Instrumentation Challenges for CLIC

T. Lefevre on behalf of the CLIC beam instrumentation team
What have BI teams done since the CDR?

T. Lefevre on behalf of the CLIC beam instrumentation team
Outline

- CLIC @ 380GeV - PIP

- Update on Instrumentation challenges
  - High precision/resolution beam instruments
  - R&D towards simpler & cheaper alternative solutions
  - R&D on Non-invasive beam instrumentation

- Conclusions
Drive beam complex

- 472 klystrons, 20 MW, 48 µs
- Drive beam accelerator: 1.91 GeV, 1.0 GHz
- Delay loop: 73 m, 2.0 km
- Decelerators, 4 sectors: Ø 95 m
- CR2: Ø 140 m

Decelerators, each 878 m

Main beam complex

- Booster linac: 2.86 to 9 GeV
- e⁻ injector: 2.86 GeV
- e⁻ DR: 359 m
- e⁺ DR: 359 m
- e⁺ PDR: 389 m
- e⁺ injector: 2.86 GeV

Main linac length: 11.4 km

- e⁻ main linac: 12 GHz, 72 MV/m
- e⁺ main linac: 3.5 km

- BC1
- BC2
- TA radius: 300 m

CR: combiner ring
TA: turnaround
DR: damping ring
PDR: predamping ring
BC: bunch compressor
BDS: beam delivery system
IP: interaction point
•: dump

380 GeV
### Beam instruments

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Drive Beam</th>
<th>Main Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity</td>
<td>50</td>
<td>130</td>
</tr>
<tr>
<td>Position</td>
<td>7,875</td>
<td>4,165</td>
</tr>
<tr>
<td>Beam Size</td>
<td>80</td>
<td>110</td>
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<tr>
<td>Energy</td>
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<tr>
<td>Energy Spread</td>
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<td>30</td>
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<tr>
<td>Bunch Length</td>
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<tr>
<td>Beam Loss / Halo</td>
<td>7,790</td>
<td>4,950</td>
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<tr>
<td>Beam Polarization</td>
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<td>Tune</td>
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<tr>
<td>Luminosity</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>15,955</strong></td>
<td><strong>9,475</strong></td>
</tr>
</tbody>
</table>
• Producing and measuring beams with **small emittance** (i.e. micron spot size)

• Producing and measuring **short Bunches** (i.e. 20fs time resolution)

• Conserving small emittance over long distances put very strict requirements on the **beam position monitor precision** (i.e. 5microns) and resolution (i.e. 10s nm)
Instrumentation challenges

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- Conserving small emittance over long distances put very strict requirements on the **beam position monitor precision** (i.e. 5microns) and resolution (i.e. 10s nm)

- Manipulating **high charge beams**
  - Impact on **Machine Protection** issues
  - Impact on **Radiation hardness** issues

- Require **non-intercepting beam diagnostics**
Instrumentation challenges

- Producing and measuring beams with small emittances (e.g., electron spot size)
- Producing and measuring short bunches (e.g., bunch length)
- Conserving scarce beam resources (e.g., requirements on the beam quality and resolution (i.e. 10s nm))

As **cheap** as possible!
As **simple** as possible!

- Manipulation of the beams
  - Attention on **Machine Protection** issues
  - Impact on **Radiation hardness** issues

- Require **non-intercepting beam diagnostics**
High resolution BPM
High resolution BPM

- CLIC cavity BPM prototype tested on CALIFES / CLEAR
  - Aperture: 8mm - Operating frequency: 15 GHz
High resolution BPM

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  - Aperture: 8mm - Operating frequency: 15 GHz

- Investigating the time response for long Bunch train observation

F. J. Cullinan et al., Long bunch trains measured using a prototype cavity beam position monitor for the Compact Linear Collider, Phys. Rev. STAB 18 112802 (2015)

- Some issues of radiation hardness observed requiring an optimization of the read-out electronic
High resolution BPM

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  - Aperture: 8mm - Operating frequency: 15 GHz

Talk on ‘An acquisition system for Cavity BPM’ by Manuel Cargnelutti – Tuesday at 15h10

Some issues of radiation hardness observed requiring an optimization of the read-out electronic
Beam Loss Monitors
Beam Loss Monitors

