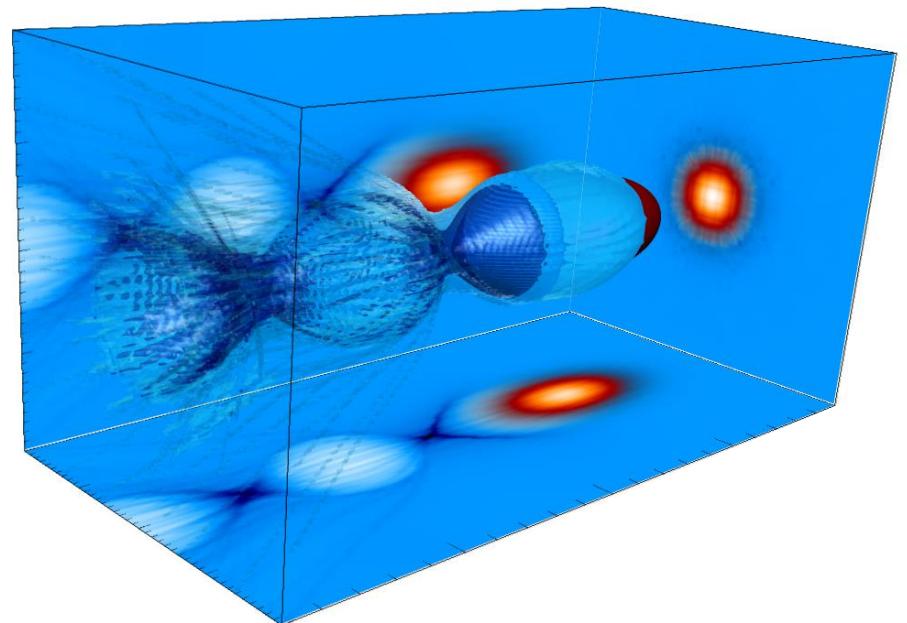


Plasma wakefield accelerators using ionization (e-) / external (e+) injection

Lígia Diana Amorim

EAAC 2021, 23/09/2021



What are plasma accelerators for?

<u>Applications</u>	European XFEL	CLIC
Energy	17.5 GeV	3 TeV (CM)
Charge	1 nC	0.6 nC
Energy spread	0.01 % (RMS)	0.35 % (RMS)
Emittance	0.97 μm	0.66/0.02 μm
Accelerator	3.4 km LINAC	50.1 km LINAC

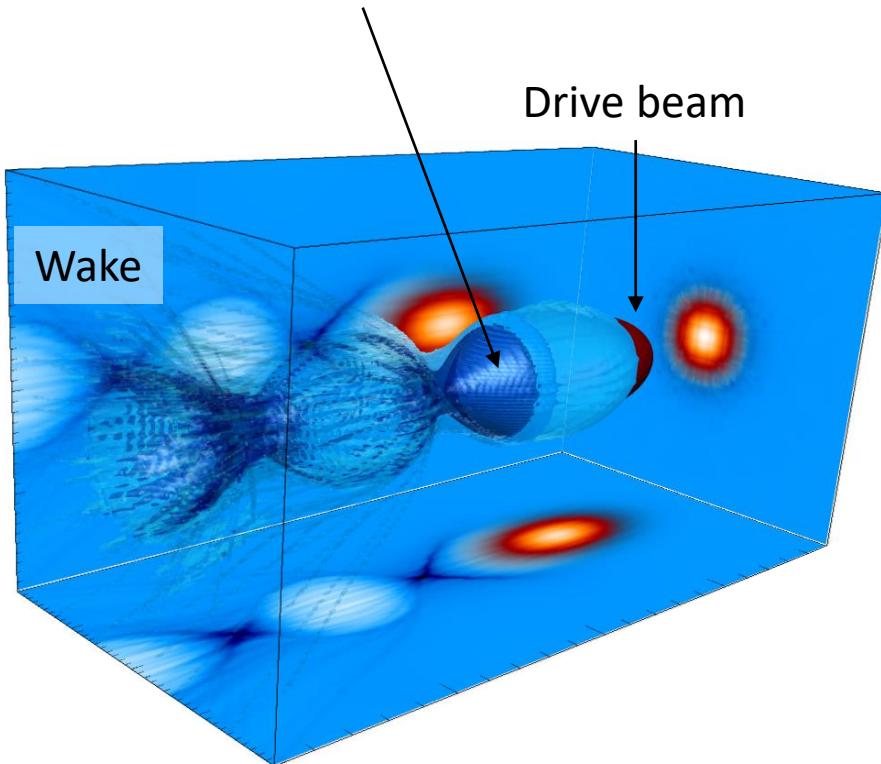
Plasma accelerators

High gradients – compact acceleration

Developed to **reduce the size** of future light sources and colliders

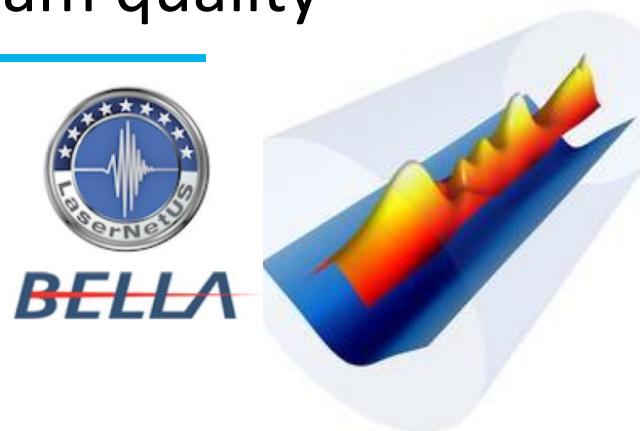
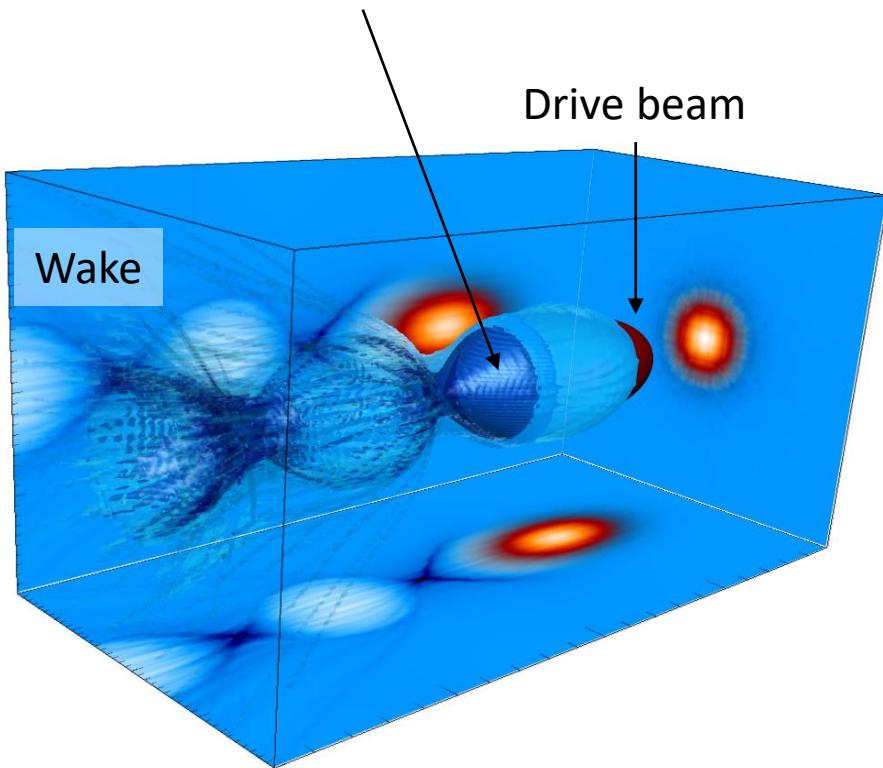
Injection is key to improving beam quality

Electrons **injected** into
accelerating and focusing phase



Injection is key to improving beam quality

Electrons **injected** into accelerating and focusing phase

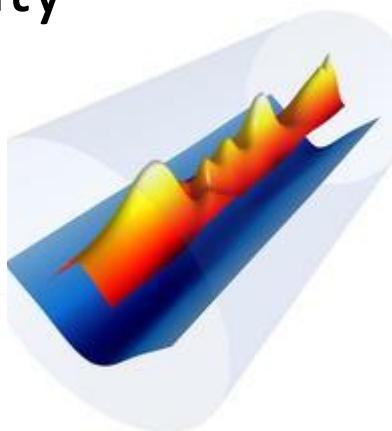
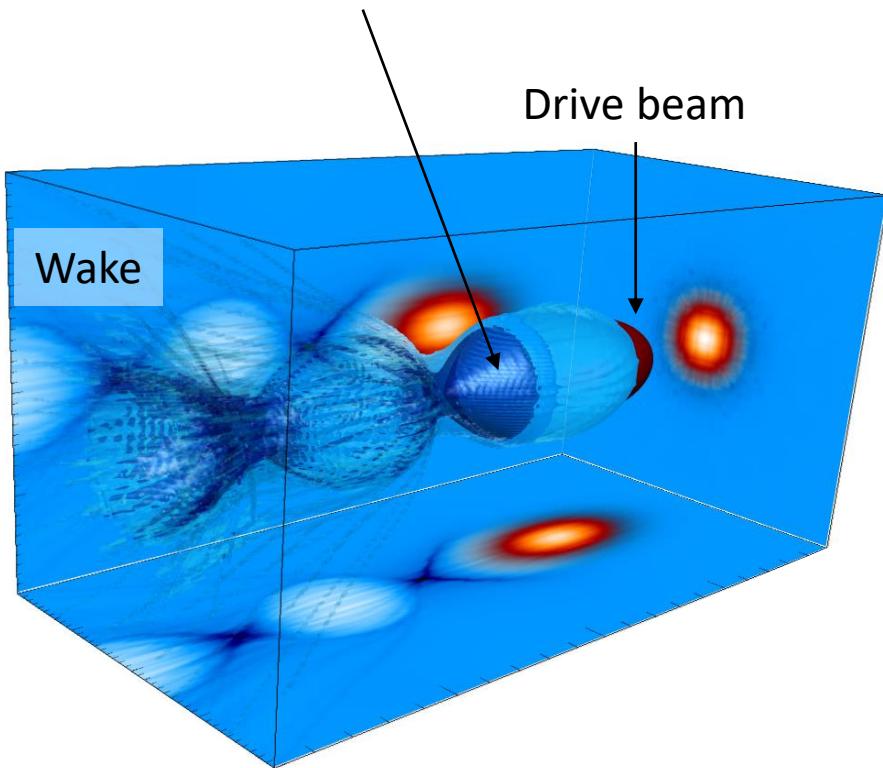


Pre-heating the 20 cm capillary allowed laser guiding and electrons to reach 0 - 8 GeV

Multiple injections – acceleration distances

Injection is key to improving beam quality

Electrons **injected** into accelerating and focusing phase



Pre-heating the 20 cm capillary allowed laser guiding and electrons to reach 0 - 8 GeV

Multiple injections – acceleration distances

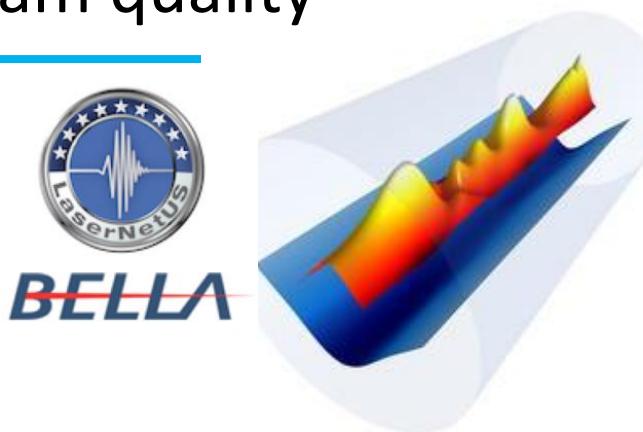
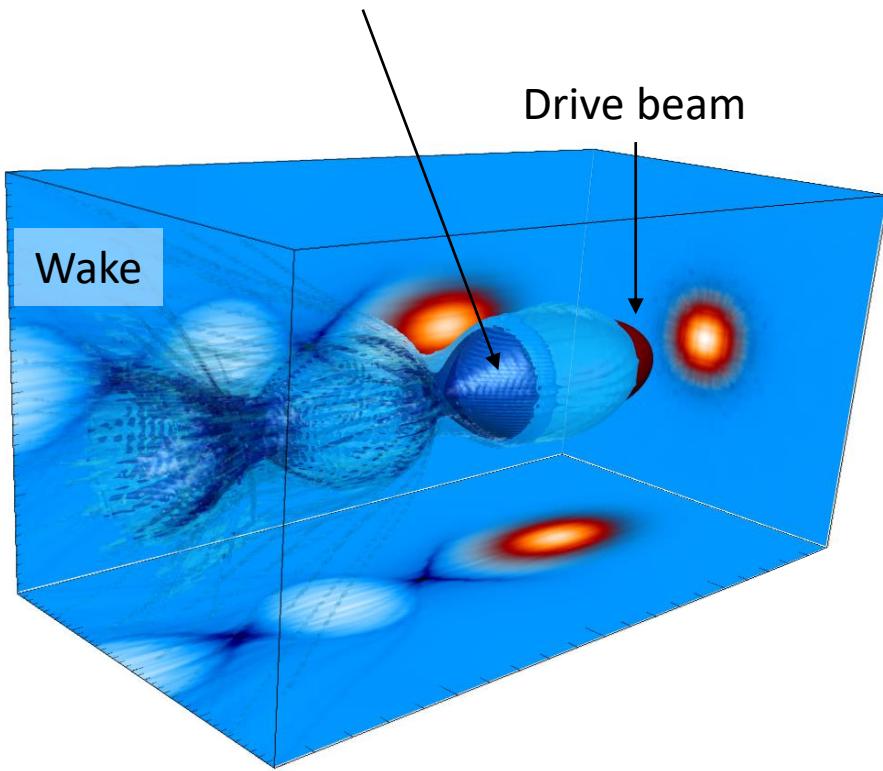


