Navid Vafaei-Najafabadi

Investigation of Plasma-Based Acceleration at Stony Brook University

Plasma Acceleration Group

Center for Accelerator Science and Education

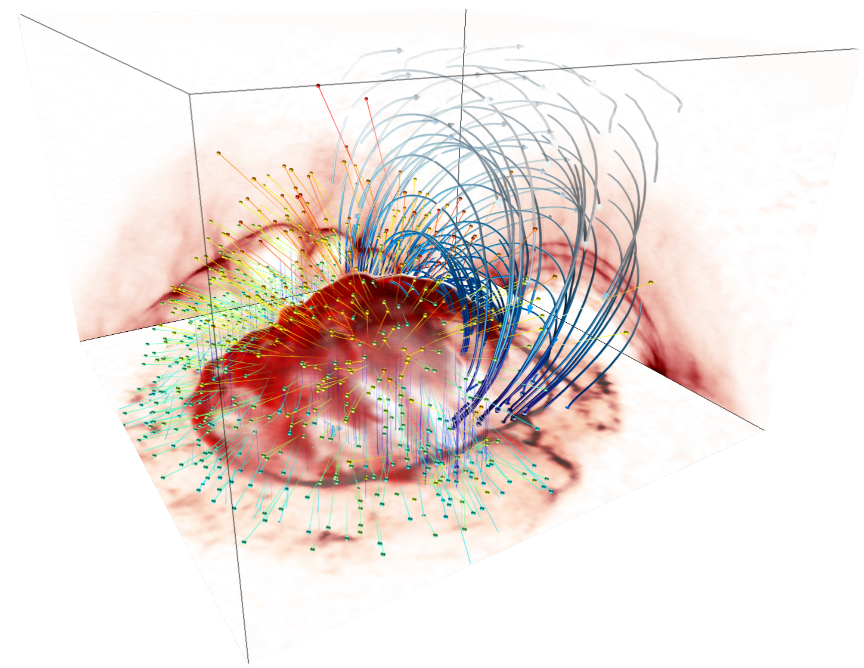
Stony Brook University

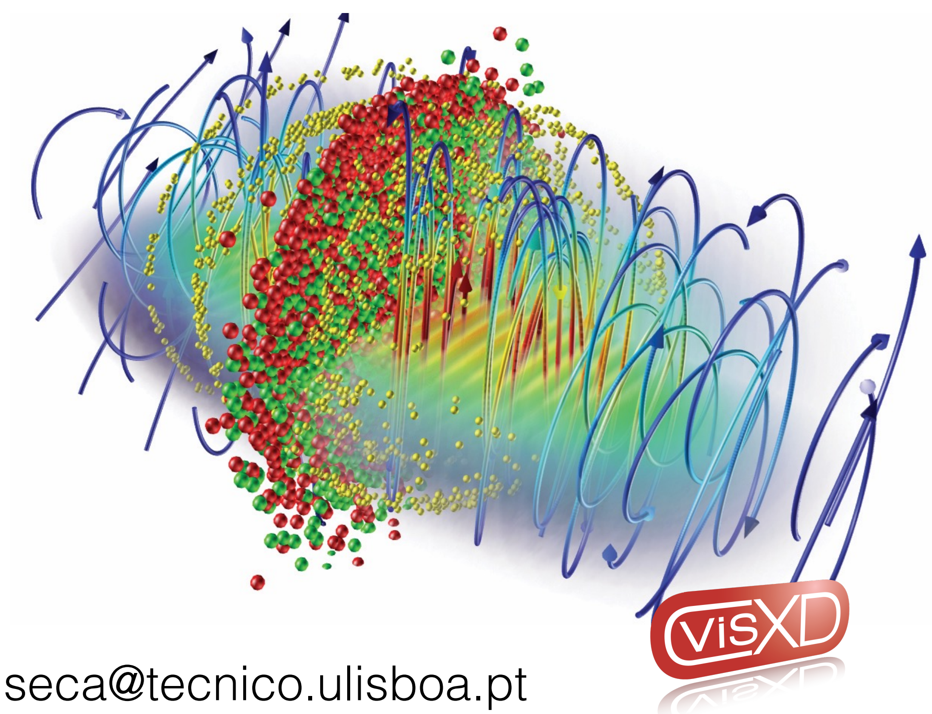
Understanding the Physics Requires Complex Simulation Tools (OSIRIS) and Supercomputers (**CORI**@NERSC and **SEAWULF**@SBU)

Osiris 4.0

osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  ⇒ UCLA + IST





TÉCNICO LISBOA

UCLA

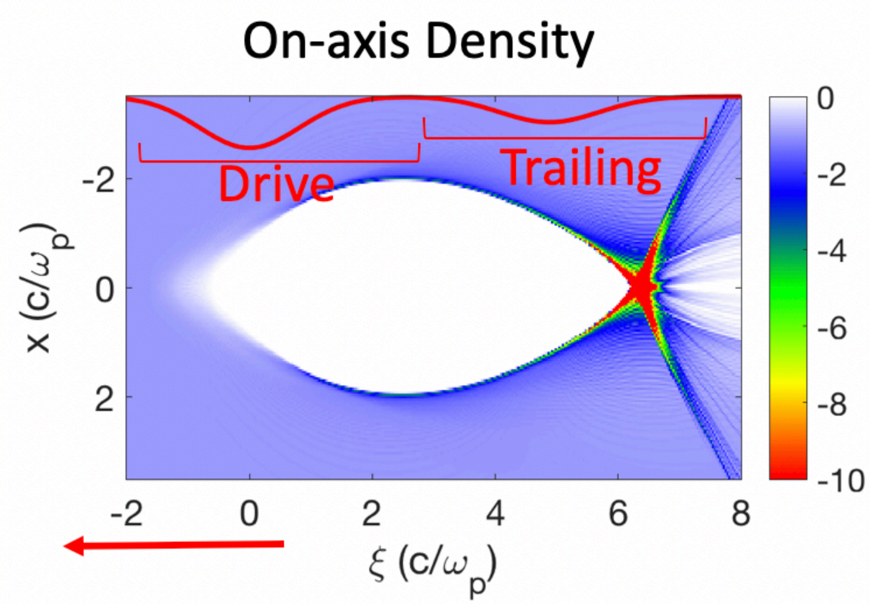
Ricardo Fonseca: ricardo.fonseca@tecnico.ulisboa.pt
Frank Tsung: tsung@physics.ucla.edu

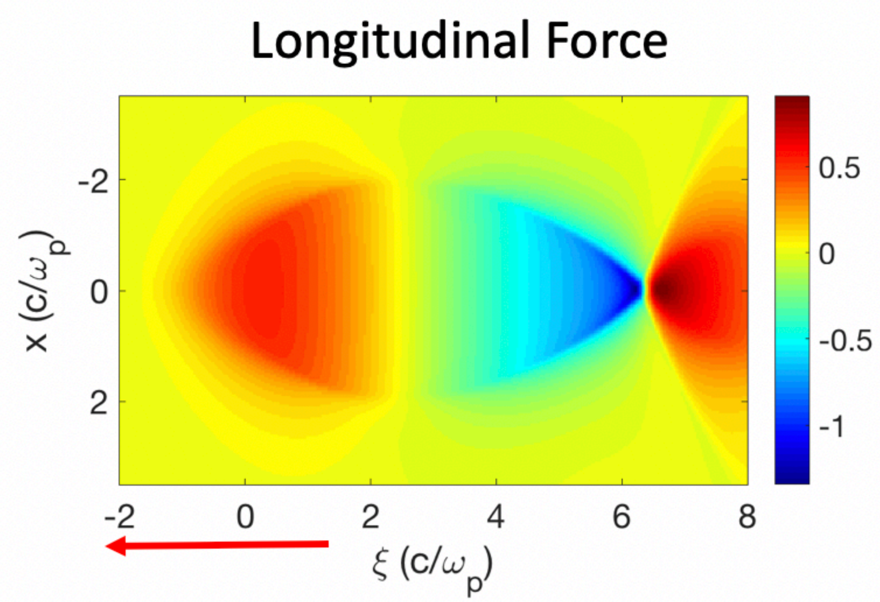
http://epp.tecnico.ulisboa.pt/
http://plasmasim.physics.ucla.edu/

