Simulations for a bunch compressor at PITZ

Study of high transformer ratios

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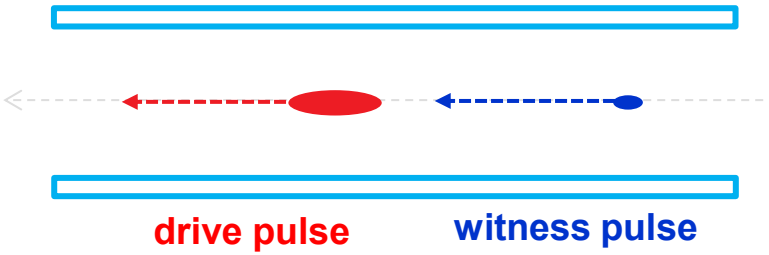
Zeuthen, 22.09.2015

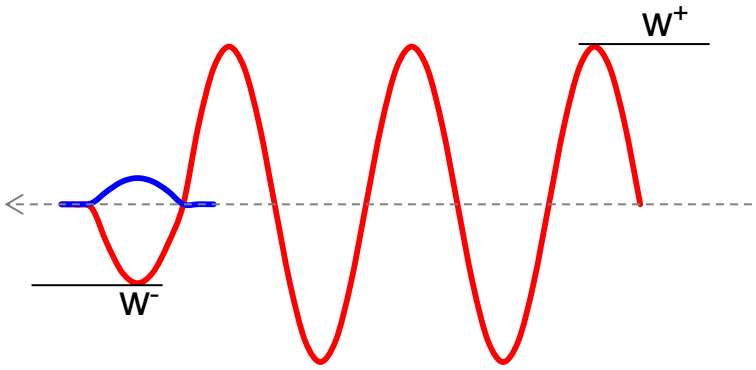
HELMHOLTZ ASSOCIATION

DESY

Transformer Ratio (TR)



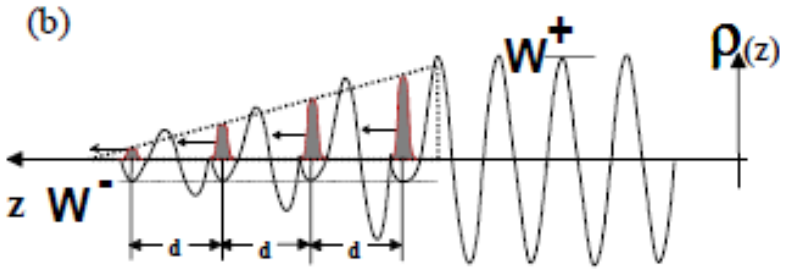
Bunches with symmetric current profile



Fundamental theorem of beam loading

$$\frac{\text{wake potential behind driving bunch}}{\text{wake potentail seen by it}} = \frac{W^+}{W^-} \leq 2$$

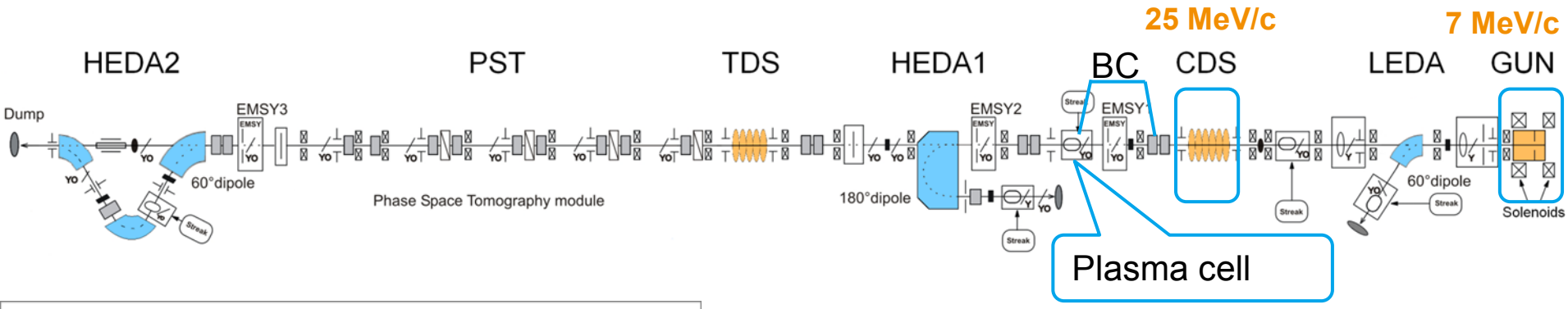
How can TR > 2? → Schütt et al. (1989)

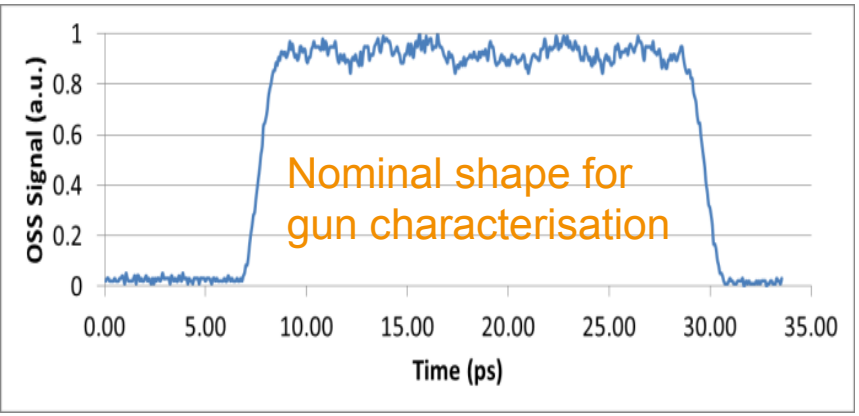


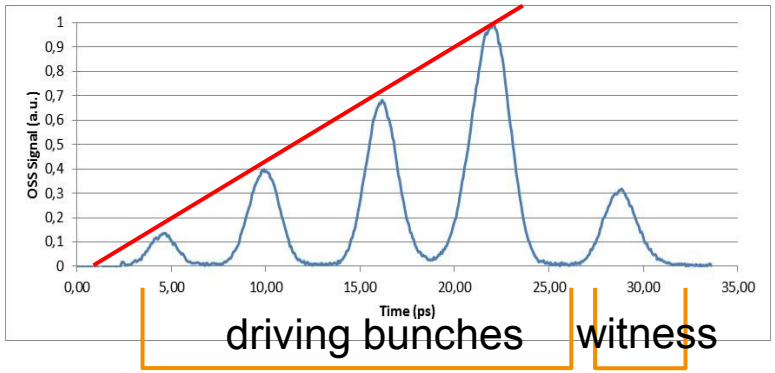
symmetric drive bunches with linearly ramped charge density

At PITZ TR ≤ 8

Photo-Injector Test facility at DESY, Zeuthen site







Laser pulse-shaping system based on 13 crystals

- The intensity of the bunches can be varied separately
- Linear increase in the pulse intensity
- Separate control of the intensity of the witness pulse
- The overall length can't be shorter than 20 ps

