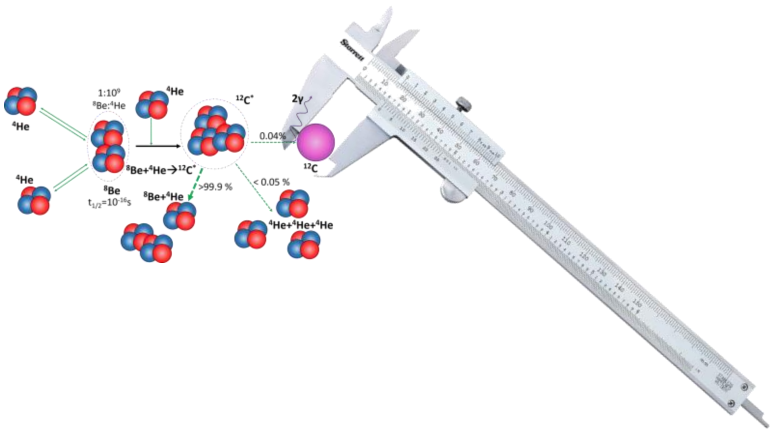
Nuclear Experimental Techniques with Rare Isotope Beams

Sunghoon(Tony) Ahn

June 25th/29th 2019



Goals of This Lecture

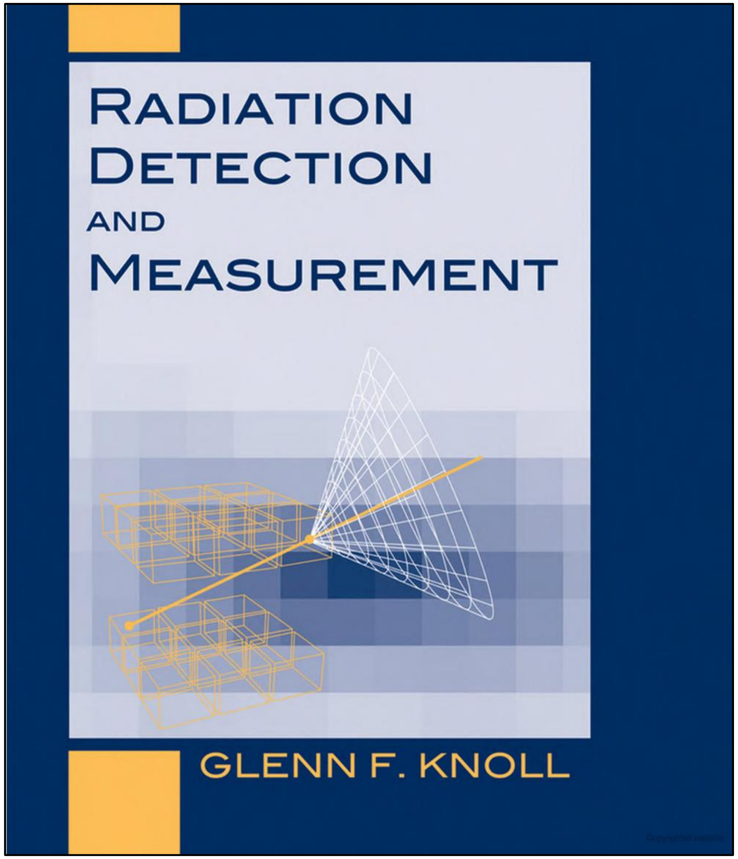
By the end of this lecture, you should be able to answer:

- How detectors actually work.
- Which parameters are actually measured, and which are inferred or calculated?
- How to process signals from detectors.
- Advantage of multi-channel signal processing.

→ **Detectors and Electronics Experts!!**

The Bible

Believe what this text book says…



Brief Contents

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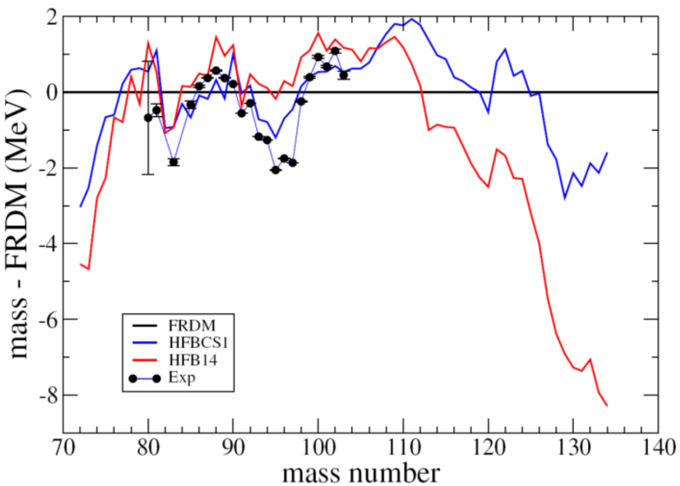
Story Line of Lecture

- ✓ Properties of nuclei we want to know
- ✓ How to study the properties
- ✓ How to detect particles
- ✓ Signal Processing
- ✓ Online Data Acquisition
- ✓ How put together for actual experiments
- ✓ Summary

Properties of Nuclei

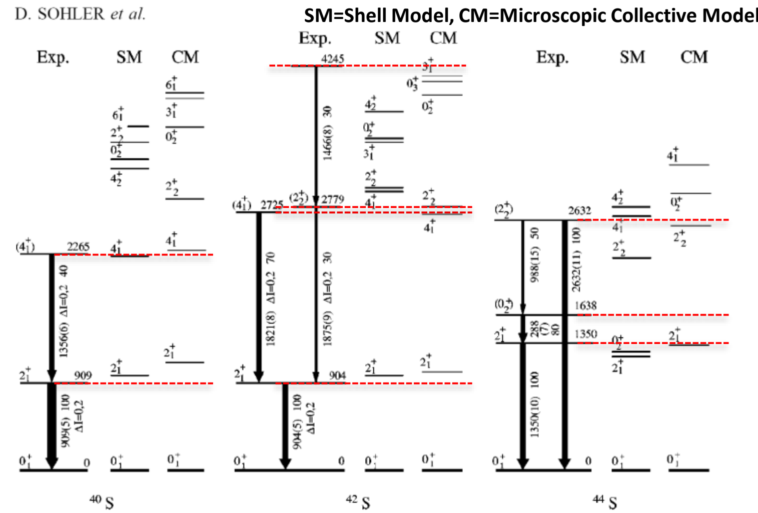
- **Nuclear Mass**

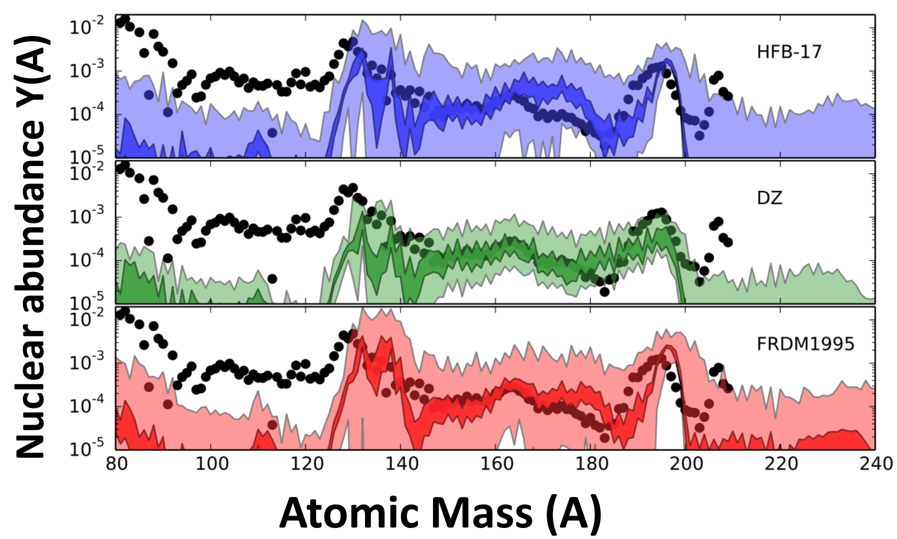


Mass differences between measurement and models for Zr isotopes

H. Schatz, TALENT 2014

- **Excitation energy, Spin and parity**

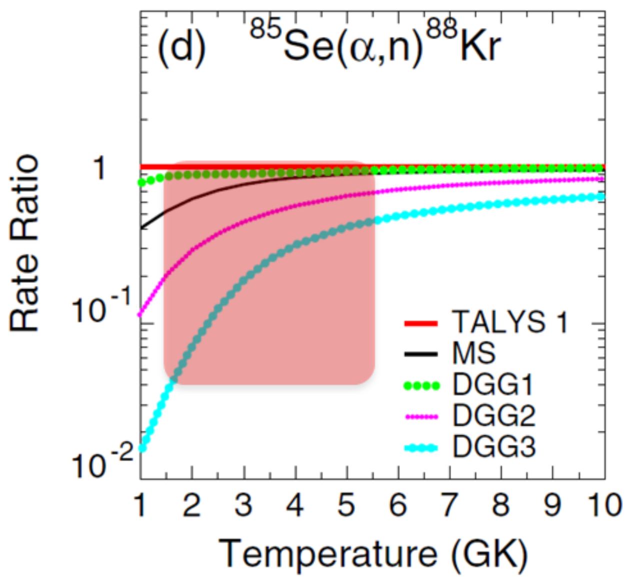




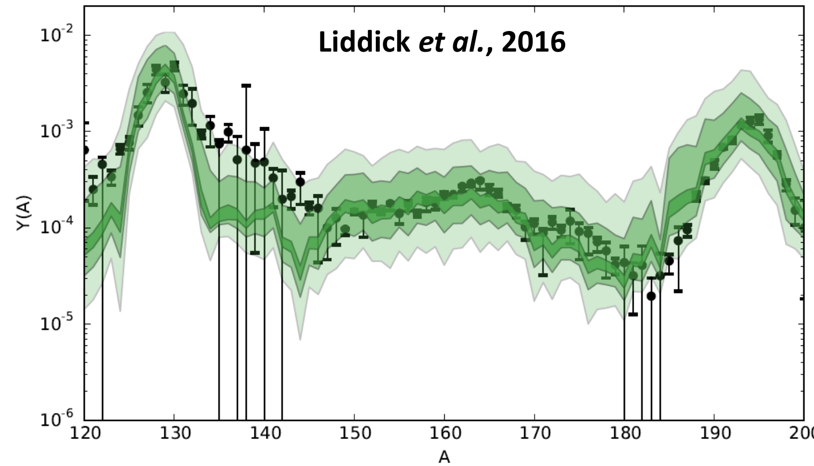
Monte-Carlo variations of nuclear properties.
Dark shaded region represents σ_{mass} = 100 keV.
Mumpower *et al.*, 2015

Properties of Nuclei

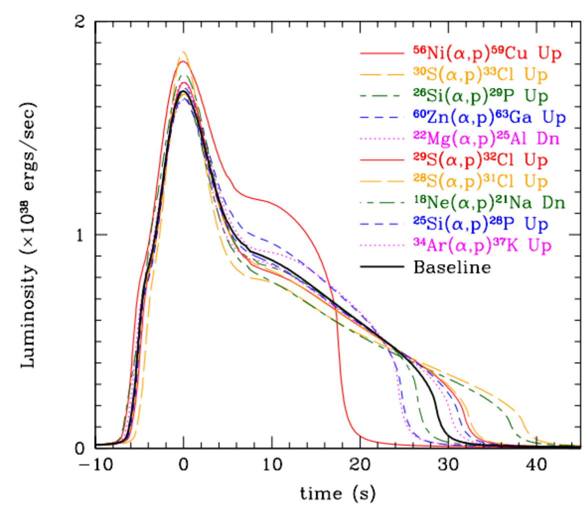
- **Reaction Cross Sections (Reaction Rates)**



$^{86}Se(\alpha,n)$ reaction rate ratios w/ various alpha OMP
J. Pereira and F. Montes, Phys Rev C 93, 034611 (2016)



Monte-Carlo variations of (n,γ) rates within a factor 100 - 10 - 2 (light - darker - dark bands)



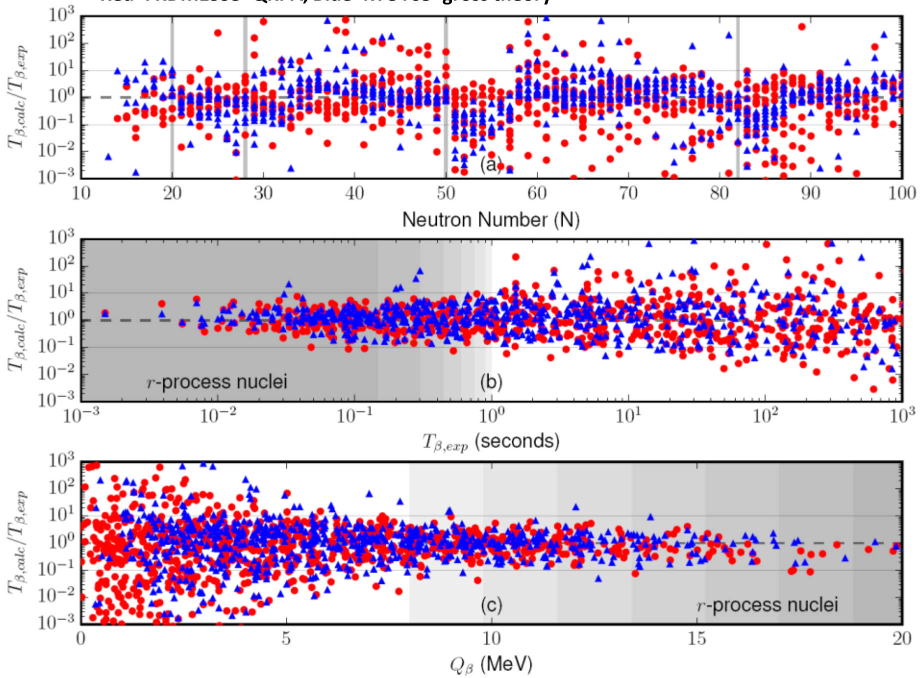
Calculated light curves of X-ray burst within a factor of 100
R. H. Cyburt *et al.*, 2016

Properties of Nuclei

- **Half-life of β-decay**

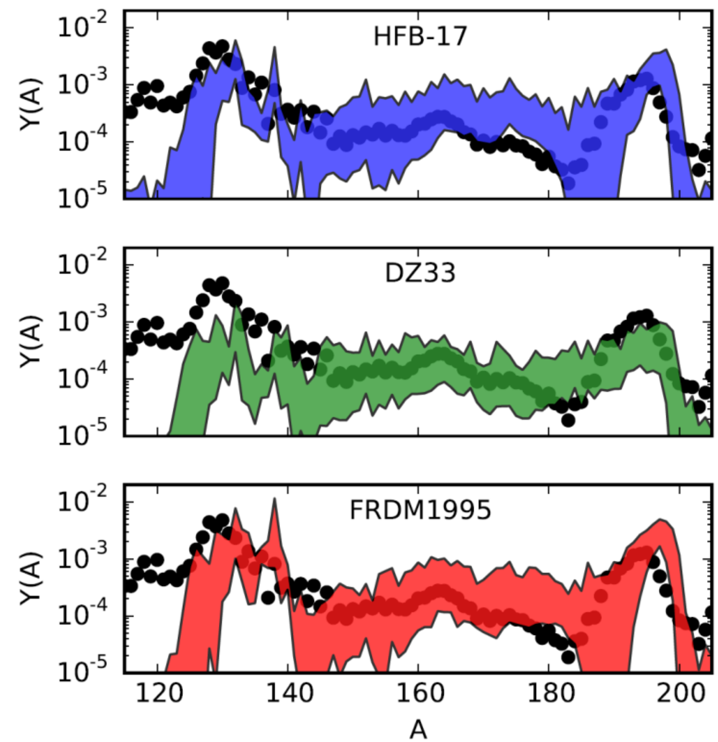
Mumpower *et al.*, 2015

Red=FRDM1995+QRPA, Blue=KTUY05+gross theory



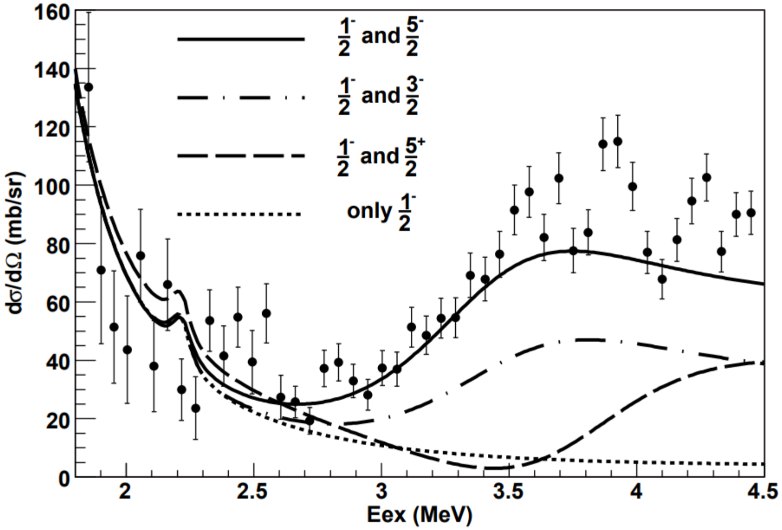
Comparison of theoretical β-decay half-lives to measured values from the NNDC database

Monte-Carlo variations of half lives ranged from 10^{-1} to 10



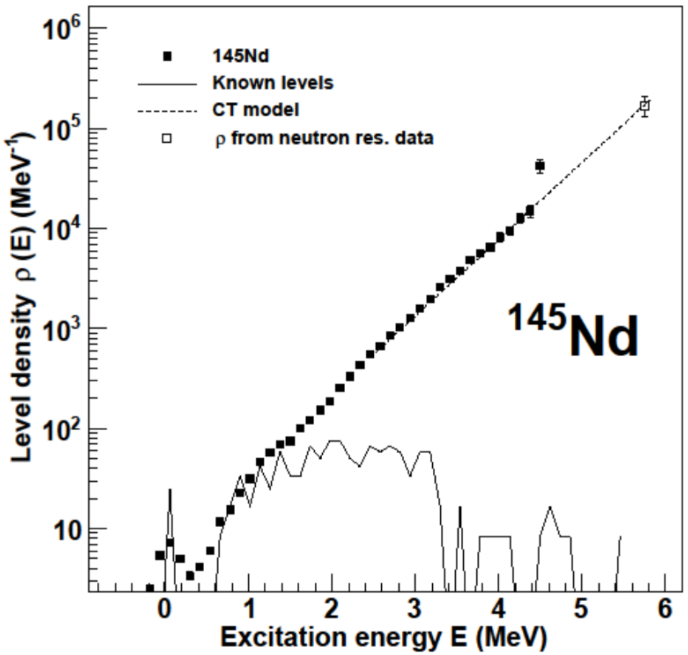
Properties of Nuclei

• **Excitation function**



Measured excitation function for $^{8}B+p$ elastic scattering in the angular range of 164±7 degree compared to R-matrix calculations
G.V. Rogachev *et al.*, 2006

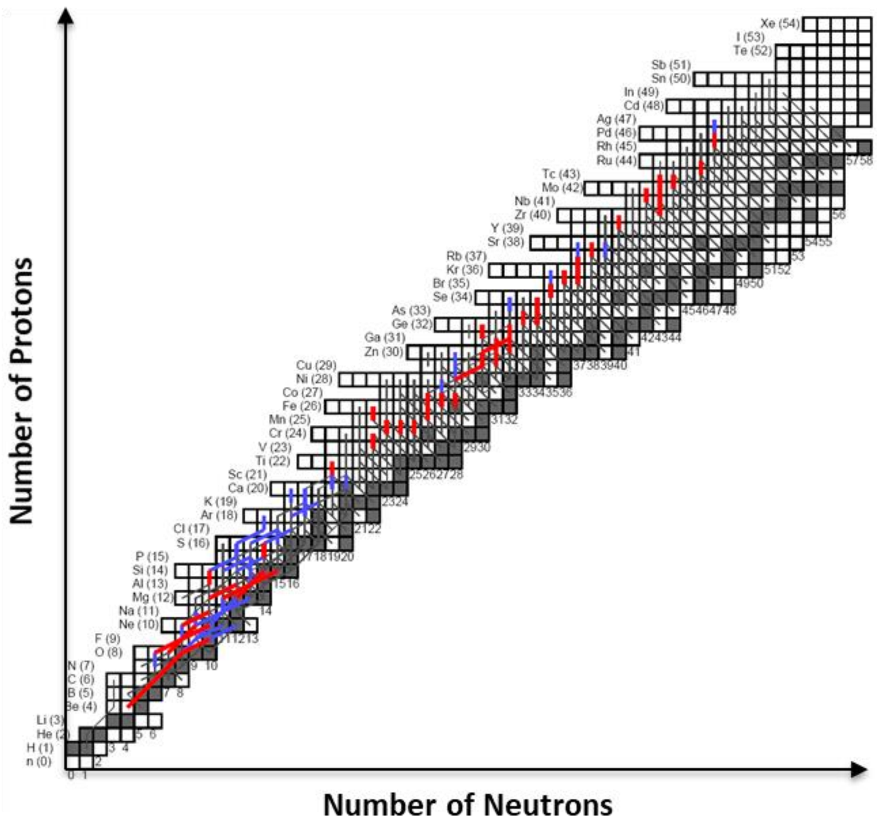
• **Nuclear Level densities and gamma-ray strength**



The level density of ^{145}Nd is normalized to known discrete levels at low energies and to (Sn) at the binding energy
K O Ay *et al.*, 2016

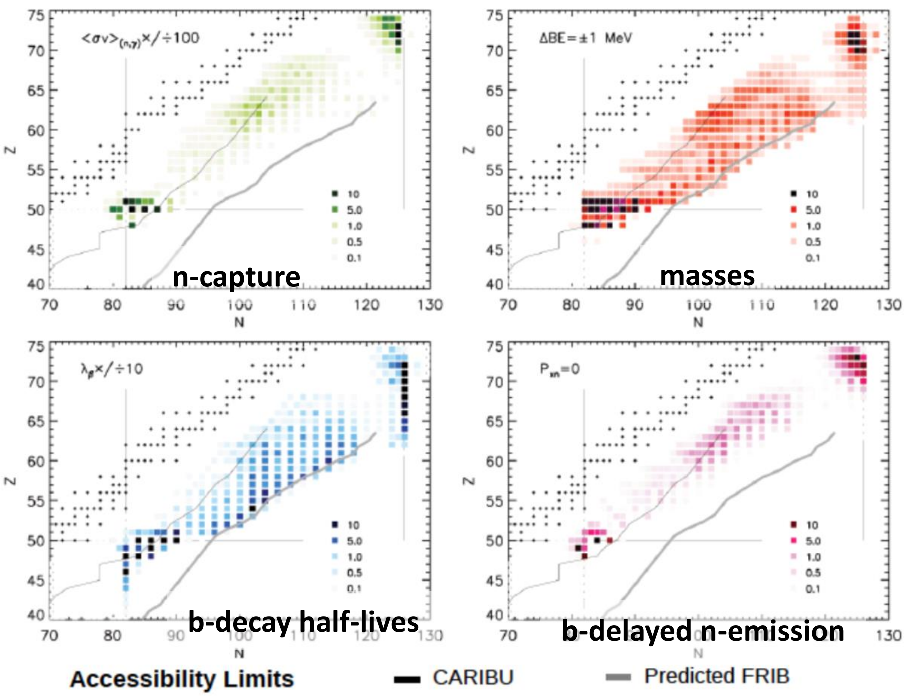
→ Will improve the statistical model (e.g. Hauser-Feshbach) for compound reaction cross section calculation.

Sensitivity Studies for Significance



Nuclear chart with most sensitive (*α,p*) reaction rates
R. H. Cyburt *et al.*, 2016

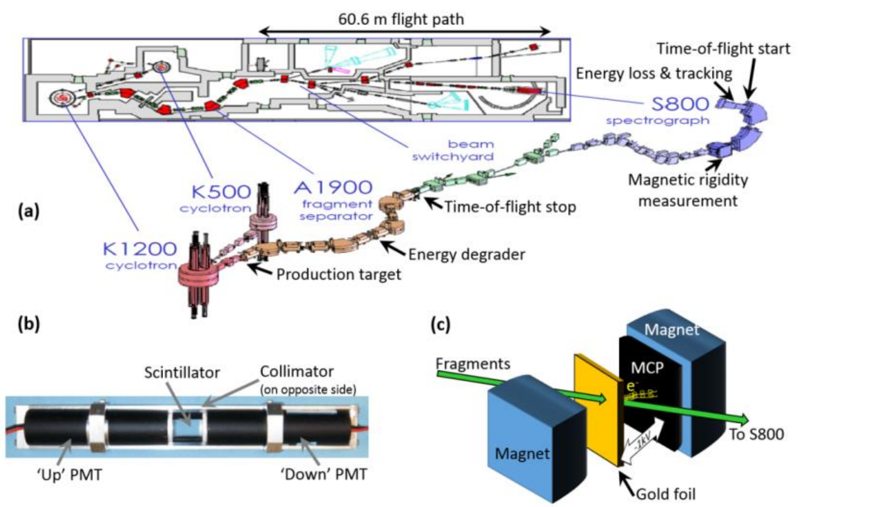
Nuclei that significantly impact final r-process abundances
Mumpower *et al.*, 2015



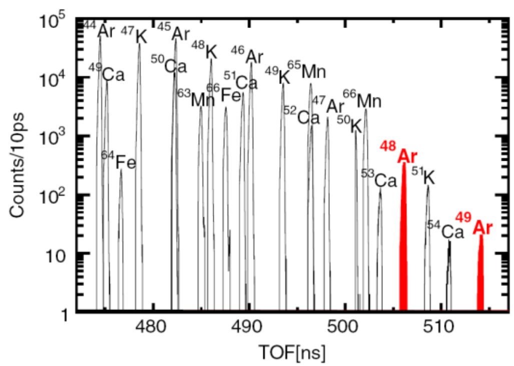
✓ **Nuclear properties of rare isotopes are important!**

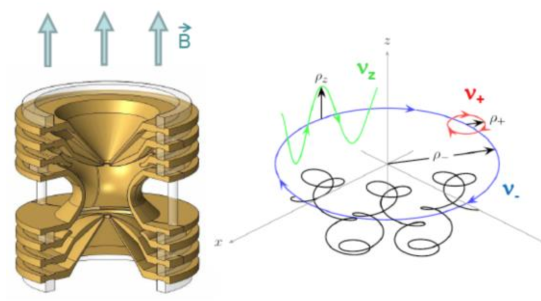
Nuclear Mass Study

- ToF Mass, MR-ToF, Penning Trap, Q-value of g.s.



$$B\rho = \frac{\gamma m_0}{q}\left(\frac{L}{TOF}\right)$$

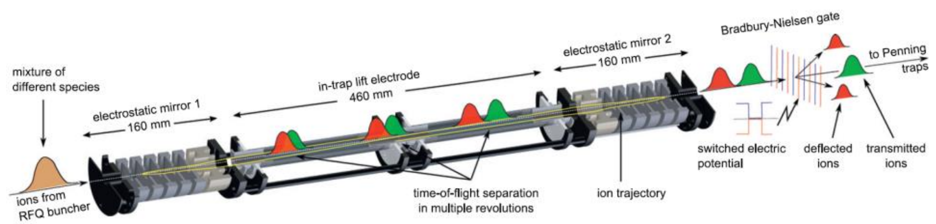




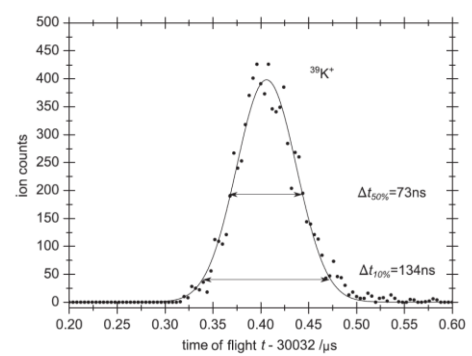
Cyclotron frequency:

$$f_c = \frac{1}{2\pi}\cdot\frac{q}{m}\cdot B$$

Penning Trap

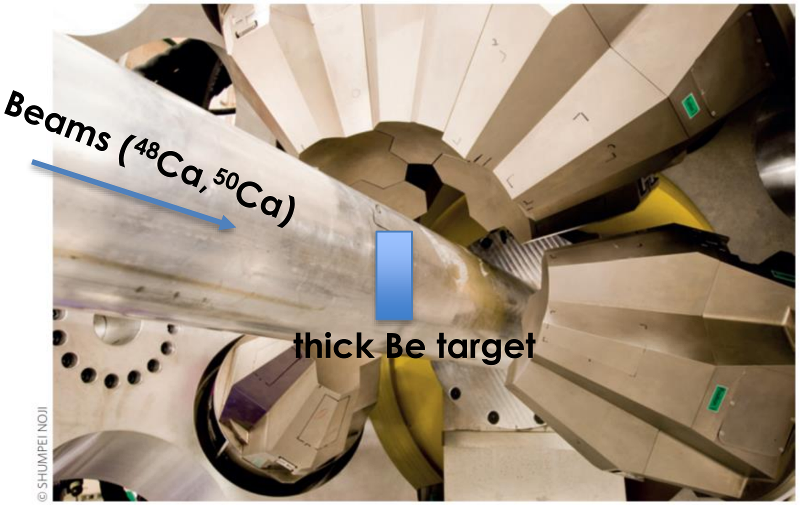


MR-ToF

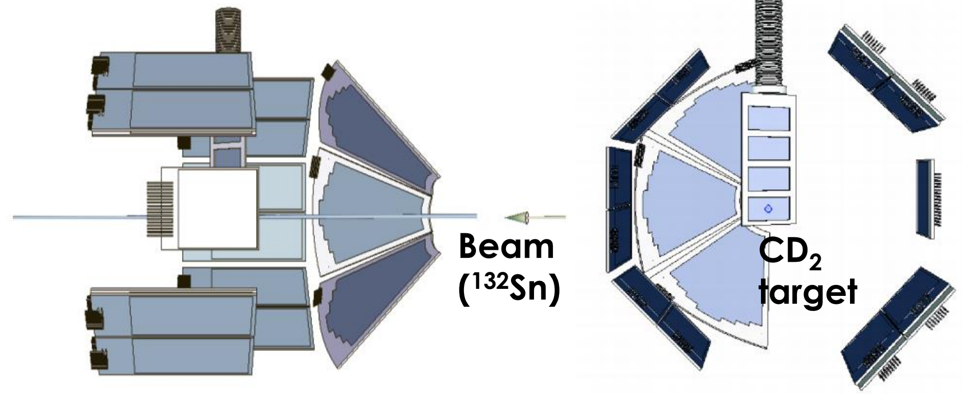


Excitation Energy Study

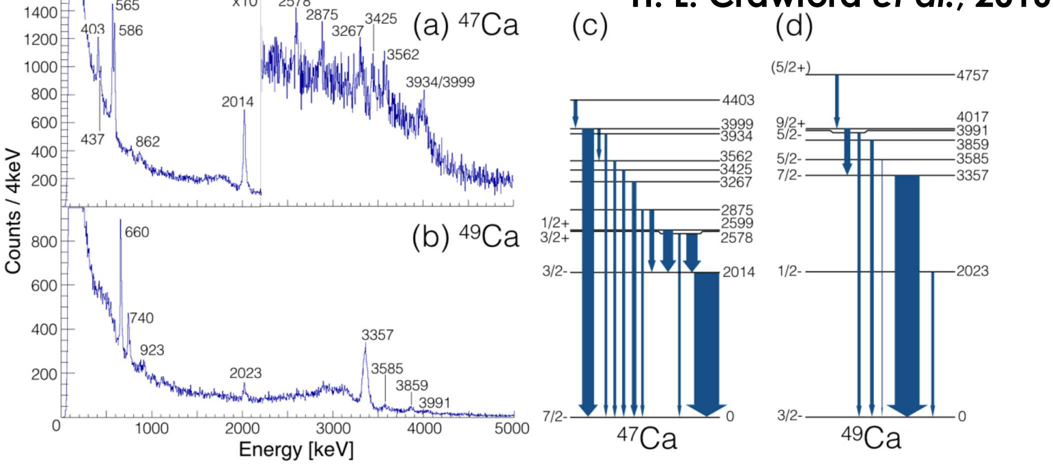
- By measuring γ-ray, Q-value of reaction

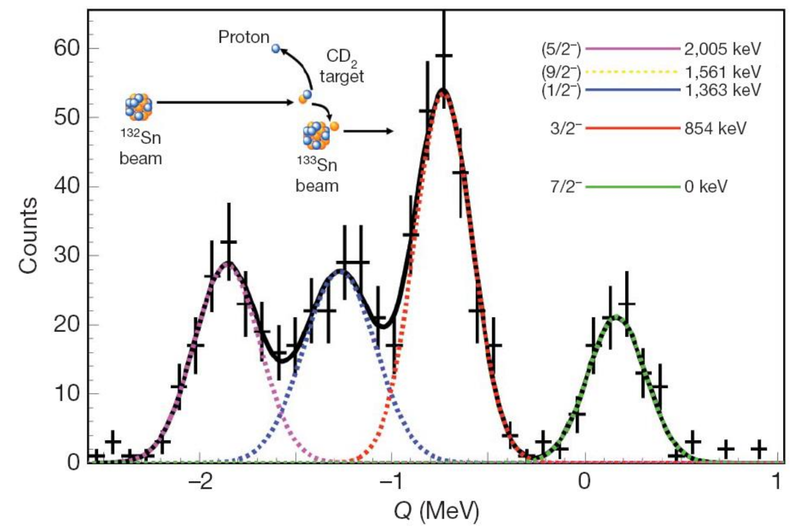


K.L. Jones *et al.*, Nature 2010



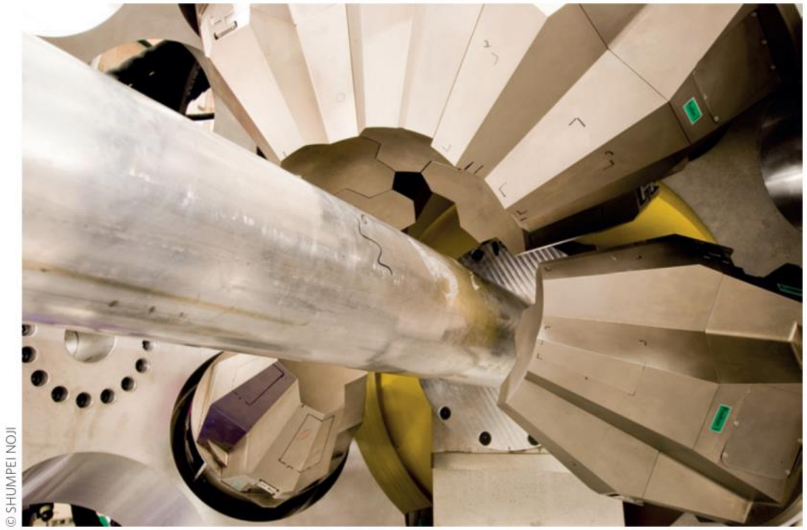
H. L. Crawford *et al.*, 2016



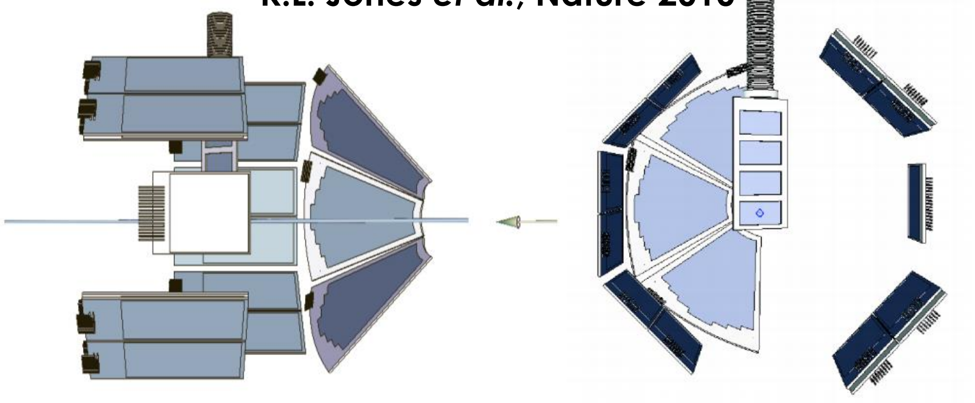


Nuclear Spin and Parity Study

- Spin and parity: level scheme, angular distribution

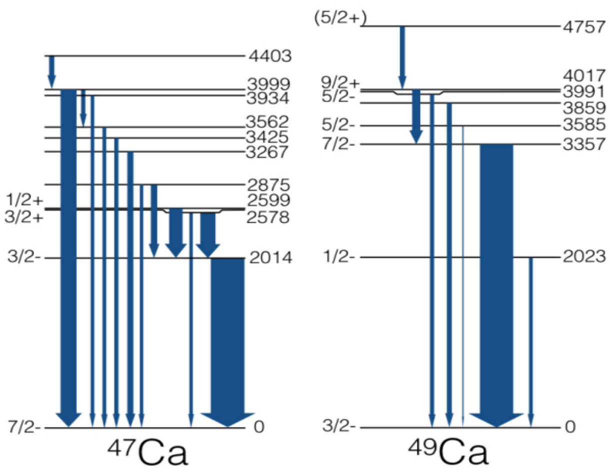


K.L. Jones *et al.*, Nature 2010

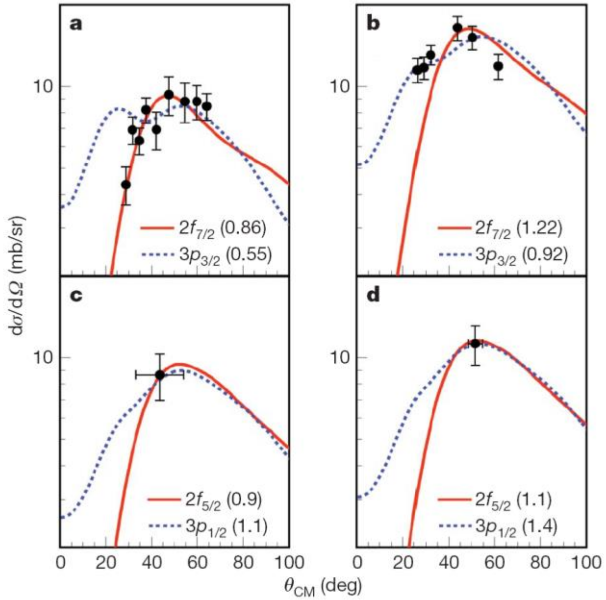


By angular Momentum and Parity Selection Rules,

$$\vec{I}_f = \vec{I}_i + \vec{l}$$
$$\pi_f = (-1)^l \pi_i \quad (E\text{-type})$$
$$\pi_f = (-1)^{l+1} \pi_i \quad (M\text{-type})$$

