Longitudinal and transverse beam manipulation for compact Laser Plasma Accelerator based free-electron lasers

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Outline

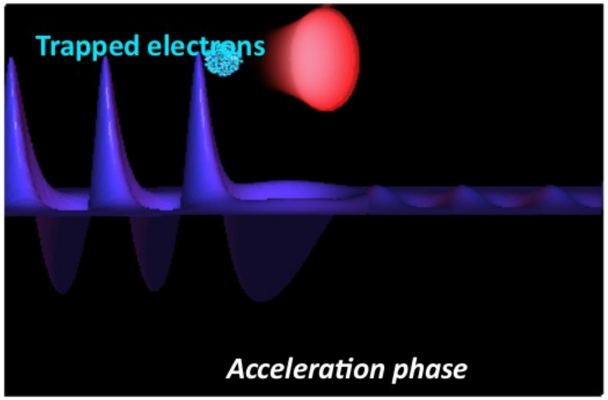
LPA beam characteristics

Beam transfer and manipulations

FEL simulations

Conclusion

LPA beams



T. Tajima and J. M. Dawson, Phys. Rev. Lett. 43, 267 (1979).

Main present characteristics :

Few hundreds MeV to 1 GeV energy

Few kA to10 kA peak current

Short bunches ~ fs level

Large energy spread ~ percent level

Large initial divergence ~ mrad level

They complicate the transfer and FEL

LPA beams

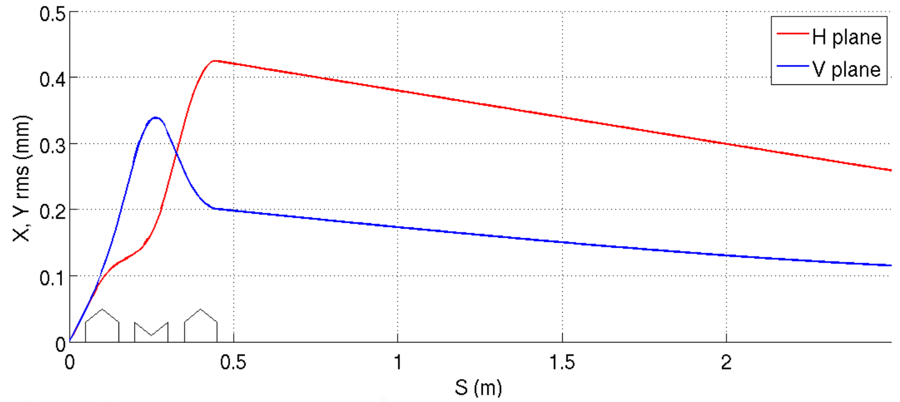
400 MeV Initial LPA beam :

- 4 kA peak
- 1 µm rms length
- 1 % rms relative energy spread
- 1 mrad rms divergence
- $\gamma\varepsilon$ = 1 π.mm.mrad rms

S. Fritzler et al., PRL 2004
W.P. Leemans et al., Nat. Phy. 2006
C. Rechatin et al., PRL 2009
O. Lundh et al., Nat. Phy. 2011

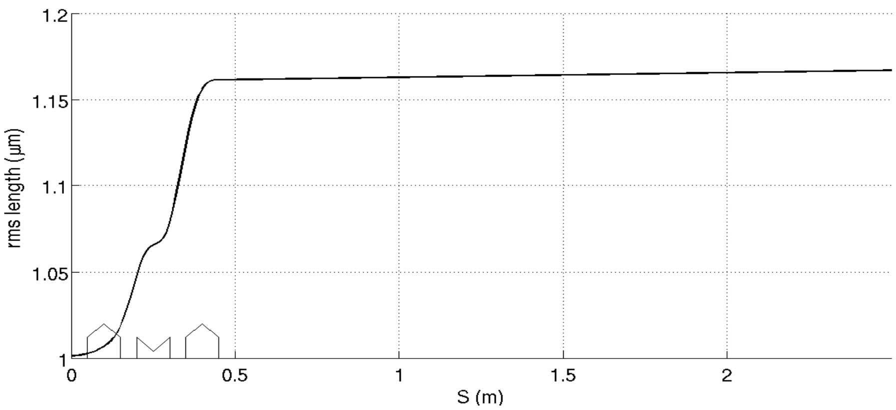
6D Gaussian distribution input (no correlation)

Beam refocusing



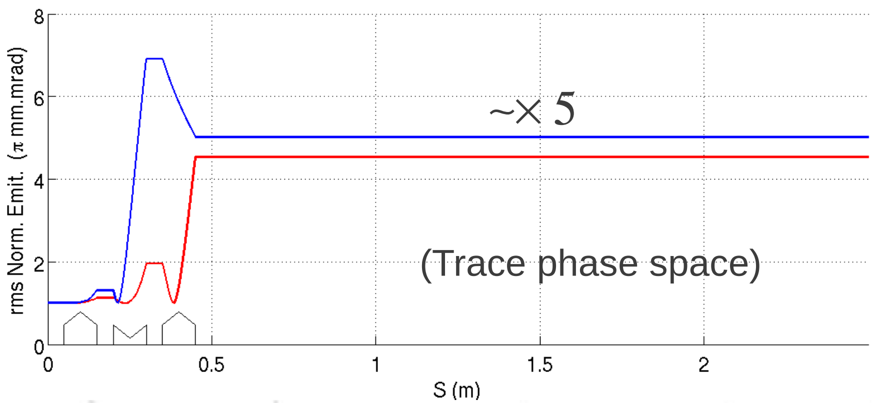
Triplet of quadrupoles
As close as possible from the source
High gradient (few hundreds T/m)
Permanent magnet

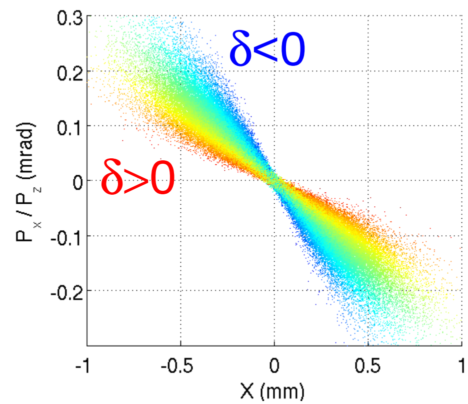
LPA beams



$$Lengtening \sim \sigma_{x'}^2$$

(quadratic offset)





$$\gamma\,\epsilon_{chrom} \sim \gamma\,\sigma_{x'}^2\,\sigma_\delta$$

(quadratic offset)

