KATRIN: Directly Measuring the Neutrino Mass

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for the KATRIN Collaboration

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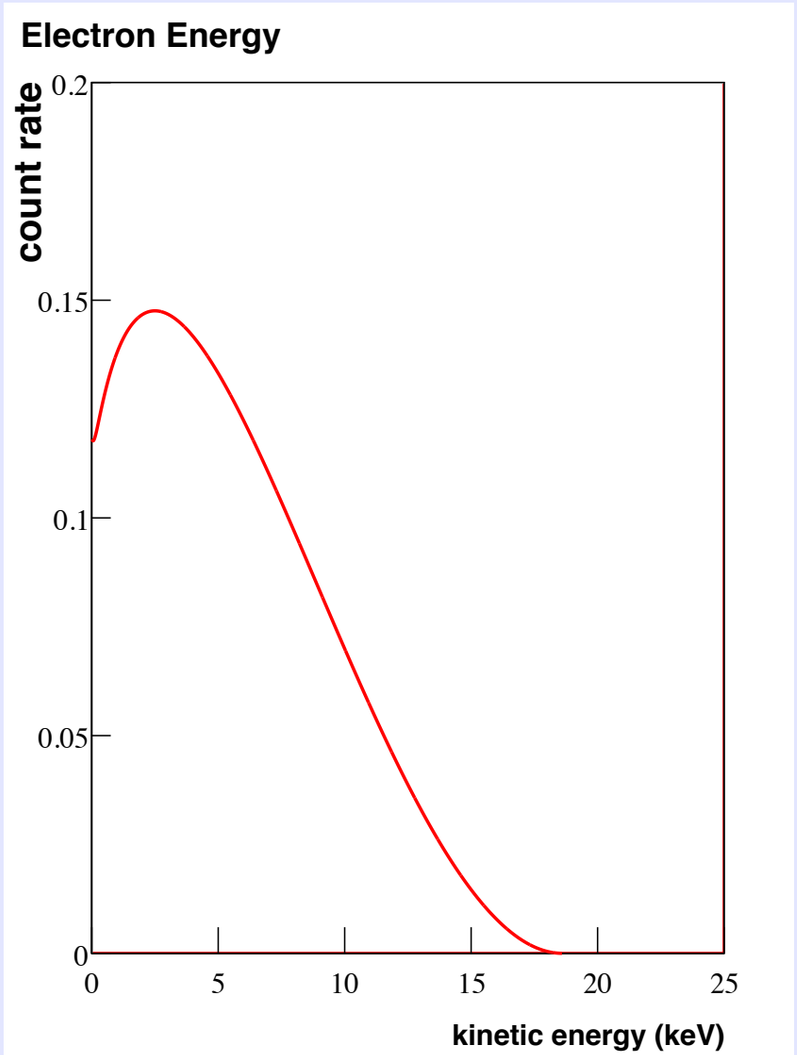
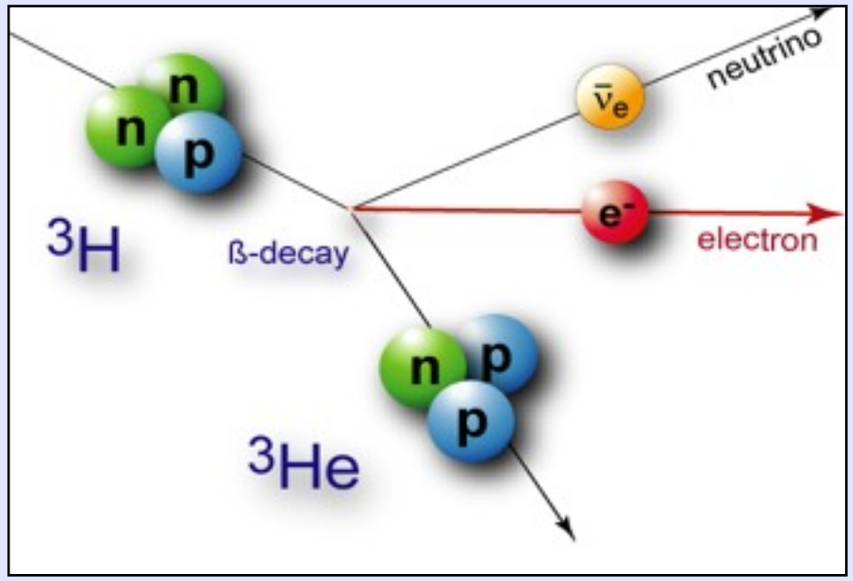
Laboratory for Nuclear Science

Determining the Neutrino Mass



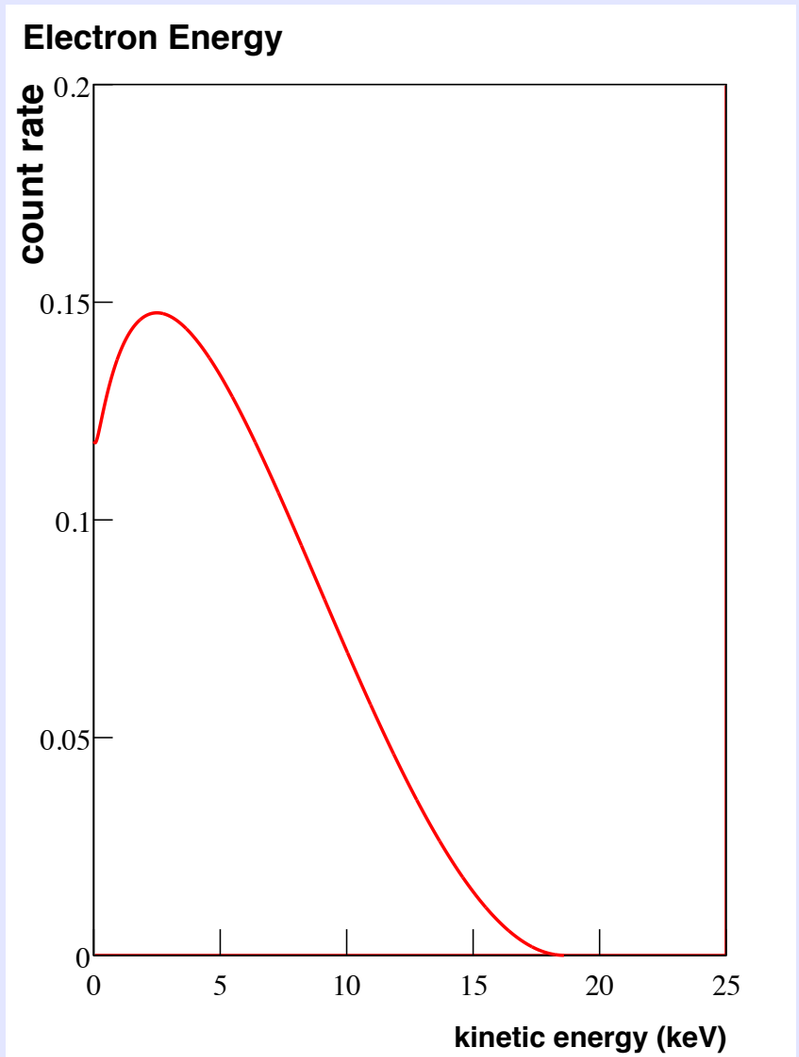


$$\frac{dN}{dE} = KF(Z,E)p(E+m_e c^2)\sum_j (E_0 - E)|U_{ej}|^2\sqrt{(E_0-E)^2 - m^2_{\nu_j}}$$

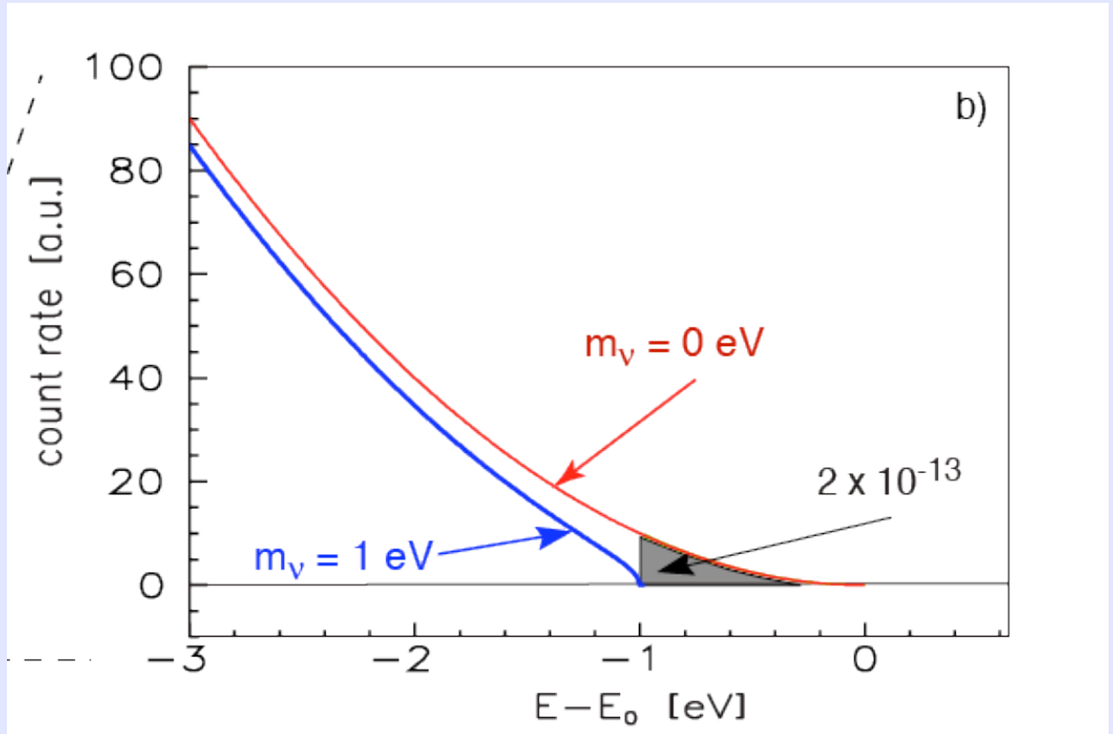
$$m_\nu = \sqrt{\Sigma_i |U_{ei}|^2 m_i^2} \approx m_i$$ in the degenerate region

K = Nuclear Matrix Element
F(Z, E) = Fermi Function

Determining the Neutrino Mass



Zoom in on the endpoint . . .



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The MAC-E Filter Technique

Magnetic Adiabatic Collimation -

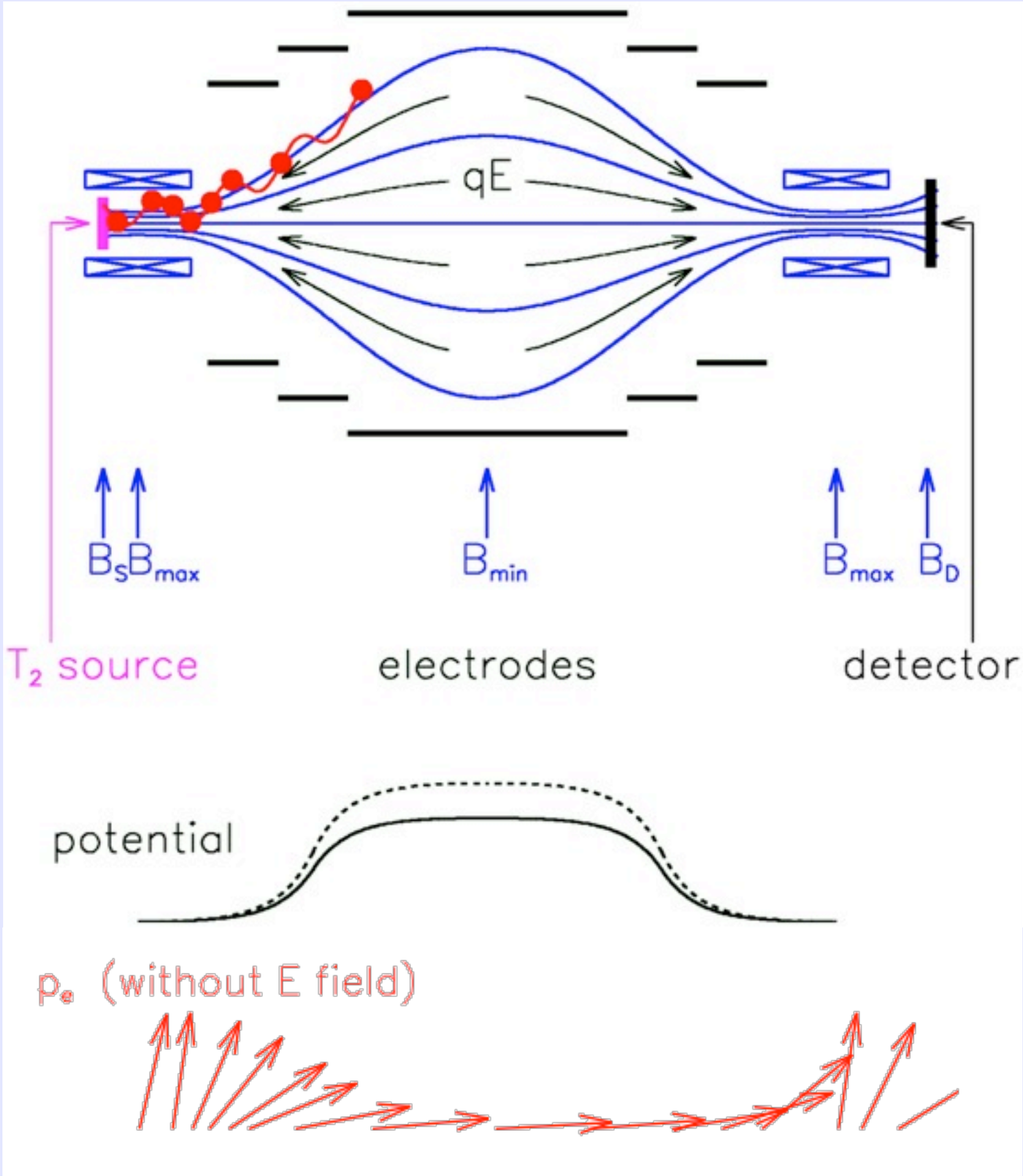
Electrostatic (Filter)

- Two solenoids create guiding B field
- Broad, parallel e^- beam at the analyzing plane
- Add electric field parallel to magnetic field
- Retarding electrostatic potential is an integrating high-pass energy filter

➡ Parallel energy analysis

$$\frac{p_\parallel^2}{2m} = E_\parallel > qU$$

$$\Delta E = \frac{B_{\min} E}{B_{\max}} = 0.93 \text{ eV}$$



KATRIN

Monitor source parameters

Provide stable tritium column density

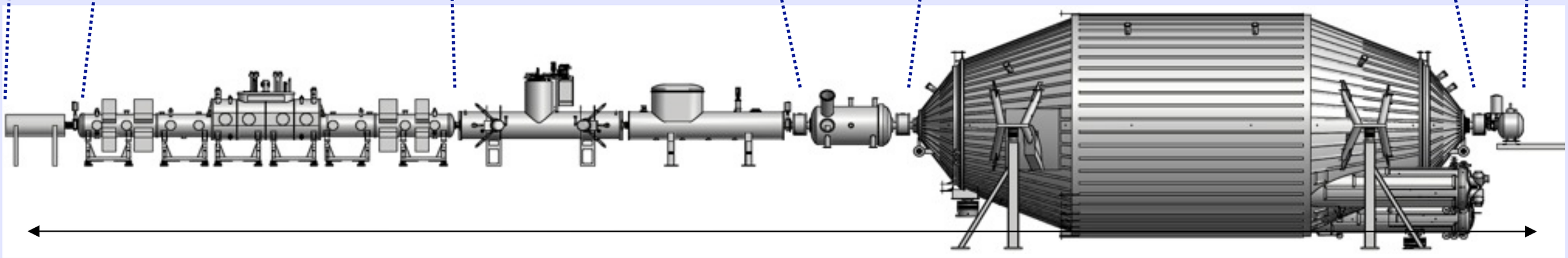
Transport electrons recycle tritium

Reject low-energy electrons

Precise energy selection of electrons

Count electrons measure their energy, position

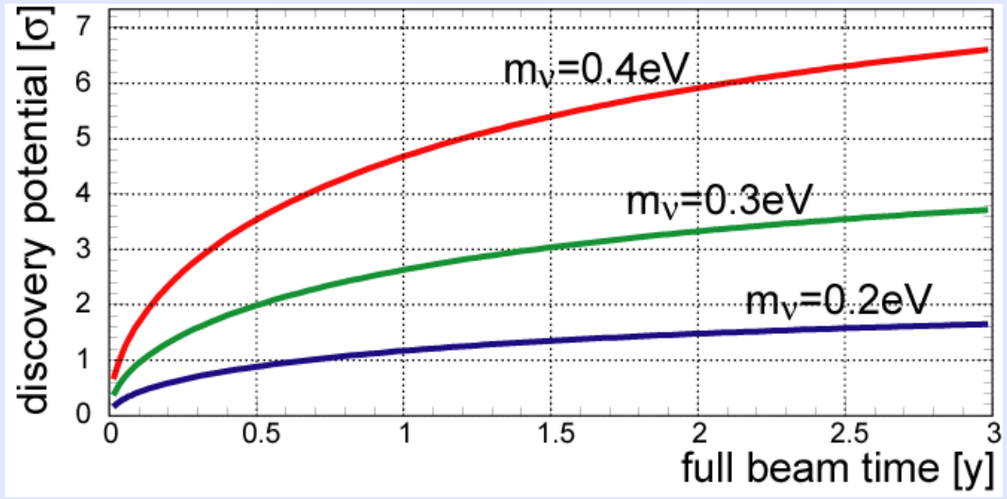
Rear	Source	Trans/pump	Pre-spectrometer	Main spectrometer	Detector
	10^{10} e⁻ /s	10^{10} e- /s	10^{3} e⁻ /s		1 e⁻ /s
	^{3}H, β-decay, ν_e, e⁻, ^{3}He	e⁻	e⁻		e⁻
	$3 \cdot 10^{-3}$ mbar ±1 kV		10^{-11} mbar -18.4 kV	10^{-11} mbar -18.574 kV	

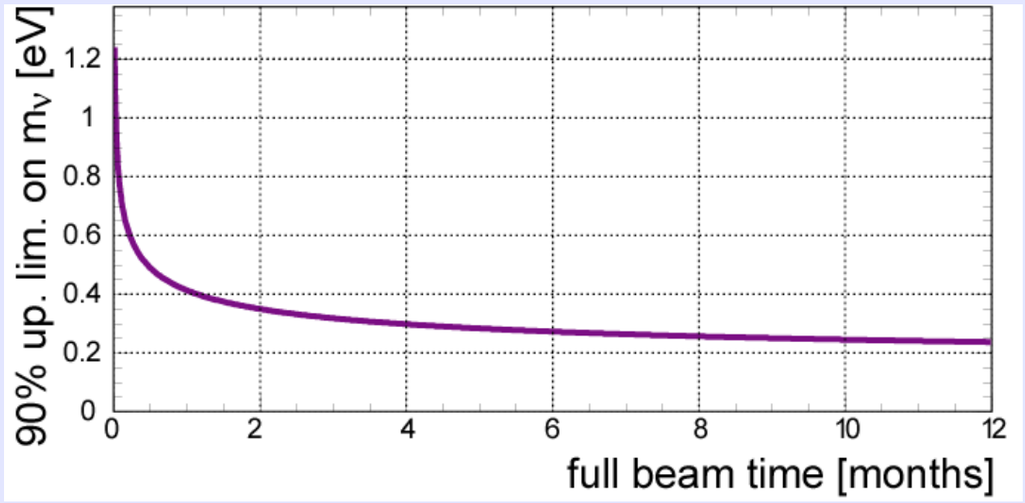


Located at the Karlsruhe Institute of Technology, Karlsruhe, Germany

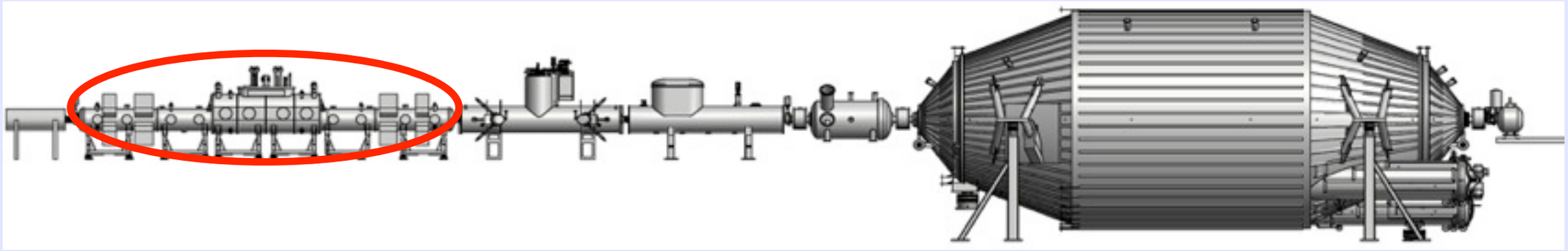
Sensitivity

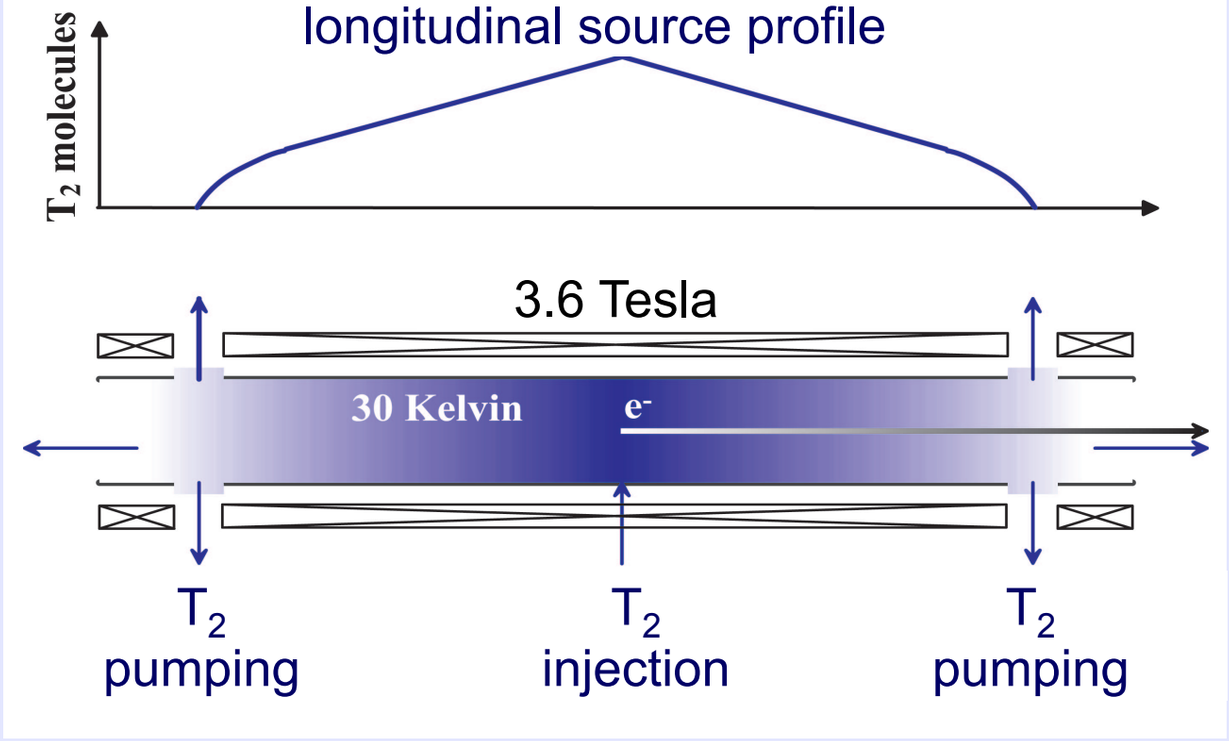
- Run time: 3 years
- Uncertainties
  - σ_{stat} = 0.018 eV^2
  - σ_{syst} = 0.017 eV^2
- Sensitivities
  - Discovery: m_ν = 350 meV (5σ)
  - Upper limit: m_ν < 200 meV (90% CL)





