Near-Field CTR beam focusing and its application to Strong Field QED

Pablo San Miguel Claveria (LOA, IP Paris / X-GoIP, IST Lisbon)

On behalf of:

E332 Collaboration (SLAC, UCLA, CU Boulder, U. Oslo, Stony Brook U., MPIK, CEA, LOA)

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Overview

1. Near-Field Coherent Transition Radiation – modelling and simulations.
2. Analytical estimates and observables of NF-CTR beam focusing with FACET-II parameters.
3. Probing Strong-Field regime of QED via NF-CTR process.

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*

(Received 25 September 2020; revised 18 December 2020; accepted 8 January 2021; published 12 February 2021)

Sources of high-energy photons have important applications in almost all areas of research. However, the photon flux and intensity of existing sources is strongly limited for photon energies above a few hundred keV. Here we show that a high-current ultrarelativistic electron beam interacting with multiple submicrometer-thick conducting foils can undergo strong self-focusing accompanied by efficient emission of gamma-ray synchrotron photons. Physically, self-focusing and high-energy photon emission originate from the beam interaction with the near-field transition radiation accompanying the beam-foil collision. This near field radiation is of amplitude comparable with the beam self-field, and can be strong enough that

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Beam focusing by near-field transition radiation

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[1]IP Paris, France
[2]CEA, France
[3]MPIK, Germany

https://hal-polytechnique.archives-ouvertes.fr/hal-02937777v2

Probing strong-field QED in ultrarelativistic beam-plasma collisions

A. Matheron,[1,a)] P. San Miguel Claveria,[1,a)] R. Ariniello,[2] H. Ekerfelt,[3] F. Fiuza,[3] S. Gessner,[3] M F. Gilljohann,[1] M. J. Hogan,[3] C. H. Keitel,[4] A. Knetsch,[1] M. Litos,[2] Y. Mankovska,[1] S. Montefiori,[4] Z. Nie,[5] B. O'Shea,[3] J. R. Peterson,[3,6] D. Storey,[3] Y. Wu,[5] X. Xu,[3] V. Zakharova,[1] X. Davoine,[7,8] L. Gremillet,[7,8] M. Tamburini,[4] and S. Corde[1,b)]

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https://arxiv.org/abs/2209.14280

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2. Analytical estimates and observables of NF-CTR beam focusing with FACET-II parameters.

3. Probing Strong-Field regime of QED via NF-CTR process.

See talk by D. Storey on Wed. 13:30 (WG 4+7) for first experimental results!

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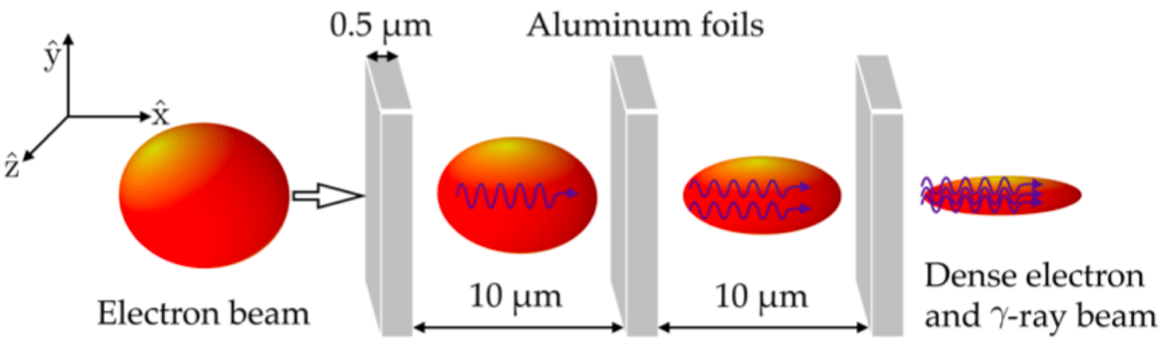
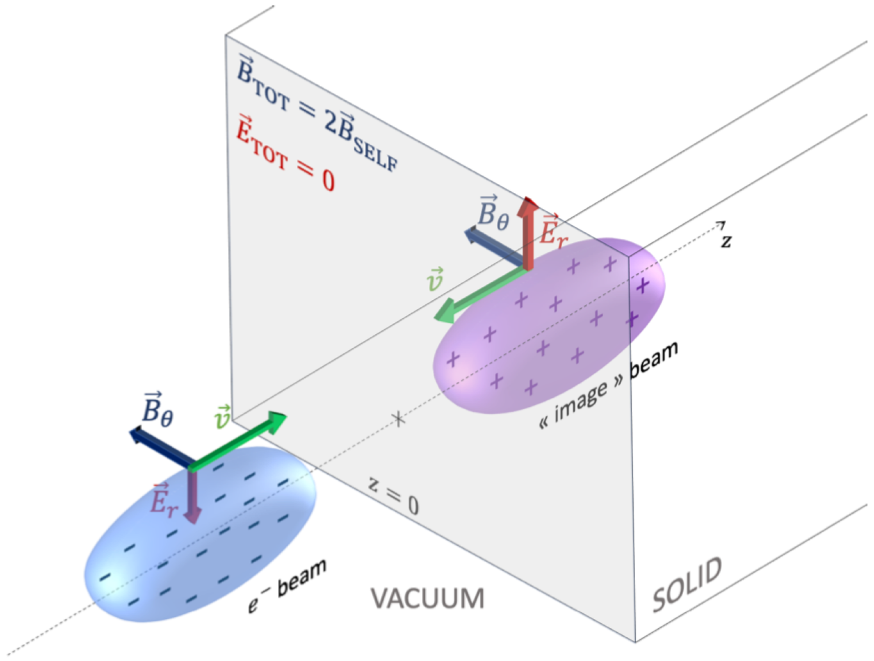
https://arxiv.org/abs/2209.14280

1. Near-Field Coherent Transition Radiation – modelling and simulations

- Transition radiation emitted by a charged beam passing through a conducting foil has a net focusing effect on the beam.
- Initially suggested in 80's for beam transport[1] – image charges.
- Focusing element to reach solid-density electron beams and bright gamma-ray source[3].





Conceptual representation of NFCTR image focusing[2]

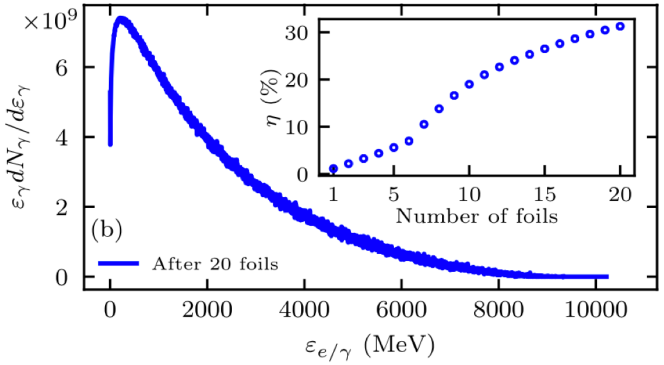
[1] R. J. Adler, Part. Accel. 12, 39 (1982). [2] A. Matheron *et. al.,* submitted to Comm. Phys. [3] A. Sampath *et. al.,* PhysRevLett.126.064801 (2021)

