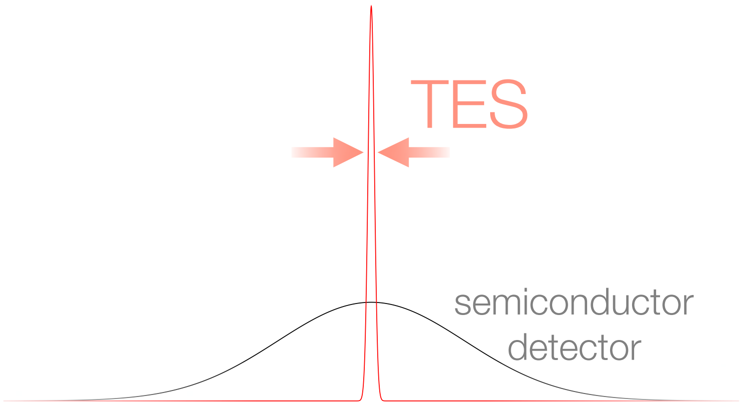
14 Feb., 2017
RIBF Seminar @ RIBF hall

High-resolution Exotic Atom x-ray spectroscopy with TES microcalorimeters



Shinji Okada (RIKEN, AMO physics lab.)
for the HEATES collaboration

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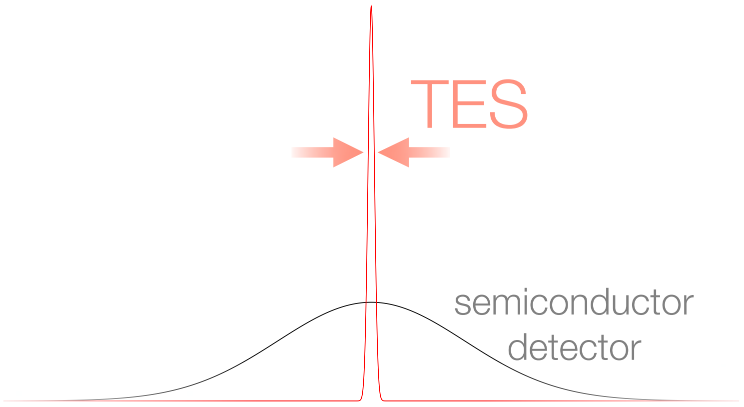

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for the HEATES collaboration

Collaboration list

~55 researchers

M. Bazzi[1], D.A. Bennett[2], C. Berucci[3], D. Bosnar[4], A. Butt[5], C. Curceanu[1], W.B.Doriese[2],
Y. Ezoe[6], J.W.Fowler[2], H. Fujioka[7], C. Guaraldo[1], F.P.Gustafsson[8], T. Hashimoto[9],
R. Hayakawa[6], R.S.Hayano[10], J.P.Hays-Wehle[2], G.C.Hilton[2], T. Hiraiwa[11], Y. Ichinohe[6],
M. Iio[12], M. Iliescu[1], S. Ishimoto[12], Y. Ishisaki[6], K. Itahashi[9], M. Iwasaki[9], S. Kitazawa[6],
Y. Ma[9], H. Noda[13], H. Noumi[11], G.C.O'Neil[2], T. Ohashi[6], H. Ohnishi[9], S. Okada[9], H. Outa[9],
K. Piscicchia[1], C.D.Reintsema[2], Y. Sada[11], F. Sakuma[9], M. Sato[9], D.R.Schmidt[2], A. Scordo[1],
M. Sekimoto[12], H. Shi[1], D. Sirghi[1], F. Sirghi[1], K. Suzuki[3], S. Suzuki[6], D.S.Swetz[2], K. Tanida[14],
H. Tatsuno[8], J. Uhlig[8], J.N.Ullom[2], S. Yamada[6], T. Yamazaki[10], J. Zmeskal[3]

[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

Nuclear physicists + TES experts + Astro physicists

(NIST , LundU) (TMU , TohokuU)

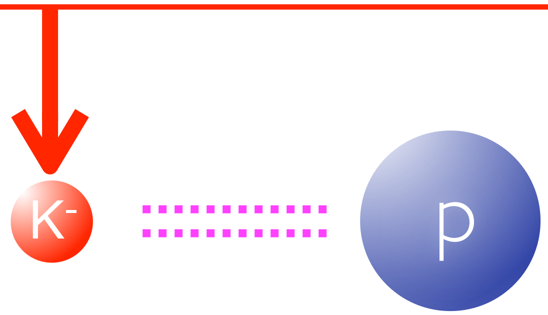
Contents

1. Introduction — Kaonic atom
2. X-ray detector, TES
3. TES with π- beam @ PSI
4. TES with K- beam @ J-PARC
5. J-PARC E62 present status
6. Summary

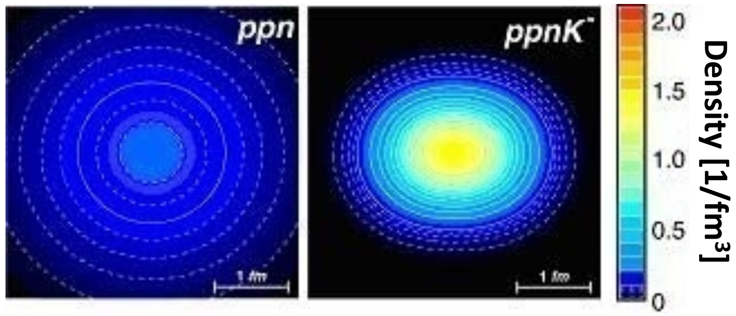
Introduction

$\bar{K}$ - nucleus interaction

$\bar{K}$ ($\bar{K}^0=\bar{d}s$ $K^-=\bar{u}s$) : The lightest hadron with a **strange quark** (mass ~ 500 MeV/c^2, life ~ 12 ns)



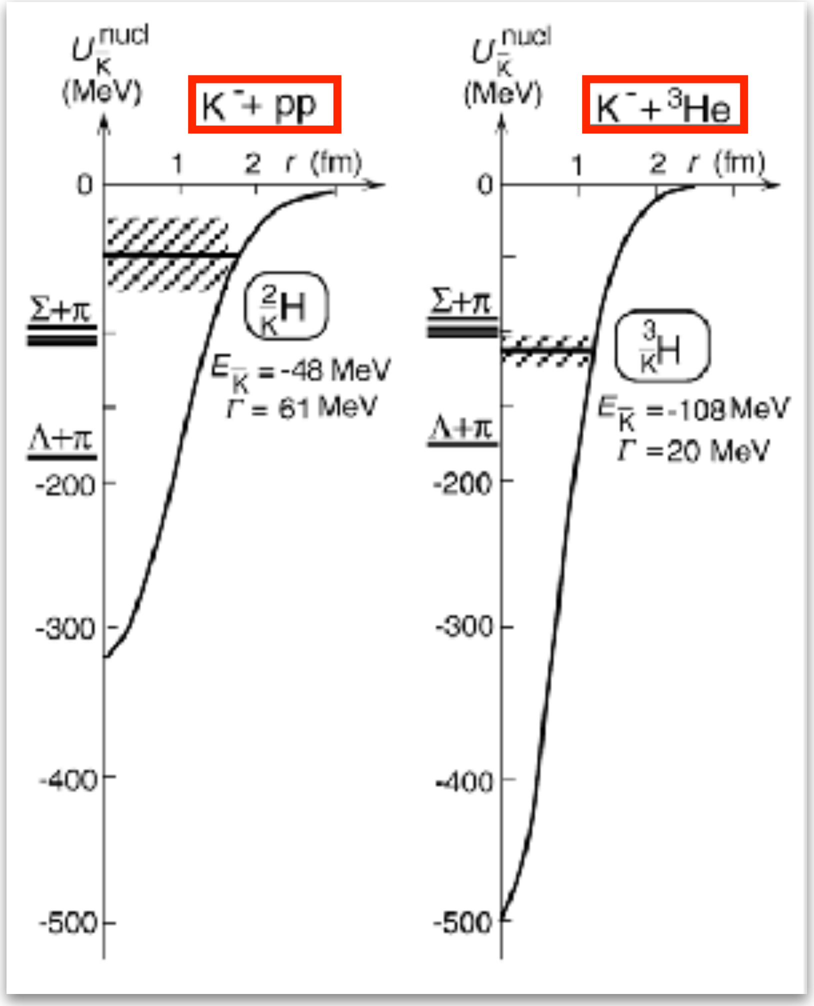
Strongly attractive!



Possible existence of deeply bound K- cluster

Phys. Lett. B587, 167 (2004)

- ✓ New form of a “matter”
- ✓ In-medium property of K



Phys. Lett. B 535, 70 (2002)

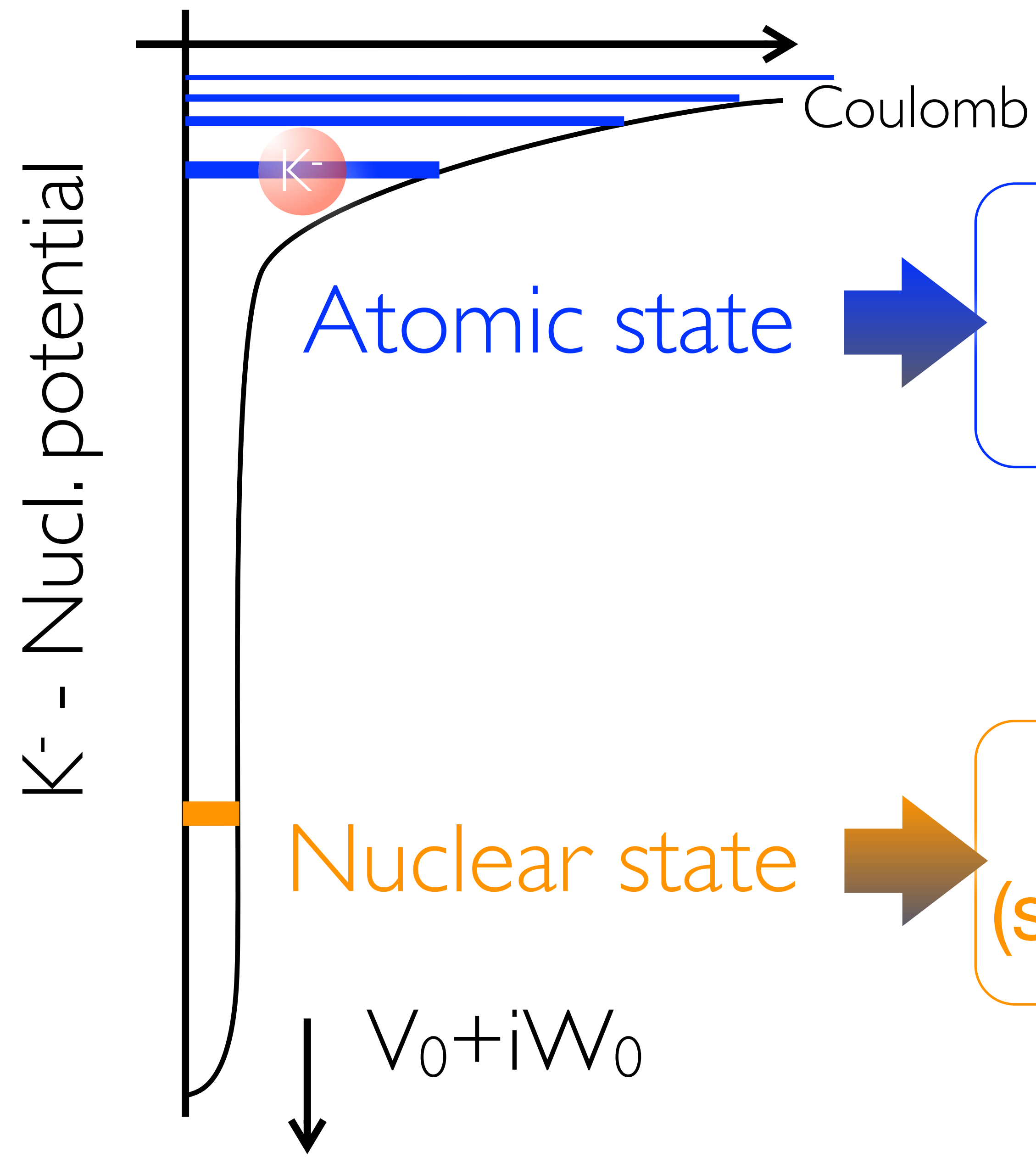
→ Depends on how much of K-nucleus potential depth

→ However the potential depth is still unknown…

Hot topic in Hadron Physics

Two experimental approaches

Study of K - nucleus interaction

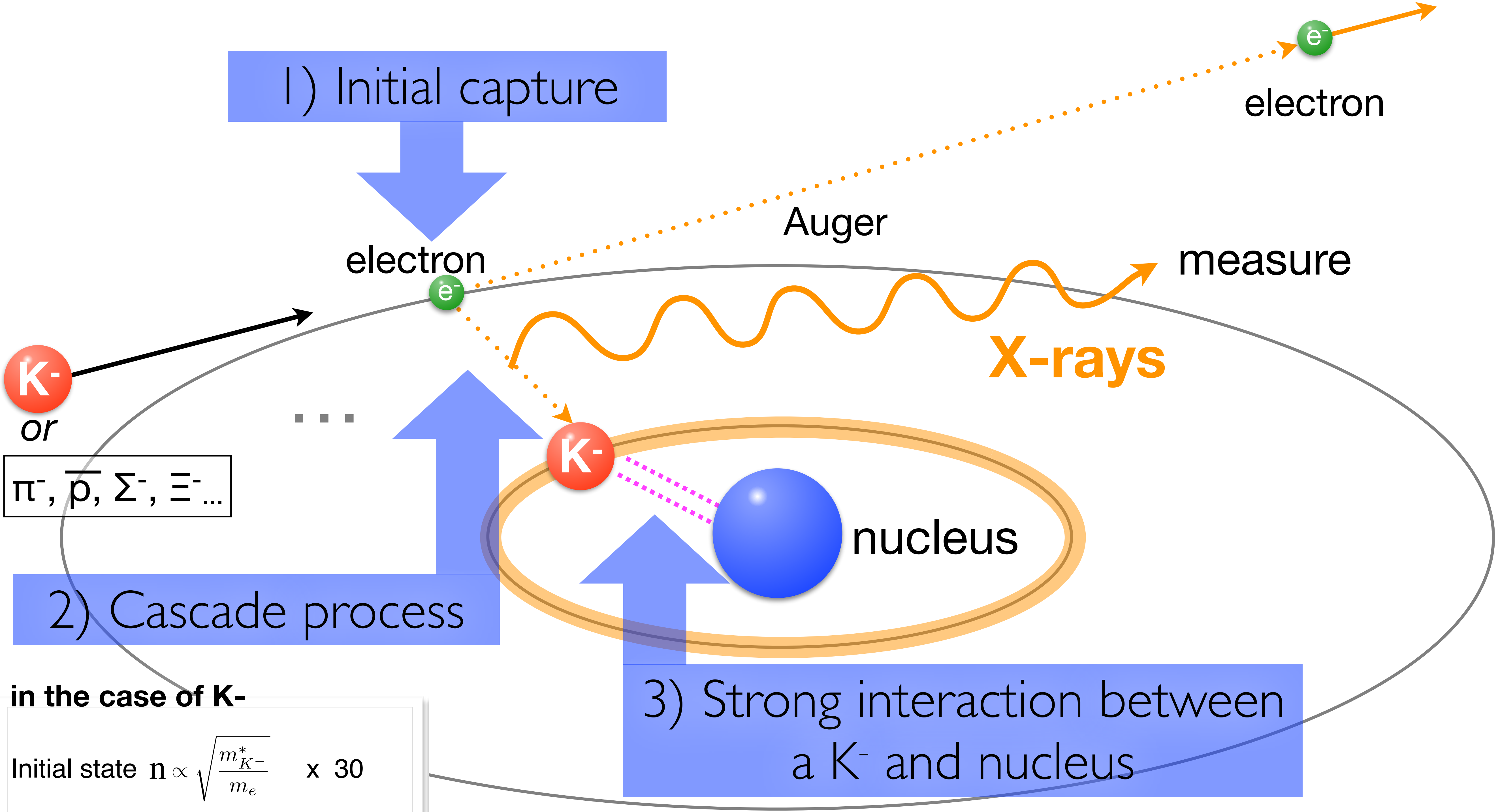


Atomic state → **Precision x-ray measurement**

complementary

Nuclear state → **Reaction formation**
(search for deeply bound K- cluster)

Kaonic atom



1) Initial capture

K- or π-, p̅, Σ-, Ξ-...

2) Cascade process

3) Strong interaction between a K- and nucleus

⇒ nuclear absorption

in the case of K-

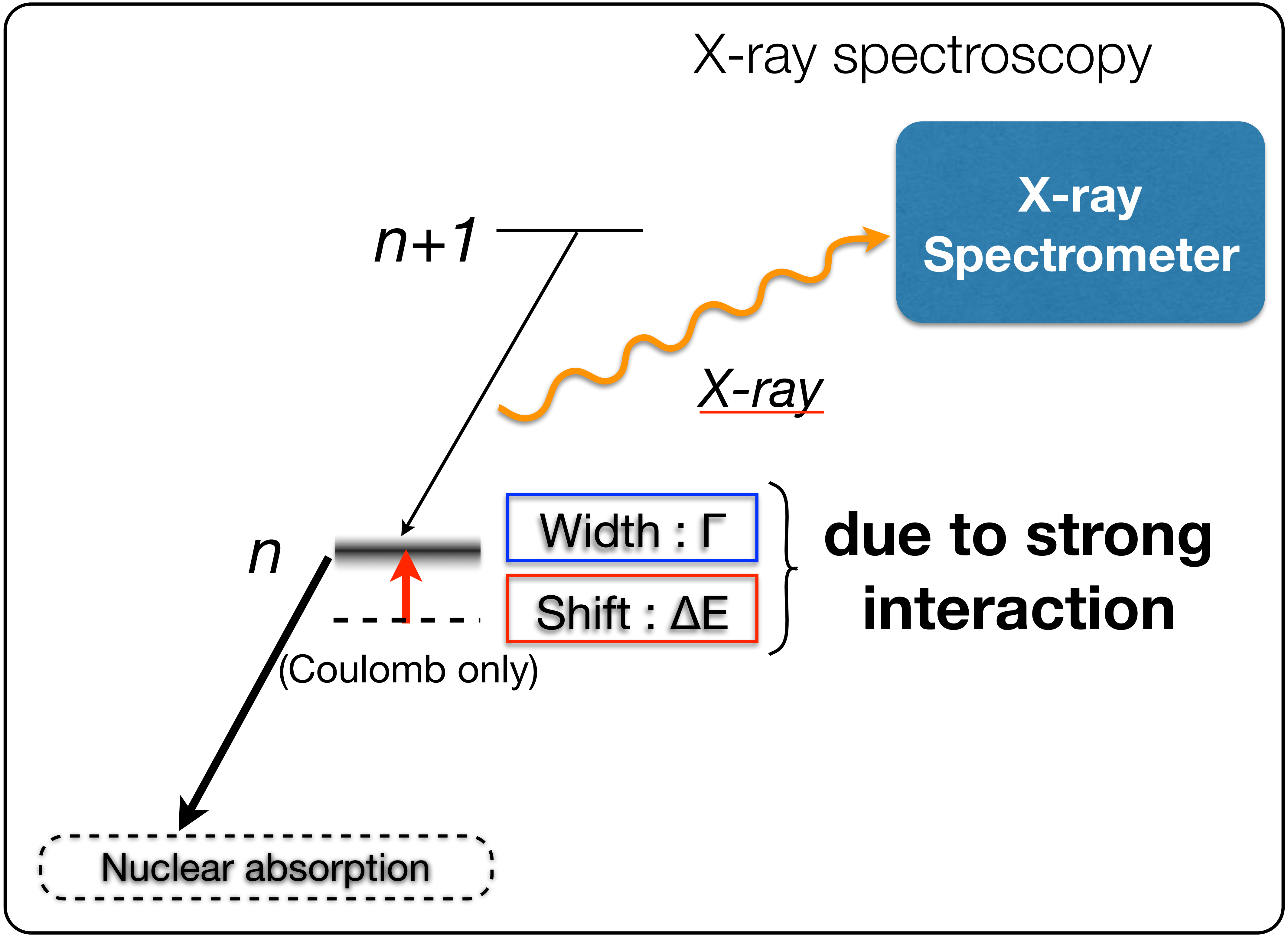
Initial state	$n \propto \sqrt{\frac{m^*_{K^-}}{m_e}}$	x 30
X-ray energy	$\propto \frac{m^*_{K^-}}{m_e}$	x 1000
Radius	$\propto \frac{m_e}{m^*_{K^-}}$	x 1/1000

($m^*_{K^-}$: reduced mass)

A tool for studying strong interaction

Strong-interaction shift & width

X-ray spectroscopy



X-ray Spectrometer

n+1

X-ray

n

Width : Γ

Shift : ΔE

(Coulomb only)

due to strong interaction

Nuclear absorption

K-atom data → scattering length

e.g., Kaonic hydrogen

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

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

Shift **Width**

K-p Kα x-ray

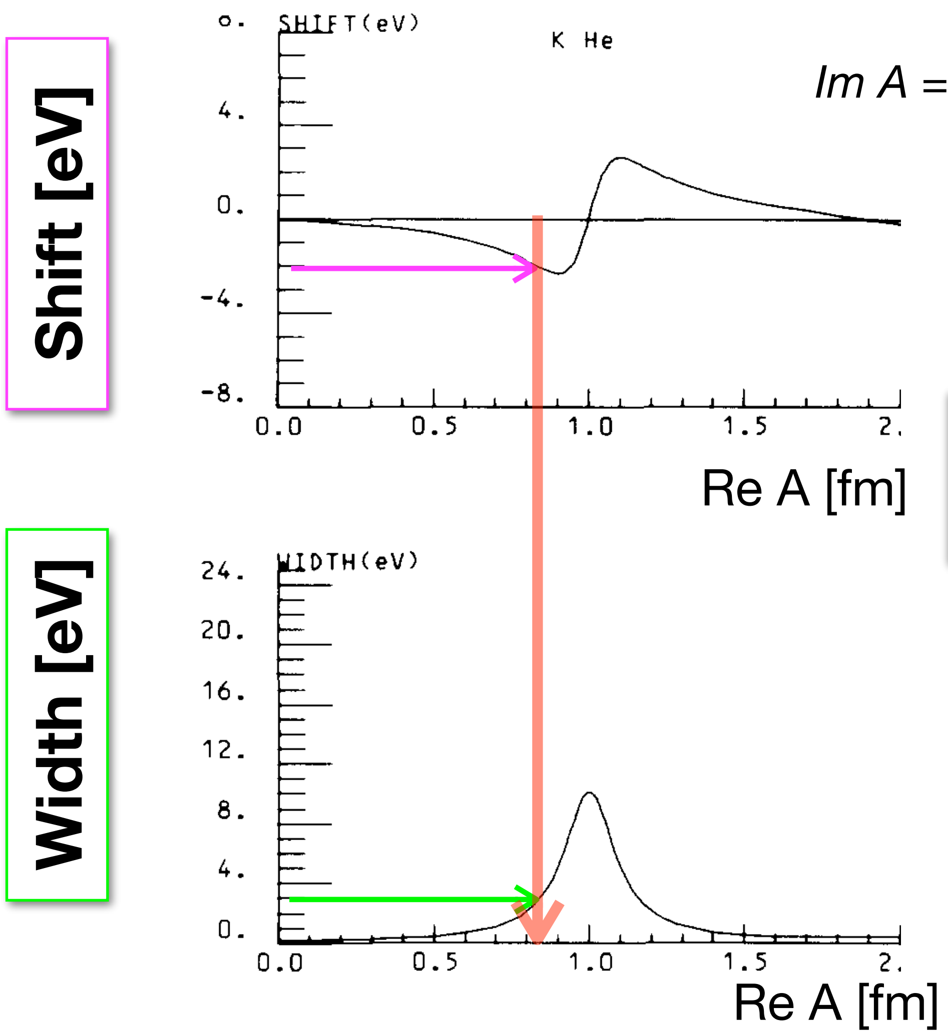
K^-p scattering length

(= K^-p scattering amplitude at threshold)

