KAMPAI - Kaonic, Antiprotonic, Muonic, Pionic and “onia” exotic Atoms: Interchanging knowledge and recent results

Experimental challenges in study kaon-nucleon interaction at low energy at DAΦNE collider

Florin Sirghi on behalf of

SIDDHARTA-2 Collaboration

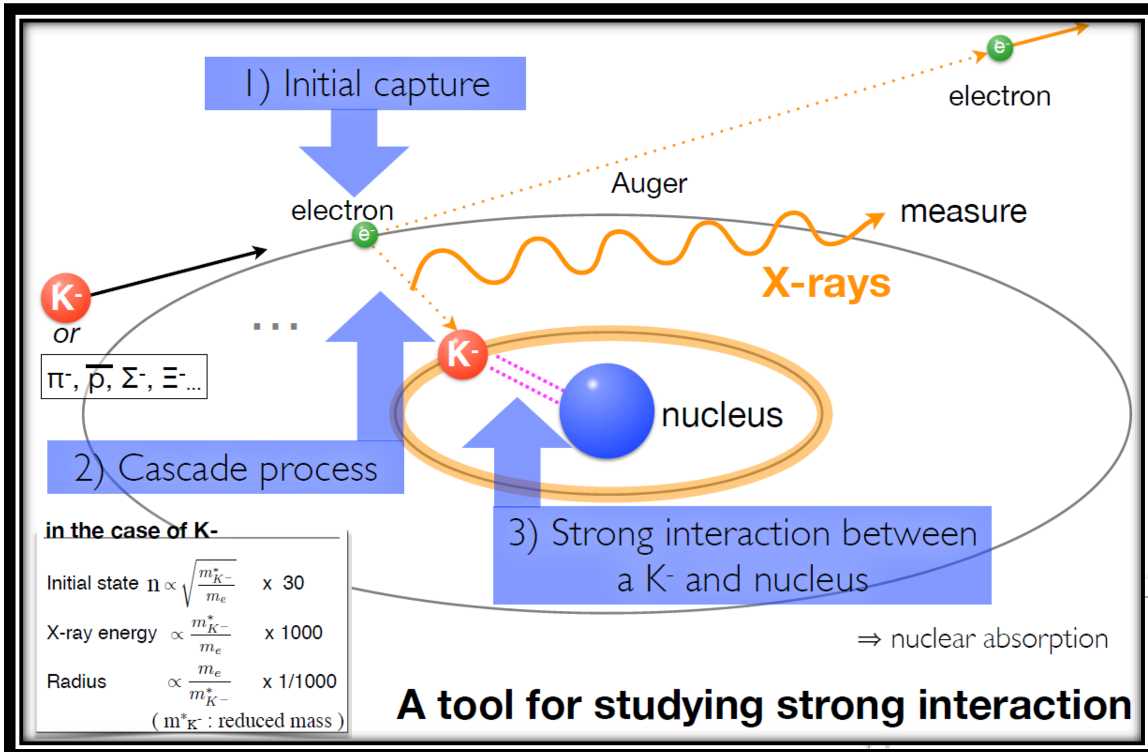
ECT* Trento, 30 October-4 November 2024

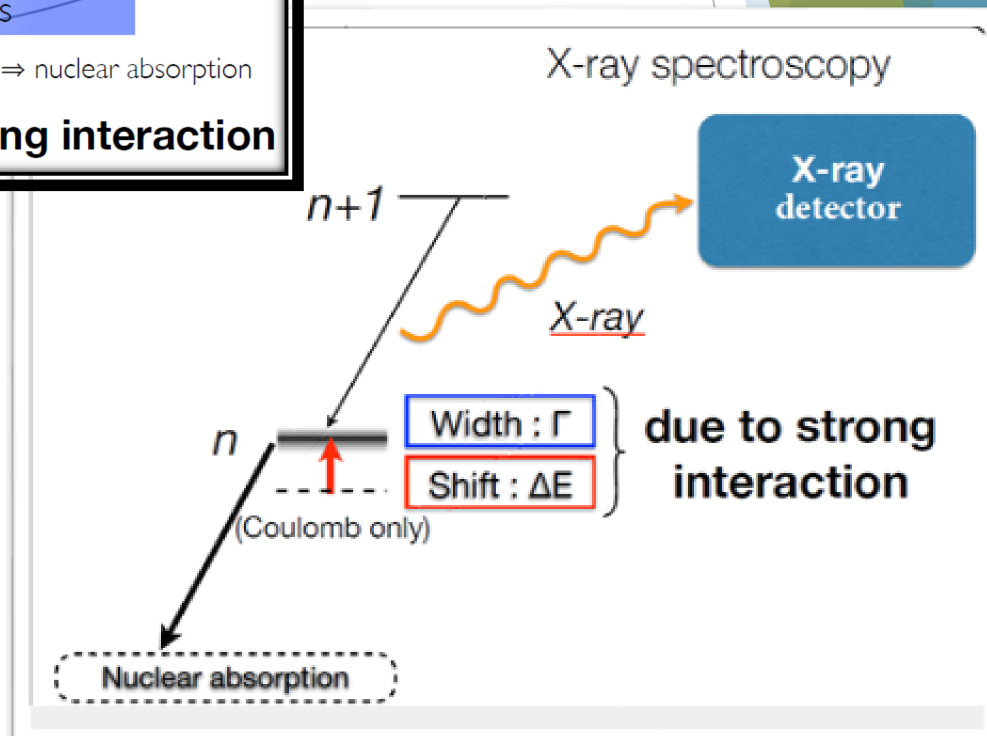
INFN Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

KAONIC ATOMS RESEARCH

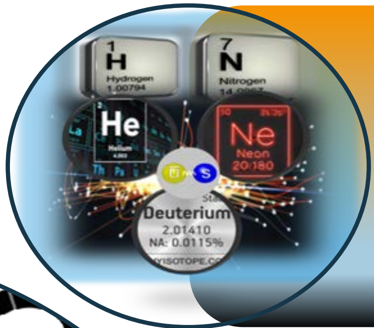
Kaonic atoms are formed by stopping a *negatively charged kaon* in a target medium

H, He, D, N, …
Li, Be, C, Al, …

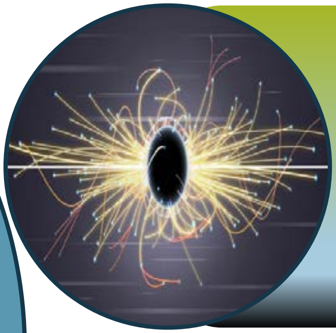




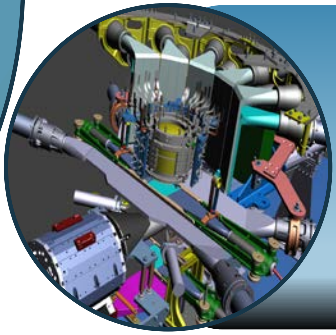
Strong interaction induced width Γ and shift ε obtained by measuring the X-rays emitted



IDEAS



Kaon Beam

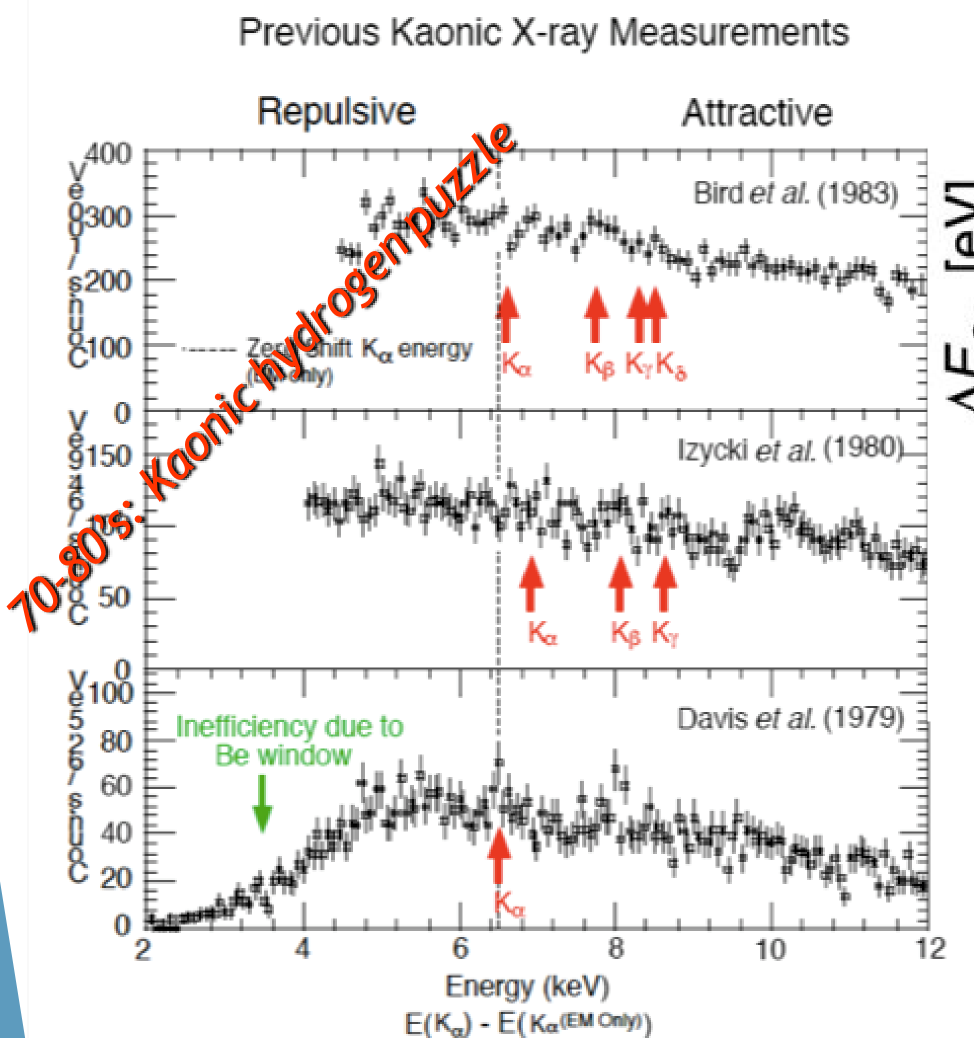


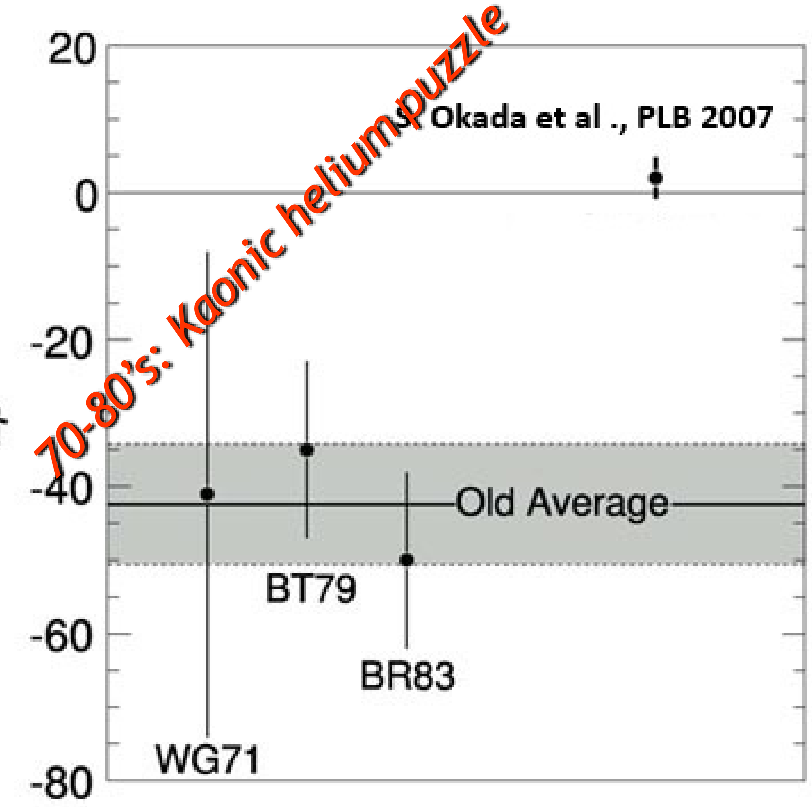
Experimental setup

Motivated TEAM

IDEAS

The study of exotic atoms were started by E. Fermi and E. Teller (1940), who postulated the existence of muonic atoms. Characteristic X-rays from pionic and muonic atoms were identified in the early 1950s.



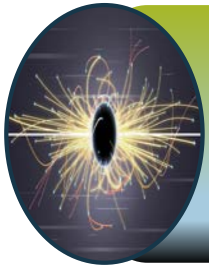


IDEAS

Carlo Guaraldo was the initiator of kaonic atoms studies at the DAΦNE collider

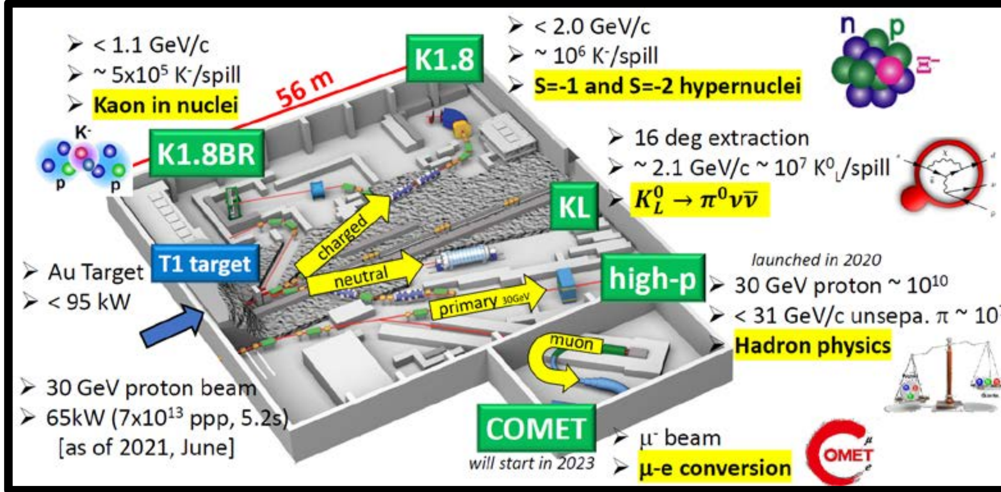
"The __most important experiment to be carried out in low energy K-meson physics today__ is the **definitive determination of the energy level shifts in the K^-p and K^-d atoms**, because of their direct connection with the physics of $\bar{K}N$ interaction and their complete independence from all other kinds of measurements which bear on this interaction".