- Simulations and Design of optical BLM system for CDR in 2012

Drive Beam 2.4GeV

\( e^+ / e^- \) fluence
Beam Loss Monitors

- Simulations and Design of optical BLM system for CDR in 2012

- Since then, ... Many experimental studies
  - RF studies (Breakdown and Dark current): M. Kastriotou et al., “A versatile beam loss monitoring system for CLIC”, IPAC, Busan, Korea, 2016, pp. 286
High resolution transverse beam size monitors
High resolution transverse beam size monitors

- Using **Laser Wire scanners** as a Baseline in CDR-2012
- Based on Compton scattering using high power lasers
High resolution transverse beam size monitors

- Performed using Laser Wire scanner as a Baseline In CDR-2012
  - Based on Compton scattering using high power lasers

- **10 years on R&D in the 2000s (ATF2)**
  
  S. T. Boogert et al., PRSTAB 13, 122801 (2010)
  
  L. Corner et al., IPAC, Kyoto, Japan (2010) pp3227
Using Laser Wire scanners as a Baseline in CDR-2012

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- Works well but expensive and complex

- Study alternative solutions to reduce the number of LWS in complex
High resolution transverse beam size monitors

- Investigating very high resolution imaging system using Optical transition radiation as a simple and cheap solution
High resolution transverse beam size monitors

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- Work started in KEK in 2010: Measuring beam size as **visibility of the OTR Point(Particle) Spread Function** (P. Karataev et al., PRL 107, 174801 (2011))
High resolution transverse beam size monitors

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- Sub-micron resolution demonstrated and used since 2015 regularly on our test-stand at ATF2 (B. Bolzon et al., PRSTAB 18, 082803 (2015))
High resolution transverse beam size monitors

- Investigating very high resolution imaging system using Optical transition radiation as a simple and cheap solution
- Work started in KEK in 2010 : Measuring the spatial profile quality of the OTR Point (Particle) Spread Function (PSF) (B. Bolzon et al., PRSTAB 18, 082803 (2015))

Talk on ‘Beam diagnostic developments at ATF2’ by Michele Bergamaschi – Tuesday at 14h00

- Sub-micron resolution demonstrated and used since 2015 regularly on our test-stand at ATF2 (B. Bolzon et al., PRSTAB 18, 082803 (2015))
Non-invasive beam size using ODR

- Studying non-invasive beam size measurements using Optical diffraction radiation from thin dielectric slits
Non-invasive beam size using ODR

- Studying non-invasive beam size measurements using Optical diffraction radiation from thin dielectric slits

The beam size is extracted from the visibility $I_{\text{min}}/I_{\text{max}}$ of the projected vertical component of the ODR angular distribution.
Non-invasive beam size using ODR

- Studying non-invasive beam size measurements using Optical diffraction radiation from thin dielectric slits

- Work started in 2011 at CESR and then ATF2 since 2015

R&D on slit configurations and technology

Maximizing emission of DR
Minimizing reflection of SR
Non-invasive beam size using ODR

- Studying non-invasive beam size measurements using Optical diffraction radiation from thin dielectric slits

- Work started in 2011 at CESR and then ATF2 since 2015

- Develop also **simulations using Zemax** suite (T. Aumeyr et al., PRAB 18, 042801 (2015))

- **Few microns resolution** recently **demonstrated** at ATF2 (L. Bobb et al., PRAB 21, 032801 (2018) and M. Bergamaschi, PhD thesis, 2018)
Non-invasive beam size using ODR

- Studying non-invasive beam size measurements using Optical diffraction radiation from thin dielectric slits
- Work started in 2011 at
- Few results have already been demonstrated at ATF2 (L. Bobb et al., PRAB 21, 032801 (2018), PhD thesis, 2018)

Talk on ‘Beam diagnostic developments at ATF2’ by Michele Bergamaschi – Tuesday at 14h00
Looking for better non-invasive monitor!
Looking for better non-invasive monitor!

- **Looking for higher light yield!**
  - Diffraction radiation from slits do not generate much photons

- **Minimizing Synchrotron radiation background** → cleaner signal
  - DR and SR are emitted at similar angles
Looking for better non-invasive monitor!

