Undulator radiation after COXINEL transport line with a Laser Plasma Acceleration source (Run 3 & 4)

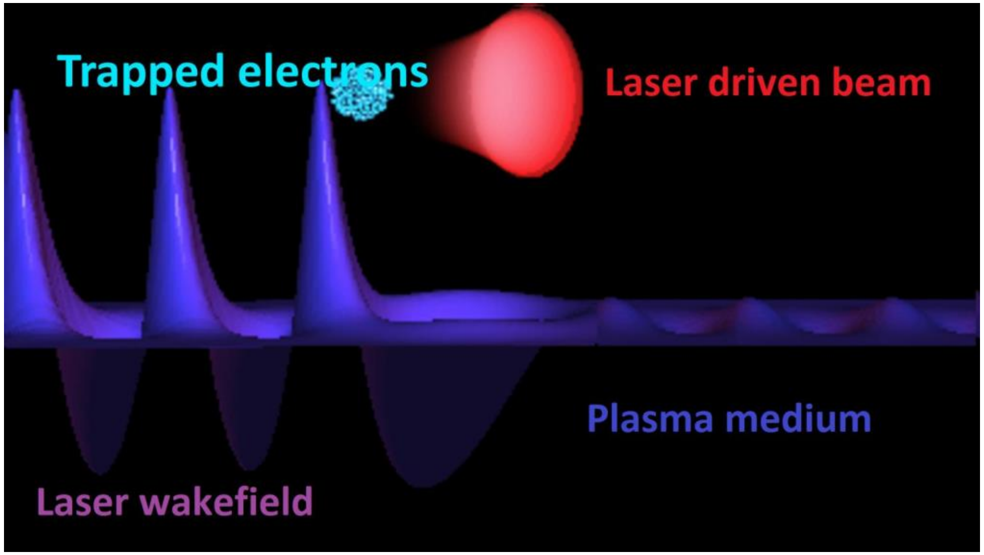
A.Ghaith on behalf of COXINEL collaboration

(SOLEIL – LOA – PHLAM)

FLS

March 3 – 9

Introduction : Laser Plasma Acceleration (LPA)



Europraxia: https://phys.org/news/2016-04-eupraxia-world-first-plasma-facility-strong.html

- New technique to accelerate particles
- Accelerator size reduced by orders of magnitude

Tajima, T., and J. M. Dawson. "Laser electron accelerator." *Physical Review Letters* 43.4 (1979): 267.

How does it works?

- Focus an intense laser at a gas chamber
- Electrons pushed away from the path of laser (ponder-motive force) whereas ions are not affected → WakeField
- Electron beam trapped between the laser pulse and the Wakefield

Introduction : Laser Plasma Acceleration

Typical beam characteristics using LPA source

Beam Quality	Value
Energy Acceleration	~ GeV/cm
Peak Current	5-10 kA
Bunch Length	few fs
Normalized emittance	few mm.rad
divergence	few mrads
Energy spread rms	1-10%

V. Malka, J. Faure, C. Rechatin, A. Ben-Ismail, J. Lim, X. Davoine, and E. Lefebvre, Laser-driven accelerators by colliding pulses injection: A review of simulation and experimental results, *Physics of Plasmas(1994-present)*, vol. 16,no. 5, pp. 056703, 2009

E. Esarey, C. Schroeder, and W. Leemans, Physics of laserdriven plasma-based electron accelerators, *Reviews of Modern Physics*, vol. 81, no. 3, pp. 1229, 2009

Undulator Radiation has been successively observed using LPA source

H.-P. Schlenvoigt, K. Haupt et a, "A compact synchrotron radiation source driven by a laser-plasma wakefield accelerator," *Nature Physics*, vol. 4, no. 2, pp. 130–133, 2008

M. Fuchs, R. Weingartner et al. "Laser-driven soft-X-ray undulator source," *Nature physics*, vol. 5, no. 11, pp. 826–829, 2009.

M. P. Anania *et al.*, "The ALPHA-X beam line: toward a compact FEL," *Proceedings of IPAC*, vol. 5, paper TUPE052, pp. 2263–2265, 2010.

….

What about FEL?

Free Electron Laser (FEL)

Pierce Parameter:

$$\rho \propto \left(\frac{I_{peak}}{\sigma_x \sigma_z}\right)^{1/3}$$

Gain length:

$$L_g = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

Saturation length:

$$L_{sat} = 20 L_g$$

Requirements:

$$\begin{cases} \epsilon_N < \dfrac{\gamma\lambda}{4\pi} \\ \sigma_{rms} < \rho \end{cases}$$

$\boldsymbol{\varepsilon_N}$: Normalized Emittance

$\boldsymbol{\gamma}$: Lorentz factor

$\boldsymbol{\sigma_{rms}}$: Energy spread

$\boldsymbol{\lambda}$: Resonant Wavelength

Free Electron Laser (FEL)

Divergence and energy spread must be decreased to enable FEL amplification

- **High gradient quadrupoles**
- **Plasma lens**

T. Hosokai et al, PRL 97, 075004 (2006)
C. Thaury et al. Nature Comm. 6, 6860 (2015)

- **Chicane**

A. R. Maier et al., Phys. Rev. X 2, 031019 (2012)

- **TGUs**

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)

COXINEL Motivation

Beam manipulation choices:

- High gradient quadrupoles are used (200 T/m) to handle the divergence
- A Chicane accompanied with a slit to reduce the energy spread

- 1st step: Control, manipulate and transport the beam
- 2nd step: Observe Undulator radiation
- 3rd step: Demonstrate FEL amplification

COXINEL Baseline reference case:

Electron Beam parameters :

After beam manipulation →

Parameters	Source	Undulator
Divergence	1 mrad	0.1 mrad
Beam size	1 μm	50 μm
Bunch length (rms)	3.3 fs	33 fs
Charge	34 pC	34 pC
Peak Current	4.4 kA	440 A
Energy spread	1% rms	0.1% rms
Normalized emittance	1 mm.mrad	1.7 mm.mrad

At 200 nm wavelength (γ=344):

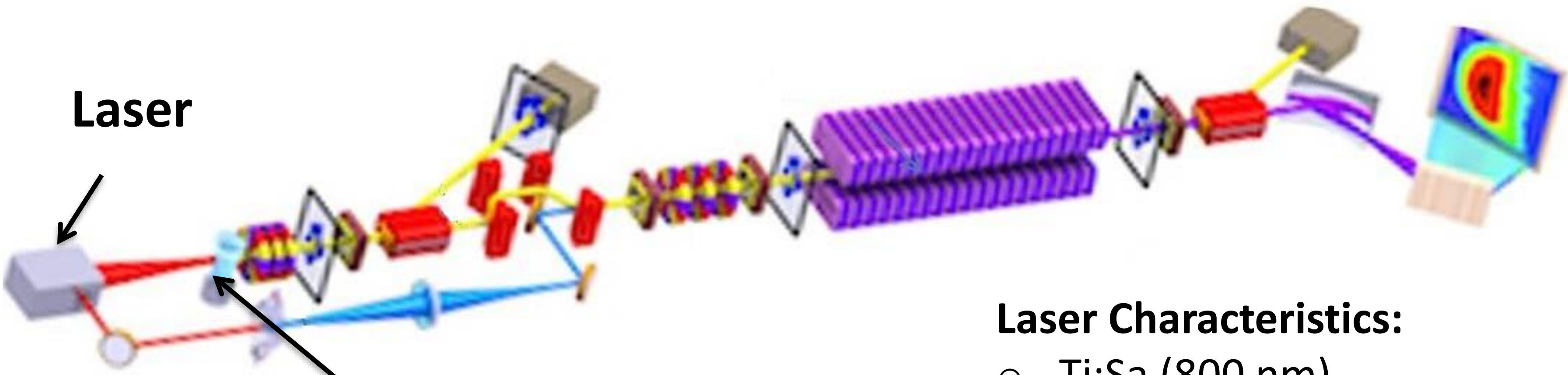
$$\rho = 1.2 \times 10^{-3}$$
$$L_g = 0.74\, m$$
$$L_{sat} = 15\, m$$

$$\begin{cases} \epsilon_N < \dfrac{\gamma\lambda}{4\pi} & = 5.48 \text{ mm.mrad} \\ \sigma_{rms} < \rho & = 0.12\% \end{cases}$$

