The Condensed Krypton Source as a Calibration Tool for KATRIN

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The KATRIN experiment

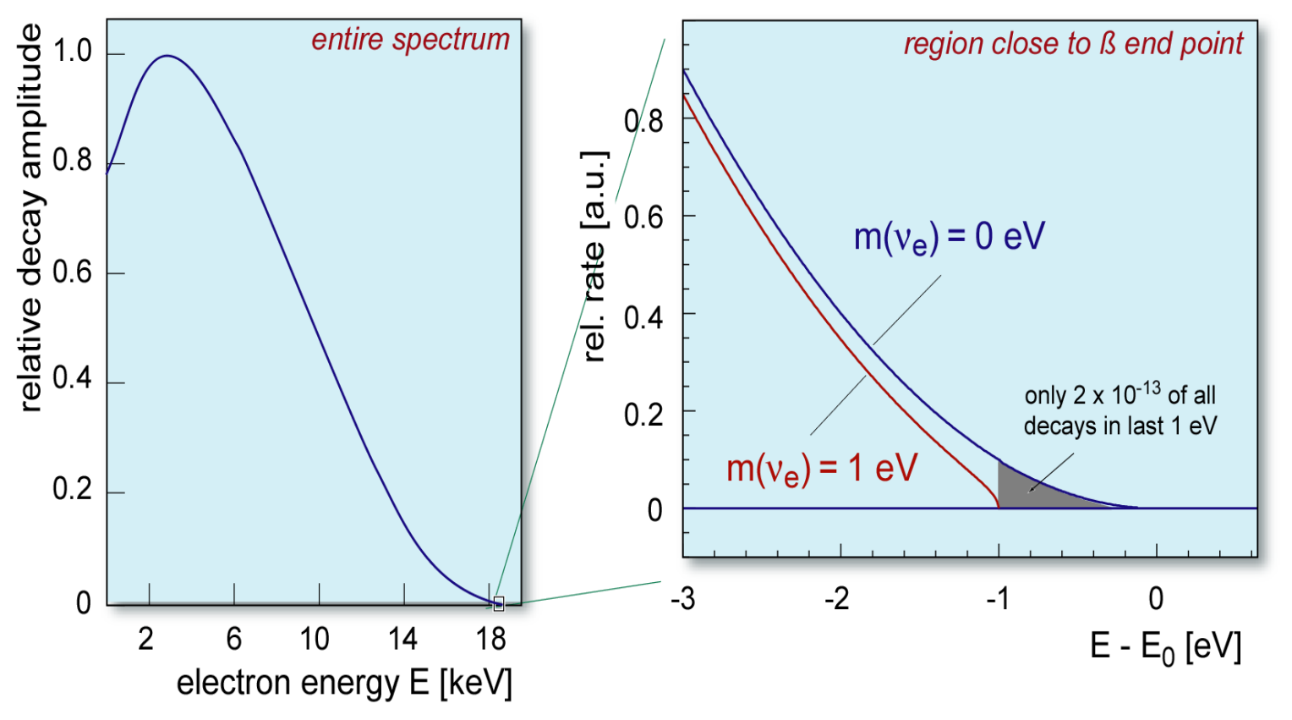
Kinematic determination of m(ν_e)

$$\frac{d\Gamma}{dE} = Cp\,(E+m_e)\,(E_0-E)\sqrt{(E_0-E)^2-m_{\nu e}^2}\,F\,(Z+1,E)\,\Theta\,(E_0-E-m_{\nu_e})\,S(E)$$

$$C = \frac{G_F^2}{2\pi^3}\cos^2\theta_C\,|M|^2$$

$$m_{\nu_e}^2 = \sum_{i=1}^{3}|U_{ei}|^2\,m_i^2$$

(modified by final states, recoil corrections, radiative corrections, …)



Requirements

- ➔ low endpoint energy
- ➔ high source luminosity
- ➔ high energy resolution
- ➔ very low background
- ➔ stability of experimental parameters on the per mil to ppm level

→ **MAC-E filter concept**

Tritium β-decay

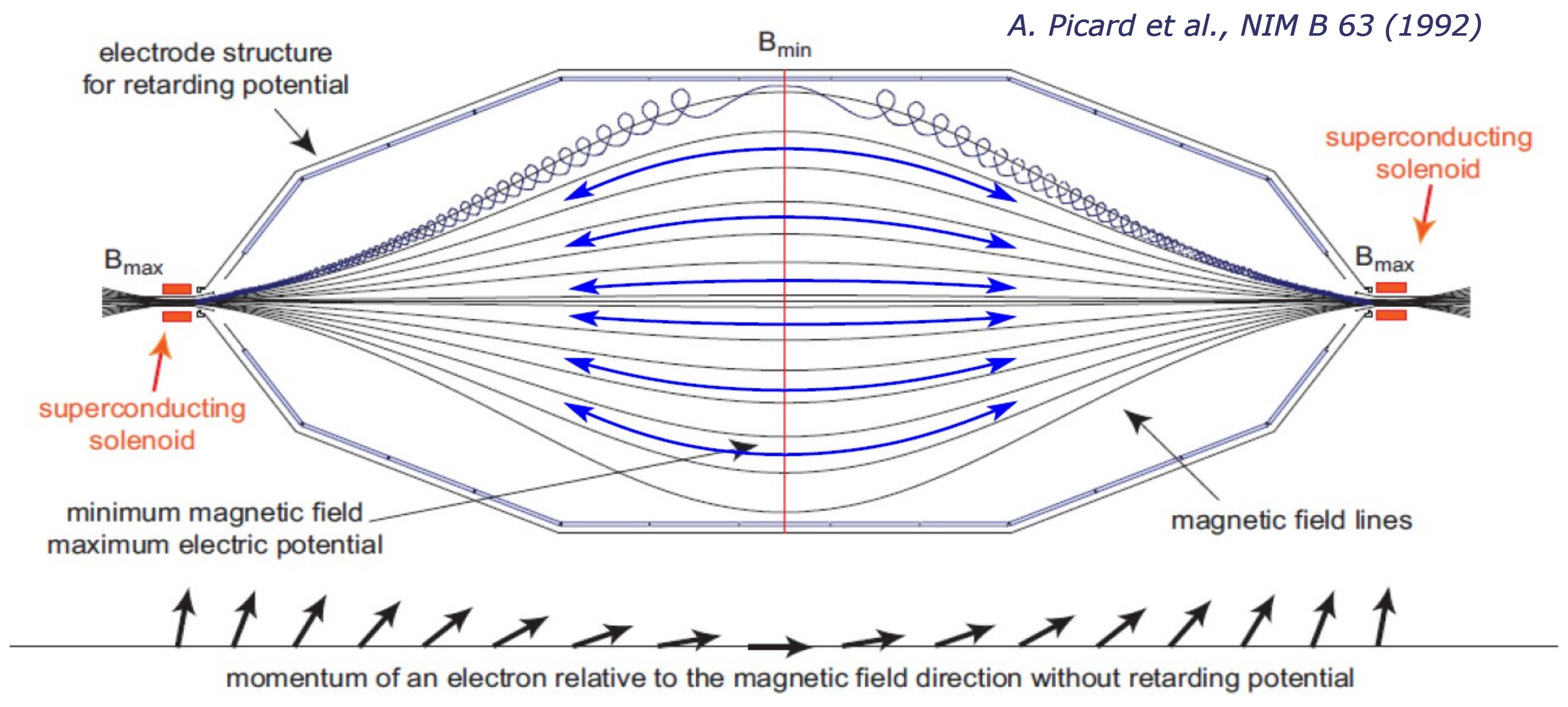
E_0 = 18.6 keV, $T_{1/2}$ = 12.3 a
S(E) = 1 (super-allowed)

