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Laboratoire de l’Accélérateur Linéaire LAL

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HIGH-GRADIENT S-BAND ELECTRON LINAC FOR THOMX

L. GAROLFI
Outline

- ThomX project;
- LINAC main specifications respect to the ThomX layout;
- Beam dynamics simulations of the photo-injector;
- PMB-LAL research collaboration for LINAC upgrade:
  - High gradient S-band accelerating structure (HGAS) for THOMX LINAC,
  - Single cell geometry optimization and 3D simulations results,
  - Prototypes design and 3D simulations results,
  - Quasi-constant field high gradient accelerating structure (preliminary configuration);
- Conclusions and prospects;
ThomX project

- French project led by LAL (budget: 12 M€, 10 M€ TTC facility & 2 M€ TTC operation).

- Compton backscattering compact hard X-rays (45-90 keV) source with high flux ($10^{11}-10^{13}$ ph/s).

- Relatively low energy machine (50-70 MeV) which allows installation in hospitals or museums.

- A demonstrator was recently funded and it is under construction in the Orsay University campus.

- Application domains:
  - Cultural heritage (collaboration with LAMS, Paris): imaging, structural & chemical studies of artefacts,
  - Medical science (collaboration with ESRF, Grenoble): imaging, high energy radiotherapy (specific tumors).

Industrialisation phase (Thales): ThomX demonstrator can be commercialised as an integrated product.
LINAC main specifications

- To fulfill the accelerator specifications, the LINAC has to be carefully designed, especially the photo-injector.

LINAC requirements

- Energy: 50 MeV,
- Bunch charge: 1 nC,
- Repetition rate: 50 Hz,
- Rms norm. emittance: $\varepsilon_N \sim 4 \text{ mm mrad} \pi$
- Rms energy spread: $< 1\%$
- Rms bunch length: $< 5 \text{ ps}$

\[ Br \sim \frac{\text{Flux} \cdot \gamma^2}{\varepsilon_N^2} \]

High brightness small e⁻ beam emittance $\varepsilon$ is required

X-ray beam

<table>
<thead>
<tr>
<th>Flux</th>
<th>$10^{13}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brithness</td>
<td>$10^{11}$</td>
</tr>
<tr>
<td>Transv. size</td>
<td>70 μm</td>
</tr>
<tr>
<td>$E_x$</td>
<td>30-90 keV</td>
</tr>
<tr>
<td>$\sigma_t$</td>
<td>10-20 ps</td>
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</table>

Conical beam

$E_e = 50 \text{ MeV}$

$\theta \sim 10 \text{ mrad} \rightarrow 22 \text{ keV}$

On axis photons $\rightarrow 45 \text{ keV}$

X-ray for users

Injectors + Linac

Laser + 4-mirrors FP cavity

Transfer line (transport and diags)

Ring 20 MHz

RF & Feedbacks

Accelerating section 50-70 MeV

Elctron gun (50 nA)

©M. Jacquet

Courtesy of M. Jacquet
Photo-injector

- Long experience achieved from LAL in the RF Gun fabrication.
- The RF Gun design is almost the same as for the Probe Beam Photo-Injector (PBPI) at CLIC Test Facility 3.
- To avoid vacuum constraints with high efficiency, a metallic magnesium photocathode has been chosen.

Specifications

<table>
<thead>
<tr>
<th>Laser wavelength</th>
<th>266 nm</th>
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<tbody>
<tr>
<td>Laser pulse duration &amp; energy</td>
<td>5ps, 100 µJ</td>
</tr>
<tr>
<td>Q-factor</td>
<td>15000</td>
</tr>
<tr>
<td>Shunt Impedance</td>
<td>50 MΩ/m</td>
</tr>
<tr>
<td>RF input power</td>
<td>5 MW, 3 µs</td>
</tr>
<tr>
<td>Peak Accelerating gradient</td>
<td>80 MV/m</td>
</tr>
<tr>
<td>Energy gain</td>
<td>~ 5 MeV</td>
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</tbody>
</table>

E field along beam axis
- 2D-field profile obtained by SUPERFISH,
- Frequency & $\Delta \Phi$: 2998.55 MHz, $\pi$-mode,
- Good field flatness achieved,

