High-gradient C-band accelerating structures

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OUTLINE

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2. **C-BAND ACCELERATORS** *(SPARC, PSI, SCSS)*

3. **C-BAND TECHNOLOGY**

4. **NEXT STEP:**
   
   - **STRONG DAMPED C-BAND ACCELERATING STRUCTURES: ELI_NP**
   
   - **C-BAND GUN DESIGN AND FULL C-BAND LINAC**
WHY C-BAND FOR ACCELERATORS?

In this presentation we refer to **high gradient room temperature pulsed electron LINACS** with typical parameters: 10-100 Hz rep. rate, 0.5-5 μs RF pulse length, single/multi bunch, 20-100 MV/m average accelerating gradients.

**S-BAND (2.856 GHz)**

- 3 m long sections
- 3.1 km total accelerator length
- 960 accelerating structures
- up to 50 GeV electron energy
- ~20 MV/m average acc. gradient

**C-BAND (5.712 GHz)**

**X-BAND (12 GHz)**

**NLC-CLIC projects:**
- 0.5-1 m long sections
- up to 100 MV/m acc. gradient

- **Accelerating gradient (∼f^{1/2})**
- **Dipole wakefield intensity (f^3)**
- Complication in fabrication technology
- Available commercial components
C-BAND ACCELERATING SYSTEM @ SPARC

The energy upgrade of the SPARC photo-injector at LNF-INFN from 150 to more than 240 MeV will be done by replacing a low gradient S-Band accelerating structure with two C-band structures. The structures are TW and CI, have symmetric axial input couplers and have been optimized to work with a SLED RF input pulse. In the SPARC photoinjector the choice of the C-band for the energy upgrade was dictated by the opportunity to achieve a higher accelerating gradient, enabled by the higher frequency, and to explore a C-band acceleration combined with an S-band injector that, at least from beam dynamics simulations was very promising in terms of achievable beam quality.

- Low gradient S-Band structure 13 MV/m
- S-Band SLAC-type structure 22 MV/m
- S-Band gun 120 MV/m
- 2 structures 1.4 m long
- >35 MV/m acc. Gradient
- Design and built @ LNF
- SLED-SKIP RF compression system (IHEP, Beijing)
Structure design criteria:

- **CONSTANT IMPEDANCE** (all equal irises) to simplify the fabrication and to reduce the unbalance between the accelerating field at the entrance and at the end of the structure, due to the combination of power dissipation along the structure and SLED pulse profile.

- **LARGE IRISES WITH ELLIPTICAL SHAPE** to
  
  - reduce the peak surface field obtaining at the same time an average accelerating field >35 MV/m with the available power from the klystron;
  
  - reduce the filling time of the structure and, consequently, the RF input pulse length thus reducing the breakdown rate;
  
  - reduce the dipole wake intensity
  
  - increase the pumping speed.

-WAVEGUIDE COUPLER design based on “low pulsed heating” couplers for high gradient operation of X Band structures (SLAC).

Also TIARA/FP7 EU funding
TEST AT HIGH POWER (@KEK) OF THE PROTOTYPE

The high-power test started on November 5, 2010 and was completed on December 13, 2010. For almost one month of processing, from November 5 until December 2, more than $10^8$ RF pulses of 200 ns width were sent into the structure with a repetition rate of 50 Hz. For a couple of days the RF pulse length was changed to 300 ns and for one day (November 12) the repetition rate was decreased to 25 Hz. On November 15, SKIP was switched on.

After the high power test the structure has been cut in slices for an internal inspection. We have identified the signs of craters and discharges mainly in the first accelerating cell after the input coupler, as expected, because the highest field values are excited at the beginning of CI structures.
FINAL C-BAND STRUCTURES AND TEST AT SPARC

Test stand for high power test

First fabricated C-band structure

Toshiba klystron and solid state modulator by Scadinova
Key Parameters:
FEL Wavelength: $\lambda = 1$ to 7 Å
Electron Beam Energy: 5.8 GeV max.
Main Linac frequency: 5.712 GHz
Bunch charge: 200 pC or 10 pC
Bunch length: 25 fs or 0.3 fs (ultrashort case)
Core slice emittance (mm·mrad) 0.43
Photon peak brightness* $\sim 10^{33}$
Bunch per pulse 2
Bunch spacing 28 ns
Total Length: 715 m

Courtesy A. Citterio and R. Zennaro (PSI)
C-band technology:

- In house development of ultra-precise machined accelerating structure **without tuning** (short structure program and 2m nominal structure)
- In house development of the brazing technique for the 2m structure

