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Nuclear Diagnostics for ICF and Pulsed Power Systems

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Outline

- Introduction
- Nuclear reaction basics
- Activation diagnostics
- Scintillation detectors
- Advanced systems
- Conclusions

What constitutes a “nuclear diagnostic”?

A nuclear diagnostic is one that uses nuclear reactions in some manner to measure various properties of plasmas or ion beams

The reaction initiating particle can be an ion, neutron, or gamma ray

Nuclear interactions

- Nuclear interactions can
  - Can create prompt radiation
  - Can produce a radioactive product
  - Can simply scatter a target nuclide
- All of these products can be measured and yield information about the reacting particles and, hence, information about the plasmas or beams of which these particles are a part

Uses of nuclear diagnostics

- Can be used to measure many properties of ICF plasmas (yield, temperature, density, isotropy, bang time, burn history, geometry of fusion burn)
- Can be used to measure many properties of ion beams and certain energetic plasmas (the ion species present, the ion energy - which is often related to voltage, energy density)

Fusion reactions

$D + D \rightarrow {}^{3}He$ (0.82 MeV) + n (2.45 MeV)

$D + D \rightarrow T$ (1.01 MeV) + p (3.04 MeV)

$D + T \rightarrow {}^{4}He$ (3.5 MeV) + n (14.1MeV)

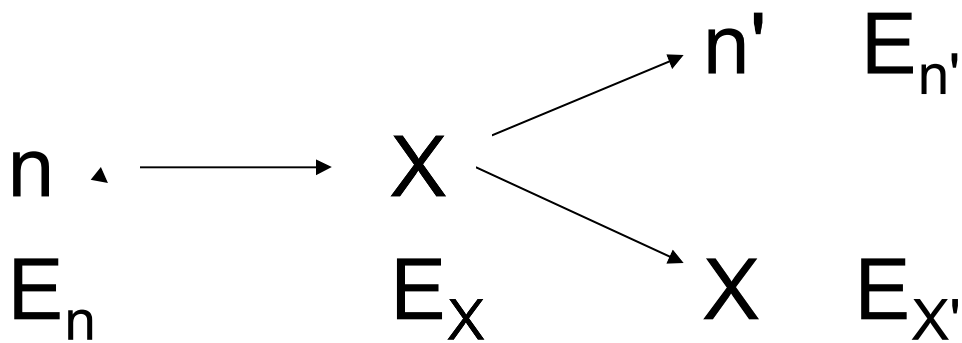
$D + {}^{3}He \rightarrow {}^{4}He$ (3.6 MeV) + p (14.7MeV)

Types of nuclear reactions

- Elastic scattering
  - $n + X \rightarrow n' + X'$
- Inelastic scattering
  - $n + X \rightarrow n' + X^*$
- Transmutation reactions
  - $A + B \rightarrow C + D$
- Neutron capture reactions
  - $n + {}^{A}X \rightarrow {}^{(A+1)}X + \gamma$

Elastic scattering

Kinetic energy conserved



$$E_n + E_X = E_{n'} + E_{X'}$$

Neutron elastic scattering off protons

Most useful elastic scattering reactions are with low Z nuclides – protons, deuterium, helium-3 and 4, and carbon – with protons being possibly the most useful because the cross section is large and the average fraction of neutron energy transferred is the highest of all nuclides

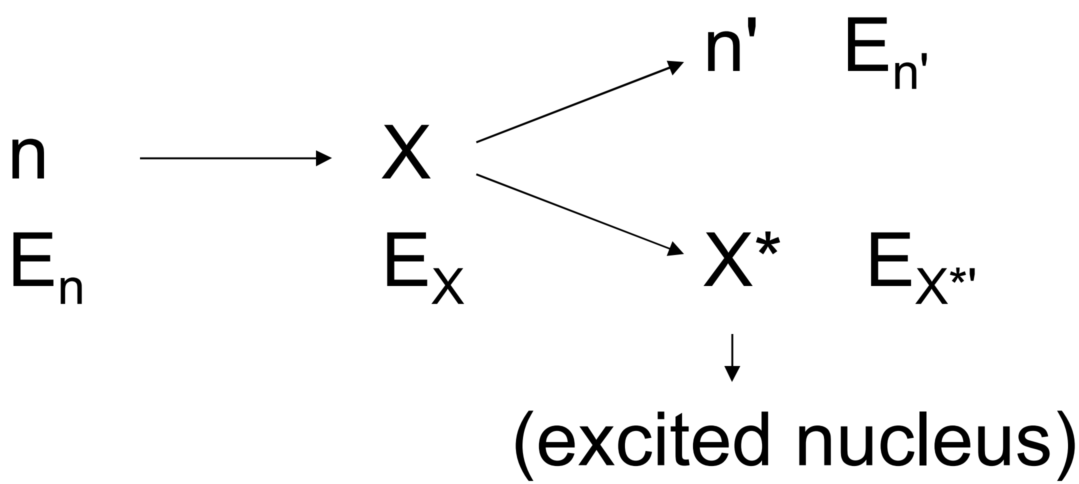
Elastic scattering continued

Types of neutron detectors that use elastic scattering include:

- Neutron/proton recoil spectrometers
- Organic scintillation detectors
- CR-39 track etch detectors
- Gas proportional counters

Inelastic scattering

Kinetic energy is **not** conserved



$E_n + E_X > E_{n'} + E_{X*'}$

X* usually emits a prompt gamma ray

Inelastic reactions continued

Because one must excite a nucleus to a level above ground state in an inelastic reaction, the energy of the bombarding particle must always exceed a threshold value for the reaction to be possible

$$\text{In-115} + n \rightarrow \text{In-115m}^* + n'$$

$$E_{th} = 0.336 \text{ MeV}$$

Transmutation reactions

In nuclear reactions reacting nuclides can be transmuted into different product nuclides

$$A + B \rightarrow C + D$$
$$\rightarrow E + F$$
$$\rightarrow \ldots$$

The probability of a given branch occurring is dependant on the types of reactants and their energies

Conservation rules

- Conservation of mass/energy

- Conservation of momentum

- Conservation of charge

- Conservation of nucleons (total number of neutrons plus protons)

Nuclear reaction examples

Al-27 + n → Al-28 + γ (no threshold)

(13p + 14n) +1n = (13p + 15n) = 28 nucleons

Al-27 + n → Mg-27 + p (E_{th} = 1.9 MeV)

(13p + 14 n) + 1n = (12p + 15n) + 1p = 28 nucleons

Al-27 + n → Na-24 + He-4 (E_{th} = 3.65 MeV)

(13p + 14n) + 1n = (11p + 13n) + (2p +2n) = 28 nucleons

Al-27 + n → Al-26 + 2 n's (E_{th} = 13.5 MeV)

(13p + 14n) + 1 n = (13p + 13n) + 2n = 28 nucleons

Plus elastic and inelastic scattering interactions

Probability of interaction

When multiple reactions are possible, one cannot predict which reaction will occur on an event by event basis but for a large number of interactions one can measure the probability that each reaction will occur and, thus, predict the fraction of the time each possible reaction will occur

Cross sections

This probability of interaction is given in terms of a “cross section” – units are “area” typically square centimeters or more commonly barns = 10^{-24} cm^2

The cross section is a complex function of the bombarding particle type and energy and the specific target nuclide

Aluminum cross sections

Ions can also initiate reactions

p + Li-7 $\rightarrow$ Be-7 + n

d + C-12 $\rightarrow$ N-13 + n

p + C-12 $\rightarrow$ N-13 + γ

Li-6 + F-19 $\rightarrow$ Na-24 + p

p + Fe-56 $\rightarrow$ Co-56 + n

These ion reactions may or may not have thresholds but they will always have a Coulombic Barrier to overcome

Gamma rays can also initiate reactions

In-115 + $\gamma \rightarrow$ In-115* + γ'

Cu-63 + $\gamma \rightarrow$ Cu-62 + n

Generally, one does not think of gamma rays interacting with nuclei or inducing radioactivity but if they are of high enough energy they can do both

Classes of nuclear diagnostics

- Have time-integrating diagnostics
  - Activation
  - CR-39
  - Magnetic Spectrometers (film/CR-39)
- Have time dependent diagnostics
  - Scintillation detectors
  - Cerenkov detectors
  - Magnetic Spectrometers (pin diodes)

Nuclear activation based diagnostics

- Activation diagnostics clearly suffer from certain limitations:
  - Time integrated
  - Low sensitivity
  - Ablation of sample
  - Timely access to sample

  So why use these types of diagnostics?

Advantages of activation diagnostics

- They can be unaffected by many background environments (emp, x-rays, etc.)
- They can provide less ambiguous results
- May allow a measurement to be made when other approaches fail
- A variety of parameters can be measured – often with a single measurement

Activation diagnostics

- Can further divide activation diagnostic into two subclasses:
  - Direct activation in which one measures activity directly induced in a sample by the reacting particles
  - Indirect activation in which the reacting particles interact with a primary target producing prompt radiation which in turn induces radioactivity in a secondary target which is then measured

Measuring ion beams on PBFA II

- PBFA II was a large pulse power accelerator at Sandia National Laboratories which was being developed for ion-beam induced ICF (this machine was later converted to the Z machine)
- Intent was to produce a lithium beam of energetic ions that could be focused onto a fusion target located at the center of PBFA II and produce ICF

Lithium beam parameters

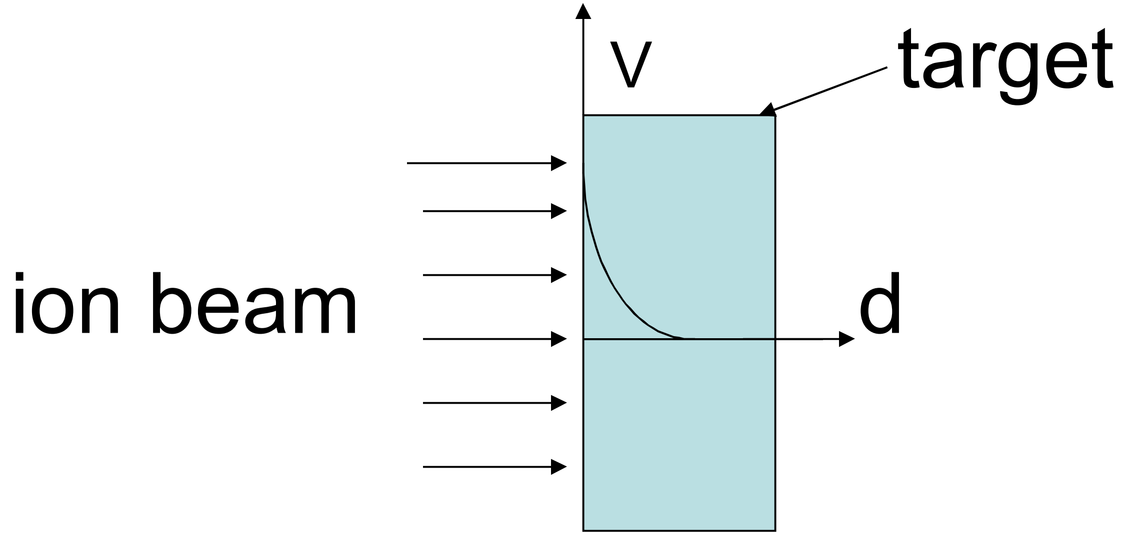
- For optimum chances of initiating fusion the following was desired:
  - The voltage needed to be about ~10 MV
  - The charge on the lithium needed to be +3 to give an ion energy of ~ 30 MeV
  - The beam needed to be “pure” lithium
  - The beam needed to be able to be focused to target size (< ~ 1 cm)
  - The current needed to be ~ 1 MA in a pulse a few 10s of nanoseconds in width

Some nuclear diagnostics employed on PBFA II

- Diagnostics employed included
  - Direct activation
  - Indirect activation
  - Magnetic spectrometer
- These diagnostics were used to measure the ion energy (voltage) as a function of time, ion beam purity, and the ability to focus the beam

Thick target yields

The moment an ion enters a material target the ion starts to slow down via Coulombic interactions with electrons



Thick target yields

- Because cross section for a given reaction is a function of ion energy, the probability of a reaction occurring changes as the ion penetrates the sample
- For an energetic ion beam that interacts with the target to form radioactive nuclides, the total activity produced by the ions as they slow down to the threshold reaction energy is called the THICK TARGET YIELD

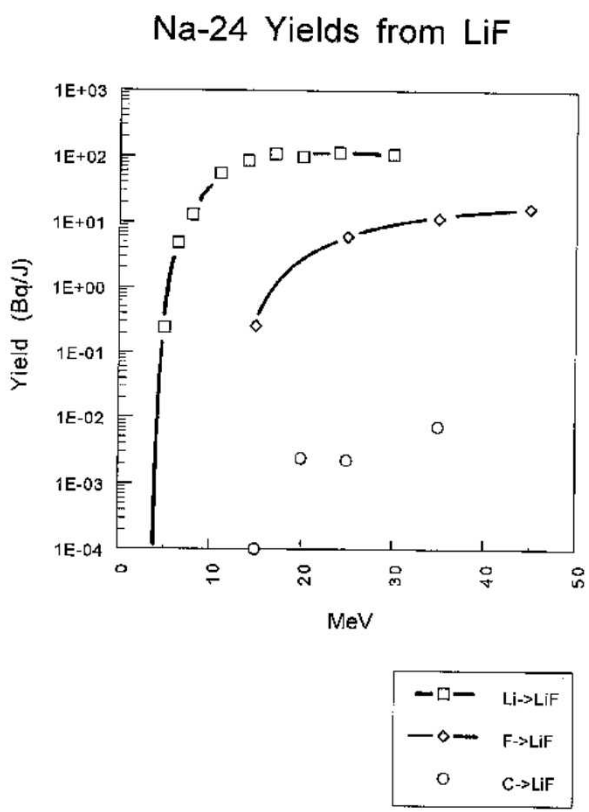
Thick target yields

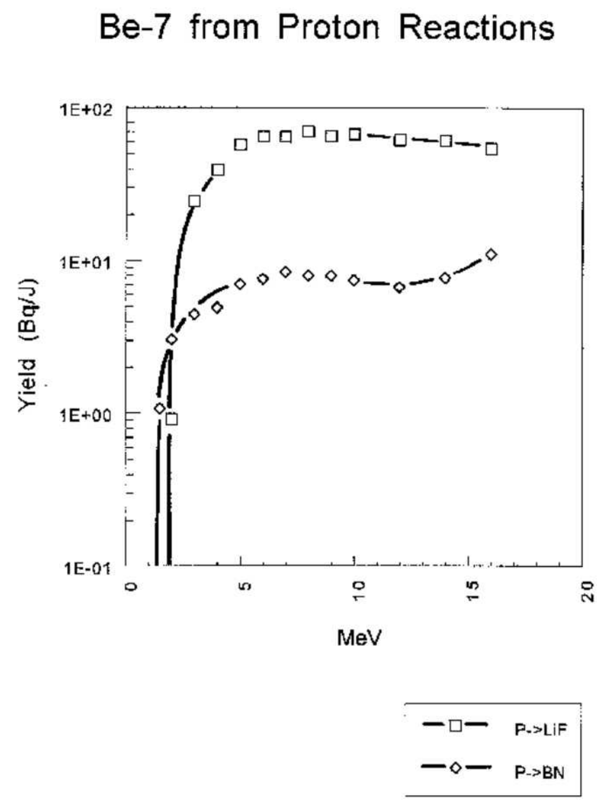
- As the energy of the ions increases, the thick target yield will always increase (or remain “flat” if the cross section at higher energies goes to “zero”) – it never decreases with energy
- Knowledge of the thick target yield can provide information on ion species present, ion energy (voltage), beam energy density