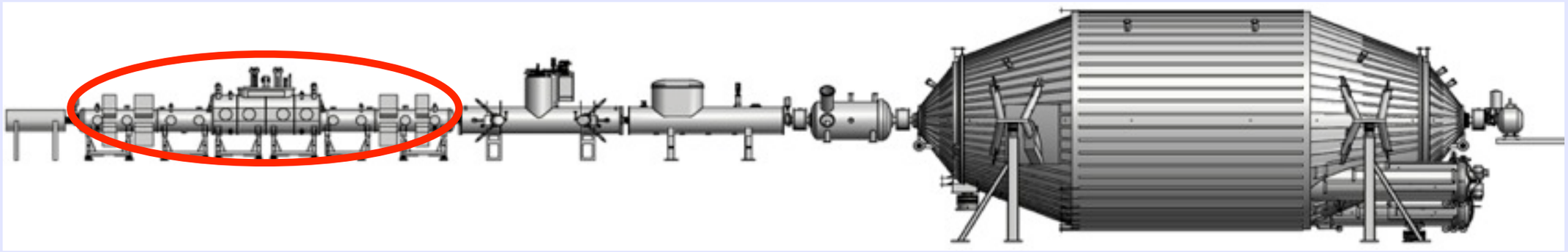
Tritium Source

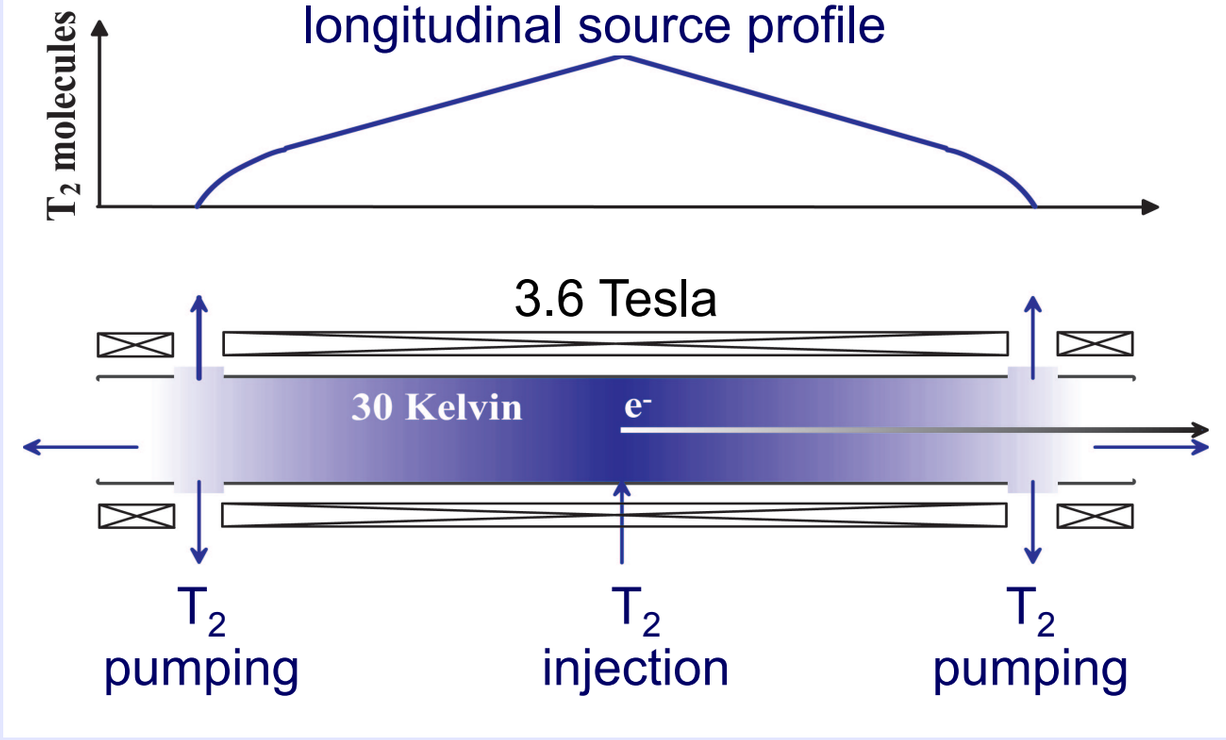




- Will deliver 10^{10} β-decay electrons per second
- Tritium loop will circulate 40g of T_2 per day
- Length: 10 m
- Diameter: 90 mm
- Stable density profile by controlling the injection rate, pumping rate, beam-tube temperature, and gas temperature

Tritium Source





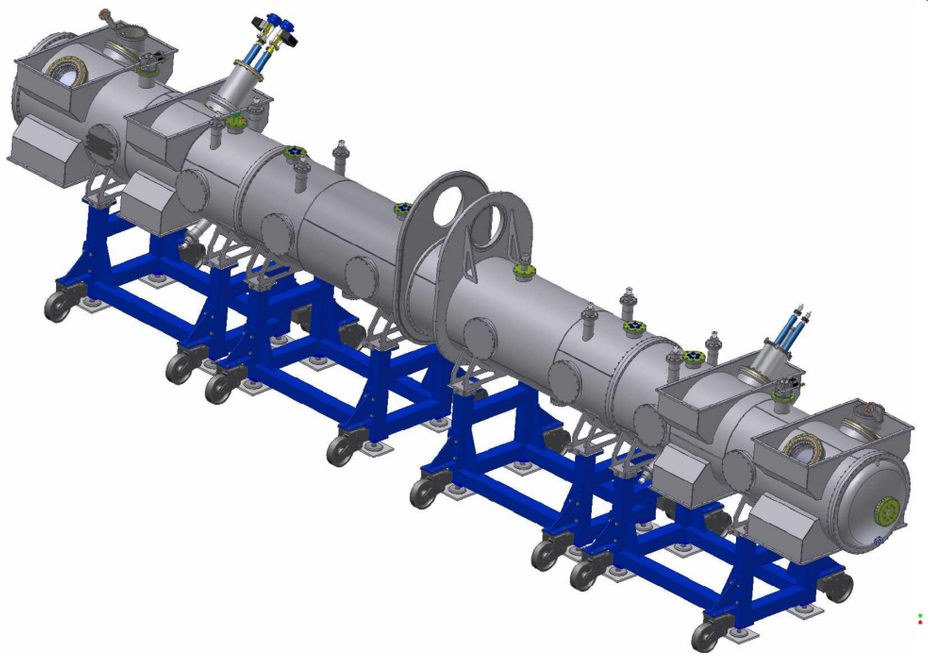
See S. Fischer's poster tonight!

Status of KATRIN's WGTS

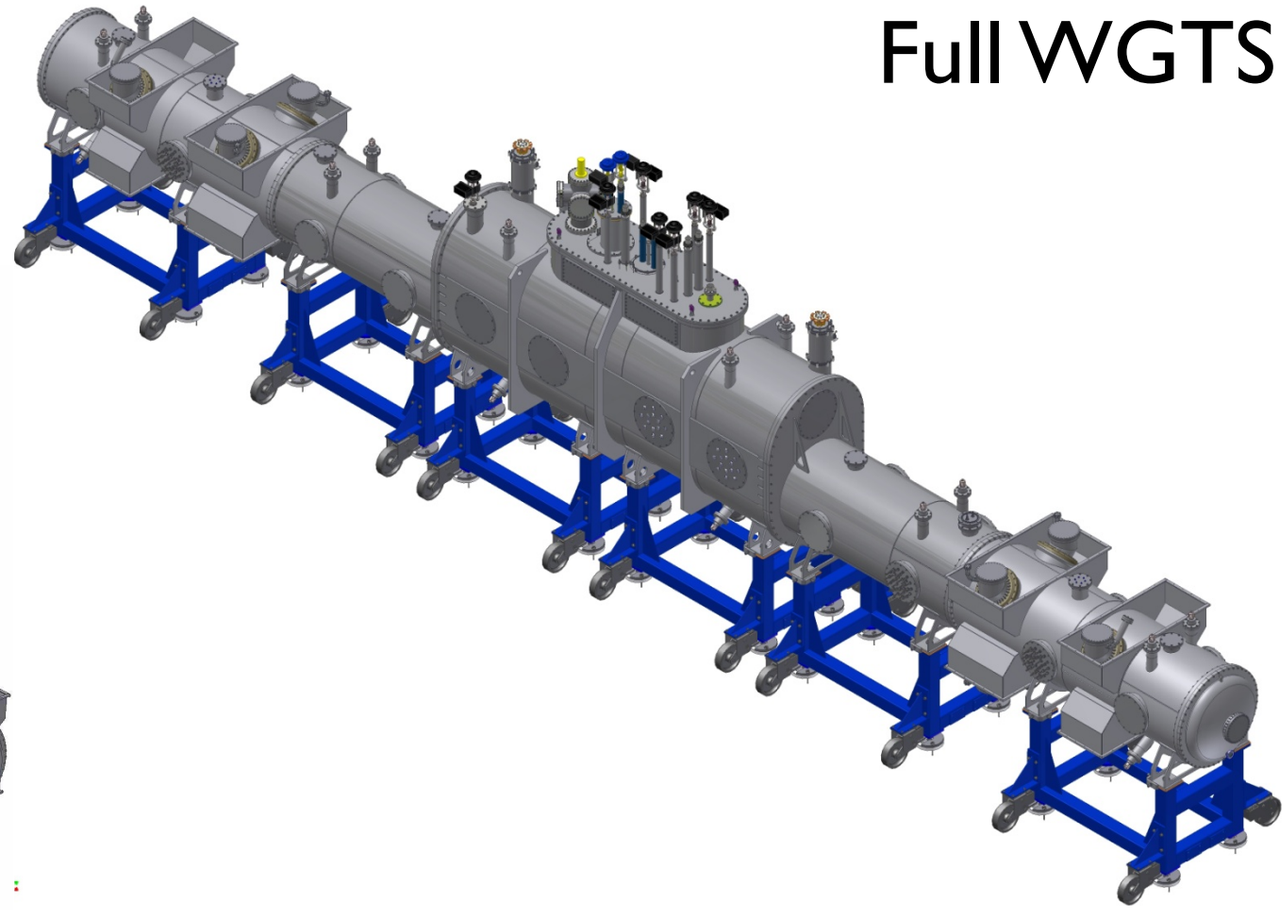
Demonstrator Module

WGTS = Windowless Gaseous Tritium Source

WGTS
Demonstrator



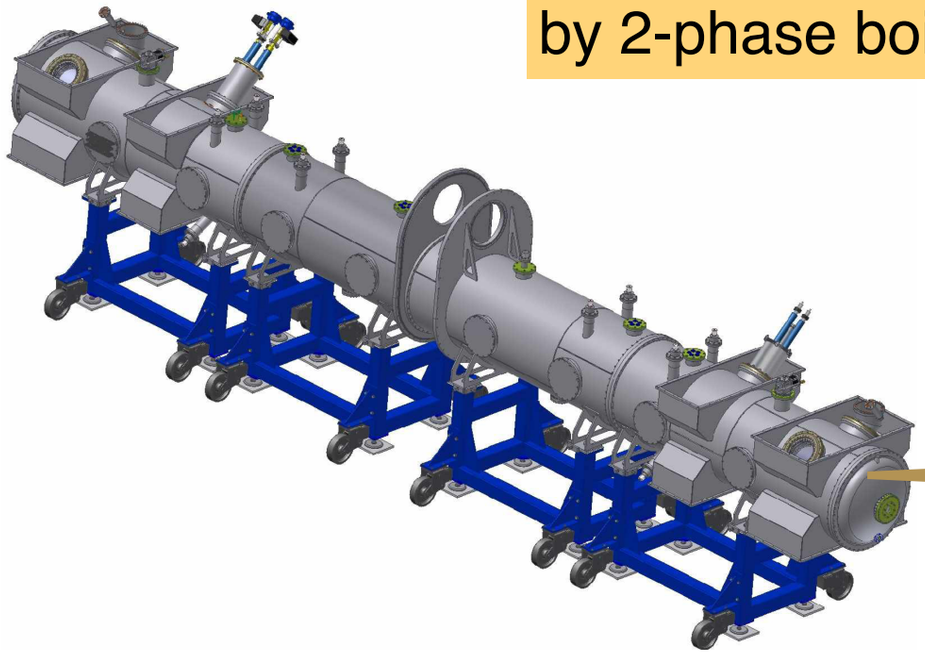
Full WGTS

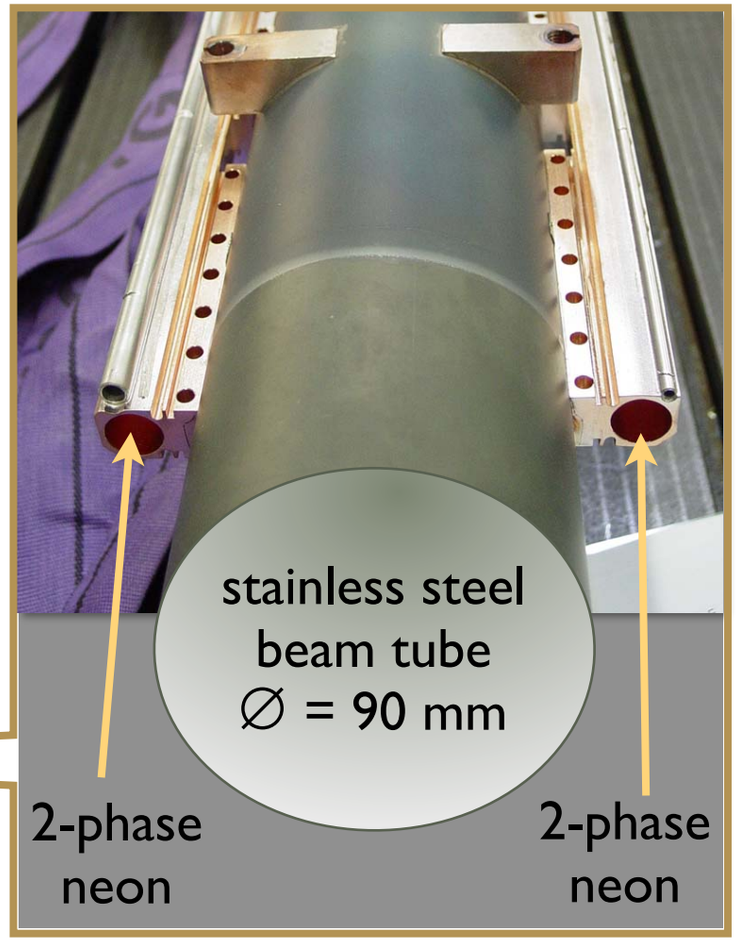


Demonstrator Module

WGTS Demonstrator

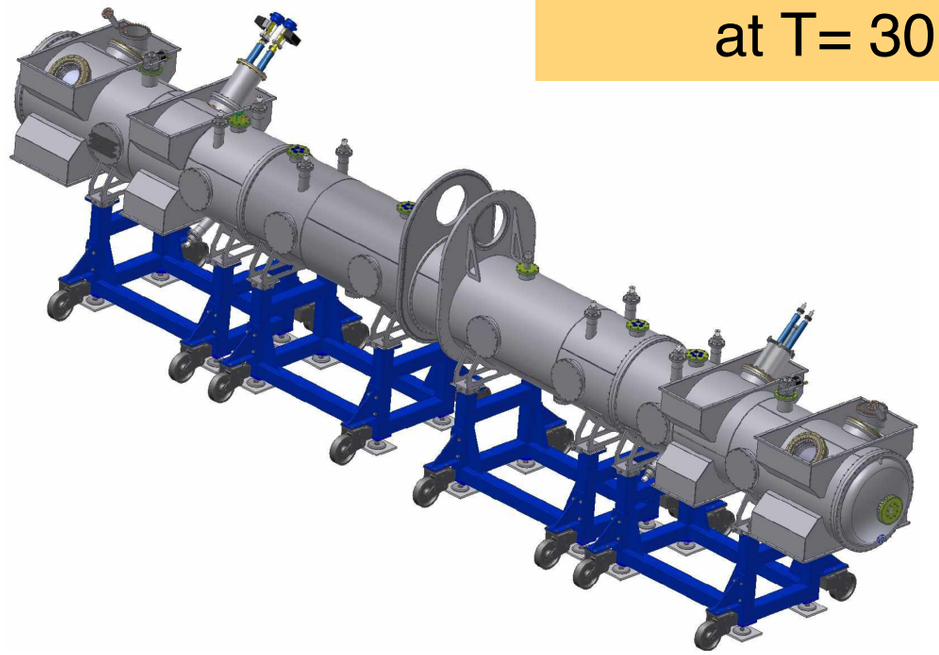
$\Delta T < 30$ mK at T= 30 K
by 2-phase boiling Neon



