


# Electron Linacs for Cargo Inspection and Other Industrial Applications

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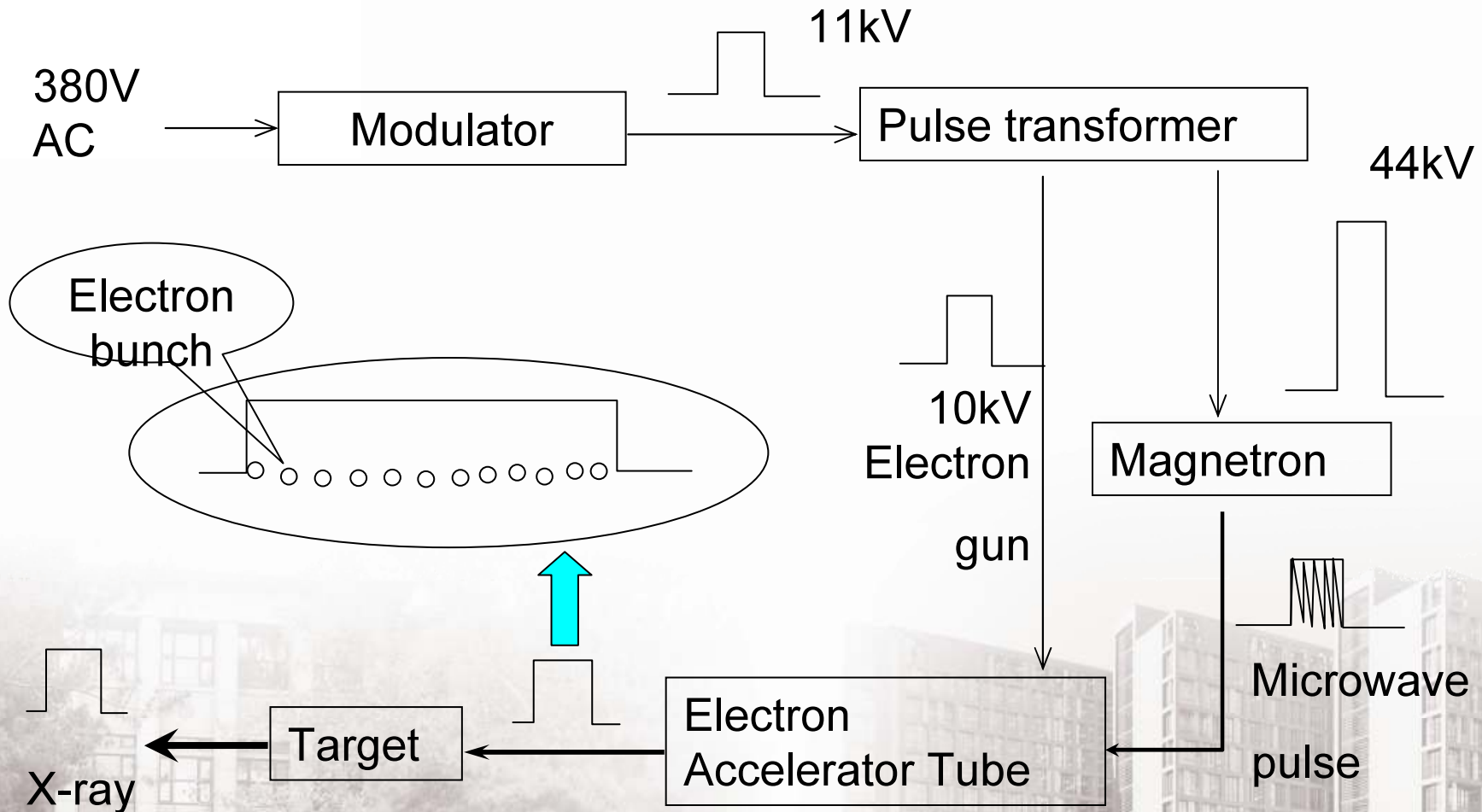
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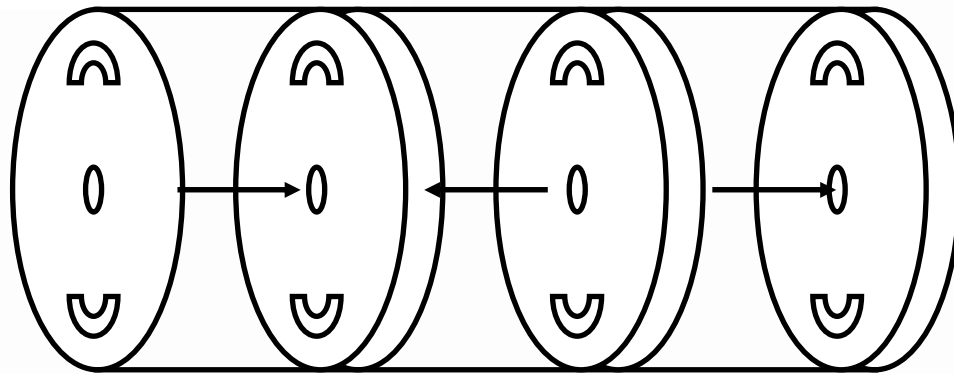
<sup>2</sup> NUCTECH Company Limited, Beijing 100084, China 

International Topical Meeting on **Nuclear Research Applications and Utilization of Accelerators**  
Vienna, Austria, 4–8 May 2009

# 1. A low energy linac system

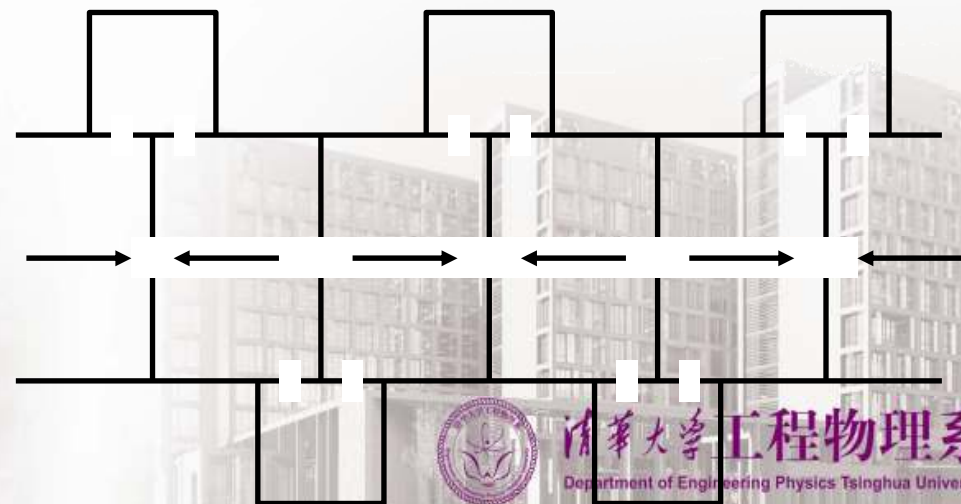


# Standing Wave Accelerating Structures



On-axis magnetic coupled bi-period structures used in Tsinghua university.

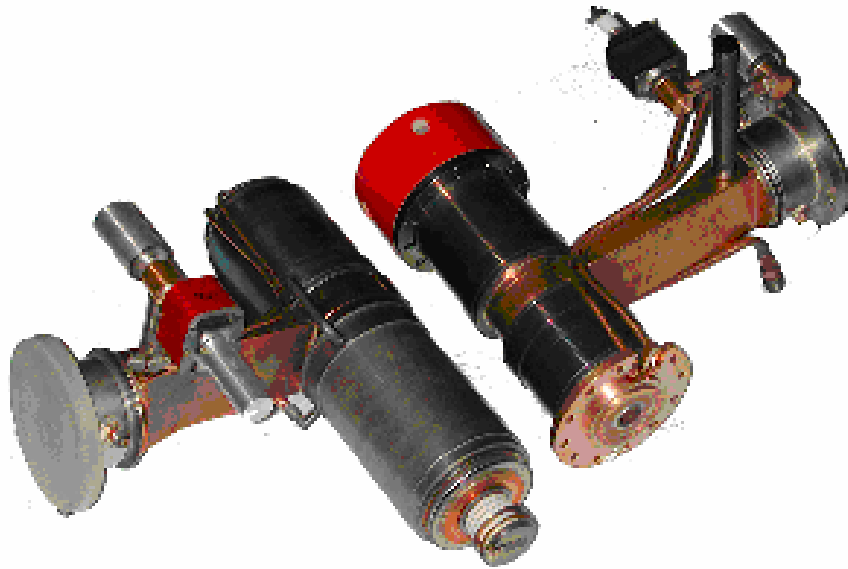
Side coupled structures used in BMEI



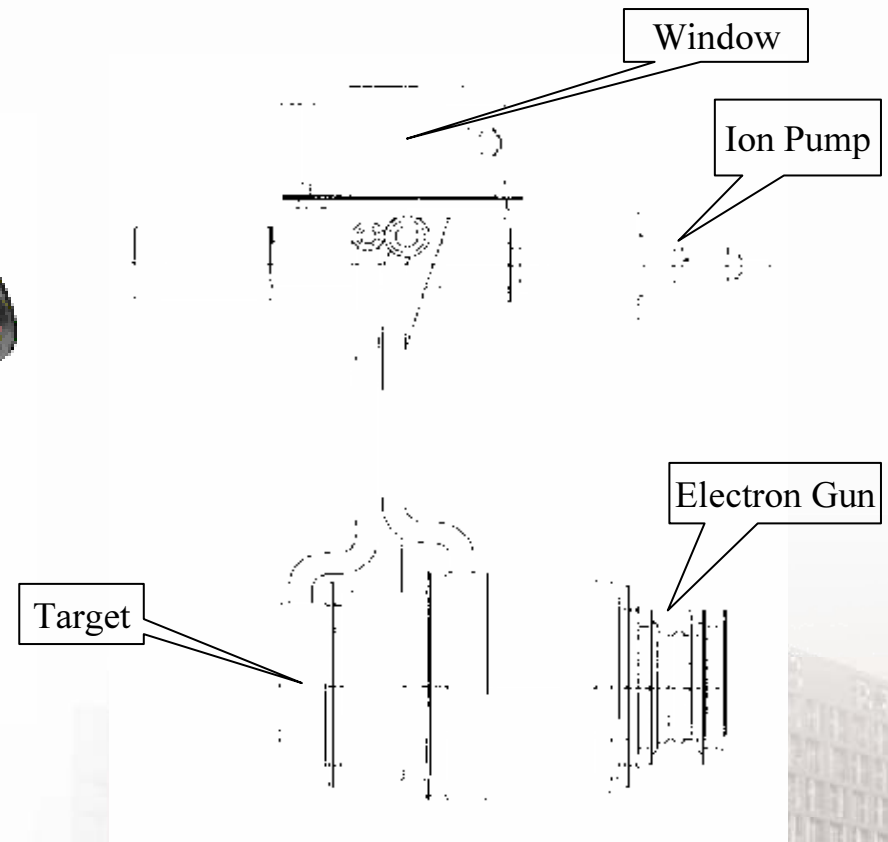
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# SW accelerating tubes

6MeV accelerating tubes



9MeV accelerating tubes



More than 300 SW 6MeV accelerating tubes has been produced by Tsinghua U. for medical therapy and NDT linacs.

# S-band Linacs for X-ray Imaging



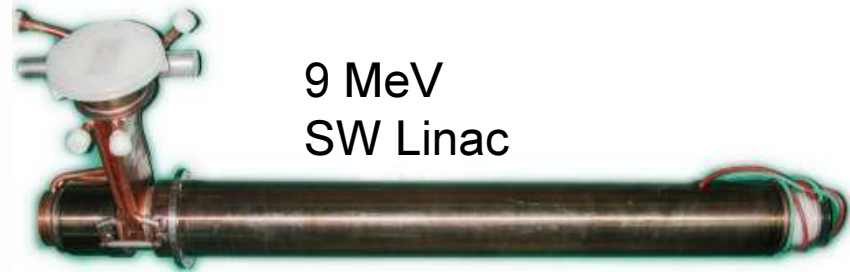
1.5 MeV  
SW Linac



2 MeV  
SW Linac



4 MeV  
SW Linac



9 MeV  
SW Linac



15 MeV  
SW Linac



6 MeV  
SW Linac

# Traveling Wave Accelerating Structures



Bunching section

Main accelerating section

- Constant impedance



A 9 MeV traveling -wave linac developed for cargo inspection systems

Length: 2.4 m

RF source: 5MW klystron

Electron Energy: 9MeV

Dose Rate: 30 Gy/min-m



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# SW vs TW

	SW	TW
Gradient:	~10MeV/m	~5MeV/m
Efficiency:	30~60%	20~50%
Capture:	20~30%	~80%
Gun voltage:	5~20kV	~40kV
Band:	~200kHz	~2MHz
AFC:	Required	not need
Size:	small and simple	large
Stability:	good	can be good



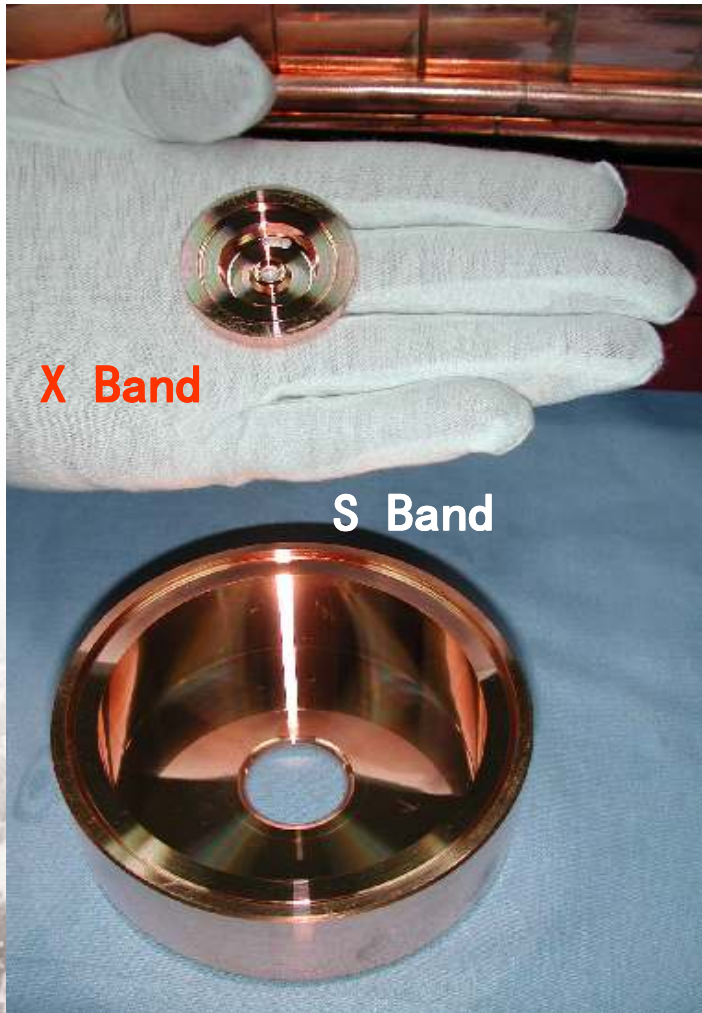
# X-band, C-band , S-band or L-band?

