DE LA RECHERCHE À L'INDUSTRIE

Simulation de l'accélération par sillage laser et de ses applications avec le code PIC CALDER

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GDR APPEL, Orsay, 2023

Pan

- Amélioration numérique de la modélisation de l'acceleration par sillage : limitation du NCR

- Confrontation à la réalité expérimentale
  - Prise en compte de paramètres laser réalistes.
  - Simulation du sillage laser avec PETAL dans le régime SMLWFA

- Quelques exemples d'applications : simulation d'interaction faisceau-cible avec CALDER

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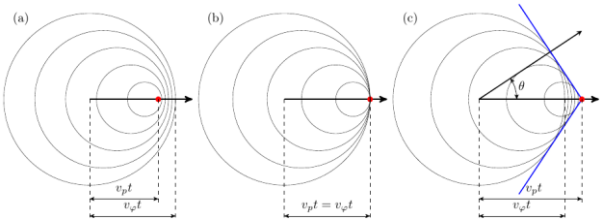
Numerical Cerenkov Radiation[1] (NCR): Principle

- (Physical) Cerenkov Radiation

  It appears when an charged particle is faster than the speed of light in a medium ($v_p > v_\phi$)



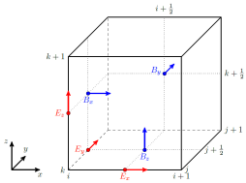
$$\cos(\theta) = \frac{c}{v_p n(\omega)} \qquad \omega = \boldsymbol{v}_p \cdot \boldsymbol{k}$$

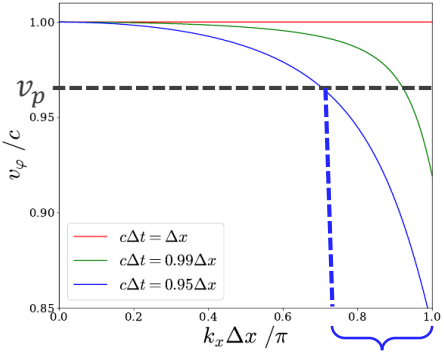
- Origin of Numerical Cerenkov Radiation (NCR) in PIC code

$$v_\varphi^{num} = \frac{2}{k\Delta t}\arcsin\left(c\Delta t\sqrt{\frac{1}{\Delta x^2}\sin^2\left(\frac{k_x\Delta x}{2}\right)+\frac{1}{\Delta y^2}\sin^2\left(\frac{k_y\Delta y}{2}\right)+\frac{1}{\Delta z^2}\sin^2\left(\frac{k_z\Delta z}{2}\right)}\right)$$

In plasma, light phase velocity $v_\phi \geq c \Rightarrow$ no CR.

In a PIC code with the standard Yee[2] scheme, we have $v_\phi^{num} < c$ in vacuum $\Rightarrow$ NCR…



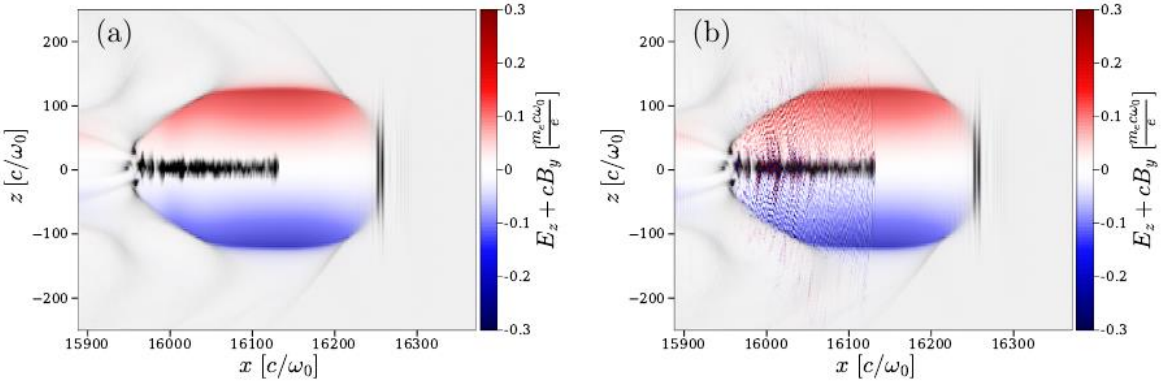


Emission of NCR in the high frequency domain

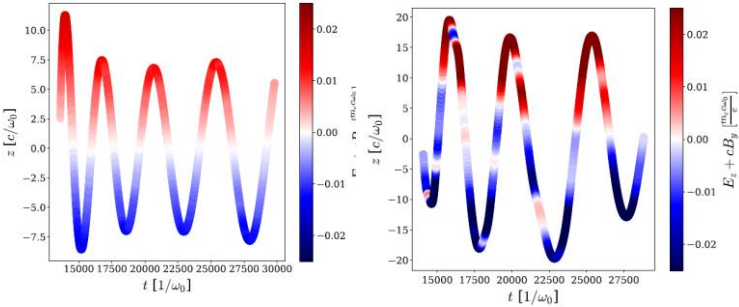
[1] B.B. Godfrey, JCP 15(4) 504–521 (1974).
[2] K. Yee, IEEE Trans. Antennas Propag. **14**, 302 (1966)