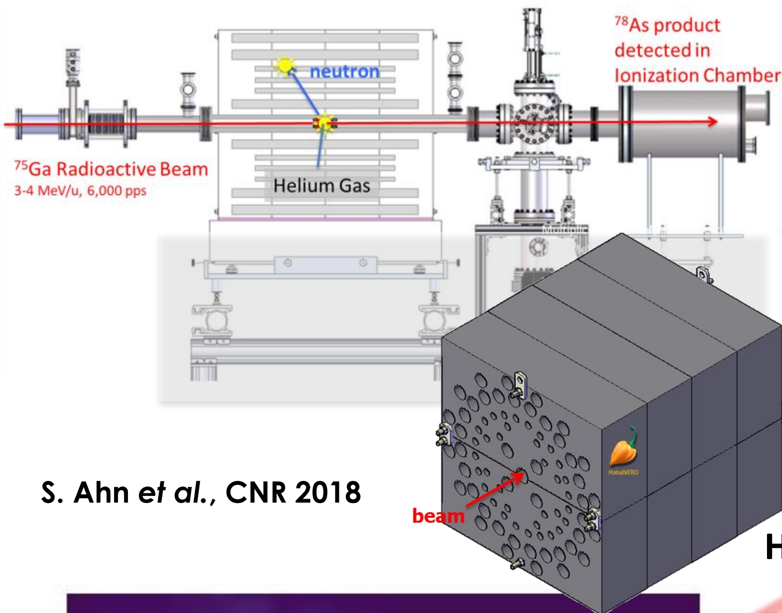


H. L. Crawford *et al.*, 2016



Reaction Cross Section Study

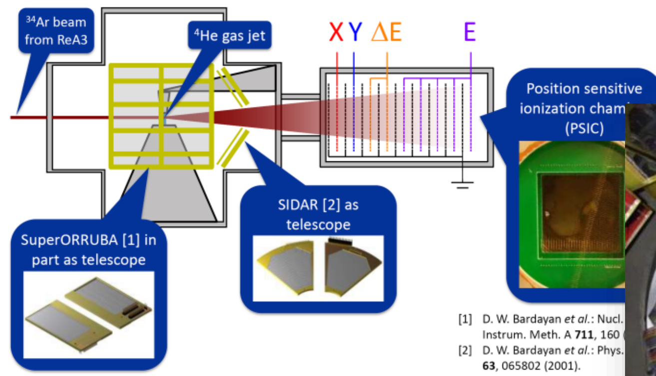
- Total Cross Sections: Yields



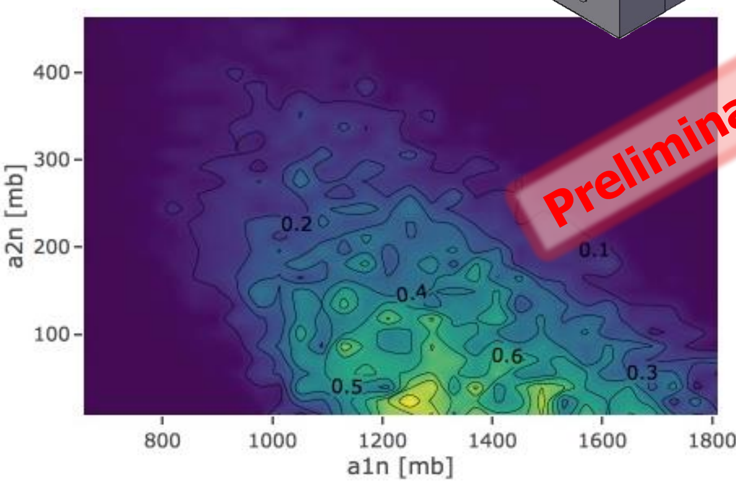
S. Ahn *et al.*, CNR 2018

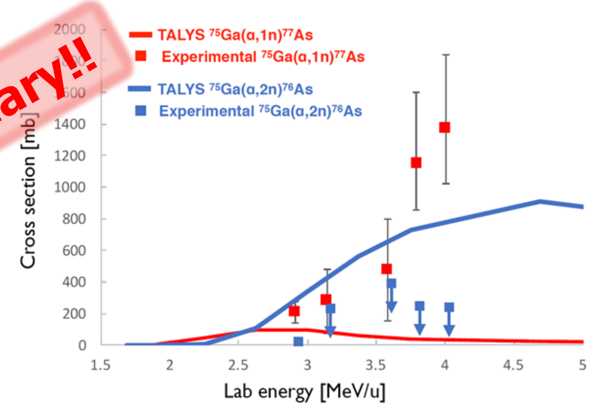
HabaNERO

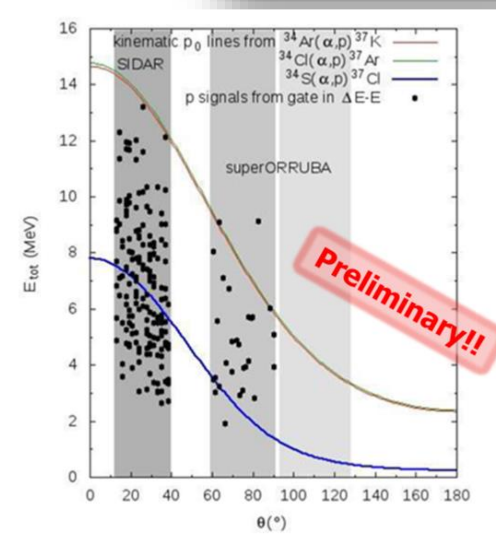
JENSA and SuperORRUBA



K. Schmidt *et al.*, NPA8 2017

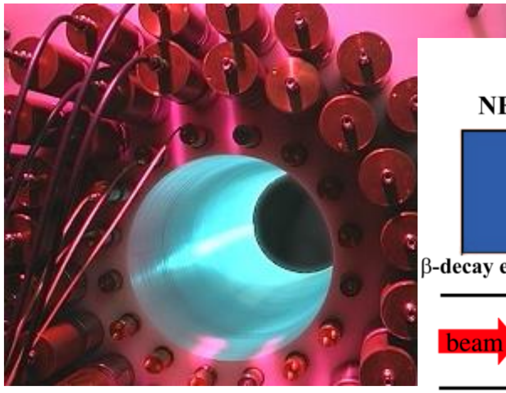


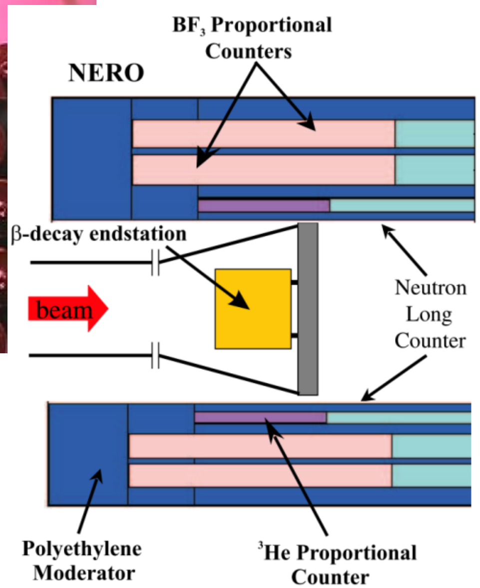




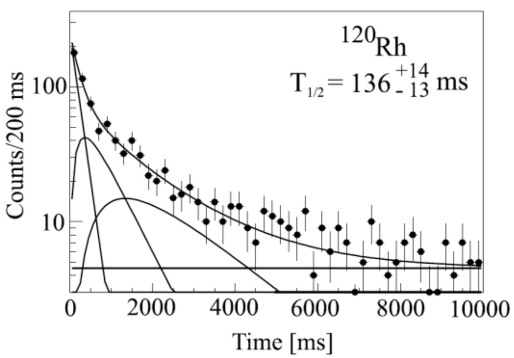
Decay Half life Study

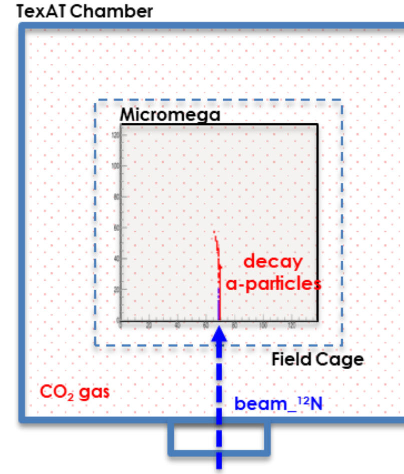
- Half life of nuclear decay: ΔTime of implants and (decay products, gamma ray or neutrons)

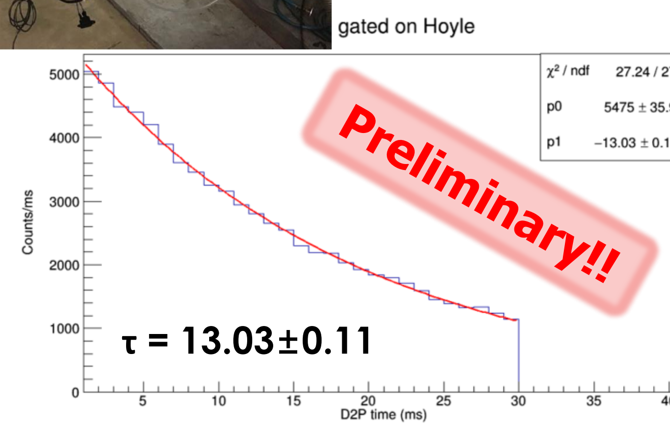




F. Montes *et al.* 2005



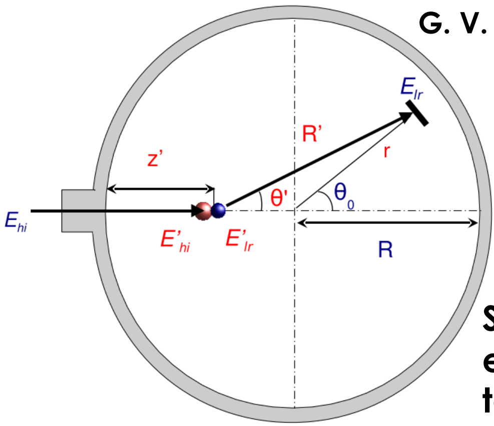




Spin and Parity of Resonance Levels

- Excitation function: Yields over CoM energy

G. V. Rogachev *et al.* 2010



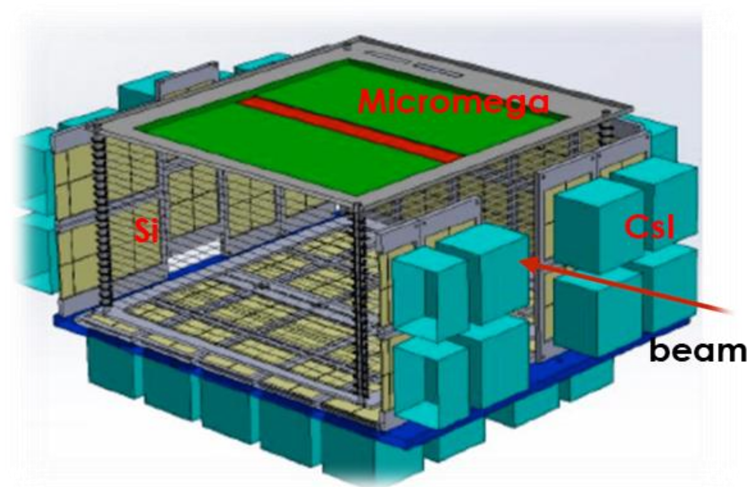
Schematic diagram of an event geometry in gas target TTIK experiment

$$E_{det} = \frac{4Mm}{(M+m)^2}\left[E_0 - \int_0^{z'}\left(\frac{dE}{dx}\right)_{h.i.}dx\right]\frac{R_x'^2}{R'^2} - \int_0^{R'}\left(\frac{dE}{dx}\right)_{l.i.}dx$$

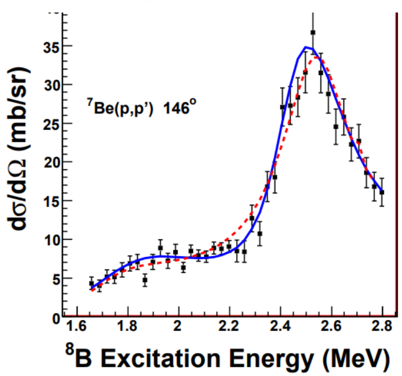
$$R'_x = R - z' + r\cos\theta_0,$$

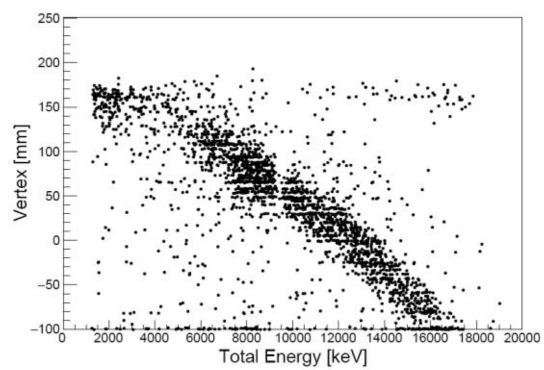
$$R' = \sqrt{r^2\sin^2\theta_0 + (R - z' + r\cos\theta_0)^2}$$

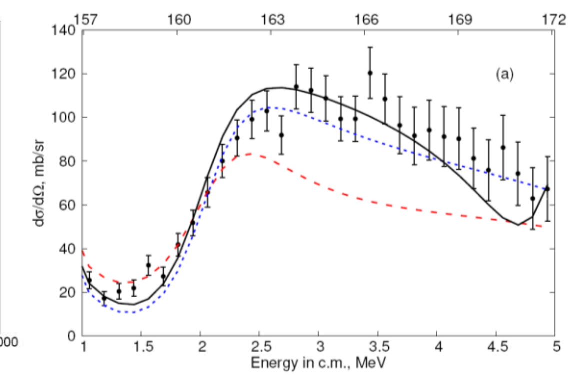
J. Hooker *et al.* 2019



Texas Active Target (TexAT) design

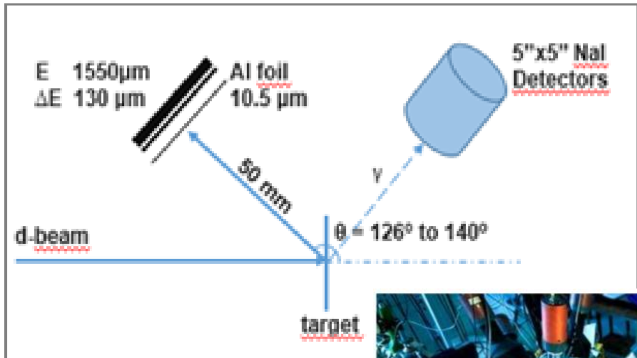






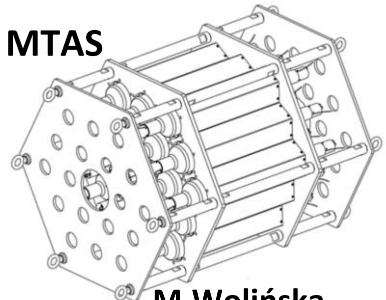
Nuclear Level Densities

- Total Absorption of γ-ray using NaI scintillators
- MTAS at ORNL, CACTUS at Oslo, SuN at NSCL



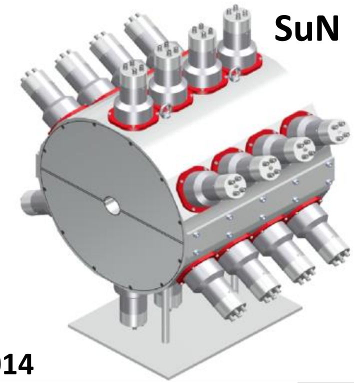
K O Ay *et al.*, 2016

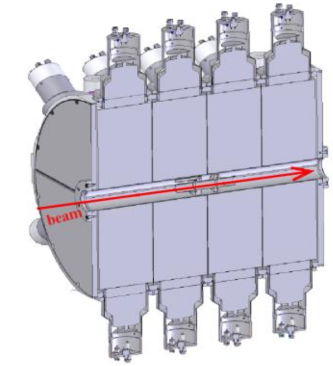
MTAS



M.Wolińska-Cichocka *et al.*, 2014

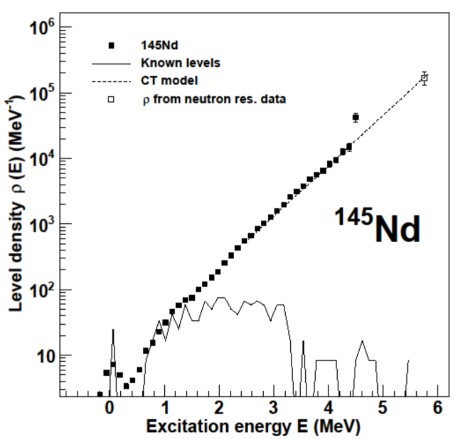
SuN

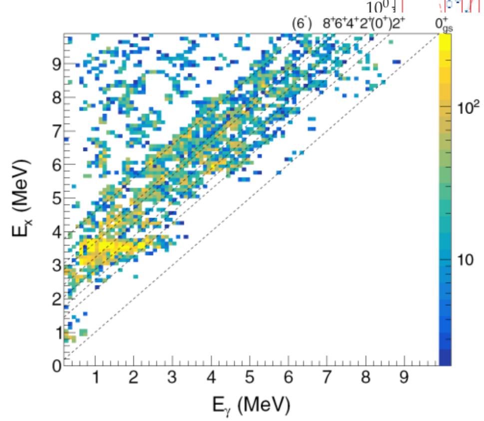


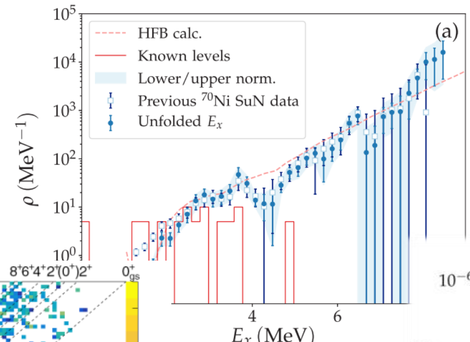


A. Simon *et al.*, 2013

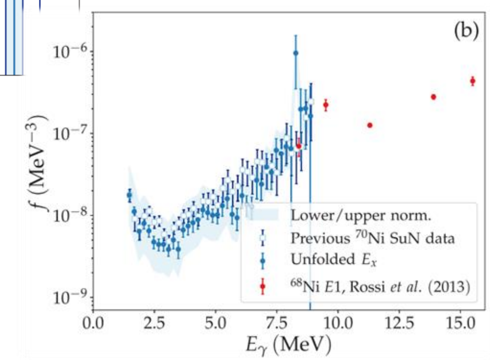
CACTUS





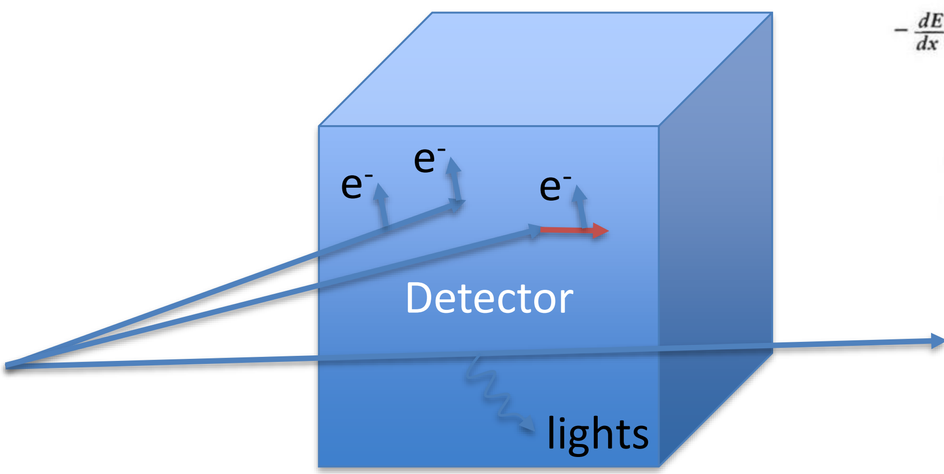


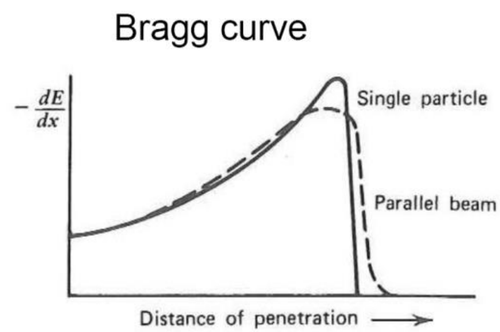
A. C. Larsen *et al.*, 2018



How to detect particles

- Interactions with matter!
- Ionizations, Scintillations, Heat, Reactions





$$-\frac{dE}{dx} \propto \frac{mz^2}{E}$$

or

$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2}{m_0 v^2} nZ \left[\ln \frac{2m_0 v^2}{I} - \ln\left(1 - \frac{v^2}{c^2}\right) - \frac{v^2}{c^2} \right]$$

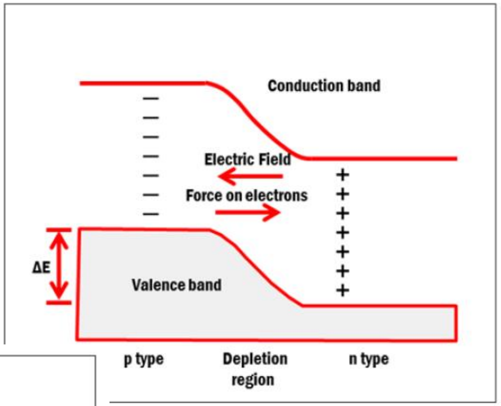
Bethe-Block formula

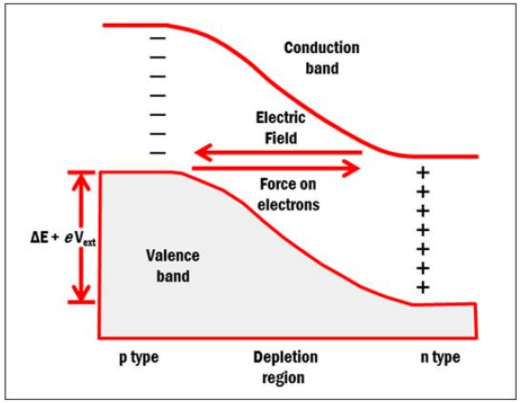
z – projectile atomic number
v – projectile velocity
m_0 - electron mass
e – electron charge

n – target number density
Z – target atomic number
nZ – target electron density
I – average excitation and ionization potential

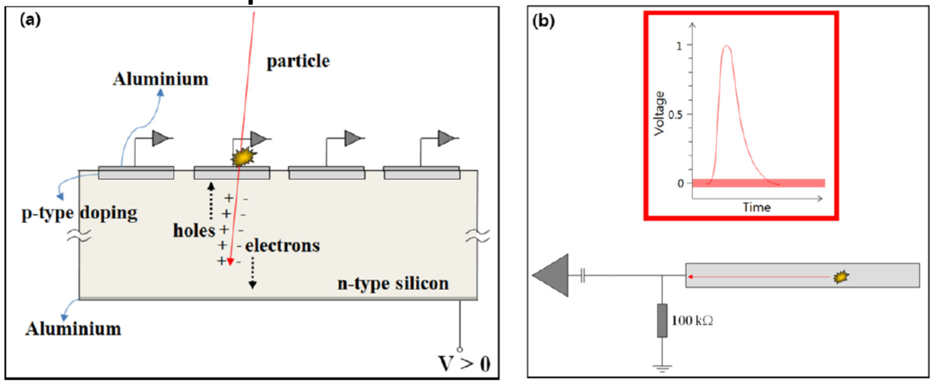
Silicon strip detectors

- Ionization energy = 3.62 eV
- Room temp (performance gains with cooling)
- Thin particle detectors (thicknesses ~20μm ~2 mm)
- Highly segmented
- Large area

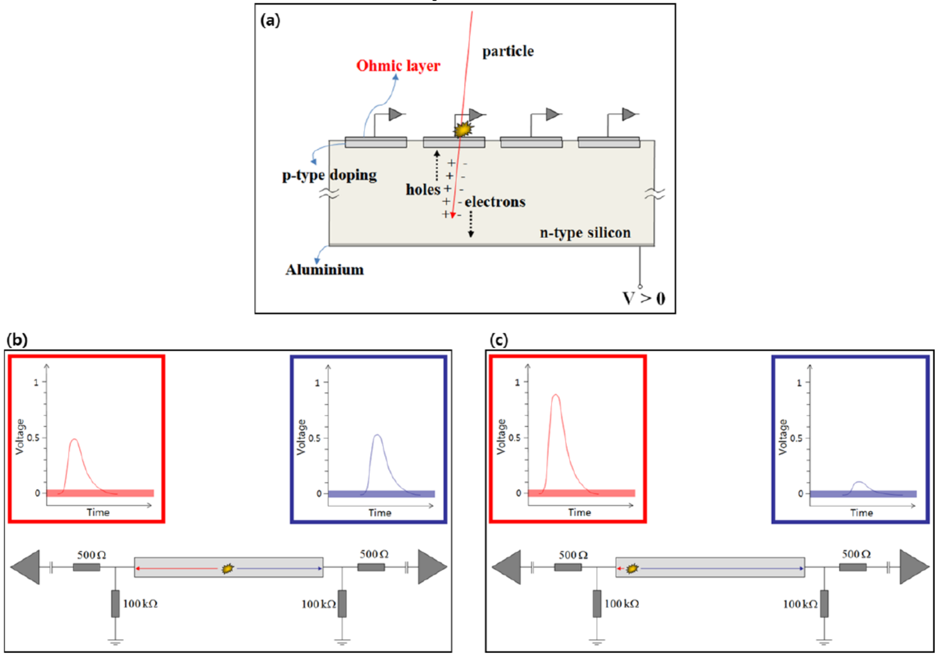




Non-resistive strip

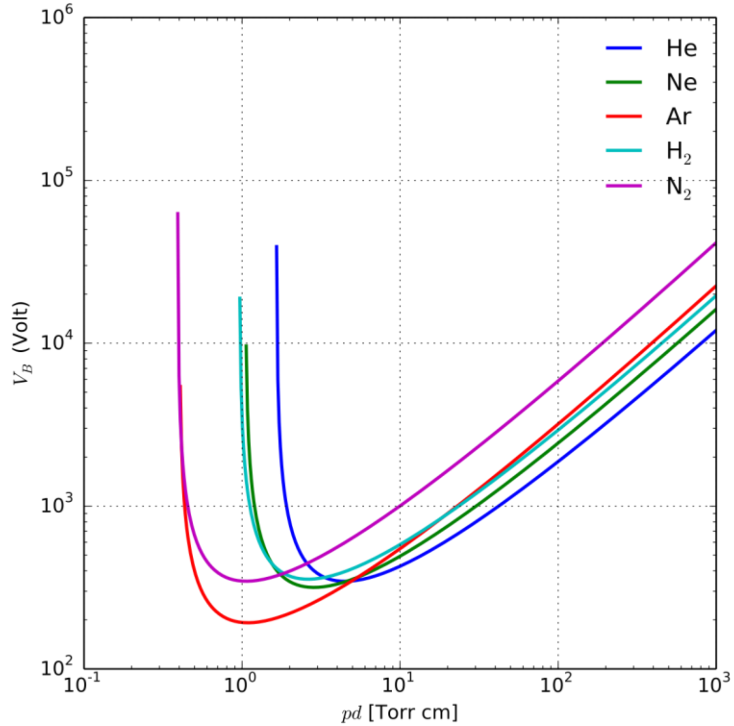


Resistive strip



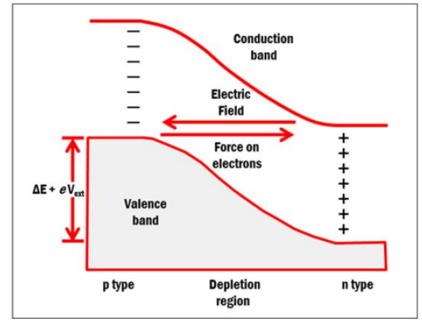
Silicon strip detectors

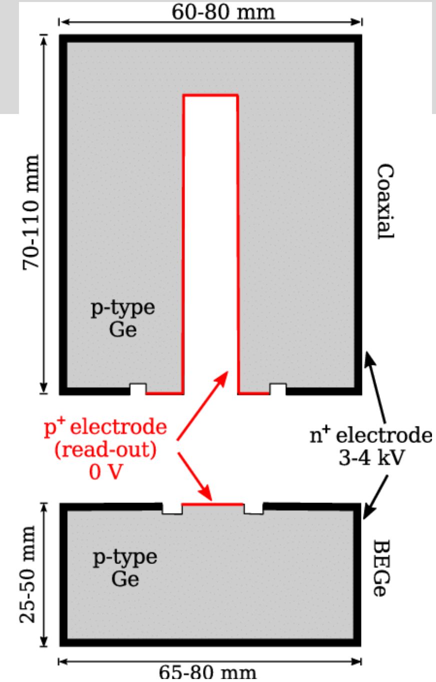
• Paschen's law: breakdown voltage necessary to start a discharge or electric arc, between two electrodes in a gas as a function of pressure and gap length.
• Check the pressure and DO NOT bias detector if uncertain!!
~~(small bias ~ 5V should be okay for testing anytime.)~~
• Monitor leakage current when biasing.



