How to detect a nuclear explosion using a SAUNA

Tomas Fritioff

FOI
Swedish Defence Research Agency

Outline

- Introduction, FOI and radionuclide detections
- Why look for radioactive noble gases in the atmosphere
- The Comprehensive Nuclear Test Ban Treaty (CTBT)
- The SAUNA II system
- What can the system detect and how
- Future development
- Conclusion

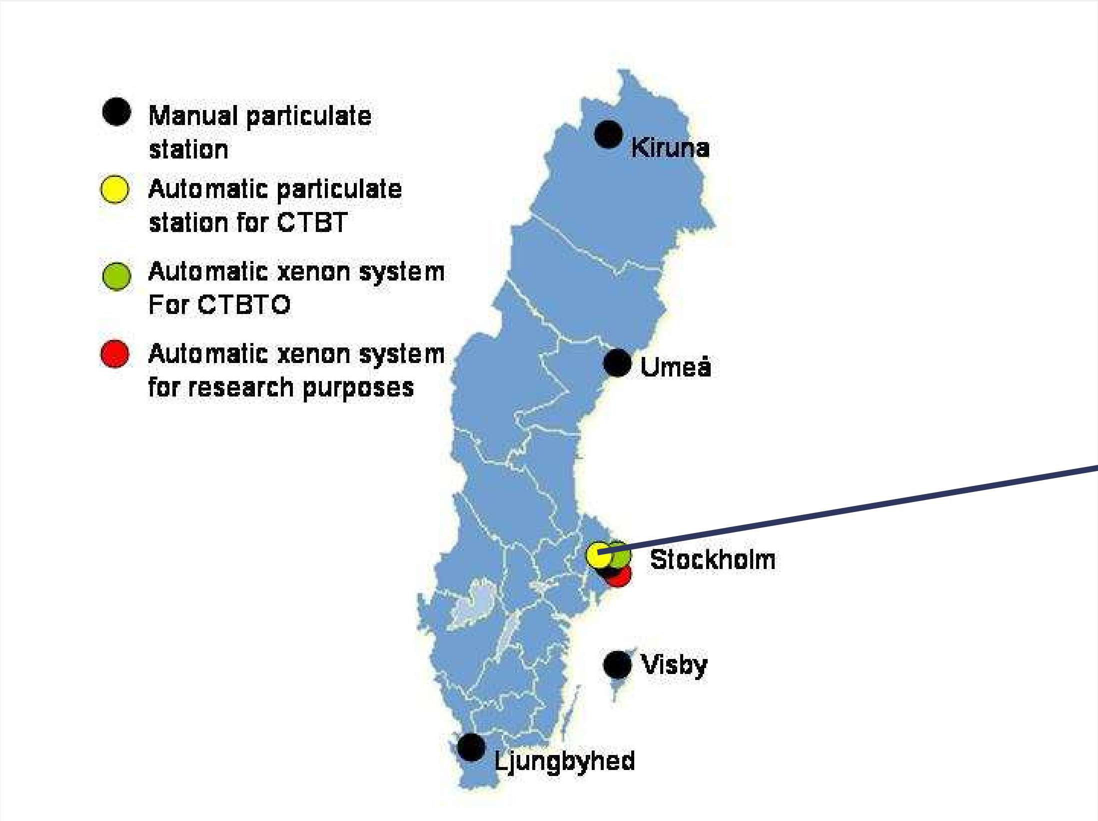
Introduction

Examples of activities at FOI related to nuclear weapons issues

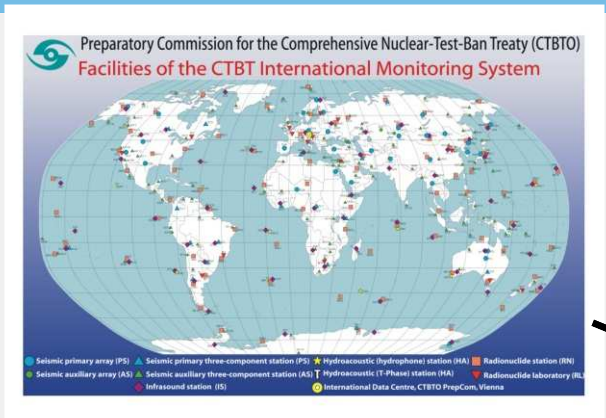
- Technical advisor to the Swedish government
  - MFA(Ministry for Foreign Affairs)

    (CTBTO – Vienna, FMCT(Fissile Material Cut-off Treaty) - Conference on Disarmament, Geneva)
  - Export control issues (Nuclear Suppliers Group)
  - NPT(Nuclear Non-Proliferation Treaty)
- Routine monitoring of airborne radioactivity (SSM)
- National Data Center for CTBT (radionuclide and seismic)
- Development of verification techniques used nationally and/or in international verification regimes
- Worked with radionuclide monitoring since the 1950ies

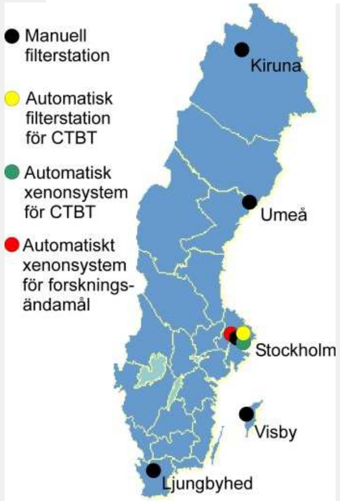
Radionuclide stations in Sweden



National Data Center for radionuclides (NDC)

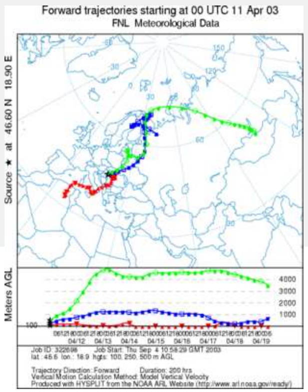


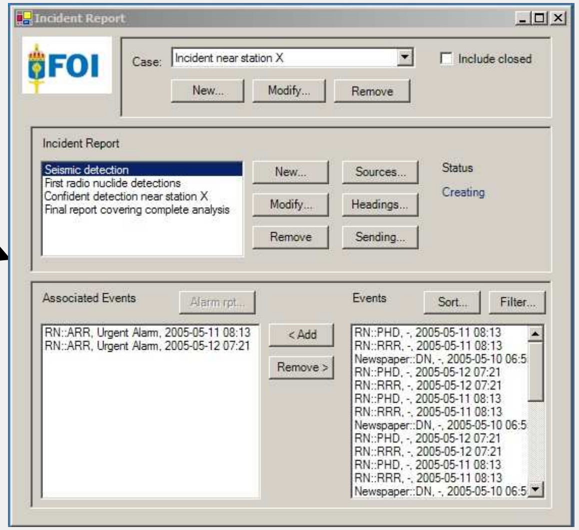
IMS



National stations

Met data





database

Software tools for
- data analysis
- Report production
- QA incident handling

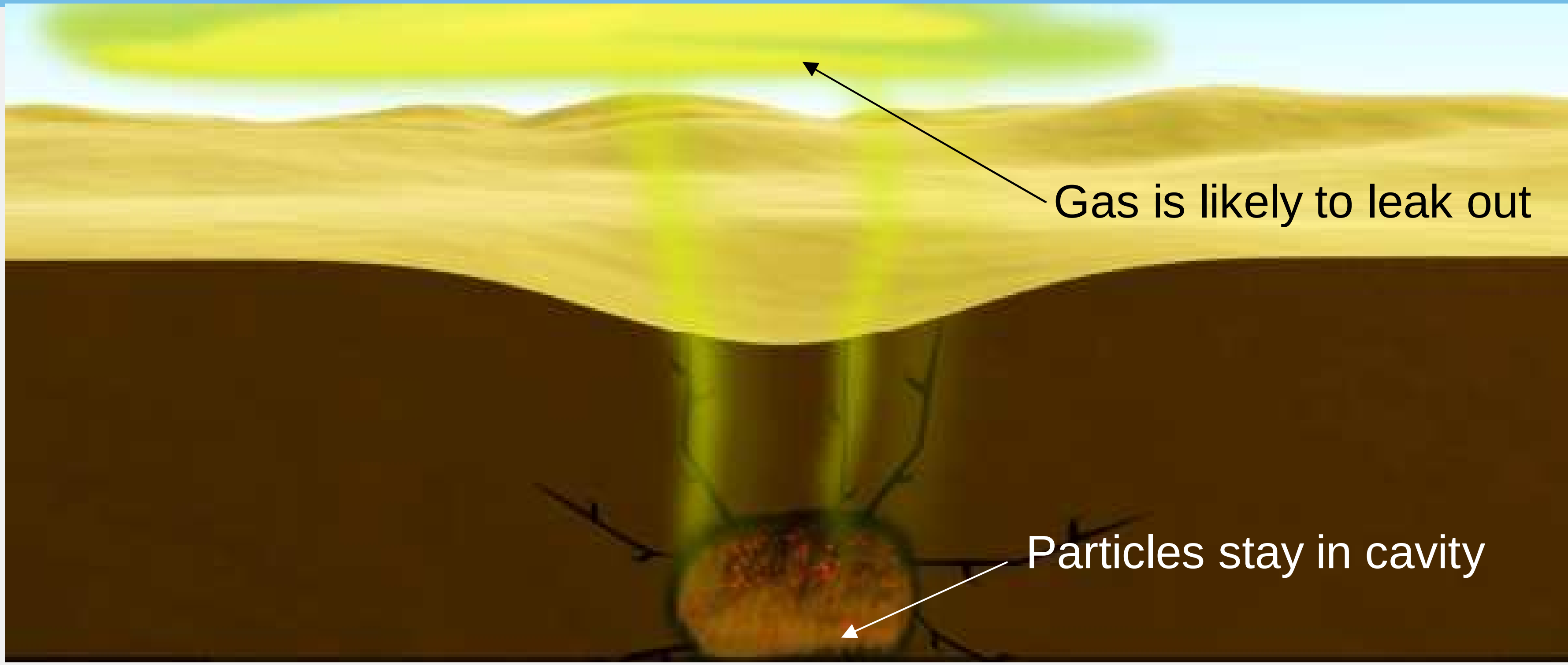
Other information

Why look for radioactive noble gases

November 1, 1951 “Dog”

December 18, 1970 “Baneberry”

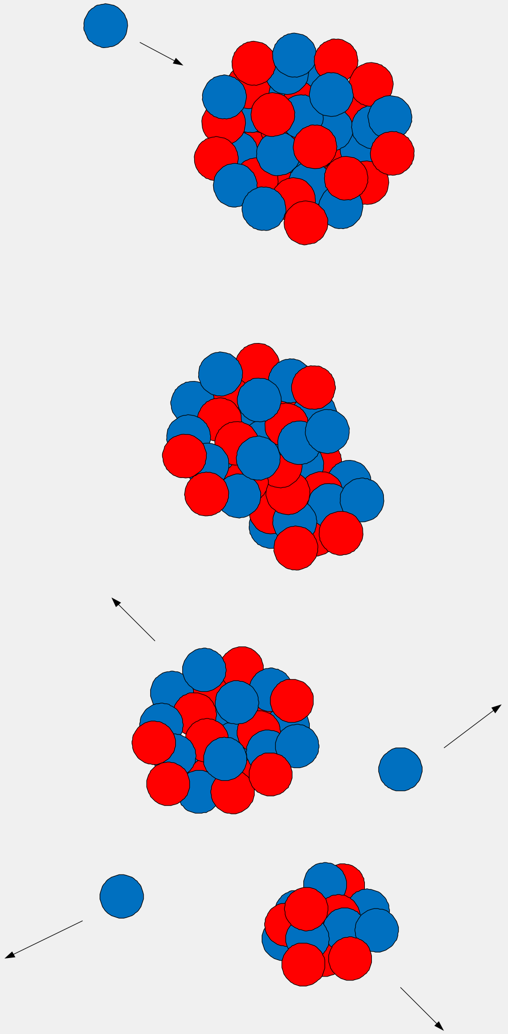
Why look for radioactive noble gases



- Volatile substance, it’s a gas
- Indicates nuclear reactor usage
- Isotope ratios can be used to determine the source
- Not washed out by rain => spread over long distances
- Is released from underground nuclear tests!
- Stable Xenon concentration is constant in atmosphere 0.087ppm

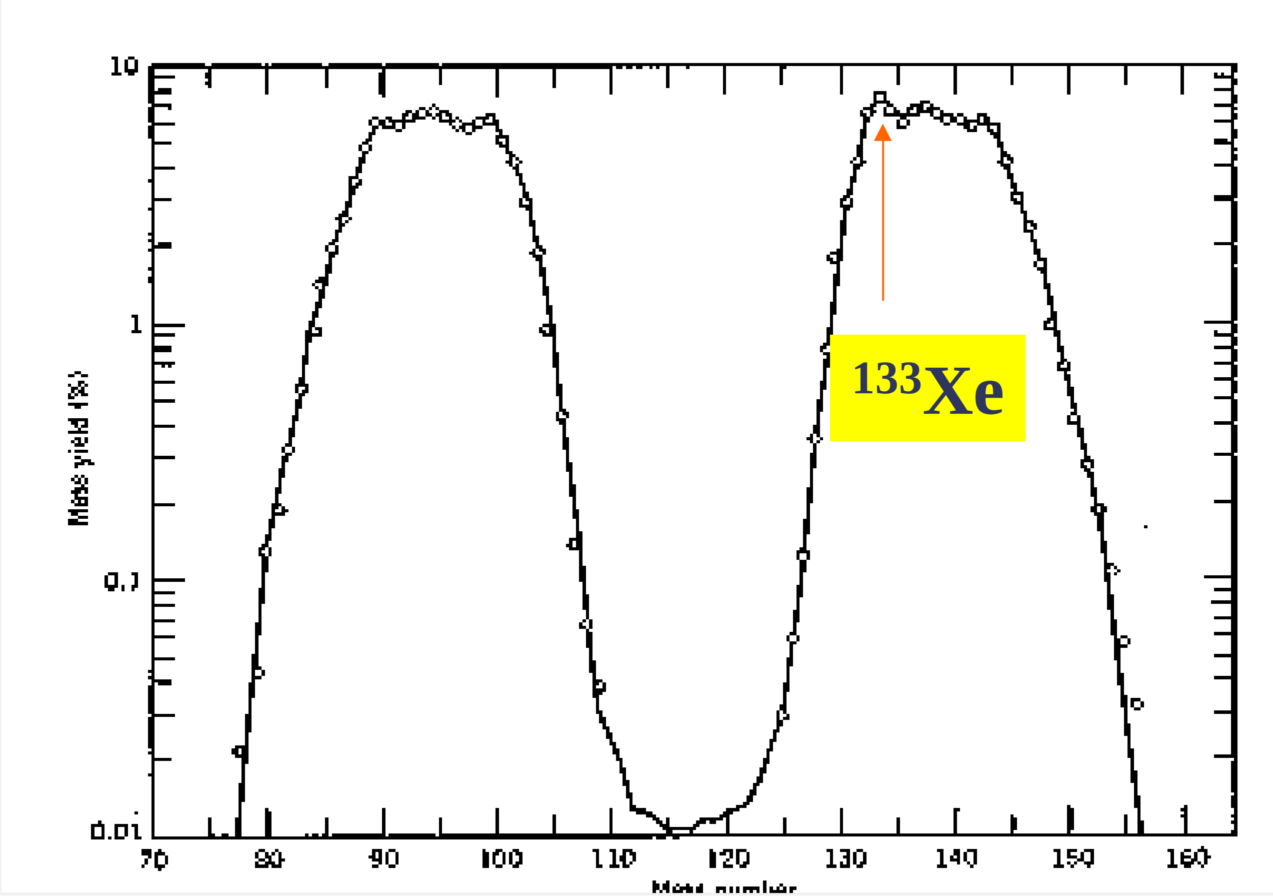
FOI

Why look for radioactive noble gases

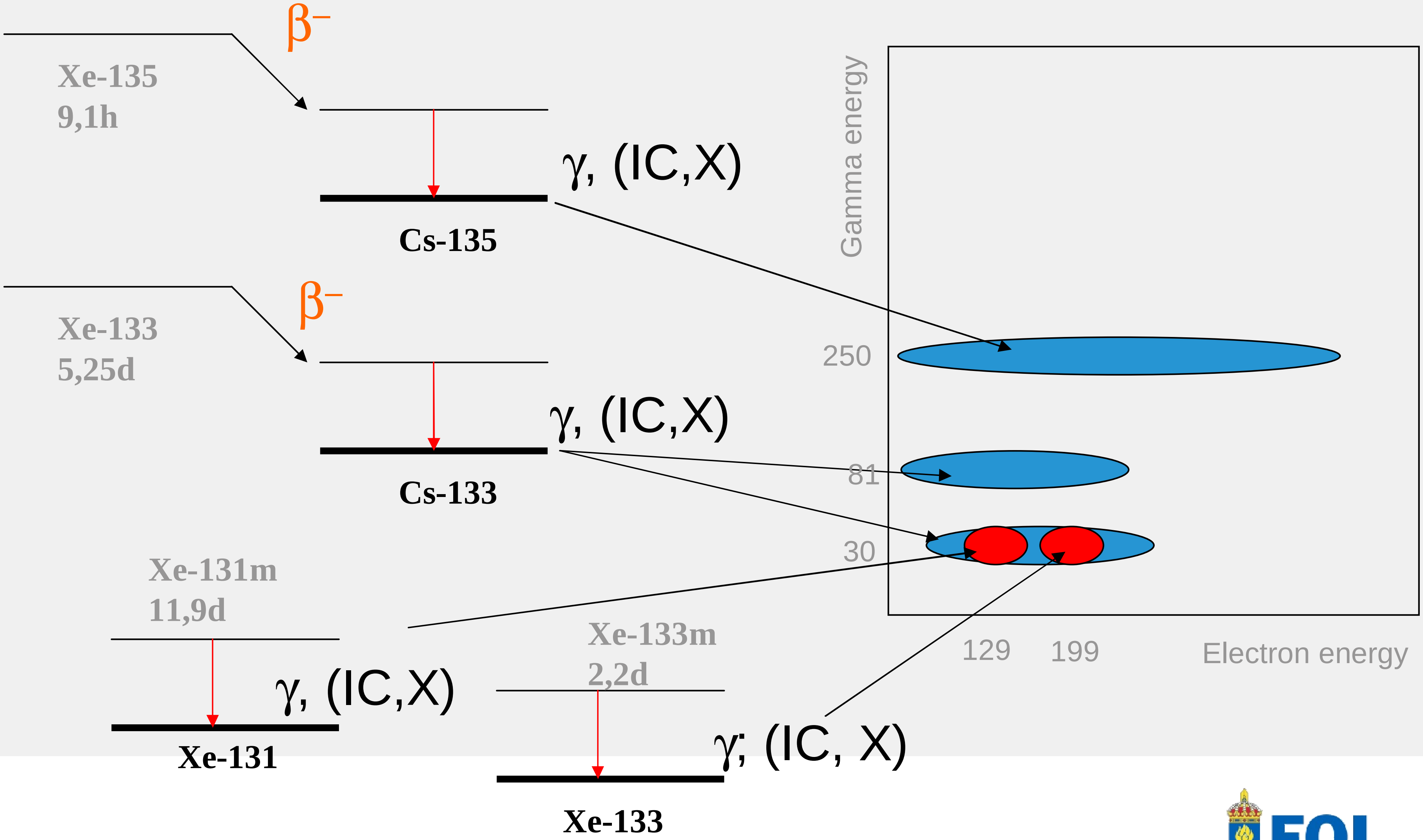


Fission products from nuclear explosions

$$^{235}U + n \longrightarrow {}^{133}Xe + {}^{101}Sr + 2n$$

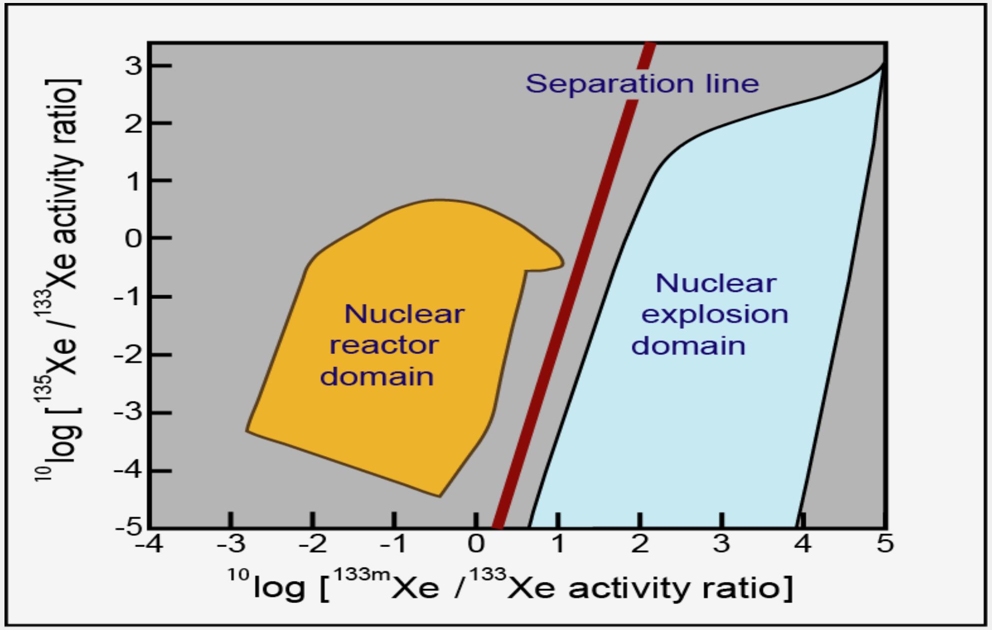


The strongest Xenon decay modes

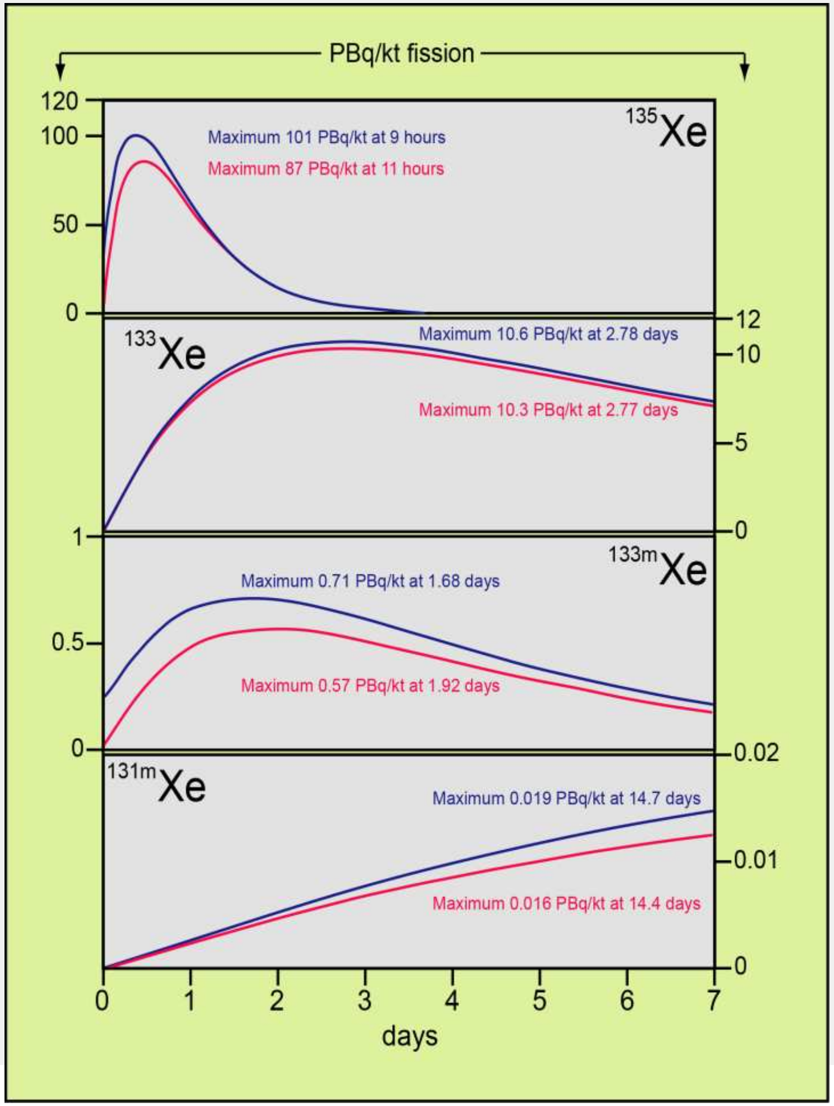


How to make use of the Xenon isotopes

^{239}Pu
^{235}U



The three isotope ratio plot
^{133m}Xe/^{133}Xe vs ^{135}Xe/^{133}Xe



CTBT Comprehensive Nuclear Test Ban Treaty (1996)