Numerical Cerenkov Radiation (NCR): Effects

- Consequences: emission of spurious and high frequency radiation, which can affect the beam/plasma dynamic



Depending on the beam charge: wrong beam divergence, transverse size, transverse emittance…



P.-L. Bourgeois, PhD, IP Paris (2020)
P.-L. Bourgeois *et al.*, JCP **413** 109426 (2020)

Numerical Cerenkov Radiation (NCR): Mitigation technics

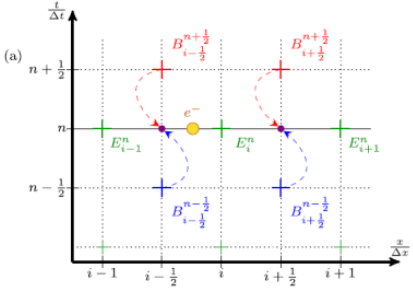
- “Standard” spatial filtering.
- Higher resolution.
- Modified Maxwell solver.
- Modified field interpolation.
- **Combination of different technics.**

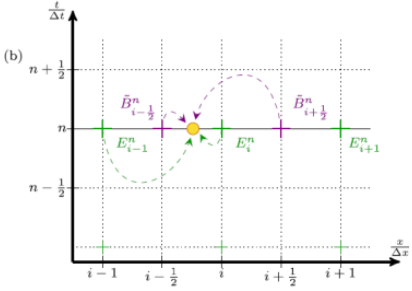
- NCI : plus complexe à combattre, apparait dans le « boosted frame »

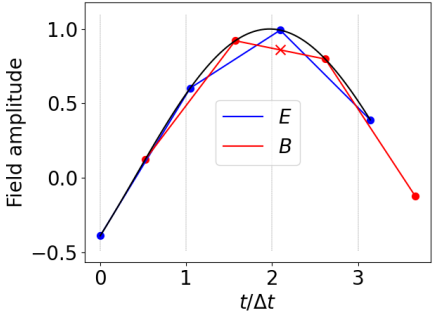
Numerical Cerenkov Radiation (NCR): Mitigation technics

- Modified field interpolation.
  - Field filters used only to push the particles **(NCI)** [1,2].
  - BTIS scheme [3-5] : NCR propagates with the beam: E and B force compensate => no transverse force on the beam. Easy to implement!

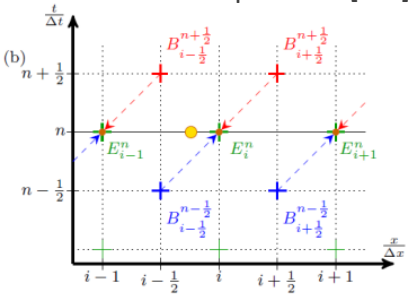
Standard interpolation

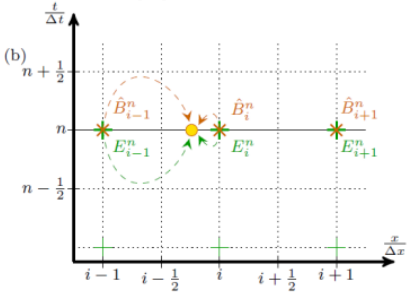






BTIS3 interpolation [3-5] in CALDER [6]





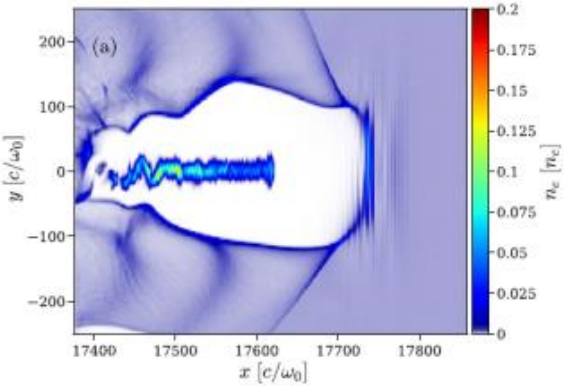
[1] B. B. Godfrey *et al.*, JCP **267** 1–6 (2014)
[2] Y. Lu *et al.*, JCP **413** 109388 (2020)

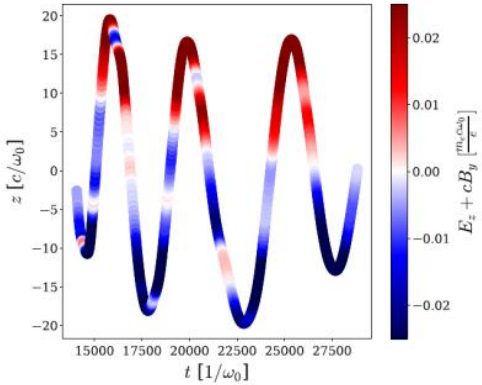
[3] P.-L. Bourgeois, PhD, IP Paris (2020)
[4] P.-L. Bourgeois, JCP **413** 109426 (2020)
[5] P.-L. Bourgeois, to be published