❖ **FEL doable with such manipulation**

Presentation of COXINEL: Electron Source

COXINEL : COherent X-ray source INferred from Electrons accelerated by Laser



- 99% Helium
- 1% Nitrogen

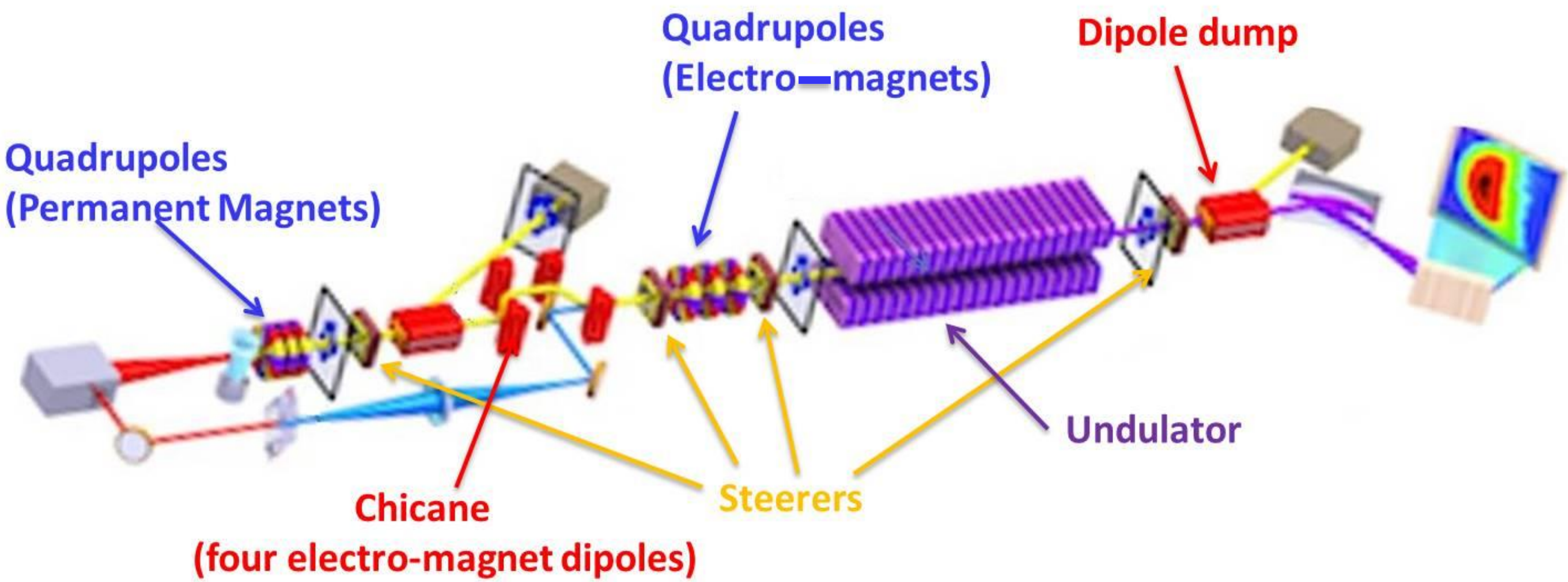
Laser Characteristics:

- Ti:Sa (800 nm)
- Power = 30 TW
- Pulse Duration = 30 fs
- Energy = 1.5 mJ

Khojoyan, M., et al. "Transport studies of LPA electron beam towards the FEL amplification at COXINEL." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 829 (2016): 260-264.

Couprie, Marie-Emmanuelle, et al. "Advances on the LUNEX5 and COXINEL Projects." (2015): WEP078.

Presentation of COXINEL: Magnetic Elements

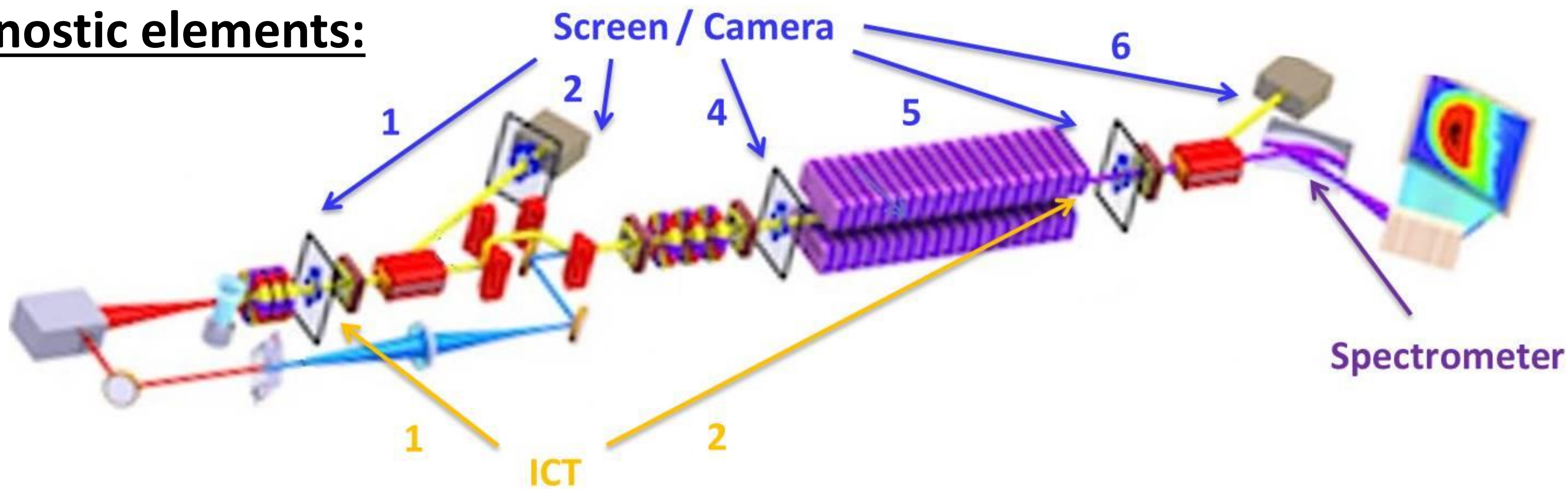


- High tunable gradient Permanent magnet based quadrupoles (QUAPEVAs) WEA2WD01
- Four steerers
- De-mixing Chicane: 4 electro-magnet dipoles
- 4 electro-magnet quadrupoles
- Cryo-ready undulator THP2WD01
- Dipole dump

Presentation of COXINEL: Diagnostic Elements

COXINEL : COherent X-ray source INferred from Electrons accelerated by Laser

Diagnostic elements:



Electrons:

- 5 cameras + scintillator screens (YAG & Lanex)
- 2 ICTs (charge measurement)

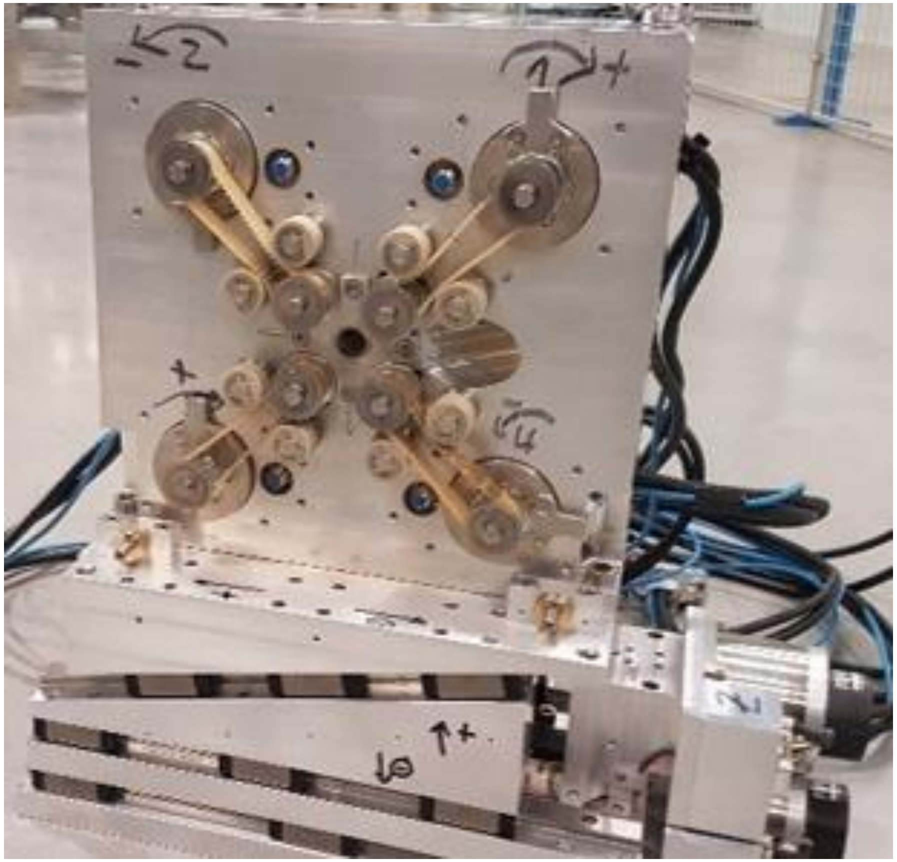
Photons:

- CCD camera "Run3"
- Spectrometer "Run4"

M. Labat et al., "Electron and photon diagnostics for plasma acceleration-based FELs." *Journal of synchrotron radiation* 25.1 (2018).