CTBT artikel 1, ”Basic obligations”:

“Each State Party undertakes not to carry out any nuclear weapon test explosion or any other nuclear explosion, and to prohibit and prevent any such nuclear explosion at any place under its jurisdiction or control”

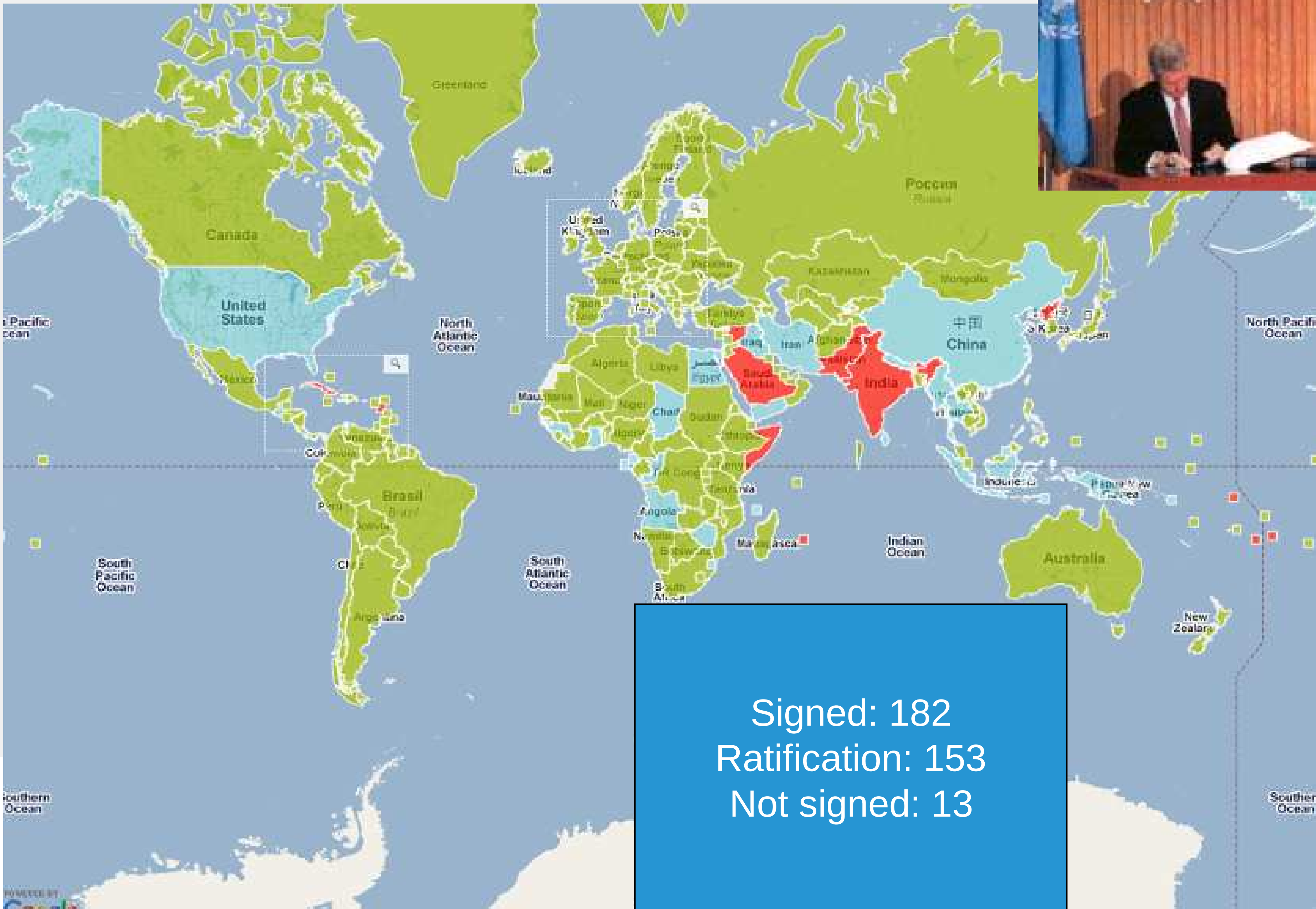
- CTBT is a treaty that forbids nuclear tests
- No promise by the signing states to reduce or to stop developing nuclear weapons

FOI

CTBT – possible effects

- Nuclear states are able to keep their stockpile functioning for decades and perform updates and new weapons of old material
- The nuclear states are not (easily) able to make radically new bomb designs
- No state is able of new-development of a two-stage thermo-nuclear device that can be trusted
- A non nuclear state can probably build a canon type Uranium bomb without breaking the treaty (but NPT). A fission type bomb can also be design but with less confidence

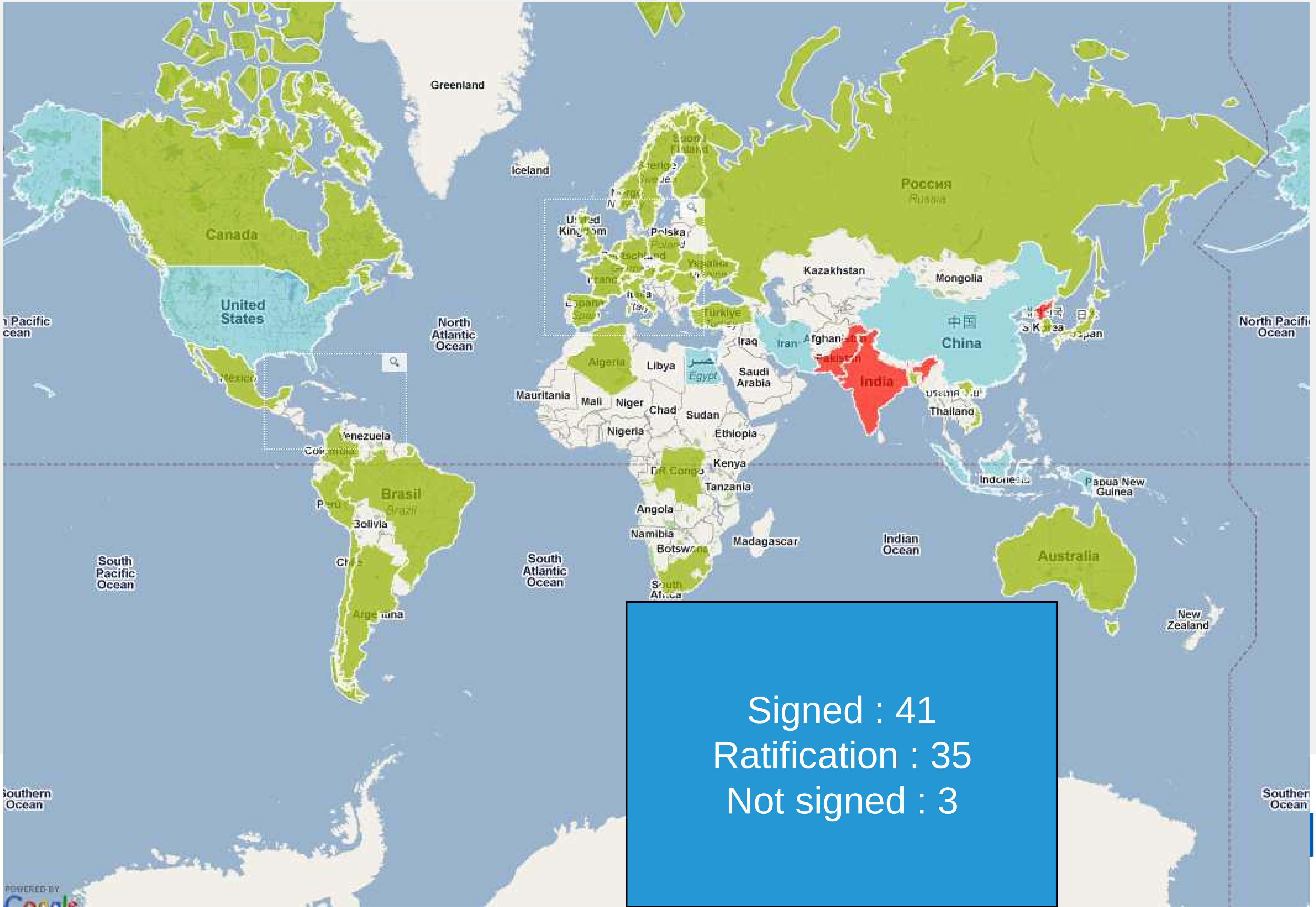
CTBT – status (195 states)



Signed: 182
Ratification: 153
Not signed: 13

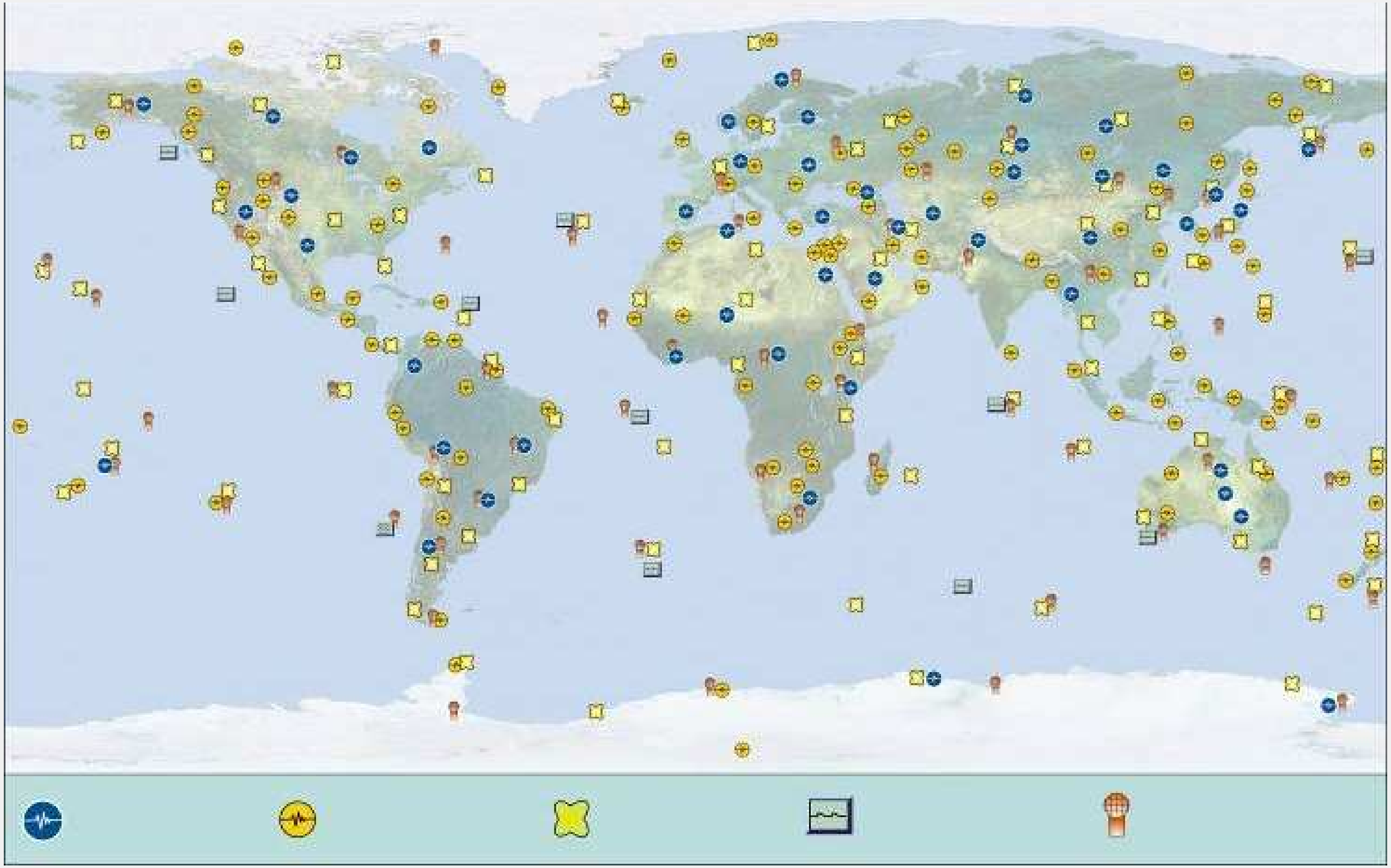
CTBT – status Annex II (44 states)

States, whose signature and ratification are required for the Treaty to enter into force



Signed : 41
Ratification : 35
Not signed : 3

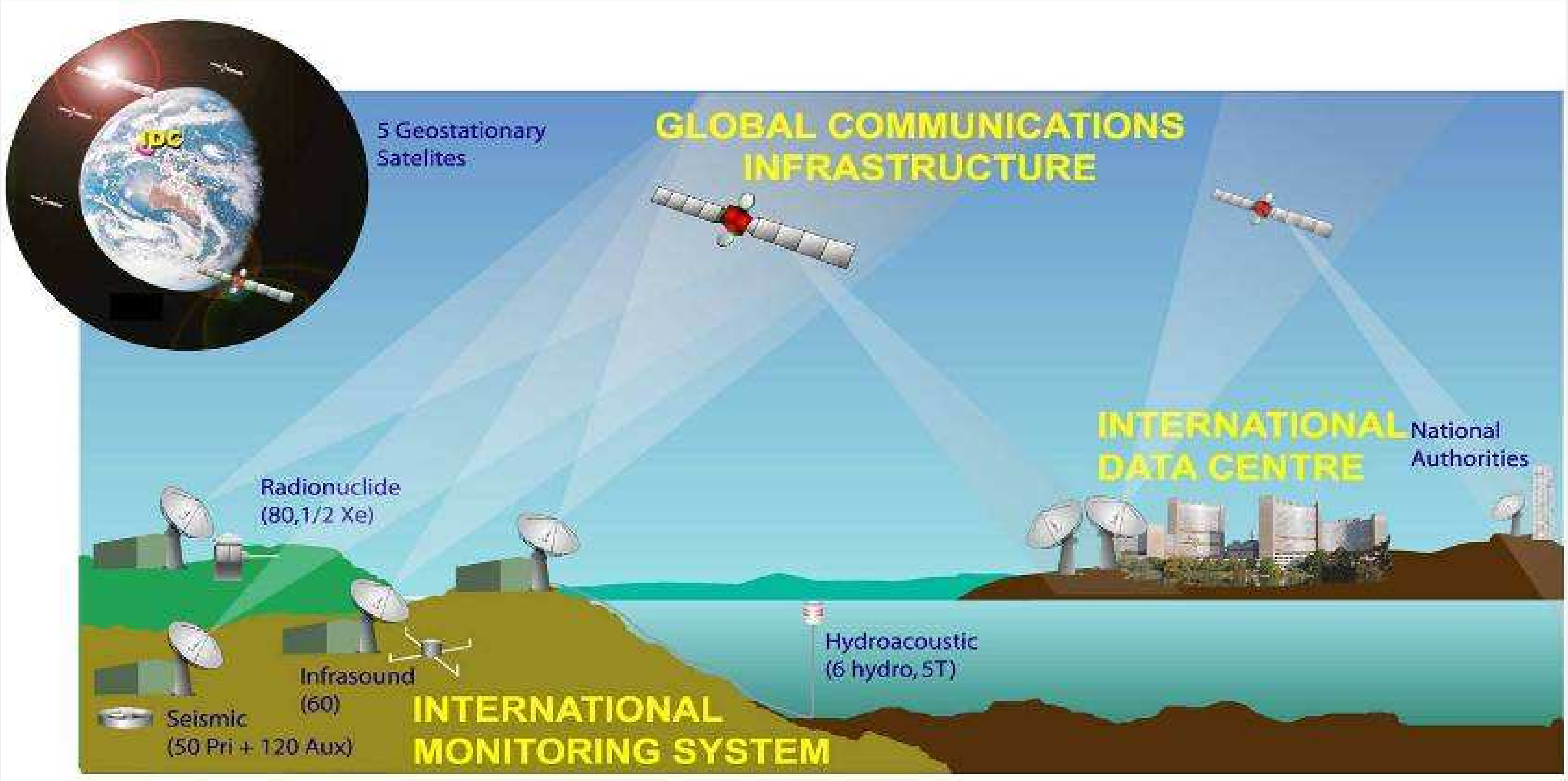
CTBT – verification - IMS



50	120	80	11	60
Seismic stations		Radionuclide	Hydroacoustic	Infrasound

FOI

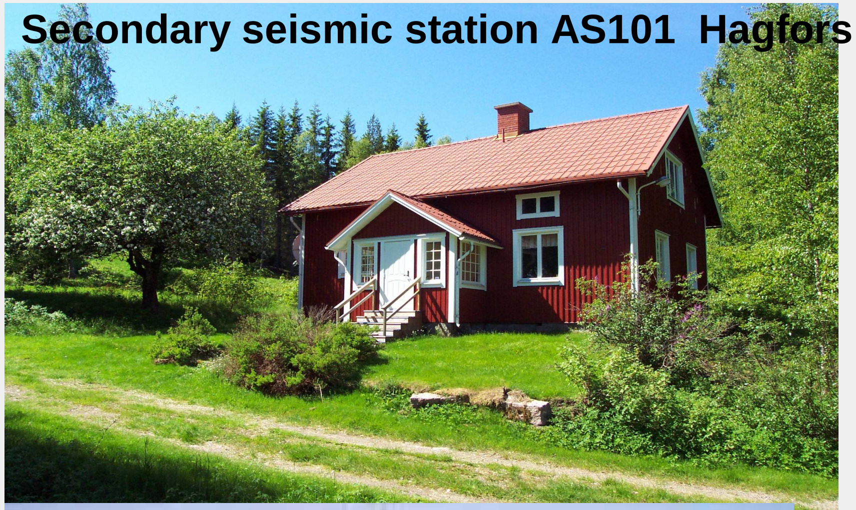
CTBT - verification



FOI

CTBT - verification

Secondary seismic station AS101 Hagfors



Hydroaucustic station HA04 Crozet Islands

Infrasound station IS48 Tunisia

Radionuclide station RN48, Spitsbergen, Norway

FOI

CTBT - verification - status

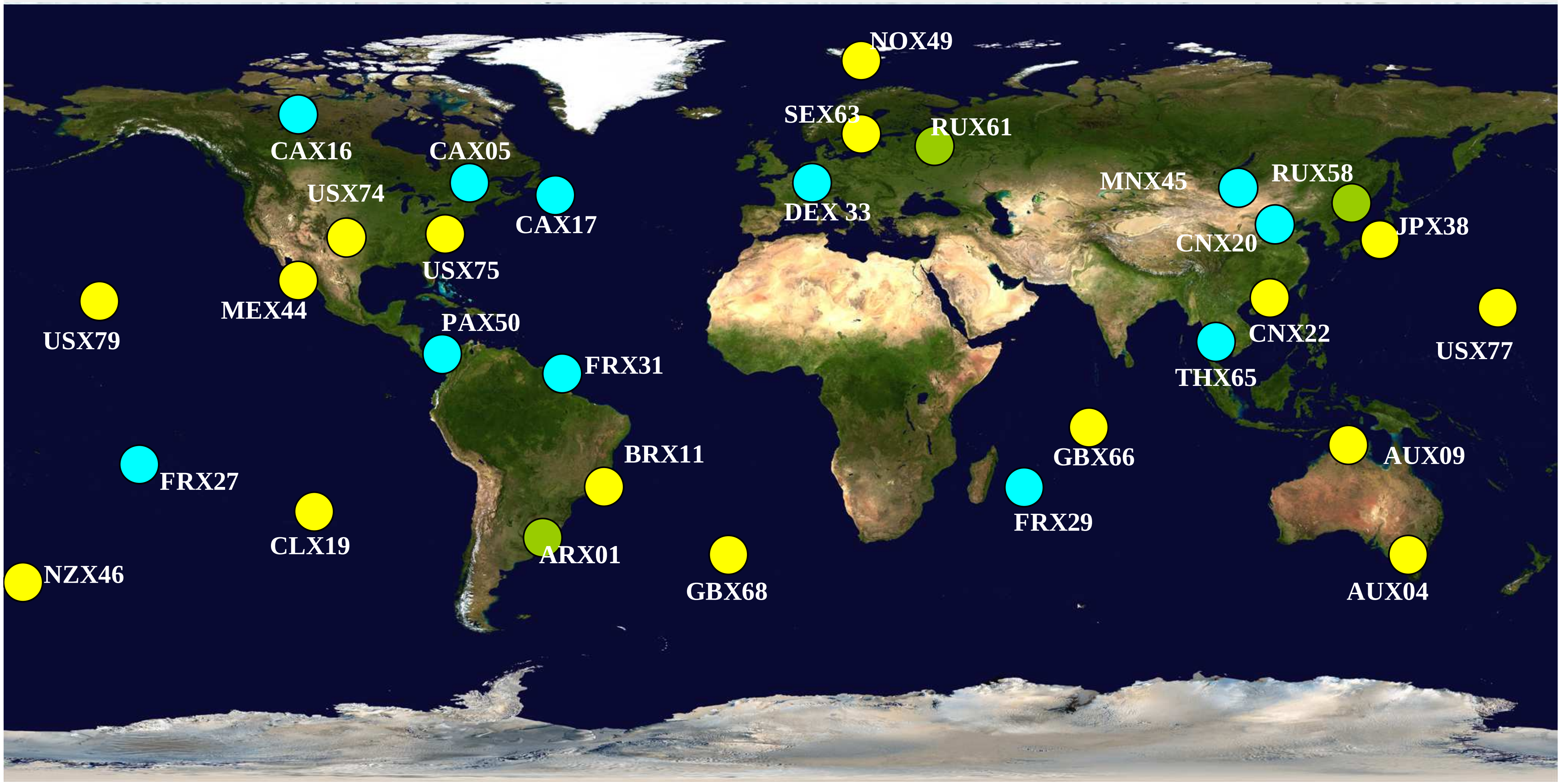
- Number of certified stations
  - Primary seismic: 82 %
  - Secondary seismic: 80%
  - Infrasound: 70%
  - Hydroacoustic: 91%
  - Radionuclide: 74%
  - Xenon stations 60% “operational”, the first stations certified 2010
    Three SAUNA II stations USX75, BRX11 and GBX68 (USX77+…)

The OSI (On Site Inspection) regimen is currently not as developed.
New project at FOI 2011-2012.

