CLIC: Overview of applications using high-gradient acceleration, from photon sources to medical physics (5/5)

CERN academic training - Compact Linear Collider

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Introduction

“Another reason to support fundamental science is that it produces ideas and devices that end up being useful in entirely unexpected ways and that have an impact far larger than the original investment in the research.”

• You’ve heard this week about the physics motivation for CLIC and the technology developed for it.
• I will now describe to you some of the ways in which CLIC high-gradient and X-band technology is being used in accelerator applications outside the field of high-energy physics.
• The other theme is that the adoption of the technology is generating important contributions back to the CLIC project (we did this on purpose!).
Disclaimer

• There are many applications so presentation will often be superficial, but the idea is to give you an overview. I am happy to give you more information after the lecture.

• This presentation is not comprehensive. In particular, I will focus only on projects with which CLIC has a direct collaboration. There are more X-band and high-gradient application activities around the world which I don’t have time to cover.
X-band and High-Gradient Technology: What is it?

1. >100 MV/m accelerating structures

Prototype performance

High-field dynamics

Fabrication technology

rf design methodology

\[ S_c = \text{Re}(S) + \frac{1}{6} \text{Im}(S) \]
X-band and High-Gradient Technology: What is it?

2. >150 MW 12 GHz peak power production

Toshiba 6 MW klystron

CPI 50 MW klystron

Pulse compressors

Scandinova solid state modulator

High-power waveguide components
X-band and High-Gradient Technology: What is it?

A SC Model Magnet proposed

<table>
<thead>
<tr>
<th>Design Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superconductor</td>
<td>MgB₂ (@ 20 K)</td>
</tr>
<tr>
<td>Current</td>
<td>50 A</td>
</tr>
<tr>
<td>Central field</td>
<td>0.7 T</td>
</tr>
<tr>
<td>Stored energy</td>
<td>~ 10 kJ</td>
</tr>
<tr>
<td>Cryo-cooler applied</td>
<td>6.7 W @ 20 K, 13.5 W @ 80 K</td>
</tr>
<tr>
<td>AC plug power</td>
<td>≤ 3 kW (≤ 1.5 kW/klystron in case of a pair)</td>
</tr>
</tbody>
</table>

3. High-efficiency klystrons

3.4% degradation in efficiency due to 2D effects. Simulated RF efficiency is 78.5%.

10-Layer model
Radial Striatification = 1.67
Spent Beam Velocity = 0.42e (outer) to 0.67e (inner)

Low beam power: CSM tube
Input: 400 m of E [Green box]

3. High-efficiency klystrons

Klystron cathode in air
Current transformer
Capacitive voltage divider

CERN academic training - Compact Linear Collider
From test stand to integrated linac

CLIC high-gradient test stand

Klystron-based CLIC tunnel layout
Applications overview

Inverse Compton Source

XFEL

Linear collider

Medical applications

Energy spread linearizer

Deflector for short bunch diagnostics
Smart*Light – compact X-ray source

Inverse Compton Scattering X-ray source

- Laboratory room scale highly monochromatic X-ray source.
- Alternative to synchrotron light source beam line, less brilliance but local facility.
Smart*Light – compact X-ray source

X-band LiNAC-based ICS sources: why?

- Compact accelerator  
  fits on a table
- Lower emittance beams  
  higher X-ray coherence
- Easier alignment, fast change of X-ray energy

ICS X-ray source - Planning

Phase 1 (+/- 2 years)
- (20 MeV e / 20 keV x-rays)
- Infrastructure in bunker
- 100 keV electron egun
- Accelerator sections + focusing
- Xband infrastructure
- Laser
- Beam dump (radiation issues)
- Control + safety system

Based on 6 MW Toshiba klystron
Smart*Light recently held kick-off and users meeting.
Thomson Scattering X-ray Source at Tsinghua University

Jiaru Shi
2017.6.13
For the TTX team

X/γ-ray source

Existing facility with 3 m S-band linac, 45 MeV
X-ray phase contrast image
X-ray CT

Peanut X-ray CT

Z. Chi
TTX upgrade plans

Progressively higher energy through increasing gradient and implementation of X-band.