PBFA II activation diagnostics

- On PBFA II wanted to produce “pure” Li beams, so we wanted a reaction that is sensitive only to Li, but wanted to measure any contaminating ions – principally protons – that might be present as well
- Ideally would like to do this with a single measurement to eliminate any spatial variations that might exist

Chose reactions Li→F and P→Li with a LiF target (thick target yields)

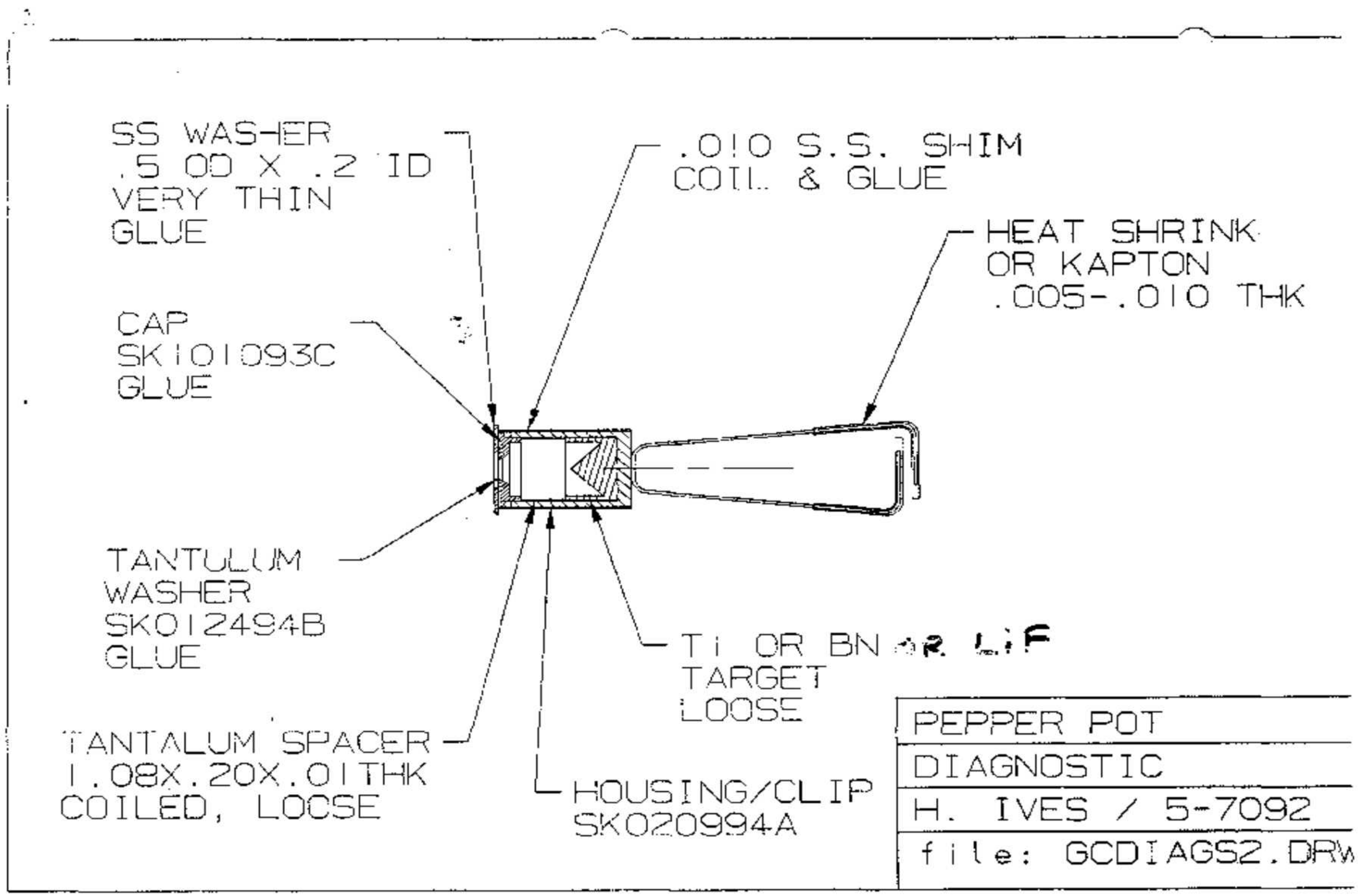




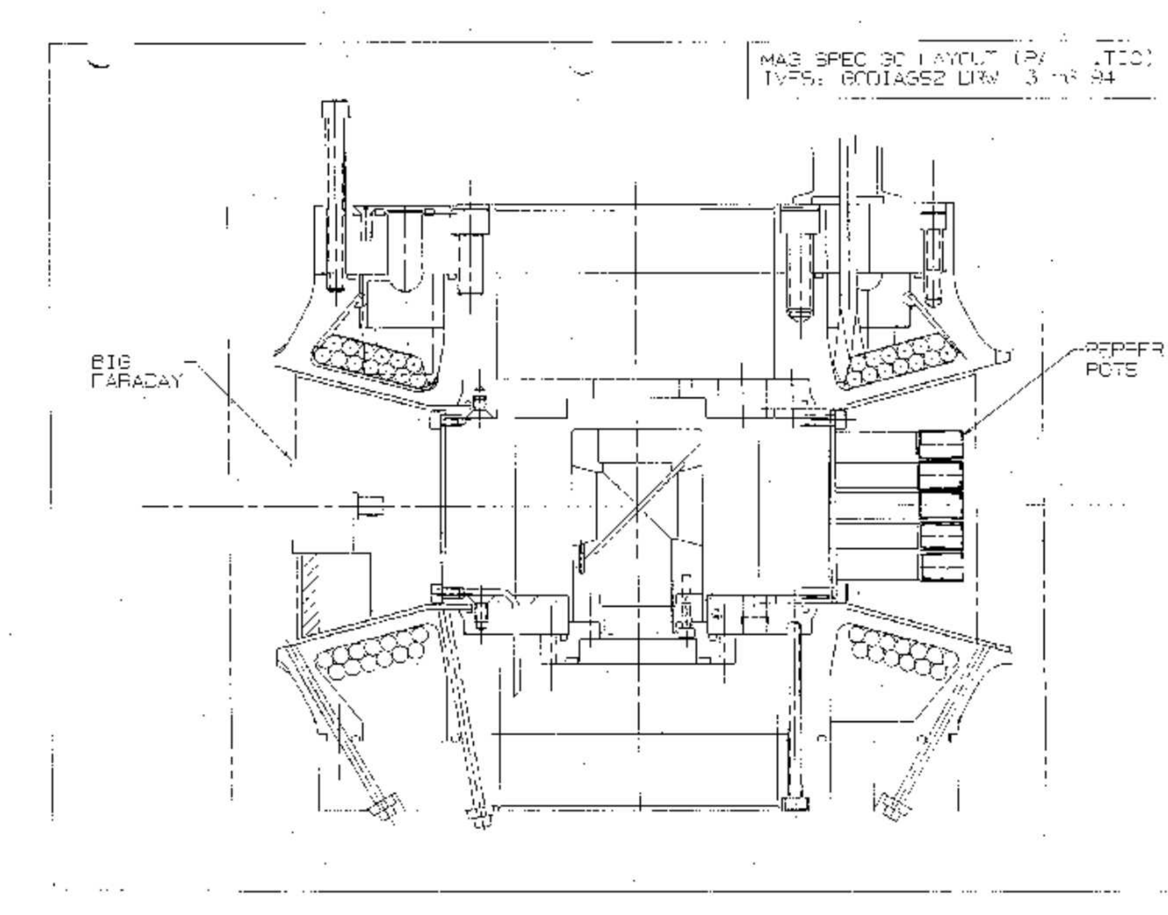
Issues

- On PBFA II energy densities were so great that we would seriously ablate our samples – if we do not recover all the sample (activity) we lose significant information and in effect get the “wrong answer”
- To address this problem in this case we used “peppershaker” geometry in which we hoped to trap all ablation products