Germanium detectors

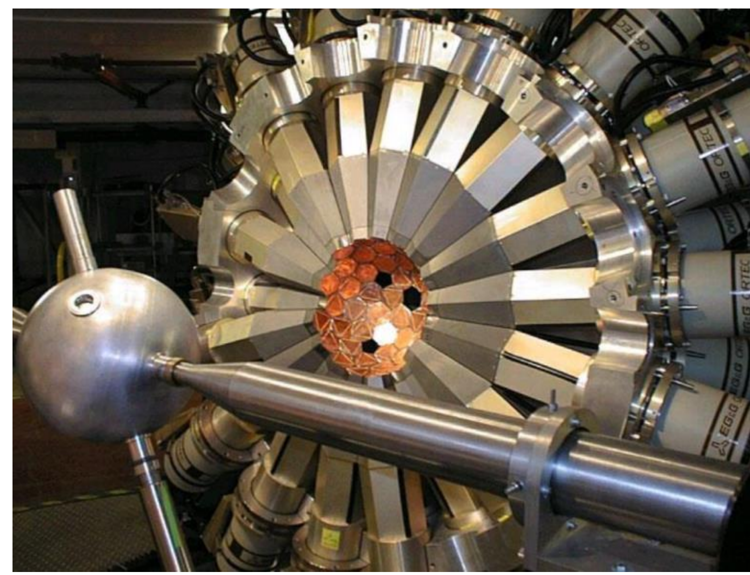
- Ionization energy = 2.96 eV
- Operation Temperature = 77 K LN2
- Energy resolution ~ eV





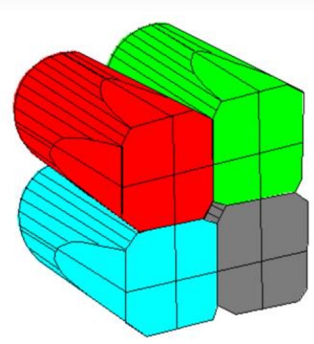
- Planar Ge detectors (similar to Si det):
  - Thin entrance window
  - Measuring low energy γ-rays and x-rays
  - Beta decay (implant)

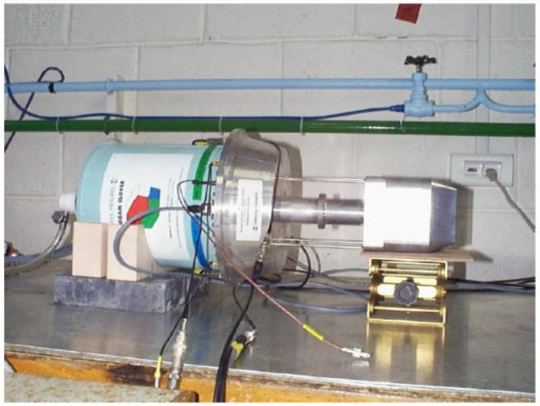
- Coaxial Ge detectors:
  - Large volume for measuring higher energy γ-rays
  - Some have coarse position from side-channels
  - Large arrays (e.g. Gammasphere)
  - Often Compton suppressed wt BGO



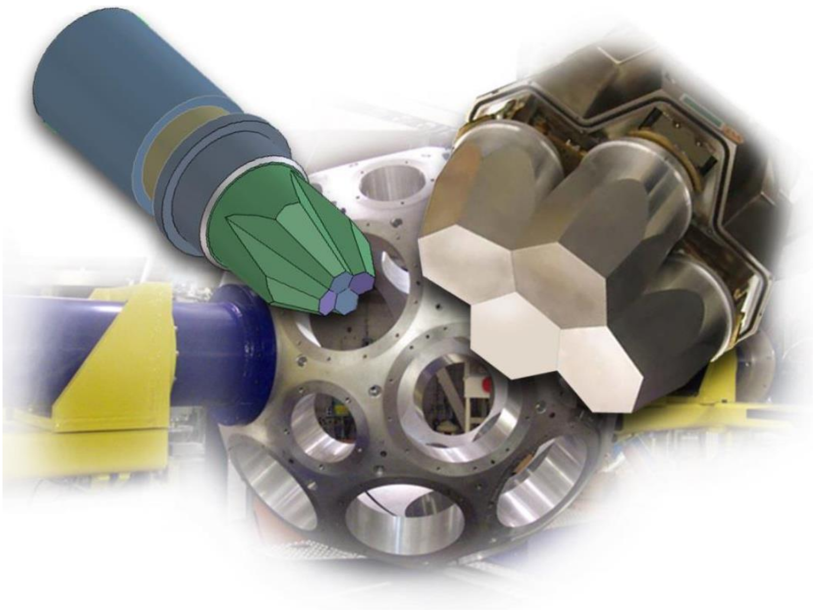
Germanium detectors

- Clover detectors:
 - Four close-packed crystals in one cryostat
 - Segmented readout for better position (Doppler) correction
 - e.g. Exogam, Clarion, Clovershare



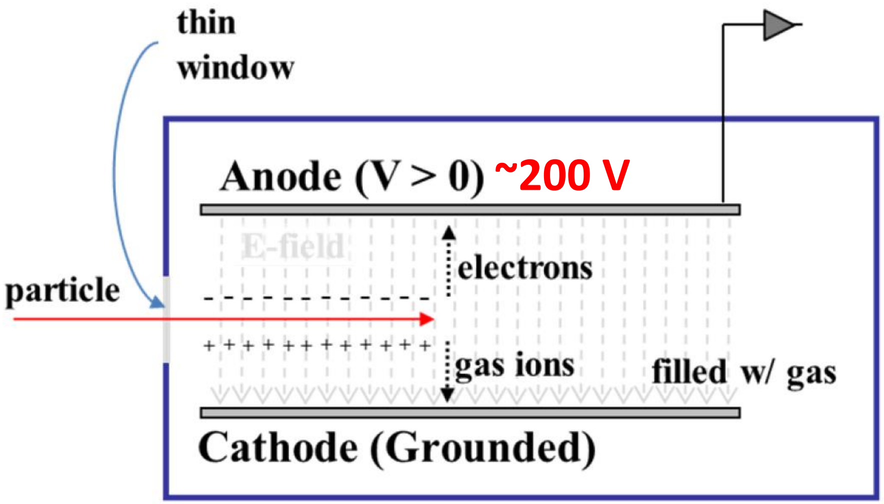


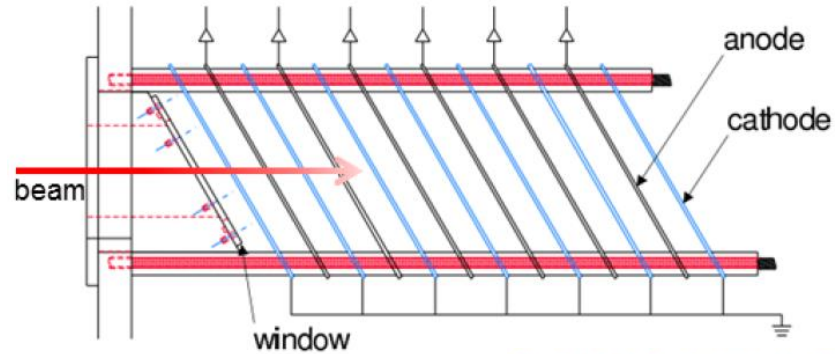
- Highly segmented tracking detectors:
 - High segmentation
 - Digital readout allows event reconstruction (tracking) using pulse shapes
 - First point of interaction (Compton reconstruction) for Doppler correction
 - Can dispense with Compton suppression to make higher efficiency possible



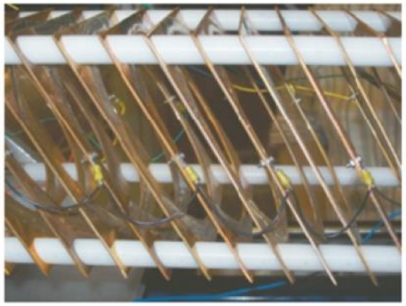
Ionization Counter

- Ionization Counter:

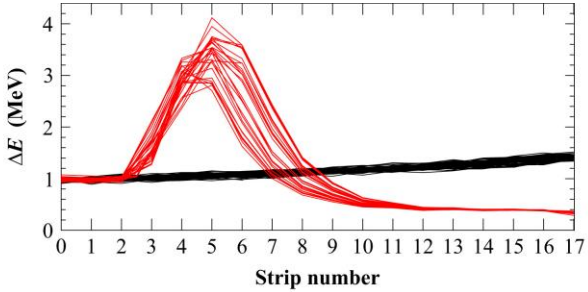


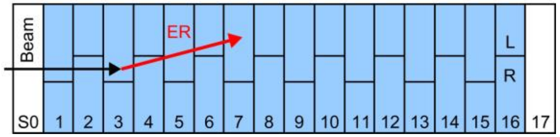


ORNL Fast Ion Counter



MUSIC detector at ANL



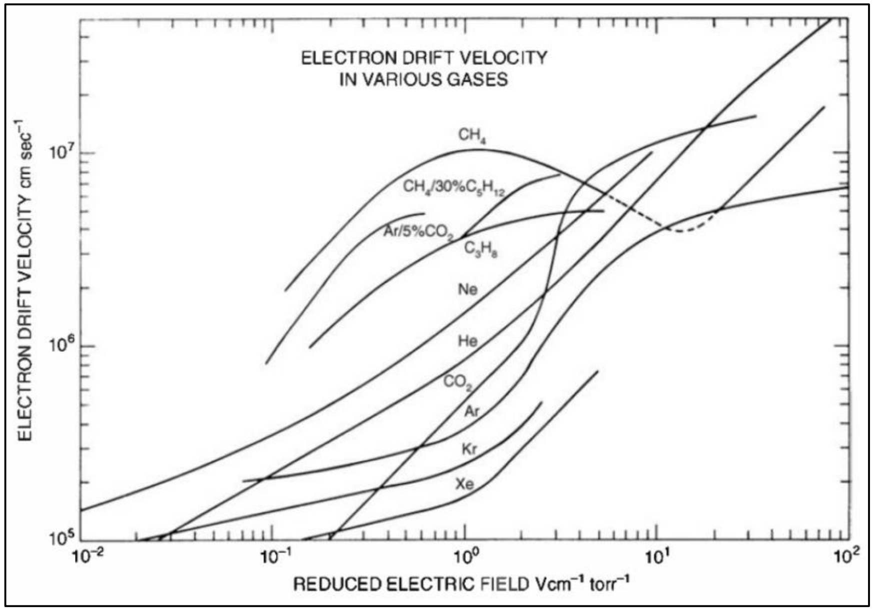


Ionization Counter

- First ionization potential = energy to remove valence electron
- W-Value = average energy per e- – ion pair (nonionizing excitations, removal of more deeply bound electrons, etc)
- Energy resolution ~ $\sqrt{N}$ ~ $\sqrt{E/w}$ → $\sqrt{F * E/w}$ (*F*: Fano factor)
- *F* ~ 0.2 for gasses, ~ 0.1 for semiconductors

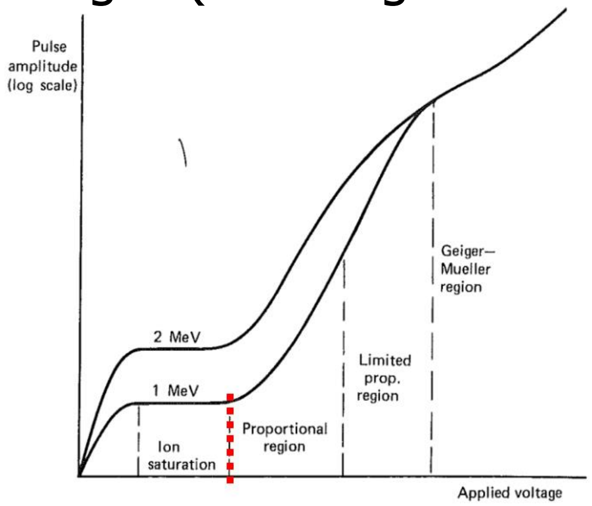
Table 5.1 Values of the Energy Dissipation per Ion Pair (the *W*-Value) for Different Gases[a]

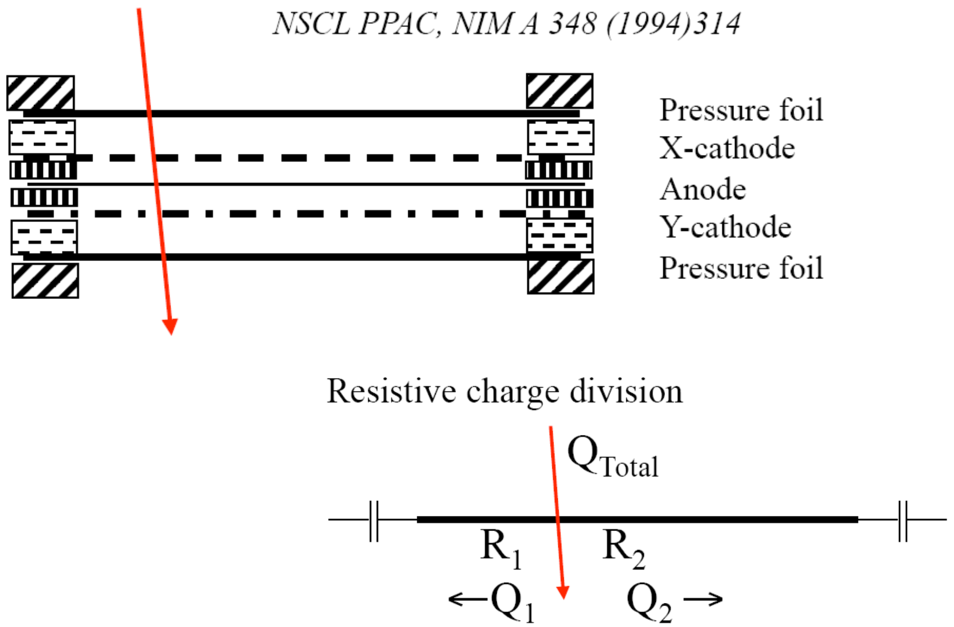
Gas	First Ionization Potential (eV)	*W*-Value (eV/ion pair) Fast Electrons	Alpha Particles
Ar	15.7	26.4	26.3
He	24.5	41.3	42.7
H_2	15.6	36.5	36.4
N_2	15.5	34.8	36.4
Air		33.8	35.1
O_2	12.5	30.8	32.2
CH_4	14.5	27.3	29.1

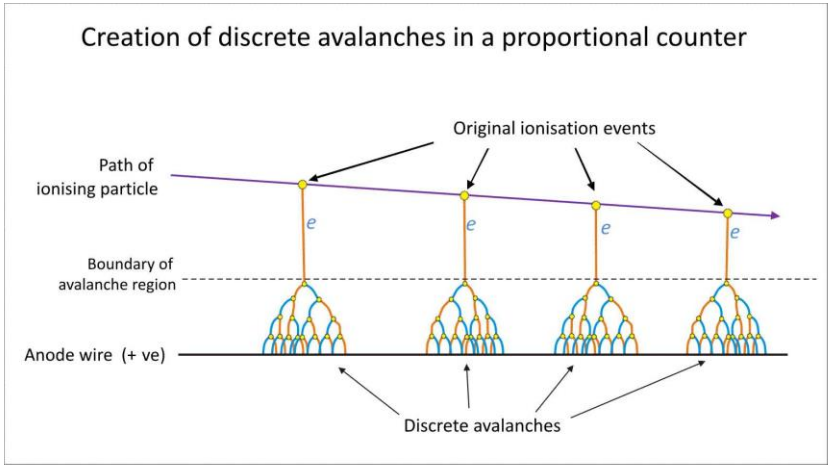


Proportional Counter and PPAC

- The high electric field produces Townsend avalanches.
- P-10 gas (90% argon and 10% methane mixture)



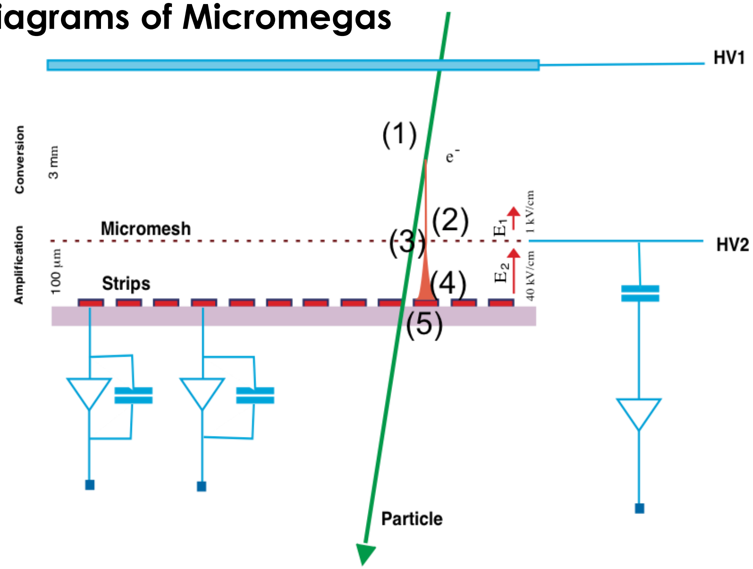


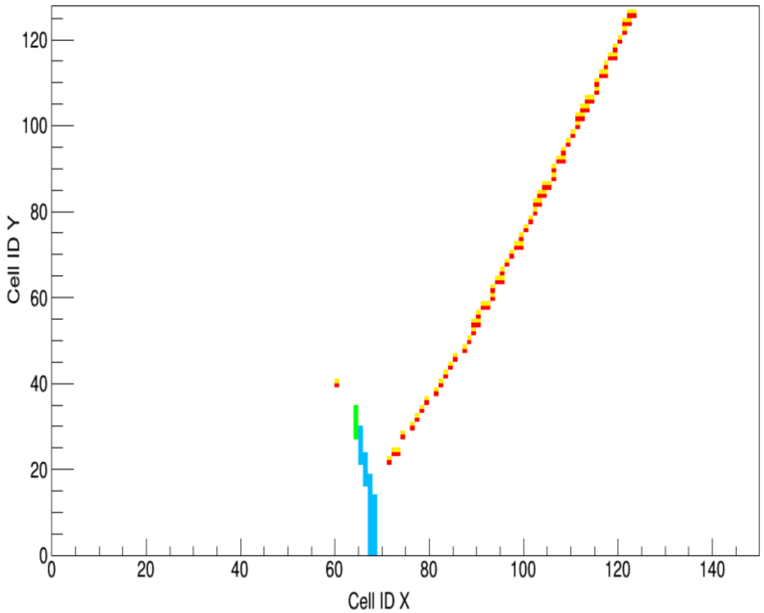


Micromegas and GEM

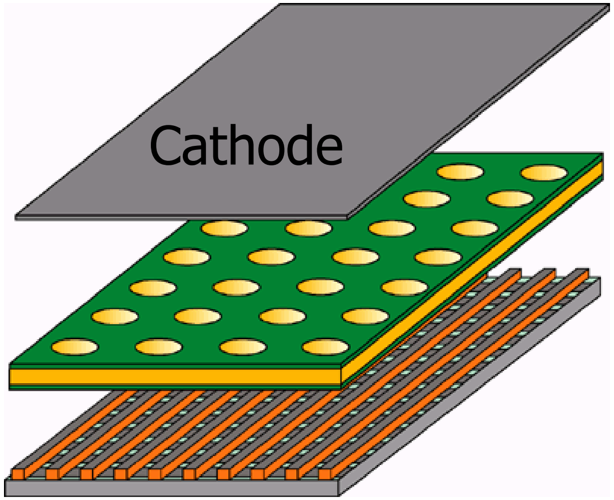
- High Electric field between gap
- Watch leakage currents for possible sparks

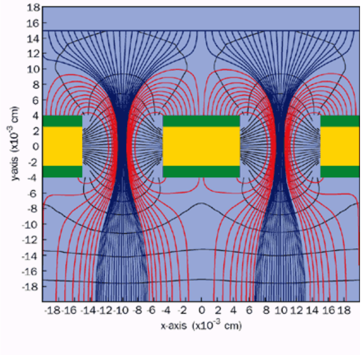
Diagrams of Micromegas





Sample Particle Track from Micromegas





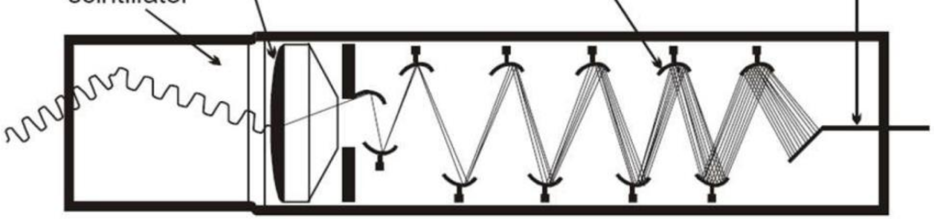
E-field of GEM

Scintillators

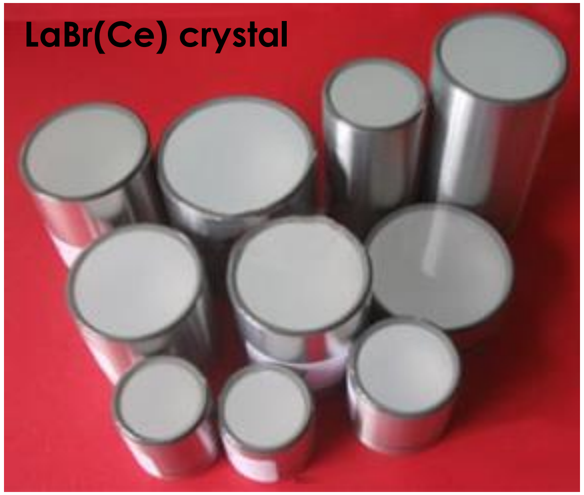
- Inorganic scintillators: NaI(Tl), BGO, LaBr(Ce), BaF2, CsI, also noble gases
- Organic scintillators: plastics (solid and liquid)

- Photomultiplier tube (PMT) or photo diode
- High voltage required on PMT

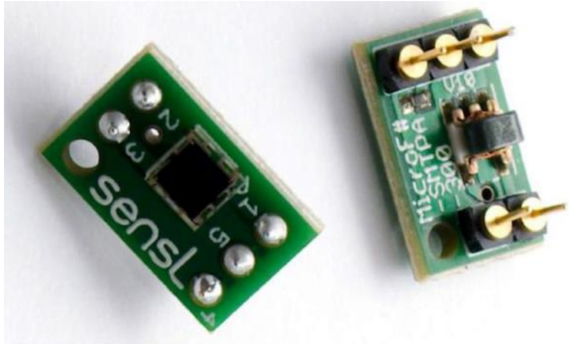
CsI crystal



Schematics of PMT



LaBr(Ce) crystal



SensL Si-PM

Low Energy (slow) Neutron Detector

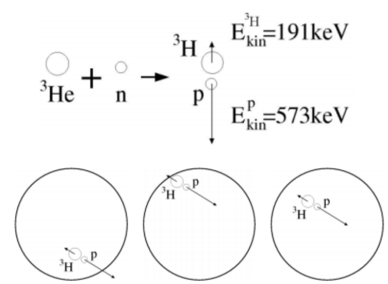
- Neutrons are generally detected through nuclear reactions that result in prompt energetic charged particles such as protons, alpha particles, and so on.
- Slow neutron: $E_n < 0.5$ eV.

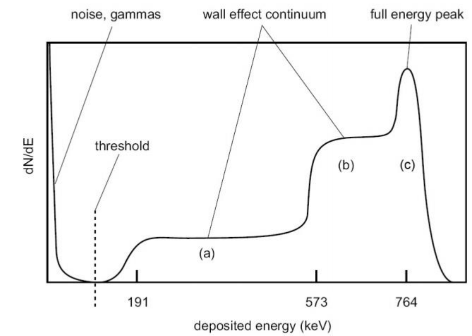
	Q-value
${}^{3}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{3}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{p}$	0.764 MeV

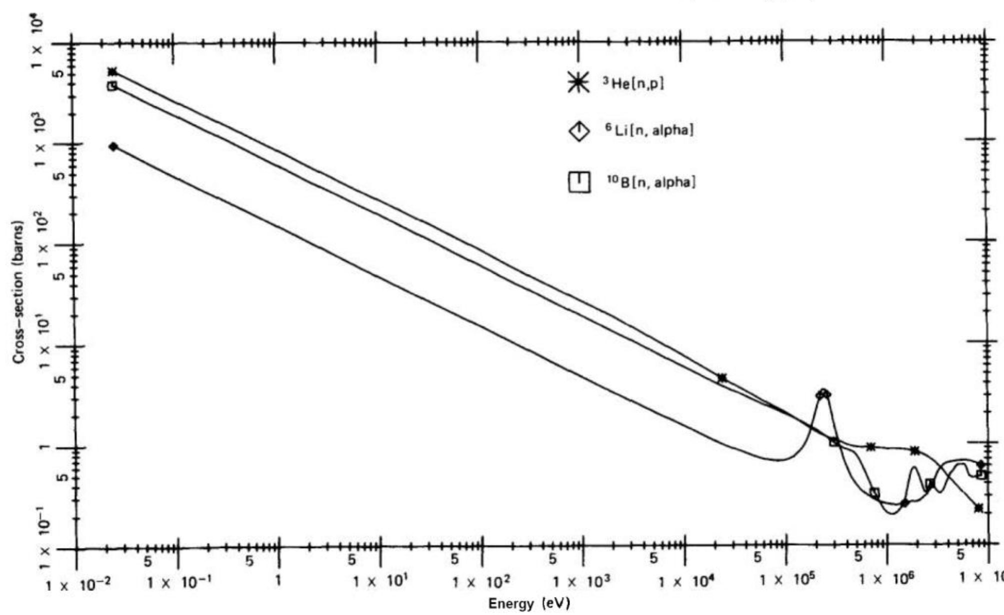
	Q-value
${}^{6}_{3}\mathrm{Li} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{3}_{1}\mathrm{H} + {}^{4}_{2}\alpha$	4.78 MeV

$${}^{10}_{5}\mathrm{B} + {}^{1}_{0}\mathrm{n} \rightarrow \begin{cases} {}^{7}_{3}\mathrm{Li} + {}^{4}_{2}\alpha & \text{2.792 MeV (ground state)} \\ {}^{7}_{3}\mathrm{Li}^{*} + {}^{4}_{2}\alpha & \text{2.310 MeV (excited state)} \end{cases}$$

Q-value

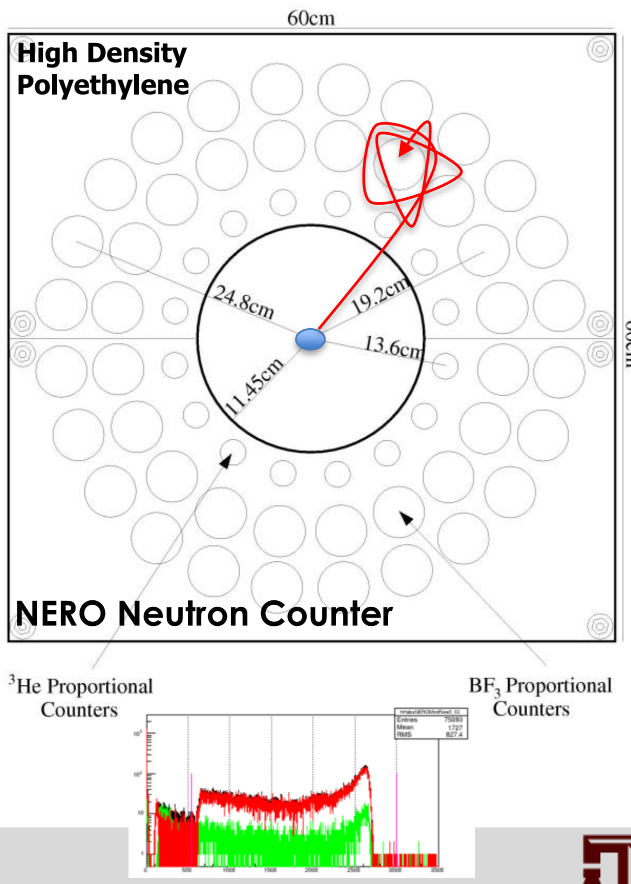


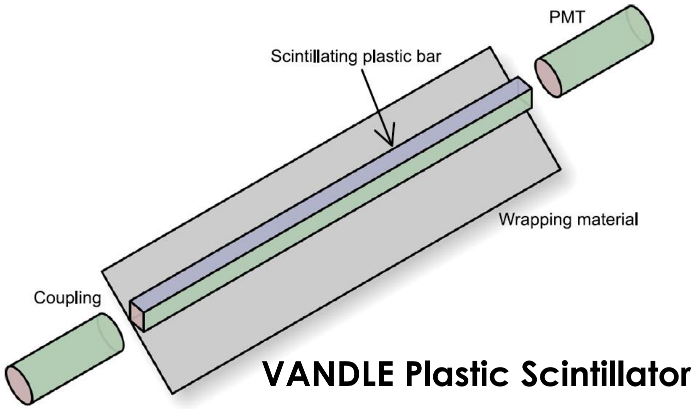


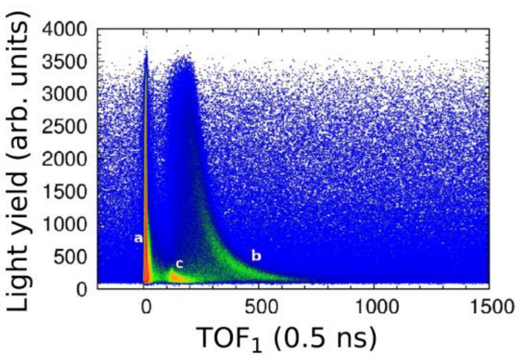


High Energy (fast) Neutron Detector

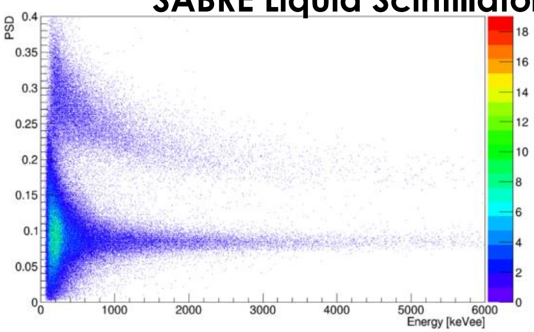
- 1 keV < E_n < a few MeV
- Moderation technique: Design of tube matrix determines efficiency.
- neutron time-of-flight (nToF) technique: Good PSD is critical.







SABRE Liquid Scintillator



PSD vs Energy

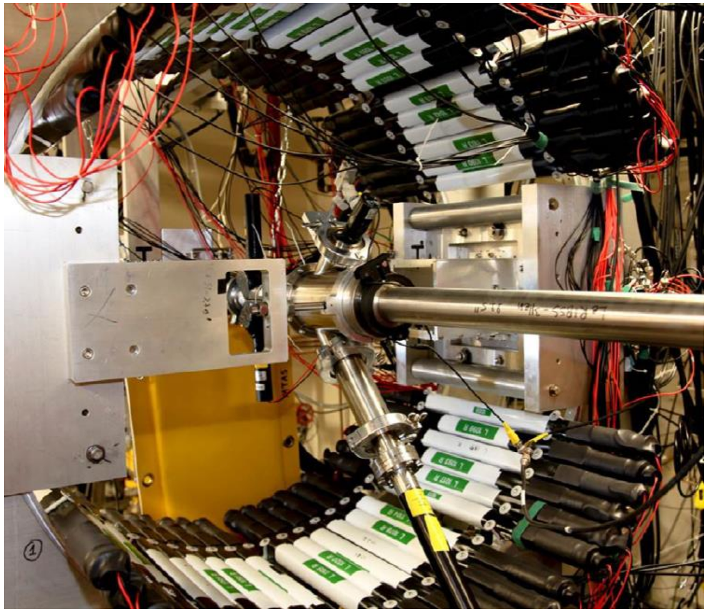
High Energy (fast) Neutron Detector

- 1 keV < E_n < a few MeV

- Moderation technique: Design of tube matrix determines efficiency.
- neutron time-of-flight (nToF) technique: Good PSD is critical.

HabaNERO Neutron Counter

S. Ahn *et al.* 2017



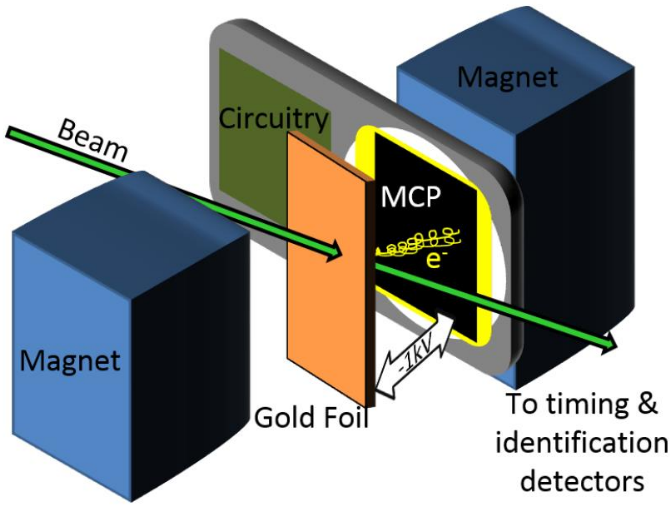
VANDLE Plastic Scintillator
W.A. Peters *et al.* 2016

SABRE Liquid Scintillator

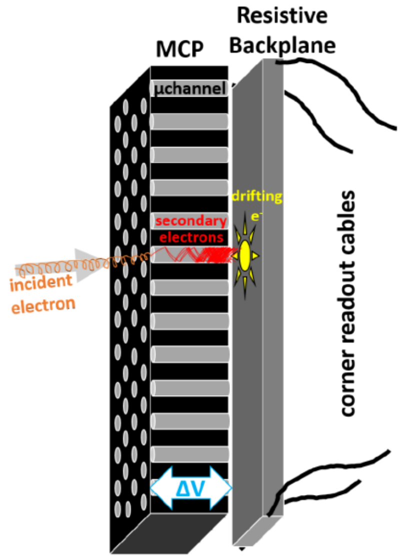
M. Febbraro *et al.* 2018

Micro-channel Plate (MCP)

- Micro-channel Plate: electron multiplication using high potential



Schematic Design of MCP Tracking Detector



Schematic Design of MCP

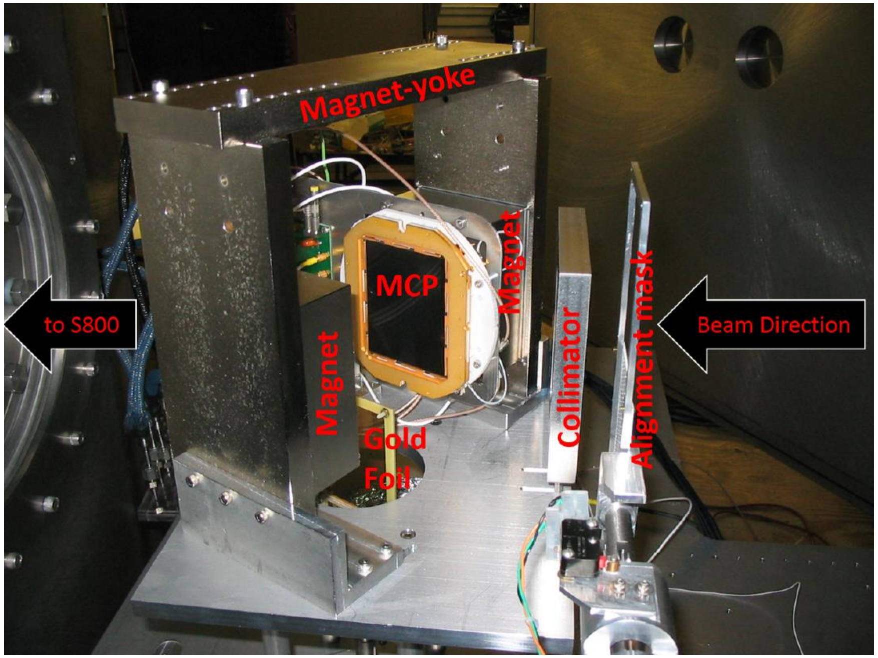
$$X = \frac{\mathrm{UR} + \mathrm{LR} - \mathrm{UL} - \mathrm{LL}}{\mathrm{UL} + \mathrm{UR} + \mathrm{LL} + \mathrm{LR}}$$

$$Y = \frac{\mathrm{UL} + \mathrm{UR} - \mathrm{LL} - \mathrm{LR}}{\mathrm{UL} + \mathrm{UR} + \mathrm{LL} + \mathrm{LR}}$$

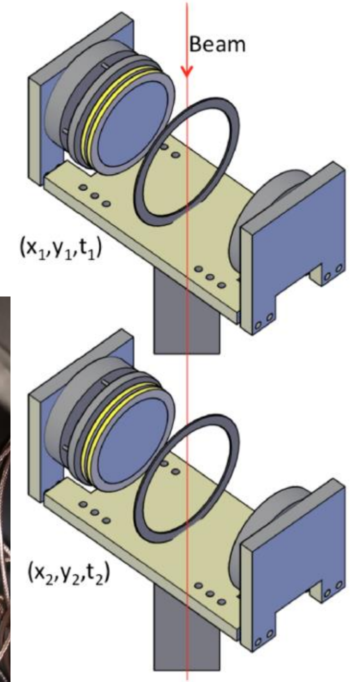
Z. Meisel *et al.*, PoS (NIC XIII) 124 (2014).

Micro-channel Plate (MCP)

- Micro-channel Plate: electron multiplication using high potential



MCP tracking detector used for ToF Mass experiment



MCP tracking detector used for ^{84}Se(*d*,*p*) experiment

Detectors Summary

- Silicon Strip Detector: depletion region by pn-junction, measuring charged particles, low rates, $E_{ionization}$ = 3.62 eV, running in room temp., highly segmented (or resistive strip), large area
- Germanium Detector: measuring higher energy γ-rays, operation temp. = 77 K LN2, energy resolution ~ eV, high segmentation, digital readout
- Ionization Counter: $E_{ionization}$ = 30 eV, electron drift velocity and distance between anode and cathode determines resolution of energy and position and beam rate.
- Proportional Counter: townsend avalanches,
- Parallel Plate Avalanche Counter: two plates with P-10 gas, commonly used for particle tracking
- Micromegas and GEM: active target and particle track of light charged particles.