LWFA powered FEL (27 nm)
shock injection - 0.5 % energy spread, 0.2 mrad divergence

But only 30 pC and 490 MeV

Injection is key to improving beam quality

Electrons **injected** into accelerating and focusing phase



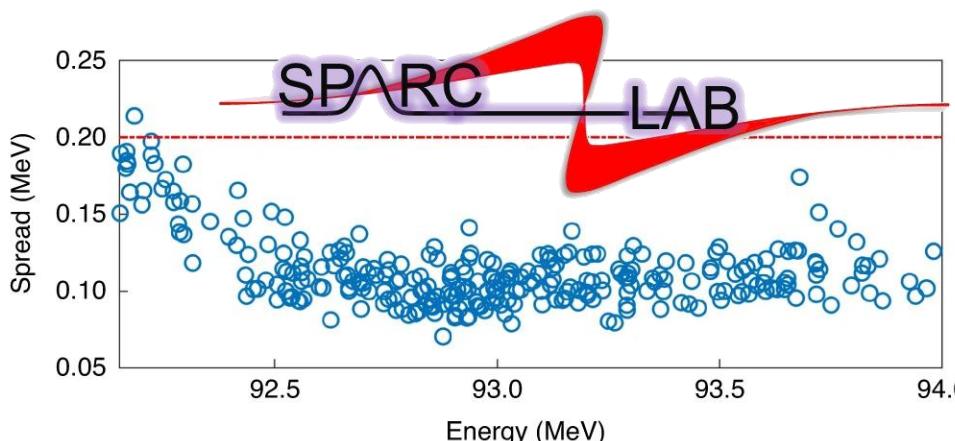
Pre-heating the 20 cm capillary allowed laser guiding and electrons to reach 0 - 8 GeV

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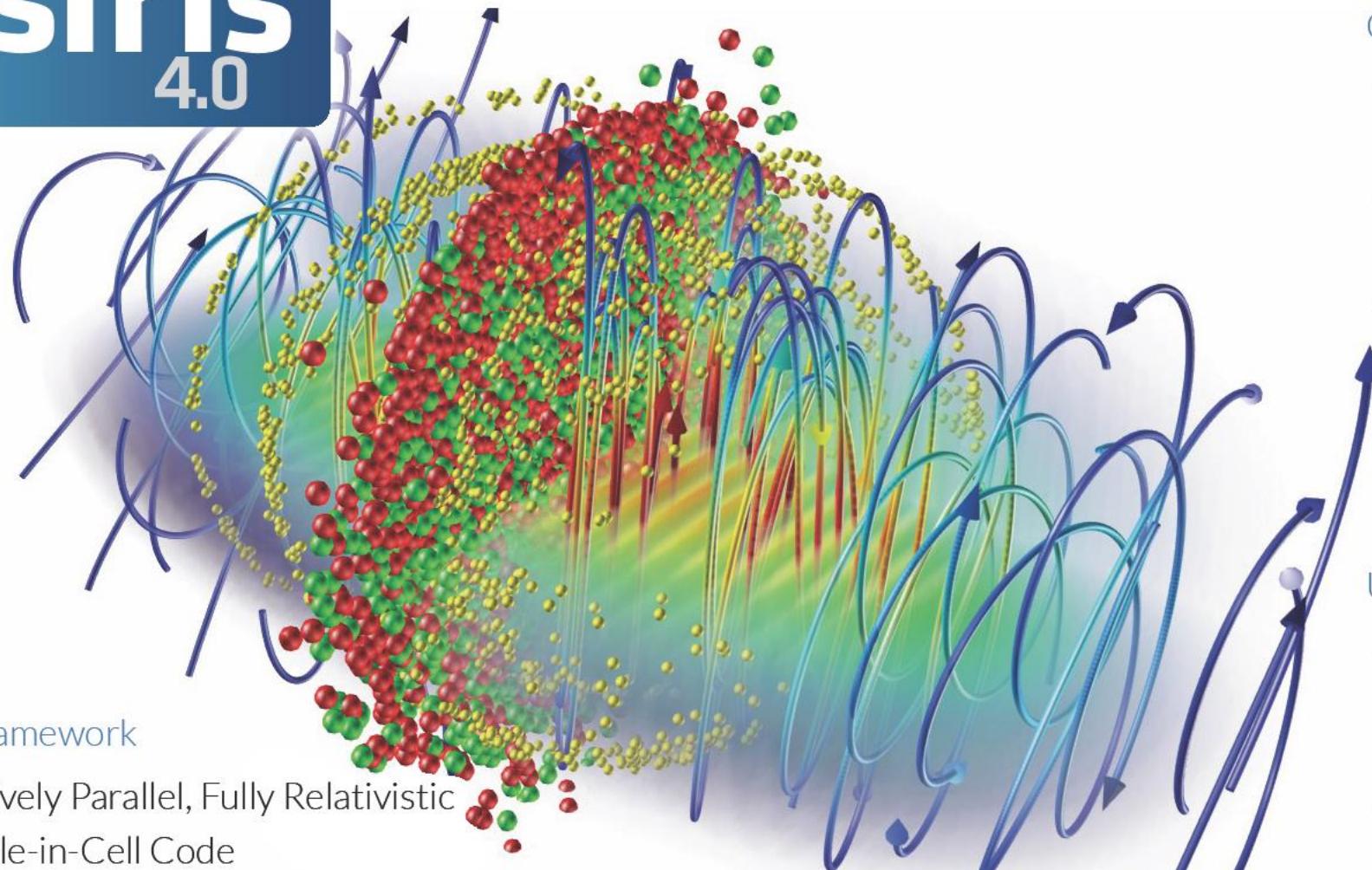


Beam with positive energy chirp was injected into PWFA

Energy spread down to 0.1
But only 20 pC and 7 MeV gain

Beam-Induced-Ionization-Injection (B-III) of high energy + charge + quality beams

Osiris 4.0



OSIRIS framework

- Massively Parallel, Fully Relativistic Particle-in-Cell Code
- Parallel scalability to 2 M cores
- Explicit SSE / AVX / QPX / Xeon Phi / CUDA support
- Extended physics/simulation models

Committed to open science

Open-access model

- 40+ research groups worldwide are using OSIRIS
- 300+ publications in leading scientific journals
- Large developer and user community
- Detailed documentation and sample inputs files available

Using OSIRIS 4.0

- The code can be used freely by research institutions after signing an MoU
- Find out more at:
<http://epp.tecnico.ulisboa.pt/osiris>

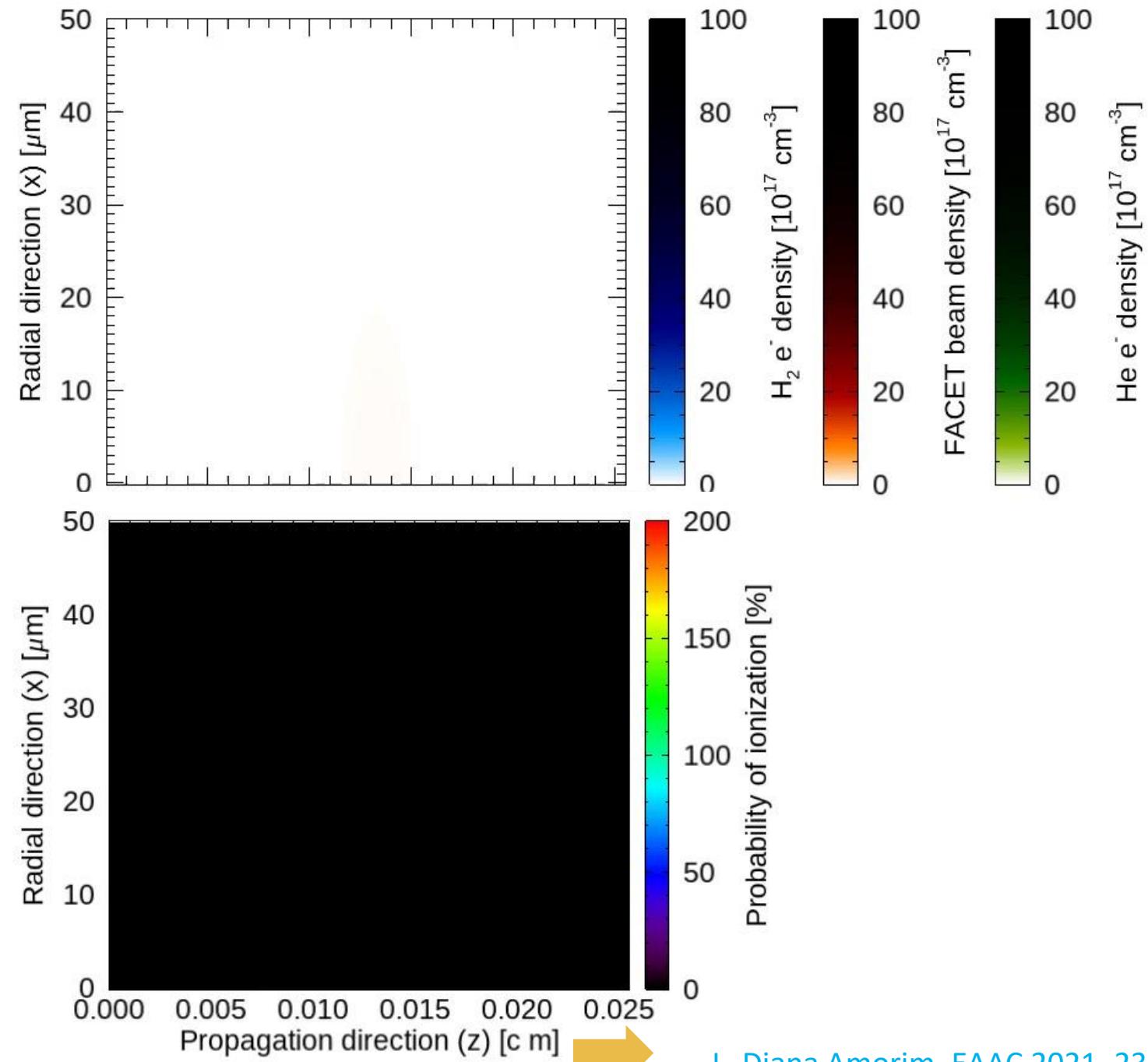
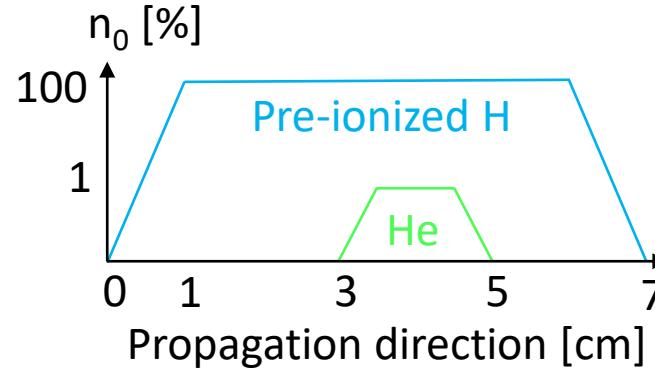


Ricardo Fonseca: ricardo.fonseca@tecnico.ulisboa.pt

Beam Induced Ionization Injection (B-III)