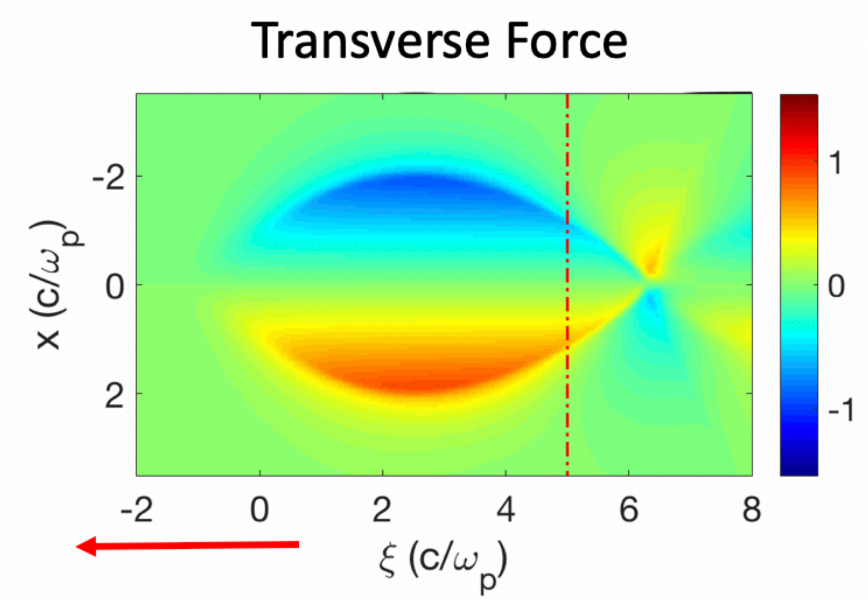
code features

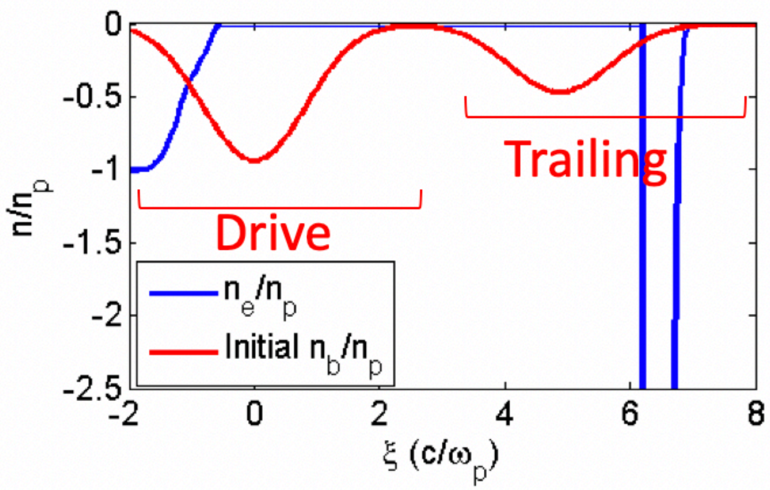
- Scalability to ~ 1.6 M cores
- SIMD hardware optimized
- Parallel I/O
- Dynamic Load Balancing
- QED module
- Particle merging
- GPGPU support
- Xeon Phi support

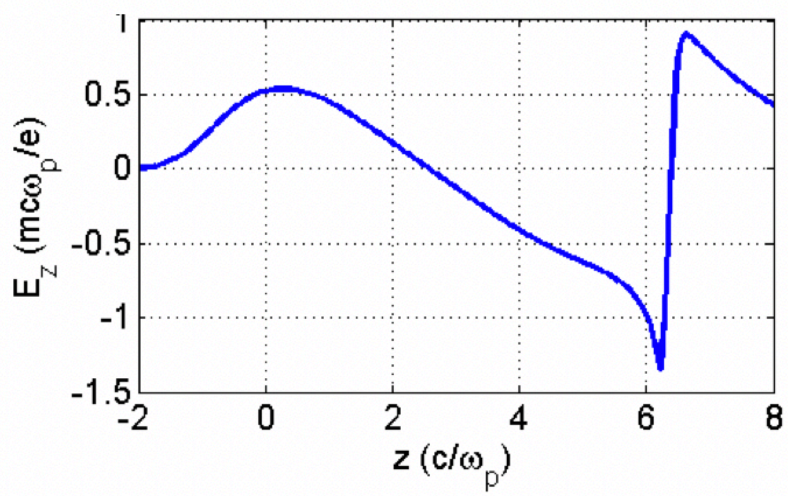
Fields Within the "Blowout" are Ideal for Accelerating and Focusing

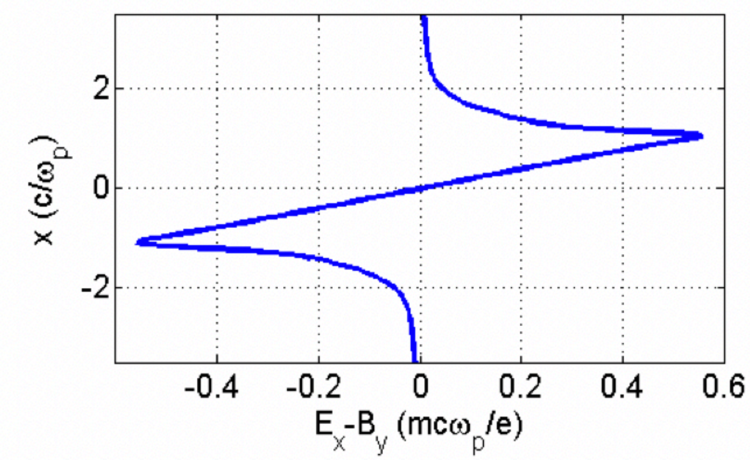












"Blowout regime" occurs as $n_e \rightarrow 0$

Nonlinear accelerating force E normalized to 50 GeV/m

Uniform transversely

Linear Focusing Force, similar to quadrupole magnets in a conventional accelerator

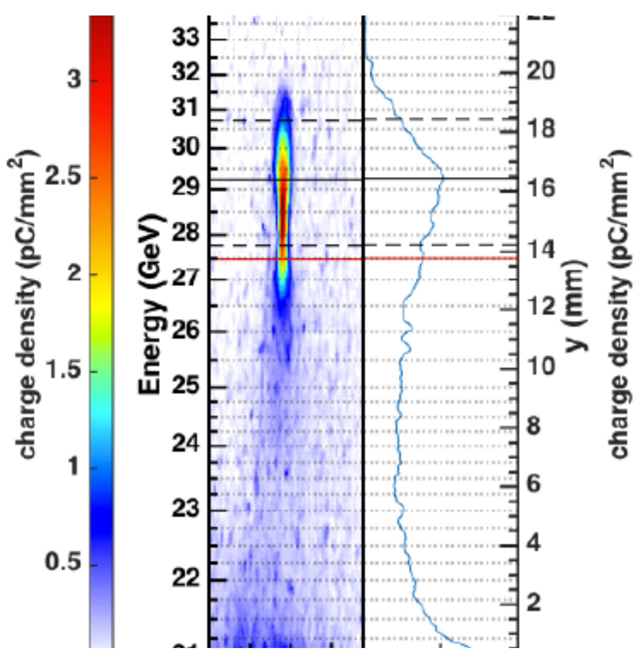
Uniform Longitudinally

SLAC National Accelerator Laboratory

- Final Focus Test Beam (FFTB, 2002-2007)
- Facility for Advanced Accelerator Experimental Tests (FACET, 2012-2016)
- FACET II scheduled to start operation later this year.
- Used the SLAC linac provide compressed, 3 nC, 10-40 GeV electron or positron beam to at 1-10 Hz
- Meter-scale pre-ionized lithium plasma source with typical density ~5x10^{16} cm^{-3}

Status of Plasma Accelerator Results for e- at FACET

HIGH EFFICIENCY ACCELERATION OF NARROW δγ/γ e- BUNCH



9 GeV ENERGY GAIN IN ~1 M IN PWFA

- 1) Scaling of energy gain up to 40+GeV with PA length up-to a meter,
- 2) Narrow energy spread `2-5% , high energy transfer efficiency ~ 20%
- 3) Up to 9 GeV energy gain demonstrated.

- I. Blumenfeld et al Nature 2007,P. Muggli et al. NJP 2010 ,M. Litos et al Nature 2014,M. Litos et al PPCF 2016

Courtesy of Chan Joshi, UCLA

PWFA Research Priorities at FACET-II
Stage 1 Funded. Stage 2 & 3 will Fully Exploit the Potential of FACET-II

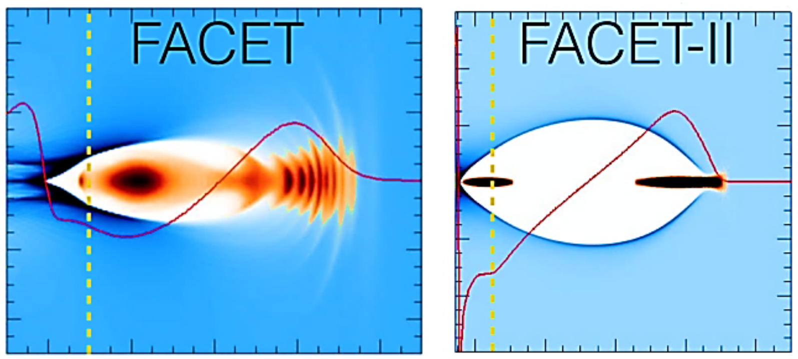
SLAC

Emittance Preservation with Efficient Acceleration

FY19-21

- High-gradient high-efficiency (instantaneous) acceleration has been demonstrated @ FACET
- Full pump-depletion and Emittance preservation at μm level planned as first experiment

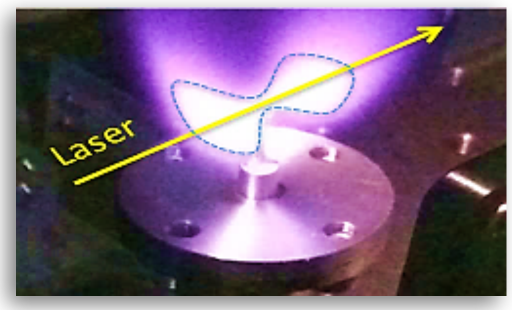
Stage 1

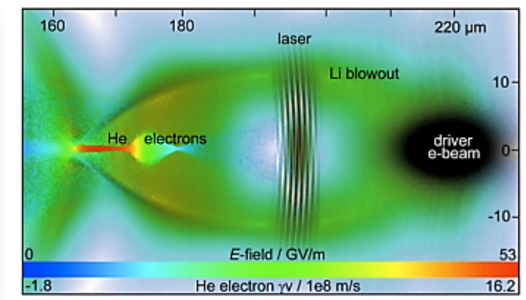


High Brightness Beam Generation & Characterization

FY20-22

- 10's nm emittance preservation is necessary for collider apps
- Ultra-high brightness plasma injectors may lead to first apps