Noble gas as a verification instrument

- 40 out of 80 stations are due to be equipped with noble gas systems
- Three system suppliers

Noble gas as a verification instrument

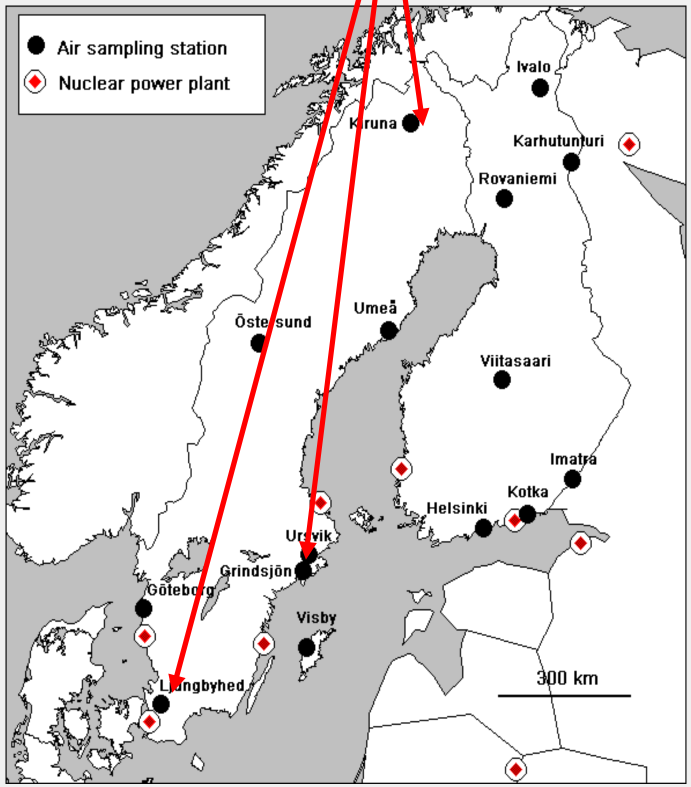


SPALAX SAUNA ARIX

History of noble gas detections in Sweden

- Development started in the 70's
- Network of stations operated 1990 – 2000. Detected the last Soviet nuclear test in 1999.
- Prototype for automatic system ready 2000 (SAUNA).
- Participated in the radioxenon equipment development within CTBTO from the start
- In 2000 a comparative test of four automatic radioxenon systems. France, Russia, United States and Sweden participated.
- SAUNA commercialized in 2003
- Mobile system developed 2006
- Detected the nuclear test in DPRK in 2006

^{133}Xe stations 1990-2000

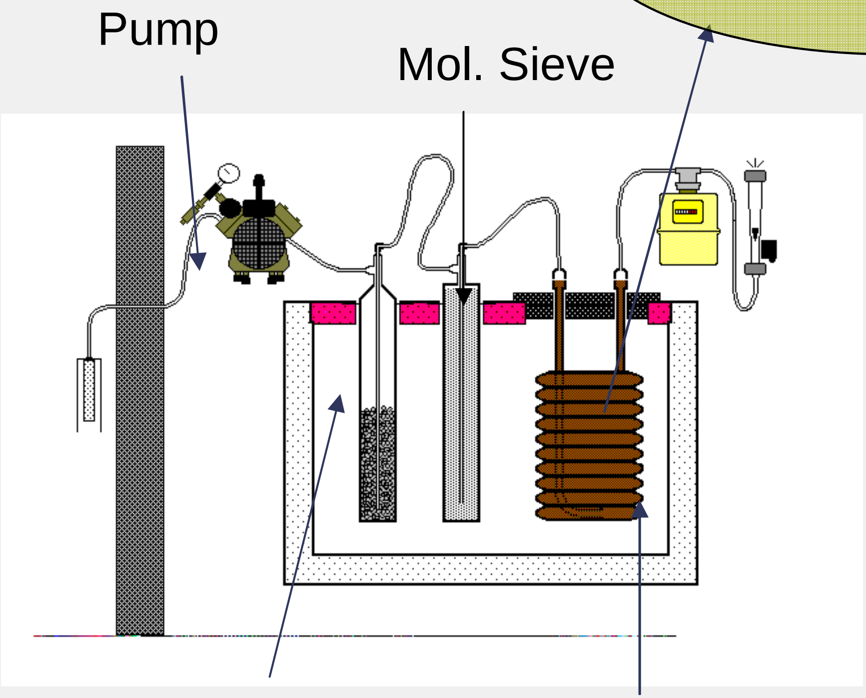


Technique used at FOI 1990 - 2000

Principle: *collection*, *separation*, *quantification* and *activity measurement*

Preparative gas chromatograpy

^{133}Xe only measured
MDC = 1-2 mBq/m^3



Sampling on cooled charcoal

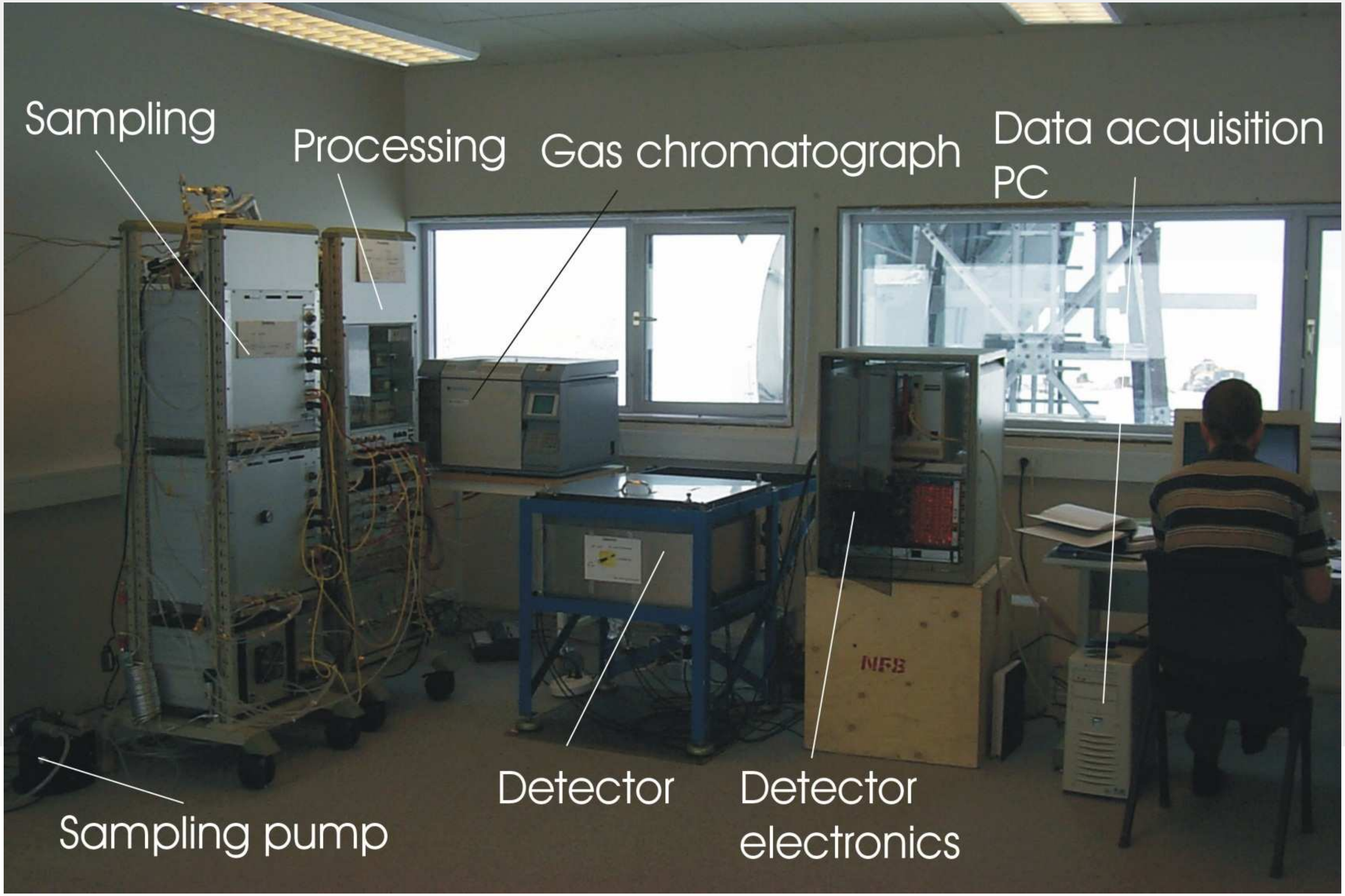
Activity analysis on HPGe

FOI

The SAUNA prototype (Spitsbergen 2000)

Swedish Automatic Unit for Noble gas Acquisition

Air sampling at *ambient temperature.* Separation using gas chromatography-Quantification of stable Xe using a GC. Beta-gamma coincidence detector



The SAUNA II system today

The commercialization of the SAUNA I prototype
Cooperation between FOI and Gammadata 2003
First SAUNA-II delivered 2004. The 16th system in the CTBT network installed during 2011

- Samples up to 16m^3 in 12h
  - Two 6h samples combined
- Xenon volume typically 1.3ml
- Activity of four Xenon isotopes
  - 133, 135, 131m and 133m
  - MDC typically < 1mBq/m^3

FOI

SAUNA Mobile

Developed by FOI in cooperation with Gammadata AB, 2005-2006
Samples and absorbs up to the same volume as a SAUNA-II on a charcoal trap

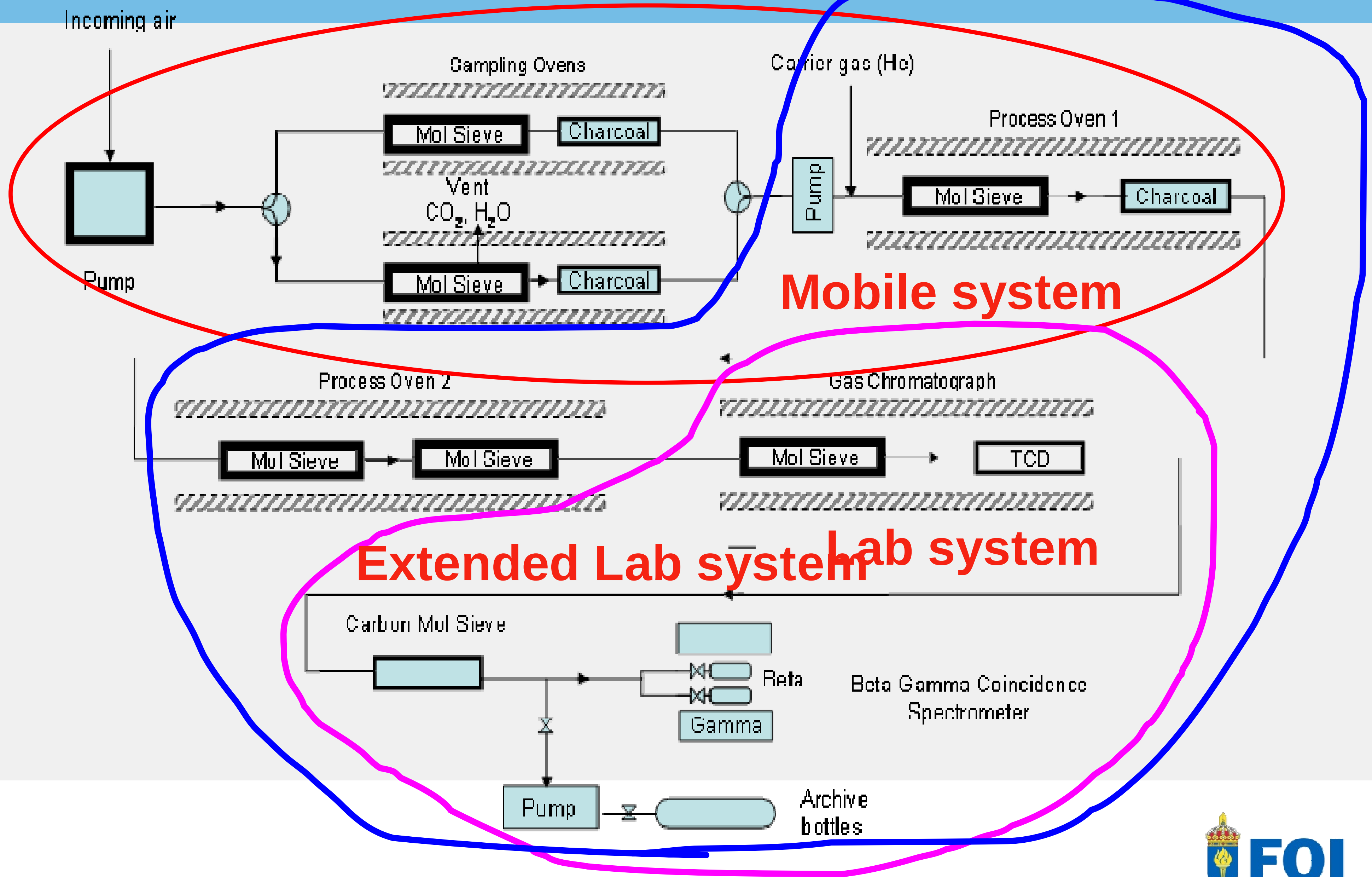
- Can collect both atmospheric and subsoil samples
- Modular construction for easy transportation
- Tested in ambient temperatures between 0-40ºC
- Xenon sample absorbed on charcoal trap
- Samples can be analyzed in an extended SAUNA LAB system a SAUNA II or “equivalent” system
- Used to detect radioxenon from North Korean test in 2006

SAUNA Lab and Extended Lab system

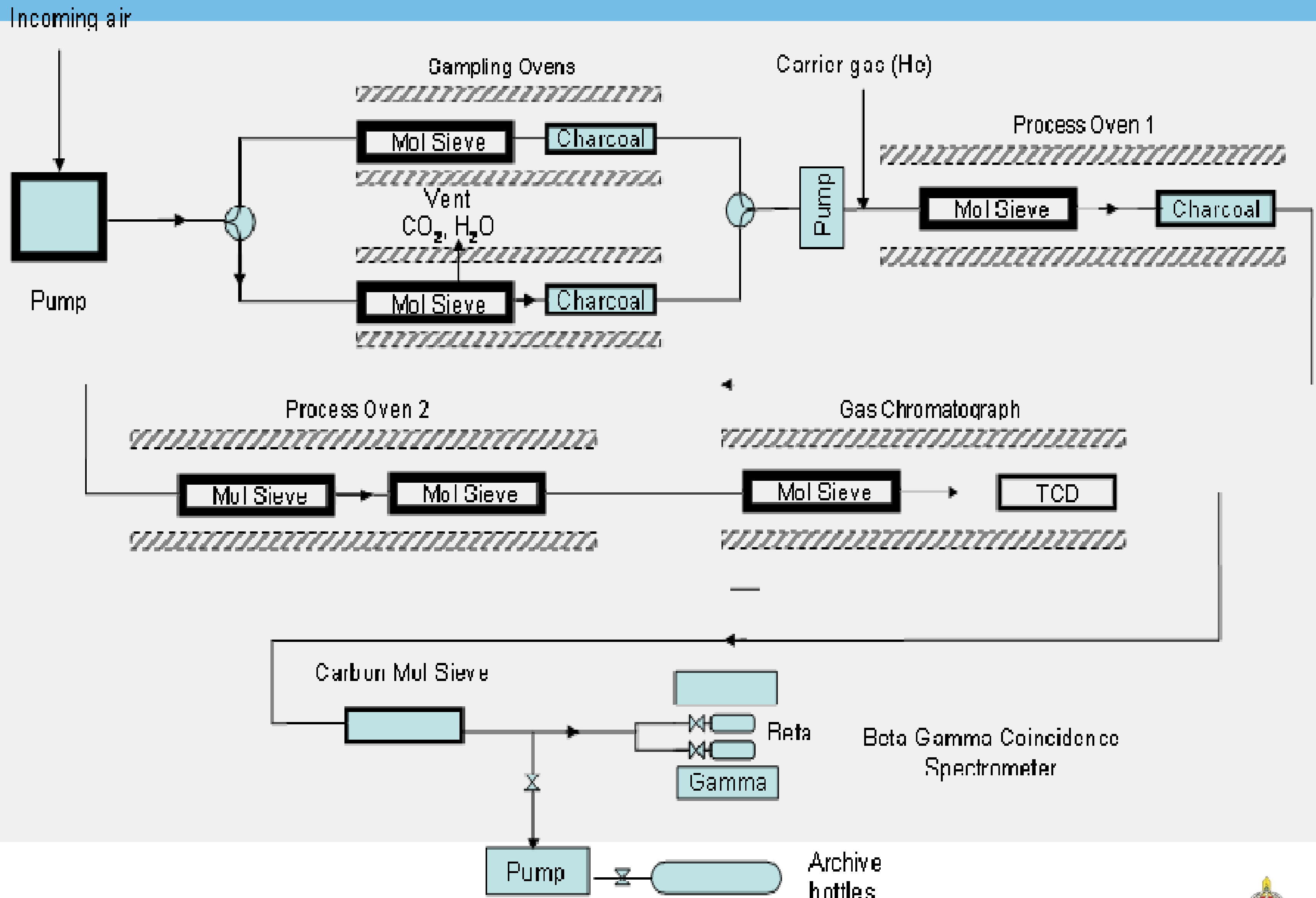
- Developed by Gammadata for radionuclide laboratories (16 within the treaty, 10 certified). Currently no obligation for Xenon capability.
- Archive bottles can be send to the labs to reanalyze samples (quality check of IMS stations)
- “Extended Lab” system are used to analyze samples from mobile systems. Processing oven for the transfer column.

