ISOLTRAP beam preparation for a Tape-Station and the Ultra-low Q-value measurement for The neutrino mass limits

André Welker

31.03.2014

GK Spring Meeting

Krippen

Outline

ISOLTRAP:

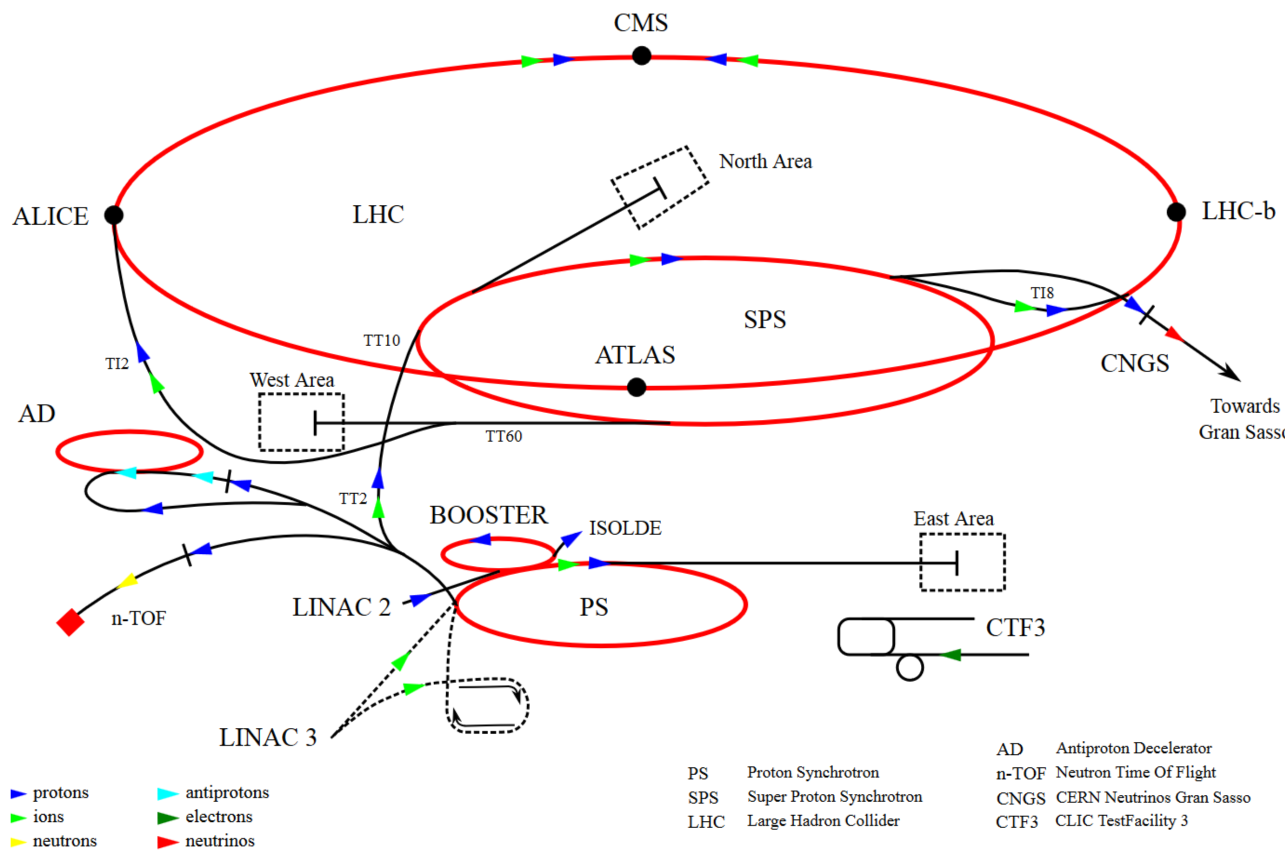
- **Setup overview and what we can do with ISOLTRAP**
- **New feedthrough system for electro optical tools**
- **Status of the first ion beam SIMION simulation**

Beta-Spectroscopy:

- **Good for more physics, ultra-low Q-value and neutrino mass measurement**
- **Ultra-Low-Beta-Spectroscopy setup at TU-Dresden**
- **First background measurement results and what we can learn**

CERN/ISOLDE/ISOLTRAP

Overview:



http://www-ap.gsi.de

ISOLDE/ISOLTRAP

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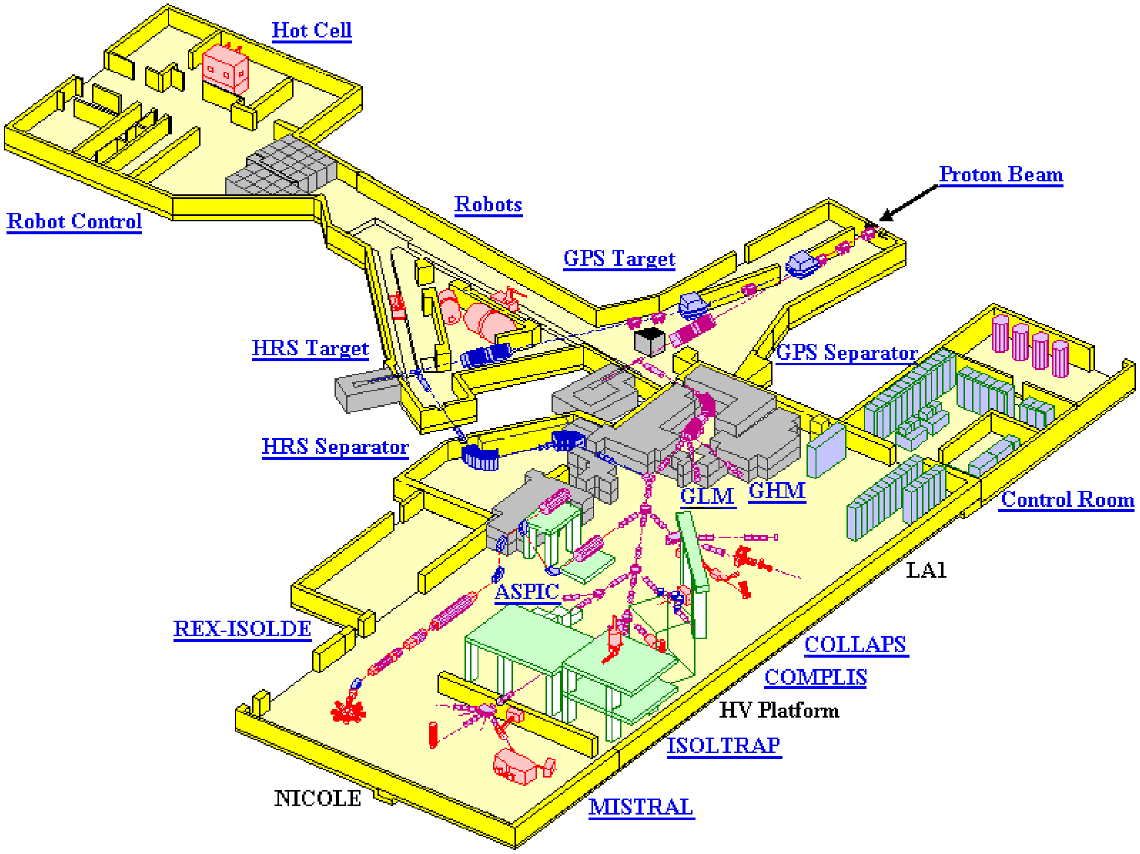

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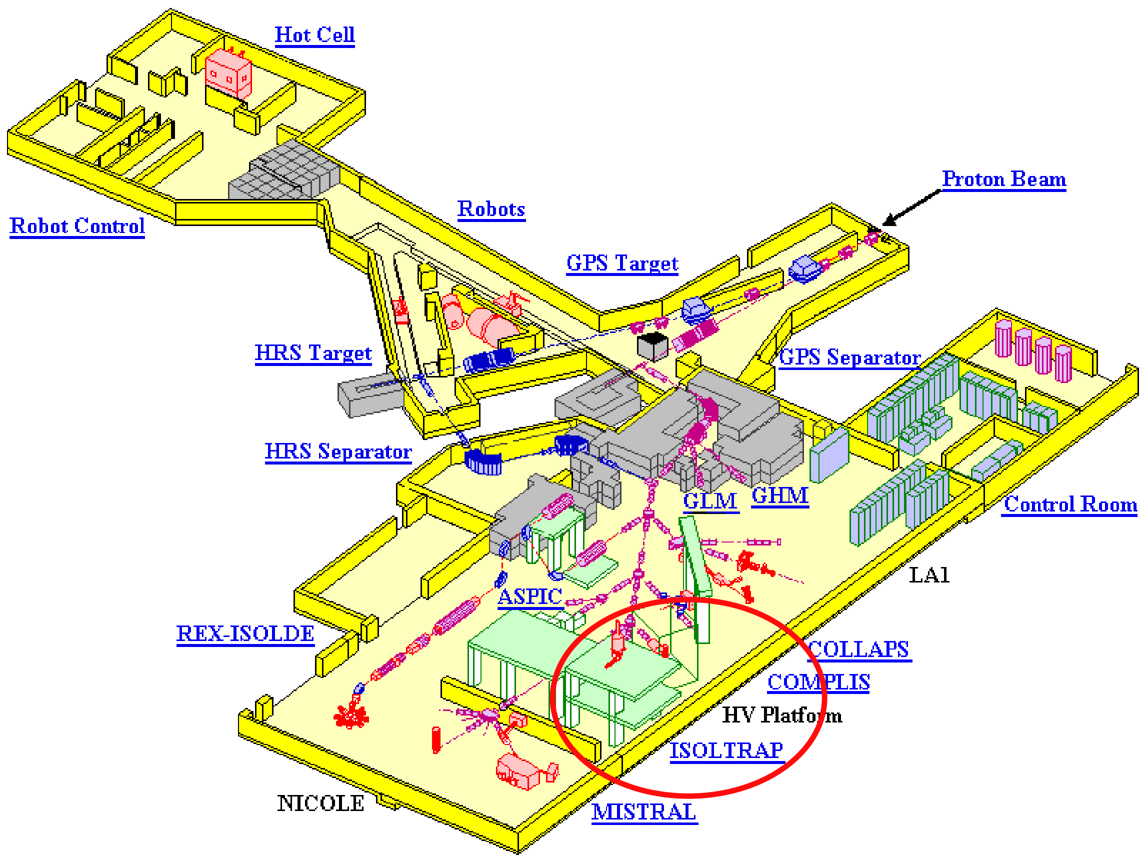
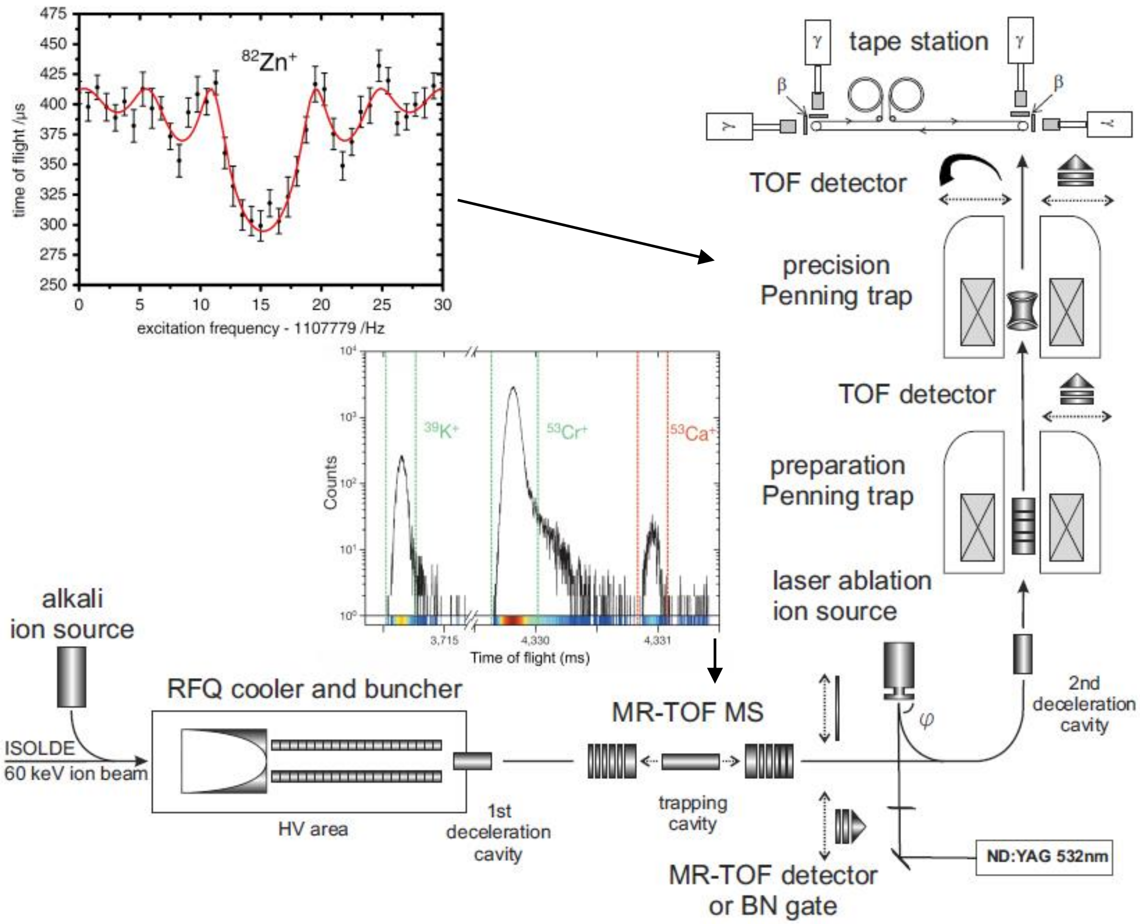
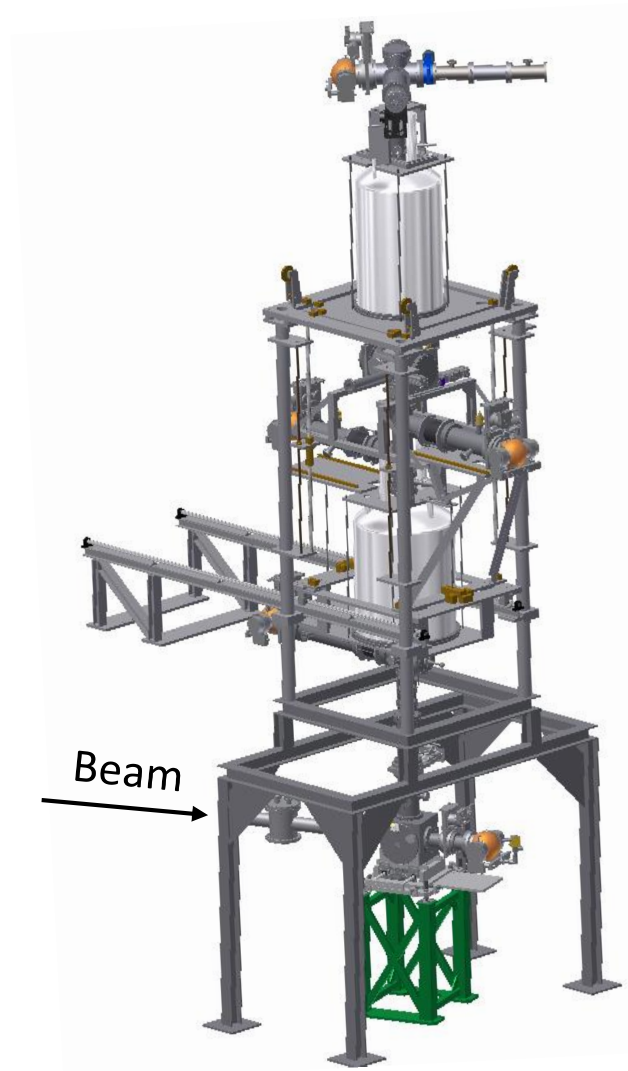


http://www-ap.gsi.de

ISOLTRAP

Mass measurement/whole setup:

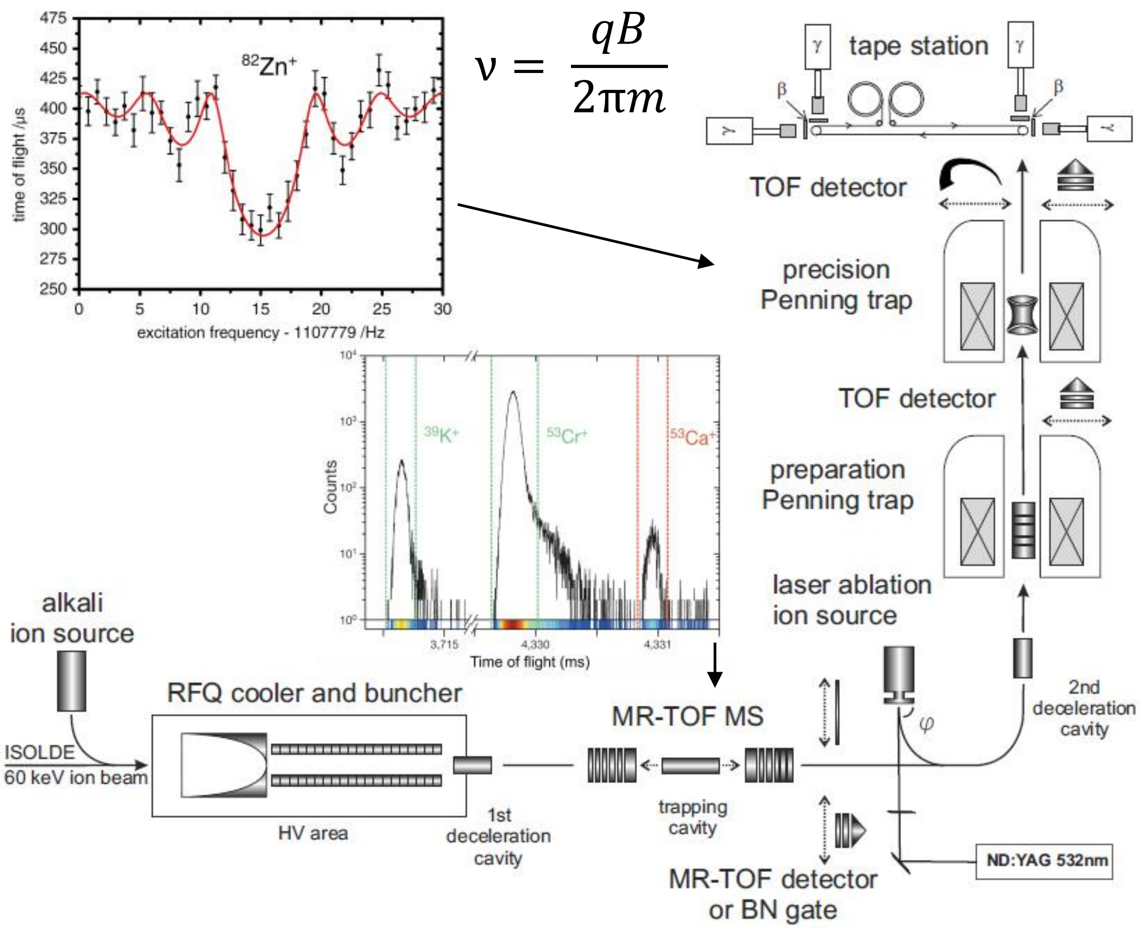


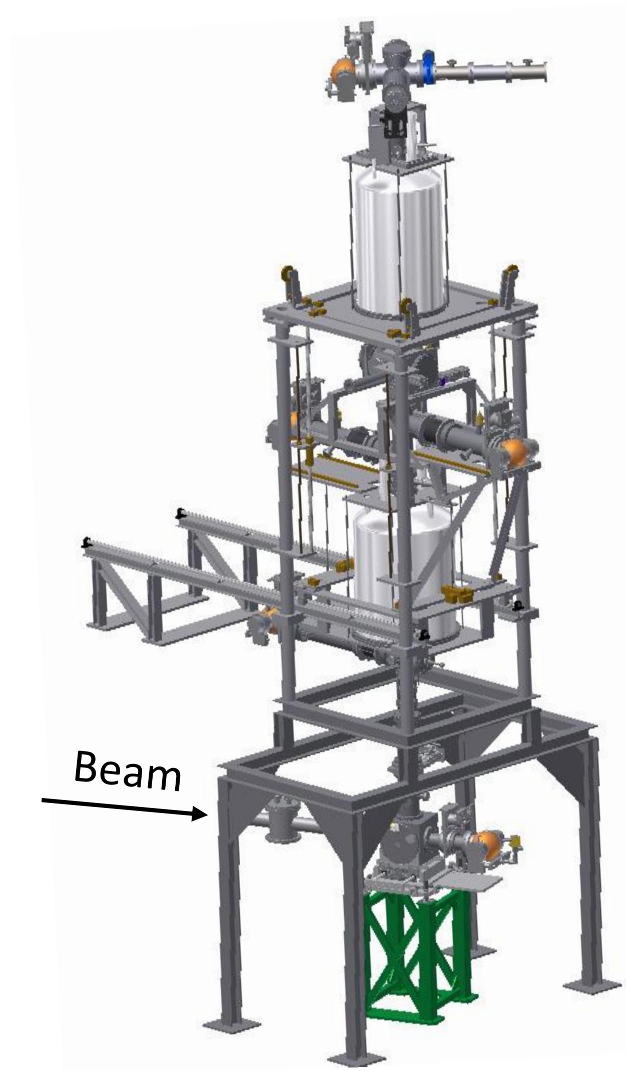


ISOLTRAP

Mass measurement/whole setup:

$$\nu = \frac{qB}{2\pi m}$$

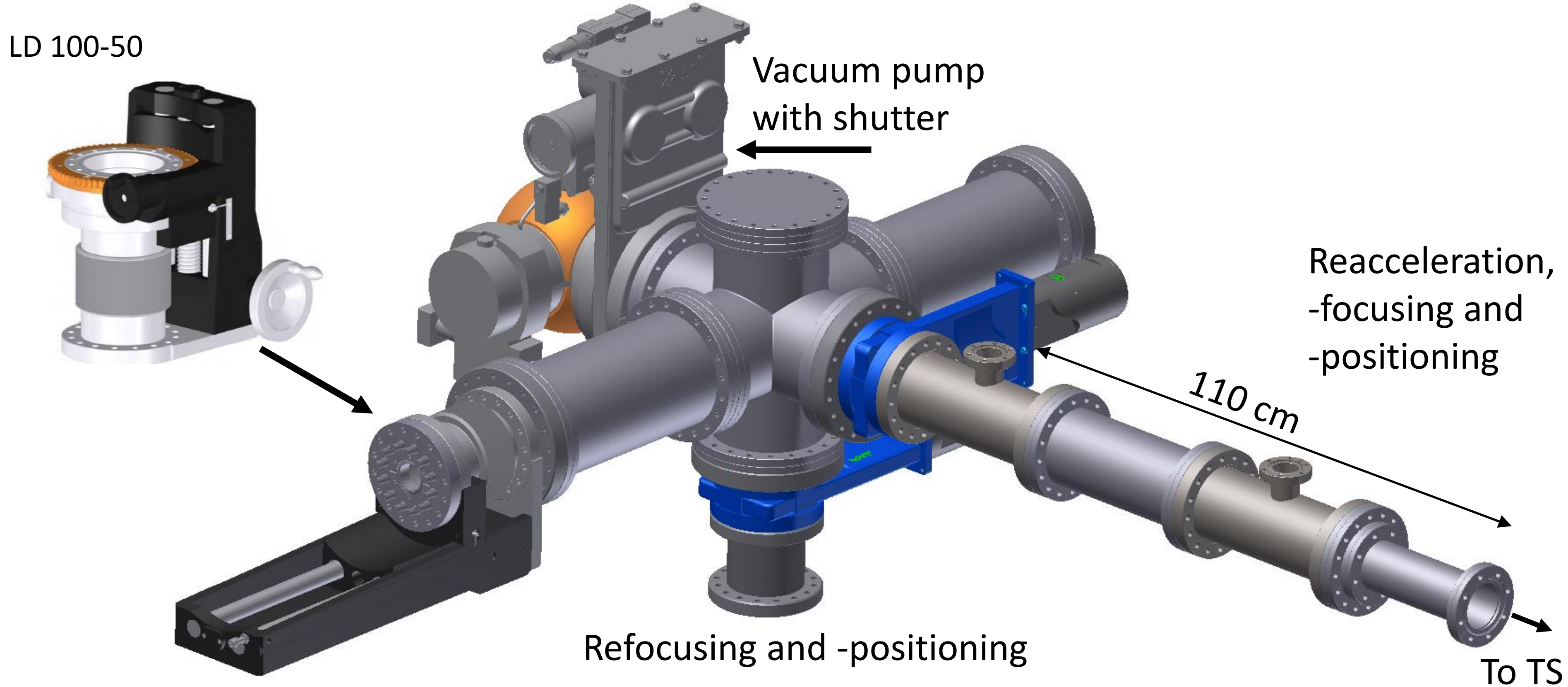




ISOLTRAP

Construct:

Reacceleration and feedthrough system:



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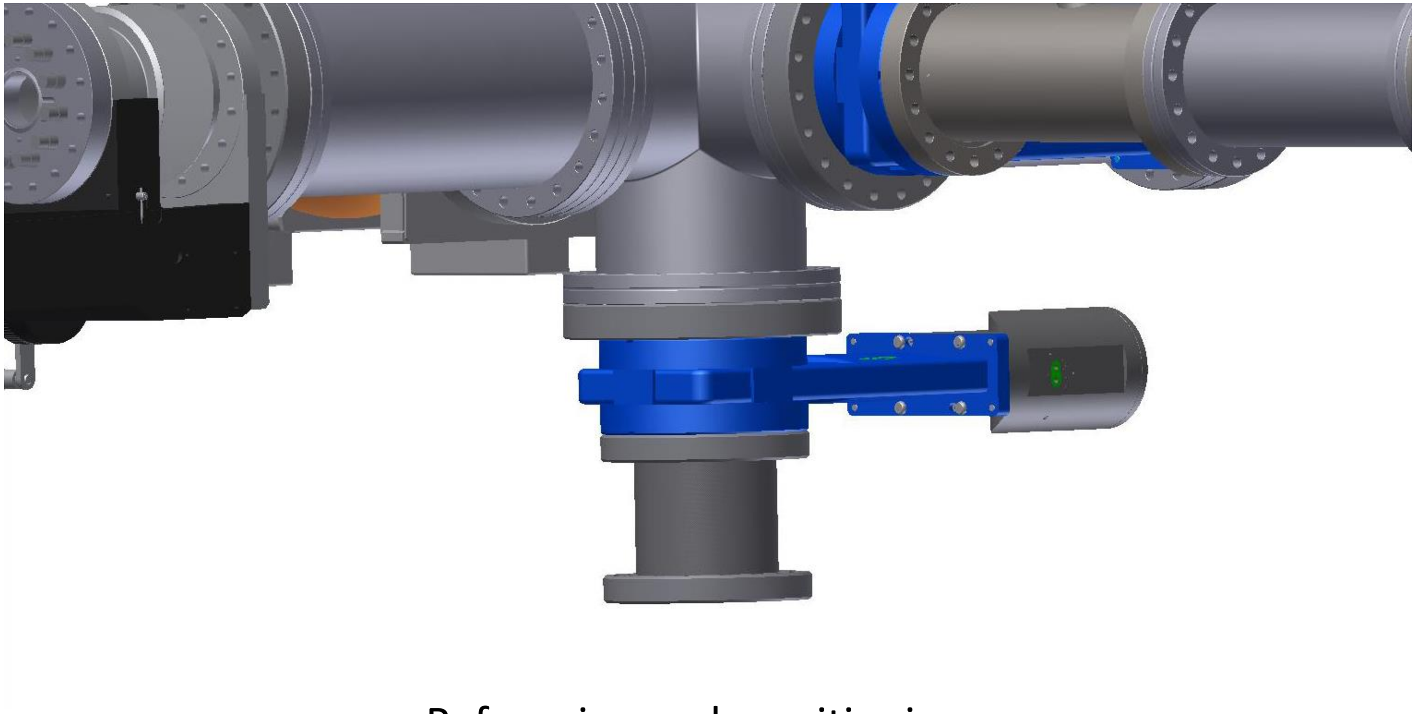

