Subpicosecond compression by velocity bunching in the DUV-FEL photo-injector at BNL

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Plan

- DUVFEL
- velocity bunching: theoretical background,
- initial conditions,
- time-domain bunchlength measurements,
- frequency-domain bunchlength measurements,
- application to TTF-II

Credits

- Haimson H., *Nucl. Instr. Meth.* **39** 13 (1966)
- Kim K.J., *Nucl. Instr. Meth.* **A 275** 201 (1989)
- Serafini L., Ferrario M., "velocity bunching in photo-injectors" AIP proceedings **581** Arcidosso workshops 2000.

Theoretical background on velocity bunching

An electron in a traveling wave accelerating structure experiences the longitudinal electric field:

$$E_z(z,t) = E_o \sin(\omega t - kz + \psi_o), \tag{1}$$

where E_o is the peak field, k the rf wavenumber and ϕ_o the injection phase of the electron with respect to the rf wave. Let $\psi(z,t) = \omega t - kz + \phi_o$ be the relative phase of the electron w.r.t the wave. The evolution of $\psi(t,z)$ can be expressed as a function of z solely:

$$\frac{d\psi}{dz} = \omega \frac{dt}{dz} - k = \frac{\omega}{\beta c} - k = k\left(\frac{\gamma}{\sqrt{\gamma^2 - 1}} - 1\right). \tag{2}$$

Theoretical background on velocity bunching

Introducing the parameter $\alpha = \frac{eE_o}{kmc^2}$, we write for the energy gradient [**?**]:

$$\frac{d\gamma}{dz} = \alpha k \sin(\psi). \tag{3}$$

The ODE system (2) and (3) with the initial conditions $\gamma(z=0) = \gamma_o$ and $\psi(z=0) = \psi_o$ is solved using the variable separation technique:

$$\alpha \cos\psi + \gamma - \sqrt{\gamma^2 - 1} = \mathcal{C} \text{ or, } .\psi(\gamma) = \arccos\left(\frac{\mathcal{C} - \gamma + \sqrt{\gamma^2 - 1}}{\alpha}\right). \tag{4}$$

$\mathcal{C} = \alpha \cos\psi_o + \gamma_o - \sqrt{\gamma_o^2 - 1}$ (set by initial conditions).

Theoretical background on velocity bunching

$$d\psi_\infty = \frac{\sin(\psi_o)}{\sin(\psi_\infty)}d\psi_o + \frac{1}{2\alpha\gamma_o^2\sin(\psi_\infty)}d\gamma_o$$