[6] E. Lefebvre et al., Nuc. Fus. 43 629 (2003)

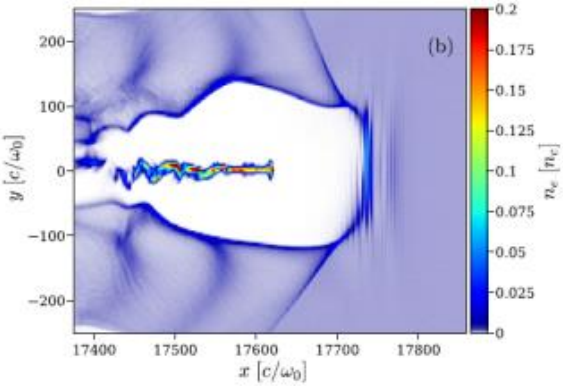
Numerical Cerenkov Radiation (NCR): Mitigation technics

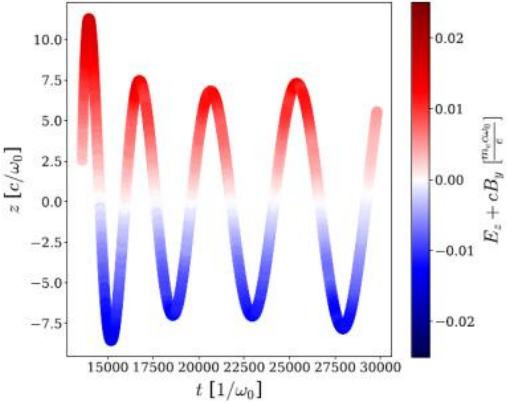
Standard interpolation





BTIS interpolation [1-3]

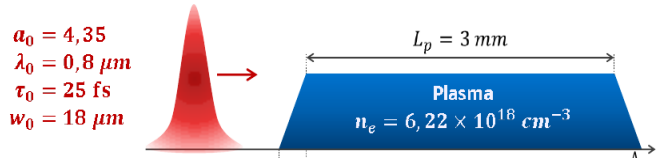


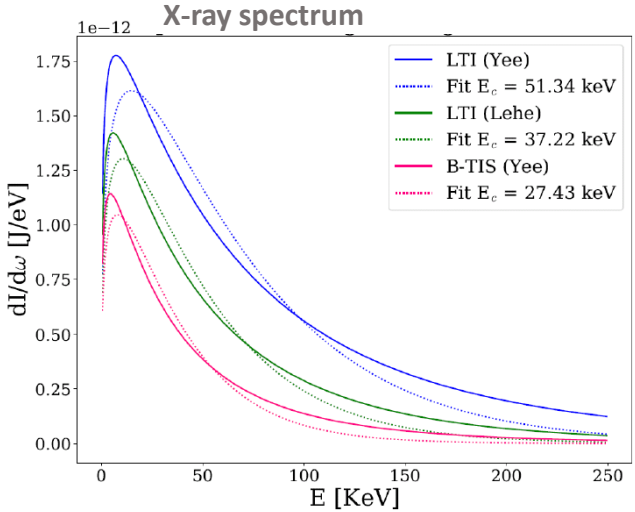


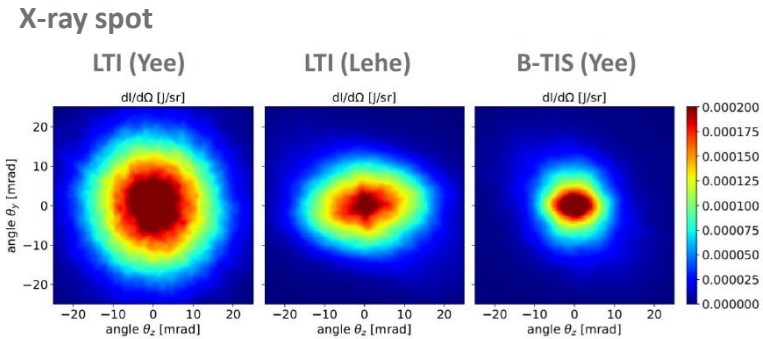
Numerical Cerenkov Radiation (NCR): Effect on a betatron source

- Benchmark between Yee[1], a modified Maxwell solver[2], and BTIS scheme[3,4]

[1] K. Yee, IEEE Trans. Antennas Propag. **14**, 302 (1966)
[2] R. Lehe, *et al.*, PRSTAB **16** 021301 (2013).
[3] P.-L. Bourgeois, PhD, IP Paris (2020)
[4] P.-L. Bourgeois, JCP **413** 109426 (2020)







