Extreme high brightness electron beam generation in a space charge regime

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On behalf of Milano BD group
(1) goal

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

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

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: $\sigma_x, \sigma_z, \varepsilon_{nx}, \sigma_E$
✓ 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/
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

- H-harmonic cavity
- (2) Velocity Bunching
- (3) Drift Bunching: No Ballistic Bunching 1.5÷3.0 m long @20 MeV
- (4) First Booster. Modular C-band Cavity (SW - 6mm iris): Stop compression & RF focusing knob

- 2m C-band TW ELI-NP-GBS
- exit @ 18 m $E_n = 150÷500 MeV$
- x-band Linac 90 MeV/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

- $\rho_z$ falls down favoring compression
- A higher phase shift between electrons and RF wave, favors VB
Turning off the SPACE charge from the drift onward

- $\sigma_x$ quasi linear rising
- $\sigma_z$ hyperbolic decreasing
- $\sigma_E$ a quasi full correction
- $\varepsilon_n$ a quasi full correction
Both optimized by GIOTTO genetic algorithm

\[ \sigma_z, \varepsilon_{nx}, \sigma_E \]

*projected values*

**Laminar Bunching (LB)**

**Velocity Bunching (LV)**

**comparision**

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

<table>
<thead>
<tr>
<th>$Q_b [pC]$</th>
<th>$\tau_{Laser} [ps]$</th>
<th>$\tau_{rising} [ps]$</th>
<th>$\varepsilon_{th} [1\mu/mm]$</th>
<th>$\sigma_x [\mu m]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>10</td>
<td>1</td>
<td>0.9</td>
<td>260</td>
</tr>
</tbody>
</table>

L. Bunching

longitudinal electric field

Gun: $\varphi=1$

$\varphi=-189$

$\varphi=-11$

$\varphi=-50$

$E_n = 160$ MeV

V. Bunching

Gun: $\varphi=-4$

$\varphi=-88$

$\varphi=-56$

$\varphi=0$

$E_n = 150$ MeV
Laminar & Velocity Bunching comparison

Laminar Bunching

Velocity Bunching

Longitudinal Phase-Space

Longitudinal Distribution
A strong simplification of the longitudinal phase space modification

Classic methods

\( \gamma \)

\( z \)

Chirping

Max. compression

Dispersive path
Vel. Bunching
Ballistic Bunc.

Lamina Bunching,
Space charge transformation
Laminar & Velocity Bunching comparison

Laminar Bunching @250 pC

GIOTTO
genetic algorithm optimization:

\( \varepsilon_{nx} = 1.4 \, [\mu m] \)
\( \sigma_z = 15 \, \mu m \)
\( \sigma_E = 0.1 \, [MeV] \)

Velocity Bunching @250 pC

GIOTTO
genetic algorithm optimization:

\( \varepsilon_{nx} = 1.5 \, [\mu m] \)
\( \sigma_z = 80 \, \mu m \)
\( \sigma_E = 1.7 \, [MeV] \)
Laminar & Velocity Bunching performances

Slice Energy Spread [keV]

Laminar Bunching

Slice Emittance norm. [μm]

Velocity Bunching

Slice Emittance norm. [μm]
Some Beam Dynamics

**Transverse envelope**

\[ \sigma'' + \frac{\gamma'}{\gamma} \sigma' + \left( \frac{k}{\gamma} \right)^2 \sigma = \frac{Qc}{2I_A \gamma^2 \sigma_0 \sigma} + \frac{\varepsilon_n^2}{\gamma^2 \sigma^3} \]

**Long. envelope equation**

\[ \sigma''_z + K_z \sigma_z + \frac{3 \gamma' \sigma'_z}{\beta^2 \gamma} = \frac{Q \varepsilon}{5 \sqrt{5} l_A \beta^2 \gamma^4 \sigma_z \sigma} + \frac{\varepsilon_n^2}{\beta^2 \gamma^6 \sigma_z^3} \]

\( \gamma \) power of 3

Coupled by \( \sigma_x \)

\( \gamma \) power of 4

**Laminar Parameters**

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

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

1) Longitudinal compression

&

2) bunch stiffness respect to the compression

Emittance compensations
Laminar parameter for LB & VB

**Laminar Bunching**
- $\rho_z$ is low but $> 1$
- A soft bunch for the compression

**Velocity Bunching**
- NO DRIFT (STANDARD case)
- $\rho_z$ starts $>> 1$
- A bunch stiff to be compressed

**Velocity Bunching**
- SI DRIFT (TEST case)
- Laminarity is lost
- $\rho_z < 1$
LB performances VS. bunch-charge: 40;90;150;250 pC

Drift @ 20 MeV

@ booster end
= 17 m (0.5 GeV)

\[ Q_b = 40 \, \text{pC} \]
\[ \sigma_z = 4.2 \, \mu m \]
\[ I_{\text{peak}} > 2.5 kA \]
\[ \varepsilon_{\text{peak}} = 0.3 \, \mu m \]
\[ B_{\text{peak}} = 3 \cdot 10^{16} \]
\[ (I_p = 1.5 kA) \]
\[ (\Delta y/y)_{@I_{\text{peak}}} \approx 8 \cdot 10^{-5} \]
compression factor 40 pc case

@ booster end
= 17 m (0.5 GeV)

$Q_b = 40 \text{ pC}$
$\sigma_z = 4.2 \mu m$
$I_{\text{peak}} > 2.5 kA$
$\varepsilon_{\text{peak}} = 0.3 \mu m$
$B_{\text{peak}} = 3 \cdot 10^{16}$
($I_p = 1.5 kA$)

$(\Delta \gamma / \gamma)@I_{\text{peak}} \approx 8 \cdot 10^{-5}$
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):

![Graph showing long phase space with annotations for correlated and uncorrelated energy spread.]