JAGIELLONIAN UNIVERSITY
IN KRAKOW

SOLARIS
NATIONAL SYNCHROTRON
RADIATION CENTRE

Novel trends in bunch length diagnostics based on coherent polarization radiation

Remote, 16/09/2020
Alessandro Curcio
National Synchrotron Radiation Center SOLARIS

Summary

- Definition of Polarization Radiation
- Use of Cherenkov-Diffraction Radiation for bunch length diagnostics @CLEAR (CERN)
- Comparison to other diagnostic methods
- Diagnostic solutions for SOLARIS NCPS: present and future plans
- Conclusions

Preliminary notes to this presentation

- We'll speak about electron bunches but the most of what said is extendable to other charged particles

- We'll mainly discuss diagnostic methods used in linear accelerators, trying at the end to discuss about their same use at circular facilities

- The overall achievements here presented are the results of fruitful collaborations among different institutes distributed all over the world, in particular CERN (Geneva, Switzerland), JAI at Royal Holloway (London, England), CEA (Le Barp, France), Tomsk Polytechnic University (Tomsk, Russia), MEPhI (Moscow, Russia), STFC Daresbury Laboratory (Daresbury, England), Jagellonian University (Krakow, Poland)

JAGIELLONIAN UNIVERSITY IN KRAKOW

SOLARIS NATIONAL SYNCHROTRON RADIATION CENTRE

Solution of the Maxwell Equations for coherent Polarization Radiation

$$\vec{H} = \vec{H}_0 - i\omega\varepsilon_0(\varepsilon - 1)\vec{\nabla}_{\vec{r}} \times \int_{V_R} \Phi(\vec{r} - \vec{r'})\vec{E}_0(\vec{r'}, \omega) d^3r'$$

Magnetic field of polarization radiation emitted out of a volume V_R due to the interaction with the field E_0 carried by a charged particle

$$\Phi(\vec{r} - \vec{r'}) = -\frac{e^{i\frac{\sqrt{\varepsilon(\omega)}}{c}\omega|\vec{r} - \vec{r'}|}}{4\pi|\vec{r} - \vec{r'}|}$$

Photon propagator expressed in the space-frequency domain

$$\frac{d^2I}{d\omega d\Omega} = \frac{\mu_0 c}{\pi} F\left(\vec{k}, \omega\right) H^2(\vec{k}, \omega) R^2$$

Radiated energy distribution via coherent radiation at the distance R

$$F\left(\vec{k}, \omega\right) = \left| \int d^3r' n(\vec{r'}, \omega) e^{i\vec{k}\cdot\vec{r'}} \right|^2$$

Form factor of the emitting bunch with particle density n

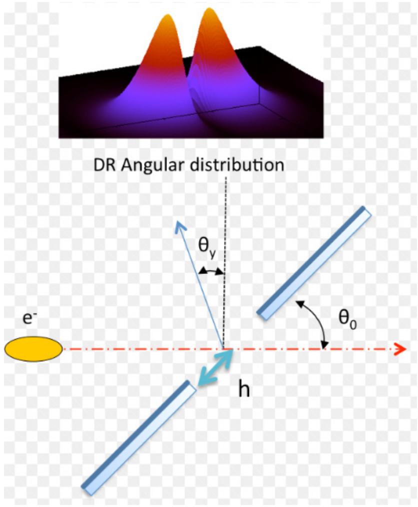
In particular geometries associated to particular symmetries the radiation integral might be worked out analytically.

This is a unique opportunity for rapid and efficient studies of the dependency upon the beam parameters or on the radiator material and shape/size

D. Karlovets and A. Potylitsyn, "Universal description for different typesof polarization radiation," arXiv preprint arXiv:0908.2336 (2009).

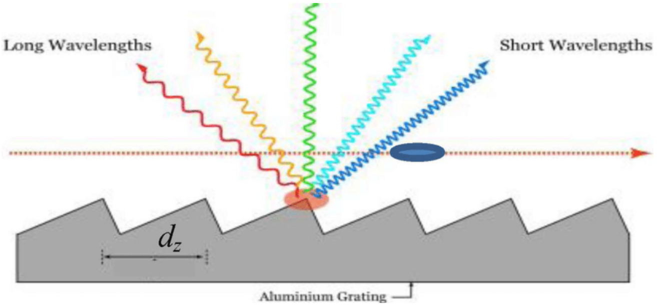
Different types of Polarization Radiation

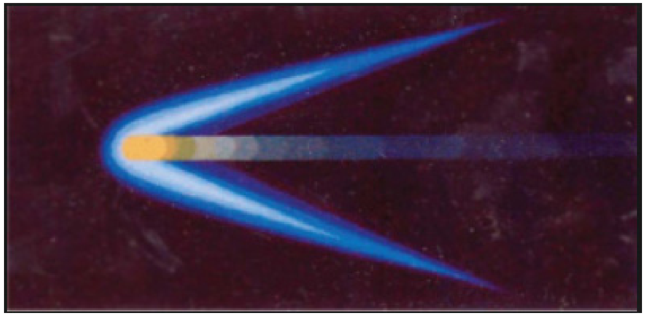
- Diffraction Radiation: a charged beam passes through an aperture or close to an edge
- Transition Radiation: a charged beam crosses the boundary between two media
- Cherenkov Radiation: a charged beam travels through a medium at a speed greater than the phase-velocity of the light in the same medium
- Smith-Purcell radiation: a charged beam travels close to a periodic structure



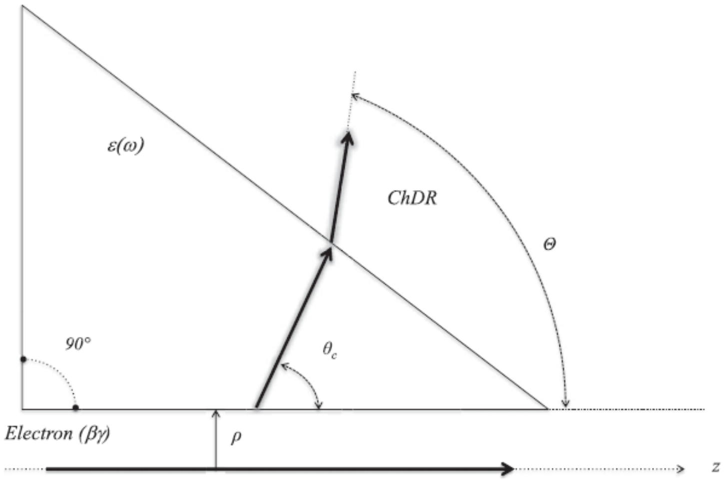
As possible to notice all the above mechanisms can be grouped in the most general class of the:

- Cherenkov-Diffraction Radiation: a charged beam travels close to a long (more than the formation length) dielectric medium

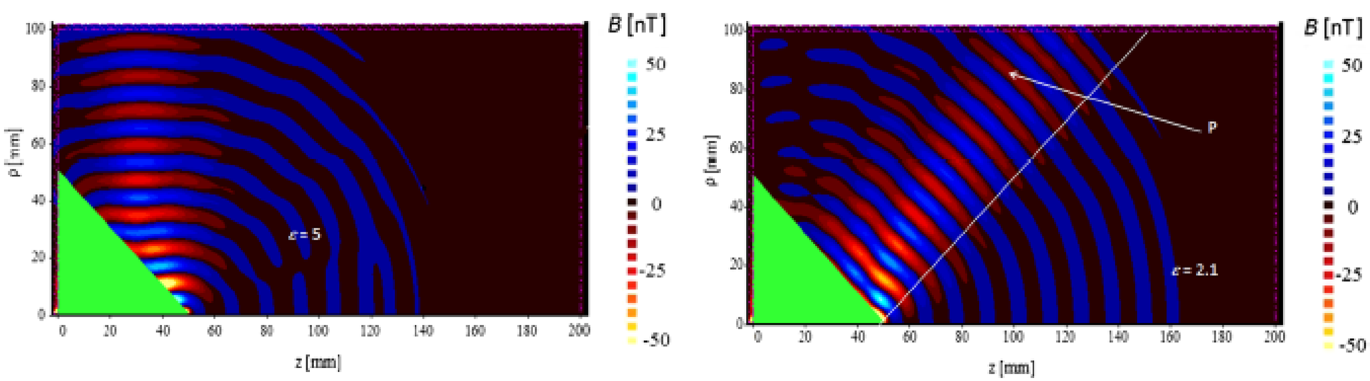




High-directivity and tunability of the directivity of the CChDR



Coherent Cherenkov-Diffraction Radiation is emitted at the Cherenkov-angle inside the dielectric material, then is refracted out into vacuum according to the radiator shape and material. The cone of emission is determined by the diffraction of the particle field.

