Advanced Acceleration at SPARC_LAB

Sources for Plasma Accelerators and Radiation Compton with Lasers And Beams

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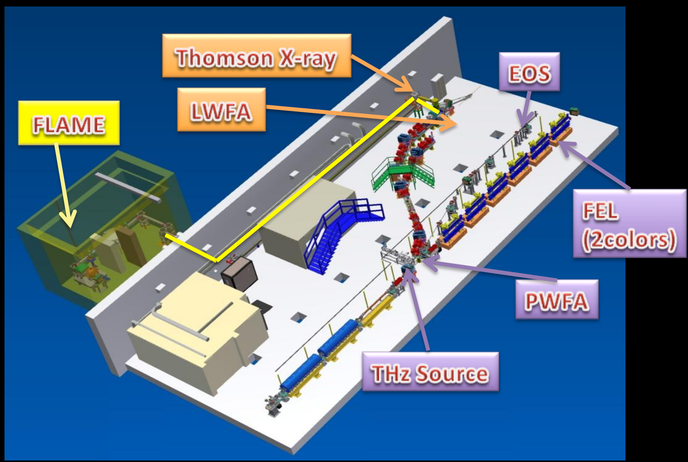
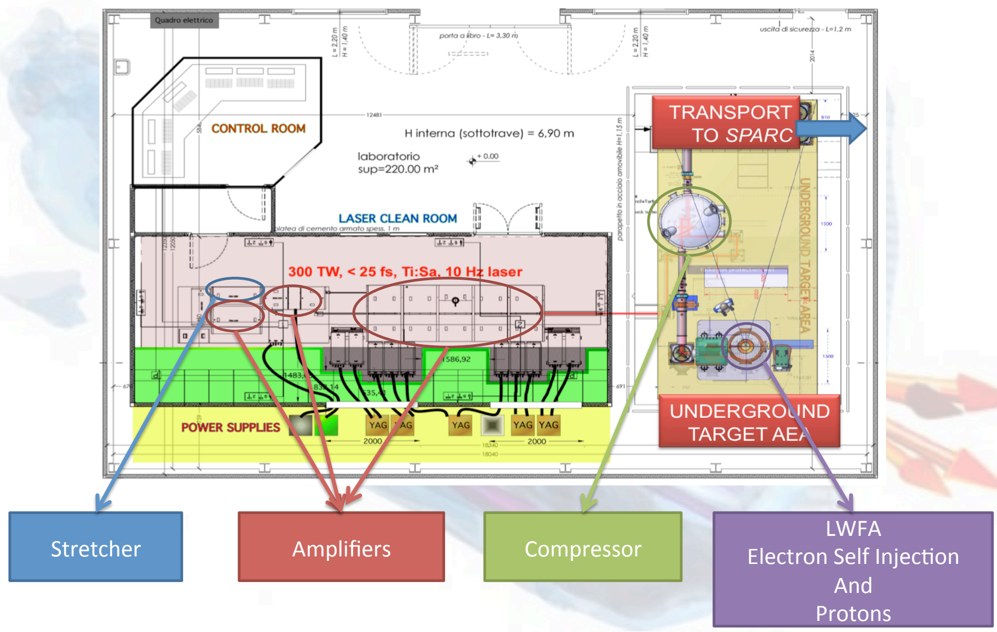
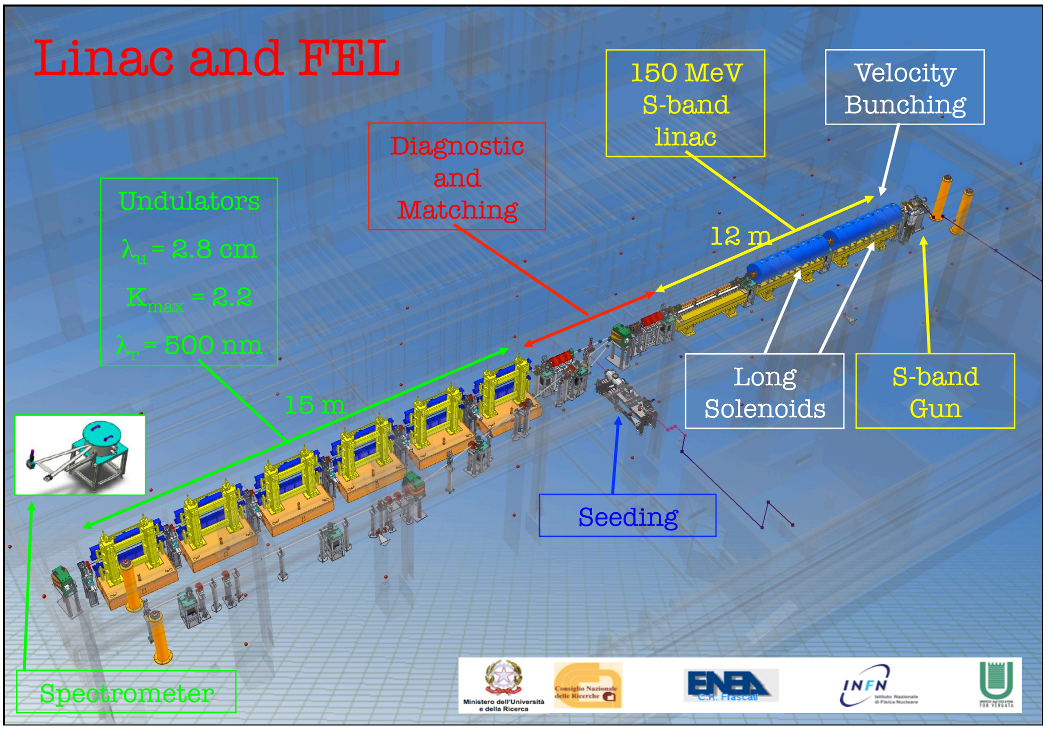
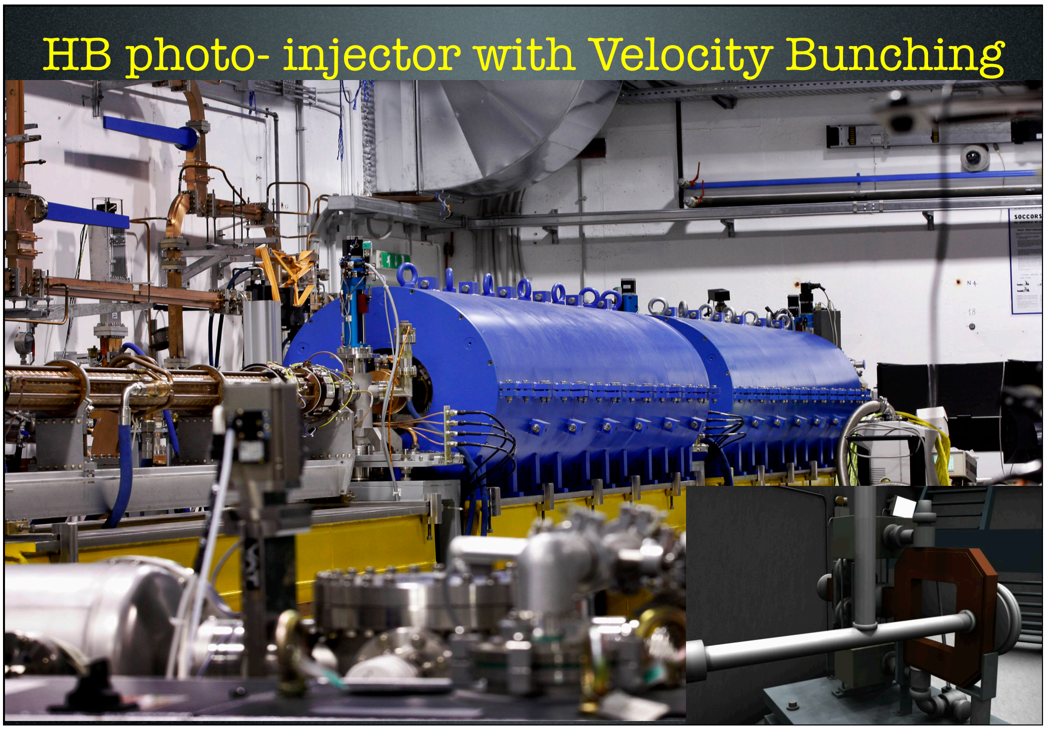