R.H. Dalitz (1982)

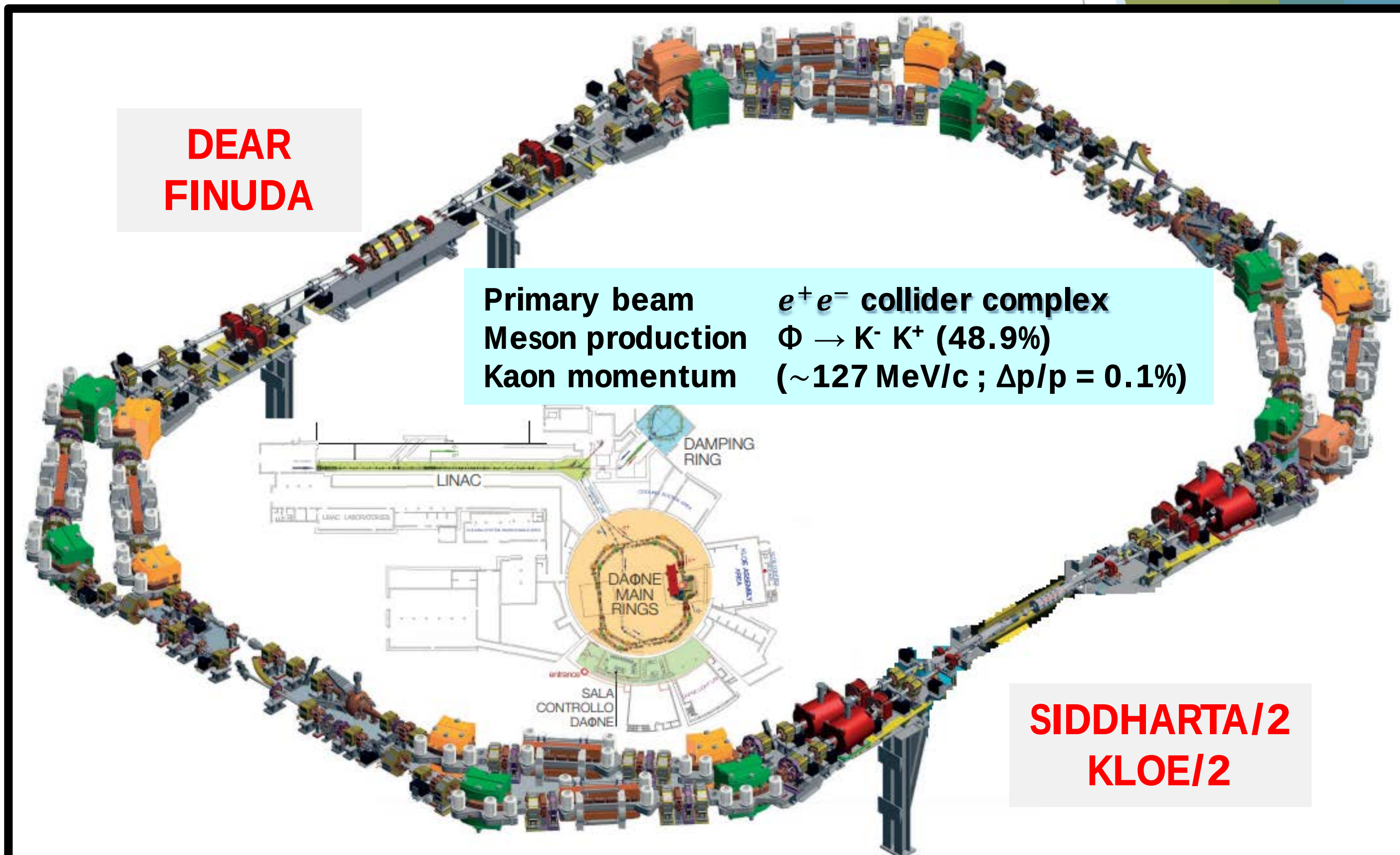


Kaon Beam

Primary beam:	30 GeV/c protons
Repetition cycle:	5 sec
Flat top:	3 sec
Production target:	Au
Kaon momentum:	1.2 GeV/c (max.)

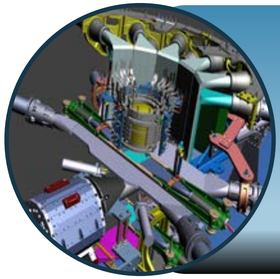


activities using the unique kaon beams available at J-PARC and DAΦNE.

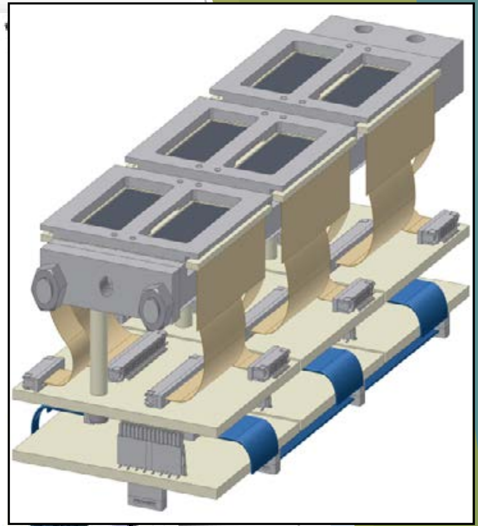


DAΦNE collider at LNF

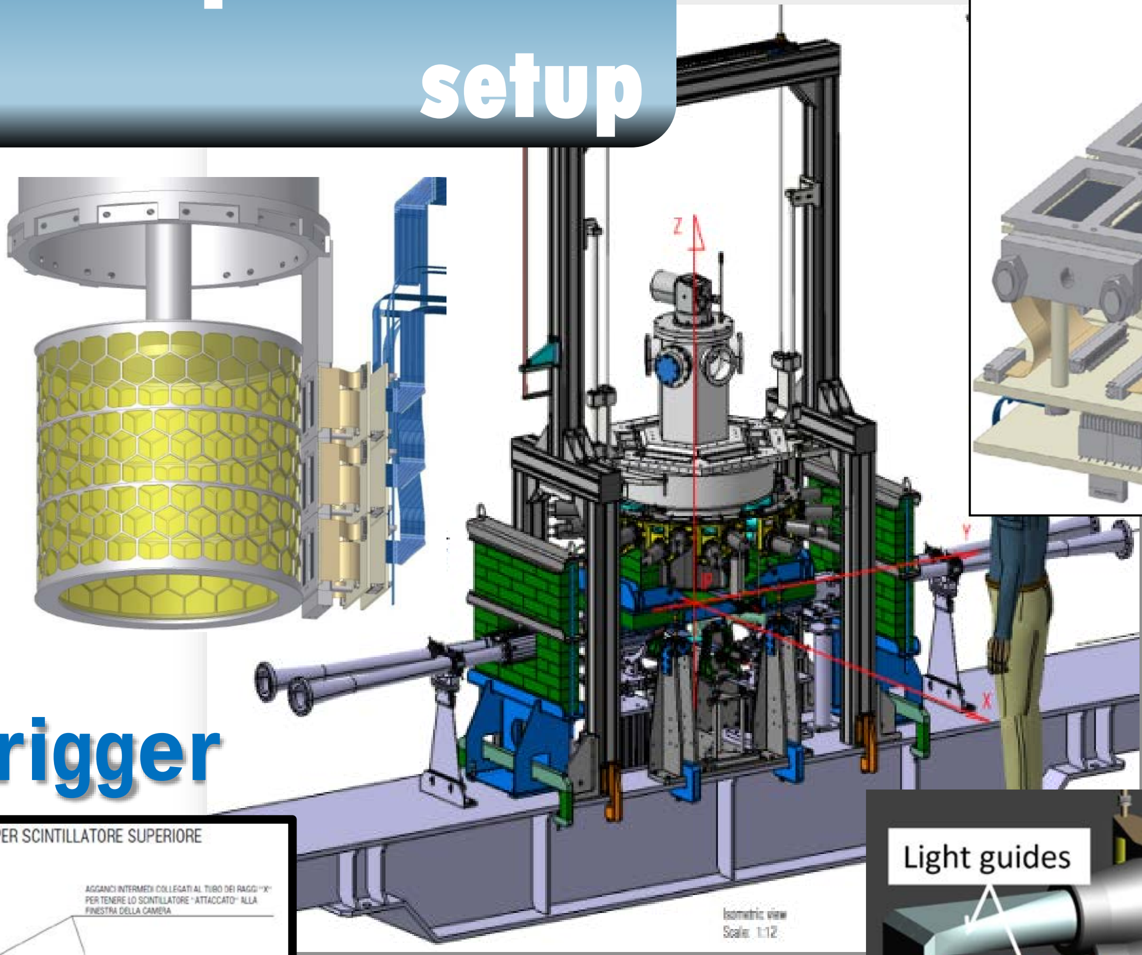
Experimental setup



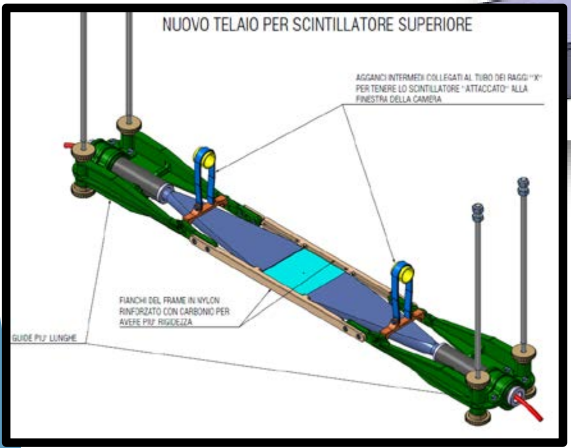
X-ray detector



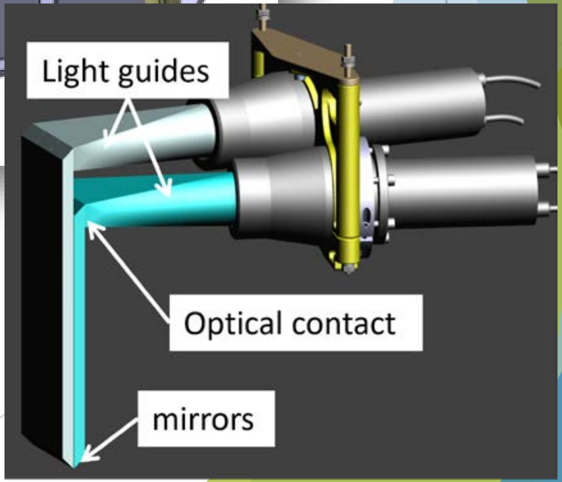
Target



Kaon Trigger



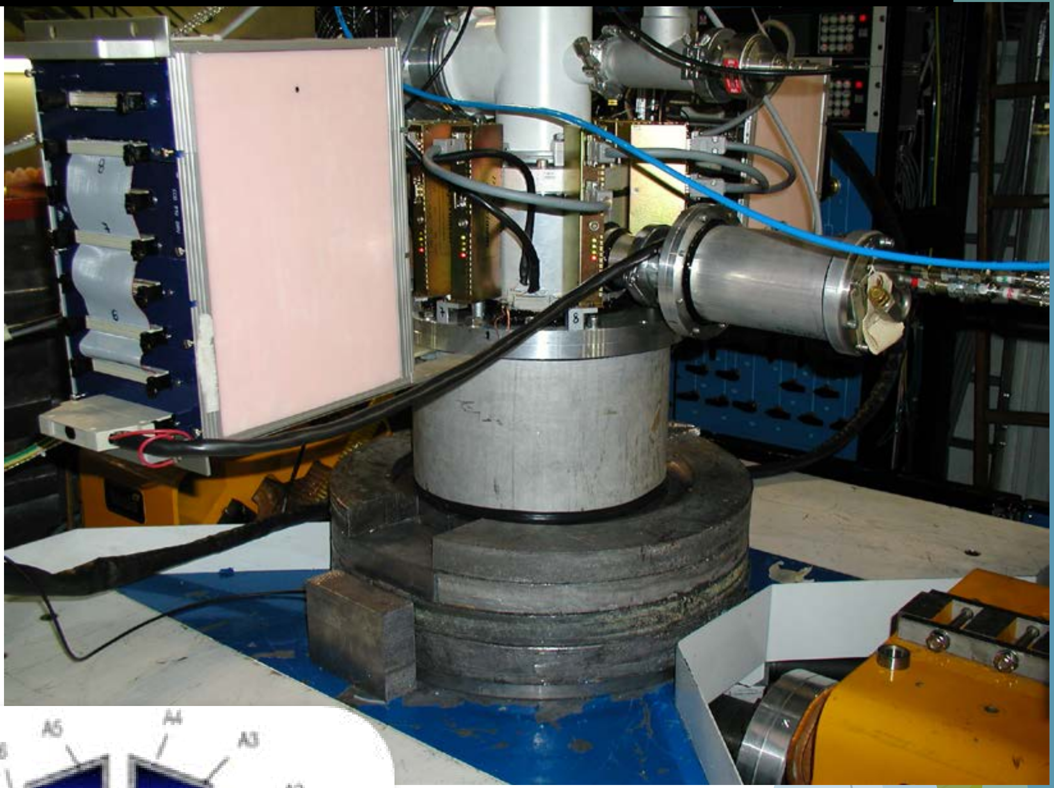
Veto systems

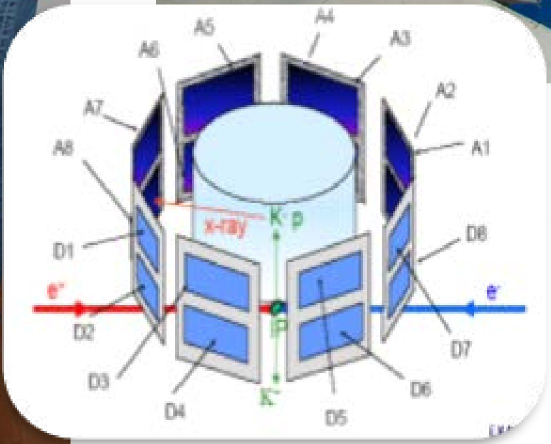


DEAR experiment (2001 - 2005)

(DAΦNE Exotic Atom Research) *kaonic hydrogen, kaonic nitrogen*

Detector technology: Charge Coupled Device (CCD)





CCD55-30 Marconi Applied Technologies
1152 x 1242 pixels / chip
pixel size 22.5 x 22.5 μm
total area per chip 7.24 cm^2
depletion depth ~ 30 μm
read-out time per CCD 120 sec.
energy resolution ~150 eV @ 6keV
temperature stabilized ~ 165 K

Charge Coupled Device (CCD)

X-ray detection
with CCDs

J.-P. Egger, EXA-02, Vienna

CCD pixel detectors
- CCD principle
- direct X-ray detection
- background
- energy resolution
- measurement time
- efficiency

Problems in soft X-ray detection:
- background } low signal
- windows (gas targets) } high background

Ideal detector: surface, energy + position
resolution, efficiency, background suppression
energy versus position mode

CCDs are excellent soft X-ray detectors!

but:
- limited energy range
- measuring time
- no trigger
- transparency of Si to X-rays

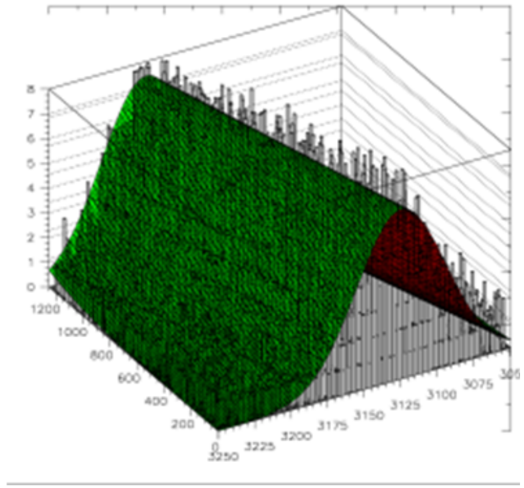
Charge Coupled Device (CCD)

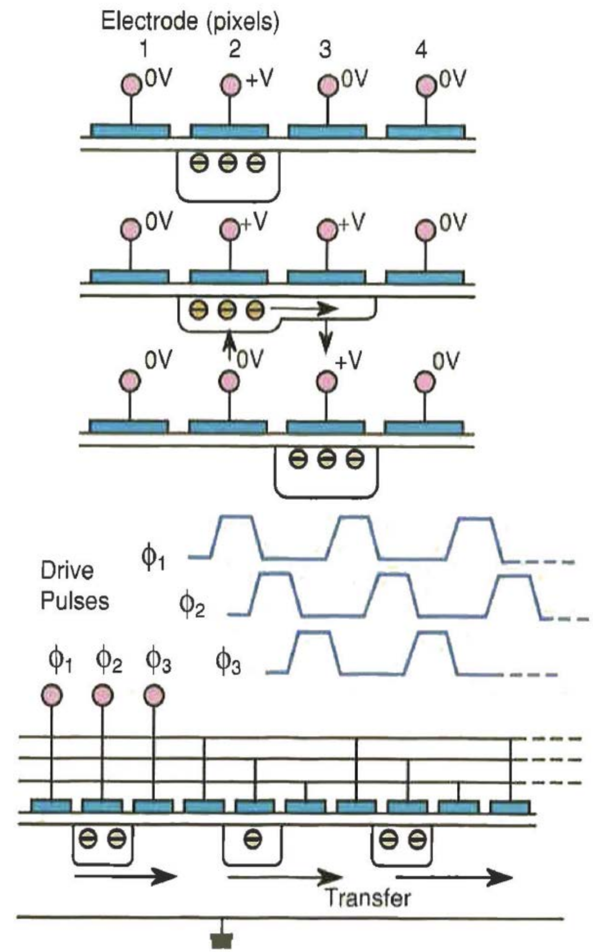
X-ray detector characterization:

- **temperature stability**
- **gain stability vs X-ray rates**
- **Good Energy resolution**
- **Linearity measurements**

