# Low-Energy Electron Linacs and Their Applications in Cargo Inspection

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NA-PAC'13

CA, US, October,2013

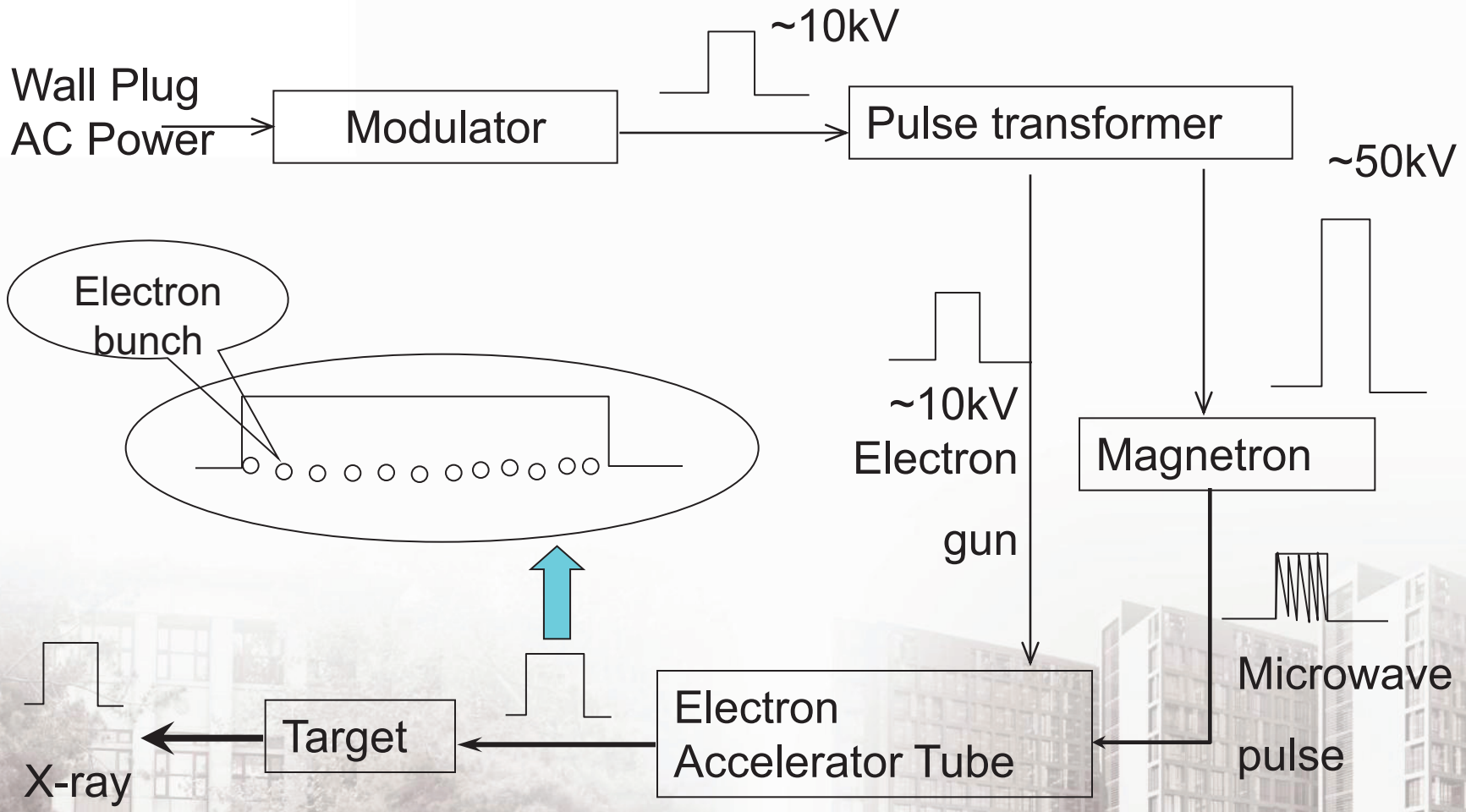
# Outline

- Low-energy Linac System
- NUCTECH Cargo Inspection System
- Dual Energy Linac for Material Discrimination
- Examples of Product

# Low-Energy Electron Linear Accelerators

- Electron Energy : From 1MeV to ~30MeV
- Accelerating Structure: SW or TW
- Electron Source: Diode or triode gun
- RF Frequency:
  - S-band ( 2856MHz, 2998MHz), X-band (9300MHz), C-band (5712MHz), L-band (1300MHz)
- RF Power Source:
  - Magnetron or Klystron
- Applications:
  - X-ray or electron Radiotherapy
  - Irradiation
  - Non-destructive test / x-ray imaging/ Cargo Inspection System

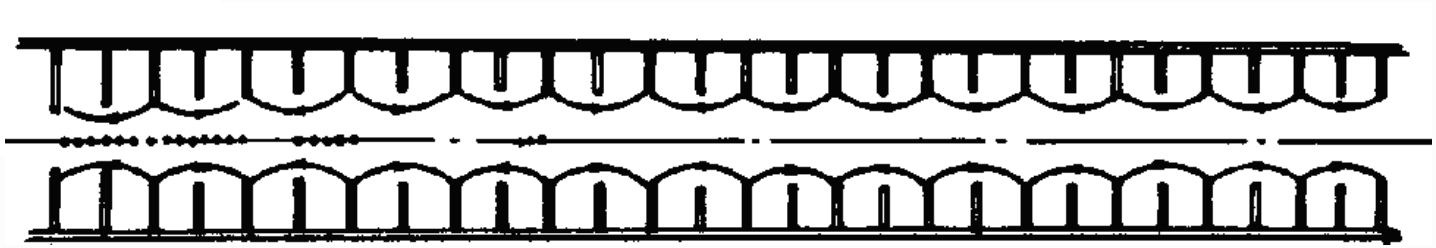
# A low-energy linac system with magnetron as its rf power source



# SW or 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 required |
| Size: | small and simple | large |
| Stability: | good | good |

# Traveling Wave Accelerating Structures



Bunching section

Main accelerating section

- Constant impedance

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

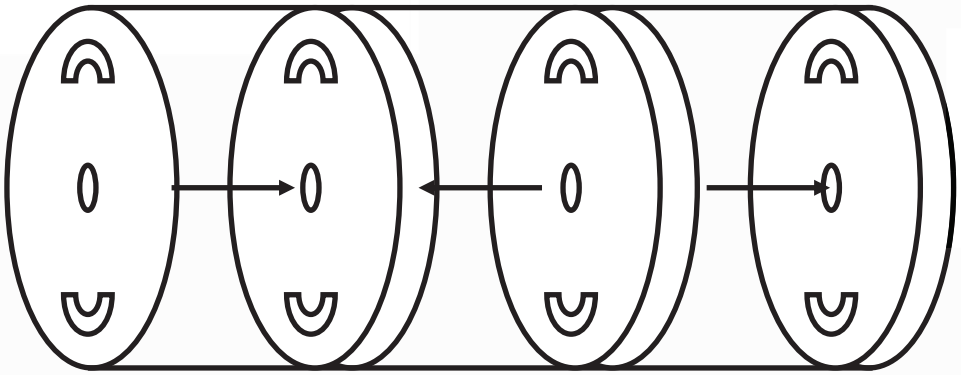
Length: 2.4 m

RF source: 5MW klystron

Electron Energy: 9MeV

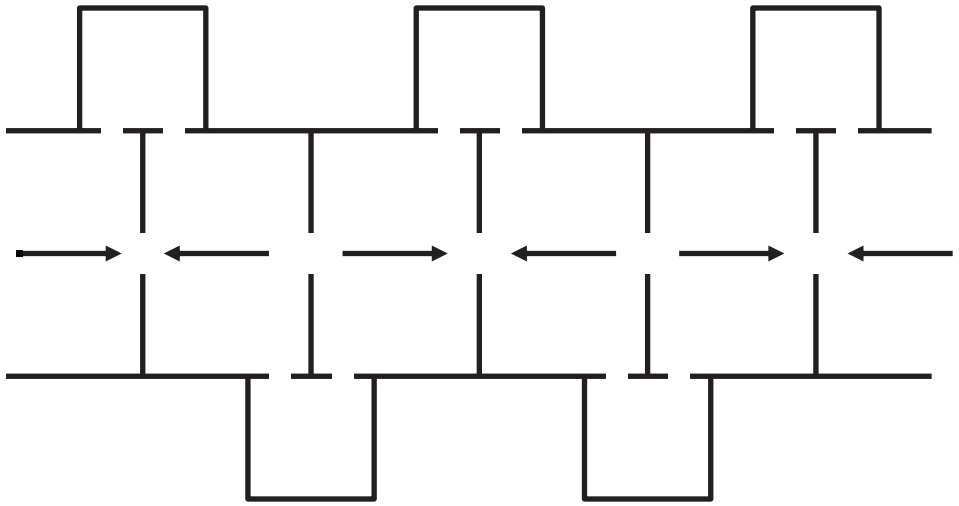
Dose Rate: 30 Gy/min-m

# Standing Wave Accelerating Structures



On-axis magnetic coupled bi-period structures

Side coupled structures



# S-band Linacs for X-ray Imaging

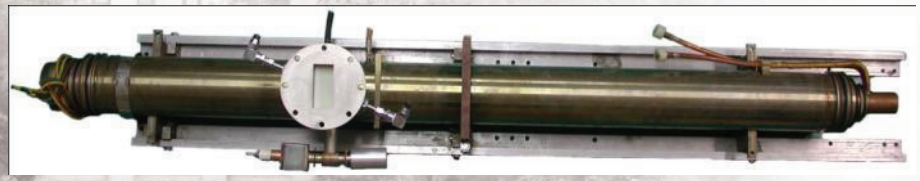
1.5 MeV
SW Linac

2 MeV
SW Linac

4 MeV
SW Linac

9 MeV
SW Linac

15 MeV
SW Linac

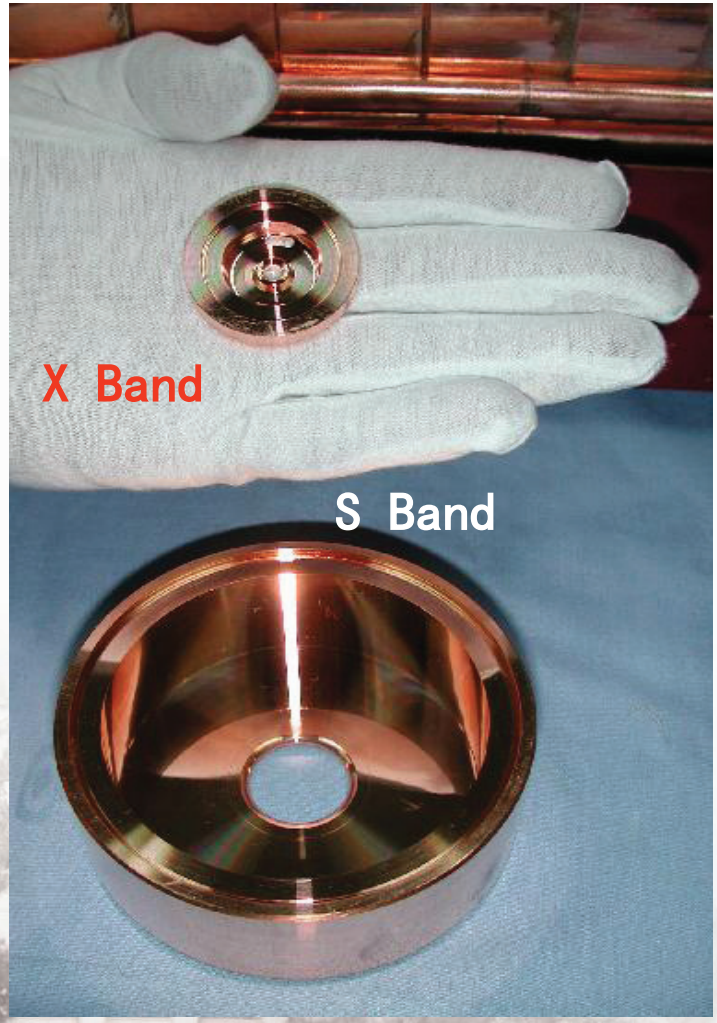


6 MeV
SW Linac

# 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 is more suitable for high average power linacs
  - For L-band power source can deliver more than 1MW average power
- C-band is becoming more and more attractive

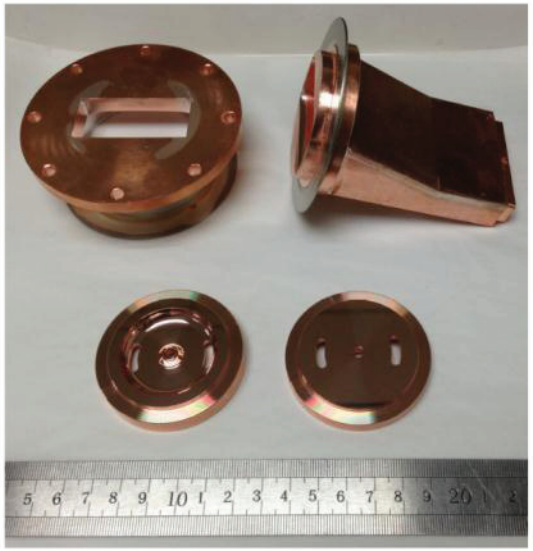
# X Band Accelerating Structure

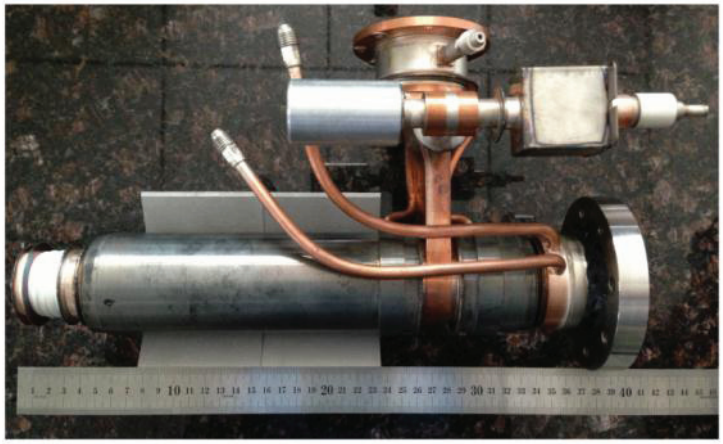


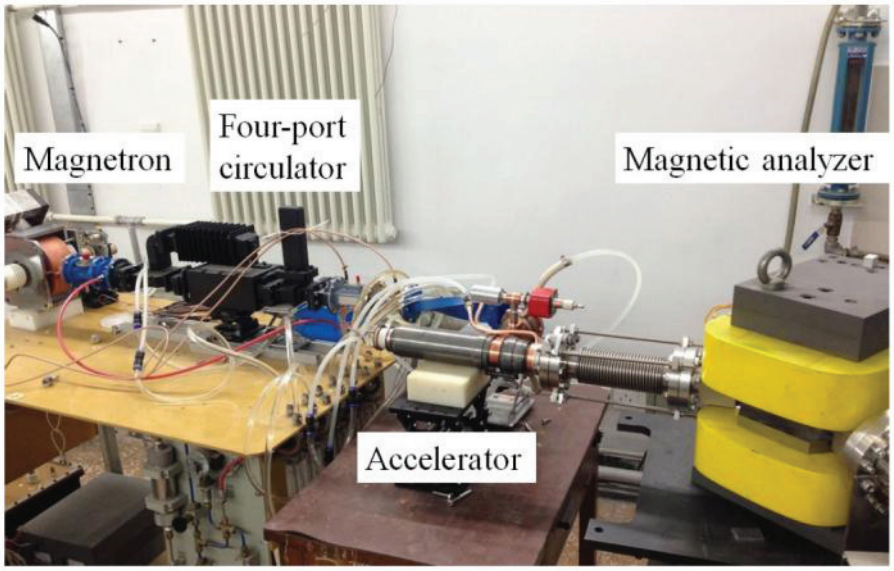

X-band 2.5MeV Accelerating tube

X-band 6MeV Accelerating tube

# C Band Accelerating Structure





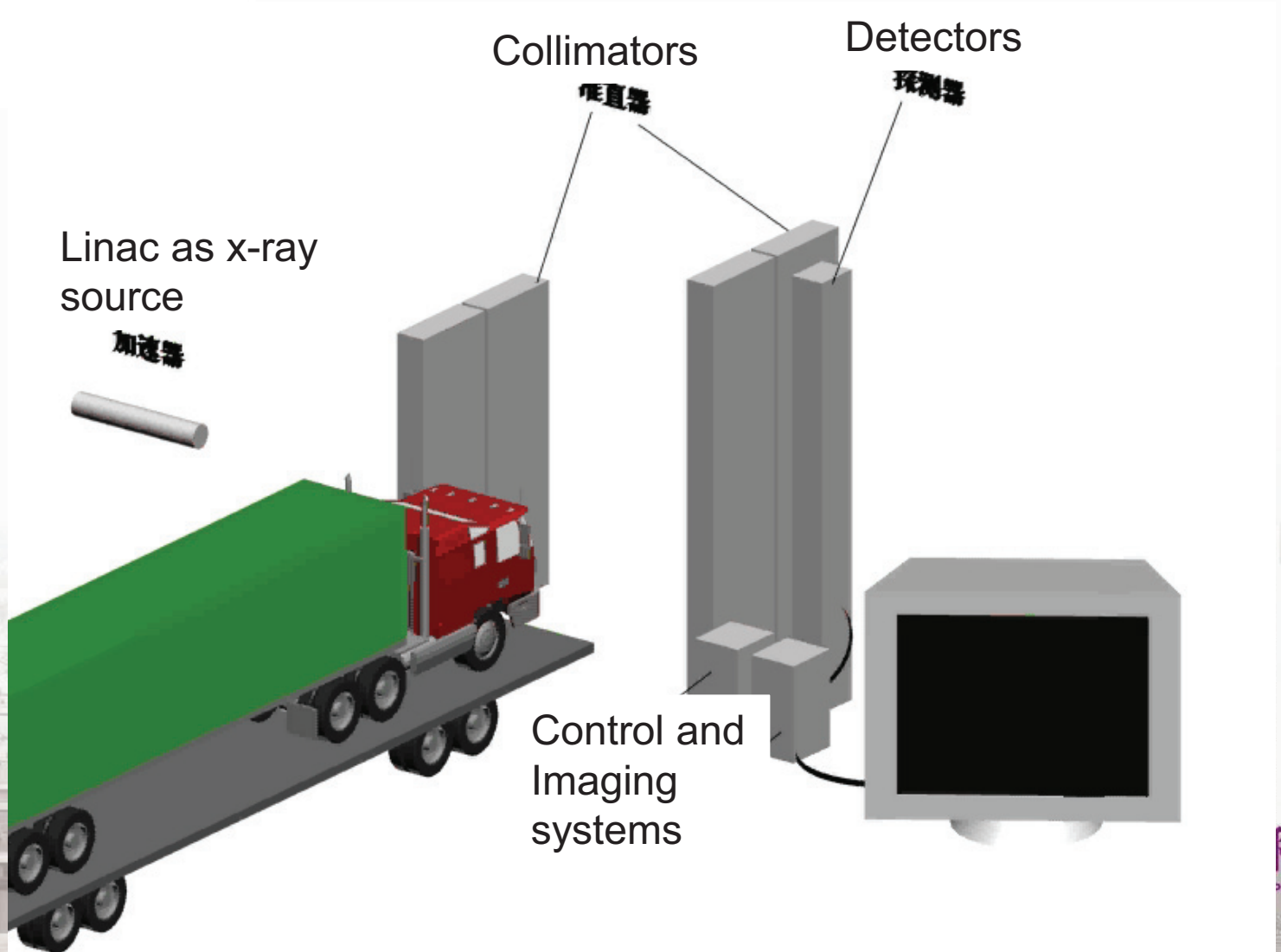



C-band 6MeV Accelerating tube

# RF Power Source: Klystron or Magnetron?

| | Klystron | Magnetron |
|---|---|---|
| Type: | Amplifier | Oscillator |
| Peak Power: | 10s MW or more | normally less 5MW |
| Price: | expensive | cheap |
| Size: | large | compact |
| Stability: | good | need more efforts to control |

# Linacs Used as the X-ray Source in the NUCHTECH Cargo Inspection System



# Cargo Inspection Systems and Their Linacs

## Fixed

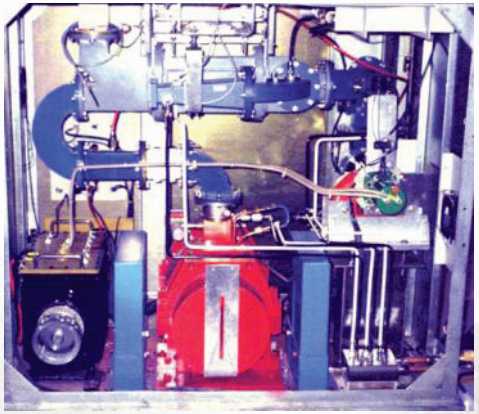
RF source: 5MW klystron

Electron Energy: 9MeV

Dose Rate: 30 Gy/min-m

Penetration: 450mm

## Relocatable

Electron energy 6MeV

Dose rate ~12cGy/min

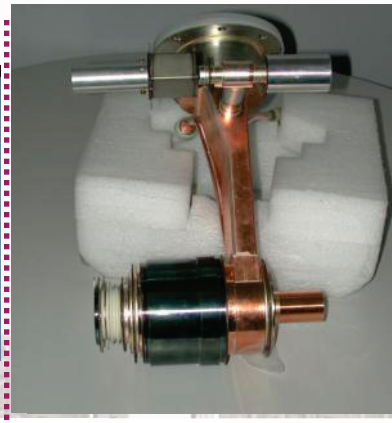
RF Source: 2.6MW Magnetron

Penetration: 400mm

## mobile

X-band 2.5MeV SW Tube

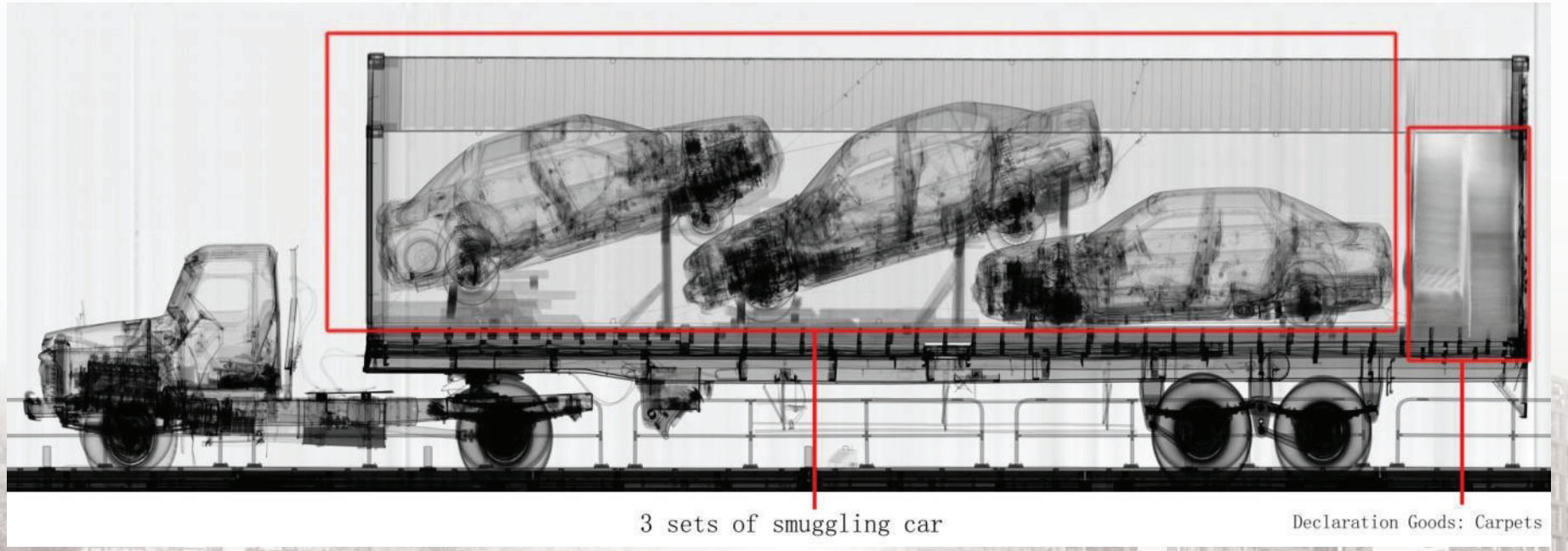
Powered by a 1MW 9300MHz magnetron



S-band 2.5MeV SW Tube

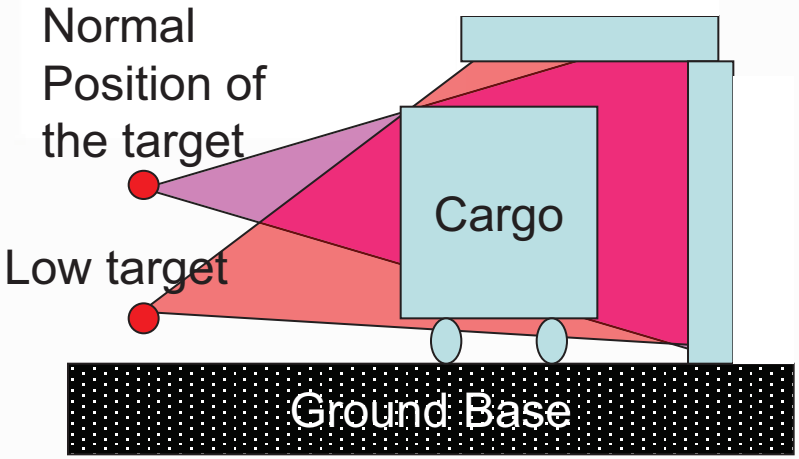
Powered by a MG5125 magnetron

# Smuggling Cars



# Low Target Mobile System-III

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

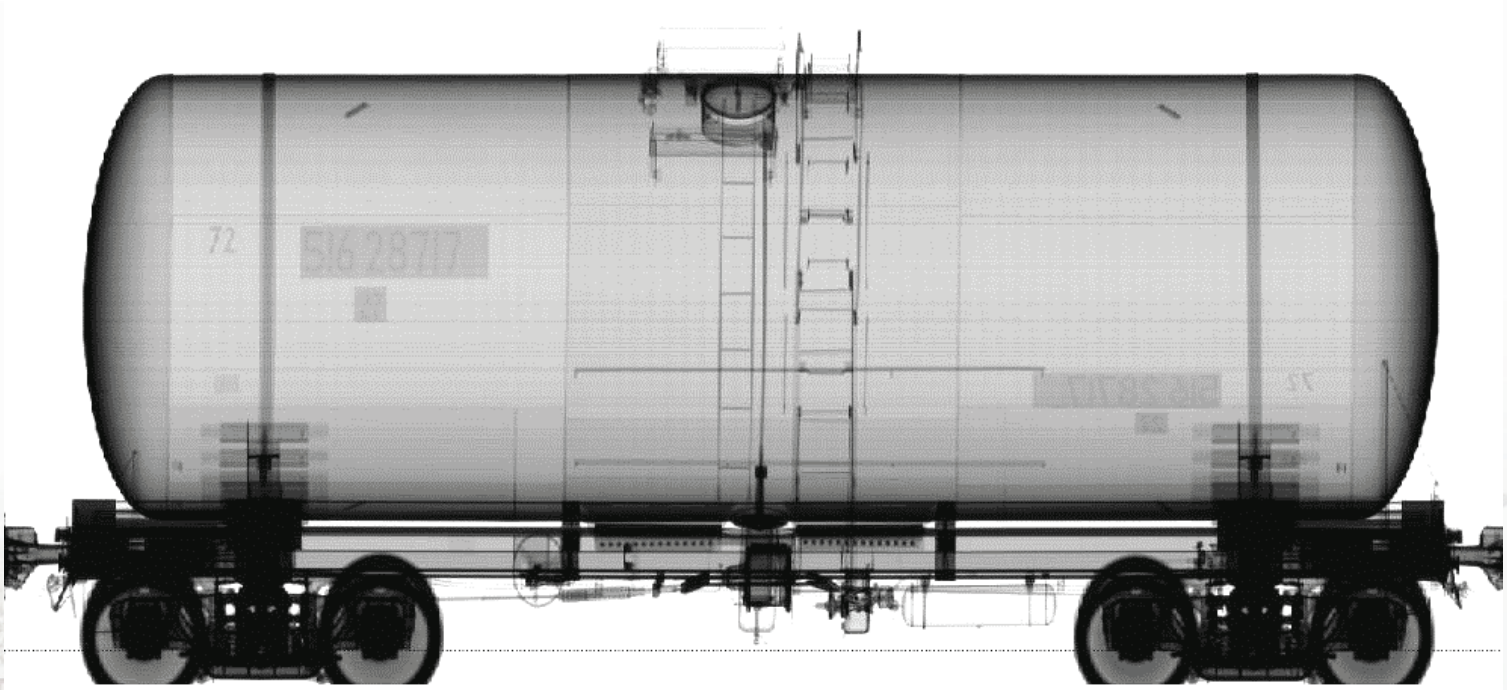


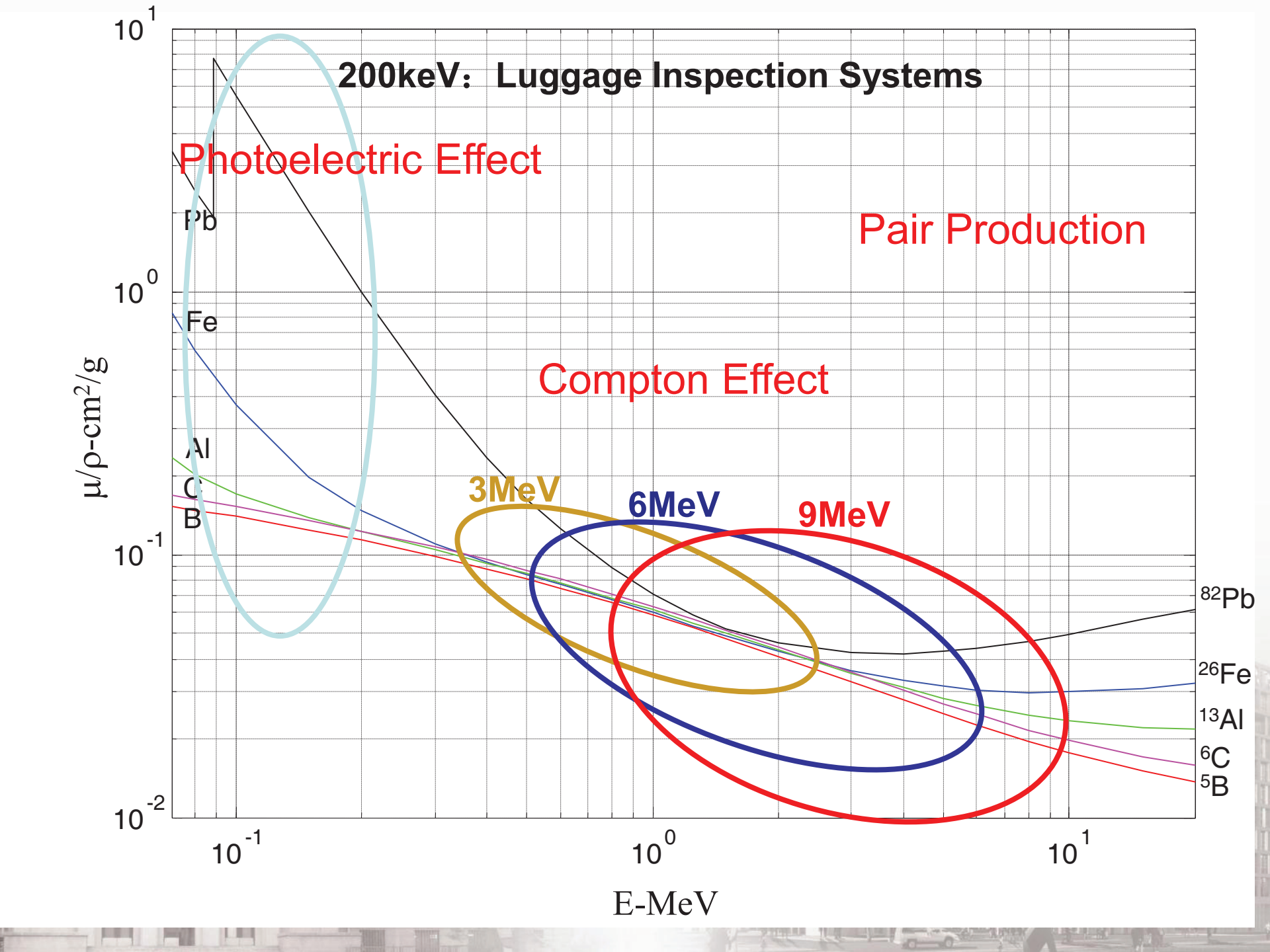


# Railcar Inspection Systems



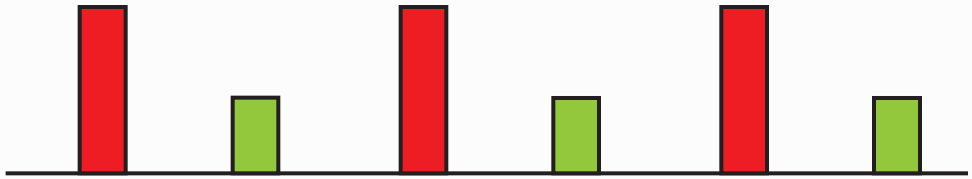

# Railcar Inspection with speed of 40km/h ( up to 60km/h )




200keV：Luggage Inspection Systems
Photoelectric Effect
Pair Production
Compton Effect
3MeV
6MeV
9MeV
Pb
Fe
Al
C
B
$10^{1}$
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-1}$
$10^{0}$
$10^{1}$
μ/ρ-cm²/g
E-MeV
$^{82}$Pb
$^{26}$Fe
$^{13}$Al
$^{6}$C
$^{5}$B

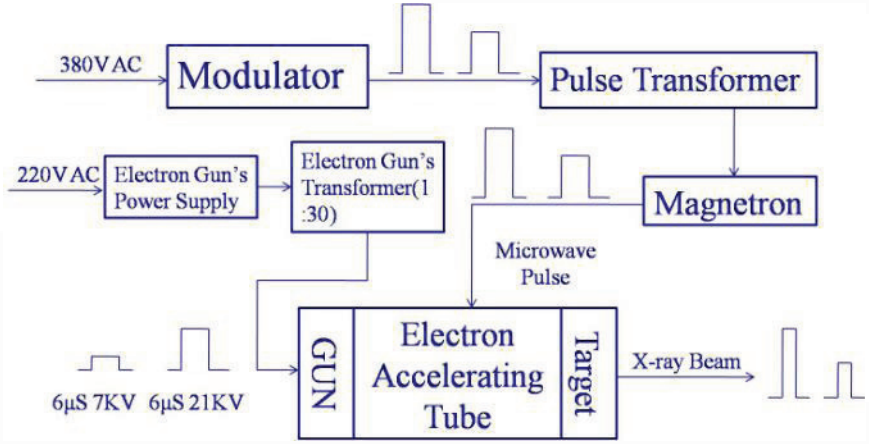
# New Challenges to Linacs for Material Identification Cargo Inspection Systems

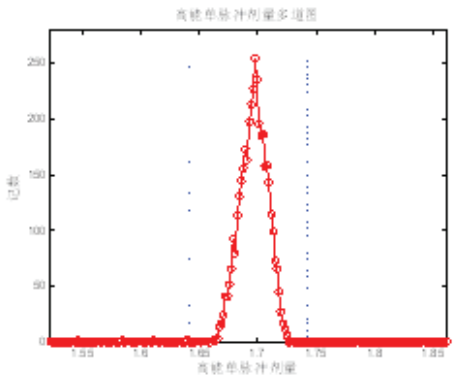
- Interlaced dual energy pulses with similar x-ray dose
- Electron energy and pulse dose stability

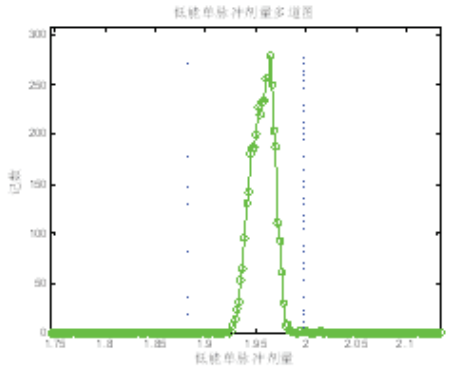


*Interlaced X-ray Pulses*

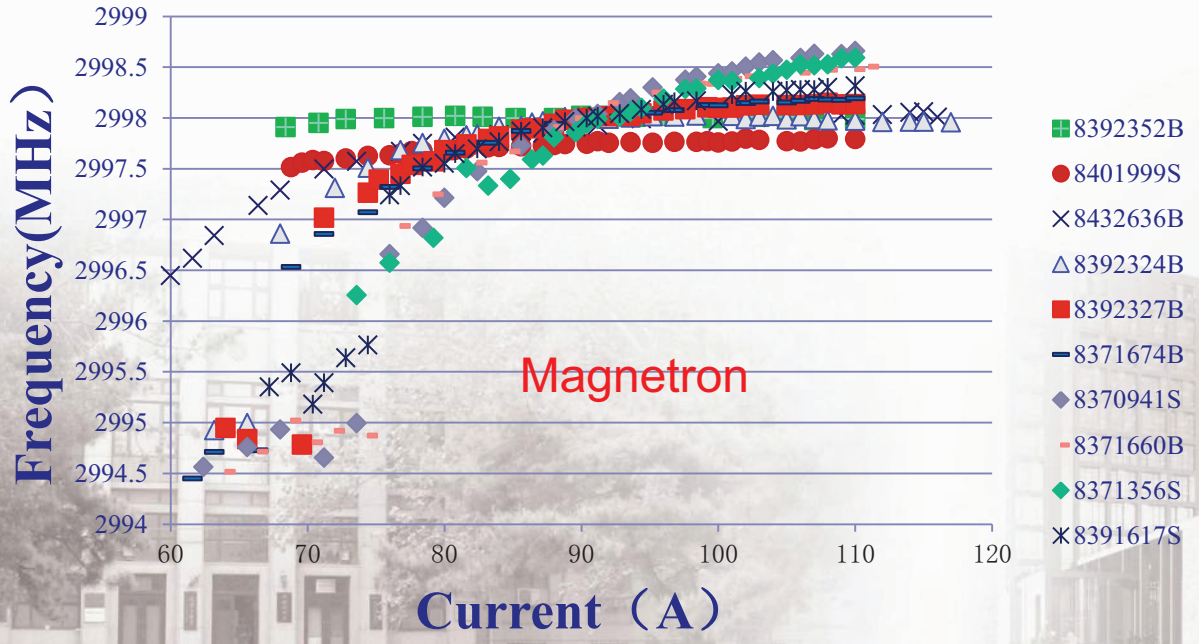
# The Dual Energy Linac

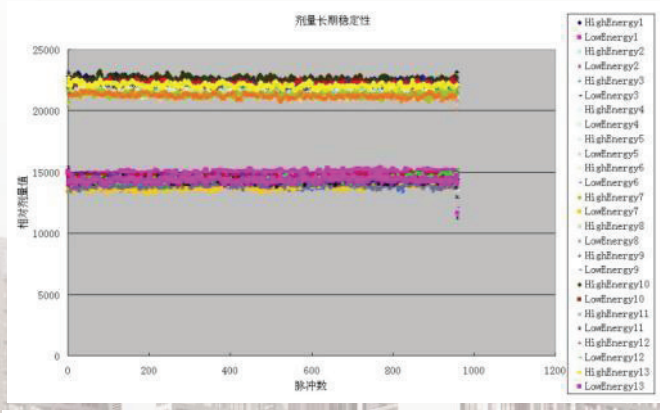




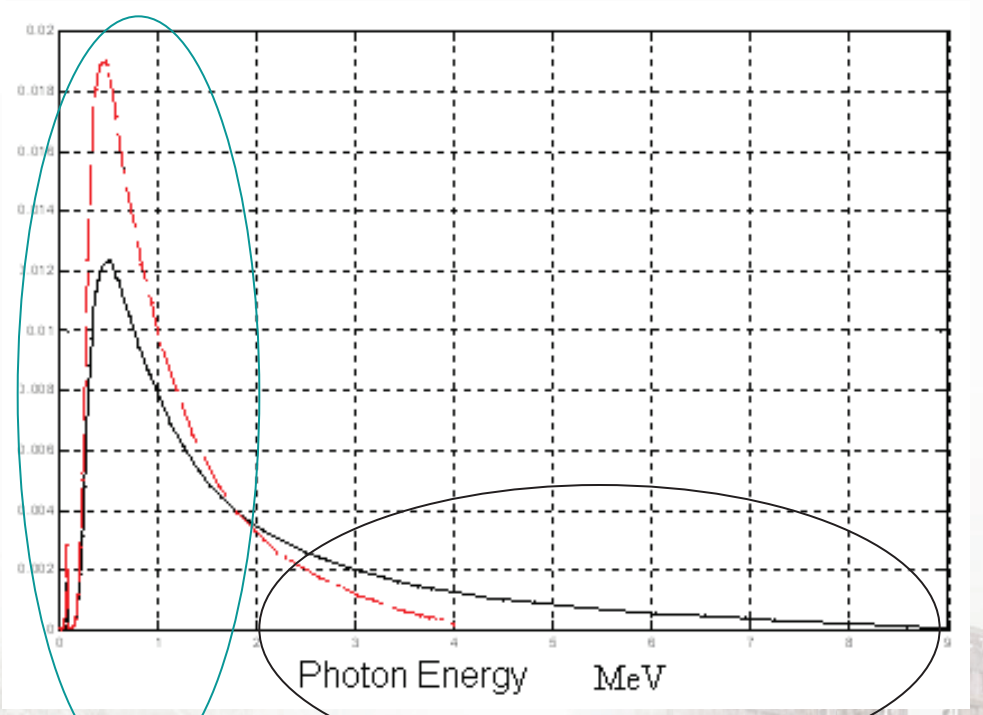
By improving the modulator to stabilize the dose rate fluctuation from pulse to pulse



By improving the AFC, to control the long time dose rate fluctuation

# Dual Energy X-ray Spectra



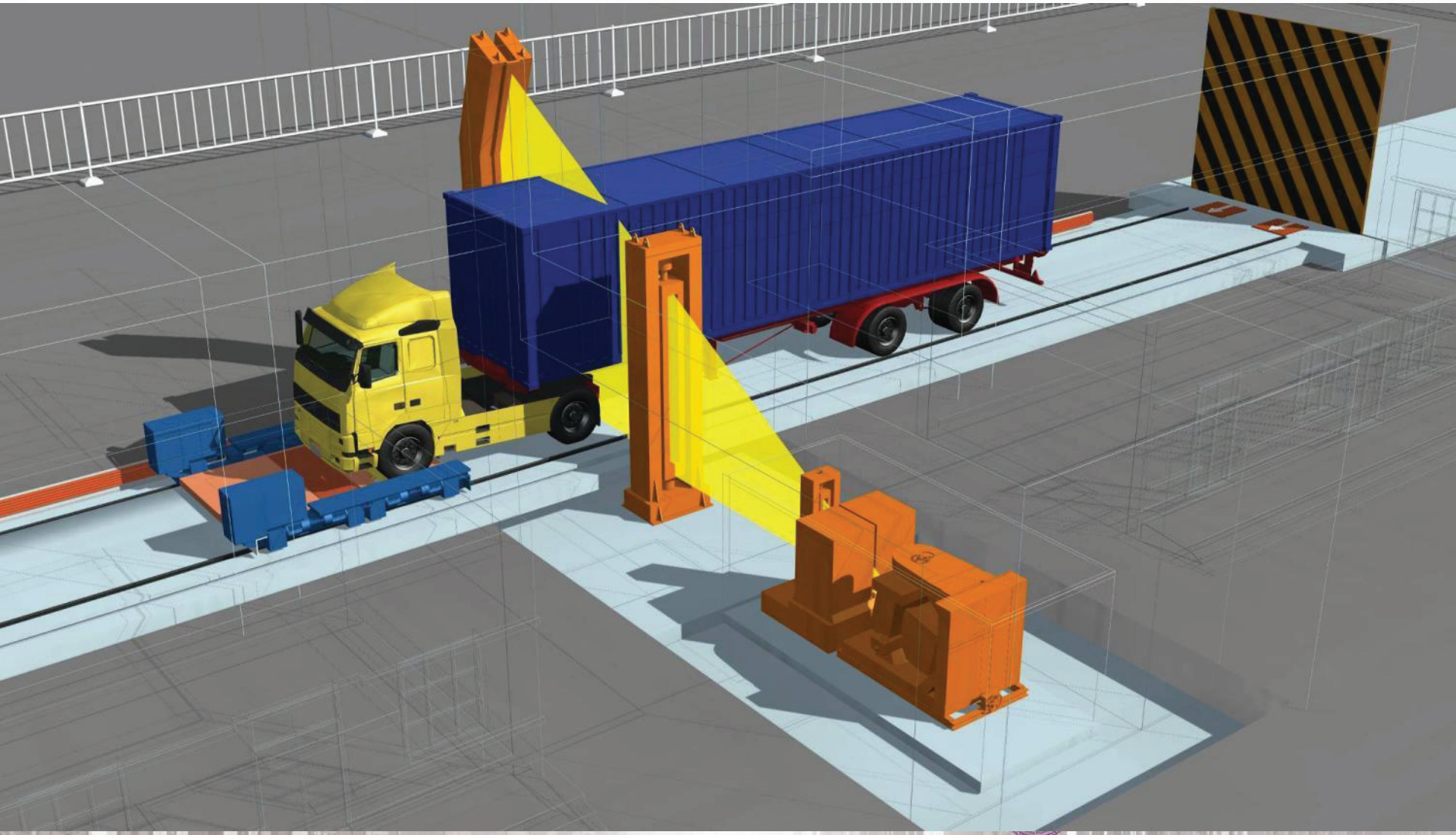

Low Energy X-ray

High Energy X-ray

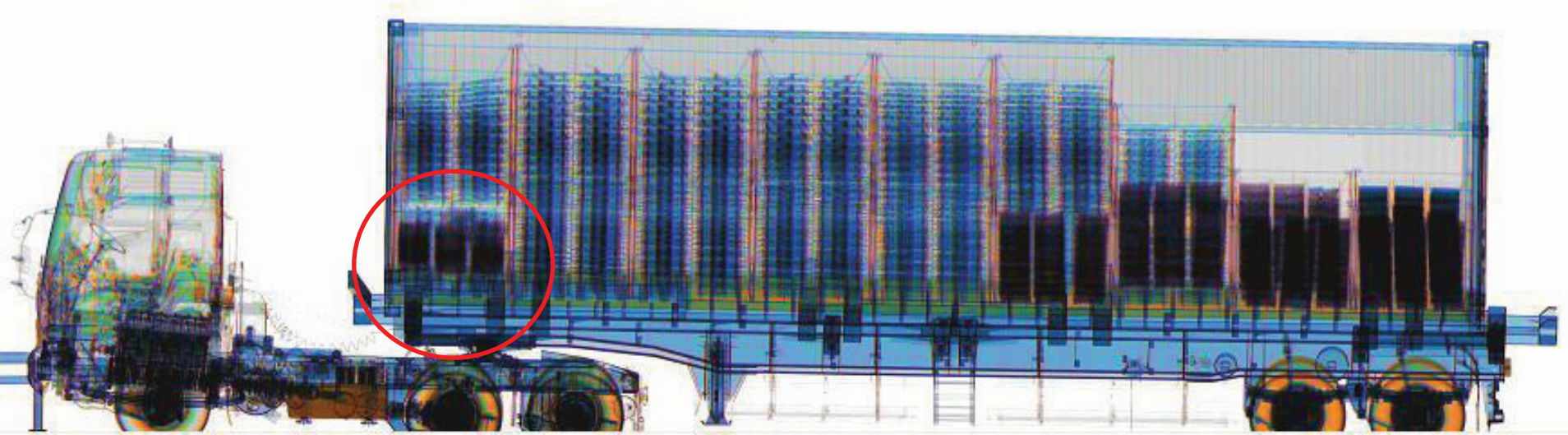
# The Dual Energy Linac

- Magnetron MG5193: 2.6MW, 2998MHz, 4~5us, 300pps
- Low-energy: 6-7MV and High-energy:9-10MV
- Maximum doserate(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
- Also available: 3/6MeV

# NUCTECH FG9000DE



# NUCTECH FG9000DE



# NUCTECH MT1213DE

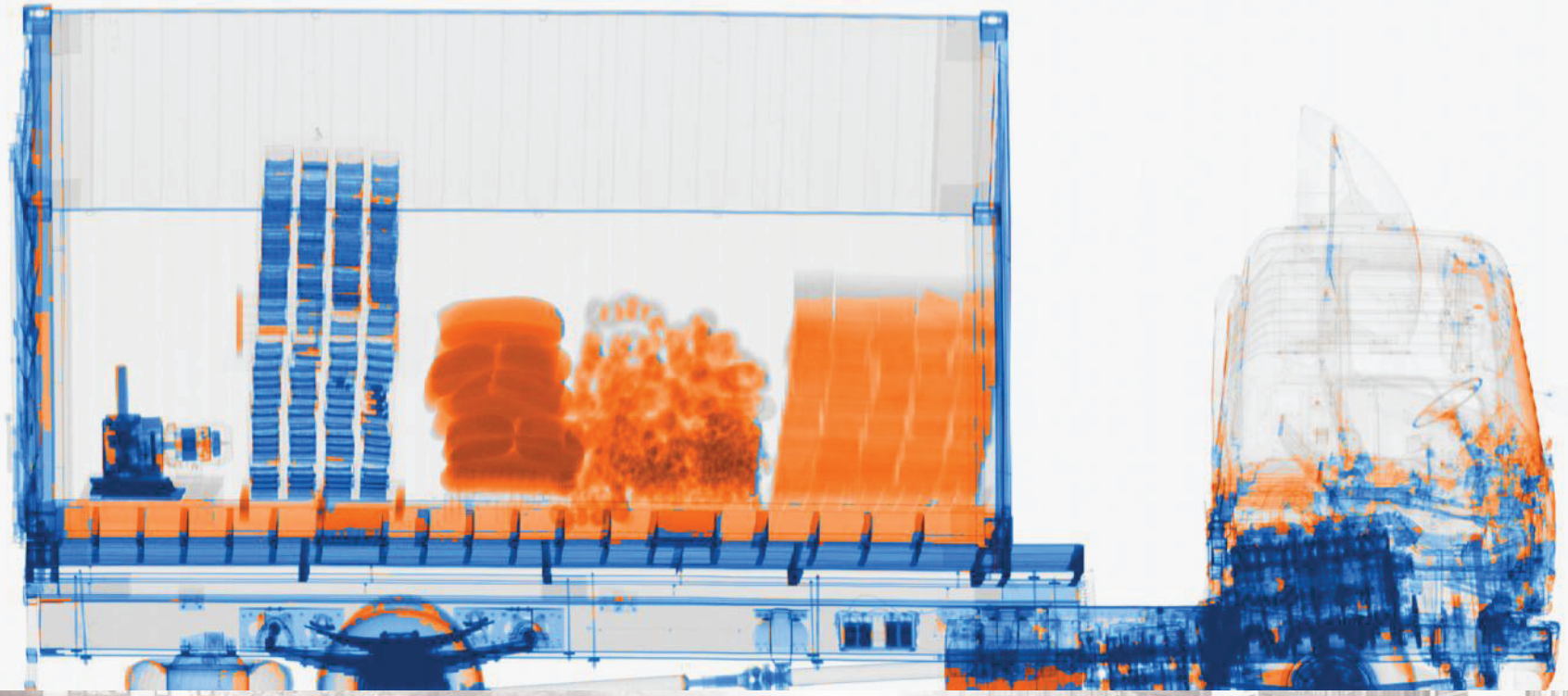
## Dual-energy technology

- Mobile system
- For ports, border


## Features

- **Material discrimination**
- **A 6MeV/3MeV accelerator**
- **Excellent flexibility**
- **Excellent image quality and high penetration (360mm)**
- **Optional Integrated radioactivity monitor**

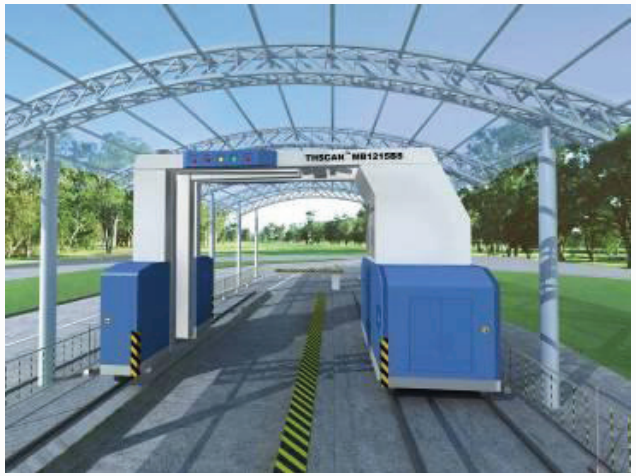
# Scanning image



# NUCTECH MB1215DE

## Dual-energy

- Relocatable system
- For ports, border

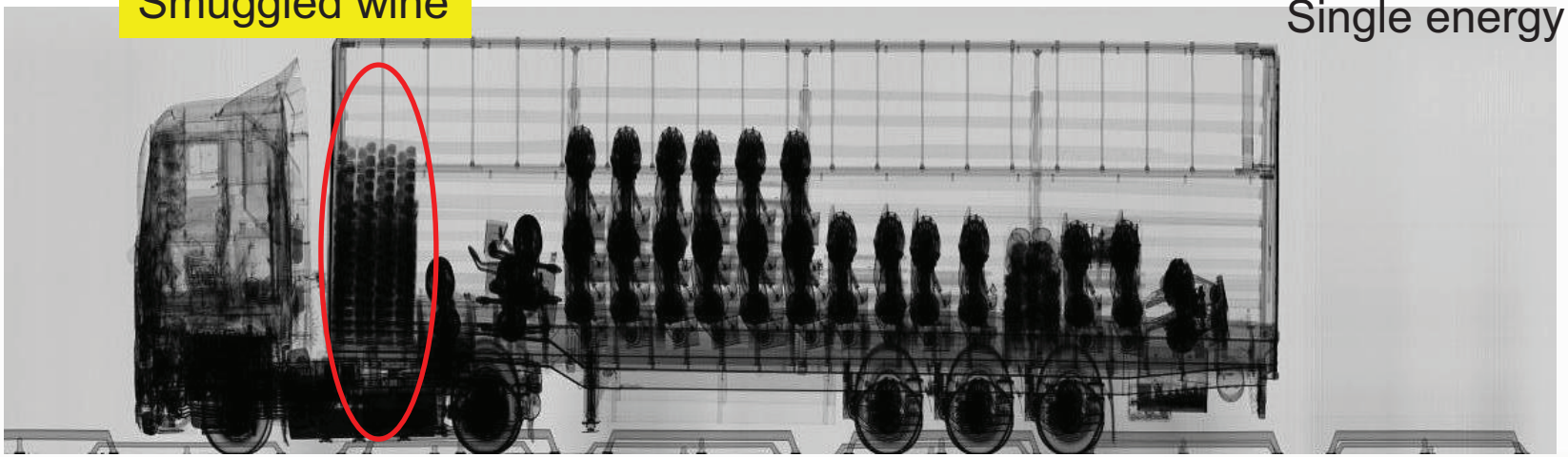



## Features

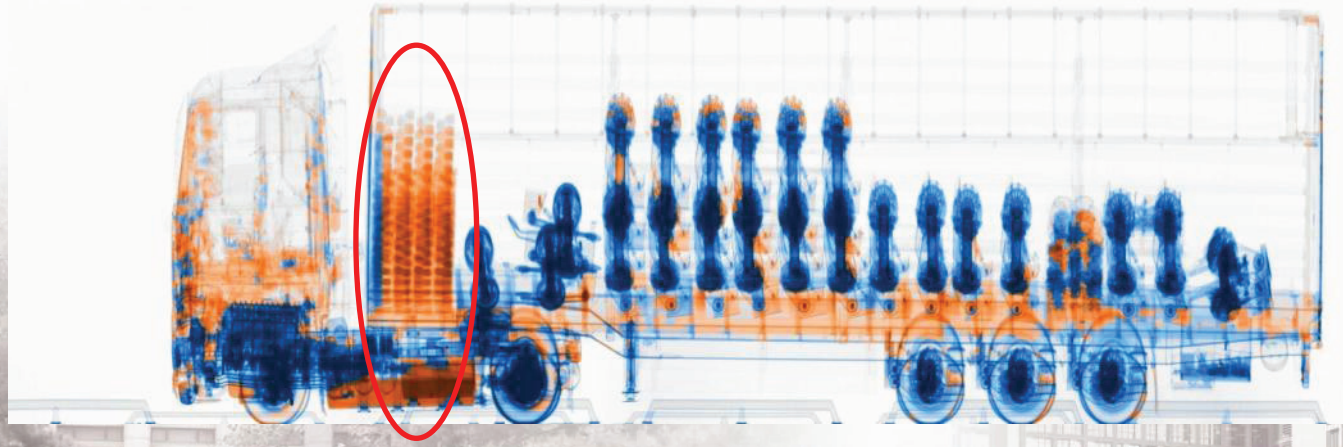
- **Material discrimination**
- **Large scanning tunnel as 5.4m(W) ×5.1m(H) for multi-purpose inspections**
- **Excellent image quality and high penetration (typical 400mm)**
- **High throughput (0.4m/s)**

# Scanning image

Smuggled wine



Single energy image



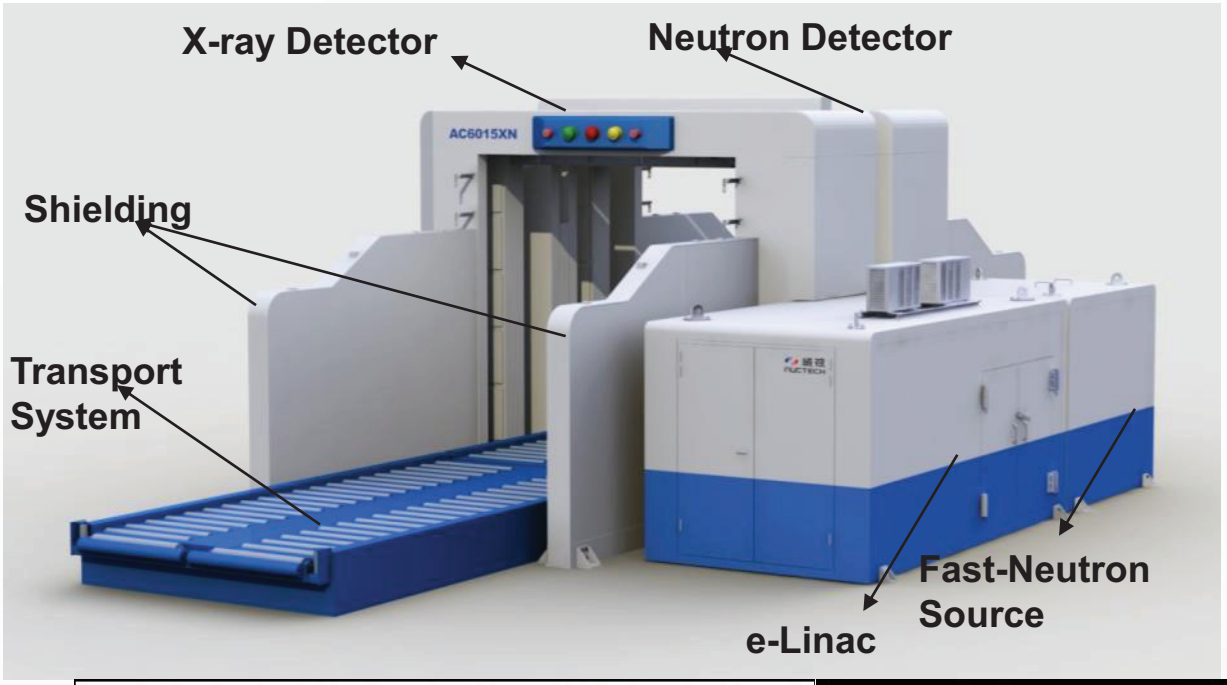
Dual energy image

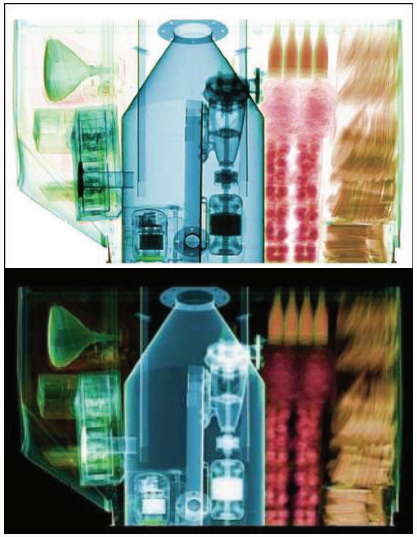
# NUCTECH PB6000

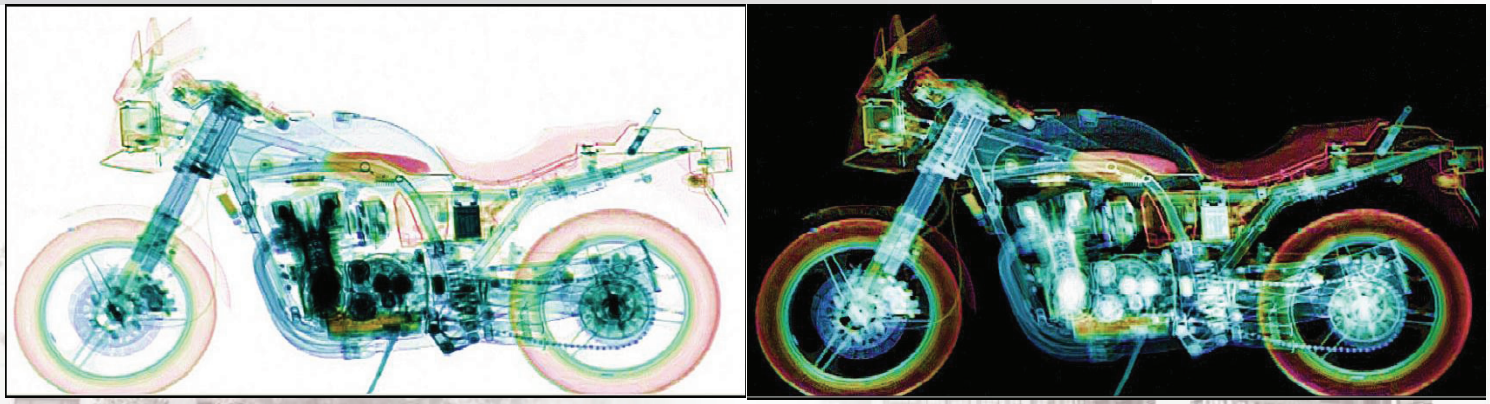
# Combined Fast Scan with Dual Energy

- **At Speed of 15km/h**

# Neutron/Dual-Energy X-ray Fast Scan Technology





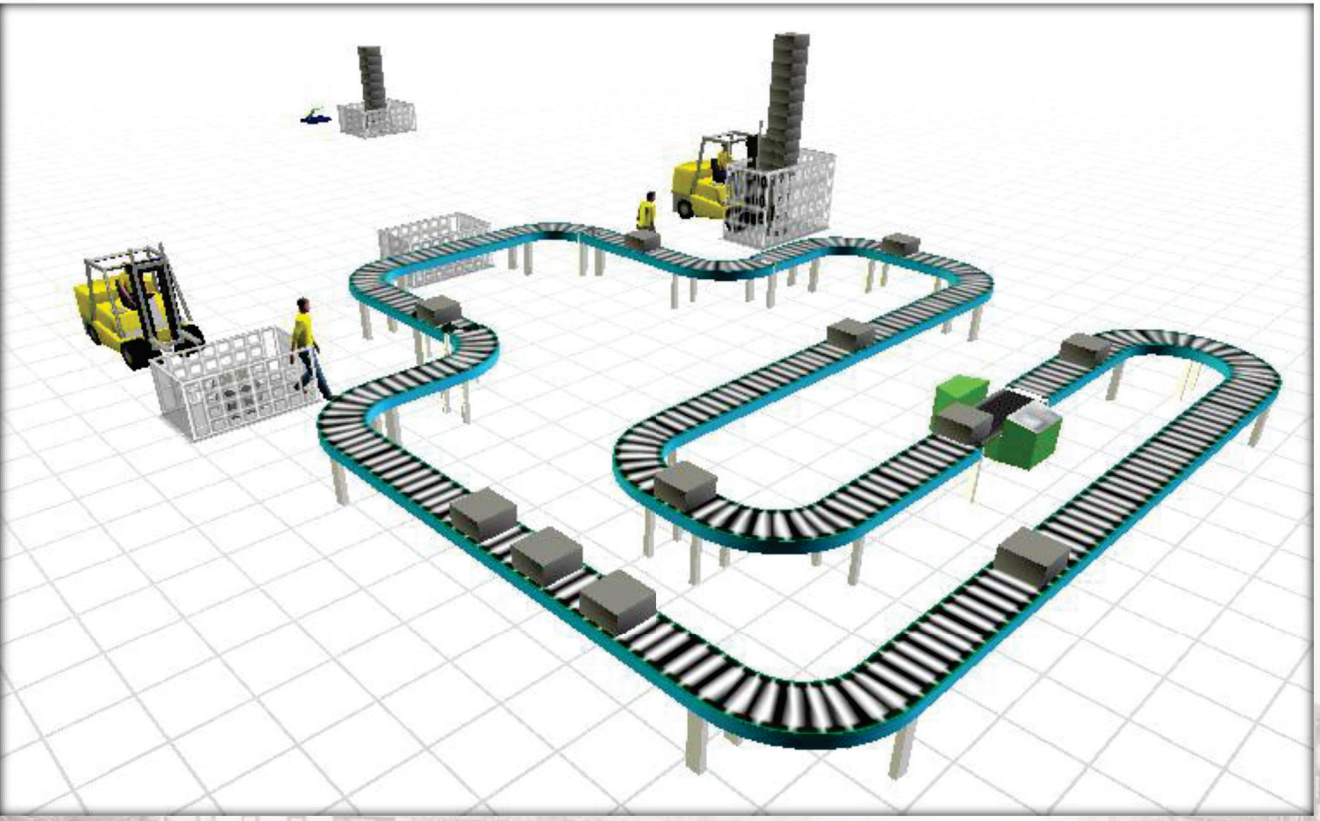
Blue: Metal, Red: hydrocarbon, organics…

# Linacs for Entry Quarantine

**Accelerator as radiation source**
**For: Post/Mail; Fruit, Grains, Logs…**


A 4.5-MeV, 2kW
Mail Quarantine system

# Fruit Irradiation System




# Summary

- In the TUB accelerator lab, a variety of low-energy electron linacs have been developed and applied for different applications.
- A large proportion of the linacs are equipped in the NUCHTECH cargo inspection systems.
- A lot of cargo inspection systems have been equipped and they are operating in the customs in China and other countries.
- We have recently developed a interlaced dual energy linac with stability for material-discrimination inspection system. A lot of products have been developed with this system
- X-ray & Neutron are combined to enhance the capacity.

# Thanks for Your Attention !