Refocusing and -positioning

ISOLTRAP

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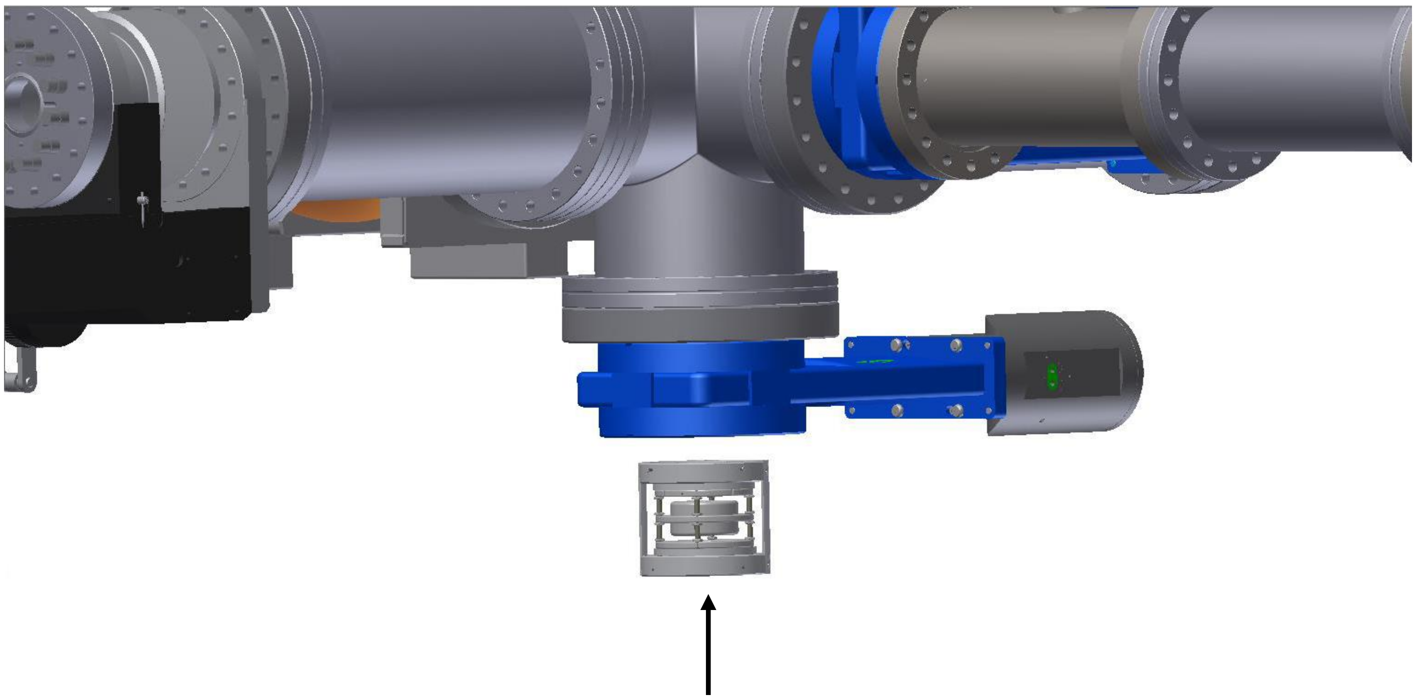
Reacceleration and feedthrough system:



XY-Steerer and einzel lens

ISOLTRAP

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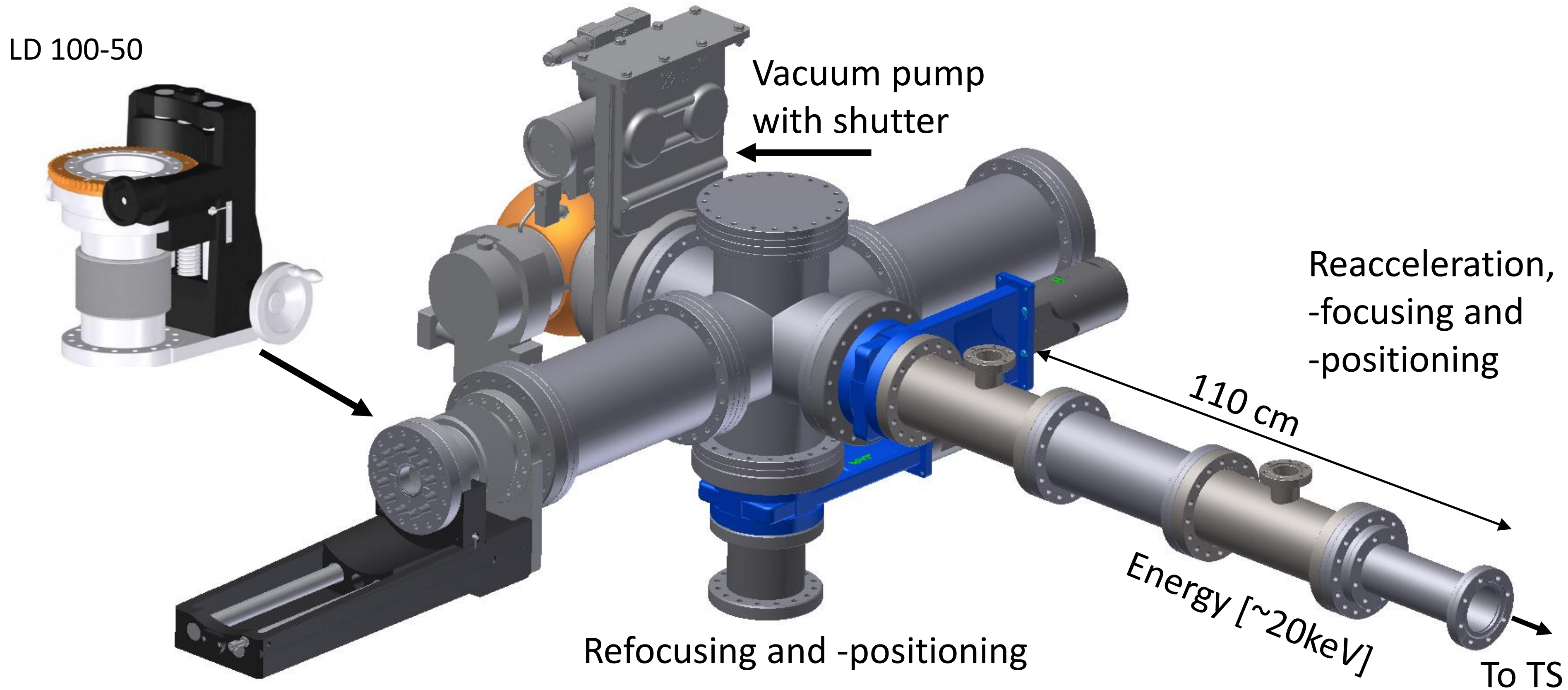

ISOLTRAP

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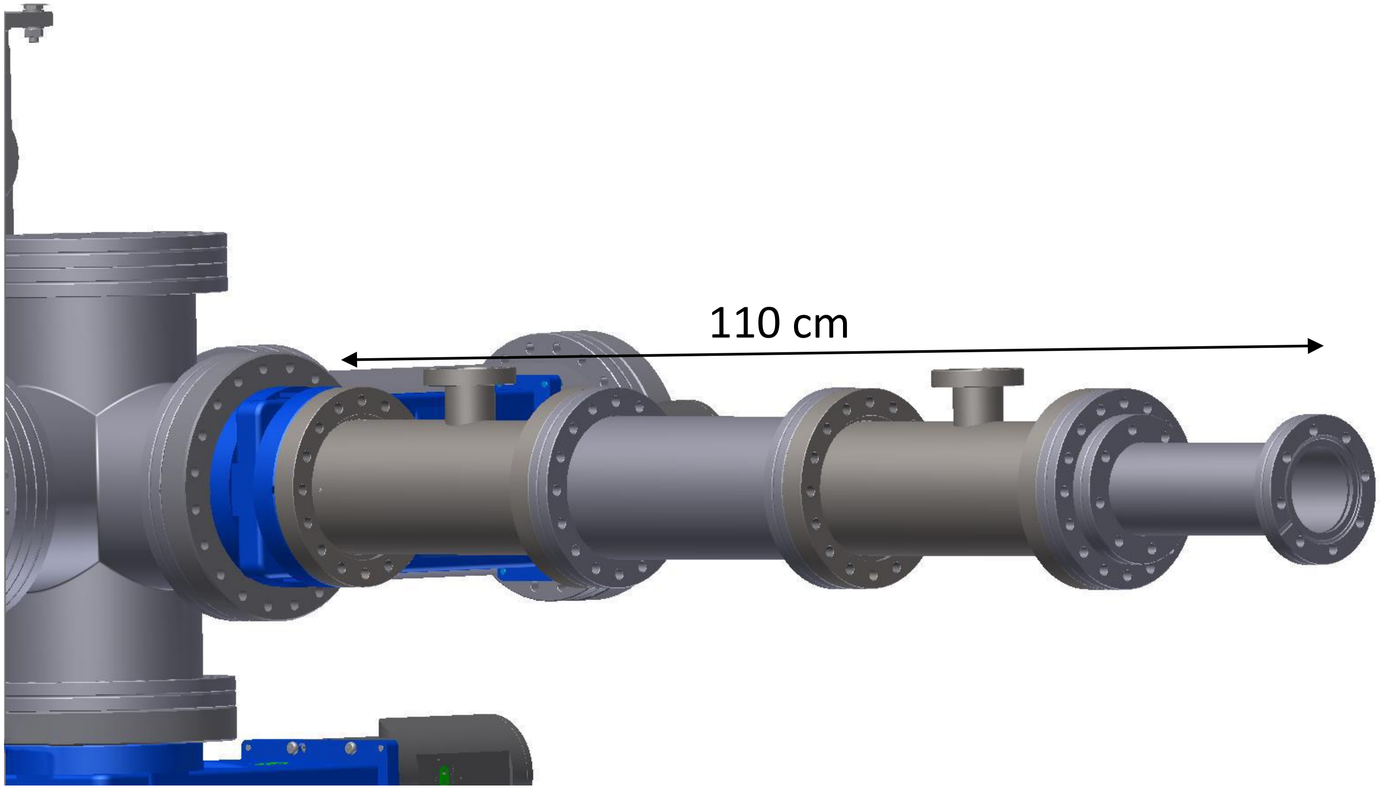

Reacceleration,
-focusing and
-positioning

ISOLTRAP

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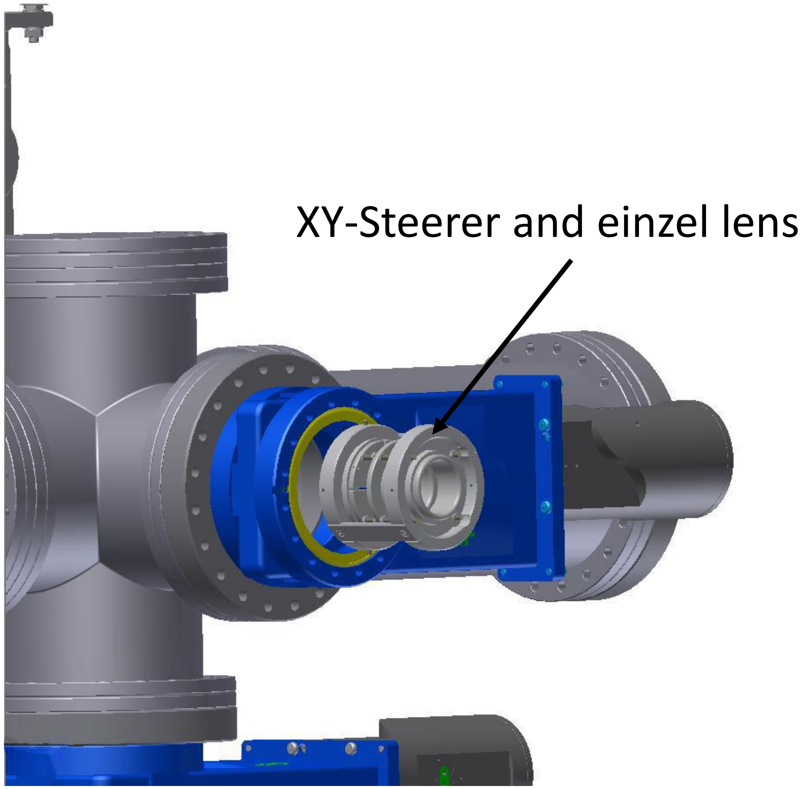
Reacceleration and feedthrough system:



ISOLTRAP

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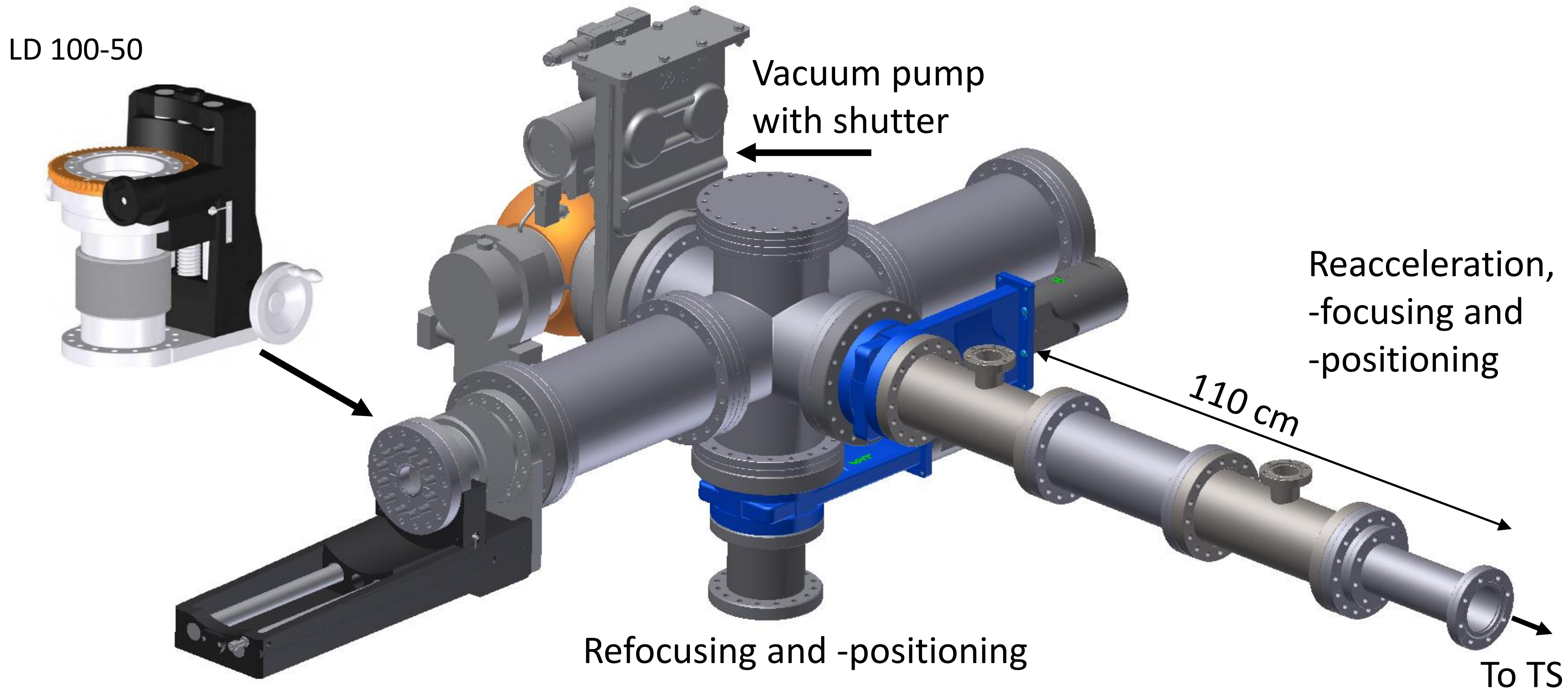
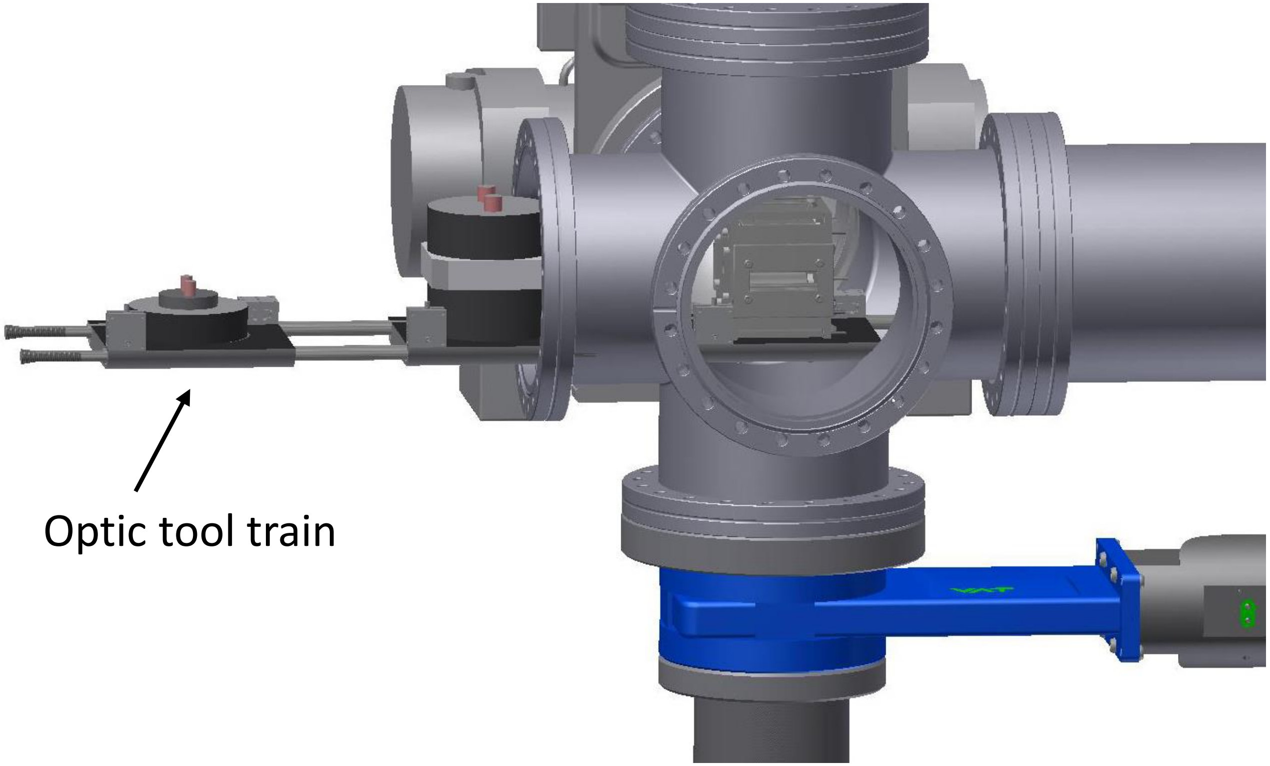


ISOLTRAP

Construct:

Cut through the feedthrough system:

It'll support e.g. PS-MCP, channeltron, quadrupole



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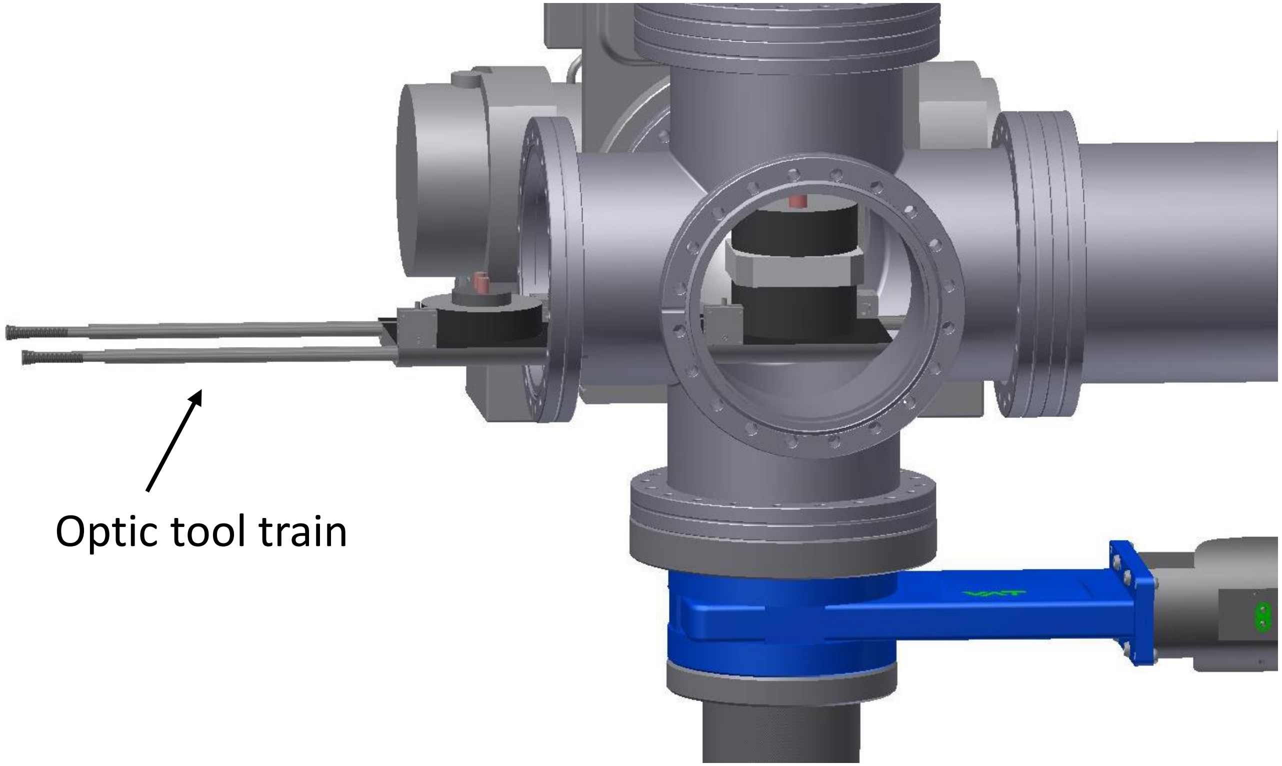

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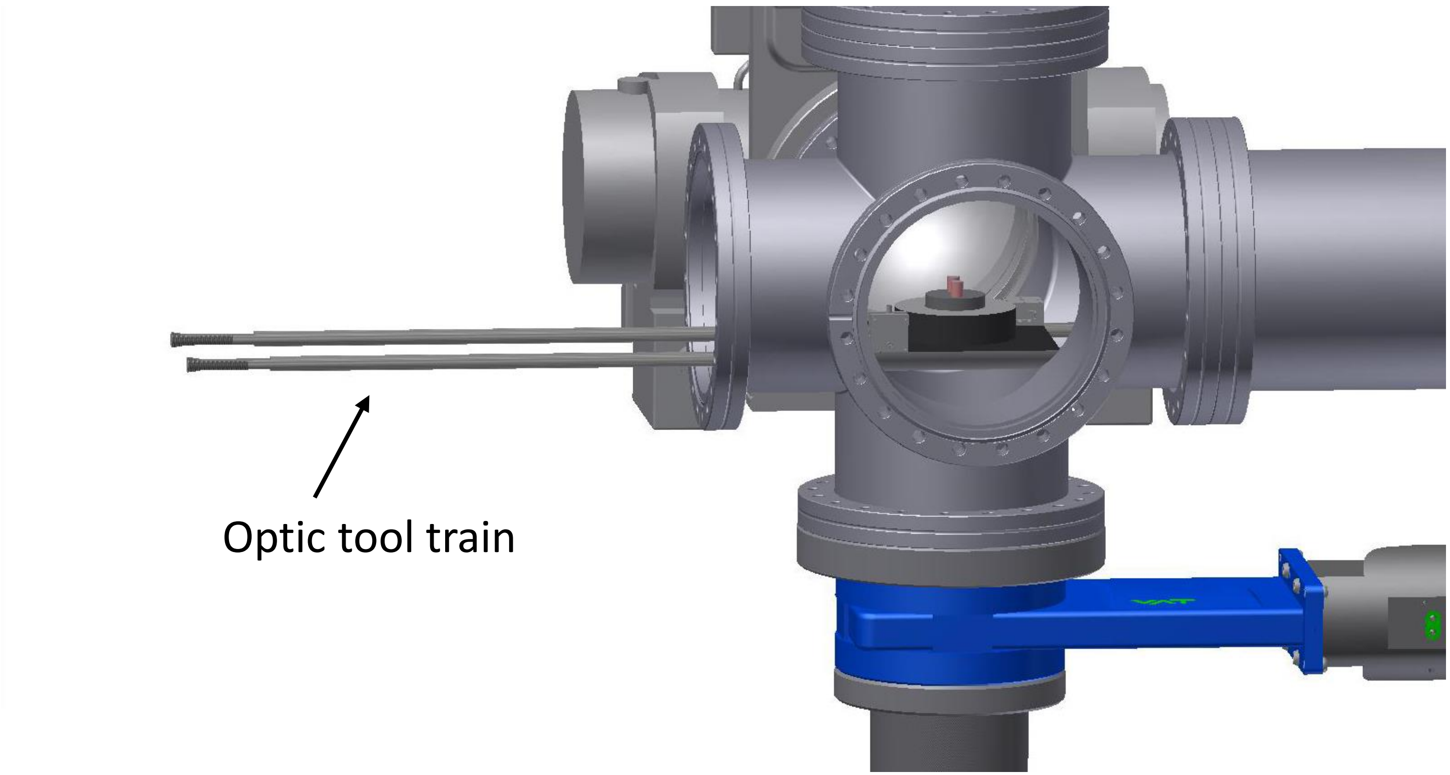
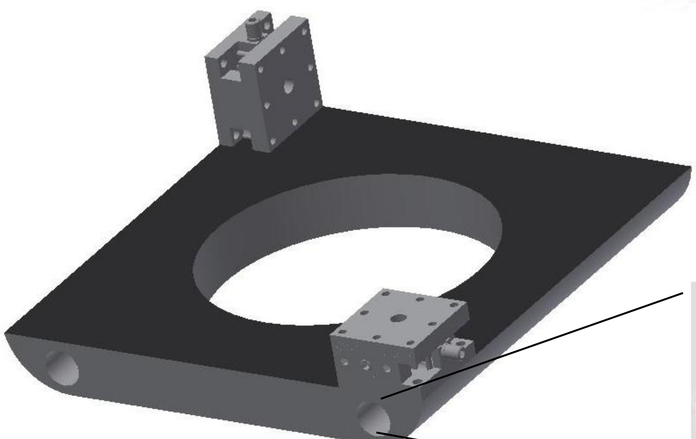


ISOLTRAP

Construct:

Tool train:

Real example



One tool train idea

Linear ball-bearings

25 mm^3

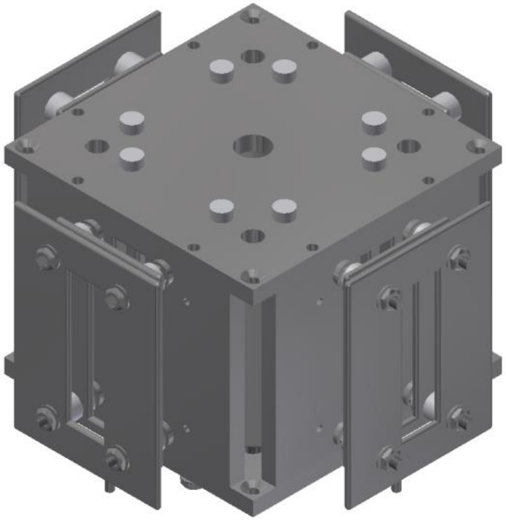
Linear compact stage
(one ore more directions)

ISOLTRAP

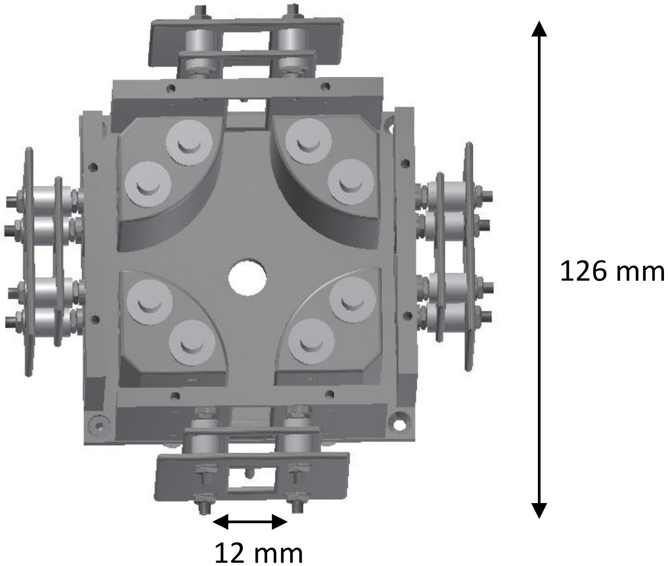
Inventor:

Quadrupole/Ion beam bender:

Side View:



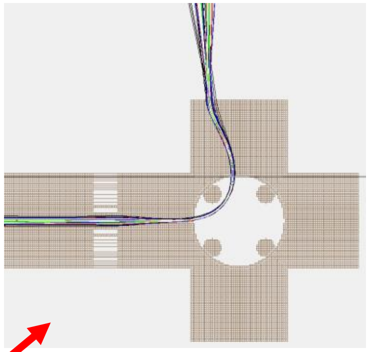
Top Side View (open):



- SIMION simulation will follow within the next few weeks

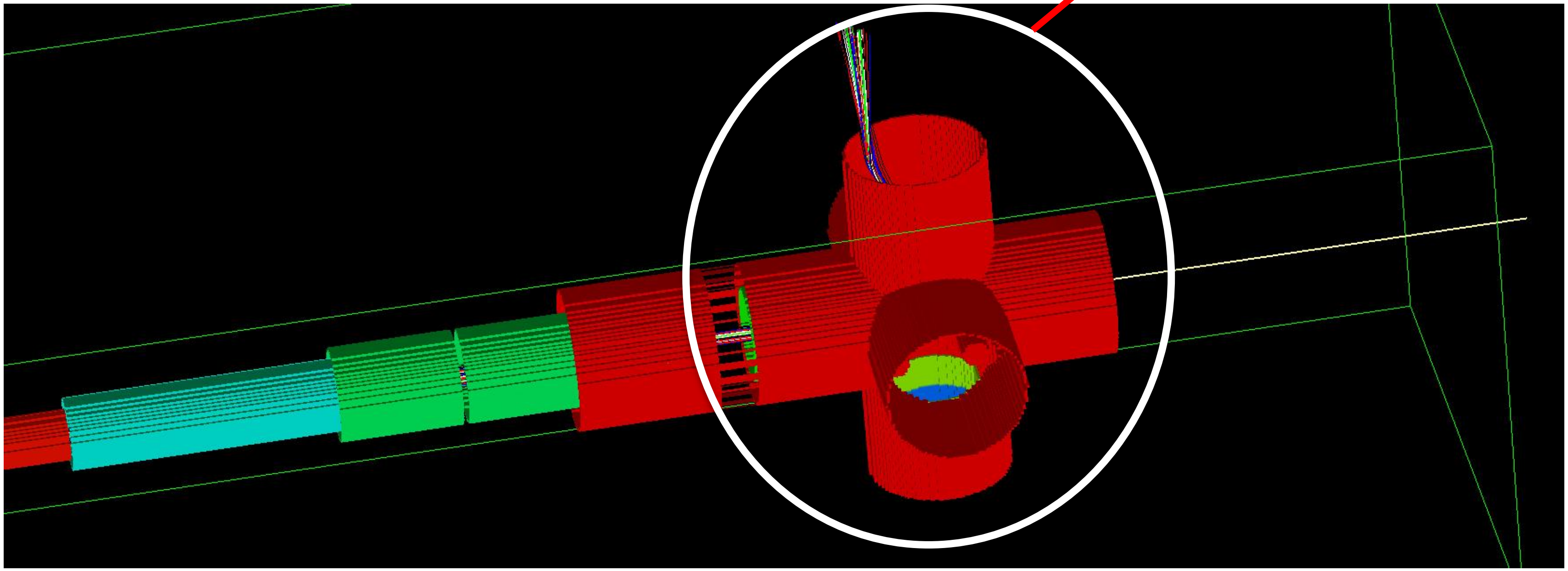
SIMION/ISOLTRAP

Simulation:



Quadrupole measurement + acceleration:

- Beam hits the wall, must be recalibrated



ISOLTRAP

New shutter system:

Problem:

- Two different pressures 10^{-5} and 10^{-9} mbar must be handled
- Shutter must open within 20 ms, not reachable for metal valves

Shutter materials/for vacuum tests:

- myRIO, as a programmable controller unit
- Two different SLR shutter are in the lab (metal, plastic)

myRIO with a Zynq (FPGA/ARM)

Connector for flexible cable

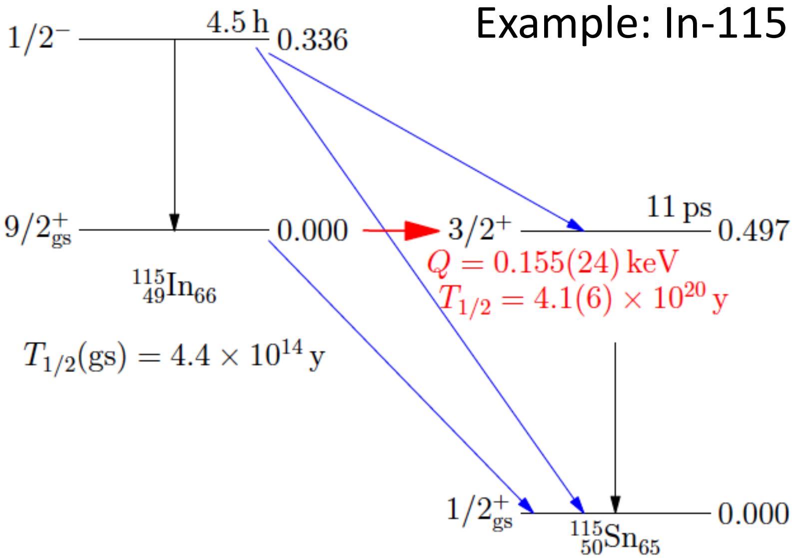
Neutrino Mass Measurement

New aim: Find ultralow Q-value

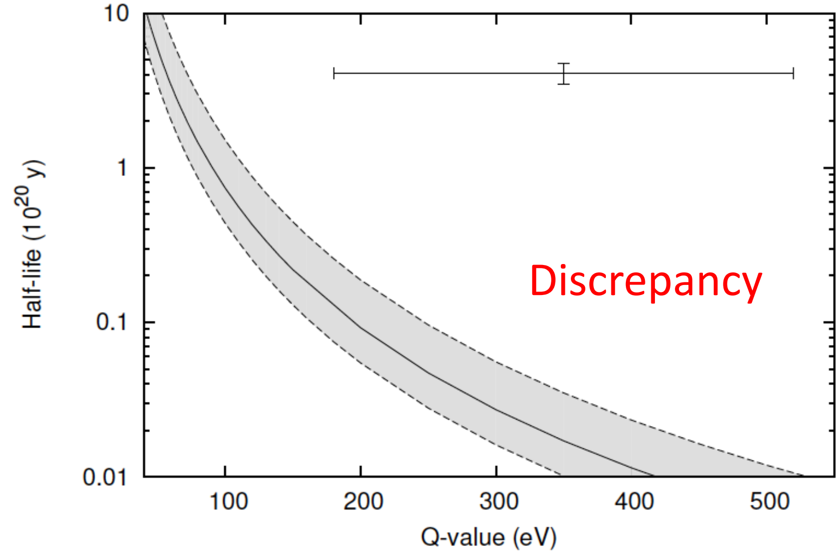
Currently used: Tritium 18.6 keV , Re-187 2.47 keV

Now isotopes are considered including beta decays into excited states

Example: In-115



Eronen et al. value

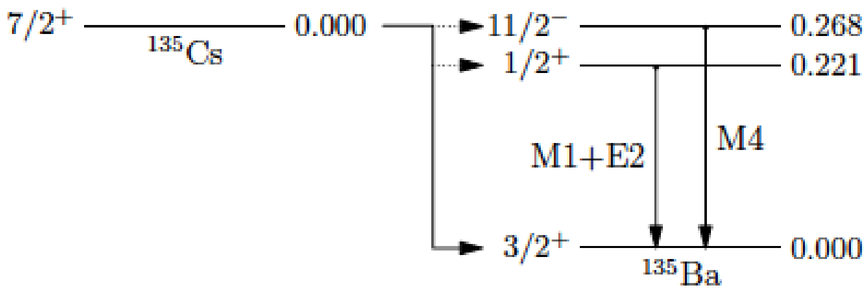


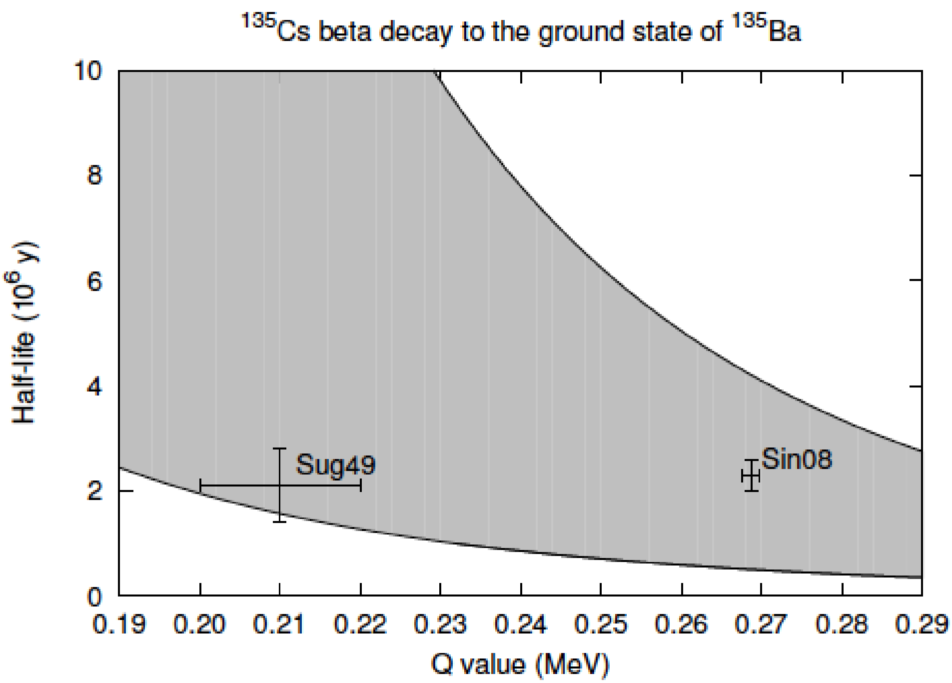
JYFLTRAP (T. Eronen et al.) Q− = 0**.35(17) keV**

Florida StU (B. J. Mount et al.) Q− = 0**.155(24) keV**

All plots/informations from J. Suhonen (Jyväskylä)

Another Example – Cs135





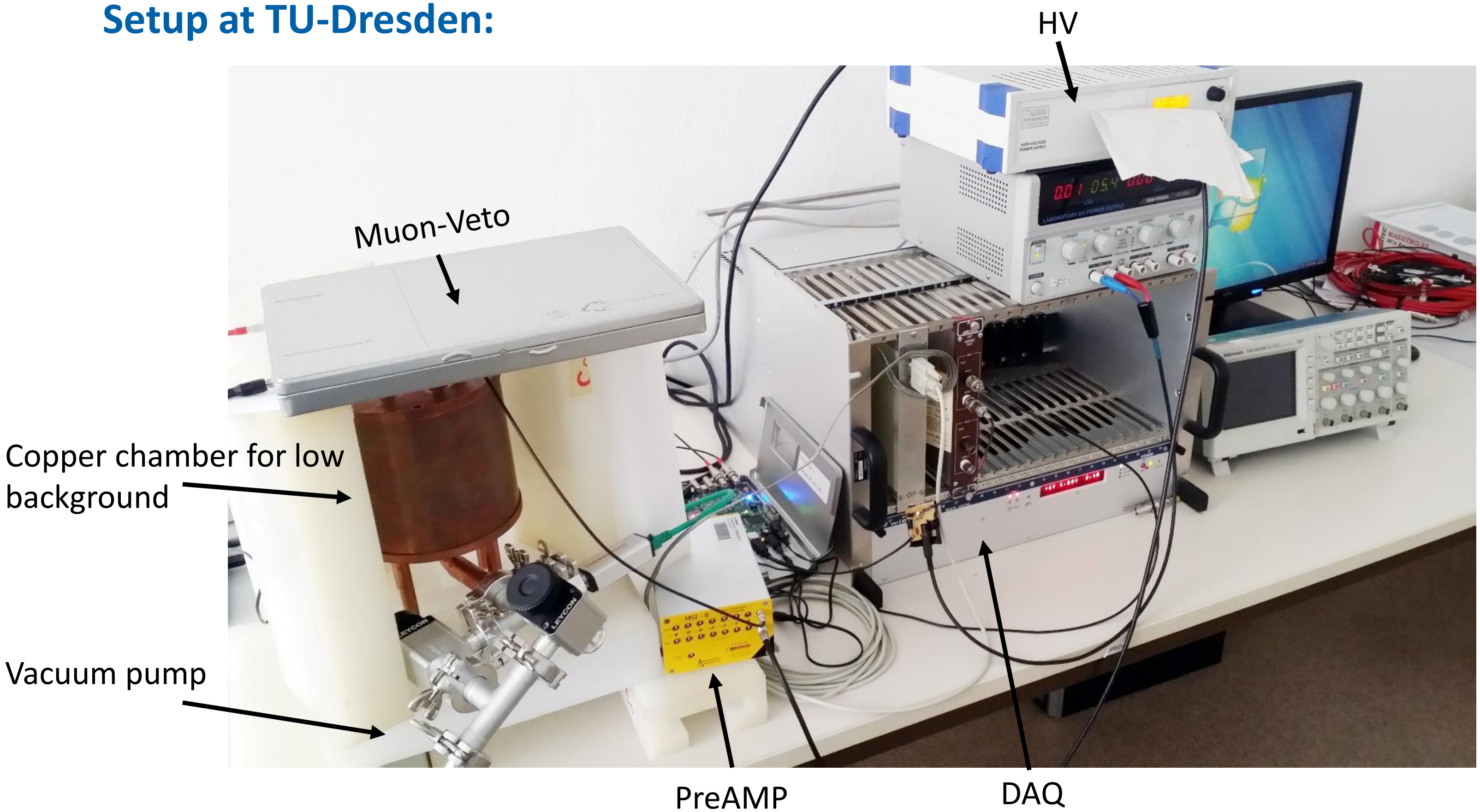
Half-life remeasuring in TU-Dresden

All plots/informations from J. Suhonen (Jyväskylä)

Beta-Spectroscopy

How we can measure it:

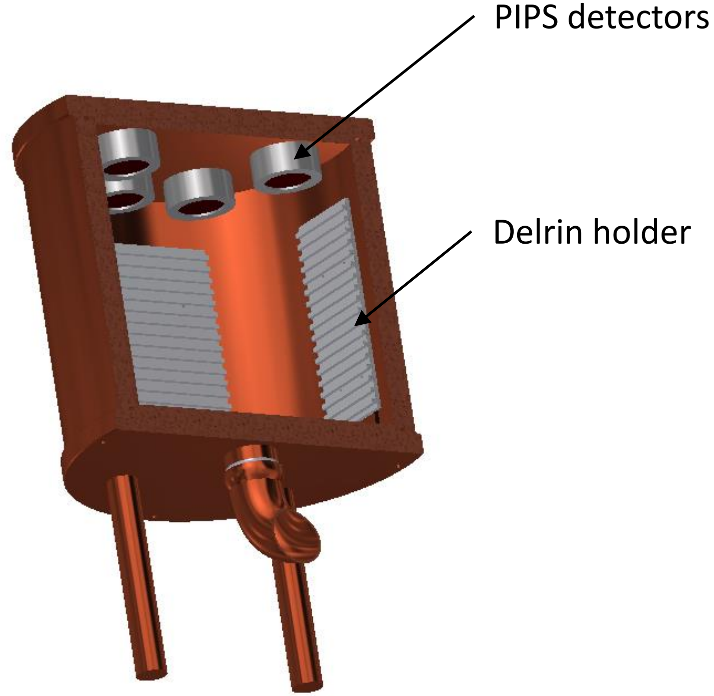
Setup at TU-Dresden:



Beta-Spectroscopy

How we can measure it:

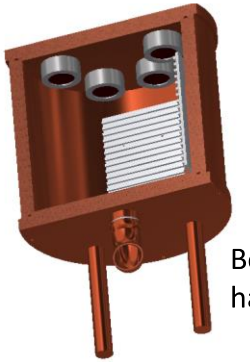
Low-Beta-Spectroscopy-Chamber at TU-Dresden:



Half-cut

Beta-Spectroscopy

PIPS Detector Values:



Beta chamber half-cut

150 and 300 mm² with 1000µm active thickness						
PD-SERIES				1000 microns		
Active Area mm2	Active Diameter mm	Diameter housing mm	FWHM (keV) α	FWHM (keV) β	Threshold (keV)	Model No.
150	13.8	23.6	14	9	27	PD150-14-1000AM
300	19.5	28.6	16	11	33	PD300-16-1000AM

Resolution is given for 241Am, 5.486 MeV alphas, using standard CANBERRA electronics and 0.5 µs shaping time constant. Electronic resolution is approximated by pulser line width (FWHM) or RMS voltmeter.

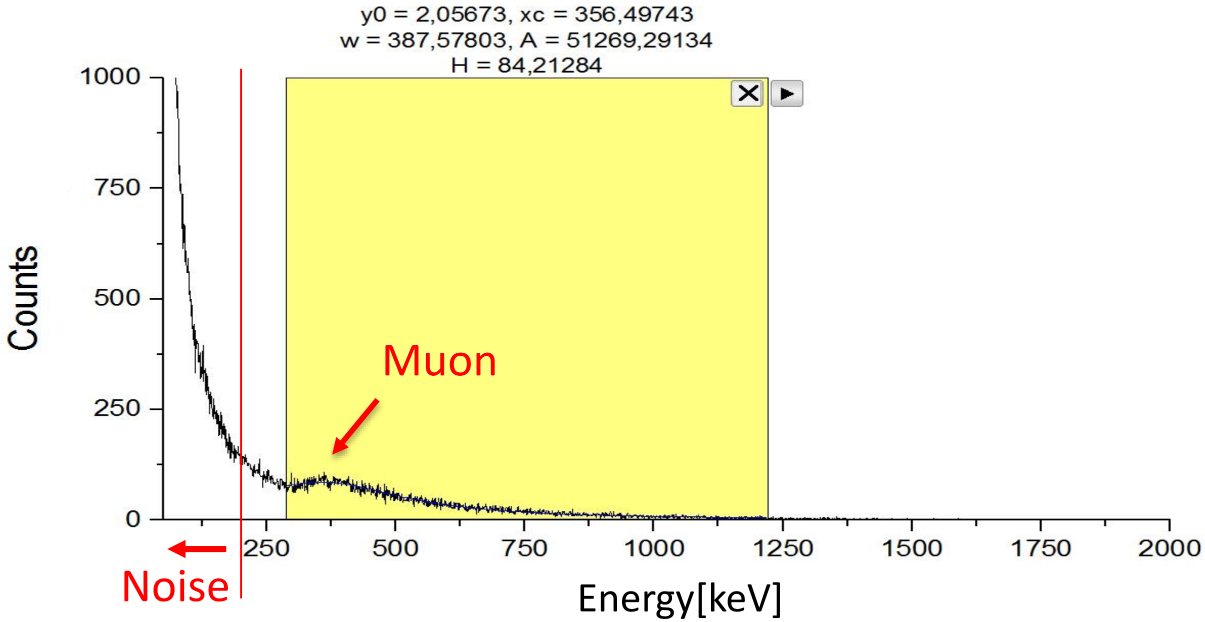
PIPS: Passivated Implanted Planar Silicon

Beta-Spectroscopy

Measurement:

First results and what we can learn:

- 4 day background



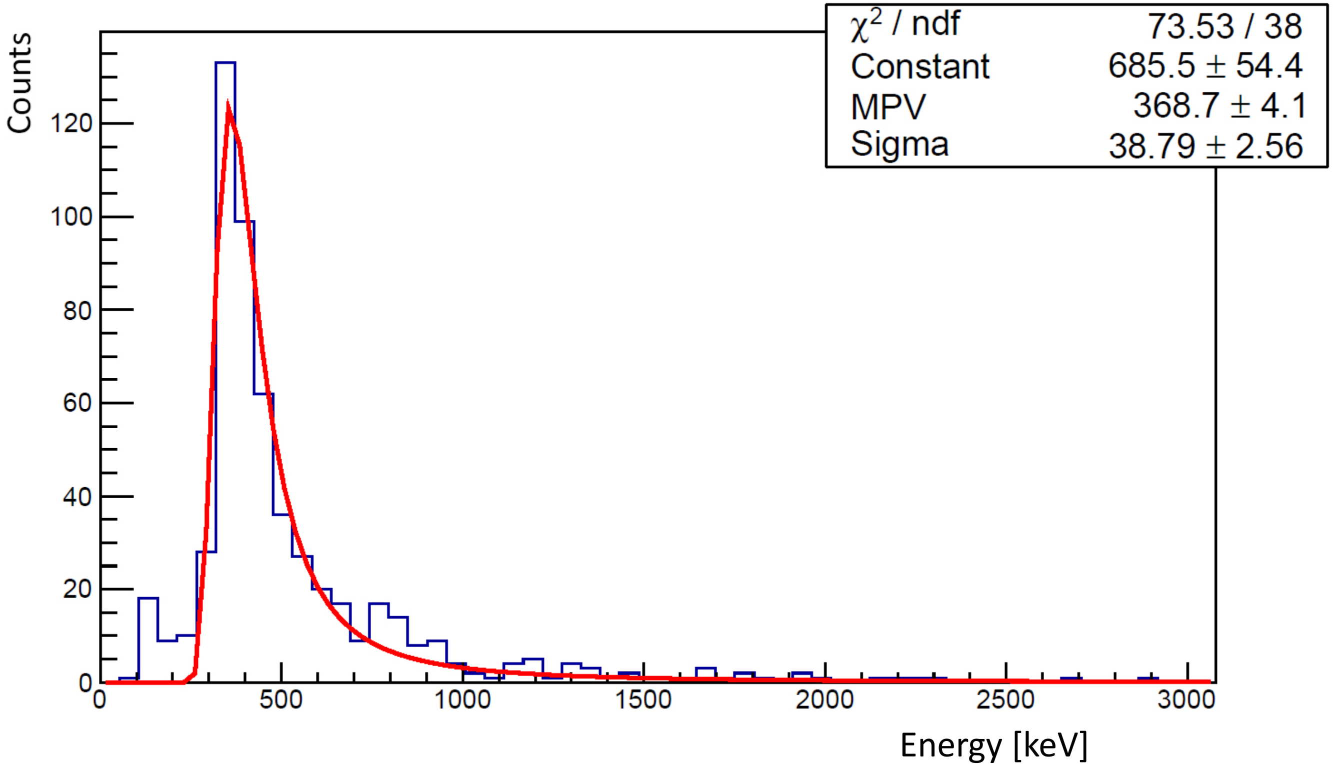
- 300 mm^2 PIPS detector calculated C = 315 pF → N(FWHM[keV]) = 170 keV
- New 2003BT PreAMP is ordered: N(FWHM) = 4 keV

Beta-Spectroscopy

Measurement:

First results of Muon background measurement:

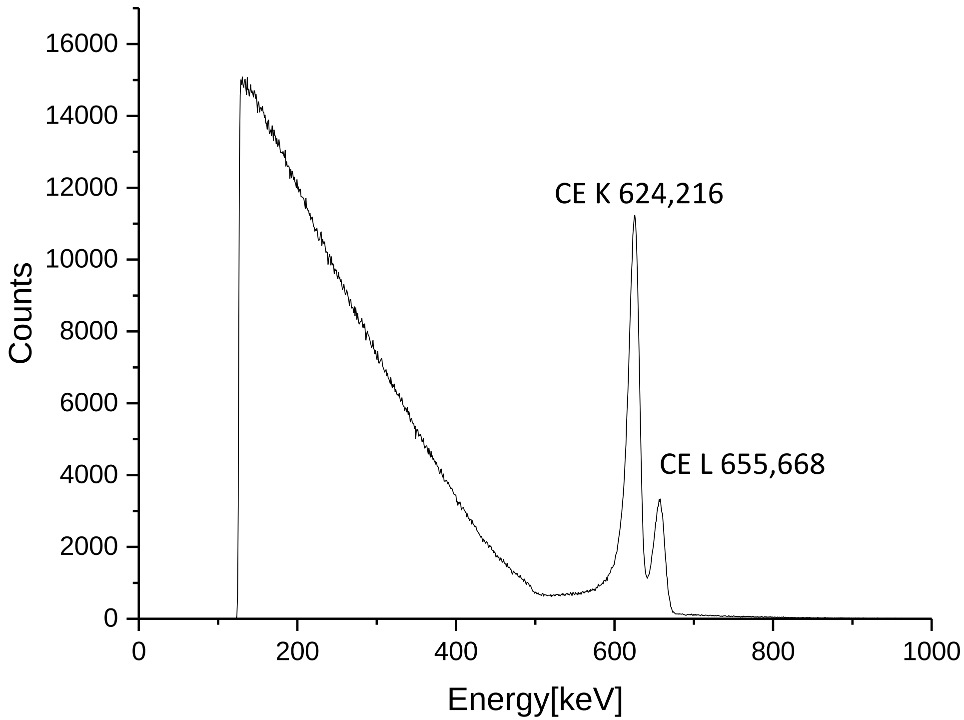
- 4 day background



Beta-Spectroscopy

Measurement:

Calibration results with the ^{137}Cs conversion electrons:



Summary

ISOLTRAP:

- Presented the ISOLTRAP experiment and how we can measure masses with this setup
- Talked about the sizes and ideas for the feedthrough system
- Mentioned the usage of LabView for stepper motion and shutter system control
- First SIMION simulations are done

Beta-Spectroscopy:

- Showed candidates for Neutrino mass measurement linked to the Low-Beta-Spectroscopy PIPS-detector setup in Dresden

Thank you for your attention!

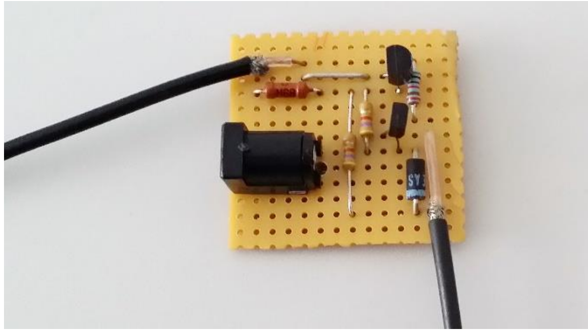
Backup

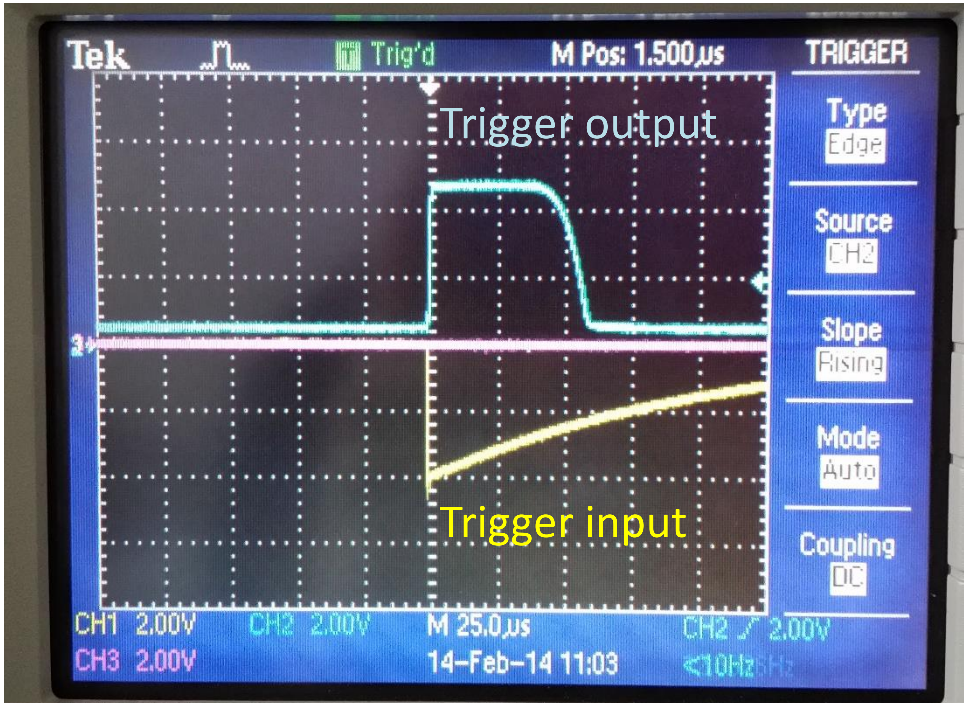
Lab Status:

Muon-Veto:

- Problems -5 V trigger signal from school Muon-Veto project.

