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Toward single e-bunch shape diagnostics using THz coherent radiation

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Motivation

One of the most pressing issues in accelerator science today is the production of sub-picosecond duration electron bunches. Such bunches are required for a broad spectrum of applications, from achieving high luminosity in a linear collider to generating short duration X-ray pulses [1,2]. Means to measure the temporal distribution of charge within a single bunch on a bunch-by-bunch basis are required to make progress in this direction. The main thrust of our project is to develop and use methods of holographic spectroscopy to measure the coherent THz spectrum from a single e-bunch.

Coherent radiation as the bunch diagnostic tool

Total intensity of the bunch radiation consists of an incoherent part proportional to the number of electrons and a coherent part proportional to the square of that number and is given by following [3].

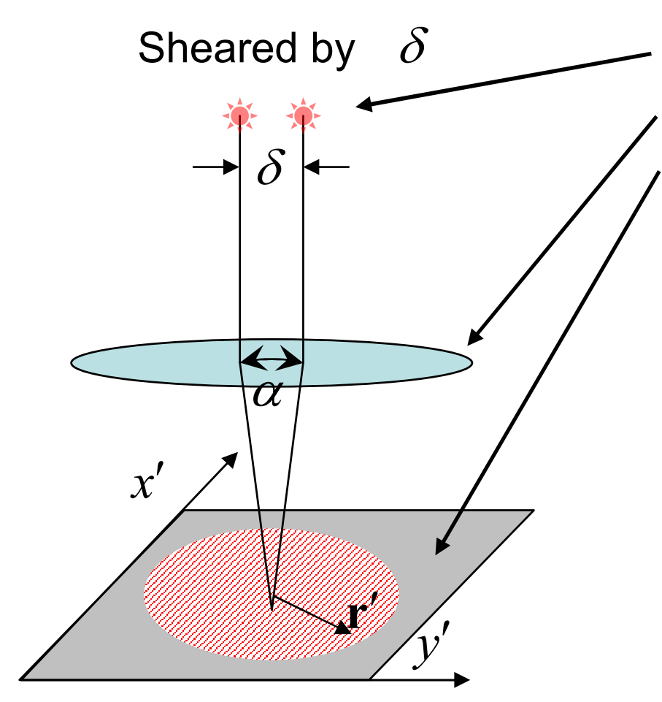
$$I_{tot}(\omega)=I(\omega)\left[N+N(N-1)F(\omega)\right],$$

where $I(\omega)$ is the single electron intensity, N is number of electrons in the bunch, $F(\omega)$ is the bunch structure factor. For highly relativistic electrons the structure factor is determined mostly by the bunch longitudinal profile.

$$F(\omega)=\left|\int_0^{\infty} dz S(z)\exp\left[i(\omega/c)z\right]\right|^2,$$

where $S(z)$ is the normalized longitudinal distribution function of particles in the bunch. Thus measurement of the coherent emission spectrum gives the necessary information to calculate the function $S(z)$. When only the intensity of the coherent spectrum is measured in general only a symmetric shape to the bunch will result. But if the experimental technique can determine both amplitude and phase of the coherent signal then complete characterization of the asymmetric bunch shape is possible. This is one of the goals of applying HFTS to this problem.

Holographic spectroscopy fundamentals



Holographic spectrometer consists of
- shearing interferometer
- Fourier transform lens
- array detector.