Pan

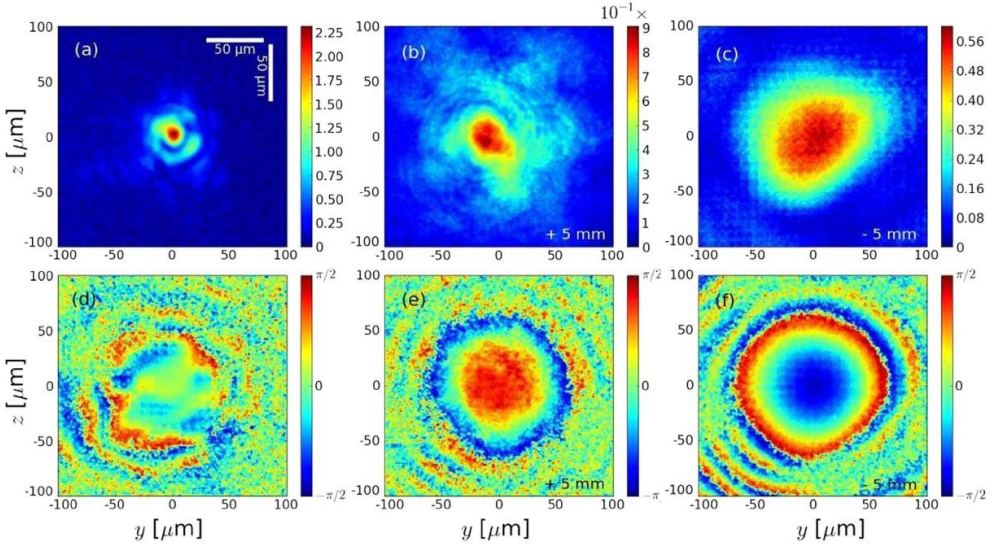
- Amélioration numérique de la modélisation de l'acceleration par sillage : limitation du NCR

- **Confrontation à la réalité expérimentale**
  - **Prise en compte de paramètres laser réalistes.**
  - Simulation du sillage laser avec PETAL dans le régime SMLWFA

- Quelques exemples d'applications : simulation d'interaction faisceau-cible avec CALDER

Effet d'imperfections dans la tache laser sur le LWFA et sur une source bétatron.

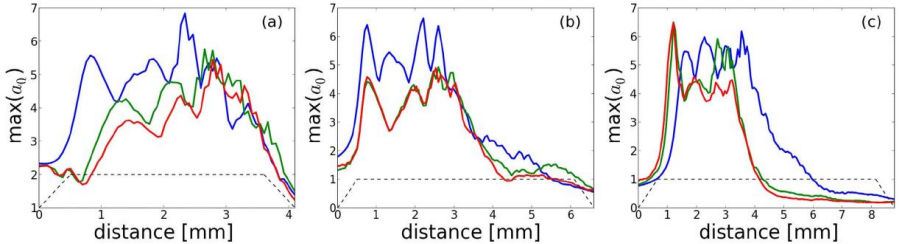
- Simulation d'une expérience réalisée à l'INRS au Canada sur le laser ALLS (2.5 J, 30 fs).
- Reconstruction de la phase du laser avec l'algorithme Gerchberg-Saxton.



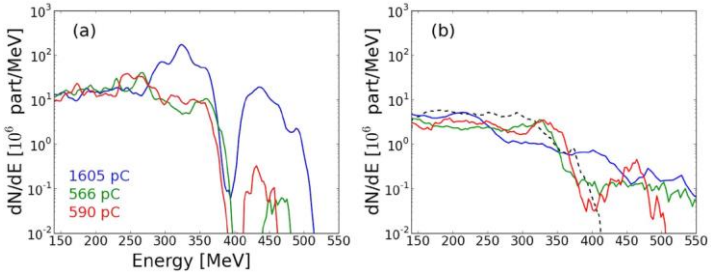
J. Ferri *et al.*, Scientific Reports 6, 27846 (2016)

Effet d'imperfections dans la tache laser sur le LWFA et sur une source bétatron.

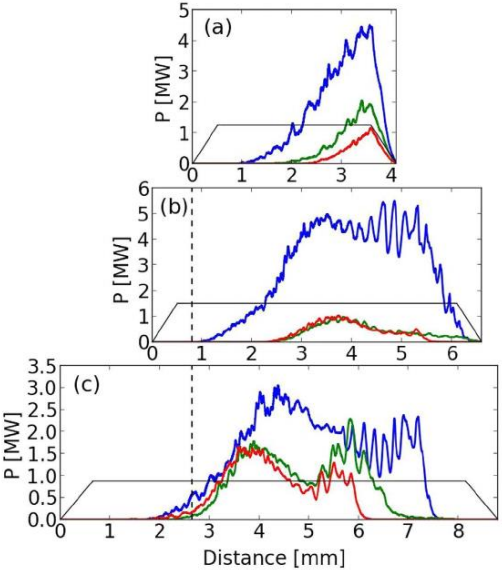
3 longueurs de buse utilisées



Spectre électronique pour la buse de 5 mm @3.5mm et 6.6mm



Puissance bêtatron rayonnée pour les 3 buses



Gaussienne, tache exp., tache+phase exp.

