Progress towards laser plasma acceleration based free electron laser on COXINEL

M. E. Couprie, T. André, F. Blache, F. Briquez, F. Bouvet, Y. Dietrich, J. P. Duval, M. El-Ajjouri, A. Ghaith, C. Herbeaux, N. Hubert, C. Kitégi, M. Khojoyan, M. Labat, N. Leclercq, A. Lestrade, A. Loulergue, O. Marcouillé, F. Marteau, D. Oumbarek, P. Rommeluère, M. Sebdaoui, K. Tavakoli, M. Valléau, Synchrotron SOLEIL, GIF-sur-YVETTE, France.

S. Corde, J. Gautier, J. P. Goddet, O. Kononenko, G. Lambert, A. Tafzi, K. Ta Phuoc, C. Thaury, Laboratoire d'Optique Appliquée, Palaiseau, France.

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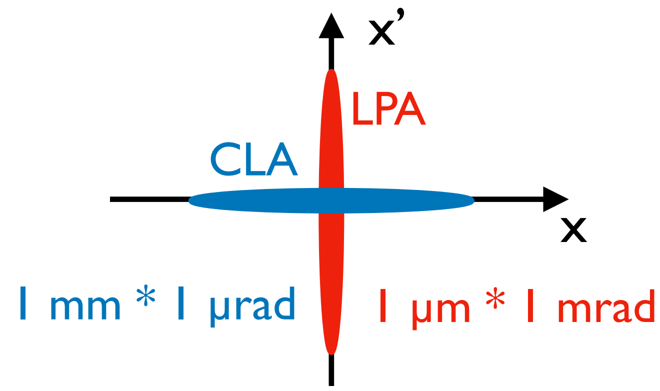
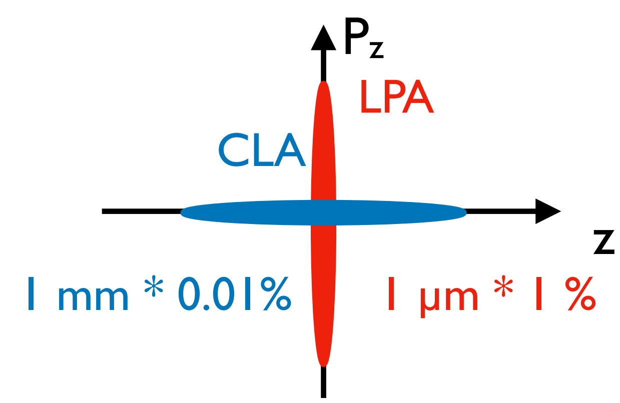
Towards laser plasma acceleration based Free Electron Lasers

Motivation : Exploit the present laser plasma acceleration performance for undulator radiation and a Free Electron Laser applications

LPA versus conventional accelerator

	Transverse	Longitudinal
Phase space		

Beam brightness

$$\mathscr{B}_{e,6D} = \frac{2I_p}{\varepsilon_{nx}\varepsilon_{nx}\sigma_\gamma/\gamma}$$

CLA : 10^{17} A/rad²/m²/%

LPA : 10^{15} A/rad²/m²/%

Chromatic effets

$$\gamma\varepsilon_{total} = \sqrt{\gamma^2\varepsilon_0^2 + \gamma^2\varepsilon_{chrom}^2}$$

$$\varepsilon_{chrom} \propto \sigma'^2\ \sigma_\gamma/\gamma$$

Lengthening ~ σ'^2_x

$$\sigma_s^2 \approx \sigma_{s0}^2 + (r_{56}\frac{\sigma_\gamma}{\gamma})^2 + (r_{522}\sigma_{x0}'^2 + r_{544}\sigma_{z0}'^2)^2.$$

K. Flöttmann, PRST-AB 6, 034202 (2003).

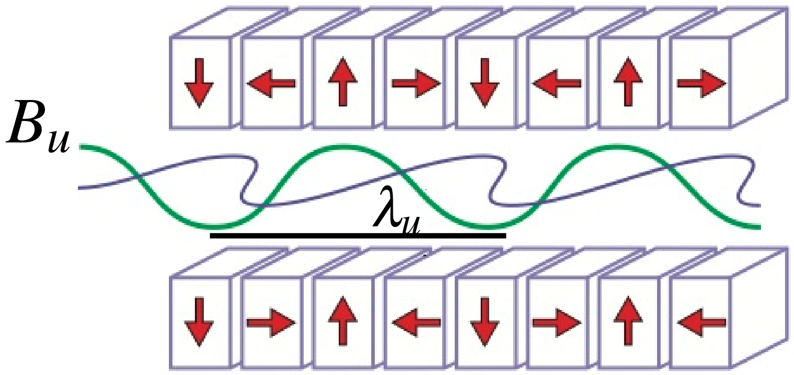
T. Mehrling et al., PRST-AB 15, 111303 (2012).

P. Antici et al., J. Appl. Phys. 112, 044902 (2012).

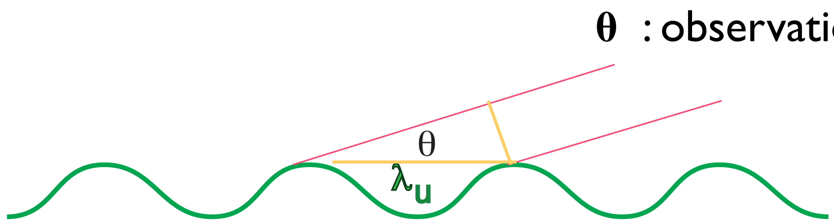
M. Migliorati et al., PTST-AB 16, 011302 (2013).

Undulator radiation

Planar undulator



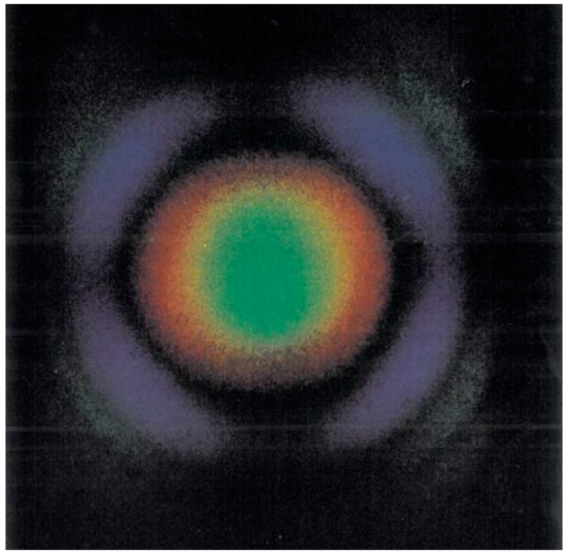
$K_u = \frac{eB_u\lambda_u}{2\pi m_o c}$ deflection parameter



$$\lambda_n = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K_u^2}{2} + \gamma^2\theta^2\right)$$

$\gamma = \frac{E}{m_o c^2}$

γ : Lorentz factor



Single electron emission : homogeneous linewidth

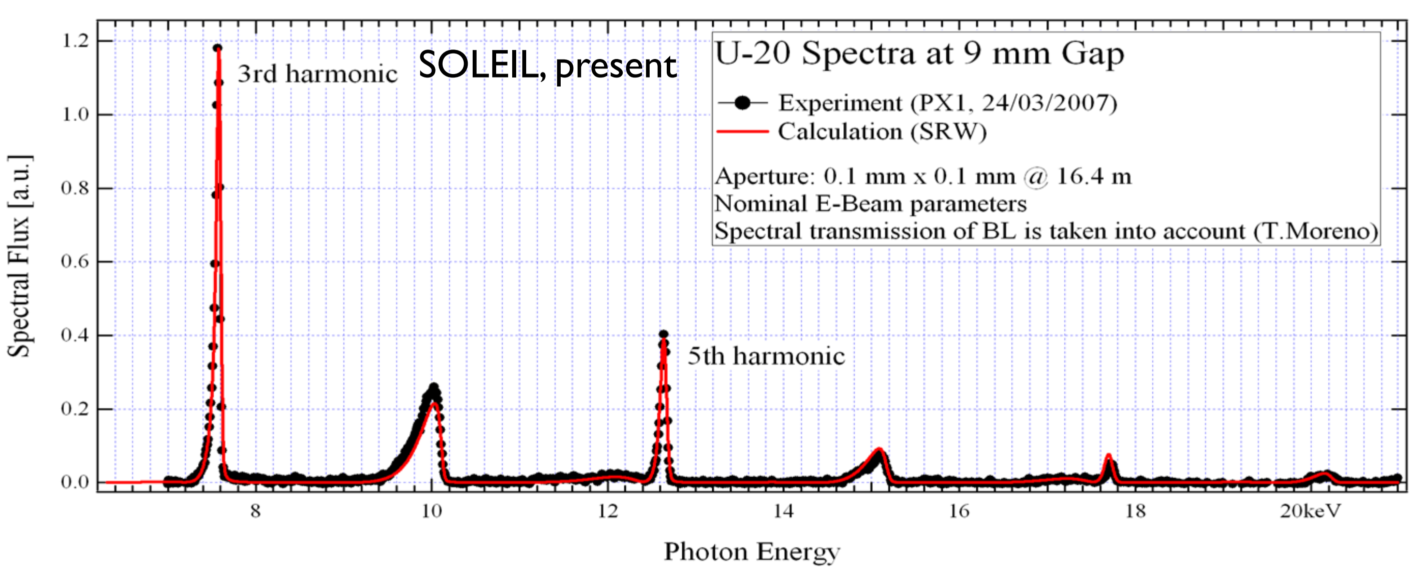
interference from trains of N_u periods :

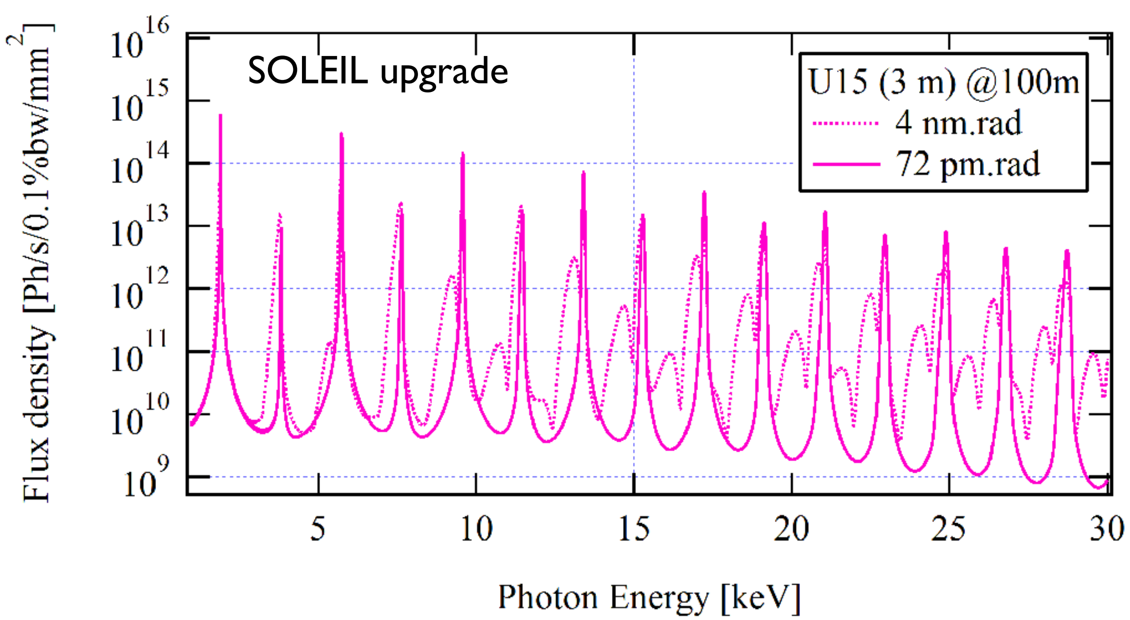
Intensity α N_u^2 $\left(\frac{\Delta\lambda}{\lambda_n}\right)_{hom} \approx \frac{1}{nN_u}$ $\mathscr{B}_{ph} \propto \frac{\Delta\lambda}{\lambda_n}$

Multi-electron emission : Inhomogeneous linewidth

energy spread divergence and size (emittance)

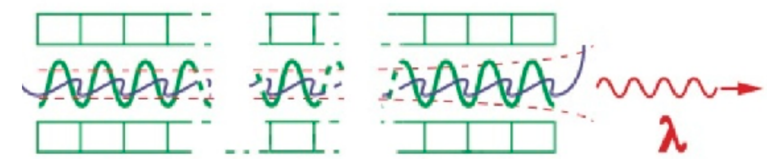
When $(\Delta\lambda/\lambda)_{inh}$ becomes dominant, Intensity α N_u