FOI

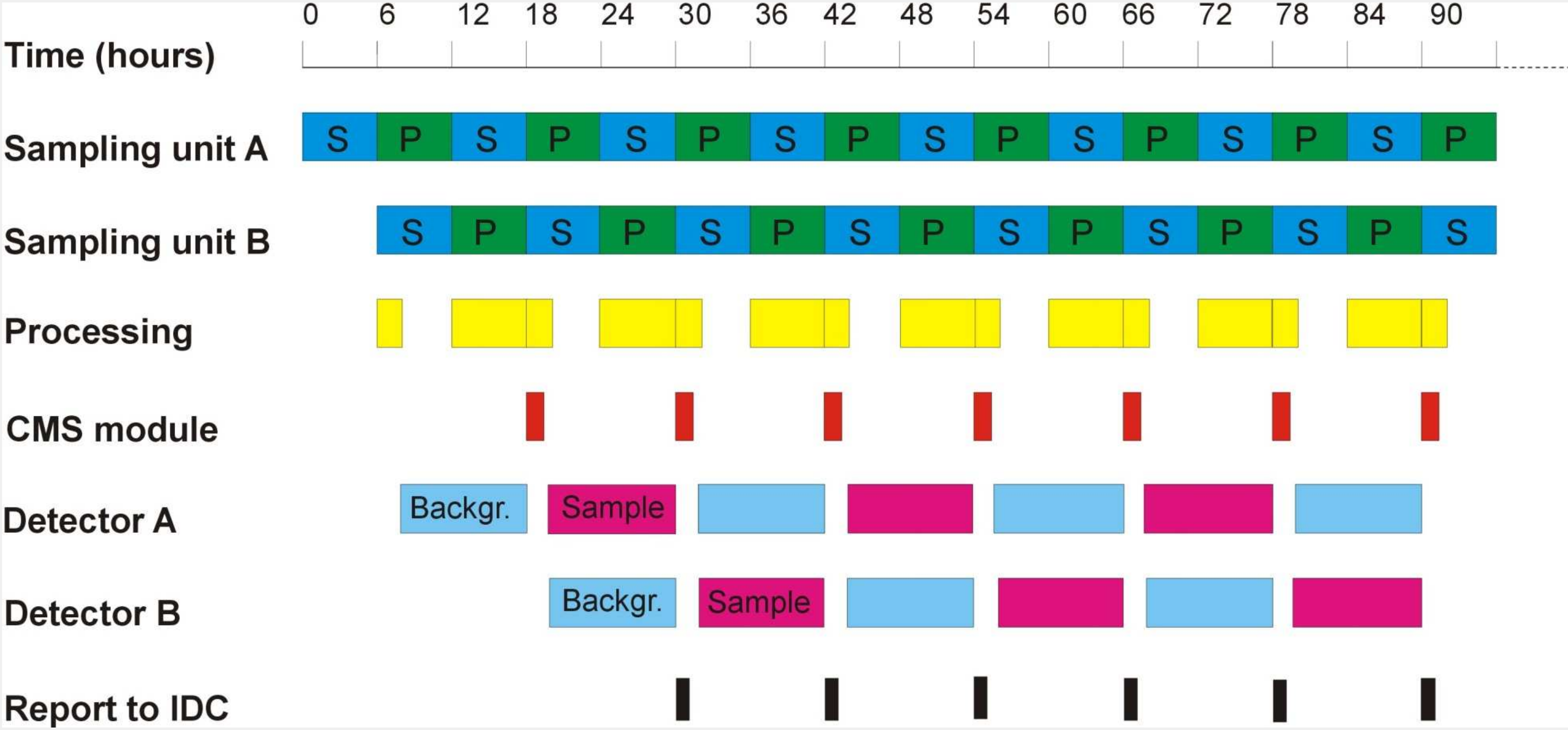
The SAUNA II process, how it works



The SAUNA II process, how it works

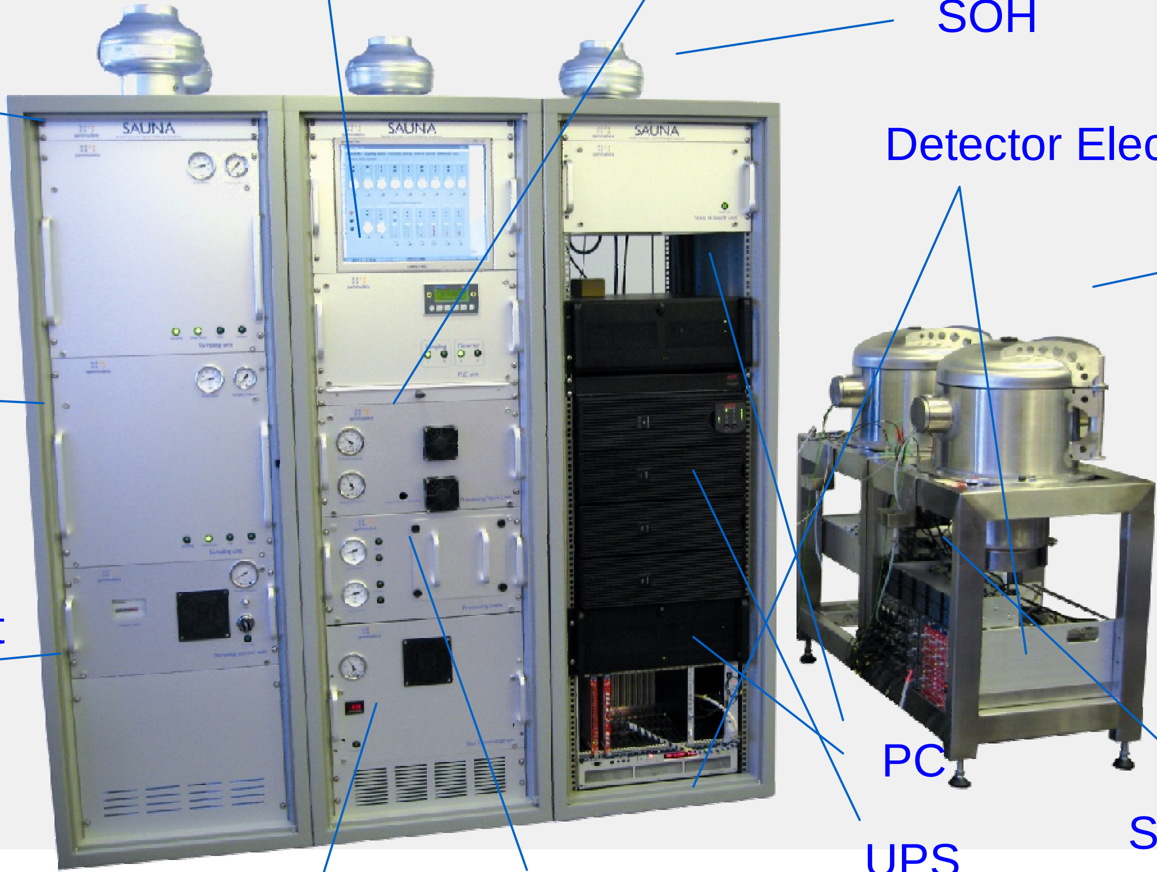


The SAUNA II process, how it works



- One full air sample / 12h, +6h processing, +11h data collection
- Full spectral data 30h after collection start (preliminary file after 19h)

The SAUNA II system layout



PLC

Programmable Logic Controller

Used for system control.

Some actions like a GC-calibration can be initiated from the front panel.

FOI

SCU-Sampling control unit

Sampling control unit

Sampling pressure, 6-7 bar.

Air flow through the system, ~23 l/min

Heat exchanger

Water filter

Commercial air dryer

Water Removal Filters mounted on Back of Sampling Control Unit

FOI

Sampling oven A and B

Sampling oven A and B

Two columns with molecular sieves

Four columns with activated charcoal

XPU and Processing ovens

Processing valve unit

Solenoid valves, gas line filters, evacuation pump.

Processing ovens

POV1:

One column with molecular sieves

One column with activated charcoal

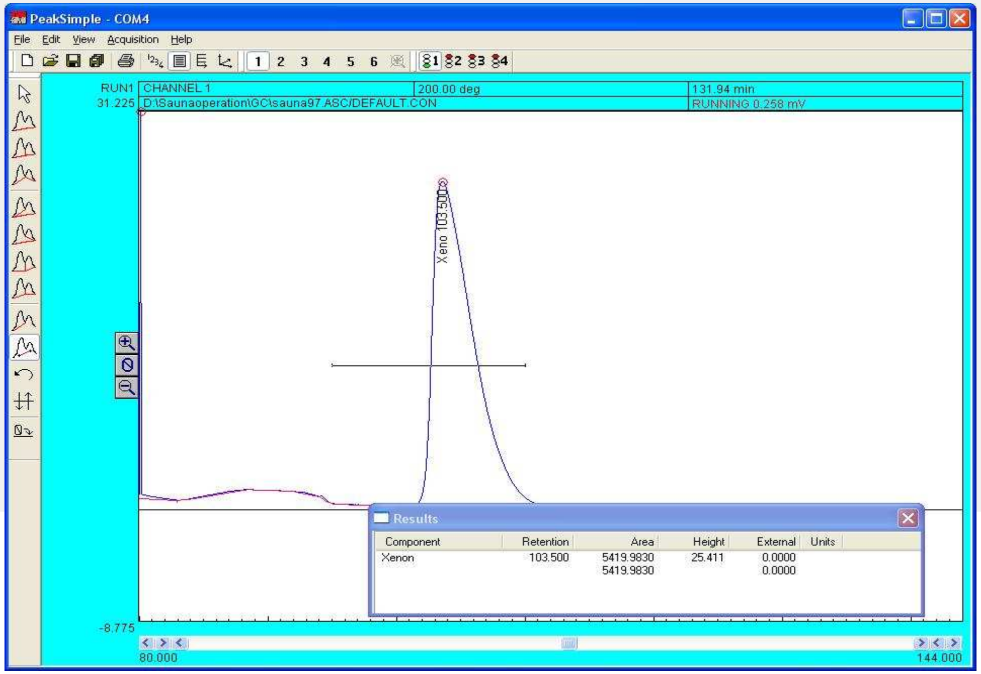
POV2:

Two columns with molecular sieves

Gas Chromatograph

Gas Chromatograph

Commercial GC. One molecular sieves column.



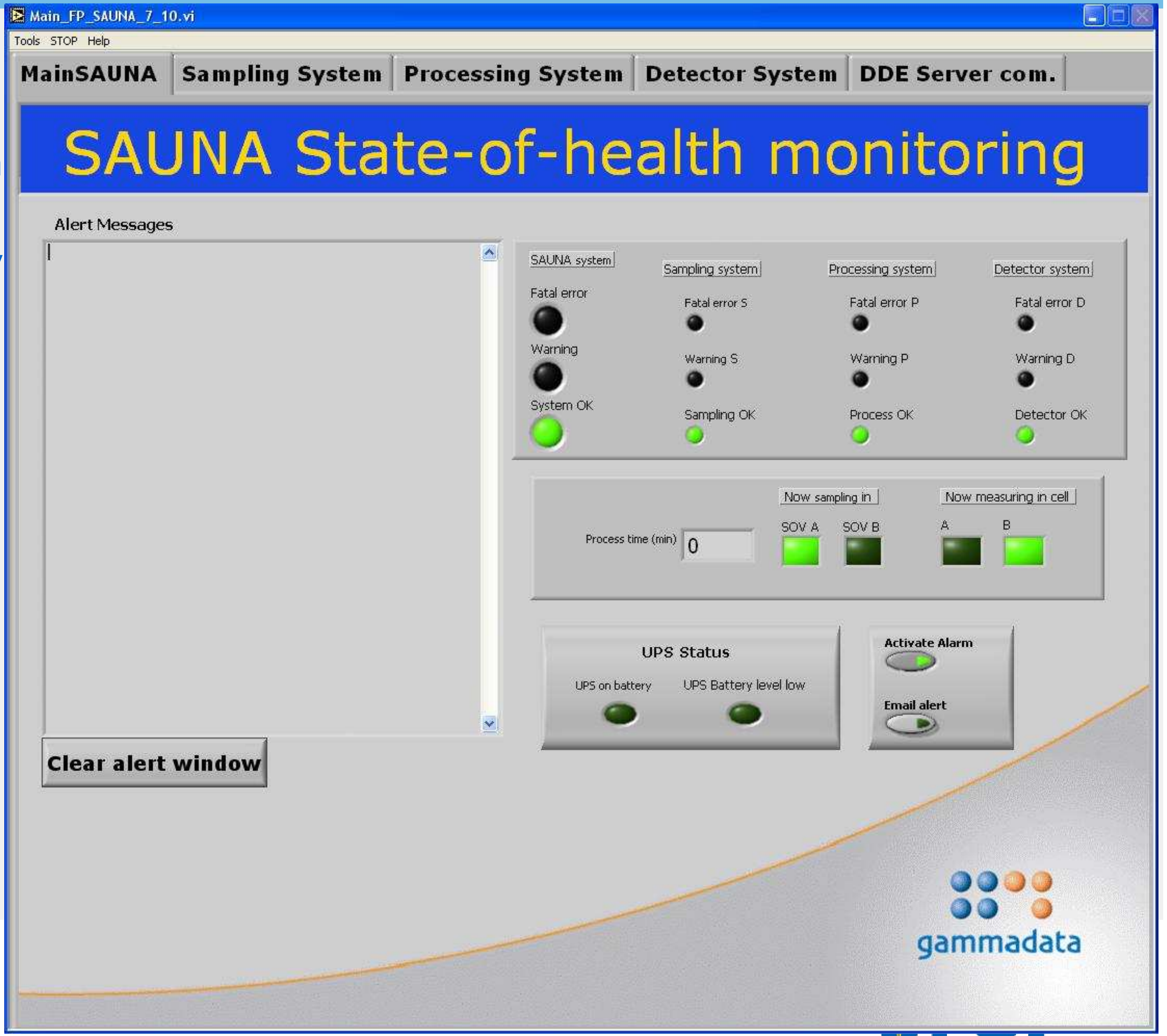
Sample transfer Unit

One column with carbogenic molecular sieves.

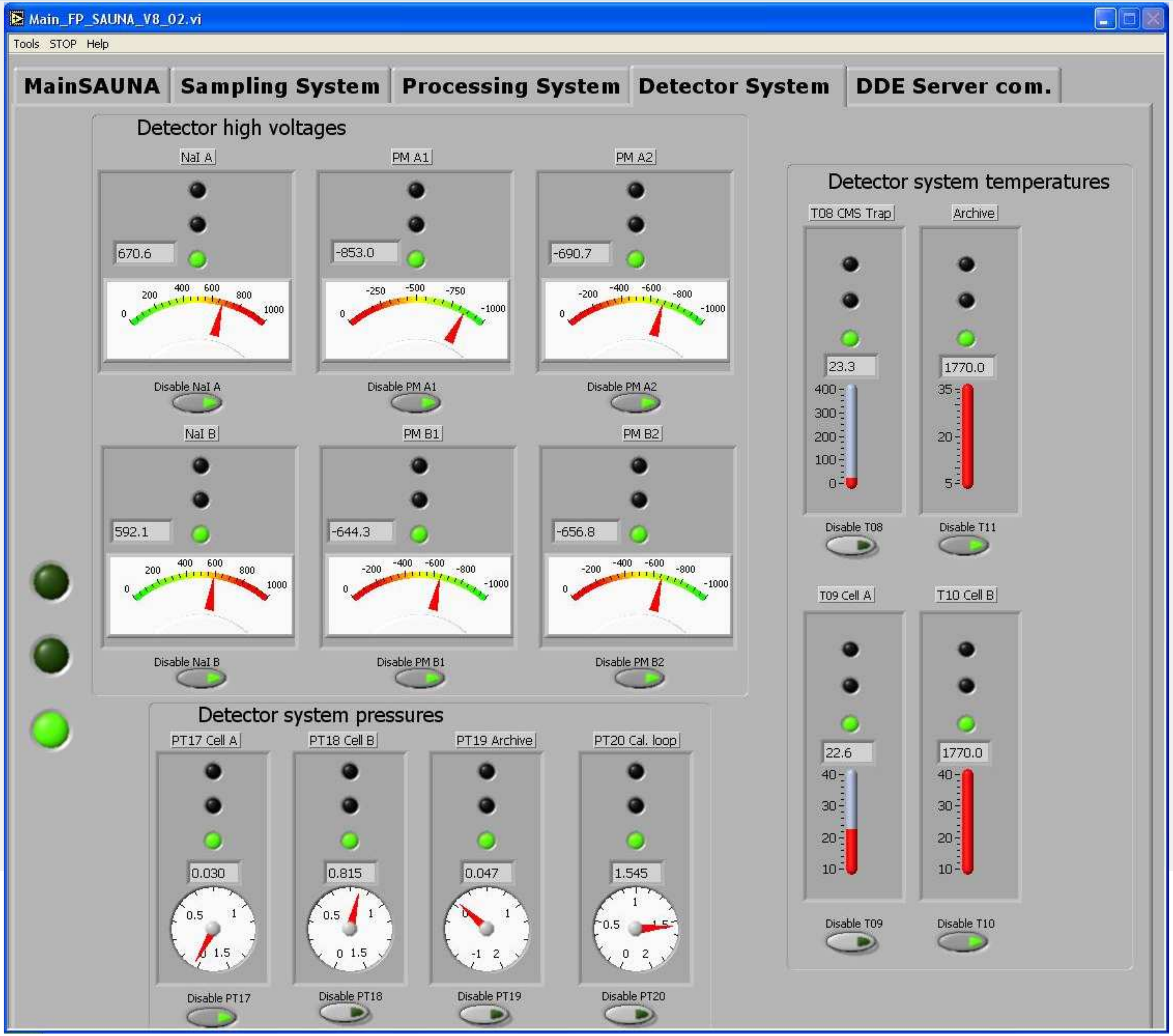
FOI

State of Health system

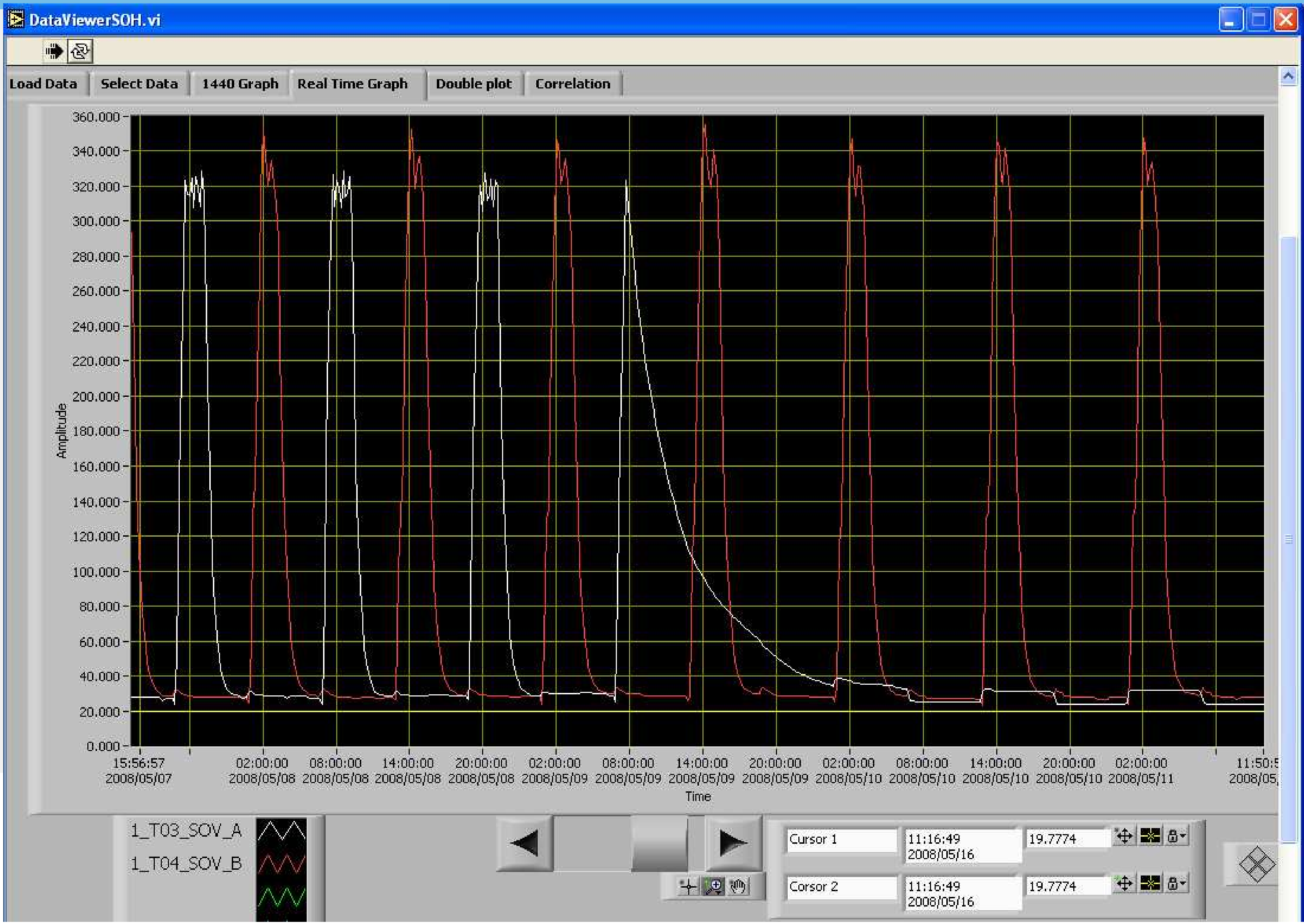
- 20 pressure sensors, 16 temperature sensors, 6 HV-readouts, 2 gas flows and a RH-sensor monitor the State-of-Health of the system.
- SOH data is reported to IMS every 2 hours. The reported data is 10 min averages based on readings faster than every minute.
- In case of a system malfunction an alert message is generated and sent ASAP.
- The alert message is graded in three levels of gravity.
  - Warning: A situation occurred that should be checked, data can be invalid
  - Critical: Technical problems, operator need to perform some action.
  - Fatal: Application stopped, operator needs to perform some action.