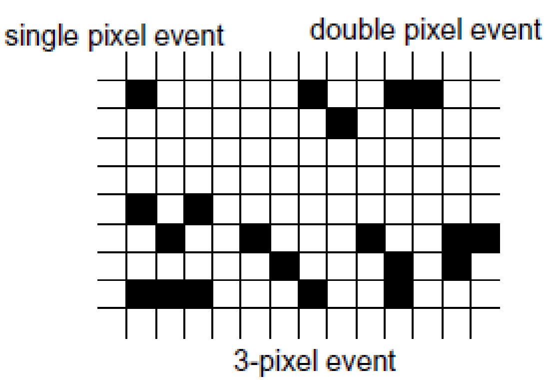
Charge transport correction

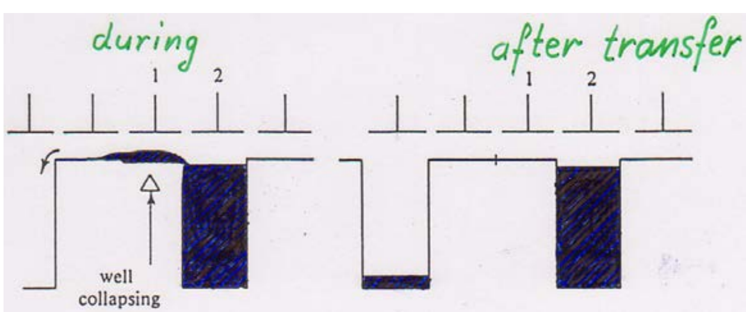
peak position vs pixel coordinates





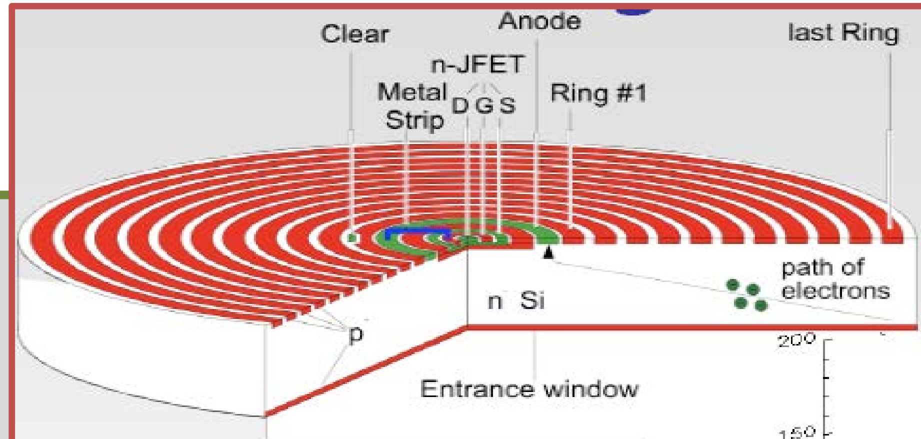
Topological selection for background reduction





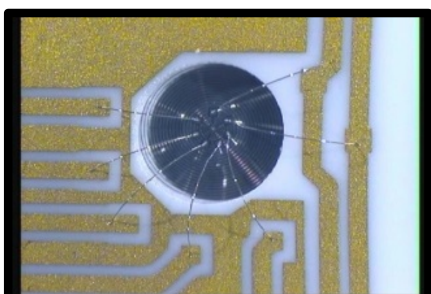
SIDDHARTA (2004 - 2010)
(SIlicon Drift Detectors for Hadronic Atoms Research by Timed Application)
KH, Kd, KHe^3, KHe^4
Detector technology : SIlicon Drift Detectors (first large area) with integrated JFET

PNSensor

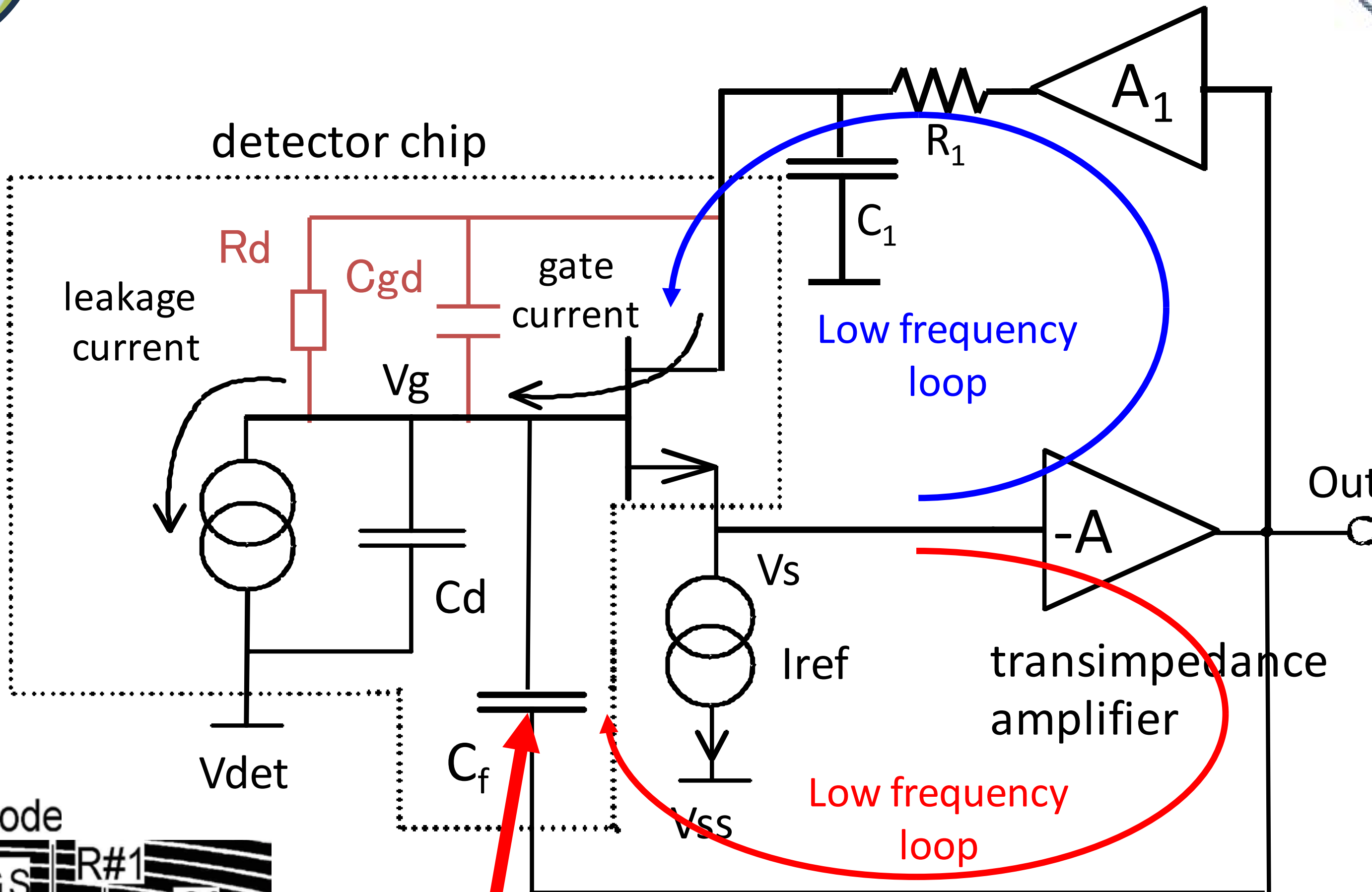


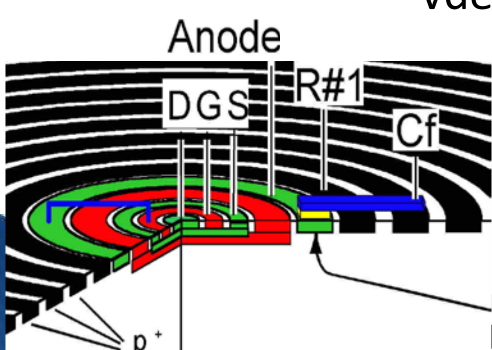
New x-ray detectors specially designed as well as readout electronics

energy range < 20 keV
energy resolution better than 150 eV (FWHM) at 6 keV;
stability and linearity better than 10^{-4};
Fast detector - > trigger system at the level of 1μs;
Operating in high radiation environment;
Custom topology – large active area (~ cm^2 / channel)



New SDD Charge Preamplifier configuration

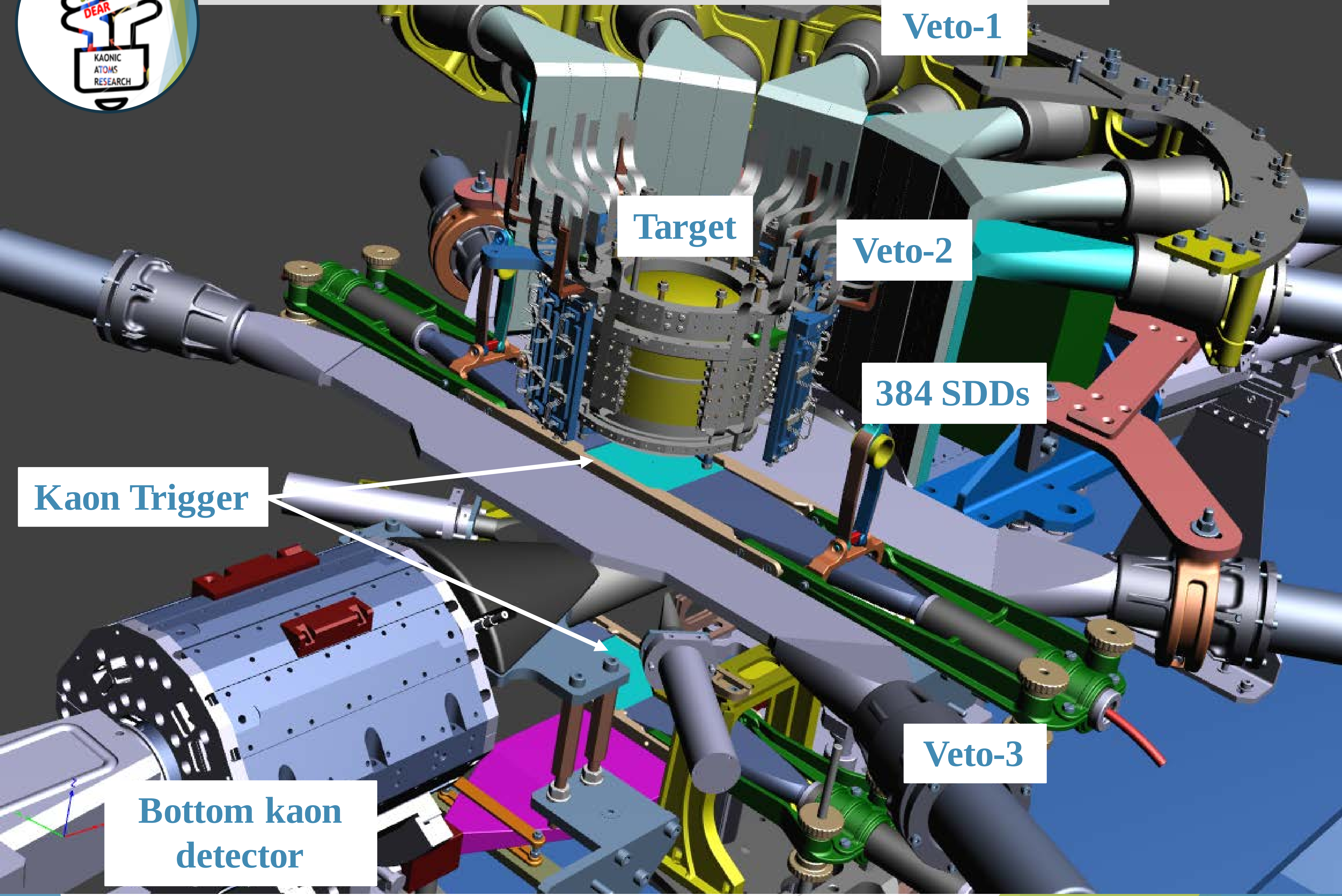




Integrated feedback capacitor

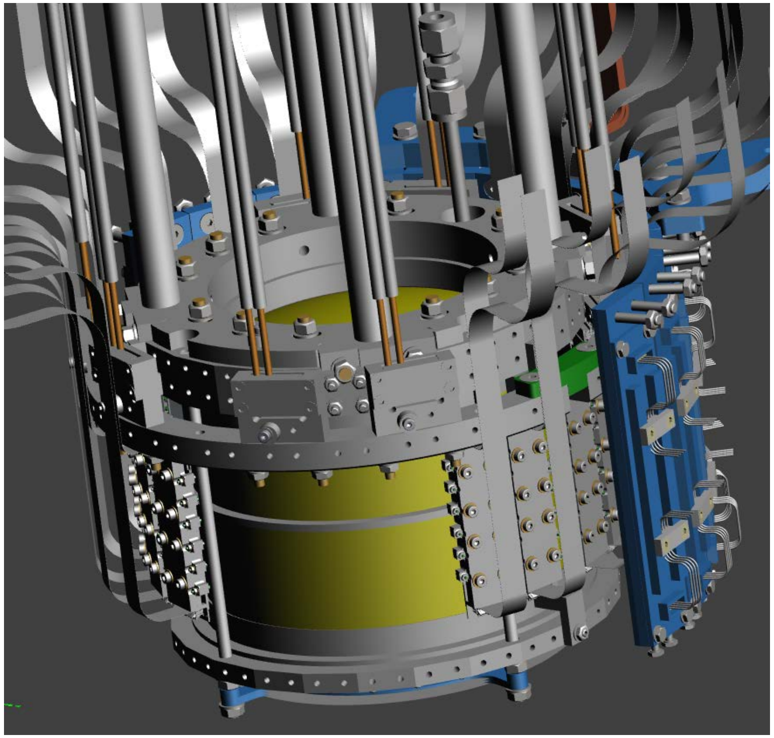
* World first application

SIDDHARTA-2 (2019 -2024)



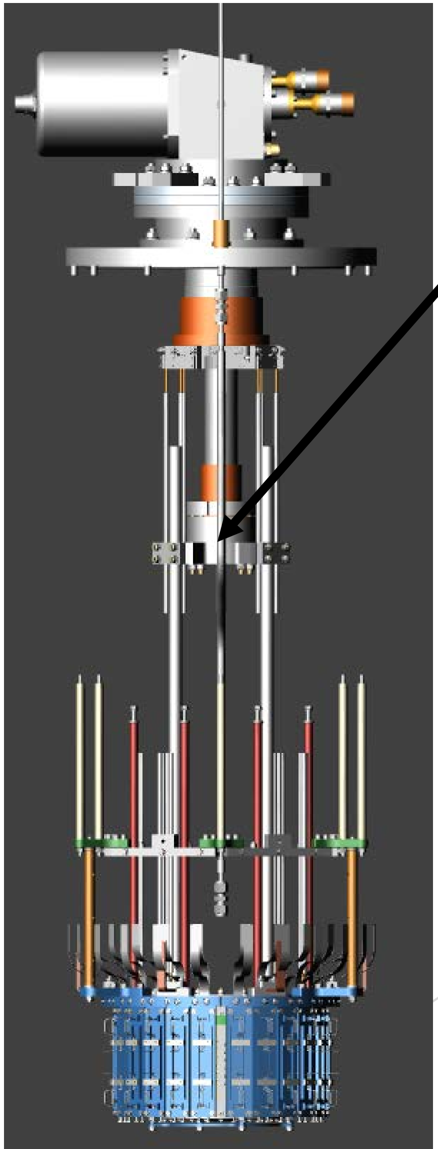
SIDDHARTA-2 setup: cryogenics

- ✓ new solutions for the cooling scheme - target separated from SDD
- ✓ Better control of target parameters (pressure, temperature, density,….)