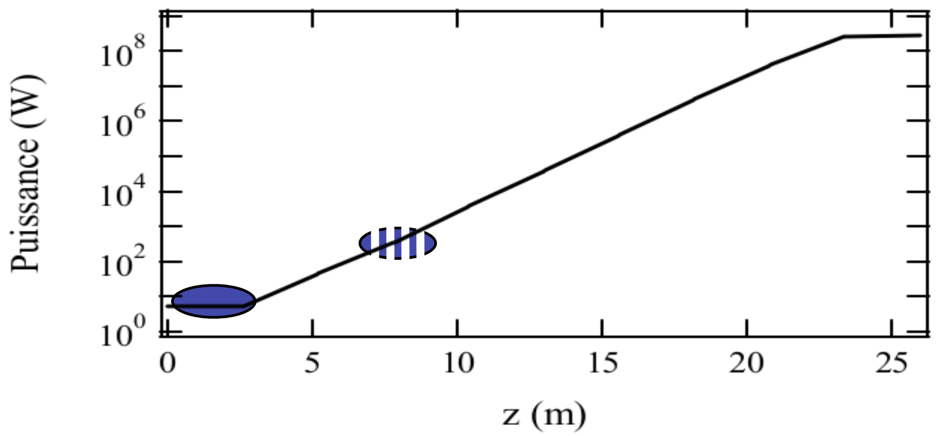




Free Electron Laser

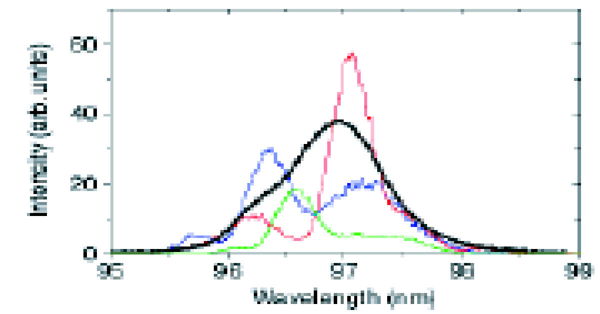
SASE (Self Amplified Spontaneous Emission)





R. Bonifacio et al, Opt. Comm. 50, 1984, 376, K. J. Kim et al, PRL57, 1986, 1871, C. Pelligrini et al, NIMA475, 2001, 1, A.M. Kondratenko et al, Sou Phys. Dokl. 24 (12), 1979, 989

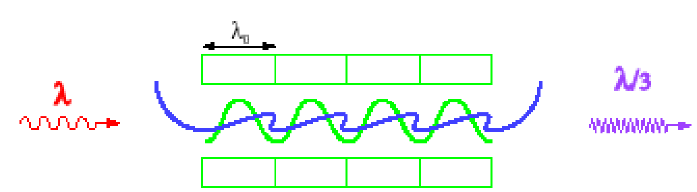
- short wavelength operation (1 Å)
- good transverse coherence • spike
- single spike (low charge, chrip/taper), self-seeding



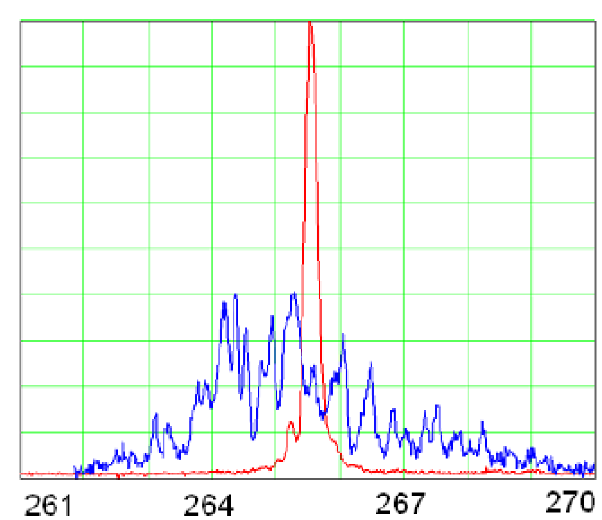
S. Reiche et al., NIMA 593 (2008) 45-48

L. Giannessi et al., Phys. Rev. Lett. 106, 144801 (2011)

Seeding : one laser-electron interaction



- temporal coherence given by the external seed laser
- improved stability (intensity, spectral fluctuations and jitter)
- quicker saturation
- good transverse coherence
- Seed : laser and HHG (160, 60, 30 nm)
- up-frequency multiplication (260 nm -> 4 nm at FERMI)



L. H.Yu et al, PRL91 2003, 074801

L. H.Yu et al, Science 289, 2000, 932

T. Saftan APAC 2004, Gyeongu

Undulator radiation and FEL requirements

In transverse (transverse sizes and divergences)

Undulator $\left(\frac{\Delta\lambda}{\lambda_n}\right)_{\sigma'} < \left(\frac{\Delta\lambda}{\lambda_n}\right)_{hom}$ $\left(\frac{\Delta\lambda}{\lambda_n}\right)_{\sigma_z} < \left(\frac{\Delta\lambda}{\lambda_n}\right)_{hom}$

FEL $\frac{\varepsilon_n}{\gamma} < \frac{\lambda}{4\pi}$

In longitudinal (energy spread and bunch length)

$$\frac{\sigma_\gamma}{\gamma} < \frac{1}{2\,nN_u}$$

$$\frac{\sigma_\gamma}{\gamma} < \rho_{FEL} \qquad \rho_{FEL} = \left[\frac{K_u[JJ]\omega_p}{4\omega_u}\right]^{2/3} = \frac{1}{2\gamma k_u}\left(\frac{\mu_o e^2 K_u^2 [JJ]^2 k_u n_e}{4 m_o}\right)^{1/3}$$

=> Handling of the divergence

- Plasma lens (passive, active)

R. Lehe et al. PRSTAB. 17, 121301 (2014)
C. Thaury et al. Nature Comm. 6, 6860 (2015)
J. Van Tilborg et al., PRL 115, 184802 (2015)
Nakanii N. et al., PRASTAB 18, 021303 (2015)
T. Hosokai et al, PRL 97, 075004 (2006)
T. Hosokai et al. „APL 96, 121501 (2010)
S. Steinke et al., Nature (2016)
R. Pompili Applied Physics Letters, 110(10), 104101.

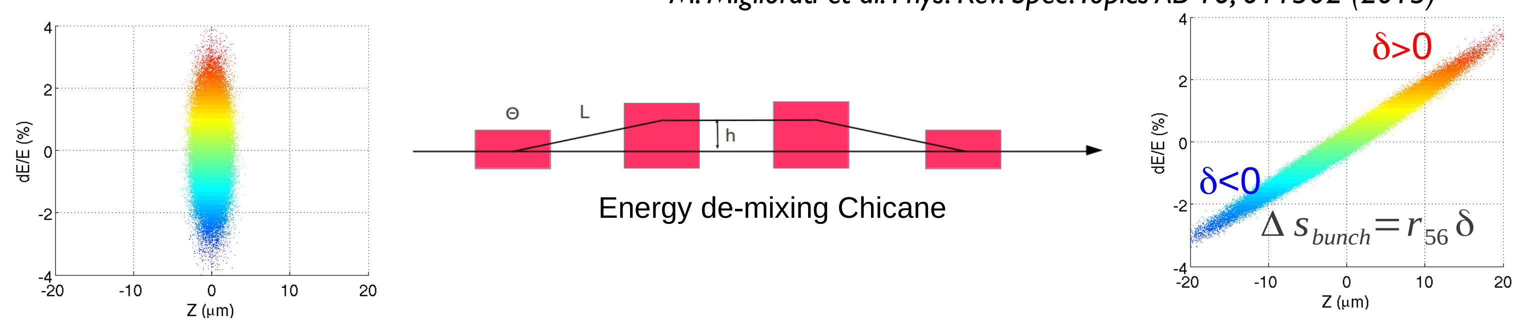
- High gradient quadrupole (permanent magnet based)

A. Ghaith et al., Instruments 2019, 3, 27; doi:10.3390/ instruments3020027 (2019)
M. P. Anania et al., Appl. Phys. Lett. 104, 264102 (2014)
F. Marteau et al., Appl. Phys. Lett. 111, 253503 (2017)

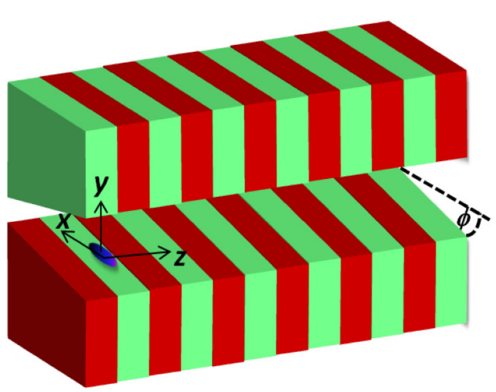
=> Handling of the energy spread

- Demixing chicane

A. R. Maier et al., Phys. Rev. X 2, 031019 (2012)
M. E. Couprie et al. J. Physics B : At., Mol. Opt. Phys. (2014) 234001
P. Antici et al., J. Appl. Phys. 112, 044902 (2012)
M. Migliorati et al. Phys. Rev. Spec. Topics AB 16, 011302 (2013)



- Tranverse gradient undulator



canted magnetic poles

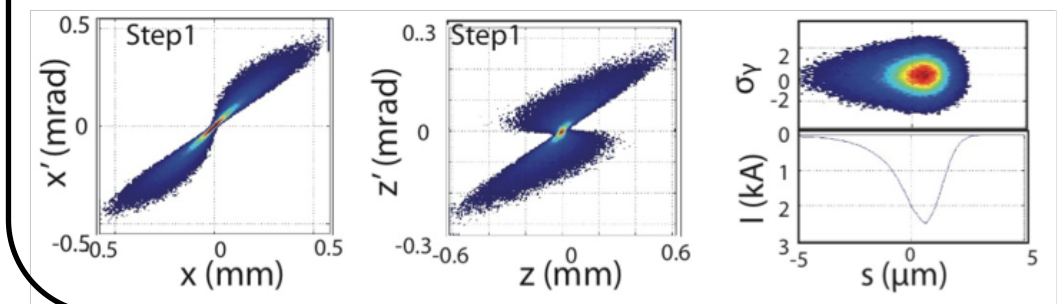
N. M. Kroll et al. Quantum Electronics, IEEE , 17(8), 1496-1507 (1981)
T. Smith, J. M. J. Madey, L. R. Elias, and D. A. G. Deacon, J. Appl. Phys. 50, 4580 (1979)
Z. Huang et al., Phys. Rev. Lett. 109, 204801 (2012)

$B_u(x)=B_{u,0}(1+\alpha x)$, α the gradient coefficient
dispersive optics => $x= \eta\Delta\gamma/\gamma$,
resonant condition fulfilled for $\eta=(2 + Ko^2)/\alpha Ko^2$.

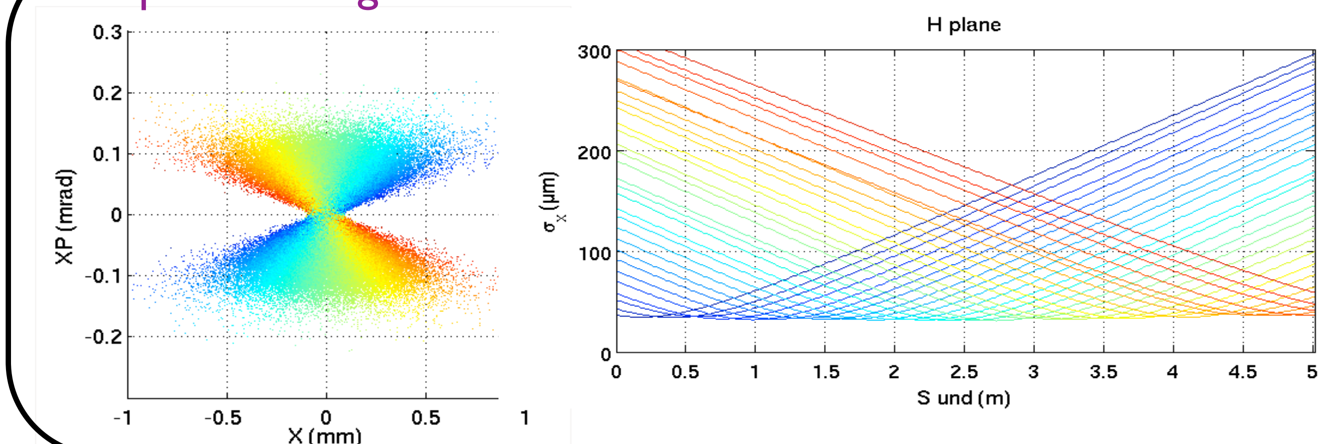
COXINEL : a test experiment towards a LWFA FEL amplification

strong focusing

start : 400 MeV, 1 µm, 1.25 mrad, 1 %, 2 fs RMS, 20 pC

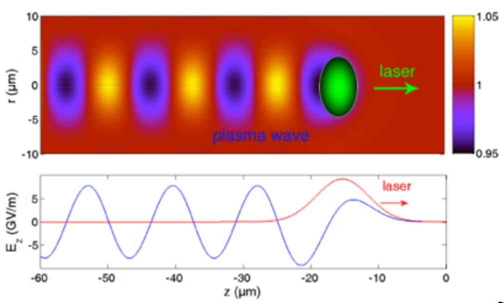


supermatching



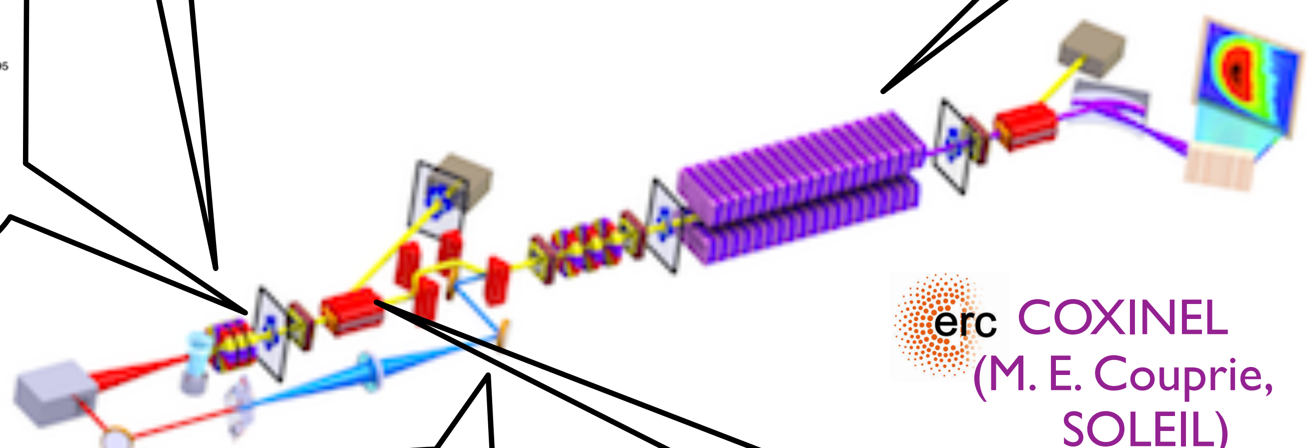
A. Loulergue et al.., New J. Phys. 17 (2015) 023028 (2015)