State of Health system



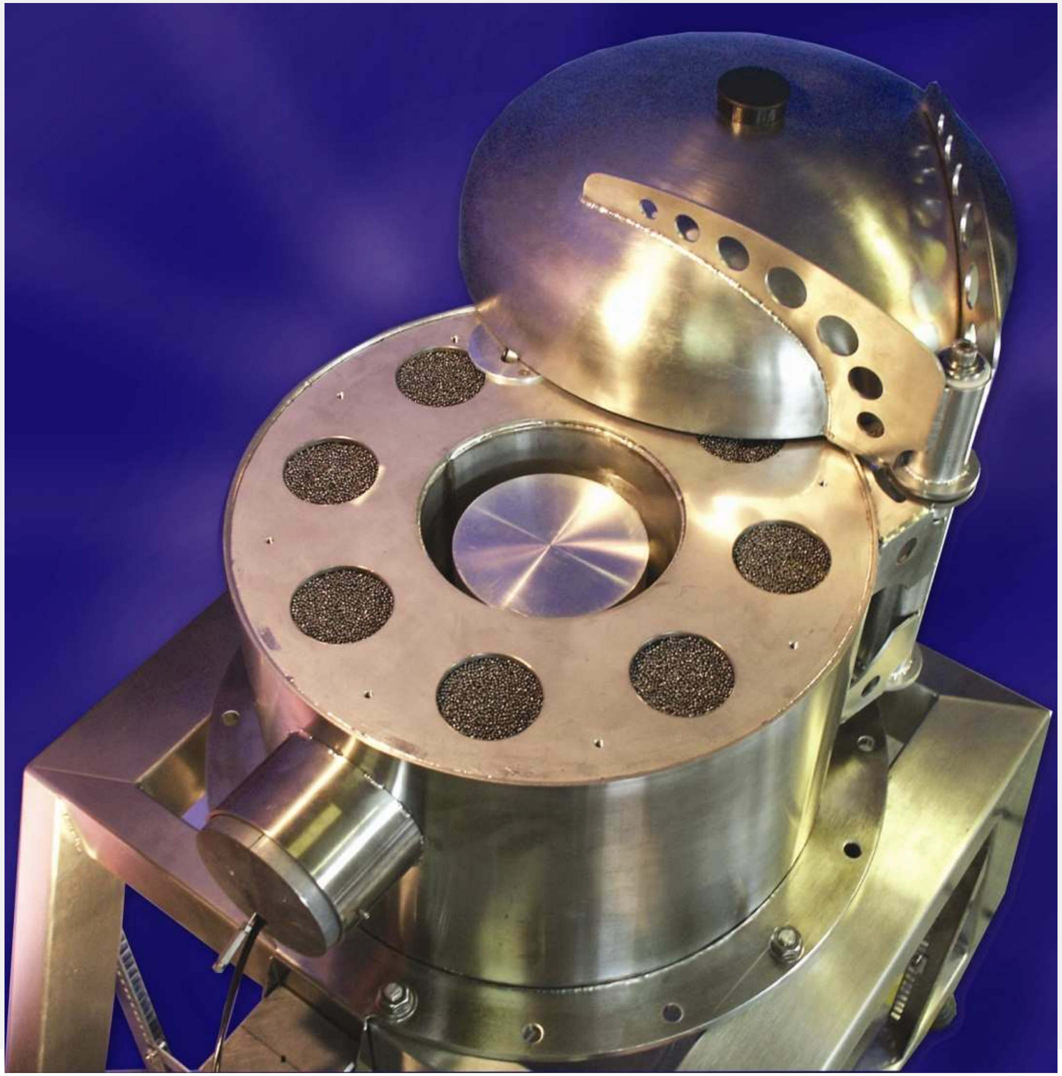
State of Health system



Beta - Gamma Coincidence Detector

FOI

Beta - Gamma Coincidence Detector



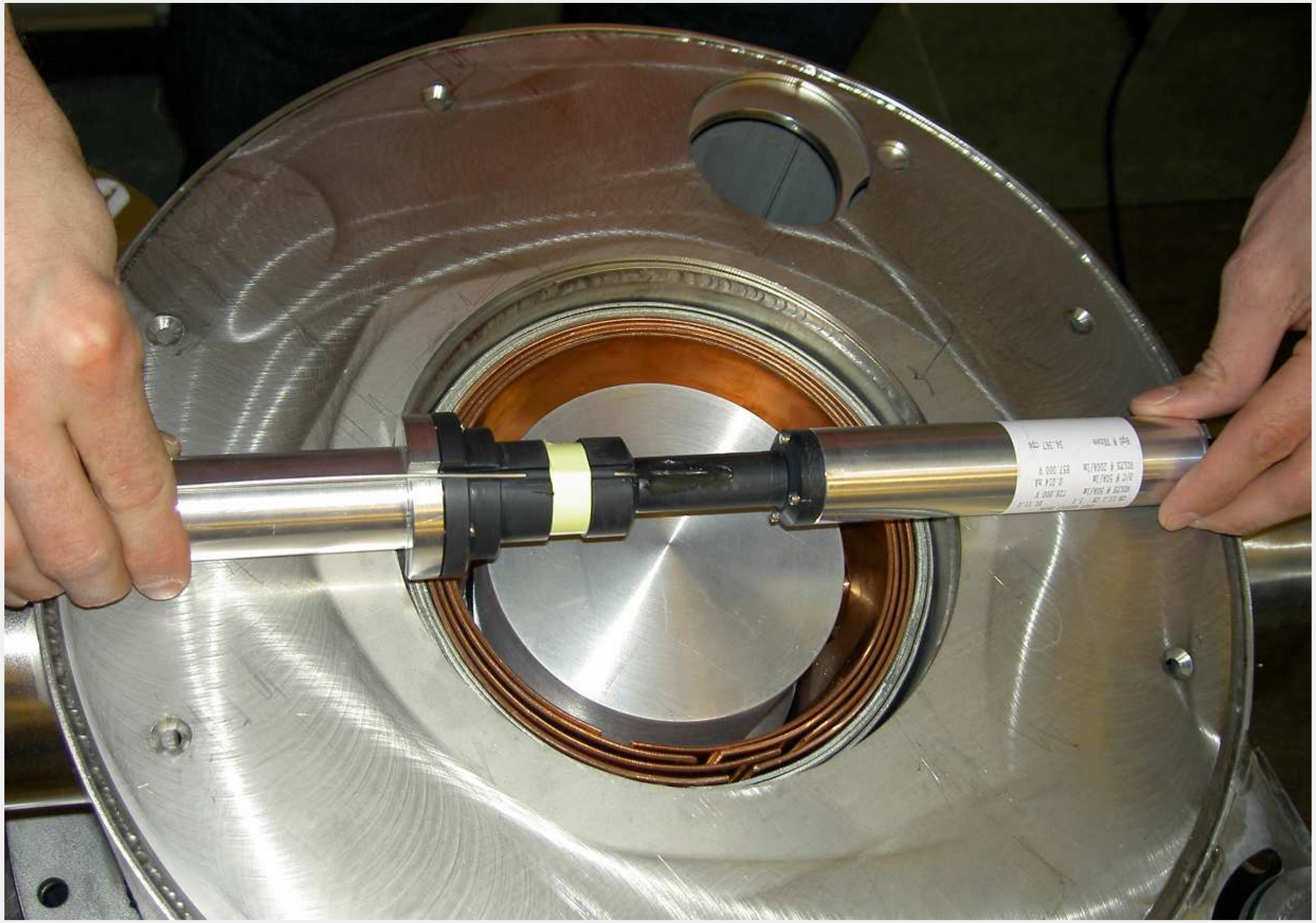
Beta - Gamma Coincidence Detector

Plastic scintillator for beta detection and sample container (volume about 6ml)

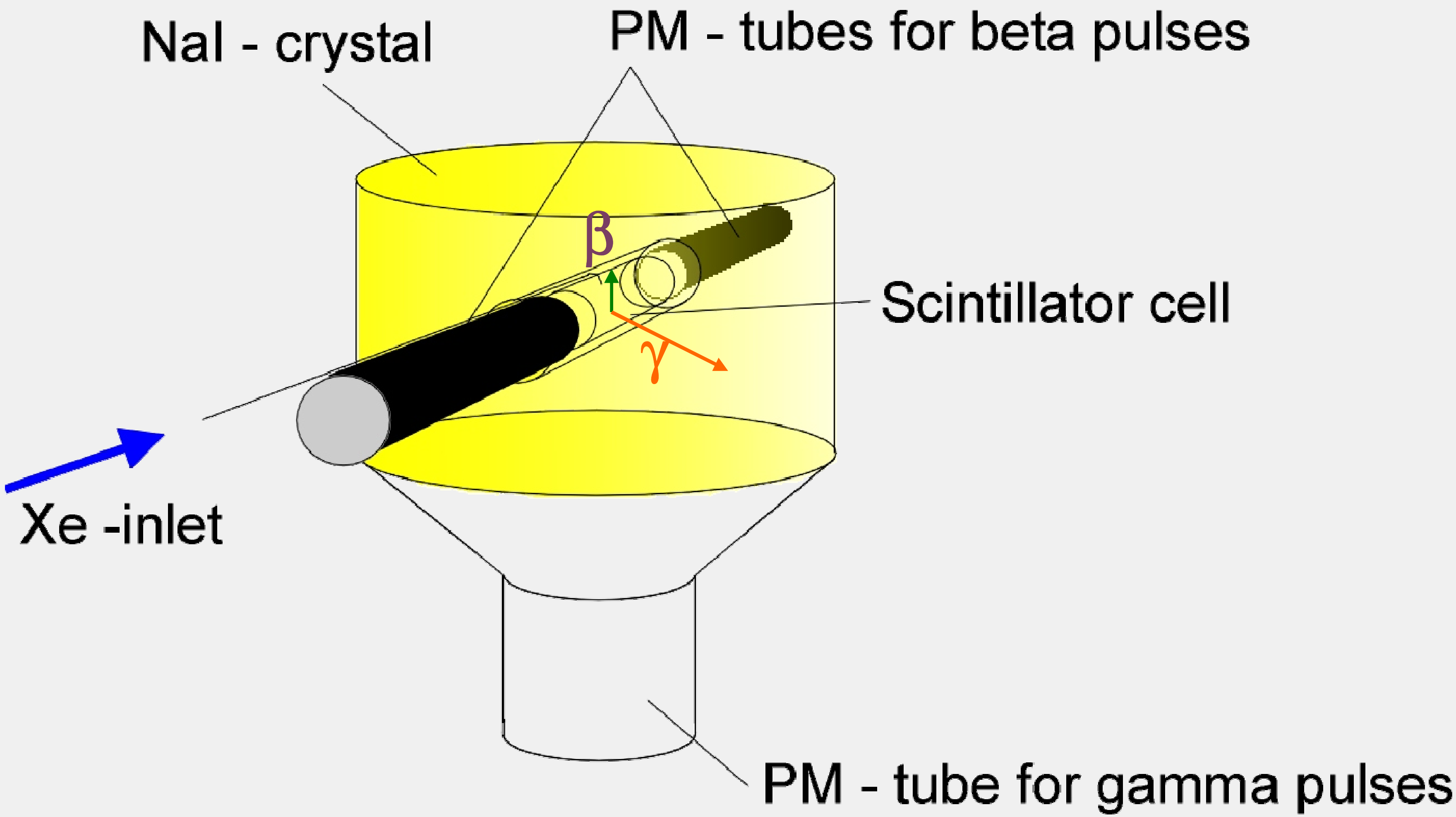
NaI(Ti) crystal for gamma detection. 4” detector with central hole for plastic scintillator.

Beta - Gamma Coincidence Detector

The beta cell is placed inside the NaI detector



Beta - Gamma Coincidence Detector

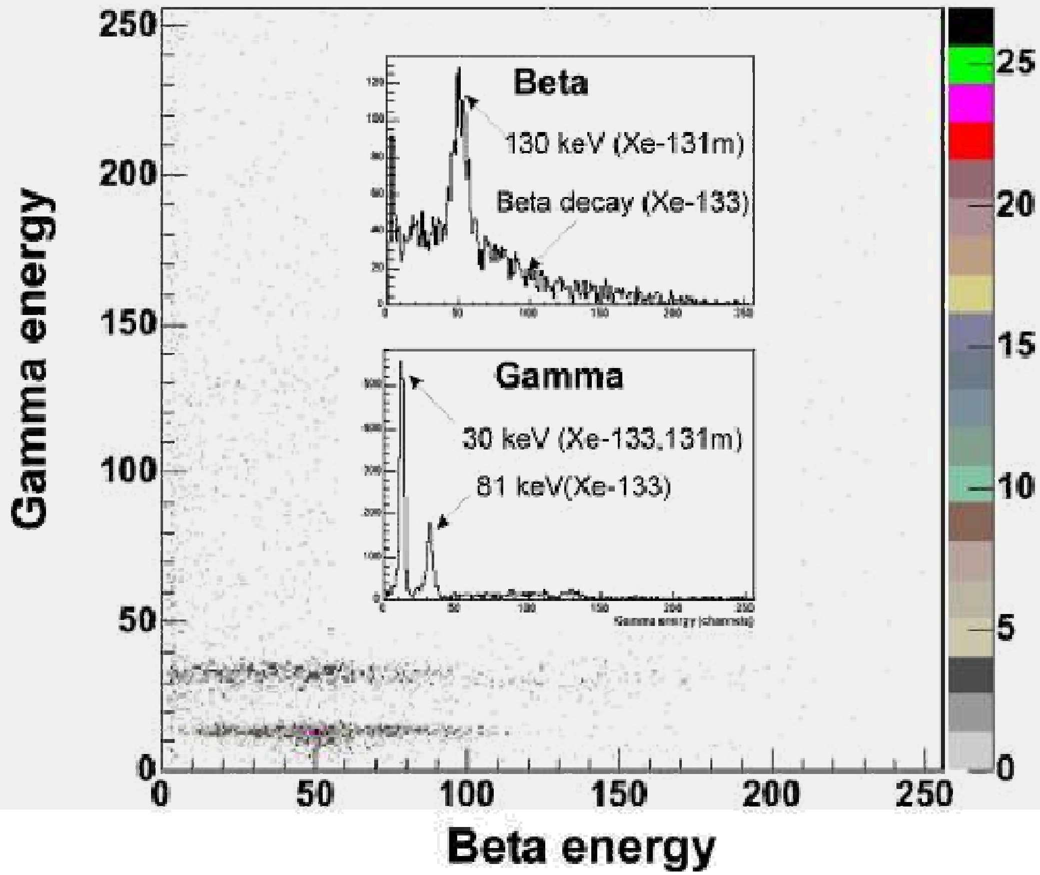


Beta - Gamma Coincidence Detector

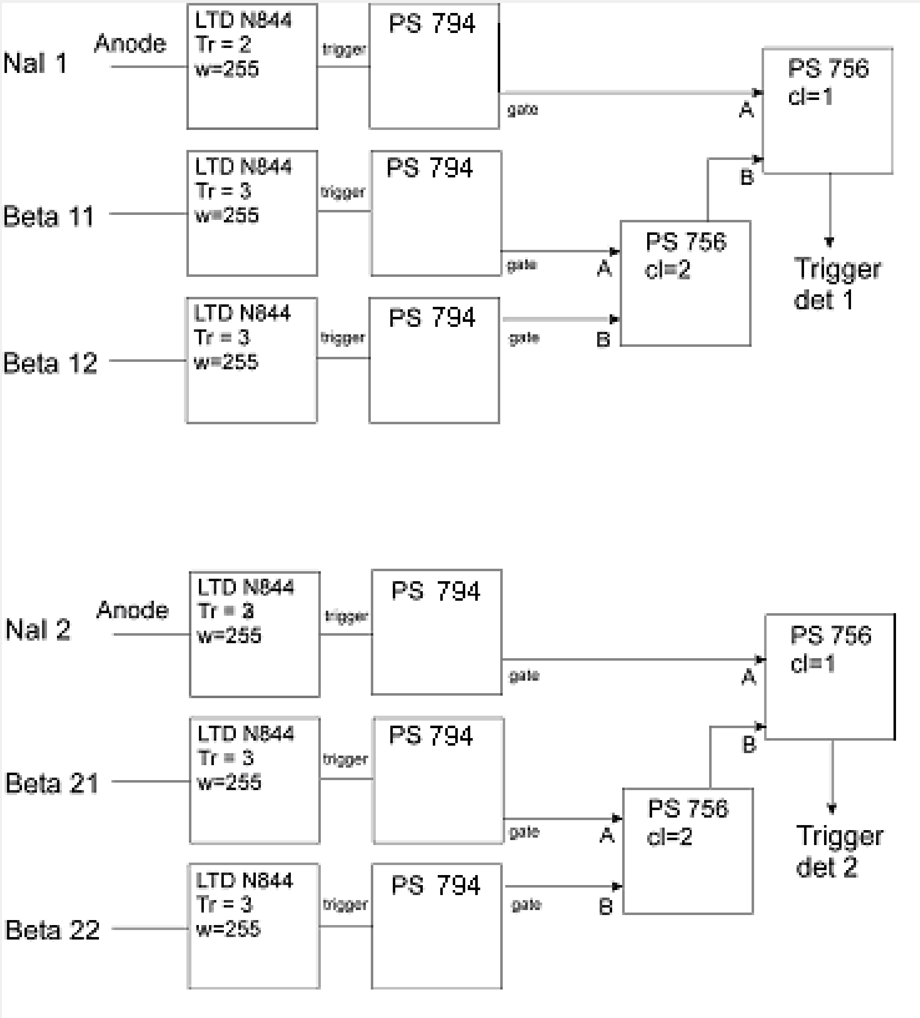
The data is presented by the software as:

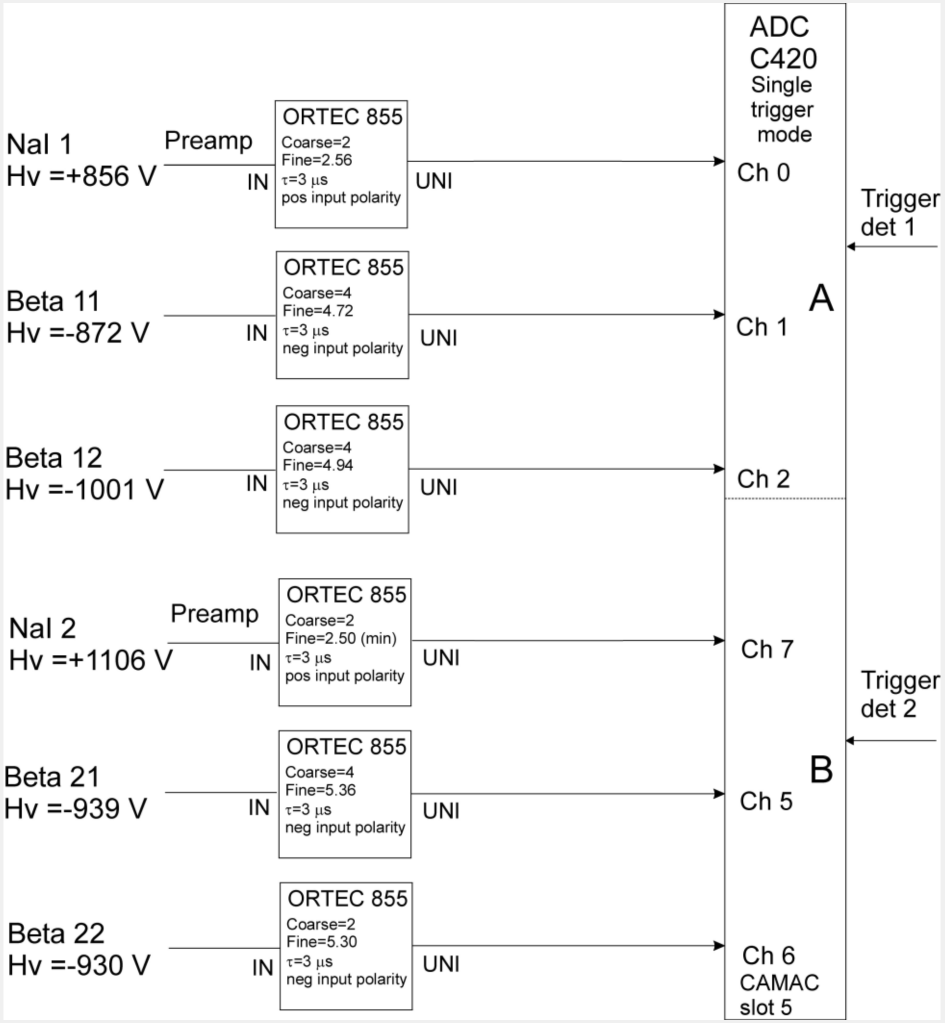
255 channels - Singles beta and singles gamma

255x255 channel beta gamma coincidence



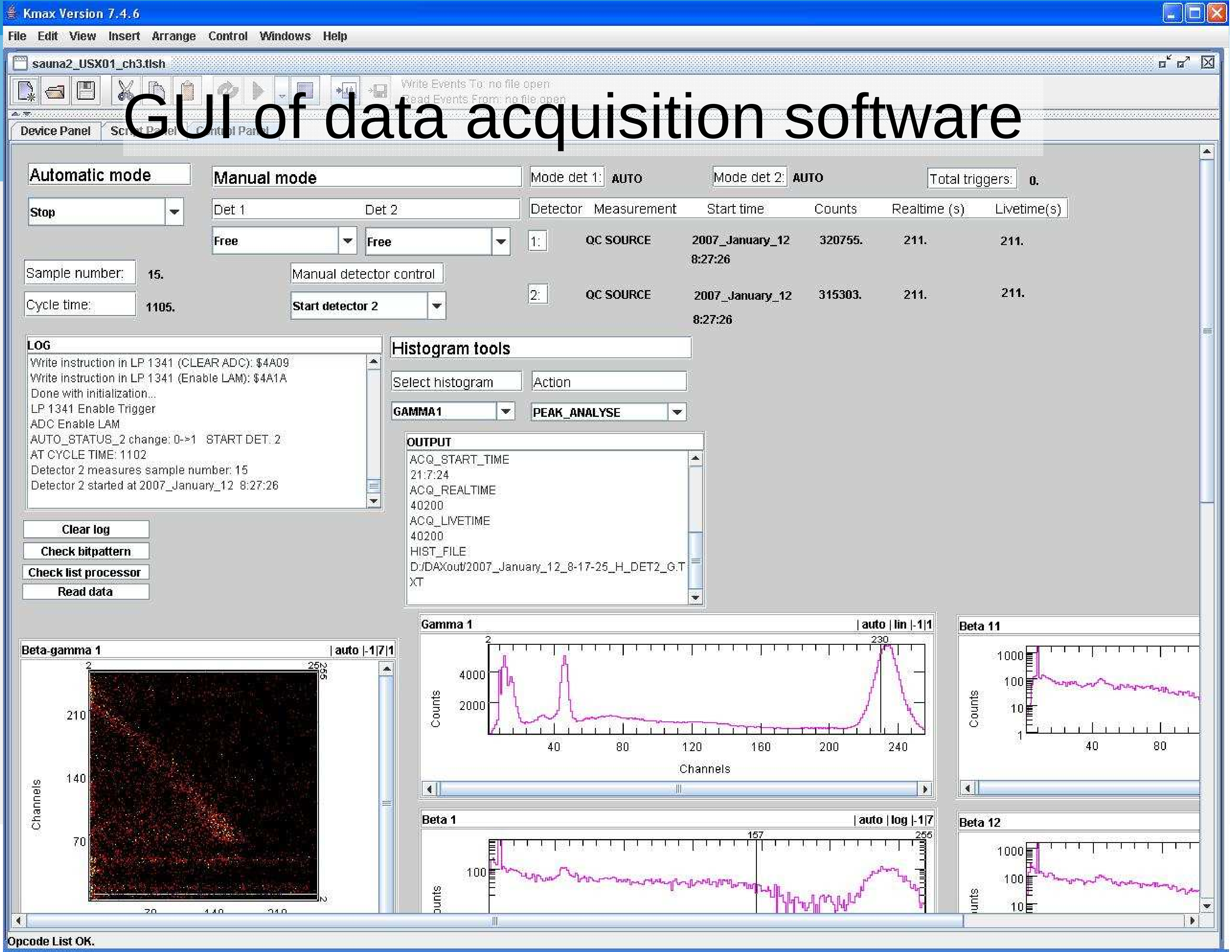
Beta - Gamma Coincidence Detector





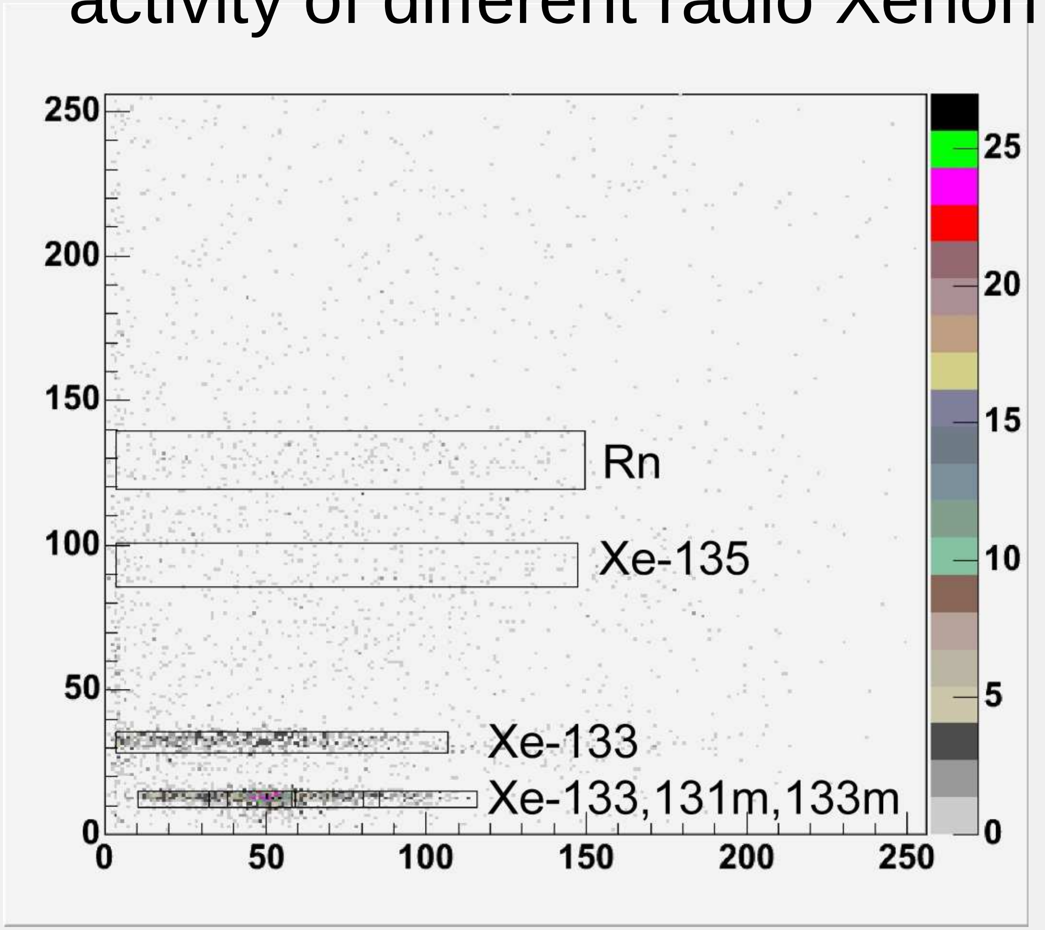
The detector electronics has two branches, one for the generation of triggers and one for the detector signals.