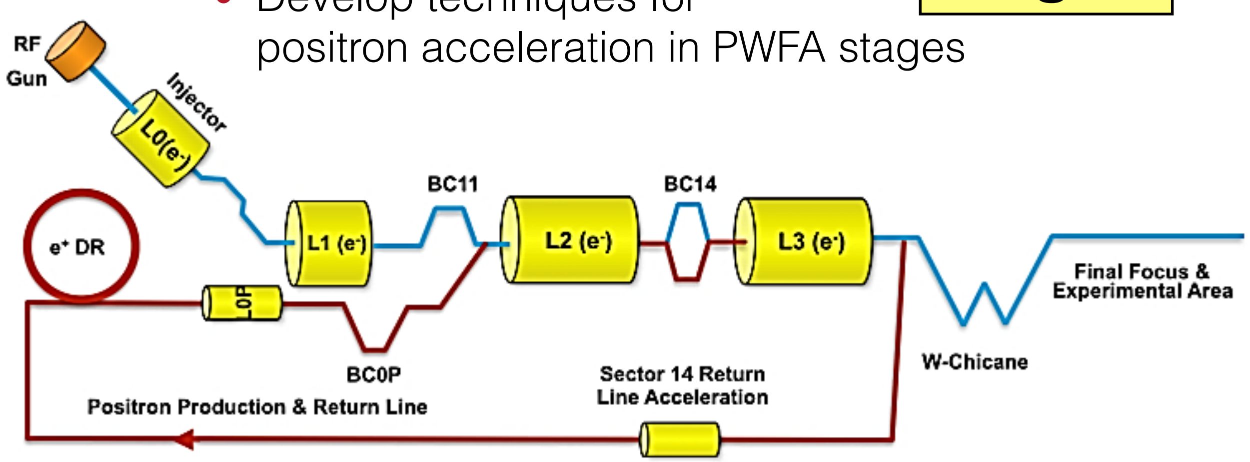
Stage 1

Positron Acceleration

FY21-24

- Only high-current positron capability in the world for PWFA research will be enabled by Phase II
  - Develop techniques for positron acceleration in PWFA stages

Stage 2

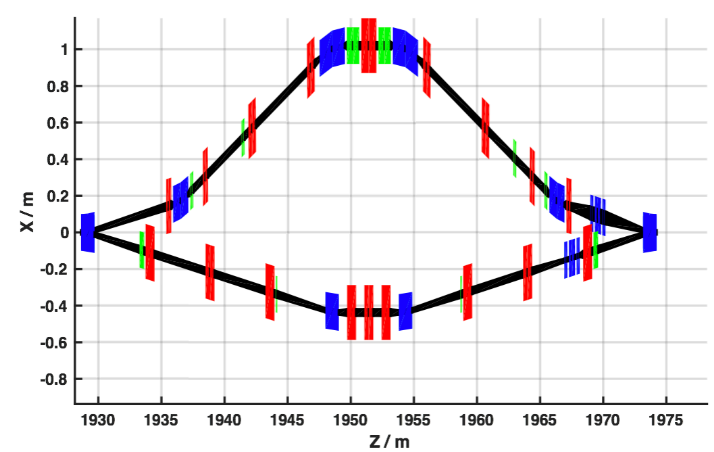


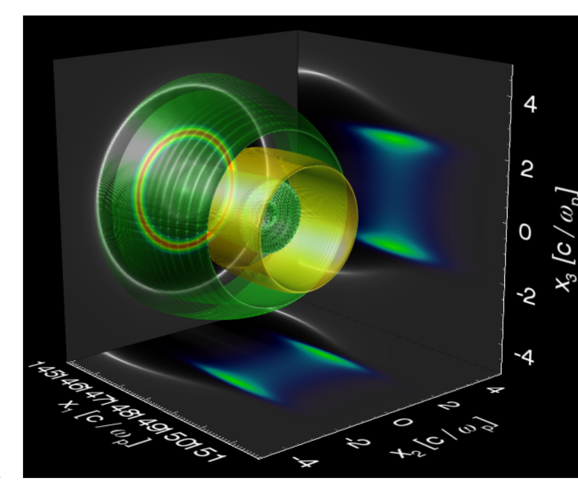
Simultaneous Deliver of Electrons & Positrons

FY22-25

- Positron Acceleration on Electron Beam Driven Wakefields

Stage 3



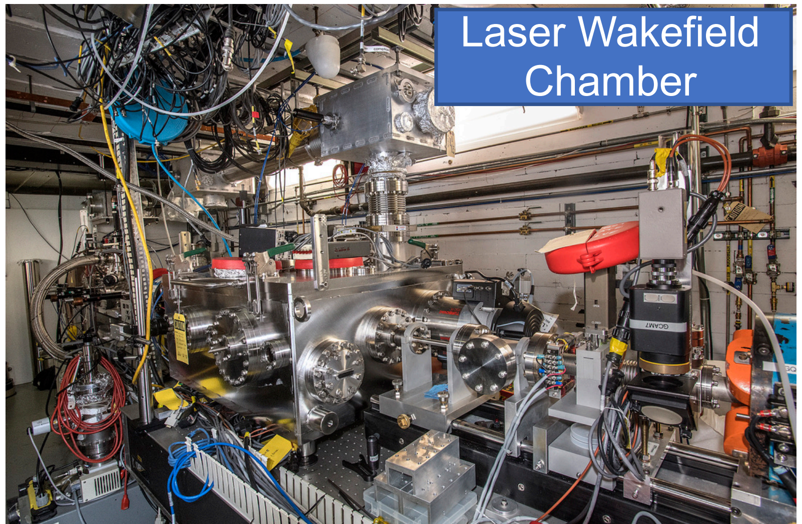


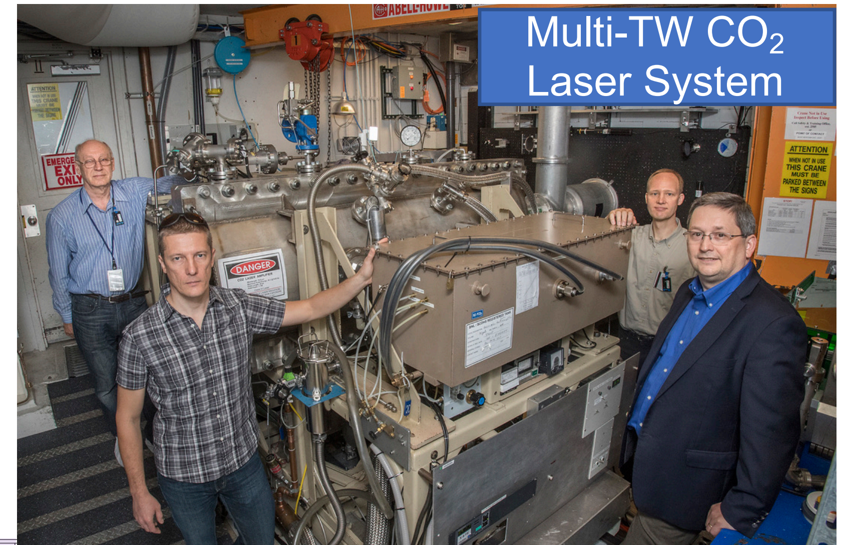
Gradual introduction of capabilities works well with level of demand for FACET-II

