Precision measurements of kaonic atoms at DAFNE

'Exotic Hadrons',

21-25 Feb. 2005,

ECT*, Trento, Italy

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LNF – INFN, Frascati

for the **DEAR/SIDDHARTA** Collaborations

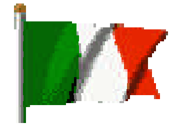
Contents

Castelli romani

1. Introduction
(Frascati)

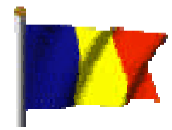
DEAR Collaboration:

LNF- INFN, Frascati, Italy

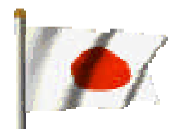


IMEP- ÖAW, Vienna, Austria

IFIN – HH, Bucharest, Romania



INFN, Trieste, Italy



RIKEN, Japan

Univ. Fribourg, Switzerland

Univ. Neuchâtel, Switzerland

Univ. Tokyo, Japan

Univ. Victoria,Canada

Caltech, USA

The scientific aim

the determination of the ***isospin dependent***
$\bar{K}N$ scattering lengths through a

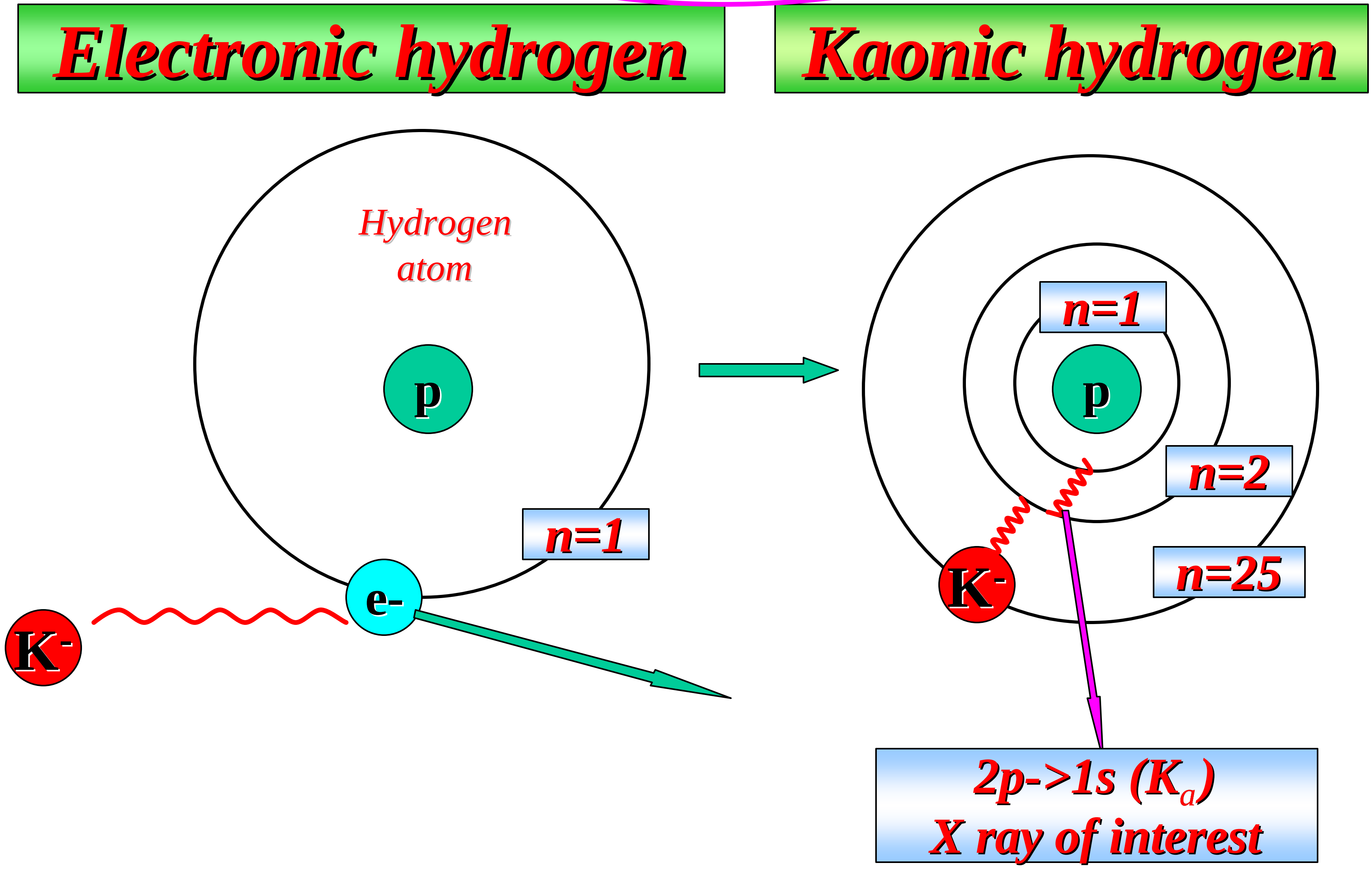
~ eV measurement of the shift
and
of the width

of the K_{α} line of **kaonic hydrogen**

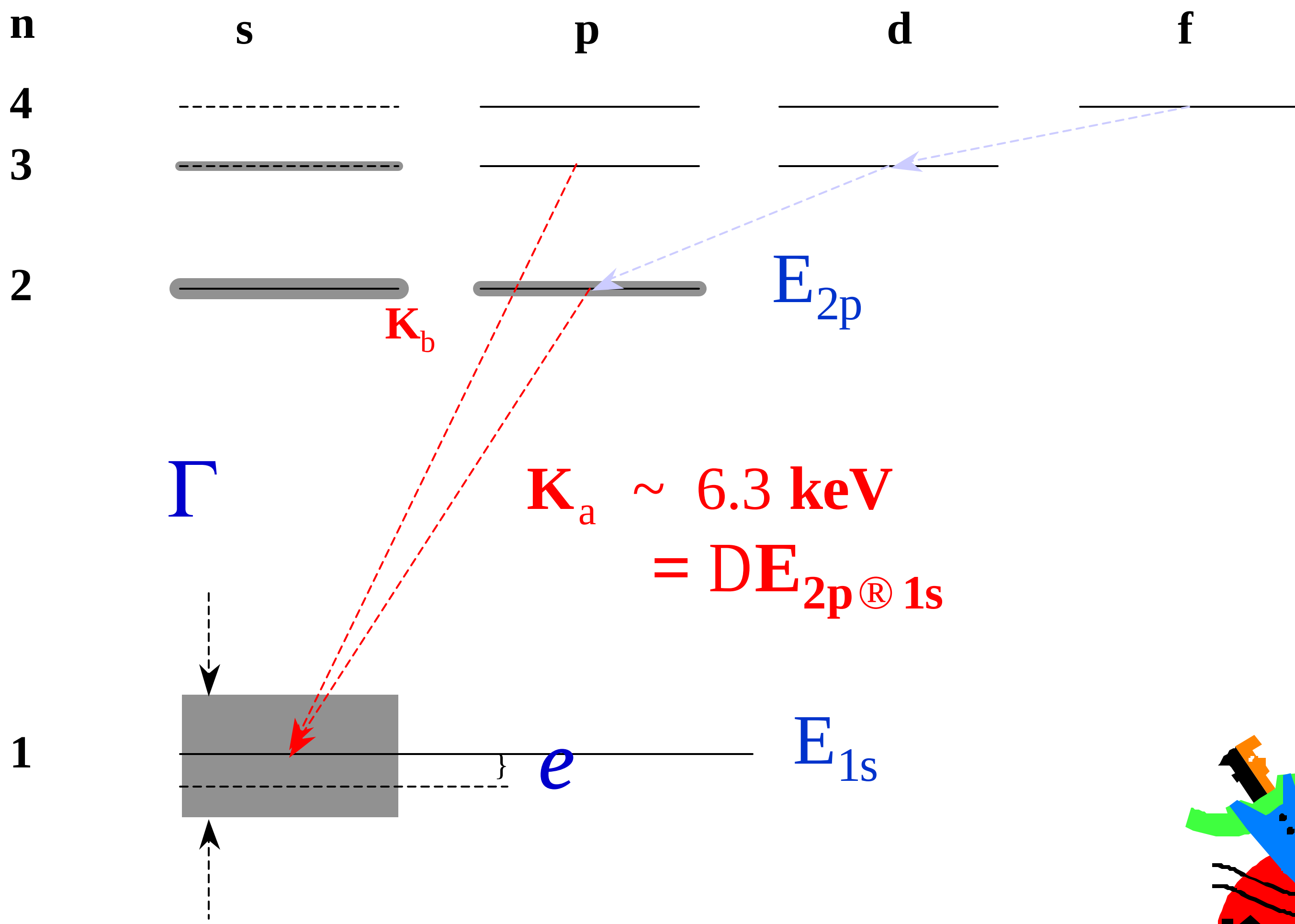
and

the *first (similar) measurement* of **kaonic deuterium**

DEAR =
DAFNE Exotic Atom Research



Kaonic cascade and the strong interaction



2. The DEAR/SIDDHARTA Scientific Programme
(Monteporzio)

How to obtain the scattering lengths

Once the shift and width of the 1s level for kaonic hydrogen and deuterium are measured, with the Deser formulae *(neglecting isospin breaking corrections):*

$$e + i\, G/2 = 412\, a_{K^-p}\ eV\ fm^{-1}$$

$$e + i\, G/2 = 602\, a_{K^-d}\ eV\ fm^{-1}$$

one can obtain the isospin dependent antikaon-nucleon scattering lengths

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

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

DEAR/SIDSDHARTA Scientific program

Measuring the $\bar{K}N$ scattering lengths with the precision of a few percent will drastically change the present status of low-energy $\bar{K}N$ phenomenology and also provide a clear assessment of the SU(3) chiral effective Lagrangian approach to low energy hadron interactions.

1. **Breakthrough in the *low-energy $\bar{K}N$ phenomenology*;**
2. **Threshold amplitude in QCD**
3. **Determination of the *KN sigma terms*, which give the degree of chiral symmetry breaking;**
4. **Determination of the *strangeness content of the nucleon* from the KN sigma terms.**

Meson-nucleon sigma terms

- Sigma terms are directly connected with the symmetry breaking part of the strong interaction Hamiltonian

- Sigma terms measure the nucleon mass shift away from the chiral limit (m_q=0), therefore parameterizing the explicit breaking of chiral symmetry in QCD due to the non-zero quark masses.

Meson-nucleon sigma terms and chiral symmetry breaking

- ***Definition:***

$$M_a(q) + N(p) \rightarrow M_b(q') + N(p')$$

$$s_N^{ba} = i < p \,|\, [Q_b^{\,5}, [Q_a^{\,5}, H_{SB}]] \,|\, p >$$

a, b SU(3) indices of the meson

$Q^5_{a,b}$ axial vector charge

H_{SB} chiral symmetry breaking part of the strong-interaction Hamiltonian

Meson-nucleon sigma terms and chiral symmetry breaking

- **H_{SB} symmetry breaking Hamiltonian:**

quark mass term of the strong-interaction Hamiltonian

$$H_{SB} = m_u \bar{u}u + m_d \bar{d}d + m_s \bar{s}s$$

by isospin invariance $\quad \bar{m} = m_u = m_d$

$$H_{SB} \approx \frac{1}{3}(m_s + 2\bar{m})(\bar{u}u + \bar{d}d + \bar{s}s) - \frac{1}{3}(m_s - \bar{m})(\bar{u}u + \bar{d} - 2\bar{s}s) = H_0 + H_8$$

H_0 preserves SU(3) symmetry**, H_8 breaks it**

- **KN and pN sigma terms:**

$$s_{KN}^{(1)} = \frac{1}{2}(\bar{m} + m_s) < p \,|\, \bar{u}u + \bar{s}s \,|\, p >$$

$$s_{KN}^{(0)} = \frac{1}{2}(\bar{m} + m_s) < p \,|\, -\bar{u}u + 2\bar{d}d + \bar{s}s \,|\, p >$$

$$s_{pN} = \bar{m} < p \,|\, \bar{u}u + \bar{d}d \,|\, p >$$

Meson-nucleon sigma terms

- ***Relation to amplitude*:**

The sigma terms can be related to the meson-nucleon scattering amplitude

$$T(\nu, t, q^2, q'^2)$$

in the soft meson limit

$\nu = (s-u)/2M = 0 \quad t = 0 \quad q^2, q'^2 \to 0$

$s = (q+p)^2 \quad t = (q-q')^2 \quad u = (q-p')^2$

$$\boxed{s_N^{ba} = -f_a f_b T_{ba}(0,0,0,0,)}$$

$f_{a,b}$ meson decay constants

Use of low-energy theorem and dispersion relations

Low-energy theorems

The low-energy theorems relate the symmetry breaking part of the total Hamiltonian to the scattering amplitude of massless particles: they would become exact in the limit where pseudoscalar masses vanish.

Therefore, more important tests of theories of chiral symmetry breaking come from studying low-energy theorems of meson-nucleon scattering, which just represent the "corrections" for the real world to the exact relations valid for massless particles.

In practice, this means calculating the

meson-nucleon sigma terms

Phenomenological determination of the sigma terms

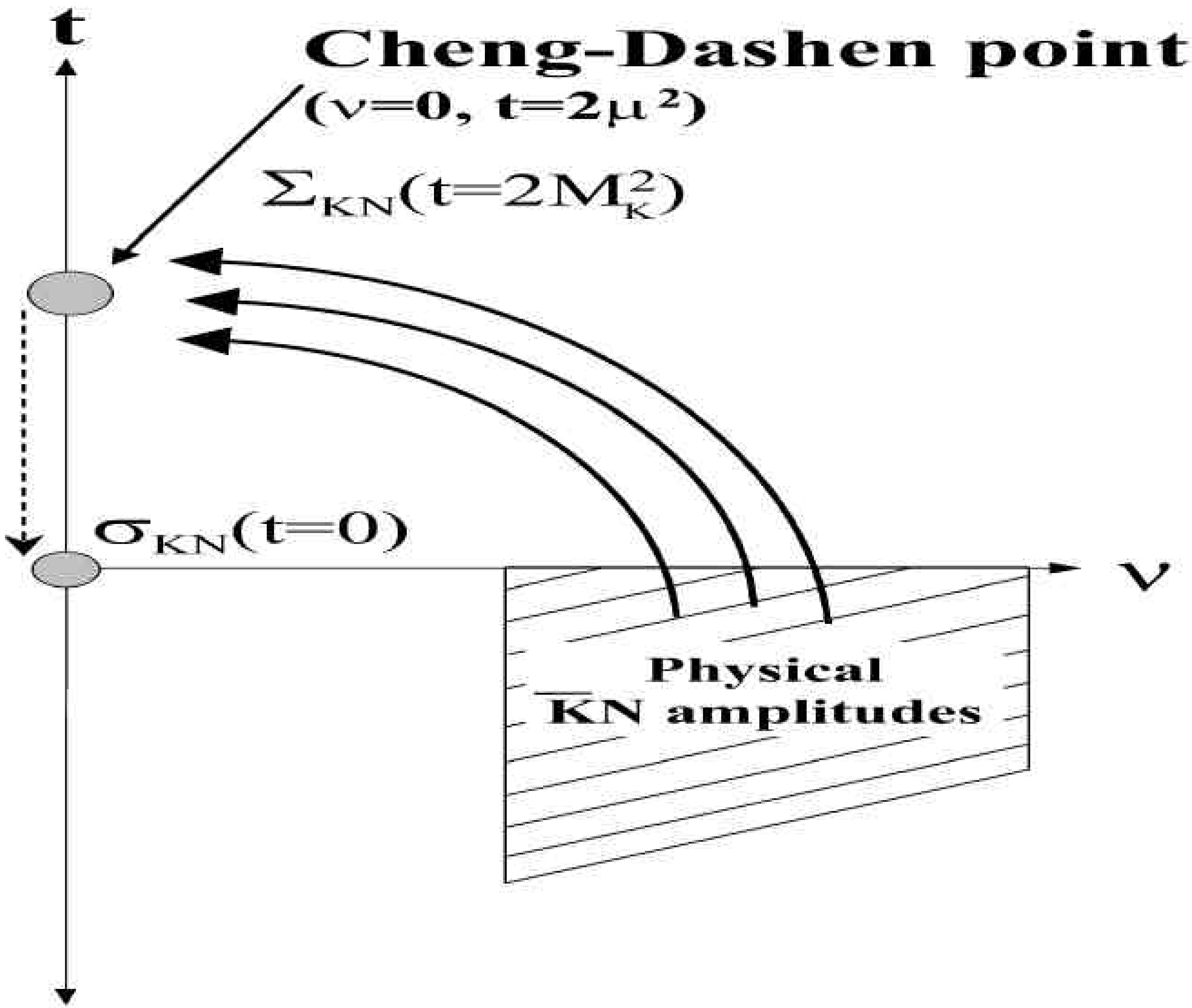
The calculation of the s**-terms from the scattering data requires an elaborate procedure**.

The problem is that the σ-term is **not** an observable. One has to introduce an **"experimental" sigma term** S_{MN} which can be **related to the experimental meson-nucleon amplitudes.**

This can be done in a favored point of the (t,ν) plane, the so-called **Cheng-Dashen point** ($t = 2\mu^2$, $\nu = 0$), by using dispersion relations.

