Development of a cryogenic x-ray detector and its application

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Instrumentation in Nobel prize

- C. Wilson 1927 Cloud Chamber
- E. Laurence 1939 Cyclotron
- F. Zernike 1953 Phase-contrast microscope
- D. Glaser 1960 Bubble chamber
- C. Towns, N. Basov, A. Prokhorov 1964 Laser
- A. Kastler 1966 Optical pumping
- L. Alvarez 1968 Liquid hydrogen bubble chamber and an analysis technique
- E. Ruska, G. Binnig, H Rohrer 1986 Electron microscope
- G. Charpak 1992 MWPC
- J. Hall, T. Hänsch 2005 Frequency comb

Evolution of Detector Technology

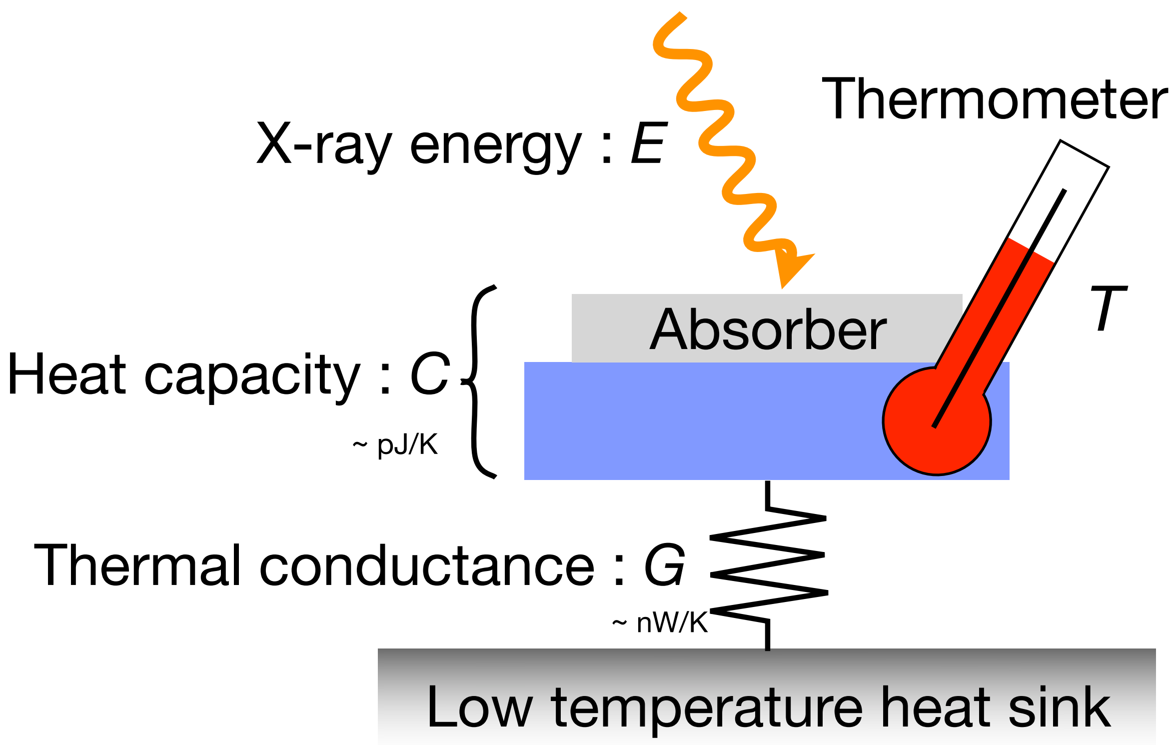
- single channel to multichannel
  - MWPC, hodoscope
- same effect by another mechanism/principle
  - photo multiplication (PMT → SiPM)
  - gas ionisation (PC → GEM, RPC)
  - ionisation (gas → semiconductor, STJ)
- same principle in a different application, readout
- different size

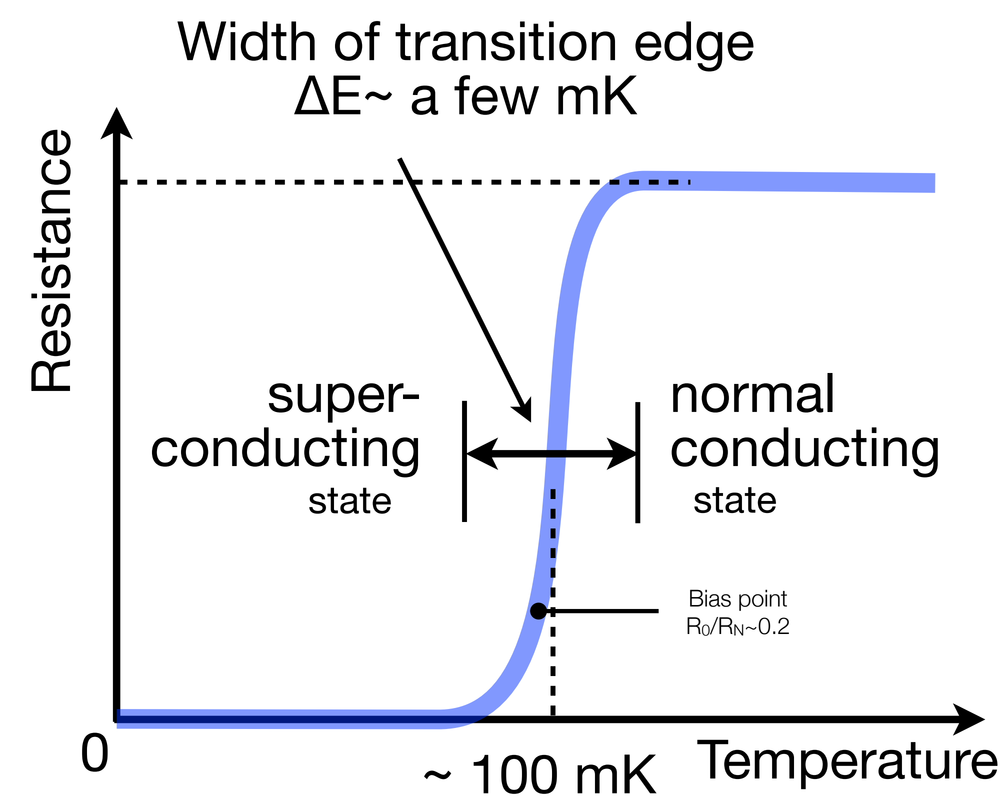
Cryogenic Particle Detector (=Low Temperature Detector)

- LTD: detectors typically operated at sub kelvin region
- Relatively new field, an increasing number of applications:
  - Dark matter search experiments: CRESST, CDMS
  - X-ray astronomy, CMB: BICEP2, South pole telescope
  - Axion search: CAST
  - Beta decay experiments, Neutrino mass measurements:
- Variety of detector working principles
  - STJ, TES, MMC, MPT
- extremely high resolution in comparison with conventional detector
  - 1-2 eV energy resolution for a 6 keV X-ray
- Applications in hadron physics about starting.

Example: Transition Edge Sensor (TES) detector

As of now, probably the most matured and widely used LTD





Detector principle in 1940's. Realisation of a practical level detector in 1990's after the invention of negative thermal feedback (K.D. Irwin) and coupling to SQUID readout.

