101 Congresso della Societa Italiana di Fisica s

X-ray spectroscopy of kaonic atoms at the DAΦNE accelerator: SIDDHARTA experiment

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INFN-LNF

on behalf of SIDDHARTA collaboration

21 - 25 September 2015
Rome, Italy

SIDDHARTA

SIlicon Drift Detector for Hadronic Atom Research by Timing Applications

SIDDHARTA Collaboration

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The scientific aim

the determination of the

isospin dependent $\bar{K}N$ scattering lengths

through a

~ precision measurement of the shift

and *of the width*

of the K_α line of **kaonic hydrogen**

and

the *first measurement* of **kaonic deuterium**

And other types of kaonic atoms

SIDDHARTA went beyond what expected, since we did:

Precision measurements of kaonic helium 3 and 4 (2p level)

Other low-Z kaonic atom transitions were measured (kaonic kapton)

Yields measurements (kaonic atoms cascade processes)

The scientific aim

SIDDHARTA measures the X-ray transitions occurring in the cascade processes of kaonic atoms

↓

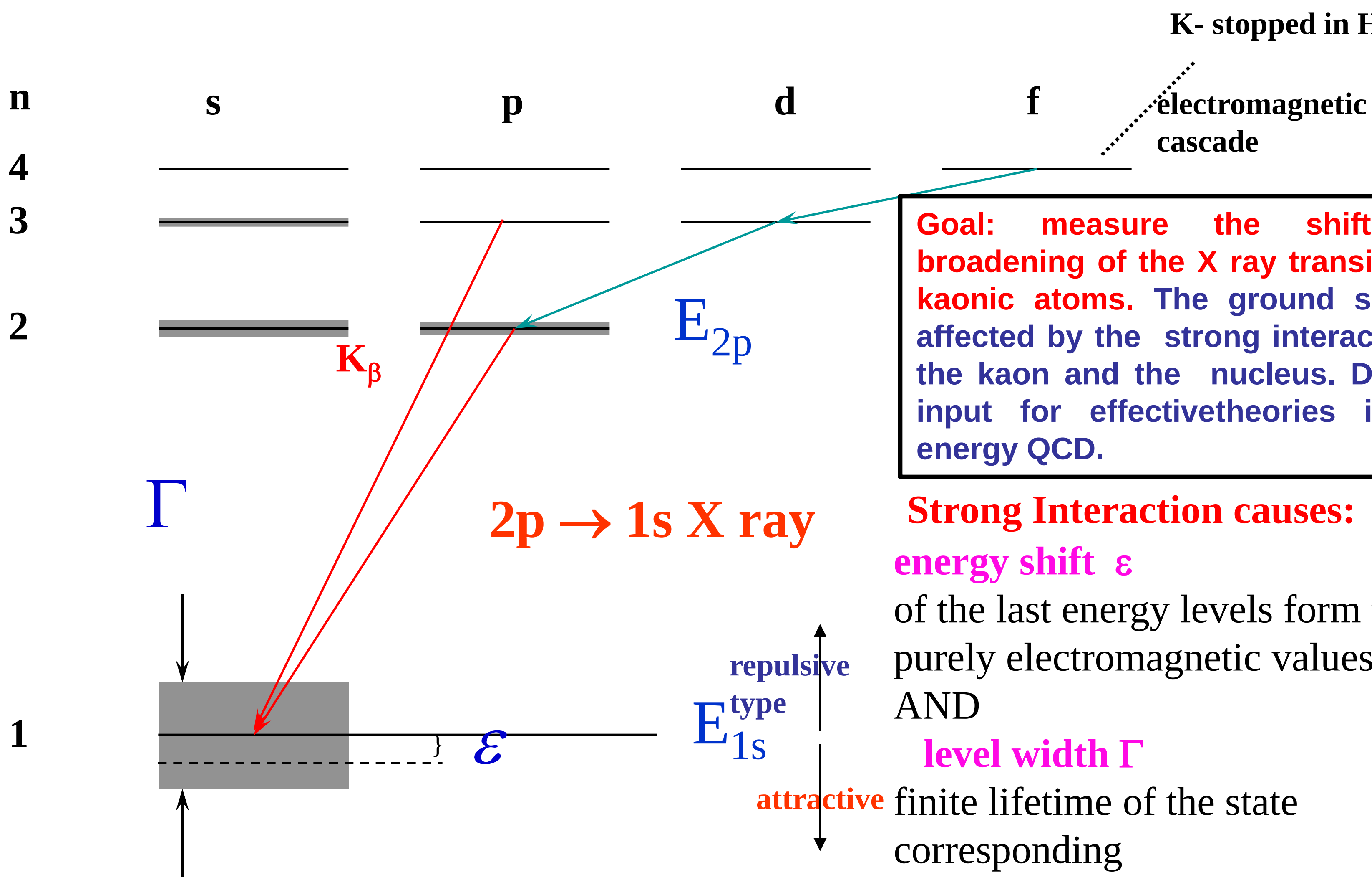
Fundamental study of **strong interaction** between anti-K & nucleus at low energy limit

The antikaon interaction on nucleons and nuclei in the low-energy regime is neither simple nor well understood. The research is concentrated on X-ray spectroscopy of simple hadronic atoms with strangeness like kaonic hydrogen and helium isotopes (^{3}He and ^{4}He), in order to extract precision data on the strong interaction observables.

The low-energy kaon-nucleon/nuclei interaction studies are fundamental for understanding QCD in non-perturbative regim.

The research field emerged about 50 years ago when meson beams became available. A special and unique source of kaons is provided by the DAΦNE collider which delivers an excellent quality low-energy charged kaons beam.

Kaonic Hydrogen atoms



Goal: measure the shift and broadening of the X ray transition of kaonic atoms. The ground state is affected by the strong interaction of the kaon and the nucleus. Delivers input for effectivetheories in low energy QCD.

Strong Interaction causes:

energy shift ε

of the last energy levels form their purely electromagnetic values

AND

level width Γ

finite lifetime of the state corresponding to an increase in the observed level width

$$\varepsilon = E_{2p\rightarrow 1s}\,(\mathrm{exp}) - E_{2p\rightarrow 1s}\,(\mathrm{e.m.})$$

SIDDHARTA experiment

$$e^+ + e^- \rightarrow \phi \rightarrow K^+ + K^-$$

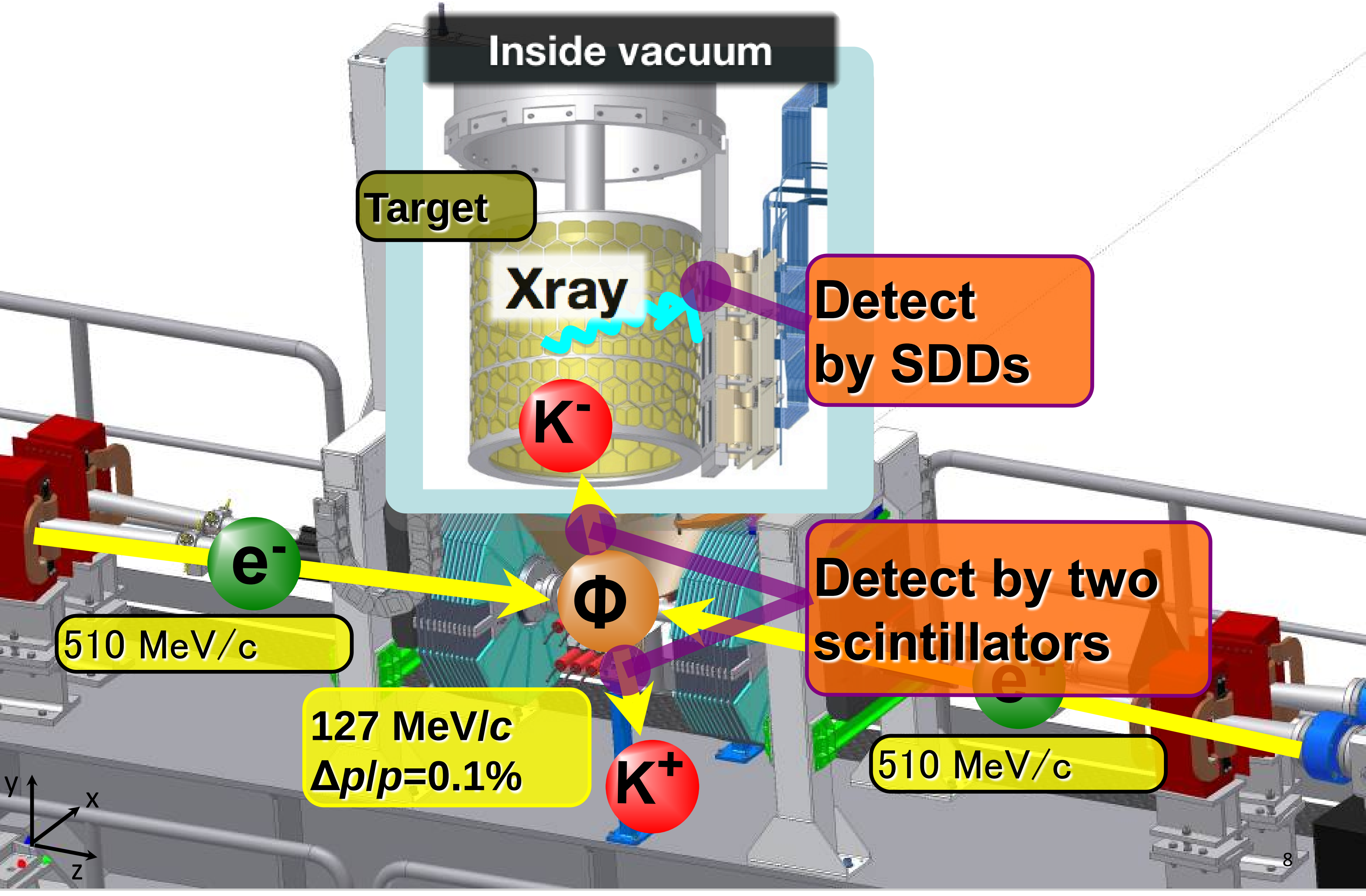
Monochromatic, low-momentum kaon beam from DAΦNE (127 MeV/c)

No hadronic background due to the beam line (compare with hadron beam line :e.g with KEK line)