The need of a bunch compressor

CSRtrack simulations

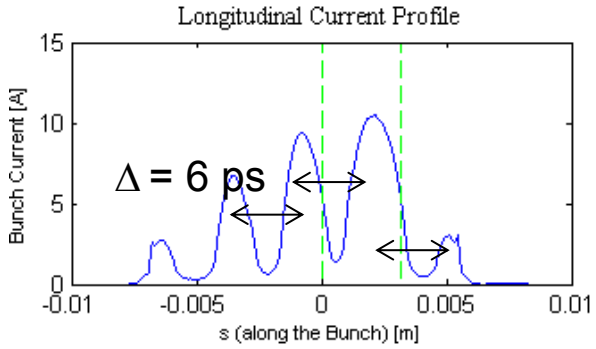
Courtesy T. Vinatier

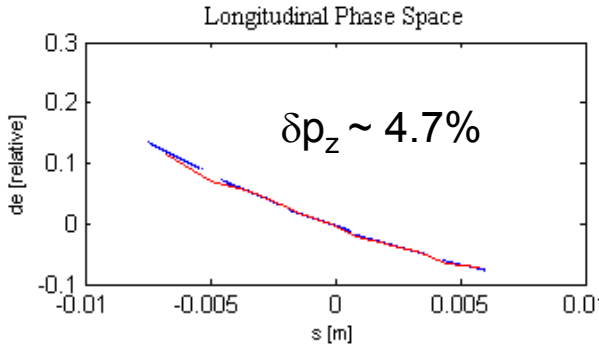
$$E_{acc} \sim N_{particles}/\sigma_z$$

GOAL:

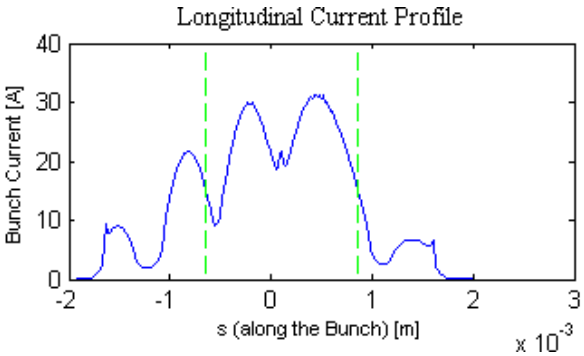
- Electron pulse with modulated charge
  10:30:50:70:10 pC
  τ = 1 ps each

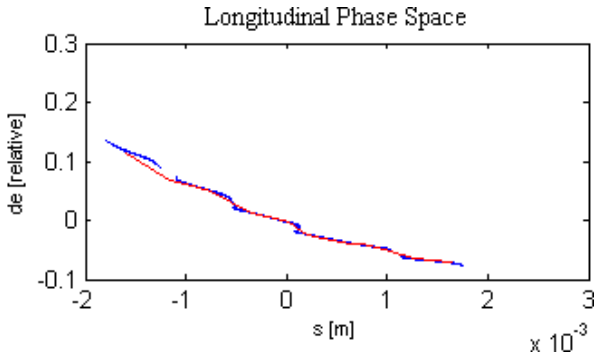
- Longitudinally compressed by a factor of 4 at the entrance of the plasma cell
  - subpulses τ = 250 fs
  - spacing Δ = 1.5 ps
  - compression depends on the shape





Before compression





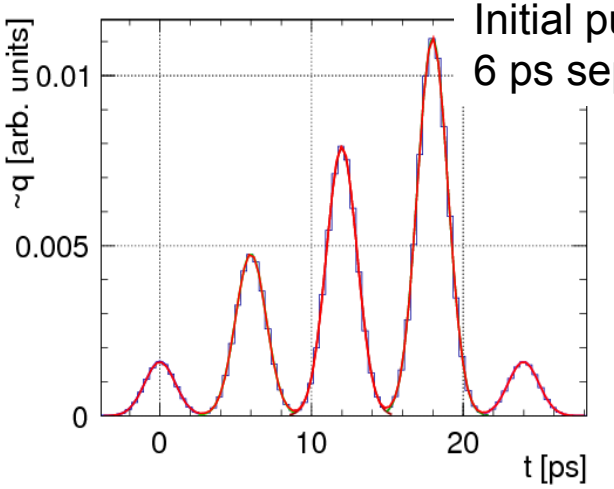
After

Lessons learned:

- separated pulses ⟹ from the gun
- the curvature of the longitudinal phase space is inverted (negative) ⟹ booster off-crest phase / 3rd harmonic cavity
- small energy spread ⟹ booster close to the crest, gradient

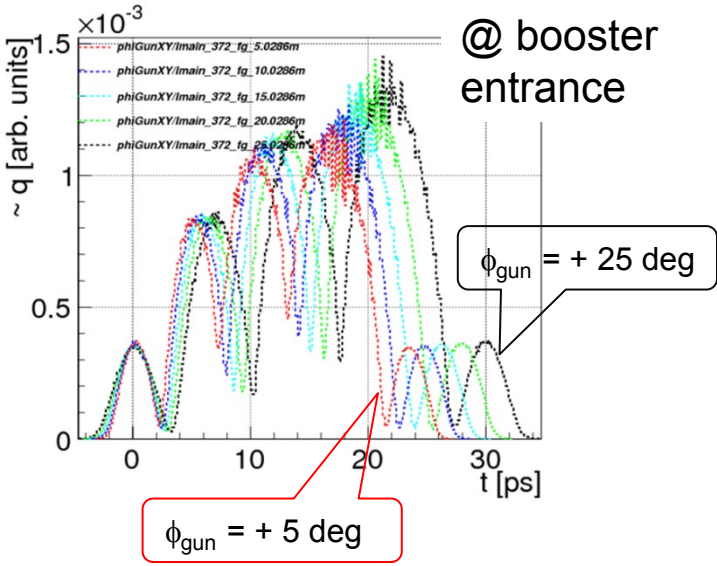
Gun optimization

ASTRA simulations



Initial pulse
6 ps separation

Low energy & longitudinal space charge →
pulsed structure degrades



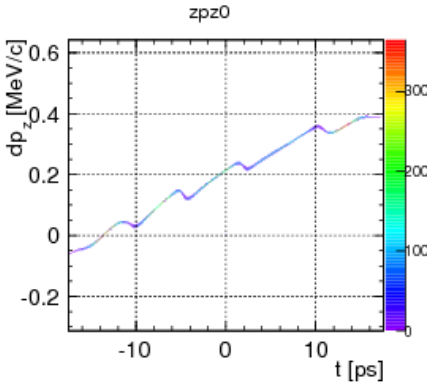
Positive gun phases

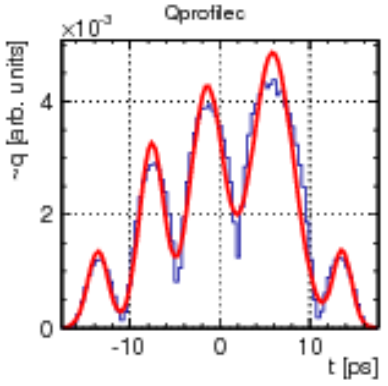
→ better separation between the pulses

→ additional cavity can't improve separation

→ longer overall pulse, faster increase in δp_z

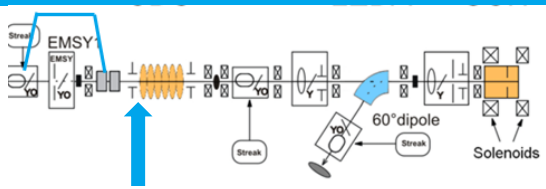
→ compromise at 17 deg w.r.t. max mean momentum gain