Equipments along the transport line

QUAPEVAs (Permanent magnet quadrupole with tunable high gradient): **Patent**



C. Benabderrahmane, M. E. Couprie, SOLEIL, F. Forest, O. Cosson Sigmaphi, "Multi-pôle magnétique réglable", patent application WO2016034490 (10 March 2016).
C. Benabderrahmane, M. E. Couprie, SOLEIL, F. Forest, O. Cosson Sigmaphi, "Adjustable magnetic multipole," Europe patent application WOBL14SSOQUA/CA (27 August 2015)

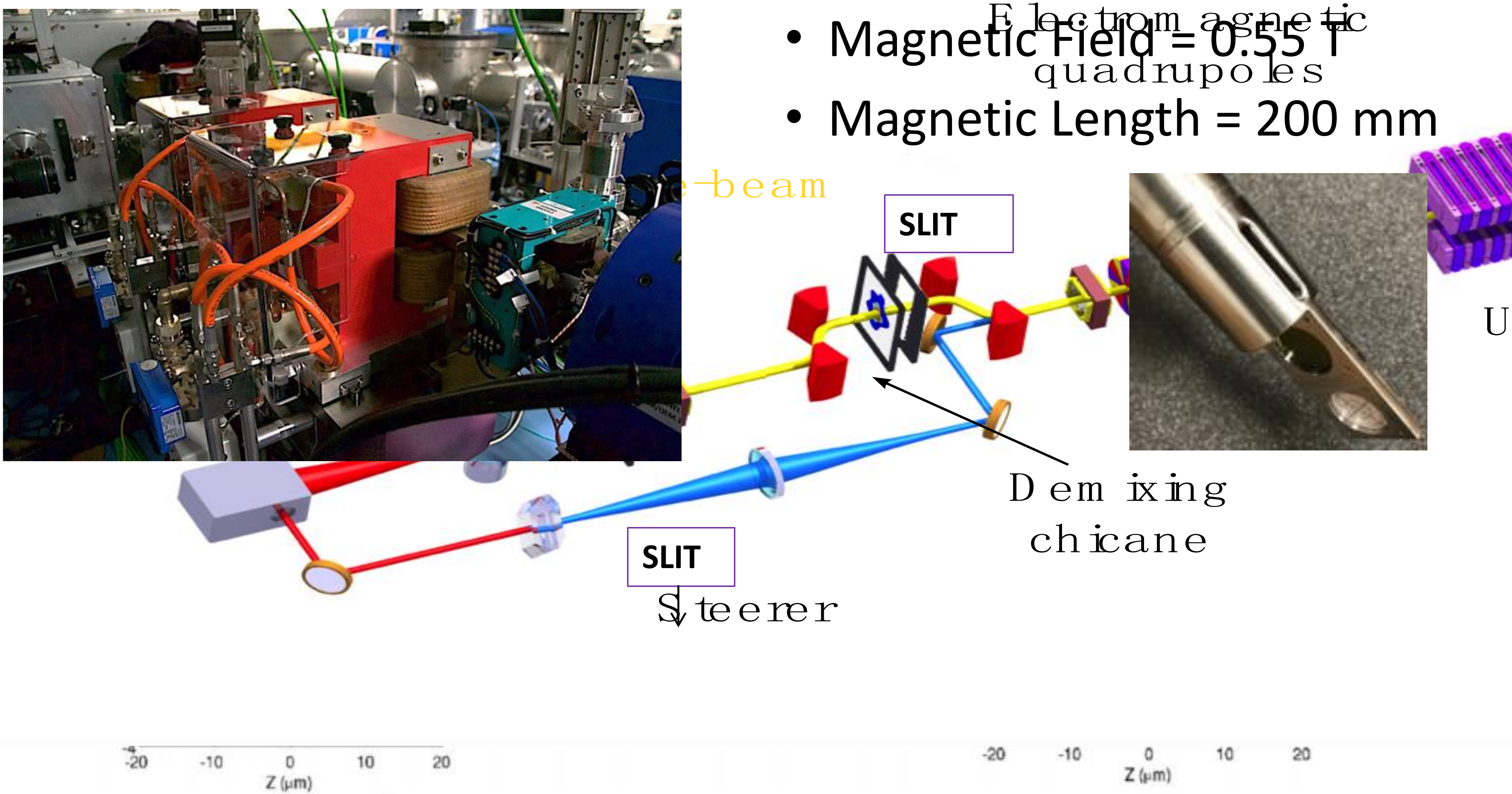
WEA2WD01

- Permanent magnet based
- Variable gradient (100 T/m :::> 200 T/m)
- Magnetic center excursion ± 15 µm
- Hor. & Vert. motorized translation to adjust alignment and BPAC

F. Marteau, A. Ghaith … M. E. Couprie (2017). Variable high gradient permanent magnet quadrupole (QUAPEVA). *Applied Physics Letters*, *111*(25), 253503.

