A Temporal Diagnostic with 10 fs Resolution

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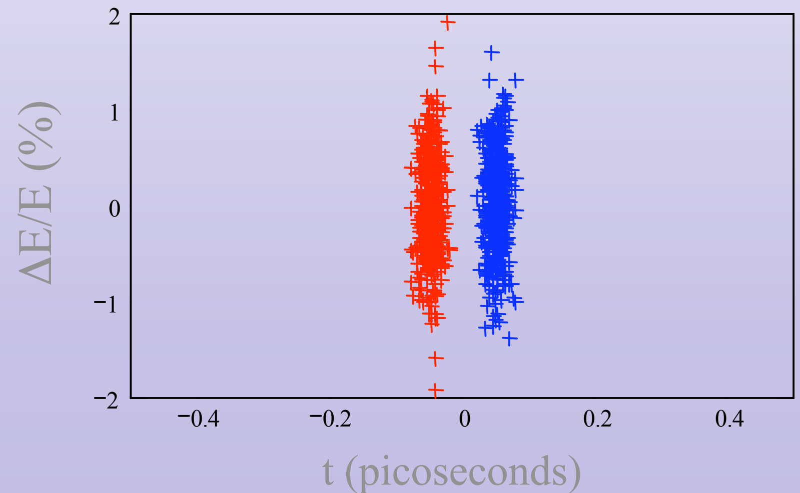
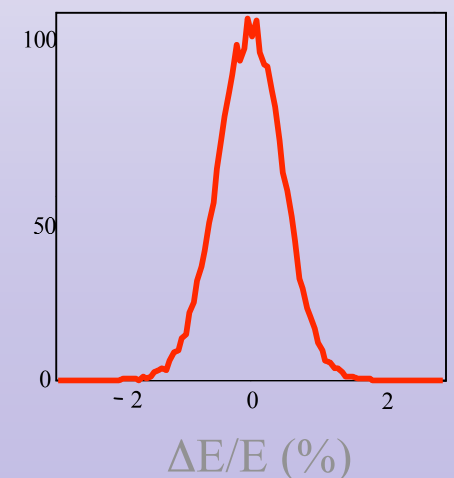
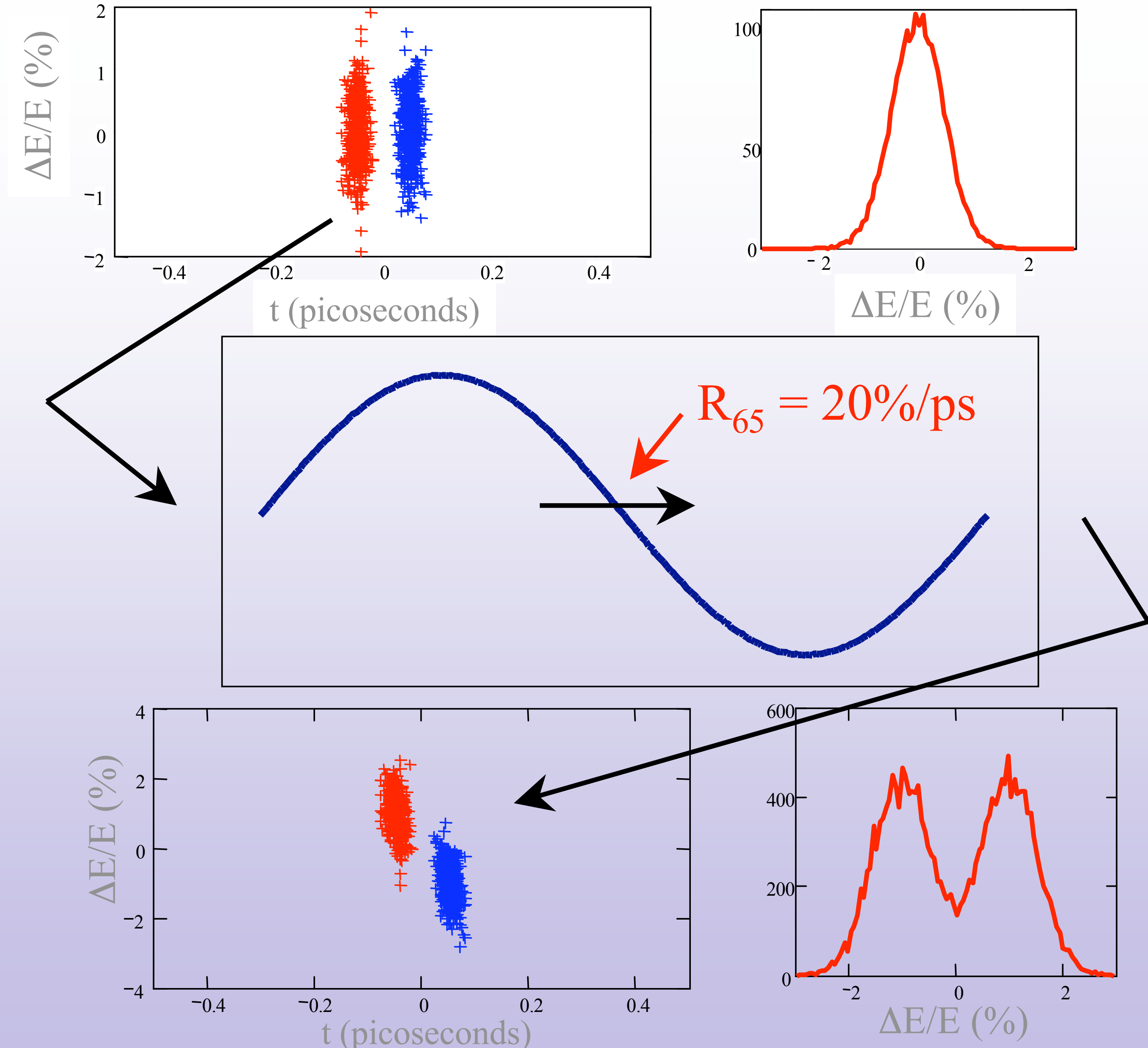
An established method of measuring the temporal profile of a beam is to pass it through an accelerator cavity phased so that particles experience an energy gain proportional to their arrival time at the cavity. A simple energy spectrometer can then be used to measure the time coordinate.

