JUNO central detector and its calibration strategy

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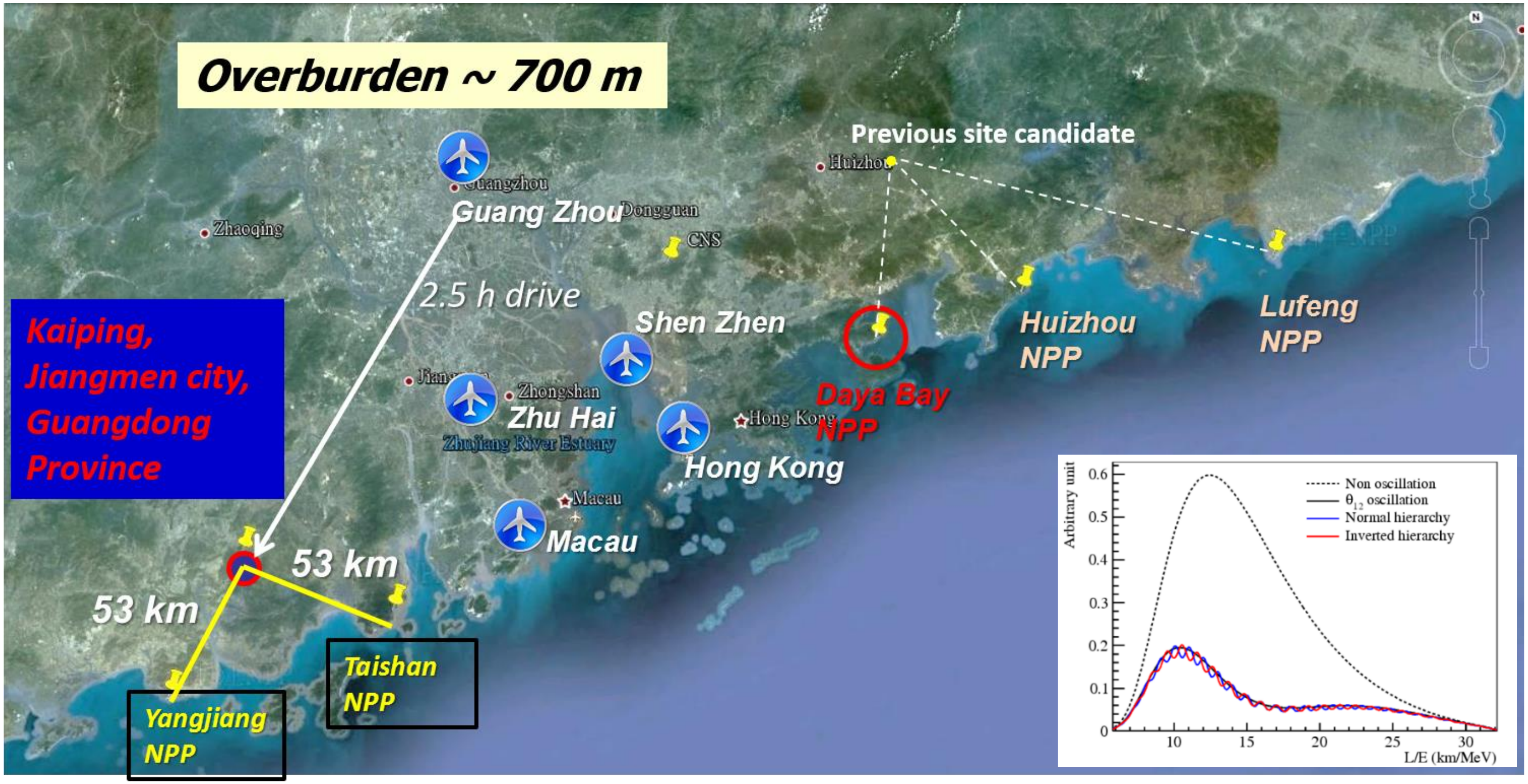
Outline

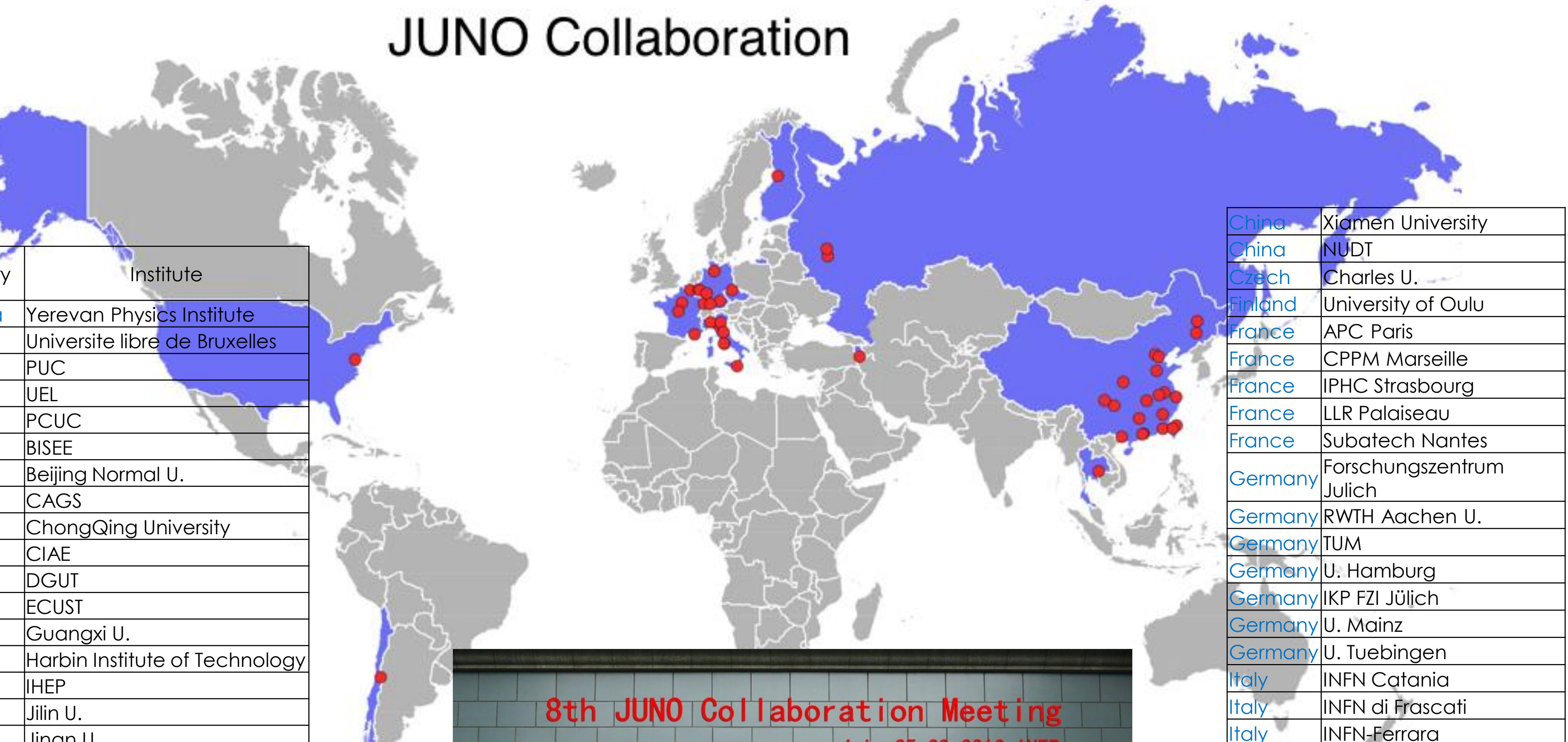
- Introduction to JUNO experiment
- JUNO central detector
- Calibration to the central detector
  - Calibration source design.
  - Calibration source deployment and positioning systems.
  - Strategy for position non-uniformity and energy non-linearity calibration (MC simulation).
- Summary

JUNO experiment

- Jiangmen Underground Neutrino Observatory, in Guangdong Province
- A multiple purpose neutrino experiment, approved in Feb. 2013



JUNO Collaboration



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Russia	MSU
Taiwan	National Chiao-Tung U.
Taiwan	National Taiwan U.
Taiwan	National United U.
Thailand	SUT
USA	UMD1
USA	UMD2

66 institutions，444 collaborators，8 observers

JUNO physics goals and potentials

- 27-36 GW reactor power, 20k ton LS detector (high statistics of inverted beta decay, positron events).
- **$3\%/\sqrt{E(MeV)}$** energy resolution, **<1%** energy scale uncertainty

Rich Physics [a] :

- Reactor neutrinos:

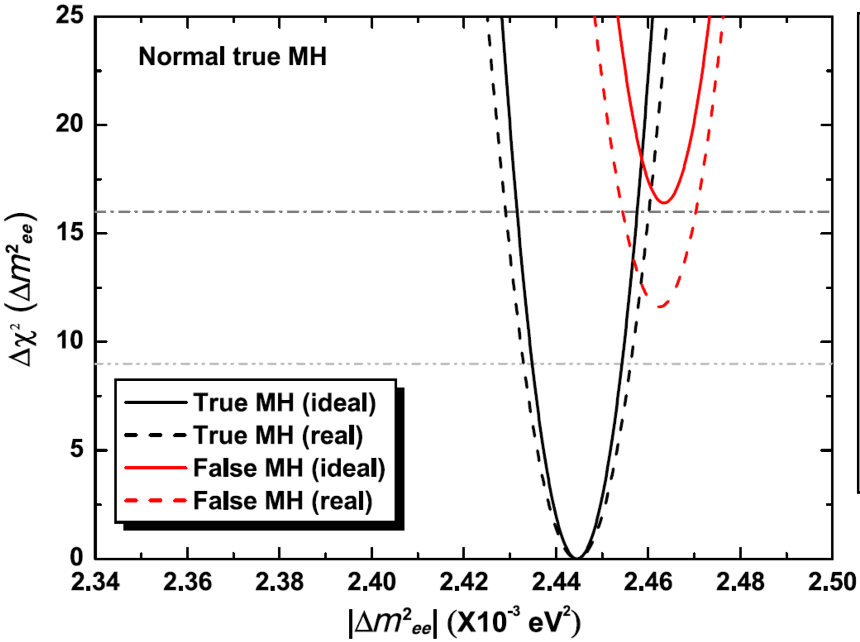
  Mass hierarchy & Precision measurement of mixing parameters
- Supernova neutrinos
- Solar neutrinos, Geo-neutrinos, Atmospheric neutrinos
- Sterile neutrinos and Dark matter searches
- Nucleon decay and other Exotic searches

- [a] Fengpeng An, et al (JUNO Collaboration): J. Phys. G 43 (2016) 030401

Sensitivity on MH

- JUNO's sensitivity with 6 years' data

PRD 88, 013008 (2013)	Relative Meas.	[a]Use absolute Δm^2
Statistics only	4σ	5σ
[b]Realistic case	3σ	4σ



- [a] If accelerator experiments, e.g NOvA, T2K, can measure $\Delta M_{\mu\mu}$ to ~1% level;
- [b] Take into account multiple reactor cores, uncertainties from energy non-linearity, etc.