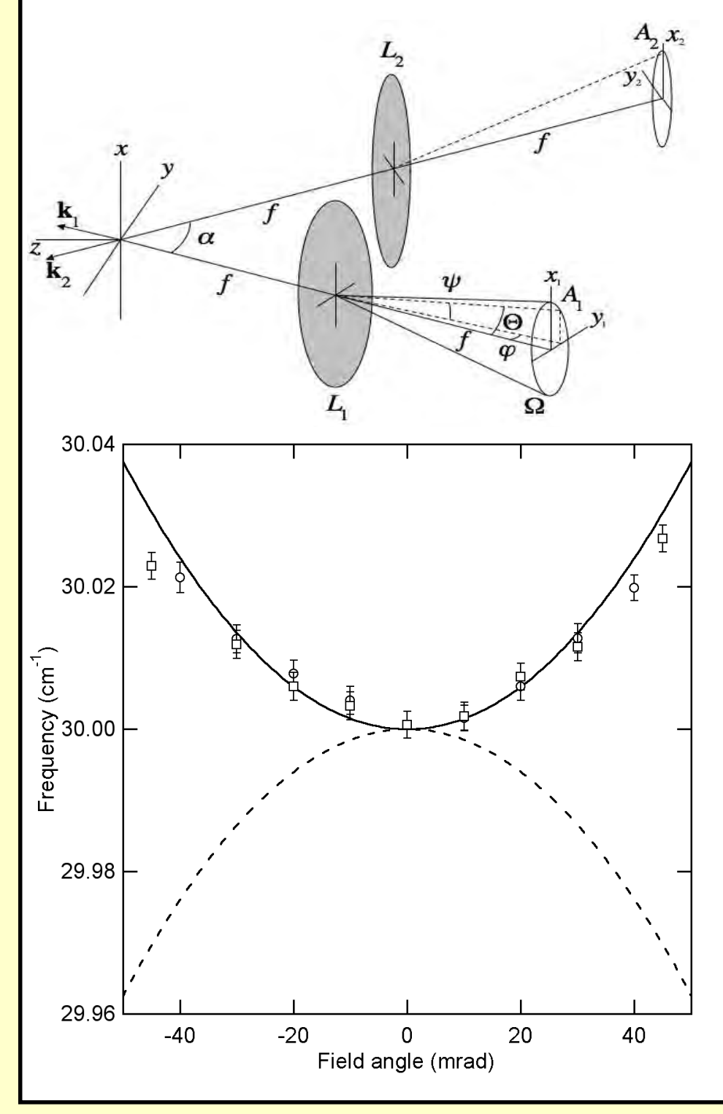
In the past the static interference pattern in the visible was recorded using a photographic plate and the Fourier transform was performed with a lens in analogy to the holographic experiments - hence the name.

Static interference pattern is the scaled analog of the interferogram in the scanning Fourier transform spectrometer [4].

$$I(\mathbf{r}')=1/2\int_0^{\infty} d\omega I_0(\mathbf{r}',\omega)\left[1+\cos\left(\frac{\omega}{c}y'2\sin\frac{\alpha}{2}\right)\right]B(\omega)$$

- No restriction on the object size – ultimate throughput!
- No need for large elements in the array

THz interferometer

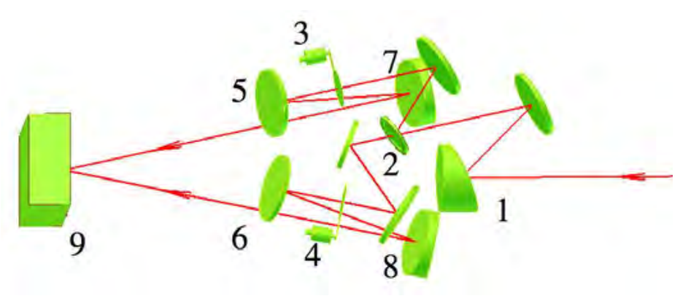


- Realistic detector array size dictates large field angles in the THz
- By dividing the Fourier optics into independent components in each arm of an interferometer aberrations are dramatically reduced
- Tilt interferometer has more symmetric optics compared to the shearing interferometer so aberrations are easier to control [5].

Figures on the left show: top - simplified geometry for a tilt interferometer based holographic FTS; bottom - the frequency shift for oblique directions φ (in plane) and ψ (out of plane) determined from ray tracing. Dashed line: the scanning FTS theoretical curve.