Suppose we want to resolve two ‘beamlets’ with a 1% energy spread and separated in time by 100 fs.

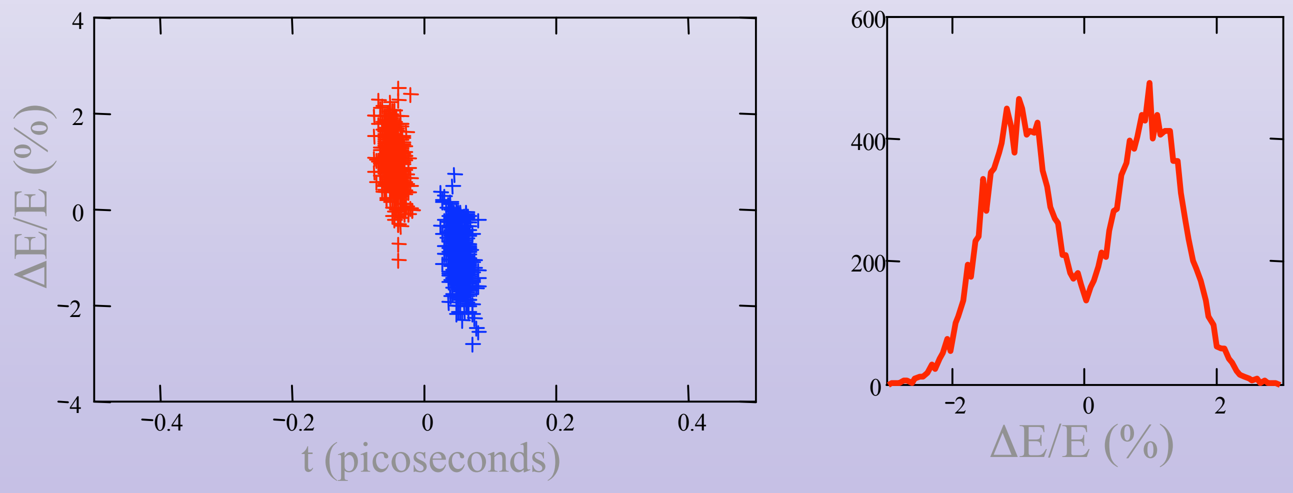






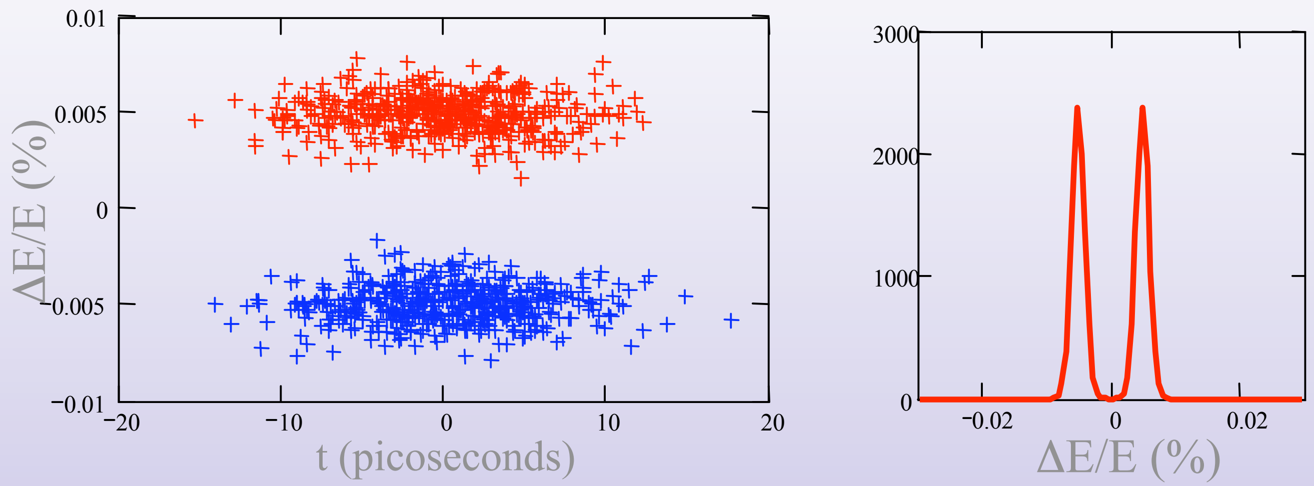
An energy spectrometer can now see each of the beamlets.

The problem is that if the beam energy is 100 Mev, and the cavity frequency is 1.3 GHz then the accelerating voltage required to produce this R_{65} is 2 GeV!



