Extreme high brightness electron beam generation in a space charge regime

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(1) goal

prove extreme high performances in compact LINACs (~20 m)

$E_n = 150 - 500$ MeV; $\varepsilon_{n,peak} \approx 0.3 - 1.0\, mm - mrad$;
$\boldsymbol{I_{peak}}$ up to: $\boldsymbol{4\, kA}$; $\boldsymbol{\sigma_E < 50\, keV}$

Ultra bright & Ultra cold: Dream beams

(2) NEW technique of bunching

Hybrid Laminar Velocity Bunching or Laminar Bunching (LB)

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Velocity Bunching + Drift Laminar Bunching

Important notes:

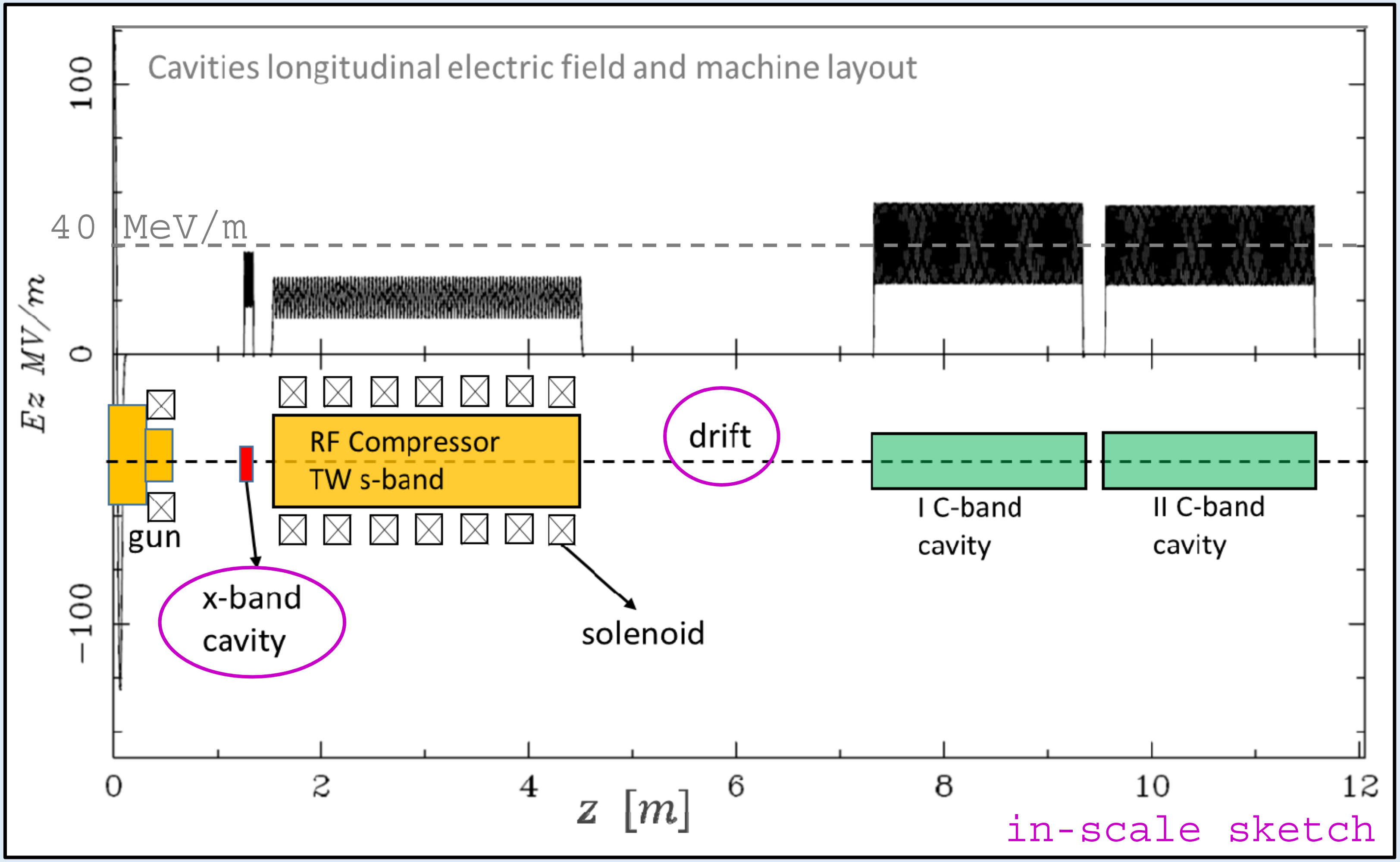
- ✓ Crowded charts show: σ_x, σ_z, ε_{nx}, σ_E
- ✓ Simulations made in ASTRA (*)
- ✓ Optimizations made in GIOTTO (**)

Outline

- ❑ Ad-hoc Laminar Bunching LAYOUT
- ❑ Point out the Laminar Bunching effects
- ❑ Laminar Bunching / Velocity Bunching COMPARISON
- ❑ Some Beam Dynamics: Laminarity parameter
- ❑ Conclusions

(*) *K. Floettmann, ASTRA–A space charge tracking algorithm, http://www.desy.de/~mpyflo/*
(**) *A. Bacci, et al. "GIOTTO: A Genetic Code for Demanding Beam-dynamics Optimizations", doi: 10.18429/JACoW-IPAC2016-WEPOY03*