Equipments along the transport line

- Magnetic Field = 0.55 T
- Magnetic Length = 200 mm

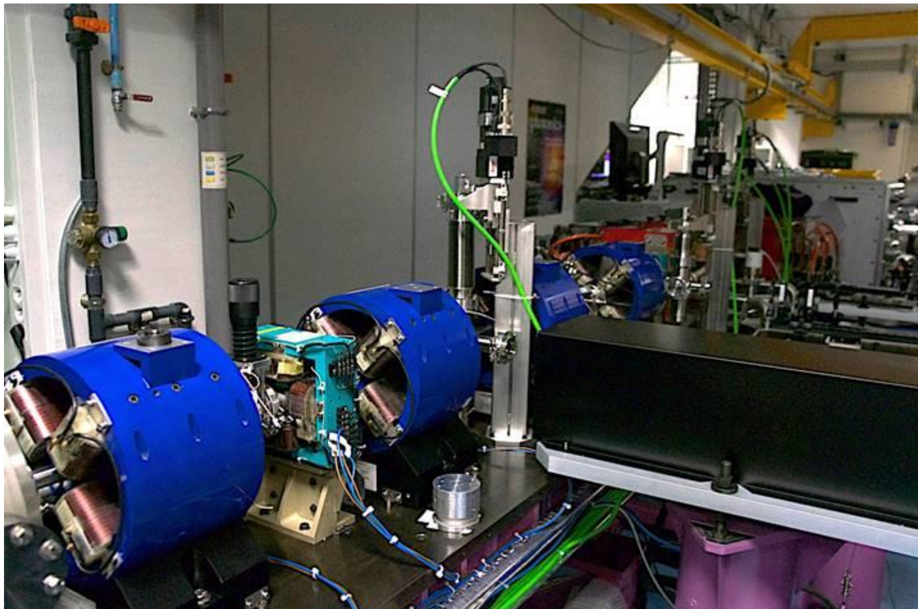


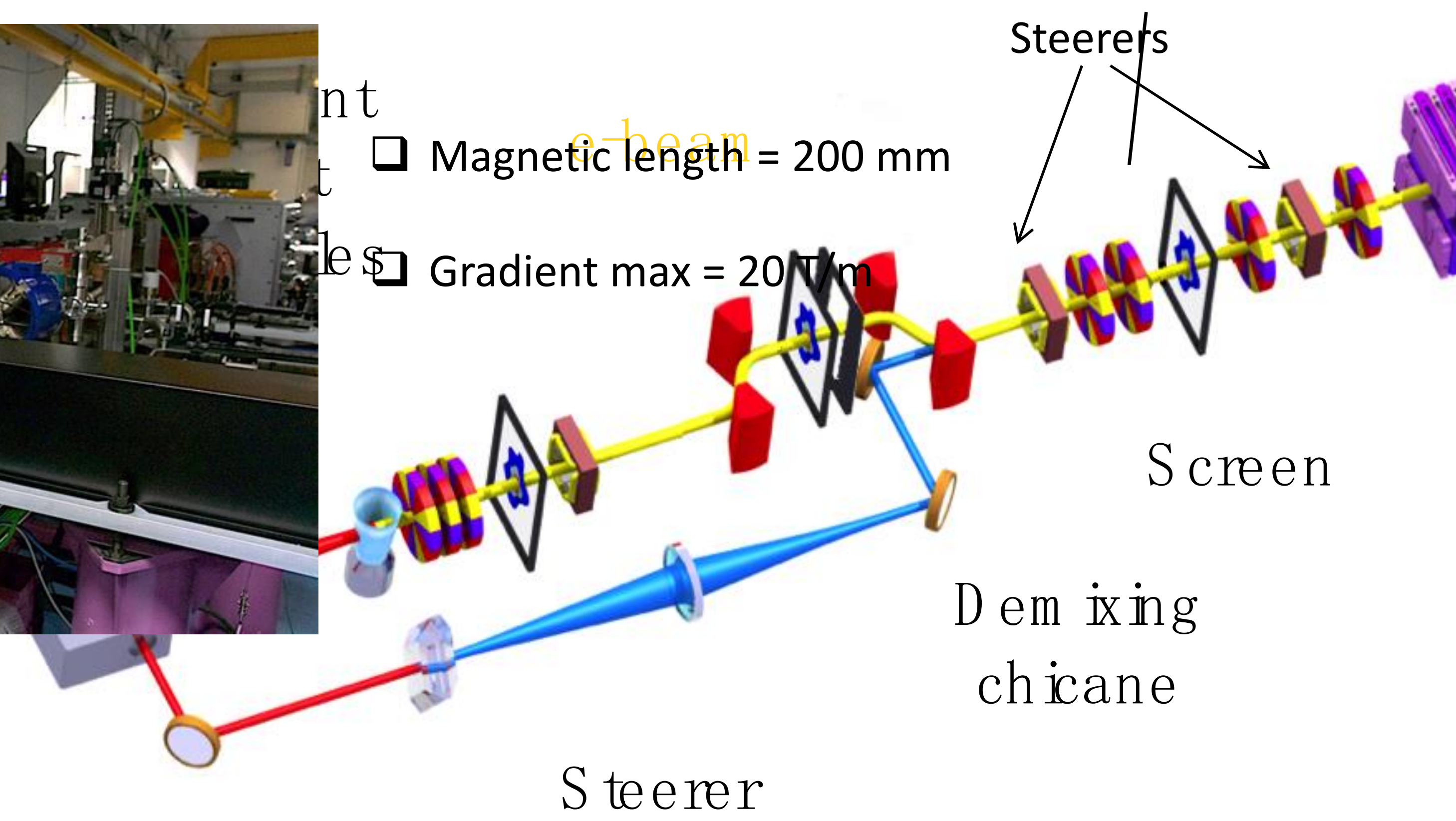
Couprie, M. E., et al. "An application of laser–plasma acceleration: towards a free-electron laser amplification." *Plasma Physics and Controlled Fusion* 58.3 (2016): 034020.

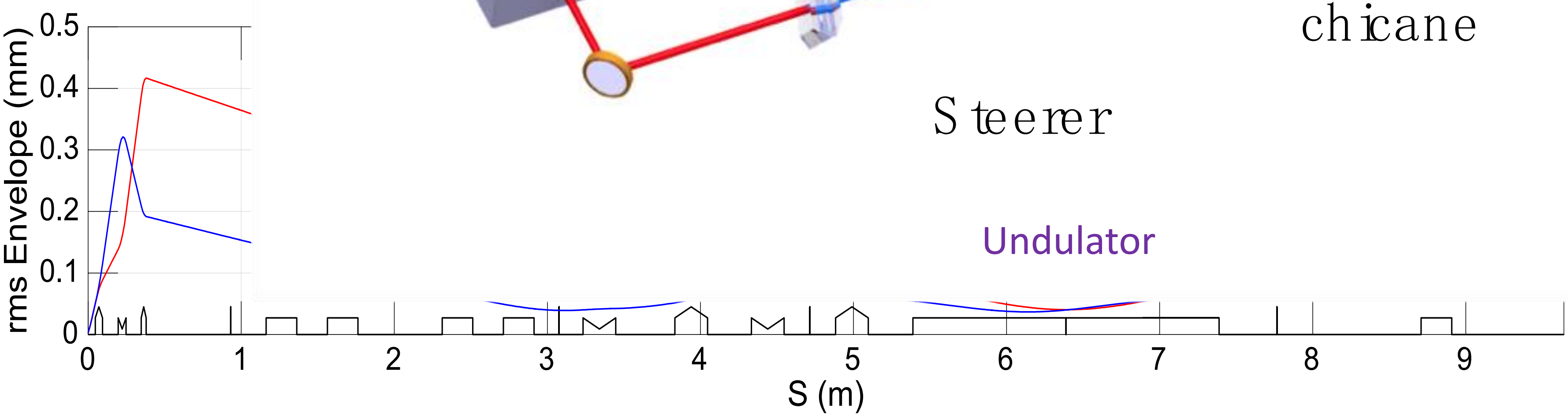
Equipments along the transport line

4 electro-magnet

- Magnetic length = 200 mm
- Gradient max = 20 T/m



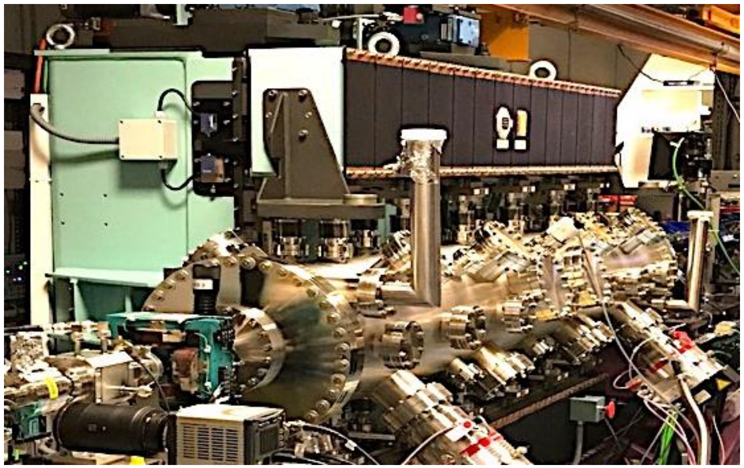




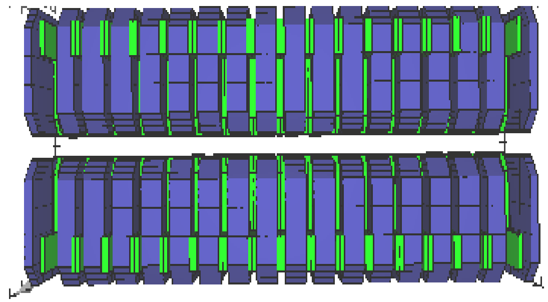
Equipments along the transport line

Cryo-ready Undulator:

Valléau, M., et al. "Development of cryogenic undulators with PrFeB magnets at SOLEIL." *AIP Conference Proceedings*. Vol. 1741. No. 1. AIP Publishing, 2016.



Operates at RT due to infrastructure reasons

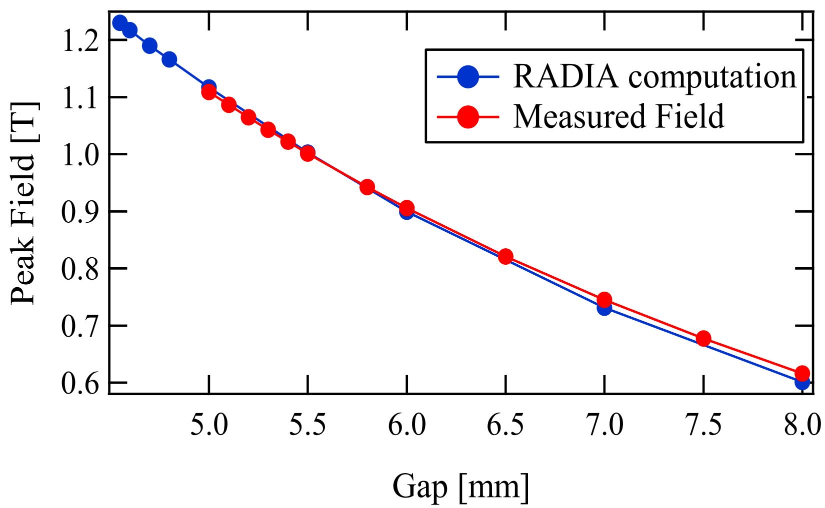


RADIA

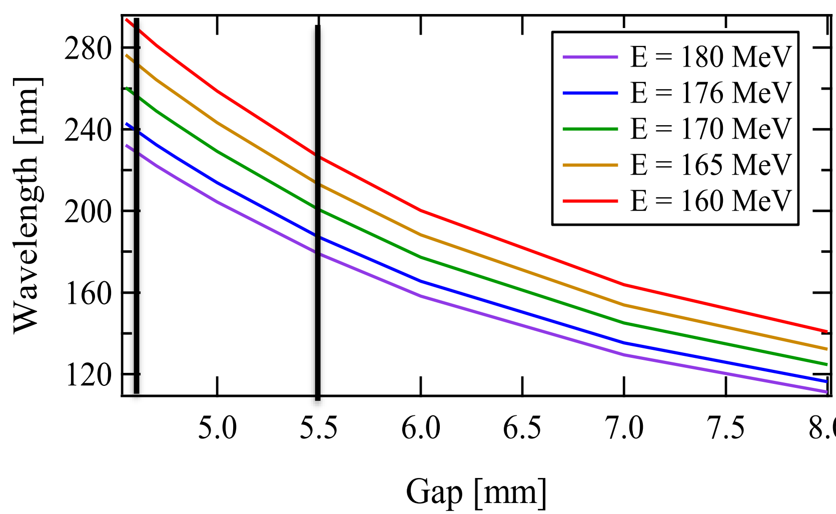
Item	Value
Technology	Hybrid
Magnet Material	Hitachi-CR53 $Pr_2Fe_{14}B$
Remanence Field	1.32 T
Coercivity H_{cj}	1.63 T
Pole material	Vanadium Permandur
Period	18 mm
Number of periods	107

O. Chubar, P. Elleaume, and J. Chavanne, ``A three-dimensional magnetostatics computer code for insertion devices,'' Journal of synchrotron radiation}, vol.~5, no.~3, pp.~481--484, 1998.