* from Gaussian fits at the entrance of the booster

Curvature of the longitudinal phase space



Drive the booster cavity off crest

Major milestones:

- decelerated beam, momentum spread

  6.2 MeV/c / 1.6% before →

  3.5 MeV/c / 17.6% after booster

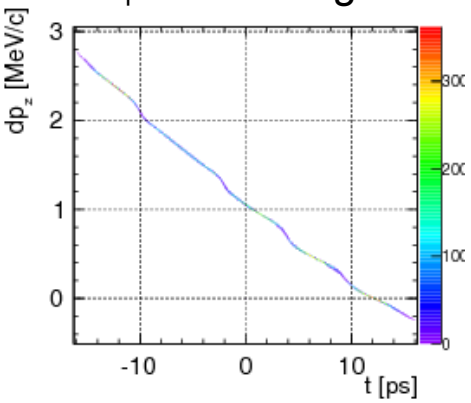
- inverted charge profile

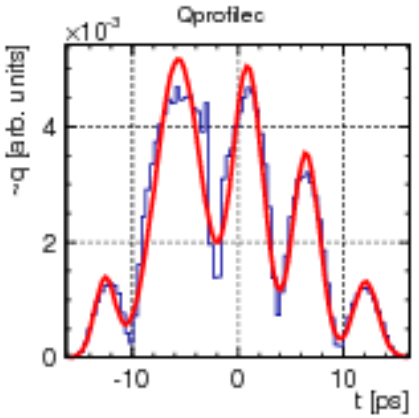
- still negative curvature, but pointing up

  20.5 MeV/c / 3% after booster

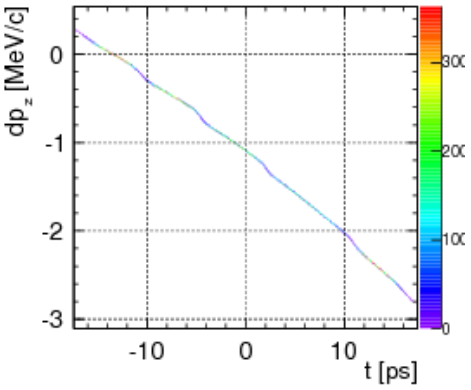
→ Additional cavity in front of booster, but SHORT

