2 Aug., 2016

Meson in Nucleus 2016 (MIN16) @YITP, Kyoto

Kaonic-atom x-ray spectroscopy with cryogenic detectors

Shinji OKADA (RIKEN)

for HEATES & J-PARC E62 (E57) collaborations

Kaonic atom experiments

High-intensity Stopped Kaons ⊗ Novel X-ray Detectors

J-PARC

K1.8BR beamline

for future

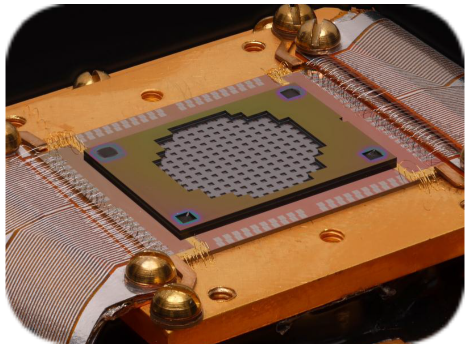
“new K1.1BR beamline”
@ Extended hadron facility

INFN-LNF (Italy)

DAΦNE
e+ e- collider

TES

Cryogenic detector

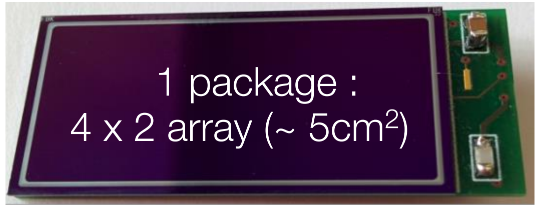


High resolution

High precision

SDD

Silicon drift detector



Large area
(> 200 cm^2)

High sensitivity

Kaonic atom experiments

High-intensity
Stopped Kaons

⊗

Novel X-ray
Detectors

J-PARC

K1.8BR beamline

for future

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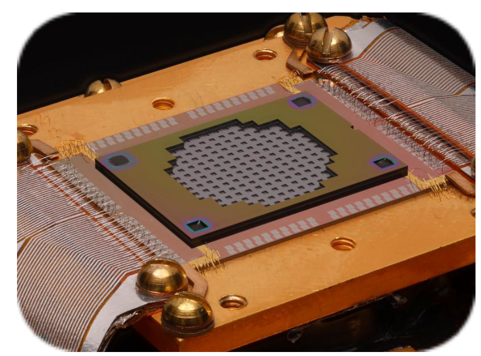


High resolution

High precision

SDD

Silicon drift detector

Large area
(> 200 cm^2)

High sensitivity

Brief history towards K-atom w/TES

2012	Collaborate with astro-physics guys developing TES
2013	get started the collaboration ← **Last workshop @ YITP "Hadron in Nuclei" in 2013**
2014	Demonstration study @ PSI — π atom w/TES
2015	Approved by J-PARC PAC (Program Advisory Committee)
2016	Commissioning run @ J-PARC … NOW !
2017	J-PARC E62 physics run in 2017 !!

progress (2014–2016)

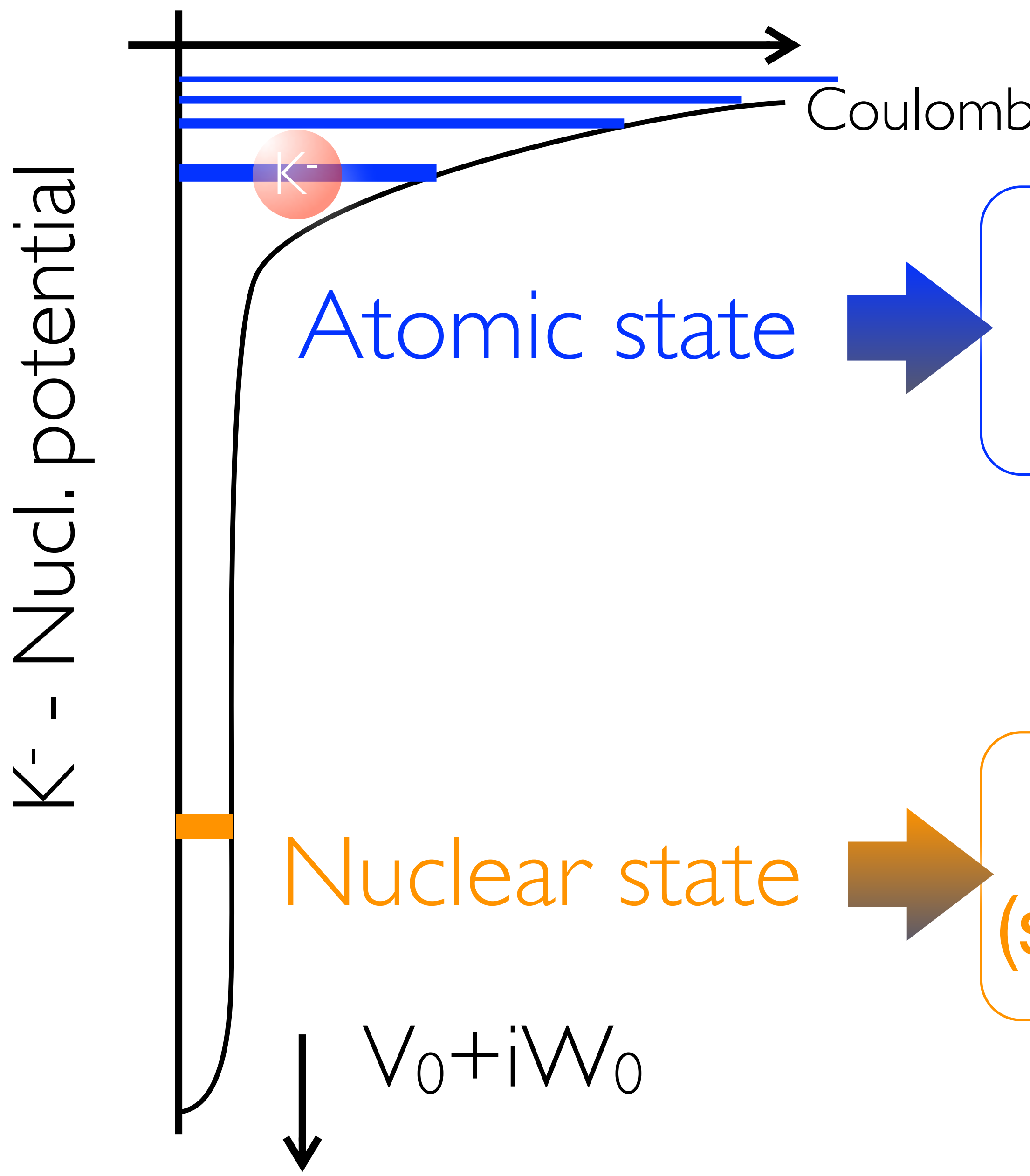
Contents

1. Introduction

Study of K-nucl. interaction

Two experimental approaches

— via K-nucleus bound system —



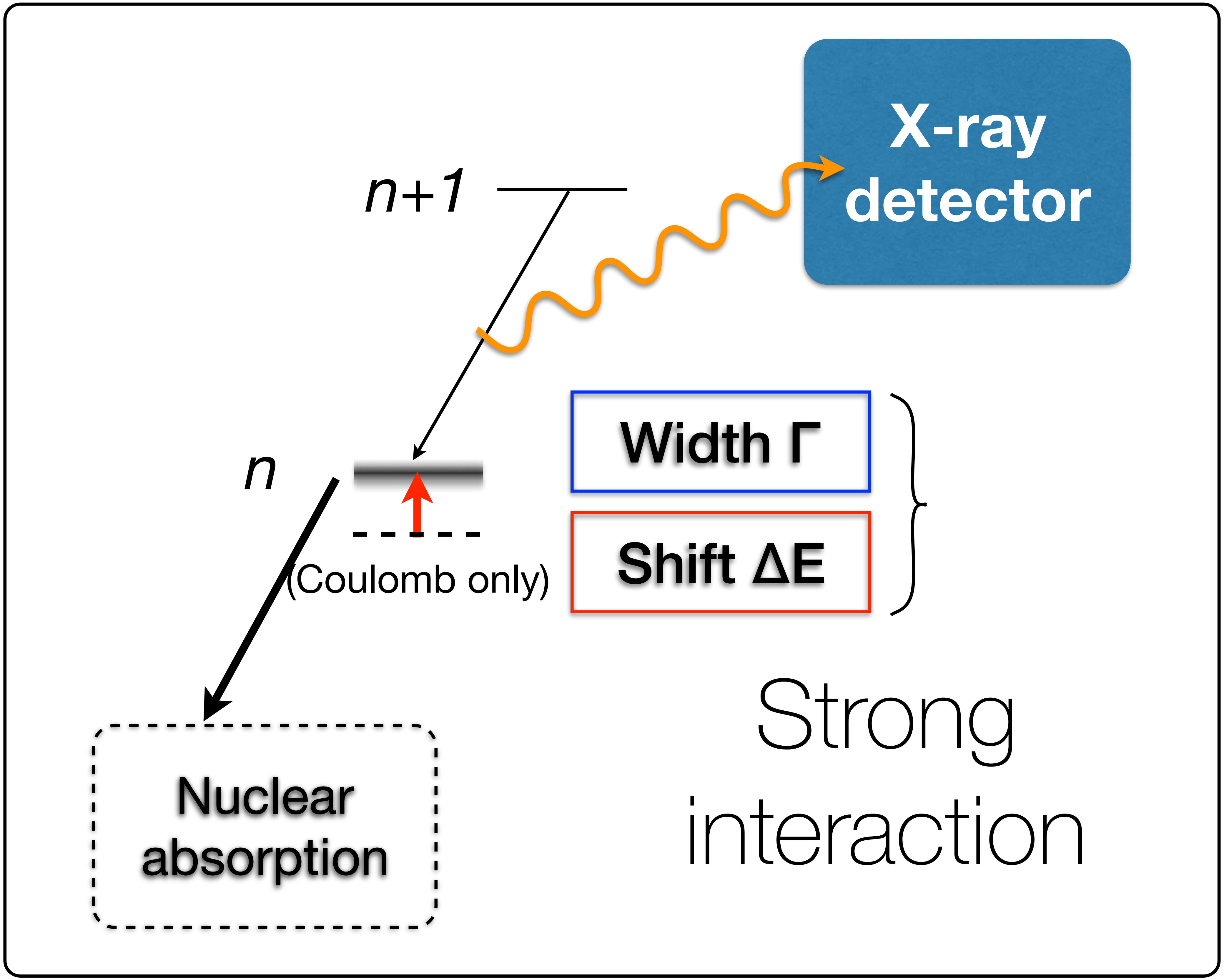
Precision x-ray measurement

complementary

Reaction formation

(search for deeply bound K- cluster)

Kaonic atom x-ray spectroscopy



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)

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

Shift **Width**

K-p Kα x-ray

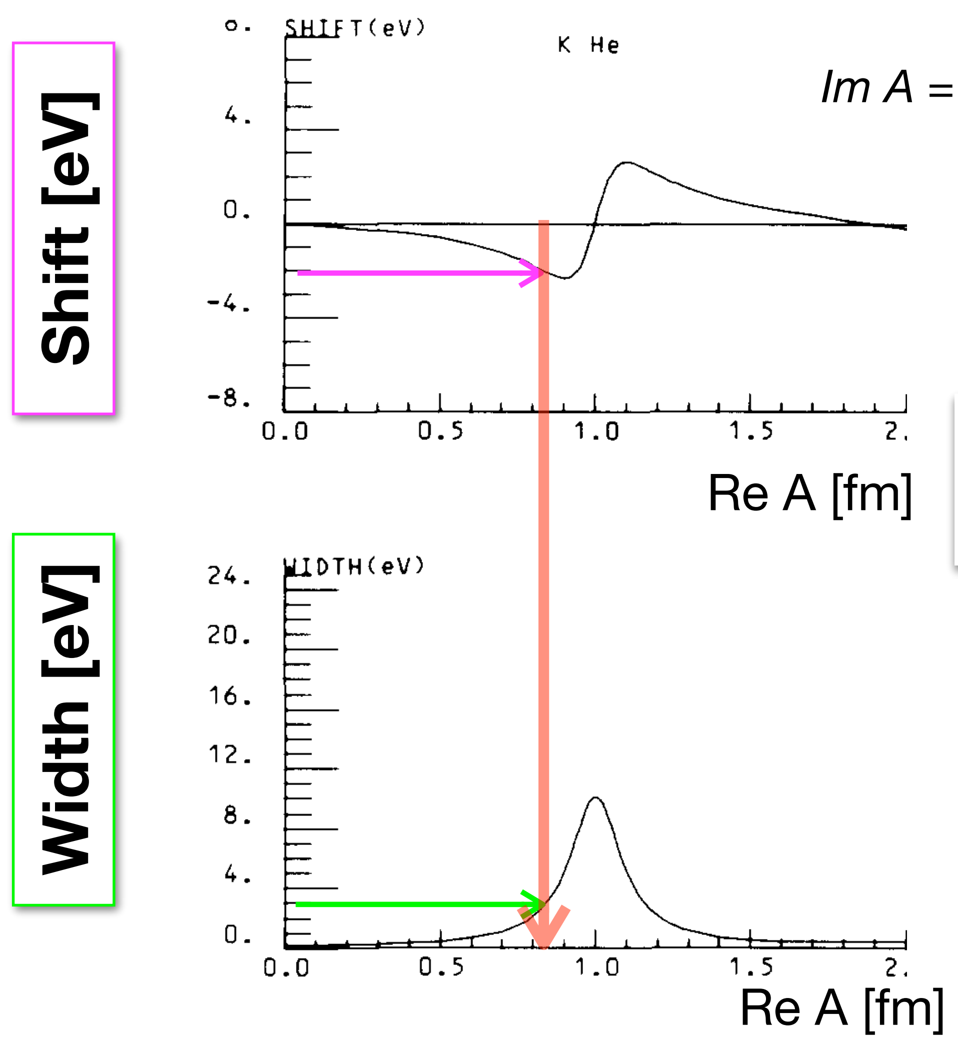
K^-p scattering length

(= K^-p scattering amplitude at threshold)

