GAMMA RESONANCE AND FISSION TECHNOLOGY (GRFT) FOR DETECTION OF EXPLOSIVE AND NUCLEAR MATERIALS IN CARGO

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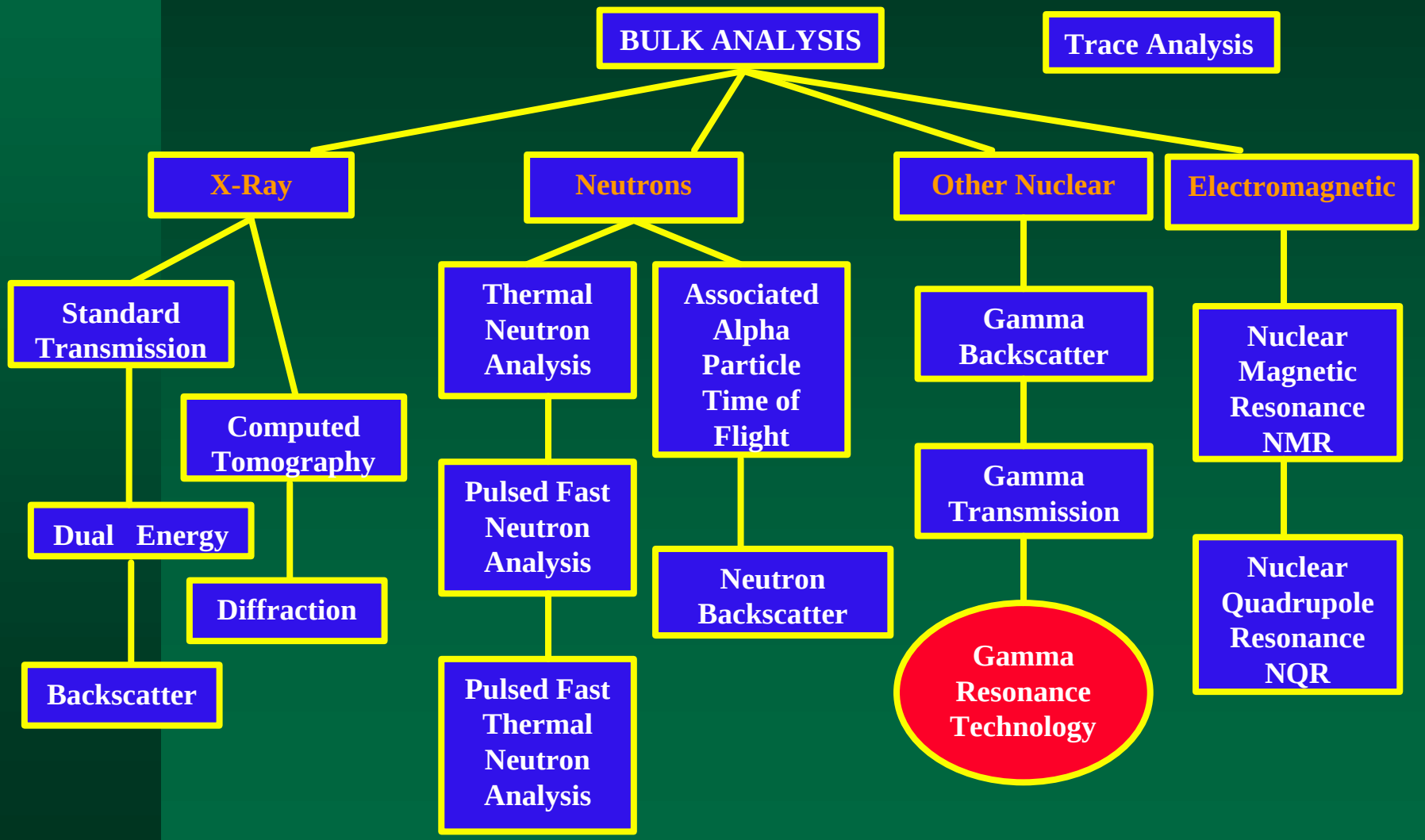
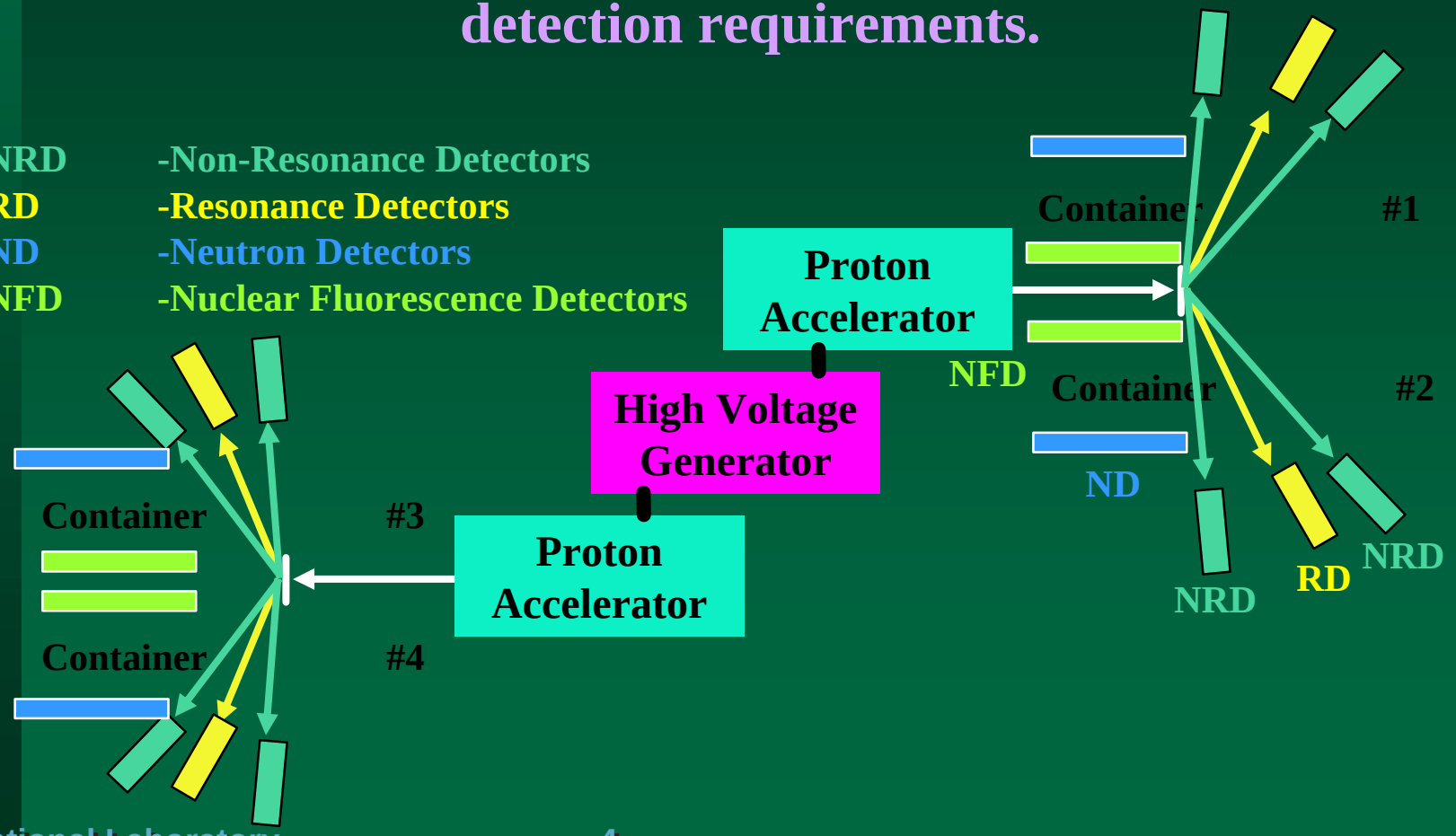
GRFT Objective



GRFT Proposed System

To present a system that is capable of detecting a variety of illicit materials and is adaptable to diverse detection requirements.

NRD -Non-Resonance Detectors
RD -Resonance Detectors
ND -Neutron Detectors
NFD -Nuclear Fluorescence Detectors



GRFT *Presentation Outline*

- **Principles**
- **System Components**
  - **Accelerator**
  - **Targets**
  - **Detectors**
- **Applications**
- **Results**
- **Summary**

GRFT Principles

1) GRT - is based on resonance interaction of gamma radiation with a specific nuclear level in the nucleus of an element of interest; N, O, Cl.
   This differs from the photoelectric, Compton, and pair production that are atomic reactions.

2) PHOTO-FISSION - is a process in which gamma rays above a threshold energy induce fission in nuclear materials producing prompt and delayed neutrons.

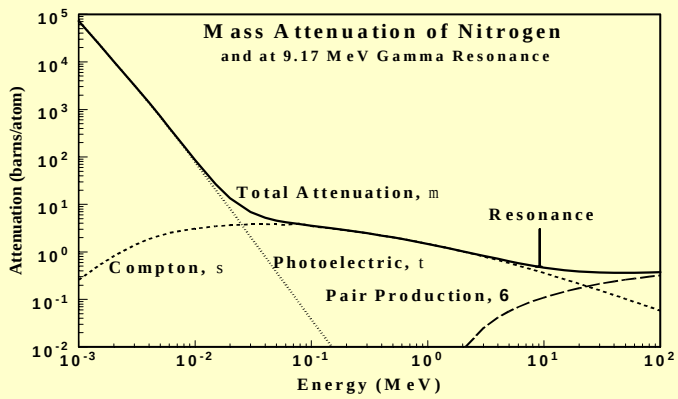
GRFT Resonance Cross Section

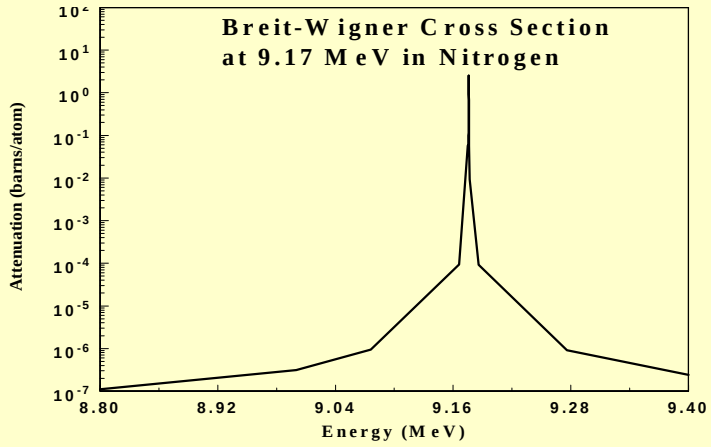
Resonance cross section is given by the Breit-Wigner formula:

$$s_{abi} = p\lambda^2 g \frac{G_a G}{(E-E_R^{bi})^2 + G^2/4}$$

where g is a statistical factor given by:

