Energy Calibration of the CUORE Bolometric Double Beta-Decay Experiment

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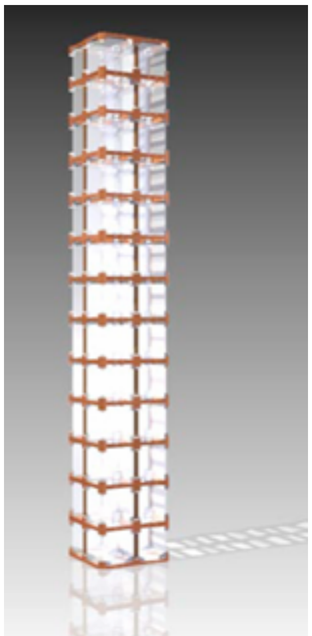
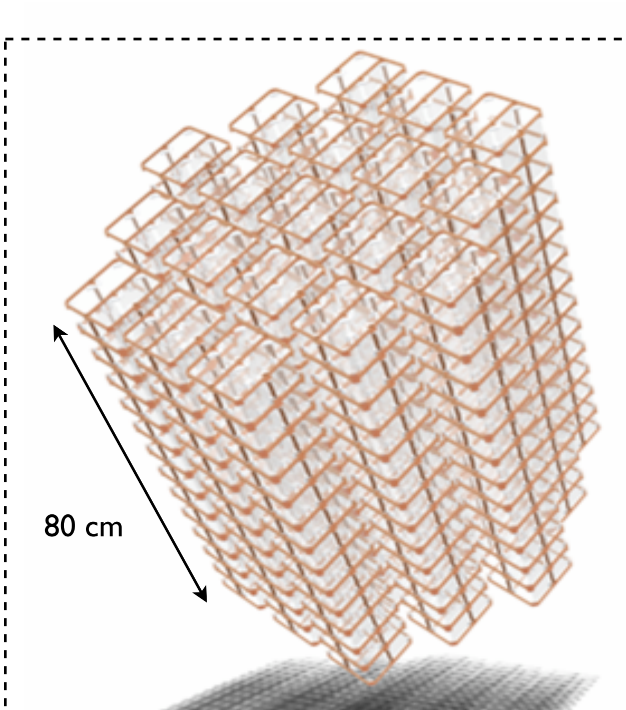
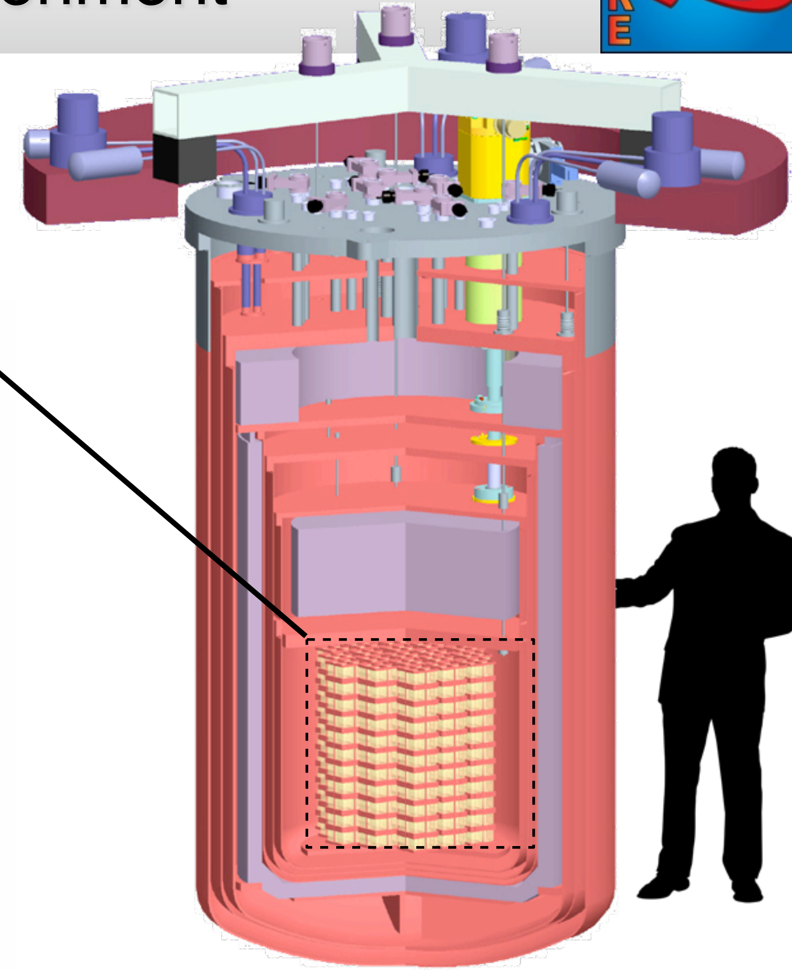
on behalf of the CUORE Collaboration

CUORE Double Beta Decay Experiment

CUORE: Cryogenic Underground Observatory for Rare Events will be a tightly packed array of 988 bolometers with mass of ~ 200 kg of ^{130}Te





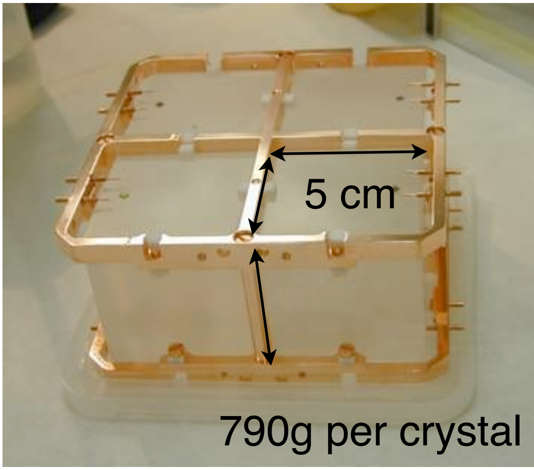


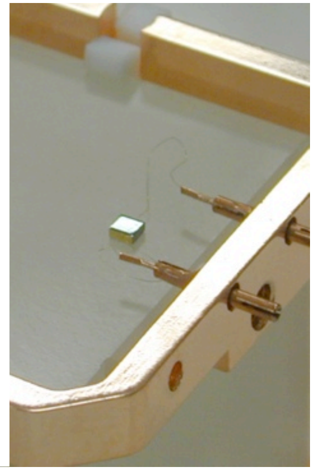
19 Cuoricino-like towers with 13 planes of 4 crystals each

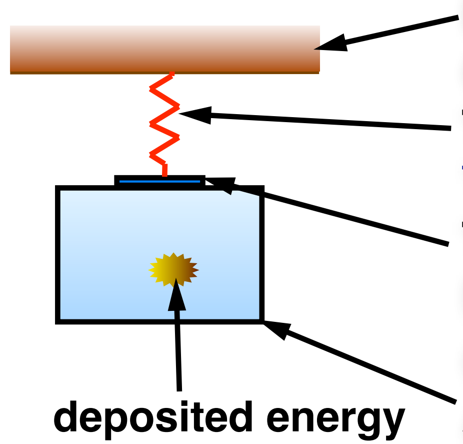
see also Y. Kolomensky "Status of the CUORE Experiment", Tues, Oct 13

- Operated at Gran Sasso laboratory
- Special cryostat built w/ selected materials
- Cryogen-free dilution refrigerator operated at ~ 10mK
- Shielded by several lead shields

TeO_2 Bolometers







Heat sink:
Cu structure (8-10 mK)

Thermal coupling:
Teflon (G = 4 pW/mK)

Thermometer:
NTD Ge-thermistor
(dR/dT ≅ 100 kΩ/μK)

Absorber:
TeO_2 crystal
(C ≅ 2 nJ/K ≅ 1 MeV / 0.1 mK)