LWFA



electron production
colliding scheme,
shock assisted
ionization injection

erc X-Five
(V. Malka, LOA)



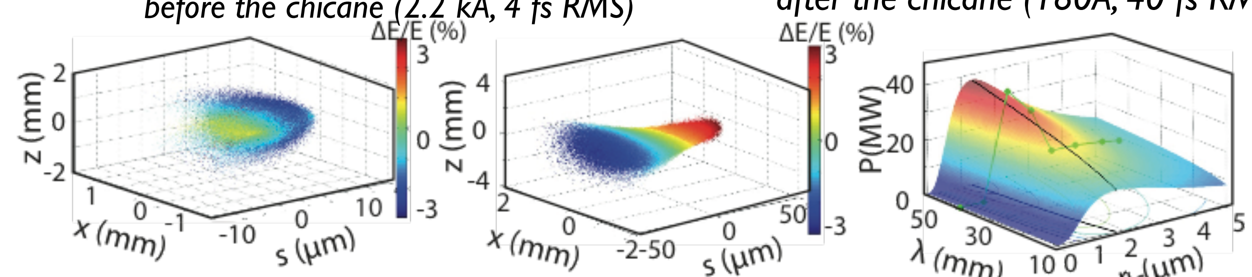
seeding

erc COXINEL
(M. E. Couprie,
SOLEIL)

Parameters	Source
Energy (MeV)	180
Charge [pC]	34
Divergence [mrad]	1
Beam size [µm]	1
Normalized emittance [π.mm.mrad]	1
Relative energy spread [%]	1
Bunch length (µm)	1
Peak current [kA]	4

decompression (1 % -> 0.1 %, 2 fs -> 20 fs)

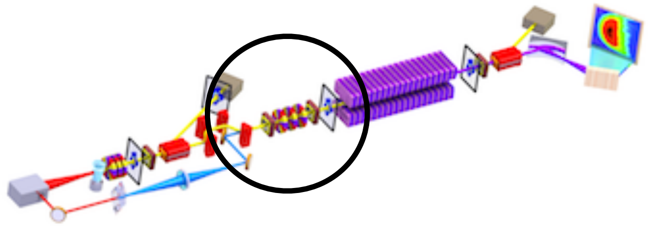
before the chicane (2.2 kA, 4 fs RMS) *after the chicane (180A, 40 fs RMS*



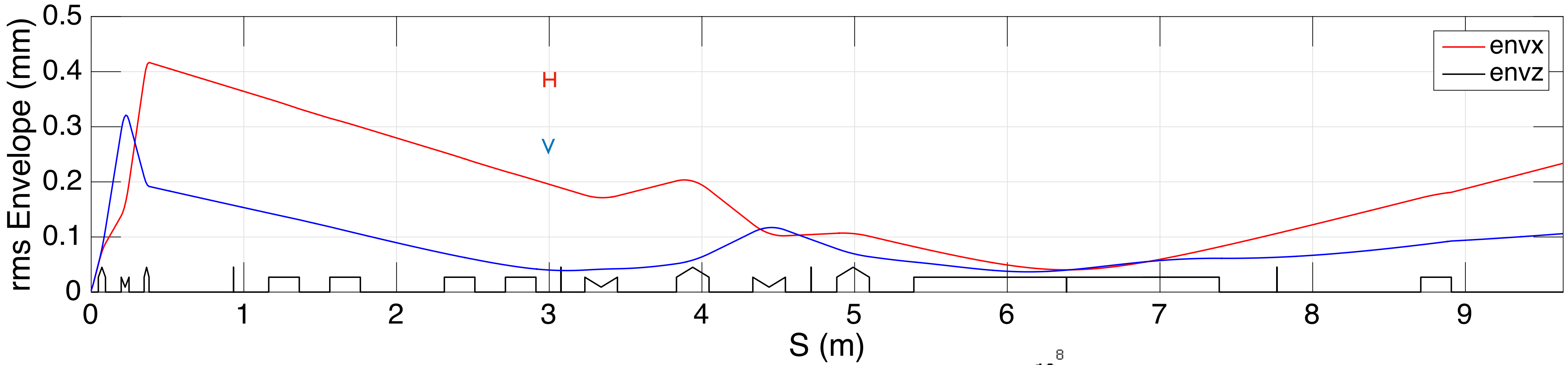
start : 400 MeV, 1 µm, 1.25 mrad, 1 %, 2 fs RMS, 20 pC

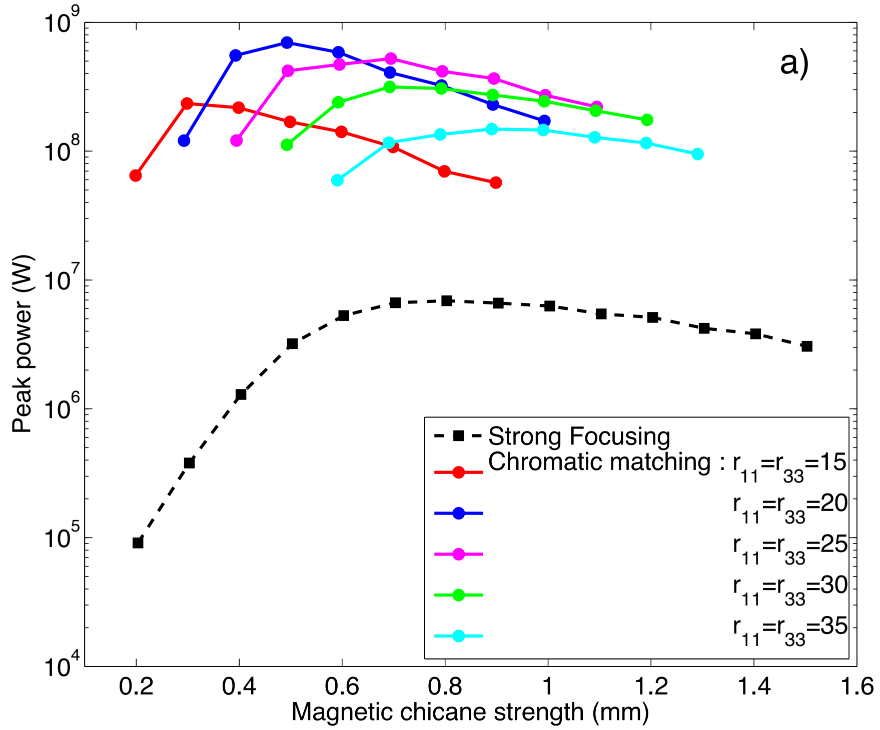
A. Loulergue et al.., New J. Phys. 17 (2015) 023028 (2015)
M. E. Couprie et al. J. Physics B :At., Mol. Opt. Phys. (2014) 234001
M. Labat et al., Robustness of a plasma acceleration based Free Electron Laser, Phys. Rev. Accelerators and beams 21, 114802 (2018)

Chromatic matching

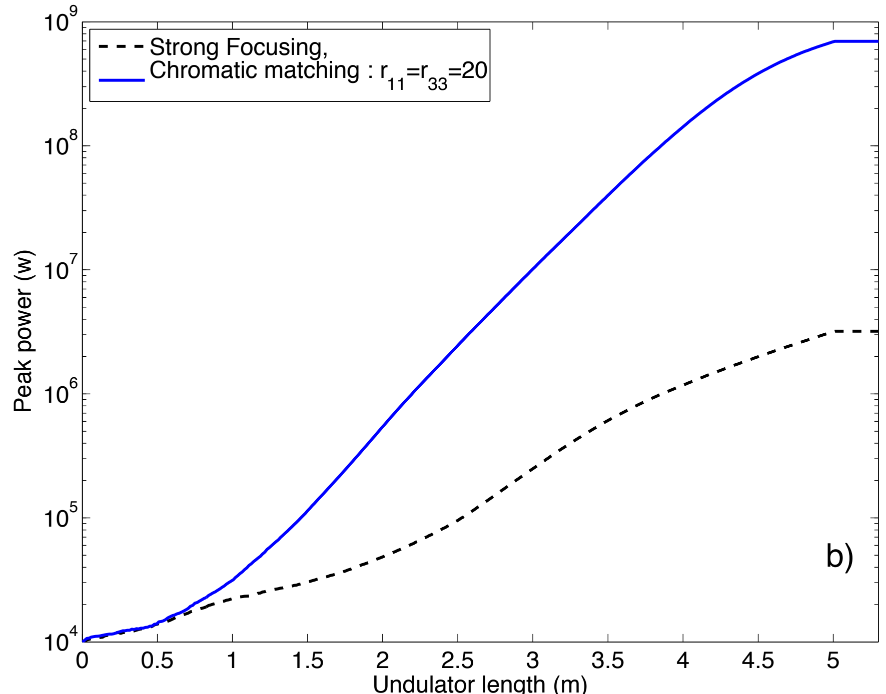


$$\gamma\varepsilon_{chrom} = \gamma\, r_{22} r_{126} \sigma_{x'}^{2} \frac{\sigma_\gamma}{\gamma}$$

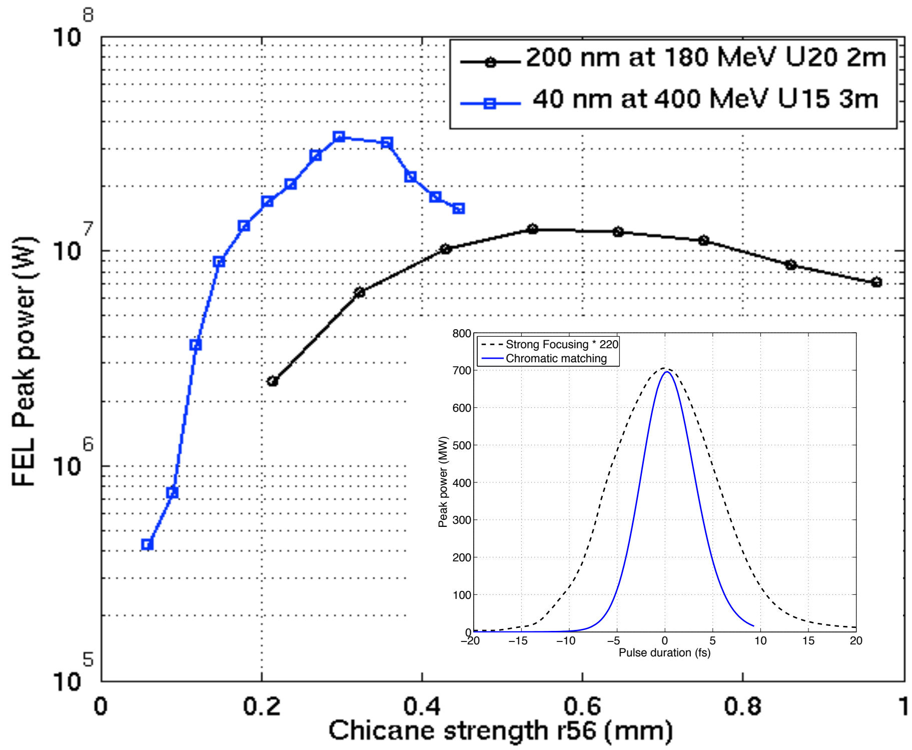




Initial beam : 4 kA, 1%, 1 µm, 1 π.mm.mrad, 1 mrad (all rms data)



chicane strength : 0.5 mm
5 m U15 undulator (1.5 T maximum field)
40 nm, 400 MeV

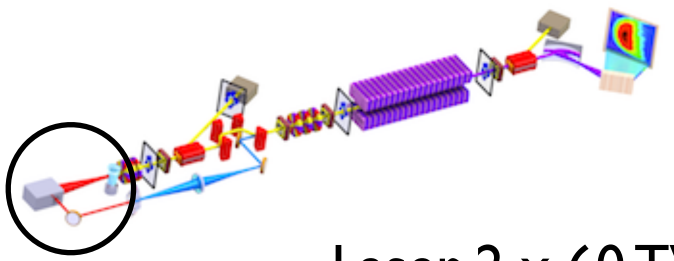


U20 of 2m targeting 200 nm at 180 MeV
U15 of 3m targeting 40 nm at 400 MeV

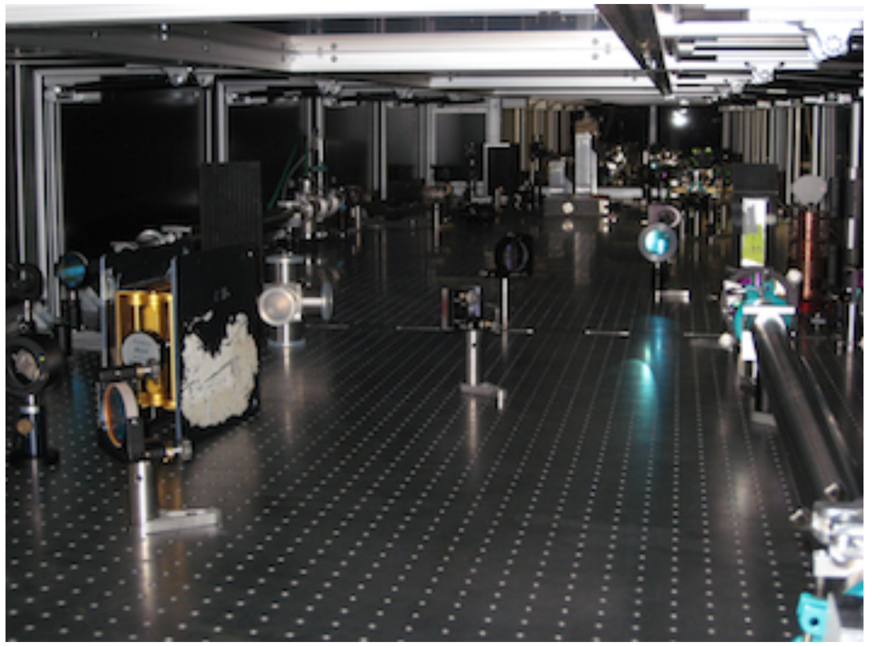
A. Loulergue, M. Labat, C. Benabderrahmane, V. Malka, M. E. Couprie, Beam manipulation for compact laser wakefield accelerator based free-electron lasers, New J. Phys. 17 (2015) 023028 (2015)