RZ quasi-nonlinear PWFA simulation

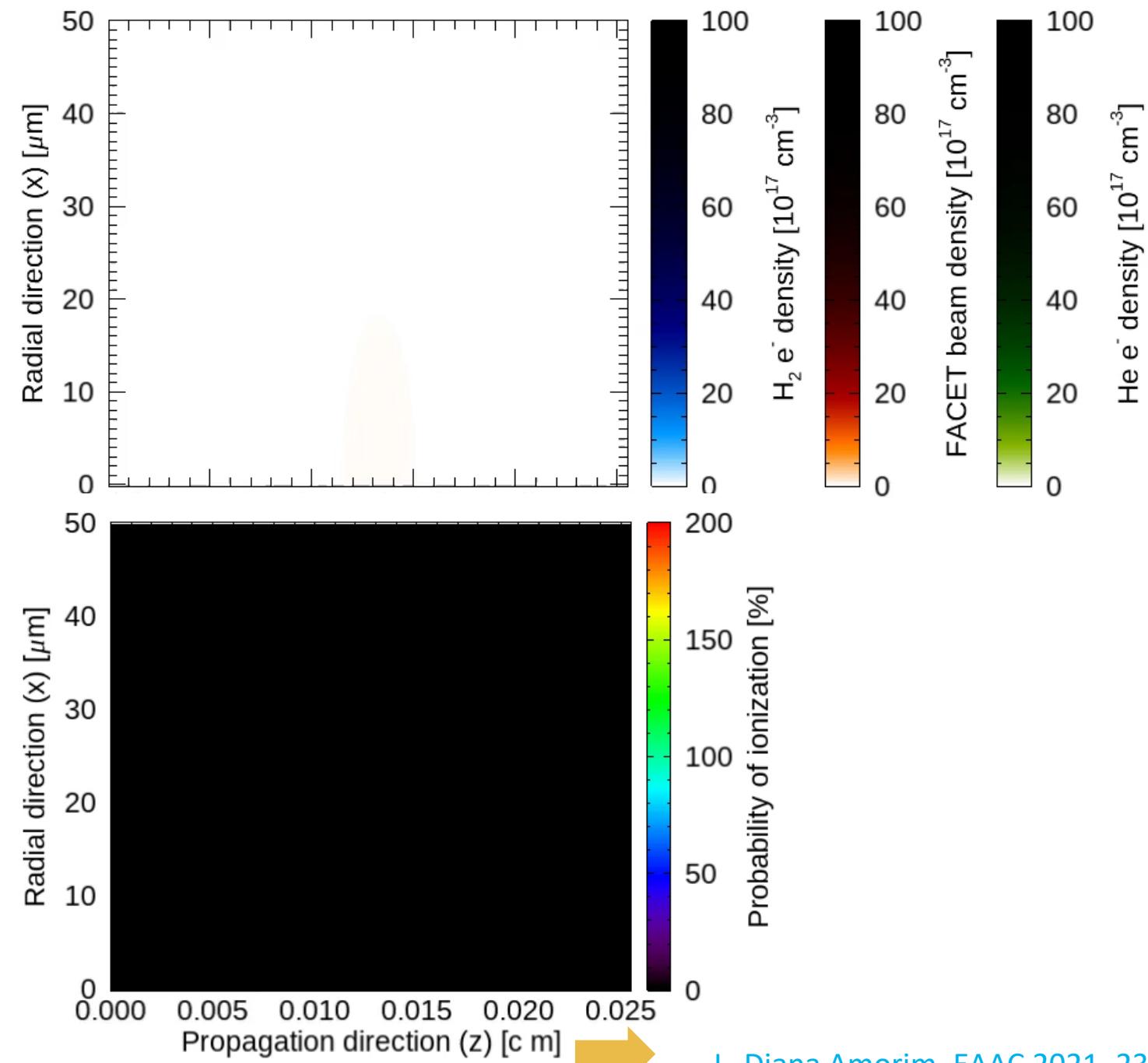
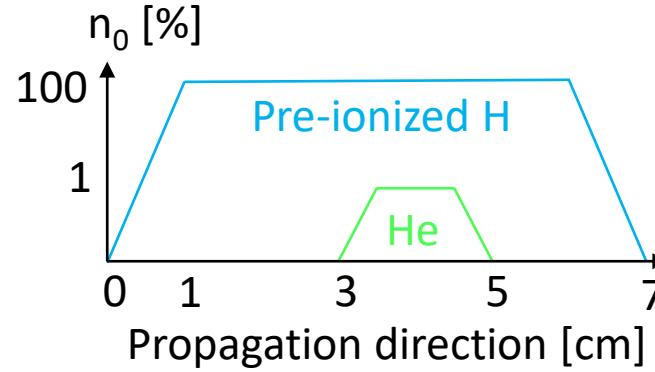
Unmatched **beam**:
20.3 GeV, 3.2 nC, 30 μm sizes



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RZ quasi-nonlinear PWFA simulation

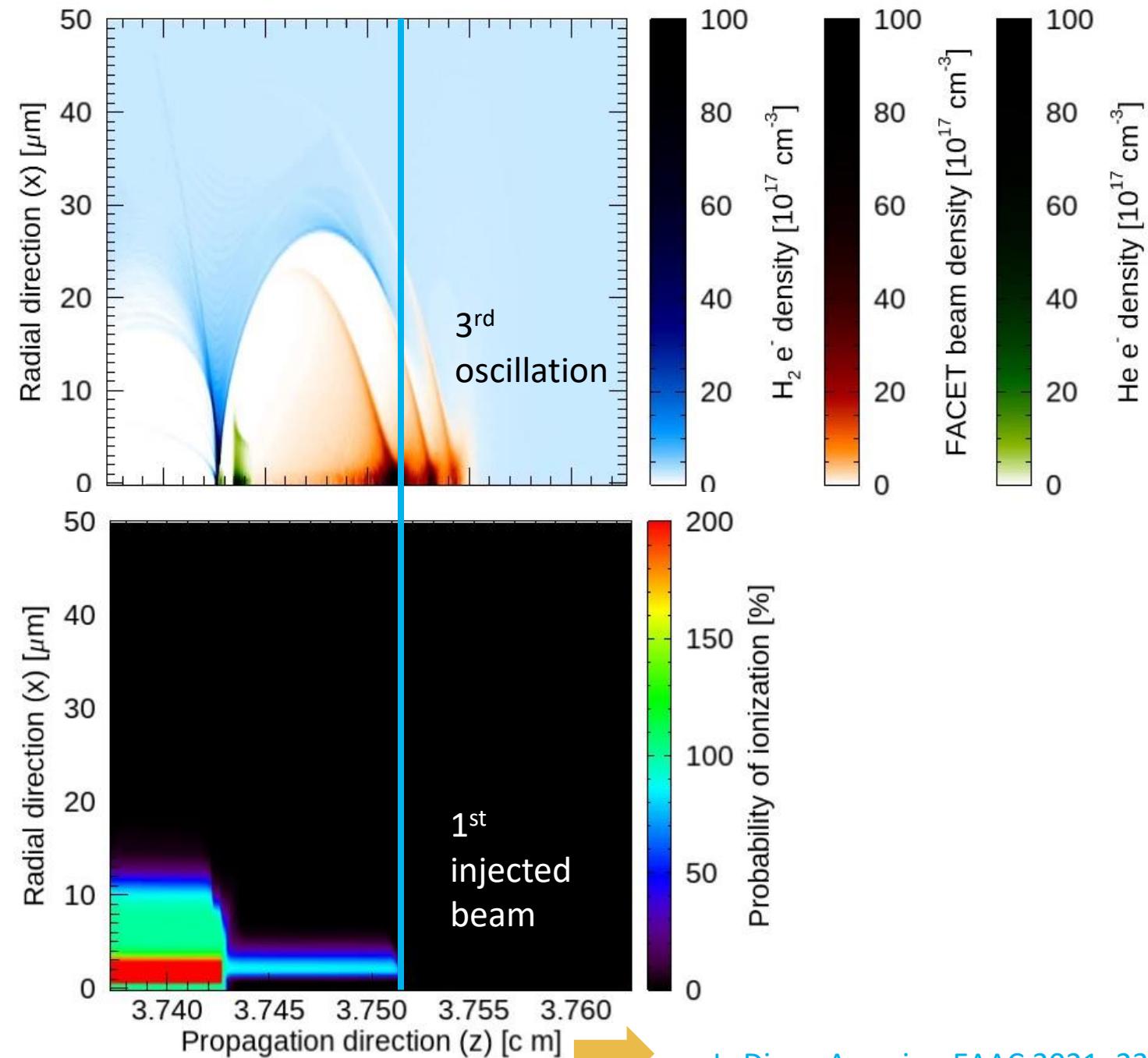
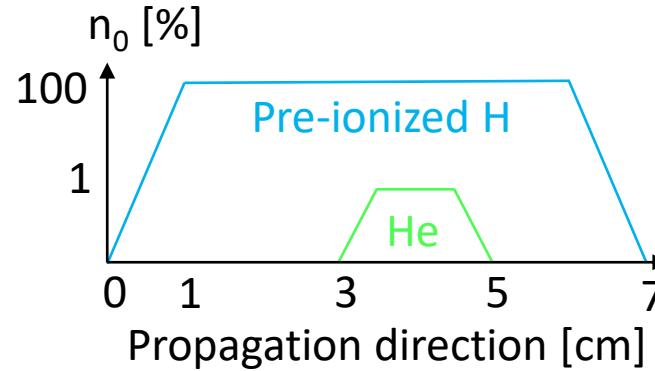
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RZ quasi-nonlinear PWFA simulation