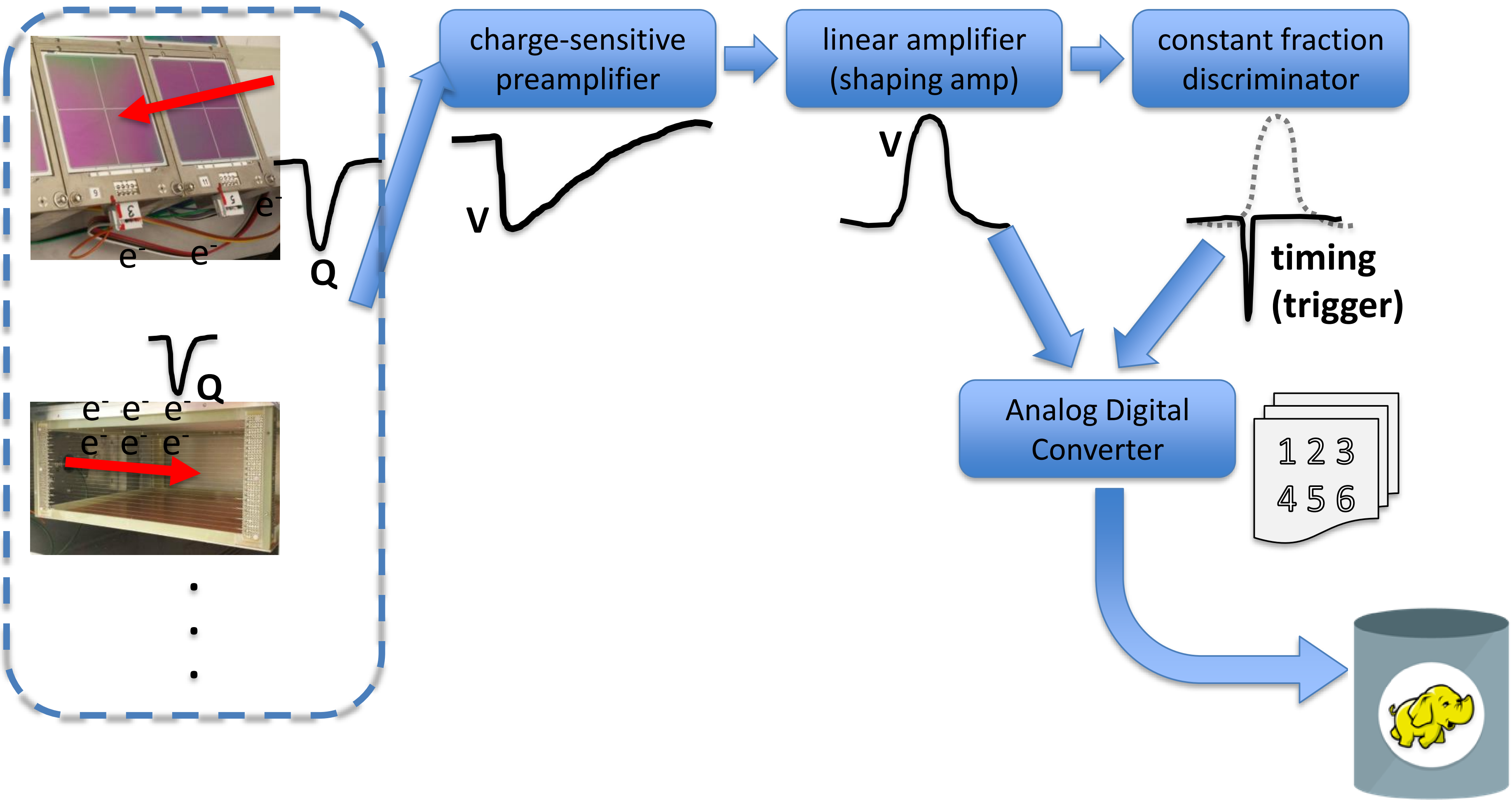
* Micromegas: Micromesh Gaseous Detector
* GEM: Gaseous Electron Multiplier

Detectors Summary

- Inorganic scintillators (NaI(Tl), BGO, LaBr(Ce), BaF2, CsI): emiting lights from γ-rays, converting lights to electric signals by PMT, high voltage
- Slow Neutron Detectors: ^{3}He(n,p), ^{6}Li(n,α), ^{10}B(n,α) in the proportional counter.
- Fast Neutron Detectors (Organic scintillators): combination of moderation with slow neutron detectors, neutron time-of-flight (nToF) technique (Pulse Shape Discrimination)
- Micro-channel Plate (MCP): electron multiplication using high potential. measuring beam particle track, high vacuum required.

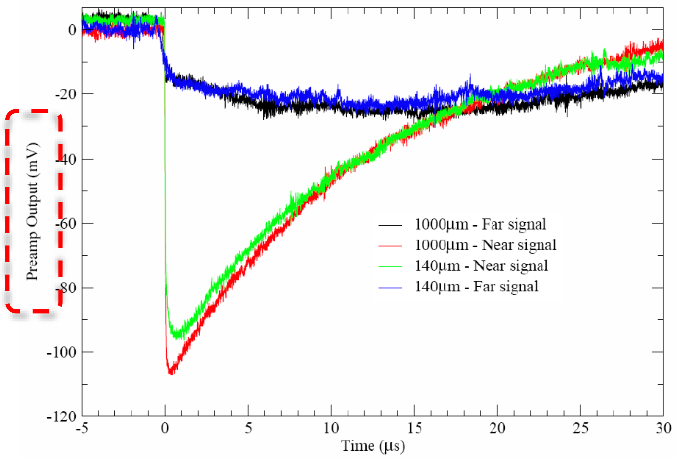
Signal Processing Diagram

- Conventional ways to process detected signals



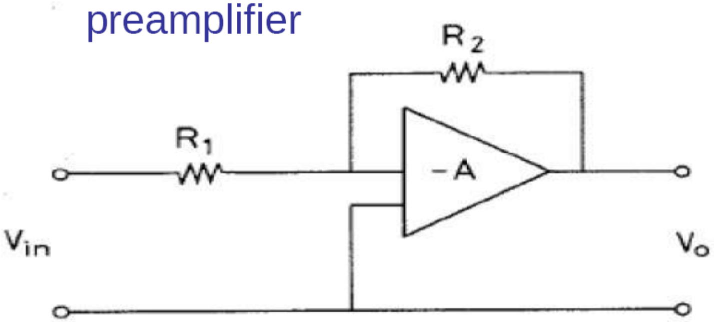
Preamplifiers

- Remember output is voltage.
- For charge sensitive, output is proportional to charge integrated of C_f, if signal is fast compared to R_fC_f.
- Noise is proportional to C_d.

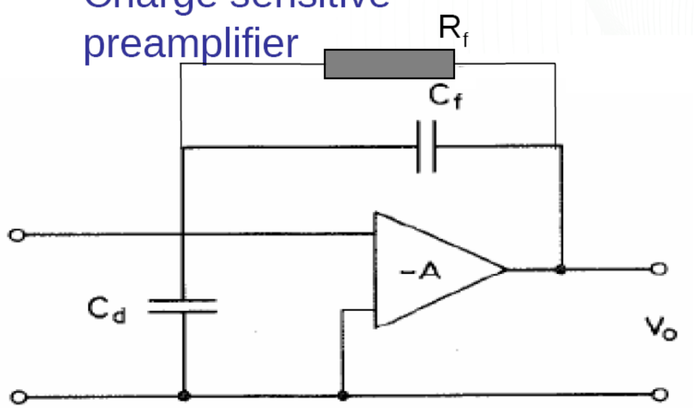


Sample preamp output signals
S.D. Pain, EBSS2016

Voltage sensitive preamplifier

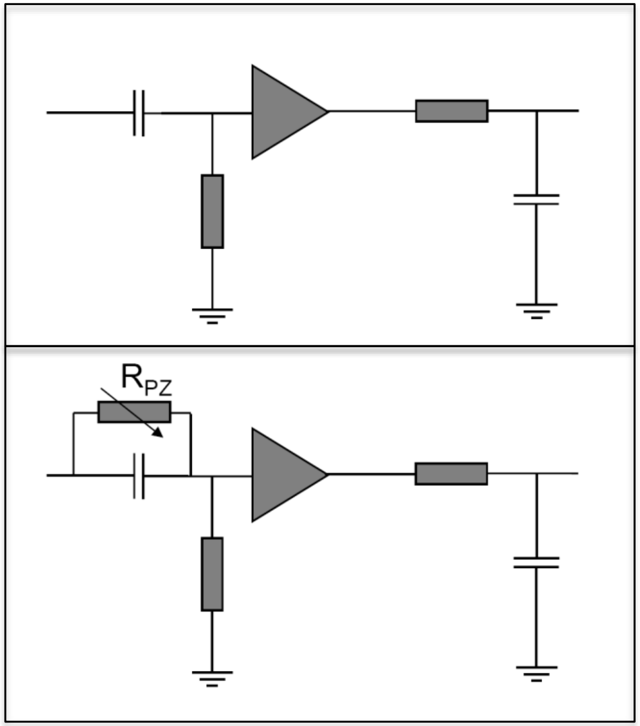


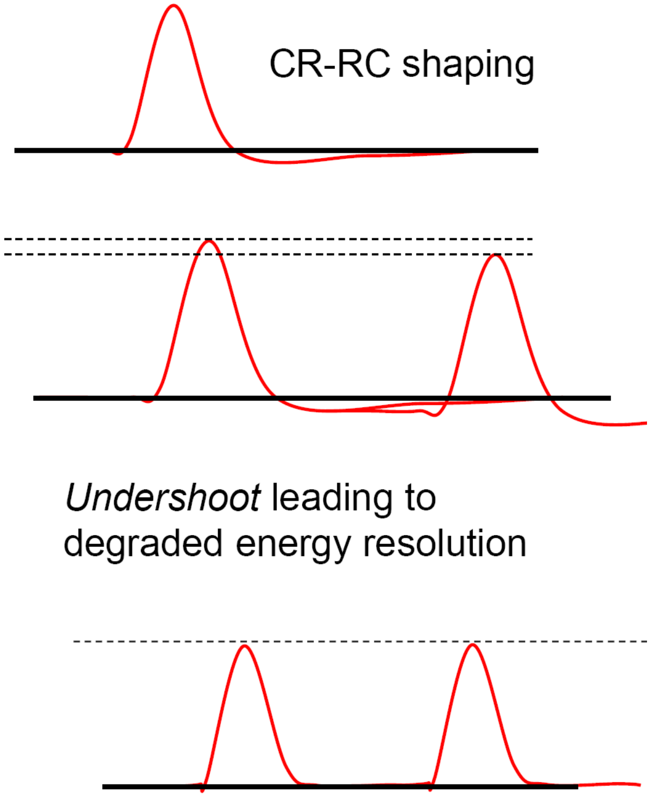
Charge sensitive preamplifier



Shaping Amplifier

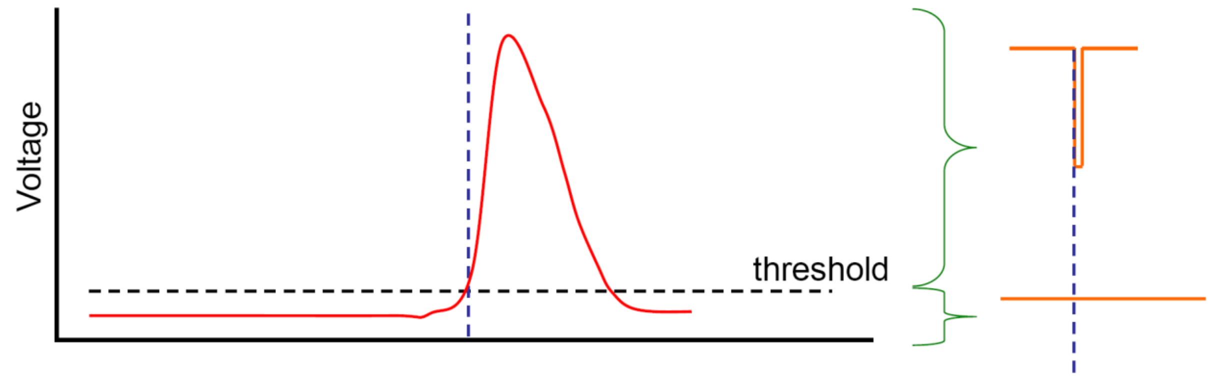
- Long tail of the preamp signal might overlap with the following signals to appear larger than it is.
- Shaping time (or peaking time) can be chosen from several values.



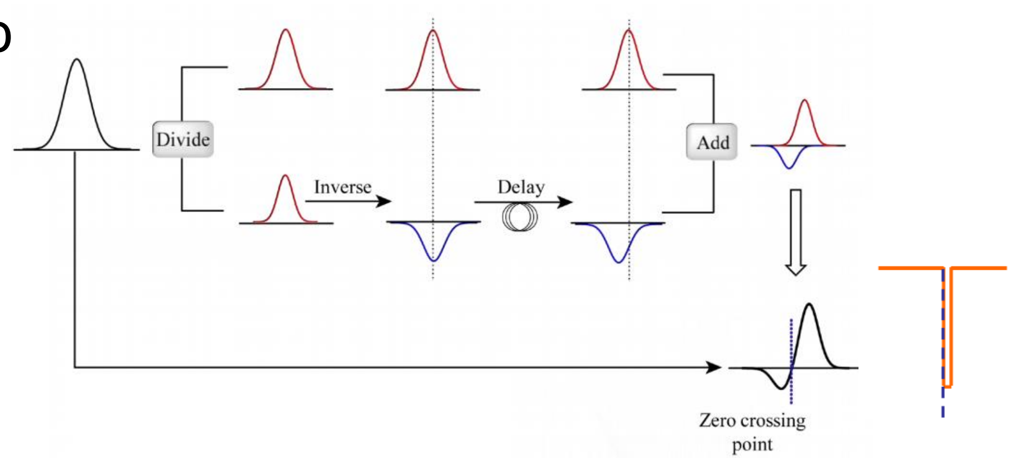


Discriminator

- Leading Edge Discriminator:
  - Noise makes a bad timing of the trigger signal.
  - timing sensitive to rise time of the signal.

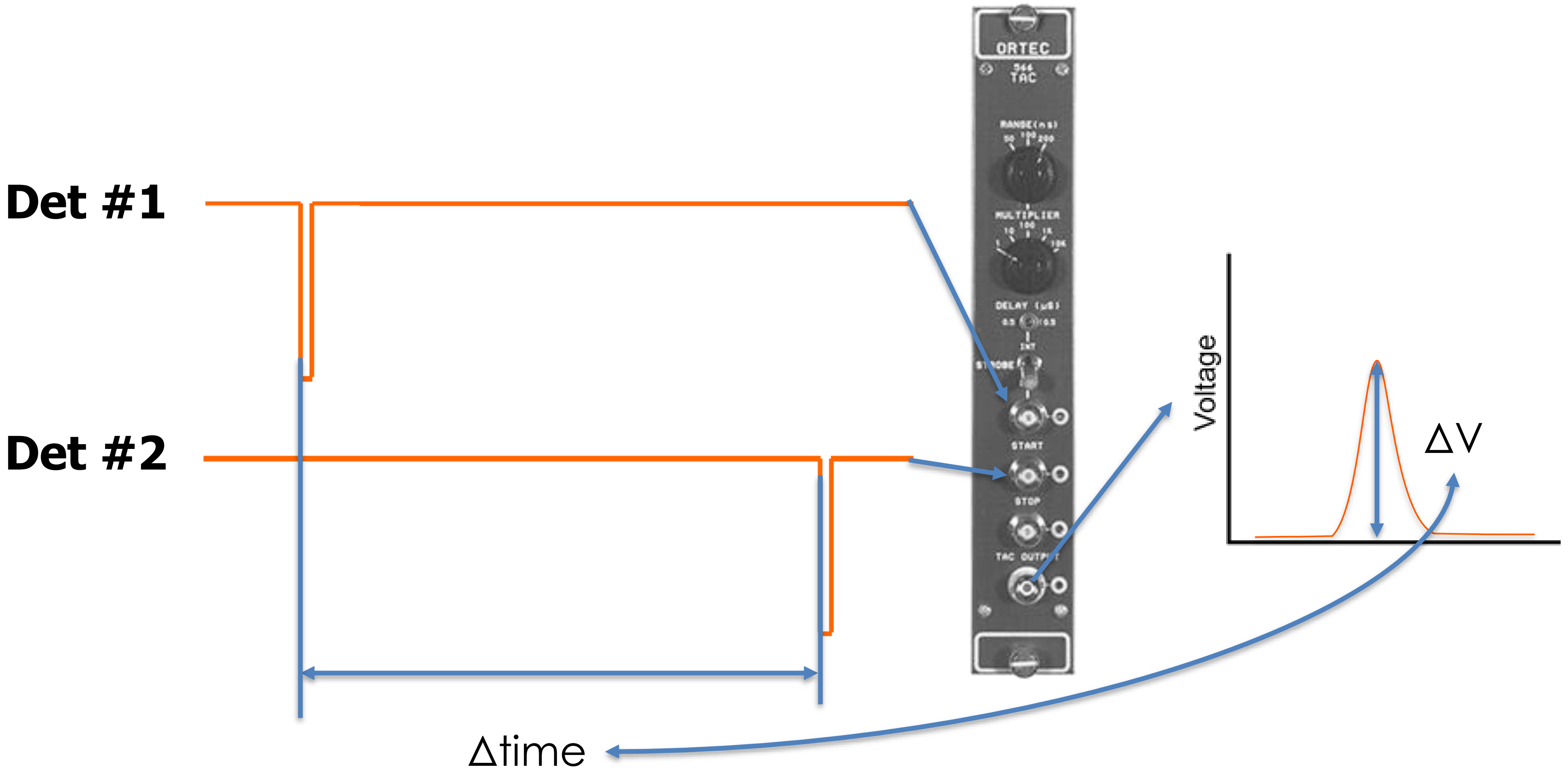


- Constant Fractional Discriminato
  - better for timing.



Time Analog Converter (TAC)

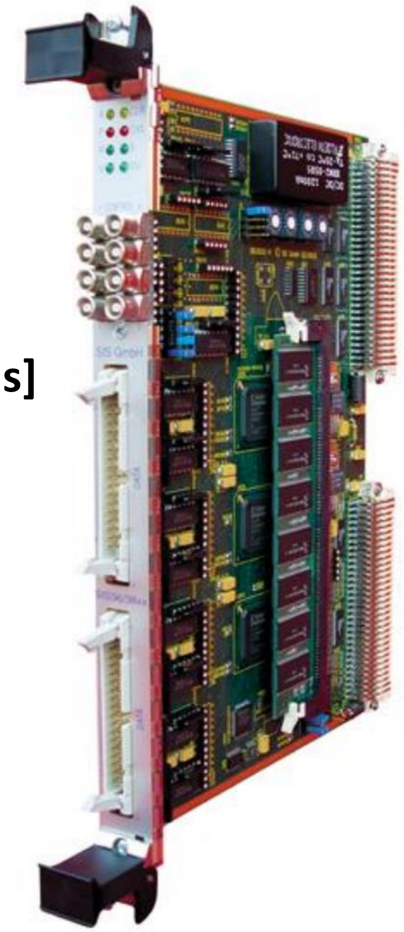
- Using trigger signals from each detectors, the time difference between the signals can be recorded for coincidences.



Scaler and Time-stamp

- Counting triggers and signal rates is important.
- Recording time of events is also important.

[Any important Logic Signals]
Clock
LiveClock
Master Trigger
Raw Trigger 1
Raw Trigger 2
Ion Counter Trig.
Prescaled Ion Counter Trig.

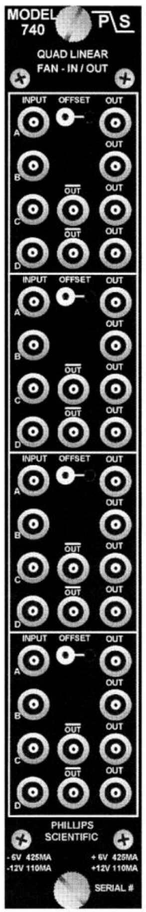


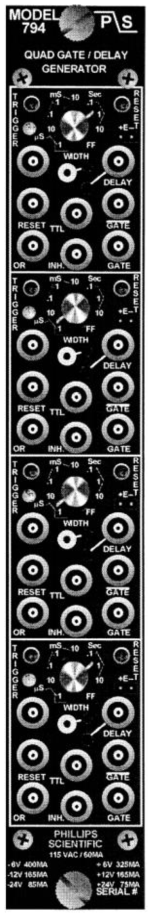
- 250 MHz counting rate
- 32 bit channel depth

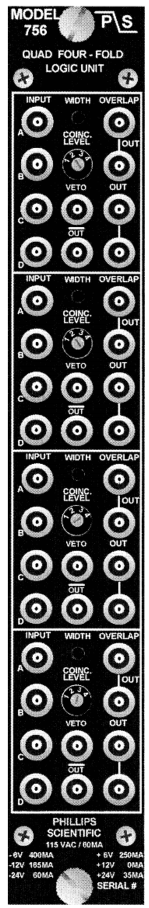
- 48bit timestamp
  wt internal clock (= 13 days wt 4ns time resolution)

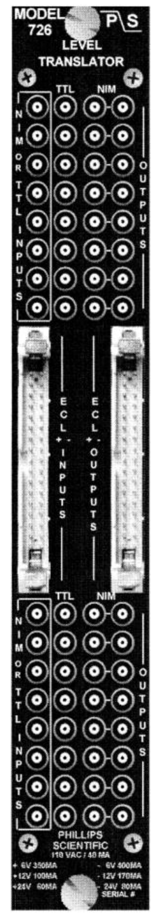
Signal Processing

- commonly used modules (Linear/Logic FIFO(inverterd), Logic Unit, GDG, ECL/NIM/TTL converter, LATCH module, Scale-down module (prescaler))
- NIM Logic = true when V < -0.8V, while TTL Logic = true when V > +1.5V



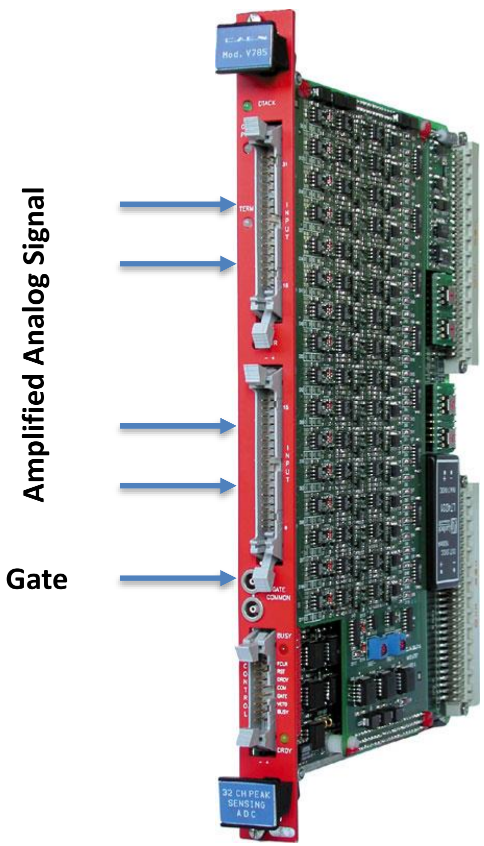


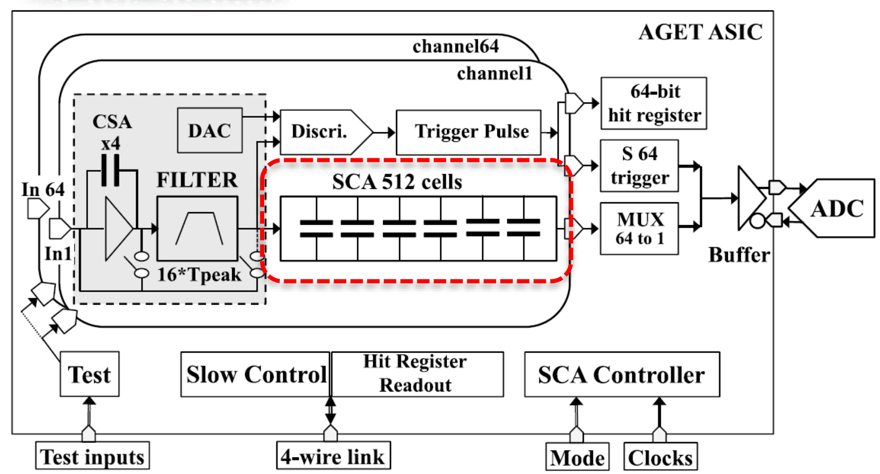




Analog Digital Converter (ADC)

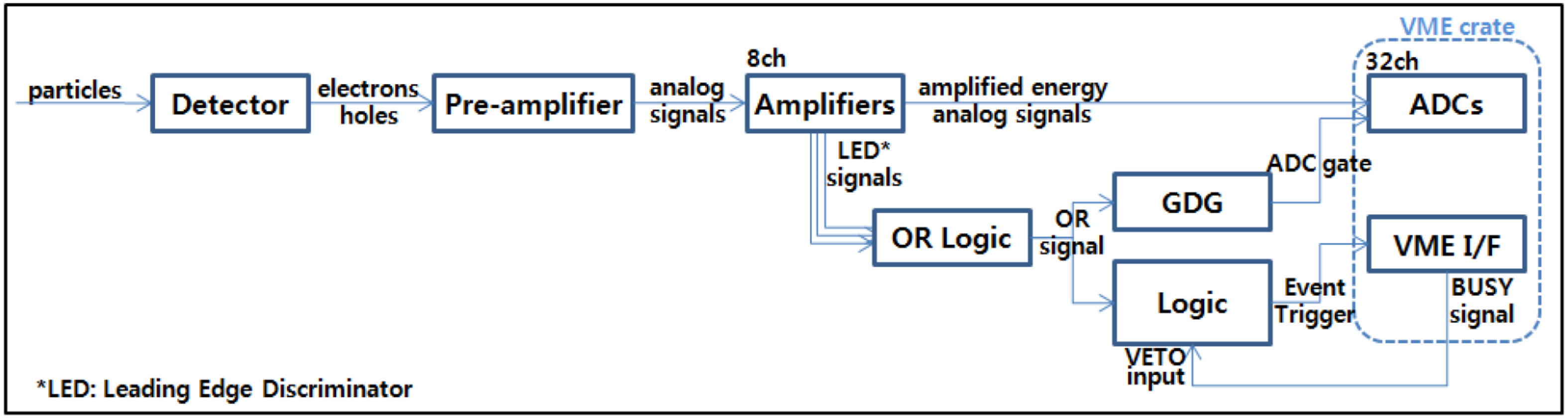
- Peak sensing ADC
- Switched Capacitor Array for waveform recording

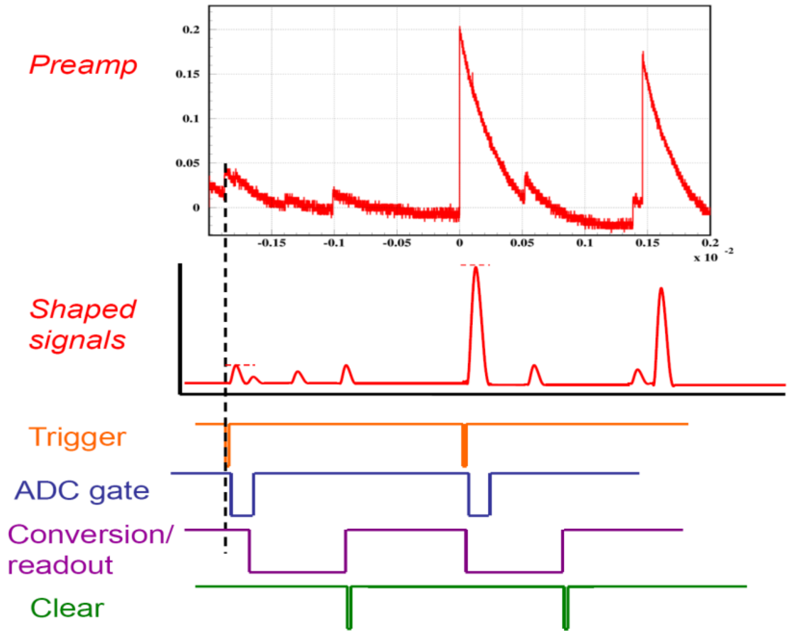




Signal Processing Summary

- From the preamp signal to DAQ readout

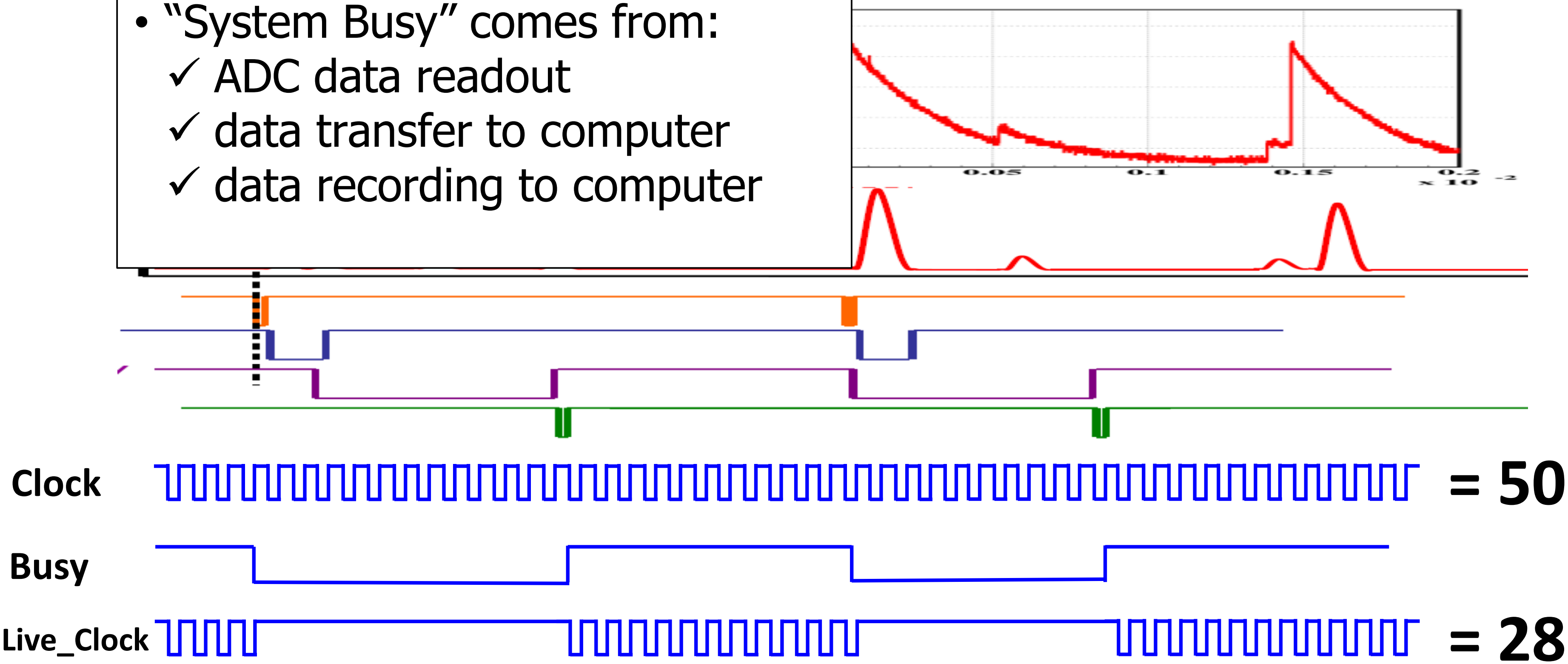




S.D. Pain, EBSS2016

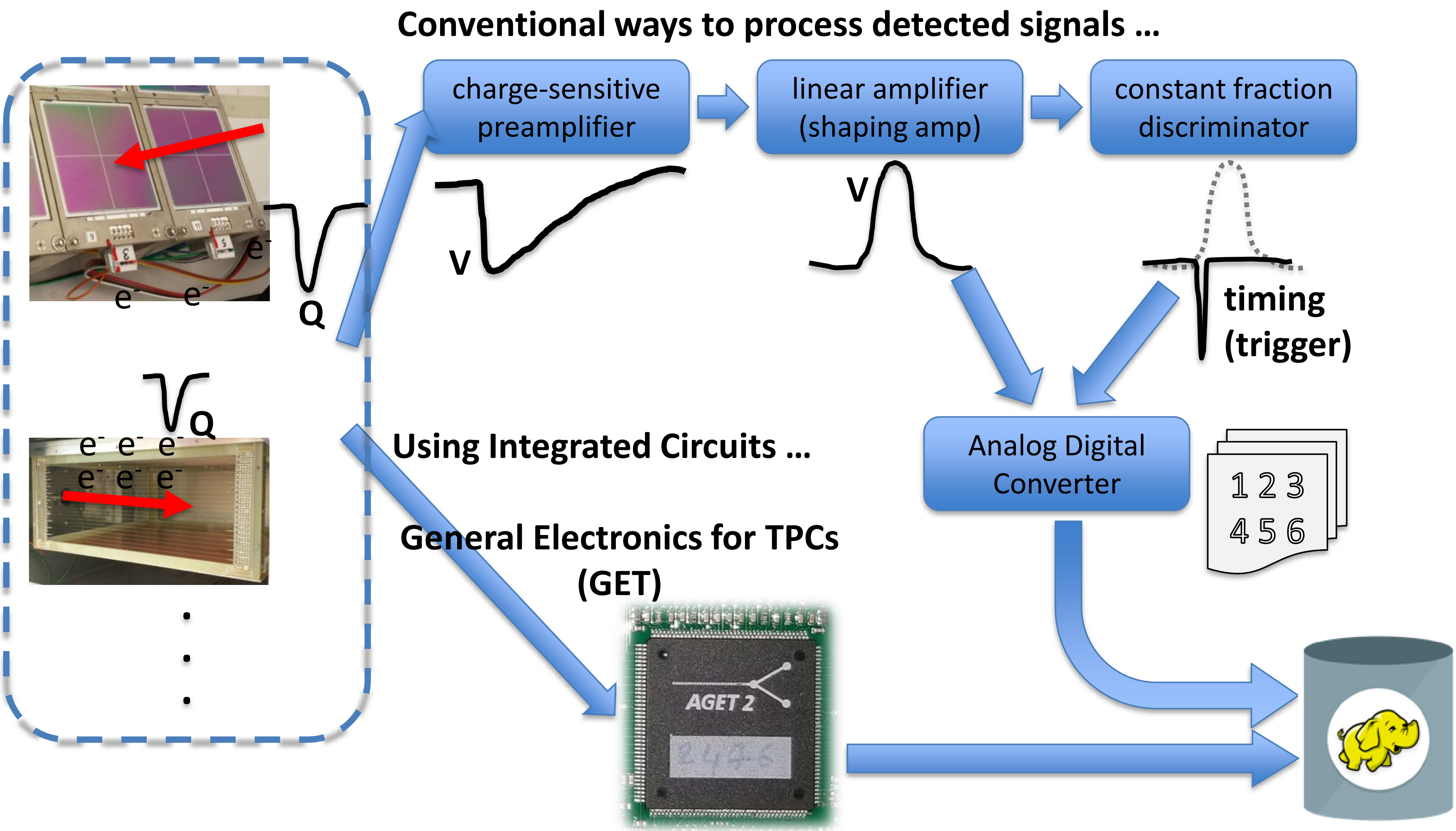
System Live Time (or Dead Time)

- "System Busy" comes from:
  - ✓ ADC data readout
  - ✓ data transfer to computer
  - ✓ data recording to computer