- Looking for higher light yield!
  - Diffraction radiation from slits do not generate much photons

- Minimizing Synchrotron radiation background ➔ cleaner signal
  - DR and SR are emitted at similar angles

In 2016, we started investigating Cherenkov diffraction radiation in longer dielectrics
Prototype installed in 2017 on CESR at Cornell University

Measuring Incoherent Cherenkov diffraction radiation emitted from Positrons in a 2cm long fused silica prism
Cherenkov diffraction radiation as a non-invasive monitor

- Prototype installed in 2017 on CESR at Cornell University
  - Measuring Incoherent Cherenkov diffraction radiation emitted from Positrons in a 2cm long fused silica prism

- Tests performed using 2.1 and 5.3 GeV particles

Cherenkov diffraction radiation as a non-invasive monitor

- **Measuring Beam size**:
  
  *Large Horizontal beam size at Cornell*
Cherenkov diffraction radiation as a non-invasive monitor

- **Measuring Beam size:**
  
  Large Horizontal beam size at Cornell

- **Installed a ChDR radiator on ATF2 in 2018**

  - On-going investigation on the *resolution limit* of such system using very small vertical beam size
Cherenkov diffraction radiation as a non-invasive monitor

- Measuring Beam size:
  
  *Large Horizontal beam size at Cornell*

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On-going investigation on the resolution limit of such system using very small vertical beam size
Cherenkov diffraction radiation as a non-invasive monitor

- Investigating also **Coherent** Cherenkov diffraction radiation for beam diagnostic of **short bunches**
Cherenkov diffraction radiation as a non-invasive monitor

- Investigating also Coherent Cherenkov diffraction radiation for beam diagnostic of short bunches
- **First tests performed on CLEAR** performed in 2018 using **Teflon radiator**

Measuring in 3 bands (60-90-110GHz)

**Bunch length monitor**

**Bunch position monitor**
Cherenkov diffraction radiation as a non-invasive monitor

- Investigating also Coherent Cherenkov diffraction radiation for beam diagnostic of short bunches
- First tests performed on CLEAR performed in collaboration with VALENTINO/CCMS

Talk on ‘THz radiation emission studies in CLEAR’ by Alessandro Curcio – Thursday at 15h00
EO detection system for very short bunches
EO detection system for very short bunches

- EO Transposition developed at Daresbury lab and Dundee University


EO detection system for very short bunches

- EO Transposition developed at Daresbury lab and Dundee University


- Moving EOT outside of vacuum system by creating a THz replica of the bunch field using Coherent Cherenkov radiation
Conclusions

- CLIC has funded a very wide and rich R&D program since the CDR in 2012.
- Many studies have led to substantial improvements in cost and performance, simplicity and reliability.
- Some R&D Studies are being co-financed by LHC and FCC:
- Several Beam instrumentation test facilities have been put in place at CLEAR@CERN, ATF2@KEK and at Diamond. Talk on ‘Diagnostic R&D in the CLEAR facility’ by T. Lefevre – Thursday at 15h20.
- Next steps towards a realistic implementation of BI in CLIC!
Thanks for your attention
Thanks for your attention

Many thanks to all the great Students, Postdocs and Collaborators
Spares
Requirements:

- High current 100A – high bunch frequency 12GHz
- In the vicinity of an RF structure producing 100MW @12GHz
- Temporal resolution of 10ns
- 2μm resolution over an aperture of 23mm (accurate calibration)
- Simple and Cheap ~ 40k units

CLIC TEST FACILITY 3 uses Inductive Pick-ups
~60 Units ~ 5μm resolution measured

Cheaper alternative based on Stripline Pick-ups (A. Benot-Morell, S. Smith, M. Wendt, L. Soby)

To be tested on CTF3 in 2013
Incoherent Cherenkov Diffraction Radiation (ChDR)

The electric field of ultra-relativistic charged particles passing in the vicinity of a dielectric radiator produce photons by Cherenkov mechanism (polarization effect).