K-atom data

↓

potential strength

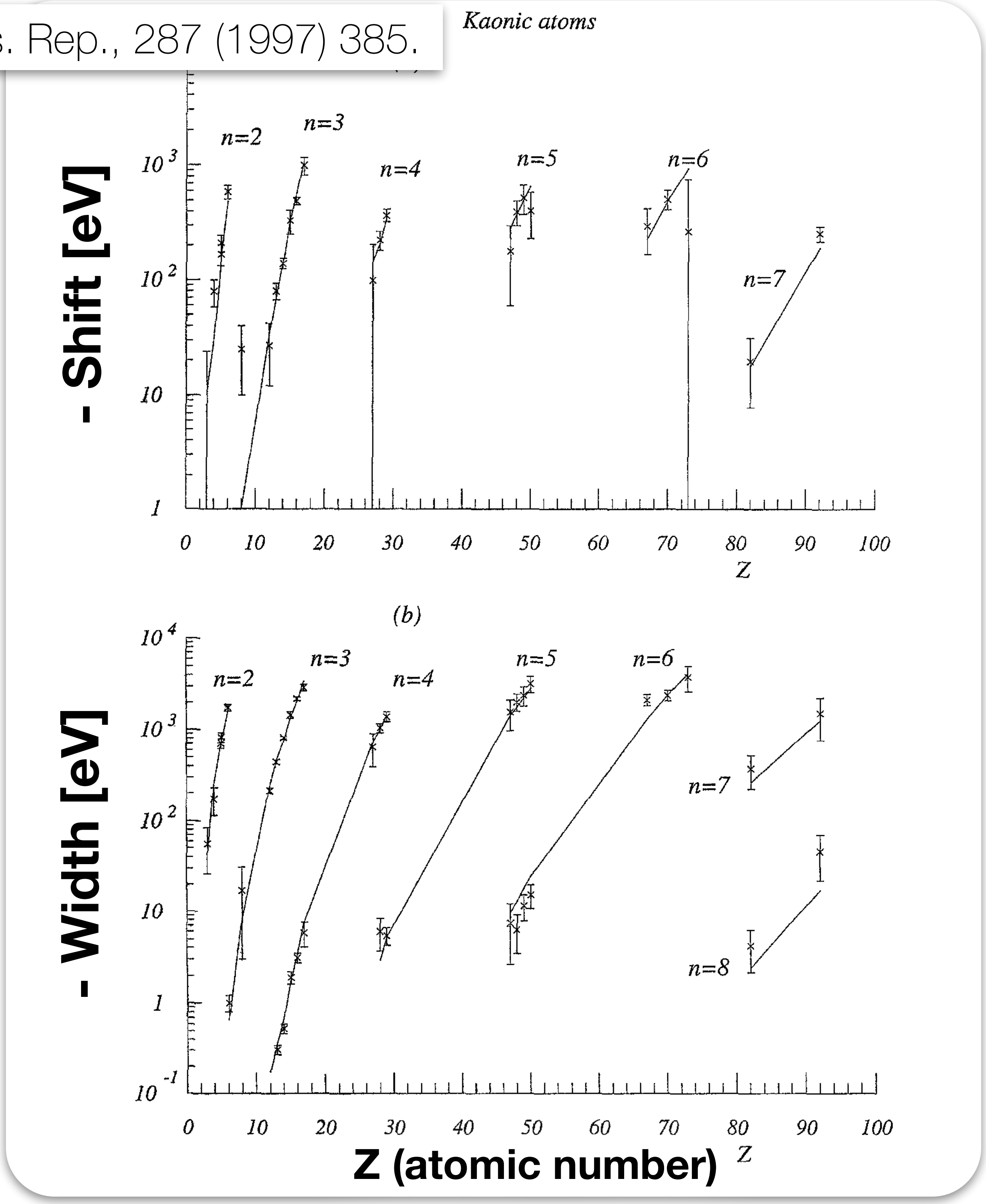


e.g., K-He atom 2p level

Real part of the effective scattering length [fm]

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

Status of K-atom study



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 :

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.

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.

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

Theories

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.