THP2WD01



λ : 200 nm – 280 nm

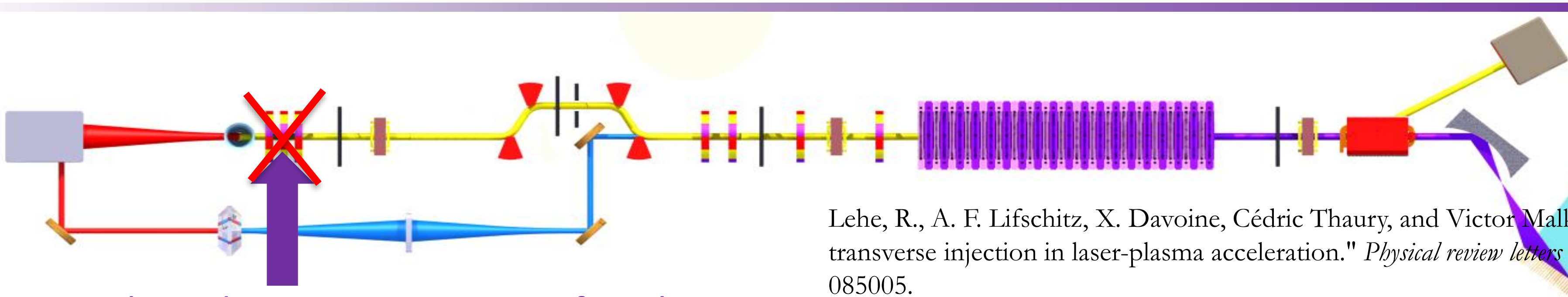


$\lambda_{res} = 200\ nm$

Development and operation of a Pr2Fe14B based cryogenic permanent magnet undulator for a high spatial resolution x-ray beam line, C. Benabderrahmane, M. Valléau, A. Ghaith, P. Berteaud, L. Chapuis, F. Marteau, F. Briquez, O. Marcouillé, J.-L. Marlats, K. Tavakoli, A. Mary, D. Zerbib, A. Lestrade, M. Louvet, P. Brunelle, K. Medjoubi, C. Herbeaux, N. Béchu, P. Rommeluere, A. Somogyi, O. Chubar, C. Kitegi, and M. E. Couprie, Phys. Rev. Accel. Beams 20, 033201(2017)

COXINEL Transport Line

Beam Transport: Electron spectrometer



Lehe, R., A. F. Lifschitz, X. Davoine, Cédric Thaury, and Victor Malka. "Optical transverse injection in laser-plasma acceleration." *Physical review letters* 111, no. 8 (2013) 085005.

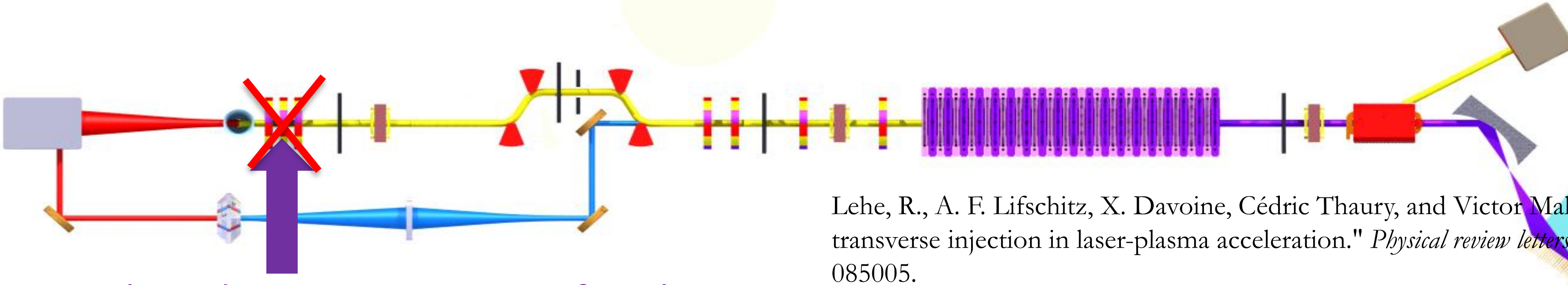
- Dipole and spectrometer just after the gas jet

- ❑ Typical spectra produced by laser plasma acceleration in a Broad Band regime (Ionization injection)
- ❑ Large energy spread (50 MeV to 200 MeV)

$$\sigma'_z = 1.5\, mrad \;-\; 3.5\, mrad$$

André, Thomas, et al. "Electron Transport on COXINEL Beam Line." *8th Int. Particle Accelerator Conf.(IPAC'17), Copenhagen, Denmark, 14â 19 May, 2017*. JACOW, Geneva, Switzerland, 2017.

Beam Transport: Electron spectrometer



Lehe, R., A. F. Lifschitz, X. Davoine, Cédric Thaury, and Victor Malka. "Optical transverse injection in laser-plasma acceleration." *Physical review letters* 111, no. 8 (2013) 085005.

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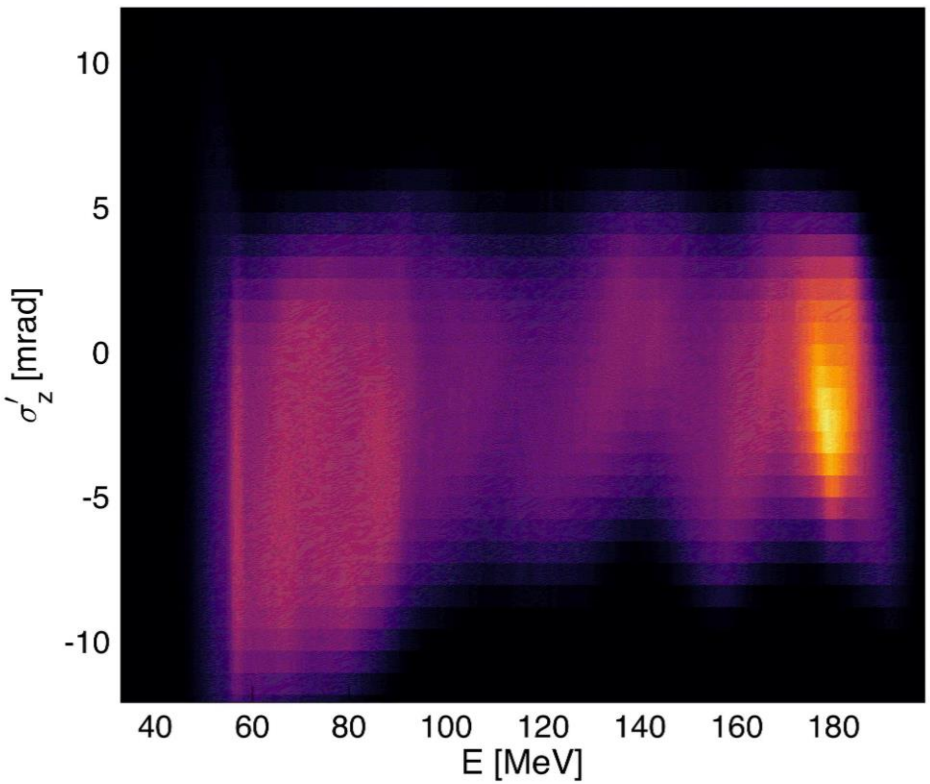