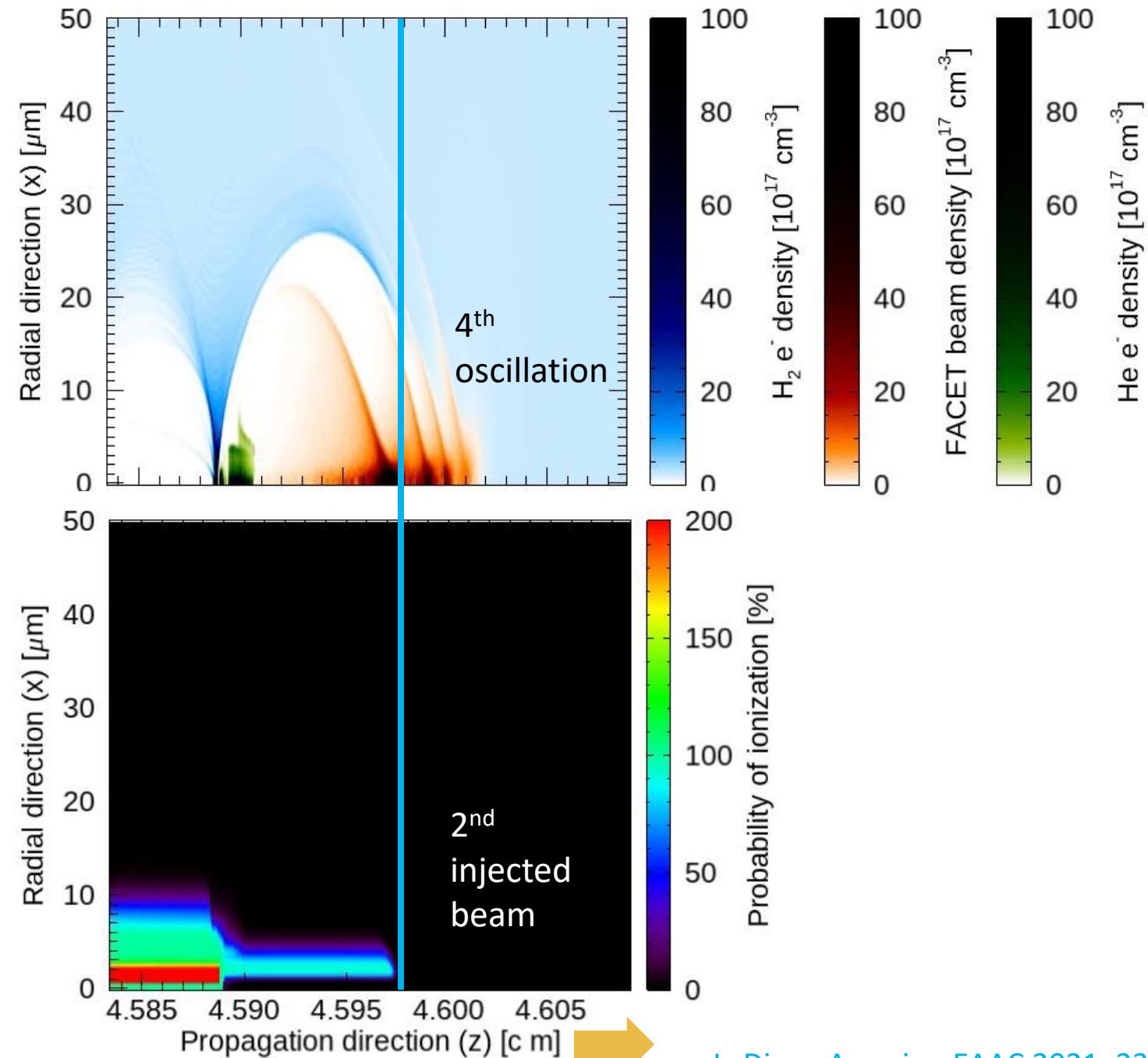
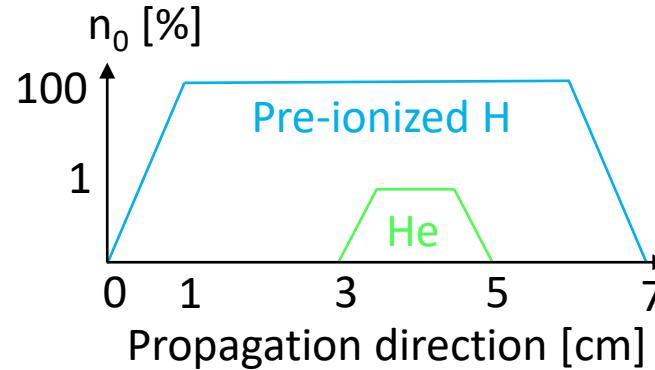
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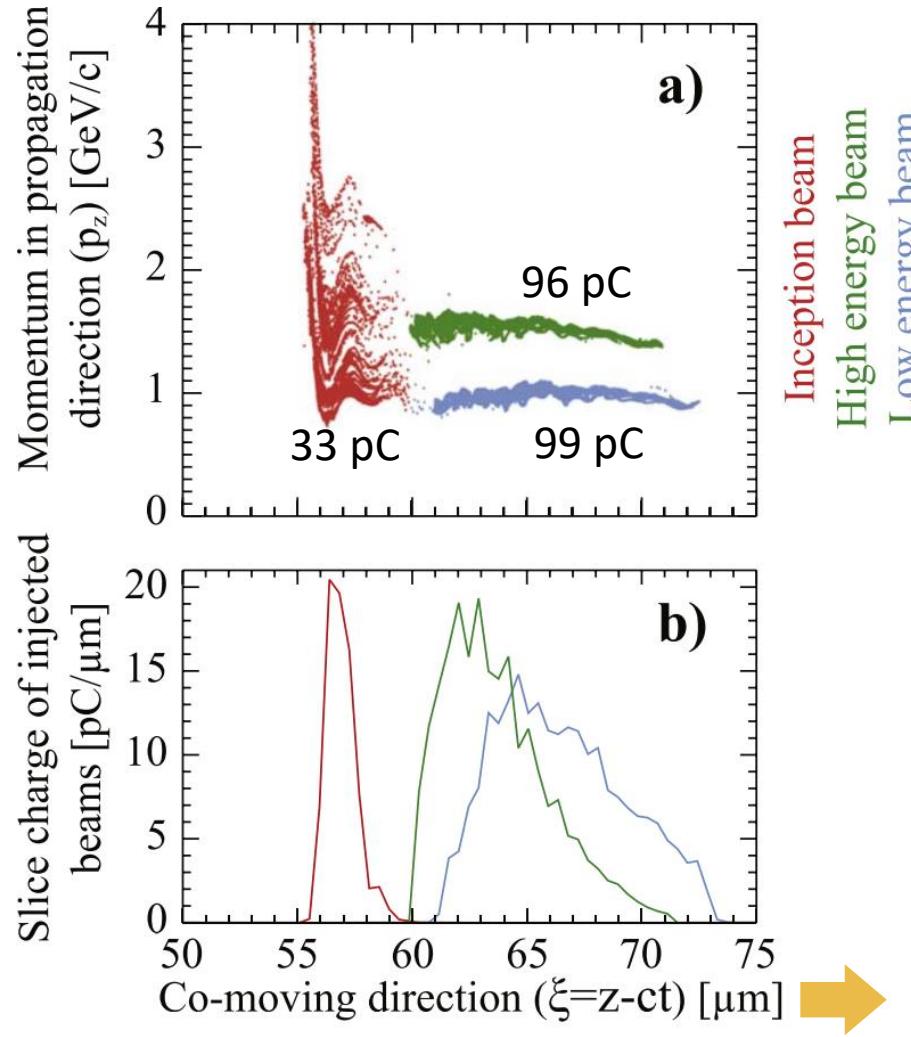
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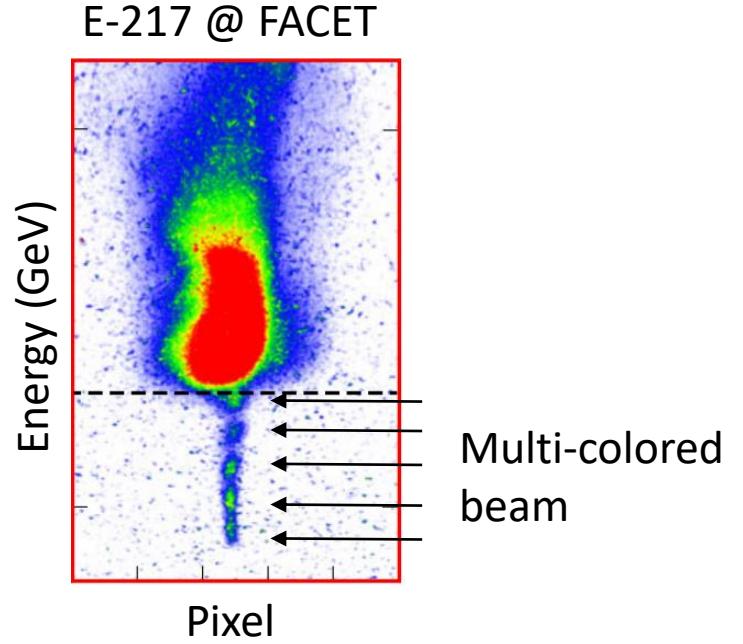
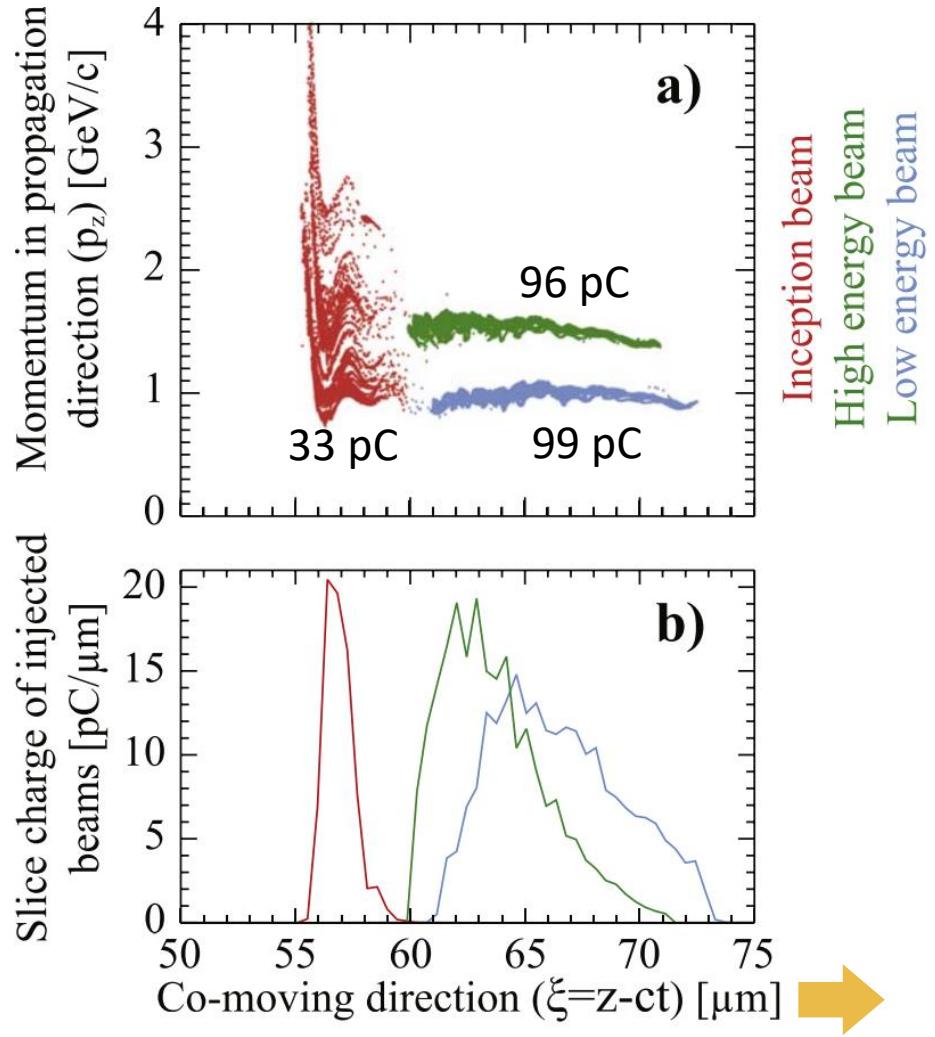
Unmatched **beam**:
20.3 GeV, 3.2 nC, 30 μm sizes



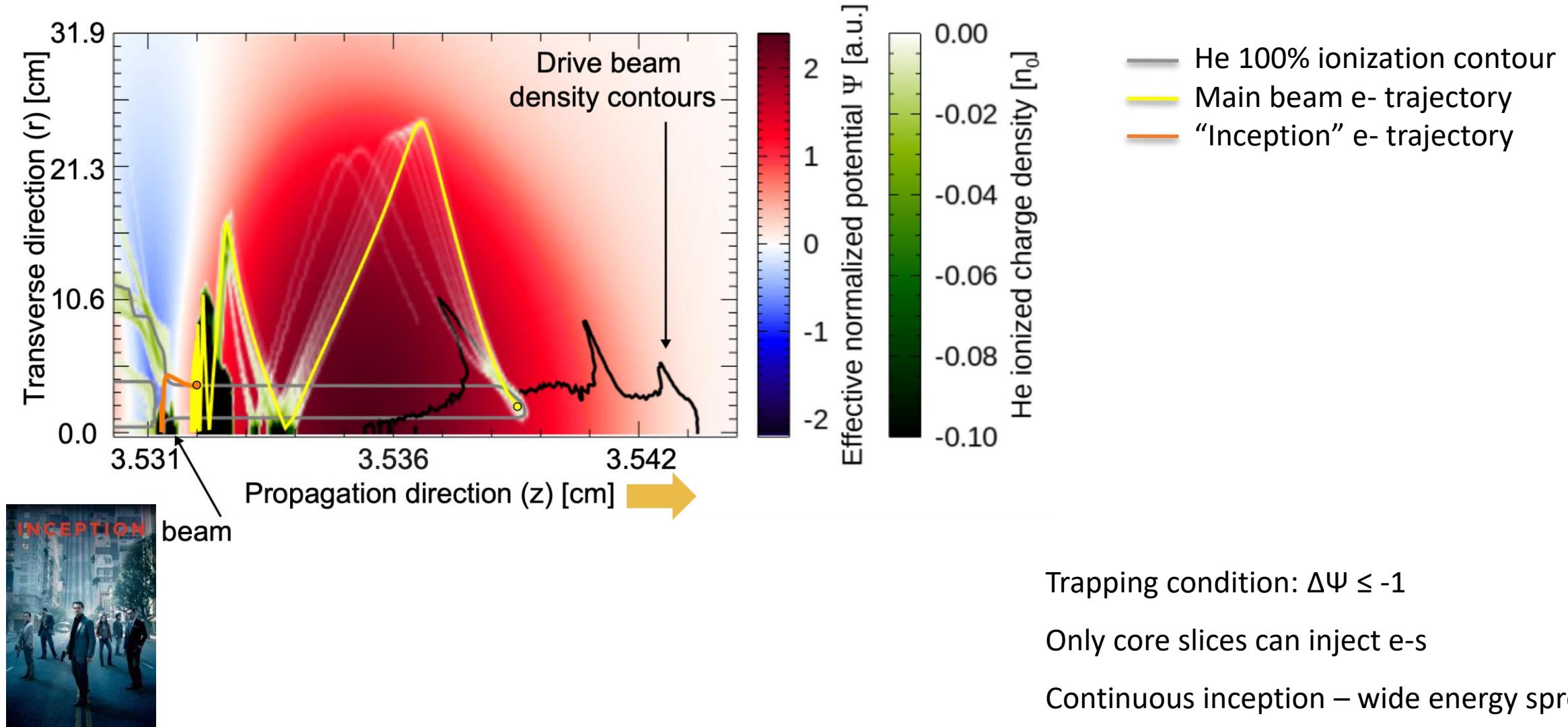
B-III generated two main beams with different energies



