CeSOX

GDR
27/11/2014

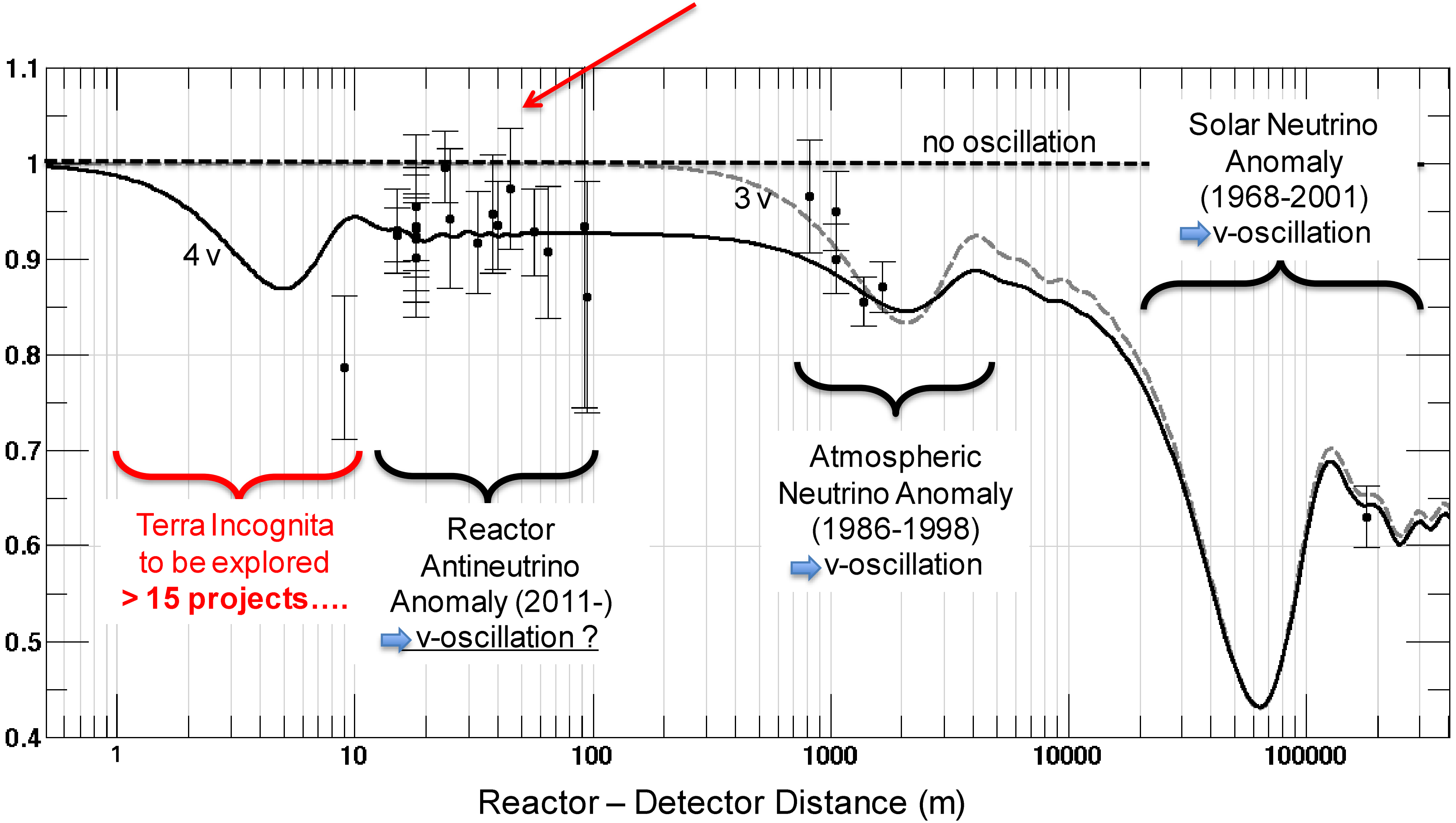
M. Durero

Outline

- Goal
- Antineutrino Generator (CeANG)
  - ^{144}Ce-^{144}Pr
  - Shielding
- Borexino detector
  - Deployment
  - Expected results
- CeANG characterization
  - Spectroscopy
  - Activity measurement
- Backgrounds
- Outlook

The Reactor Anomaly

- **Observed/predicted averaged event ratio: R=0.938±0.023 (2.7 σ)**



Testing $\overset{(-)}{\nu}_e$ disappearance anomalies

- **RAA : comparison between data and event prediction**
  - Search for L, E, L/E pattern (<u>shape only</u>)
  - Complement with a <u>rate analysis</u>

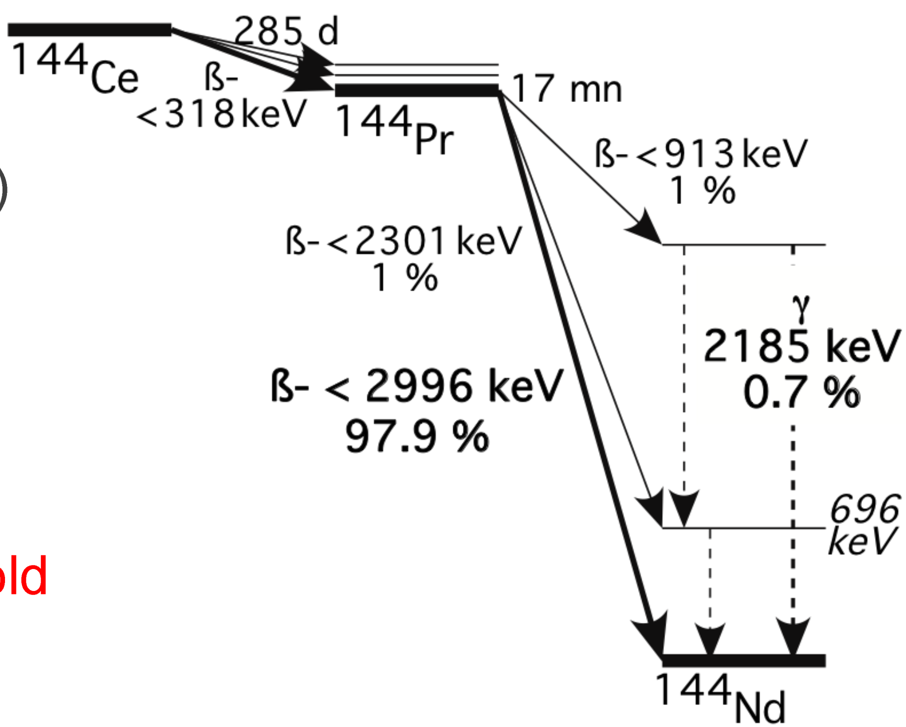
- **Input from Sterile Neutrino Fits**
  - $\Delta m^2 \approx 0.1\text{-}10\ eV^2$ ⇨ $L_{osc}(m) = 2.5 \frac{E(MeV)}{\Delta m^2 (eV^2)} \approx 1 - 10\ m$
  - $\sin^2(2\theta_{new}) \approx 0.01 - 0.2$

- **Experimental Specifications**
  - $\Delta m^2 \approx eV^2$: <u>compact source</u> << 1m & <u>vertex resolution</u> << 1m
  - $\sin^2(2\theta_{new})$: experiment with <u>few % stat. syst. uncertainties</u>

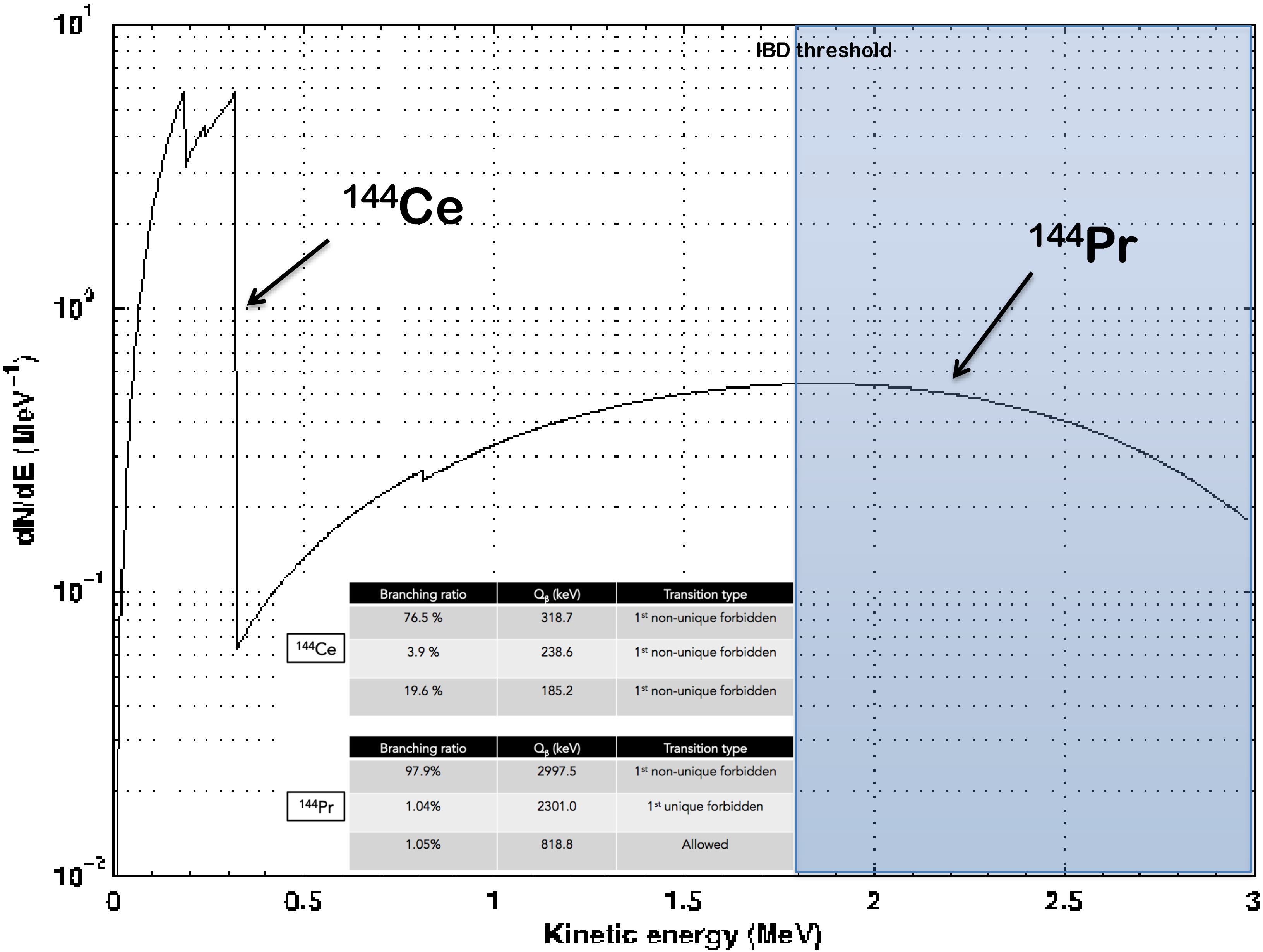
Antineutrino Source: ^{144}Ce-^{144}Pr

(ITEP N°90 1994, PRL 107, 201801, 2011)

- $\bar{\nu}_e$ **source detected via** $\bar{\nu}_e + p \rightarrow e^+ + n$ **(Q=1.8 MeV)**
  - **High IBD cross section → > 3 PBq activity**
  - **(e^+,n) detected in coincidence → low backgrounds**
- **^{144}Ce-^{144}Pr**
  - Abundant fission product (5%)
  - ^{144}Ce: long-lived & low-Q_β
    Enough time to produce, transport and use
  - ^{144}Pr: short-lived & high-Q_β
    $\bar{\nu}_e$-emitter above IBD threshold



^{144}Ce-^{144}Pr ν Spectra



^{144}Ce

Branching ratio	Q_β (keV)	Transition type
76.5 %	318.7	1st non-unique forbidden
3.9 %	238.6	1st non-unique forbidden
19.6 %	185.2	1st non-unique forbidden

^{144}Pr

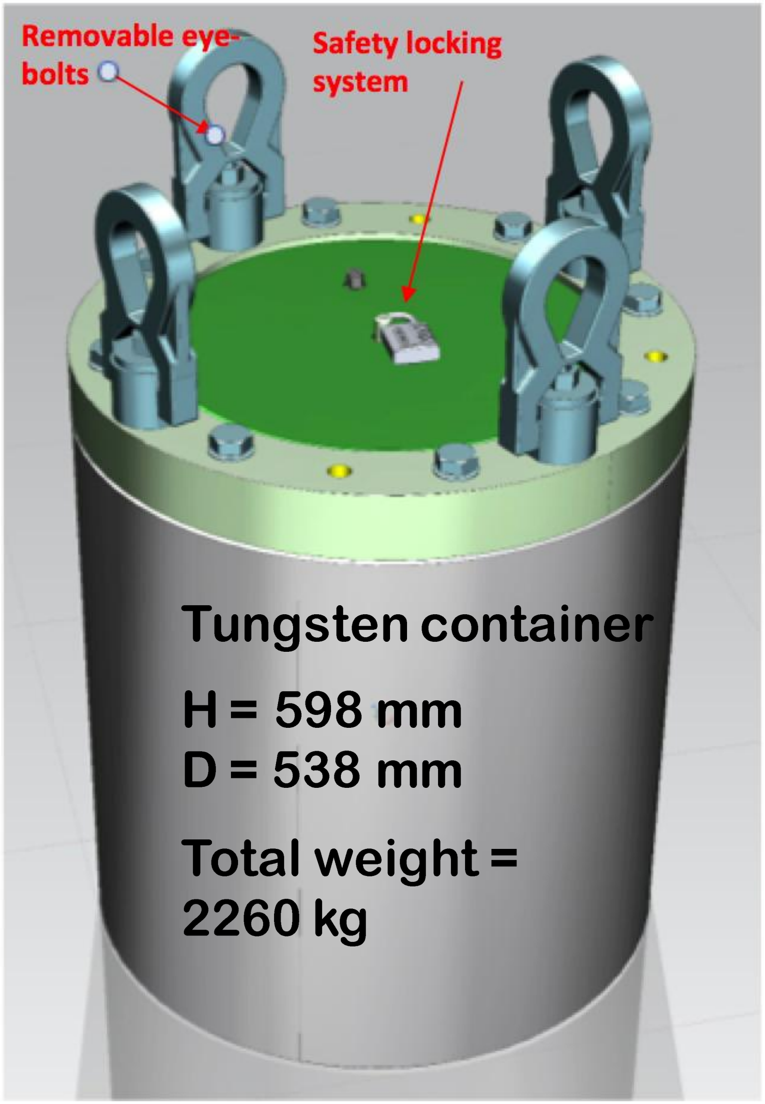
Branching ratio	Q_β (keV)	Transition type
97.9%	2997.5	1st non-unique forbidden
1.04%	2301.0	1st unique forbidden
1.05%	818.8	Allowed