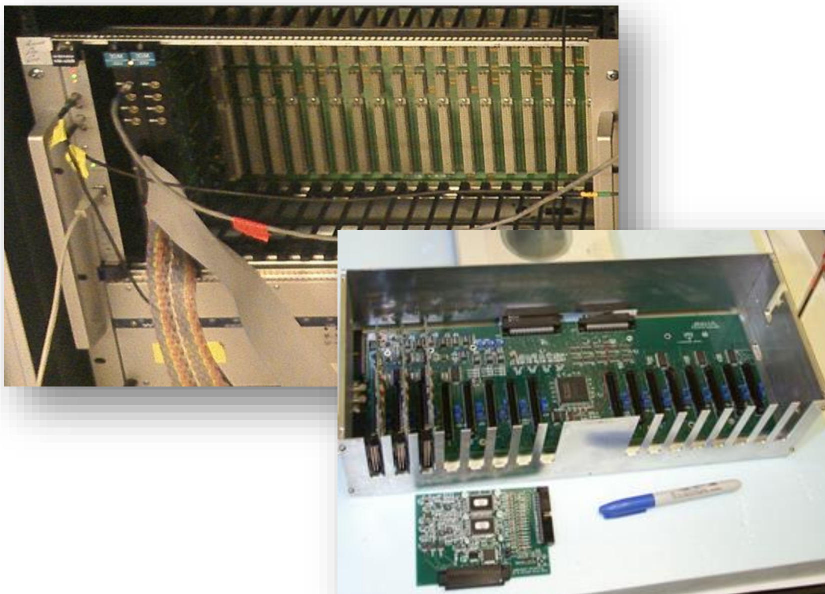
- ✓ **Live Time = 28/50 = 56 %**
- ✓ **Dead Time = 22/50 = 44 %**

Integrated Circuits (ASICs)

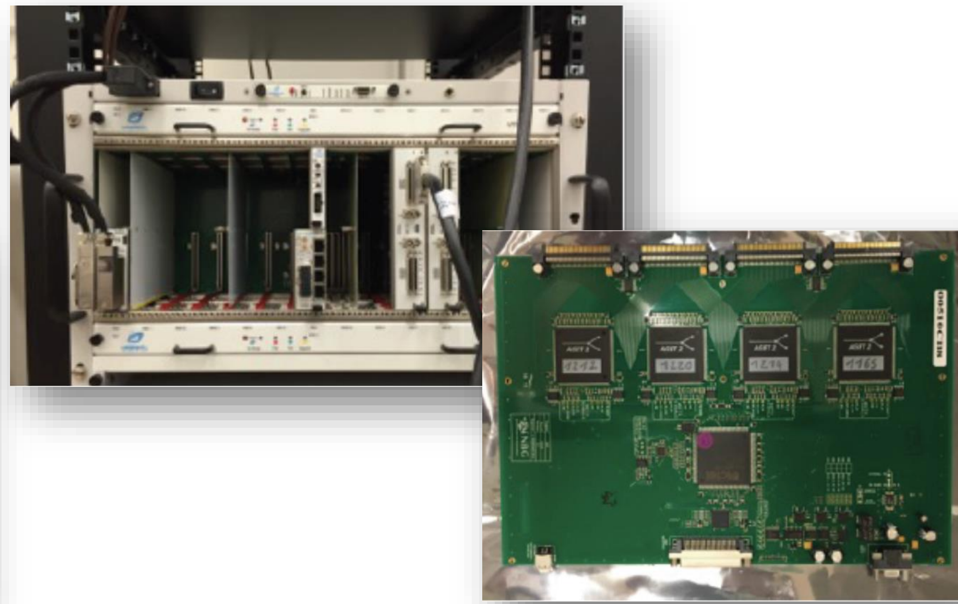


Integrated Circuits (ASICs)

- Large number of channels from the detector setup:
  - ✓ Conventional Electronics: space and cost problems, complicated setup, easy signal tracing.
  - ✓ ASIC Electronics: low cost (~1/10) and small space (~1/5), simple setup.
- HINP (Heavy Ion Nuclear Physics) Chip: 16 channels per chip, 512 channels per motherboard
- GET (Generic Electronics for TPC): 64 channels per chip, 256 channels per AsAd board



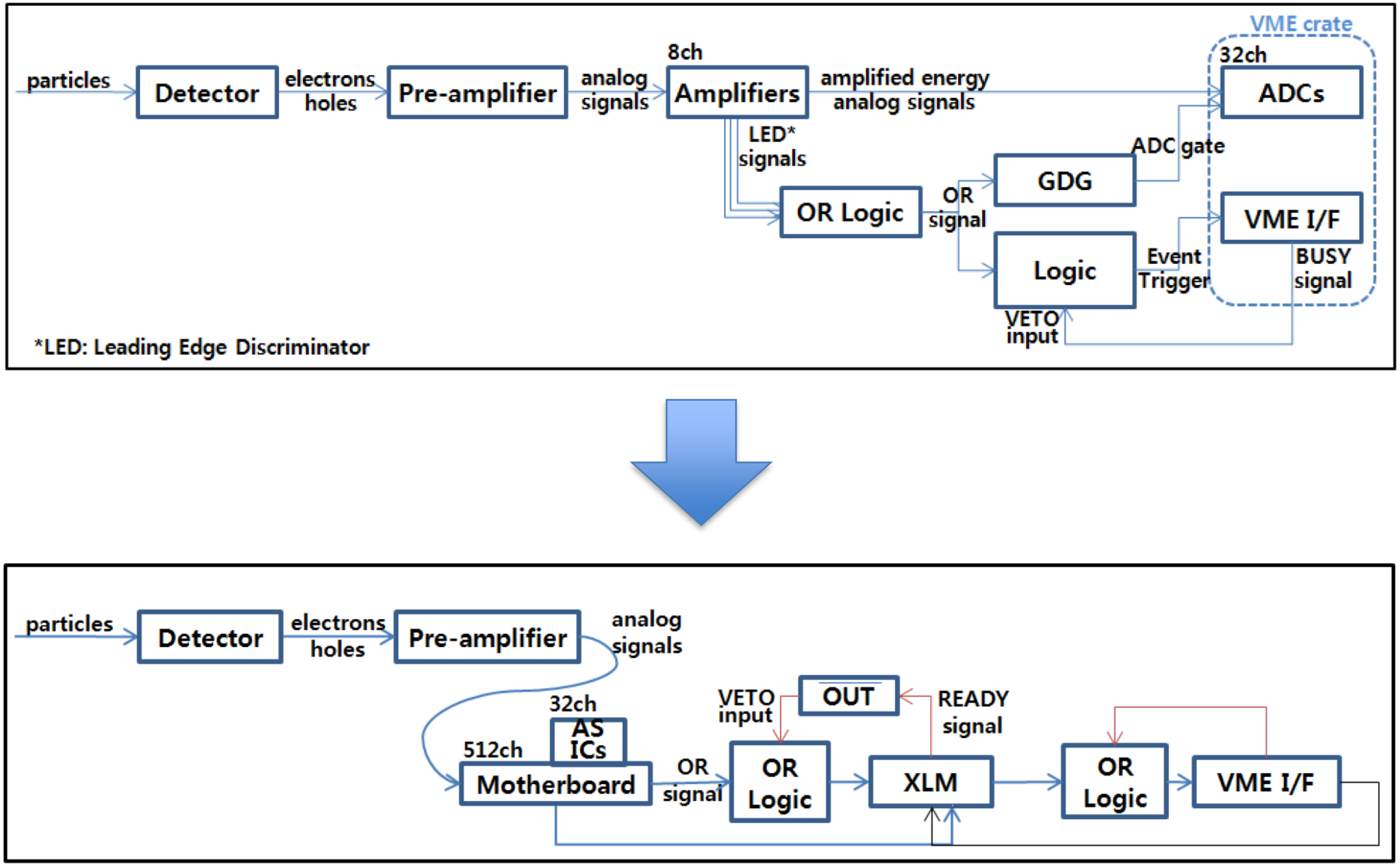
A picture for HINP16C chip and motherboard
G.L. Engel, CAARI Conference (2010)



A picture for µTCA crate and AsAd board (4 AGET chips)
G. Rogechev, Gas Detections Systems Workshop (2018)

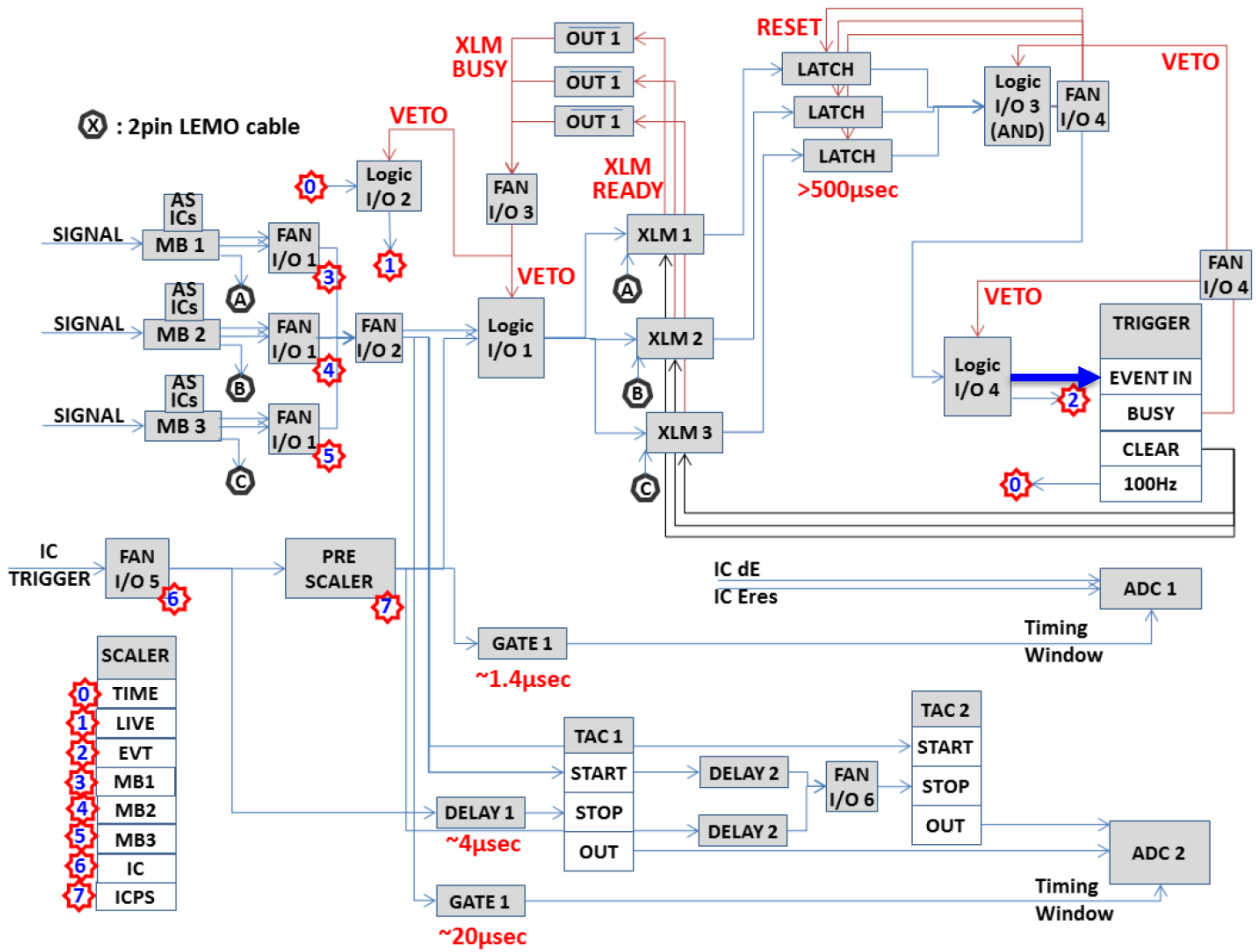
Signal Processing Diagram

- From the preamp signal to DAQ readout



Signal Processing with HINP ASICs

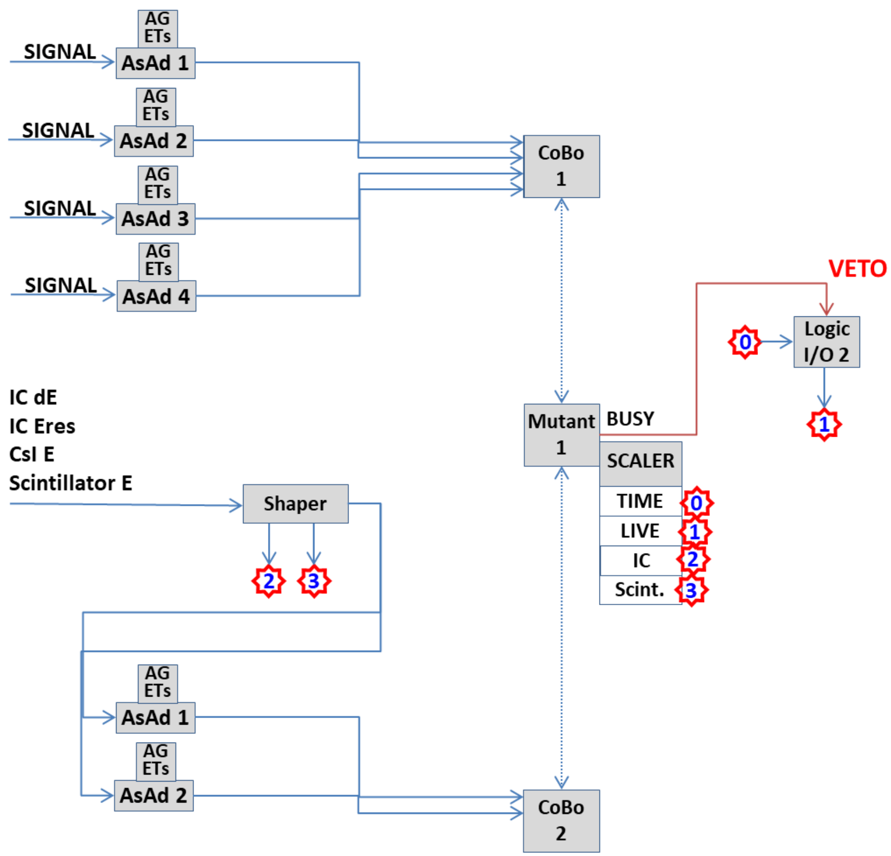
- For processing signals from 1000 channels,



Signal processing diagram using HINP ASICs device

Signal Processing with GET ASICs

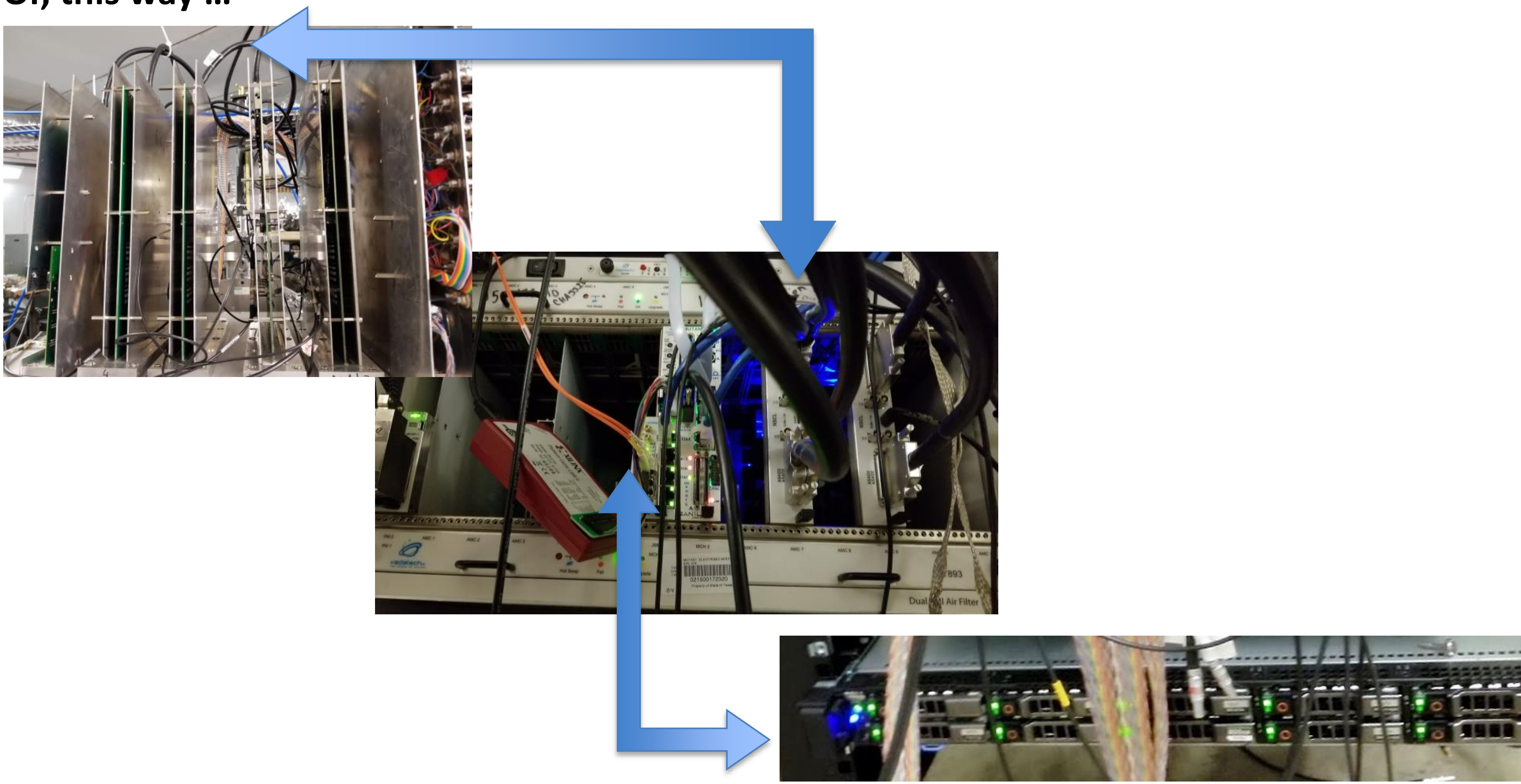
- For processing signals from 1000 channels,



Signal processing diagram using GET electronics

Signal Processing with GET electronics

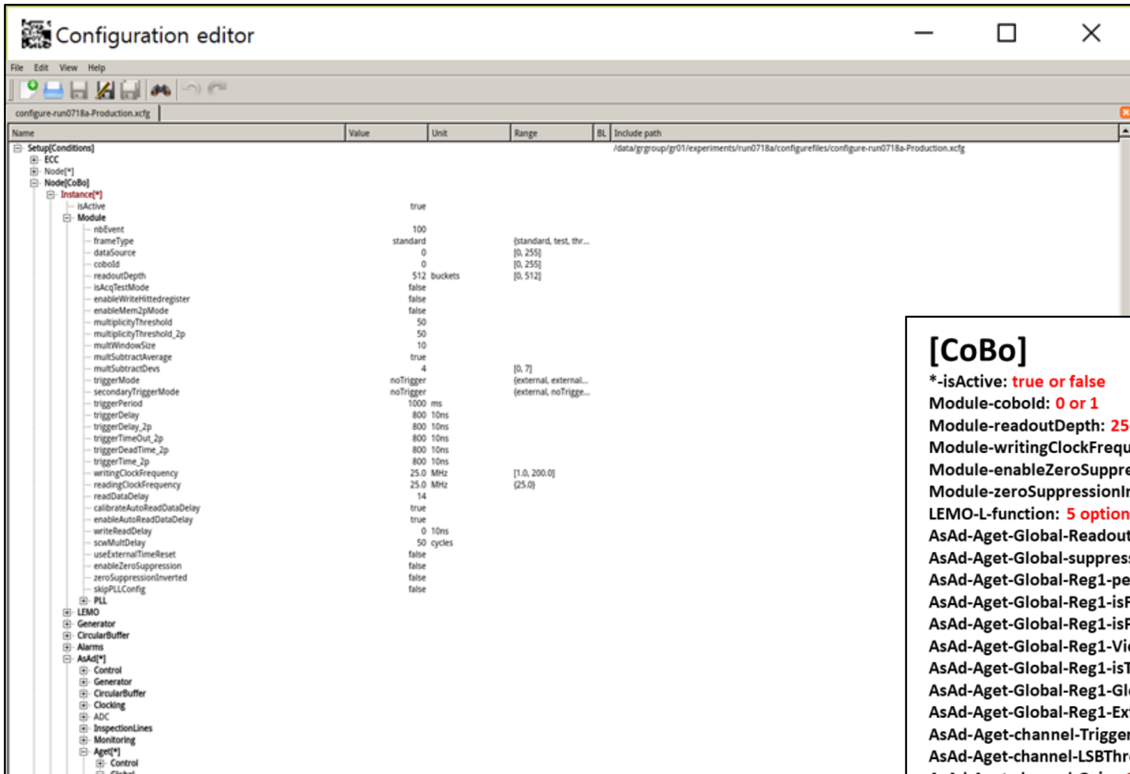
Or, this way …



Photos of GET Data Acquisition Hardware

Too Many Setting Parameters

However, ...



[CoBo]

*-isActive: true or false
Module-cobold: 0 or 1
Module-readoutDepth: 256 or 512 buckets
Module-writingClockFrequency: 25 MHz
Module-enableZeroSuppression: true or false
Module-zeroSuppressionInverted: false
LEMO-L-function: 5 options (Inspection output)
AsAd-Aget-Global-ReadoutPointerOffset: 0
AsAd-Aget-Global-suppressMultiplicity: false
AsAd-Aget-Global-Reg1-peackingTime: 502 ns
AsAd-Aget-Global-Reg1-isFPNRead: true or false
AsAd-Aget-Global-Reg1-isPositivePolarity: true or false
AsAd-Aget-Global-Reg1-Vicm: 1.55V or 1.35V
AsAd-Aget-Global-Reg1-isThresholdSignedPositive: true or false
AsAd-Aget-Global-Reg1-GlobalThresholdValue: 0 - 7
AsAd-Aget-Global-Reg1-ExternalLink: 4 options (for CsI signals)
AsAd-Aget-channel-TriggerInhibition: 3 options (none for selftrig)
AsAd-Aget-channel-LSBThresholdValue: 0 - 15
AsAd-Aget-channel-Gain: 10pC, 1pC, 240fC, 120fC
AsAd-Aget-channel-Reading: 3 options (only_if_hit for selftrig)
AsAd-Aget-channel-zeroSuppressionThreshold: 200

[2pmode setting]
Module-enableMem2pMode: true or false
AsAd-Global-Reg1-SCA_Splitting: true or false

[Mutant]

*-isActive: true or false
Master-readoutModeEnabled: true
Master-centrumScalerInterface: Scalers
Master-levelPriority: L0L1, L1L0
Level[0]-isEnabled: true or false
Level[0]- gateDelay: 0 - 655.35 us (10.0 us)
Level[0]- gateDuration: 0.01 - 655.35 us (40.0 us)
Level[1]-isEnabled: true or false
Level[1]-selection: 4 options (LOW)
Level[1]-postTriggerDelay: 0 - 655.35 us (18.0 us)
Level[2]-isEnabled: true or false
Level[2]-hitPatternModified: true or false

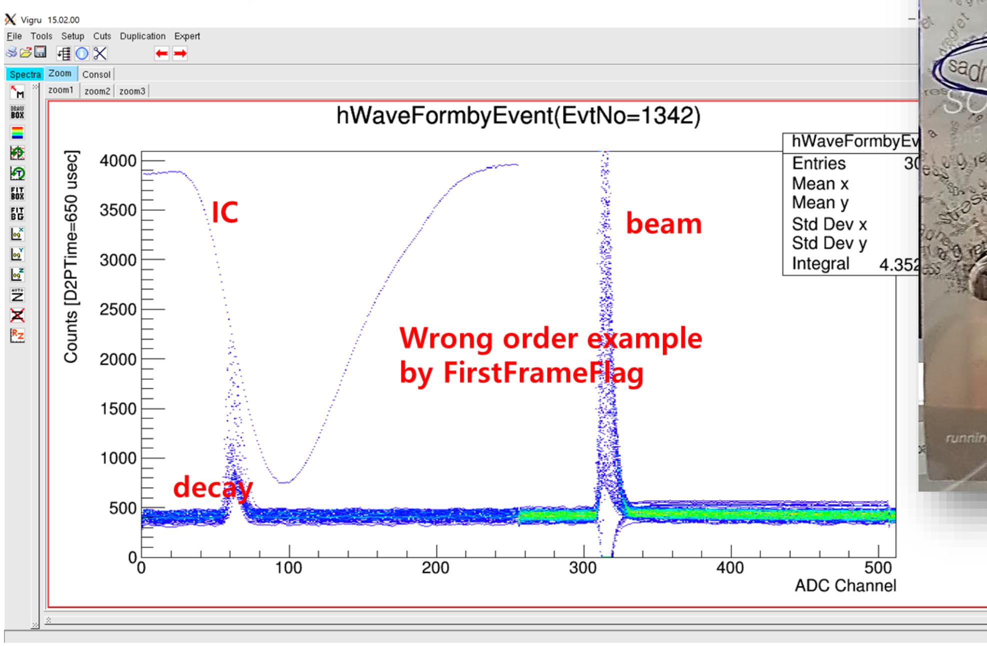
[2p mode setting]
Level[1]-L1A-lowMultThreshold: 0 - 65535 (1)
Level[1]-L1A-lowNumBuckets: 1 - 511 (5) buckets
Level[1]-L1B-lowMultThreshold: 0 - 65535 (1)
Level[1]-L1B-lowNumBuckets: 1 - 511 (5) buckets
Level[1]-L1B-timeout: 0 - 1677000 us (2000 us)
TwoProtonDecayMode-isEnabled: true
TwoProtonDecayMode-halfEventReadout: true or false

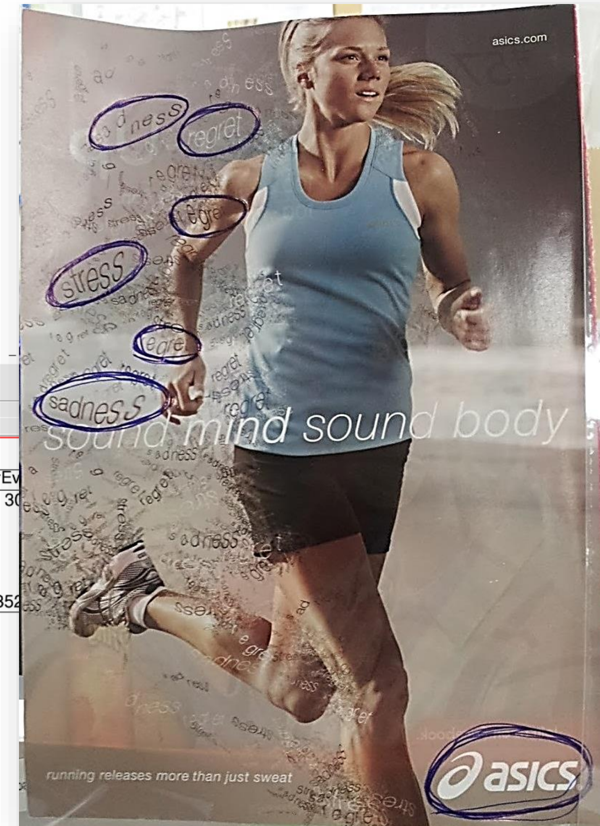
Photos of GET Data Acquisition Hardware

Difficult Troubleshooting

However, …



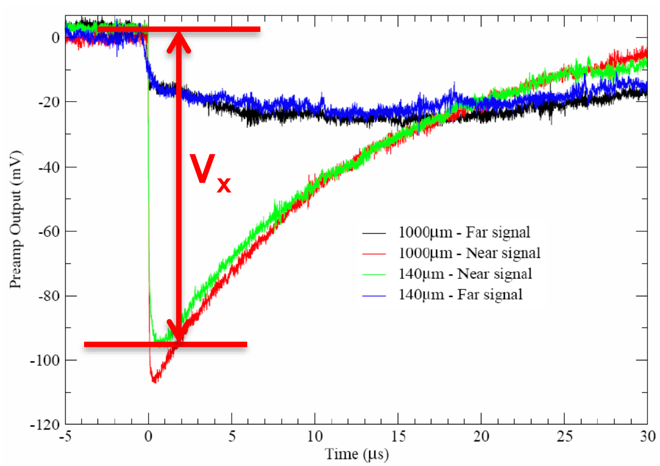





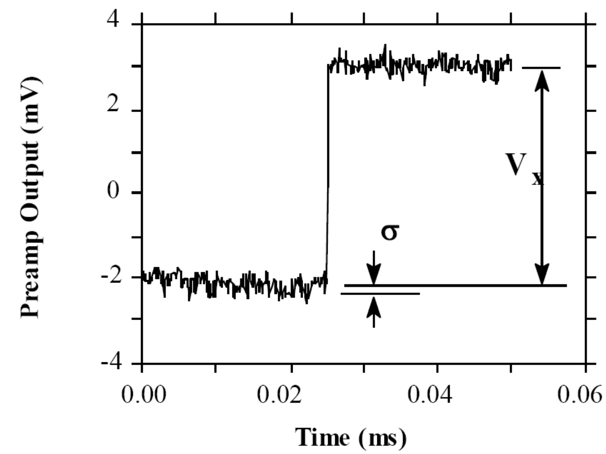
Sample waveforms spectrum of GET electronics

Digital Signal Processing

- Single Channel Signal Processing (Self Trigger) → almost no dead-time!!
- Recording amplitude and timing (100MHz/250 MHz/a few GHz Sampling rate)
- Correlation in time can be done later.
- We can record the waveform (trace) of the preamp signals for better pulse shape analysis.



Sample preamp output signals
S.D. Pain, EBSS2016



Digital Signal Processing

- Single Channel Signal Processing (Self Trigger) → almost no dead-time!!
- Recording amplitude and timestamp using Trapezoidal filter (100MHz/250 MHz/a few GHz Sampling rate)
- Correlation in time can be done later.
- We can record the waveform (trace) of the preamp signals for better pulse shape analysis.

$$LV_{x,k} = -\sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i$$

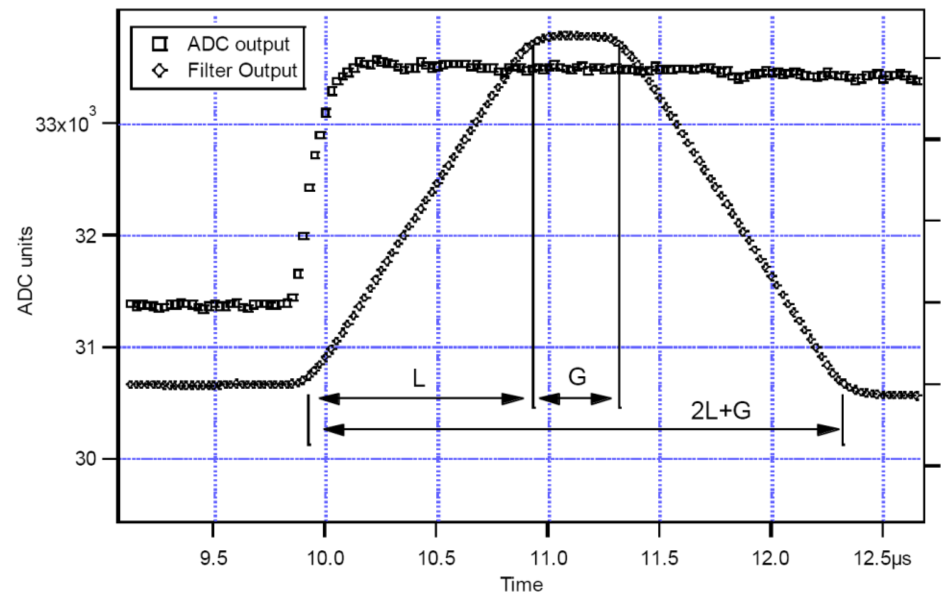
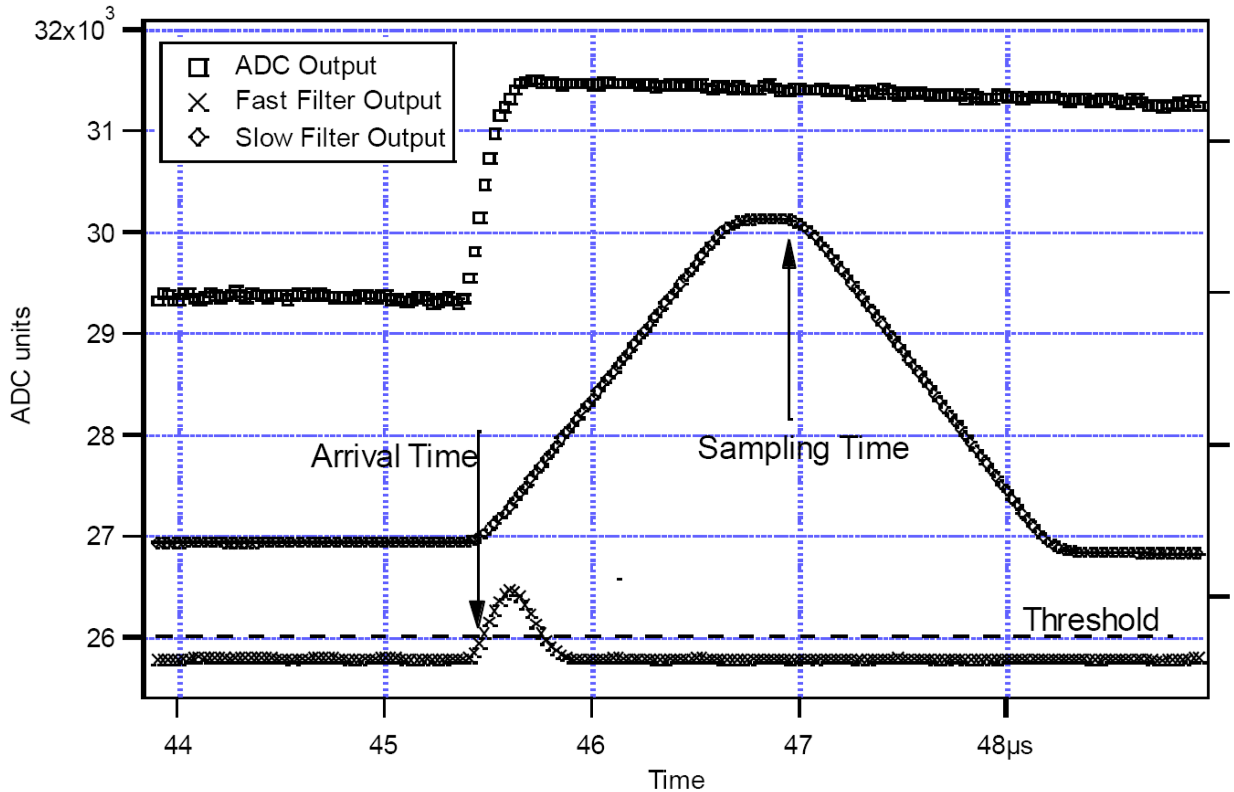


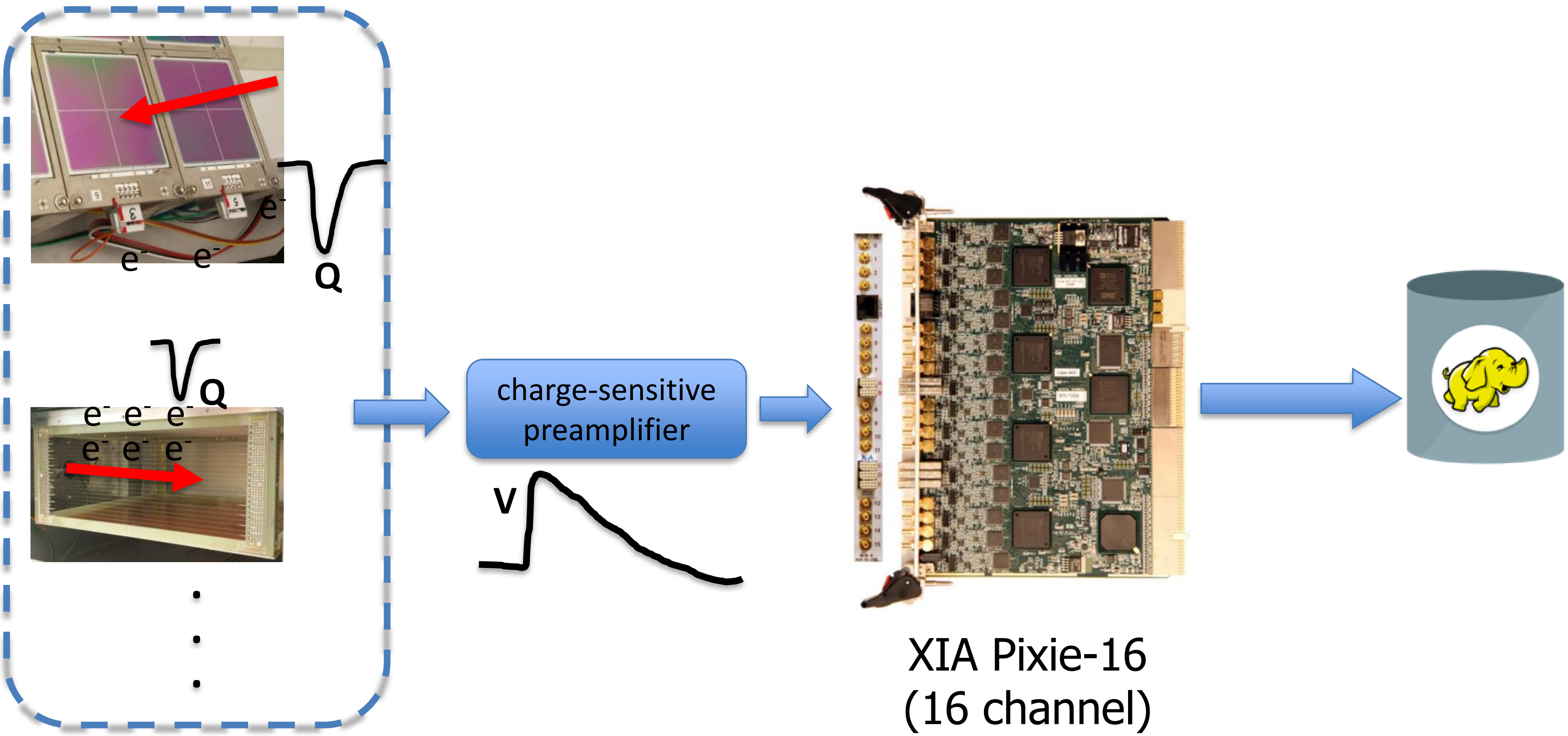
Figure 6-3: Trapezoidal filtering of a preamplifier step with L=1μs and G=0.4μs.