50 MW CPI klystron, Scadinova modulator being commissioned in Tsinghua.
TTX – the intellectual return path

X-band pulse compressor for TTX

- X-band RF system for TTX
  - X-band Klystron
    - 11.411 MHz
    - 50 MW 1.5 μs
  - Pulse compressor:
    - β = 120,000
    - β = 1.5

Correction cavity chain for CLIC

- Mechanical design
- Storage Cavity
- Coupling
- Load design
- For vacuum pumping
ELI-NP – Large-scale inverse Compton Source

- Advanced source of Gamma-ray photons in construction in Magurele (Bucharest, Romania) in the context of the ELI-NP Research Infrastructure by the "EuroGamma" Association (composed by the INFN, the "Association leader", the University of Rome "La Sapienza", the CNRS, ACI'S.A.S., AixCom S.A.S., Comel-ScL, and Nine Systems SRL);
- The photons will be generated by Compton back-scattering in the collision between high quality electron beams and a high power laser;
- The machine is expected to achieve:
  - energy of the gamma photons tunable 0.2-19.5 MeV
  - narrow bandwidth (<0.3%)
  - high spectral density (>10^11 photons/sr/MeV)

Higher-order-mode damping for stability of high current beam developed by CLIC

D. Alesini

CLIC disk
Direct beam measurement in 1999.

Recent experiment done at SLAC

Outstanding agreement between simulation and experiment
Free electron laser

EU funded design study for next generation compact and low cost XFEL.
Compact

Bring together technology advances in key accelerator systems for XFEL
SwissFEL C-band linac: Approximately 30 MV/m

CLIC prototypes: Over 100 MV/m
SwissFEL

- Recent implementation of a large-scale normal-conducting linac – 5.8 GeV, over 100 accelerating structures.
- Strong linear collider technology heritage and with implementation many important lessons have been learned.
SwissFEL rf unit

Same rf “topology” as CLIC klystron
SwissFEL micron tolerances

Sub-micron precision achieved in production!
SwissFEL gradient

Two PSI-built X-band structures installed in Xboxes – both operating over 115 MV/m.

Gradient only limited by C-band power source

- Structures are machined “on tune”, no provisions for dimple tuning!
- Cup manufacturing with micron precision at VDL ETG Switzerland
- Coupler manufacturing at VDL ETG
- Stacked by robot at PSI
- Vacuum-brazed at PSI
- Production rate: 1-2 / week
- Production finished August 2016

High power results for first structure:
- Conditioned to 52 MV/m
- Break-down rate at 52 MV/m = $2 \times 10^{-6}$
- At nominal 28MV/m, break-down rate negligible (well below the specified threshold of $10^{-6}$)
High-gradient upgrade at FERMI, XFEL in Trieste

First prototype high gradient S-band section

**GOALS**
- Higher energy (1.8 GeV), 50 Hz even at high energy
- Higher peak current
- Low breakdown rate (<1x10^{-8} bpp/m)

**PRESENT LINAC ENERGY**
1.5 GeV @ 10 Hz

**TARGET LINAC ENERGY**
1.8 GeV @ 50 Hz

**CONSTRAINTS**
- Available space
- Active acceleration length is fixed

**SOLUTION**
High Gradient Structures (30 MV/m) for replacing BTW ones

Ref. C. Serpico

SAC–MAC Joint Meeting – 21 February 2018
A first (short) prototype is being built in collaboration with PSI.

**TEST FACILITY @ ELETTRA**

The Test Facility has been upgraded and the new RF components conditioned to 42 MW and 4.2 μs pulse width.