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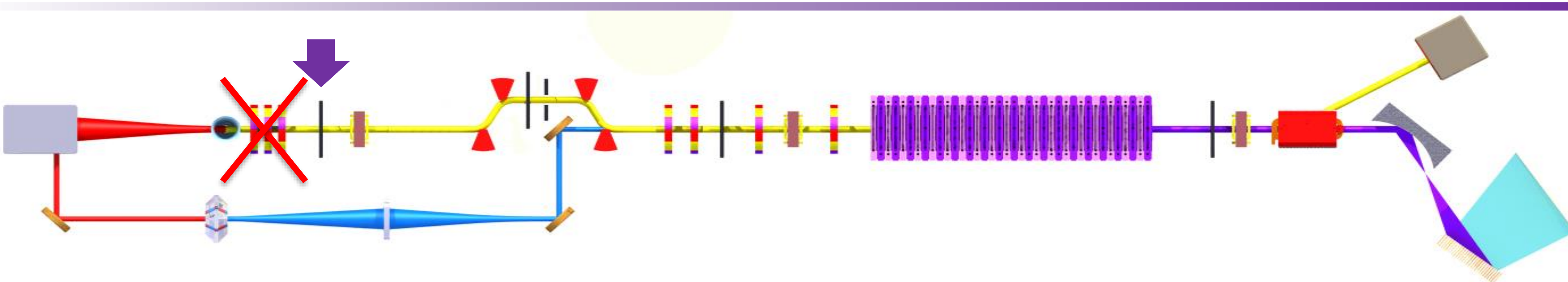
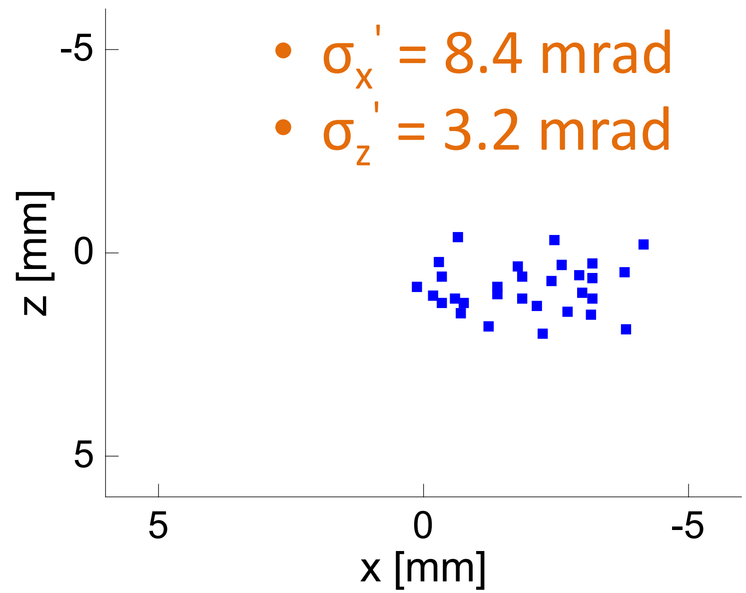
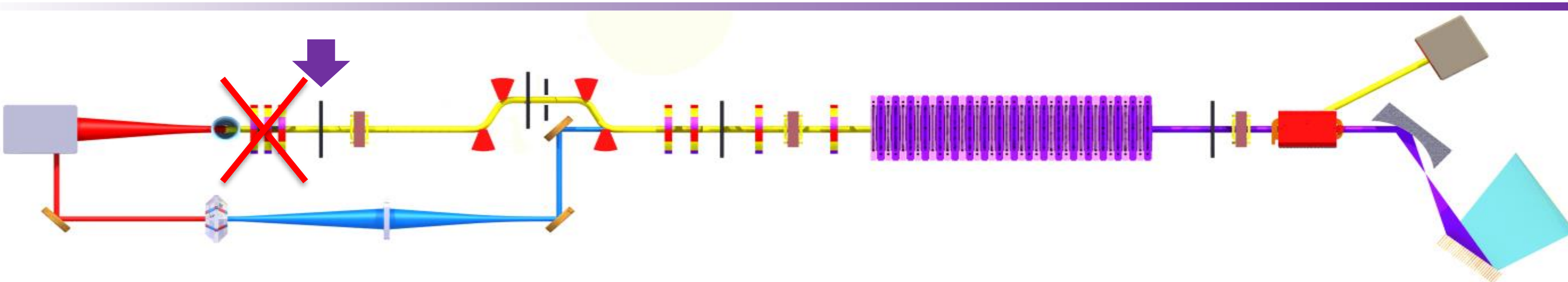
Beam Transport: Screen 1

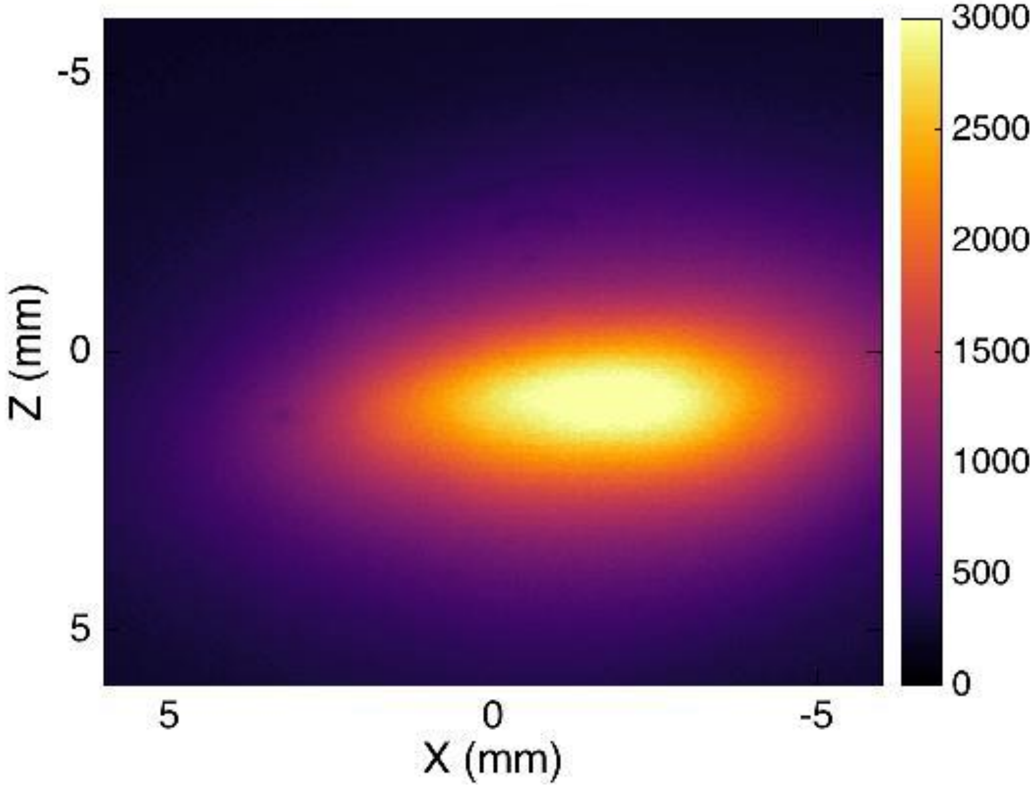


- ❑ Beam pointing stability
- ❑ Divergence (rms)



Beam Transport: Screen 1





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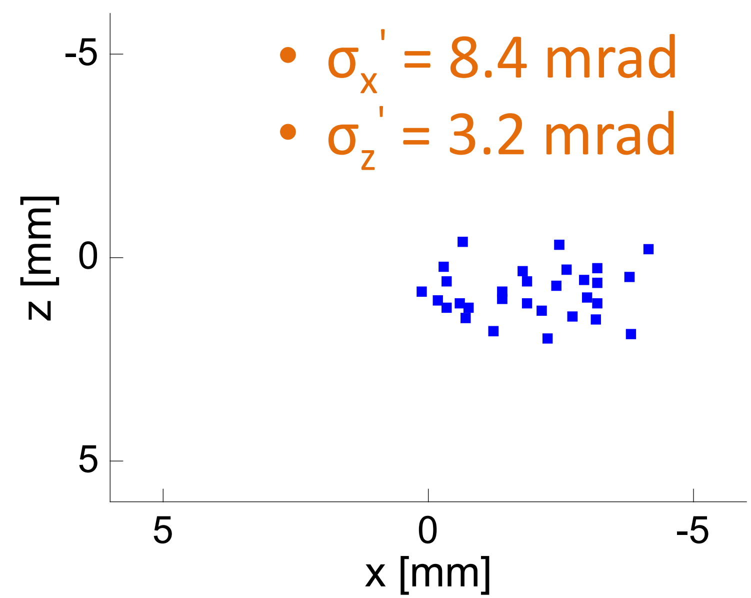


