New applications of high-gradient RF linacs
High gradient is not only cool but also compact and potentially cheaper

State-of-the art acceleration:
Normal conducting:
28 MV/m SwissFEL
35 MV/m SACLA
Superconducting:
24 MV/m European XFEL
31.5 MV/m ILC

I will talk about the future:
100 MV/m CLIC
60-80 MV/m compact XFELs
50 MV/m low-β proton therapy linacs
Outline

• Introduction
  • Initial motivation for high-gradient acceleration
  • The CLIC R&D towards 100 MV/m acceleration
• New applications
  • Energy upgrade of existing FELs (e.g. FERMI@Elettra, Trieste)
  • Compact hard X-ray FELs (e.g. SINAP, Shanghai)
  • Compton and neutron sources (e.g. University of Tokyo)
  • Proton therapy linacs (e.g. TULIP-2, TERA)
• Conclusions
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• Conclusions
• For a very long linac optimum accelerating gradient is high.
• It is around 100 MV/m for CLIC 3 TeV main linac
• Vacuum breakdown and peak RF power production are the most important limitations for high gradient
• A significant effort was made to address these two issues
CLIC test structures towards high gradient

1. T18_Disk_#2
2. TD18_Disk_#2
3. T24_Disk_#3
4. TD24_Disk_#4
5. TD26CC under test now

undamped
damped

Nextef, KEK, Higo
High gradient testing infrastructure

- 11.424 GHz at SLAC and KEK
  - NLCTA (SLAC)
  - ASTA (SLAC)
  - Nextef (KEK)

- 11.994 GHz at CERN
  - Xbox1
  - Xbox2
  - Xbox3
Xbox1 layout

Clockwise from top-left:
- Modulator/klystron (50MW, 1.5us pulse)
- Pulse compressor (250ns, ratio 2.8)
- DUT + connections
- Acc. structure (TD26CC)
X-band klystrons: High gradient driving force
From “fait maison” to production in industry

50 MW
1.5 μs
50 Hz

SLAC XL-5

6 MW, 5 μs, 400 Hz

Toshiba E37113*
Tested at Toshiba last week

Pulsed klystron operating at 11.994 GHz, 50 MW peak, 5 kW average power. Electromagnet focused, liquid cooled. Waveguide output WR-90, vacuum flange.

Now a catalogue item
Accelerating structure performance summary based on testing at SLAC, KEK and CERN
Geometrical dependency – our understanding of what is important for RF design of the high gradient structures

The functions which determine the high-gradient operation of the structures are:

\[
\frac{P}{\lambda C} = \text{const} \quad S_c = \|\text{Re}(S)\| + \frac{1}{6}\|\text{Im}(S)\|
\]

Global power flow \hspace{1cm} \text{Local modified Poynting vector}

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FERMI@Elettra: present layout and energy upgrade
FERMI@Elettra: present layout and energy upgrade

FERMI current layout and performance

- $E_{\text{beam}}$ up to 1.5 GeV
- FEL-1 at 80-10 nm and FEL-2 at 10-4 nm
- Long e-beam pulse (up to 700 fs), with “fresh bunch technique”

More details in MOPP023

Beam input energy
~ 0.7 GeV

1.5 GeV

High gradient X-band linac extension

- Active accelerating length 40 m
- Accelerating gradient 70 MV/m
- Beam energy gain 2.8 GeV
- Injection energy 0.7 GeV

New FEL beamline expected performance

- Undulator period 30 mm
- Undulator parameter 1
- Fundamental wavelength 0.5 nm
- Peak power at saturation 5.6 GW

N.B. The new layout could also provide two electron beams at the same time (@25 Hz) with different energies
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Shanghai Photon Science Center at SINAP

Compact hard X-ray FEL (X-band, S-band)
Energy: 6.5GeV, 8GeV (200m linac)

SXRF: Shanghai Soft X-ray FEL
S-band, C-band, X-band
Energy: 0.84GeV (Phase I), 1.3GeV (Phase II)

SSRF: Shanghai Synchrotron Radiation Facility
Energy: 3.5GeV, user operation
C-band and X-band plans for soft X-ray FEL (SXFEL started in 2014)