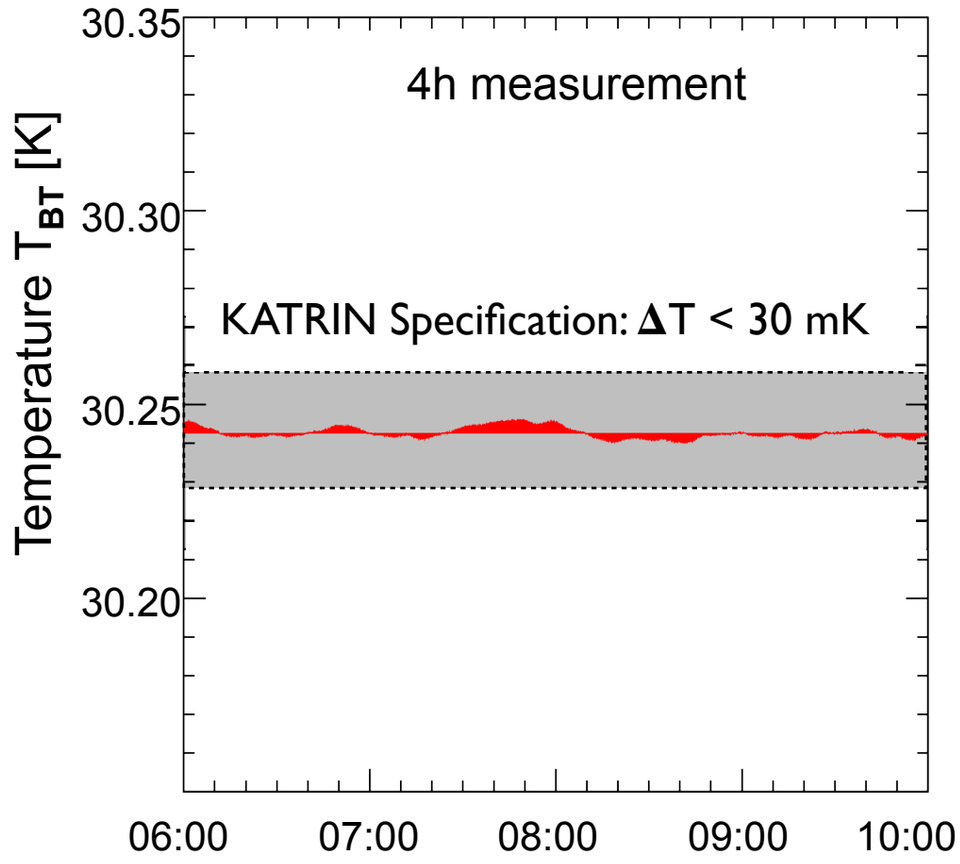


Demonstrator Module

WGTS Demonstrator



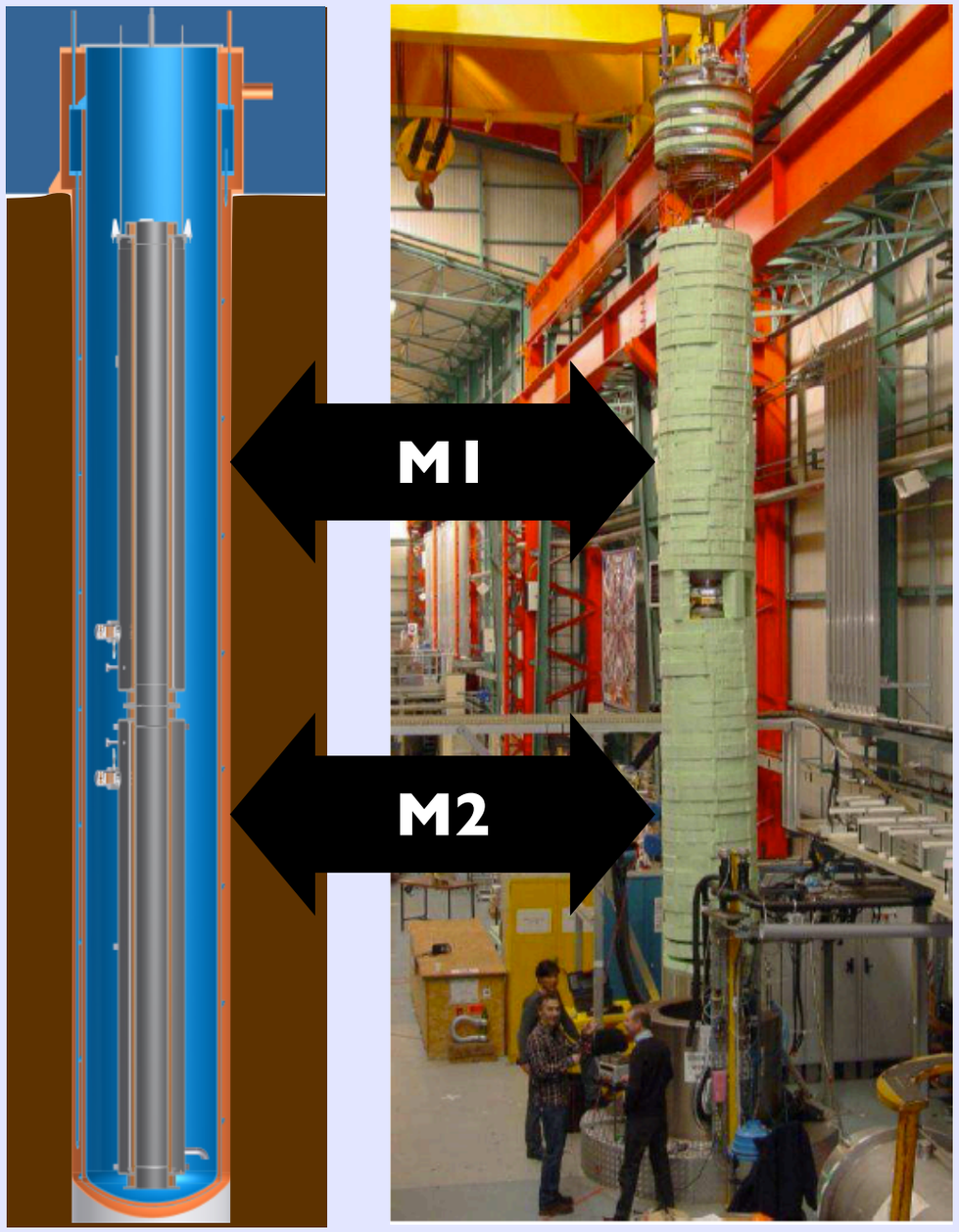
Achieved ΔT ≈ 1.5 mK
at T= 30 K



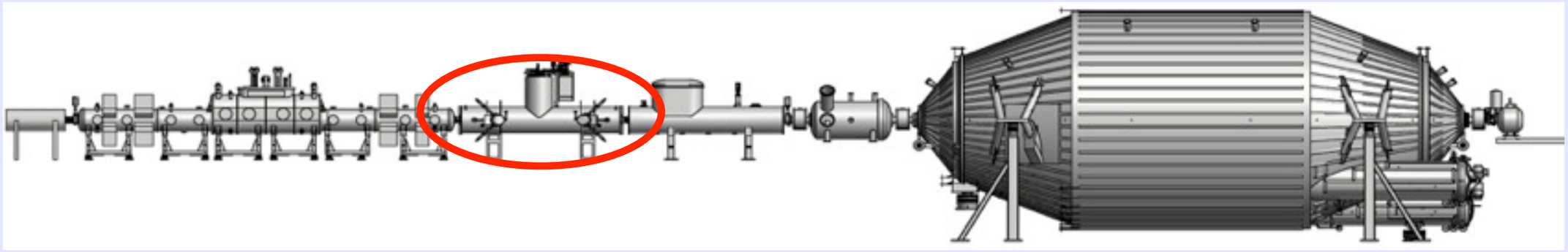
S. Grohmann, T. Bode, M. Hötzel, H. Schön, M. Süßer, T. Wahl, 10.1016/j.cryogenics.2013.01.001.

WGTS Magnet Tests

- Performed at CEA Saclay
- To demonstrate:
  - ❖ Energy dump during quench
  - ❖ Magnetic forces during quench
  - ❖ Driven mode operation
- Performed in 8-m long buried cryostat



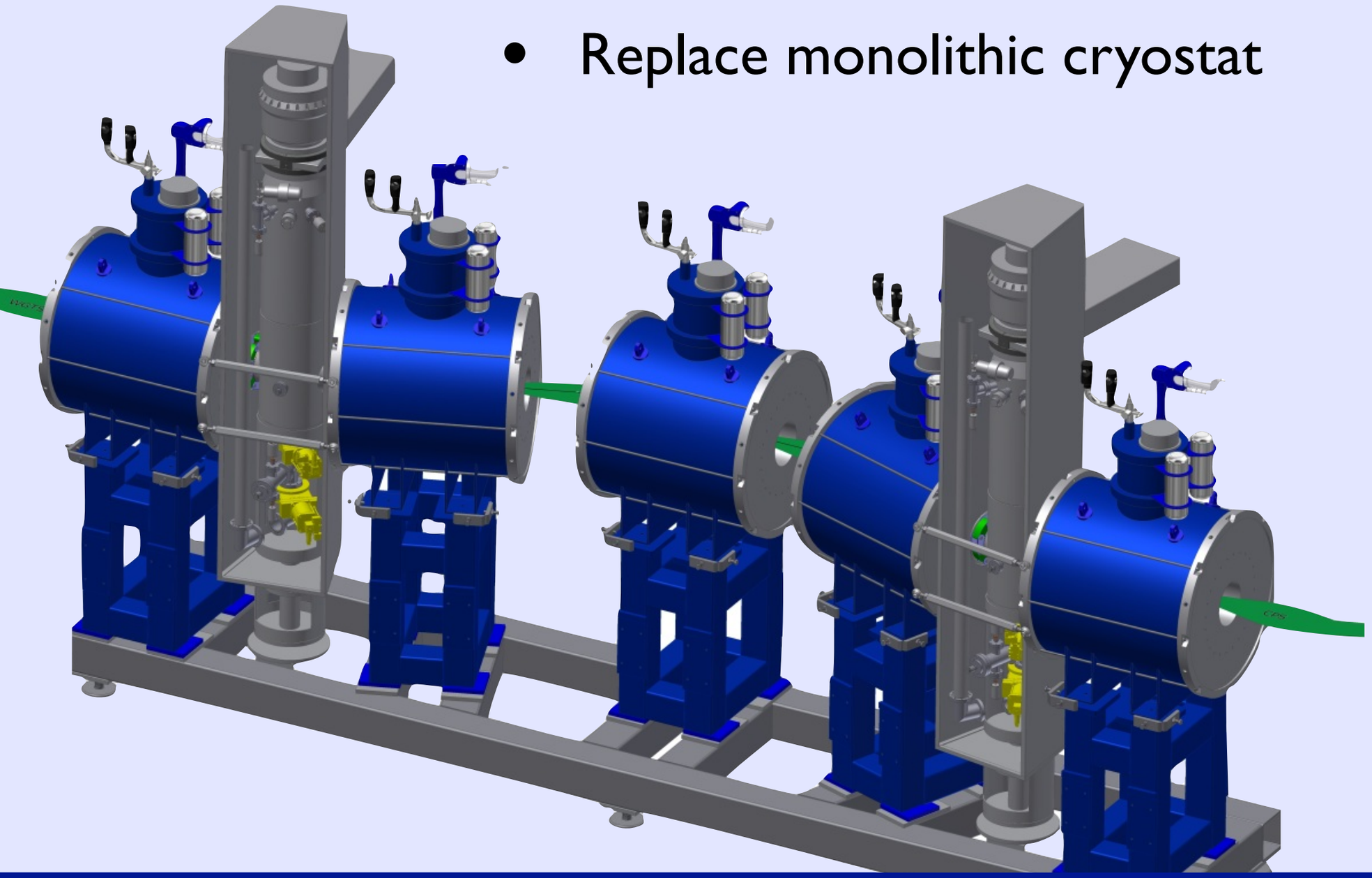
Differential Pumping



- Adiabatic electron guidance
- Reduction of T_2 flow by factor of ~10^5
- Redesign needed to fix protection diodes

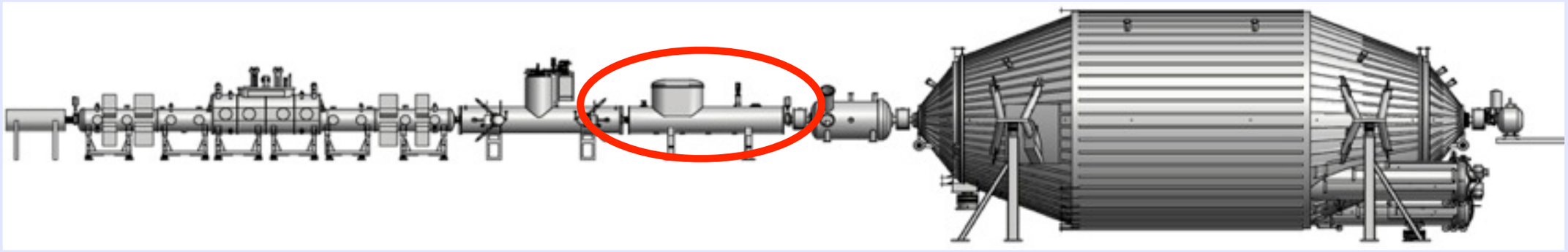
New Magnet Design

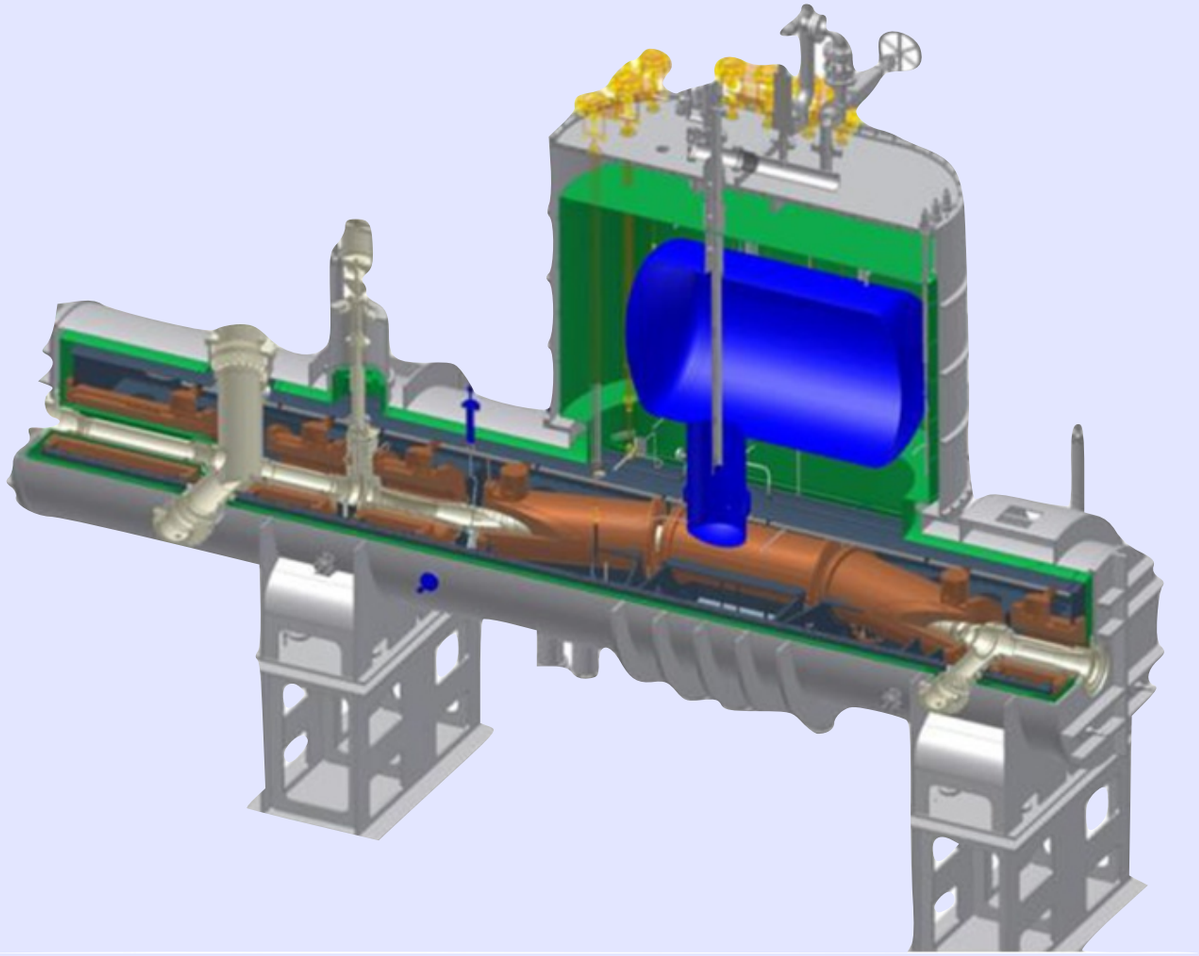
- 5 standalone magnets; warm beam tube
- Used successfully in the detector section
- Replace monolithic cryostat



- 5 pump ports for turbo pumps
- New magnets arrive by early 2014

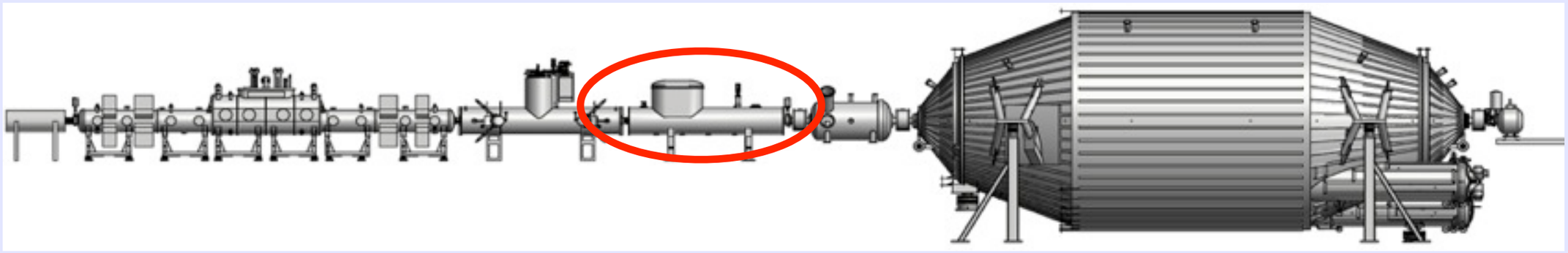
Cryogenic Pumping

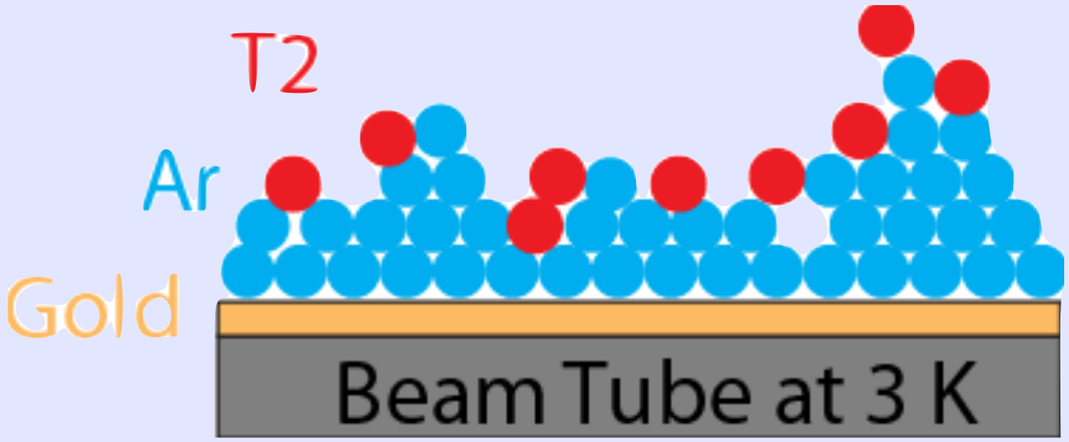




- Adiabatic electron guidance
- Reduction of T_2 flow by factor of ~10^7 with cryosorption onto Ar frost
- Under construction; completion in early 2014

Cryogenic Pumping





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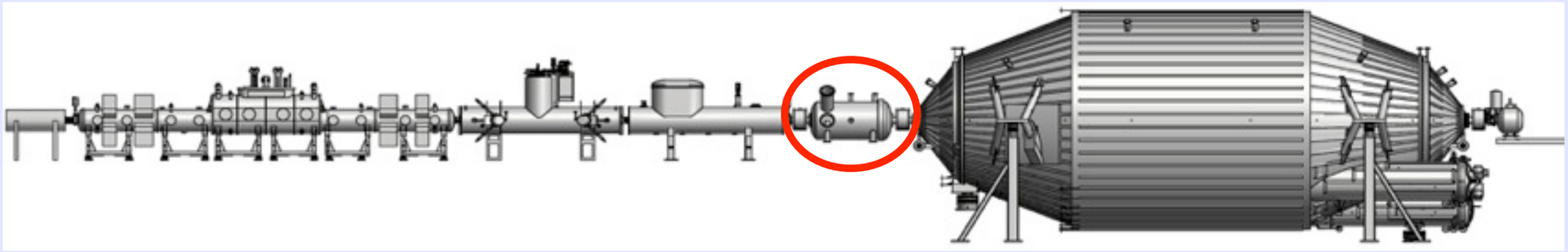
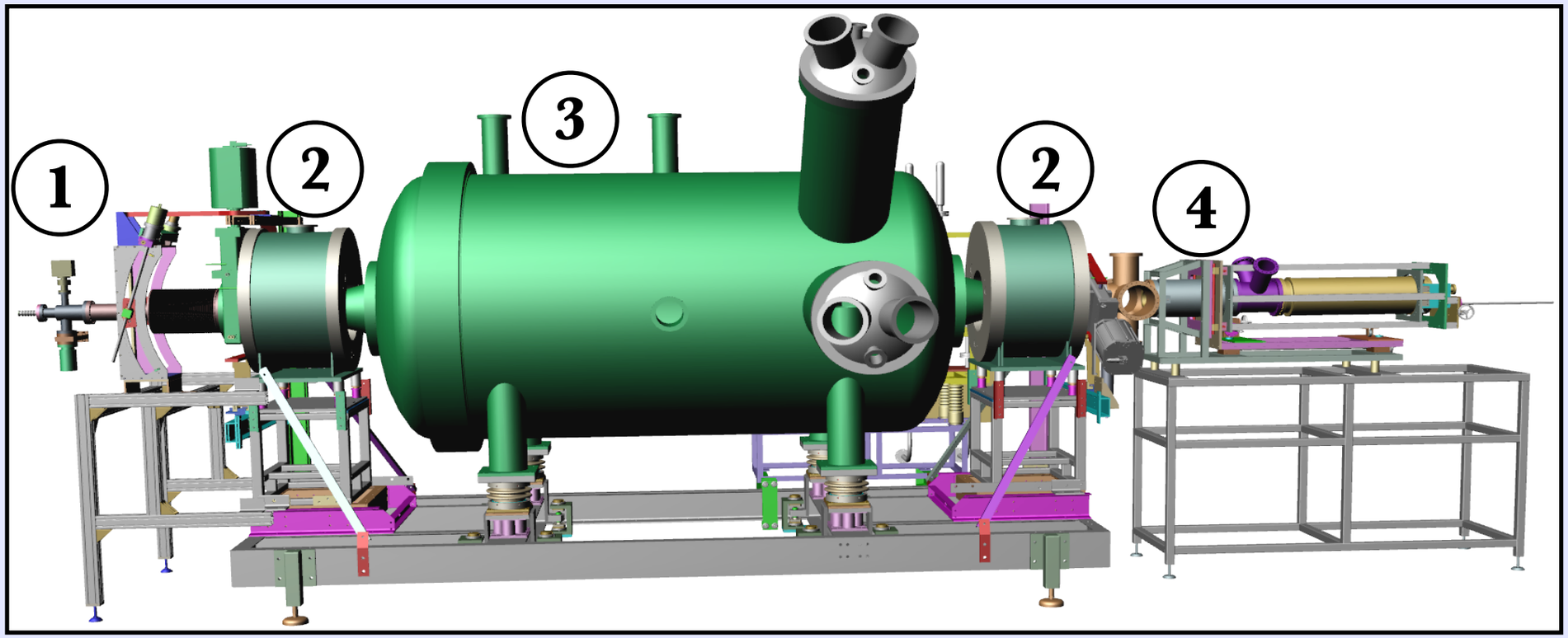
Pre-Spectrometer



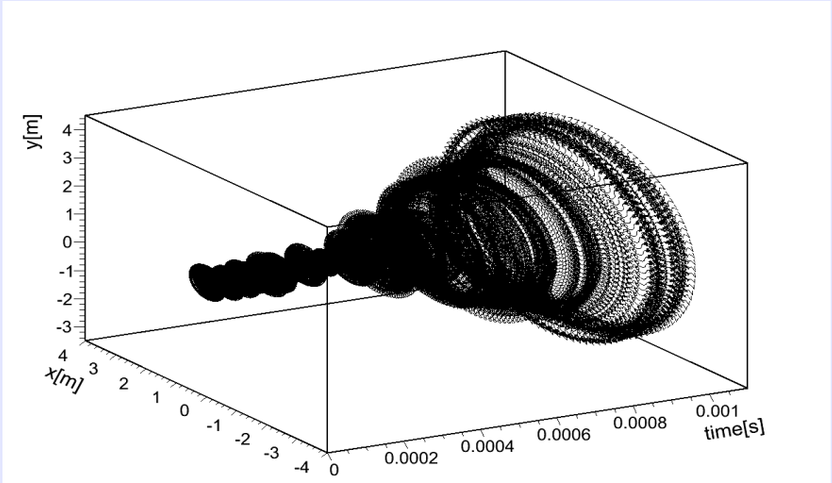
Pre-Spectrometer Test Setup -- Until 2011