K-atom data

↓

potential strength



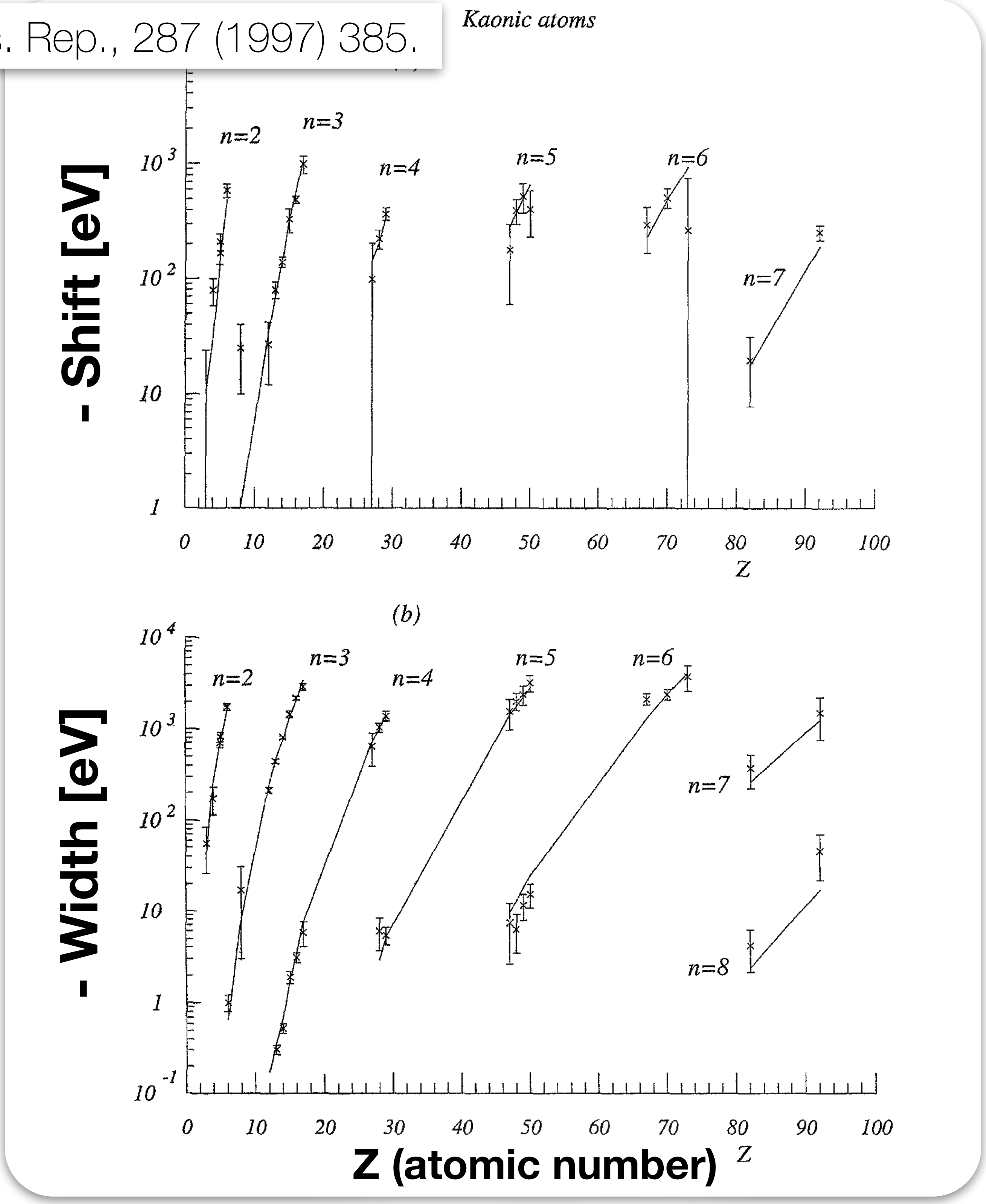
e.g., K-He atom
2p level

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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  Friedman, Gal, NPA 899 (2013) 60.

Current data quality is not good enough to determine K-nucl. potential strength

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

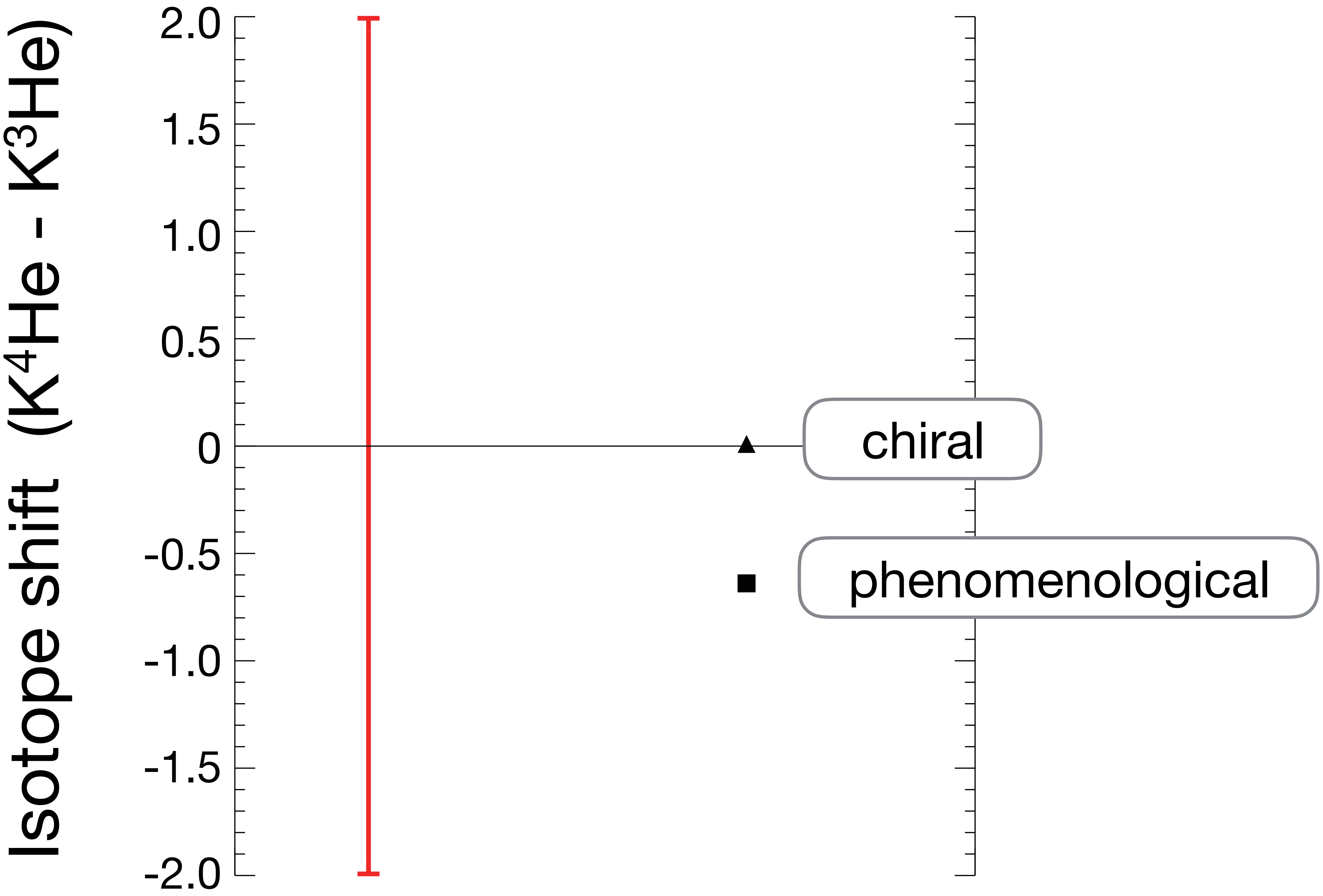
	deep	**shallow**
Choosing the following two typical models : *[Pheno.] Mares, Friedman, Gal, NPA770(06)84* *[Chiral] Ramos, Oset, NPA671(00)481*	**Phenomenological** $V_{opt}(r=0) \sim -(180 + 73i)$ MeV	**Chiral** $V_{opt}(r=0) \sim -(40 + 55i)$ MeV
K-^{4}He	-0.41 eV	-0.09 eV
K-^{3}He	0.23 eV	-0.10 eV
Isotope shift (K-^{4}He - K-^{3}He)	**-0.64 eV** ↔	**0.01 eV**

↑ 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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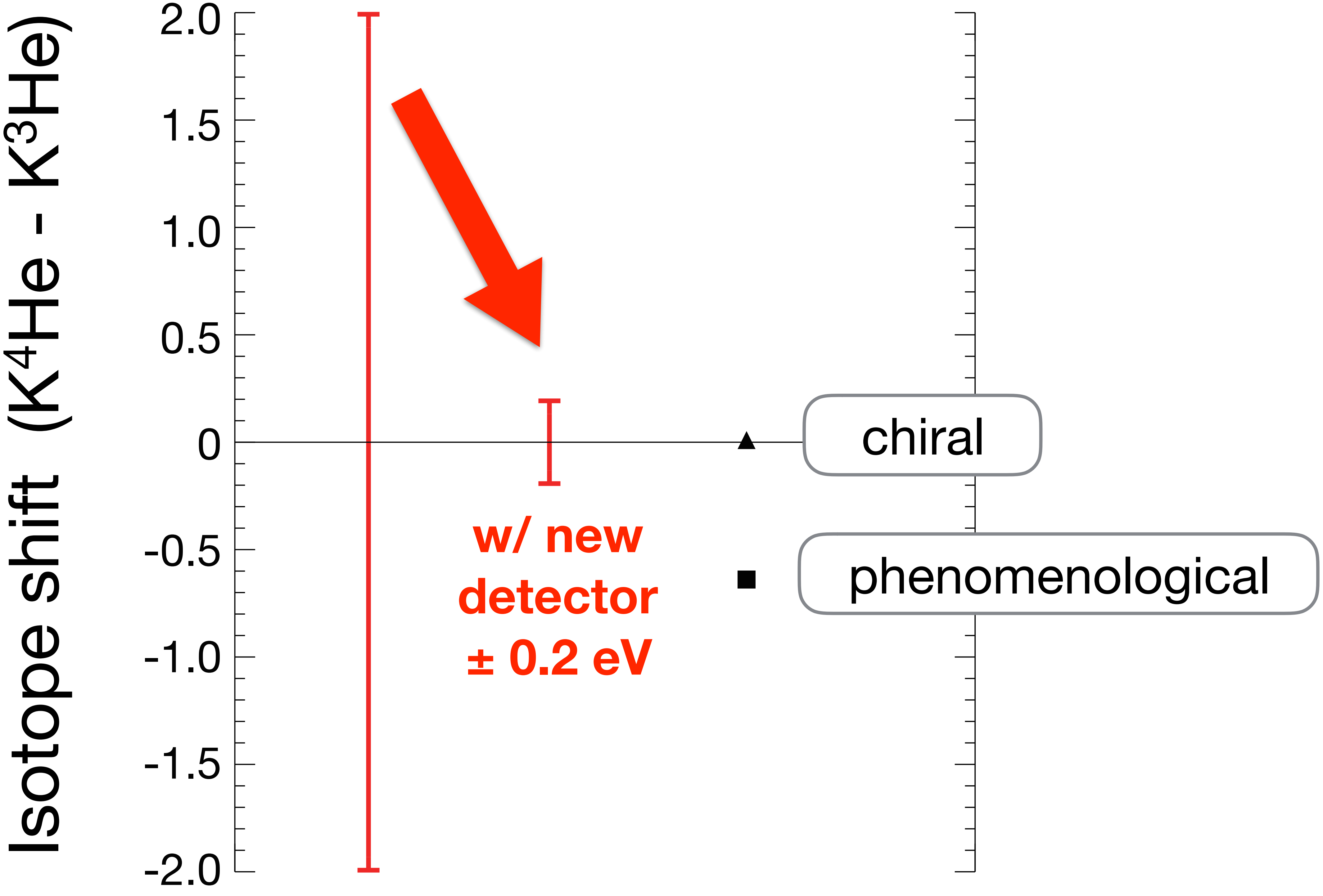
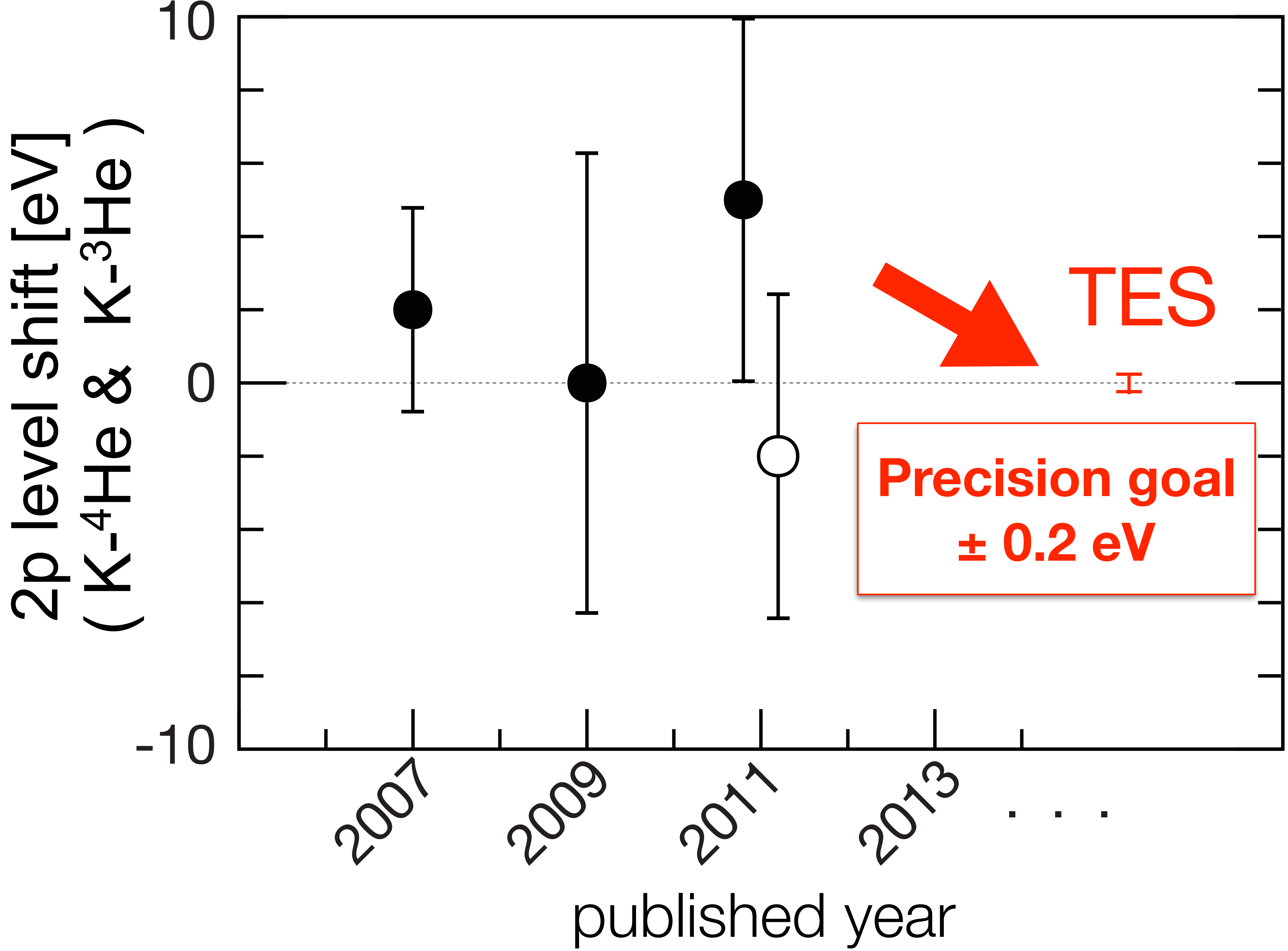
Past experiments : ± 2 eV