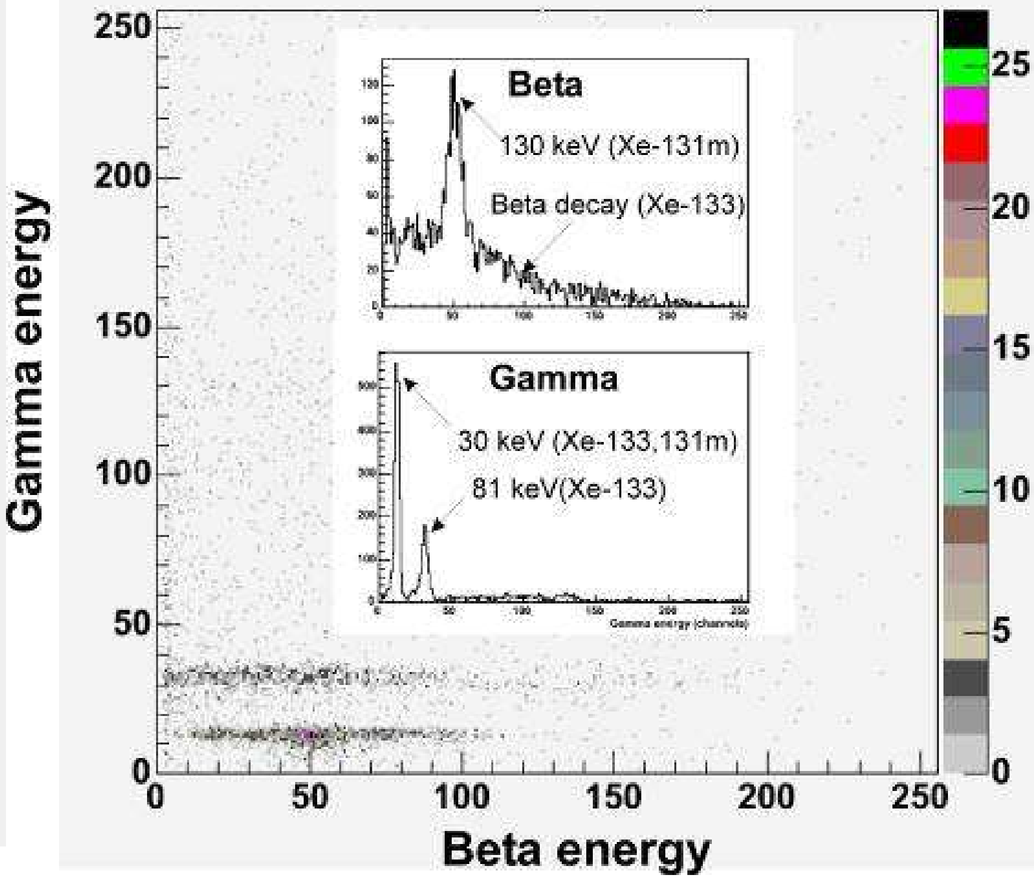
GUI of data acquisition software



Beta-Gamma Spectra

ROI's (Region Of Interest) are used to determine the activity of different radio Xenon isotopes in a sample





Detector calibration

The detector calibration is a non routine operation, normally performed only at the installation.

1. Detector background measurement
2. Gamma calibration

    Point sources:

    ^{137}Cs 31 and 662 keV

    ^{241}Am 60 keV

    ^{152}Eu 122, 245 and 344 keV

3. Beta calibration

    Compton scattering of ^{137}Cs gamma

4. Efficiency calibration

    Radioactive ^{133}Xe and ^{131m}Xe gas in cell

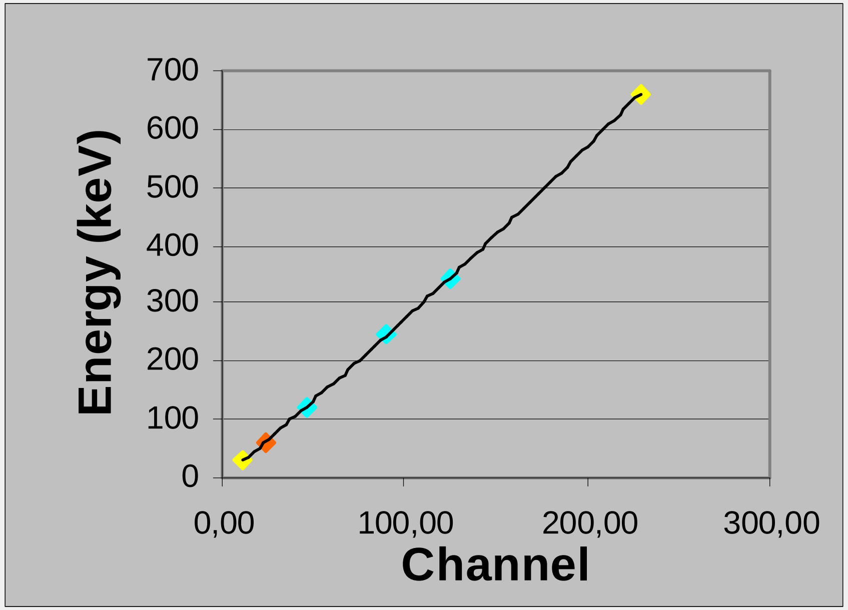
5. Radon measurement

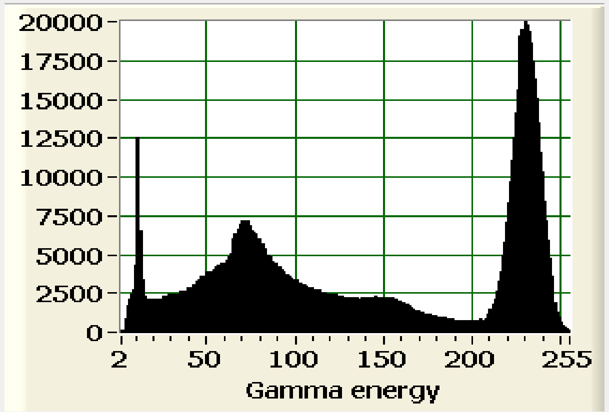
    Rn gas in cell

Gamma calibration

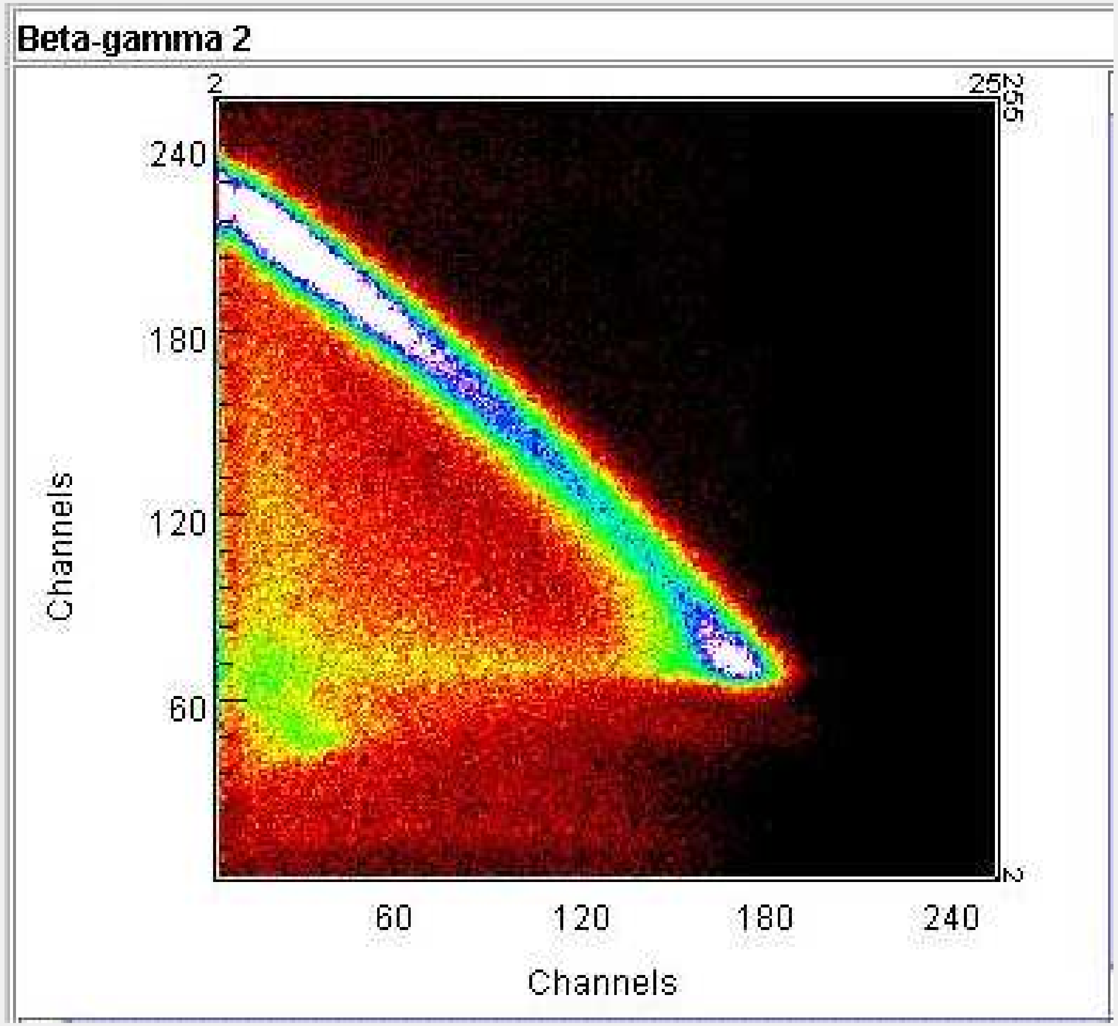
Point sources on top of detector, inside the lead shield. Typical sources that cover 30 to 670 keV.

- **^{137}Cs 31 and 662 keV**
- **^{241}Am 60 keV**
- **^{152}Eu 122, 245 and 344 keV**





Beta calibration



Compton scattered gammas from a ^{137}Cs source positioned on the outside of the detector.

The resulting diagonal in the two dimensional beta-gamma spectrum corresponds to $E_\beta + E_\gamma = 662$ keV.

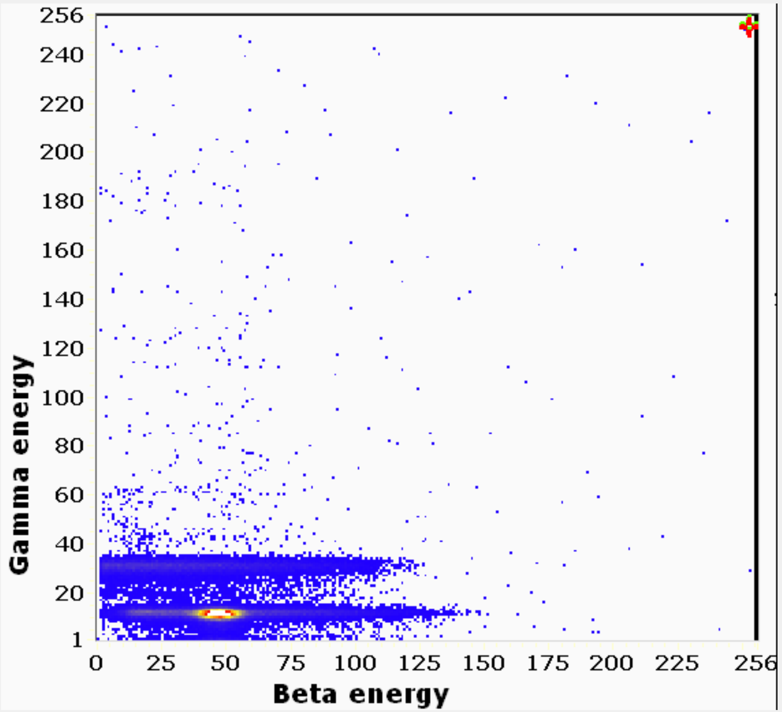
Efficiency calibration

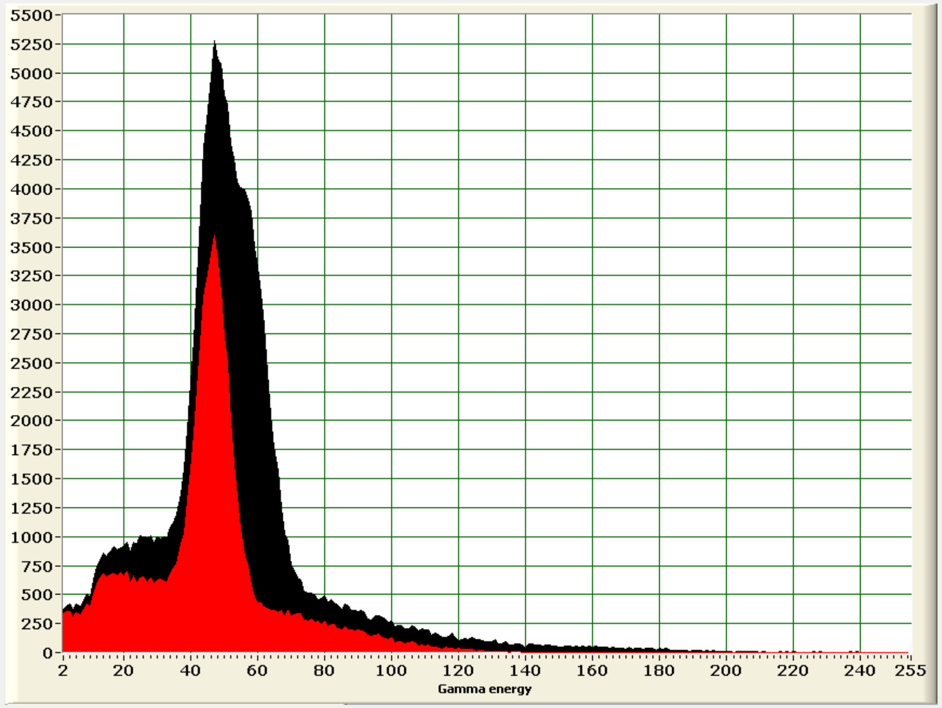
Absolute gamma efficiency calibration:

•The absolute gamma efficiency at 30keV is calculated from the known ratio between beta gamma coincidence (129keV) and the total beta events 129 keV + 169 keV from ^{131m}Xe.

•80keV efficiency is derived from relative eff. between 30-81keV.

•250 keV derived from 30 keV eff and MC simulation



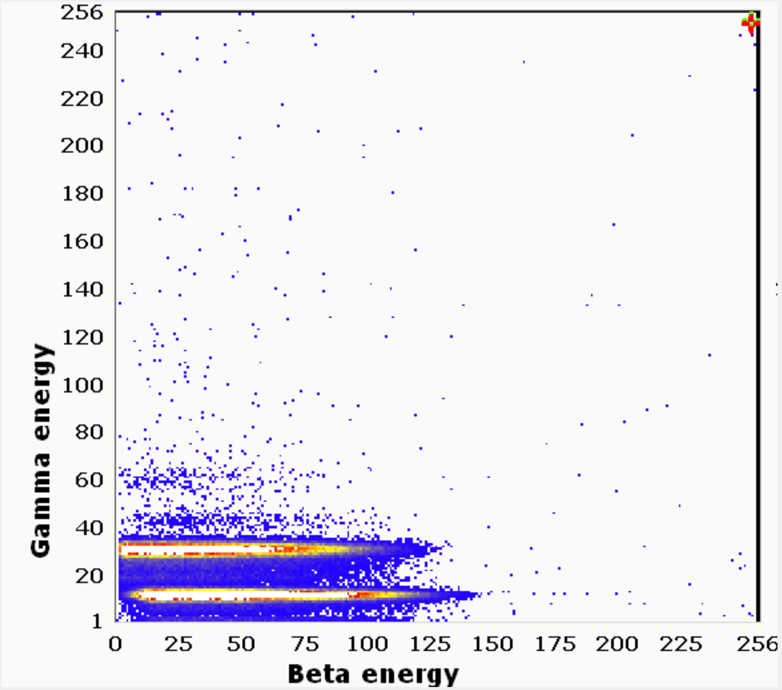


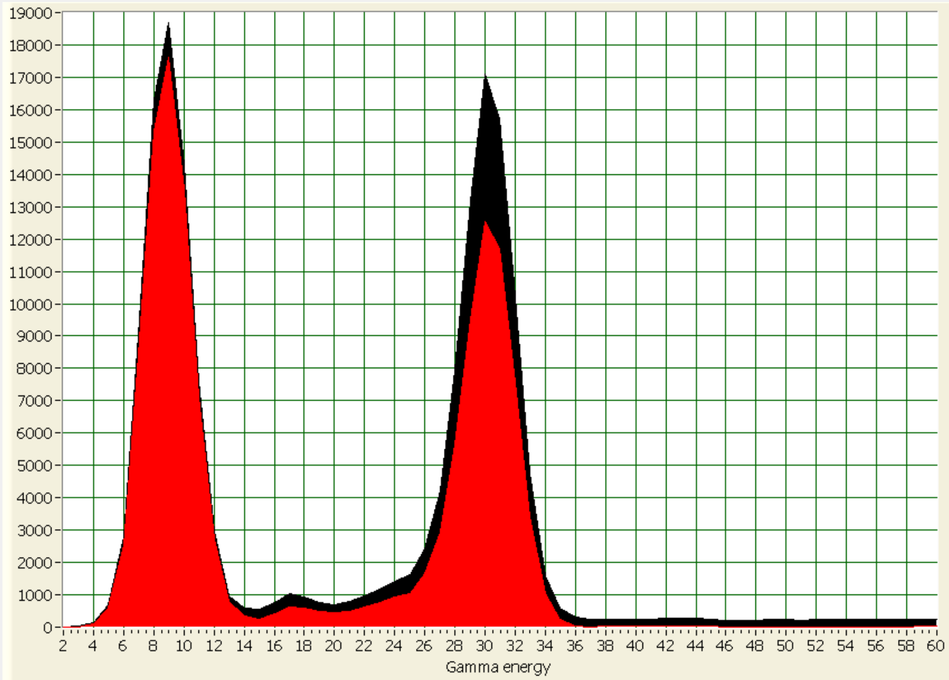
Coincidence spectra and beta spectra measured after injecting active ^{131m}Xe. The ratio between the number of counts in β-singles and γ-gated β-spectrum is used to calculate the gamma detection efficiency

Efficiency calibration

Absolute beta efficiency calibration:

•Beta efficiency up to 346 keV from 81 keV gamma, ratio between beta gated gamma and single gamma. This value is extrapolated to 908 keV. 346 keV + 46 keV CE from absolute gamma efficiency ratios 81/30 keV. 129 keV and 198 keV are assumed to have an efficiency of 1 (5% error).

