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MAXIMUM BRIGHTNESS OF LINAC-DRIVEN ELECTRON BEAMS IN THE PRESENCE OF COLLECTIVE EFFECTS

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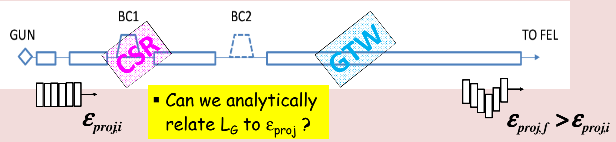
References:
S. Di Mitri, Phys. Rev. ST – Accel. Beams, 16, 050701 (2013).
S. Di Mitri, S. Spampinati, Phys. Rev. ST – Accel. Beams, 17, 110702 (2014).

Linear accelerators capable of delivering high brightness electron beams are essential components of a number of research tools, such as free electron lasers (FELs) and elementary particle colliders. In these facilities the charge density is high enough to drive un-desirable collective effects (wakefields) that may in-crease the beam emittance relative to the injection level, eventually degrading the nominal brightness. We formulate a limit on the final electron beam bright-ness, imposed by the interplay of geometric transverse wakefield in accelerating structures and coherent synchrotron radiation in energy dispersive regions. Numerous experimental data of VUV and X-ray FEL drivers validate our model. This is then used to show that a normalized brightness of 1016 A/m2, promised so far by ultra-low charge beams (1-10 pC), can in fact be reached with a 100 pC charge beam in the Italian FERMI FEL linac, with the existing machine configuration.

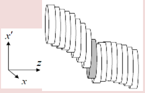
PROBLEM:

Collective effects (**C**oherent **S**ynchrotron **R**adiation, **G**eometric **T**ransverse **W**akefield) "misalign" bunch slices in the transverse phase space: **ε_{proj} is increased** albeit ε_{slice} may be not, whereas $L_{slice} \approx L_{coop} \ll L_{bunch}$.

- This is the picture we have in mind:



- Can we analytically relate L_G to ε_{proj} ?



PROJECTED EMITTANCE GROWTH:

We now consider ***error kicks*** that affect ***individual slices***, e.g. from CSR in a dipole, and from GTW in an RF cavity. The "Σ-matrix" provides an *RMS estimate* of $\Delta\varepsilon_{proj}$ induced by those perturbations. As an example, for a pure angular error (~Δx′):

$$\varepsilon_{x,1} \cong \sqrt{\det \varepsilon_{x,0}\begin{pmatrix} \beta_x & -\alpha_x \\ -\alpha_x & \gamma_x + \langle \Delta x'^2 \rangle / \varepsilon_{x,0} \end{pmatrix}} = \varepsilon_{x,0}\sqrt{1+\frac{\beta_x \langle \Delta x'^2 \rangle}{\varepsilon_{x,0}}}$$

RMS kick averaged over all the slices.

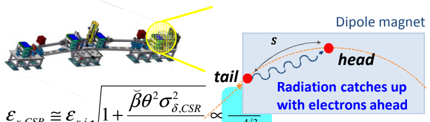
Twiss functions are at the location of the perturbation

Optics can be designed to minimize the effect on the emittance.

COLLECTIVE EFFECTS (Coherent Sunchrotron Radiation, Geometric Transverse Wakefield)

Consider the *uncorrelated* sum of CSR kicks in magnetic compressors and GTW kicks in the linac.

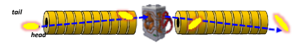
CSR in a 4-Dipole Compressor[4]:



Radiation catches up with electrons ahead

$$\varepsilon_{x,CSR} \cong \varepsilon_{x,i}\sqrt{1+\frac{\breve{\beta}\theta^2\sigma^2_{\delta,CSR}}{\varepsilon_{x,i}}} \propto \sigma_z^{4/3}$$

GTW in RF cavities[5]:



$$\varepsilon_{x,GTW} \cong \varepsilon_{x,i}\sqrt{1+2\left(\frac{\pi r_e}{Z_0 ce}\right)^2 \frac{Q^2\overline{W}_\perp^{\,2}(2\sigma_z)L_{FODO}L_{tot}\overline{\beta}}{\varepsilon_{x,i}\sqrt{\gamma_0\gamma_f}}\Delta^2} \propto \sigma_z^{1/2}$$

$$\varepsilon_{n,f} \cong \varepsilon_{n,i}\sqrt{\left(1+P^{L1}_{GTW}\right)\left(1+P^{BC1}_{CSR}\right)\ldots\left(1+P^{Lm}_{GTW}\right)\ldots\left(1+P^{BCn}_{CSR}\right)\ldots} \approx \varepsilon_{n,i}\sqrt{1+\sum_{i=1}^{n}P^i_{CSR}+\sum_{j=1}^{m}P^j_{GTW}}$$