- Mainly depends on:
  - Requirement of different applications
  - Commercial microwave power source available
  - The knowledge and technology
- Most of the low energy linacs are s-band
  - The microwave power source are common and cheaper
  - Size and weight are medium
  - Technologies are easy now
  - Electron parameters are enough for most applications
- X-band is used for mini-systems or portable systems
  - Cybernife and Mobitron for radiotherapy
  - Mobile cargo inspections
- L-band and C-band used not common
  - For L-band power source can deliver more than 1MW average power, suitable for high power electron linac used in irradiation
  - C-band less of commercial power source





# X Band Accelerating Structure



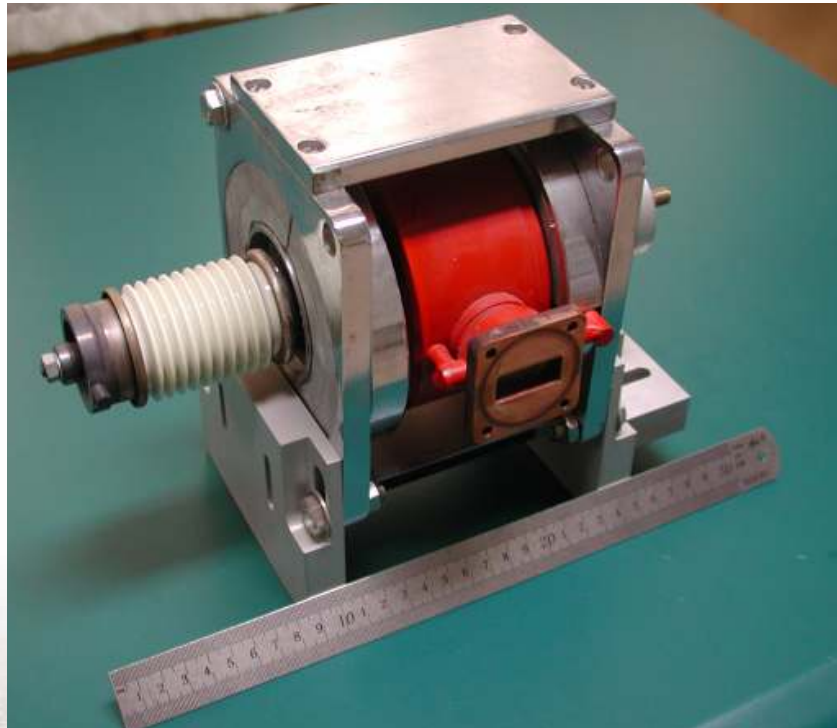
X-band 2.5MeV Accelerating tube



X-band 6MeV Accelerating tube



# X-band Magnetron is one of the main bottleneck for x-band linac's application



BVERI X-band magnetron:  
9300MHz, 1.~1.5MW, 4 $\mu$ s, 250Hz



E2V X-band magnetron:  
9300MHz, 1.~1.5MW, 4 $\mu$ s, 250Hz



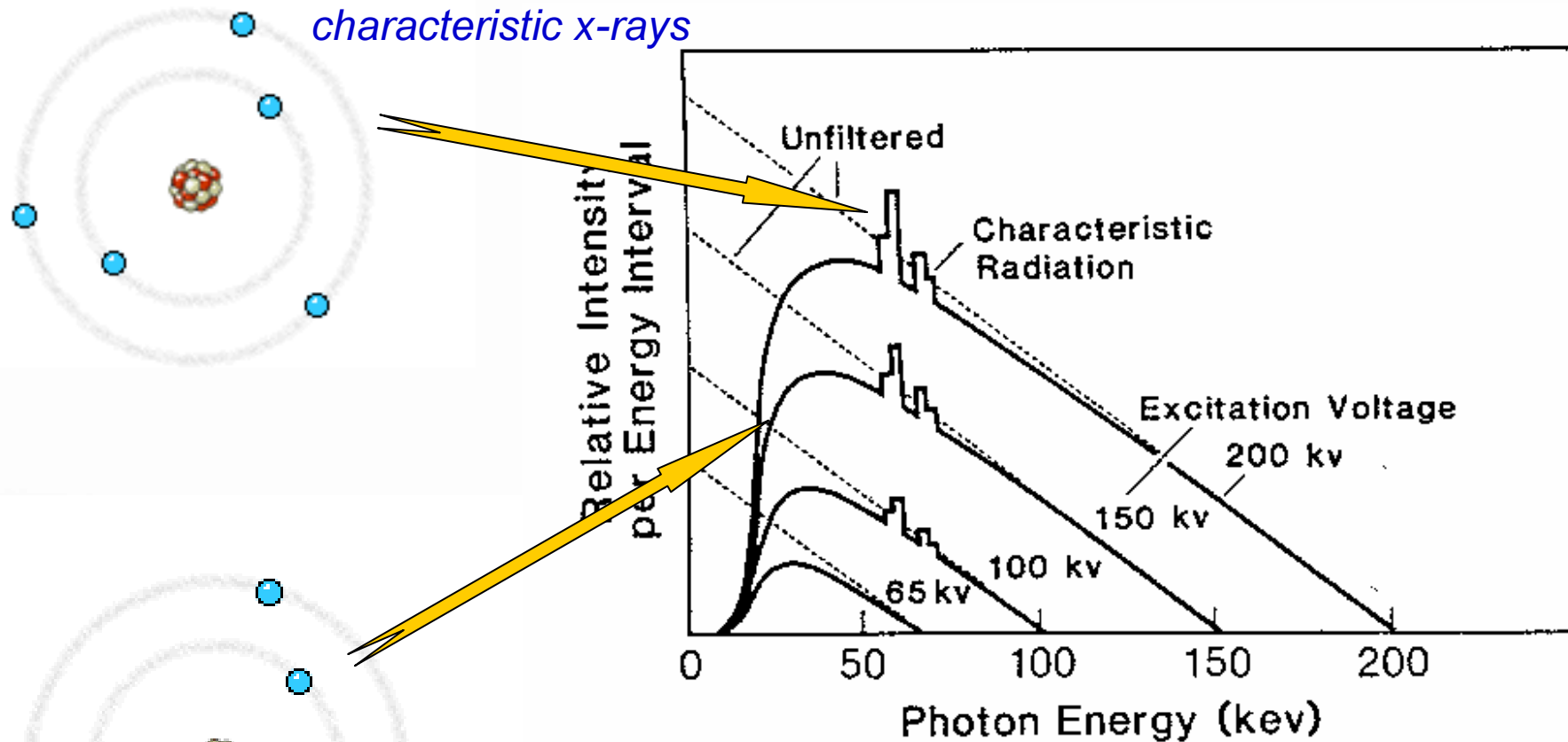
# What's important for developing a linac of industrial applications?

- Reliability and Stability
  - Modulator
  - Cooling System
- Performance meeting the requirement
- The simpler, the better
- Easy for operating and maintenance



# 2. X-ray Sources

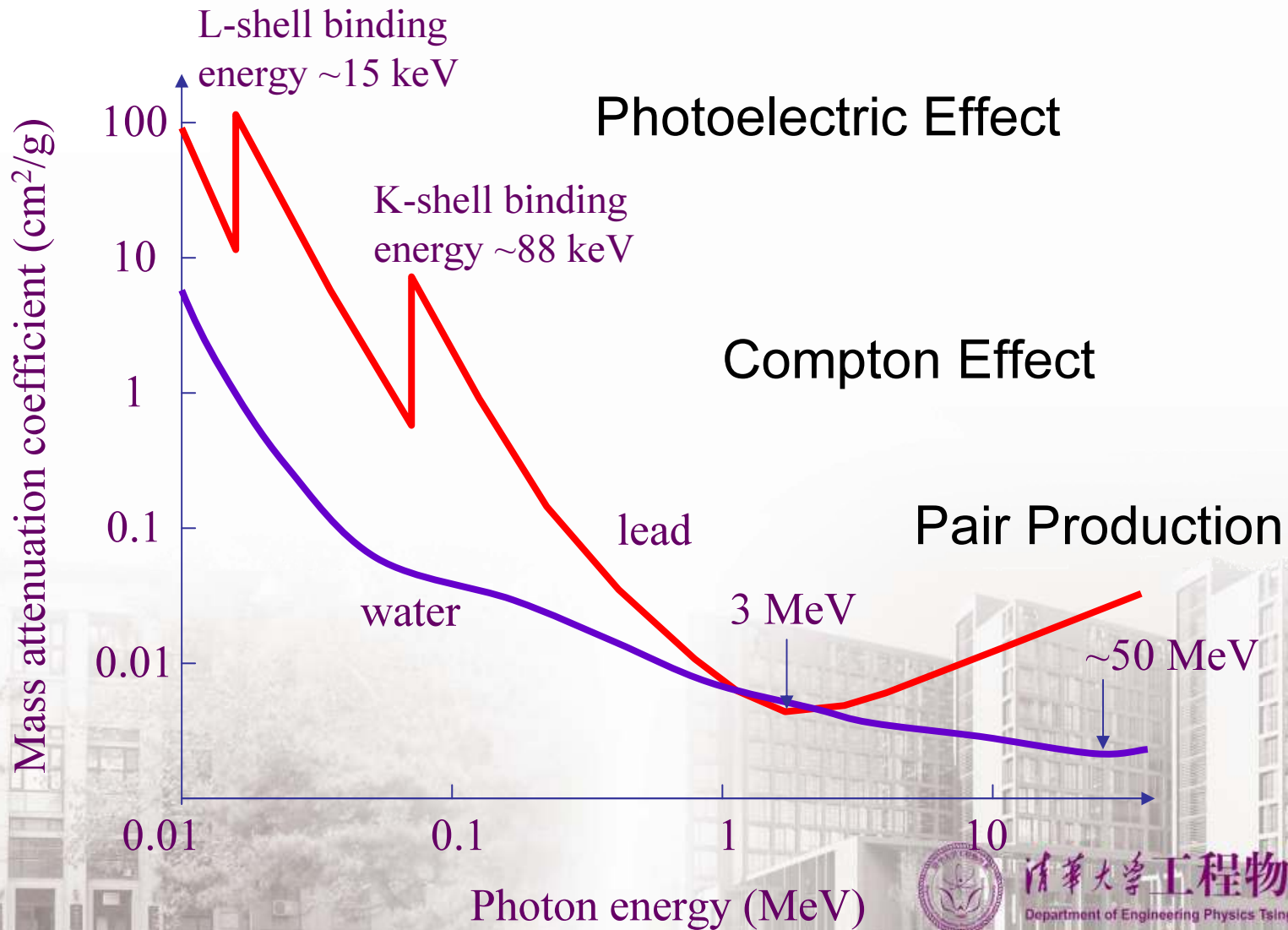
A typical x-ray energy spectrum from an electron beam hitting a target



*bremsstrahlung x-rays*

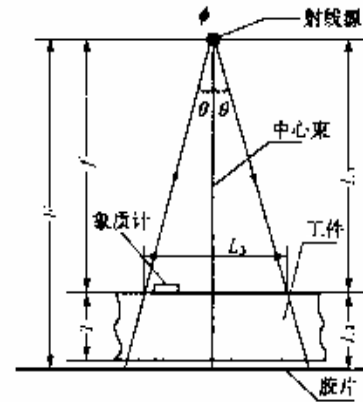


# Photons absorbed by materials

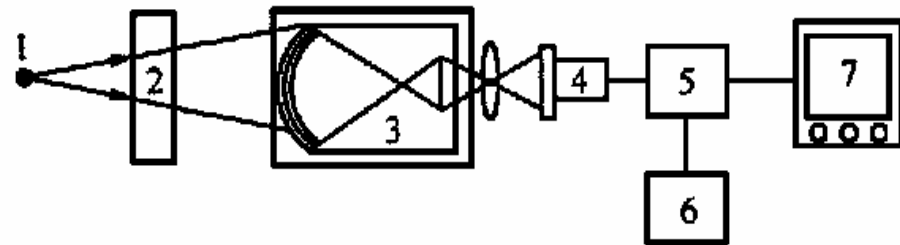


# X-ray Imaging

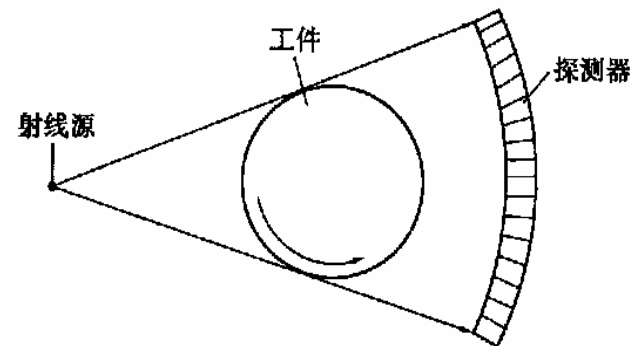
- X-ray Photography



- Real-time Imaging



- CT imaging



# Attenuation of X-ray

$$J = J_0 e^{-\mu x}$$

where

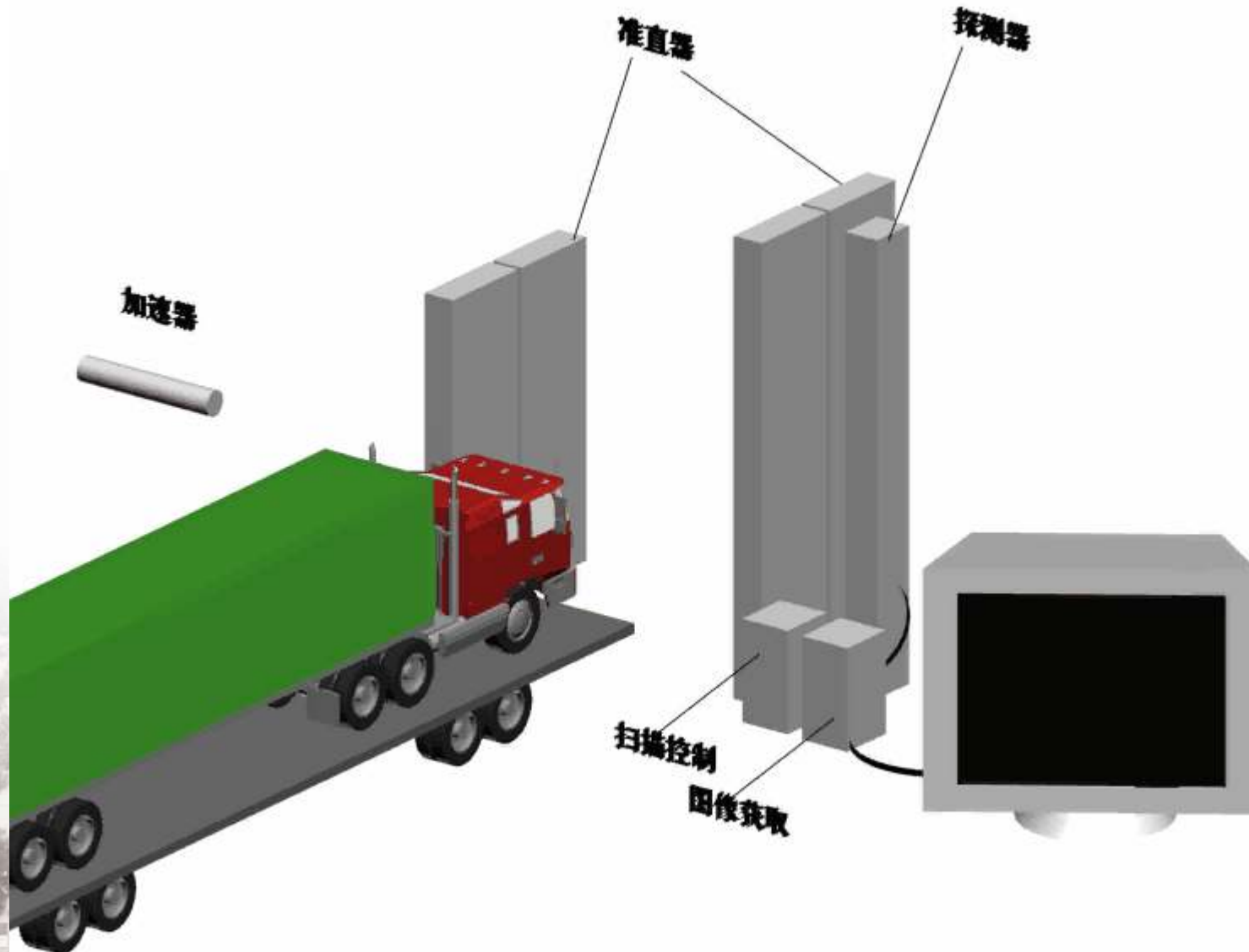
$J$  — intensity of the x-ray after the materials

