An X-band Compact Electron Linac Development For A Neutron Radiography

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Neutron Radiography

Typical neutron radiography images:
(a) injection nozzle for diesel engines
(b) dried fish (Piranha)

“Mercure from Thalwil” statue made of Roman bronze
Image from IAEA-TECDOC-1604, Neutron Imaging: A Non-Destructive Tool for Materials Testing
Neutron Radiography

For neutron radiography
- $10^5$ n/cm$^2$/s of thermal neutron is needed.
- Using Photoneutron reaction tungsten target for gamma, Be target for neutron 15 MeV, ~100 uA electron linac is needed.
Goal for the Research

High-energy X-ray

X-band, 6 MW Klystron

WR90 Waveguide

Power Supply

Power Divider

Phase Shifter

Circulator

RF Window

Be Target

Target

x ~60 cm

Accelerating Section 1

Accelerating Section 2

E-Gun

Circulator

RF Window

High-energy X-ray

Neutron

Asian Forum for Accelerators and Detectors (AFAD) 2018
**Toshiba E37113 Klystron**

**Table 1: Specification and Design Target**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Specification</th>
<th>Design target</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Frequency</td>
<td>GHz</td>
<td>11.9942</td>
<td>11.9942</td>
</tr>
<tr>
<td>Peak RF power</td>
<td>MW</td>
<td>≥6</td>
<td>6</td>
</tr>
<tr>
<td>Power Efficiency</td>
<td>%</td>
<td>&gt;40</td>
<td>≥45</td>
</tr>
<tr>
<td>Power Gain</td>
<td>dB</td>
<td>-</td>
<td>≥43</td>
</tr>
<tr>
<td>RF pulse length</td>
<td>µs</td>
<td>≥5</td>
<td>5</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>pps</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>RF average power</td>
<td>kW</td>
<td>≥12</td>
<td>12</td>
</tr>
<tr>
<td>Peak beam voltage</td>
<td>kV</td>
<td>-</td>
<td>≤175</td>
</tr>
<tr>
<td>Peak beam current</td>
<td>A</td>
<td>-</td>
<td>≤115</td>
</tr>
<tr>
<td>Output cavity type</td>
<td>-</td>
<td>-</td>
<td>3 cell</td>
</tr>
<tr>
<td>Number of window</td>
<td>-</td>
<td>-</td>
<td>one</td>
</tr>
<tr>
<td>Waveguide size</td>
<td>-</td>
<td>-</td>
<td>WR-90</td>
</tr>
</tbody>
</table>

Data from Yoshihisa Okubo, DEVELOPMENT OF AN X-BAND 6 MW PULSED KLYSTRON, Toshiba E37113 Klystron
# Requirements of the Electron Linac

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Frequency</td>
<td>11.9942 GHz</td>
</tr>
<tr>
<td>Input RF power (pulsed)</td>
<td>&lt; 5 MW</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>4 us</td>
</tr>
<tr>
<td>Duty Factor</td>
<td>0.002</td>
</tr>
<tr>
<td>Output Beam Current (Pulsed Maximum)</td>
<td>50 mA</td>
</tr>
<tr>
<td>Average Beam Current</td>
<td>100 uA</td>
</tr>
<tr>
<td>Output Beam Energy</td>
<td>15 MeV</td>
</tr>
<tr>
<td>Effective Shunt Impedance per Unit Length</td>
<td>150 MΩ/m</td>
</tr>
<tr>
<td>Structure Type</td>
<td>Side-coupled Cavity</td>
</tr>
<tr>
<td>Length of the Accelerating Structure</td>
<td>~ 60 cm</td>
</tr>
</tbody>
</table>
Design Process of the Electron Linac

Compact Electron Linac Design

<table>
<thead>
<tr>
<th>1st Stage</th>
<th>2nd Stage</th>
<th>3rd Stage</th>
<th>4th Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gathering Information</td>
<td>Single Cell Design</td>
<td>Beam Dynamics</td>
<td>Full Cell Design</td>
</tr>
</tbody>
</table>

**Limitations**
- Size
- Thickness
- Length

**System Requirement**
- Beam energy
- Beam Current
- Beam size
- Frequency
- RF Power

**1st Stage**
- Maximize shunt impedance

**2nd Stage**
- Genetic algorithm adapted design

**3rd Stage**
- Minimize beam size
  - Maximize acceleration
  - Maximize capture coefficient

**4th Stage**
- Side-coupling cell design
- RF power coupler design
- Whole cell simulation

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Representative Cell Design

Parameters to be Concerned

Accelerating Cell Optimization

- Total 11 parameters are controlled simultaneously in 1 cavity module during optimization process.
- Usually optimal RF cavity design depends on designer’s experience or can be found using parametric searching method.
Things About Genetic Algorithm

Mimicking the Nature – Biological Evolution

- Population
- Mating Pool
- Selecting Mates
- Mating Process
- Offspring
- New Population

Applying to Computing Algorithm

- Selection
- Crossover
- Mutation
- Generation
Genetic Algorithm

Pseudo-code of the Genetic Algorithm

Procedure of Genetic Algorithm
Set \( k = 0 \);
Create an initial population \( P(k) \) – generate individuals;
Evaluate \( P(k) \);

While <the termination conditions are not met>
    Set \( k = k + 1 \);
    Reproduce mating pool \( \tilde{P}(k) \) from \( P(k-1) \) using tournament selection;
    Crossover \( \tilde{P}(k) \) to form a tentative population \( P(k) \);
    Mutate \( \tilde{P}(k) \) to form the new population \( P(k) \);
    Evaluate \( P(k) \);
End While
Output the solution;
Genetic Algorithm