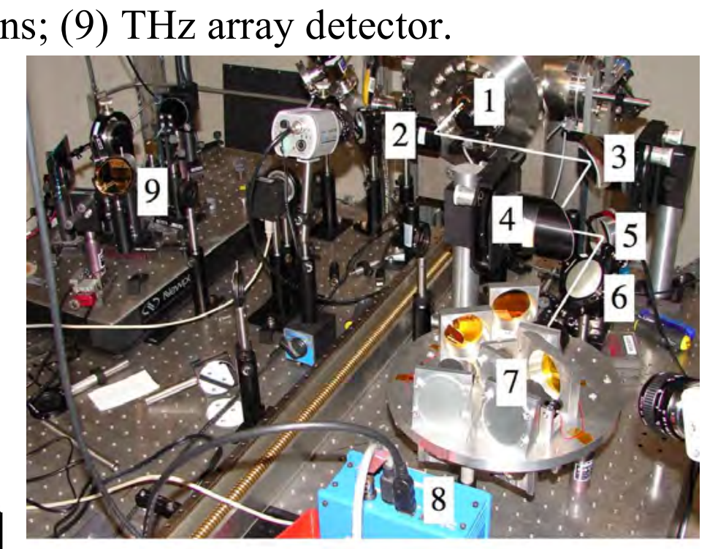
THz holographic FTS

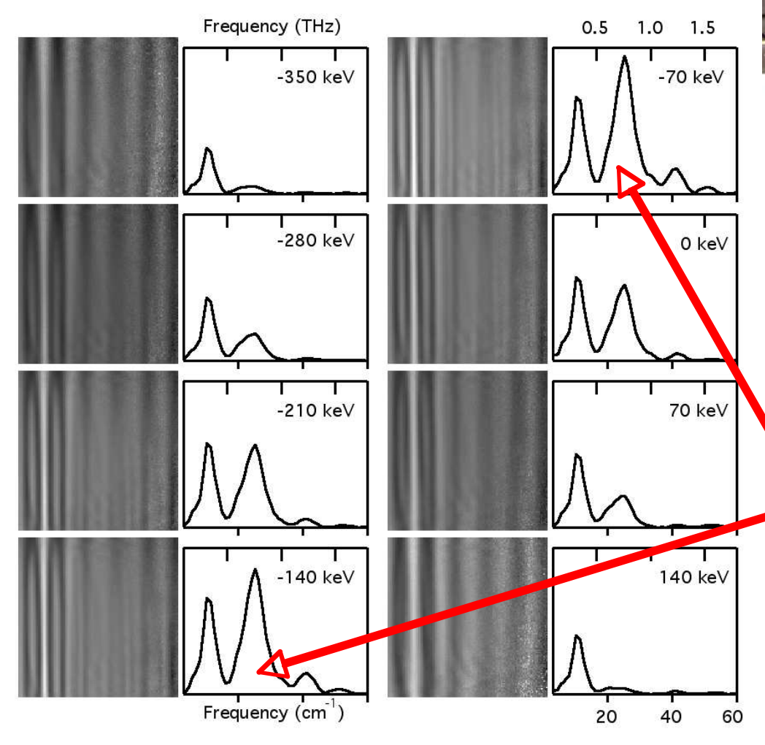
Experimental tests of the new THz HFTS instrument were performed using coherent synchrotron radiation produced in the energy recovery linac of the free electron laser facility at Jefferson Laboratory.



In the optical schematic to the left: (1) 45° off-axis parabolic mirror – fore optics; (2) wire grid beamsplitter; (3,4) shutters; (5,6) tilted mirrors; (7,8) 30° off-axis parabolic mirrors - analog of the Fourier transform lens; (9) THz array detector.

In the photograph of the experimental setup at JLab: (1) diamond mirror of the THz beamline; (2) parabolic collimator; (3,4) pair of parabolic mirrors forming the intermediate focal position; (5) flat mirror; (6) flip mirror; (7) THz interferometer; (8) THz array; (9) EO setup.



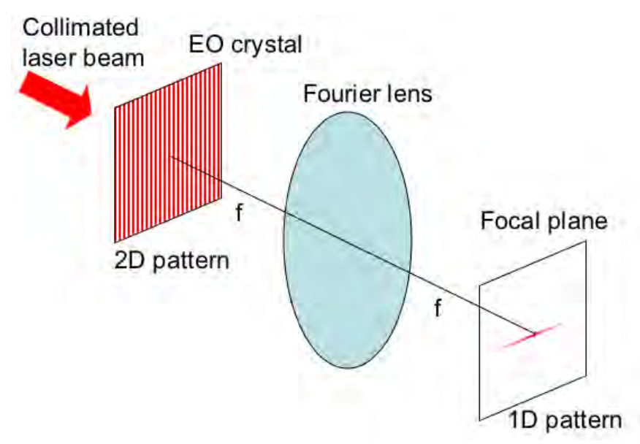


Examples of normalized static interference patterns and corresponding spectra are shown to the left. Detuning of the bunch energy by changing the gradient field in the RF cavities varied the electron bunch length.