1. Near-Field Coherent Transition Radiation – modelling and simulations

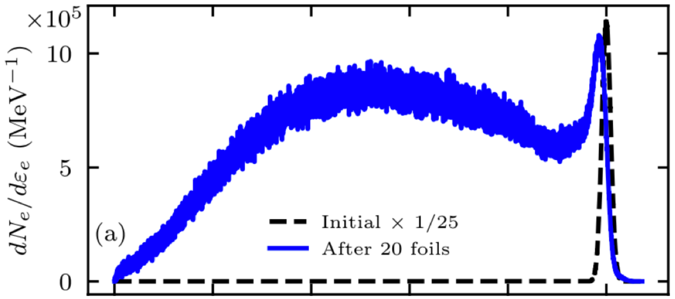
- 3D PIC simulation of e[-] beam interaction with stack of Al foils of 0.5 μm thickness.
  - Total charge $Q = 2\,nC$.
  - Initial beam energy $E = 10\,GeV$.
  - Initial beam size $\sigma_{\parallel} = \sigma_{\perp} = 0.55\,\mu m$.
  - Initial beam normalized emittance $\varepsilon_n = 3\,\mu m$

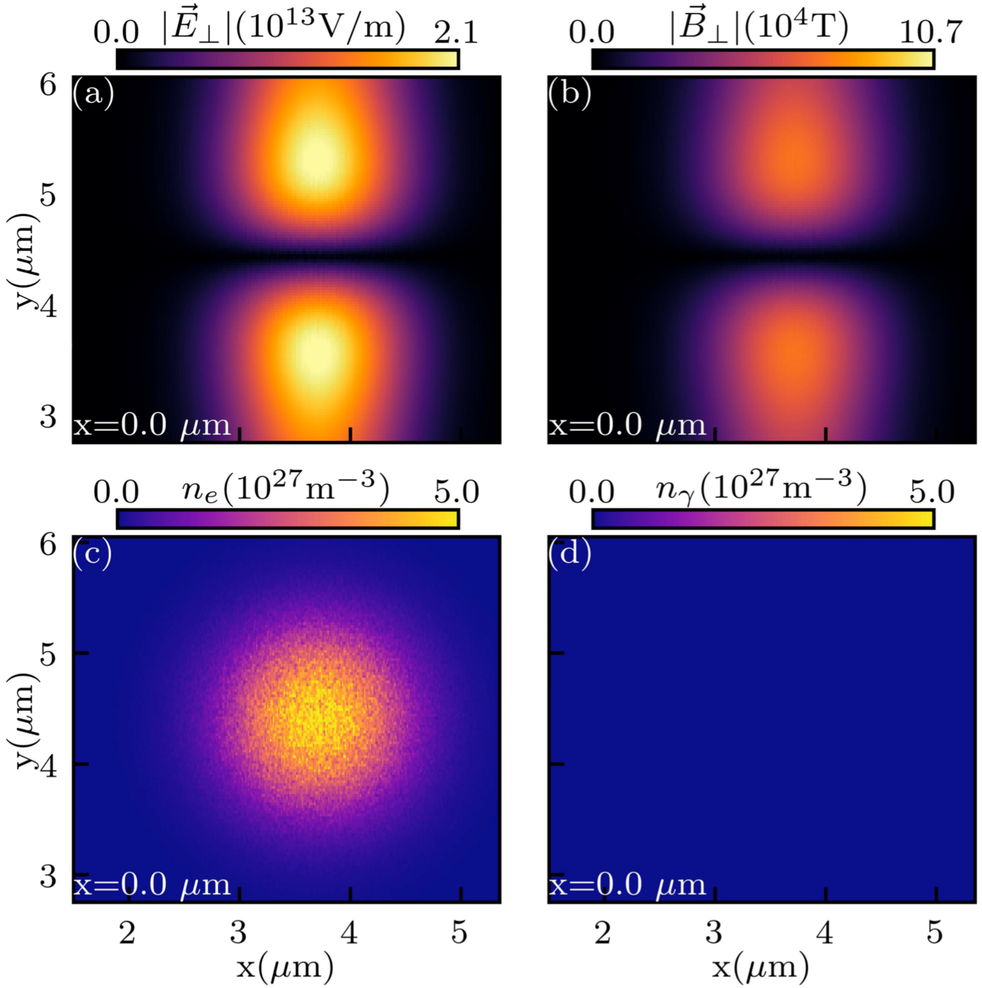
- Conversion efficiency of $\approx 30\%$ after 20 foils

γ-ray spectrum after 20 foils



electron spectrum after 20 foils





[3] A. Sampath *et. al.*, PhysRevLett.126.064801 (2021)

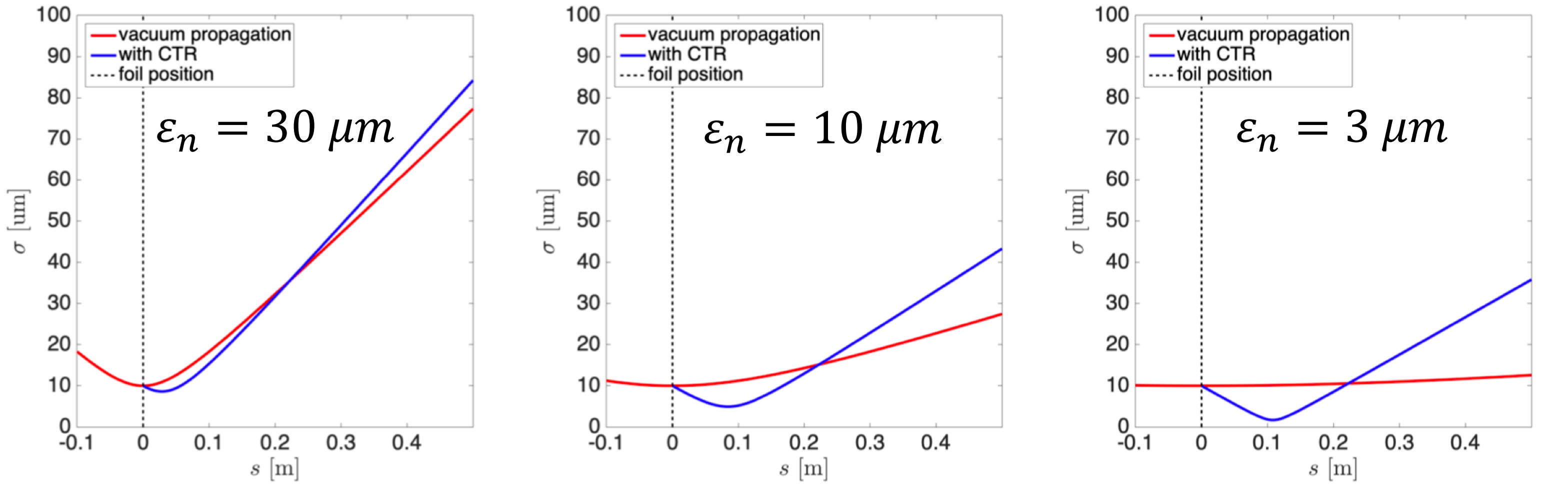
2. Analytical estimates and observables of NF-CTR beam focusing

- Motivation for E332 experimental collaboration at FACET-II.

- First goal: measure focusing effect on the beam.