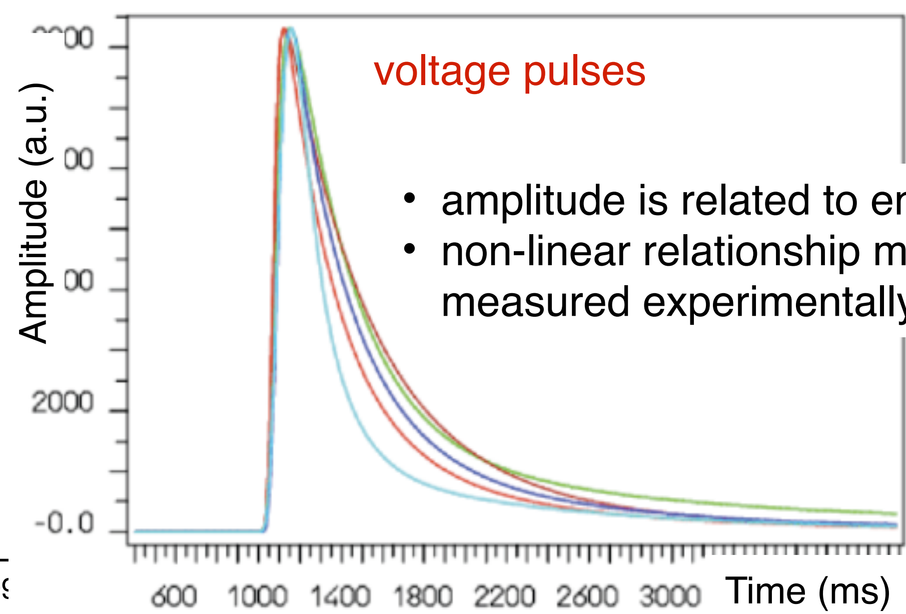
TeO_2 Bolometer: Source = Detector

For E = 1 MeV: ΔT = E/C ≅ 0.1 mK
Signal size: 1 mV

voltage signal ∝ energy deposited

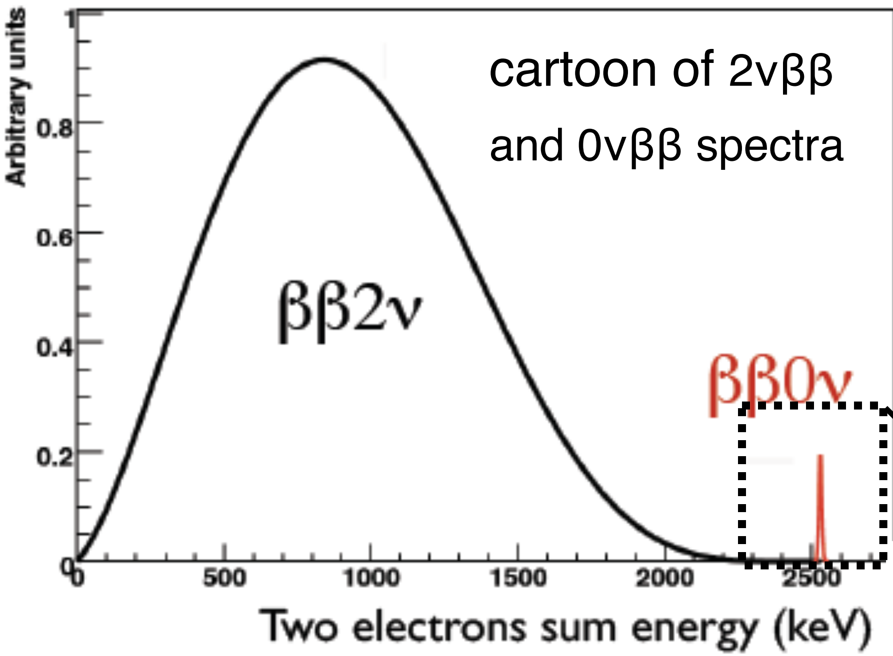
Time constant: τ = C/G = 0.5 s

Energy resolution: ~ 5-10 keV at 2.5 MeV



- amplitude is related to energy
- non-linear relationship must be measured experimentally

Search for 0νββ in ^{130}Te



→ energy is the key event signature of candidate events

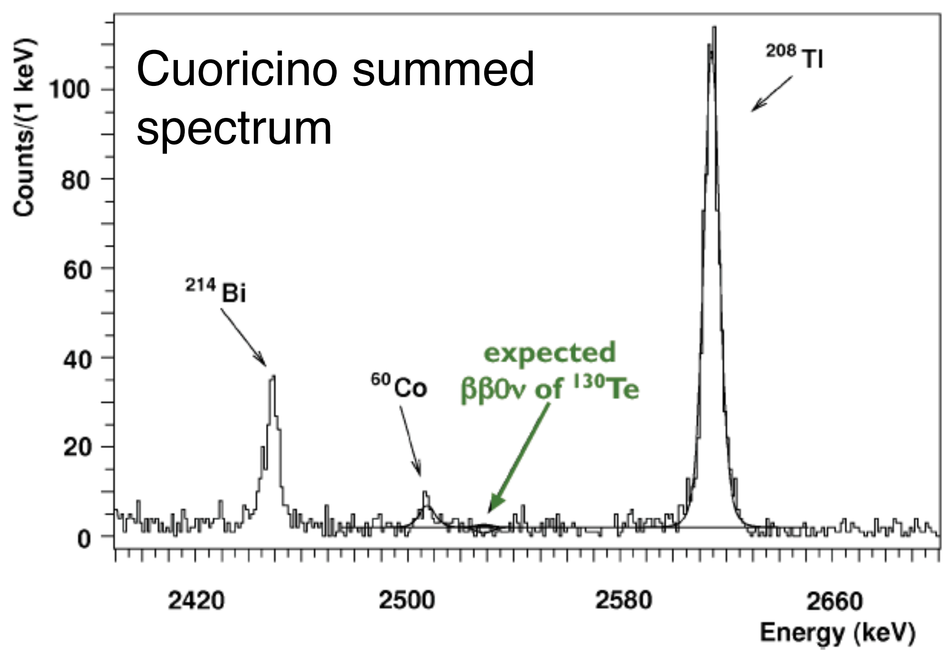
→ individual energy calibration of all 988 bolometers critical for summing energy spectra

Experimental Signature of 0νββ

- peak at the transition Q-value
- enlarged by detector resolution over unavoidable background due to 2νββ

Q(^{130}Te)=2527.518 ± 0.013 keV
Redshaw et al. nucl-ex/0902.2139

Q(^{130}Te)=2527.01 ± 0.32 keV
*N. D. Scielzo et al., arXiv:nucl-ex/0902.2376 (2009)



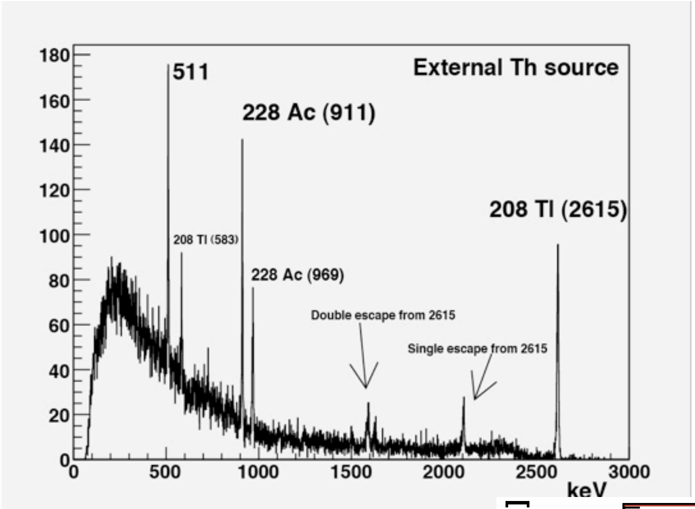
Calibration of Cuoricino/CUORE Bolometers

Gain Stabilization

For each bolometer an energy pulse generated by a Si resistor is used to correct pulse amplitudes for gain instabilities (→ every 5 min).

Voltage-Energy Conversion

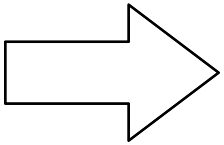
Fit of a calibration measurement with a gamma source (e.g. ^{232}Th) of known energy. Energy calibration performed regularly. (~ monthly).