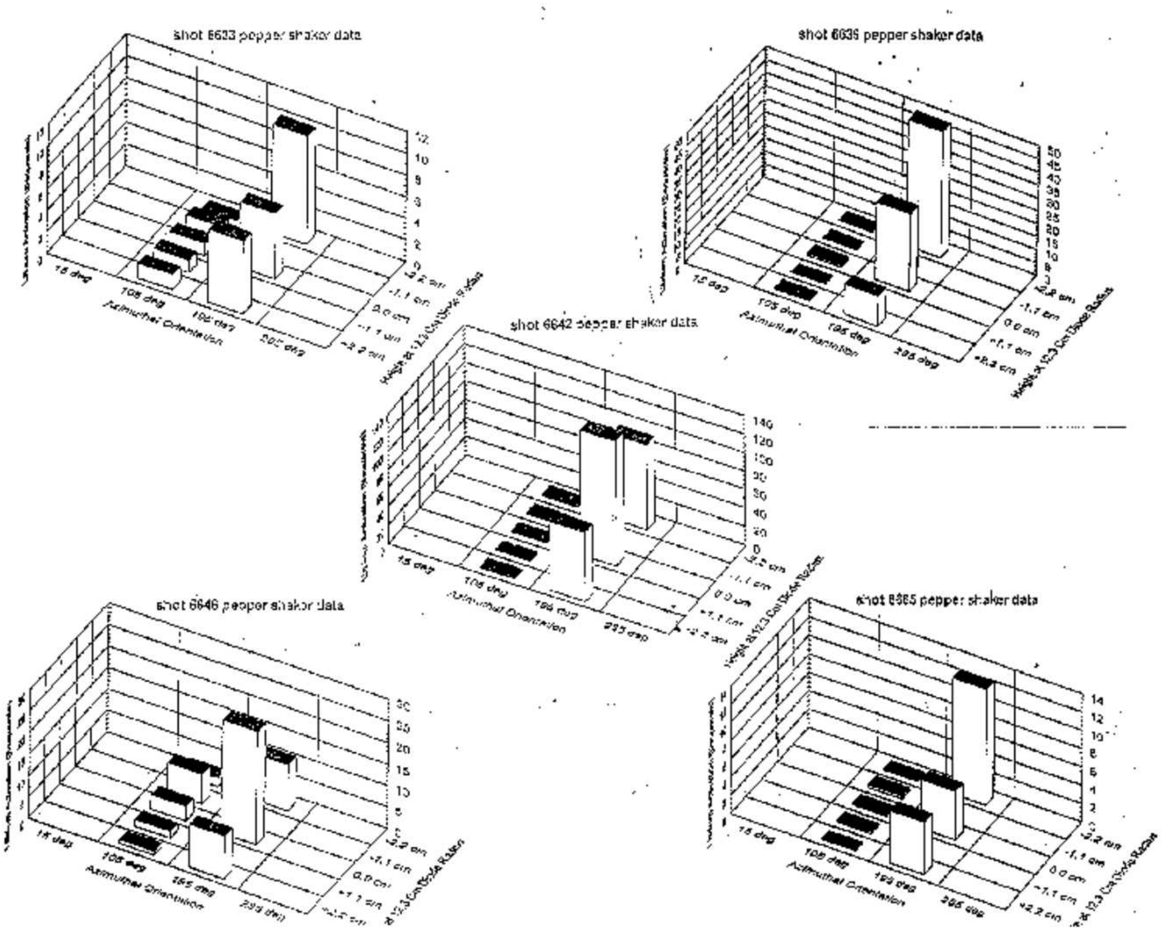
Peppershaker geometry



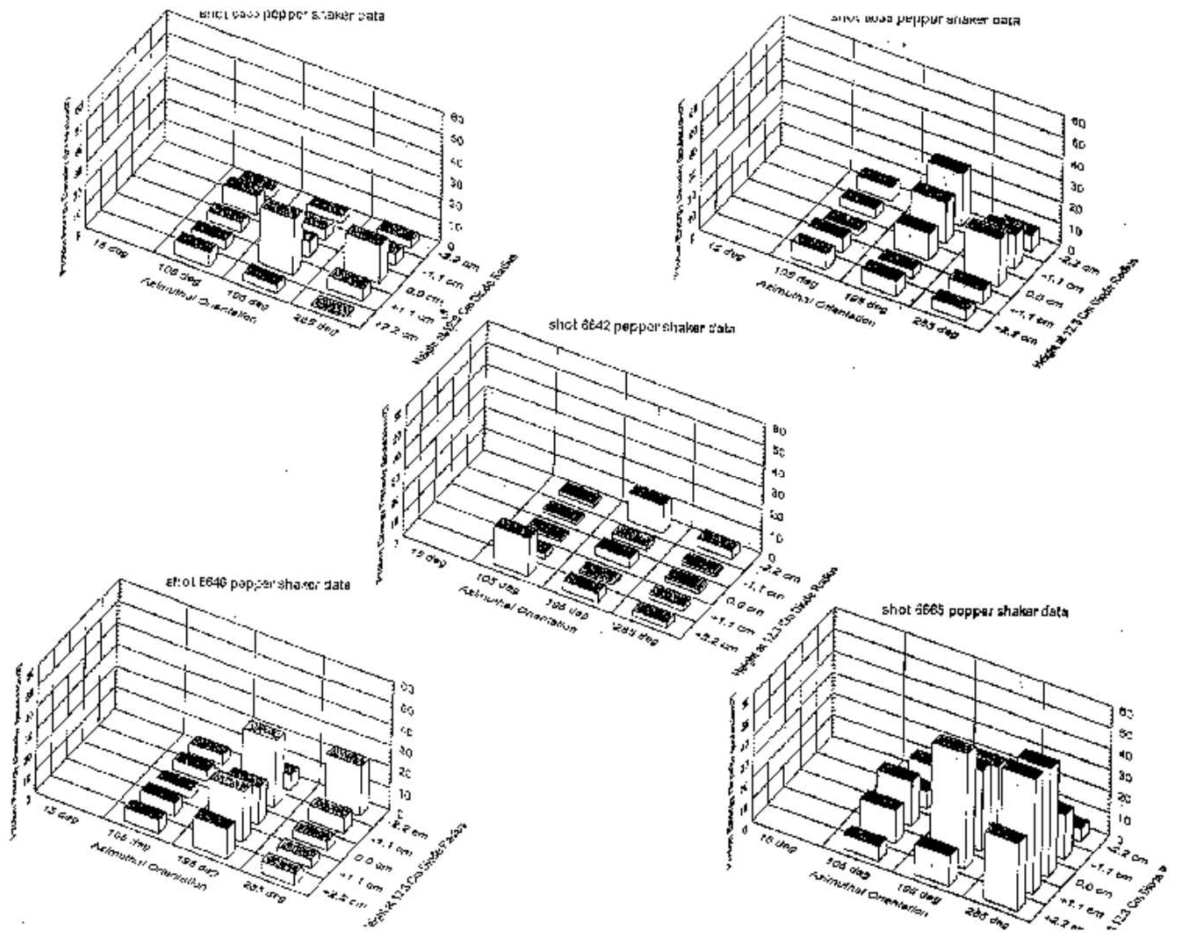
Fielded arrays of pepper pots to get indication of spatial variations



Li induced Na-24 activity



Proton induced Be-7 activity



General conclusions

- Li beam was present but not “pure”
- Li beam was not uniform
- Magnetic spectrometer seemed to indicate that there were no protons present but eventually it was recognized that it was insensitive to protons as operated
- B-dot probes had a more “global” response and seemed to indicate much more uniform beam than did the activation diagnostic

Indirect activation diagnostic

- A second approach to the ablation problem was to use indirect activation
- In this approach a sacrificial target intercepts the beam, driving a nuclear reaction that yields a unique, prompt radiation. The prompt radiation in turn activates a second target located away from the ion beam and which therefore survives
- The ErD target, although destroyed by the beam, survives for the duration of the beam

Indirect activation diagnostic

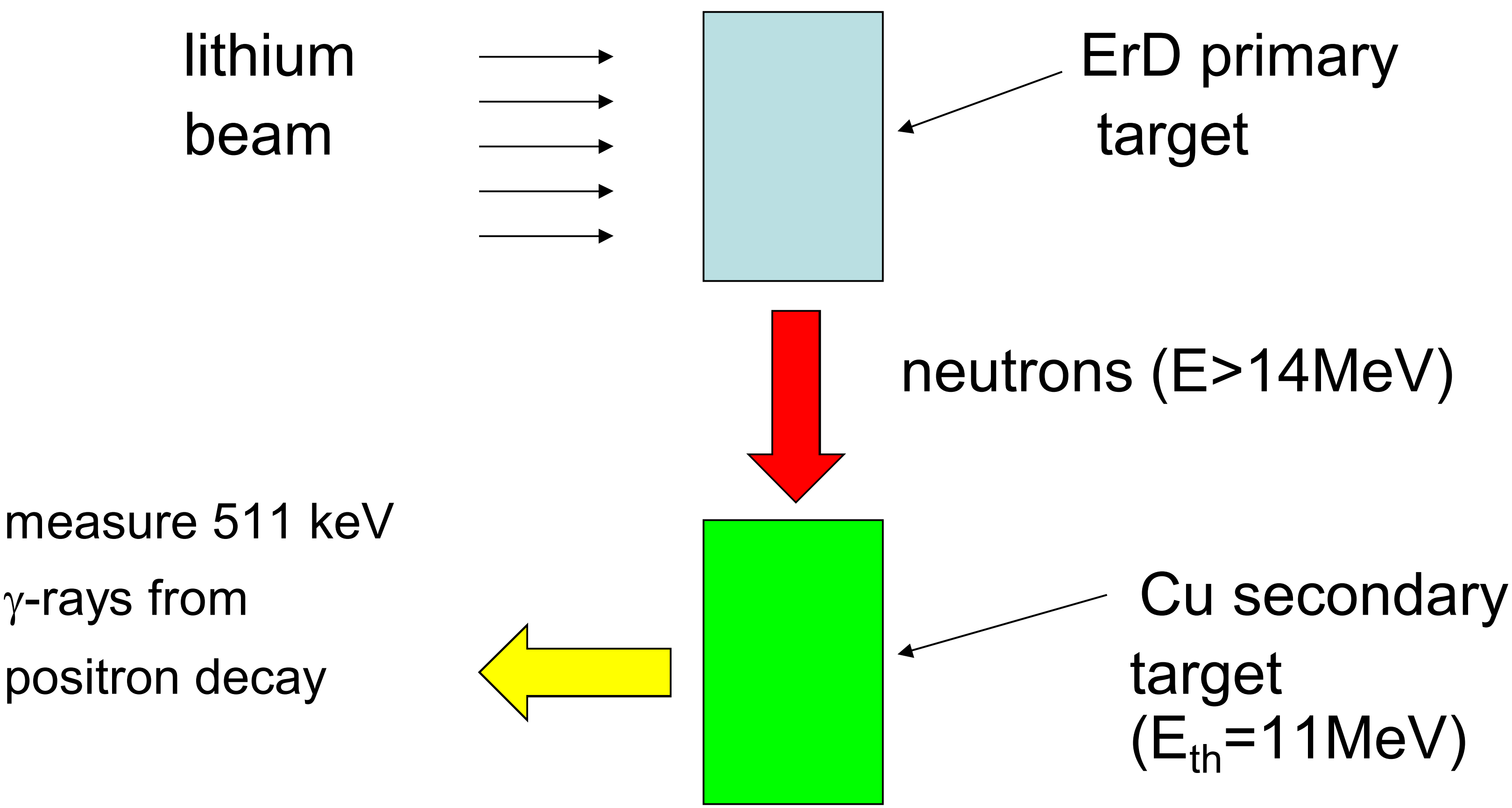
One example used on PBFA II

Li-7 + d → n + Be-8 $E_n > 14$ MeV

→ + Cu-63 → Cu-62(β+) + 2n's

Li ions irradiated ErD target producing n's which activate Cu which is counted

Indirect activation



Competing copper reactions

Have primary copper reaction:

Cu-63 + n $\rightarrow$ Cu-62(β+) + 2n's

But also have complicating reactions:

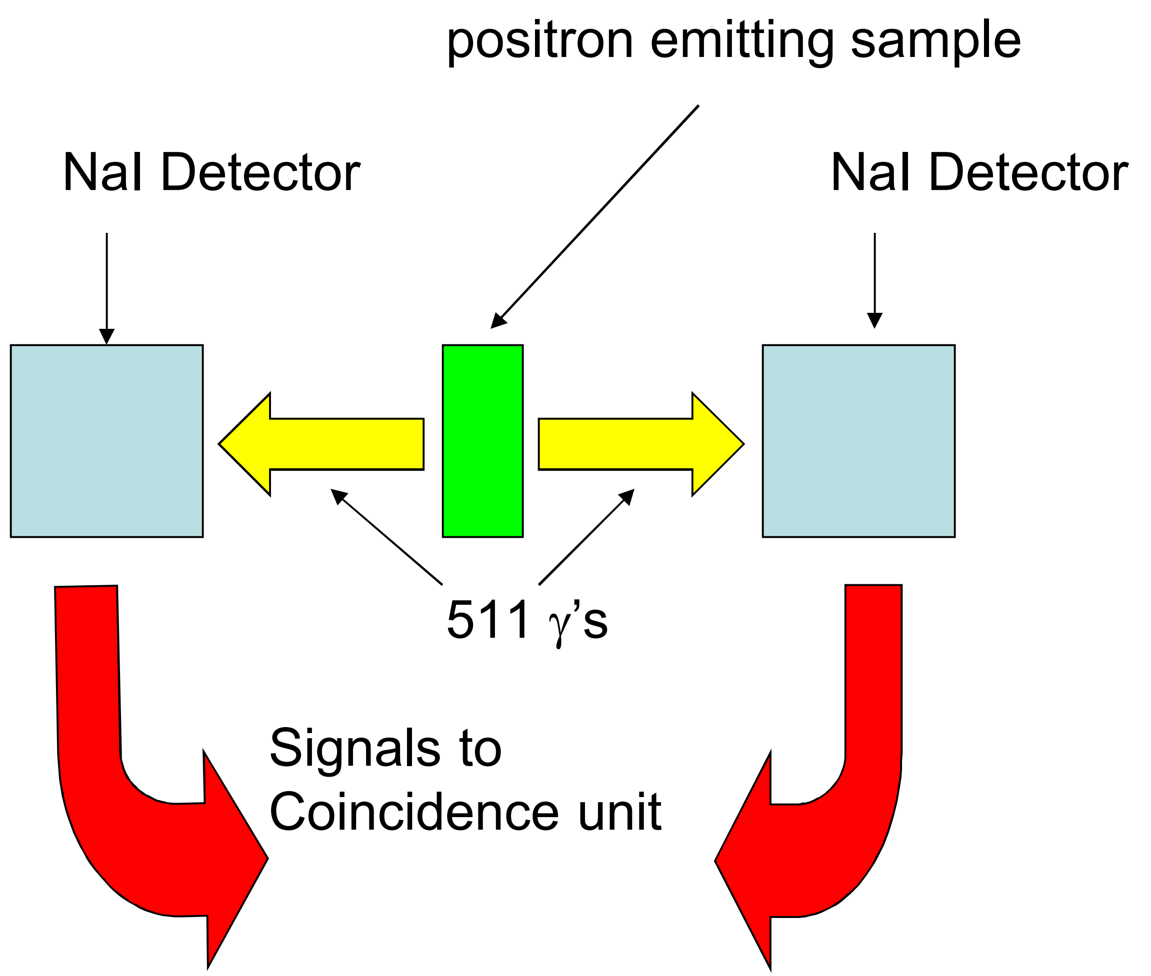
Cu-65 + n $\rightarrow$ Cu-64(β+) + 2n's

Cu-63 + n $\rightarrow$ Cu-64(β+) + γ

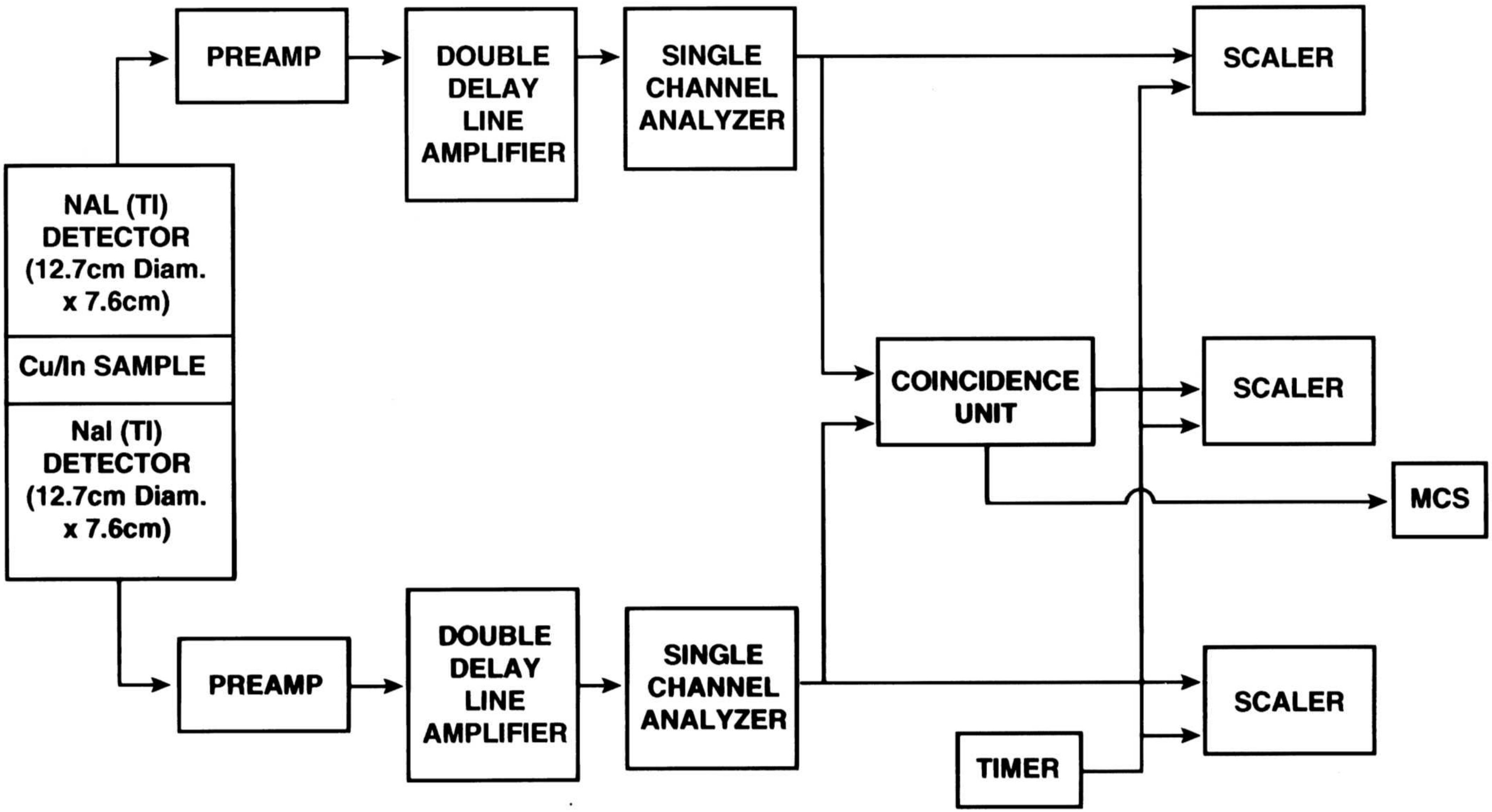
Measuring copper activity

- Both Cu-62 and Cu-64 are positron emitting radionuclides so they can be counted very accurately with a γ-γ coincidence system
- Activities of Cu-62 and Cu-64 must be separated based on their different half lives (Cu-62 has a 9.7 minute half life while Cu-64 has a 12.7 hours half life)

