Calorimetric Low Temperature Detectors for Applications in Atomic and Nuclear Physics

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Calorimetric Low Temperature Detectors for Applications in Atomic and Nuclear Physics

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III. CLTD`s for High Resolution Detection of Heavy Ions - Status and Perspectives

IV. CLTD`s for High Resolution X-Ray Spectroscopy - Status and Perspectives

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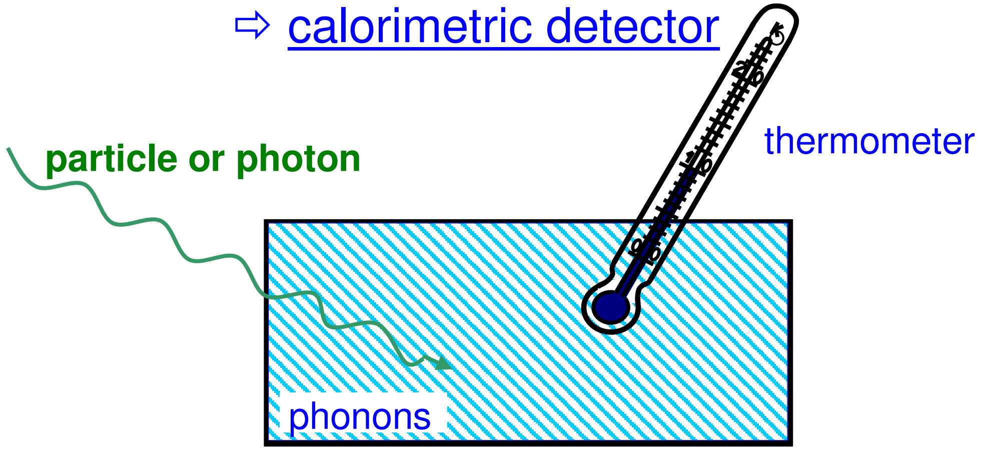
I. Introduction

The success of experimental physics and the quality of the results generally depends on the quality of the available detection systems !

⟹ idea: detection of radiation independent of ionisation processes

⇨ calorimetric detector



interaction of radiation with matter:

primary: ionization, ballistic phonons (conventional ionisation detectors)

secondary: thermalization: conversion of energy to heat

⇒ detection of thermal phonons

⇒ calorimetric detectors

potential advantage:

- energy resolution
- energy linearity
- detection threshold
- radiation hardness

⇒ various applications in many fields of physics

Applications of Low Temperature Detectors - an Overview

Astrophysics:

- dark matter
  ⇒ low detection threshold
- solar neutrinos
  ⇒ low detection threshold
- cosmic x-rays
  ⇒ high energy resolution

Particle physics:

- $\beta\beta0\nu$-decay
  ⇒ absorber = source (^{130}Te)
- neutrino mass from β- endpoint determ.
  ⇒ absorber = source (^{187}Re)

Atomic and Nuclear physics:

- X-ray detection
  ⇒ high energy resolution
- Ion detection
  ⇒ high energy resolution
  ⇒ good energy linearity

Applied physics:

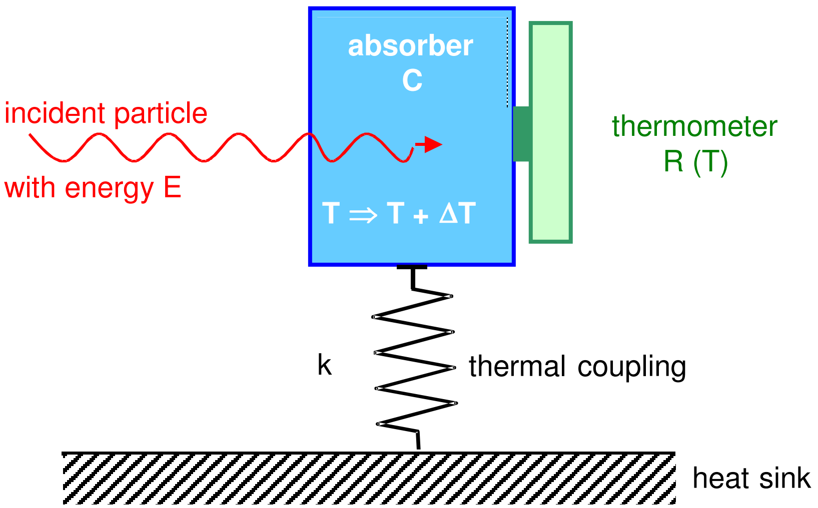
- x-ray material analysis
  ⇒ high energy resolution
- life sciences (MALDI)
  ⇒ high energy resolution

for more detailed information see:

- Cryogenic Particle Detection,
  Topics in Applied Physics 99 (2005)
- Proceedings 14th Int. Workshop on
  Low Temperature Detectors,
  JLTP (2012), 320 participants!

II. Detection Principle and Basic Properties of Calorimetric Low Temperature Detectors

detection principle:



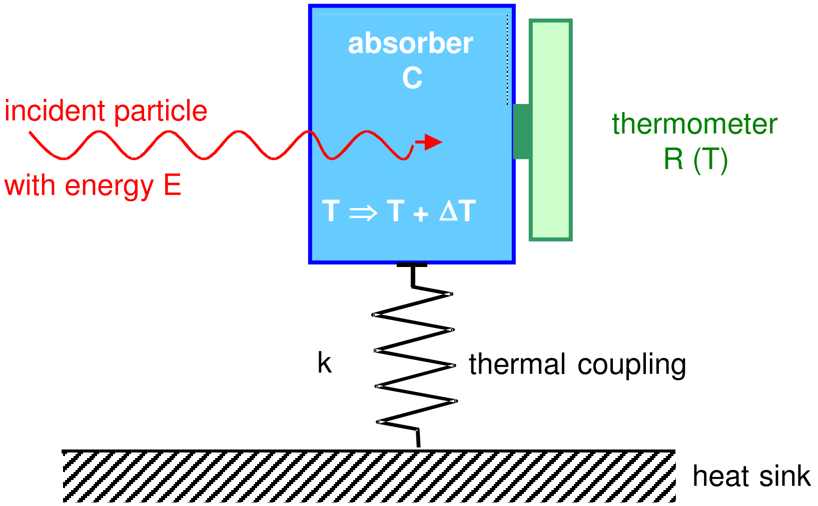
after particle absorption and decay of excite electronic states ($\approx 10^{-8}$ sec):

- thermalisation ⇒ energy is converted to heat (thermal phonons)
- energy transport to the heat sink

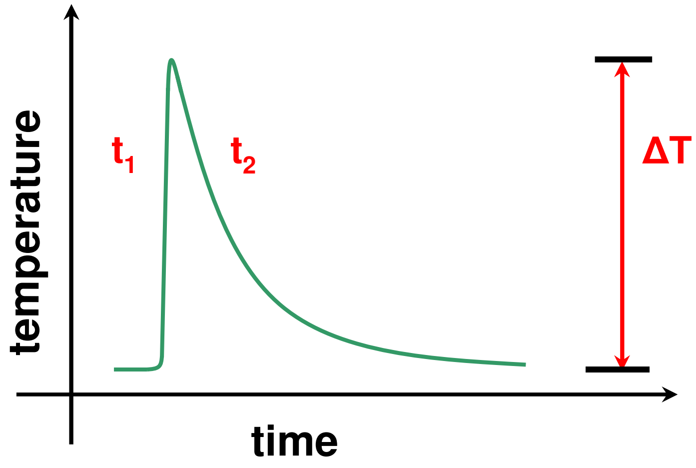
amplitude:	$\Delta T = E/C$	($C = c \bullet m$ = heat capacity)
rise time:	$\tau_1 \geq \tau_{therm}$	($\approx 1 - 10\ \mu$sec)
fall time:	$\tau_2 = C/k$	($\approx 100\ \mu$sec – 10 msec)

II. Detection Principle and Basic Properties of Calorimetric Low Temperature Detectors

detection principle:



thermal signal:



amplitude: $\Delta T = E/C$ (C = c • m = heat capacity)

rise time: $\tau_1 \geq \tau_{therm}$ (≈ 1 – 10 µsec)

fall time: $\tau_2 = C/k$ (≈ 100 µsec – 10 msec)

Optimization of the Sensitivity

a) <u>absorber:</u> maximum sensitivity $\Delta T = E/mc$ for

– small absorber mass m

– small specific heat c

due to: $c = \underbrace{\alpha T}_{\text{electrons}} + \underbrace{\beta (T/\theta_D)^3}_{\text{lattice}}$ (θ_D = Debye-temperature)

⇒ low operating temperature ⇒ „<u>low-temperature detector</u>“

(αT dominating for $T \leq 10K$ ⇒ insulators ($\alpha = 0$) or superconductors)

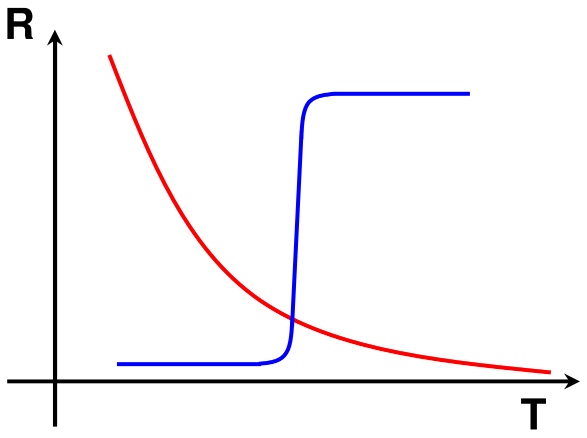
b) <u>thermometer:</u> for thermistor (bolometer): $\Delta T \rightarrow \Delta R \rightarrow \Delta U$

⇒ maximum sensitivity for large dR/dT

– semiconductor thermistor

due to appropriate doping ⇒ exponential behavior of R(T)

– superconducting phase transition thermometer



Potential Advantage over Conventional Detectors

- small energy gap ω

  ⇒ better statistics of the detected phonons

  semiconductor detector: $\omega \approx 1$ eV

  calorimetric detector: $\omega \leq 10^{-3}$ eV

$$\frac{\Delta E_{calorimeter}}{\Delta E_{semicond.\mathrm{det}.}} = \sqrt{\frac{N_{electr.}}{N_{phon.}}} = \sqrt{\frac{\omega_{phon}}{\omega_{electr.}}} \leq \frac{1}{30}$$

- more complete energy detection ⇒ better linearity and resolution

  energy deposited in phonons and ionisation contributes to the signal
  (for ionisation detectors: losses up to 60-80% due to: - recombination
  - direct phonon production)

- small noise power at low temperatures

- method independent on absorber material

  ⇒ optimize radiation hardness, absorption efficiency, etc.