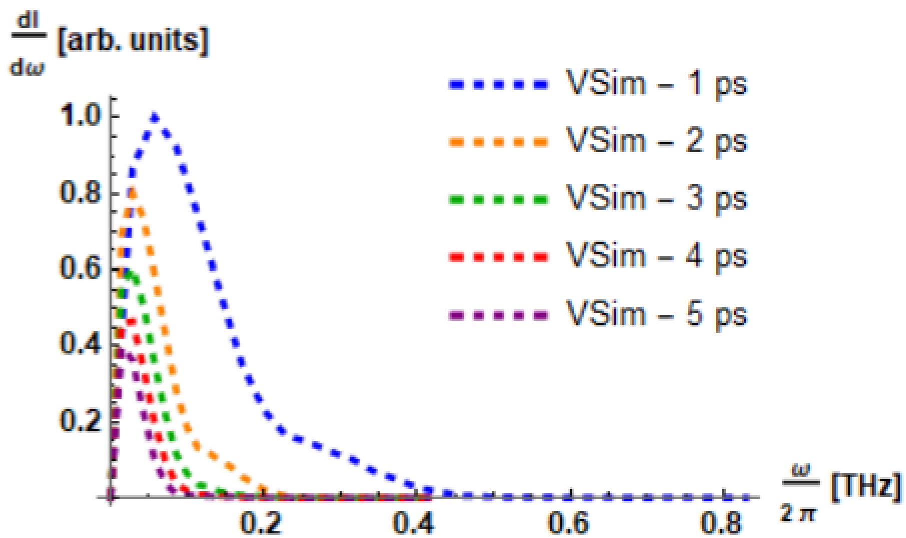


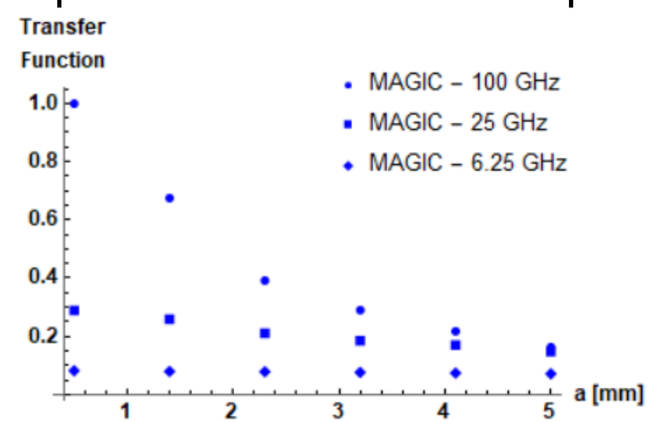
With the courtesy of Jacques Gardelle for the MAGIC simulations

The diffraction "problem": low frequency suppression

$$\frac{d^2 I}{d\Omega d\omega} \propto e^{-\frac{2\omega a}{\gamma c}}$$

The frequency component ω of the field associated to the charged particle is damped within the radiator aperture *a*