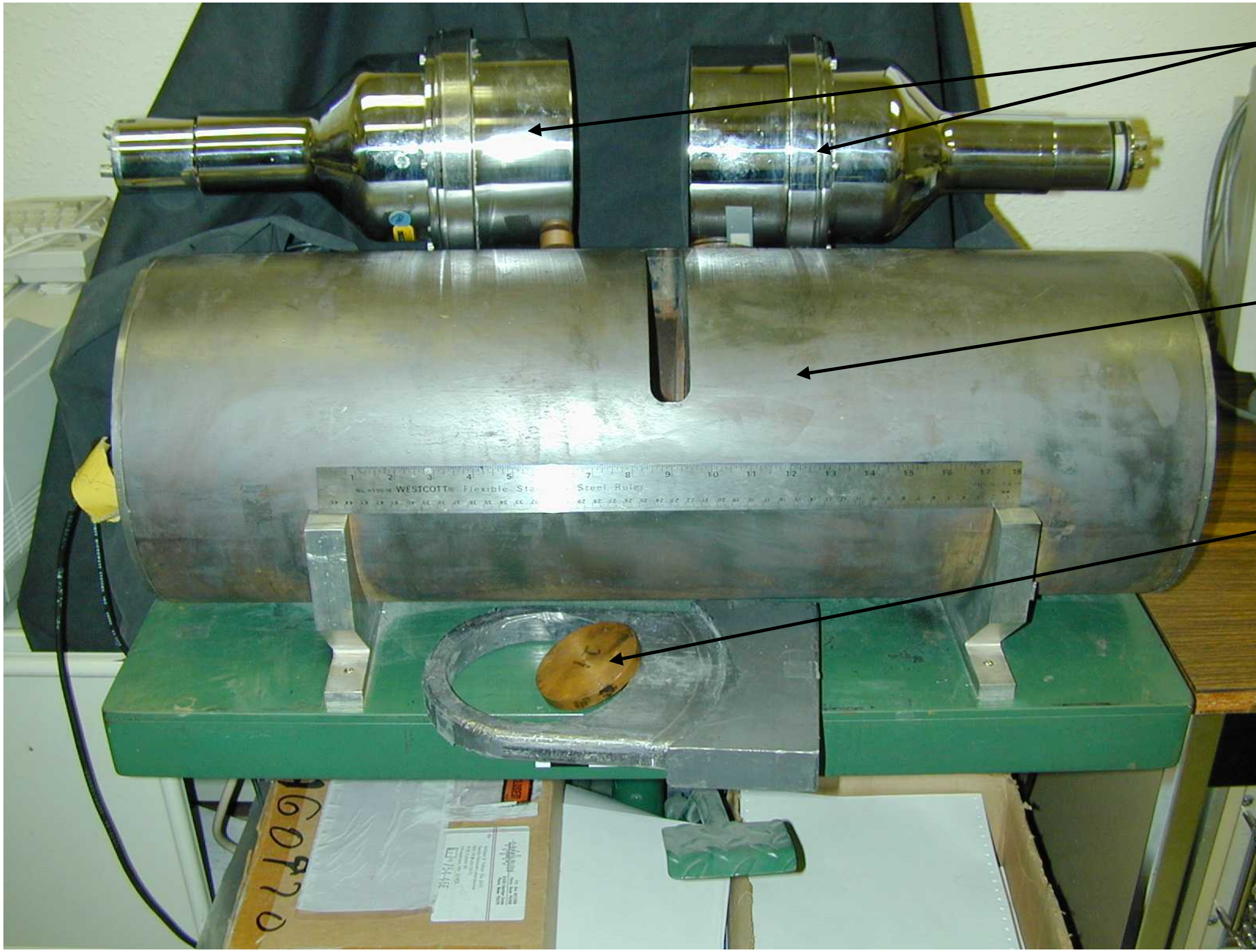
γ-γ coincidence system



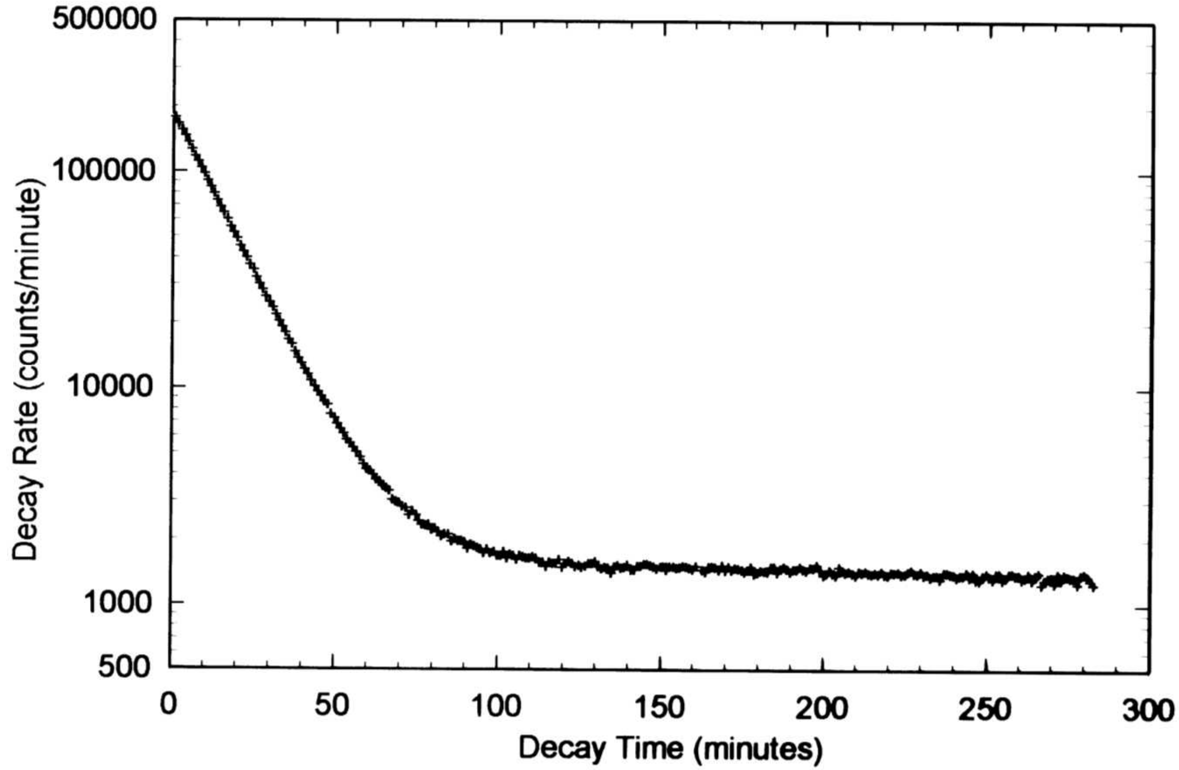
Coincidence counting arrangement used with activation detectors is shown here



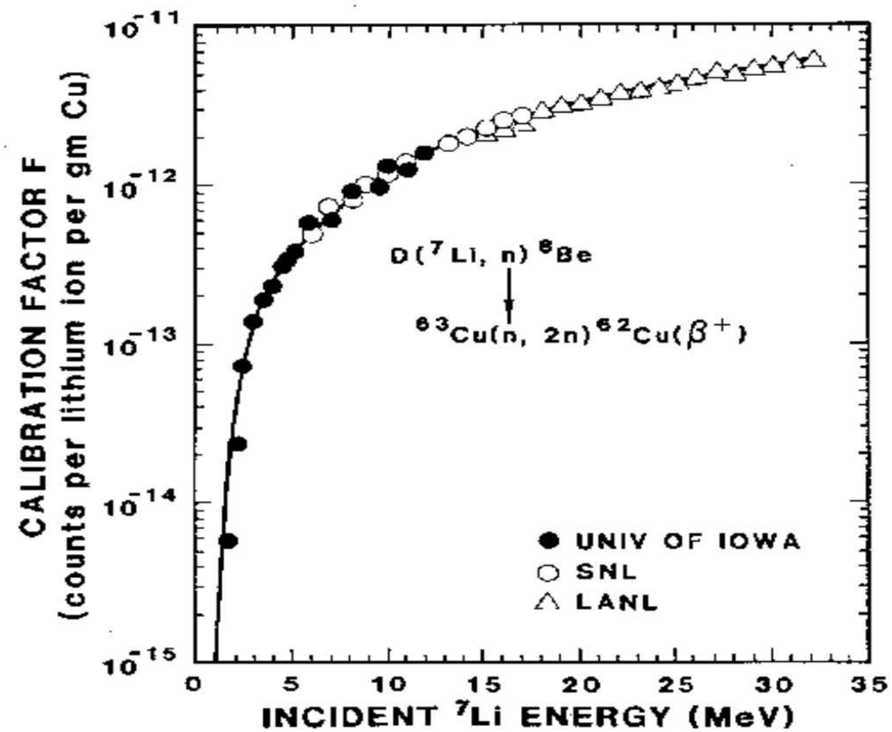
Cu activation coincidence counting system: NaI detectors and Pb shield



Decay curve from a copper activation sample is shown



Calibration curve for indirect activation diagnostic



Comparison of lithium beam energy results

From the measurement of the activities for both direct and indirect activation measurements, knowing the respective yield curves, knowing the voltage and current wave forms, and estimating ratio of total beam area to sampled beam areas, we can obtain an estimate for the total beam energy carried by the lithium ions

Comparison of lithium beam energy results

Shot Number	Direct Activation	Indirect Activation	Magnetic Spectrometer
6711	98 kJ	96 kJ	89 kJ
6717	61 kJ	85 kJ	91 kJ
6725	64 kJ	44 kJ	------
6737	121 kJ	122 kJ	------

Activation voltage diagnostic

- In previous examples we need to know the voltage and current wave forms to calculate the energy density of the beam
- If you can drive two separate reactions, the ratio of the yield of the two reactions can be a sensitive function of the ion energy over a limited energy range and since ion energy is related to the voltage one can get peak voltage directly

Ratio of thick target yields

Consider two reactions driven by deuterium ions incident on a sample of boron nitride (BN):

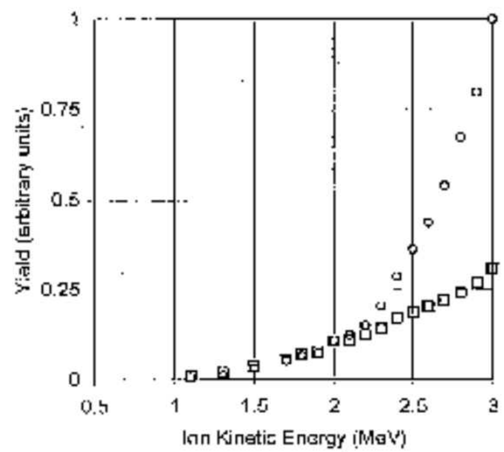
$$\text{B-10} + d \rightarrow \text{C-11}(\beta+) + n$$

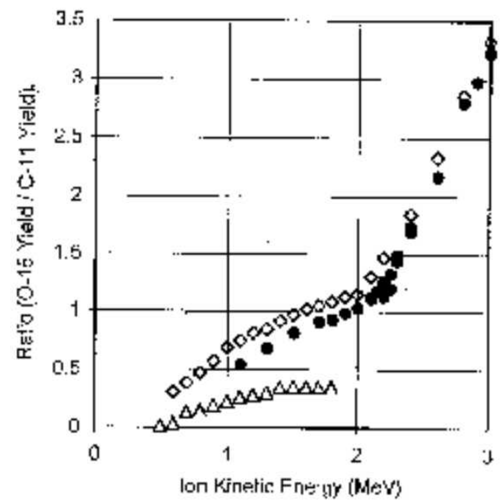
And

$$\text{N-14} + d \rightarrow \text{O-15}(\beta+) + n$$

Ratio of the thick target yields of these reactions is a sensitive function of ion energy between about 0.5 and 3 MeV

Thick target yield curves for D on BN and the ratio of these yields

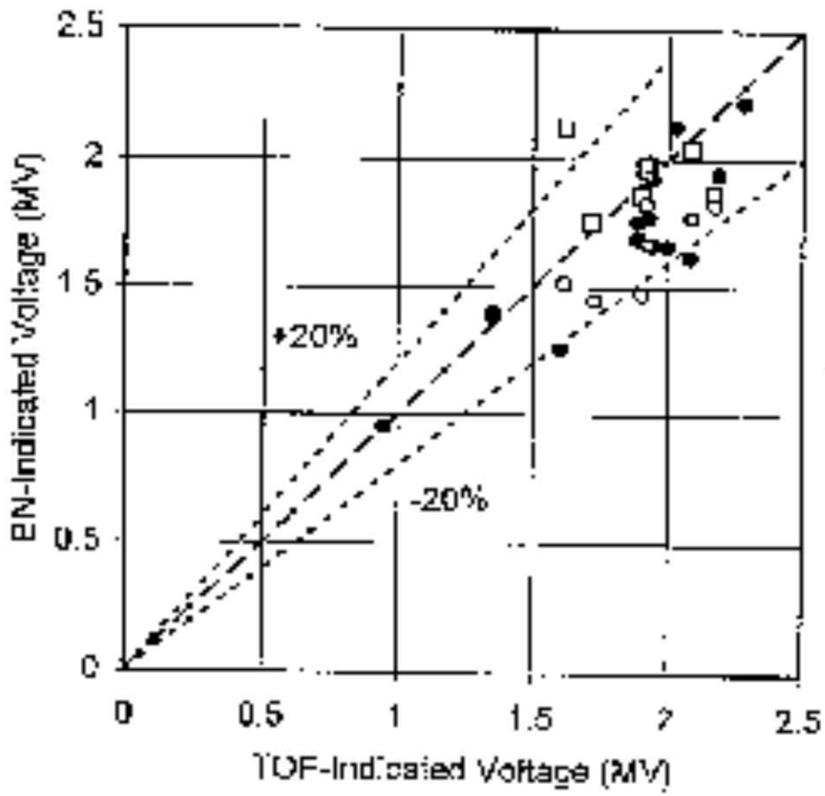




Measuring activities

- In the case of these two reaction products both decay by pure positron emission. As with copper can only differentiate between the two activities based on the difference in their half lives (C-11 has an 20.3 minute half life and O-15 a 2 minute half life)