1. Electron Gun
2. Magnets (4.5 T)
3. Vessel
4. Detector

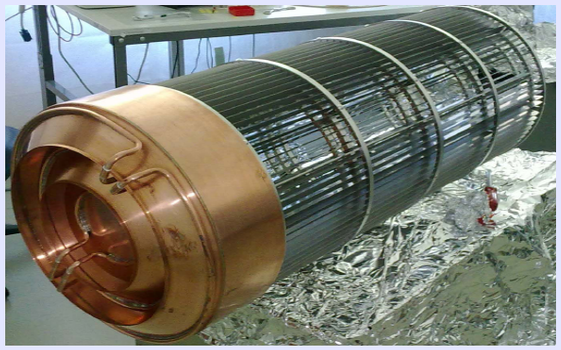
Lessons Learned

Electromagnetic Design



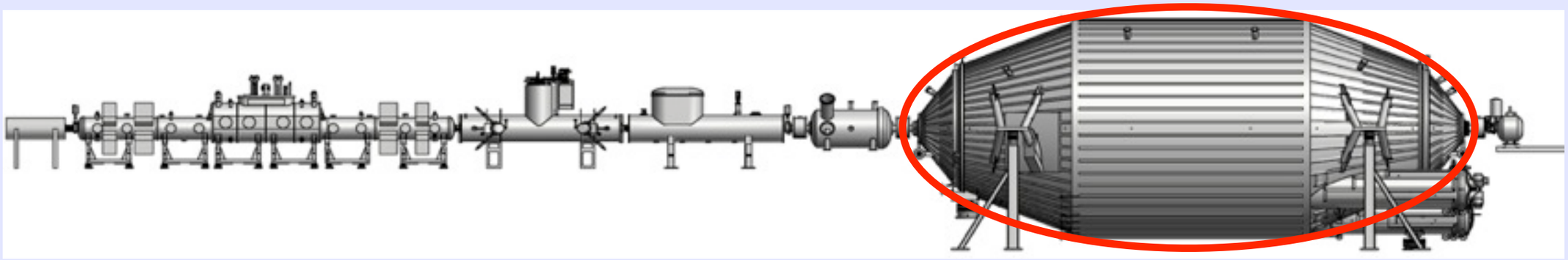
Electrode Optimization

Background Suppression



Ultra-High Vacuum (10^{-11}mbar, routinely)

Main Spectrometer



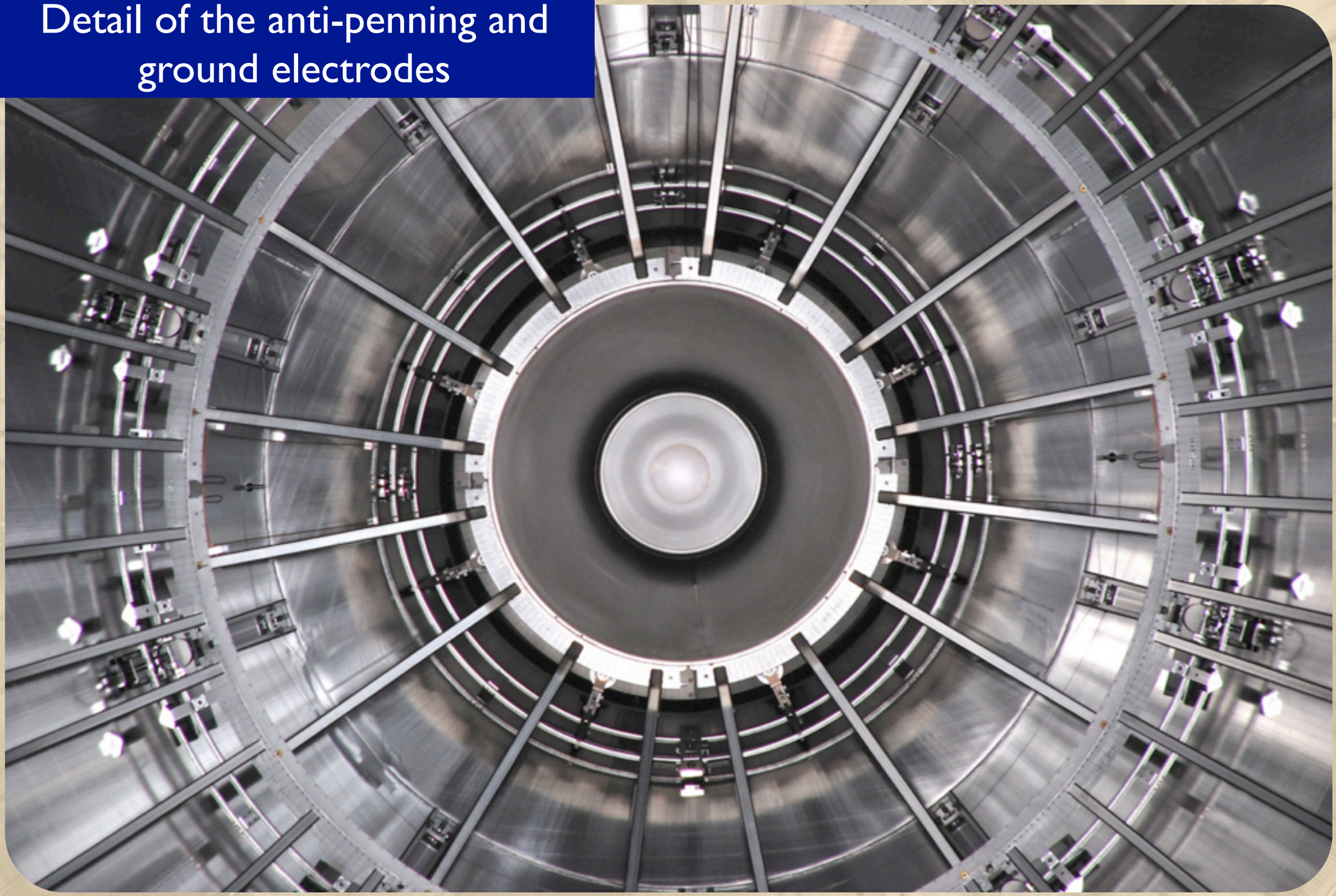
- Precision high-pass energy filter
- Uses the MAC-E filter technique
- Energy resolution: 0.93 eV @ 18.6 keV
- Volume: 1240 m^3
- Pressure: < 10^{-11} mbar
- Inner electrode system to reduce backgrounds

Wire electrode modules
Installation finished January 2012

Final view inside the spectrometer

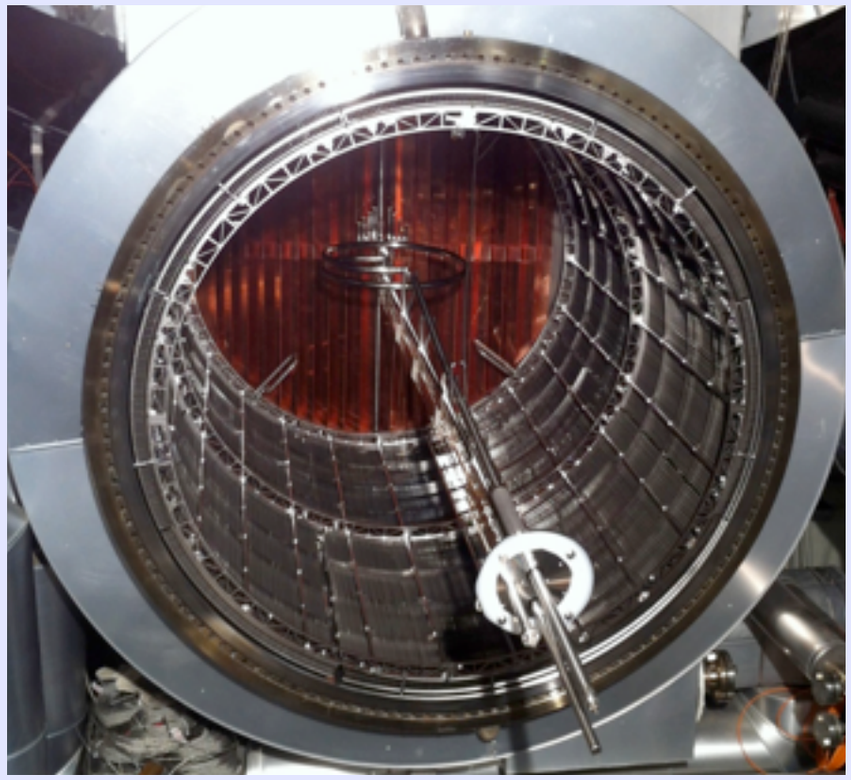
Final view inside the spectrometer

Detail of the anti-penning and ground electrodes



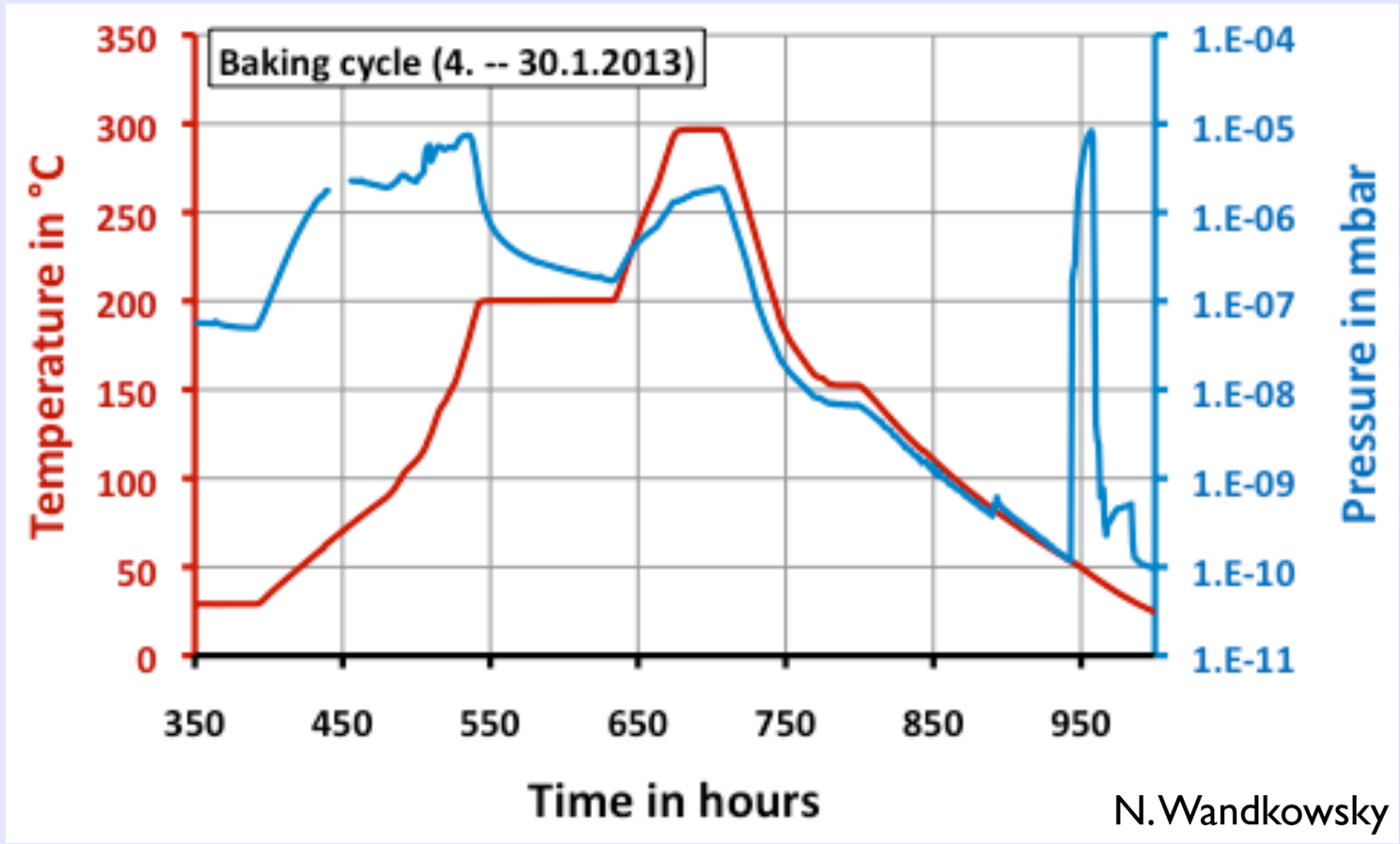
Bakeout: Motivation

- Achieve UHV ($< 10^{-11}$ mbar)
- Remove water absorbed on surfaces
- Activate non-evaporable getter material

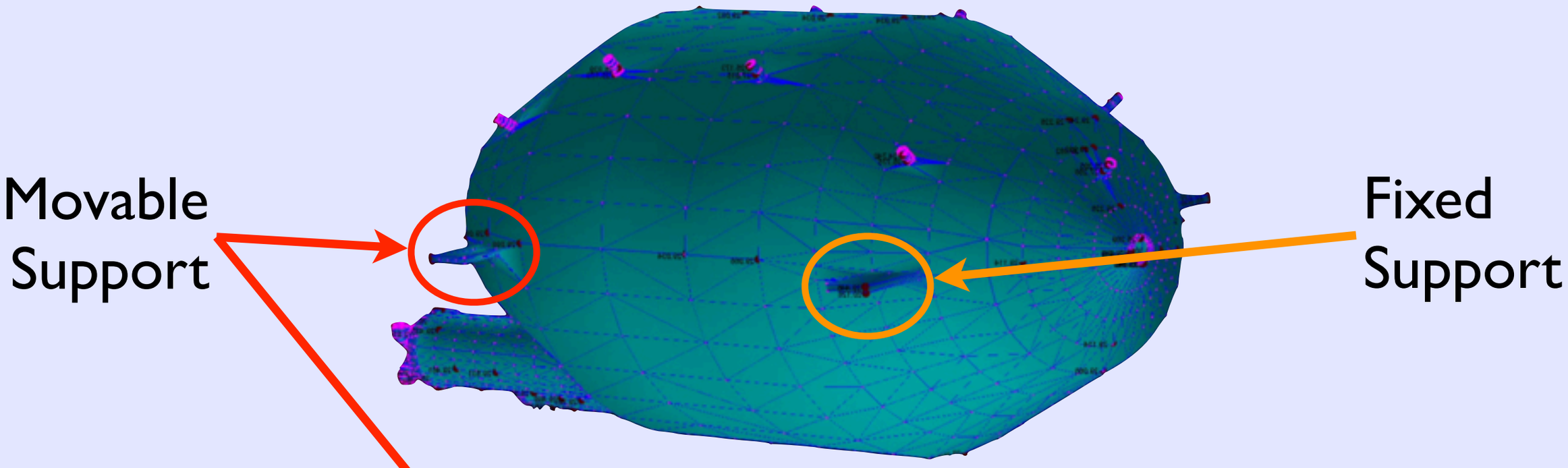


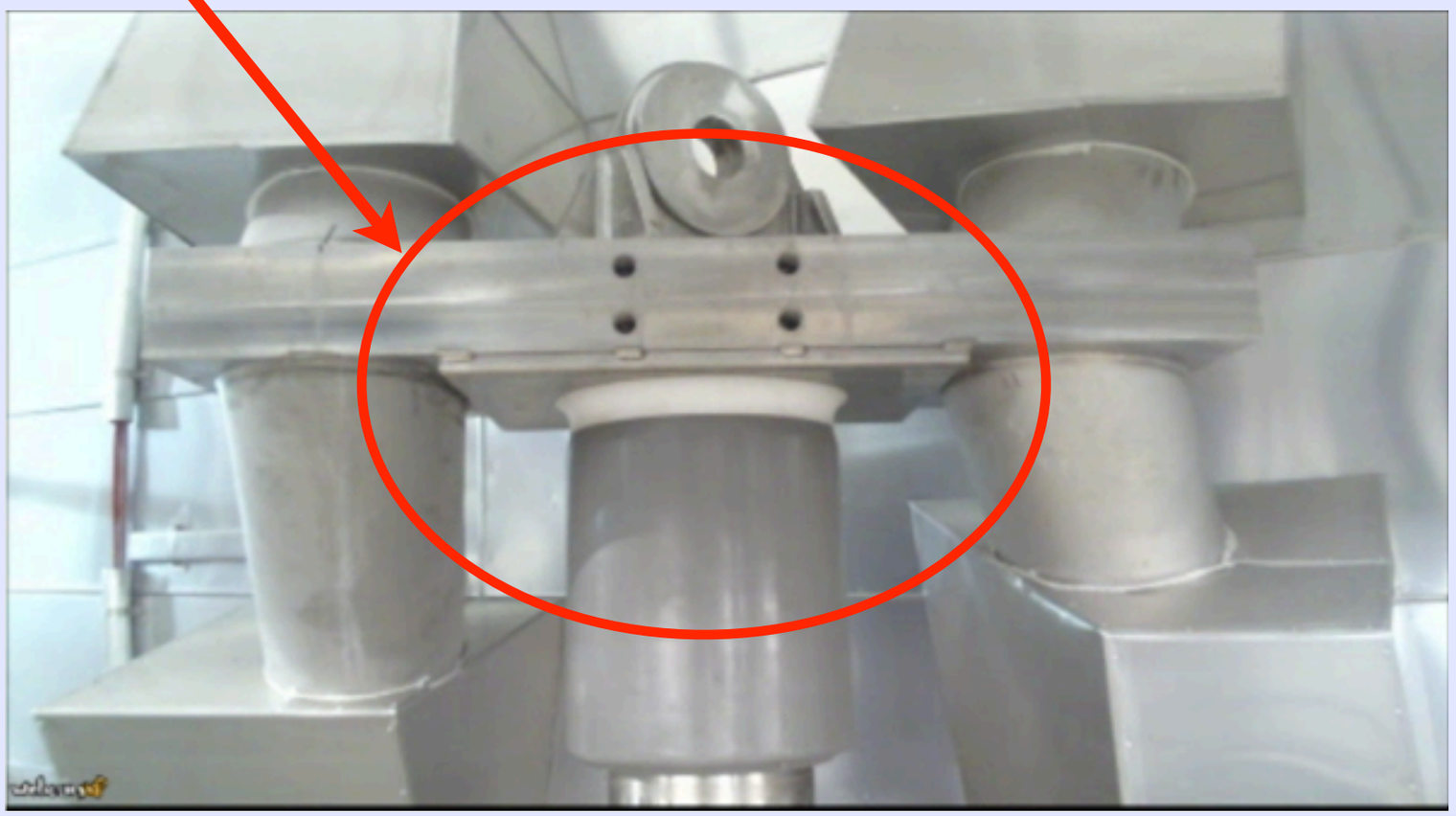
Bakeout: Procedure

- Slow Heating/ Cooling (~1 °C/hr)
  - ❖ Thermal expansion of vessel and electrode
- Key temperatures
  - ❖ 200 °C – Water removed from surfaces
  - ❖ 350 °C – Best getter activation