w/ new detector ± 0.2 eV

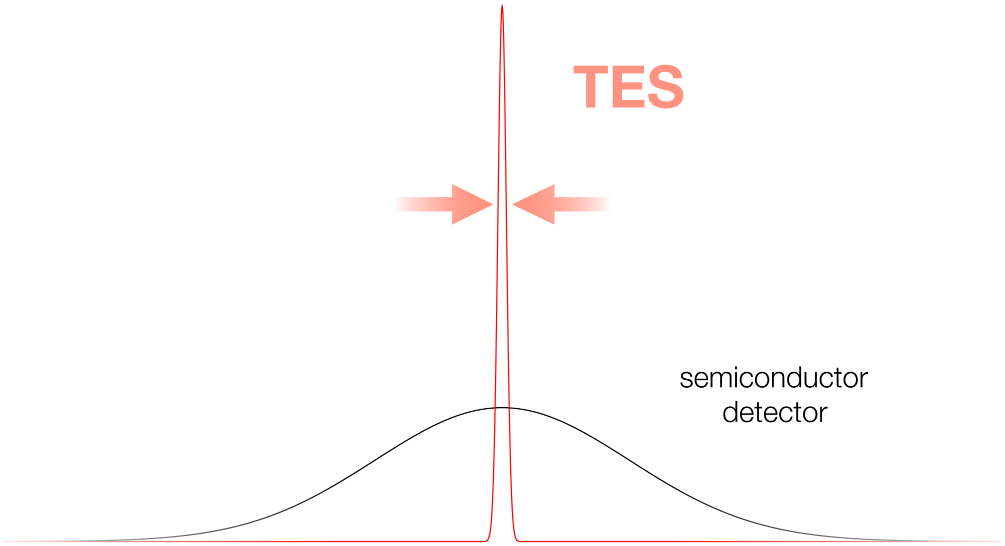
Past measurements & precision goal

Past measurements
with SDDs : ± 2 eV



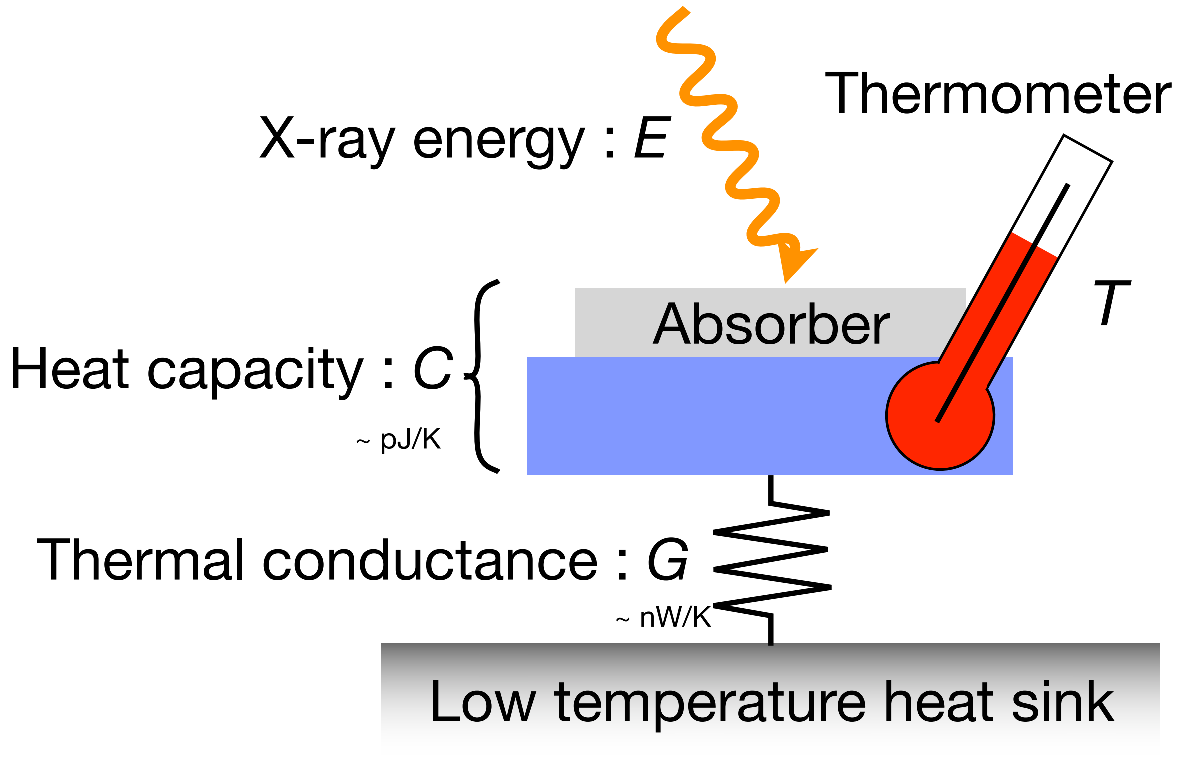
Precision goal
± 0.2 eV

X-ray detector : TES

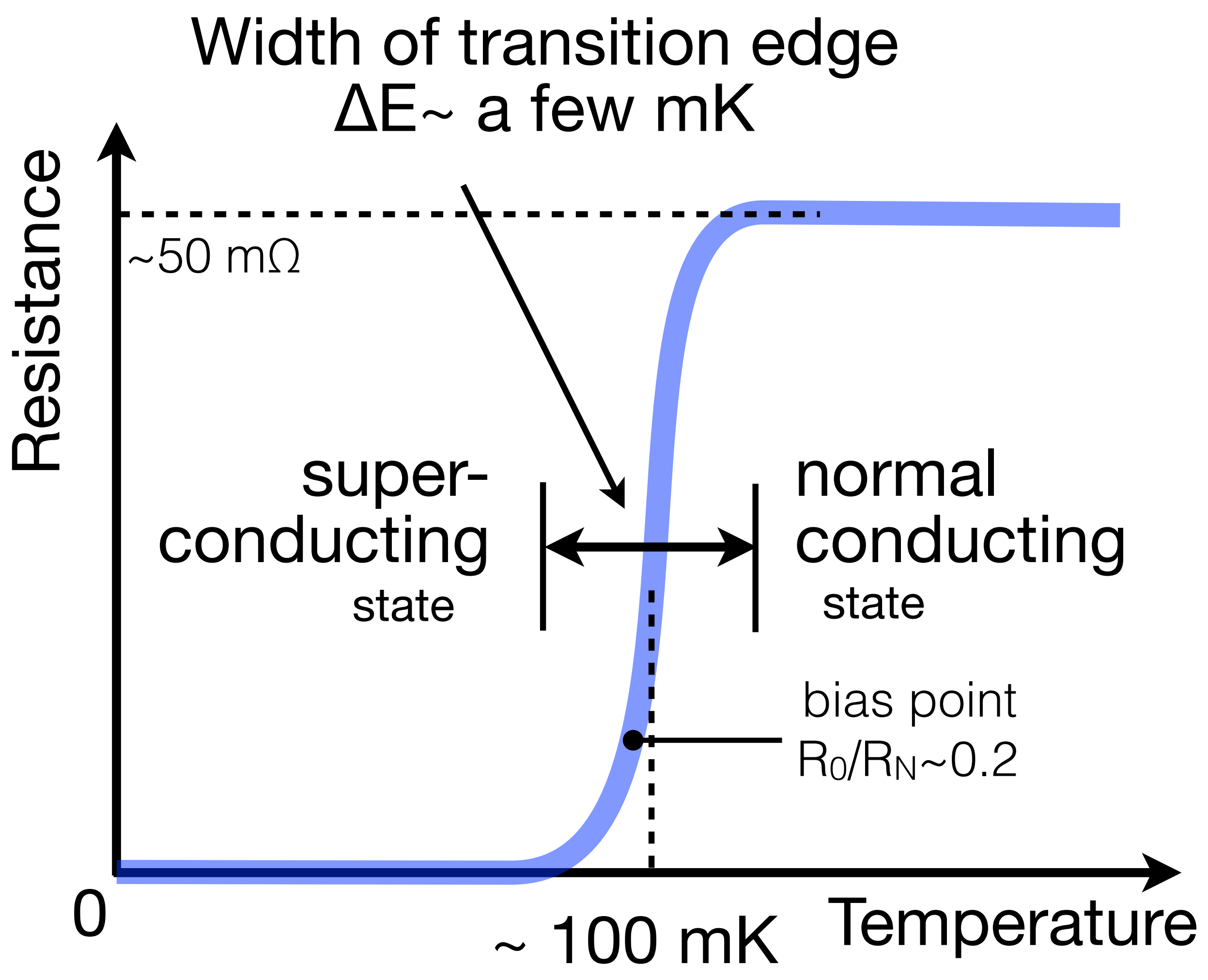


Transition-Edge-Sensor microcalorimeter

Microcalorimeter



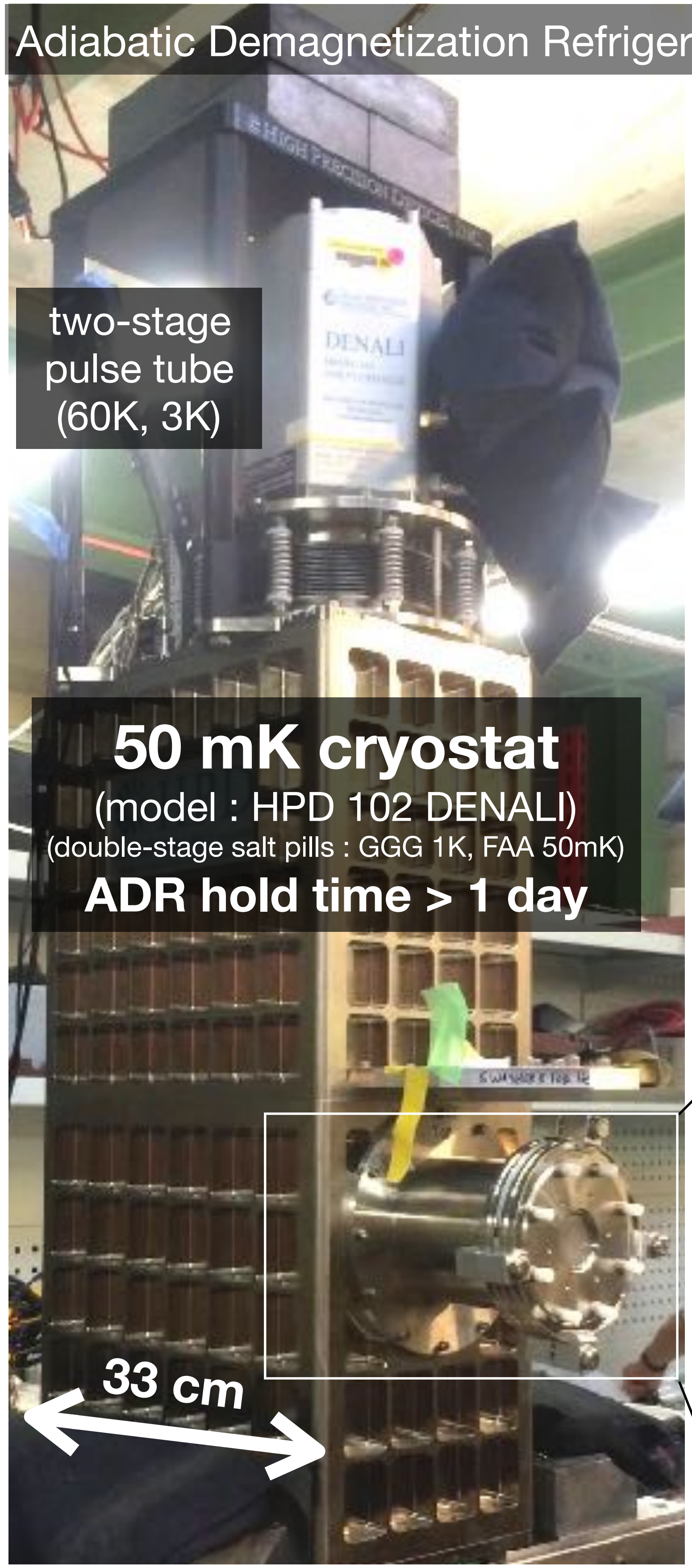
Transition Edge Sensor (TES)



- ✓ 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



Adiabatic Demagnetization Refrigerator

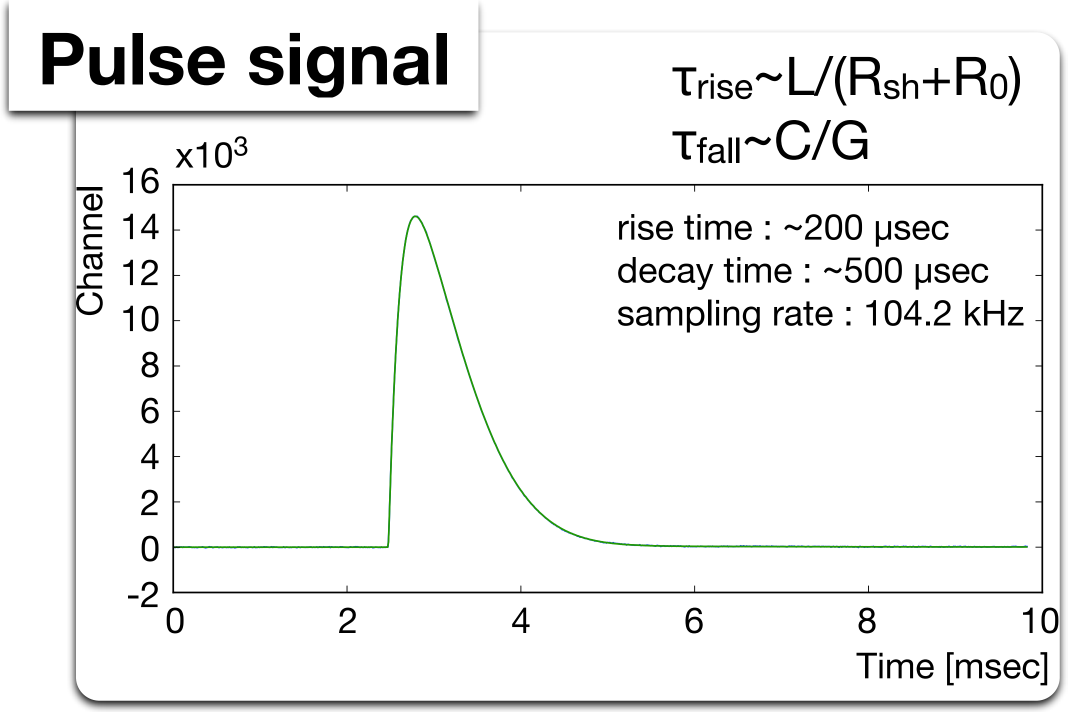
two-stage pulse tube (60K, 3K)

50 mK cryostat
(model : HPD 102 DENALI)
(double-stage salt pills : GGG 1K, FAA 50mK)
ADR hold time > 1 day

✓ Compact and portable

✓ Large effective area w/multiplexing tech.

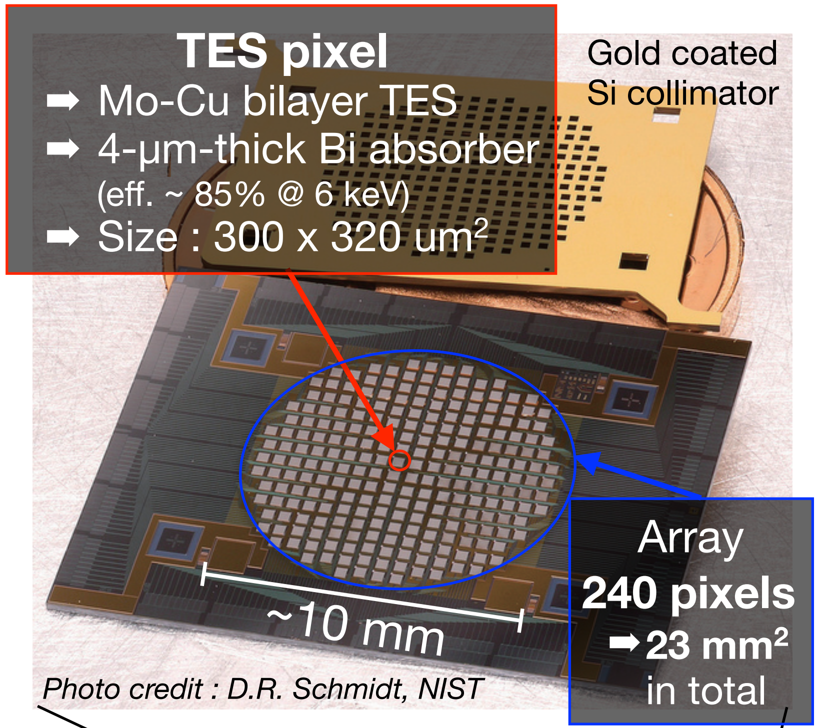
Pulse signal



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

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

rise time : ~200 μsec
decay time : ~500 μsec
sampling rate : 104.2 kHz

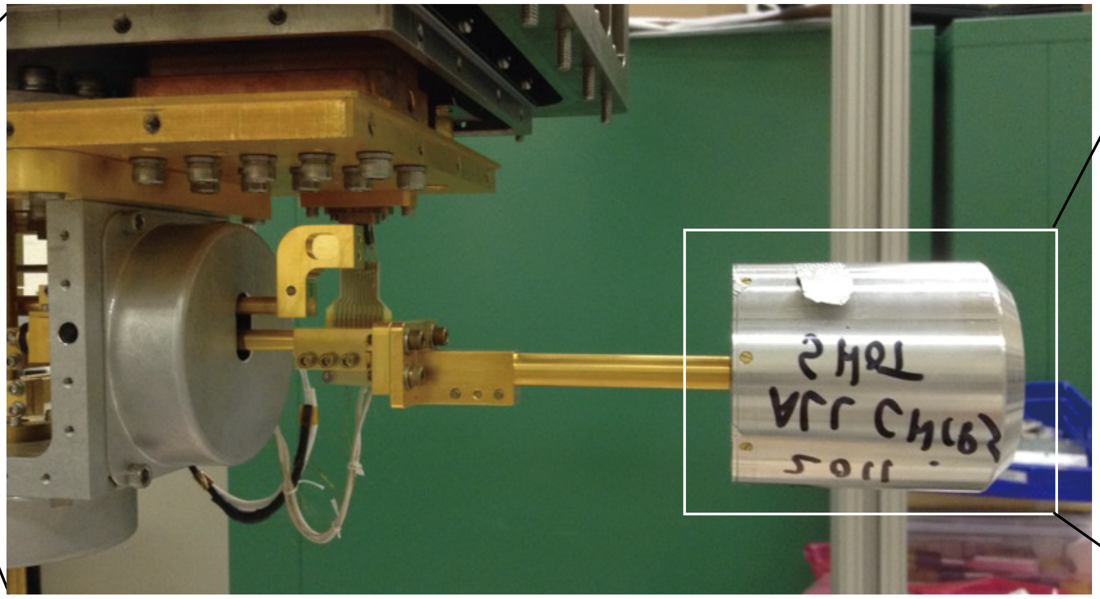


TES pixel
- ➡ Mo-Cu bilayer TES
- ➡ 4-μm-thick Bi absorber (eff. ~ 85% @ 6 keV)
- ➡ Size : 300 x 320 um^2

Gold coated Si collimator

Array **240 pixels** ➡ **23 mm^2** in total

Photo credit : D.R. Schmidt, NIST



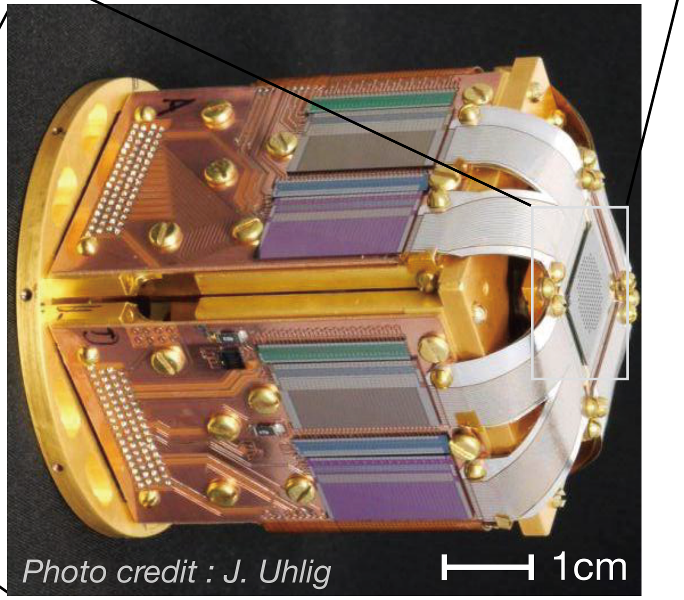


Photo credit : J. Uhlig

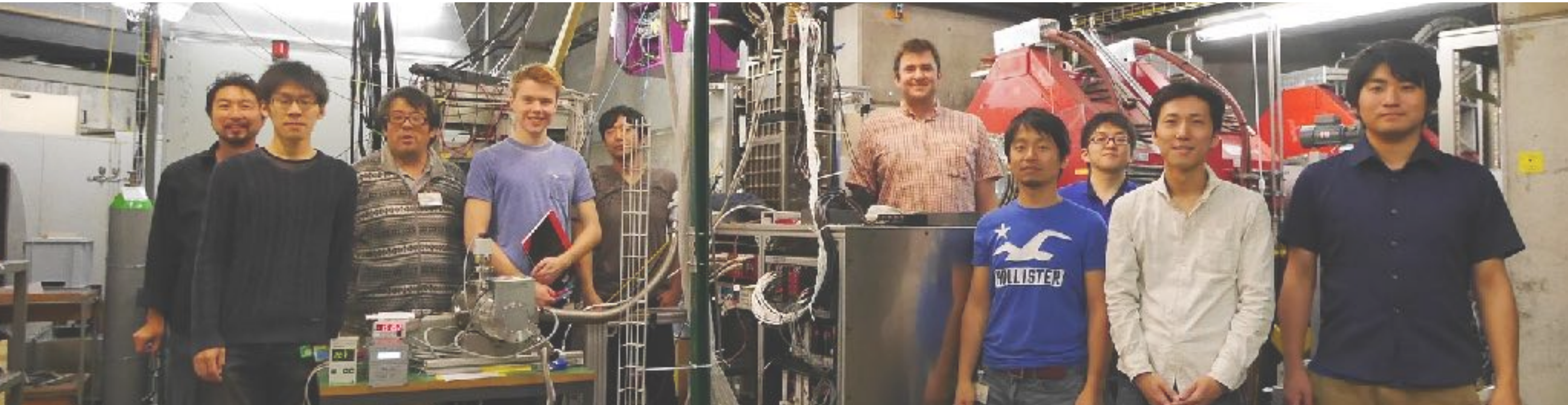
Status of HEATES project

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 or later	J-PARC E62 physics run	

Two performance evaluations

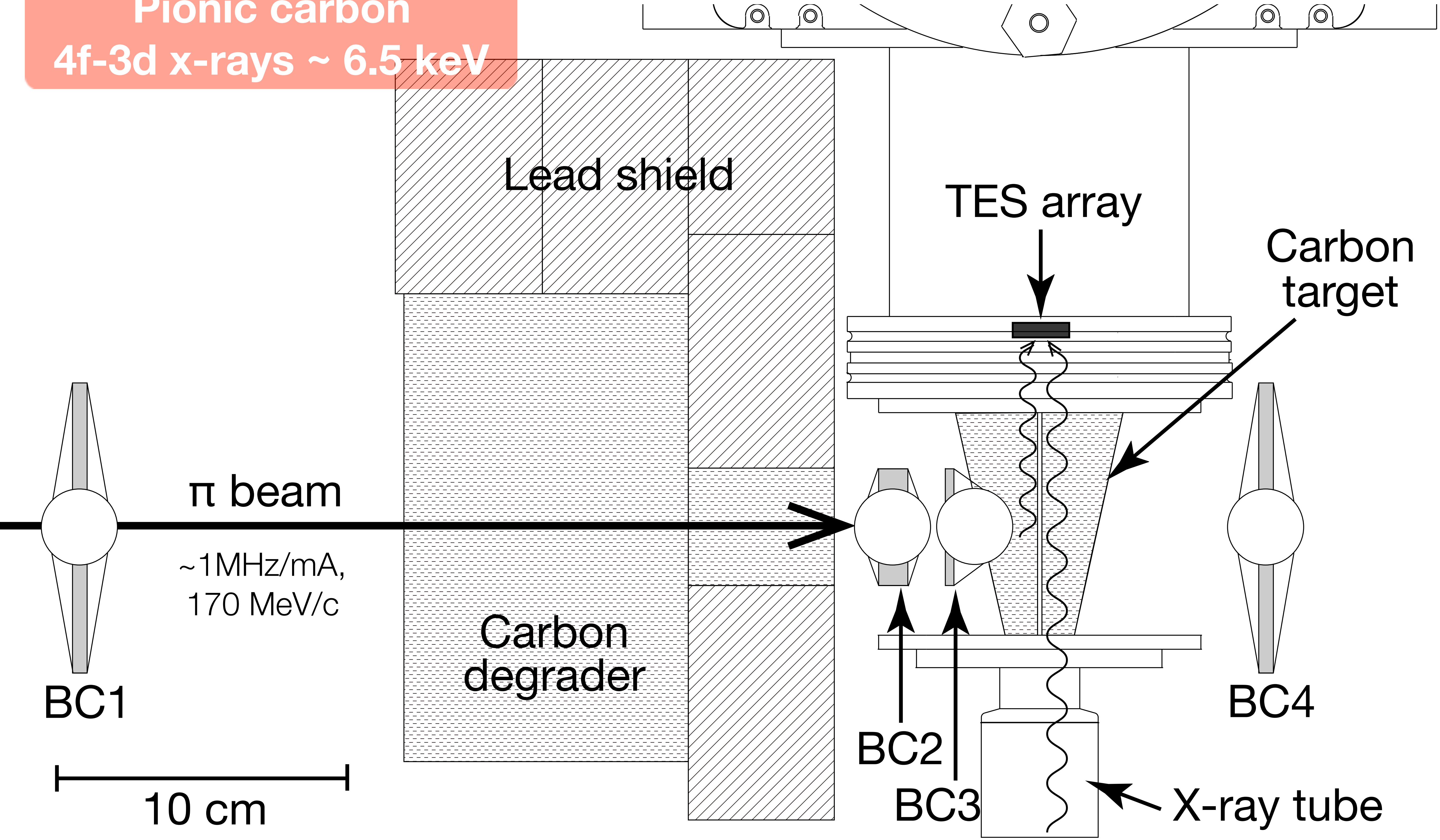
	①	②
location	PSI (Switzerland)	J-PARC (Japan)
beam line	πM1	K1.8BR
particle	π-	K-
purity	~ 0.4	~ 0.3
momentum	170 MeV/c	900 MeV/c
intensity (sum of all particles)	1.4 ~ 2.8 x 10^6 cps	8 x 10^5 / spill
hadronic atom x-rays	π ^{12}C 4-3 (6.4 keV)	K-^{3}He 3-2 (6.2 keV) K-^{4}He 3-2 (6.4 keV) to be measured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