J. Ferri *et al.*, Scientific Reports 6, 27846 (2016)

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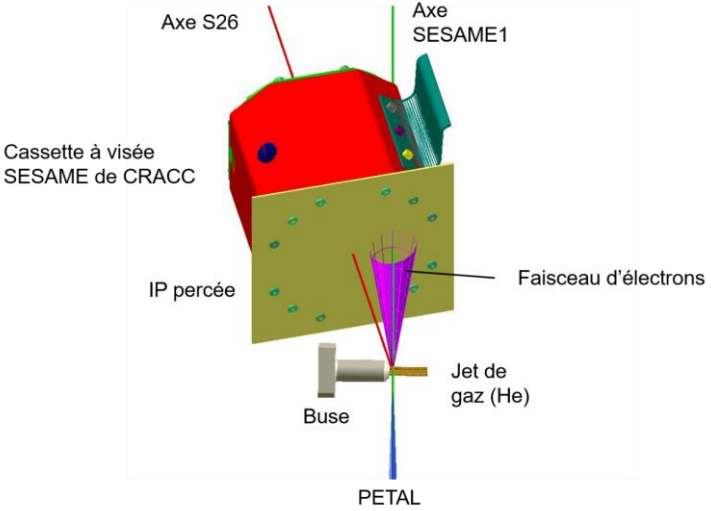
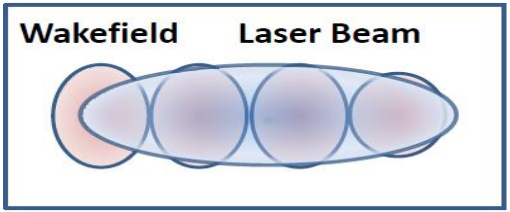
PETAL : laser de ~400 J sur le LMJ (CEA Bordeaux)

- PETAL : ~ 400 J, 50 µm, 700 fs, 10^{19} W/cm^2, quelques tirs sur une campagne. Campagne prévue en 2023, PI : F. Albert (LLNL - USA)
- Etude du régime SM-LWFA
- Possibilité de créer une source d'électrons énergétiques et/ou bêtatron sur le LMJ.

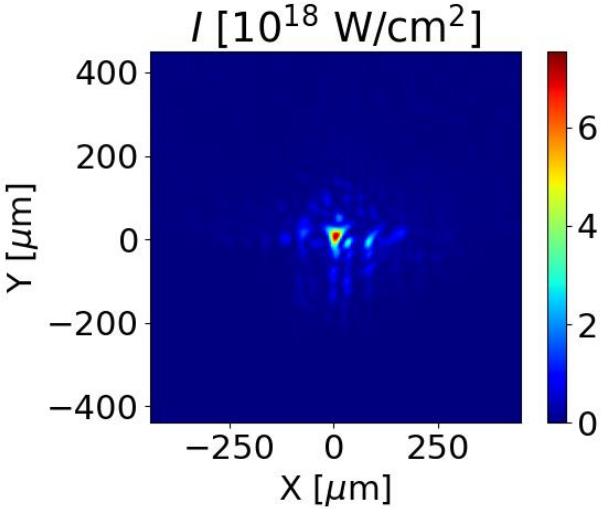


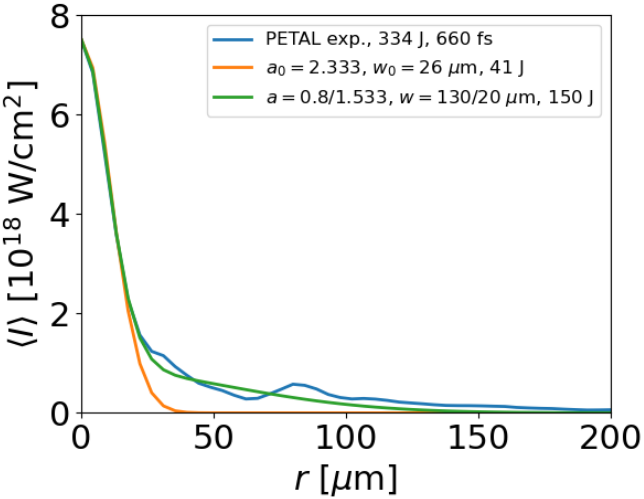


- Spectre attendu non mono-énergétique, mais > 100 MeV et de très forte charge

PETAL : laser de ~400 J sur le LMJ (CEA Bordeaux)

- Difficulté pour la simulation :
  - très peu de tirs,
  - besoin d'être prédictif pour designer au mieux l'expérience et les diagnostiques,
  - « Gros » laser à simuler (700 fs), laser imparfait : prise en compte des ailes de taches ? Les première simulation montre qu'*a priori* non, à confirmer…