- Solved with a small converter.



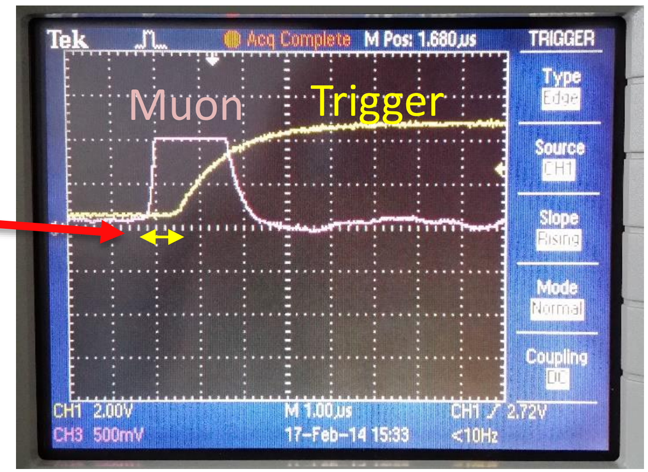


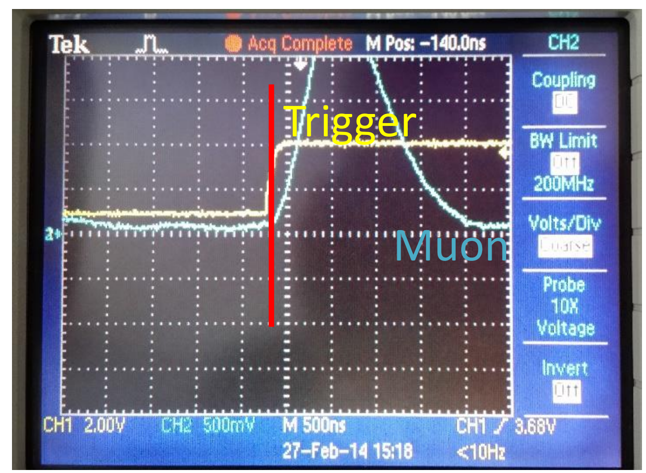
Backup

Lab Status:

Muon-Veto:

- Zoomed view:
  Timing problems, to slow
  for the ADC trigger gate. τ = 3 µs





- Solved with a faster transistor
  and new resistor values. τ = 250 ns

- New results will follow.

Backup

Idea:

- Theory of Mustonen/Suhonen
  (pnMQPM: Proton-Neutron Microscopic Quasiparticle
  Phonon Model)

The measurable quantities in β-decay and electron capture do not depend on the nucleus alone, they are also determined by processes within the atomic shell.

(Behrens and Jänecke 1969)

e.g.

- Better understanding of the electron wave functions
- Electron polarization
- $\beta - \gamma$ directional and circular polarization correlation
- Electron emission from oriented nuclei
- Shapes of beta spectra

Backup

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Backup

Equation - short form:

Probability for emitting an e^- → Shape of beta decay

$$P(W_e)dW_e = \frac{G_F^2}{(\hbar c)^6}\frac{1}{2\pi^3\hbar}F_0(Z,W_e)C(W_e)\,p_e c\,W_e(W_0-W_e)^2\,dW_e$$

- G_F = Fermi coupling constant
- p_e = $\sqrt{W_e^2 + (m_e c^2)^2}$ = electron momentum
- W_e = $\sqrt{p_e^2 + 1}$ = total electron energy
- W_0 = maximum value of W_e
- p_ν = W_0 - W_e
- Z = atomic number of the daughter nucleus
- $F_0(Z, W_e)$ = Fermi function, takes the distortion by the electron wave function into account by nuclear charge
- $C(W_e)$ = spectrum shape function

Backup

Equation – a bit expanded:

Probability for emitting an e^- → Shape of beta decay

$$P(W_e)dW_e = \frac{G_F^2}{(\hbar c)^6}\frac{1}{2\pi^3\hbar}F_0(Z,W_e)C(W_e)\,p_e c\,W_e(W_0 - W_e)^2\,dW_e$$

Spectrum shape function

$$C(W_e) = \sum_{k_e k_\nu K} \frac{F_{k_e-1}(Z,W_e)}{F_0(Z,W_e)}\Big[M_K^2(k_e,k_\nu) + m_K^2(k_e,k_\nu) - \frac{2\mu_{k_e}\gamma_{k_e}}{k_e W_e/(m_e c^2)}M_K(k_e,k_\nu)m_K(k_e,k_\nu)\Big]$$

- $F_{k_e-1}(Z,W_e)$ = generalized Fermi function
- k_e, k_ν = relativistic quantum numbers
- K = transfered angular momentum
- μ_{k_e} = Coulomb function
- γ_{k_e} = $\sqrt{k_e^2 + (\alpha Z)^2}$

Backup

Theory to remember :

- **Half-Life**

$$T_{1/2} = \frac{1}{M_K^2 \cdot f_K(W_0, Z, R)} = \frac{\ln(2)}{\lambda_{f,i}}$$

- M_K = Nuclear matrix element
- $f_K(W_0, Z, R)$ = phase-space function
- $\lambda_{f,i}$ = decay constant
- $T_{1/2}$ = half-life
- Z = atomic number of the daughter nucleus

Backup

Theory to remember:

- Rules for unique/non-unique and allowed transitions

ΔJ	$\pi_i \pi_f$	name	relevant form factors
0 or 1	$+1$	allowed	$^VF^{(0)}_{000}$, $^AF^{(0)}_{011}$
0 or 1	-1	1st forbidden non-unique	$^VF^{(0)}_{101}$, $^VF^{(0)}_{110}$, $^AF^{(0)}_{111}$, $^AF^{(0)}_{211}$, $^AF^{(0)}_{000}$, $^AF^{(0)}_{011}$, $^VF^{(0)}_{101}(k_e, 1, 1, 1)$, $^AF^{(0)}_{110}(k_e, 1, 1, 1)$, $^AF^{(0)}_{111}(k_e, 1, 1, 1)$
2	-1	1st forbidden unique	$^AF^{(0)}_{211}$
2	$+1$	2nd forbidden non-unique	$^VF^{(0)}_{211}$, $^VF^{(0)}_{220}$, $^AF^{(0)}_{221}$, $^AF^{(0)}_{321}$, $^VF^{(0)}_{220}(k_e, 1, 1, 1)$, $^AF^{(0)}_{221}(k_e, 1, 1, 1)$
3	$+1$	2nd forbidden unique	$^AF^{(0)}_{321}$
3	-1	3rd forbidden non-unique	$^VF^{(0)}_{321}$, $^VF^{(0)}_{330}$, $^AF^{(0)}_{331}$, $^AF^{(0)}_{431}$, $^VF^{(0)}_{330}(k_e, 1, 1, 1)$, $^AF^{(0)}_{331}(k_e, 1, 1, 1)$
4	-1	3rd forbidden unique	$^AF^{(0)}_{431}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$
K	$(-1)^K$	Kth forbidden non-unique	$^VF^{(0)}_{K,K-1,1}$, $^VF^{(0)}_{KK0}$, $^AF^{(0)}_{KK1}$, $^AF^{(0)}_{K+1,K,1}$, $^VF^{(0)}_{KK0}(k_e, 1, 1, 1)$, $^AF^{(0)}_{KK1}(k_e, 1, 1, 1)$
$K+1$	$(-1)^K$	Kth forbidden unique	$^AF^{(0)}_{K+1,K,1}$

J = L + S (total angular momentum)

π = parity

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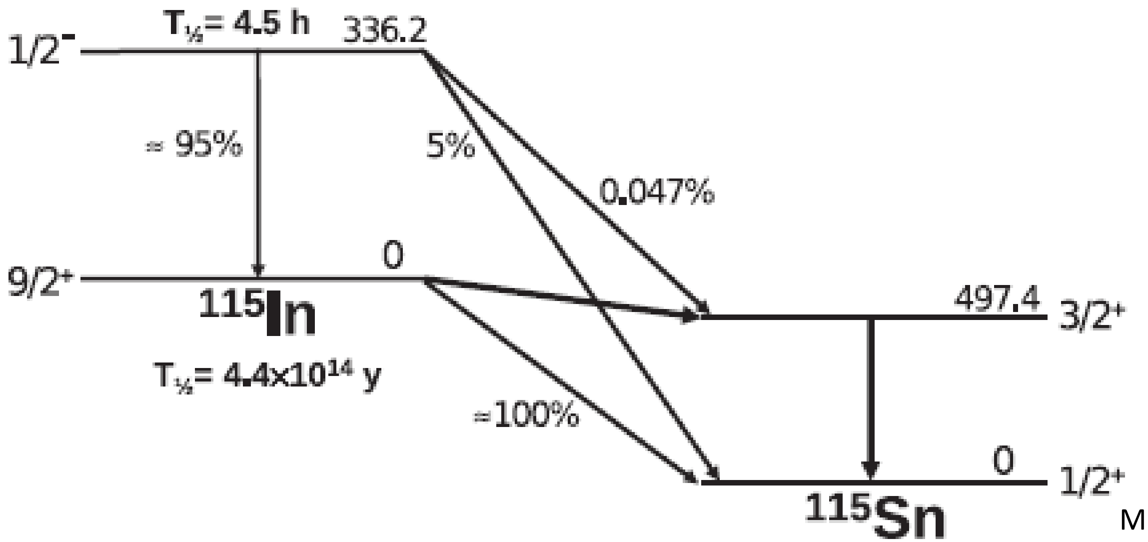
Backup

^{115}In transition:



Mustonen
Phys. Rev. Lett. 103 (2009), 122501

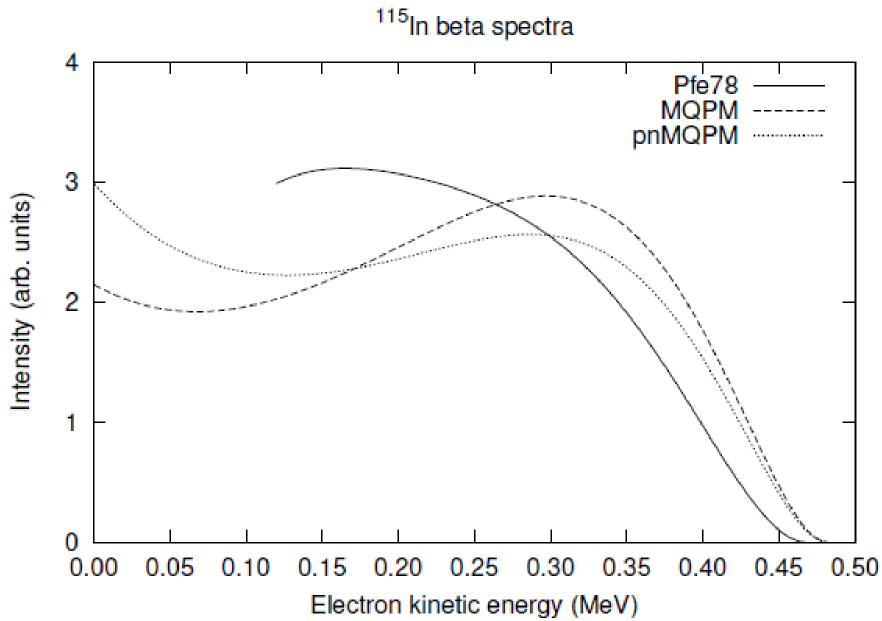
- Fourfould forbidden non-unique transition $^{115}_{49}\mathrm{In} \rightarrow ^{115}_{50}\mathrm{Sn}$

Backup

Tasks:

Theoretical ^{115}In fourfold forbidden non-unique spectrum:

- Calculated with the presented theory



Mustonen UNIVERSITY OF JYVÄSKYLÄ RESEARCH REPORT No. 5/2010

- Theory agrees with the experimental Q-value, half-life, log ft-value
- Problem to measure the real shape in the lower energy region

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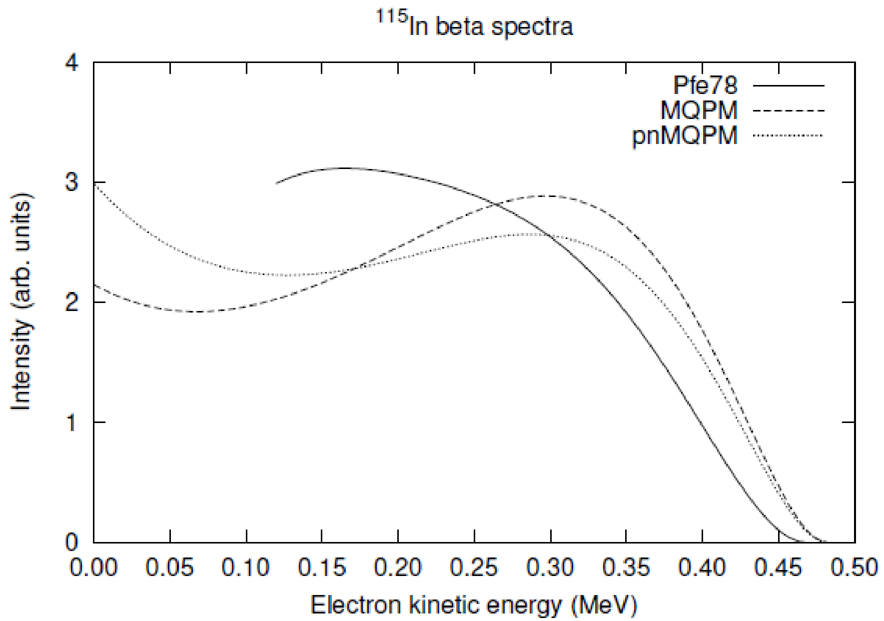

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- Problem to measure the real shape in the lower energy region

Backup

Tasks:

As thin as possible/countable foil to suppress electron interferences:

- ^{115}In

  $Q =$ 497.489 keV $t_{1/2} = 4.41 \times 10^{14} a$ $A = 0.26\ Bq/g$

  with 300 mm^2, 10 µm foil → 4.5mBq
  efficiency at 10 mm distance (12%) → 0.54mBq