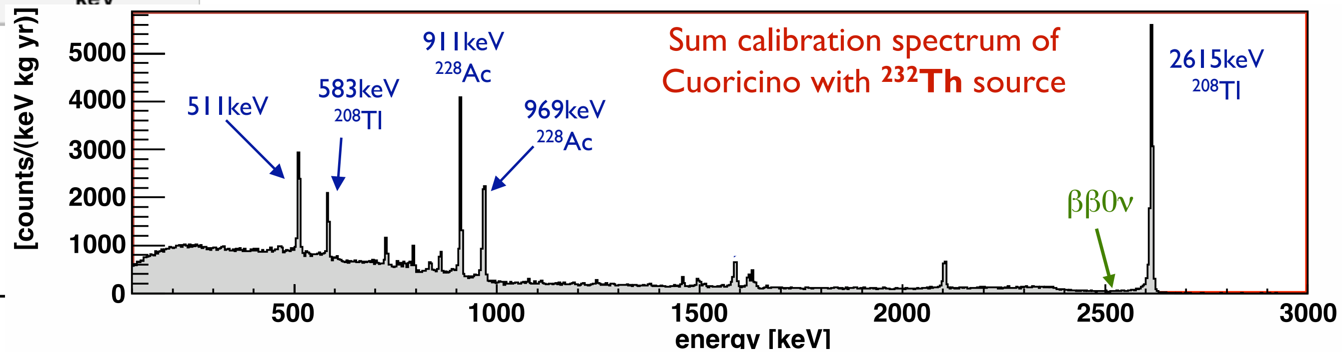


Calibration of individual bolometer

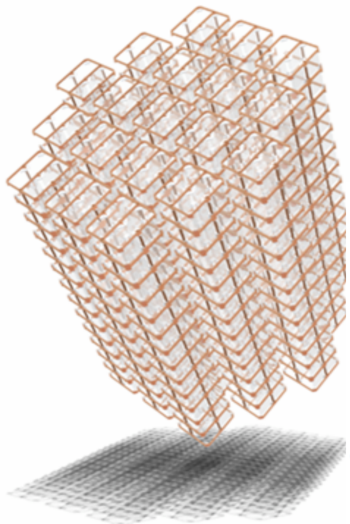
- calibrate with γ-sources
- need 5+ lines visible in calibration spectrum
- energy accuracy goal: < 0.05 keV

Summed spectrum from all detectors

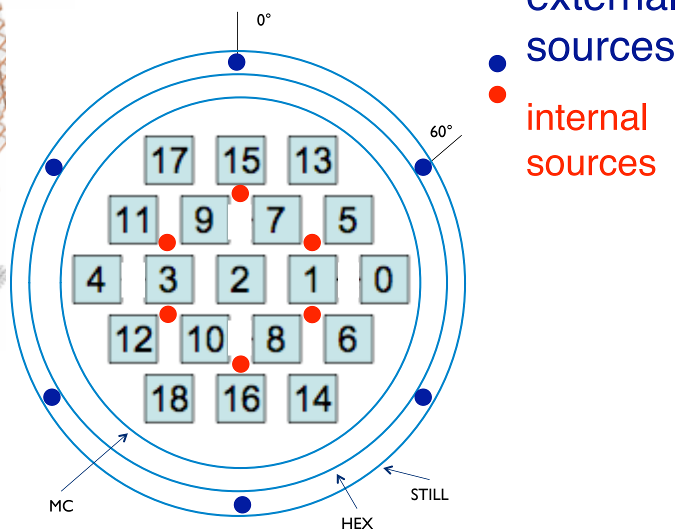




Calibration Source Simulations



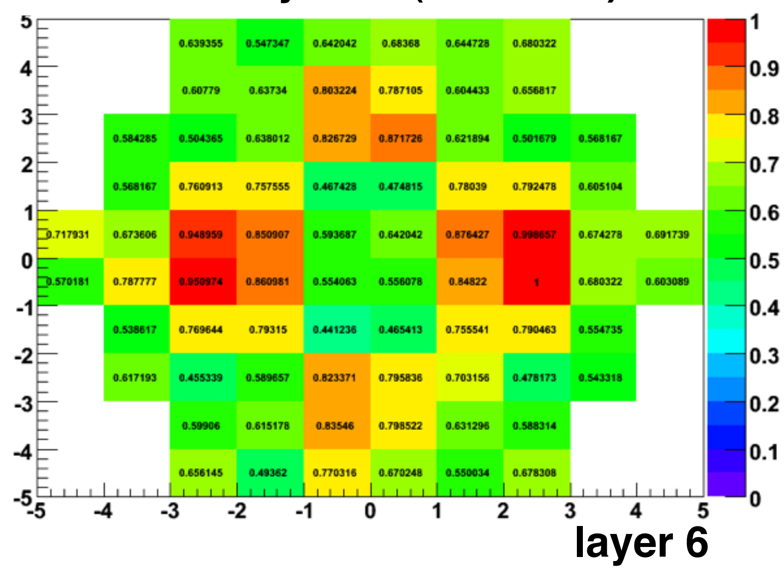
source positions



Optimization of Source Strength, Position, and Distribution

- achieve uniform illumination of all crystals with internal/external sources
- determine max source activity, minimize calibration time

event rate in crystals (2615 keV)

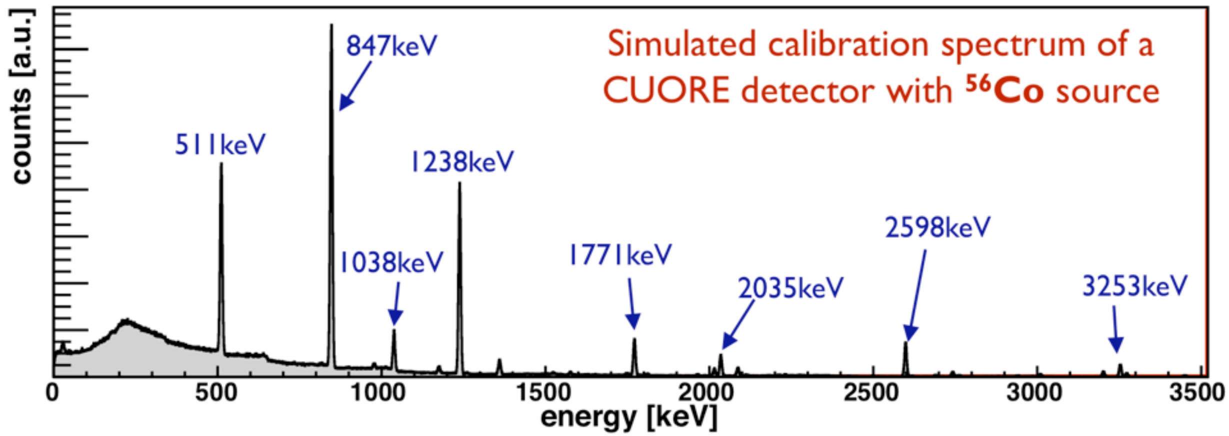


Max hit rate of 150 mHz per crystal to avoid pile-up, based on Cuoricino experience

Activity per discrete source:

- internal/external sources: 87 mBq/430 mBq
- internal/external sources edges: 126 mBq/1010 mBq