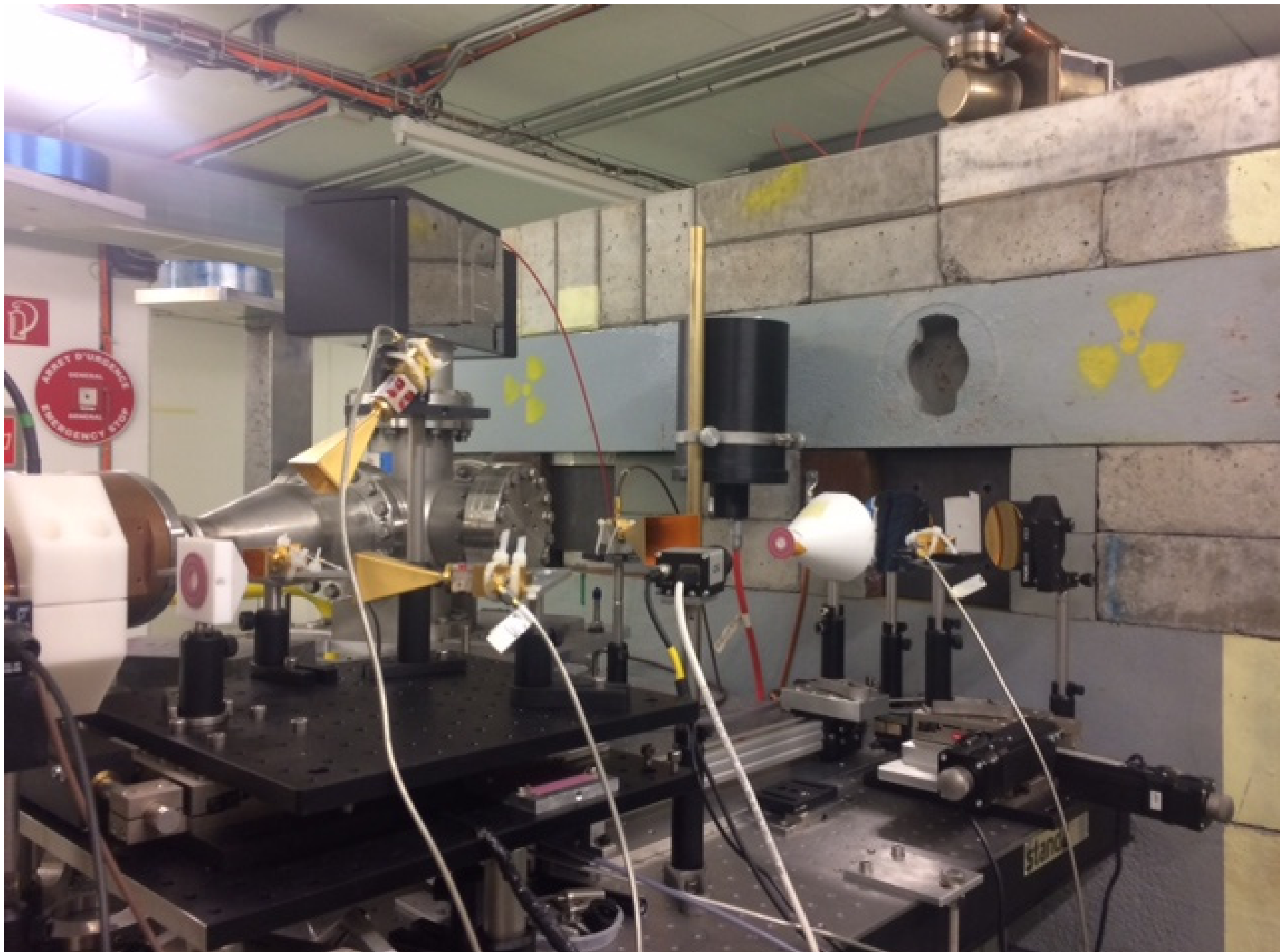




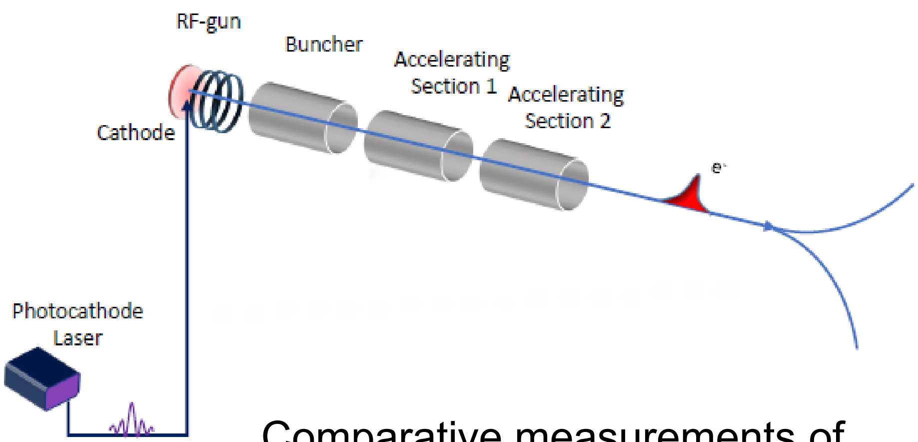
The high-frequency-region of the CChDR is dominated by the bunch-length, while the side at low-frequency is determined by the diffraction of the particle's field over the outer surface of the radiator

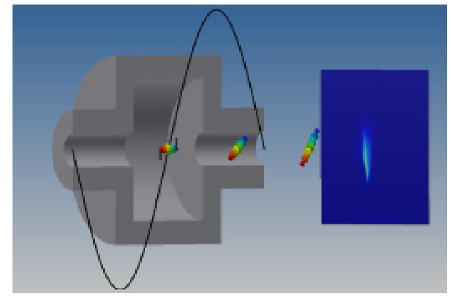
With the courtesy of Konstantin Lekomtsev for the VSim simulations

Setup for the Cherenkov-Diffraction Radiation studies @CLEAR

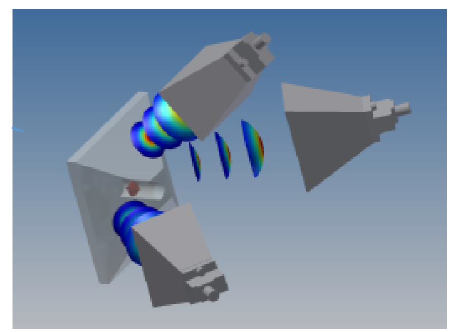


A Coherent Cherenkov-Diffraction-based Bunch Length Monitor





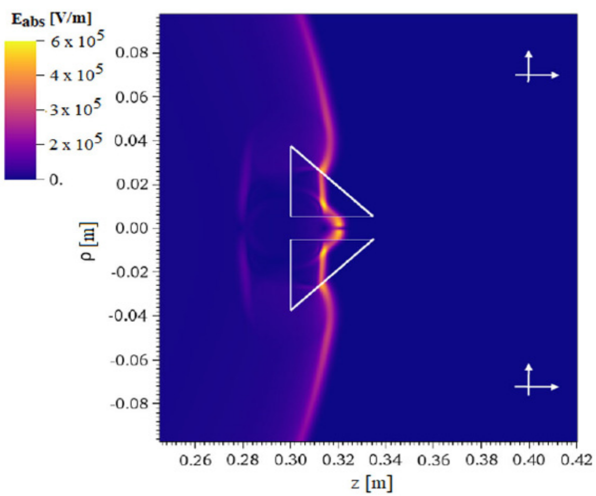
Deflector Cavity + Screen

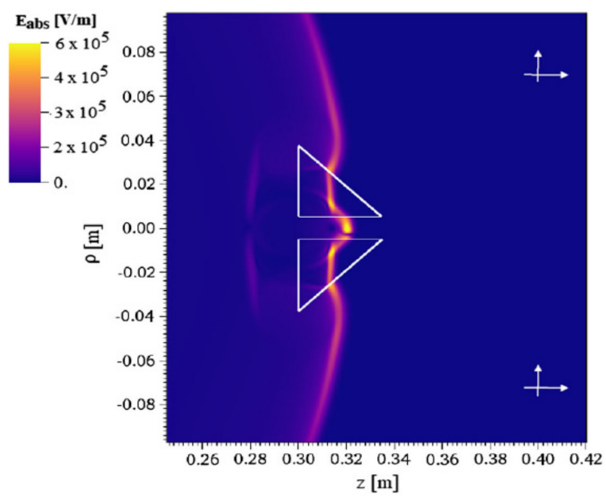


Cherenkov-Diffraction Radiation prism + Detectors

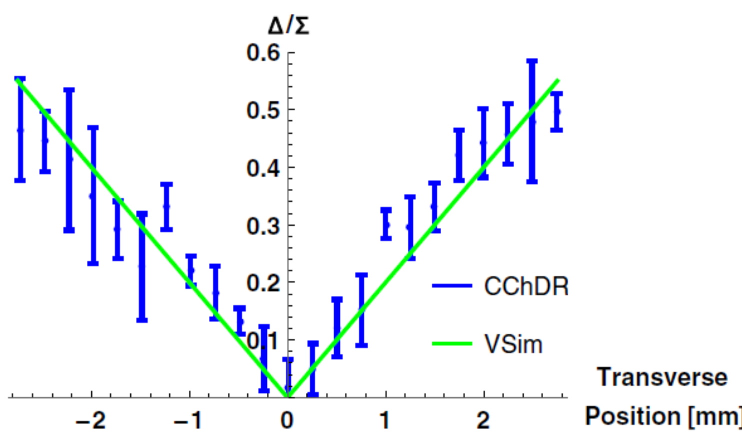
Comparative measurements of bunch length have been done exploiting either a S-band RF-deflector or the CChDR prism coupled to Schottky diodes

Alignment procedure of the beam inside the prism





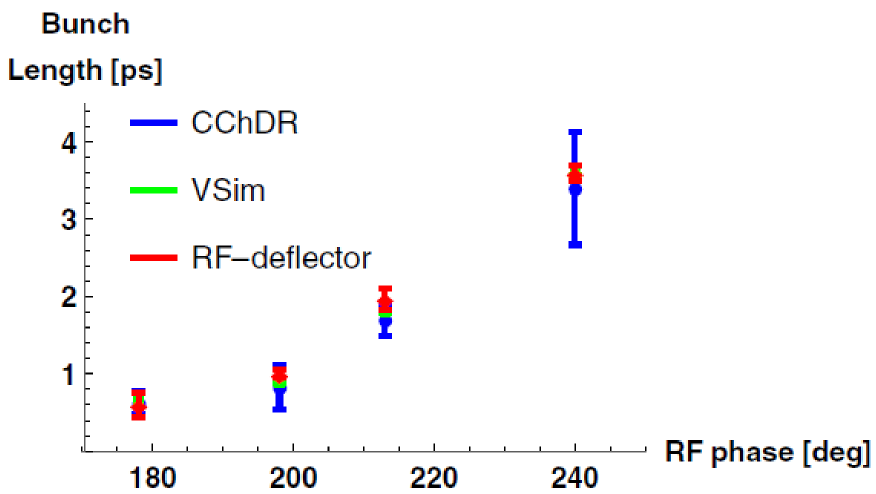
The emitted spectral power strongly depends on the position of the beam inside the hollow-channel of the prism. The alignment is made moving the radiator w.r. to the beam and considering the difference over the sum of the left-right (up-down) signals as in a Beam Position Monitor (BPM)

