WP3
Magnetic Compressor Design Study

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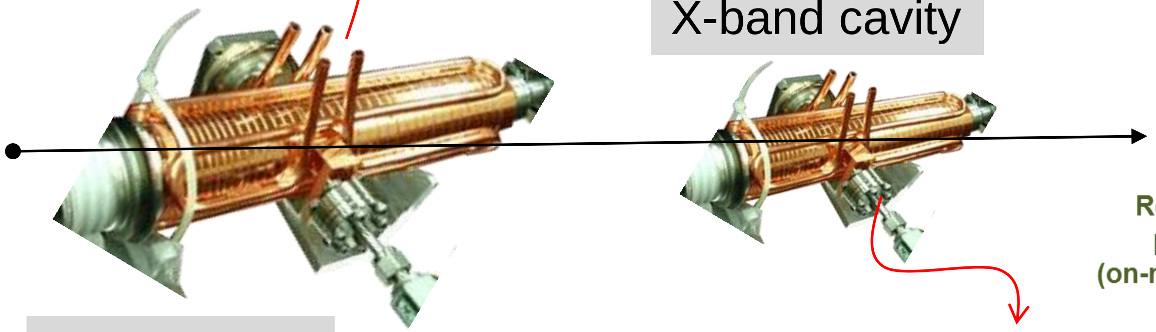
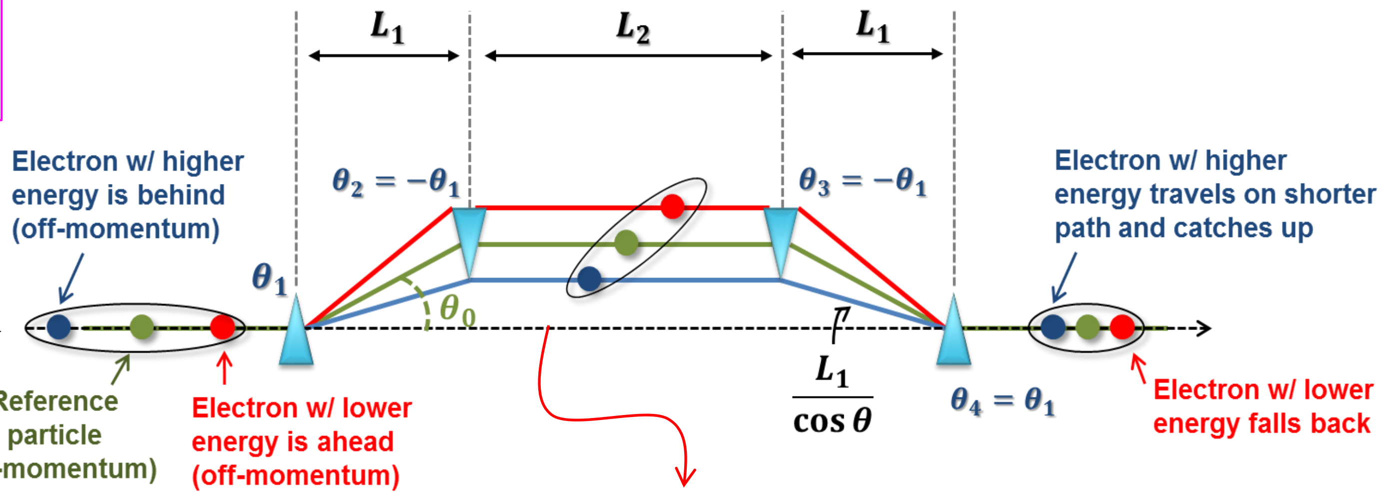
Analytical Estimates