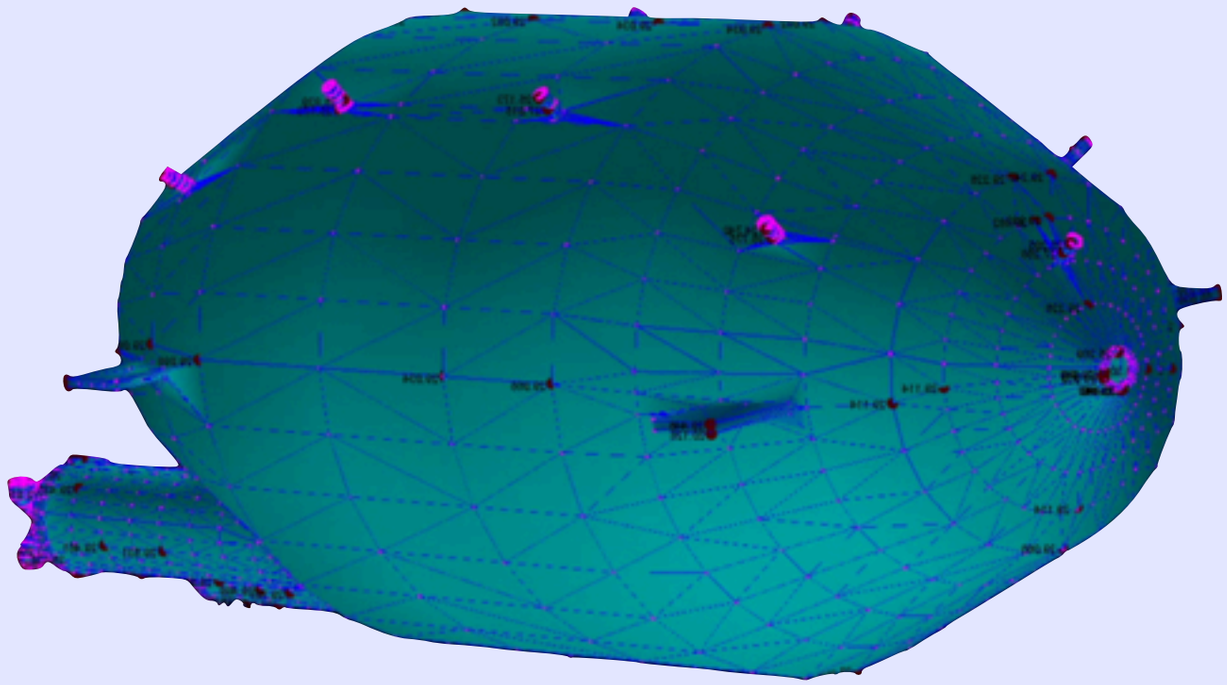


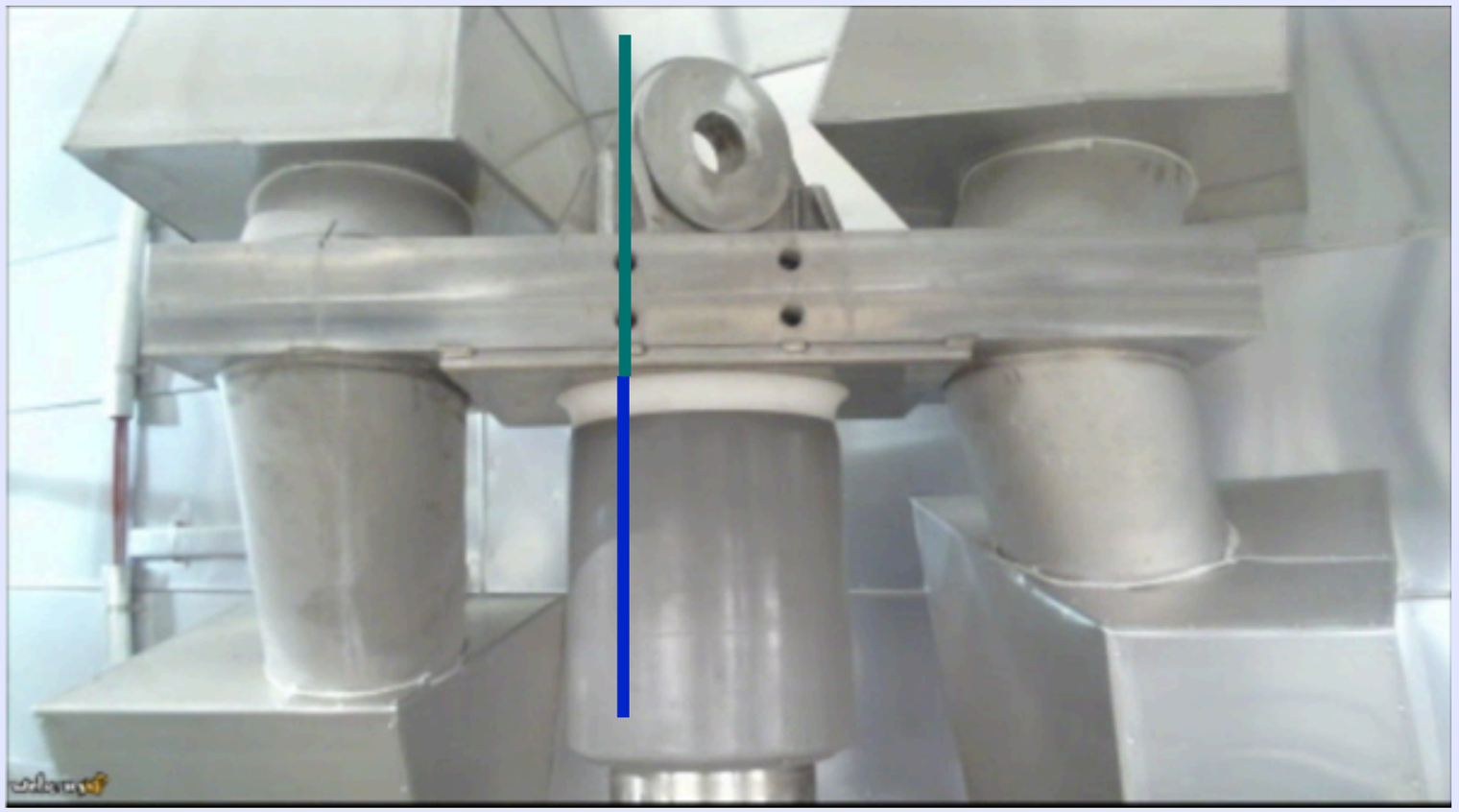
Bakeout: Expansion





Bakeout: Results





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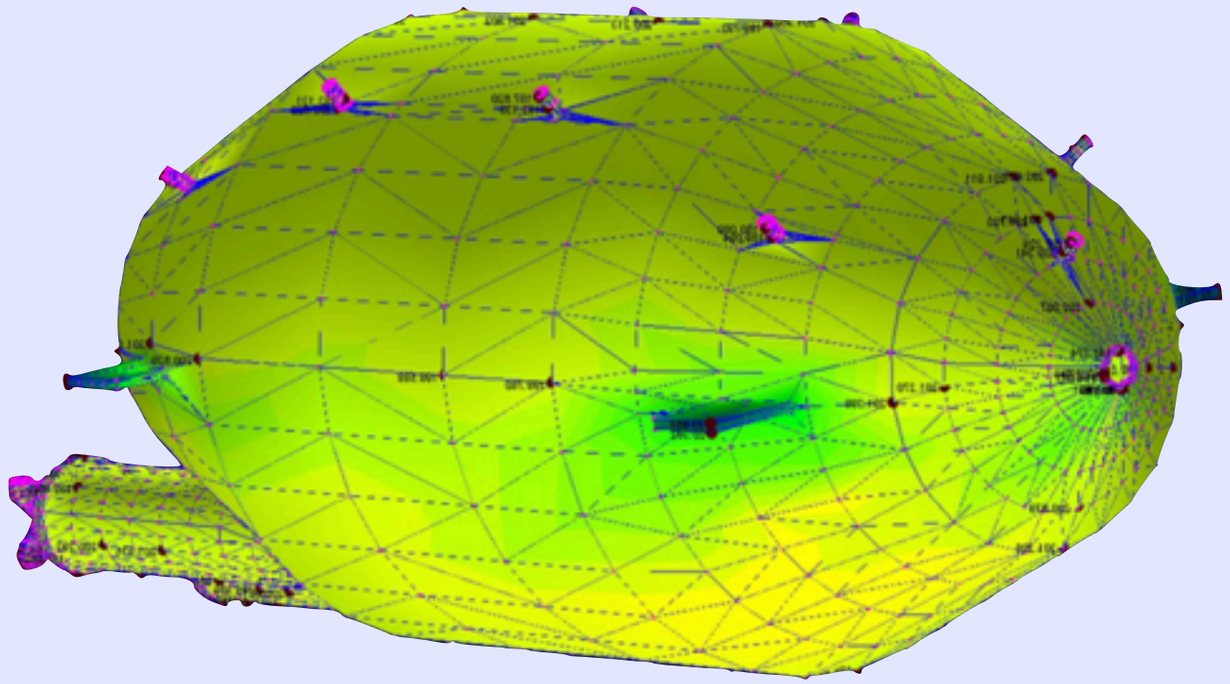
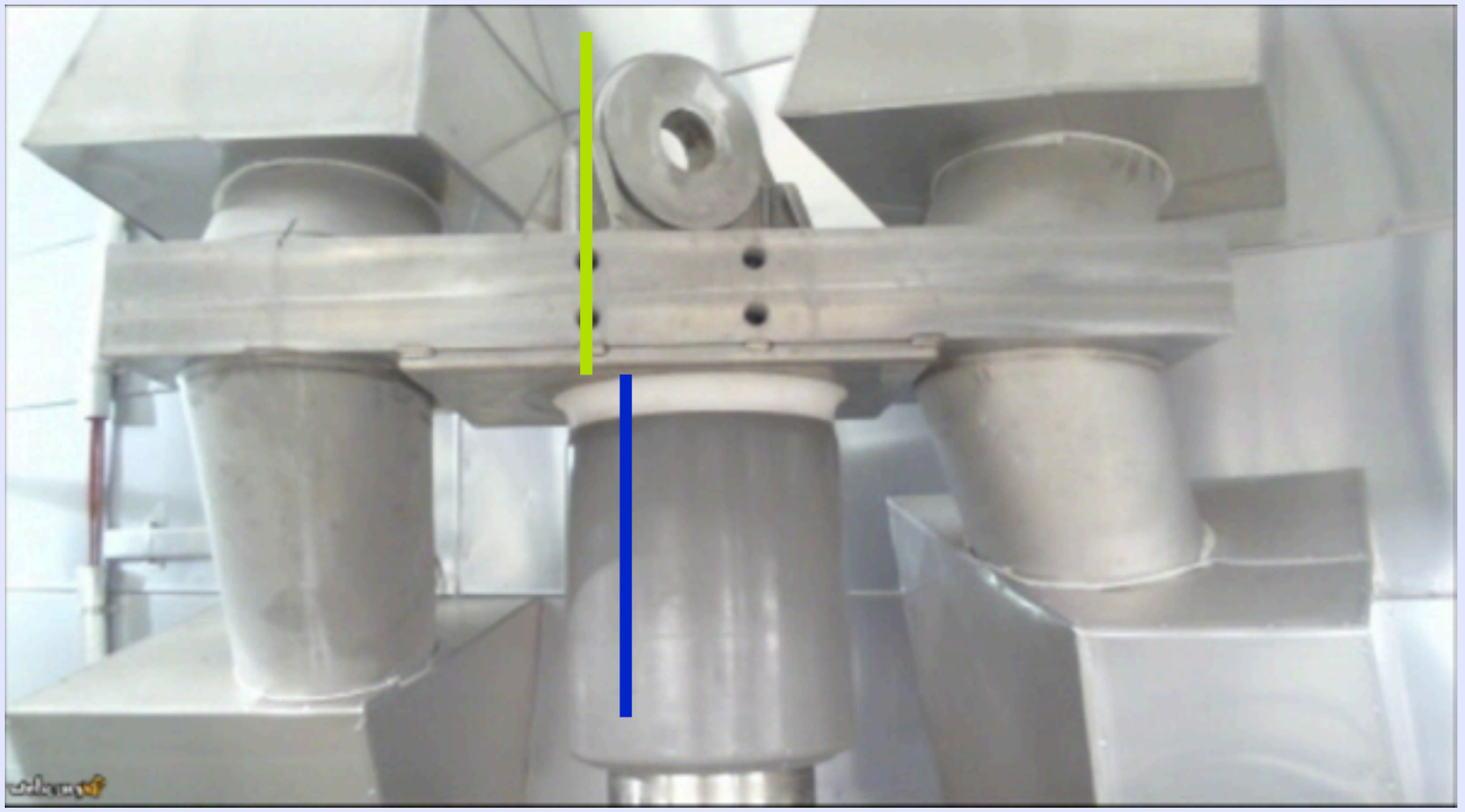
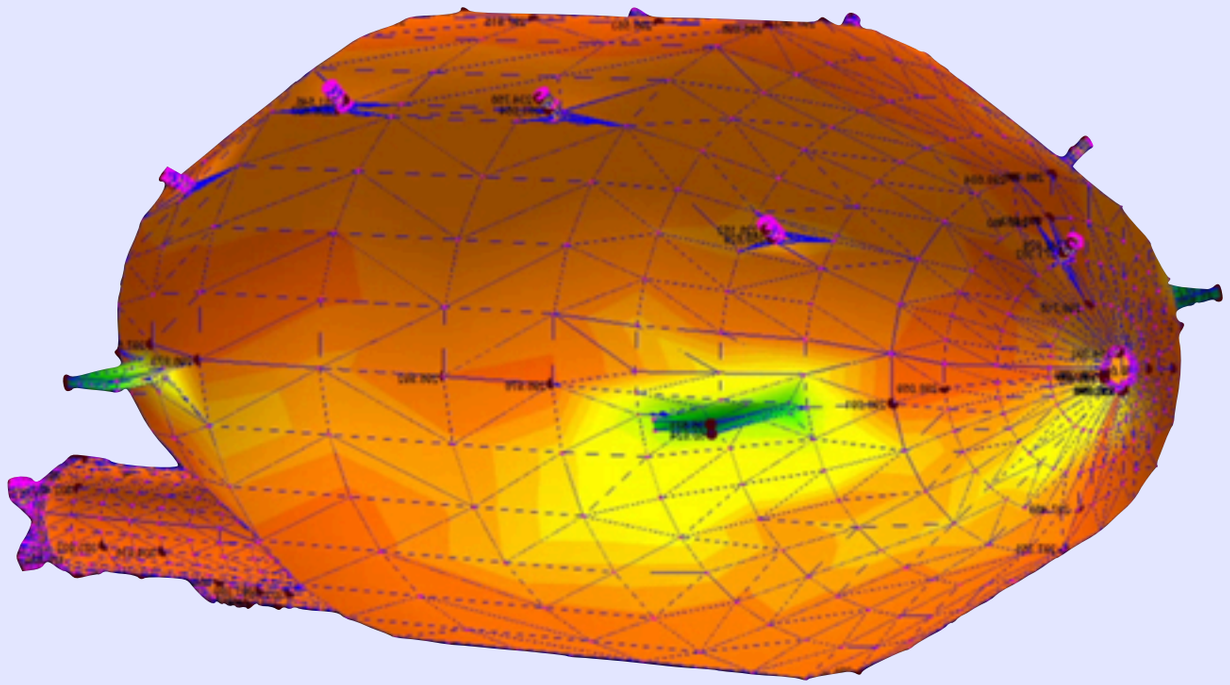
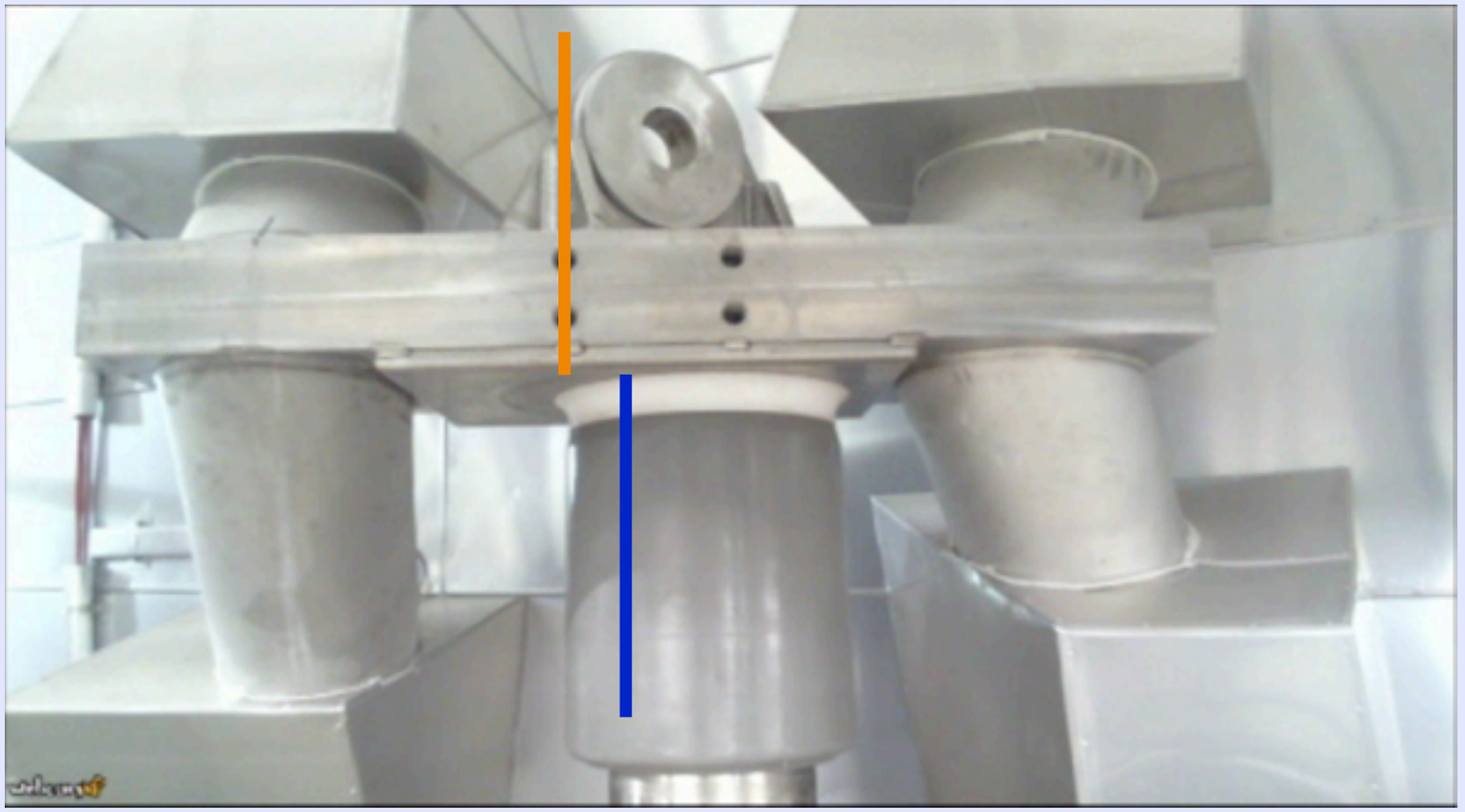




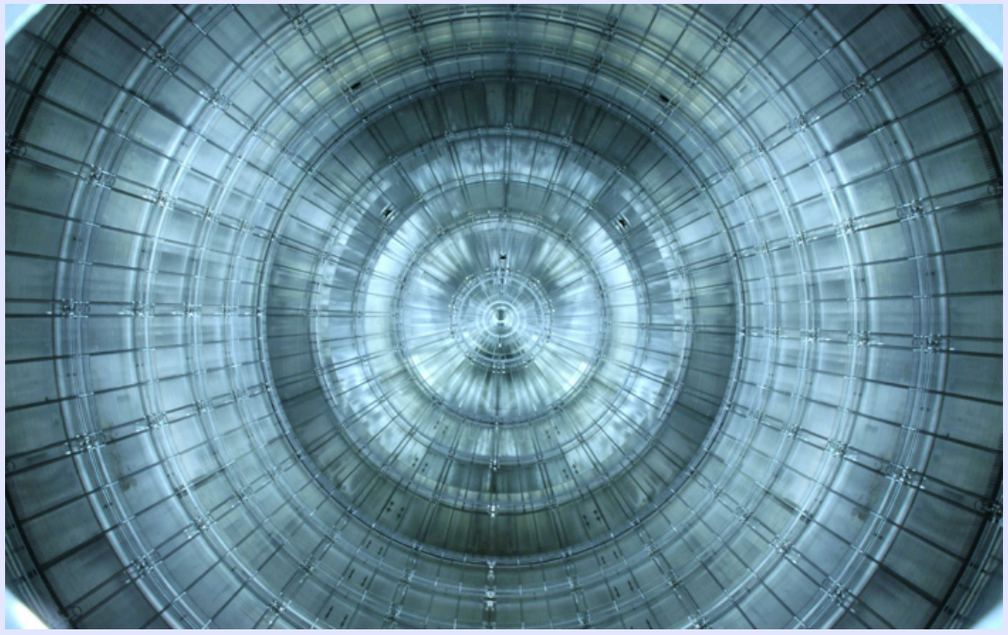
Bakeout: Results

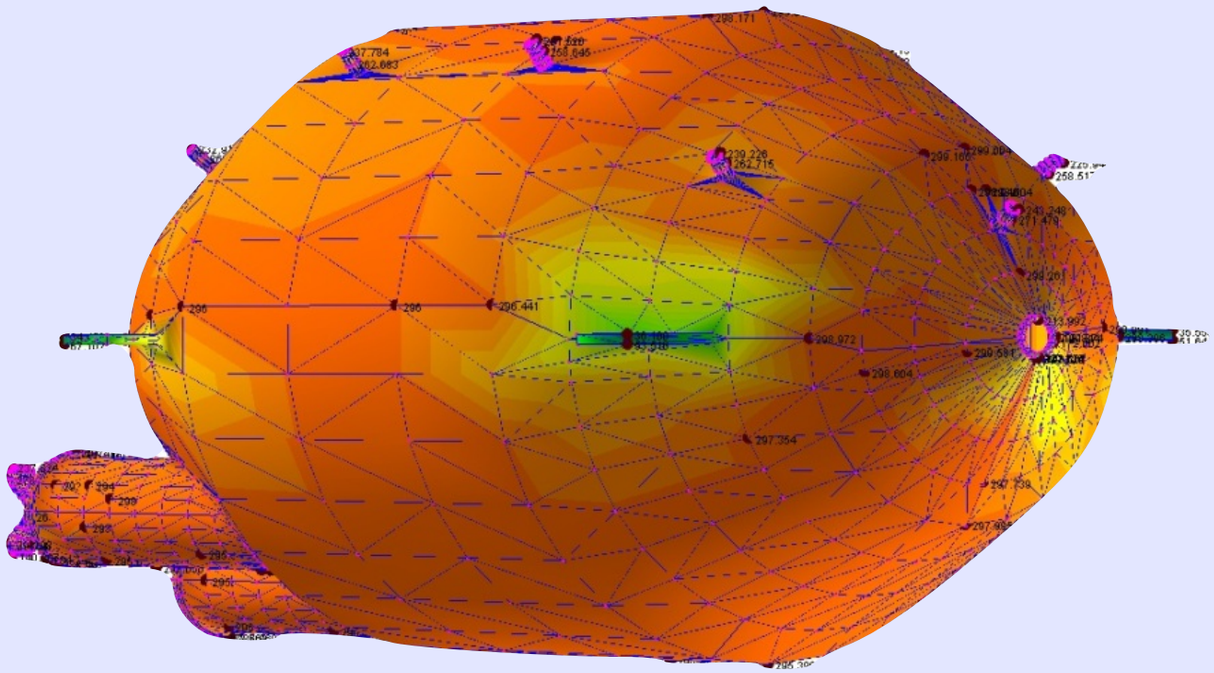


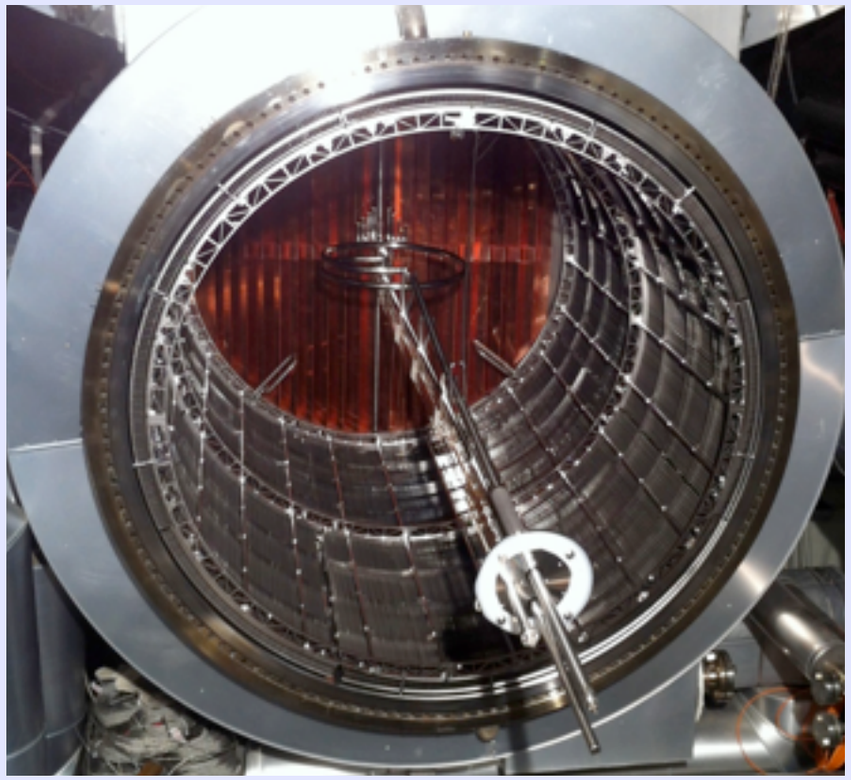


Bakeout: Results

- Wire electrode unharmed
- Getter only partially activated
- Vacuum achieved: 9×10^{-11} mbar