LNF Test Lab – Frascati, June 18, 2014

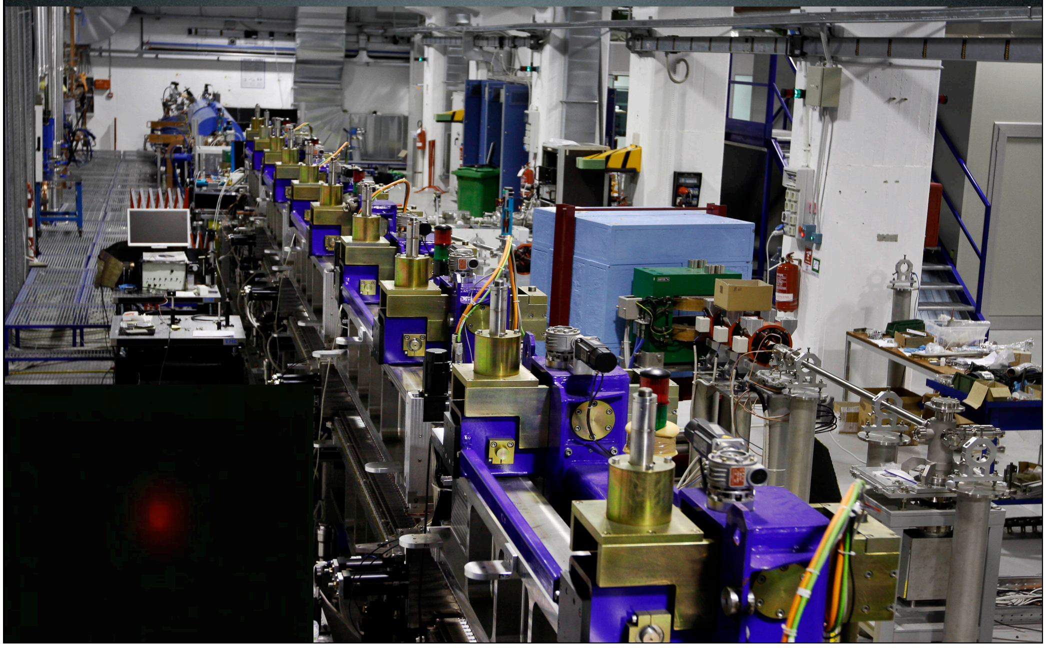
Ti:Sa FLAME laser



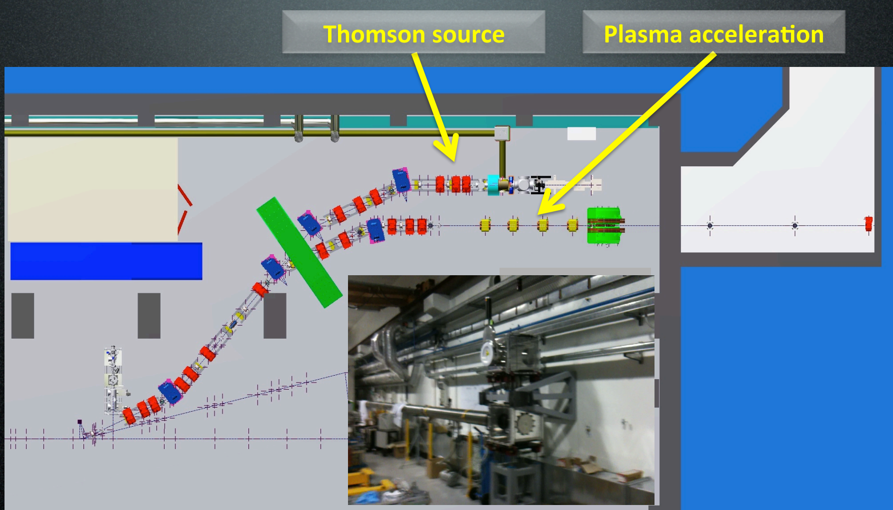

Linac and FEL
150 MeV
S-band
linac
Velocity
Bunching
Diagnostic
and
Matching
Undulators
λ_u = 2.8 cm
K_{max} = 2.2
λ_r = 500 nm
12 m
15 m
Long
Solenoids
S-band
Gun
Seeding
Spectrometer
ENEA
INFN