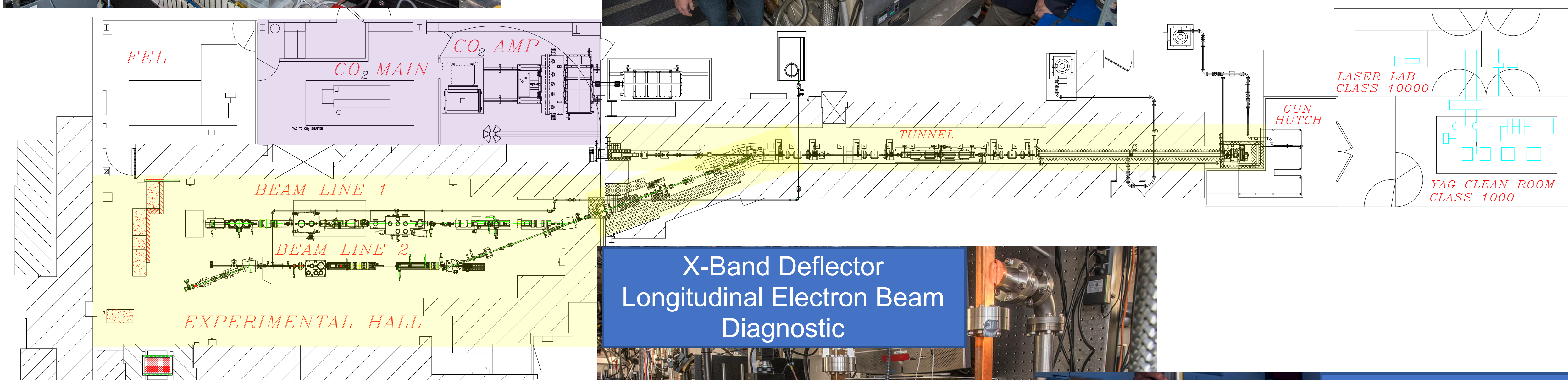
Stony Brook University

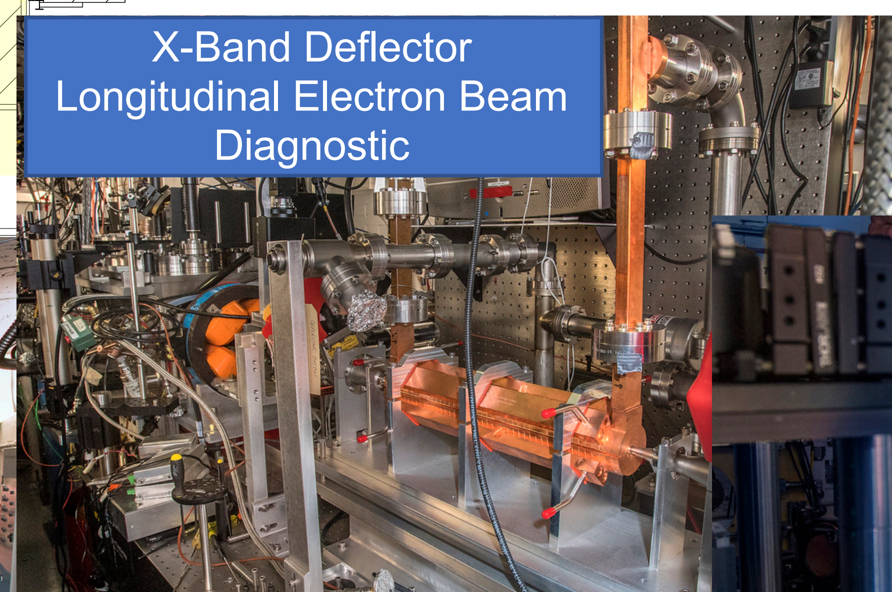
Accelerator Test Facility, BNL

The ATF at B820

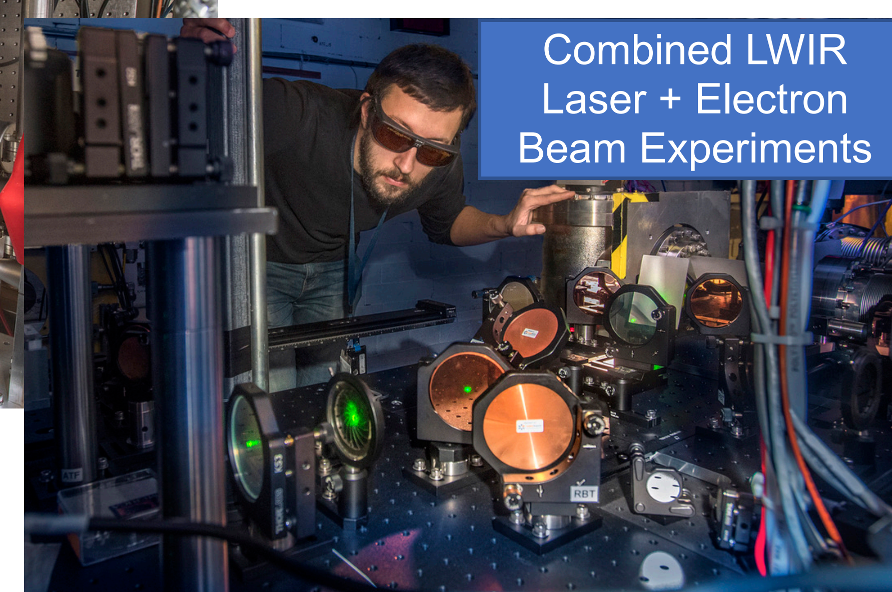

Laser Wakefield Chamber


Multi-TW CO_2 Laser System




X-Band Deflector Longitudinal Electron Beam Diagnostic


ATF Team in Experimental Hall


Combined LWIR Laser + Electron Beam Experiments

Long Term Research Vision at ATF

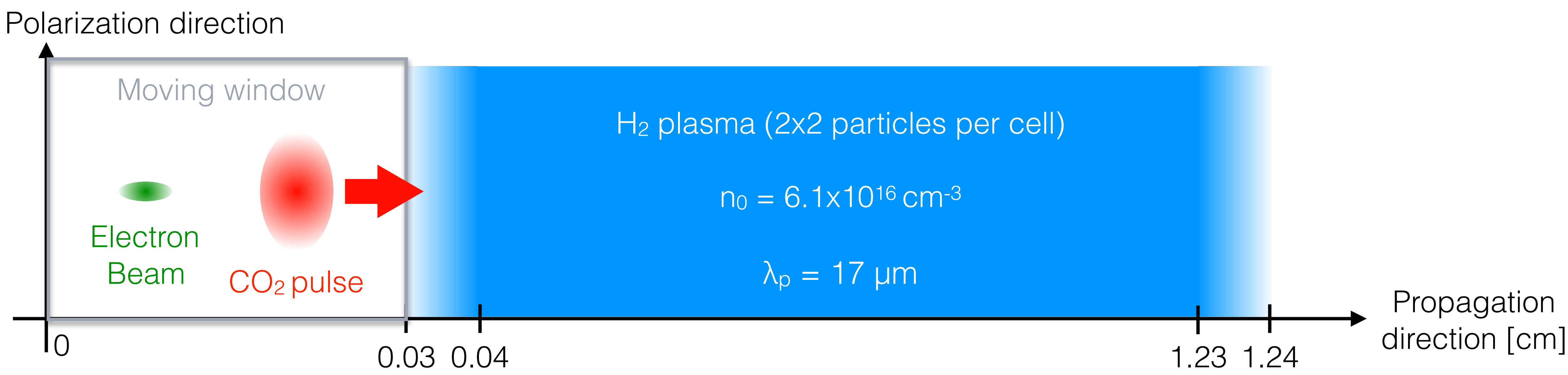
CO_2 Laser power upgrade will enable experimentation in the ideal “blowout” regime

Combination of this high power laser and a linac-produced electron beam makes ATF a unique facility in the US

Future upgrades allows for the study the properties of the fields in the blowout regime as well as the physics of coupling the electron beam to the plasma wake

CO_2 Laser Pulse and H_2 Plasma Chosen for External Injection of ATF Beam Into Wake

Stony Brook University



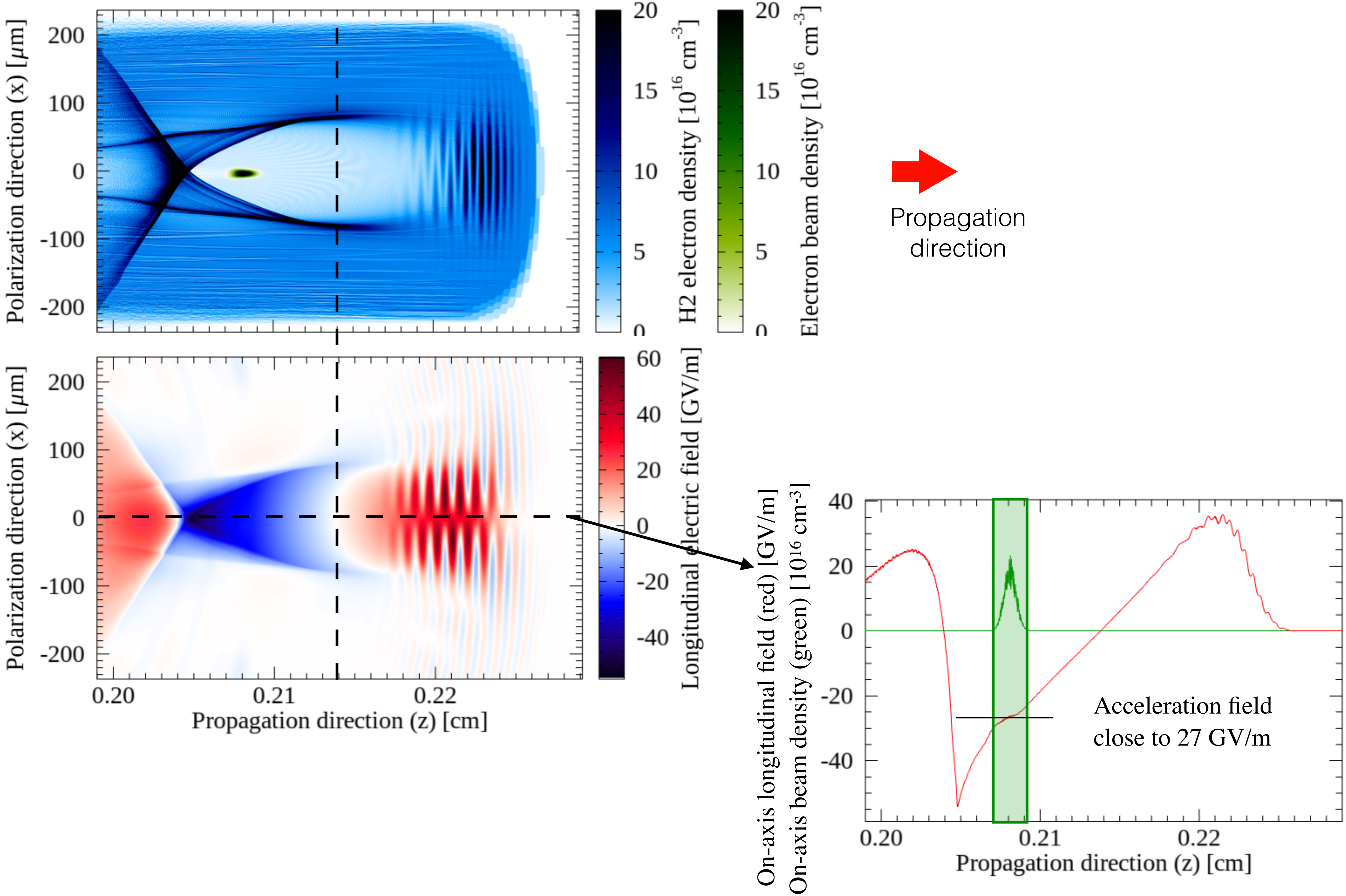
	Duration	Power	λ_0	Spot size	Energy	Intensity	a_0	Rayleigh length	Critical power	Critical Density	Depletion length	Dephasing length
Laser	0.2 ps	20 TW	9 μm	80 μm	4.3 J	3.2×10^{18} W/cm^{-2}	14	0.014 cm	0.06 TW	1.4×10^{19} cm^{-3}	1.4 cm	1.2 cm