- $\sigma_x' = 8.4$ mrad
- $\sigma_z' = 3.2$ mrad

Undulator Radiation

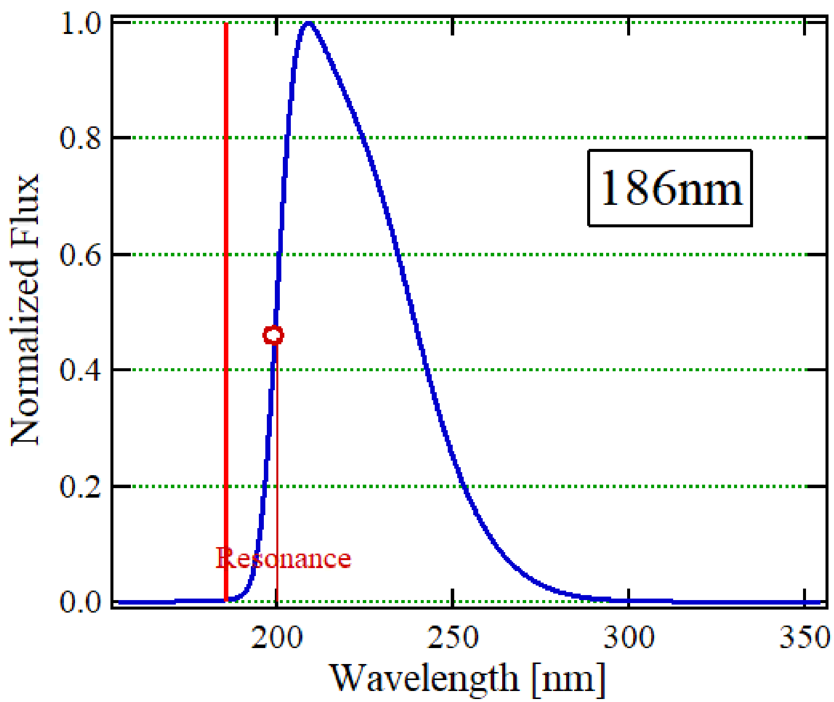
$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

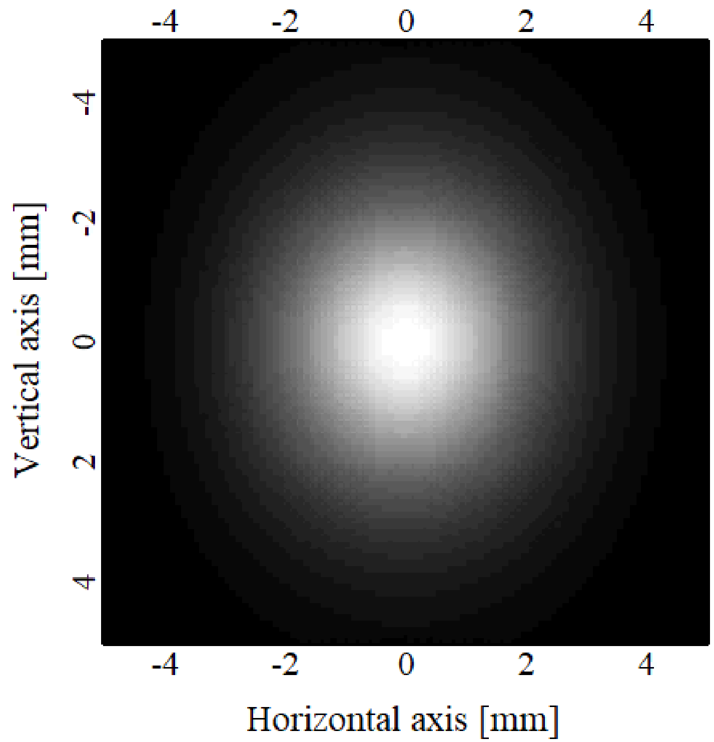
λ_u: Undulator period
γ: Lorentz factor
K: Deflection parameter
θ: Angle of observation

COXINEL case (gap = 5.5 mm)

B = 1.06 T
λ_u = 18.16 mm
E = 176 MeV

$\lambda_{res} = 200\ nm$





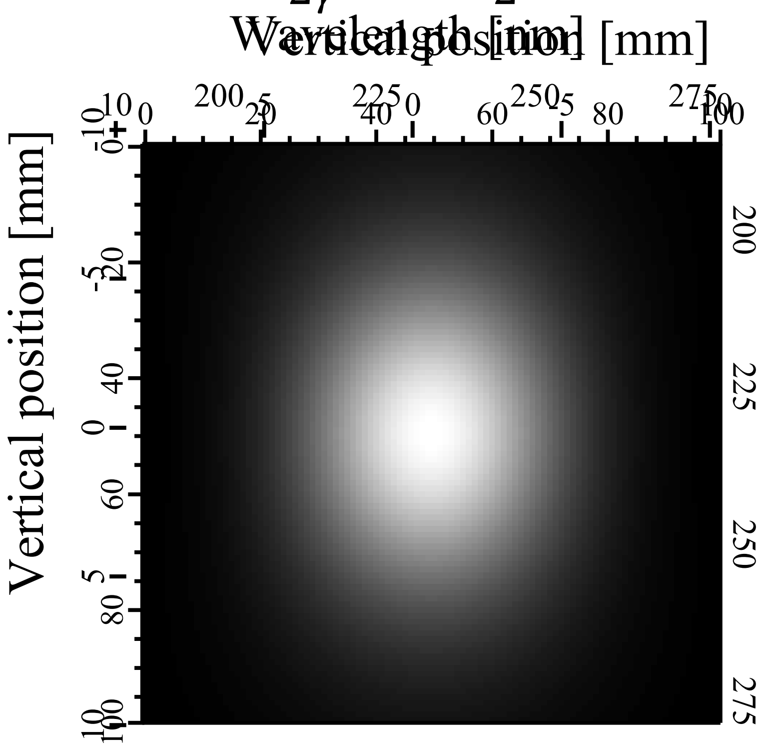
1% rms energy spread; Divergence and Beam size (1 mrad, 1mm)

Photon Beam Emitted (SRWE simulation)

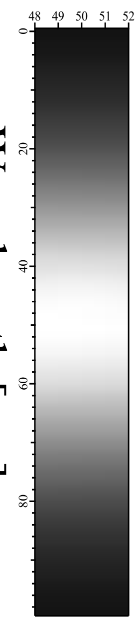
Chubar, Oleg, and P. Elleaume. "Accurate and efficient computation of synchrotron radiation in the near field region." *proc. of the EPAC98 Conference*. 1998.

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

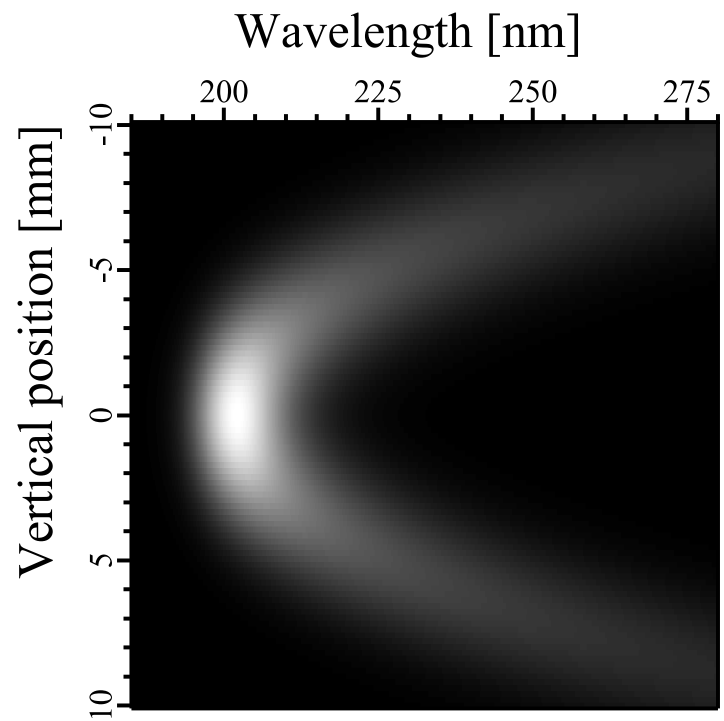
Radiation wavelength (λ) proportional to angle (θ)