Phase I: 8 C-band acc for 4 units
Upgrade: X-band accelerating structure

**Parameters** | **Phase I** | **Upgrade** | **Unit**
---|---|---|---
Output Wavelength | 9 | 3 | nm
Bunch charge | 0.5~1 | 0.5~1 | nC
Energy | 0.84 | 1.2~1.3 | GeV
**Gradient** | 40 | 70-80 | MV/m
Energy spread (sliced) | 0.1-0.15 (0.02) | 0.15 (0.03) | %
Normalized emittance | 2.0~2.5 | 2.0~2.5 | mm.mrad
Pulse length (FWHM) | 1 | 1 | ps
Peak current | ~0.5 | 0.5 | kA
Rep. rate | 1~10 | 1~10 | Hz

Commissioning Phase I in 2016-2017
X-band plan for compact hard X-ray FEL (On proposal)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Wavelength</td>
<td>0.07 nm</td>
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<tr>
<td>Bunch charge</td>
<td>250 pC</td>
</tr>
<tr>
<td>Energy</td>
<td>6.5 GeV</td>
</tr>
<tr>
<td>Normalized emittance</td>
<td>0.4 μm</td>
</tr>
<tr>
<td>Energy spread (projected)</td>
<td>0.02%</td>
</tr>
<tr>
<td>Pulse length (Full)</td>
<td>40 fs</td>
</tr>
<tr>
<td>Peak current</td>
<td>3 kA</td>
</tr>
<tr>
<td>Rep. rate</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Peak power</td>
<td>10 GW</td>
</tr>
<tr>
<td>Peak brightness</td>
<td>$2 \times 10^{33}$</td>
</tr>
</tbody>
</table>

X-band: Phase I: 6.5 GeV@65 MV/m
Upgrade: 8 GeV@80 MV/m

Photo injector
Low-emittance
E=330 MeV
I=300 A, $\sigma_z=78 \mu$m

130 meters X-band linac

Undulator SASE-FEL
E=6.5 GeV, I=3 kA
$\sigma_z=7 \mu$m, $\sigma_\delta=0.021\%$

X-ray users
0.1 nm

580 m

1. S-band 20 MV/m
2. E=300 MeV
3. 130 meters X-band linac
4. $E=1900 \text{ MeV}$
$I=300 \text{ A}$, $\sigma_z=78 \mu$m
5. Upgrade: $E=8 \text{ GeV}$
$I=80 \text{ MV/m}$
# X-band accelerating structure for XFEL for 65MV/m, 80MV/m

<table>
<thead>
<tr>
<th>Frequency</th>
<th>11424MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase advance</td>
<td>$4\pi/5$</td>
</tr>
<tr>
<td>Cell No.</td>
<td>89+2</td>
</tr>
<tr>
<td>Effective length</td>
<td><strong>944.73 mm</strong></td>
</tr>
<tr>
<td>Cell length, $d$</td>
<td>10.497mm</td>
</tr>
<tr>
<td>Iris thickness, $2a$</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>Ratio of elliptic radius, $b/a$</td>
<td>1.8</td>
</tr>
<tr>
<td>Aperture, $a_r$</td>
<td><strong>4.3~3.05 mm</strong></td>
</tr>
<tr>
<td>Group velocity, $Vg/c$</td>
<td>3.45%~1.12%</td>
</tr>
<tr>
<td>Shunt impedance, $R$</td>
<td>86.7~108.7MΩ/m</td>
</tr>
<tr>
<td>Attenuation factor, $\tau$</td>
<td>0.61</td>
</tr>
<tr>
<td>Filling time, $t_f$</td>
<td>150 ns</td>
</tr>
<tr>
<td>$Sc$</td>
<td>4.14~2.33 MW/mm²</td>
</tr>
<tr>
<td>$E_{max}/E_0$</td>
<td>2.68~2.02</td>
</tr>
<tr>
<td>$H_{max}/E_0$</td>
<td>2.68~2.39 mA/V</td>
</tr>
<tr>
<td>Input power, $P_{in}$</td>
<td>52MW @65MV/m, 80MW @80MV/m</td>
</tr>
<tr>
<td>Two-Klystrons units</td>
<td>34 @65MV/m, 30 MW/klystron @80MV/m</td>
</tr>
</tbody>
</table>