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

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

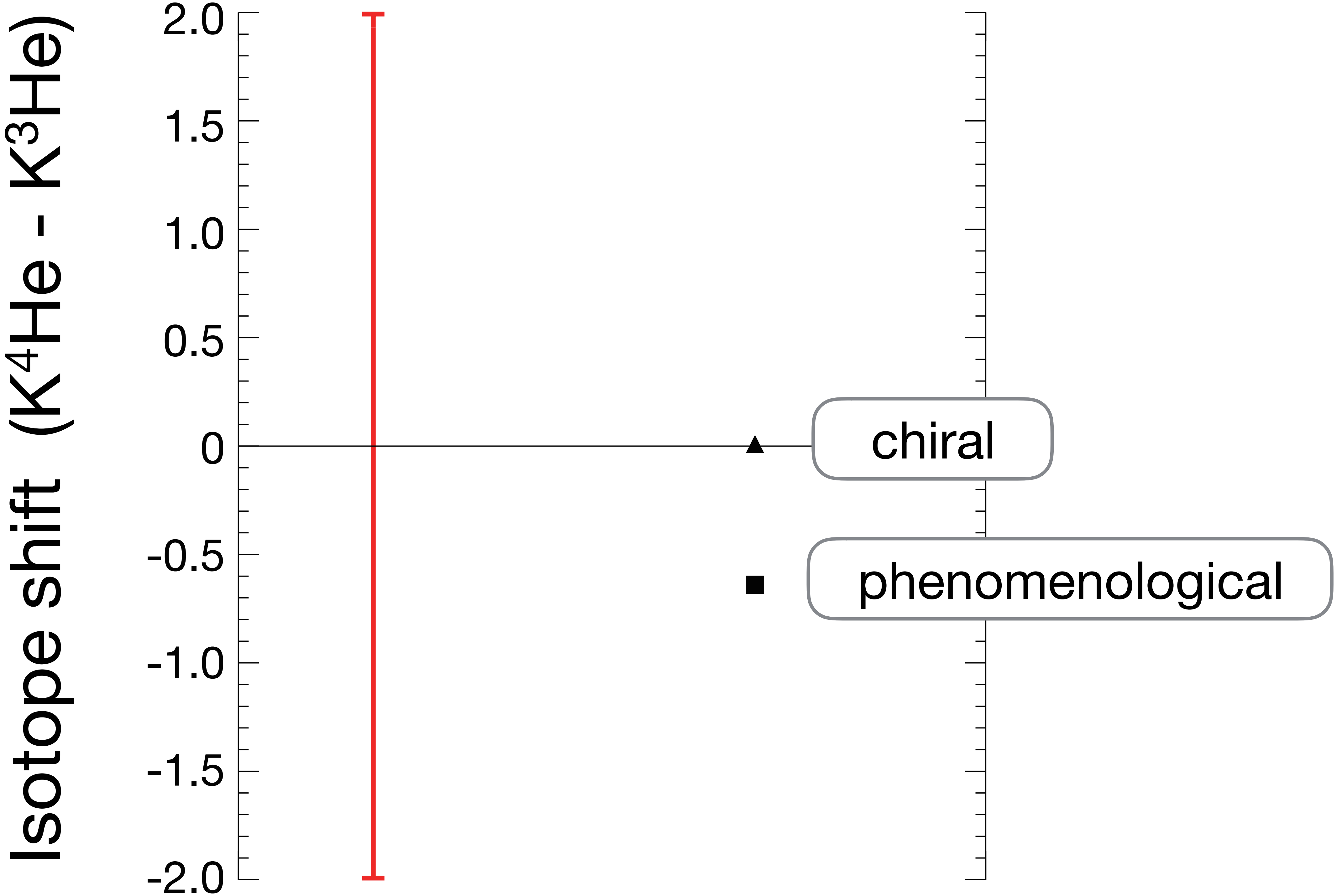
preliminary

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

Width : 2 ~ 4 eV

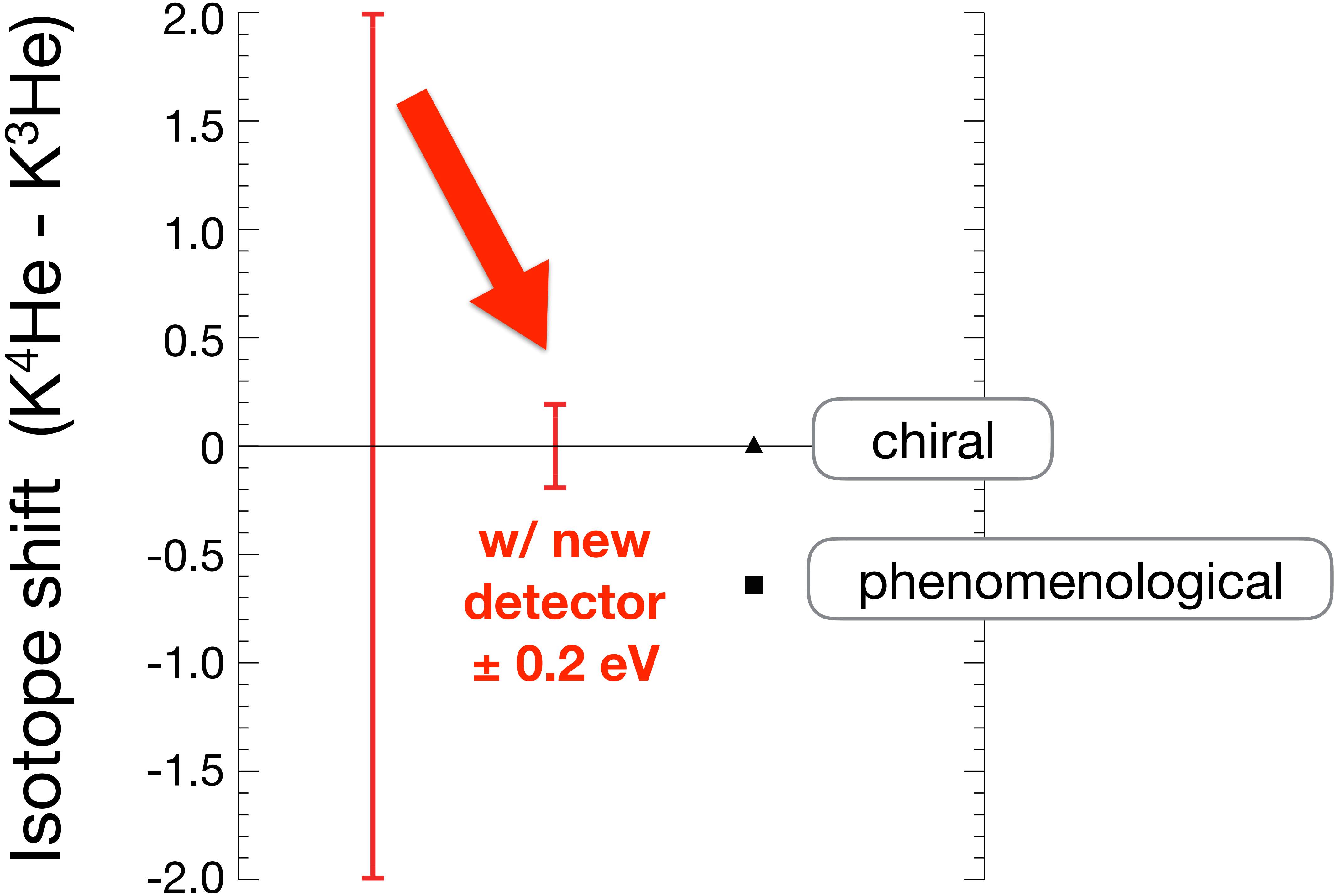
Experimental accuracy

Past experiments : ± 2 eV

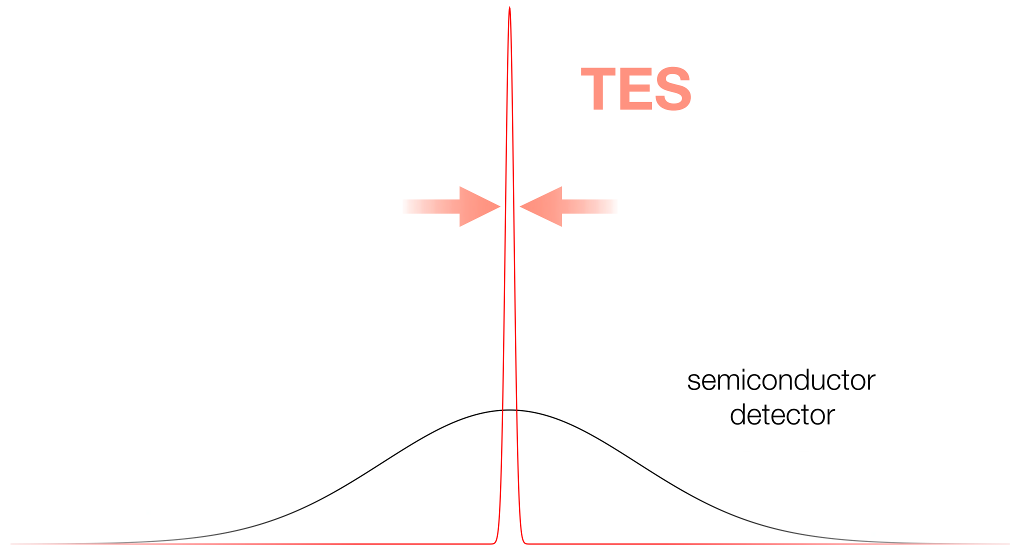


Experimental accuracy

Past experiments : ± 2 eV



2. X-ray detector : TES

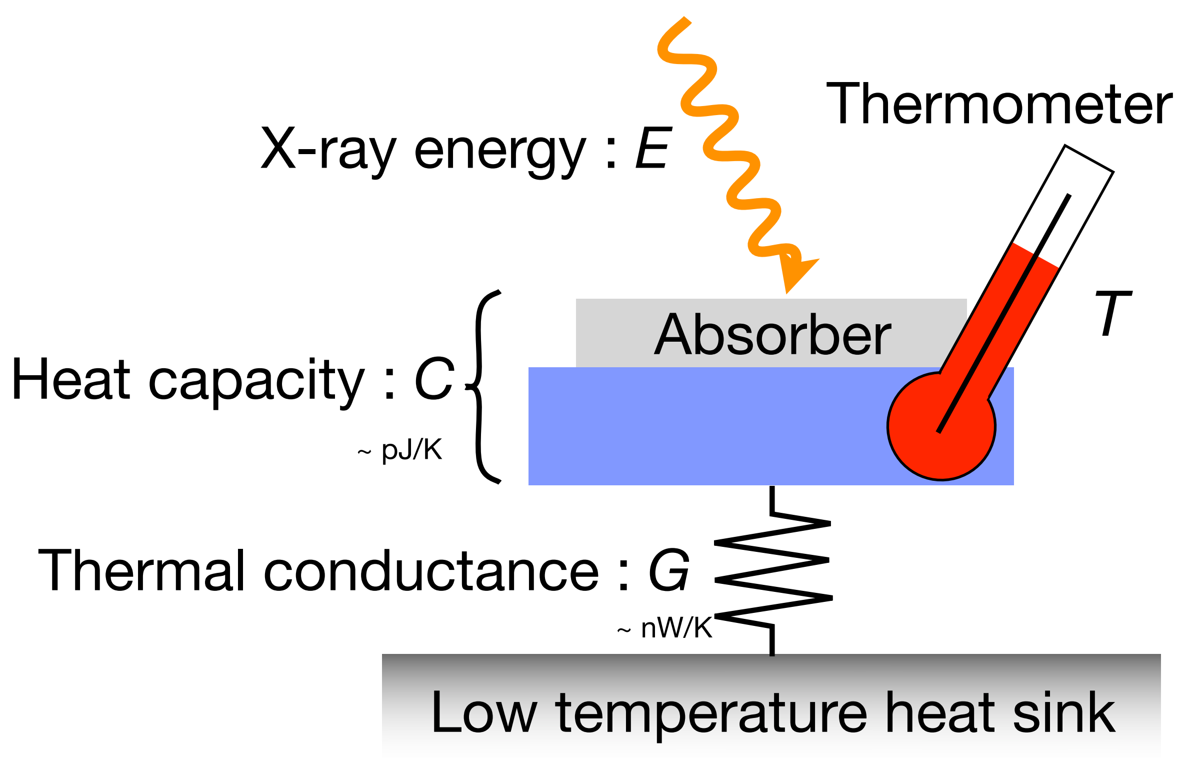


Transition-Edge-Sensor microcalorimeter

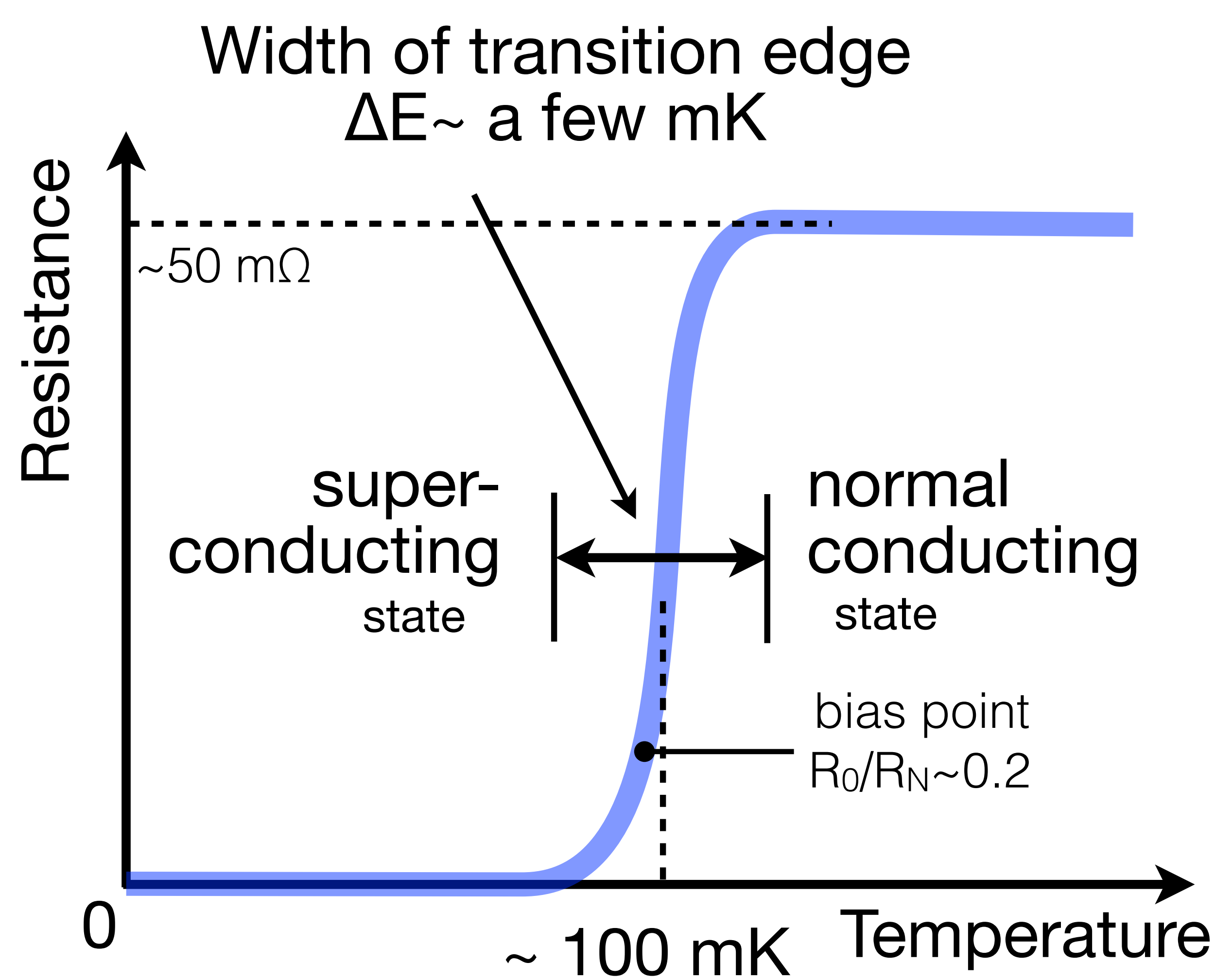
✓ High energy resolution :~2 eV FWHM @ 6 keV

✓ Wide dynamic range

Microcalorimeter



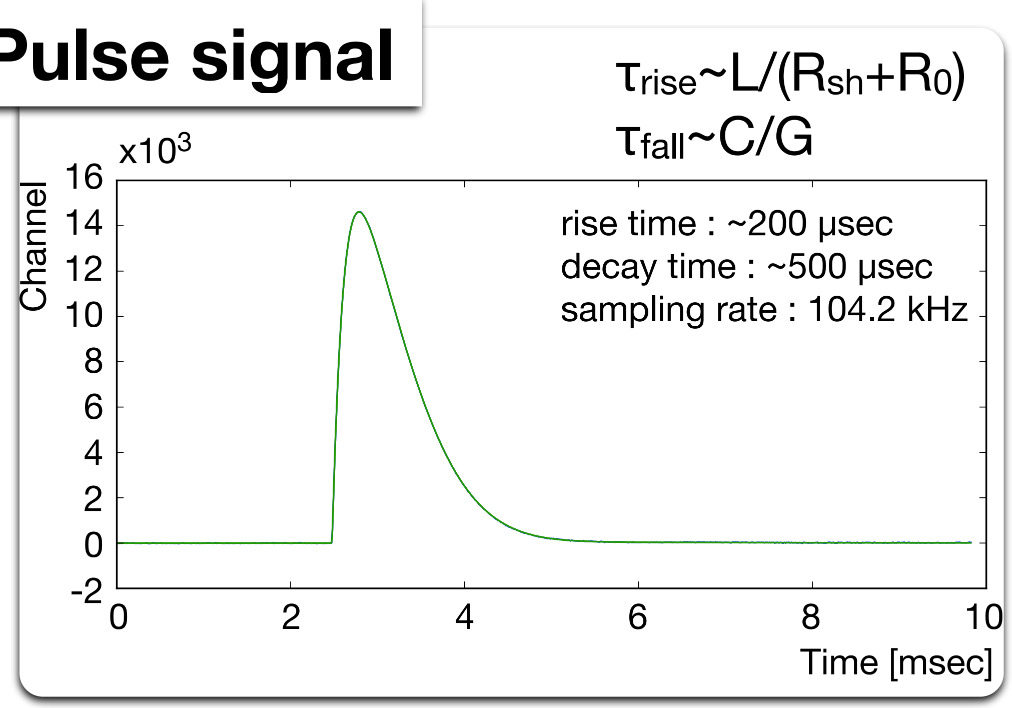
Transition Edge Sensor (TES)



NIST's TES array system

- ✓ Compact and portable
- ✓ Large effective area w/multiplexing tech.

Pulse signal



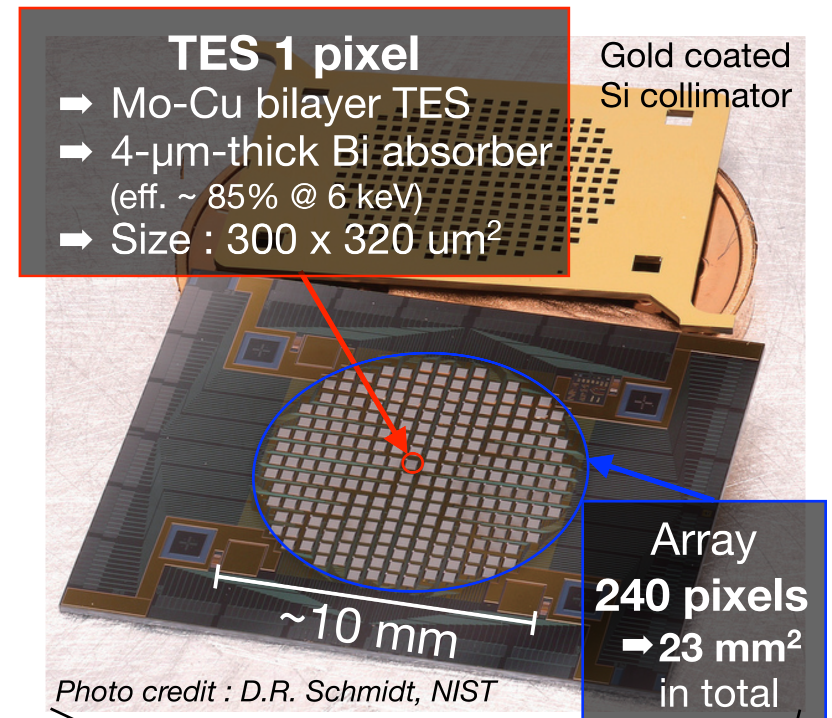
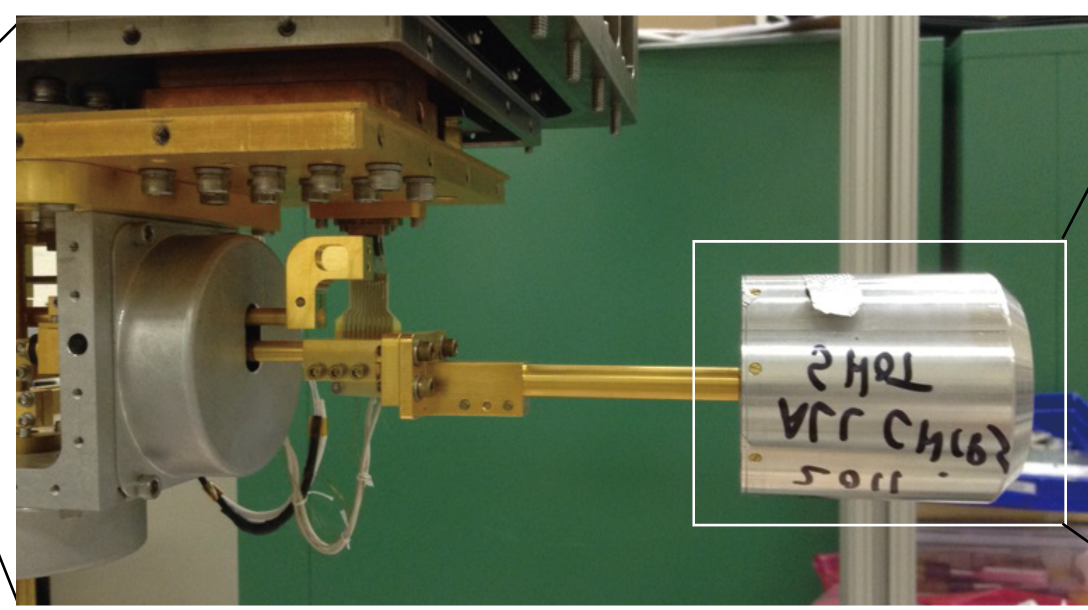