Calibration Source Simulations

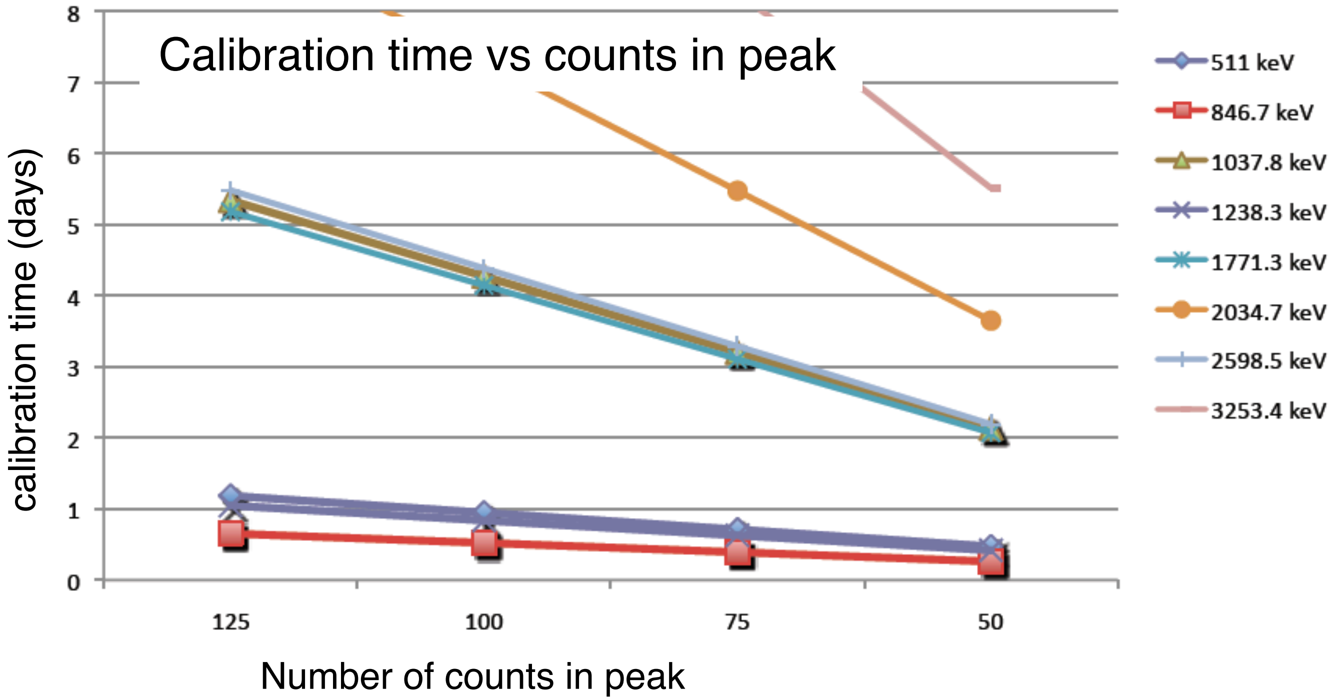


radioactive sources:
^{56}Co and/or ^{232}Th

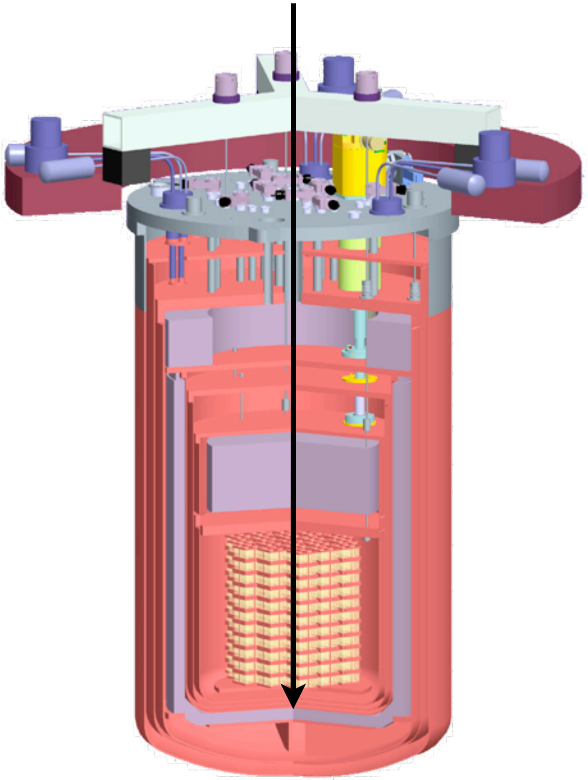
^{56}Co: proton activated Fe wire;
^{232}Th: Thoriated Tungsten wire

both have been used in Cuoricino

~100 events over background per peak are required for successful calibration



Detector Calibration System



Key Issues

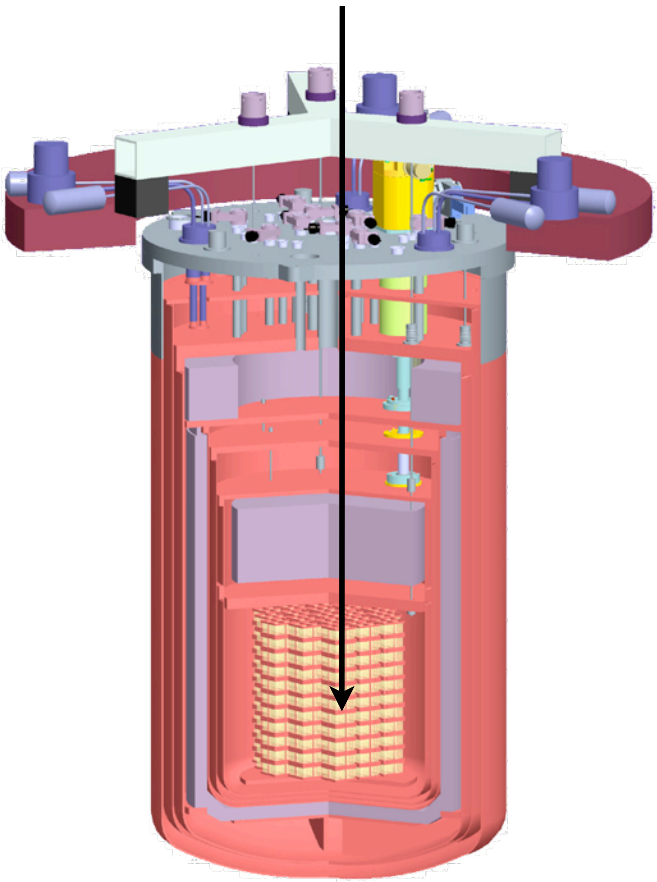
- Thermal loads meet heat load requirements of cryostat
- Calibration rate of < 150mHz for each bolometer to avoid pile-up
- Sources can be replaced. Other source isotopes can be used if necessary (e.g. ^{56}Co has been studied)
- Calibration time does not significantly affect detector live time
- Negligible contribution to radioactive background in the ββ0ν region
- Minimize the uncertainty in the energy calibration (< 0.05 keV)
- reasonable calibration time (< 1 week), minimize loss in detector livetime

Calibration uncertainty

- affects the resolution of the detectors
- is one of the systematic errors in the determination of the 0νββ half life

Detector Calibration System

insertion of 12 γ sources that move under own weight

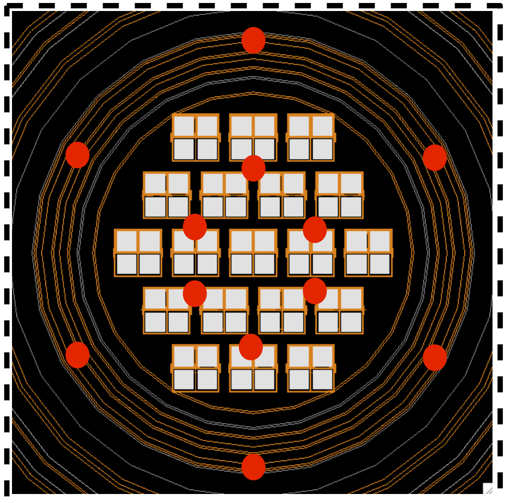


motion system:
insertion and extraction of sources in and out of cryostat

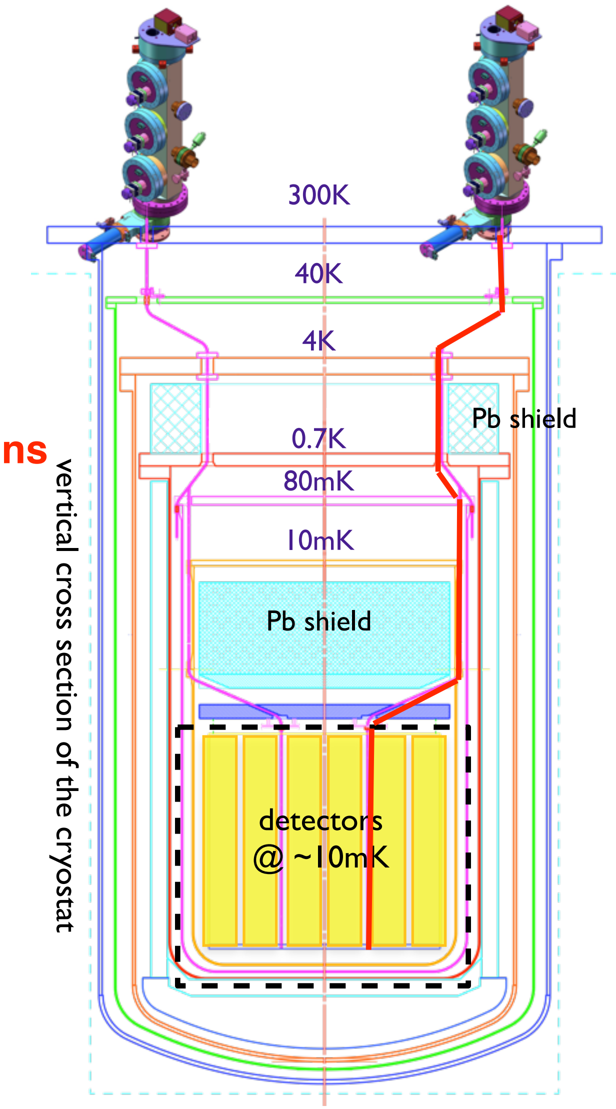
guide tubes:
no straight vertical access