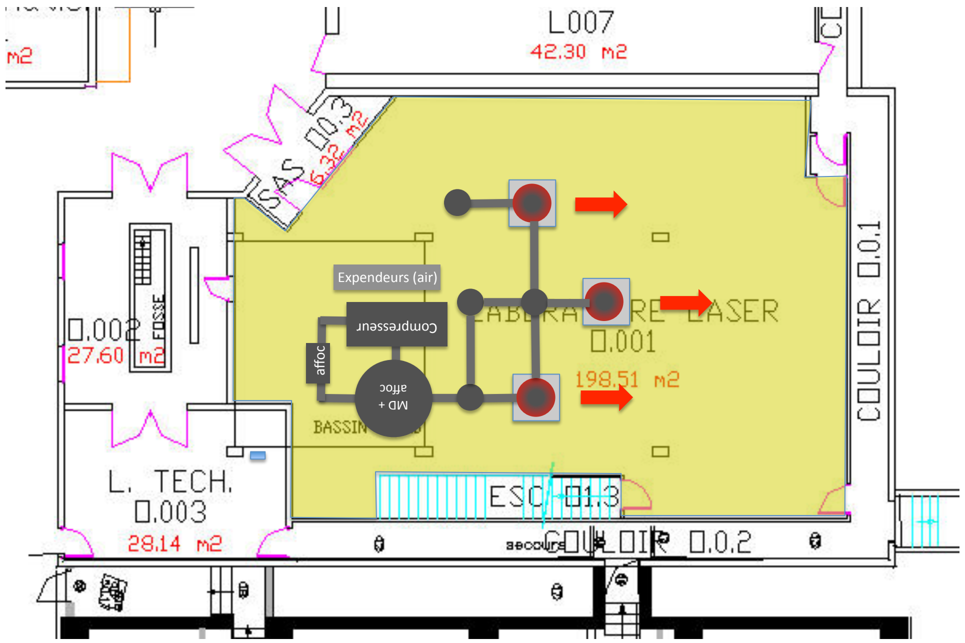
The laser and electron source

Responsability Laboratoire d'Optique Appliquée (LOA),
S. Corde, C. Thaury



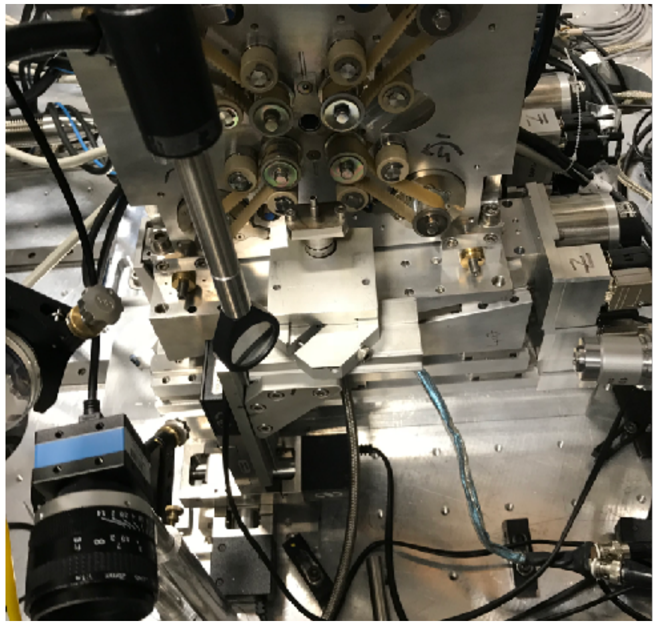
Laser 2 x 60 TW of LOA, used for 3 different fields





Laser Characteristics:
Ti:Sa (800 nm)
Pulse Duration = 30 fs
Energy = 1.2-1.5 J on target

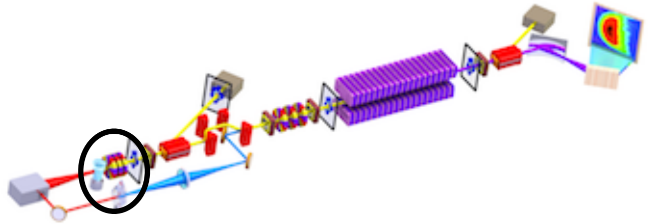
Ionization injection
99% He, 1 % N_2
Robustness
High charge



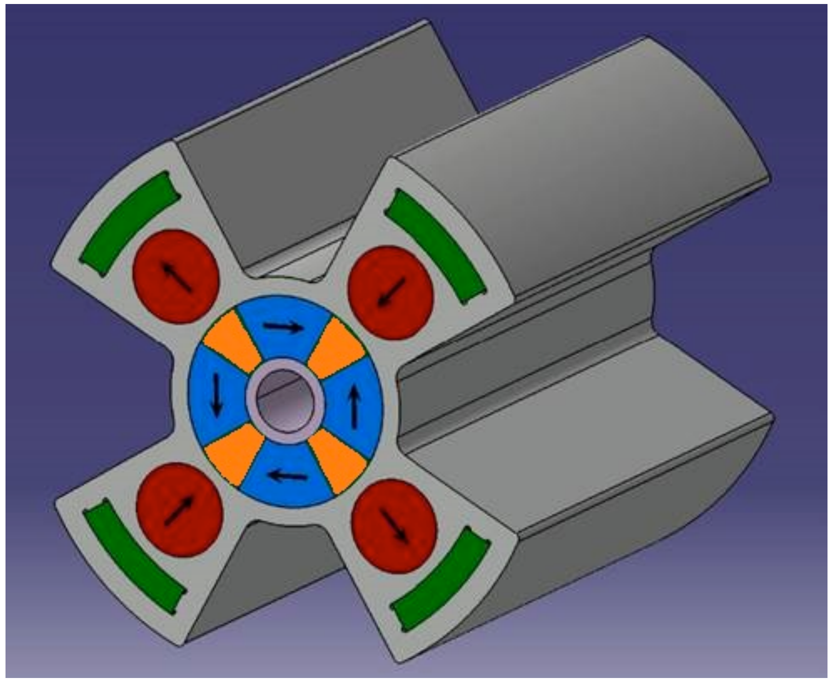
Laser upgrade : 120 TW, 25 fs, 2.75-3.5 J on target for the main pulse

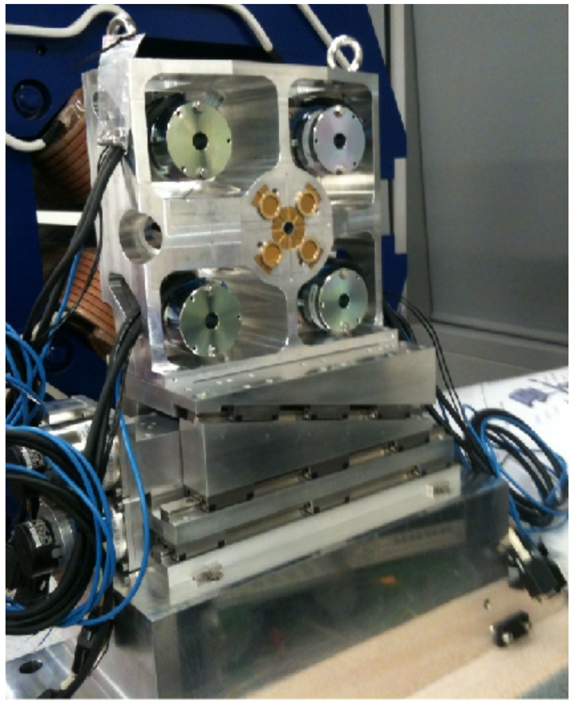
Permanent magnet quadrupole with variable gradient for the LPA beam divergence handling

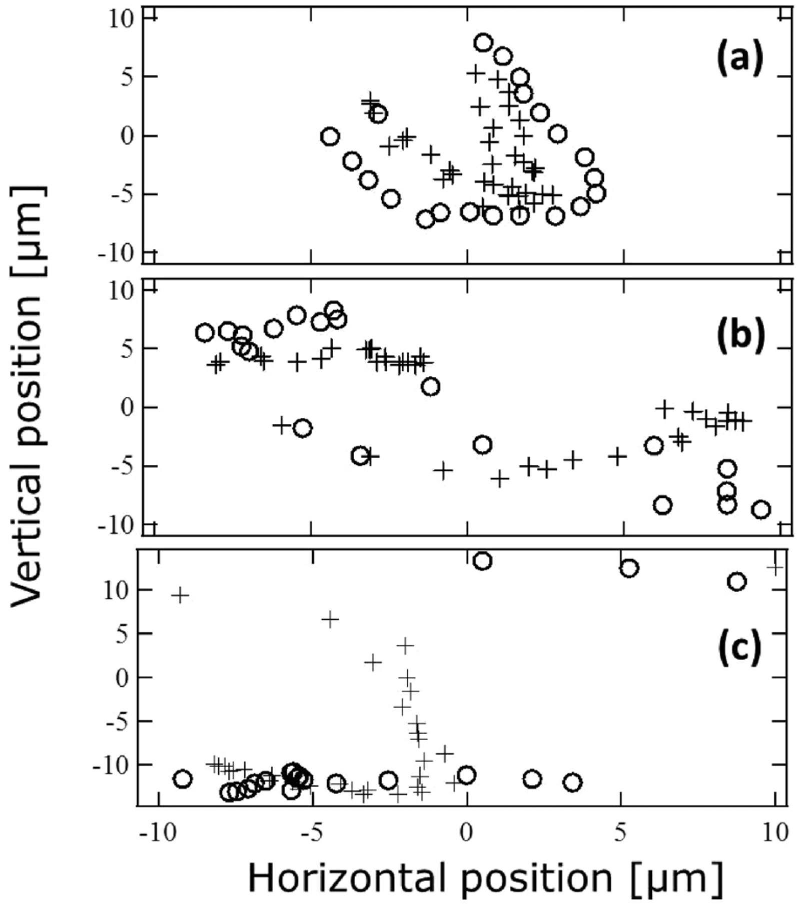
Valorisation



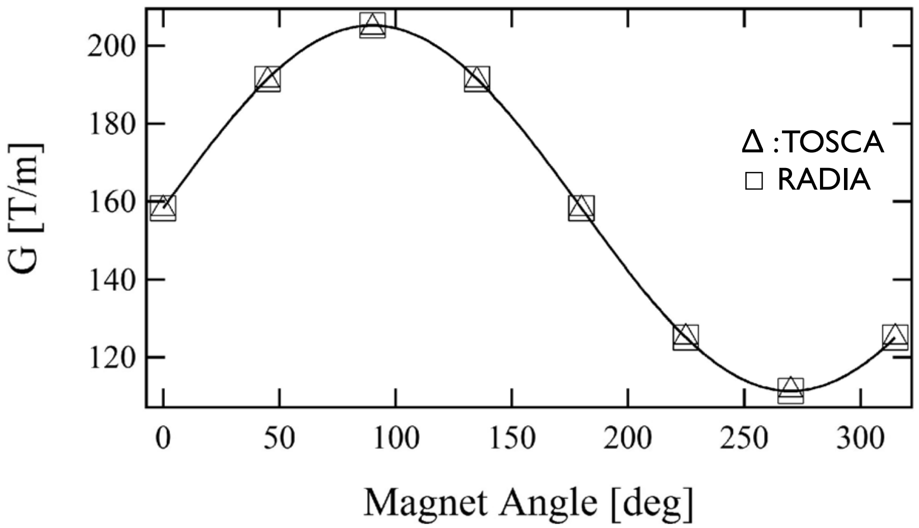
Gradient : up to 200 T/m
Variability by 50 %
Integrated gradient : 10 T
Bore diameter : 10 mm