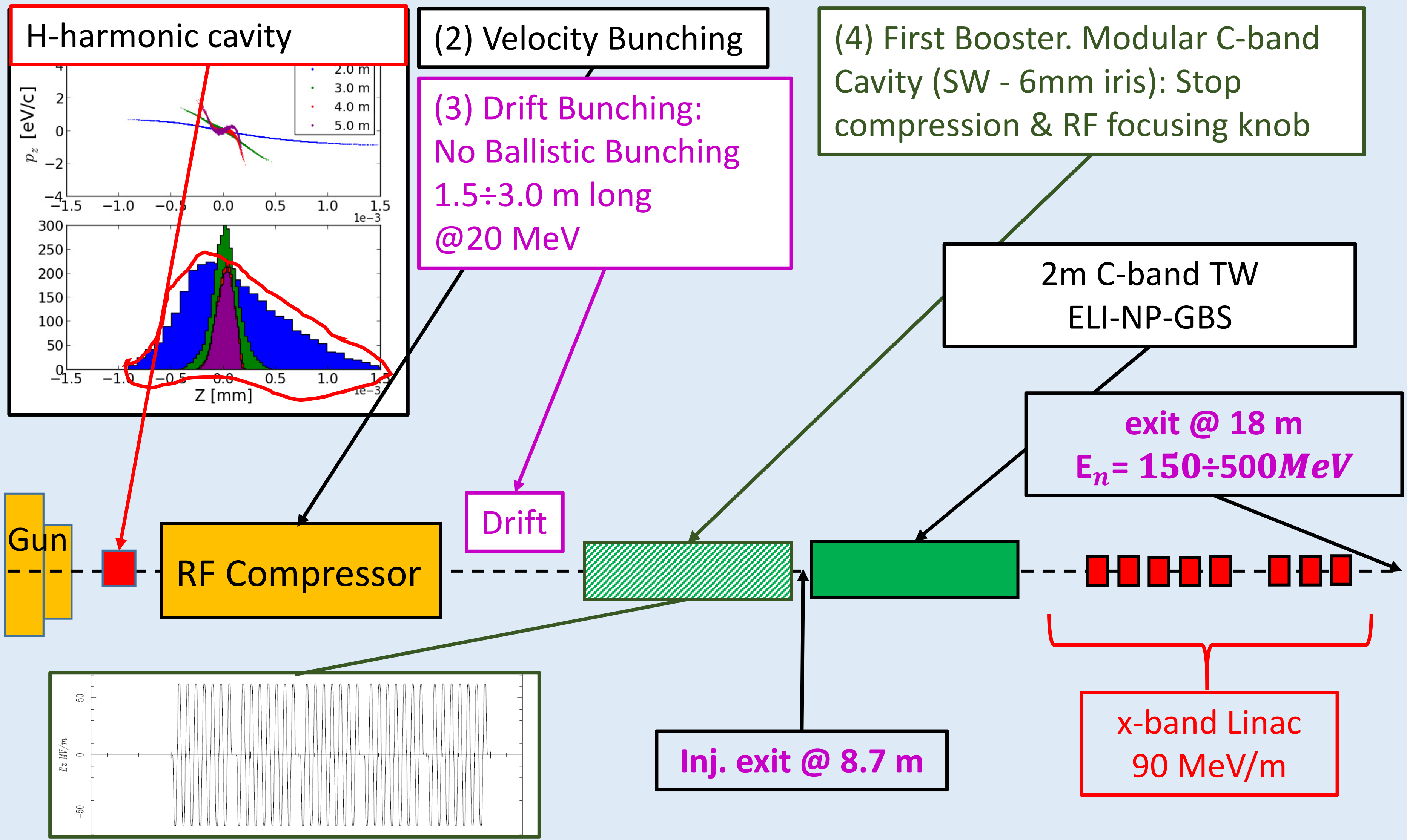
Ad-hoc layout for Laminar Bunching



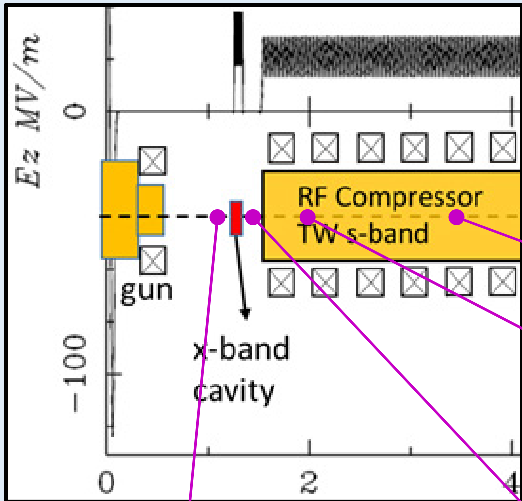
For Velocity Bunching refs to: *M. Ferrario, et. al., PRL 104, 054801 (2010)*

A compact machine layout working in Laminar Bunching

(1) HighHarm-cavity current pre-correction; (2) Velocity Bunch.;
(3) Drift Laminar Bunching (balanced accordion effect);
(4) Rf-focusing tunable booster



High harmonic cavity current pre-correction

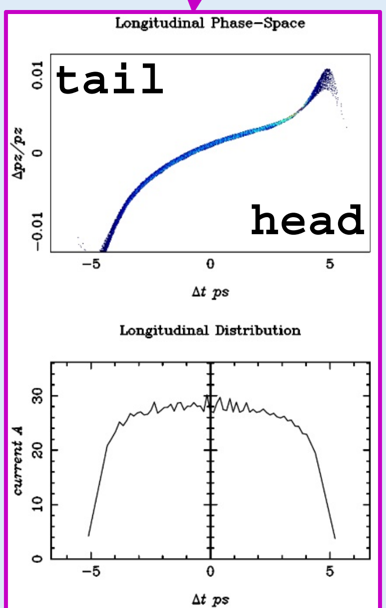


1.2 m

1.4 m

2.0 m

1.4 m



So many different good effects

-rf curvature pre-correction

-current pre-correction

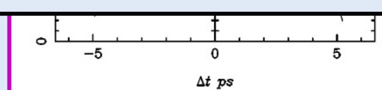
-it starts to compress (\ chirping)