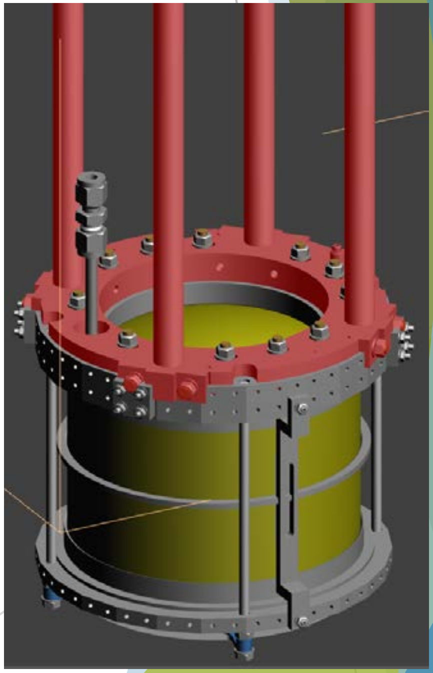


❖ Target + SDD cooling

Leybold MD10 - 18 W @ 20 K
target cell and SDDs are cooled
via ultra pure aluminum bars
T_{TC} = 20-30 K
T_{SDD} ~ 130 K

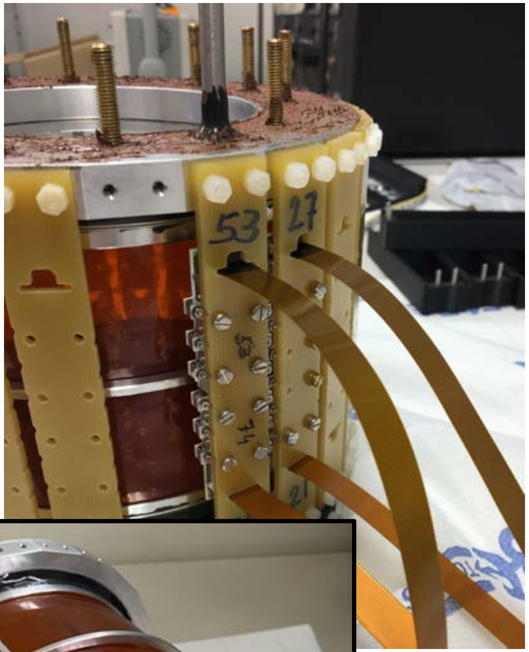


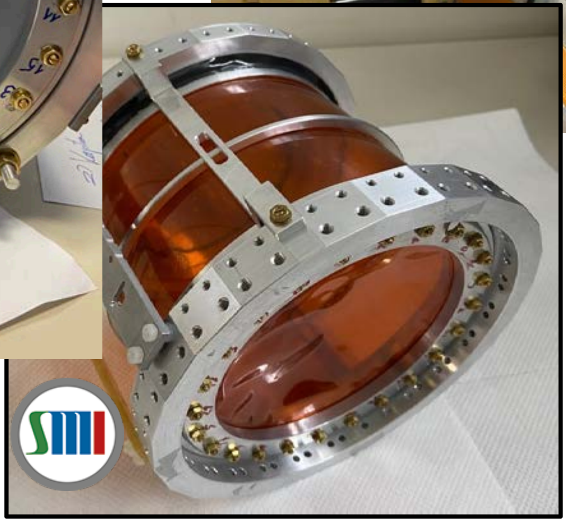
✓ Second stage dedicated to target cooling

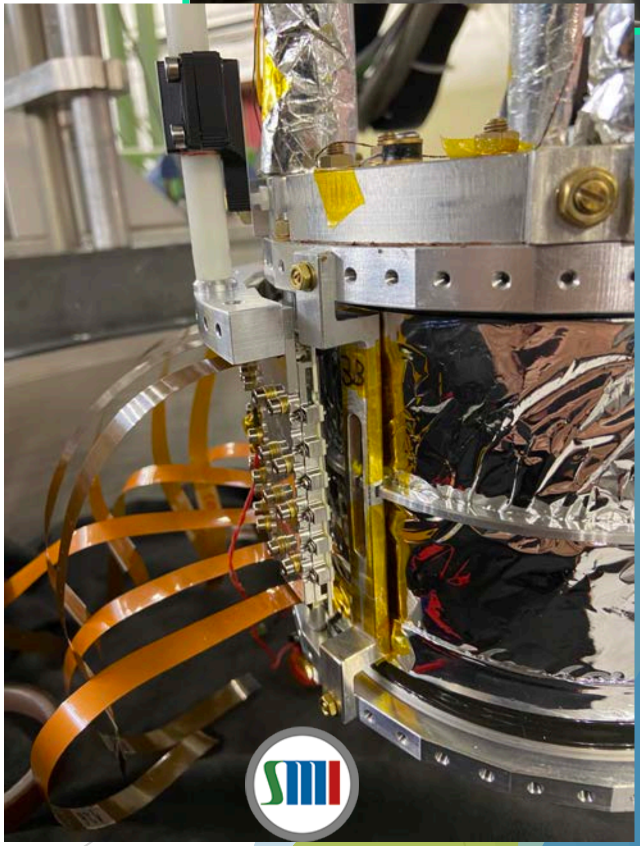


SIDDHARTA-2 setup: cryogenic targets

- ✓ **Selected materials in different configuration:**
  - **vacuum entrance windows**
  - **target walls**
  - **cooling supports**



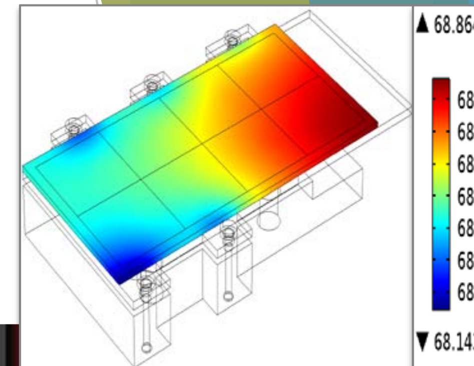




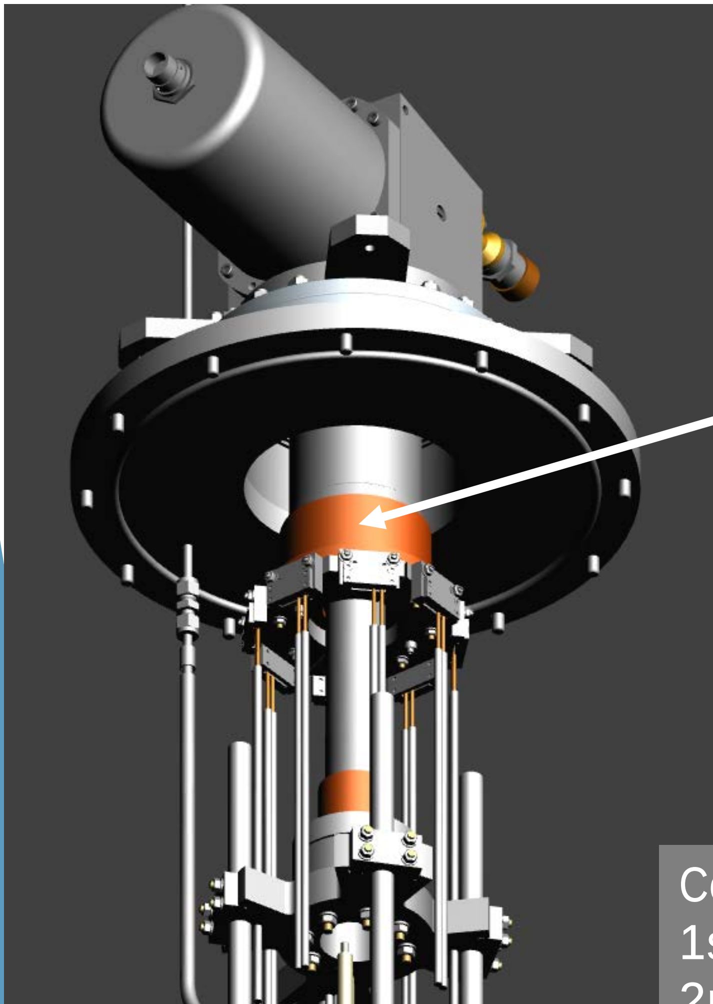
would eliminate Nitrogen and Oxygen contamination

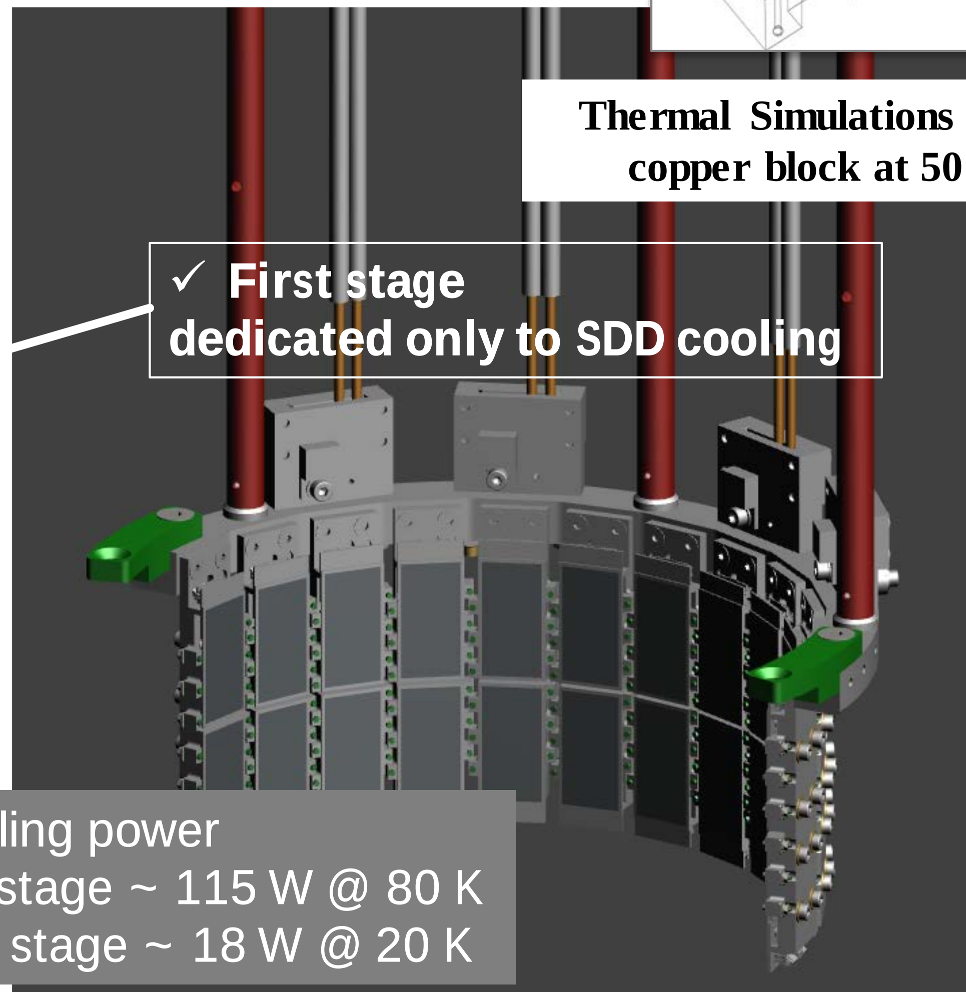
SIDDHARTA-2 setup: cryogenics

- ✓ Dedicated lines for SDD cooling
- ✓ Better control of target parameters
- ✓ (pressure, temperature, density,….)



Thermal Simulations with copper block at 50 K





✓ **First stage dedicated only to SDD cooling**

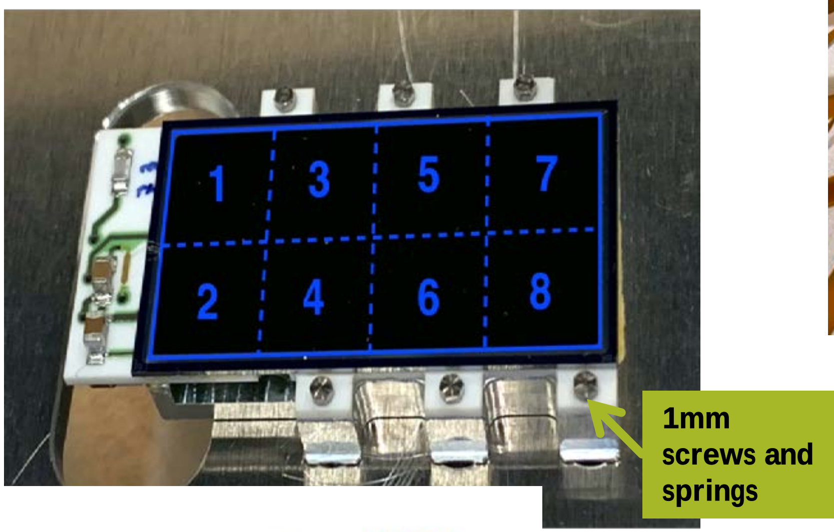
Cooling power
1st stage ~ 115 W @ 80 K
2nd stage ~ 18 W @ 20 K

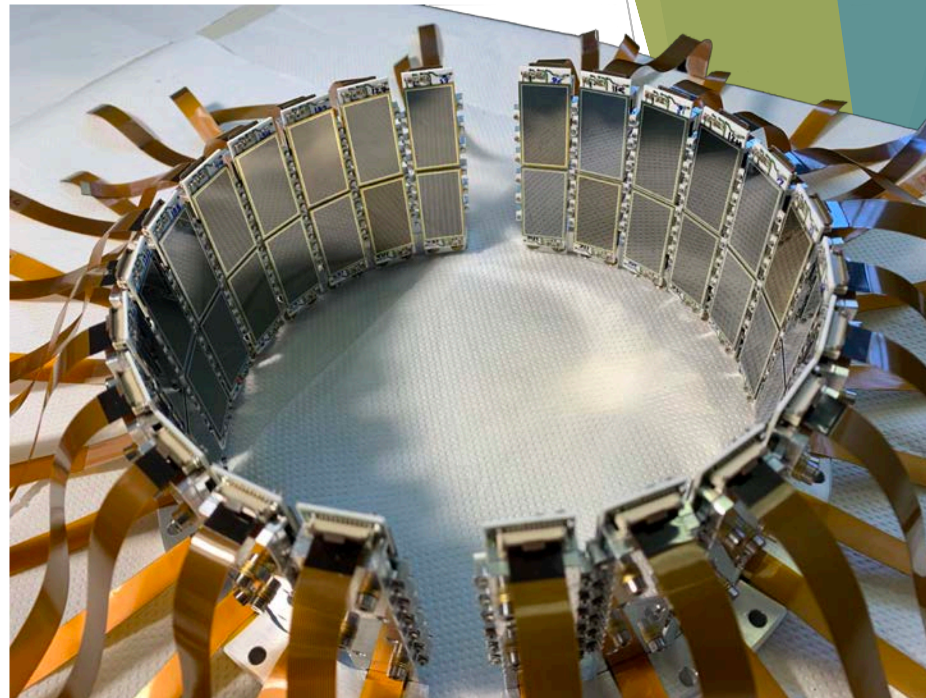
SDD with external CUBE preamplifier

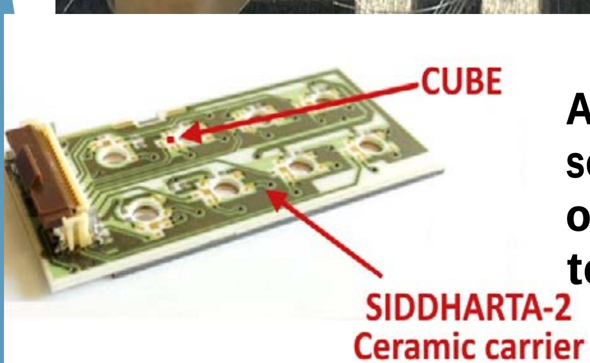
New monolithic SDDs arrays have been developed by Fondazione Bruno Kessler

new technology, lower production cost

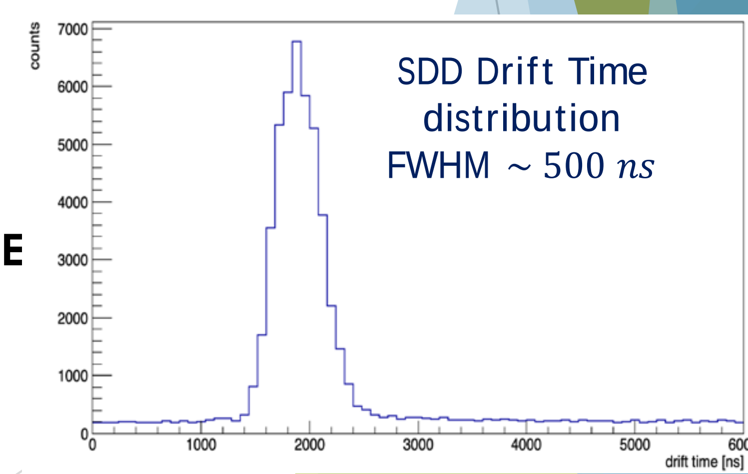
- **2x4 matrix SDD units (0.64 cm^2)**
- **active/total surface ratio of 0.75**



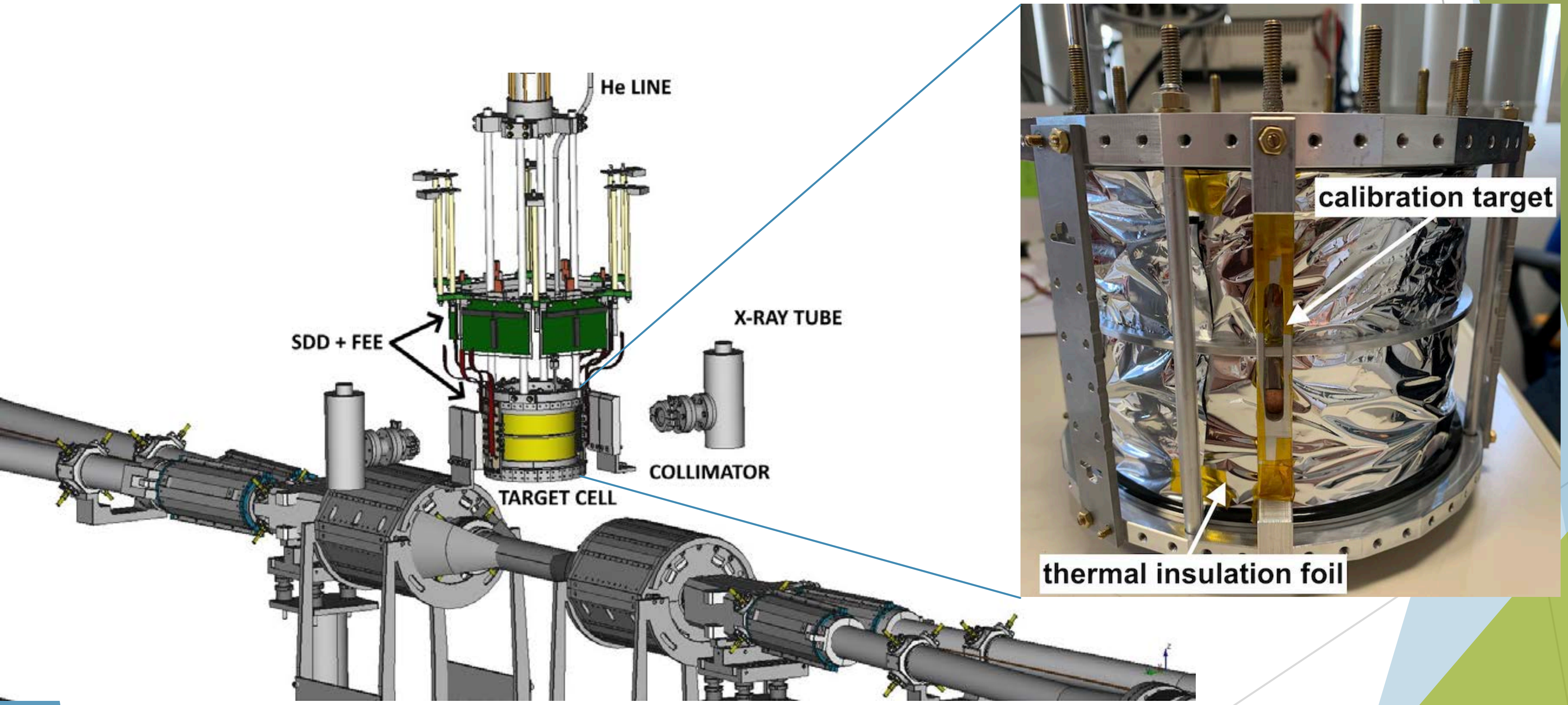




A CMOS low-noise charge sensitive preamplifier (CUBE operate at lower cryogenic temperature (up to 50k)

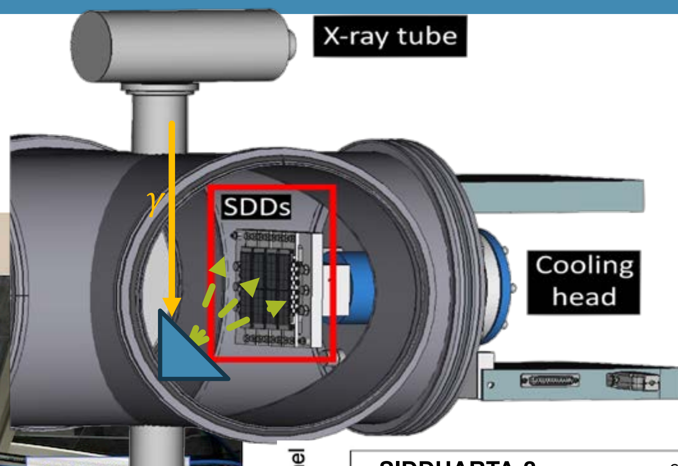


SDDs Calibration Procedure in DAΦNE



Silicon Drift Detectors (2020-2021) laboratory tests

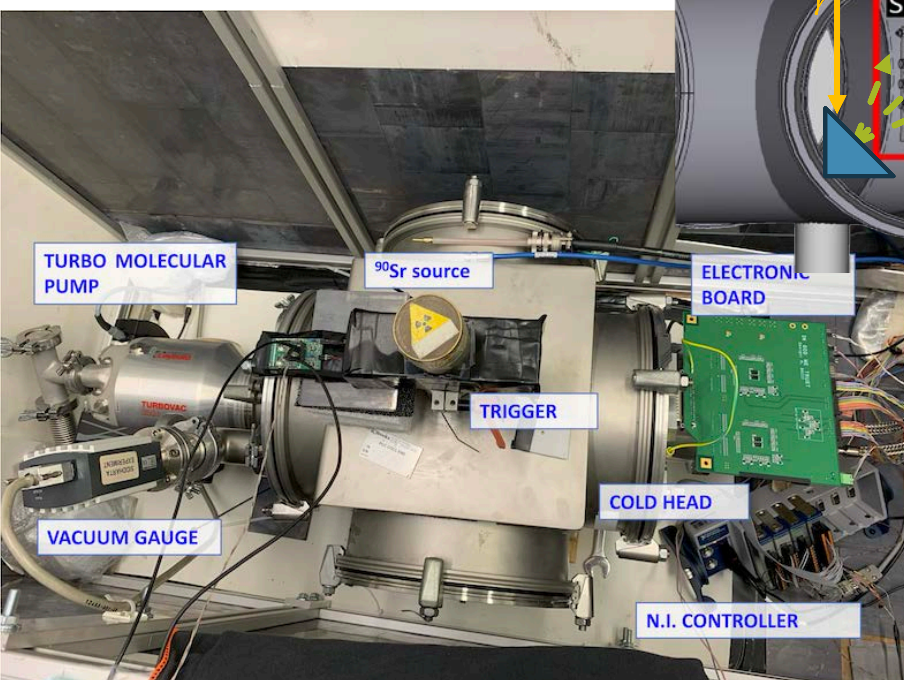
Characterization and optimization of the SDDs energy and time response in preparation for the SIDDHARTA-2 experiment

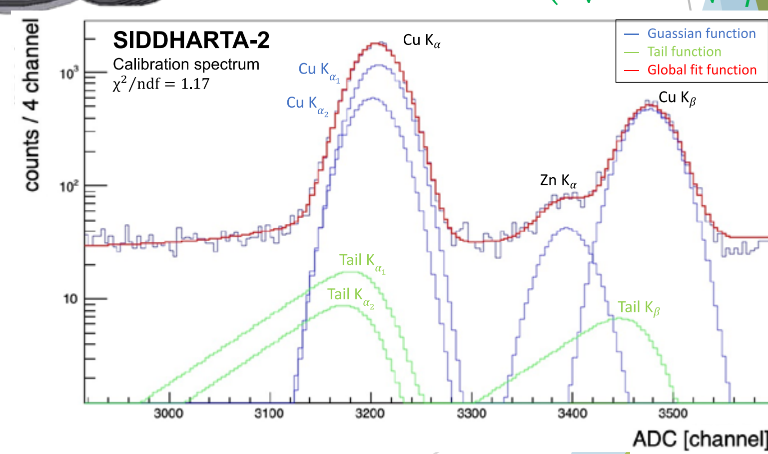


$$Gauss\ func.:\ H_G \cdot e^{\frac{-(x-x_0)^2}{2\sigma^2}}$$

$$\sigma = \sqrt{FF \cdot E \cdot \epsilon + \frac{noise^2}{2.35^2}}$$

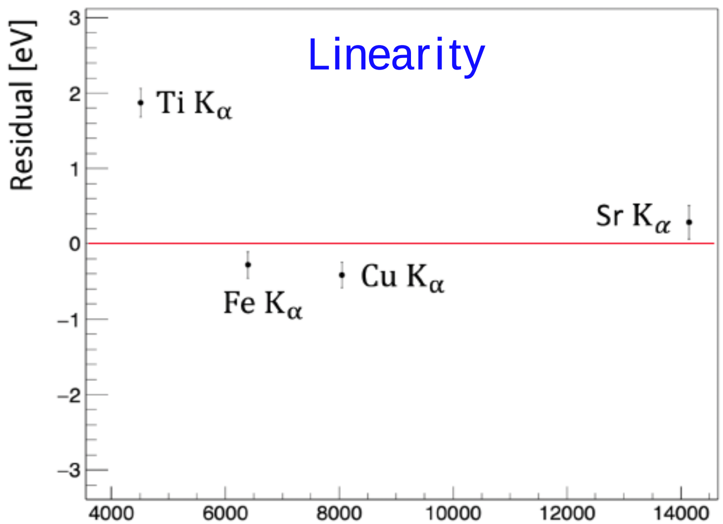
$$Tail\ func.:\ H_T \cdot e^{\frac{x-x_0}{\beta\sigma}+\frac{1}{2\beta^2}} \cdot erfc\left(\frac{x-x_0}{\sqrt{2}\sigma}+\frac{1}{\sqrt{2}\beta}\right)$$

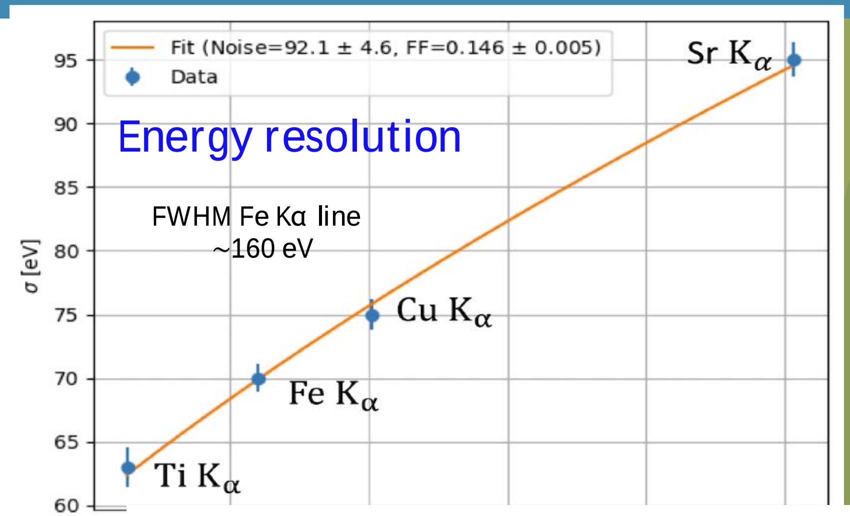


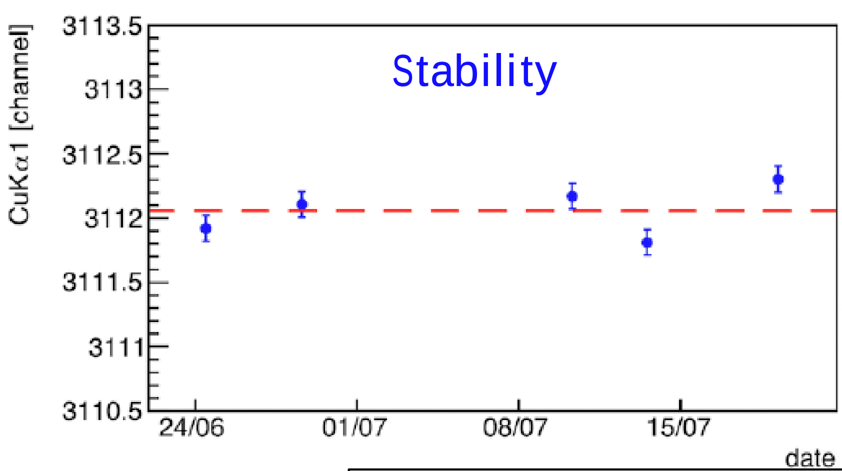


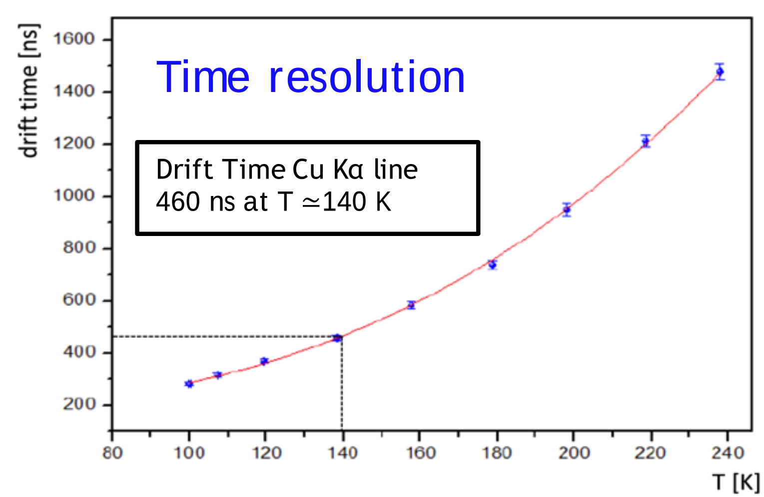
Silicon Drift Detectors spectroscopy response

The energy response is linear within few (<5 eV between 4 keV and 14 keV)
Excellent energy and time resolution @ 140 K

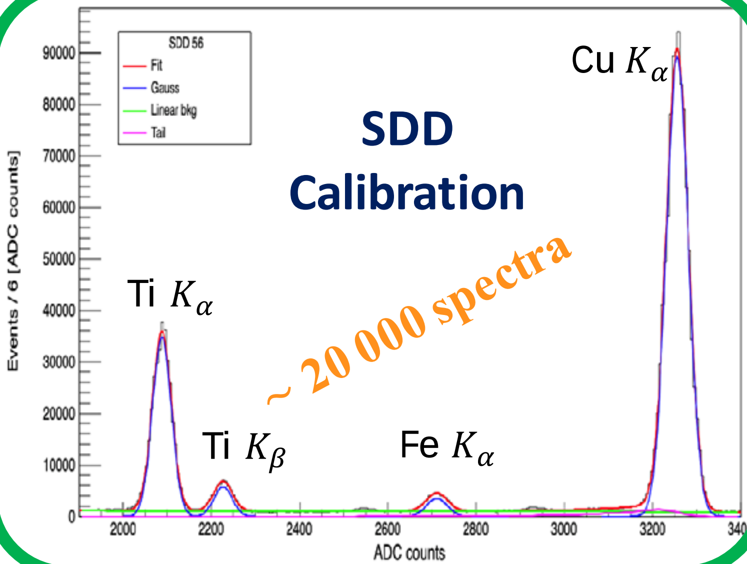




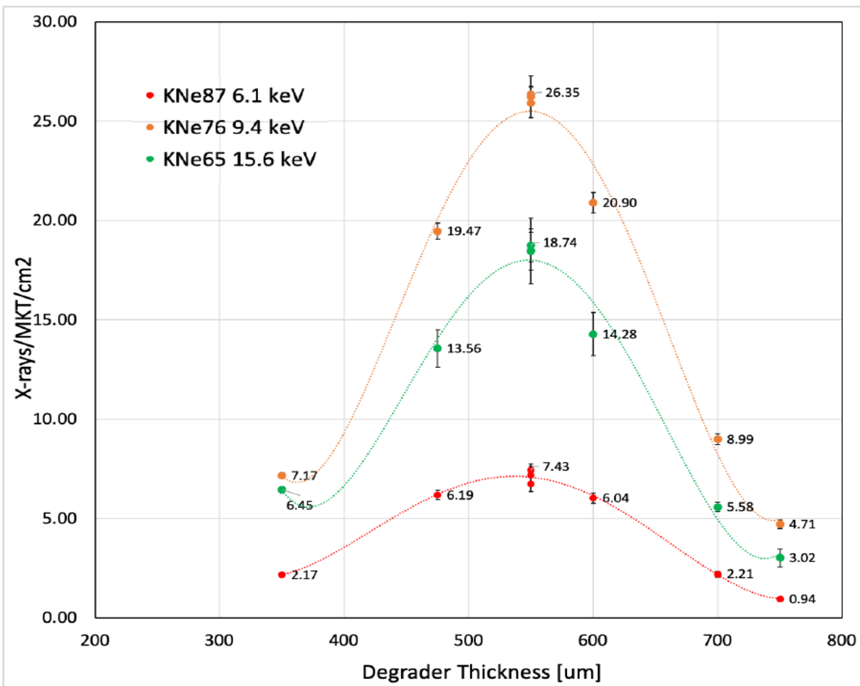


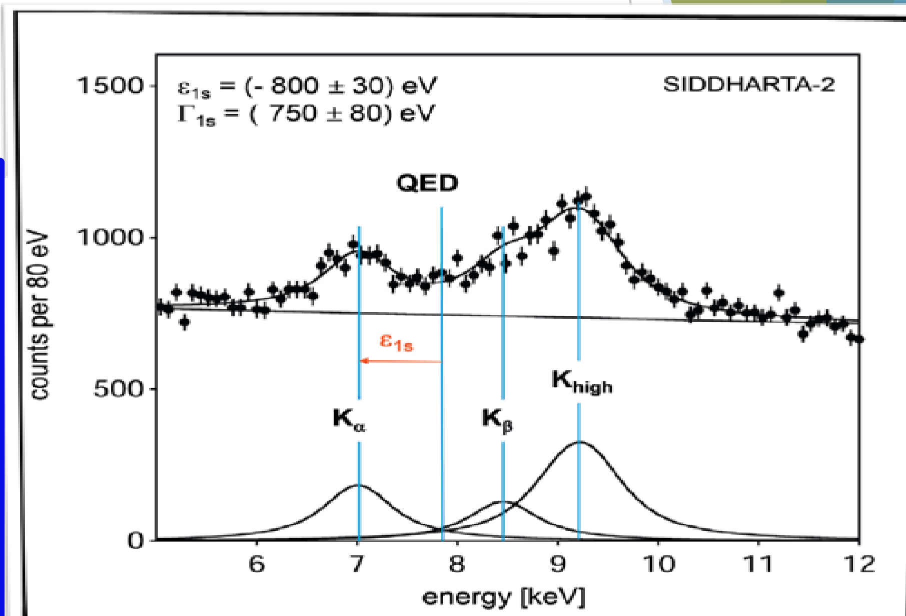


Miliucci M., Iliescu M., **Sgaramella F.,** et al., 2022, Meas. Sci. Technol., 33 (9) 95502



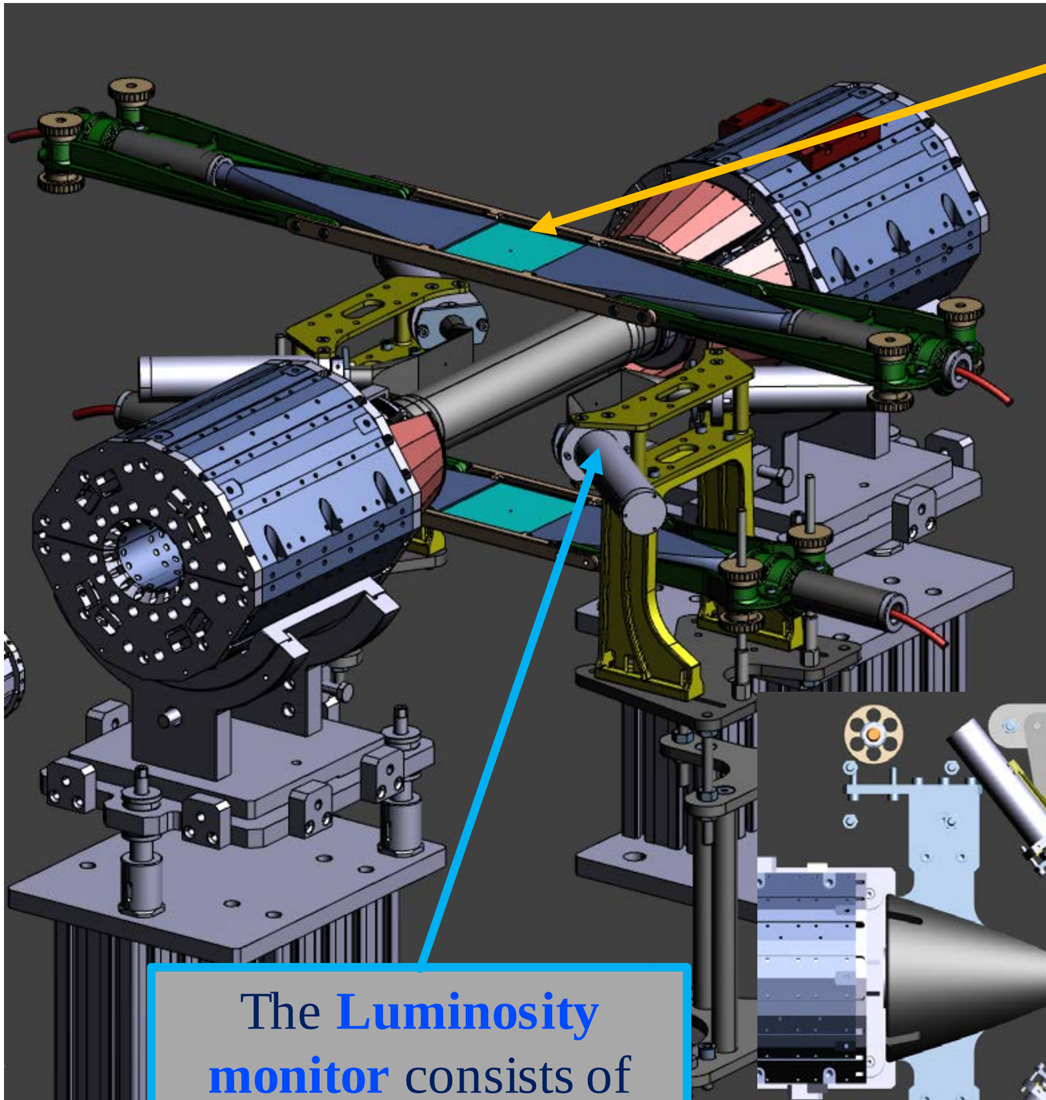
Monte Carlo simulations, modern algorithms and machine learning techniques



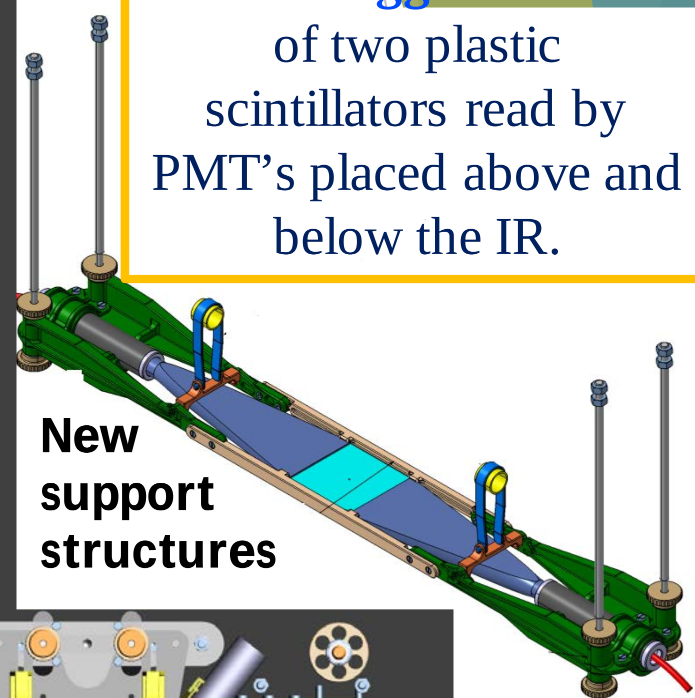


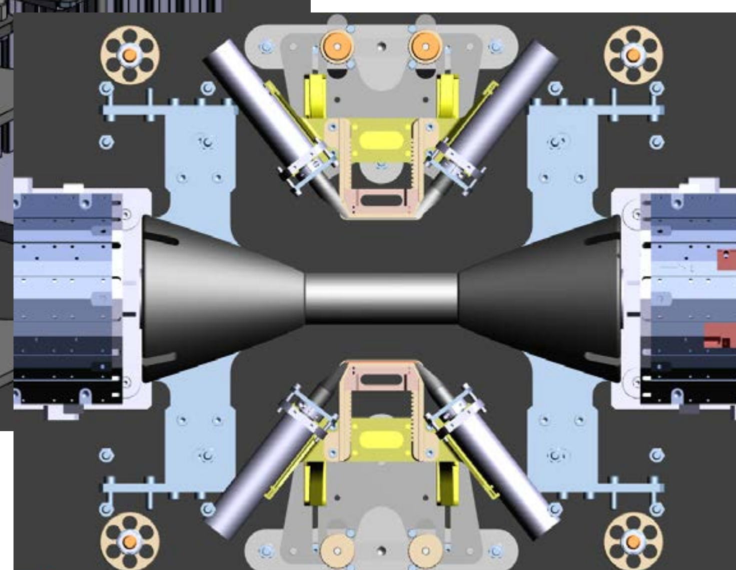
Optimization of the setup and detectors response (degrader curve, trigger, SDDs, veto, ...)

SIDDHARTA-2 setup: kaon trigger and luminosity monitor



Kaon Trigger consists of two plastic scintillators read by PMT's placed above and below the IR.

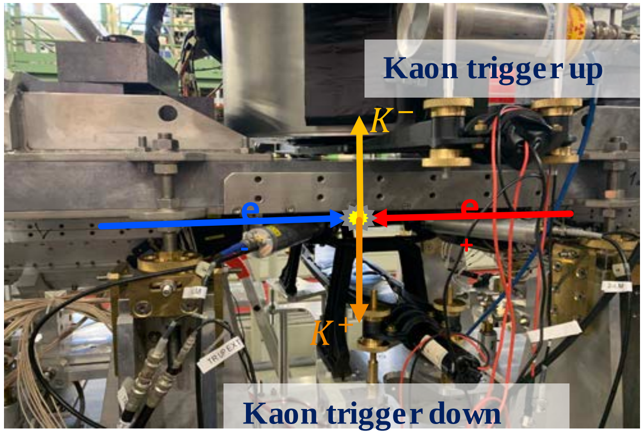


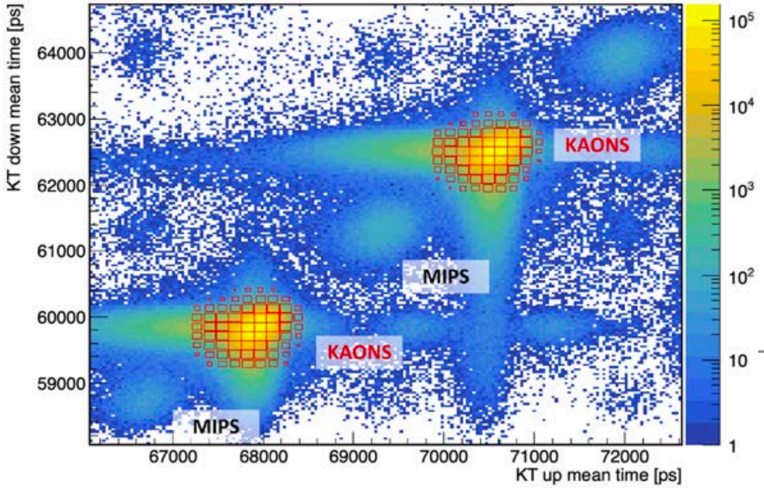


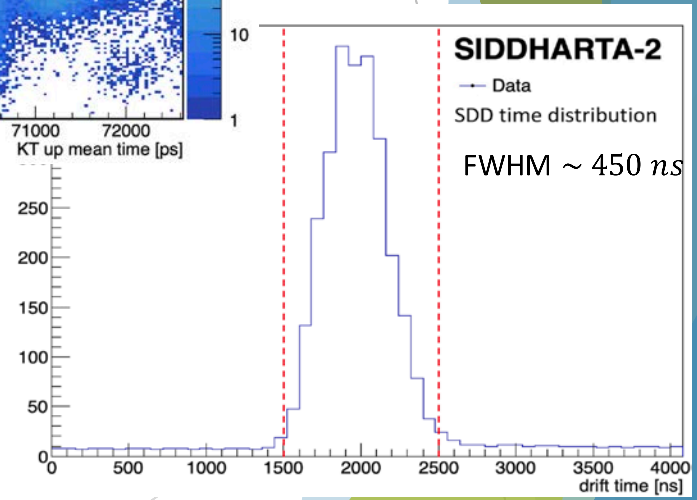
The **Luminosity monitor** consists of two plastic scintillators in the horizontal plane

SIDDHARTA-2 setup: kaon trigger and luminosity monitor

The combined used of Kaon Trigger and SDDs drift time allows to reduce the asynchronous background by a factor $\sim 2 \cdot 10^4$







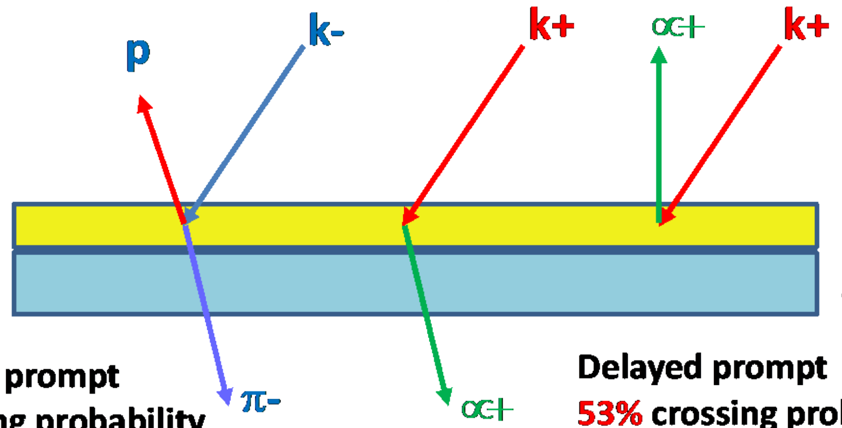
The trigger is generated by the coincidence of 2 back-to-back scintillators

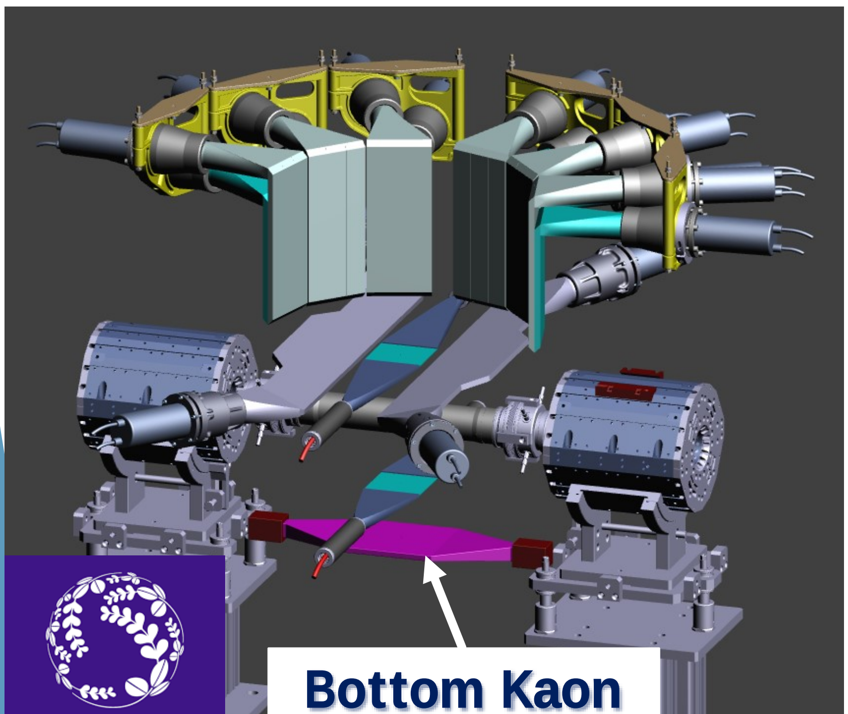
The ToF is different ($\sim 2\ ns$) for Kaons, m(K)~500 MeV/c^2 and light particles originating from beam-beam and beam-environment interaction (MIPs).

Can efficiently discriminate by ToF Kaons and MIPs!

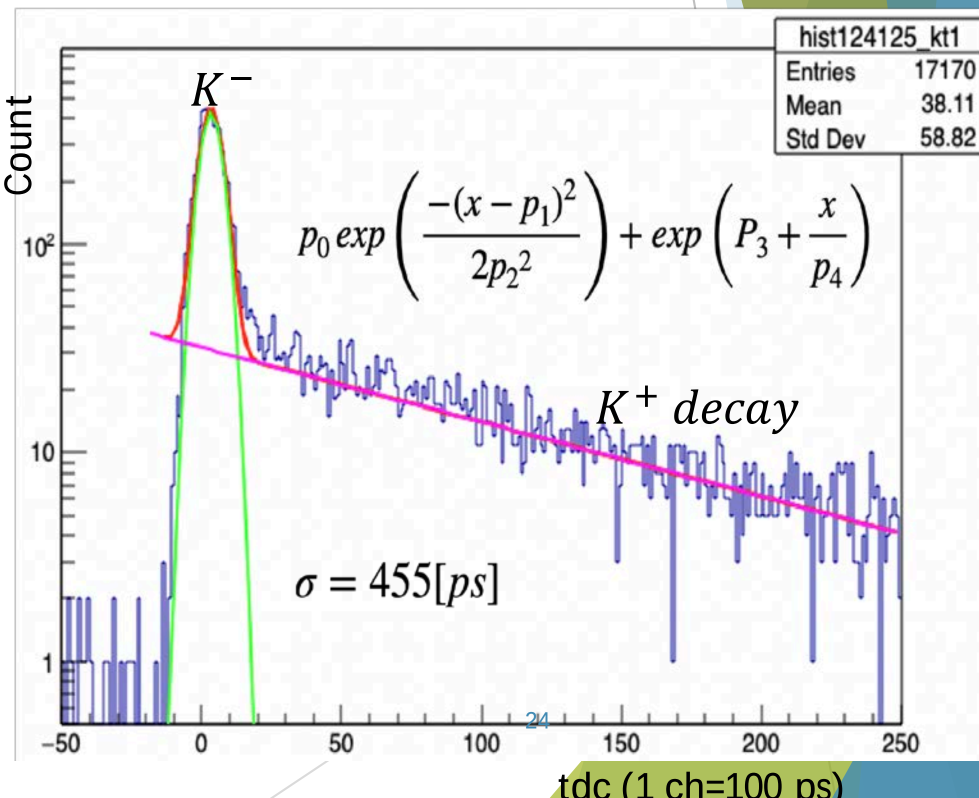
SIDDHARTA-2 setup: Bottom Kaon Detector

Stop both K^+ and K^- in a passive layer (Teflon) and detect secondaries in a scintillator





Bottom Kaon detector

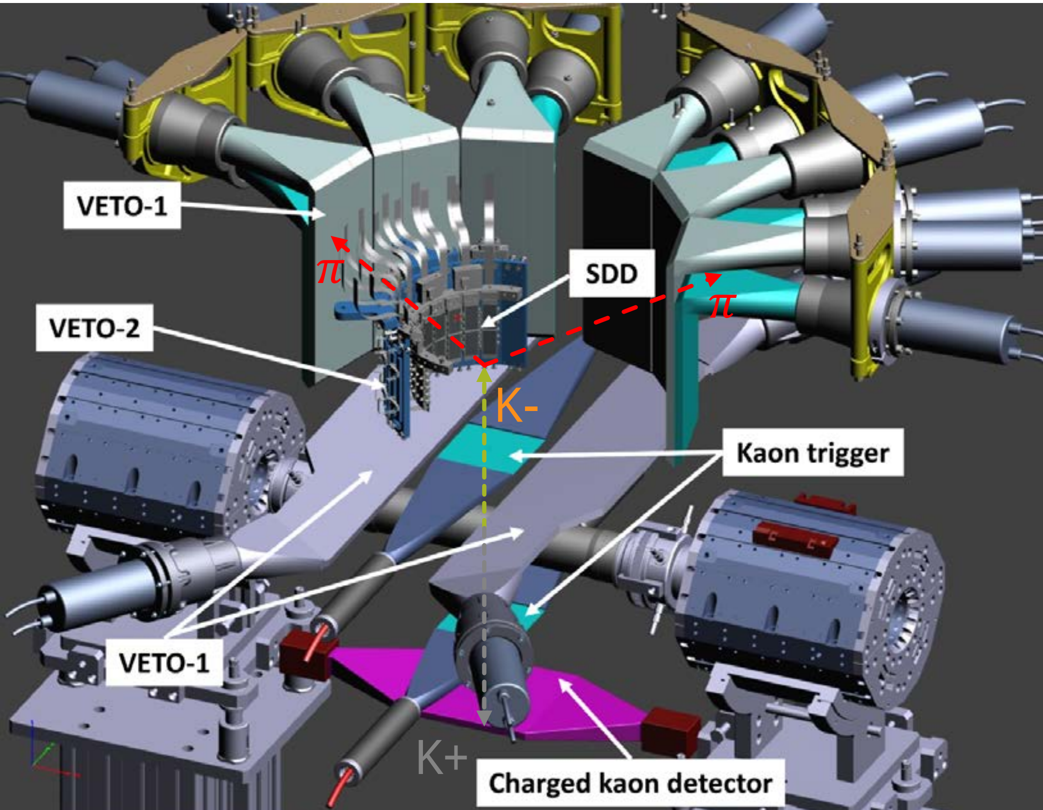


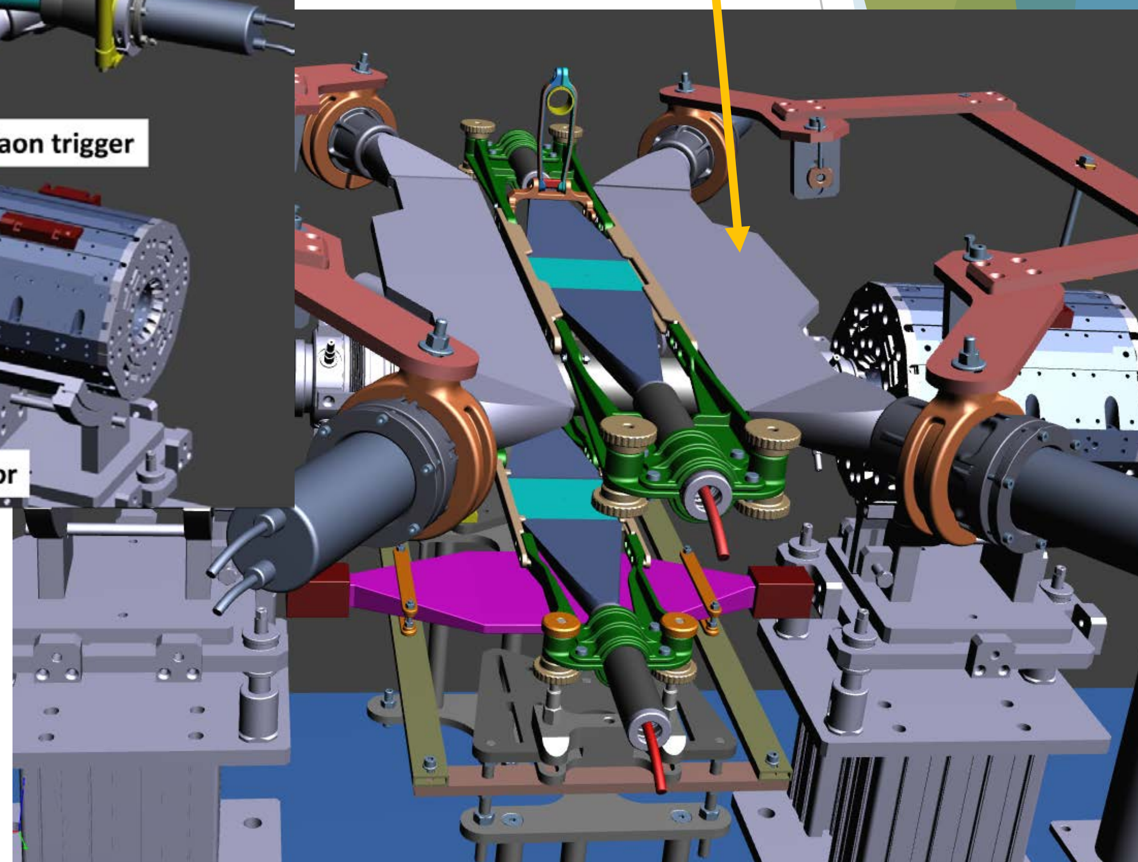
TOHOKU UNIVERSITY

SIDDHARTA-2 setup: veto systems

VETO system adds – VETO-3

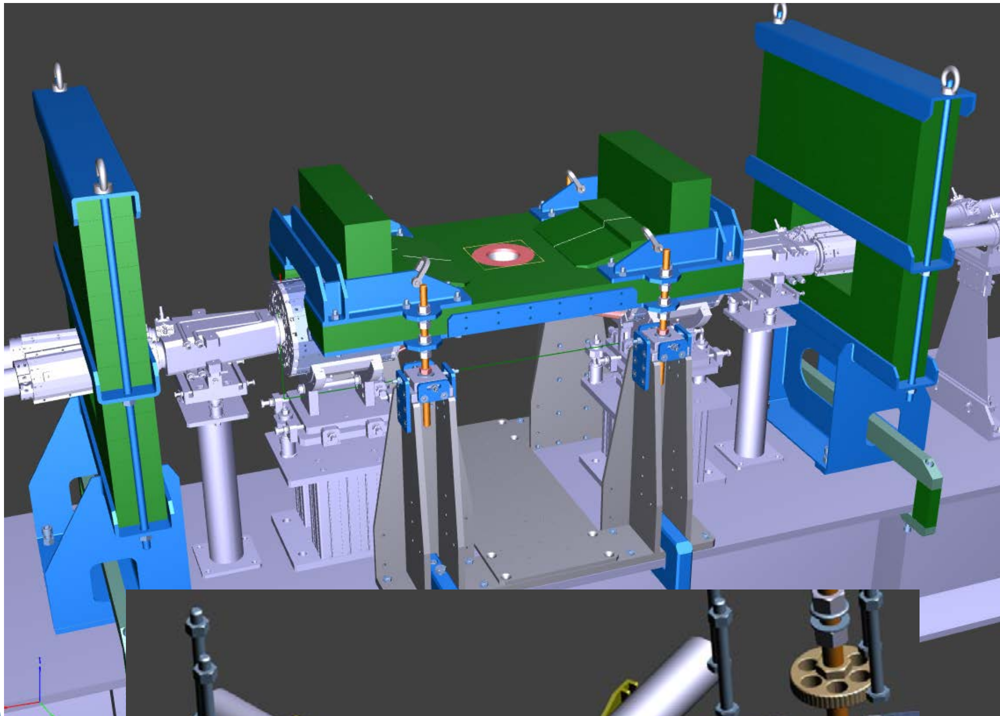
- 2 pairs of scintillator 640 x 130 x 10 mm^3 Scionix EJ-200
- R10533 PMTs Hamamatsu



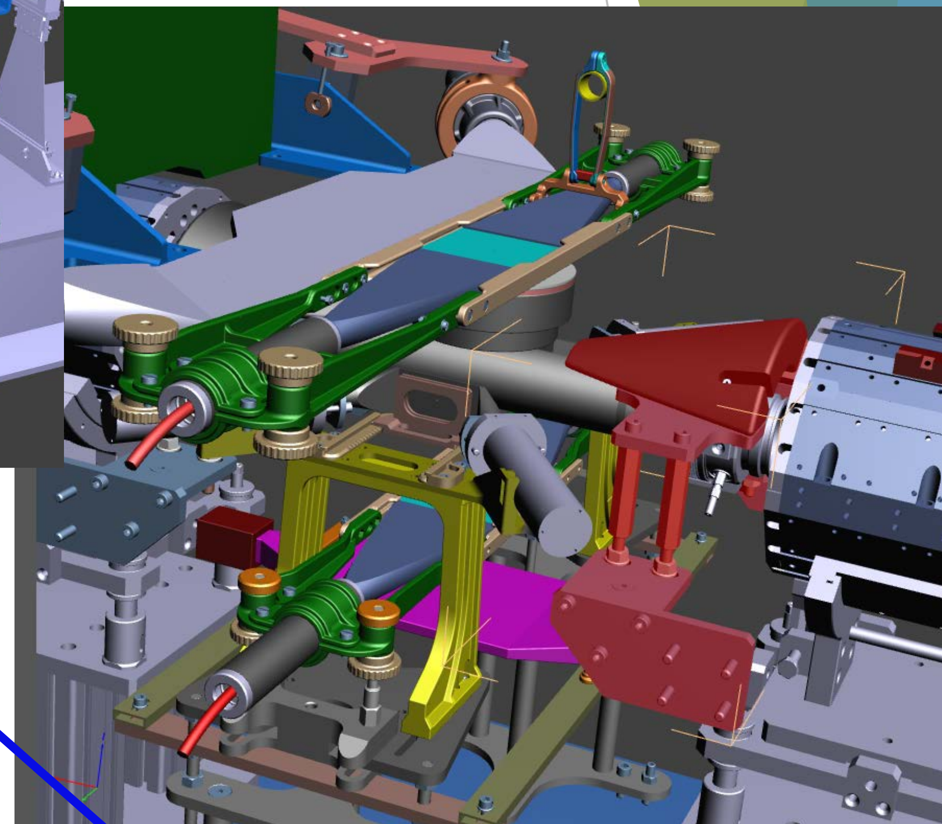


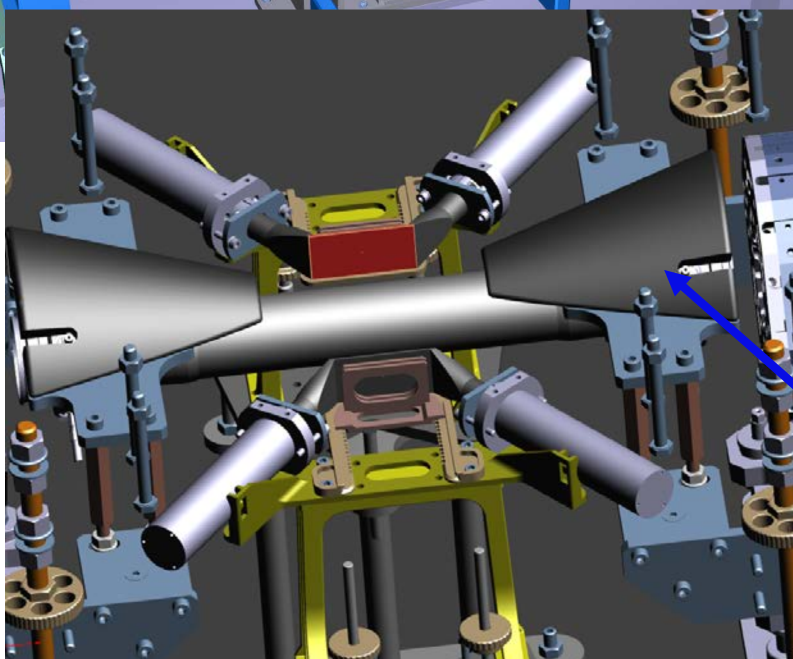
- light-guides
- Al tube + μMetal (0.1mm)
- reflective and light proof foil
- optical cement

SIDDHARTA-2 setup: shielding



- Improve the lateral shielding around the vacuum chamber after adding VETO3 detector