B-III with long impurities produces multi-colored beams

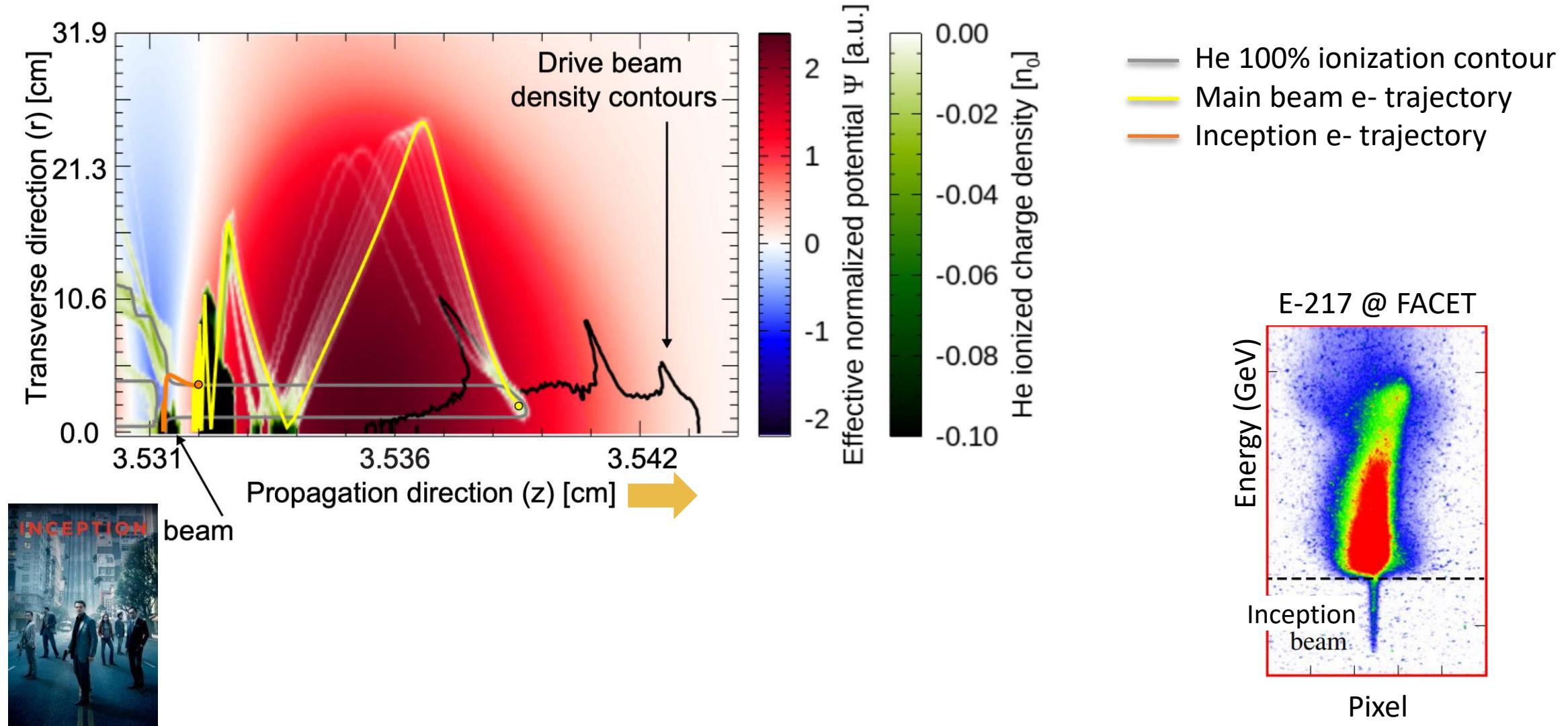


Uncontrolled B-III generates inception beams



Amorim L. D. and Vafaei-Najafabadi N., PPCF 61, 105015 (2019),
 Amorim L. D. and Vafaei-Najafabadi, IEEE Proc AAC doi: 10.1109/AAC.2018.8659382. (2018)

Uncontrolled B-III generates inception beams

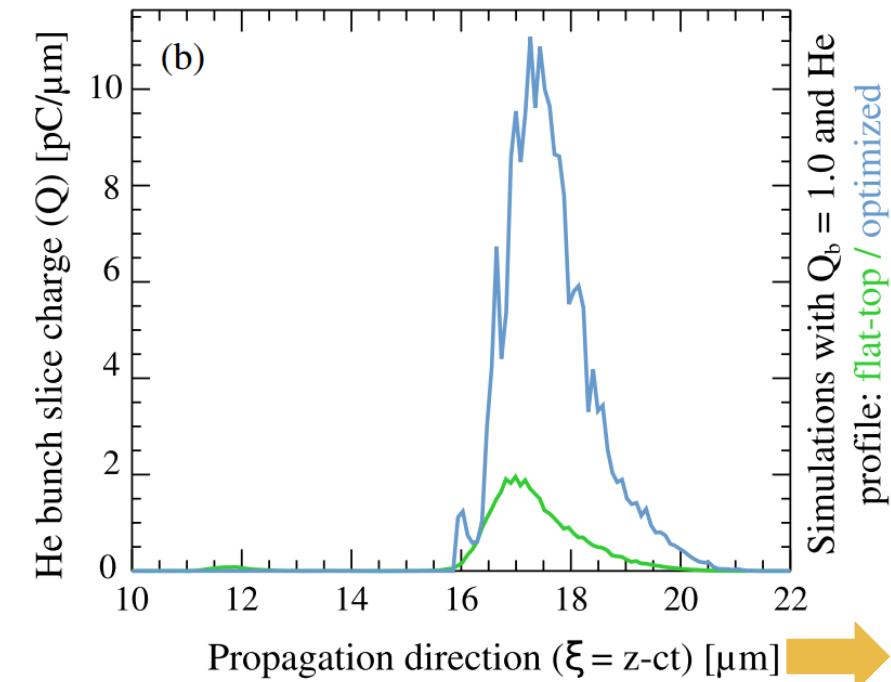


Amorim L. D. and Vafaei-Najafabadi N., PPCF 61, 105015 (2019),
 Amorim L. D. and Vafaei-Najafabadi, IEEE Proc AAC doi: 10.1109/AAC.2018.8659382. (2018),
 Vafaei-Najafabadi N., Amorim L. D., et al., Phil. Trans. R. Soc. A 377: 20180184 (2019)

L. Diana Amorim, EAAC 2021, 23/09/2021

Controlled B-III to produce high energy + charge + quality beams

Control over \ of	Injected Beam
Plasma density	Higher energy
Driver density	Ionization threshold Narrower = higher quality Higher charge
Impurity density	Higher charge + quality
Impurity length	Multi or single color



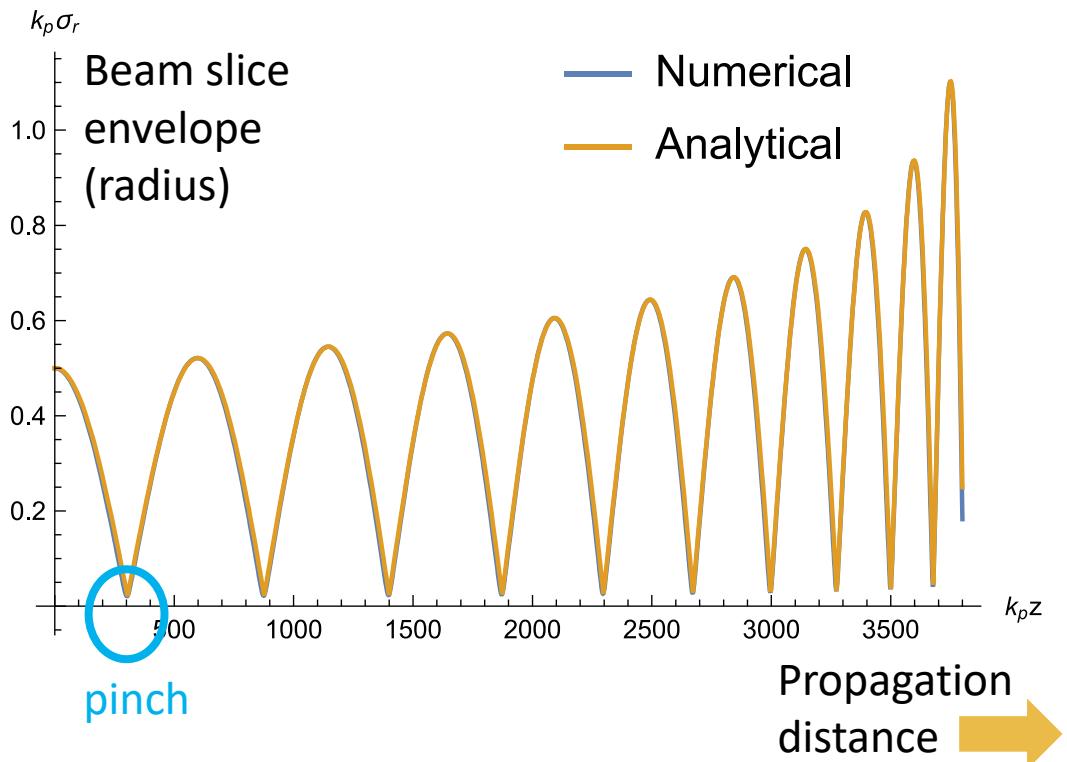
Corrected analytical model to control ionization and injection

Envelope performs Betatron oscillations:

$$\frac{d^2\sigma_r(z)}{dz^2} + \boxed{\frac{\gamma(z)'}{\gamma(z)}\sigma'_r(z)} + k_\beta^2\sigma_r(z) - \frac{\epsilon_N^2}{\gamma(z)^2\sigma_r^3(z)} = 0$$

Energy variation term included to get pinch size $\Delta\sigma_r = \sqrt{\frac{2}{\gamma(z)}} \frac{\epsilon_N c}{\omega_p \sigma_{r0} \left(\frac{\gamma_0}{\gamma(z)} \right)}$

Trapping condition via Hamiltonian approach: $H_{critical} \approx \frac{1}{2p_z}$

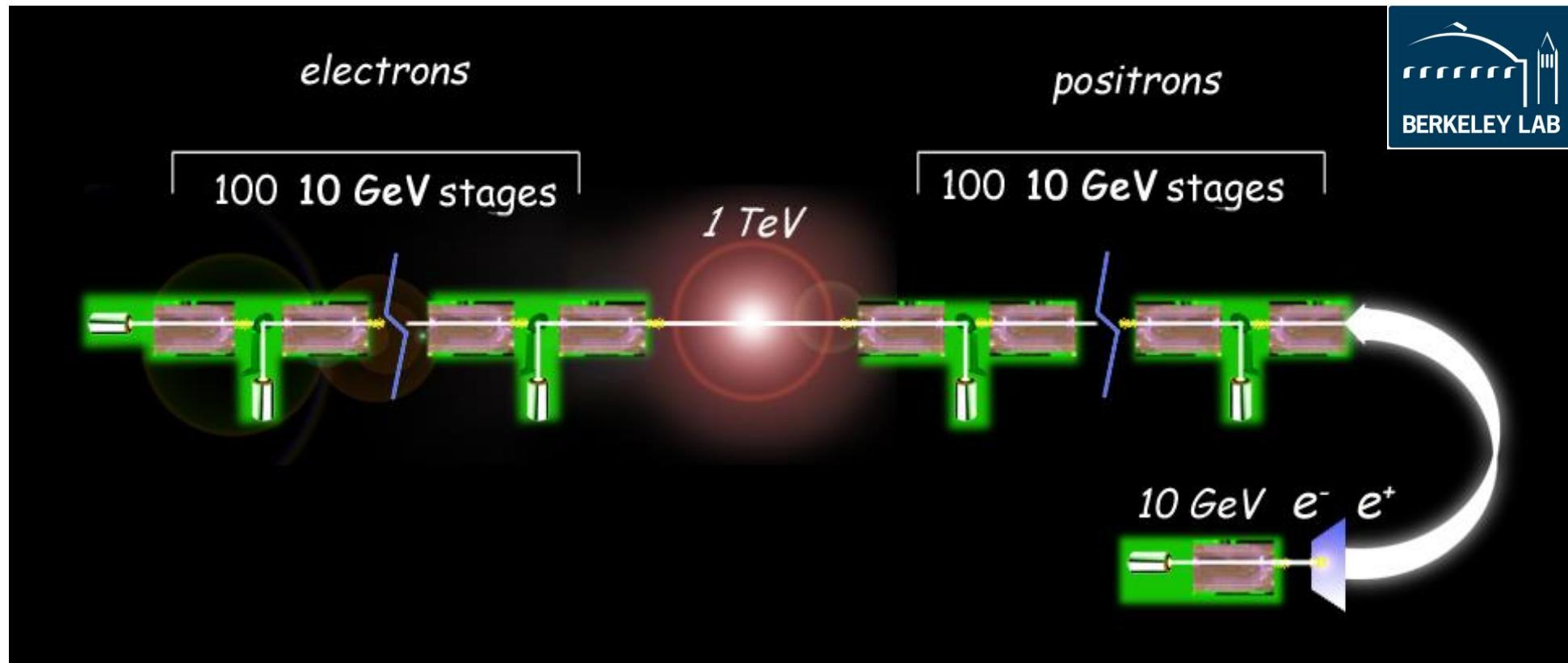


Jiayang Yan @ SBU

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Beam-Induced-Ionization-Injection (B-III) of high energy + charge + quality beams

Positron source to test future collider plasma stages



WarpX: open-source particle-in-cell code with advanced algorithms at Exascale

PI: Jean-Luc Vay (LBNL); DoE Exascale Computing Project (ECP)

Main contributors*: R. Lehe, M. Thévenet, W. Zhang, A. Myers, A. Huebl, A. Almgren, L. Fedeli, D. Grote, E. Zoni, R. Jambunathan, Y. Zhao, L. Ge, N. Zaim, G. Richardson, J.-L. Vay, M. Rowan, R. Groenewald, L. Giacomet, O. Shapoval, J. Gu, B. Loring, D. Amorim, H. Vincenti + >21 smaller contributors. (physicists + applied maths + comput. sc. + software dev.)

