High-Gradient Radio-Frequency Applications
Introduction and outline

My objective is to give you an overview of applications under development which benefit from high-gradient rf structures:

- **CLIC** – very large scale high-energy physics facility
- **XFELs** – medium scale user facility for material science, biology, chemistry, etc.
- **Compton-scattering sources** – laboratory to room-sized X-ray sources
- **Medical** – compact linacs for proton and carbon ion cancer treatment
- **Pulsed neutrons** – very short neutron bunches for nuclear physics
We recently held in Beijing a workshop dedicated to high-gradient and X-band applications 
https://indico.cern.ch/event/358352/.
Accelerating structure

Outside

Inside

11.994 GHz X-band

6 mm diameter beam aperture

beam propagation direction

MeVArc 2015, 2 September 2015

Walter Wuensch, CERN
CLIC – very large scale accelerator for high-energy physics
CLIC is an international collaboration based at CERN dedicated to developing the technology for an \( e^+e^- \) linear collider for the range of 250 GeV to 3 TeV.

It is based on high-gradient, 100 MV/m, normal conducting rf, low emittance beams and a two-beam power generation scheme. A klystron-based initial energy stage is also being considered.
A dramatic moment

The crucial background for the CLIC study is LHC run 2 which has just started at CERN. The LHC is running at nearly full energy, 13.5 TeV compared to 7 TeV in the first run.

The physics landscape in this energy range should emerge in the next two years or so. The nature of new discoveries, or their absence, will have a tremendous impact on future high energy physics studies.
CLIC near CERN

Legend
- CERN existing LHC
- Potential underground siting:
  - CLIC 500 Gev
  - CLIC 1.5 TeV
  - CLIC 3 TeV

Tunnel implementations (laser straight)

Central MDI & Interaction Region
Accelerator collaboration has ≈ 50 institutes and the detector collaboration ≈ 25.
Key performance limitation is achievable gradient

11.994 GHz X-band

6 mm diameter beam aperture

beam propagation direction

Outside

Inside

Concept

MeVArc 2015, 2 September 2015

Walter Wuensch, CERN
High-gradient data and analysis

MeVArc 2015, 2 September 2015

Walter Wuensch, CERN
Progress in understanding and feedback on rf design
LHC results, energy staging and rebaselining

Conclusions

<table>
<thead>
<tr>
<th>Parameter Routine</th>
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<tbody>
<tr>
<td>Luminosity, RF+beam constraints</td>
</tr>
<tr>
<td>$L_{\text{structure}}$, $a_1$, $a_2$, $d_1$, $d_2$, $G$</td>
</tr>
</tbody>
</table>

HZ production
$\sqrt{s} \sim 250-450 \text{ GeV}$

Top at threshold
$\sqrt{s} > 350 \text{ GeV}$

Recoil Mass
$\sqrt{s} < 400 \text{ GeV}$

$\sqrt{s} \sim 380 \text{ GeV}$

Top pair production
$\sqrt{s} > 360 \text{ GeV}$

Still good for HZ
Provides valid top quark program

Top pair BSM
$\sqrt{s} > 360 \text{ - } ? \text{ GeV}$

Most efficient structure is very similar to CLIC_G

MeVArC 2015, 2 September 2015
Baseline manufacturing flow

- RF DESIGN
- ENGINEERING DESIGN (3D models, 2D drawings)
- ULTRA PRECISION MACHINING
- QUALITY CONTROL AT FACTORY
- NOT CONFORM
- CONFORM

- PRELIMINARY RF CHECK
- ASSEMBLY OF COUPLERS (brazing, machining)
- CLEANING (LIGHT ETCHING)
- QUALITY CONTROL AT CERN

- DIFFUSION BONDING OF DISC STACK
- BRAZING OF COUPLERS, TUNING STUDS, COOLING CIRCUITS
- LEAK TIGHTNESS TEST
- RF CHECK AND TUNING

- ULTRA PRECISION MACHINING
- INSTALLATION
- PACKAGING AND SHIPPING
- BAKING (vacuum 650 °C, 10 days)

Add a final dimensional control
One of our top priorities is to complete Xbox-3 this year and operate all our three X-band klystron-based tests stands through at least 2018.
In order to facilitate the use of the XBoxes by collaborators we have proposed to include them in EUCARD3 as a Trans National Access. If approved this would be a source of funding for collaborators to come to CERN to make tests.

Independently from the call at which we will apply, we must take note that Integrating Activities for Advanced Communities in H2020 are different from FP7 (as seen in the first call) and in particular need:

1. More focus on **Transnational Access**
2. Innovation and **partnership with industry**.
3. Demonstration of the **added value and the progress** beyond current achievements of a continuation project.

