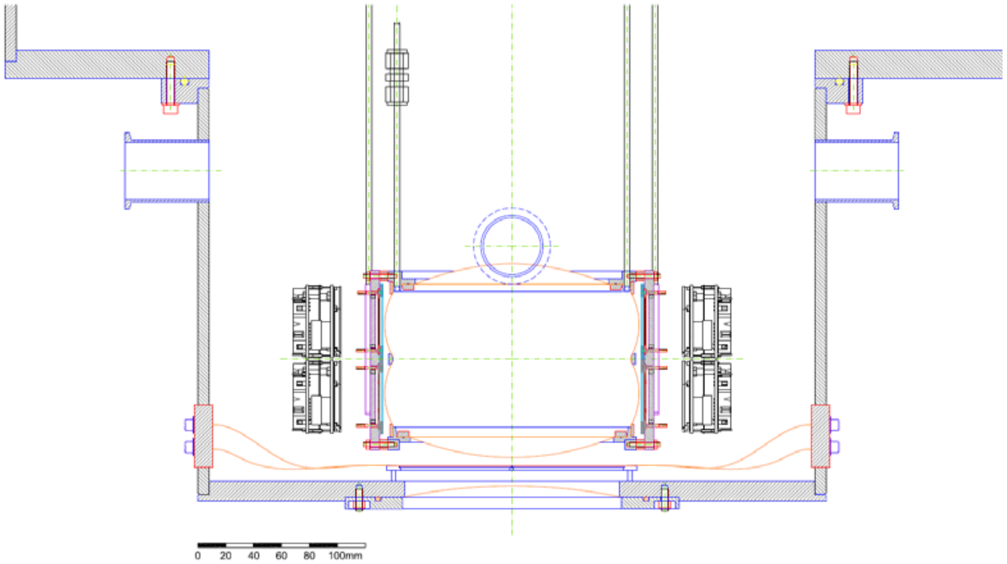

SIDDHARTA-2
the kaonic deuterium case

Upgrade of the SIDDHARTA apparatus for

the measurement of kaonic deuterium

14 April 2011

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Chapter 1 – Introduction

With the SIDDHARTA experiment (Silicon Drift Detector for Hadronic Atom Research by Timing Application) at the upgraded DAΦNE collider, measurements of kaonic atom transitions were performed. The data taking was completed in November 2009.

SIDDHARTA's original goal was to determine the shift and width of the ground levels in kaonic hydrogen and deuterium caused by the strong interaction between the kaons and the nuclei. Therefore the X-rays emitted in transitions of the kaons to the ground level are measured. And by comparing the measured X-ray energies with the values expected from QED only the strong interaction induced shift and width are obtained.

SIDDHARTA achieved to measure the energies of the transitions to the 2p level with a precision of a few eV in kaonic helium 4 and for the very first time also in helium 3 and in addition performed a new measurement on kaonic hydrogen.

For the kaonic deuterium, only an exploratory measurement could be performed, due to limitations in the beam time assigned to this measurement (100 pb^{-1}) and the difficult experimental conditions resulting in an unfavourably high background. The kaonic deuterium measurement however is mandatory in order to be able to extract the isospin-dependent antikaon-nucleon scattering lengths, fundamental quantities in the low-energy QCD in the strangeness sector.

The SIDDHARTA-2 proposal, presented by a reinforced collaboration, was put forward in June 2010. The proposal contains both a rich scientific case, with many proposed measurements, and the technical ideas for the upgrade, together with the gain factors.

The present report can be considered as an addendum to the SIDDHARTA-2 proposal, and is presenting the details of the technical solution for the realization of the kaonic deuterium measurement. The detailed description of all other measurements (kaonic helium 3 and 4 and many others) will be presented in a separate report.

In the following we discuss the main ideas related to the planed upgrades and modifications of the experimental setup. The resulting gain factors are presented as well as results from Monte Carlo simulations.

At the end of the document, we also include a time schedule for the realization of the upgraded setup and a beam time request.

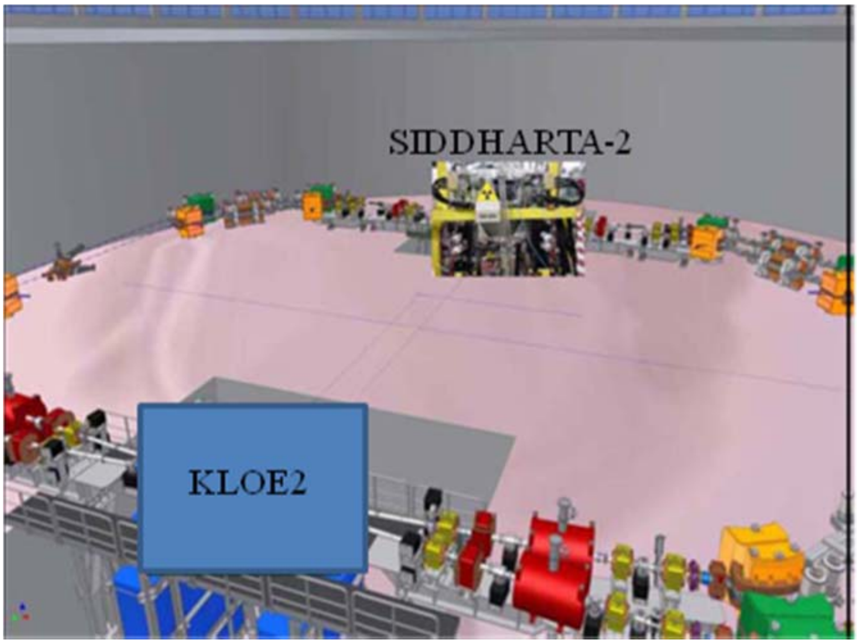

Figure 1: The possible SIDDHARTA-2 setup in the DEAR/FINUDA interaction region of DAΦNE

Chapter 2 – Physics case, a short note

The measurement of the X-ray transitions to the 1s level in kaonic deuterium will allow together with the available results from kaonic hydrogen, to extract the isospin-dependent antikaon-nucleon scattering lengths, fundamental quantities which are essential for understanding the low-energy QCD in the strangeness sector.

What actually is needed to be measured are the shifts and broadening of the 1s level in both, kaonic hydrogen and kaonic deuterium, with respect to the values expected from pure QED calculations (see fig. 2).

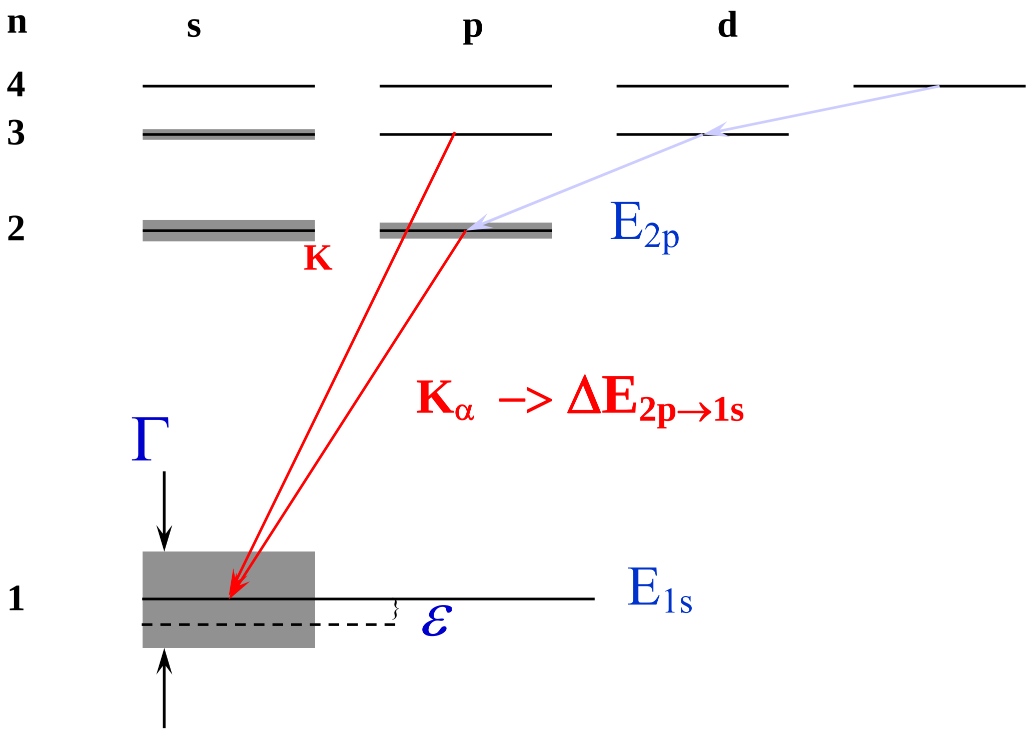

Figure 2: Strong Interaction effect on the 1s level in kaonic hydrogen (deuterium). The 1s level (E_{1s}) is shifted by epsilon and the width Γ is increased.

The measured shifts and broadening of the 1s level, due the strong interaction, are connected to the kaon-proton and kaon-neutron scattering lengths, which in turn are related to the isospin dependent scattering lengths. The extraction of the isospin-dependent scattering lengths from the measured kaonic hydrogen and kaonic deuterium shifts and widths is a rather complicated procedure which is presently object of intensive theoretical studies. The determination of the isospin-dependent scattering lengths will indeed represent a breakthrough in the low-energy QCD in strangeness sector, since it:

1. Gives the threshold amplitude in QCD.

2. Allows to obtain additional information on the still not well kaon sub-threshold resonance Λ(1405).

3. Contributes to the determination of the antikaon-nucleon sigma term, which give the degree of chiral symmetry breaking, even if the procedure to do this is not yet worked out and might be rather difficult. However, the experimental data will certainly trigger both theoretical effort and additional experimental ones in order to obtain the necessary missing information (scattering data at low energies for example).

4. Point 3 is also related to the determination of the strangeness content of the nucleon.

A detailed analyses of the kaon-nucleon scientific case can be found in C. Guaraldo, Frascati Physics Series, 16 (1999) page 643-658. Even though it does not include the latest results on this topic, it gives a clear and comprehensive, as well as exhaustive, phenomenological view of the importance of these types of measurements.

At this point, is mandatory to mention that apart from the SIDDHARTA exploratory measurement on kaonic deuterium, no other measurement was performed and will be performed in foreseeable future, in spite of its utmost importance. This situation is due to the extreme difficulty of such measurement: The yield is a few times smaller than in the hydrogen case, while the width is larger. Based on some theoretical calculations and on estimates obtained from SIDDHARTA, one expects the yield to might be a factor 3 to 10 smaller while the width could be around 800-1000 eV. Of course, whether these assumptions are valid or not will only be known when the measurement has been performed. But having these figures in mind, we will show in the following chapter that the measurement of kaonic deuterium in the framework of SIDDHARTA-2 becomes feasible.

The implications of the determination of the isospin-dependent scattering lengths, not only on nuclear physics but also on particle and astroparticle physics have been intensively debated at the "Strangeness in nuclei" workshop, held at ECT*, Trento in October 2010.

Chapter 3 – SIDDHARTA-2 setup, improvements for the kaonic deuterium measurement (phase 1)

In what follows we shall present the main changes to be performed to the SIDDHARTA setup to become the SIDDHARTA-2 setup, in order to perform the kaonic deuterium measurements. The relative gain factors will be discussed in the next chapter.

3.1 The new vacuum chamber

The main changes to be performed for the first phase of SIDDHARTA-2 are mechanical improvements related to the vacuum chamber in order to allow adding additional cooling power to the SDD and target cooling systems.

A stronger closed loop helium refrigerator for cooling the new target cell (see below) was already purchased, with more than twice the cooling power of the old one, namely 20 watt at 20 K, and is currently under test.

In addition, a part of the vacuum chamber has to be rebuilt to gain space for an additional CryoTiger system (so far 3 devices have been used), which will considerably improve the cooling of the SDDs.

Further on, we plan to mount a segmented planar silicon detector between the entrance window of the vacuum chamber and the target window, which needs additional feed-throughs close to the mounting position.

Finally, to improve the X-ray calibration system an additional port has to be foreseen. The design of the new vacuum chamber is sketched in figure 2.

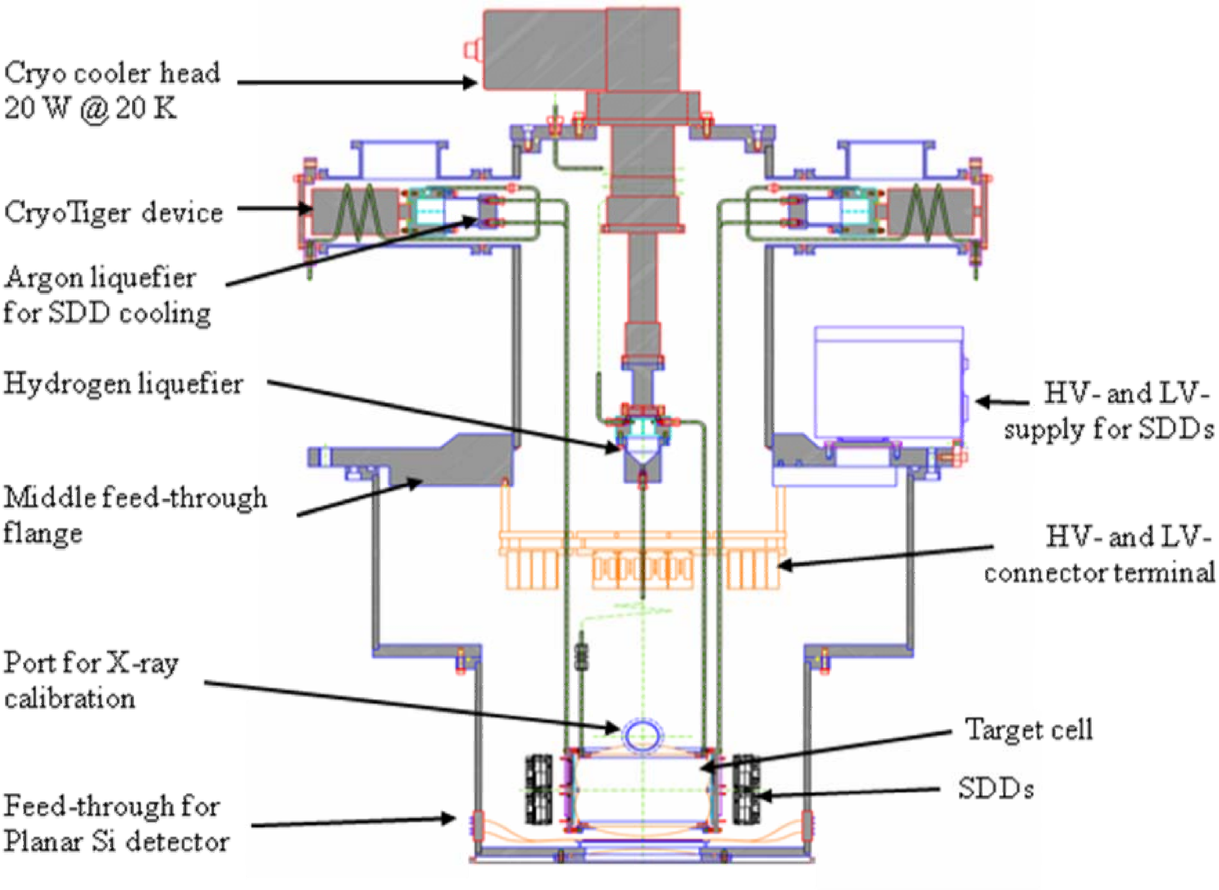

Figure 2: Side view of the new vacuum chamber design. Only the middle part with the vacuum feed-through flange can be reused.

3.2 New target cell and new SDDs geometry

A new target cell will be built with less material budget using Hostaphan as wall material and for the reinforcement structure pure aluminium covered with a thin layer of pure titanium (for in-situ calibration). The used materials are selected to avoid unwanted fluorescence X-rays or kaonic X-ray lines from stopped kaons in the target material. The new target dimensions are: 140 mm in height with a diameter of 180 mm (see fig. 3).

The arrangement of the SDDs around the target cell will be improved to increase the acceptance. The SDDs will be moved as close as possible to the target yet having regard to the temperature difference between target (20 K) and detectors (100 K).

The new SDD arrangement is shown in figure 3 and 4.

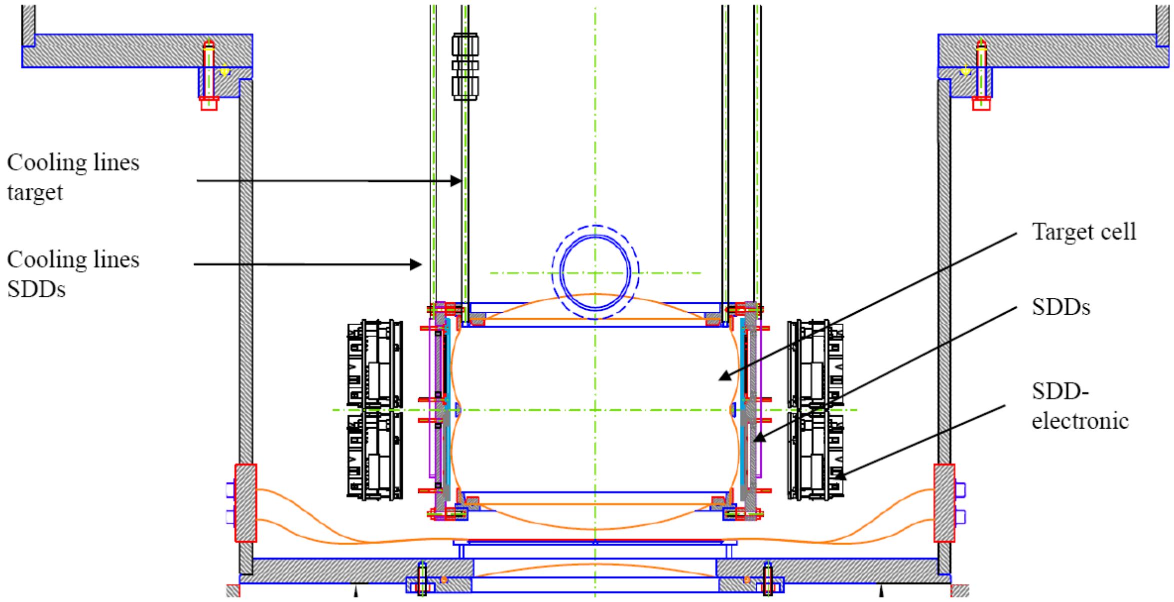

Figure 3: Design of the new target cell and new SDD arrangement

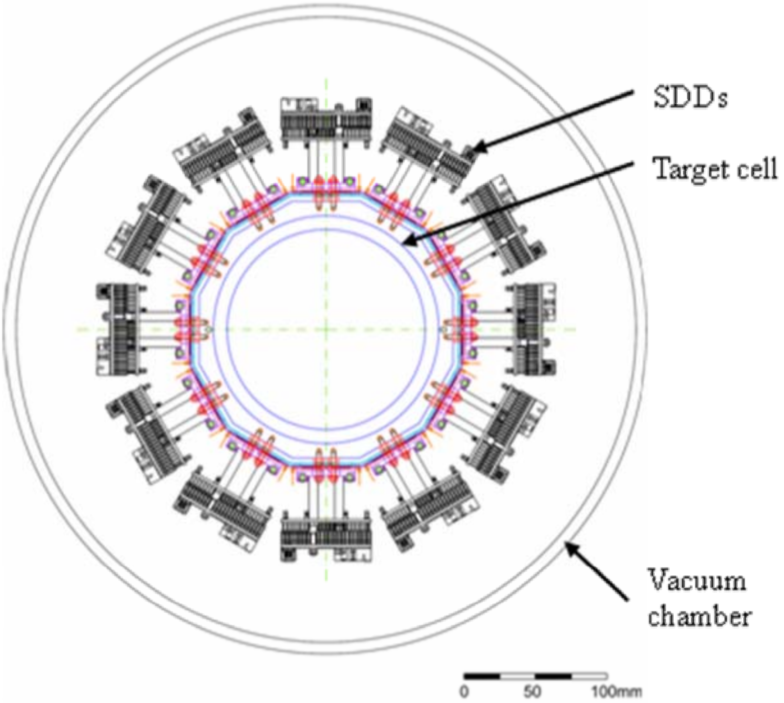

Figure 4: Design of the new target cell and new SDD arrangement, top view

The new target cell will be coupled to a more powerful cryogenic system, which will make it possible to run with higher gas densities, thus increasing the number of stopped kaons and, consequently, the signal. A totally new target cooling technique will be used: the target will be cooled due to evaporation of liquid hydrogen. This technique will allow a reduction of the material budget around the target cell and even the material budget on top of the target cell can be drastically reduced. This material reduction is essential, because it is a source of Bremsstrahlung close to the SDDs.

With this new target cell gas densities up to 3% LDD (liquid deuterium density) are reachable, which will increase the kaon stopping rate inside the target. This high density is still acceptable in order not to lose too many kaonic X-rays due to the Stark-mixing.

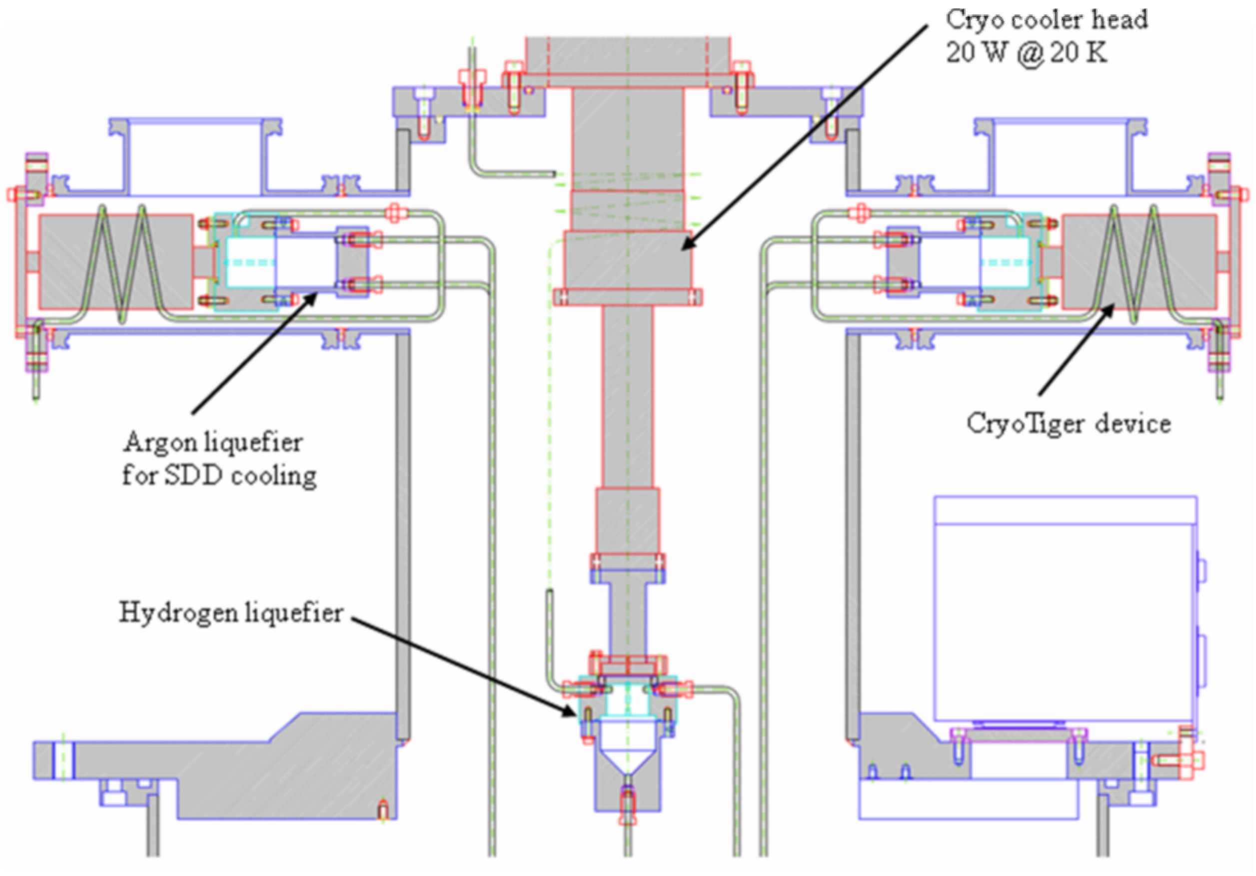

Figure 5: New design of the cooling cycles for target and SDDs.

3.3 New X-ray calibration scheme

Two different fluorescence X-ray tube calibration schemes are foreseen to improve the accuracy of the calibration procedure and therefore to minimize the systematic error:

- The low rate "in-situ calibration" process will run all the time and will allow a determination of the in-situ energy value to check the validity of the "energy calibration" procedure.

- The high rate energy calibration procedure, performed twice a day, will allow to set the energy scale equal for each SDD and therefore summation of the signals of all SDDs will be possible.

3.4 Improved trigger scheme

In order to increase the S/B ratio one has to selectively trigger on kaons entering the target volume. This was realized in SIDDHARTA only partially, since the trigger system (scintillators read by PMs) was positioned outside vacuum chamber and lead shielding – about 12 cm away from the target entrance window. Therefore, although the size of the kaon trigger was optimized, a certain number of triggered kaons were not entering the target volume, but were absorbed on the lead side walls and were producing background events.

For SIDDHARTA-2 we plan:

- To move the upper scintillator panel of the kaon monitor as close as possible to the entrance window of the vacuum chamber.

- To install a veto detector, located around the upper scintillator panel of the kaon monitor.

- To place in front of the target entrance window a segmented planar silicon detector to obtain additional spatial information of incident kaons as close as possible to target cell.

In Fig. 6 the scheme of the new trigger system is shown.

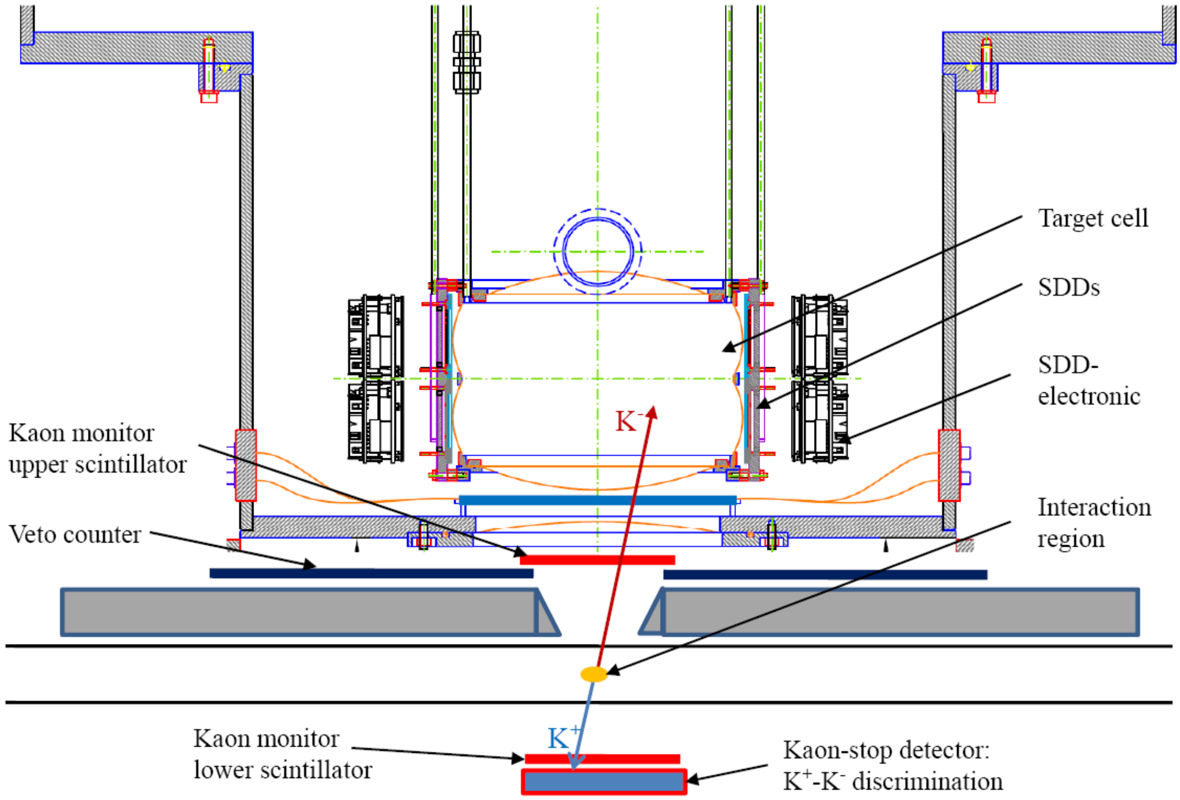

Figure 6: Sketch of the new position of the kaon monitor and of the veto counter. The planar silicon detector is placed in the vacuum chamber, close to the target entrance window. The good spatial resolution gives additional information of the kaon position entering the target (important for systematic studies of X-rays coming from kaons stopped in the side wall of the target cell).

3.5 New shielding and active shielding

In the framework of SIDDHARTA, due to the very limited space caused by the presence of the machine luminosity monitor, it was not possible to optimize the shielding (as it was eventually done in DEAR). Thanks to the extra available space at the new interaction region a more sophisticated grated shielding structure (lead-copper-aluminiun-plastic) around the SDD detectors can be constructed, following the lesson learned in the framework of DEAR (layers of various decreasing Z-materials all around the setup).

Moreover, we are considering the option of an additional veto (anticoincidence) system to be positioned around the target cell in order to reject those events which still pass the lead shielding around the target. The new trigger system and anti-coincidence help to suppress the background and to obtain a better S/B ratio.

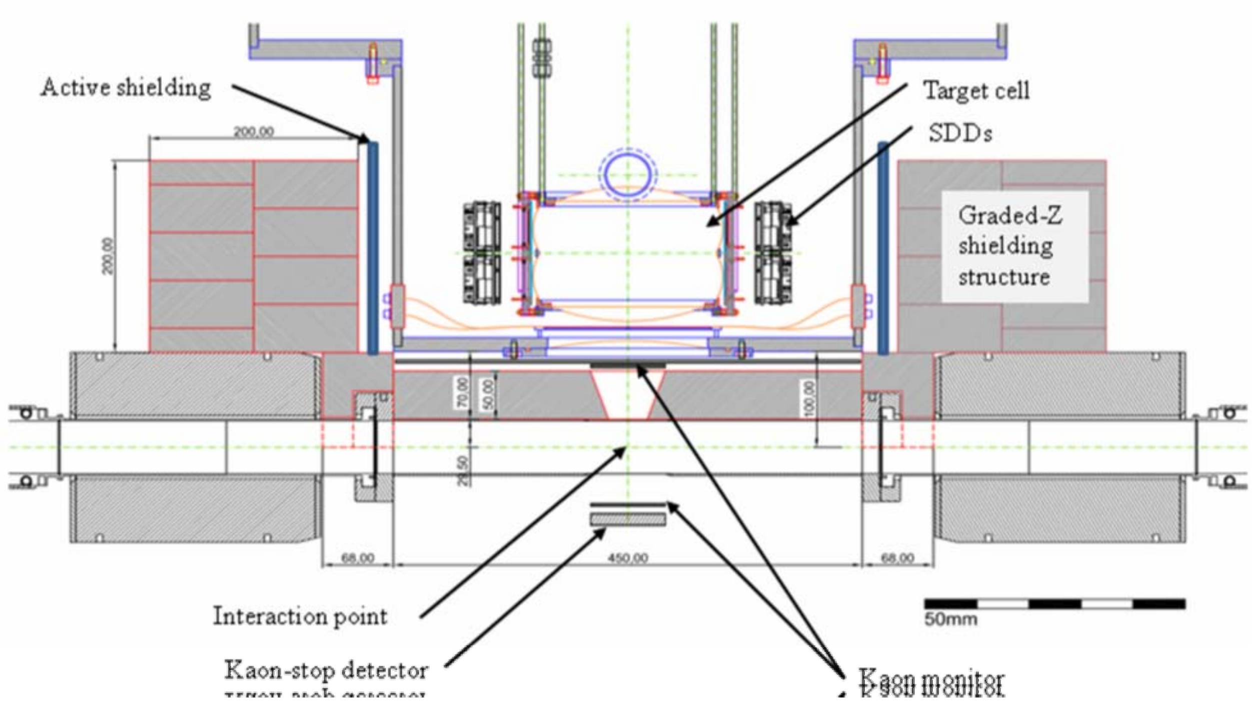

Figure 7: Sketch of the grated-shielding and active veto configuration.

3.6 K$^+$ identification and rejection, going into background rejection

The trigger system of SIDDHARTA was not able to differentiate between the different charge states of the incident kaons. The accepted events were though a mixture of K$^-$ (incuding singnal) and K$^+$ (representing bakground) induced events. For SIDDHARTA-2 we plan to implement a third scintillator below the beam pipe, right after the one giving the trigger, making full use of the available space (see fig. 6 and 7). This additional scintillator - in the following also denoted as "kaon-stop detector" - will be able to detect positively charges kaons by their decay into muons and thus allows to select exclusively events in which the K$^+$ does not enter the target cell (see next chapter for details and calculations).

Chapter 4 – Monte Carlo simulations for SIDDHARTA-2

Monte Carlo simulations were performed to evaluate the gain factors for the new SIDDHARTA-2 setup.

4.1 Geometric effects and gas density

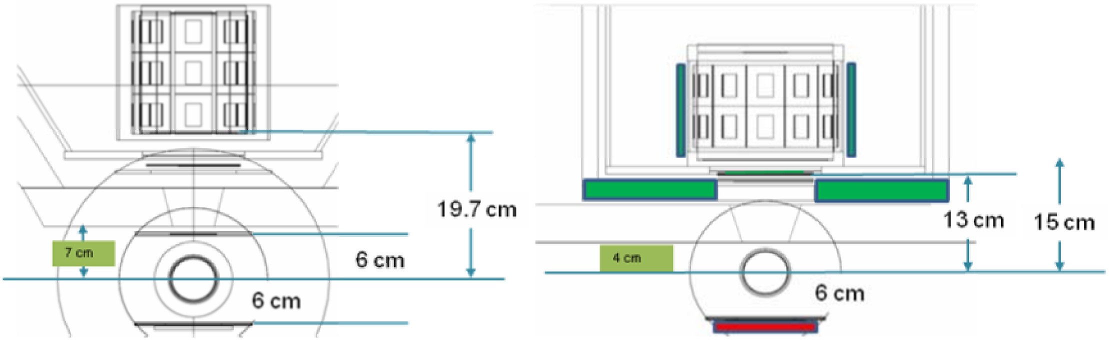

Figure 8: Sketch, with the important numbers used in the MC simulation for the SIDDHARTA setup (left) and for comparison the dimensions of the new design for SIDDHARTA-2 (right).

The main changes in SIDDHARTA-2 are:

- Improved target and SDD configuration – gain in S/B ratio.
- Target cell for gas densities up to 3% (LHD) – gain due to higher stopping density and therefore more good X-ray events.
- Upper scintillator of the kaon monitor moved close to the entrance window of the vacuum chamber – gain due to less background and therefore an improvement in the S/B ratio.
- Below the lower scintillator a kaon live time detector (kaon-stop detector) will be installed to discriminate between K^+ and K^- – gain due to reduction of background (approx. 50%) events.

The result of the MC simulation for the SIDDHARTA setup as running in 2009 is shown in figure 9, with the following main parameters:

- Gas density = 1.5 % LHD
- Upper scintillator size 49 mm x 60 mm, 60 mm above IP

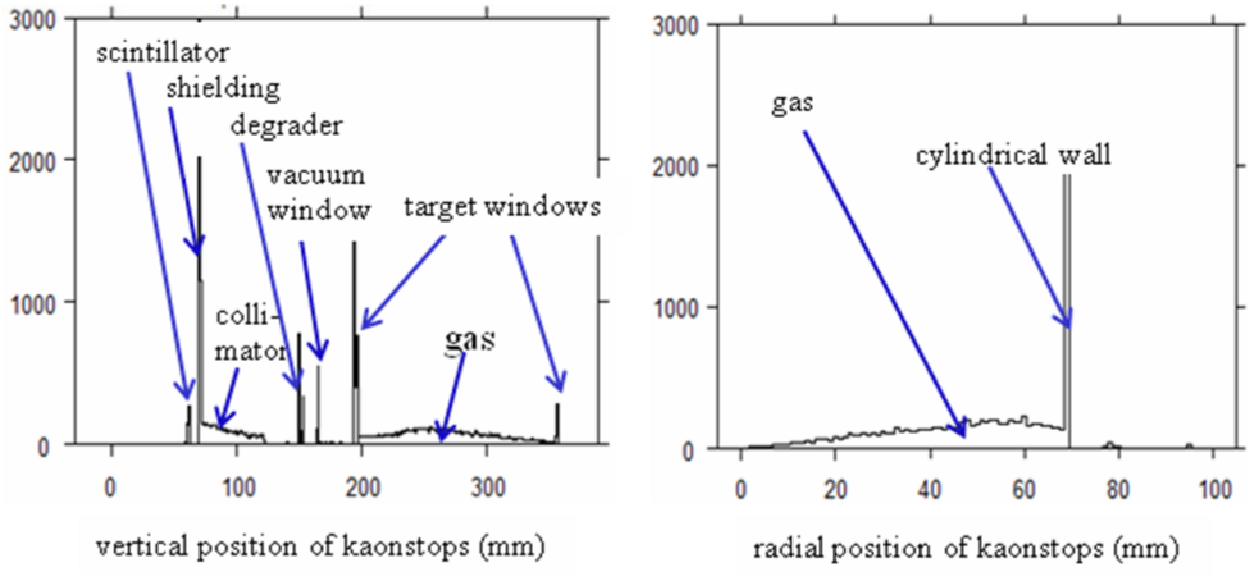

Figure 9: Target setup SIDDHARTA experiment 2009. Left side: Distribution of the kaon stops from the interaction point to the top of the target cell; right side: kaon stop distribution of the radial position from the centre line of the target cell to the target wall.

The result of the MC simulation for the SIDDHARTA-2 setup is shown in figure 10, with the following main parameters:

- Gas density = 3.0 % LHD
- Upper scintillator 90 mm diameter, 130 mm above IP (close to target)

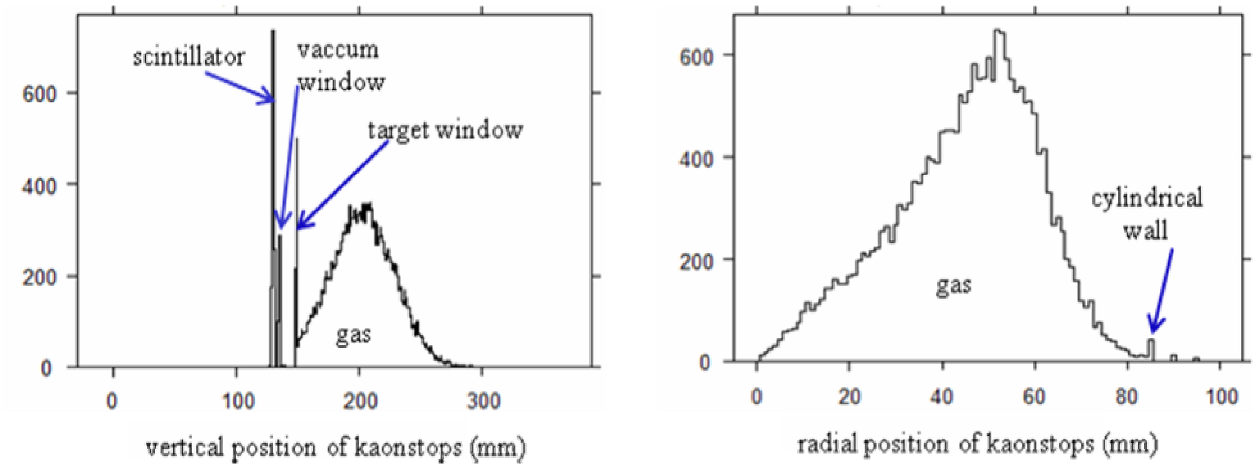

Figure 10: Left side: Distribution of the kaon stops from the interaction point to the top of the target cell; right side: kaon stop distribution of the radial position from the centre line of the target cell to the target wall.

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It is striking that the new geometry of the upper kaon-trigger scintillator along with the higher gas density results in a drastic reduction of the number of kaons stopping in the trigger counters and target walls, whereas the number of kaons stopping in the target gas is significantly increased. Compare the intensity of the spectra regions denoted as “gas” with the one of the spikes from wall (window) stops. The fraction of triggered kaons stopping in the wall materials can be reduced by a factor of 20, which of course reduces the problem of the background coming from kaonic lines.

4.2 K^+K^- discrimination

The gate of the kaon-stop detector (see fig. 11) will open 2 ns after the signal in the lower scintillator. 2 ns are enough, because in the case of a stopped K^- the nuclear capture process is much faster than 2 ns. Therefore, if the stopped kaon was a K^+ we will see the decay particles with high probability: $e^{(-2/12.2)} = 0.85$.

The background situation without and with K^+K^- discrimination is compared in figure 12 and shows quite clearly the expected reduction factor.

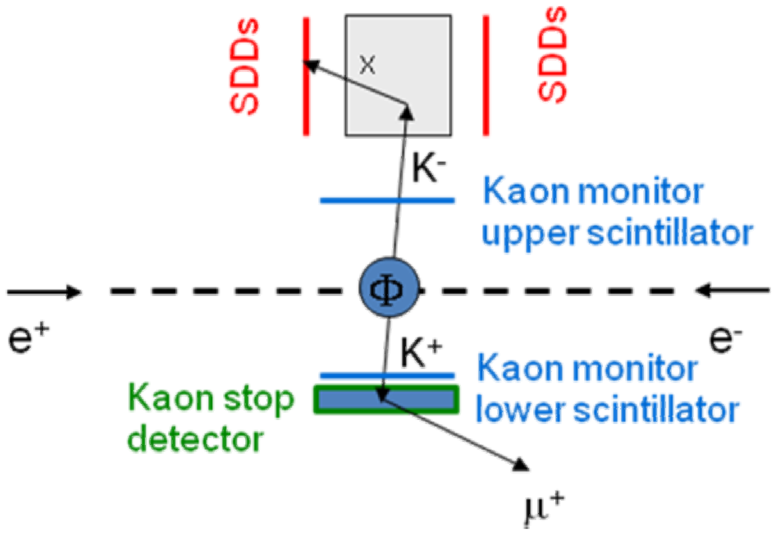


Figure 11: Arrangement of the kaon-stop detector for K^+K^- *discrimination*

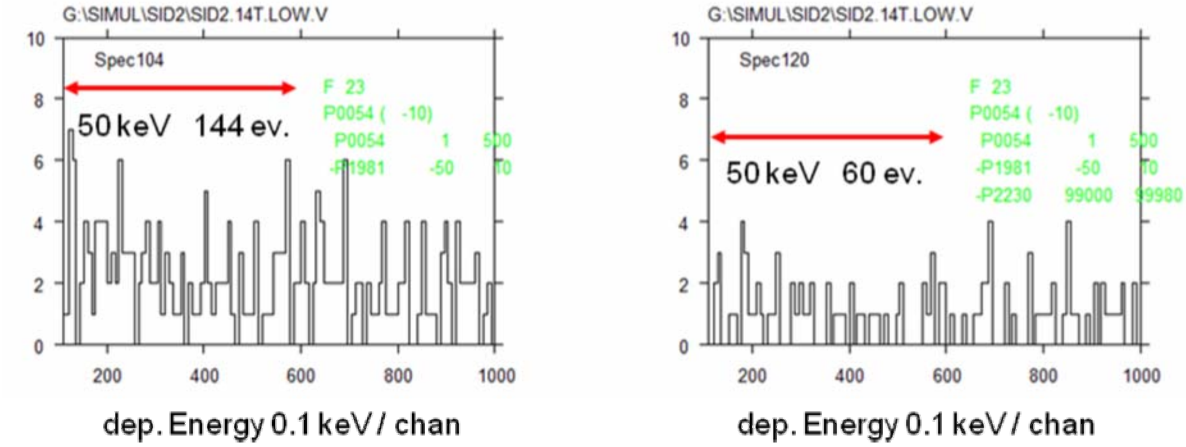
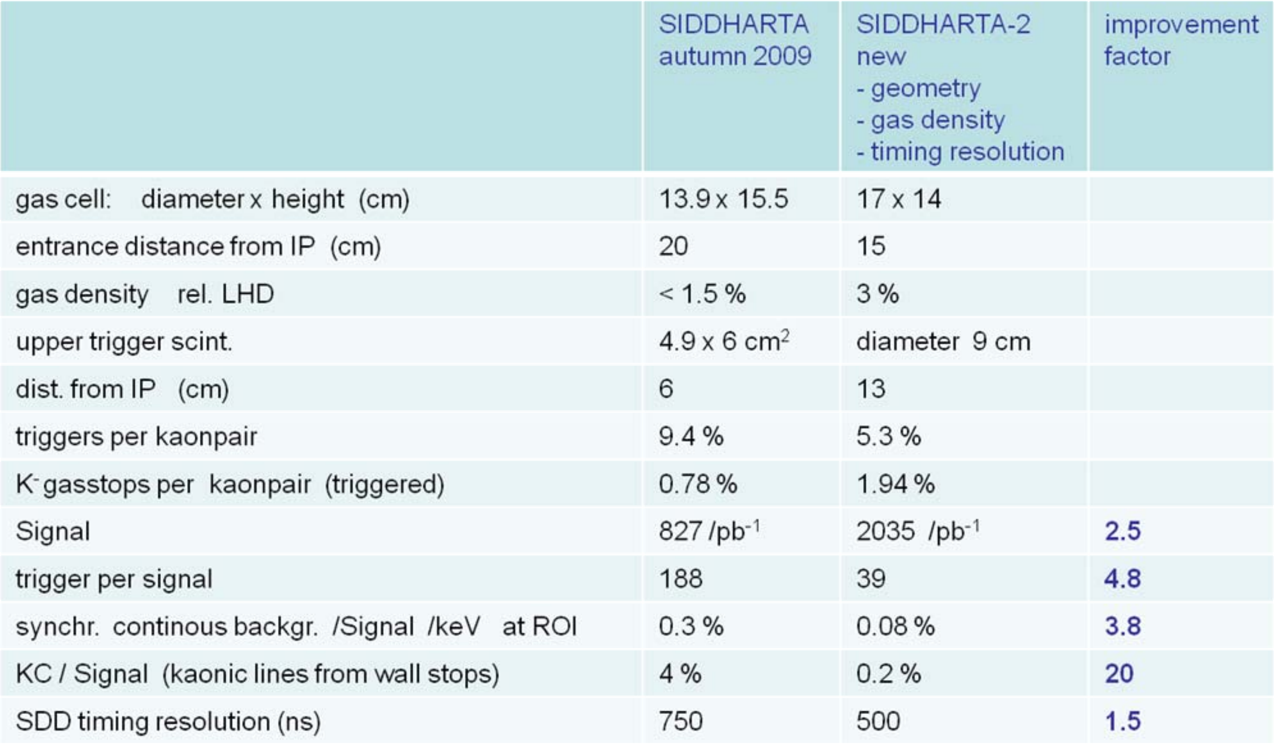


Figure 12: Expected background without (left) and with K^+K^- *discrimination.*

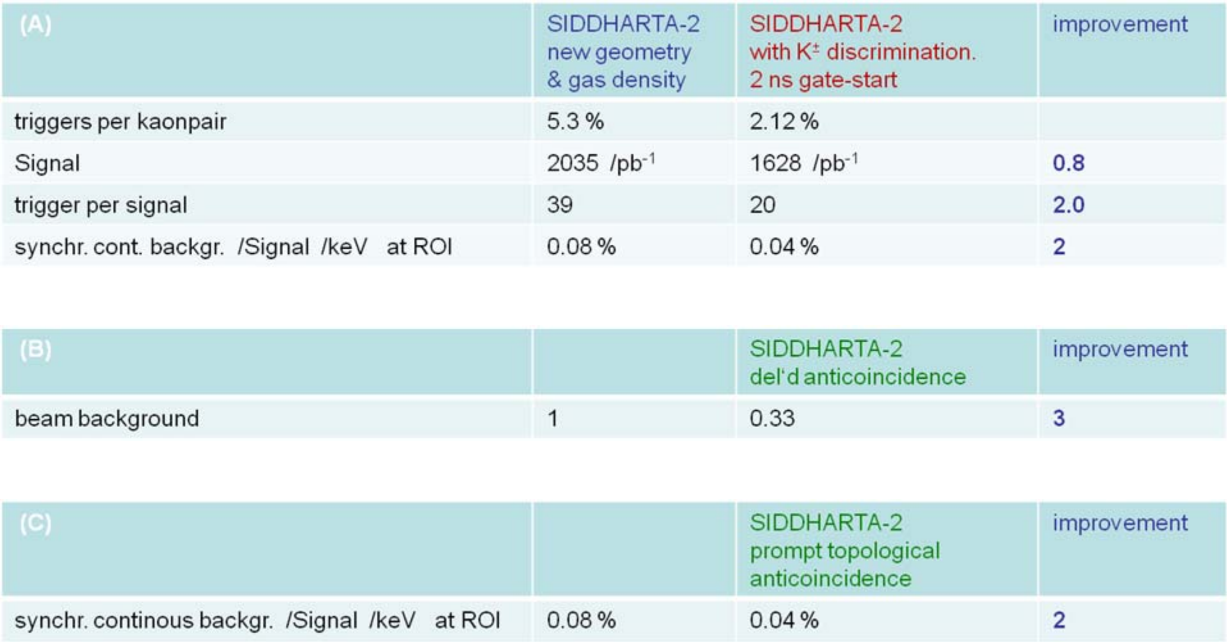
4.3 Summary of results

In table 1 and 2 the results of the MC simulation are summarized for the new target-SDD and trigger geometry, the higher gas density, improved SDD timing resolution, K^+K^- discrimination and delayed anti-coincidence.



	SIDDHARTA autumn 2009	SIDDHARTA-2 new - geometry - gas density - timing resolution	improvement factor
gas cell: diameter x height (cm)	13.9 x 15.5	17 x 14	
entrance distance from IP (cm)	20	15	
gas density rel. LHD	< 1.5 %	3 %	
upper trigger scint.	4.9 x 6 cm^2	diameter 9 cm	
dist. from IP (cm)	6	13	
triggers per kaonpair	9.4 %	5.3 %	
K^- gasstops per kaonpair (triggered)	0.78 %	1.94 %	
Signal	827 $/pb^{-1}$	2035 $/pb^{-1}$	**2.5**
trigger per signal	188	39	**4.8**
synchr. continous backgr. /Signal /keV at ROI	0.3 %	0.08 %	**3.8**
KC / Signal (kaonic lines from wall stops)	4 %	0.2 %	**20**
SDD timing resolution (ns)	750	500	**1.5**

Table 1: Compilation of features due to changed geometry and gas density. Region of interest (ROI) 7-10 keV



(A)	SIDDHARTA-2 new geometry & gas density	SIDDHARTA-2 with K± discrimination. 2 ns gate-start	improvement
triggers per kaonpair	5.3 %	2.12 %	
Signal	2035 /pb^{-1}	1628 /pb^{-1}	**0.8**
trigger per signal	39	20	**2.0**
synchr. cont. backgr. /Signal /keV at ROI	0.08 %	0.04 %	**2**

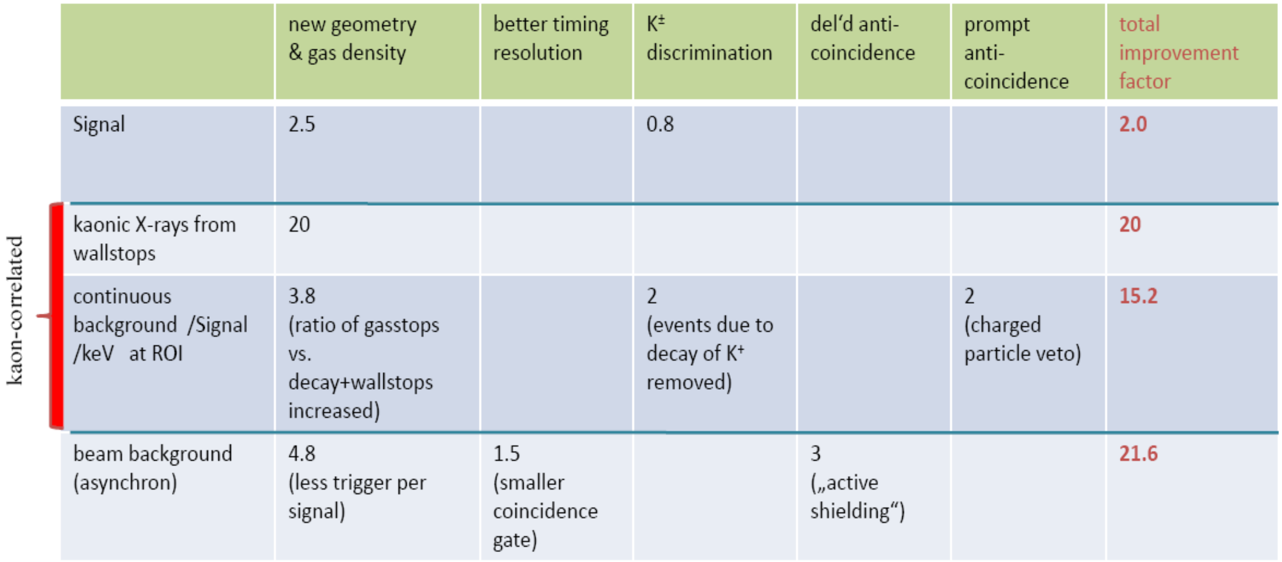
(B)		SIDDHARTA-2 del'd anticoincidence	improvement
beam background	1	0.33	**3**

(C)		SIDDHARTA-2 prompt topological anticoincidence	improvement
synchr. continous backgr. /Signal /keV at ROI	0.08 %	0.04 %	**2**

Table 2: Compilation of improvements due to (A) K^+-discrimination : ~ half of the events can be rejected right away, because the K^- was going downwards; (B) delayed anticoincidence: if during the K^-X coincidence width (~500 ns, but 2 ns after the kaon stop) a hit on the active shielding counters is detected, the SDD hit is most likely originated by beam background and can be discarded; (C) prompt „topological“ anticoincidence: the synchronous (kaon-correlated) continuous background in the SDDs is mainly produced by charged particles of which a small fraction can produce signals in the keV range. If an charged particle is detected in the active shielding anticoincidence counter a nearby fired SDD („topological“) could be discarded, because the signal was most likely not a good X-ray event.

Chapter 5 – Summary of gain factors for SIDDHARTA-2

In order to do evaluate the gain factors and the required luminosity to perform the K^{-}d measurement, we assumed as input parameters a factor 10 smaller yield of K^{-}d with respect to K^{-}p and a factor 2 larger width. One can say that in order to obtain with K^{-}d a signal of similar quality as the one obtained with K^{-}p in Sep. 2009, we need to compensate for the assumed reduced yield and the assumed enlarged width of K^{-}d, which make the signal height to be reduced by a factor of approximately 20! Therefore, to make up for the expected reduced signal strength we need all the improvements described above and an integrated luminosity of about 600 pb^{-1}. In table 3 the final numbers are summarized.



	new geometry & gas density	better timing resolution	K$^{\pm}$ discrimination	del'd anti-coincidence	prompt anti-coincidence	total improvement factor
Signal	2.5		0.8			**2.0**
kaonic X-rays from wallstops	20					**20**
continuous background /Signal /keV at ROI	3.8 (ratio of gasstops vs. decay+wallstops increased)		2 (events due to decay of K^{+} removed)		2 (charged particle veto)	**15.2**
beam background (asynchron)	4.8 (less trigger per signal)	1.5 (smaller coincidence gate)		3 („active shielding“)		**21.6**

Table 3: As shown in the rightmost column, a reduction factor or ~ 20 in background /signal looks feasible. To obtain enough statistics in the signal events, the factor 2 (see first line) helps, but enough integrated luminosity of about 600 pb^{-1} is necessary.

In figure 13 the simulated K^-d energy spectrum is shown. Under the described assumptions the shift can be determined with a precision of about 40 - 50 eV and the width with about 150 eV.

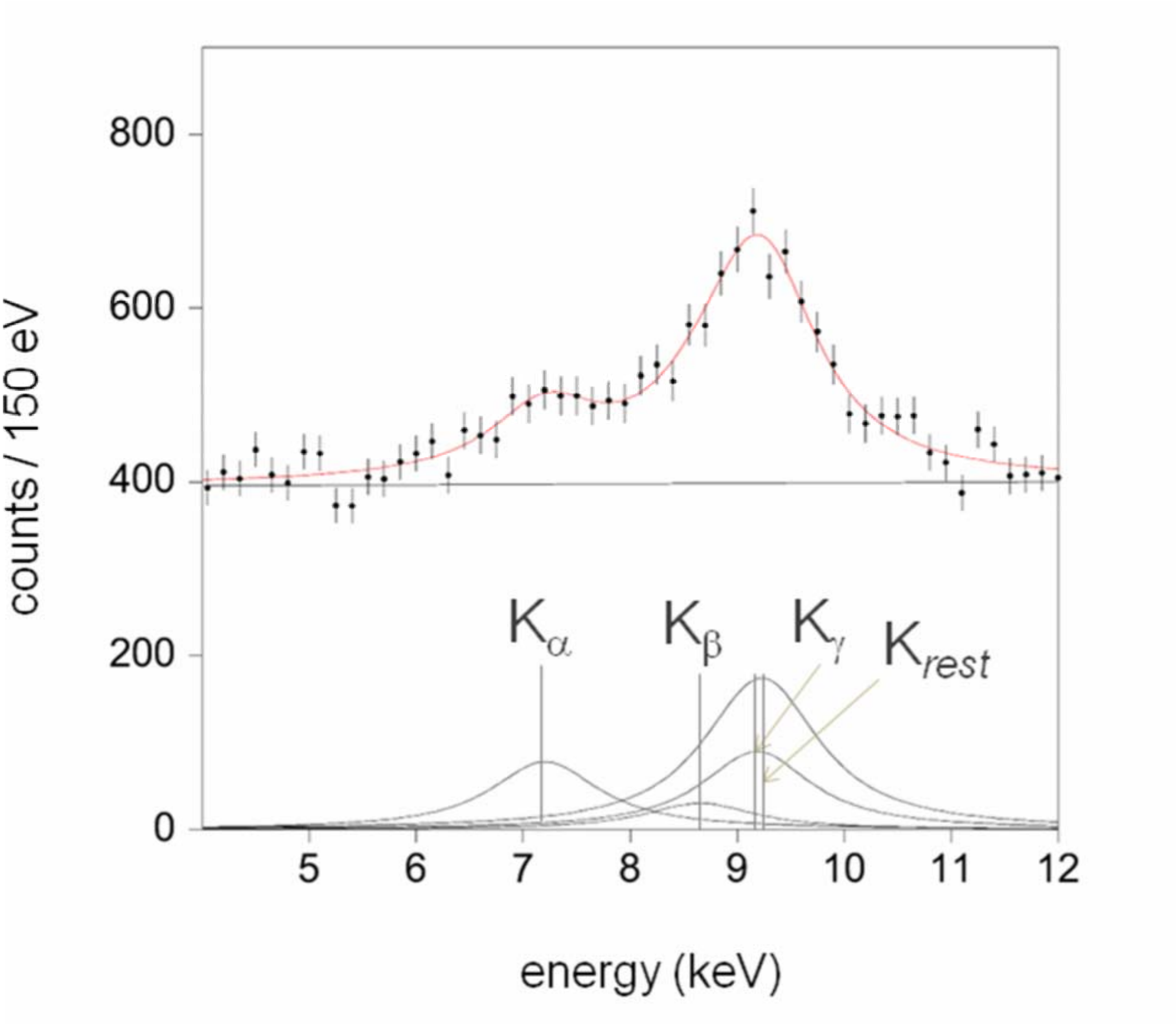
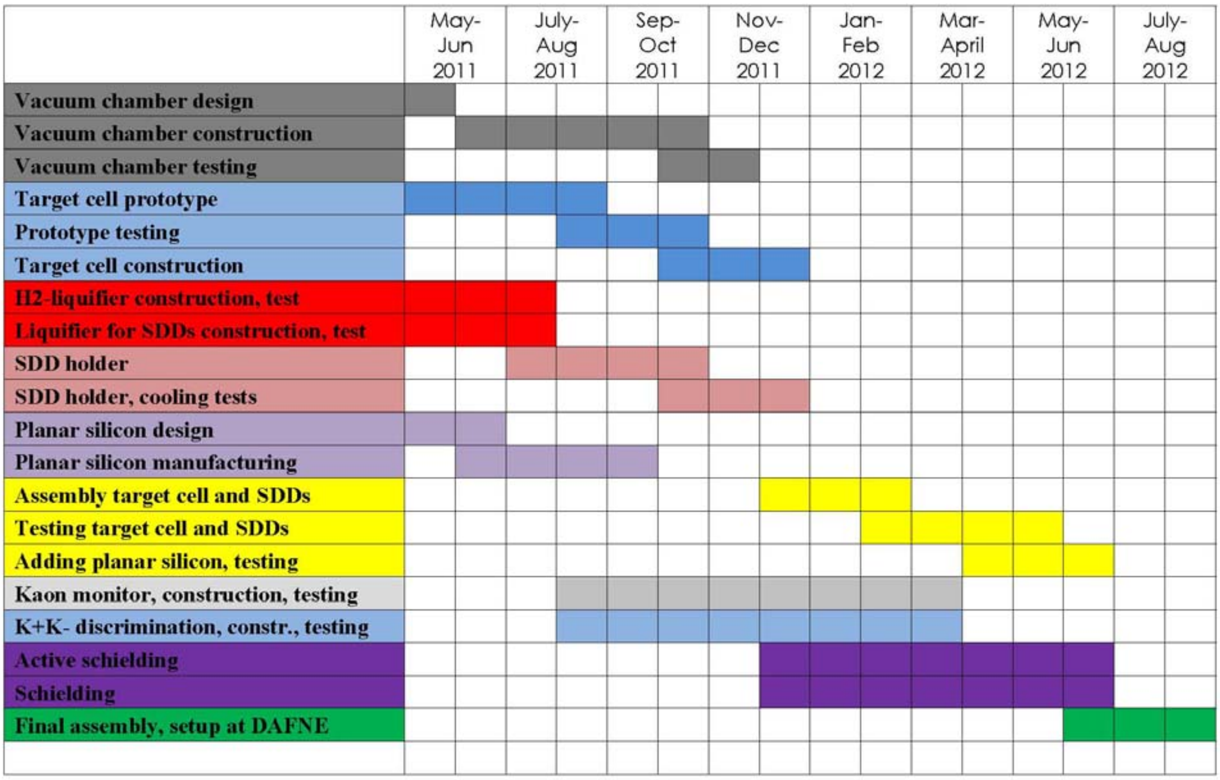


Figure 13: Fig. 7: MC simulation of the expected K^-d spectrum taking the SIDDHARTA measurement into account. For an integrated luminosity of 600 pb^{-1} the shift could be extracted with a precision of about 40-50 eV and the width with about 150 eV.

Chapter 6 –Time table and beam time request

The anticipated time table for the realization of the SIDDHARTA-2 setup is shown in the table below. According to this plan SIDDHARTA-2 will be ready to start data taking by September 2012.



	May-Jun 2011		July-Aug 2011		Sep-Oct 2011		Nov-Dec 2011		Jan-Feb 2012		Mar-April 2012		May-Jun 2012		July-Aug 2012	
Vacuum chamber design	■															
Vacuum chamber construction		■	■	■	■	■										
Vacuum chamber testing						■	■									
Target cell prototype	■	■	■	■												
Prototype testing				■	■	■										
Target cell construction						■	■	■								
H2-liquifier construction, test	■	■	■													
Liquifier for SDDs construction, test	■	■	■													
SDD holder			■	■	■	■										
SDD holder, cooling tests						■	■	■								
Planar silicon design	■	■														
Planar silicon manufacturing		■	■	■	■											
Assembly target cell and SDDs								■	■	■						
Testing target cell and SDDs										■	■	■	■			
Adding planar silicon, testing												■	■	■		
Kaon monitor, construction, testing				■	■	■	■	■	■	■	■					
K+K- discrimination, constr., testing				■	■	■	■	■	■	■	■					
Active schielding								■	■	■	■	■	■	■		
Schielding								■	■	■	■	■	■	■		
Final assembly, setup at DAFNE														■	■	■

In order to measure the shift and width of the K-d with a precision of approximately 40 eV and 150 eV respectively, we request an integrated luminosity of 600 pb^{-1}. Our beam time request is based on Monte Carlo simulations using as input the, to our knowledge, most realistic values for the K-d level width.

Chapter 7 – Conclusions and outlook

The experimental case of the kaonic deuterium measurement is the object of the present report. We are confident that with the planned setup improvements and with an integrated luminosity of 600 pb^{-1}, SIDDHARTA-2 will be able to perform a first X-ray study of the strong interaction parameters - the energy displacement and the width of the kaonic deuterium ground state – data which are eagerly awaited by theoreticians. The shift will be determined with a precision of 40 – 50 eV (expected shift 800 – 1000 eV) and the width with 150 eV (expected width 1000 eV).

Together with the results of the kaonic hydrogen measurement performed by SIDDHARTA, the kaonic deuterium one will allow to extract the isospin-dependent antikaon-nucleon scattering lengths, with all the important implications (see chapter 2 for a short overview).

Of course, the K^-d measurement is very challenging concerning the technical and the beam issues (new Interaction Region, beam time assignment and interference with KLOE2) but we want to stress once more that SIDDHARTA-2 will be a unique measurement, fundamental to understand the behaviour of strong interaction in "three dimensions" in flavor space (i.e. with strangeness thus beyond the well-studied pion-nucleon sector), entering a new era. We and all the community working in the field (there is a dedicated Network, LEANNIS-WP9 in HadronPhysics2 Program of EU FP7) are confident that SIDDHARTA-2 will be a powerful combination of an experienced and active community with a world-wide unique kaon source and optimized techniques. This window of opportunity should be realized.

We underline that SIDDHARTA-2, as a top level experiment, performed within a collaboration of mainly young scientists, has added values: SIDDHARTA-2 provides based on the physics fields involved, time and human scales, a real school for young scientists – where they can get trained and start their career in best possible conditions.

Finally, it has to be pointed out that the SIDDHARTA-2 collaboration has plans and the necessary man power to extend the range of measurements to kaonic helium (3 and 4, to 1s and

2p levels) and to heavier targets, and will contribute so to the solution of old pending puzzles (see SIDDHARTA Proposal). A new measurement of the charged kaon mass – with far reaching implications in sectors of particle and fundamental physics – are also included in the ambitious goals of SIDDHARTA-2 which will lead to a many years time schedule with a modular strategy having as a first fundamental step – the kaonic deuterium measurement – to which this report was dedicated.

SIDDHARTA-2 is a broad international collaboration, having worldwide recognized representatives in the experimental sector of exotic atoms physics. The scientific programme is pursued in collaboration with the best theoreticians working in the field.

SIDDHARTA-2 is, as well, taking full advantage of two of the HadronPhysics2 FP7 initiatives: the LEANNIS WP9 Network, and the SiPM WP28 Joint Research Activity. We just learned in addition that the new HadronPhysics3 program was successful; it does contain dedicated activities to the kaonic atoms physics (continuation and upgrade of LEANNIS) and detectors and is going to be active in the time window of SIDDHARTA-2.

In summary the SIDDHARTA-2 experiment has the huge potential to be **the decisive experiment** in the sector of kaonic atoms measurements. Such measurements are **fundamental in understanding the low-energy strong interaction with strangeness**.