  Focusing effect depends on beam size $\sigma_\perp$, beam energy E and beam charge Q

Effective focal length[4] : $f = \frac{8\pi\epsilon_0\sigma_\perp^2 E}{eQ}$, to be compared to β-function $\beta/f = \frac{e^2 N}{8\pi\epsilon_0 mc^2\varepsilon_n} \propto \frac{\boldsymbol{Q}}{\boldsymbol{\varepsilon_n}}$



Normalized emittance ε_n	β/f
100 μm	0.176
30 μm	0.586
10 μm	1.76
3 μm	5.86

$Q = 2\ nC$, E $= 10\ GeV$, $\sigma_\perp = 10\ \mu m$

[4] S. Corde *et. al.,* Beam focusing by near-field transition radiation. [Research Report] IP Paris; CEA; MPIK. 2020. hal-02937777v2

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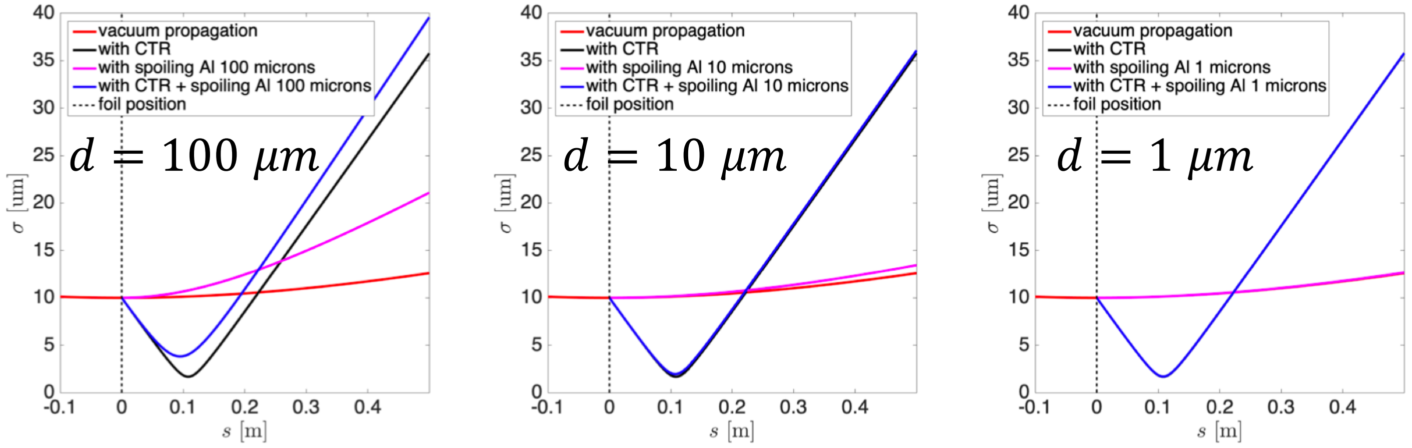
Divergence increase due to multiple scattering in the foil: depends on foil thickness *d*.



$$\varepsilon_n = 3\ \mu m$$

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- Optimized experimental parameters**: low beam emittance, high beam charge, thin foils.**

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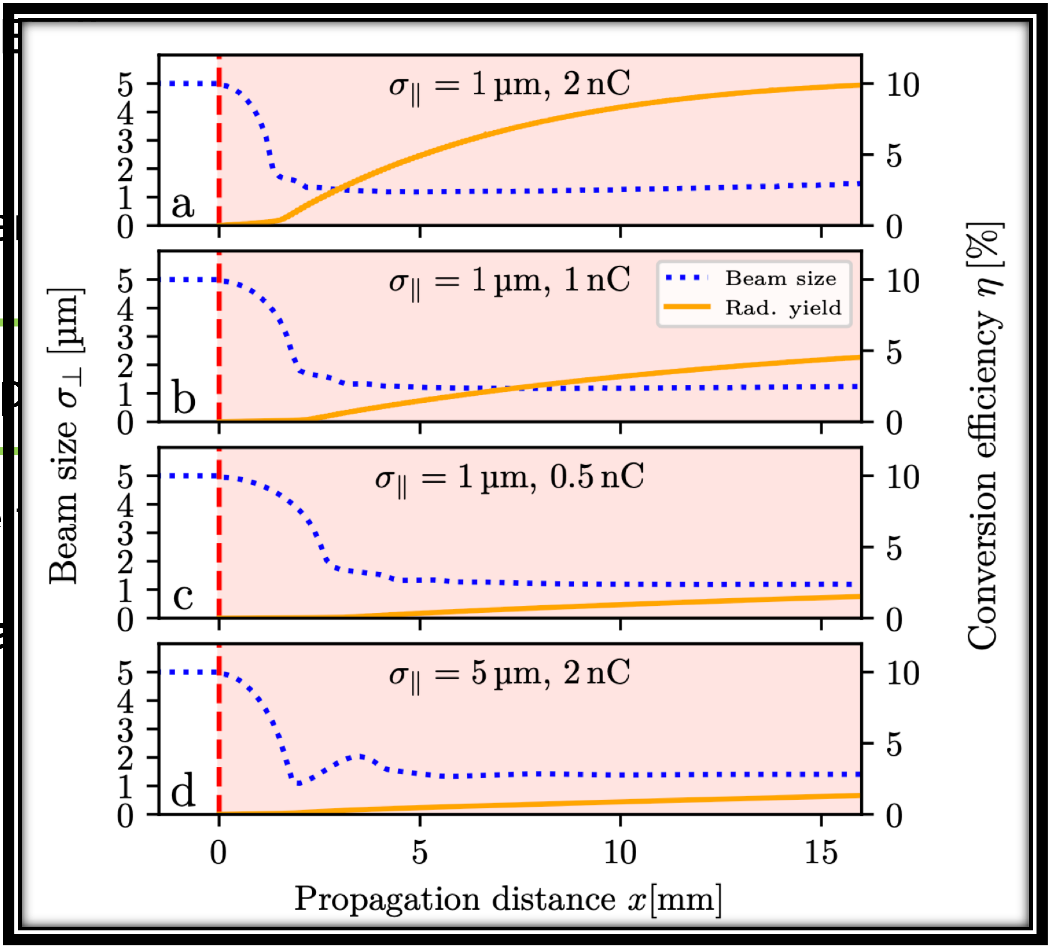
  Divergence increase due to multiple scattering in the

- Optimized experimental parameters: **low beam emitta**

- Measure energy conversion to gammas with "relaxed" beam parameters?

$$\sigma_\perp = 5\ \mu m, \epsilon_n = 3\ \mu m,\ E = 10\ GeV$$

with stack of $1\ \mu m$ Al foils with $100\ \mu m$ spacing



Rotationally symmetric PIC simulation results

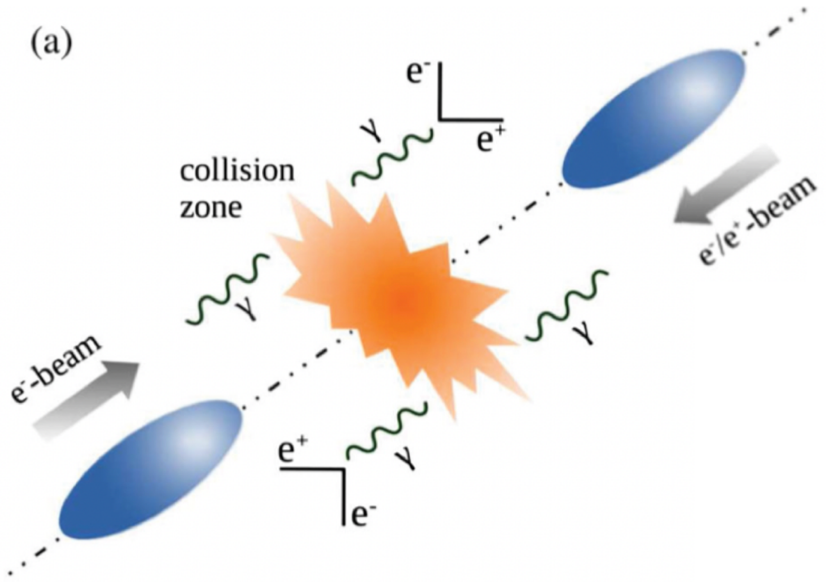
[4] S. Corde *et. al.,* Beam focusing by near-field transition radiation. [Research Report] IP Paris; CEA; MPIK. 2020. hal-02937777v2

3. Probing Strong-Field regime of QED via NF-CTR process.

$E^* =$ Electric field in the e^- rest frame

- Strong-Field regime of QED: $\chi = {E^*}/{E_{cr}} > 1 \rightarrow$ QED effects (pair production) become prominent.