$J_0$  — The initial intensity of the x-ray

$\mu$  — the attenuation factor,  $\text{cm}^{-1}$



# 3 Cargo Inspection Systems





# Cargo Inspection Systems and Their Linacs

Fixed



RF source: 5MW klystron  
 Electron Energy: 9MeV  
 Dose Rate: 30 Gy/min-m

Relocatable



Electron energy 6MeV  
 Dose rate ~12cGy/min  
 RF Source: 2.6MW  
 Magnetron

mobile



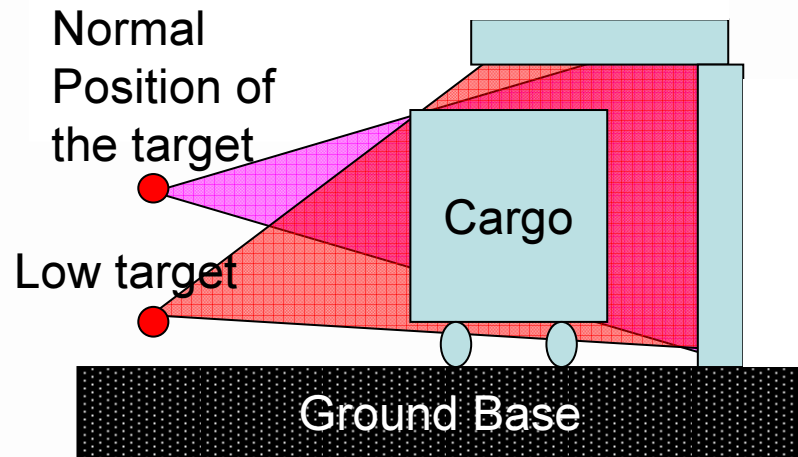
X-band 2.5MeV  
 SW Tube  
 Powered by a  
 1MW 9300MHz  
 magnetron



S-band 2.5MeV  
 SW Tube  
 Powered by a  
 MG5125  
 magnetron

# Low Target Mobile System-III

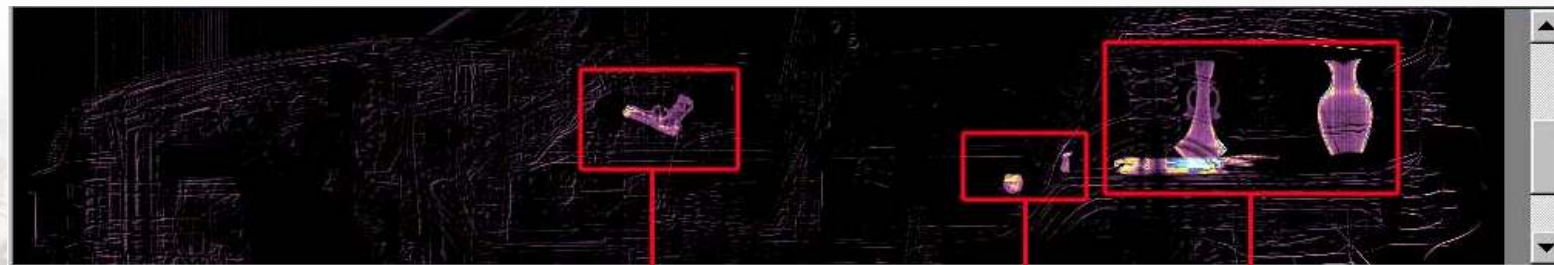
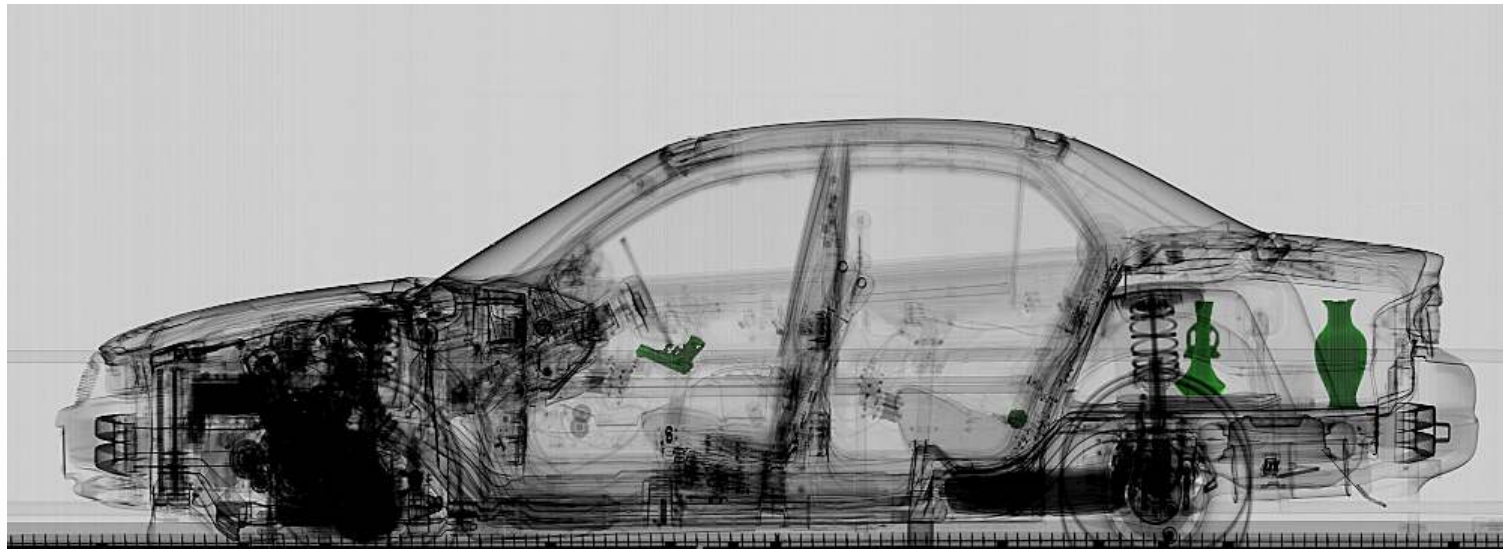
with An S-band 2.5 MeV electron linac as x-ray source