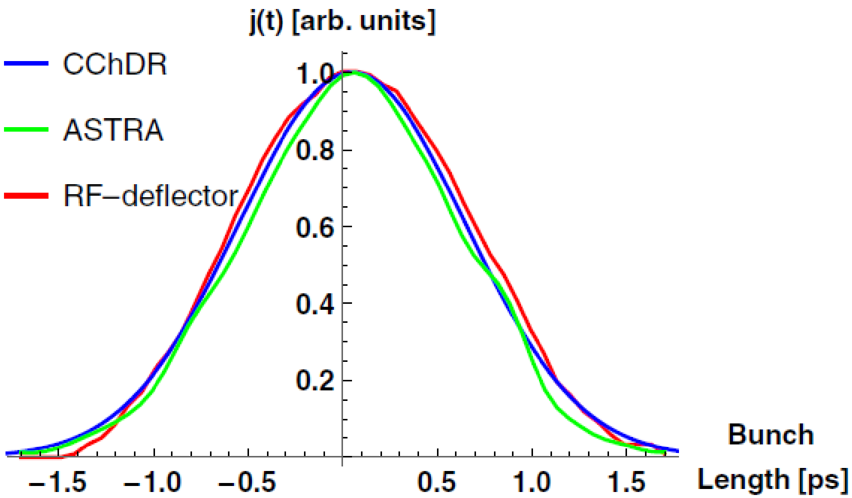


With the courtesy of Konstantin Lekomtsev for the VSim simulations

Measuring gaussian bunches

Using two diodes (E-band @84 GHz and F-band @113.5 GHz)





$$\sigma_\tau = \sqrt{\left| \frac{1}{\omega_1^2 - \omega_2^2} \left[\log\left(\frac{S_1 \omega_2}{S_2 \omega_1} \right) + \frac{(\omega_1 - \omega_2) a}{\gamma c} \right] \right|}$$

Measurement made by exploiting a one-parameter formula for a gaussian bunch. Bunch charge 100 pC, ballistic compression.

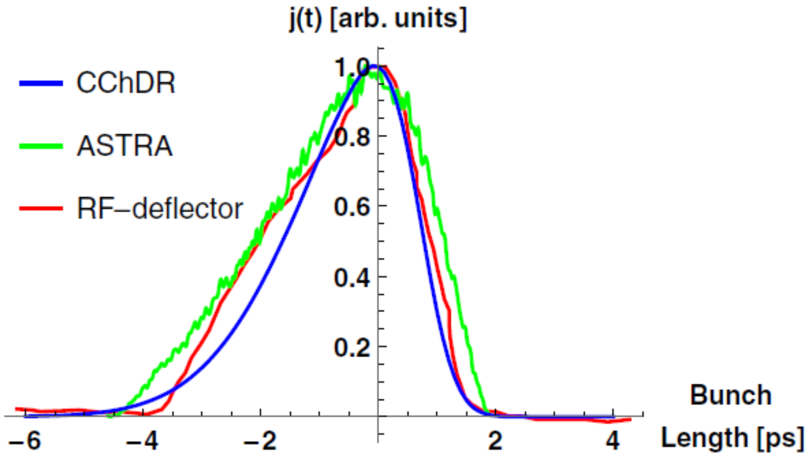
Curcio, A., et al. "Noninvasive bunch length measurements exploiting Cherenkov diffraction radiation." *Physical Review Accelerators and Beams* 23.2 (2020): 022802.

Measuring skew-gaussian bunches

$$\frac{S_1}{S_2} = \frac{|j(\omega_1,\sigma_\tau,\alpha)|^2}{|j(\omega_2,\sigma_\tau,\alpha)|^2}\frac{\omega_1}{\omega_2}e^{-\frac{(\omega_1-\omega_2)a}{\gamma c}}$$

$$\frac{S_1}{S_3} = \frac{|j(\omega_1,\sigma_\tau,\alpha)|^2}{|j(\omega_3,\sigma_\tau,\alpha)|^2}\frac{\omega_1}{\omega_3}e^{-\frac{(\omega_1-\omega_3)a}{\gamma c}}$$

Using three diodes
(V-band @60 GHz, E-band @84 GHz and F-band @113.5 GHz)

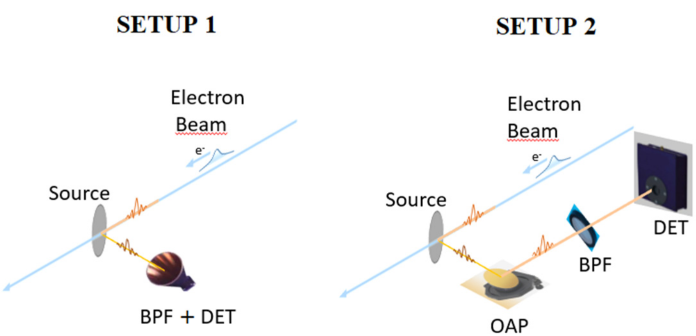


Measurement made by exploiting a two-parameter system for a skew-gaussian bunch. Bunch charge 400 pC, ballistic compression.

$$j(\omega,\sigma_\tau,\alpha) = Q_0 e^{-\frac{\sigma_\tau^2\omega^2}{2}}\left[1 + erf\left(i\frac{\alpha\sigma_\tau^2\omega}{\sqrt{1+2\alpha^2\sigma_\tau^2}}\right)\right]$$

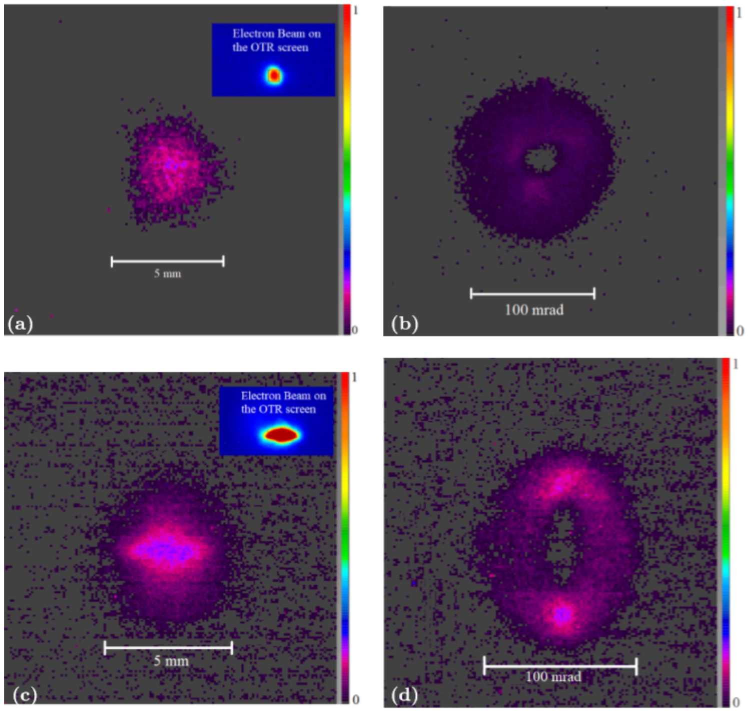
Curcio, A., et al. "Noninvasive bunch length measurements exploiting Cherenkov diffraction radiation." *Physical Review Accelerators and Beams* 23.2 (2020): 022802.