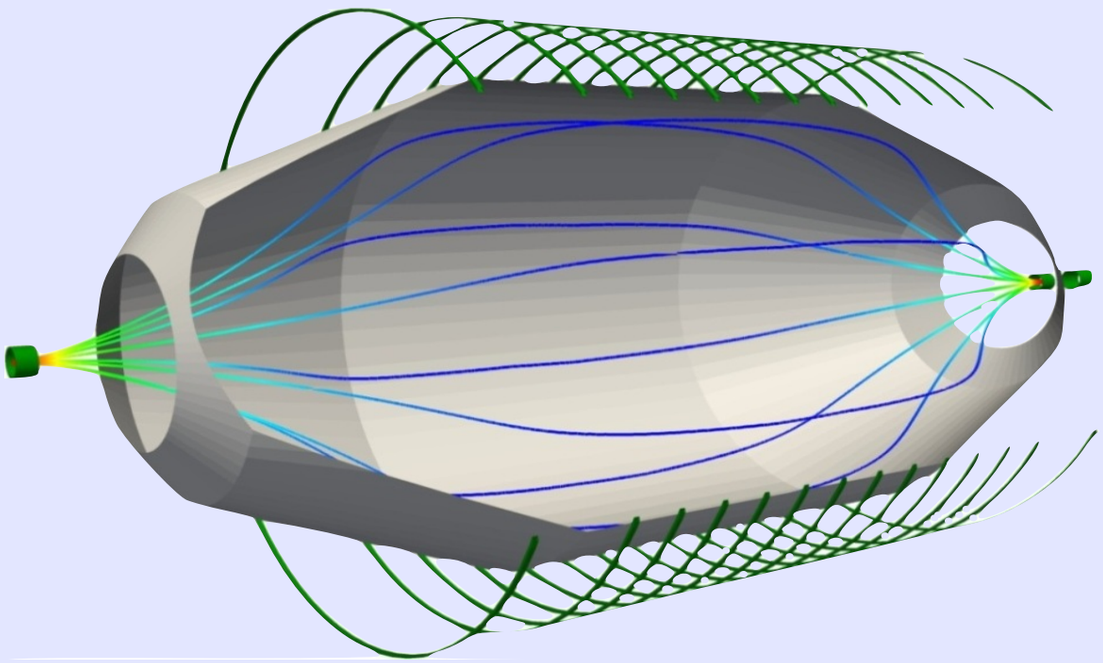




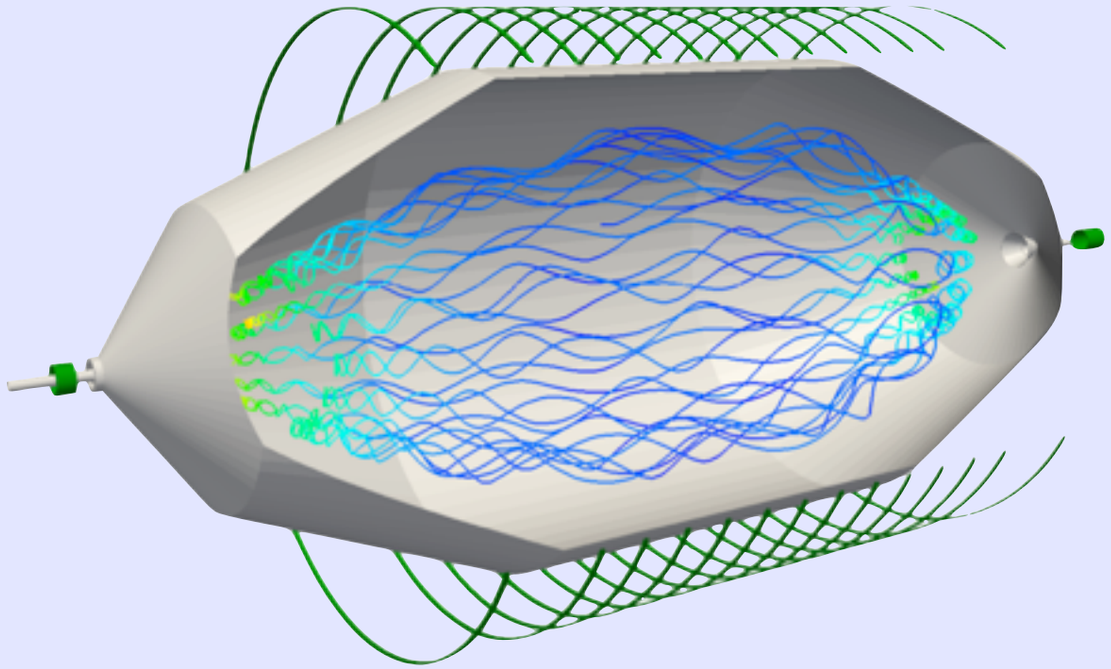


Spectrometer Commissioning

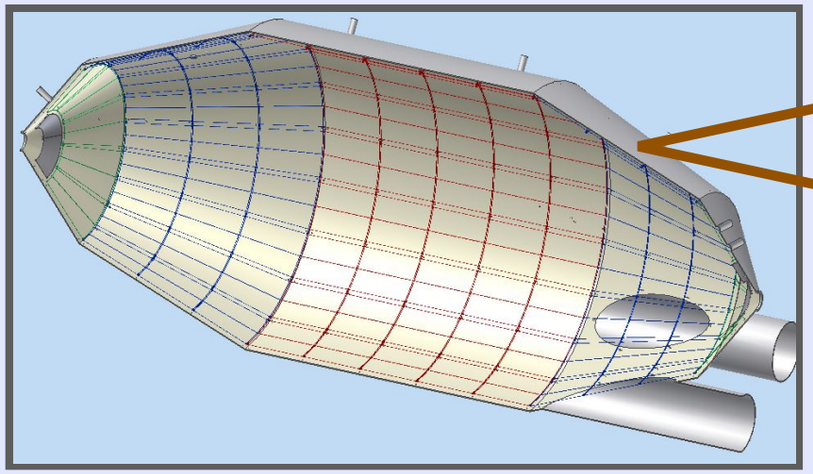
Transmission of
β electrons

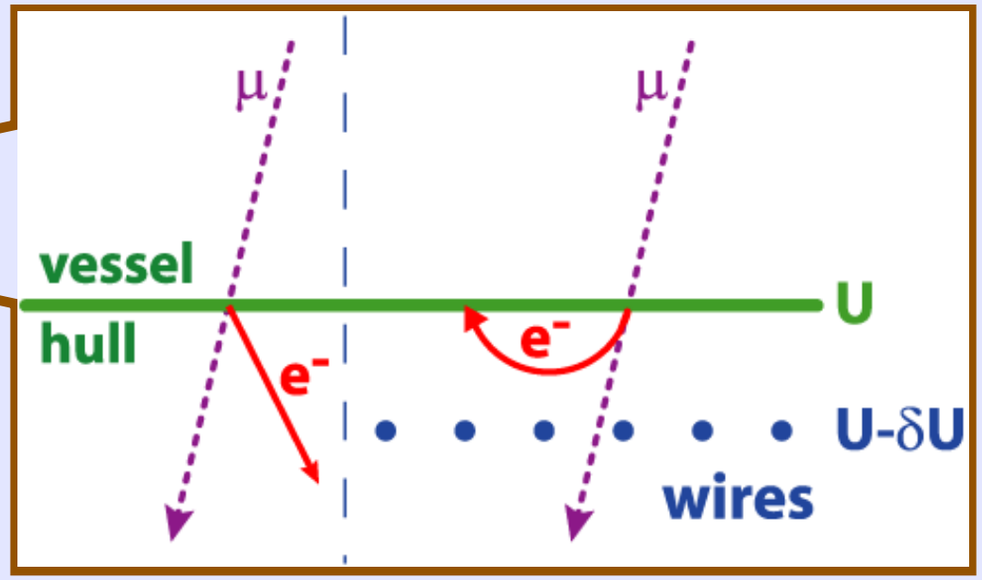


Eliminating trapped
electrons



Background e^- Sources

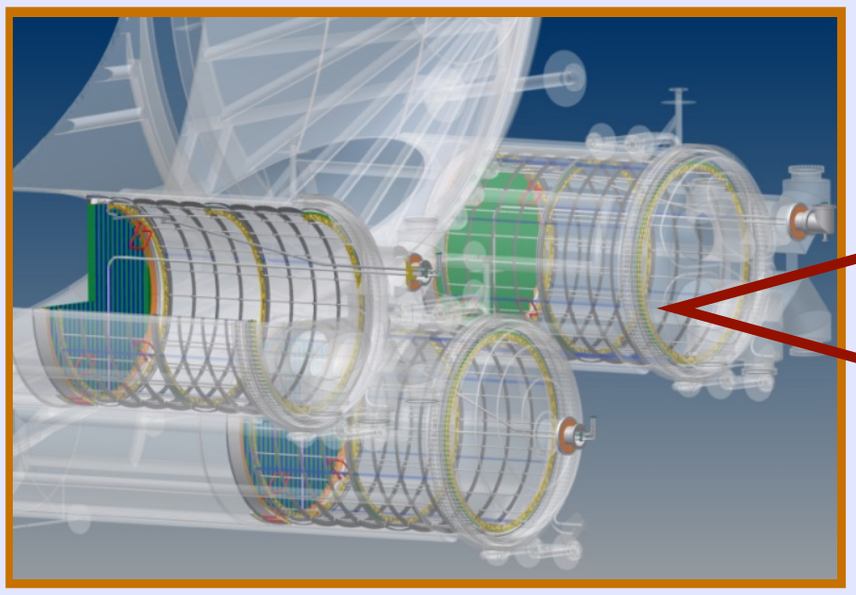


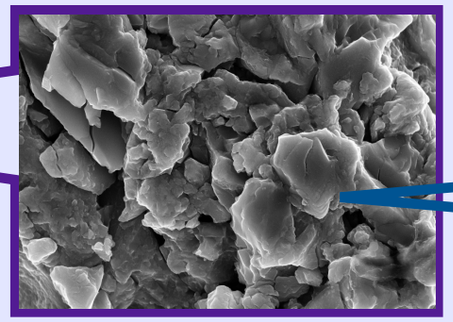


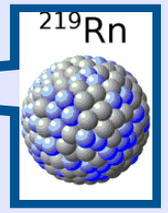
Cosmic rays knock electrons from the vessel hull

Radon emanation from the getter material

Electrons generated by shakeoff, conversion, relaxation …

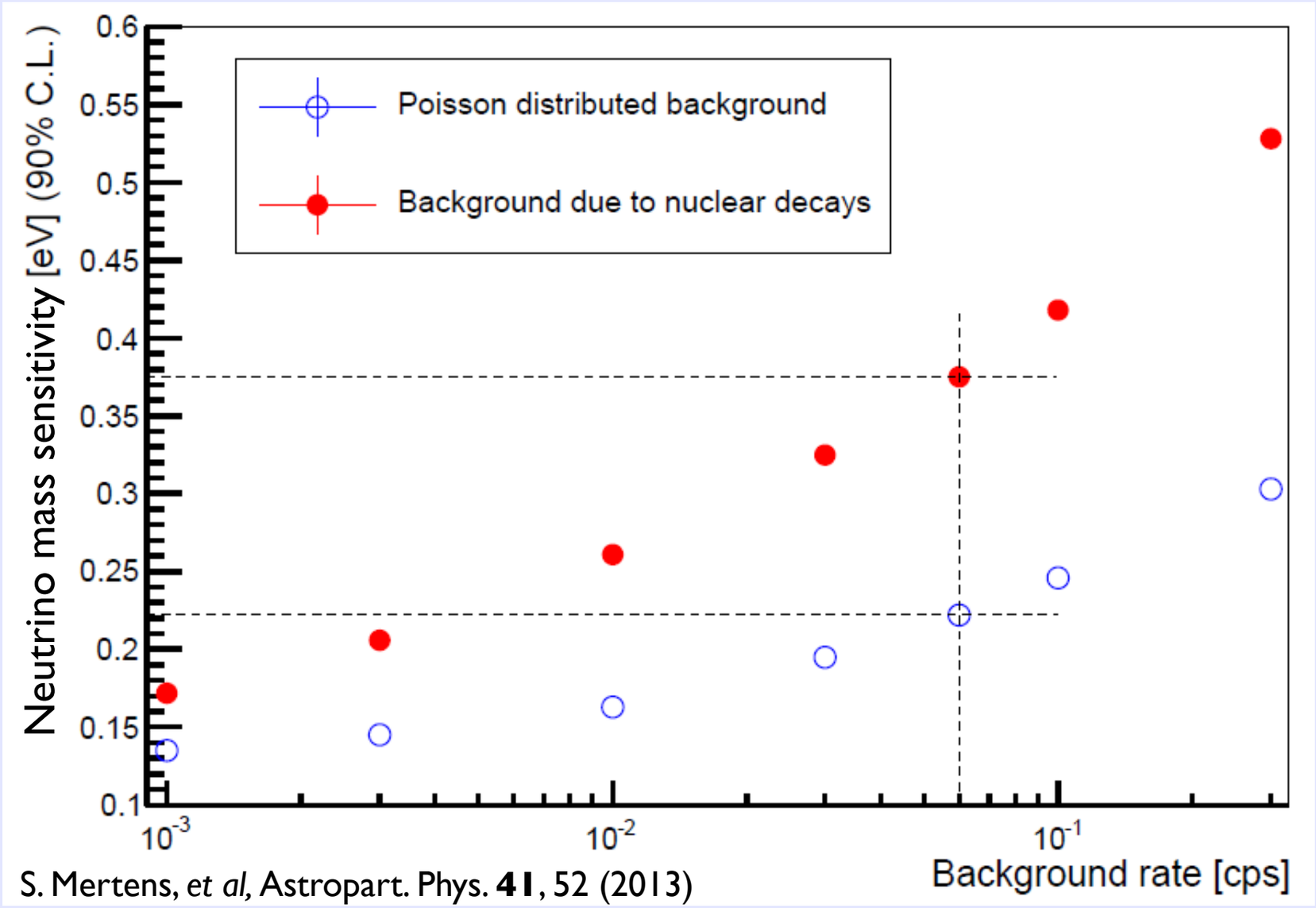






Radon-Induced Background

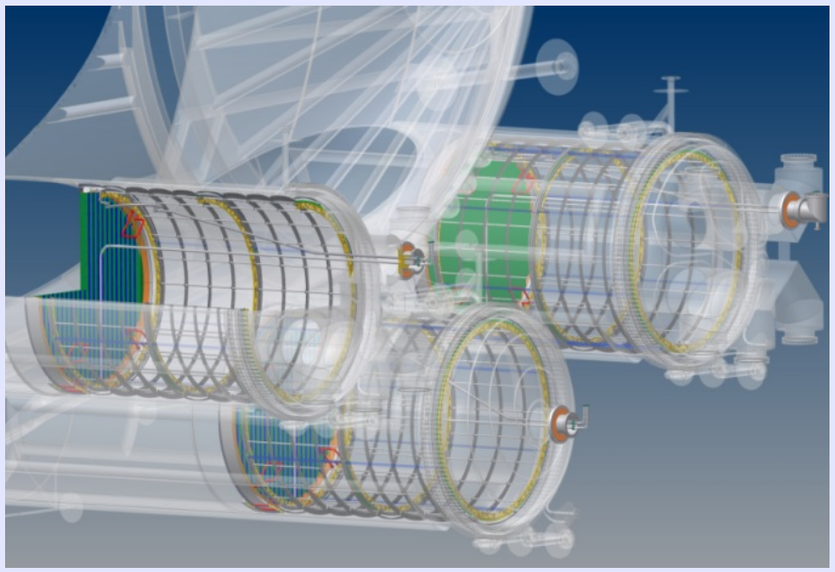
- Background may be 6-times worse than otherwise expected
- Statistical sensitivity would decrease by a factor of 1.7
- Results depend on run lengths, voltage scan characteristics, etc.



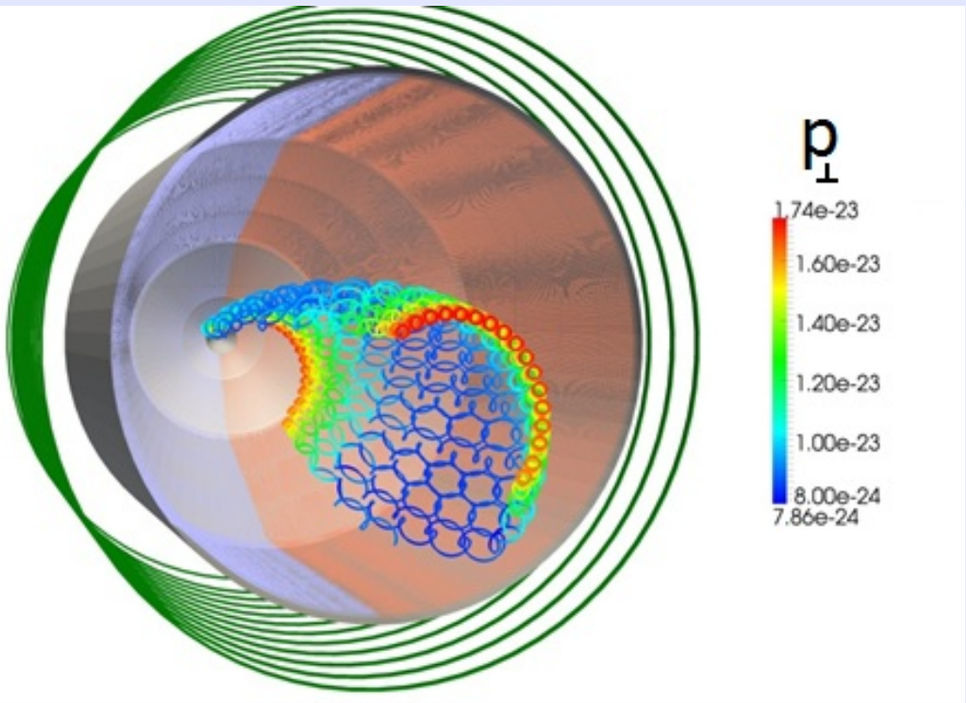
S. Mertens, *et al,* Astropart. Phys. **41**, 52 (2013)

Stored e^- Reduction

- Passive: trap Rn atoms
  - ❖ Cryo-Baffle
  - ❖ Pumping speed decreases by 55%

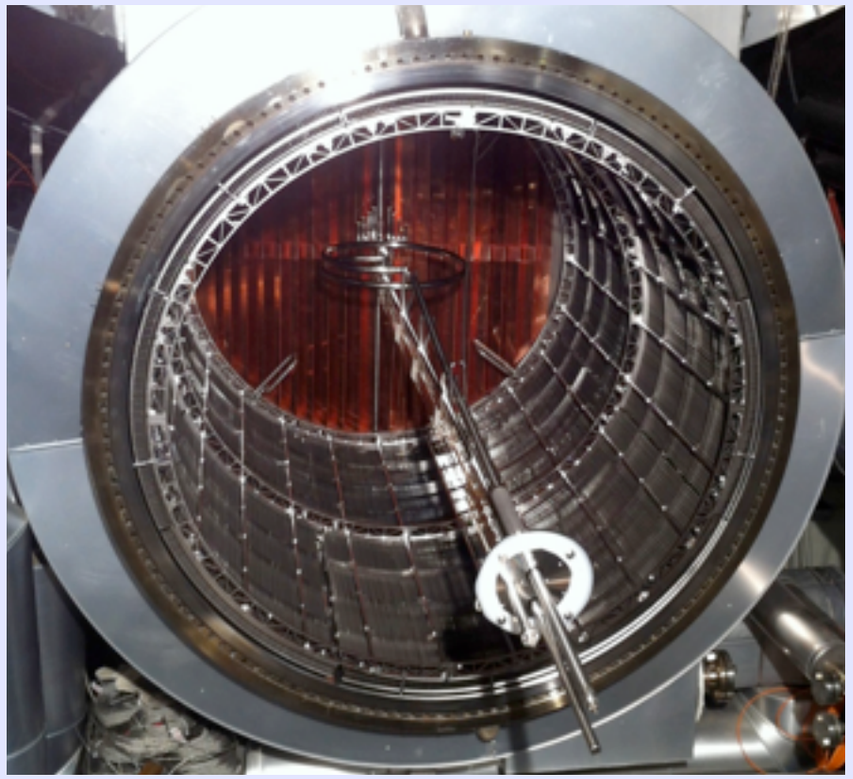


- Active: force e^- into hull
  - ❖ Dipole Electric Field

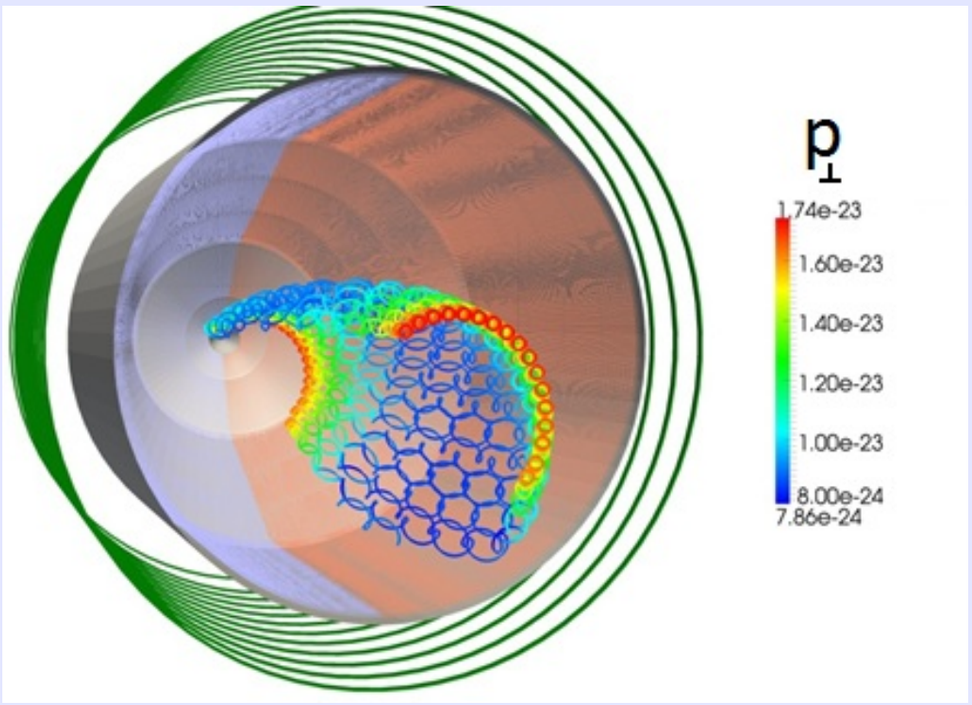


Stored e^- Reduction

- Passive: trap Rn atoms
  - ❖ LN-cooled copper baffle
  - ❖ Pumping speed decreases by 55%