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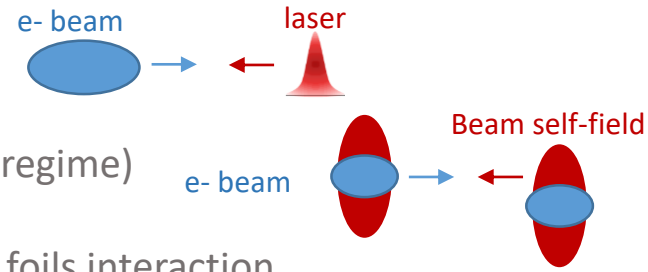
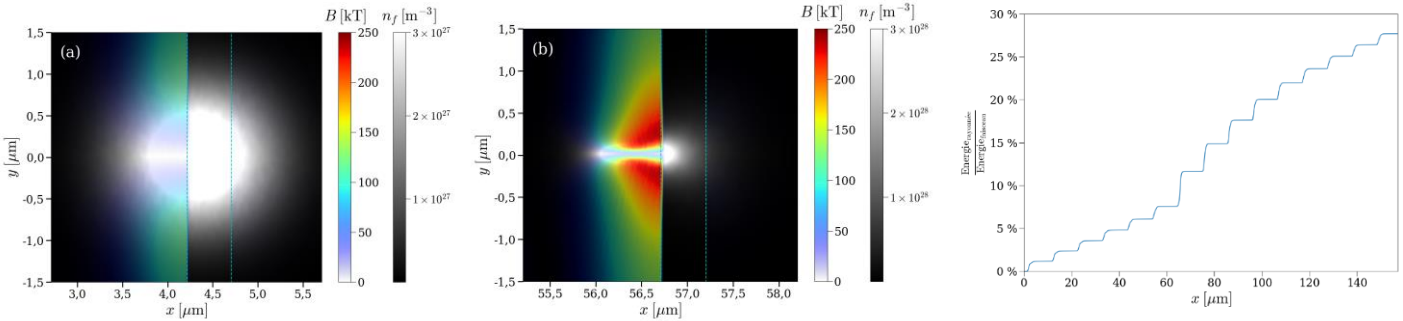
- **Quelques exemples d'applications : simulation d'interaction faisceau-cible avec CALDER**

Study of the Strong-Field QED regime (SF-QED)
Production of intense γ ray sources, e+e- pairs

- Laser-Beam interaction
  M. Lobet et al., PRAB 20 043401 (2017), …
- Beam-Beam collision (beamstrahlung regime)
  V. Yakimenko *et al.*, PRL **122**, 190404 (2019)
- Beam-foil interaction and beam-multi foils interaction





10 GeV, 2 nC, 0.55 µm
0.5 µm Al foil

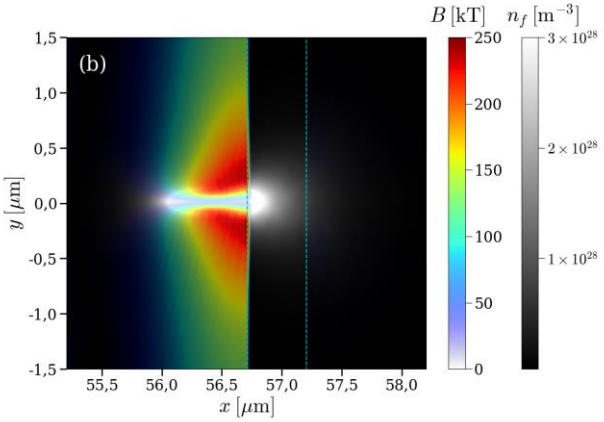
A. Sampath *et al.*, PRL 126, 064801 (2021)
Collaborators of the SLAC E332 experiment

PHYSICAL REVIEW LETTERS **126,** 064801 (2021)

Extremely Dense Gamma-Ray Pulses in Electron Beam-Multifoil Collisions

Archana Sampath,[1] Xavier Davoine,[2,3] Sébastien Corde,[4] Laurent Gremillet,[2,3] Max Gilljohann,[4] Maitreyi Sangal,[1] Christoph H. Keitel,[1] Robert Ariniello,[5] John Cary,[5] Henrik Ekerfelt,[6] Claudio Emma,[6] Frederico Fiuza,[6] Hiroki Fujii,[7] Mark Hogan,[6] Chan Joshi,[7] Alexander Knetsch,[4] Olena Kononenko,[4] Valentina Lee,[5] Mike Litos,[5] Kenneth Marsh,[7] Zan Nie,[7] Brendan O'Shea,[6] J. Ryan Peterson,[6,8] Pablo San Miguel Claveria,[4] Doug Storey,[6] Yipeng Wu,[7] Xinlu Xu,[6] Chaojie Zhang,[7] and Matteo Tamburini[1,*]
[1]*Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany*
[2]*CEA, DAM, DIF, 91297 Arpajon, France*
[3]*Université Paris-Saclay, CEA, LMCE, 91680 Bruyères-le-Châtel, France*
[4]*LOA, ENSTA Paris, CNRS, Ecole Polytechnique, Institut Polytechnique de Paris, 91762 Palaiseau, France*
[5]*University of Colorado Boulder, Department of Physics, Center for Integrated Plasma Studies, Boulder, Colorado 80309, USA*
[6]*SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA*
[7]*University of California Los Angeles, Los Angeles, California 90095, USA*
[8]*Stanford University, Physics Department, Stanford, California 94305, USA*