- The stronger and broader spectra are observed for shorter bunches
- Periodic oscillations in the spectra were produced by the THz array detector construction [6]

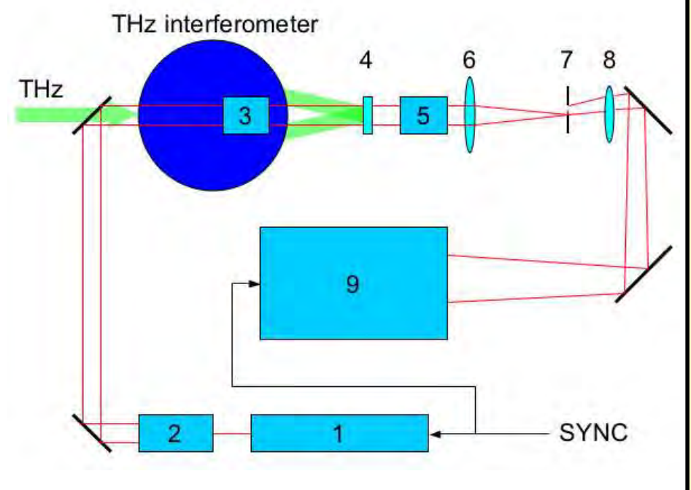
THz HFTS with EO detection and optical Fourier transform

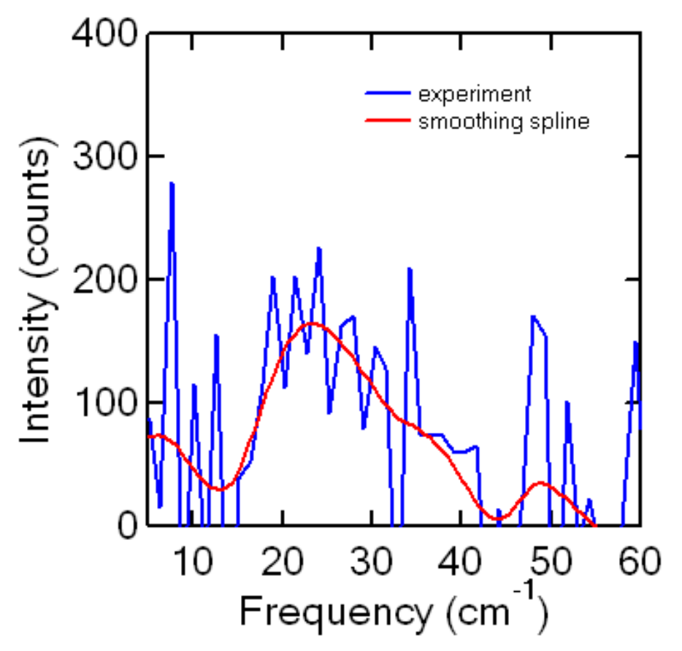
The absence of the spectral grade THz arrays requires the use of the EO effect to detect the static interference pattern in the THz HFTS. By using an optical Fourier transform a pulsed diode laser can be used instead of a synchronized femtosecond laser.



The idea is illustrated in the picture to the left. The laser beam samples the 2D interference pattern produced inside the EO medium by the THz field. The Fourier transform lens converts the 2D pattern into the 1D spectrum across the visible camera.

Benefits are presence of the signal only during the THz pulse and its concentration in 1D improving the signal-to-noise ratio. Setup is shown to the right. It consists of the pulsed diode laser (1), beam expander (2), crossed polarizers (3, 5), EO crystal (4), Fourier transform lens (6), aperture (7), magnifying lens (8) and camera (9).



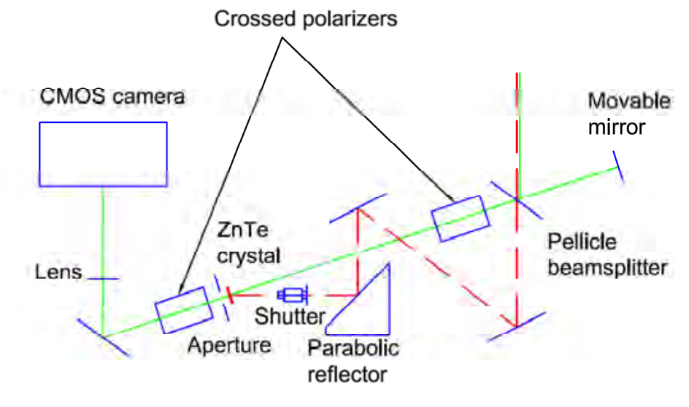


Results from our experiments at DESY (figure to the left).