Prototype’s RF conditioning up to **50 MV/m** will be possible

**PSI PROTOTYPE**

**TEST FACILITY DIAGNOSTIC**

CERN-like breakdown diagnostic is being developed at Elettra.
First prototype high gradient S-band section

- Short prototype of high gradient S-band section under realization at PSI. It is constructed following the recipe of the SwissFEL C-band structures.
- The prototype will be brazed by week 10 (9th of March). RF measurements in March.
- The prototype will be installed in the cavity test facility in April.
- High RF Power test at Elettra between May and August 2018 with the goal to demonstrate gradients as high as 30 MV/m at low breakdown rates (< 1x10^{-8} bpp/m).

Meanwhile.....

<table>
<thead>
<tr>
<th>Compact Pulse Compressor* based on a single-spherical cavity</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>660 x 460</td>
<td>mm</td>
</tr>
<tr>
<td>Op. Mode</td>
<td>TE113</td>
<td></td>
</tr>
<tr>
<td>Q0</td>
<td>145000</td>
<td></td>
</tr>
<tr>
<td>Beta</td>
<td>7</td>
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*Waveguide components are being developed in collaboration with CERN

<table>
<thead>
<tr>
<th>Compact S-Band Load* Based on CeraSiC or EkaSiC absorbers</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>N. Shafqat, I. Cudin</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Regular Cell and Input Coupler at PSI. All components are almost ready for brazing.
We will return to the X-band infrastructure later in lecture.
EuSPARC – electron linac facility for XFEL and plasma acceleration research

**LNF X-band test stand and linac plans**

*Alexander Gallo*

on behalf of the INFN LNF X-band Team

**EuSPARC RF / X-band Team:**


**INFN – Laboratori Nazionali di Frascati**

**European Source for Plasma Accelerators and Radiation user Communities**

Study for a future extension of SPARC at Frascati, led by Massimo Ferrario. New project for INFN Frascati, Rome.

From SPARC_LAB to EU-SPARC

SPARC_LAB is a multidisciplinary test facility of the INFN Frascati Labs based on 2 pillars: a conventional high brightness RF photo-injector (SPARC) and a multi-hundred TW laser system (FLAME). Several experiments have been performed and many others are in preparation using the photo-injector and the laser either independently or jointly. The experimental activities cover various fields such as FEL, THz radiation production, Thomson scattering, beam dynamics and beam diagnostics studies.

In the last years plasma acceleration research, in situ, injection and external injection (both particle and laser driven) modulation, has become a relevant part of the SPARC_LAB scientific program.

Capillary Discharge at SPARC_LAB

C-band accelerating structure and LWFA chambers
EuSPARC 1 GeV X-band linac

XFEL and advanced acceleration development test facility at INFN Frascati. Based on 1 GeV, X-band, short bunch, low emittance linac.
Getting ready – X-band test stand

The INFN Frascati X-box

SPARC_LAB
Building #7

it will be located in LNF building #7, very close to the SPARC_LAB area, formerly used for testing and conditioning of the DAFNE RF power plants and cavities.

Pulsed Modulator: to be procured by INFN

X-band klystron: provided by CERN

<table>
<thead>
<tr>
<th>Typical Operating Parameters</th>
<th>Value</th>
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<tr>
<td>Beam Voltage</td>
<td>450 V</td>
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<tr>
<td>Beam Current</td>
<td>310 A</td>
</tr>
<tr>
<td>Frequency</td>
<td>11.384 GHz</td>
</tr>
<tr>
<td>Peak Power</td>
<td>50 MW</td>
</tr>
<tr>
<td>Axil. Power</td>
<td>5 kW</td>
</tr>
<tr>
<td>Solo. Gain</td>
<td>42 dB</td>
</tr>
<tr>
<td>Efficiency</td>
<td>40 %</td>
</tr>
<tr>
<td>Duty</td>
<td>0.000 %</td>
</tr>
</tbody>
</table>

Other components:
- Low level RF and controls;
- RF driver amplifier;
- Rectangular waveguides;
- Ceramic windows;
- Vacuum pumps and power supplies;
- ... All components will be either provided by CERN or procured by INFN in full conformity with the original CERN X-box parts.
Physics with e-beams, example LDMX