$$\sigma_C^2 \cong (C-1)^2 \frac{\sigma_\phi^2}{\tan^2 \phi}$$

- C>>1, $\sigma_\phi = 0.1$deg
- $\sigma_C < 5\%$

→ **$\Delta\phi_{RF} < 25$ deg**





$$e\Delta V_H = \frac{1}{\left(k_H^2/k^2 - 1\right)} \left\{ E_{BC} \left[1 + \frac{2}{k^2} \frac{T_{566}}{|R_{56}|^3} \left(1 - \frac{1}{C}\right)^3 \right] - E_i \right\}$$

$$R_{56} \cong -2\theta_0^2 \left(L_1 + \frac{2}{3} l_d \right)$$

- C>>1, $E_{BC1} < 300$ MeV
- H = 4

→ **$\Delta V_{Xb} < 25$ MV**

- Practical θ to limit CSR-induced ε_x-growth is < 0.1 rad
- Total length < 15 m

→ **$R_{56} < 50$ mm**

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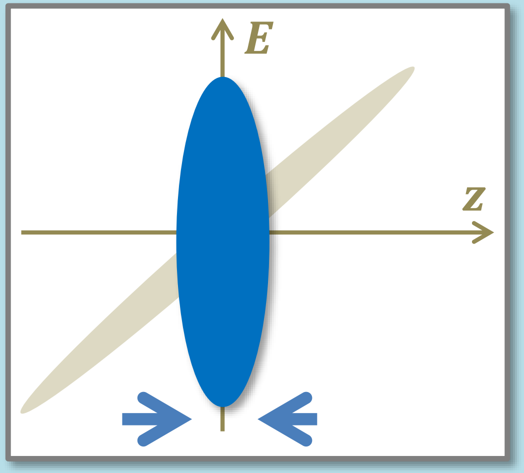
Bunch Length, Slice Energy Spread

$$1 + R_{56}h_1 = 0$$



"Full-compression" (min. bunch length set by uncorrelated energy spread

$$\sigma^2_{u,f} = \sigma^2_{u,i}\left(1 - Ch_i R_{56}\right)^2 = C^2\sigma^2_{u,i}$$

SX FEL looks OK

HX FEL looks critical:
Nonlinear compression (single spike) ?

$$dz_f = dz_i + R_{56}d\delta \cong dz_i + R_{56}\frac{dE}{E_0} = dz_i\left(1 + R_{56}\frac{1}{E_0}\frac{dE(z)}{dz_i}\right) + R_{56}\frac{dE_{unc}}{E_0} = dz_i\left(1 + h_i R_{56}\right) + R_{56}\delta_{unc} \equiv dz_i/C + R_{56}\delta_{unc}$$

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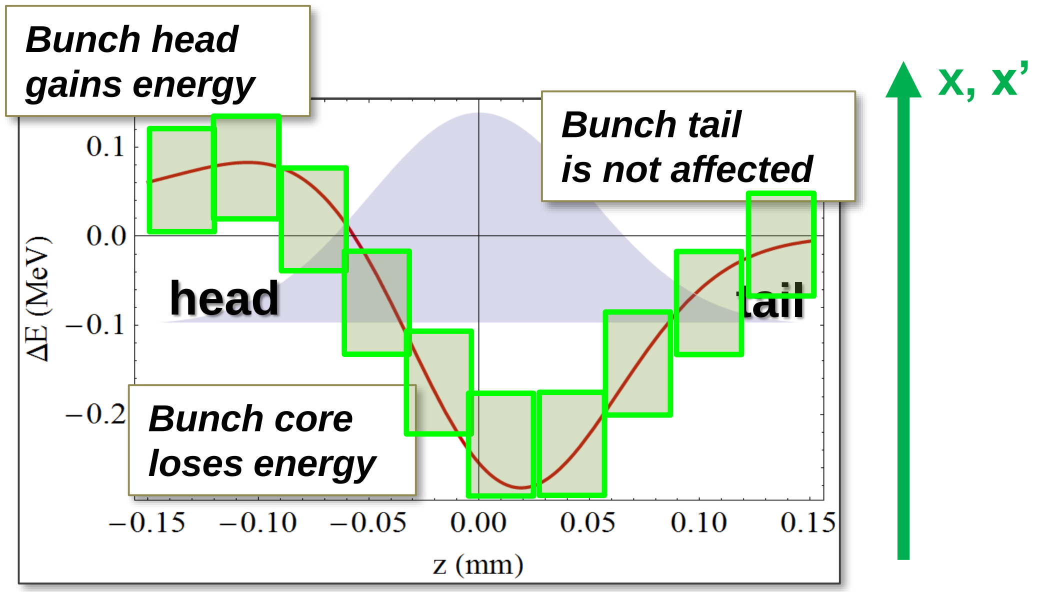
CSR – Projected Emittance Growth