	Charge	FWHM length	σ_z	σ_r	n_p/n_0	Energy	Emittance	Particles per cell
e^- beam	0.16 nC	30 fs	3.8 μm	11 μm	2.3	60 MeV	7.5 μm	2x2

	Simulation box - Longitudinal			Simulation box - Transversal			
	Size	Cells per λ_0	Cells per c/ω_p	Size	Cells p. spot size	Cells per c/ω_p	Ionization
Simulation box	303 μm	120	288	475 μm	80	296	Active - ADK

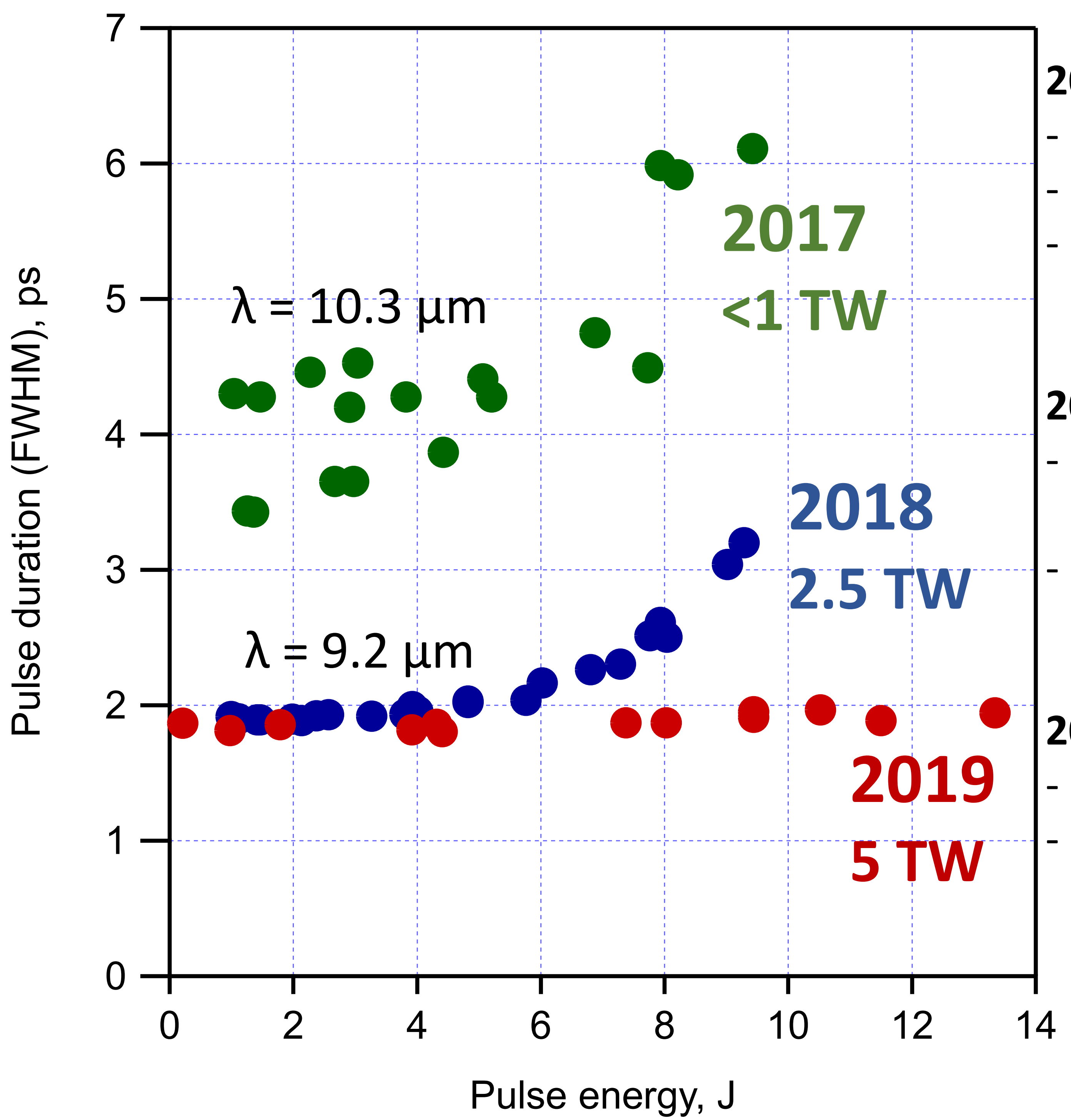
Stony Brook University

Blowout Regime of ~ 200 μm Support Accelerating Field of 27 GV/m



Towards Sub-ps CO_2 Pulses at ATF

Recent CPA CO_2 laser development



2017

- mixed-isotope regen
- 66 % of energy in 1st pulse
- compressor efficiency 50 %

2018

- mixed-isotope regen <u>and</u> final amplifier
- 87 % of energy in 1st pulse

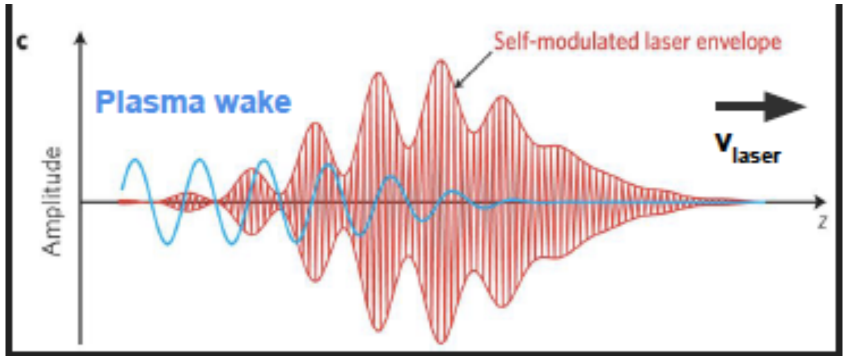
2019

- 2× chirp (denser gratings)
- compressor efficiency 70 %

Current Research

The available laser pulse is currently much longer than the plasma wavelength

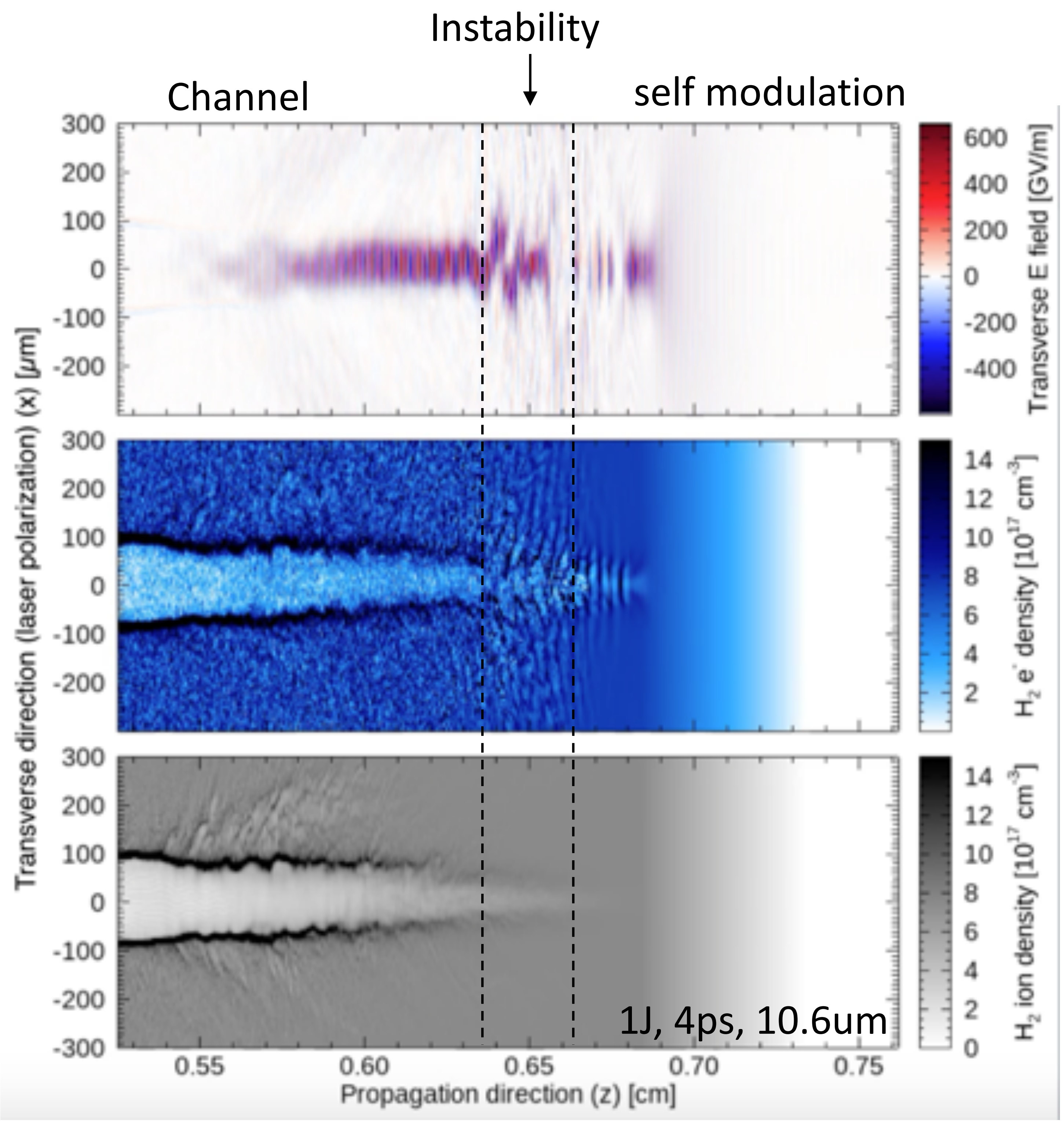
Our experiments are in a regime called self modulation, where the laser pulse is modified by the plasma wave