- Beam-beam collisions were proposed[5] as a laser-less scenario to study the nonperturbative regime $(\alpha\chi^{2/3} > 1)$



- The beam-beam scenario benefits from:
  - The large Lorentz factor ɣ of the relativistic e^- beams.
  - The high amplitude electromagnetic fields generated by tightly focused bunches.

[5] V. Yakimenko *et. al.,* Phys. Rev. Let. 122, 190404 (2019)

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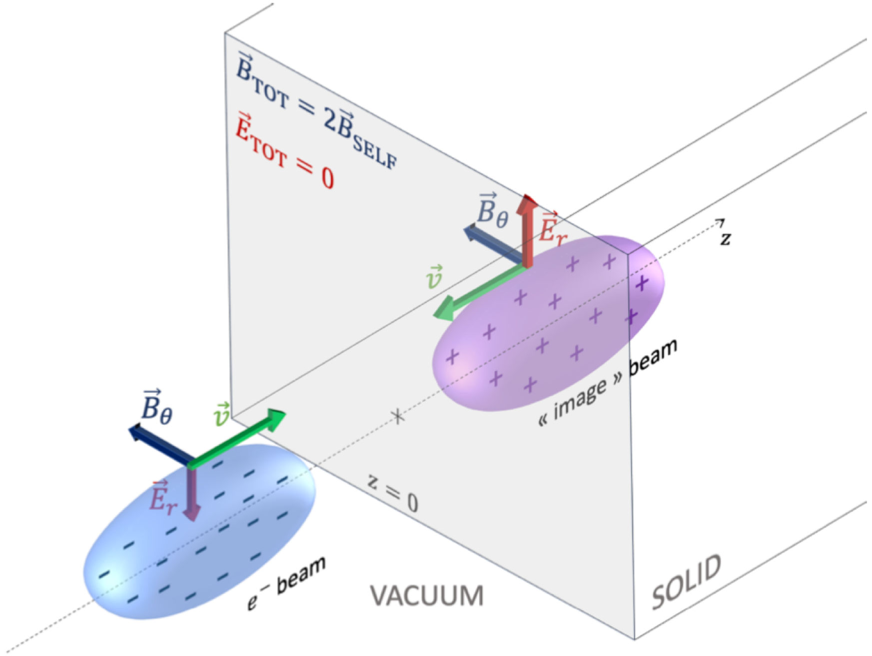

- The beam-beam scenario benefits from:
  - The large Lorentz factor ɣ of the relativistic e- beams.
  - The high amplitude electromagnetic fields generated by tightly focused bunches.

- **Idea:** Via the NFCTR process, one e- beam can be replaced by a conductor.
  - The beam experiences its own self-fields.
  - Offers a significant simplification of the experiment.

[2] A. Matheron *et. al.,* submitted to Comm. Phys. [5] V. Yakimenko *et. al.,* Phys. Rev. Let. 122, 190404 (2019)

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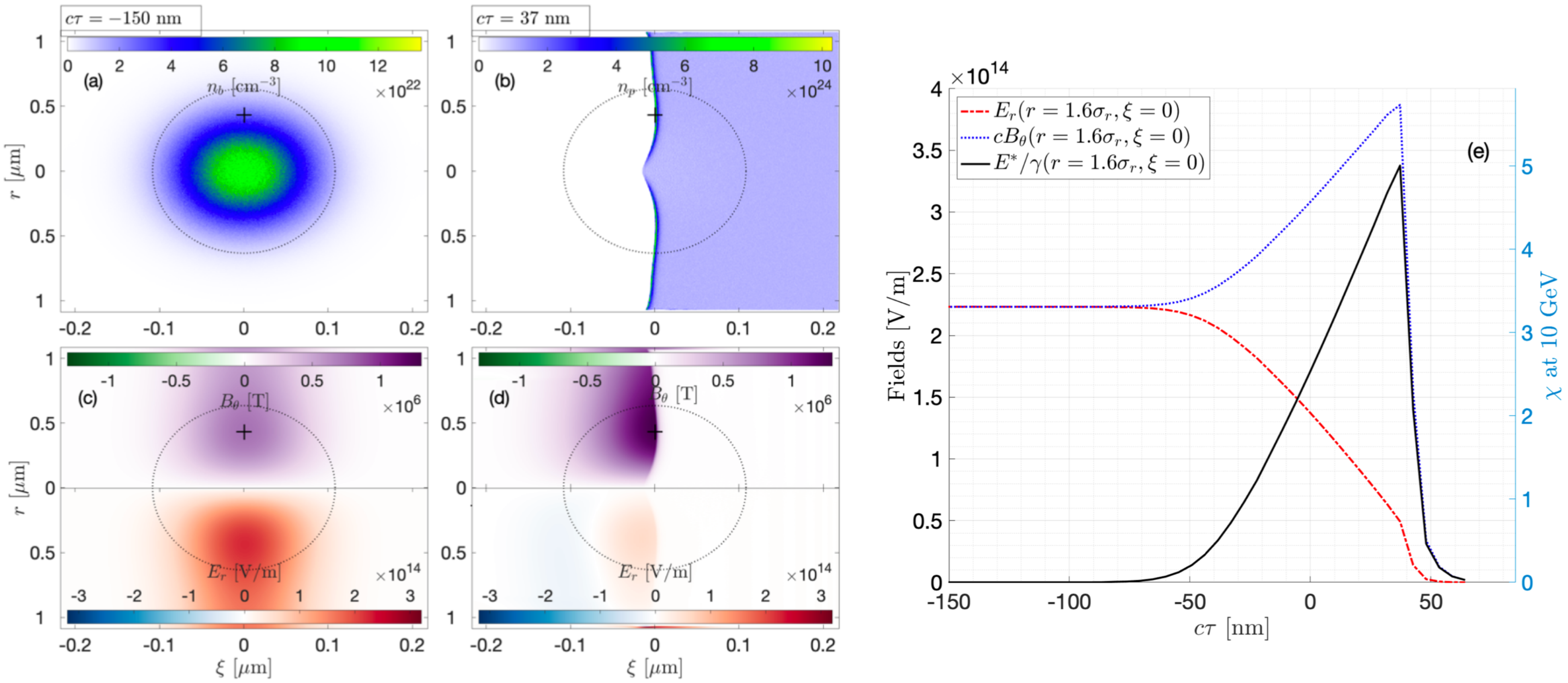

PIC simulation parameters:

Beam charge $Q = 2\,nC$.

Beam energy $E = 10\,GeV$.

Bunch length $\sigma_\parallel = 54\,nm$.

Beam size $\sigma_\perp = 271\,nm$.

Plasma density $n_p = 10^{24} cm^{-3}$.

