HIGH-GRADIENT S-BAND ELECTRON LINAC FOR THOMX

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Outline

• ThomX project
• ThomX Linac upgrade
• SW RF gun
• HG gradient accelerating structure Design
• Beam dynamics simulations
• Conclusions and perspectives
ThomX project

ThomX is a Compton source project in the range of the hard X rays (45 / 90 keV). The machine is composed of an injector Linac and a storage ring where an electron bunch collides with a laser pulse accumulated in a Fabry-Perot resonator. The final goal is to provide an X-rays average flux of $10^{11} - 10^{13}$ ph/s. This demonstrator was funded (12 M€) and is being built in the Paris Sud University Campus.

Linac: Rep. rate= 50 Hz; Energy: 50 MeV
upgrade to 70 MeV forseen

The 1nC electron bunch is stored over 20 ms in a ring (Rev. freq ~ 17 MHz Circumference= 18 m)
Overview of the Thomx machine under construction

ScandiNova Modulator

Toshiba Klystron E37310
ThomX Linac upgrade

Power Sources: 35 MW peak power, Klystron
\( f_{RF} = 2998.55 \text{ MHz @ } 30^\circ \text{ C} \), in vacuum,
Repetition rate = 50 Hz,
RF pulse width (flat top) = 3 µs

Commissioning phase

Upgrade phase

<table>
<thead>
<tr>
<th>Parameters</th>
<th>LIL structure</th>
<th>Compact High Gradient (HG) structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length flange to flange</td>
<td>4.8 m (135 cells)</td>
<td>3.5 m (96+2 cells)</td>
</tr>
<tr>
<td>Linac energy gain (MeV)</td>
<td>50 MeV</td>
<td>70 MeV</td>
</tr>
</tbody>
</table>

Direct impact on X-rays energy:
- 50 MeV \( \rightarrow E_x \sim 45 \text{ keV} \) --\> Medical imaging
- 70 MeV \( \rightarrow E_x \sim 90 \text{ keV} \) --\> Radiotherapy

CTS: Cathode transfer System

RF gun designed and fabricated @LAL

CTS installation

More compactness

More energy gain
Standing wave RF gun for THOMX

Long experience achieved from LAL in the RF Gun design and construction

**CST Particle in cells simulation results**

- **RF gun specifications**
  - **Operation frequency**: 2998.55 MHz (30° C, in vacuum)
  - **Charge**: 1 nC
  - **Laser wavelength**: 266 nm
  - **Pulse energy**: 100 µJ
  - **Q and r_s**: 15000, 49 MΩ/m
  - **Accelerating gradient**: 80 MV/m @ P_in = 5 MW

- **THOMX RF Gun with its coils**
  - The bucking coil current is set to cancel the B-field at the cathode
  - The distance between two coils is calculated in order to move beam waist closer to the accelerating structure entrance, maintain smaller beta function and avoid transverse emittance degradation in TL

**RF gun specifications**

**Accelerating gradient** ($TM_{010-\pi}$ mode)

- **RF power (5MW)**

**Mg Photo-cathode**

- **Bucking coil**
- **Focusing coil**

**Short circuit**

Coupling slot compensating the field distortion

**Energy gain** = 5 MeV for $P_{in} = 5$ MW

**06/06/2018 Dr. El Khaldi**
High Gradient TW Structure: RF parameters

Amplitude variation of the axial E-field

Phase variation of the axial E-field

Good field flatness

Optimal phase advance: 120 ± 0.7°

S-parameters at the operating frequency:
Transmission coefficient, \(|S_{12}| \approx -5.4\ \text{dB}\)
Reflection coefficient, lower than -38 dB

Constant gradient structure type

Regular cells:
- Double roundings to increase the \(Q_0\)
- Elliptical shape of the iris to decrease \(E_{surf}\)
- 2 Quasi-symmetric single feed couplers
- Number of regular cells = 96