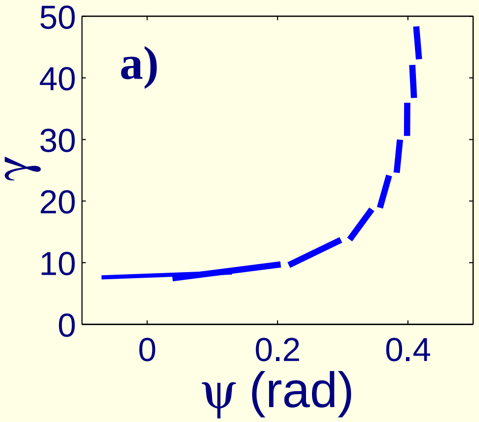
init. phase spread: $d\psi_o$

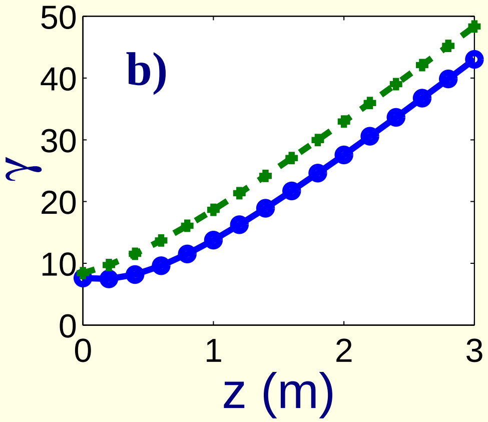
init. energy spread: $d\gamma_o$

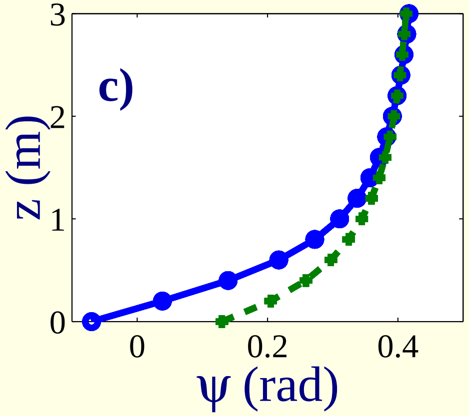
final phase spread: $d\psi_\infty$

injection phase: ψ_o

extract. phase : ψ_∞

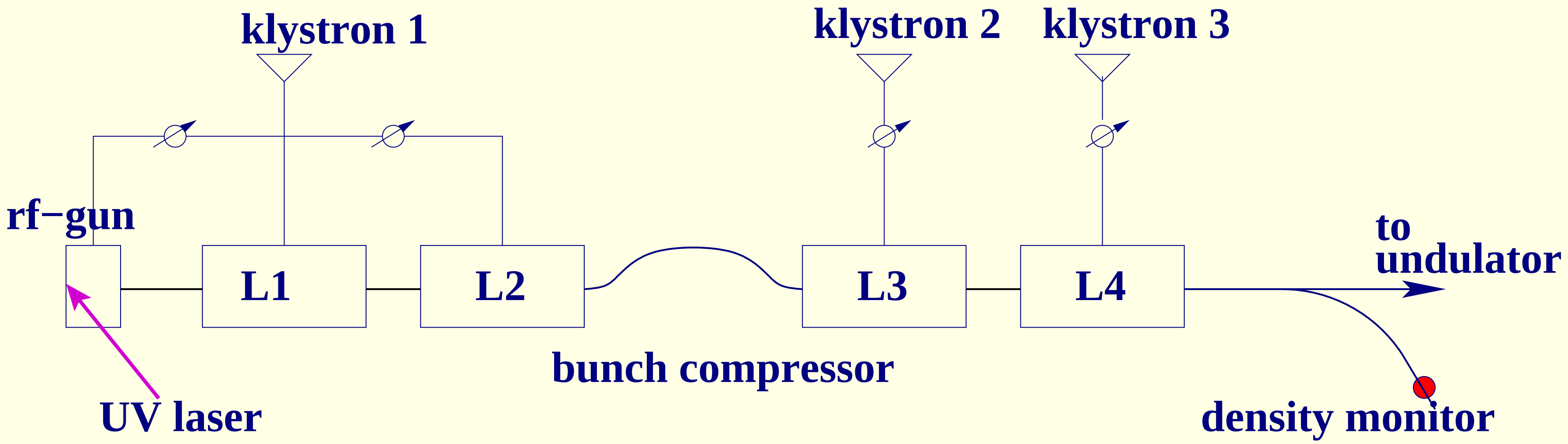






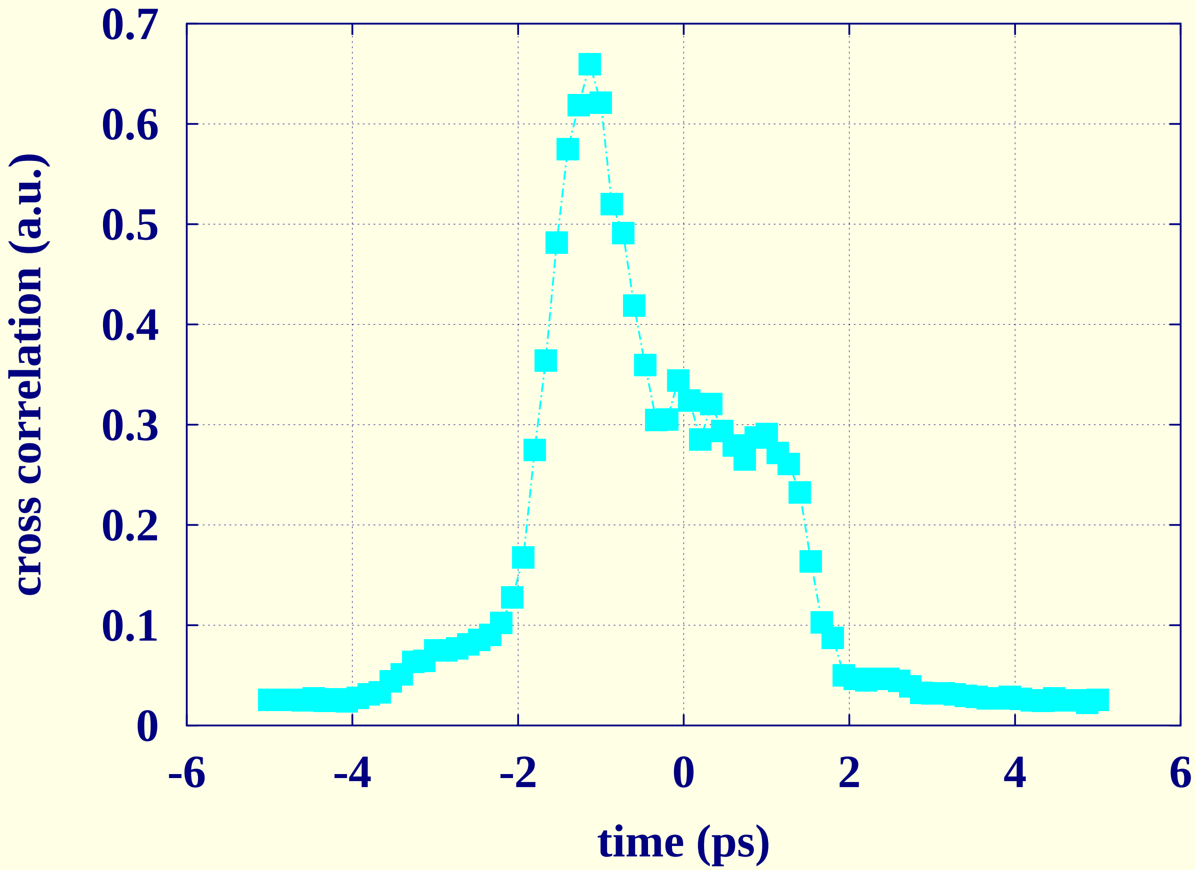
The Deep Ultraviolet FEL (DUV-FEL)

- BNL-type 1.6 cell rf-gun ($E_o \sim 100$ MV/m)
- four TW SLAC-type tank (S-band) ($\bar{G}_{rf} \sim 20$ MV/m)
- magnetic bunch compressor
- extensive and well-developped diagnostics suite



Initial conditions

- laser time-profile can be measured (single shot)
- assumed a uniform transverse profile with the measured rms values: 0.75 mm