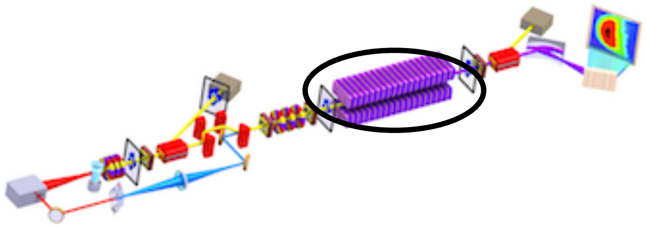


QUAPEVA 1: +102.8 T/m , QUAPEVA 2: −101.2 T/m, QUAPEVA 3: +88.17 T/m



Patent :
- « Multi-pôle magnétique réglable », C. Benabderrahmane, M. E. Couprie, SOLEIL, F. Forest, O. Cosson Sigmaphi, Numéro de dépôt : 1458335
Adjustable magnetic multipole, 5/09/2014- WO 2016034490 A1, publication : 10 mars 2016
- Europe : PCT/EP2015/069649 of 27/08/2015

F. Marteau et al., Variable high gradient permanent magnet quadrupole (QUAPEVA), Appl. Phys. Lett. 111, 253503 (2017)
A. Ghaith et al., Tunable High Gradient Quadrupoles For A Laser Plasma Acceleration Based FEL, Nuclear Inst. and Methods in Physics Research, A 909 (2018) 290–293
A. Ghaith et al. Permanent Magnet Based Quadrupoles, Submitted to Intruments, MDPI, (2019)

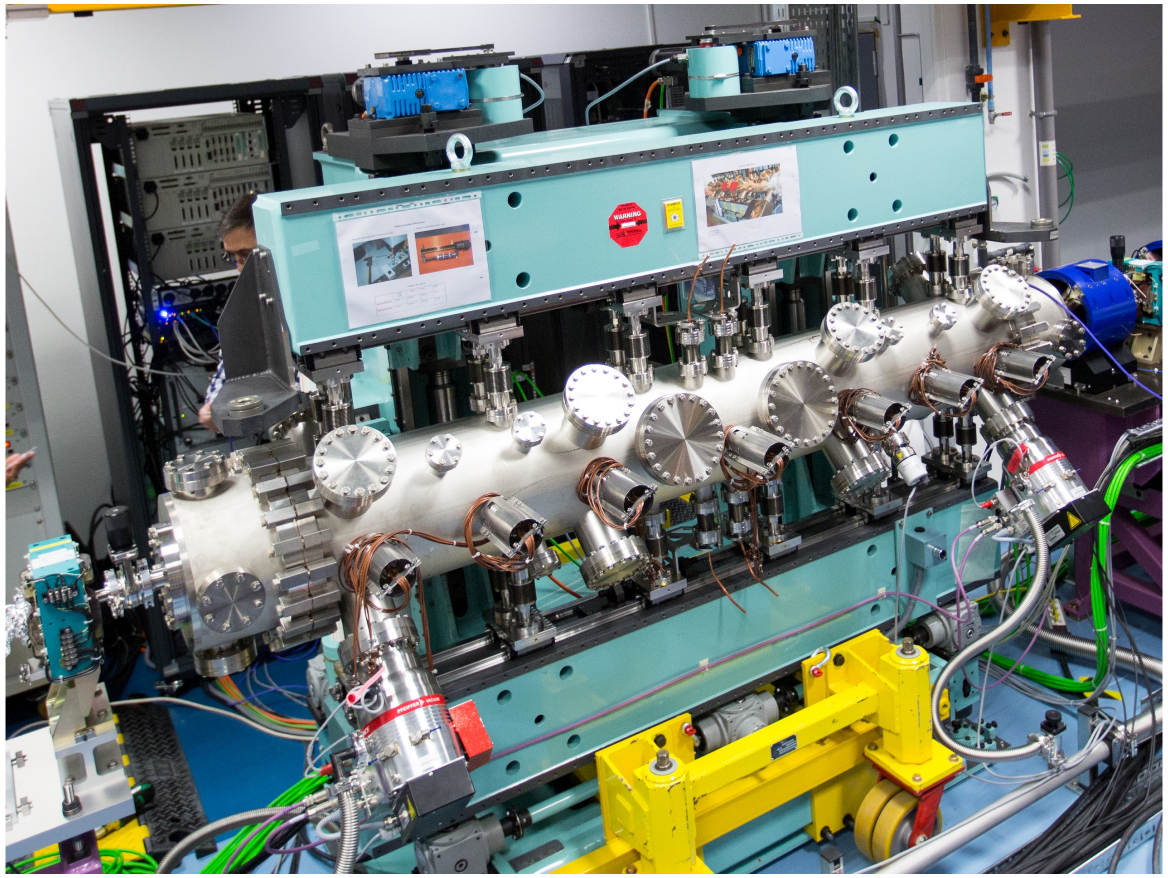


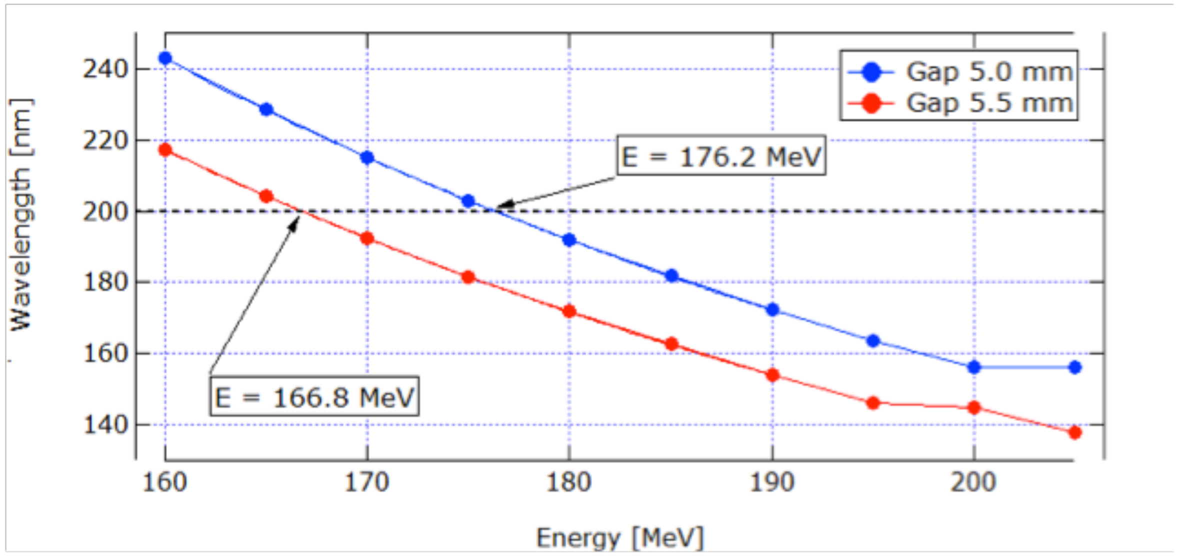
The undulator

U18 n°2 undulator (cryo-ready, used at room temperature)

U18 n2 : 2 m cryo-ready hybrid PrFeB U18 undulator
18 mm period

Remanent field :1.35 (1.57)T @ 300 (77) K
Hcj : 1.63 (7.6) T @ 300 (77) K
Minimum gap : 5.5 mm
B= 1.15 T at 77 K, K = 1.93



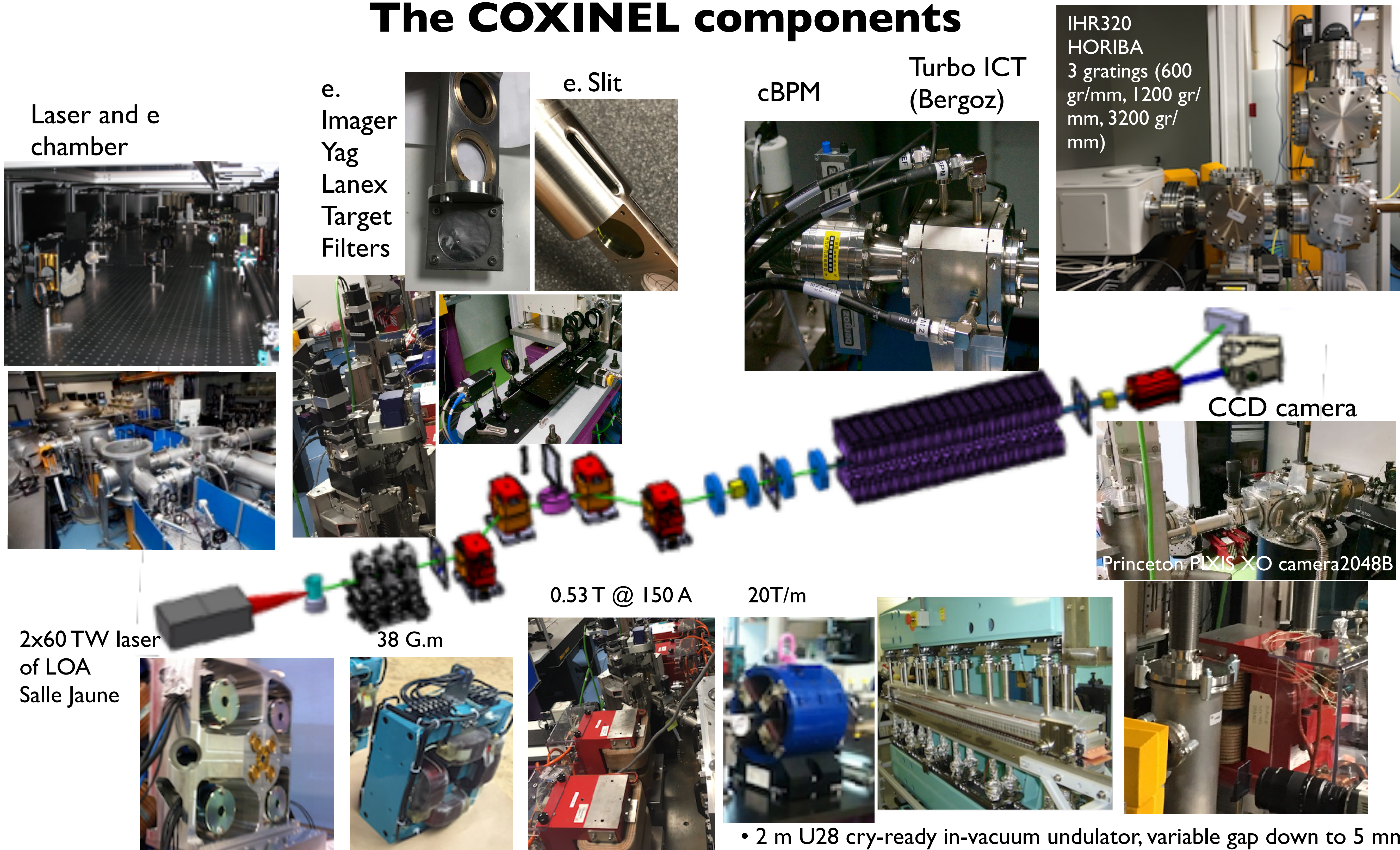


Valléau, M., Benabderrahmane, C., Briquez, F., Berteaud, P., Tavakoli, K., Zerbib, D., ... & Vétéran, J. (2016, July). Development of cryogenic undulators with PrFeB magnets at SOLEIL. In AIP Conference Proceedings (Vol. 1741, No. 1, p. 020024). AIP Publishing.
M. Valléau, et al., Development of Cryogenic Undulators with PrFeB magnets at SOLEIL, Journal of Physics : Conferences Series (proceedings of SRI 2015)