① π^- beam



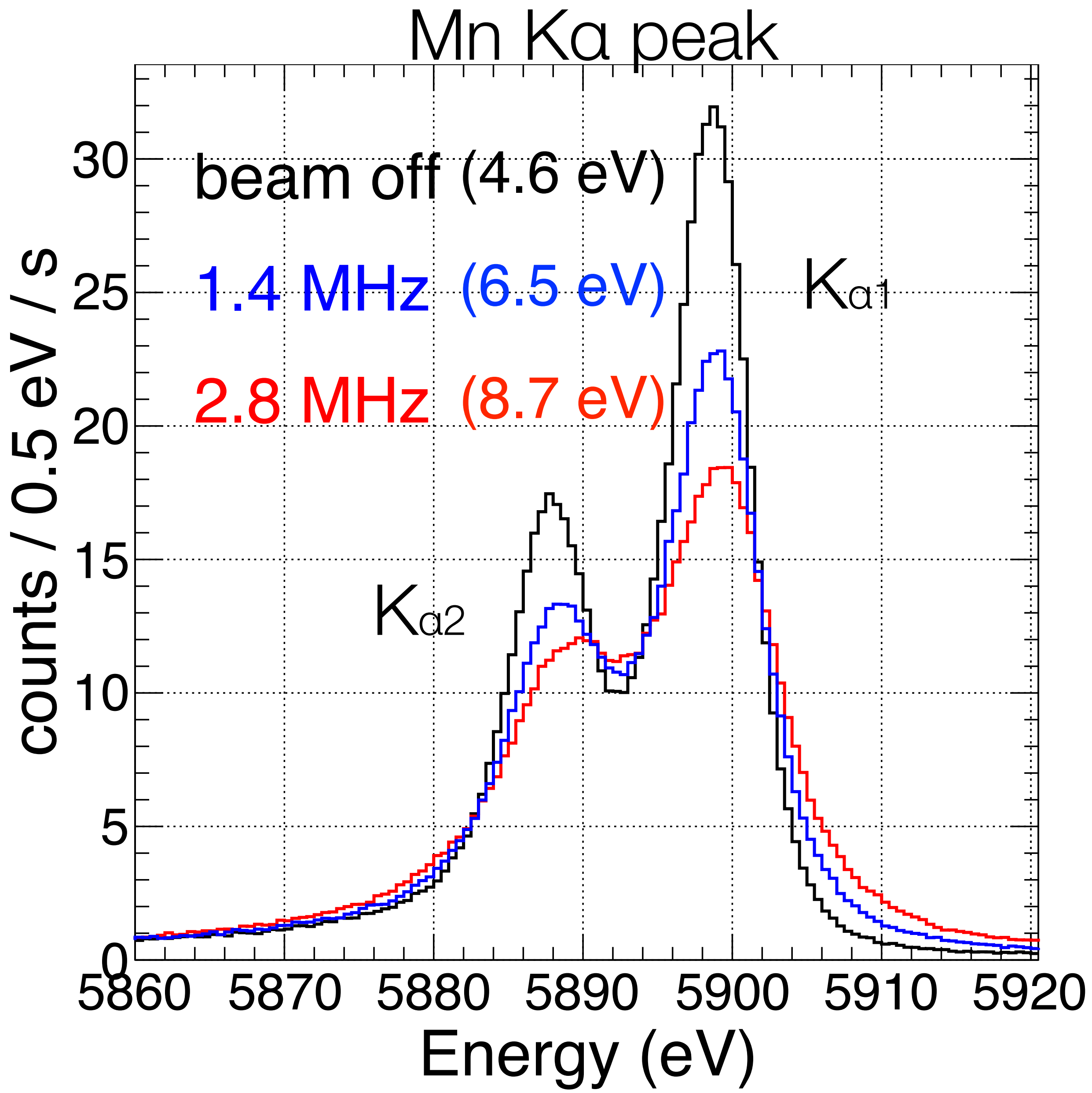
π atom expt @ PSI πM1 beamline

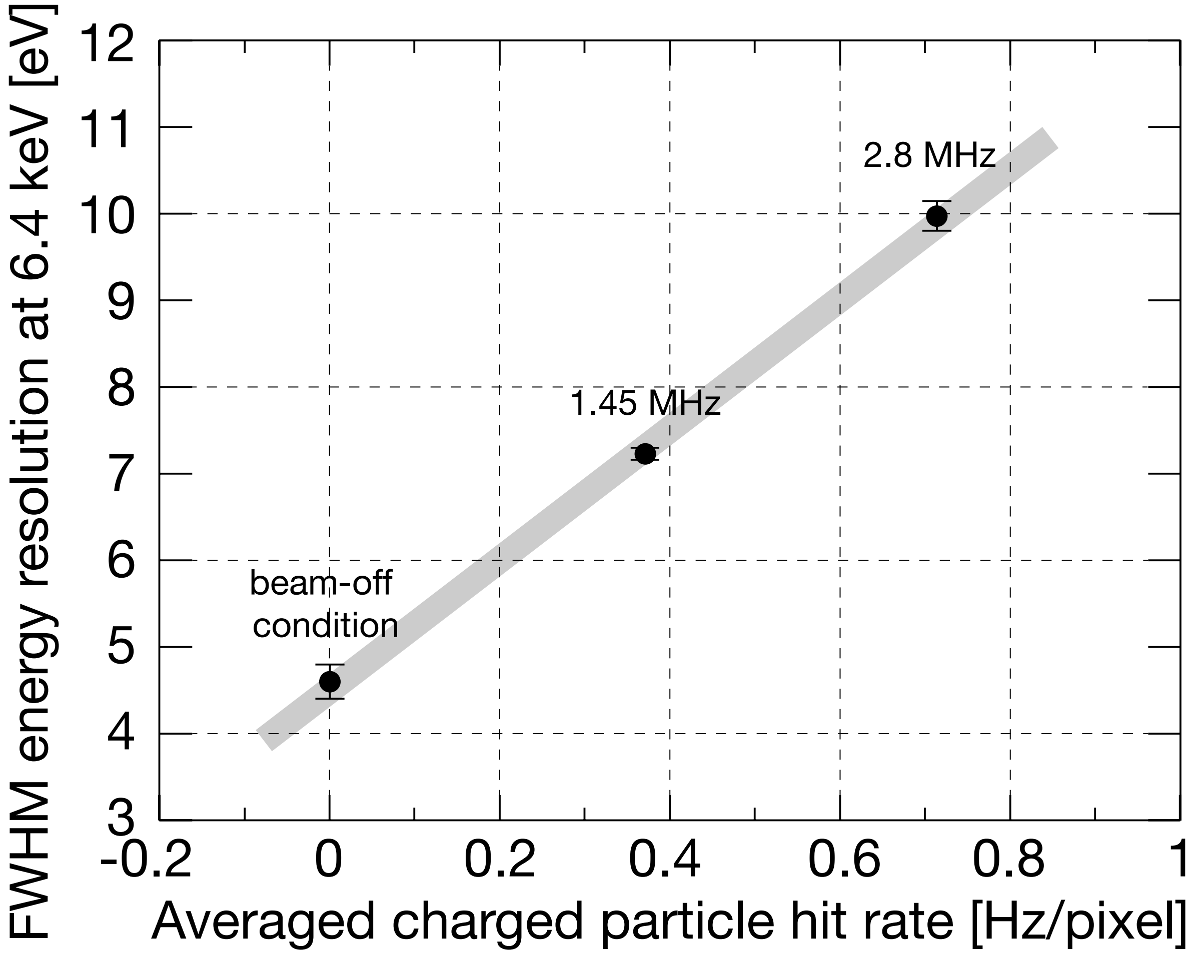
Pionic carbon
4f-3d x-rays ~ 6.5 keV



Resolution

In-beam performance





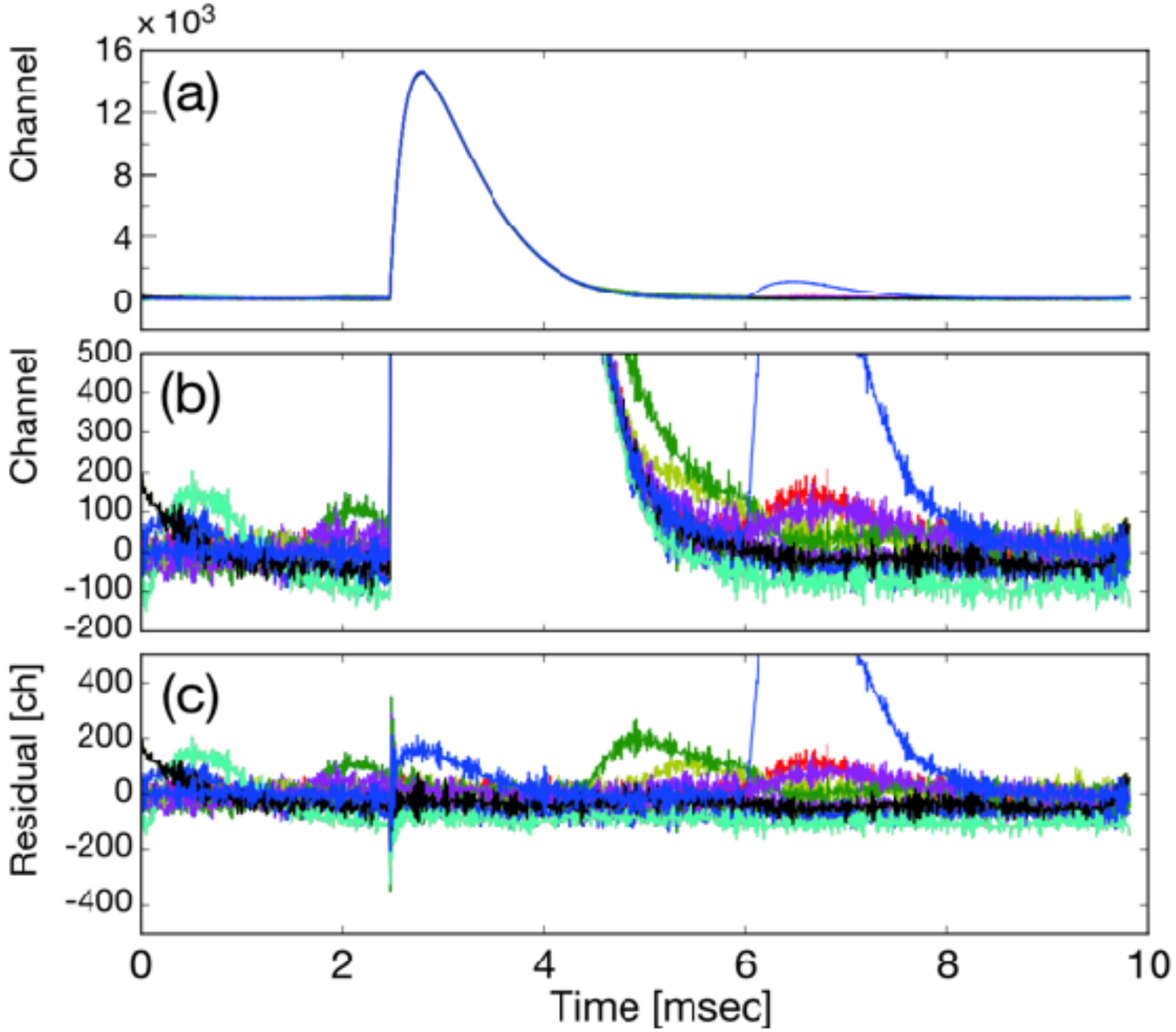
Hit-rate difference between beam-on and off conditions

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

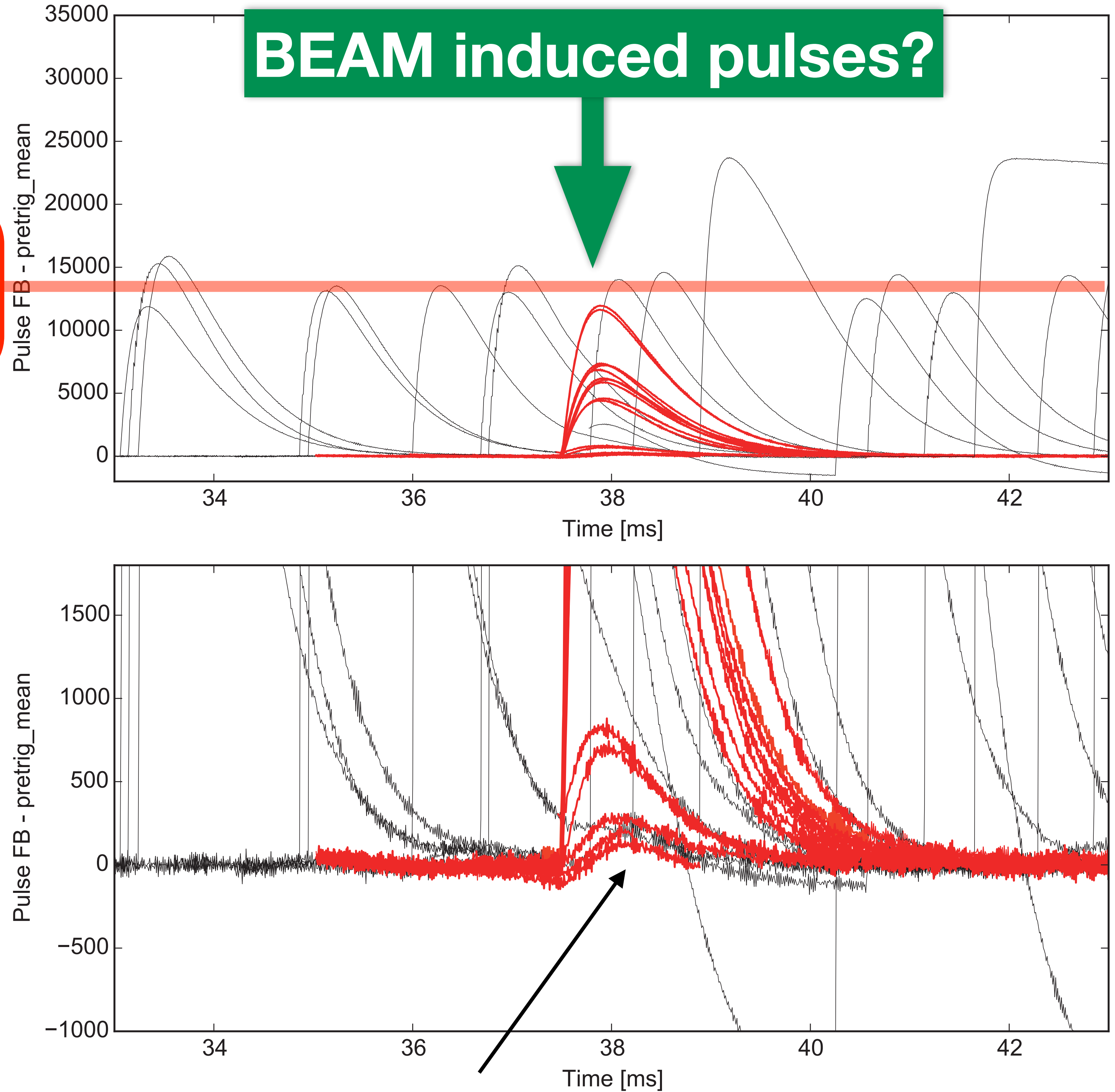


Enlarged view

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*

Example : beam + Mn x-rays



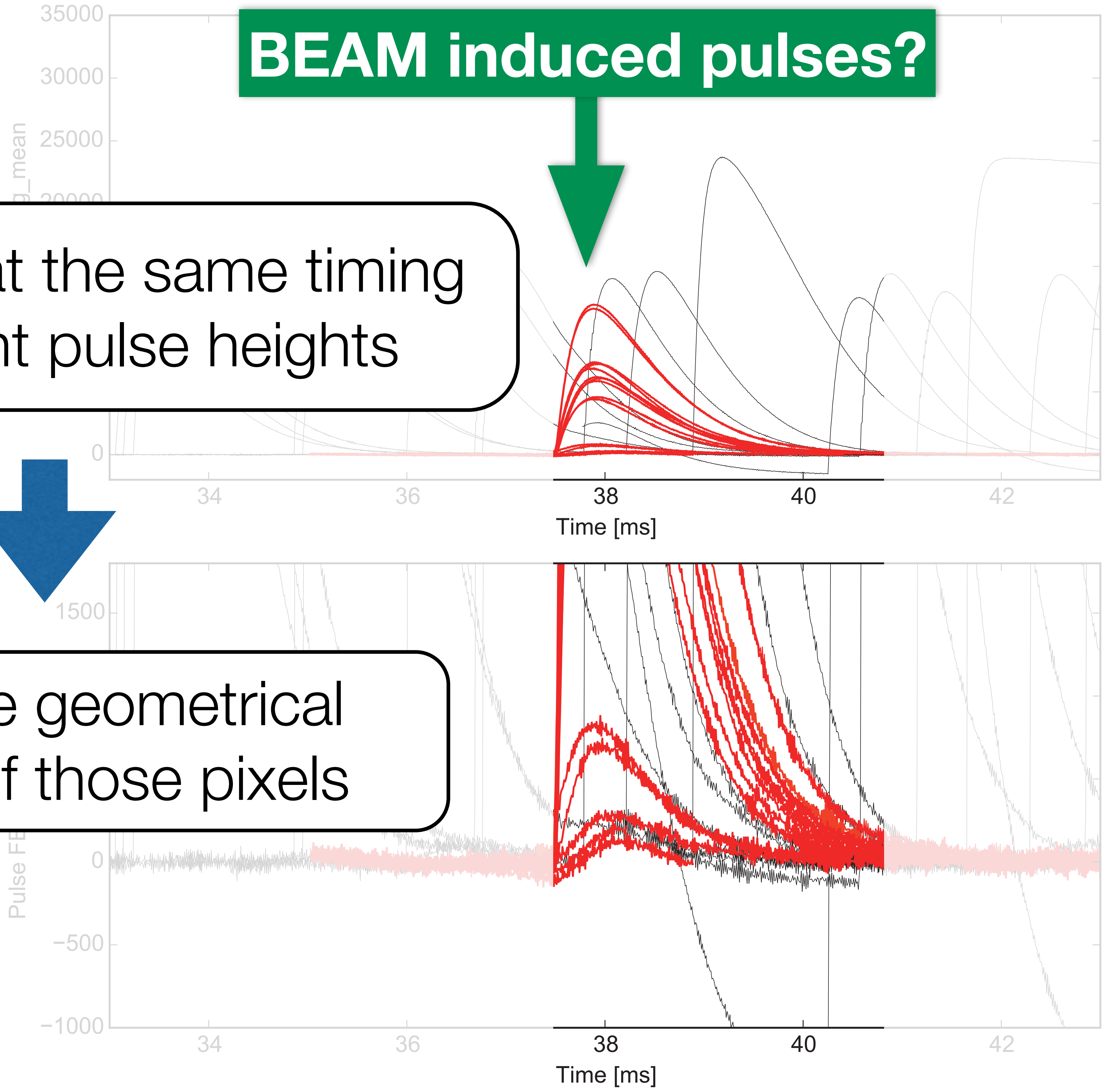
BEAM induced pulses?

normal Mn x-ray pulse height

enlarged view

Cluster events w/ slow rise time -> thermal cross-talk?

Example : beam + Mn x-rays



BEAM induced pulses?

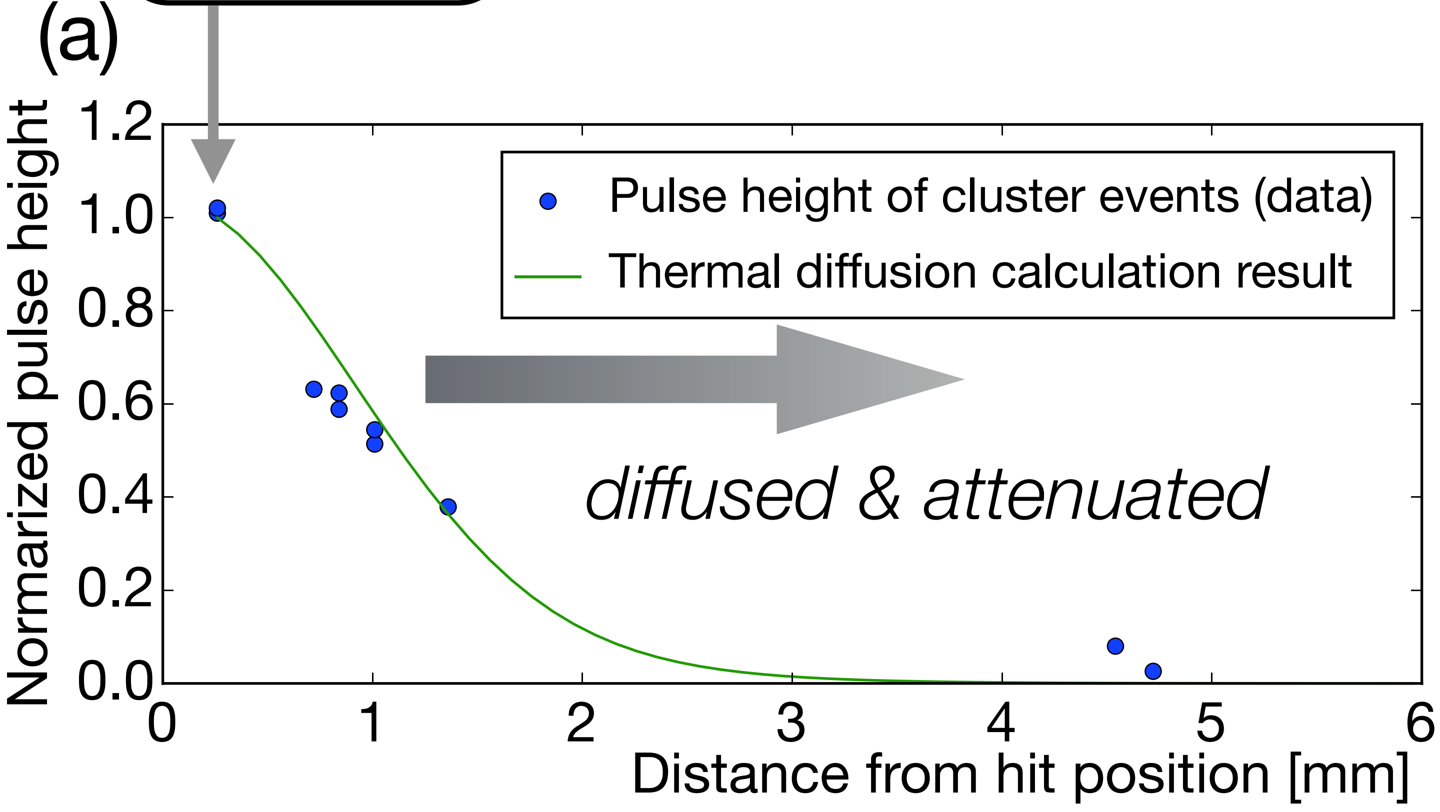
Many pulses at the same timing with different pulse heights

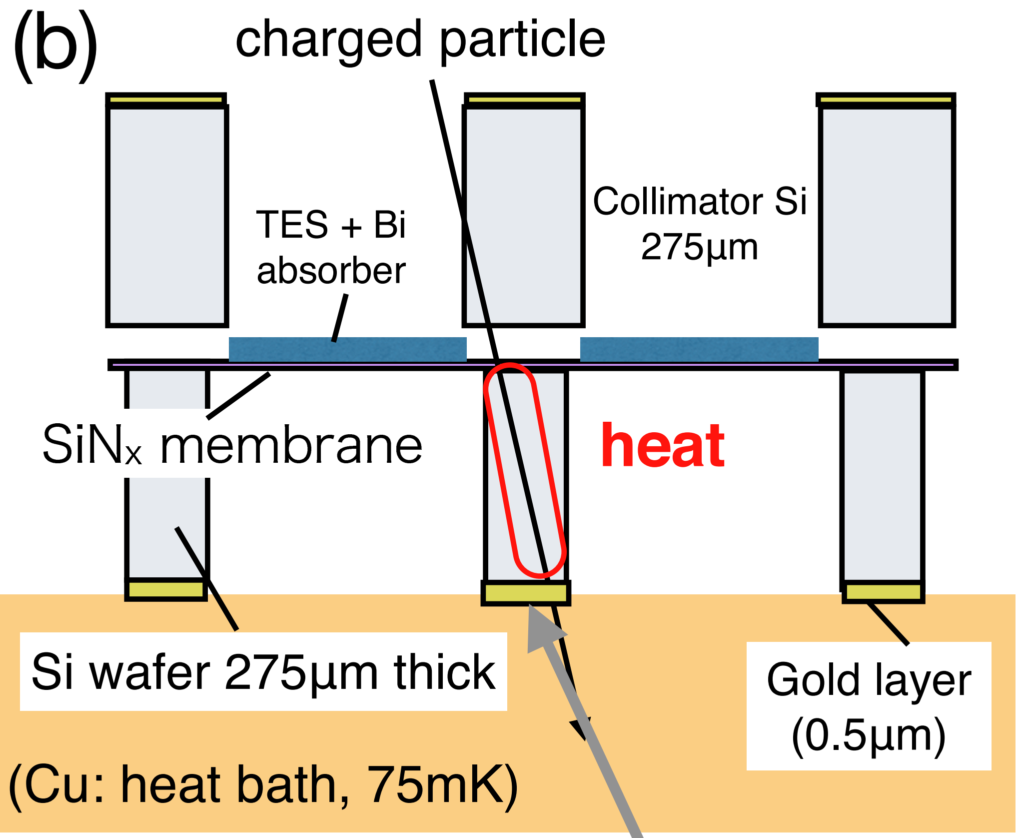
Check the geometrical position of those pixels

enlarged view

Pulse height vs. distance from hit position

Charged particle hit





The heat is diffused and attenuated within several **μsec**.
-> This time scale is much faster than the **msec** TES response.

Large energy deposition
at 275-um Si substrate

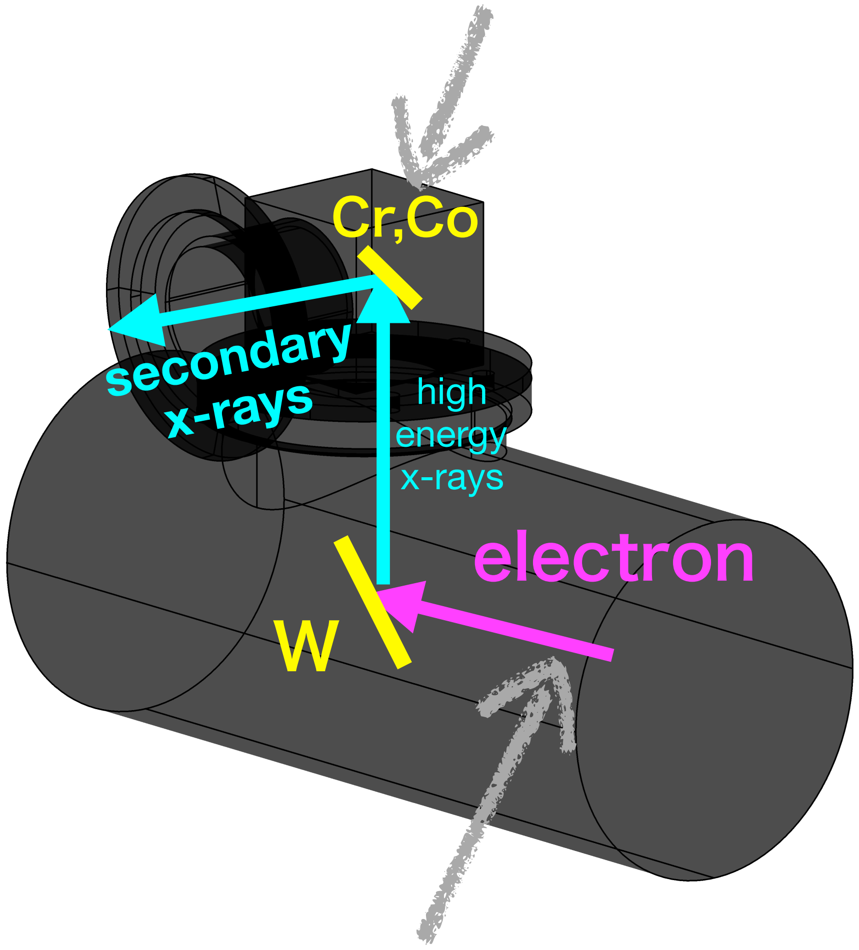
Calibration

X-ray tube for energy calib.