MAC-E filter concept

V.M. Lobashev et al., Nucl. Instrum. Methods, A240 (1985)

Magnetic Adiabatic Collimation with Electrostatic Filter

A. Picard et al., NIM B 63 (1992)

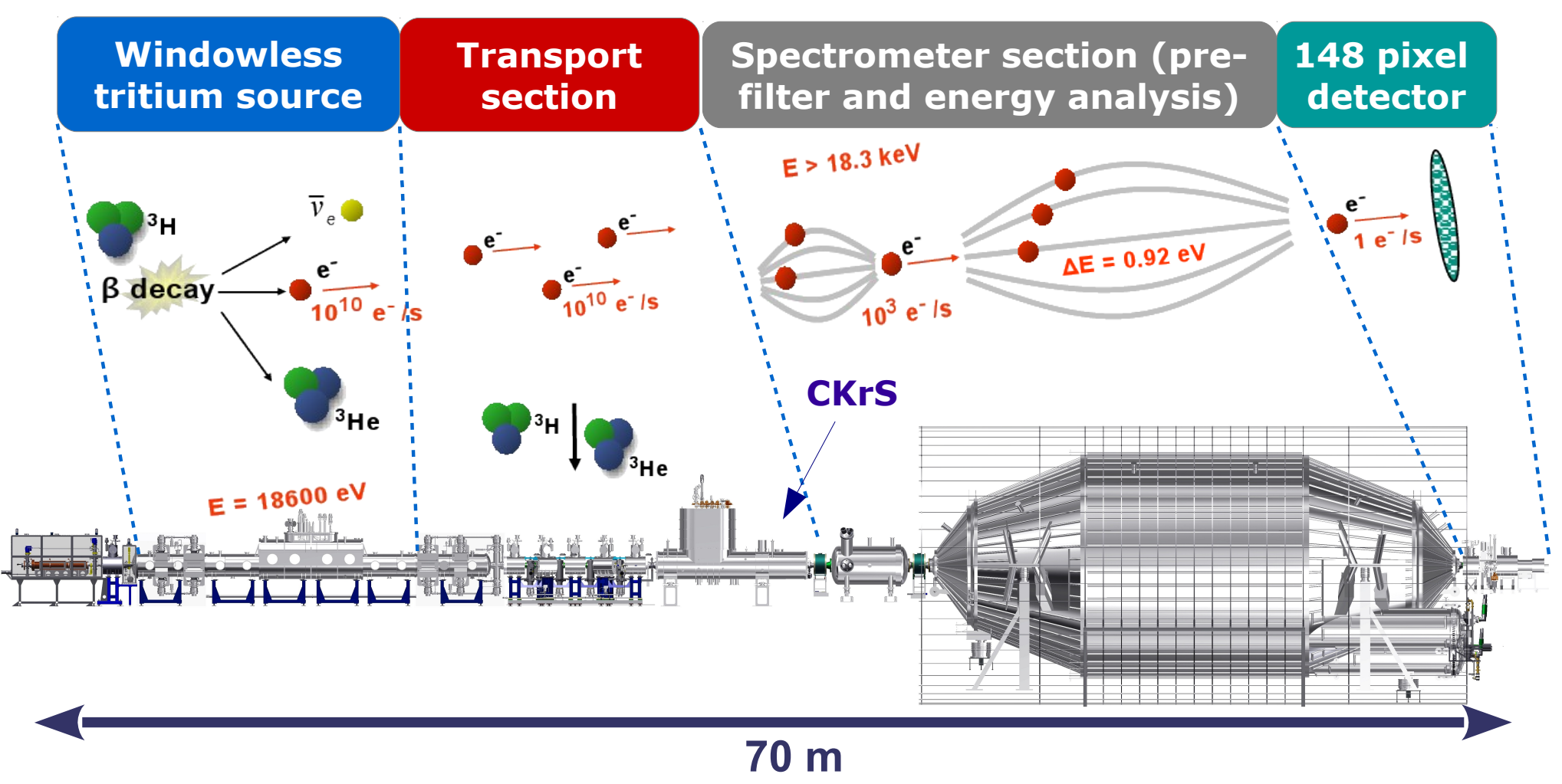


- ➔Adiabatic transport, $\mu = E_\perp / B$ = const.