- Amount of expected and measured electrons: $\sim 10^5$/a, with 6 detectors

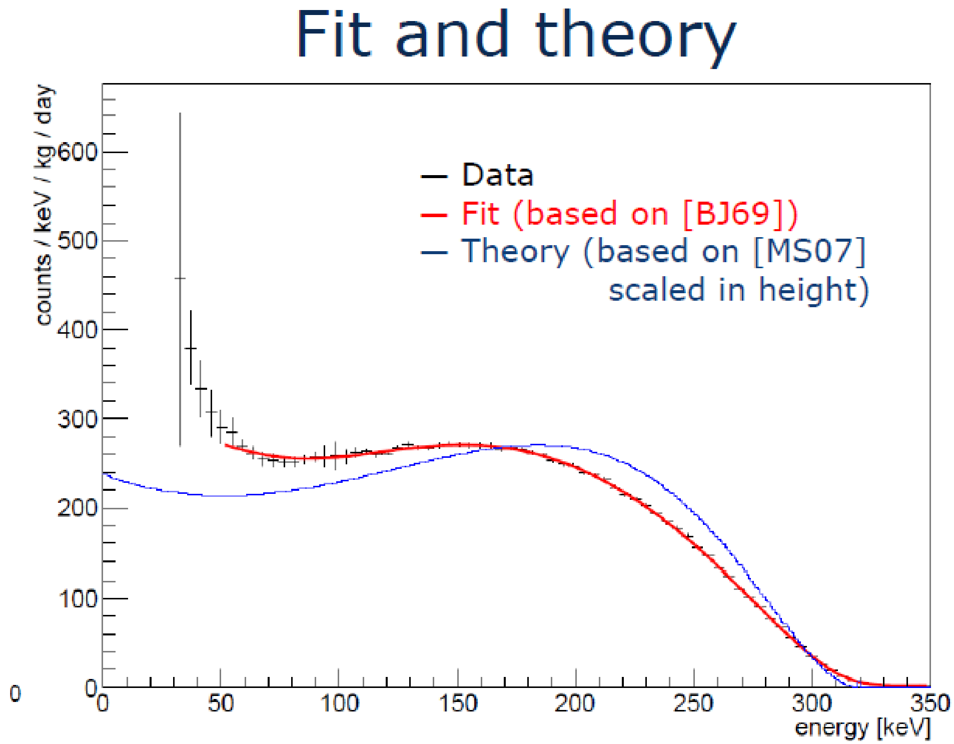
- Other possible candidates for the beta decay shape measurement are ^{50}V and ^{113}Cd

Backup

Measurement:

Theoretical and experimental ^{113}Cd fourfold forbidden non-unique spectrum:

- Calculated with the presented theory and measured with real data

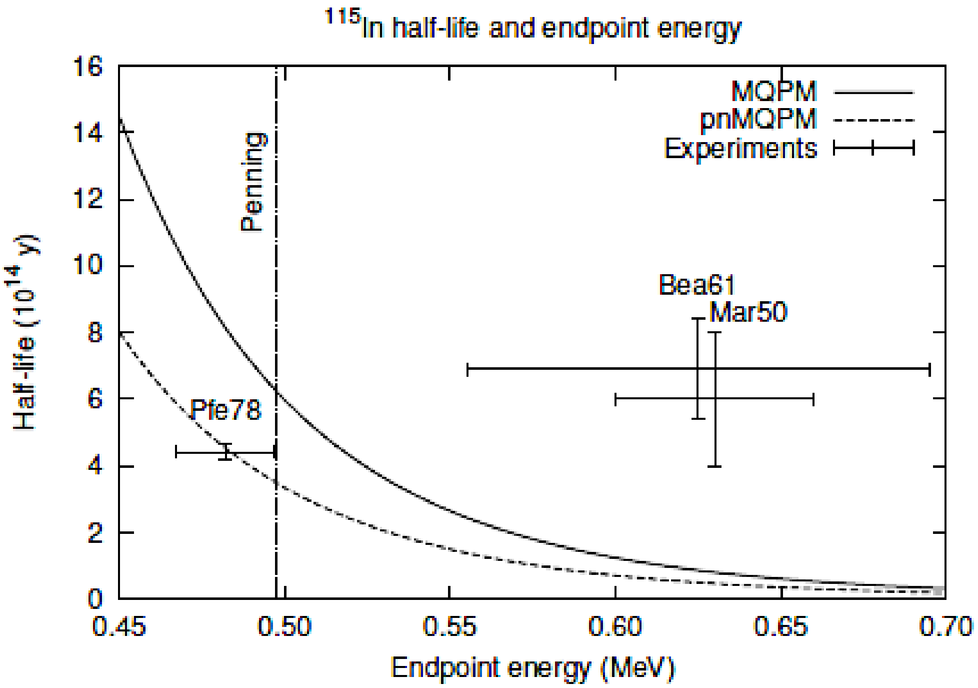


Mo: 17:45 HK11.05
Fabian Heisse

Backup

Plots:

Half-life and endpoint energy:



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$$P(W_e)dW_e = \frac{G_F^2}{(\hbar c)^6}\frac{1}{2\pi^3\hbar}F_0(Z,W_e)C(W_e)\,p_e c\,W_e(W_0-W_e)^2\,dW_e$$

Nuclear Matrix Element

if $\qquad k_e + k_\nu = L+1\,,\quad L = \Delta J\,,\quad \pi_i\pi_f = (-1)^L:$

$$\begin{aligned} M_L(k_e,k_\nu) = K\ (p_e R)^{k_e-1}\ (p_\nu R)^{k_\nu-1}\Bigg\{&-\sqrt{\frac{2L+1}{L}}\sum_{n=0}^{\infty}{}^{\mathrm{V}}F^{(n)}_{L,L-1,1}\Big(H_{2n}+\frac{1}{2L+1}N_1 D_{2n-1}+ \\ &+N_2 H_{2n-2}\Big)-\sum_{n=0}^{\infty}{}^{\mathrm{V}}F^{(n)}_{LL0}\left(D_{2n+1}+N_1 H_{2n}+N_2 D_{2n-1}\right)-\sqrt{\frac{L+1}{L}}\times \\ &\times\sum_{n=0}^{\infty}{}^{\mathrm{A}}F^{(n)}_{LL1}\left(D_{2n+1}-N_1 H_{2n}+N_2 D_{2n-1}\right)+2\sqrt{\frac{L+1}{2L+1}}\sum_{n=0}^{\infty}{}^{\mathrm{V}}F^{(n)}_{L,L+1,1}N_1 D_{2n+1}\Bigg\}\end{aligned}$$

- F_{Lls} = Form factor coefficient
- H_{2n}, D_{2n+1} = energy dependent functions

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Equations in detail:

Half-life with integrating the probability density:

$$T_{1/2} = \kappa \left((m_e c^2)^{-5} \int_{m_e c^2}^{W_0} F_0(Z, W_e) C(W_e)\, p_e c\, W_e (W_0 - W_e)^2\, dW_e \right)^{-1}$$

Where W_0 is:

$$W_o = \frac{E_e^{max}}{m_e c^2} \approx \frac{Q_\beta}{m_e c^2} + 1$$

Where κ is:

$$\kappa = \frac{2\pi^3 \hbar \ln 2}{(m_e c^2)^5 G_F^2 / (\hbar c)^6}$$

With:

$$\lambda_{f,i} = \frac{\ln(2)}{T_{1/2}}$$

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Equations in detail:

Decay constant:

$$\lambda_{f,i} = \frac{g^2 m_e^5 c^4 |\overline{M}'_{f,i}|^2}{2\pi^3 \hbar^7} \int_1^{W_o} F(Z,W) W \sqrt{W^2-1} (W_o - W)^2 \mathrm{d}W$$

Where W_0 is:

$$W_o = \frac{E_e^{max}}{m_e c^2} \approx \frac{Q_\beta}{m_e c^2} + 1$$

$$\downarrow$$

$$\lambda_{f,i} = \frac{g^2 m_e^5 c^4 |\overline{M}'_{f,i}|^2}{2\pi^3 \hbar^7} f$$

With:

$$\lambda_{f,i} = \frac{\ln(2)}{T_{1/2}}$$

$$\downarrow$$

$$ft = \frac{1}{g^2 |\overline{M}'_{f,i}|^2} \frac{2\pi^3 \hbar^7 \ln 2}{m_e^5 c^4}.$$

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Equations in detail:

Generalized Fermi function:

$$F_{k_e-1}(Z,W_e) = 4^{k-1}(2k)(k+\gamma_k)[(2k-1)!!]^2 e^{\pi y}\left(\frac{2p_e R}{\hbar}\right)^{2(\gamma_k-k)}\left(\frac{|\Gamma(\gamma_k+iy)|}{\Gamma(1+2\gamma_k)}\right)^2$$

- $y = \alpha Z W_e/(p_e c)$
- $\Gamma(z)$ = Gamma function

Statistical rate function

$$f_K(W_0,Z,R) = \frac{g_A^2}{\kappa(\hbar c)^{2K}(m_e c)^5}\frac{(2K)!!}{(2K+1)!!}\int_{m_e c^2}^{W_0} dW_e\, p_e c\, W_e \times \sum_{k_e+k_\nu=K+2} F_{k_e-1}(Z,W_e)\frac{[W_e^2-(m_e c^2)^2]^{k_e-1}(W_0-W_e)^{2k_\nu}}{(2k_e-1)!(2k_\nu-1)!}$$

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Equations in detail:

To evaluate the shape factor → multipole expansion of the nuclear current:

$$(-i)\langle f|V_\mu(0)+A_\mu(0)|i\rangle\gamma_0\gamma^\mu = \sum_{KLMS}(-1)^{J_f-M_f+M}(-i)^L\sqrt{4\pi}\widehat{J}_i \times \begin{pmatrix} J_f & K & J_i \\ -M_f & M & M_i \end{pmatrix} T_{KLS}^{-M}(\hat{q})\frac{(qR/\hbar)^L}{(2L+1)!!}F_{KLS}(q^2)$$

- $T_{KLS}^{-M}(\hat{q})$ = operator acting on the lepton spinors

Form factor (q is small compared to the charge of nucleus):

$$F_{KLS}(q^2) = \sum_n \frac{(-1)^n(2L+1)!!}{(2n)!!(2L+2n+1)!!}\left(\frac{qR}{\hbar}\right)^{2n} F_{KLS}^{(n)}$$

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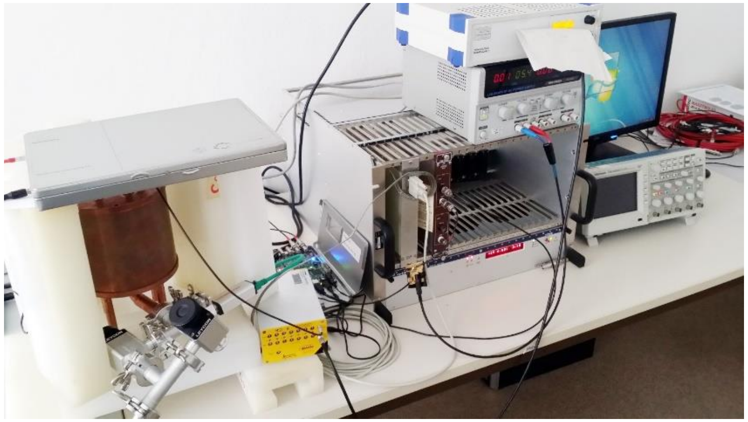
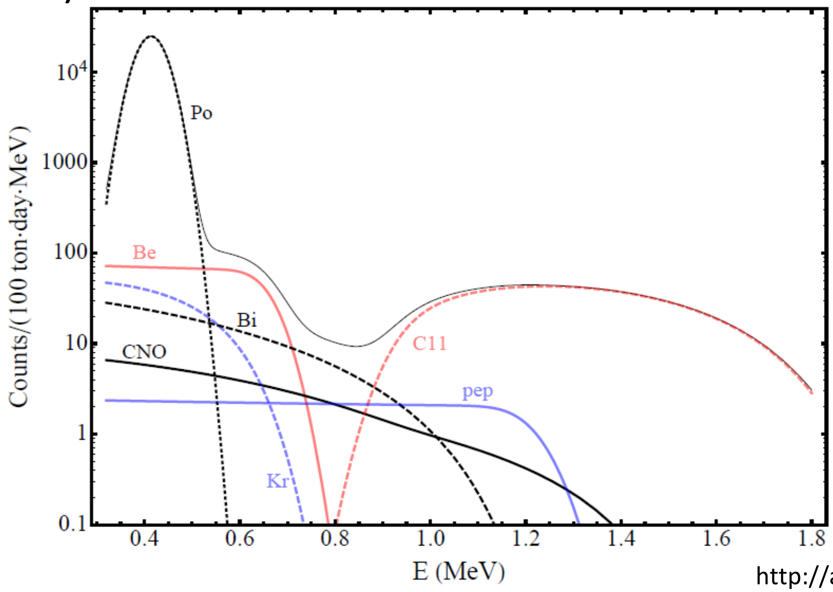
Setup can also be used for:

TU-Dresden:



- Measure the spectrum for Bi210/C14
  (important to reduce the background for Borexino which measure the CNO process for solar neutrinos)



http://arxiv.org/pdf/1104.1335v1

Other Interesting Isotops

initial state	final state	E^* in keV	decay type	Q in keV
^{77}As$(3/2^-)$	^{77}Se$(5/2^+)$	680.1046(16)	1st non-unique β^-	2.8 ± 1.8
^{111}In$(9/2^+)$	^{111}Cd$(3/2^+)$	864.8(3)	2nd unique EC	-2.8 ± 5.0
	^{111}Cd$(3/2^+)$	866.60(6)	2nd unique EC	-4.6 ± 5.0
^{131}I$(7/2^+)$	^{131}Xe$(9/2^+)$	971.22(13)	allowed β^-	-0.4 ± 0.7
^{146}Pm(3^-)	^{146}Nd(2^+)	1470.59(6)	1st non-unique EC	1.4 ± 4.0
^{149}Gd$(7/2^-)$	^{149}Eu$(5/2^+)$	1312(4)	1st non-unique EC	1 ± 6
^{155}Eu$(5/2^+)$	^{155}Gd$(9/2^-)$	251.7056(10)	1st unique β^-	1.0 ± 1.2
^{159}Dy$(3/2^-)$	^{159}Tb$(5/2^-)$	363.5449(14)	allowed EC	2.1 ± 1.2
^{161}Ho$(7/2^-)$	^{161}Dy$(7/2^-)$	857.502(7)	allowed EC	1.4 ± 2.7
	^{161}Dy$(3/2^-)$	858.7919(18)	2nd non-unique EC	0.1 ± 2.7

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