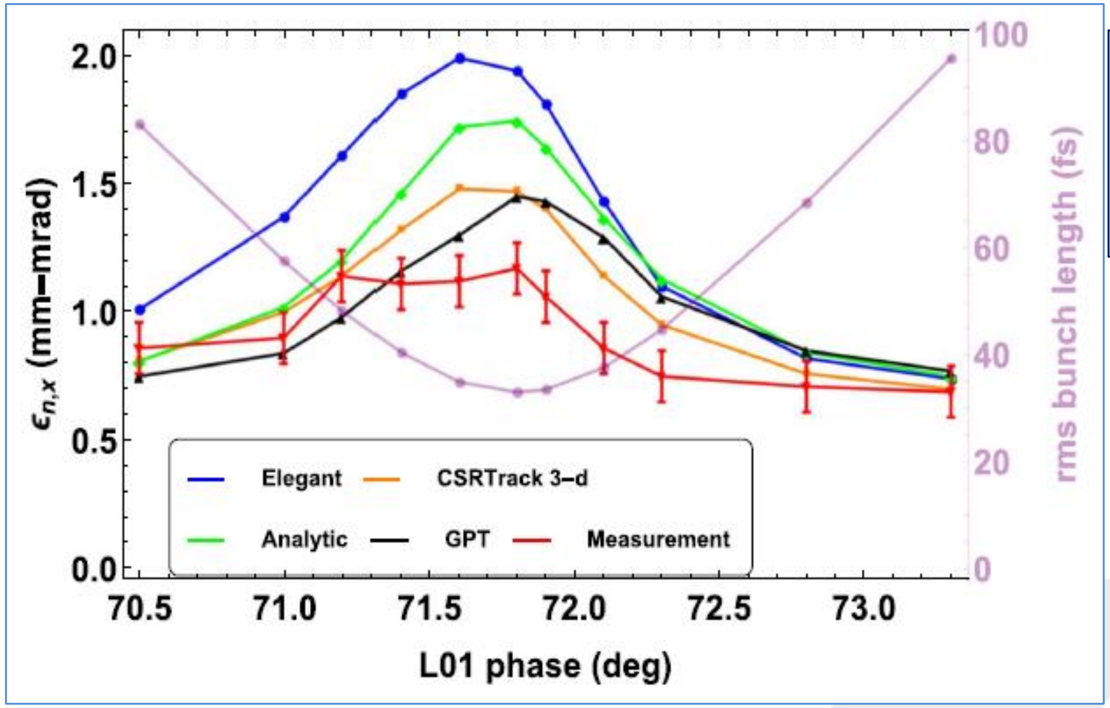
- In a 4-dipoles chicane, the CSR effect is ***stronger*** in the last dipole, where the bunch is ***shorter:***

$$\varepsilon_x^2 = \varepsilon_{x,0}^2 + \varepsilon_{x,0}\left(\beta_x\left\langle \Delta x'^2\right\rangle + 2\alpha_x\left\langle \Delta x \Delta x'\right\rangle + \gamma_x\left\langle \Delta x^2\right\rangle\right)$$

$$\left\langle \Delta x^2\right\rangle = \eta_x^2\sigma_{\delta,CSR}^2, \left\langle \Delta x'^2\right\rangle = \eta'^2_x\,\sigma_{\delta,CSR}^2$$

$$\sigma_{\delta,CSR} = 0.2459 r_e C^{4/3}\frac{N_e R^{1/3}\theta}{\gamma\sigma_{z,i}^{4/3}},$$





100pC
300 MeV
θ=0.105rad
R_{56}=-50 mm

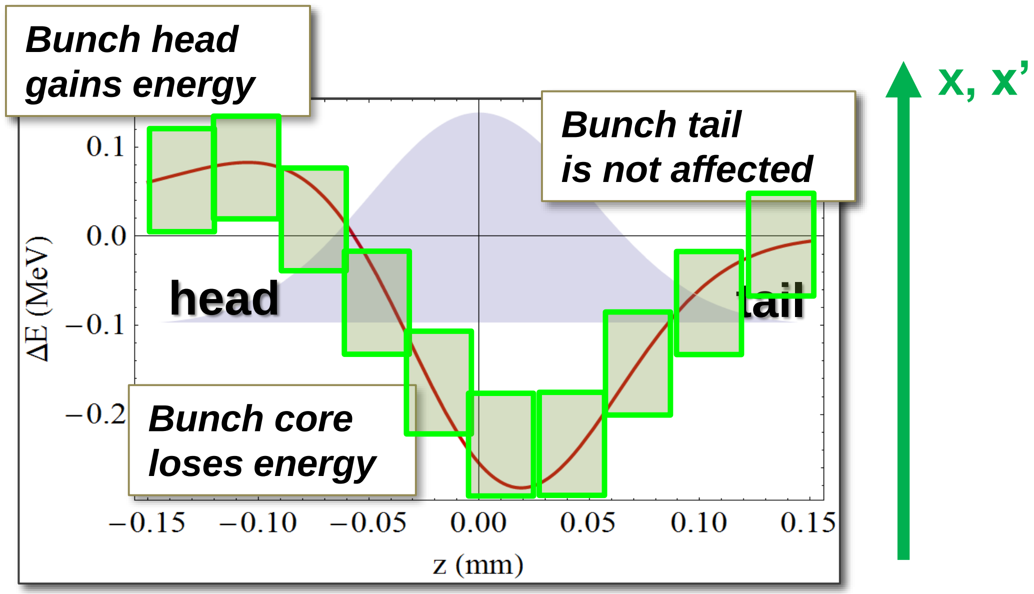
A. Brynes et al., NJP (2018)