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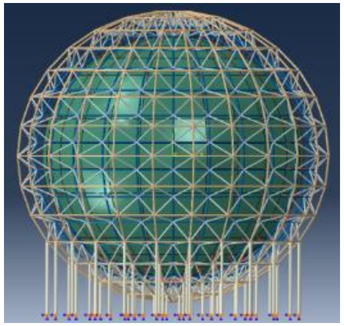
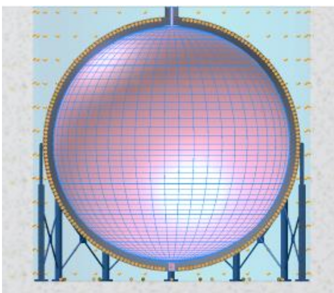
History of the Central Detector Design

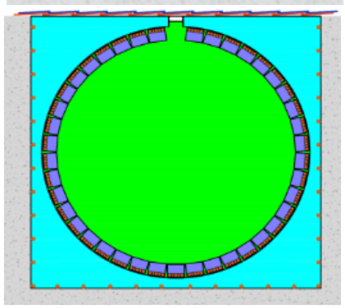
Acrylic sphere+ SS truss



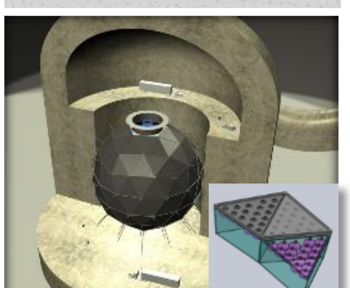
Balloon+ SS tank



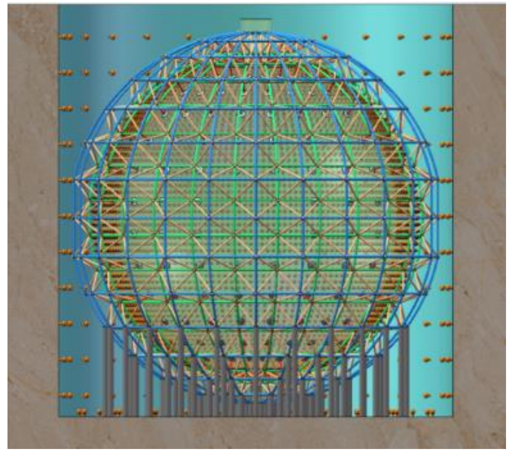
Acrylic module+ SS tank



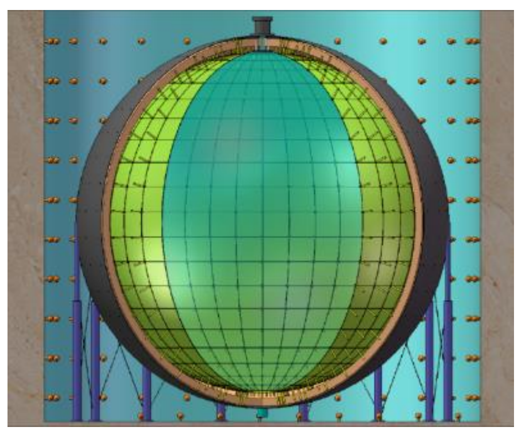
Acrylic sphere+ SS tank



March, 2014

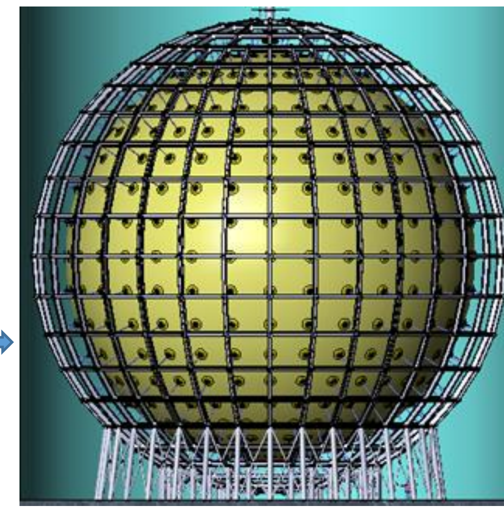


SS truss+ Acrylic sphere

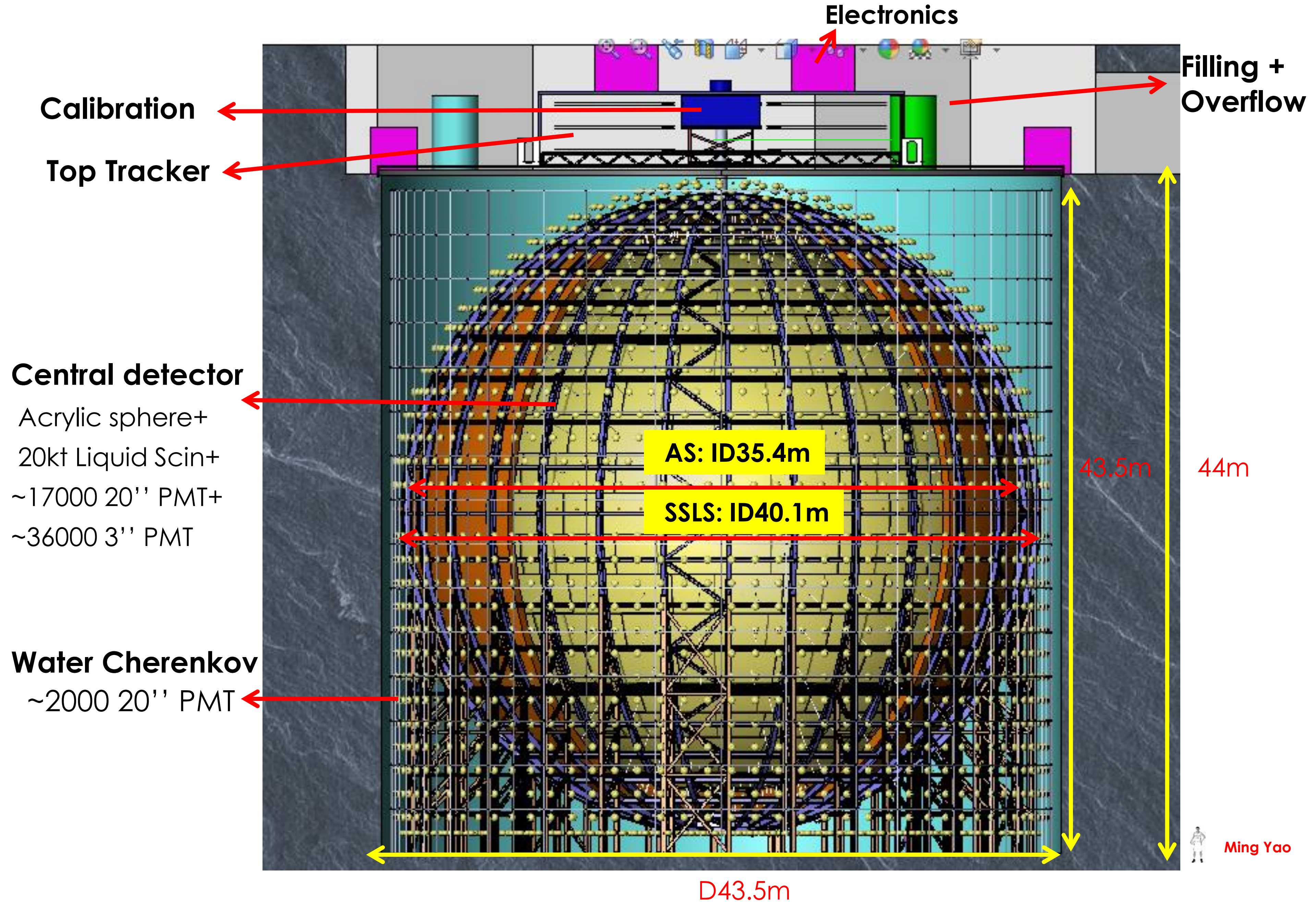


Balloon + Acrylic support+ SS tank

July, 2015



Final decision:
Acrylic sphere + SS truss



AS: Acrylic sphere; SSLS: stainless steel latticed shell

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Calibration source selection:

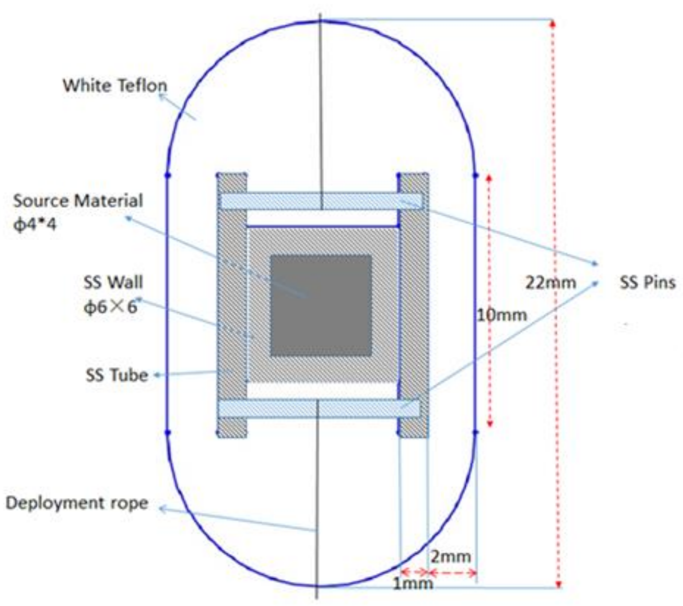
1. Radioactive sources:

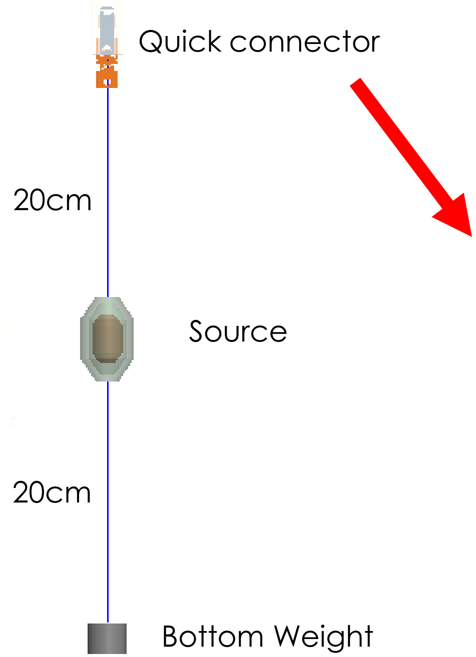
Source	Type	Radiation
^{137}Cs	γ	0.662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	1.173 + 1.333 MeV
^{40}K	γ	1.461 MeV
^{68}Ge	e^+	annil 0.511 + 0.511 MeV
^{22}Na	e^+	annil + 1.275 MeV
^{40}K	e^-	0~1.31 MeV
^{90}Sr	e^-	0~2.28 MeV
^{241}Am-Be	n, γ	neutron + 4.43 MeV
^{241}Am-^{13}C or ^{241}Pu-^{13}C	n, γ	neutron + 6.13 MeV
^{252}Cf	multiple n, multiple γ	prompt γ's, delayed n's

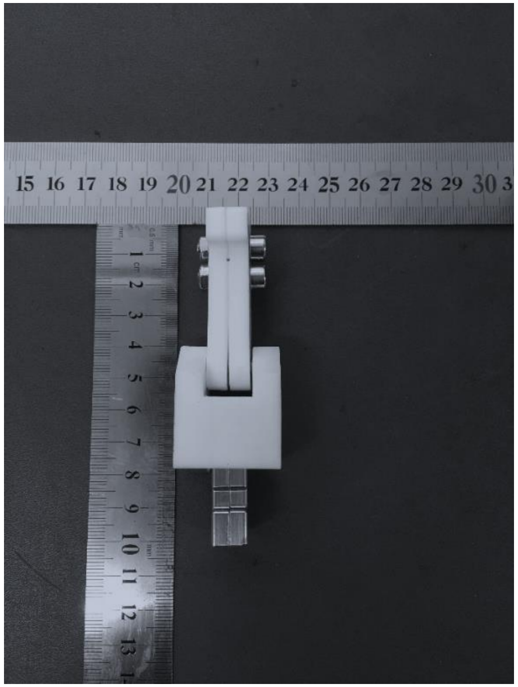
2. Optical source: fast Laser (ns) /LED + Fiber + Diffuser

Radioactive source enclosure (γ and neutron)