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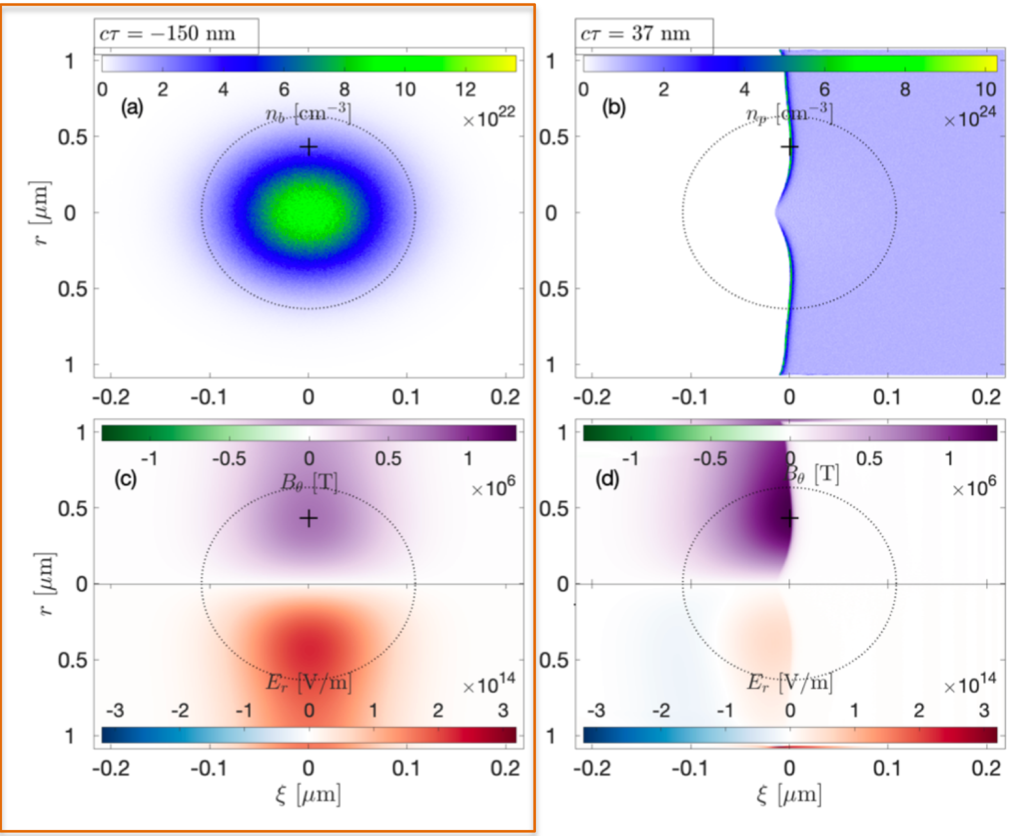

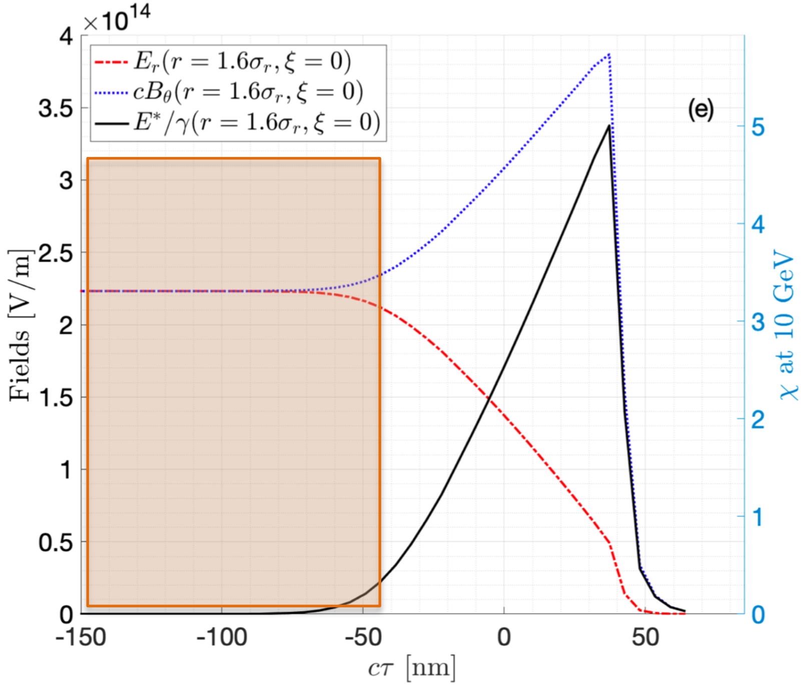

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In vacuum the beam self-fields compensate with each other ($\chi \approx 0$).

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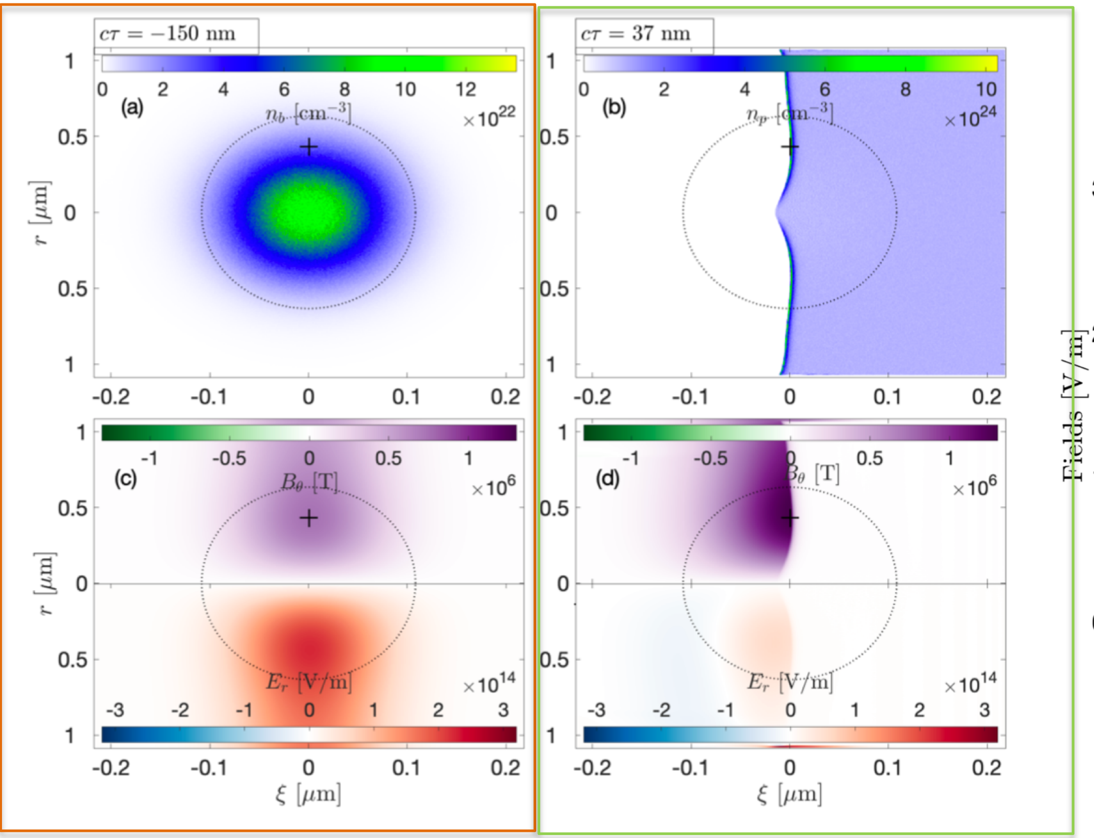

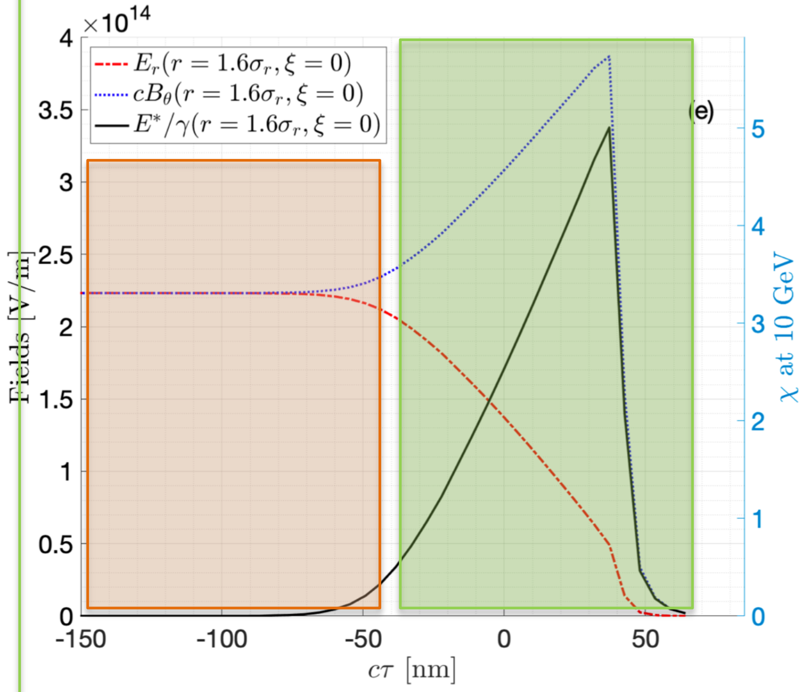

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At the plasma surface (NFCTR)