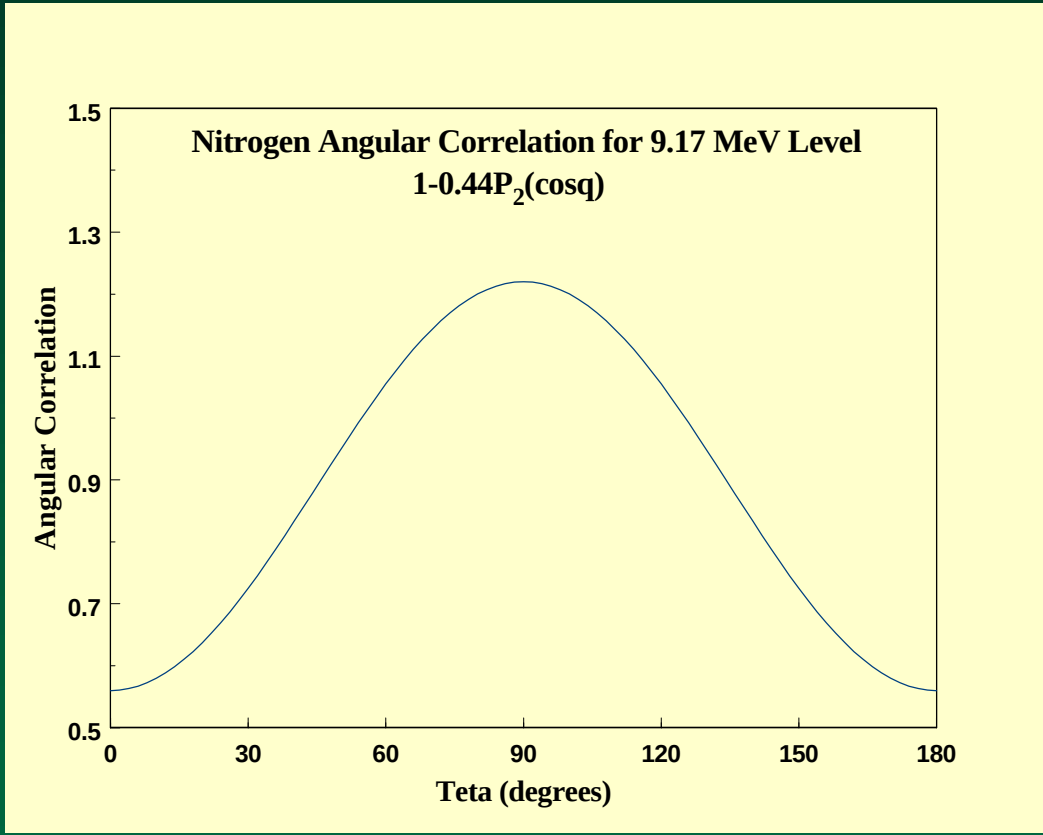
$$g = \frac{2J + 1}{(2s + 1)(2i + 1)}$$





GRFT Fluorescence

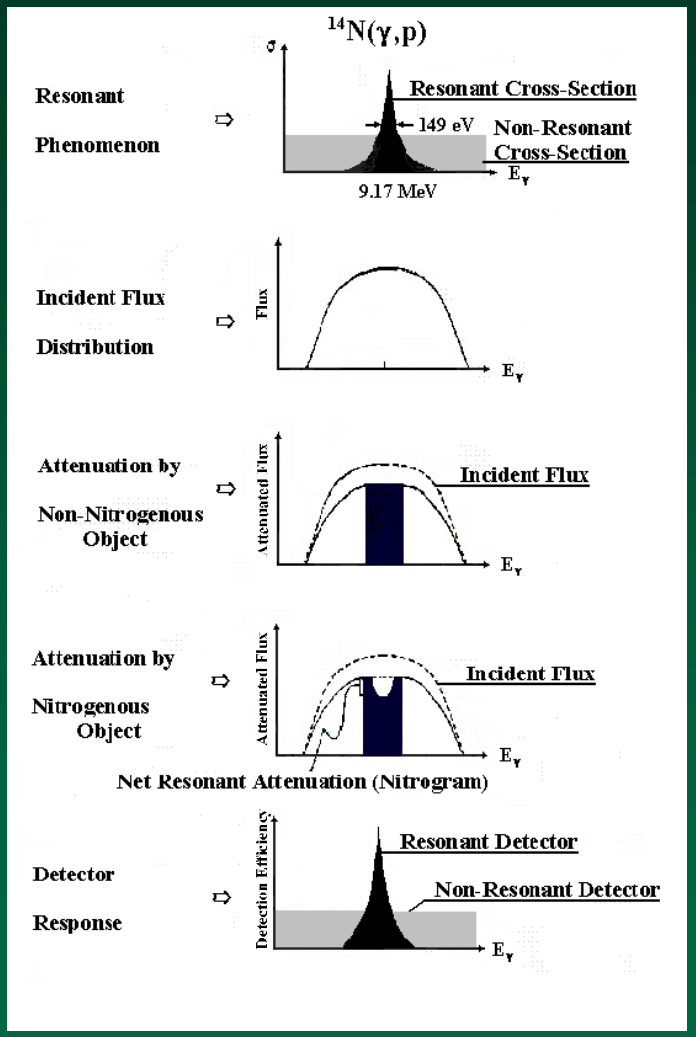
The angular correlation is maximum at 90° that needs to be considered when optimizing a stand off system based on nuclear fluorescence.



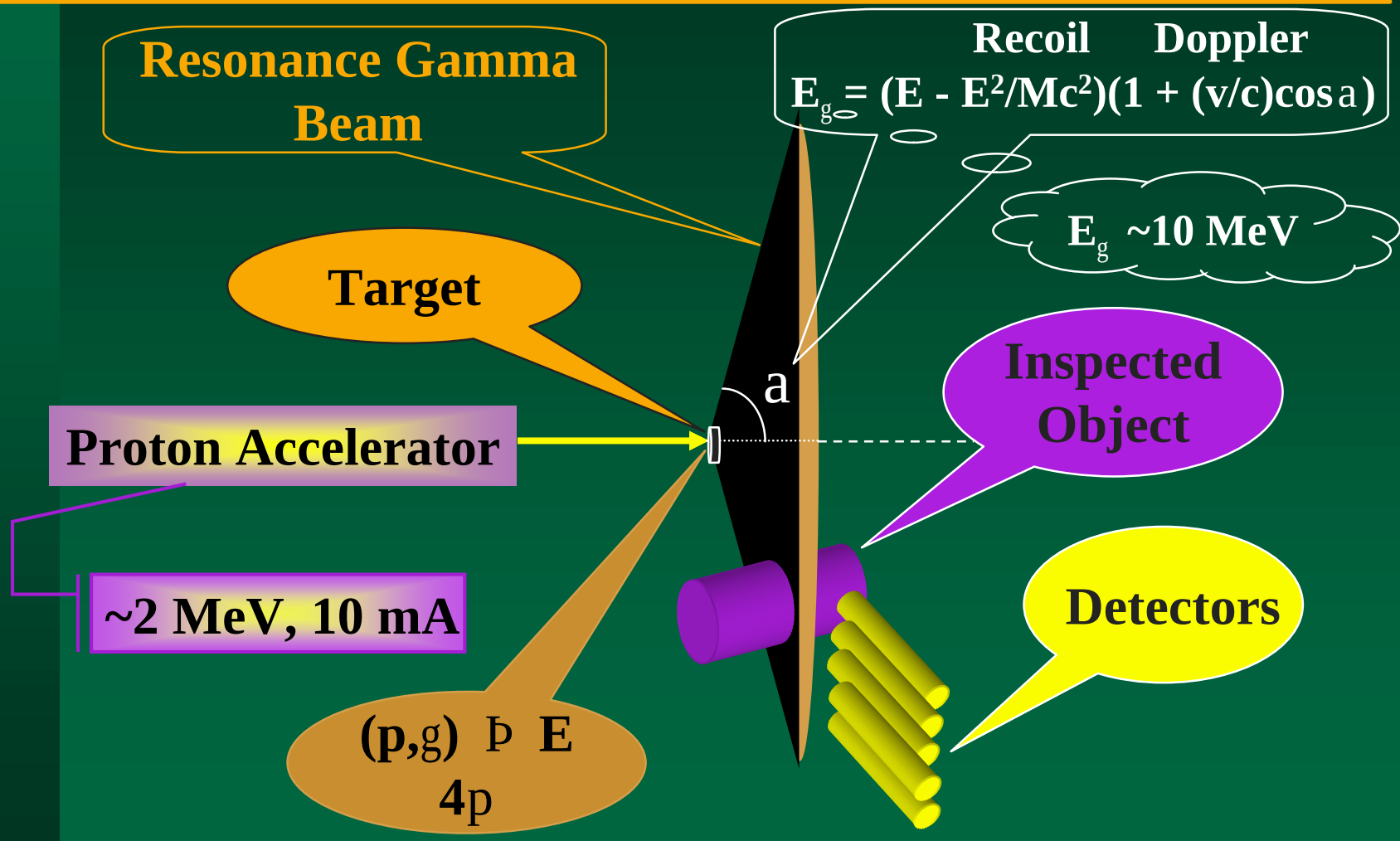
GRFT Fluorescence Process

The process of the conventional- and nuclear resonance-attenuation of gamma radiation in presence and absence of nitrogenous material.

At 10 MeV the total attenuation in N is about 0.5 barns/atom. The resonance attenuation is about 2 barns/atom.



GRFT System Main Components

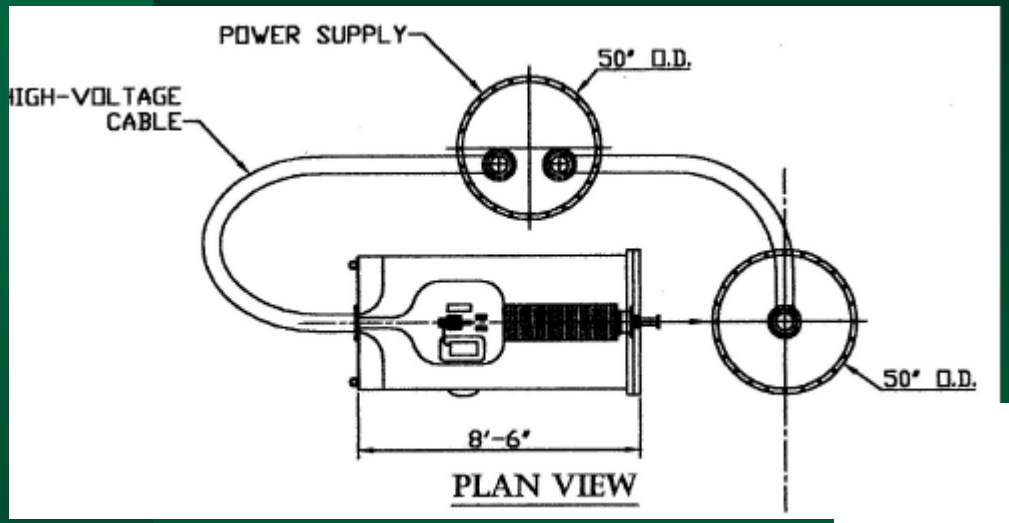


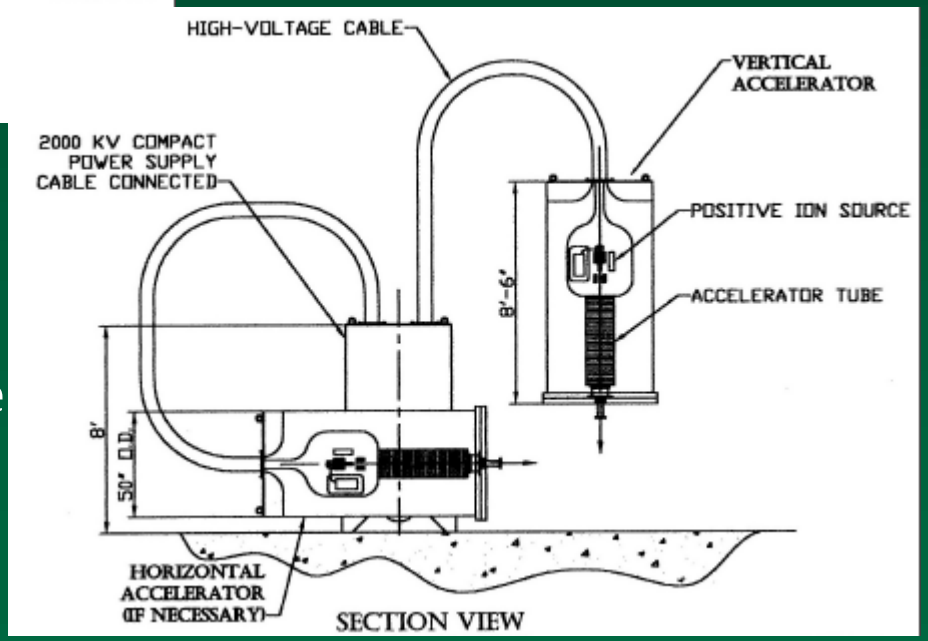
GRFT Single Stage Accelerator

A new single stage proton accelerator is chosen to replace the tandem accelerator

