20th Advanced Accelerator Concepts Workshop

Spatiotemporal dynamics of beam-plasma instabilities in the ultra-relativistic regime

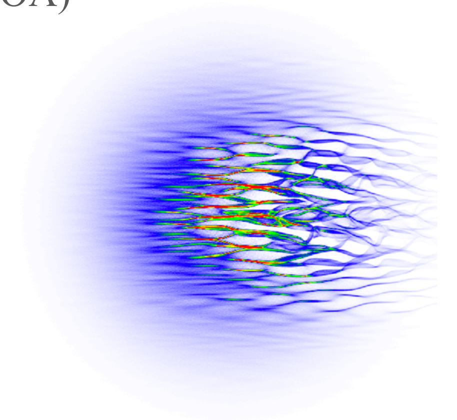
Pablo San Miguel Claveria (LOA, IP Paris / X-GoIP, IST Lisbon)

On behalf of:

E305 Collaboration (SLAC, UCLA, CU Boulder, U. Oslo, Stony Brook U., MPIK, CEA, LOA)

Work supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Miniature beam-driven Plasma Accelerators project, Grant Agreement No. 715807) and by the ANR (UnRIP project, Grant No. ANR- 20-CE30-0030)

Numerical simulations were performed using HPC resources from PRACE (Grant No. 2017174175) and GENCI-TGCC (Grants No. 2018- A0040507594, No. 2019-A0060510786, 2020-A0080510786 and 2021- A0100510786 to run PIC simulations.



ENSTA IP PARIS

cnrs dépasser les frontières

l'X ÉCOLE POLYTECHNIQUE IP PARIS

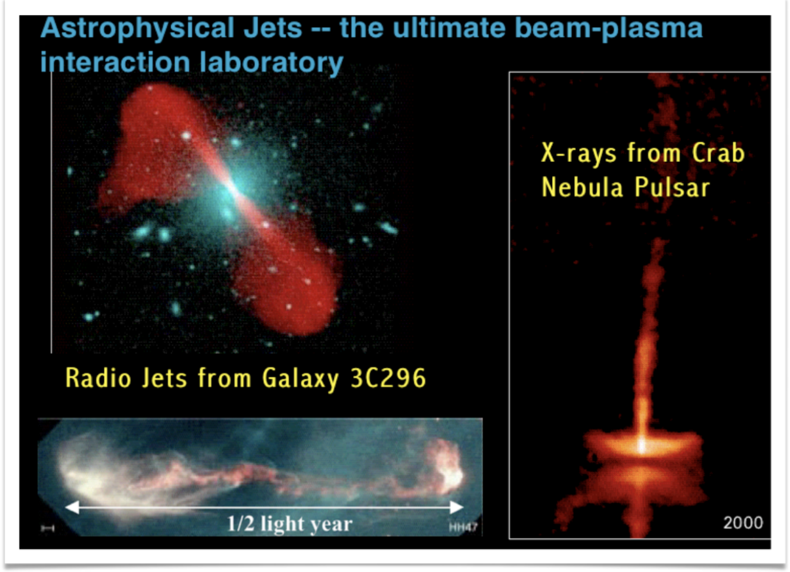
INSTITUT POLYTECHNIQUE DE PARIS

loa

erc European Research Council Established by the European Commission

Motivations

Relativistic streaming instabilities are pervasive in astrophysics…

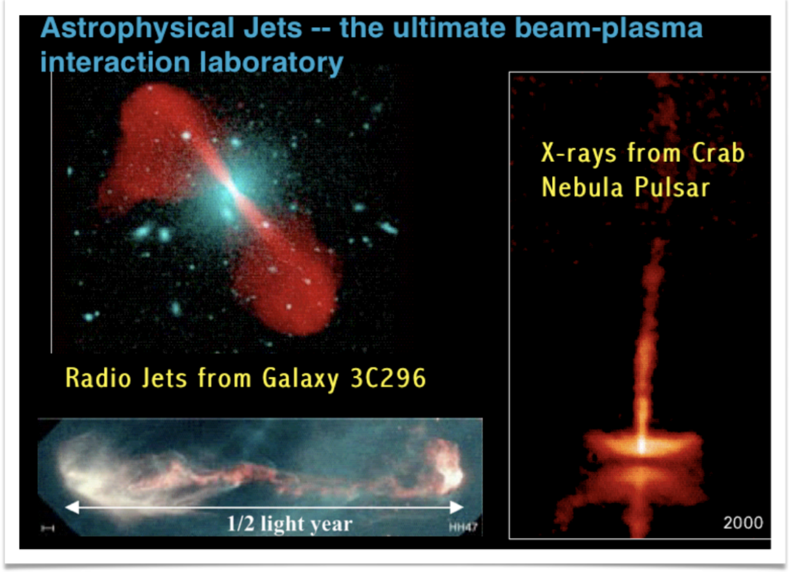


T. Katsouleas, role of Weibel instability in astrophysics and cosmic jets.

- They are thought to play a key role in **blazars**, cosmic magnetisation at interstellar and intergalactic scales and high-energy explosive transients (e.g. **GRB**).
- Are of fundamental importance as provide a mechanism for energy conversion from particles to EM fields and to **gamma rays.**

Motivations

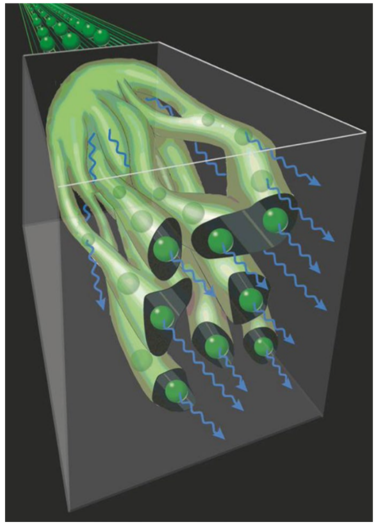
Relativistic streaming instabilities are pervasive in astrophysics…



T. Katsouleas, role of Weibel instability in astrophysics and cosmic jets.

- They are thought to play a key role in **blazars**, cosmic magnetisation at interstellar and intergalactic scales and high-energy explosive transients (e.g. **GRB**).
- Are of fundamental importance as provide a mechanism for energy conversion from particles to EM fields and to **gamma rays.**