- Accumulated 1000 pulses
- Main source of noise – scattering at optical inhomogeneities of the EO crystal
- For a single shot a diode laser with peak power > 1W and pulse duration shorter 100 ps is needed

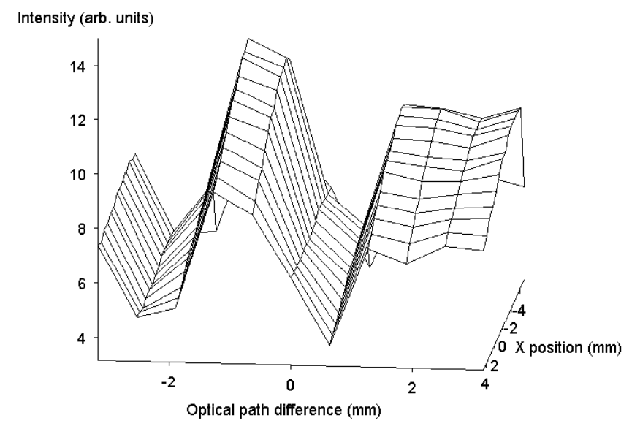
Coherent/incoherent pulse EO overlapping for bunch length measurement

By overlapping both THz coherent and the visible incoherent pulses inside the EO crystal a simple self-contained bunch shape analyzer can be realized.



The setup of the proof-of-principle experiment at JLab is shown in the figure to the left. Time dependences of both THz and visible pulses are related to the shape of the bunch. The delay dependence of the signal gives the autocorrelation function.

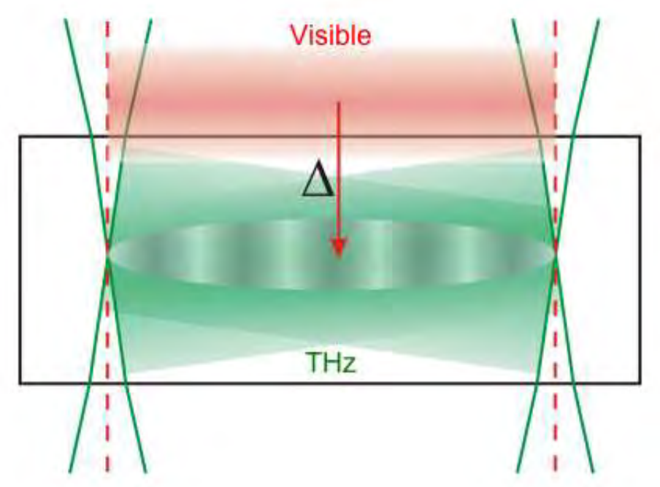
Result of this experiment is shown below. The horizontal axis shows the delay between the coherent and the incoherent pulses. The other axis gives shift in the vertical position related to the bunch transverse size.