**Specifications:**

- Phase adv. \(2\pi/3\)
- Filling Time: 329 ns (th.)
- \(v_g/c\): 3.1\% - 1.2\% (th.)
- Iris radius (20°C): 7.238 mm – 5.447 mm
- Length: 2 m
- Accelerating gradient 28 MV/m

Courtesy A. Citterio and R. Zennaro (PSI)
A reduction of the machine size for widespread distribution of XFEL sources is the main idea for the SPring-8 compact SASE source (SCSS). Here, the use of an in-vacuum shorter-period undulator combined with a high gradient C-Band accelerator allows us to realize a compact XFEL machine with a lower-energy accelerator. Although a reduction of the facility scale gives a significant advantage, a new technical challenge was requested for generating and accelerating the extremely high-quality electron beam with a small normalized-slice emittance of less than 1 mm mrad. For this purpose, we proposed to use a thermionic cathode gun, which has a stable emission property and a long lifetime compared to photocathode rf guns. In order to make up for its low emission current, a velocity bunching section, which can push the total bunch compression factor up to a few thousands, was added to the injector.

TABLE I. Main accelerator parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>250 MeV</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>~0.3 nC</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>60 Hz (maximum)</td>
</tr>
<tr>
<td>Peak current</td>
<td>~300 A</td>
</tr>
<tr>
<td>Bunch length</td>
<td>~0.7 ps (FWHM)</td>
</tr>
</tbody>
</table>

-Nominal accelerating gradient up to 35 MV/m
-length 1.8 m
-C-Band damped structures in operation
C-BAND TECHNOLOGY

The C-Band technology can be considered “commercial” and the “state of the art” in high gradient electron LINACS.

Waveguides standard components

RF pulse compression BOC (PSI)

Klystrons (TOSHIBA)

RF pulse compression SKIP
In the context of the ELI-NP Research Infrastructure, to be built at Magurele (Bucharest, Romania), an advanced Source of Gamma-ray photons is planned, capable to produce beams of mono-chromatic and high spectral density gamma photons. The Gamma Beam System is based on a Compton backscattering source. Its main specifications are: photon energy tunable in the range 1-20 MeV, rms bandwidth smaller than 0.5% and spectral density larger than $10^4$ photons/sec.eV, with source spot sizes smaller than 10-30 microns.

For this LINAC high gradient/high rep rate and damped structures (for multi-bunch operation) are required to allow an high gamma flux and a compact source.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch charge</td>
<td>250 pC</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>32</td>
</tr>
<tr>
<td>Bunch distance</td>
<td>16 ns</td>
</tr>
<tr>
<td>C-band average accelerating gradient</td>
<td>33 MV/m</td>
</tr>
<tr>
<td>Norm. emittance</td>
<td>0.2-0.6 mm·mrad</td>
</tr>
<tr>
<td>Bunch length</td>
<td>&lt;300 μm</td>
</tr>
<tr>
<td>RF rep Rate</td>
<td>100 Hz</td>
</tr>
</tbody>
</table>

![Diagram of the Gamma Beam System](image)
ELI-NP operates in multi-bunch mode. The passage of electron bunches through accelerating structures excites electromagnetic wakefield. This field can have longitudinal and transverse components and, interacting with subsequent bunches, can affect the longitudinal and the transverse beam dynamics.

**TRANSVERSE EFFECTS** ⇒ Cumulative beam break-up (BBU)

**LONGITUDINAL EFFECTS** ⇒ beam loading

\[ E_{\text{acc}} = \text{average accelerating field} \]

\[ E_{\text{inj}} = \text{beam energy after injector} \]

**Injector S-band**

**Booste LINAC (C-band)**

Normalized Courant Snyder Invariant at the exit of the linac for an initial displacement of all bunches of 500 μm
Advantages

1. Strong damping of all modes above waveguide cut-off
2. Possibility of tuning the cells
3. Good cooling (high rep. rate)

Disadvantages

1. Machining: need a 3D milling machine
2. Multipole field components (octupole) but not critical at least for CLIC

Advantages

1. Easy machining of cells (turning)
2. 2D geometry: no multipole field components

Disadvantages

1. Critical e.m. design: notch filter can reflect also other modes.
2. Not possible to tune the structure
4. Cooling at 100 Hz, long pulse length (?)
DAMPING: HFSS AND GDFIDL SIMULATIONS

First dipole mode passband

w=13 mm

w=7 mm
ACCELERATING STRUCTURES DESIGN

The power released by the beam on the dipole modes is dissipated into SiC absorbers. Several different solutions are possible to design the absorber. The final geometry has been optimized to:

- simplify the realization procedure and the overall cost of the structures.
- Reduce the transverse size dimensions to allow solenoids positioning