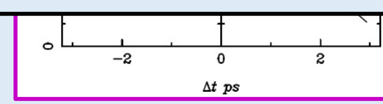
En decrease of 2.3 MeV on 6 MeV

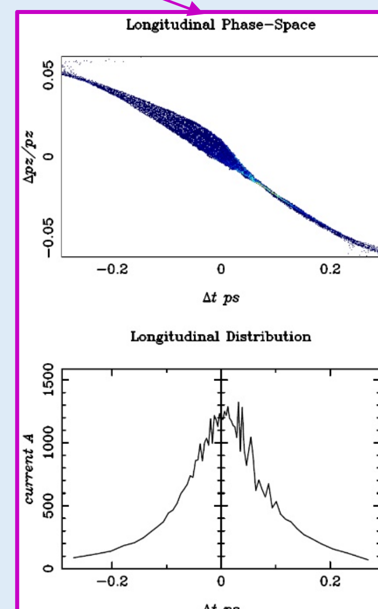
↓

-ρ_z falls down favoring compression

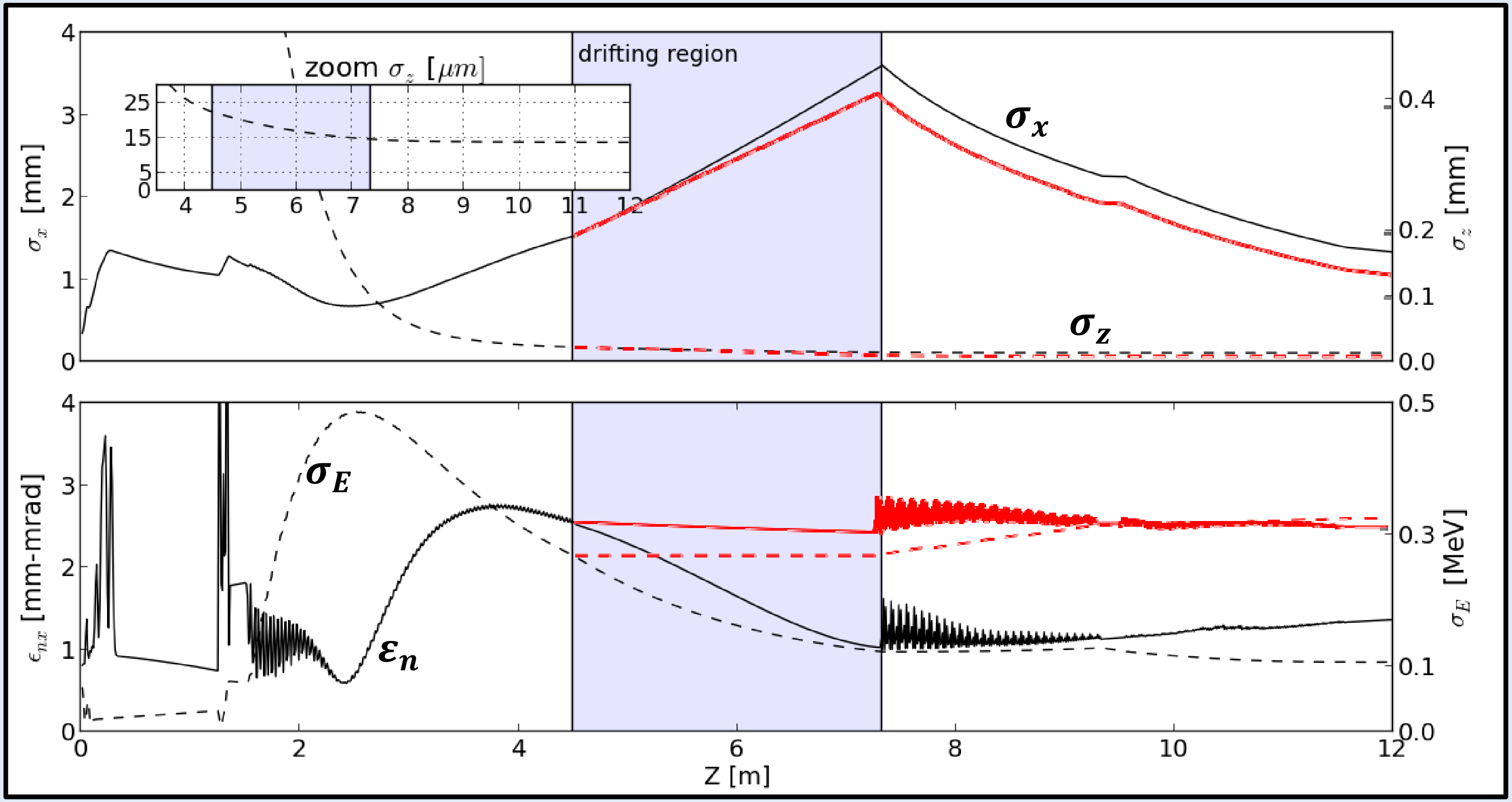
-A higher phase shift between electrons and RF wave, favors VB







σ_x , σ_z, ε_{nx}, σ_E curves in Laminar Bunching



Turning off the SPACE charge from the drift onward

- σ_x quasi linear rising
- σ_z hyperbolic decreasing
- σ_E a quasi full correction
- ε_n a quasi full correction

Both optimized by
GIOTTO genetic algorithm
$\sigma_z, \varepsilon_{nx}, \sigma_E$
projected values

Laminar Bunching (LB)

Velocity Bunching (LV)

comparison

LB & VB are relatives, but their final results are quite different.

The aim:
outline LB peculiarities versus the VB known technique. Both compress linearly and works @ same energies
Just a comparison, not to say what is the best technique

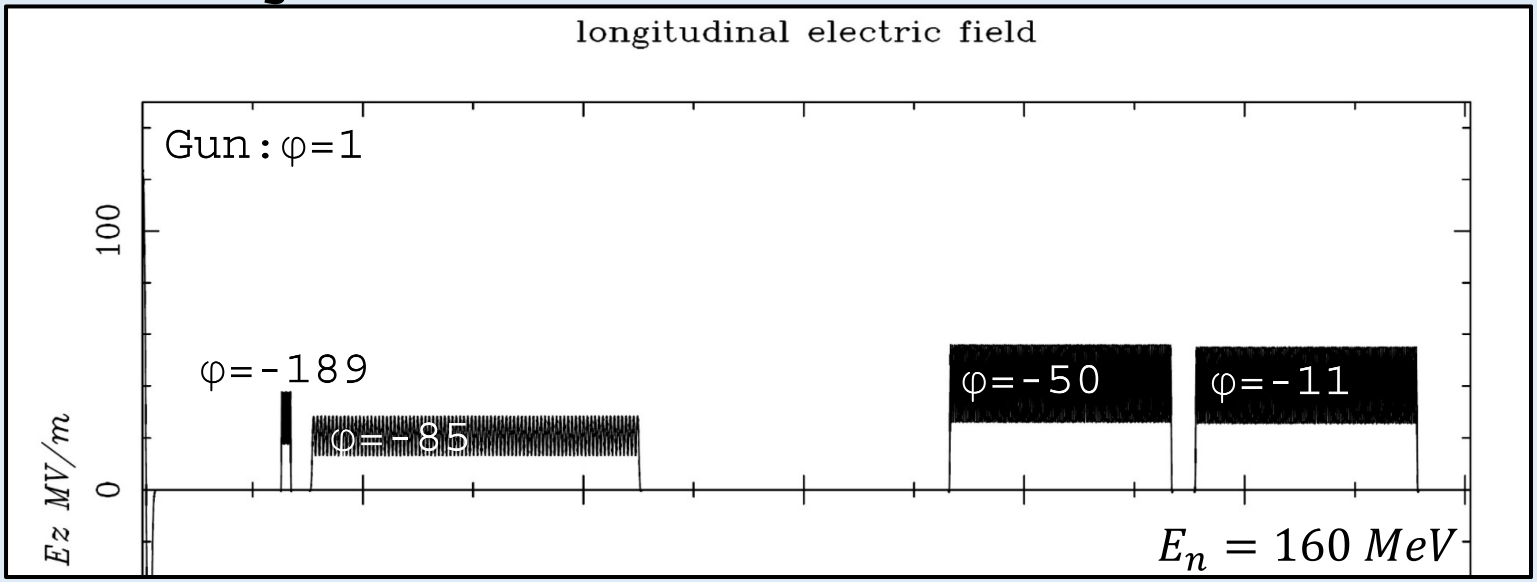
LB works almost on all whole bunch charge

