Low-Energy Electron Linacs and Their Applications in Cargo Inspection

Yawei Yang on behalf of

Huaibi Chen*,1,
Chuanxiang Tang¹, Yaohong Liu²

*chenhb@tsinghua.edu.cn

¹Department of Engineering Physics, Tsinghua U., Beijing 100084, China
²NUCTECH Company Limited, Beijing 100084, China

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

Wall Plug
AC Power

Modulator

~10kV

Pulse transformer

~50kV

Electron bunch

Electron Accelerator Tube

~10kV Electron gun

Magnetron

Microwave pulse

X-ray

Target

Department of Engineering Physics Tsinghua University
<table>
<thead>
<tr>
<th></th>
<th>SW</th>
<th>TW</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gradient:</strong></td>
<td>~10MeV/m</td>
<td>~5MeV/m</td>
</tr>
<tr>
<td><strong>Efficiency:</strong></td>
<td>30~60%</td>
<td>20~50%</td>
</tr>
<tr>
<td><strong>Capture:</strong></td>
<td>20~30%</td>
<td>~80%</td>
</tr>
<tr>
<td><strong>Gun voltage:</strong></td>
<td>5~20kV</td>
<td>~40kV</td>
</tr>
<tr>
<td><strong>Band:</strong></td>
<td>~200kHz</td>
<td>~2MHz</td>
</tr>
<tr>
<td><strong>AFC:</strong></td>
<td>Required</td>
<td>not required</td>
</tr>
<tr>
<td><strong>Size:</strong></td>
<td>small and simple</td>
<td>large</td>
</tr>
<tr>
<td><strong>Stability:</strong></td>
<td>good</td>
<td>good</td>
</tr>
</tbody>
</table>
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 6MeV Accelerating tube

X-band 2.5MeV Accelerating tube

X-band 6MeV Accelerating tube
C Band Accelerating Structure

C-band 6MeV Accelerating tube
<table>
<thead>
<tr>
<th></th>
<th>Klystron</th>
<th>Magnetron</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type:</strong></td>
<td>Amplifier</td>
<td>Oscillator</td>
</tr>
<tr>
<td><strong>Peak Power:</strong></td>
<td>10s MW or more</td>
<td>normally less 5MW</td>
</tr>
<tr>
<td><strong>Price:</strong></td>
<td>expensive</td>
<td>cheap</td>
</tr>
<tr>
<td><strong>Size:</strong></td>
<td>large</td>
<td>compact</td>
</tr>
<tr>
<td><strong>Stability:</strong></td>
<td>good</td>
<td>need more efforts to control</td>
</tr>
</tbody>
</table>
Linacs Used as the X-ray Source in the NUCHTECH Cargo Inspection System

Collimators

Detectors

Control and Imaging systems

Linac as x-ray source
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

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

Mobile

- 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

Normal Position of the target

Low target

Cargo

Ground Base
Railcar Inspection Systems

RF9066

RF9010

RF6010

RF4010
Railcar Inspection with speed of 40km/h (up to 60km/h)
200keV: Luggage Inspection Systems

- Photoelectric Effect
- Pair Production
- Compton Effect

Axes:
- E- MeV
- $\mu\rho/cm^2/g$

Materials:
- $^{82}$Pb
- $^{26}$Fe
- $^{13}$Al
- $^6$C
- $^5$B

Energy Levels:
- $3MeV$
- $6MeV$
- $9MeV$
- $200keV$
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
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

Photon Energy MeV
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 FG90000DE
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
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
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
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!