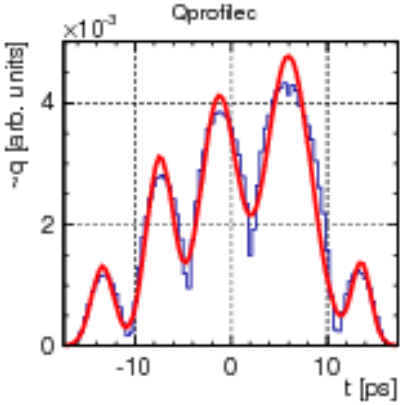
ϕ = -129 deg



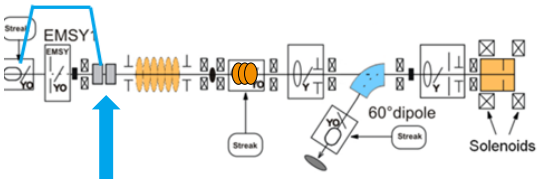


ϕ = -45 deg

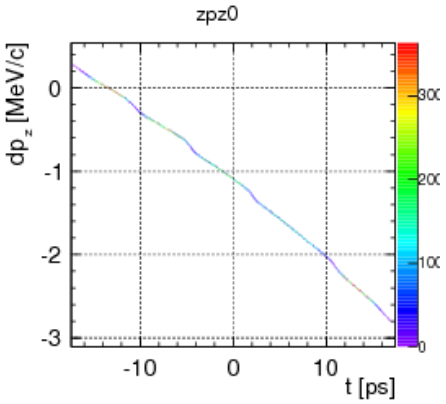


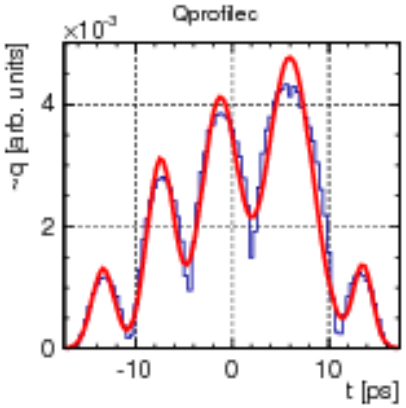


Only booster or also 3rd harmonic



Only booster

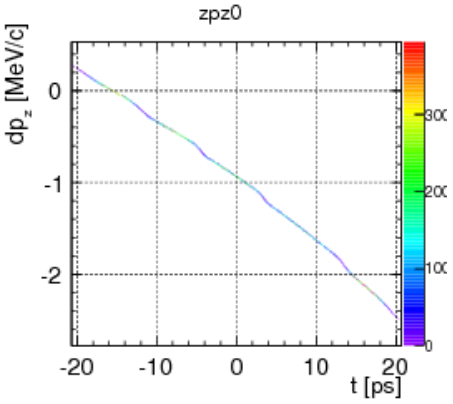


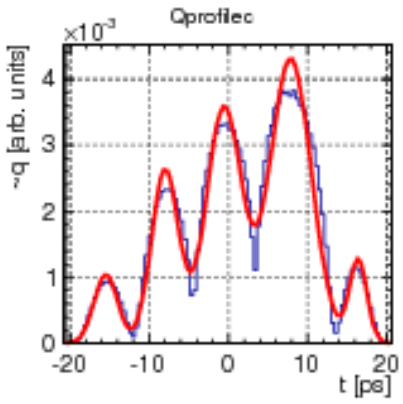


p_z = 20.5 MeV/c
δp_z = 3%

and shorter

3rd harmonics

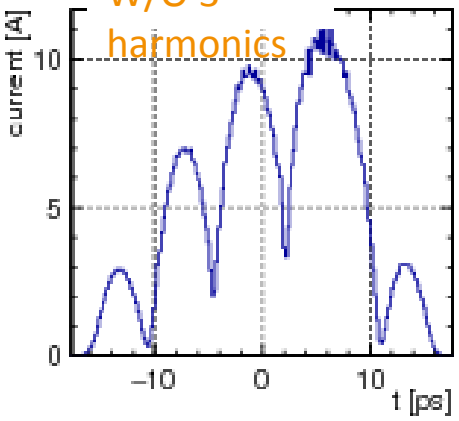




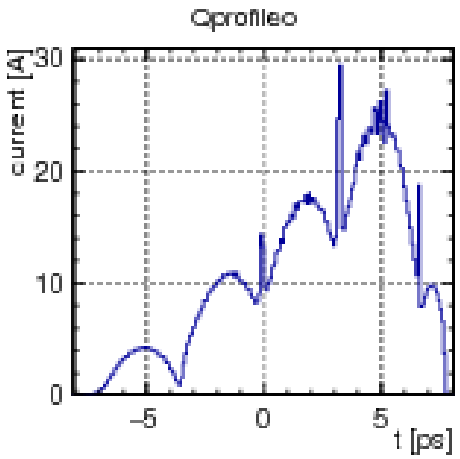
p_z = 18.9 MeV/c
δp_z = 3%

Gun + booster + BC

W/O 3rd harmonics



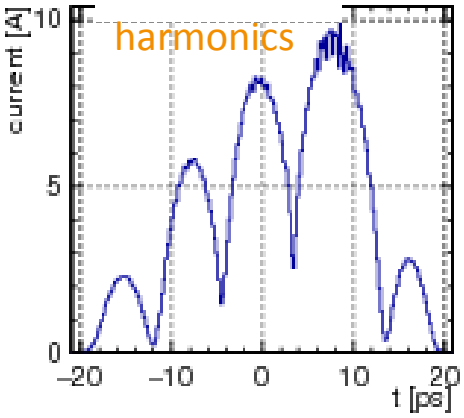
σ_z = 2.1 mm (7 ps)



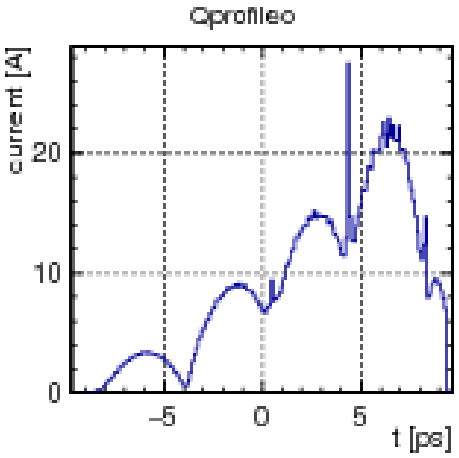
σ_z = 1. mm (3.3 ps)

Head/Tail bunchlets compression different → vary $\sigma_{z,\ bunchlet}$ from laser

With 3rd harmonics



σ_z = 2.5 mm (8.2 ps)



σ_z = 1.19 mm (4 ps)

Compression cannot be defined in absolute units!

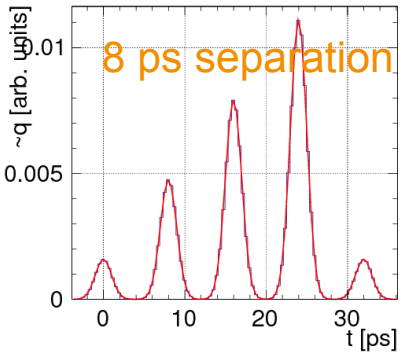
Or

Does not work

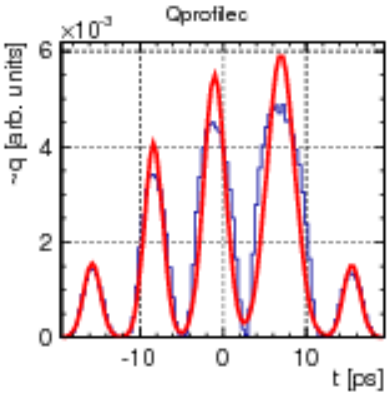
Possibilities to separate bunchlets

- Increase pulse separation from 6 to 8 ps

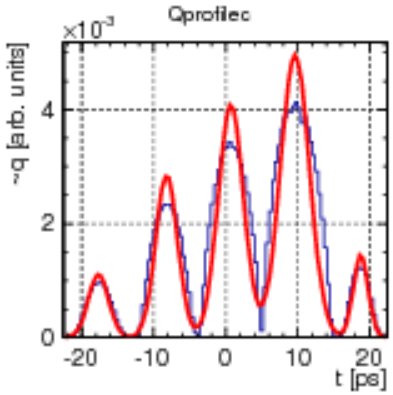
  3rd harmonics cavity in front of the booster, ϕ_{gun} , $\phi_{3rd\ harmonic}$, $\phi_{booster}$ optimized



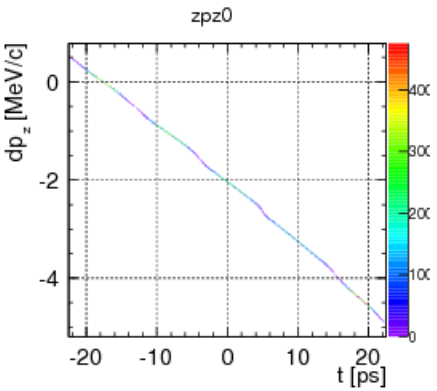
Laser



Gun exit

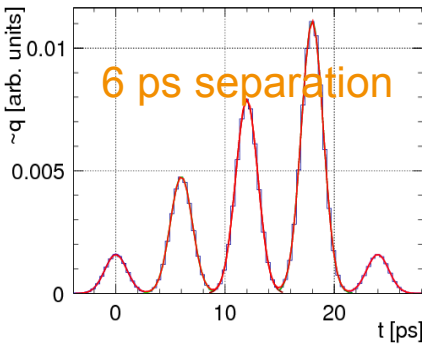


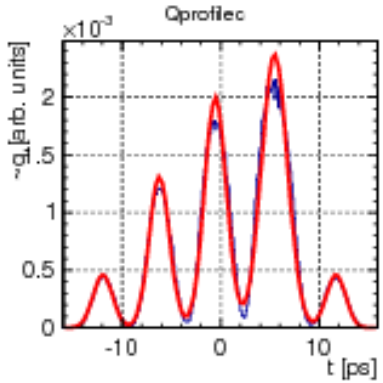
BC entrance



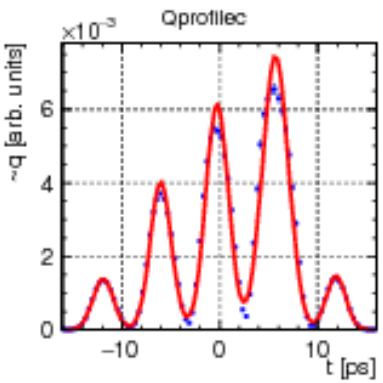
δp_z = 8%, longer pulses

- Gun at 100 MV/m with the 6 ps





Gun exit



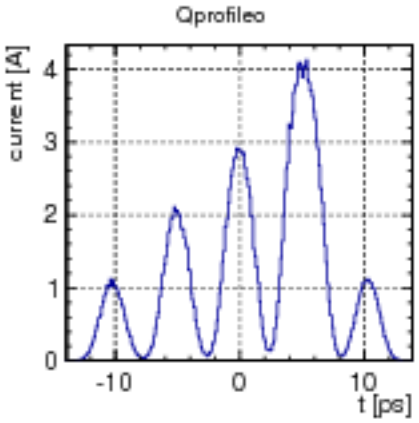
BC entrance

Charge profile kept.