# Railcar Inspection Systems



# Typical Pictures

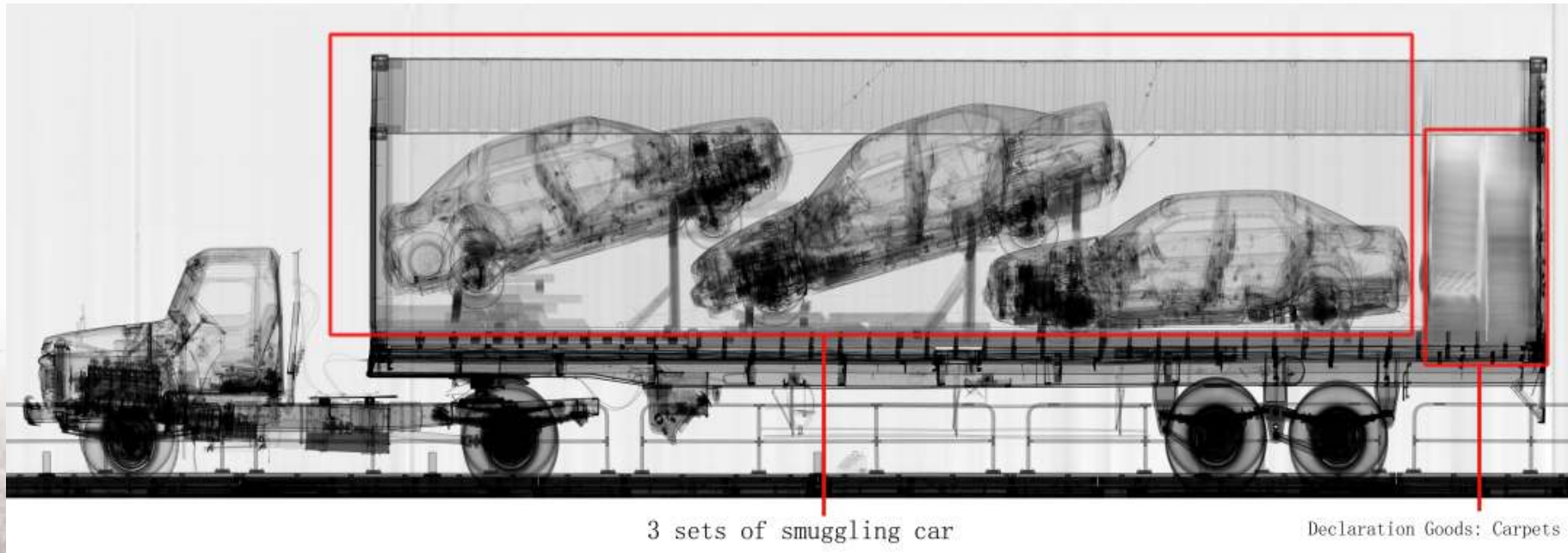


Pistol

Grenade Simulant

Smuggling Cultural Relic

# Smuggling Cars

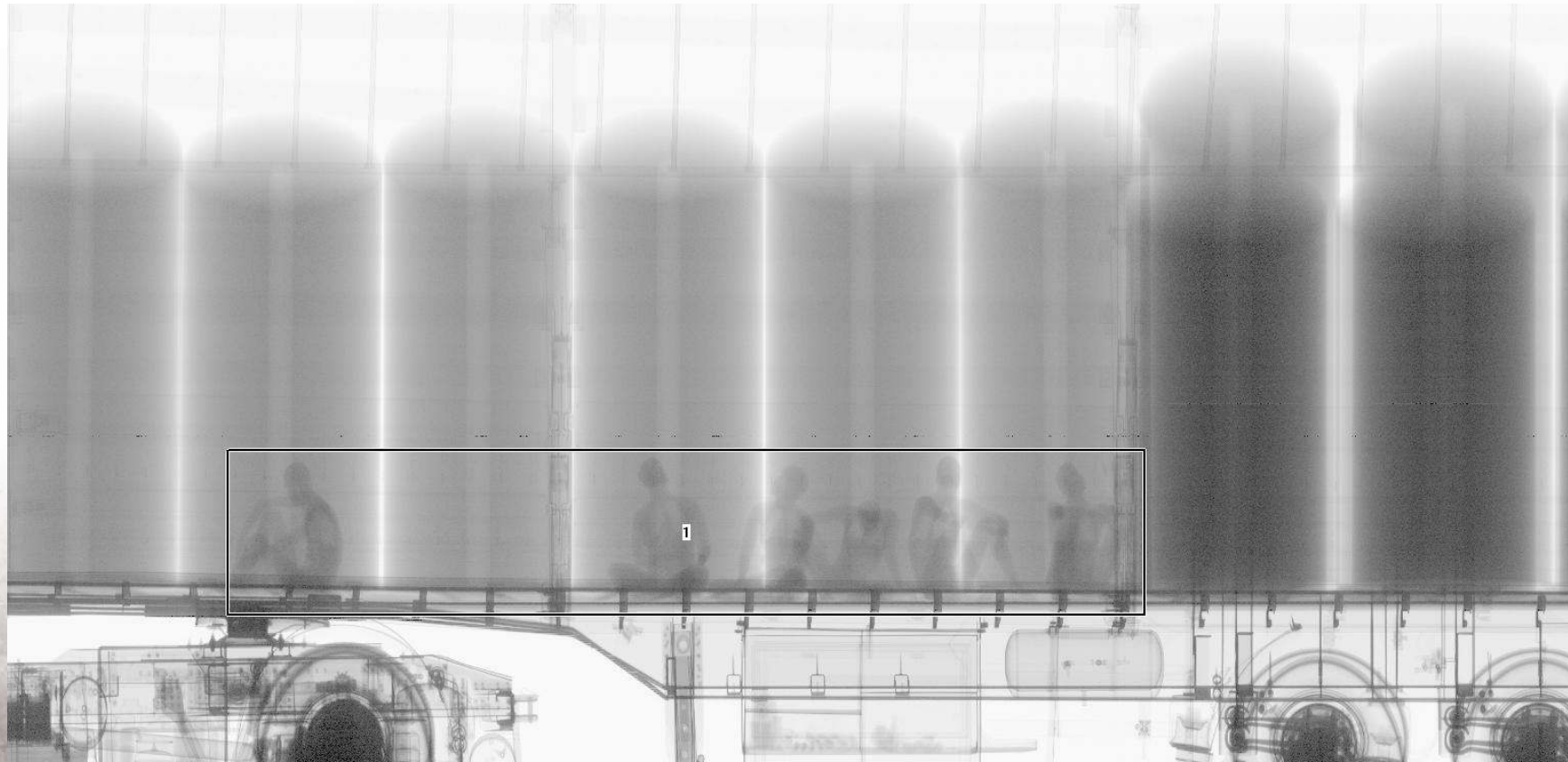


3 sets of smuggling car

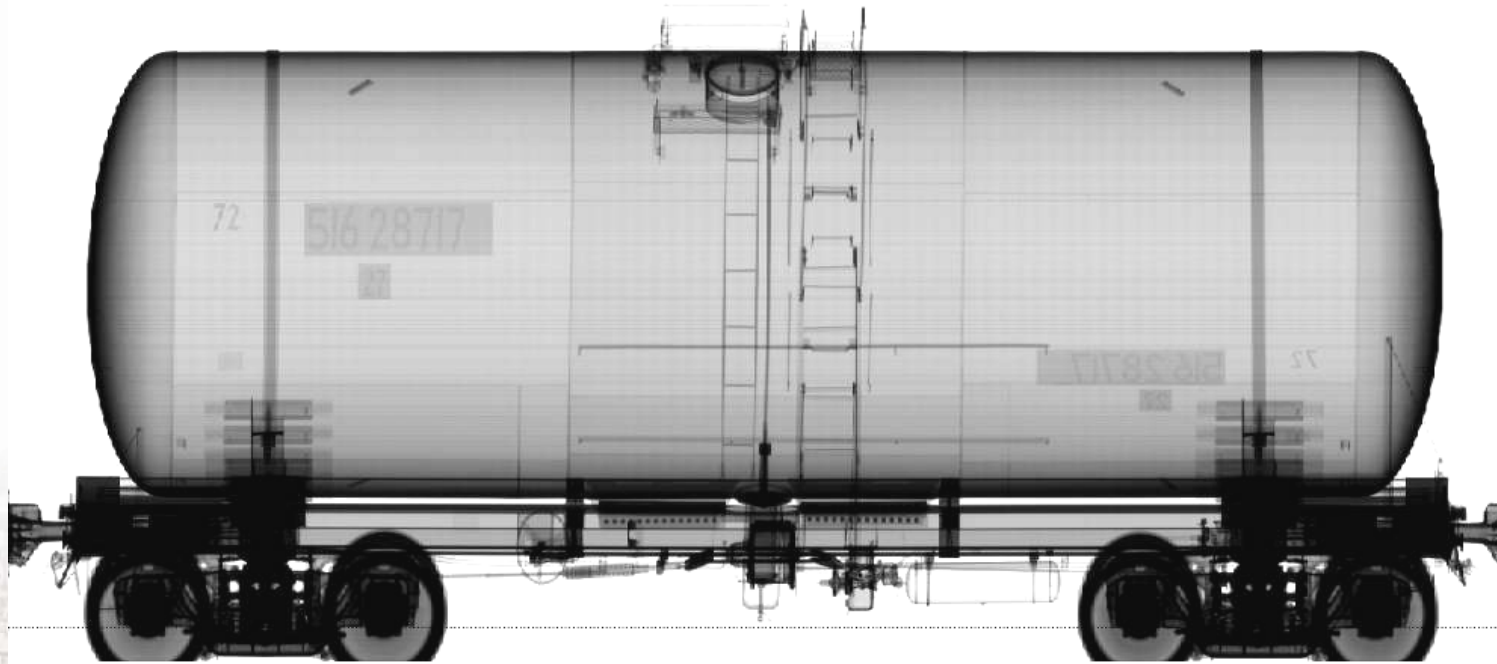
Declaration Goods: Carpets



# Stowaway



# Railcar Inspection with speed of 40km/h

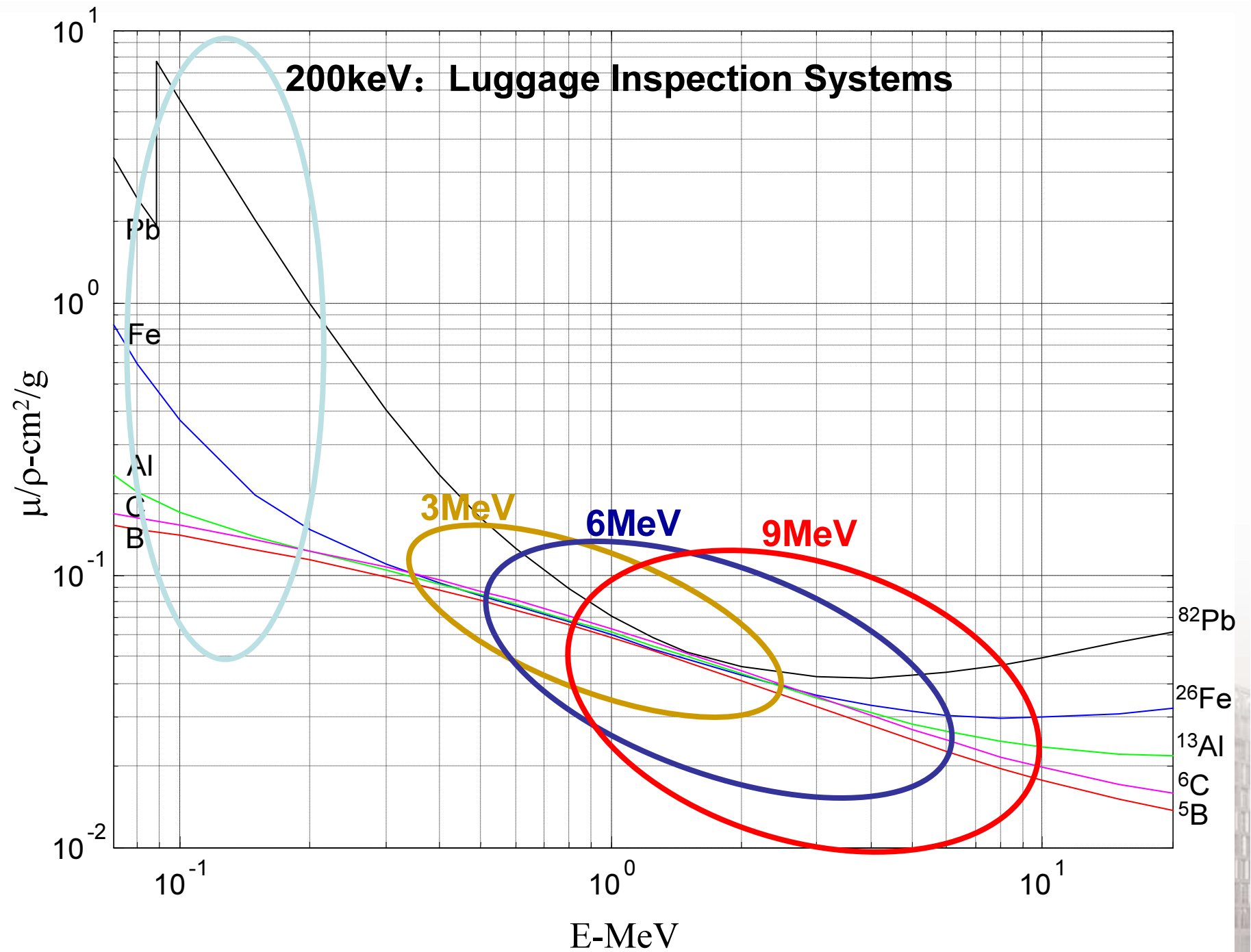


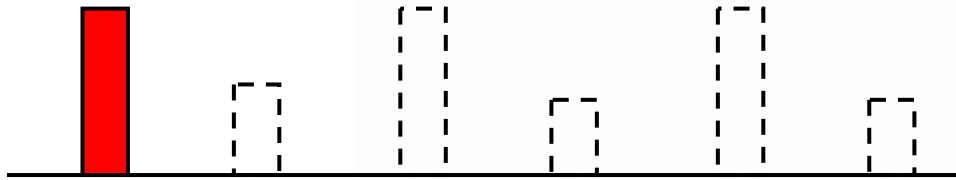
# New Challenges

- Material Identification
  - Dual Energy X-rays are the most prospected technology
  - Neutron technology is still under way
  - CT is hard to be used for large container inspection
- High throughput
  - Cargo driven through the inspection area
  - Integrate the inspection to the container transfer process





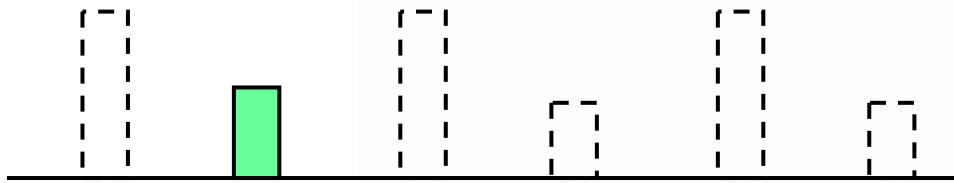




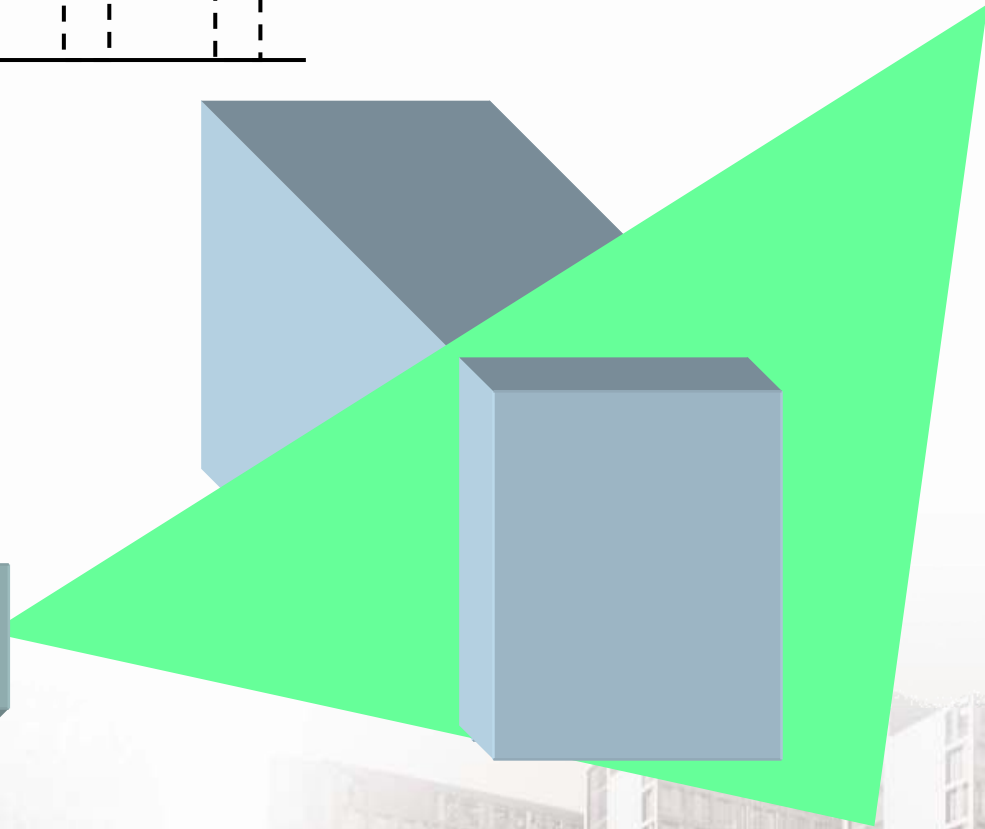
Dual Energy Linac



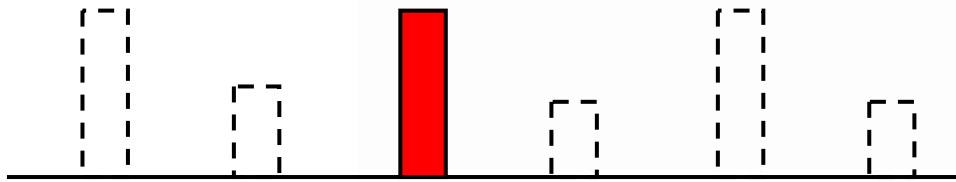
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Dual Energy Linac



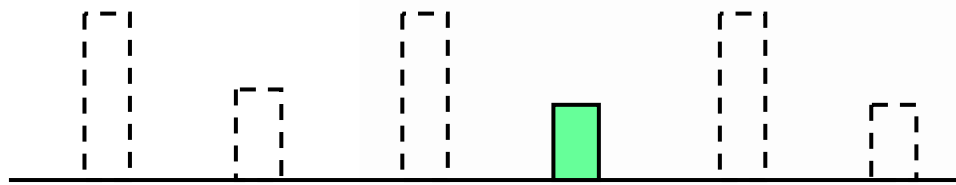
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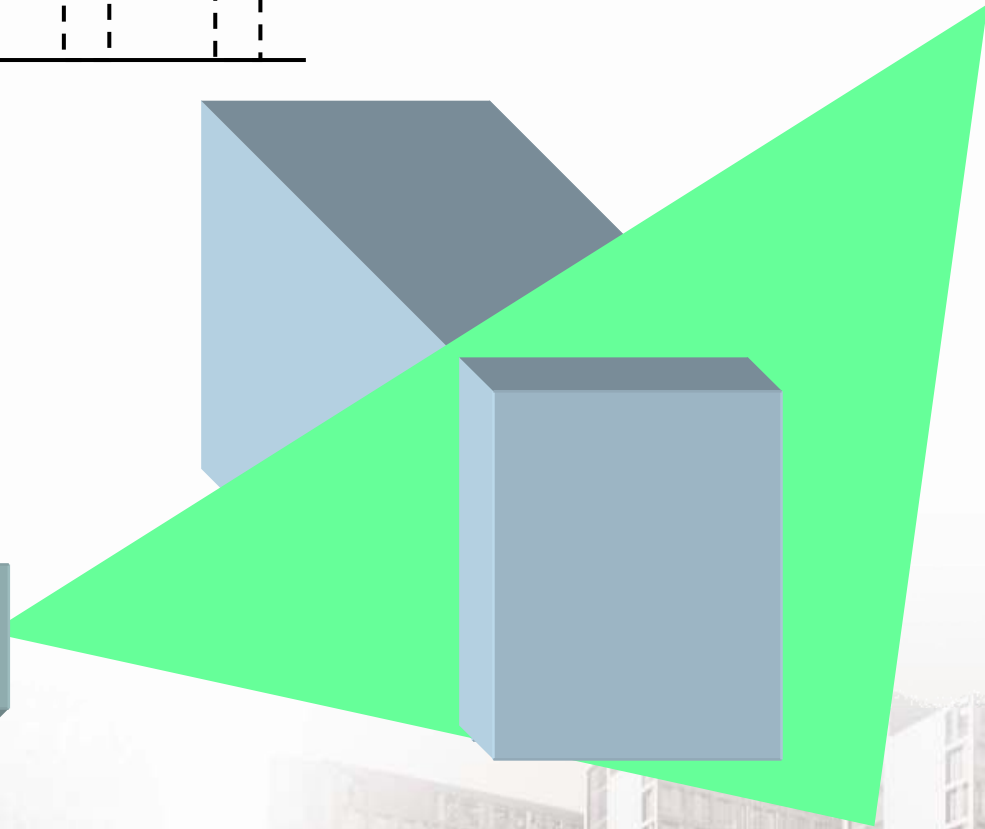
Dual Energy Linac



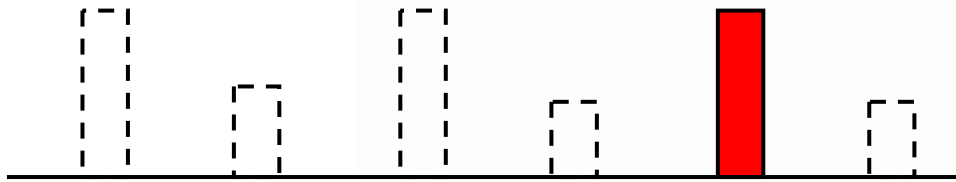
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Dual Energy Linac



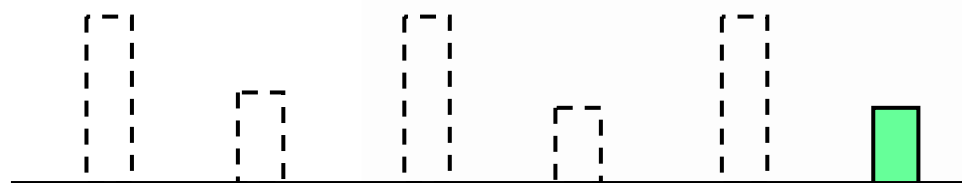
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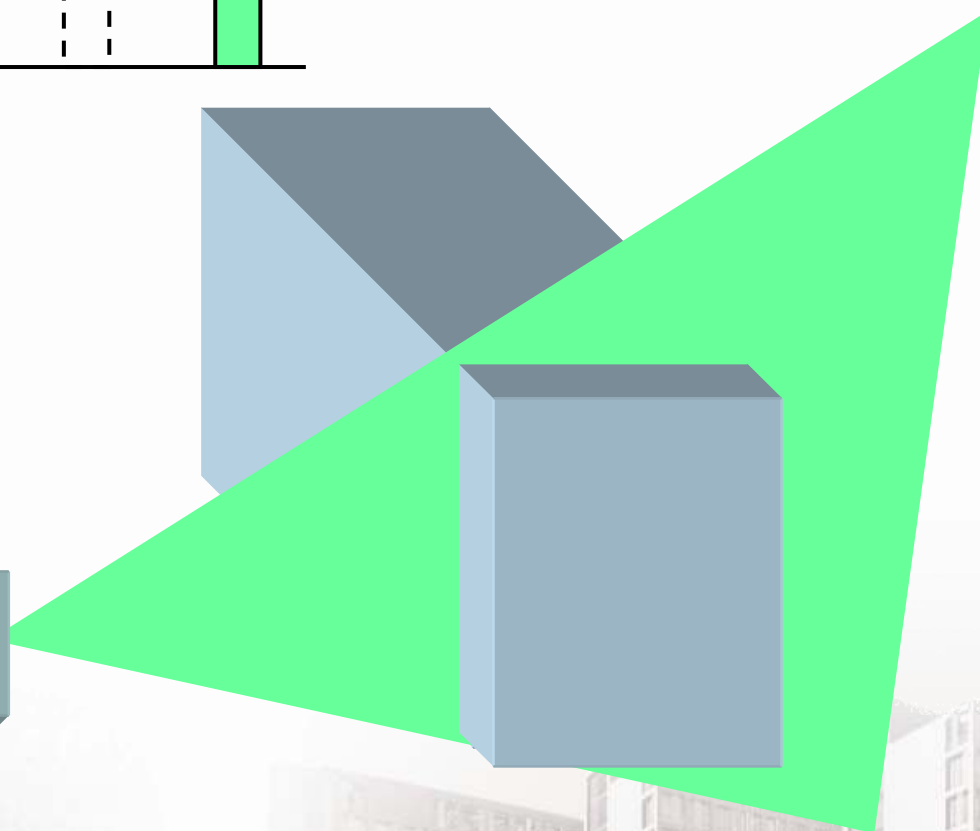
Dual Energy Linac



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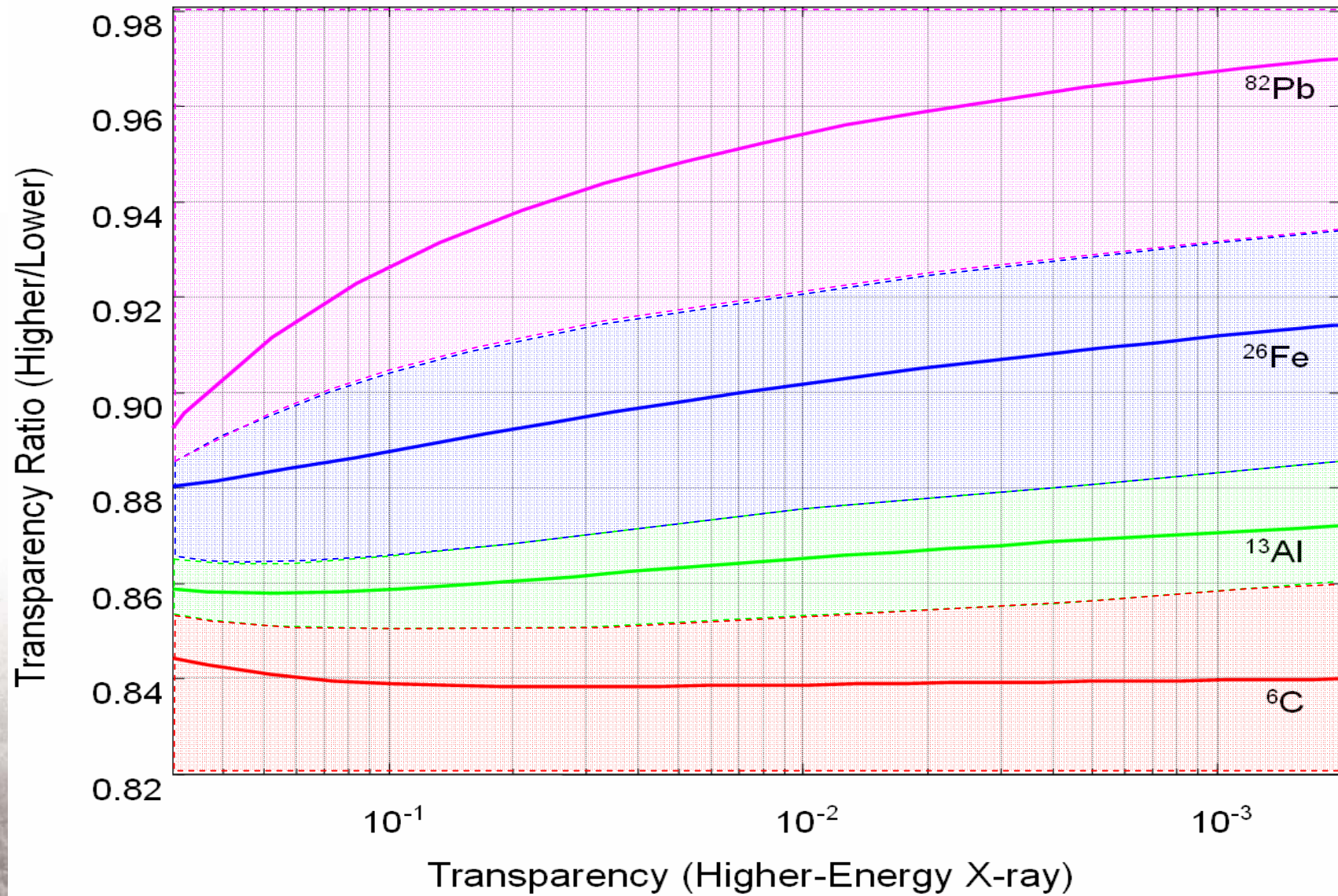


Dual Energy Linac



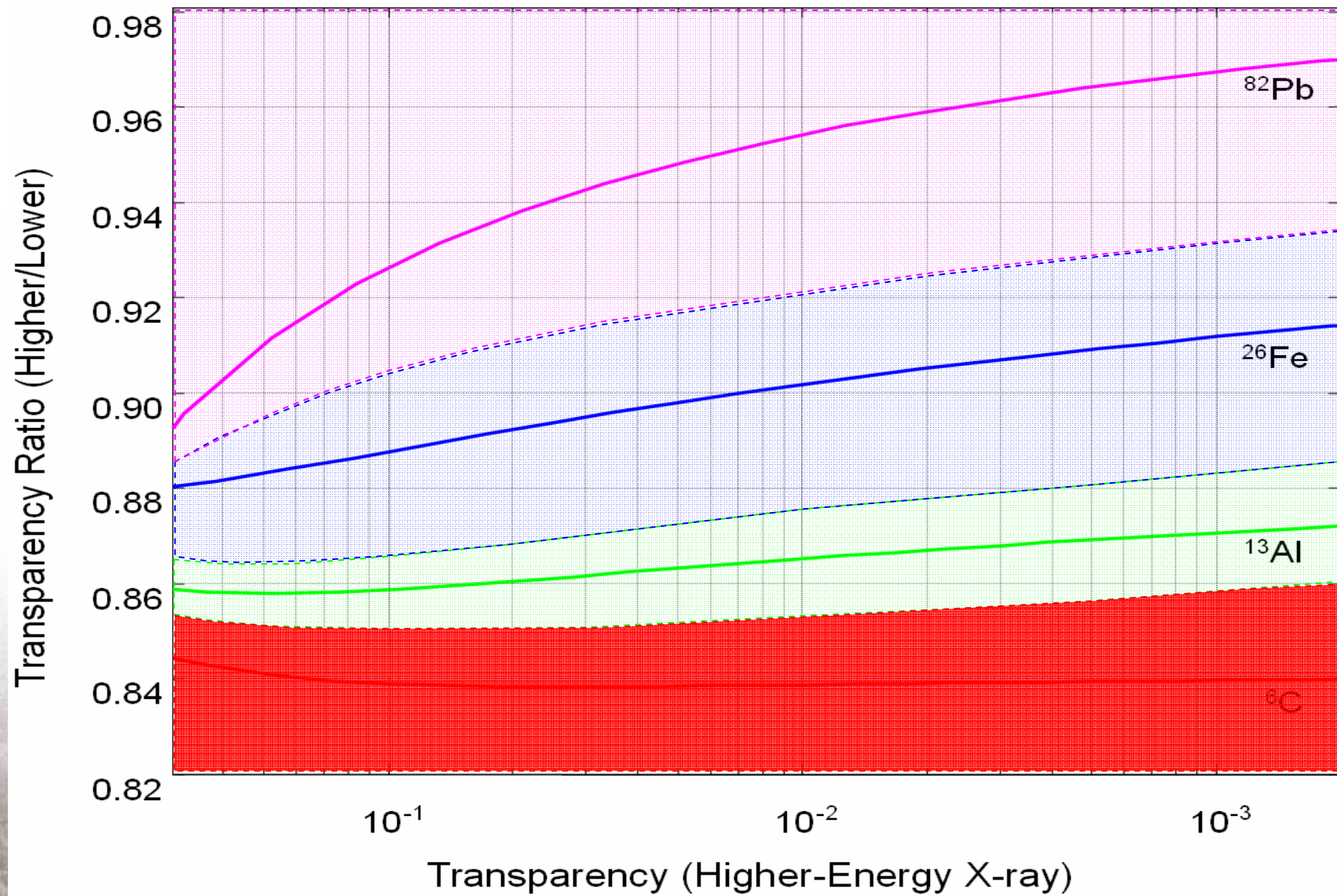
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# Material Discrimination Coordinate

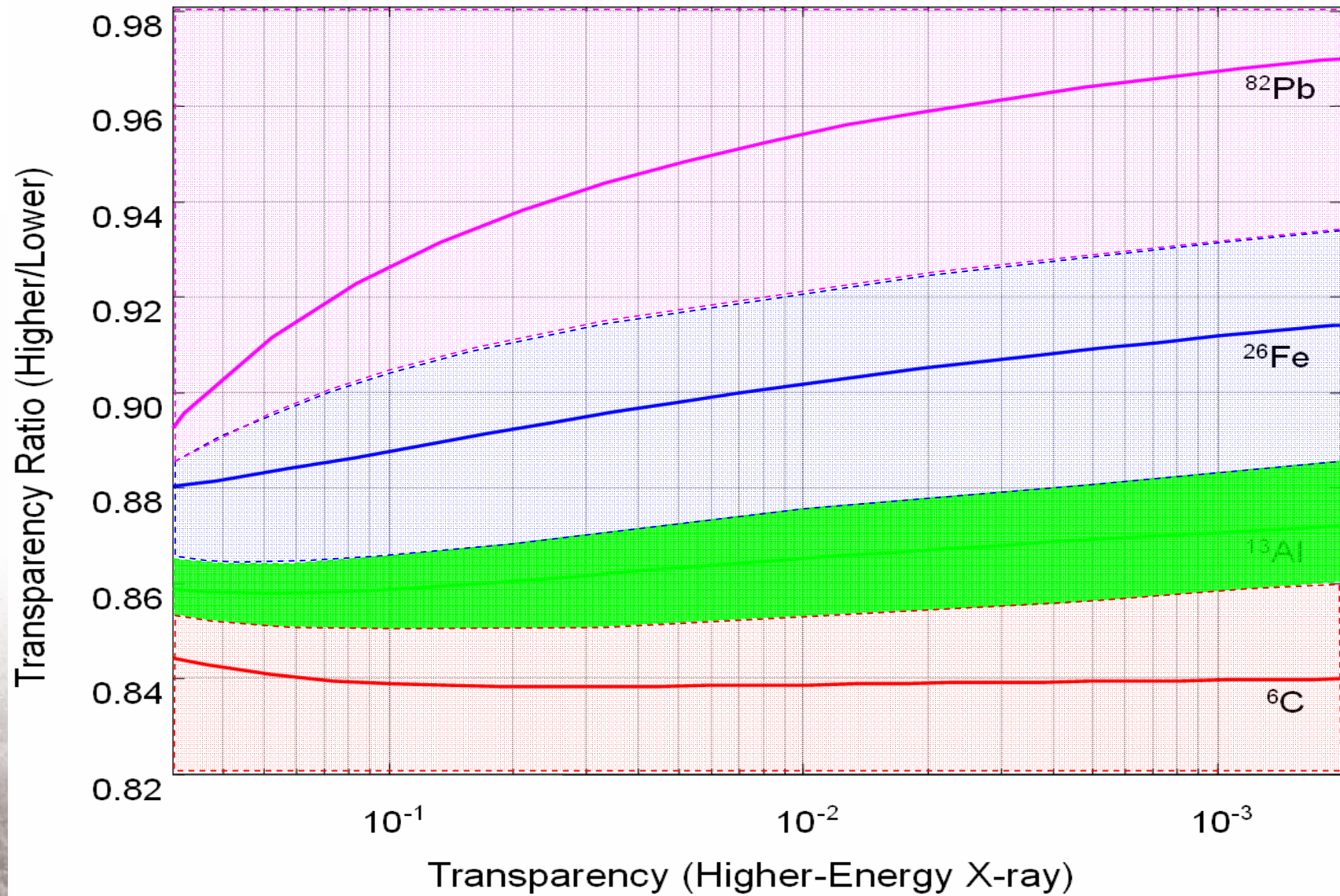




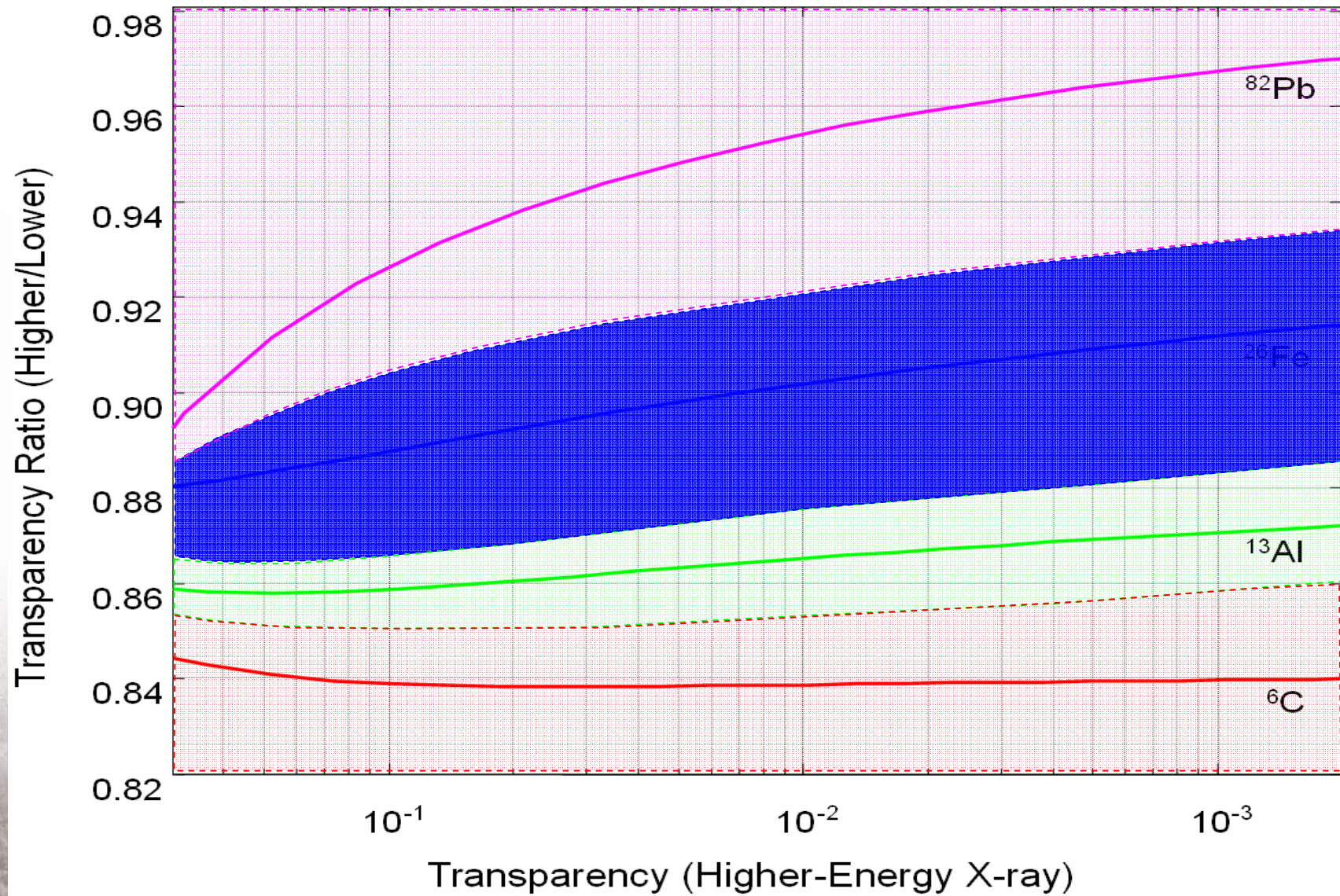
# Organic Material



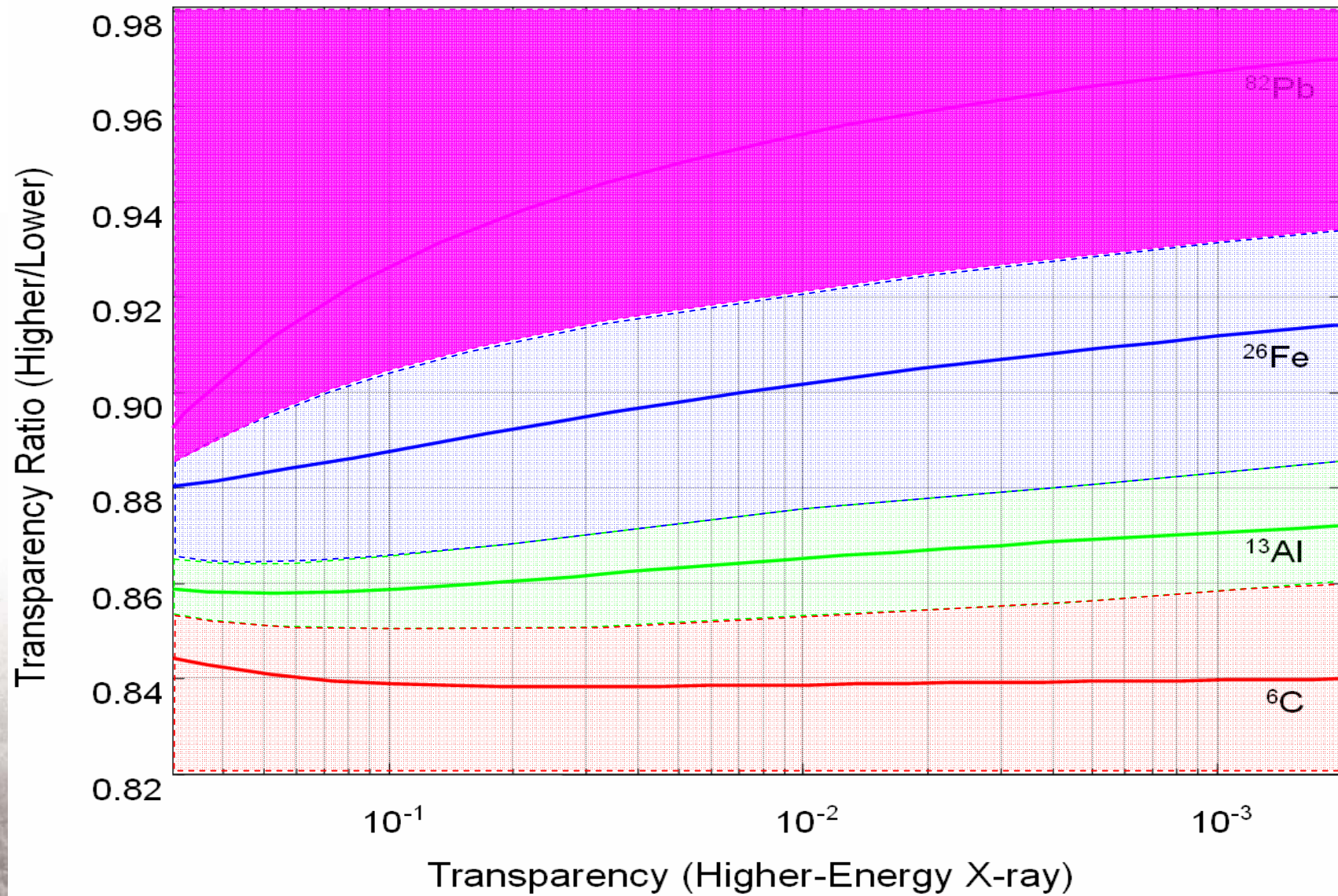
# Light Metal



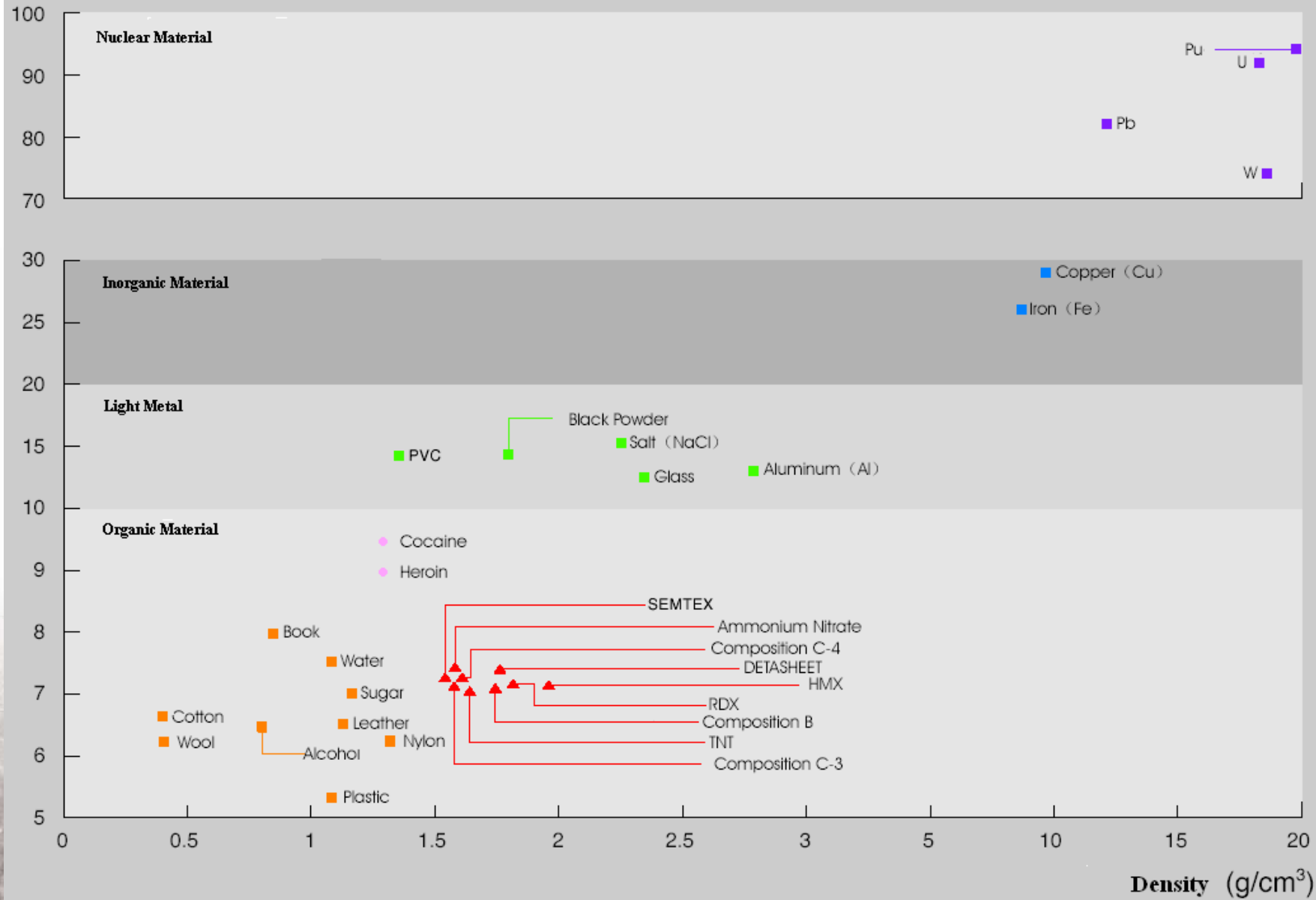
# Inorganic Material



# Heavy Metal



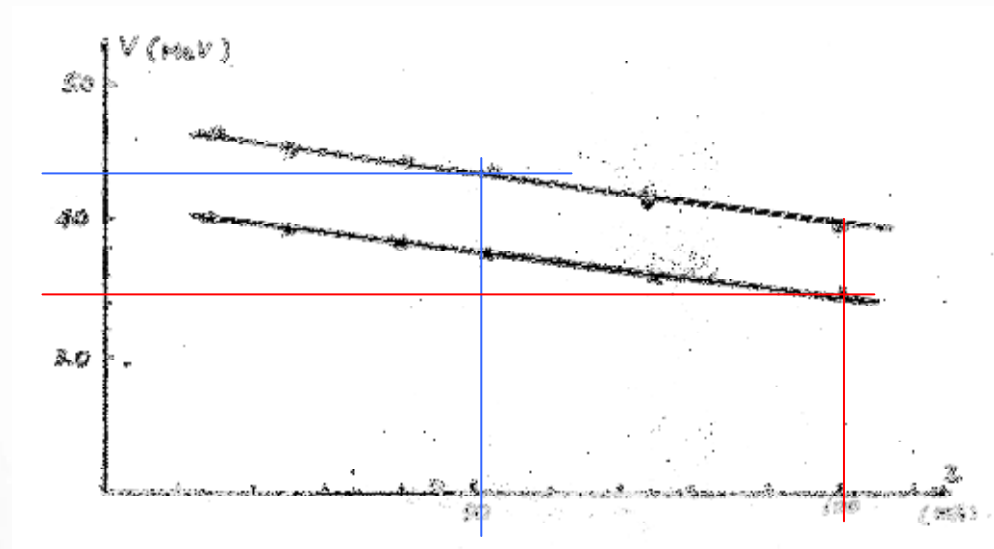
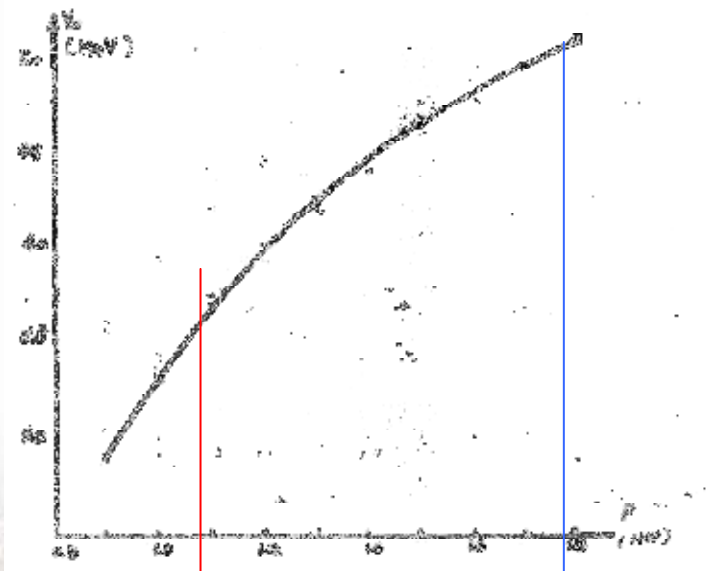
# Atomic Number



Density (g/cm<sup>3</sup>)

# X-ray Source-The Dual Energy Linac

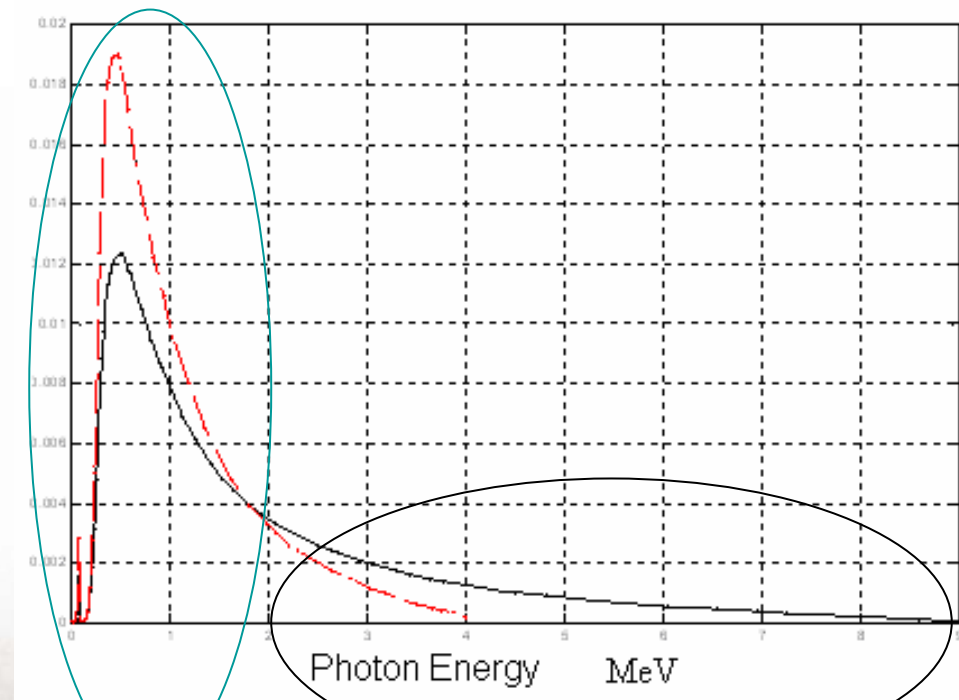
- Interlaced Dual Energy



$$V = a \cdot \sqrt{P} - b \cdot I$$



# Dual Energy X-ray Spectra



Low Energy X-ray

High Energy X-ray



# The Dual Energy Linac

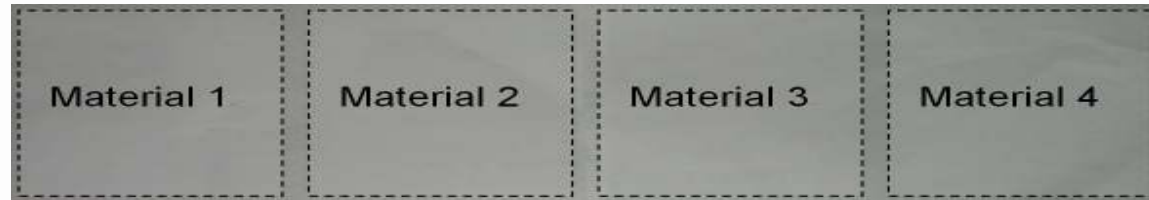
- Magnetron MG5193: 2.6MW, 2998MHz, 4~5ms, 300pps
- Low-energy: 6-7MV and High-energy:9-10MV
- Maximum dose rate(un-filter):
  - 6MV non-interlaced: 1000cGy/min@1m
  - 9MV non-interlaced: 3000cGy/min@1m
  - 6/9MV interlaced:  
1500cGy/min@1m(500 of 6MV & 1000 of 9MV)
- 300pps in non-interlaced mode, and 150pps+150pps in interlaced mode
- X-ray focal spot size: smaller than 2 mm diameter at FWHM



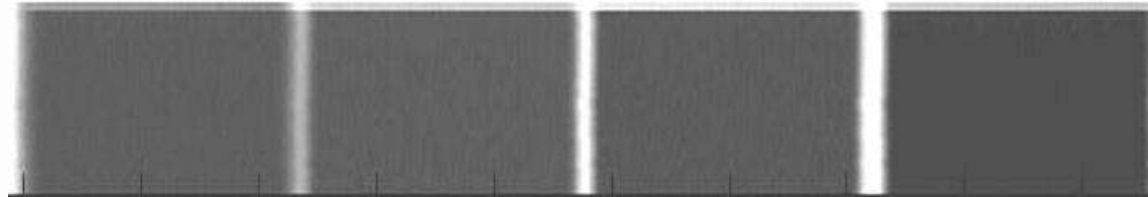


# Material Discrimination

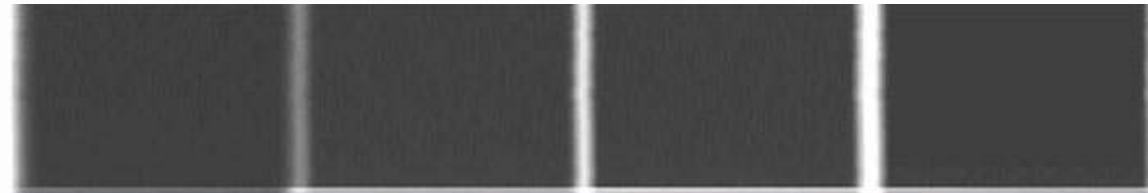
- Unknown material



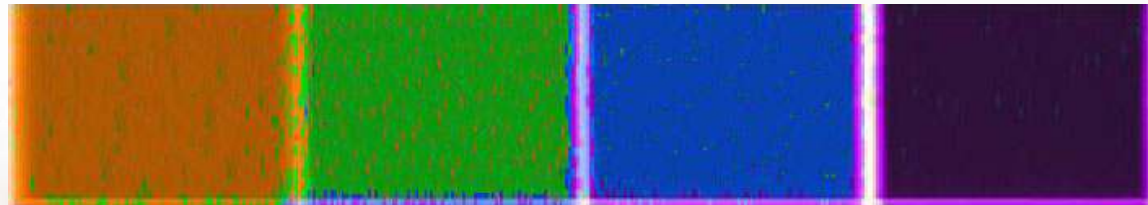
- High-energy image



- Low-energy image



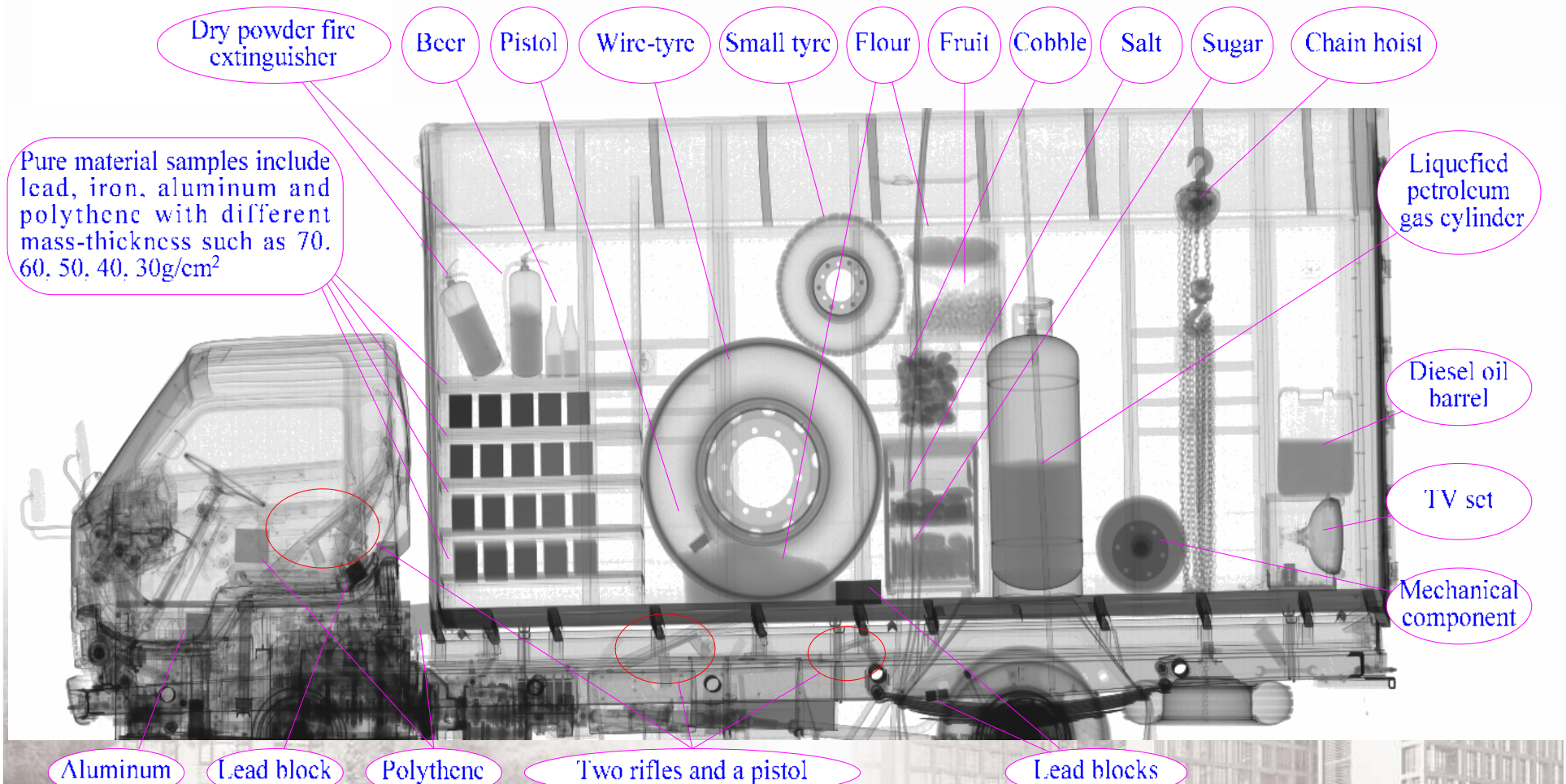
- Dual-energy image



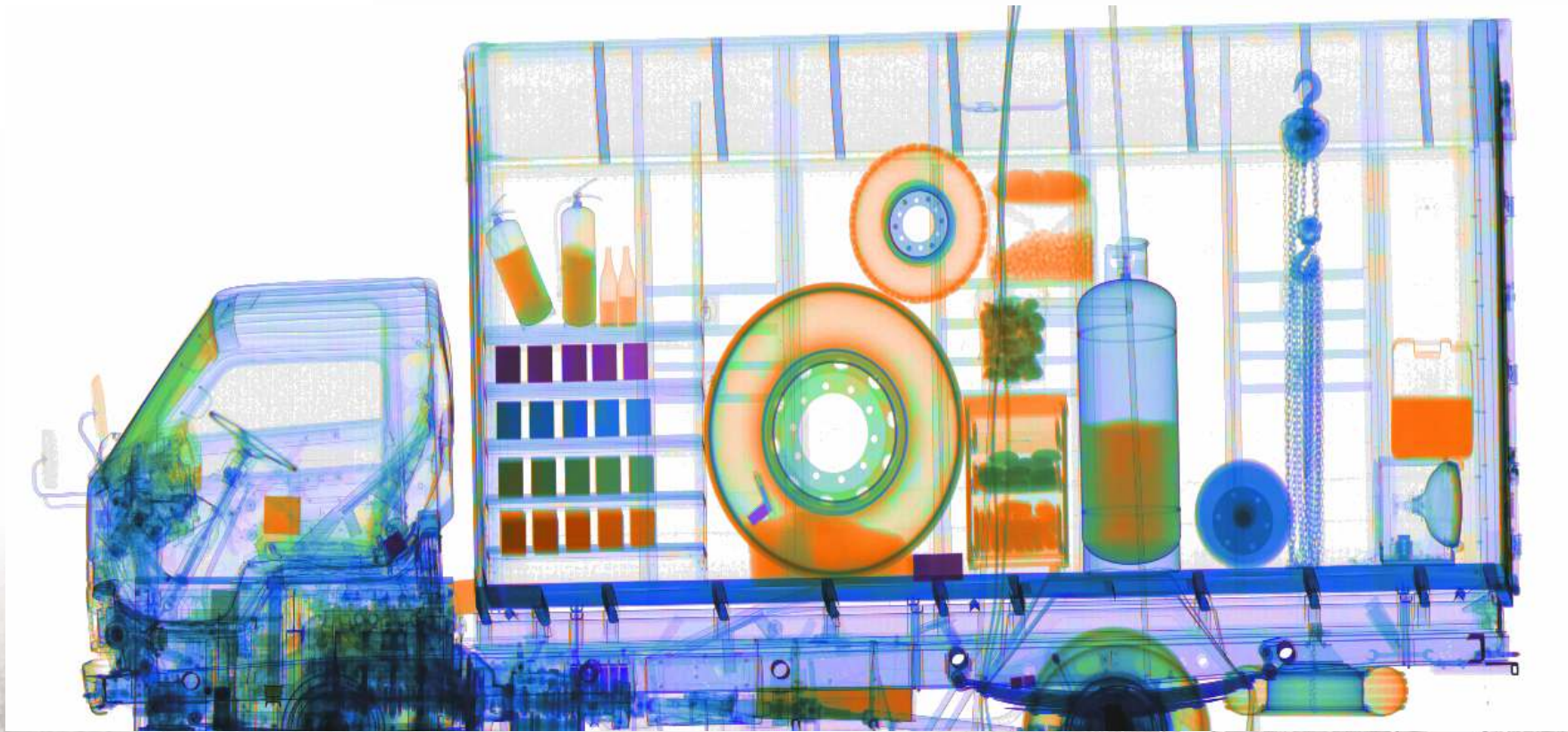
- Unveil the scanned object



# Image Example and Photo Grey Image of a Van with Different Tested Samples



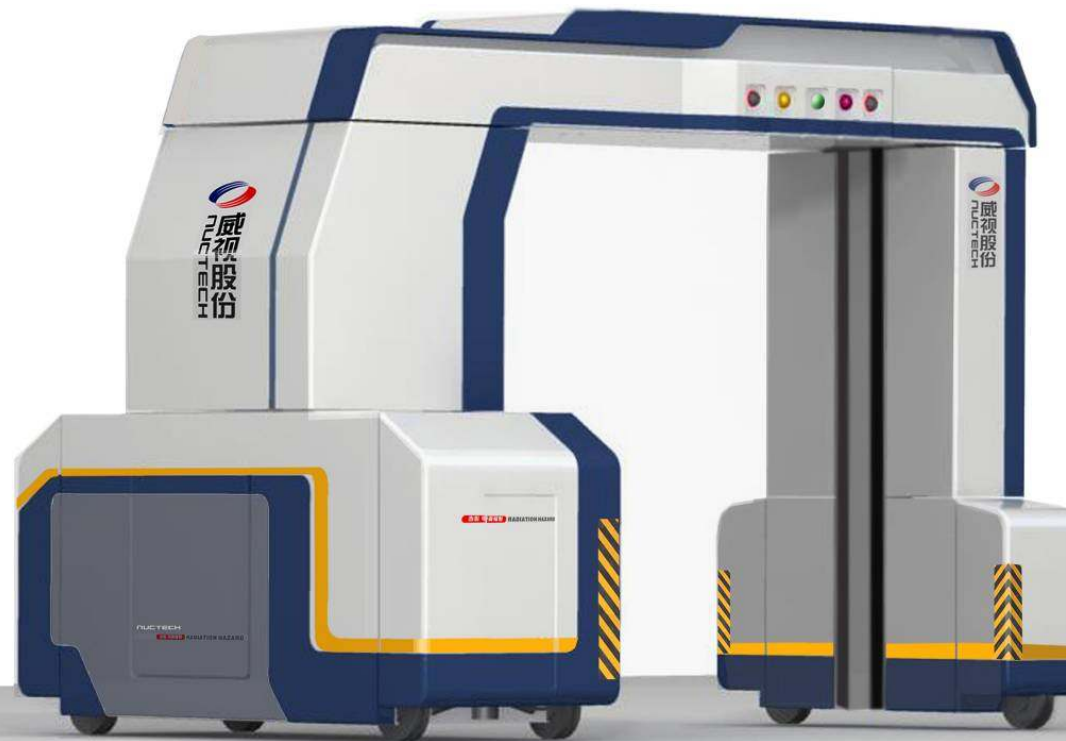
# Image Example and Photo Dual-Energy Color Image of a Van with Different Tested Samples