- Radial electric component vanish ($E_r \longrightarrow 0$)
- Azimuthal magnetic component
  - Doubles (radiative regime, $\sigma_{\parallel} \ll \sigma_{\perp}$)
  - Remains constant (stationary regime, $\sigma_{\parallel} \gg \sigma_{\perp}$)

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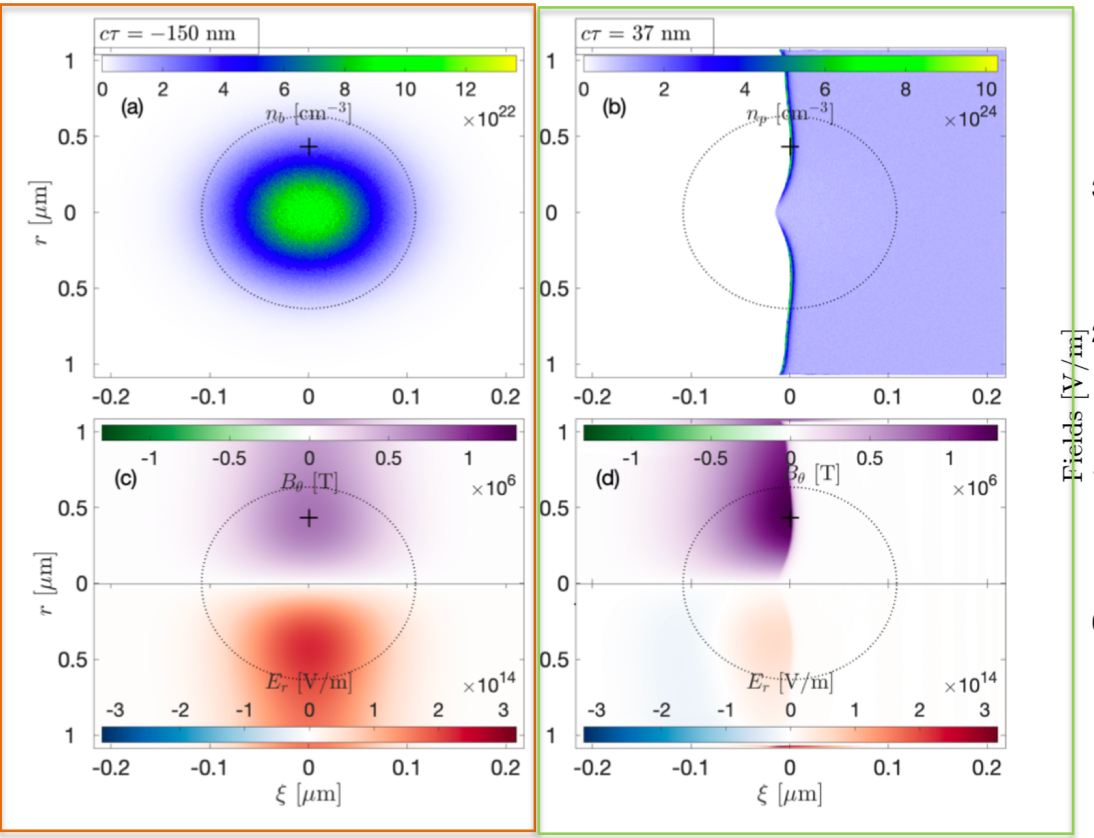

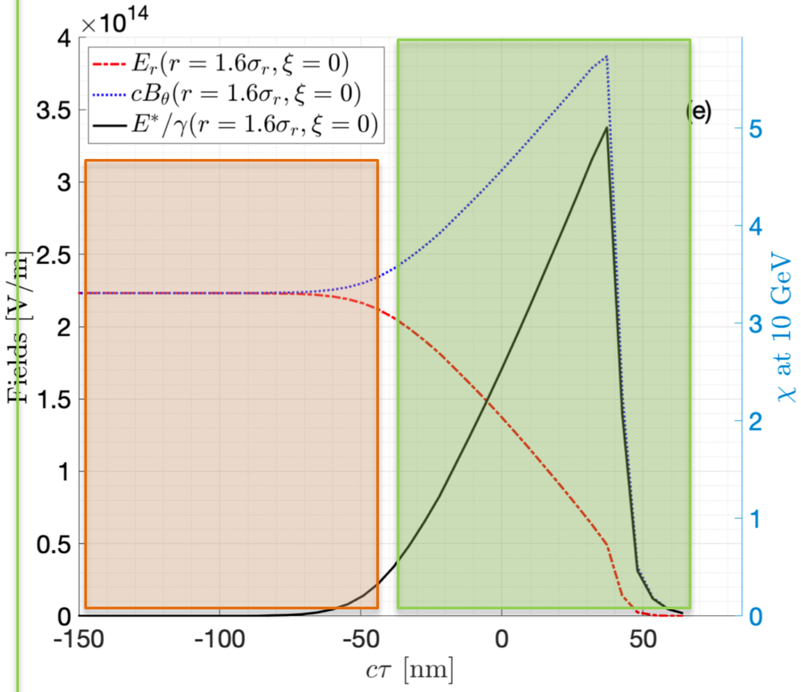

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Control beam parameters
⇩
Precision studies of SFQED

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3. Probing Strong-Field regime of QED via NF-CTR process.

Can we reach an arbitrarily high χ ?
- Increase beam energy ($\chi \propto \gamma$)
- **Increase beam self-fields amplitude → Increase beam density n_b**

However, NFCTR fails if $n_b \gtrsim n_p$ (plasma is not able screen the beam self-fields).

The maximum achievable plasma density n_p in an experiment limits the highest value of χ