HB photo- injector with Velocity Bunching

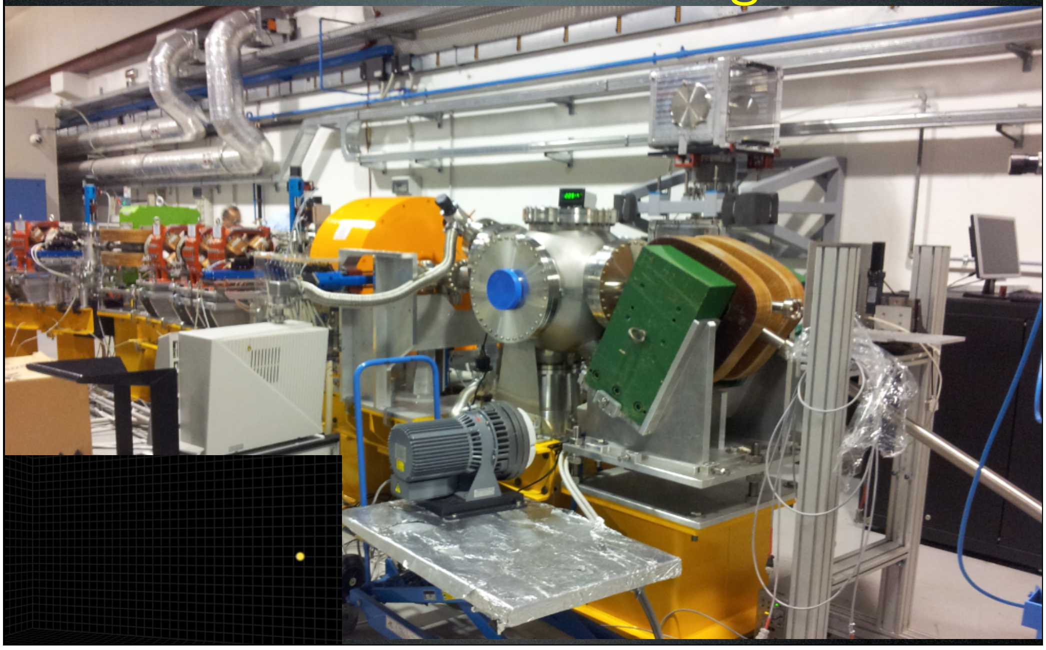
Free Electron Laser



New installations



Thomson back-scattering source

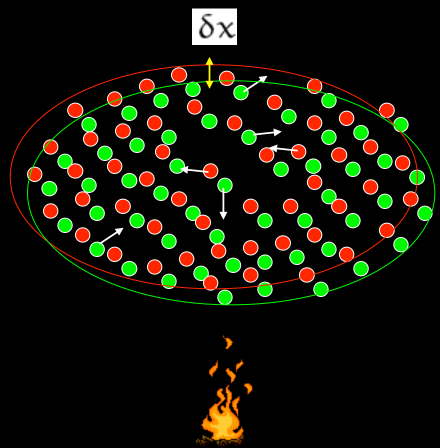


Space Charge induced emittance oscillations in a laminar beam

Neutral Plasma

Surface charge density

$$\sigma = e\,n\,\delta x$$



Surface electric field

$$E_x = -\sigma/\epsilon_0 = -e\,n\,\delta x/\epsilon_0$$

Restoring force

$$m\,\frac{d^2\delta x}{dt^2} = e\,E_x = -m\,\omega_p^{\,2}\,\delta x$$

Plasma frequency

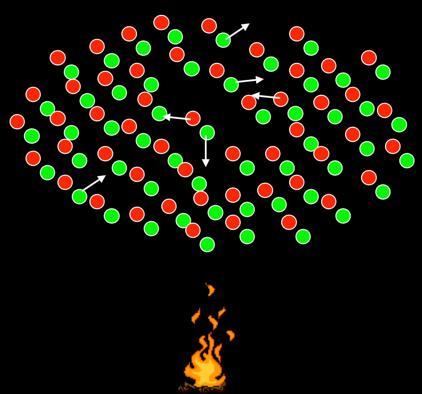
$$\omega_p^{\,2} = \frac{n\,e^2}{\epsilon_0\,m}$$

Plasma oscillations

$$\delta x = (\delta x)_0 \cos(\omega_p\,t)$$