VB favors a spike compression, on the bunch head

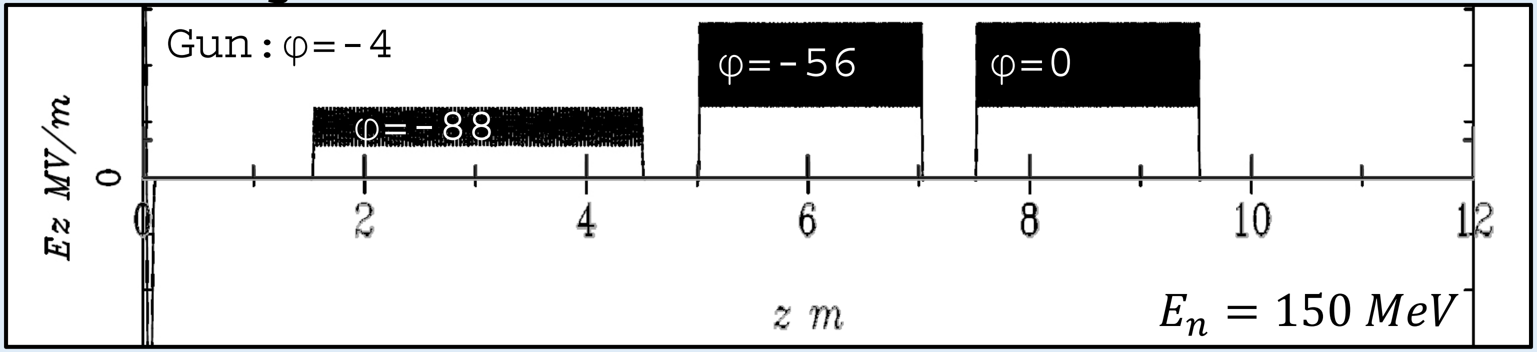
Laminar & Velocity Bunching Layout

@ chatode for both LB & VB	Q_b [pC]	τ_{Laser} [ps] flat-top	τ_{rising} [ps]	ε_{th} [1μ /mm]	σ_x [μm]
	250	10	1	0.9	260

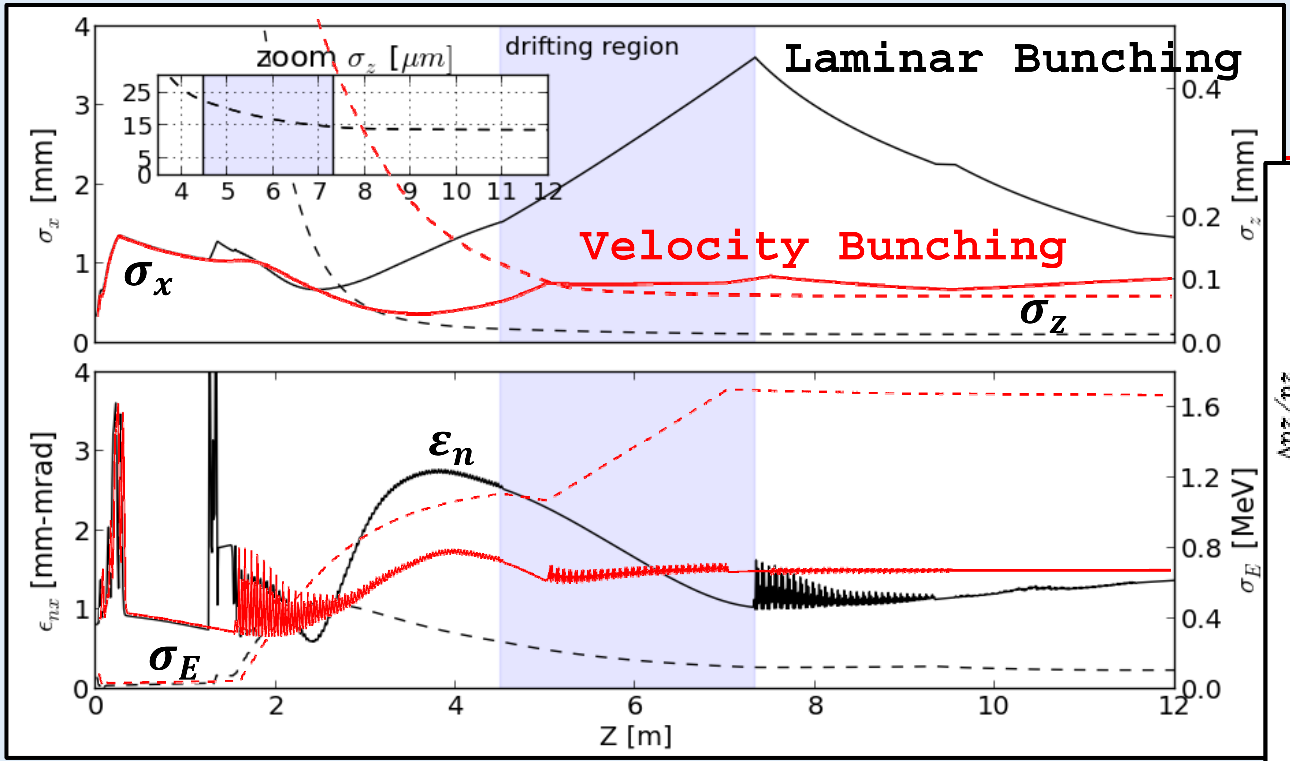
L.Bunching

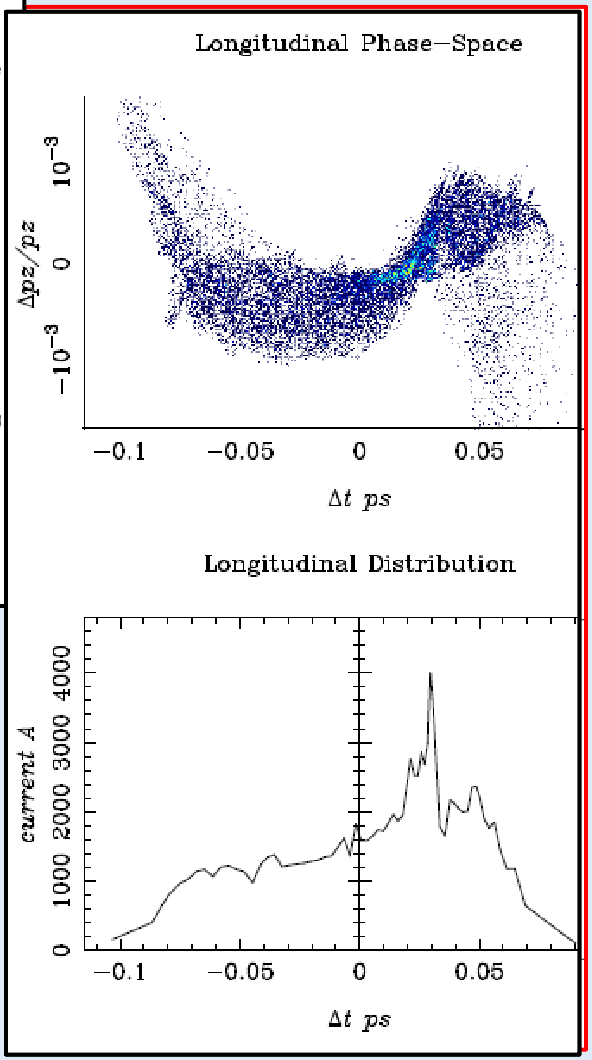


V.Bunching



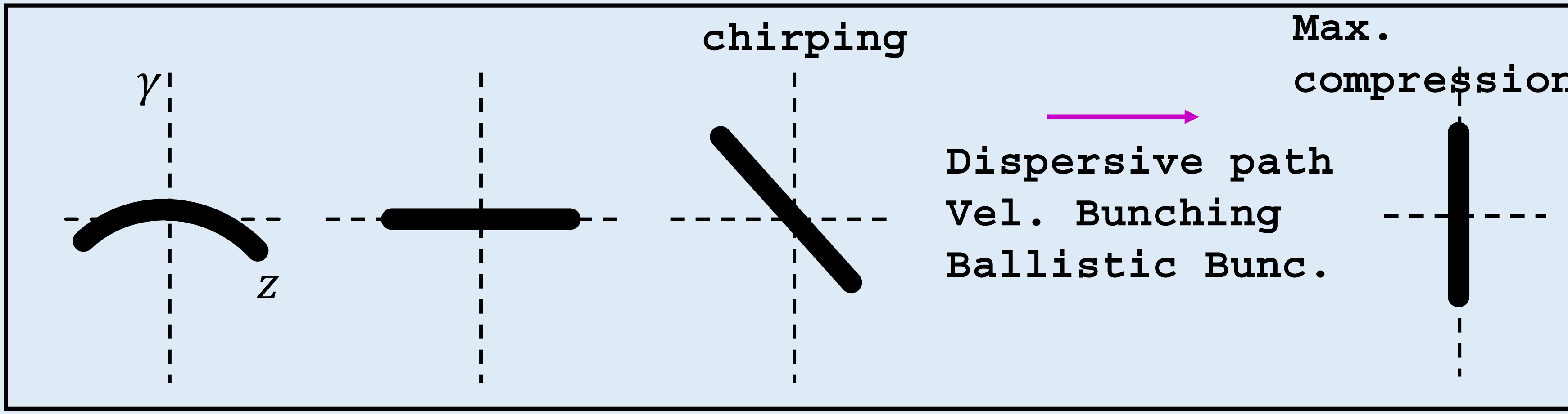
Laminar & Velocity Bunching comparison

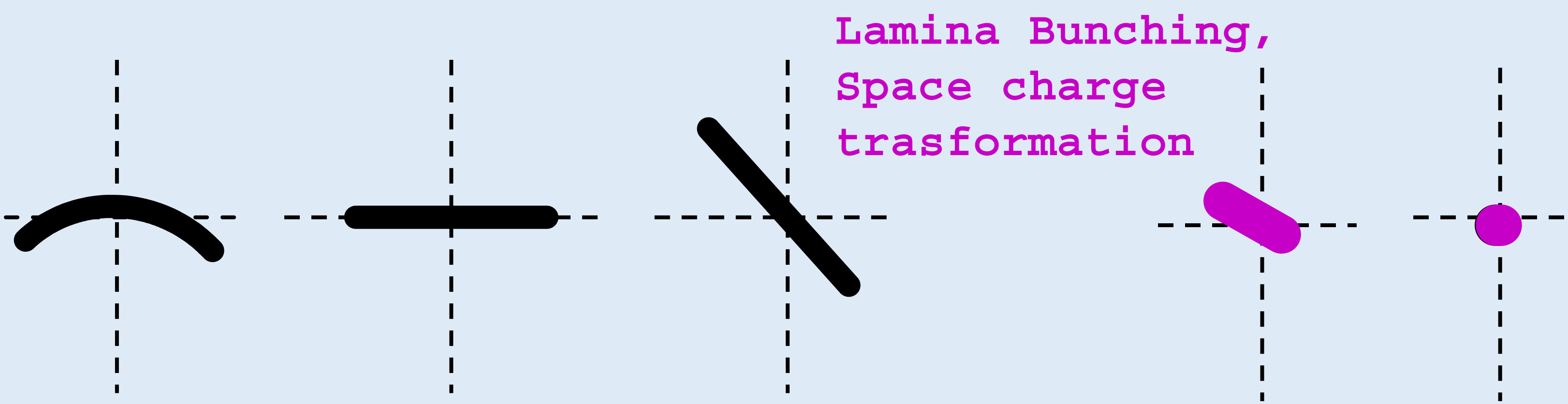




A strong simplification of the longitudinal phase space modification

Classic methods





Laminar & Velocity Bunching comparison

Laminar Bunching @250 pC

GIOTTO
genetic algorithm
optimization:

ε_{nx} = 1.4 $[\mu m]$

σ_z = 15 μm

σ_E = 0.1 $[MeV]$

Velocity Bunching @250 pC

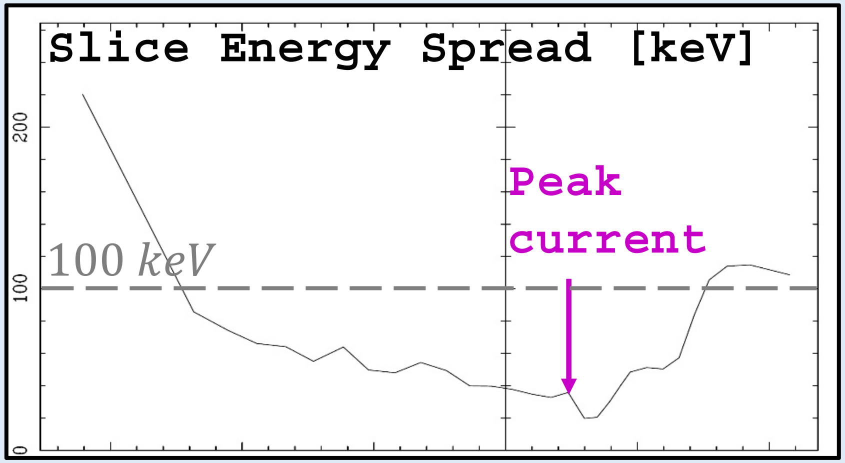
GIOTTO
genetic algorithm
optimization:

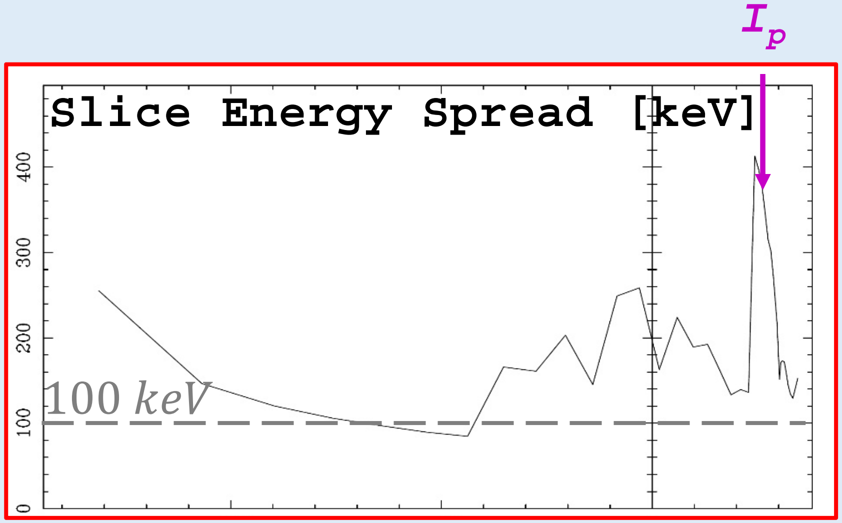
ε_{nx} = 1.5 $[\mu m]$

σ_z = 80 μm

σ_E = 1.7 $[MeV]$

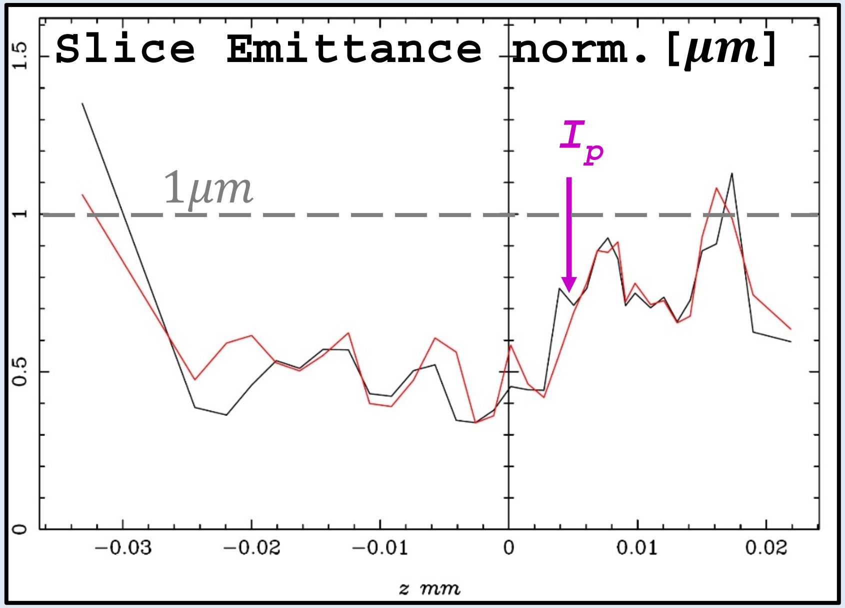
Laminar & Velocity Bunching performances

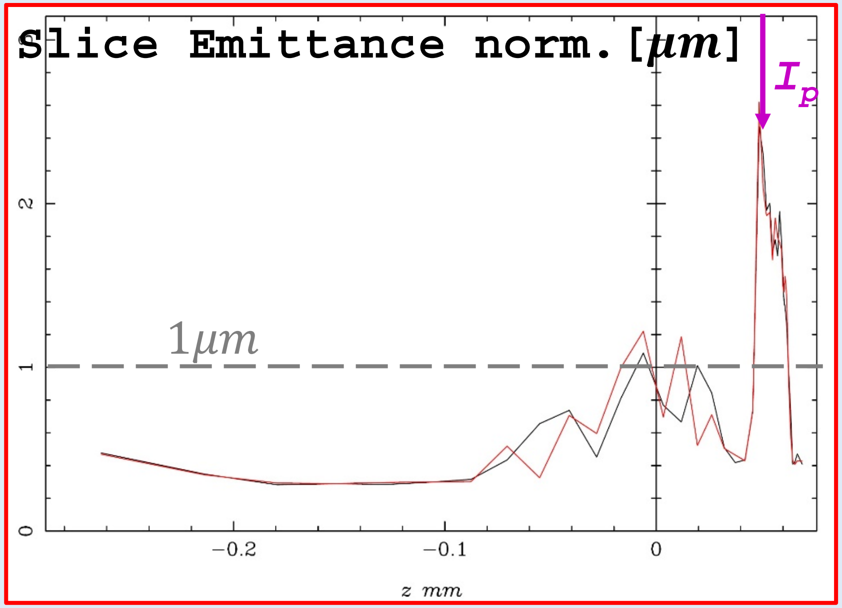




Laminar Bunching

Velocity Bunching





Some Beam Dynamics

Transverse envelope

$$\sigma'' + \frac{\gamma'}{\gamma}\sigma' + \left(\frac{k}{\gamma}\right)^2 \sigma = \frac{Qc}{2I_A\gamma^3\sigma_z\sigma} + \frac{\varepsilon_n^2}{\gamma^2\sigma^3}$$

γ power of 3

Long. envelope equation

$$\sigma_z'' + K_z\sigma_z + \frac{3\gamma'\sigma_z'}{\beta^2\gamma} = \frac{Q_b c}{5\sqrt{5}I_A\beta^2\gamma^4\sigma_z\sigma} + \frac{\varepsilon_{nz}^2}{\beta^2\gamma^6\sigma_z^3}$$