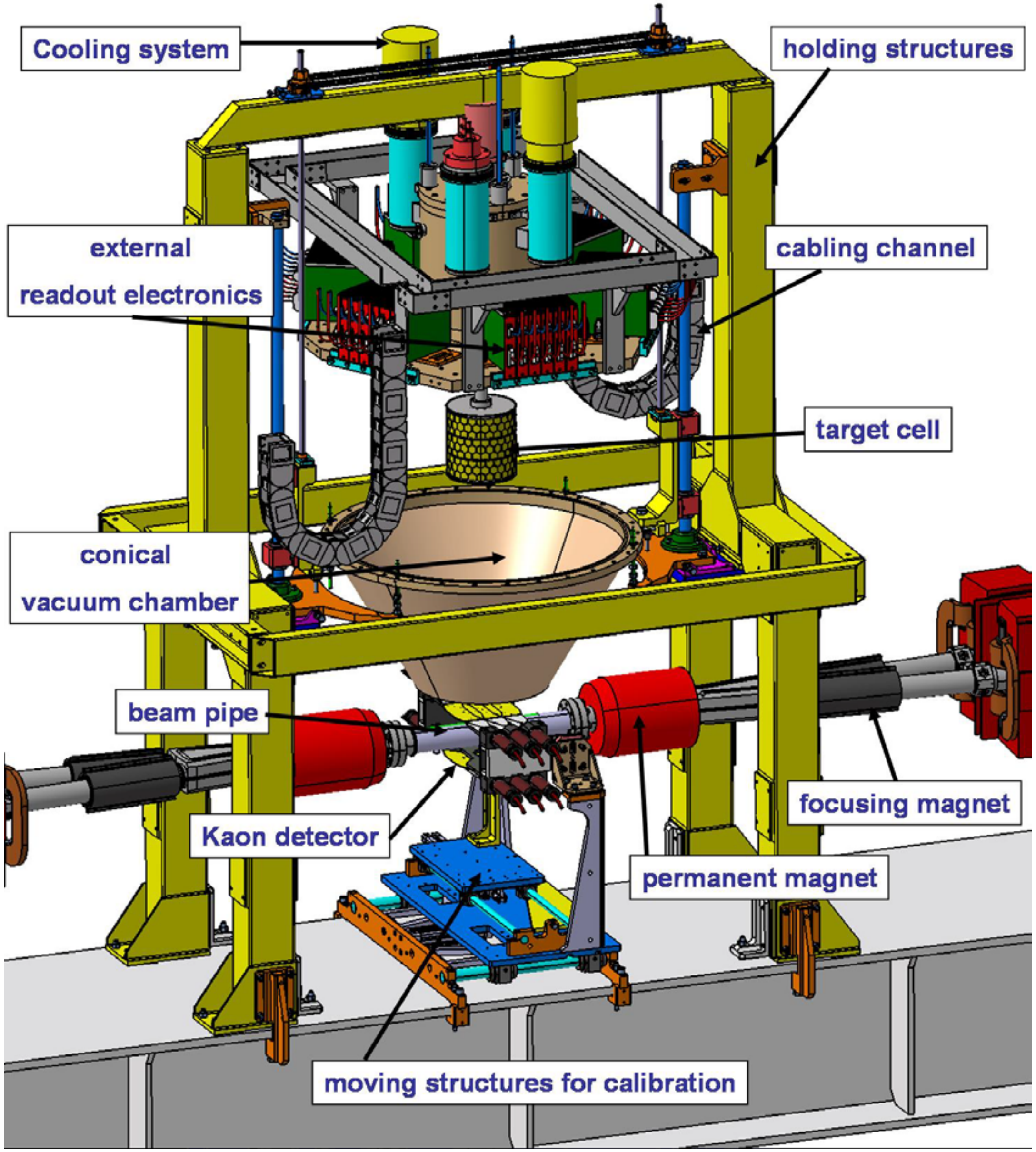
Big advantages of the SIDDHARTA experiment:

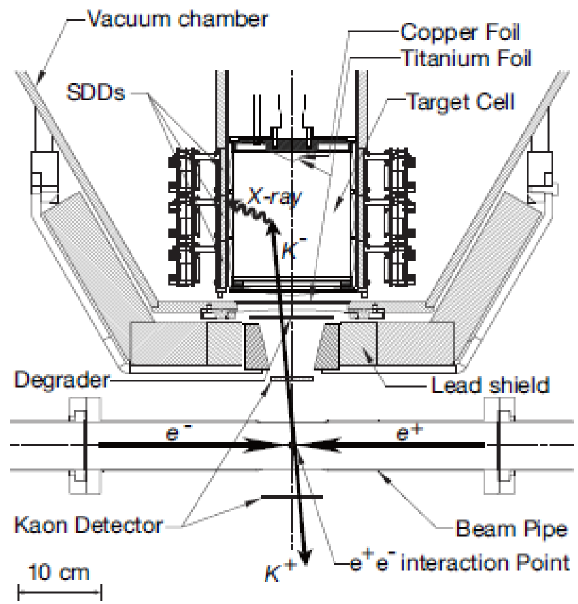
- **Low density gas target (higher yields of the atomic state in gaseous helium over the liquid one, due to the density dependent Stark mixing; negligible Compton scattering in helium).**
- **The availability of kaons with low energy and low momentum spread results in efficient kaon stopping in gas target.**
- **Silicon Drift Detector (SDDs) as detector**

SIDDHARTA overview



The experimental setup





Target size: r = 72 mm height = 155 mm

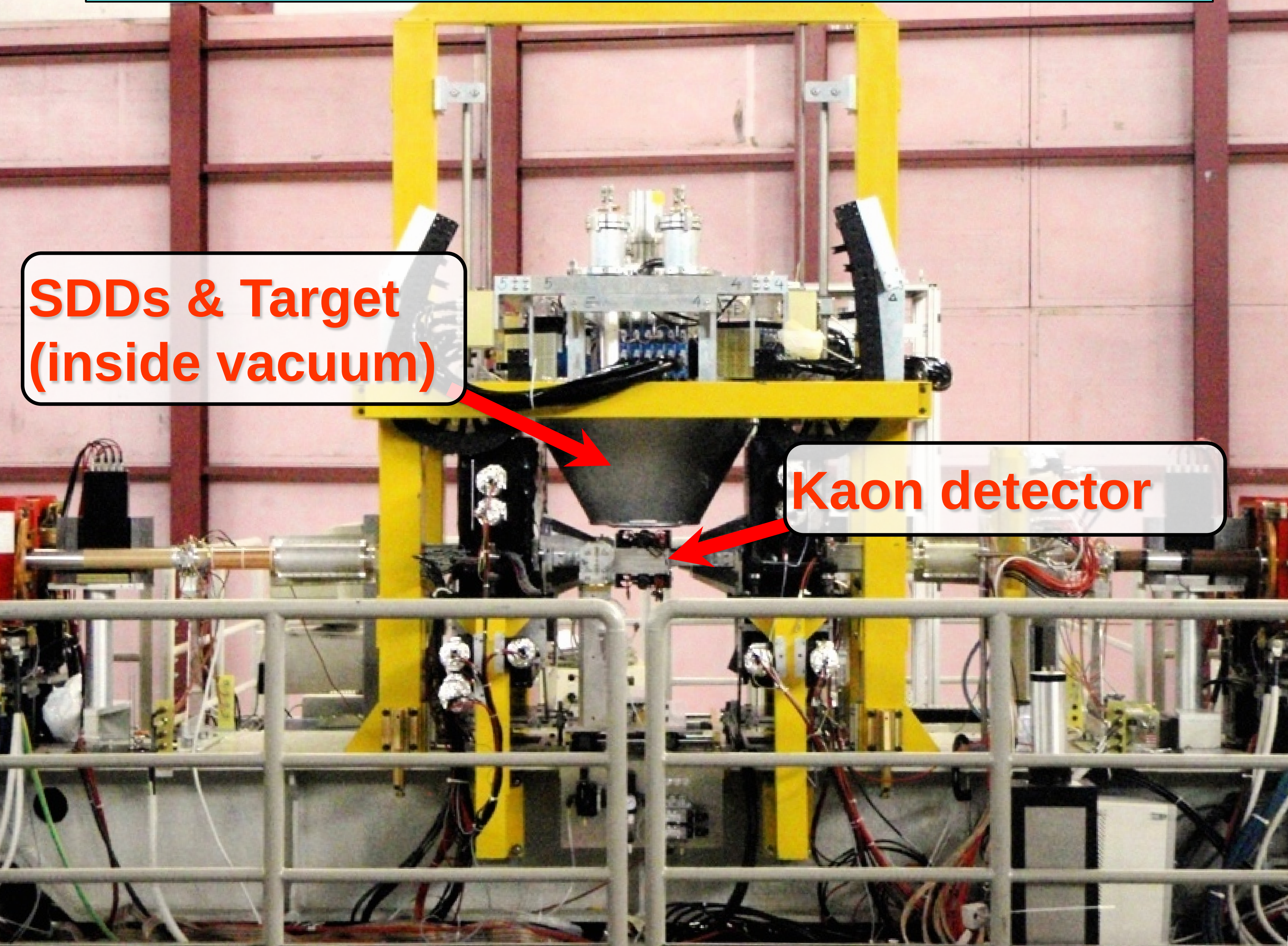
For He3: Temp. of gas: 20K

Pressure: 1 bar

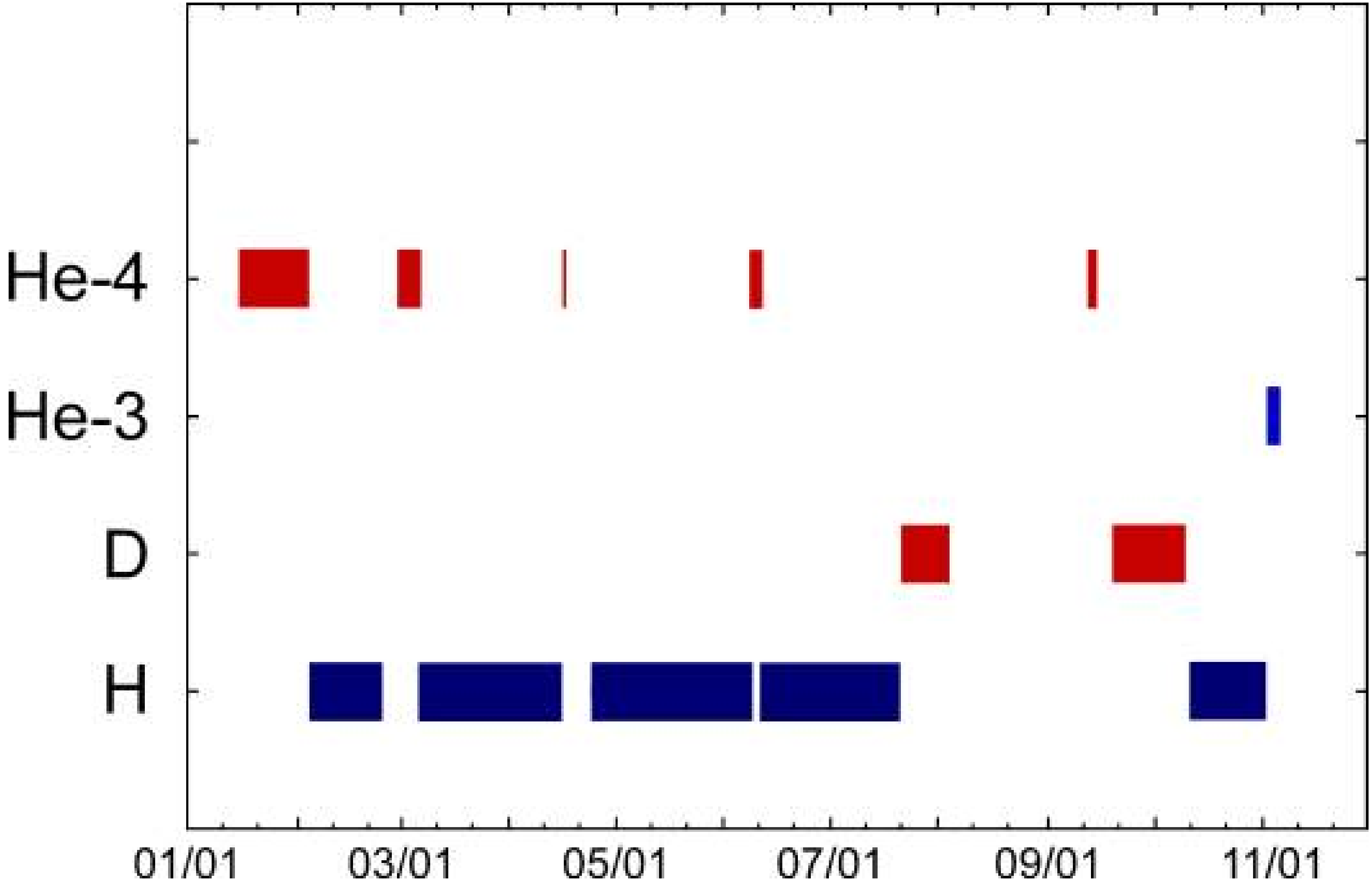
Installed SDD: 144 cm^2

SDD operation temp: 170 K

SDD Energy resolution: ≈150 eV (at 6 keV)