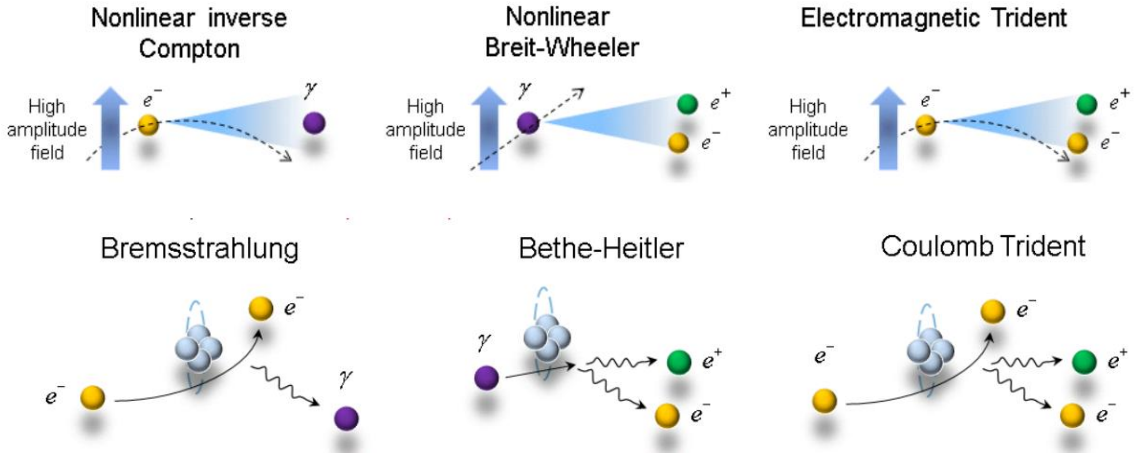
Study of the Strong-Field QED regime (SF-QED)
Production of intense γ ray sources, e+e- pairs



Implemented in CALDER [1-4]:

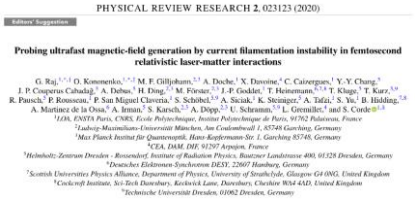
- Filed ionization
- Collisions (elastic + ionization)
- SF-QED processes
- Coulomb processes

[1] M. Lobet *et al.*, J. Phys.: Conf. Ser. **688**, 012058 (2016).
[2] B. Martinez *et al.*, POP **26**, 103109 (2019).
[3] M. Lobet, PhD, Université de Bordeaux (2015)
[4] B. Martinez, PhD, Université de Bordeaux (2018)



Study of relativistic beam-plasma instabilities

- Probing Current Filament Instability (CFI) on short time-scale
  - CFI in laser-solid target interaction
  - Probing CFI with LWFA e- beam

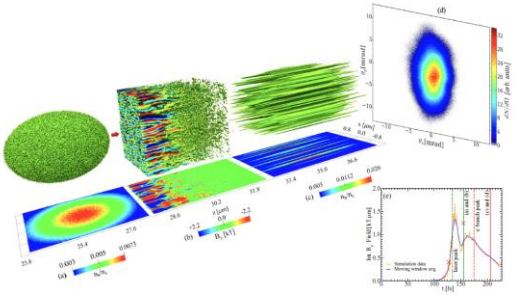

PHYSICAL REVIEW RESEARCH 2, 023123 (2020)

Editors' Suggestion

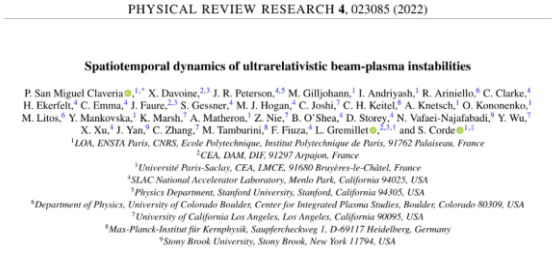
Probing ultrafast magnetic-field generation by current filamentation instability in femtosecond relativistic laser-matter interactions

G. Raj,[1,*,†] O. Kononenko,[1,*,‡] M. F. Gilljohann,[2,1] A. Doche,[1] X. Davoine,[4] C. Caizergues,[1] Y.-Y. Chang,[3] J. P. Couperus Cabadağ,[2] A. Debus,[2] H. Ding,[2,2] M. Füvester,[2,2] J.-P. Goddet,[1] T. Heinemann,[5,3,4] T. Kluge,[2] T. Kurz,[3,6] R. Pausch,[2] P. Rousseau,[1] P. San Miguel Claveria,[1] S. Schöbel,[2,2] A. Sicuia,[1] K. Steiniger,[2] A. Tafzi,[1] S. Yu,[1] B. Hidding,[7,8] A. Martinez de la Ossa,[9] A. Irman,[2] S. Karsch,[2,2] A. Döpp,[2,2] U. Schramm,[2,2] L. Gremillet,[1] and S. Corde[1,†]

[1]*LOA, ENSTA Paris, CNRS, Ecole Polytechnique, Institut Polytechnique de Paris, 91762 Palaiseau, France*
[2]*Ludwig-Maximilians-Universität München, Am Coulombwall 1, 85748 Garching, Germany*
[3]*Max Planck Institut für Quantenoptik, Hans-Kopfermann-Str. 1, Garching 85748, Germany*
[4]*CEA, DAM, DIF, 91297 Arpajon, France*
[5]*Helmholtz-Zentrum Dresden - Rossendorf, Institute of Radiation Physics, Bautzner Landstrasse 400, 01328 Dresden, Germany*
[6]*Deutsches Elektronen-Synchrotron DESY, 22607 Hamburg, Germany*
[7]*Scottish Universities Physics Alliance, Department of Physics, University of Strathclyde, Glasgow G4 0NG, United Kingdom*
[8]*Cockcroft Institute, Sci-Tech Daresbury, Keckwick Lane, Daresbury, Cheshire Wa4 4AD, United Kingdom*
[9]*Technische Universität Dresden, 01062 Dresden, Germany*



- Competition between CFI and Oblique Two Stream Instability (OTSI).