Photo credit : D.R. Schmidt, NIST



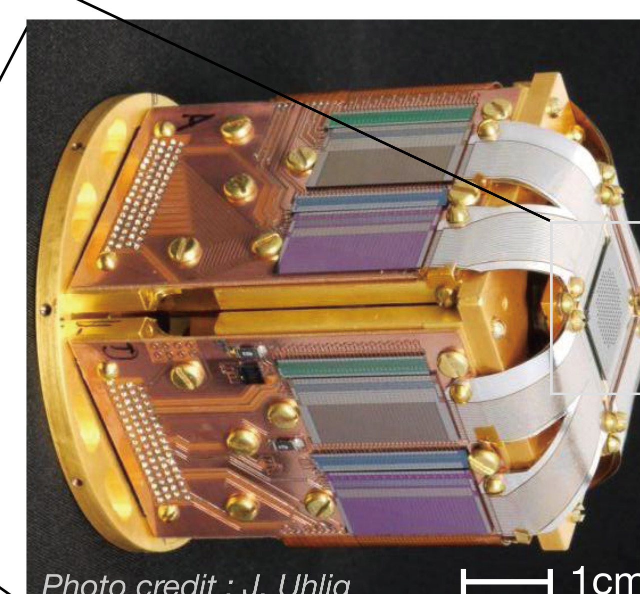
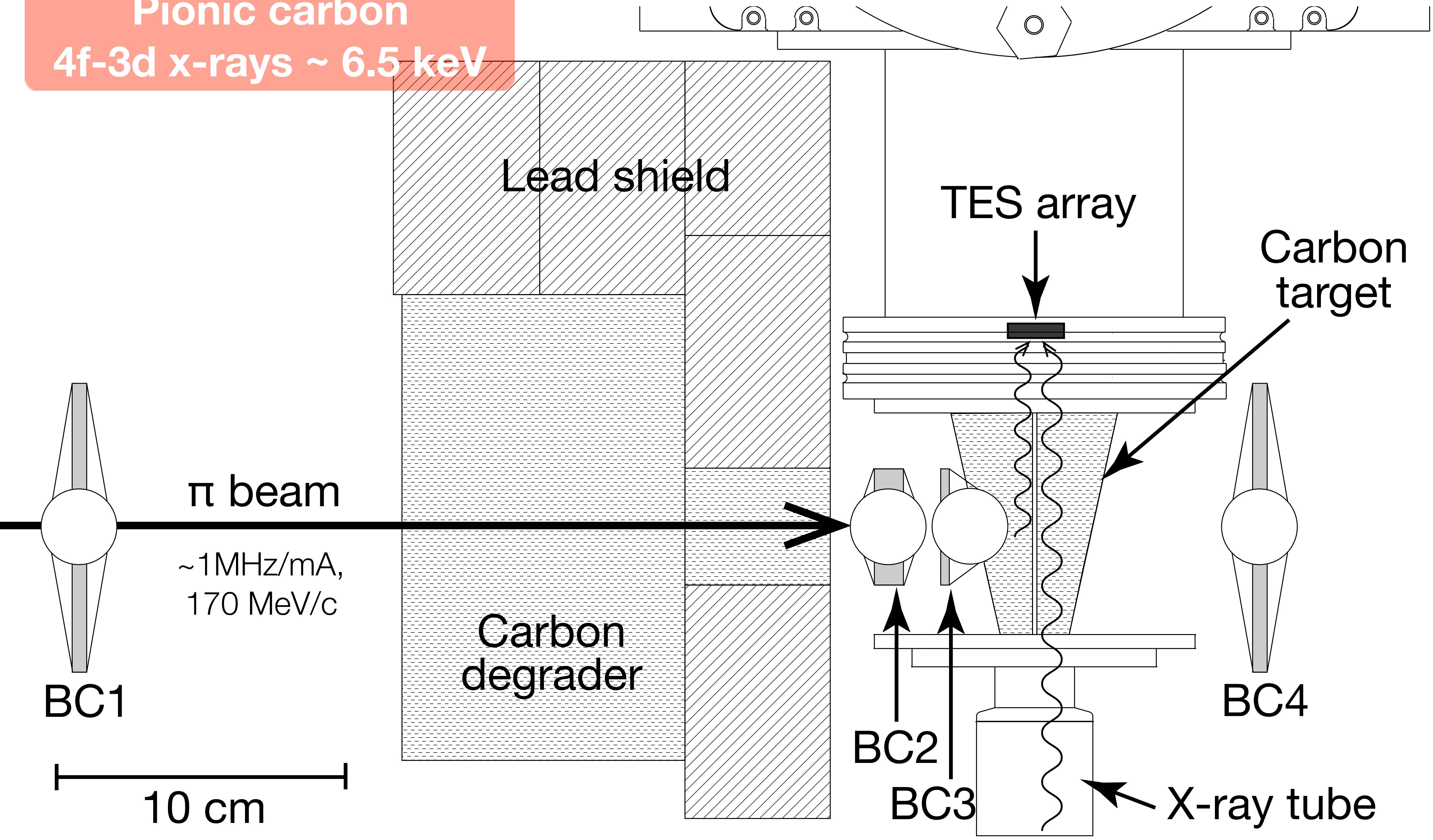


Photo credit : J. Uhlig

3. Demonstration with π beam

π atom expt @ PSI πM1 beamline

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



submitted the paper

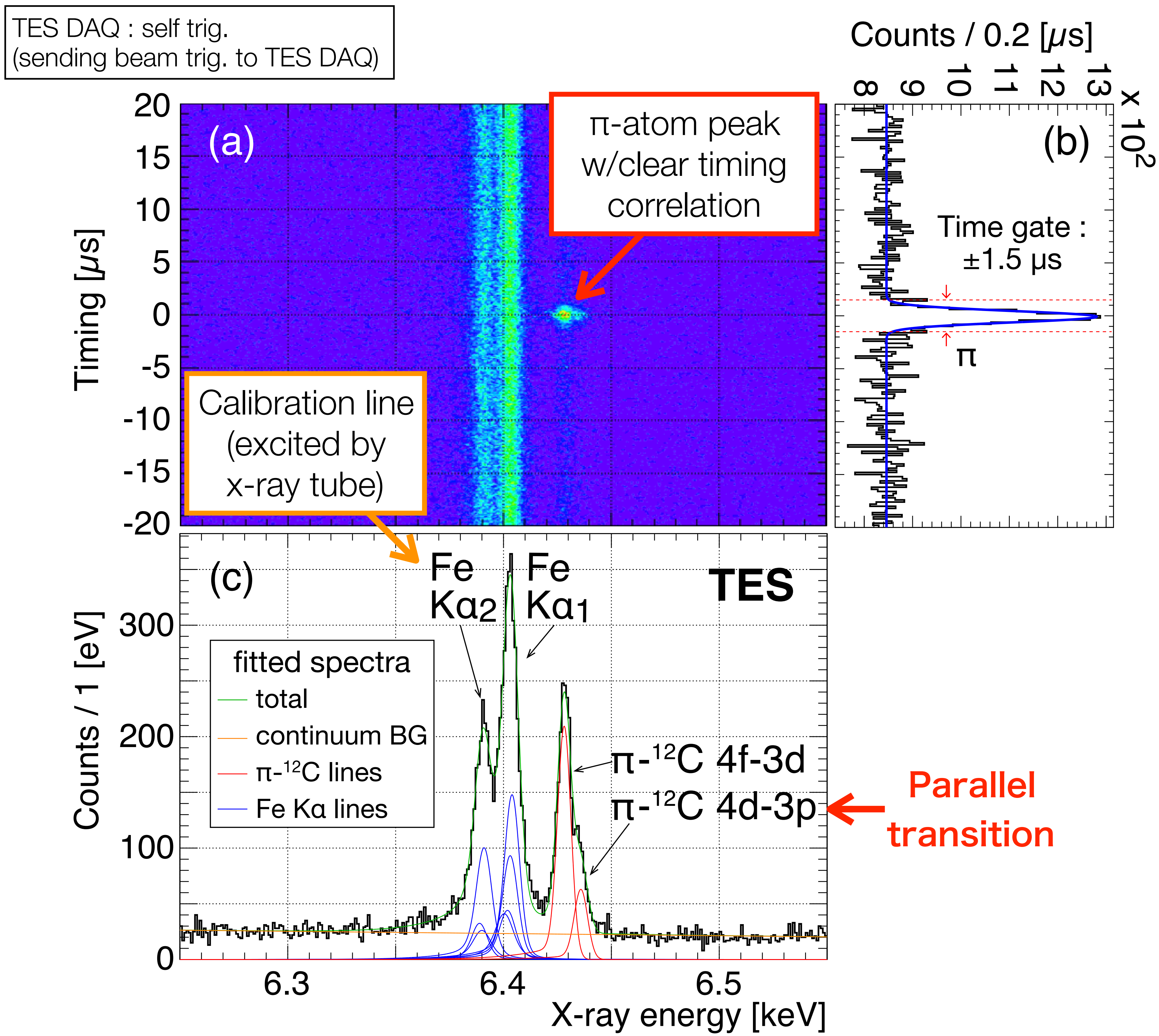
very recently (on June 21)

PTEP

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

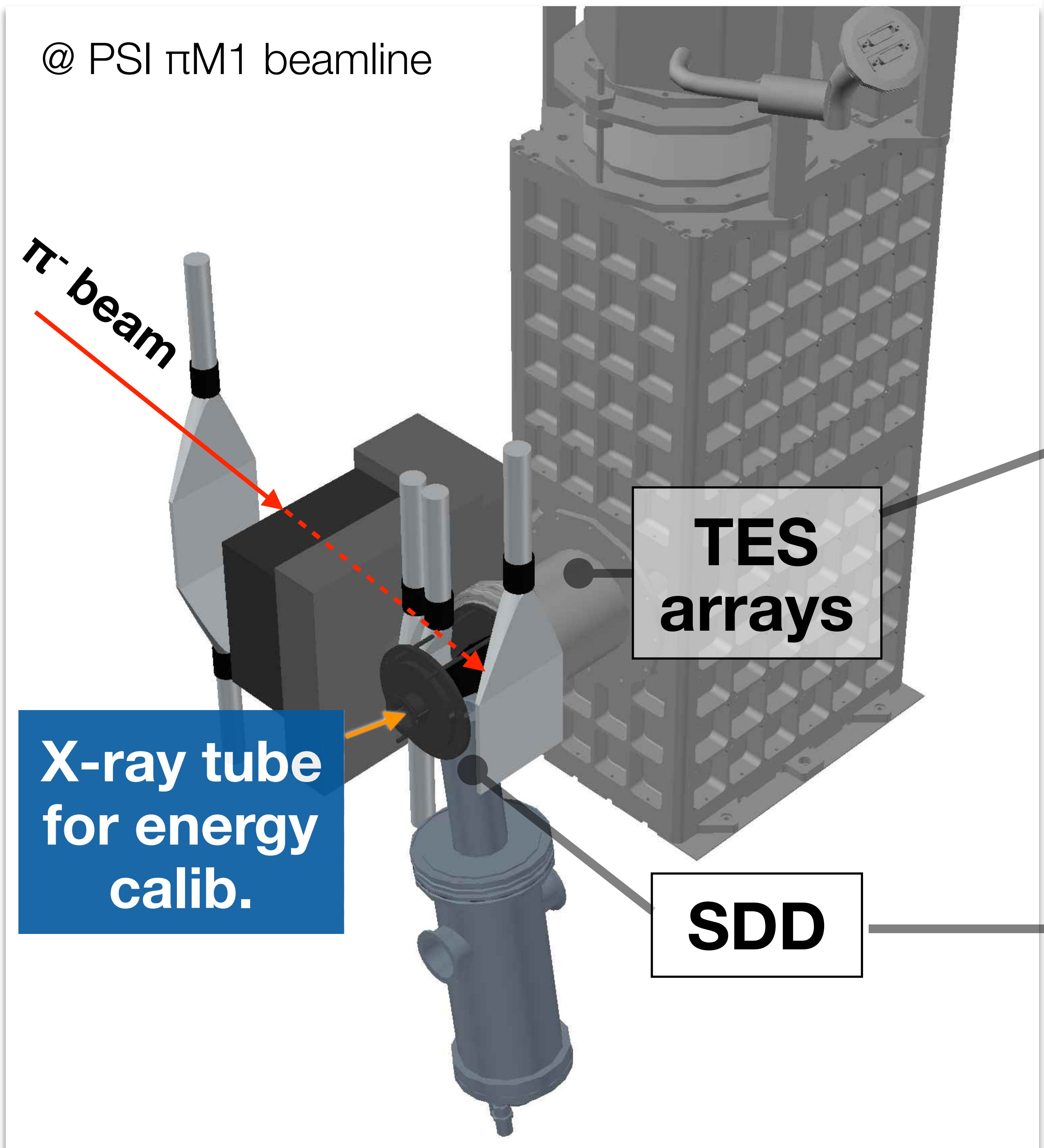
HEATES Collaboration
S. Okada[†1,*], D. A. Bennett[2], C. Curceanu[3], W. B. Doriese[2], J. W. Fowler[2], J. Gard[2], F. P. Gustafsson[4], T. Hashimoto[1], R. S. Hayano[5], S. Hirenzaki[6], J. P. Hays-Wehle[2], G. C. Hilton[2], N. Ikeno[7], M. Iliescu[3], S. Ishimoto[8], K. Itahashi[1], M. Iwasaki[1], 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]