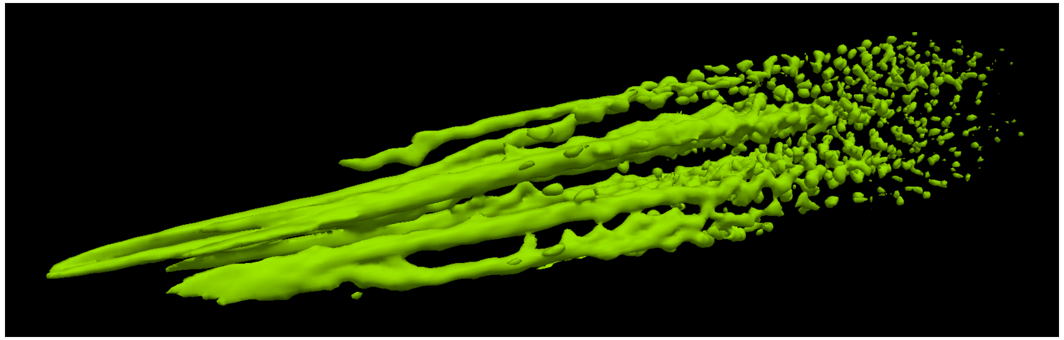
… but also in laboratory plasmas



- They set important limitations on the feasibility of experimental concepts such as **ICF** or a **plasma-based acceleration**.
- They can channel beam kinetic energy into ɣ-rays (*Benedetti, A., Tamburini, M. & Keitel, C.H. Giant collimated gamma-ray flashes. [Nature Photon 12, 319–323 (2018)]*)

Towards controlled experiments at SLAC - the E305 experiment

E-305: Beam filamentation and bright gamma-ray bursts



Simulated beam density at saturation of FACET-II beam propagating in an Al target (credits to G. Raj).

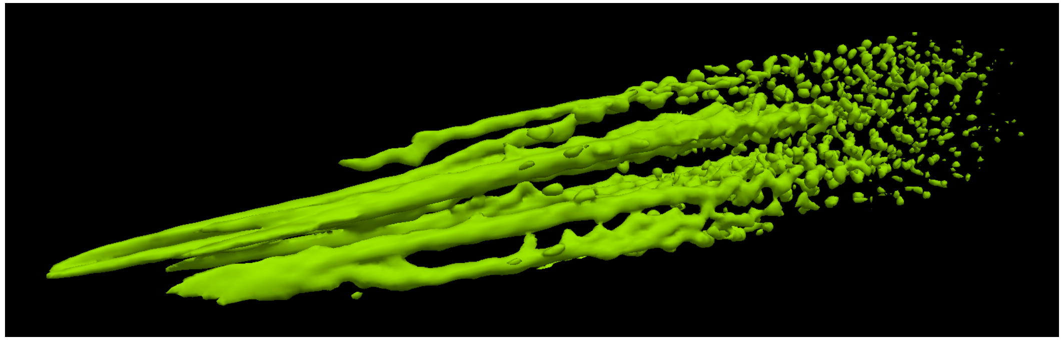
E-305 experiment at FACET-II facility at SLAC with the goal of:

- Study relativistic beam-plasma instabilities with plasma densities in the range $10^{18\text{-}24}$ cm^{-3} , by sending FACET-II 10 GeV electron beams into gaseous or solids targets.
- Charaterize resulting ɣ-ray radiation
- Study the interplay of different modes in the nonlinear stage
- Investigate additional physics such as collisional effects in exotic nonequilibrium warm dense matter states (solid), **finite bunch length and finite beam size effects**, **and competition with plasma wakefields** (gas)

Towards controlled experiments at SLAC - the E305 experiment

E-305: Beam filamentation and bright gamma-ray bursts

See A. Knetsch talk for experimental results



Simulated beam density at saturation of FACET-II beam propagating in an Al target (credits to G. Raj).

E-305 experiment at FACET-II facility at SLAC with the goal of:

- Study relativistic beam-plasma instabilities with plasma densities in the range 10^{18-24} cm^{-3} , by sending FACET-II 10 GeV electron beams into gaseous or solids targets.
- Charaterize resulting ɣ-ray radiation
- Study the interplay of different modes in the nonlinear stage
- Investigate additional physics such as collisional effects in exotic nonequilibrium warm dense matter states (solid), **finite bunch length and finite beam size effects**, **and competition with plasma wakefields** (gas)

Relativistic beam-plasma instabilities

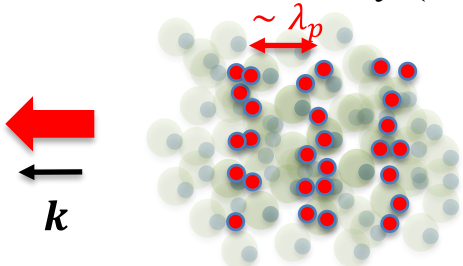
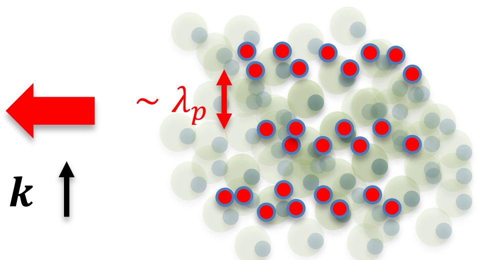
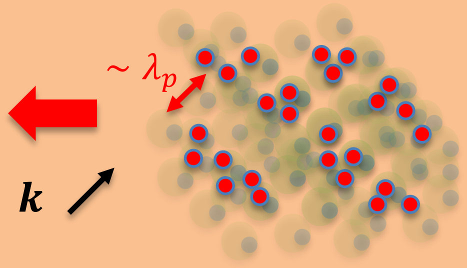
Unstable electromagnetic modes exponentially growing from noise

$\alpha = {}^{n_b}/_{n_p}$ γ_b = beam Lorentz factor

In the ultra-relativistic regime ($\gamma_b \gg 1$), oblique modes dominate the interaction

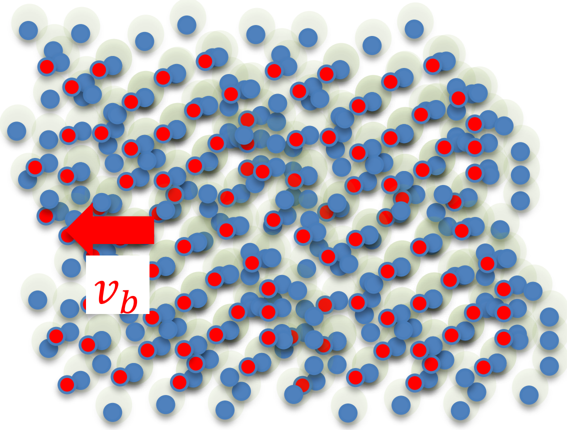
Depending on the orientation ($\boldsymbol{k}$) of the mode w.r.t. the beam propagation, there exist three types of beam-plasma instabilities