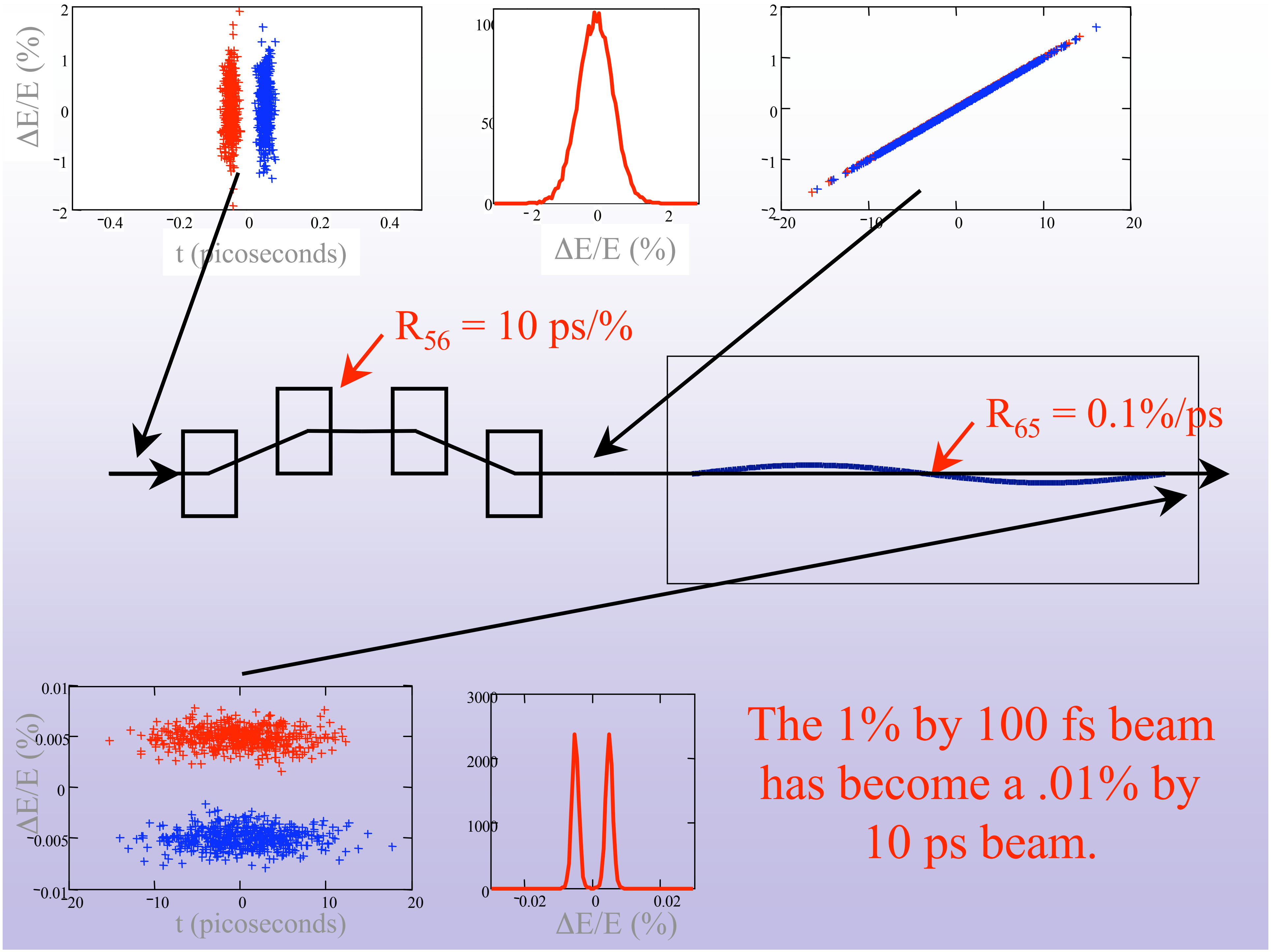
Enhanced technique

- Pass the beam through a chicane with an R_{56} of 10 ps/% (typical of those used in FELs) and then through an accelerator cell with an R_{65} of only 0.1%/ps. The phase space distribution becomes:

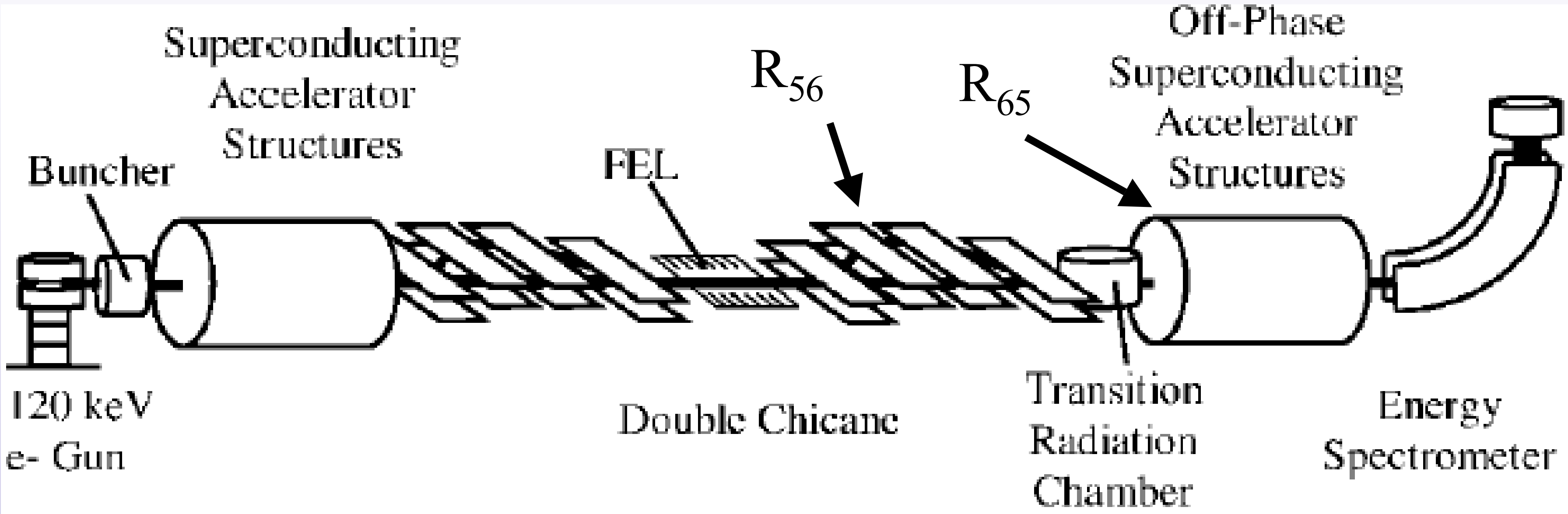


- The beamlets are now fully resolved. The production of this R_{65} requires only a 10 MeV, 1 GHz accelerator cell-a factor of 200 reduction from the previous example.

- The 1% by 100 fs beam is now a .01% by 10 ps beam.


ΔE/E (%)
t (picoseconds)
ΔE/E (%)
R_{56} = 10 ps/%
R_{65} = 0.1%/ps
ΔE/E (%)
t (picoseconds)
ΔE/E (%)
The 1% by 100 fs beam has become a .01% by 10 ps beam.

- Theory is good, but experiment is better. Our superconducting linac/FEL system just happens to be configured in just the right way to test the enhanced temporal resolution concept.