source strings:
move under own weight in guide tubes

source locations



top view of detector array with source positions



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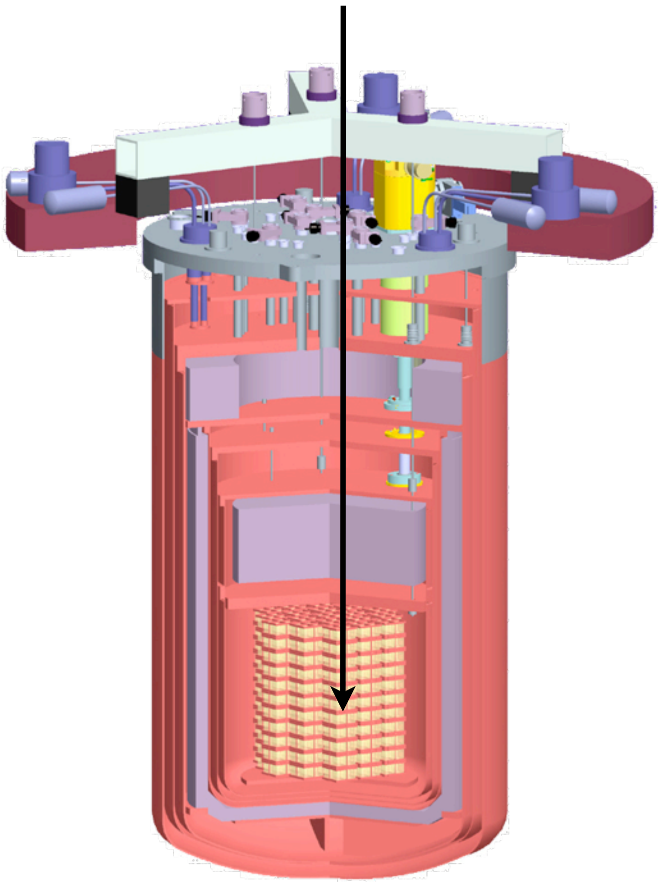

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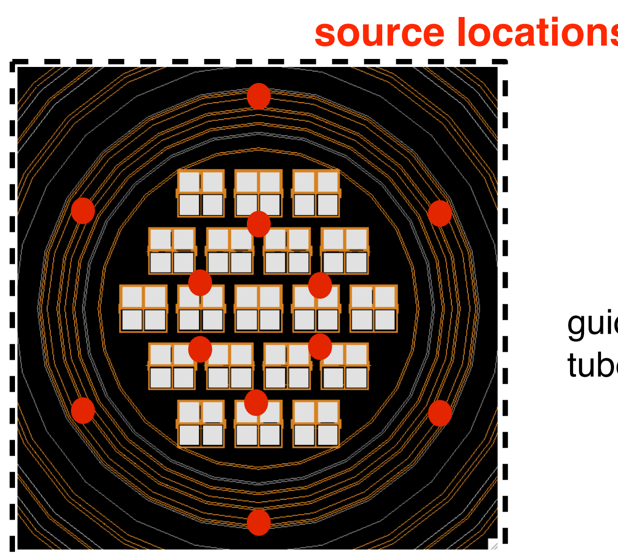

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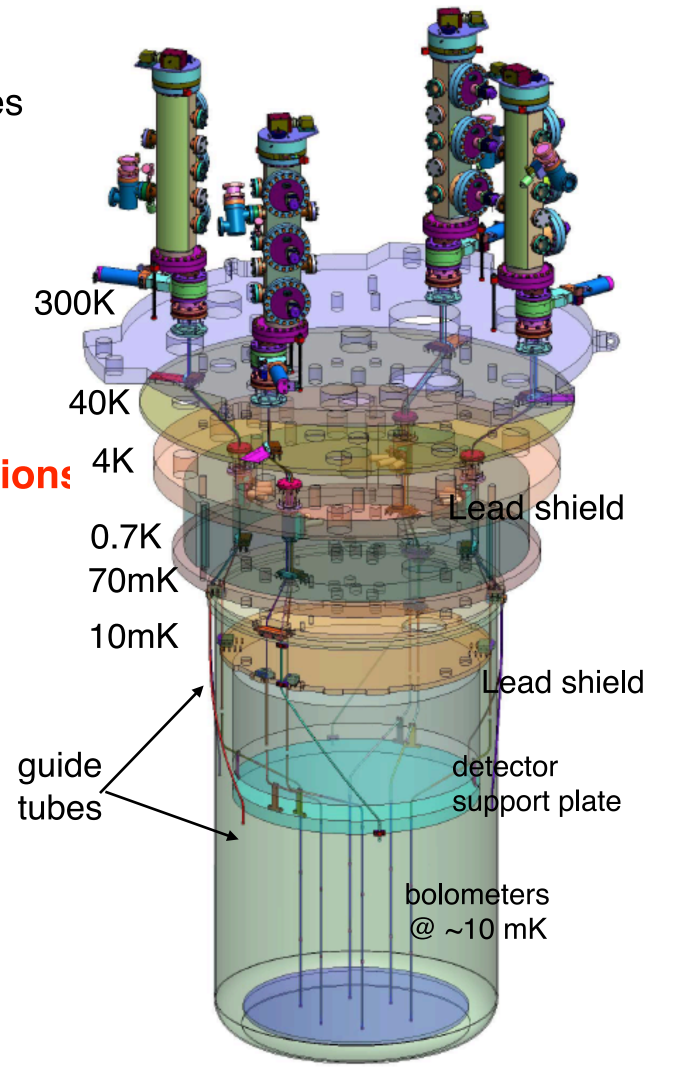