M. Valléau

II- COXINEL components

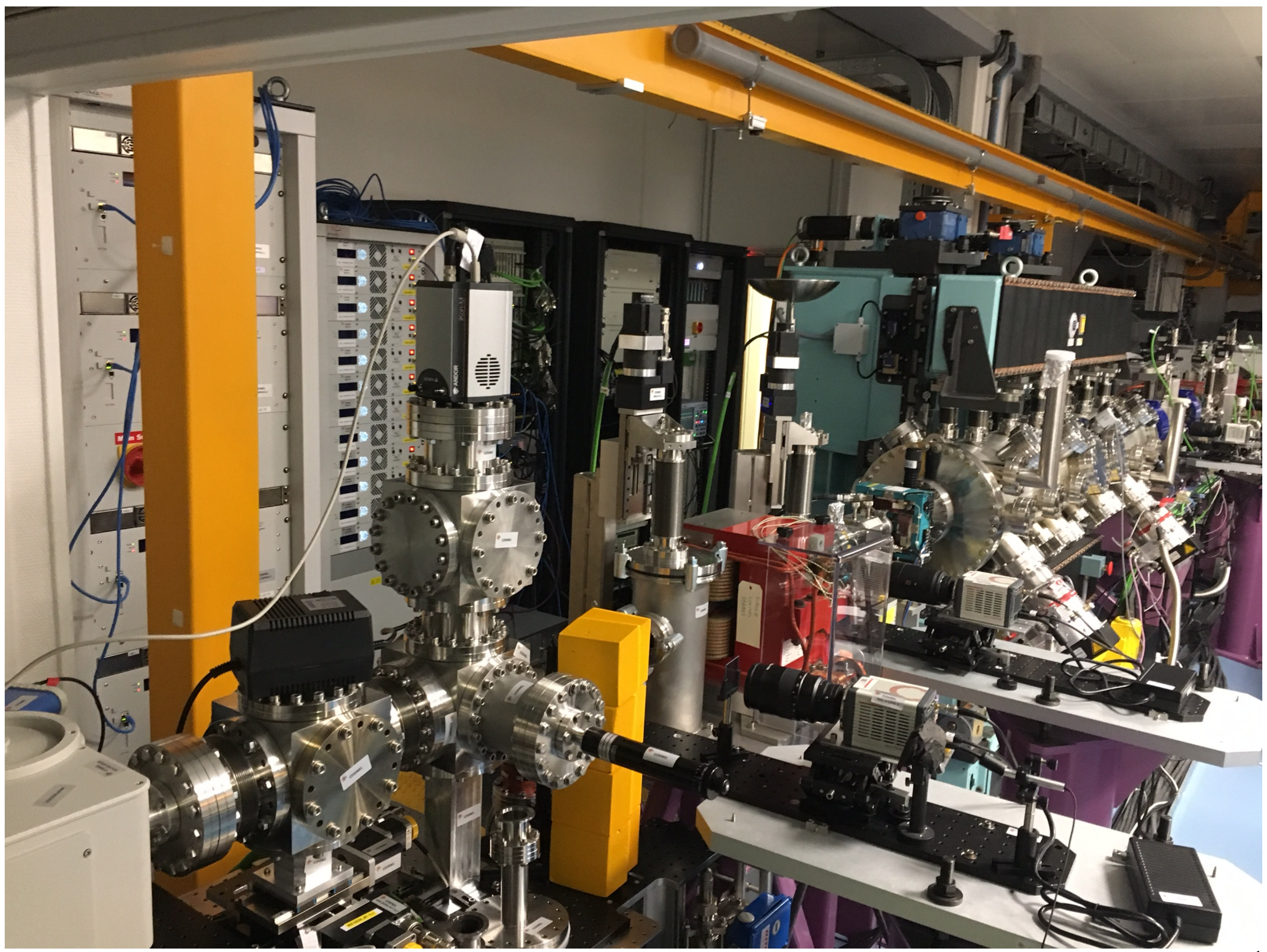
The COXINEL components

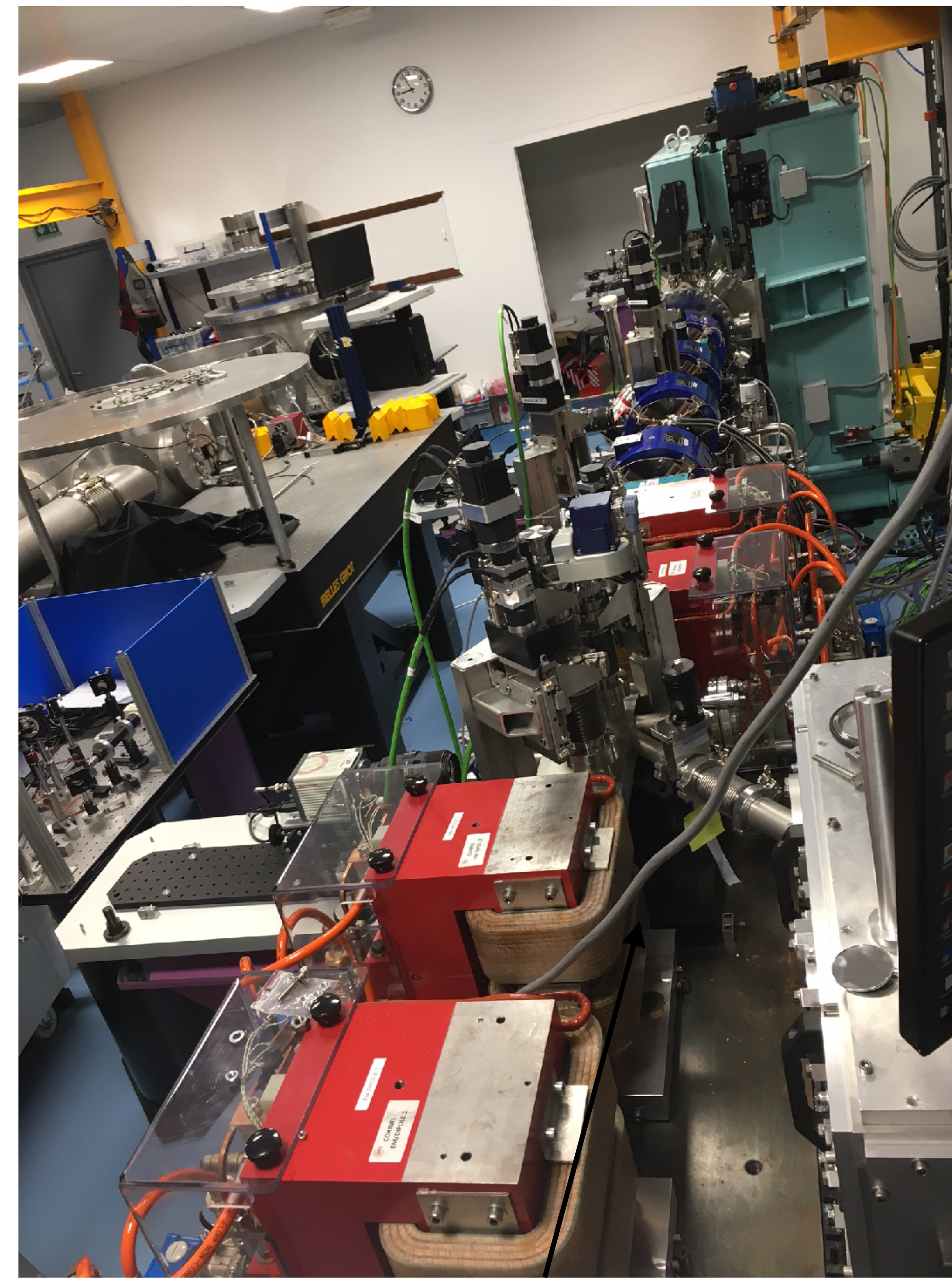


• 2 m U28 cry-ready in-vacuum undulator, variable gap down to 5 mm
• 3 m U15 cryo-ready undulator (coll. Sweden)

M. E. Couprie, Plasma Physics and Controlled Fusion, Volume 58, Number 3 (2016), M. Labat et al. J. Synchrotron Rad. (2018). 25, 68-71 https://doi.org/10.1107/S1600577517015284, M. Labat et al., "Electron and photon diagnostics for plasma acceleration-based FELs." Journal of synchrotron radiation 25.1 (2018).