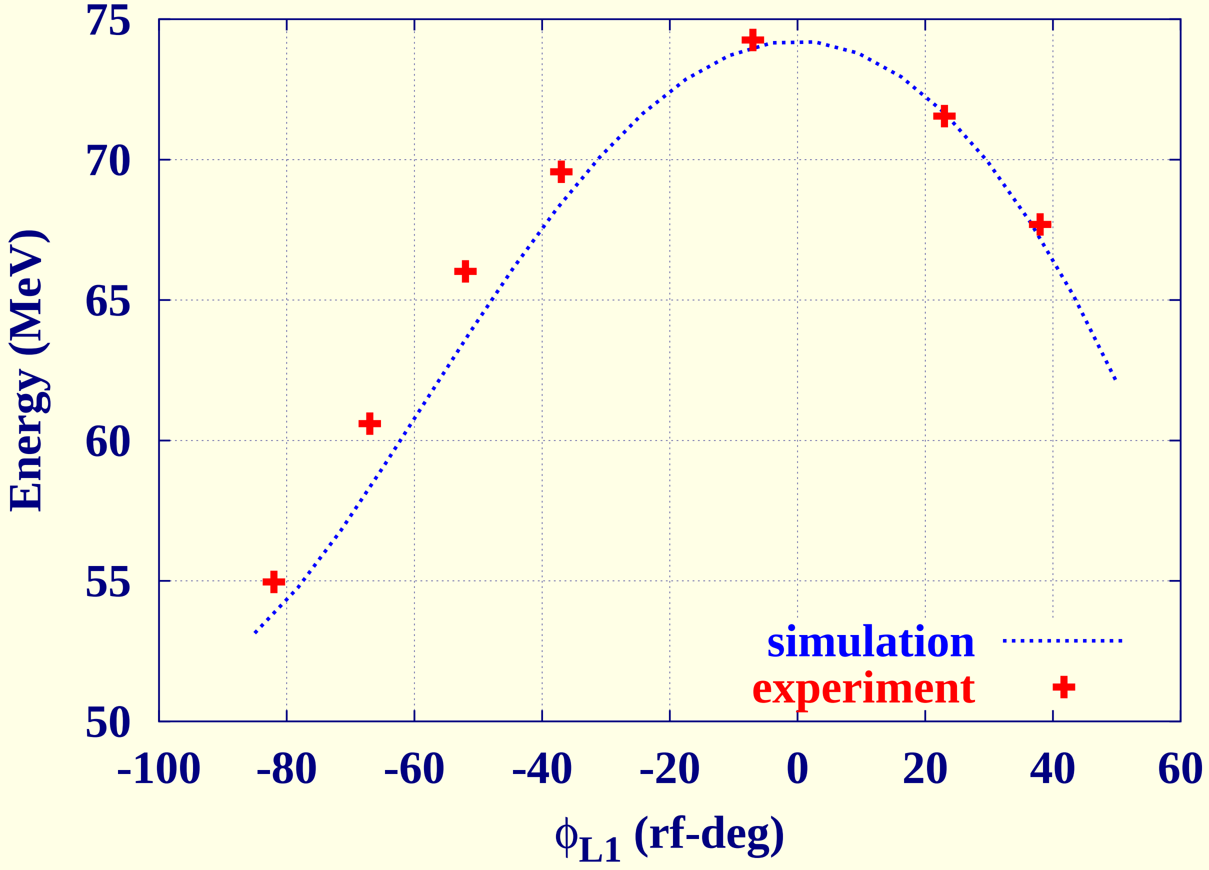
Machine conditions

parameter	value	units
bunch charge	200 ± 10	pC
laser injection phase	40 ± 5	rf-deg
laser radius on cathode	0.75 ± 0.1	mm
laser rms length	1.15 ± 0.1	ps
E-peak on cathode	83 ± 1	MV/m
L1 average accelerating field	10.5 ± 0.1	MV/m
L2 average accelerating field	13.2 ± 0.1	MV/m

Table 1: *RF and photo-cathode drive-laser settings. The values have been directly measured or inferred from beam properties.*