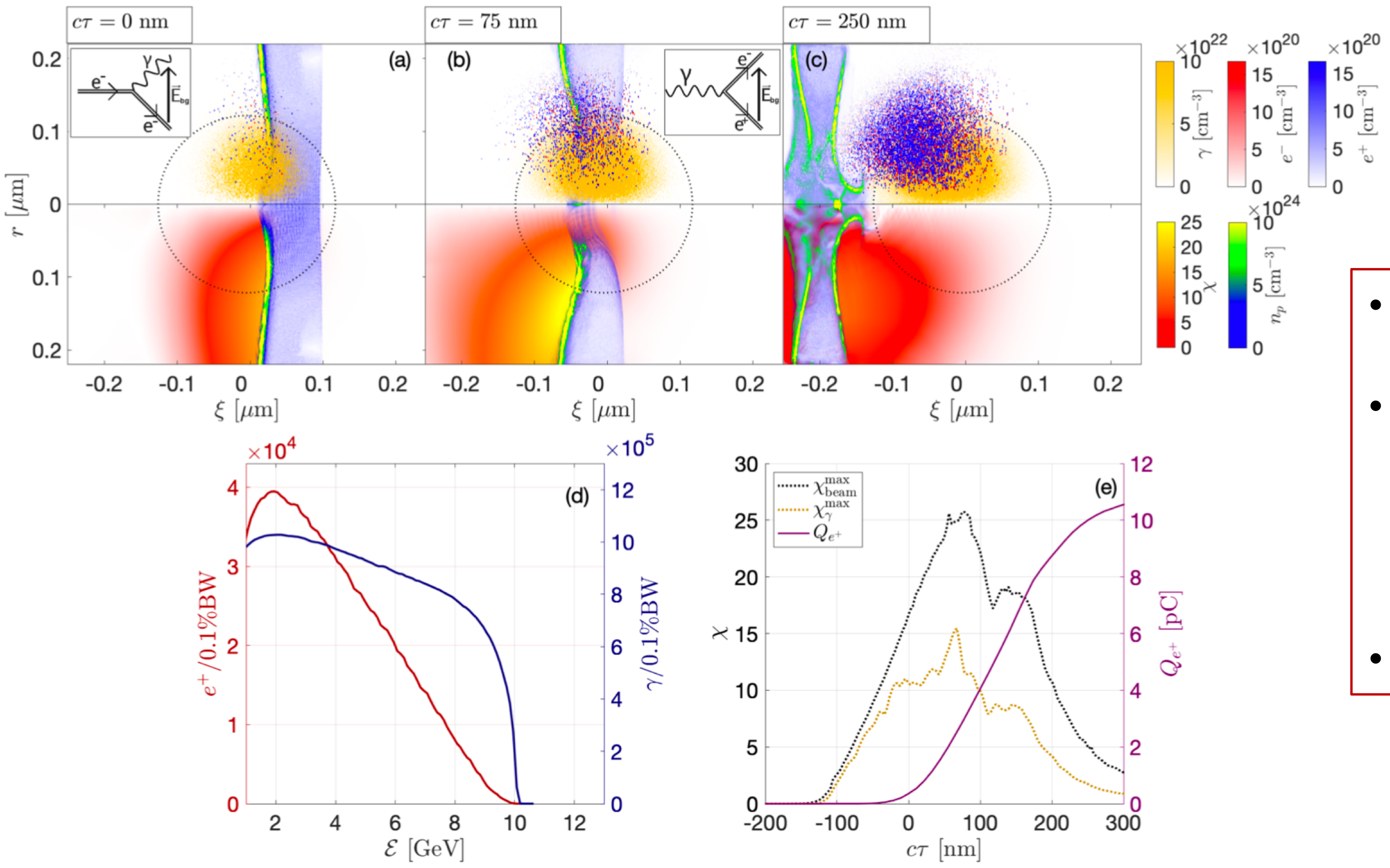
- Due to large field ionization of solid atoms and plasma surface compression[6], PIC simulations show that for $n_b \approx n_p$ the beam self-fields are reflected leading to $\chi \approx \gamma E_{self}/E_{cr}$.

Furthermore, the beam shape $\sigma_{\parallel}/\sigma_{\perp}$ also affects the reflection (radiative vs. stationary regimes), and thus also limits the maximum χ of a given experimental configuration.

[2] A. Matheron *et. al.,* submitted to Comm. Phys. [6] X. Xu *et. al.* Phys. Rev. Lett. 126, 094801 (2021).

3. Probing Strong-Field regime of QED via NF-CTR process.

Taking into account all the limiting phenomena, a QED-PIC simulation[7] with an optimized set of parameters results in:



Beam charge $Q = 2\,nC$.
Beam energy $E = 10\,GeV$.
Beam size $\sigma_{\parallel} = \sigma_{\perp} = 55\,nm$.
Initial Au^{1+} foil

- $\chi_{max} \approx 25$
- Abundant high energy gamma-ray and Breit-Wheeler pair production, well above competing processes such as Bremsstrahlung or Bethe-Heitler.
- 10 pC of positron charge above 1 MeV

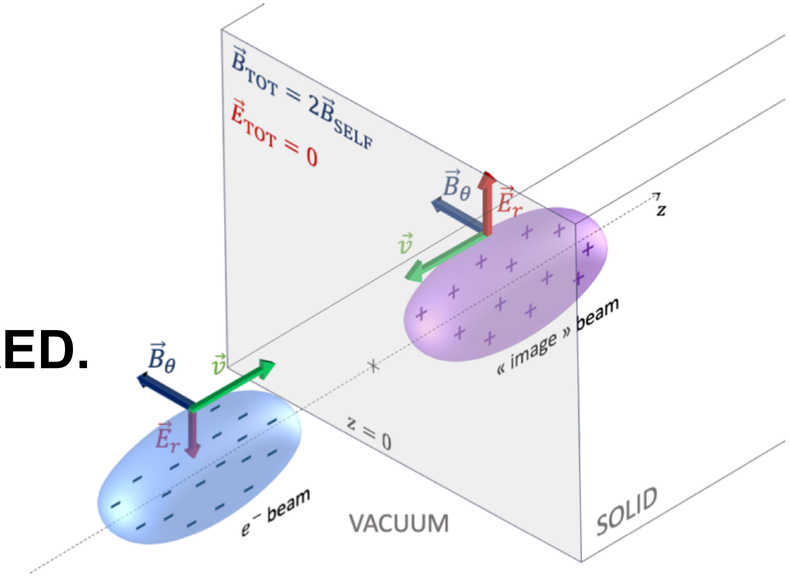
[2] A. Matheron *et. al.,* submitted to Comm. Phys.
[7] M Lobet et al 2016 J. Phys.: Conf. Ser. 688 012058

Summary and conclusions

The intense EM fields produced at the surface of a solid conducting foil when interacting a high peak-current beam (**Near-Field CTR**) are interesting as:

- **Beam focusing elements to reach solid-density beams → bright gamma-ray source.**

  Main motivation of E332 experiment at FACET-II:
  - need high charge, low emittance and thin foils.
  - Simulations show that substantial conversion efficiency should be measured with FACET-II nominal parameters



- **Laser-less scenario to probe the Strong-Field regime of QED.**
  - Precision studies of SFQED.
  - QED signal above competing processes.
  - Intermediate step before beam-beam collisions.

Thanks: E332 Collaboration

LOA (IP Paris): S. Corde, M. Gilljohann, A. Knetsch, O. Kononenko, Y. Mankovska, A. Matheron, G. Raj, P. San Miguel Claveria, V. Zakharova

UCLA: C. Joshi, K. A. Marsh, N. Zan, C. Zhang

SLAC: R. Ariniello, H. Ekerfelt, F. Fiuza, S. Gessner, M. Hogan, B. O'Shea, J. Peterson, D. Storey