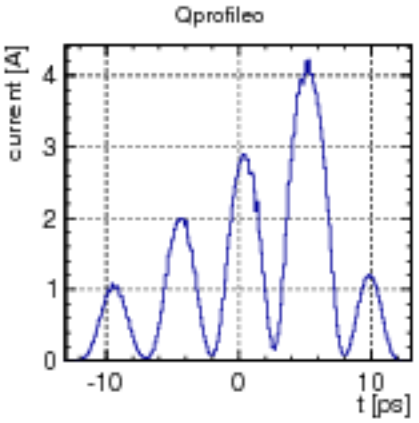
Decreasing bunch charge

Q/4 (1:2:3:5:1)

2.5/5/7.5/12.5/2.5 pC/pulse



Gun exit



Booster exit

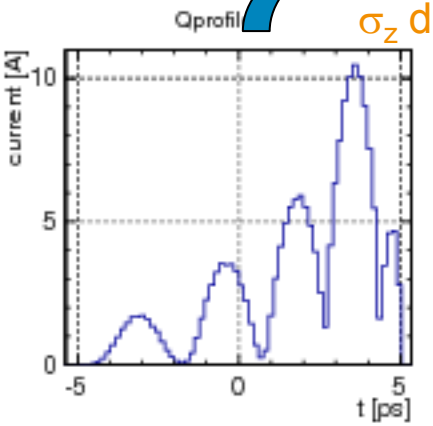
$\Delta\tau$ [ps]: 5.1, 4.86, 4.89, 4.78

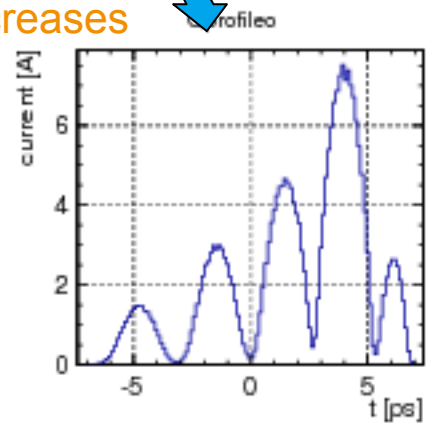
p_z = 17.09 MeV/c, δp_z = 670 keV/c (4%)

Compression **x2**

ρ increases

σ_z decreases



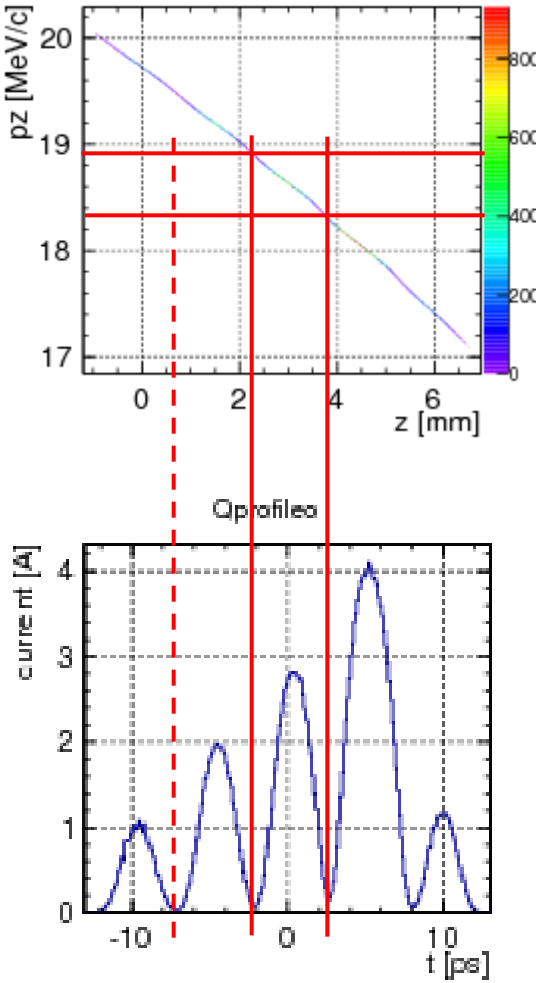


BC exit

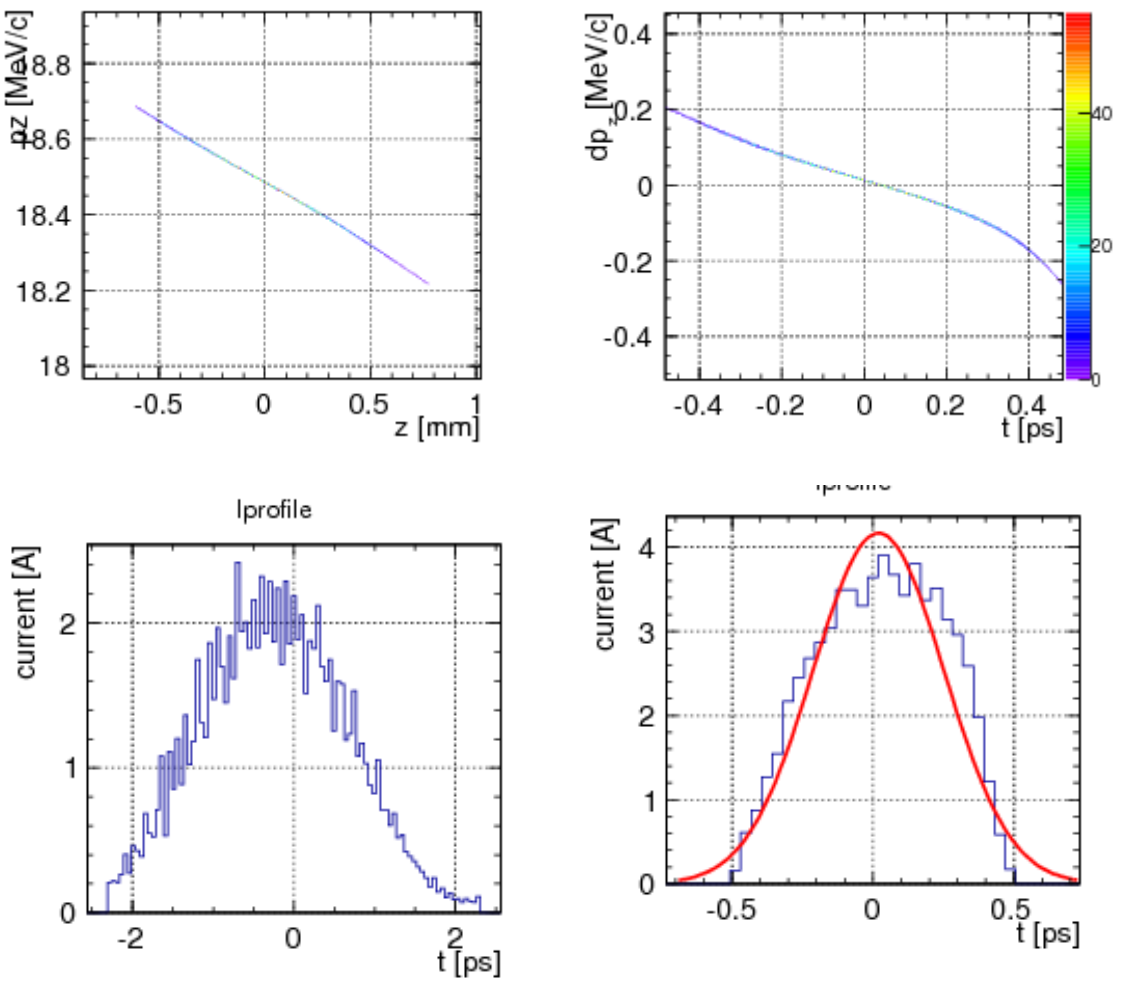
Bunch always shrinks more towards Tail than towards Head.