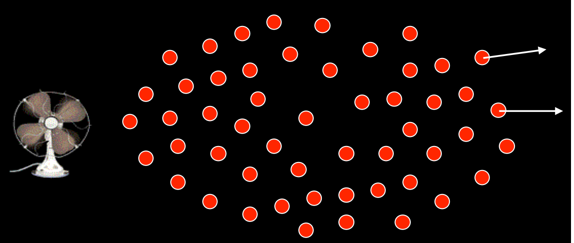
Neutral Plasma

- Oscillations
- Instabilities
- EM Wave propagation



Single Component Cold Relativistic Plasma

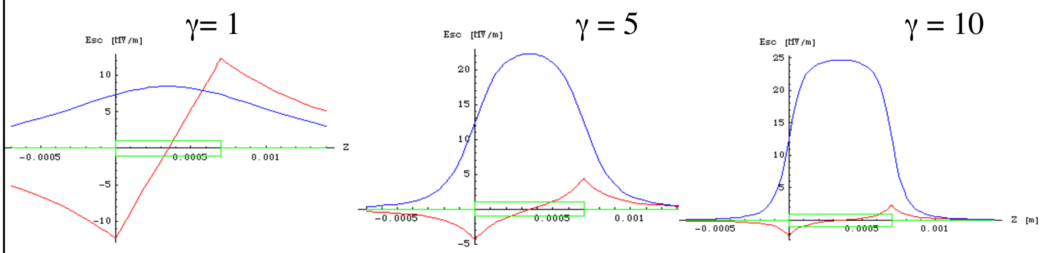
Magnetic focusing



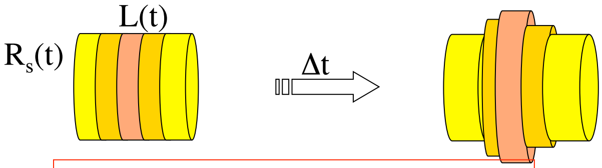
Magnetic focusing

$$E_z(0,s,\gamma) = \frac{I}{2\pi\gamma\varepsilon_0 R^2 \beta c} h(s,\gamma)$$

$$E_r(r,s,\gamma) = \frac{Ir}{2\pi\varepsilon_0 R^2 \beta c} g(s,\gamma)$$



$$F_r = \frac{eE_r}{\gamma^2} = \frac{eIr}{2\pi\gamma^2\varepsilon_0 R^2 \beta c} g(s,\gamma)$$



$$\sigma_x'' + \frac{(\beta\gamma)'}{\beta\gamma}\sigma_x' + k^2\sigma_x = \frac{\varepsilon_n^2}{(\beta\gamma)^2\sigma_x^3} + \frac{k_{sc}(s,\gamma)}{\sigma_x}$$