A. Bret, L. Gremillet, and M. E. Dieckmann, Phys. Pla. 17, 120501 (2010).

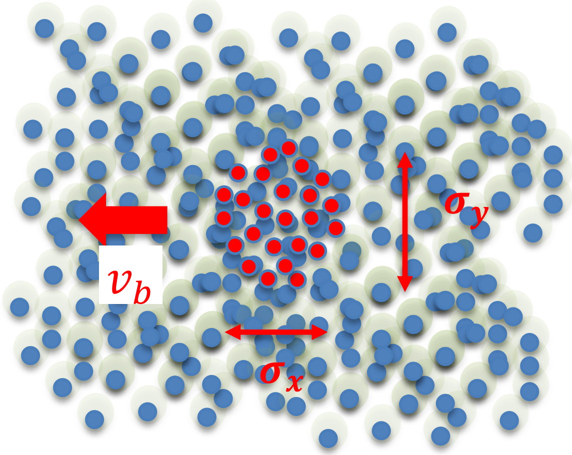
	Two-Stream Instability (TSI)	Current Filamentation Instability (CFI)	Oblique Instability (OTSI)
	 Electrostatic longitudinal mode	 Electromagnetic transverse mode	 Electrostatic oblique mode
Maximum Growthrate (Kinetic theory for cold colissionless **unbounded** systems)	$\Gamma_{\mathrm{TSI}} = \frac{\sqrt{3}}{2^{4/3}} \frac{\alpha^{1/3}}{\gamma_b} \omega_p$	$\Gamma_{\mathrm{CFI}} = \beta \sqrt{\frac{\alpha}{\gamma_b}} \omega_p$	$\Gamma_{\mathrm{Obl}} = \frac{\sqrt{3}}{2^{4/3}} \left(\frac{\alpha}{\gamma_b}\right)^{1/3} \omega_p$

Finite beam effects in ultra relativistic beam-plasma instabilities

Unbounded system

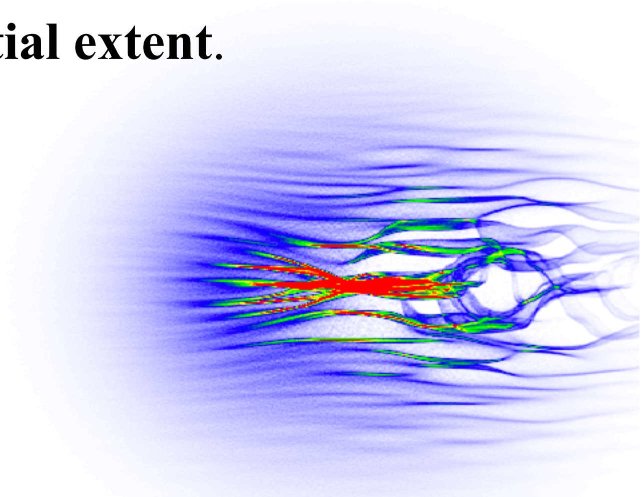


Finite beam



In accelerator facilities, particles beams have a **finite spatial extent**.

- **Finite bunch length** (longitudinal): $\longrightarrow$ **Spatiotemporal dynamics***
- **Finite beam size** (transverse): $\longrightarrow$ **Electron beam self-focusing**



Simulated FACET-II-like beam propagating in uniform plasma

*A. Bers, in Handbook of Plas. Phys., (North-Holland Physics Publishing, 1983): TSI

*V. B. Pathak,*et. al.*, New J. Phys. 17, 043049 (2015): CFI

Finite beam effects in ultra relativistic beam-plasma instabilities

PHYSICAL REVIEW RESEARCH **4**, 023085 (2022)

Spatiotemporal dynamics of ultrarelativistic beam-plasma instabilities

P. San Miguel Claveria,[1,*] X. Davoine,[2,3] J. R. Peterson,[4,5] M. Gilljohann,[1] I. Andriyash,[1] R. Ariniello,[6] C. Clarke,[4] H. Ekerfelt,[4] C. Emma,[4] J. Faure,[2,3] S. Gessner,[4] M. J. Hogan,[4] C. Joshi,[7] C. H. Keitel,[8] A. Knetsch,[1] O. Kononenko,[1] M. Litos,[6] Y. Mankovska,[1] K. Marsh,[7] A. Matheron,[1] Z. Nie,[7] B. O'Shea,[4] D. Storey,[4] N. Vafaei-Najafabadi,[9] Y. Wu,[7] X. Xu,[4] J. Yan,[9] C. Zhang,[7] M. Tamburini,[8] F. Fiuza,[4] L. Gremillet,[2,3,†] and S. Corde[1,‡]

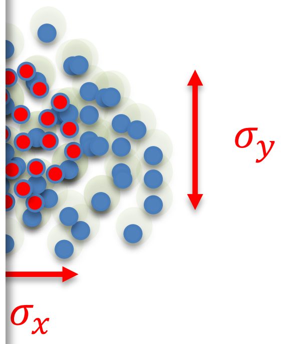
[1]*LOA, ENSTA Paris, CNRS, Ecole Polytechnique, Institut Polytechnique de Paris, 91762 Palaiseau, France*
[2]*CEA, DAM, DIF, 91297 Arpajon, France*
[3]*Université Paris-Saclay, CEA, LMCE, 91680 Bruyères-le-Châtel, France*
[4]*SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA*
[5]*Physics Department, Stanford University, Stanford, California 94305, USA*
[6]*Department of Physics, University of Colorado Boulder, Center for Integrated Plasma Studies, Boulder, Colorado 80309, USA*
[7]*University of California Los Angeles, Los Angeles, California 90095, USA*
[8]*Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany*
[9]*Stony Brook University, Stony Brook, New York 11794, USA*

(Received 27 June 2021; accepted 28 February 2022; published 2 May 2022)

An electron or electron-positron beam streaming through a plasma is notoriously prone to microinstabilities. For a dilute ultrarelativistic infinite beam, the dominant instability is a mixed mode between longitudinal two-stream and transverse filamentation modes, with a phase velocity oblique to the beam velocity. A spatiotemporal theory describing the linear growth of this oblique mixed instability is proposed which predicts that spatiotemporal effects generally prevail for finite-length beams, leading to a significantly slower instability evolution than in the usually assumed purely temporal regime. These results are accurately supported by particle-in-cell (PIC) simulations. Furthermore, we show that the self-focusing dynamics caused by the plasma wakefields ... finite-width beams can compete with the oblique instability. Analyzed through PIC si... these two processes in realistic systems bears important implications for ... ultrarelativistic beam-plasma interactions.