A Strong Candidate: Hidden Sector DM

Simple, familiar particle content
Simple, predictive cosmology
Motivated (broader) mass range

DM with thermal freeze-out origin

Basic Concept & Beam Requirements

Electron beam impinging on target:
- multi-GeV electrons
- 1-200 MHz bunch spacing
- Ultra-low Q1 (<1) electrons per bunch

Measure recoiling low-energy-fraction electron & its pT
- Forward tracking in (small) B-field
- Reject events with visible particles carrying remaining energy
- Deep, highly segmented calorimeter

Targets for Thermal Relic DM

Phase II: 4x10^{14} @ 4 GeV
0.1-0.3 Xe target

Talk by P. Schuster
"Physics Beyond Colliders" Nov 21, 2017
An e-beam facility at CERN

Accelerator implementation at CERN of LDMX type of beam

- X-band based 60m LINAC to 3 GeV in TT4-5.
  - Fill the SPS in 2s (bunches 5ns apart) via TT60
  - Accelerate to ~10 GeV in the SPS
  - Slow extraction to experiment in 10s as part of the SPS super-cycle
  - Experiment(s) considered in UA2 area or – better - bring beam back on Meyrin site using TT10

Beyond LDMX type of beam:

S. Stapnes

Other physics experiments can be considered (for example heavy photon searches)
Several other possible uses of linac and SPS beams for R&D
GREEN: ~10+ GeV electron beam in SPS
Acc. in SPS, can also be a damped small emittance beam. Long bunches.
- Extracted to Meyrin side for LDMX like experiment.
- Can also – possibly – be guided to AWAKE.
- Other uses, either extracted or circulating to be worked out.

PURPLE: 3 GeV x-band linac with excellent beam quality
Short bunch electrons from X-band linac, only used 5% for filling the SPS. Can be used right after linac (TT4), in new experimental area, and/or possibly directed to the current AWAKE area.
- CLEAR type of research programme.
- Electrons for drive and/or probe beam exploring novel accelerating techniques, including second gun (drive and probe bunches with variable distances and charges).
- Longer term possibilities for positrons if deemed crucial.
Medical accelerators – proton therapy

State-of-the-art and market leader: IBA superconducting synchrocyclotron (image taken from IBA website).

Can a linac based solution be competitive? ADAM is trying. Offers distinct advantages: pulsed with fast energy variation for tumor painting, follow body motion, cost (image taken from ADAM website).
By applying CLIC high-gradient technology, we think we can raise the accelerating gradient from the <20 MV/m in LIGHT to 50 MV/m, making single room facilities like TULIP possible.
What’s the problem challenge?

Our electron linac technology is for particles moving near the speed of light. Protons and ions in a medical linac need to be accelerated when they are still moving slowly, in the range of half the speed of light.

For relativistic electrons/positrons, $\beta=1$:
- 100 MV/m

For $\beta=0.38$:
- 50 MV/m
Hard to extend this to lower $\beta$, higher is easy.
Let’s give it a try

• CERN KT fund accepted our application for funding to build two such structures based on CLIC design, fabrication and operation technology.

• CLIC study members designed and are testing the structures (we get important data on high-gradients from these tests).

• Two have been built and the first is under high power test.
High-gradient testing

We have adapted and used experience, diagnostics, software and algorithms from the CLIC high-gradient program.
Conditioning status of the high-gradient medical linac structure

\[ \beta = 0.38 \text{ c}, \text{ 50 MeV/m expected} \]

Just passed 60 MV/m, testing continues.
We are very excited!