- Active: force e^- into hull
  - ❖ Dipole Electric Field



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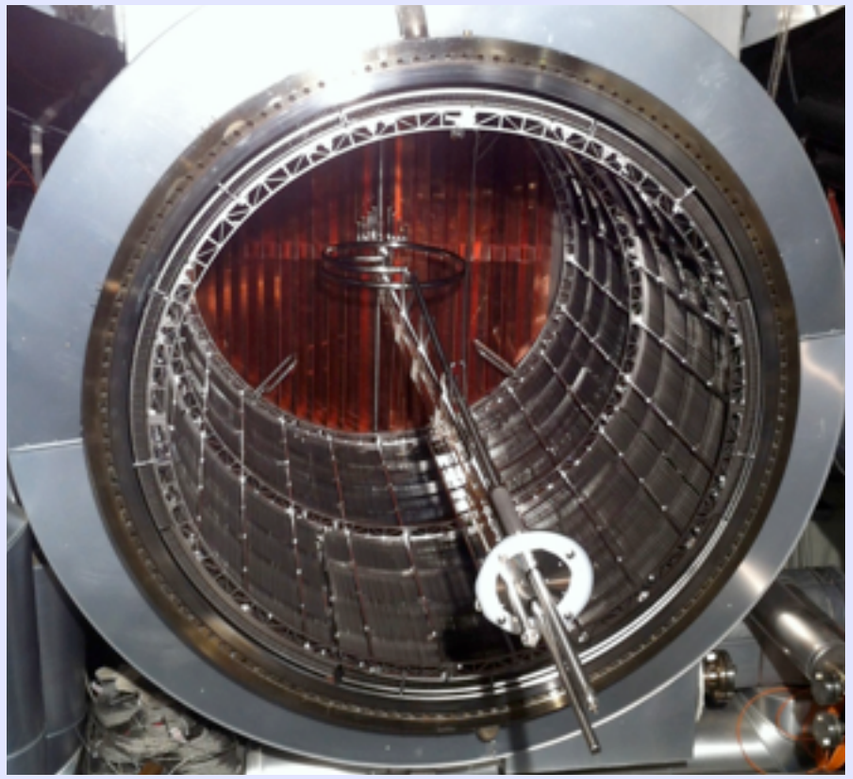

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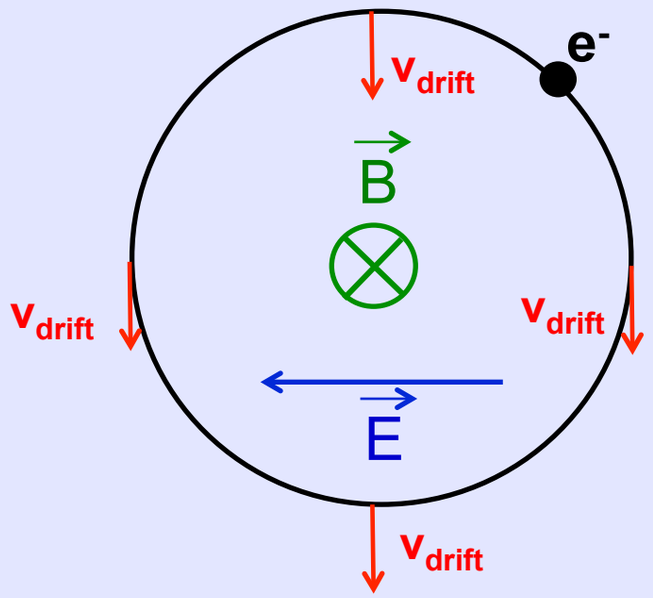
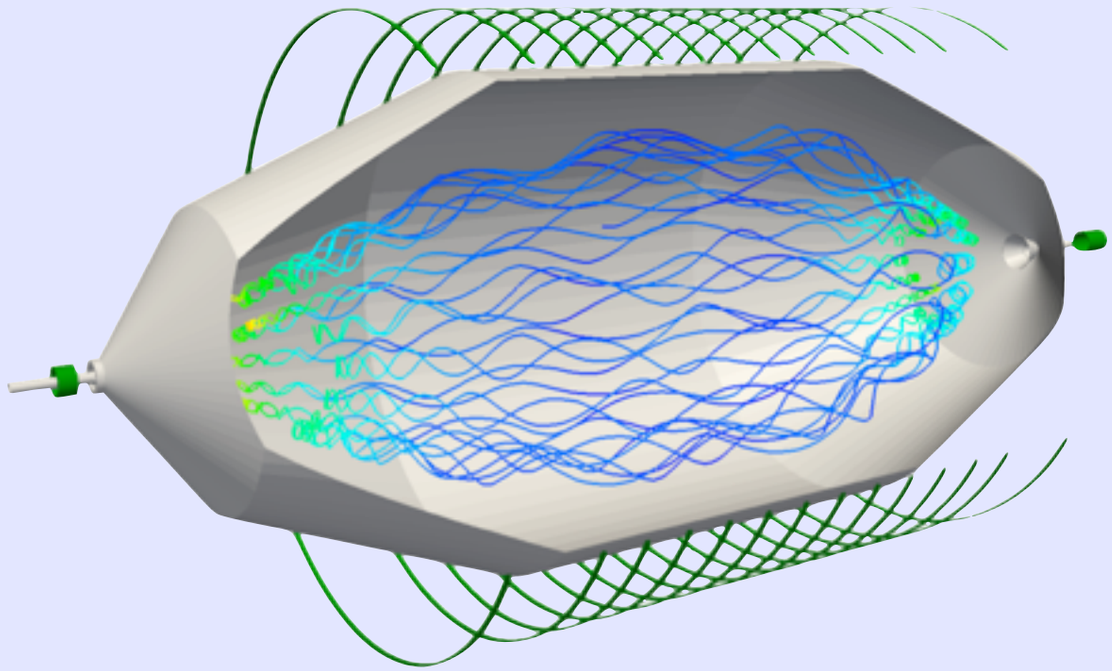
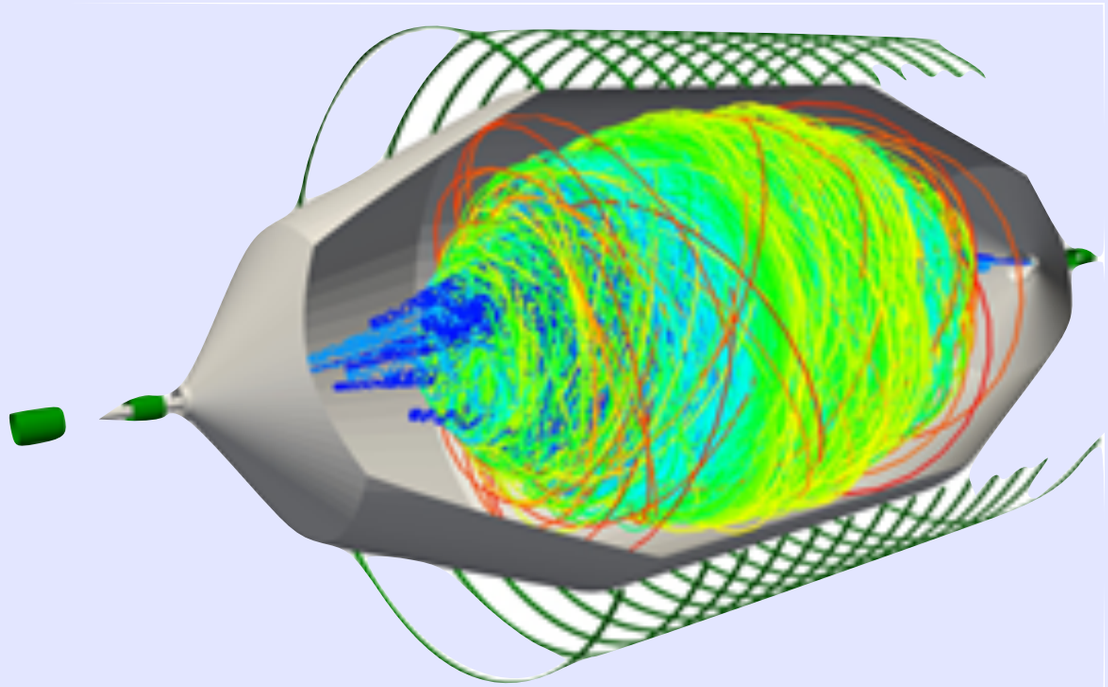


Simulations: Kassiopeia

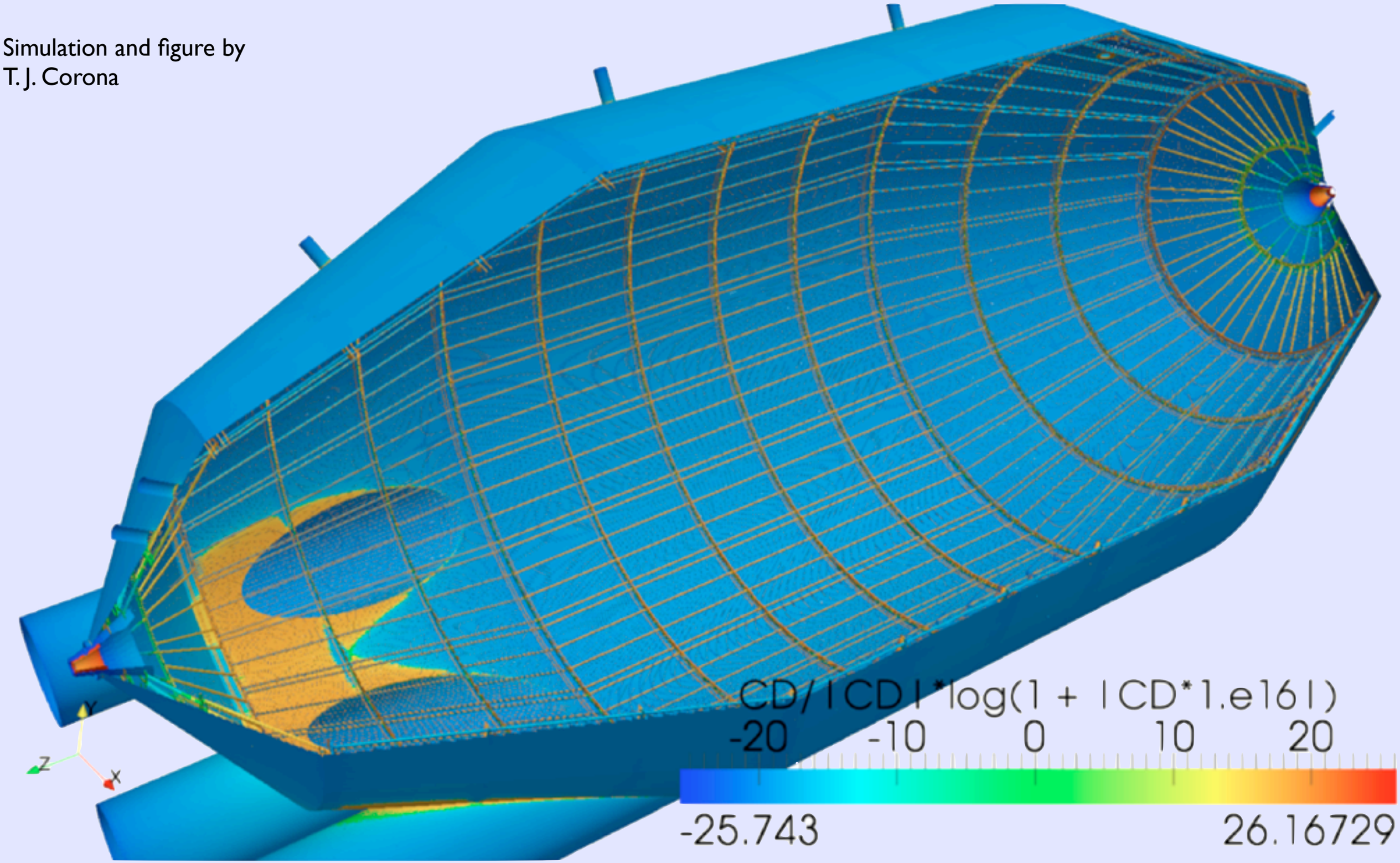
- Simulations of electric and magnetic fields
- Low-energy particle tracking in EM fields
- Available to the public (open source) in a few months



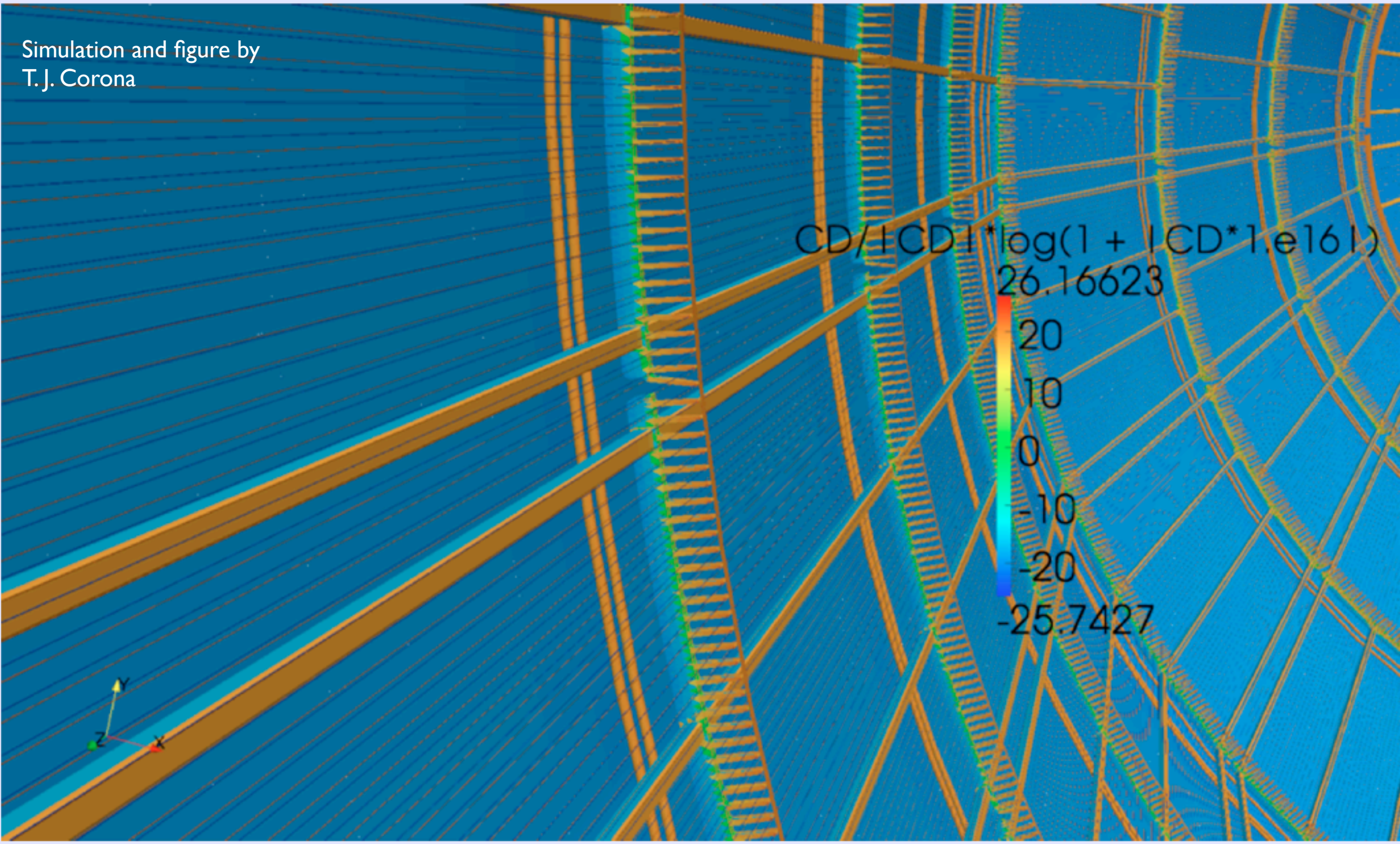


Simulations: Kassiopeia

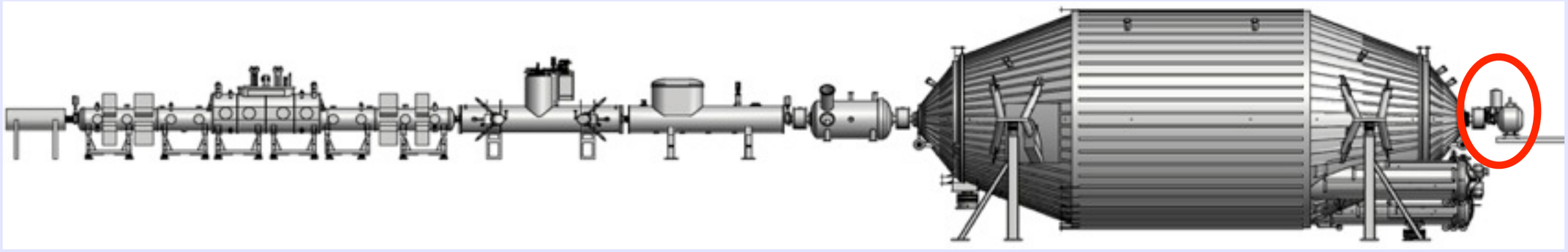
Simulation and figure by
T. J. Corona



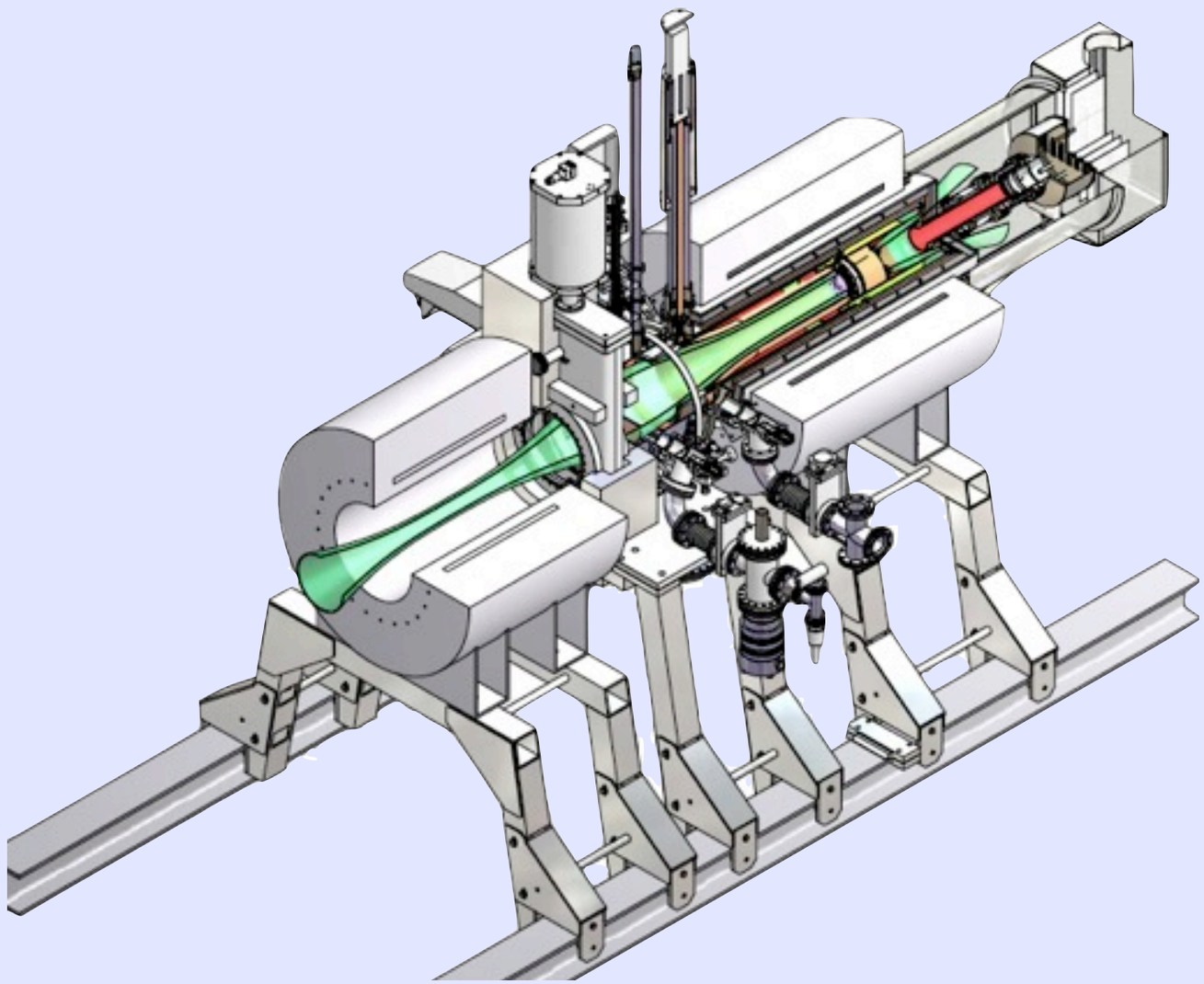
Simulations: Kassiopeia



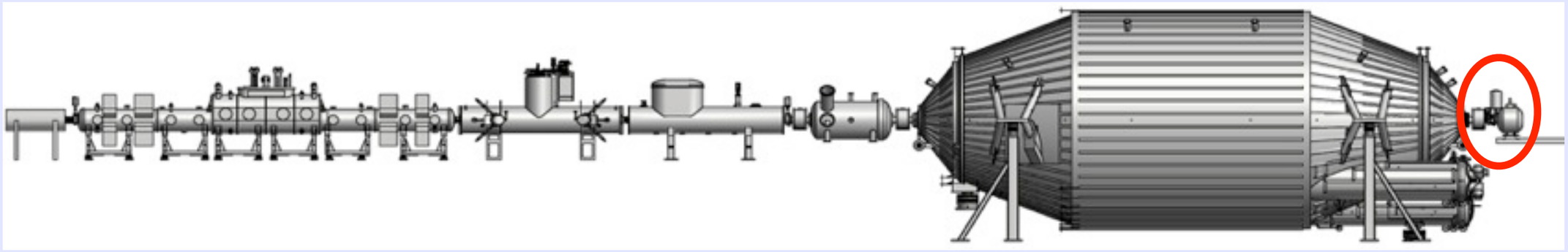
Detector



- Pinch Magnet
  - ❖ Provides the maximum magnetic field (6T)
  - ❖ Defines the energy resolution of the spectrometer
- Detector Magnet
  - ❖ Strong magnetic field (3-6 T)
  - ❖ Focuses electrons onto the detector
- Focal Plane Detector
  - ❖ Segmented Si PIN diode array
  - ❖ 148 pixels; area = 50 mm^2
- Muon Veto
  - ❖ Passive: copper & lead
  - ❖ Active: plastic scintillator