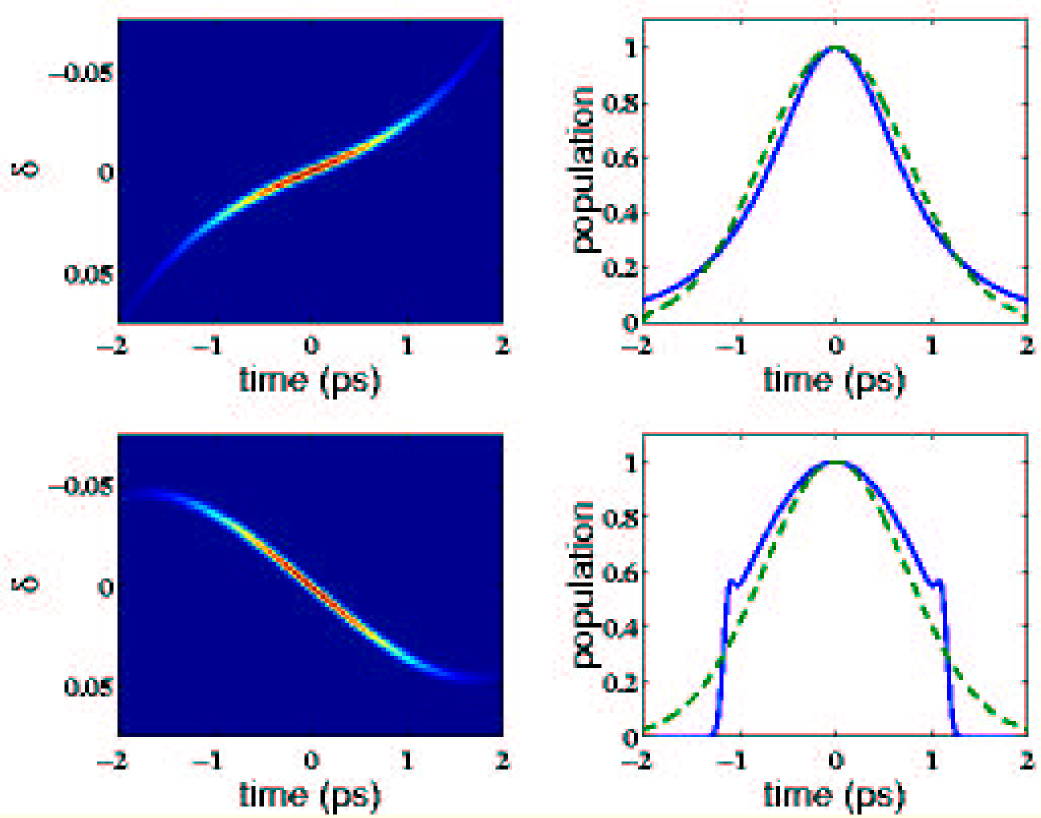
Energy versus phase of L1

- phase of linac section L1 is varied
- for each settings of L1, linac L2 is tuned for maximum energy gain
- fairly good agreement simulation/experiment



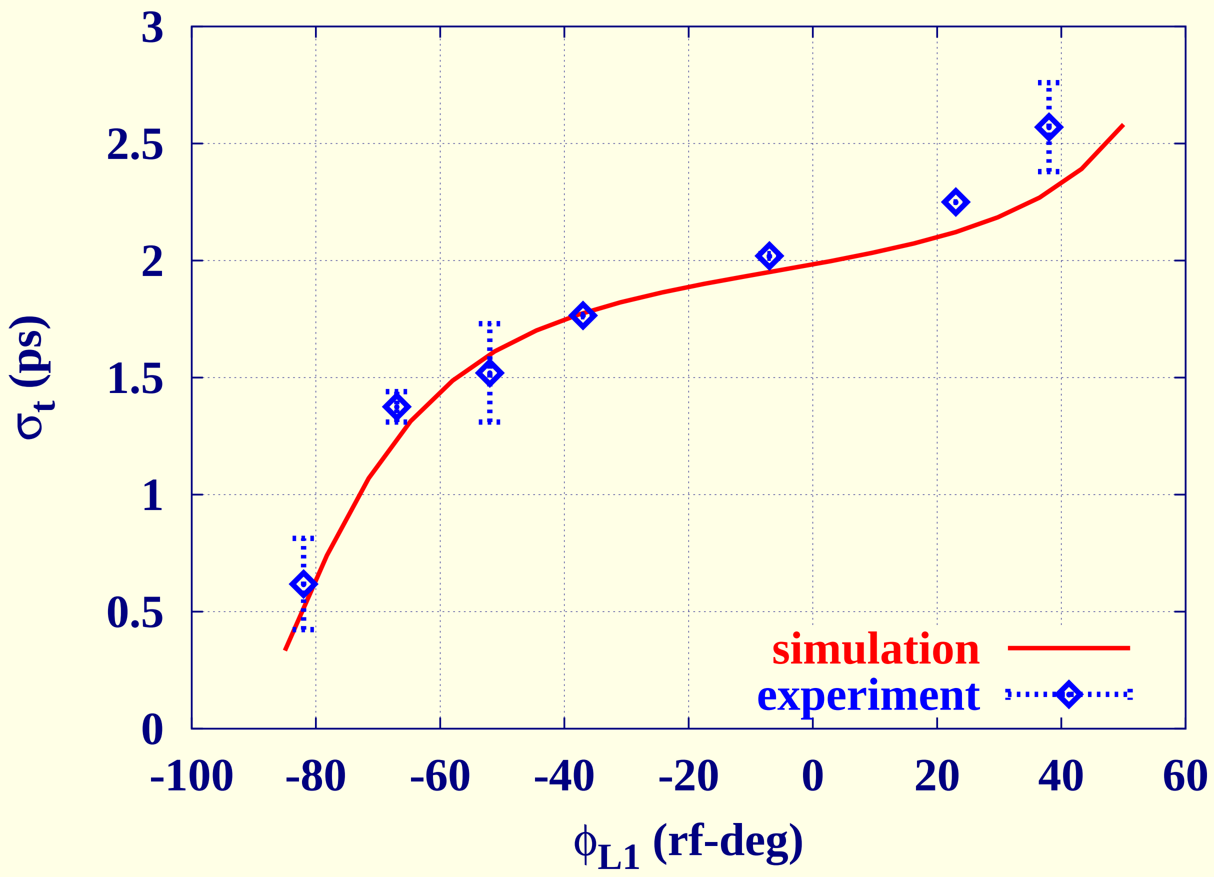
Bunch length versus phase of L1

- but long. phase space has distortions
- bunch length measured using the zero-phasing technique