1) **It is an intense electrostatic electron accelerator converted to accelerate protons and will be procured from a commercial supplier as a turn key unit.**
2) **Uses a reliable Insulated Core Transformer (ICT) power supply designed for 100 kW. Single unit can feed several accelerators. About 250 units have been deployed.**
3) **Electron Cyclotron Resonance (ECR) reliable ion source for currents above 10 mA, no filaments, long life, very low maintenance.**
4) **The system is simple to operate, can be computerized, no skilled operator required, one or more units can be supplied within short time.**

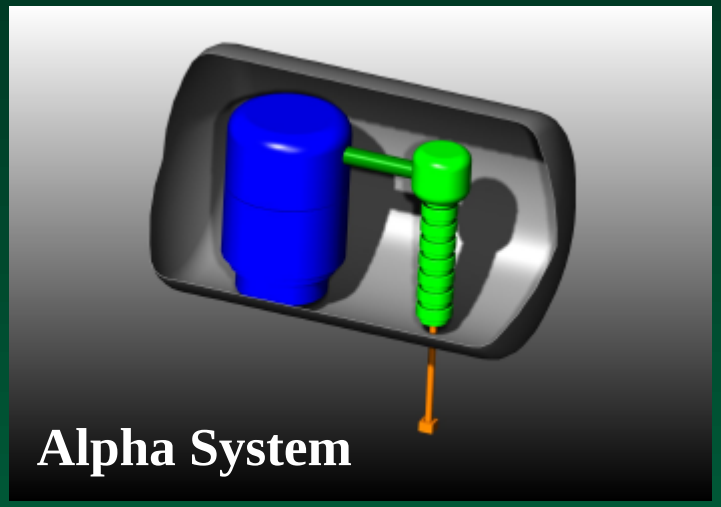
GRFT Compact Accelerator Footprint

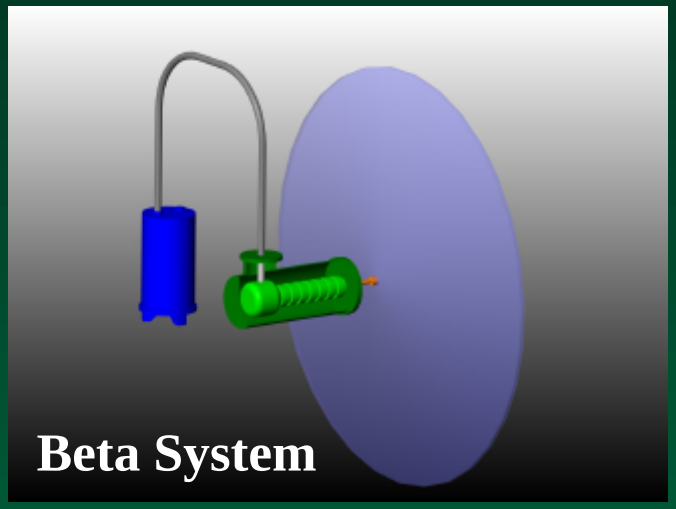


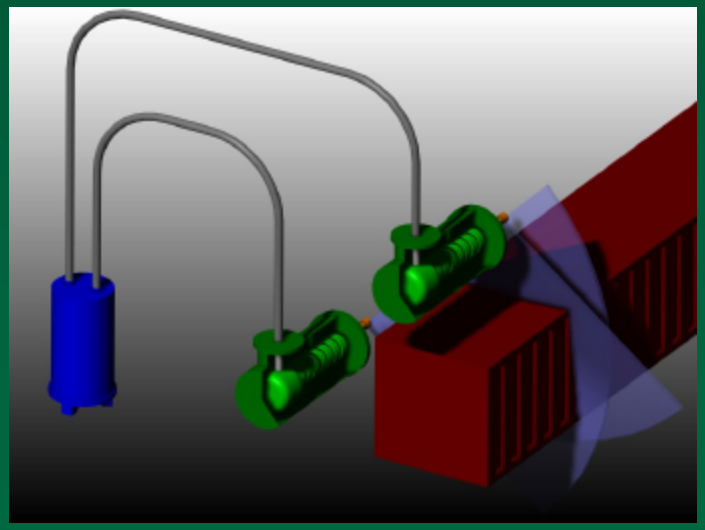


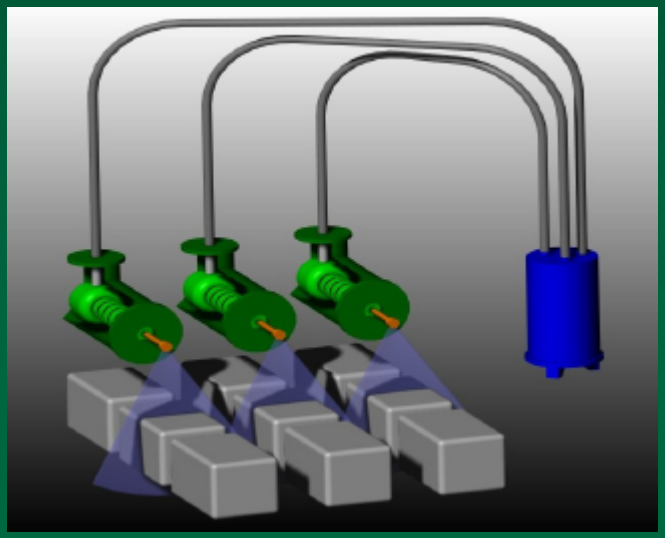
Two compact accelerators (can be expanded to four) attached to a single power supply occupy a very small footprint. With a flexible cable they can be placed in any arbitrary configuration.

GRFT Accelerator Configurations

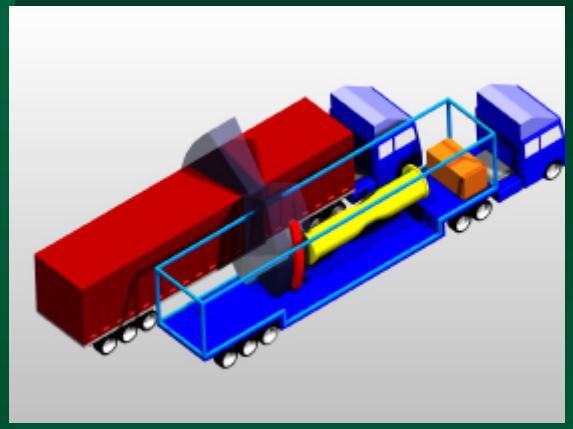


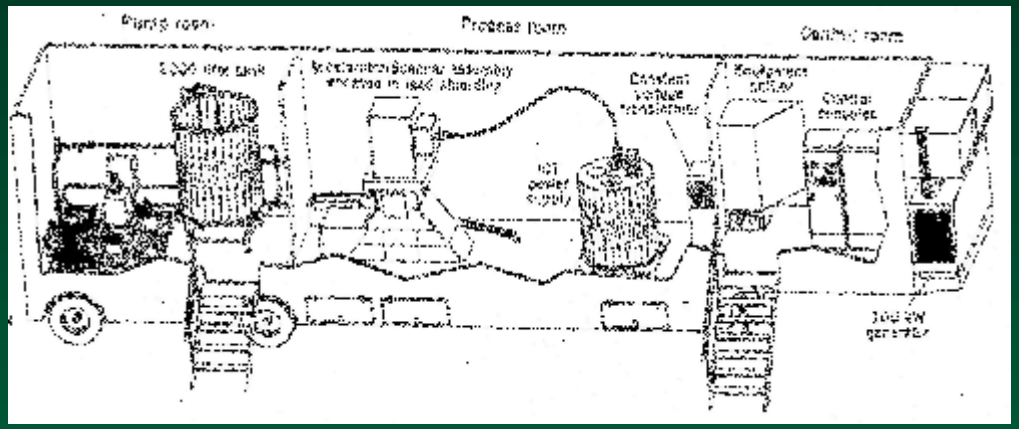




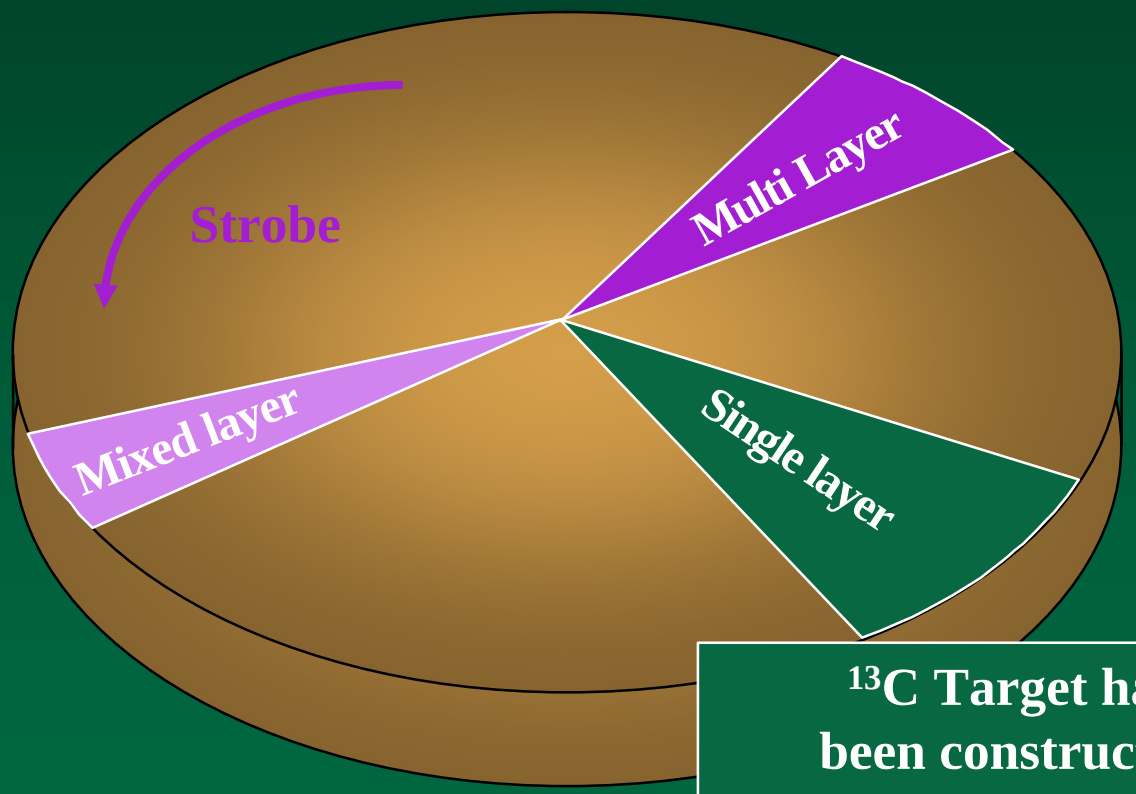


GRFT Applications





GRFT Rotating Target System



^{13}C Target has been constructed and heat tested for 10 mA

GRFT Targets For O and Cl

By using different target material or a combination of materials elements other than nitrogen can also be investigated

Layered Targets

- CS_2 – Enriched in ^{13}C and ^{34}S for detection of N and Cl.
- BN (Boron Nitrate enriched with ^{13}C) ^{13}C; ^{11}B; ^{15}N; with E_p @ 1.75; 1.1; 0.6; MeV respectively, we can measure N; C; and O, simultaneously.