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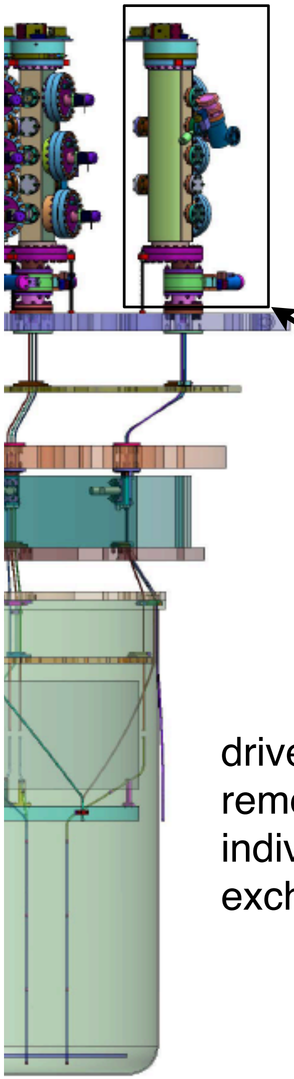
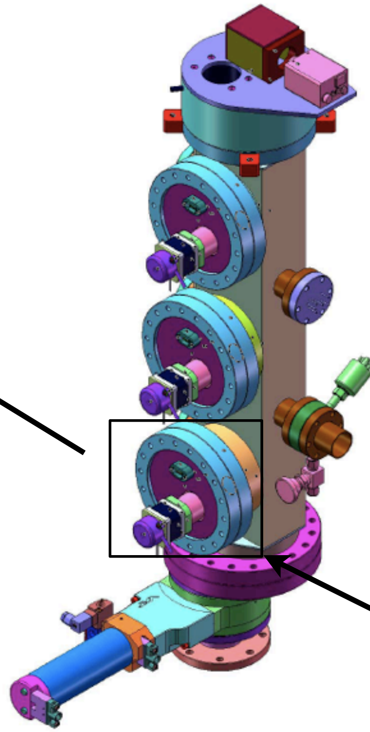
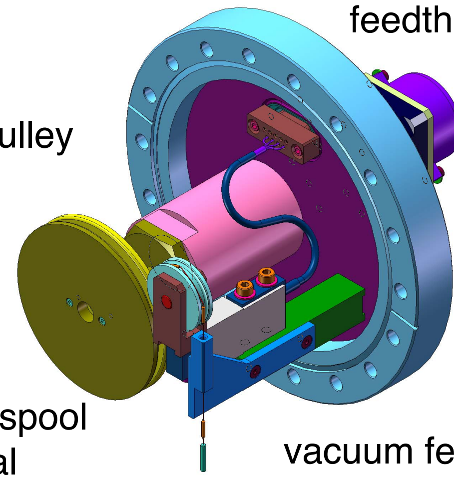
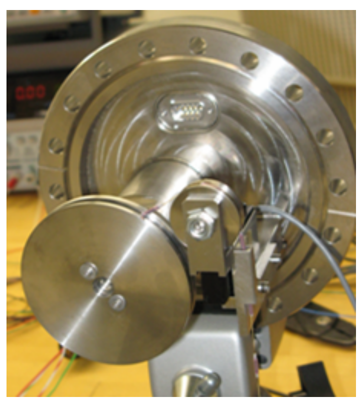


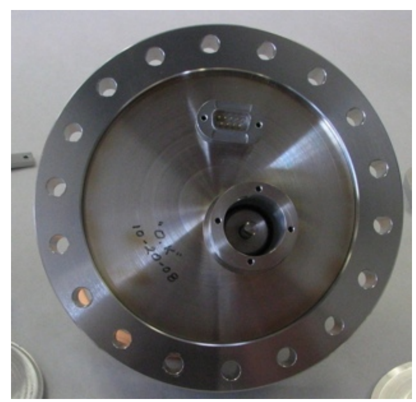


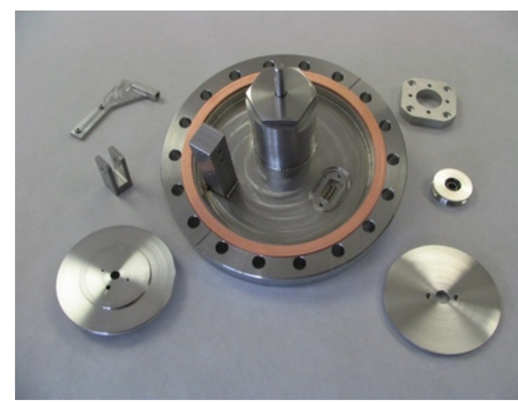
Motion Box and Drive Spool System



drive spools can be removed for individual source exchange







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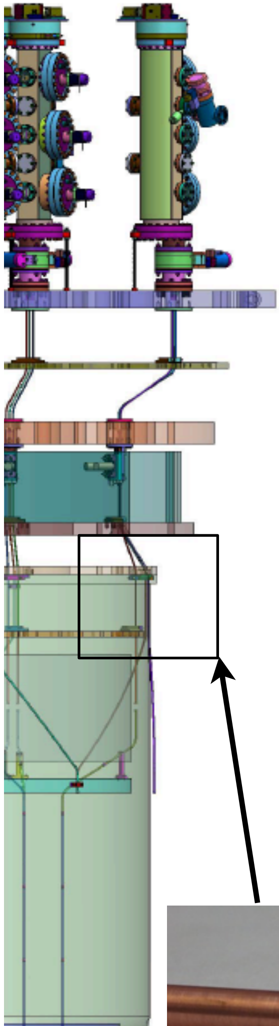
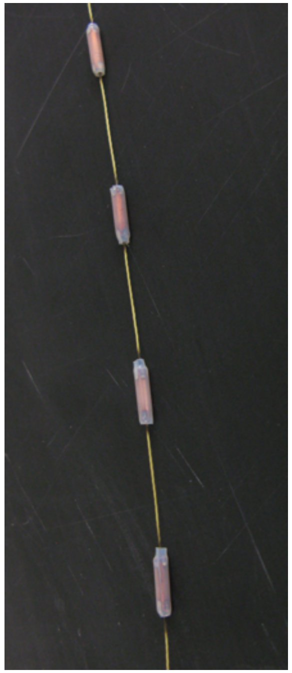
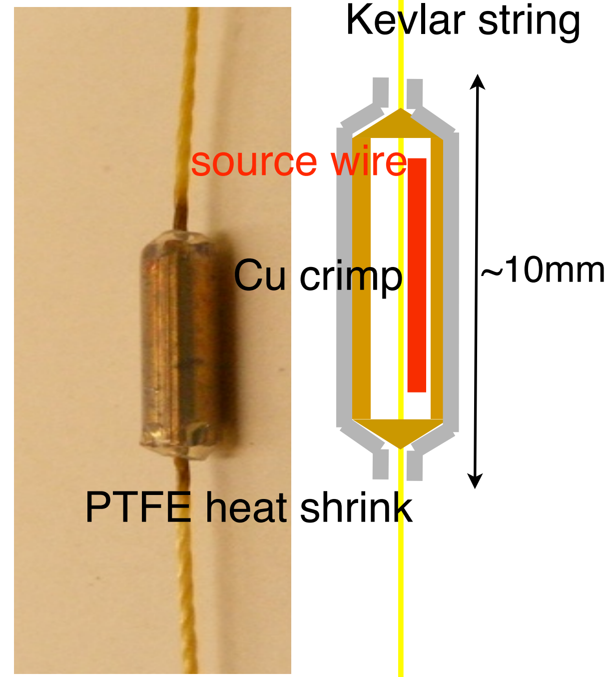




Source String

- flexible, moves under gravity in guide tube
- small mass: < 5 grams
- vertical distribution of source activity can be adjusted
- 30 capsules crimped and evenly spaced over 85 cm of Kevlar string

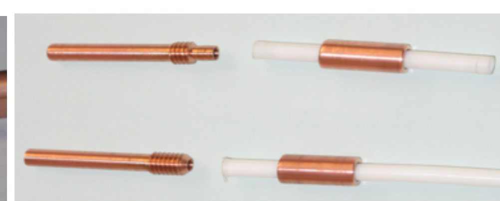


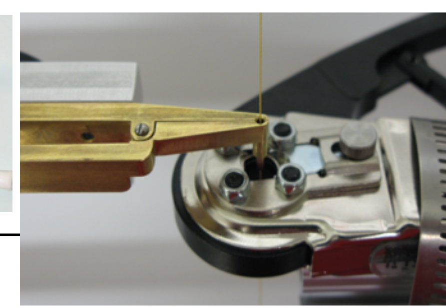
Guide Tubes

• stainless and/or machined from solid, low-background copper

radioactive source wire

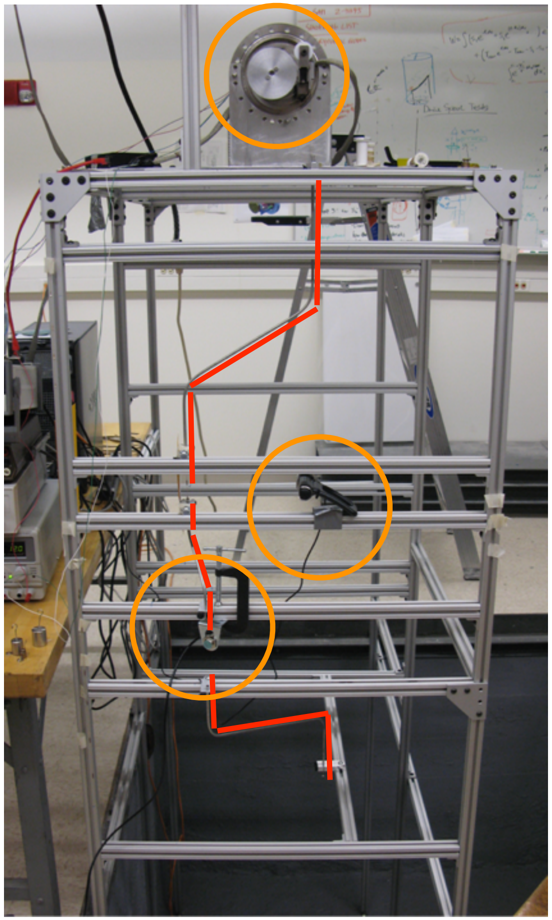
•^{232}Th: Thoriated Tungsten wire
• ^{56}Co: proton activated Fe wire





Prototype Motion Tests

Mock-up of guide tube routing and motion system



Source Motion Monitoring

- encoder
- USB camera → absolute position
- proximity sensor → senses capsules
- load cell → string tension

Motion Tests

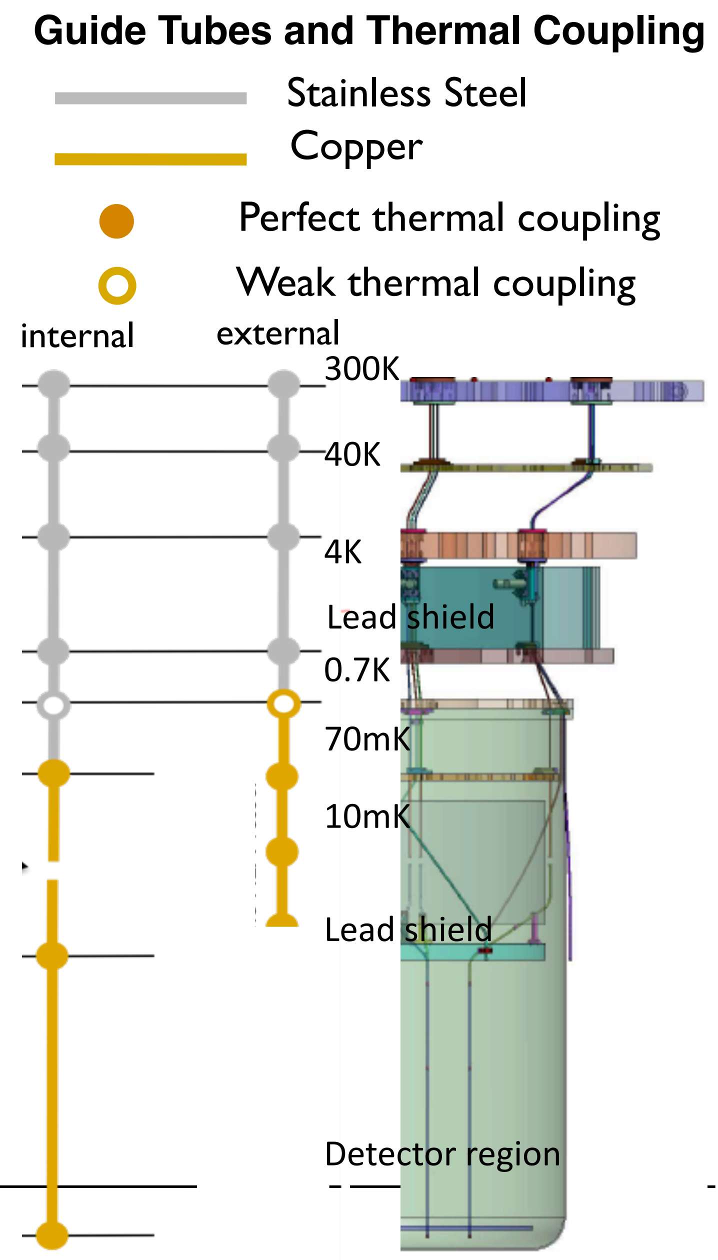
- source moves reliably under its own weight
- position accuracy ~ 5 mm
- reproducible load cell pattern allows safe operation

Cryogenic Considerations

- Calibration system must be integrated with complex detector cryostat
- Must meet available cooling power requirements at all thermal stages

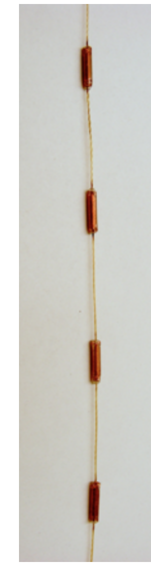
Stage	T [K]	Cooling power available to calibration [W]	Static heat load from guide tubes	Radiation from source string at 4K
40K	40 – 50	~ 1	~1	--
4K	4 – 5	0.3	0.02	--
0.7K	0.6 – 0.9	0.55m	0.13m	0.08μ
70mK	0.05 – 0.1	1.1μ	negligible	0.3μ
10mK	0.01	1.2μ	1.07μ	0.08μ
detector	0.01	< 1μ	--	0.25μ

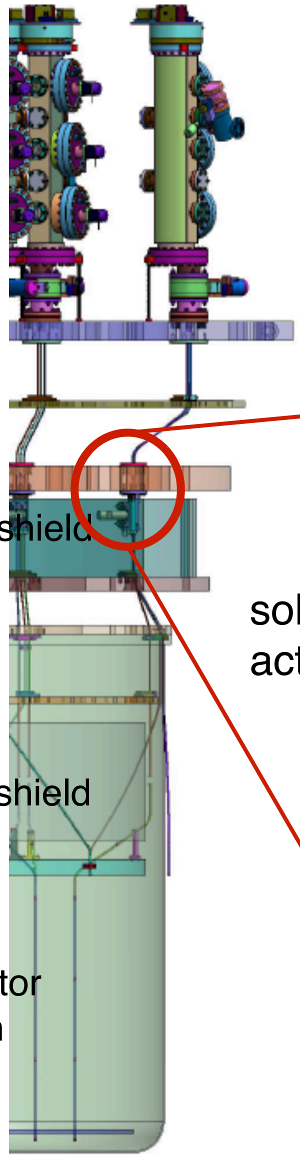
- Thermal conductivity of guide tubes
- Radiation heat inflow from 300 K
- Heat radiated by the source strings
- Thermal conductivity of the source strings
- Friction heat during source string motion