“EU funding will be provided to support the trans-national access to European research infrastructures, as well as the cooperation, networking and joint developments between research infrastructures, their scientific communities, industries and other stakeholders. Integrating Activities in particular should contribute to fostering the potential for innovation of research infrastructures by reinforcing the partnership with industry, through e.g. transfer of knowledge and other dissemination activities, activities to promote the use of research infrastructures by industrial researchers, involvement of industrial associations in consortia or in advisory bodies. A specific work package on innovation is therefore recommended in all Integrating Activity proposals”.

**Results of the consultation**

- **50 Lol’s** received until February 2015, for a total requested budget of 32.6 M€ (3.2 x maximum budget).
- **10 Networks, 40 R&D, no TNA.**
- **Origin of Lol’s**: 25 Germany, 7 UK, 7 CERN, 5 Spain, 2 Switzerland, 2 shared, 1 Sweden, 1 France.
- **Notable absences**: no high-field magnets (community busy with HL-LHC, high cost for continuing HTS). Little on RF (only thin films and some SC).
- **A few new potential partners.**
XFEL – large scale accelerator for biology, chemistry, material science, etc.
XFELs – operating and under construction

Typically needs 6 to 20 GeV electron beams
The aim of the XbFEL Collaboration is to promote the use of X-band technology for FEL based photon sources.

http://xbandfel.web.cern.ch/

ST Elettra - Sincrotrone Trieste, Italy.
CERN CERN Geneva, Switzerland.
JU Jagiellonian University, Krakow, Poland.
STFC Daresbury Laboratory Cockcroft Institute, Daresbury, UK
SINAP Shanghai Institute of Applied Physics, Shanghai, China.
OSLO University of Oslo, Norway.
IASA National Technical University of Athens, Greece.
UU Uppsala University, Uppsala, Sweden.
ASLS Australian Synchrotron, Clayton, Australia.
UA-IAT Institute of Accelerator Technologies, Ankara, Turkey.
ULANC Lancaster University, Lancaster, UK.
The demand for new FEL facilities is worldwide continuously increasing, spurring plans for new dedicated machines. This led to a general reconsideration of costs and space issues, particularly for the hard X-ray sources, driven by long and expensive multi-GeV NC linacs.

For these machines the use of X-band technology can greatly reduce cost and capital investment, reducing the linac length and the size of buildings, opening the way to the construction of a multitude of affordable “Regional Facilities”.
Proposed Layout

It consist of:

- **RF photocathode gun** → S band structure delivering beam @7 MeV with 250 pC charge, 2.5 ps (800μm) length and 0.25 mm rad emittance
- **Injector** → S-band structures and one X-band structure as linearizer, accelerating beam up to 300 MeV
- **Two main linacs** → Two X-band modules: stage one 0.3 GeV → 2.0 GeV, stage two 2.0 GeV → 6.0 GeV
- **Two bunch compressors, Beam delivery lines, Undulator(s), Laser transport line(s)**

The advantage of using X-band:

- Compact reduction of length with high gradient
- Costs reduction
- Possibility to go to a high repetition rate (up to kHz regime)

Courtesy of A. Aksoy
FERMI perspectives

S-band linac
two e-bunches/RF pulse

1.5 GeV
λ 4-80 nm

3.5 GeV
λ < 1 nm

HF bunch separator

Two separate linacs at 50 Hz
S-band → 1.5 GeV
X-band → 3.5 GeV
X-Band Activities in Australia

- Part of the XbFEL Collaboration spun out from CLIC, planning XbFEL as an upgrade path for the Australian Synchrotron light source.
- Modelling all XbFEL linac with novel linearisation scheme.
- Propose an “XBOX3” type test stand at the University of Melbourne.

Concept drawing of AXXS Australian X-Band X-Ray Source. (M. Boland)


Bunker for former 35 MeV betatron at the University of Melbourne. (M. Boland)

Courtesy of M. Boland
SXFEL: 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

Compact hard X-ray FEL (X-band, S-band)
Energy: 6.5GeV, 8GeV (200m linac)
Total length: About 550 meters
Compton-scattering X-ray source – very high energy X-rays and/or compact sources for biology, chemistry, material science, etc.
Compton Back Scattering

\[ x = \frac{\theta}{4} \left( 1 + \frac{2}{\gamma^2} \right) \]

- X-rays emitted in narrow cone, half angle \( \gamma^{-1} \)
- X-ray energy dependent on emission angle
- 1% energy spread if \( \theta < 0.1 \gamma^{-1} \)