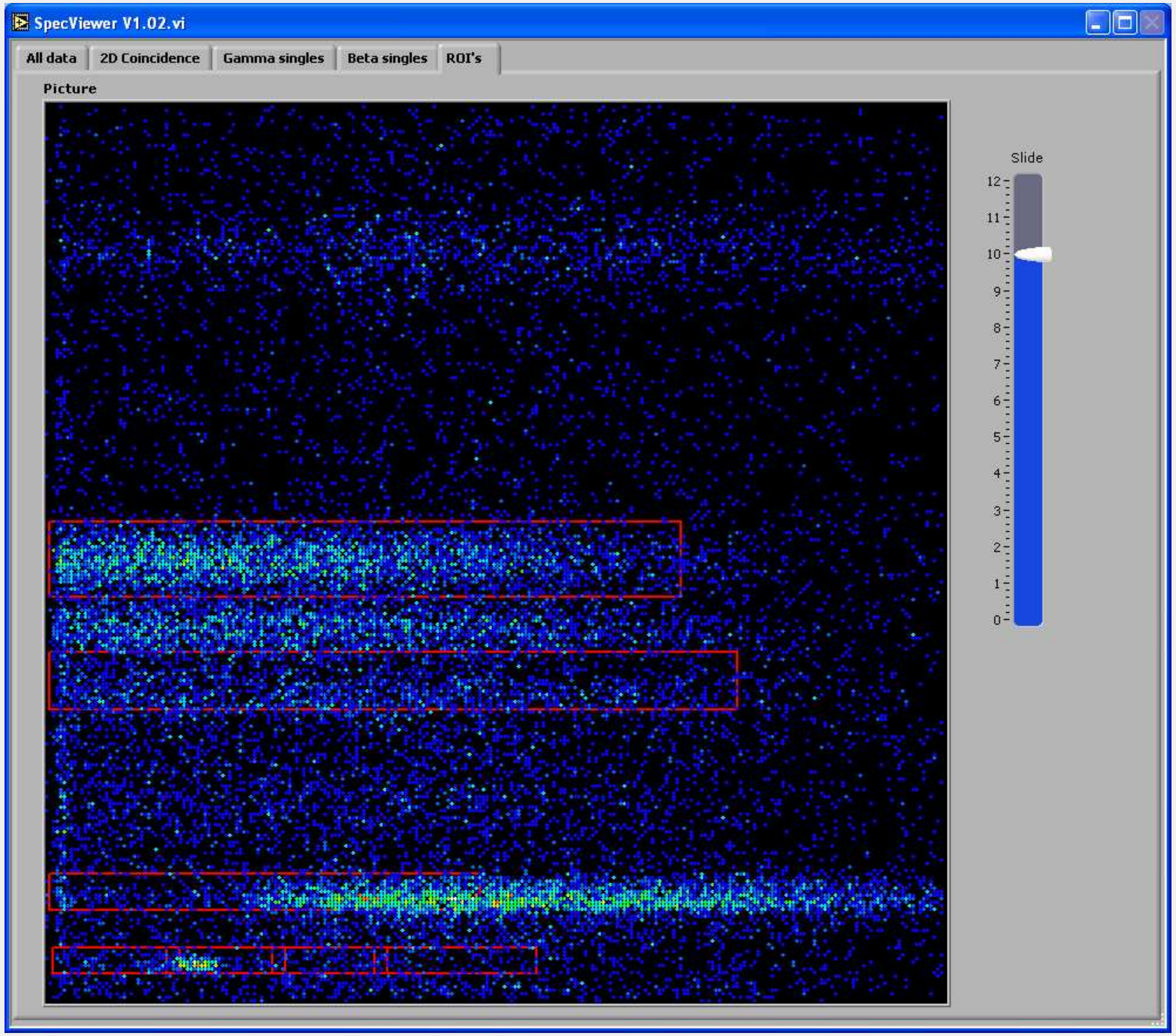




Gamma-ray spectra measured after injecting active ^{133}Xe. The ratio between the number of counts in γ-singles and β-gated γ-spectrum is used to calculate the beta detection efficiency

Radon calibration

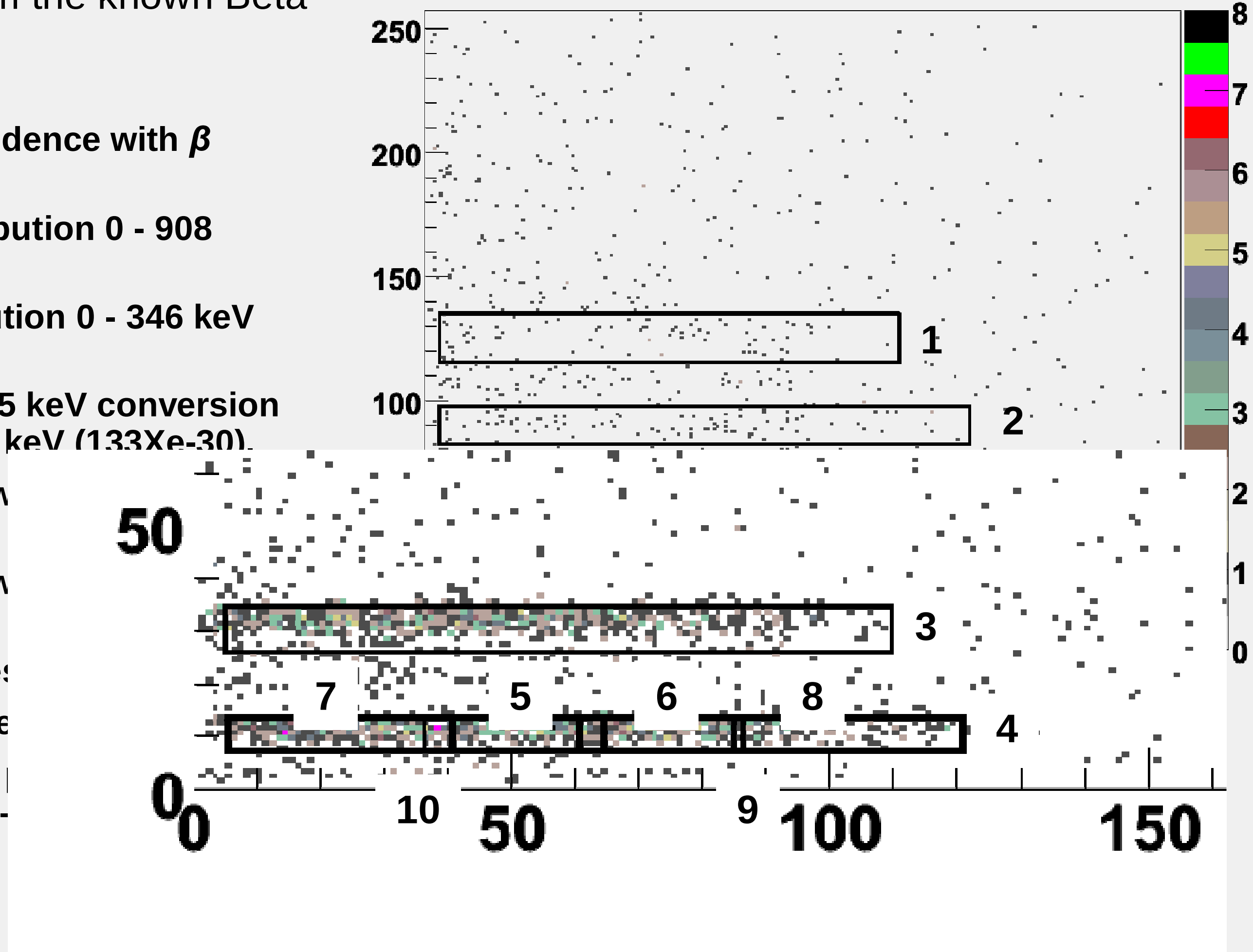
Finally Radon is injected into the cell to determine the effect of Rn daughters in the different ROI’s



Activity Determination

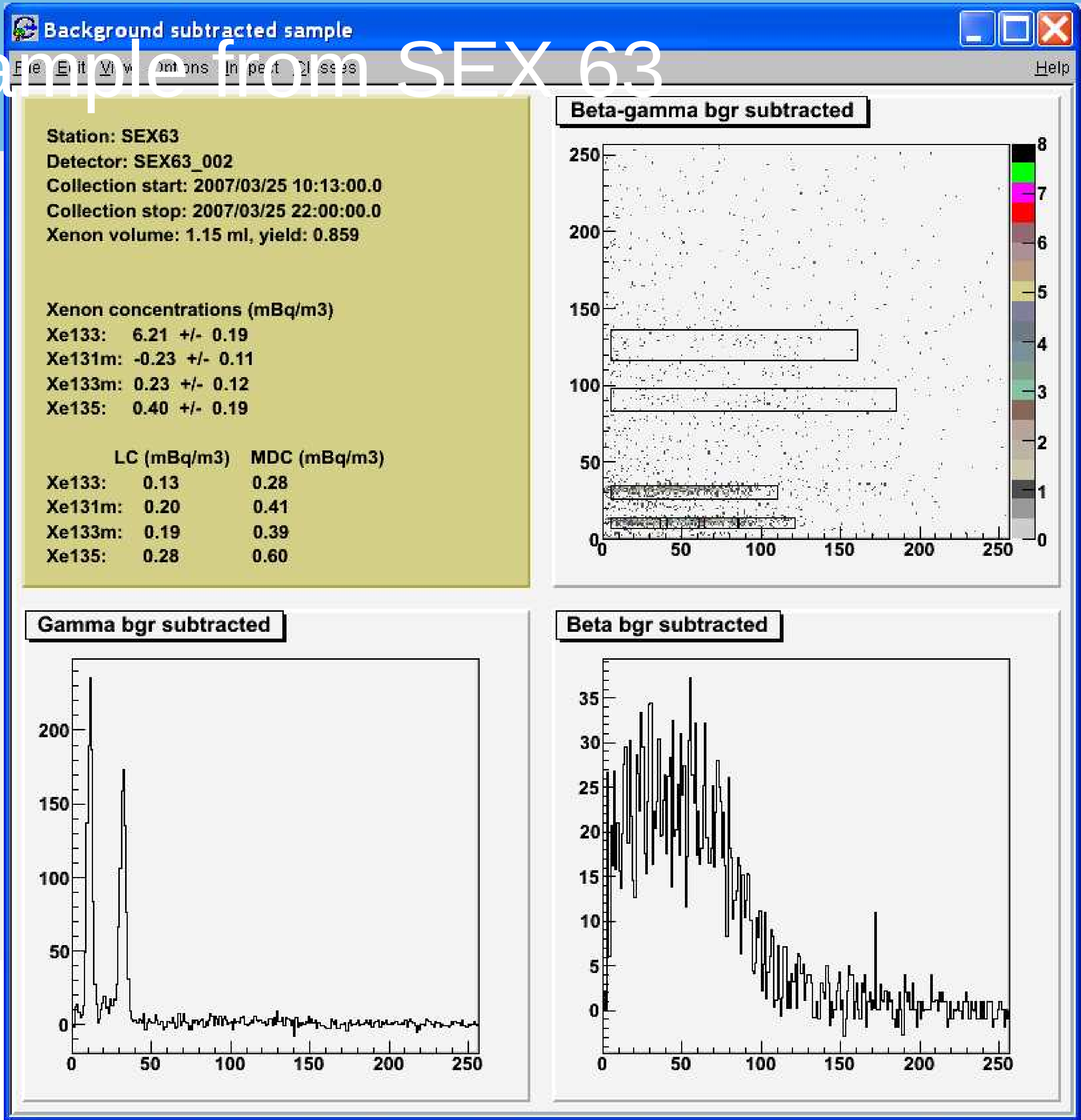
The following 10 ROI's are calculated from the known Beta Gamma coincidence distributions:

1. **The ^{222}Rn daughter ^{214}Pb 352 keV γ in coincidence with β distribution 0 - 678 keV (Rn/Pb-214).**
2. **^{135}Xe 250 keV γ in coincidence with β distribution 0 - 908 keV (Xe-135).**
3. **^{133}Xe 81 keV γ in coincidence with β distribution 0 - 346 keV (Xe-133-81).**
4. **^{133}Xe 30keV X-rays in coincidence with β +45 keV conversion electrons gives the distribution 0 - (346+45) keV (133Xe-30).**
5. **129 keV β peak from ^{131m}Xe in coincidence w rays.**
6. **198 keV β peak from ^{133m}Xe in coincidence w rays.**
7. **low end of ^{133}Xe-30, for use when ^{131m}Xe pre**
8. **hi end of ^{133}Xe-30, for use when ^{131m}Xe prese**
9. **hi end of ^{133}Xe-30, for use when ^{131m}Xe NOT**
10. **low end of ^{133}Xe-30, for use when ^{131m}Xe NO**



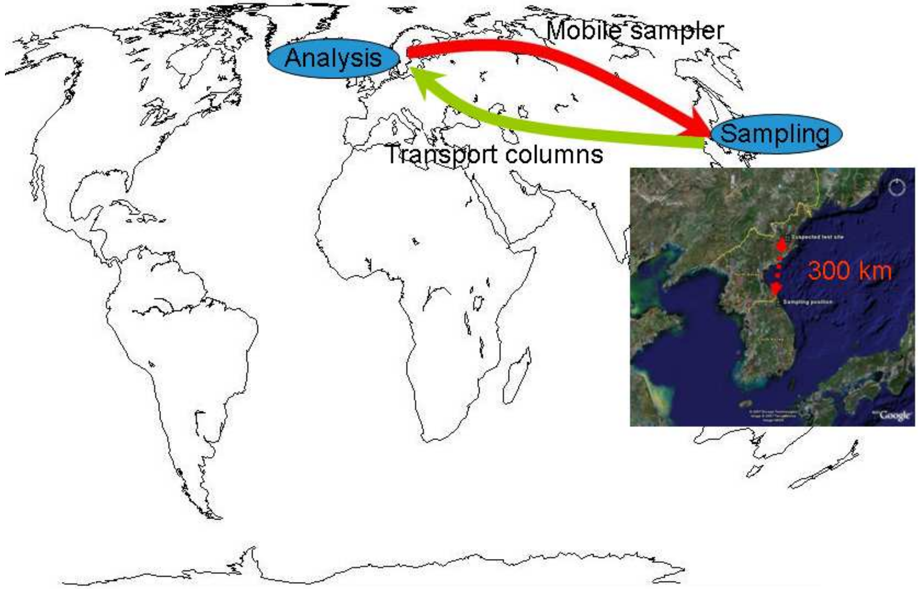
FOI

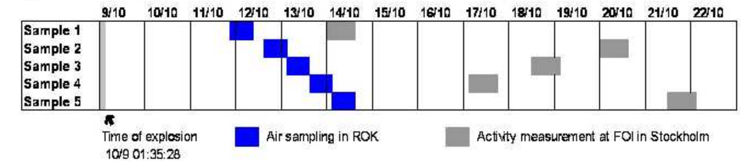
Example from SEX 63

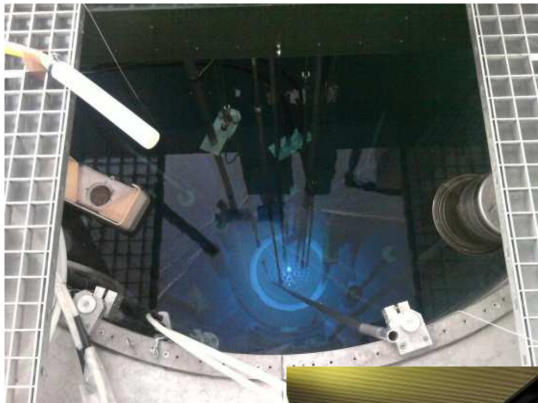


What has been done with the SAUNA?

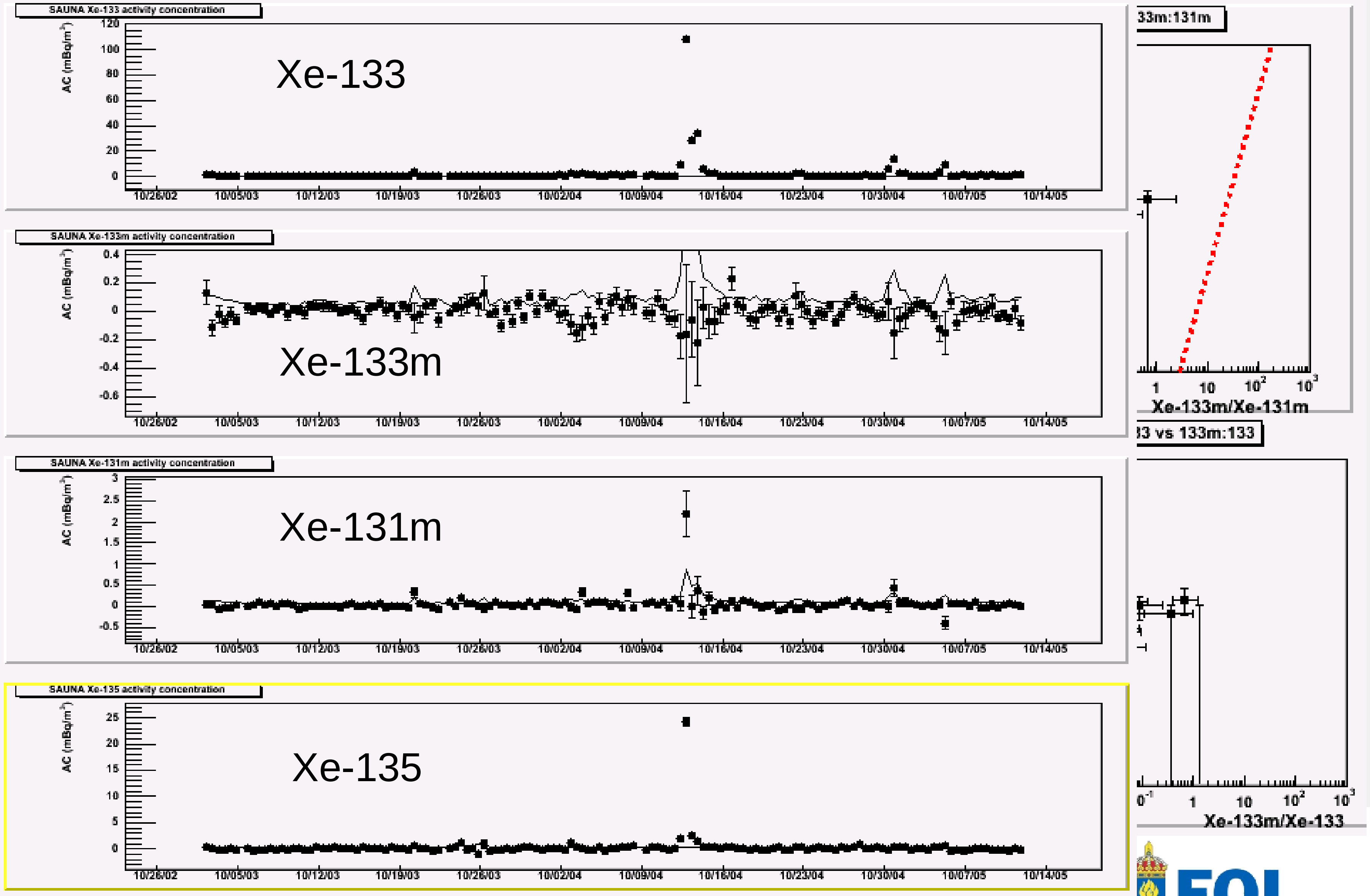
- In the IMS network 16 systems installed 2011. Data evaluated to understand the background of Xenon in the atmosphere
- +EU/JA-project with full SAUNA installation, Kuwait South Africa and Thailand
- Seibersdorf 2006
- Korea 2006, samples analyzed in Stockholm
- Belgium 2008, samples analyzed in Stockholm
- Austria. TRIGA reactor, samples analyzed in both Freiburg and Stockholm
- Germany
- Slovakia, NG09



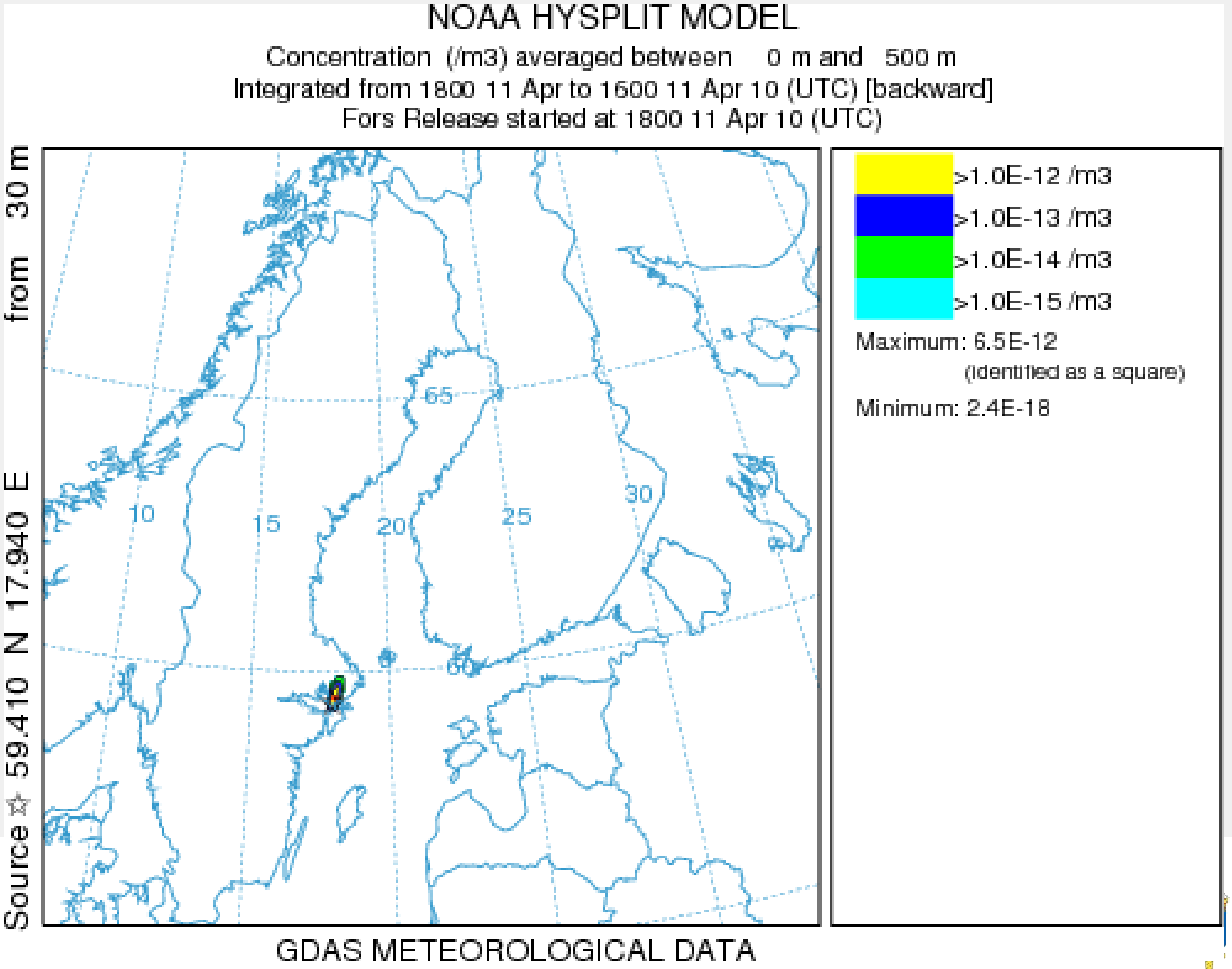




Example from SEX63 (FOI/Kista), April 2010



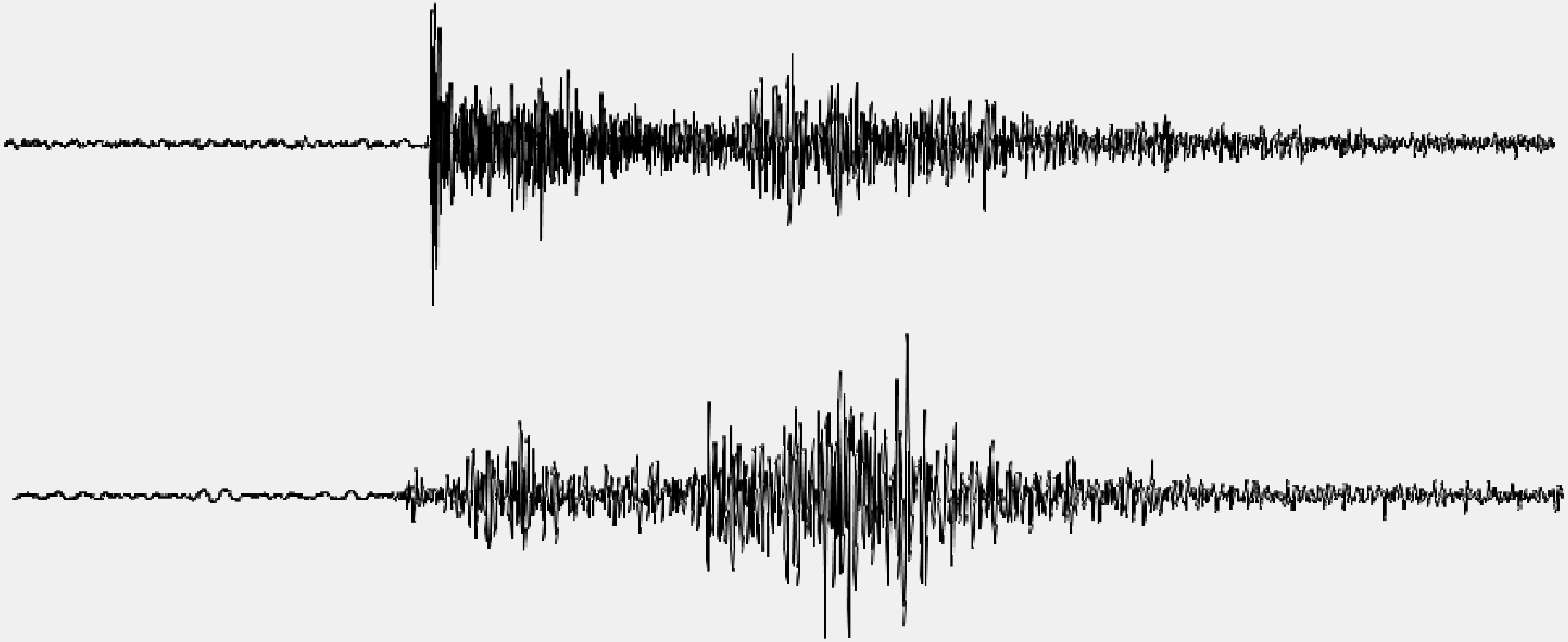
Example from SEX63 (FOI/Kista), April 2010