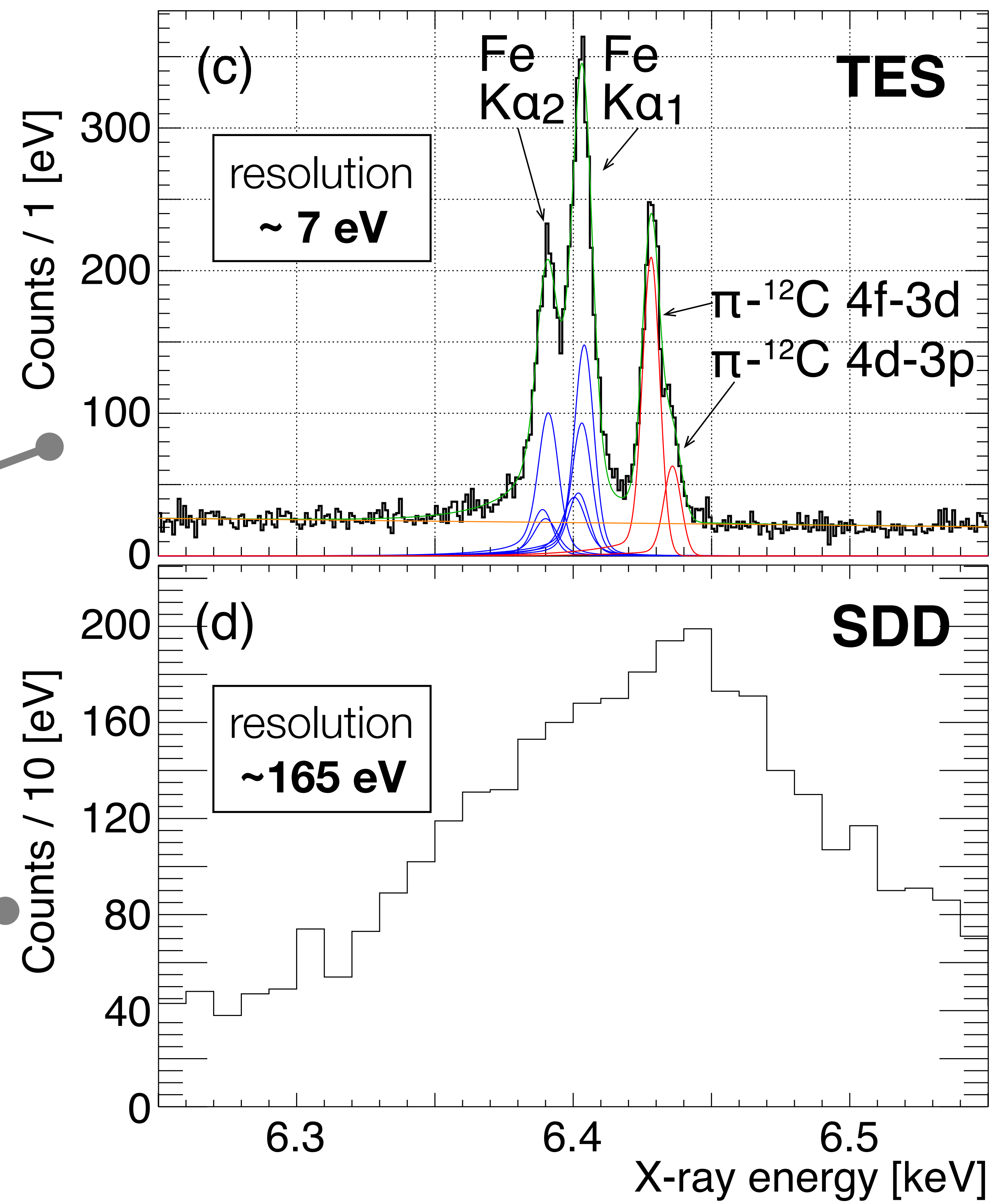
Successful demonstration w/ π- atom



Parallel transition

Comparison with SDD spectrum





Fit results

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

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

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

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

Pionic atom lines :

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

⇒ comparison with EM calc?

EM values & strong-int calc.

EM calc. (T. Koike)

State	K.G. energy (eV)	Vacuum polarization $\alpha(Z\alpha)$ (eV)	$\alpha^2(Z\alpha)$ (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)

⇒ Non-negligible contribution from 3p level

Electron screening effects

calc. by T. Koike

Transitions	Configuration	K-shell contribution	L-shell contribution	Transition energy (eV)
		Electron screening effect (eV)		
$4f \to 3d$	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) :			$6428.39 \pm 0.13 \pm 0.09$
$4d \to 3p$	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) :			$6435.76 \pm 0.30\ ^{+0.11}_{-0.07}$

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

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**

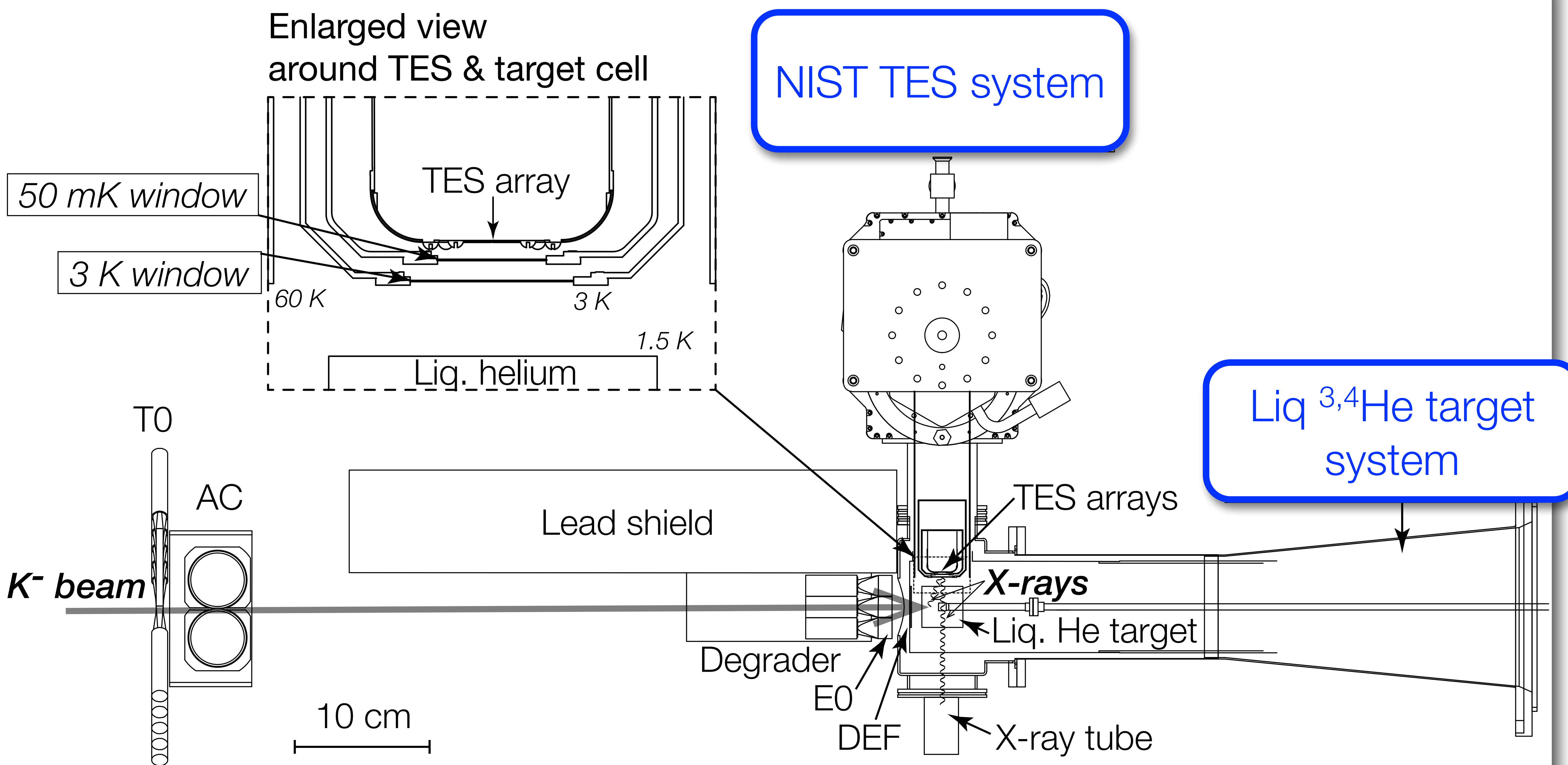
4. J-PARC E62 exp. plan

J-PARC E62 collaboration

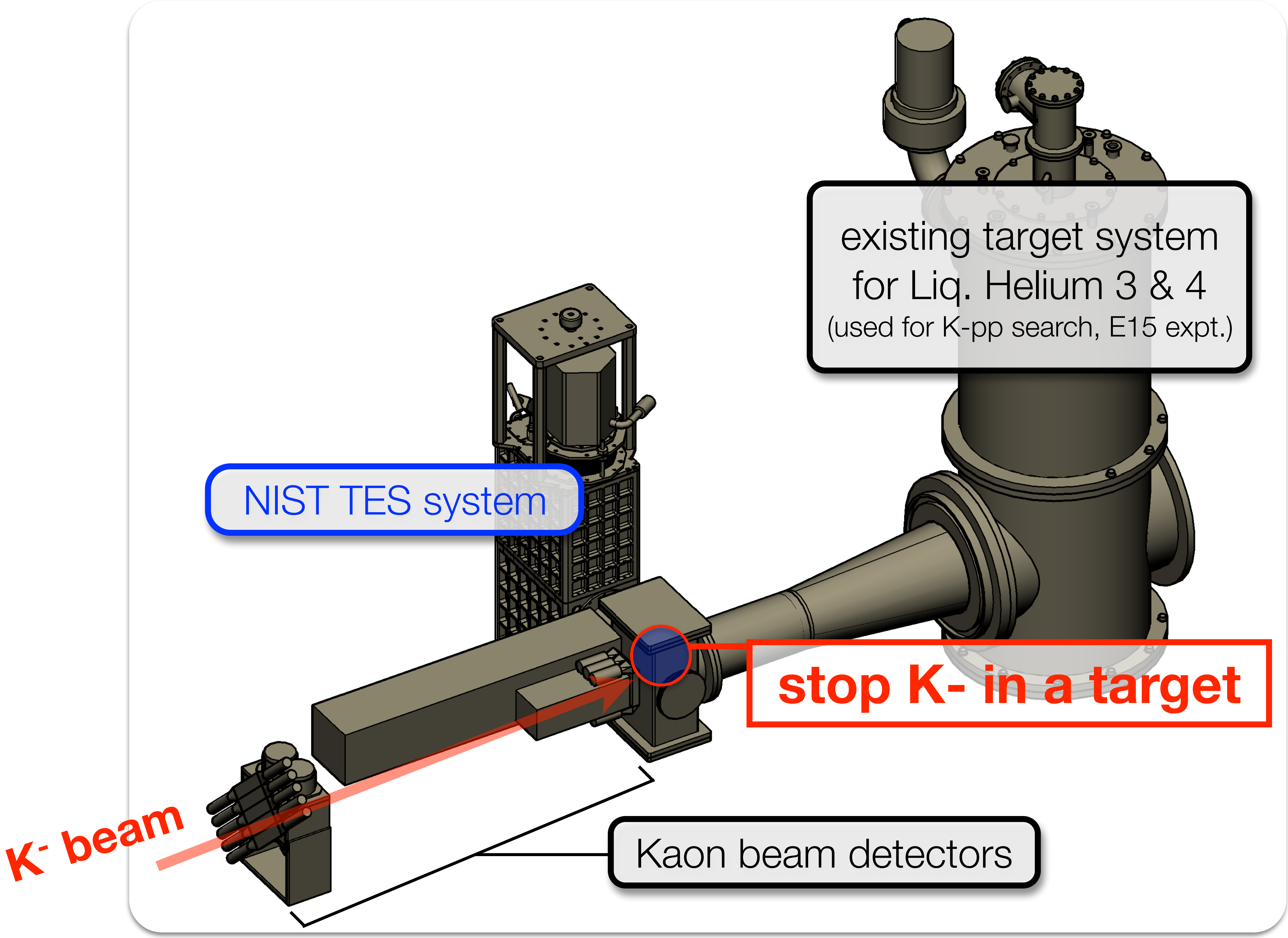
M. Bazzi[a], D.A. Bennett[b], C. Berucci[c], D. Bosnar[d], C. Curceanu[a], W.B. Doriese[b],
J.W. Fowler[b], H. Fujioka[e], C. Guaraldo[a], F. Parnefjord Gustafsson[f], T. Hashimoto[g],
R.S. Hayano[h*], J.P. Hays-Wehle[b], G.C. Hilton[b], T. Hiraiwa[i], M. Iio[j], M. Iliescu[a],
S. Ishimoto[j], K. Itahashi[g], M. Iwasaki[g,l], Y. Ma[g], H. Noumi[i], G.C. O'Neil[b], H. Ohnishi[g],
S. Okada[g†], H. Outa[g‡], K. Piscicchia[a], C.D. Reintsema[b], Y. Sada[i], F. Sakuma[g],
M. Sato[g], D.R. Schmidt[b], A. Scordo[a], M. Sekimoto[j], H. Shi[a], D. Sirghi[a], F. Sirghi[a],
K. Suzuki[c], D.S. Swetz[b], K. Tanida[k], H. Tatsuno[b,i], M. Tokuda[l], J. Uhlig[f],
J.N. Ullom[b,m], S. Yamada[n], T. Yamazaki[h], and J. Zmeskal[c]

Experimental setup @ K1.8BR

J-PARC E62 experiment



Experimental setup (bird's-eye view)