Compressing smaller charge density

Initial



Cut slice



σ_z = 0.266 mm → σ_z = 0.07 mm (0.22 ps)

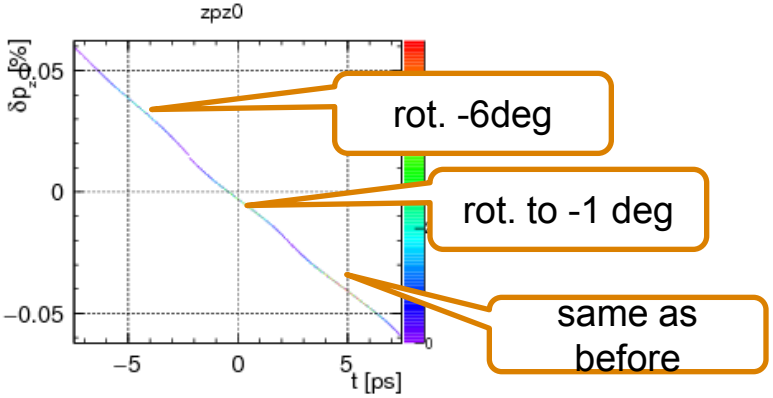
x4

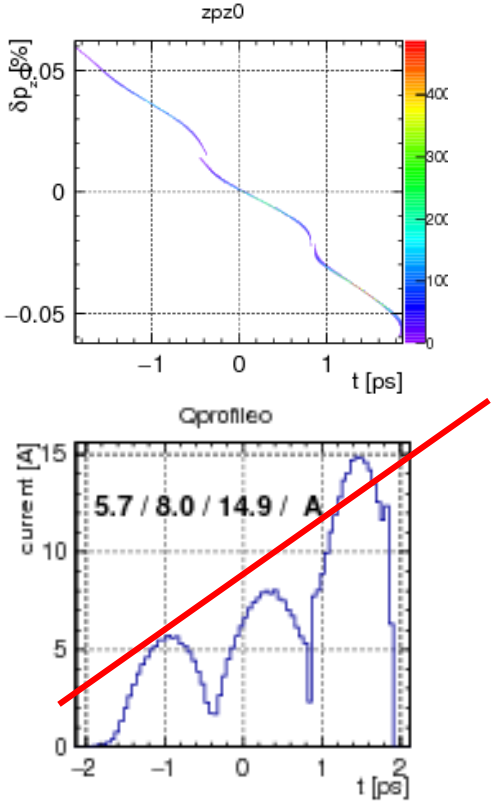
Shown central slice cut from the astra distribution

$-2.034 \le t \le 2.581$ ps

3 pulses “constructed” by hand, smaller charge density

Add the left/right-most pulses





Compression factor of 4 possible.

4-5 pulses impossible if linear ramp starts from the laser.

σ_z = 1.16 mm
0.27/0.28/0.31 mm

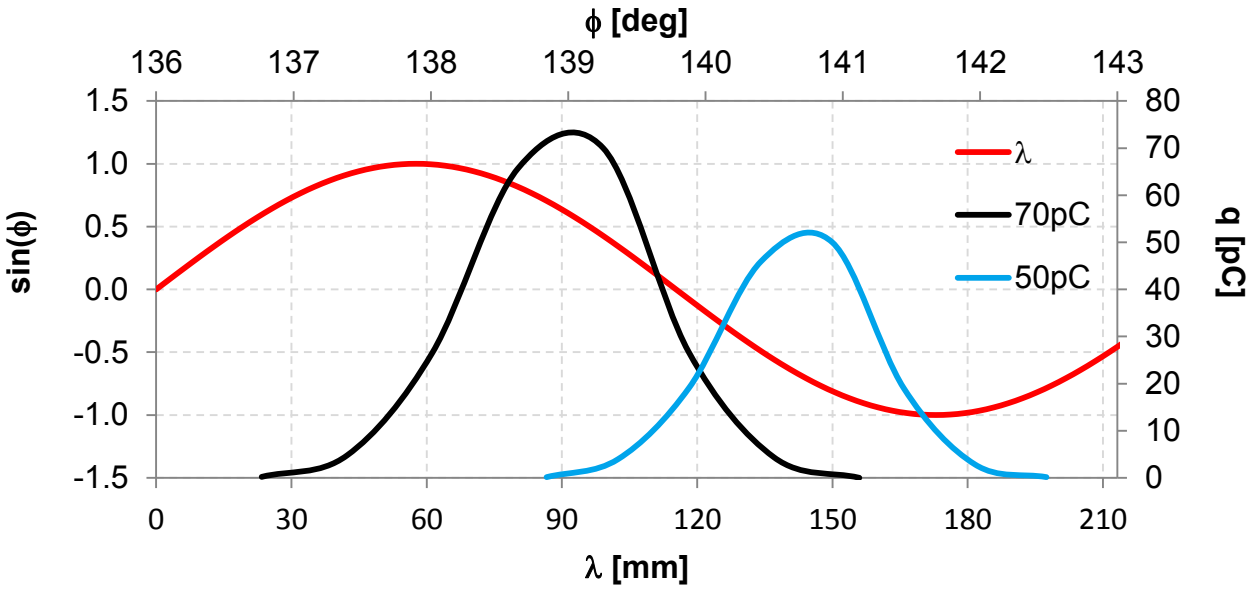
σ_z = 0.291 mm
0.09/0.093/0.082 mm

Outlook

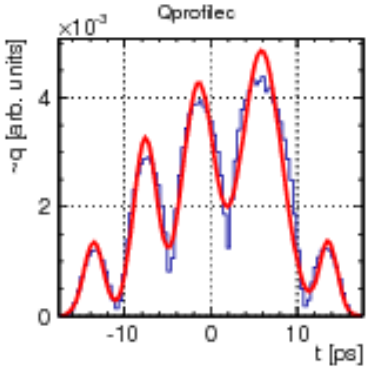
- Still we have to understand "How do we define compression".
  - each single bunchlet has to be properly compressed
- Plasma simulations badly needed to see what parameters actually matter.
  - Spacing between pulses is more important than overlap
  - accepeted tolerances in shape/spacing/…
- Adjust the laser profile to what plasma simulations show and try to obtain it with machine settings (back tracking).
- Machine studies for bunchlet transport needed with realistic laser shape (OSS, TDS, HEDA2) also as input for plasma simulations.
- Gregor: parameter space definition.