PHYSICAL REVIEW RESEARCH 4, 023085 (2022)

Spatiotemporal dynamics of ultrarelativistic beam-plasma instabilities

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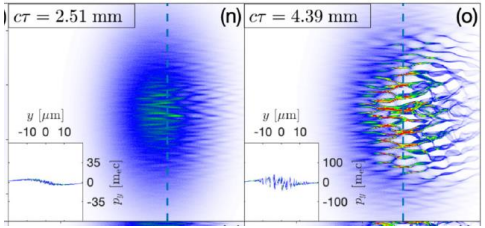
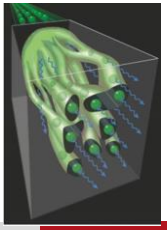
E305 SLAC experiment



- Fundamental studies relevant to beam propagation, laser-plasma interaction, astrophysics, γ ray emission.

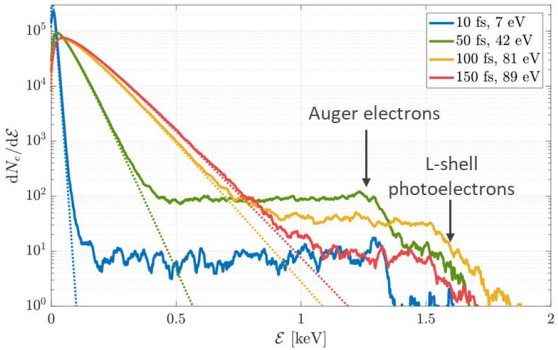


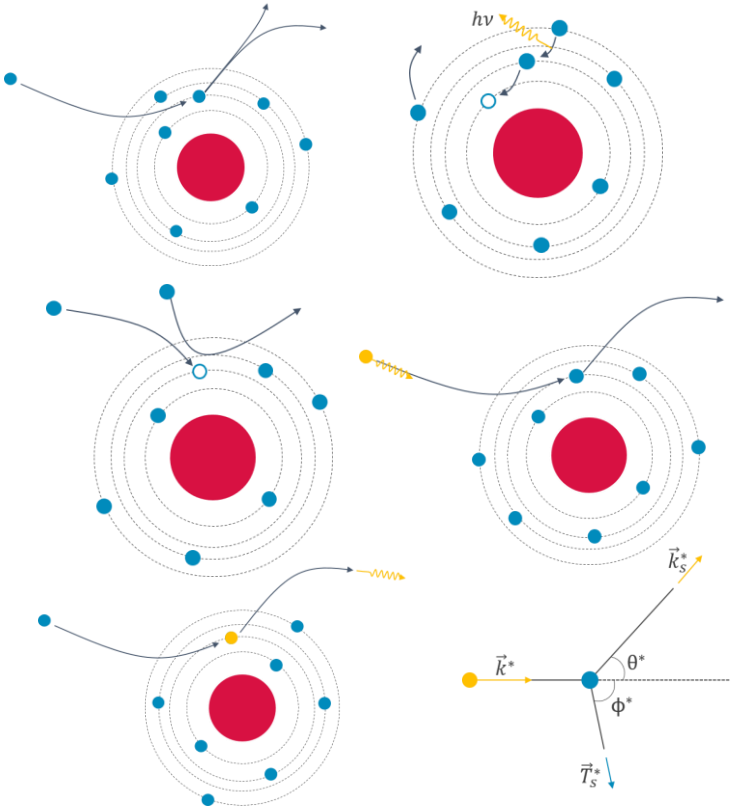
A. Benedetti et al., Nat. Phot. **12** 319–323 (2018)

XFEL pulse interaction with matter implementation of “simple” atomic model

- Implemented in CALDER:
  - Collisional ionization
  - Atomic deexcitation
  - Three-body recombination
  - Photoionization (from X-ray)
  - Radiative recombination
  - Compton scattering
  - Ionization potential depression

Self-consistent simulation of XFEL pulse interacting with Al target





D. Tordeux, PhD, Université Paris-Saclay (2022)
R. Royle *et al.*, Phys. Rev. E **95**, 063203 (2017).

Conclusion

- Développements pour réduire les erreurs numériques (e.g. NCR) et mieux prendre en compte la réalité expérimentale.

- Les codes PIC sont un bon outil pour simuler l'accélération par sillage, mais aussi certaines applications
  - Ces applications peuvent être communes aux accélérateurs plasma et conventionnels => permet de rapprocher ces deux communautés.
  - Certains développements spécifiques sont nécessaires (numériques, modules de physique).