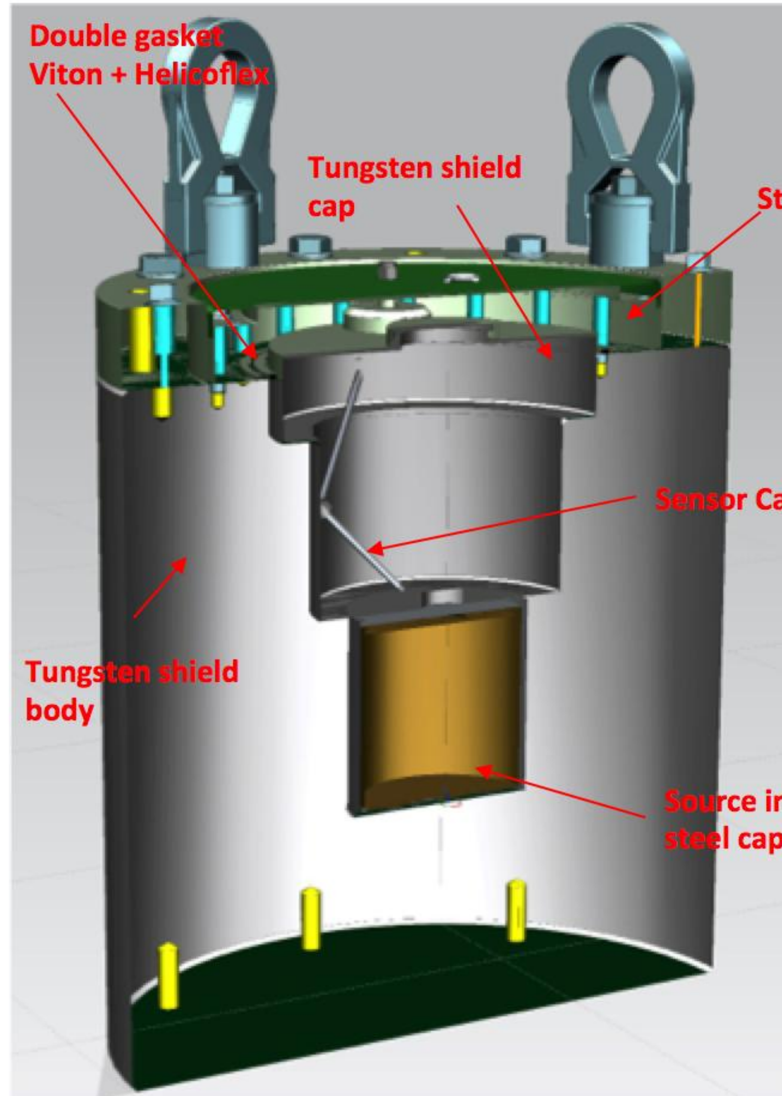
^{144}Ce-^{144}Pr Antineutrino Generator (CeANG) : Specifications

- ß activity (in ^{144}Ce)
  - Between 3.7 and 5.5 PBq
- Extracted from fresh spent nuclear fuel (<2 years)
- Chemical form : cerium oxyde CeO_2
- Density : between 4 and 6 g/cm^3

- Fitting inside a D:H=15:15 cm double capsule of Special Form of Radioactive Material (SFRM, IAEA regulation)
- Purity data from ^{147}Pm production line
  - Content of any others RE (*γ-emitters*) in *Ce* $\leq 10^{-3}$ Bq/Bq
  - Content of Pu and TPE (*n-emitters*) in Ce $\leq 10^{-5}$ Bq/Bq

High-Density Tunsten Alloy Shielding



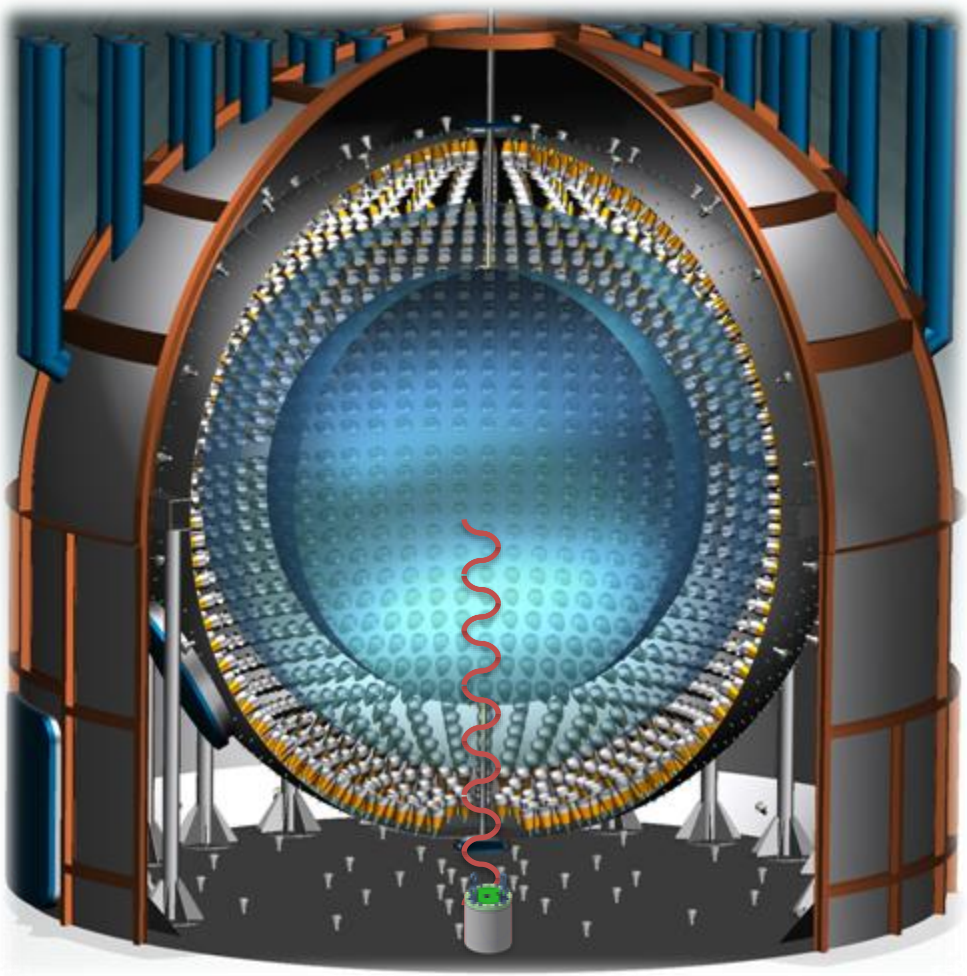


Transport Route to LNGS

- IAEA Regulations for the Safe Transport of Radioactive Material
- Train / Dedicated vessel / Truck : AAPC published on 15/10/2014

Oscillometry in BOREXINO

Search for an oscillation pattern inside LS target
Compare observed to expected ν rate



Experimental layout

- Radioactive ν source in tunnel below the detector (d=8.3 m)

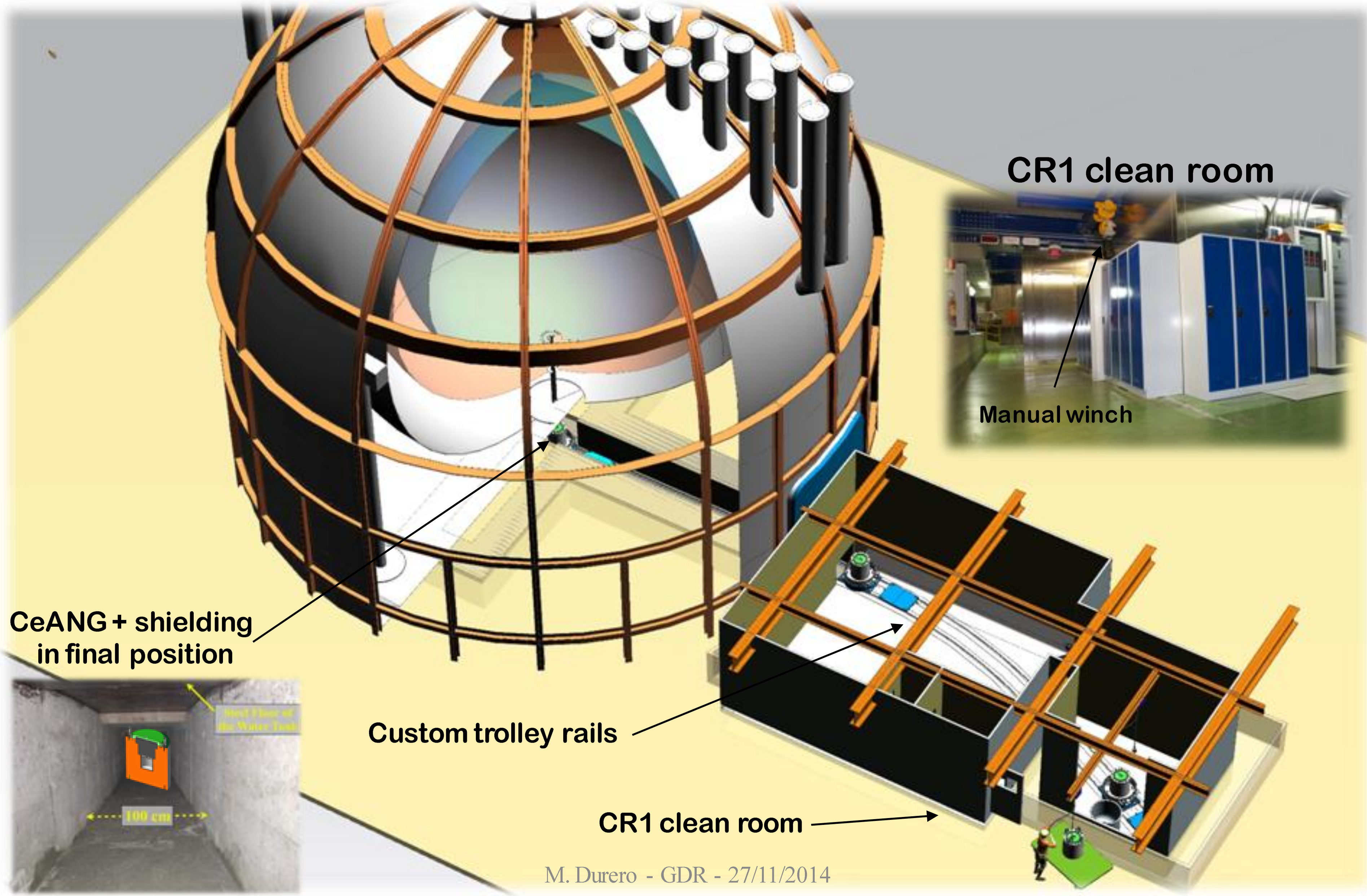
Detector Specifications (1 MeV)

- Energy resolution: 5%
- Vertex resolution: 15 cm
- Fiducial mass: 280 tons
- #H: 1.7 10^{31}
- R < 4.25 m

Antineutrino Generator

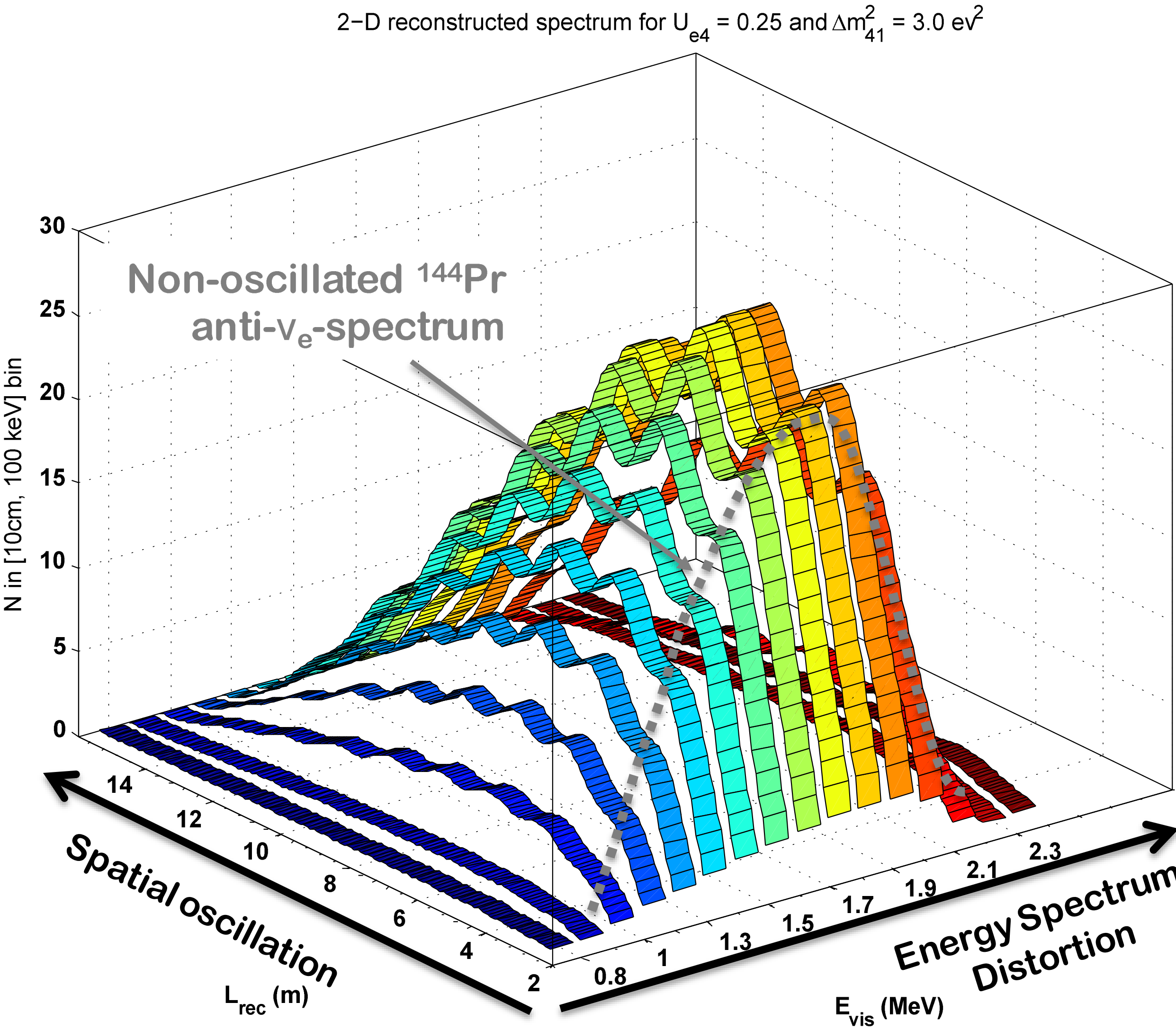
- $^{144}Ce/Pr$ β^- E_ν < 3 MeV
- ^{144}Ce-^{144}Pr > 3.7 PBq
- Exposure: 1.5 yrs
- Events (1.5yrs) ~10^4

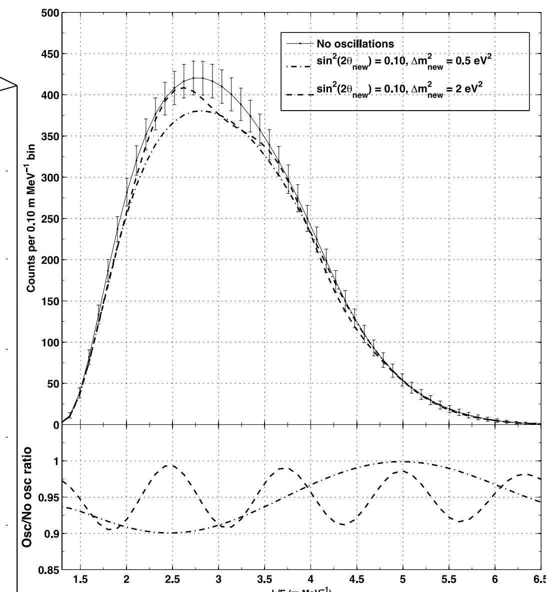
Inserting the CeANG beneath BX



Expected $\nu_e \rightarrow \nu_s$ Oscillation Signal

$$\frac{d^2N(R,E_\nu)}{dRdE_\nu} = \mathcal{A}_0 \cdot n \cdot \sigma(E_\nu) \cdot \mathcal{S}(E_\nu) \cdot \mathcal{P}(R,E_\nu) \int_0^{t_e} e^{-t/\tau} dt,$$