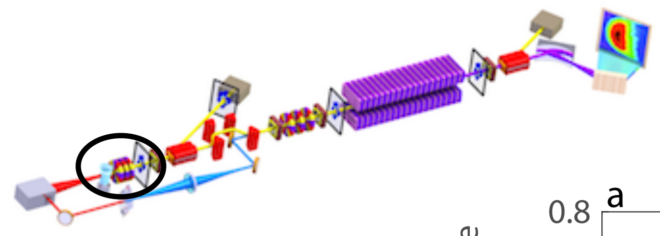
The COXINEL line

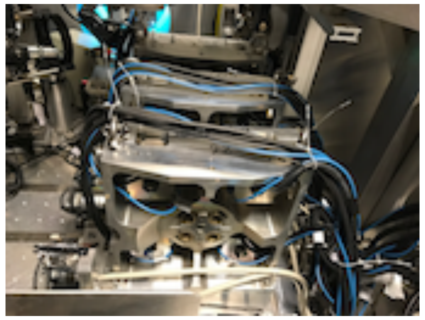


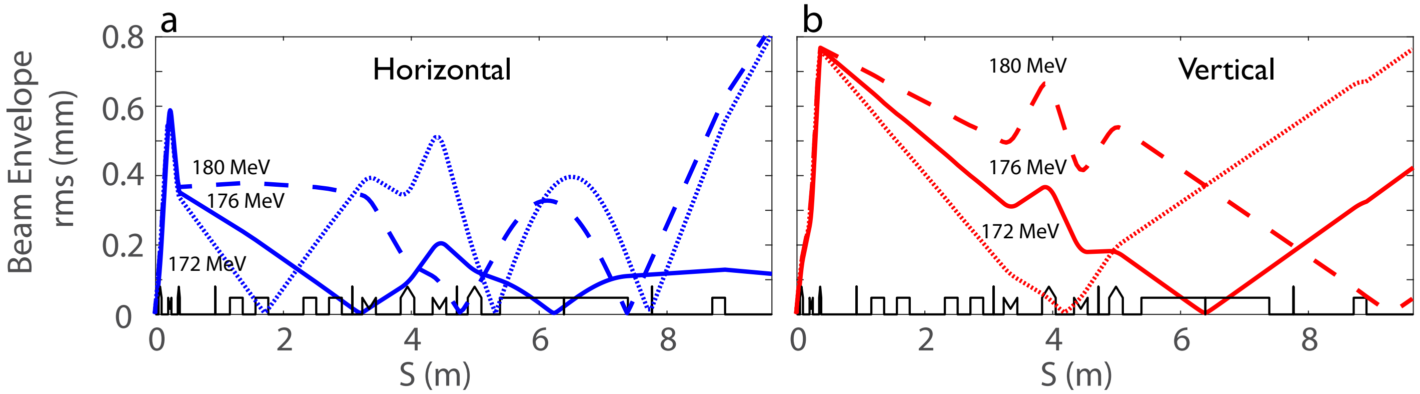


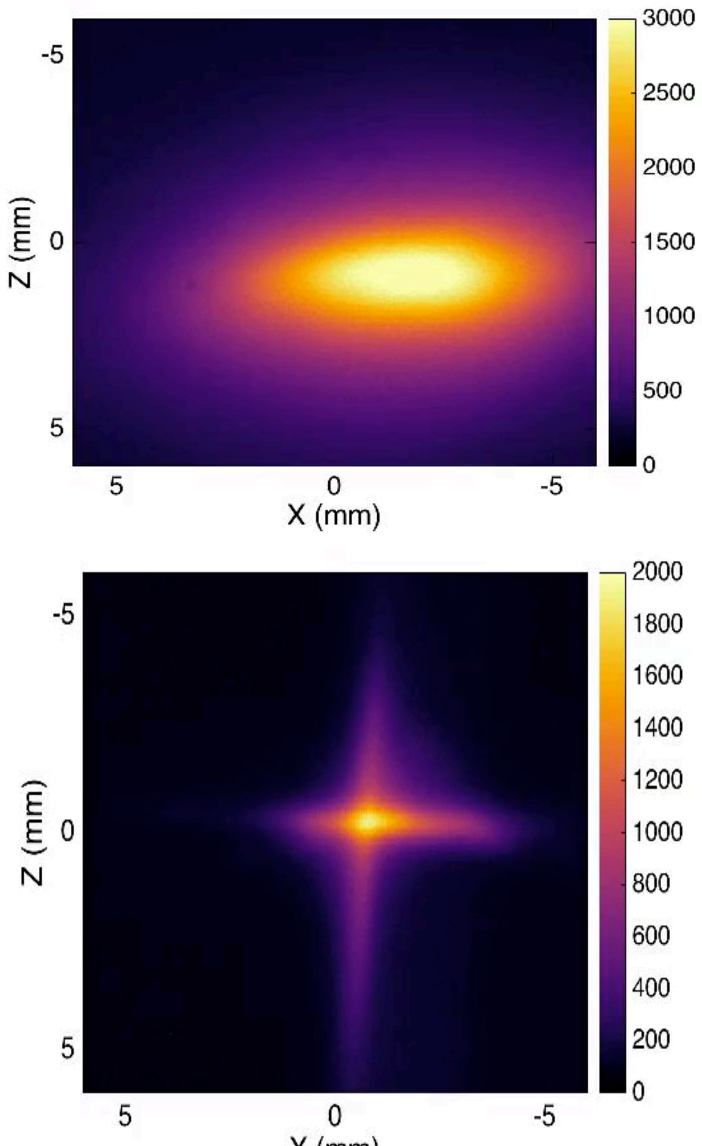
Electron beam

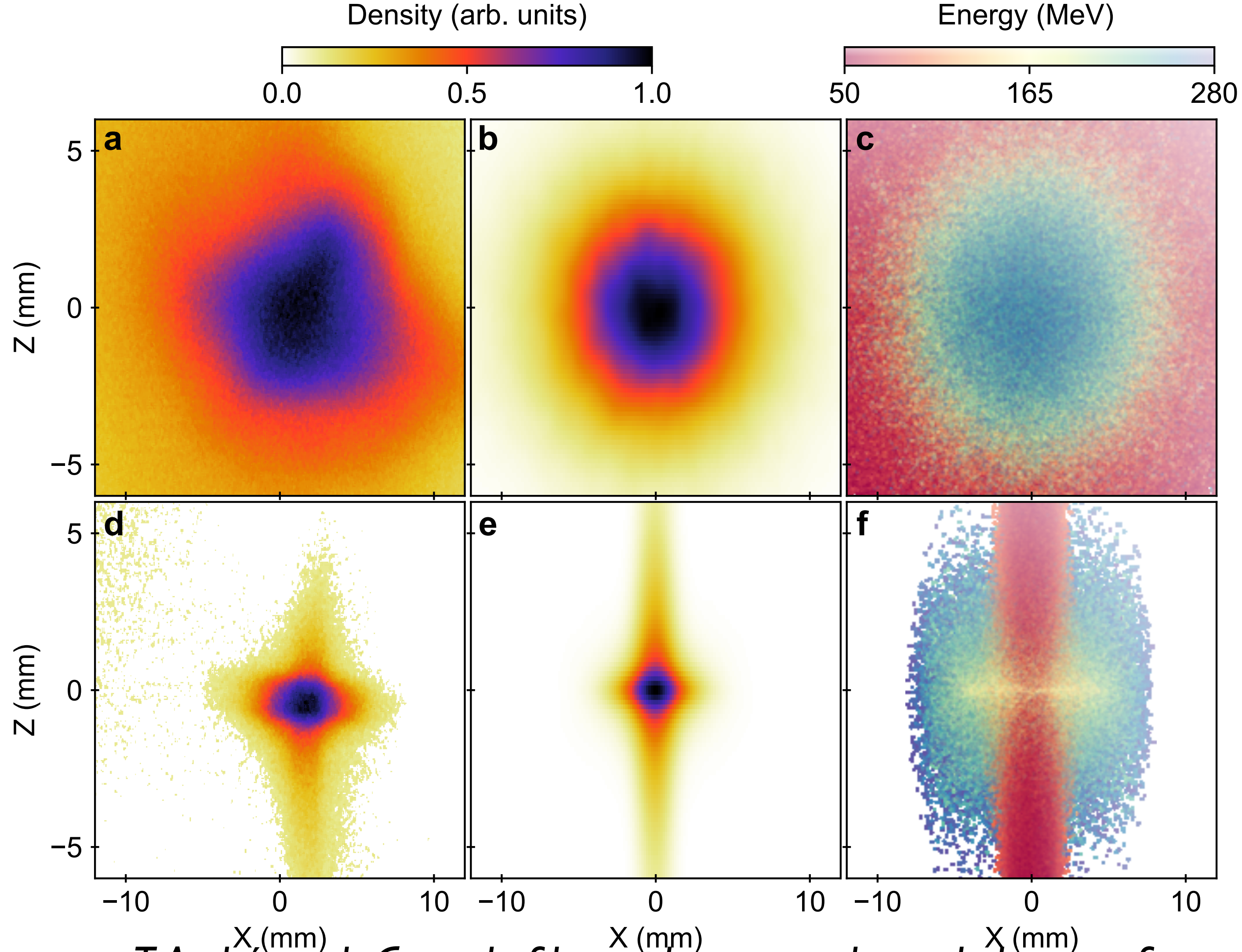
First focusing





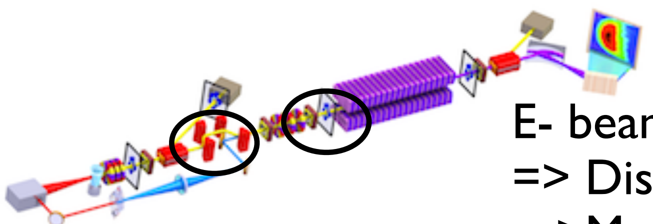






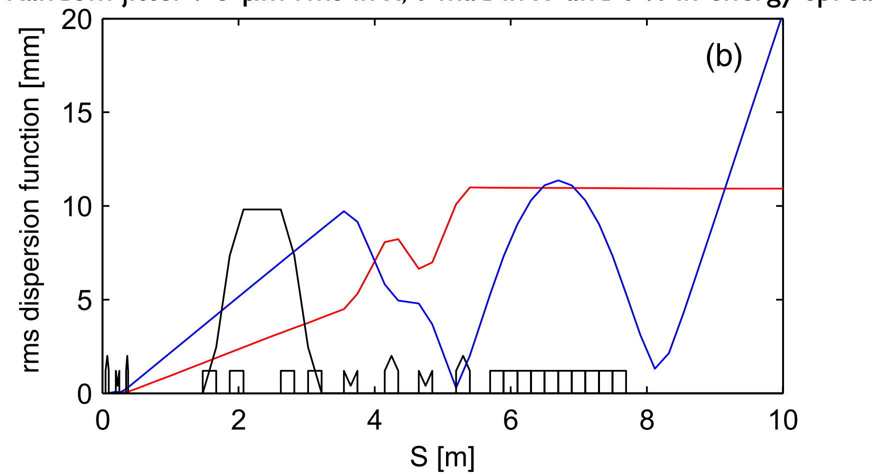
T. André et al., Control of laser plasma accelerated electrons for light sources, Nature Communications (2018) 9:1334

Adjustment of the vertical dispersion in the chicane

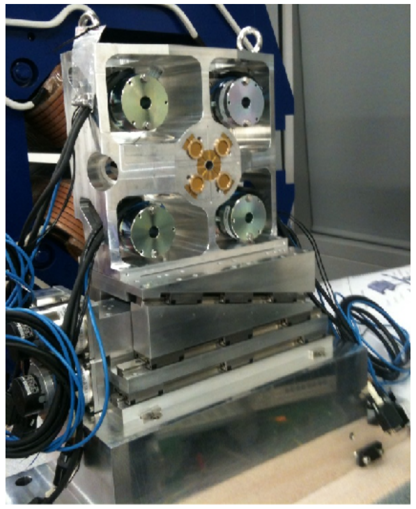


E- beam pointing defect
=> Dispersion introduced
=>Modification of the electron beam shape

Random jitter : 5 µm rms in x, 1 mrad in x' and 1 % in energy spread



QUAPEVA magnetic center change



Beam Pointing Alignment Compensation

Matrix response method :

$$\begin{pmatrix} \vec{X} \\ D_X \end{pmatrix} = A\ \Delta_{\vec{X}\ qap} \qquad \Delta_{\vec{X}\ qap} = A^{-1} \begin{pmatrix} \vec{X} \\ D_X \end{pmatrix}$$

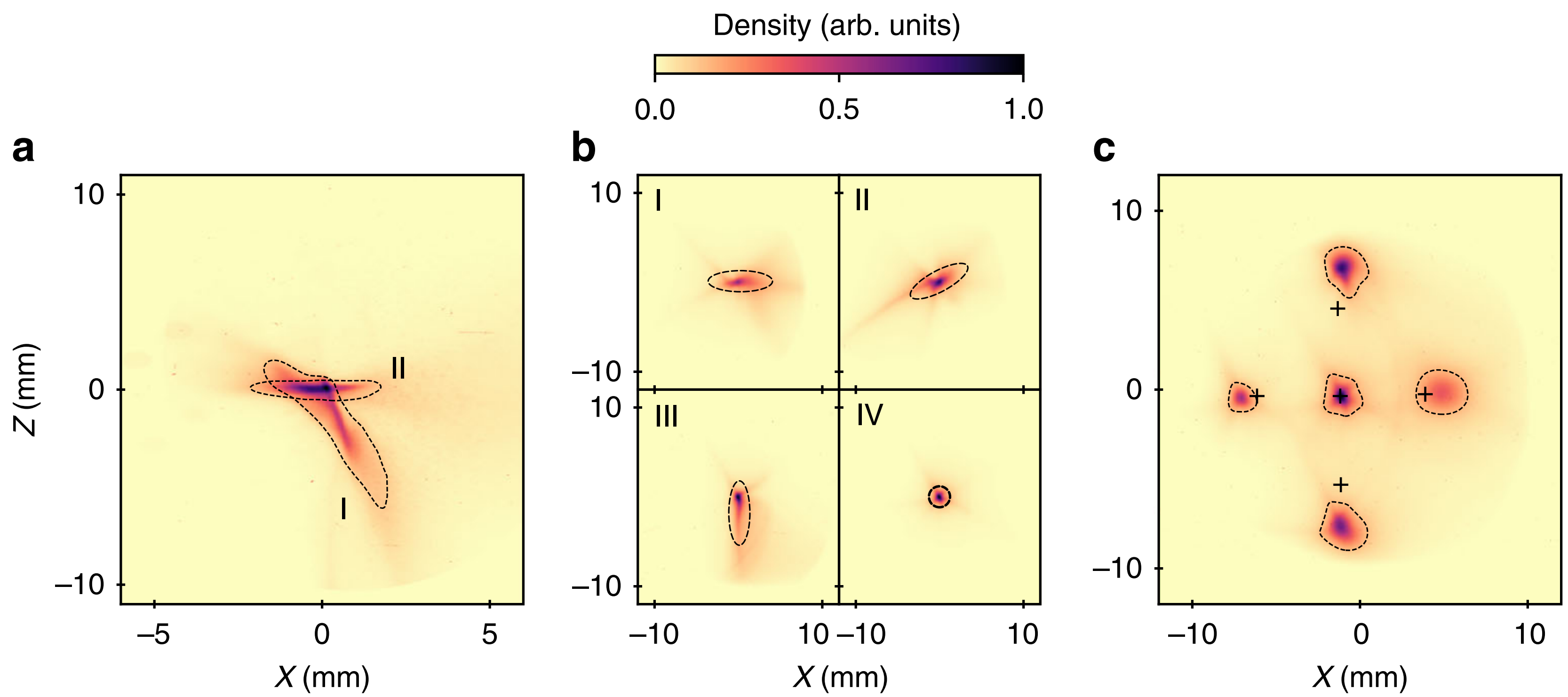
$$\mathbf{A}_x(s) = \begin{pmatrix} x_1(s) & x_2(s) & x_3(s) \\ D_{x,1}(s) & D_{x,2}(s) & D_{x,3}(s) \end{pmatrix}$$

$$\mathbf{A}_z(s) = \begin{pmatrix} z_1(s) & z_2(s) & z_3(s) \\ D_{z,1}(s) & D_{z,2}(s) & D_{z,3}(s) \end{pmatrix}$$

$$\begin{pmatrix} x(s) \\ D_x(s) \end{pmatrix} = \mathbf{A}_x(s) \cdot \begin{pmatrix} \Delta x_1 \\ \Delta x_2 \\ \Delta x_3 \end{pmatrix}$$

$$\begin{pmatrix} z(s) \\ D_z(s) \end{pmatrix} = \mathbf{A}_z(s) \cdot \begin{pmatrix} \Delta z_1 \\ \Delta z_2 \\ \Delta z_3 \end{pmatrix}$$

Independent adjustment of position and dispersion



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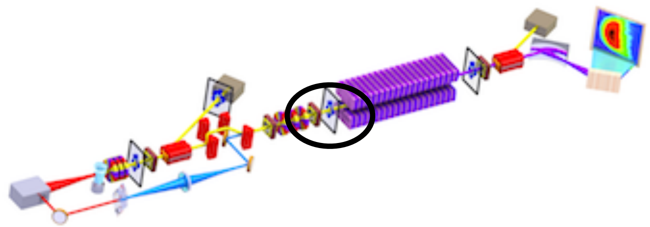
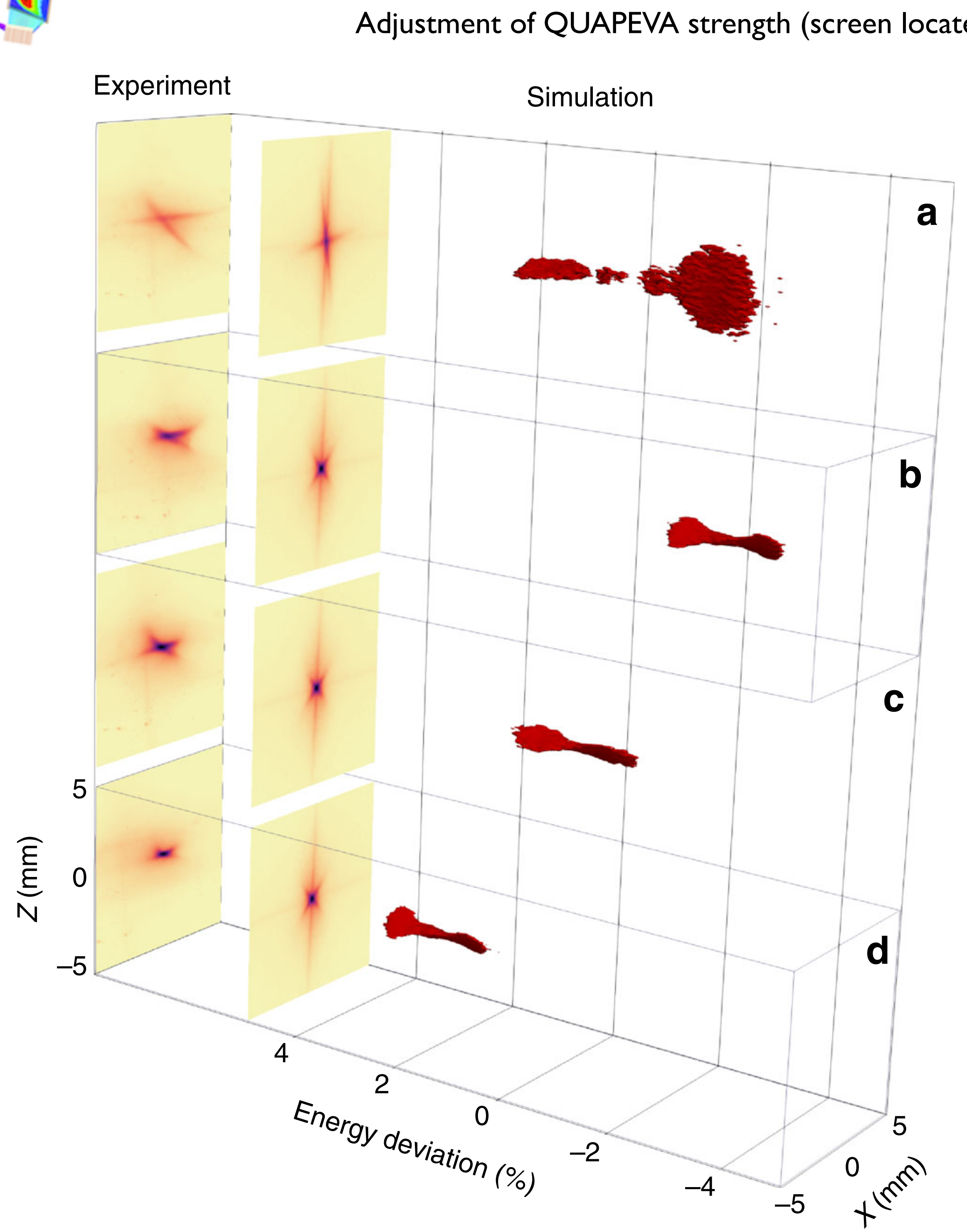
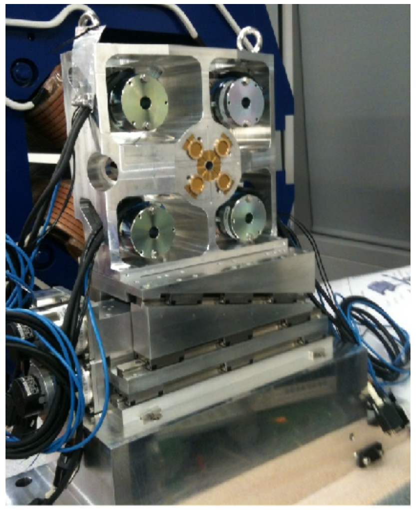
Adjustment of the focused electron beam energy