**Dual-Energy Color Image: obtained by processing of dual-energy material discrimination algorithm according to effective atomic number**



# A Simplified Gantry Type System with Electron Energy 3/6MeV



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# High Throughput Fast Scant Systems



# Overview

- A new system especially designed for high throughput and 100% inspection
- A LINAC of 2.5MeV or 4MeV as its X-ray source
- Avoiding scanning the driver cab automatically, the vehicles pass through the scanning tunnel directly
- Small footprint fits for seaports, border crossings, airports and so on
- Suitable for cargo container, empty container and container truck inspection



## Feature—High throughput

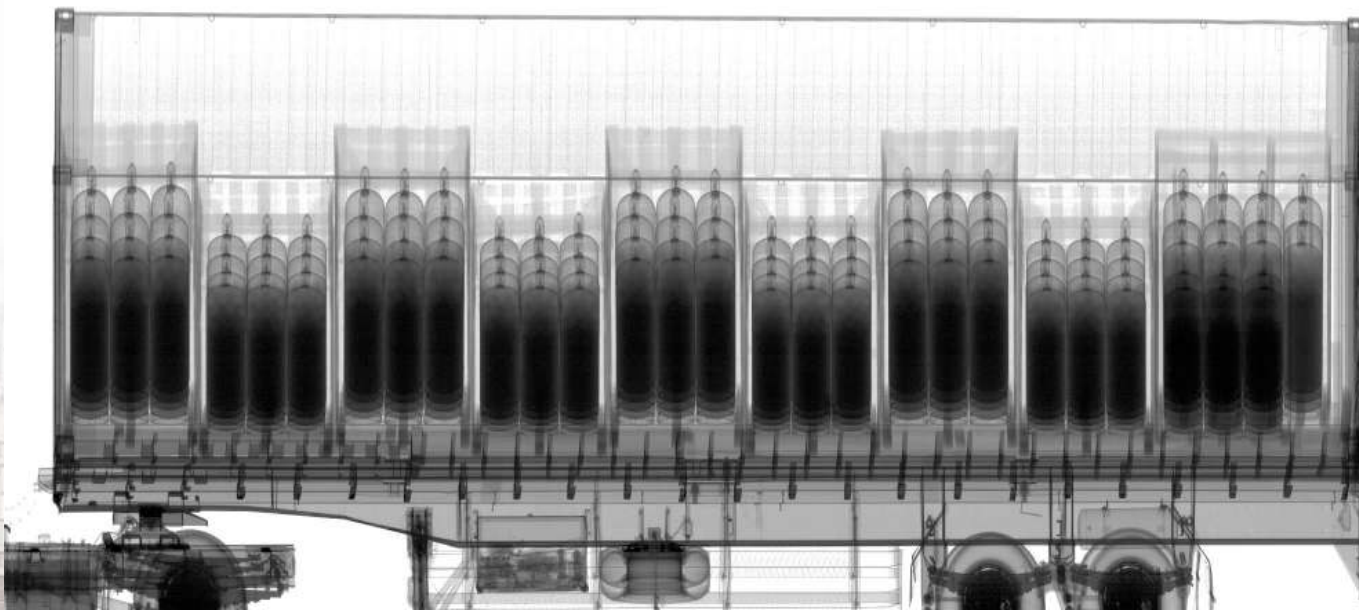
- The driver drives the vehicle through the scanning tunnel directly without stopping
- The system could avoid scanning the driver cab automatically
- The X-ray will be shut off as soon as the scanning finishes
- Scanning speed: 1m/s~4m/s (3.6km/h~15km/h)
- Throughput: 200-400 units of 40ft containers per hour





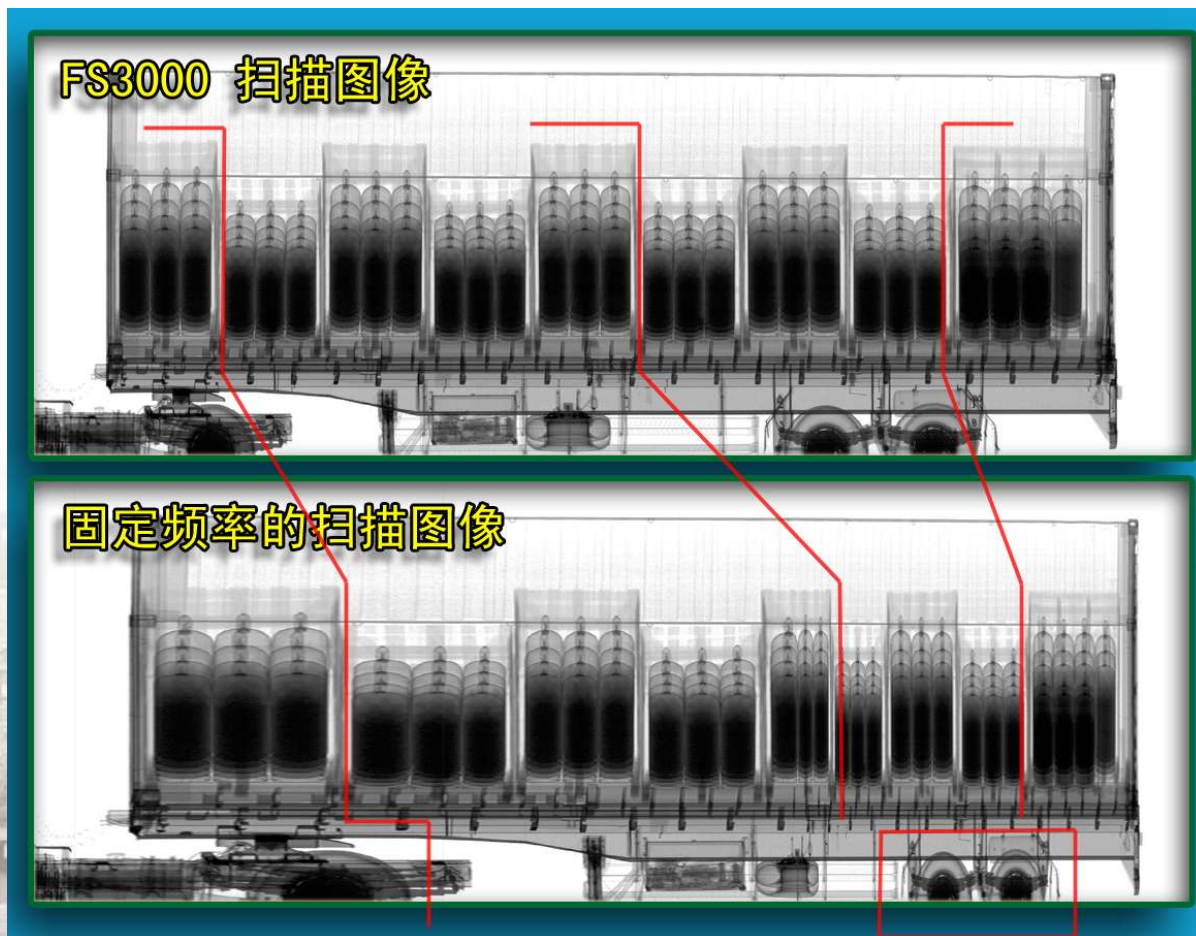
# Feature — Excellent image quality

- New generation of accelerator and detector enhances the system's capability



# Feature—Non-distortion scanning images

- The frequency of X-ray pulse adjusted automatically according to the speed of the scanned vehicles, ensures the scanning images non-distortion.



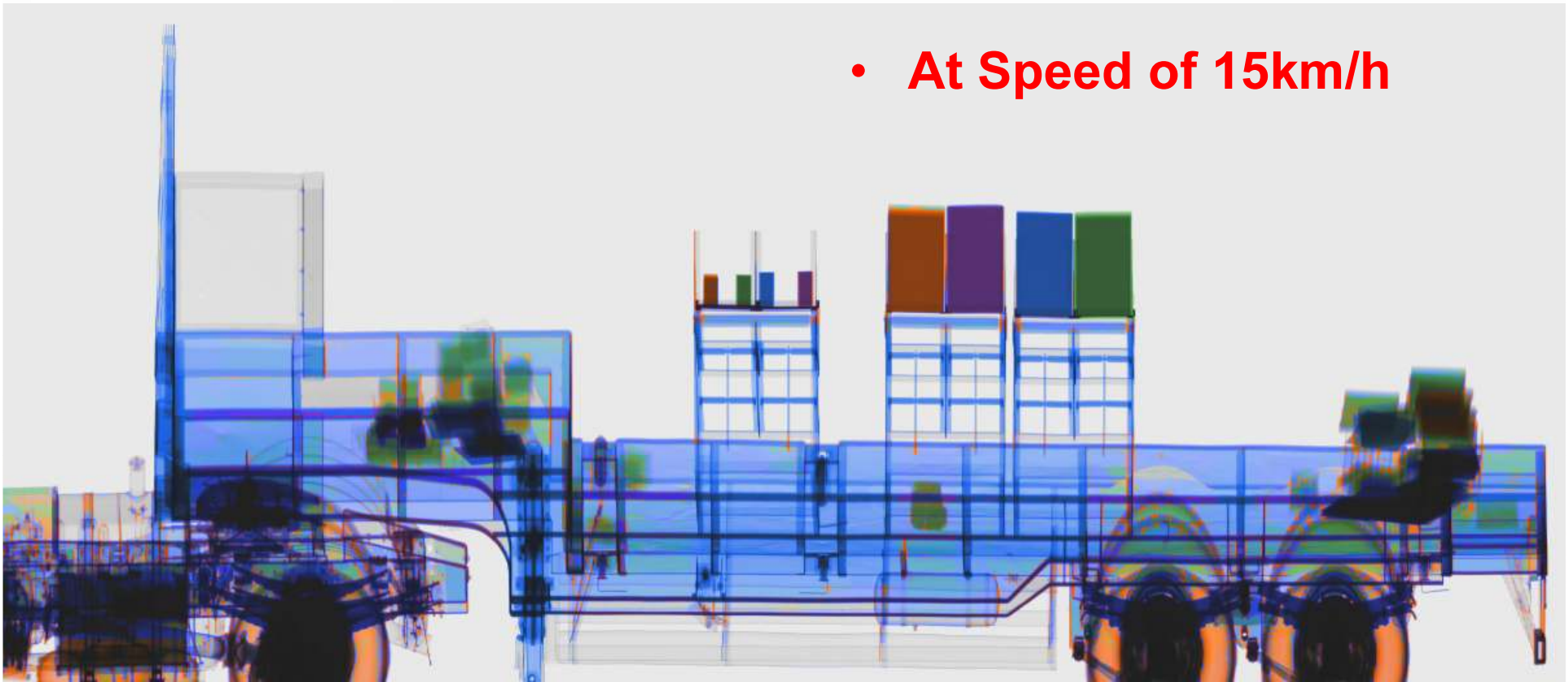
# New Challenges of The Linac for Fast-Scan System

- **Fast Beam On:**
  - Normal Linac needs about 5s to have a stable beam
  - Cargo moving at 1m/s~4m/s means the cargo will be scanned at an unstable beam.
  - We designed a linac which needs less than 5 pulses ( about 0.1s)
  - This is very important for driver's safety and image quality
- **Variable Repeat Frequency**
  - The repeat frequency of the linac must change according to the cargo's speed



# Combined Fast Scan with Dual Energy

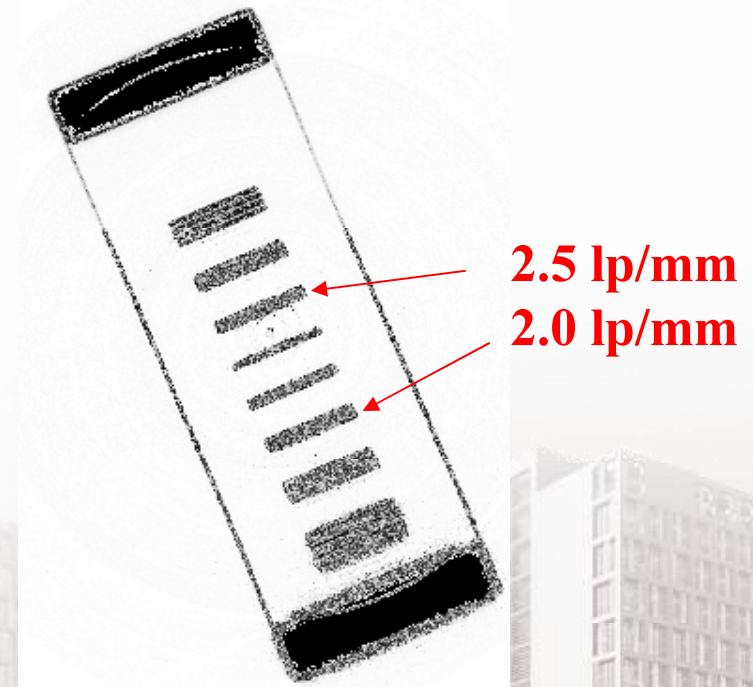
- At Speed of 15km/h



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# 4 Other Applications of Low Energy Linacs

CT imaging with 9MeV Linacs in Tsinghua U.



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# Electron Linac

High Stability  
High Dose Rate  
Small X-ray Spot



Electron Energy	15MeV
Repetition Rate	230pps
Dose rate	200Gy/min@1m
Spot size	1.5mm



# Linac for sterilization

- Frequency:
  - 2998MHz
- Electron Energy:
  - 5MeV
- Beam Power:
  - >2kW
- Macro-pulse width:
  - 4.7ms
- Repetition rate:
  - 250Hz



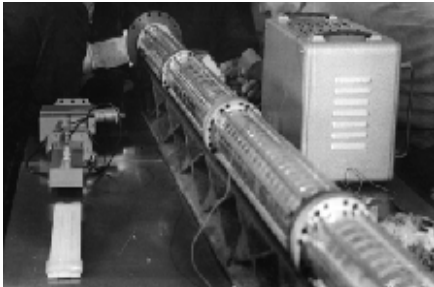
# Mobile Sterilization System

- Frequency:
  - 2998MHz
- Electron Energy:
  - 2.5MeV
- Beam Power:
  - >1kW
- Macro-pulse width:
  - 4.7ms
- Repetition rate:
  - 250Hz





# Low Energy Electron Linacs for Medical Applications



**TW 10MeV  
Linac BJ-10**

**SW 6MeV Linac  
WDVE-6**

**SW 14MeV  
Medical Linac**

**SW 20MeV Linac  
with ES**



Thanks for Your  
Attention!