Composite Target of ^{26}Mg & ^{30}Si

At E_p 1.94 & 1.91 MeV respectively to detect ^{14}N, ^{16}O, and ^{35}Cl

^{26}Mg (p,☎) & ^{30}Si (p,☎) → ^{27}Al → @ 🗎~40 — 7.117 MeV ^{16}O

^{27}Al → @ 🗎~117 — 9.082 MeV ^{35}Cl

^{30}Si (p,☎) → ^{31}P → @ 🗎~86 — 9.173 MeV ^{14}N

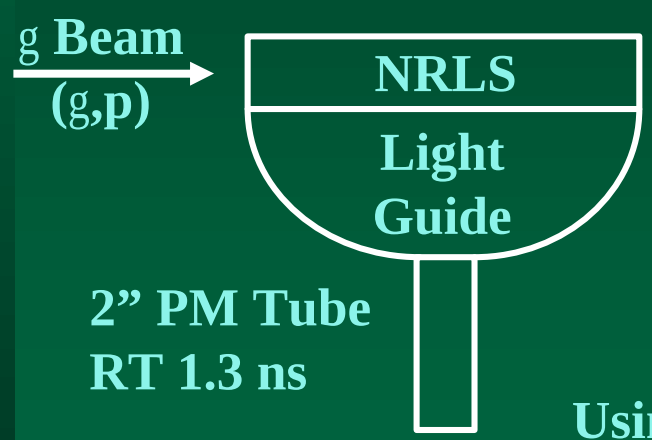
GRFT Alternative Targets

Element	Target	E_p (MeV)	☞ abs (barns)	E☎ (MeV)	Reaction
^{14}N	^{13}C	1.75	2.6	9.17	$^{13}C(p,☎)^{14}N$
^{40}Ca	^{39}K	2.04	5.0	10.32	$^{39}K(p,☎)^{40}Ca$
^{35}Cl	^{34}S	1.89	1.0	8.21	$^{34}S(p,☎)^{35}Cl$
^{16}O	^{19}F	2.6	2.4	6.92	$^{19}F(p,✂☎)^{16}O$
^{12}C	^{15}N	2.6	1.1	4.43	$^{15}N(p,✂☎)^{12}C$

GRFT Resonance Detection System

NE – 213 Nitrogen Rich Liquid Scintilator

Organic Solvent	+ Primary Solute	+ Wavelength Shifter
(~90%)	(~10%)	(~0.5%)
p-xylene	naphtalene	PPO+POPOP
emiss. ~280nm	emiss. ~330nm	emiss. ~425 nm



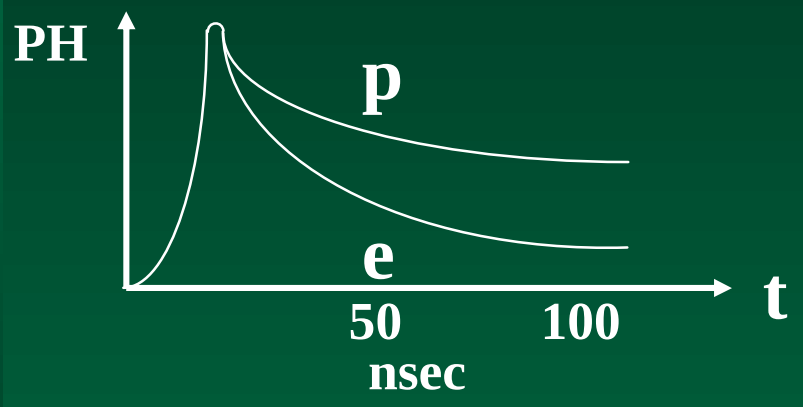
Pyrex Vessel
20x20x240 mm

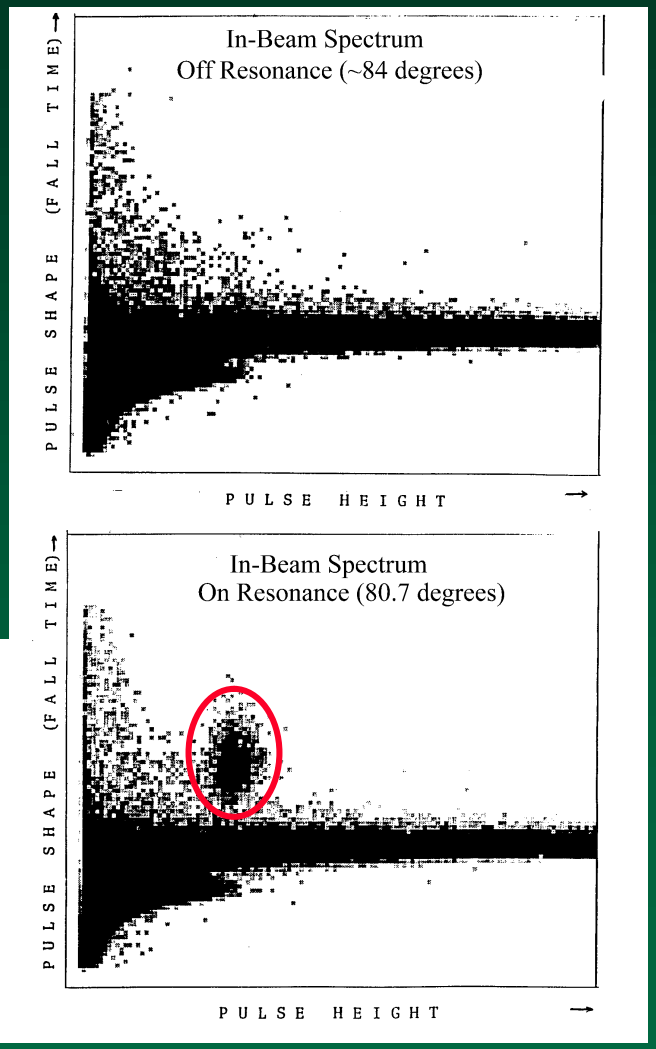
ϵ_R = ~24%, Max(ϵ) ~ 41%

Using pulse shape discrimination resonance detectors measure simultaneously total and nitrogen attenuation.

GRFT Resonance Detection System

Particle Identification

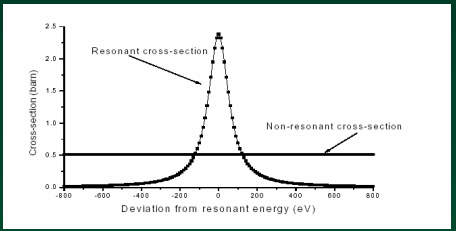




Two dimensional pulse height distribution from a resonance detector clearly separates proton pulses from electron pulses. Proton pulses at 1.5 MeV are produced in the detector by the inverse (☎,p) reaction of the resonance radiation with the N in the detector.

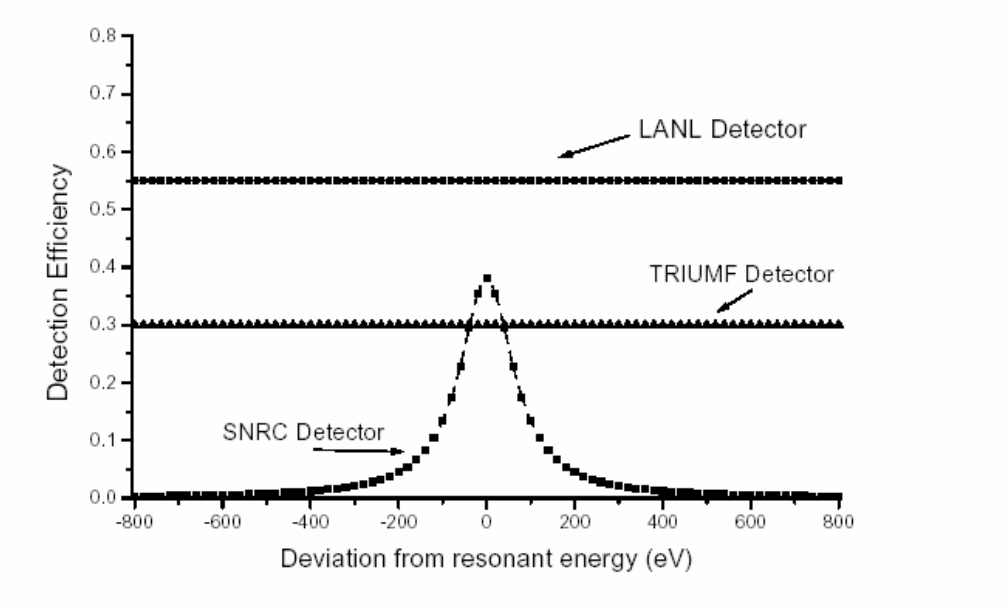
GRFT Detection Efficiency

$$\mathrm{eff}_R(E) = \frac{\mu_{\gamma p}(E)\,\rho_N}{\Sigma_T(E)}\left[1 - \exp(-\Sigma_T(E)\,d)\right]$$



Detectors:

- **LANL – BGO, 50x29x90 mm^3**
- **TRIUMF – Segmented BGO 50x50x50 mm^3 blocks 12x12 subvolumes 4x4x50 mm^3, 4 PMT**
- **SNRC – Resonance Detector**

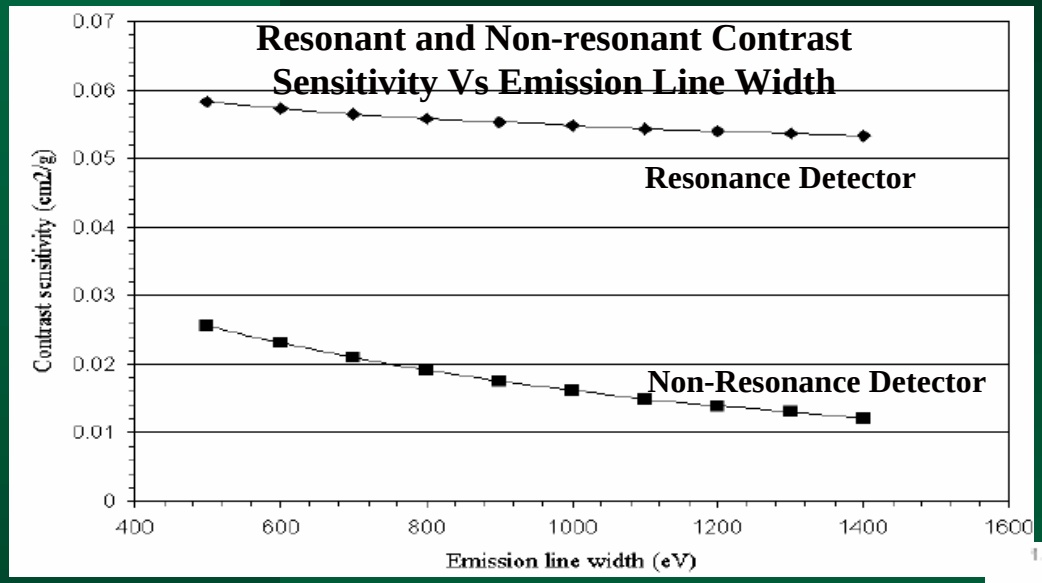


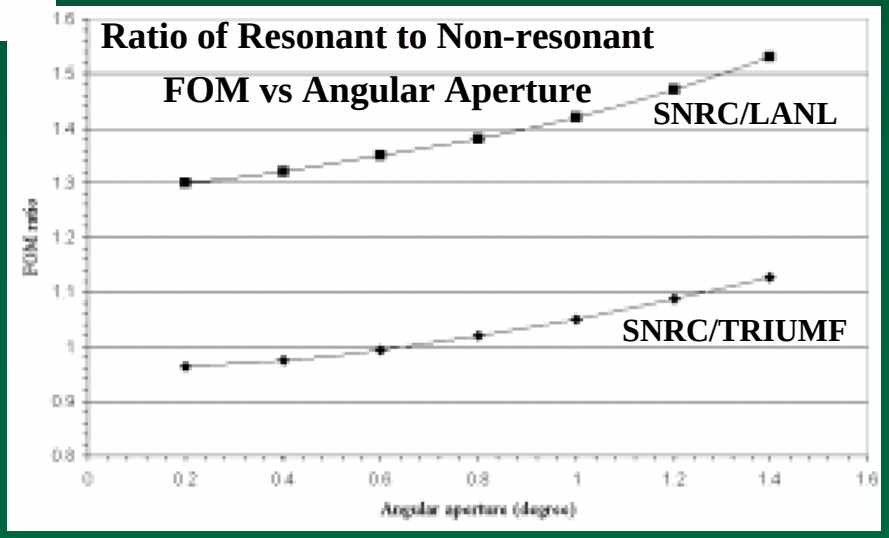
GRFT Performance of the Detectors

$$\mathbf{F.O.M} = m_{\mathbf{eff,N}} \cdot \square\mathbf{N}$$

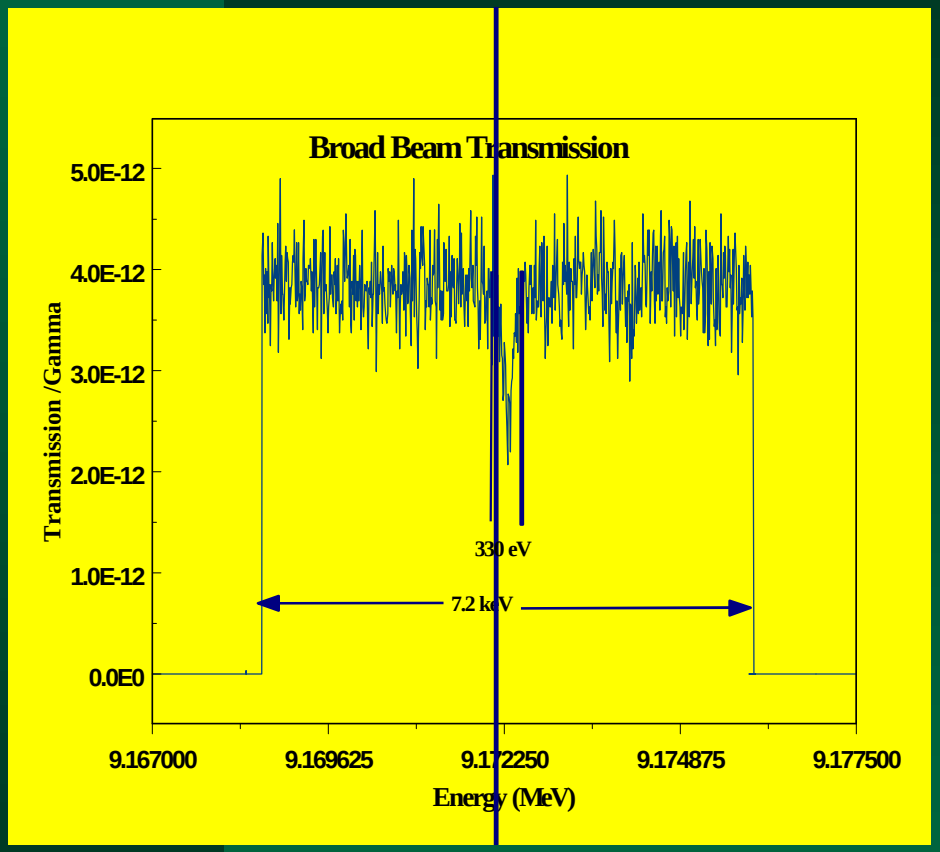
Parameter	Resonant Detector	Non-Resonant Detector
Contrast_sensitivity (thin absorber)	$\dfrac{\int_{-\infty}^{\infty} \mu_A(E)\, \Phi(E)\, \mathrm{eff}_R(E)\, dE}{\int_{-\infty}^{\infty} \Phi(E)\, \mathrm{eff}_R(E)\, dE}$	$\dfrac{\int_{-\infty}^{\infty} \mu_A(E)\, \Phi(E)\, dE}{\int_{-\infty}^{\infty} \Phi(E)\, dE}$
Number_of_detected_events	$\int_{-\infty}^{\infty} \Phi(E)\, \mathrm{eff}_R(E)\, dE$	$\mathrm{eff}_{NR} \int_{-\infty}^{\infty} \Phi(E)\, dE$

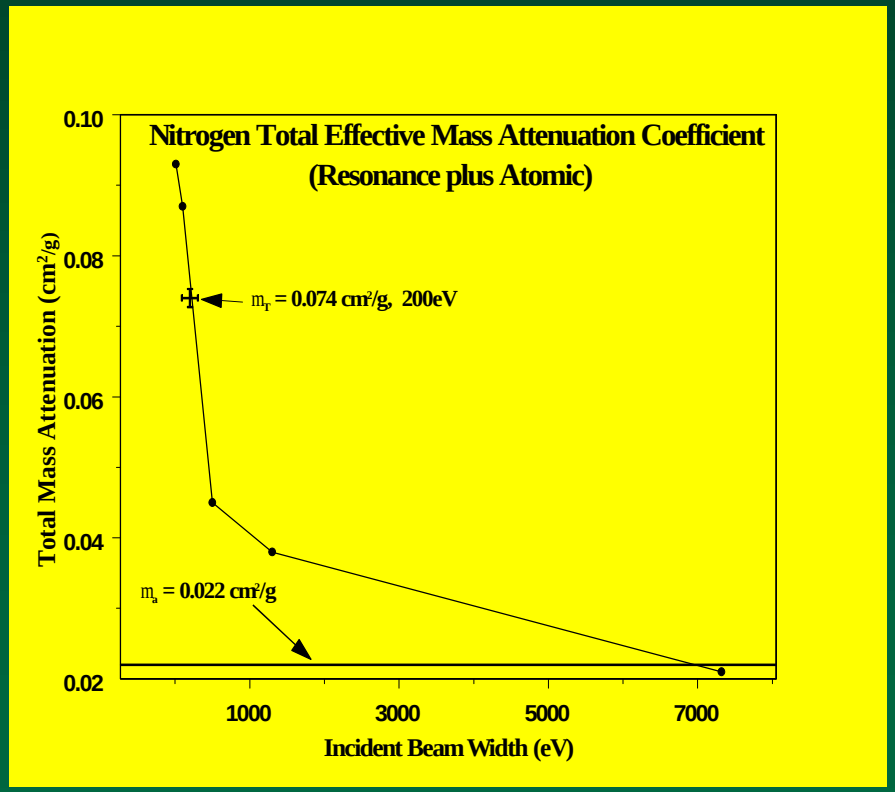
GRFT Performance of the Resonance Detectors