B field along beam axis
- 2D-field profile obtained by OPERA,
- B strength without & with shielding plate,
- $B = 0$ T @ $z = 0$ m (photocathode position),
Beam Dynamics Simulations of the Photo-injector

- Transverse normalized total beam emittance in RF Gun \( \epsilon_{n,x,y,tot} \) dependence of RF field (\( \epsilon_{RF} \)), space charge (\( \epsilon_{SC} \)), thermal photoemission (\( \epsilon_{th} \)).
  \[ \epsilon_{n,x,y,tot} = \sqrt{\epsilon_{RF}^2 + \epsilon_{SC}^2 + \epsilon_{th}^2} \]
- Beam dynamics simulations has been performed using A Space charge TRacking Algorithm (ASTRA).
- Electron bunch distribution setting in ASTRA: 10000 particles, bunch charge \( Q \), laser pulse duration \( \sigma_t \), rms size \( \sigma_{x,y} \).
- Shielding plate is much more effective on the beam size (\( \sigma_{x,y} = 9.7 \) mm without shielding, \( \sim 3 \) mm with shielding).
- Transverse emittance compensation: \( \epsilon_{x,y} = 13.7 \) mm mrad \( \pi \) without shielding, 10.6 mm mrad \( \pi \) with shielding.

Solenoids effect

- \( \epsilon_{n,x,y,tot} vs B strength \)

WS: emittance growth is linear.

- The effect of the shielding plate is effective on the transverse beam size.

\[ \epsilon_{n,x,y,tot} function of z is calculated for different magnetic field strengths. \]

- Intersection with the zero cross line gives the right value of B.

L. Garolfi (LAL) - LAL, 11/05/2016
The collaboration agreement between PMB and LAL has been established from October, 1st, 2014 to September, 30th, 2017.

**Commissioning phase: LIL structure**
- Total length: 4.5 m (135 cells),
- Travelling wave section (TW),
- Quasi-constant gradient structure,
- Phase advance per cell: $2\pi/3$-mode,
- Average acc. field: 14.6 MV/m @ 18 MW,
- Filling time $\sim 1.35 \mu$s,

**Upgrade phase: PMB-LAL**
- Total length: 3.2 m (96 cells),
- Travelling wave section (TW),
- Quasi-constant gradient structure,
- Phase advance per cell: $2\pi/3$-mode,
- Average acc. Field: 18.5 MV/m @ 18 MW,
- Filling time $\leq 1 \mu$s,

**S-band Linac:**
- $f_{RF} = 2998.55$ MHz @ 30 ° C under vacuum,
- Repetition rate max = 50 Hz,

Direct impact on X-rays energy:
- 50 MeV $\rightarrow$ $\gamma \sim 45$ keV
- 70 MeV $\rightarrow$ $\gamma \sim 90$ keV
PMB ALCEN-LAL Research Coll.: Single cell geometry optimisation

- Optimization of the cell shape (HFSS & CST MWS) → Improvement of the main RF figure of merit: $r/Q$, $v_g$, $\alpha$, $E_{peak}/E_{a}$, $S_c/E_{a}$, etc.

- Single cell has been designed exploring the different TW cell parameters as a function of the iris aperture ($a$), iris thickness ($t$), ellipticity ratio ($r_2/r_1$) and radius $\rho$.
  - Irises with elliptical shape ($r_2/r_1=1.7$): reduce the peak surface field of 10-15%
  - Rounding of the cell edge ($\rho=10$ mm): improves the quality factor more than 10% and reduces the wall power consumption.

- Minimum power consumption and the minimum risk of breakdown → modified Poynting vector $S_c$

$$\eta \equiv \frac{\rho}{\frac{S_c}{E_{a}}^2} \cdot \frac{S_c}{E_{a}}^2 = \frac{v_g}{\omega} \cdot \frac{S_c}{E_{a}}^2$$

Surface Magnetic Field
For $P_{in} = 20$ MW

$H_{peak} = 65$ kA/m

Surface Electric Field
For $P_{in} = 20$ MW

$E_{peak} = 44$ MV/m

Modified Poynting Vector
For $P_{in} = 20$ MW

$S_{c\text{ max}} = 0.185$ MW/mm$^2$

Both $E_{peak}$ and $S_c$ are localized in the iris area

L. Garolfi, M. El Khaldi, “3 GHz SINGLE CELL CAVITY OPTIMIZATION DESIGN”, Proceedings of IPAC2015, Richmond, VA, USA.
PMB ALCEN-LAL Research Coll.: prototype design

- Constant Impedance (CI) prototypes with a reduced number of cells (7 cells): design, fabrication & high power tests.
- Goals: analysis of RF, mechanical issues, improving the machining of cells and brazing processes.