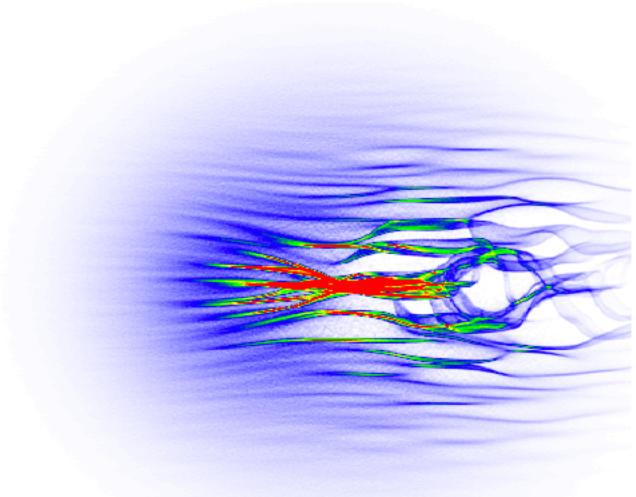
DOI: 10.1103/PhysRevResearch.4.023085

... beam



... **spatial extent**.

- ➢ I...
- ➢ I...



Simulated FACET-II-like beam propagating in uniform plasma

Spatiotemporal dynamics of ultra-relativistic beam-plasma instabilities

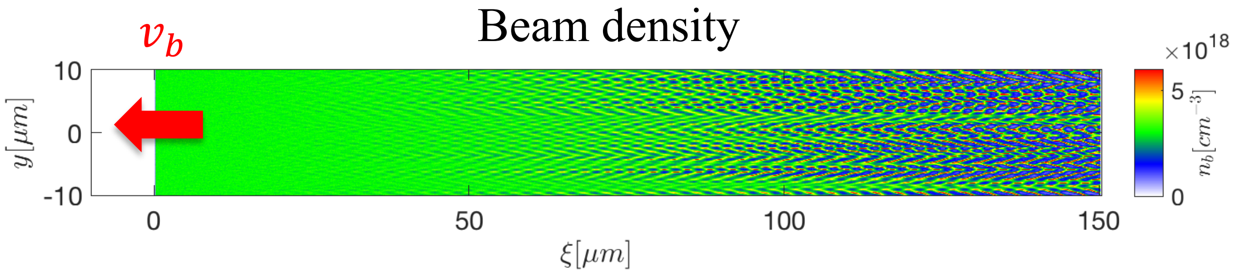
Analytical model: cold semi-inifinite beam in uniform plasma, ($\xi = v_b t - x, \tau = t$)

$$\left(\partial_\tau^3 + v_b \partial_\tau^2 \partial_\xi + \frac{8i}{3^{3/2}} \Gamma_{\mathrm{OTSI}}^3\right) \delta n_p\left(\tau, \xi\right) = 0$$

Spatiotemporal coupling

Envelope of plasma density perturbation

Oblique growthrate for unbounded system

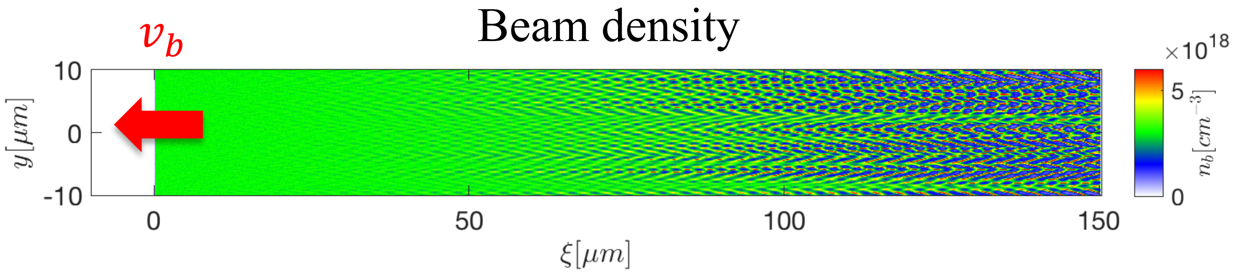


Simulated semi-inifinite beam showing OTSI spatiotemporal dynamics

DOI: 10.1103/PhysRevResearch.4.023085

Spatiotemporal dynamics of ultra-relativistic beam-plasma instabilities

Anlytical model: cold semi-inifinite beam in uniform plasma, ($\xi = v_b t - x, \tau = t$)



Simulated semi-inifinite beam showing spatiotemporal dynamics

$$\left(\partial_\tau^3 + v_b \partial_\tau^2 \partial_\xi + \frac{8i}{3^{3/2}} \Gamma_{\mathrm{OTSI}}^3 \right) \delta n_p \left(\tau, \xi \right) = 0$$

Spatiotemporal coupling

Envelope of plasma density perturbation

Oblique growthrate for unbounded system

Temporal evolution

Initial conditions:

$$\delta n_p(\tau = 0, \xi) = \delta n_p(\tau, \xi = 0) = S$$

$$\partial_\tau \delta n_p(\tau = 0, \xi) = \partial_\tau^2 \delta n_p(\tau = 0, \xi) = 0$$

$$\delta n_p(\xi, \tau) \propto \begin{cases} \exp\left(\Gamma_{\mathrm{OTSI}} \tau\right) & \text{for } \tau \le \xi / v_b \\ \exp\left[\frac{\sqrt{3}}{2^{2/3}} (\sqrt{3} + i) \Gamma_{\mathrm{OTSI}} \left(\frac{\xi}{v_b} \right)^{1/3} \tau^{2/3} \right] & \text{for } \tau \gg \xi / v_b \end{cases}$$