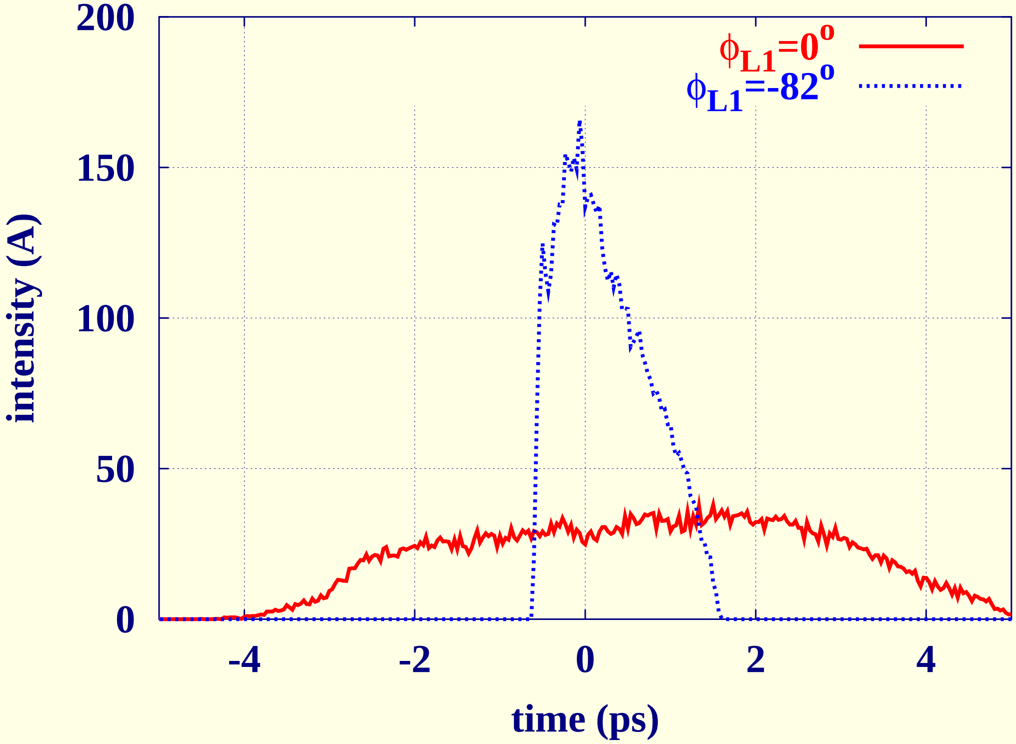


Bunch length versus phase of L1

- phase of linac section L1 is varied + L2 kept on-crest

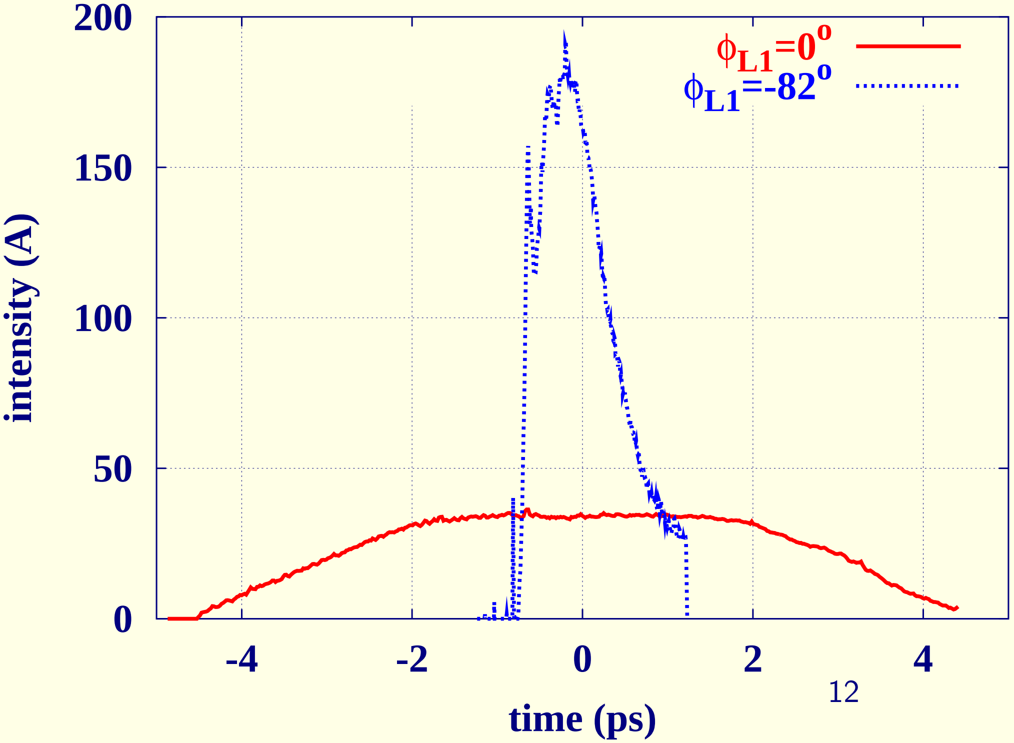


Example of time-distribution



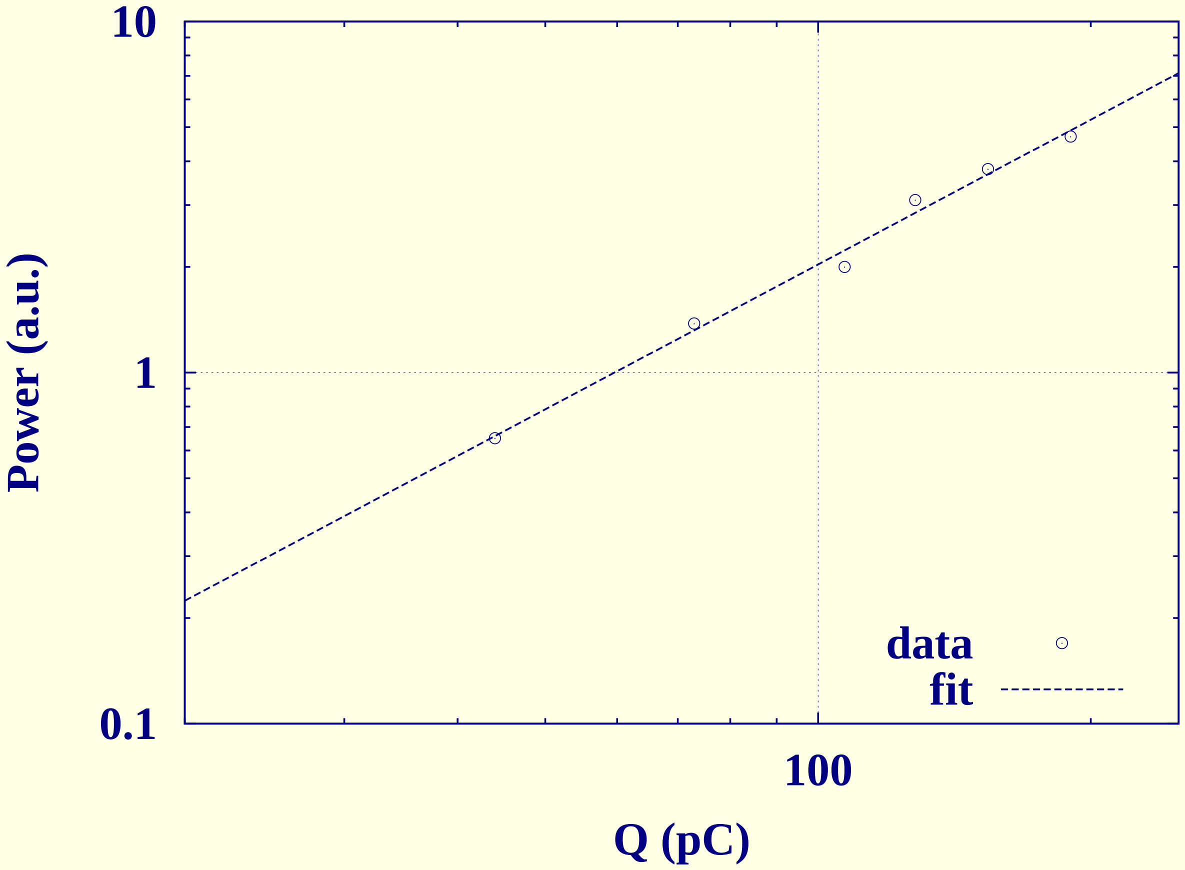
⟵ SIMULATIONS

MEASUREMENTS ⟶