4-days beamtime
on June, 2016

5. Commissioning run @ J-PARC

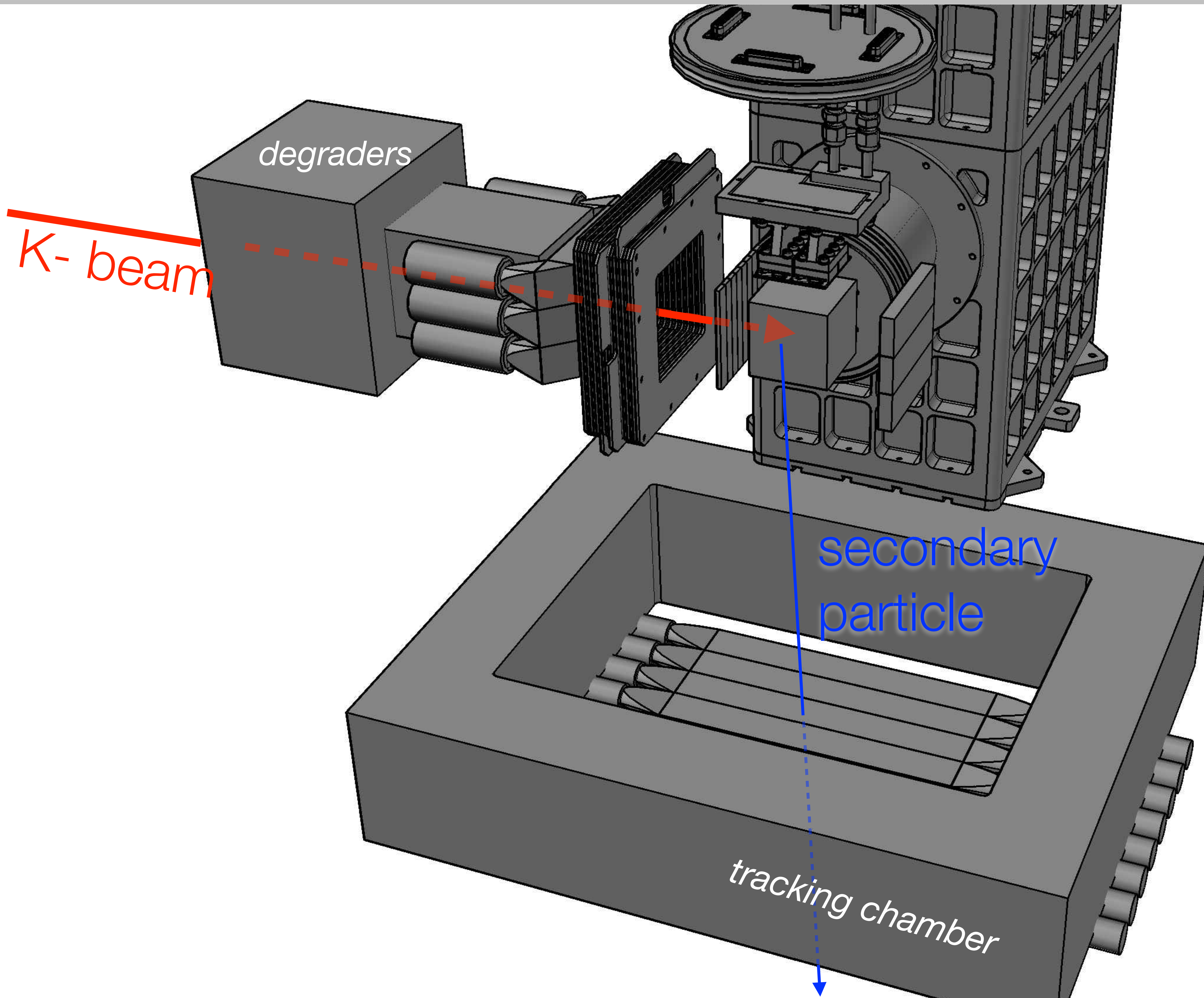
J-PARC E62 collaboration (K-He)

M. Bazzi[a], D.A. Bennett[b], C. Berucci[c], D. Bosnar[d], C. Curceanu[a], W.B. Doriese[b], J.W. Fowler[b], H. Fujioka[e], C. Guaraldo[a], F. Parnefjord Gustafsson[f], T. Hashimoto[g], R.S. Hayano[h*], J.P. Hays-Wehle[b], G.C. Hilton[b], T. Hiraiwa[i], M. Iio[j], M. Iliescu[a], S. Ishimoto[j], K. Itahashi[g], M. Iwasaki[g,l], Y. Ma[g], H. Noumi[i], G.C. O'Neil[b], H. Ohnishi[g], S. Okada[g†], H. Outa[g‡], K. Piscicchia[a], C.D. Reintsema[b], Y. Sada[i], F. Sakuma[g], M. Sato[g], D.R. Schmidt[b], A. Scordo[a], M. Sekimoto[j], H. Shi[a], D. Sirghi[a], F. Sirghi[a], K. Suzuki[c], D.S. Swetz[b], K. Tanida[k], H. Tatsuno[b,i], M. Tokuda[l], J. Uhlig[f], J.N. Ullom[b,m], S. Yamada[n], T. Yamazaki[h], and J. Zmeskal[c]

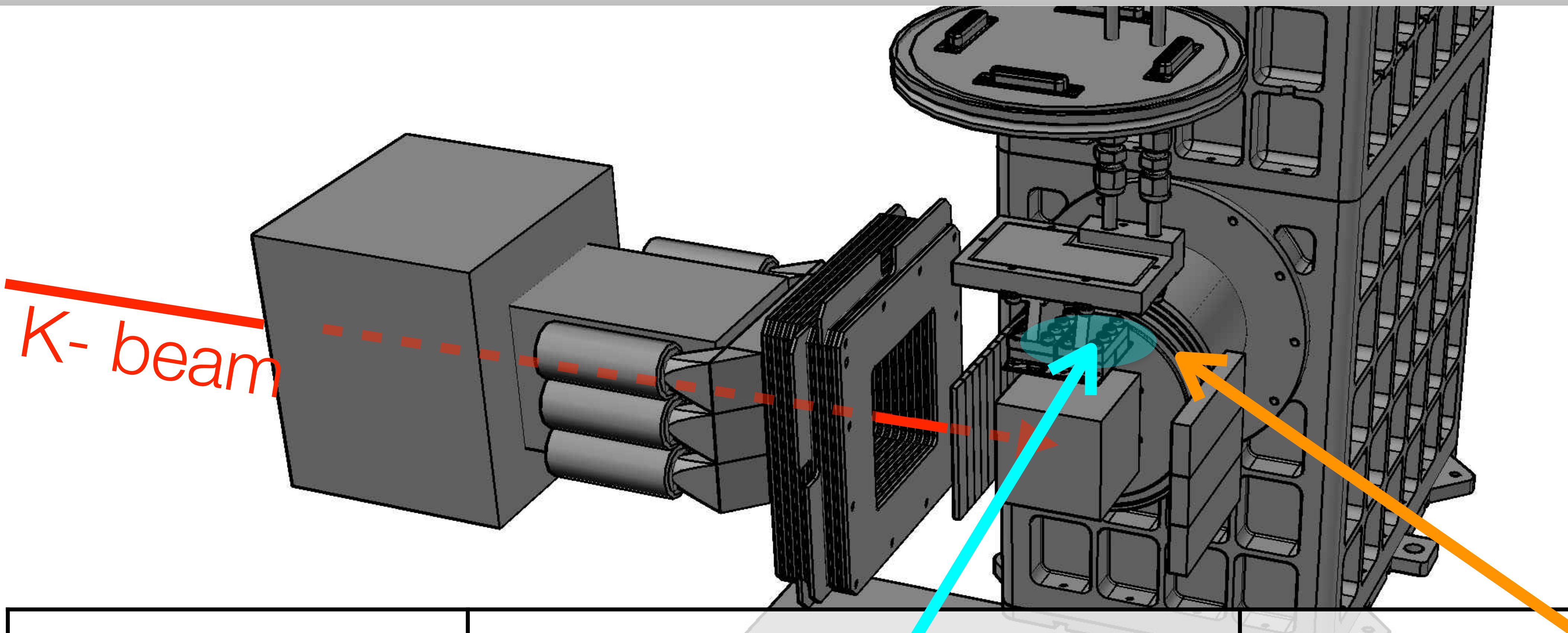
J-PARC E57 collaboration (K-d)

J. Zmeskal[1] (spokesperson), M. Sato[2] (co-spokesperson), S. Ajimura[3], M. Bazzi[4], G. Beer[5], C. Berucci[1], H. Bhang[6], D. Bosnar[7], M. Bragadireanu[8], P. Buehler[1], L. Busso[9,10], M. Cargnelli[1], S. Choi[6], A. Clozza[4], C. Curceanu[4], A. D'uffizi[4], S. Enomoto[11], L. Fabbietti[12], D. Faso[9,10], C. Fiorini[13,14], H. Fujioka[15], F. Ghio[16], R. Golser[17], C. Guaraldo[4], T. Hashimoto[2], R.S. Hayano[18], T. Hiraiwa[3], M. Iio[11], M. Iliescu[4], K. Inoue[19], S. Ishimoto[11], T. Ishiwatari[20], K. Itahashi[2], M. Iwai[11], M. Iwasaki[2,21], S. Kawasaki[19], J. Lachner[17], P. Levi Sandri[4], Y. Ma[2], J. Marton[1], Y. Matsuda[22], Y. Mizoi[23], O. Morra[9], P. Moskal[24], T. Nagae[15], H. Noumi[3], H. Ohnishi[2], S. Okada[2], H. Outa[2], D. Pietreanu[8], K. Piscicchia[4,25], M. Poli Lener[4], A. Romero Vidal[26], Y. Sada[3], A. Sakaguchi[19], F. Sakuma[2], E. Sbardella[4], A. Scordo[4], M. Sekimoto[11], H. Shi[4], M. Silarski[4,24], D. Sirghi[4,8], F. Sirghi[4,8], K. Suzuki[1], S. Suzuki[11], T. Suzuki[18], K. Tanida[6], H. Tatsuno[11], M. Tokuda[21], A. Toyoda[11], I. Tucakovic[4], K. Tsukada[27], O. Vazquez Doce[12], E. Widmann[1], T. Yamaga[19], T. Yamazaki[2,18], Q. Zhang[2]