Digital Signal Processing

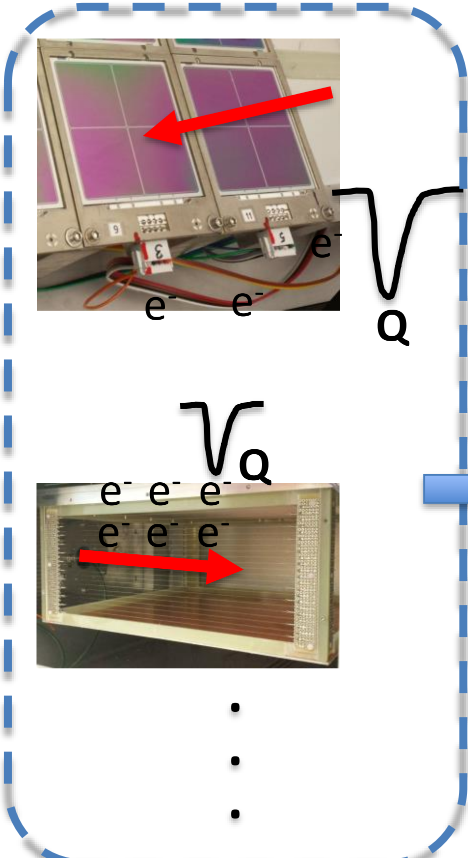
- Single Channel Signal Processing (Self Trigger) → almost no dead-time!!
- Recording amplitude and timing (100MHz/250 MHz/a few GHz Sampling rate)
- Correlation in time can be done later.
- We can record the waveform (trace) of the preamp signals for better pulse shape analysis. (~ μsec)



Digital Signal Processing

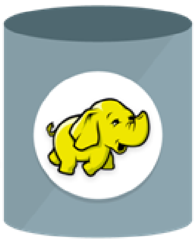


Digital Signal Processing



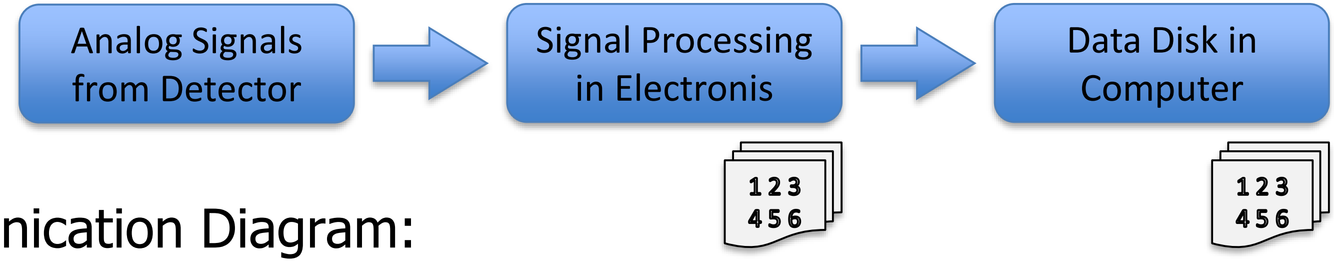
In reality...

160 channels total

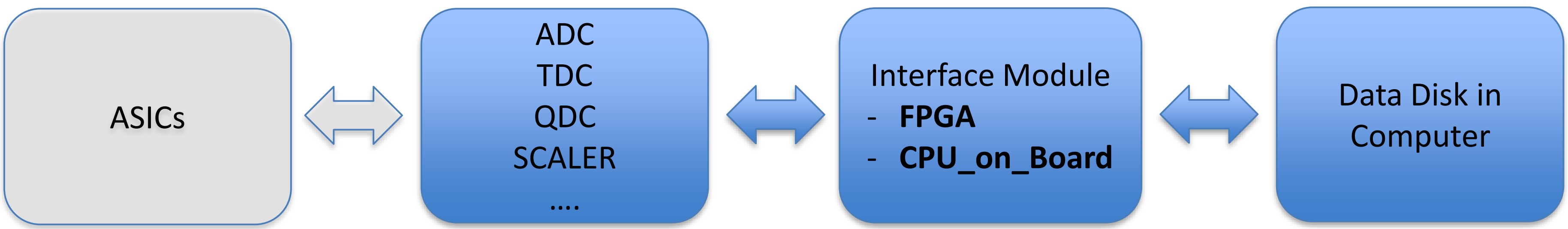


Online Data Acquisition

- Digitized Data Transfer:



- Communication Diagram:

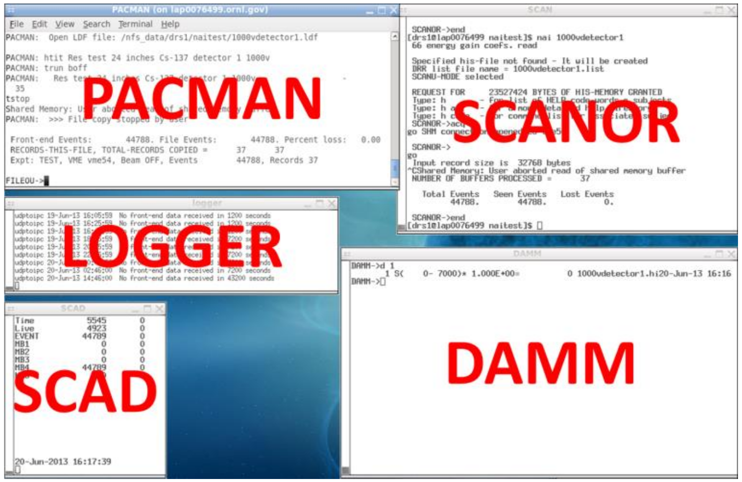


- Slow Control for parameter settings

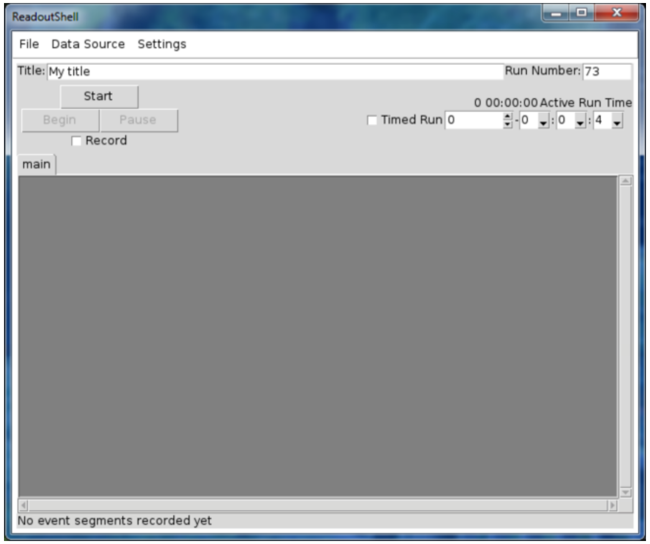
- Fast Control for Start/Stop taking data

← Don't worry! This is done by C/S Engineers! Field Programmable Gate Array (FPGA) programming (so called firmware).

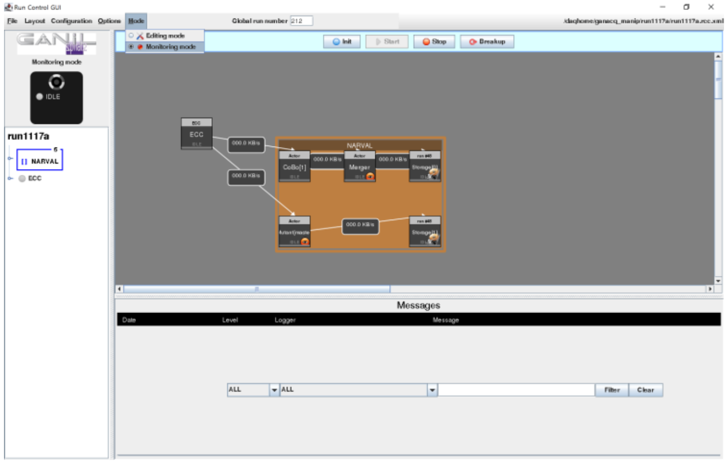
DAQ Graphic User Interface



ORNL DAQ



NSCL DAQ



GANIL DAQ

Data Storage and Analysis System

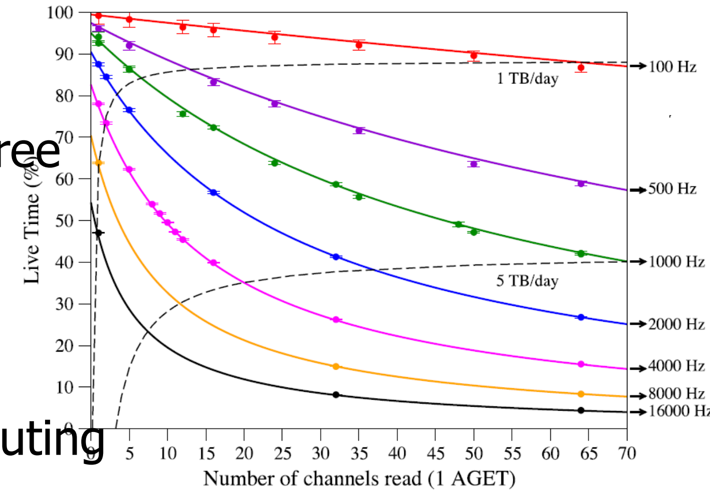
- Each hit channel contains 2 KB.

→ For 100 evts/s wt 100 channels per evt, total data rate = 2*100*100 = 20MB/s or 70GB/hr.

- High data rate causes problems:
  - ✓System dead time increased.
  - ✓Long conversion time from raw format to ROOT tree

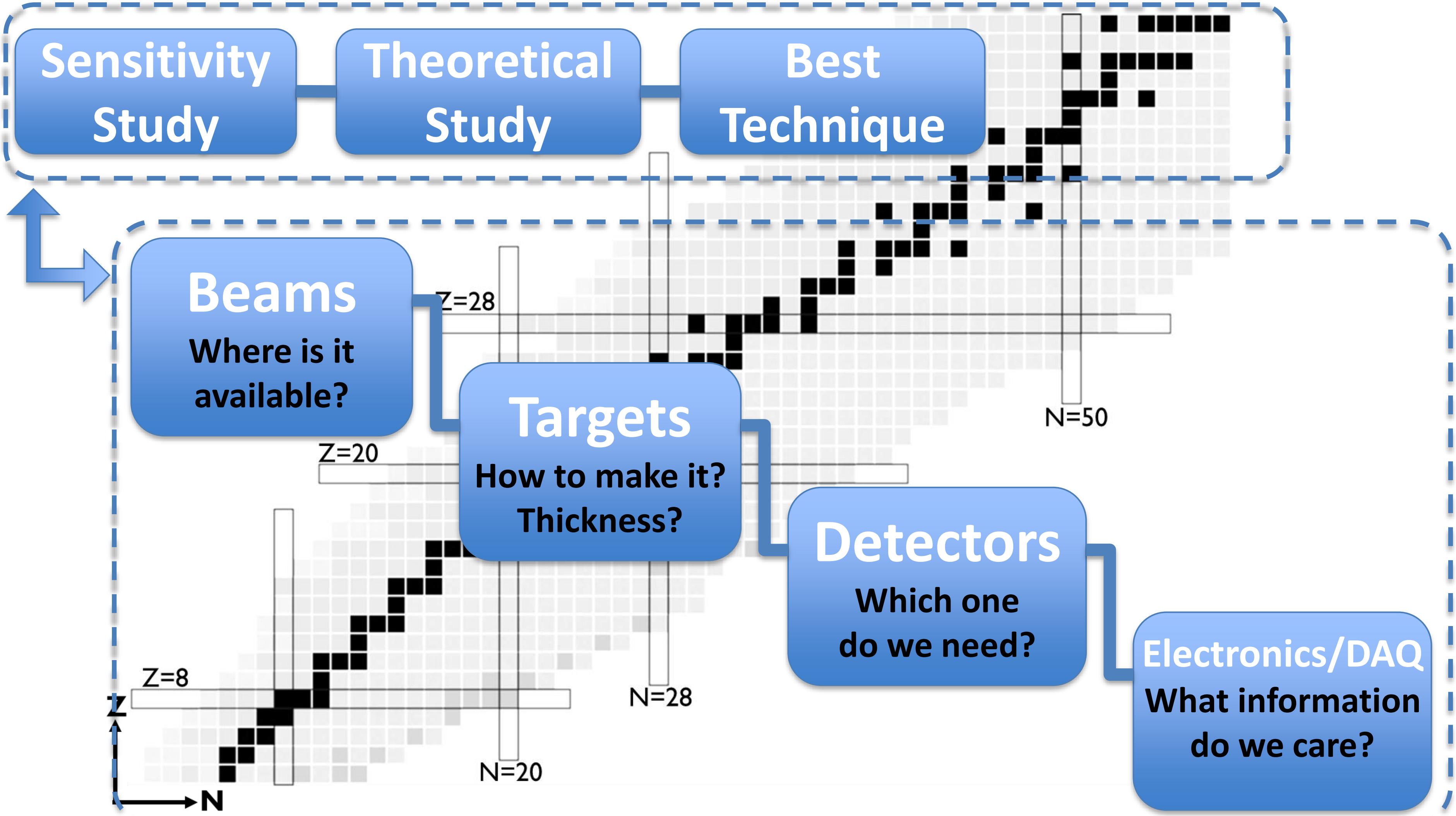
- 112 CPUs and 116GB Memory
- Apache Spark: cluster-computing framework
- Apache Hadoop: software utilities for cluster-computing
- Docker: operating-system-level virtualization

E.C. Pollacco *et al.*, NIM A 2018

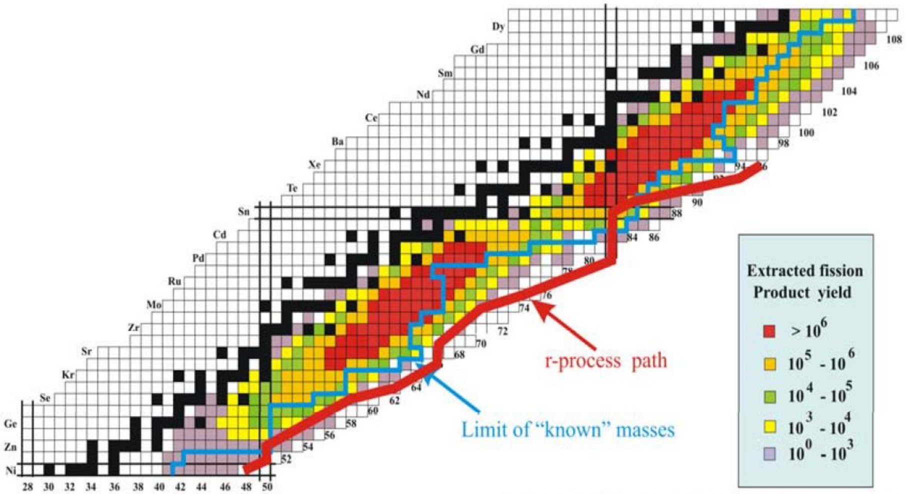


Live Time and Data Rate of GET

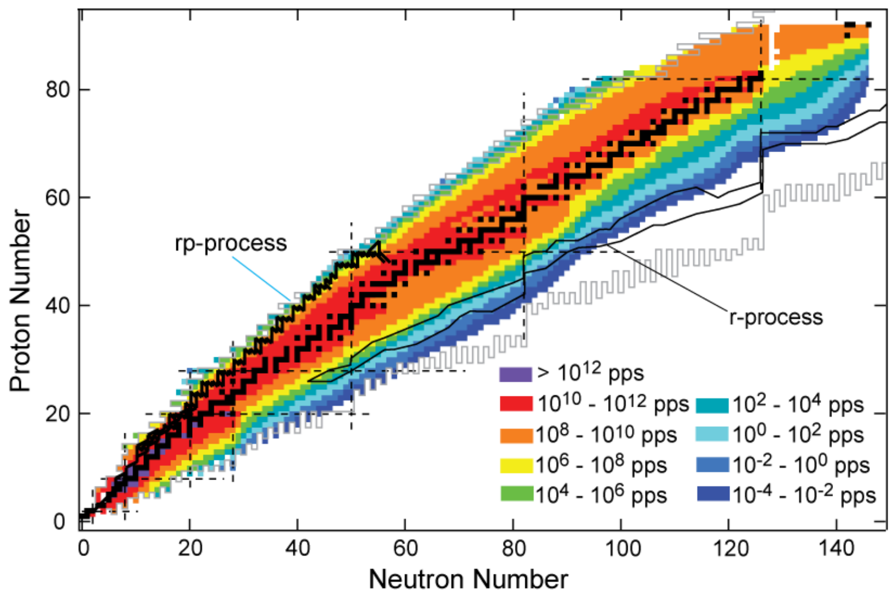
Experimental Techniques



RIB beam productions

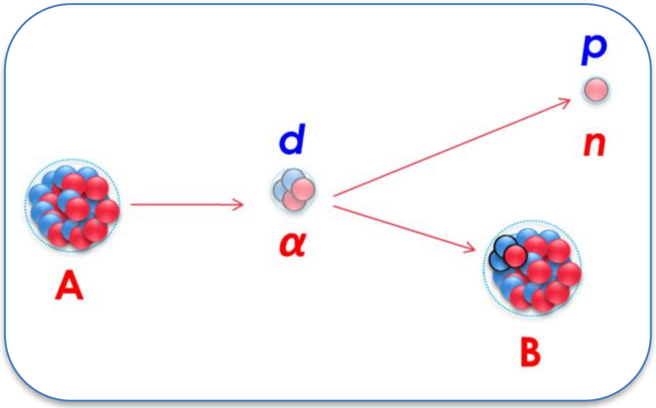


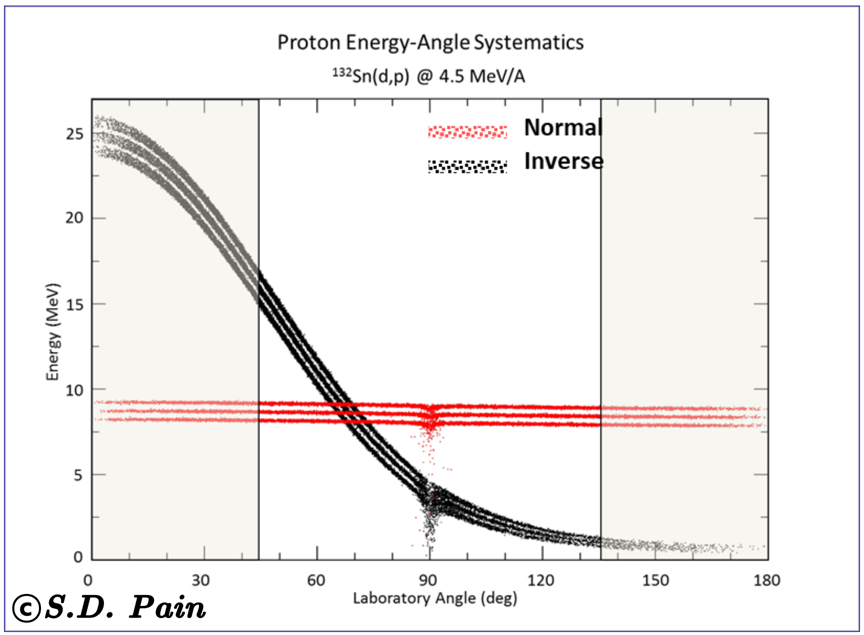
Beam production and delivery at CARIBU, Argonne National Laboratory



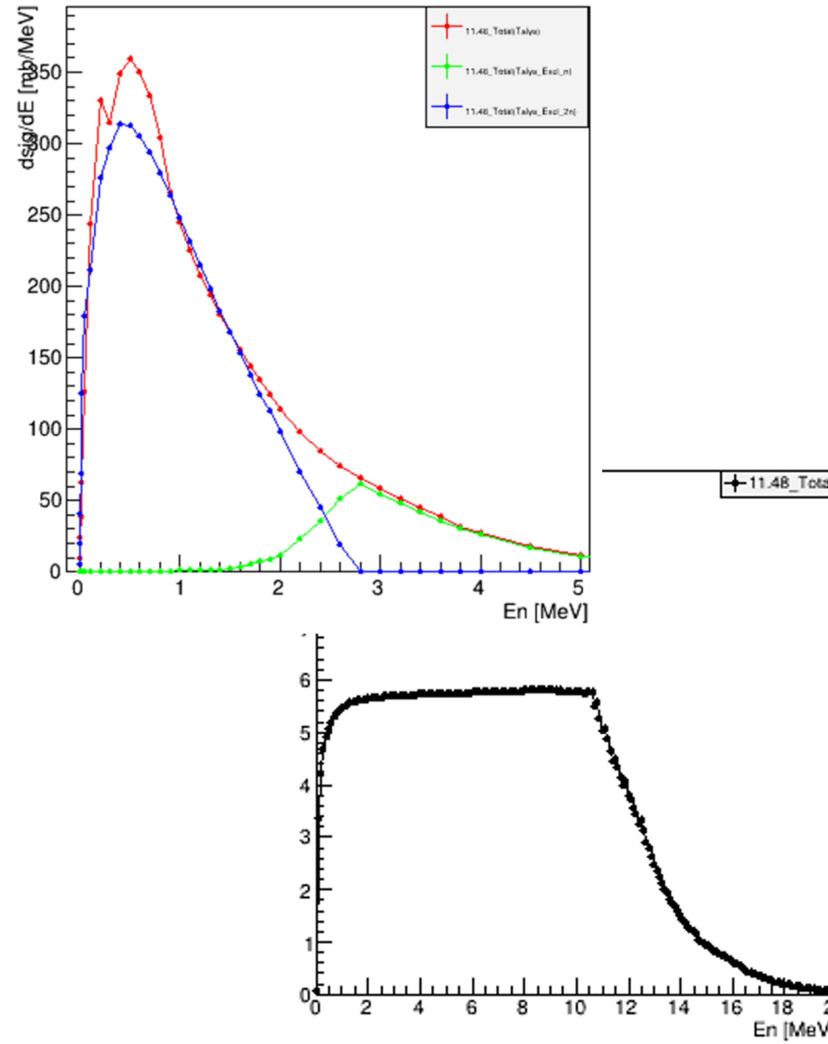
Projected beam rate by future FRIB

Challenges on Reaction in Inverse Kinematics



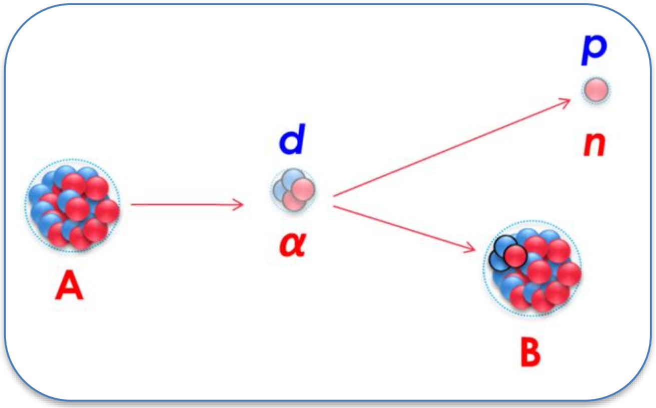


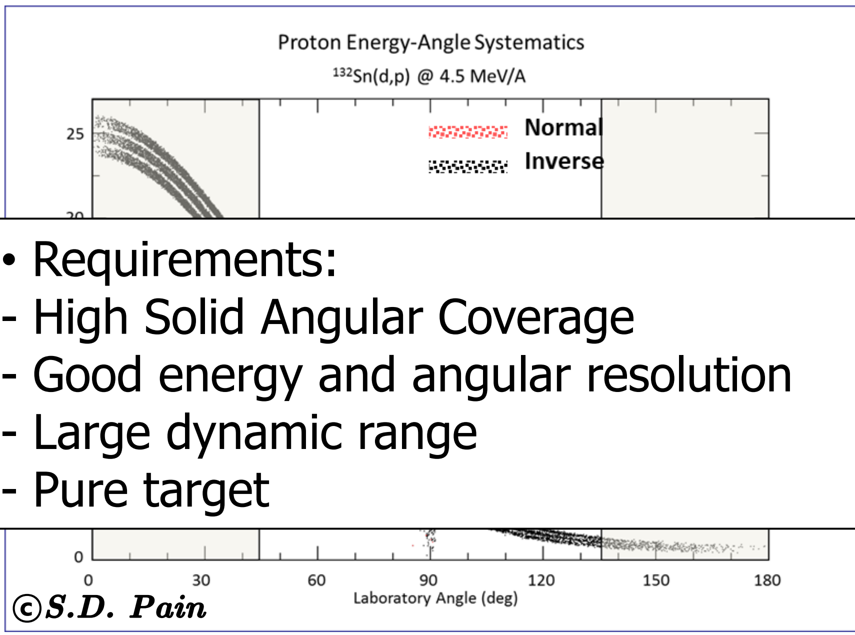
Simulations of Normal kinematics vs. Inverse kinematics on ^{132}Sn(d,p)^{133}Sn



Neutron Spectrum of Normal kinematics vs. Inverse kinematics on ^{75}Ga(α,n)^{78}As

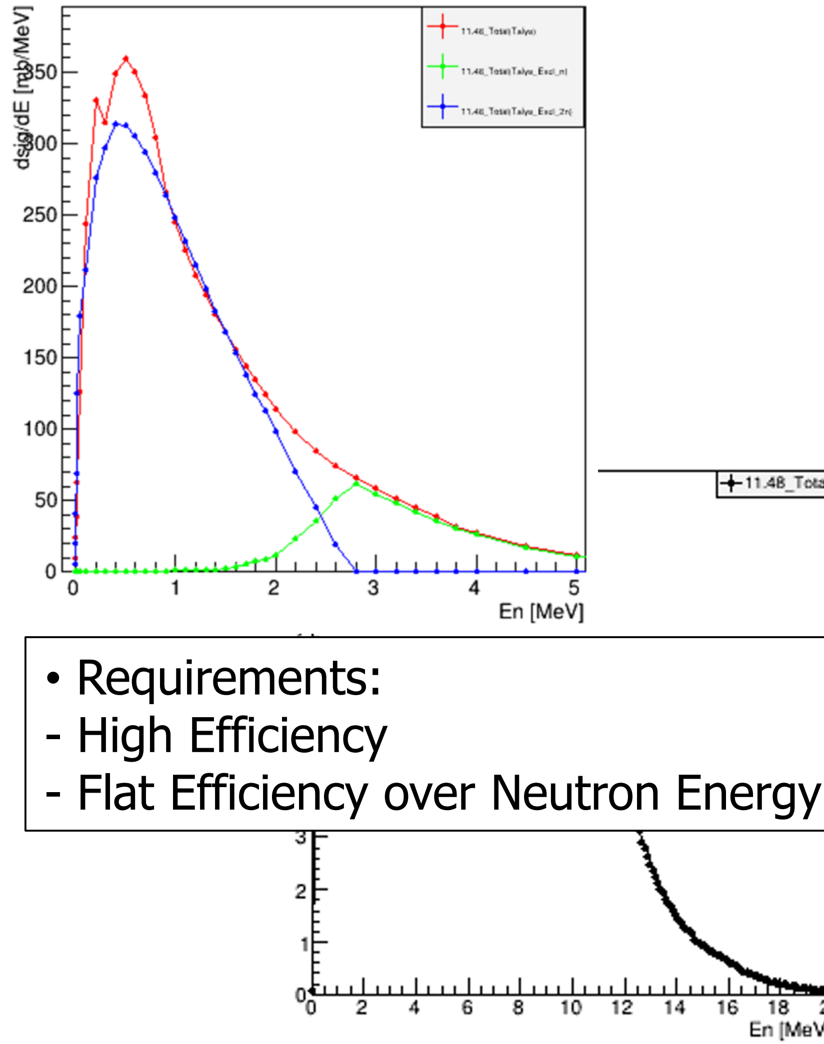
Challenges on Reaction in Inverse Kinematics





- Requirements:
- High Solid Angular Coverage
- Good energy and angular resolution
- Large dynamic range
- Pure target

Simulations of Normal kinematics vs. Inverse kinematics on ^{132}Sn(*d,p*)^{133}Sn



- Requirements:
- High Efficiency
- Flat Efficiency over Neutron Energy

Simulations of Normal kinematics vs. Inverse kinematics on ^{75}Ga(*α*,n)^{78}As

To-Do List

Collecting Parts
- Vacuum parts
- Targets
- Detector parts
- Electronics and DAQ

Device Tests
- Alignment
- Vacuum Test
- Target Test
- Detector Test
- Electronics Test

Calibrations
- Energy Calibration
- Detector Efficiency
- Geometry Efficiency
- Target Thickness
- System Synchronization

Online Analysis Preparation
- Check Beam Condition
- Diagnostics code
- Analysis code
- Calibration params
- Make Shift Instruction

Beam Diagnostics
- Beam profile check
- Contaminations

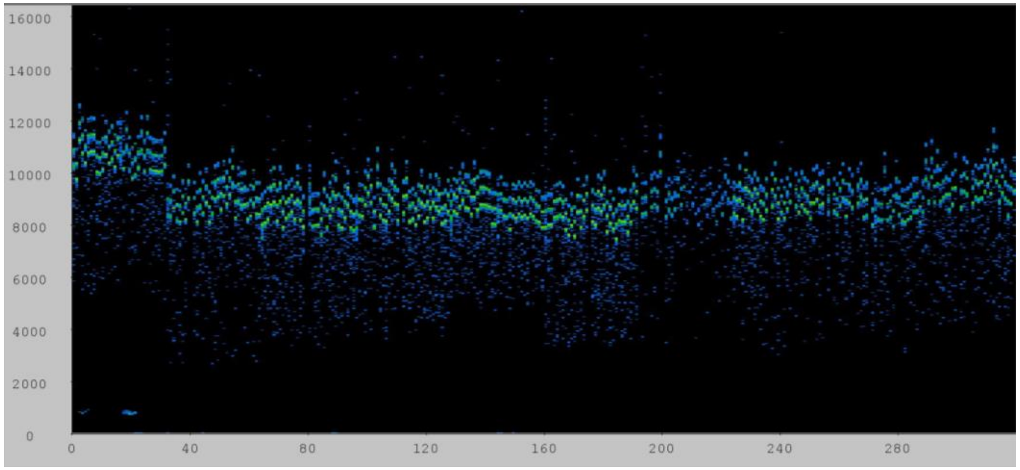
Production Mode
- Taking shifts
- Check coincidence
- Check data integrity
- Online Analysis

Experiment End
- Calibrations
- Measurement of setup
- Electronics Cables log
- Break-down

Checklist for Data Analysis

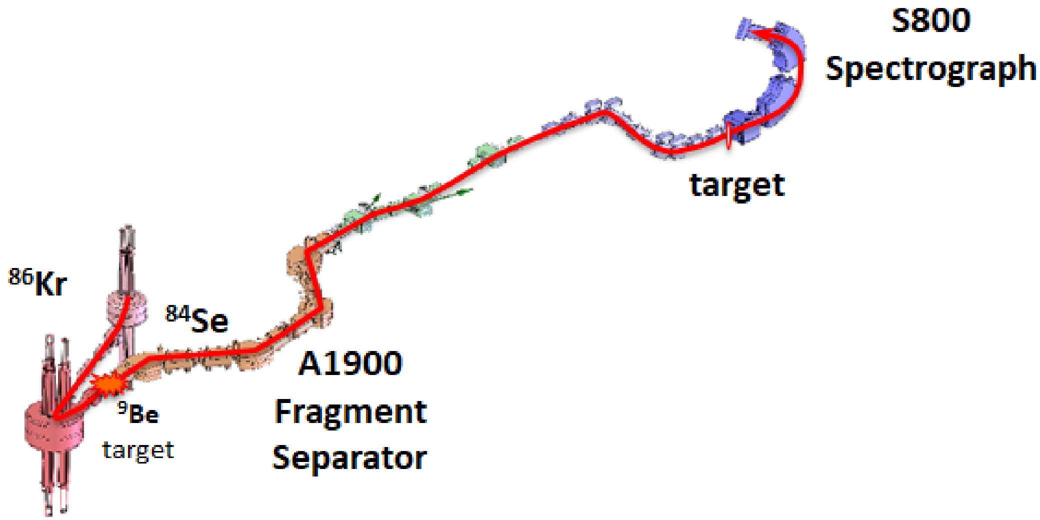
- 1D and 2D hit patterns over channels are useful for system diagnostics.
- Beam normalization and Particle Identification (PID) plot
- Don't forget to measure length and distance!
- Do energy and solid angle calibration!
- Correlation is important! (among detected particles/gammas)
- Check Data Rate and System Live Time and your disk space!
- Do you have theoretical calculations to compare with data online?