Peak voltages in MITE POS as measured with activation and time-of-flight ion spectrometer



Fusion reactions/neutron diagnostics

$D + D \rightarrow {}^{3}He\ (0.82\ MeV) + n\ (2.45\ MeV)$

$D + D \rightarrow T\ (1.01\ MeV) + p\ (3.04\ MeV)$

$D + T \rightarrow {}^{4}He\ (3.5\ MeV) + n\ (14.1 MeV)$

$D + {}^{3}He \rightarrow {}^{4}He\ (3.6\ MeV) + p\ (14.7 MeV)$

Fusion neutron measurements

- Measurement of ICF neutrons can give information about
  - Fusion yield
  - Fusion temperature
  - Fuel density
  - Bang time
  - Burn history
  - Geometry of burn

Fusion yield measurements

- For both dd and dt fusion, one of the products is a neutron which is very penetrating and can easily activate materials with which they interact
- By measuring the activity induced in a sample, one can estimate the total fusion yield assuming that the yield is isotropic or, alternatively, by using many such samples one can determine if the yield is indeed isotropic

To measure yields using activation want selective reactions

For dd have 2.45 MeV neutrons:

In-115 + n $\rightarrow$ In-115m + n' E_{th} = 0.336 MeV

For dt have 14.1 MeV neutrons:

Cu-63 + n $\rightarrow$ Cu-62(β+) + 2n's E_{th} = 11 MeV

Competing indium reactions

Primary Indium activation reaction is:

In-115 + n $\rightarrow$ In-115m + n'

But also have (can only be produced by neutrons):

In-115 + n $\rightarrow$ In-116m + γ

And (direct interference with primary reaction):

In-115 + γ $\rightarrow$ In-115m + γ'

("Gateway state" is at about 1 MeV)

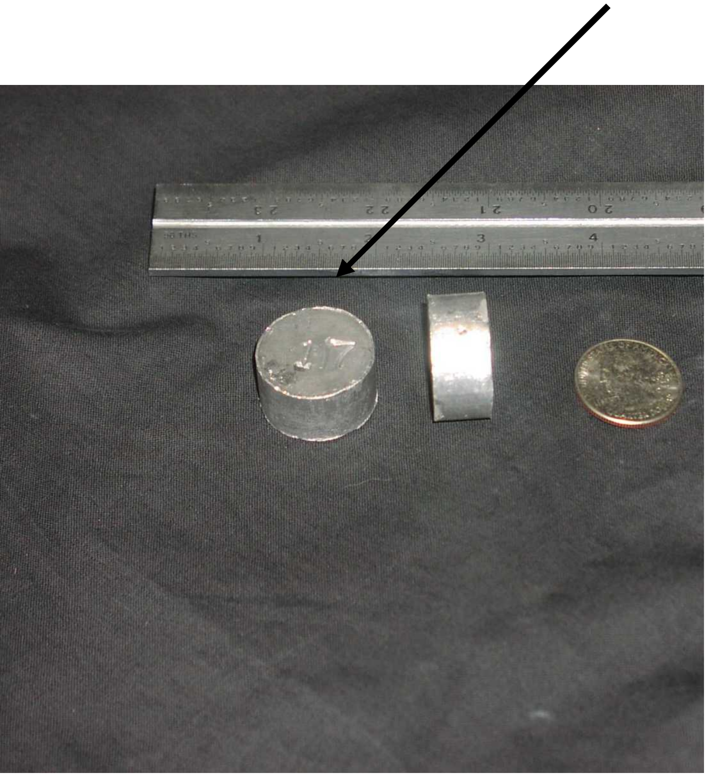
In activation counting system: Germanium detector

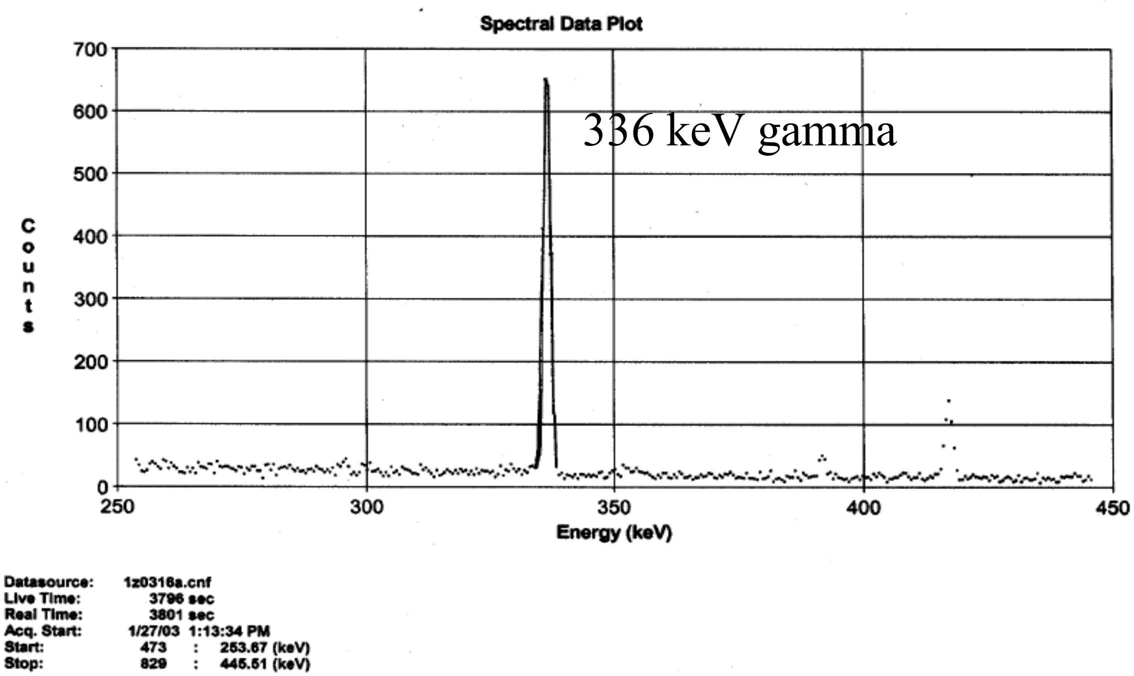
HP Ge Detector

In samples

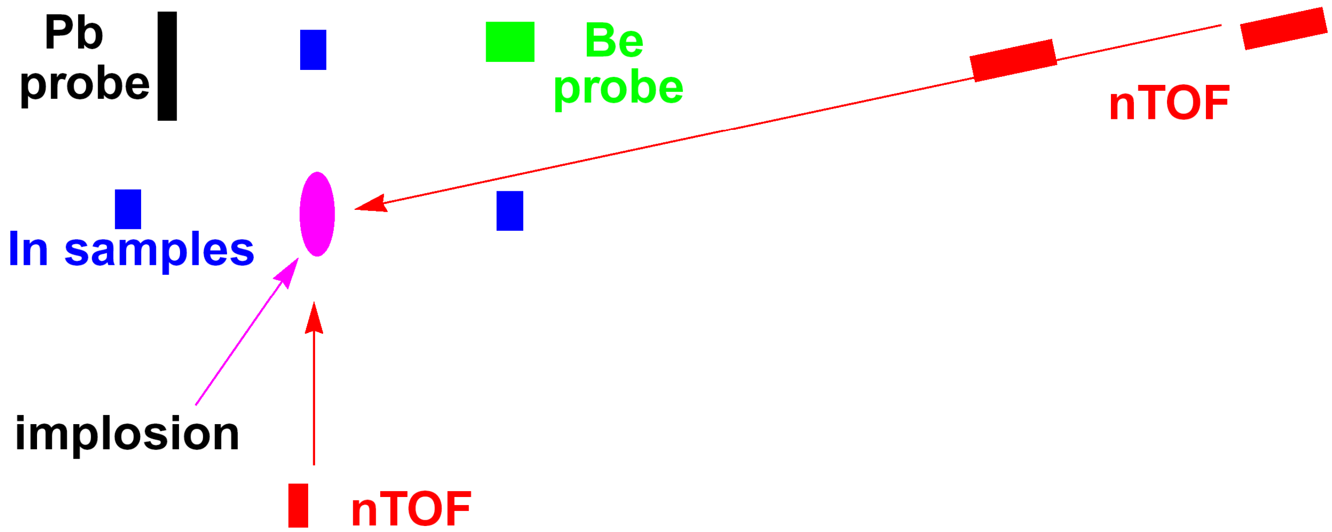
Indium samples and ^{115m}In spectrum

Indium sample

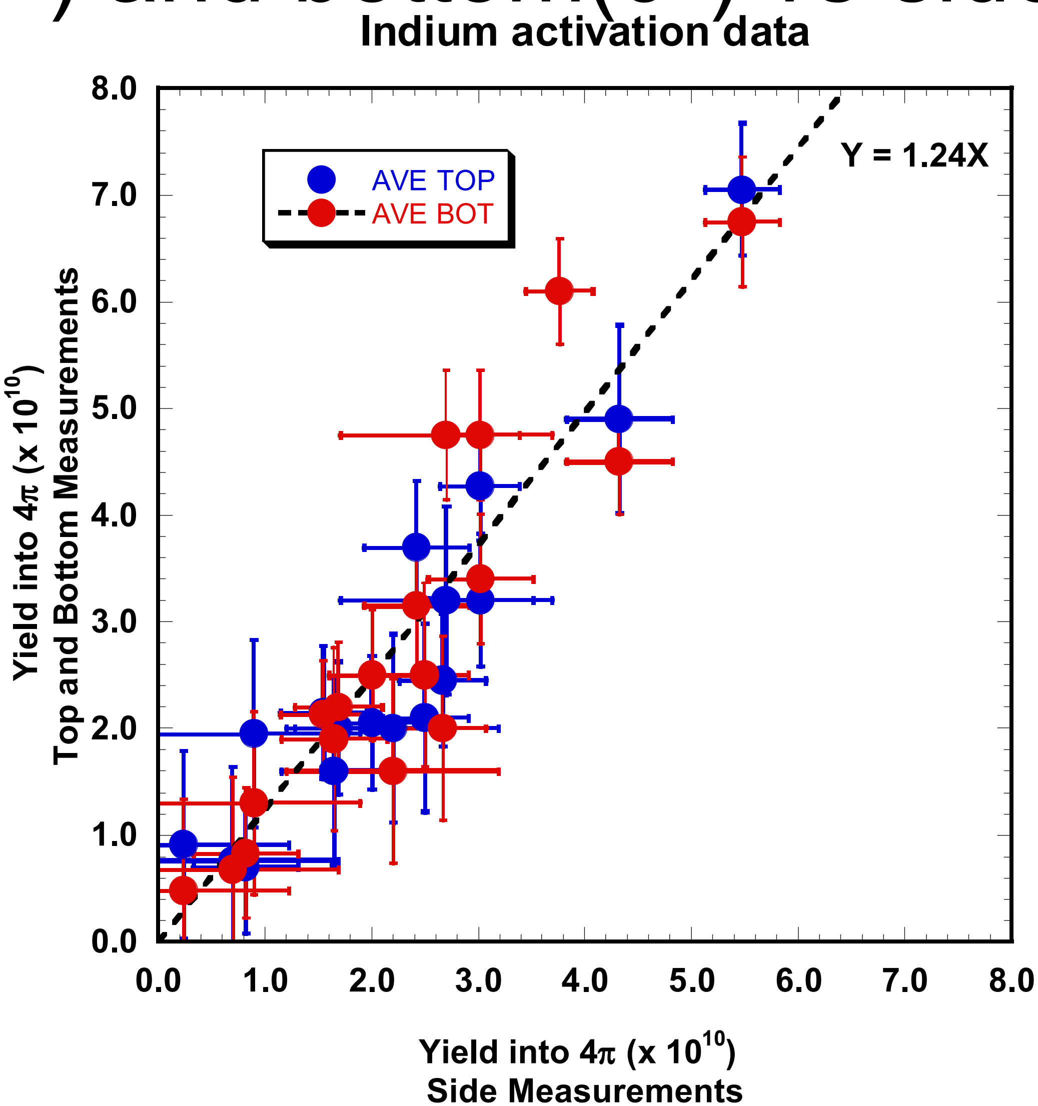




Schematic of a typical neutron diagnostic arrangement used in high energy density experiments



Asymmetry of neutron yields as measured by indium activation: top (180^o) and bottom(0^o) vs side (90^o)