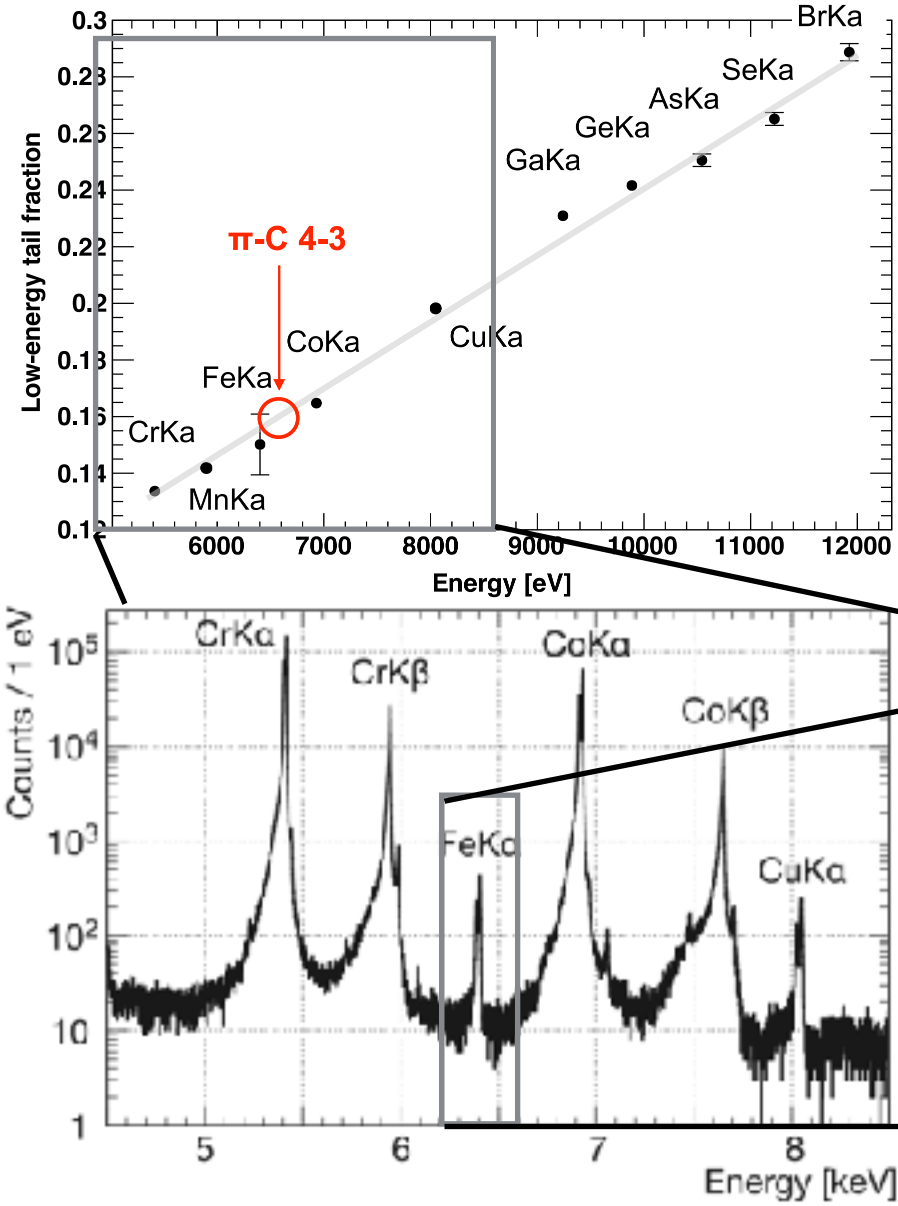
LTD in Hadron Physics

- T. Ishiwatari (~2011??)
  - mentioned TES for an application of future kaonic atom experiment
  - Bragg diffractometer (π-H experiment@PSI, A. Scordo)
- HEATES collaboration (S. Okada, H. Tatsuno, T. Hashimoto, ..)
  - Physics driven
  - Buy an existing system from NIST and adopt
- ASPE!CT (K. Suzuki, K. Phelan, J. Zmeskal, …)
  - Technology driven project
    - ↔ Market driven (Industry)
  - Supported by EUROSTARS programme of Eureka

HEATES collaboration

- S. Okada, H. Tatsuno, T. Hashimoto, S. Yamada and NIST-Boulder.
- E17⇒E62: Kaonic Helium at J-PARC.
- Buy the established TES system of NIST, including operator.
- Successful measurement and publication of pionic atom (C).

Pionic Carbon @PSI



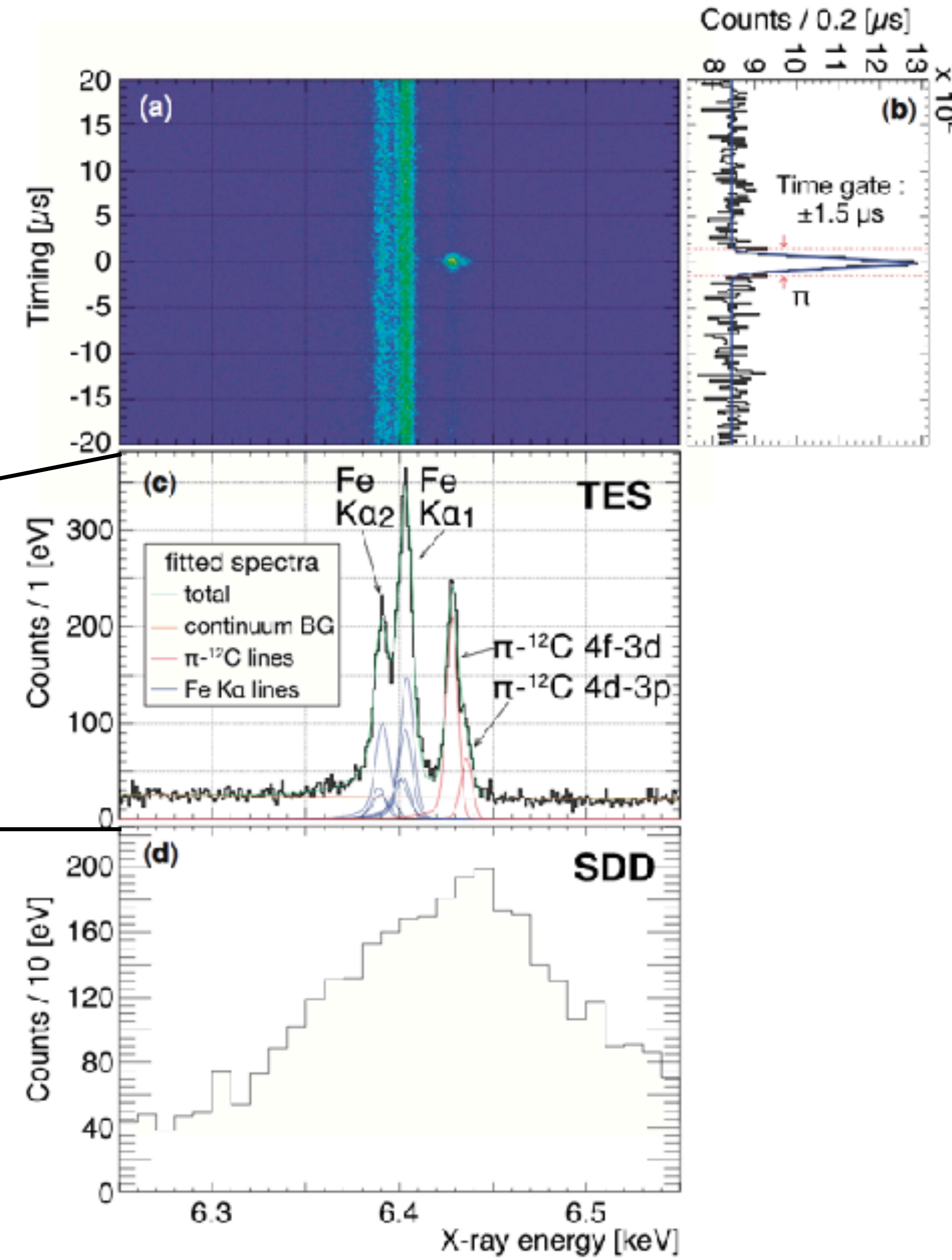
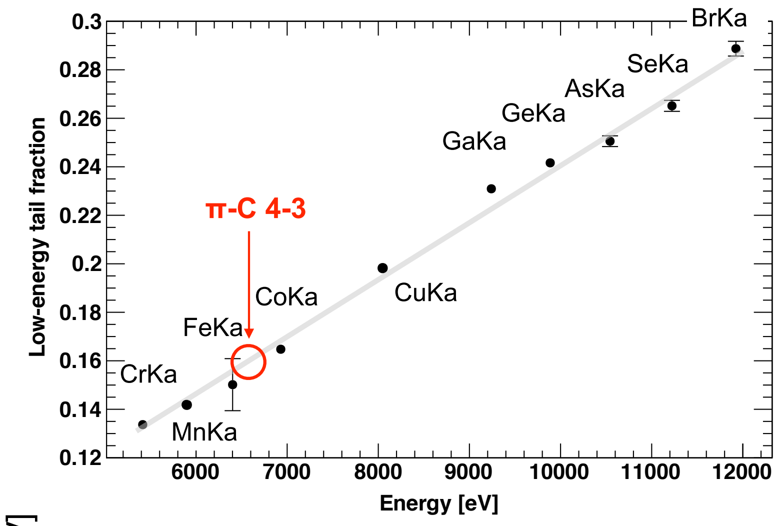


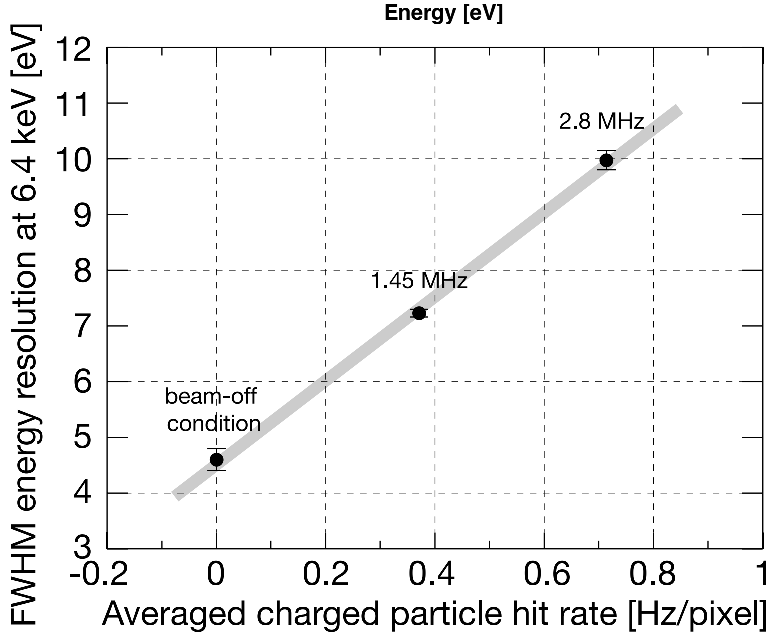
Fig. 2. An X-ray energy spectrum obtained from a tube source X-ray generator shining on Cr and Co calibration pieces without a pion beam. The Cr K_α, Cr K_β, Co K_α, and Co K_β lines are used for the energy calibration. Lower-yield X-rays, Fe K_α (6.4 keV) and Cu K_α (8.0 keV), originate respectively from the stainless steel vacuum fittings of the tube source and the metal structure of the 50 mK detector package.