Coherent radiation emitted by the bunch

- prior to L3 we detected coherent radiation (emitted via wake fields)



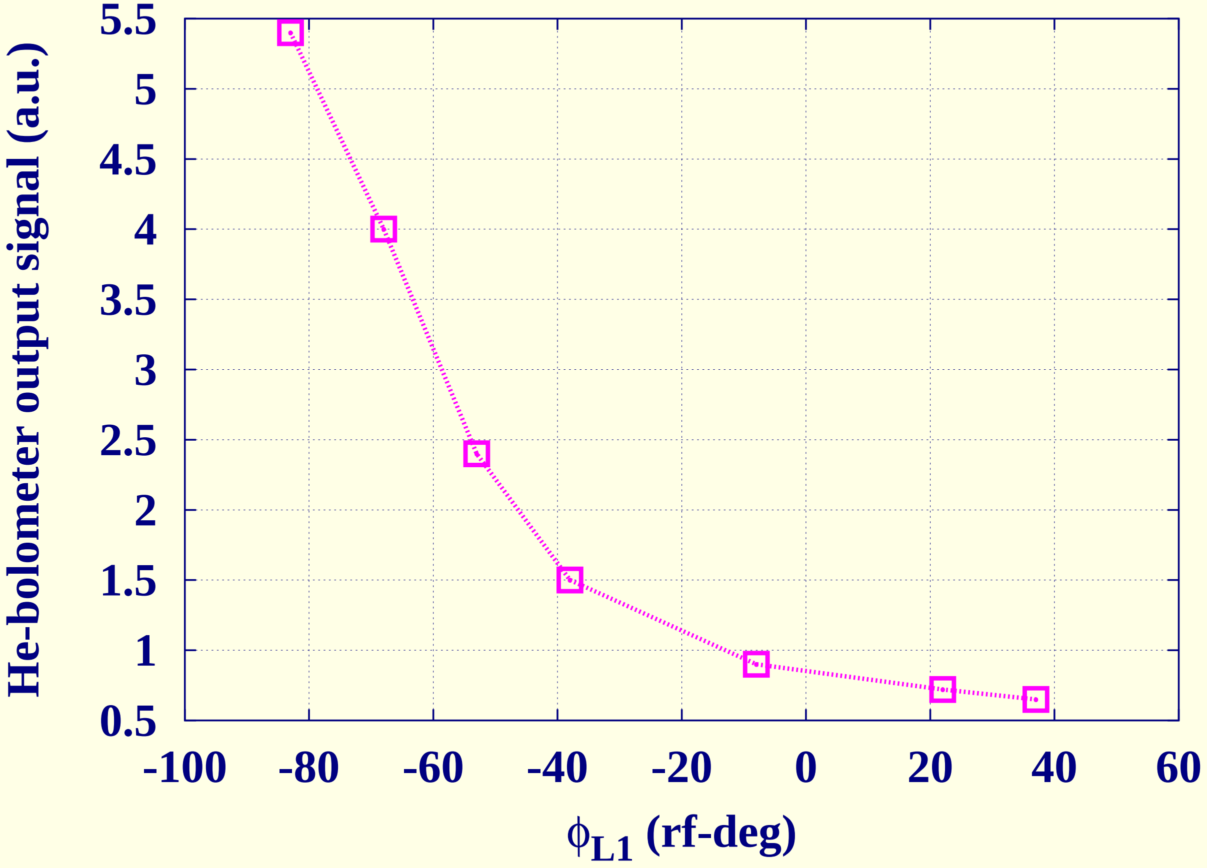
fit with $\alpha \times Q^{\beta}$

expe.: $\beta = 1.37 \pm 0.06$

simu.: $\beta = 1.57$

Coherent radiation emitted by the bunch (CNT'D)