Detector



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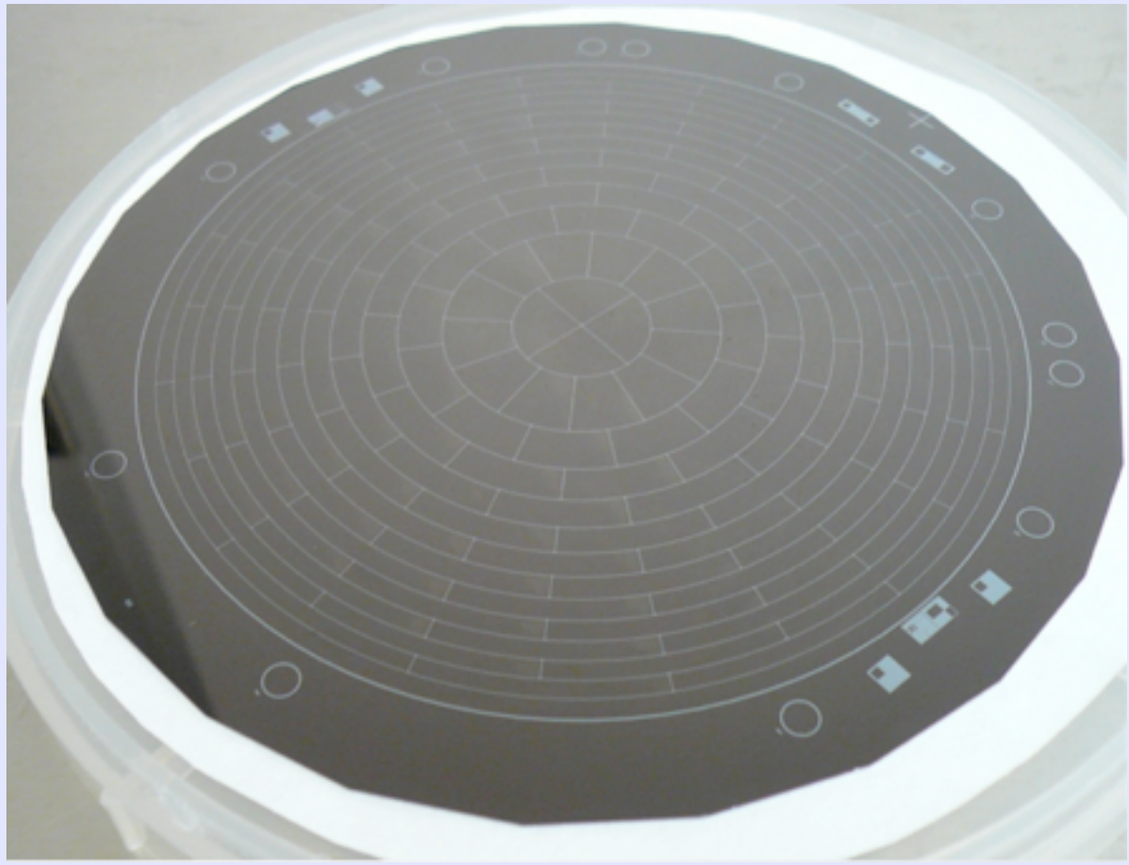
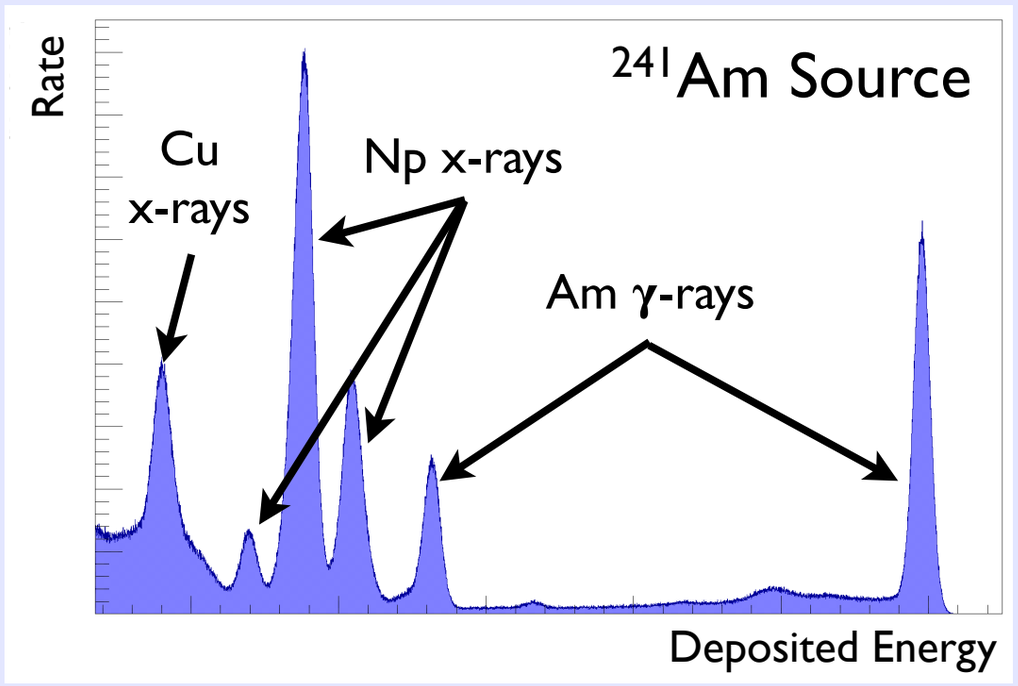


Commissioning

- Ensure detector pixels are functioning
- Check ability to reach XHV
- Calibrate electronics response
- Measure the energy resolution

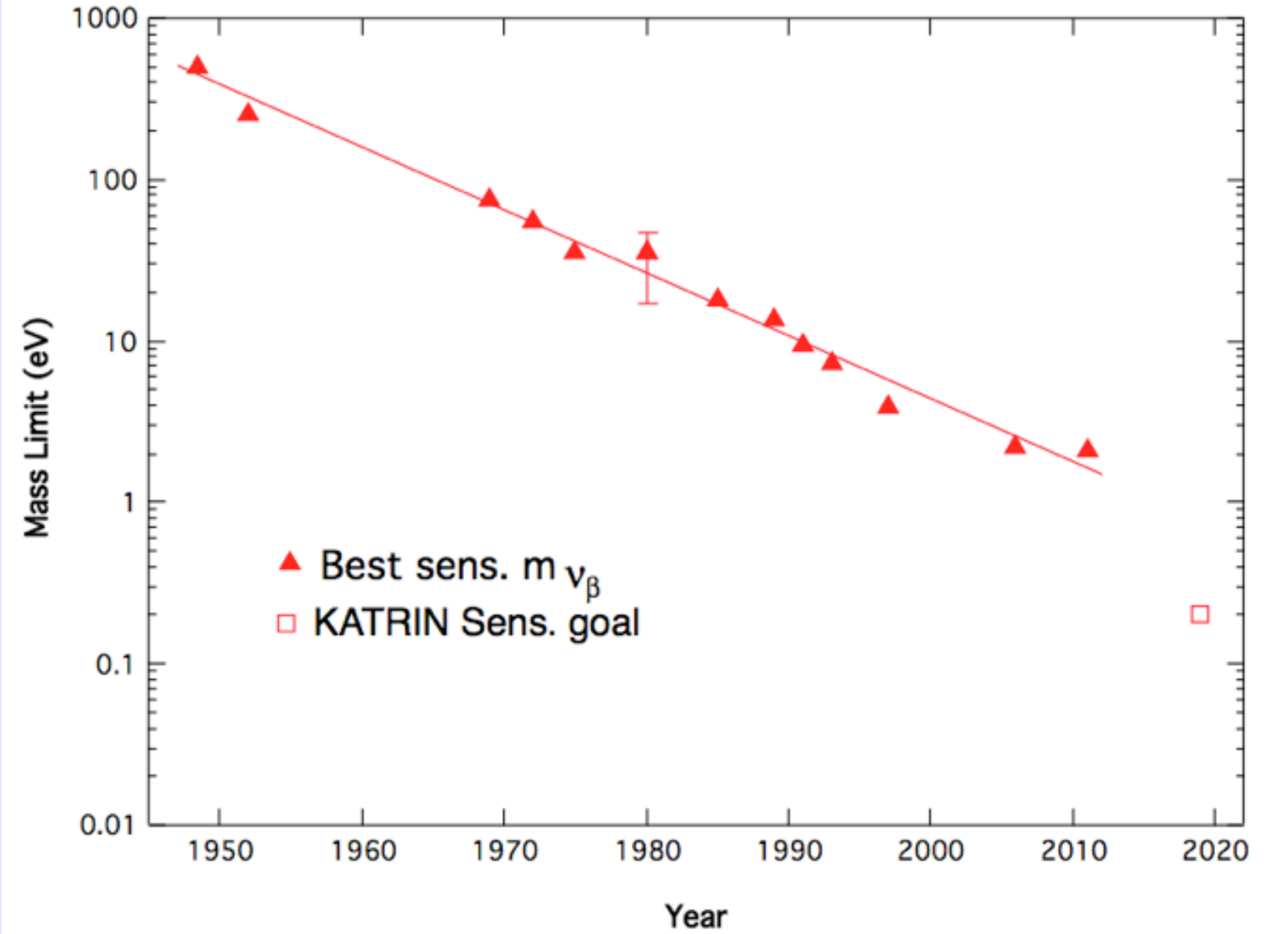
Energy Calibration



KATRIN's Sensitivity

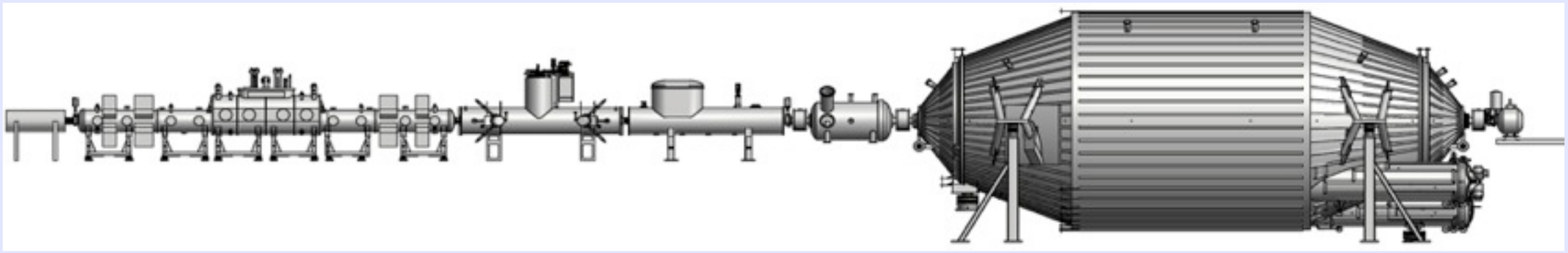
- 3 years of runtime
- $\sigma_{stat} \approx \sigma_{sys}$
- Discovery:
  $m_\nu = 350$ meV (5σ)
- Upper limit:
  $m_\nu < 200$ meV
  (90% CL)

T_2 Experiment Sensitivity History



J. F. Wilkerson, Neutrino 2012

Summary and Outlook



- Progress on all components
  - ❖ WGTS … Differential pumping … Cryogenic Pumping … Main Spectrometer … Detector
- Sensitivity still to be proven, but so far we're on track
- Data taking planned for 2015

Backup Slides

KATRIN's Sensitivity

- 3 years of runtime
- $\sigma_{stat} \approx \sigma_{sys}$
- Discovery:
  m_ν = 350 meV (5σ)
- Upper limit:
  m_ν < 200 meV
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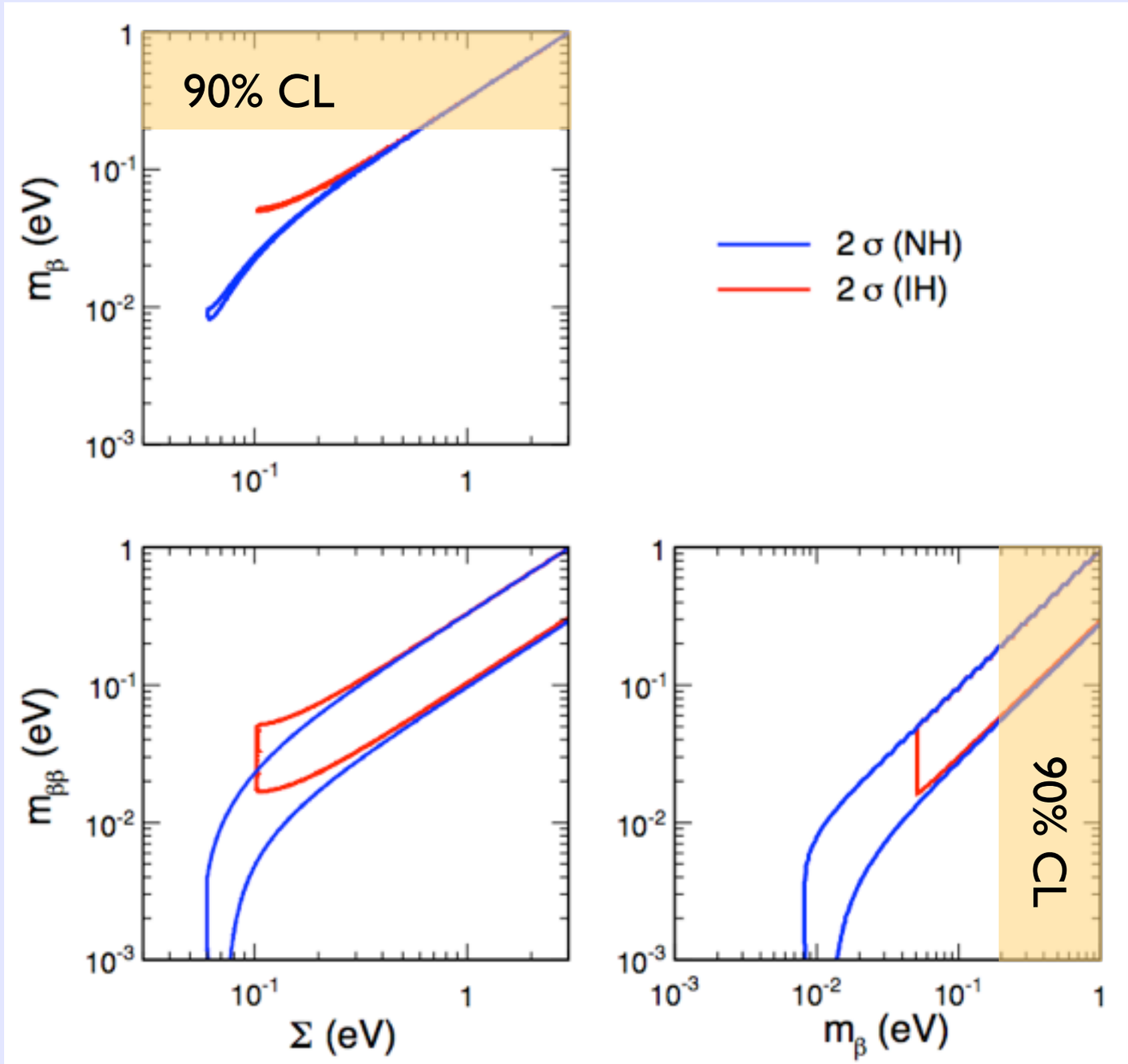
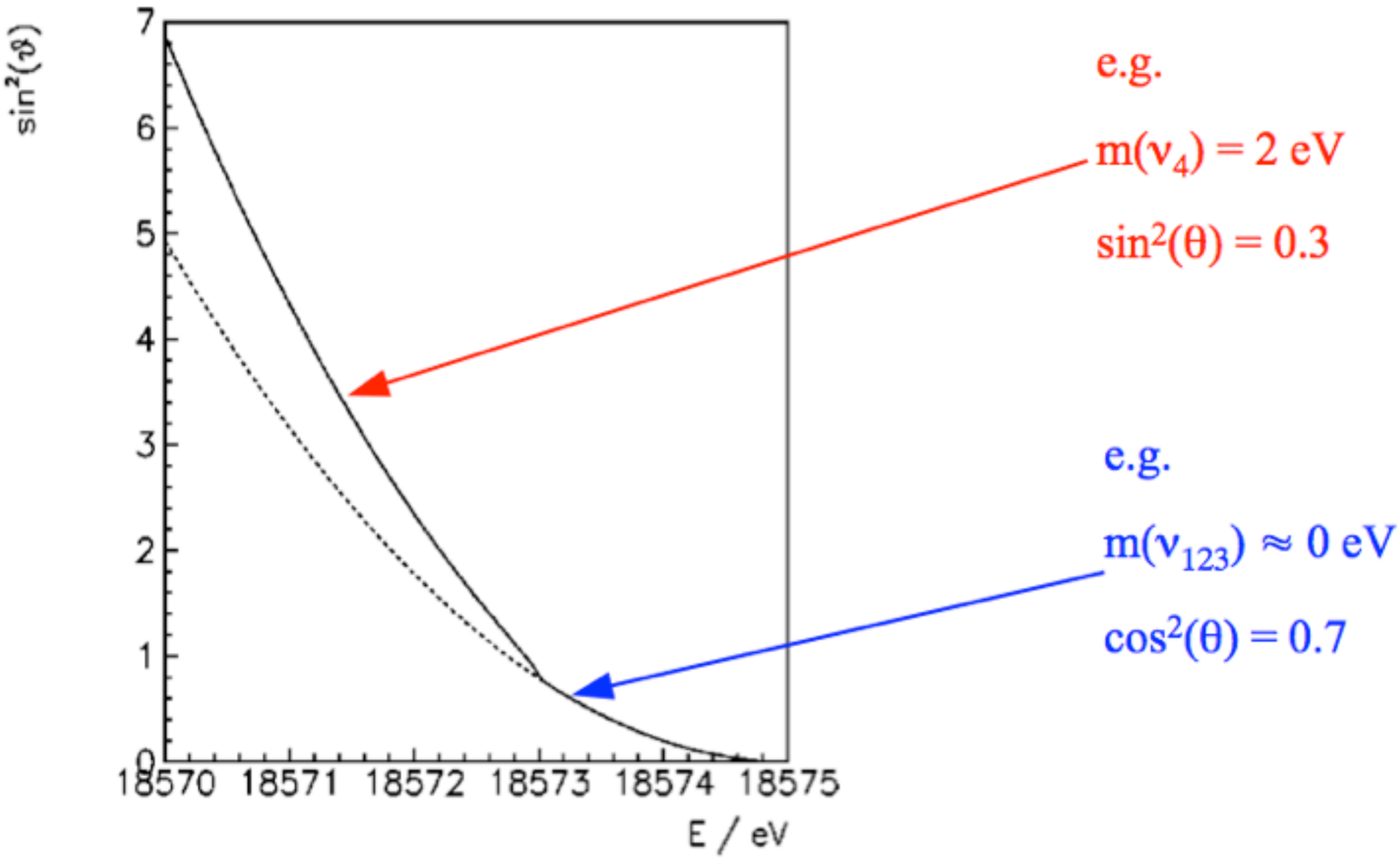


E. Lisi, Tuesday; G. L. Fogli, *et al.*, arXiv:1205.5254 [hep-ph]

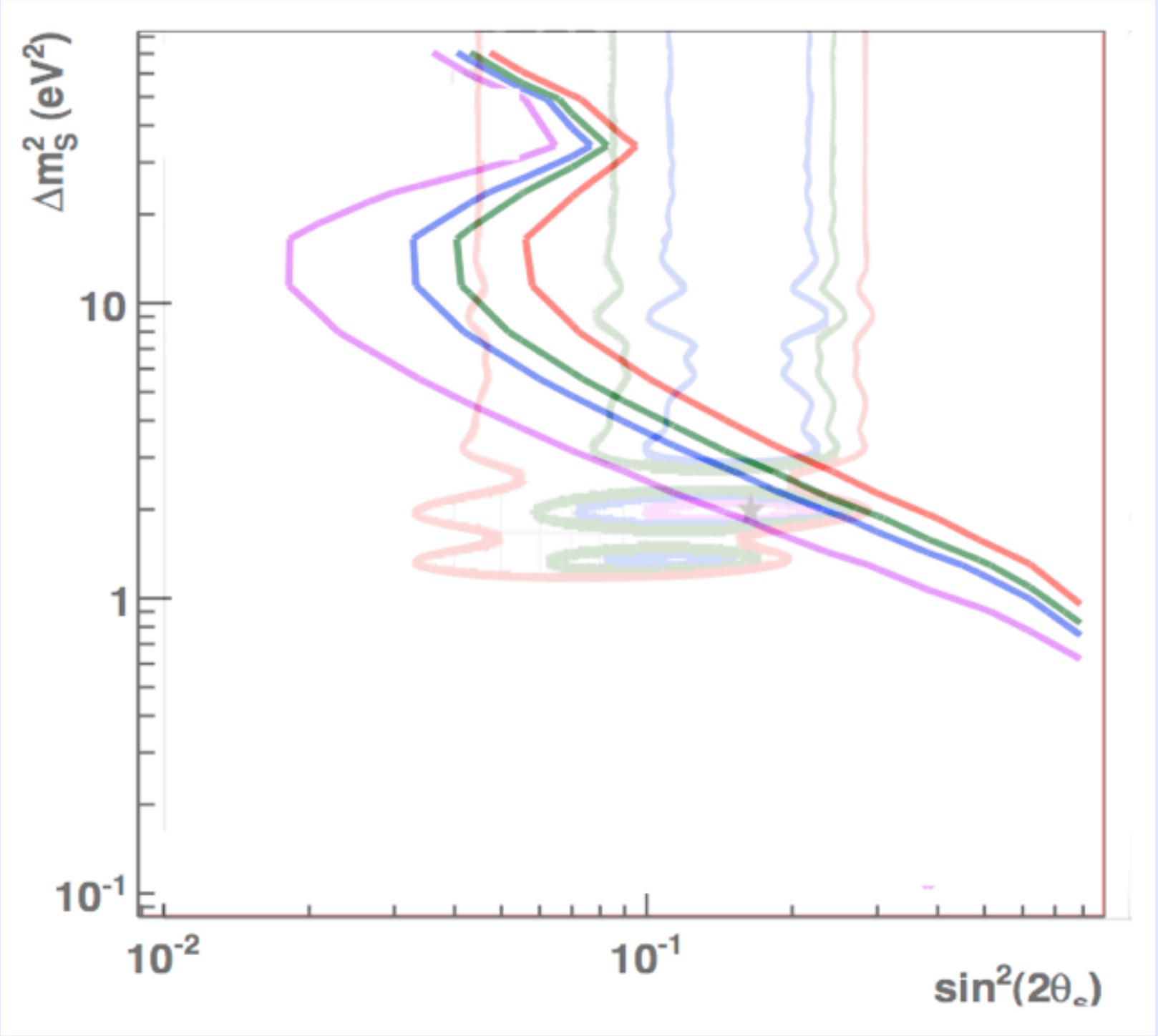
Detecting Steriles

$$dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e)\ \left(\cos^2(\theta)\sqrt{(E_0-E_e)^2 - m(\nu_{1,2,3})^2} + \sin^2(\theta)\sqrt{(E_0-E_e)^2 - m(\nu_4)^2} \right)$$



C. Weinheimer, NuMass 2013

Reactor Anomaly



J. Formaggio, J. Barrett, arXiv:1105.1326 [nucl-ex]