LTD in Hadron Physics

- "dirty" hadronic secondary beam environment
- TES for pionic atom x-ray at PSI (HEATES collaboration)
  - Beam (π^- & e^-): 1.45 MHz
  - Calibration x-ray 4.4 Hz/pixel
  - Beam direct hit: 0.4 Hz/pixel
  - Beam hit on array: ~400 Hz

H. Tatsuno LTD16





ASPE!CT® Collaboration

aspect || cryogenic || spectrometers ||®

- is actually the name of the first project funded by EUREKA-EUROSTARS.
  - 2 SMEs and 1 SMI, 2 years, 1M€.
  - Development of commercial product, cryostat.
  - Core members of the former “Vericold”, who produced the world first commercial TES system.
  - SMI participates as an α-user, providing a use case, contributes to the specification and design and give feedbacks.
  - Development of Low Temperature Detector (LTD), X-ray detector

PAYR Engineering | Low T-Solutions your Cryogenic Partner | ÖAW | SMI | eurostars | DLR | FFG FORSCHUNG WIRKT.

ASPE!CT Collaboration

The ASPE!CT project is a collaboration of industrial and research companies, and the Stefan Meyer Institute in Vienna. We are developing a commercially viable, cryogenic detector platform. The first phase of the project will produce a cryogen-free, single-stage, adiabatic demagnetisation refrigerator for use at sub-Kelvin temperatures. The project aims to advance the technology into the realm of reliable, compact, black-box, touch-button devices, which can be used for a wide range of cryogenics sensors. Later stages of the project will push the temperature range to 30mK, and introduce continuous, high-power, low-temperature cooling.

ÖAW Österreichische Akademie der Wissenschaften

PAYR Engineering

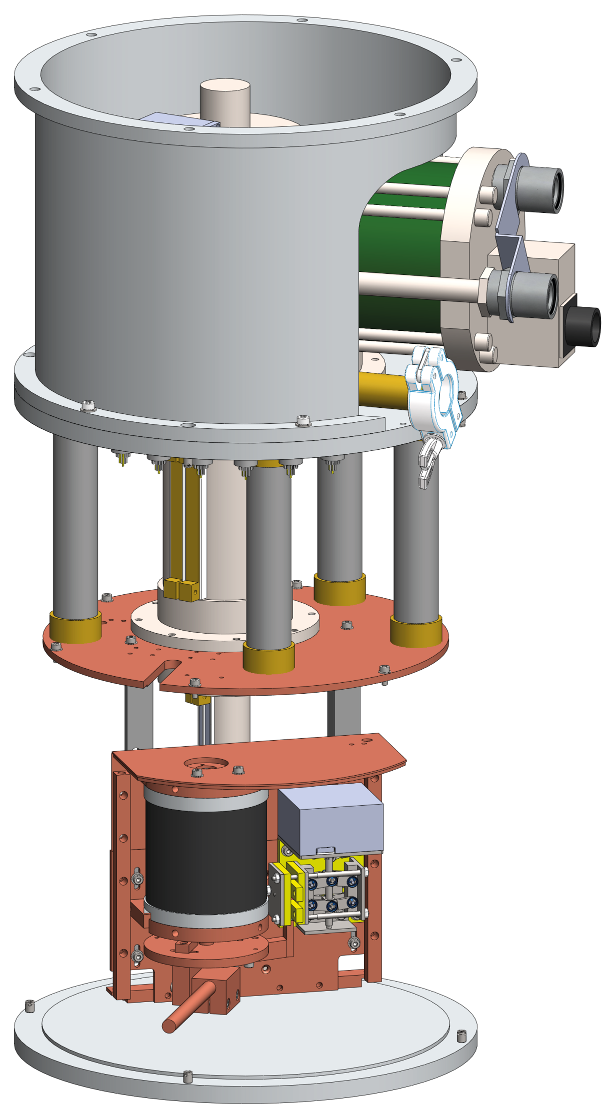
low T-Solutions your Cryogenic Partner

Cryostat

A cryostat especially designed for use with LTDs is being constructed. Based on a GM-4K cooler and a single-stage ADR, it will be cost-competitive, orientation-free, and usable at temperatures between 1K and 30mK.

A high-level of integration, new heat-switch, magnet and electronics designs should make the cryostat robust, reliable and very easy to use.

The product will be put into a market shortly after the end of the first funding period.



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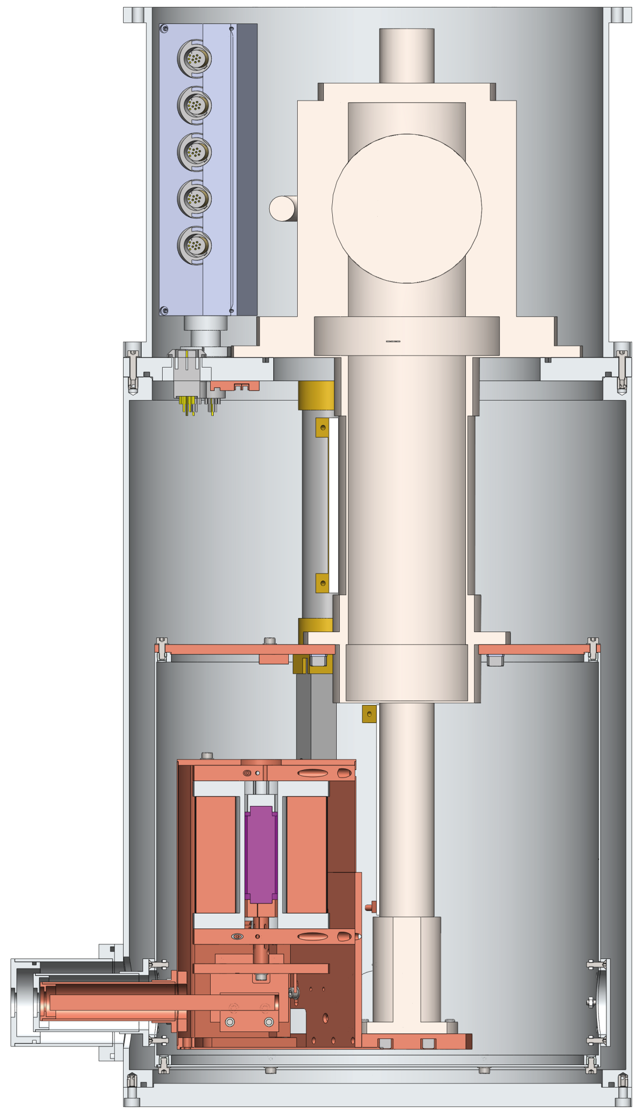