Late-Stage Self-Modulated Wakefield [1]

We are using laser and electron beam probe to characterize this plasma wave in preparation for our ultimate goal: the external injection of ATF beam into a plasma wakefield in blowout regime

Three Interaction Regions Reflect the Rich Plasma Physics of the Interaction



Radiation and Electron beams generated in this interaction as well as probing the structures with e-beam are the subject of near-term studies

Collaboration of SBU & BNL

Established
November 19, 2008

Educating the Next Generation of Accelerator Physicists and Engineers

CASE
Center for Accelerator Science and Education

The goals of CASE are:

- To train scientists and engineers with the aim of advancing the field of accelerator science;
- To develop an unique educational program that will provide broad access to research accelerators;
- To expand interdisciplinary research and education program utilizing accelerators.

The Accelerator Base

- BNL has the largest assembly of advanced accelerators in the U.S. engaged in a broad spectrum of sciences;
- An Accelerator Test Facility has a national user program in accelerator research;
- Many outstanding BNL scientists already affiliated with and teaching at SBU.

http://case.physics.stonybrook.edu/index.php/Main_Page

Conclusions

- Plasma wakefield accelerators use particle and laser beams to create high accelerating field in blowout regime in plasma
- Stony Brook University is an active collaborator in plasma wakefield research at National User Facilities, in particular FACET and ATF.
  - FACET: Experiments at FACET aim to investigate energy doubling and quality preservation, novel methods of injection for producing high brightness electron beams and plasma acceleration of positrons
  - ATF at BNL: Experiments at ATF aim to demonstrate high quality injection of electron beams in a large plasma wakefield driven by a CO_2 mid-IR laser
    - Laser upgrades at ATF pave the path for enabling the blowout regime of experimentation with a mid-IR laser
    - Meanwhile experiments are ongoing to investigate the interaction of long-pulse laser with plasma

Stony Brook University

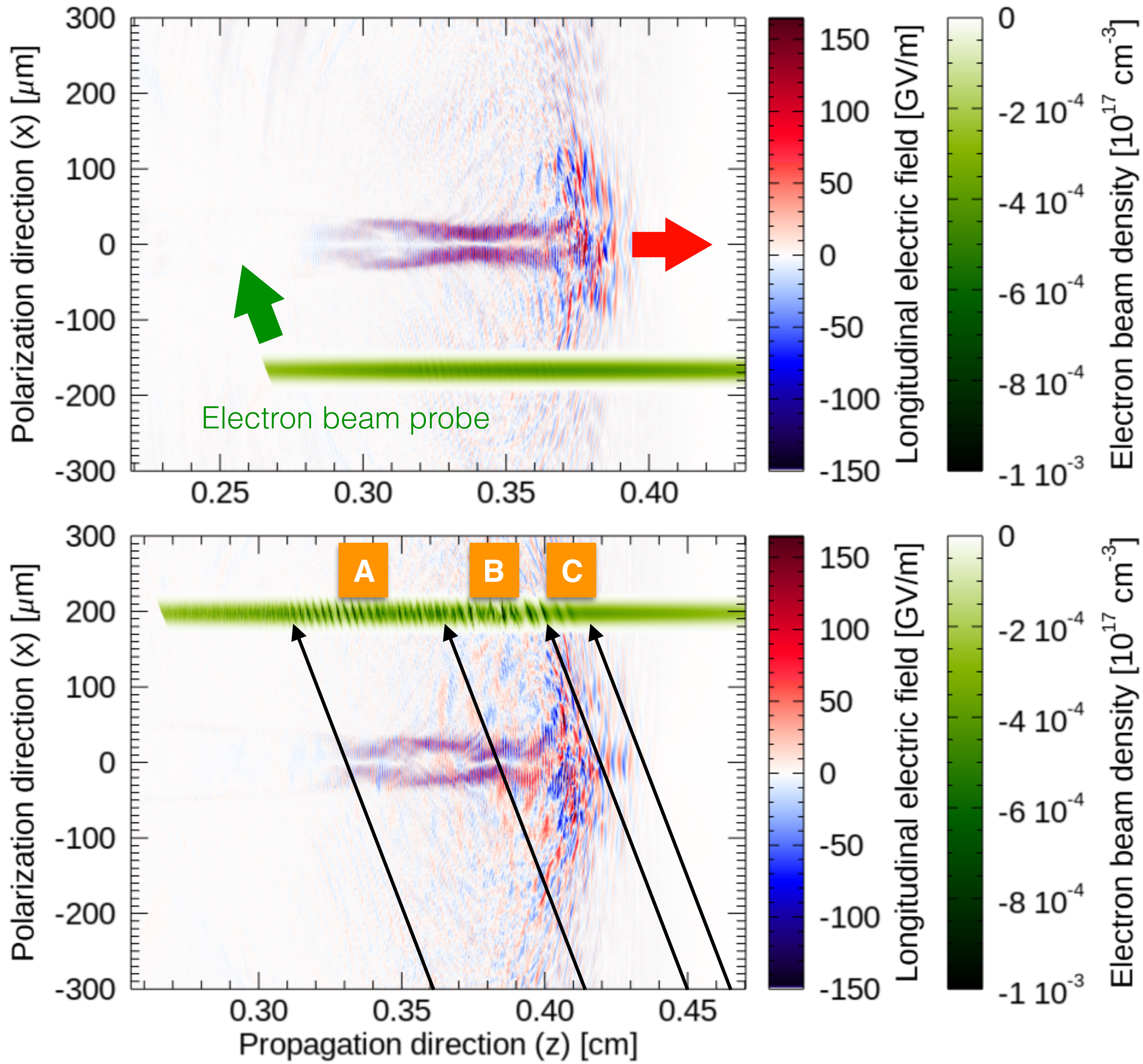
The End

Electron Beam Probe will Encode the Density Modulations in ATF Experiments

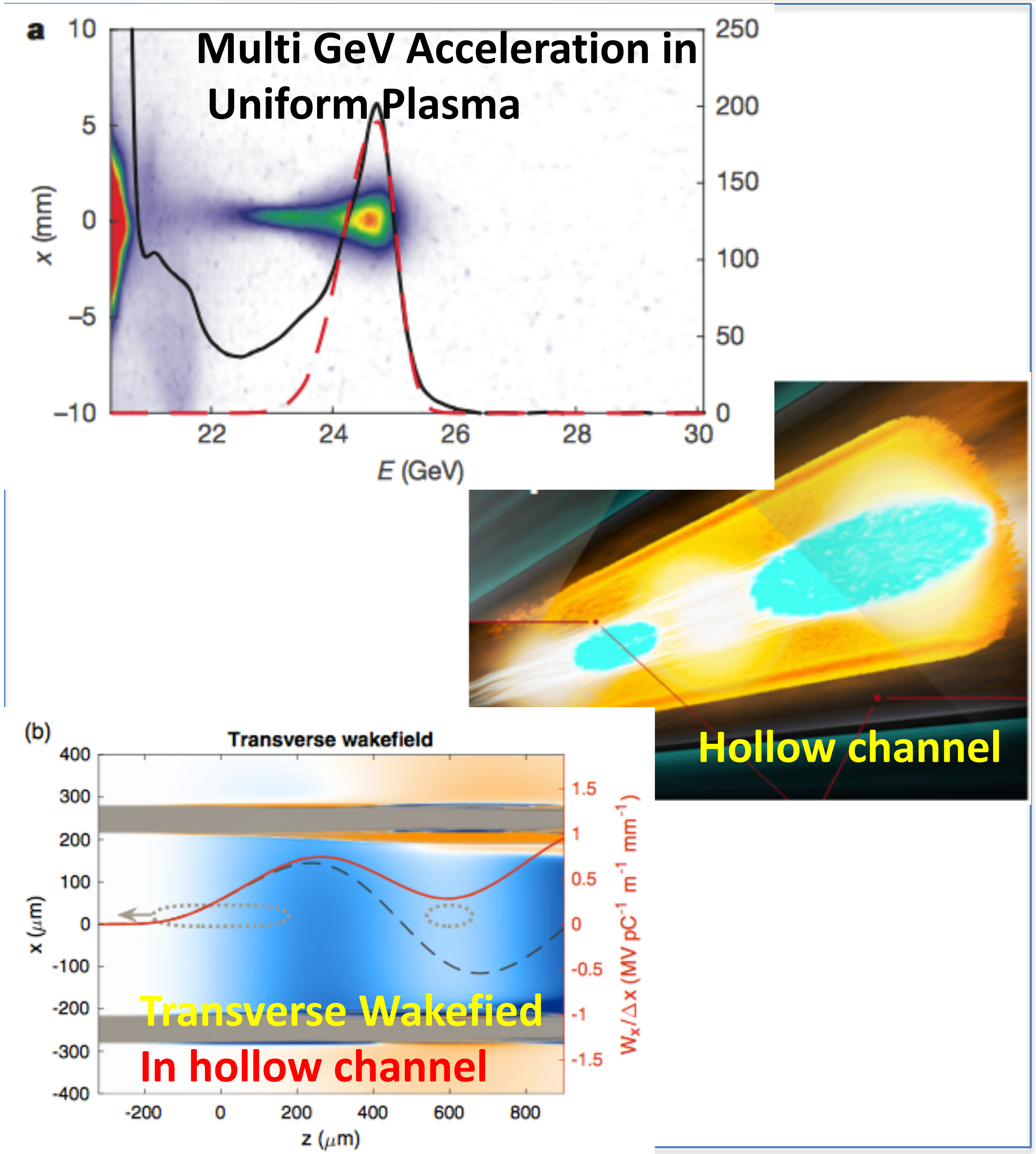
Part A of probe beam is modulated close to CO2 frequency (inside the channel)