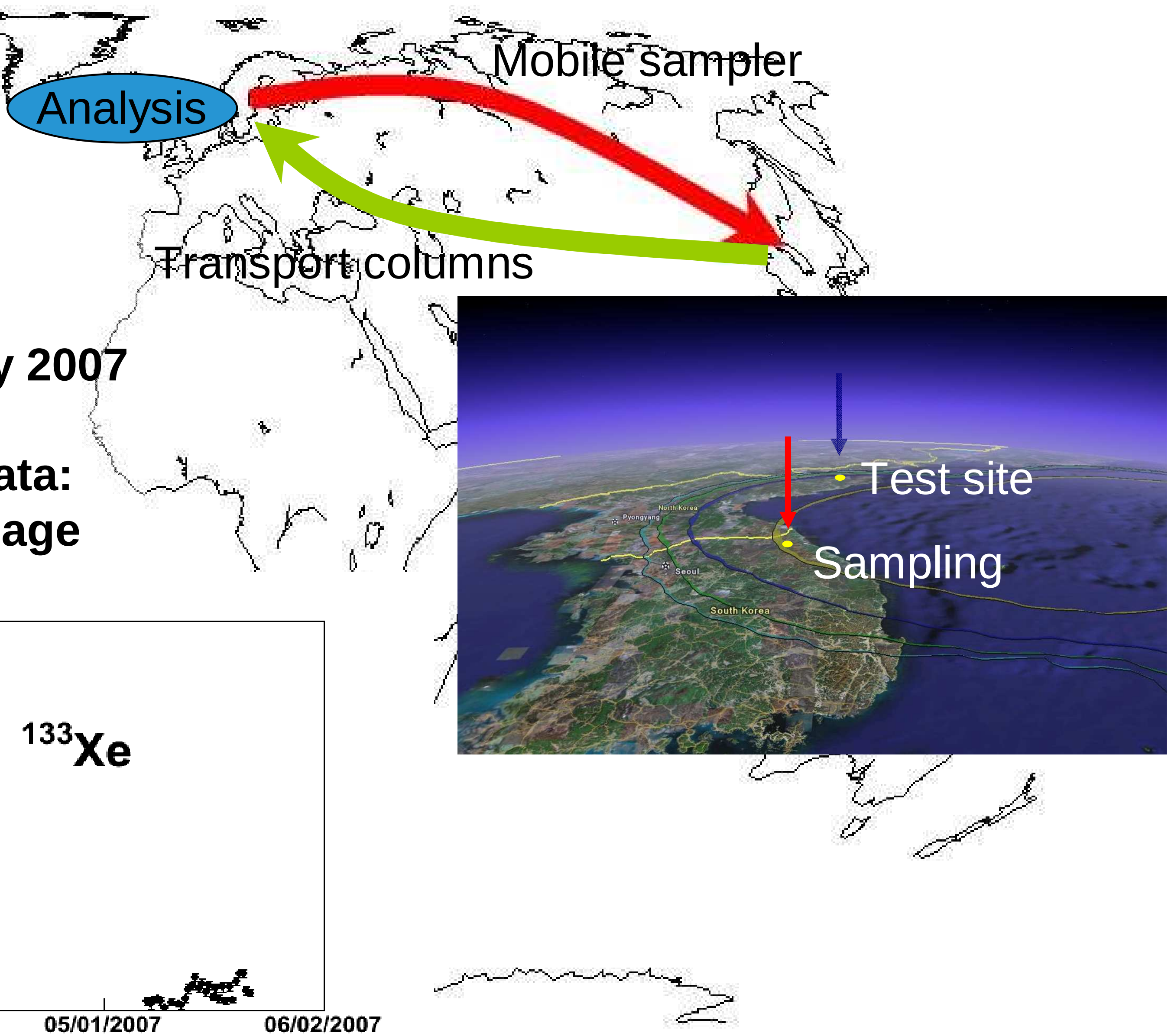
FOI

DRPK seismic even 2006

Top graph from DRPK even below an earthquake from same area

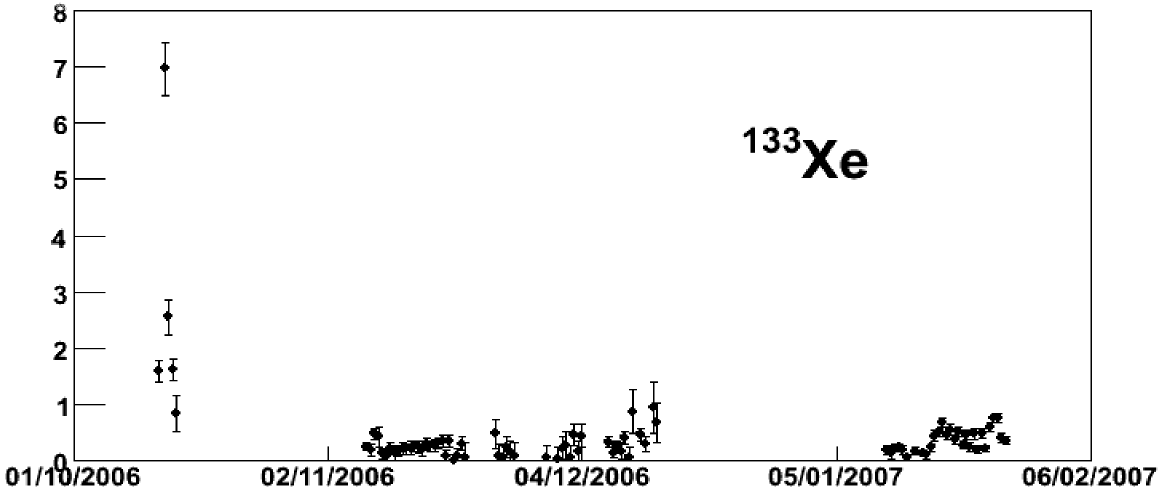


DRPK in 2006



Mobile system on site
11-14 October 2006
IMS system on site
November, 2006 - January 2007

Realistic scenario from data:
Prompt release plus seepage
for 2-3 days.

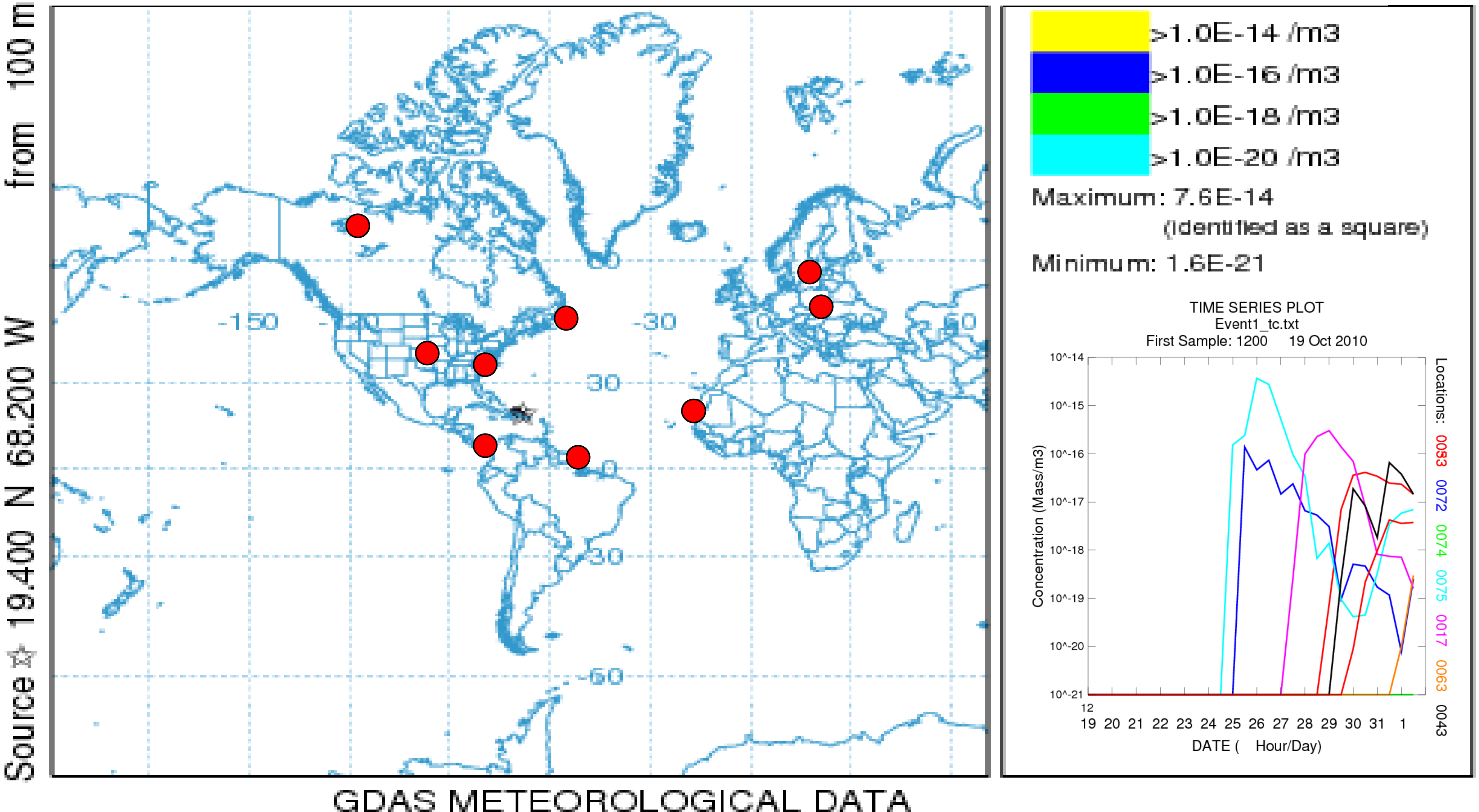


Time of explosion

Pictures from South Korea in 2006

A test scenario

Using ATM modeling from a seismic events one can determine if there is a correlation between Xenon signals at several different sites.

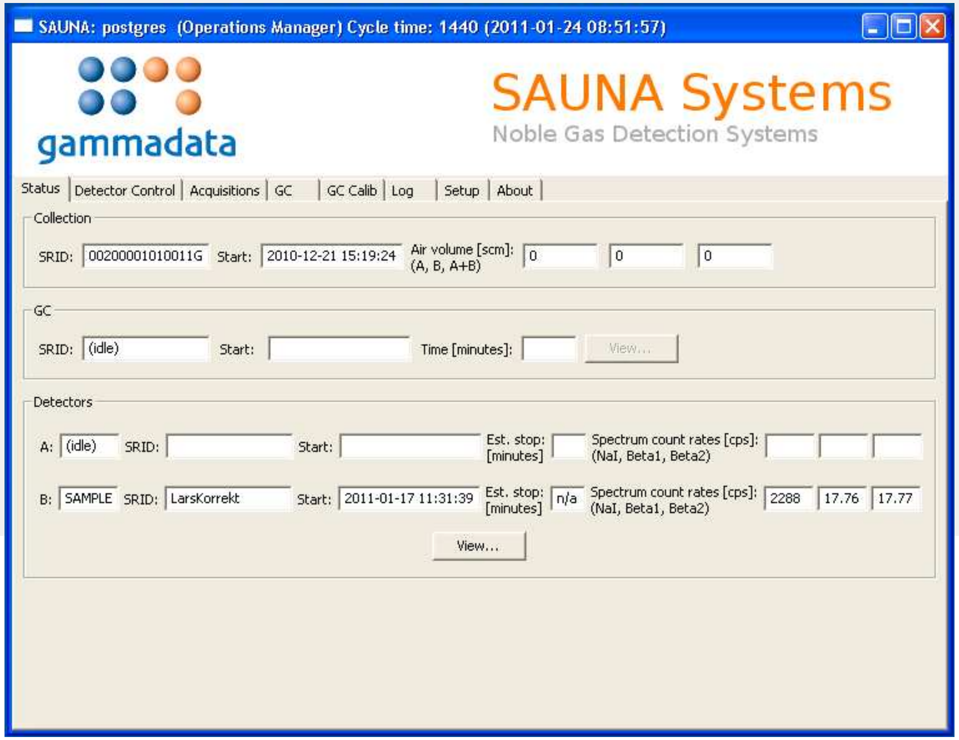


Upgrades, research and new development

- Detector electronics and software
- Reduced memory effect
- Next generation of SAUNA systems

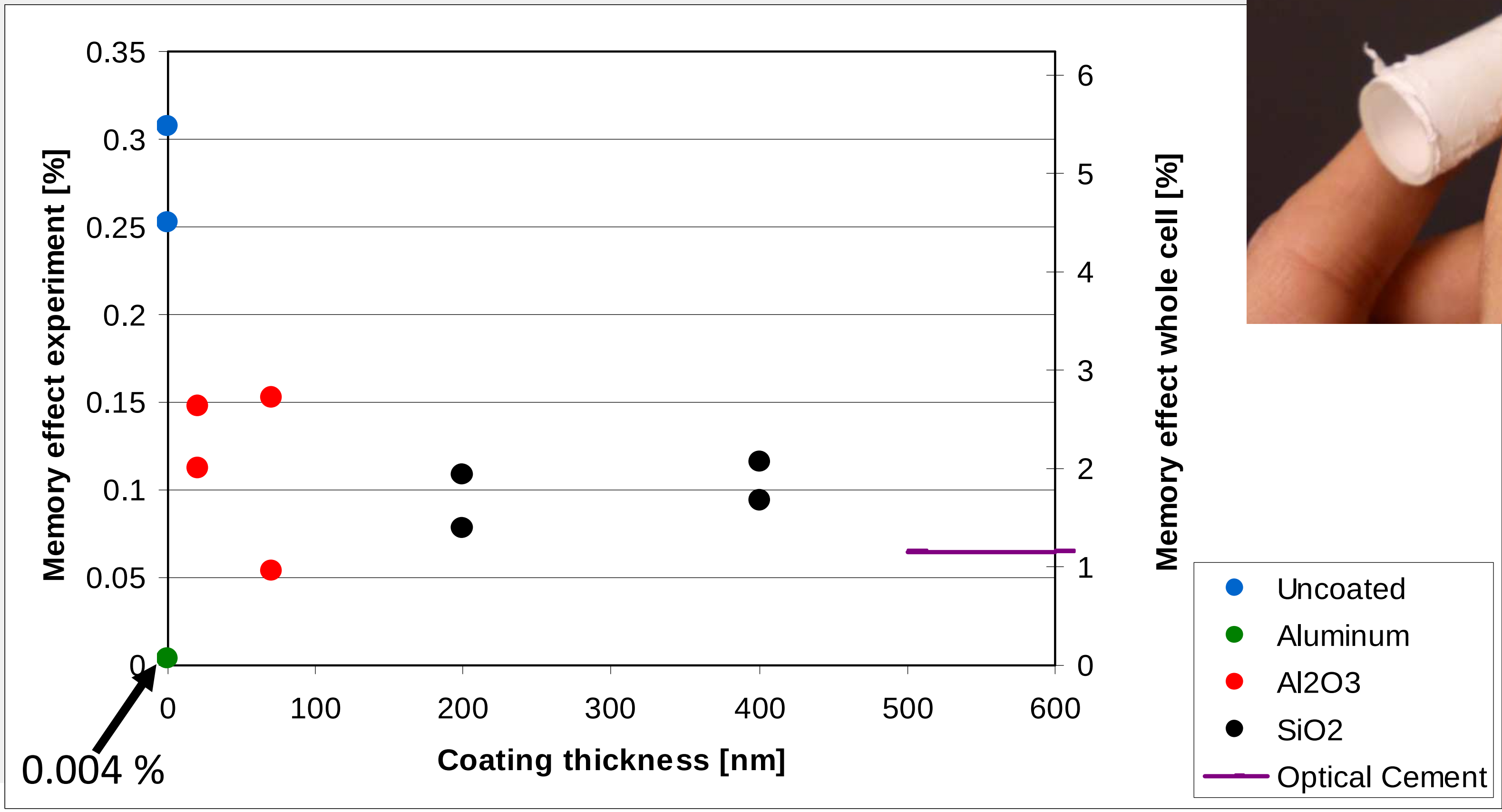
Detector electronics and software

- New electronics replacing old NIM and CAMAC equipment
  - Gammadata developed HV and preamp unit
  - Pixie-4, 4-Channel Compact-PCI Digital Spectrometer
- New data acquisition software developed by Gammadata
  - User accounts with different levels of privileges
  - More spectral information stored than IMS format allows for
  - Data stored locally in a database



Reduced memory effect: MER project

- Xenon diffuses into the plastic cell, reduced sensitivity after strong spike
- Different types of coating are under testing
- Atomic Layer Deposition of Al_2O_3



- Statistical uncertainty ~1%

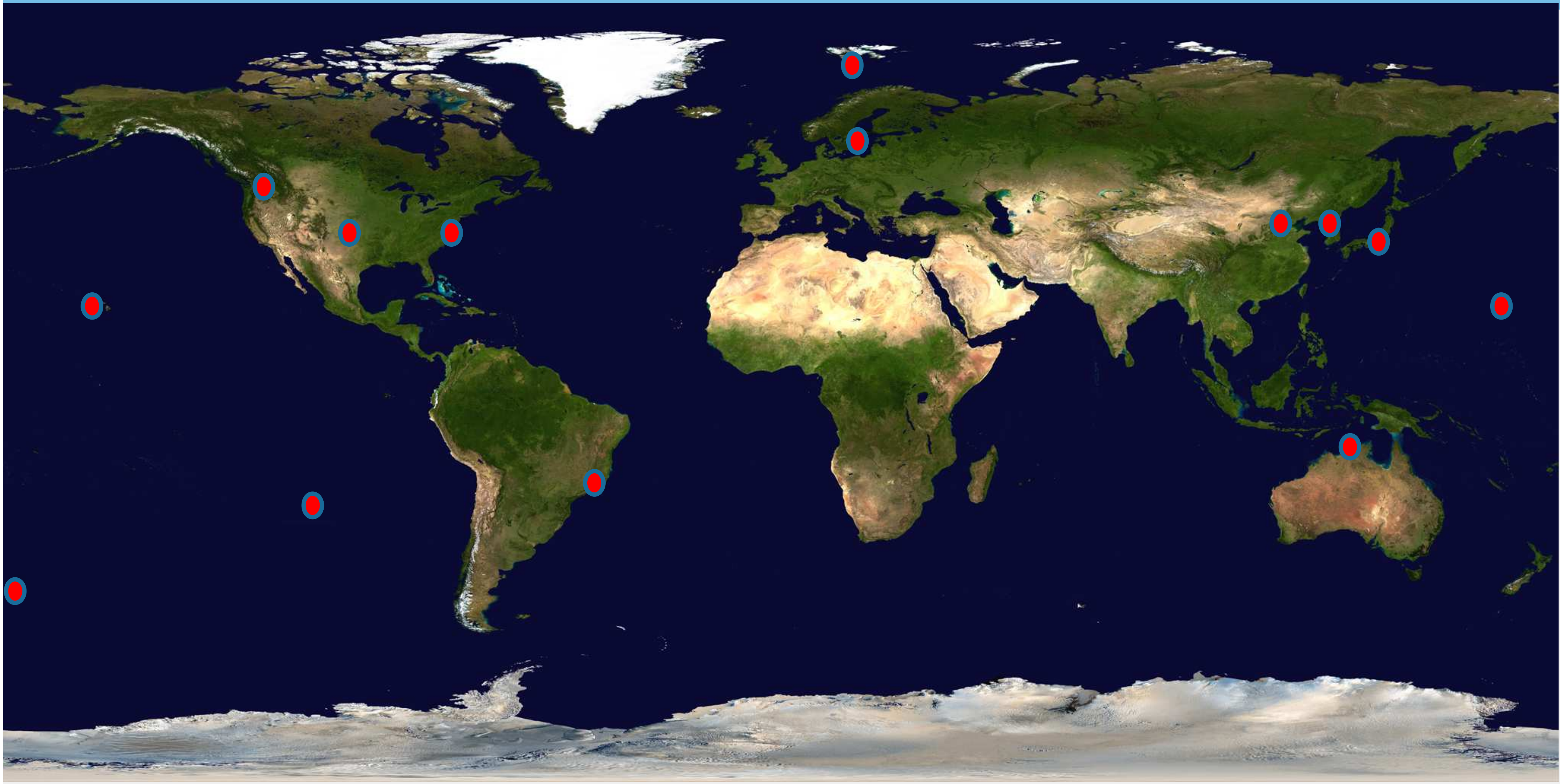
FOI

Next generation of SAUNA systems

- 2011-12 a new processing system for OSI use will be developed. The focus is to improve the sample throughput.
  - An OSI inspection will require a drastically increased throughput of the system
  - Expected about 100 samples/day, sample mixing (newtoning search)
- Useful input for the next generation of systems, SAUNA III
  - Higher throughput
  - Higher time resolution, more samples/day
- Krypton system…

Conclusion and outlook

- CTBT:s verification network is almost built. It will be capable of detecting small underground nuclear bombs. The main noble gas system is the FOI developed SAUNA II system
- More than 20 SAUNA-II systems built so far
  - 16 in the IMS network plus a few mobile and lab systems
- Can detect trace levels of radioxenon, <1mBq/m3
  - If three or four isotopes are detected, possible to distinguish between peaceful or bomb origin
  - Combined with seismic signals and ATM modeling a stronger case can be made
- Ongoing and future development
  - New detector hard- and software, improved stability and functionality
  - Reduced memory effects in detector cells, improved sensitivity
  - A transportable processing system with a higher through put



Thank you for your attention