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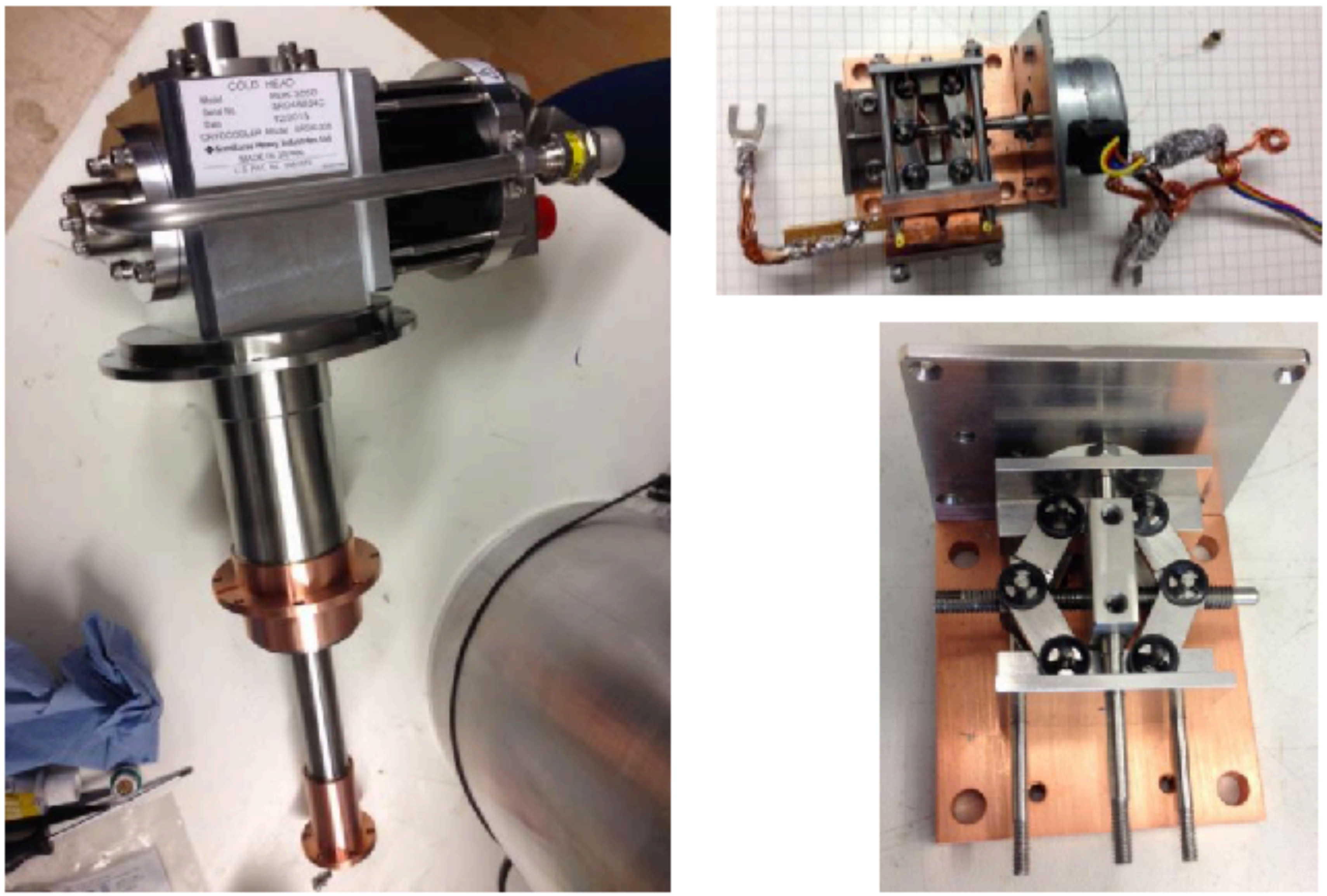
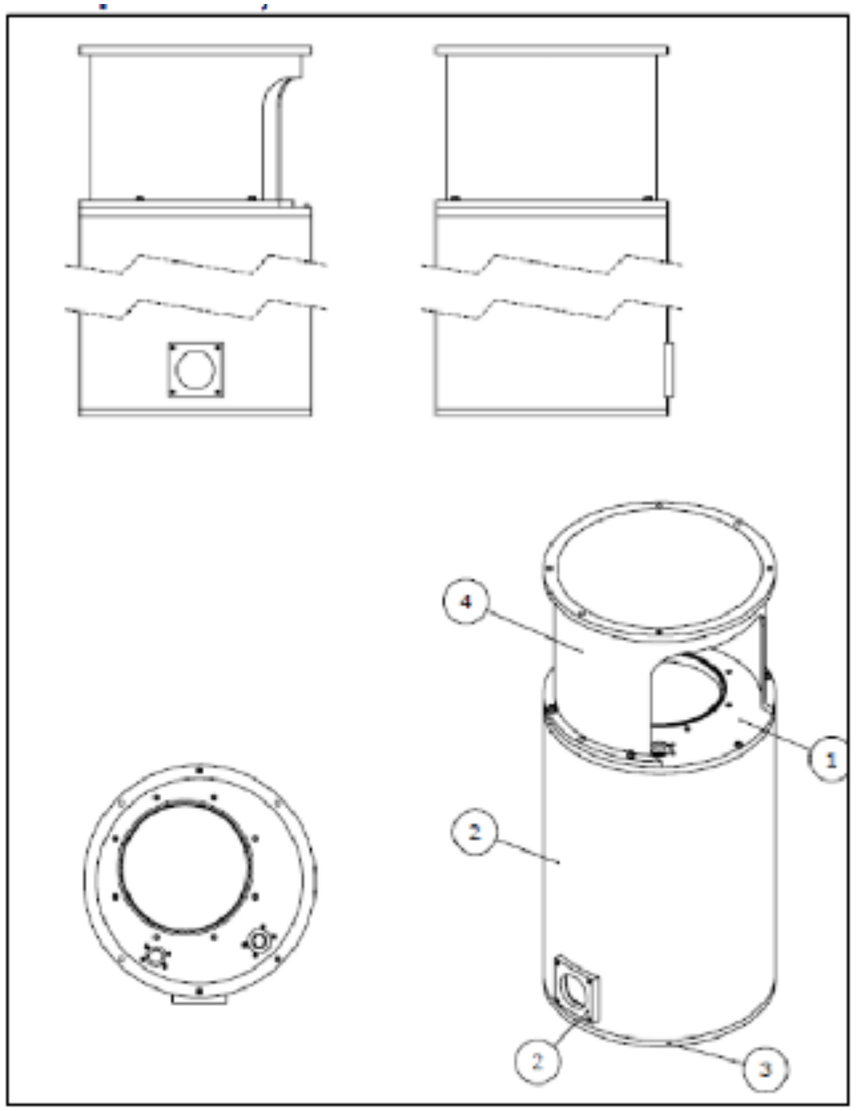
Status



Sumitomo Cold Head and innovative heat-switch prototype

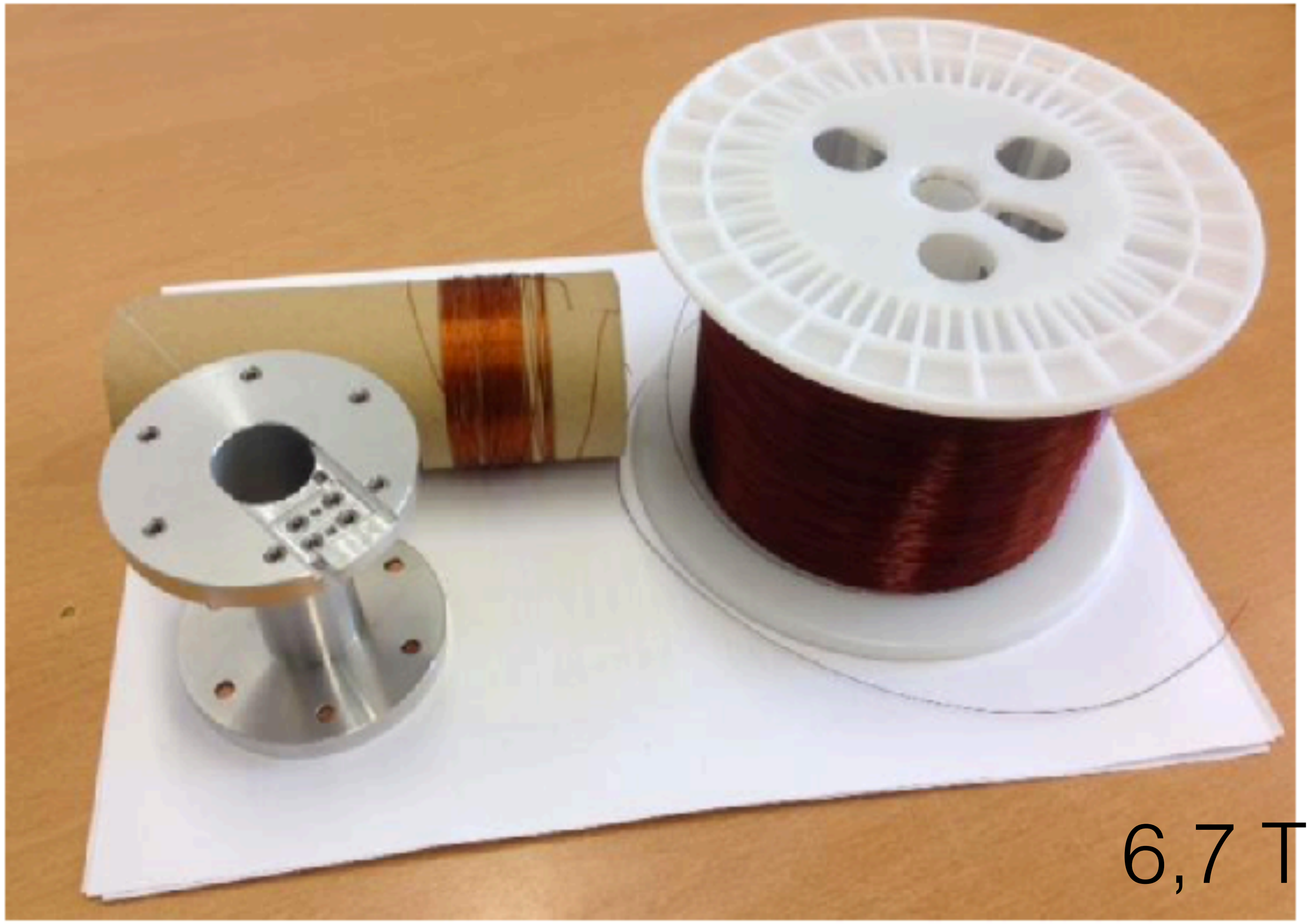
Status



Vacuum chamber module

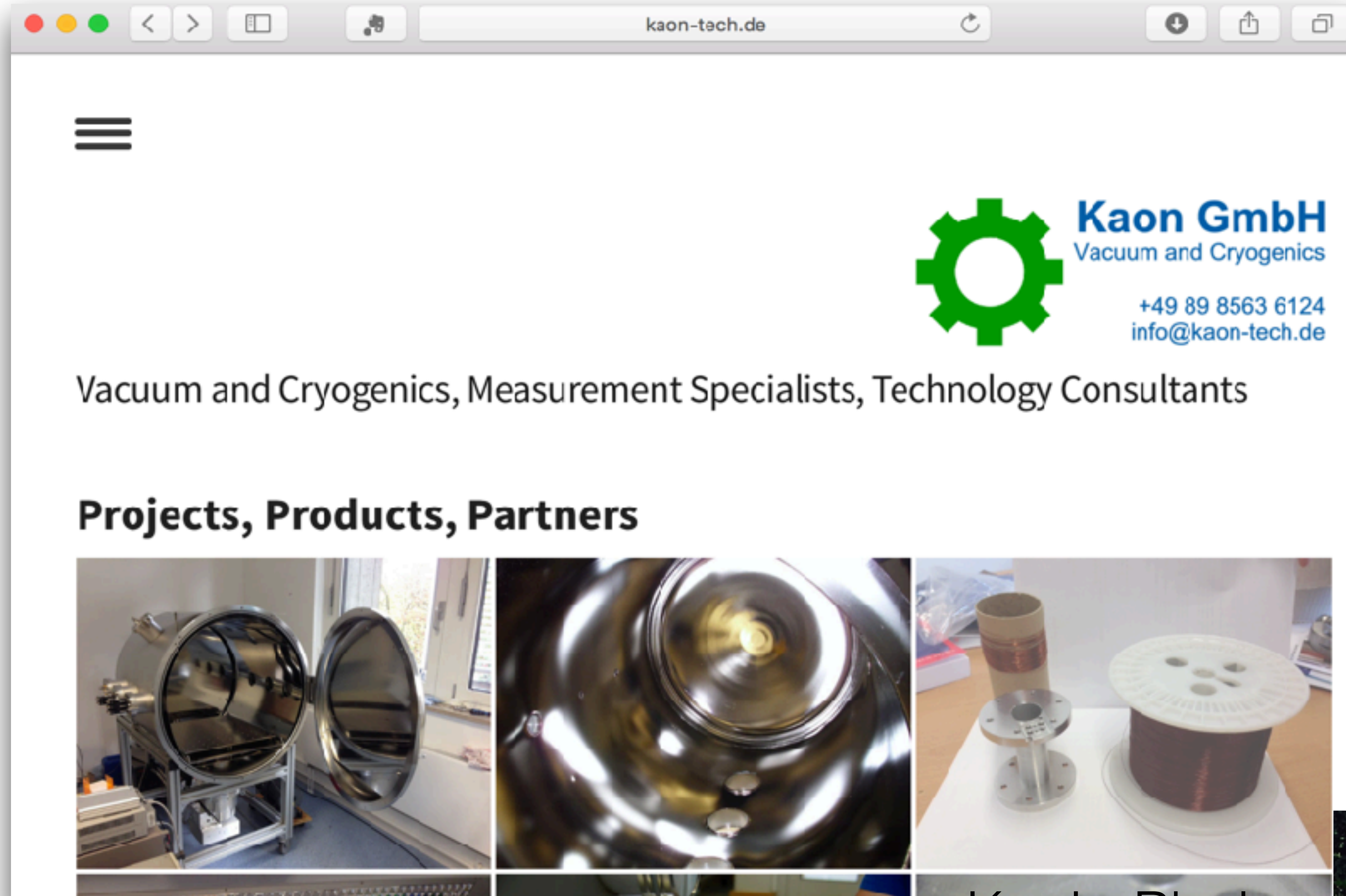
Dewar prototypes manufactured by Payr Production GmbH

Status



Superconducting Magnet former and superconducting wires

“Spin-off” Company



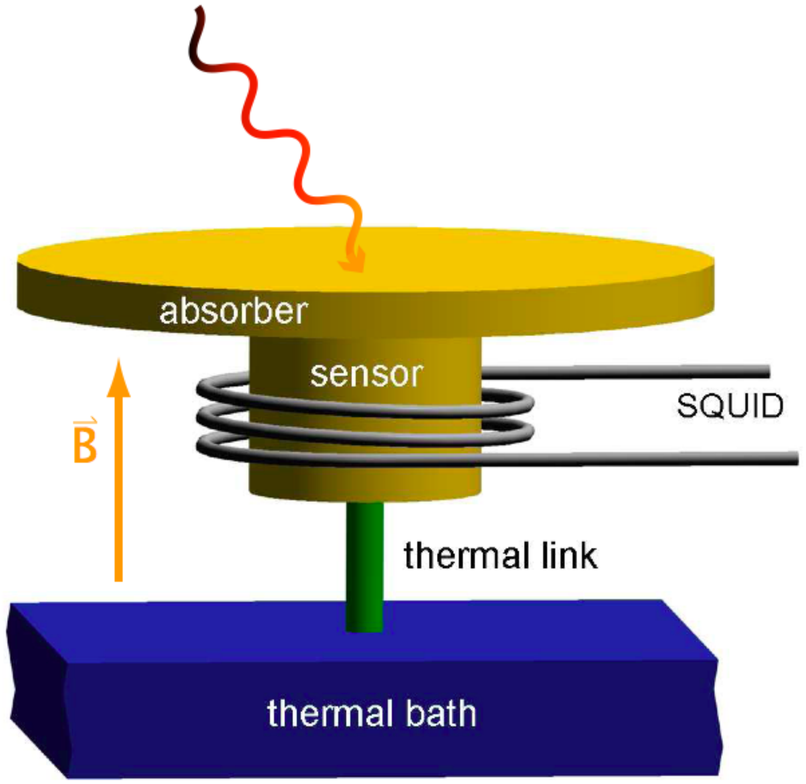
founded Sep. 2015

Kevin Phelan

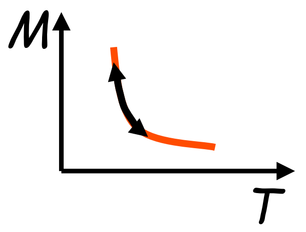
Detector Supply

- highly sophisticated detector, detector should be provided by an expert.
- NIST (US, TES, commercial products)
    - AIST (JP, STJ)
    - KIP-HD (DE, new sensor principles)
- Collaboration with KIP-HD

Metallic Magnetic Calorimeter (MMC)



paramagnetic sensor: Au:Er$_{500ppm}$, Ag:Er



signal size:

$$\delta M = \frac{\partial M}{\partial T}\delta T = \frac{\partial M}{\partial T}\frac{E_\gamma}{C_{tot}}$$

M and **C** of weakly interacting spins
well understood ➡ **numerical optimization**

main differences to calorimeters with resistive thermometers

no dissipation in the sensor

no galvanic contact to the sensor

A. Fleischmann, 2015

Magnetic Penetration Thermometer (MPT)

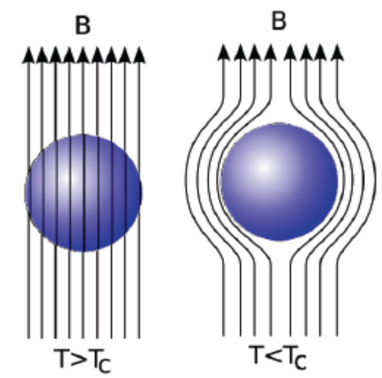
μ-calorimeters with magnetic penetration thermometers (MPT):

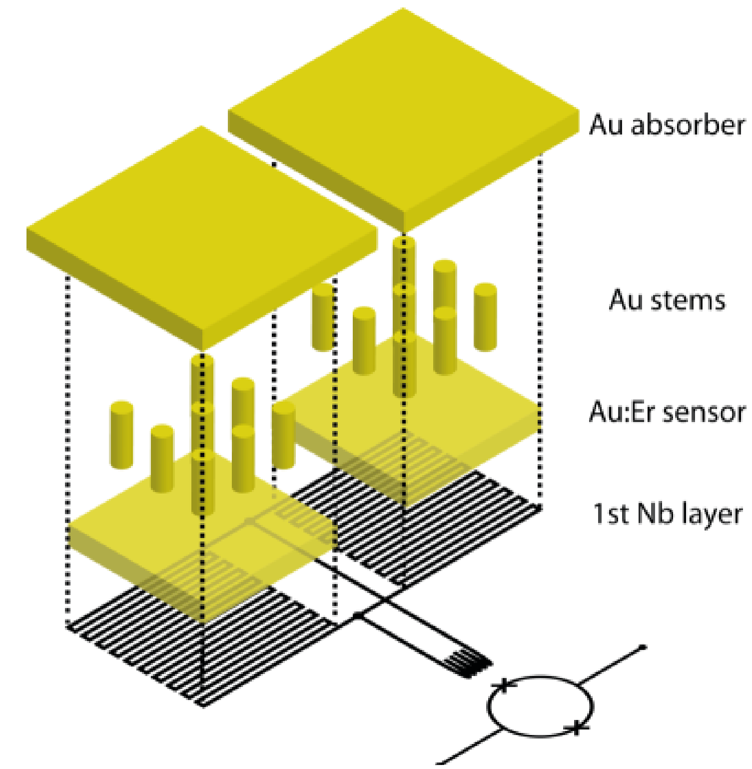
Replace paramagnetic T-sensor with superconductor with low T_c

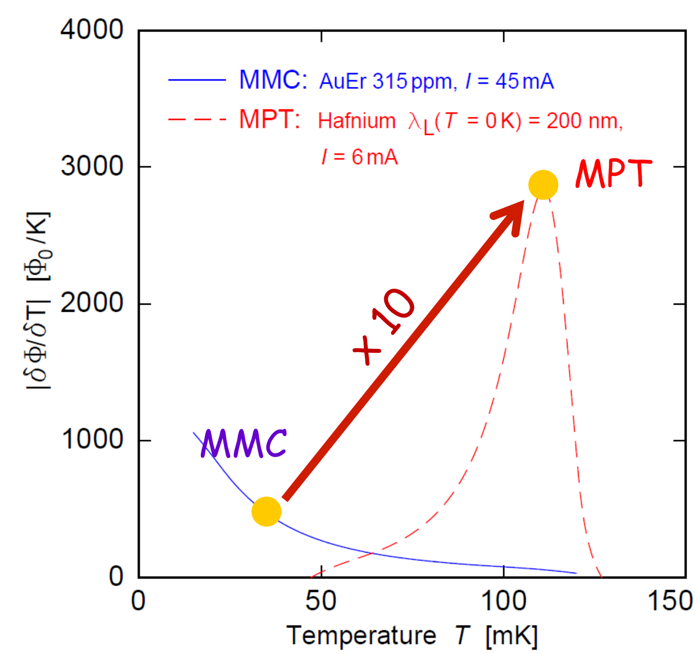
Use T-dependent flux penetration as thermometer

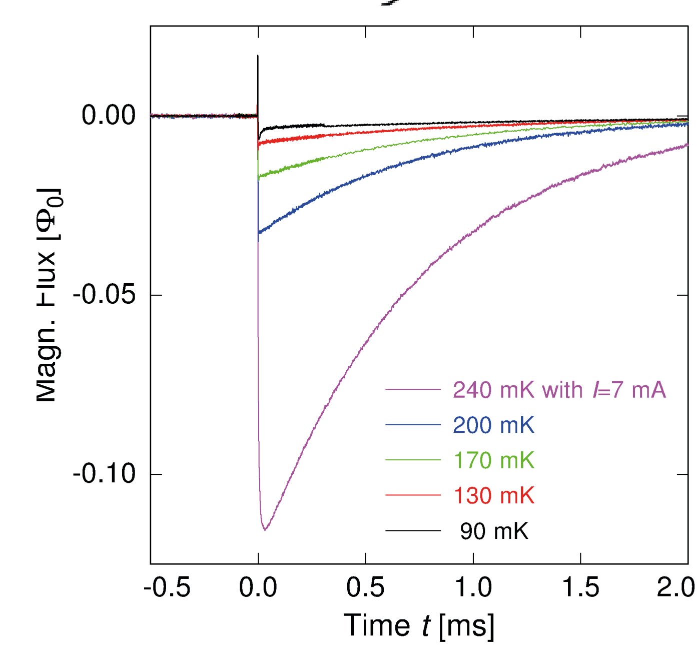
Has all good properties of MMCs:
No intrinsic power dissipation
No galvanic contact to sensor

In addition:
Smaller sensor heat capacity
10x Larger temperature sensitivity dΦ/dT
Operation at higher temperature
⇒ larger noise margin for multiplexing …









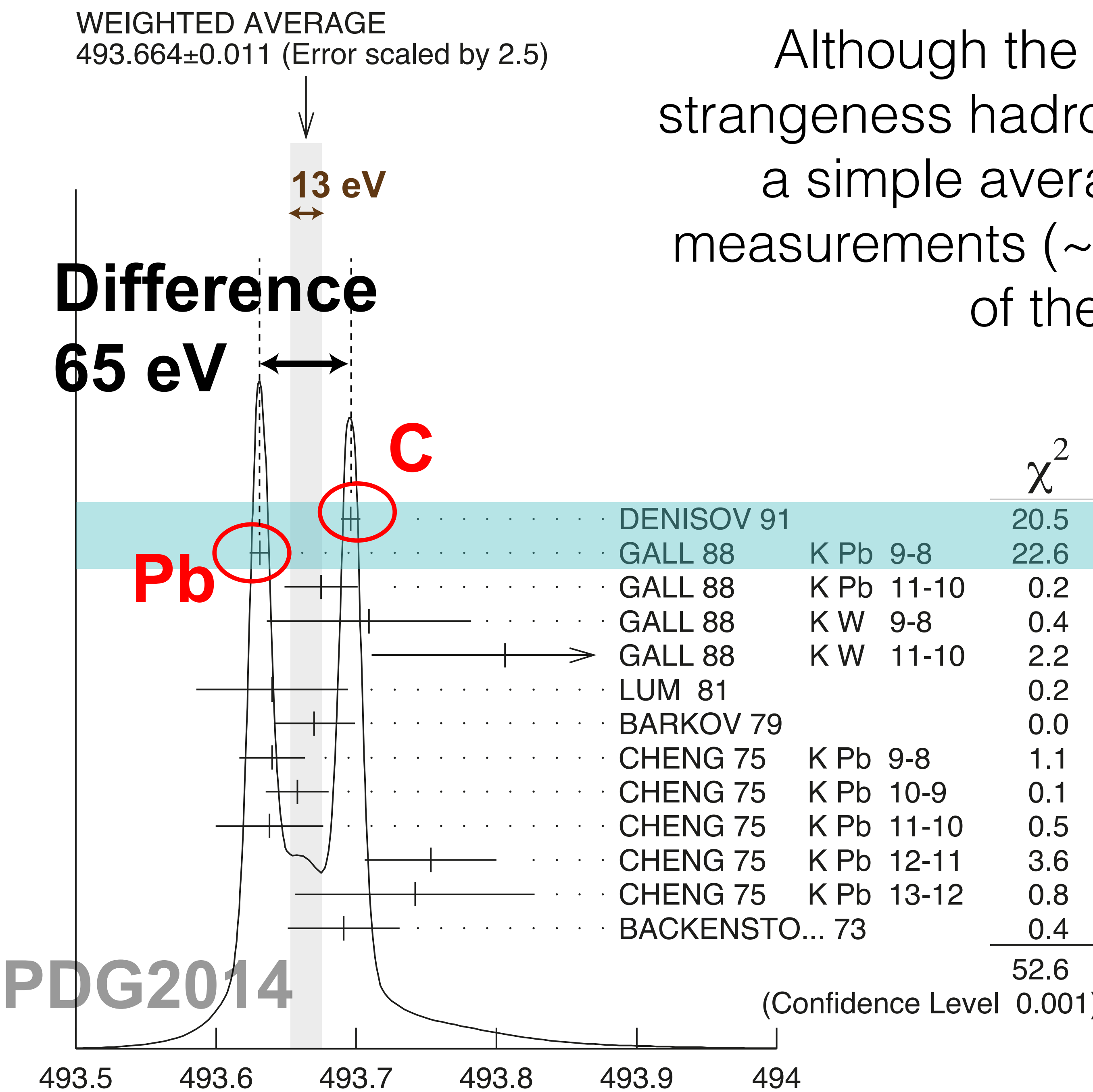
A. Fleischmann, 2015

Applications

Kaon Mass Measurement

T. Ishiwatari ~2011??

Although the kaon mass is an essential input for strangeness hadron physics, it is currently determined as a simple average between two largely separated measurements (~3σ, 60 eV), making a current estimates of the kaon mass inconclusive .



Two most recent and stringent data

493.696 ± 0.007 [MeV]

493.631 ± 0.007 [MeV]

Applications

E. Friedman and S. Okada, (2013). Feasibility guidelines for kaonic atom experiments with ultra-high-resolution X-ray spectrometry. Nuclear Physics A, 915(C), 170–178. http://doi.org/10.1016/j.nuclphysa.2013.07.005