Indium activation

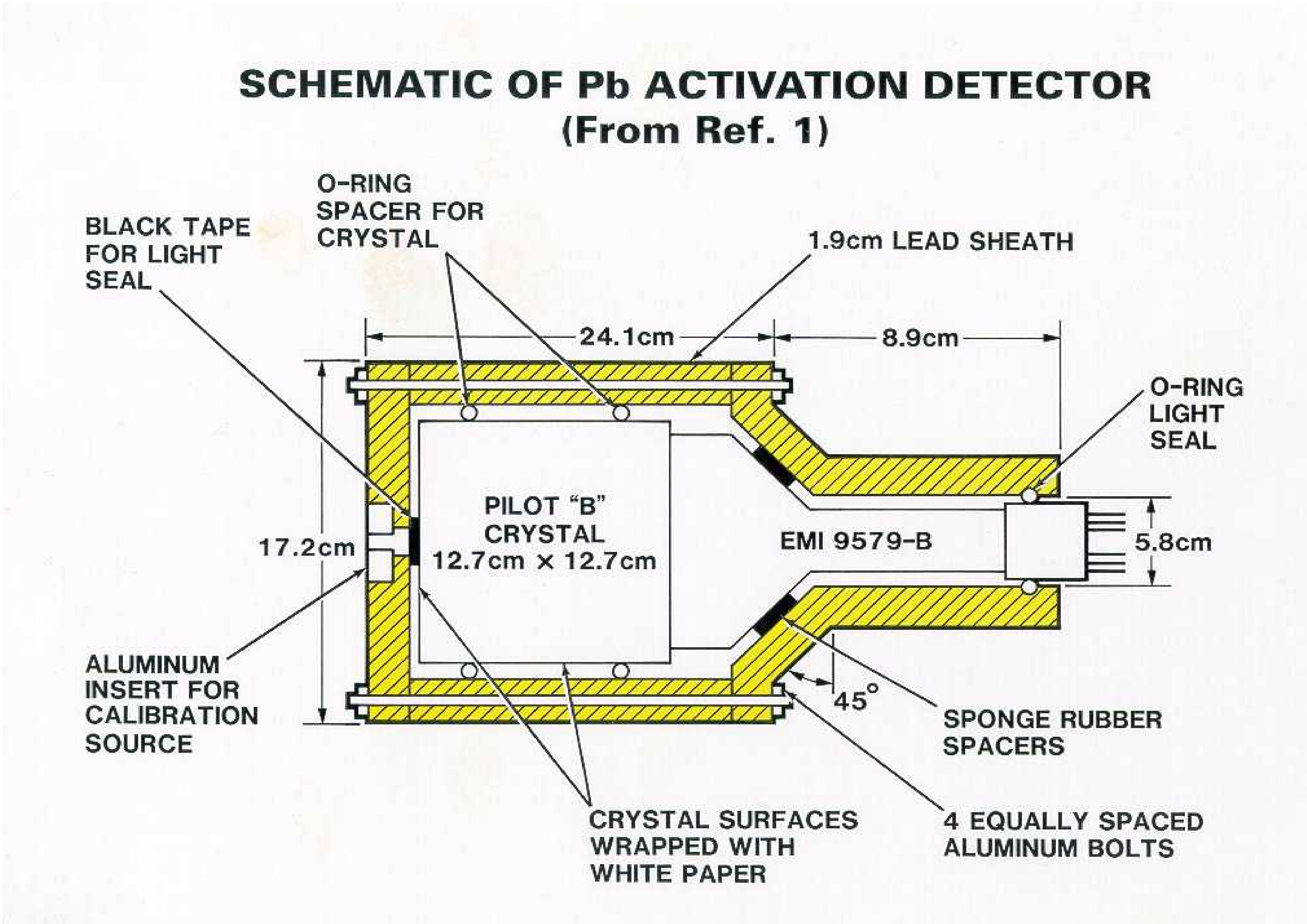
- Indium activation is a standard of the industry and has been in use for decades, however:
  - In-115m half-life is 4.5 hours which can make it very time-consuming
  - On Z, Indium diagnostic does suffer from gamma-ray background interference
  - Instead we can use alternative activation diagnostics

Alternative activation reactions

- Lead probe detector: (1.63 MeV threshold)
  $^{207}Pb(n,n')^{207m}Pb$ (E_γ = 0.57, 1.064 MeV, $t_{1/2}$ = 0.8 s)

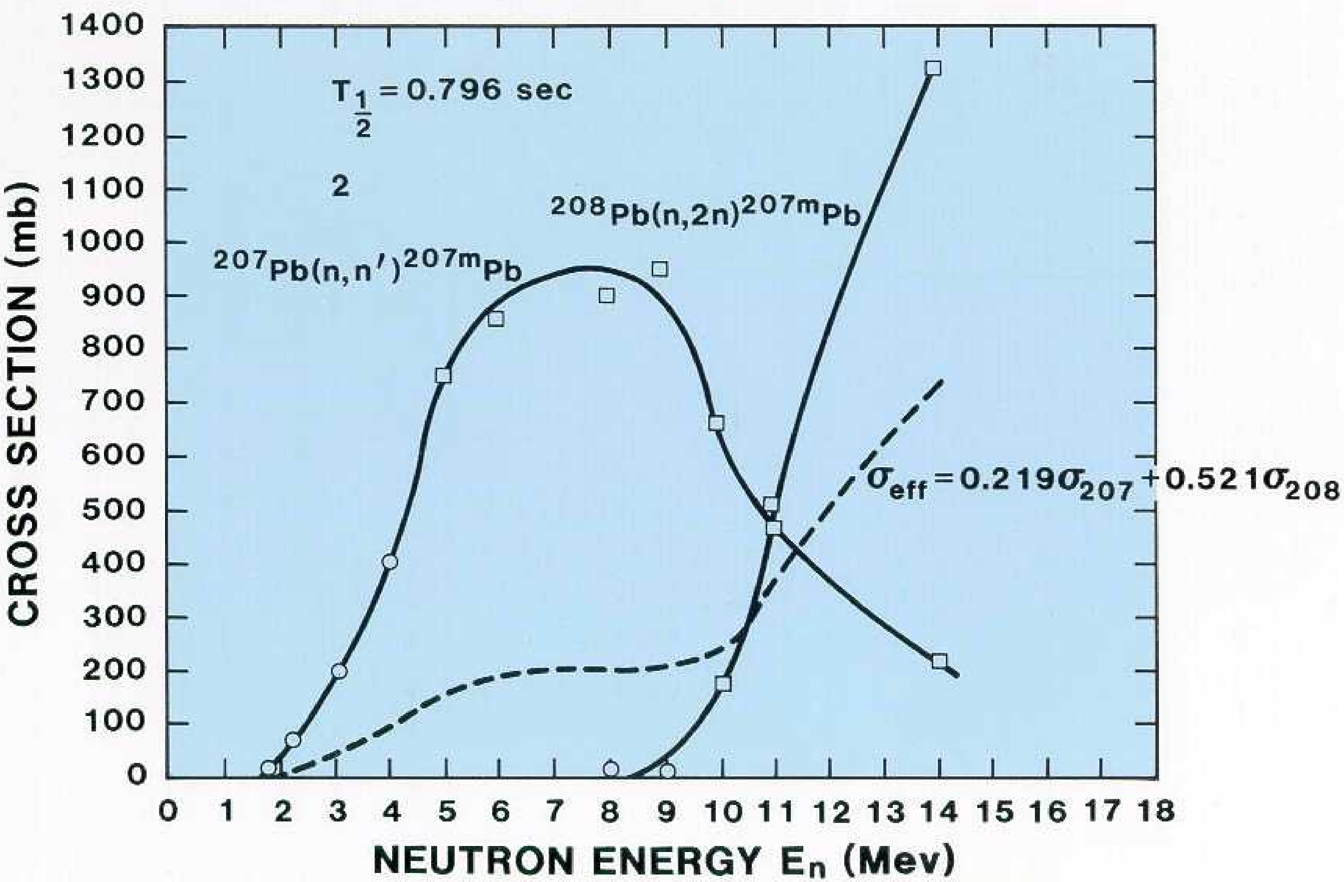
- Beryllium layer cake detector: (0.67 MeV threshold)
  $^{9}Be(n,\alpha)^{6}He$ (β^-, $t_{1/2}$ = 0.8 s)

A Pb activation detector has been adapted for the measurement of DD total neutron yield



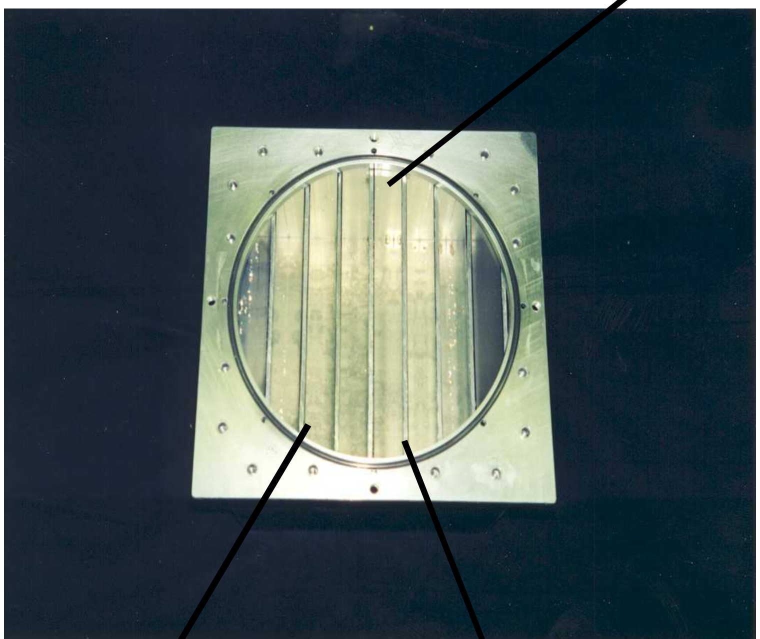
Absolutely calibrated SNL Pb activation detector

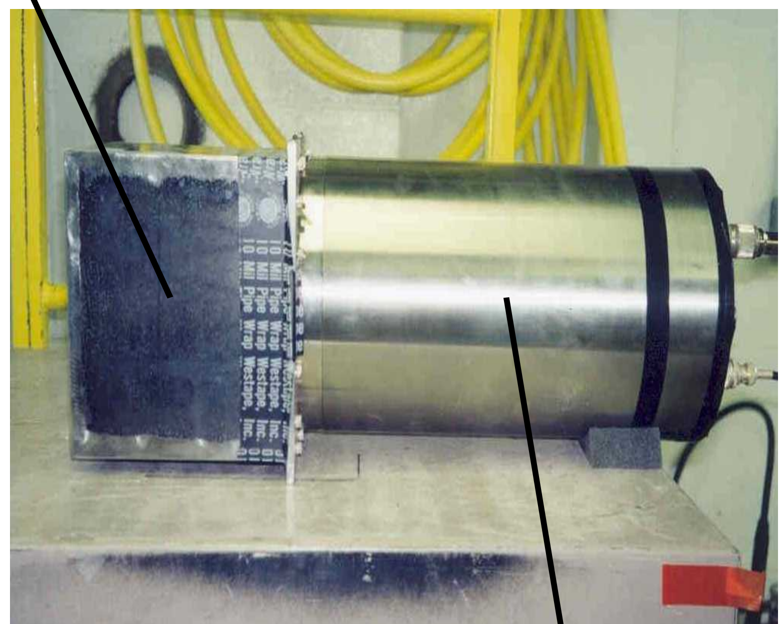
CROSS SECTION CURVES FOR $^{207}Pb\ (n,n')\ ^{207m}Pb$ AND $^{208}Pb\ (n,2n)\ ^{207m}Pb$ (From Ref. 1)



Beryllium layer cake

Layer cake portion





Plastic scintillator layer

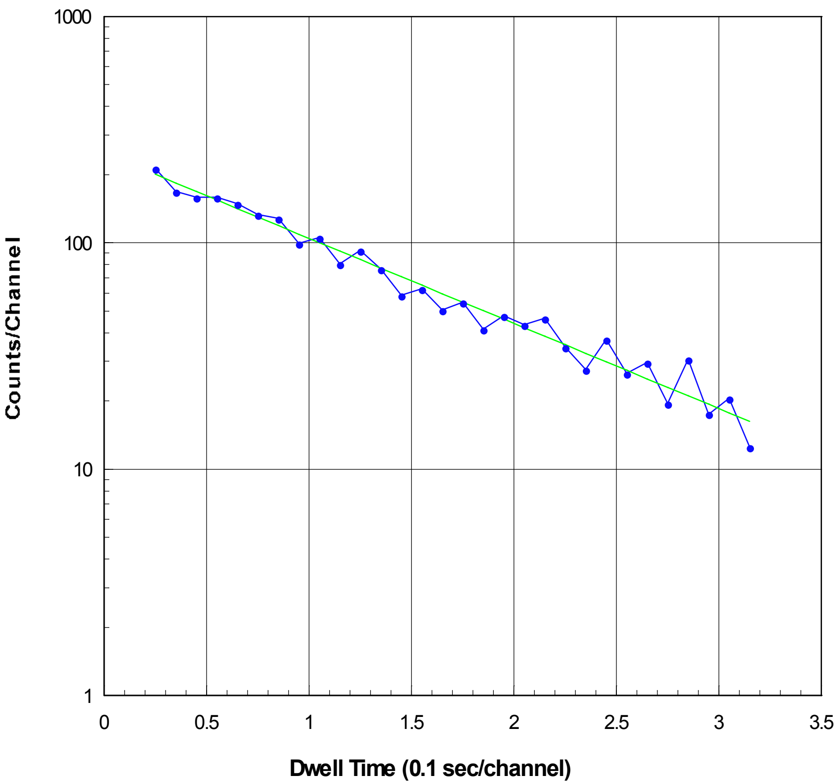
Beryllium layer

Photo-multiplier housing

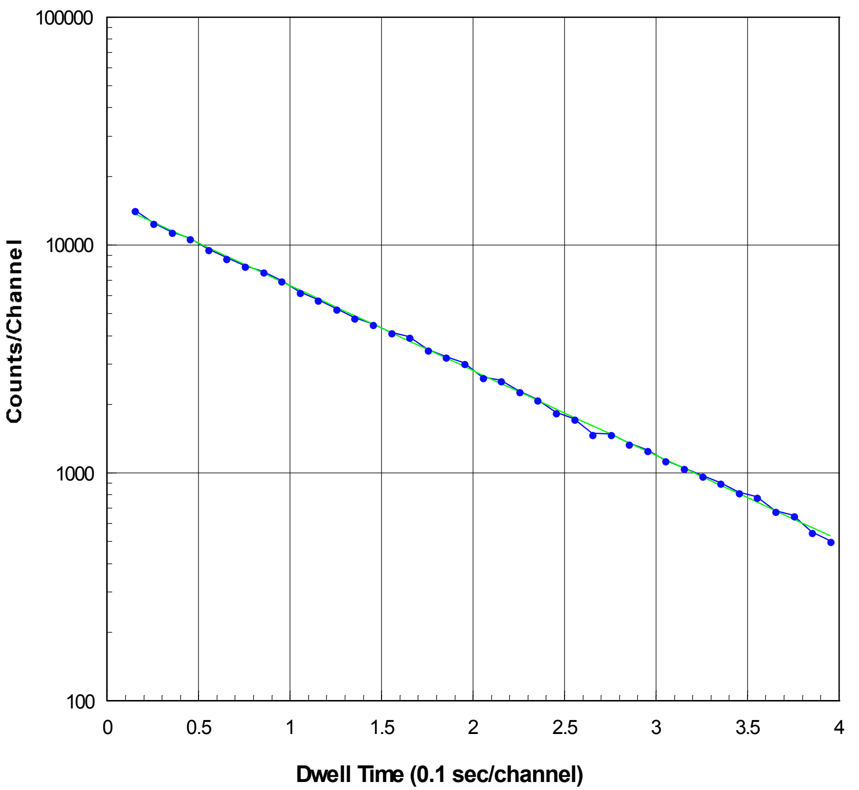
Pb and Be multi-channel scaling (MCS) time spectra. These are calibration runs.