2\text{nd} structure is complete and ready to go.
Radio-frequency power source efficiency is also a crucial issue for CLIC. 3 GHz, > 60% efficiency, 70 kV klystron built by VDBT. Has potential to reduce investment and operating cost.
More – proton radiography

PROBE: PROTON BOOSTING EXTENSION FOR IMAGING AND THERAPY

Sara Fitton
Dr Grenene Burt
Dr Hywel Owen
Dr Robert Alpaimon

FINAL STRUCTURE

- 3 GHz- S-Band
- Side coupled 54MV/m
- Aggressive gradient limits
- Bpeak < 200MV/m
- Thin septum (2mm)
- r/2 mode
- 11 cell prototype cavity
- β=0.59

PROTON TOMOGRAPHY

Several modalities can aid range verification.
CT images used for treatment planning — connection from treatment unit produces error.
Proton imaging measures proton stopping power.
Prompt Gamma also measures dose.
250 MeV sufficient to image children and adults.
Nosed 350 MeV protons to image through anybody. Energy peaks must not occur inside patient.

9 March 2018
CERN academic training - Compact Linear Collider
The sincerest form of flattery

High-gradient low-β structure based on acceleration with the first negative spatial harmonic

Sergey V Kutsaev

June 15, 2017

Low beta structure for ACCIL

- We used CERN TULIP backward travelling wave (BTW) as a reference*
- We found that at β~0.4, the required peak surface field is ~200 MV/m to sustain 50 MV/m accelerating gradient
  - Reducing these fields lead to 160 MV/m lead to a significant shunt impedance drop
- Different approach is required for β=0.3 section


Carbon Therapy Linac

- An Advanced Compact Carbon high gradient Ion Linac (ACCIL) is being developed by collaboration of Argonne National Laboratory and RadiBeam Systems
- ACCIL must provide 1 GV accelerating voltage in a 40m length
  - To achieve this footprint, ~35 MV/m real-estate gradients and 50 MV/m accelerating gradients are required.
  - The project goal is to develop a 50 MV/m β=0.3 structure

Test Cell Fabrication

- The single test cell was fabricated to develop the machining capabilities and verify that the achieved tolerances are plausible

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CST (Vacuum)</th>
<th>Measurements w/ corr to vacuum</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-mode freq. MHz</td>
<td>2856.11</td>
<td>2855.06</td>
</tr>
<tr>
<td>Q-factor of n mode</td>
<td>4700</td>
<td>4300 (w/ end caps)</td>
</tr>
</tbody>
</table>
And back at CERN – PIMS2

2. The compact carbon therapy accelerator

Considered the alternative options to synchrotrons: SC cyclotron, FFAG, Linear accelerator.

The linear accelerator looks as the most promising option on terms of size, complexity, energy variability (pulse to pulse) and match to CERN competences and experience.

A 430 MeV/u Linac could be about 50 m long, folded in 2 sections. Accelerator footprint 200 m².

Carbon ion therapy - Another potential application of high-gradient technology? PIMS2 project recently approved.
A new direction - VHEE

Very High Energy Electron (VHEE) therapy to complement existing X-ray, proton, and ion therapy. Use 200-300 MeV electron beam to treat tumors. Radiology is not well understood, but 100 MV/m acceleration makes attracts interest in this technique again.
VHEE – dosimetry studies

EXPERIMENTS AT CLEAR USER FACILITY @ CERN

Using both EBT3 (< 12 Gy) and EBT-XD (< 50 Gy) radiosensitive films

PLAN:
1) Dose profiles with 8 varied-density inserts (~20 mm)
2) Dose profiles in water at 50, 100 and 150 MeV
3) Scattering foil impact on VHEE dose distribution

BEAM PARAMETERS:

- Energy: 155 MeV
- Energy spread: < 0.5 MeV FWHM
- Bunch charge: 15 pC
- Train length: 20 - 90 bunches
- Beam spot size: 1.2 - 4.6 mm
- Charge jitter: 20 %
High-gradient acceleration will be crucial for feasibility. 300 MeV electrons in a compact facility is not easy but we are eager to have a go.
Bunch manipulation with X-band – Fast and Furious
(high frequency and high gradient)
Energy spread linearization