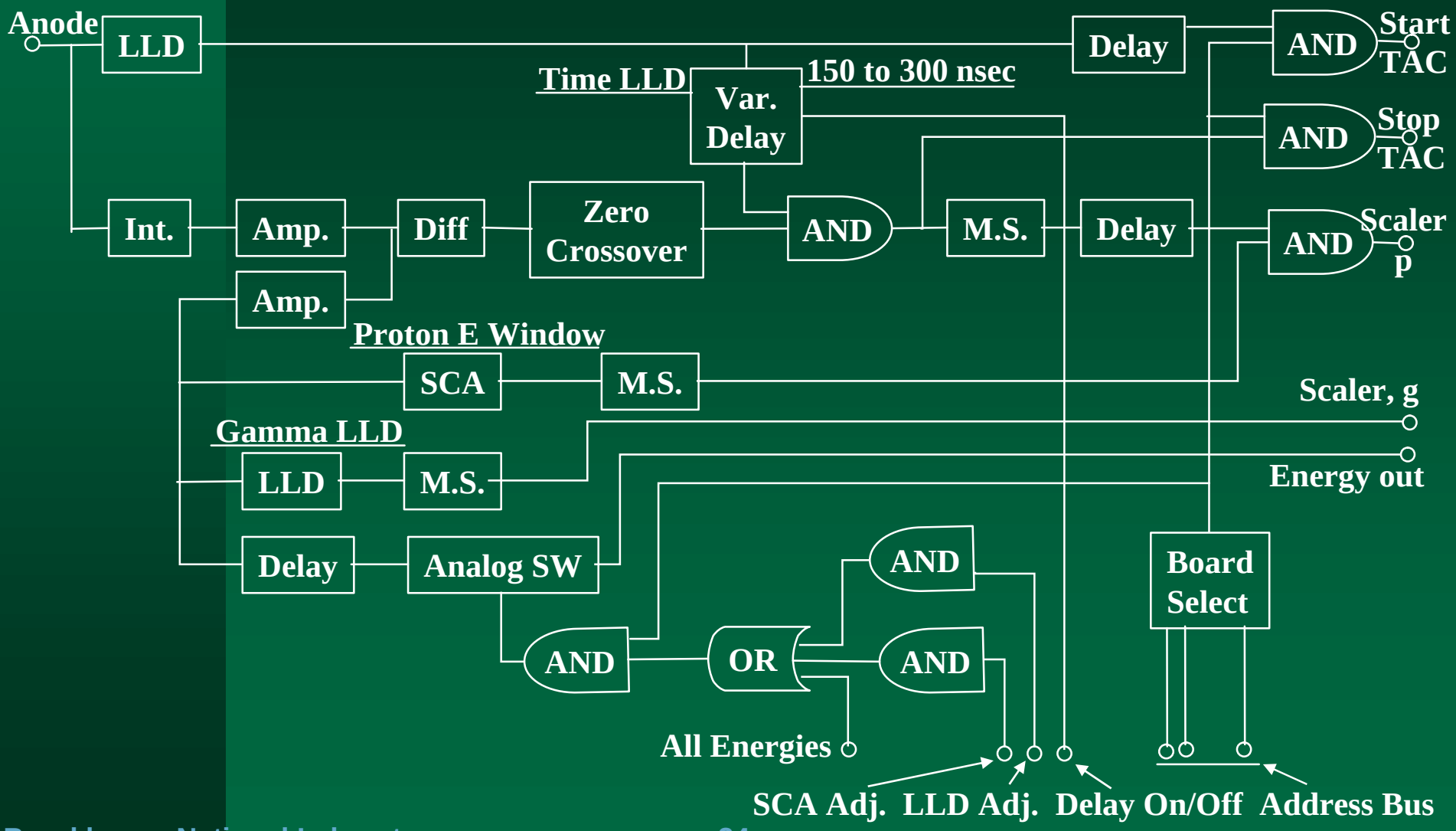


GRFT Broad Beam Attenuation





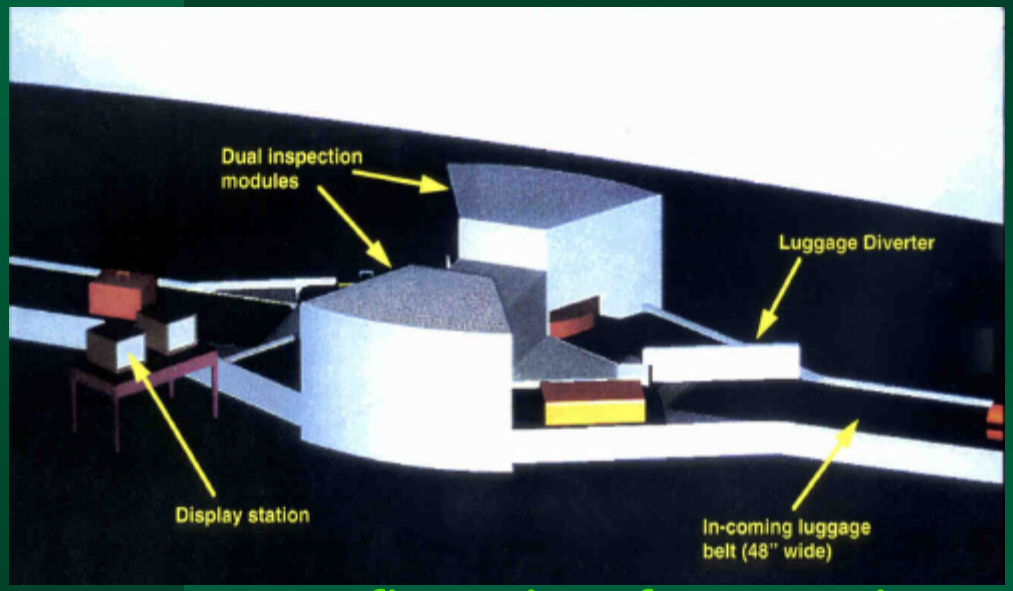
GRFT Broad Beam Attenuation



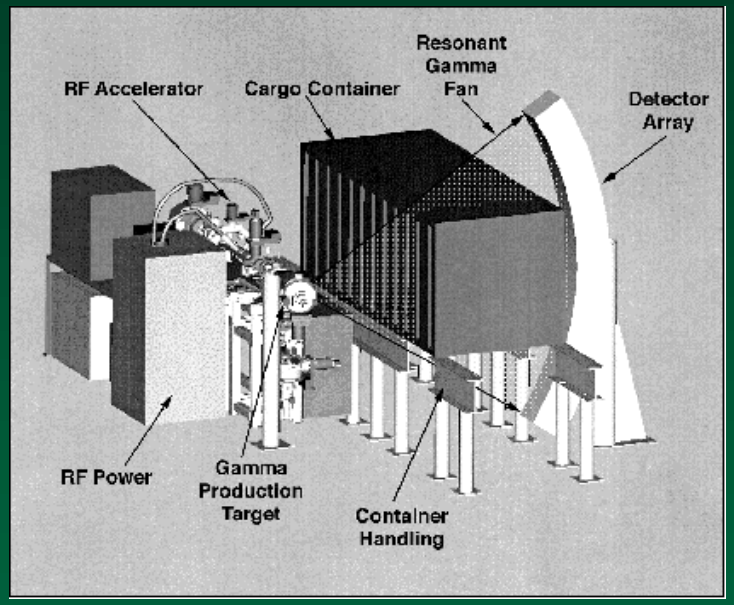
GRFT Performance of the Resonance Detectors

1. Simultaneous detection of the resonant and non-resonant attenuation.
2. No parallax resulting from two different paths at two angles.
3. Improved contrast due to resonance energy resolution of the detector.
4. Independent of the energy width of the incident beam
5. Ratio of the resonant to the non-resonant radiation independent of beam beam stability.
6. Liquid scintillator is a very cheap detection system.
7. Arbitrarily large detectors for remote detection can be easily constructed.

GRFT Applications



A configuration of a system in an airport feeding simultaneously two inspection stations for bags.



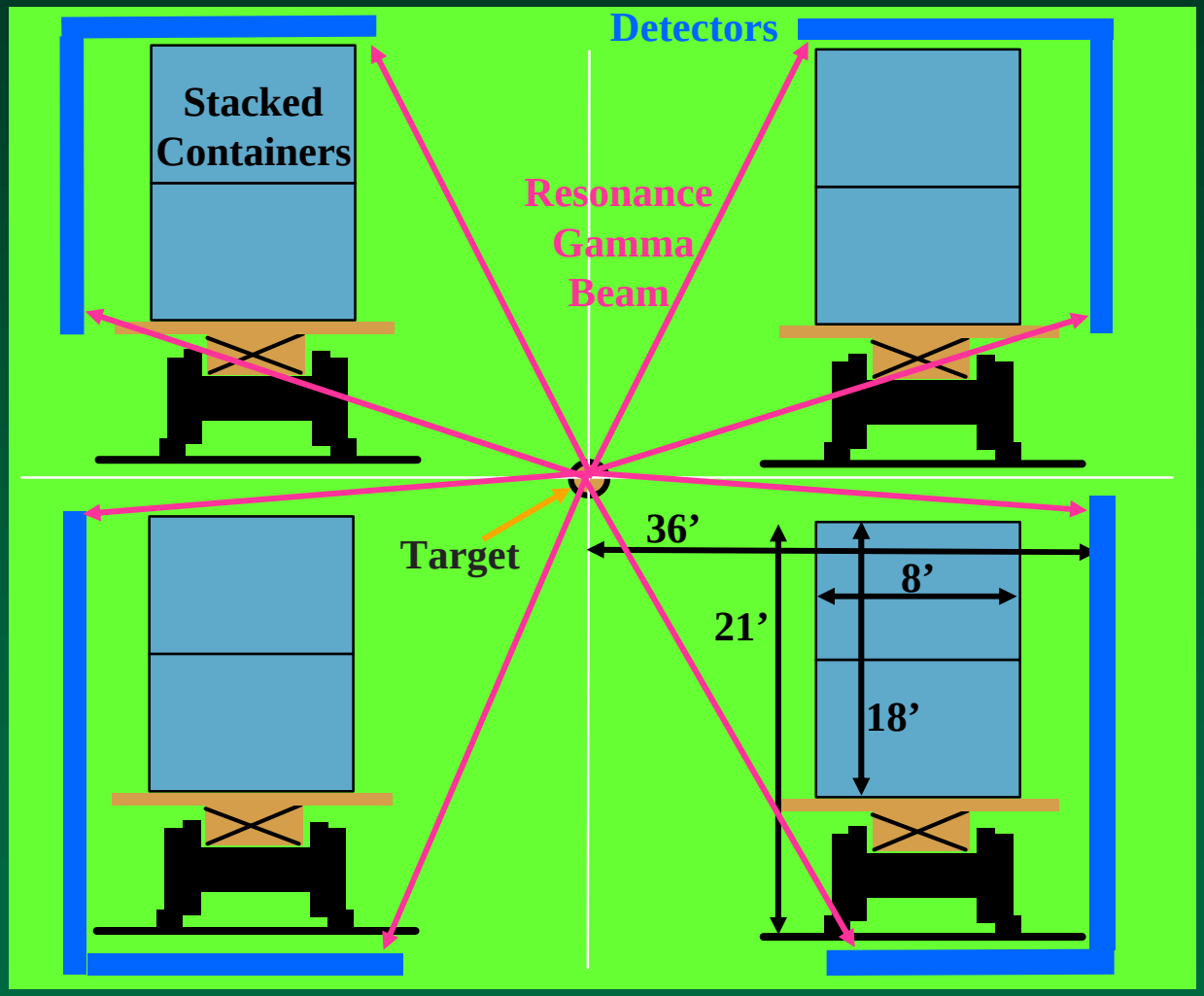
A possible configuration for scanning large containers

The same system can inspect small and large objects

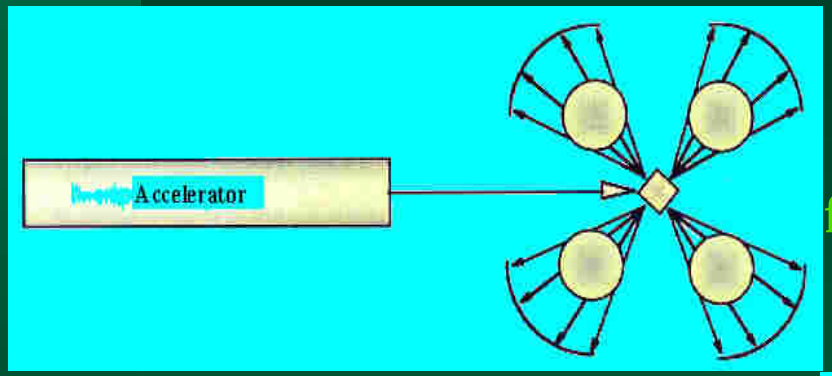
GRFT Applications

Using four ramps may inspect simultaneously 40 foot container in about 3 to 4 minutes, stacked containers will double the capacity.

(Times extrapolated from experiments)

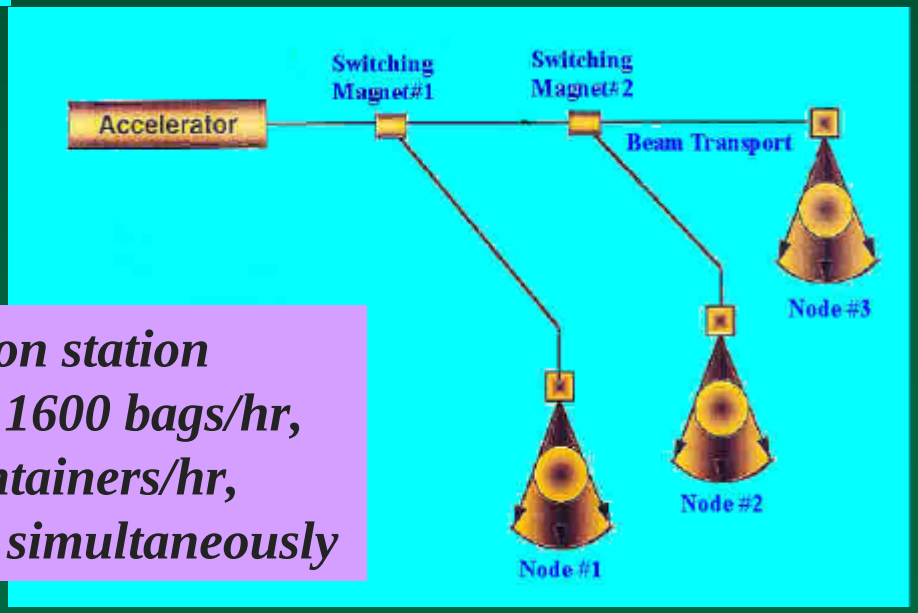


GRFT Applications



Single system feeds simultaneously four inspection stations at one location.