Kaon-stop tuning setup

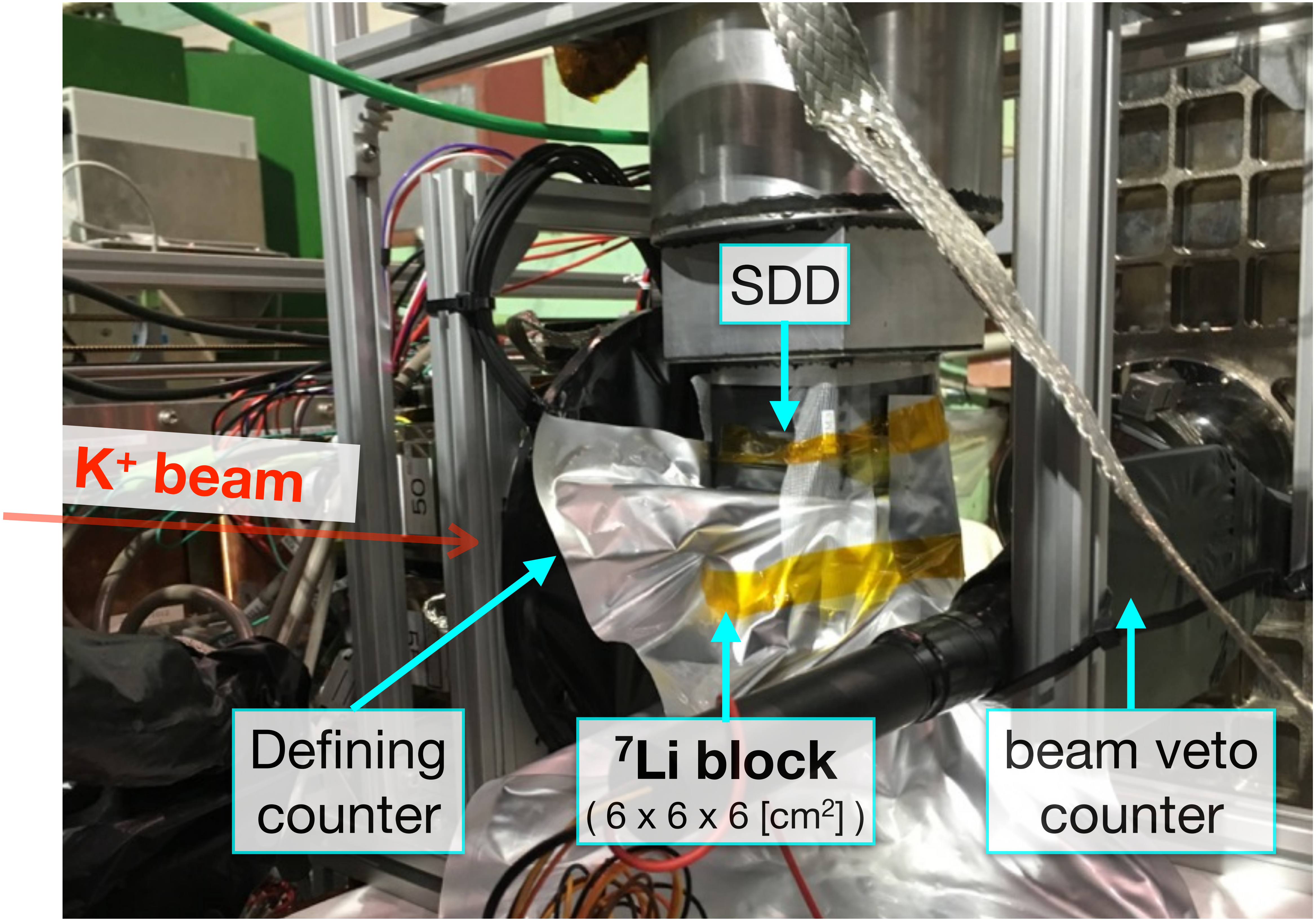


X-ray detectors

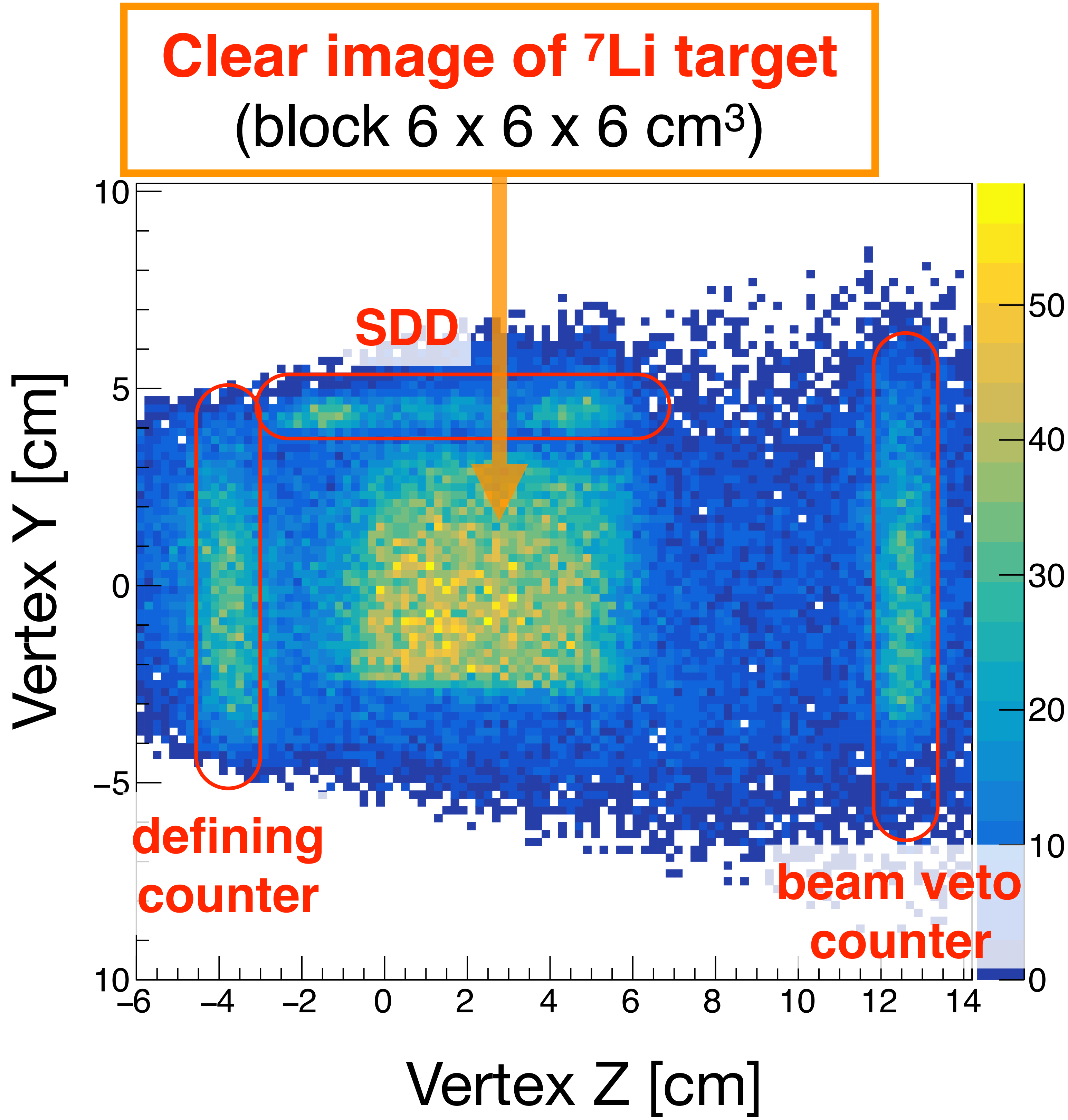


Detector	**SDD** prototype	**TES**
X-rays to be measured	K^{-}-^{7}Li 3d-2p	Mn Kα from ^{55}Fe source — ***NOT* Kaonic x-rays** —
Items to be checked	**K-stop rate** w/ K-Li x-rays	**in-beam resolution** (check rate dependence etc.)
	realistic background condition	