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**More details in TUPP127**

1. Magnetically coupling
2. Dual port coupler
3. Race-track coupler
4. Round shape cell

![Graph of $Sc$ distribution](image)
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• Conclusions
Application of Compact Accelerator Neutron Sources

- S-band 40MeV 1kW Electron Linac
- L-band 30MeV 6kW Electron Linac
- Canadian Light 35MeV 20-40kW Electron Linac
- X-band 30MeV 0.4kW Electron Linac
- S-band 35MeV 60kW Electron Linac
- 7MeV Proton Linac
- 8MeV Proton Linac
- 2.5MeV Proton Linac
- Non-Destructive Testing
- 30MeV Proton Cyclotron + D+ Cyclotron + C Target
- BNCT
- RI Production for Nuclear Medicine
- 30MeV D+ Cyclotron + C Target

1-100ns Short pulse for thermal~epi~keV Neutrons and Nuclear data

- 1-100ns Short pulse for thermal~epi~keV Neutrons and Nuclear data

LINAC 2014, 3 September 2014

Alexej Grudiev, CERN
Spectrum and pulse shape of neutrons

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Power</td>
<td>375 W</td>
</tr>
<tr>
<td>Target intensity</td>
<td>$1.3 \times 10^{11}$ n/s</td>
</tr>
<tr>
<td>Pulse width behind moderator (10 – 100 keV neutron)</td>
<td>6.66 ns</td>
</tr>
<tr>
<td>Neutron flux at measurement point (5m TOF)</td>
<td>$1.1 \times 10^3$ n/cm$^2$/s</td>
</tr>
</tbody>
</table>
Linac will be moved from **Compton source** to the area of decommissioned research reactor “Yayoi” for a **neutron source**.

The Linac will be moved from Compton source to the area of decommissioned research reactor “Yayoi” for a neutron source.

Application of the system is to measure more accurately the nuclear data for analysis of the fuel debris at Fukushima (F-1), nuclear transformation at ADS and design of new reactors in future.

**Compact X-band 30 MeV electron linac at Univ. of Tokyo**

- **30 MeV X-band Linac**
- **70 cm accelerator tube**
- **Klystron and power source are set around the reactor**
- **20 keV electron gun + 5 MeV buncher + 30 MeV structure + Neutron target**

**Linac will be moved from Compton source to the area of decommissioned research reactor “Yayoi” for a neutron source.**

**Application of the system is to measure more accurately the nuclear data for analysis of the fuel debris at Fukushima (F-1), nuclear transformation at ADS and design of new reactors in future.**
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TULIP (TUrnning LIinac for Protontherapy)

"Proton and Carbon Linacs for Hadron Therapy", Ugo Amaldi, Friday 11:30, LINAC14
TULIP at 3 GHz with $E_0 = 30$ MV/m

Present technology: 30 MV/m
CLIC high gradient technology applied to S-band:
100 MV/m for $\beta=1$ electron linac and
50 MV/m for low-$\beta$ proton linac
have similar limitations
in terms of high gradient
Cells are optimized to have minimum:

\[
\frac{P}{E_a^2} \cdot \frac{S_c}{E_a^2} = \frac{S_c}{E_a^2} . \frac{v_g}{\omega} . \frac{E_a^2}{R'} . \frac{1}{Q}
\]

First prototype is being built by CERN and TERA in the framework of CERN KT funded project: “High-gradient accelerating structures for proton therapy linacs”

More details in THPOL08 and THPP061
Conclusions

- For large linac-based installations, like a linear collider, the optimum gradient is high. It approaches the highest possible gradient limited by the fundamental physical phenomena.

- For medium and small sized linac-based installations, built in a “green field”, the optimum gradient is usually not the highest possible.

- BUT there are many cases where high gradient is required:
  - Given the final energy of the linac and the space limitations of existing infrastructure (e.g., research labs., universities).
  - The cost of infrastructure is very high (e.g. medical facilities).
Acknowledgements

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- Mitsuru Uesaka (University of Tokyo)
- Ugo Amaldi (TERA)

Thank you for your attention.

Last but not least, I would like to apologize for not being able to cover all high gradient linacs related projects and activities.