MCS examples below were obtained with a 5e10 DPF dd neutron source located at Texas A&M

TAM2 Shot 29 Original Lead Probe, 78", -1830V, -64mV, Half Life = 0.80 sec, A(0) = 248.8 Counts/0.1 sec



TAM2 Shot 37 Beryllium Layer Cake, 78", -2000V, -56mV, Half Life = 0.81 sec, A(0) = 15,617.9 Counts/0.1 sec



Density measurement of dd ICF capsule

- Recall that one of the products of one of the two dd reactions is a triton which in turn can react with the deuterium fuel to yield 14.1 MeV neutrons.
- Over a certain parameter range, the ratio of the number of dd primary reactions to dt secondary reactions is a sensitive function of the ICF capsule's ρR and thus can be used to measure dd capsule density

Density measuremnts

- For dd fueled experiments can get ratio from indium and copper activation diagnostics OR
- From scintillation detector measurements to be discussed next
- For dt fueled experiments can get density from measurement of tertiary reactions (14.1 MeV n's scatter off d or t. The resulting extra-energetic ions undergo dt reactions yielding very energetic neutrons which are a measure of the density)

Scintillation detectors

- A scintillation material is one that emits light when it absorbs ionizing radiation
- This scintillation light can then be detected with a photomultiplier tube or micro-channel plate
- There are two important facts: all the processes in a scintillation detector are linear with energy deposited and one can measure the time dependence of the signal

Scintillation detectors for ICF

- Scintillation detectors are commonly used for ICF neutron measurements
- Requires organic (usually plastic) scintillators which contain lots of hydrogen with which the neutrons can undergo elastic scattering interactions – it's the scattered proton that actually excites the scintillator

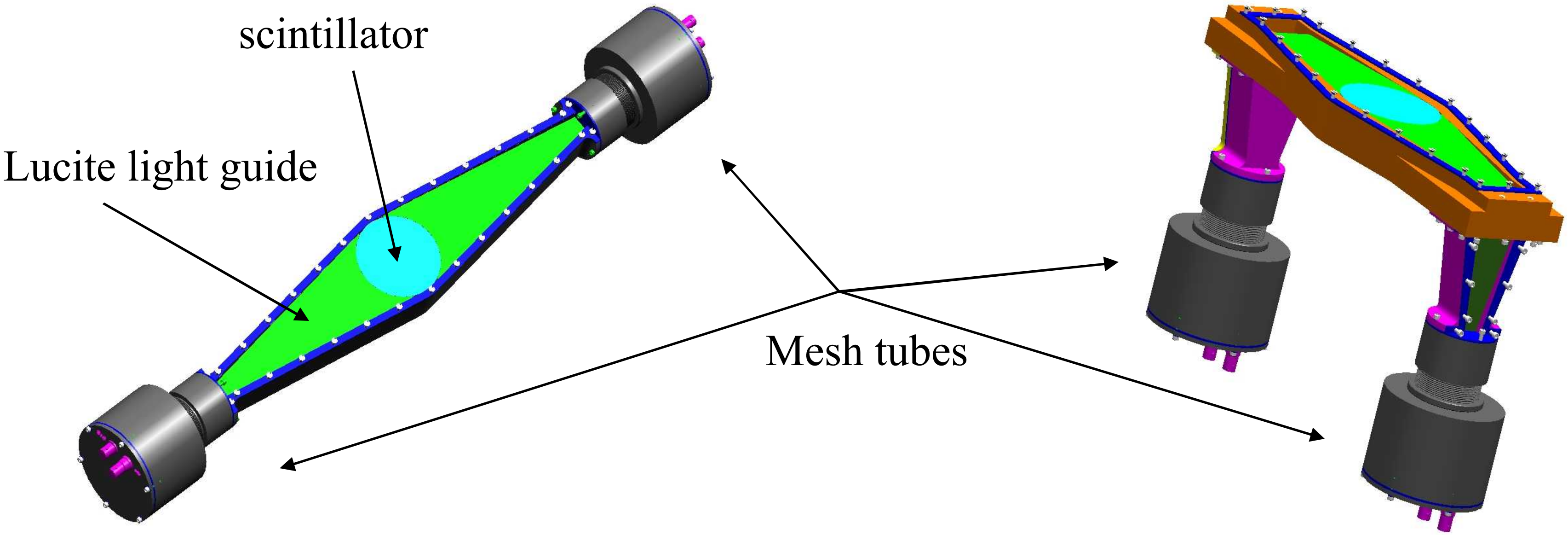
Scintillation detectors for ICF

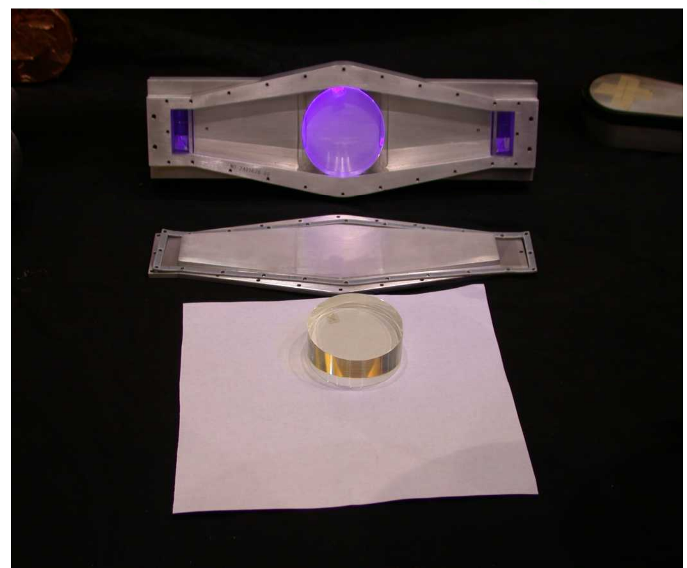
- Most scintillation detectors (such as the NaI detectors in the γ-γ coincidence systems discussed earlier) operate in the single particle counting mode
- In ICF applications the neutrons arrive in such a short burst that they cannot be individually resolved and, as a result, the detector is operated in the current mode (and PMT's should be modified for optimal performance)

Scintillation detector applications in ICF

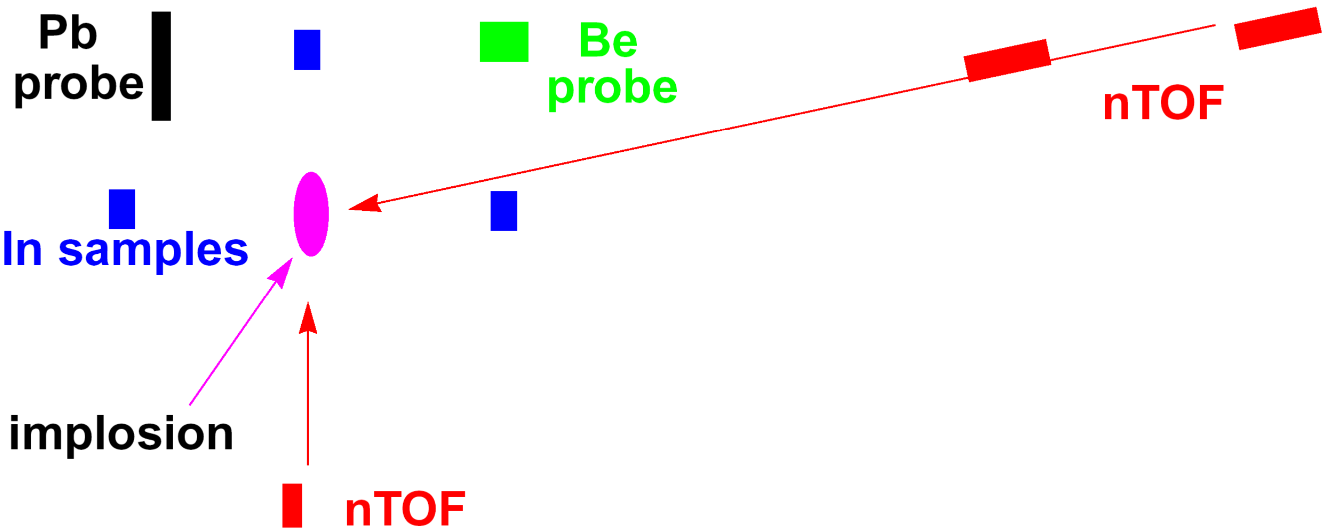
- Scintillation detectors can be used to
  - Measure yield
  - Measure ion temperature
  - Measure density
  - Measure bang time
  - Measure spatial distribution of fusion burn

Dual paddle nTOF detectors

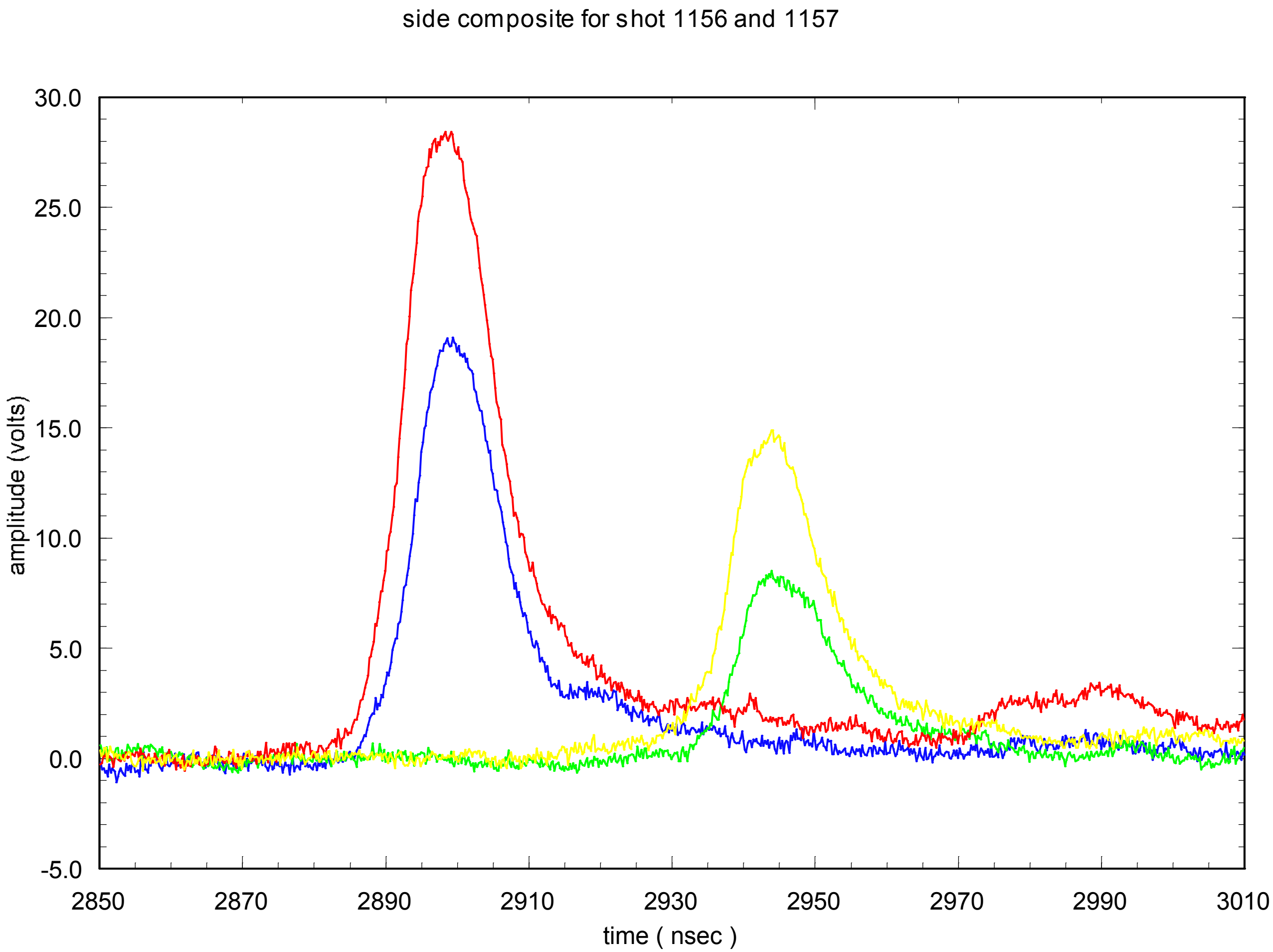




Schematic of a typical neutron diagnostic arrangement used in high energy density experiments



Typical scintillation signals on Z



Yield measurements

- To get a yield measurement using scintillation detectors the neutron signal must be integrated and the detector response to dd and dt neutrons known
- All attenuation and scattering must also be accurately calculated or measured
- An *in situ* calibration can also be done by comparing the scintillation signal to the yield as measured with activation

A 9000 lbs. shield is required for neutron time-of-flight measurements on Z

Scintillation density measurements

- Because dd and dt neutrons are non-relativistic, they will have different velocities and therefore will arrive at a detector located some distance from the source (> than many meters) at different times
- Thus, dd and dt yields can be separately measured and again the density of a dd capsule determined by the ratio of the two yields