B drops by $2\cdot10^4$ from solenoid to analyzing plane, $E_\perp \rightarrow E_{||}$

- ➔Only electrons with $E_{II} > eU_0$ can pass the retarding potential
- ➔Energy resolution $\Delta E = E_{\perp,\text{max, start}}\cdot B_{min} / B_{max} \approx 1$ eV

KATRIN experiment at KIT



KATRIN design sensitivity:

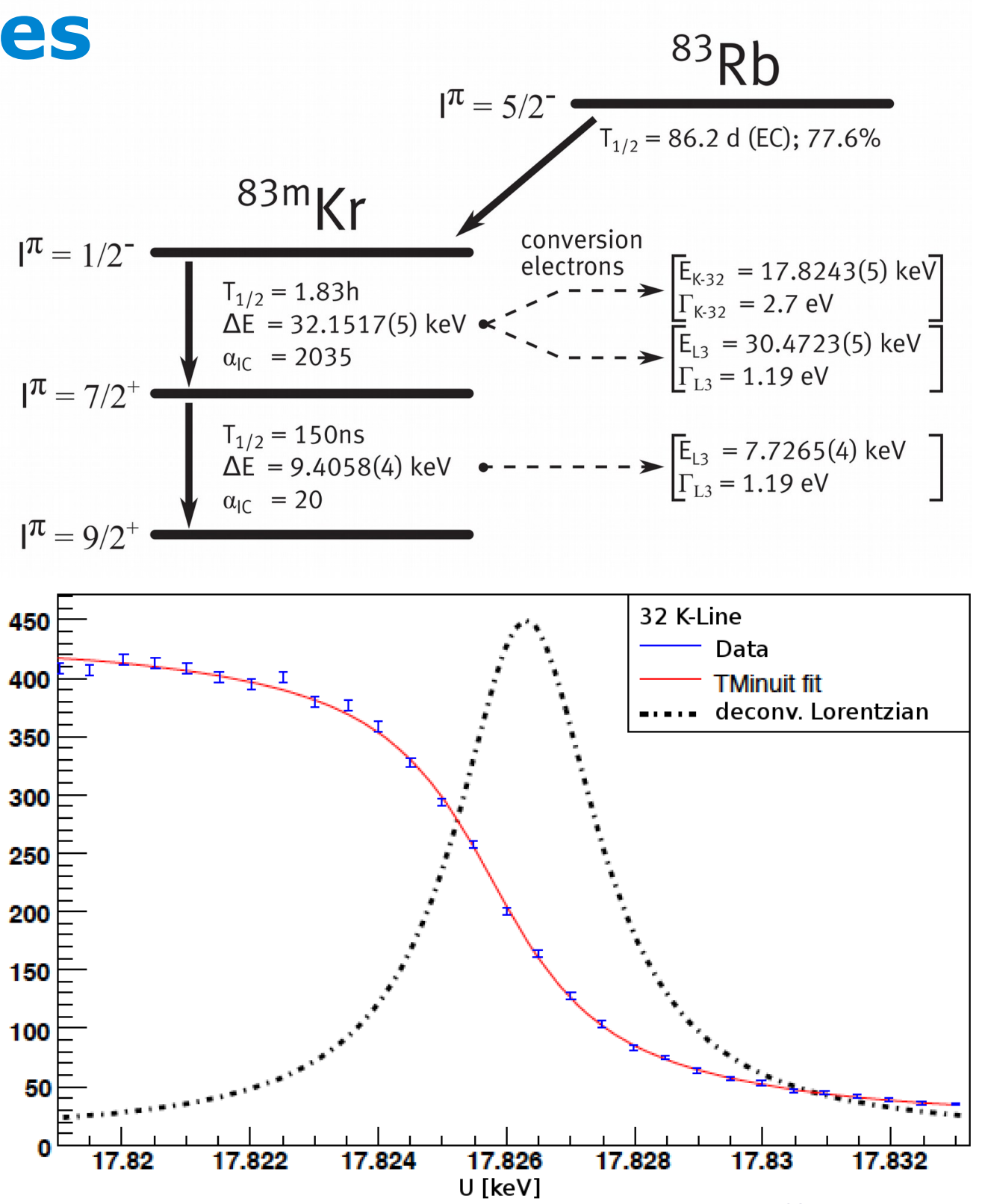
5 year measurement (eff. 3 y of data)

- ➔ statistical uncertainty σ(stat) ≈ 0.018 eV²
- ➔ systematic uncertainty σ(sys,tot) ≈ 0.017 eV²
- ➔ sensitivity for upper limit 0.2 eV/c² (90 % C.L.)
- ➔ 5σ discovery potential: m(ν_e) = 0.35 eV

The Condensed Krypton Source (CKrS)