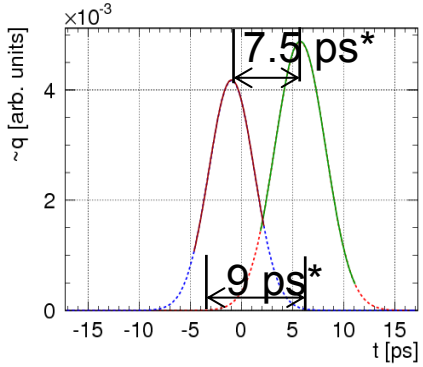
Pulse separation

> A few degree difference in the phases two pulses see



> maybe clear separation if the pulses are moved aside as much as they overlap behind the gun

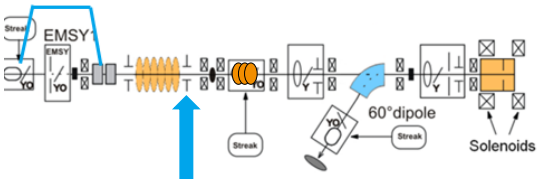




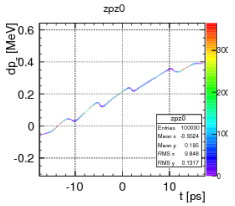
ooster

3rd harmonic upstream the booster

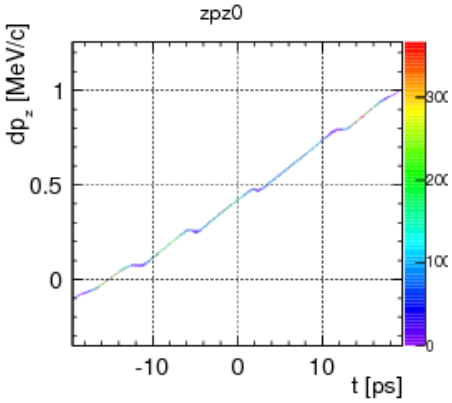
Correct **nonlinearities induced only by the gun**

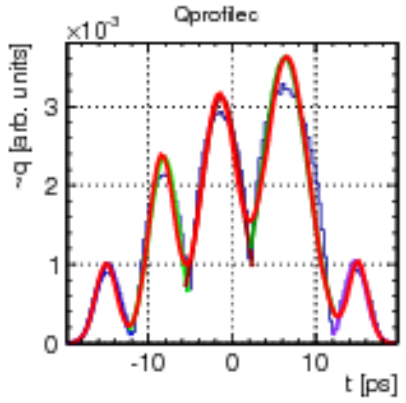


First thought: just linearize (z, p_z) @ booster entrance



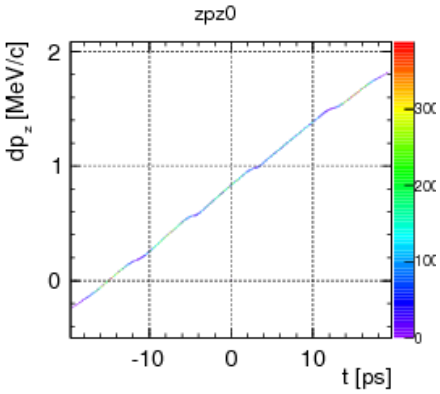
Gradient compensating only gun

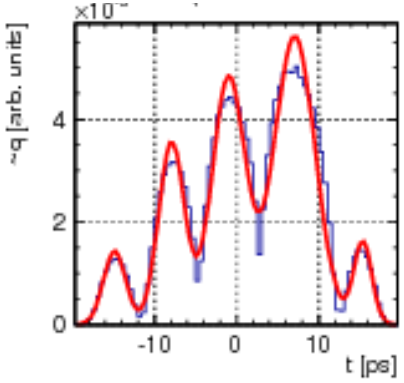




p_z = 5.1 MeV/c
δp_z = 4.5%

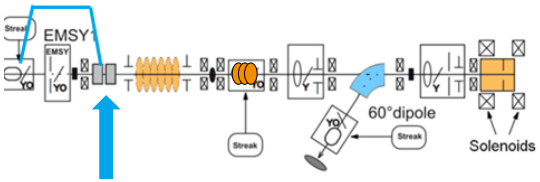
Gradient as if it would compensate booster