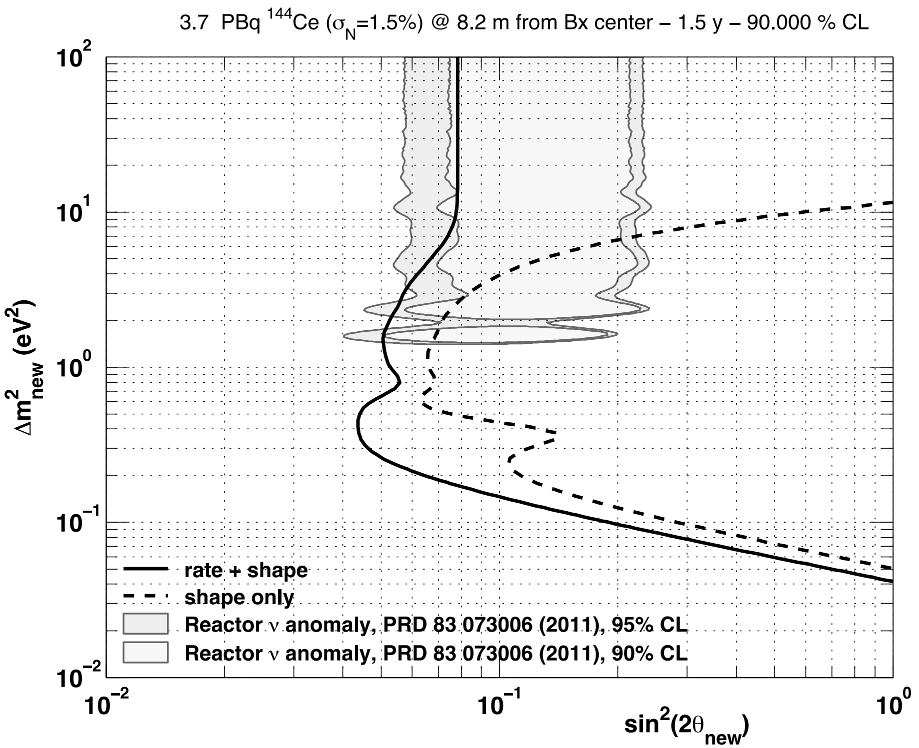




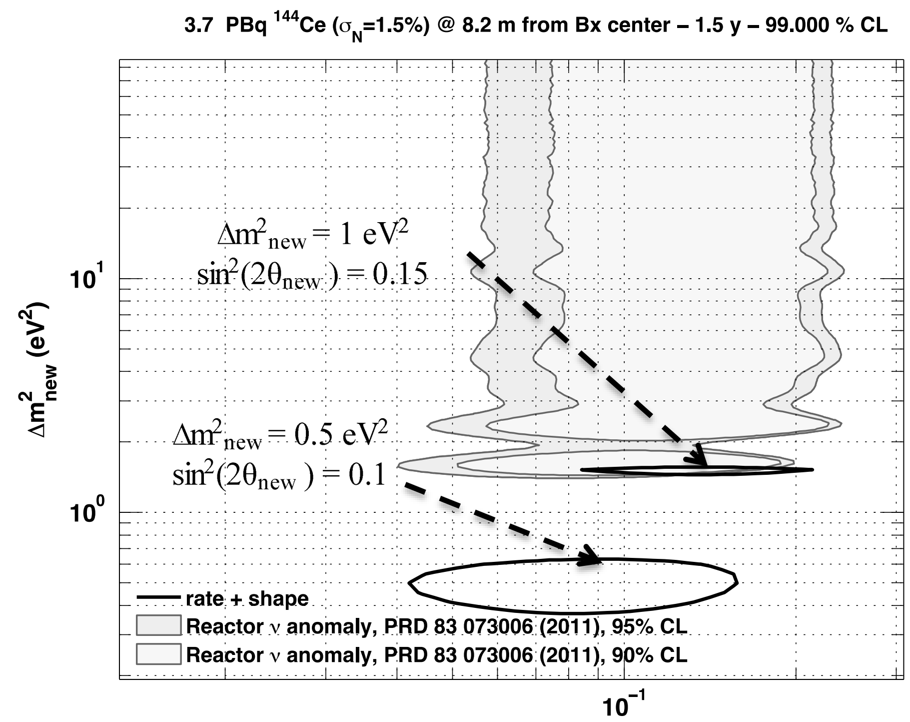
L/E (m.MeV^{-1}) signal

Possible outcomes

Exclusion contour



Discovery potential



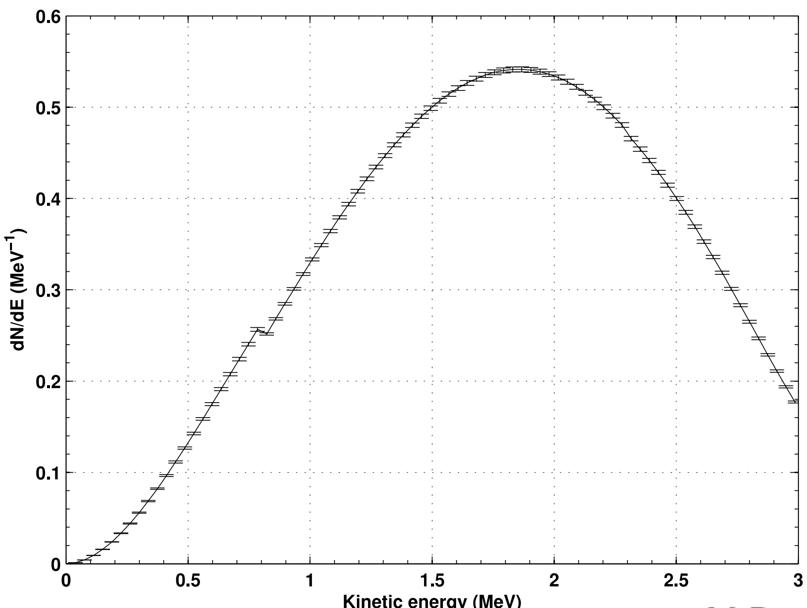
^{144}Pr Antineutrino Spectra

- **^{144}Ce-^{144}Pr β/ν spectra needed with % level precision**
  - Power-to-activity conversion factor: 216.0 ± 1.2 W/PBq
  - Prediction of the IBD rate depends on the ^{144}Pr spectral shape

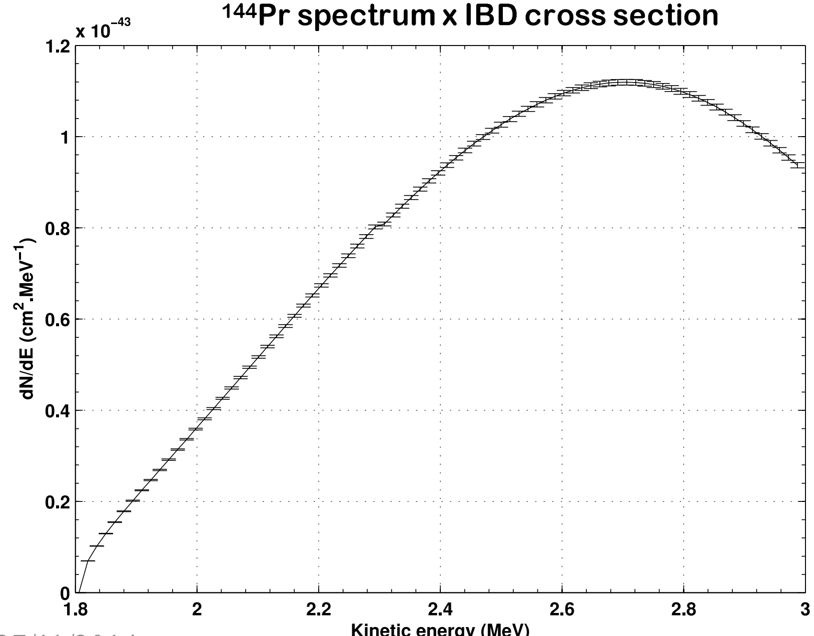
- **Modeling of the ^{144}Ce-^{144}Pr β/ν spectra**
  - Fermi theory + nucleus finite-size effects + screening + QED corrections + weak magnetism + recoils and mass effects 1% uncertainty (theory)

- **But non-unique forbidden β-branches → need for a measurement** (shape factor determining)

Simulation of ^{144}Pr from nuclear database data

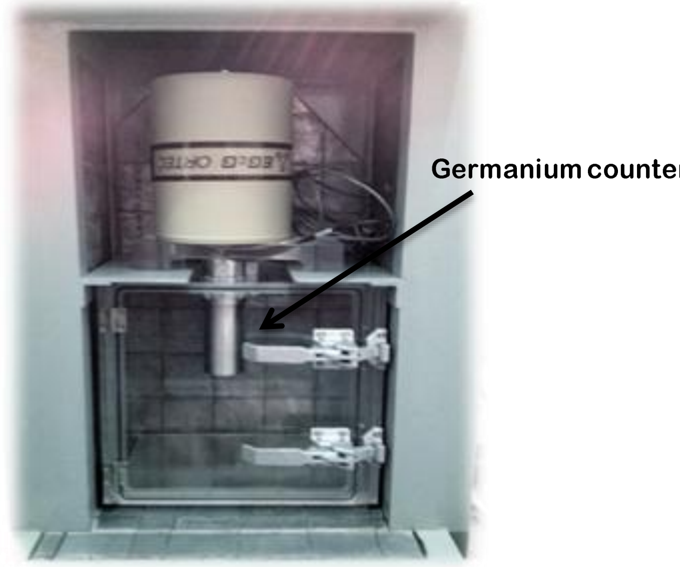


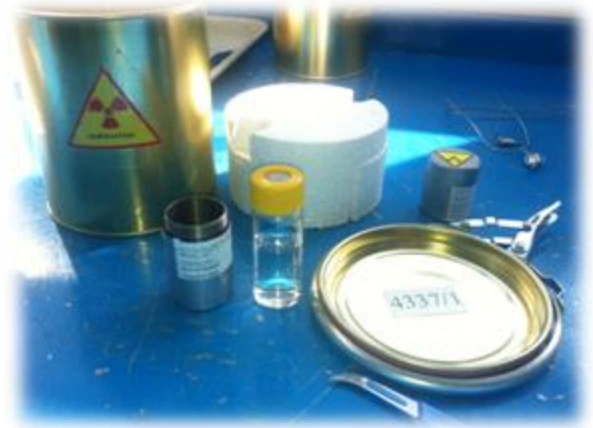
^{144}Pr spectrum x IBD cross section



^{144}Ce-^{144}Pr samples spectroscopy

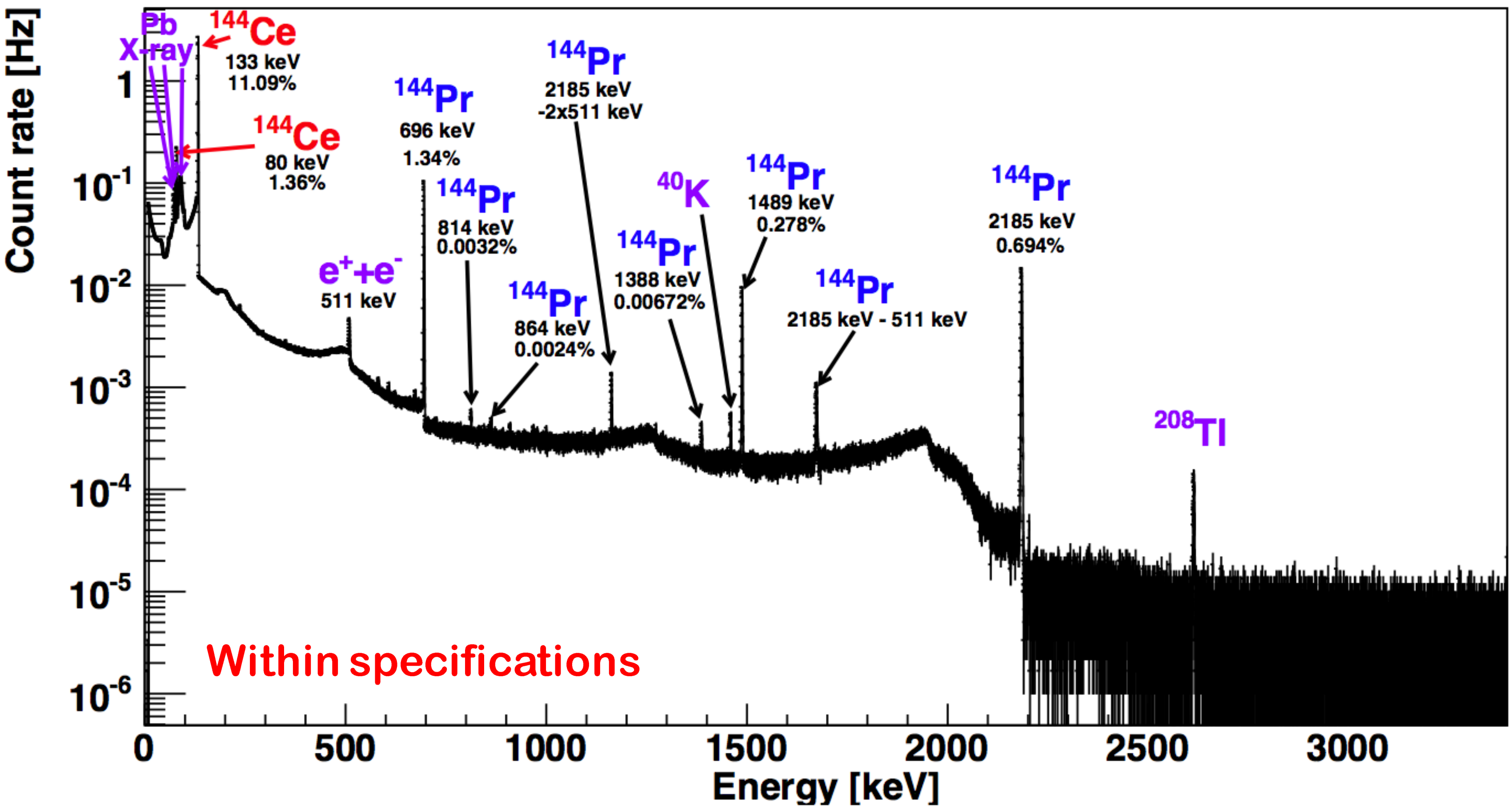
- 3 x 10 cm^3 $Ce(NO_3)_3$ - 59 kBq in ^{144}Ce each
- γ–spectroscopy (CEA-IRFU)
  - Goal: Characterization of β / γ impurity content
- β–spectroscopy (CEA- LNHB & TUM)
  - Goal: Measure ^{144}Ce & ^{144}Pr β–spectra. Predict the ^{144}Pr ν–spectrum
  - Realization of β–spectrometers in collaboration with Laboratoire National Henri Becquerel & TU München
- ICPMS mass spectroscopy
  - Goal: characterization of neutron impurity content
    Collaboration with CEA/DEN/DPC/SECR





^{144}Ce-^{144}Pr samples: γ spectroscopy

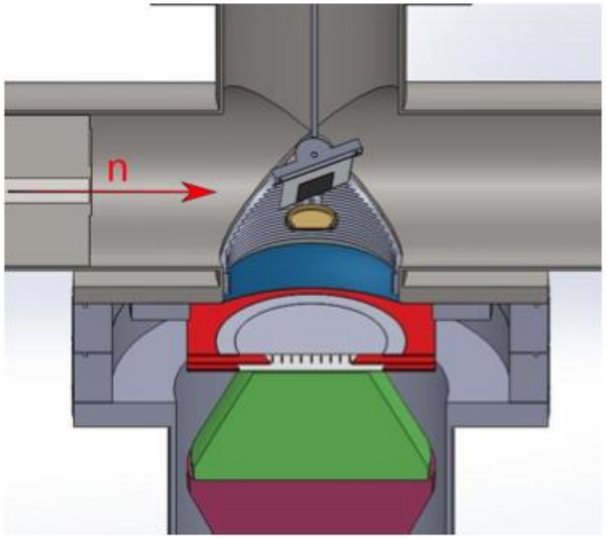
- Absence of impurities emitting γ's
  - <10^{-4} Bq/Bq of ^{144}Ce for E>500 keV
  - <10^{-3} Bq/Bq of ^{144}Ce for E<500 keV
- Activity measurement
  - 01/10/2014
  - 58,9 (2.5) kBq in ^{144}Ce



^{144}Ce-^{144}Pr samples: β spectroscopy

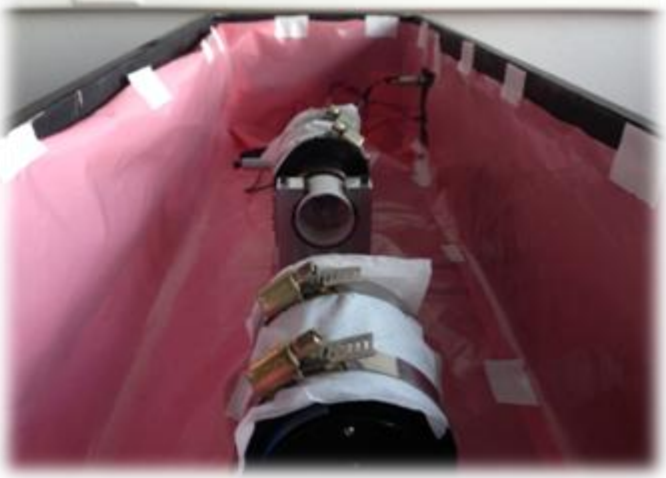
- ^{144}Ce-^{144}Pr (TUM & CEA)
- Use of TUM spectrometer
  cf. PRL. 112, 122501
  - Multiwire chamber (γ veto) & plastic scintillator
- IRFU-LNHB new setup
  - Source encased in plastic scintillator
  - 2*High quantum efficiency PMTs
- But low energy β's from ^{144}Ce pollute the determination of the ^{144}Pr-ν