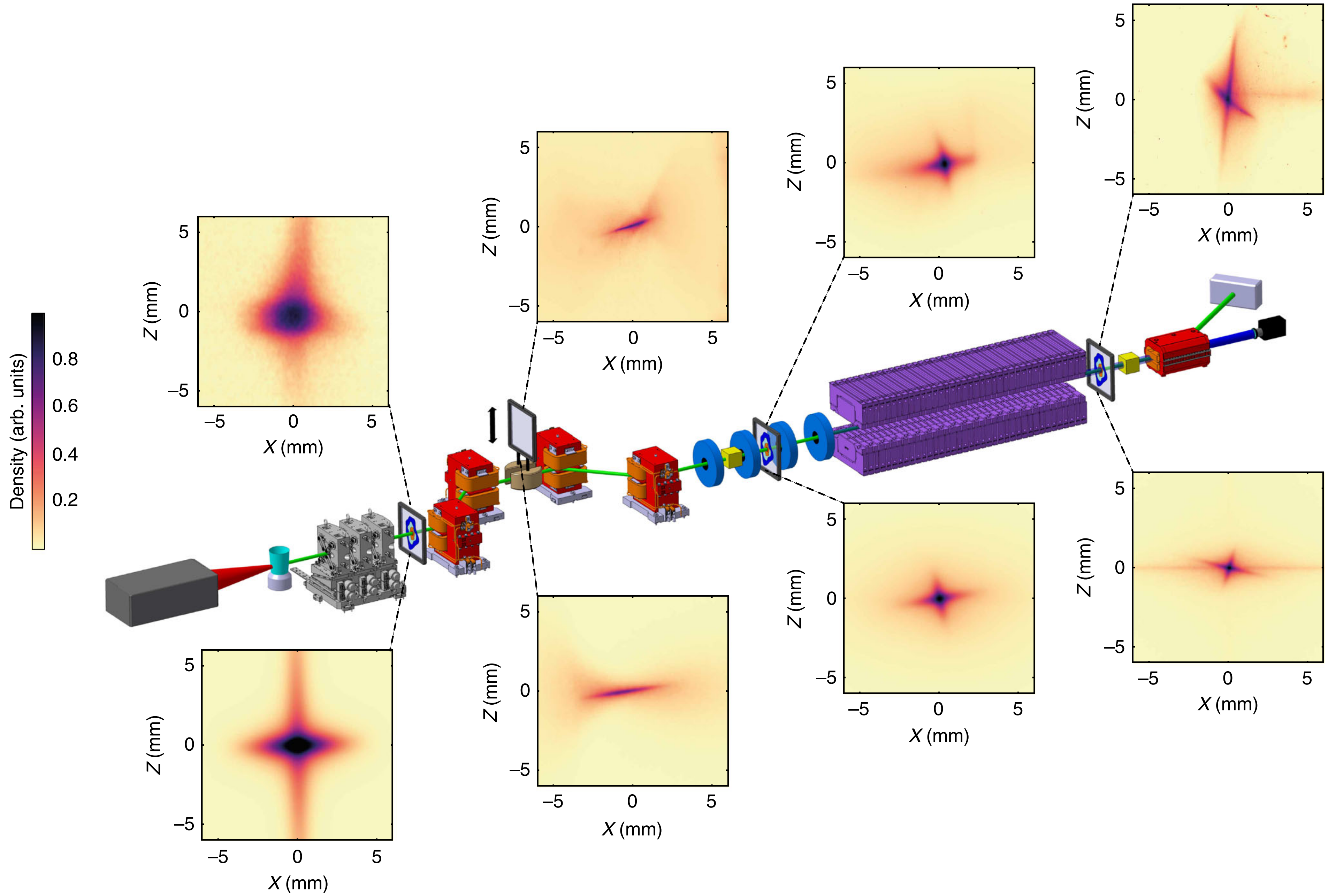


Gradient change



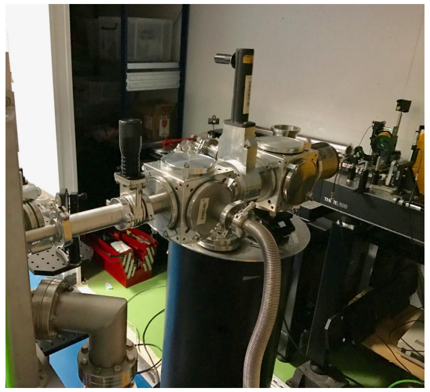
T. André et al., Control of laser plasma accelerated electrons for light sources, Nature Communications (2018) 9:1334, T. André PhD 2018

COXINEL : proper transport along the line



T. André et al., Control of laser plasma accelerated electrons for light sources, Nature Communications (2018) 9:1334, T. André PhD 2018

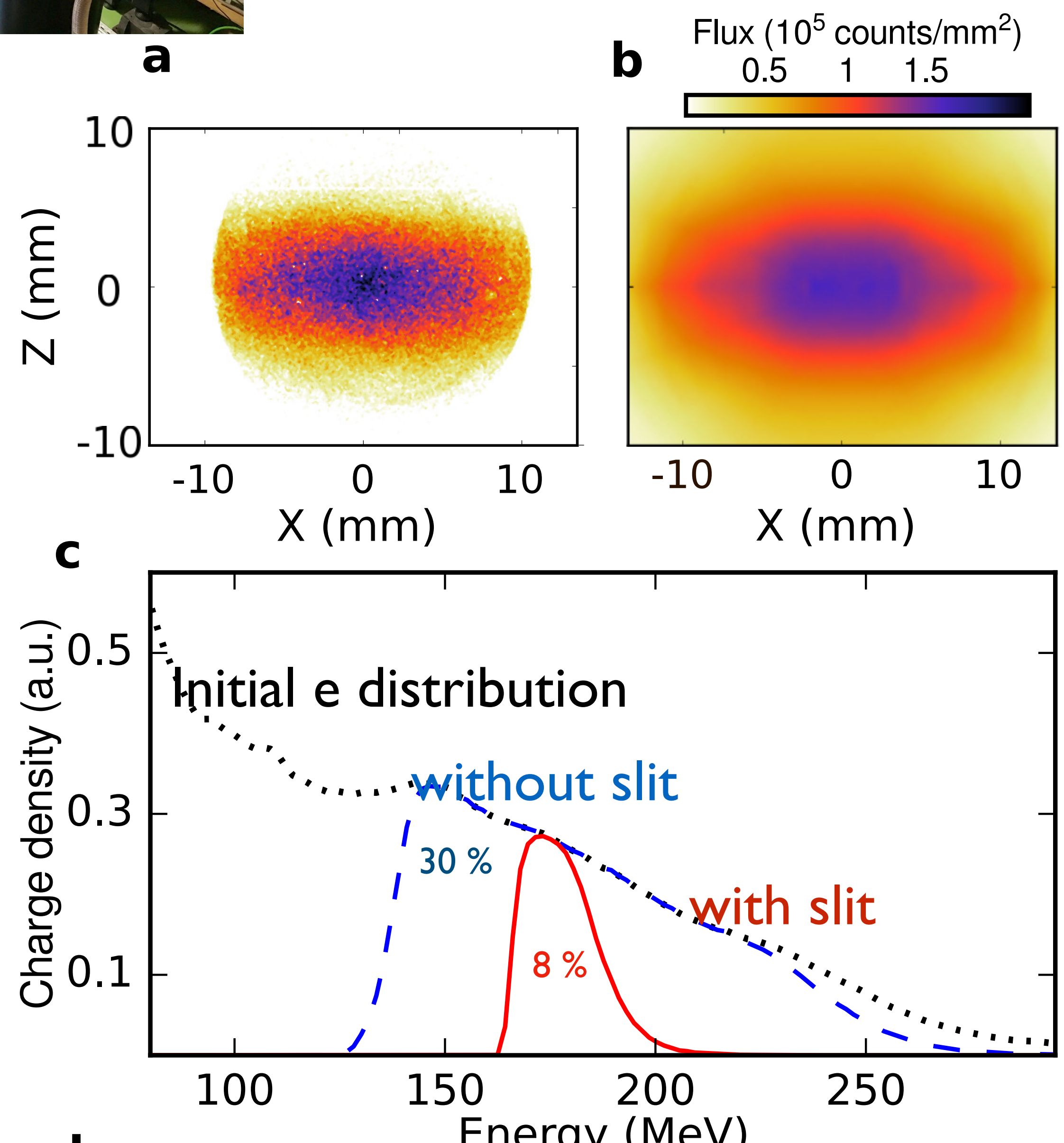
D. Oumbarek_Espinos et al., Skew quadrupole effect of laser plasma electron beam transport, Applied Science, 9(12), 2447 (2019).

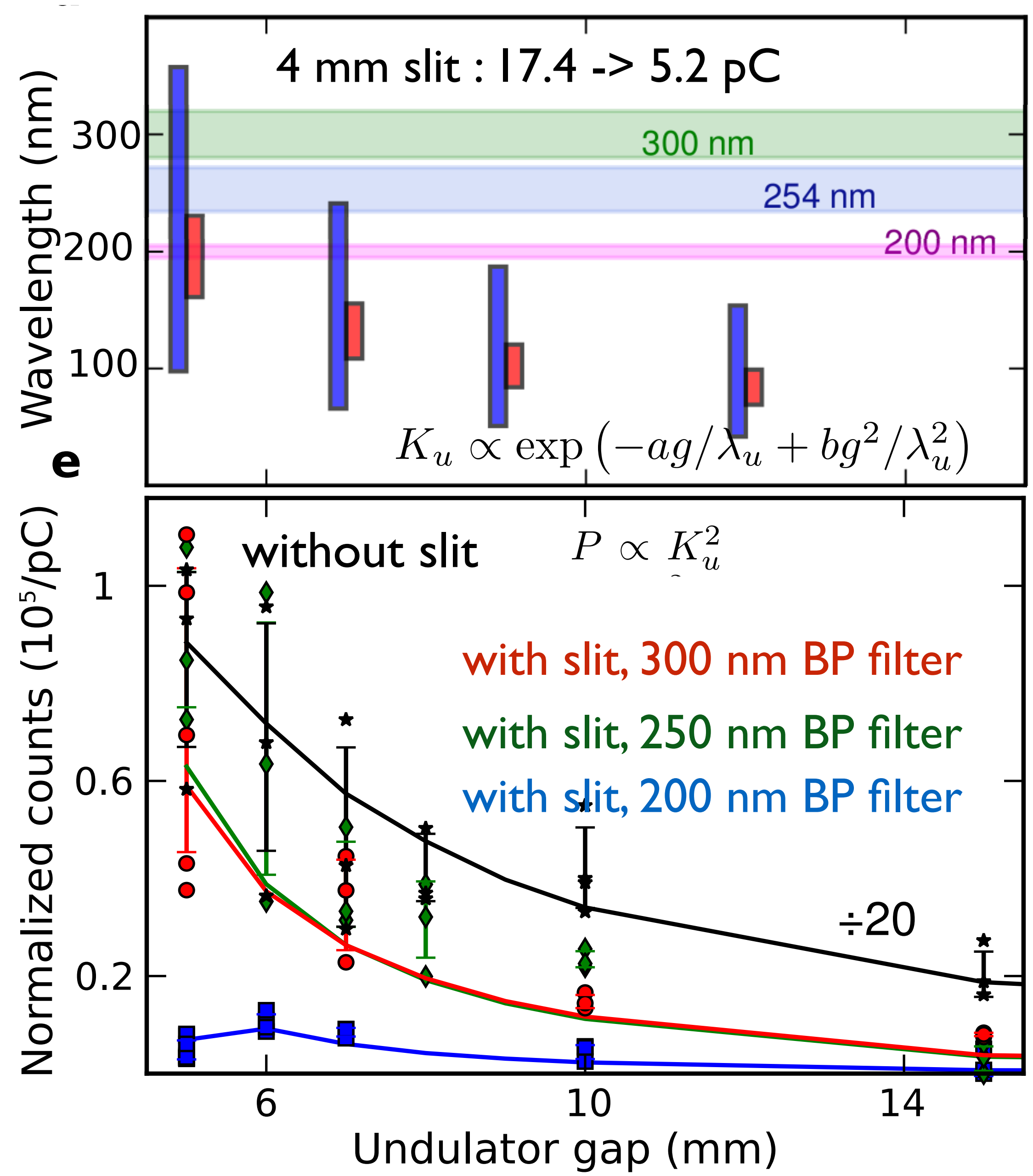


Transverse pattern measured with a CCD camera

$$\lambda_n = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K_u^2}{2} + \gamma^2\theta^2\right)$$

Undulator set to radiate at 200 nm for 176 MeV





$N_{ph} \sim 3\ 10^7$ ph/pC

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Conclusion

• Electron beam transport over 9 m enabling beam manipulation with a broadband energy beam:

Beam pointing alignment compensation method

Fine tuning of the electron beam energy

Limited emittance growth at the undulator location

• Undulator spontaneous emission measured after transport beam manipulation: