LWFA electron beam manipulations for FEL amplification

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OUTLINE

- LWFA beam properties

- Beam manipulations for FEL

- FEL simulations

- Conclusion
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.
Decompress the bunch to cope with the large energy spread

\[ \delta > 0 \]
\[ \delta < 0 \]

Decompression or slice energy de-mixing

\[ \Delta s_{\text{bunch}} = r_{56} \delta \]
Longer bunch also allows for the FEL slippage

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

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 ...

Z. Huang
Trailing particles

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

Lengthening $\sim \sigma_x^2$

$\Rightarrow$ Slice energy re-mixing
Chromatic emittance

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

\[ \gamma \epsilon_{\text{chrom}} \sim \gamma \sigma_{x}^{2} \sigma_{\delta} \]

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 $\Rightarrow \sim 4 \pi \text{mm.mrad rms}$
2 2% $\Rightarrow \sim 32 \pi \text{mm.mrad rms}$

$\gamma \epsilon_{\text{chrom}} \sim \gamma \sigma_x^2 \sigma_\delta$
Chromatic emittance

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

\[ \sim 5 \text{ m} \]

\[ \begin{array}{cccc}
\text{LWFA} & Q_1 & Q_2 & Q_3 & \text{BM1} & Q_{41} & Q_5 & Q_{42} & \text{BM2} & Q_6 & Q_7 & Q_8 & \text{TGU} \\
\text{triplet 1} & \text{achromat} & \text{triplet 2} \\
\end{array} \]

\[ \text{C. Widman et al} \]

\[ \Rightarrow \text{Very challenging due to very large chromatic effects ...} \]

\[ \Rightarrow \text{Induce large phase space distortions} \]

\[ \text{To give an idea: The chromaticities are as large as Synchrotron rings!} \]

\[ \text{(Few hundred of meters and hundred of sextupoles)} \]
Chromatic emittance

Refocus the beam by means of plasma lens:

C. Thaury et al., Nat. Com. 2014

Very strong focusing (electrical monopole) in both planes
Very close : $L \sim $ millimeter scale

$\Rightarrow$ Divergence experimentally reduced by 2.6
$\Rightarrow$ Able to reduce, in principle, the chromatic terms

$\gamma \epsilon_{chrom} \sim \gamma \sigma_x^2 \sigma_\delta$

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

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

TRANSPORT code notation 2\textsuperscript{nd} order

For large divergence
No initial correlation

\[\gamma \epsilon_{chrom} = \gamma \frac{r_{126}}{r_{11}} \sigma_x^2, \sigma_\delta\]

Source to Image
\[r_{12} = 0\]

Just quadrupole settings
Independent from the initial beam

Works in both planes ...
Chromatic matching

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

- **Chicane**
  - Energy De-mixing
  - $r_{56} \sim 1\, \text{mm}$, $B \sim 0.2\, \text{T}$

- **Source**
  - 400 MeV

- **First triplet**
  - Re-focusing
  - $G < 200\, \text{T/m}$

- **Second triplet**
  - Chromatic matching
  - $G < 20\, \text{T/m}$

- **5 m In-Vac Cryo ready Undulator (PrFeB)**
  - 15 mm period
  - $B \sim 1.5\, \text{T} @ \text{gap}=3.6\, \text{mm}$

~ 10 m
Chromatic matching

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

Synchronization slippage: Electron slice waist = Photon FEL wave

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

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

\( = \Rightarrow \) Not sensitive to initial divergence, energy spread, pointing ...

The chicane has a weak effect on the transverse focusing (1\(^{\text{st}}\) and higher order)

\( = \Rightarrow \sim \) Act only on the longitudinal plane

\textbf{In practice}: Set the quadrupoles and scan the chicane strength \( r_{56} \)}
Chromatic matching

400 MeV Initial LPA beam:

\begin{align*}
4 \text{ kA peak} \\
1 \mu m \text{ rms length} \\
1 \% \text{ rms relative energy spread} \\
1 \text{ mrad rms divergence} \\
\gamma_e = 1 \pi \text{mm.mrad rms}
\end{align*}

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 along the undulator (A/mm²)

\[ \frac{I_{\text{slice}}}{\sigma_x \sigma_z} \]

No chromatic matching

Chromatic matching

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Chromatic matching

Chicane strength

$R_{56} = 0$ mm

No chromatic matching

$R_{56} = 0.5$ mm

With chromatic matching

$R_{56} = 1$ mm
Chromatic matching

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

No chromatic matching

Chromatic matching

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Chromatic matching

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

Peak FEL power at exit

With Chromatic matching

Without chromatic matching

Peak FEL along the und.

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

Seeded with 10 kW at 40 nm

GENESIS code
S. Reiche, NIM 1999

Linear Field Tapering
N. M. Kroll et al., PQE, 1980
L. Giannessi et al., PRL 2011
Chromatic matching movie
TGU vs chromatic matching

W. Qin et al. FEL 2015

500 MeV - SASE at 30 nm over 6 m

Emittances rise from 0.1 to ~ 6 \( \pi \text{mm.mrad} \) rms (Elegant code)
Experiment preparation ...

... to get an FEL amplification

Berkeley
CFEL
JAEA
JENA
Shanghai
SOLEIL – LOA
SPARC
Strathclyde
...

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Experiment preparation

COXINEL

Salle jaune, LOA

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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 ...
Envelopes, emittance and bunch length

180 MeV
200 nm

rms envelopes

rms emittances

Trace space

rms length
COXINEL SIMULATION

Transverse beam density

GENESIS : FEL power

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

==> chicane strength knob

S. Reiche, NIM 1999
PMQ sensitivities vs FEL

Tolerance = ±10 µm

Very tight!

Tolerance = 0.5 %
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)*
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

With Chromatic matching ~ 6 fs fwhm

Without chromatic matching * 220
Magnification variation

For different magnifications \( r_{11} = r_{33} \)

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