3-D GAIN LENGTH ("PROJECTED"):

$$L_{G,3D} = L_G\left[1+\Lambda\left(\varepsilon_{x,y},\sigma_\delta\right)\right]$$ Single slice dynamics

$$L_{G,SKE} \approx \frac{L_G}{1-\pi\theta^2_{SKE}/\theta^2_c}$$ De-bunching

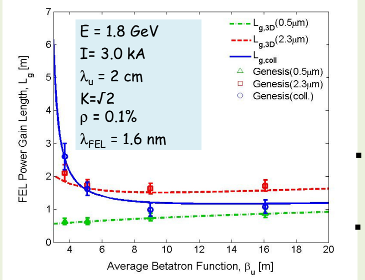
$$\varepsilon_{n,f} \approx \varepsilon_{n,i}\sqrt{1+\frac{\gamma\beta_u\langle\theta^2_{coll}\rangle}{\varepsilon_{n,i}}}$$ Projected dynamics

We propose[7]:

This depicts the slice dynamics

$$L_{G,coll} \approx \frac{L_{G,3D}}{1-\pi\langle\theta^2_{coll}\rangle/\theta^2_{th}}, \qquad \theta_{th} \equiv \sqrt{\lambda/L_{G,3D}}$$

This depicts the projected dynamics

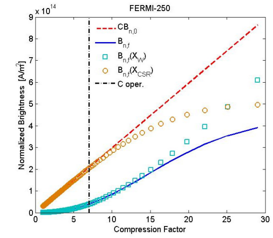


❑ Tested with Genesis, t-dependent simulations:
1) - - - $\varepsilon_{n,proj} = \varepsilon_{n,slice}$ = 0.5 μm
2) - - - $\varepsilon_{n,proj} = \varepsilon_{n,slice}$ = 2.3 μm
3) - - - $\varepsilon_{n,proj}$ = 2.3 μm > $\varepsilon_{n,slice}$ = 0.5 μm

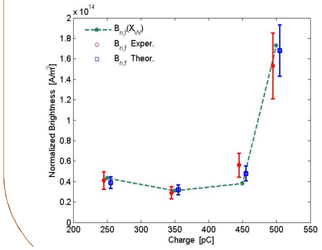
- Intuitively, we expect L_G of 3) in between that of 1) and 2); confirmed by simulations.
- $\beta_u := (\langle\beta_x\rangle\langle\beta_y\rangle)^{1/2}$; the scan spans different scenarios of radiation diffraction.

BRIGHTNESS (MEASUREMENT VS. THEORY):

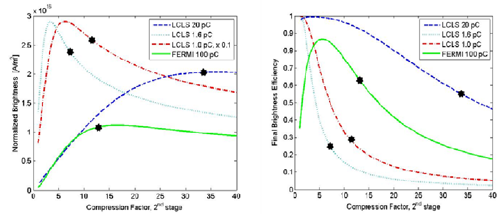
A first hint comes from the case of a bunch subjected to ***dipole-like kicks*** in the ***undulator***[2], e.g. from steerers or misaligned quadrupoles.



Theoretical final normalized brightness in the FERMI linac as a function of the compression factor, for 250pC beam charge.



Measured (circles) and predicted (squares) normalized brightness at the end of the FERMI linac as a function of the beam charge. The compression factors are 7, 6, 6 and 12 for beam charge values of 250, 350, 450 and 500 pC, respectively.



Final normalized brightness (top) and brightness effi-ciency (bottom) as a function of the compression fac-tor in the second compressor, for the scenarios depict-ed in Tab.2. The star identifies the compression factor that is needed to a reach 1.5 kA final peak current.

COLLECTIVE ANGLE:

This is solely determined by the linac dynamics.

$$\varepsilon_{n,f} \approx \varepsilon_{n,i}\sqrt{\prod_{i=1}^{m}\left(1+P^i\left(\varepsilon_{n,i-1}\right)\right)} \equiv \varepsilon_{n,i}\sqrt{1+\frac{\gamma\beta_u\langle\theta^2_{coll}\rangle}{\varepsilon_{n,i}}}$$

This is the resultant angular spread of the bunch slices' centroids.

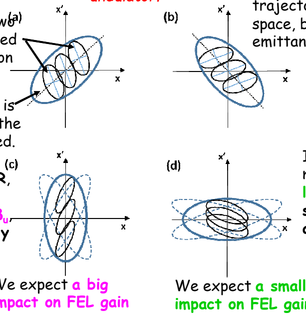
This is <β> in the undulator.

In the LINAC, two slices are displaced along the direction of the kick.

The slice emittance is unperturbed, while the projected is enlarged.

AFTER the kick(s), the slices follow different trajectories in phase space, but the projected emittance is preserved:

$$\beta\langle\theta^2_{coll}\rangle = cte$$



In the UNDULATOR, if the beam is matched to a **small β_u**, the **slices are largely dispersed in angle:**

$$\langle\theta^2_{coll}\rangle \neq 0$$

We expect **a big impact on FEL gain**

If the beam is matched to a **large β_u**, the **slices overlap in angle:** $\langle\theta^2_{coll}\rangle \to 0$

We expect **a small impact on FEL gain**

CONCLUSIONS: **1) The degradation of the beam transverse projected emittance affects the FEL performance even though the slice emittance is preserved. 2) The enlargement of the FEL power gain length due to a dilution of the projected emittance can be counteracted by a relatively large average betatron function in the undulator line. 3) The analytical model allows one to investigate and to optimize an accelerator layout by scanning the FEL properties vs. the compression strength, the linac-to-beam misalignment, and the betatron function in the magnetic compressor.**

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