TUM spectrometer (just deployed in Saclay)



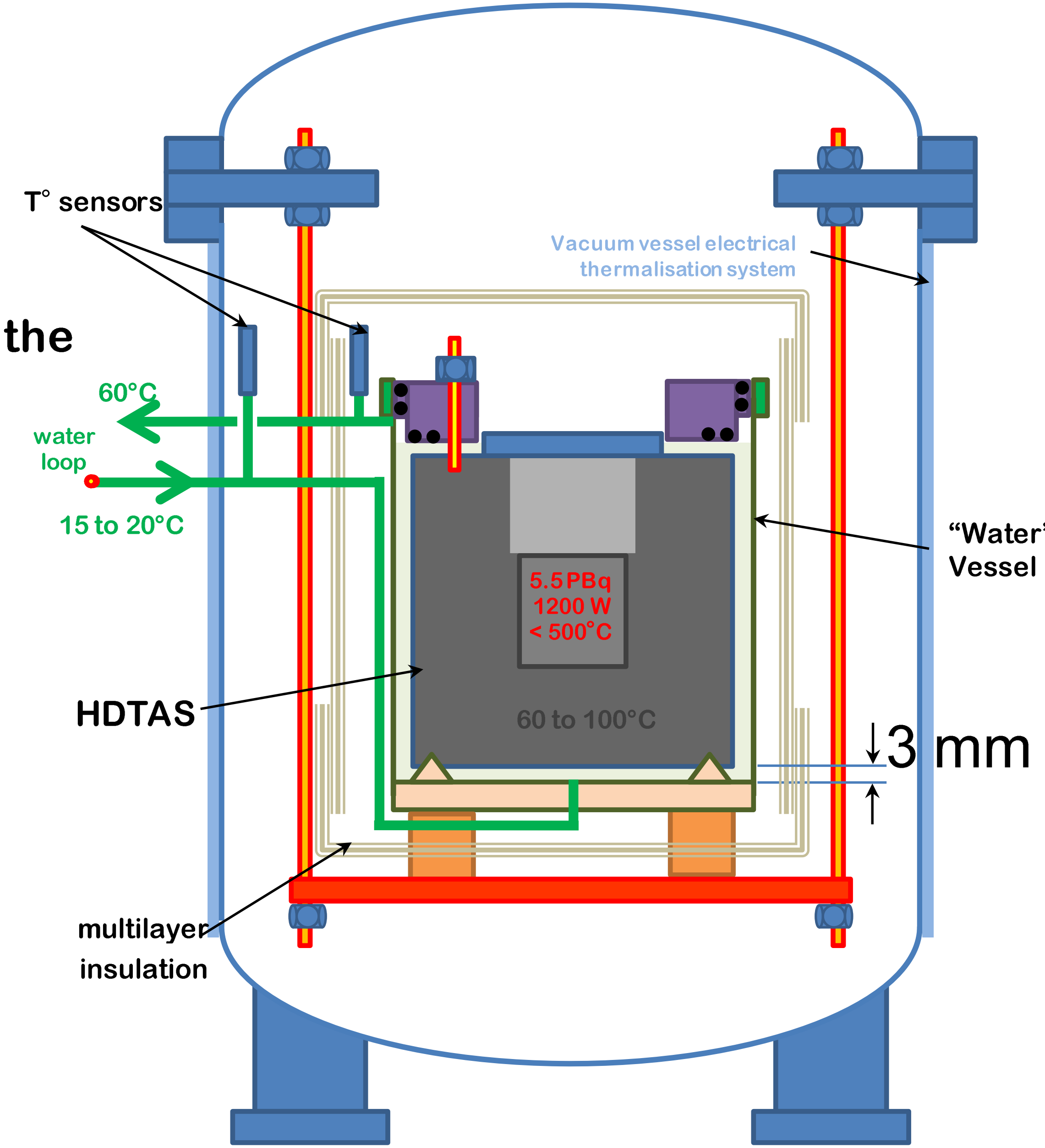
- ^{144}Pr only (CEA)
- Need chemical separation of ^{144}Pr from ^{144}Ce (LNHB)
- ^{144}Pr mean life time: 17 min
  - Spectrometers set up close to the chemical lab
- Detection methods:
  - ^{144}Pr solution in liquid scintillator + PMTs
  - ^{144}Pr solid deposit in PS + PMTs
  - ^{144}Pr solid deposit onto silicon detector
- Complementing each others:
  - ≠ sensitivity to backscattering
  - ≠ measuring range
  - ≠ simulation flaws
- 1st measurements in 2014. Need by 2016

CEA spectrometer (under calibration)



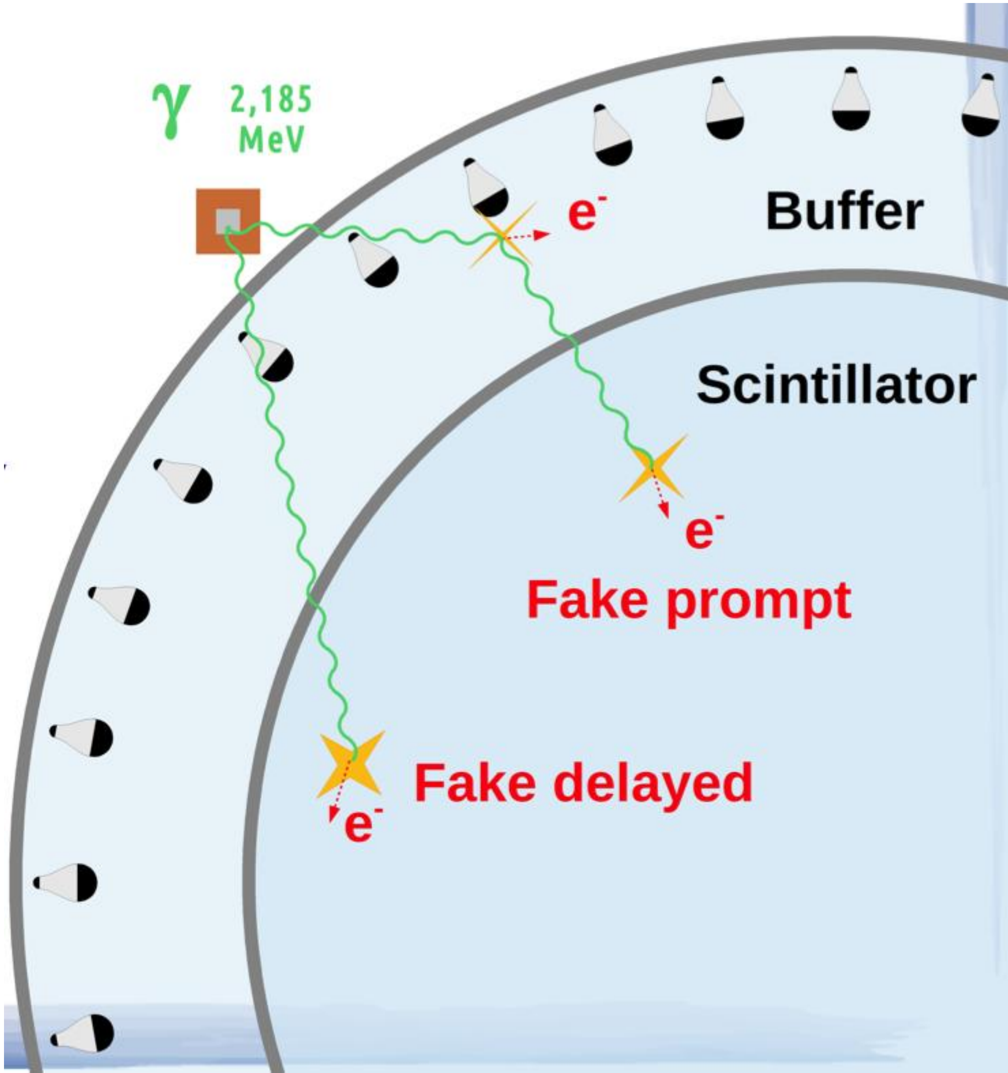
CEA Calorimeter

- **Measure CeANG Heat with a ≈1.5% precision**
- **Mesure water flow and T° at the in/outlets: $\dot{Q} = \dot{m}C(T_{in}-T_{out})$**
- **Preventing heat leaks**
  - Conduction
    - Suspension platform
    - Insulation
  - Convection
    - Vacuum vessel
  - Radiation
    - Multilayer insulation
    - Vessel thermalization
- **Calibration with a dummy electrical source**



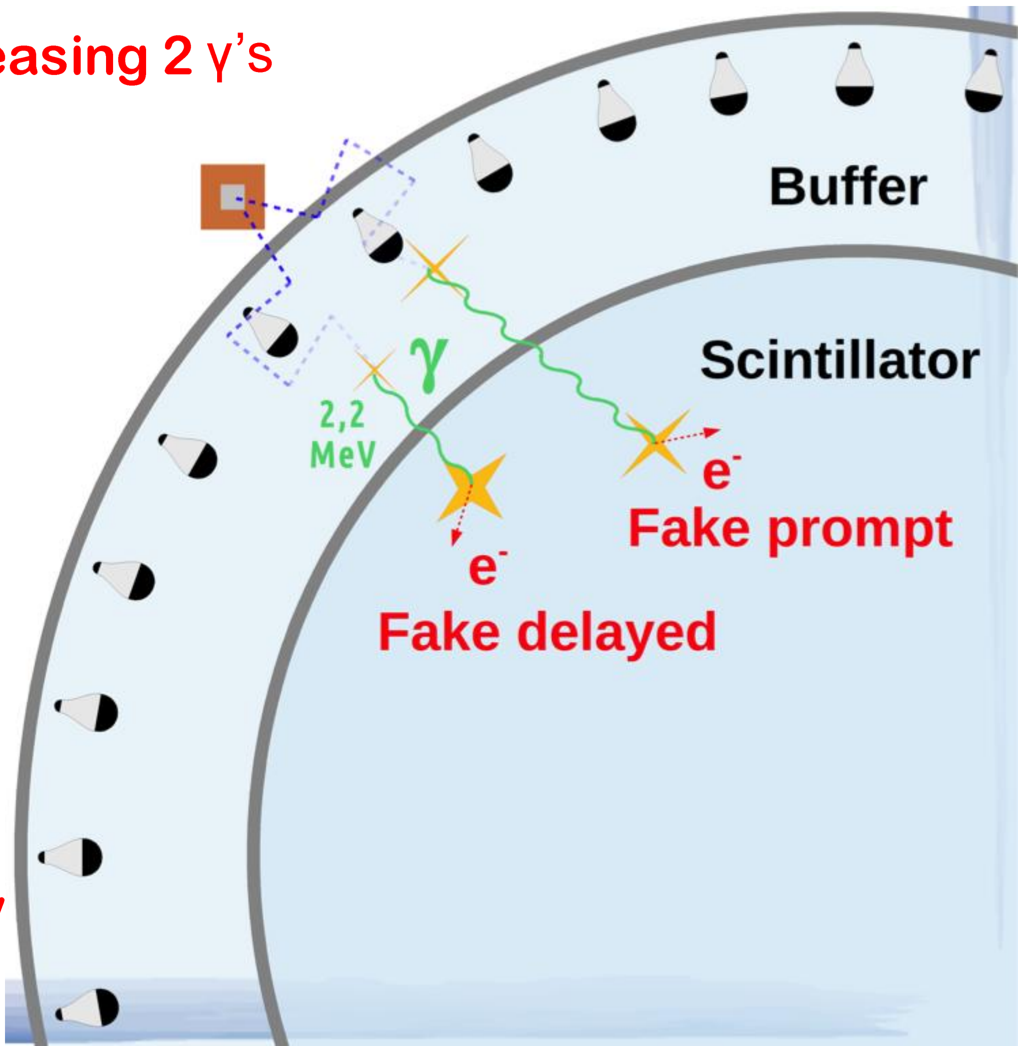
Gamma Background

- Random coincidence between two γ's from CeANG
- IDB-like event:
  - Prompt: E_γ > 1 MeV
  - Delayed: E_d in [2 – 2.4] MeV
  - Time window: 1 ms (3 τ)
- Simulations
  - GEANT4 (limited)
  - TRIPOLI-4
- Results:
  - 2 10^{-4} event/day (w/o E cut)
  - O(10^{-5}) event/day (w E cut)
  - 50% uncertainty
  - Negligible (HDTAS design)



Neutron Background

- Possible traces of minor actinides → spontaneous fission
- Most dangerous nuclei: ^{244}Cm
  - Specification: 10^{-5} Bq ^{244}Cm / Bq ^{144}Ce
- 2 neutrons captured in BX releasing 2 γ's
- IDB-like event:
  - Prompt: $E_\gamma > 1$ MeV
  - Delayed: E_d in [2 – 2.4] MeV
  - Time window: 1 ms (3 τ)
- Simulations
  - TRIPOLI-4
- Results:
  - < O(10^{-2}) event/day
  - 50% uncertainty
- Checked with mass spectrometry



Outlook

- SOX will test reactor anomaly with a characteristic energy and baseline dependent signal
- Cerium Antineutrino Generator is on track
  - >3.7 PBq ^{144}Ce-^{144}Pr production in 2015 – Negotiation ongoing
  - Settled transport plan – authorization process ongoing
  - Shielding tender closed – To be ordered by end of November
- Borexino detector fits the needs
- Serious challenge: accurate CeANG characterization
  - Multiple cross-checked measurements
- Goal: Start Data Taking by December 2015

Thanks for your attention !

More information on the CeLAND proposal, arXiV:1312.0896, the SOX proposal, arXiV:1304.7721, and the article arXiV:1411.6694 to be published.