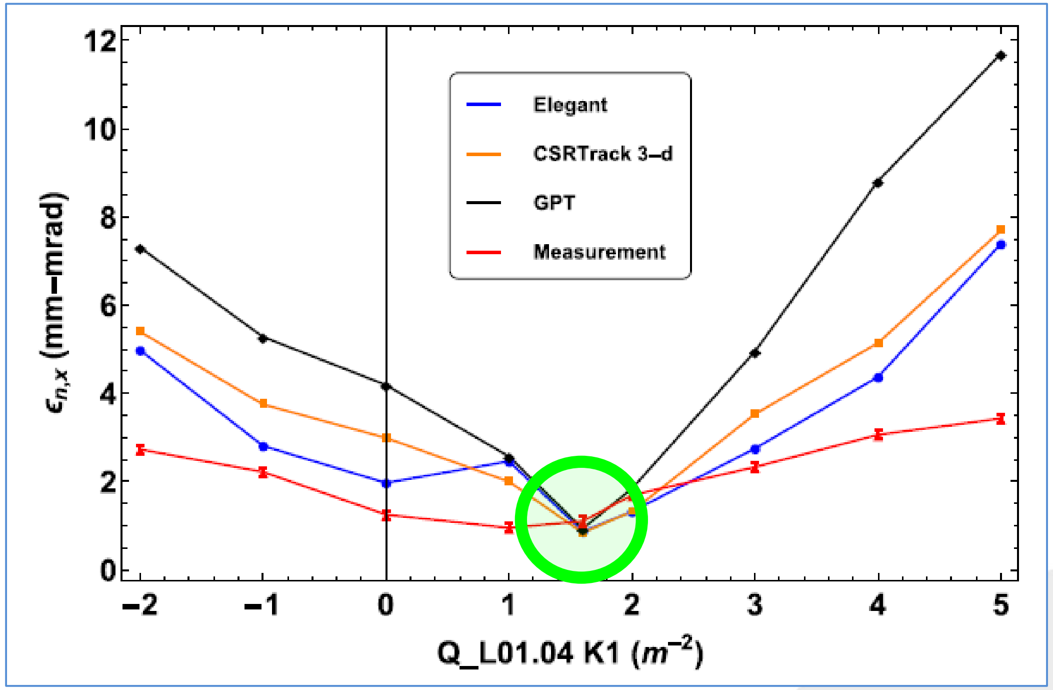
CSR – Linear Optics

- In a 4-dipoles chicane, the CSR effect is ***stronger*** in the last dipole, where the bunch is ***shorter:***

$$\varepsilon_x^2 = \varepsilon_{x,0}^2 + \varepsilon_{x,0}\left(\beta_x\langle\Delta x'^2\rangle + 2\alpha_x\langle\Delta x\Delta x'\rangle + \gamma_x\langle\Delta x^2\rangle\right) \approx \varepsilon_{x,0}^2 + \varepsilon_{x,0}\left(\breve{\beta}_x\theta^2\sigma_{\delta,CSR}^2\right)_{4th\ dipole}$$