- as expected: the signal increases as the bunch get compressed



Coherent radiation emitted by the bunch (CNT'D)

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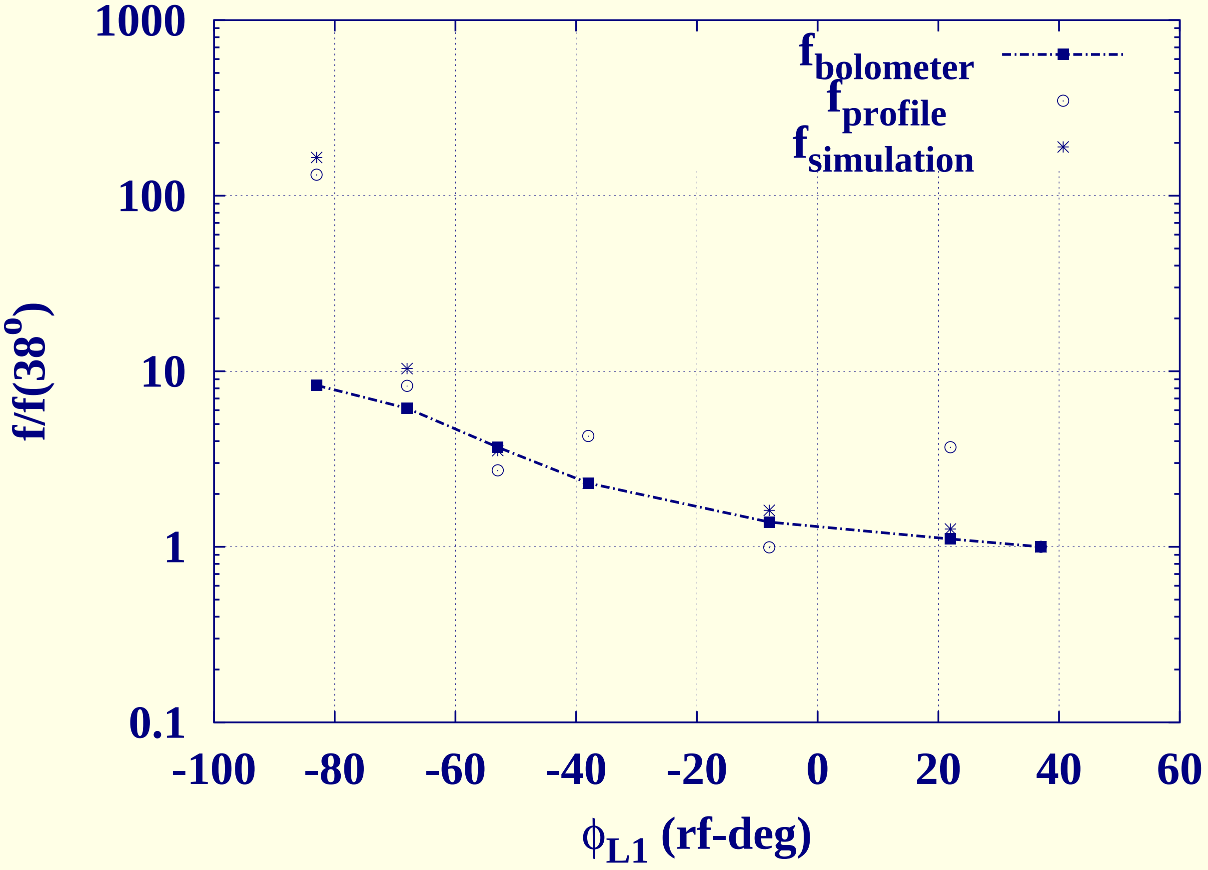
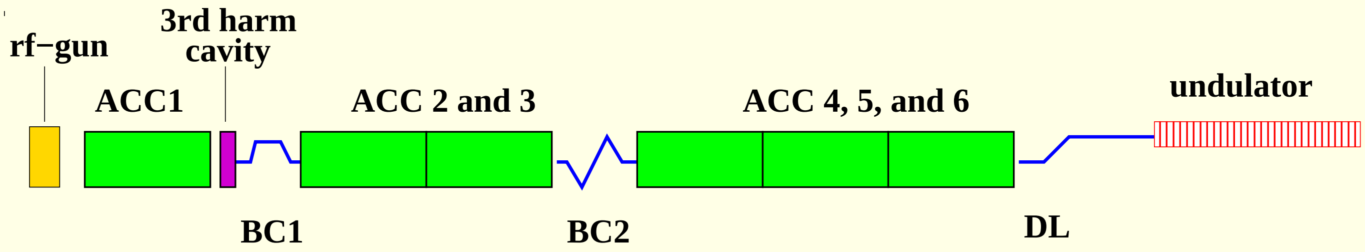
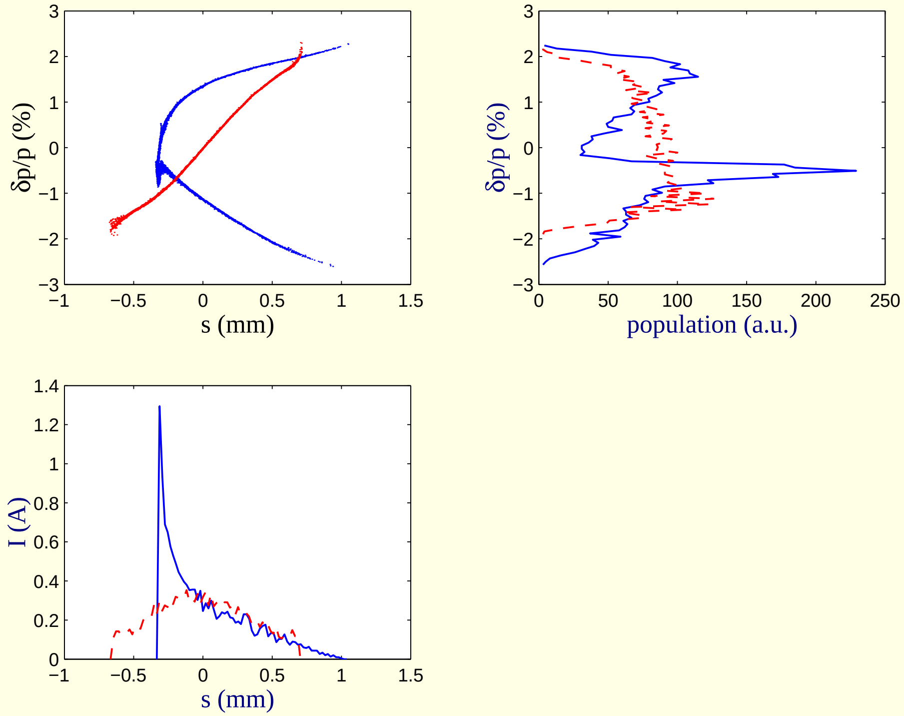