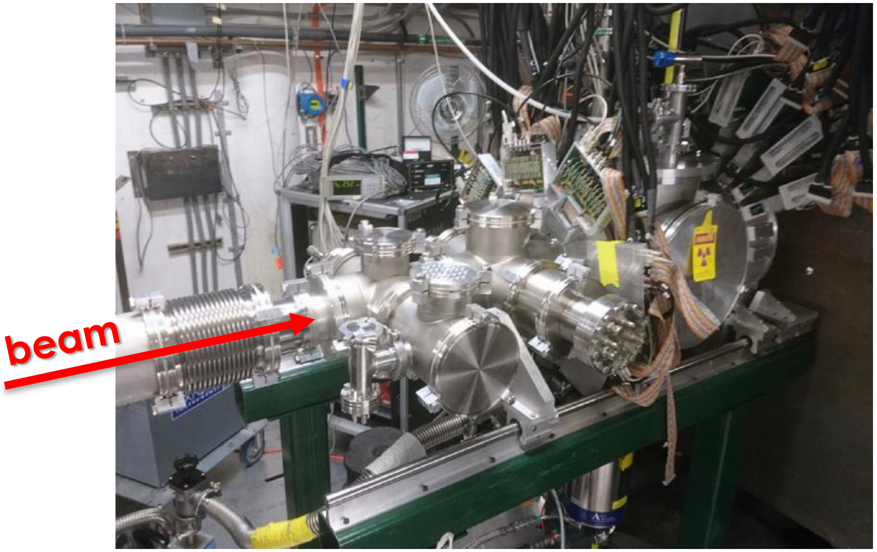
- **Error Analysis:**
- Resolution (FWHM)
- Statistical error
- Systematic error
- Theoretical error



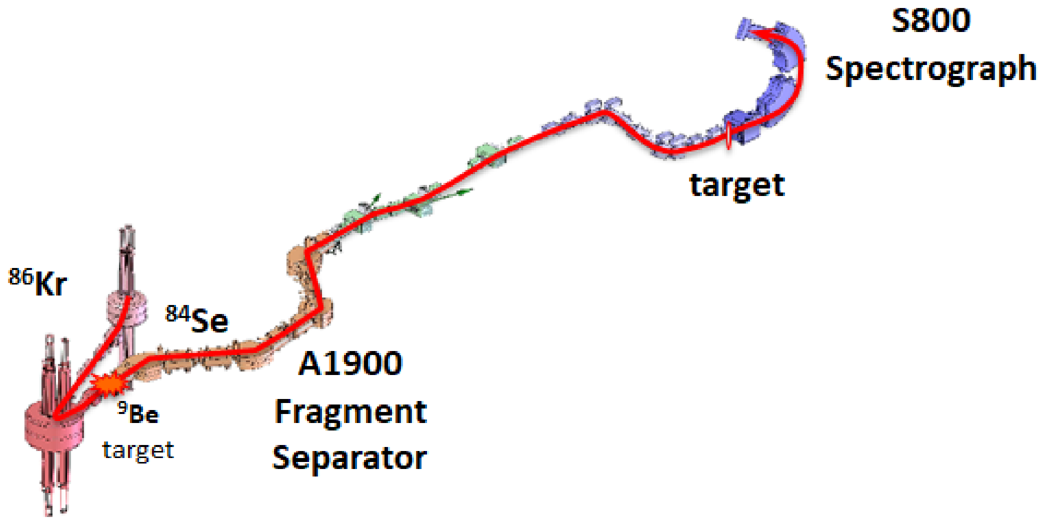
2D Hit Pattern of ADC amplitude vs electronics channels

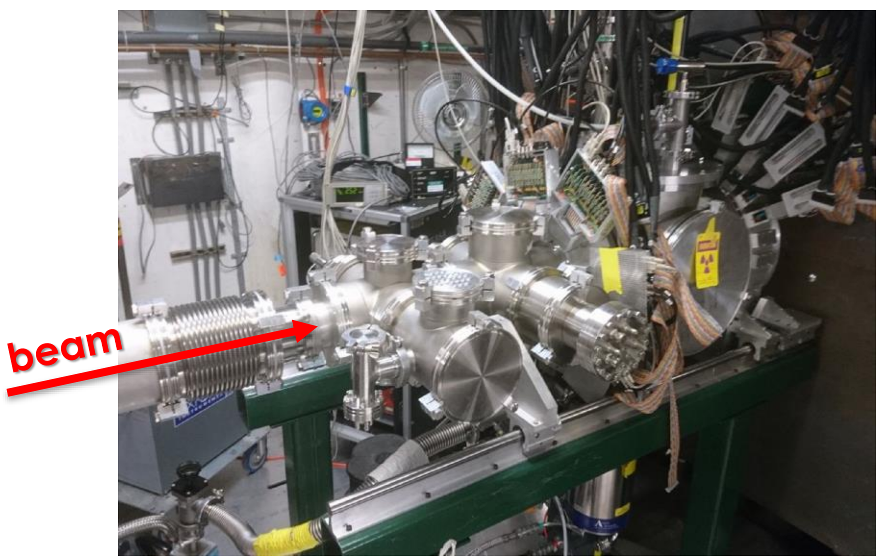
$^{84}Se(d,p)$ Neutron Transfer Reaction Experiment

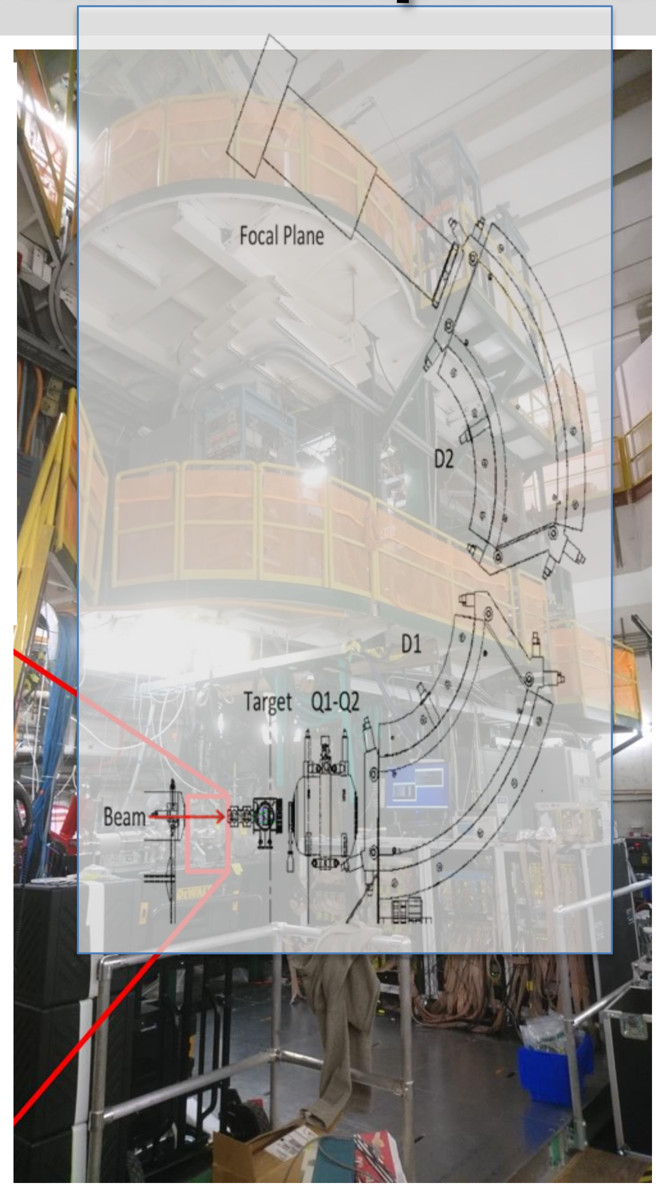




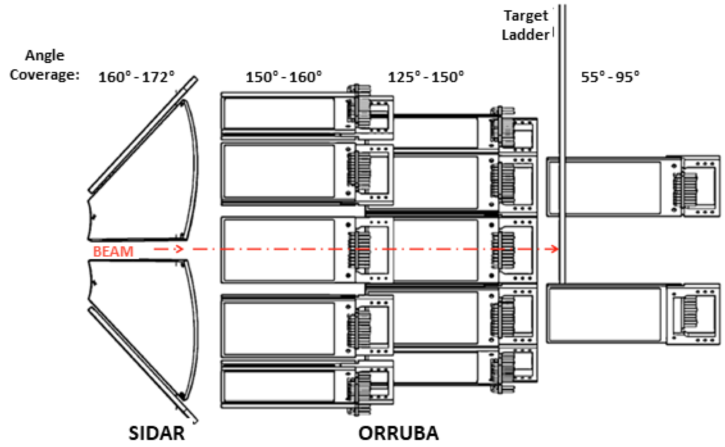
^{84}Se(d,p) Neutron Transfer Reaction Experiment

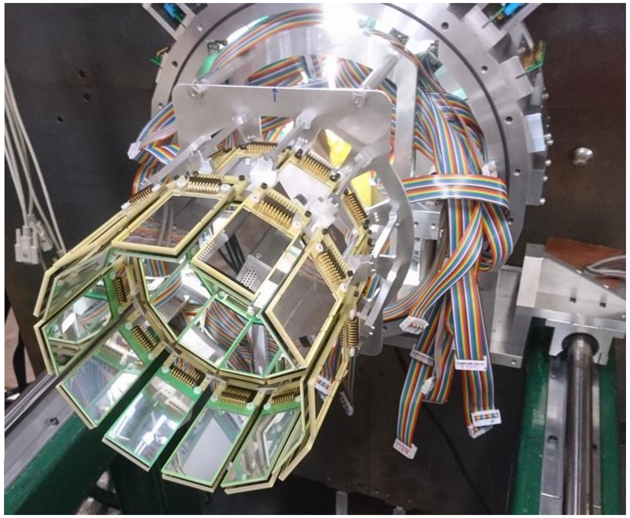






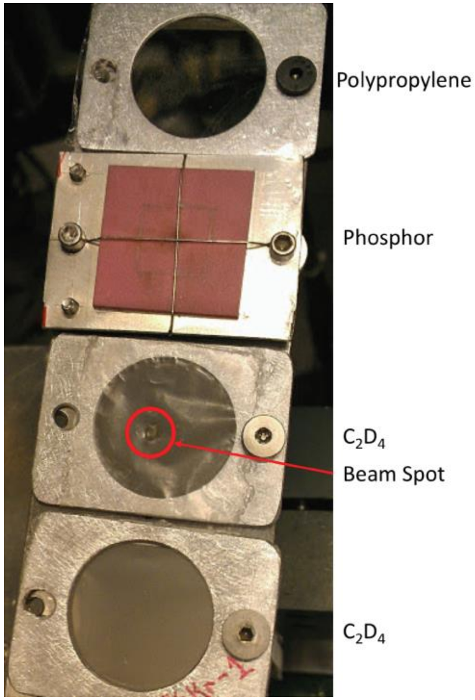
^{84}Se(*d,p*) Experiment Set-up





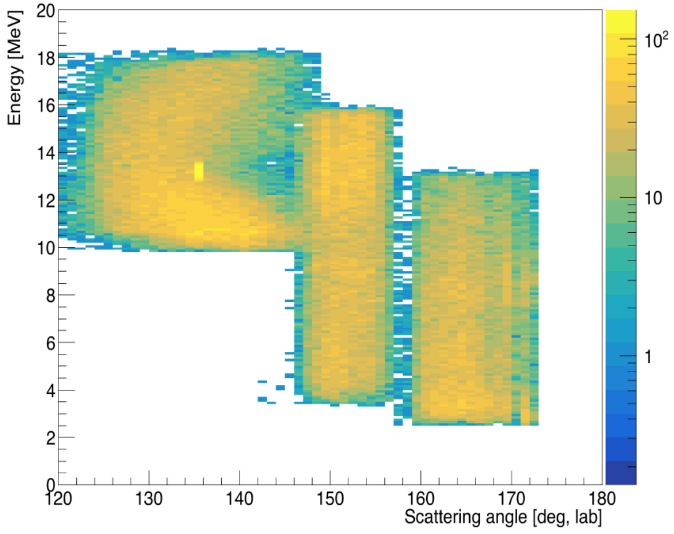
ORNL Rutgers University Barrel Array (ORRUBA)

Targets

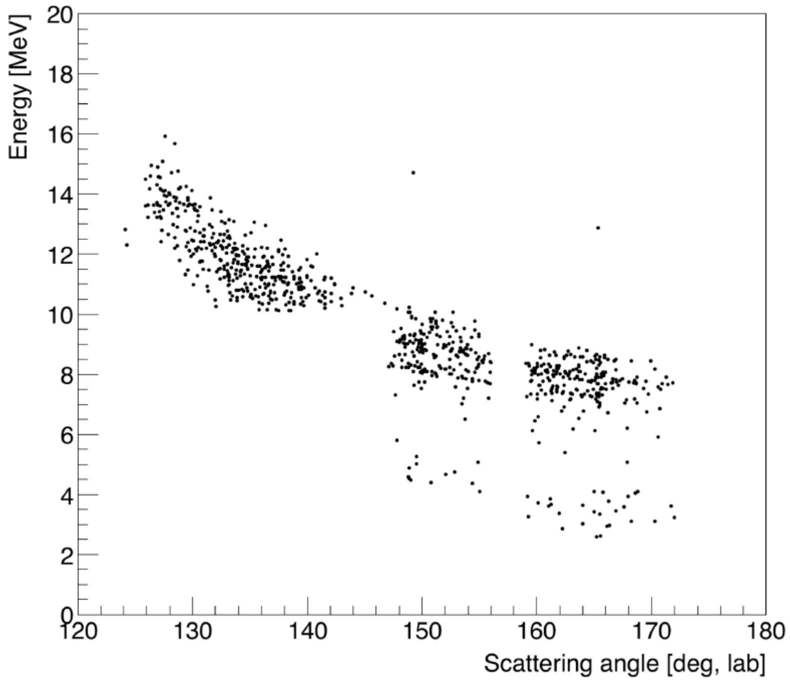


Conventional Electronics Set-up

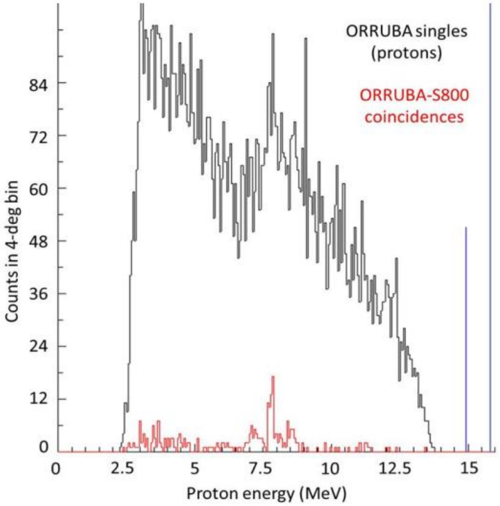
$^{84}Se(d,p)$ Experiment Histograms



Raw Light particle Energy vs angle

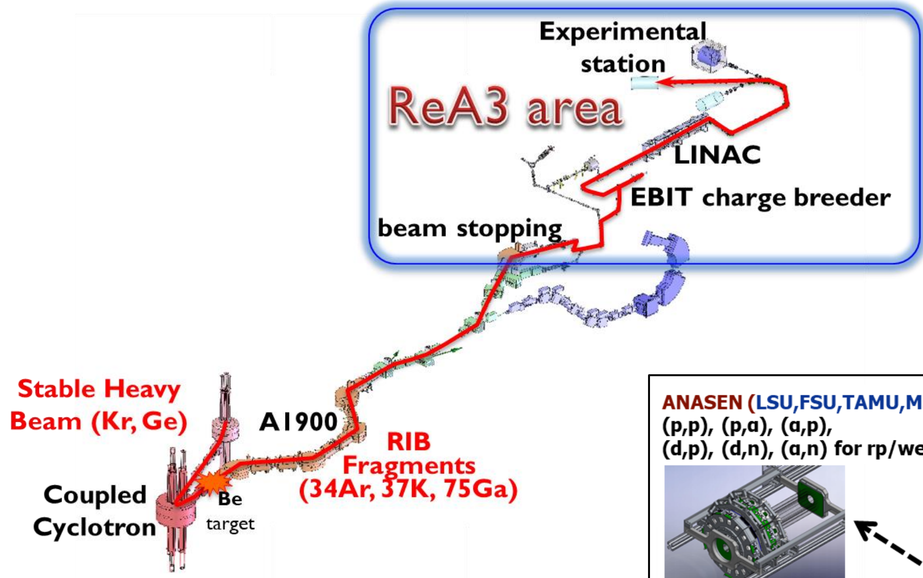


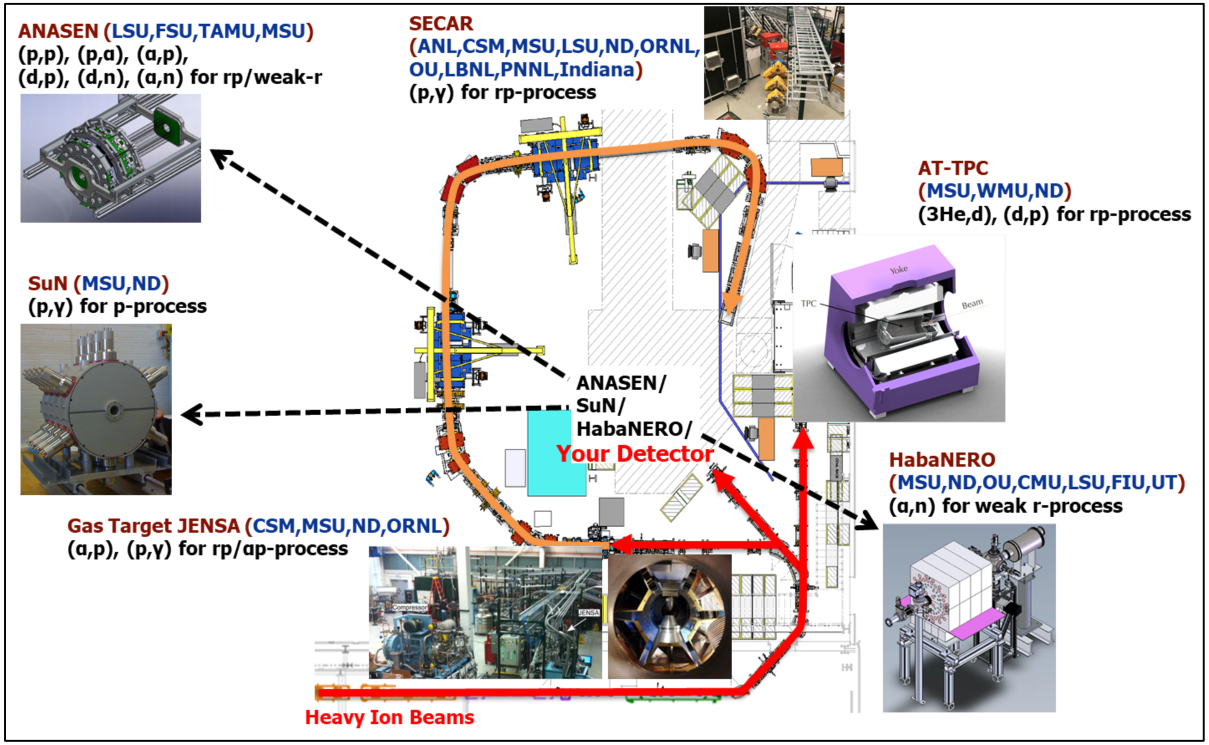
Light particle Energy vs angle gated on S800 events



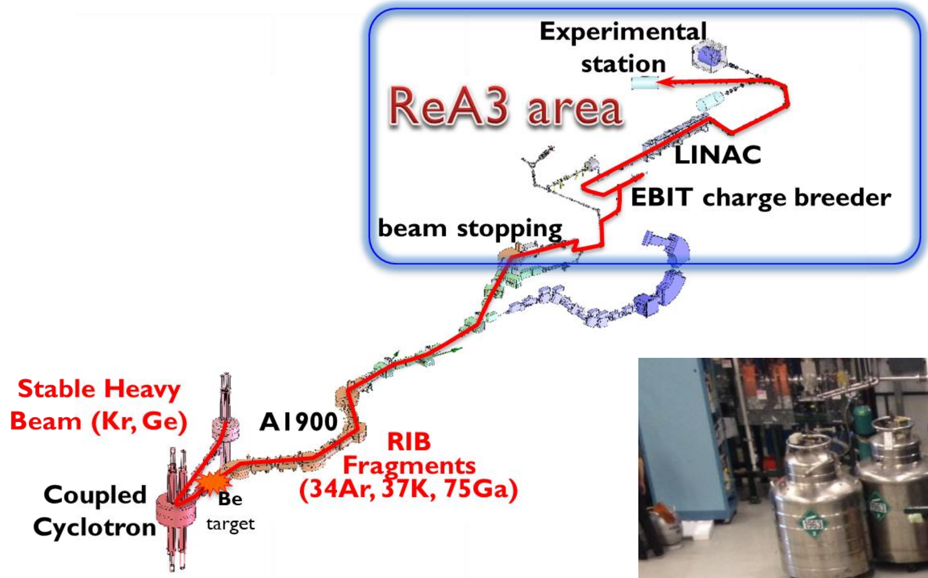
1D correlated Energy spectrum

Experiments in ReA3/NSCL

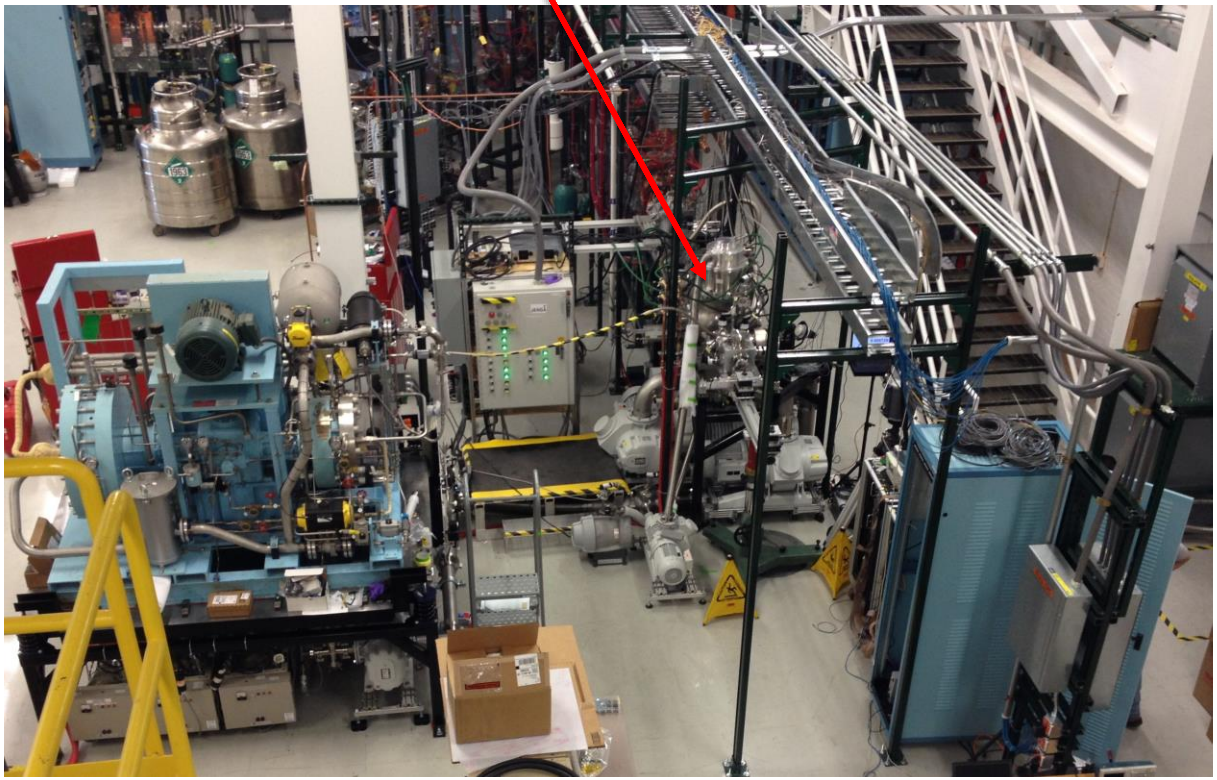




JENSA Setup for ^{34}Ar(α,p) Reaction

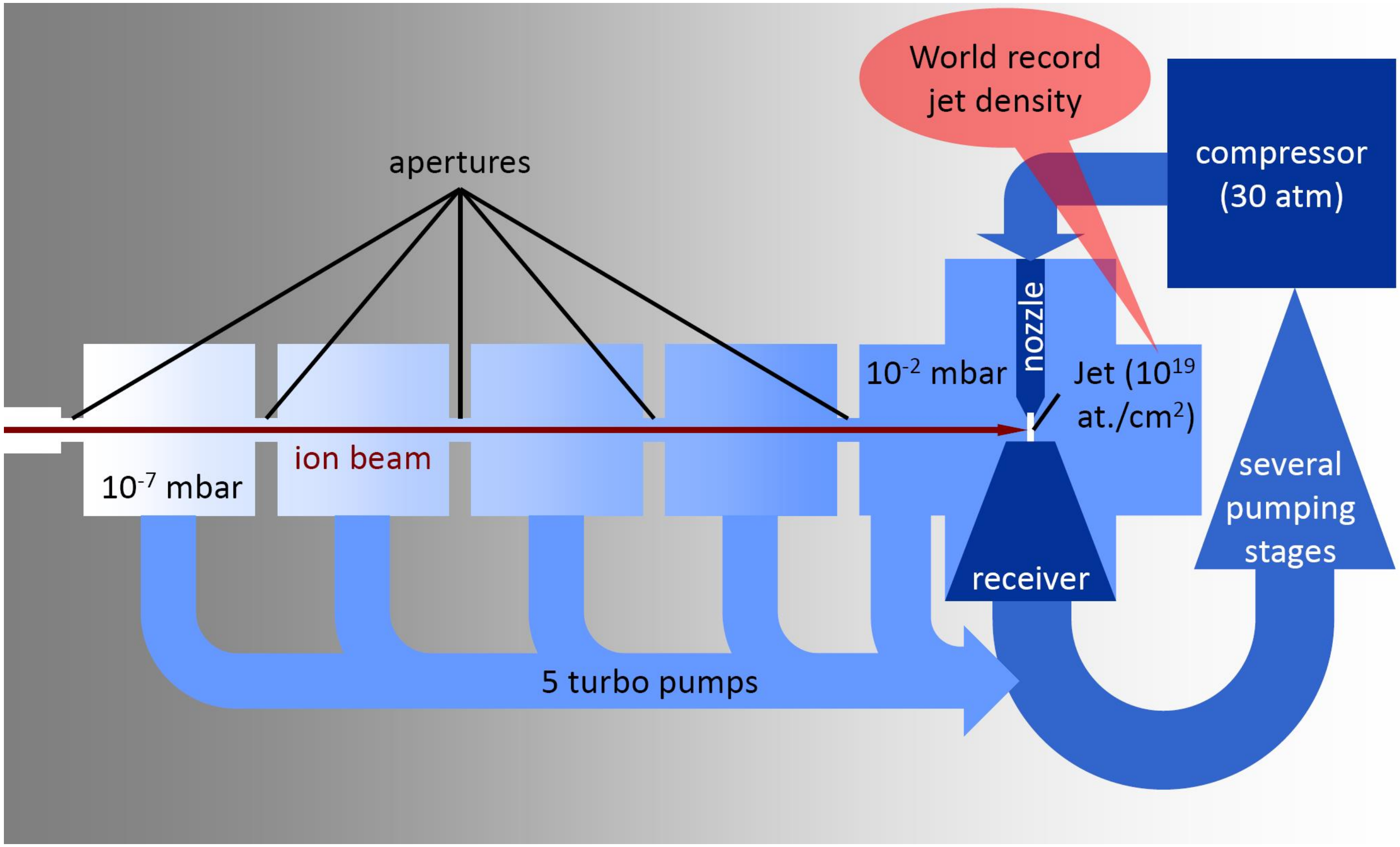


beam



JENSA: Jet Experiments in Nuclear Structure and Astrophysics

- JENSA gas jet target: Chemically pure, highly localized He target with high density and low energy straggling.

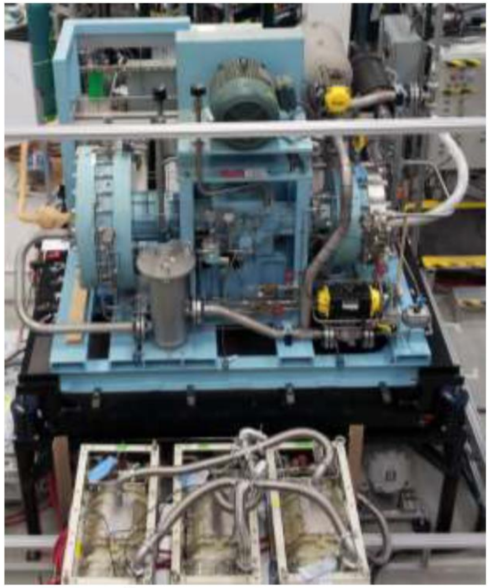


K. Schmidt, NPA8 2017

Conceptual Design of the gas jet

JENSA: Jet Experiments in Nuclear Structure and Astrophysics

K. Schmidt, NPA8 2017


Diaphragm compressor


Target chamber and pumps

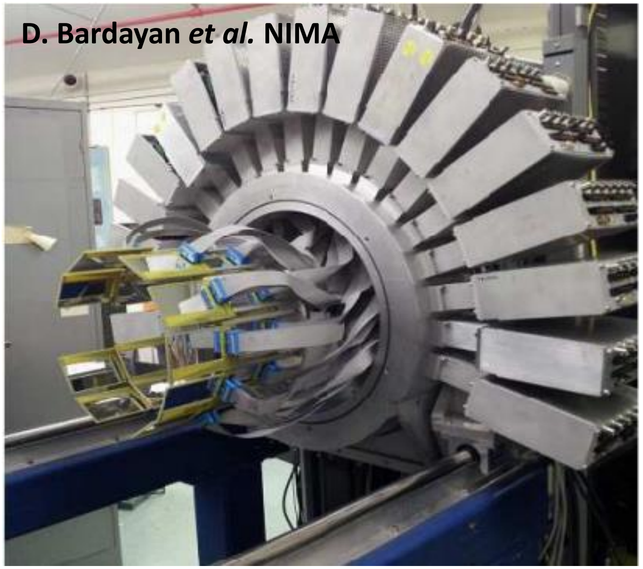

Nozzle, receiver and Si detectors

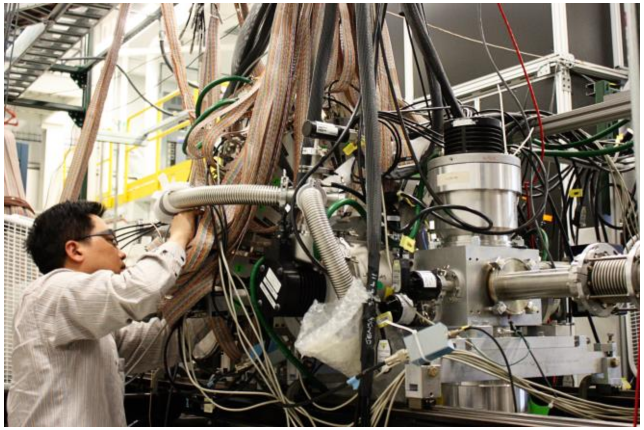
Photos of the gas jet system

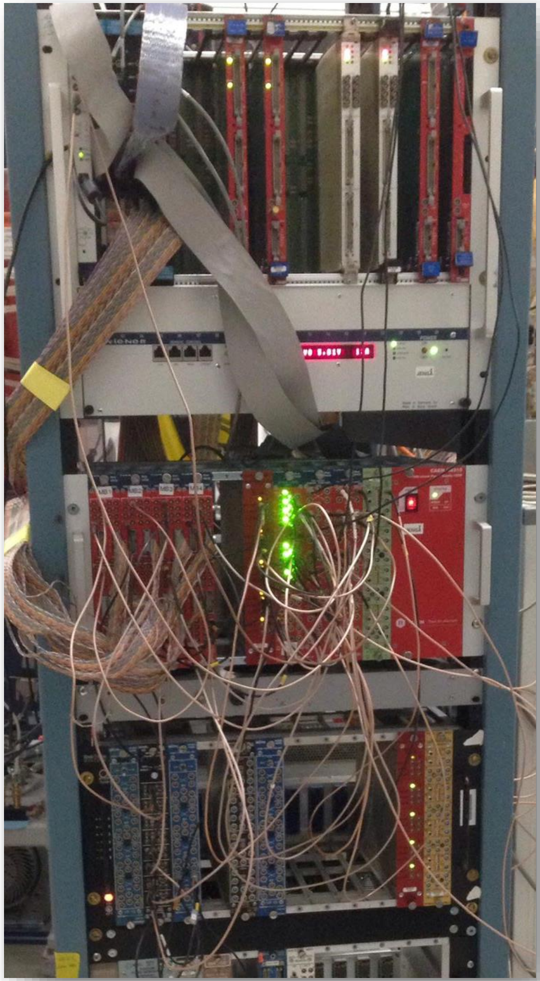
JENSA Setup for ^{34}Ar(*α,p*) Reaction

- Beam: ^{34}Ar Fragmentation → Gas Stopping →ReA3 (E_{com} = 5.822 and 6.13 MeV/u)
- Beam intensity: 3,000 ions/s
- Target: $6x10^{18}$ atom/cm^2

D. Bardayan *et al.* NIMA



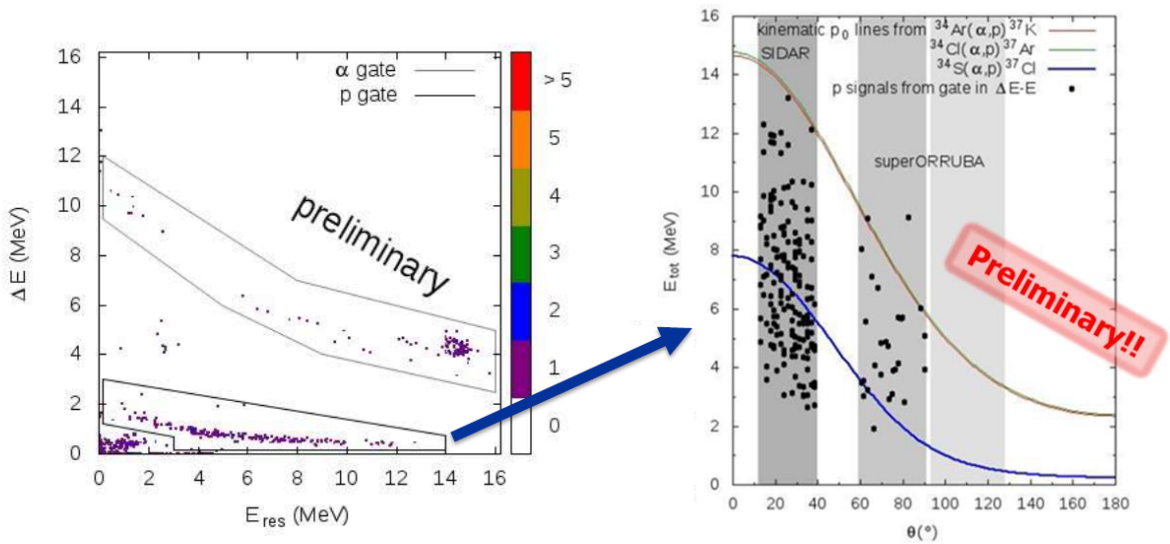




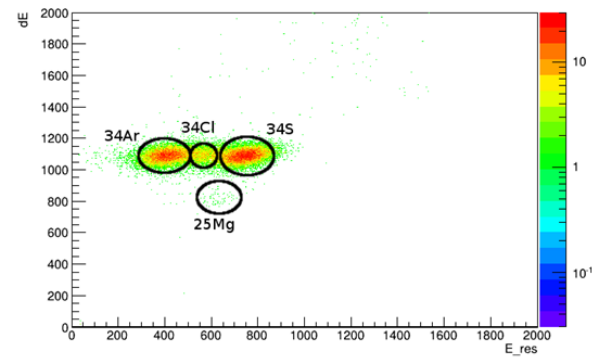
Photos of ^{34}Ar(*α*,*p*) experiment setup