Features

- Boosted frame technique for plasma acceleration
- Advanced algorithms (spectral solvers, instability mitigation, mesh refinement**)
- openPMD I/O & in-situ I/O
- Multi-physics (collisions, field ionization, QED, advanced boundaries)
- Dynamic Load Balancing
- Performance-portability (amrex::ParallelFor)
OpenMP, CUDA, HIP, DPC++

**in development

Implementation (C++)

- Built on AMReX (LBNL, ECP co-design center)
- Documented, modular, tested (CI)
- Easy to install: Spack, Conda, Pip, Homebrew**, CMake
- Users/contributors welcome! >40 contributors from



Achievements

- Demonstrated scaling on full Summit (OLCF)
- today: 10 multi-GeV stages
- Goal 2023: TeV multi-stage collider

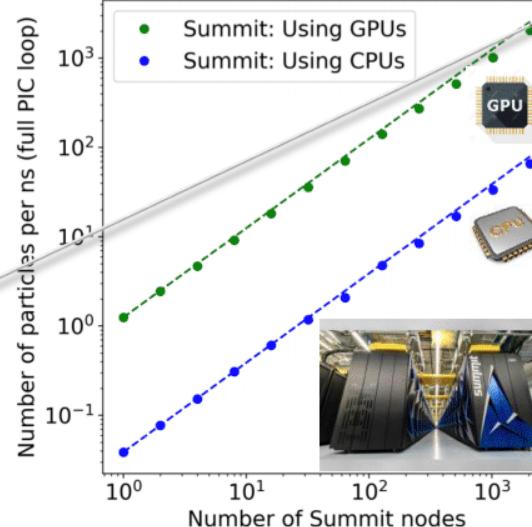
*<https://ecp-warpx.github.io>

<https://amrex-codes.github.io>

<https://www.openpmd.org>

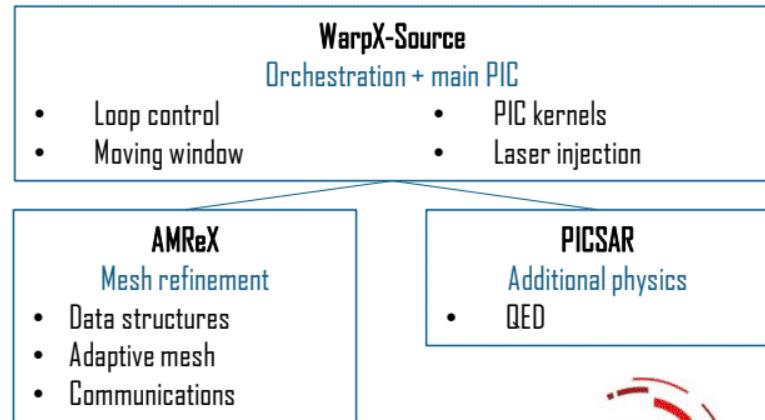
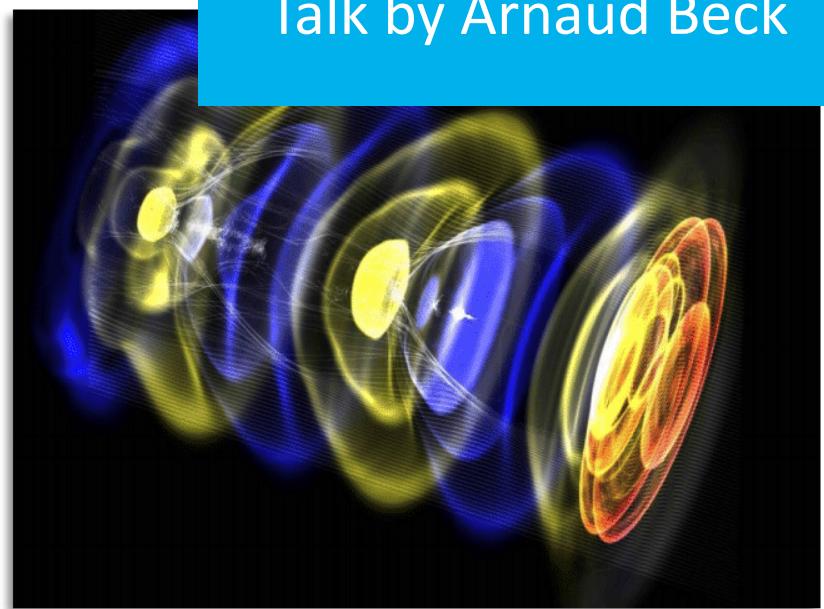
<https://blast.lbl.gov>

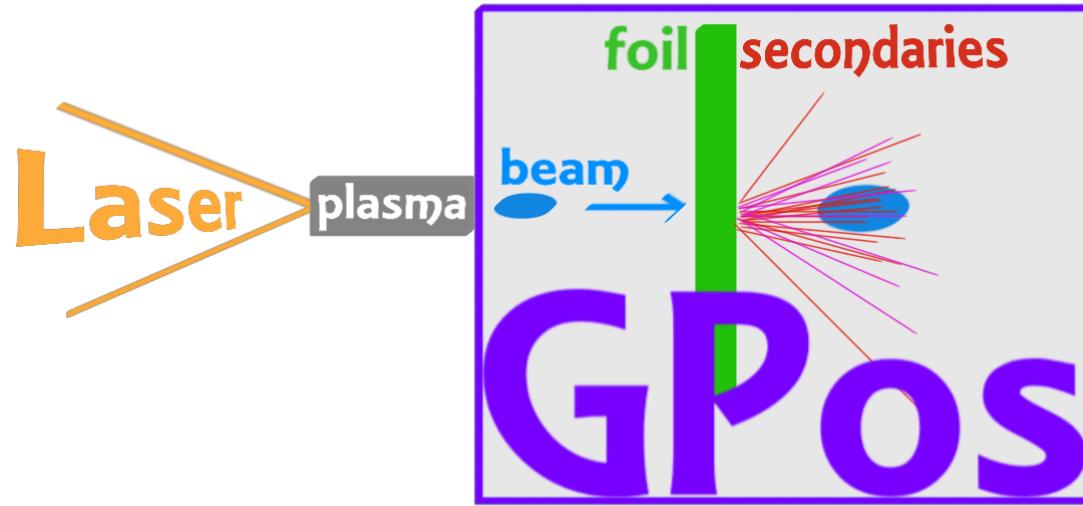
<https://github.com/ECP-WarpX/picsar>



Vay, J.-L., et al., Nucl. Instrum. Meth. A 909 (2018): 476-479
Myers, A., et al., arXiv:2101.12149 (2021)

Talk by Arnaud Beck





<https://github.com/LDAmorim/GPos>



Readthedocs
Doxygen

Simple to use C++ & MPI tool

Simulates particle sources using relativistic beam and solid target sources

Relies on 3D Monte Carlo based Geant4 library to model interactions

Includes initial realistic primaries (divergence, energy spread, focus)

Determines particle properties after drift propagation with(out) focusing lens

Uses openPMD API (HDF5) for direct input to WarpX

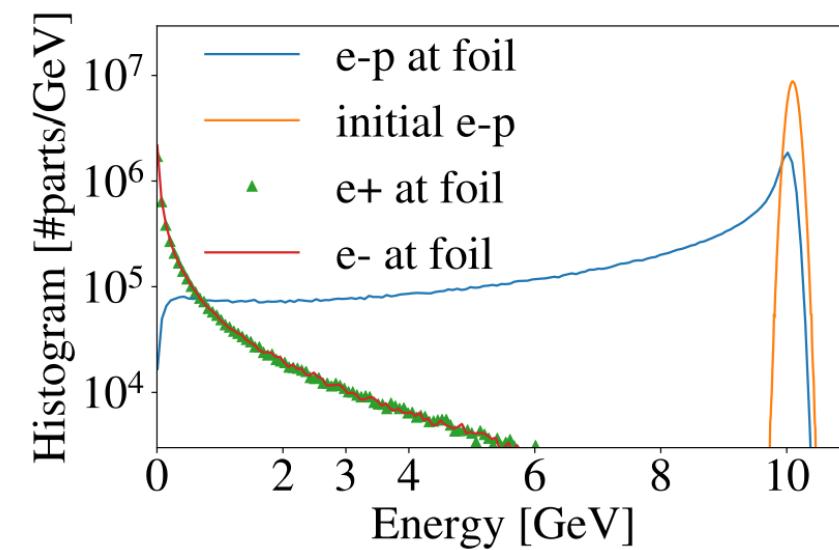
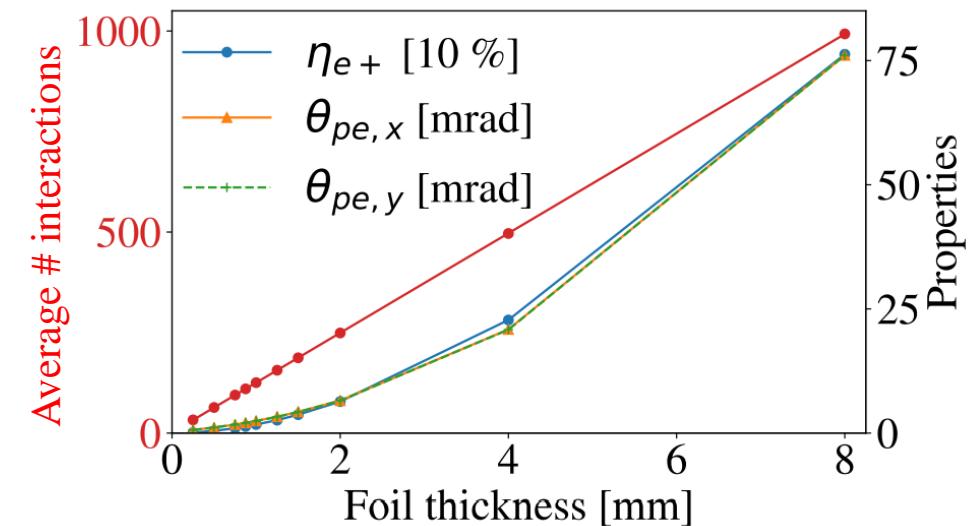
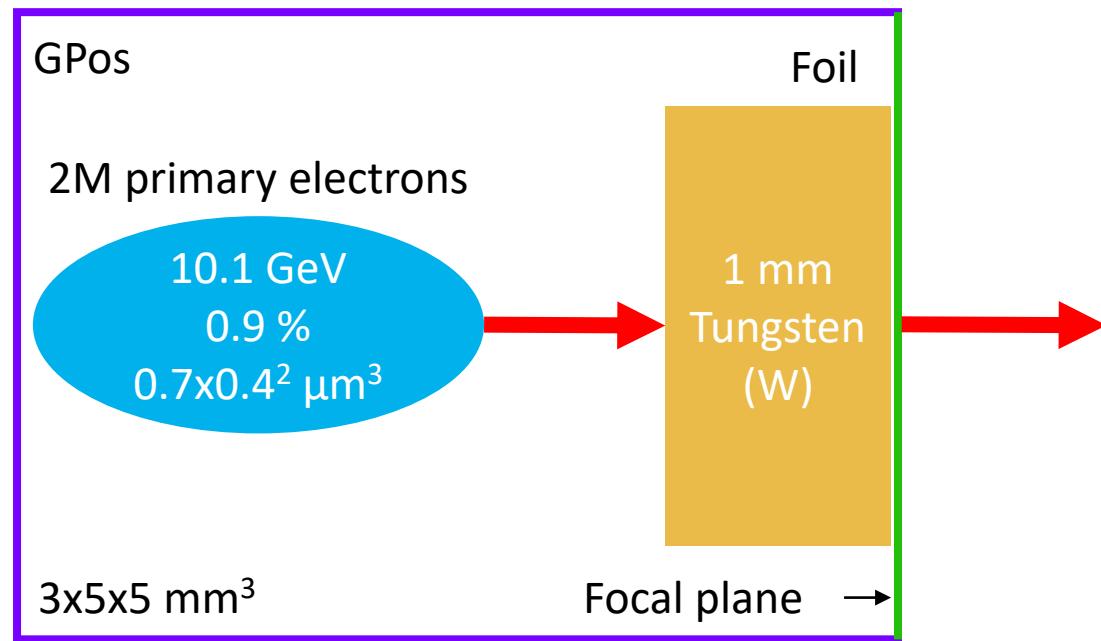