γ power of 4

Coupled by $\boldsymbol{\sigma_x}$

Laminar Parameters

$$\rho_\perp = \frac{Q_b c\sigma^2}{2I_0\gamma\varepsilon_n^2}$$

Emittance compensations

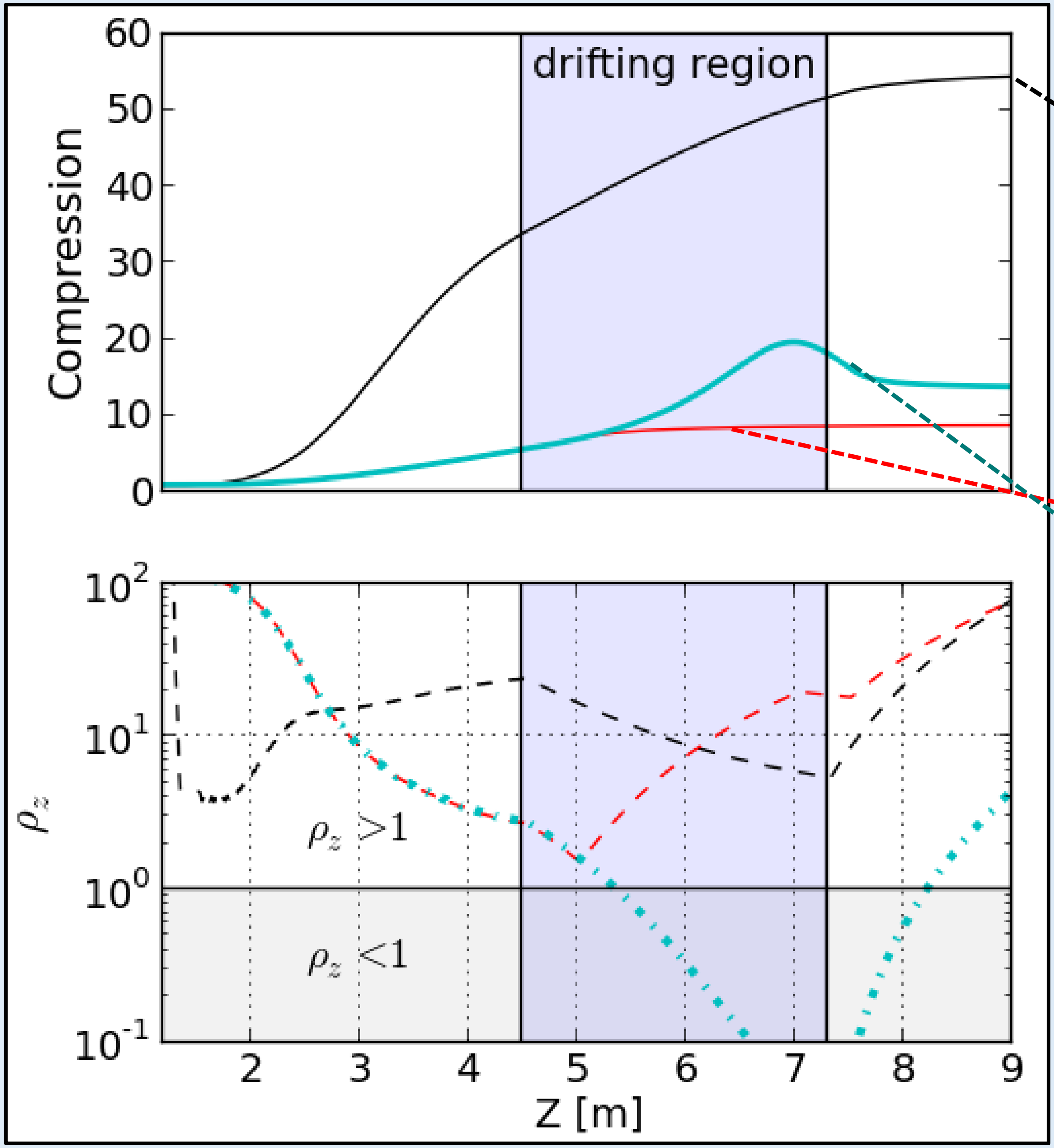
$$\rho_z = \frac{Q_b c(\gamma\sigma_z)^2}{I_0\sigma\varepsilon_z^2}$$

1) Longitudinal compression

&

2) bunch stiffness respet to the compression

ρ_z Laminar parameter for LB & VB

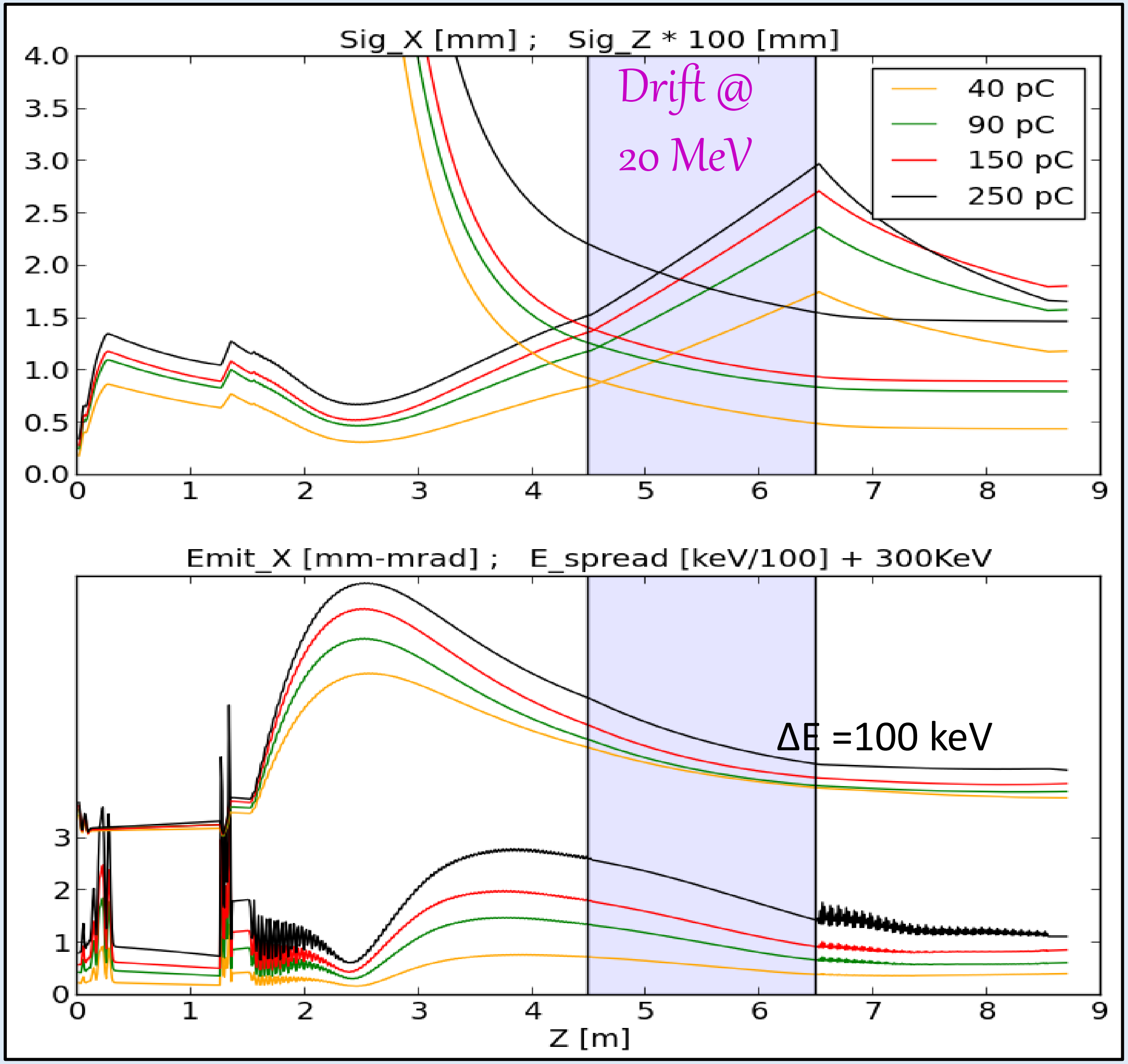


Laminar Bunching
ρ_z is low but > 1
A soft bunch for the compression

Velocity Bunching NO DRIFT (STANDARD case)
ρ_z starts >> 1
A bunch stiff to be compressed