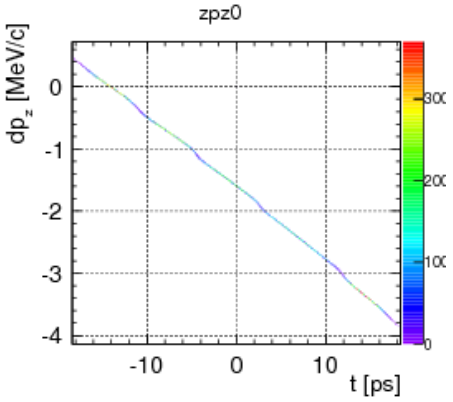


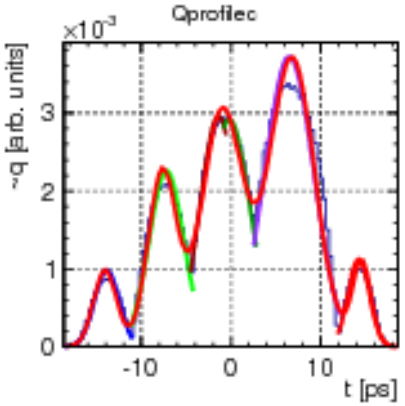
p_z = 6 MeV/c
δp_z = 7%

Negative position-energy chirp with the booster



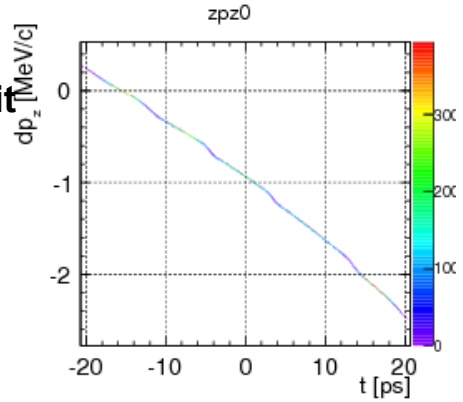
Gradient compensating only gun

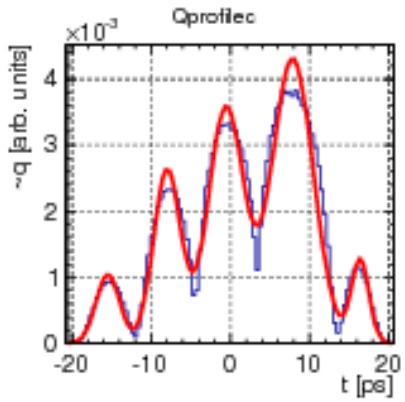




p_z = 14.5 MeV/c
δp_z = 6%

Gradient as if it would compensate booster

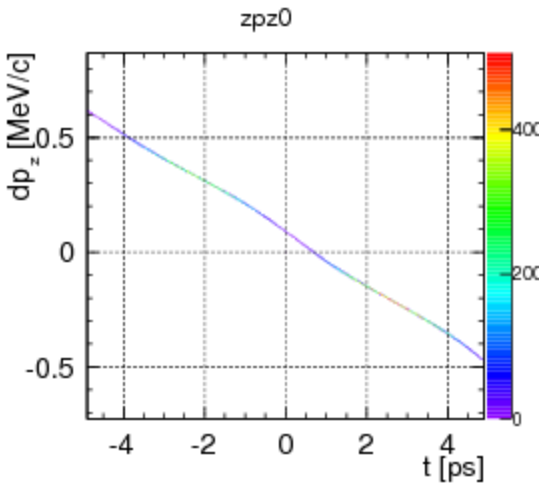


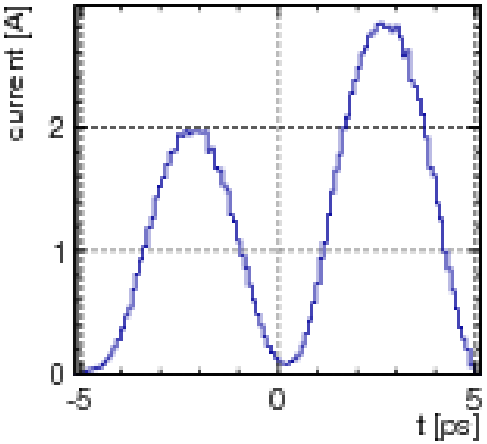


p_z = 18.9 MeV/c
δp_z = 3%

Try compression of central slice + one to the right

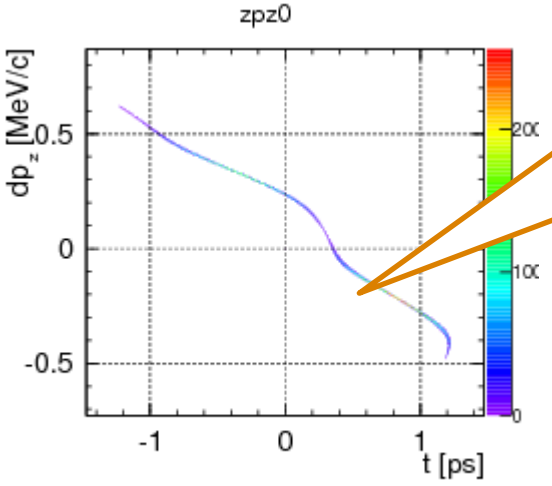
Cut slice



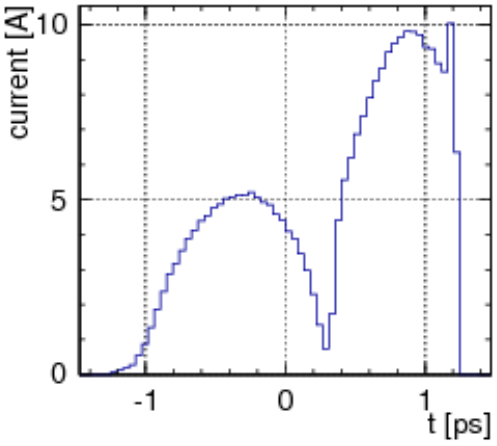


σ_z = 0.768 mm (2.56 ps)

σ_z = 0.92/0.94 ps



As the right one compresses more try to change manually the chirp of the left one and then compress? What chirp would deliver better compression?



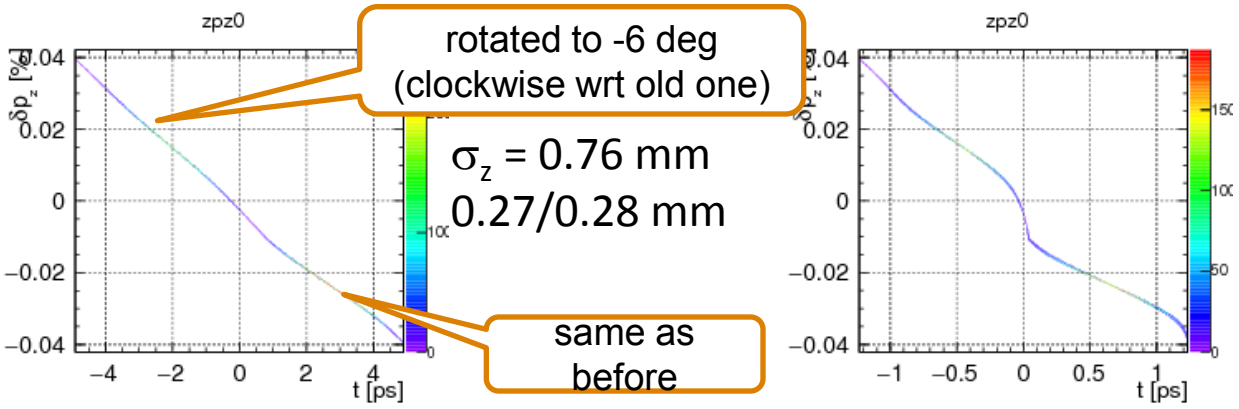
Again H/T compress differently.

Compression X4 but not on single pulse.

σ_z = 0.1922 mm (0.64 ps)

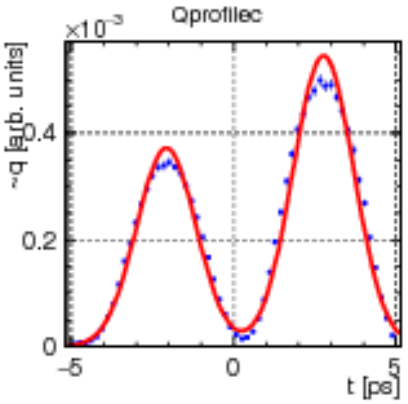
σ_z = 0.31/0.26 ps

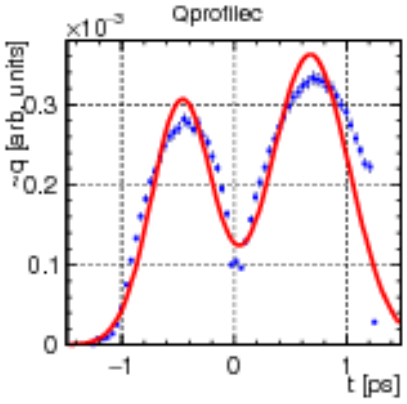
Compressing smaller charge density



σ_z = 0.76 mm
0.27/0.28 mm

σ_z = 0.19 mm
0.08/0.09 mm





Rotation to angles smaller than -6 deg -> factor 4 compression reached but with overcompressed tail always!