Horizontal waist between 3rd and 4th dipole; θ <<1





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CSR – Nonlinear Optics

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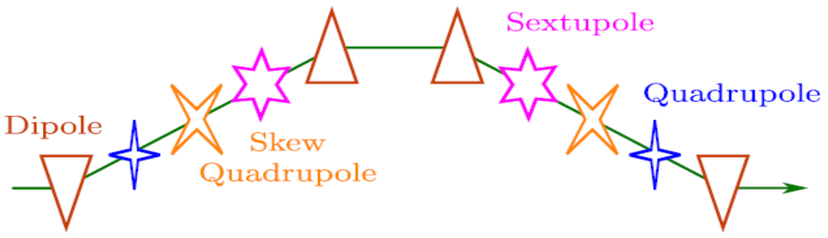
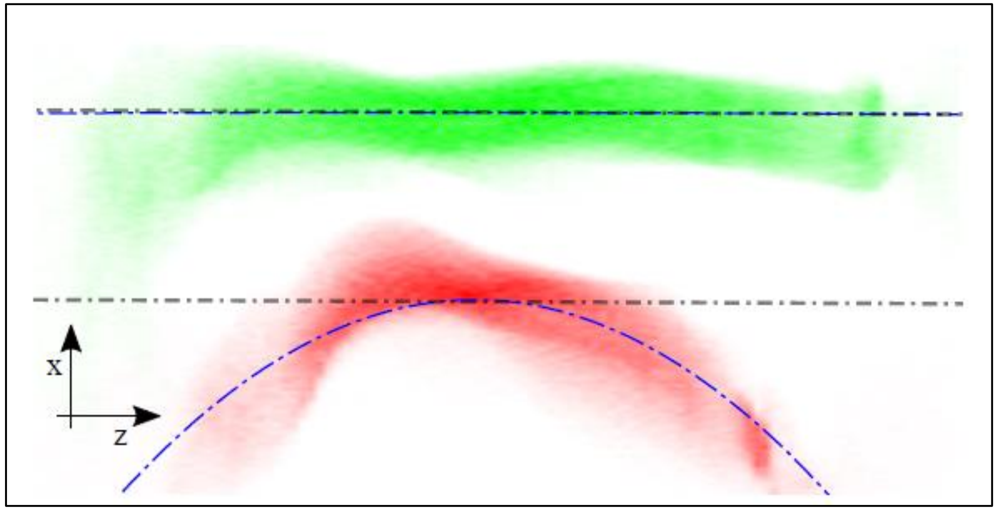
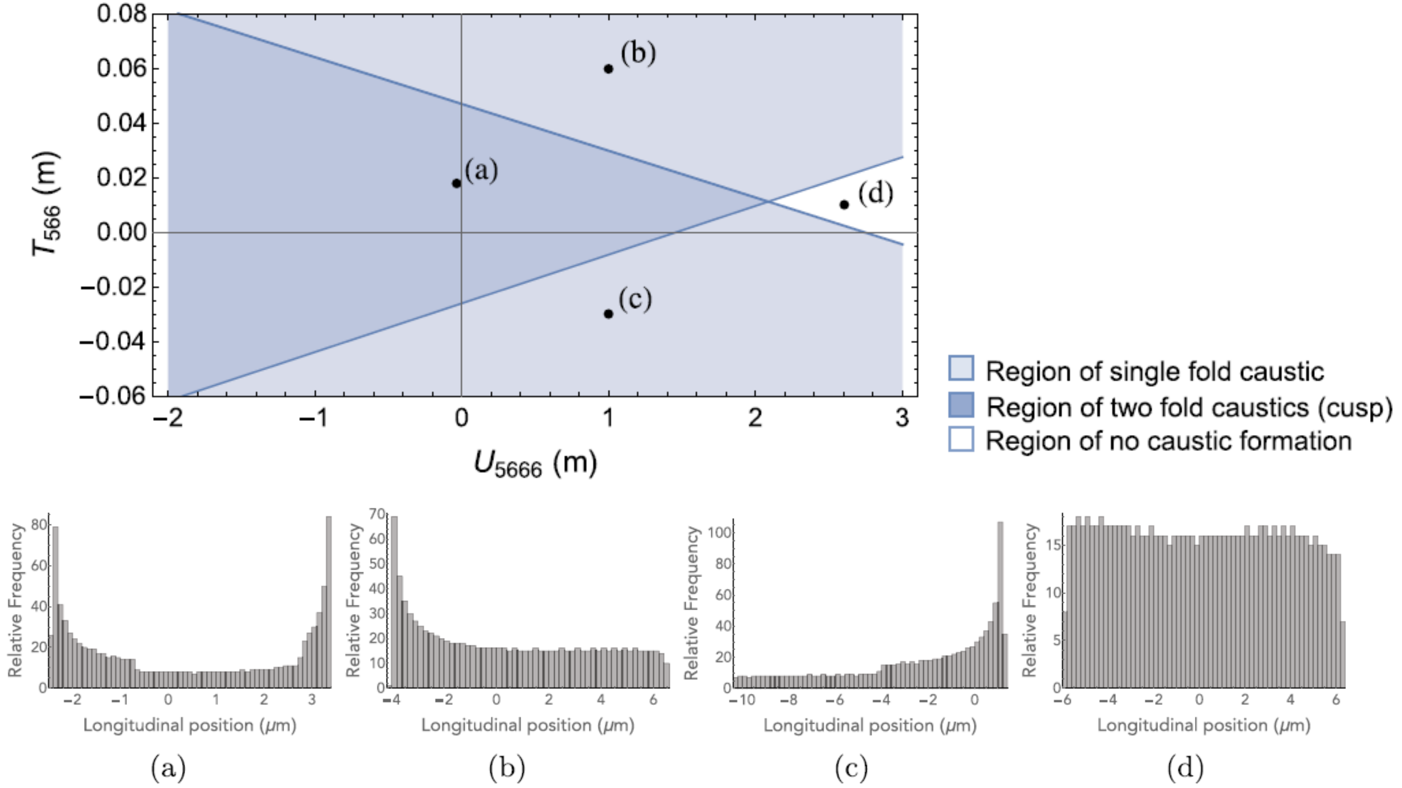
M. Guetg (2013)





T. Charles (2016)



- ❑ Multiple optical knobs (quads, skew quads, sextupoles) to align slice centroids in (x,x′,y,y′).
- ❑ Current profile almost unchanged.
- ❑ Weak sextupoles for control up to 3rd order.
- ❑ Current spikes are suppressed, compression "efficiency" increased.

