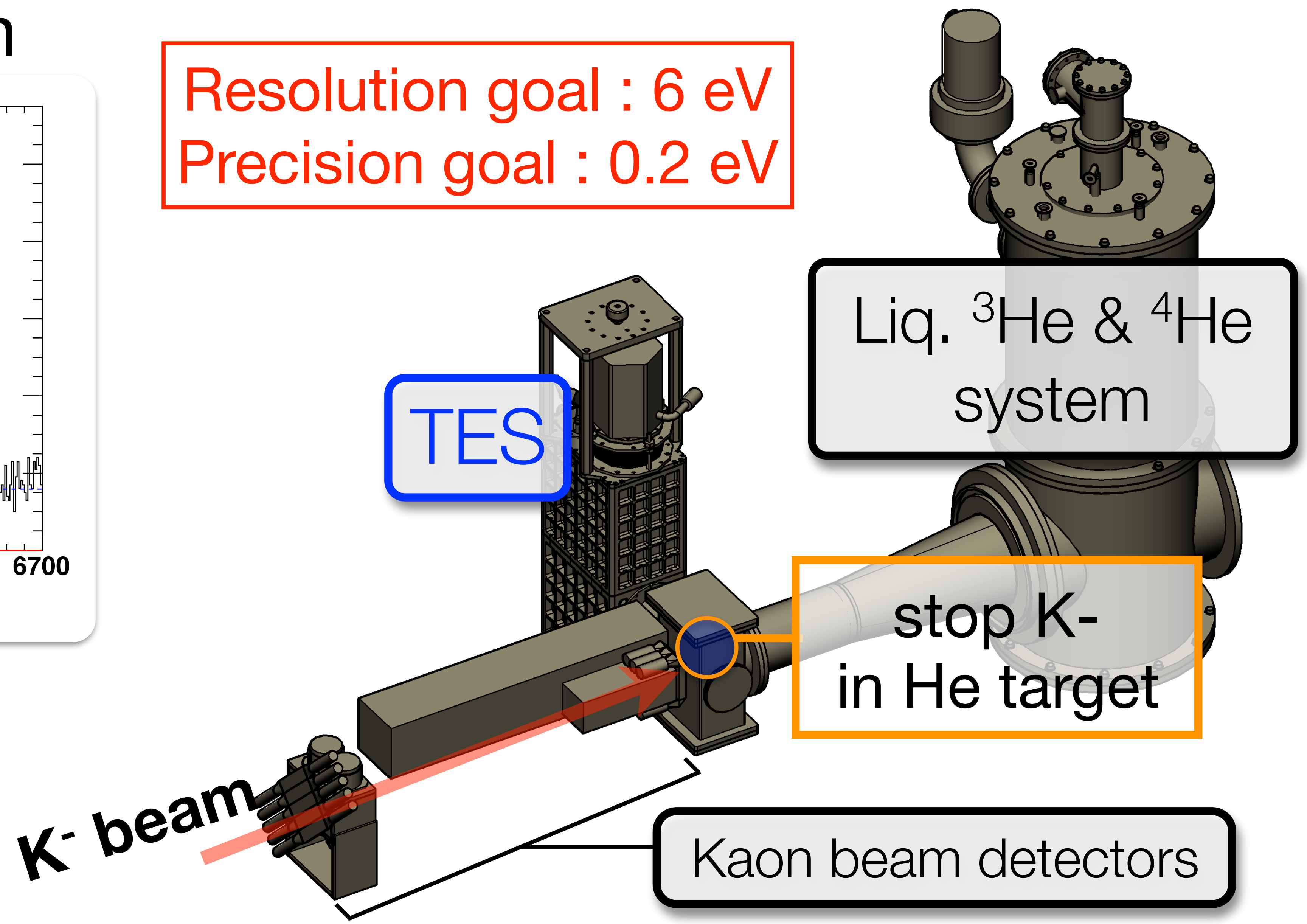
K-He atom exp.

Expected spectrum

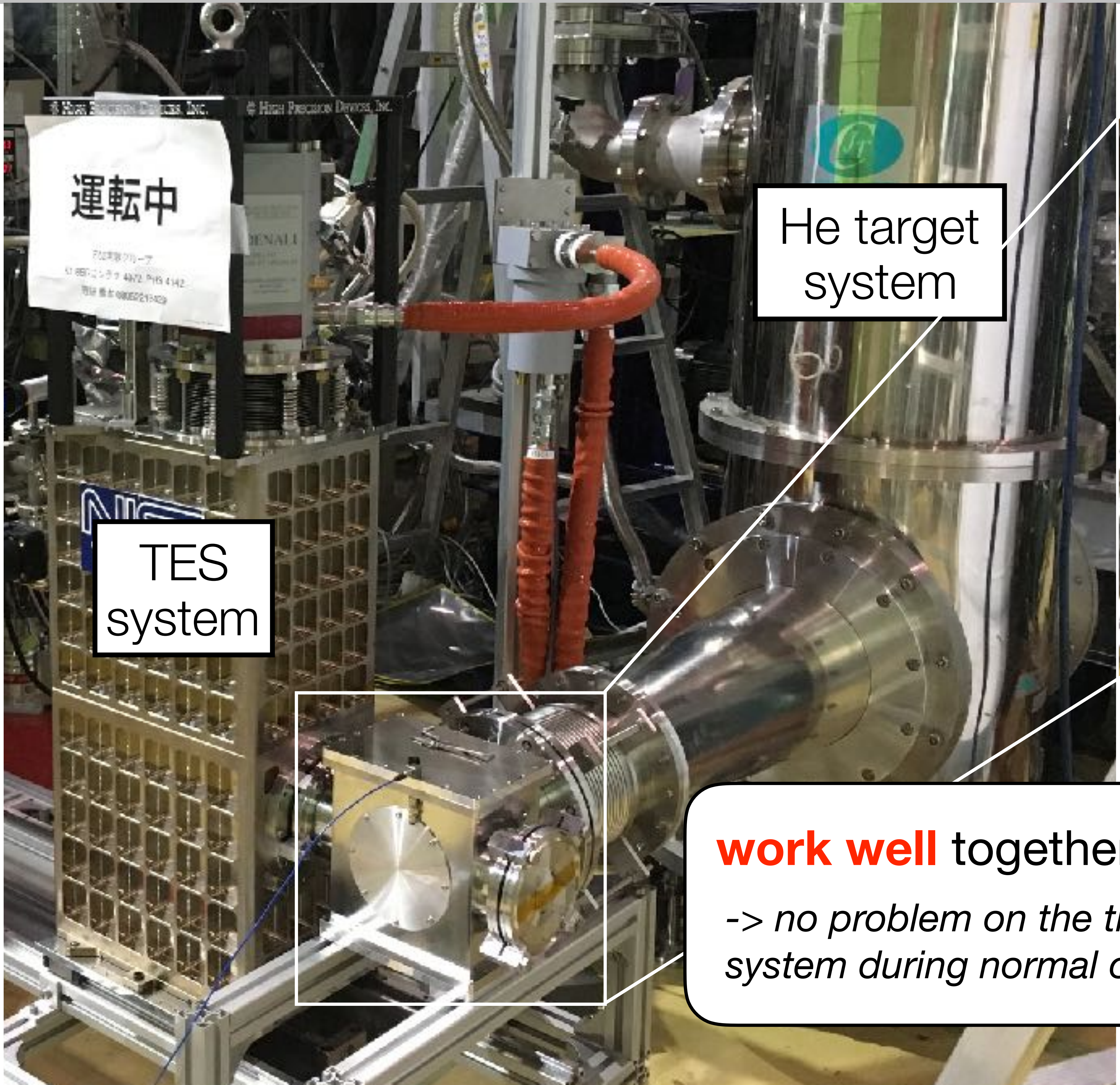


Asynchronous bg. : 1.5 counts /eV
Synchronous bg. : 6 counts /eV

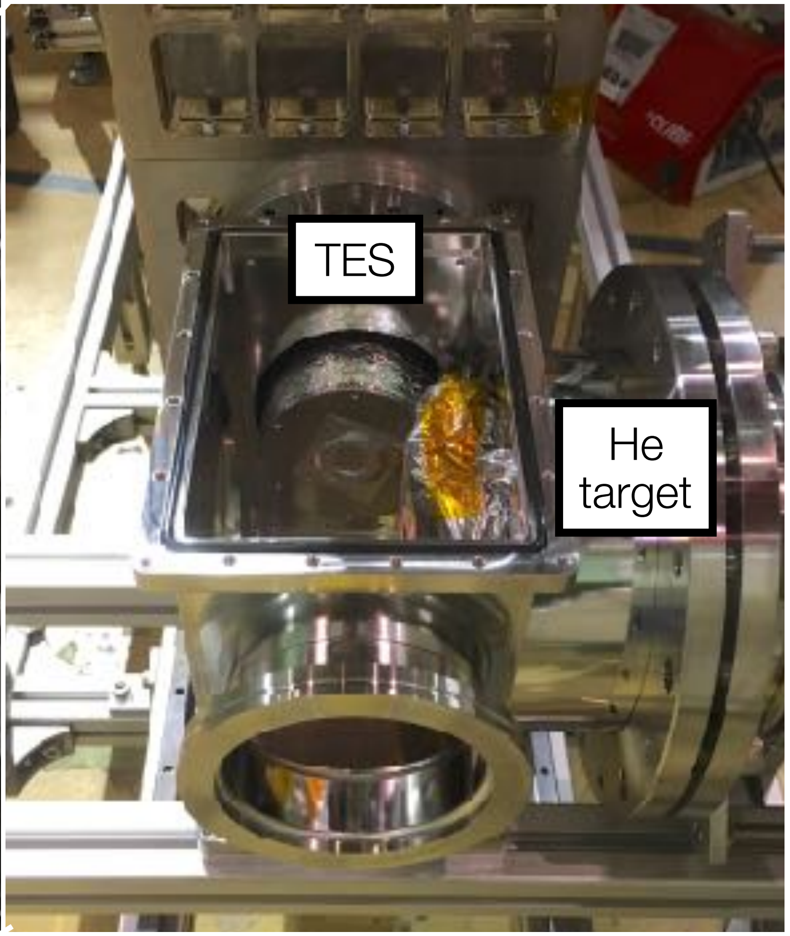
Resolution goal : 6 eV
Precision goal : 0.2 eV



TES + He target



top view (inside)



work well together with target cryostat

-> no problem on the thermal fluctuation of TES system during normal operation of target system

Summary

Summary

◉ High-precision K-atom x-ray spectroscopy with TES

◉ 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 2018