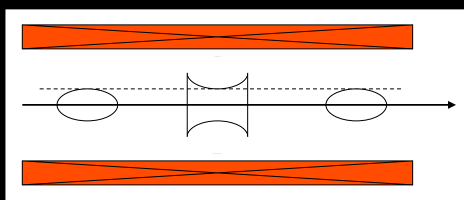
Single Component Relativistic Plasma

$$\sigma'' + k_s^2\sigma = \frac{k_{sc}(s,\gamma)}{\sigma}$$

$$k_s = \frac{qB}{2mc\beta\gamma}$$

Equilibrium solution:

$$\sigma_{eq}(s,\gamma) = \frac{\sqrt{k_{sc}(s,\gamma)}}{k_s}$$



Small perturbation:

$$\sigma(\zeta) = \sigma_{eq}(s) + \delta\sigma(s)$$

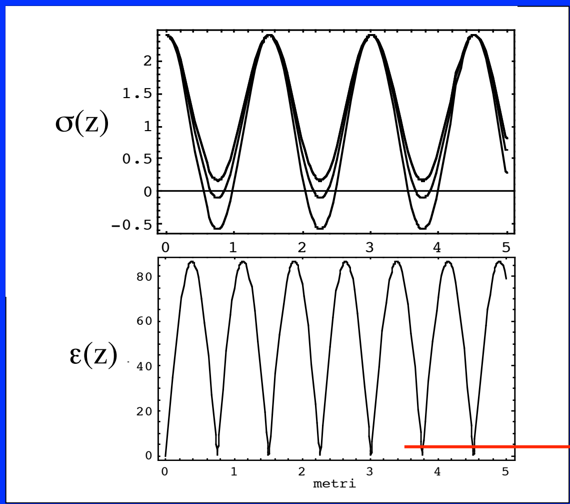
$$\delta\sigma''(s) + 2k_s^2\delta\sigma(s) = 0$$

$$\delta\sigma(s) = \delta\sigma_o(s)\cos\left(\sqrt{2}k_s z\right)$$

Perturbed trajectories oscillate around the equilibrium with the same frequency but with different amplitudes:

$$\sigma(s) = \sigma_{eq}(s) + \delta\sigma_o(s)\cos\left(\sqrt{2}k_s z\right)$$

Envelope oscillations drive Emittance oscillations

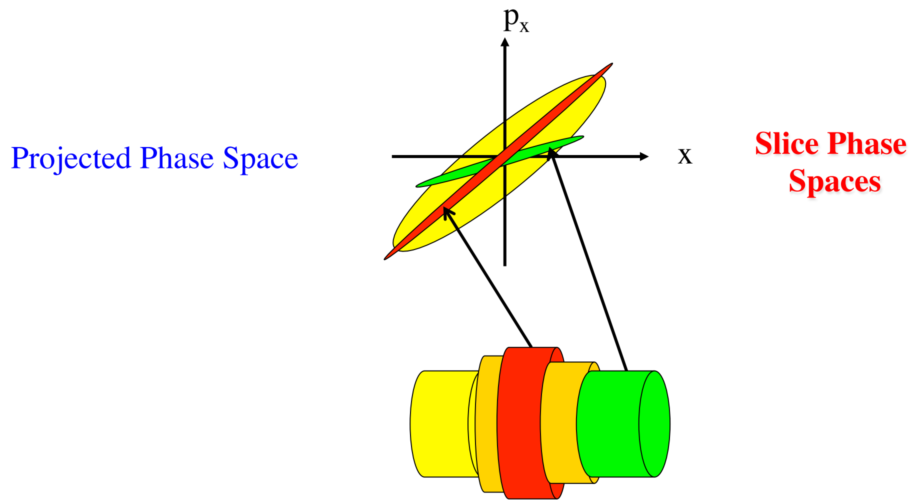


$$\frac{\delta\gamma}{\gamma} = 0$$

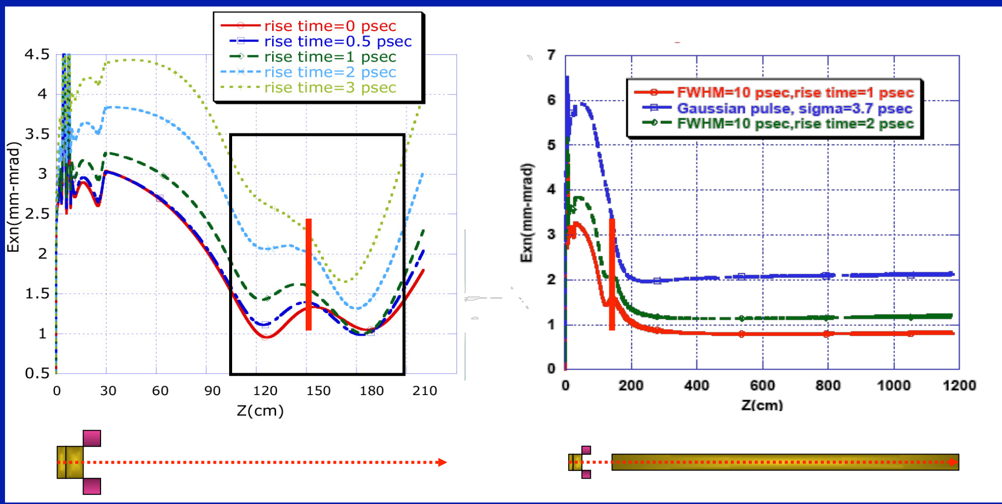
$$\sigma' = 0$$

$$\varepsilon_{rms} = \sqrt{\sigma_x^2 \sigma_{x'}^2 - \sigma_{xx'}{}^2} = \sqrt{\left(\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2\right)} \approx \left| sin\left(\sqrt{2} k_s z\right) \right|$$

Emittance Oscillations are driven by space charge differential defocusing in core and tails of the beam



Emittance evolution for different pulse shapes



Optimum injection in to the linac with:

$$\sigma' = 0$$

$$\gamma' = \frac{eE_{acc}}{mc^2} = \frac{2}{\sigma}\sqrt{\frac{I}{2\gamma I_A}}$$

PRL 99, 234801 (2007) PHYSICAL REVIEW LETTERS week ending 7 DECEMBER 2007

Direct Measurement of the Double Emittance Minimum in the Beam Dynamics of the Sparc High-Brightness Photoinjector

M. Ferrario,[1] D. Alesini,[1] A. Bacci,[3] M. Bellaveglia,[1] R. Boni,[1] M. Boscolo,[1] M. Castellano,[1] L. Catani,[2] E. Chiadroni,[1] S. Cialdi,[3] A. Cianchi,[2] A. Clozza,[1] L. Cultrera,[1] G. Di Pirro,[1] A. Drago,[1] A. Esposito,[1] L. Ficcadenti,[5] D. Filippetto,[1] V. Fusco,[1] A. Gallo,[1] G. Gatti,[1] A. Ghigo,[1] L. Giannessi,[4] C. Ligi,[1] M. Mattioli,[7] M. Migliorati,[5] A. Mostacci,[5] P. Musumeci,[6] E. Pace,[1] L. Palumbo,[5] L. Pellegrino,[1] M. Petrarca,[7] M. Quattromini,[4] R. Ricci,[1] C. Ronsivalle,[4] J. Rosenzweig,[6] A. R. Rossi,[3] C. Sanelli,[1] L. Serafini,[3] M. Serio,[1] F. Sgamma,[1] B. Spataro,[1] F. Tazzioli,[1] S. Tomassini,[1] C. Vaccarezza,[1] M. Vescovi,[1] and C. Vicario[1]

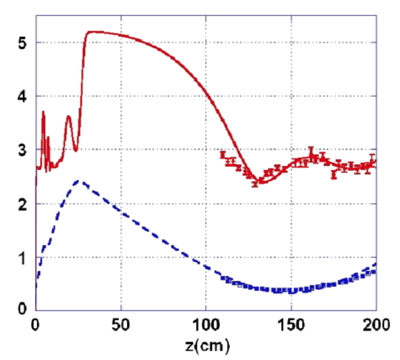
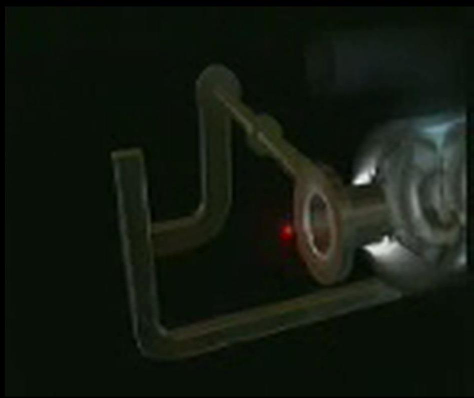


FIG. 6 (color online). rms envelope and rms norm. emittance evolution from the cathode up to the beam line end as computed by PARMELA, compared to measurements taken in the emittance-meter range.