- Large emission angle: \( \cos(\theta_{Ch}) = \frac{1}{\beta n} \)
- Photons emitted along the target

For a cylindrical geometry

\[
\frac{d^2 N_{Dcph}}{d\Omega d\lambda} = \frac{\alpha n (\frac{L}{\lambda})^2}{\lambda} \left( \frac{\sin \left( \frac{\pi L}{\beta \lambda} \left( 1 - \beta n \cos \theta \right) \right)}{\frac{\pi L}{\beta \lambda} \left( 1 - \beta n \cos \theta \right)} \right) \sin^2 \theta \cdot e^{-4\pi \frac{h}{\gamma \beta \lambda}}
\]

\( \alpha \), fine structure constant  
\( \beta \), normalised beam velocity  
\( \gamma \), beam relativistic factor  
\( \theta \), angle of observation

T. Lefevre, CLIC workshop 2018, CERN
Experimental set-up on CESR (1/3)

- Re-using the DR vacuum chamber and optical system

T. Lefevre, CLIC workshop 2018, CERN
Design a 2cm long SiO2 (n=1.46) Cherenkov Diffraction Radiation target

Testing with 2.1GeV e⁻ and measuring in IR (0.9-1.7um) – April 2017

The red curve has been scaled down by 1/3 for better presentation.

Xenics Bobcat 640 GigE
- Cooled InGaAs 640x512 pixels: 20um pixel pitch
- QE up to 80% at 1.6um
- 14bit ADC
- 1us-40ms integration window


T. Lefevre, CLIC workshop 2018, CERN
Design a 2cm long SiO2 (n=1.46) Cherenkov Diffraction Radiation target

Testing with 5.3GeV e⁻ / e⁺ and measuring in visible (0.3-0.7um) – October 2017


T. Lefevre, CLIC workshop 2018, CERN
Experimental data: Electron at 2.1 GeV

- Steering the beam vertically: comparison with simulations

No wavelength filter – No polarizer

Light integral (arb. units) vs. Impact parameter (µm)

- Measured data
- Theory
Experimental data: Positron at 5.3 GeV

- Steering the beam vertically
  - Wavelength 600±10nm
  - Vertical Polarization component

Cherenkov photons yield increasing strongly for smaller impact parameter
Perspectives for beam instrumentation

- Imaging system for relativistic beam
  - What is the smallest beam size measurable?
    - The Cherenkov diffraction PSF should be smaller than transition radiation PSF
    - possible tests in 2018 with micron beam sizes on ATF2
  - What is the smallest the beam tilt angle measurable?
    - A non linear response depending on wavelength, beam energy and impact parameter
- Measuring counter-propagating beams with very high directivity: BPM for FCC, HE-LHC, ...
- A Beam Position Monitor for Crystal collimator on LHC

T. Lefevre, LER 2018, CERN
The HNFS technique

- Heterodyne Near Field Speckles is a novel stochastic interference technique that gives 2D coherence / beam size information
- Measures visibility of interference fringes between transmitted beam (synchrotron radiation) and spherical waves produced by nanoparticles
- 3 years collaboration between ALBA, U. Milan and CERN funded by CLIC & FCC
- In HNFS: intensity is measured at distance $z$ from the scatterers. In case of a single particle:

$$I(z, r) \propto F(q) \cos\left(\frac{kr^2}{2z}\right)$$

Where $F(q)$ is the particle form factor, $q$ the scattering wave vector.
The HNFS technique

- When number $N$ of scatterers is LARGE, scattered intensity can be retrieved through the square modulus of Fourier Transform:

$$I(z) \propto F(q) \cos \left( \frac{kr^2}{2z} \right)$$

$$I(q) \propto S(q) \sin^2 \left( \frac{zq^2}{2k} \right)$$

Single particle interferogram modulated by particle form factor

From analysis of $I(q)$ the transverse coherence is measured

intensity profile of the source through Van Cittert Zernike Theorem!
• Beam size tests based on HNFS at NCD-SWEET beamline at ALBA in July and Sept. 2018
• 12.4 KeV X-ray radiation from undulator
• Target (a): 500 nm SiO$_2$ spheres suspended in water at $z_1 = 32.5$ m from the source. (b) 0.1 mm thick YAG:Ce crystal at $z_2 = 252$ mm, imaged with a 20X microscope objective (c) onto a CCD camera (d)

H beam size: $115 \pm 6 \mu$m (expected $131 \mu$m)
V beam size: $14.7 \pm 1.8 \mu$m (expected 8 $\mu$m)

PRELIMINARY!