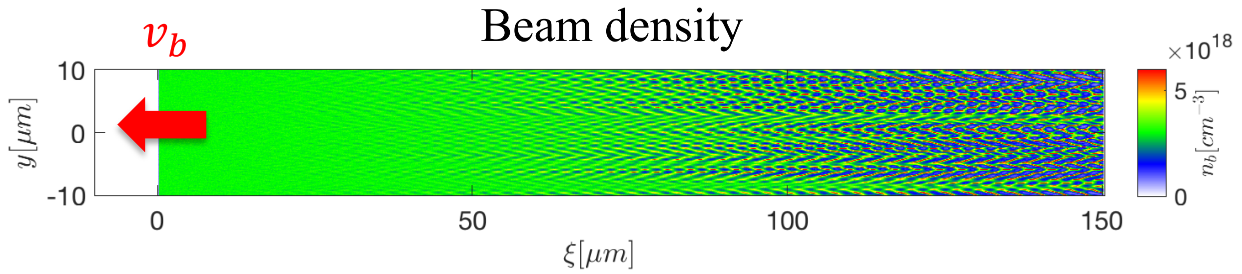
Spatiotemporal evolution

DOI: 10.1103/PhysRevResearch.4.023085

Spatiotemporal dynamics of ultra-relativistic beam-plasma instabilities

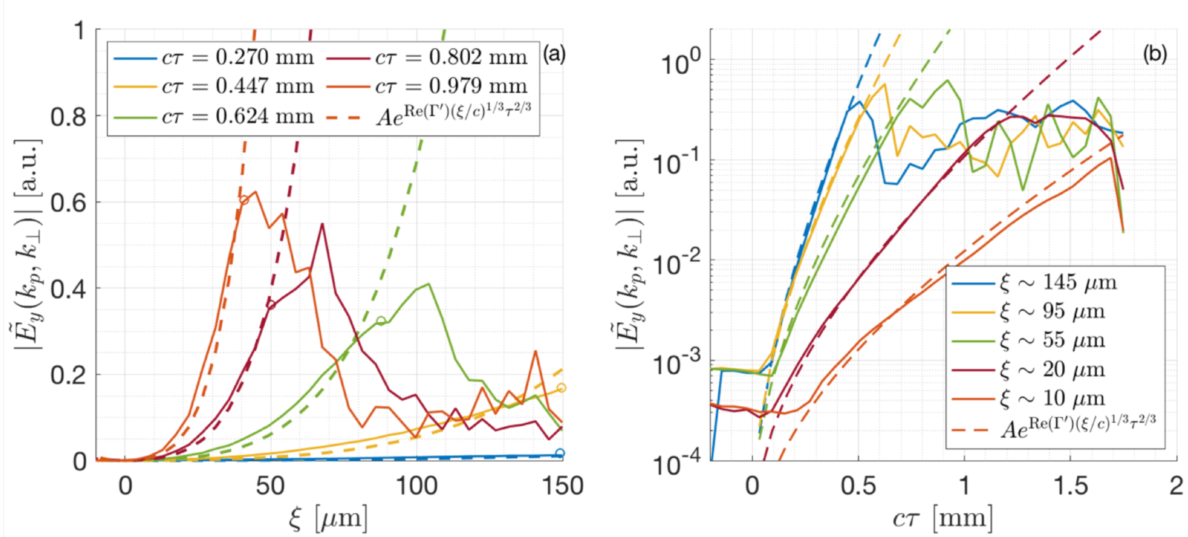
Anlytical model: cold semi-inifinite beam in uniform plasma, ($\xi = v_b t - x, \tau = t$)

$$\left(\partial_\tau^3 + v_b \partial_\tau^2 \partial_\xi + \frac{8i}{3^{3/2}} \Gamma_{\mathrm{OTSI}}^3\right) \delta n_p = 0$$

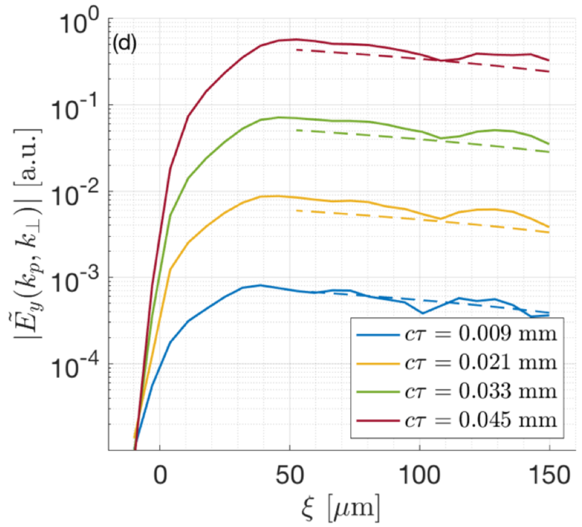


Pic simulations show good agreement with the model

Spatio-temporal growth with $\gamma \approx 2\times10^4$



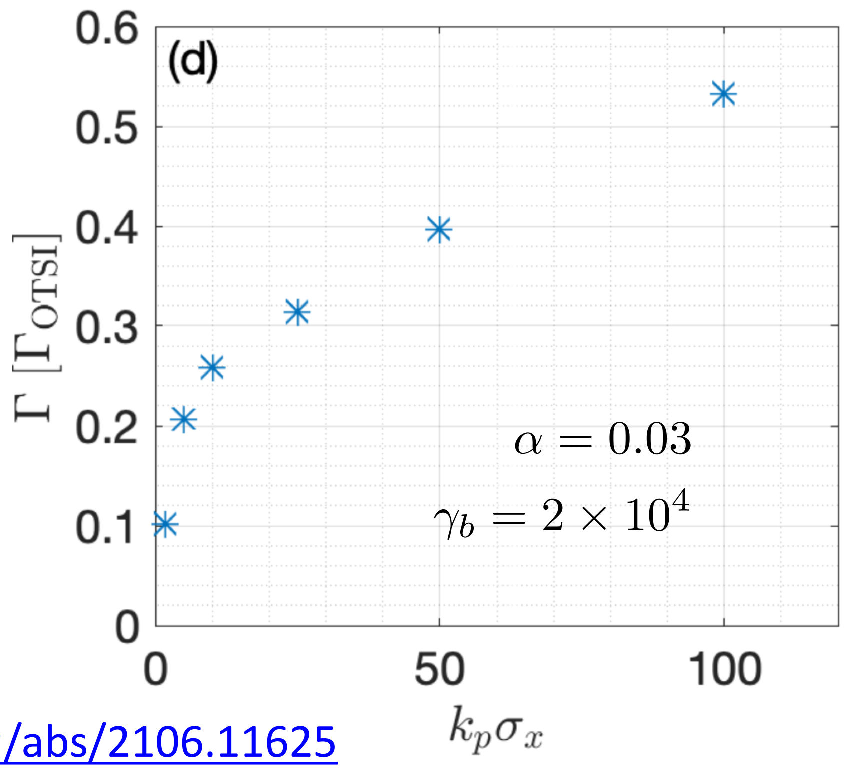
Purely temporal growth with $\gamma \approx 20$



DOI: 10.1103/PhysRevResearch.4.023085

Spatiotemporal dynamics of ultra-relativistic beam-plasma instabilities

$$\delta n_p(\xi,\tau) \propto \begin{cases} \exp\left(\Gamma_{\mathrm{OTSI}}\tau\right) & \text{for } \tau \leq \xi/v_b \\ \exp\left[\dfrac{\sqrt{3}}{2^{2/3}}(\sqrt{3}+i)\Gamma_{\mathrm{OTSI}}\left(\dfrac{\xi}{v_b}\right)^{1/3}\tau^{2/3}\right] & \text{for } \tau \gg \xi/v_b \end{cases}$$



For finite length particle bunches such that $\sigma_x/c \ll \Gamma_{\mathrm{OTSI}}^{-1}$ the instability is dominated by spatiotemporal growth

- Significant slow-down of the OTSI instability for short ultra-relativistic particle bunches

https://arxiv.org/abs/2106.11625

Finite transverse beam-size: transverse wakefields vs. instability

- Beam self-focusing from plasma wakefields excited by finite-size, nonneutral beams can quench the instability.