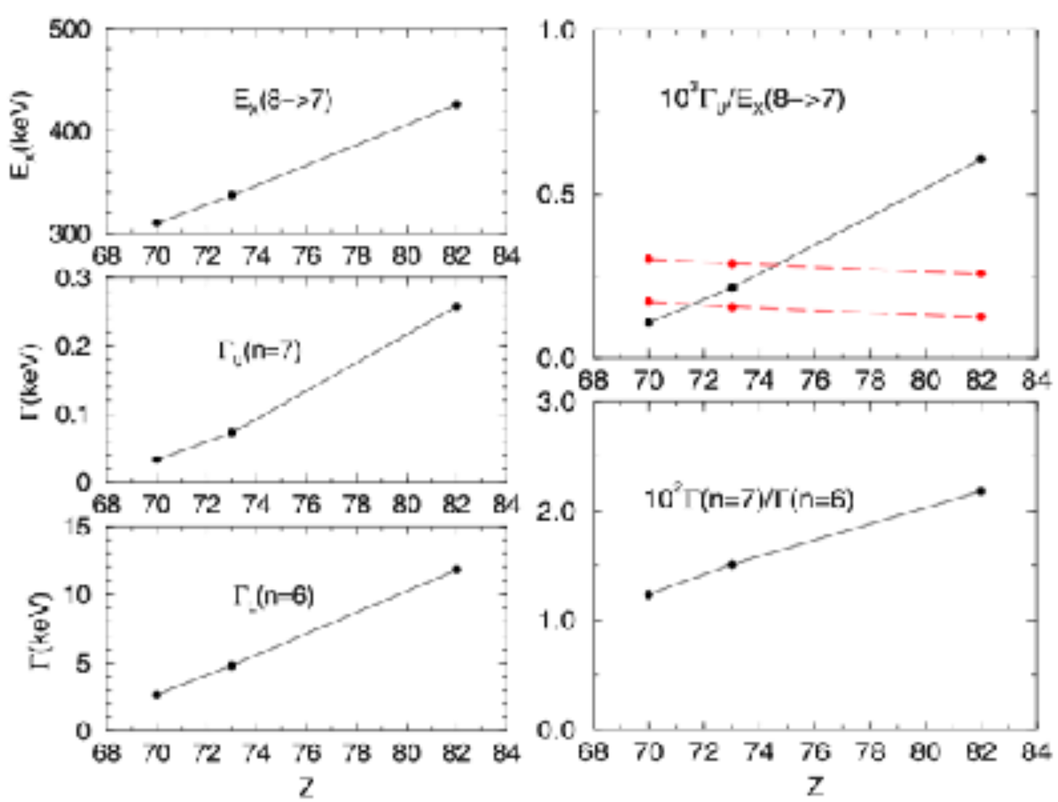


Fig. 4. Same as Fig. 1 but for the 6h and 7i levels.

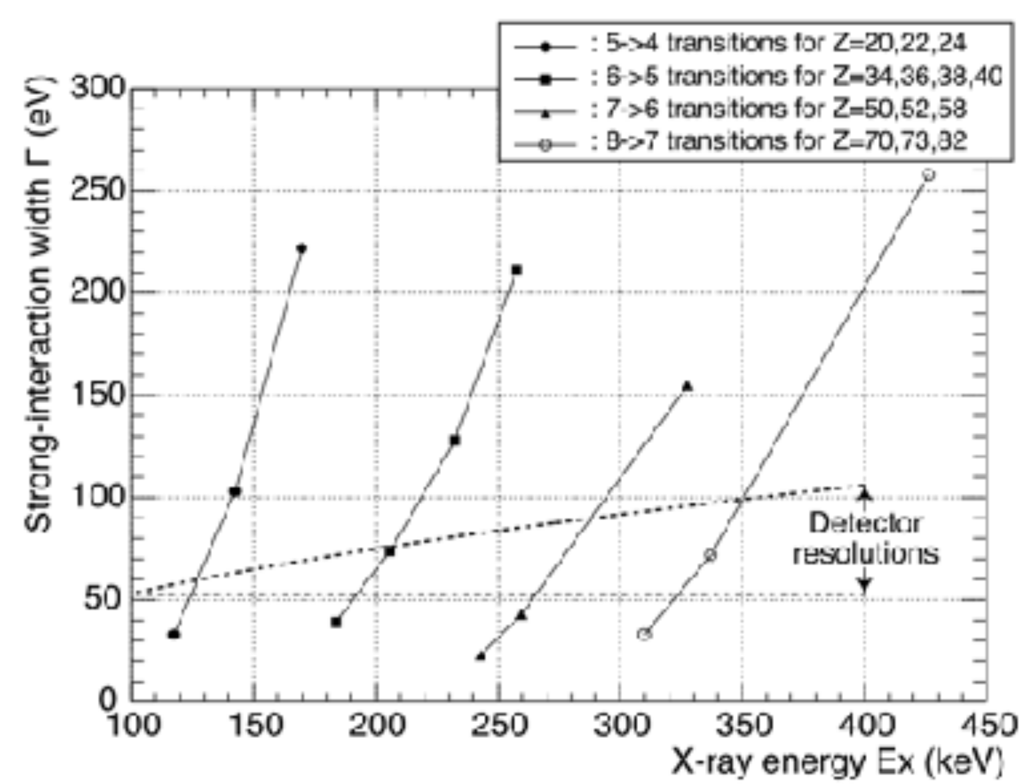
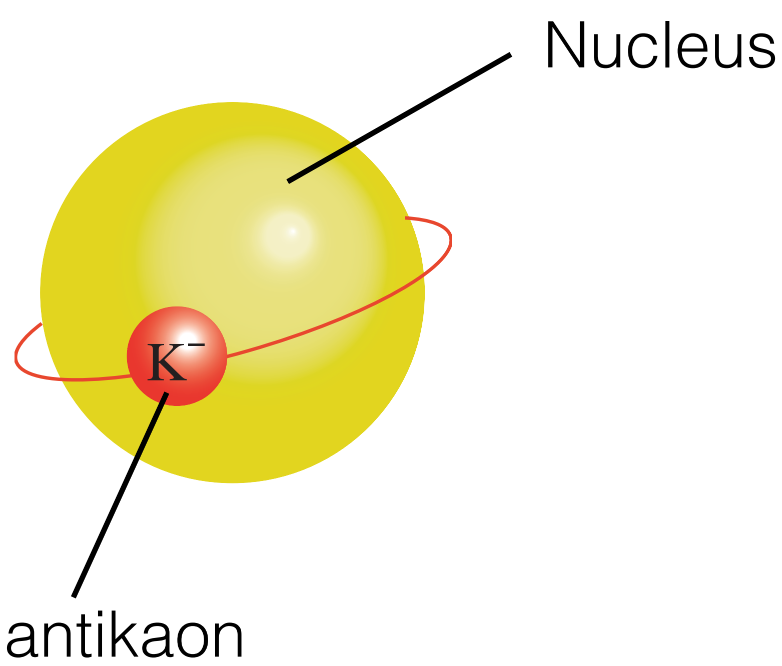


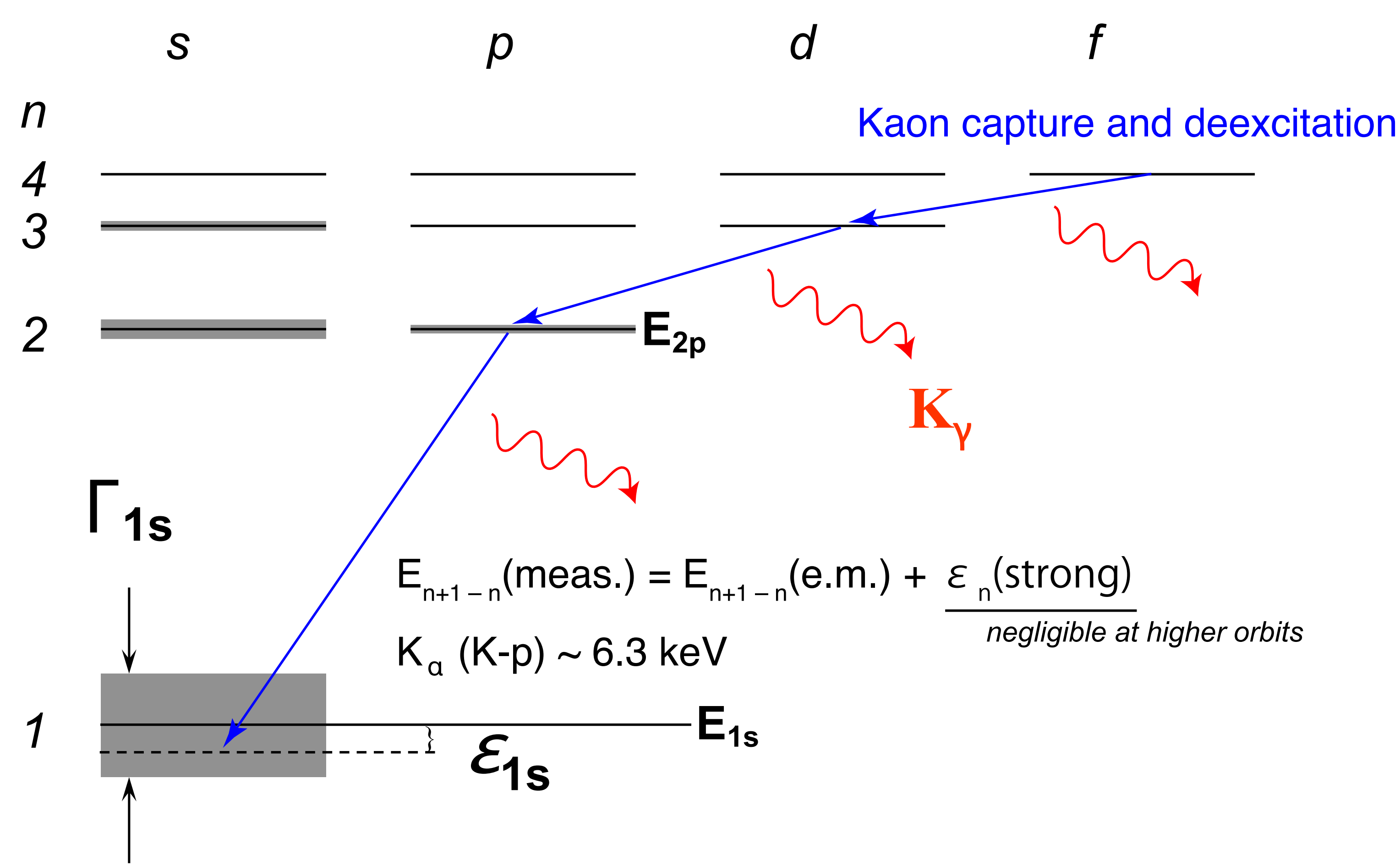
Fig. 5. Summary of upper-level results and the feasibility guideline due to the detector resolution.