Accelerating field $\text{TM}_{010, 2\pi/3}$ mode

Constant Impedance (CI) prototype design

Electric field amplitude & phase advance per cell

$S$ parameters

M. EL Khaldi, L. Garolfi, "RF DESIGN OF A HIGH GRADIENT S-BAND TRAVELLING WAVE ACCELERATING STRUCTURE FOR THOMX LINAC", Proceedings of IPAC2015, Richmond, VA, USA
Preliminary configuration of the whole HG accelerating section 3.2 m:

- Electric field & energy gain along the structure for $P_{\text{in}} = 20, 22 & 25 \text{ MW}$,
- 5 MeV energy at the entrance of the accelerating section (provided by the RF Gun),
- For $P_{\text{in}} = 22 \text{ MW}$:
  - $\langle E_a \rangle \approx 20.5 \text{ MV/m}$ average accelerating field acting on the particles.
  - Energy gain at the end of the LINAC: 70 MeV

- $73.5 \text{ M}\Omega/m \leq \rho_s \leq 89.3 \text{ M}\Omega/m$
- $0.13 \leq \alpha \text{ (Neper/m)} \leq 0.43$
- $0.005 \leq v_g/c \leq 0.016$
- Filling time $\sim 1 \mu s$

Other configurations are under study for energy gain optimisation & filling time reduction, considering for example an iris diameter in the range $17 \text{ mm} \leq \phi \text{ iris} \leq 22.6 \text{ mm}$. 

High-Gradient S-band electron Linac for ThomX
Conclusions et perspectives

▶ Normalised transverse beam emittance compensation of the THOMX RF Gun has been estimated by means of ASTRA code.

▶ The nominal transverse emittance value ($\varepsilon_{n,x,y,\text{tot}} = 4 \pi \text{ mm mrad}$) is fulfilled for a transverse laser spot of $\sigma_{x,y} = 0.2 \text{ mm}$.

▶ RF design has been performed & main requirements accomplished,

▶ Prototype mechanical drawing (reduced number of cells) are completed,

▶ Aluminium prototype fabrication is finished (check out & validation of all technical choices),

▶ Low power tests will be expected on May, 2016,

▶ Thermal analysis of the RF Gun has been performed,


▶ Thermal analysis of the 7 cells prototype is underway,

▶ To get the final beam parameters at the end of the LINAC, beam dynamics simulations of the accelerating section are currently underway.
Thank you
Why X-ray users need “compact” X-ray source?

Current panorama of the X-ray source brightnesses

- **Compact Compton Sources (CCS)**
  - Compactness (surface ~ 100 m²)
  - High intensity (10^{12} – 10^{14} ph/sec)
  - Tunable beam
  - High quality beam
    (brightness 10^{11} – 10^{15} ph/sec / mm² / 0.1% bw / mrad²)
\[ \varepsilon_{n,x,y,tot} \text{ vs laser spot} \]

Trasnverse emittance compensation (Q = 1 nC, sigt = 4 ps)

- \( B = 0.2574 \) T
- \( B = 0.2566 \) T
- \( B = 0.2592 \) T
- \( B = 0.2618 \) T
- \( B = 0.2631 \) T
- \( B = 0.2235 \) T
- \( B = 0.1855 \) T

Transverse emittance [mm mrad pl]

Laser spot size [mm]
The collaboration agreement between PMB and LAL has been established from October, 1st, 2014 to September, 30th, 2017.