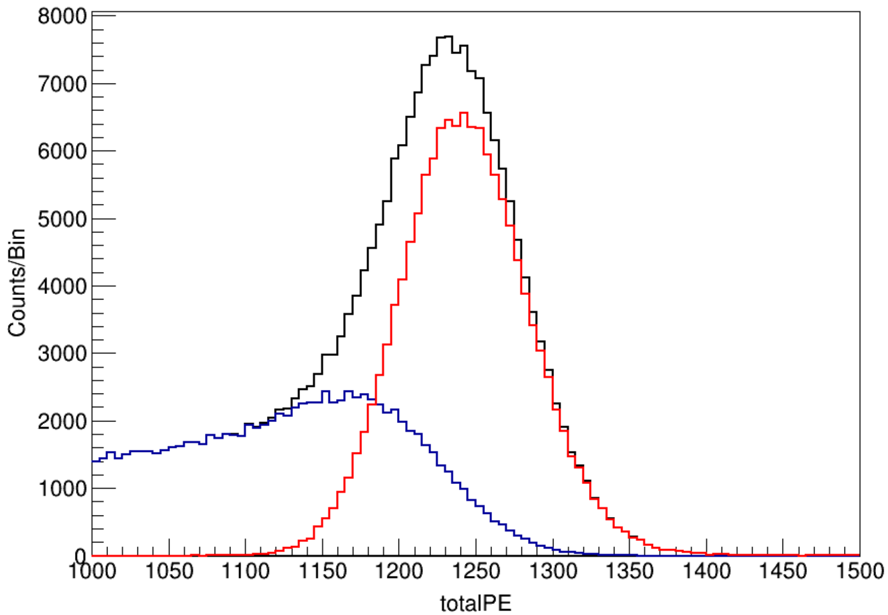
- Main issues: the shadowing effects (more important) and the energy loss on the dead volume (less important);
- Solution: make the source to be small (generic SS enclosure Ø6×6 mm is possible) and with highly reflective surface





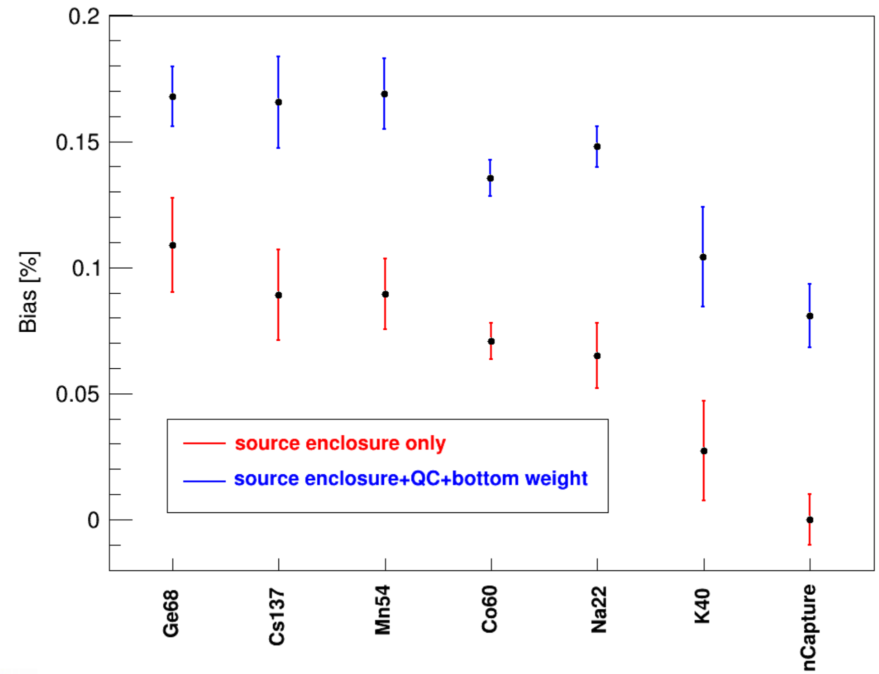


Bias of full abs peak due to enclosure (MC)



- Full absorption peak determine: Compton edge + Gaussian fitting

$$Bias = \frac{Mean(enclosure) - Mean(naked)}{Mean(naked)}$$



- Bias due to the enclosure <0.2%

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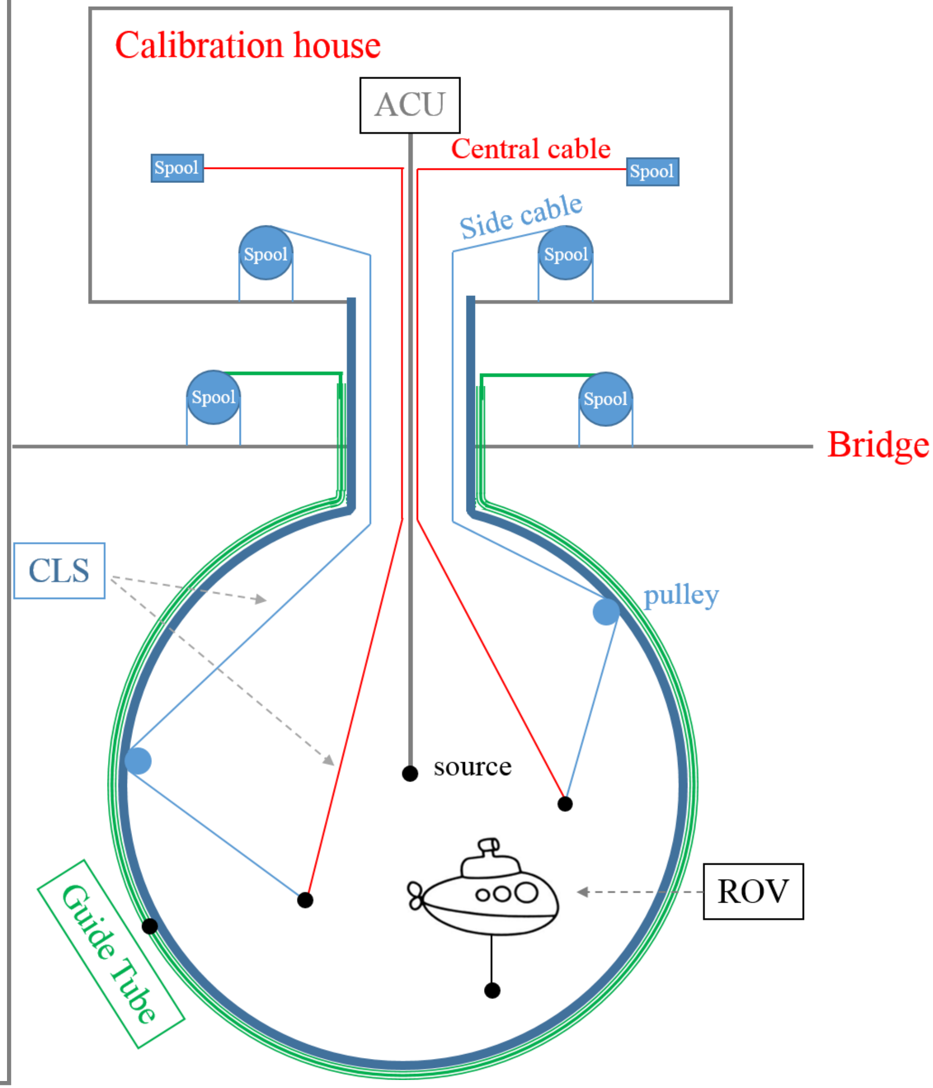
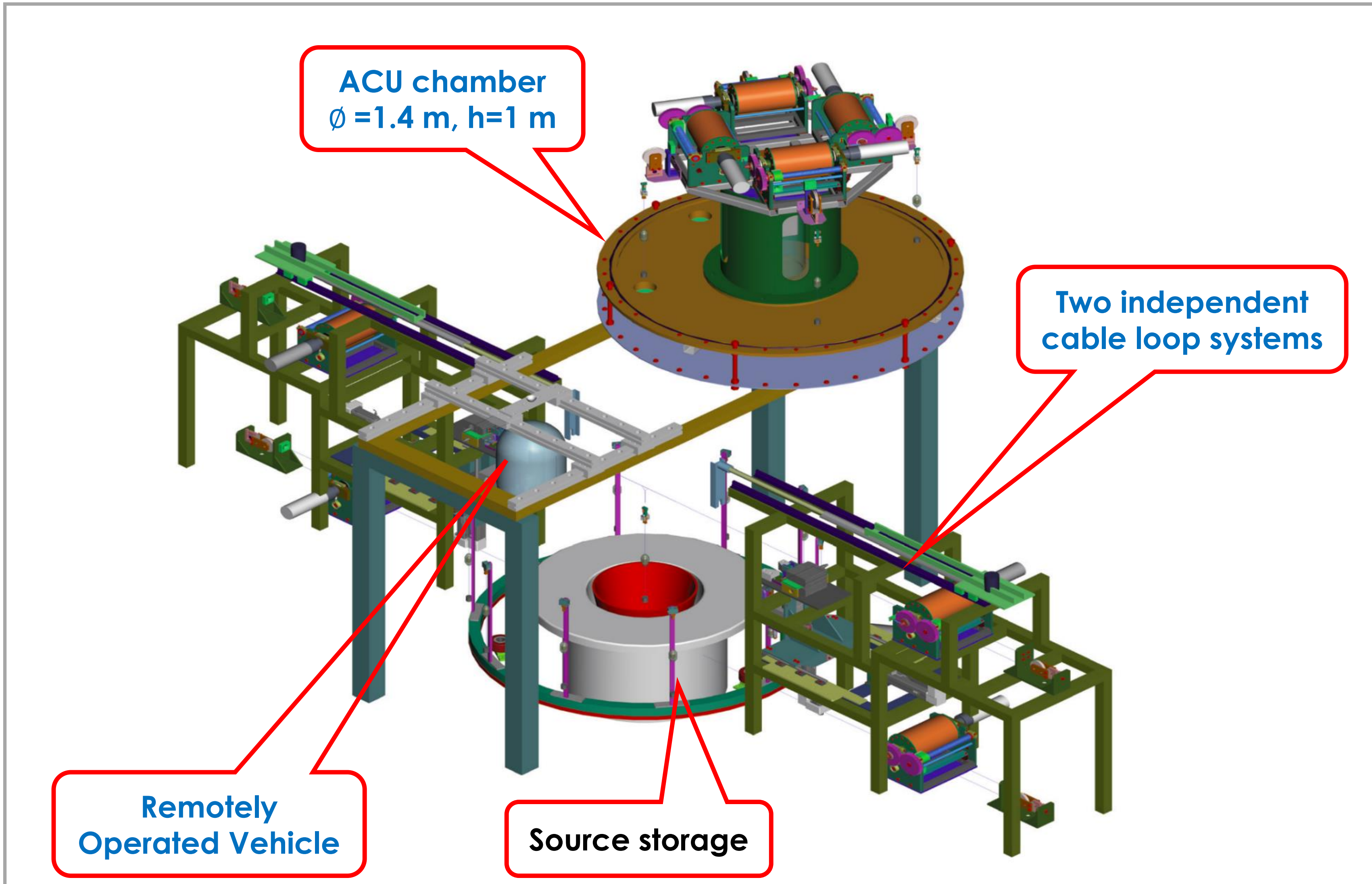
Overview of source deployment systems