Structure RF parameters

<table>
<thead>
<tr>
<th>Frequency</th>
<th>2998.55 MHz @ 30° C in vacuum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective length</td>
<td>3263 mm</td>
</tr>
<tr>
<td>Phase advance</td>
<td>(2\pi/3)</td>
</tr>
<tr>
<td>Iris diameter (2a)</td>
<td>23 → 17.36 mm</td>
</tr>
<tr>
<td>Average (Q_0) (unloaded)</td>
<td>15175</td>
</tr>
<tr>
<td>Output power</td>
<td>(0.29 \times P_{in})</td>
</tr>
<tr>
<td>Filling time</td>
<td>990 ns</td>
</tr>
<tr>
<td>(R_{sh})</td>
<td>71 → 85 ((\Omega/m))</td>
</tr>
<tr>
<td>Group velocity, (V_g/c)</td>
<td>1.71% → 0.67%</td>
</tr>
</tbody>
</table>
High Gradient TW Structure: RF parameters

For $P_{in}=25$ MW, RF pulse width (Flat Top) = 3 µs:

- $E_{surf, Max} = 35$ MV/m
- $S_{c, Max} = 0.25$ MW/mm²
- Pulsed surface heating $\Delta T < 6 ^\circ C$
- BDR = $10^{-18}$ bpp/m
- Effective Acc. Gradient, $E_a = 21$ MV/m
- Unloaded Energy gain = 66 MeV

This is valid for structures which will be constructed based on the high gradient assembly procedure which includes keeping everything rather clean (maybe not as clean as for SRF) and having high temperature bonding or brazing cycle in Hydrogen or in vacuum.
**RF-track simulations**

- RF-Track is a novel tracking code developed at CERN for the optimization of low-energy linacs in presence of space-charge effects. The RF structures are described by means of the 3D electromagnetic fields and it is able to treat directly the output of HFSS or CST programs.

- Subsequent calculations are performed using the full 3D EM field of the HG accelerating structure generated via CST.

- The next beam optimization are planned to be performed using the RF track.

A. Vnuchenko et al, Proceedings of IPAC 2018, Vancouver, Canada

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**Beam performances at the exit of linac**

| E [MeV] | 67 |
| ΔE/E [%] | 0.2 |
| εx, y [mm mrad] | 5.31/5.40 |
| σx, y [mm] | 0.66/0.65 |
| βx, y [m] | 10.97/10.3 |
Conclusions and perspectives

Ph D thesis of Luca Garolfi under my supervision defended on 12 January 2018:

• Electromagnetic design (regular cell, couplers, prototypes and final accelerating section), cooling system design have been performed

• Beam dynamics studies using ASTRA code of the ThomX Linac have been performed in order to validate the Linac design and find an optimised working point delivering a beam with high charge, low emittance, low energy spread, small transverse beam size,

• 7-cell Aluminum prototype has been realized

Future actions:

• Fabrication of a copper prototype with a reduced number of cells
  The goals of this prototype are:
  ❖ test all design and fabrication procedure
  ❖ test the structure at high power
• Fabrication of 3.2 m long high-gradient S-band accelerating section

We are looking for collaborator partners with an extensive experience in the development of HG accelerating sections,
Thank you for your attention.
Cathode Transfer System (CTS)
Cathode Transfert System (CTS)

- Chambre pompage + jauges
- Réserve Cathodes
- Bras tournant
- Soufflet assiette DN63 c500mm
- Traversée tournante
- Platine réglable
- Chassis support
- Valise sur XPS
- 4 cathodes
- Cathode Transfert System (CTS)
**High Gradient TW Structure: regular cell design**

Regular Cells are optimized to have minimum of the merit function $\mu$:

$$
\mu = \frac{P_{\text{in}} S_c}{E_a^2 E_a^2} = \frac{v_g S_c}{E_a^2} \frac{S_c}{E_a^2} = \frac{r_s/Q}{r_s/Q}
$$