SDDs & Target
(inside vacuum)
Kaon detector

SIDDHARTA data



SIDDHARTA results:

- Kaonic Hydrogen: 400pb^{-1}, most precise measurement ever,Phys. Lett. B 704 (2011) 113, Nucl. Phys. A881 (2012) 88; Ph D

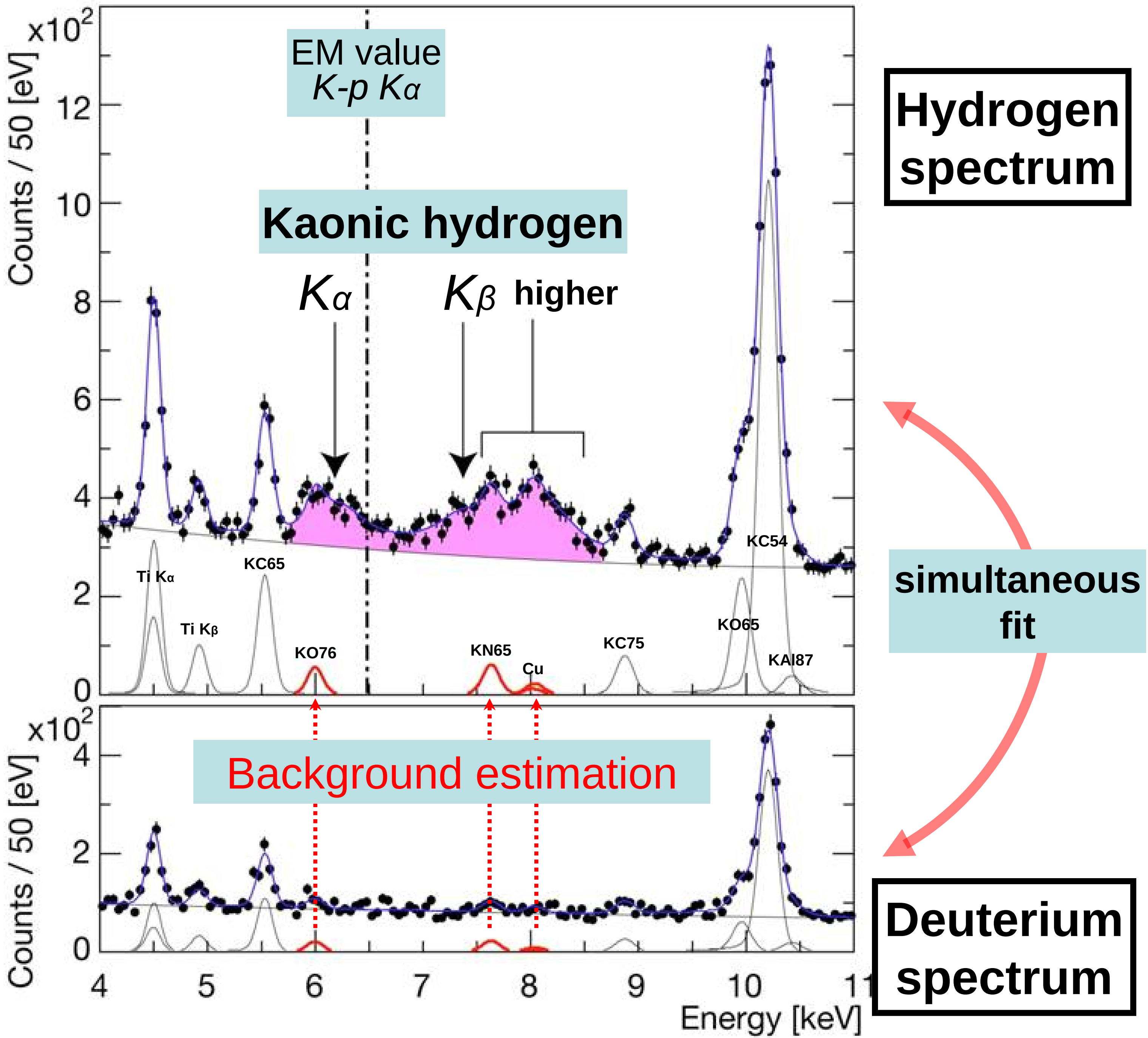
- Kaonic deuterium: 100 pb^{-1}, as an exploratory first measurement ever, Nucl. Phys. A907 (2013) 69; Ph D

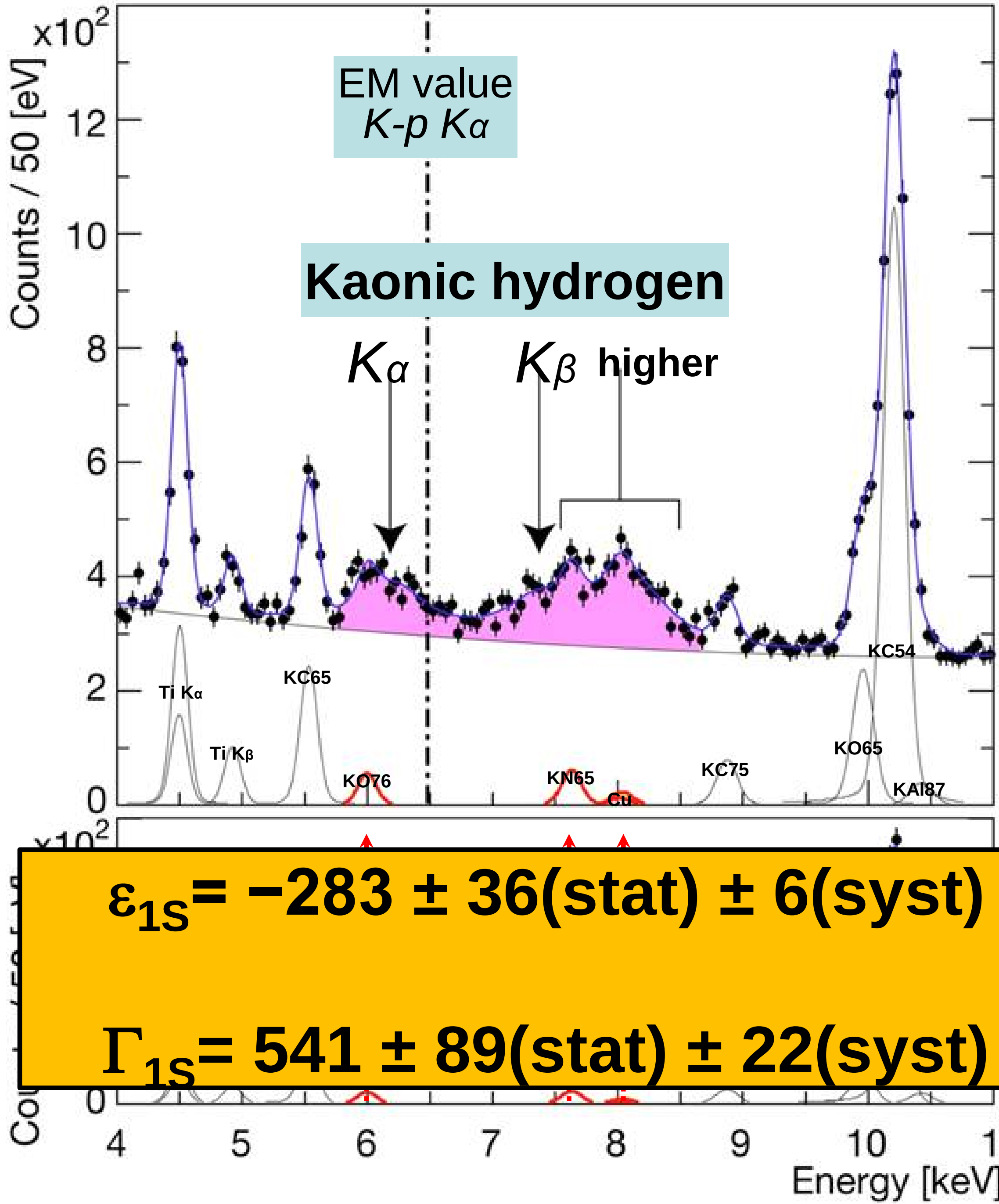
- Kaonic helium 4 – first measurement ever in gaseous target; published in Phys. Lett. B 681 (2009) 310; NIM A628 (2011) 264 and Phys. Lett. B 697 (2011);; PhD

- Kaonic helium 3 – 10 pb^{-1}, first measurement in the world, published in Phys. Lett. B 697 (2011) 199; Ph D

- Widths and yields of KHe3 and KHe4 - Phys. Lett. B714 (2012) 40; ongoing: KH yields; kaonic kapton yields; yields of the KHe3 and KHe4 –EPJ A(2014) 50.

SIDDHARTA – important TRAINING for young researchers


EM value
K-p Kα
Kaonic hydrogen
Kα
Kβ
higher
Hydrogen spectrum
simultaneous fit
Deuterium spectrum
Background estimation
Ti Kα
Ti Kβ
KC65
KO76
KN65
Cu
KC75
KO65
KC54
KAl87
Counts / 50 [eV]
x10^2
Energy [keV]



