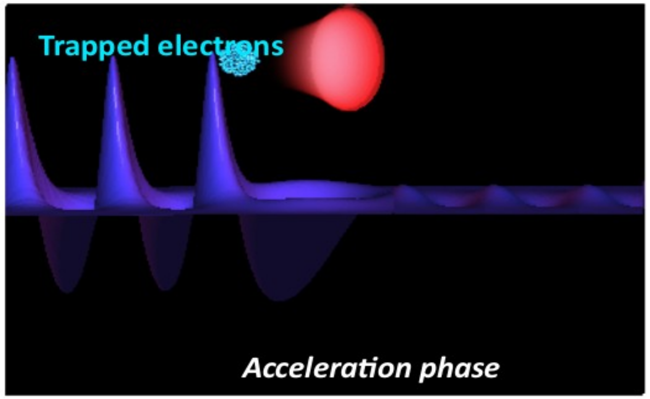
LWFA electron beam manipulations for FEL amplification

A. Loulergue, SOLEIL
EAAC 2015 Workshop
Sept. 17

OUTLINE

- LWFA beam properties
- Beam manipulations for FEL
- 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 to 10 kA peak current

Short bunches ~ fs level

Large energy spread ~ percent level

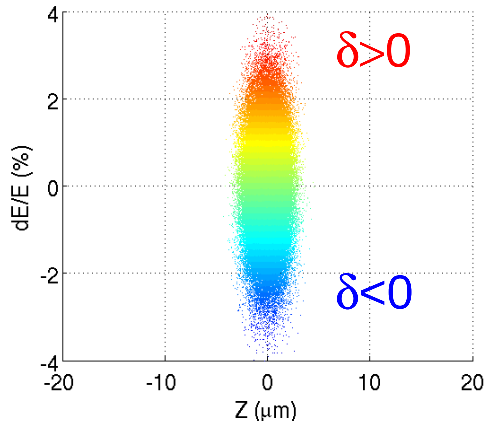
Large initial divergence ~ mrad level

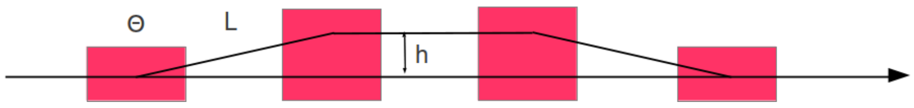
They complicate the transfer and FEL

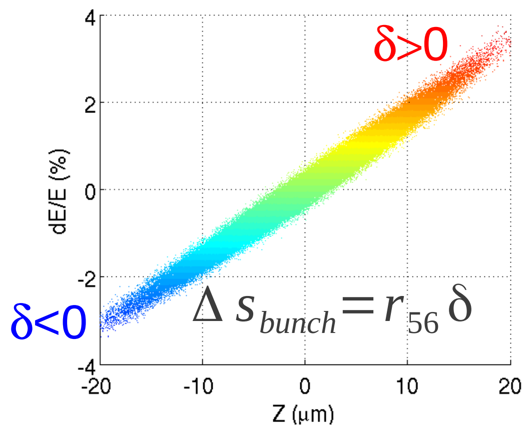
BEAM DECOMPRESSION

A. R. Maier et al., PRX 2012

Decompress the bunch to cope with the large energy spread

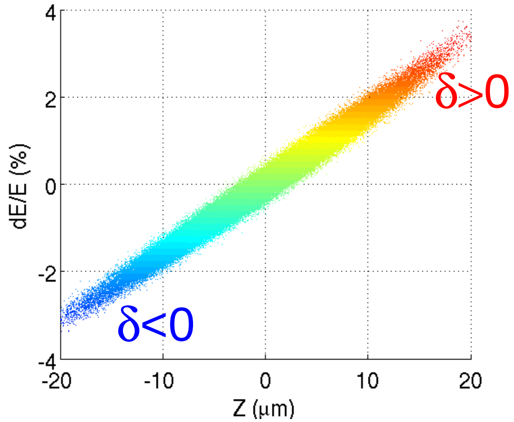


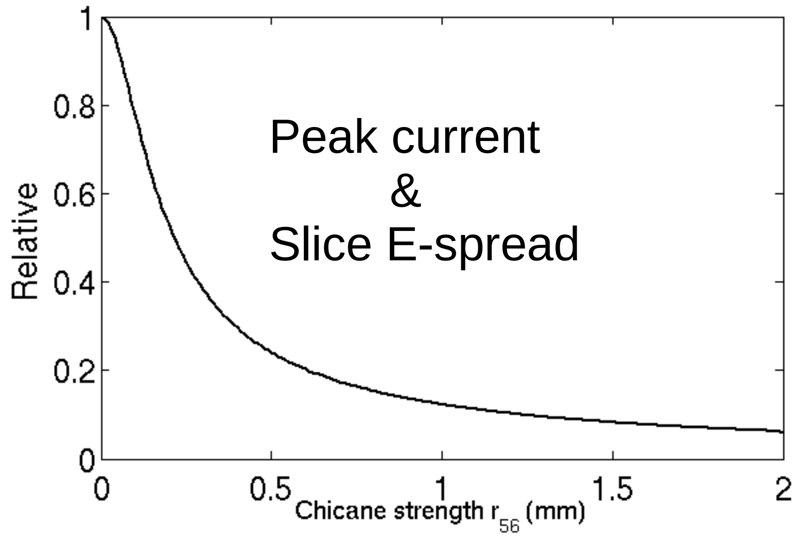




Decompression
or
slice energy de-mixing

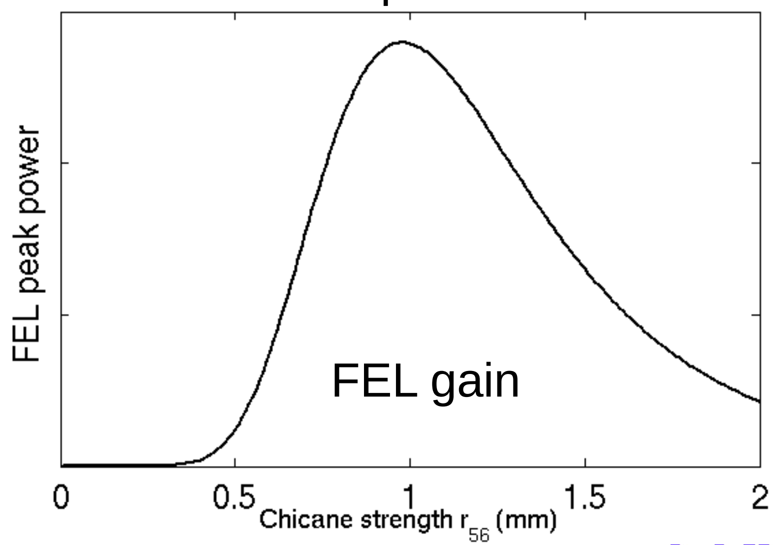
BEAM DECOMPRESSION





Longer bunch also allows
for the FEL slippage

Decompression

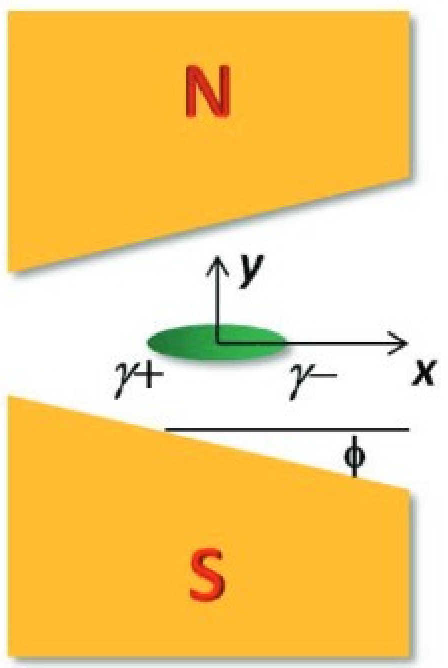


Trade-off giving a maximum FEL gain

Transverse Gradient Undulator

T. Smith et. al., J. Appl. Phys. 50, 4580 (1979) : Low gain
Z. Huang et al., PRL 109, 204801, 2012 : High gain

Use a Transverse Gradient Undulator (TGU) to cope with the large energy spread



Z. Huang

Gradient and horizontal dispersion

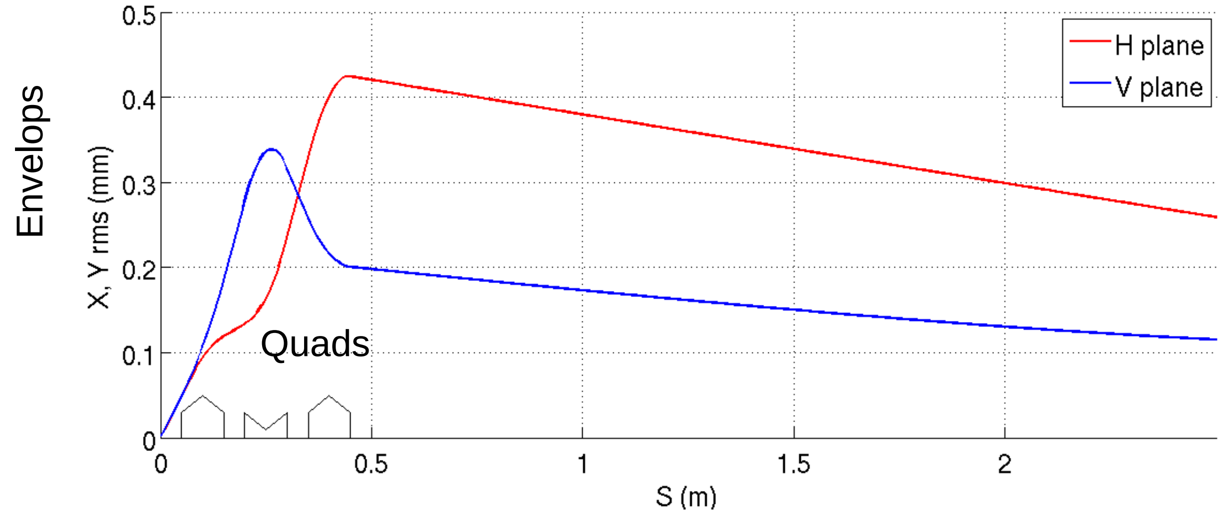
All electrons are matched to the resonant wave length and participate to the FEL amplification

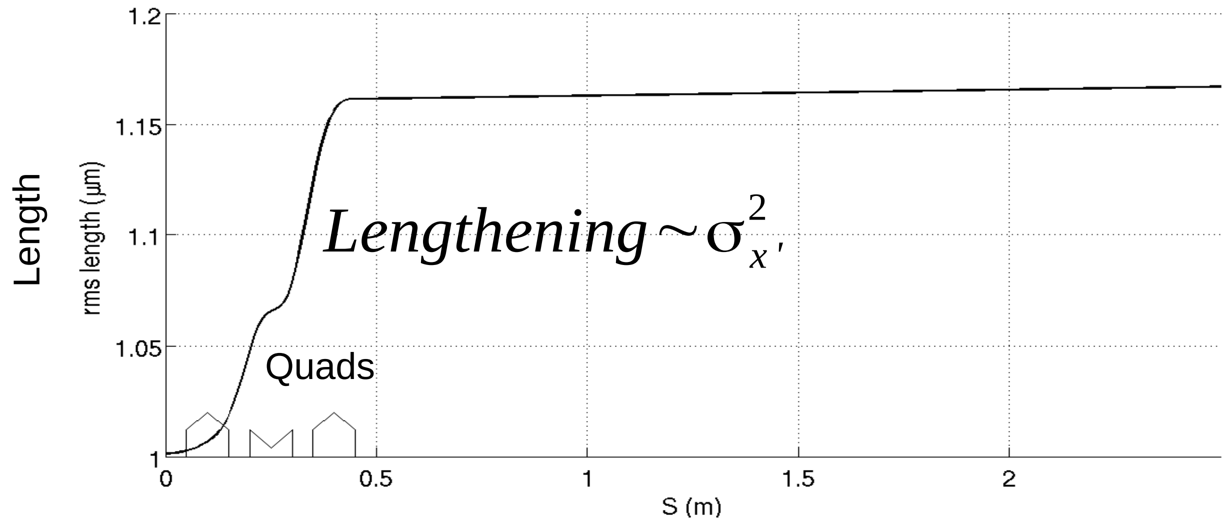
No decompression and high peak current

Potentially high peak FEL power

Beam transfer from the source very challenging regards to the large transverse chromatic emittance ...

Trailing particles



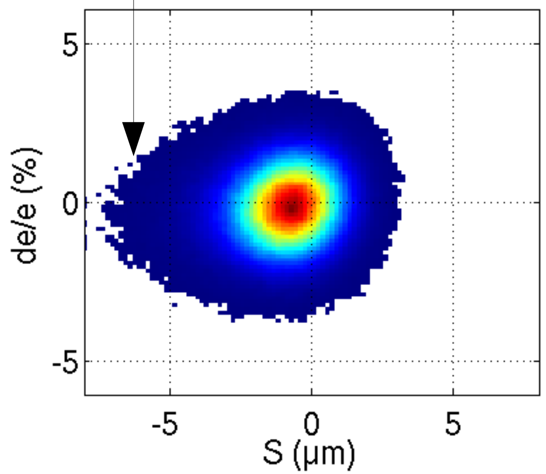


$$Lengthening \sim \sigma_{x'}^2$$

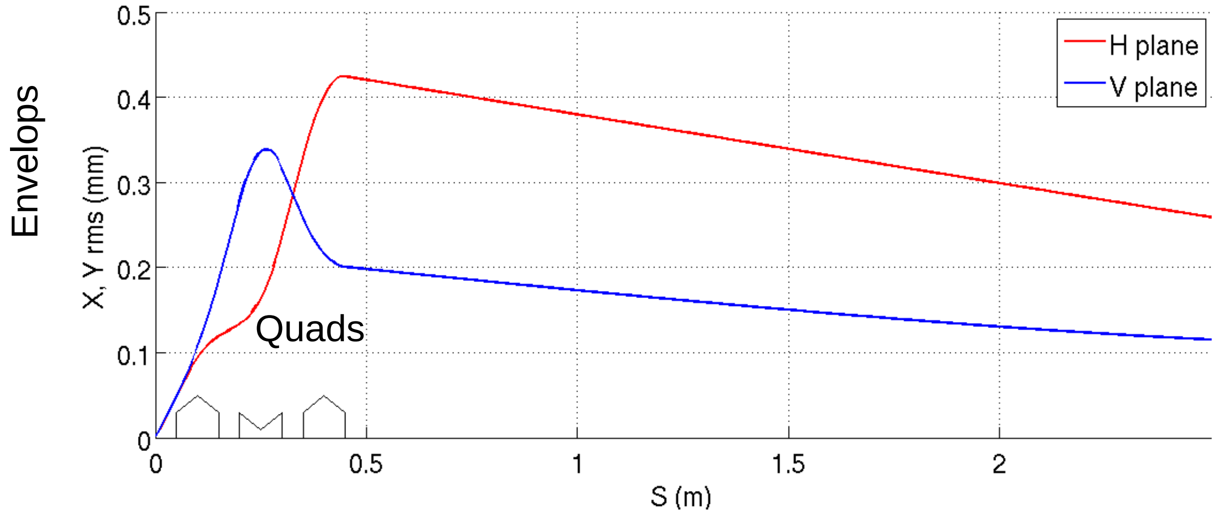
The large diverging beam needs to be refocused by means of compact and strong quadrupoles

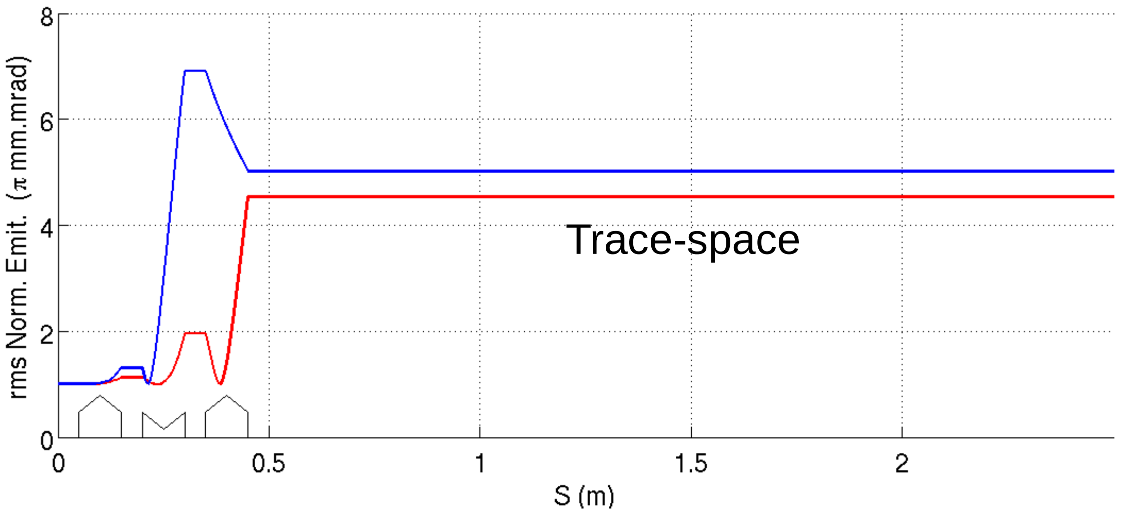
Trailing particles

=> Slice energy re-mixing



Chromatic emittance

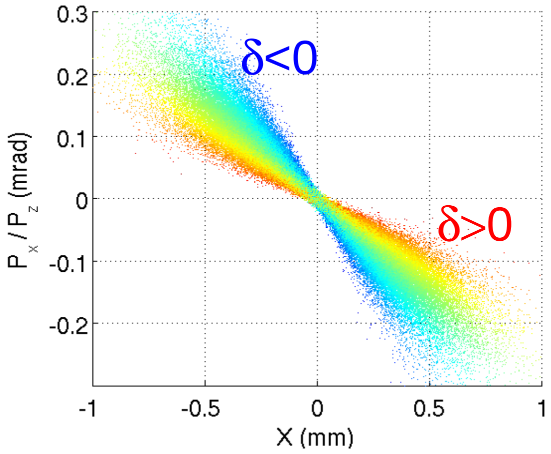




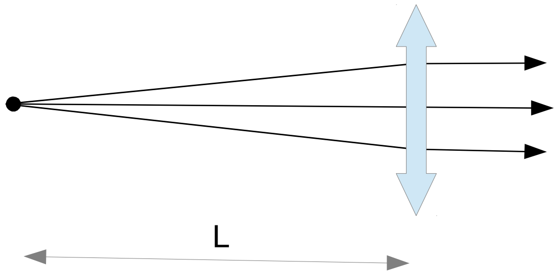
The large diverging beam needs to be refocused by means of compact and strong quadrupoles

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

K. Floettmann, PRSTAB 2003
P. Antici et al., JAP 2012
M. Migliotari et al., PRSTAB 2013



Chromatic emittance



Chromatic emittance $\propto$ L

Divergence lengthening $\propto$ L

Quadrupole strength $\propto$ 1 / L

Electromagnetic quadrupole not compact and not strong enough

Use of Permanent Magnet Quadrupoles (PMQ) : few hundreds of T/m
L few cm

The normalized chromatic emittances are still rather large

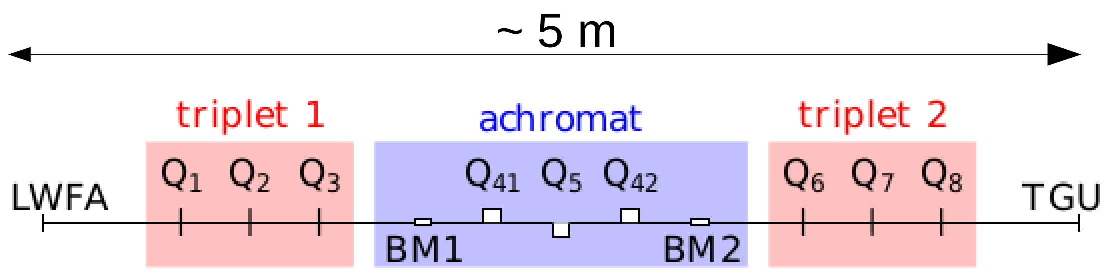
at 400 MeV with 1 mrad and 1% rms ==> ~ 4 π.mm.mrad rms
2 2% ==> ~ 32 π.mm.mrad rms

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

Chromatic emittance

C. Widman et al., IPAC 2014

Correct it (or reduce) by means of sextupoles in dispersive area :



C. Widman et al

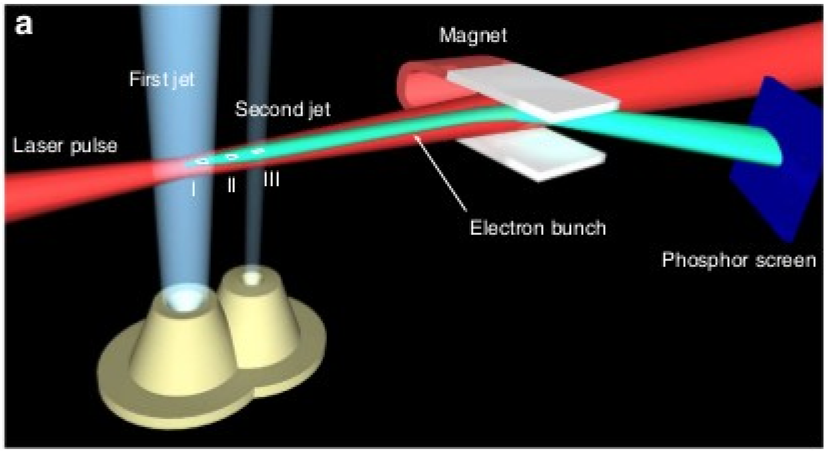
==> Very challenging due to very large chromatic effects …
==> Induce large phase space distortions

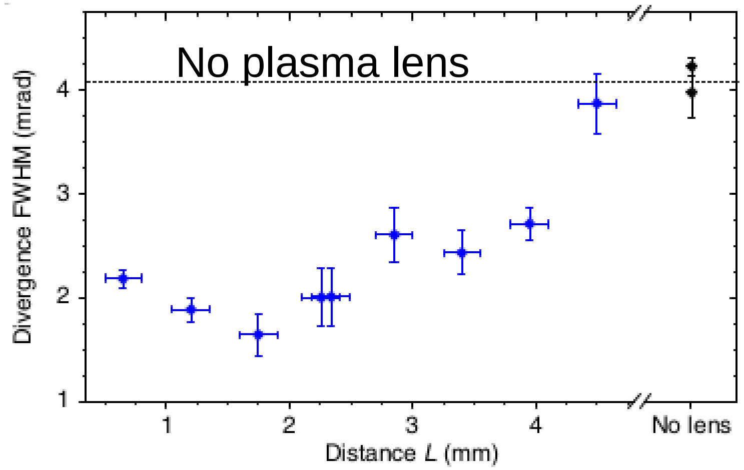
To give an idea : The chromaticities are as large as Synchrotron rings !
(Few hundred of meters and hundred of sextupoles)

Chromatic emittance

C. Thaury et al., Nat. Com. 2014
R. Lehe et al., Phy. Plasma, 2014

Refocus the beam by means of plasma lens :





Very strong focusing (electrical monopole) in both planes
Very close : L ~ millimeter scale

==> Divergence experimentally reduced by 2.6
==> Able to reduce, in principle, the chromatic terms

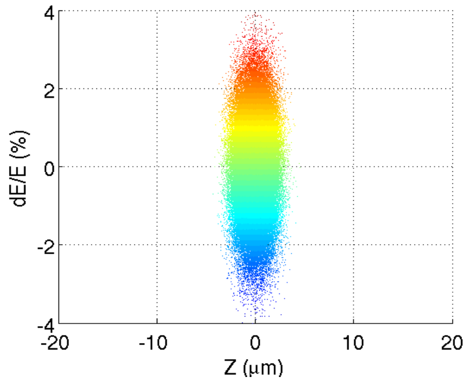
~ / 7

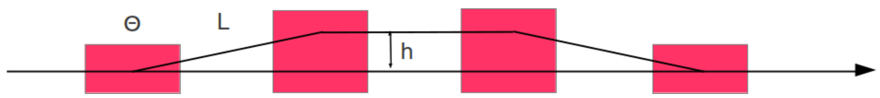
$$\gamma\,\epsilon_{chrom} \sim \gamma\,\sigma_{x'}^2\,\sigma_\delta$$

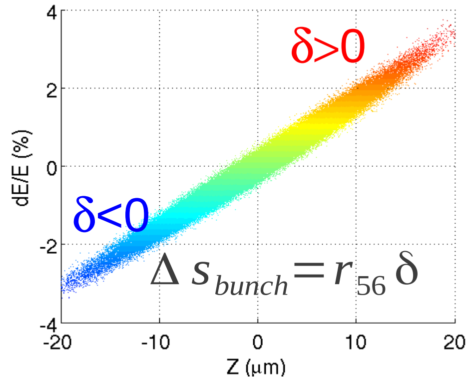
$$Lengthening \sim \sigma_{x'}^2$$

Chromatic matching

Longitudinal phase space

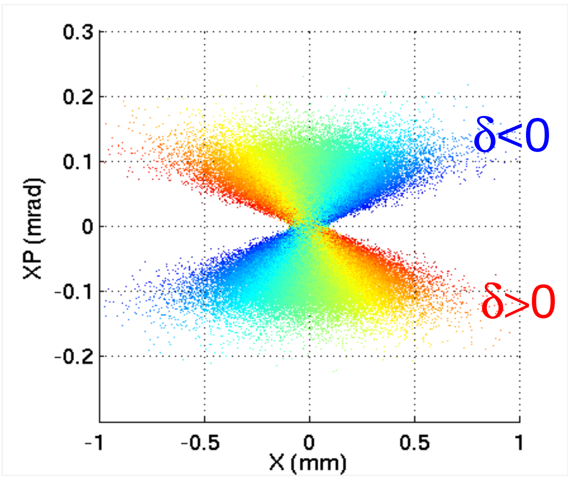


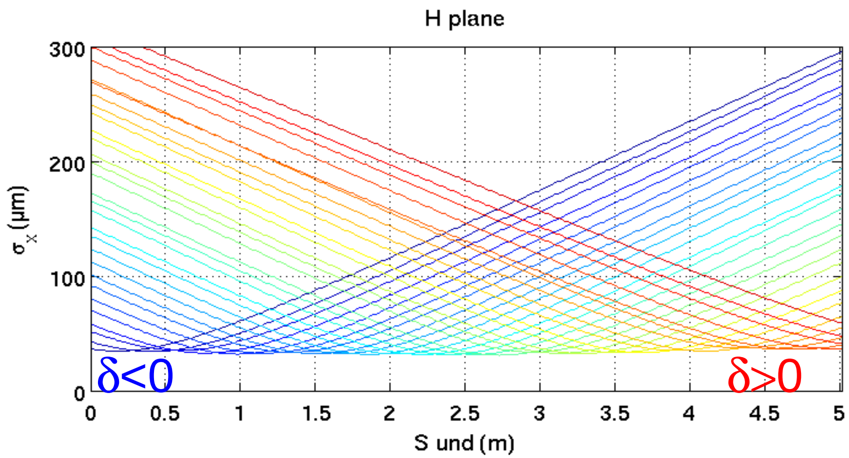




Transverse phase spaces

(In both H & V planes)





Chromatic matching

Channel of quadrupoles from source to undulator centre

Linear — Chromatic

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

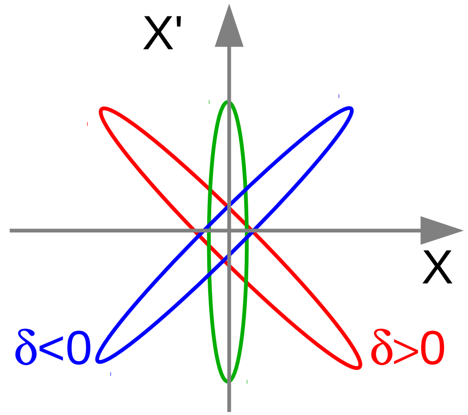
TRANSPORT code notation 2nd order

$$r_{12} = 0$$

Source to Image

$$r_{226} = 0$$

For large divergence
No initial correlation



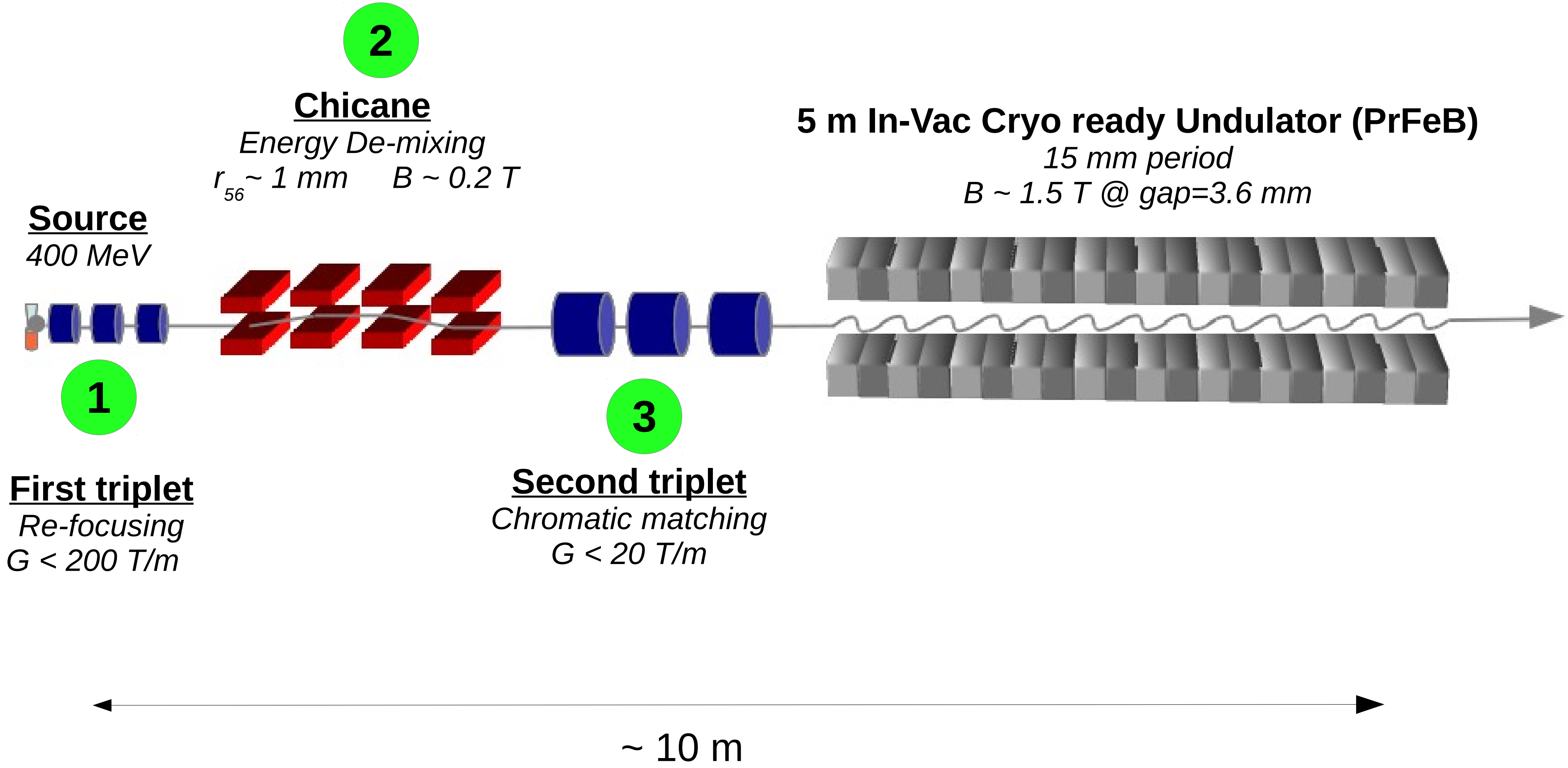
Just quadrupole settings
Independent from the initial beam

Works in both planes …

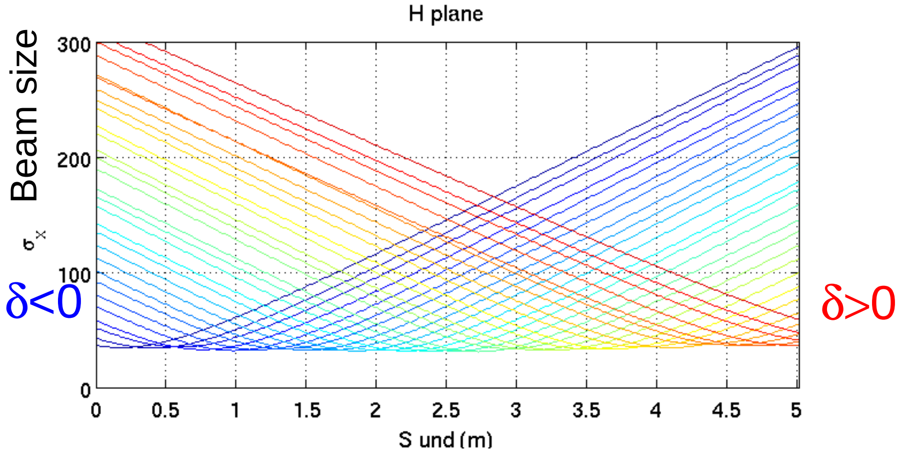
$$\gamma \epsilon_{chrom} = \gamma \frac{r_{126}}{r_{11}} \sigma_{x'}^2 \sigma_\delta$$

Chromatic matching

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



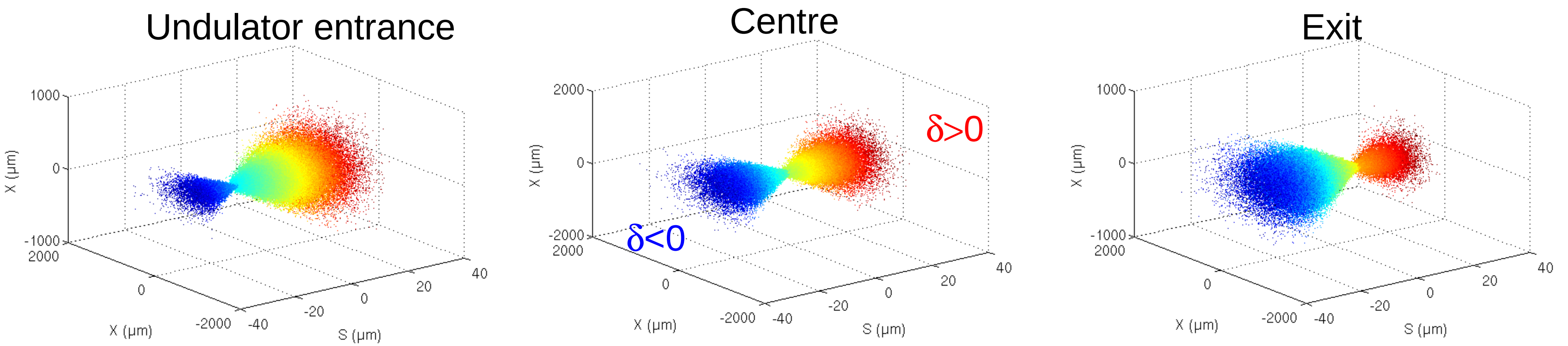
Chromatic matching



<= undulator =>

View of the slipping focusing from the tail toward the head

Bunch 3D view ...



==> The chromatic matching provides a high electron density + a constant transverse size

Chromatic matching

A. Loulergue et al., NJP 2015

Synchronization slippage : Electron slice waist = Photon FEL wave

Fix the chicane strength : $r_{56} = -\frac{1}{3} r_{11} r_{126} \frac{\lambda_{photon}}{\lambda_{undulator}} = -\frac{1}{3} r_{11}^2 c_{11} \frac{\lambda_{photon}}{\lambda_{undulator}}$ } 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)

==> ~ Act only on the longitudinal plane

<u>In practice</u> : Set the quadrupoles and scan the chicane strength r_{56}

Chromatic matching

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

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

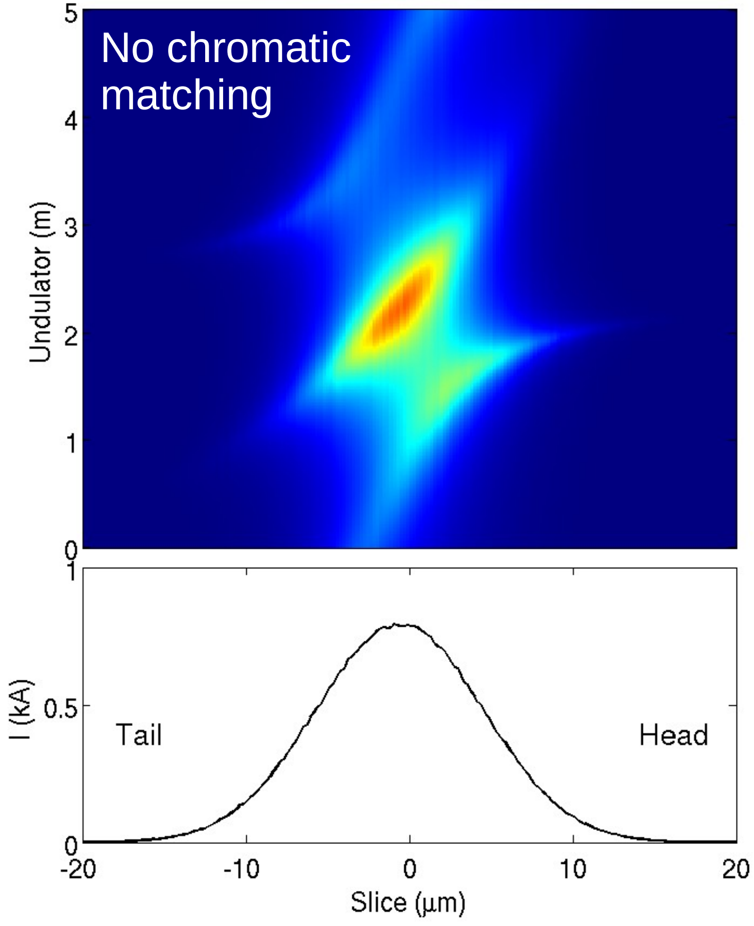
6D Gaussian distribution input model (no correlation)

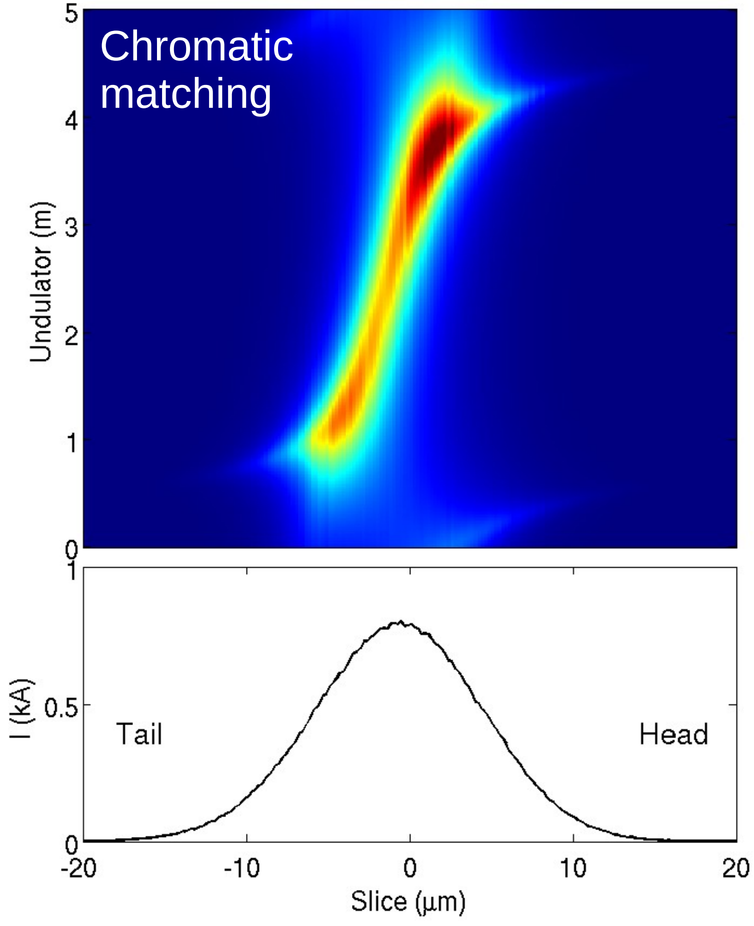
+ Electrons tracking including higher order terms

+ FEL tracking with GENESIS code (*S. Reiche, NIM 1999*)