<table>
<thead>
<tr>
<th>Electron energy</th>
<th>Lorentz factor ( \gamma )</th>
<th>X-ray wavelength</th>
<th>X-ray energy</th>
<th>Emission angle 0.1 ( \gamma^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 MeV</td>
<td>11</td>
<td>8.6 Å</td>
<td>1.4 keV</td>
<td>9 mrad</td>
</tr>
<tr>
<td>15 MeV</td>
<td>30</td>
<td>1.1 Å</td>
<td>11 keV</td>
<td>3 mrad</td>
</tr>
<tr>
<td>30 MeV</td>
<td>60</td>
<td>0.28 Å</td>
<td>44 keV</td>
<td>1.7 mrad</td>
</tr>
<tr>
<td>45 MeV</td>
<td>89</td>
<td>0.13 Å</td>
<td>98 keV</td>
<td>1.1 mrad</td>
</tr>
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</table>
An advanced **Source of Gamma-ray photons** will be built in Magurele (Bucharest, Romania) in the context of the ELI-NP Research Infrastructure by the "EuroGammaS" Association. The photons will be generated by **Compton back-scattering** in the collision between a high quality electron beam and a high power laser. The machine is expected to achieve an energy of the gamma photons tunable between 1 and 20 MeV with a narrow bandwidth (0.3%) and a high spectral density ($10^4$ photons/sec/eV). The machine is based on a RF Linac operated at C-band (5.712 GHz) with an S-band photoinjector delivering a high phase space density electron beam in the **300-720 MeV energy range**. The repetition rate of the machine is **100 Hz** and, within the RF pulse, up to **32 electron bunches** will be accelerated, each one carrying **250 pC** of charge, separated by **16 ns**. The linac booster is composed of **12 TW C-Band** disk loaded accelerating structures, each structure, 1.8 m long, is a quasi-constant gradient structure with $2\pi/3$ field phase advance per cell.

<table>
<thead>
<tr>
<th>Bunch charge</th>
<th>250 pC</th>
</tr>
</thead>
<tbody>
<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>0.4 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>

The **"EuroGammaS" Association** is composed by the INFN, the "Association leader", the University of Rome "La Sapienza", the CNRS, ACP S.A.S., Alsyom S.A.S., Comeb Srl, ScandiNova Systems AB.
MOTIVATION OF THE ACCELERATING STRUCTURES CHALLENGES IN THE ELI-NP GBS PROJECT

To increase the gamma flux we need to increase the number of collision per second:
- **100 Hz repetition rate**
- **Multi bunch**

To reduce the accelerator overall dimensions: compact system:
- **High gradient**
  - Damping of HOM in RF structures to avoid BBU instabilities
  - Compensation of beam loading effects
  - Accurate thermal design (high average dissipate power)

-C-band LINAC combined with an S-band Injector is the best compromise between BD and compactness of the system
The aim of the RF conditioning is to reach 40 MW at the input coupler at 100 Hz repetition rate and 820 ns pulse width. The conditioning started at 10 Hz, 100 ns input pulse and minimum power. The forward/reflected power signals at the input coupler and output coupler were measured using diodes from INFN and an oscilloscope. These readings were recorded to the Labview GUI which calculates the corresponding power levels.

The conditioning of the structure started on 18.03.2015 and ended on 23.04.15. The klystron power was progressively increased (by increasing the HV of the modulator) and the current of three ion pumps connected around the structure and the RF signals from pickups were monitored.

The conditioning procedure was semi-automatic and the switch-off on the HV were caused by:

(a) operators;
(b) threshold on the ion pumps current absorption (>1x10^-7 mBar)
(c) reflected power to the klystron exceeding a certain threshold.

The RF conditioning for the first RF structure lasted about 190 hours.
Tsinghua Thomson scattering X-ray source (TTX)

<table>
<thead>
<tr>
<th>Electron beam</th>
<th>Laser beam</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong></td>
<td>45MeV</td>
</tr>
<tr>
<td><strong>Bunch length</strong></td>
<td>1~4ps</td>
</tr>
<tr>
<td><strong>Charge</strong></td>
<td>~0.7nC</td>
</tr>
<tr>
<td><strong>Beam size</strong></td>
<td>30x25um</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Parameters of Scattering X-ray</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Photon energy</strong></td>
</tr>
<tr>
<td><strong>Pulse duration</strong></td>
</tr>
<tr>
<td><strong>Number photons</strong></td>
</tr>
</tbody>
</table>
200MeV linac layout (Preliminary design)

- S-band @ 30MV/m
  - 1m x 1

- X-band @ 70MV/m
  - 0.6m x 4

- RF Gun
- PC 1:4
- 50MW
- 7MW x 2
- 50MW
Compton Back Scattering source

UNIVERSITY OF TWENTE.