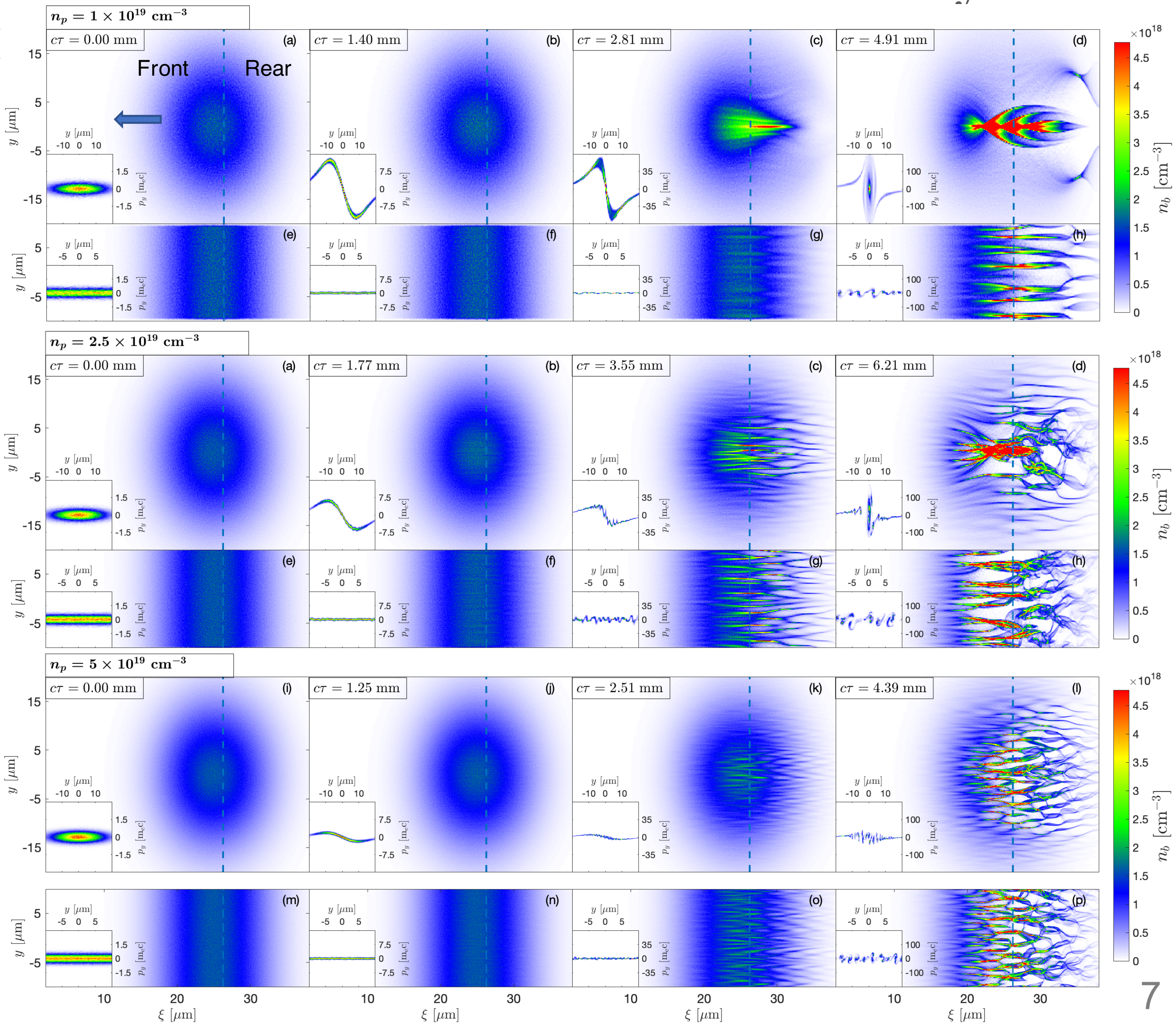
- Such inhibition occurs if the betatron frequency*

$$\omega_\beta^{-1} = \sqrt{\gamma_b m_e / \partial_r W_\perp}$$

gets larger than the effective (spatiotemporal) OTSI growth rate

$$\tau_{OTSI} = 2\left(\frac{N_{\mathrm{exp}}}{3\Gamma_{\mathrm{Obl}}}\right)^{3/2}\left(\frac{v_b}{\xi}\right)^{1/2}, \; \xi = \sigma_x$$

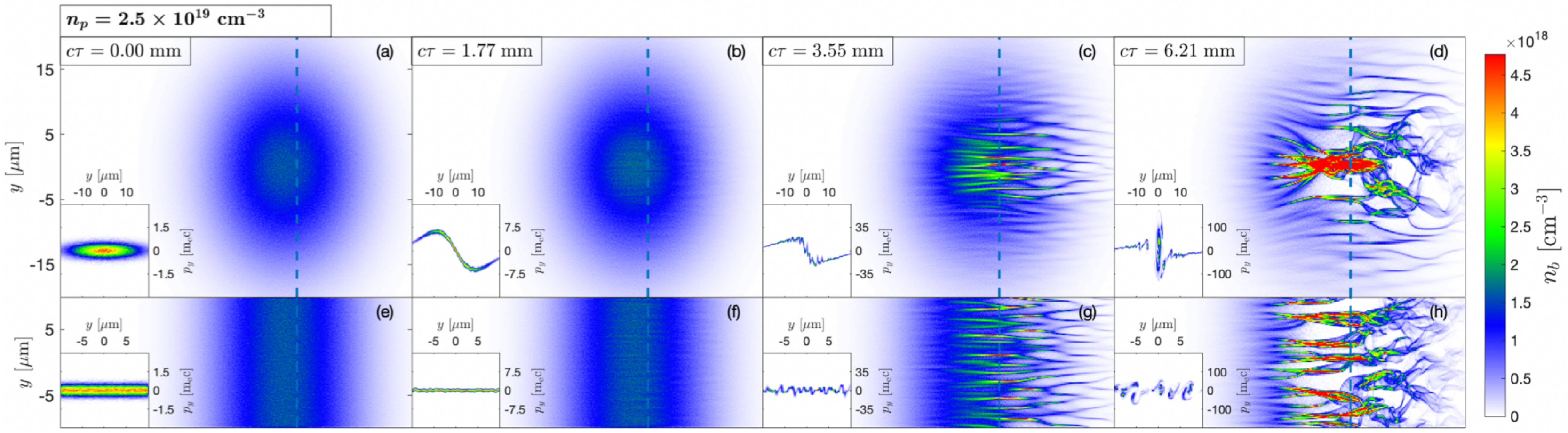
- For a given beam charge, increasing plasma density density favors the instability.