### Tasks sharing

<table>
<thead>
<tr>
<th>LAL</th>
<th>PMB</th>
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<tbody>
<tr>
<td>Electromagnetic study, thermal analysis, beam dynamics.</td>
<td>Drawing of mechanical plans according to RF design provided by LAL.</td>
</tr>
<tr>
<td>RF design and check out of mechanical plans.</td>
<td>Realization of Aluminium (Al) prototypes for checking out the geometry.</td>
</tr>
<tr>
<td>Realization follow up of the prototypes and complete structure at PMB.</td>
<td>Realization of Copper (Cu) prototypes for checking out the « standard » and « improved » fabrication processes.</td>
</tr>
<tr>
<td>High power RF tests of prototypes.</td>
<td>Low power RF tests of prototypes.</td>
</tr>
<tr>
<td>Conditioning process of the final accelerating section.</td>
<td>Fabrication of the final section: (adjustments, recovery, tests, brazing, surface treatments, etc.)</td>
</tr>
<tr>
<td>Commisionning of HGAS on ThomX machine.</td>
<td>Checking and testing.</td>
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</table>
S-band prototype

Energy gain in periodic structures

- The electromagnetic wave (EM) is attenuated along the structure,
- Along the accelerator, power is dissipated in the cavity walls and the electric field is attenuated:

\[
\frac{d < E_a >}{dz} = -\alpha(z) < E_a > \quad \Rightarrow \quad \frac{dP}{dz} = -2\alpha(z)P(z)
\]

where \( \alpha \) is the attenuation factor

- Definitions:

\[
Q = \omega \frac{w}{-dP/dz}
\]

\[
w = \frac{P}{v_g}
\]

\[
-\frac{dP}{dz} = \omega \frac{w}{Q} = \omega \frac{P}{Q \cdot v_g}
\]

\[
\frac{dP}{dz} = -\omega \frac{P}{Q \cdot v_g} = -2\alpha \cdot P(z)
\]

\[
\alpha(z) = \frac{\omega}{2 \cdot Q \cdot v_g(z)}
\]

\[
d = \frac{\lambda}{3}
\]
**S-band prototype**

**Constant impedance section (CI)**

- uniform iris aperture: $a = \text{constant}$,
- constant attenuation factor $a(z) = \text{constant} = a$,
- $Q$, $v_g$, $r_s$, are independent from the length $z$, so:
  \[
  < E_a > (z) = < E_a >_0 e^{-\alpha z} \quad P(z) = P_0 e^{-2\alpha z}
  \]

- In the end of the structure:
  \[
  < E_a > (L_{\text{tot}}) = < E_a >_0 e^{-\tau} \quad P(L_{\text{tot}}) = P_0 e^{-2\tau}
  \]
  \[
  \tau = \alpha \cdot L_{\text{tot}} = \frac{\omega \cdot L_{\text{tot}}}{2 \cdot Q \cdot v_g}
  \]

- The energy gain is:
  \[
  \Delta W = q \cos \theta \int_0^{L_{\text{tot}}} E_a(z) \, dz = qE_0L \frac{1 - e^{-\tau}}{\tau} \cos \theta
  \]
  \[
  \Delta W = q\sqrt{2r_sP_{\text{tot}}} \frac{1 - e^{-\tau}}{\sqrt{\tau}} \cos \theta
  \]

\[
\alpha = \frac{\omega}{2 \cdot Q \cdot v_g} = \text{const}
\]
Constant gradient section (CG)

- iris aperture varies along the structure $a(z)$,
- attenuation factor varies along the structure $a(z)$,
- $r_s$ does not vary significantly with the length $z$,
- velocity group varies along the structure $v_g(z)$ to compensate for the power decrease by the reduction of the iris radius,

$$\frac{dP}{dz} = -2\alpha(z)P(z) = -2\alpha_0 P_0 = \text{const} \quad \text{with} \quad \alpha_0 = \alpha(0) \quad P_0 = P(0)$$

- Results that

$$P(z) = P_0(1 - 2\alpha_0 z) \quad r_s = \frac{<E_a>^2}{-dP/dz} \sim \text{const}$$

$$\alpha(z) = \frac{\alpha_0}{(1 - 2\alpha_0 z)}$$

$$<E_a>^2 = \frac{\omega \cdot r_s \cdot P}{Q \cdot v_g} = \text{const}$$

$$v_g(z) = v_g(0)(1 - 2\alpha_0 z)$$

- The energy gain is:

$$\Delta W = q\cos \theta \int_0^{L_{tot}} E_a(z) \, dz = qE_0 L \cos \theta$$

$$\Delta W = q\sqrt{2r_s P_0 L_{tot} (1 - e^{-2\tau}) \cos \theta}$$