Velocity Bunching SI DRIFT(TEST case)
Laminarity is lost
ρ_z < 1

LB perfomances VS. bunch-charge: 40;90;150;250 pC



@ booster end = 17 m (0.5 GeV)

$Q_b = 40\ pC$

$\sigma_z = 4.2\ \mu m$

$I_{peak} > 2.5 kA$

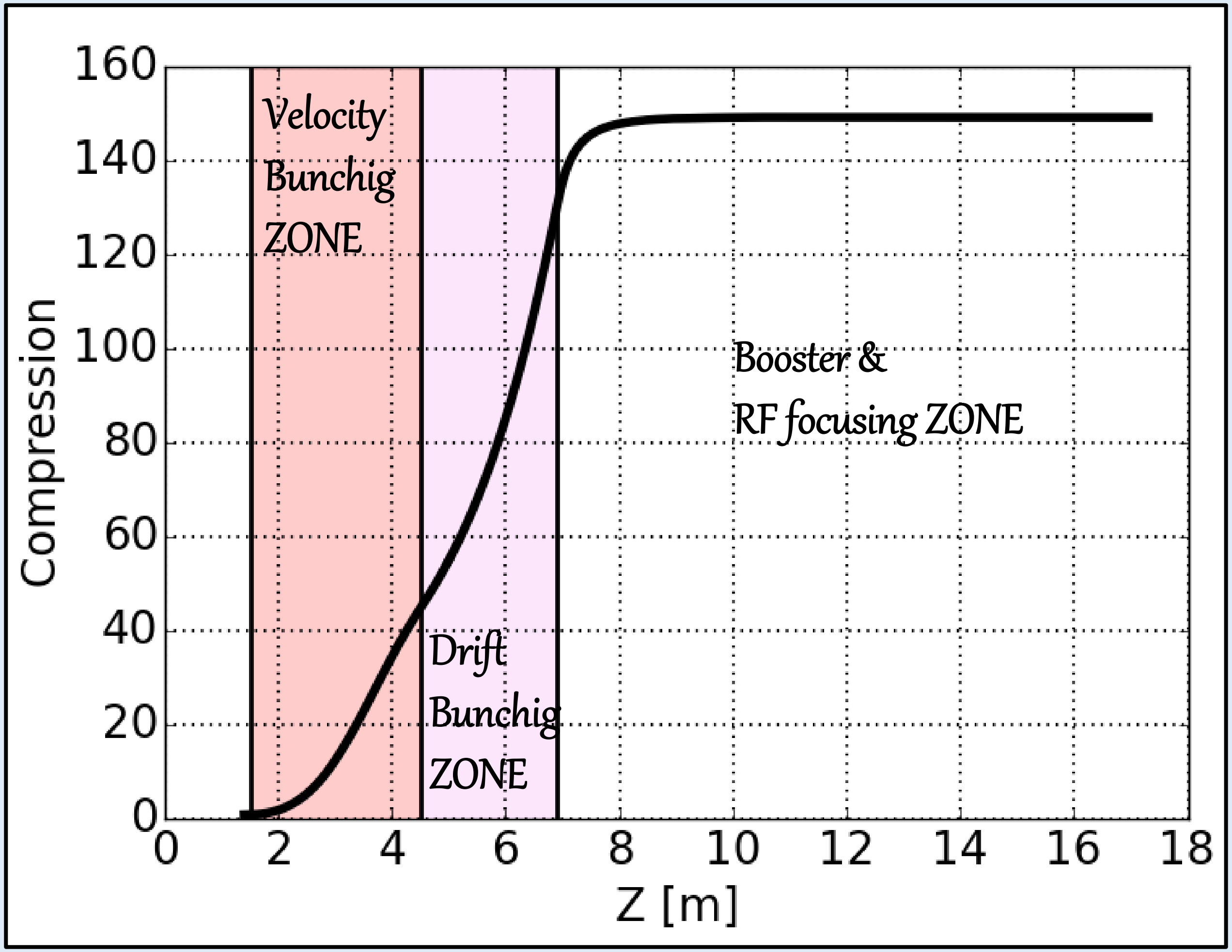
$\varepsilon_{peak} = 0.3\ \mu m$

$B_{peak} = 3 \cdot 10^{16}$

$(I_p = 1.5 kA)$

$(\Delta\gamma/\gamma)_{@I_{peak}} \cong\ 8 \cdot 10^{-5}$

compression factor 40 pc case



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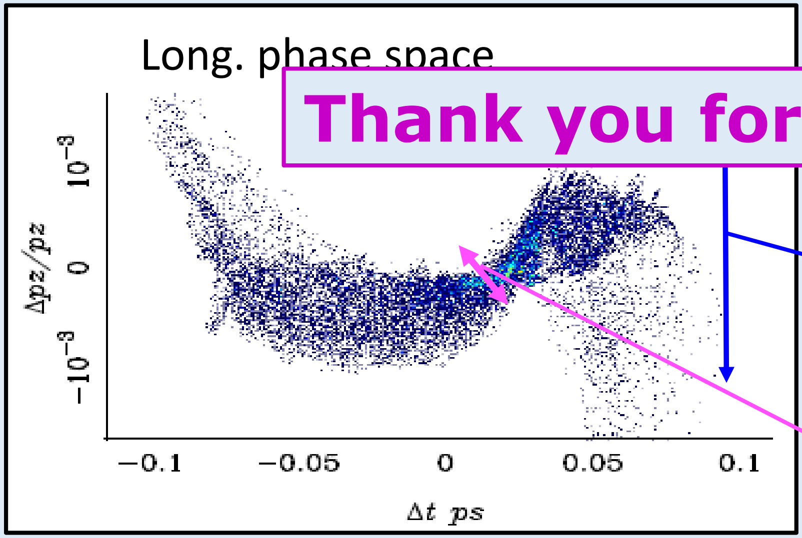
$(I_p = 1.5kA)$

$(\Delta\gamma/\gamma)_{@I_{peak}} \cong\ 8 \cdot 10^{-5}$

CONCLUSIONS

We saw a new compression technique: the Laminar Bunching

- **A compression that works on the whole bunch distribution**
- **It is reproduced for a large range of charge: 40-250 pC**
- **ULTRA brightness and ULTRA low energy spread (10^{-4}÷ 10^{-5});**
  A combination difficult to find!
- **Drawback: Large envelopes for $Q_b > 100\,pC$.**
  An Ad-hoc large iris cavity can be used (rf-focusing knob)
- **No Laser Heater (High un-correlated Energy Spread):**



Thank you for your attention

Correlated Espread

Incorrelated Espread ≈ 20 keV than 2 – 5 keV