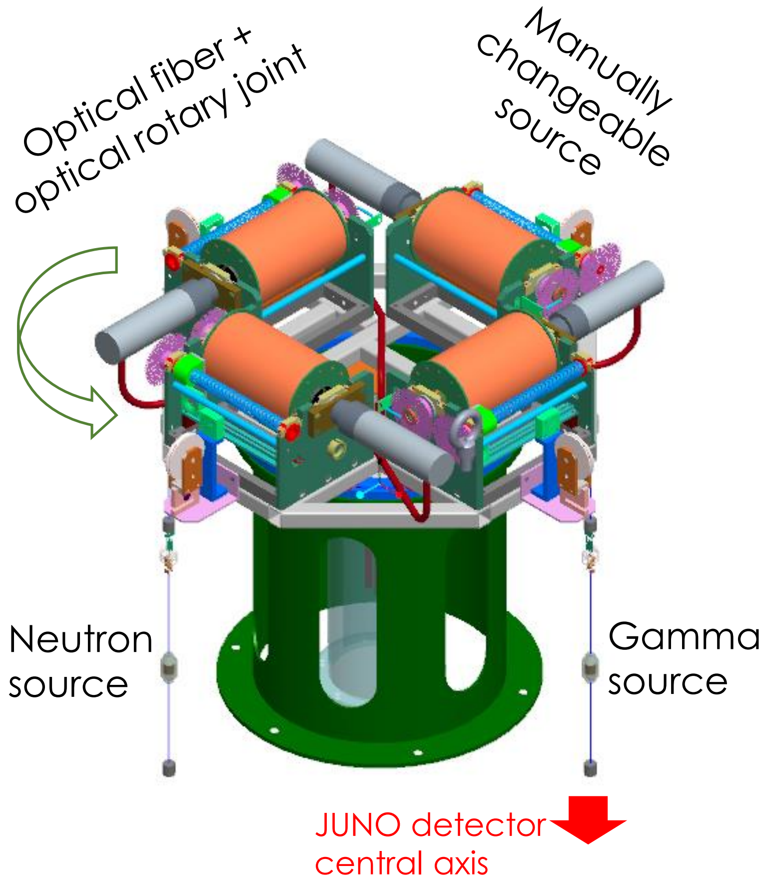
- Internal source deployment:
  - ➢ Automatic Calibration Unit (ACU)
    - Scan the central axis (1D)
  - ➢ Cable Loop System (CLS)
    - Scan one vertical plane (2D)
  - ➢ Remotely Operated Vehicle (ROV)
    - Scan "everywhere" (3D)
- External source deployment:
  - ➢ Guide Tube (GT)
    - Scan CD outer surface (boundary)

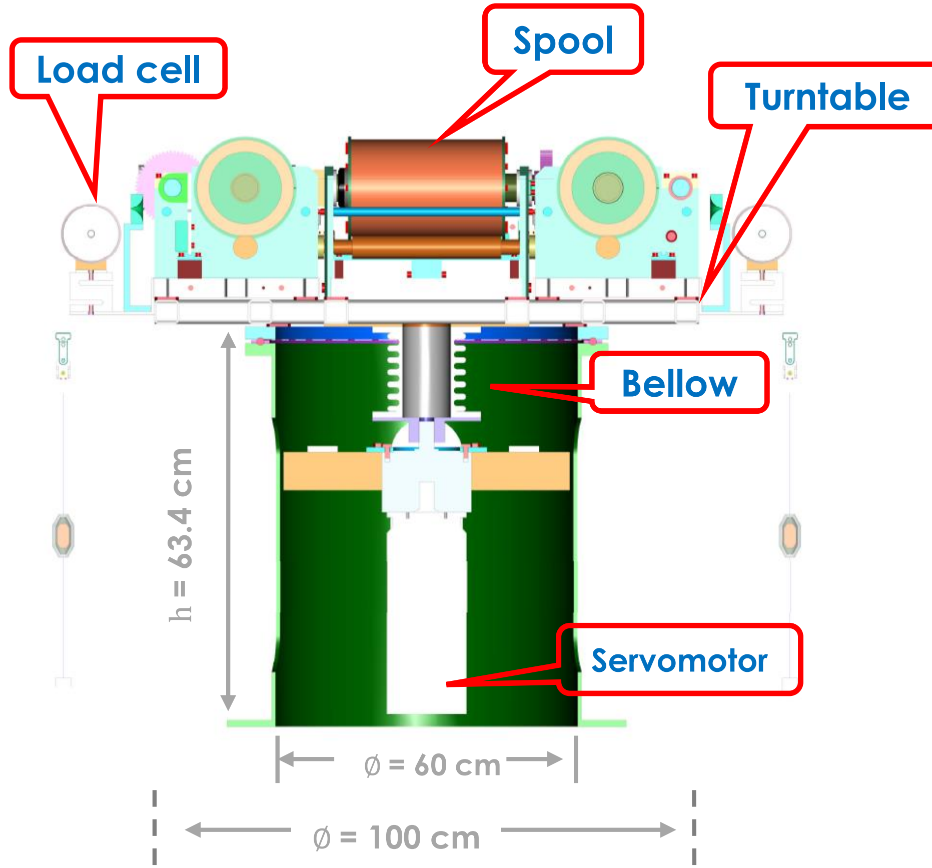


Overview of Internal Source Deployments



Design of ACU





- Regular deployment (every week)， very similar to Daya Bay’s design
- Deployment of radioactive and optical source along the central axis
- The rotation motor: 100 rpm (100:1), and the deployment motor: 20 rpm (10:1)

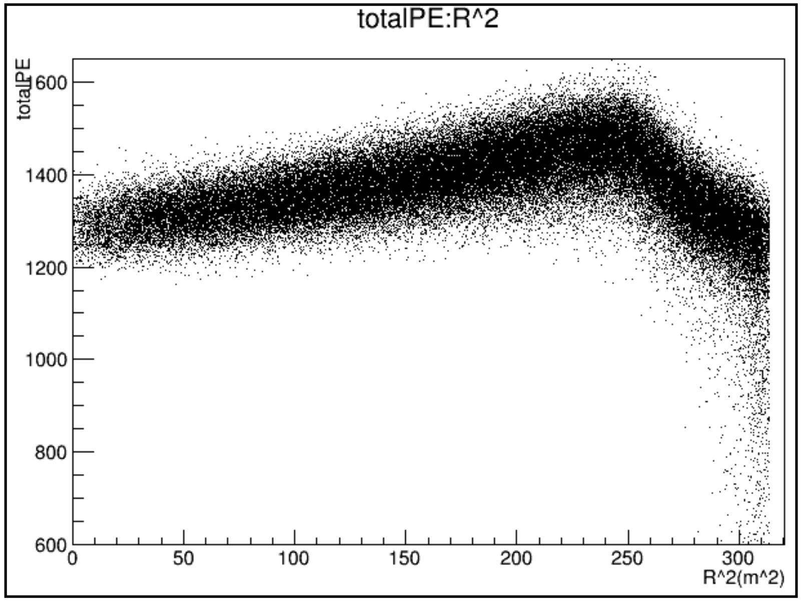
Cable loop system (CLS)

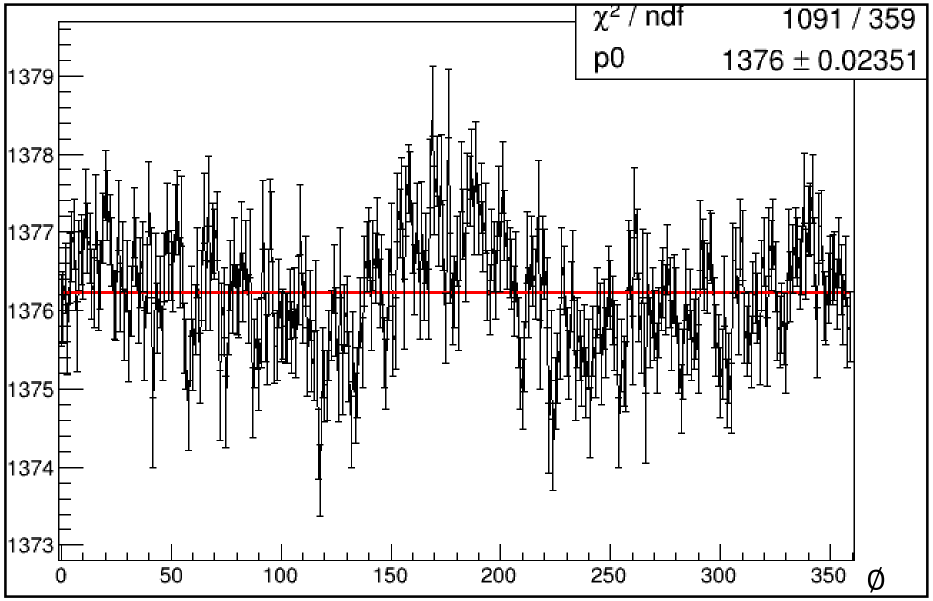
- The central detector has obvious non-uniformity, especially at large R;

⇒ very necessary to scan the position at large R (CLS is needed)

- MC simulation found that the detector has good symmetry in ø (ROV can be used to calibrate the detector's response in ø);

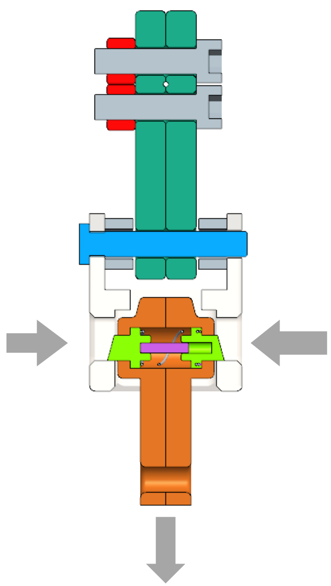
⇒ plate scanning can be extended to whole volume (CLS is meaningful)