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>TW- quasi CG</td>
</tr>
<tr>
<td>Frequency ($f_{RF}$)</td>
<td>5.712 [GHz]</td>
</tr>
<tr>
<td>Phase advance per cell</td>
<td>$2\pi/3$</td>
</tr>
<tr>
<td>Structure Length</td>
<td>1.8 m (102 cells)</td>
</tr>
<tr>
<td>Iris aperture (a)</td>
<td>6.8-5.8 mm</td>
</tr>
<tr>
<td>group velocity ($v_g/c$)</td>
<td>0.034-0.013</td>
</tr>
<tr>
<td>Quality factor (Q)</td>
<td>8800</td>
</tr>
<tr>
<td>Shunt imp. (r)</td>
<td>67-73 [MΩ/m]</td>
</tr>
<tr>
<td>RF input power</td>
<td>40 MW</td>
</tr>
<tr>
<td>$E_{ACC_average}$ @ $P_{IN}$=40 MW</td>
<td>33 MV/m</td>
</tr>
<tr>
<td>Rep. Rate ($f_{rep}$)</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Average dissipated power</td>
<td>2.3 [kW]</td>
</tr>
</tbody>
</table>
First prototypes have been realized to verify the feasibility of the machining of the cells and of the brazing process. We are now focalizing in the realization of two prototypes previous the realization of the first complete structure.

-The **first prototype** is a full scale device without precise internal dimensions that we would like to build in order to test the full brazing process, verifying eventual structure deformations and vacuum.

-The **second prototype** is a device with a reduced number of cells that we would like to realize to test the RF properties of the structure at low and high power.
**2nd STEP: A FULL C-BAND LINAC**

All existing (under realization) C-Band LINACS have an S-band injector. A full C-band linac with a C-Band RF gun is the next and definitive step in C-Band photoijnjectors.

**SPARC**

S-Band injector

C-Band Booster

**PSI SWISSFEL**

Accelerator (S-band)

Harmonic cavity (X-band)

Deflecting cavity 2 (S-band)

Compression

FODO cells

Diagnostic section

**SCSS- SPRING 8**

Injcctor

Bunch Compressor

50MeV Dump

M1 M2 M3 M4 M5 M6

M7 M8 M9 M10 M11

250MeV Dump
C-BAND RF GUN

The designed gun integrate a **waveguide coupler** that allows:

- **high efficiency cooling** of the accelerating cells
- **low pulsed heating** of the coupler surfaces
- **arbitrary solenoids position** around the accelerating cells and on the beam pipe
- **100 Hz operation** in multi bunch
- **fabrication of the gun without brazing processes** (hard copper->higher gradients)

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$ [GHz]</td>
<td>5712</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>10900</td>
</tr>
<tr>
<td>$E_{\text{cathode}} @10$ MW Pin</td>
<td>200 [MV/m]</td>
</tr>
<tr>
<td>$\beta$</td>
<td>2</td>
</tr>
<tr>
<td>Filling time $\tau$</td>
<td>200 [ns]</td>
</tr>
</tbody>
</table>

**NEXT STEP:** $/€/time/people for the first prototype realization
POSSIBLE CONFIGURATION OF A MULTI-BUNCH C-BAND INJECTOR

42 MW, 100 Hz

7 MW

35 MW

TOSHIBA E37210 (Nominal output power 50 MW)

1.1 μs

Flat top

L=1.8 m

E\text{acc} = 31 \text{ MV/m}

E_{\text{cathode}} = 170 \text{ MV/m}

32 bunches

250 pC

16 ns bunch spacing

60 MeV beam

PARAMETER

C-BAND INJECTOR

Charge

250 pC

Laser pulse length

8.5 ps

Laser spot size

250 μm

Output energy

95 MeV

Output emittance

0.25 mm mrad

Output bunch length

800 fs

Output energy spread

0.38%

A. Bacci

Beam loading compensation
CONCLUSIONS

1. C-Band accelerators developed all over the world have made the **C-Band technology accessible and commercial**. It is now the state of the art in room temperature electron LINACS.

2. C-Band adventure started @ LNF for the SPARC energy upgrade - single bunch operation.

3. **Gradients >50 MV/m** have been reached in several structures.

4. **Damped C-band structures for multi-bunch acceleration** with >100 Hz rep. rate have been developed for ELI-NP and are now under construction. They are the next step in C-Band accelerating structure technology and their interest goes above the ELI_NP proposal.

5. The **full C-band injector (>100 Hz, Multi-bunch)** is now the next and definitive step in this technology. It includes a **C-Band RF GUN** at gradients >170 MV/m that has been designed but have to be fabricated and tested if we want to go in this direction.
THANKS TO...

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