K. Floettmann, PRSTAB 2003
P. Antici et al., JAP 2012

Bunch length & emittance preservation is very sensitive the initial beam divergence

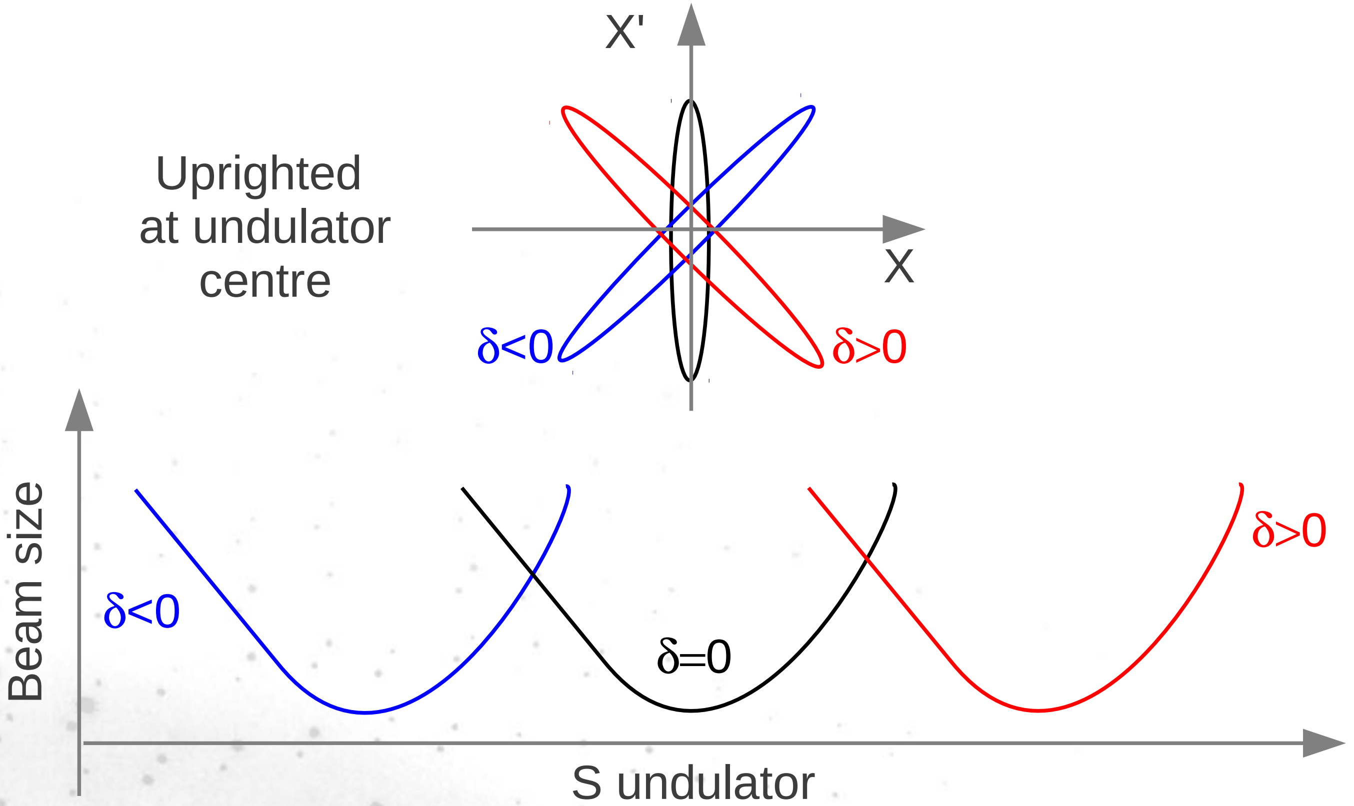
Also scale with the quadrupoles separation to the source

Beam manipulation

The transverse phase spaces exhibit some correlation between ellipse orientation and energy deviation

==> information that may be used

Uprighted at undulator centre



Beam manipulation

Channel of quadrupoles from source to undulator centre

Linear   Chromatic

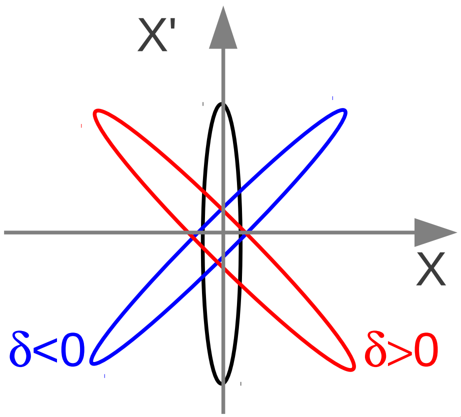
$$\begin{pmatrix} x \\ x' \end{pmatrix} = \left[\begin{pmatrix} r_{11} & r_{12} \\ r_{21} & r_{22} \end{pmatrix} + \delta \begin{pmatrix} r_{116} & r_{126} \\ r_{216} & r_{226} \end{pmatrix} \right] \begin{pmatrix} x_0 \\ x'_0 = \dfrac{p_{x0}}{p_{z0}} \end{pmatrix}$$

TRANSPORT code notation
2nd order

Waist
Size

$$r_{226} = 0$$

For large divergence
No initial correlation



$$\gamma\, \epsilon_{chrom} = \gamma\, r_{22}\, r_{126}\, \sigma_{x'}^2\, \sigma_\delta$$

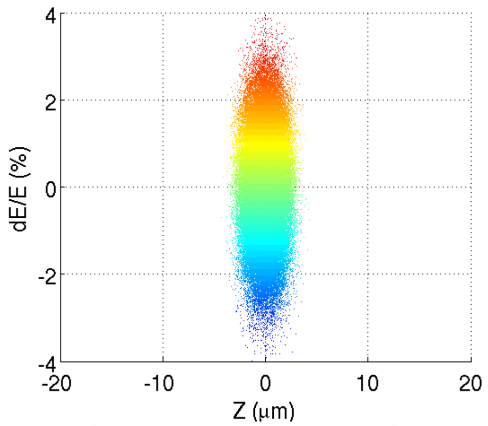
Waist position vs δ : $S_{und}(\delta) = -\dfrac{r_{126}}{r_{22}}\delta$ in a drift

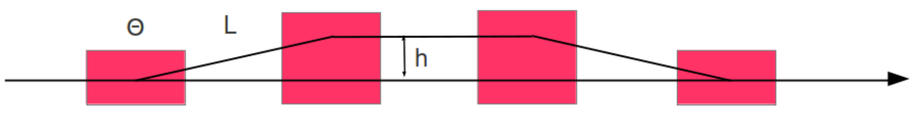
==> Waist - Energy correlation

Beam manipulation

The chicane decompression ease the FEL : Reduce the slice energy spread (expense of peak current)
Lengthen the bunch ==> FEL Slippage

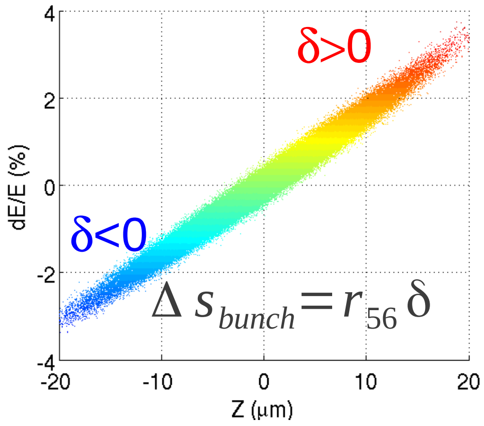
A. R. Maier et al., PRX 2012





Energy de-mixing

==> Energy – Position correlation



$$\Delta s_{bunch} = r_{56}\,\delta$$

==> Waist – Energy corr. + Energy – position corr. = Waist – Position corr.

The chicane decompression makes the waist slipping from tail to head :

$$\left.\frac{\Delta s_{bunch}}{\Delta S_{und}}\right|_{waist} = -\frac{r_{126}}{r_{22}\,r_{56}}$$

… as the FEL wave do :

$$\left.\frac{\Delta s_{bunch}}{\Delta S_{und}}\right|_{FEL} = \frac{1}{3}\,\frac{\lambda_{photon}}{\lambda_{undulator}}$$

Beam manipulation

Synchronization slippage : Electron slice waist = Photon FEL wave

Fix the chicane strength : $$r_{56} = -\frac{1}{3}\frac{r_{126}}{r_{22}}\frac{\lambda_{photon}}{\lambda_{undulator}}$$ } Naturally positive

Up to second order, with large divergence, this relation is independent from the electron source :

==> Not sensitive to initial divergence, energy spread, pointing ...

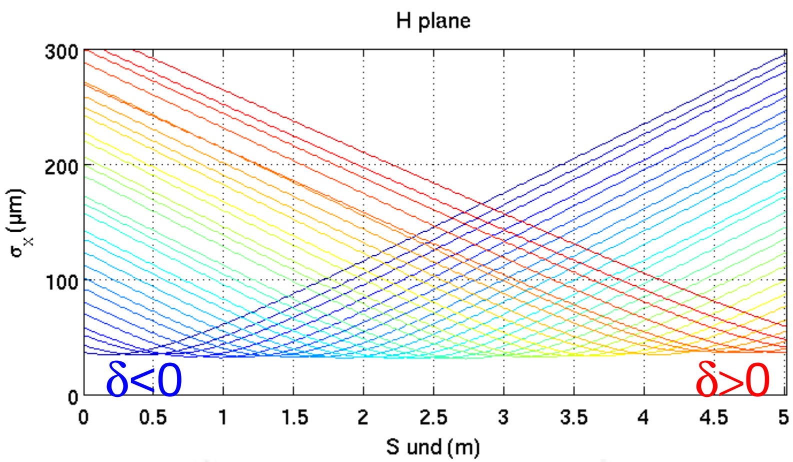
The chicane has a weak effect on the transverse focusing (1st and higher order)
1) by construction 2) weak strength

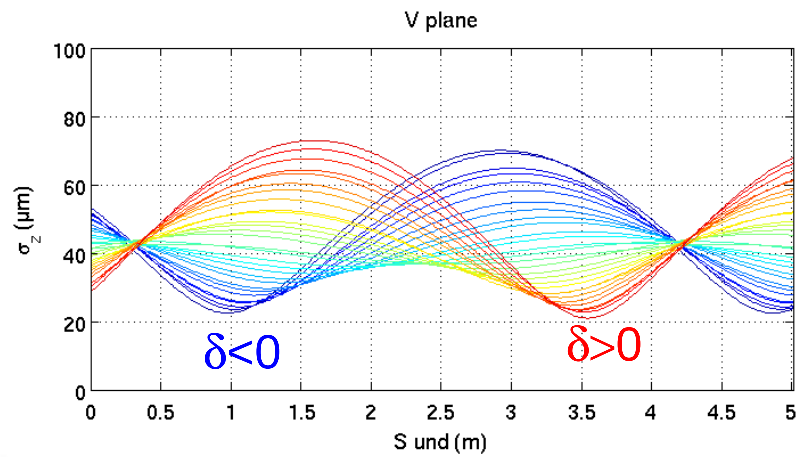
==> ~ Act only on the longitudinal plane

<u>In practice</u> : Set the quadrupoles and scan the chicane strength

Beam manipulation

In a plane undulator, this synchronization works for the horizontal drift and may be perturbed by the strong vertical focusing, nevertheless it ~works ...





A possible second manipulation is to “transfer” the chromatic emittance from the vertical plane to the horizontal by simply refocus strongly the vertical plane with the first quadrupole (not dominant)

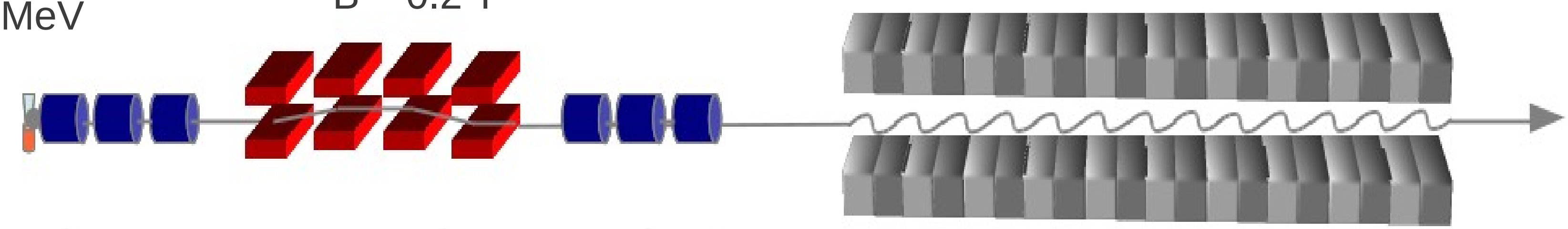
Beam manipulation

An second triplet of quadrupole (at least) is mandatory to operate the chromatic tuning

Chicane
Energy De-mixing
r_{56} ~ 1 mm
B ~ 0.2 T

5 m In-Vac Cryo ready Undulator (PrFeB)
15 mm period
B ~ 1.5 T @ gap=3.6 mm

Source
400 MeV



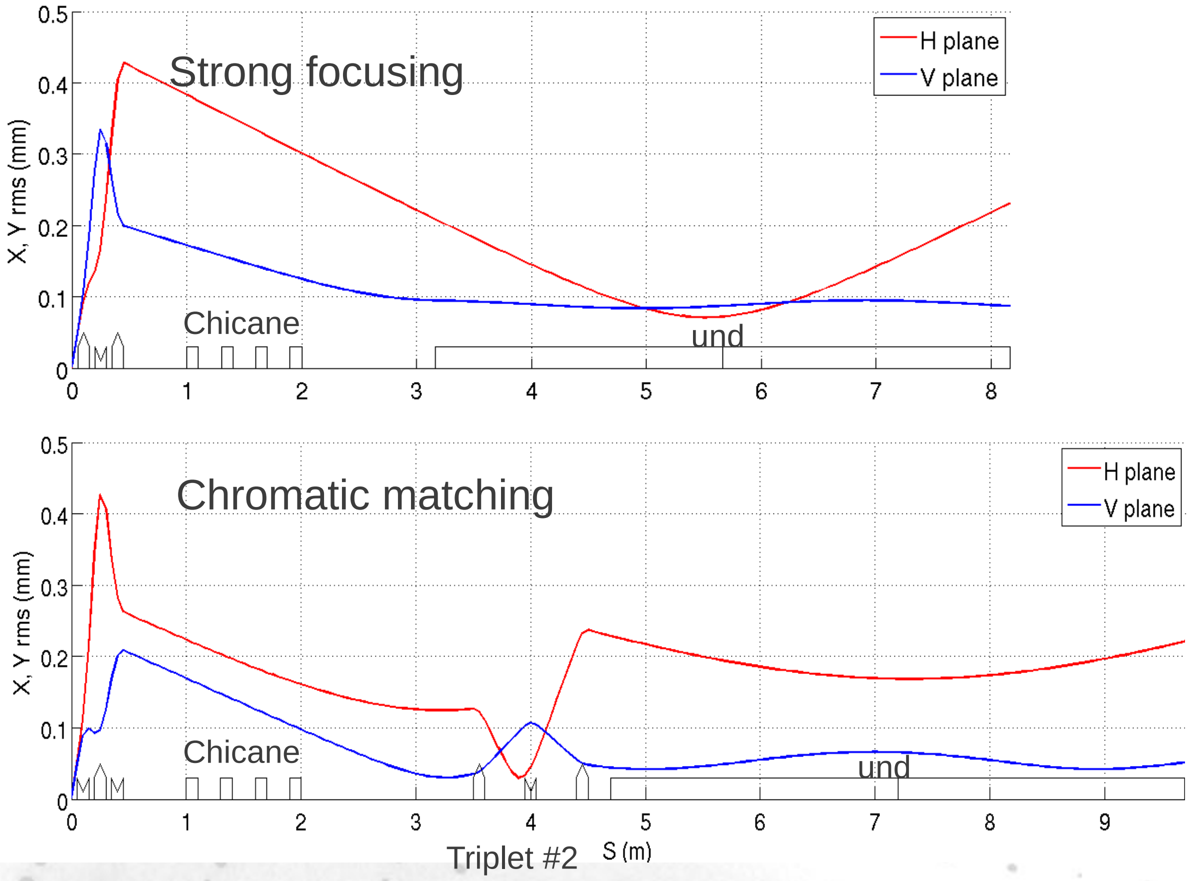
First triplet
Re-focusing
G < 200 T/m
Bore = 100 mm length
10 mm radius

Second triplet
Chromatic matching
G < 40 T/m
(+ ~1.5 m)

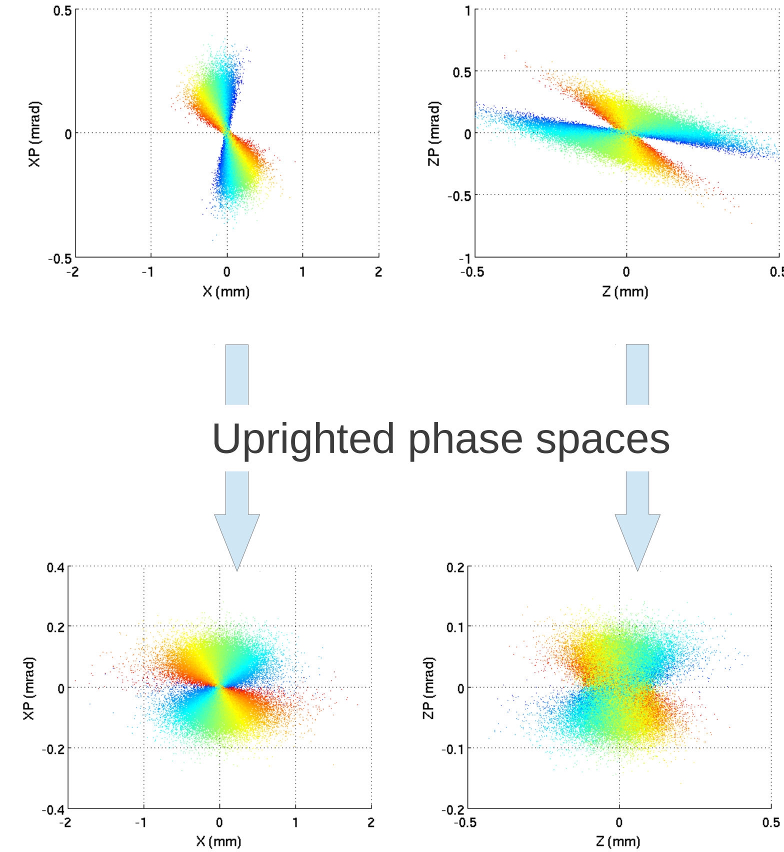
~ 10 m

Beam manipulation

2 optics comparison :



At undulator centre



Beam manipulation

Some tracking informations:

Collective effects are not too strong in these cases (Space charge 3D & CSR 1D)

Slice emittances are weakly affected (< 10%)
Small projected emittances

Magnet tracking including non linear optics aberrations

Higher order terms do not affect the chromatic matching (initially limited to 2nd order)

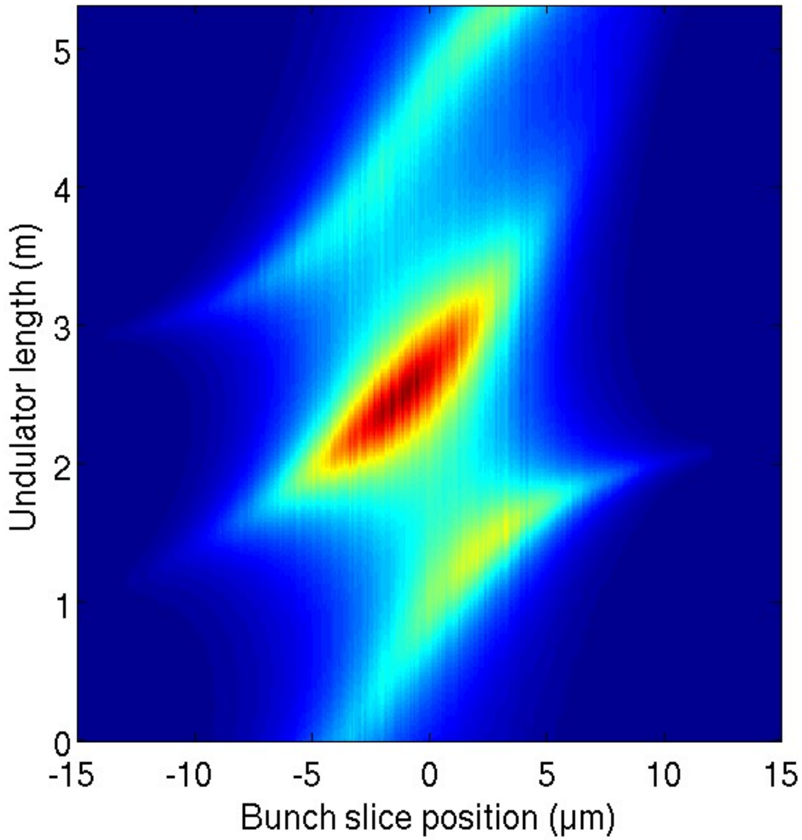
Tools : BETA (*J. Payet, Beta Code, CEA, SACLAY)*
Symplectic integrator + Coll. (*home made* -)
ASTRA (*K. Floettmann, https://www.desy.de/mpyflo/*)
CSRTrack (*M. Dohlus and T. Limberg,* http://www.desy.de/xfel-beam/csrtrack/)

Not included : Magnet imperfections that may be large with permanent magnet technology
Ex : PMQ dodecapole of few 1% may spoil the emittances …

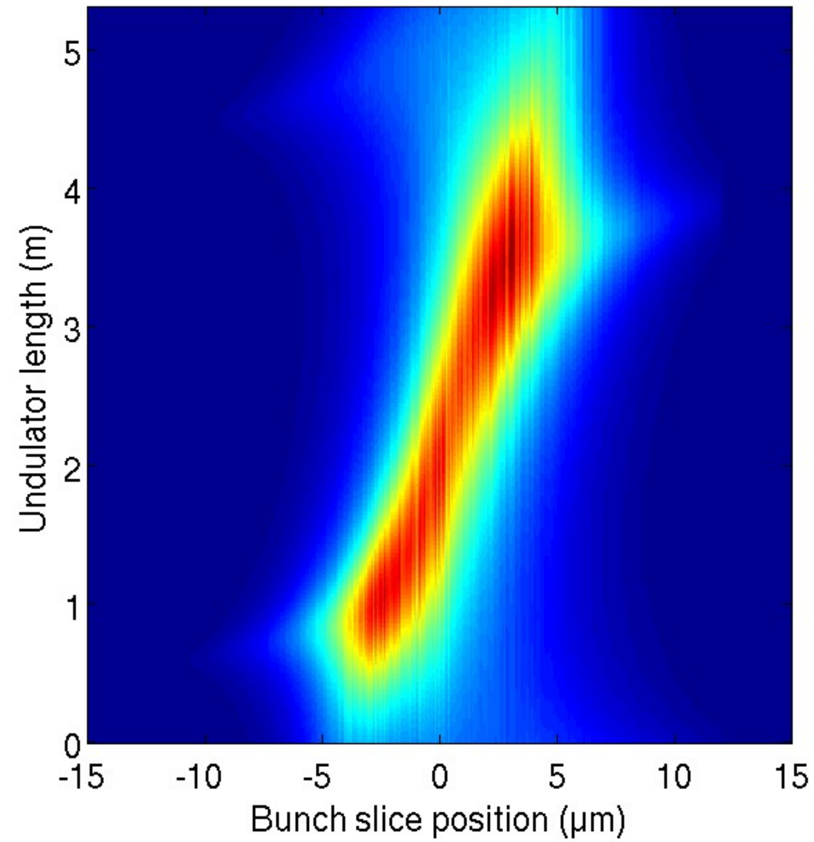
Beam manipulation

Electron density pattern $\frac{I_{slice}}{\sigma_x \sigma_z}$ along the undulator (A/mm^2)

Strong focusing



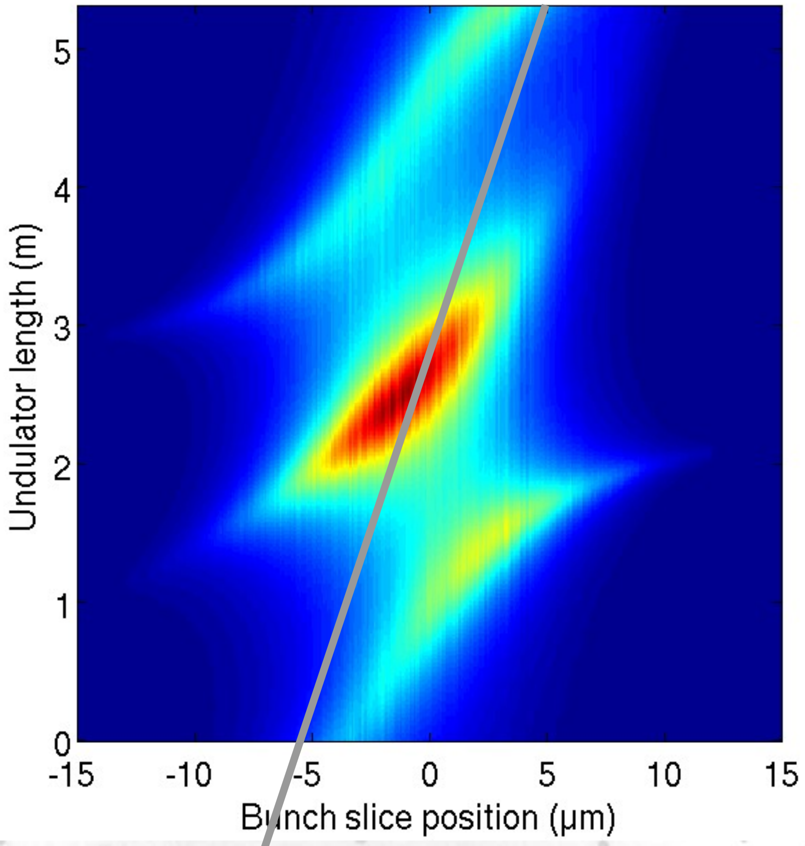
Chromatic matching



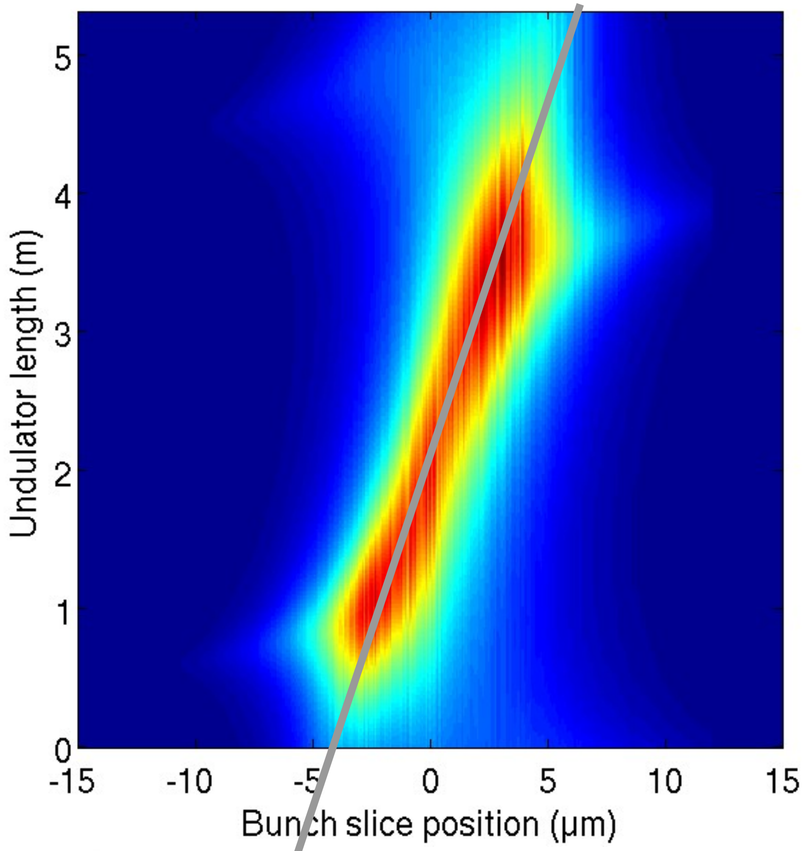
Beam manipulation

Electron density pattern $\frac{I_{slice}}{\sigma_x \sigma_z}$ along the undulator (A/mm²)

Strong focusing

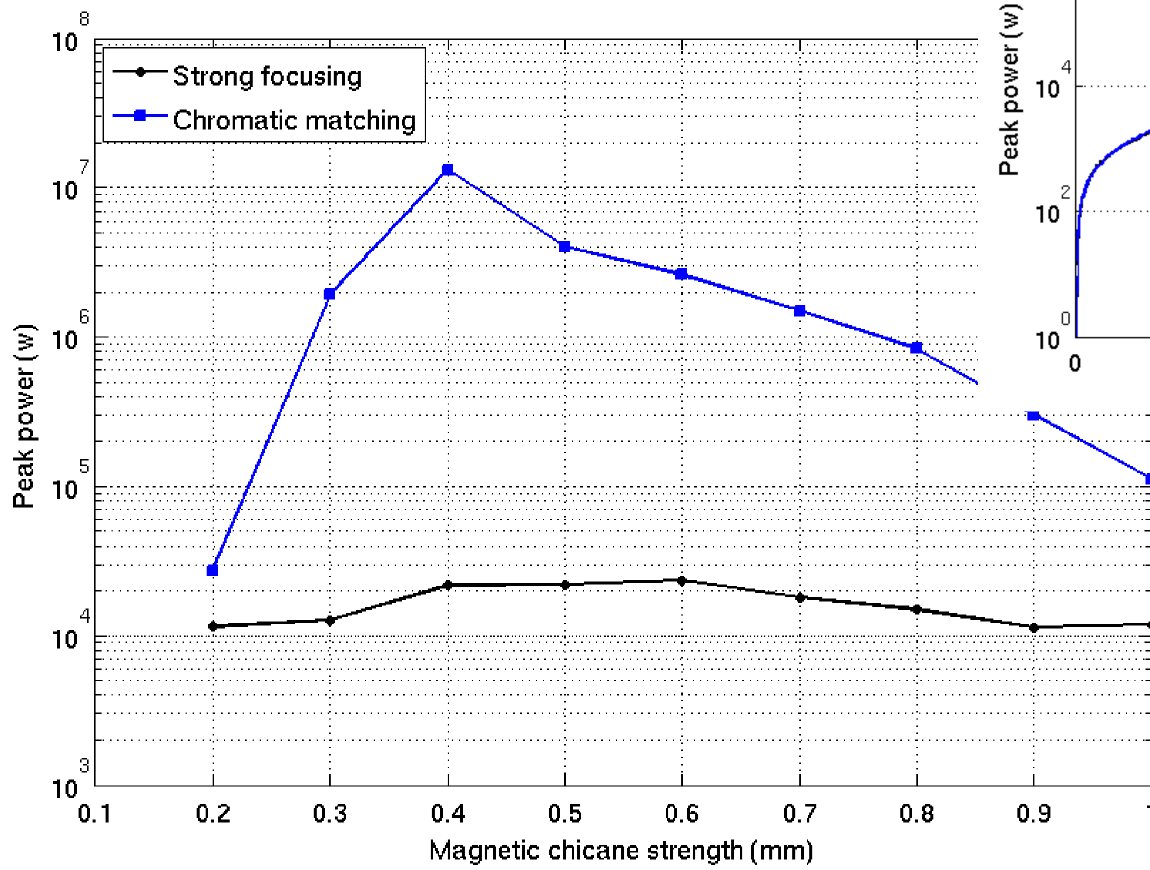


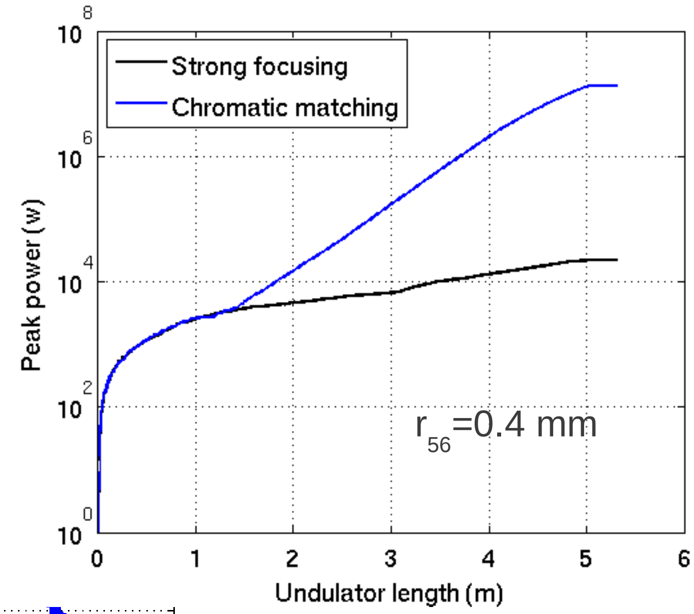
Chromatic matching



Effective electron density increased by 2 ~ 3

40 nm SASE simulations





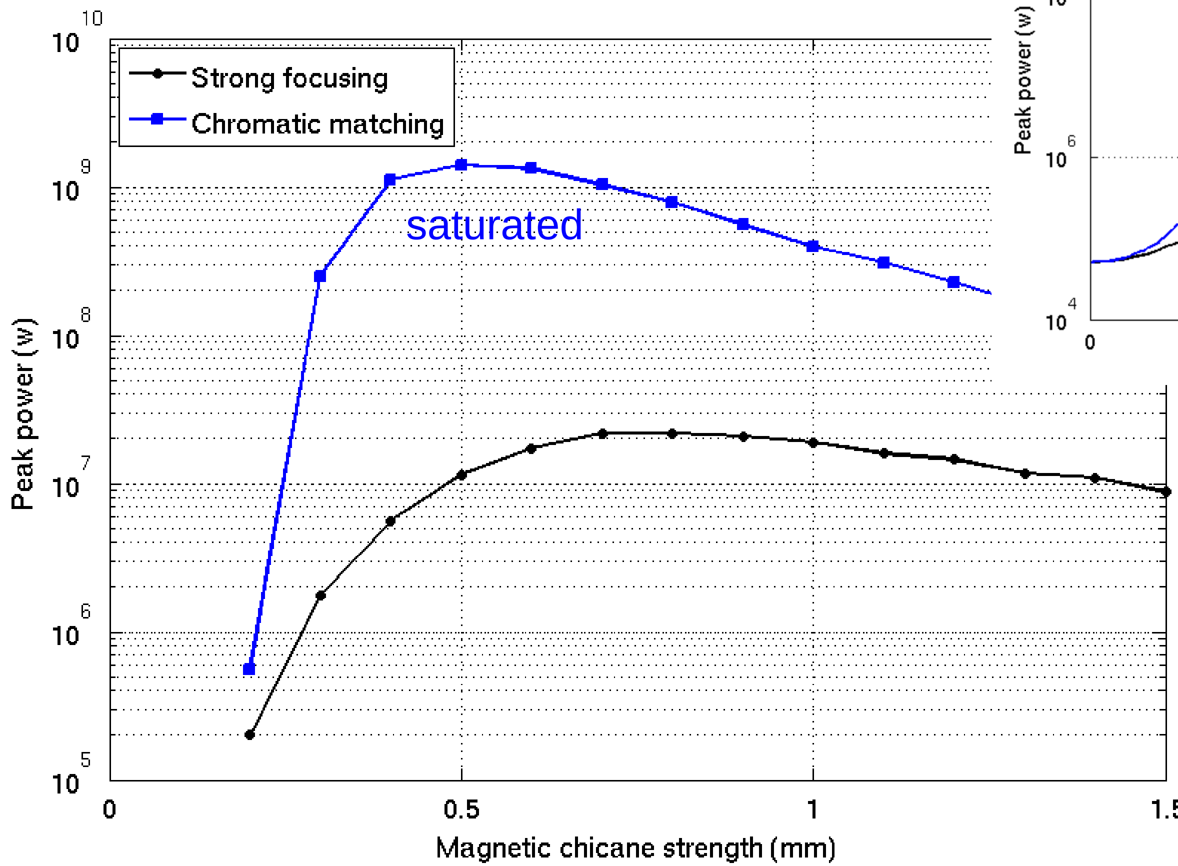
GENESIS code
S. Reiche, NIM 1999

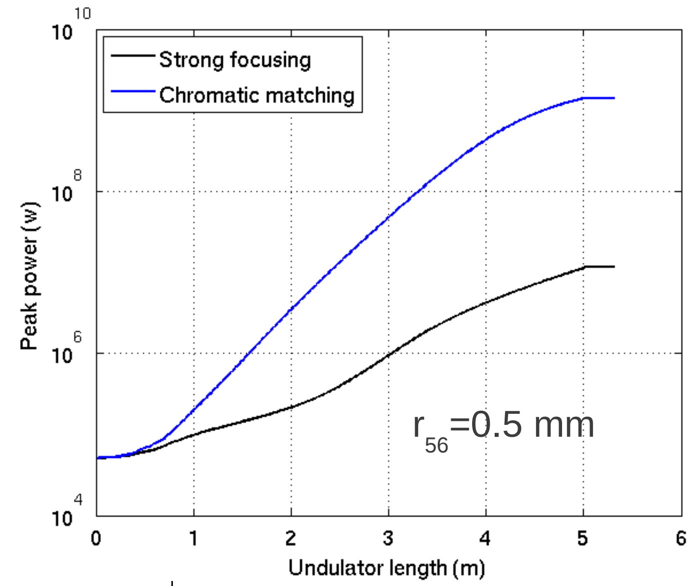
Linear Field Tapering
N. M. Kroll et al., PQE, 1980
L. Giannessi et al., PRL 2011

Hardly FEL with the Strong focusing case …
Significant improvement including the chromatic matching, evolve in single spike
==> Slippage synchronization seems not too sharp ...