The last step consists in **calculating** S **in the zero momentum point**, where the σ-term is defined.

Phenomenological determination of the sigma terms



Meson-nucleon sigma terms and strangeness content of the nucleon

- **Fraction of strangeness content in proton**

$$y = \frac{2 < p \mid \bar{s}s \mid p >}{< p \mid \bar{u}u + \bar{d}d \mid p >}$$

- **Strangeness content in the proton from KN and pN sigma terms:**

$$y = \frac{4\overline{m}}{\overline{m} + m_s} \frac{s'_{KN}}{s_{pN}} - 1$$

The impact of the DEAR results (1)

One order of magnitude in the precision of the K^-p scattering length

Breakthrough in low-energy $\overline{K}N$ phenomenology

Possibility of **discriminating** theoretical approaches and methods of analysis

The impact of the DEAR results (2)

Presently only estimates exists of KN sigma terms.

A measurement of KN scattering lengths at the percent level would enable the determination of the KN sigma terms with a **precision of about 20%** or less.

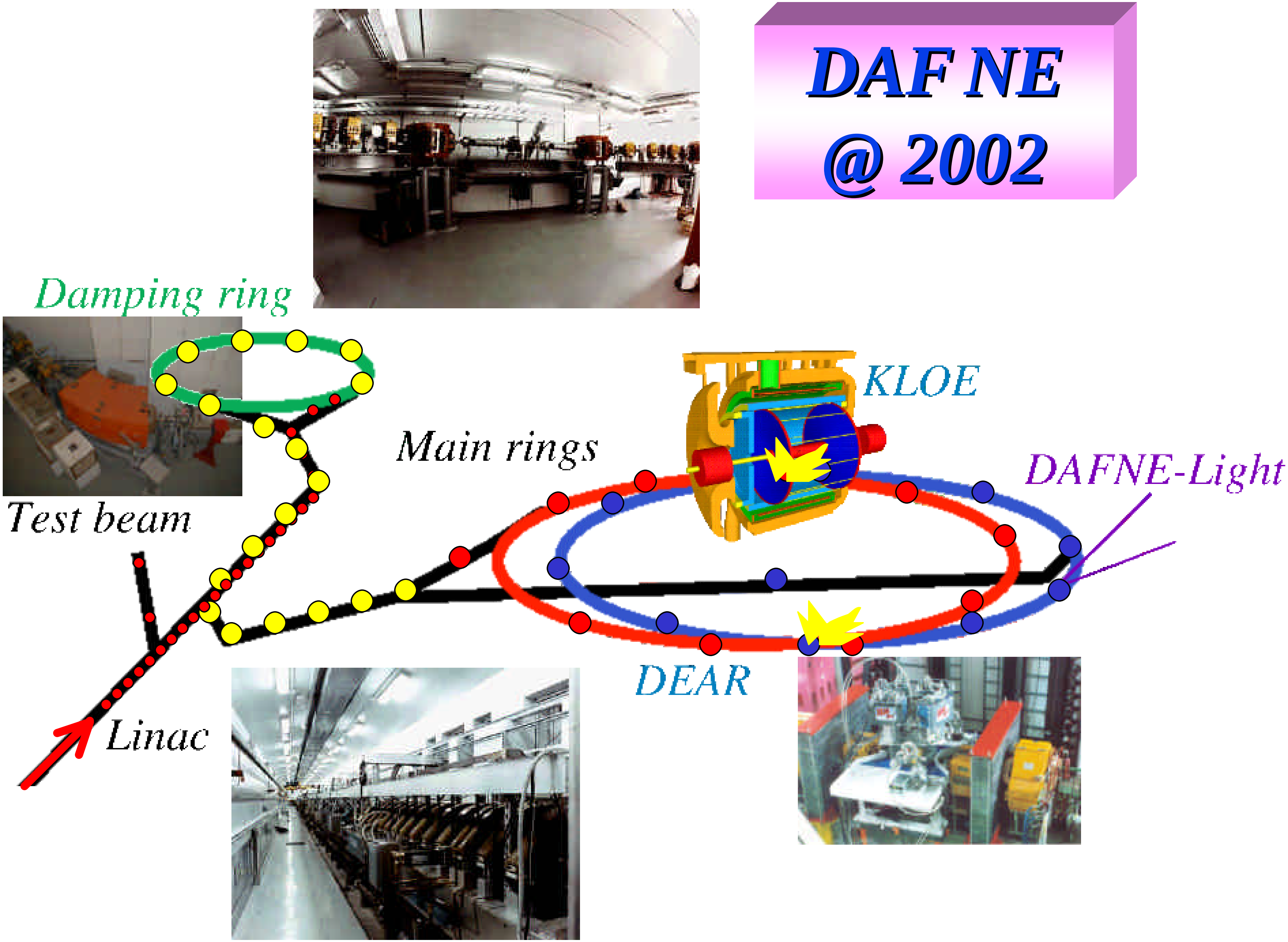
3. DA F NE Collider

(Montecompatri)

DAFNE at LNF (1)

DAFNE at LNF (2)

DAF NE @ 2002


Damping ring
Test beam
Main rings
KLOE
DAFNE-Light
DEAR
Linac

DAF NE

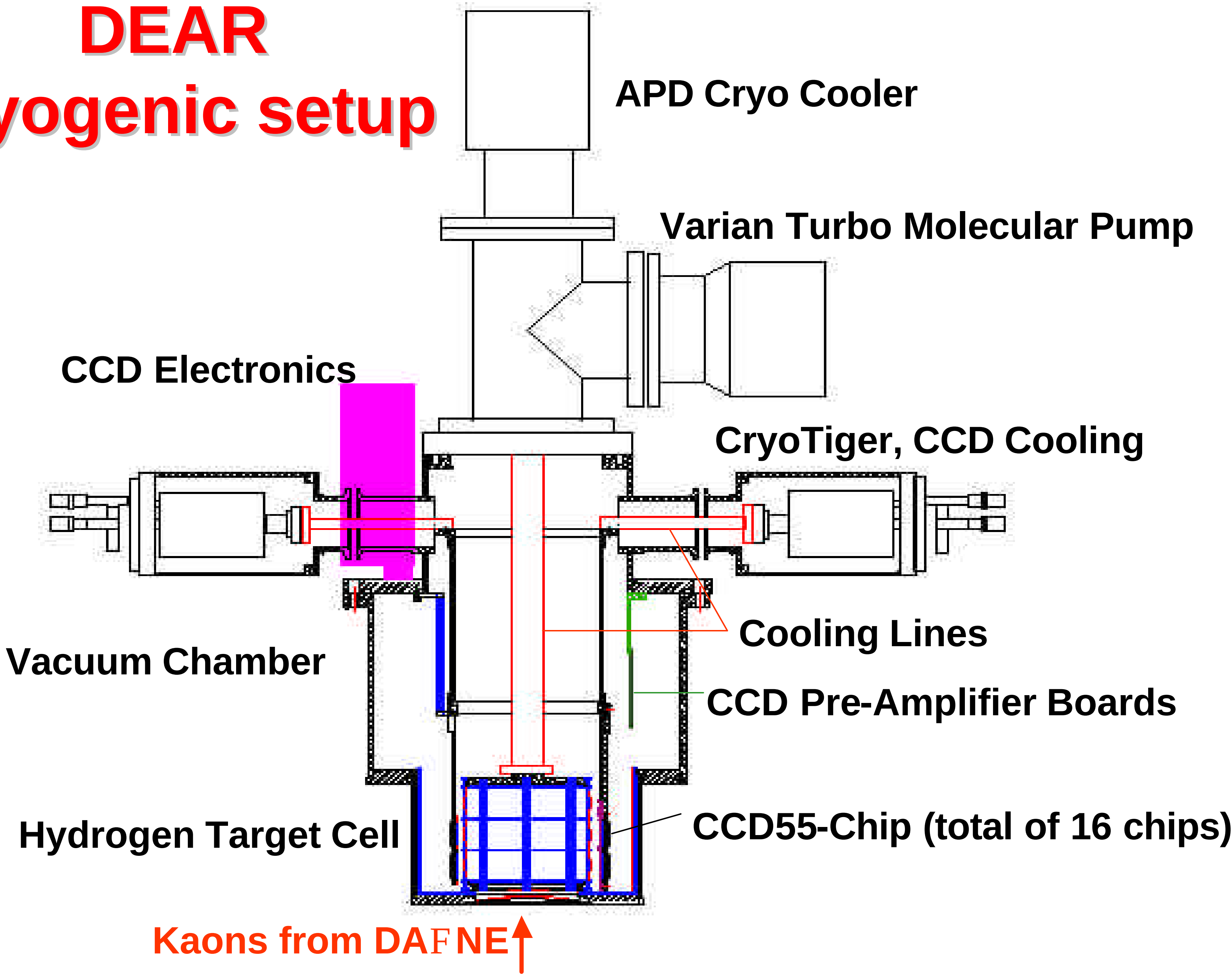
Performances obtained in 2002 in the DEAR I.P.

- Number of bunches per beam 95 + 95
- Total current per beam e-/e+ (A) ˜ 1.3/1
- Peak luminosity(cm -2 s -1) 0.7 x10 ^{32}
- Average luminosity (cm -2 s -1) ˜ 2 x10 ^{31}
- Integrated luminosity per day (pb -1) 2.2 (best)
- Luminosity lifetime (h) ˜ 0.6
- Number of fillings per hour ˜ 1.7
- Injection frequency e-/e+ (Hz) 2/1
- Data acquisition during injection off

Total integrated luminosity in 2002 about 70 pb^{-1}

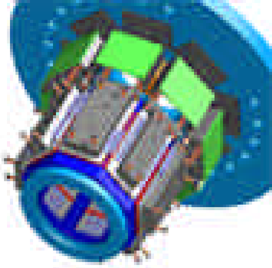
4. The DEAR setup
(Nemi)