https://arxiv.org/abs/2106.11625

Summary and Overview

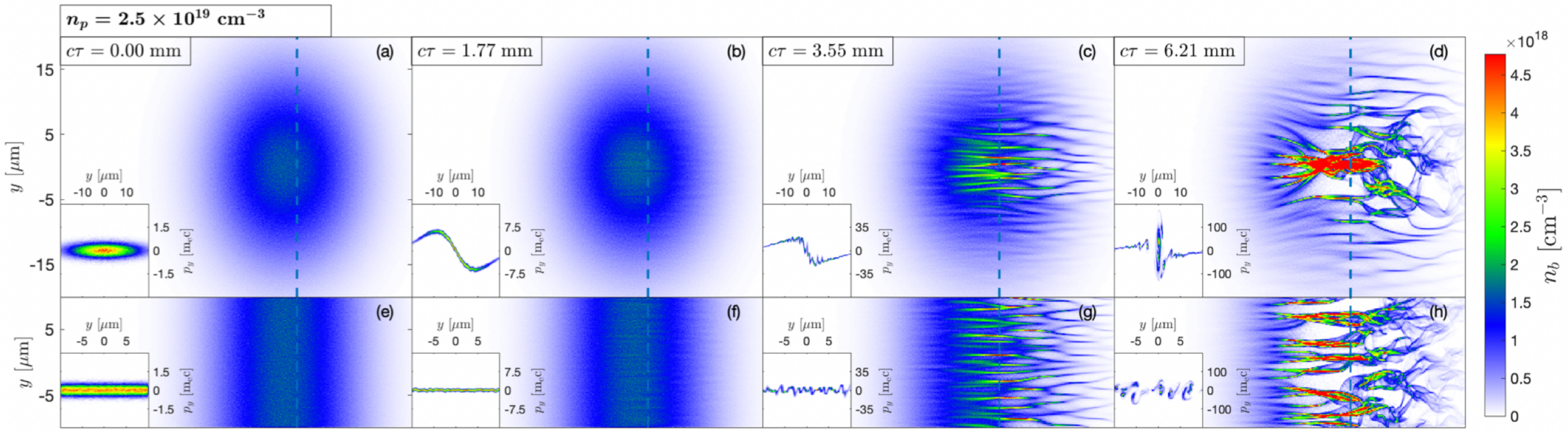
- The finite extent of particle beams from accelerators has an impact on the dynamics of the instability
  - Spatiotemporal effects lead to a significantly slower evolution of the instability.
  - Competition with self-focusing dynamics can quench the instability.
- Results relevant to design and interpret future accelerator experiments on ultrarelativistic beam-plasma instabilities.



Summary and Overview

- The finite extent of particle beams from accelerators has an impact on the dynamics of the instability
  - Spatiotemporal effects lead to a significantly slower evolution of the instability.
  - Competition with self focusing dynamics can quench the instability.
- Results relevant to design and interpret future accelerator experiments on ultrarelativistic beam-plasma instabilities.

Ongoing experimental campaign: see A. Knetsch talk .



Thanks: E305 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

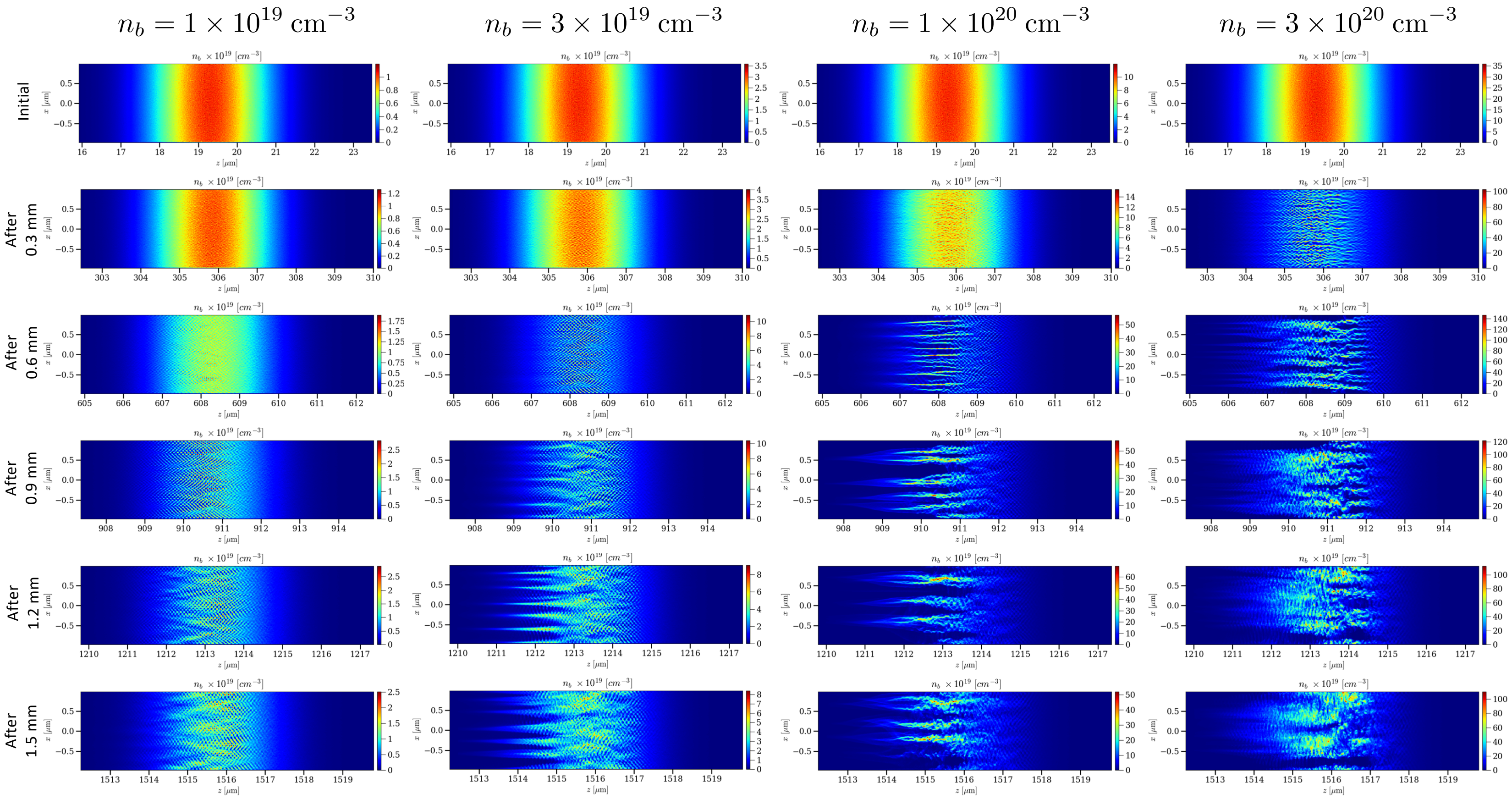
MPIK: C. Keitel, M. Tamburini, A. Sampath,

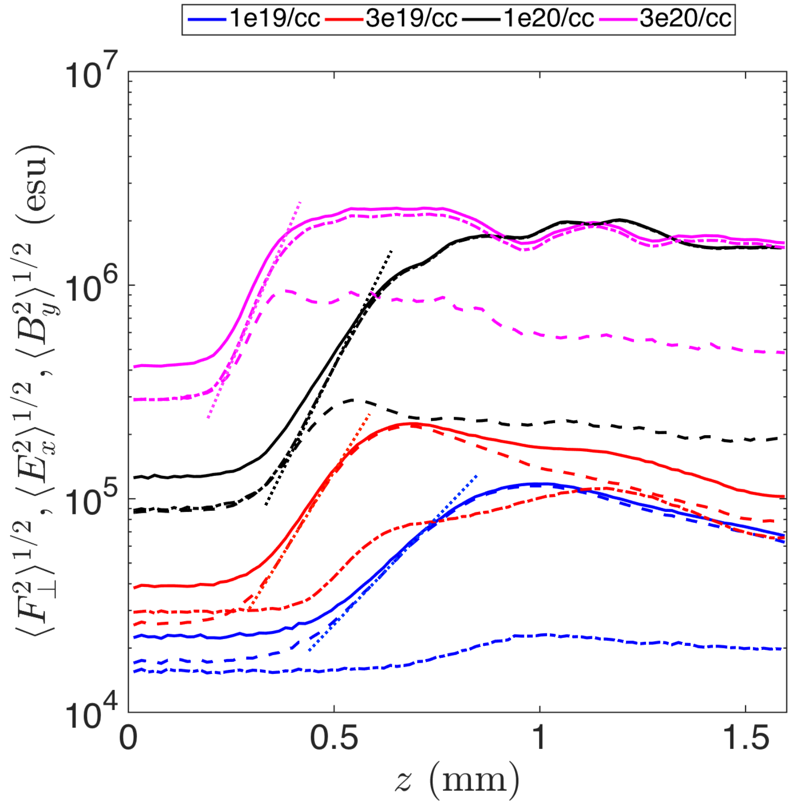
CEA: X. Davoine, J. Faure, L. Gremillet

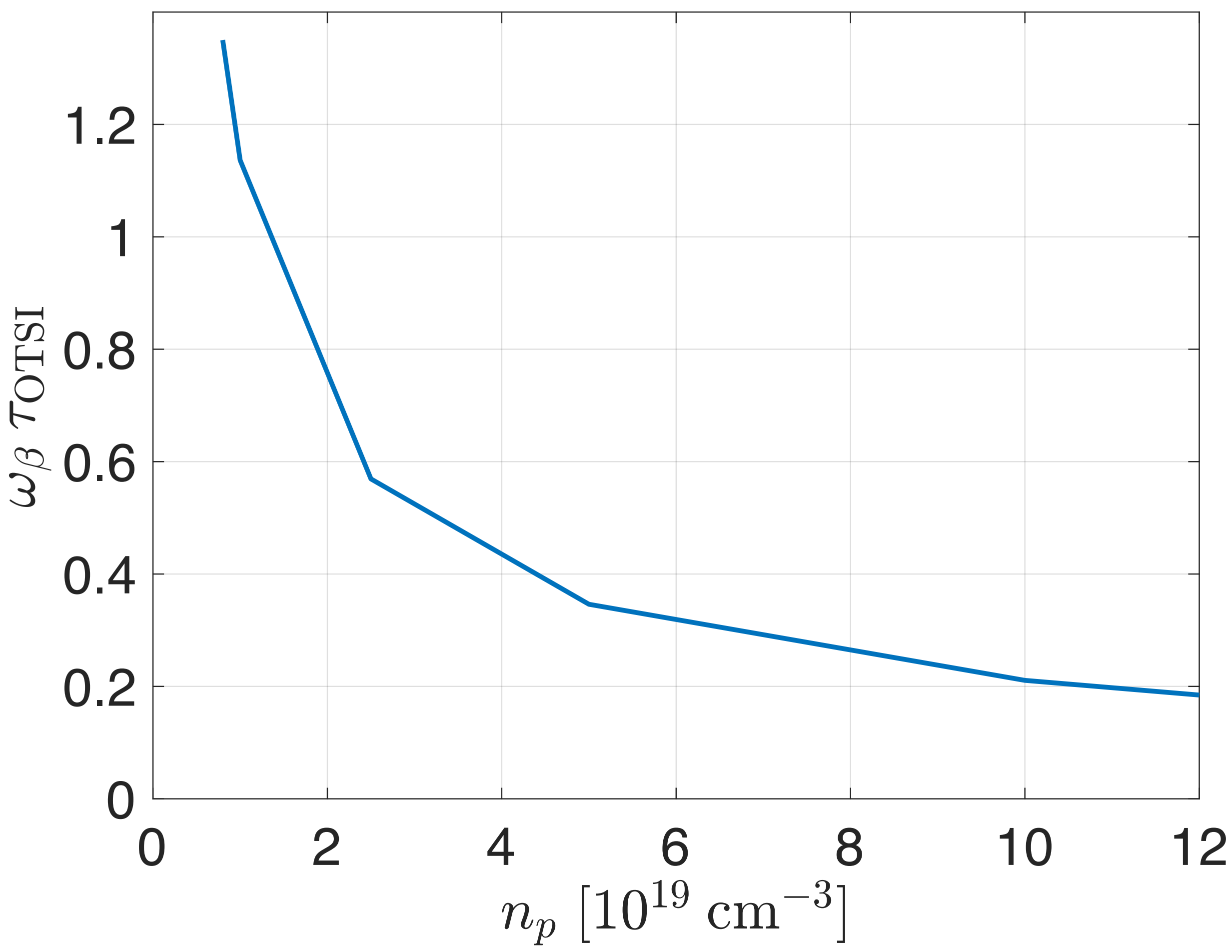
Thank you for your attention

Back-up

Finite transverse beam-size: transverse wakefields vs. instability







$\omega_\beta\,\tau_{\mathrm{OTSI}}$
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
$n_p\ [10^{19}\ \mathrm{cm}^{-3}]$