40 nm seeded simulations

Seeded with 50 kW at 40 nm

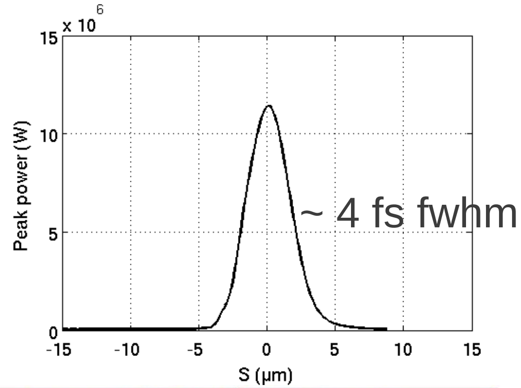


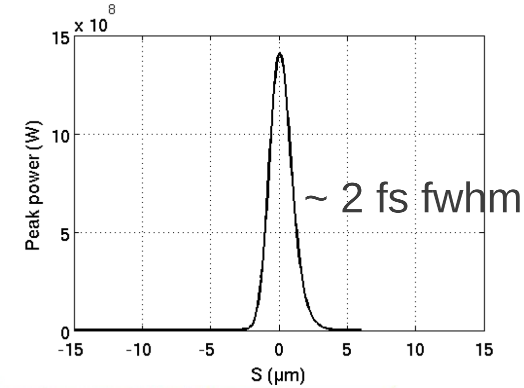


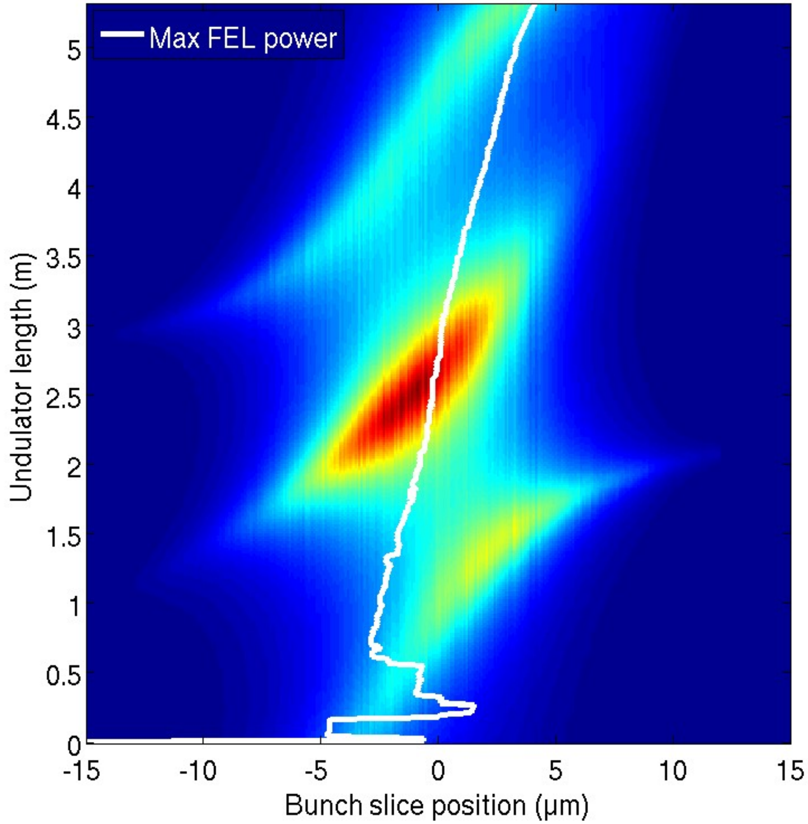
~ Same significant power increase
Reach saturation with about few GW in chromatic matching

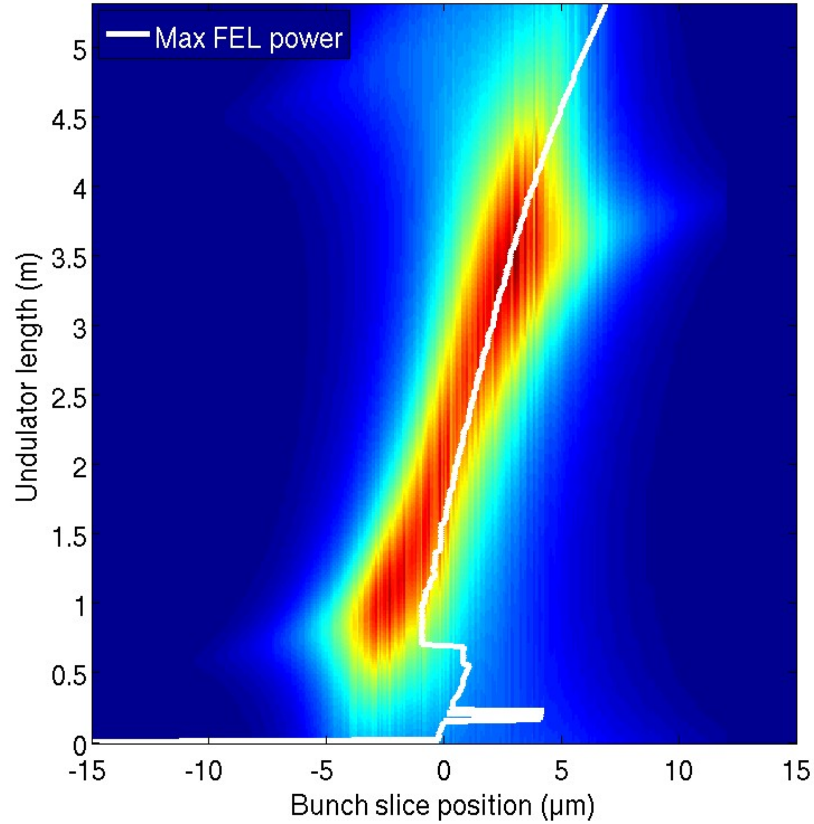
40 nm seeded simulations

From GENESIS output ….









Conclusion

It may be possible to turn the LPA chromatic emittance to direct FEL advantage by dedicated 2nd order quadrupole tuning

Being almost independent of the source, as far as the divergence is large, it is robust regards to the source jitters

Finally, some initial divergences are needed … but not to much!

COST :

An additional triplet is needed, PMQ not mandatory
More accurate gradient setting < 1% (absolute)

Thank you for your attention