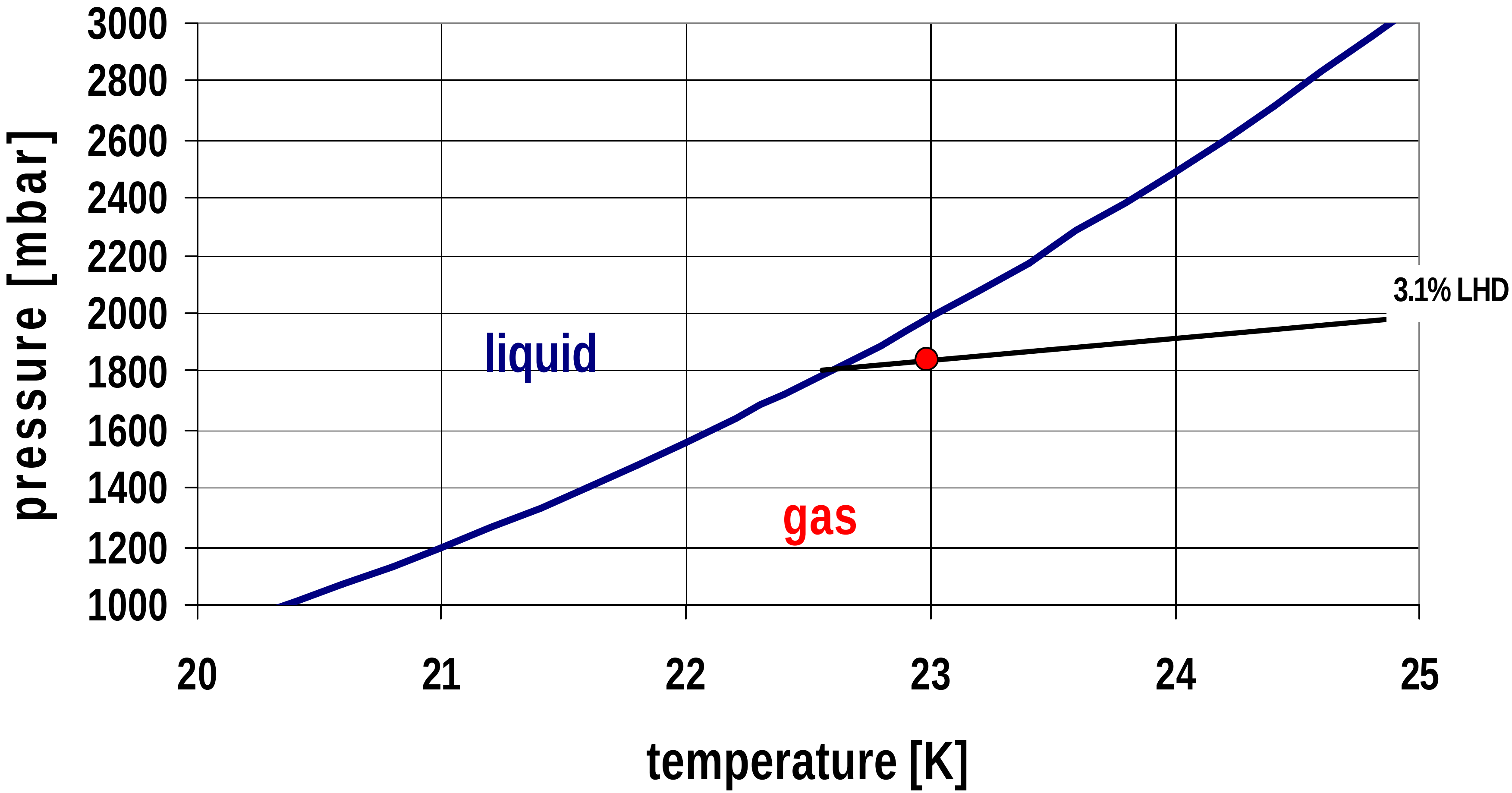
DEAR
Cryogenic setup



Cryogenic Hydrogen Target

working point: T = 23 K, P = 1.82 bar
hydrogen density: 3.1% of LHD, 2.2 g/l

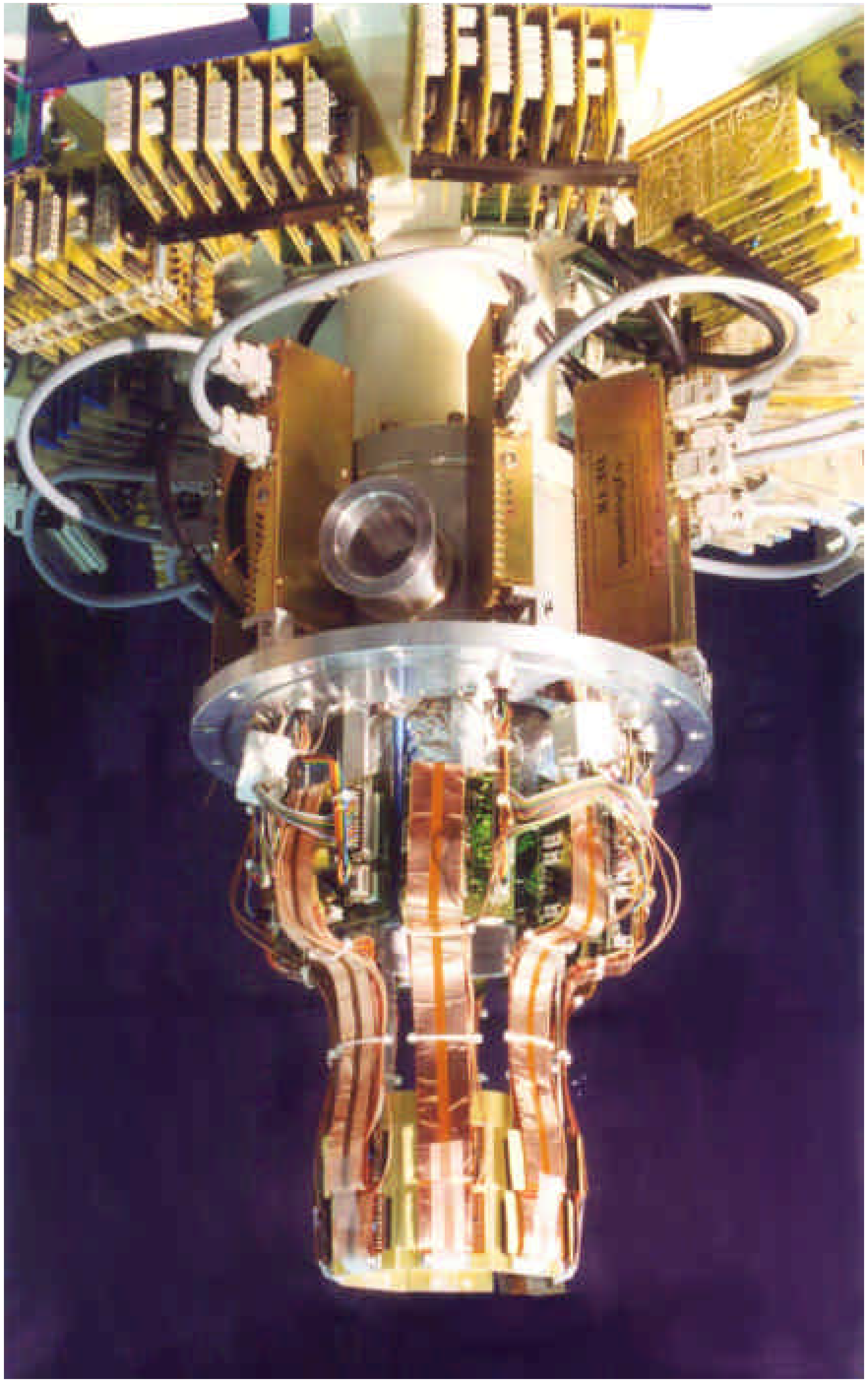




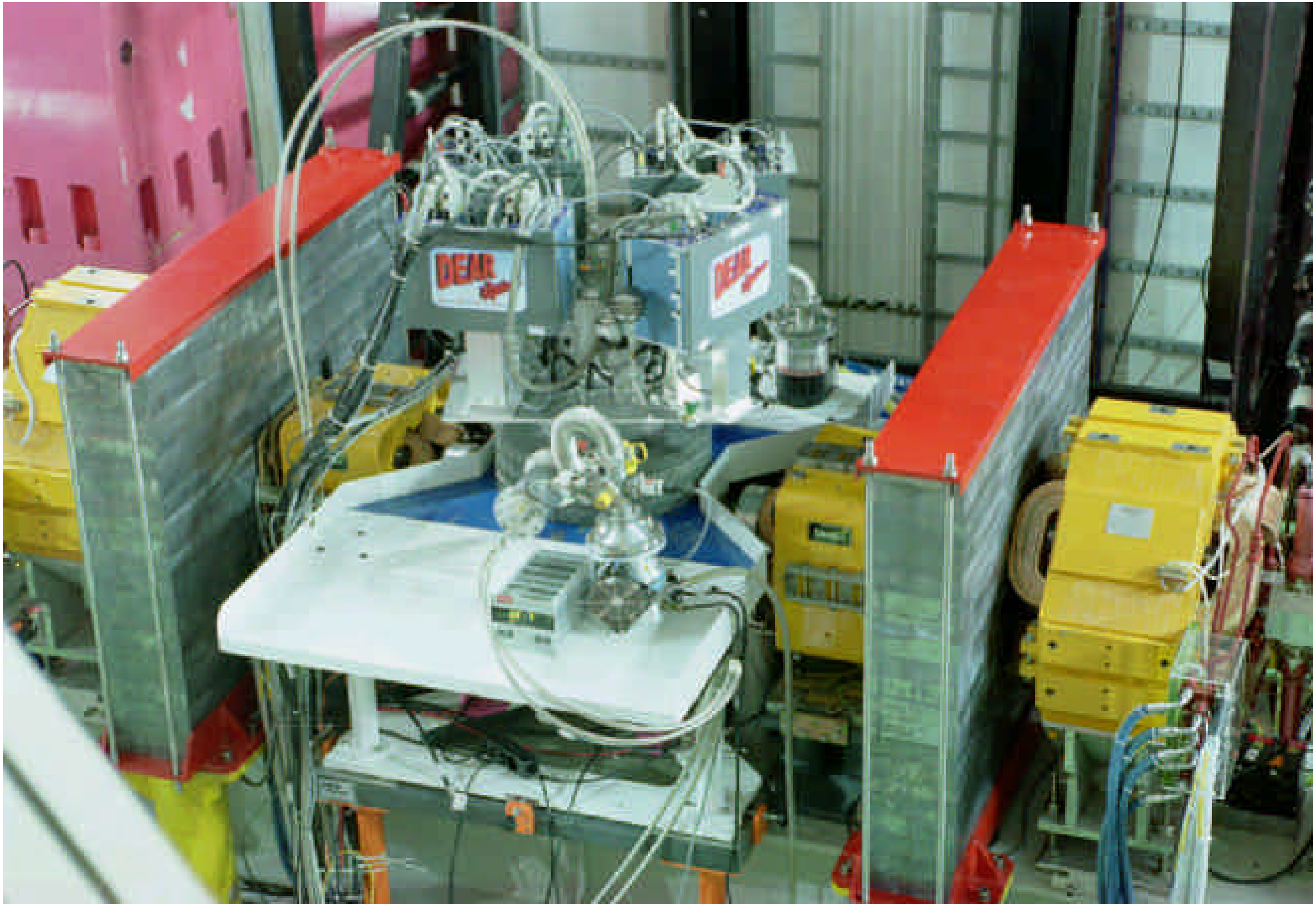
DEAR Cryogenic Target Cell

CCD mounting, cryogenics and on-cell electronics

- fiber-glass frames
- cooling system mounted on the top
- minimized Al cold finger (behind CCDs)
- reduced diameter of the socket group and, consequently, of the vacuum chamber



DEAR on DAFNE



5. Kaonic nitrogen results
(Castel Gandolfo)

Objectives of kaonic nitrogen measurement

 # First exotic atom measurement at DAΦNE -> 2001

 # Optimization of the kaon stopping point distribution (i.e. degrader shaping) and background reduction

 # *KN Physics:* **-** ***yield measurements (exotic atom cascade)***

- test of a future precision measurement of the charged kaon mass

October – December 2002 DAQ set of "good quality" data

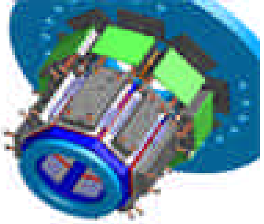
Collected data:

-Kaonic Nitrogen:

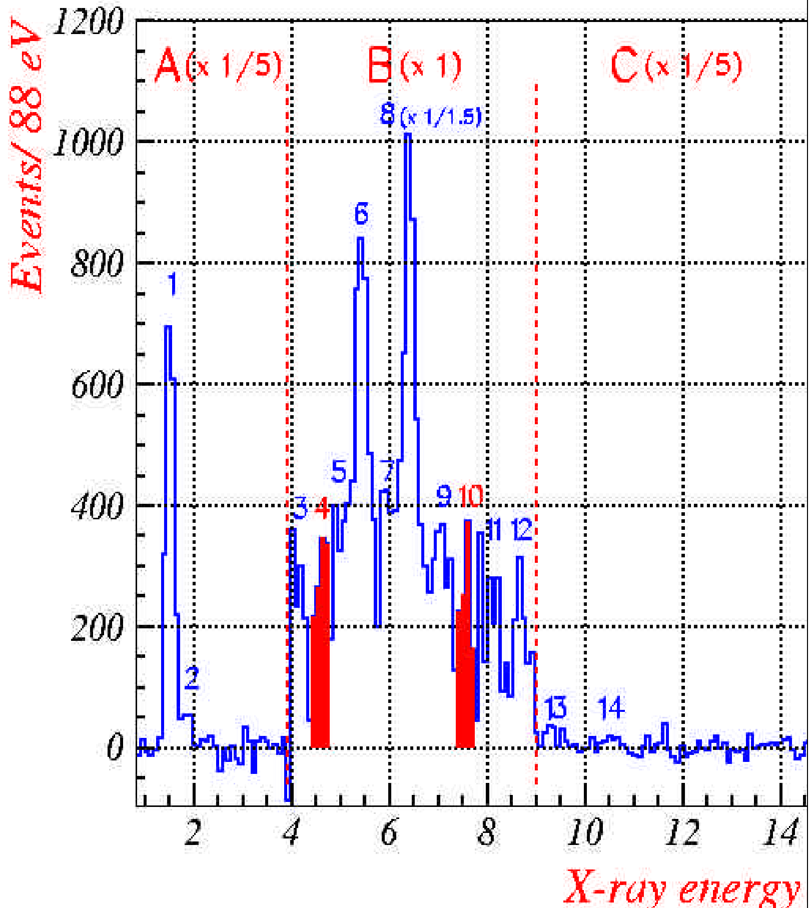
6 – 28 October (about 17 pb^{-1} – 10 pb^{-1} in stable conditions selected for analysis);

[redacted]

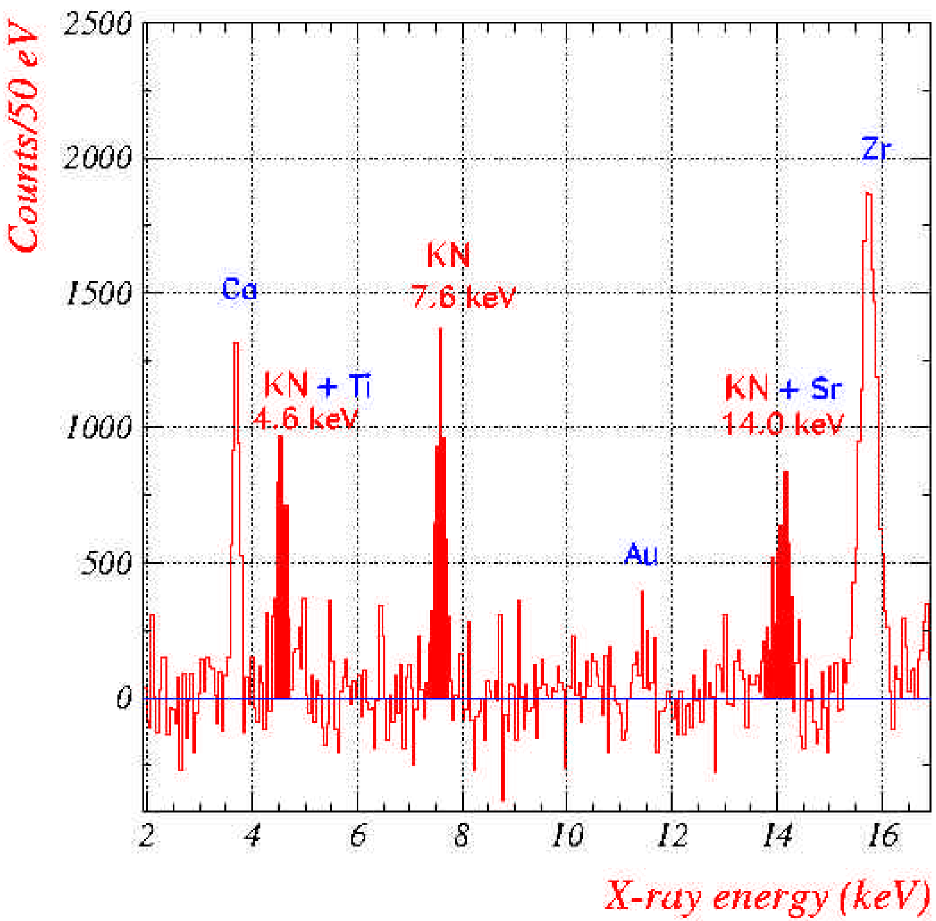
Kaonic Nitrogen



Kaonic Nitrogen, 2001, ~ 3 pb^{-1}
Background subtracted spectrum



Kaonic Nitrogen, 10 pb^{-1} (October 2002)
Background subtracted spectrum



Kaonic Nitrogen Physics

- ***First determination*** **of the yield of 3 Kaonic Nitrogen X-ray transitions:**

7 → 6 (41.5 +/- 8.7 +/- 4.1)%
6 → 5 (55.0 +/- 3.9 +/- 5.5)%
5 → 4 (57.4 +/- 15.2 +/- 5.7)%

stimulated activity in the the field of atomic **cascade** ***for exotic atoms***

- ***Mass of the kaon*** **– as a test measurement:**

m_{K^-} **= 493.884 +/- 0.314 MeV**

(Ph. D. thesis, Tomo Ishiwatari,
Phys. Lett. B593 (2004) 48)

6. Kaonic hydrogen

(Genzano)

October – December 2002 DAQ set of "good quality" data

Collected data:

[redacted]

-Kaonic Hydrogen:

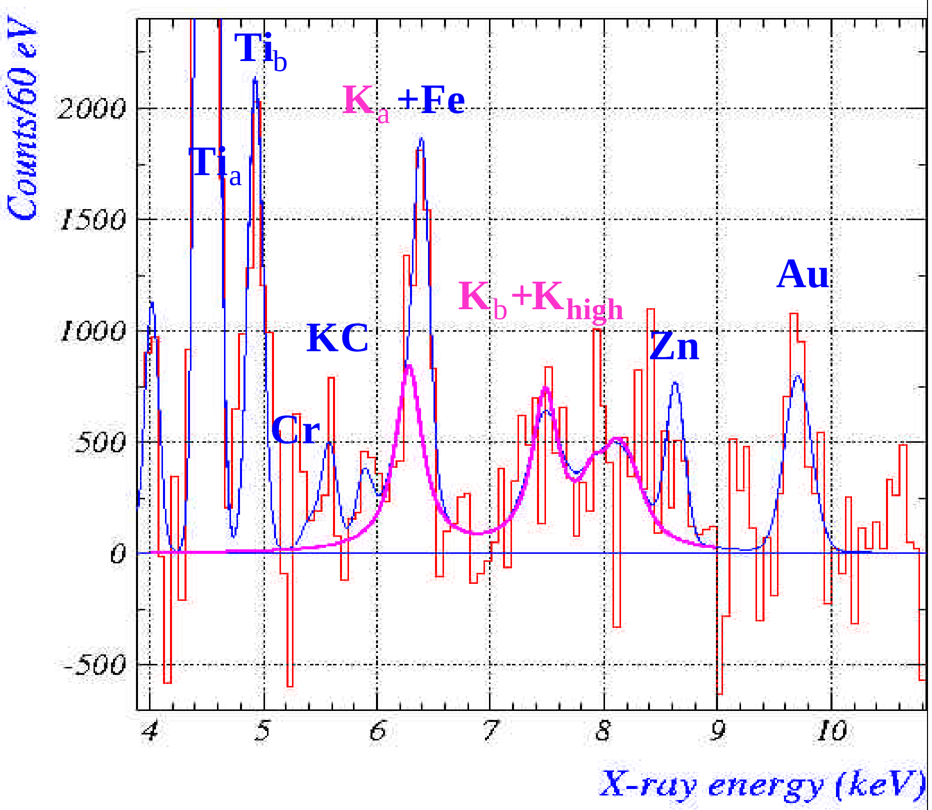
30 October – 16 December: about 60 pb^{-1}

-Background data (no collisions) for KH:

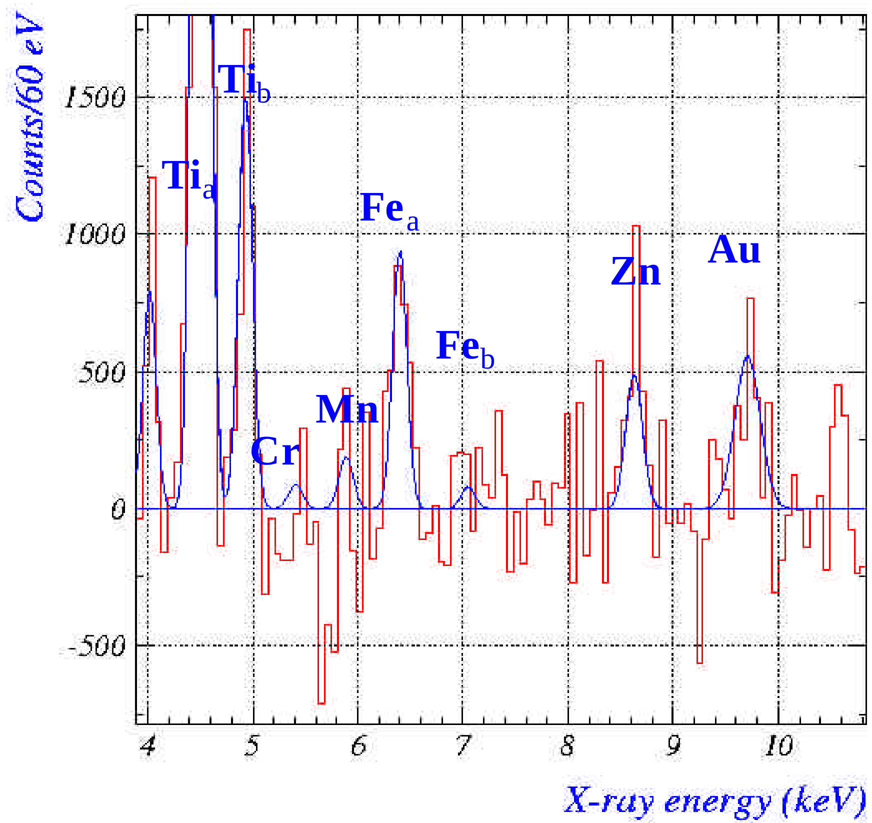
16 – 23 December

Kaonic hydrogen and background spectra

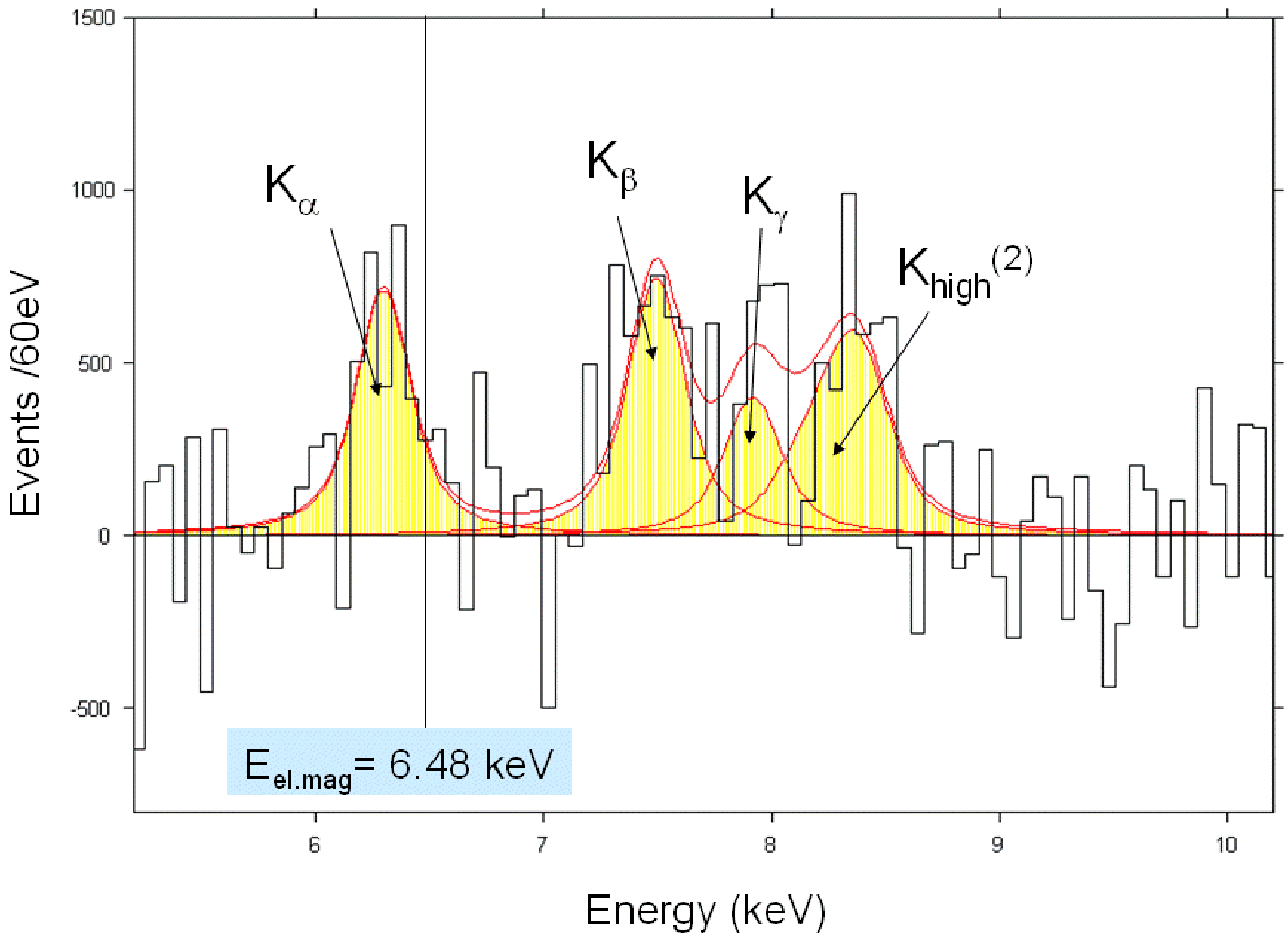
Kaonic Hydrogen spectrum after continuous background subtraction



Structured background spectrum after continuous background subtraction



“K⁻p-alone“ Spectrum
(all background fit-components subtracted)



Results on the Shift and Width

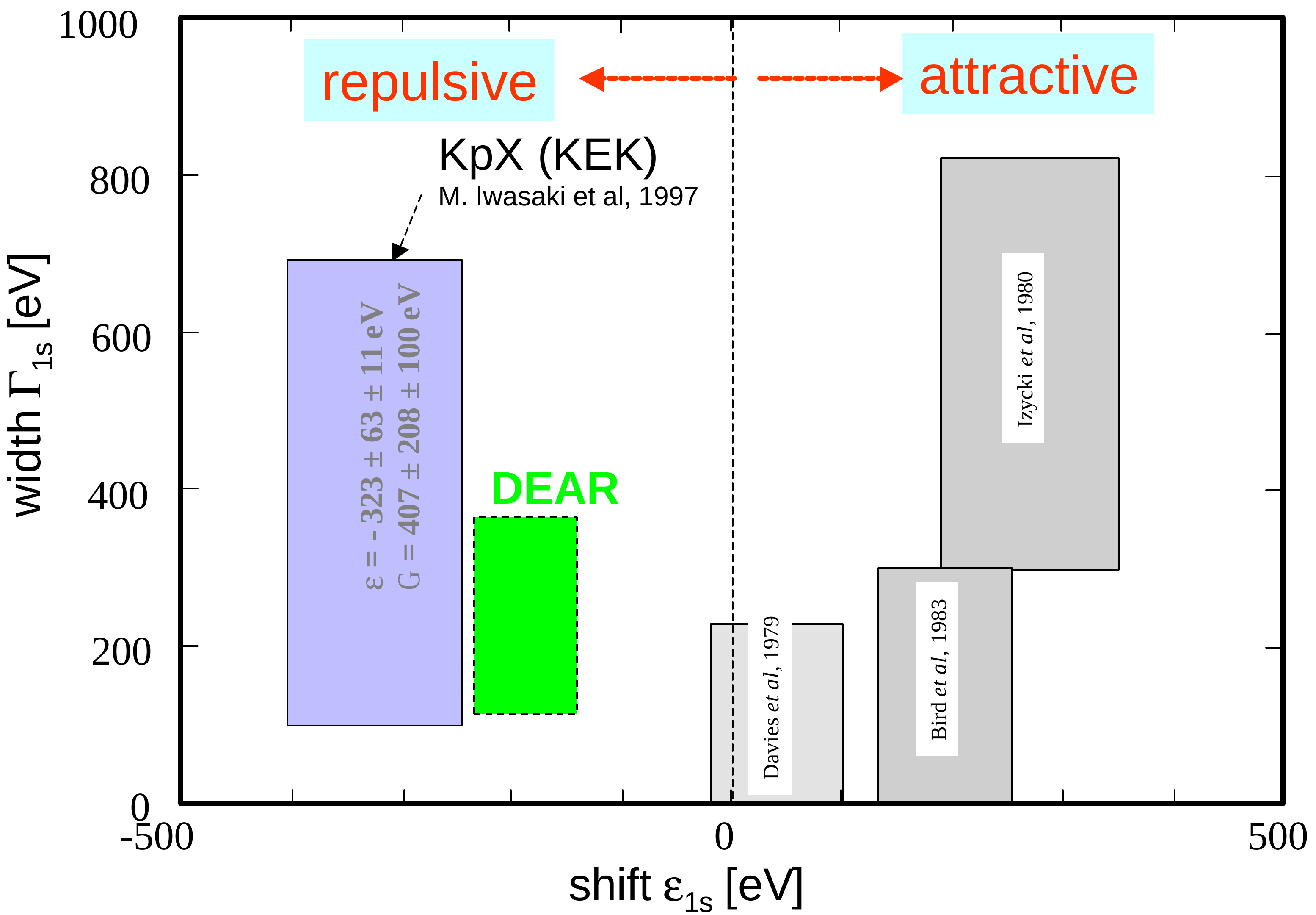
Sent to Phys.Rev.Lett.

Shift: e_{1s} = - 194 ± 37 (stat.) ± 6 (syst.) eV

Width: G_{1s} = 249 ± 111 (stat.) ± 30 (syst.) eV

a_{K^-p} = – 0.466 (± 0.104) + i 0.299 (± 0.174) fm
(no isospin breaking corrections)

DEAR Results on kaonic hydrogen



7. From DEAR to SIDDHARTA
(Grottaferrata)

Conclusions to the KH analysis

The obtained DEAR result:

represents indeed the <u>best measurement performed on Kaonic Hydrogen up to now</u>

BUT

what we are aiming for is =>

Next Steps of the Scientific Program

 # few eV precision measurement of *kaonic hydrogen* 1s level shift;

 # first measurement of *kaonic deuterium*

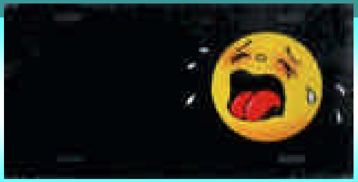
in order to determine the isospin dependent antikaon nucleon scattering lengths at percent level precision

In the DEAR framework ?

S/B ~ 1/80

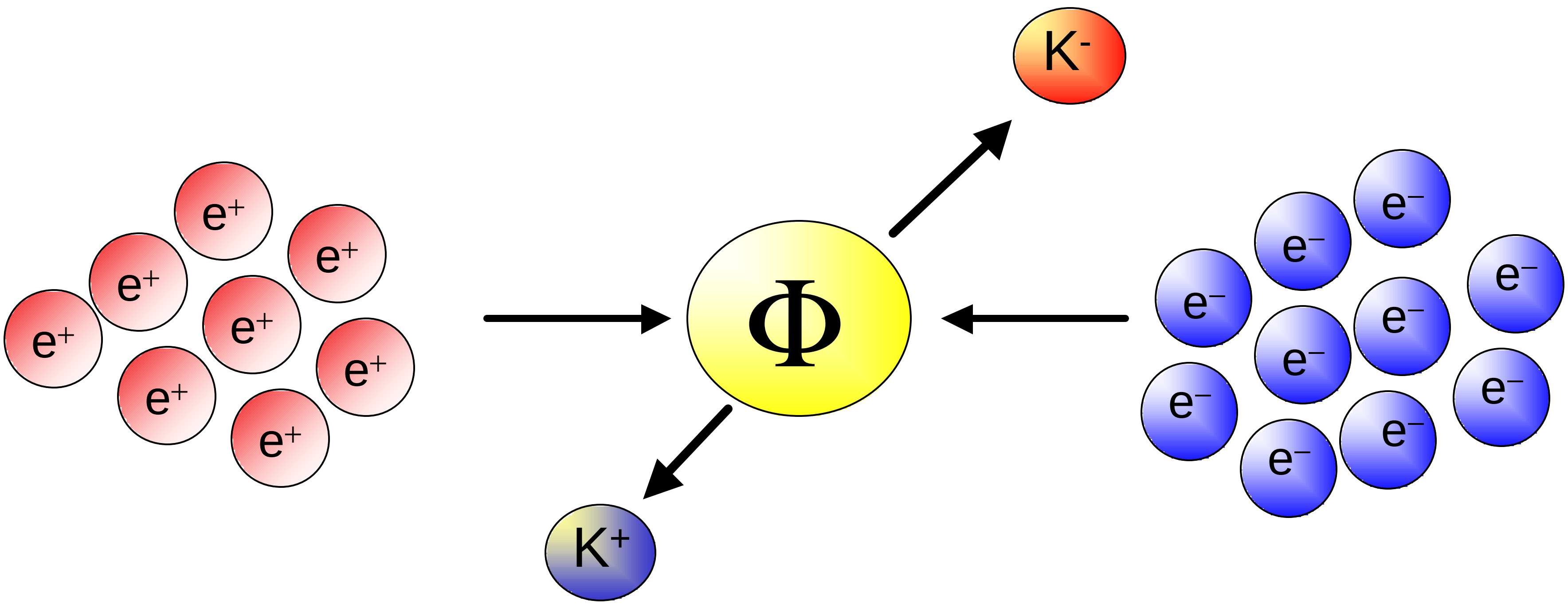
no space left for *important* background reduction;

The answer is NO



to learn how to reduce them

K^- "beam" at DAΦNE



K^- produced in a back-to-back process - > trigger on it

Background sources in the kaonic atom measurement on DAFNE

Event signal:

Definition: Soft X-ray transitions (1-15 keV) between levels of target gas atoms where a kaon from f-decay is stopped in an atomic orbit

Synchronous background

Definition: **Particles produced synchronous with the primary kaon, hitting the detector with energy in the region of interest**

Specifically: **Secondary particles created by the primary kaons absorbed by the setup materials, via associated hyperon production and decay:**

$K^{-}p$ -> p Y; $p = p^{+/-}, p^{0}$; Y=$S^{+/-}, S^{0}, L$; $S^{+/-}$ -> Np, S^{0} -> Lg

In particular: **Low-energy X rays (~ keV) final products of the e.m. cascades initiated by high-energy g- rays (> 100 MeV), coming from p^{0}s directly produced together with hyperon or from hyperon decay**

Other high-energy gs come from f-decay channels like: $p^{+}p^{-}p^{0}$, rp, eg and subsequent p^{0}-decay.

The synchronous background cannot, in principle, be suppressed.

Background sources in the kaonic atom measurement on DAΦNE

Asynchronous background

Definition: Particles not correlated with the event signal, hitting the detector with deposited energy in the region of interest

Nature: Products of the e.m. cascades originated in the beam pipe and in the setup materials by the particles lost from the circulating electron and positron beams, due mainly to:

-Touschek effect;

-Dynamic aperture of the machine (intrinsical component);

-Beam-beam dynamics (non-linear component);

--Beam-gas interaction

Other sources of asynchronous background:

-synchrotron light;

-Bhabha scattering;

-Radiative Bhabha scattering;

-Beam-beam bremsstrahlung

The latter give a negligible contribution (orders of magnitude) with respect to the four above background sources.

-Cosmic Rays and Radiation from volcanic rocks of Castelli Romani

The asynchronous background can be suppressed = > trigger ->

Use of triggerable device

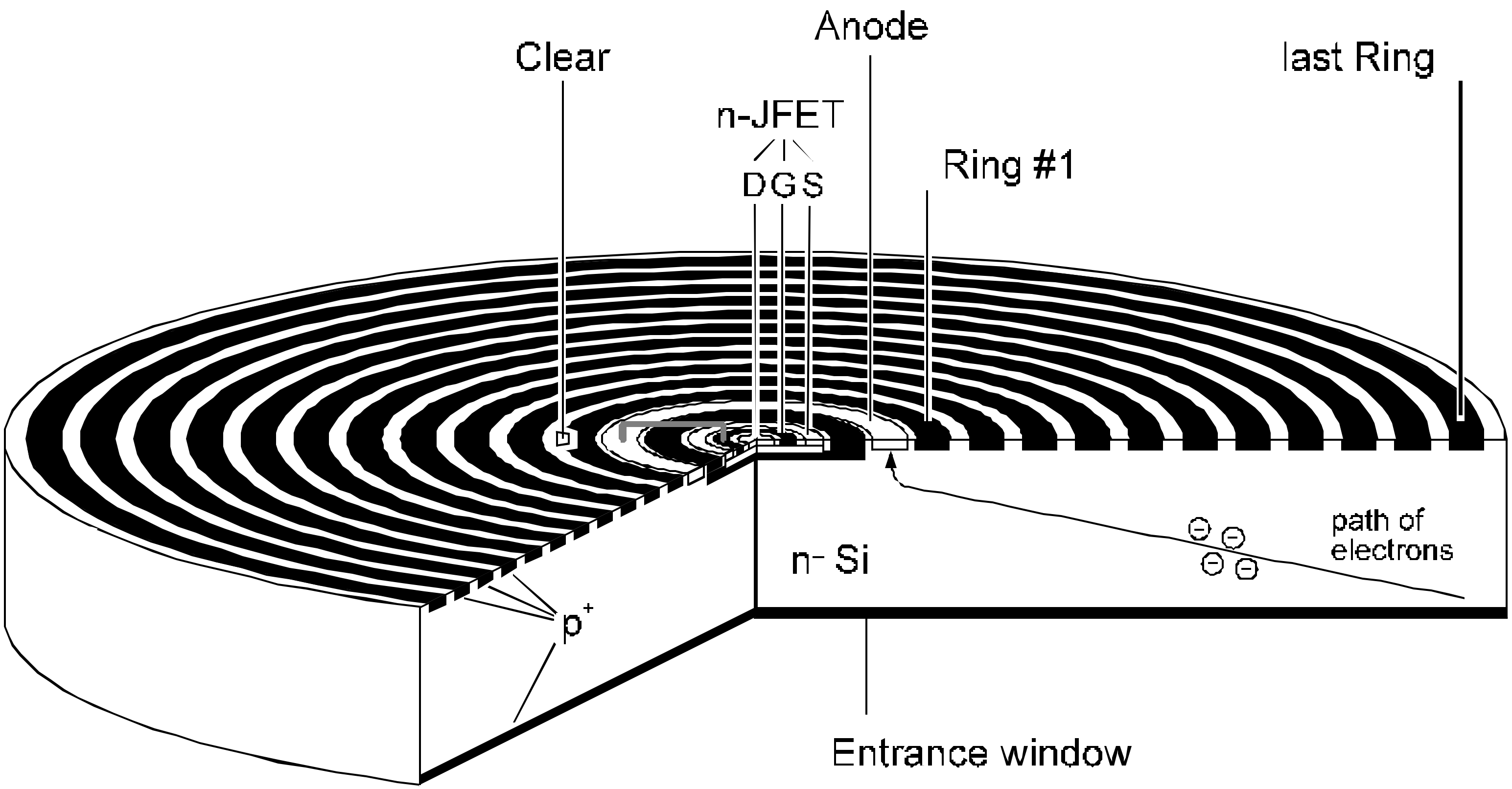
<u>Choice of the detector based on criteria:</u>