Kaonic Atom



Kaon feels strong interaction in addition to the coulomb interaction. For a study of the strong interaction a spectroscopy of lower orbit is interesting, however the strong interaction effect is negligible at higher orbit, therefore one can measure the kaon mass. Right now it's the most precise measurements.

An exotic atom, one atomic electron is replaced by a negatively charged kaon. A bound system primarily by the Coulomb interaction. When slow K⁻s are stopped in a target, K⁻ is first capture at higher orbit, then cascades down, emitting X-rays.



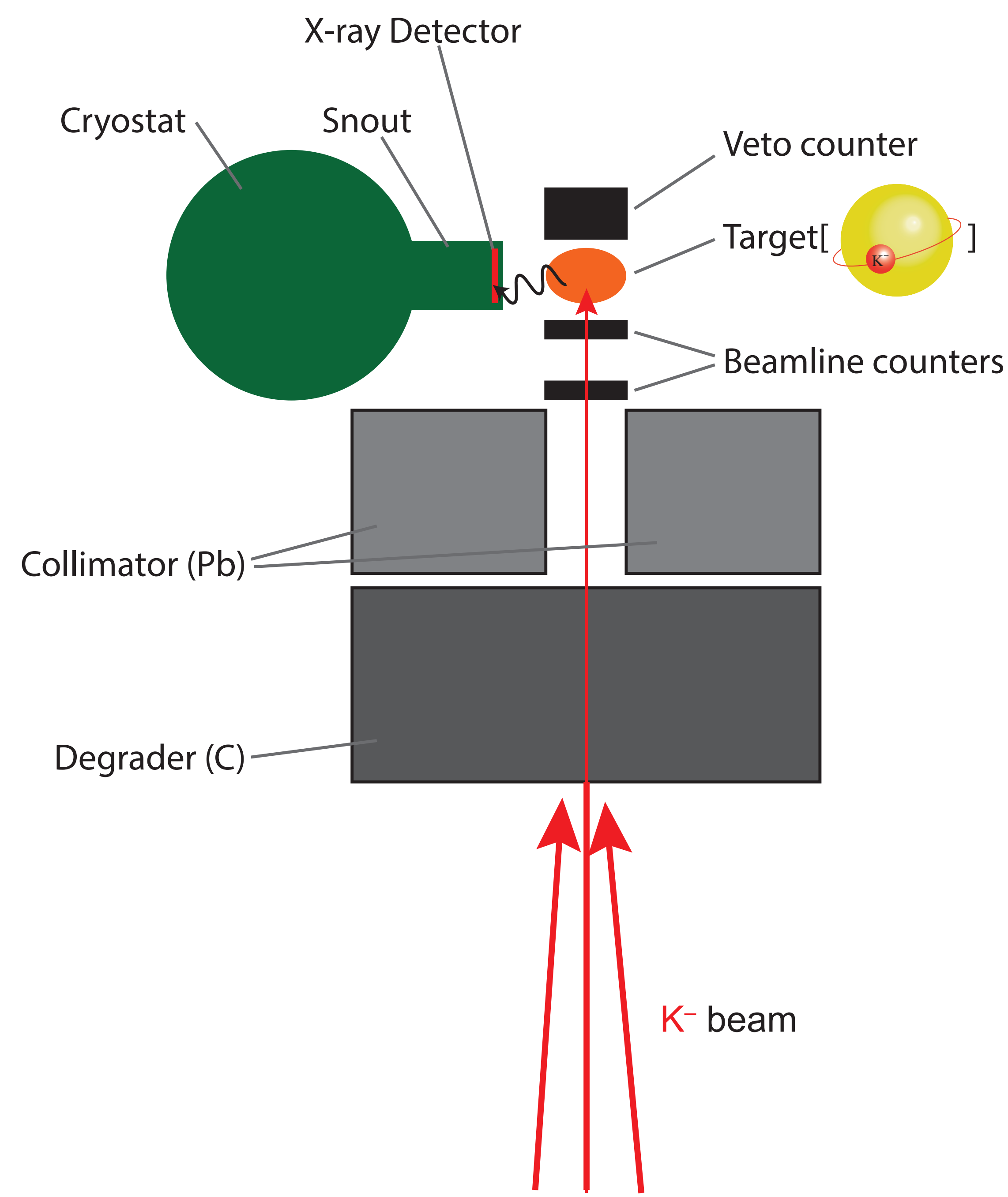
Kaonic Atom Experiment

Typical experimental setup would look like this,

composed by a kaon energy degrader, beam collimator and the target. Several beam line counters to ensure that Kaon stopped in the target.

A LTD system would have a snout to come as close to the target as possible with very thin window. The sensor as well as cryostat should be well protected by the beam halos and other energetic particles that spoils the energy resolution.

Kaon beam is to be provided by the **J-PARC (Tokai, Japan)** or **DAFNE (Frascati, Italy)** facility.



ASPE!CT Project Status

- Cryostat has been built.
  - <500 mK (GGG/FAA)
- KIP-HD has made a detector sample (MPT) optimised at 300 mK - 1 K operation.

- Another EUREKA-EUROSTARS project funded. Start End 2017
  - 1M€, 3 partners (!SMI), 2 years.
- KS applied the "Innovation Fund" of ÖAW
  - 250k€, 1 partner, 2 years.

Innovation Fund, ÖAW

ÖAW AUSTRIAN ACADEMY OF SCIENCES

Abstract for the project

"Development of a compact sub-Kelvin detector system for nuclear forensics and nuclear accountancy applications"

In 2015/2016, the Stefan Meyer Institute successfully conceived and built a dry sub-Kelvin cryostat as a platform for cryogenic detectors with very high resolution. The intended use was to measure the mass of the kaon, a sub-atomic particle, by measuring the energies of x-rays emitted from kaonic atoms. During the development it became apparent that the remarkable properties of the cryogenic detectors in question could be put to effective use outside the original physics use-case.

We want to combine the recently developed cryogenic infrastructure at the SMI with novel superconducting detector technologies to make a versatile, compact, portable, high-resolution, cryogenic spectrometer for x- and γ -ray detection up to 200 keV, which is specifically aimed to address nuclear safety issues including forensics and accountability for the validation of international nuclear non-proliferation treaties. This area of application lies outside the traditional subatomic arena of the Stefan Meyer Institute, but we find it very important to exploit our newly found expertise for a topical, real-world application with societal relevance.

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7 May 2017

Supporting Letter for the Project

Cryogenic High Resolution Spectrometer for Advanced Nuclide Analysis

Quantitative isotopic analysis, such as measurements of ^{235}U enrichment or isotopic and composition of Pu, is a one of the key elements of nuclear material verifications for safeguards purposes.

Methods of gamma ray spectroscopy are used for isotopic analysis. The gamma spectroscopy of the energy range of 80-100keV (for uranium enrichments), 120-150keV and around 200keV (for plutonium isotopic compositions) are mainly used for the nuclear safeguards verification activities by International Atomic Energy Agency (IAEA). Due to the complicity of nuclear energy levels, which involve many gamma lines in an energy range, the analysis relies on the peak fitting method on the gamma spectrum acquired by means of Ge detectors. The analysis results give relatively large uncertainties due to the fitting errors in cases.

Cryogenic high resolution Spectrometers may result significantly better energy resolutions in relatively low gamma energy range. They will give clear separations between gamma lines in acquired spectrum, thus analysis result significantly small uncertainties for uranium enrichment or plutonium isotopic composition measurements. Development of portable, robust cryogenic high resolution spectrometer will certainly improve the quality of IAEA nuclear safeguards verification in the field.

Significant improvement of energy resolution of relatively low energy gamma ray measurements may also give large impacts in the fields which involve isotopic analysis of heavy elements, such as impurity analysis in nuclear materials, which can be used unique finger printing to identify the origin of the materials, detection of radioactive noble gas, such as radioactive xenon or argon 37, which are caused by nuclear explosions.

The development of cryogenic high resolution spectrometer will give significant impacts for verifications on nuclear non proliferation and disarmament. This technique can be applied in many different verification methods, including verifications mentioned above, and will improve qualities of verifications significantly.

Summary and Outlook

- LTD, extremely good resolution, wide applications, still rarely used in Hadron physics experiments
- HEATS collaboration (S. Okada, H. Tatsuno, T. Hashimoto, ..)
- ASPE!CT Collaboration (K. Suzuki, K. Phelan, ..)
- Application, kaonic atom x-ray measurements, nuclear forensics and more.