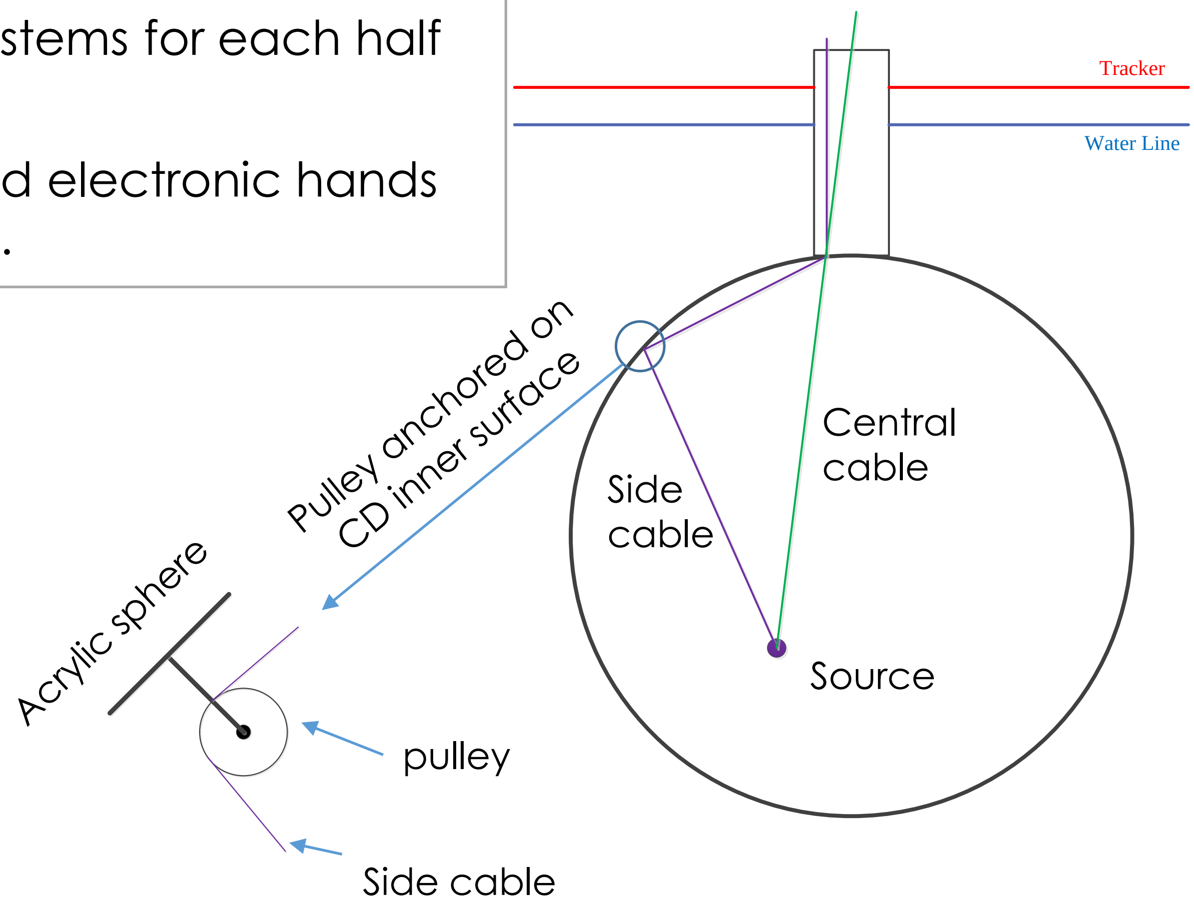


Cable Loop System

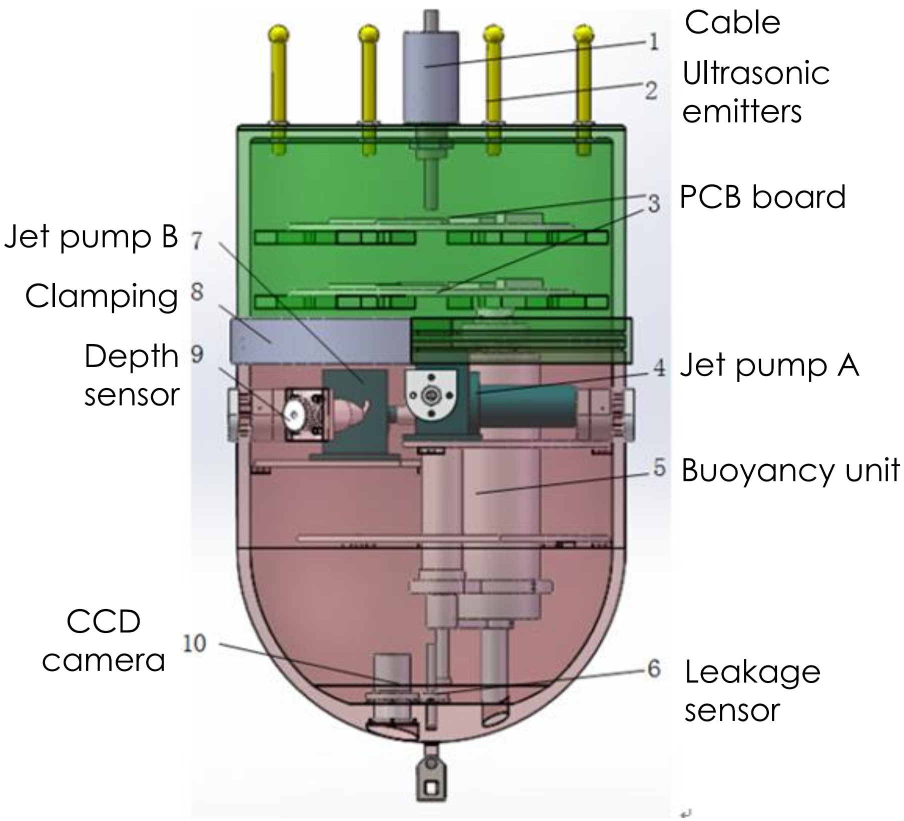
- Scan the off-center plane (every month);
- Two independent systems for each half plane scanning;
- Quick connector and electronic hands for source changing.



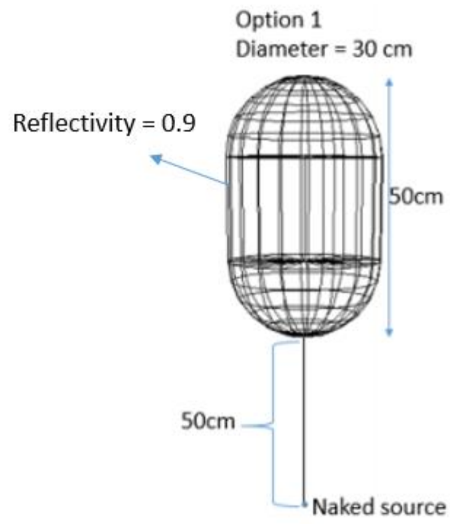
Quick connector

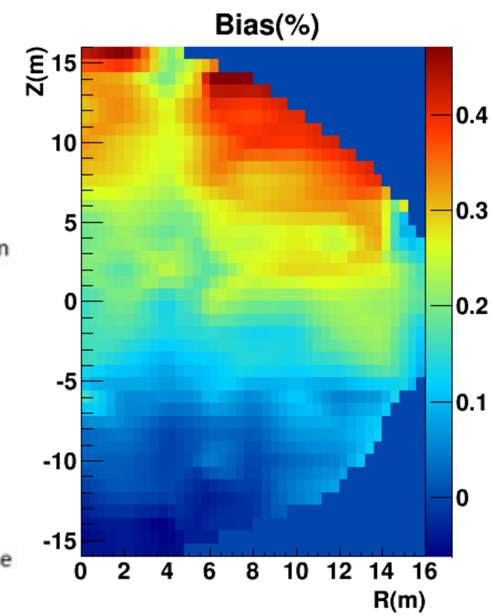


Overview of the ROV design (section view)



Horizontal: two orthogonal jet pumps
Vertical: buoyancy device



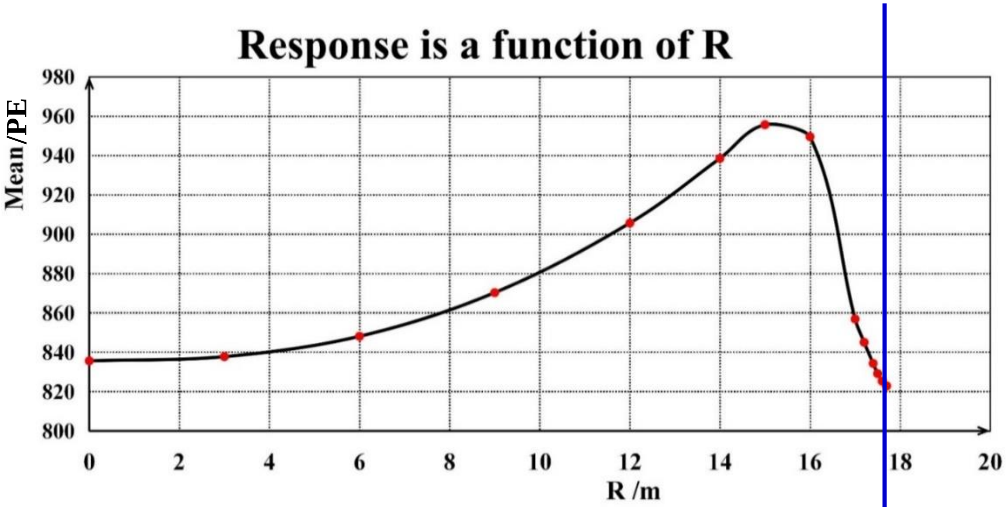


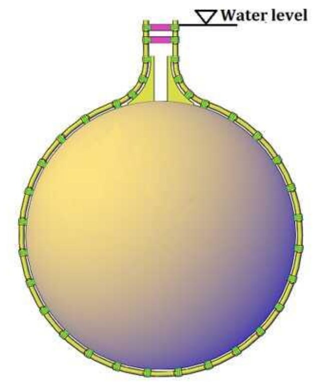
- Computed several ROV shapes, difference insignificant (everywhere source!)
- No deployment cable in the model yet
- Full volume bias is ~0.3%

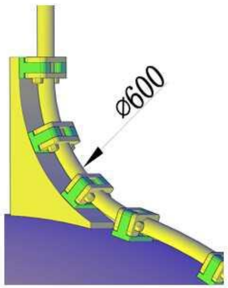
Guide Tube for boundary study

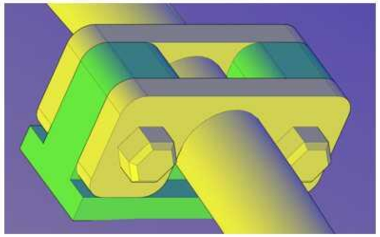
Boundary Effect:

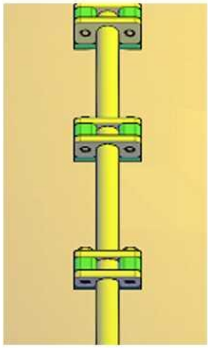
- Calibration in the area that ACU, CLS and ROV can not reach.
- Neutron Spill in/out effect study





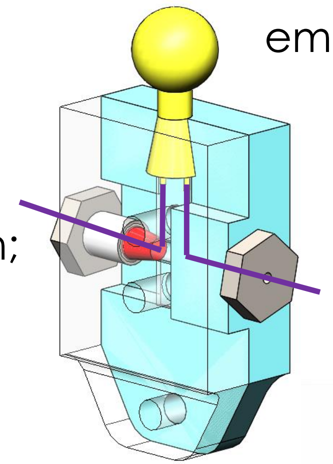




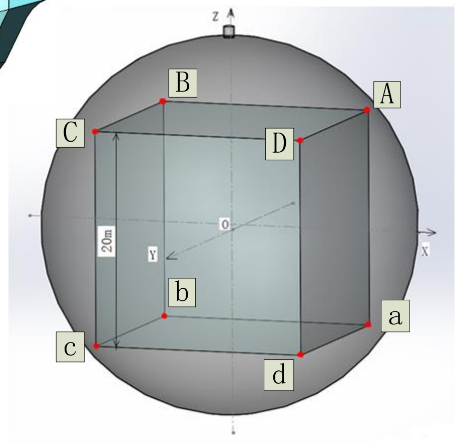


Source positioning system

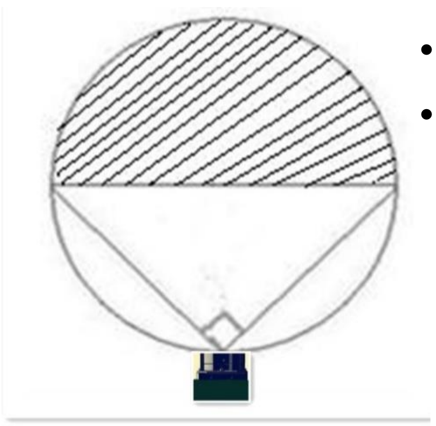
- Ultrasonic positioning system (primary):
  - Serves for both ROV and CLS;
  - Ultrasonic emitter and receiver array (150 kHz);
  - Time of flight method to reconstruct the position;
  - Positioning error <30 mm, positon resolution better than 5 mm.



receivers



- Infrared CCD monitor/positioning system:
  - Active infrared light source (940 nm);
  - Infrared CCDs take pictures for position reconstruction.



- Ultrasonic works as the primary and CCD as assistant (monitoring).