RAA references

PHYSICAL REVIEW C **83**, 054615 (2011) **245 citations**

Improved predictions of reactor antineutrino spectra

Th. A. Mueller,[1] D. Lhuillier,[1,*] M. Fallot,[2] A. Letourneau,[1] S. Cormon,[2] M. Fechner,[3] L. Giot,[2] T. Lasserre,[3] J. Martino,[2] G. Mention,[3] A. Porta,[2] and F. Yermia[2]

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(Received 14 December 2010; revised manuscript received 9 March 2011; published 23 May 2011)

PHYSICAL REVIEW D **83**, 073006 (2011) **374 citations**

Reactor antineutrino anomaly

G. Mention,[1] M. Fechner,[1] Th. Lasserre,[1,2,*] Th. A. Mueller,[3] D. Lhuillier,[3] M. Cribier,[1,2] and A. Letourneau[3]

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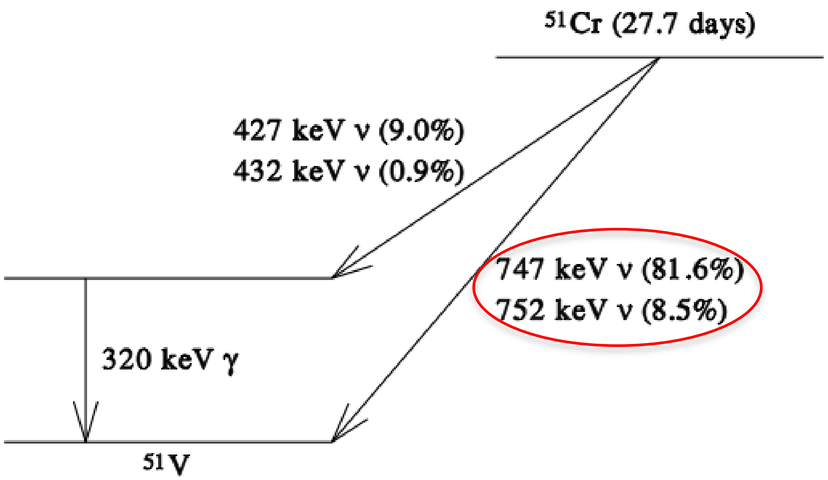
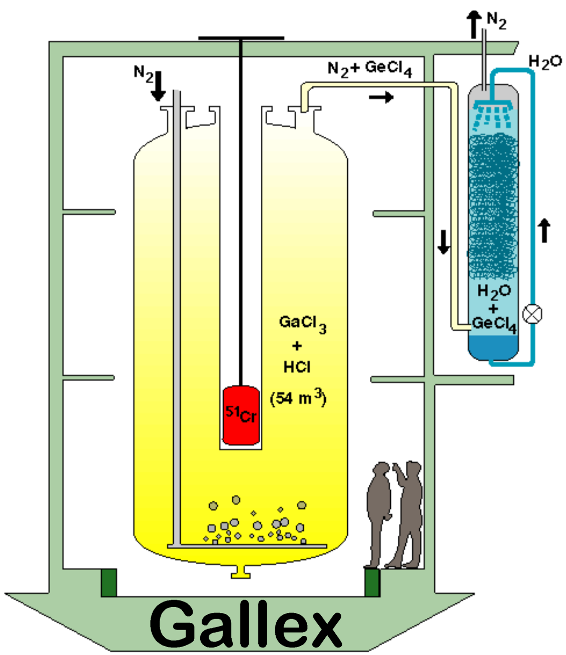
(Received 14 January 2011; published 29 April 2011)

The Gallium Anomaly

- Test of solar neutrino radiochemical detectors GALLEX and SAGE
  - $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$
- 4 calibration runs with 20-60 PBq Electron Capture ν_e emitters
  - Gallex, <L>=1.9 m
    - ^{51}Cr, 750 keV
  - Sage, <L>=0.6 m
    - ^{51}Cr & ^{37}Ar (810 keV)
- Deficit observed
  - 3σ anomaly
  - Supported by new ^{71}Ga (^{3}He,^{3}H) ^{71}Ge cross section measurement

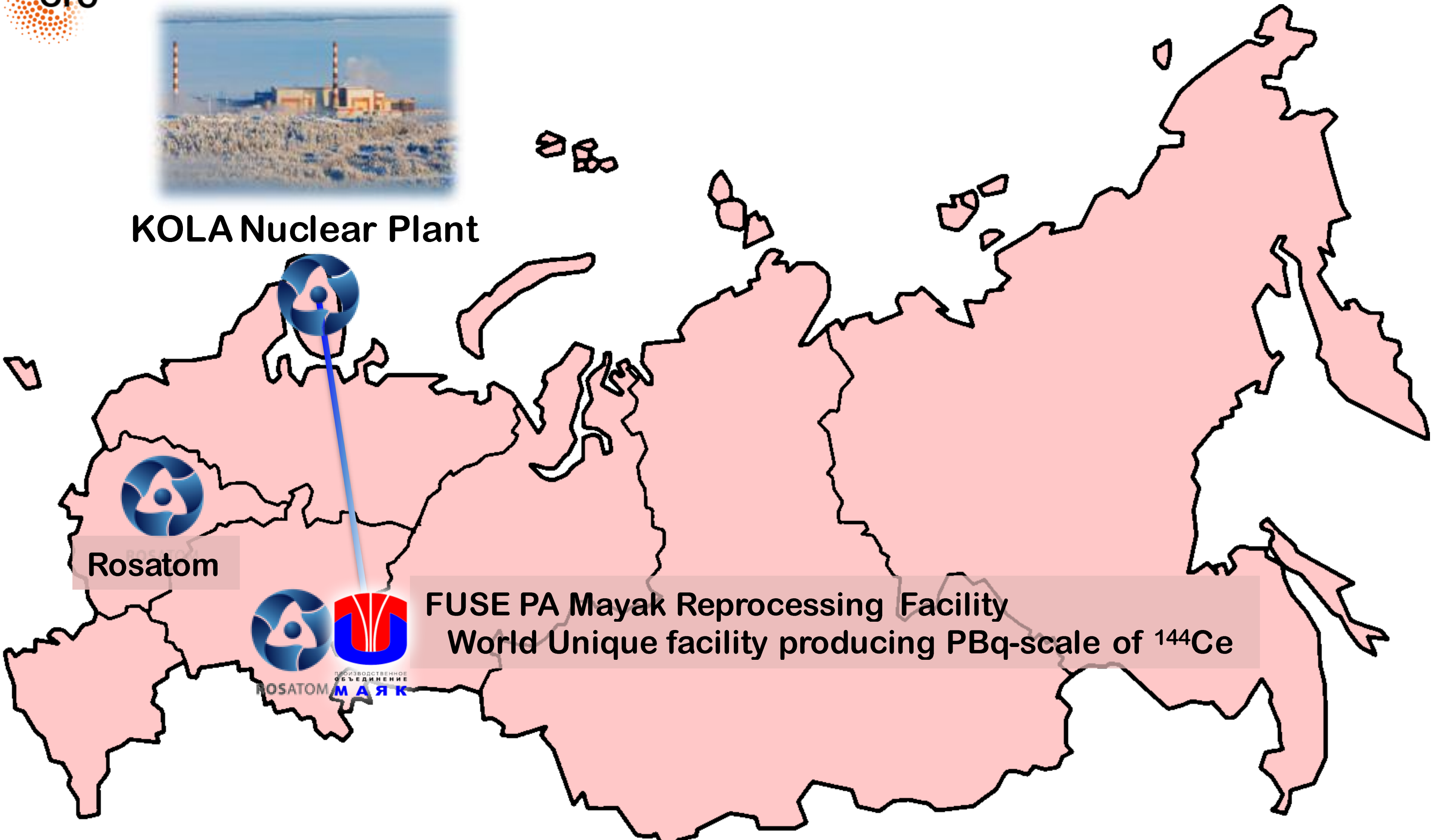




ν Generator Proposals

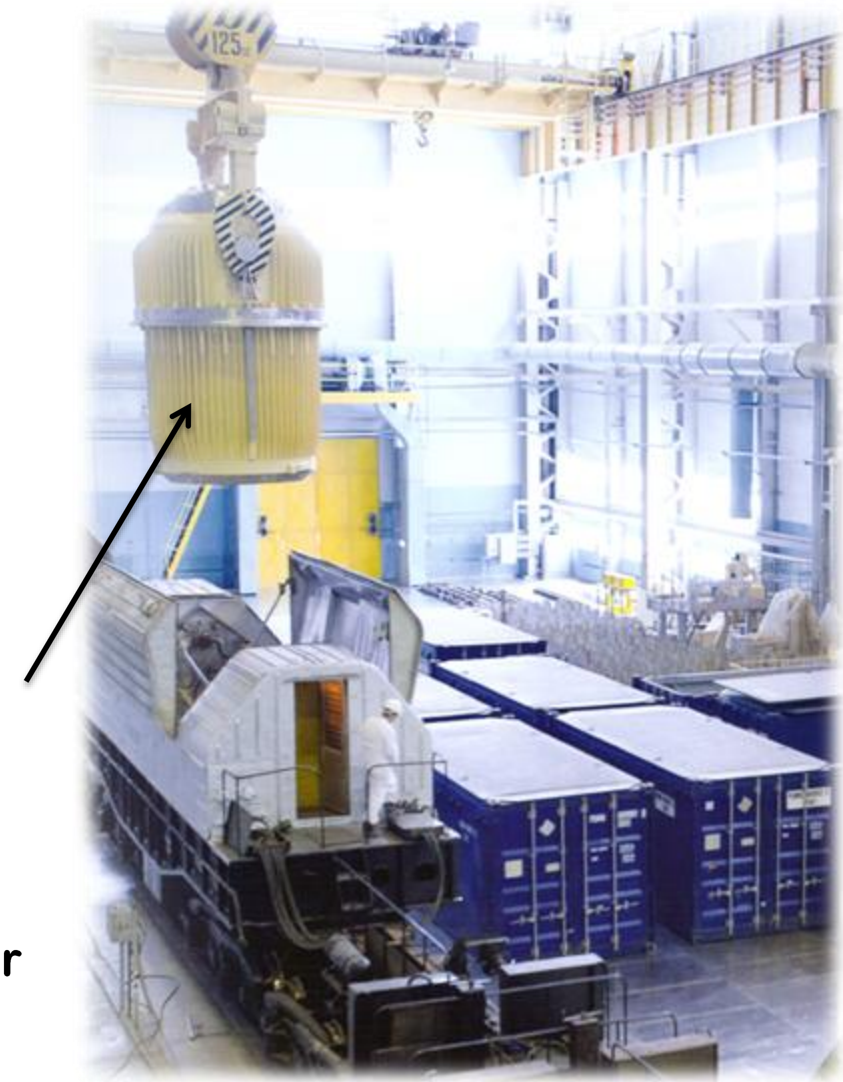
Type	Detection	Background	Isotope	Production	Activity	Projects
ν_e	$\nu_e e \to \nu_e e$ 5% E_{res} 15cm R_{res} or Radio-chemical	Detector Radioactivity Solar ν (irreducible) ν generator impurities	^{51}Cr 0.75 MeV $t_{1/2}$=26d	n_{th} irradiation in Reactor	>110 PBq	Sage LENS
					>370 PBq	CrSOX (SNO+)
			^{37}Ar 0.8 MeV $t_{1/2}$=35d	n_{fast} irradiation in Reactor (breeder)	>37 PBq	-
					185 PBq	Ricochet
$\bar{\nu}_e$	$\bar{\nu}_e p \to e^+ n$ E_{th}=1.8 MeV (e^+,n) 5% E_{res} 15cm R_{res}	reactor ν, geo ν, ν generator impurities	^{144}Ce E<3MeV $t_{1/2}$=285d	spent nuclear fuel reprocessing + REE extraction	3.7-5 PBq	CeLAND CeSOX
					18.5 PBq	Daya-Bay
			^{90}Sr ^{106}Rh		-	-
	$^3H \to He\ e^- \bar{\nu}_e$ EC/β-decay	Kink search	^3H E<18 keV	Irradiation in reactors	110 GBq	KATRIN (Mare/Echo)

Russian Institutions & Facilities



Spent Nuclear Fuel

- ^{144}Ce: 5.5% / 3.7% in the fission products of U / Pu
- ^{144}Ce: 411 d half-life. 3 years after last irradiation
  - m(^{144}Ce)/m(all Ce) = 1 / 130
- Selection of best SNFE at Cola NPP (fresh fuel)
  - 5 tons – 1.7 y cooling
  - 66 Ci/g of Ce isotopes
- Delivery of SNF from Cola NPP to FSUE "Mayak" PA (3000 km)
  - TUK-6 container
- PA Mayak will receive fresh fuel for ^{144}Ce prod. in Feb. 2015



Overview of the process

- Radiochemical Plant
  - Standard radiochemical re-processing of SNF (Purex)
  - Separation of CeO_2
  - Primary encapsulation
  - Activity measurement (5%)

- Radioisotope Plant
  - Source manufacture
  - Certification ISO 9978
  - Loading into HDTAS
  - Loading into transport cask

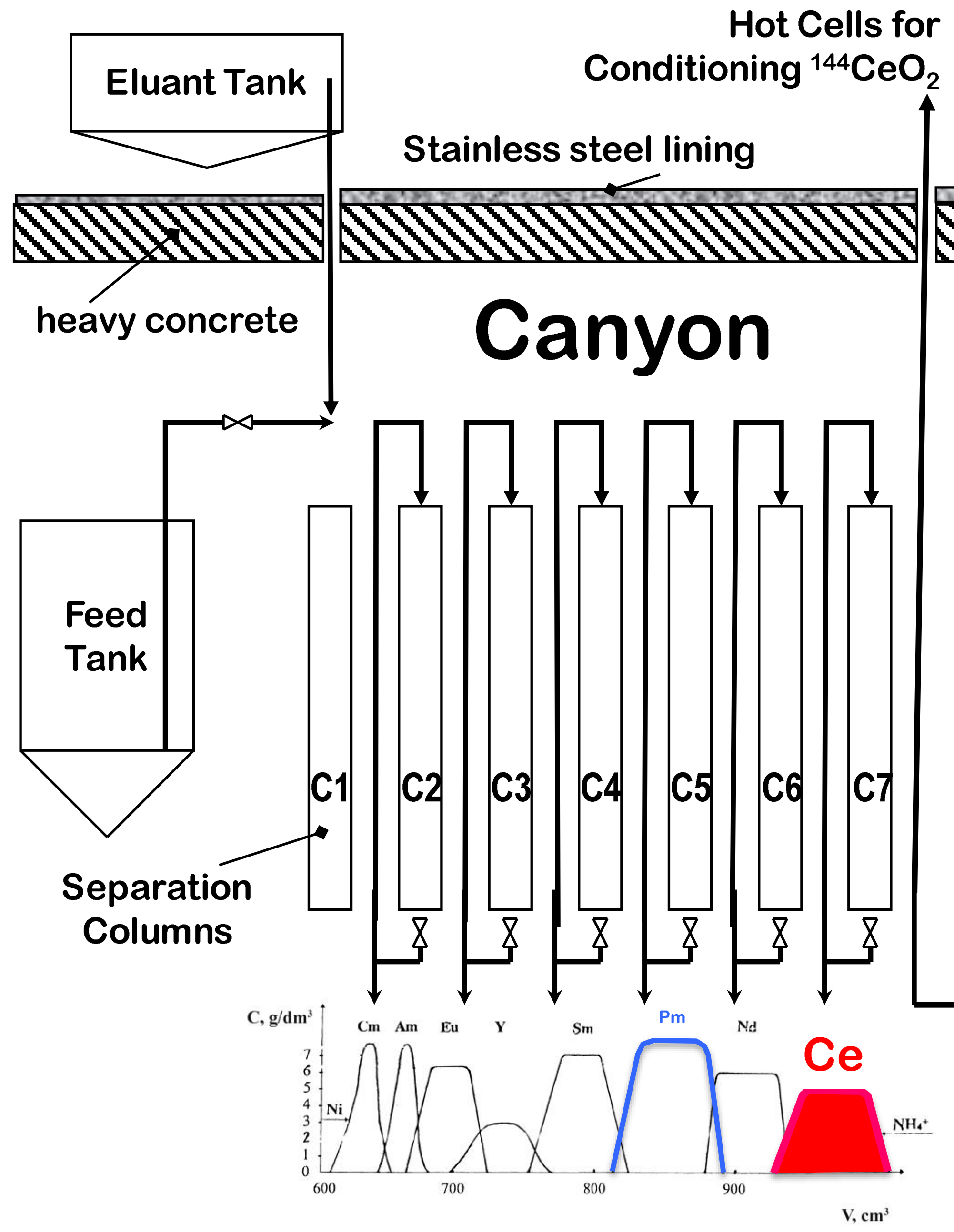
- Upgrade of PA Mayak facilities for CeANG production ongoing