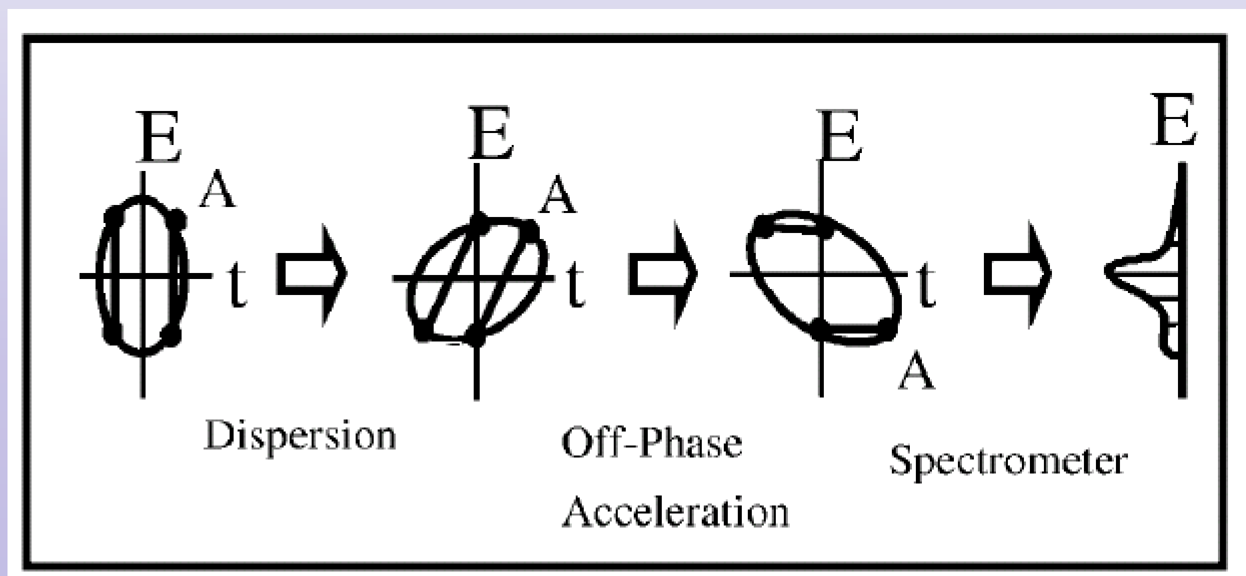


- The results of an experiment to observe the microbunching expected to be imposed by the beam-FEL interaction are shown on the next slide. A temporal resolution of better than 150 fs was demonstrated.

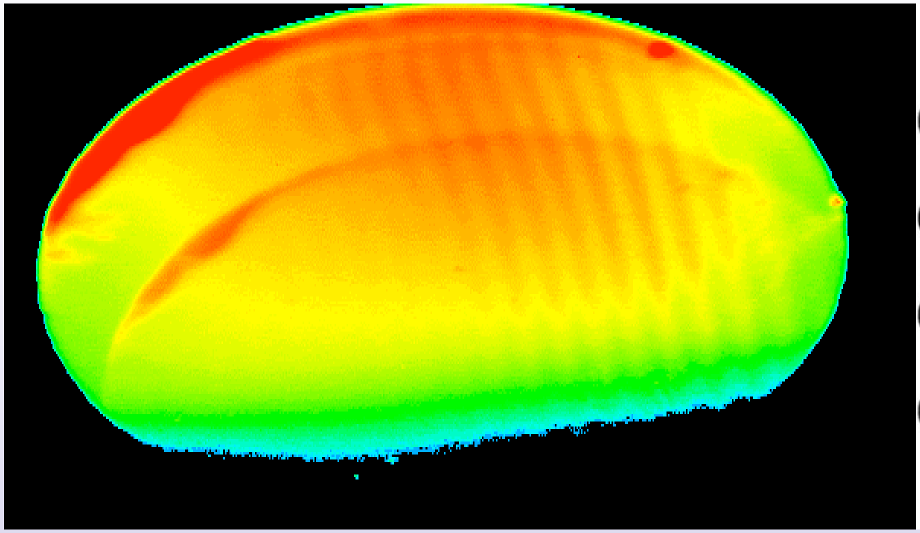
Using TRANSPORT notation the process can be described to first order by:

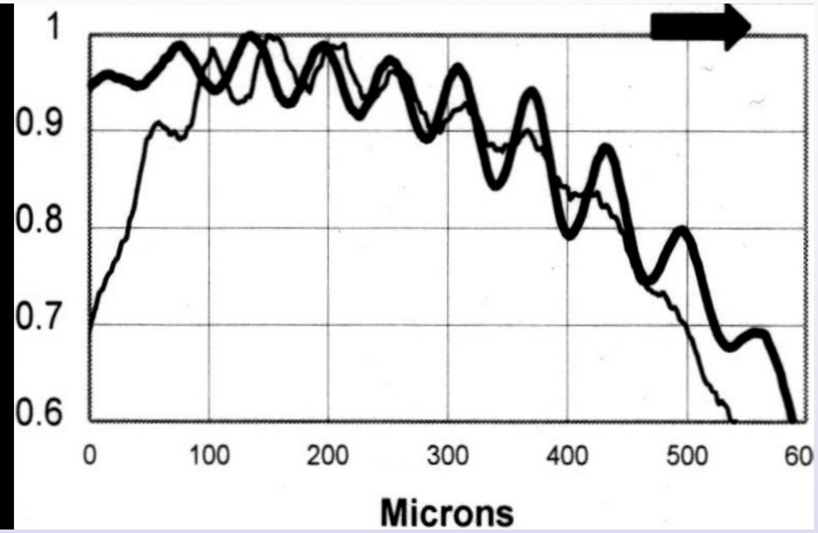
$$\begin{pmatrix} t \\ E \end{pmatrix}_1 = \begin{pmatrix} 1 & R_{56} \\ R_{65} & 1 + R_{56}R_{65} \end{pmatrix} \begin{pmatrix} t \\ E \end{pmatrix}_0$$

Writing the output energy coordinate explicitly,

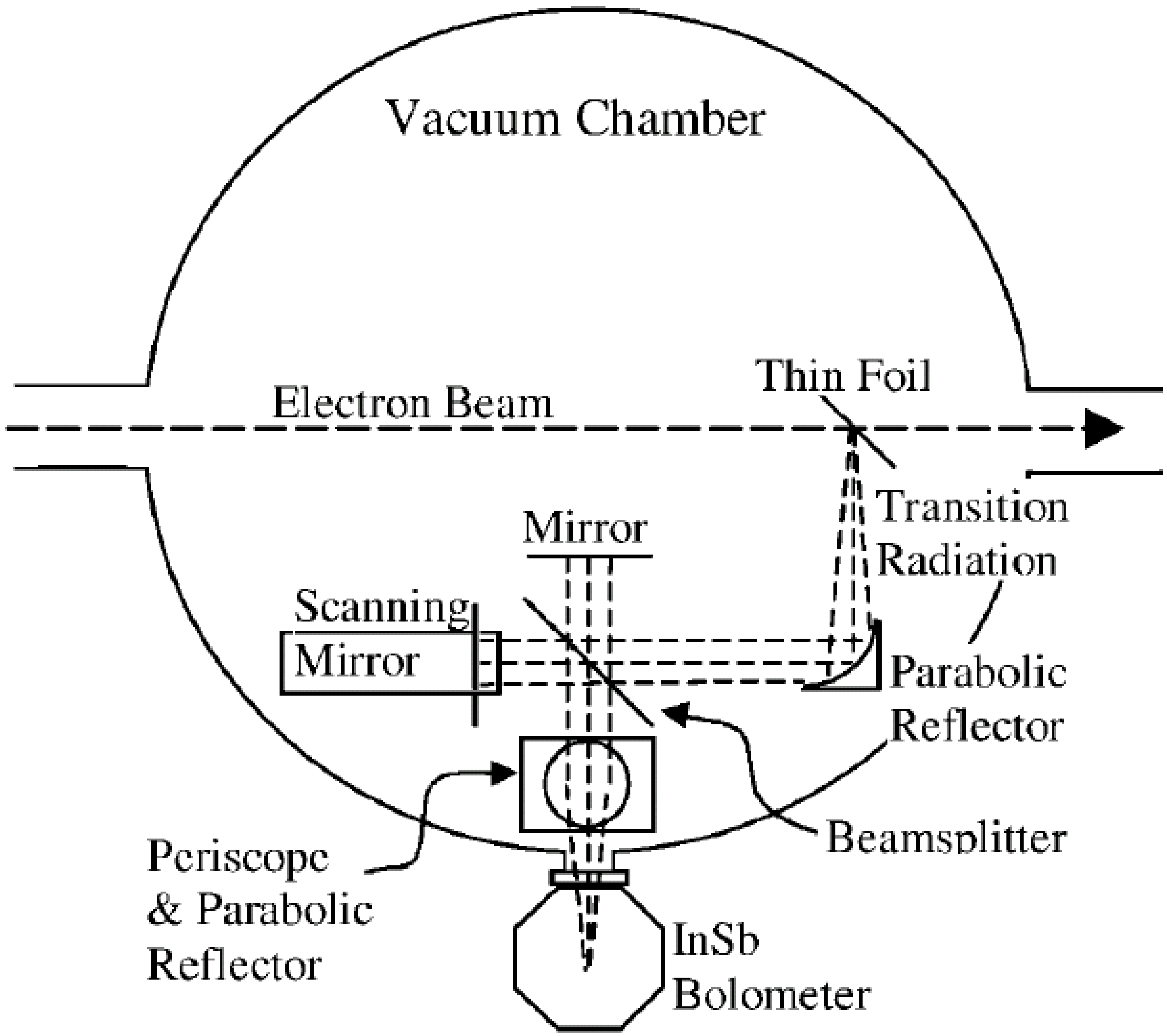


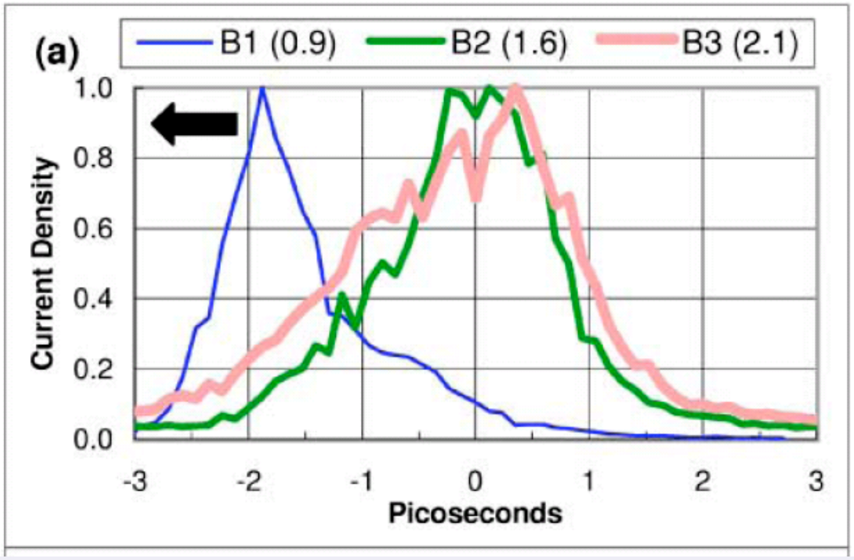
First observation of electron microbunches at the exit of an FEL

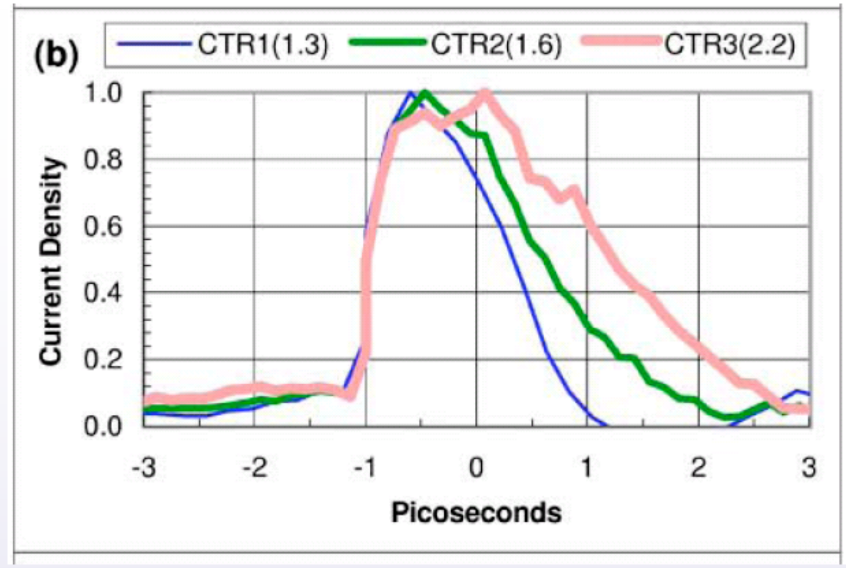




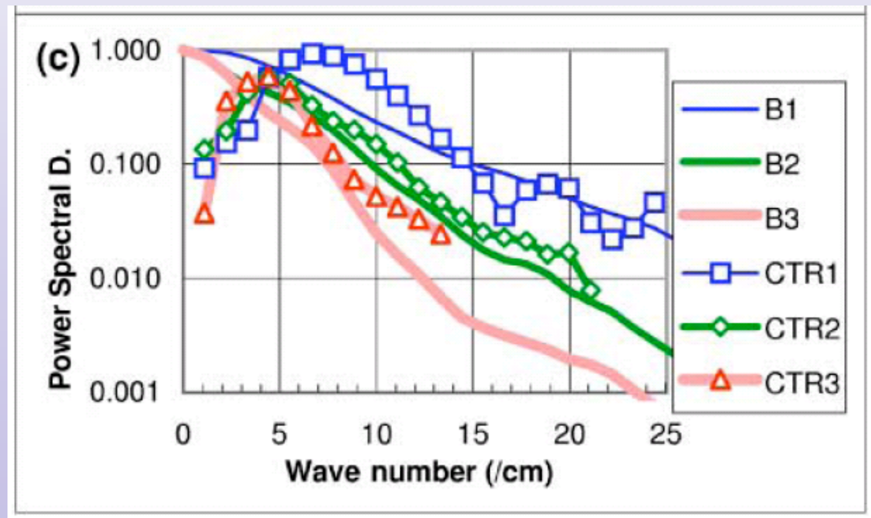
False-color image of a microbunched electron beam generated by FIREFLY lasing at 60µm. The temporal distribution of the beam is dispersed horizontally in this energy spectrum, using the longitudinal-dispersion-phased-acceleration technique. The red arc in the image is an artifact– a reflection from the quartz window at the energy spectrometer.


Vacuum Chamber
Thin Foil
Electron Beam
Transition
Radiation
Mirror
Scanning
Mirror
Parabolic
Reflector
Beamsplitter
Periscope
& Parabolic
Reflector
InSb
Bolometer

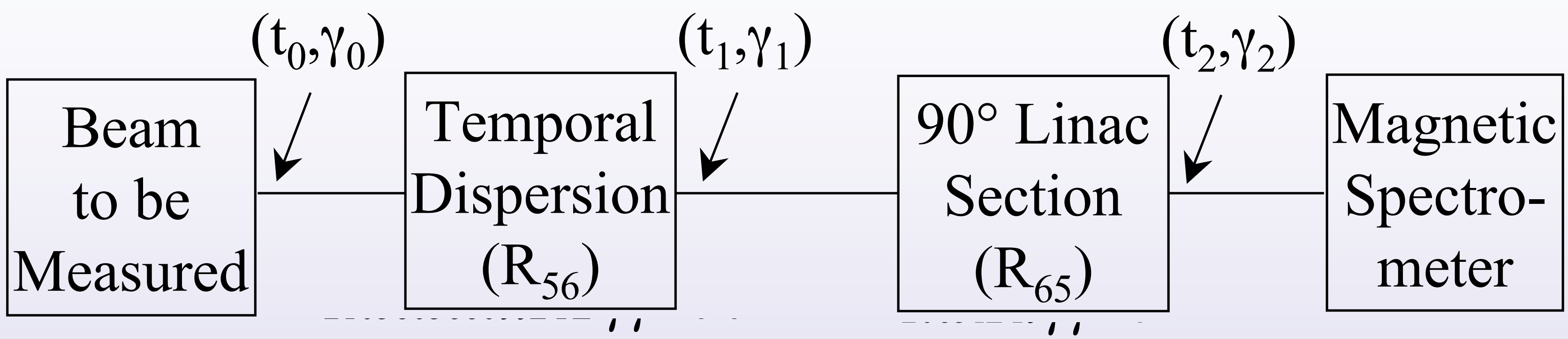




Comparison of off-phase acceleration and CTR bunch shape measurements. (a) At three different accelerator settings, bunch shapes B1, B2, and B3 were observed by the new off-phase acceleration method. The peak heights have been normalized for ease in identifying their full width at half maximum (FWHM), given in parentheses (in picoseconds) for each bunch. The black arrow in the upper left indicates the direction of bunch travel (leading edge). (b) The shapes of the same three bunches were reconstructed by a CTR spectral method, which recovered the correct length and degree of asymmetry for bunches B2 and B3, but could not distinguish between the original bunch shape and its temporal reflection. The spectral method also failed to discover the sharpness of the peak and the shallow tail of bunch B1. (c) On a log scale, the normalized numerical power spectra of measured bunch shapes B1–B3 are compared with the measured CTR spectral data CTR1–CTR3 to show how detector response may affect bunch shape retrieval.



Temporal Resolution possible with accelerator structure phased at 90°



Two specific cases of interest:

a) $R_{56} = 0 = T_{566}$ (conventional method)

b) $R_{56} * R_{65} = -1$ (enhanced method)

($T_{566} \sim 1.5\ R_{56}$)

Example: Assume a 10 GHz system, a 0.01% (.001%) spectrometer, a 10 MeV slewing section and a 100 MeV beam. Then,

$$R_{65} = -2\%/\text{mm} \quad R_{56} = 0.5\ \text{mm}/\%$$

$$\Delta t_{ideal} = (100/10)\ (10^{-10}/2\pi)\ (10^{-4}) \sim 16\ \text{fs}\ (1.6\ \text{fs})$$

	$(\Delta E/E)_b$=1%	$(\Delta E/E)_b$=0.1%	$(\Delta E/E)_b$=0.01%
Conventional $R_{56} = 0 = T_{566}$	1.6 ps 1.6 ps	161 fs 160 fs	23 fs 16.1 fs
Enhanced $R_{56}*R_{65} = -1$	28 fs 23 fs	16 fs 1.62 fs	16 fs 1.6 fs