Undulator radiation through a window : CCD camera



slit



Undulator radiation: Spectrometer

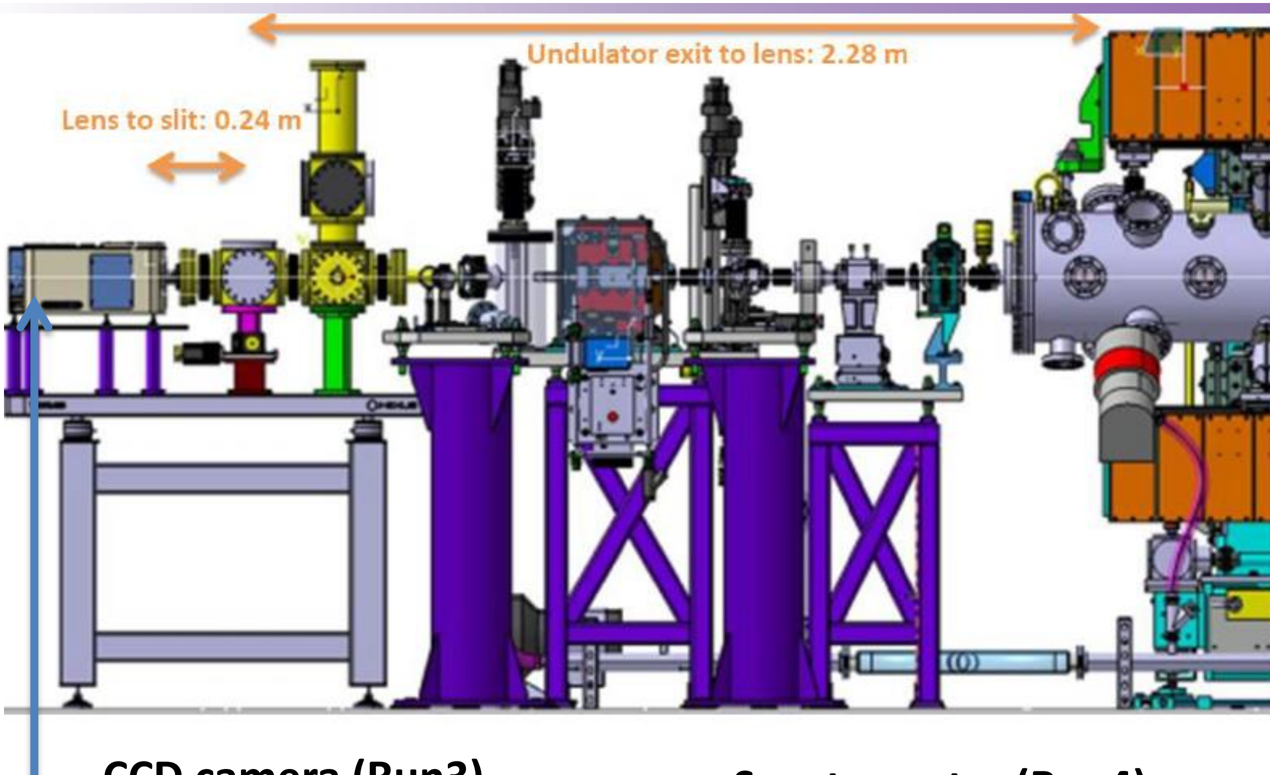
Energy spread = 1% rms

Divergence = 400 µrad;

Beam size = 700 µm

❖ Hence the so-called moon shape!

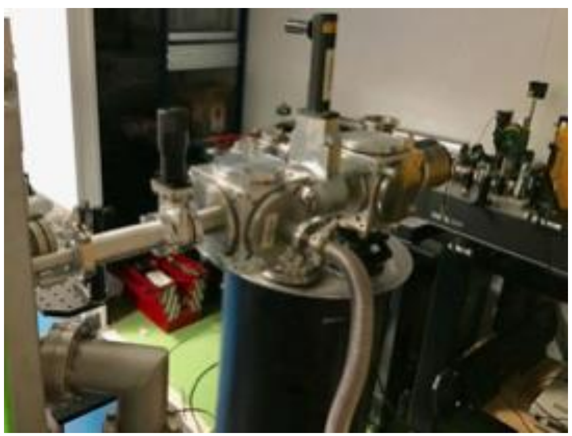
Photon Beam Diagnostics line



Undulator:
- Planar (linear polarization)
- 2 m long (18 mm period)
- Peak Field = 1.23 T at 4.55 mm gap

Lens:
- Material: Calcium Flouride
- Shape: spherical
- Focal length = 240 mm

CCD camera (Run3)



Spectrometer (Run4)

- IHR320 HORIBA
- 3 gratings (600 gr/mm, 1200 gr/mm, 3200 gr/mm)

Undulator radiation have been observed for different gaps and different electron slit width:

- Transverse beam shape using a CCD camera
- Flux using a spectrometer

Results are not uploaded to avoid issues with publishing the results

Conclusion:

- ❑ Beam pointing alignment compensation enabled good handling of a highly divergent beam along an 8 m long transport line with different magnetic elements
- ❑ Observation of undulator radiation after manipulation beam line
- ❑ Undulator radiation gives an insight on the electron beam quality

Free Electron Laser Results

Free Electron Laser Results

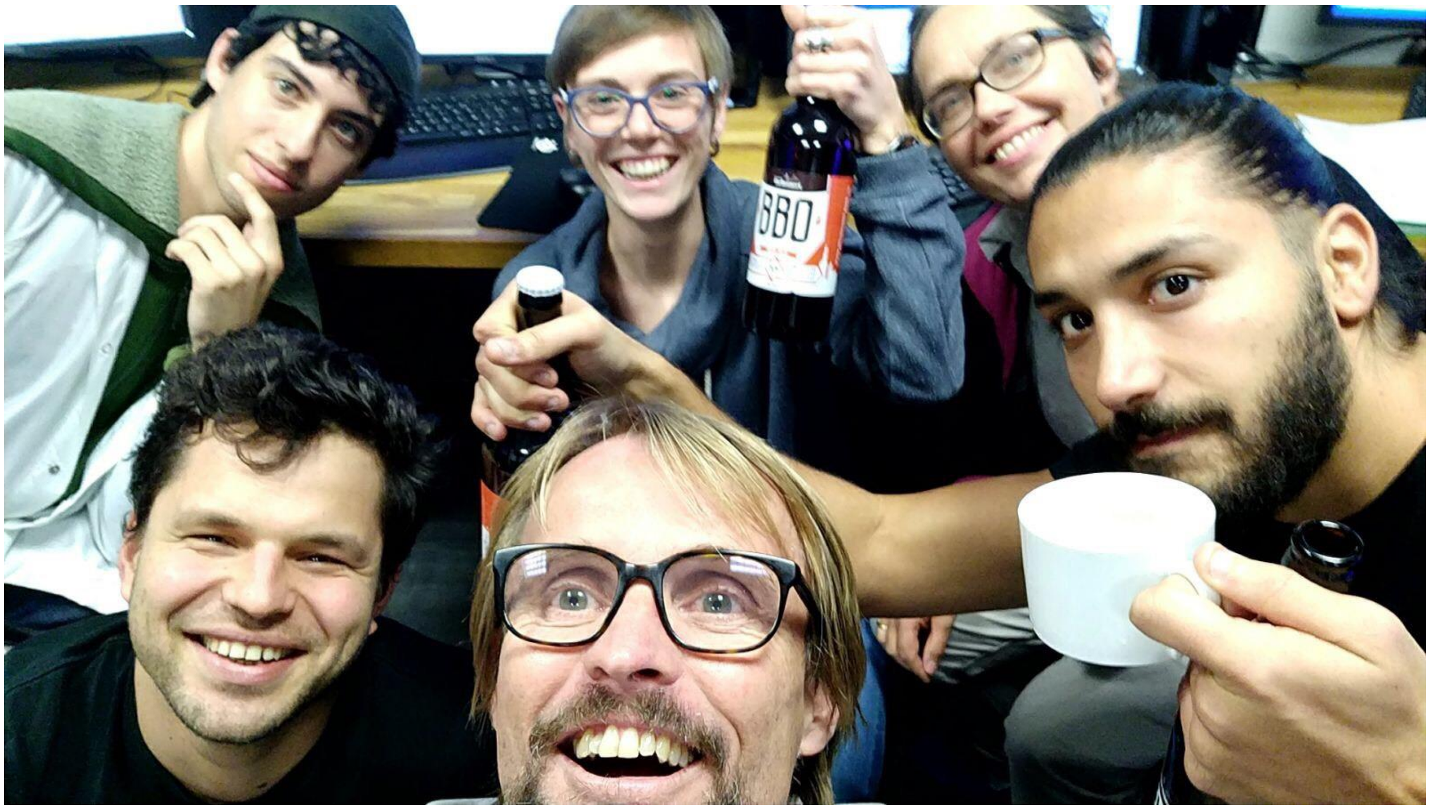
Free Electron Laser Results

~~Free Electron Laser Results~~

Just Kiding

~~Free Electron Laser Results~~

Just Kiding



~~Free Electron Laser Results~~

Just Kiding

Thank you for your attention