Extraction of Cerium Solution

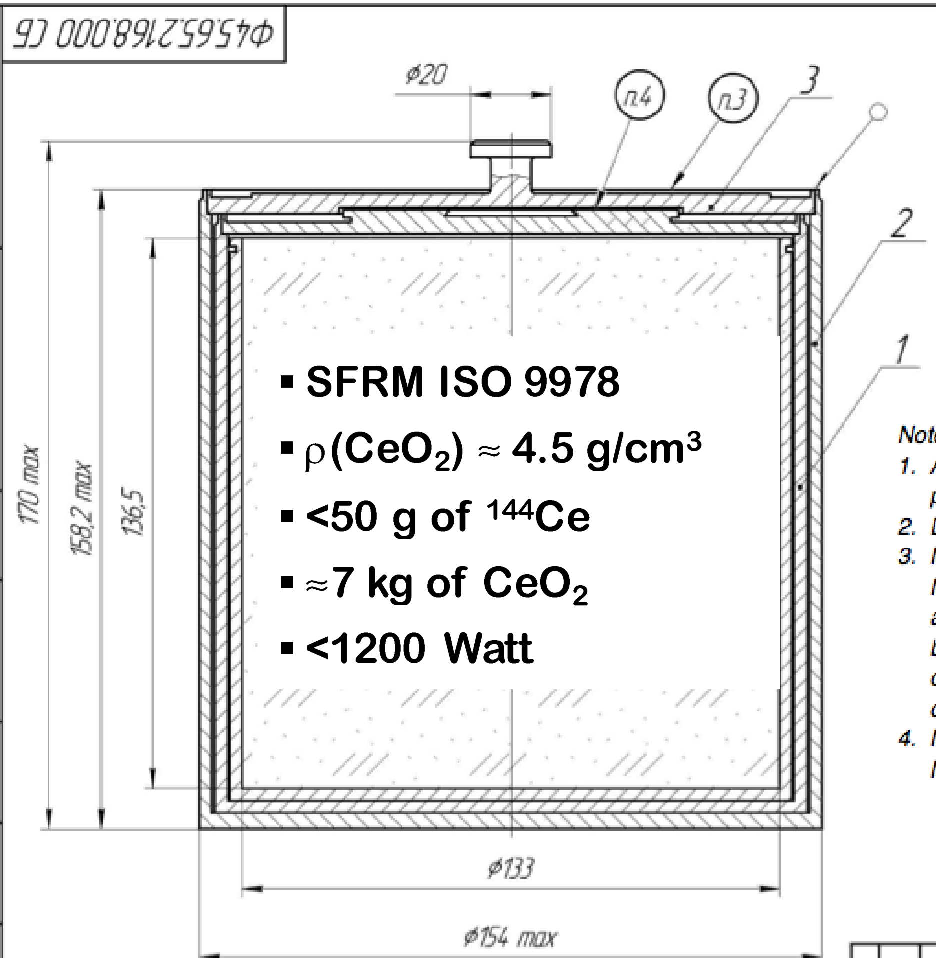
- Complexing agent displacement **chromatography** for Rare Earth elements (REE)

- **VVR-440 Spent Nuclear Fuel:**
  - PA Mayak: 100 t SNF/y
  - 1 ton SNF:
    - 13 kg REE
    - 22 g ^{144}Ce (3 y, 70 kCi)

- **Production**
  - Start in Feb. 2015
  - 9 months Nov. 2015
  - Material for up to 175 kCi
  - Schedule to be consolidated



^{144}Ce-^{144}Pr SFRM capsule



- SFRM ISO 9978
- $\rho(CeO_2) \approx 4.5$ g/cm^3
- <50 g of ^{144}Ce
- $\approx$7 kg of CeO_2
- <1200 Watt

Notes:

1. Assembled and welded using manufacturer's technological process; penetration depth not less than 0.6 mm.
2. Dimensions without tolerances are given for reference only.
3. Marking.
   Marking content:
   a) Serial Number;
   b) chemical symbol of the element – Ce-144;
   c) basic trefoil symbol;
   d) year of manufacture
4. Marking.
   Marking content: Serial Number

Ф45.65.2168.000 СБ

Ce-144
Assembly Drawing

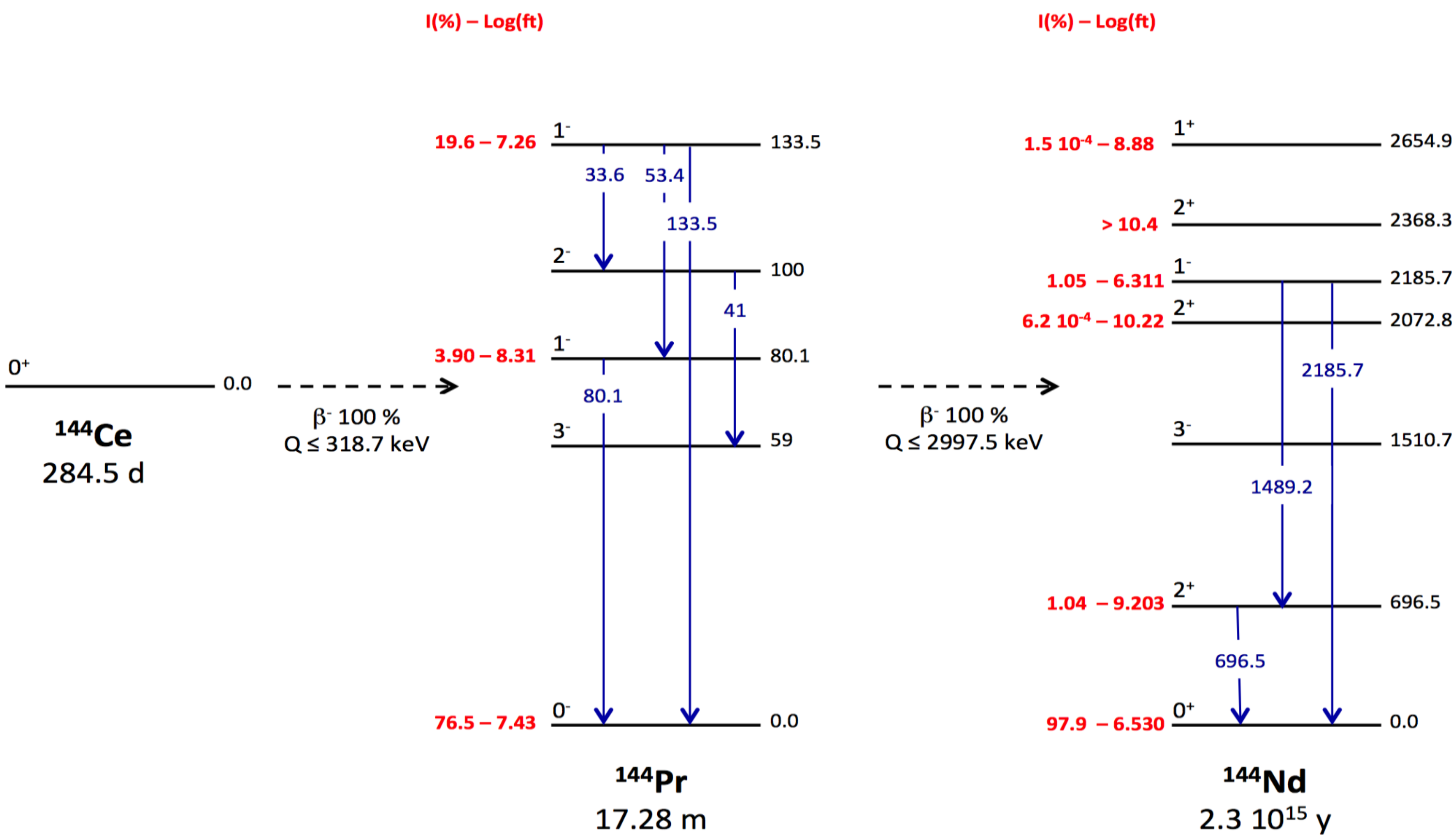
Steel 12X18H10T-ИД** to State Standard ГОСТ 5632-72

FSUE "Mayak" PA

Scale 1:1

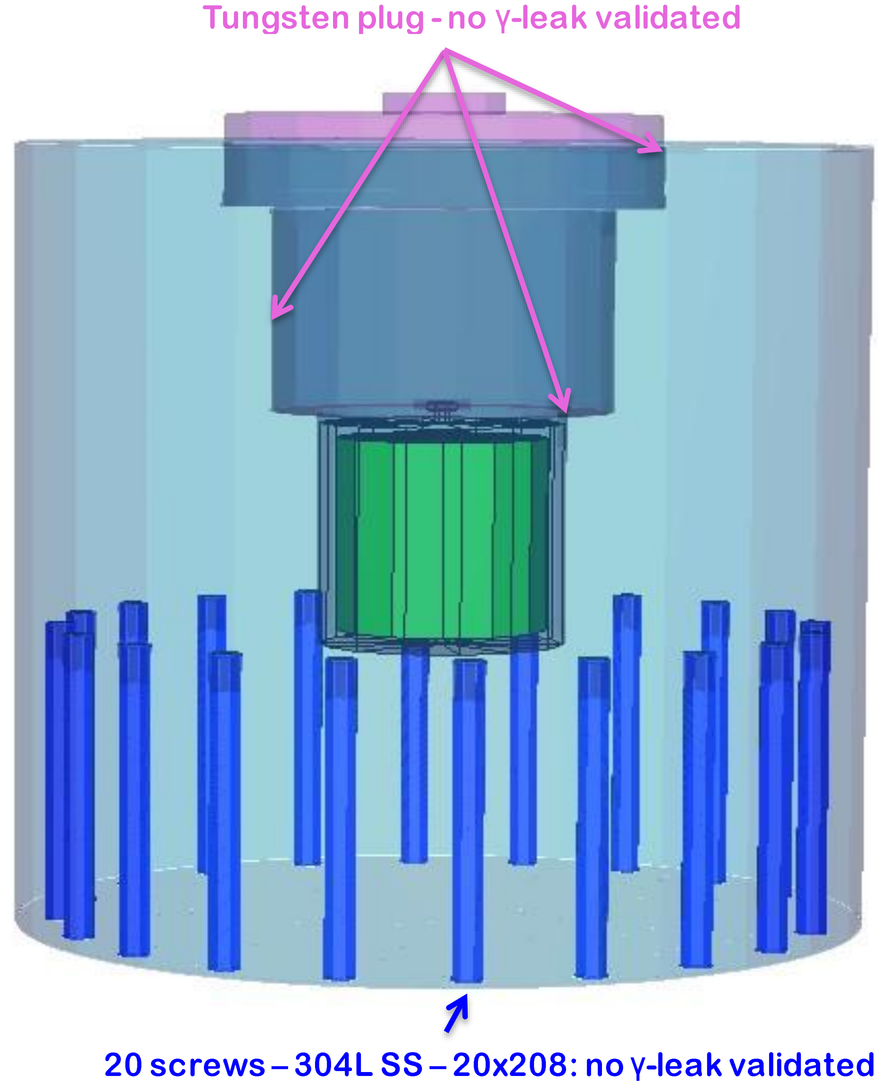
Gamma Backgrounds of ^{144}Ce-^{144}Pr

- γ rays produced by the decay through excited states of ^{144}Pr
  - Intensity γ>1 MeV
    - 1380 keV – 0.007 %
    - 1489 keV – 0.3 %
  - Intensity γ>2 MeV
    - 2185 keV – 0.7 %
      (2.10^{10} γ/sec for 3.7 PBq)



HDTAS: Radiation Dose

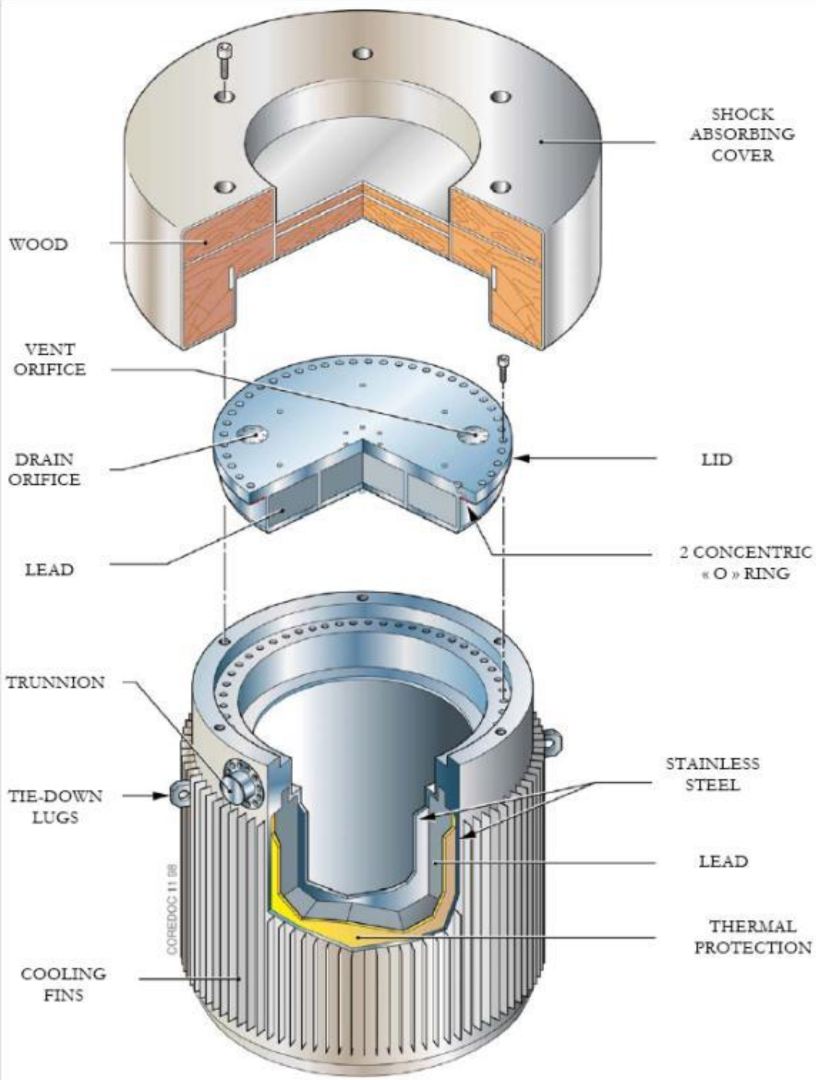
- **Computation by CEA/SPR**
  - Code Mercurad v1.10
  - Code MCNPX v2.7.0
- **Hypothesis**
  - 5.5 PBq in ^{144}Ce
  - γ -emitters in Ce < 10^{-3} Bq/Bq
  - n emitters in Ce < 10^{-5} Bq/Bq
- **Gamma Radiation dose**
  - at contact <120 µSv/h
  - at 1 m <7 µSv/h
  - Source: ^{144}Pr de-excitation
- **Neutron Radiation dose**
  - 'at contact' <100 nSv/h
  - at 1 m <4 nSv/h
  - Source: ^{244}Cm SF (2.10^4 n/s)



Transport Routes: Logistics

- Empty cask + HDTAS
  - From CEA-Cadarache to Mayak via St-Petersburg
- CeANG in HDTAS, HDTAS in cask, cask to LNGS
  - Mayak to St Petersburg
  - St Petersburg to Le Havre
  - Le Havre to CEA
  - Temporary storage at CEA-Saclay
  - CEA to Gran Sasso
- Empty cask back from LNGS to CEA-Marcoule