Overall Procedures of the Genetic Algorithm

Setting Parameters & Objective functions

Convergence Test

Create Population

Fitness Evaluation

Selection (Reproduction)

Crossover (Recombination)

Mutation

Stop
Genetic Algorithm

Overall Procedures of the Genetic Algorithm

1st Generation
Population

Individual 1  Individual 2  Individual 3  Individual 4

Individual N-3  Individual N-2  Individual N-1  Individual N

Fitness = Effective Shunt Impedance

Selection, Crossover, Mutation

2nd Generation
Population

Individual 1  Individual 2  Individual 3  Individual 4

Individual N-3  Individual N-2  Individual N-1  Individual N

Final Generation

Individual 1  Individual 2  Individual 3  Individual 4

Individual N-3  Individual N-2  Individual N-1  Individual N

Best Value
Accelerating Structure Design by Using Genetic Algorithm

Optimized Results – Accelerating Cell

Effective Shunt Impedance Evolution
Through Whole Generation
### Accelerating Structure Design by Using Genetic Algorithm

#### Properties of the Accelerating Cell

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Frequency</td>
<td>11994.19999 MHz</td>
</tr>
<tr>
<td>Transit-time factor</td>
<td>0.7851013</td>
</tr>
<tr>
<td>Stored energy</td>
<td>0.0057181 Joules</td>
</tr>
<tr>
<td>Power dissipation</td>
<td>98.558 kW</td>
</tr>
<tr>
<td>Quality factor</td>
<td>8744.63</td>
</tr>
<tr>
<td>Shunt impedance</td>
<td>264.534 MΩ/m</td>
</tr>
<tr>
<td>Rs*Q</td>
<td>249.855 Ω</td>
</tr>
<tr>
<td>Effective shunt impedance</td>
<td>163.055 MΩ/m</td>
</tr>
<tr>
<td>r/Q</td>
<td>115.607 Ω</td>
</tr>
<tr>
<td>Peak H-field</td>
<td>97145.1 A/m</td>
</tr>
<tr>
<td>Peak electric field</td>
<td>186.676 MV/m, 2.08363 Kilp.</td>
</tr>
<tr>
<td>Ratio of peak fields $B_{peak}/E_{peak}$</td>
<td>0.6539 mT/(MV/m)</td>
</tr>
<tr>
<td>Peak to average ratio of electric field</td>
<td>4.0711</td>
</tr>
</tbody>
</table>
Accelerator Fabrication

Surface Roughness

Ra = 39 nm

2D distribution

Roughness Profile

Developed at Sungkyunkwan University

Ra = 25 nm

Developed at CERN

Peak electric field > 300 MV/m can be operated.
Beam Dynamics Design

Optimized Beam Line Design

Electric Field Distribution

Energy Gain of the Electron Beam

Below 0 means deceleration
Beam Dynamics Design

ASTRA Results – Multi-particle Simulation

Particles taken into account  \( N = 40191 \)
total charge  \( Q = -2.0095E-02 \) nC
horizontal beam position  \( x = -1.2416E-03 \) mm
vertical beam position  \( y = 1.4949E-04 \) mm
longitudinal beam position  \( z = 0.5758 \) mm
horizontal beam size  \( \sigma x = 0.2156 \) mm
vertical beam size  \( \sigma y = 0.2178 \) mm
longitudinal beam size  \( \sigma z = 35.58 \) mm
average kinetic energy  \( E = 13.04 \) MeV
energy spread  \( dE = 3904 \) keV
transverse beam emittance  \( \epsilon x = 4.545 \) pi mrad mm
correlated divergence  \( \delta x = -0.1475 \) mrad
transverse beam emittance  \( \epsilon y = 4.658 \) pi mrad mm
correlated divergence  \( \delta y = -0.1404 \) mrad
longitudinal beam emittance  \( \epsilon z = 1.3596E+05 \) pi keV mm
correlated energy spread  \( \epsilon z = 801.6 \) keV
emittance ratio  \( \epsilon y/\epsilon x = 0.9758 \)

- **Capture coefficient** is 40 %
  100 k particles are involved to the calculation. 40,191 particles are survived
- Average Energy is 13.04 MeV, Energy spread is 3.9 MeV
- A kinetic energy of electron can be calculated from a momentum
  \[ p = 15.51 \text{ MeV/c} = E_k = 15 \text{ MeV for electron} \]
- High energy particles are concentrated on the head of bunch
Beam Dynamics Design

ASTRA Results – Multi-particle Simulation
Beam Dynamics Design

ASTRA Results – Multi-particle Simulation

- Most of particles are concentrated at the head of the bunch and accelerated more than 15 MeV/c
- Length of bunch in time is **83.37 ps** which is 1 RF period of 11.9942 GHz, in other word, **25 mm** in length.
Beam Dynamics Design

ASTRA Results – Multi-particle Simulation

Transverse beam cross section

5 Beam bunches just before the target

- The size of the accelerated beam is roughly 2 mm diameter but most of the low energy particles are located at the halo of the beam bunch. Therefore, those low energy particle can be eliminated to reduce energy spread and decrease beam size.
Summary

- **Compact electron linac** using an **X-band** RF technology to get a **15 MeV electron** for an X-ray generation was developed for a **compact neutron radiography machine**.
- **ASTRA** code was used for beam dynamics design stage, **Poisson/Superfish** was used for RF cavity design.
- **Genetic algorithm** was adapted for an efficient accelerating cell design.
- Design of **coupled structure** of accelerating cells and coupling cells, **power coupler** design is remained.
- For further works, **CST Microwave Studio** will be used for 3D electromagnetic simulation.
Thank you for your attention