Bremsstrahlung radiation creates electron-positron clouds

Source: relativistic electrons produce Bremsstrahlung radiation that decays into pairs near high-Z atoms

Scan showed foil thickness (type) & beam energy were key

Trade-off between positron yield and beams quality



Drift and lens are insufficient to increase extraction & capture

RZ WarpX simulations:

Optimal beams sent into plasma after X mm
with(out) drift and lens tuned for positrons

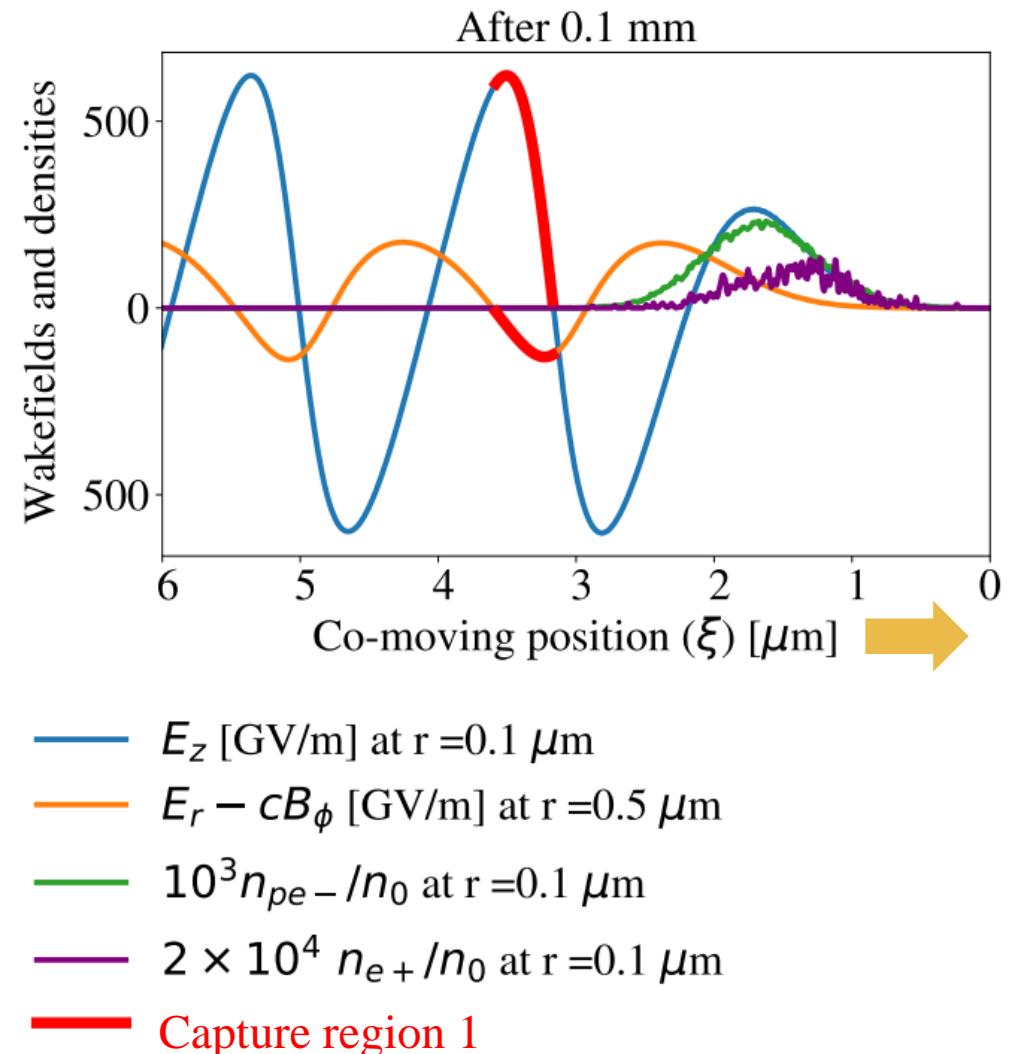
Results:

No drift led to non-linear regime & positrons loss

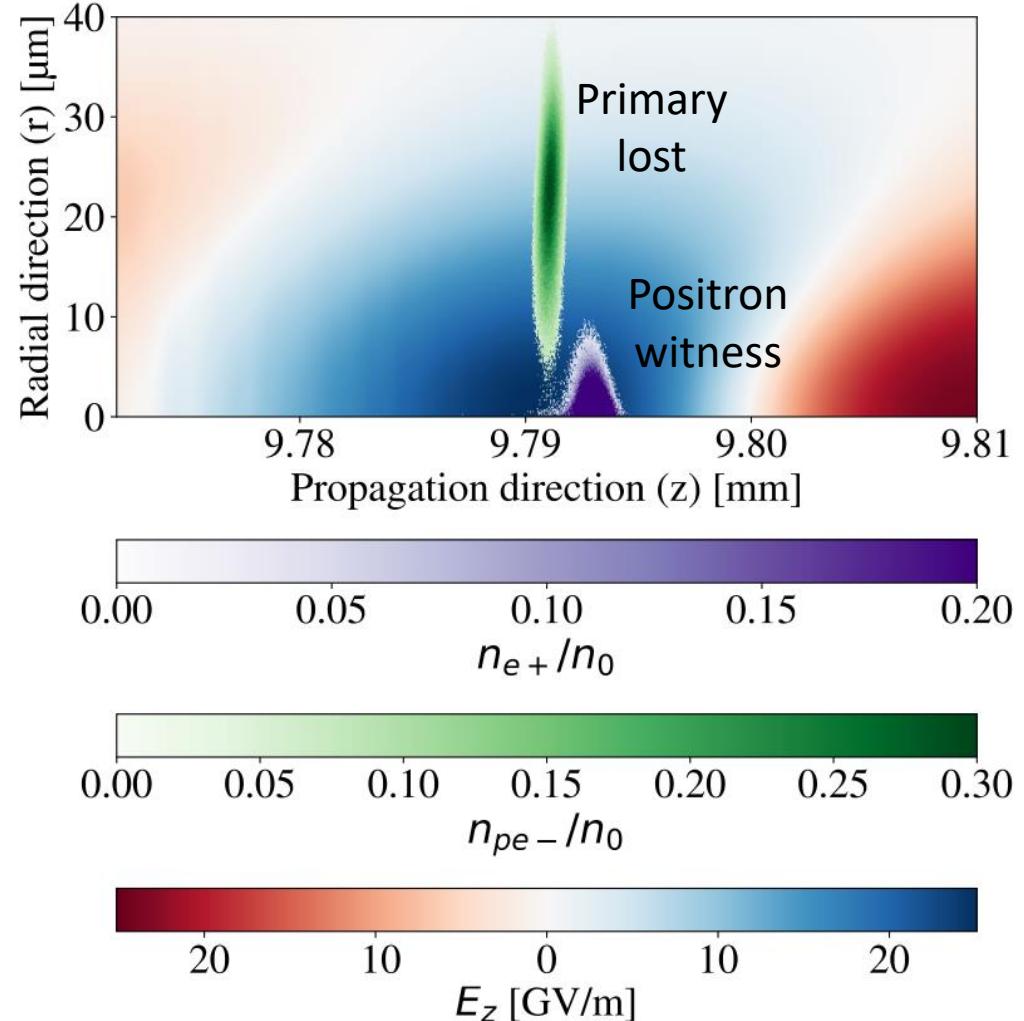
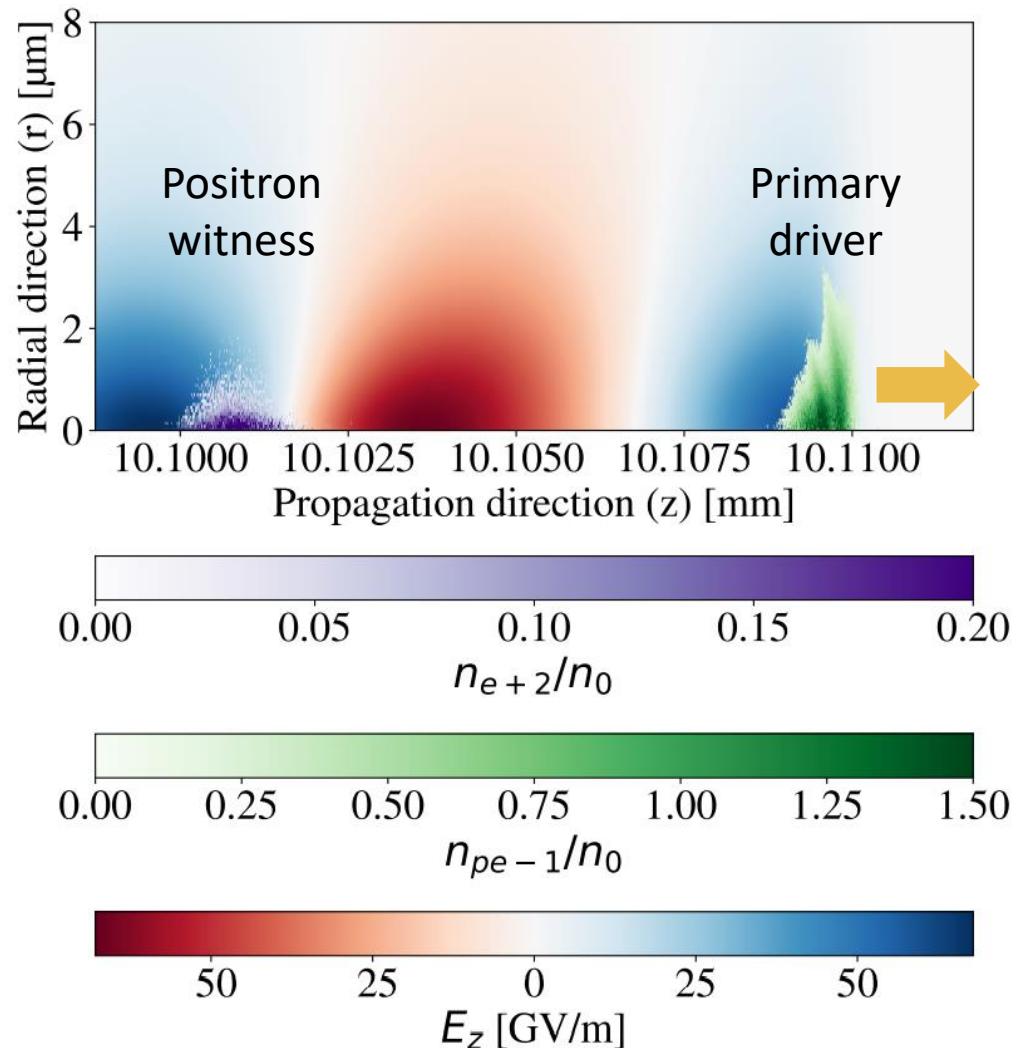
Drift allowed separation of longitudinally overlapping beams with different energies