Single system feeds alternatively three inspection locations.



Each detection station can process 1600 bags/hr, 24 LD-3 containers/hr, 4 conveyors simultaneously

GRFT Proof-of-Principle For GRT

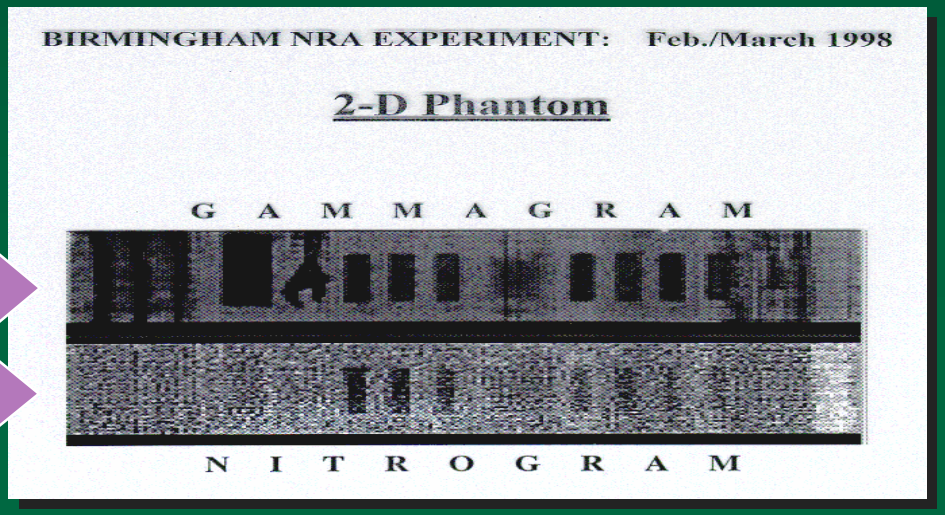
Nitrogenous and non-nitrogenous objects placed in a beam.

Experiments carried out by Nahal Soreq Group

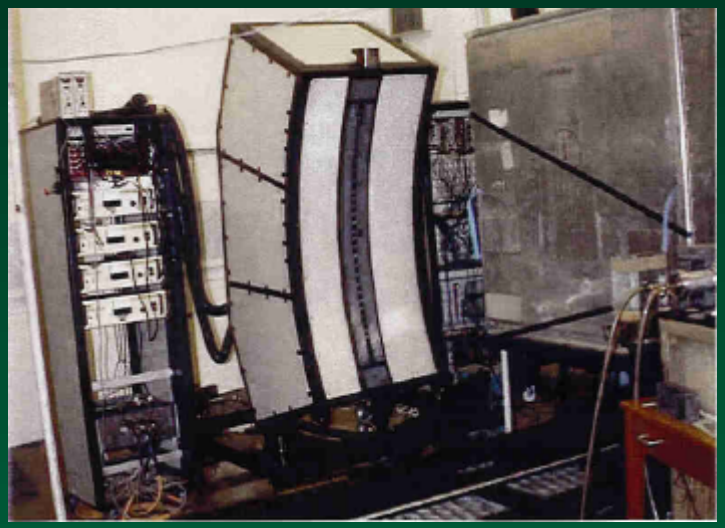
Images:

Out of resonance

In resonance



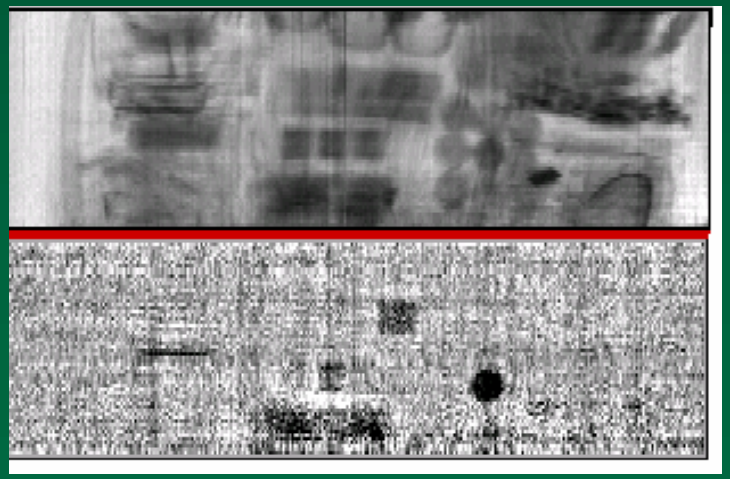
GRFT Proof-of-Principle For GRT



Six explosives were hidden in a LD-3 container loaded with a mixed cargo.

Experiments carried out

by Nahal Soreq Group



The gammagram (upper)and the nitrogram (lower) are created simultaneously. There is separation of the explosives from the remaining items.

GRFT *Experimental Results*

ROC curves, detection probability versus false alarm probability, were established
DP>90%, FAP<5%

Resonance Mass Attenuation (μ_{Nres}) 0.052 cm^2/g

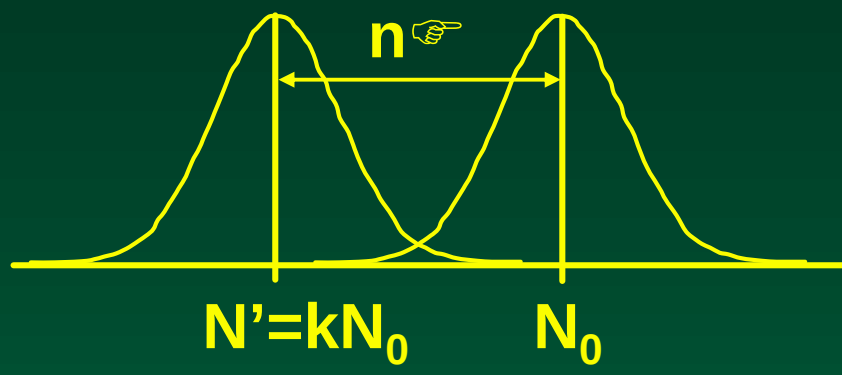
Resonance Count Rate (protons) 0.041 C/s·A
Non-Resonance Count Rate (electrons) 0.820 C/s·A

Since the detectors covered the entire width of the resonance beam these count rates are independent of the source distance.

GRFT Scanning Time Estimates

Gamma Resonance Counts

$N_0 - kN_0 = n\Delta = n\Delta N_0$



Cont-ainer	Explosive Dimensions cm	Explosive Mass g	Time/ Slice s	Scan Time min
LD3*	20x20x0.5	300	8	10
LD3	5x5x5	190	1.4	1.75
C#	10x10x10	1500	1.8	3.66

CR_p 200 C/s(5mA)

* 153x156x163 cm^3, Max. 1588 kg, ρ 0.4 g/cc, Att. Factor 4

\# 8'x8'x20', 246x246x610 cm^3, Max. 20000 kg, ρ 0.54 g/cc, Att. Factor 12

GRFT Photo-Fission Threshold Energies

- Photo-neutrons (☎,n) are produced with every material producing prompt neutrons.
- Photo-fission (☎,fission) occurs only with fissile materials producing prompt and delayed neutrons.
- Threshold energies in fissile materials

Nuclear Isotope	(☎,n) [MeV]	(☎,fission) [MeV]
– Pu-239	5.6	5.6
– U-235	5.3	5.8
– U-238	6.1	5.8
– Th-232	6.4	6.0