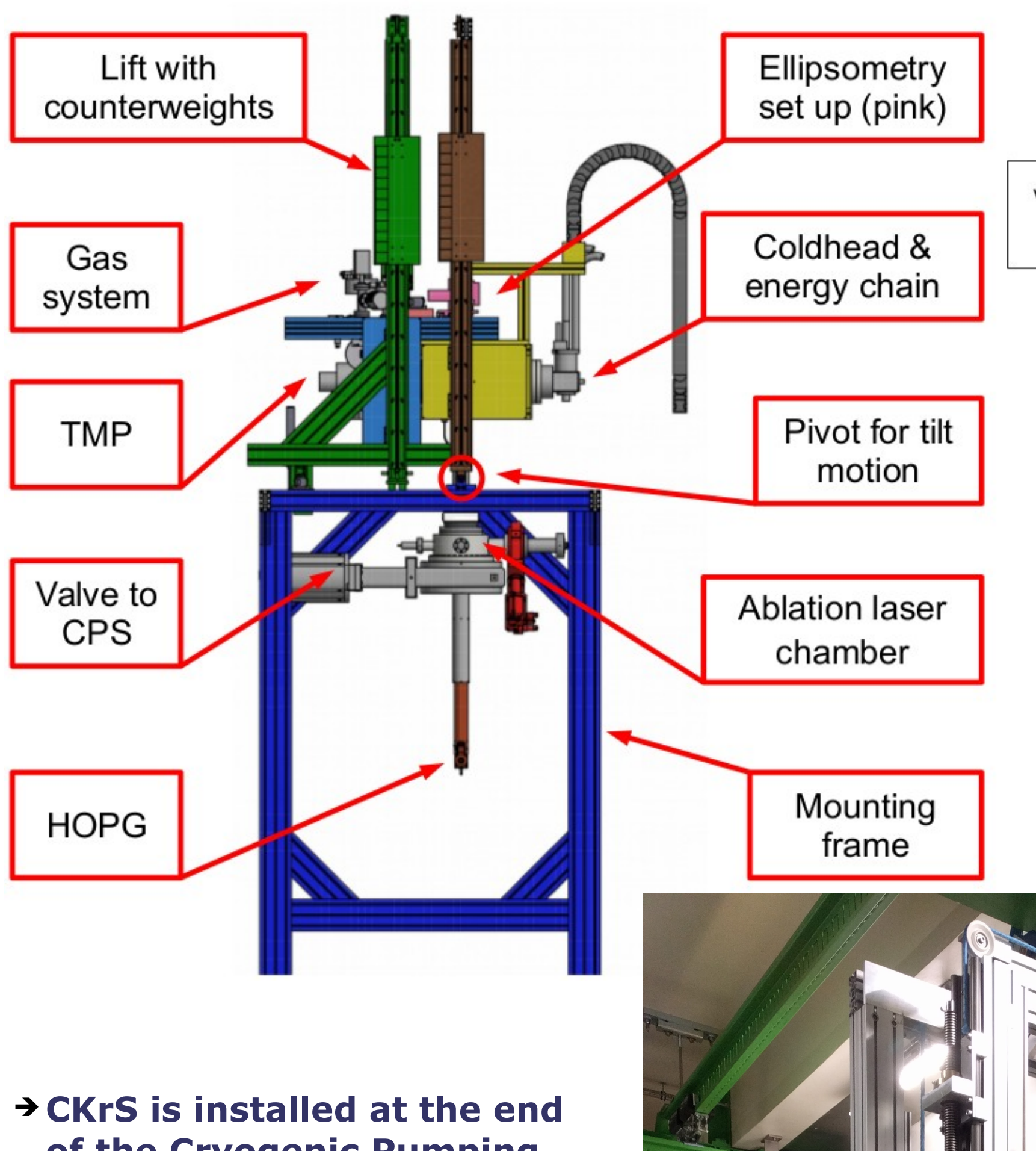
Motivation and features

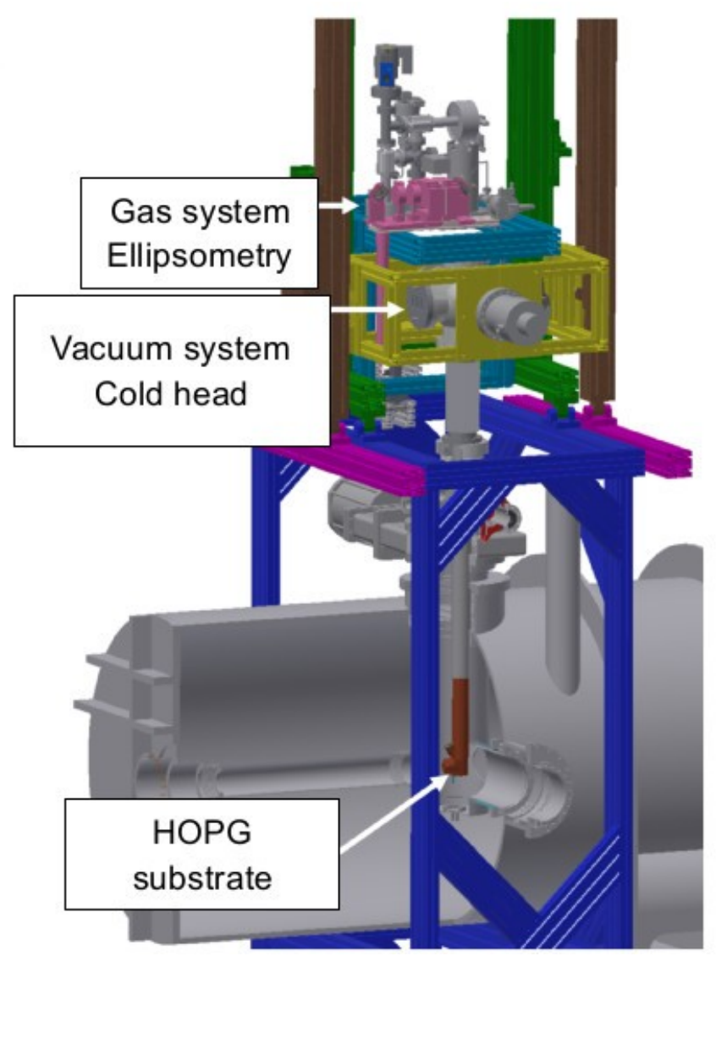
- ➔ Energy calibration of KATRIN by a nuclear standard
- ➔ Meta stable ^{83m}Kr is condensed onto a Highly Oriented Pyrolytic Graphite (HOPG) substrate
- ➔ Isotropically emitting conversion electron source
- ➔ Several nearly mono-energetic lines of different energy to check the transmission function
- ➔ K-32 line near the tritium endpoint
- ➔ Short life-time of ^{83m}Kr prevents contamination of spectrometers
- ➔ Motion system allows for per-pixel calibration
- ➔ Energy stability of conversion lines in the ppm range demonstrated at former Mainz Neutrino experiment
- ➔ *In-situ* monitoring of film properties via laser ellipsometry



Adapted from: B. Ostrick, Eine kondensierte ^{83m}Kr-Kalibrationsquelle für das KATRIN-Experiment (2008)

Experimental setup

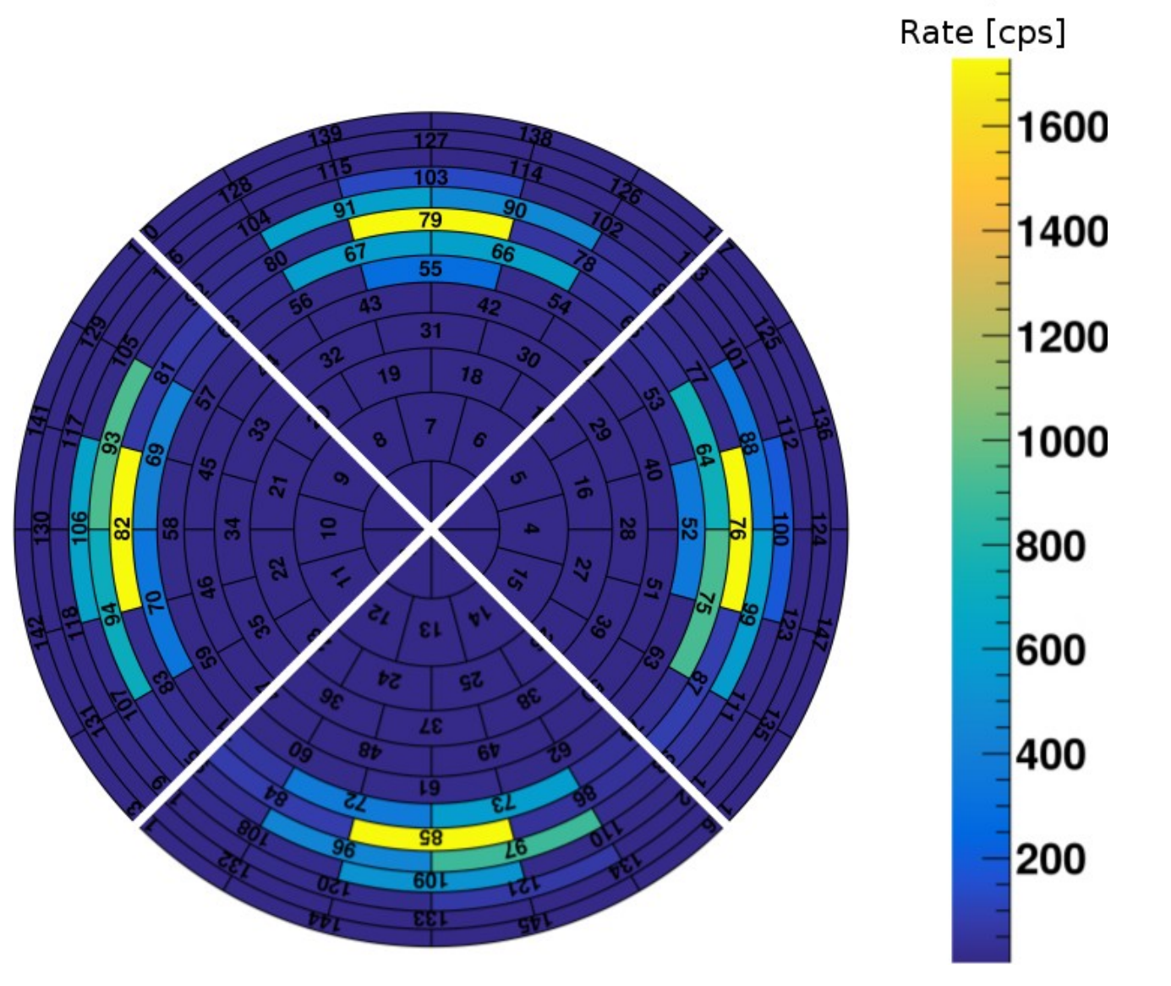




- ➔ CKrS is installed at the end of the Cryogenic Pumping Section
- ➔ Subsystems are placed on a scaffolding, which can be driven vertically as well as horizontally
- ➔ This allows film preparation and ellipsometry measurements outside of the beam-tube
- ➔ Insertion and retraction is fast, so calibration runs with the CKrS do not interfere with neutrino mass measurements
- ➔ The lift can be put onto high voltage to shift the K-32 conversion line to the tritium endpoint energy

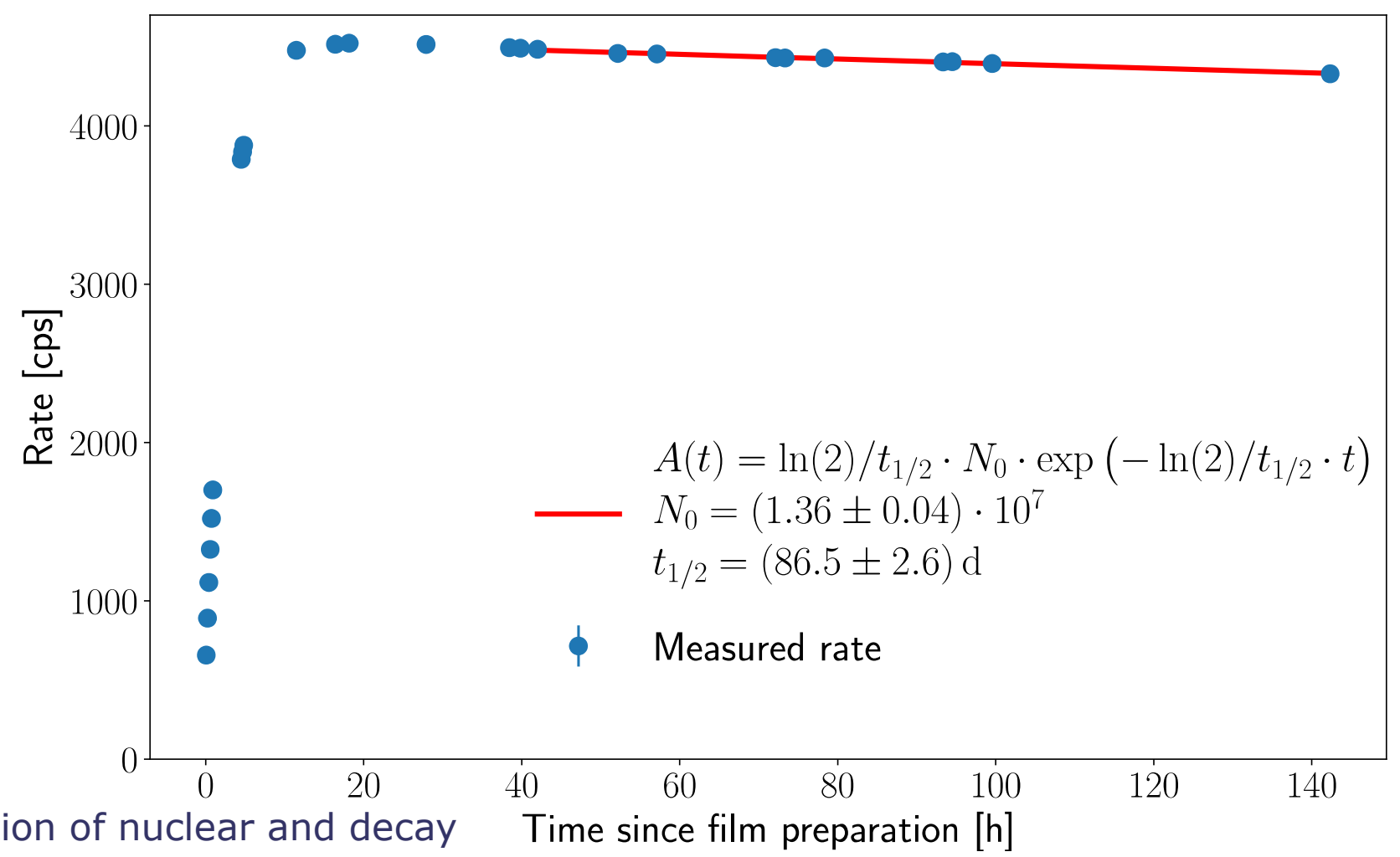
First measurements

- ➔ CKrS positioning inside the flux tube via two motors
- ➔ Ability to illuminate each of the 148 detector pixels for full spectrometer characterization
- ➔ Safety software and hardware end switches to prevent collisions with the beam-tube



^{83m}Kr film preparation

- ➔ For defined starting conditions, the substrate is heated up to around 120 K and then ablated with a frequency doubled Neodym-YAG-Laser (2 W @ 532 nm) before it is cooled down to 27 K
- ➔ After opening the valve to the rubidium generator, the gaseous krypton streams through a capillary towards the cold substrate
- ➔ Radioactive ^{83m}Kr is continuously condensed onto the HOPG substrate
- ➔ Count rate development after first inlet has been measured with stability runs at a fixed spectrometer voltage (31212 V)
- ➔ The conversion electron rate saturates after about 15 hours and follows the ^{83}Rb half-life (86.2 d*) in the long term

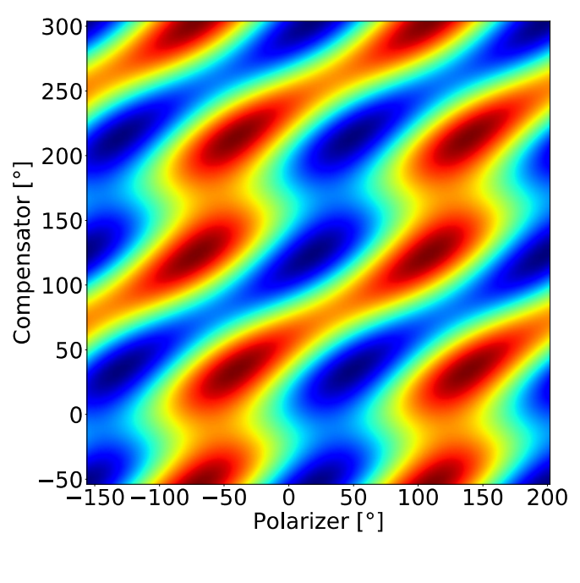


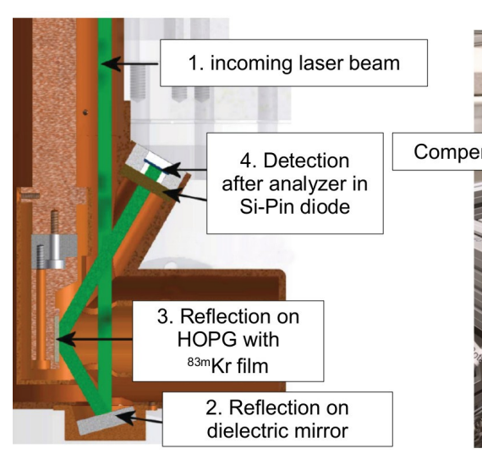
$$A(t) = \ln(2)/t_{1/2}\cdot N_0\cdot\exp\left(-\ln(2)/t_{1/2}\cdot t\right)$$
$$N_0 = (1.36\pm0.04)\cdot10^7$$
$$t_{1/2} = (86.5\pm2.6)\,\mathrm{d}$$

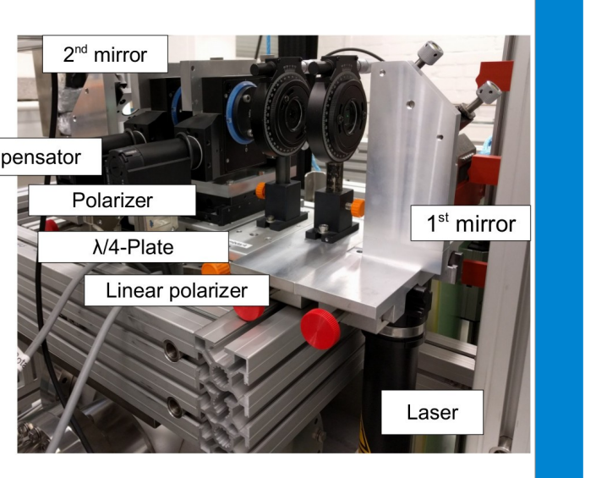
[*] G. Audi et al. ,"The NUBASE evaluation of nuclear and decay properties". Nuclear Physics A. 729: 3–128 (2003)

Laser ellipsometry system

- ➔ Thin film investigation by measuring polarization changes upon reflection
- ➔ Null ellipsometry: find polarizer and compensator angle for which the reflected light is minimal, this depends on refractive index and film thickness
- ➔ Condensation of radioactive krypton alone should not lead to a shift since the used amount is too low to yield an observable effect
- ➔ Ellipsometry can be used to monitor the vacuum conditions very precisely and to produce input data for modeling of the film



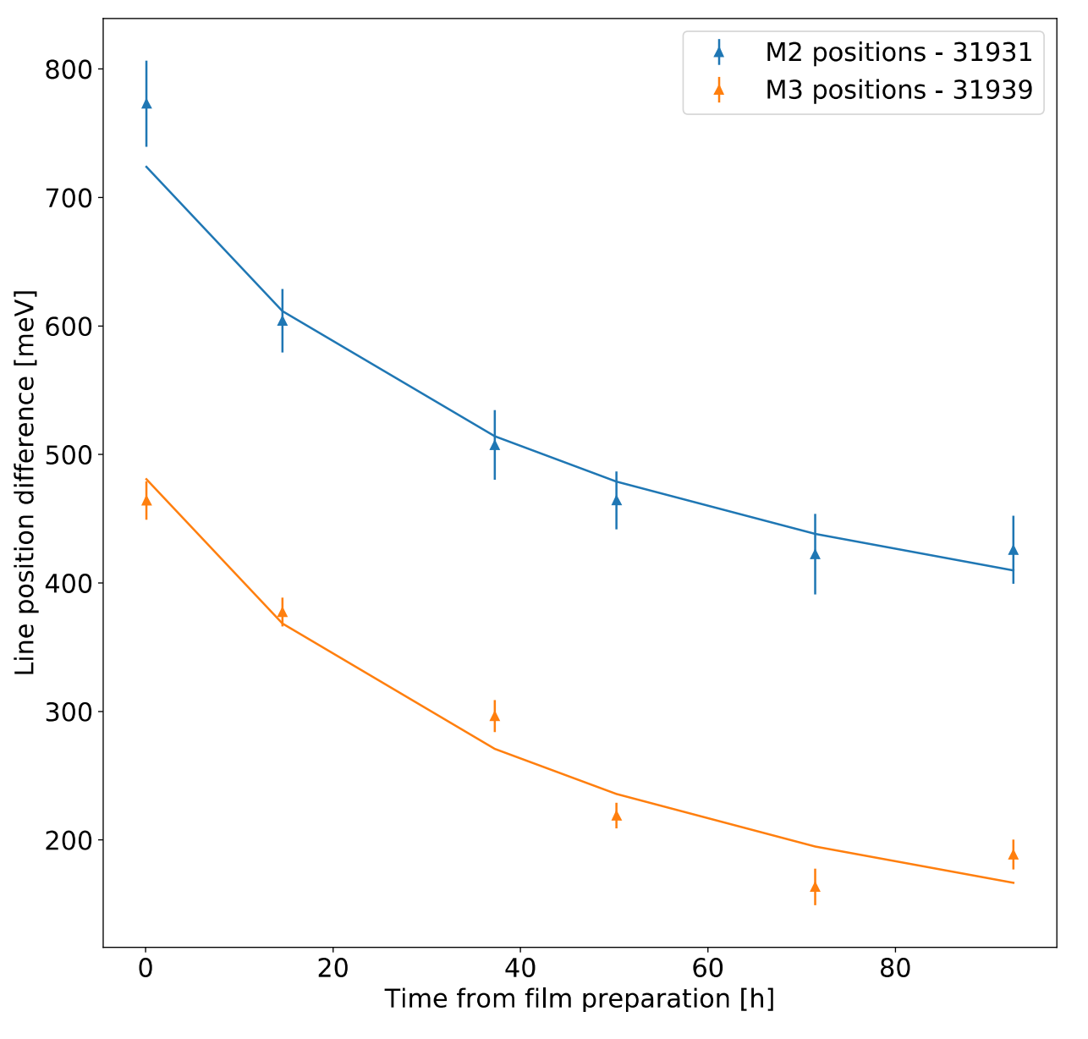




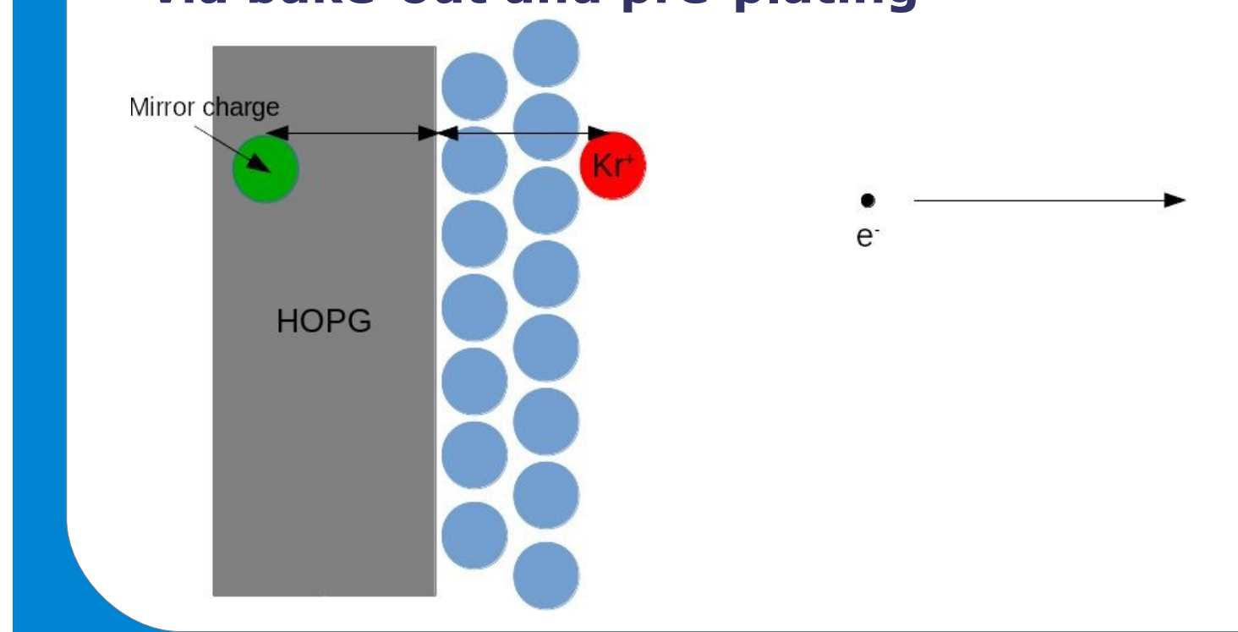
from: M. Fedkevych

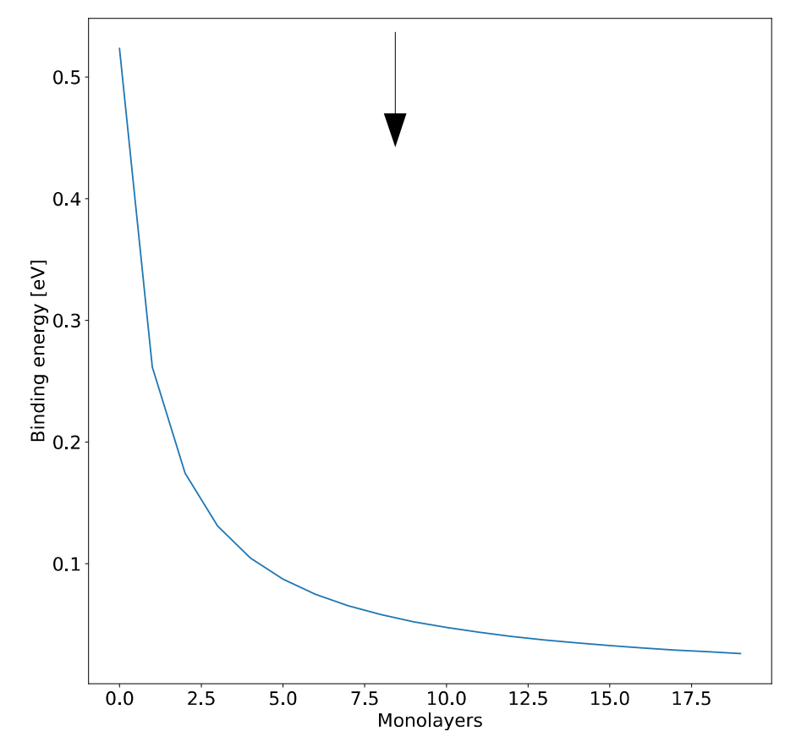
Line stability

- ➔ Drift of line position towards lower energies over time
- ➔ Energy seems to stabilize for longer times
- ➔ Same behavior for different lines
- ➔ Positive krypton ion and its image charge in the substrate form a bound system
- ➔ Binding energy is given to the electron as additional kinetic energy
- ➔ As more residual gas condenses onto the substrate, the distance between a decaying krypton atom and the substrate becomes larger and the binding energy decreases
- ➔ Assuming a linear growth (backed by ellipsometry data) the line position can be fitted with the image charge model
- ➔ For use as a calibration source the energy stability must be improved via bake-out and pre-plating



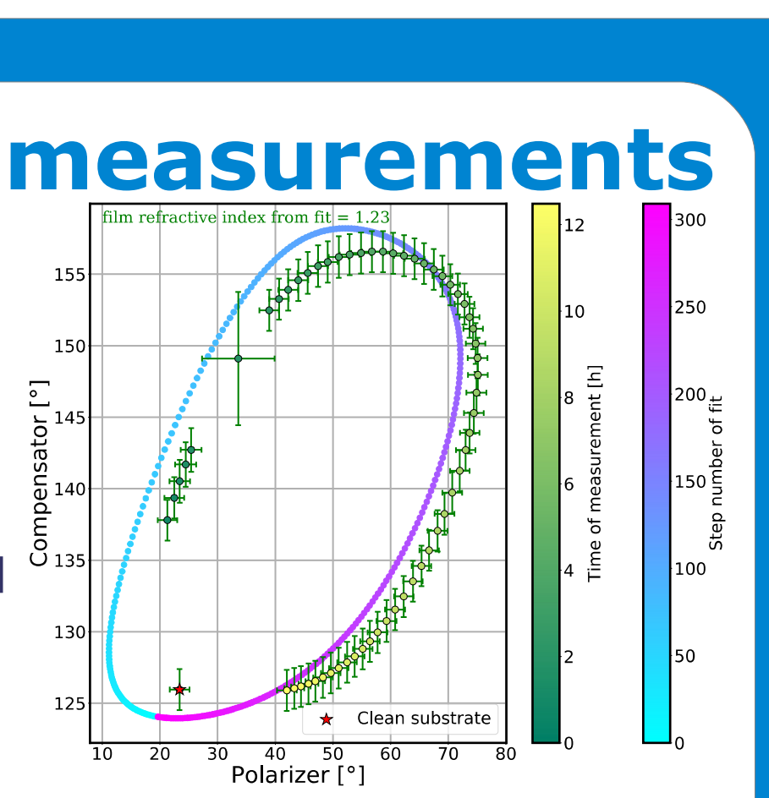
$$V(t) = \frac{1}{2}\frac{1}{4\pi\epsilon_0}\frac{q\cdot q}{2(a\cdot t+b)a_{\mathrm{Kr}}}+c$$

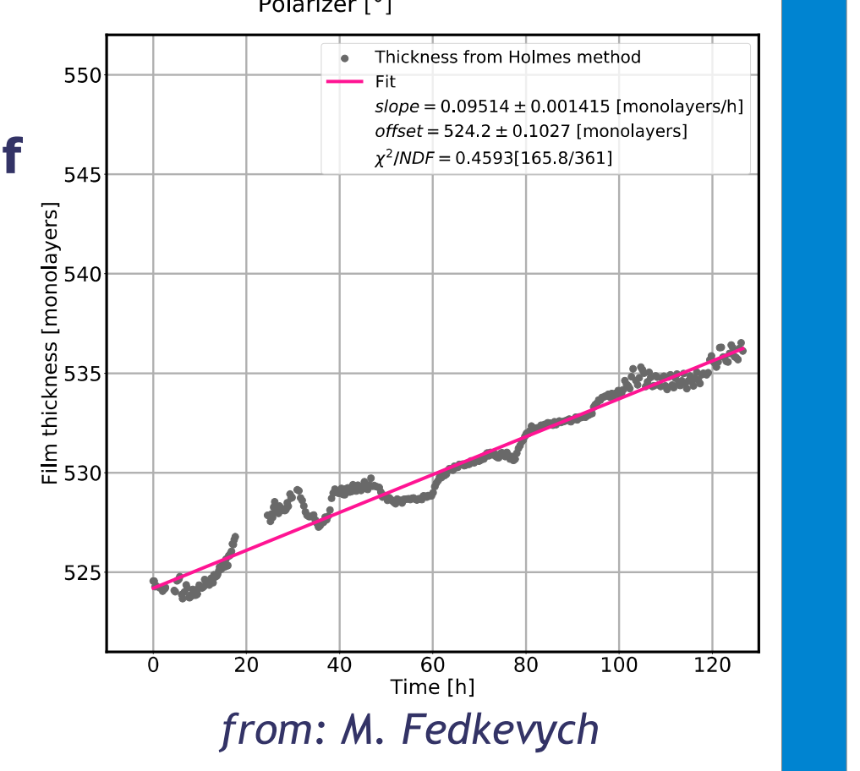




Ellipsometry measurements

- ➔ Large amounts of stable krypton can be condensed onto the substrate for tests
- ➔ Data can be compared to a calculated "ellipse" or film parameters can be extracted via the Holmes method* (analytical solution of the inverse ellipsometry problem)
- ➔ For the radioactive films the growth is linear and the rate decreases for later films
- ➔ This indicates an improvement of the vacuum conditions over time
- ➔ The ellipsometry system may also provide additional information about the structure of the film





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- ➔ The Holmes method yields a growth speed of 0.095 monolayers/h krypton equivalent for the last film, whereas the image charge fit gives 0.029 monolayers/h
  - ➔ further investigations required

[*] D. A. Holmes, "On the Calculation of Thin Film Refractive Index and Thickness by Ellipsometry," Appl. Opt. 6, 168-169 (1967)

Summary/Outlook

- ➔ Successful commissioning of the CKrS @ KATRIN, conversion electrons can be analyzed by the spectrometer and detected at the FPD
- ➔ Rate stabilizes around 15 hours after beginning of film preparation
- ➔ Drift of line positions with time
  - ➔ can be explained by the image charge model and residual gas freezing onto the substrate
  - ➔ backed by ellipsometry data
  - ➔ need for better vacuum conditions and additional methods (e.g. pre-plating) to stabilize the line energy
  - ➔ extended bake-out this June
- ➔ Ellipsometry measurements provide valuable data and allow for *in-situ* measurements of film properties
  - ➔ additional data about the residual gas composition from a RGA can be included for the next measurements
- ➔ Next measurements with the spectrometer and detector system in July & August with two main goals:
  - ➔ 1. find a configuration where the line position is stable over several hours/days
  - ➔ 2. scan the analyzing plane of the main spectrometer to map inhomogeneities and check the alignment of the subsystems

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