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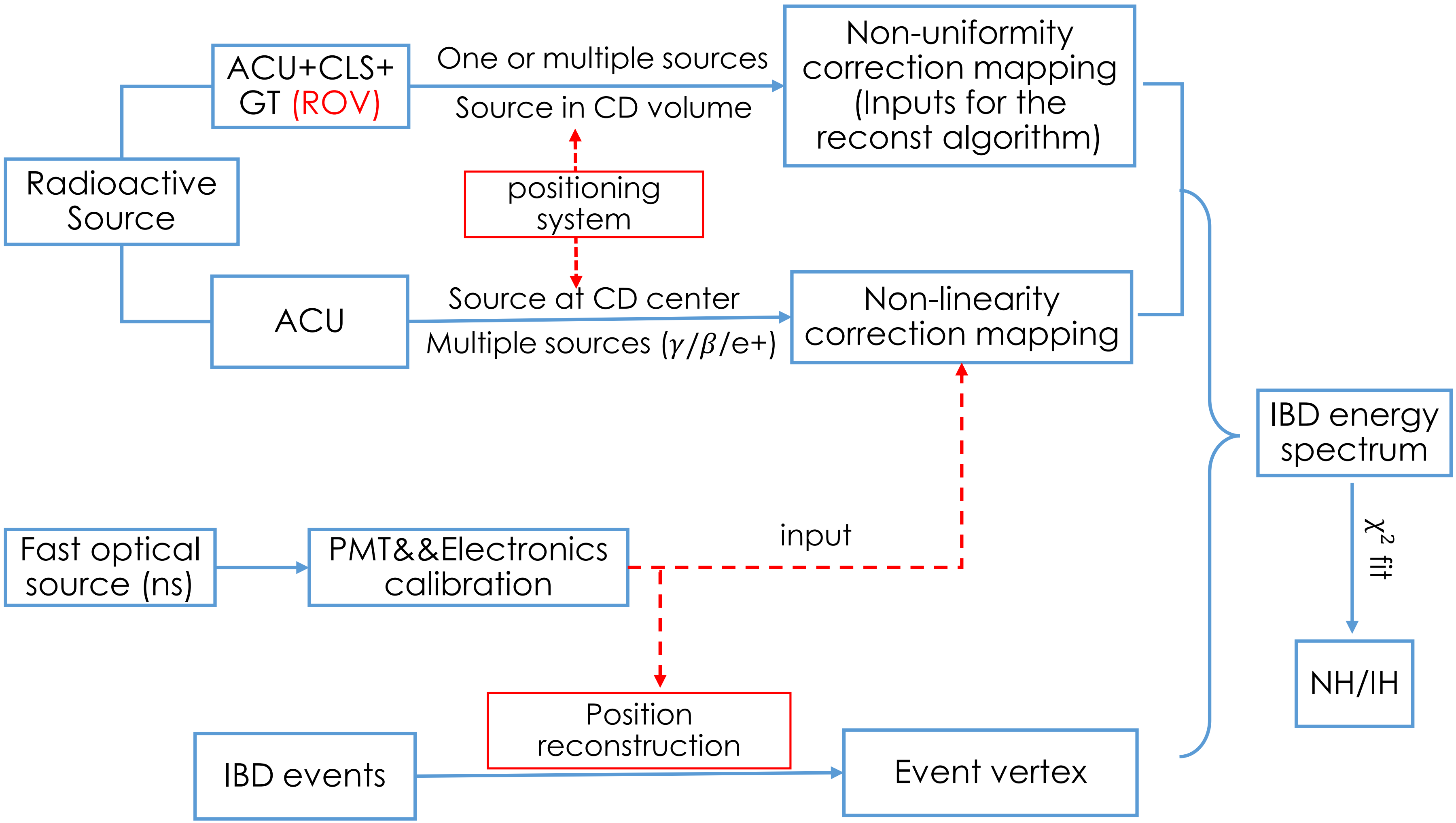
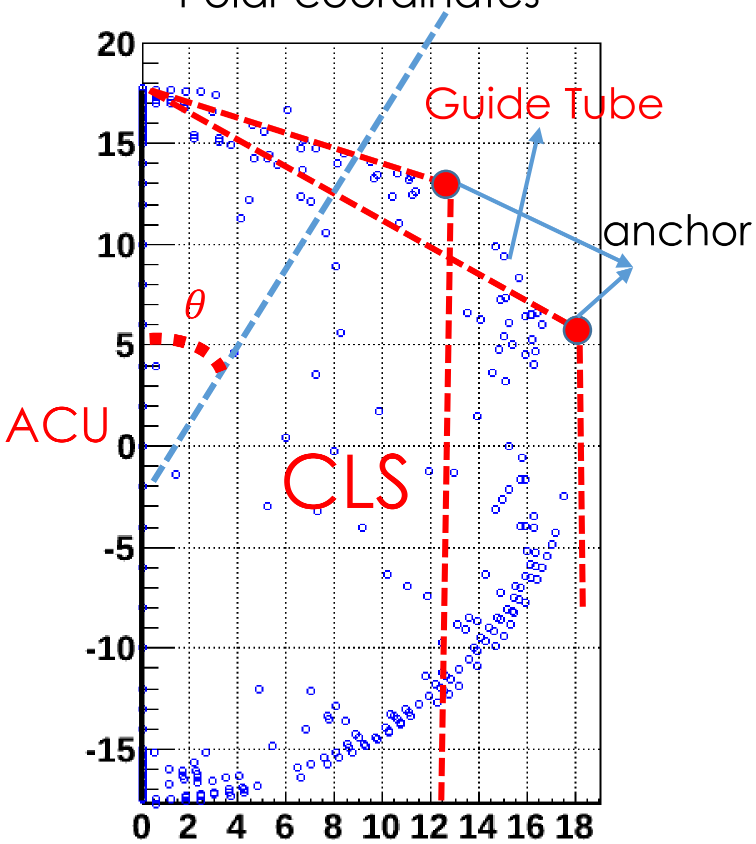
Overview of JUNO calibration strategy (Preliminary)

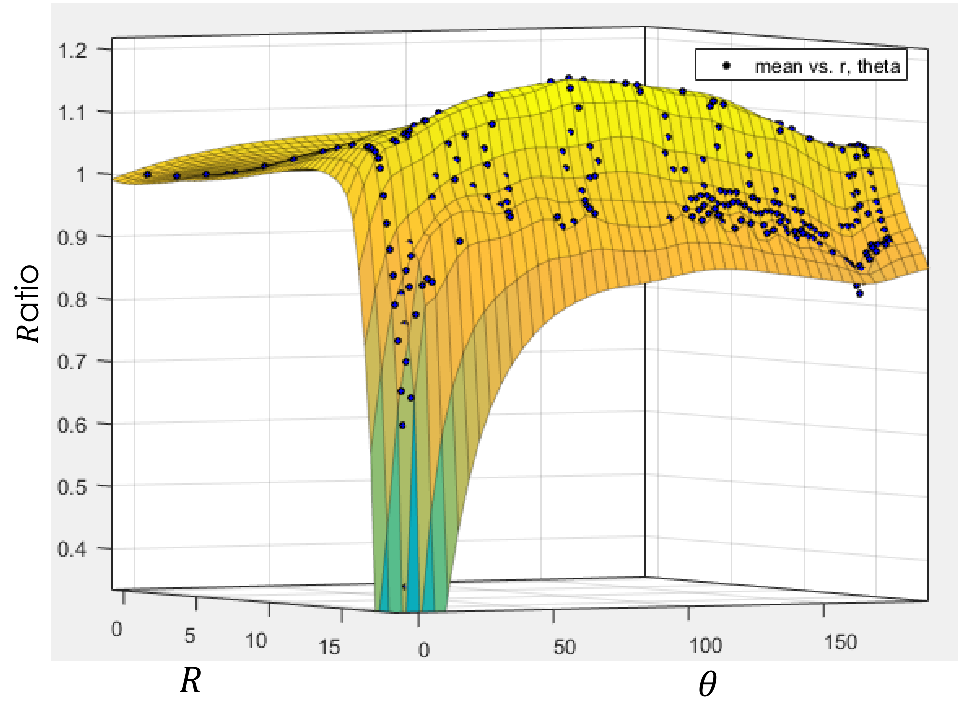


Non-uniformity correction with ACU/CLS/GT



~266 calibration positions

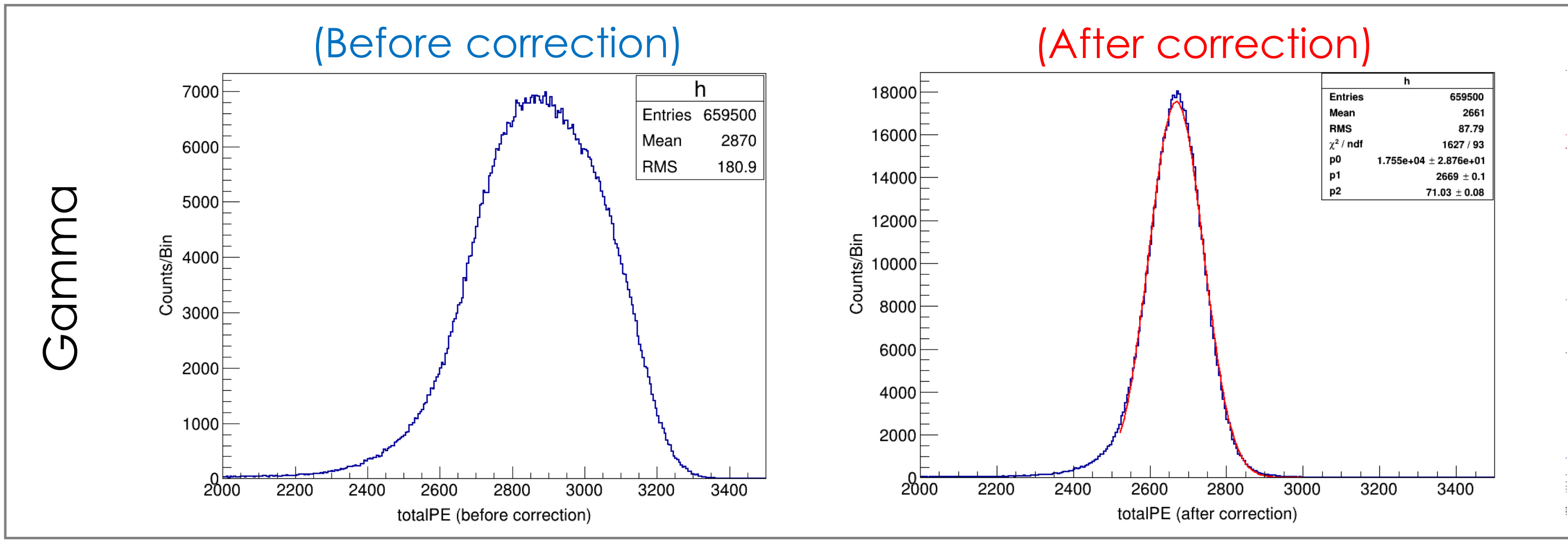
Ratio to center as function of R and θ
Fit it with spline function to get $f(R,\theta)$

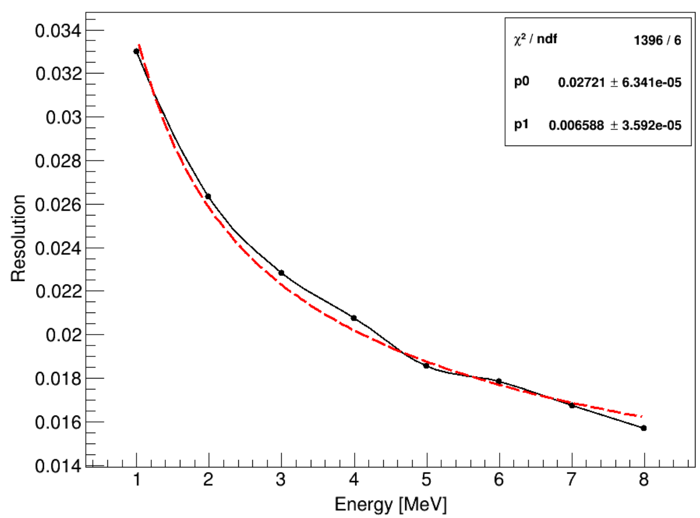


$f(R,\theta)$ mapping for position non-uniformity correction: (Co60, 100 Hz and 5-mins data taking).

Non-uniformity correction for gamma events

- Uniformly distribute mono-energy gamma events in CD;
- Correct every event to the center of the detector.