- Linear energy profile along bunch is best suited for bunch compression in magnetic chicane.
- Harmonic can take out curvature induced by acceleration.
- 12 GHz ideal for 3 GHz-based injectors
- Basically just accelerating system running on decelerating phase to take out curvature induced by acceleration.
- X-Band linearizer systems operational at FERMI and SwissFEL made in collaboration between CERN/Trieste/PSI and first klystrons purchased from SLAC.
Energy spread linearization at PSI

X-band linearizer installed in injector test linac and moved to SwissFEL.
Energy spread linearization at ELETRA
Energy spread linearization at SINAP

X-band system in SXFEL

Mechanical design and Fabrication
Energy spread linearization at SINAP

X-band system in SXFEL

Linearizer compression

Modulator: 20 KV
Klystron: 1 µs
SLED: 0.2 µs

Klystron output is unstable for different operation voltage. Maybe klystron is not optimized to reach full power.

Without X-band RF power, the energy distribution is non-linear along bunch length. When bunch is compressed in this case, the bunch has a very obvious tail and the flow intensity distribution is asymmetry extremely from head to tail.

Better bunch for lasing
Energy spread linearization at Daresbury

CLARA

- S-band linear acceleration up to 250 MeV
- Bunch charge 20-250 pC
- High repetition rate up to 400 Hz
- Electron bunch lengths 250-850 fs
- FEL wavelengths in the UV

Proposed system

- CERN/PSI type X-band RF structure with integrated alignment monitors
- 16.3 MW required at the cavity for 30 MV/m operation
- 6 MW Toshiba klystron with Scandinaiva K200 modulator
- SLED I type pulse compression
- LLRF from industry
- Vacuum WR90 waveguide

CLARA XFEL test facility is under construction. They are implementing an Xbox-3, Toshiba 6 MW klystron, type rf system for energy spread linearization. Procurement underway.
Collaboration between DESY, CERN and PSI;
Design and realisation of a X-band Transverse Deflecting Structure (TDS) with a novel Variable Polarization Feature;
A common mechanical design matches the space and voltage requirements of three experiments at DESY (FLASHForward, FLASH2, SINBAD) and one experiment at PSI (ATHOS and at SwissFEL);
The TDS will allow for fs and sub-fs bunch characterization in the time domain;
The variable polarization feature offers new opportunities for novel diagnostics techniques.

Will result in three new X-band installations!
Innovative variable polarization deflector, rf design by CERN. DESY and PSI are procuring rf power systems based on Xbox test stands. PSI will build structures using experience of SwissFEL and X-band accelerators.
Deflector at SINAP

X-Band TDS layout for SXFEL User Facility

Fabrication plan

Plan of 2018 (Workshop at SINAP)
20 cells deflector (12GHz, test at CERN)
T24 (12GHz, test at CERN)

Plan of 2018 (Company)
Six 600mm x-band deflectors for SXFEL user facility
1m x-band accelerator (11.4GHz, test at SINAP)

X-Band TDS layout for Shanghai Coherent Light Facility (SCLF)

Demand for SCLF:
Energy: 8690 MeV
Deflecting voltage: 560kV
Input power: 560kW
Total length: 1m

Non-resonant perturbing method

S-band and C-band deflectors are tuned by non-resonant perturbing method
560mm x-band deflectors on SXFEL for beam test
Proven reliable and efficient for long period structures
Conclusions

• Dynamic and growing community of high-gradient and X-band users.
• Initial period of growth driven by linear colliders.
• Proliferation of smaller-scale applications, total level of activity now overtaking linear colliders.
• We look forward to exciting and interesting times as the cross fertilization takes off.
• The benefit for CLIC has far exceeded the investment in helping other applications get started.
I would like to express my sincere thanks:

• To my CLIC high-gradient colleagues,
• To the many colleagues from the different applications I described today,
• To those from whom I have taken slides,
• To you the audience for your attention!