Part B experiences the strongly nonlinear “hosing-like” fields

Part C goes through wakefields in more linear regime where CO_2 self-modulates



Status of PWFA Results for e+ at FACET



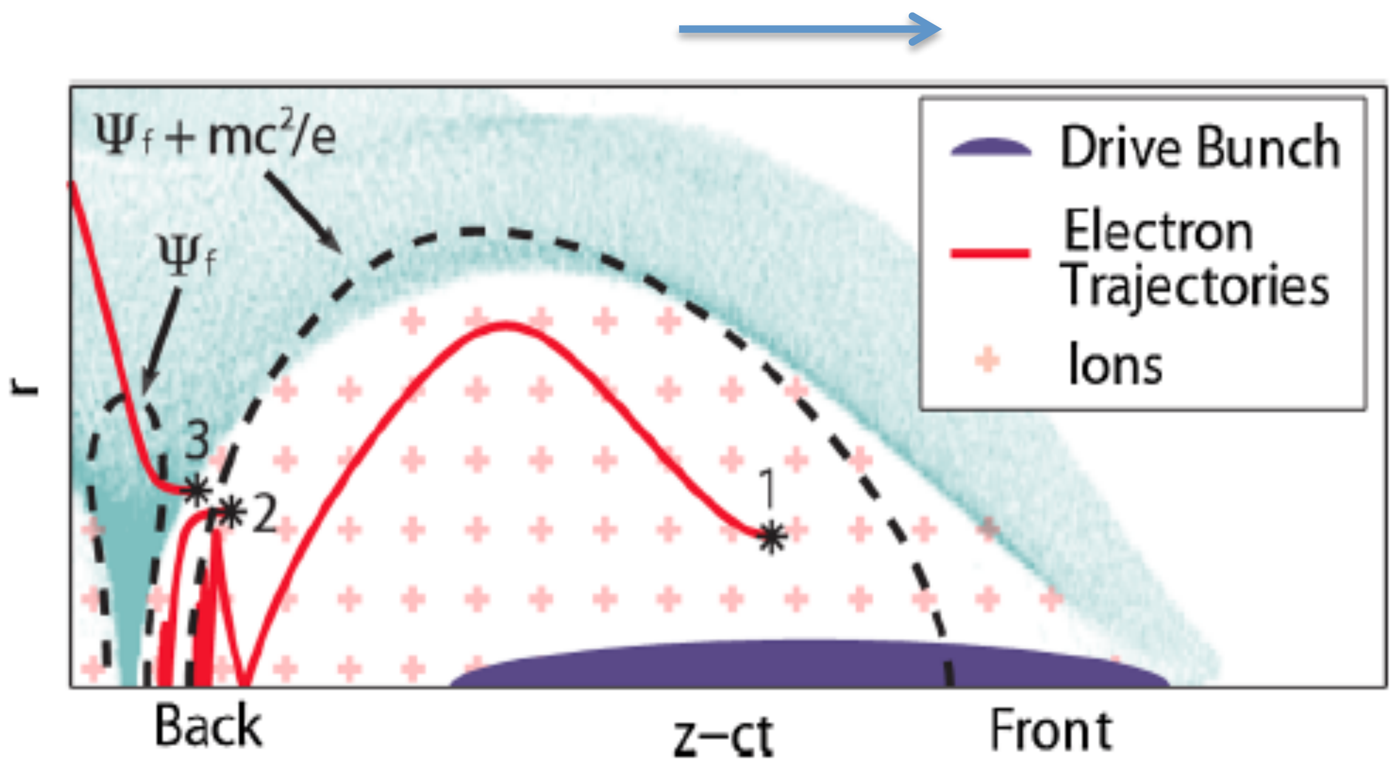
A New Regime for splitting of a positron bunch and energy transfer from the front to the split part of the bunch.
4+ GeV energy gain with a 5% energy spread obtained.
S. Corde et al Nature 2015

Positron propagation, wake excitation, acceleration and in a 30 cm hollow plasma channel
S. Gessner et al Nature Com 2016 ,

Accurate mapping of transverse wakefields in a hollow plasma channel due to off-axis drive bunch propagation
C. Lindstrom et al PRL 2018

Courtesy of Chan Joshi, UCLA

A Method for Injecting Accelerating Bunches: Ionization Injection



E. Oz, et al., PRL, 98, 084801 (2007)
N. Kirby, et al., PRSTAB,12, 051302(2009)

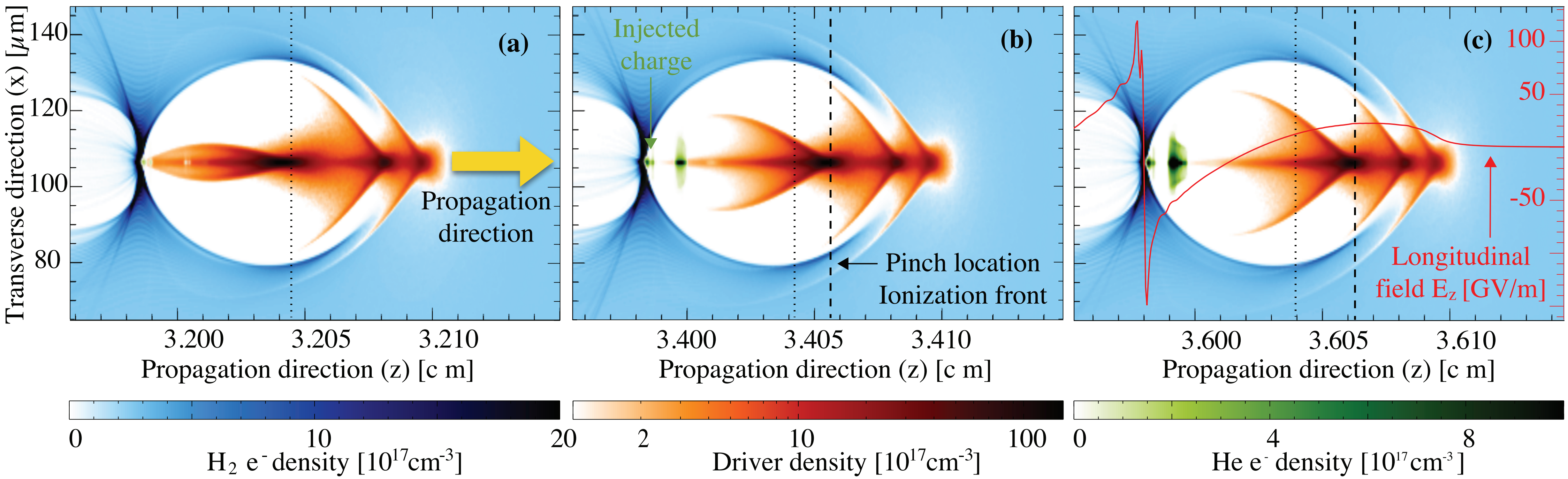
Trapping Condition: $\Delta\bar{\Psi} \leq -1$