-preserve good features of CCDs (efficiency, resolution);

-offer a timing ~ 1 ms – trigger

=> Silicon Drift Detector

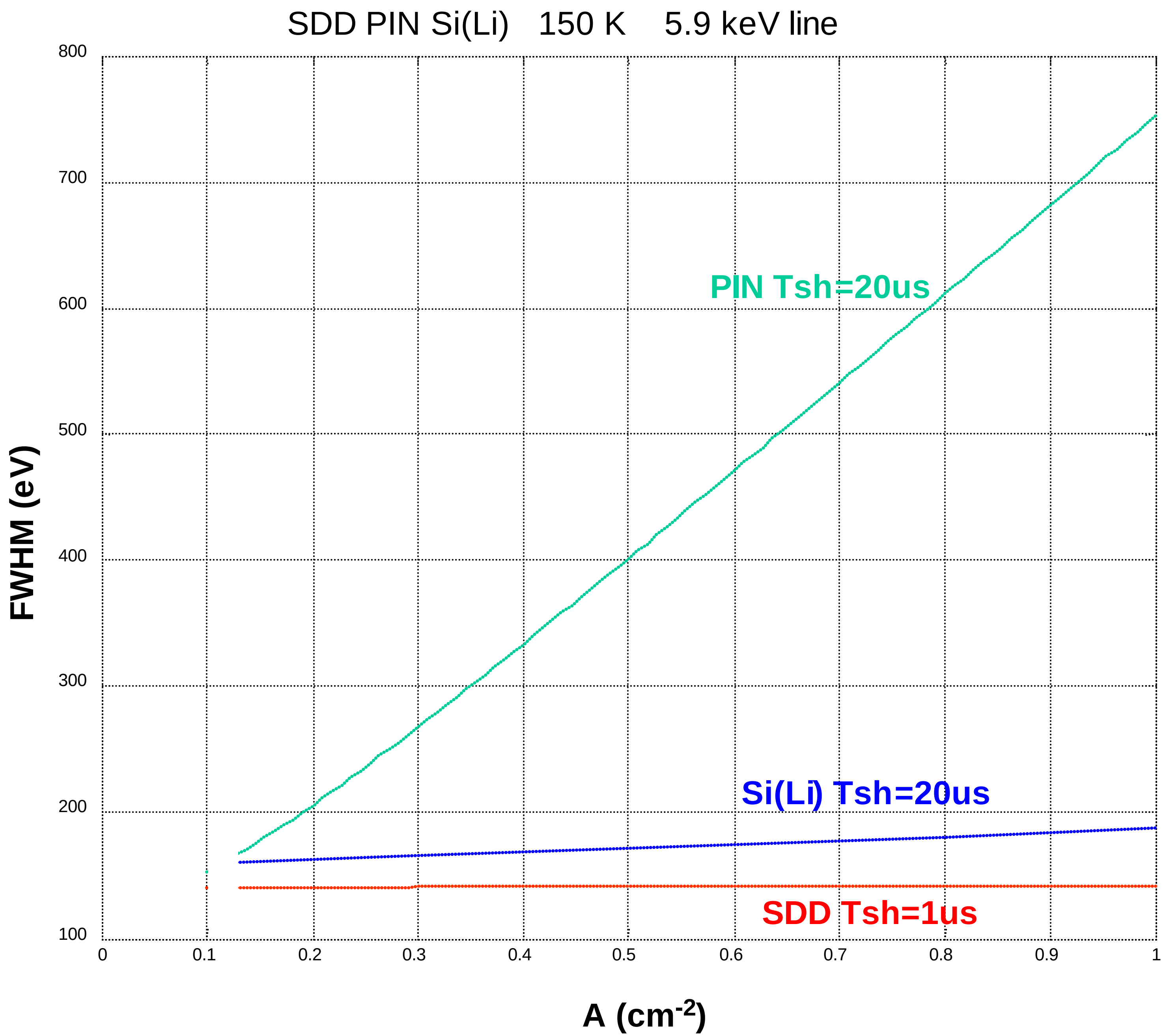
The Silicon Drift Detector with on-chip JFET



JFET integrated on the detector

- capacitive ‘matching’: $C_{gate} = C_{detector}$
- minimization of the parasitic capacitances
- reduction of the microphonic noise
- simple solution for the connection detector-electronics in monolithic arrays of several units

Spectroscopic resolution and timing : detector comparison



SIDDHARTA Collaboration:

LNF- INFN, Frascati, Italy

IMEP- ÖAW, Vienna, Austria

IFIN – HH, Bucharest, Romania

Politecnico, Milano, Italy

MPE, Garching, Germany

PNSensors, Munich, Germany

RIKEN, Japan

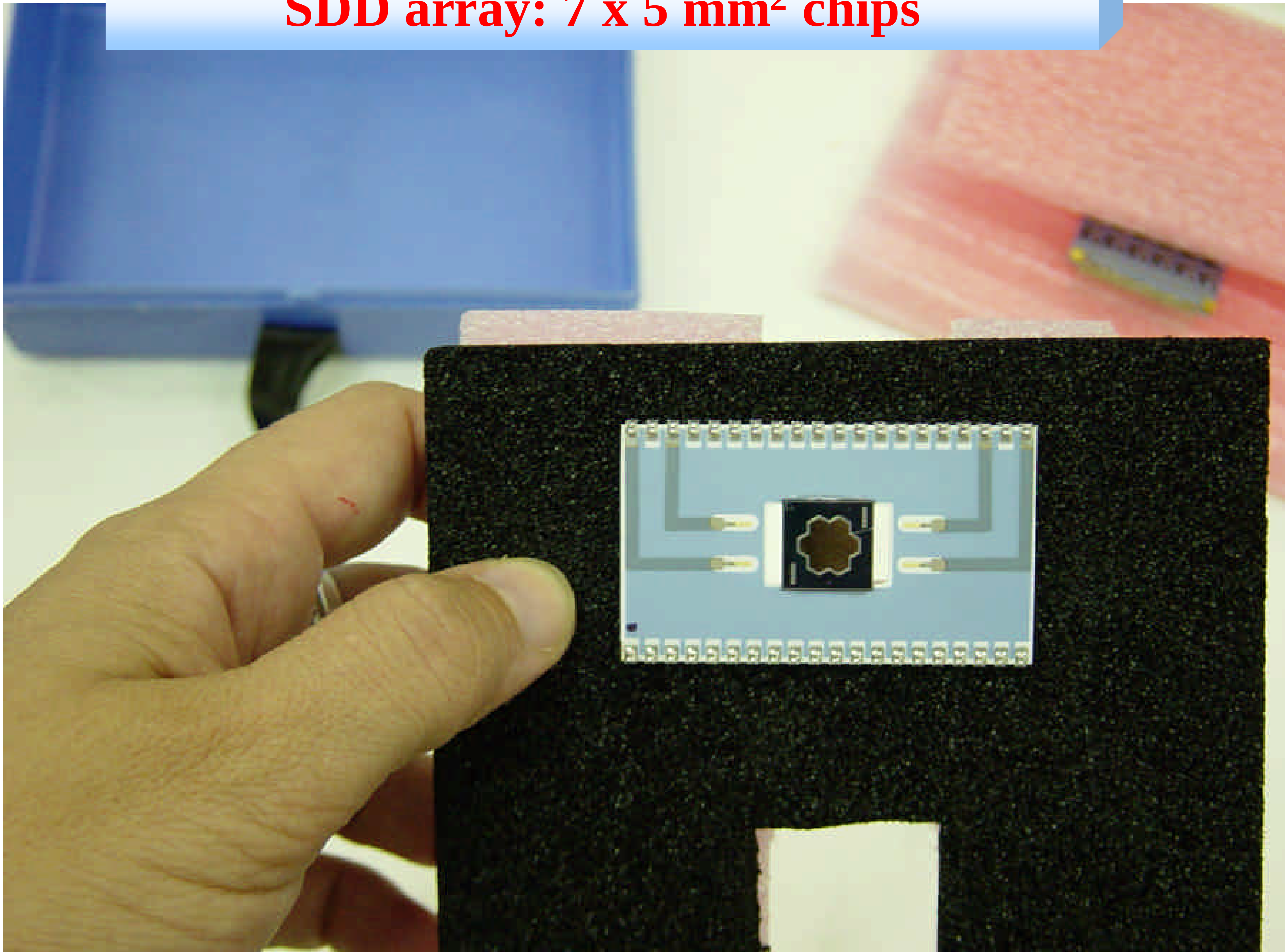
Victoria Univ., Canada

SIlicon Drift Detector for Hadronic Atom Research by Timing Applications

8. Preliminary SDD tests
(Rocca di Papa)

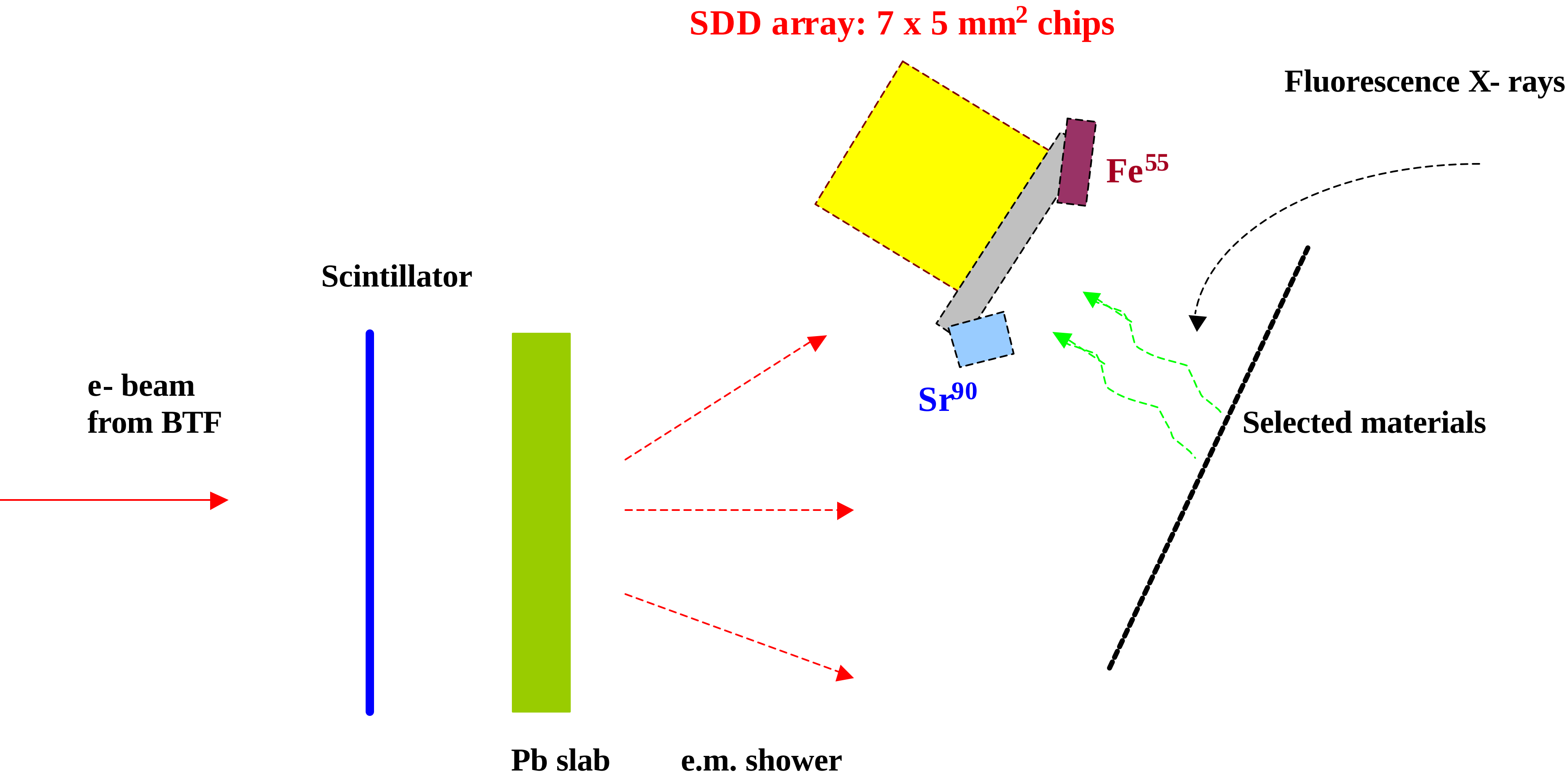
Beam Test Facility tests of an array of 7 x 5 mm^2 SDD chips

SDD array: 7 x 5 mm^2 chips

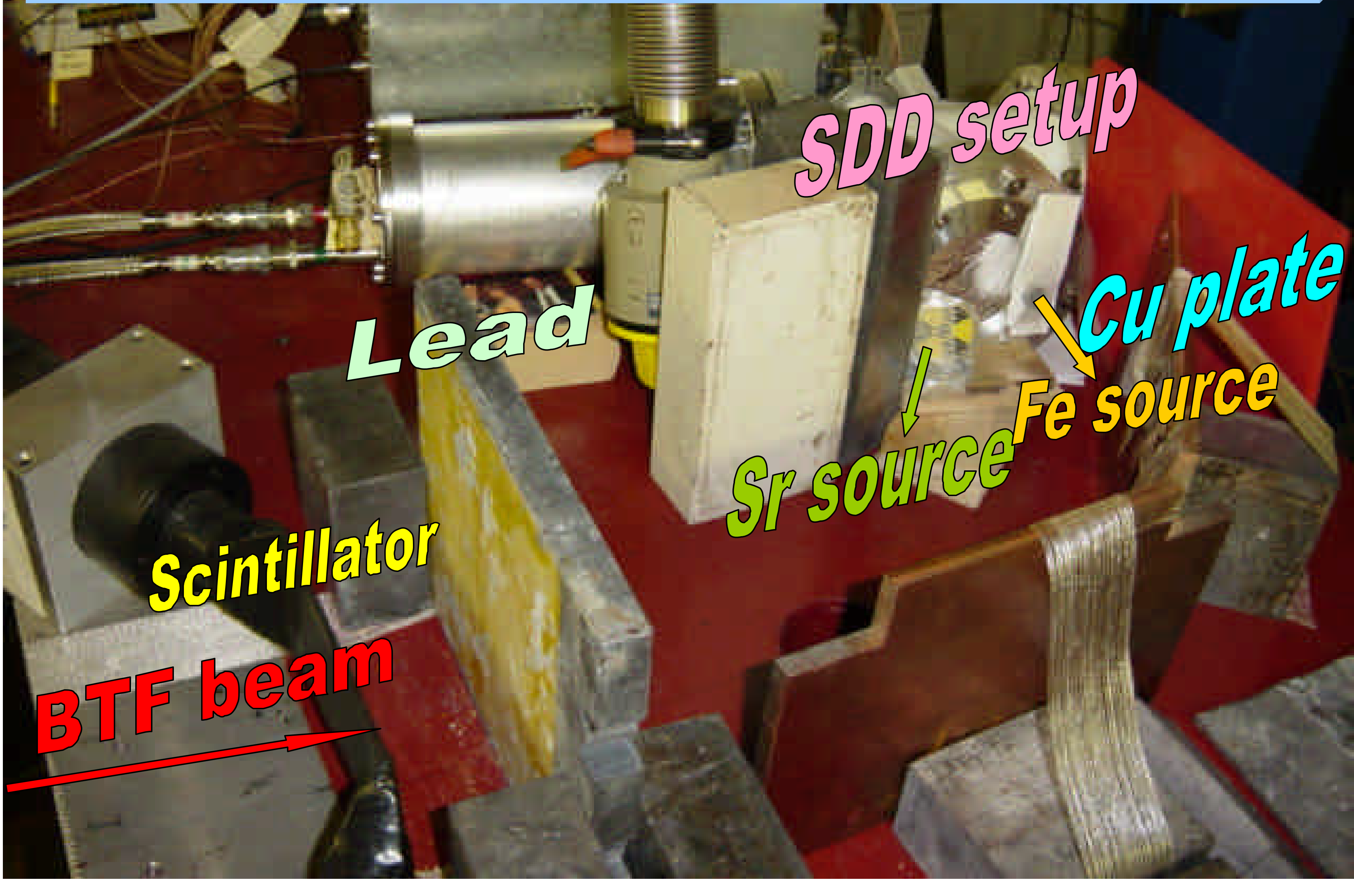


Mounting of the SDD test setup in the BTF area

Test setup mounted at BTF



The test setup installed at BTF with the two sources (Fe and Sr) to generate asynchronous background