CSR – Other Methods

1. Bunch **current shaping** (ramped, trapezoidal, etc.) from the injector to "linearize" the CSR wake.
   - This implies most likely non-uniform slice optics and emittance. Emittance compensation can be limited.
2. **Shielding** of CSR wake with low gap chambers.
   - Typically not practical (beam losses and resistive wall wakefields) as < 2 mm (or so) radius pipe is required.
3. **Linear optics** cancellation of CSR kicks by combination of **multiple compressors.**
   - This requires very accurate optics tuning along a large portion of the accelerator. It strongly depends on specific beam parameters at the compressors.
4. **"Adiabatic" compression** – split compression in multiple (> 2) stages.
   - This is adopted at PAL XFEL with good results. On paper, 3 chicanes give a lower emittance than 2. In reality, 3 chicanes are the nominal configuration.

Lessons Learned & Plan

1. Assumption: **Q = 50 – 100 pC, I = 2 / 9 kA, CF > 150**
2. **Chicanes** are most suitable devices for allowing E-chirp compensation at a later linac stage
3. **2-stage** compression (+ VB ?) are most likely mandatory for the **HX FEL**
4. Projected normalized emittance growth will be **> 0.2 μm rad** for C>100
5. Minimization of CSR effect mainly through **linear and nonlinear optics tuning** through each BC.

- Semi-analytical setting of compression scheme (Elettra)
- S2E run with Tstep + Elegant, including CSR and ways to overcome it (INFN)
- S2E run finalized with GPT/Tstep + Placet (ALBA, CERN)
- Comparison of performance vs. passive linearizer (LAL, CERN)

SX FEL – F. Nguyen 18 Oct.'18

Undulator parameters	
undulator period	1.7 cm
undulator gap	3 mm
deflection parameter (RMS)	1.9
Bunch parameters	
beam energy	4 GeV
pulse duration (FWHM)	10 fs
bunch charge	20 pC
peak current	1.9 kA
norm. emittance	0.12 mm×mrad
energy spread	0.01 %
Potential reach	
FEL wavelength ($\hbar\omega$)	0.66 nm (1.9 keV)
N_γ/pulse	5.6×10^{11}
E_{FEL}/pulse	0.2 mJ
saturation length	21 m

Small increase in E_{beam} allows to reach for 0.6 nm (2 keV) comfortably

Emittance stays well between Pellegrini's and Di Mitri's limits

Variable polarization & Two Colours operations require careful feasibility studies with these undulator parameters, in particular at small period:

H. M. Castaneda Cortes is tackling this issue in WP5 and is greatly acknowledged

Please, stay FEL-tuned

HX FEL – F. Nguyen 18 Oct.'18

Undulator parameters	
undulator period	1.3 cm
undulator gap	3 mm
deflection parameter (RMS)	1.17
Bunch parameters	
beam energy	9 GeV
pulse duration (FWHM)	7.5 fs
bunch charge	75 pC
peak current	9 kA
norm. emittance	0.12 mm×mrad
energy spread	0.01 %
Potential reach	
FEL wavelength ($\hbar\omega$)	0.05 nm (25 keV)
N_γ/pulse	2.5×10^{11}
E_{FEL}/pulse	1 mJ
saturation length	25 m

Stay in the middle!

Hard to reach for 1 mJ energy/pulse with much lower charge or much higher emittance

Hard to achieve much lower emittance with such a charge

Bottom line: this is our choice, but feel free to round up values at your convenience and risk!

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