Theoretical Limit for the Energy Resolution

for ideal calorimetric detector:

- thermodynamic fluctuations (quantum statistics)
- Johnson noise
- amplifier noise

$$\Rightarrow\ < \Delta E > = \underset{\text{noise}}{\xi} \bullet \underbrace{\sqrt{k_B T^5 c\ m}}_{\text{thermodynamic fluctuations}} \qquad 1 < \xi < 3$$

example: 1 MeV particle in a 1 mm^3 sapphire absorber

T	C	ΔT	ΔE_{theor}
300 K	$3 \bullet 10^{-3}$ J/K	$5 \bullet 10^{-11}$ K	1.8 GeV
10 K	$4 \bullet 10^{-7}$ J/K	$4 \bullet 10^{-7}$ K	700 keV
1 K	$4 \bullet 10^{-10}$ J/K	0.4 mK	2.2 keV
100 mK	$4 \bullet 10^{-13}$ J/K	400 mK	7 eV

⇒ for low temperature: microscopic particle affects the properties of a macroscopic absorber

Theoretical Limit for the Energy Resolution

for ideal calorimetric detector:

- thermodynamic fluctuations (quantum statistics)
- Johnson noise
- amplifier noise

$$\Rightarrow \; < \Delta E >= \underset{\text{noise}}{\xi} \bullet \underbrace{\sqrt{k_B T^5 c\; m}}_{\text{thermodynamic fluctuations}} \qquad 1 < \xi < 3$$

example: 50 keV X-ray, 1 mm² tin absorber with a thickness of 50 µm

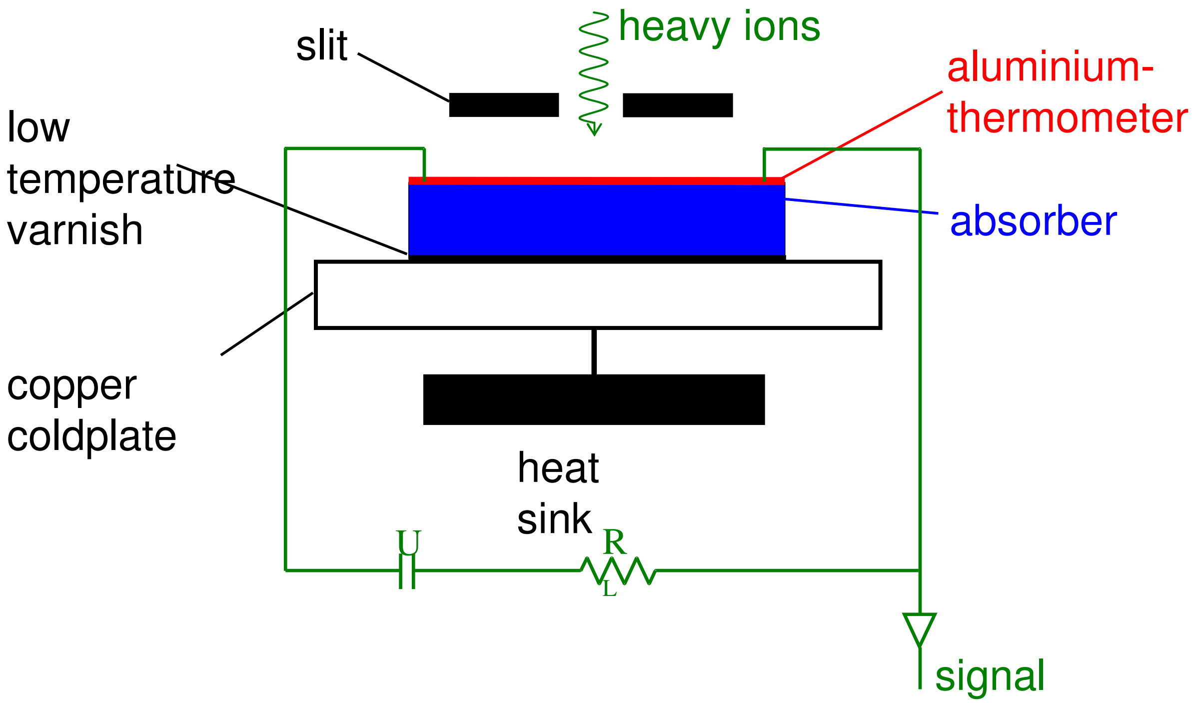
T	C	ΔT	$\Delta E_{theor.}$
300 K	$8 \cdot 10^{-5}$ J/K	$1 \cdot 10^{-10}$ K	295 MeV
1 K	$1{,}2 \cdot 10^{-9}$ J/K	$6{,}7 \cdot 10^{-6}$ K	3,8 keV
0,1 K	$1{,}2 \cdot 10^{-12}$ J/K	$6{,}7 \cdot 10^{-3}$ K	12 eV
0,05 K	$1{,}5 \cdot 10^{-13}$ J/K	$5{,}3 \cdot 10^{-2}$ K	2 eV

(theoretical limit for a conventional semiconductor detector: $\Delta E_{theor} = 350$ eV)

⇒ for low temperature: microscopic photon affects the properties of a macroscopic absorber

III. CLTD`s for High Resolution Detection of Heavy Ions - Status and Perspectives

Detector Design and Perfomance:

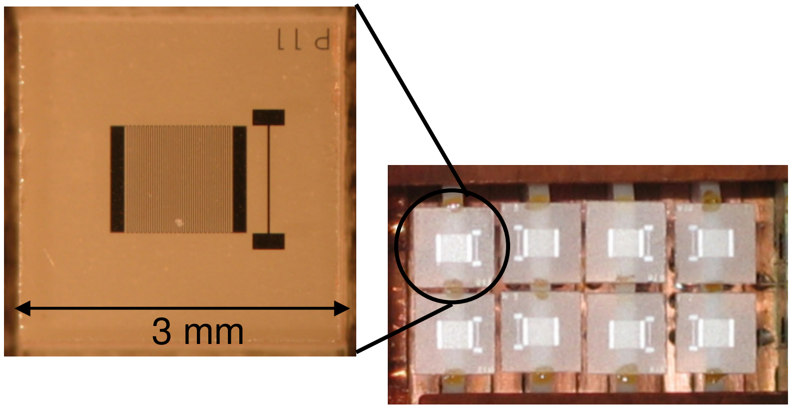


absorber: sapphire-crystal: V= 3 x 3 mm² x 300 µm

thermometer: aluminium-film (d = 10 nm), $T_C \approx 1.5$°K (in the range of a ^{4}He-cryostat)
(for impedance matching to the amplifier: ⇒ meander structure)

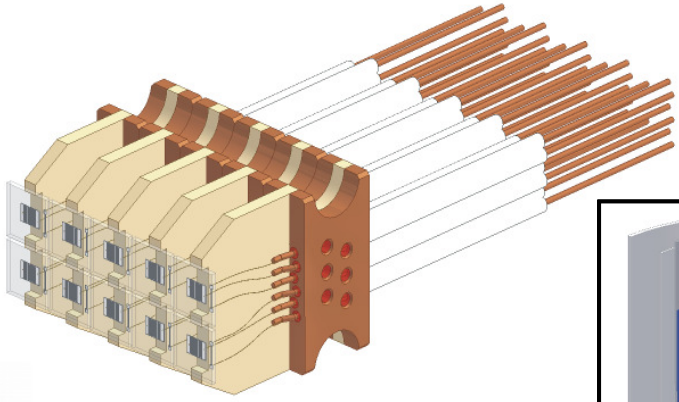
readout: conventional pulse electronics +Flash-ADC`s +Digital Filtering

CLTD`s for High Resolution Detection of Heavy Ions
- Status and Perspectives



detector design:

- sapphire absorber
- pixel size: 3 x 3 mm^2
- operated at T_c = 1.4 – 1.6 K
- superconducting Al thermistor
  10 nm Meander structure
  ⇒ photolithography (high purity!

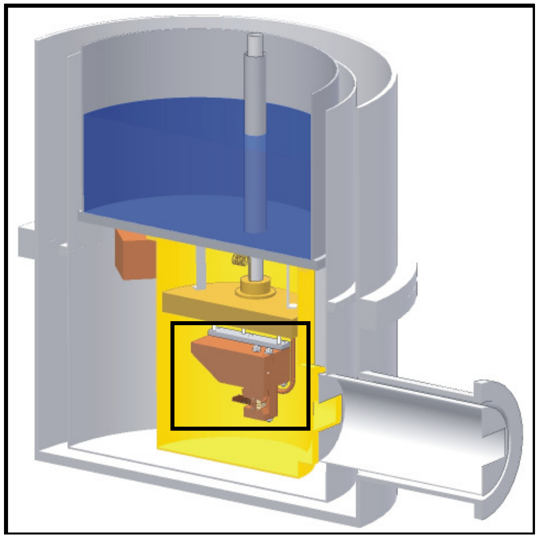


detector array:

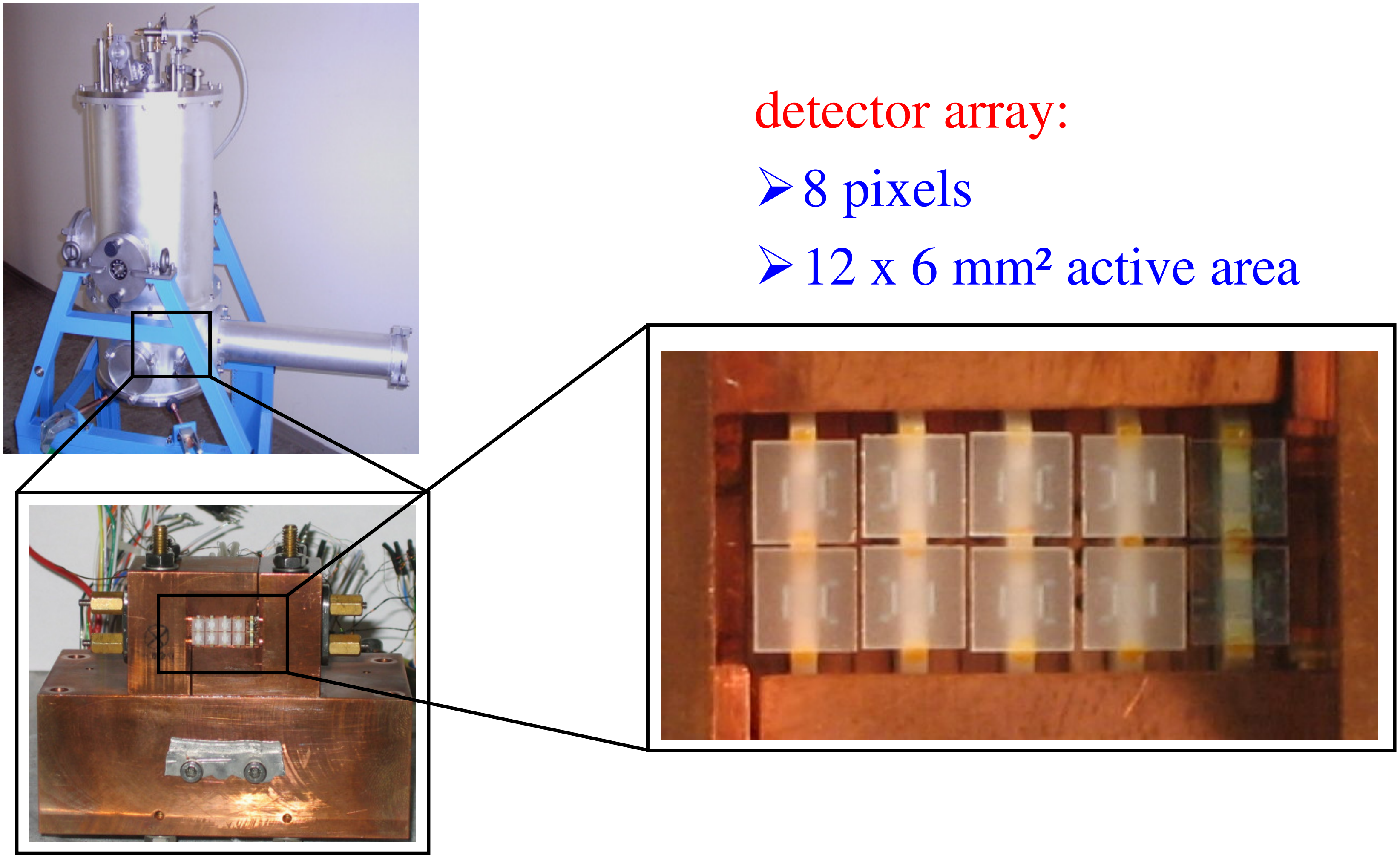
- 8 pixels with individual temperature
  stabilization in operation
- active area: 12 x 6 mm^2

cryostat:

-windowless
^{4}He bath cryostat
- operated at 1.4 -1,6 K



Implementation in the Cryostat



detector array:

- 8 pixels
- 12 x 6 mm² active area

CLTD`s for High Resolution Detection of Heavy Ions - Status and Perspectives

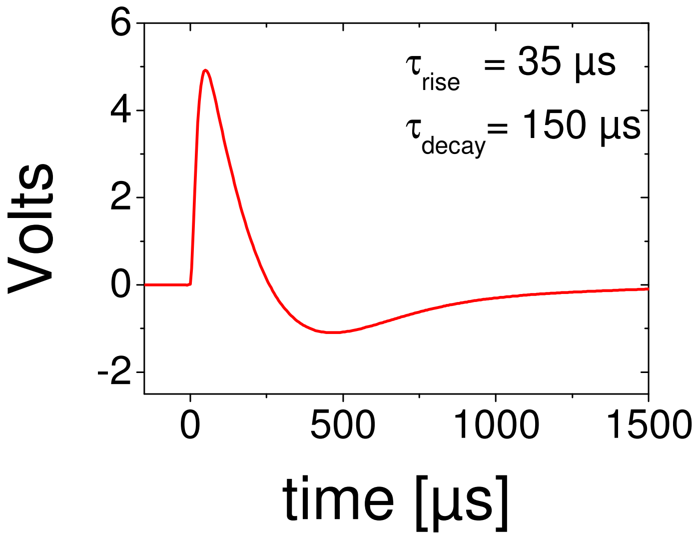
detector performance: response to ^{32}S ions @ 100 MeV

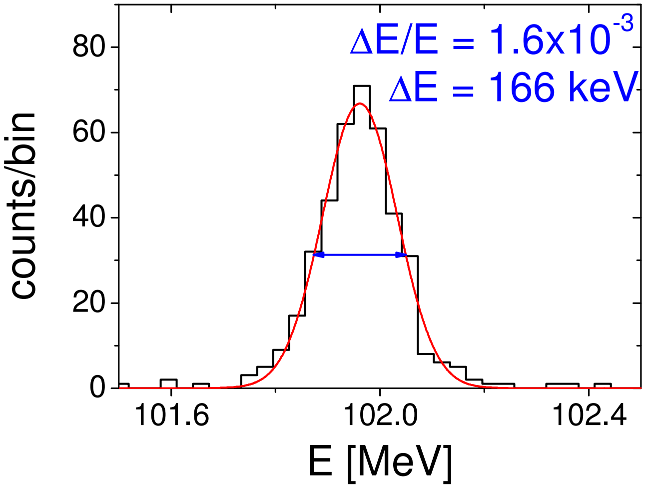
rate capability:

≥ 200 sec^{-1}

resolution:

$\Delta E/E = 1.6 \times 10^{-3}$





systematical investigation of energy resolution:

with UNILAC-beam: for ^{209}Bi, E = 11.6 MeV/u ⇒ $\Delta E/E = 1.8 \times 10^{-3}$

with ESR-beam: for ^{238}U, E = 360 MeV/u ⇒ $\Delta E/E = 1.1 \times 10^{-3}$

with Tandem-beam: for ^{152}Sm, E = 3.6 MeV/u ⇒ $\Delta E/E = 1.6 \times 10^{-3}$

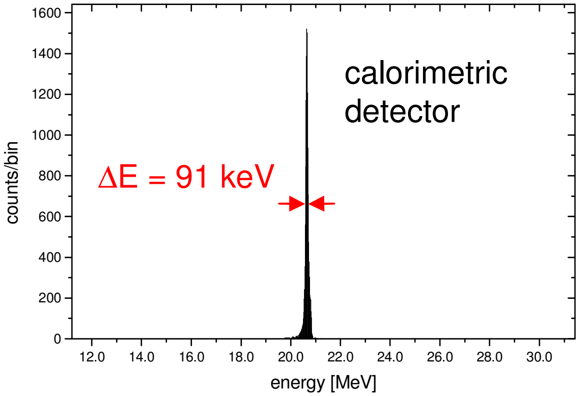
⇒ for heavy ions: ≥ 10 x improvement over conventional Si detectors

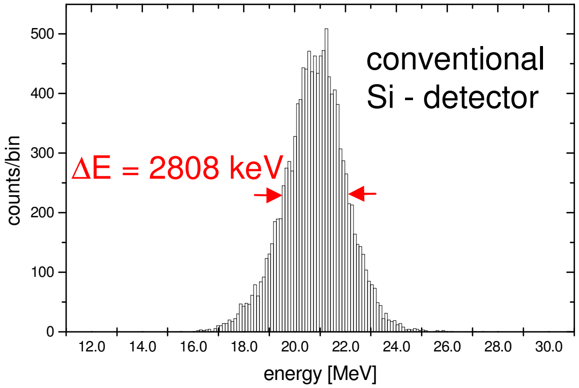
Comparison of Detector Performance: CLTD – Conventional Si Detector

<u>energy resolution:</u>

example:

^{238}U @ 20.7 MeV)

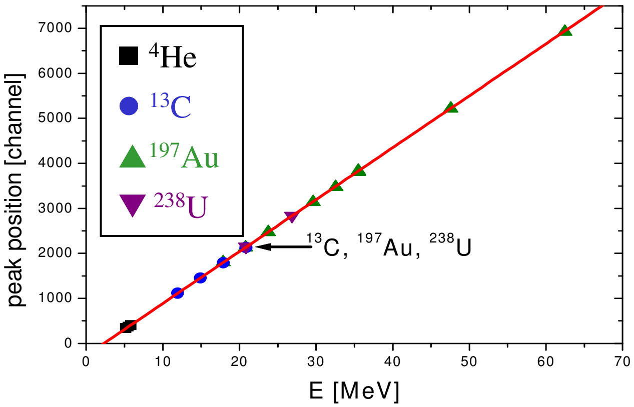


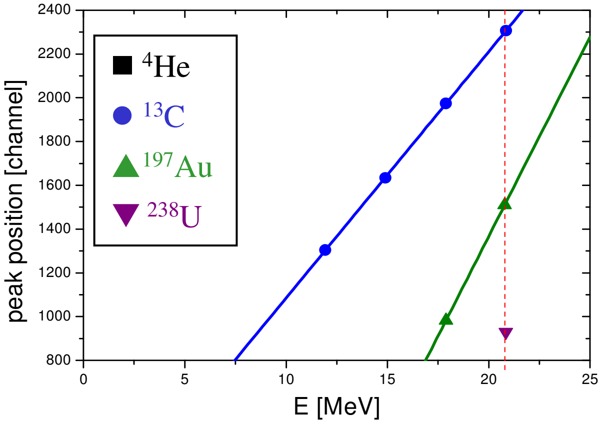


<u>energy linearity:</u>

example:

^{13}C, ^{197}Au, ^{238}U





<u>for conventional ionization detector:</u>

high ionization density leads to charge recombination

⇒ pronounced pulse height defects ⇒ nonlinear energy response

⇒ fluctuation of energy loss processes ⇒ limited energy resolution

Perspectives for Applications in Heavy Ion Physics

nuclear spectroscopy:

- elastic and inelastic scattering ⇒ separation of inelastic channels
- nuclear reactions ⇒ identification of reaction channels

Example:

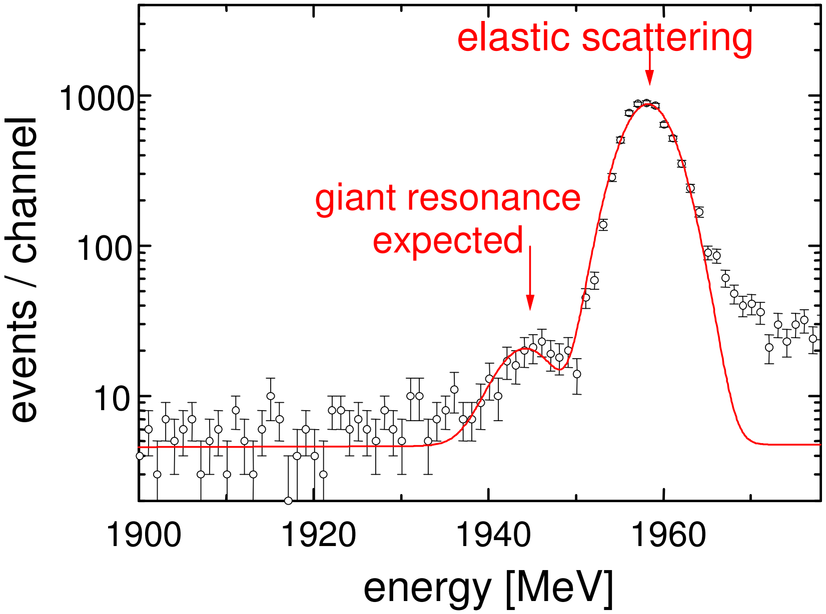
investigation of giant resonances

(collective excitation of nuclear matter)

J. Meier et al.

Nucl. Phys. A 626 (1997) 451c

^{Nat}Pb (^{20}Ne, $^{20}Ne'$), E = 100 MeV/u



of high interest:

⇒ new excitation modes

⇒ higher order modes: multi phonon giant resonances

High Resolution Mass Identification

important for many applications: isotope mass identification

standard method:

$$\left.\begin{array}{ll} B \bullet \rho & \Rightarrow p \\ \text{TOF} & \Rightarrow v \end{array}\right\} \boxed{m = \frac{p}{v}}$$

disadvantage:

- needs big magnet spectrometer
- small solid angle
- charge state ambiguity because of B • ρ = p/Q (especially for slow heavy ions!)

alternative method:

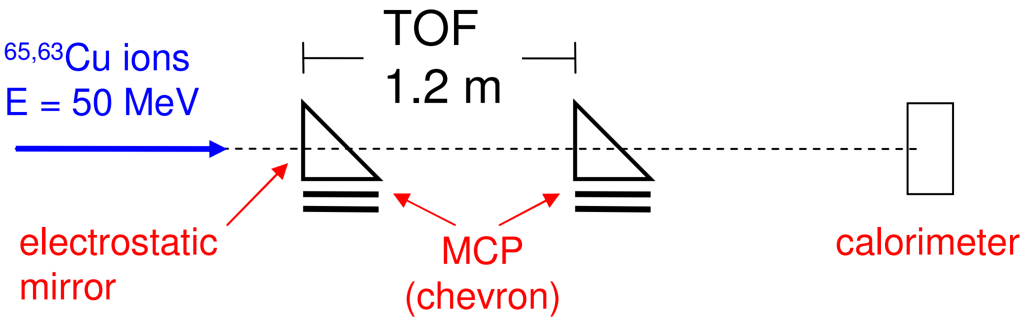
$$\left.\begin{array}{ll} \text{energy} & \Rightarrow E \\ \text{TOF} & \Rightarrow v \end{array}\right\} \boxed{m = \frac{2E}{v^2}}$$

$$\boxed{\left(\frac{\Delta m}{m}\right)^2 = \left(\frac{\Delta E}{E}\right)^2 + \left(2\frac{\Delta t}{t}\right)^2}$$

mass resolution is limited by energy resolution! ⇒ calorimetric detectors

High Resolution Mass Identification

measured at Tandem accelerator at MPI in Heidelberg



^{65,63}Cu ions

E = 50 MeV

TOF

1.2 m

electrostatic mirror

MCP (chevron)

calorimeter

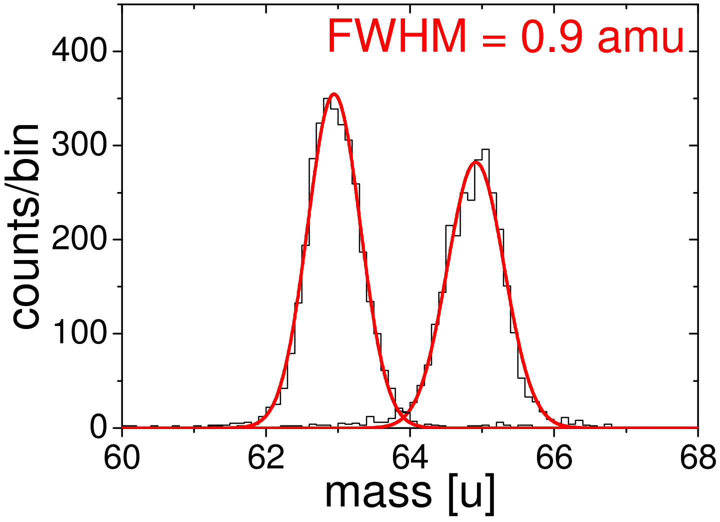
energy ⇒ E

TOF ⇒ v

$$m = \frac{2E}{v^2}$$

$$\left(\frac{\Delta m}{m}\right)^2 = \left(\frac{\Delta E}{E}\right)^2 + \left(2\frac{\Delta t}{t}\right)^2$$