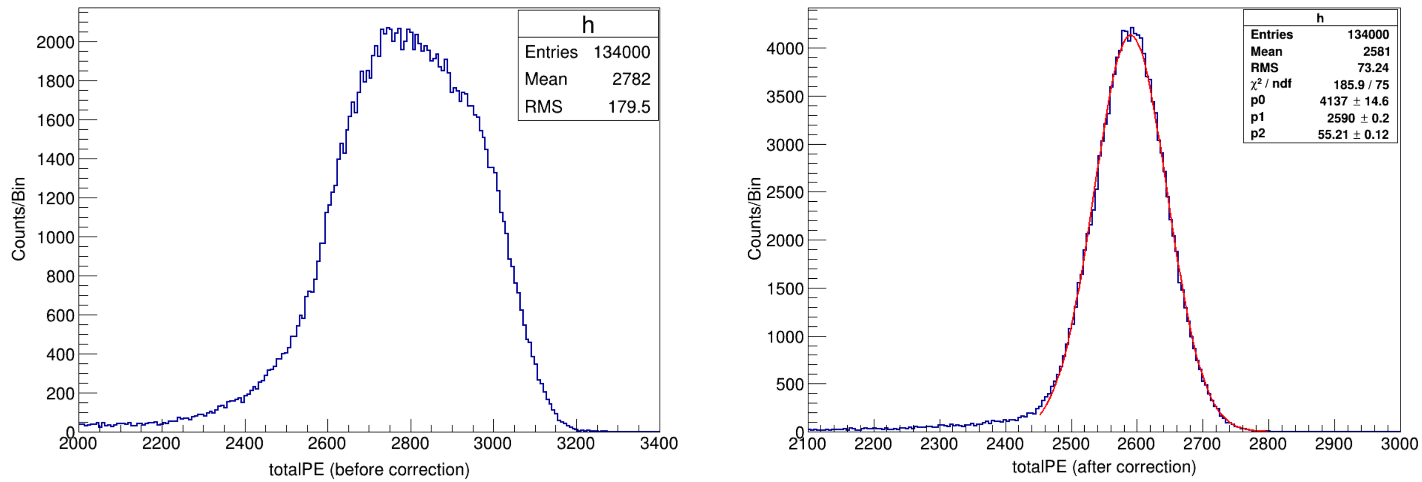
- Energy resolution improves significantly after the position non-uniformity correction.
- Energy resolution follows $\propto \frac{1}{\sqrt{E}}$

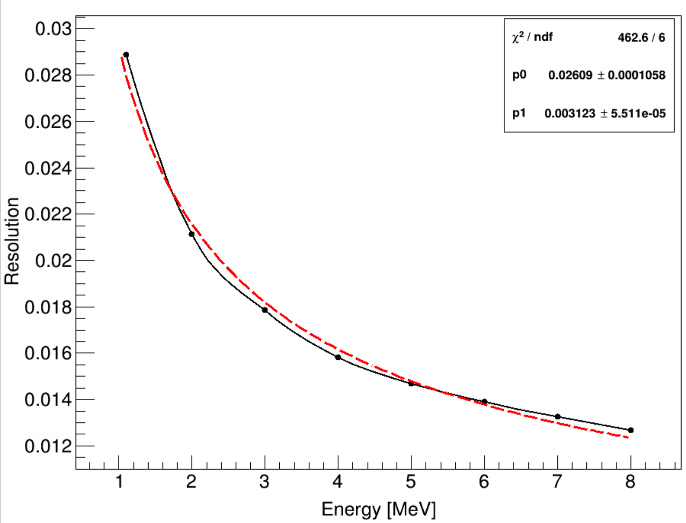
Non-uniformity correction for positron events

- Same correction mapping is applied to positron events

Positron

(Before correction) (After correction)

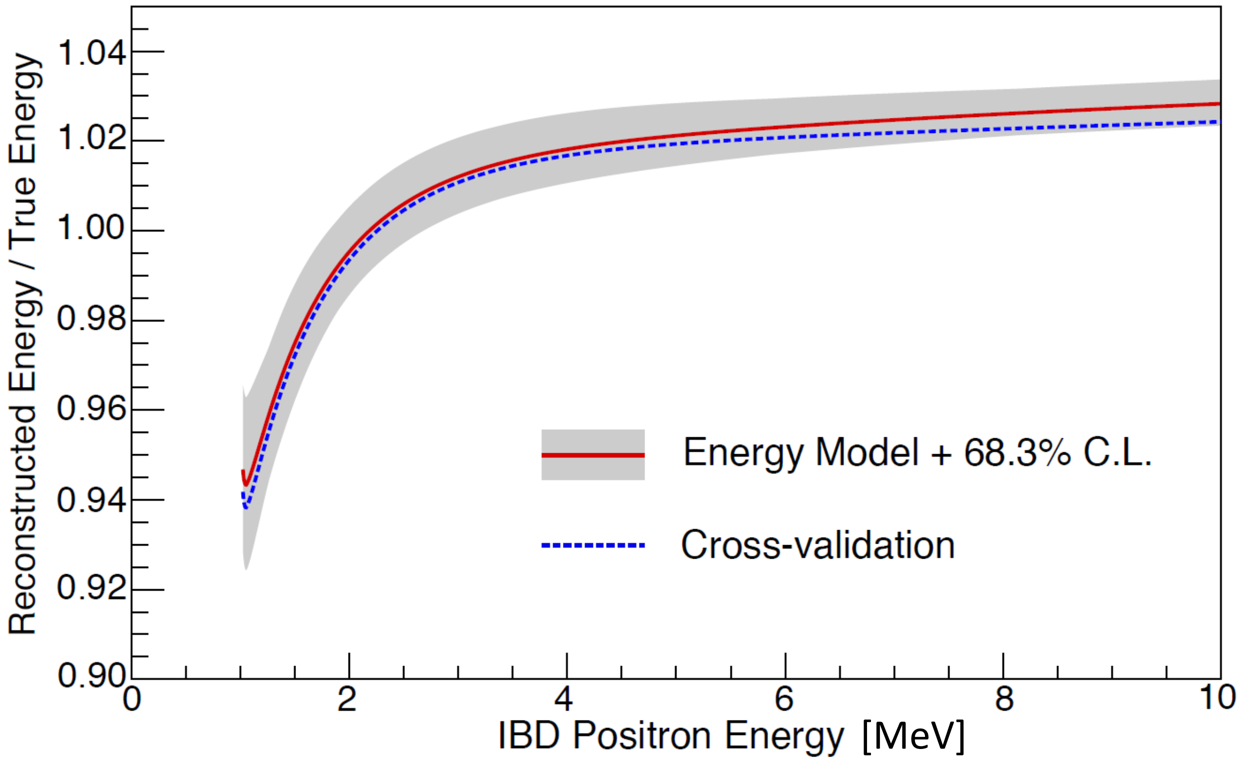




- It's possible to use a single source (Co60) to correct the detector's non-uniformity and reach a good energy resolution (**3%/√E**)!
- Source change system makes it possible to use multiple sources

Positron energy non-linearity

- Positron E non-linearity in Daya Bay experiment [a]:
  - Most energy scale uncertainty at the low energy region



- [a] Daya Bay Collaboration: arXiv:1610.04802 [hep-ex]

JUNO Energy non-linearity calibration

Approach-1:

- Based on the gamma energy calibration, use gammas as workhorse to nail e+ nonlinearity.

Nonlinearity (γ) = PDF (γ-to-electron) x Nonlinearity (electron)

Approach-2:

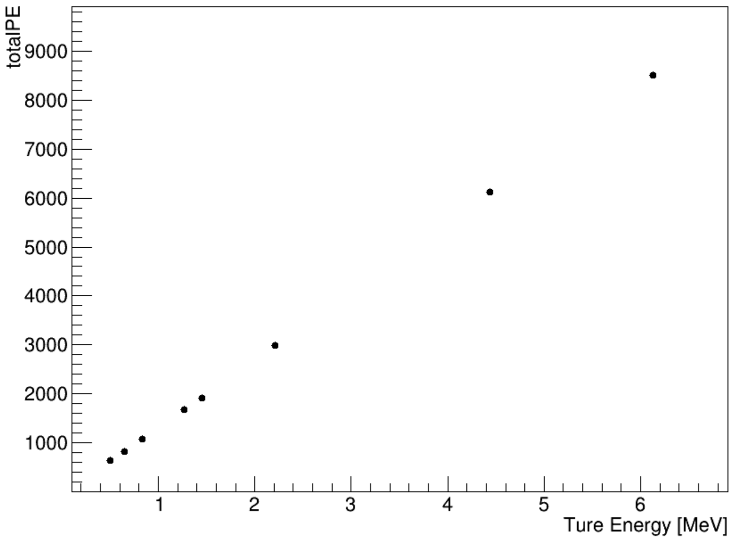
- Develop the special "windowless" source;
- Locate positron (^{68}Ge, ^{22}Na) and beta sources (^{40}K, ^{90}Sr) at the detector center with ACU and get the detector's response in PE spectrum;
- Based on the MC, fit the PE spectrum and extract the parameterized function between PE and deposited energy;
- Reconstruct the electron energy with the parameterized function;

Two methods can be crosschecked with each other!

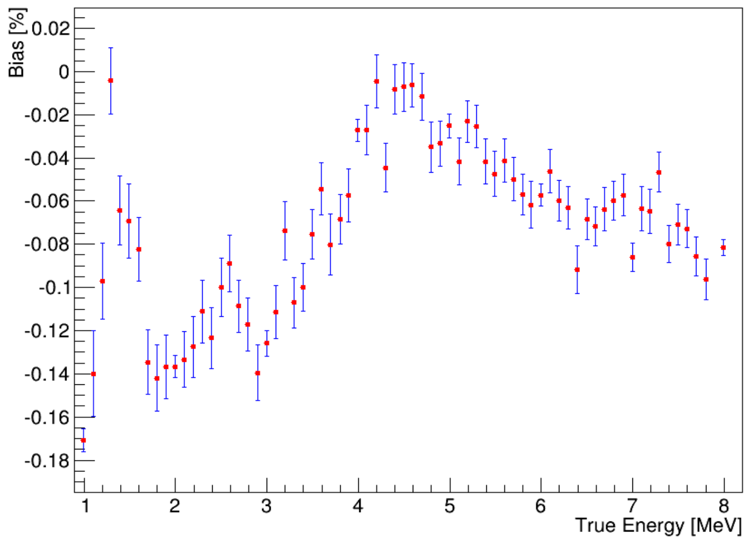
Gamma energy non-linearity calibration

- Locate various gamma (^{137}Cs, ^{54}Mn, ^{40}K)、electron (^{68}Ge, ^{22}Na) and neutron sources ($^{241}AmBe$, ^{241}Am-^{13}C or ^{241}Pu-^{13}C) at the detector center with ACU;
- Study the detector's response to different gamma energies (0.511, 0.662, 0.835, 1.275, 2.22, 1.46, 4.43, 6.13 MeV) ;
- Reconstruct the gamma energy with the spline fitting.

Detector's response to gamma energies

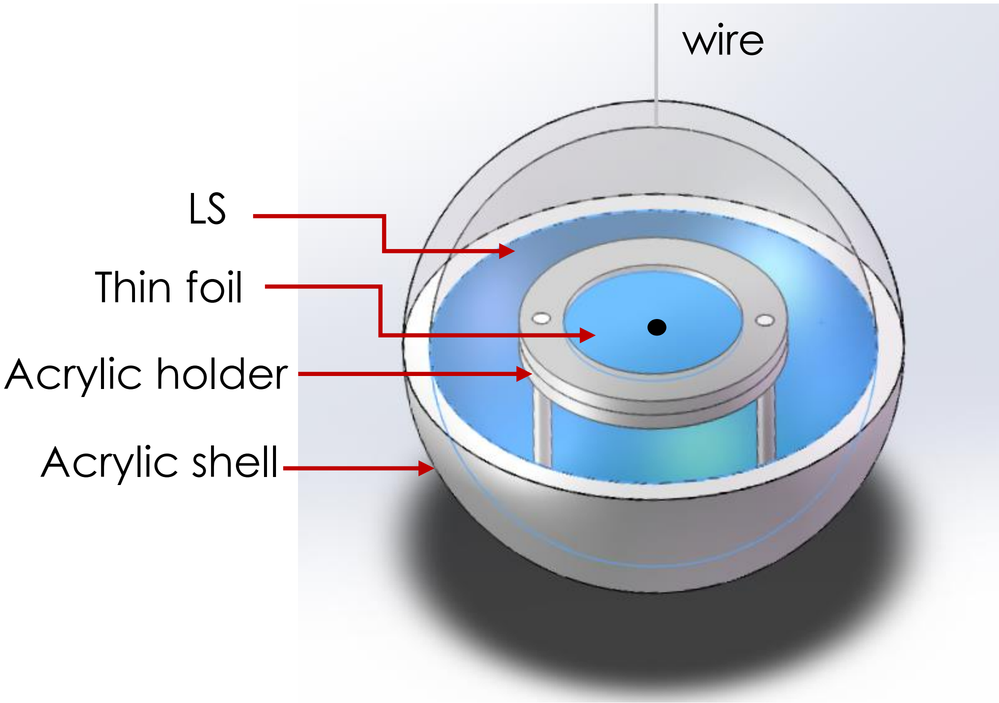


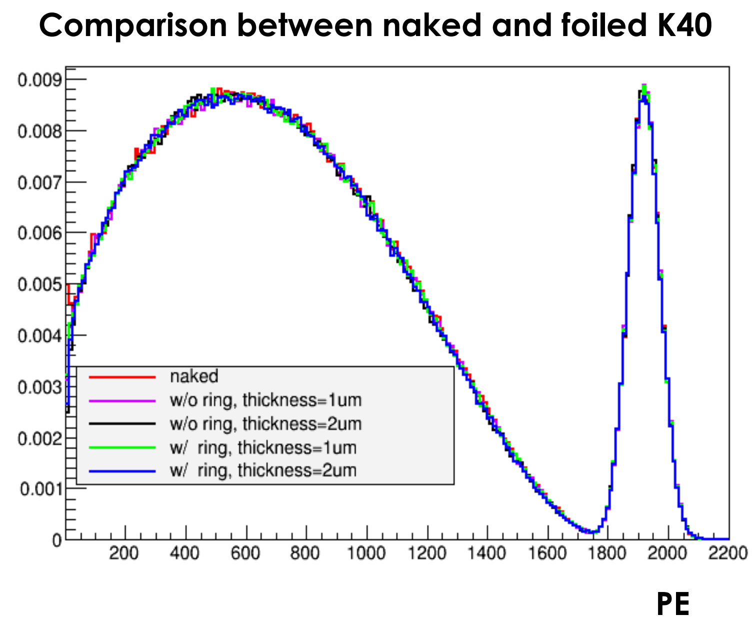
Bias of the reconstructed gamma energy



The bias is less than **0.2%** in MC (assuming 100 Hz event rate and 30-min data taking as well as 5-cm reconstruction resolution).