CU Boulder: J. Cary, C. Doss, K. Hunt-Stone, V. Lee, M. Litos

Stony Brook U.: N. Vafaei-Najafabadi

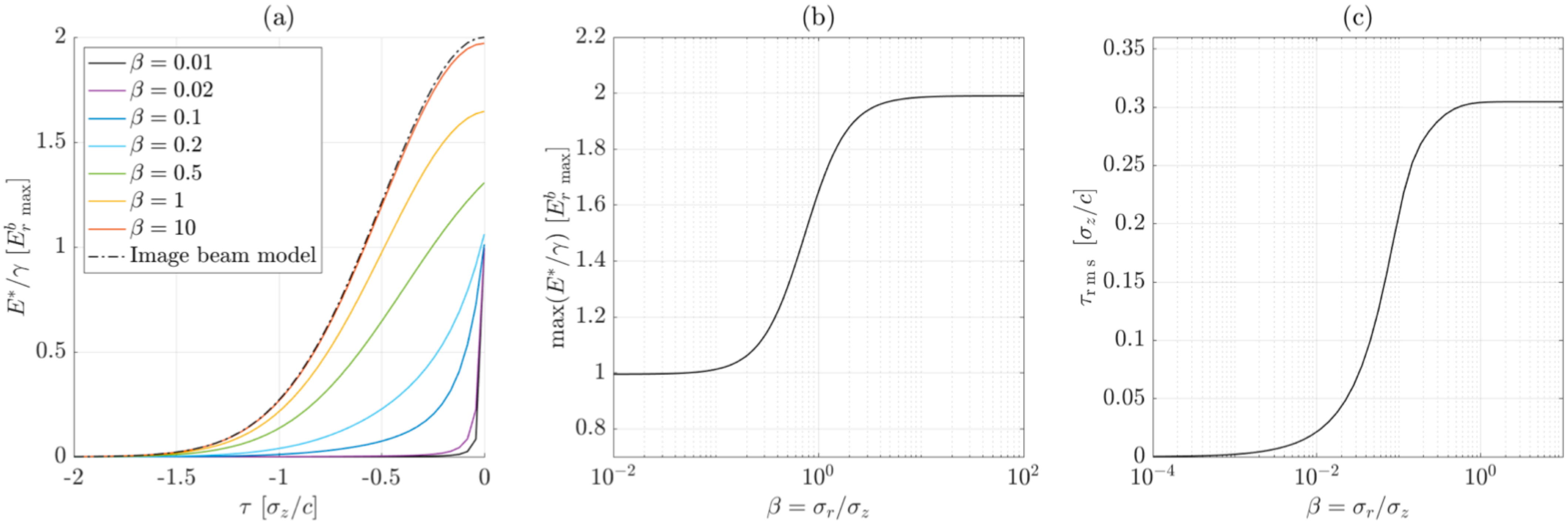
U. Oslo: G. Cao, E. Adli

MPIK: C. Keitel, M. Tamburini, A. Sampath,

CEA: X. Davoine, J. Faure, L. Gremillet

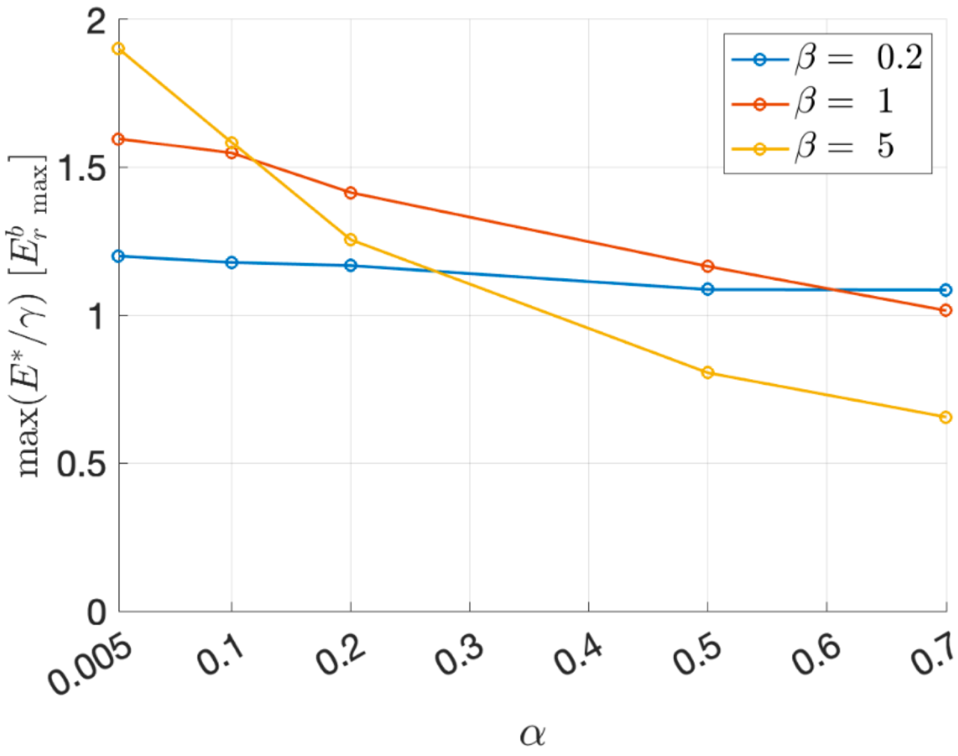
Back ups

Back ups



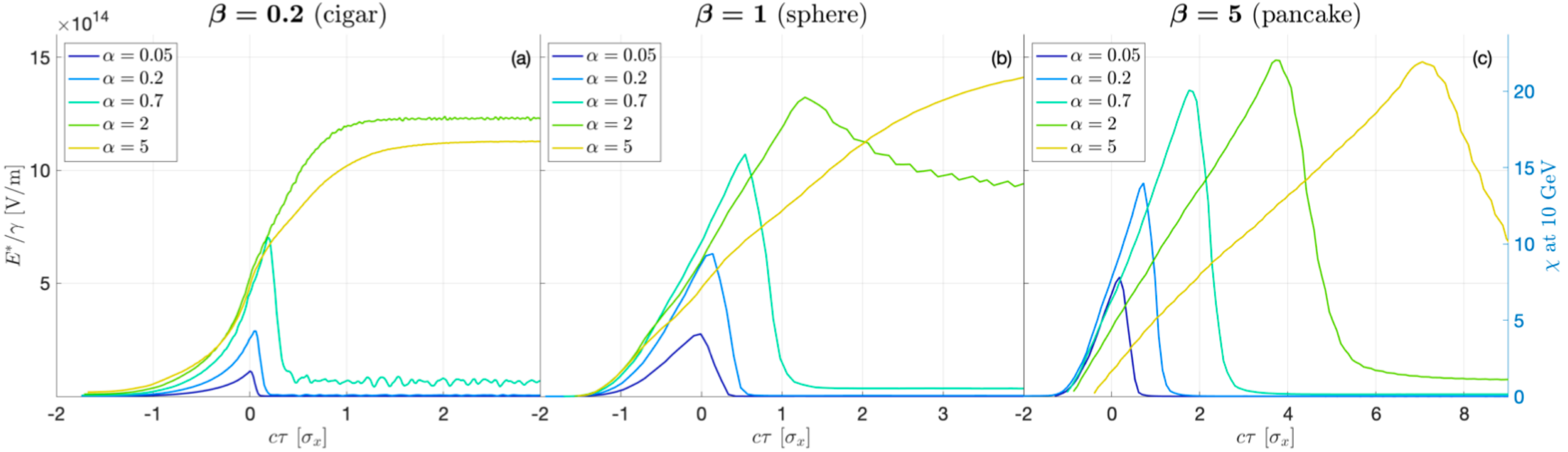
(a)
$\beta = 0.01$
$\beta = 0.02$
$\beta = 0.1$
$\beta = 0.2$
$\beta = 0.5$
$\beta = 1$
$\beta = 10$
Image beam model
E^*/γ $[E^b_{r\ \max}]$
τ $[\sigma_z/c]$
(b)
$\max(E^*/\gamma)$ $[E^b_{r\ \max}]$
$\beta = \sigma_r/\sigma_z$
(c)
τ_{rms} $[\sigma_z/c]$
$\beta = \sigma_r/\sigma_z$

Back ups



$\beta =$ 0.2
$\beta =$ 1
$\beta =$ 5
2
1.5
1
0.5
0
0.005
0.1
0.2
0.3
0.4
0.5
0.6
0.7
α
$\max(E^*/\gamma)$ $[E_{r\ \max}^b]$

Back ups



$\boldsymbol{\beta} = \mathbf{0.2}$ (cigar)
$\boldsymbol{\beta} = \mathbf{1}$ (sphere)
$\boldsymbol{\beta} = \mathbf{5}$ (pancake)
$\times 10^{14}$
E^*/γ [V/m]
χ at 10 GeV
$\alpha = 0.05$
$\alpha = 0.2$
$\alpha = 0.7$
$\alpha = 2$
$\alpha = 5$
(a)
(b)
(c)
$c\tau$ $[\sigma_x]$