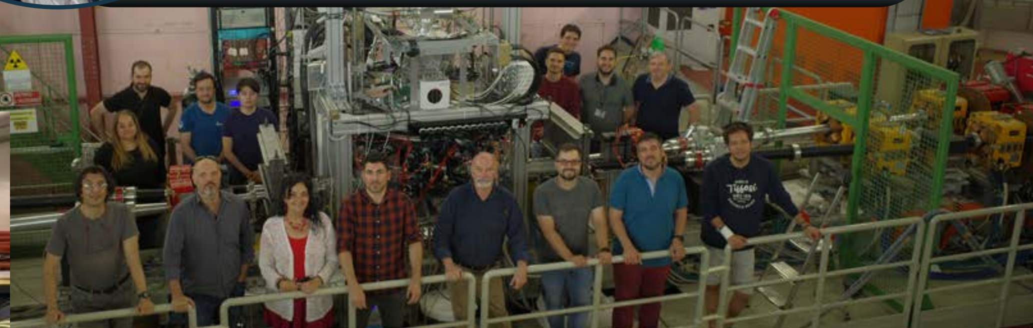


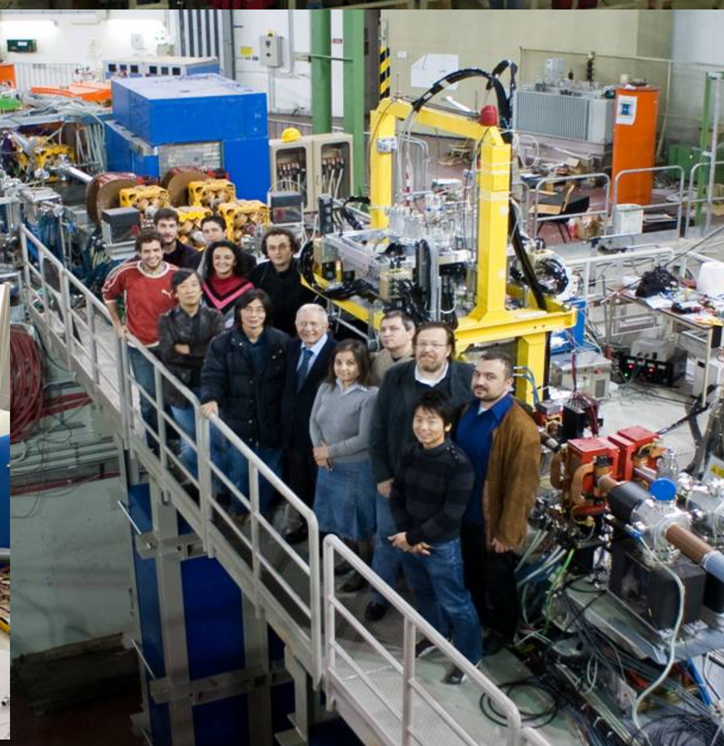


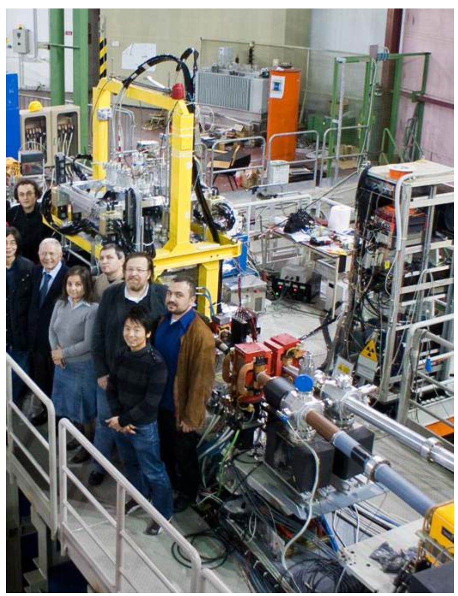
- Redesign and complete the bottom shielding near to IR

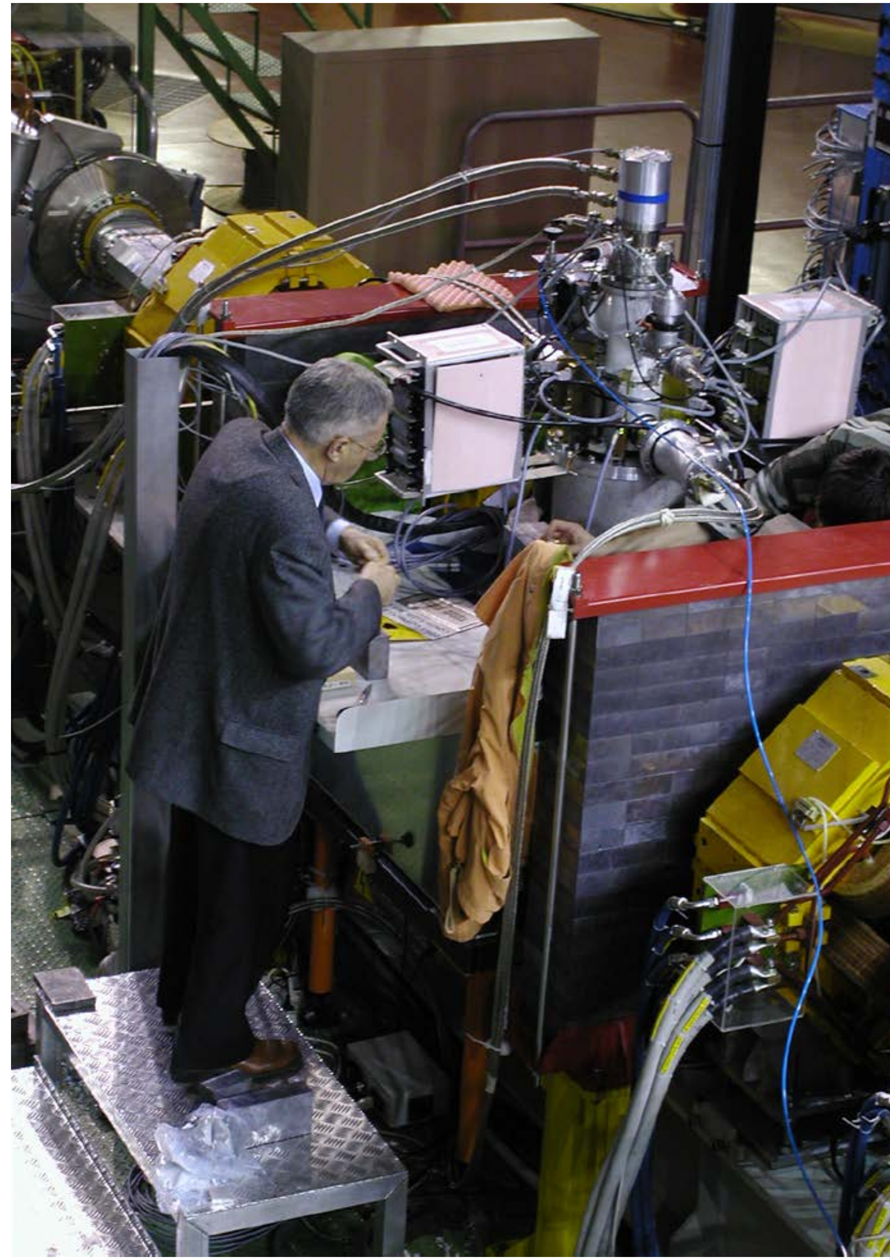
Motivated TEAM







Kaonic Atoms measurements

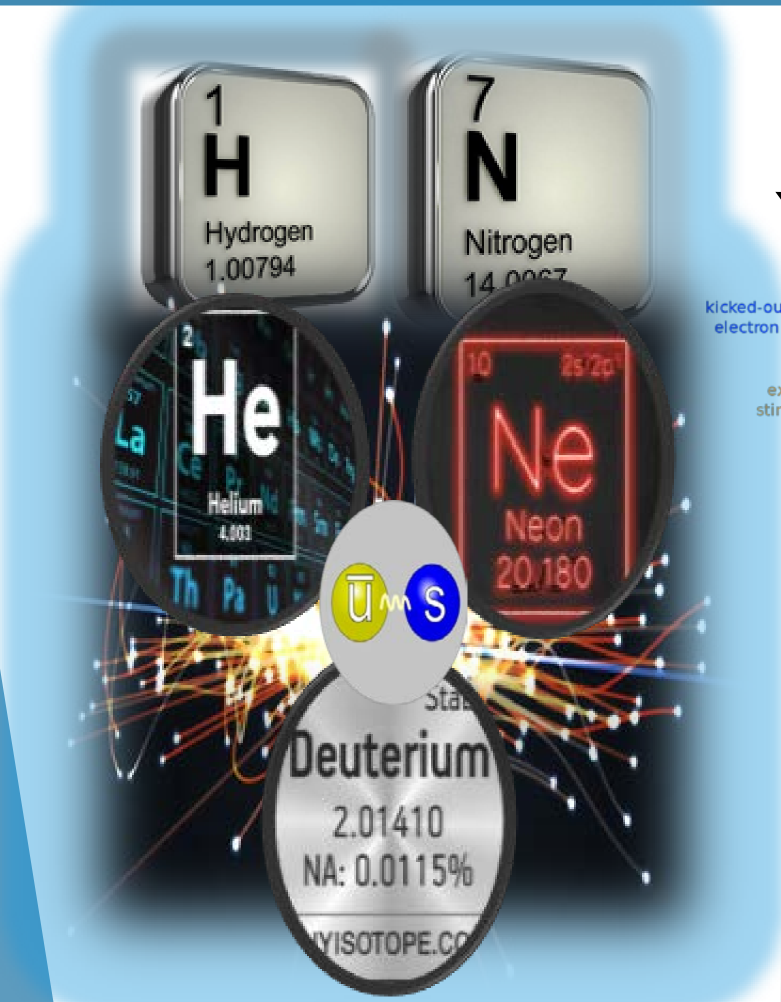
The road to the first Kaonic Deuterium measurement

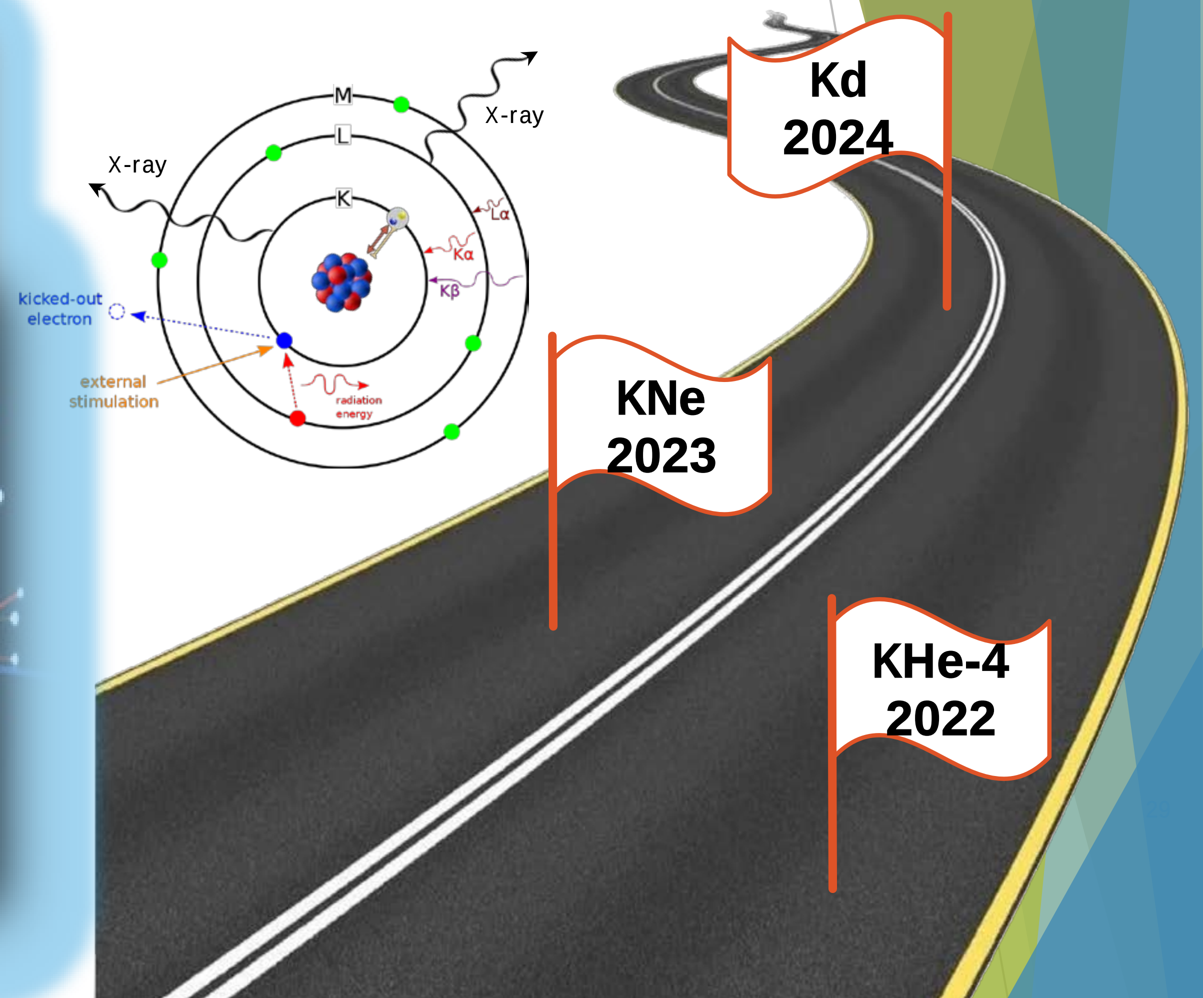
DEAR 2002

SIDDHARTA 2009

SIDDHARTA-2 2022

EXKALIBUR





Project Timeline – Kaonic deuterium run completed

- First run with SIDDHARTA-2 optimized setup for 200 pb^{-1} integrated luminosity: May – July 2023 - completed
- Second run Autumn – Winter 2023 goal: estimated 300-400 pb^{-1} completed
- Third run 2024 – goal: 400 pb^{-1} – completed
- Post-Calibration: goal100-150 pb – completed

Goal: integrated luminosity ~ 200 pb^{-1} (with injections)

End of kaonic deuterium Run1

2023, July

Total: ~200pb^{-1}

Goal: integrated luminosity ~ 300 - 400 pb^{-1}

End of kaonic deuterium Run2

2023, December

Total: ~344 pb^{-1}

HPGe and CdZnTe

Goal: integrated luminosity ~ 400pb^{-1}

End of kaonic deuterium Run3

2024, April

Total: ~450 pb^{-1}

(to ensure 800 pb^{-1} of useful data)

Integrated luminosity 150-200 pb^{-1} (1 month)

Extension of the SIDDHARTA-2 run, also as post-calibration

2024, July

Total: ~200 pb^{-1}

(low density run)

~ 1200 shifts for a total of ~ 10 000 hours of data taking and ~ 1700 pb^{-1} deliverd by DAΦNE allowed to perform the kaonic deuterium, helium, neon and hydrogen measurements

SPARE

Future plans

EXtensive
Kaonic
Atoms research: from
LIthium and
Beryllium to
URanium

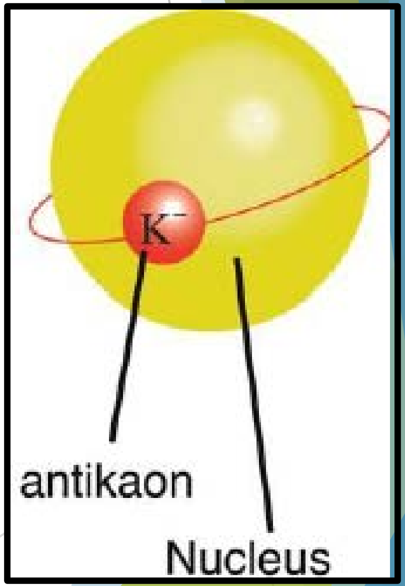
- *proposal to perform fundamental physics at the strangeness frontier at DAΦNE for a 3-years period (post-SIDDHARTA-2)*
- *presented in varies Scientific Comity and INFN commissions*

Kaonic Hydrogen: 200 pb^{-1} - with SIDDHARTA2 setup - to get a precision < 10 eV (KH)

Selected light kaonic atoms (LHKA)

Selected intermediate and heavy kaonic atoms charting the periodic table (IMKA)

Ultra-High precision measurements of Kaonic Atoms (UHKA)



Dedicated runs with different types of detectors:
SDD 1mm, CZT detectors – R&D in advanced phase
HPGe, crystal HAPG spectrometer-VOXES project