JENSA Setup for $^{34}Ar(\alpha,p)$ Reaction

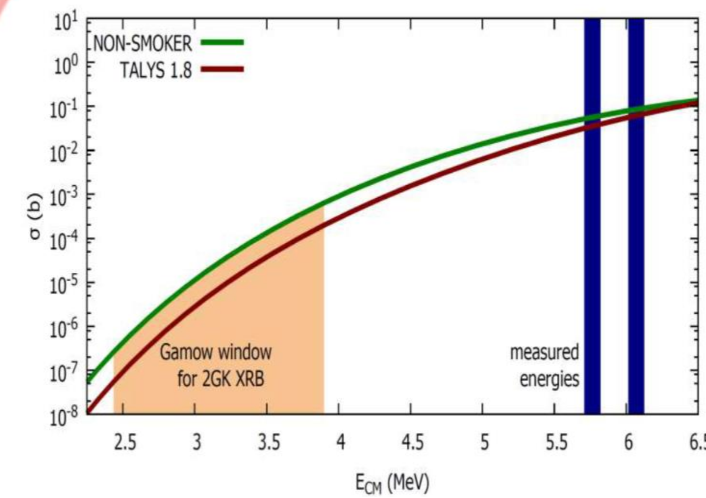
K. Schmidt, NPA8 2017



dE vs E of silicon detectors (left) and energy vs angle gate by the protons in the left plot (right)



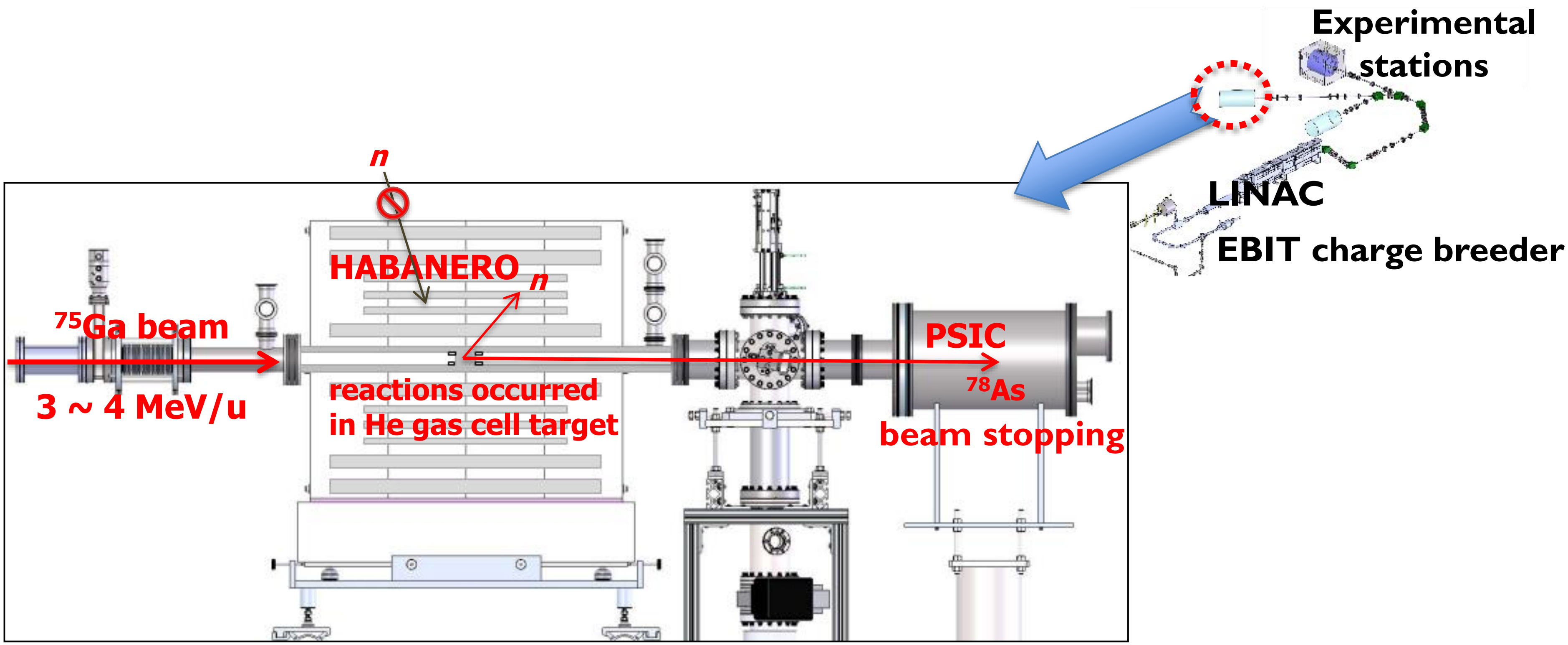
PID of Ionization Counter



Extrapolation of measurements

Experimental Setup for ^{75}Ga(α,x*n*) Reaction

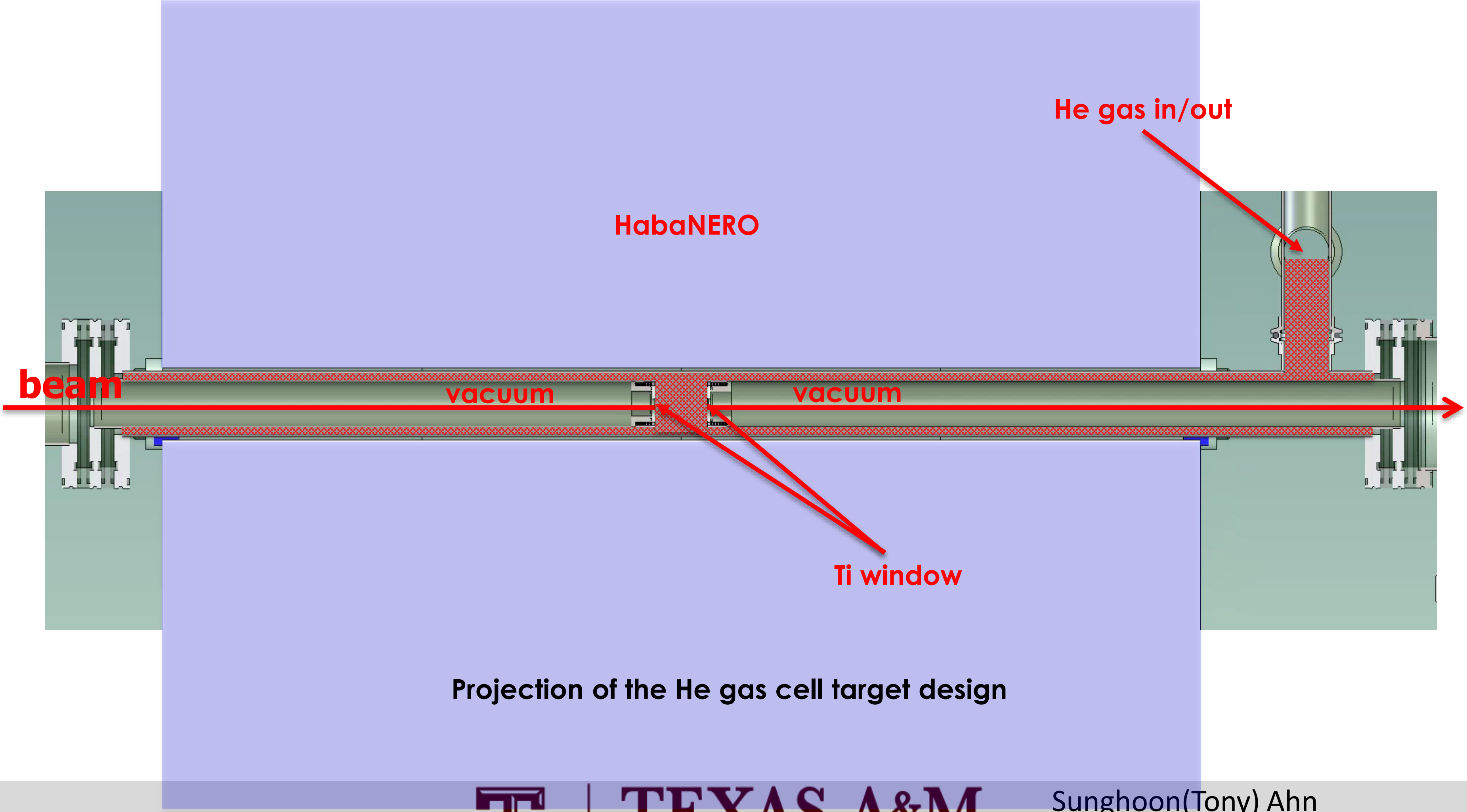
- ^{75}Ga reaccelerated beams by ReA3, NSCL, bombard ^{4}He gas target (T=355ug/cm^2) in the middle of the HABANERO.
- Position Sensitive Ionization Chamber (PSIC) provides beam current and PID.



Experimental Setup Design

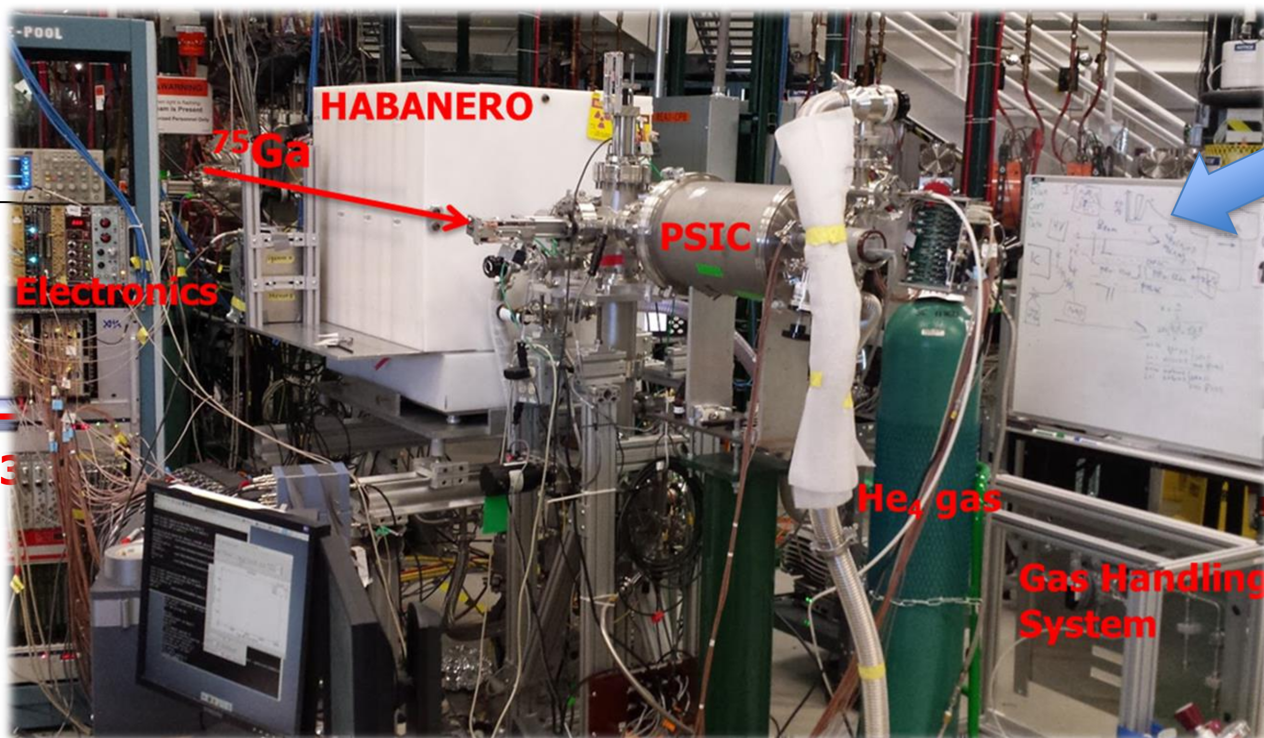
He gas cell target

- 2um thickness Ti window foil
- large gas volume

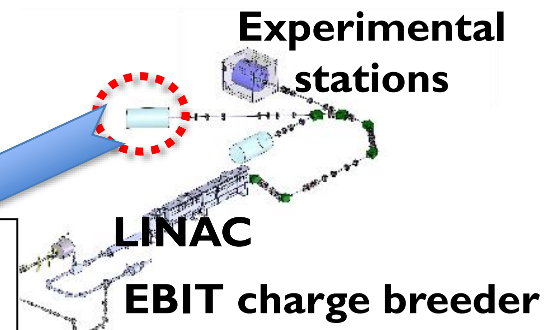


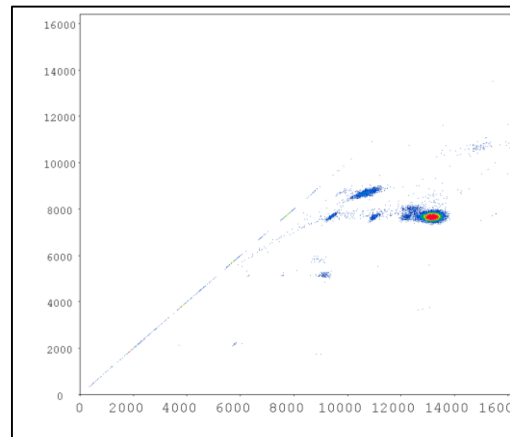
Experimental Setup for ^{75}Ga(*α,xn*) Reaction

- RIB ($^{75}Ga^{26+}$) beam of five energies (4.0, 3.79, 3.58, 3.14 and 2.91 MeV/u)
- Beam intensity: 6,000 ions/s
- Purity: ^{75}Ga = 95%



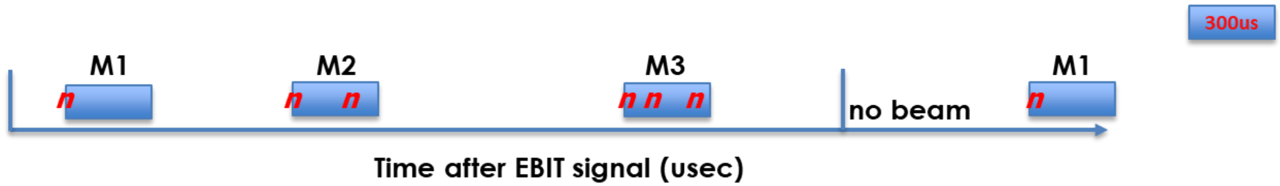
Experimental Setup Photo

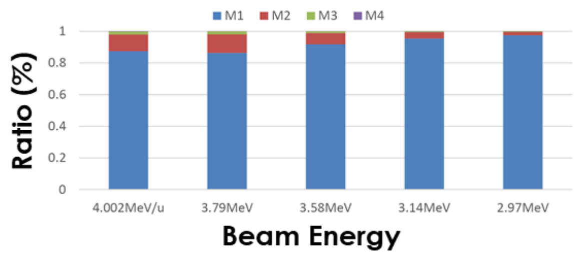




PID plot in the PSIC

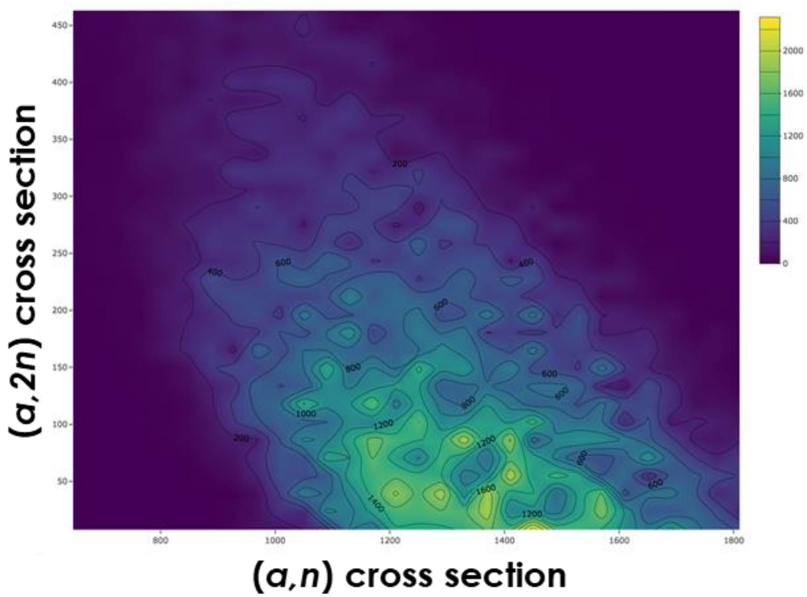
Data Analysis of $^{75}Ga(\alpha,xn)$ Reaction Study

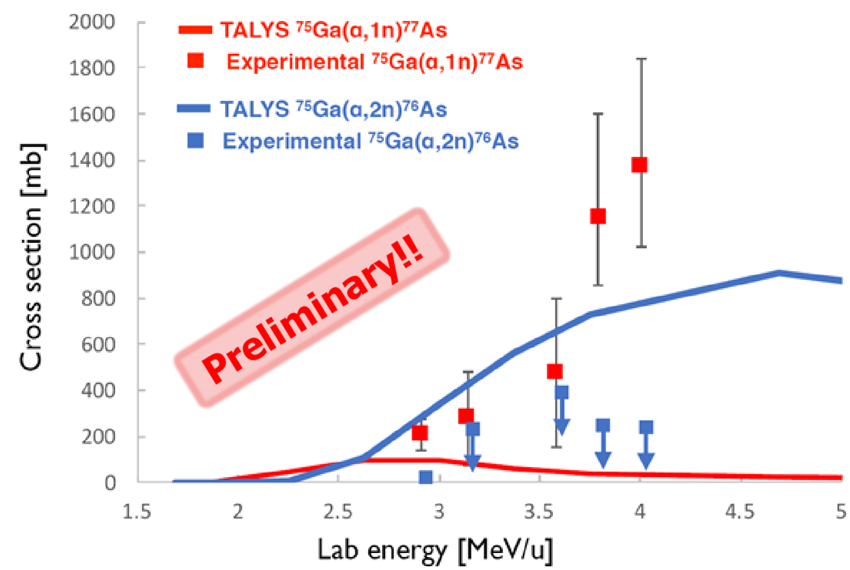




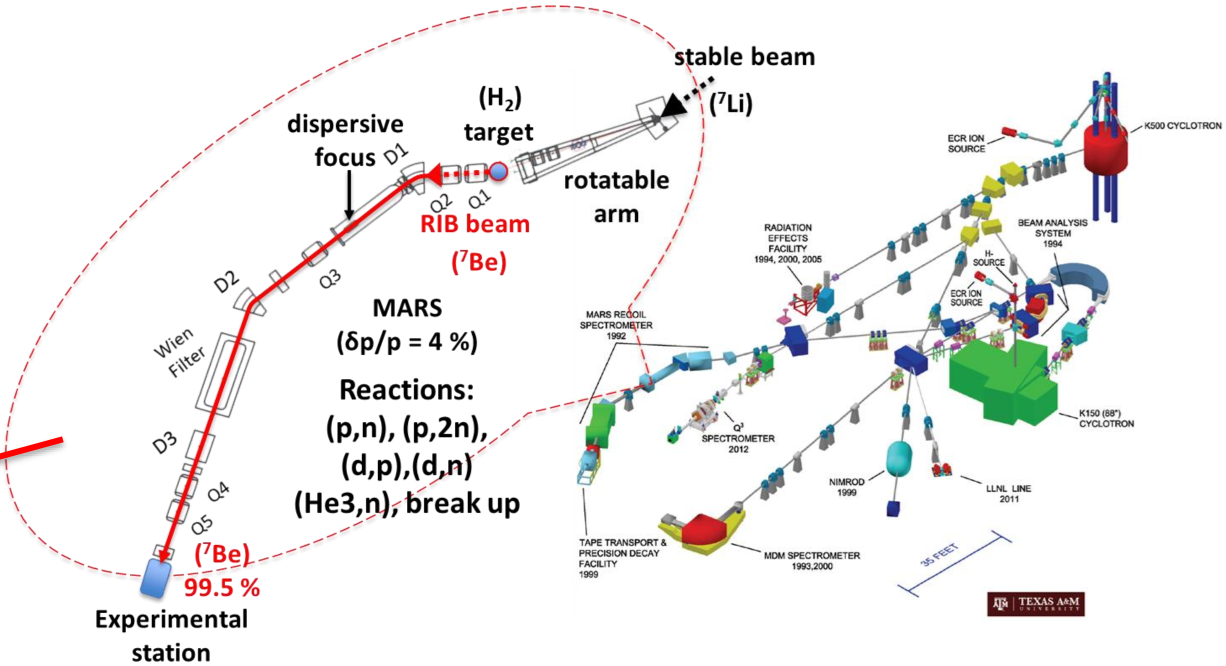
$$\begin{pmatrix} M_1 \\ M_2 \\ M_3 \\ M_4 \end{pmatrix} = \begin{pmatrix} P_{11}(\epsilon) & P_{12}(\epsilon) & P_{13}(\epsilon) & P_{14}(\epsilon) \\ P_{21}(\epsilon) & P_{22}(\epsilon) & P_{23}(\epsilon) & P_{24}(\epsilon) \\ P_{31}(\epsilon) & P_{32}(\epsilon) & P_{33}(\epsilon) & P_{34}(\epsilon) \\ P_{41}(\epsilon) & P_{42}(\epsilon) & P_{43}(\epsilon) & P_{44}(\epsilon) \end{pmatrix} \begin{pmatrix} \sigma_{(\alpha,1n)} \\ \sigma_{(\alpha,2n)} \\ \sigma_{BG_{beam}} \\ \sigma_{BG_{room}} \end{pmatrix}$$

Observables



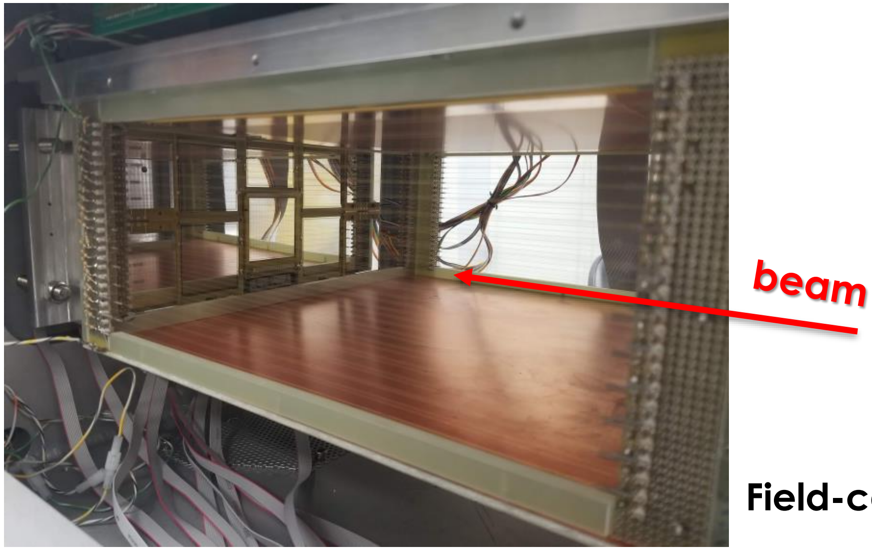


TexAT Active Target Experiments at Texas A&M

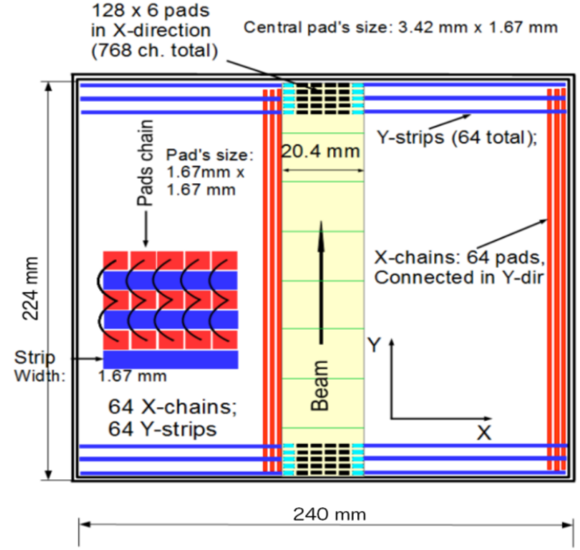


A picture for TexAT and GET setup
G. Rogechev, Gas Detections Systems Workshop (2018)

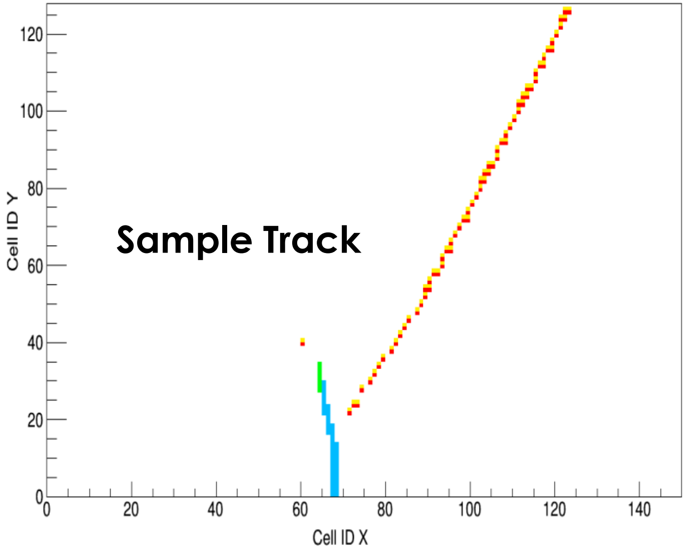
TexAT Active Target



Field-cage

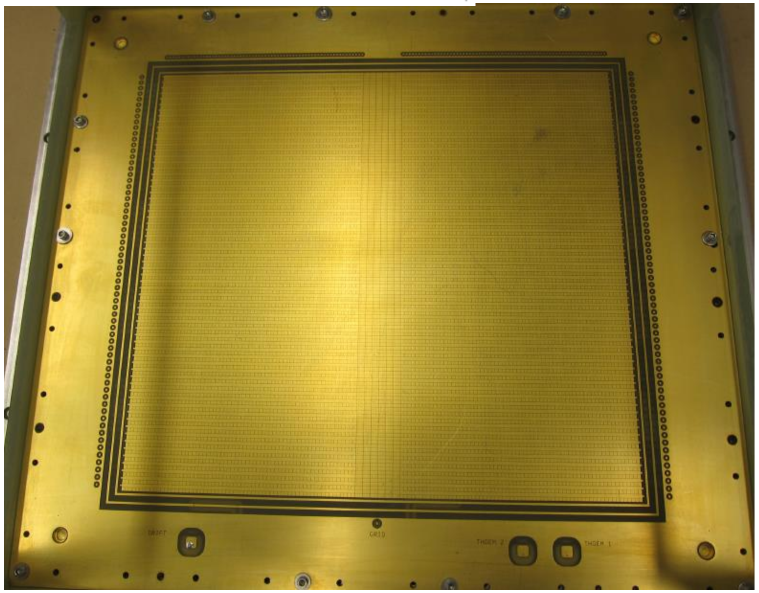


Readout pad design

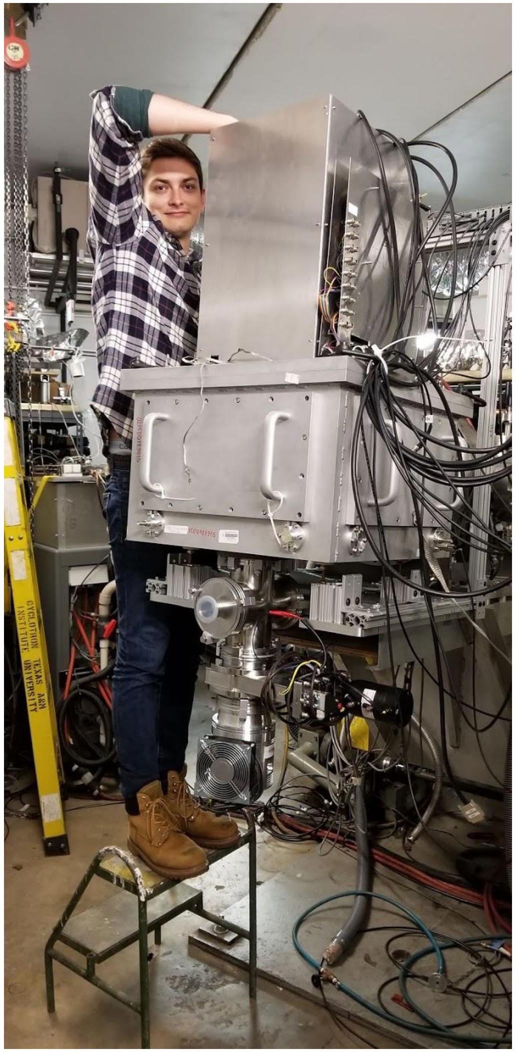


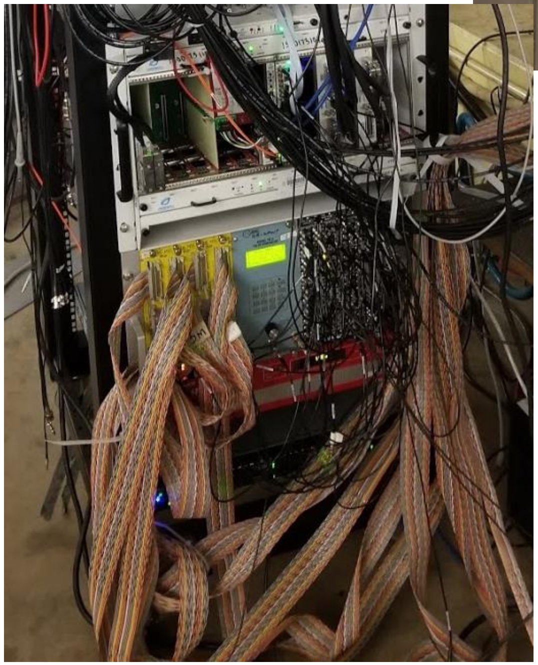
Sample Track

Readout Pad



TexAT Active Target

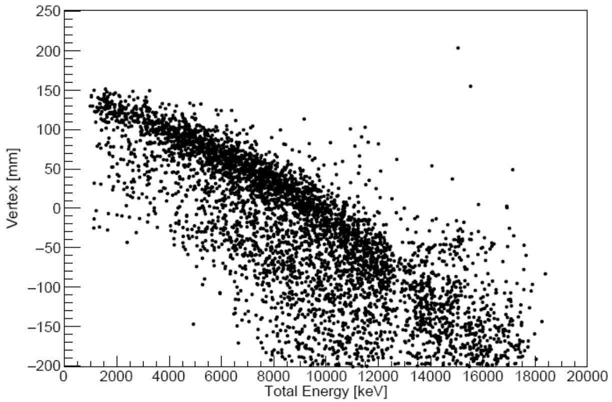


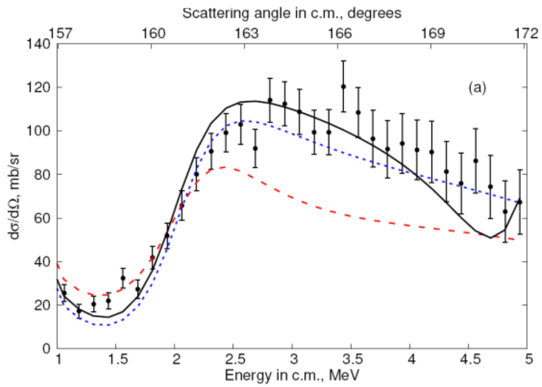


TexAT Active Target Experiments at Texas A&M

- Structure of ^{9}C -

- Reaction: ^{8}B + p with 7.5 MeV/u ^{8}B beam and 10^3 pps from MARS
- Target: Methane at 500 Torr

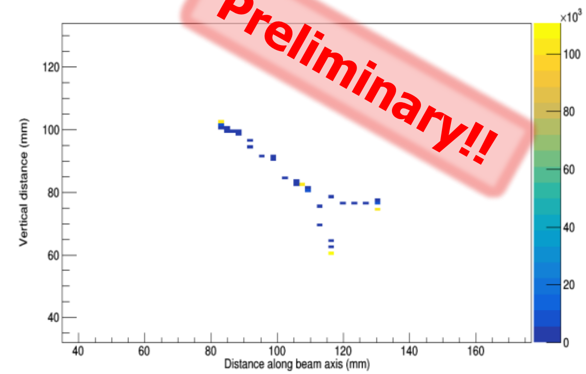


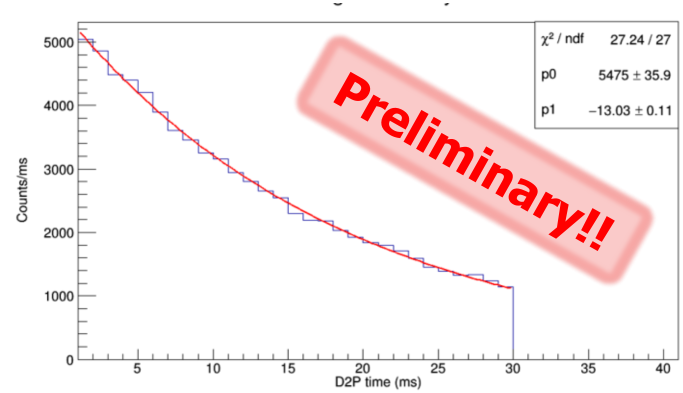


J. Hooker *et al.*, *PRC* submitted

- Looking for "Y"s -

- Reaction: ^{12}N → ^{12}C* → ^{8}Be + α → α+α+α
- TexAT for measuring decay α particles
- CO_2 gas stops ^{12}N beams in the chamber.



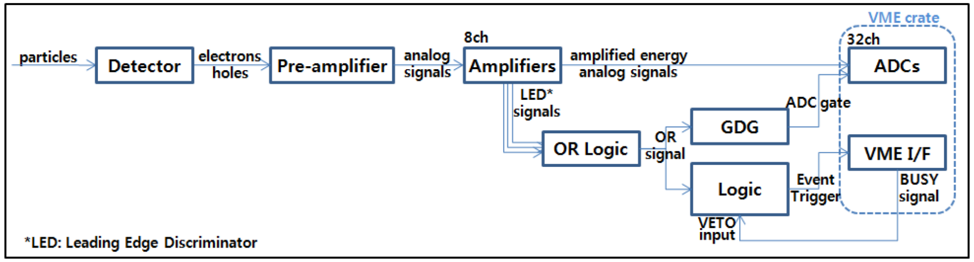


Summary

- Properties of nuclei we want to know: Nuclear Mass, Excitation energy and Spin and parity, Reaction Cross Sections, Half life of nuclear decay, Excitation function and level densities
  ➔ **Experimental measurements are necessary to reduce the uncertainties.**

- How to study the properties

- How to detect particles
  - Semiconductor (Silicon and Germanium)
  - Gaseous detectors
  - Scintillators
  - Neutron Detectors
  - Micro Channel Plate (Beam Tracker)



- Signal Processing: Conventional, ASICs and Digital (Advantages and Disadvantages!)
- Data Acquisition System
- Some examples of experiments focused on techniques

Goals of This Lecture

This is the end of my lecture. Can you answer below questions?

- How detectors actually work.
- Which parameters are actually measured, and which are inferred or calculated?
- How to process signals from detectors.
- Advantage of multi-channel signal processing.

→ If so, You are a Detectors and Electronics Expert!!

The End.

Good luck with your journey of the Nuclear Physics Studies!