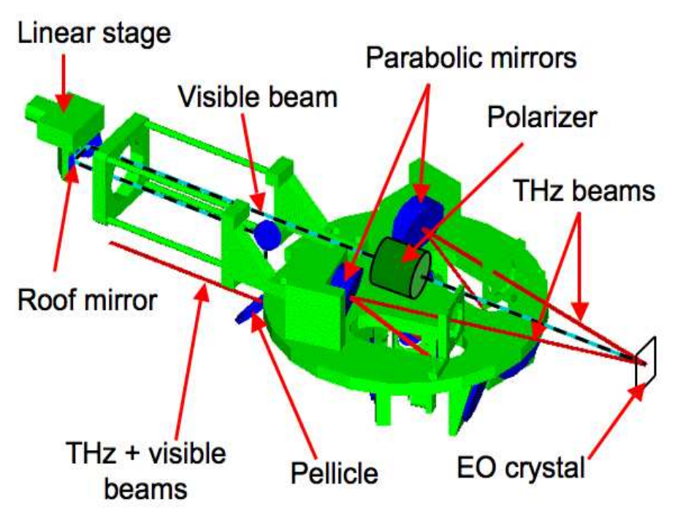


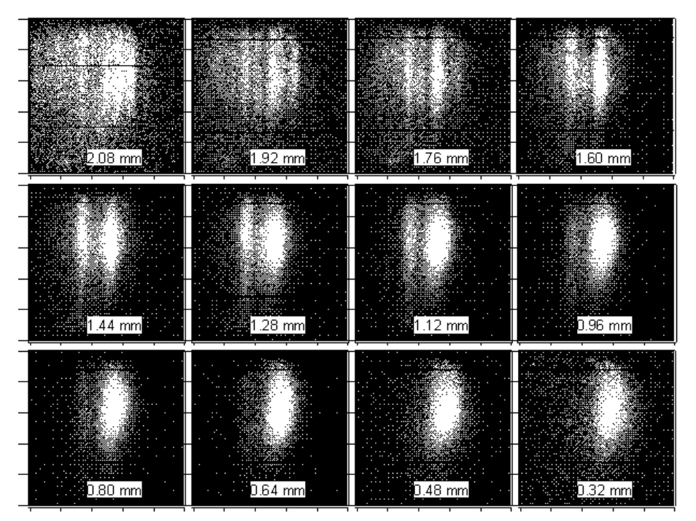
- Preliminary results confirm the idea
- Effects of crystal dispersion on the EO response function should be investigated.

EO sampling using incoherent radiation from the same bunch

The overlap of the coherent THz radiation with the incoherent visible light can also be used to detect the THz HFTS interference pattern. This idea is illustrated in the figure to the left. Two THz pulses produced by the interferometer overlap inside the EO crystal and produce the moving 3D interference pattern. The visible incoherent pulse is sent perpendicular to the crystal. Polarization change in the visible beam corresponds to the electric field distribution of the THz interference pattern and it is observed through crossed polarizer and an imaging system with a CCD camera. The delay Δ between the coherent and the incoherent pulses can be varied using the linear stage as shown in the figure to the right. This enables detection of the pulse asymmetry since the THz interferogram changes depending on the delay, reflecting spectral properties of different slices of the coherent pulse.