Measurements performed at BTF with an array of 7 x 5 mm^2 chips

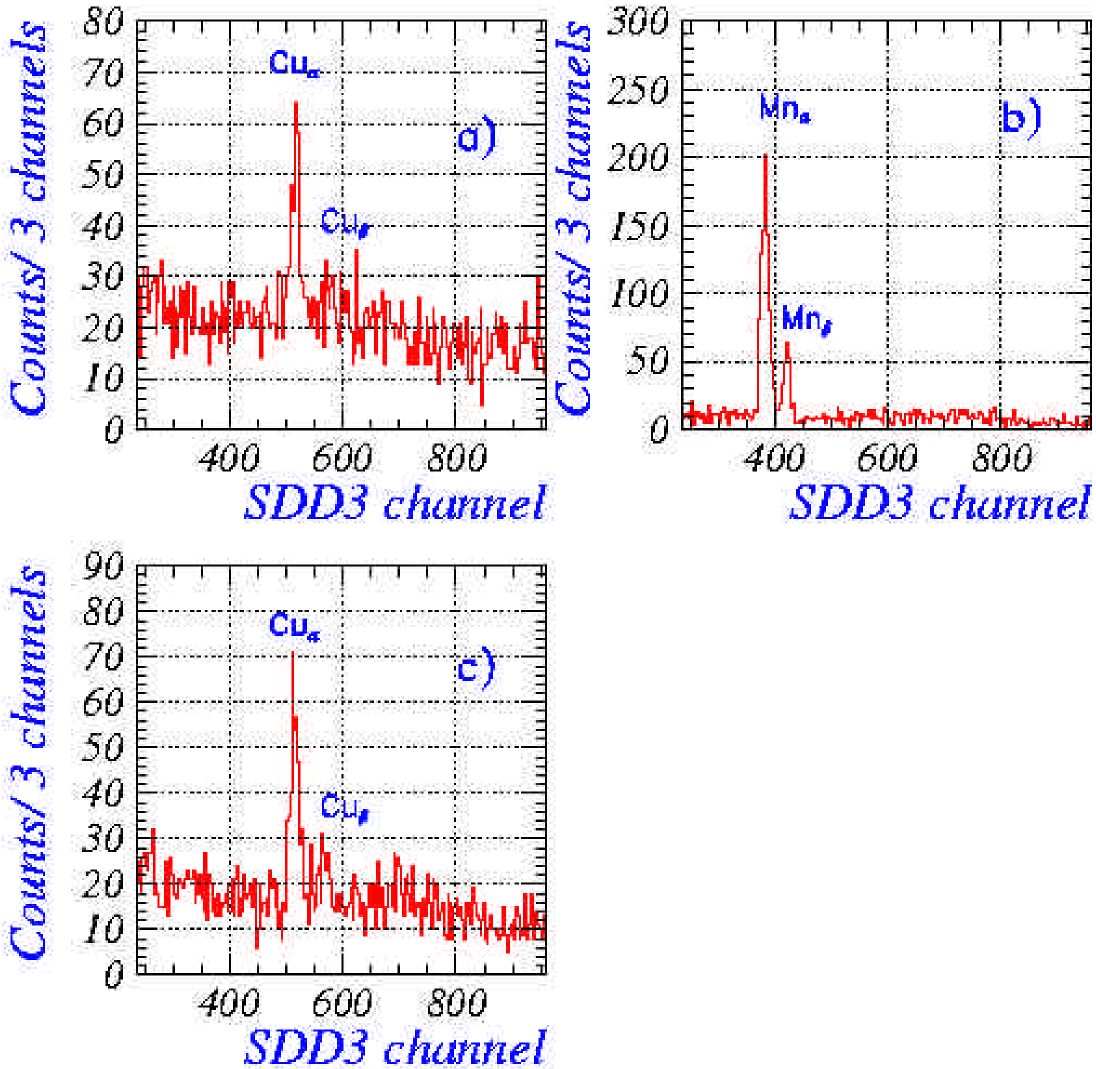
-Energy resolution

-Stability of energy calibration

-Linearity

-Test of triggering capability

Incident rate: 60 Hz on 7 channels => 8.5 Hz/channel

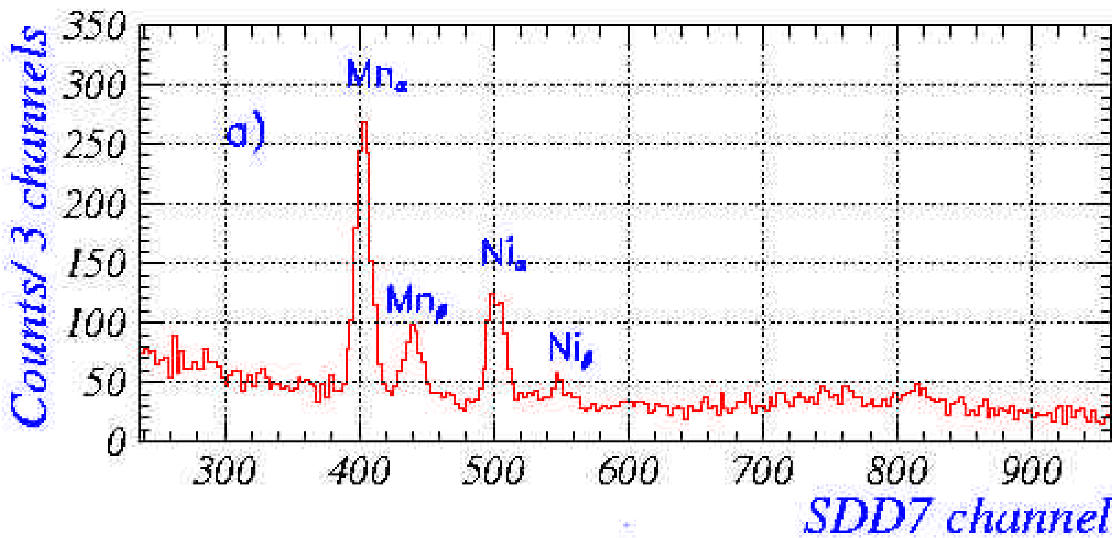


a) **# Trigger OFF (16 hours.)**
Cu signal visible;
No asynchronous backgr (55Fe and 90Sr)
Continuous background:
- synchronous from primary beam
 # 5 Hz

b) **# Trigger OFF (20 min.)**
Cu signal embedded in backc.
Structured asynchronous backgr:
- Mn Ka and Kb from 55 Fe
Continuous background:
- synchronous from primary beam
- asynchronous from 90 Sr source
 # 60 Hz

c) **# Trigger ON, 1 ms (~ 16 hours)**
Cu signal visible
Structured asynchronous backgr. completely cut;
Continuous background:
- synchronous from primary beam
 # 5 Hz – as a)

Incident rate: 1000 Hz on 7 channels => 142 Hz/channel



a) **# Trigger OFF (18 min.)**

Cu signal embedded in backc.

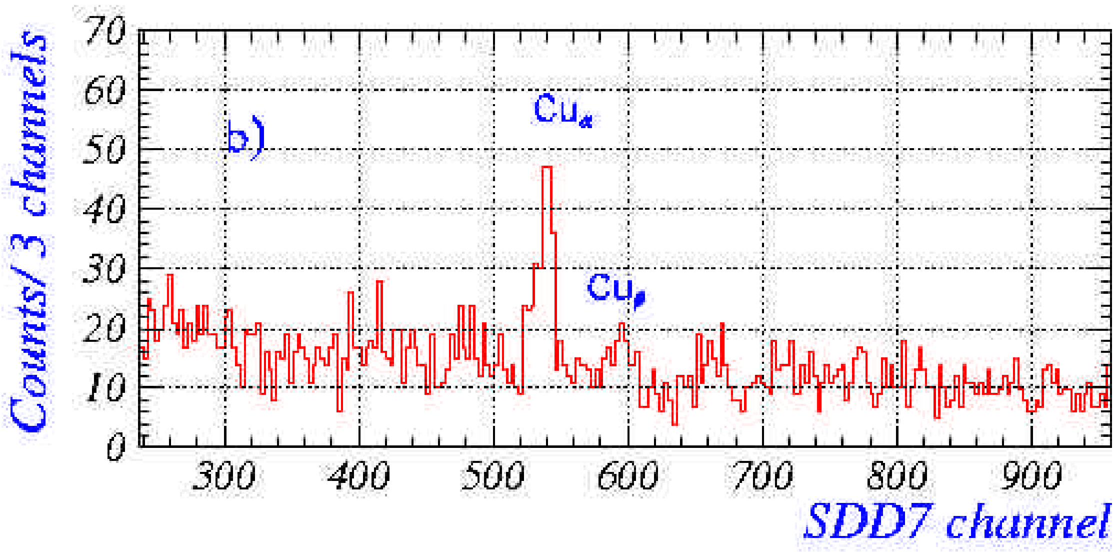
Structured asynchronous backgr:

- Mn Ka and Kb from 55 Fe
- Ni Ka and Kb excited from Sr90

Continuous background:

- synchronous from primary beam
- asynchronous from 90 Sr source

 # 1000 Hz



b) **# Trigger ON 1ms (~ 13 hours)**

Cu signal visible

Structured asynchronous backgr. completely cut;

Continuous background:

- synchronous from primary beam

 # 5 Hz

Background reduction with triggered acquisition for SIDDHARTA setup (asynchronous background)

r =number of detected kaons per detected X-ray = 0.5×10^3

B_r=background rate = 10^3 events/s

T_w=sinchronization window

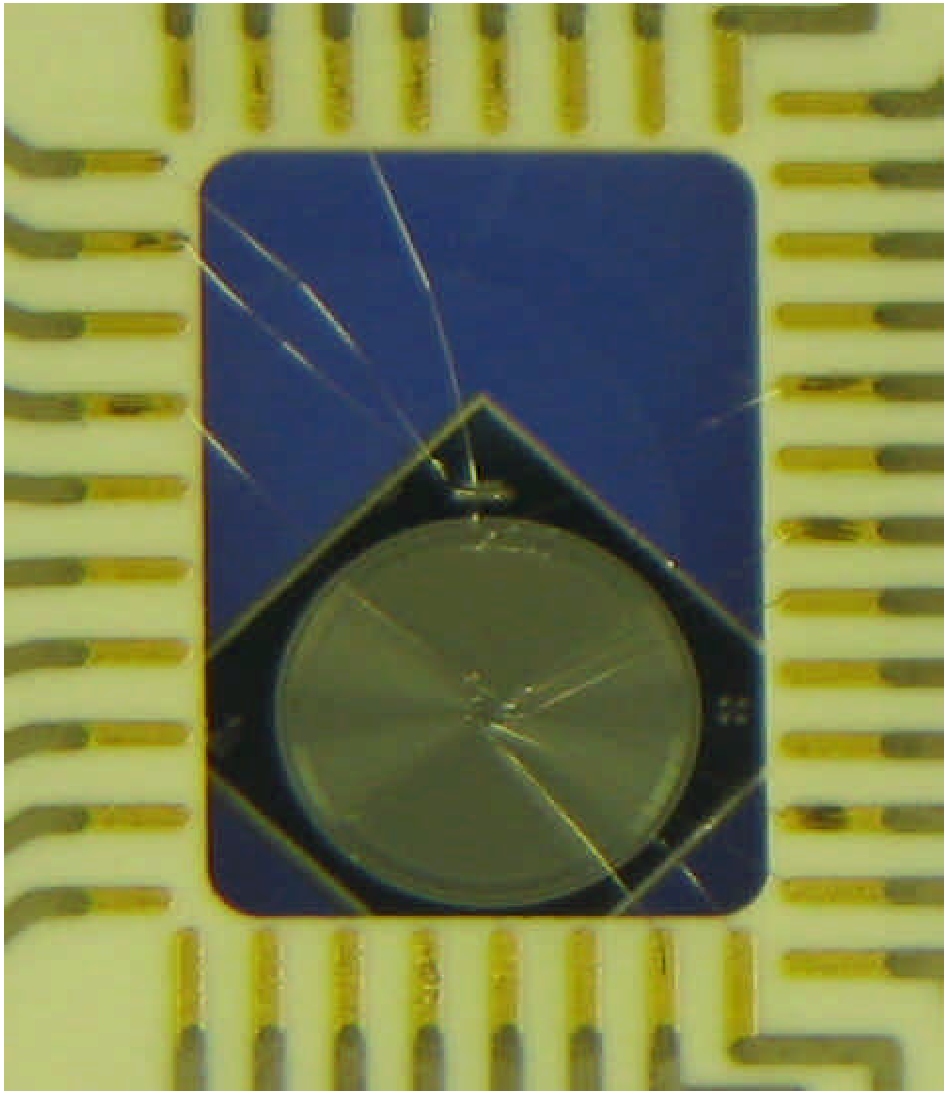
$$T_w = r \times t_{drift\ max} = 0.5 \times 10^3 \times 1\ ms = 0.5ms$$

$$B = B_r \times T_w = 10^3\ s^{-1} \times 0.5 \times 10^{-3}\ s = 0.5$$

S/B = 2/1 -> on all energy range =>

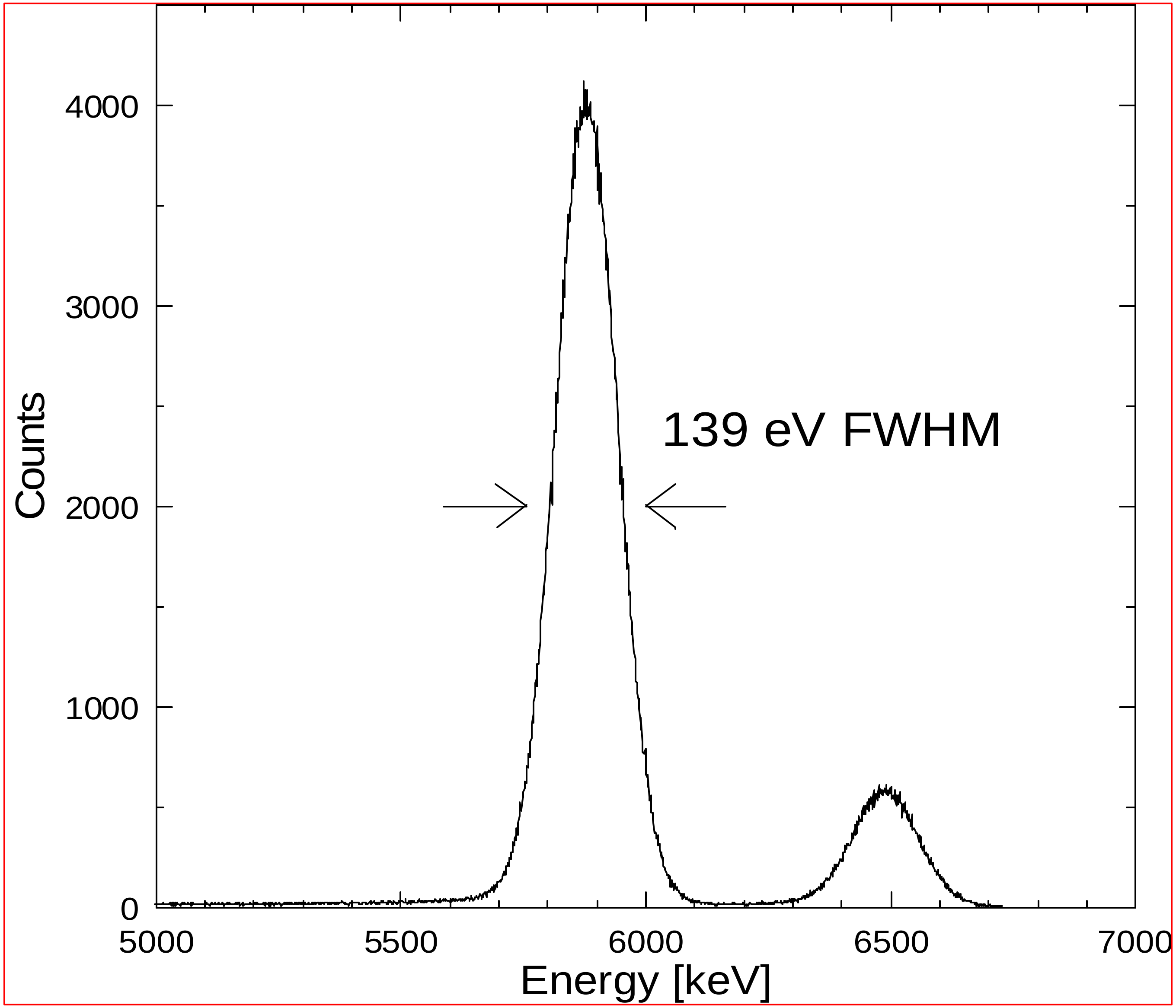
S/B < 20/1 (extrapolating to interested energy region taking into account DEAR results)

Test of the 30 mm² SDD (2004)



Detector biasing parameters

electrode	Voltage	Current
R#1	- 10 V	20.8µA
IGR	- 18 V	0.5µA
Back	- 91 V	<0.1µA
R#N	- 178 V	20.9µA
IS,OS	gnd	-
Drain	+12 V	400µA