Application to TTF-II



- nominal setup uses a linearizer
- w/o linearizer CSR-driven effects in BC1 are more important



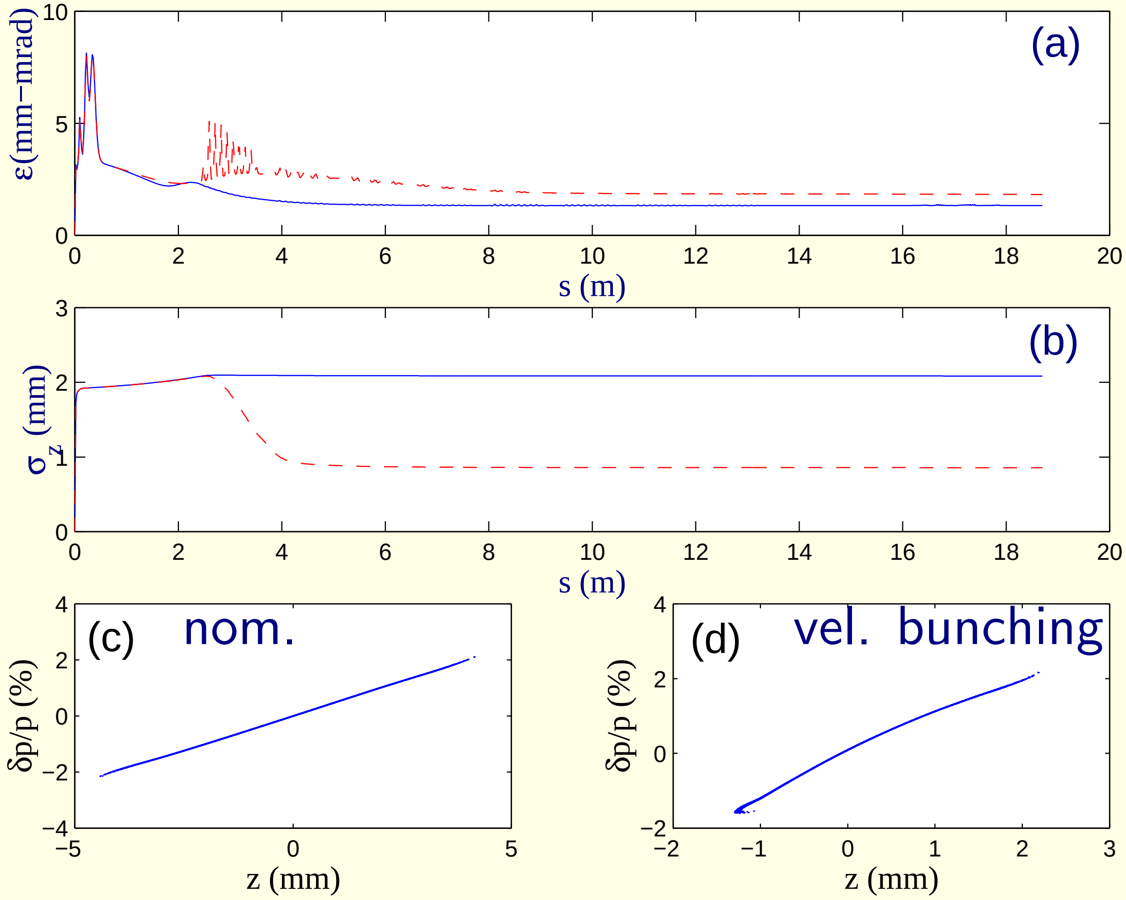
Application to TTF-II (CNT'D)

Few statements:

1. without the linearized longitudinal phase space the maximum reachable current wiil be ~ 1.5 kA
2. for such operating mode and because we want to avoid picking up too much rf-curvature, the compression has to occur in BC2,
3. (2) implies BC3 will be USELESS,
4. HOWEVER if one slighly compress using first cavity of ACC1 as an velocity buncher, we can then share the compression between BC2 and BC3; this has to be paid in term of emittance...

Application to TTF-II (CNT'D)

- idea: compress using the 1st cavity of ACC1



- blue: nom. setup
- red: vel. bunching setup