But due to wide energy spread of positrons

Capture efficiency remained below 1%



Two alternatives that can be explored for BELLA



Laser driven wake captures and accelerates positrons more efficiently



LWFA capillary produced 2 beams with 9 μm gap
PWFA 1 cm plasma

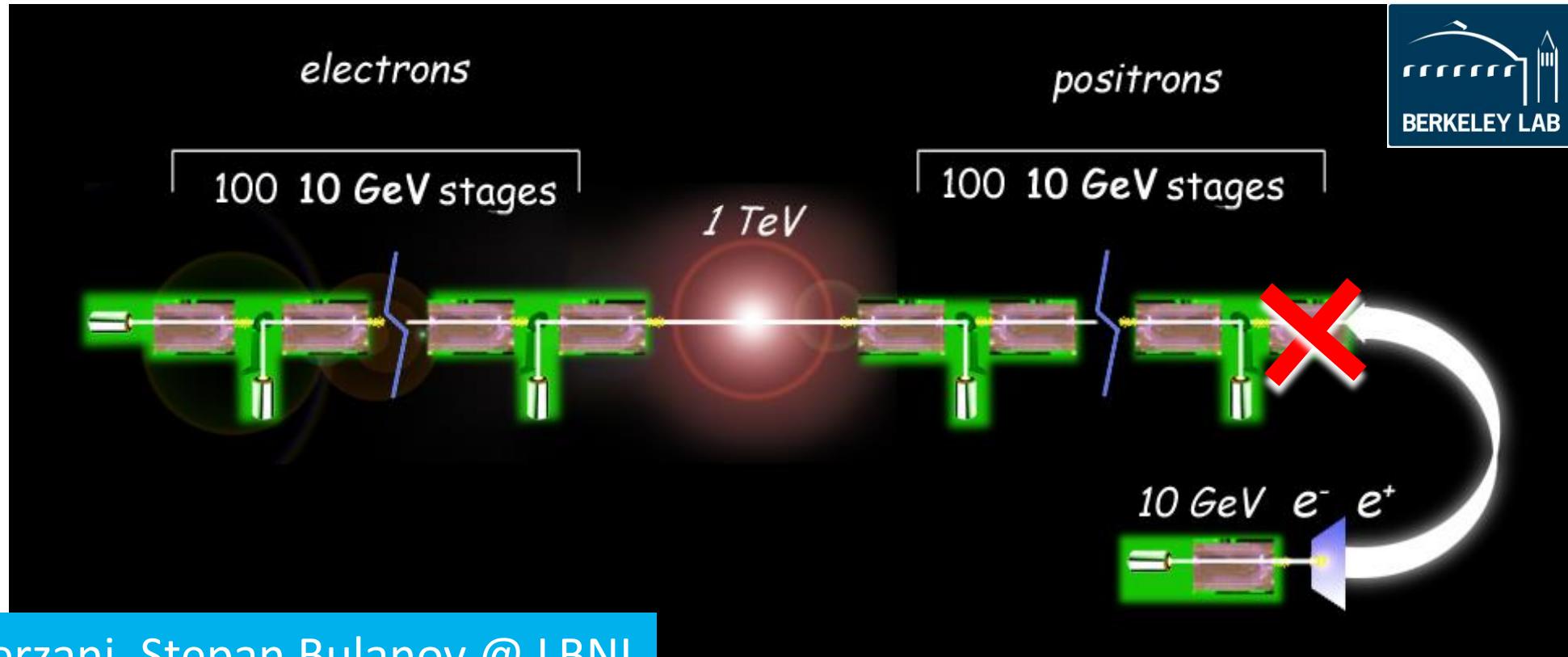
Capture of 11.4 %
 $\sim 12 \text{ GeV/m}$

LWFA capillary produced optimal beam
2nd LWFA 1 cm plasma

Capture of 44.5 %
 $> 20 \text{ GV/m}$ (w beam-loading)

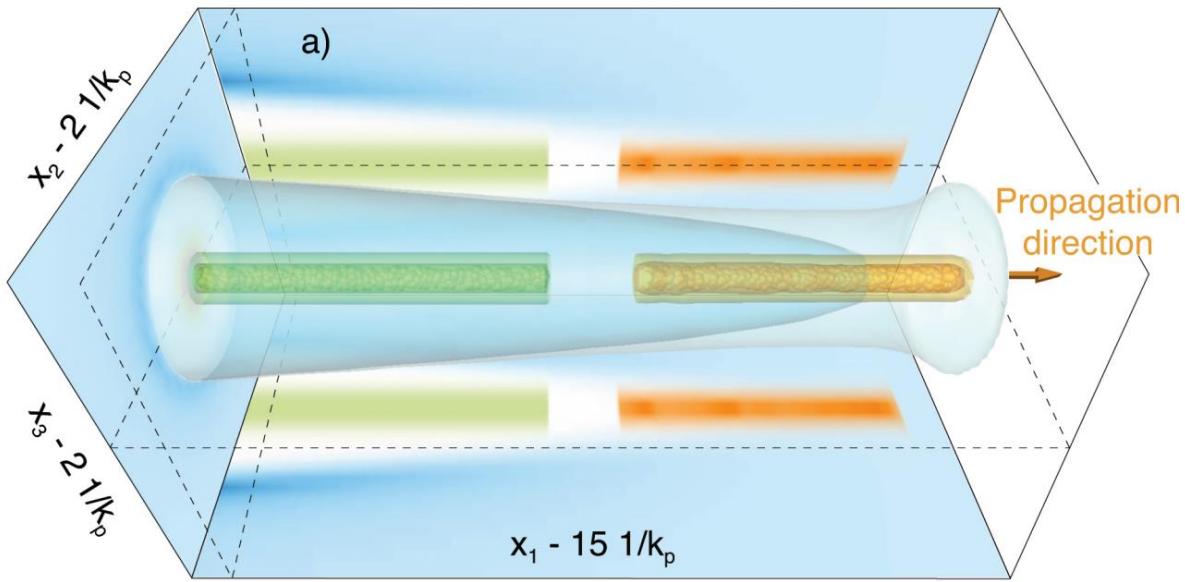
In capture region	Initial	Final
Q [pC]	5.7	4.2
$\langle En \rangle$ [GeV]	1.1	1.6
δEn_{pe} [%]	141.2	110.9
$\sigma_{x,y}$ [μm]	5.59	3.48
σ_r [μm]	7.90	4.92
σ_z [μm]	0.47	0.50
$\theta_{x,y}$ [mrad]	10.1	3.4
$\varepsilon_{x,y}$ [μm]	32.1	20.7

Goal: positron source for future collider plasma stages



Davide Terzani, Stepan Bulanov @ LBNL
dterzani@lbl.gov, sbulanov@lbl.gov

2 positron beams PWFA

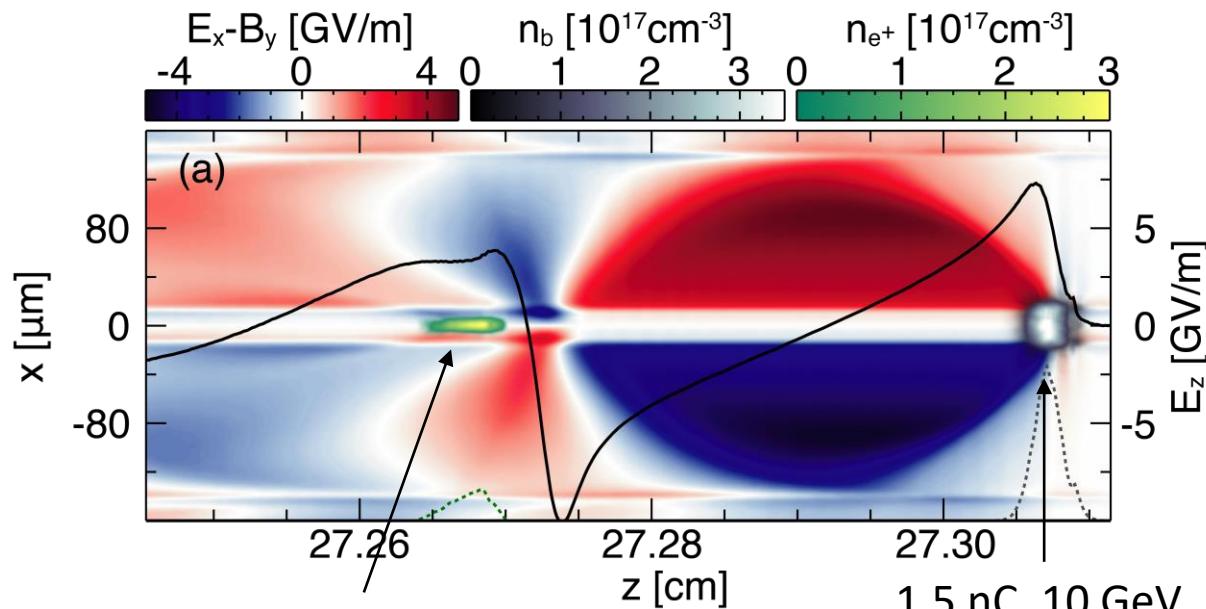


Tightly focused driver defocuses ions and creates hollow channel

Channel accelerates & focuses positrons due to overshooting electrons

Challenge: trailing beam needs low charge

Thin channels with warm electrons



100 pC, 0.5 GeV
positron beam

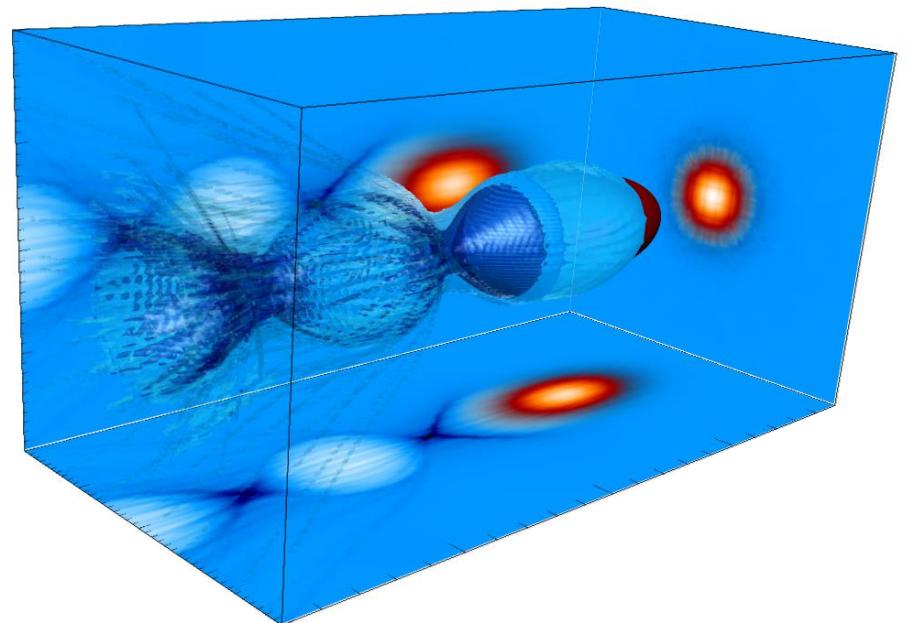
beam breakup damped!

Thales Silva @ IST
thales.silva@tecnico.ulisboa.pt

Plasma wakefield accelerators using ionization (e-) / external (e+) injection

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EAAC 2021, 23/09/2021



Thank you!

Supervisors/PIs	Jorge Vieira, Luís O. Silva, Warren B. Mori, Chandrashekhar J. Joshi, Navid Vafaei-Najafabadi, Jean-Luc Vay
Mentors	Patric Muggli, Ricardo Fonseca, Marija Vranic, Frederico Fiúza, Nuno Lemos and E. Paulo Alves
Collaborators and co-workers	Paulo Ratinho, Mariana Moreira, Rui Torres, Rui Calado, André Lopes, Andrea Ciraci, Anton Helm, Fábio Cruz, Giannandrea Inchingolo, Nitin Shukla, Thales Silva, Elisabetta Boella, Catarina Bastos, Ujjwal Sinha, Kevin Schoeffler, Anne Stockem, V. Bandhu Pathak, Joana L. Martins, Gareth Williams, Thomas Grismayer and Marta Fajardo, Veronica K. B. Olsen, James Allen, Joel England, Selina Green, Christine Clarke, Carl A. Lindstrom, Brendan D. O'Shea, Spencer Gessner, Michael Litos, Sébastien Corde, Eric Adli, Mark J. Hogan, Vitaly Yakimenko, Eric Welch, Thamine N. Dalichaouch, Asher Davidson, Peicheng Yu, Fei Li, Jeremy Pigeon, Jessica Shaw, Xinlu Xu, Weiming An, Kenneth Marsh, Chris E. Clayton, Benjamin J. Winjum, Felicie Albert, Frank S. Tsung, Sergei Tochitsky and Vitor K. Decyk, Pietro Iapozzuto, Mael Flament, James Welch, Jiayang Yan, Prabhat Kumar, Christine Swinson, Rafal Zgadzaj, Karl Kusche, Mikhail Polyanskiy, Mikhail Fedurin, Chris Cullen, Igor V. Pogorelsky, Marcus Babzien, Roman Samulyak, Vladimir Litvinenko, Michael Downer, Mark A. Palmer, Wes Tabler, Rafael Flores, Fumika Isono, Liona Fan-Chiang, Eloise Yang, Neil Zaim, Severin Diederichs, Luca Fedeli, Yinjian Zhao, Michael Rowan, Edoardo Zoni, Revathi Jambunathan, Tobias Ostermayr, Lieselotte Obst-Huebl, Axel Huebl, Kevin Gott, Hai-En Tsai, Tong Zhou, Olga Shapoval, Lixin Ge, Maxence Thévenet, Cho-Kuen Ng, Sam Barber, Rémi Lehe, David Grote, Henri Vincenti, Andrew Myers, Weiqun Zhang, Stepan S. Bulanov, Carlo Benedetti, Kei Nakamura, Anthony Gonsalves, Csaba Toth, Jeroen van Tilborg, Carl B. Schroeder, Ann Almgren, Cameron G. R. Geddes and Eric Esarey

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FCT SFRH/BD/84851/2012



EuPRAXIA-GA No.653782



Office of Science

Office of Science, US DOE, No. DE-AC02-05CH11231



Office of Science, US DOE and the National Nuclear Security Administration ECP 17-SC-20-SC



Thank you

Enjoy Italy

Questions?

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