Special e^+/e^- source consideration: foil source





Key points:

- Very thin foil (can be 1~2 μm): introduce the neglectable energy loss for electrons;
- High optical transparency source enclosure (acrylic): small shadowing effect.

Looks quite promising to achieve <1% energy scale uncertainty.

Summary

- JUNO is a multiple purpose project and will measure the neutrino mass hierarchy (3-4 σ in 2026).
- The design of the central detector is finalized and construction and R&D are on schedule.
- Energy resolution and scale uncertainty are the key to mass hierarchy measurement.
- With the MC simulation, the current calibration strategy should allow us to achieve $3\%/\sqrt{E}$ energy resolution and $<1\%$ energy scale uncertainty.

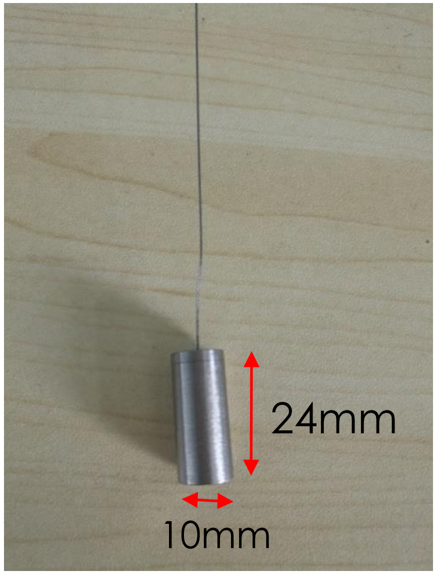
Thank you!

Backup slides

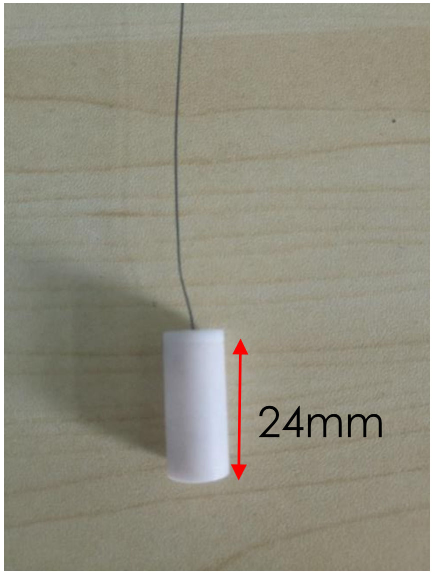
Source enclosure test in the prototype detector

Naked source

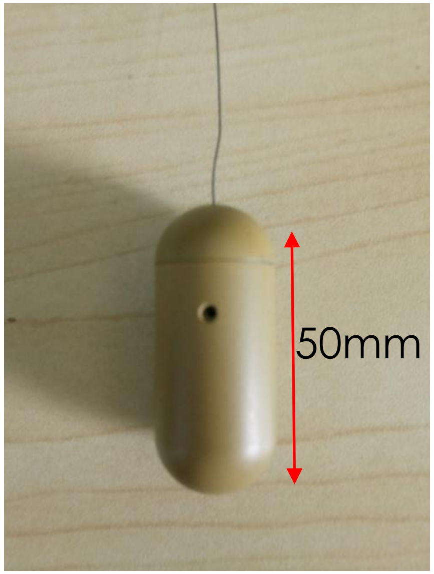
Steel enclosure



Teflon enclosure



Daya Bay enclosure



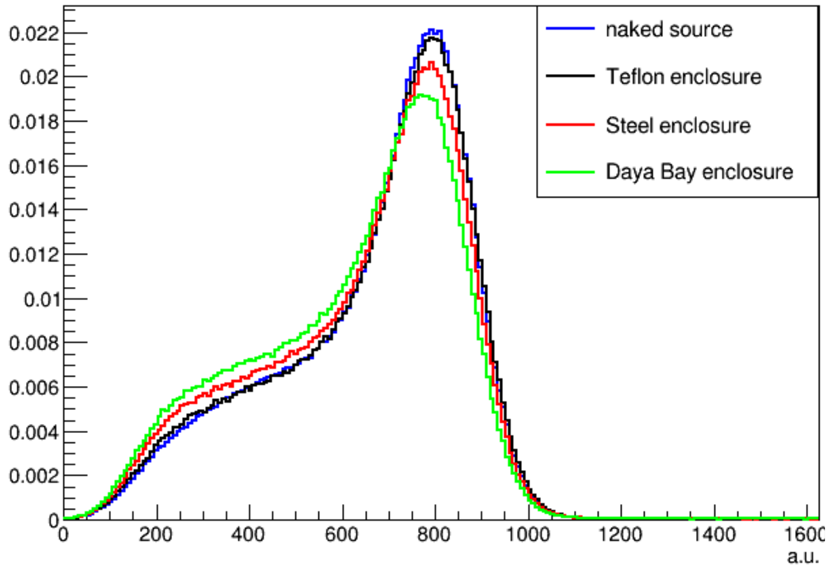
Co60: 4π, 6×6mm

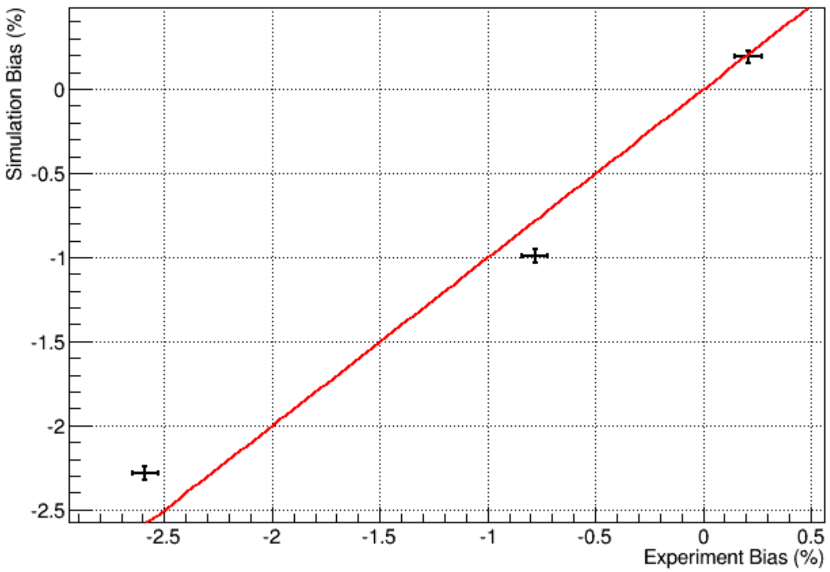
Cs137: 2π, 3×5×10mm

Bias introduced by the source enclosure (data)

Spectrum for Cs137

$$bias = \frac{mean(enclosure) - mean(naked)}{mean(naked)}$$



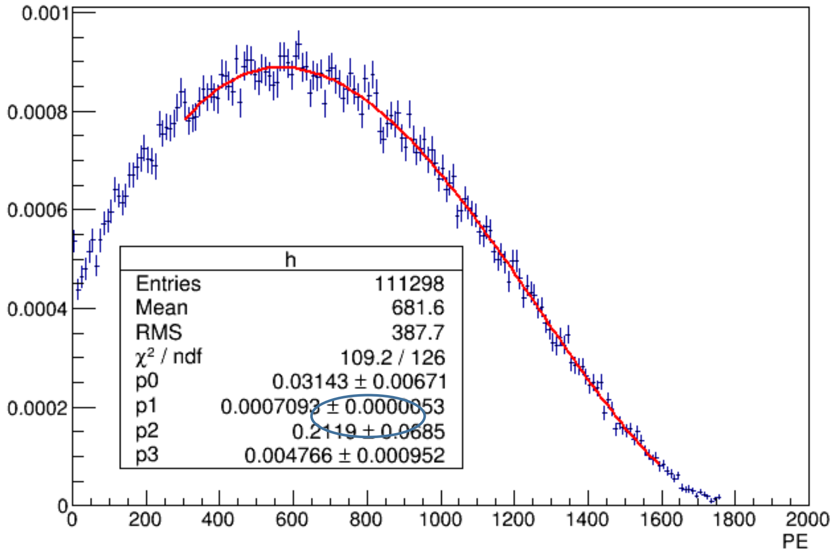


	Naked	Teflon enclosure	Steel enclosure	Daya Bay enclosure
Mean (**MC**)	790.4(0.2)	791.9(0.2)	782.6(0.2)	772.4(0.2)
Bias (%) (**MC**)	0	+0.19(0.04)	-0.99(0.04)	-2.28(0.04)
Bias (%) (**Measurement**)	0	+0.21(0.006)	-0.78(0.006)	-2.59(0.006)

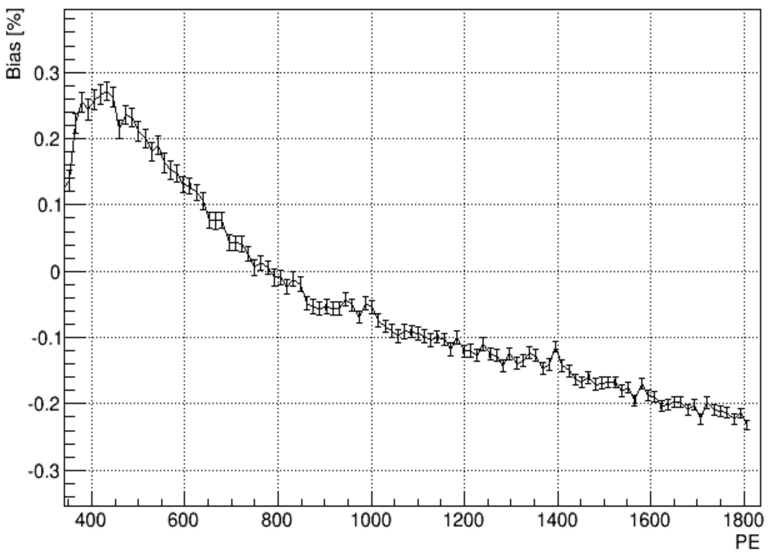
Energy bias with foil beta source (preliminary)

- Energy response: $E = f(PE) = \frac{p_0 + p_1 \cdot PE}{1 + p_2 \cdot e^{-p_3 \cdot PE}}$

K40 PE spectrum fitting



Bias of the reconstructed energy



It's very promising to achieve less than 1% energy scale uncertainty