GRFT Photofission Proof-of-Principle

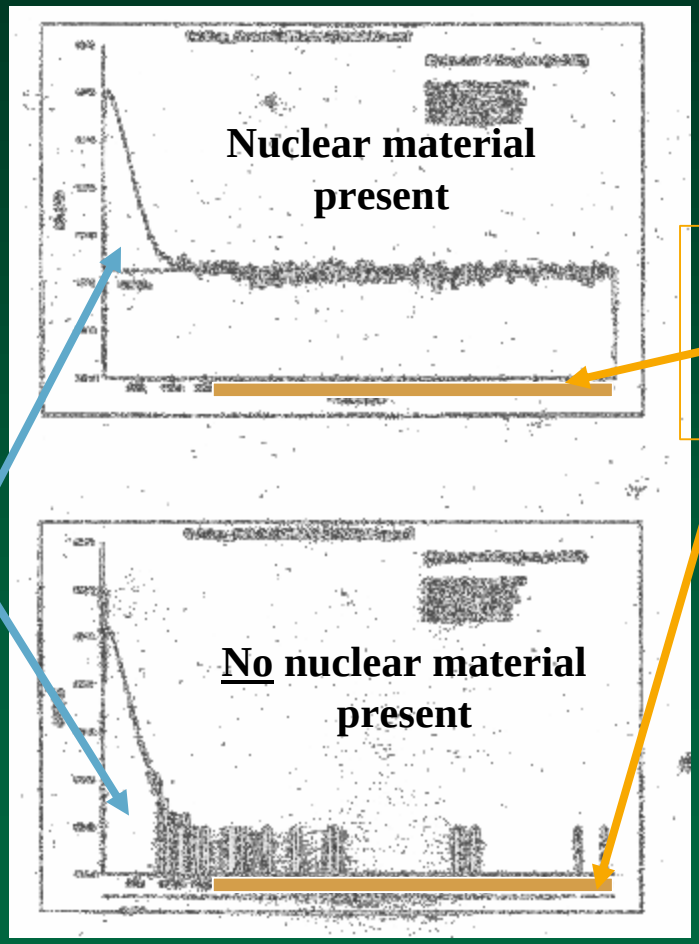
^{3}He Neutron Detector

MCS

PC with Acquisition Program

Analysis Program

Accelerator Pulses



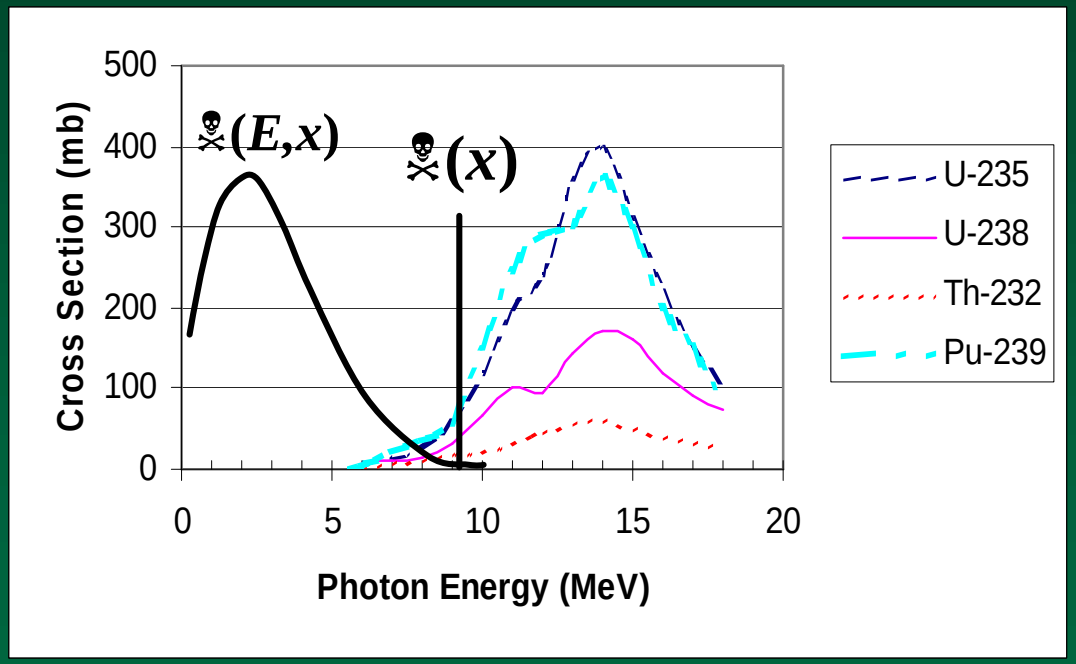
Region Of Interest

Time after pulse →

Experiments carried at INEEL

GRFT Photofission Yield

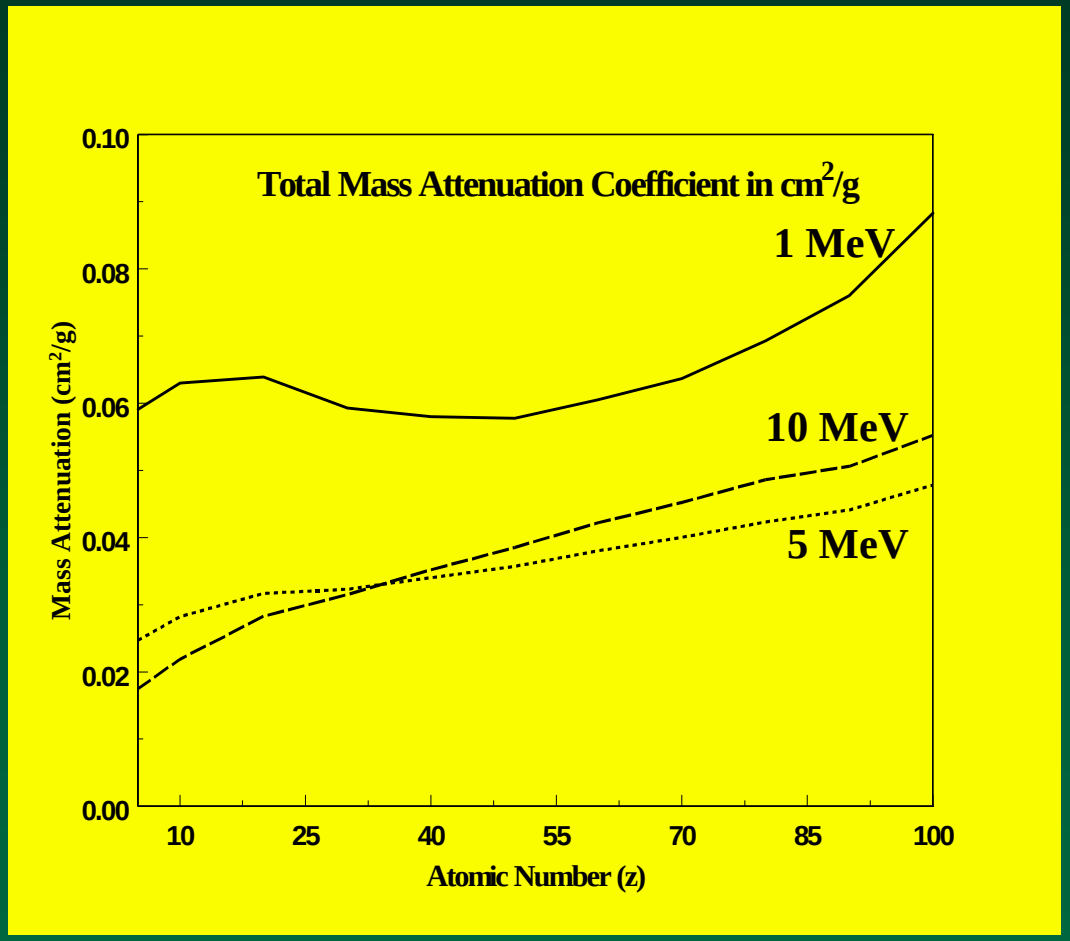
$$n = \int_{E_{thres}}^{E_{max}} dr^3 \int \sigma(E,x) N(x,t) \Phi(E) dE$$



GRFT Dual Energy Absorptiometry

$$\ln\left(\frac{I}{I_0}\right)^{L_E} = S(m_i\ r_i\ L_i)$$

$$\ln\left(\frac{I}{I_0}\right)^{H_E} = S(m_i\ r_i\ L_i)$$



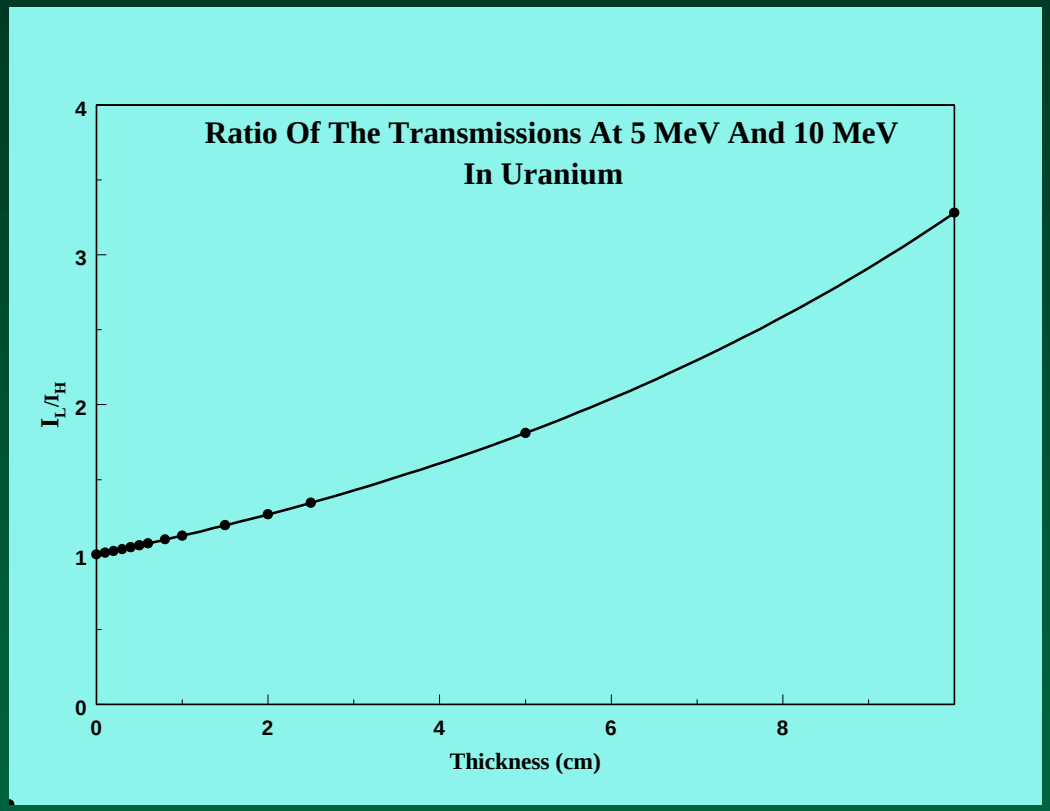
GRFT Dual Energy Absorptiometry

$$\frac{I_L}{I_H} = R = (m_H - m_L)\,r\,x)$$

For:

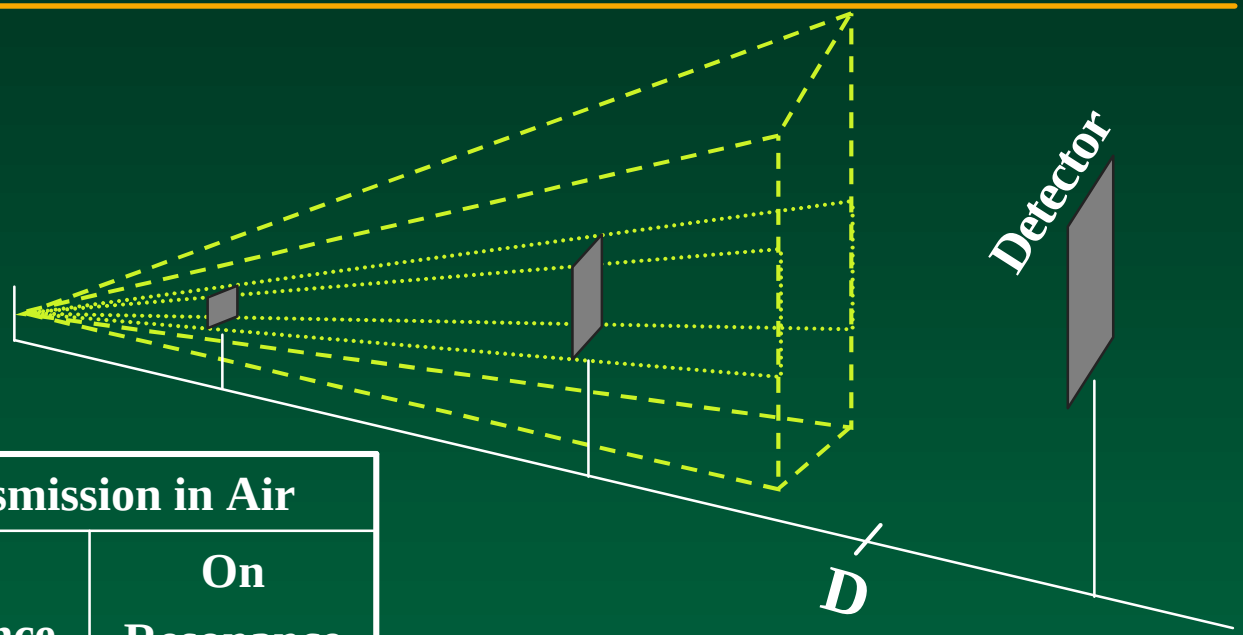
x=0.1 cm, R=1.012, CR=333c/s5mA, @ 3s

$$I_L = \left(\frac{3}{1 - 1/R}\right)^2$$



I_L = 253 counts. **<u>This will require 0.76 s.</u>**

GRFT Air Attenuation for Remote, Stand Off



Distance D (m)	Transmission in Air	
	Off Resonance	On Resonance
10	97%	95%
50	88%	79%
100	77%	62%
200	60%	38%
300	46%	23%

GRFT Site Development

BNL test site for container scanning system

GRFT Summary

- High detection probability (>90%) for explosives
- Low false alarm rate (<5%)
- High throughput
- Single source can feed multiple inspection stations
- Suitable for inspecting shipping containers
- Offers dual high energy gamma ray absorptiometry
- Capable of detecting fissile materials
- Elemental specificity 3-D imaging capability
- No residual activation or site contamination