The “problem” of relativistic bunch compression

Low energy electron bunch injected in a linac:

$\gamma \approx 1$
$L_b = 3mm \approx L'_b$
$I = 100A$



Length contraction?

~~$\gamma = 1000$~~
~~$L_b = \dfrac{L'_b}{\gamma} = 3\mu m$~~
~~$I = 100kA$~~

Why do we need a bunch compressor?

Bunch length in the moving frame S’

More interesting is the bunch dynamics as seen by a moving reference frame S’, that we assume it has a relative velocity V with respect to S such that at the end of the process the accelerated bunch will be at rest in the moving frame S’. It is actually a deceleration process as seen by S’

Inverse Lorentz transformations:

$$\begin{cases} ct' = \gamma\left(ct - \dfrac{V}{c}z\right) \\ z' = \gamma(z - Vt) \end{cases}$$

leading for the tail particle to:

$$\begin{cases} t'_{o,t} = t_o = 0 \\ z'_{o,t} = z_{o,t} = 0 \end{cases}$$

and for the head particle to:

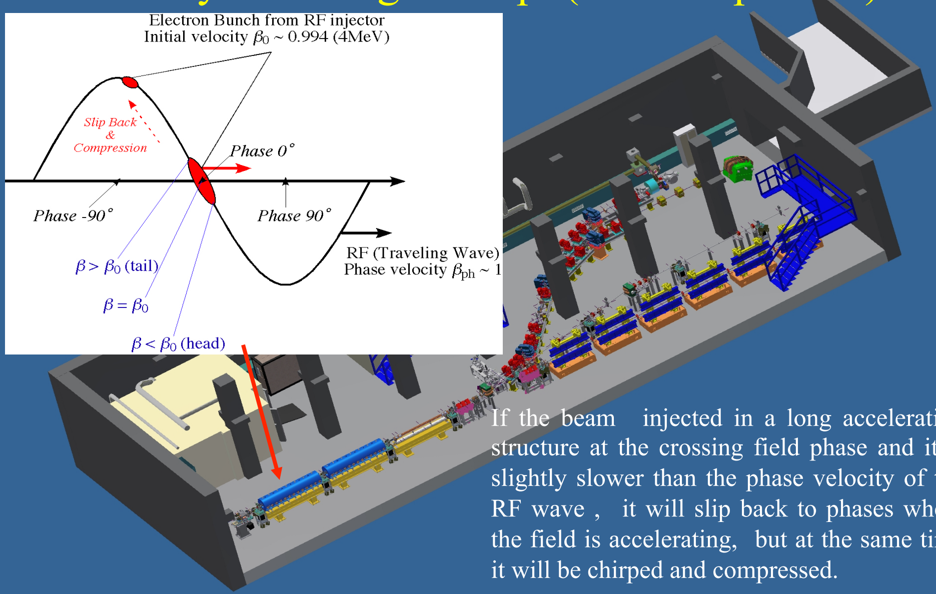
$$\begin{cases} t'_{o,h} = -\dfrac{V}{c}\gamma'_o L_o < t_o \\ z'_{o,h} = \gamma'_o L_o > z_{o,h} \end{cases}$$

The key point is that as seen from S’ the decelerating force is not applied *simultaneously* along the bunch but with a *delay* given by:

$$\Delta t'_o = t'_{o,h} - t'_{o,t} = -\frac{V}{c}\gamma'_o L_o < 0$$

Velocity Bunching

Velocity bunching concept (RF Compressor)



If the beam injected in a long accelerating structure at the crossing field phase and it is slightly slower than the phase velocity of the RF wave , it will slip back to phases where the field is accelerating, but at the same time it will be chirped and compressed.

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Experimental Demonstration of Emittance Compensation with Velocity Bunching

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