X-ray tube

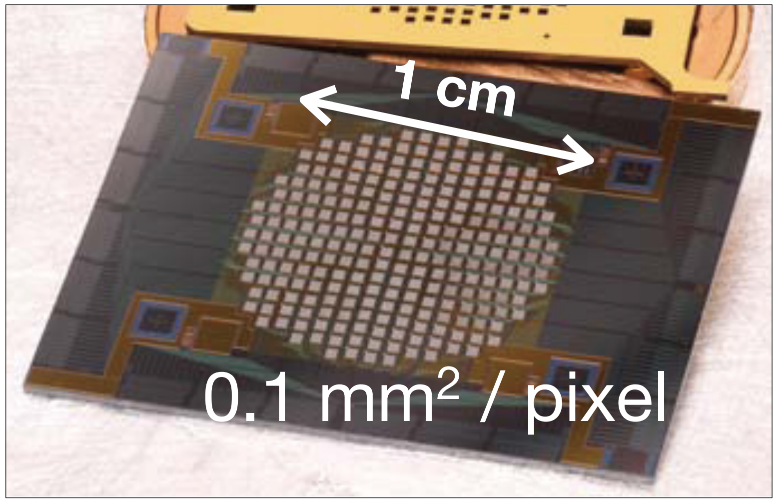
pure metals

as secondary target



electron gun

1. **need intense x-rays** for energy calib. of TES

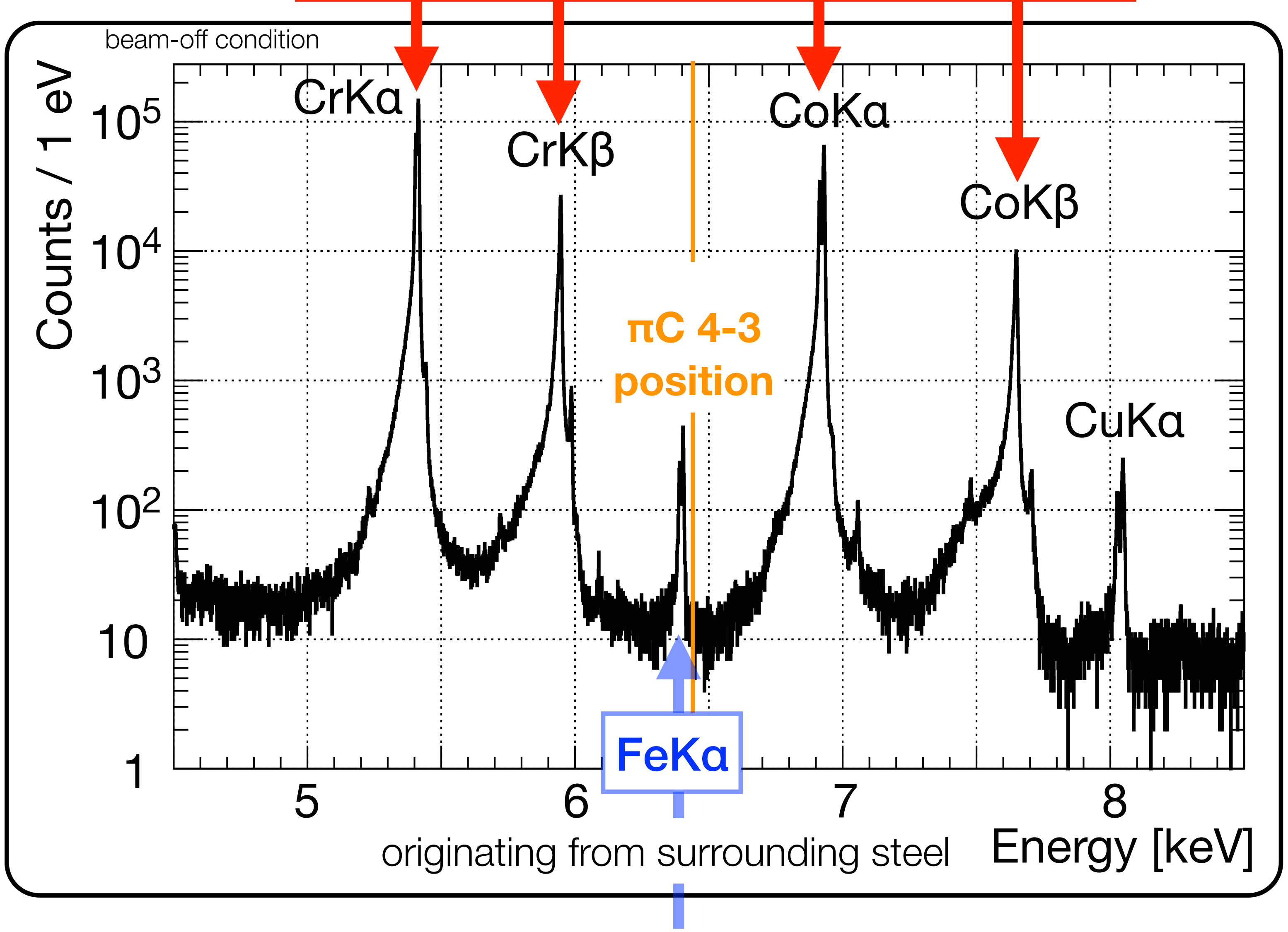


2. use secondary x-ray (Cr Kα, Co Kα line …) which is **unavailable with radioactive source**

In-situ energy calibration

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

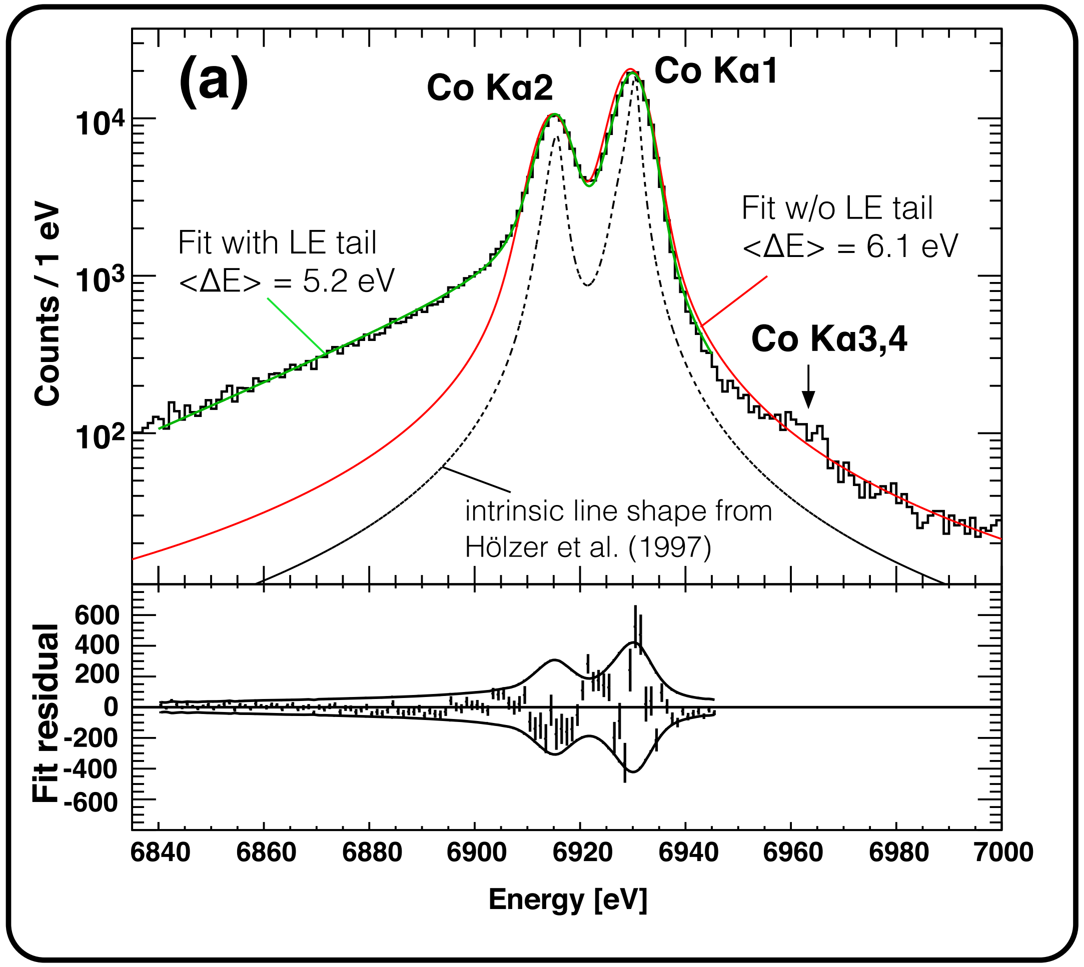
Used high-intensity **4 lines**



originating from surrounding steel

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

Fit example

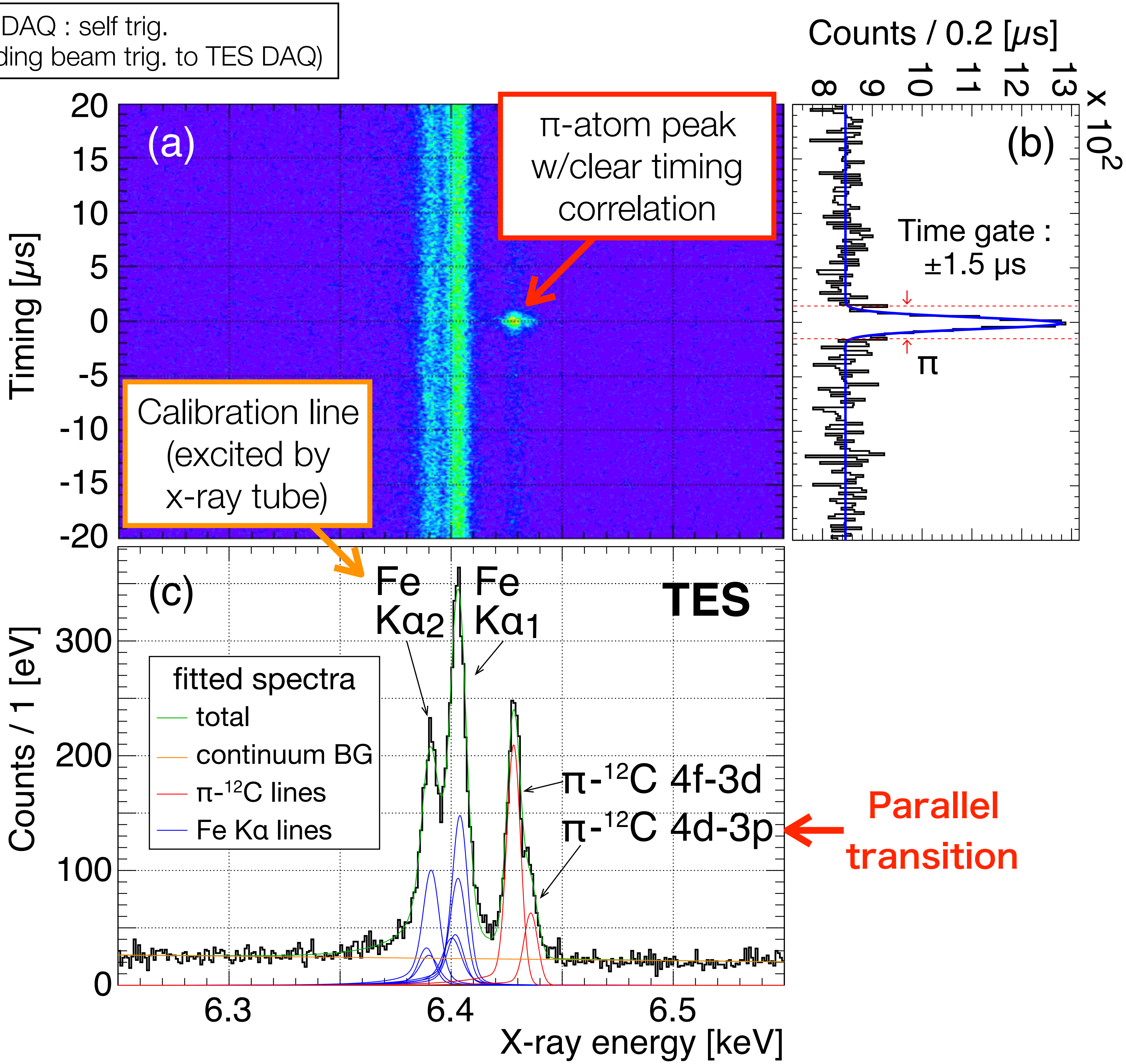


H. Tatsuno et al.,
J Low Temp Phys 184 (2016) 930-937

Results

Successful demonstration w/ π- atom

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

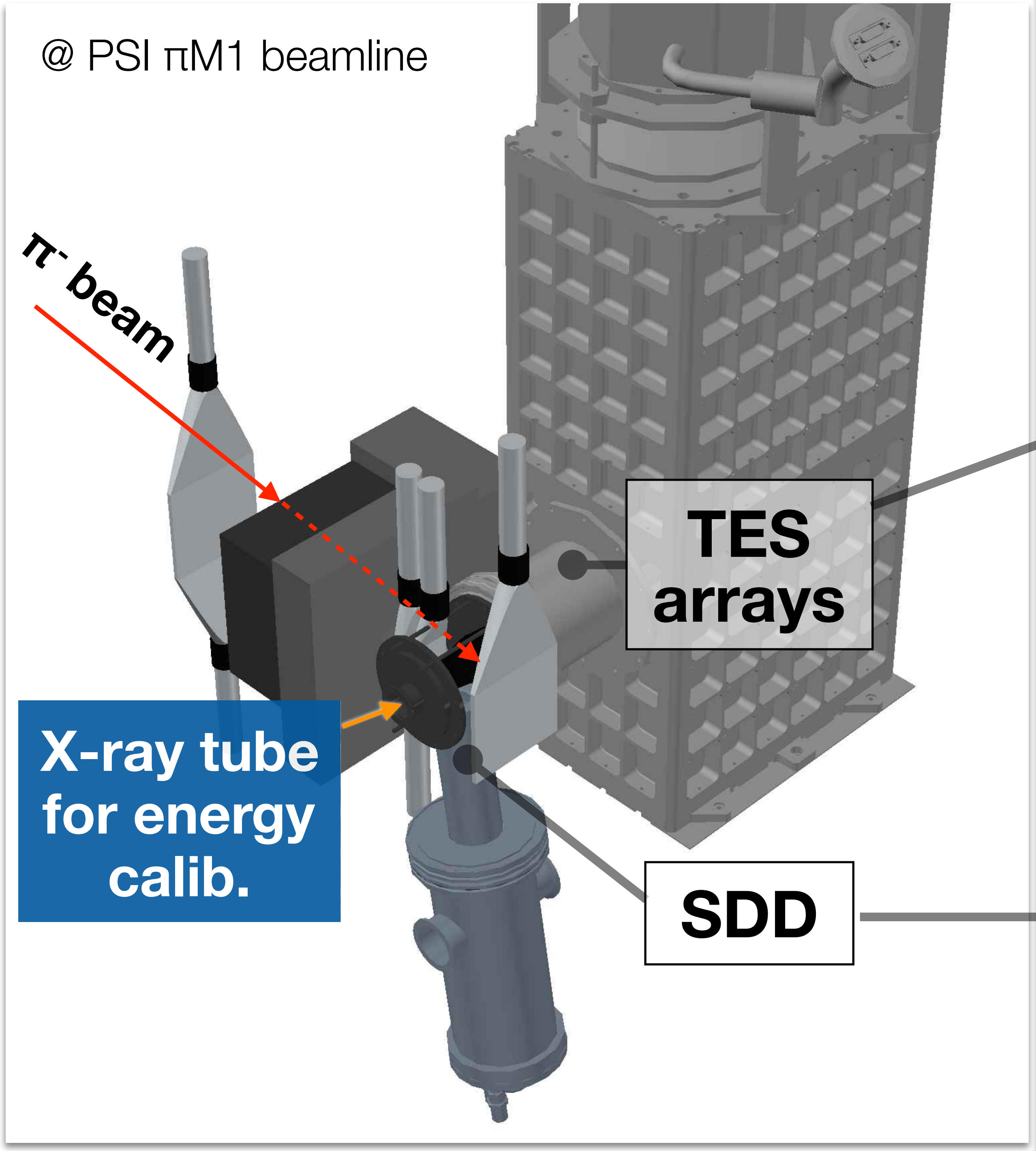


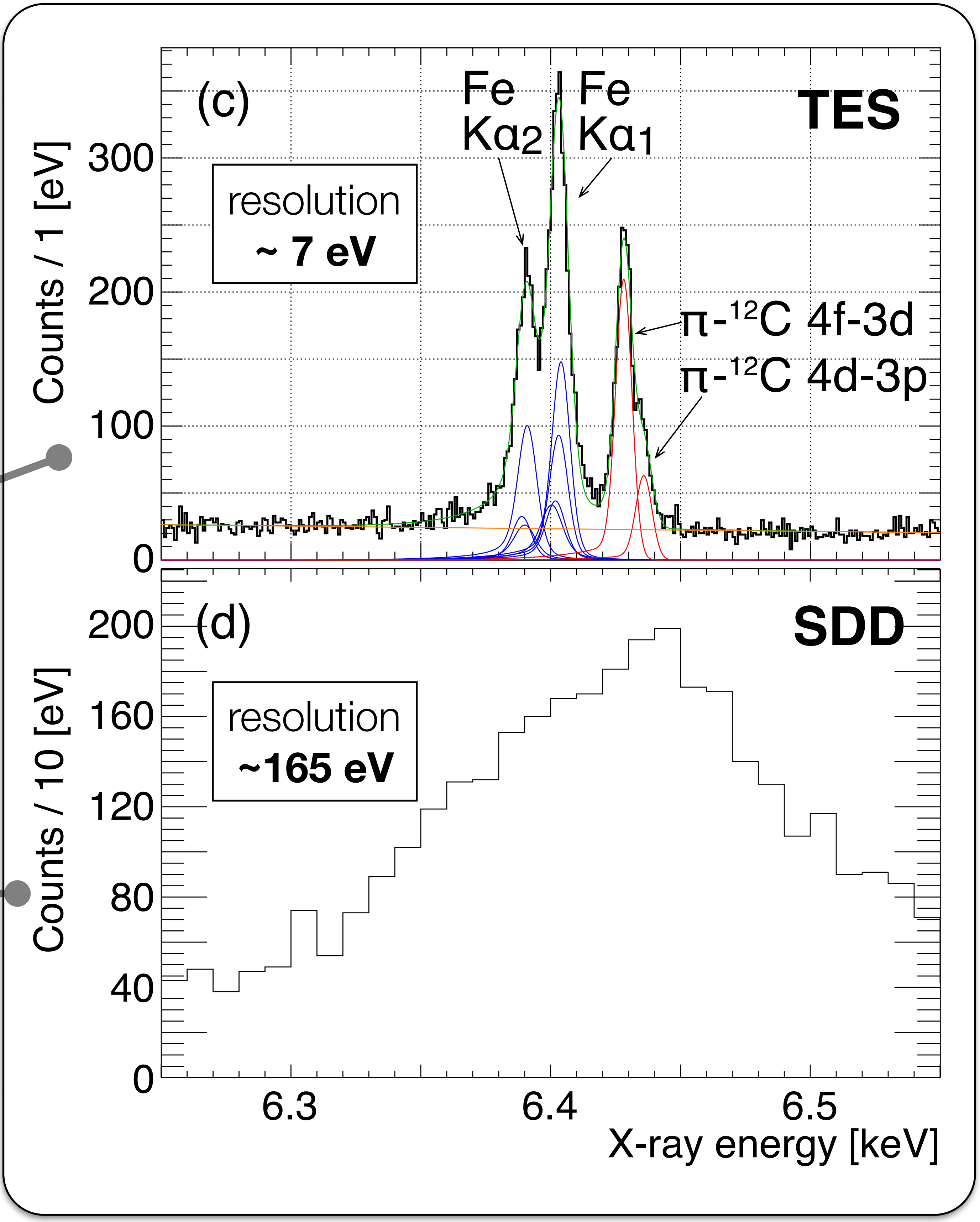
π-atom peak w/clear timing correlation

Calibration line (excited by x-ray tube)

Parallel transition

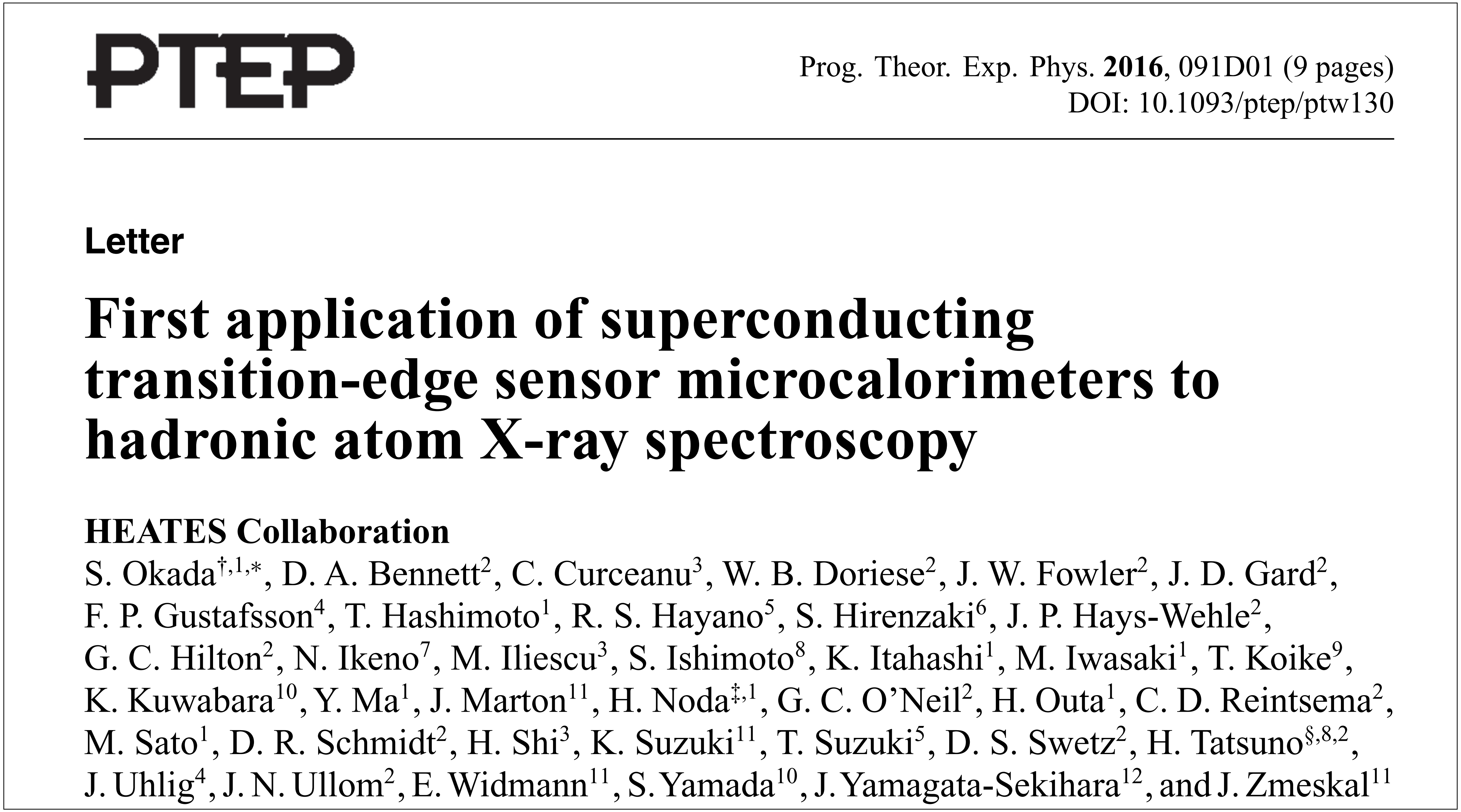
Comparison with SDD spectrum





Published

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
S. Okada[†,1,*], D. A. Bennett[2], C. Curceanu[3], W. B. Doriese[2], J. W. Fowler[2], J. D. Gard[2], F. P. Gustafsson[4], T. Hashimoto[1], R. S. Hayano[5], S. Hirenzaki[6], J. P. Hays-Wehle[2], G. C. Hilton[2], N. Ikeno[7], M. Iliescu[3], S. Ishimoto[8], K. Itahashi[1], M. Iwasaki[1], T. Koike[9], K. Kuwabara[10], Y. Ma[1], J. Marton[11], H. Noda[‡,1], G. C. O'Neil[2], H. Outa[1], C. D. Reintsema[2], M. Sato[1], D. R. Schmidt[2], H. Shi[3], K. Suzuki[11], T. Suzuki[5], D. S. Swetz[2], H. Tatsuno[§,8,2], J. Uhlig[4], J. N. Ullom[2], E. Widmann[11], S. Yamada[10], J. Yamagata-Sekihara[12], and J. Zmeskal[11]

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 :

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

⇒ comparison with EM calc?

EM values & strong-int calc.

EM calc. (T. Koike)

State	K.G. energy (eV)	Vacuum polarization		Nuclear finite size effect (eV)	Relativistic recoil effect (eV)	Strong interaction effect (eV)	Total energy (eV)
		$\alpha(Z\alpha)$ (eV)	$\alpha^2(Z\alpha)$ (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)

⇒ Non-negligible contribution from 3p level

Electron screening effects

calc. by T. Koike

one e- in K-shell
two e- in K-shell

Transitions	Electron screening effect (eV)			Transition
	Configuration	K-shell contribution	L-shell contribution	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 :

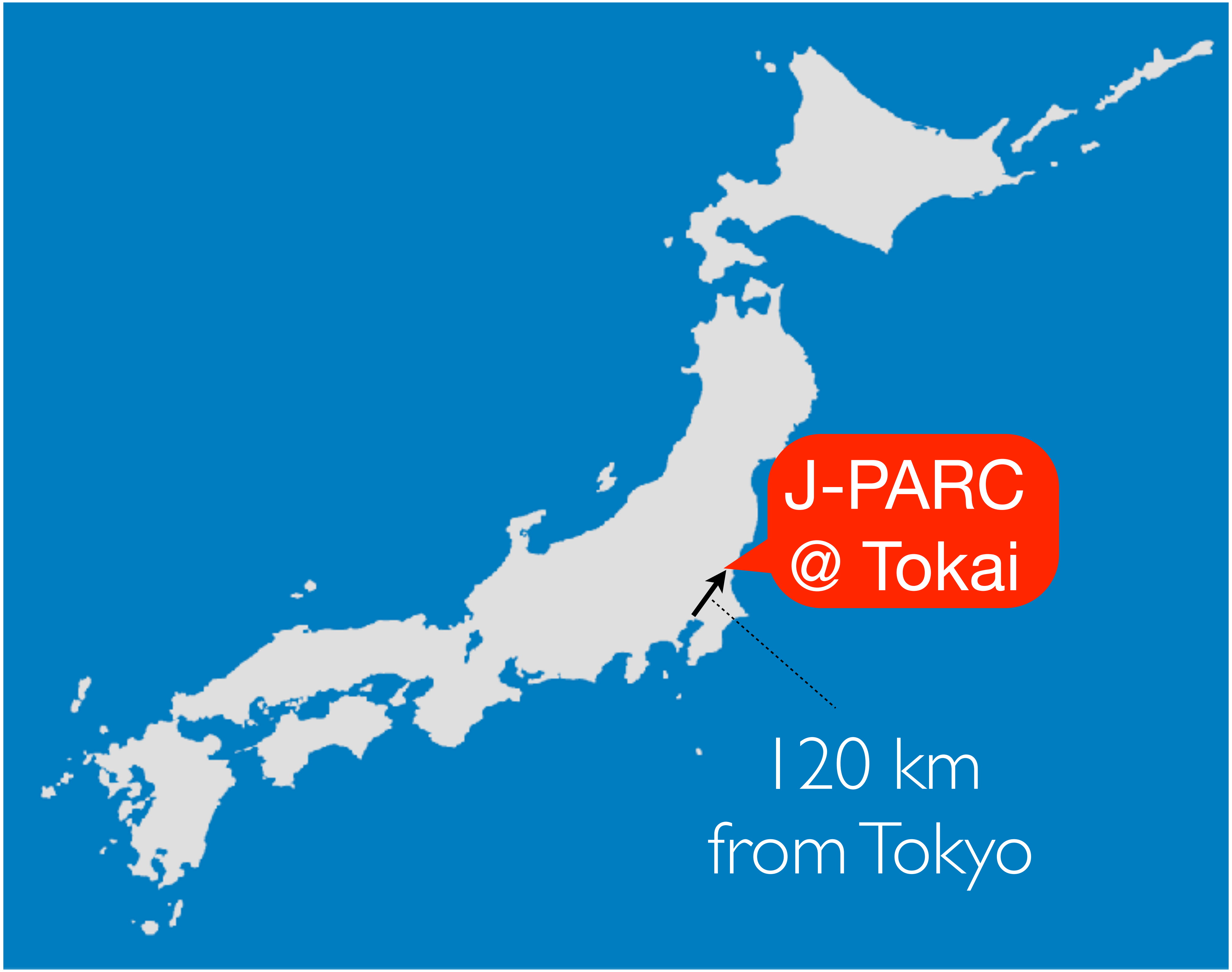
✓ **favor two 1s electrons** in the K-shell

✓ energy shift of measured parallel-transition is **consistent** with strong-int effect assessed via **Seki-Matsutani potential**

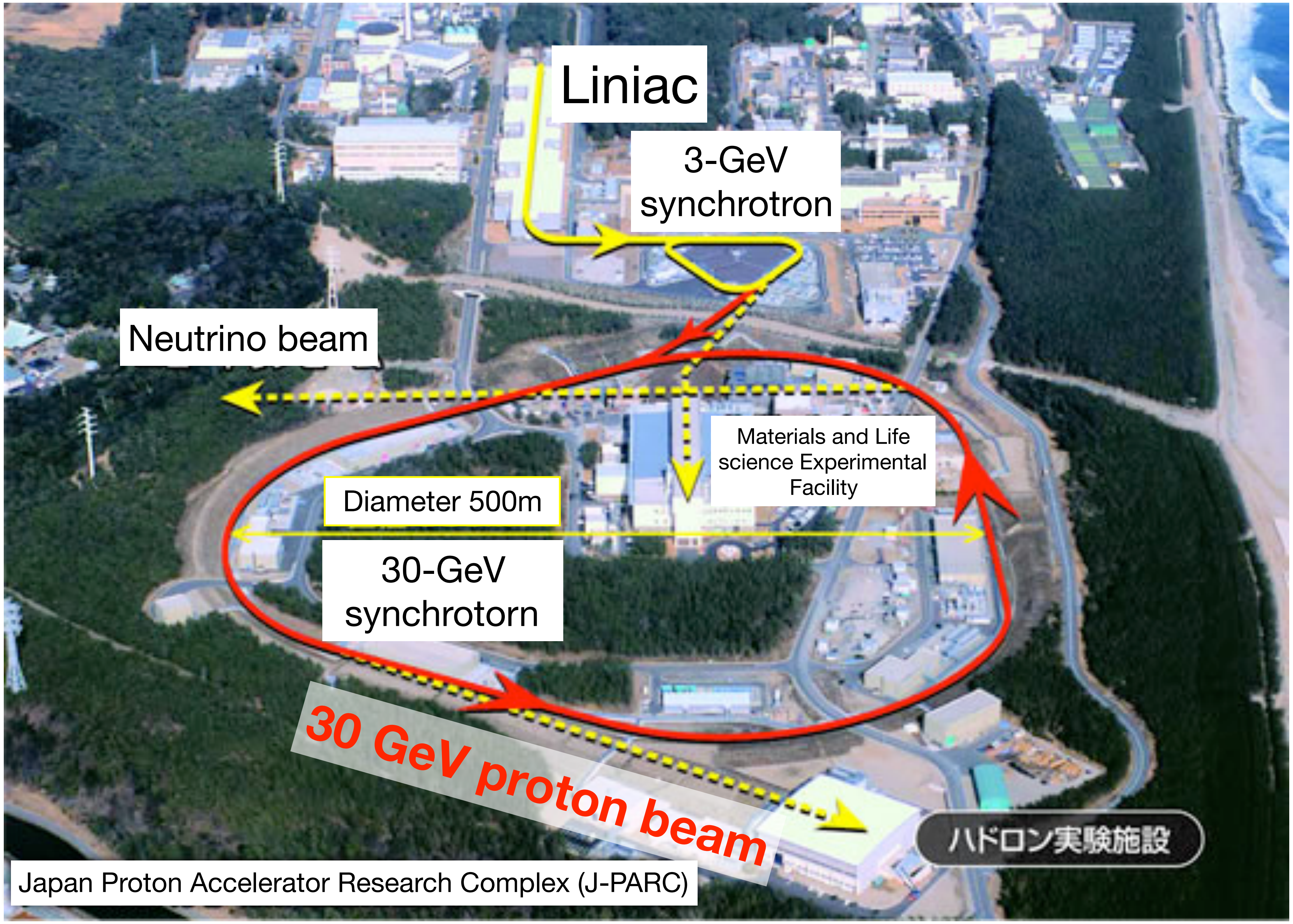
② K^- beam

4-days beamtime
in June 2016

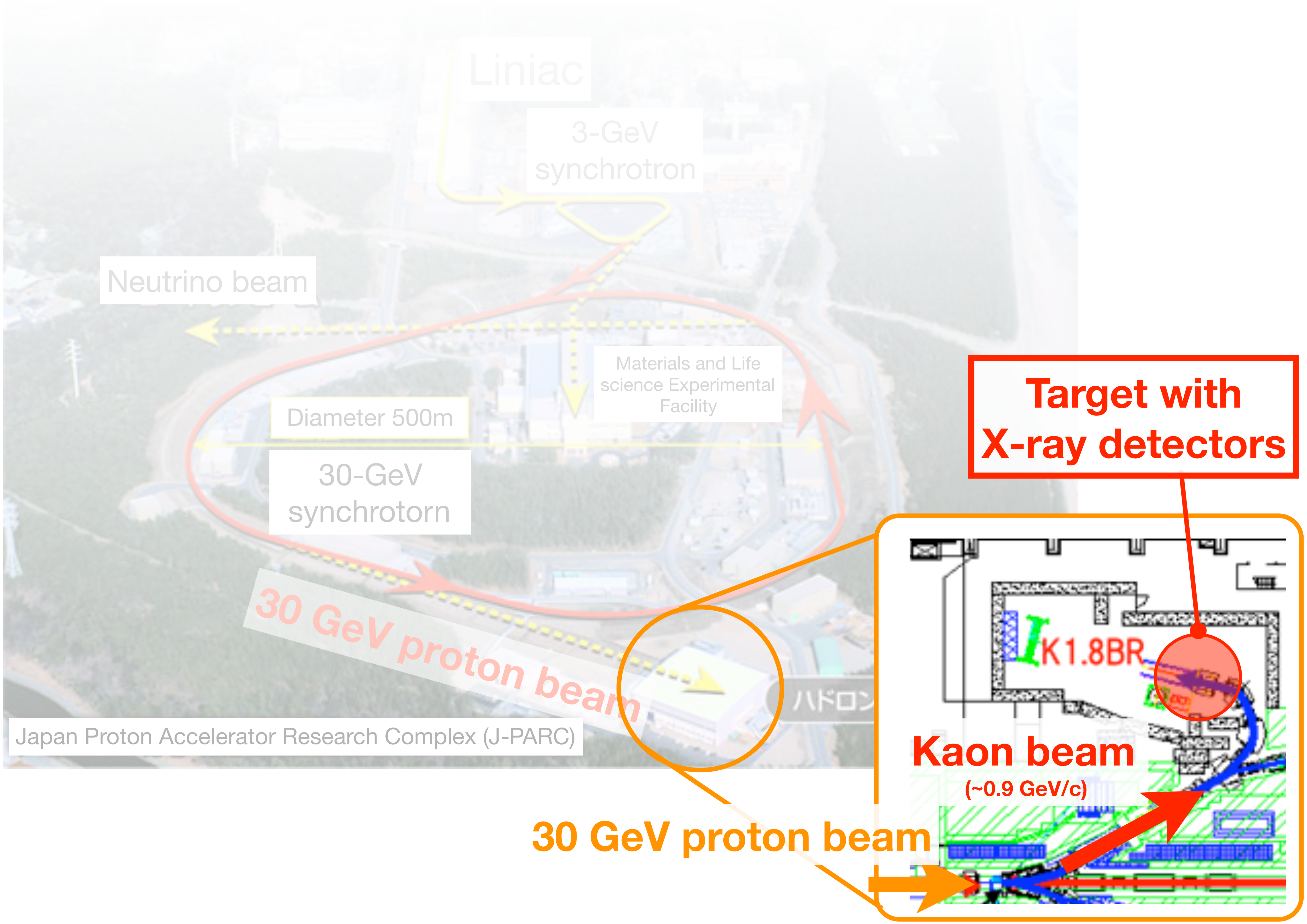
J-PARC



J-PARC


Liniac
3-GeV synchrotron
Neutrino beam
Materials and Life science Experimental Facility
Diameter 500m
30-GeV synchrotorn
30 GeV proton beam
ハドロン実験施設
Japan Proton Accelerator Research Complex (J-PARC)

J-PARC



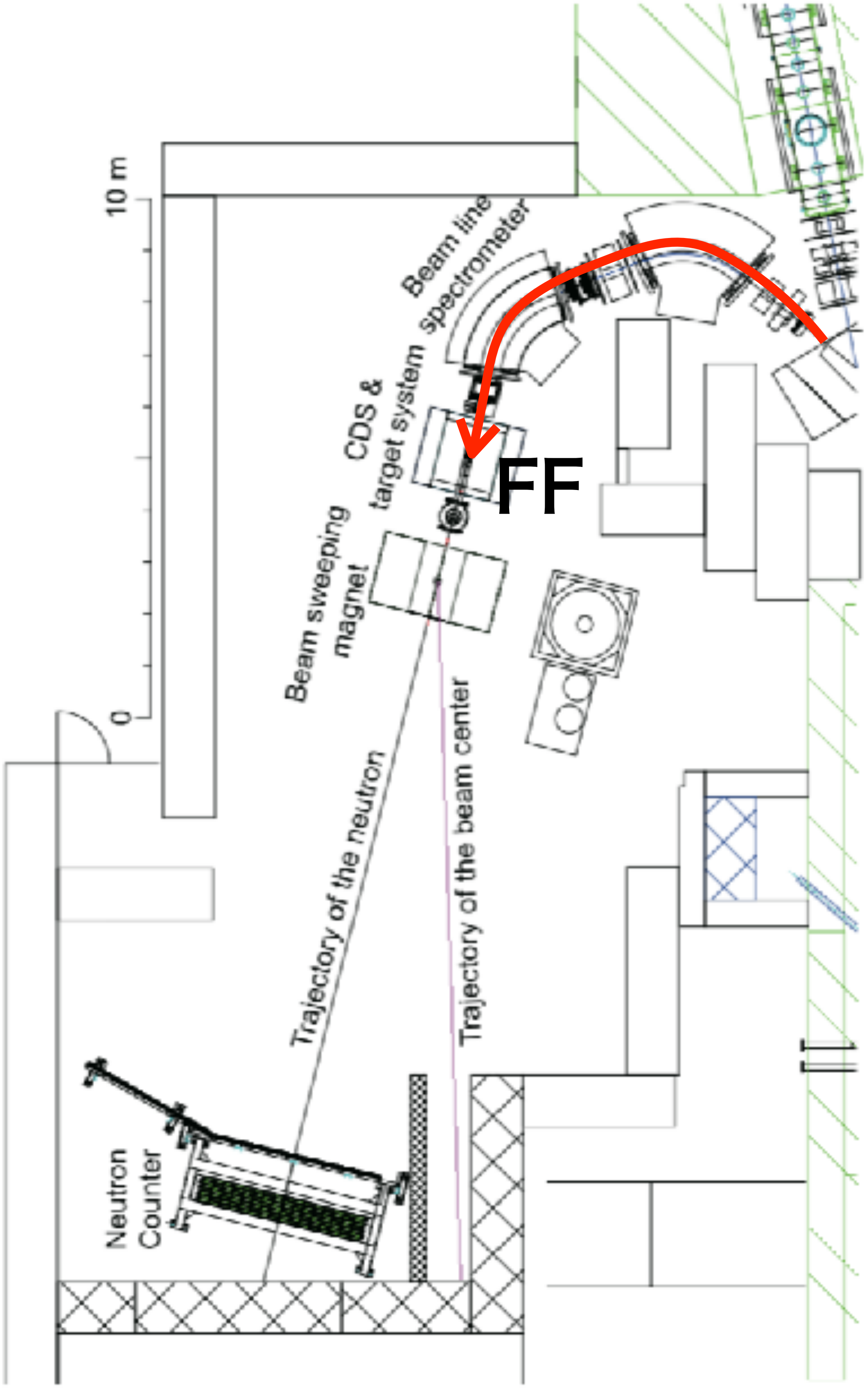
Japan Proton Accelerator Research Complex (J-PARC)

Target with X-ray detectors

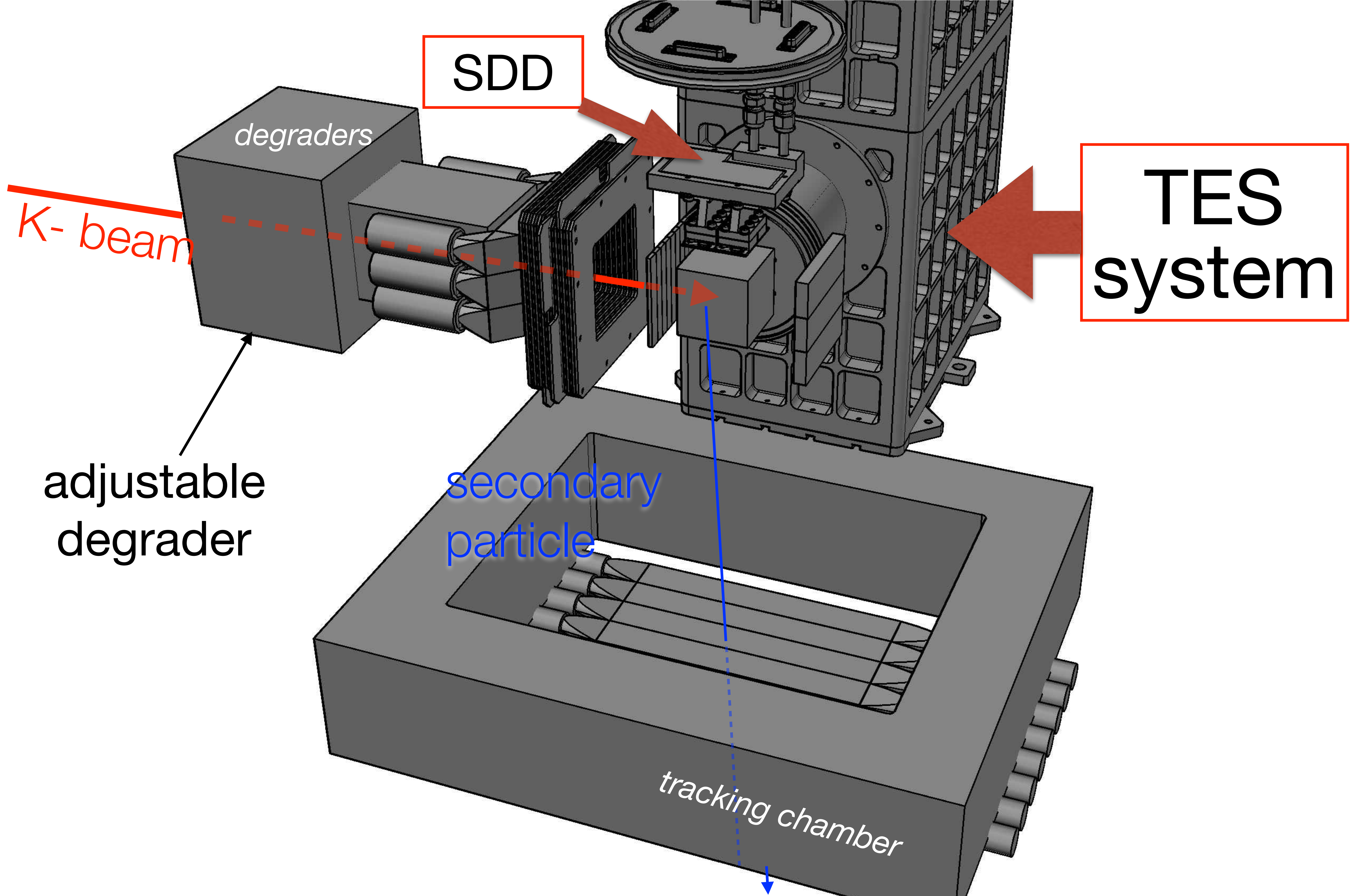
Kaon beam
(~0.9 GeV/c)

30 GeV proton beam

Experimental hall (K1.8BR)



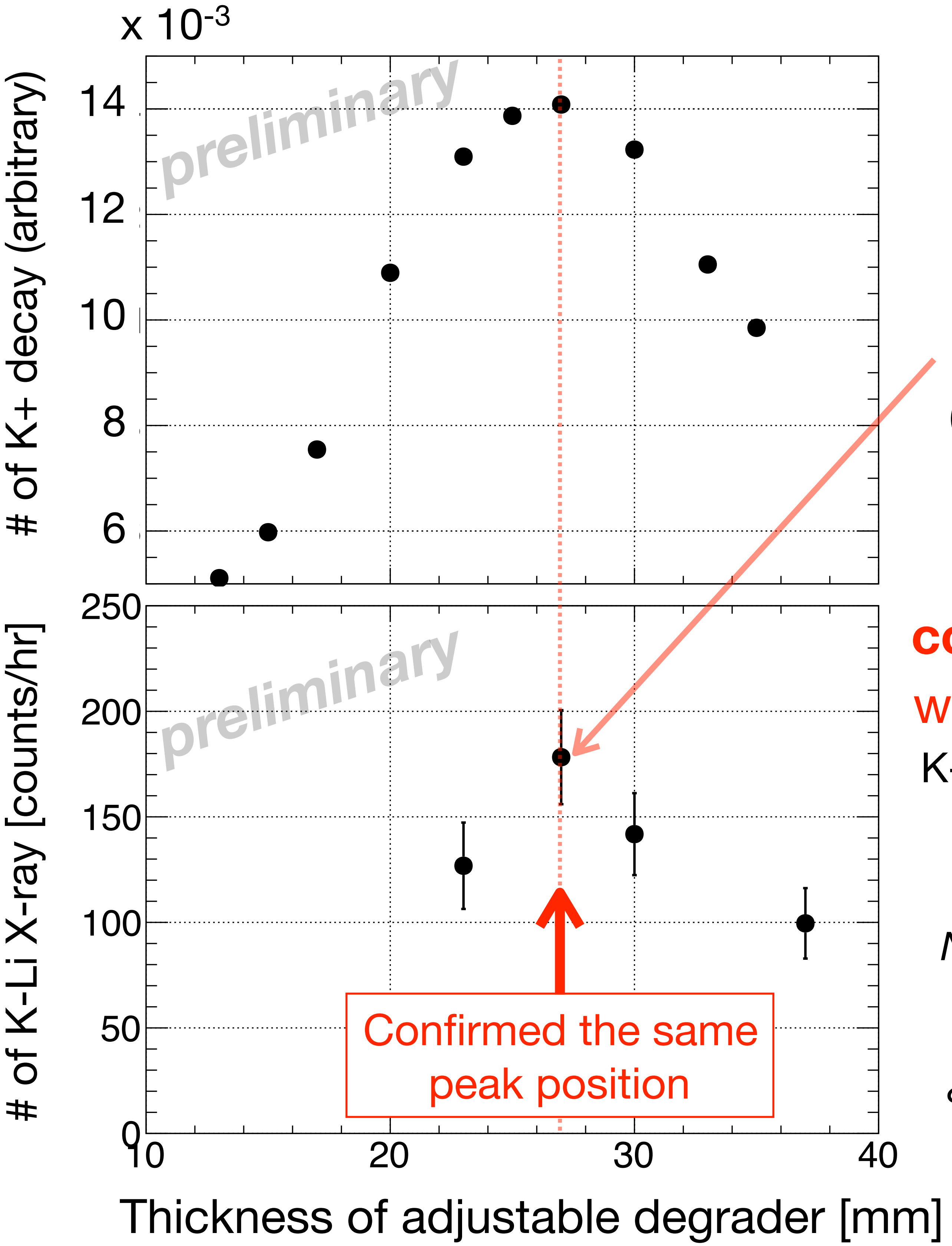
Kaon-stop tuning setup



K- stop tuning

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

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



Confirmed the same peak position

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

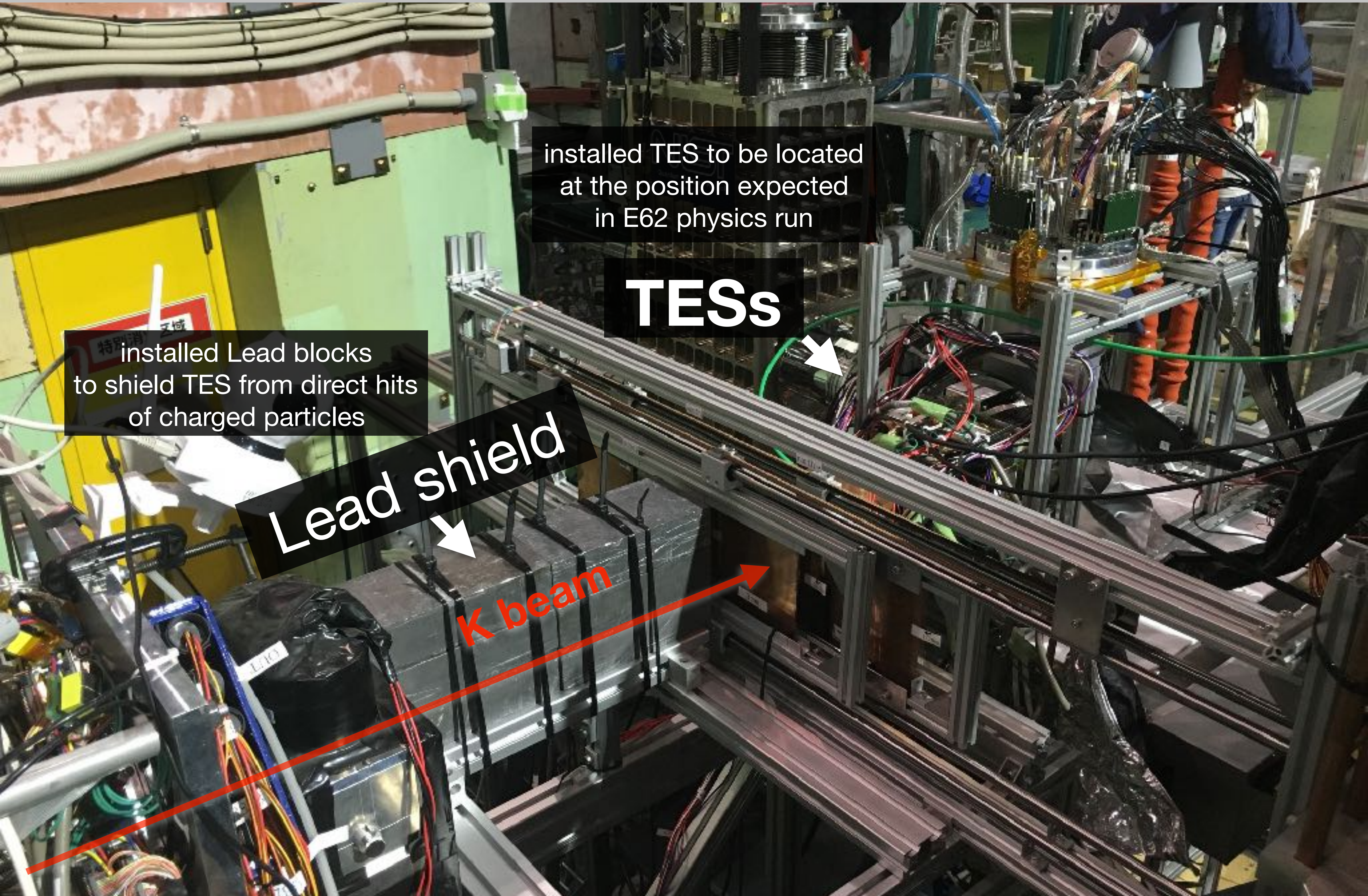
consistent with G4 sim

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



installed TES to be located at the position expected in E62 physics run

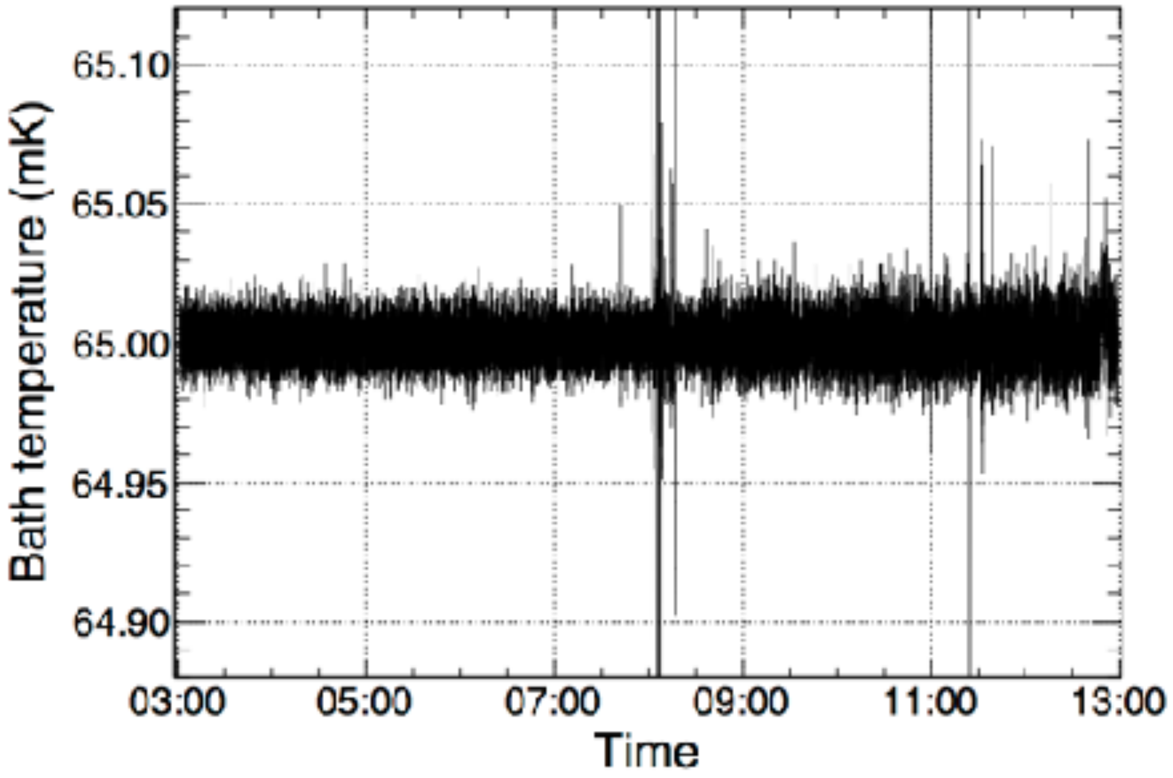
installed Lead blocks to shield TES from direct hits of charged particles

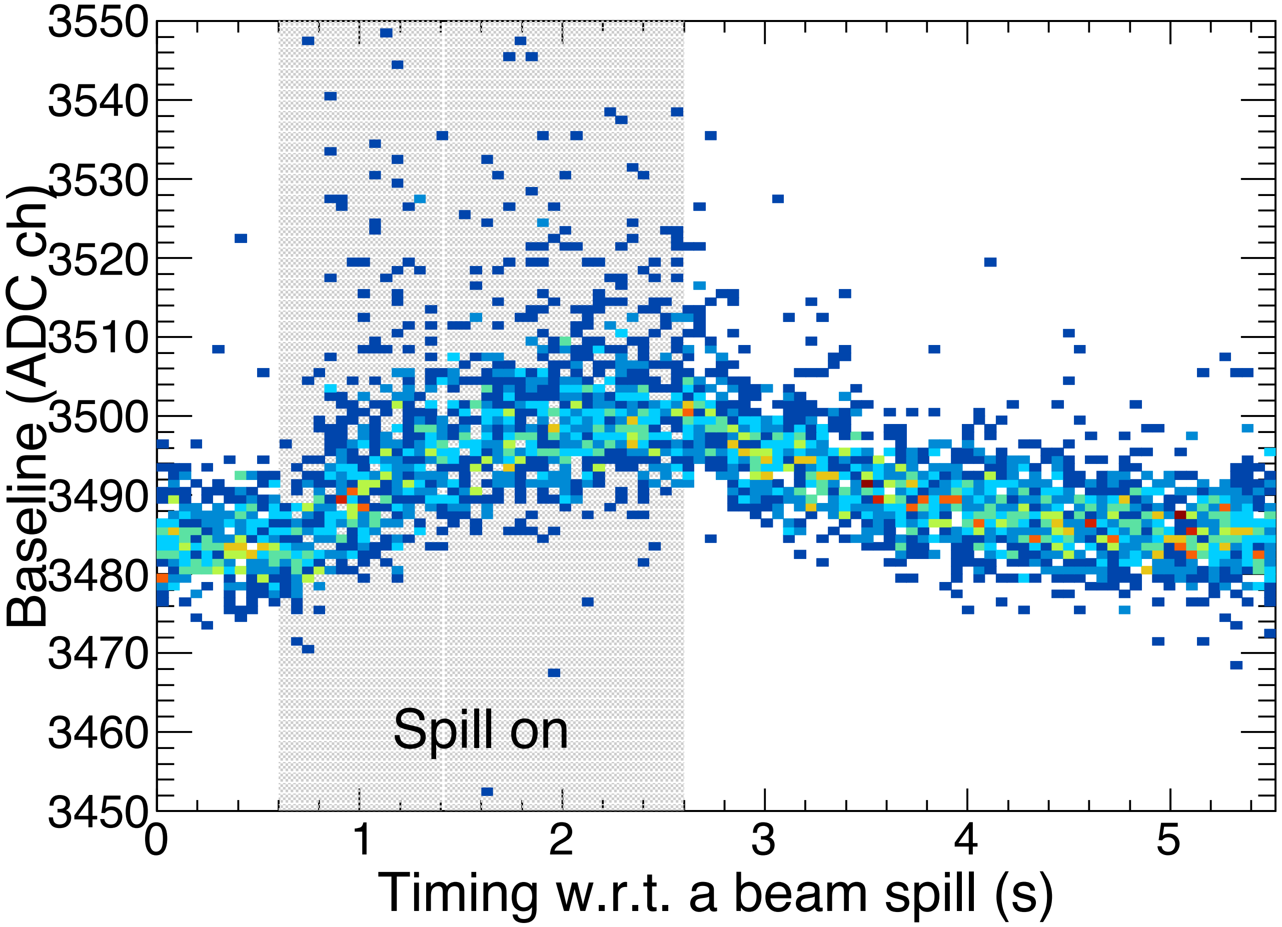
Beam structure

~3.5 sec beam off

~2 sec beam on

ΔT ~7.7 mK (rms) ~9.7 mK (rms)

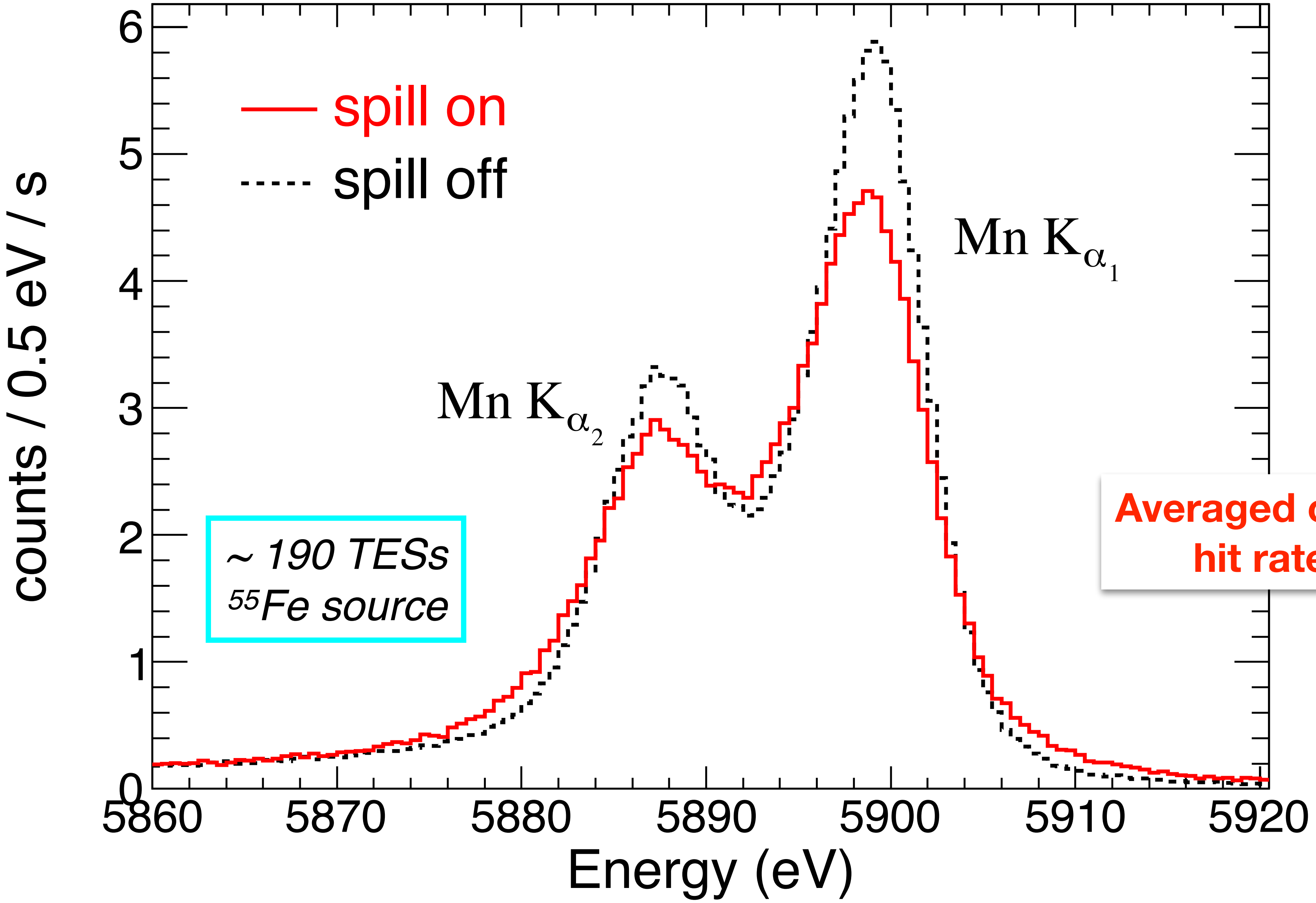




- Temperature regulation holds in the pulsed beam
- TES temperature clearly increases during a beam spill

⇒ this effect can be compensated in the standard analysis procedure

Mn Kα spectrum

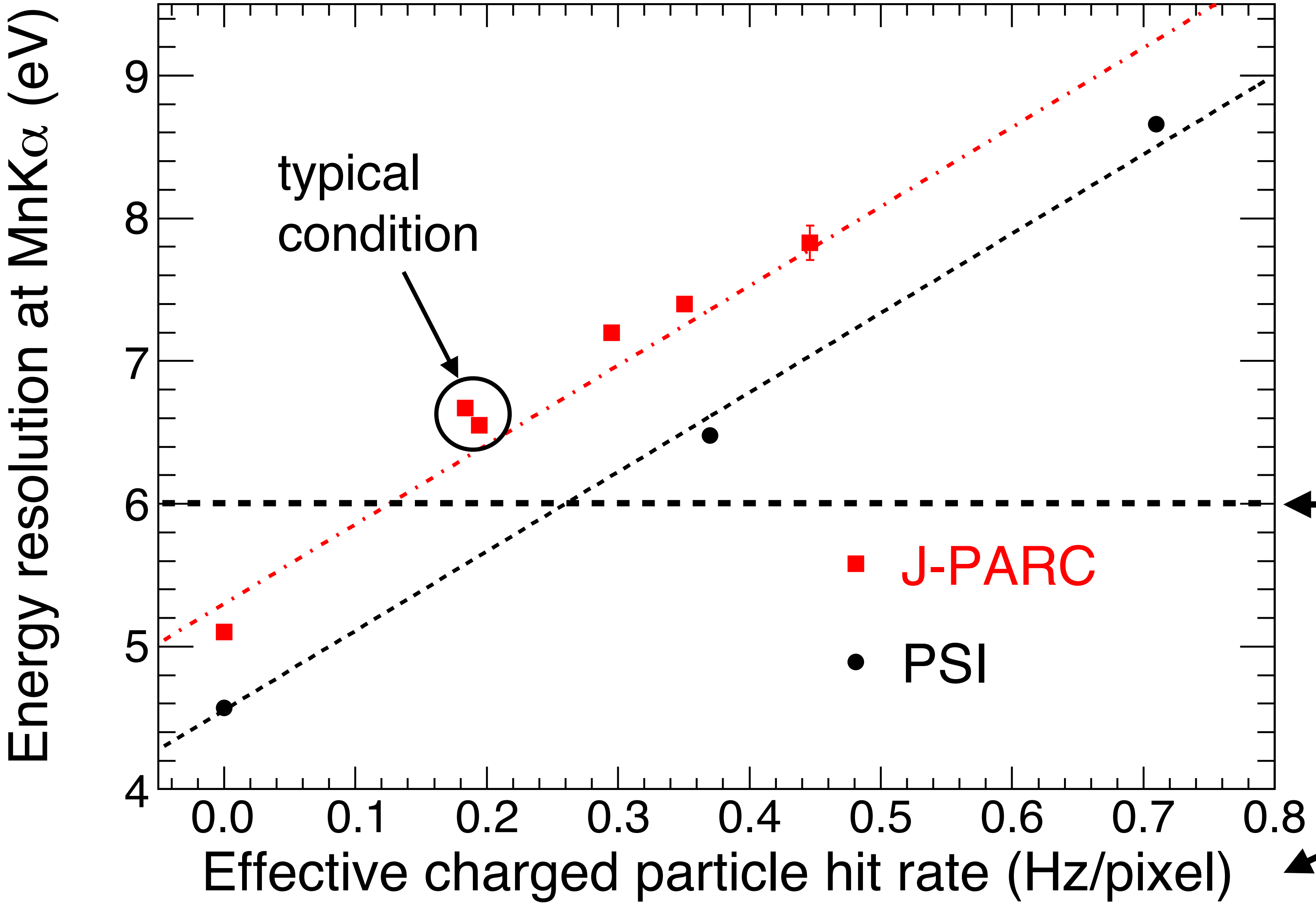


~ 190 TESs
^{55}Fe source

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



our goal: < 6 eV

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

✓ Similar correlation in the two different beams

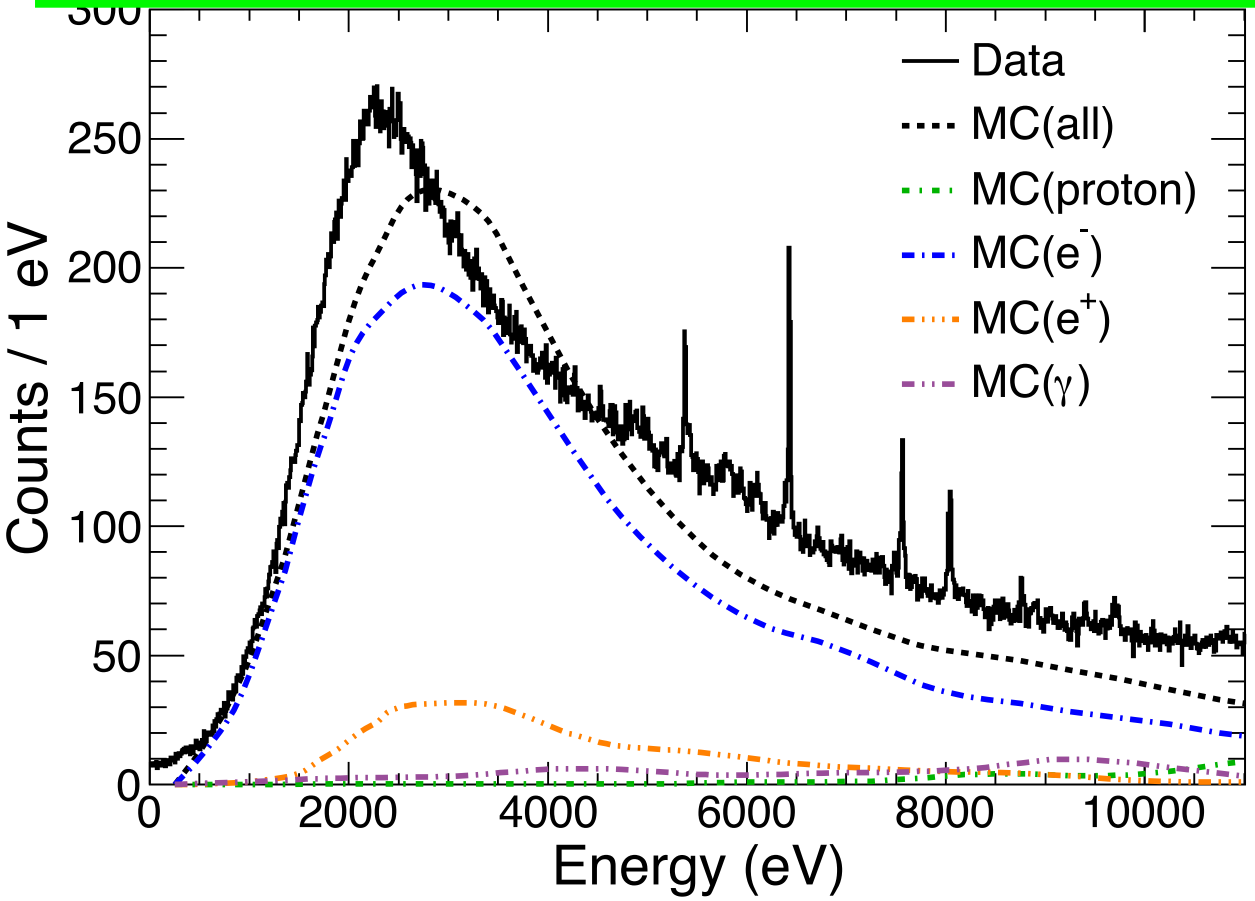
✓ Promising to achieve our goal at J-PARC

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

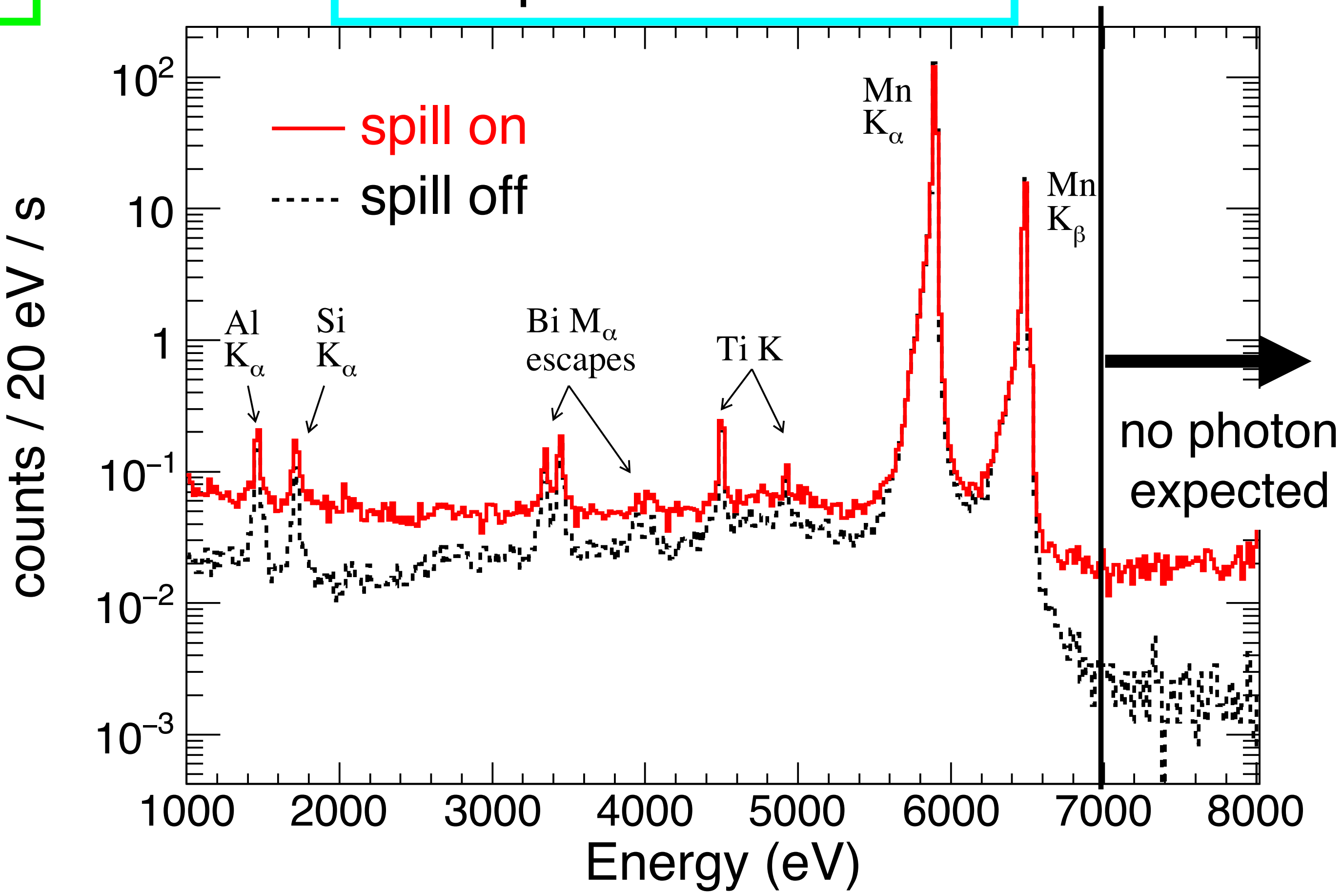
Charged particle background

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

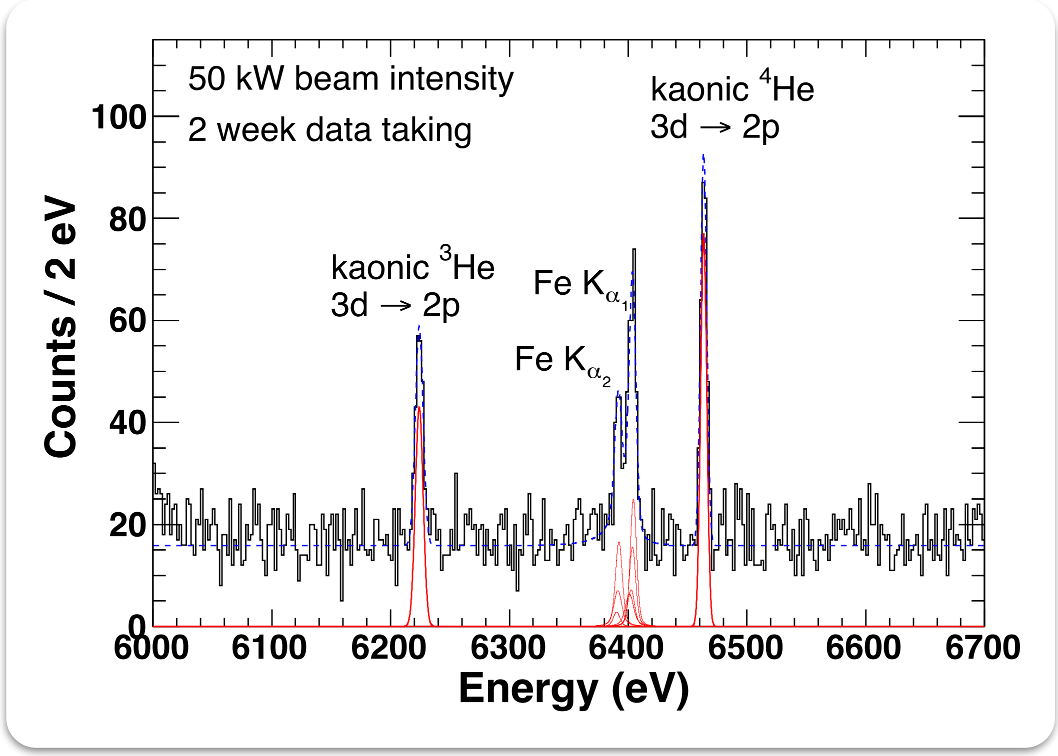


We understand the beam-induced background

- ✓ explained PSI spectrum well by simulation including its intensity
- ✓ J-PARC background level is consistent with the MC

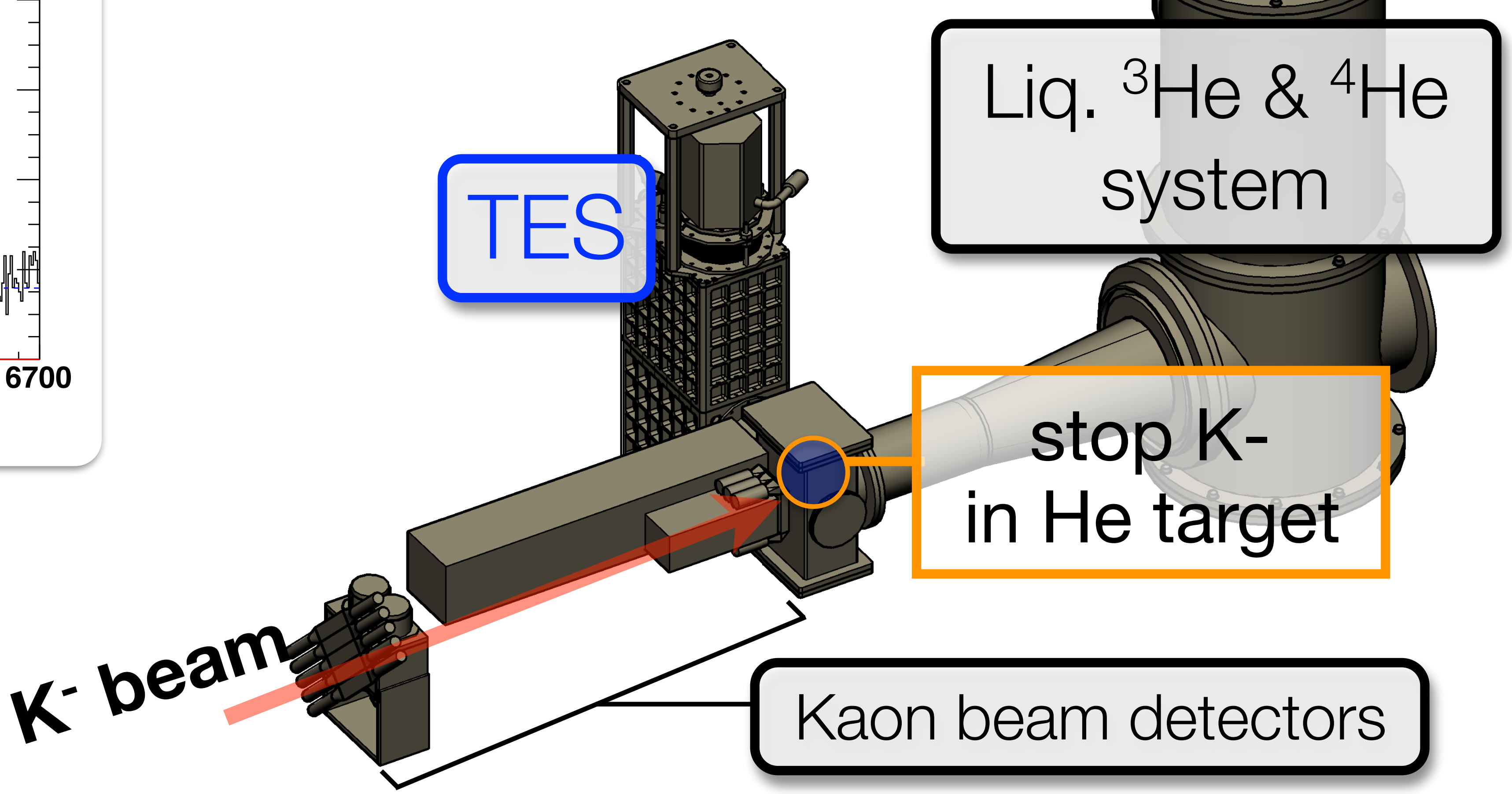
J-PARC E62 : K-He atom exp.

Expected spectrum



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

Resolution goal : 6 eV
Precision goal : 0.2 eV

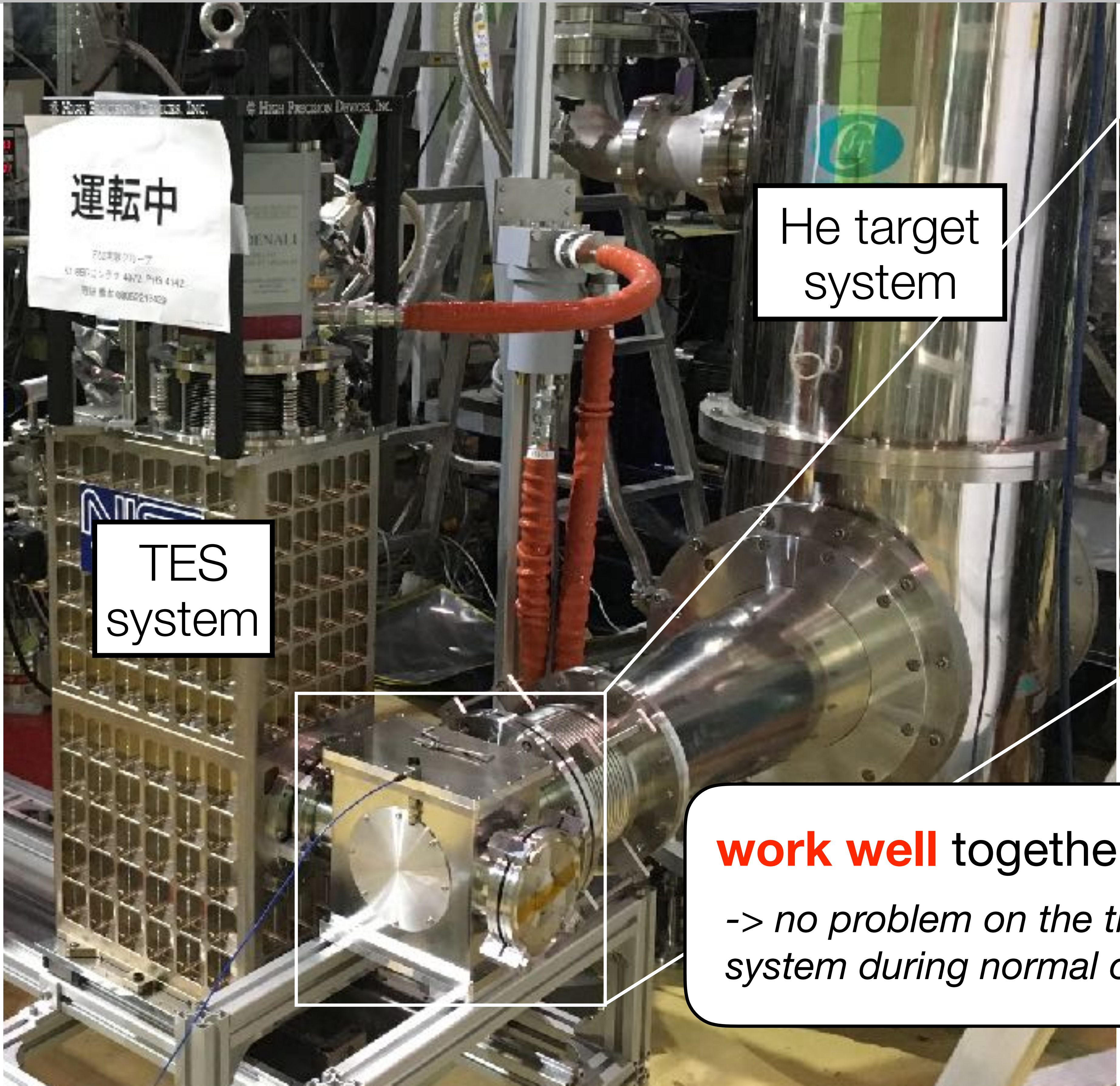


To do :

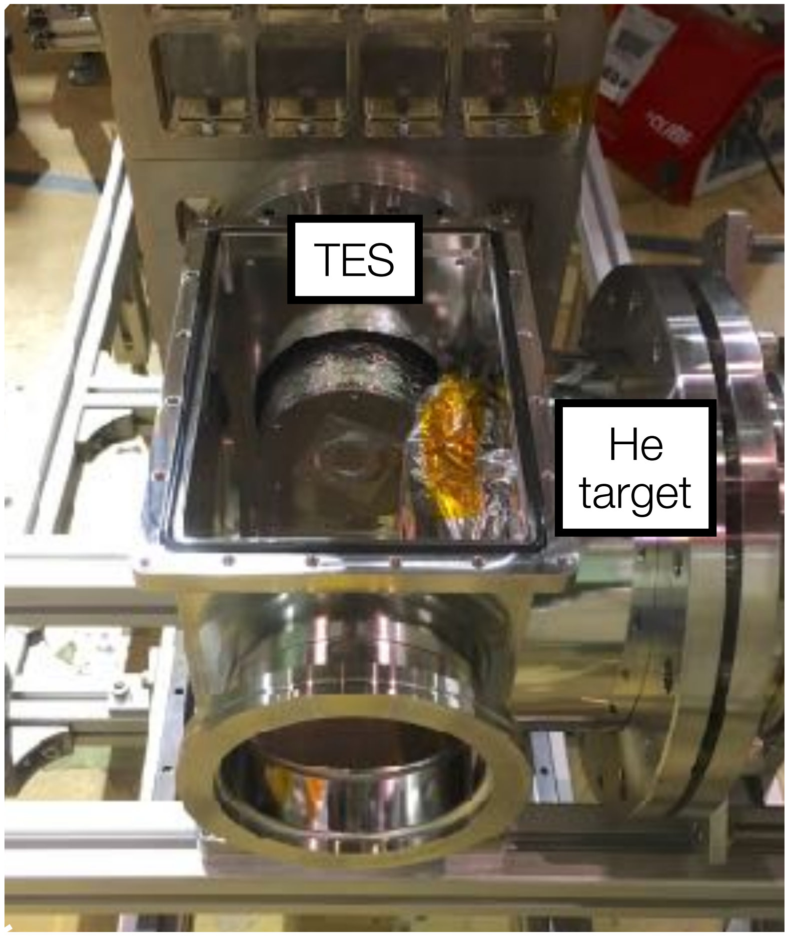
- Increase the number of working pixels (now ~190/240)
- Detailed study with an X-ray tube and radioactive sources
- Combine the TES spectrometer with the liquid helium target

E62 preparation status

TES + He target



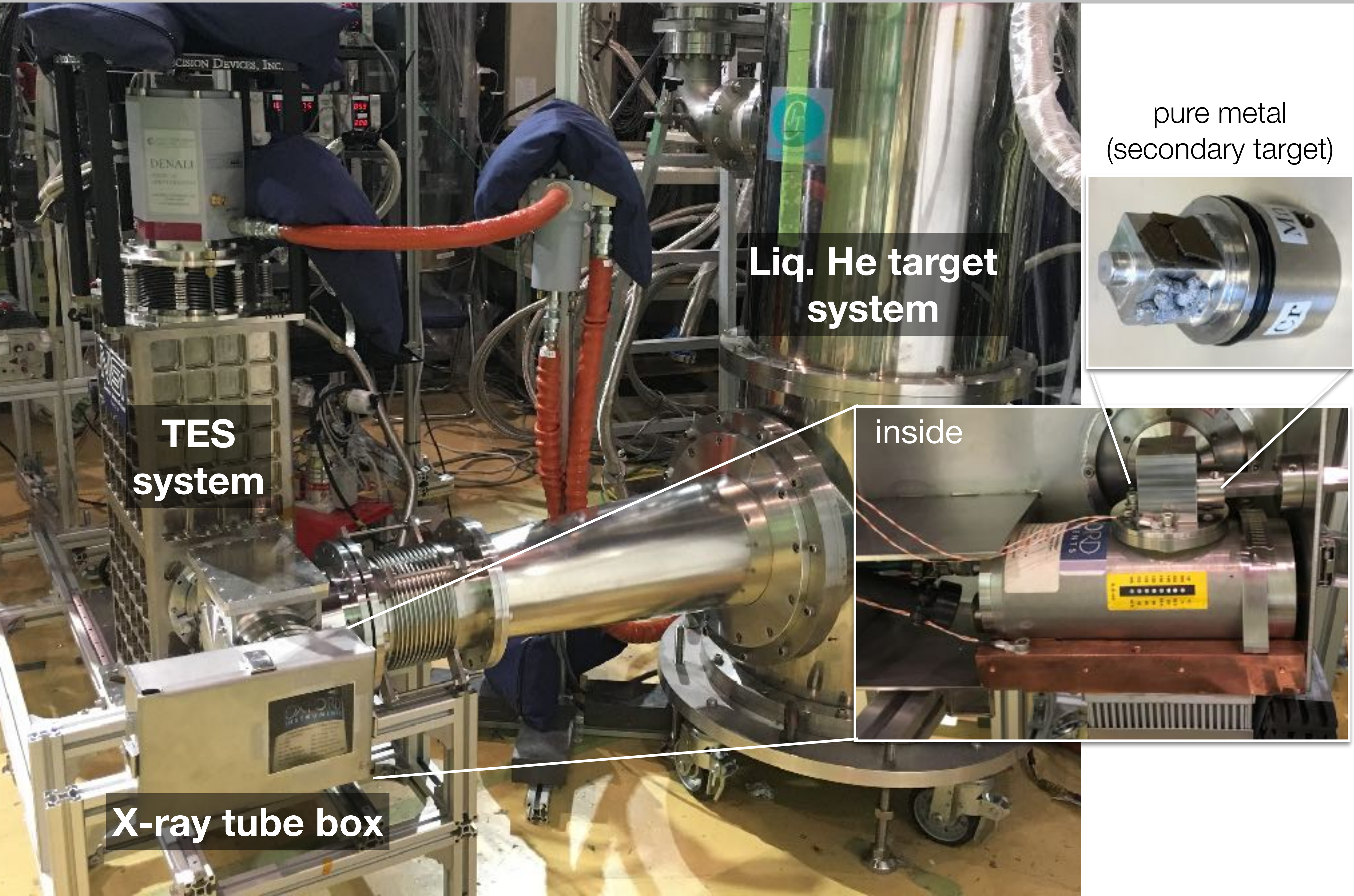
top view (inside)



work well together with target cryostat

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

X-ray tube for energy calib.



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

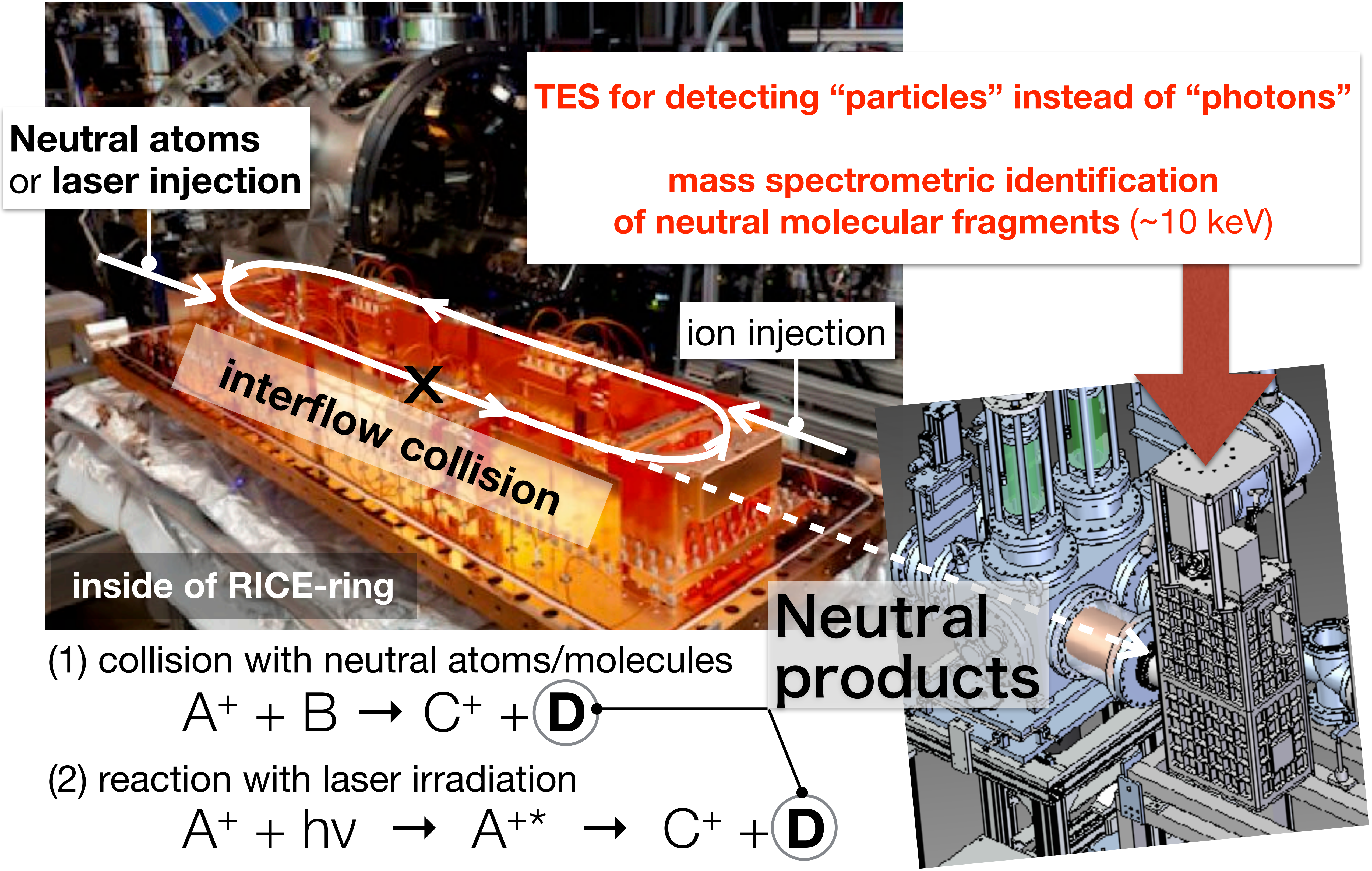
② **K^- beam** : good performance at actual beamline as well

◉ J-PARC E62 (K-He atom x-ray) physics run in 2018?

Appendix

New application at RIKEN RICE-ring

Cryogenic electrostatic ion strage ring



Neutral atoms
or **laser injection**

TES for detecting "particles" instead of "photons"

mass spectrometric identification
of neutral molecular fragments (~10 keV)

ion injection

Neutral products

(1) collision with neutral atoms/molecules

$$A^+ + B \rightarrow C^+ + \boxed{\mathbf{D}}$$

(2) reaction with laser irradiation

$$A^+ + hv \rightarrow A^{+*} \rightarrow C^+ + \boxed{\mathbf{D}}$$