high-power pulsed laser

X-band LINAC

e-gun

optical cavity

sample

TU Delft

PANalytical

The Analytical X-ray Company
detector

CERN

NIKHEF

VDL Enabling Technologies Group

TU/e

Technische Universiteit Eindhoven
University of Technology
Low-emittance pulsed electron gun

- 100 keV DC electron gun;
- pulsed operation by femtosecond laser photoemission;
- 1 pC bunches @ 40 nm rad normalized emittance;
- 10 pC bunches @ 120 nm rad normalized emittance;
- developed @ TU/e, sold through AccTec BV;
- currently under development: pulsed CeB₆ thermionic operation.
Basic Layout for ICS

- RF gun
- 1 meter long linac
- Quads
- Dipole
- X-ray optic
- Laser cavity
- Laser amplifier
- Sample
- Electron dump
- Detector
- ICS
- <4 m
Compact X-ray Light Source (CXLS)

Compact x-ray source based on burst-mode inverse Compton scattering at 100 kHz

Objectives: Research, expertise and support for curators and conservators thanks to physico-chemical analyses.

Ø Necessity of non-destructive testing with high sensitivity because the studied materials are very complex.

1989: Installation of the accelerator AGLAE in the Louvre = ion beam analysis with an external microbeam (elemental analysis, direct on the artifacts).

1997: Development of synchrotron radiation analysis = structural and molecular analysis but necessity of samples.

2009: Project of combination of AGLAE with an ICS in the Louvre for non-destructive structural and elemental analysis (XRF, XANES, XRD) as well as for 3D imaging of works of art.
Medical linacs – proton and carbon ion beams for cancer therapy
CNAO at Pavia

MedAustron is being completed in Wiener Neustadt

MedAustron bought from CNAO Foundation the construction drawings for 4 million Euro (agreement with CERN-CNAO-INFN)

CNAO = Centro Nazionale di Adroterapia Oncologica

Sandro Rossi
Robert Orecchia

Synchrotron building

Hospital building

Protons have been sent to treatment room
With linacs the dose deposition depth can be adjusted every 3 ms

linac pulses: 200 - 400 times per second

spot depth:
± 3 mm every pulse

To follow moving organs in 4D - with spot scanning, motion feedback and more than 10 paintings - the beam time structure of linacs is better than the ones of cyclotrons and synchrotrons

Centre offered by A.D.A.M. – a CERN spin-off Company

RFQ  SCDTL  CCL
1  150 MeV
2  230 MeV
3  230 MeV

Linac for Image Guided Hadron Therapy
The TULIP Project

new 3 GHz bwTW structure

230 MeV

11m ← 5-6 m

70 MeV

5 MeV

750 MHz RFQ
CERN

Low β structure

TERA foundation
RF design and diamond machined disk

\[ E \]

\[ B \]

\[ S_c \]
Mechanical design
Pulsed neutrons – very short neutron bunches for time-flight-measurements for nuclear physics
Neutron Source in Univ. of Tokyo

- Reactor doesn’t have so large space, so small accelerator with x-band linac is developed.
- X-band linac has 4 times as large frequency as S-band linac, which is generally used. So it is possible to make accelerator tube smaller.

Thermal Electron Gun
Energy: 100 keV
Beam current: 500 mA

Accelerator
Max Energy: 35 MeV

Ce:LiCaF Detector
- Inorganic, solid state neutron detector scintillator
- Fast decay time
- Can discriminate neutron events from gamma-ray events
Debris in TMI-2 have been analyzed by INEL (USA). EC and Canada also analyzed debris supplied by USA. JAERI (JAEA) also analyzed debris obtained at 1991.

Sampling Positions

1) Upper core fuel rod segment
2) Upper core loose debris
3) Crust debris
4) Molten pool debris
5) Fuel stab
6) Lower head loose debris
7) Lower head hard debris


Non-destructive measurement method of nuclear fuels in melted core hasn’t been developed yet.

Quantity of nuclear materials in melted cores which are generated in nuclear accident like Fukushima is measured by non-destructive and high accuracy methods
By NRTA, 3-7 kg of small sized MF will be measured within 20 min. (The 3-7 kg: a MF area of 300-700 cm² and a thickness of 10 g/cm²).

By NRCA, 30 g of MF including $10^9$ Bq (mainly $^{137}$Cs) will be measured within 1 hour for each beam line.
Conclusions

High-gradient rf is a rapidly maturing technology. There are a number of applications which are considering its use. We hope to see it used in many applications in the coming years.
Thank you for your attention!