TN MTR Transport Cask

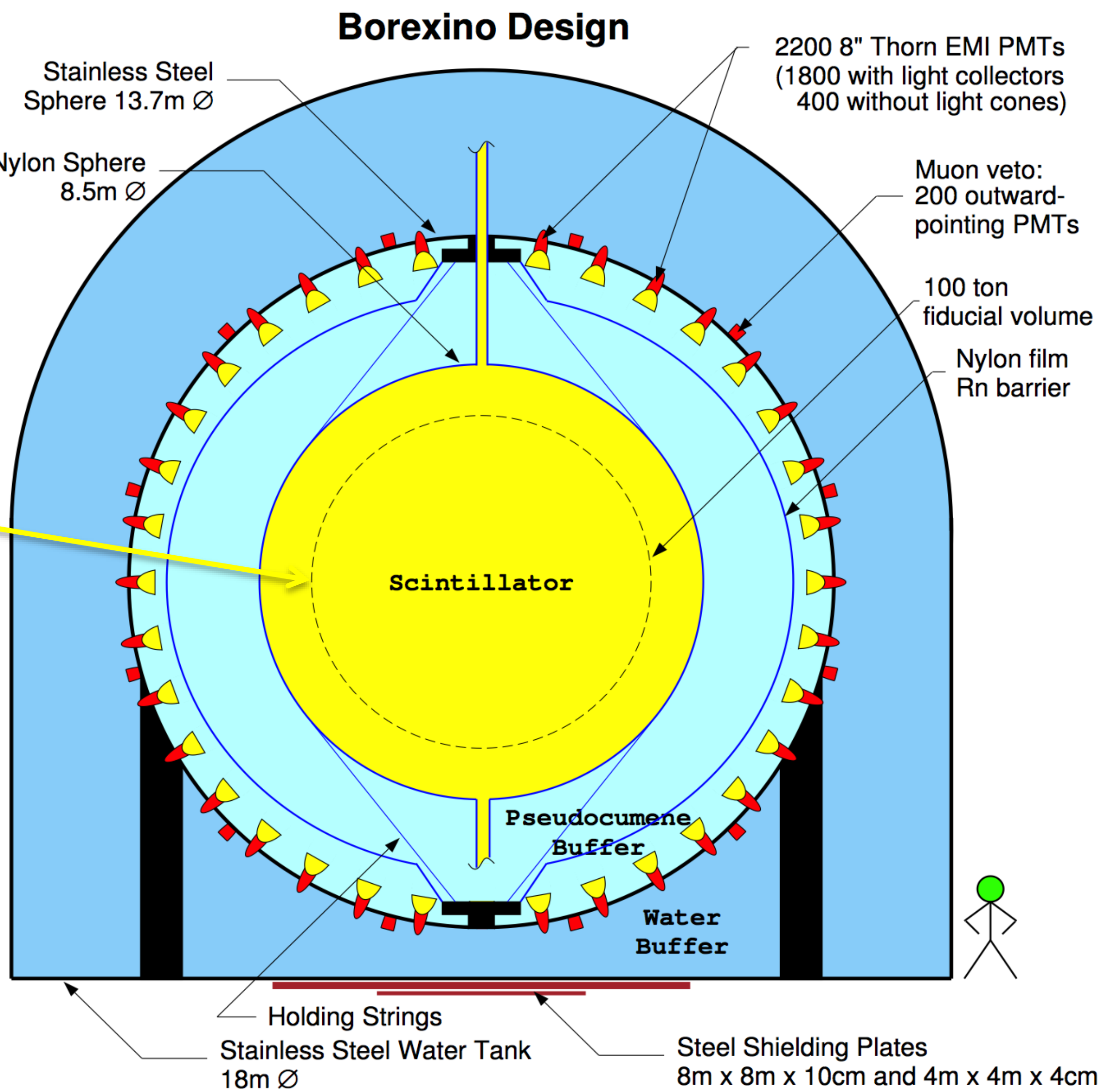


Custom AREVA spreader

Borexino details

CeSOX target

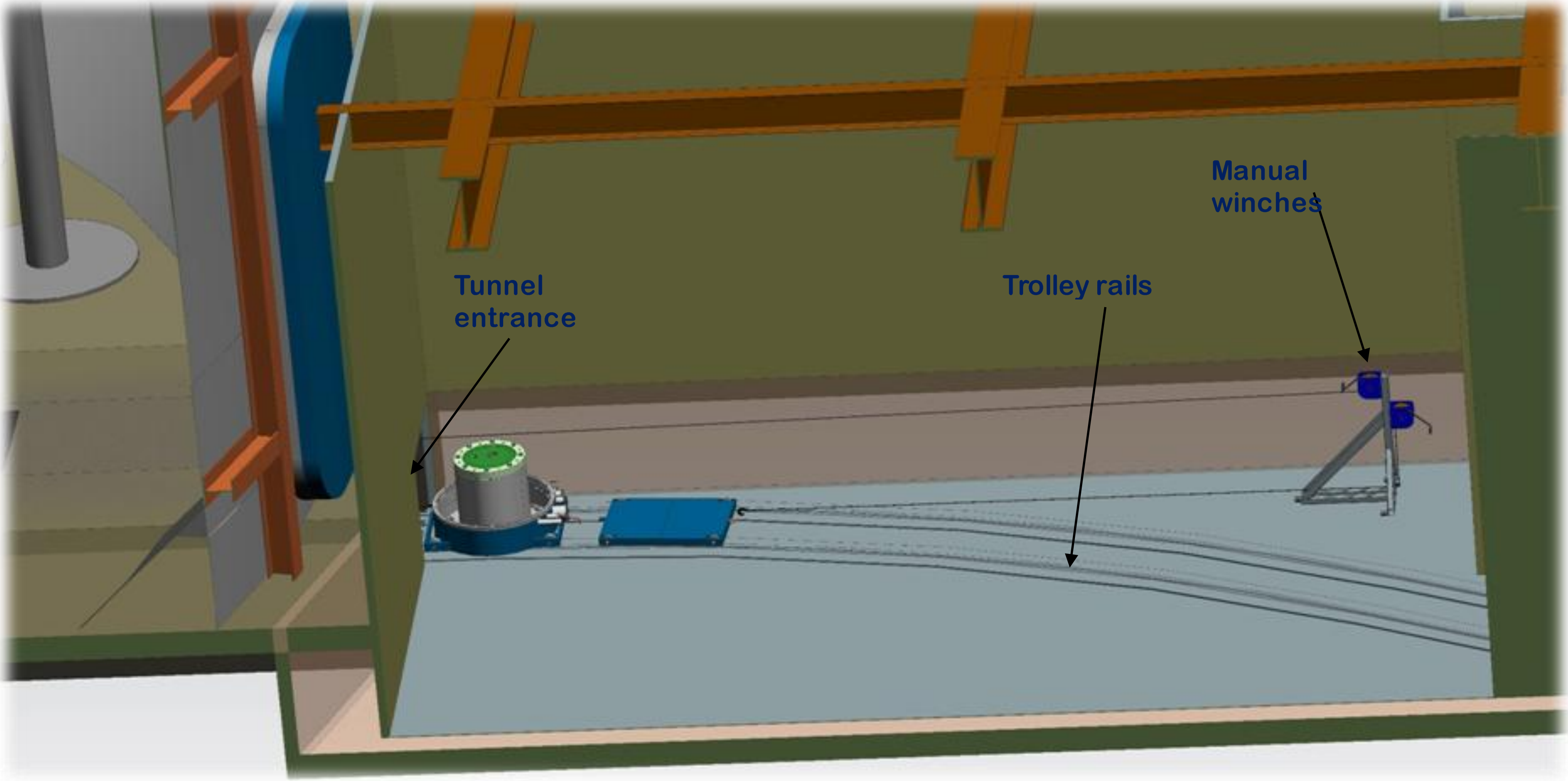
- R < 4.25 m
- 280 tons
- C_6H_{12}
- #H: $1.7\ 10^{31}$



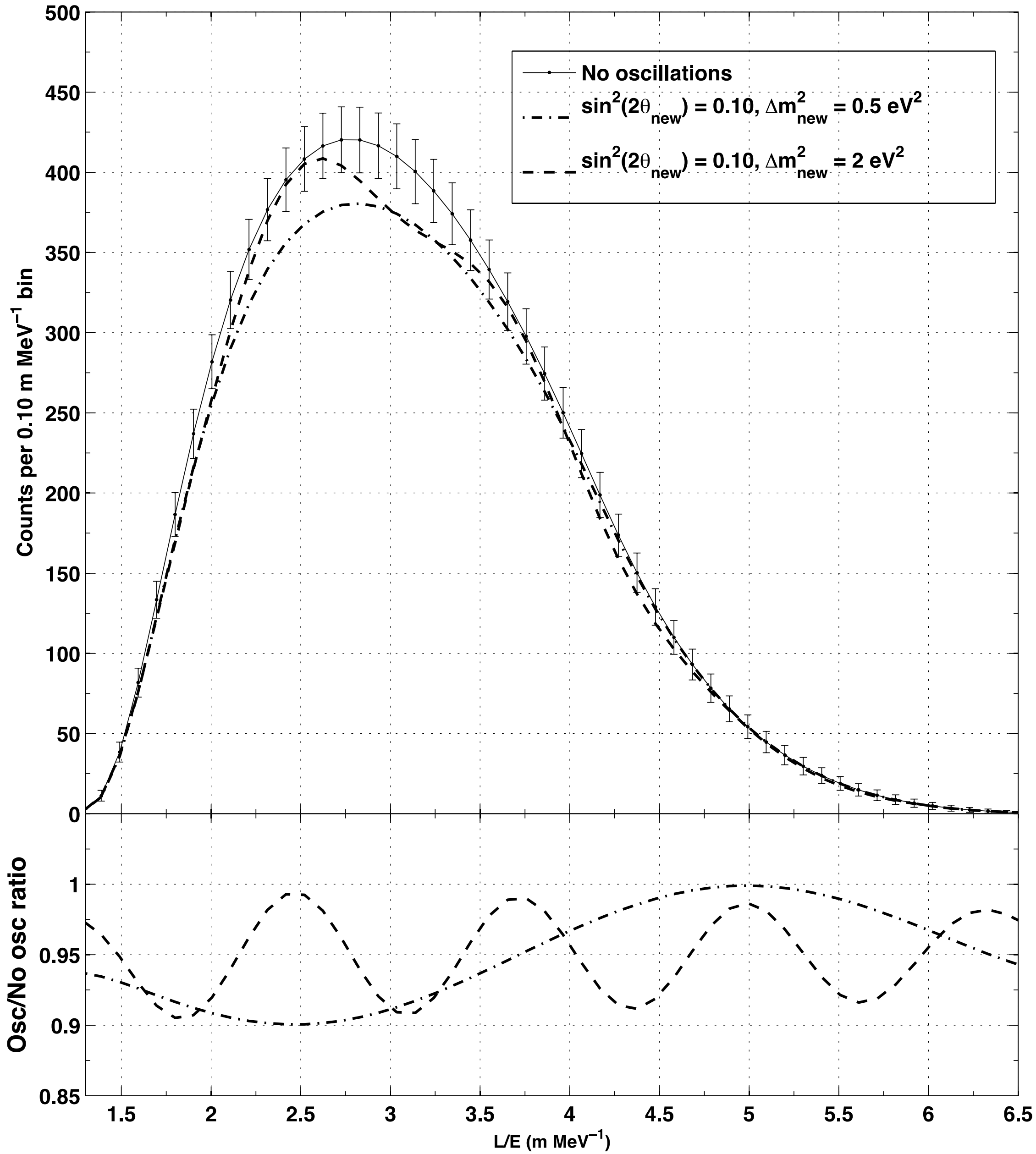
Moving the CeANG in Hall C

CeANG inside SOX pit @ LNGS

- Use the base of the Cr-Calorimeter as trolley & cooling device
- Slide the CeANG into the pit – Radiation dose controls (0.5 y)