^{63,65}Cu ions @ 50 MeV



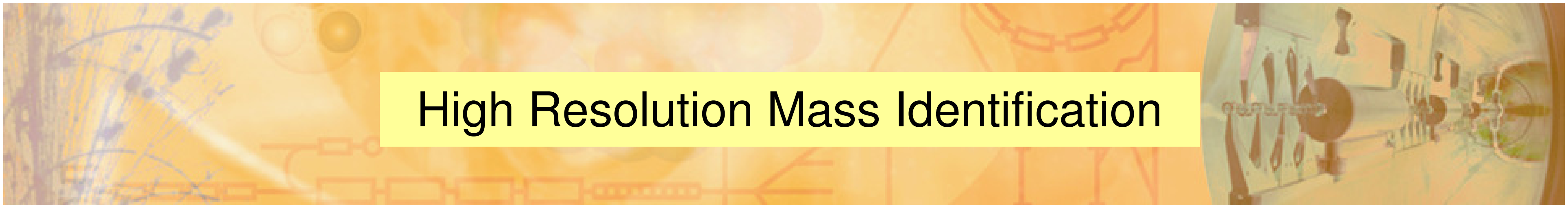
Δt = 680 ps

ΔE = 330 keV

limitation: TOF measurement !

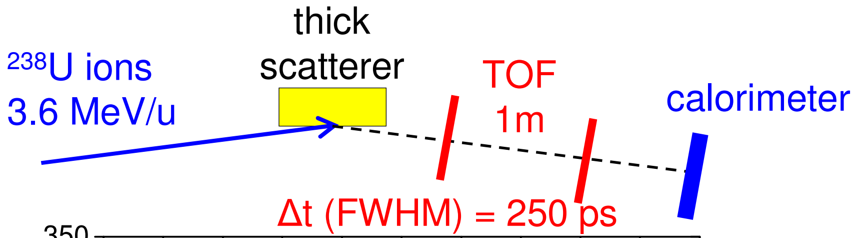
A. Echler et al.

(2012) to be published

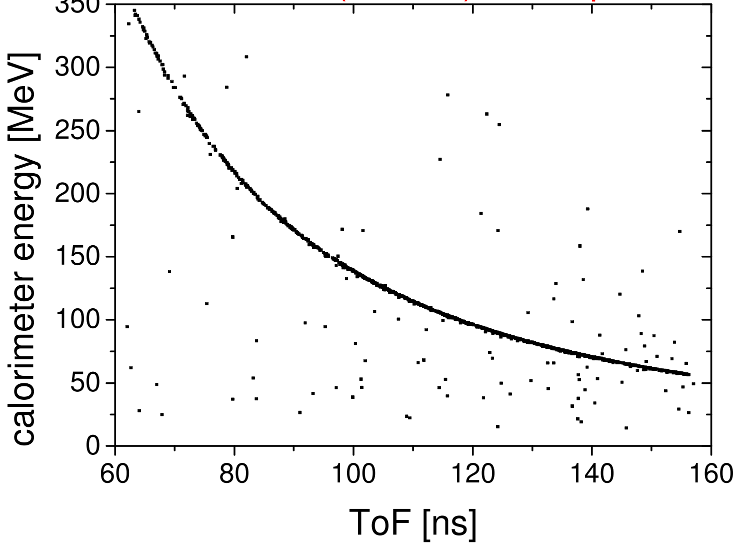


High Resolution Mass Identification

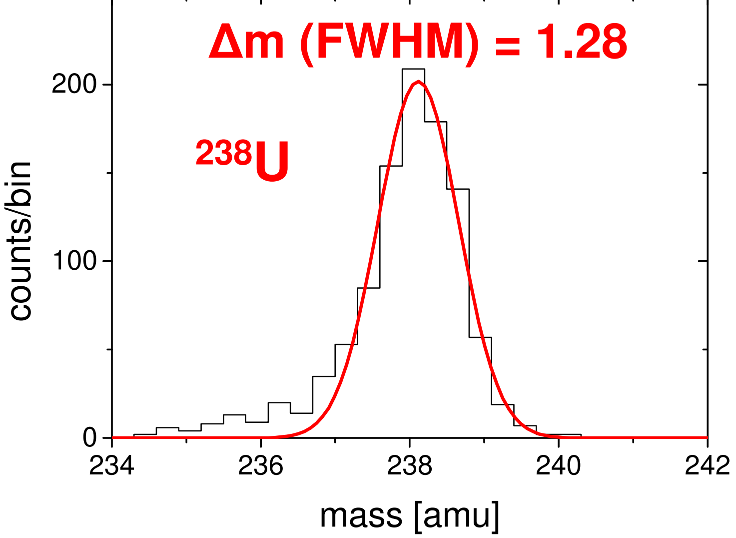
experimental setup: low energetic ^{238}U ions @ UNILAC accelerator at GSI



→ broad energy distribution
(0 - 3.6 MeV/u)

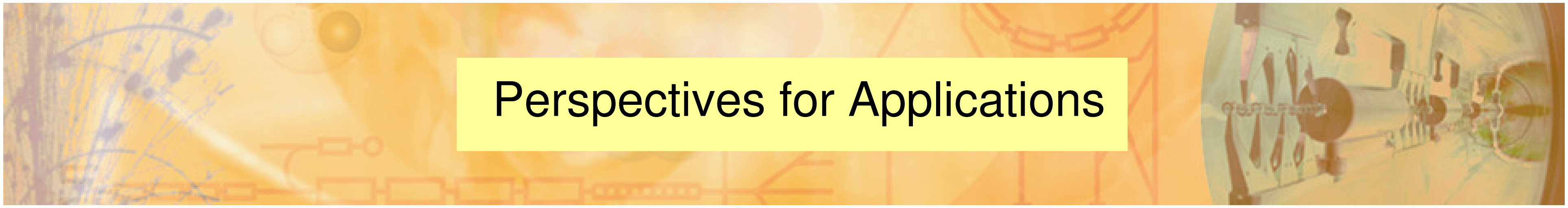


energy range: 65 - 150 MeV



- ➢not reachable with conventional E-ToF system
- ➢advantage to Bρ-ToF method: ▪ high dynamic range
  - ▪ not affected by charge state ambiguities

most recent result from measurements at Jyväskylä: **Δm (FWHM) = 0.83 for ^{131}Xe ions**



Perspectives for Applications

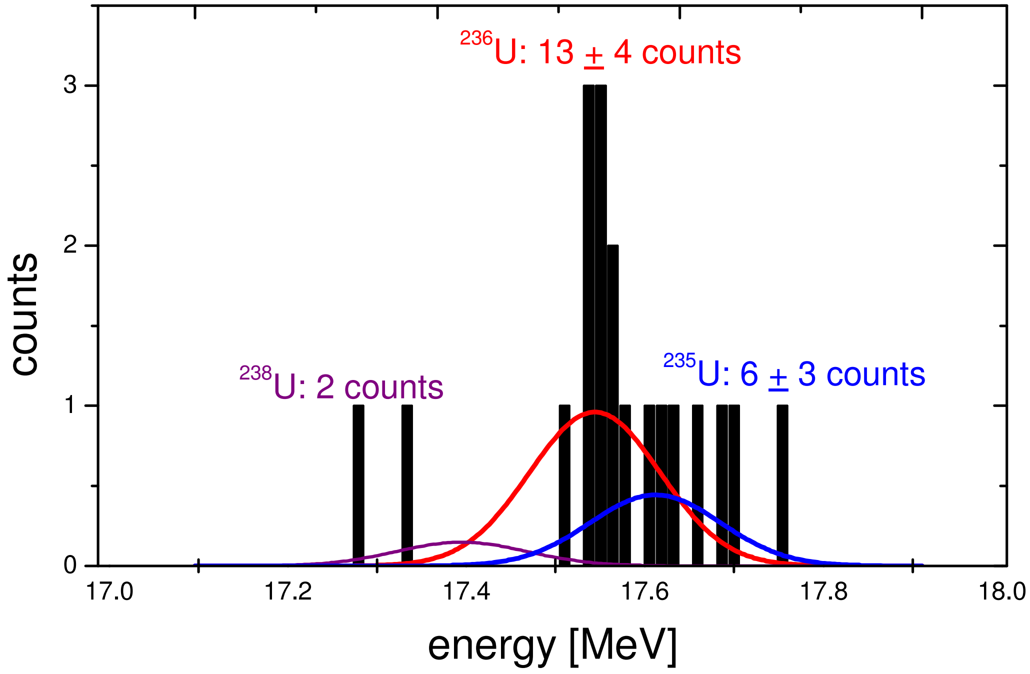
High Resolution Mass Identification for:

- identification of reaction products from reactions with radioactive beams (for slow heavy ions: no charge state ambiguities, high dynamic range)
  ⇒ potential application at NUSTAR LEB, VAMOS, etc.
- identification of isotopes after in-flight gamma spectroscopy
  ⇒ potential application at NUSTAR HISPEC (LYCCA)
- identification of superheavy elements (for $Z \geq 113$: decay chain does not feed a known α chain): $\Delta m \leq 1$ for $m = 300$ reachable
- identification of rare isotopes in accelerator mass spectrometry
  ⇒ high sensitivity
- identification of fission fragments (replace the COSI FAN TUTTE spectrometer)
  ⇒ investigate structures in the mass distribution

Applications of CLTD`s

application for Accelerator Mass Spectrometry:
(in collaboration with: R. Golser, W. Kutschera et al., VERA facility, Vienna)

aim: determination of small isotope ratios $^{236}U/^{238}U$ in natural uranium samples
⇒ ^{236}U known as monitor for flux of thermal neutrons



results:
substantial improvement in background discrimination and detection efficiency

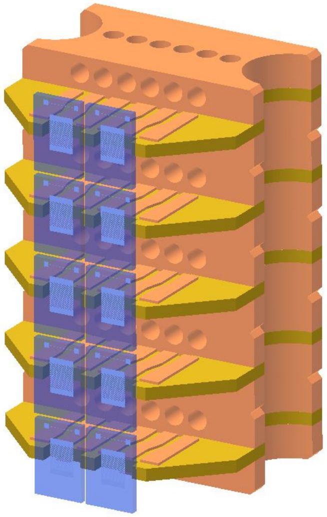
⇒ level of sensitivity improved by one order of magnitude:

$$^{236}U/^{238}U = 7 \times 10^{-12}$$

S. Kraft-Bermuth et al.

Rev. Sci. Instr. 80 (2009) 103304

Design of a Next Generation Array



detector-layout:

96 pixels with F = 5 x 5 mm^2 each

active area: 3 x 8 cm^2

position resolution: 5 mm

α-resolution: $\Delta E \leq 30$ keV

mass resolution: $\Delta E/E \leq 3 \times 10^{-3} \Rightarrow \Delta m \leq 1$ amu

rate capability: ≥ 300 sec^{-1}/pixel

Applications: Investigation of Stopping Powers of Heavy Ions in Matter

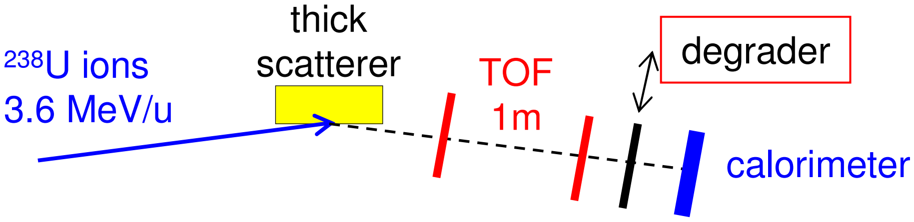
motivation:

- precise data needed for improving semi-empirical predictions (SRIM, etc.)
- data for very slow heavy ions are still scarce

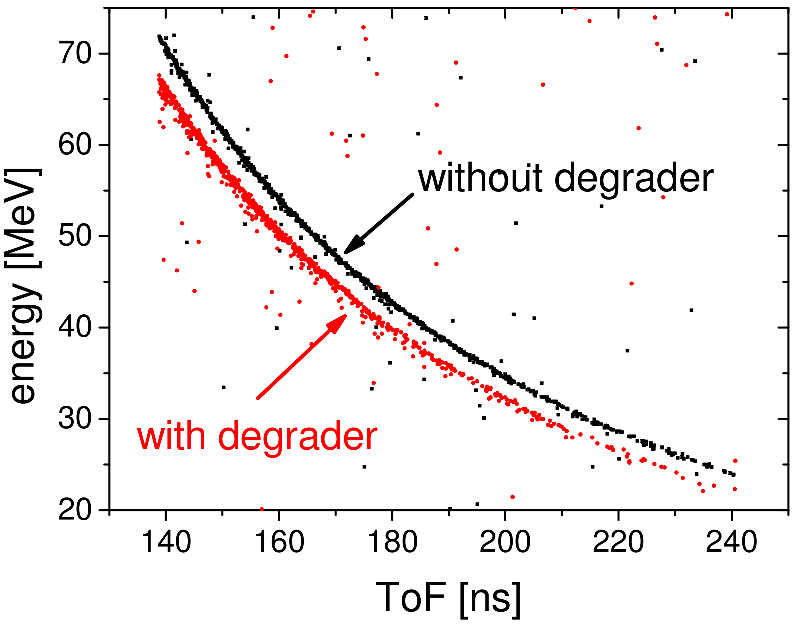
A. Echler et al.

PHD thesis 2012

low energetic ^{238}U ions @ UNILAC accelerator at GSI



→ stopping power values over a wide range of energies in a single measurement



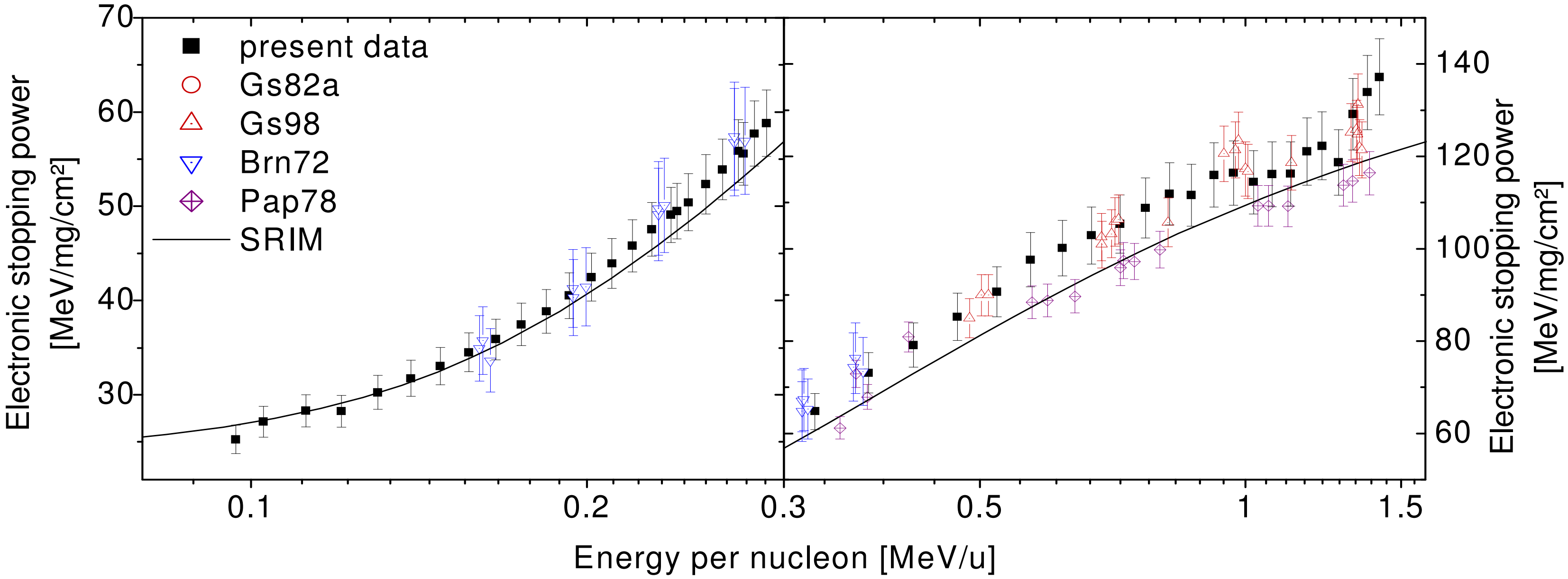
as compared to conventional setups:

- ➢higher sensitivity (energy resolution)
- ➢better energy determination (no pulse height defect)

Results on Stopping Powers of Heavy Ions in Matter

- uncertainties presently still dominated by foil thickness (~6%, to be improved)
- statistical error < 2%

^{238}U on carbon



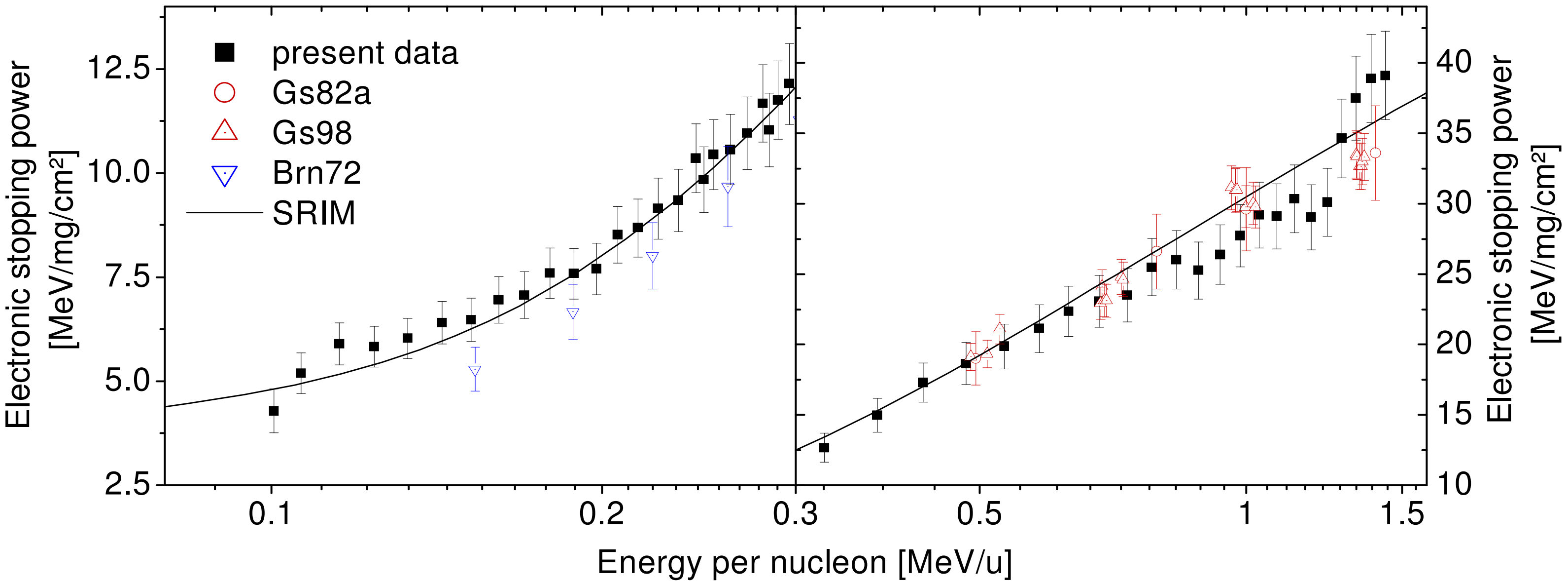
- ➢ data extended to E = 0.1 MeV/u
- ➢ discrepancies to E- dependence of theoretical prediction (SRIM)
- ➢ deviations to data of Pape et al. (Pap78)
- ➢ agreement with data of Geissel et al. and Brown et al. (Gs82a,Gs98,Brn72)

literature references: H. Paul, http://www.exphys.uni-linz.ac.at/stopping/

Results on Stopping Powers of Heavy Ions in Matter

- uncertainties presently still dominated by foil thickness (~8%, to be improved)
- statistical error < 3.5%

^{238}U on gold



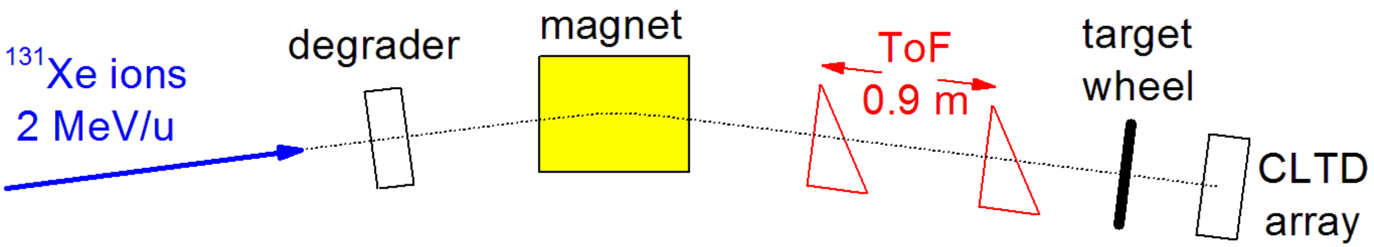
➢ good agreement with literature data and theoretical calculations