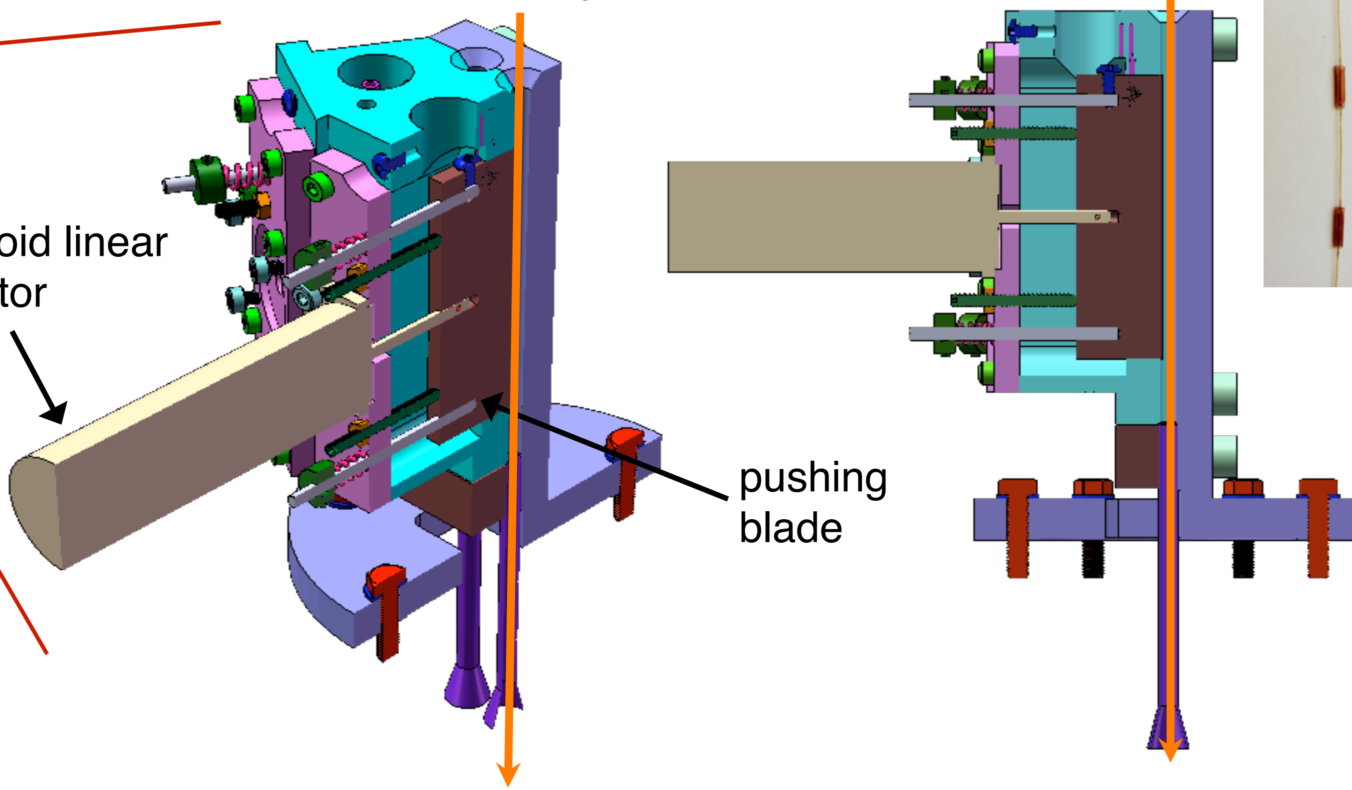
Cooldown of the Source Strings

- Sources must be cooled to < 4K to meet heat load requirements
- Strong mechanical contact is needed between the source carrier and a heat sink at 4K

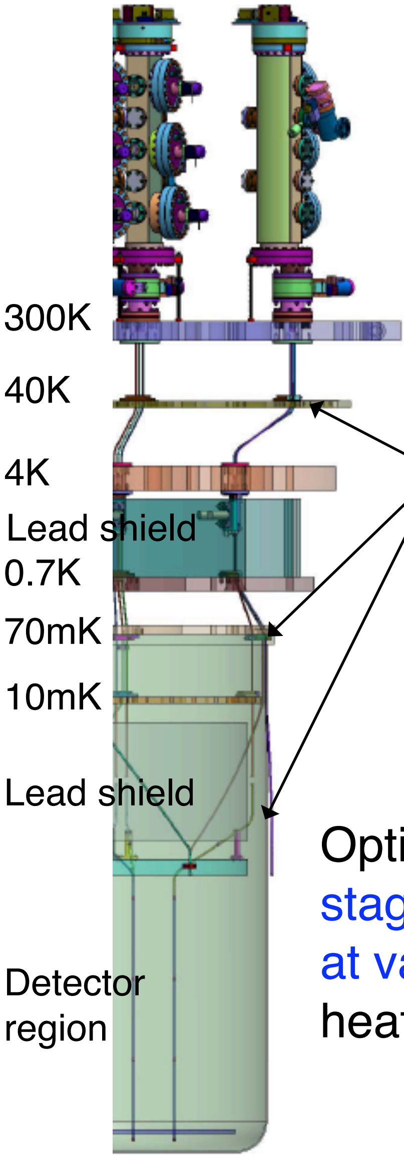




Squeezing mechanism



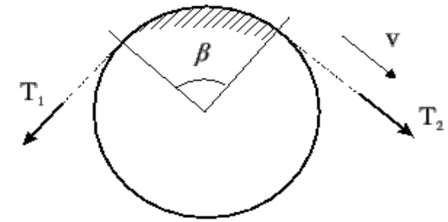
Friction During Source Motion



Friction during source motion

- sliding friction in sloped guide tubes
- friction at bends

(exponential dependence on the bending angle and the friction coefficient)

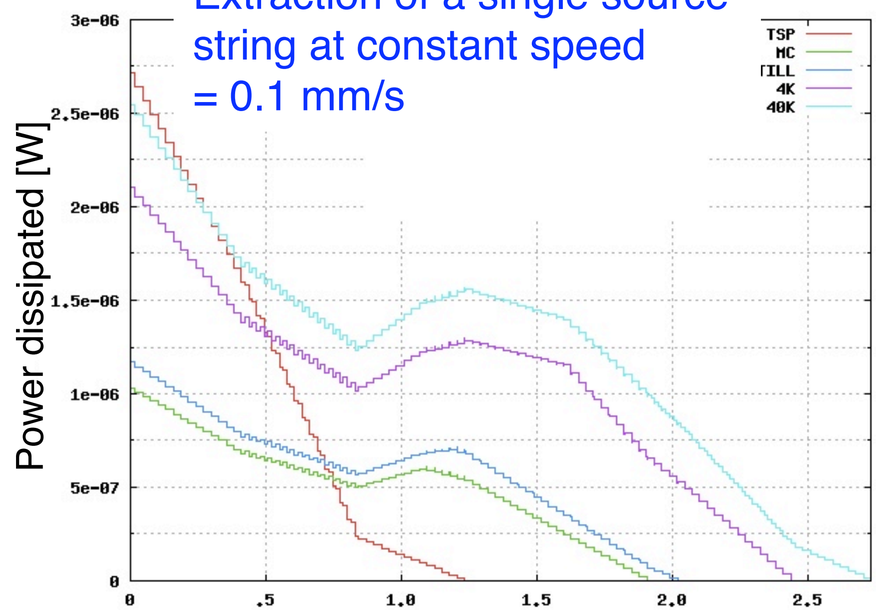


$$\frac{T_2}{T_1} = e^{\mu_k \beta}$$

each guide tube routing has several bends and sloped sections

Optimize sequence of staggered source extraction at variable speed to meet heat load requirements

Extraction of a single source string at constant speed = 0.1 mm/s



Distance traveled by source [m] during extraction at constant speed

CUORE and Calibration System Schedule

2009 | 2010 | 2011 | 2012

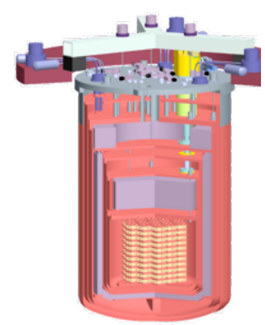
3-tower test → CUORE-0 construction → CUORE-0 data taking

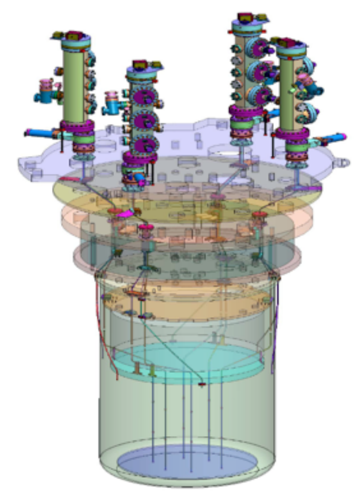
background R&D

assembly tests
single tower assembly (in Cuoricino cryostat)

CUORE construction → CUORE data taking

utilities
clean room
external shielding





cryostat assembly
calibration system 4k test
cryostat test cooldown

detector assembly: - 18+1 towers
- ~1000 detectors

front-end electronics DAQ

calibration system
installation & commissioning

Conclusions

- Energy is the key event signature for $0\nu\beta\beta$ candidate events in CUORE and for discriminating backgrounds.
- Energy calibration is critical for summing the spectra from the 988 individual CUORE detectors.
- The successful operation of CUORE, in the search for neutrinoless double beta decay, requires a reliable and efficient energy calibration system
- The design and integration of the calibration system is technically challenging and stringent requirements must be met.
- A complete design of the calibration system has been developed, prototype parts are being tested, and preparations for a 4K test of the system are under way.
- A 4K test of the system in the CUORE cryostat is planned for 2010.
- Commissioning of the full calibration system is expected for 2011.

CUORE Collaboration

18 institutions,
101 collaborators

Europe, US, China

special thanks to Samuele Sangiorgio, Larissa Ejzak, and Angelo Nucciotti, for slides and figures on the calibration system