Hydrogen spectrum

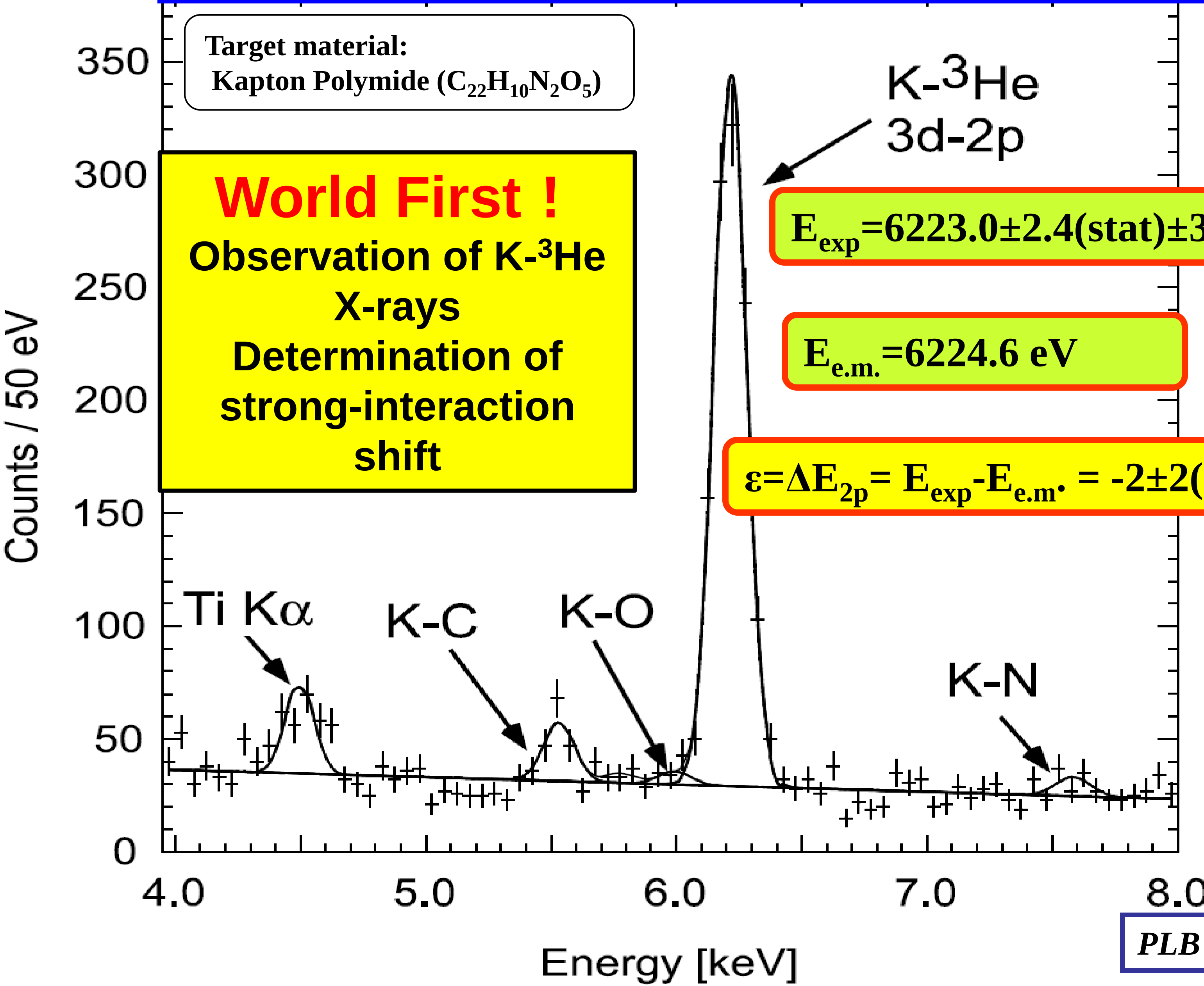
simultaneous fit

Deuterium spectrum

$$\varepsilon_{1S} = -283 \pm 36(\text{stat}) \pm 6(\text{syst})\ \text{eV}$$

$$\Gamma_{1S} = 541 \pm 89(\text{stat}) \pm 22(\text{syst})\ \text{eV}$$

Kaonic Helium-3 energy spectrum extraction of the strong interaction shift



Target material:
Kapton Polymide ($C_{22}H_{10}N_2O_5$)

World First !

Observation of K-^{3}He X-rays
Determination of strong-interaction shift

E_{exp}=6223.0±2.4(stat)±3.5(syst.) eV

$E_{e.m.}$=6224.6 eV

$\varepsilon = \Delta E_{2p} = E_{exp} - E_{e.m.}$ = -2±2(stat)±4(syst)

PLB 697 (2011) 199

EXOTIC ATOMS

Kaonic hydrogen casts new light on strong dynamics

Hadronic bound systems with strange quarks, such as kaonic hydrogen, are well suited for testing chiral dynamics, especially in view of the interplay between spontaneous and explicit symmetry breaking. Effective field theories with coupled channels based on chiral meson–baryon Lagrangians have become well established as a framework for describing $\bar{K}$–nucleon interactions at threshold, including much disputed $\Lambda(1405)$ resonances and deeply bound antikaonic nuclear clusters lying just below the respective thresholds.

A recent precision measurement at the Laboratori Nazionali di Frascati of the strong-interaction-induced shift and width of the 1s level in kaonic hydrogen sheds new light on these basic problems in strong-interaction binding and dynamics. Kaonic hydrogen, in which a $\bar{K}$ replaces the electron, is produced by the capture of stopped $\bar{K}$ from the decay of ϕ mesons in hydrogen gas. The ϕ mesons are generated nearly at rest at the DAΦNE e^+e^- collider, operating in a new, high-luminosity collision mode.

The SIDDHARTA collaboration with the apparatus. (Image credit: C Curceanu.)

The shift and width of the kaonic 1s state is deduced from precision X-ray spectroscopy of the K-series transitions in the kaonic hydrogen. The emitted K-series X-rays, with energies of 6–9 keV, were detected by the recently developed Silicon Drift Detector for Hadronic Atom Research by Timing Application (SIDDHARTA) experiment, which performs X-ray–kaon coincidence spectroscopy using microsecond timing and the excellent energy resolution of about 180 eV FWHM at 6 keV of 144 large-area (1 cm^2) silicon drift detectors that surround the hydrogen target cell. This method reduces the large X-ray background from beam losses by orders of magnitude. It has led to the most precise values for the 1s level shift, $\varepsilon_{1s} = -283 \pm 36$ (stat.) ± 6 (syst.) eV, and width $\Gamma_{1s} = 541 \pm 89$ (stat.) ± 22 (syst.) eV for kaonic hydrogen (Bazzi *et al.* 2011).

A recent study using next-to-leading-order chiral dynamics calculations of the shift and the width has shown excellent agreement with these measurements (Ikeda *et al.* 2011). Further measurements with similar accuracy are planned for the K-series X-rays from kaonic deuterium, using an improved SIDDHARTA-2 set-up to disentangle the isoscalar and isovector scattering lengths.

• Further reading

M Bazzi *et al.* *Phys. Lett.* **B704** (2011) 113.
Y Ikeda, T Hyodo and W Weise 2011 arXiv:1109.3005[nucl-th].

HYP2012

Concluding Remarks

Tomofumi NAGAE,

Kyoto University

HIGHLIGHTS

HYP2012

... And a lot of intensive discussions.

Future plans

The upgrade of the SIDDHARTA experimental setup

DAFNE

Precise measurements for the X-ray transitions for kaonic hydrogen and kaonic deuterium

Measuring, with higher precision, the X-ray transitions for Kaonic ^{4}He and Kaonic ^{3}He to the 2p level and the first tentative to the 1s level

Other kaonic atoms (light and heavy) (ex: Si, Pb, etc)

Charged kaon mass precision measurement

SIDDHARTA2 strategy – phases

1) Kaonic deuterium measurement
(priority of LNF-INFN – stated by Director and SC)

2) Kaonic helium transitions to the 1s level – 2nd measurement, R&D

3) Other light kaonic atoms (KO, KC,…)

4) Heavier kaonic atoms measurement (Si, Pb…)

5) Kaon radiative capture – $\Lambda(1405)$ study

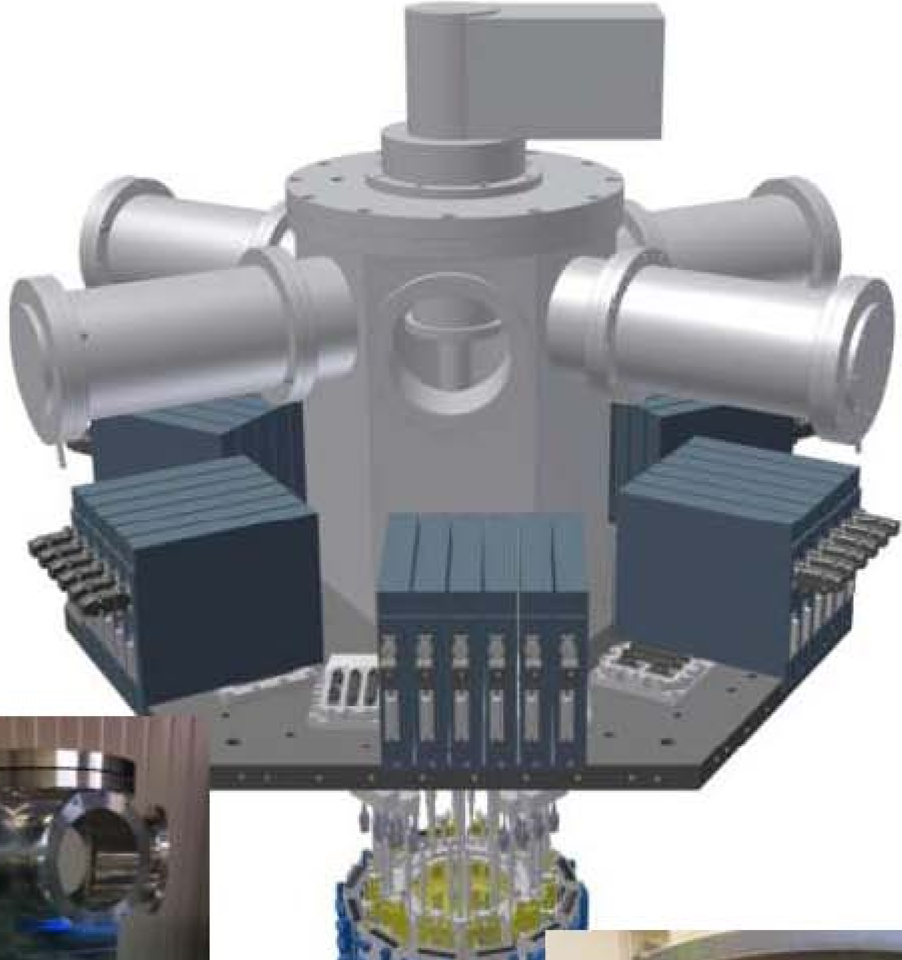
6) Investigate the possibility of the measurement of other types of hadronic exotic atoms (sigmonic hydrogen ?)

7) Kaon mass precision measurement at the level of <10 keV

The SIDDHARTA-2 setup

- new target final tests
- new SDD arrangement
- vacuum chamber final tests
- more cooling power
- improved trigger scheme
- shielding and anti-coincidence (veto)
- Assembly and tests
- New SDDs (FBK)

SIDDHARTA-2:

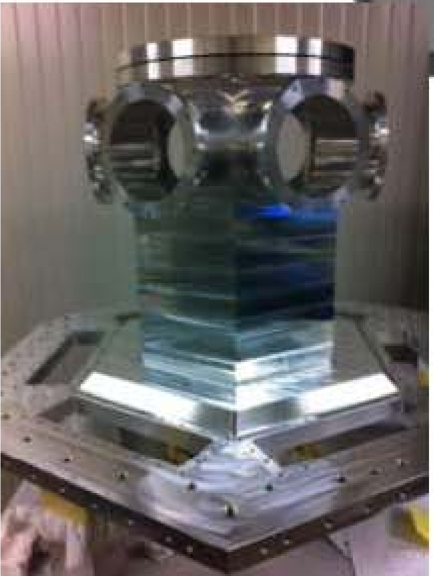


- Vacuum chamber
  ready and tested

- Cryogenic target
  ready and first cooling tested successfully

- SDD cooling unit
  prototype tested, components under construction

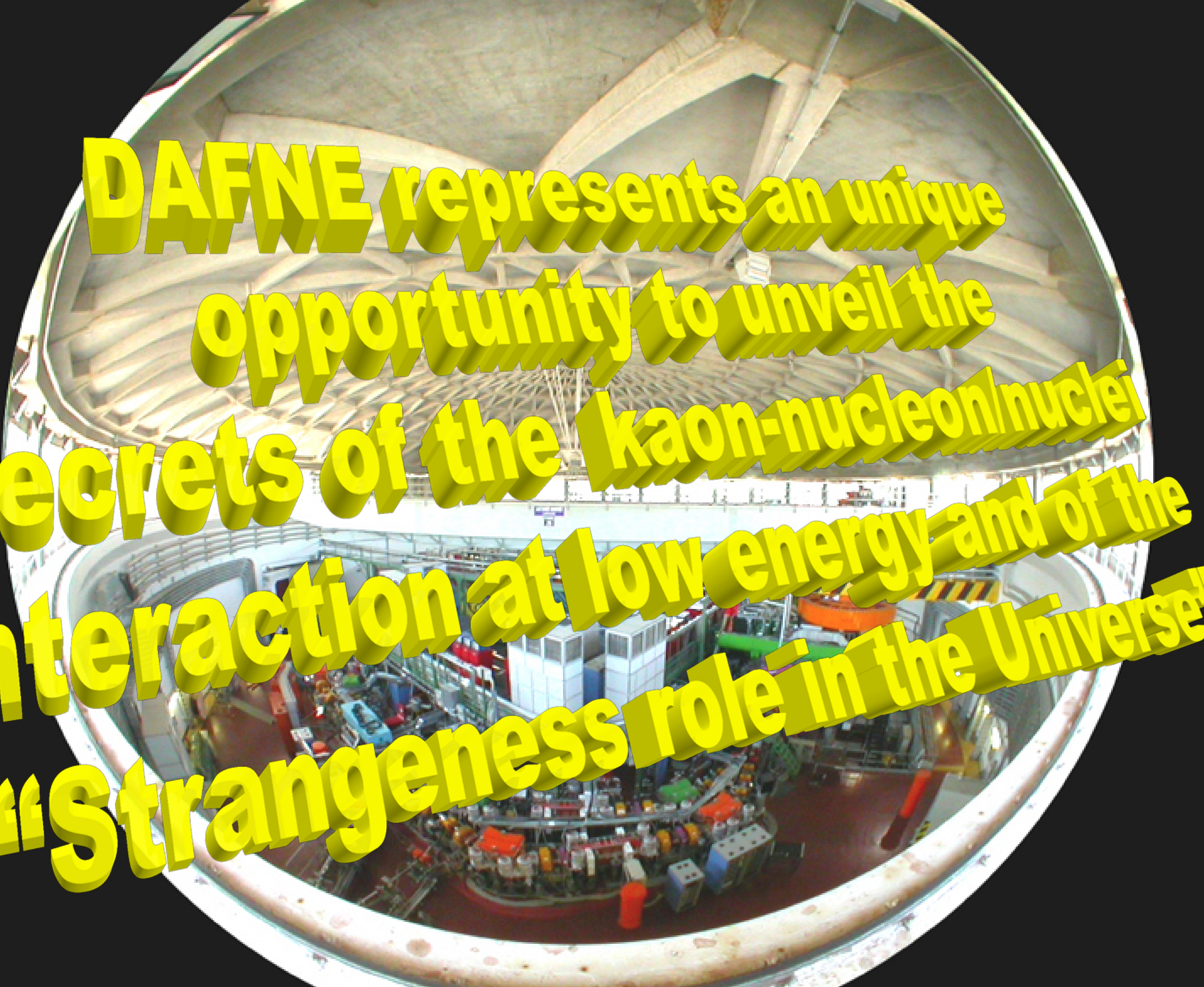
- Veto(1) system –
- built and tested



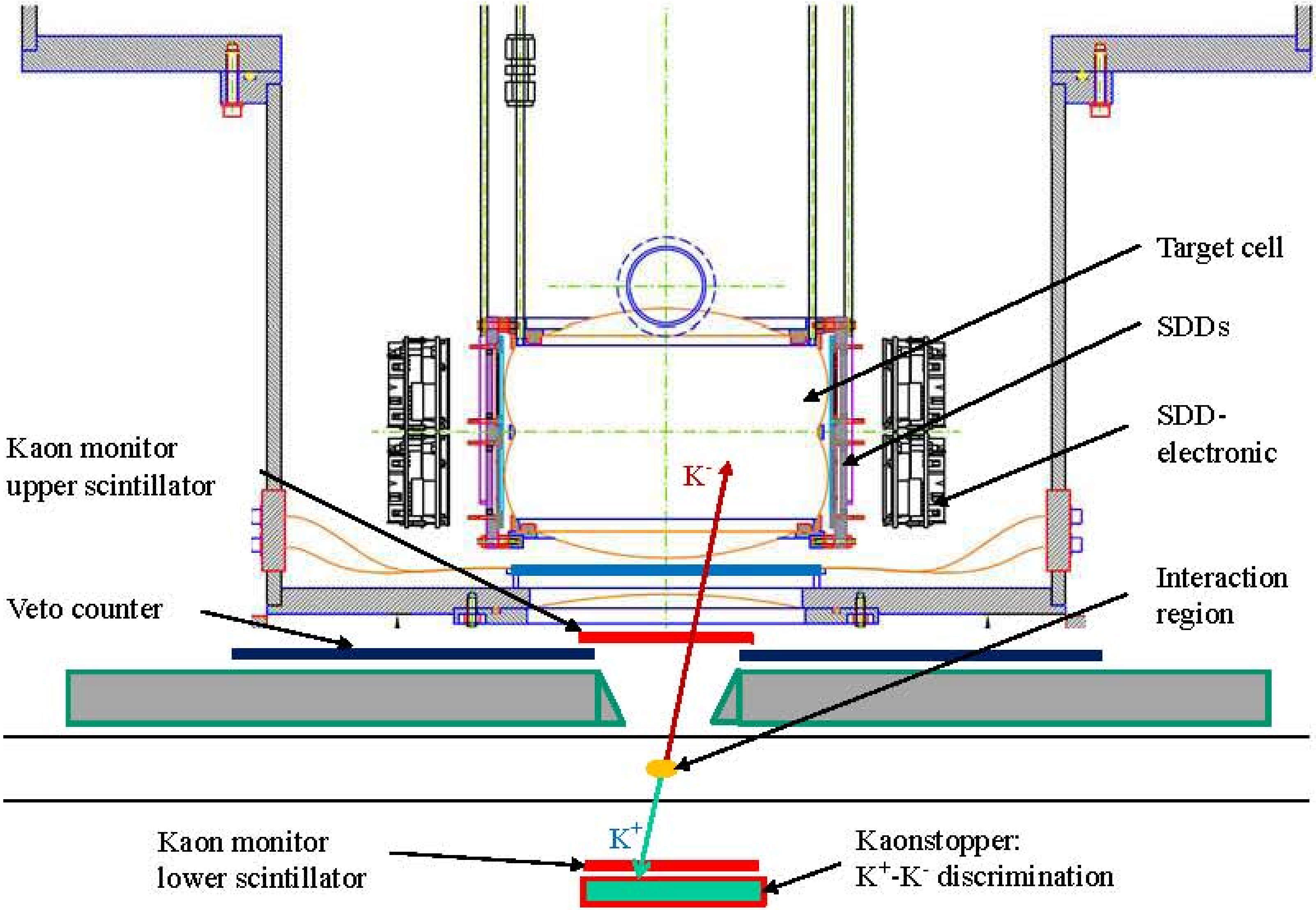
DAΦNE represents (as always did) an (THE) EXCELLENT FACILITY in the sector of low-energy interaction studies of kaons with nuclear matter.

It is actually the IDEAL facility for kaonic atoms studies as SIDDHARTA has demonstrated

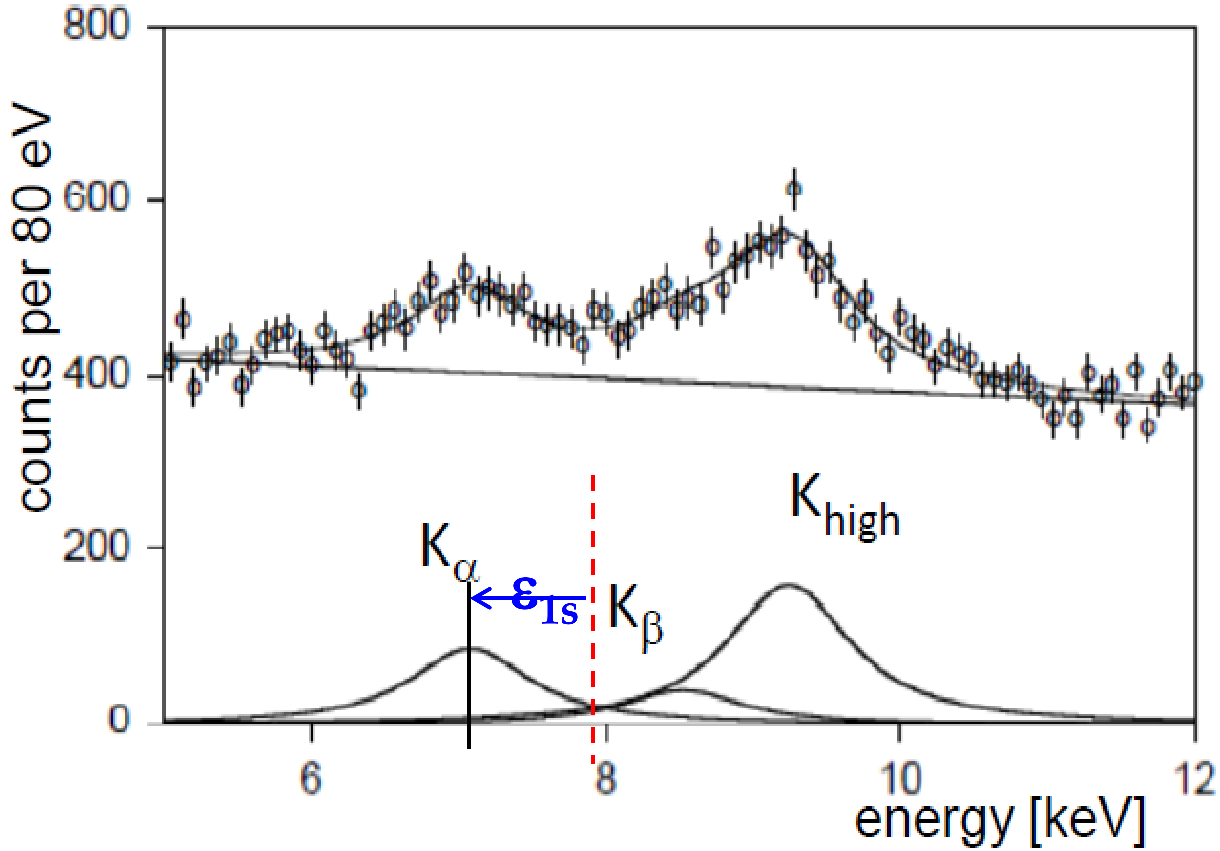
SIDDHARTA-2 team is ready to restart the measurements, having a multi-step strategy, starting with the Kaonic deuterium.