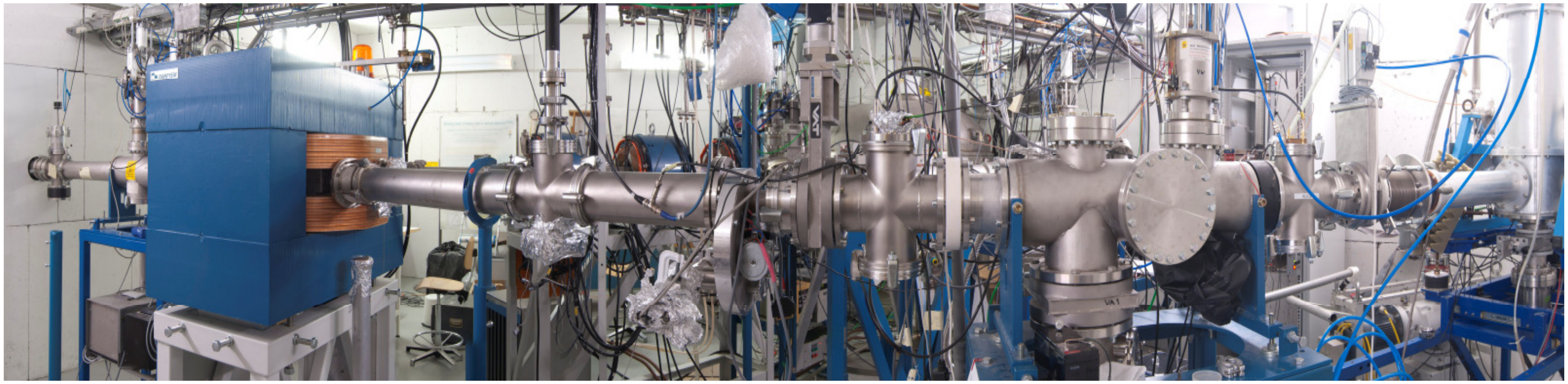
literature references: H. Paul, http://www.exphys.uni-linz.ac.at/stopping/

Results on Stopping Powers of Heavy Ions in Matter

most recent experiment:
joint experiment with the Jyväskylä group at the Jyväskylä facility

experimental setup:

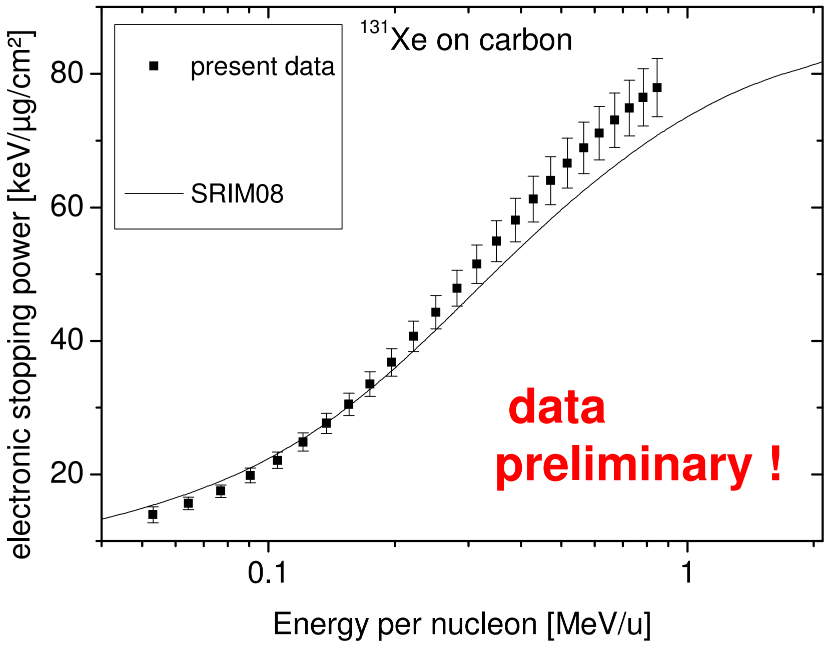




Results on Stopping Powers of Heavy Ions in Matter

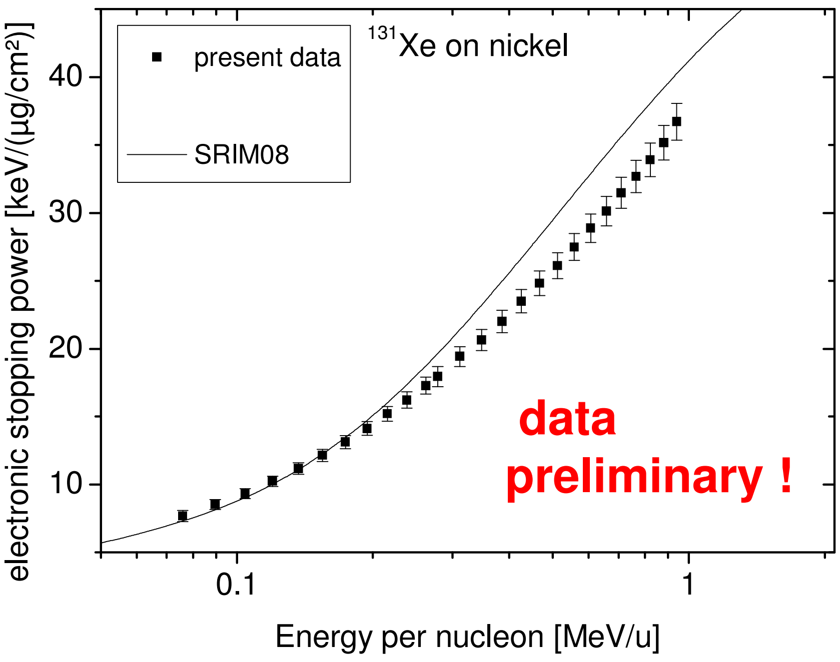
A. Echler et al.
PHD thesis 2012

^{131}Xe on carbon



data preliminary !

^{131}Xe on nickel



data preliminary !

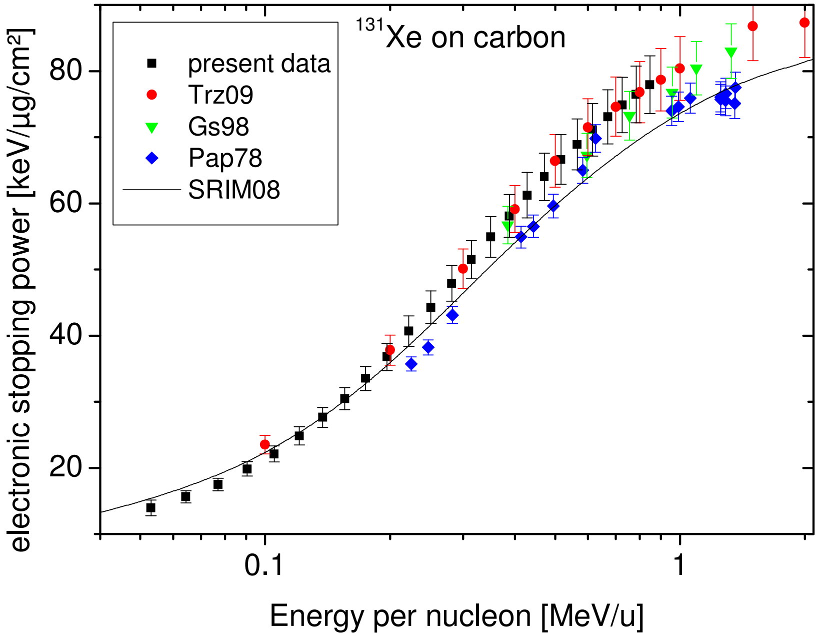
- systematic deviations in the energy dependence from the SRIM predictions

Results on Stopping Powers of Heavy Ions in Matter

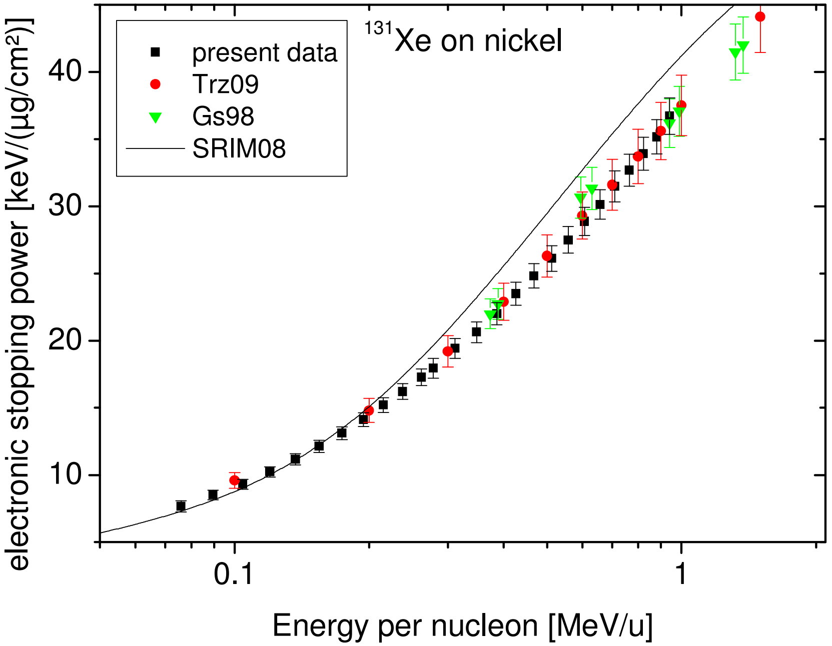
A. Echler et al.

PHD thesis 2012

^{131}Xe on carbon



^{131}Xe on nickel



[Trz09] W.H. Trzaska et al., Nucl. Instrum. Methods Phys. Res. B **267** (2009), 3403

[Gs98] H. Geissel et al., Various datasets summarized in electronic library of H. Paul

[Pap78] H. Pape, H.G. Clerc, K.H.Schmidt. Z. Phys. A **286** (1978) , 159

- data extended to lower energies < 0.1 MeV/u
- good agreement with literature values except those from Pape et al.

IV. CLTD`s for High Resolution X-Ray Spectroscopy - Status and Perspectives

detection scheme:

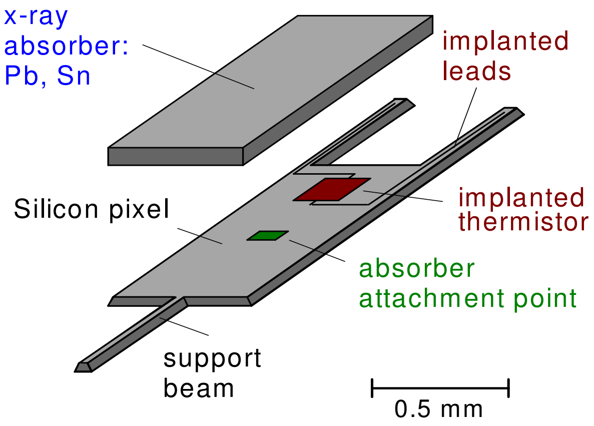
- 36 pixel Si thermistors (from NASA/Goddard)
- Sn, Pb absorbers
- each pixel: ≈ 0.5 mm² x 85 µm
-- operated at 50 mK

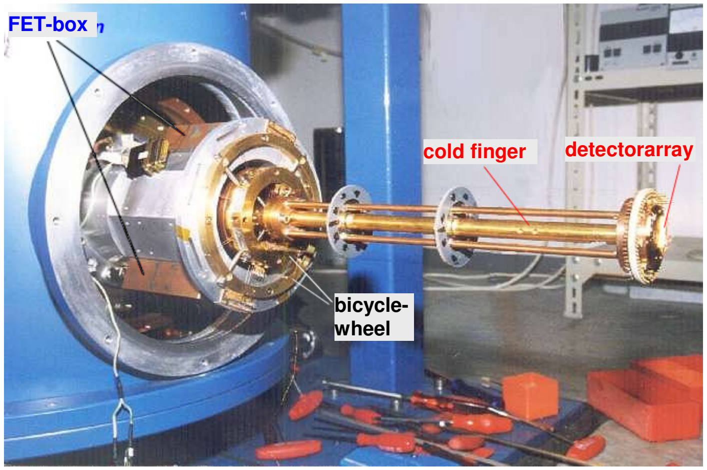
detector performance:

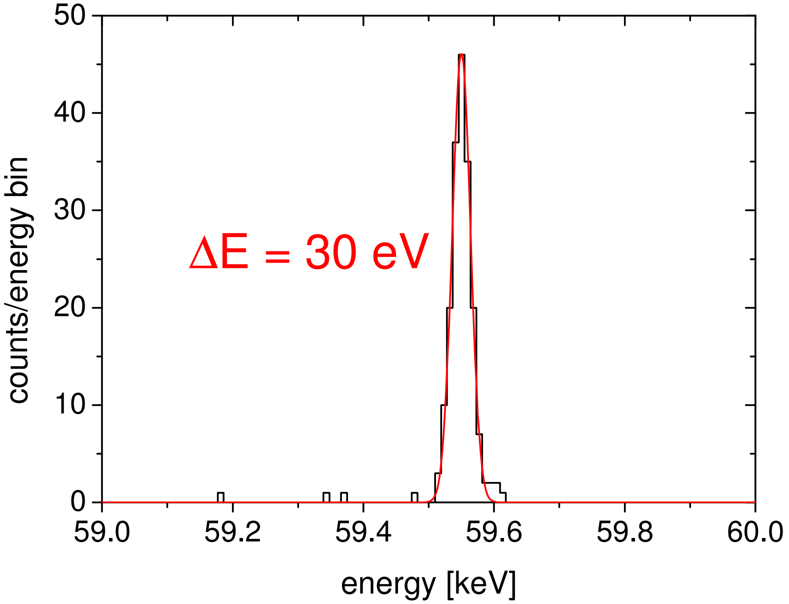
- ΔE = 30 – 40 eV @ 60 keV (theoretical limit of conventional Si detector: ≥ 350 eV)

present status:

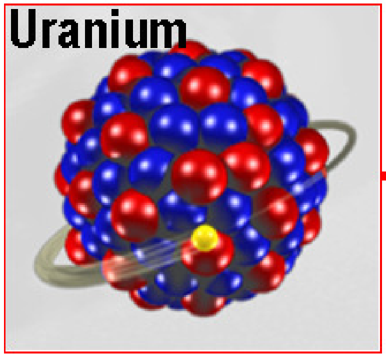
- detector with 24 pixels tested
- active area: 10 mm²

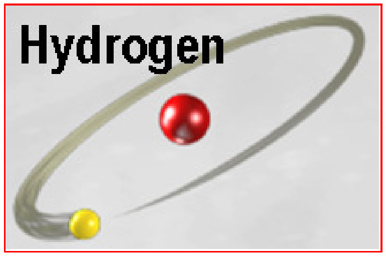


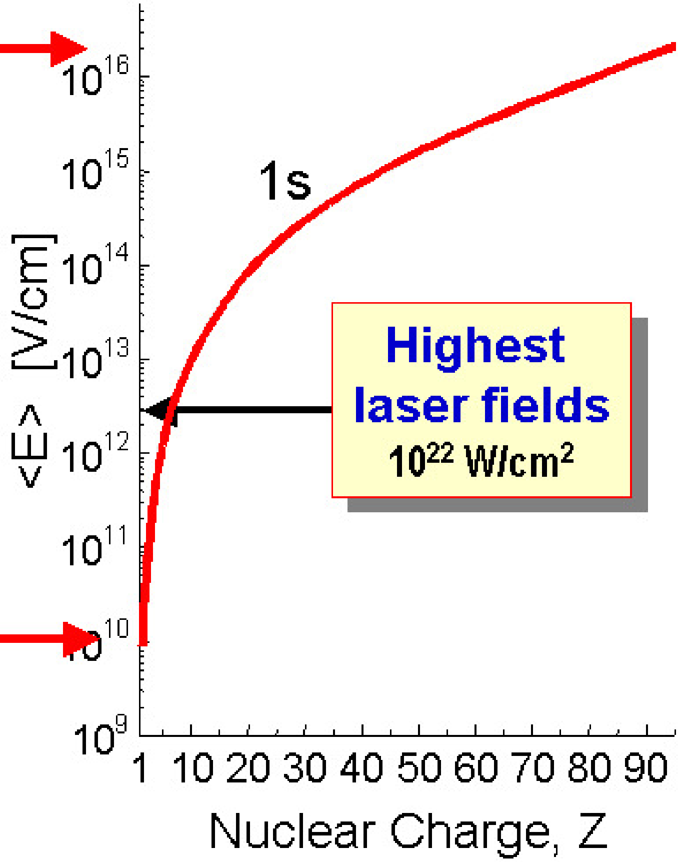




Perspectives: Test of QED in Extreme Static Electromagnetic Fields







Highest laser fields
10^{22} W/cm^2

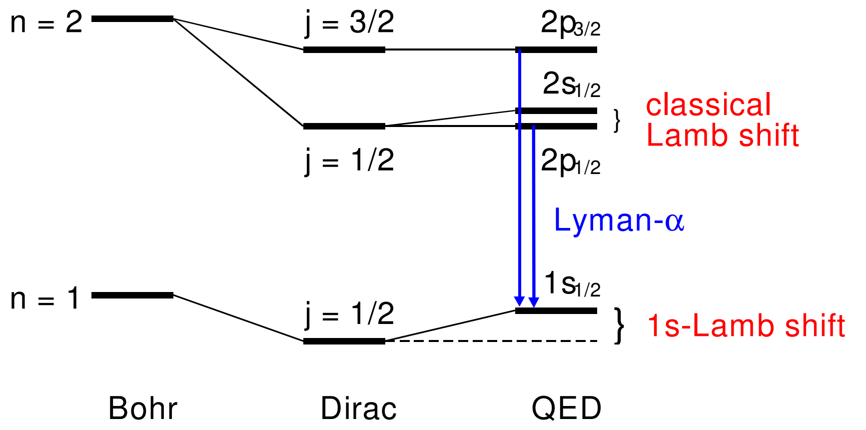
H-like Uranium
$\langle E \rangle = 1.8\times10^{16}$ V/cm
$E_K = -132\times10^3$ eV
$\Delta E_{Lamb} \approx 500$ eV
$Z\ \alpha \approx 1$

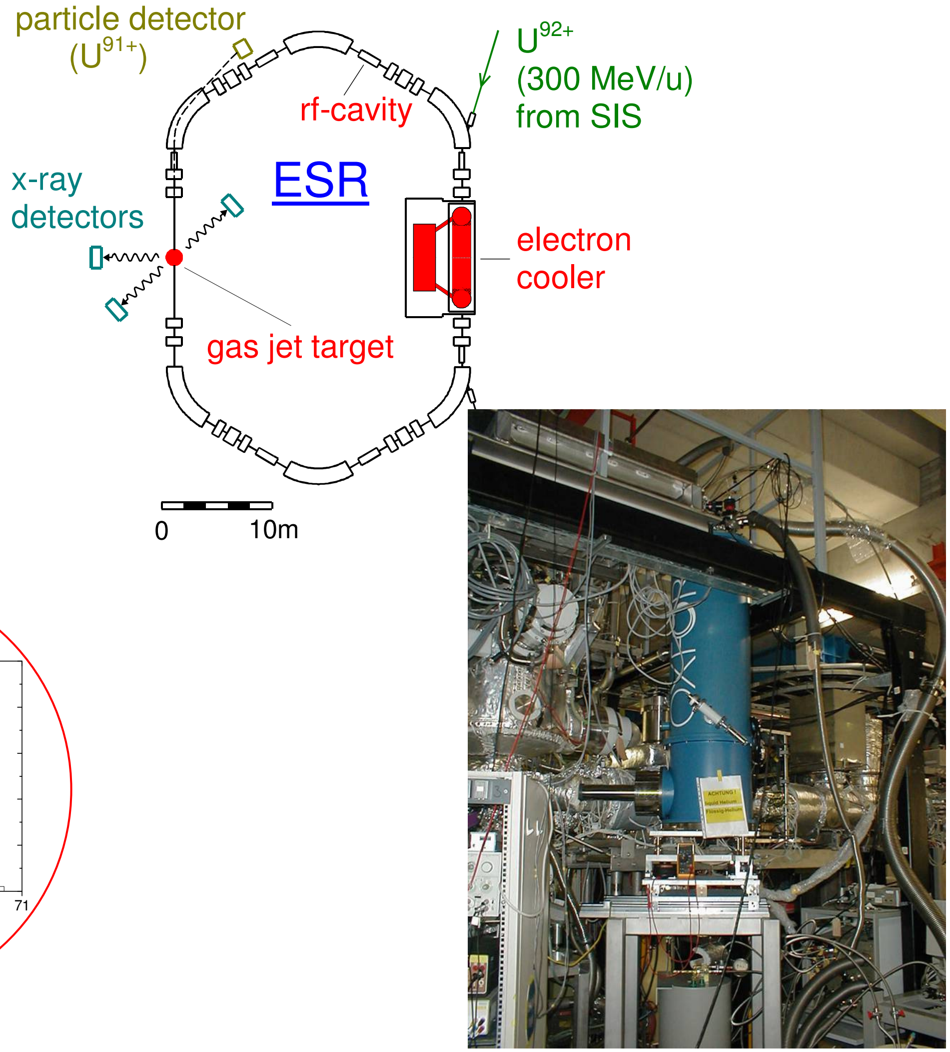
***Q**uantum*
***E**lectro-*
***D**ynamics*

Hydrogen
$\langle E \rangle = 1\times10^{10}$ V/cm
$E_k = -13.6$ eV
$\Delta E_{Lamb} \approx 10^{-5}$ eV
$Z\ \alpha \approx 10^{-2}$

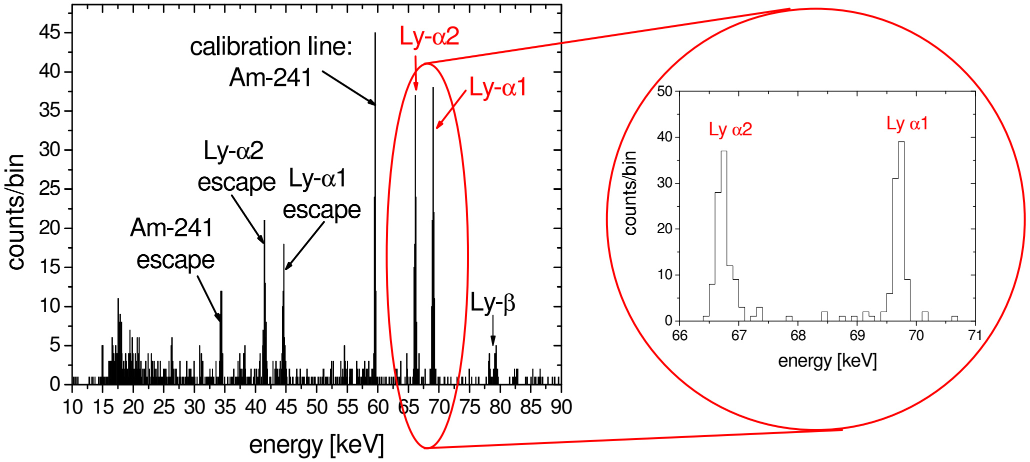
CLTD`s for the Lambshift Experiment on Hydrogen-Like Heavy Ions – Present Status

idea of the experiment: determine absolute transition energy of the Lyman-α line
⇒ most sensitive test of QED ($Z\alpha \to 1$, higher order terms)





proof of principles for $^{238}U^{91+}$ and $^{207}Pb^{82+}$:



CLTD`s for the Lambshift Experiment on Hydrogen-Like Heavy Ions – Present Status

results of a joint experiment with the Atomic Physic Group (FOCAL crystal spectrometer):

beam: $^{207}Pb^{82+}$ at 219 MeV/u

overall efficiency: 2.5 x 10^{-7} (only 3 pixels)