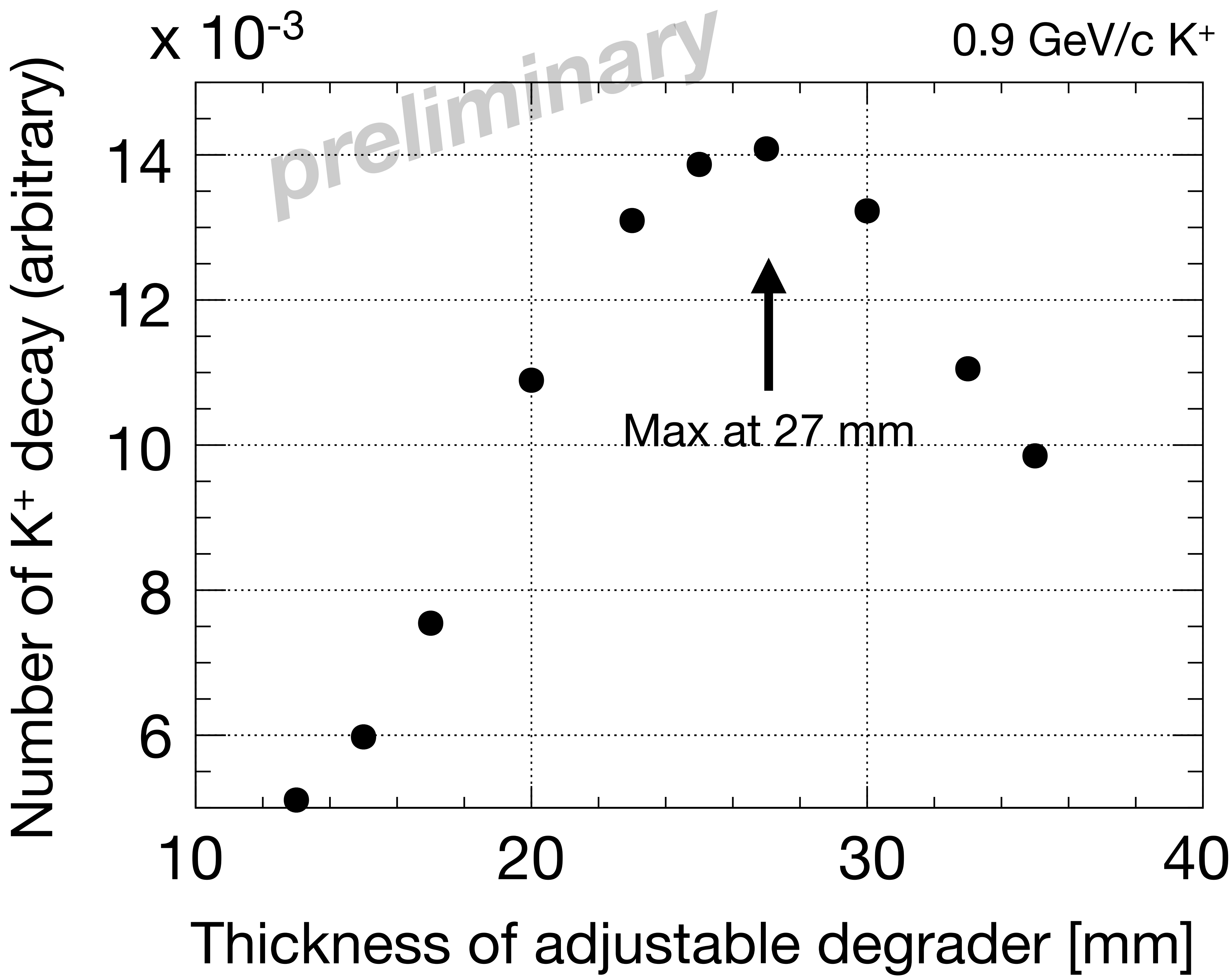
Experimental target : ^{7}Li block



Vertex reconstruction & TOF

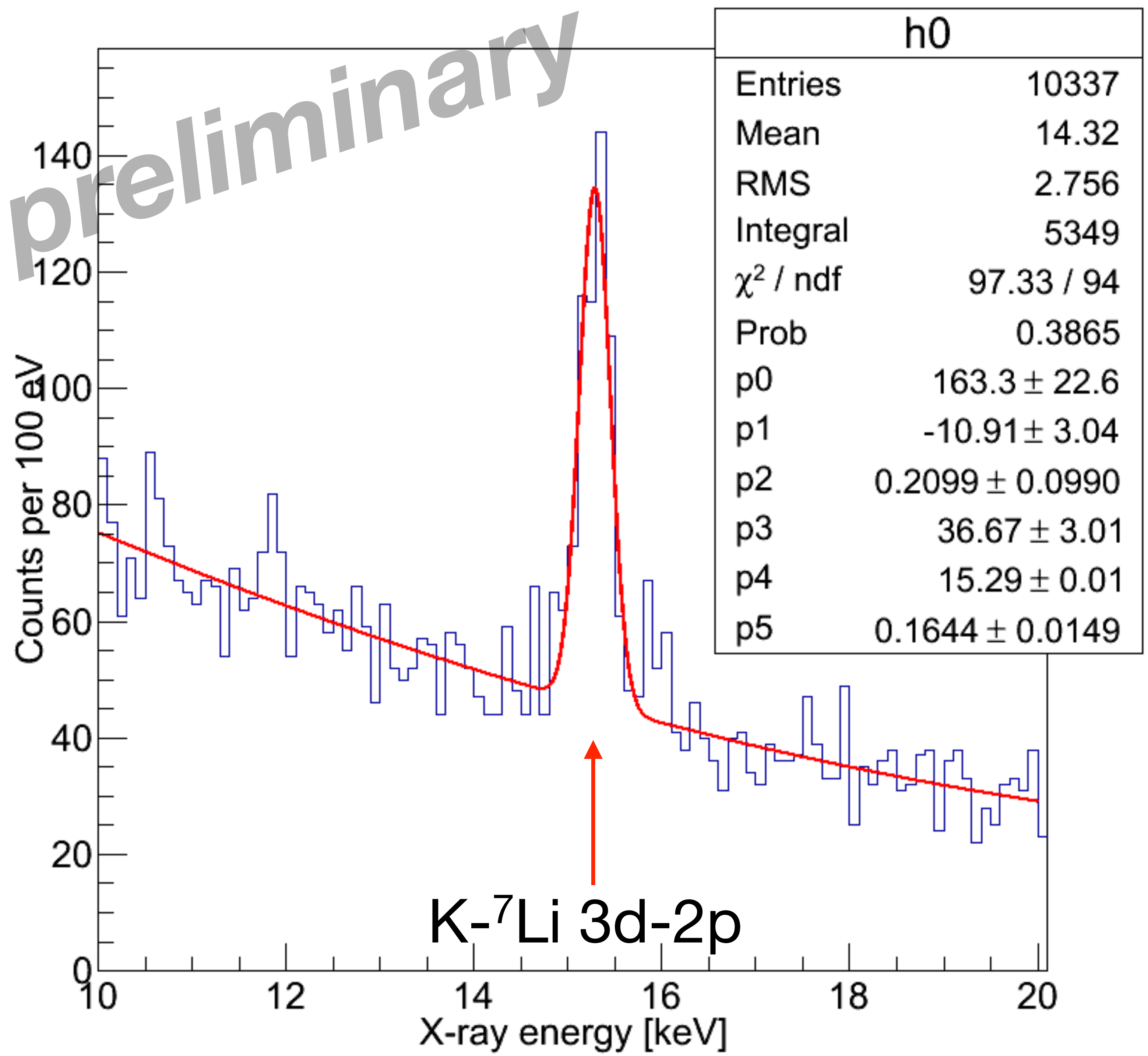


Range curve for K^+ stop



observed K-^{7}Li 3d-2p x rays via SDD

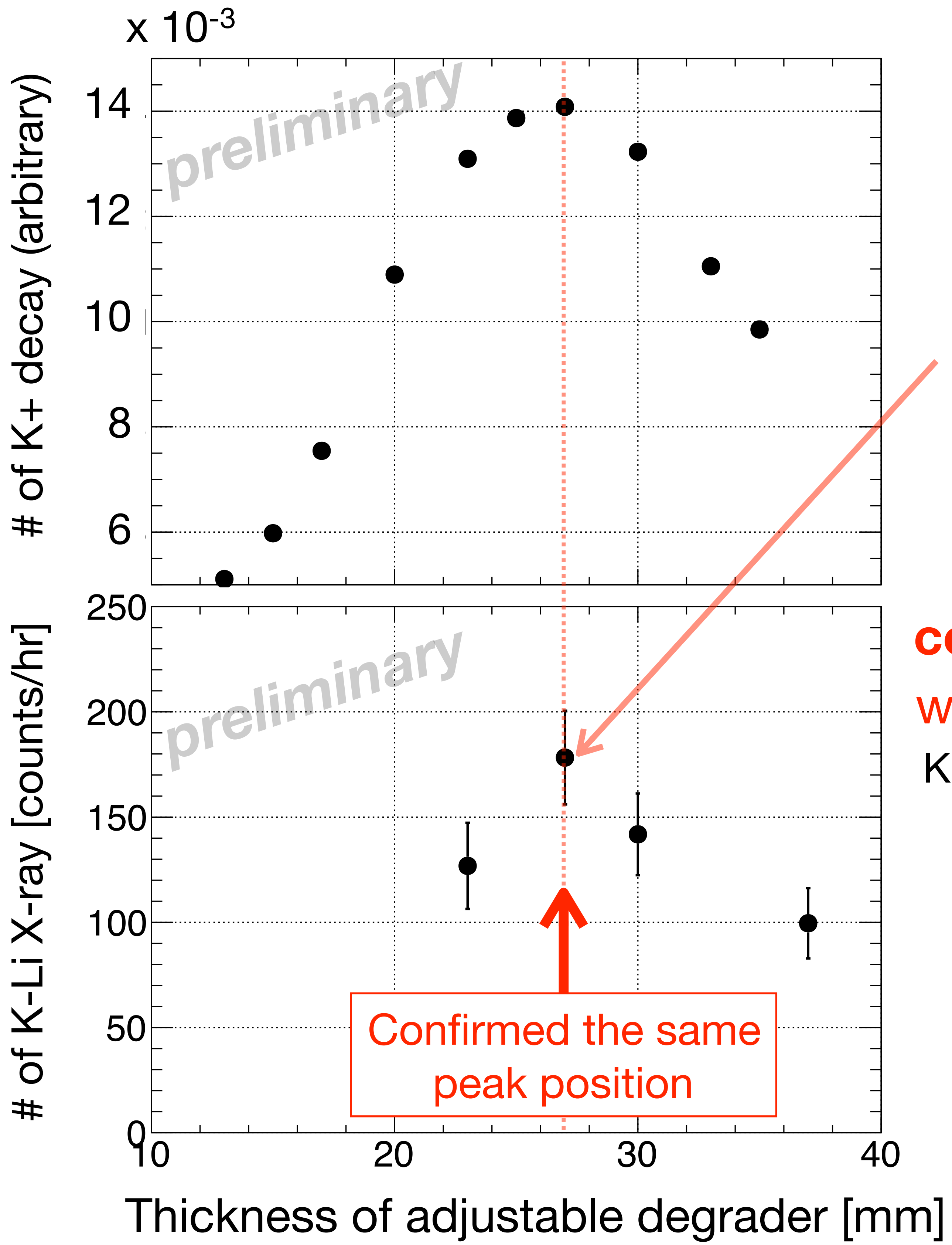
0.9 GeV/c K-



Range curve comparison

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

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



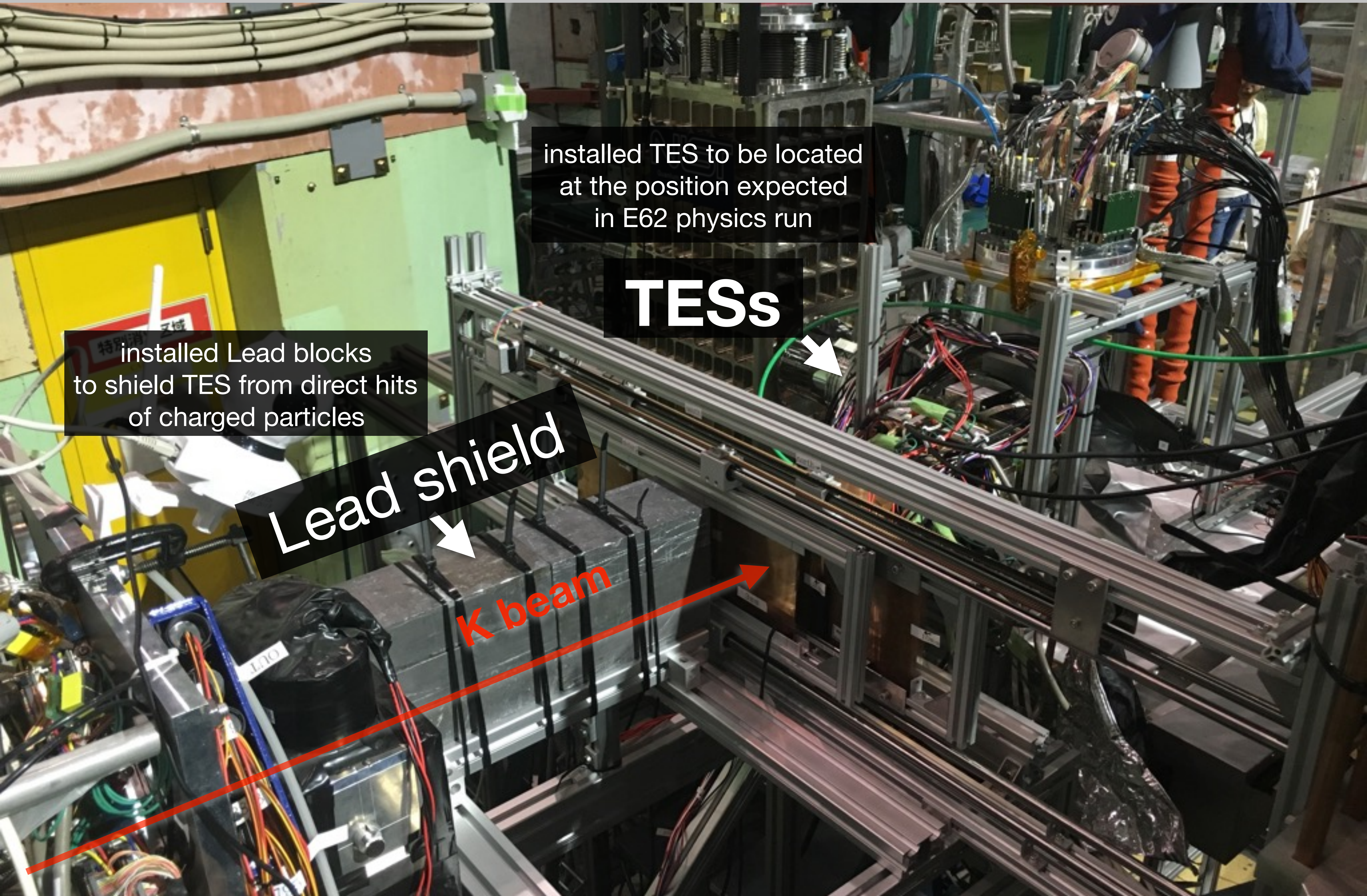
K-Li x-ray yield :
~180 counts / hr
(with 24 good SDDs)

consistent with G4 sim

within error of ref. value:

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

Setup from upstream

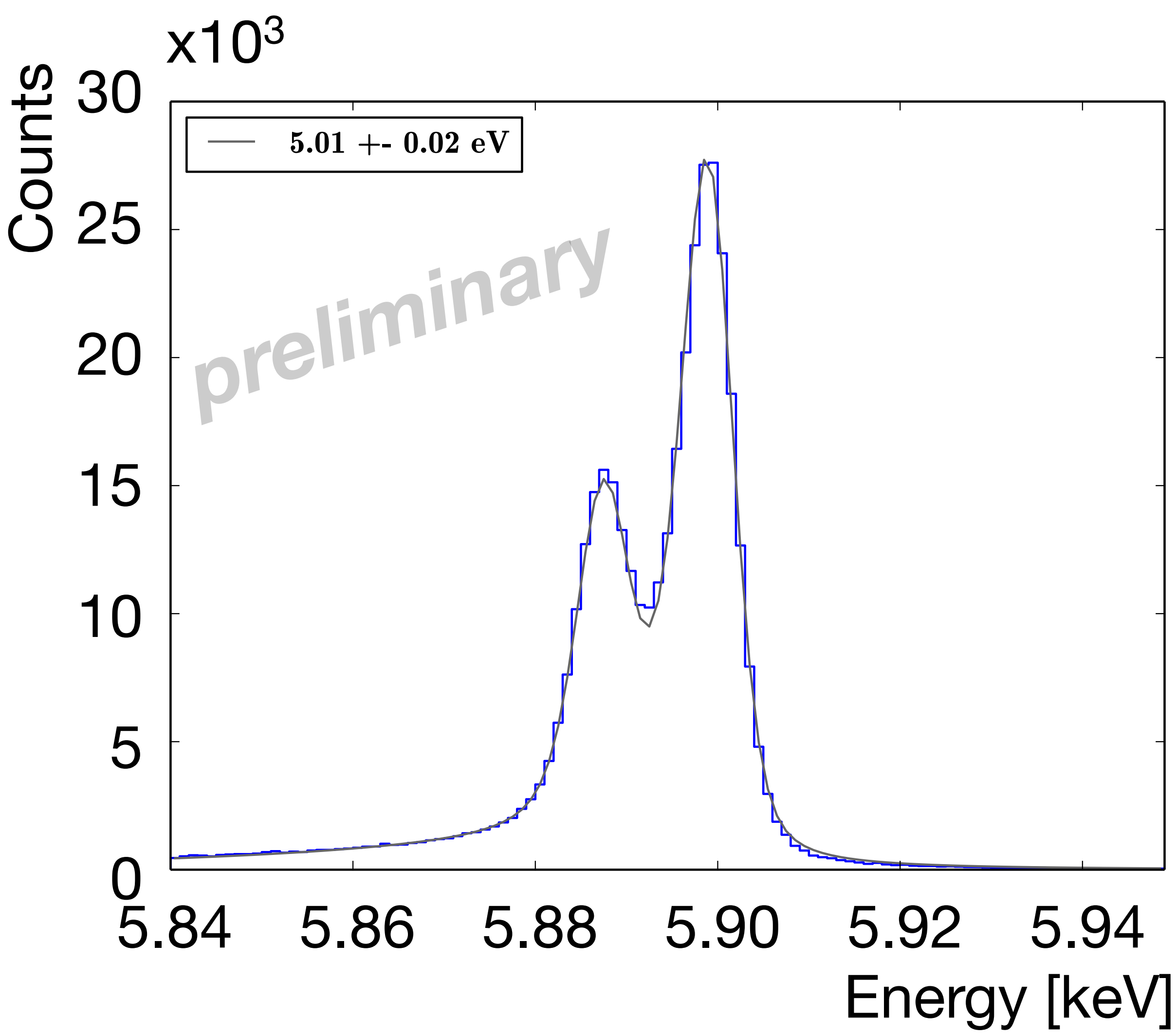


TES typical spectra

- Typical run with -0.9 GeV/c
- Summed up all pixels having <10 eV resolution (~80% TES pixels)

Spill OFF

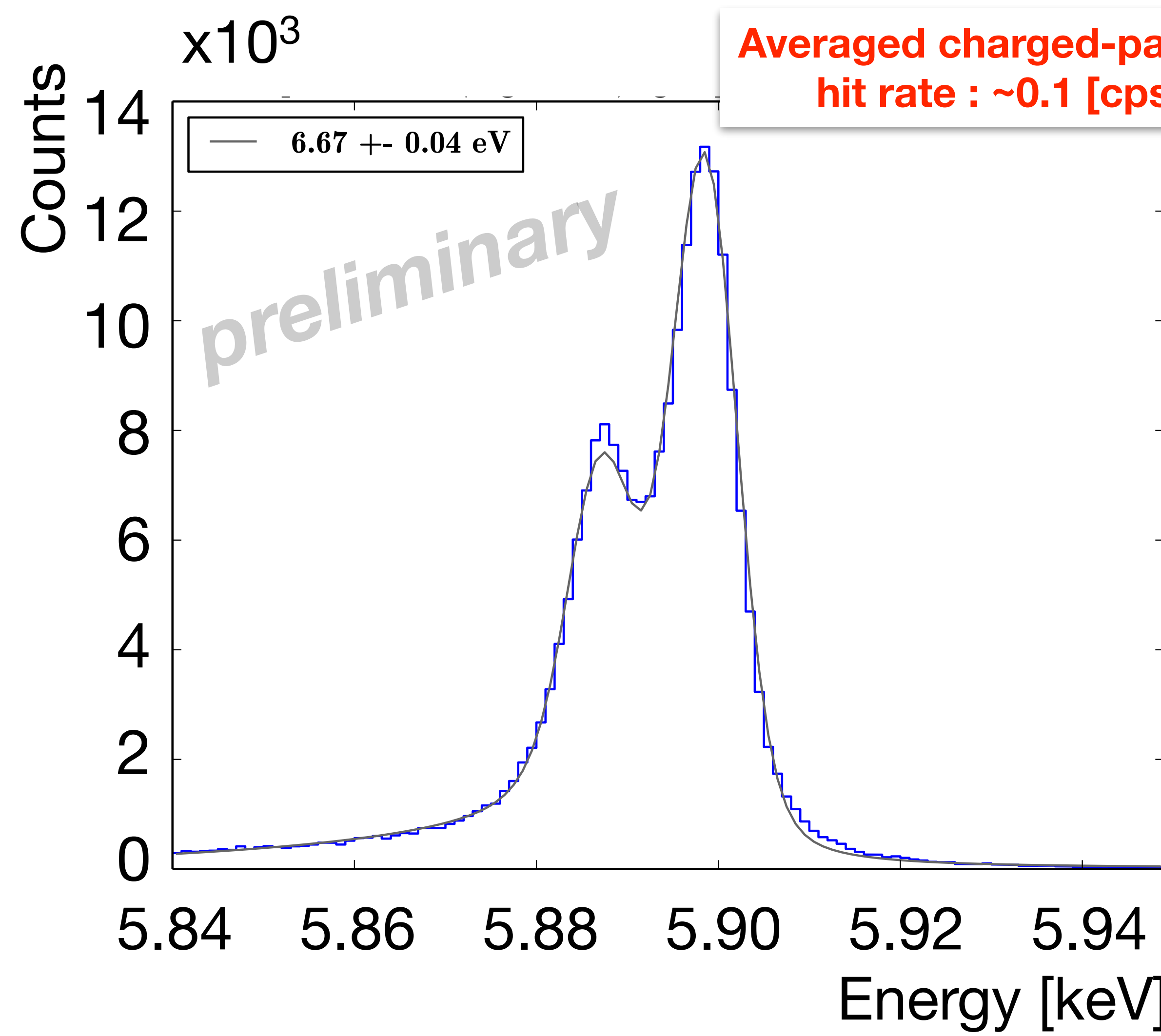
ΔE = 5.0 eV (FWHM)



Spill ON

ΔE = 6.7 eV (FWHM)

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



If no lead shield, <u>ΔE > 10 eV</u>. ⇒ **Lead shield was quite effective**.

6. Summary

Summary

◉ K-atom data is not good enough to determine K-nucl. potential

-> **High-resolution kaonic-atom x-ray spectroscopy with TES**

◉ 2014 : **demonstrated** the feasibility via π-atom w/TES @ PSI

◉ 2015 : **approved** by J-PARC PAC (Program Advisory Committee)

◉ 2016 : **commissioning** run (K-stop tune & TES test) @ J-PARC

◉ Ready for physics run — in 2017 !