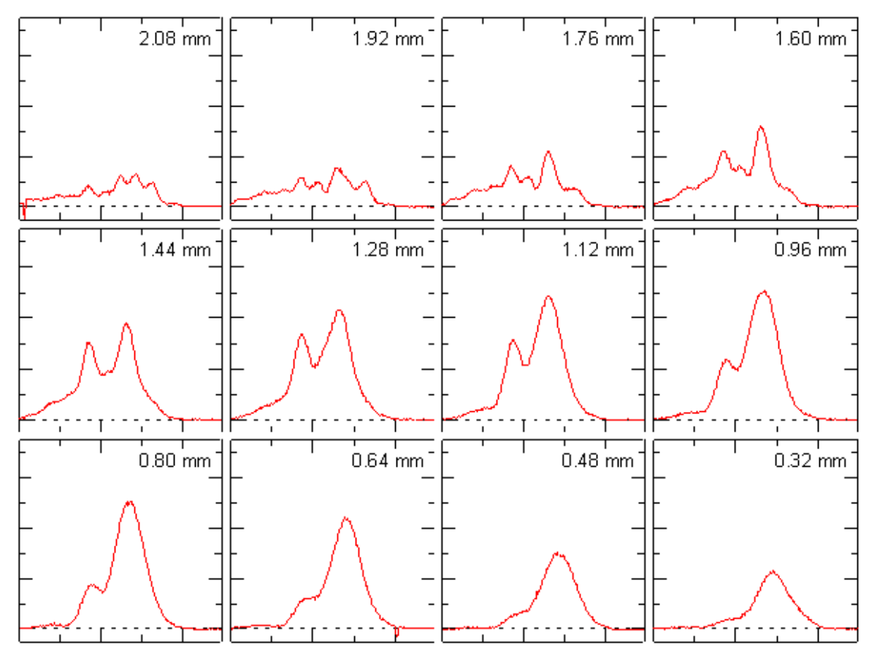






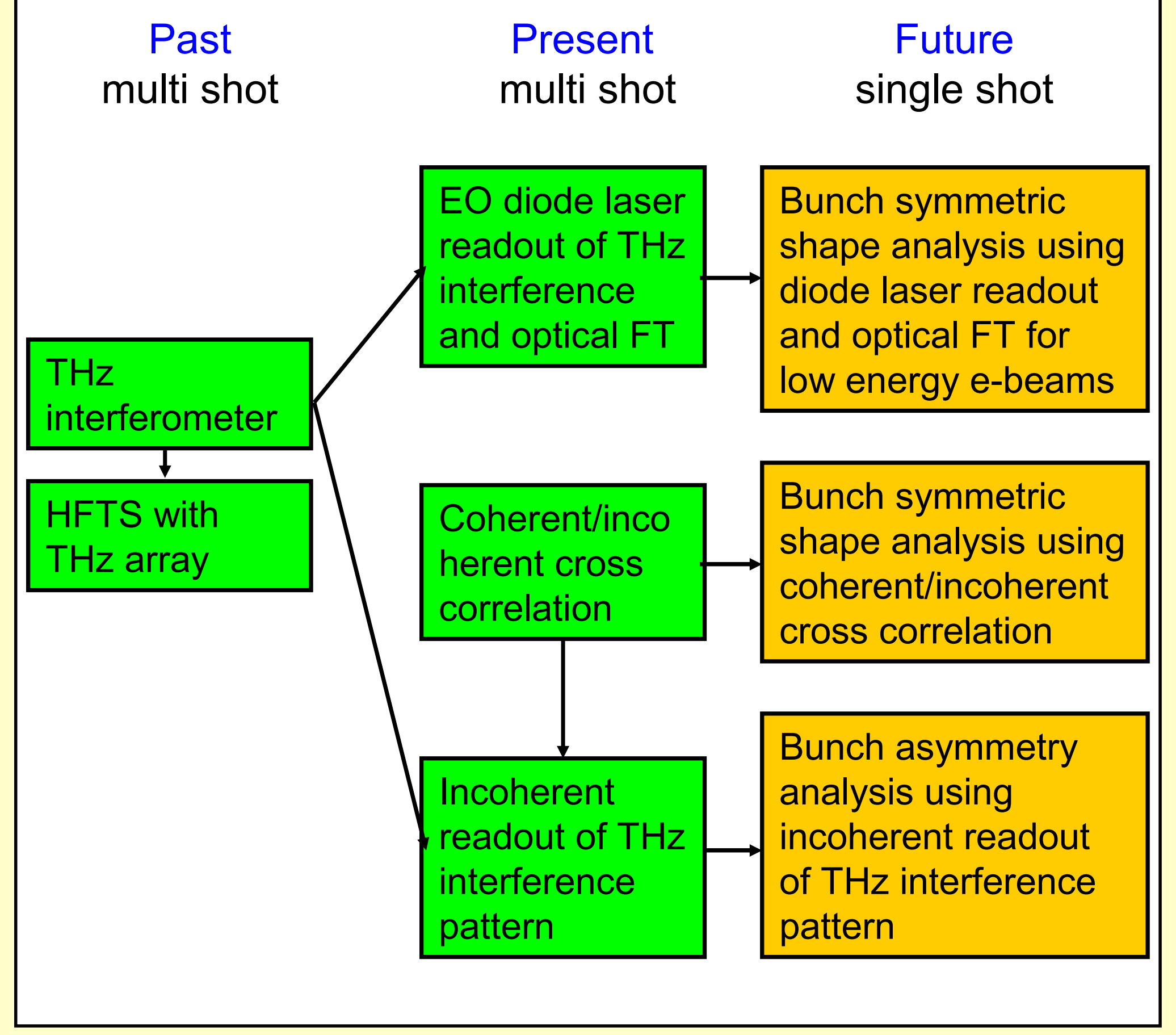
Currently the bunch asymmetry extraction from the coherent spectrum measurement relies on using the Kramers-Kroning dispersion relations. But since this method only works for packets of Gaussian shapes it cannot be used as a general method for asymmetry determination. The ability to sample the spectral time dependence of the coherent pulse is an analog of the frequency resolved optical gating (FROG) technique used for complete characterization of femtosecond laser pulses [7].

The preliminary experiment was conducted at JLab. In the figure above is shown the EO signal dependence on the delay Δ between the coherent and the incoherent pulses. At first the visible pulse is behind the THz pulse and with decreasing delay (corresponding to frames from the right bottom to the left top) the interference pattern becomes visible and is progressively displaying the spectral time evolution of the coherent pulse. From the EO signal images were calculated the interferogram signals shown to the right. The higher frequencies visible in the front part of the THz pulse point to a more structured bunch leading edge shape compared to its smoother tail.



- Experimental results confirm idea.
- No synchronized laser
- Single shot possible
- Asymmetry capable

Timeline



Past
multi shot

Present
multi shot

Future
single shot

THz interferometer

HFTS with THz array

EO diode laser readout of THz interference and optical FT

Coherent/incoherent cross correlation

Incoherent readout of THz interference pattern

Bunch symmetric shape analysis using diode laser readout and optical FT for low energy e-beams

Bunch symmetric shape analysis using coherent/incoherent cross correlation

Bunch asymmetry analysis using incoherent readout of THz interference pattern

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Acknowledgments

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