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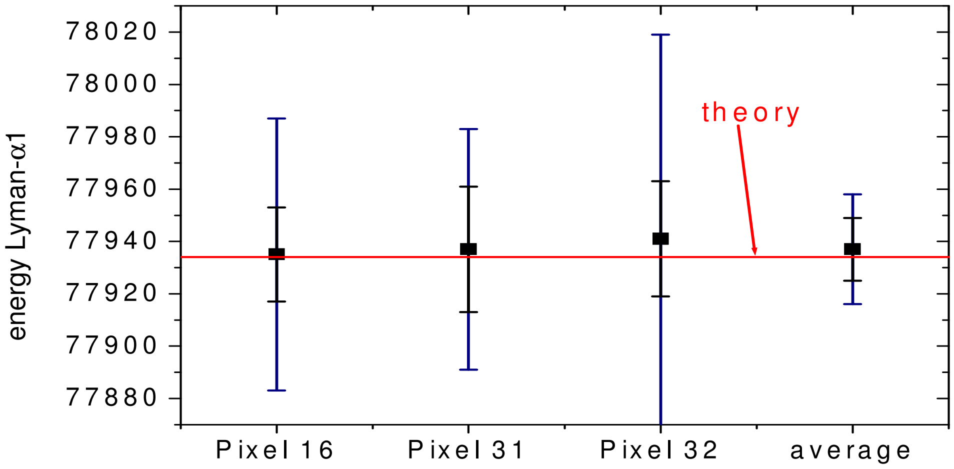


result:

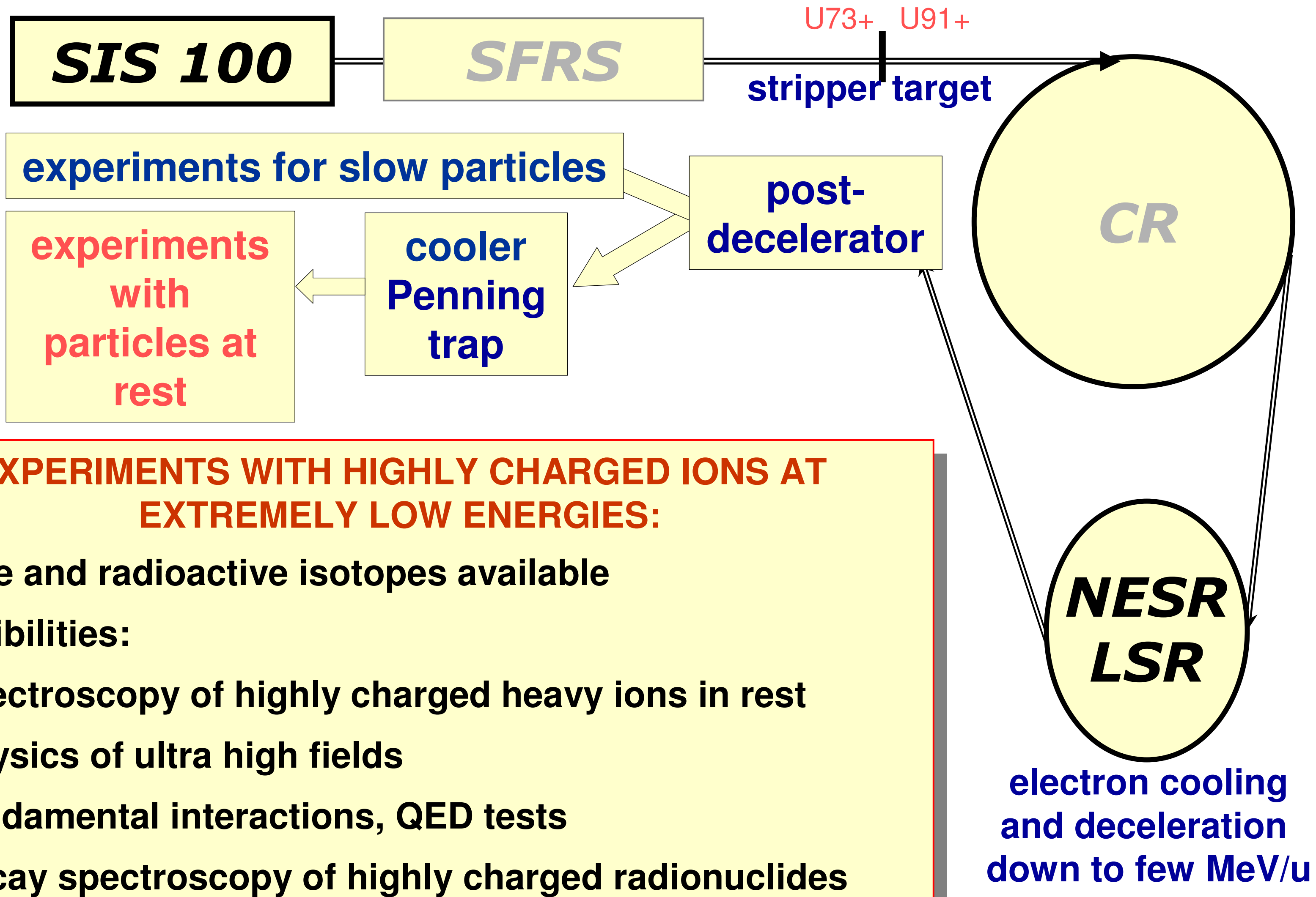
E(Ly-a1) = (77937 ± 12_{stat} ± 25_{syst}) eV

- good agreement with theory
- systematic uncertainty dominant

next steps:

- production run with improved statistic and systematic error (aim: 1 eV accuracy)
- application in other atomic physics experiments (proposal submitted)
- at FAIR: HITRAP (highly charged ions at rest)

Perspectives with HITRAP@FAIR

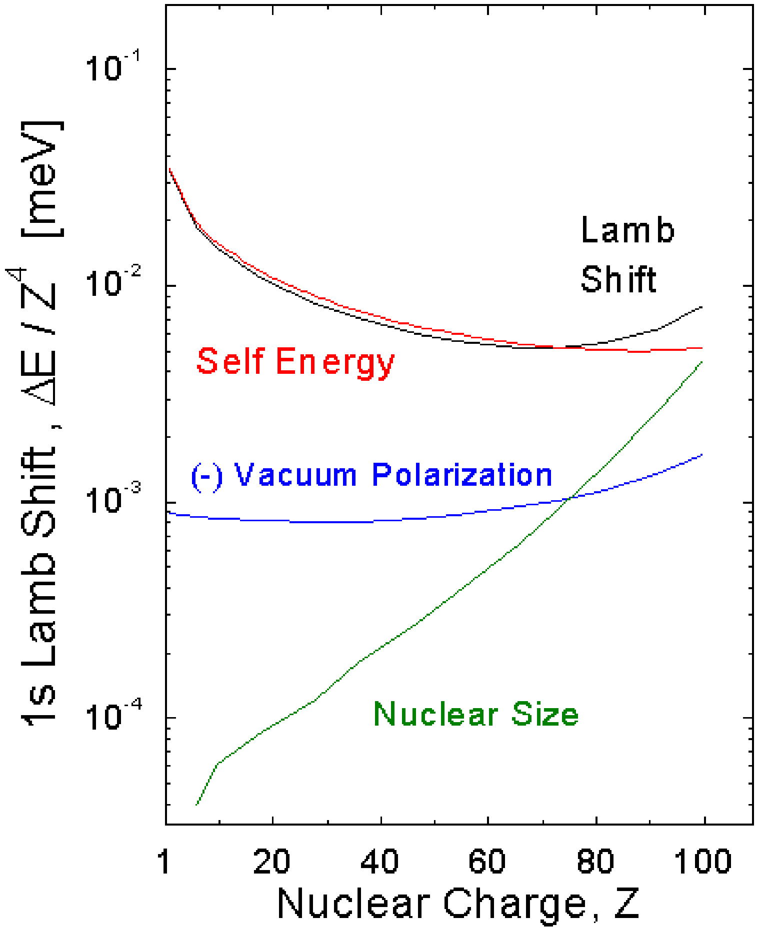


electron cooling
and deceleration
down to few MeV/u

EXPERIMENTS WITH HIGHLY CHARGED IONS AT EXTREMELY LOW ENERGIES:

- stable and radioactive isotopes available
- possibilities:
  - spectroscopy of highly charged heavy ions in rest
  - physics of ultra high fields
  - fundamental interactions, QED tests
  - decay spectroscopy of highly charged radionuclides
  - determine nuclear ground state properties (charge radii)

The 1s-Lamb Shift in Hydrogen-like Ions

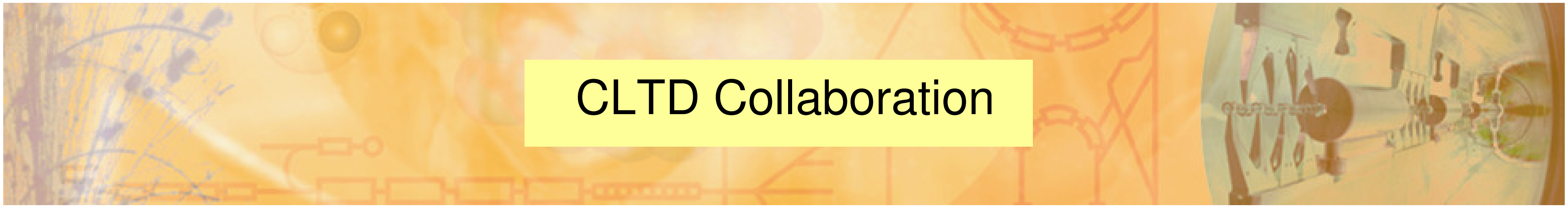


contributions to the 1s Lamb Shift:

for U^{91+}:			
	Self Energy:	355 eV	(≈ 80%)
	Vacuum Polarization:	-89 eV	(≈ -20%)
	Nuclear Size	199 eV	(≈ 40%)

determination of nuclear charge radii:

- test QED for stable isotope with known rms-radius
- from Lamb shift measurement for chains of isotopes
  ⇒ determine charge radii with ≤ 1% accuracy



CLTD Collaboration

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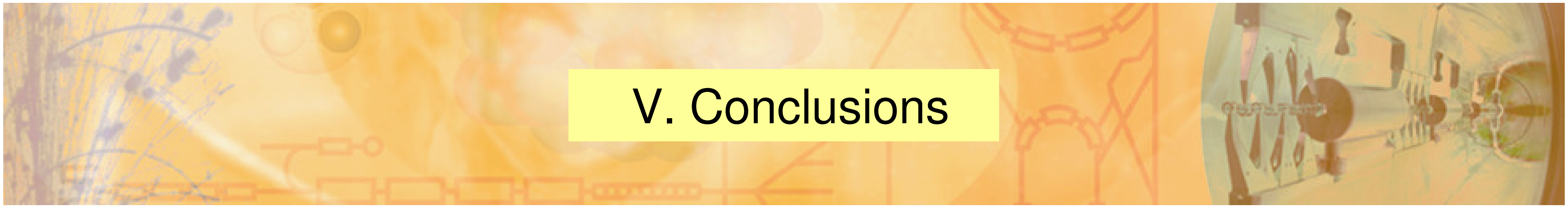

V. Conclusions

- Calorimetric Low Temperature Detectors have Substantial Advantage over Conventional Detection Systems concerning Resolution, Linearity, etc.
- CLTD`s for Heavy Ion Physics have been designed, tested and used in First Experiments.
- Possible Applications within NUSTAR, SPARC and other Projects seem to be attractive.