Fusion temperature measurements

- Neutrons will not only have kinetic energy from the “Q” (mass → energy) of the reaction but will have some of the initial kinetic energy carried by the reactants
- This results, for a thermonuclear plasma, in a spread of neutron energies about the Q value energy (2.45 MeV for dd and 14.1 MeV for dt

Fusion temperature measurements

- Thus, the full width at half maximum of the neutron energy spread can be related to the fusion burn temperature
- Since the spread in neutron energies is too small to measure directly, we use a time-of-flight technique to convert this spread in energy to a spread in time at a distant detector

nTOF technique

- In the nTOF technique we assume that all the neutrons are born at the same time (a reasonable assumption in ICF)
- Because the neutrons are non-relativistic, the differing energy neutrons have correspondingly differing velocities, so the fastest ones arrive at the detector first, the slowest ones last

Time width of nTOF signals from side detectors for shots 1148-1157 are used to give a preliminary estimate of ion temperature(T)

The temperature is given by

$$T = (\Delta E / 82.5)^{2.0}$$

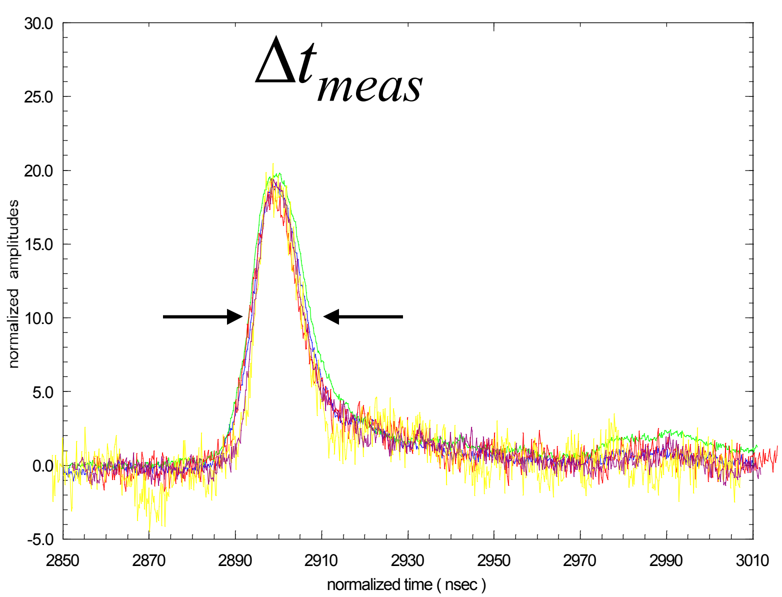
where ΔE is calculated from

$$\Delta E = 2 \Delta T (V)(E) / L$$

and ΔT is defined by

$$\Delta T = \sqrt{\Delta t^2_{meas} - \Delta t^2_{scint} - \Delta t^2_{tube}}$$

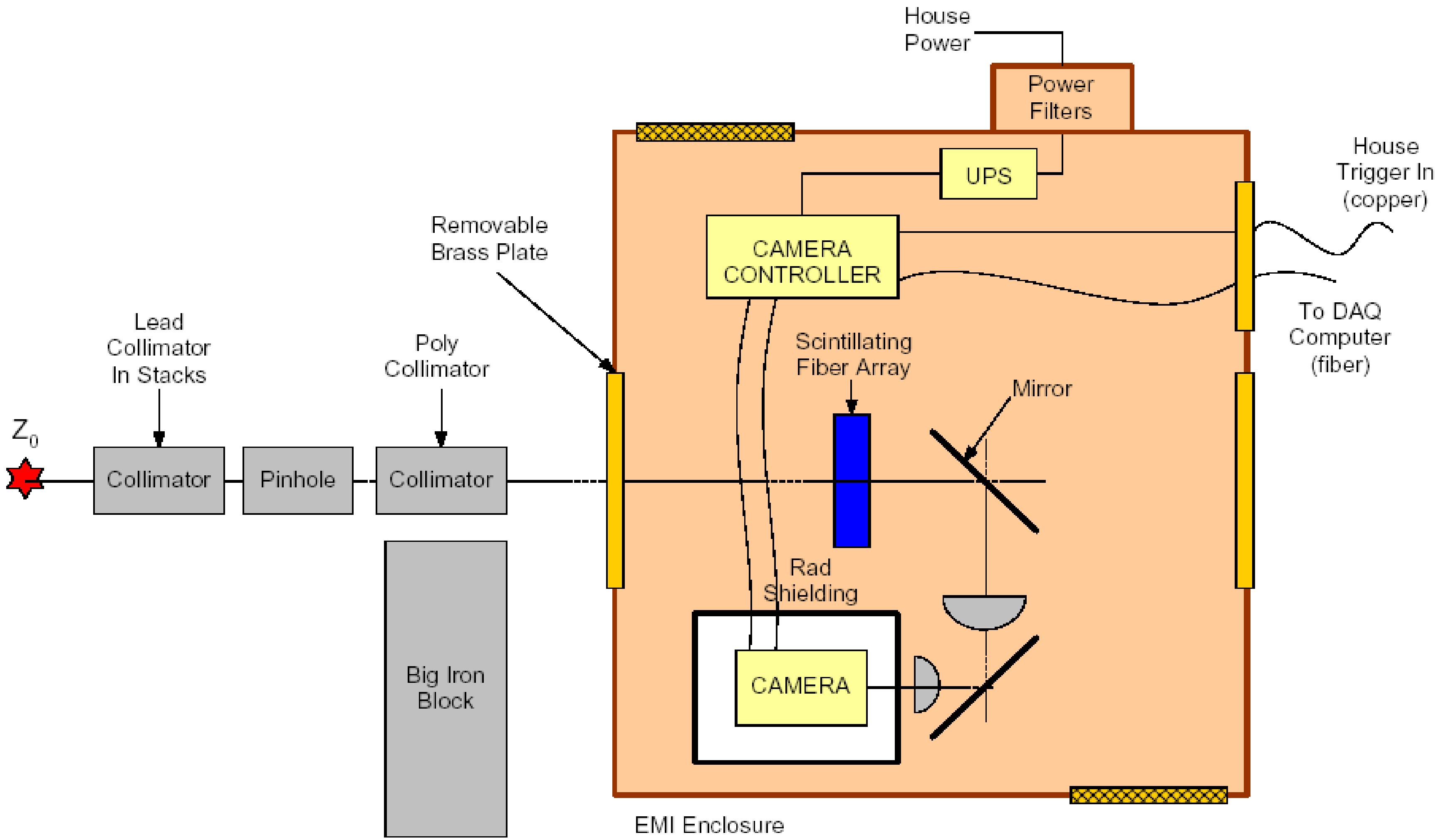
Averaged temperature measured on side and on-axis detectors for shots 1148-1157 is 4.8 +/- 1.5 keV



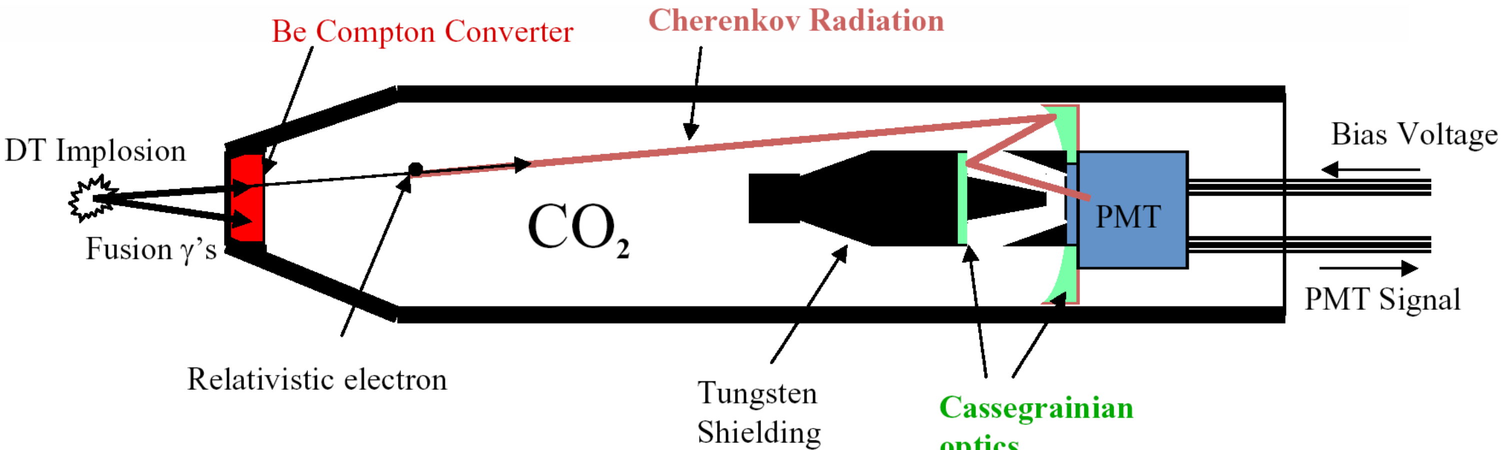
Advanced diagnostics

- Neutron imaging
- Cerenkov detector (burn history)
- Neutron-proton recoil magnetic spectrometer

Neutron imaging



Burn history can be measured from the 16.7 MeV gamma produced in the reaction D + T → ^{5}He + γ reaction



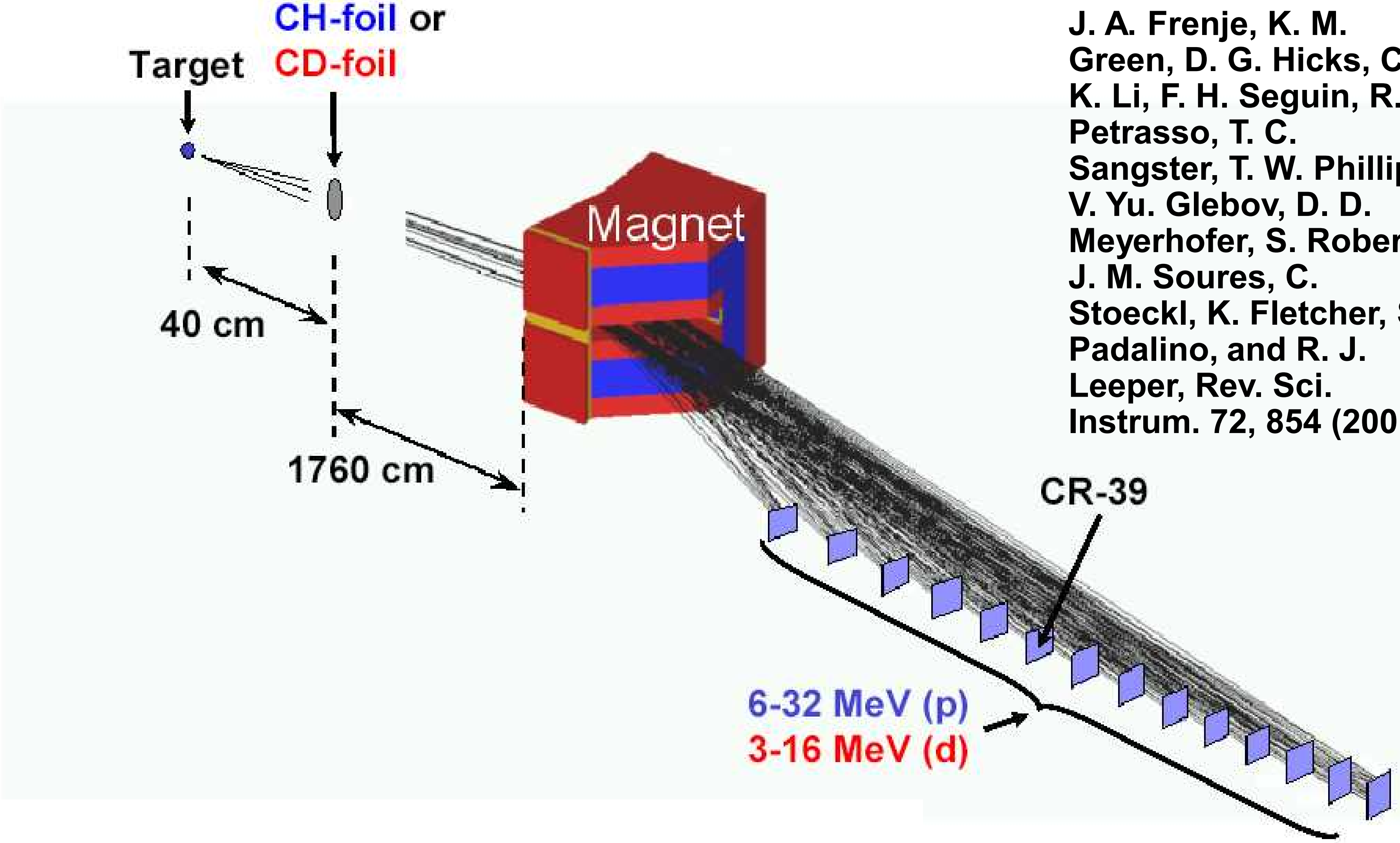
D+T → n+α, branching ratio ~1

D+T → n+α+γ(16.75 MeV), branching ratio ~1e-4

Gas Press (psia)	Energy Threshold (MeV)
30	12
100	6.3

- Why use Gammas?
  - No Doppler Spreading → High Bandwidth measurement at large Standoff!
    - Neutron Spreading: for Ti=10 keV, Δt≈40 ps at 10 cm (Omega), Δt≈2 ns at 5 m (NIF?)
  - Speed of Light Signal → easy to temporally discriminate γ signal from later signals
  - Energy Thresholding → distinguishes fusion γ's from secondary γ's

Proton recoil spectrograph has been designed to measure the neutron energy spectrum on NIF ignition experiments by MIT/LLE/LLNL/SNL



J. A. Frenje, K. M. Green, D. G. Hicks, C. K. Li, F. H. Seguin, R. D. Petrasso, T. C. Sangster, T. W. Phillips, V. Yu. Glebov, D. D. Meyerhofer, S. Roberts, J. M. Soures, C. Stoeckl, K. Fletcher, S. Padalino, and R. J. Leeper, Rev. Sci. Instrum. 72, 854 (2001).

Conclusions

Nuclear diagnostic can be used to measure a wide variety of parameters of energetic ions and plasmas as well as many properties of fusing plasmas

References?