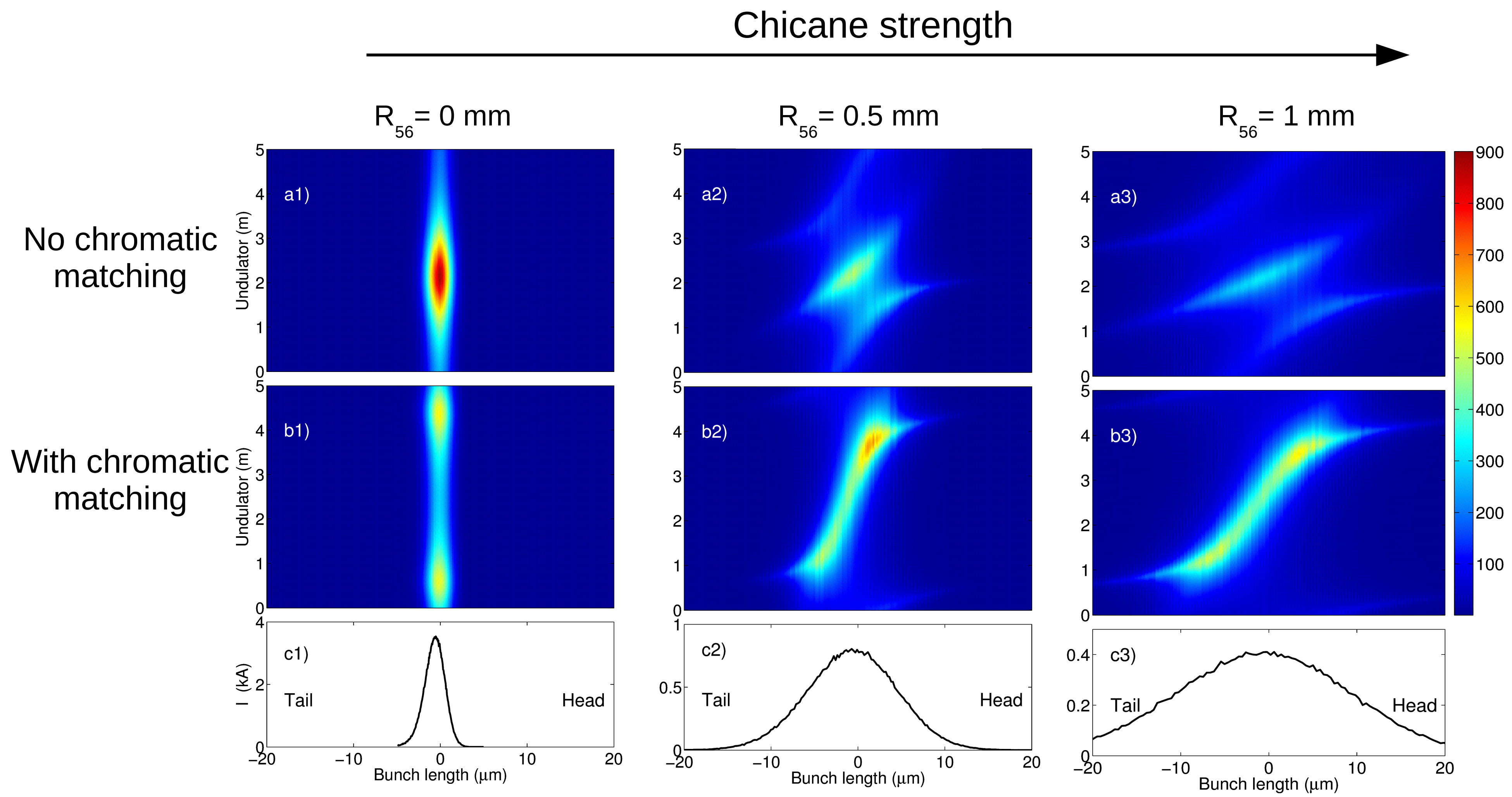
Chromatic matching

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



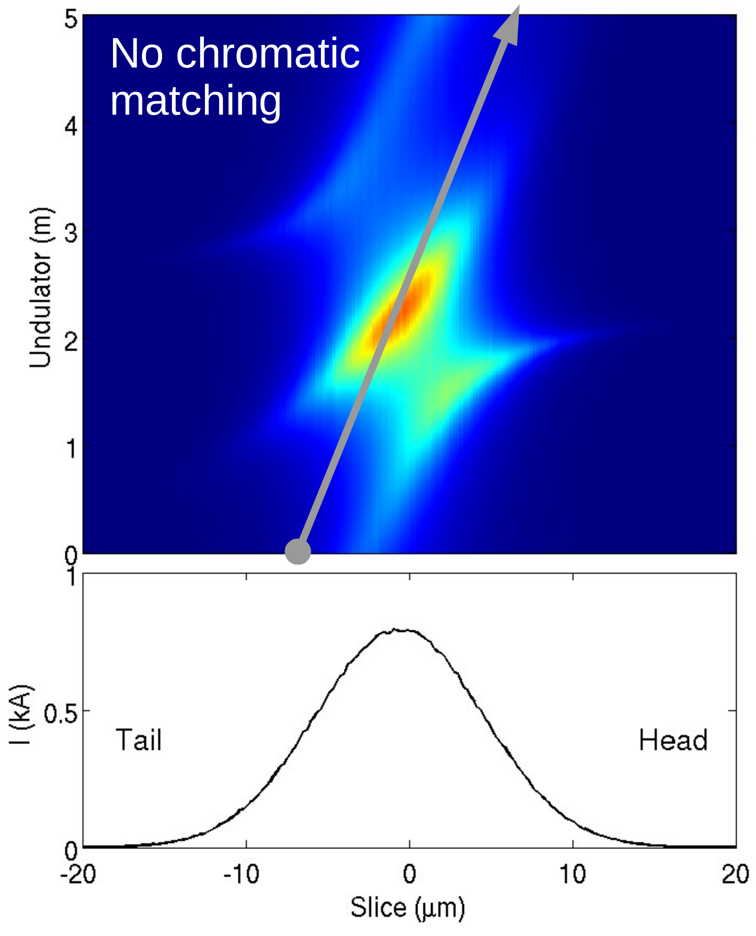


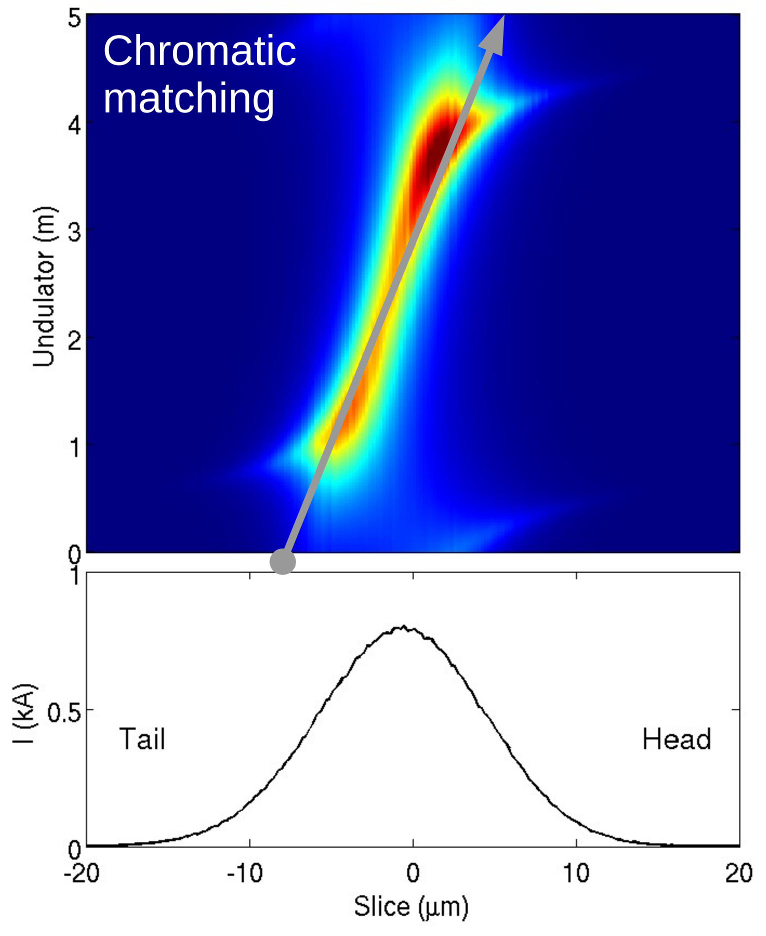
Chromatic matching



Chromatic matching

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

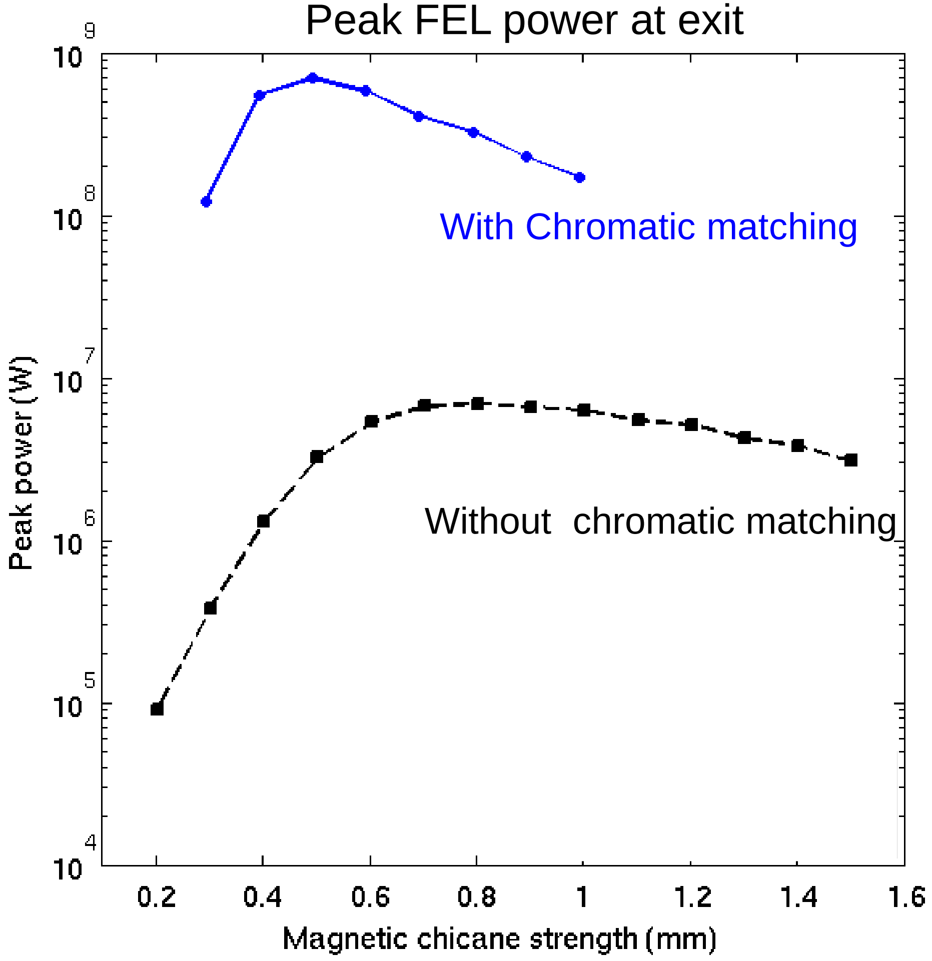




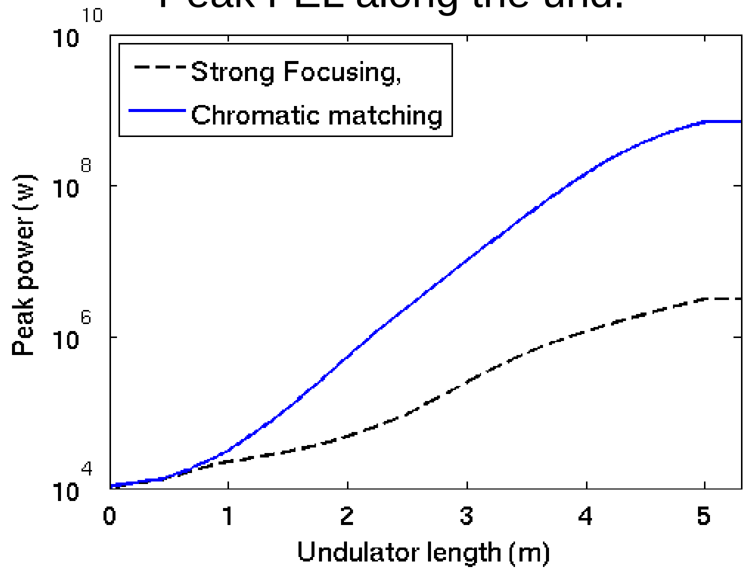
Chromatic matching

400 MeV – 10 kW SEED at 40 nm over 5 m

Peak FEL power at exit



Peak FEL along the und.



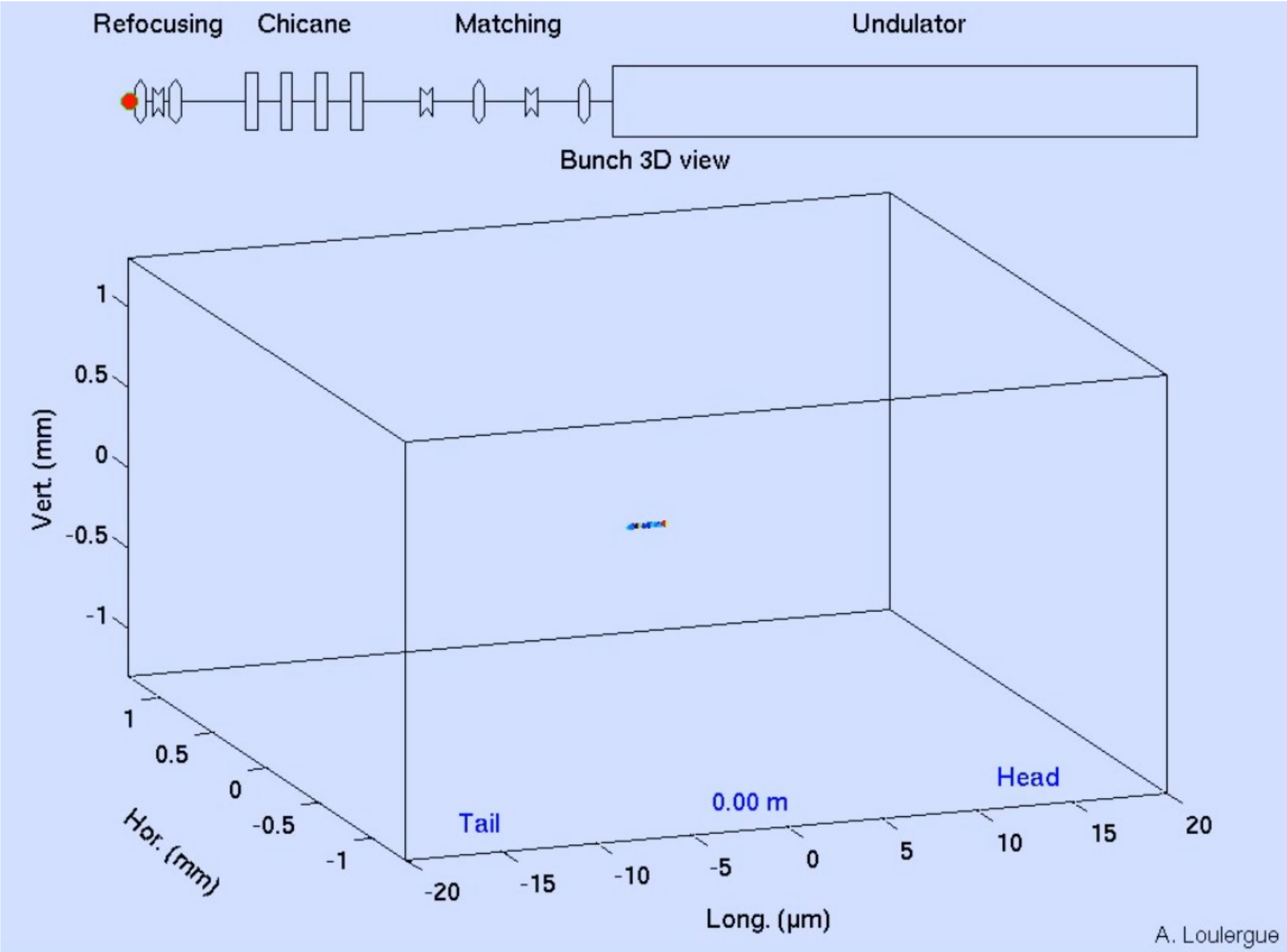
GENESIS code
S. Reiche, NIM 1999

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

Seeded with 10 kW at 40 nm

==> The chromatic matching provides a significant increase of FEL peak power

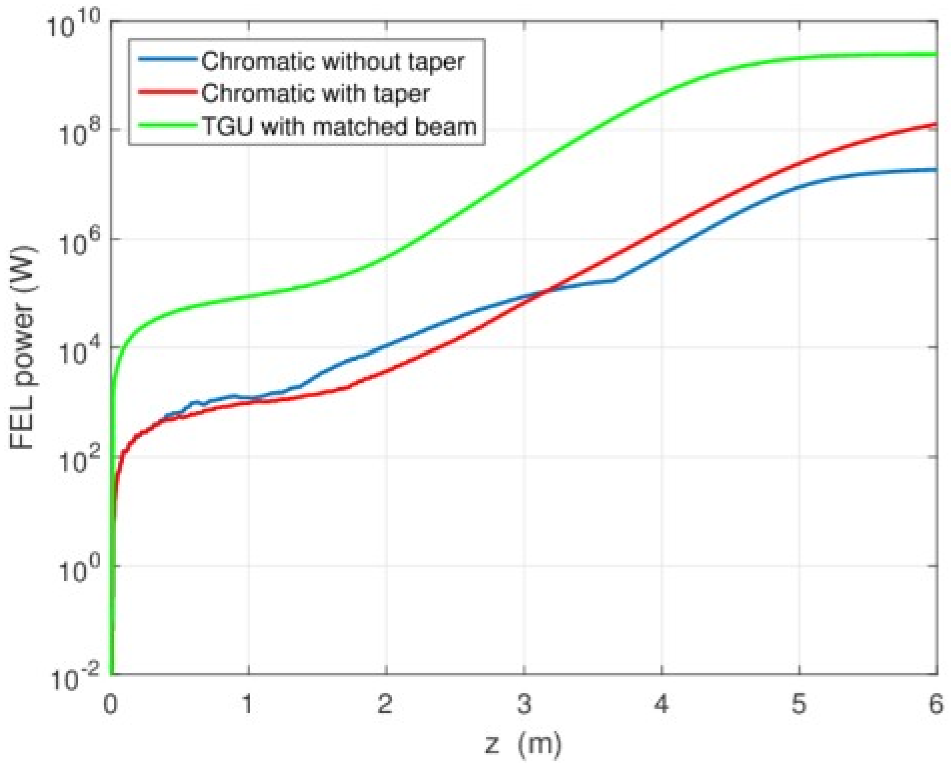
Chromatic matching movie



TGU vs chromatic matching

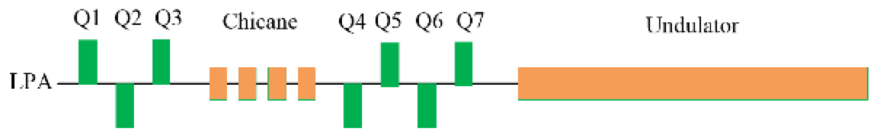
W. Qin et al. FEL 2015

500 MeV - SASE at 30 nm over 6 m



TGU with direct matching

Chromatic matching
via transfer line



Emittances rise from 0.1 to ~ 6 π.mm.mrad rms

(Elegant code)

Experiment preparation …

… to get an FEL amplification

Berkeley

CFEL

JAEA

JENA

Shanghai

SOLEIL – LOA

SPARC

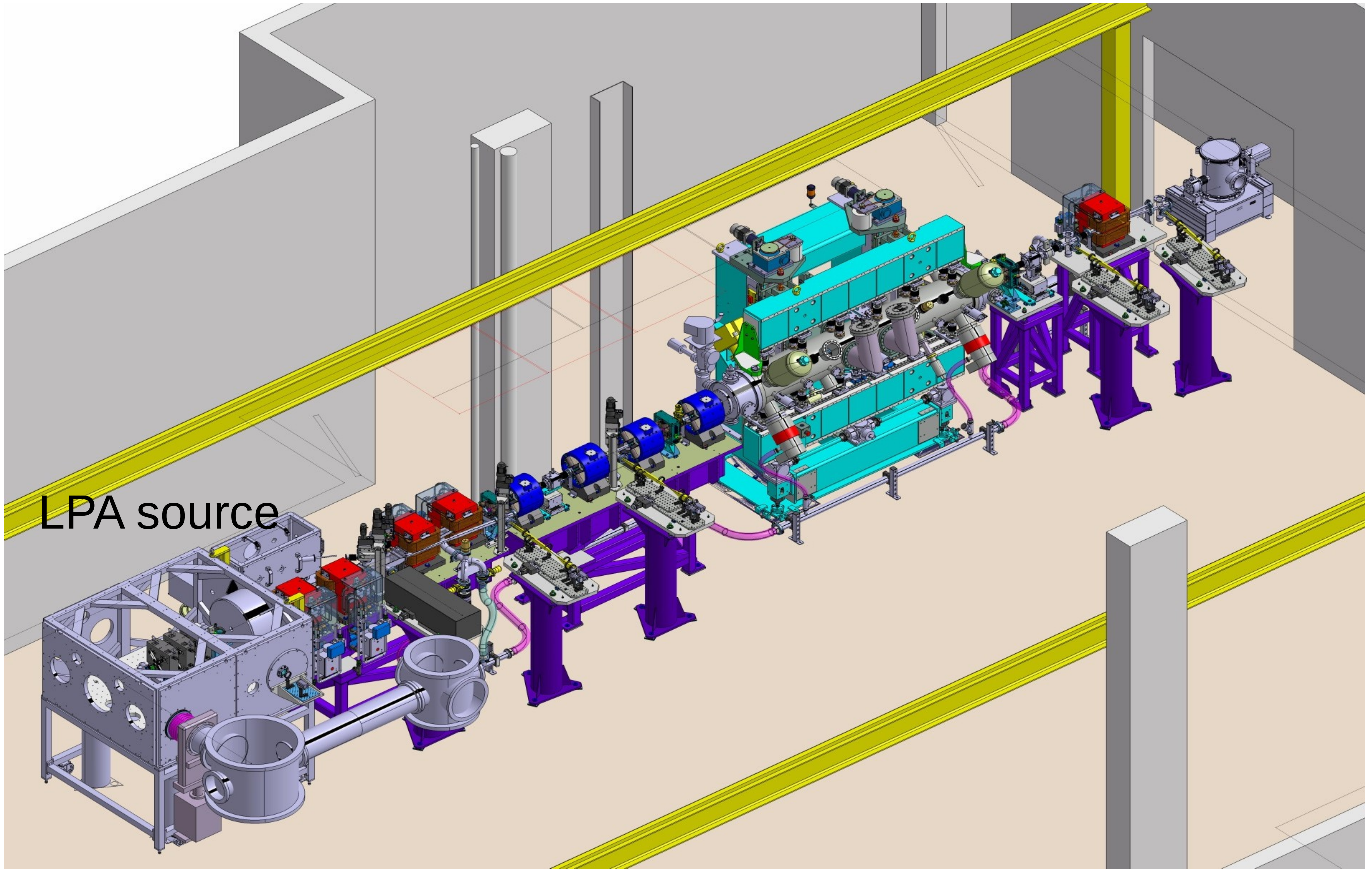
Strathclyde

…

Experiment preparation

COXINEL

Salle jaune, LOA



Thanks to the European Research Council for
COXINEL (340015) and X-Five (339128) advanced grants.

Conclusion

What ever is the beam manipulation, matching the beam from LPA to undulator for FEL experiment is still very challenging …

Stability

Low charge, low rep. rate

Magnet alignment

Optic tuning

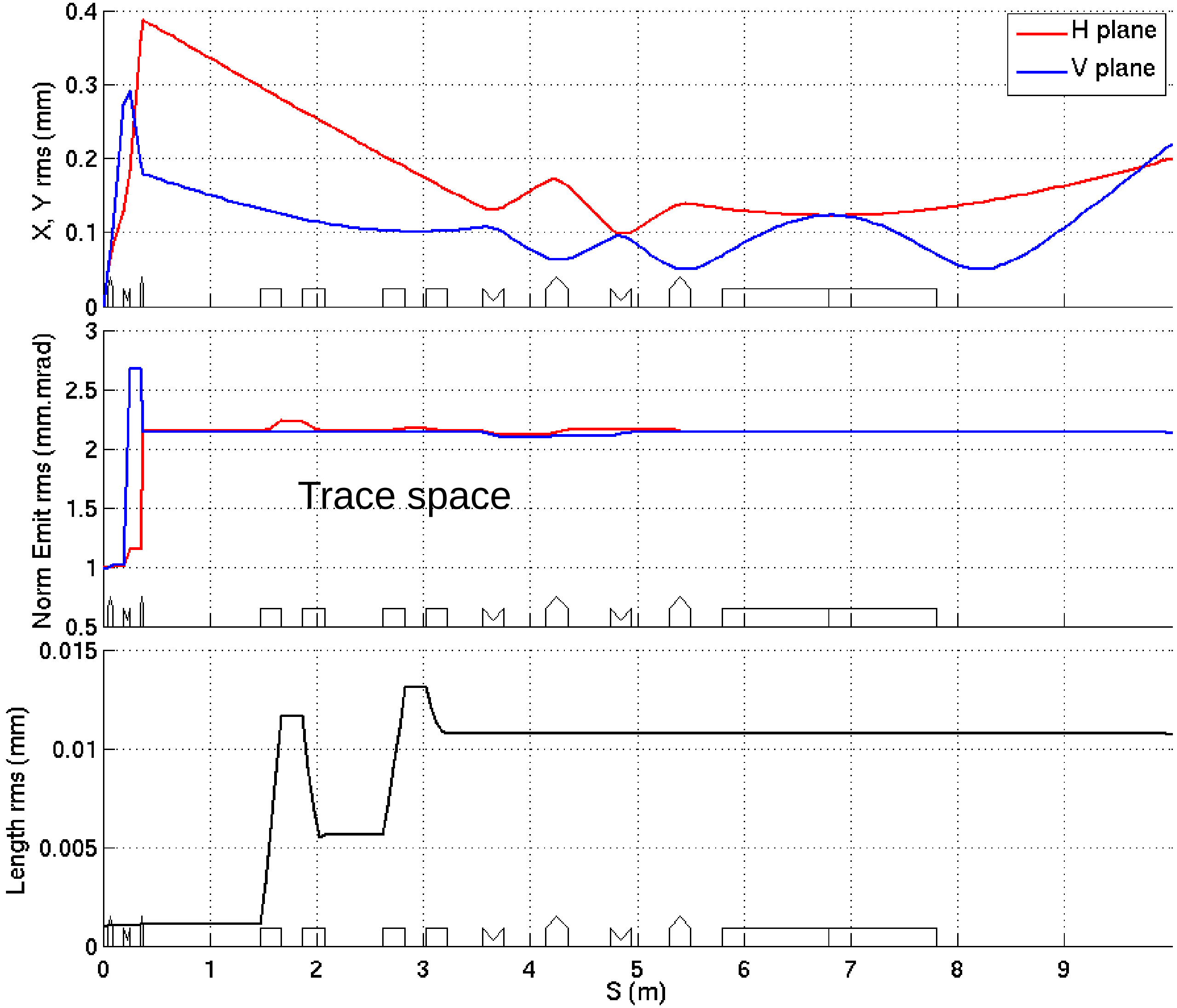
Beam based fine tuning, fine alignment !

==> Need beam time

Thank you for your attention ...

Envelops, emittance and bunch lenght

180 MeV
200 nm



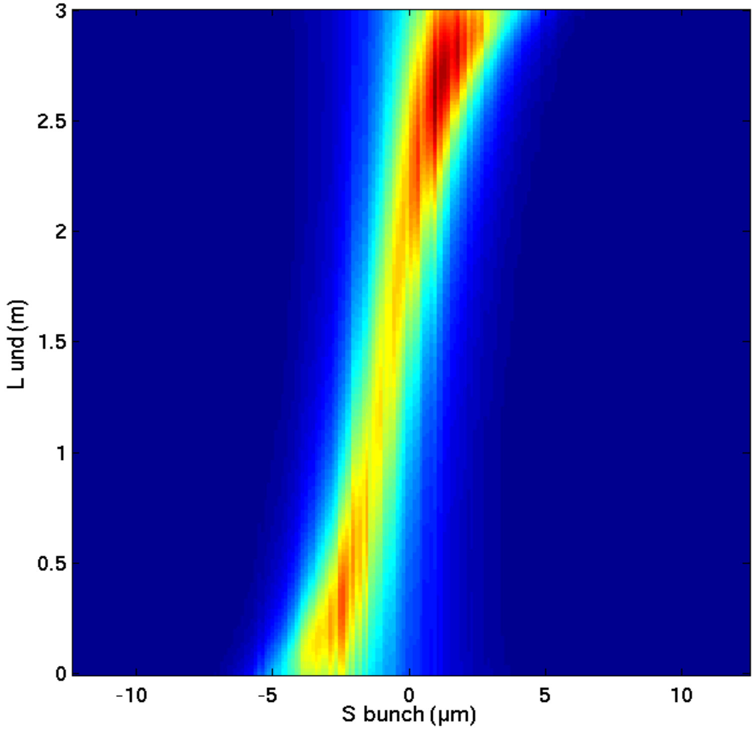
rms envelops

rms emittances

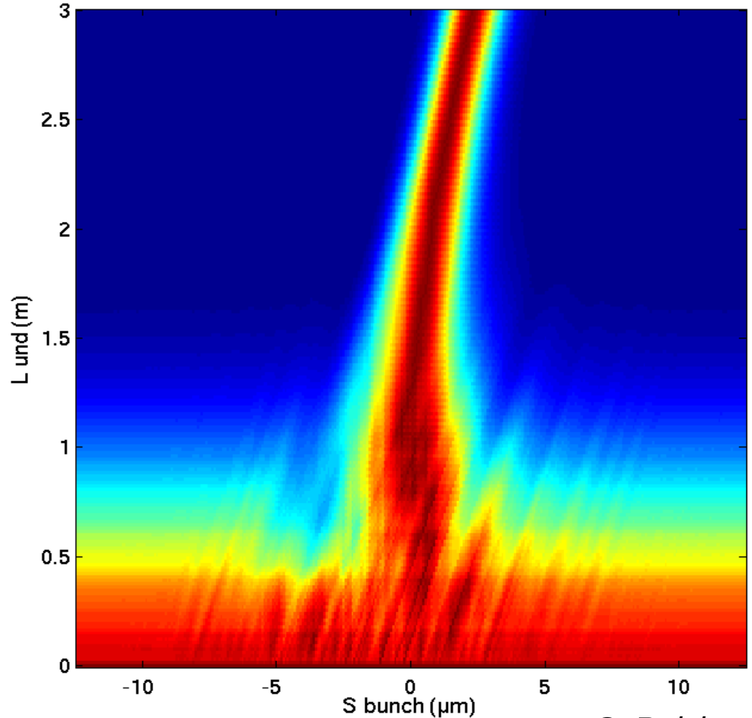
rms length

COXINEL SIMULATION

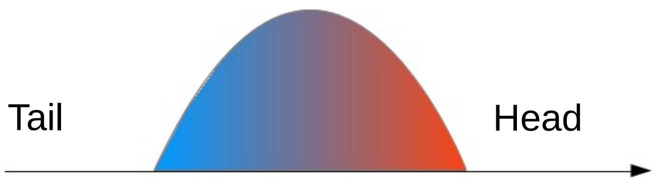
Transverse beam density



GENESIS : FEL power



S. Reiche, NIM 1999

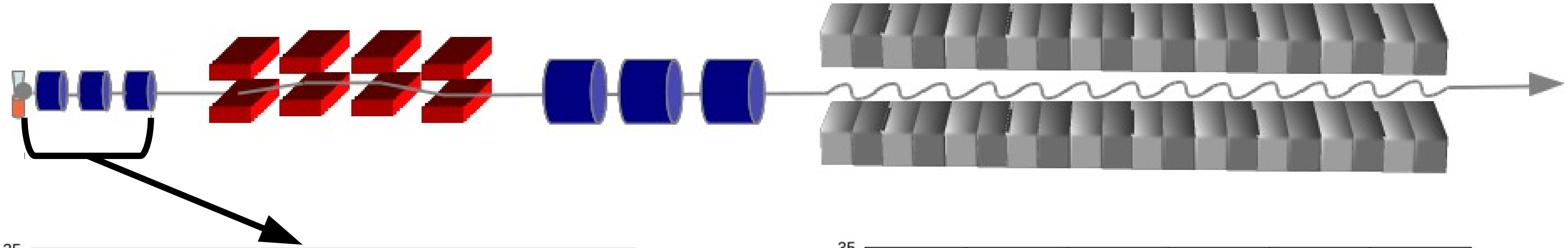


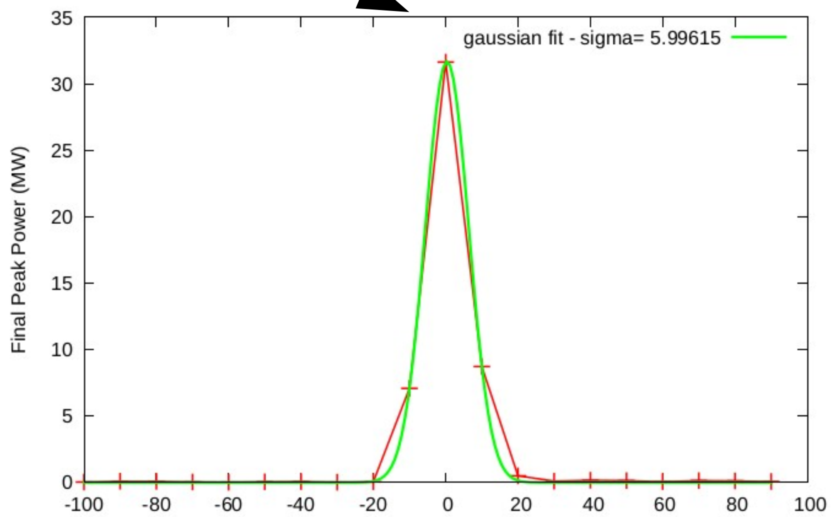
Bunch profile

Peak power maximum when electron waist slippage is synchronized with the FEL optical wave slippage :

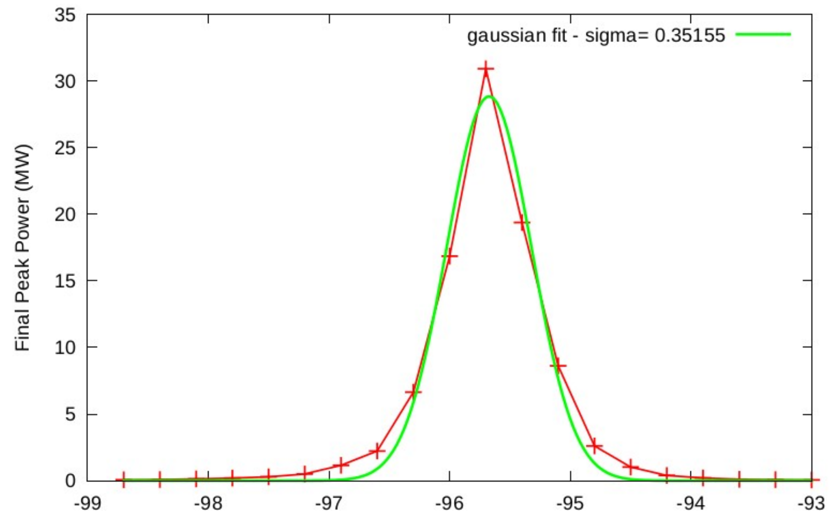
==> chicane strength knob

PMQ sensitivities vs FEL





Horizontal displacement (µm)



Gradient (T/m)

Tolerance = $\pm 10\,\mu m$

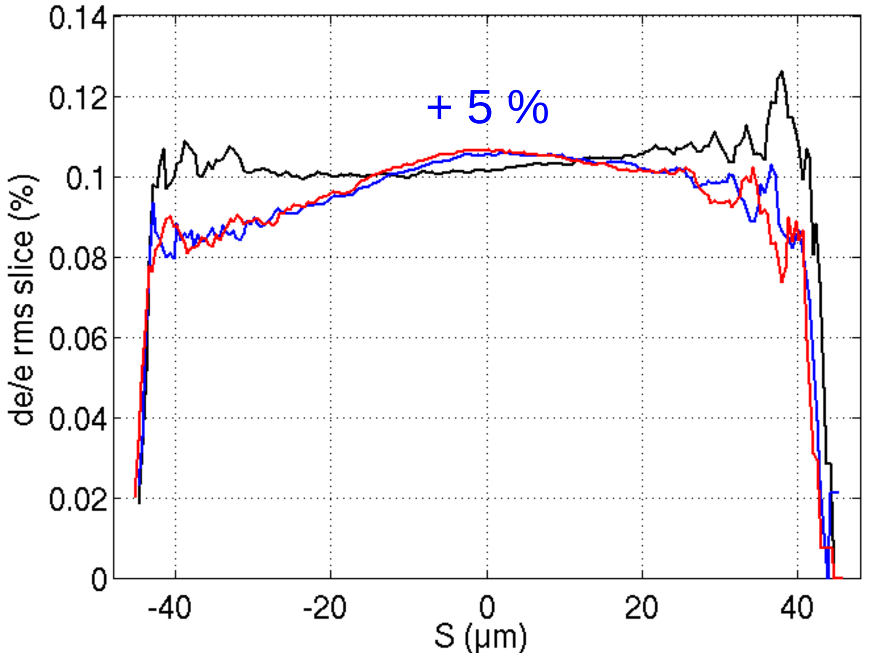
Tolerance = 0.5 %

Very tight !

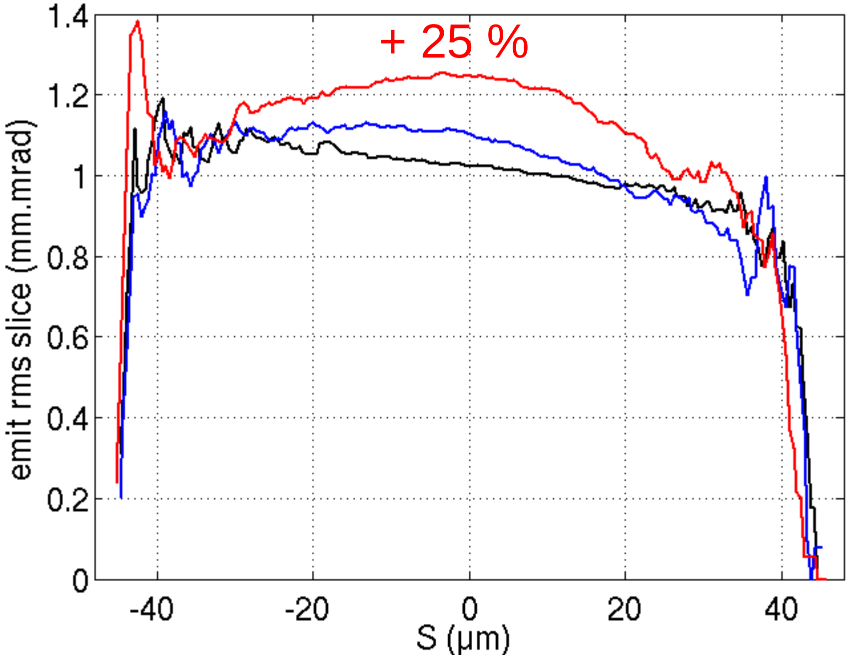
Collective effects on slices

180 MeV : 4 kA decompressed to 400 A, r_{56}= 1 mm

No wakes + 3D Space charge + 1D CSR



SC enlarges the decompression

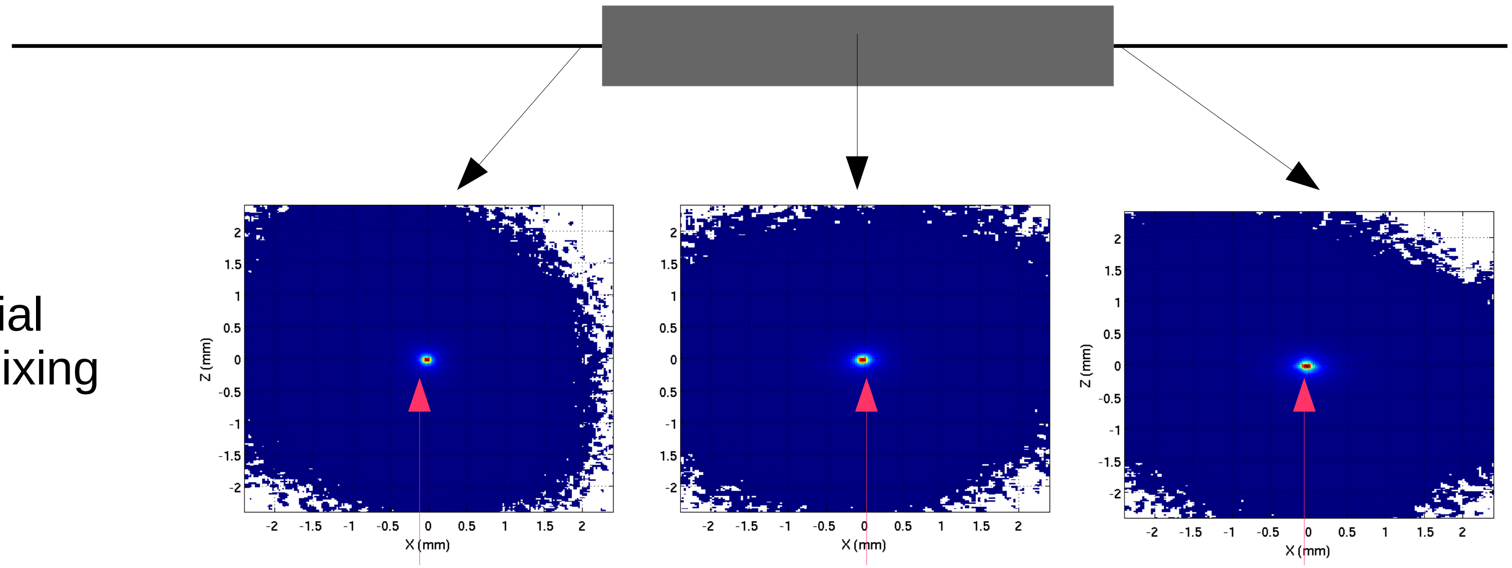


SC & CSR enlarge the slice emittances

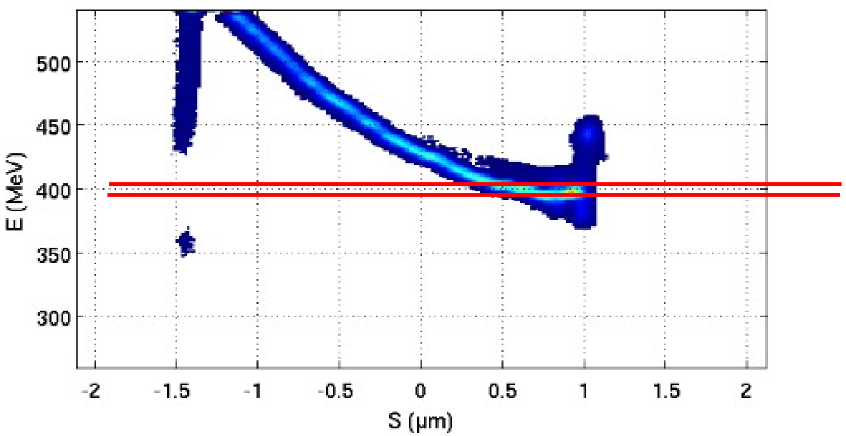
(Long. excursion from emittance & optics M. Dohlus, T. Limberg, IPAC 2005)

Extra slide

Radial demixing



-0.63 % 0 % +0.63 %



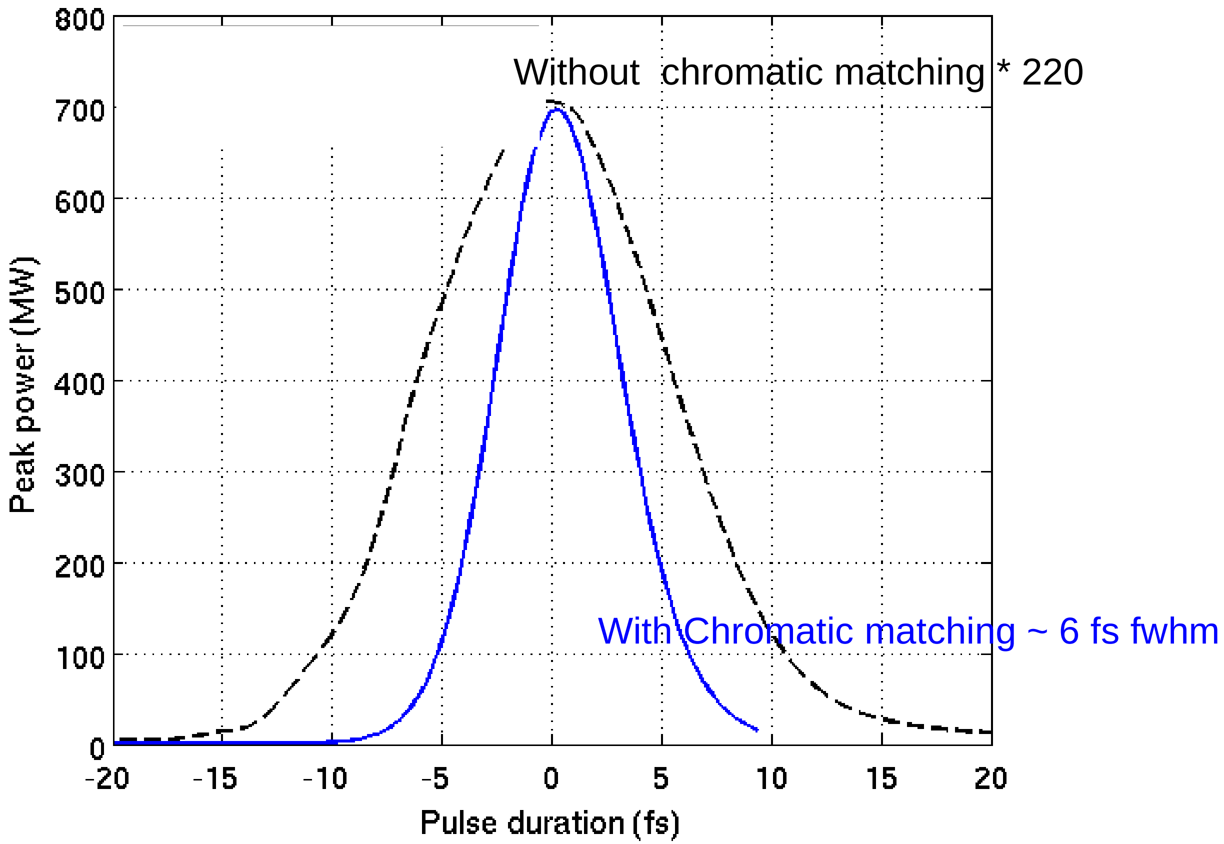
Small fraction are focused In the undulator :

Here between +- 2.5 MeV
< 5 % of the total charge

Input beam from CALDER simulation : X. Davoine

Single spike

400 MeV – 10 kW SEED at 40 nm over 5 m



Magnification varaition

400 MeV – 10 kW SEED at 40 nm over 5 m

For different magnifications r11=r33