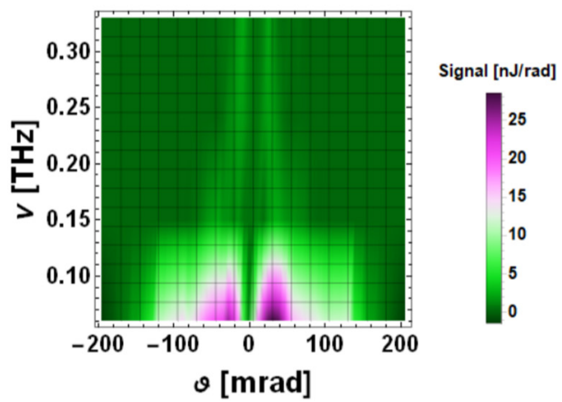
Coherent Transition Radiation (CTR) studies

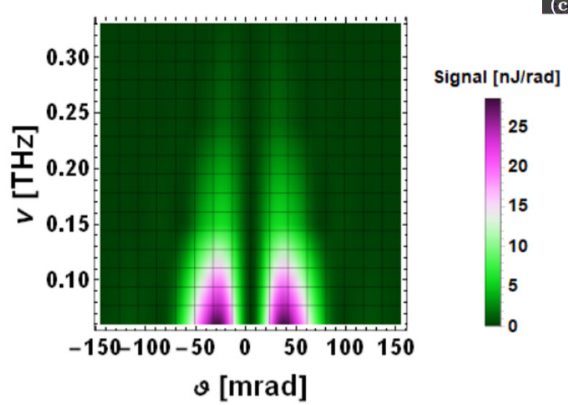


Spectrally and angularly characterized CTR source, by means of Band-Pass-Filtered Schottky diodes

Source characterized both in near and far-field by means of a THz camera, angular distribution/polarization shaping by different beam focusing at the radiator plane

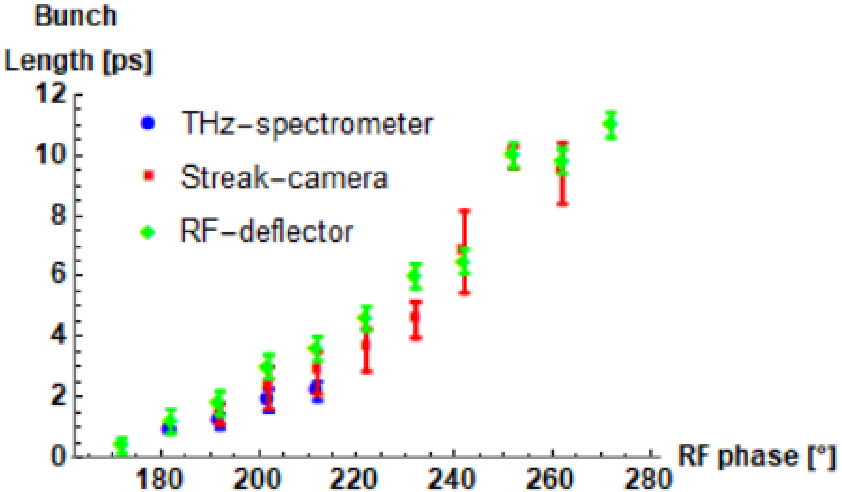






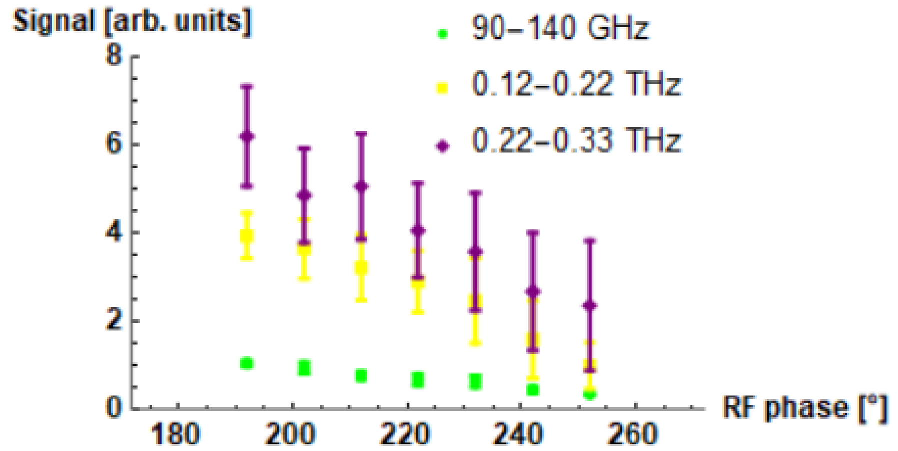
Curcio, A., et al. "A beam-based (sub-)THz source at the CERN Linear Electron Accelerator for Research" *Physical Review Accelerators and Beams* (2019).

Bunch Length measurements with CTR



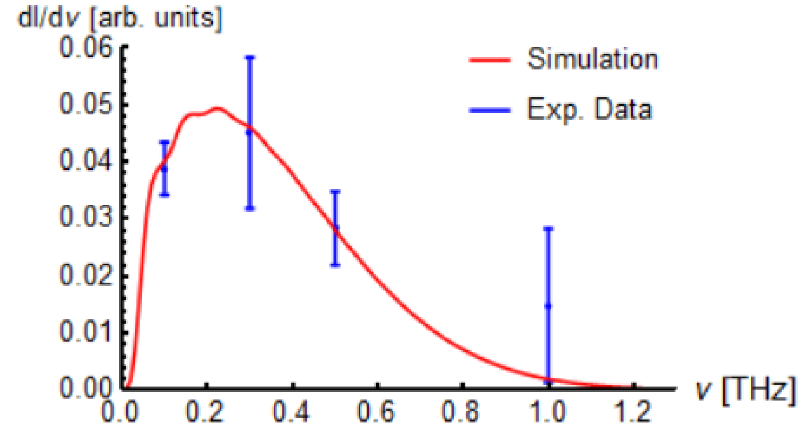
Comparison among different diagnostics: RF-deflector, OTR coupled into a Streak-Camera and finally CTR signals S in the V and E- bands detected by Schottky diodes, from which the bunch length is retrieved as

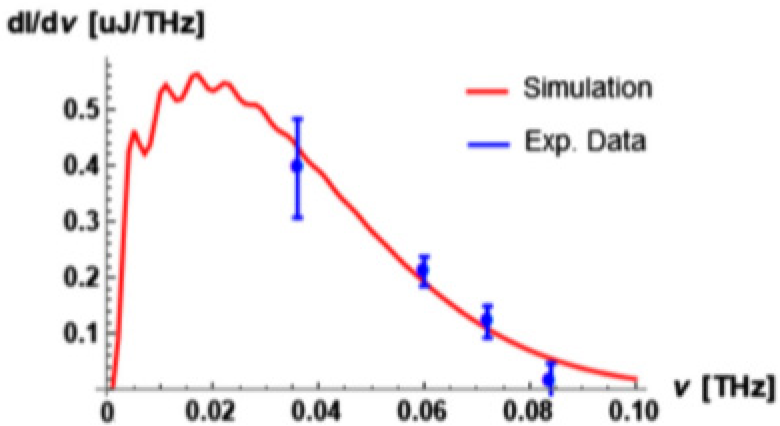
$$\sigma_\tau = \sqrt{\left| \frac{1}{\omega_1^2 - \omega_2^2} \log \left\{ \frac{\frac{dI_{sp}^2}{d\Omega d\omega}(\omega_2,\Omega_2) S_1(\omega_1,\Omega_1)}{\frac{dI_{sp}^2}{d\Omega d\omega}(\omega_1,\Omega_1) S_2(\omega_2,\Omega_2)} \right\} \right|}$$



Simultaneous coherent diffraction radiation (CDR) measurements in the high-frequency bands made by Schottky diodes as qualitative indication of the bunch compression

Comparison of Bunch Length measurements with CTR and CDR

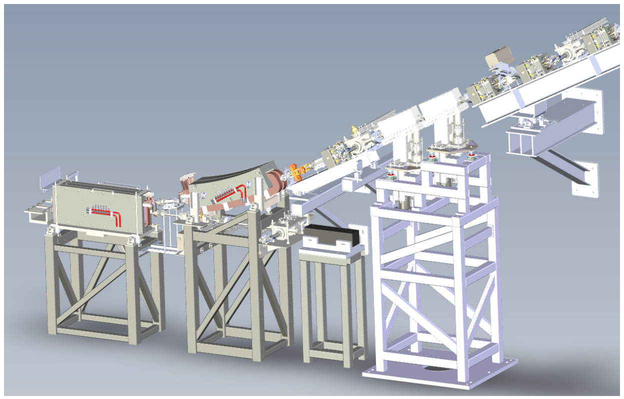




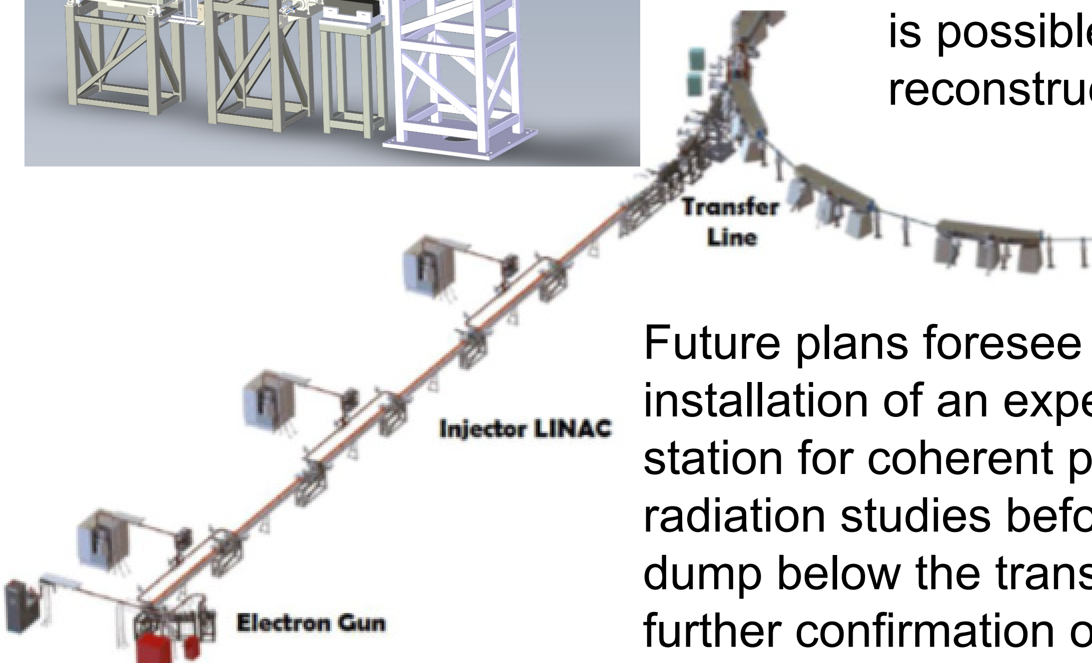
CDR measurements in the D, G and higher-bands performed by band-pass THz-grid-filters in front of a pyroelectric detector, then compared to a simulation considering 0.3 ps rms gaussian bunch. Non-intercepting measurement

CTR measurements in the Ka, V and E-bands performed by band-pass-filtered Shottky diodes, then compared to a simulation considering 3 ps rms gaussian bunch. Intercepting measurement

Diagnostic solution for the SOLARIS injector



In absence of coherent radiation stations and other standard diagnostic devices as a RF-deflector cavity or a Streak-Camera coupled to OTR light, it is possible to use the dispersive line for reconstructing the bunch length.



Future plans foresee the installation of an experimental station for coherent polarization radiation studies before the beam dump below the transfer-line, for further confirmation of the preliminary results obtained this year (next slides).

Exact solution of the Liouville equation for the longitudinal phase space

$$\frac{\partial \rho}{dt}(z, p_z; t) = \hat{L}\rho(z, p_z; t)$$

Liouville equation for the phase-space density

$$\hat{L} = \left[\frac{\partial H}{\partial z}\frac{\partial}{\partial p_z} - \frac{\partial H}{\partial p_z}\frac{\partial}{\partial z}\right]$$

Liouville operator

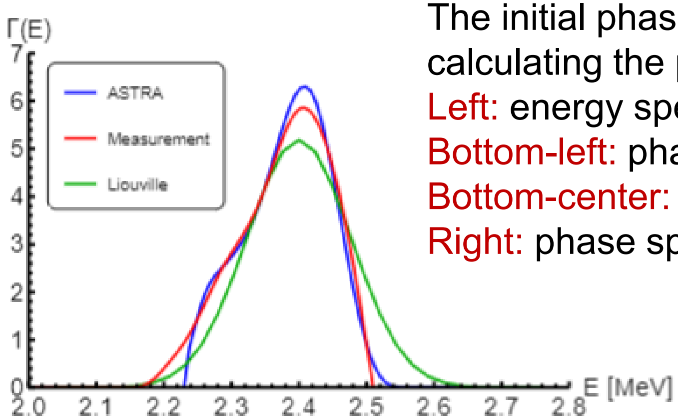
$$\rho(z, p_z; t) = e^{-\int_0^t dt F_z \frac{\partial}{\partial p_z} - \int_0^t dt v_z \frac{\partial}{\partial z}} \rho(z, p_z; 0) = $$
$$= \rho\left(z - \int_0^t dt v_z, p_z - \int_0^t dt F_z; 0\right)$$

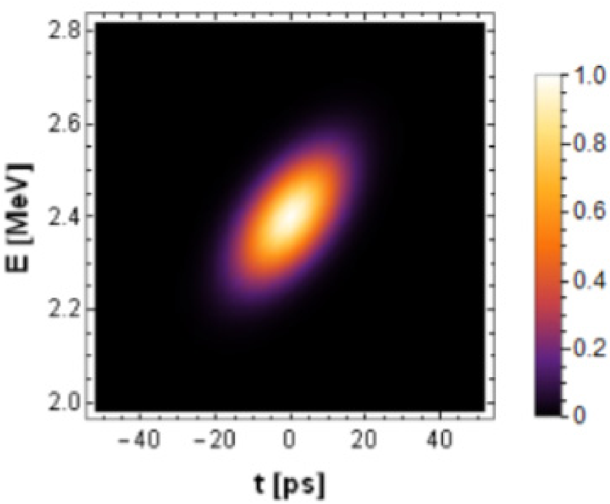
Exact solution for fully analytic studies (strongly dependent upon the phase-space density at t=0)

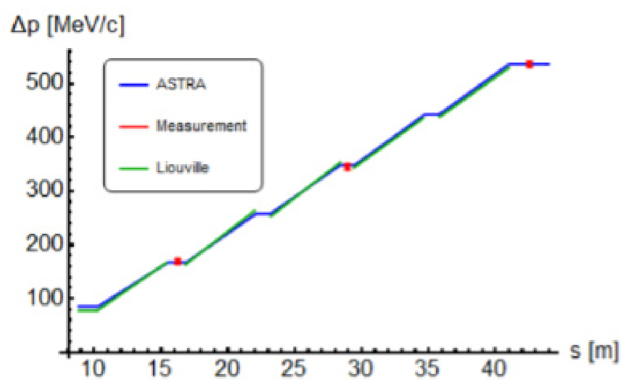
Babusci, D., et al. "Relativistic harmonic oscillator, the associated equations of motion, and algebraic integration methods." *Physical Review E* 87.3 (2013): 033202.

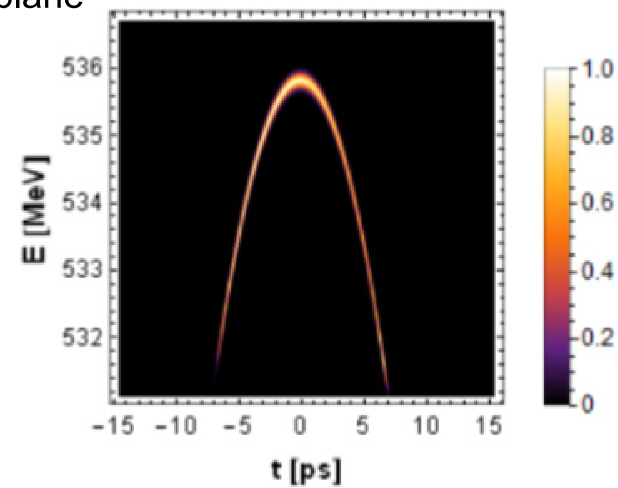
The problem of the initial phase-space density

The initial phase-space distribution is fundamental for calculating the phase-space evolution along the lattice.
Left: energy spectrum at the exit of the gun
Bottom-left: phase space density at the same plane
Bottom-center: energy gain along the machine
Right: phase space at the end of the LINAC









Bunch length reconstruction in the dispersive line/1

$$Y^D(y) = \int_{-\infty}^{\infty} Y\left(y - D_y \frac{\Delta E(z)}{E_r}\right) T(z)dz$$

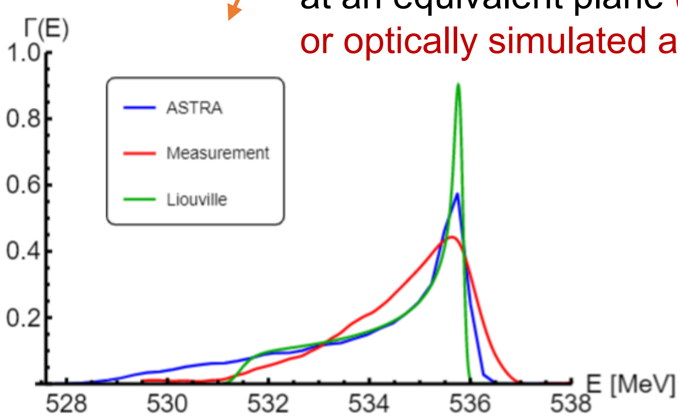
Longitudinal profile of the bunch (to be found!)

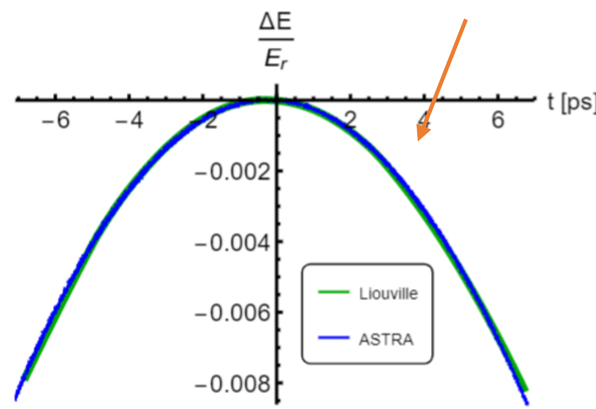
Dispersed beam profile (measured)

Dispersion at the observation plane (measured)

Relative energy-spread (calculated or simulated)

Beam profile on the straight line at an equivalent plane (measured or optically simulated as gaussian)





Bunch length reconstruction in the dispersive line/2

$$Y^D(y) \rightarrow Y^D_y$$

The dispersed profile is discretized into a vector

$$Y\left(y - D_y \frac{\Delta E(z)}{E_r}\right) \rightarrow Y_{yz}$$

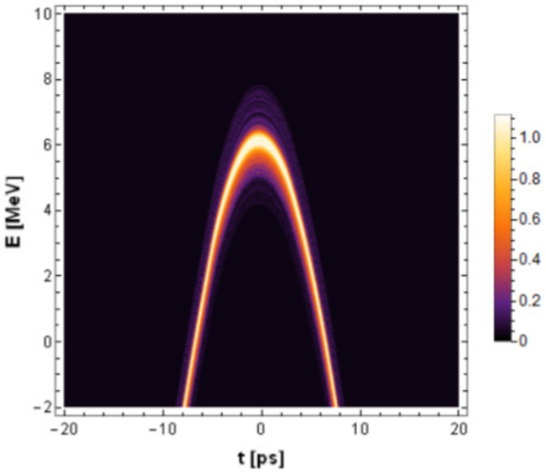
The beam-profile on the straight line becomes a matrix

$$T(z) \rightarrow T_z$$

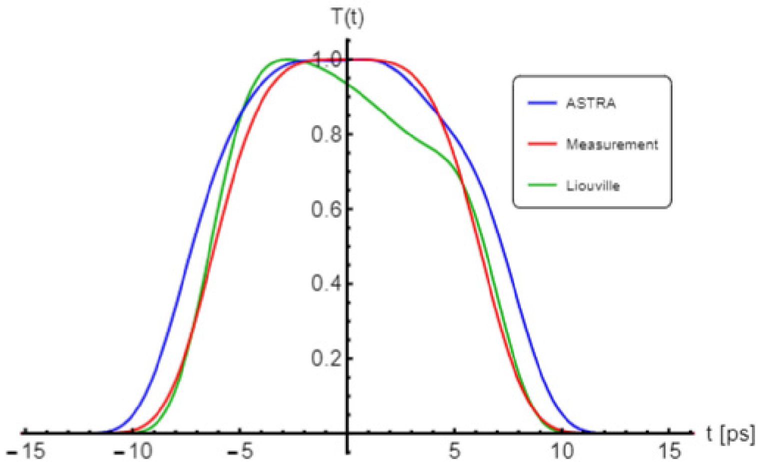
The longitudinal profile can be considered as a vector as well

$$T_z = Y^{-1}_{yz} Y^D_y$$

The previous integral equation reduces a matrix-inversion problem

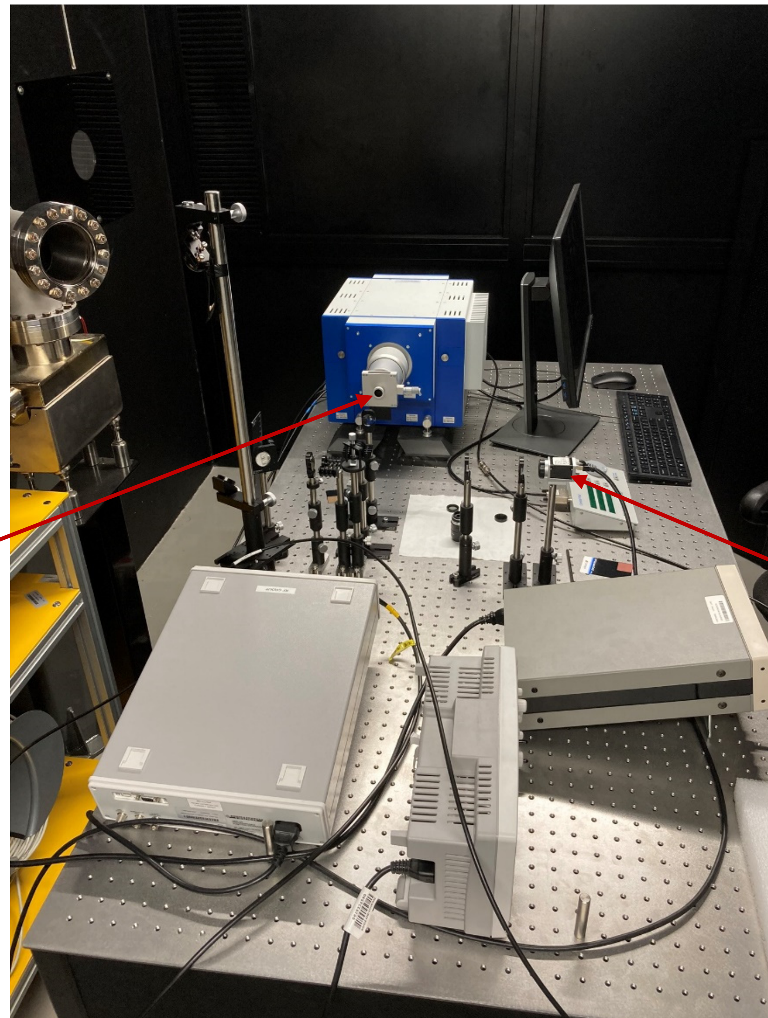


Matrix Y_{yz} built starting from the measured beam profile on the straight line and the calculated relative energy spread