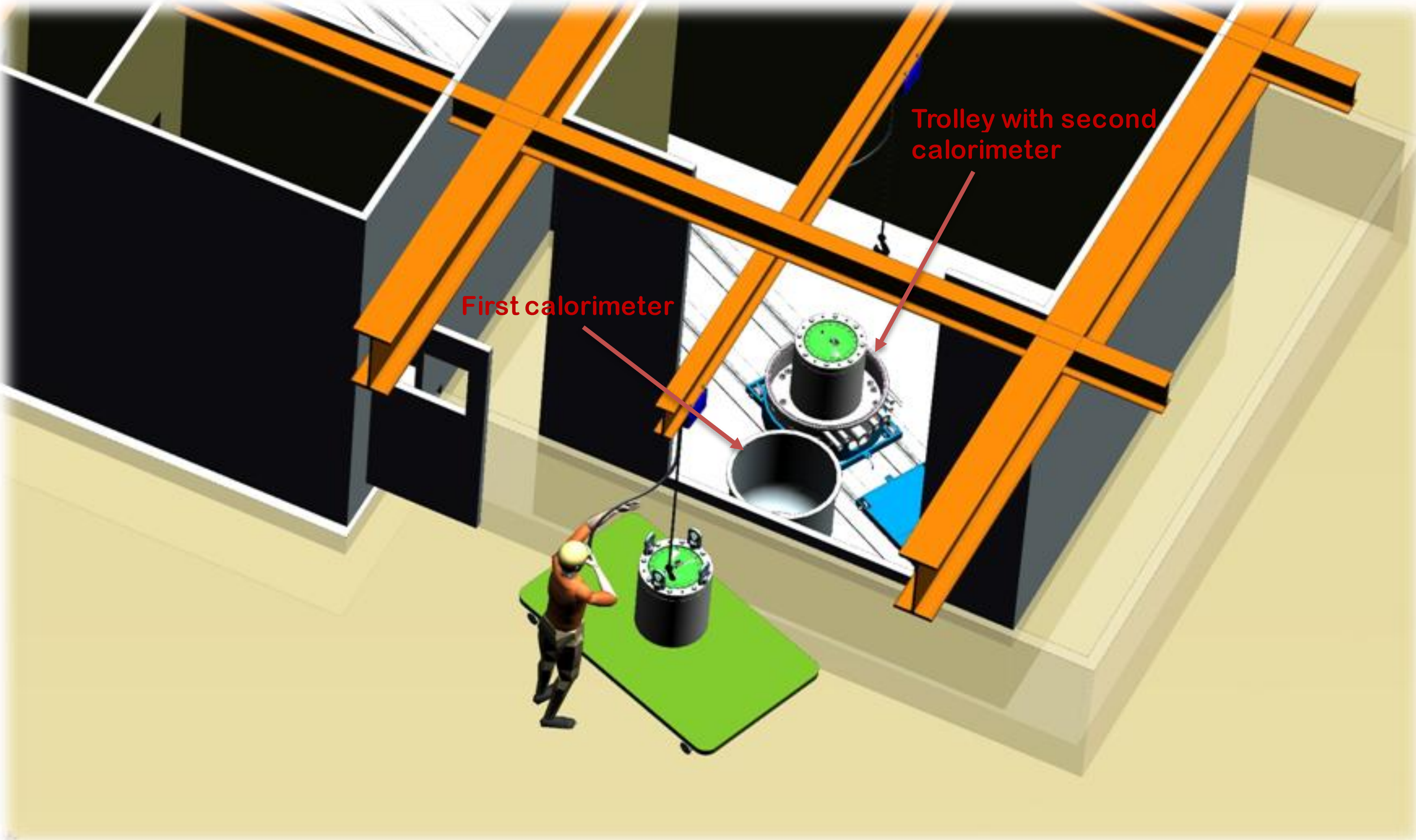


Expected $\nu_e \rightarrow \nu_s$ Oscillation Signal



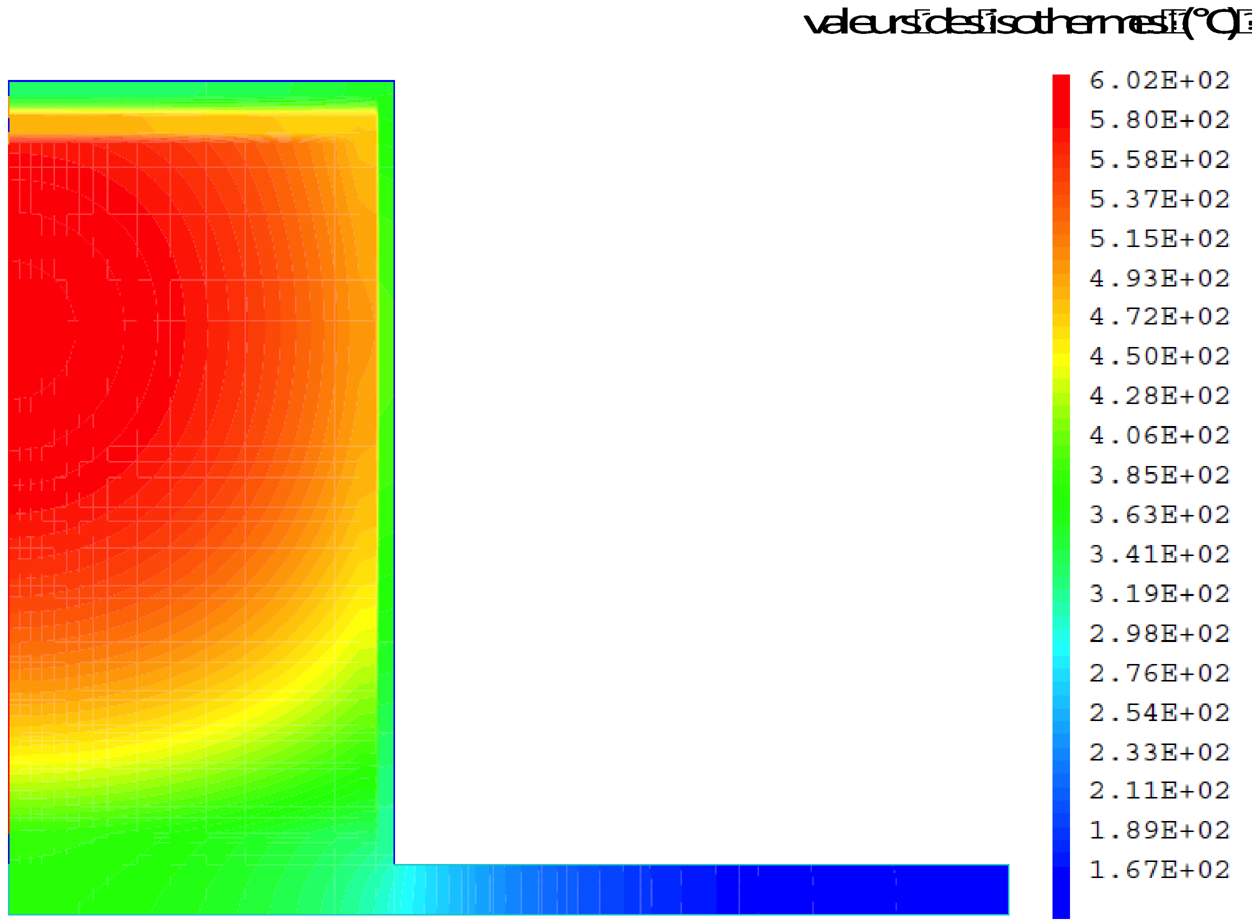
Bigger picture

CeANG on site calorimetry



CeANG Thermal Features

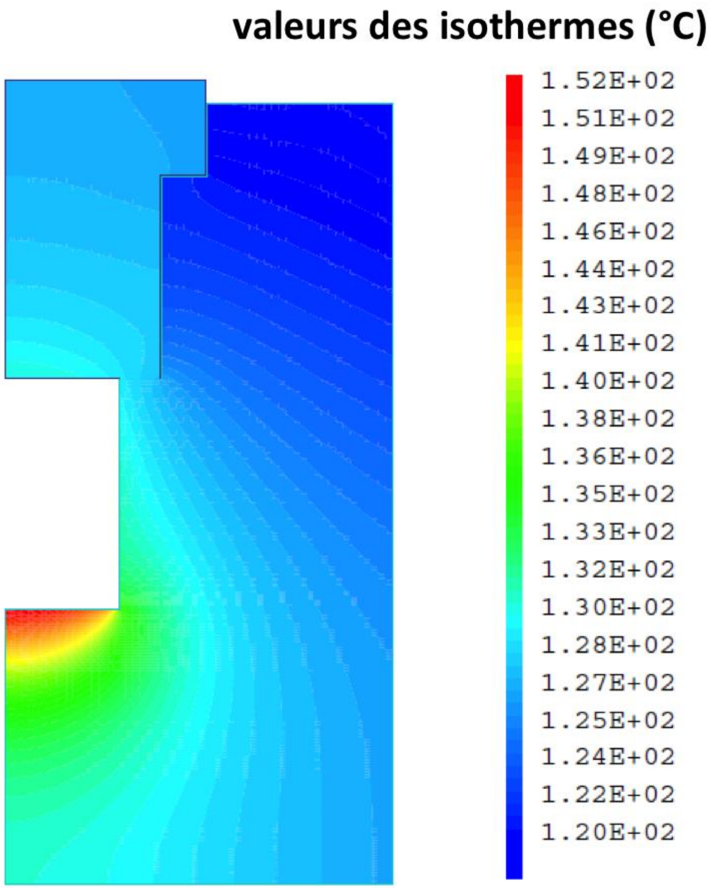
4.6 PBq (1000 W) CeANG temperature distribution alone in air at 38°C, lying on a massive steel supporting structure.

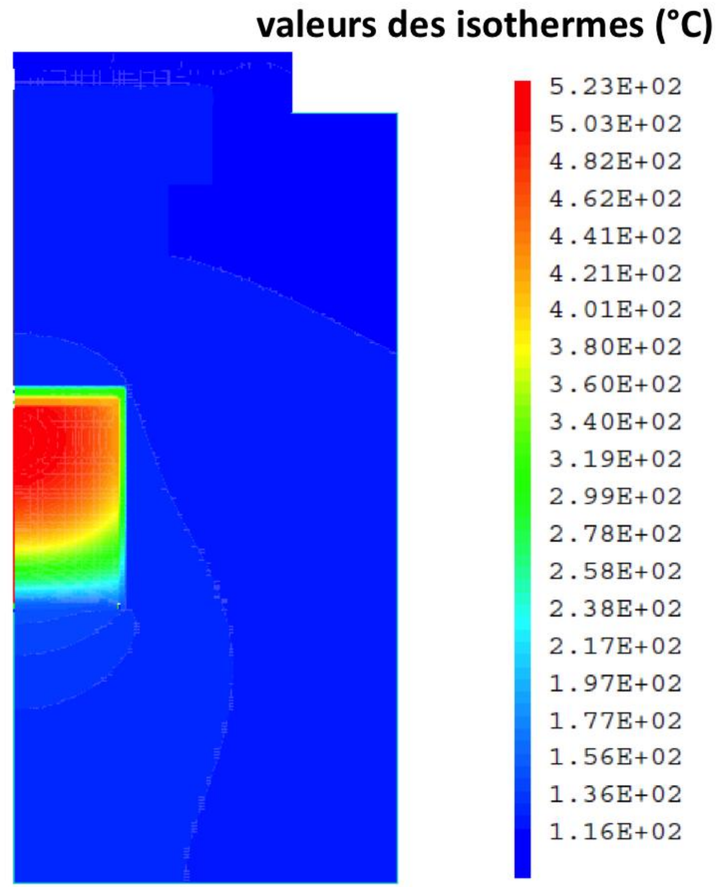


T°C max in Cerium	Averaged T°C in Cerium	T°C max on internal capsule	T°C max on intermediate capsule	T°C max on external capsule	T°C min on steel support
605	509	502	401	384	149

HDTAS: Thermal Features

4.6 PBq (CeANG)-W temperature distribution alone in air at 38°C. Assuming a temperature of 20°C. The temperature of the shield surface will be 80°C.

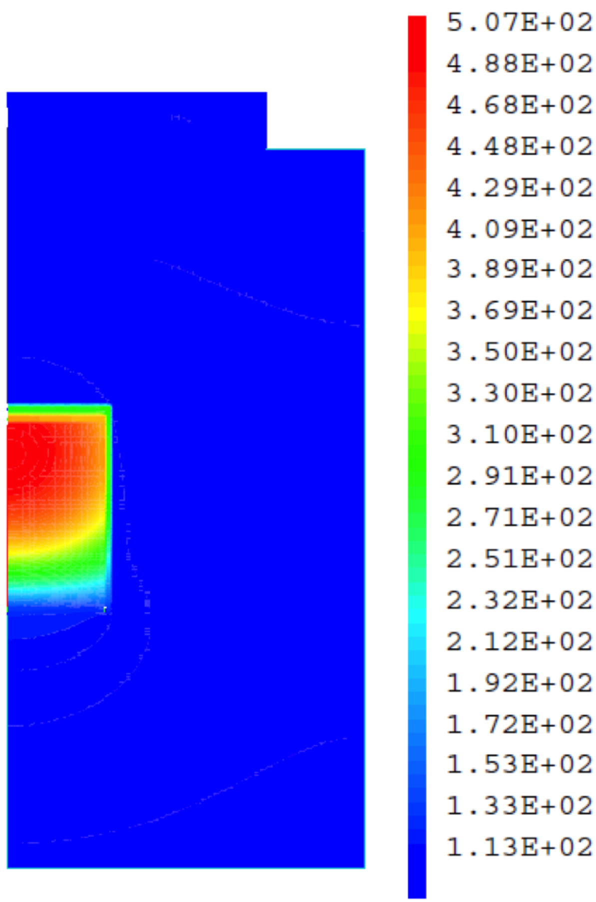


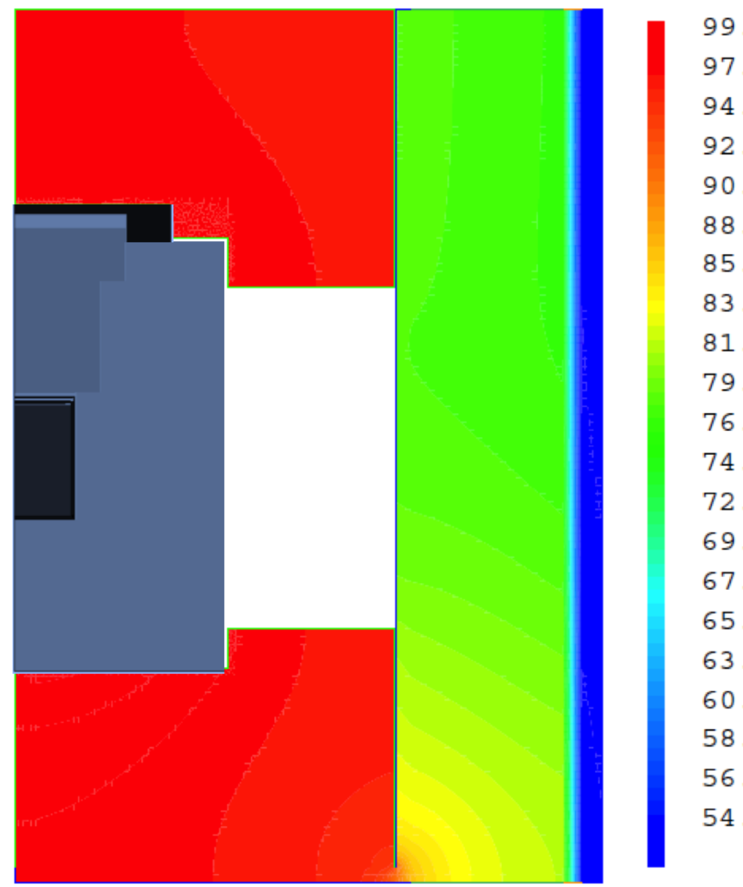


HDTAS			HDTAS + Capsule		
T°C max in Cerium	Averaged T°C in cerium	T°C max of inner capsule	T°C max of external capsule	T°C max of HDTAS	External HDTAS T°C
526	398	434	338	153	119

TN MTR : Thermal Features

Temperatures of the CeANG, its shield and the TN-MTR during transportation



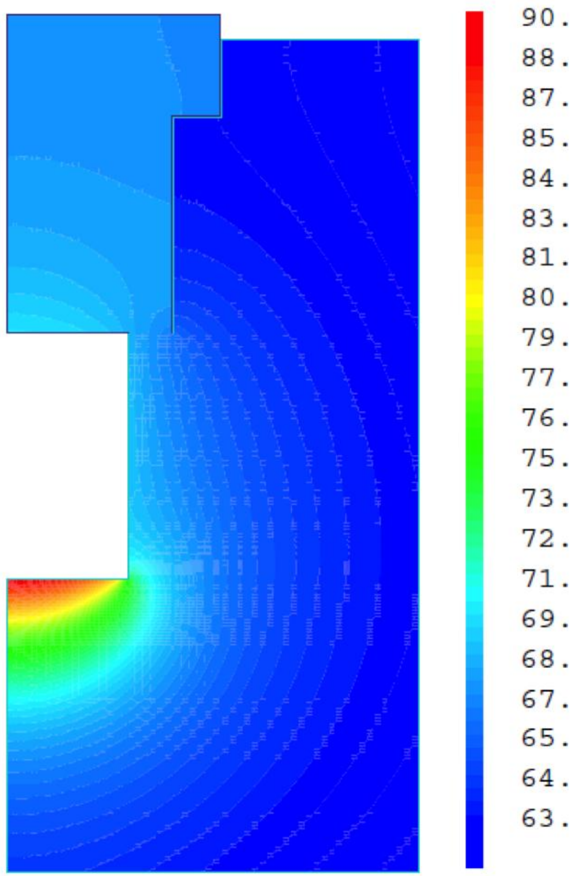


HDTAS				TN-MTR transport container		
T°C max in cerium	Averaged T°C of cerium	T°C max of capsules	T°C max of HDTAS	External HDTAS T°C	T°C max of TN-MTR	External T°C of TN-MTR
512	380	419	127	97	97	52

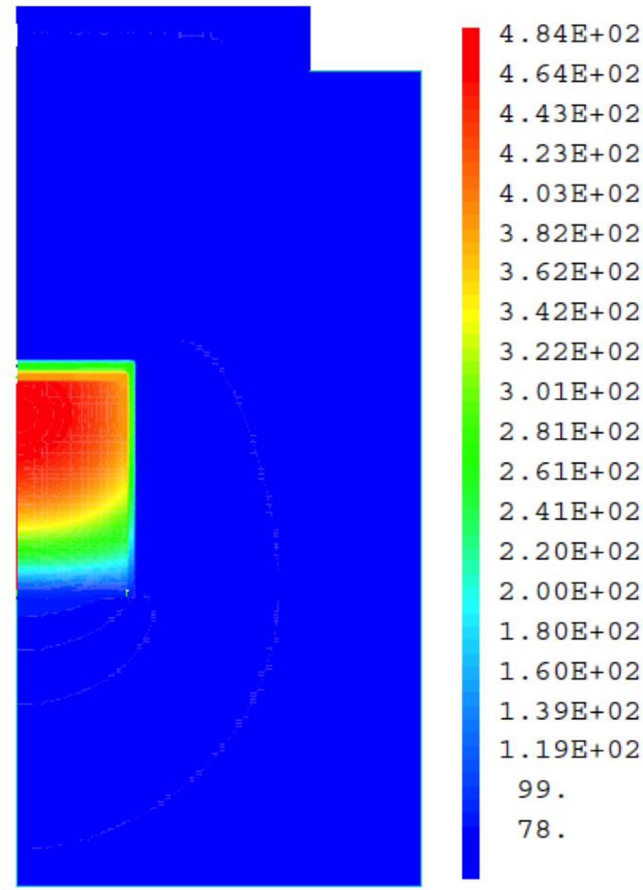
Calorimeter: Thermal Features

Temperature in the calorimeter during the measurement

valeurs des isothermes (°C)



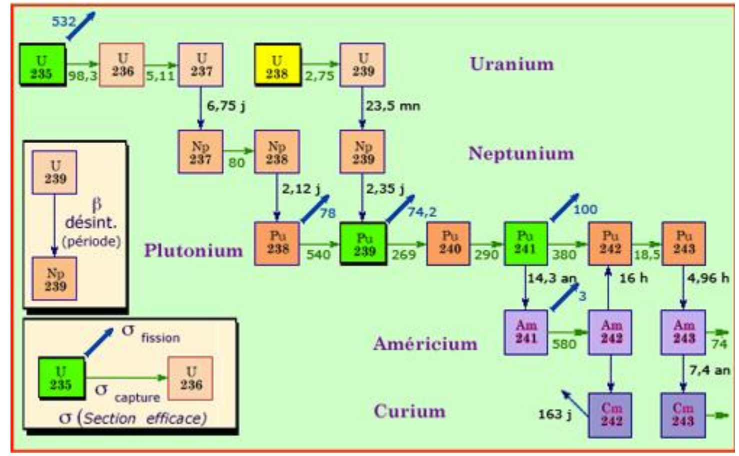
valeurs des isothermes (°C)



HDTAS			HDTAS + CeANG		
T°C max of cerium	Averaged T°C of cerium	T°C max of middle capsule	T°C max of external capsule	T°C max of HDTAS	External HDTAS T°C
487	352	396	297	90	62

Neutron Background

- **Traces of minor actinides**
  - Am, Cm, Bk, Cf,…
  - Spontaneous fission (SF)
    - Few neutrons released
  - α,n reaction
    - 2 orders of magnitude lower than SF rate (MePHI/SCALE 5)



- **Most dangerous nuclei: ^{244}Cm**
  - ^{244}Cm ~ all Cm after 3 years
  - T = 18,1 y ; I_{SF} = 1.4.10^{-6} ; 2,7 n/SF
  - Heavier minor actinides
    - Higher branching ratio to SF
    - But much less produced during irradiation

Isotope	Half-life	I_{SF} (%)	Specific neutron activity (n/g)
^{241}Am	432.2 y	4.0 10^{-10}	1.2
^{242m}Am	141 y	4.7 10^{-9}	46
^{243}Am	7370 y	3.7 10^{-9}	0.72
^{243}Cm	29.1 y	5.3 10^{-9}	2.6 10^{2}
^{244}Cm	18.10 y	1.4 10^{-4}	1.6 10^{7}
^{245}Cm	8.5 10^{3} y	6.1 10^{-7}	1.1 10^{2}
^{246}Cm	4.73 10^{3} y	3.0 10^{-2}	1.0 10^{7}
^{248}Cm	3.40 10^{5} y	8.39	4.2 10^{7}

- **Measurement of MA traces**
  - Mass spectrometry
  - CEA/DEN - DPC/SECR