T = - 40°C,
t_{sh}=0.75μs

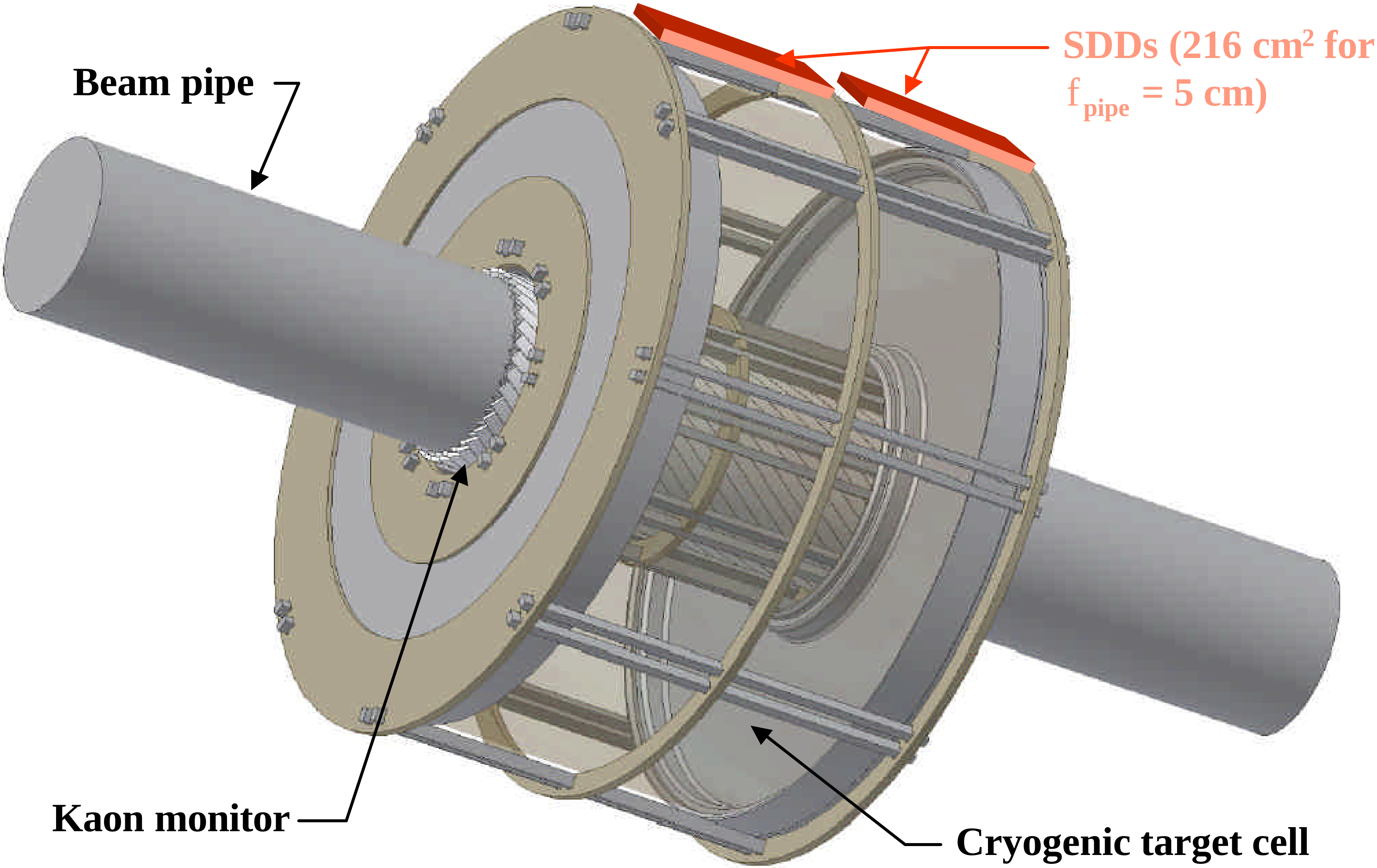
Synchronous background

Studied via MCarlo

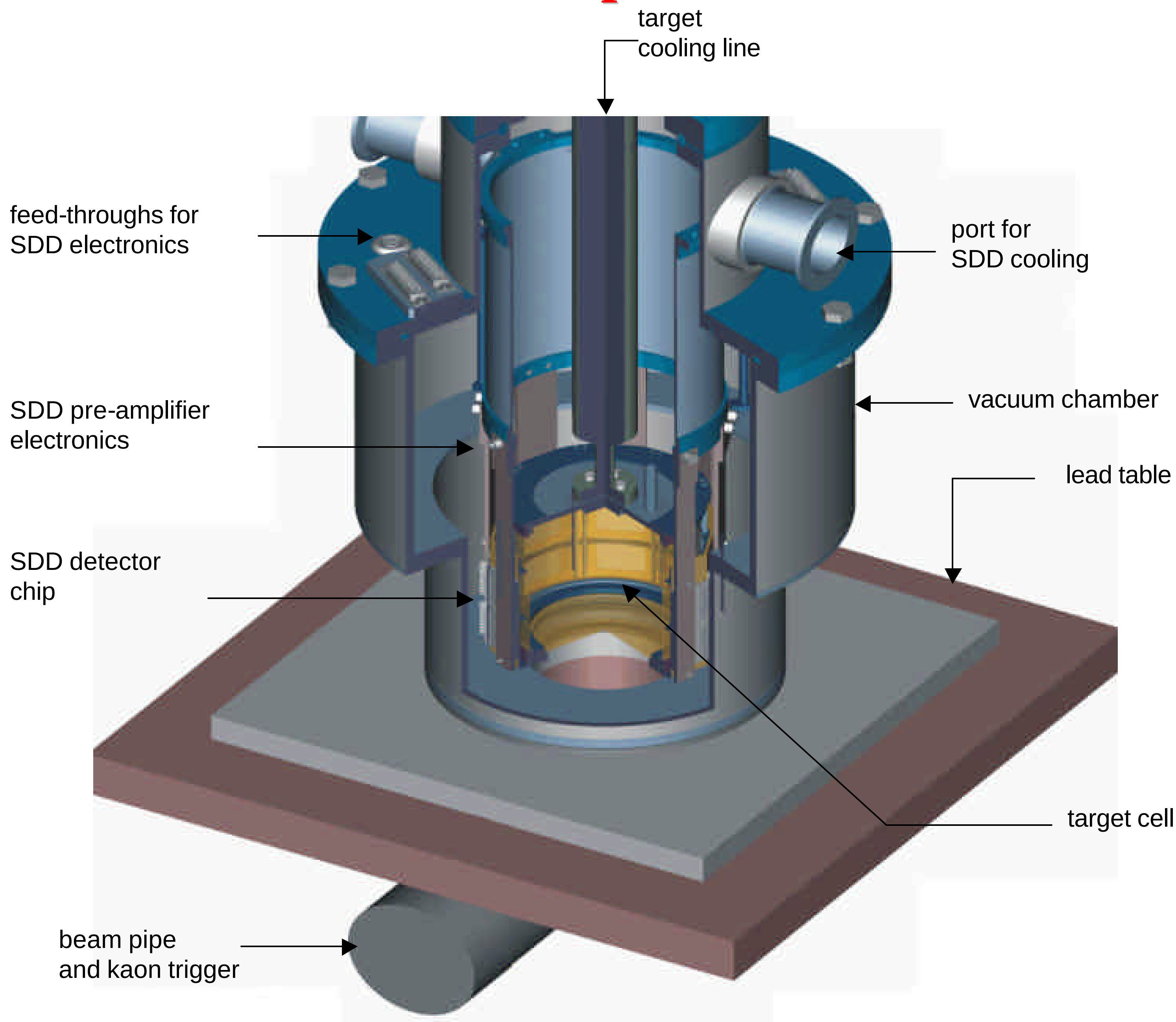
9. SIDDHARTA preliminary setup and Monte Carlo simulations

(Albano)