Bunch length reconstruction (12.3±2.2 ps FWHM) obtained inverting Y_{yz} and applying it on the measured beam spectrum at the previous slide

View of the LUMOS diagnostic beamline

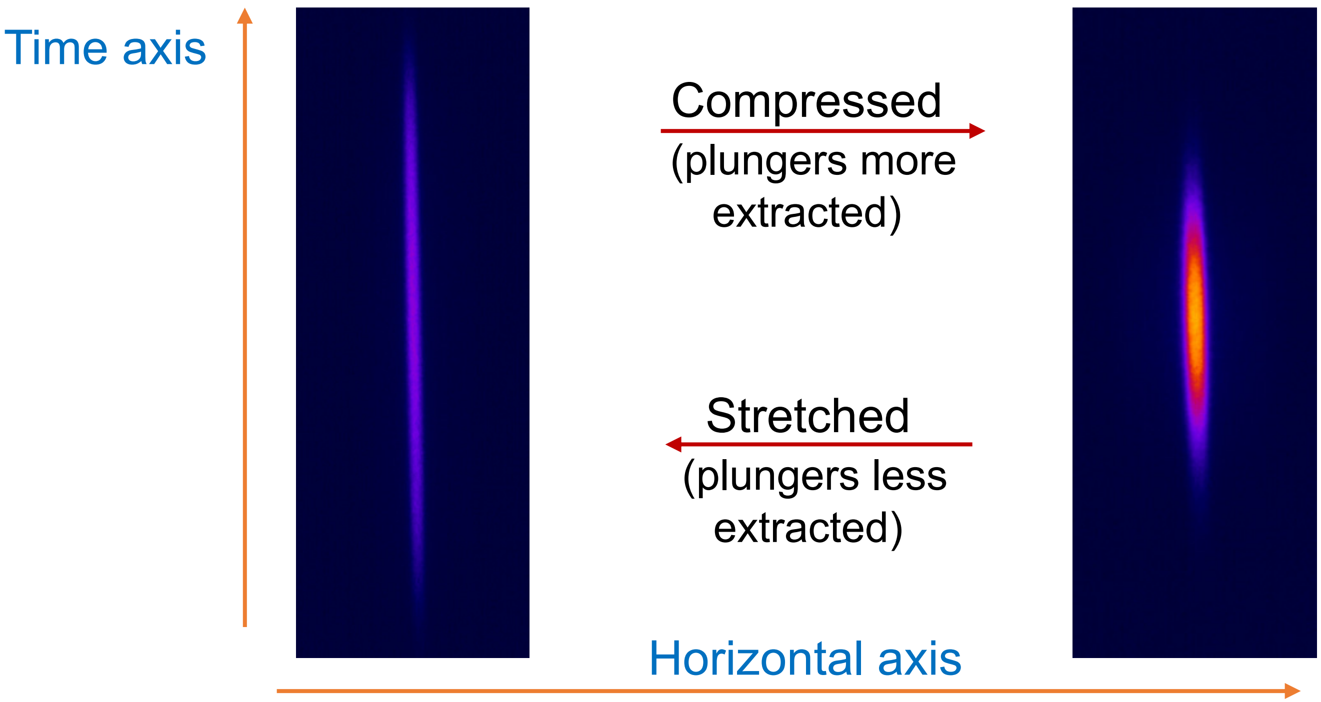


Longitudinal beam diagnostics with the Streak Camera

Transverse beam diagnostics with the CCD Camera

Streak-camera measurements @SOLARIS Storage Ring/1

1.5 GeV, 30 mA, all bunches overlapped, one sweep unit

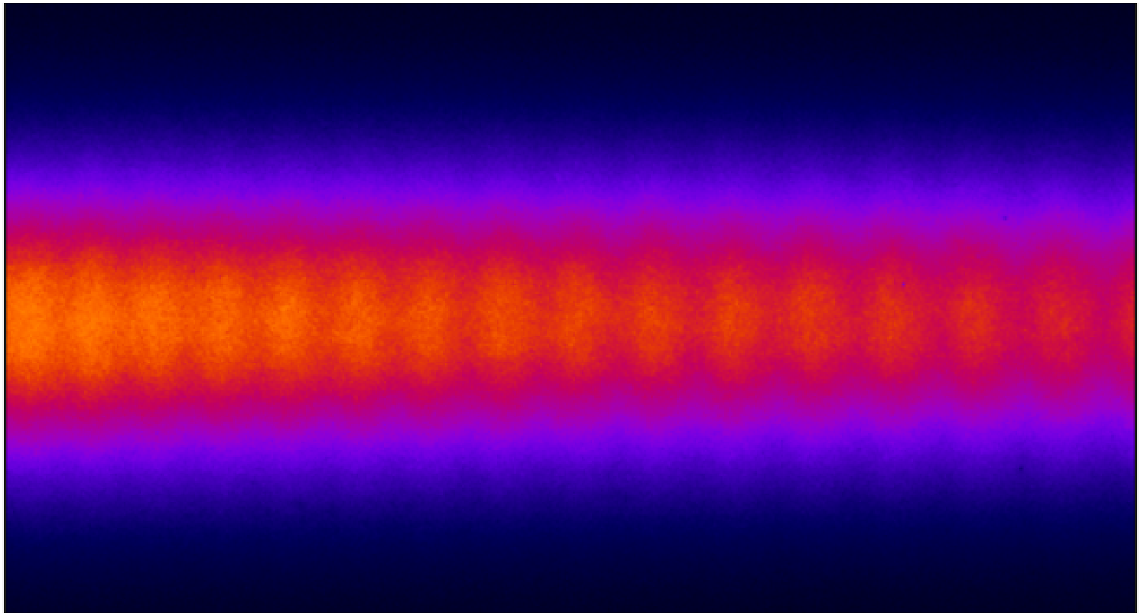


Measured bunch lengths 415-130 ps rms

Streak-camera measurements @SOLARIS Storage Ring/2

1.5 GeV, 30 mA, portion of the filling pattern, two sweep units

Fast time axis



Slow time axis (bunch separation 10 ns)

Measured bunch length 130 ps rms

Discussion on the use of CChDR in the storage ring

- At least for the SOLARIS case the output temporal signal would not give more information than the filling pattern signal obtained from a stripline which already is in use
- In fact, for having time-resolution at the fast-time scale, a large-bandwidth-scope would be needed, but still the same measurement could be done by coupling the signal from the stripline into the fast scope
- Spectral measurements would be likely not easy at so long wavelengths (1-10 GHz)
- Even if Synchrotron Radiation coupled into the Streak-Camera seems to be already a great diagnostic solution, CChDR radiators would provide, beside the bunch length diagnostics, also sensitivity to beam position, which could be an interesting additional feature

Conclusions

- We introduced the coherent Polarization Radiation (PR) as solution of the Maxwell equations for a beam of charged particles passing nearby or through a polarizable surface/volume
- We reviewed an experimental and theoretical activity towards the use of CChDR for bunch length diagnostics
- We mentioned the possibility to use other kind of PR mechanisms highlighting the main differences with respect to CChDR
- We discussed the current and future plans for bunch length diagnostics @SOLARIS
- The conclusion is that CChDR or in general PR will be more useful for the injector LINAC