DAFNE represents an unique opportunity to unveil the secrets of the kaon-nucleon/nuclei interaction at low energy and of the "Strangeness role in the Universe"


Target cell
SDDs
SDD-
electronic
Kaon monitor
upper scintillator
K-
Veto counter
Interaction
region
K+
Kaon monitor
lower scintillator
Kaonstopper:
K+-K- discrimination

Monte Carlo calculated X-ray spectrum of Kaonic deuterium

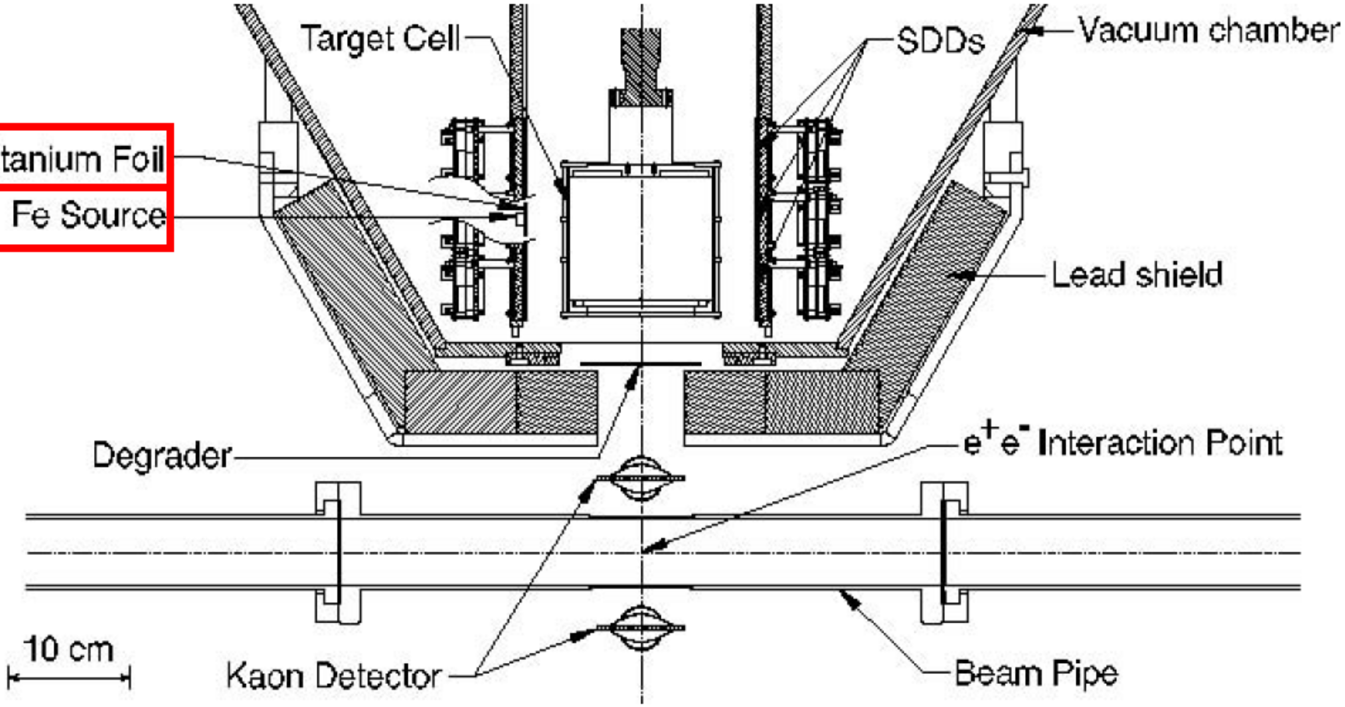


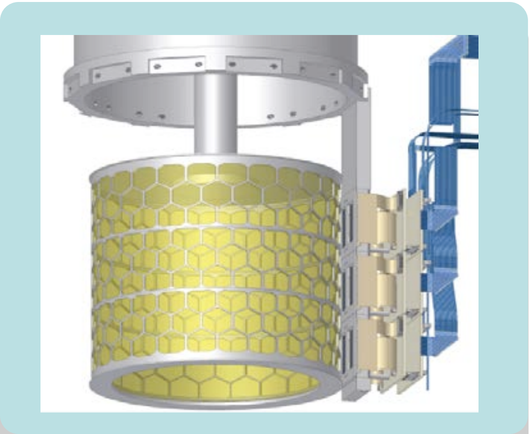
Assumptions
signal: shift - 800 eV
width 750 eV
density: 5% (LHD)
detector area: 246 cm^2

Kα yield: 0.1 %
yield ratio as in K^-p

An estimated precision of 70 eV in the shift and 150eV in the width

The experimental setup





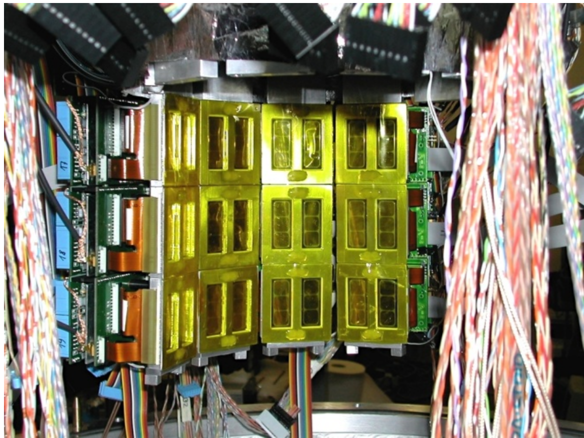
Target size: r=6 cm, height=12 cm

Target density: 0.01 of liquid hydrogen density (8.7 STP)

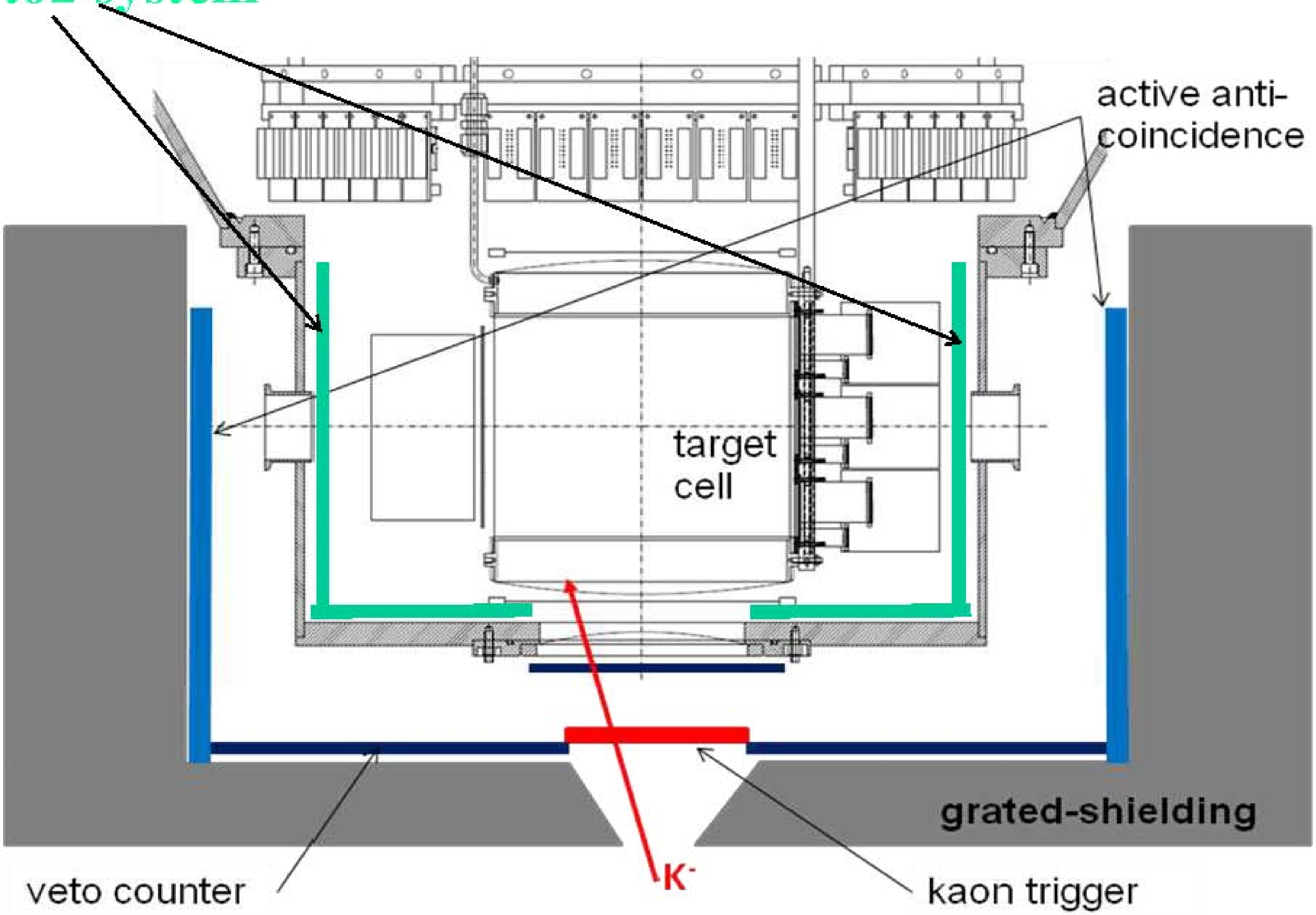
Installed SDD: 144 cm^2

SDD operation temp: 23 K

SDD Energy resolution: ≈150 eV (at 6 keV)

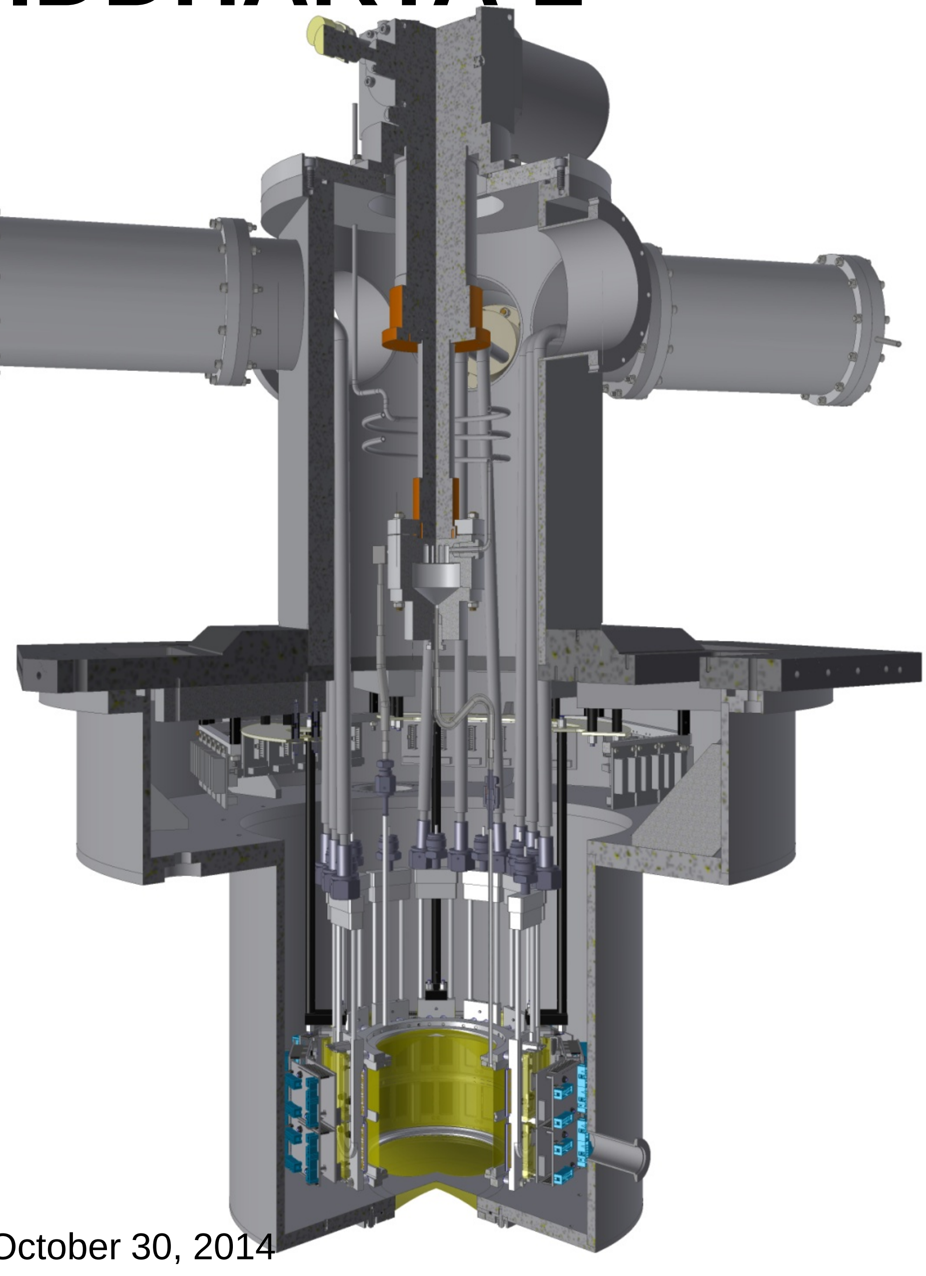


Veto2 system



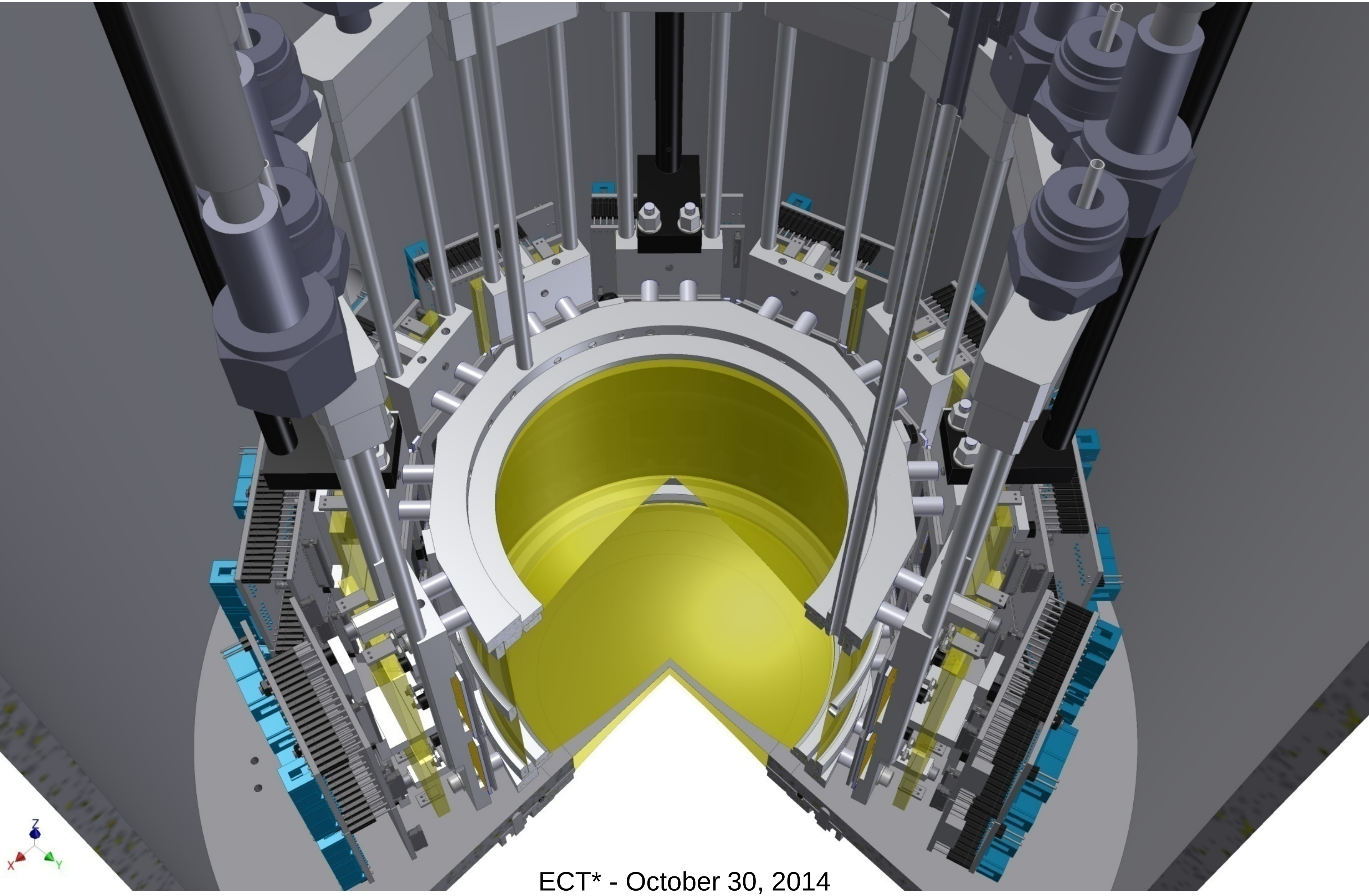
$K^{-}d$ at DAΦNE - SIDDHARTA-2

Target cooling:
1 Leybold – 16 W @ 20 K
Liquid hydrogen cooling lines,
new target cell

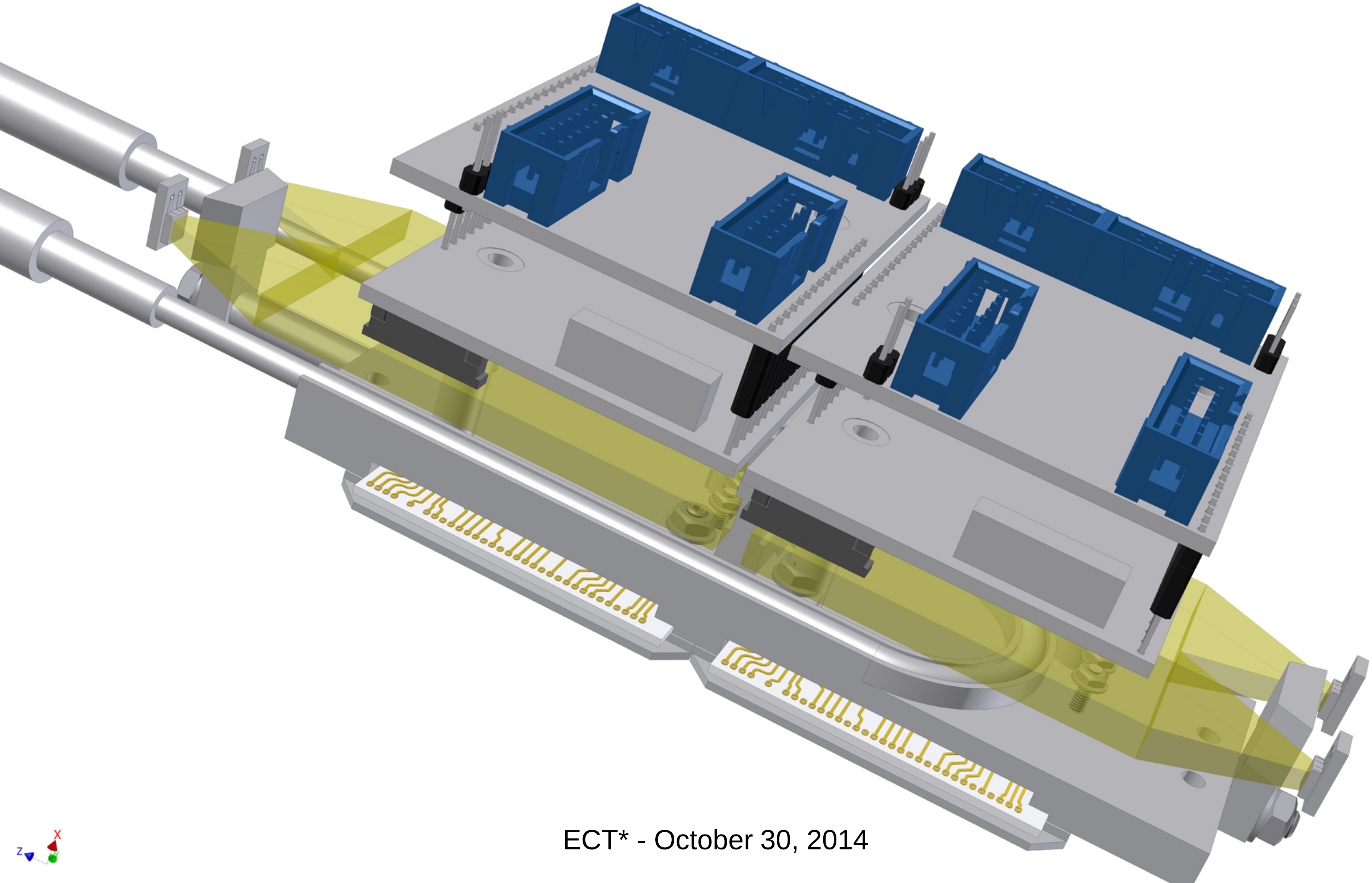


SDD cooling:
4 CryoTiger – 60 W @ 120 K
Liquid argon cooling lines:
SDD cooling to 100 – 120 K

SIDDHARTA-2 setup



SIDDHARTA-2: SDD charge particle veto

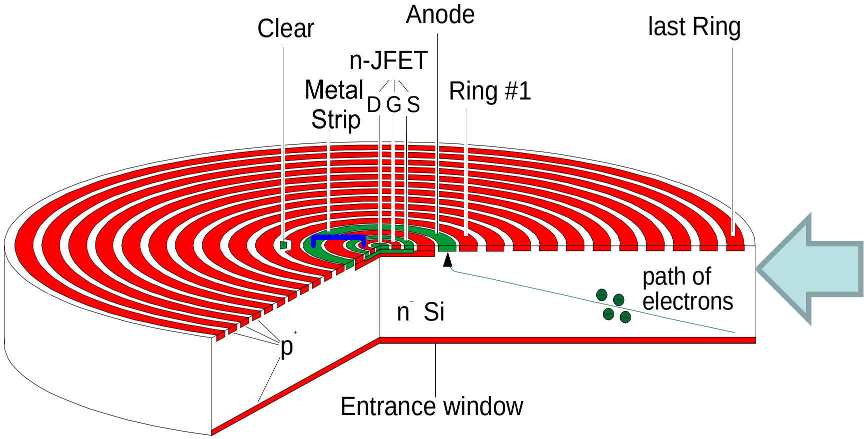


New SDDs

JFET integrated on the SDD
lowest total anode capacitance

limited JFET performances

sophisticated SDD+JFET technology



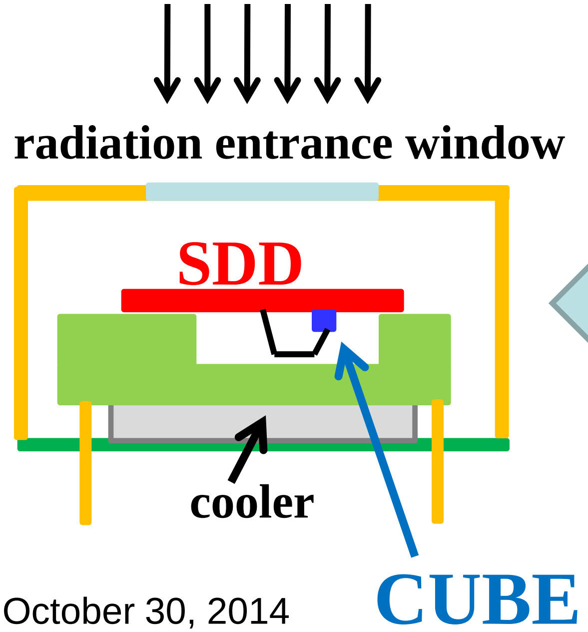
Now in SIDDHA RTA

external CUBE preamplifier (MOSFET input transistor)

larger total anode capacitance

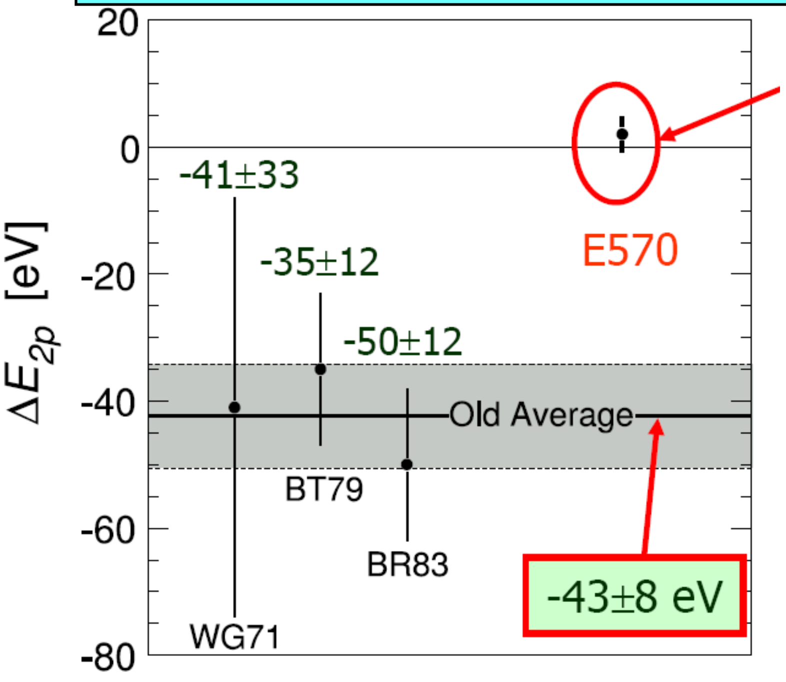
better FET performances

standard SDD technology



Proposed for SIDDHART A-2

Solving the kaonic helium puzzle



Theory:
ΔE2p ≈ 0 eV
or
< ± 10 eV

Old experiments:
Large shift
(-43±8 eV)

Difference between the new and the old experiments

E570 experiment:
Small shift
(+2±2±2 eV)

Experimental confirmation need!
SIDDHARTA experiment

Kaonic ^{4}He data
SIDDHARTA experiment

The **Kaonic ^{4}He X-ray data** were taken for about **two weeks in January 2009**.

In this period, an **integrated luminosity of about 20pb^{-1}** was collected.

This corresponds to about **4.7×10^6 kaons** detected by the kaon detector.

Antikaon-nucleon scattering lengths

Once the shift and width of the 1s level for kaonic hydrogen and

deuterium are measured -) scattering lengths

(isospin breaking corrections):

$$\varepsilon + i\ \Gamma/2 \Rightarrow a_{K^-p}\ \text{eV fm}^{-1}$$

$$\varepsilon + i\ \Gamma/2 \Rightarrow a_{K^-d}\ \text{eV fm}^{-1}$$

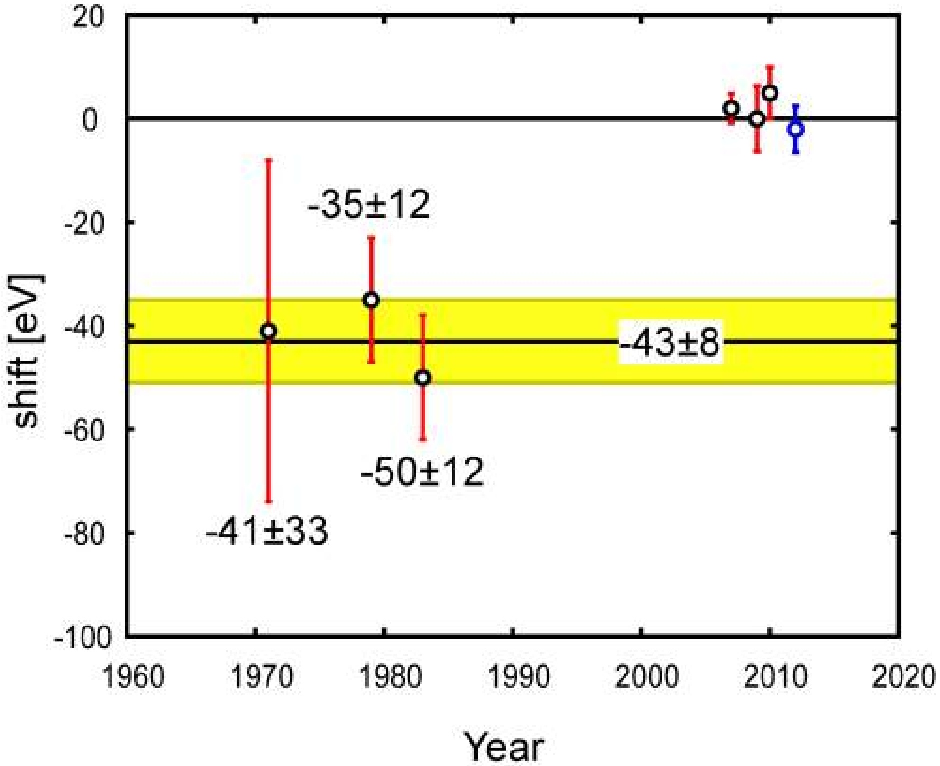
one can obtain the isospin dependent antikaon-nucleon scattering lengths

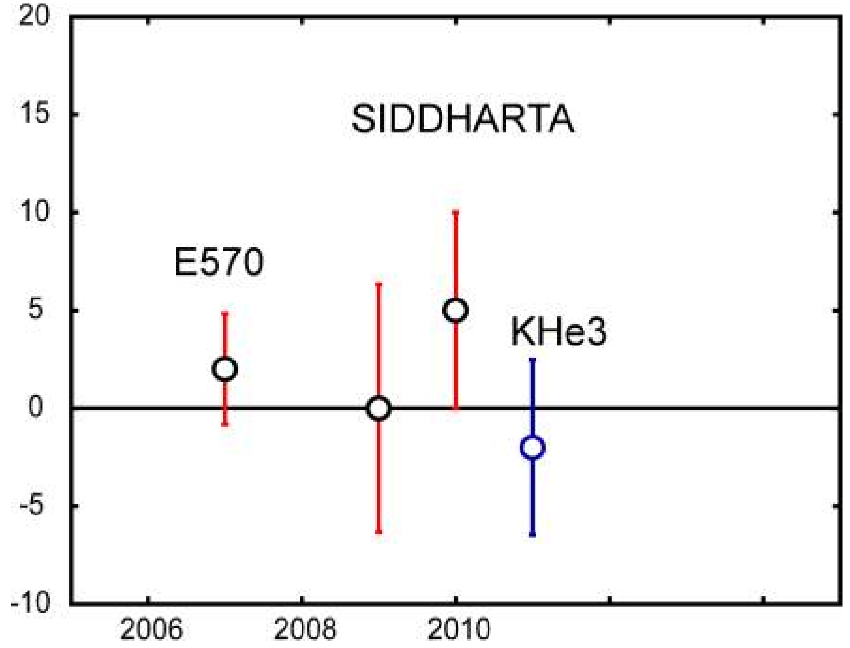
$$a_{K^-p} = (a_0 + a_1)/2$$

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

Summary of the results

Experiment	Target	Shift [eV]	Reference
KEK E570	Liquid	+2±2±2	PLB653(07)387
SIDDHARTA (He4 with 55Fe)	Gas	+0±6±2	PLB681(2009)310
SIDDHARTA (He4)	Gas	+5±3±4	arXiv:1010.4631, PLB697(2011)199
SIDDHARTA (He3)	Gas	-2±2±4	





***error bar** $= \pm\sqrt{(stat)^2 + (syst)^2}$

The scientific aim of SIDDHARTA

To perform precision measurement of kaonic atoms X-ray transitions -> unique info about the QCD in non-perturbative regime in the strangeness sector not obtainable otherwise

Precision *measurement of the shift* and *of the width*

of the 1s level of **kaonic hydrogen** and

the *first measurement* of **kaonic deuterium**

And other types of kaonic atoms

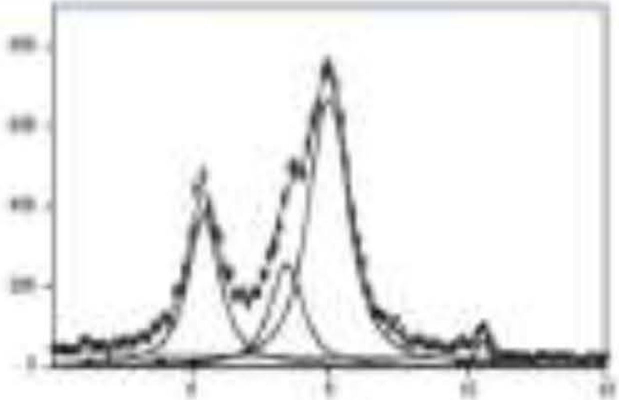
SIDDHARTA went beyond what expected, since we did:

Precision measurements of kaonic helium 3 and 4 (2p level)
Other low-Z kaonic atom transitions were measured (kaonic kapton)
Yields measurements (kaonic atoms cascade processes)

- total background 1/2

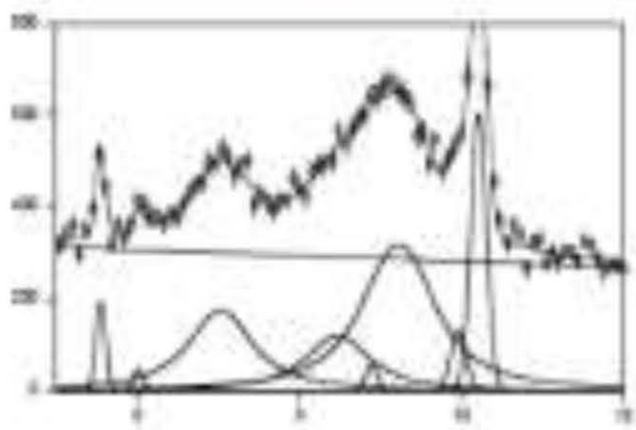
100 pb⁻¹ hydrogen

K_α peak 4000 events
S/B 14:1
sigma(shift) = 7 eV sigma(width) = 13 eV



800 pb⁻¹ deuterium

K_α peak 3000 events
S/B 1:1.5
sigma(shift) = 27 eV sigma(width) = 72 eV



With the new 200 cm**2 SDDs:

Kaonic hydrogen precision: 7 eV with 100 pb^{-1} – very important (Weise, Meissner)

Kaonic deuterium precision: about 30 eV with 600 pb^{-1}

Kaonic helium 2p at < 1 eV with 50 pb^{-1}

Kaonic helium 1s – 150 events?