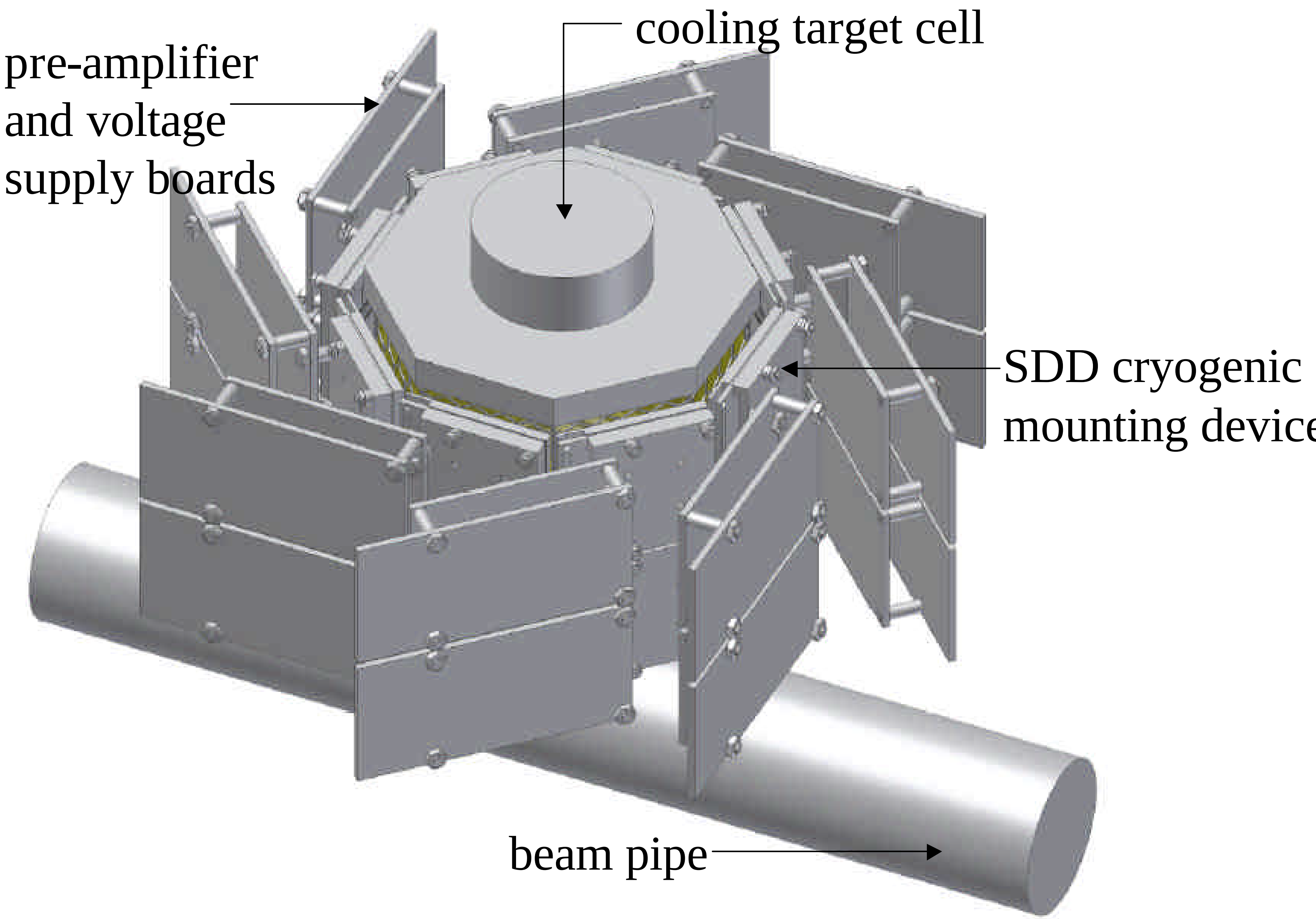
SIDDHARTA setup: 3D- view, version 1



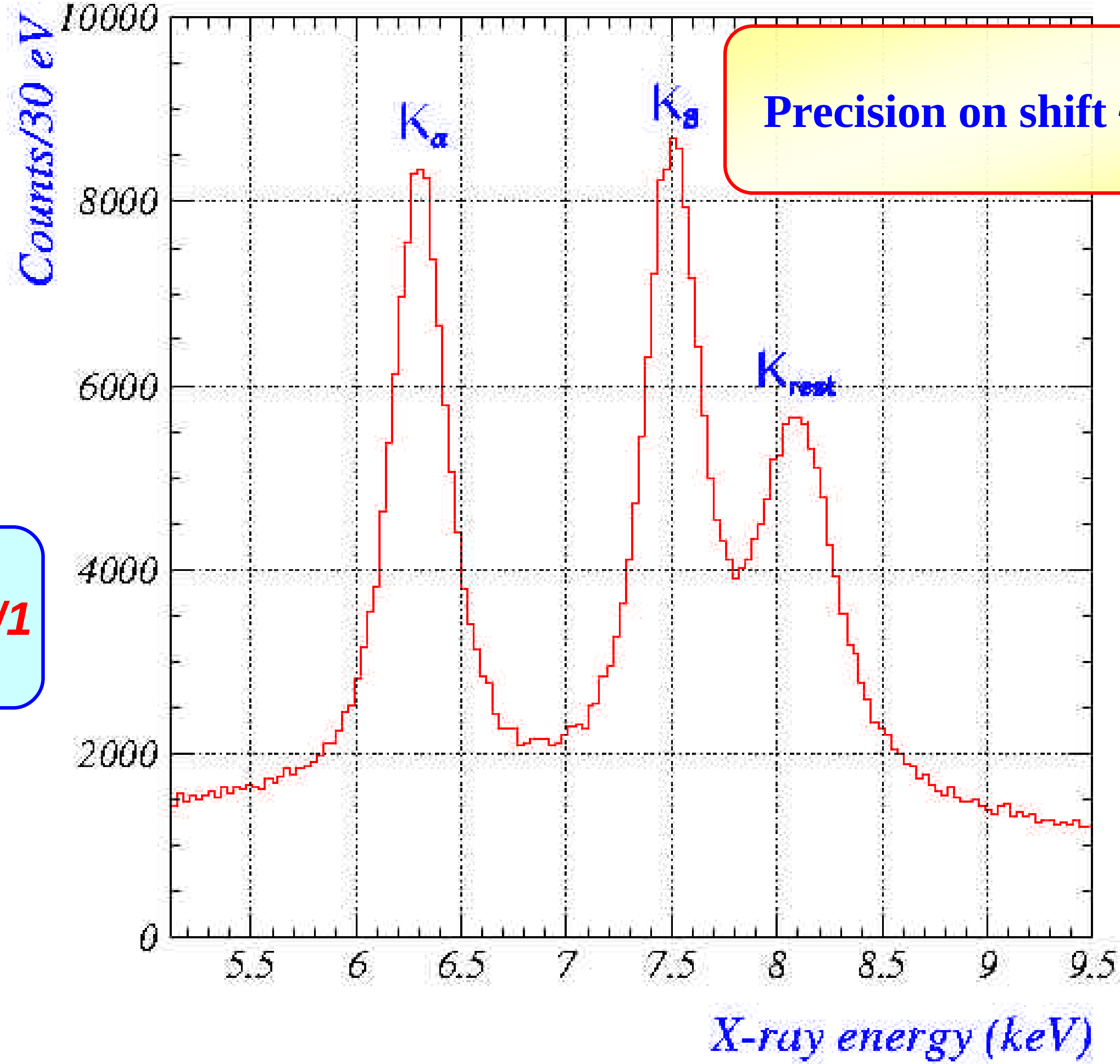
SIDDHARTA setup version 2



SIDDHARTA setup version 2



SIDDHARTA Kaonic hydrogen simulated spectrum

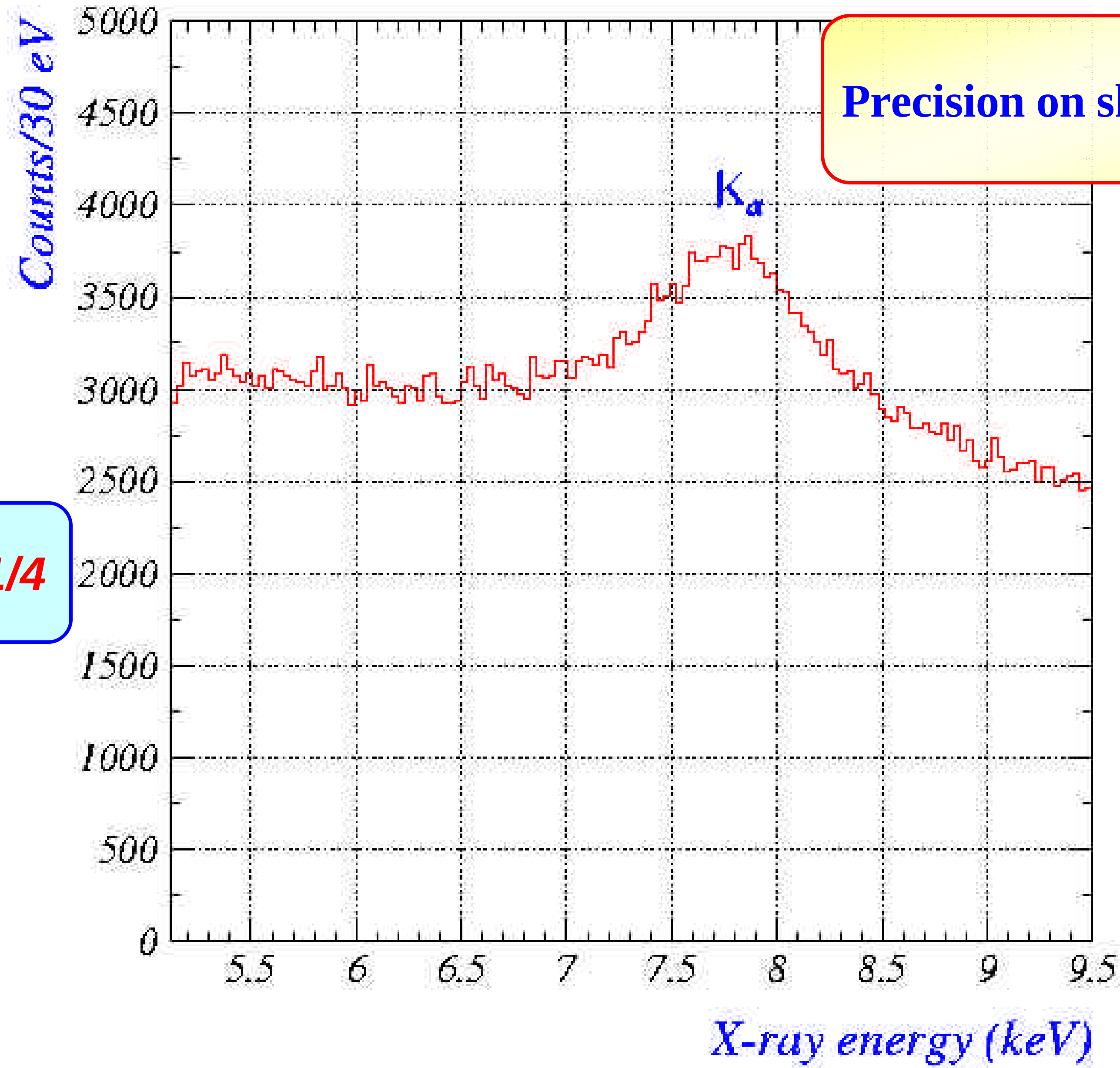


Precision on shift ~1 eV

~100 pb^{-1}

S/B = 5/1

SIDDHARTA Kaonic deuterium simulated spectrum



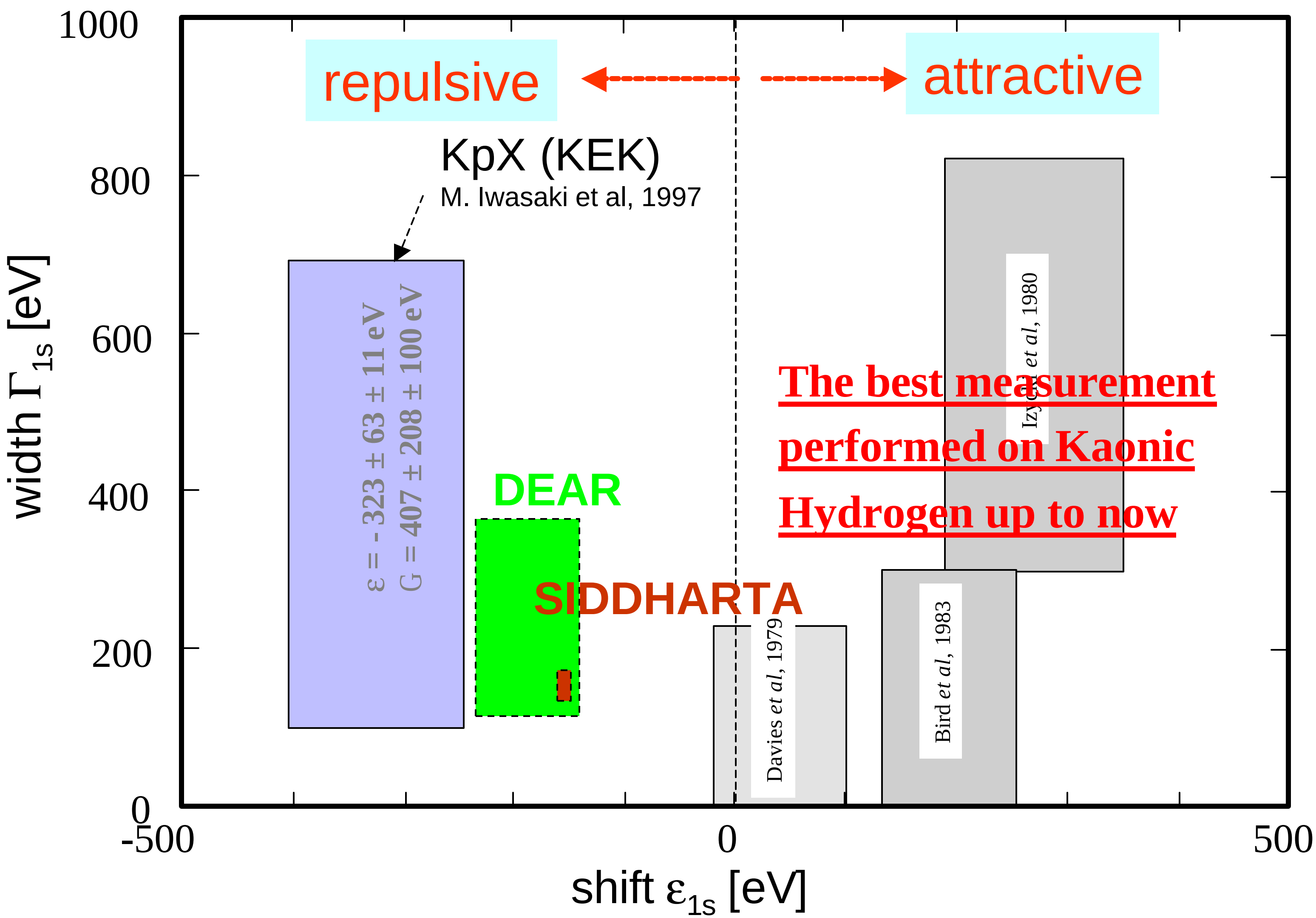
Precision on shift < 10 eV

300 pb^{-1}

S/B = 1/4

10. Conclusions

DEAR Results



SIDDHARTA future plans

1) ~ eV level precision measurement of kaonic hydrogen;

2) first measurement of kaonic deuterium

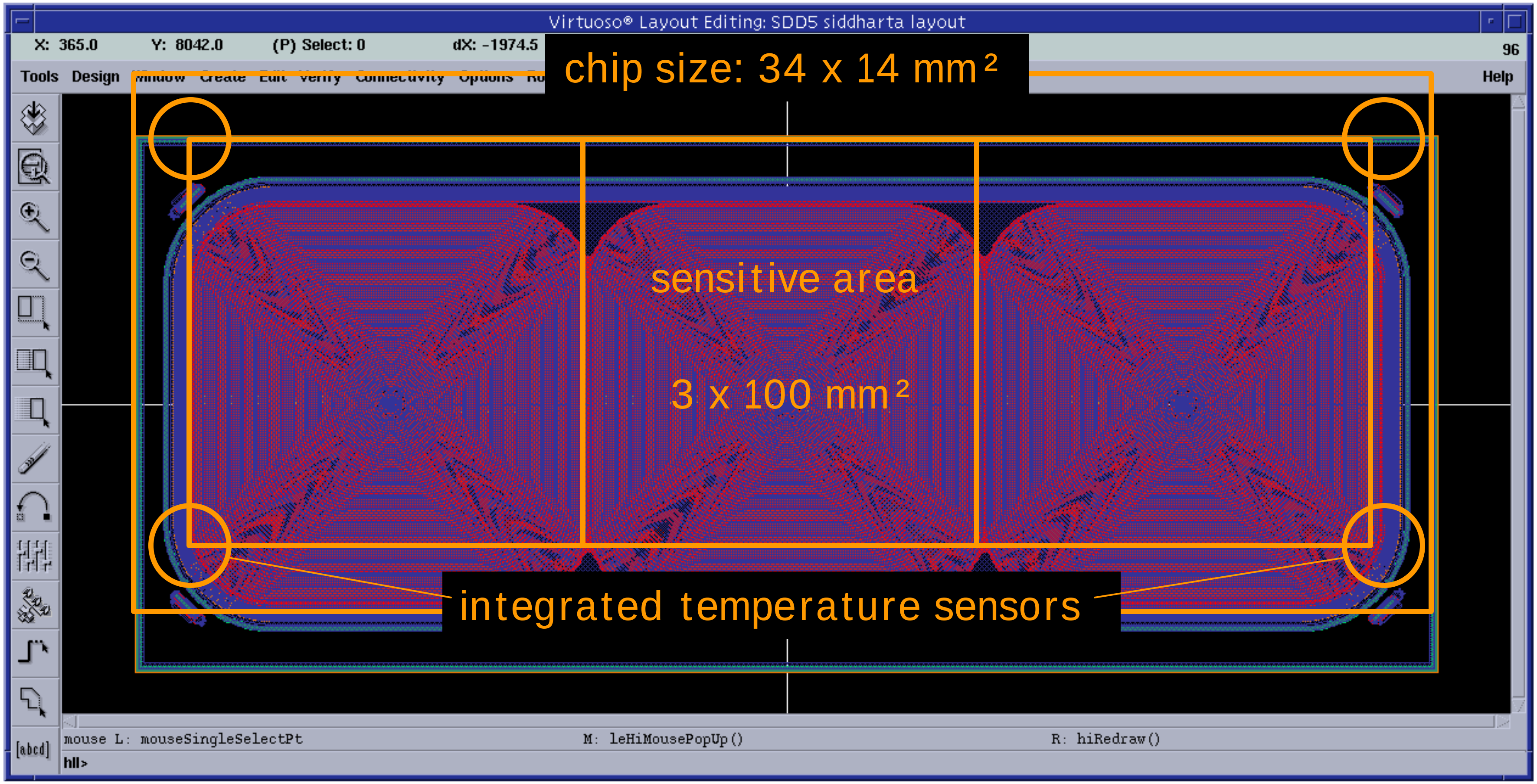
3) Kaonic helium measurement (“kaonic helium puzzle” and implications on deeply bound kaonic nuclear states);

4) Kaon mass precision measurement at the level of 10 keV

5) Other light kaonic atoms measurement (Li, Be…);

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

SDD layout – readout side



2005:

- Characterization of large area SDDs;

- End of front-end electronics production;

- End of data acquisition production;

- Finish and test of the experimental setup: mechanics, cryogenics, vacuum;

- Slow-controls system ;

- Assembly of the setup and tests on BTF

SDD-ceramic, bonding
Test on dummy
January 2005

bondtest @ IZM using an Al dummy chip

optical inspection by D. Mießner and P. Lechner

Munich, 03.02.05

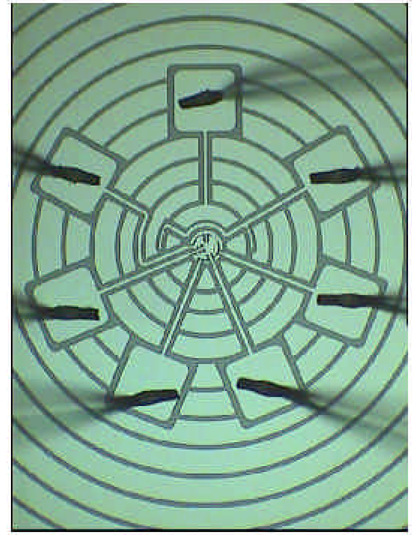


fig. 5 – readout structure 1

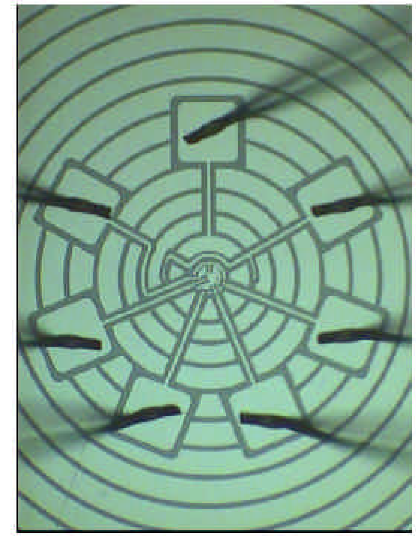


fig. 6 - readout structure 2

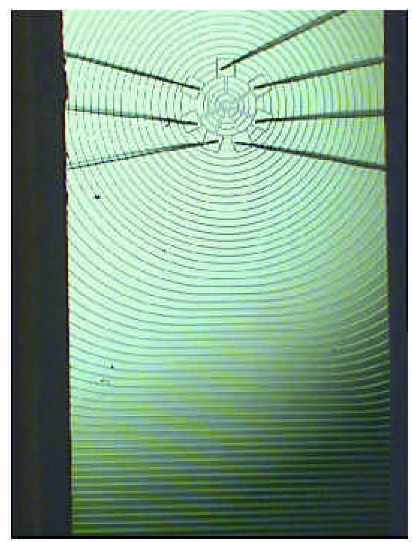


fig. 7 - readout structure 2, large scale

fig. 8 – temp diode, outer substrate

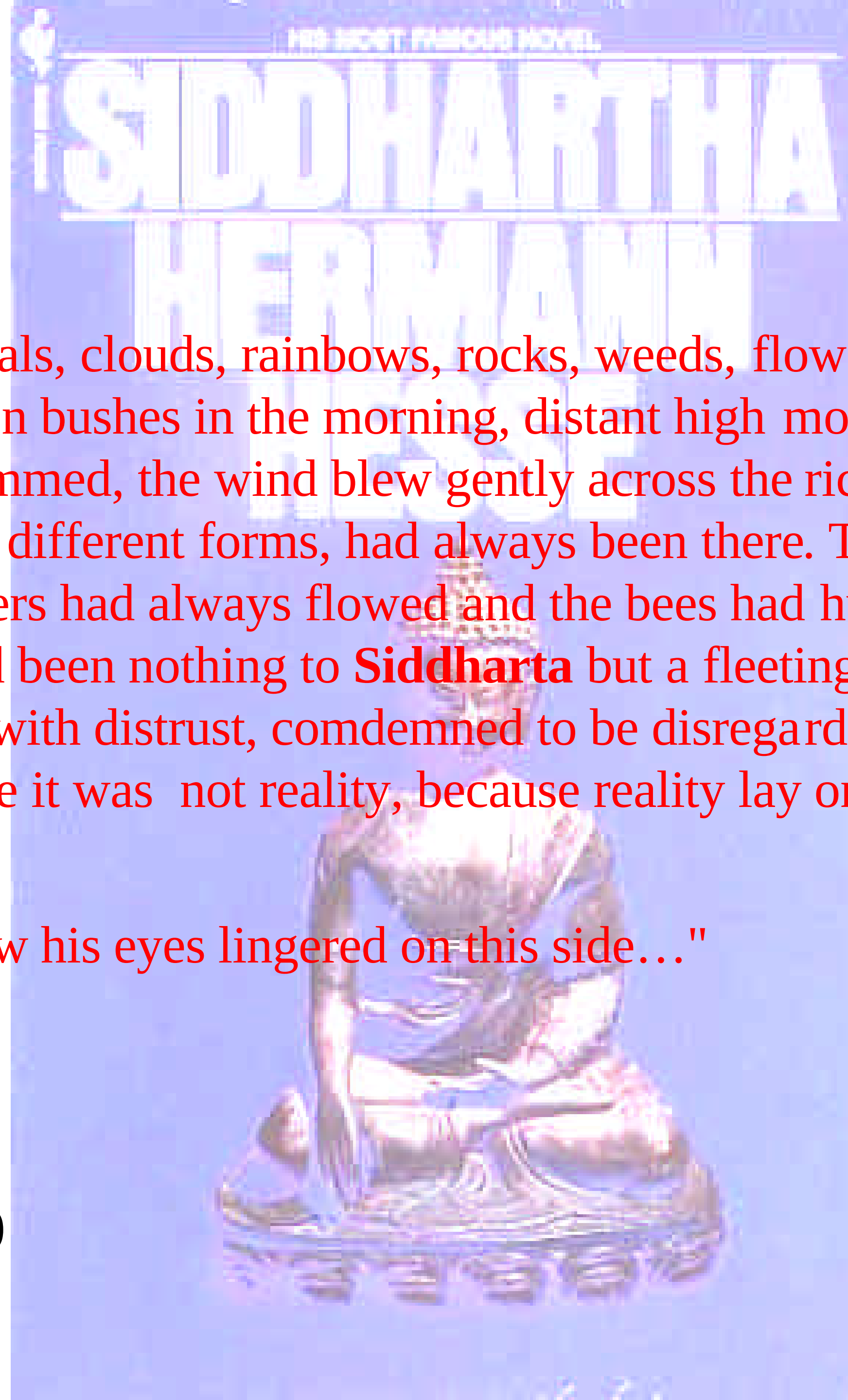
2006:

- Assemby of the SDD large area detectors in the setup;

- Assembly of the final setup on DAFNE;

- Tests on DAFNE;

- Install on DAFNE



"He saw trees, stars, animals, clouds, rainbows, rocks, weeds, flowers, brook and river, the sparkle of dew on bushes in the morning, distant high mountains blue and pale; birds sang, bees hummed, the wind blew gently across the rice fields. All this, colored and in a thousand different forms, had always been there. The sun and moon had always shone; the rivers had always flowed and the bees had hummed, but in previous times all this had been nothing to **Siddharta** but a fleeting and illusive veil before his eyes, regarded with distrust, comdemned to be disregarded and ostracized from the thoughts, because it was not reality, because reality lay on the other side of the visible.

But now his eyes lingered on this side…"

(H. Hesse, SIDDHARTA)