- Min: low breakdown rate
- Max: reduced power consumption and high RF efficiency
- Reduced filling time

- The final choice of the geometrical parameters has been chosen: $t = 5 \text{ mm}$; $\rho = 10 \text{ mm}$, considering an elliptical iris shape and a reasonable iris aperture range: $17 \text{ mm} \leq 2a \leq 23 \text{ mm}$ in order to guarantee:
  - High-accelerating efficiency with minimum risks of breakdown
  - Short filling time compared to the RF pulse
  - Good pumping speed

- We have well developed RF design criteria which predict the gradient of pulsed high gradient structures. The criteria cover the physical phenomena which limit the accelerating gradient:
  - Power flow (modified Poynting vector $S_c = ||Re(S)|| + \frac{1}{6} ||Im(S)||$)
  - Surface Electric field ($E_s$)
  - Surface Magnetic field/Pulsed surface heating ($\Delta T \propto H_s^2 \sqrt{E_p} < 50^\circ C$)
**Electron-photon interaction**

- $e^-$ beam (MeV, GeV)
- $e^-$ laser

$E_{ph}$ initial photon energy
$E_x$ scattered photon energy

**Compton interaction**

$E_x \sim \frac{2 \gamma^2 E_{ph} [1 + \cos(\theta_{ph})]}{1 + (\gamma \theta)^2}$

**X source geometry**

**Energy tunable beam**

An example

- $E_e = 50$ MeV
- $\gamma = 99$
- $E_{ph} = 1.4$ eV

head-on collision

$E_x = 45$ keV

On-axis

**Brightness** $\sim 0.0015 \frac{Flux}{(2\pi)^2} \left( \frac{\sigma_e^2 + \sigma_i^2}{\sigma_i^2} \right) \left( \frac{\gamma^2}{\epsilon_N^2} \right)$

High Flux

Low beam emittance

High Brightness

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Application: Imaging

1. Using the 2D divergent beam
(biomedical and cultural heritage applications)

   - Conventional radiography
   - K-edge subtraction imaging
   - Phase contrast imaging
     - Magnification
     - RADIOThERAPY

2. Using the central part of the beam
(cultural heritage / material science applications)

   - Fluorescence Spectroscopy
     → chemical composition
   - Diffraction
     → structural analyses

- bw 2-3%
- Small source size (to have transv. coherence)

   • 45 keV, bw 2-3%
   • \( d_s = 3 \text{ cm} \) (D ~ 10 m)
   • \( 4 \times 10^{11} \text{ ph/s} \)

   - Hospital sources:
     large focal spot size, broad spectrum, low flux

   - a 300 \( \mu \text{m} \)
   - nylon wire

CS Lycean Tech. (only CCS in operation in the world)

   - 13.5 KeV, 3% bw
   - \( 10^5 \text{ ph/sec} \)
   - \( \sigma = 165 \text{ \( \mu \text{m} \)} \)

   - Proof of principle

Courtesy Marie Jacquet (LAL)

06/06/2018
Application: Therapy

1. Using the 2D divergent beam
   (biomedical and cultural heritage applications)
   - Conventional radiography
   - K-edge subtraction imaging
   - Phase contrast imaging
   - Magnification
   - RADIOThERAPY

2. Using the central part of the beam
   (cultural heritage / material science applications)
   - Fluorescence Spectroscopy
     → chemical composition
   - Diffraction
     → structural analyses

- High energy (~ 80KeV)
- bw ~ 10%

Ex. : Human head tumor irradiation
(tumor deliver dose ~ 10-20 Gy)

- ThomX → 0.5 Gy/min
  → ~ 20 min of irradiation
- ESRF/ID17 = ~ 10⁹ ph/s/mm²

(Hospital sources → broad spectrum, and continuously operation not possible)

Courtesy Marie Jacquet (LAL)

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