$$\bar{\Psi} = \frac{e}{mc^2}(\phi - v_\phi A_z)$$

Pseudo potential

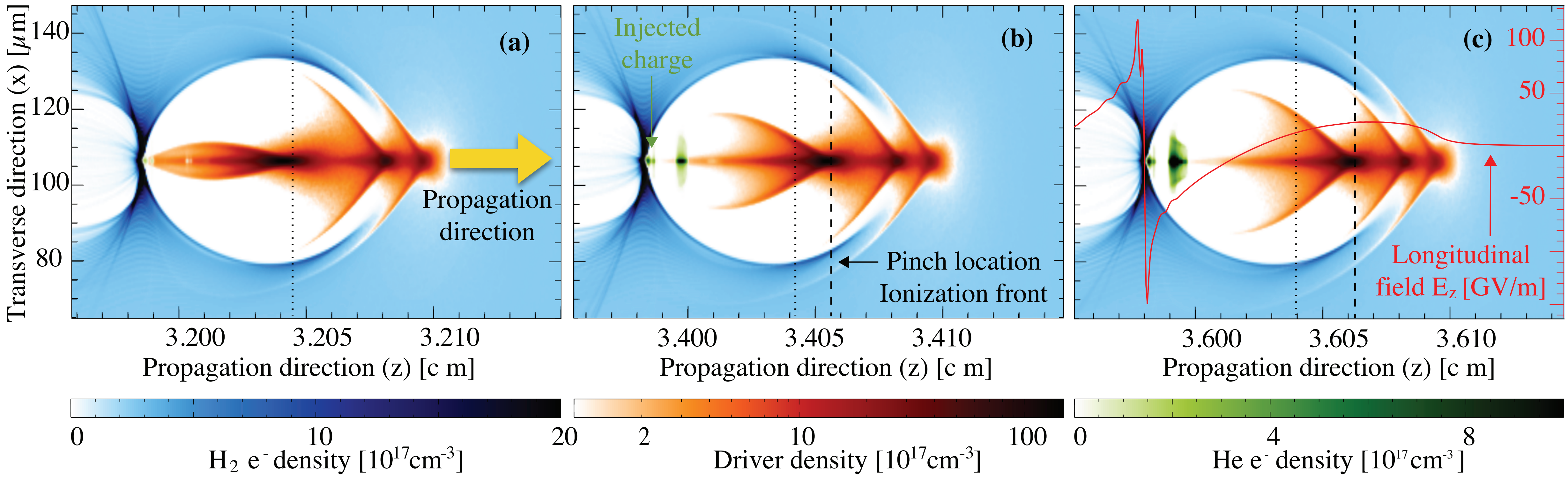
Phase velocity

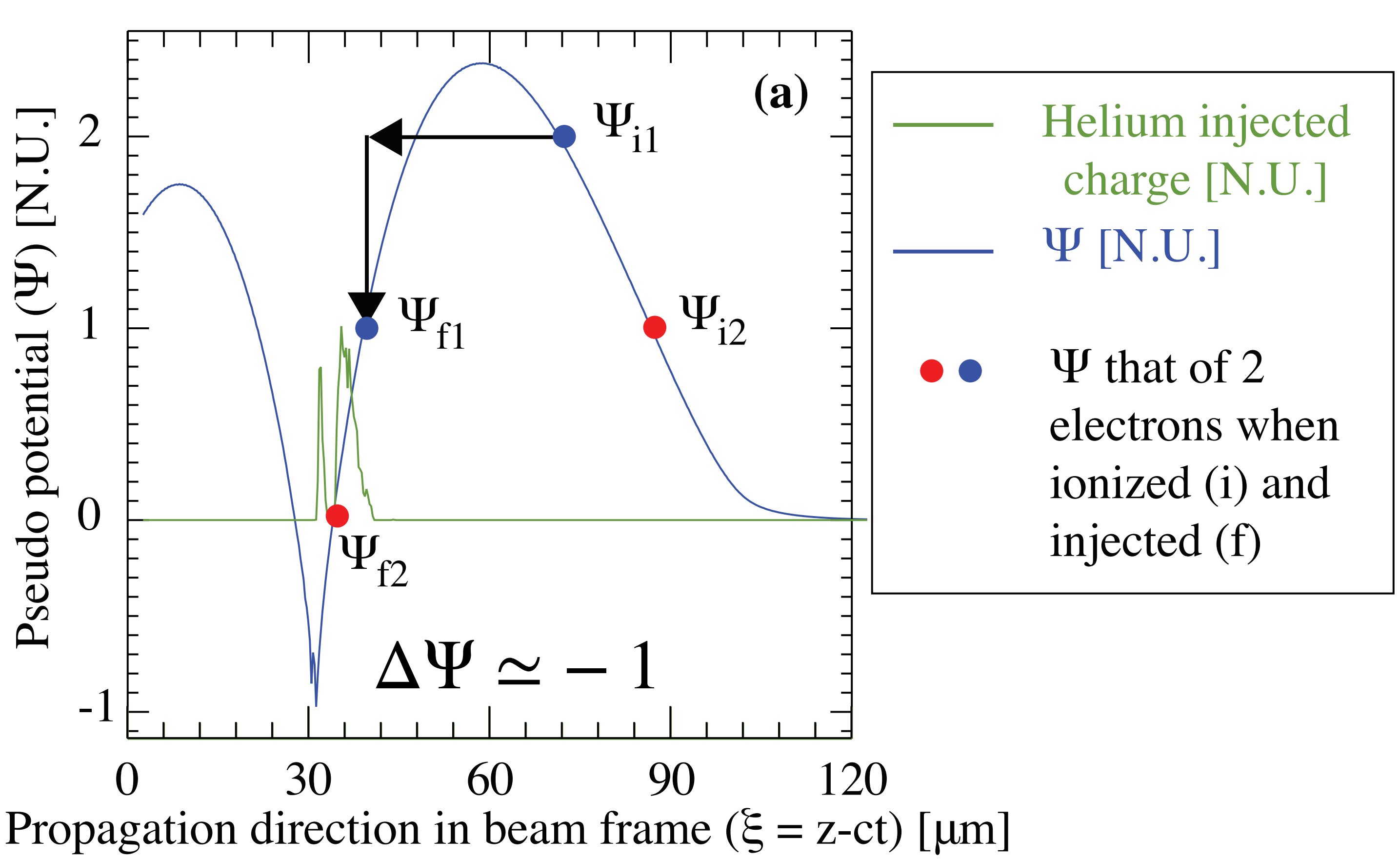
"Pinch" Feature

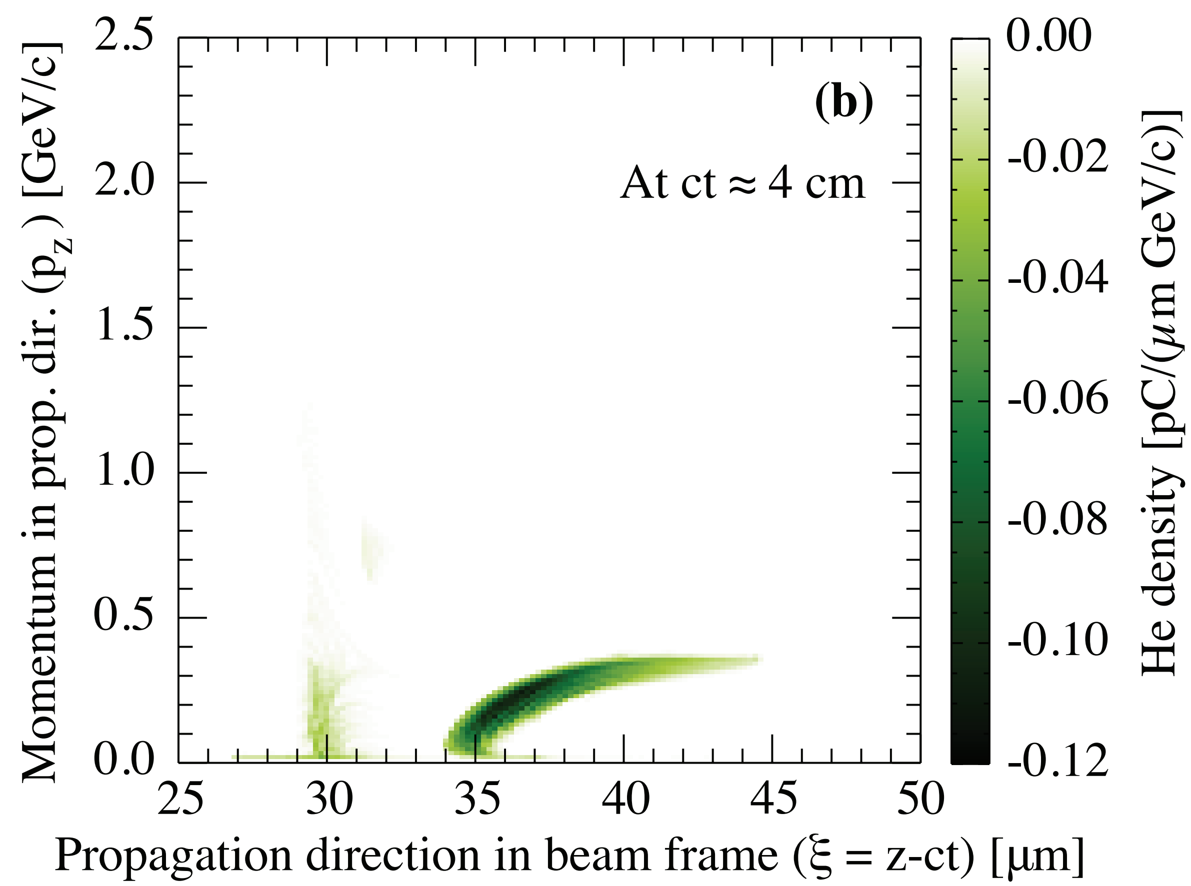


Ionization front identified on the moving dashed line

One-to-One Mapping Between Ionization and Injection Allows Bunch Shaping

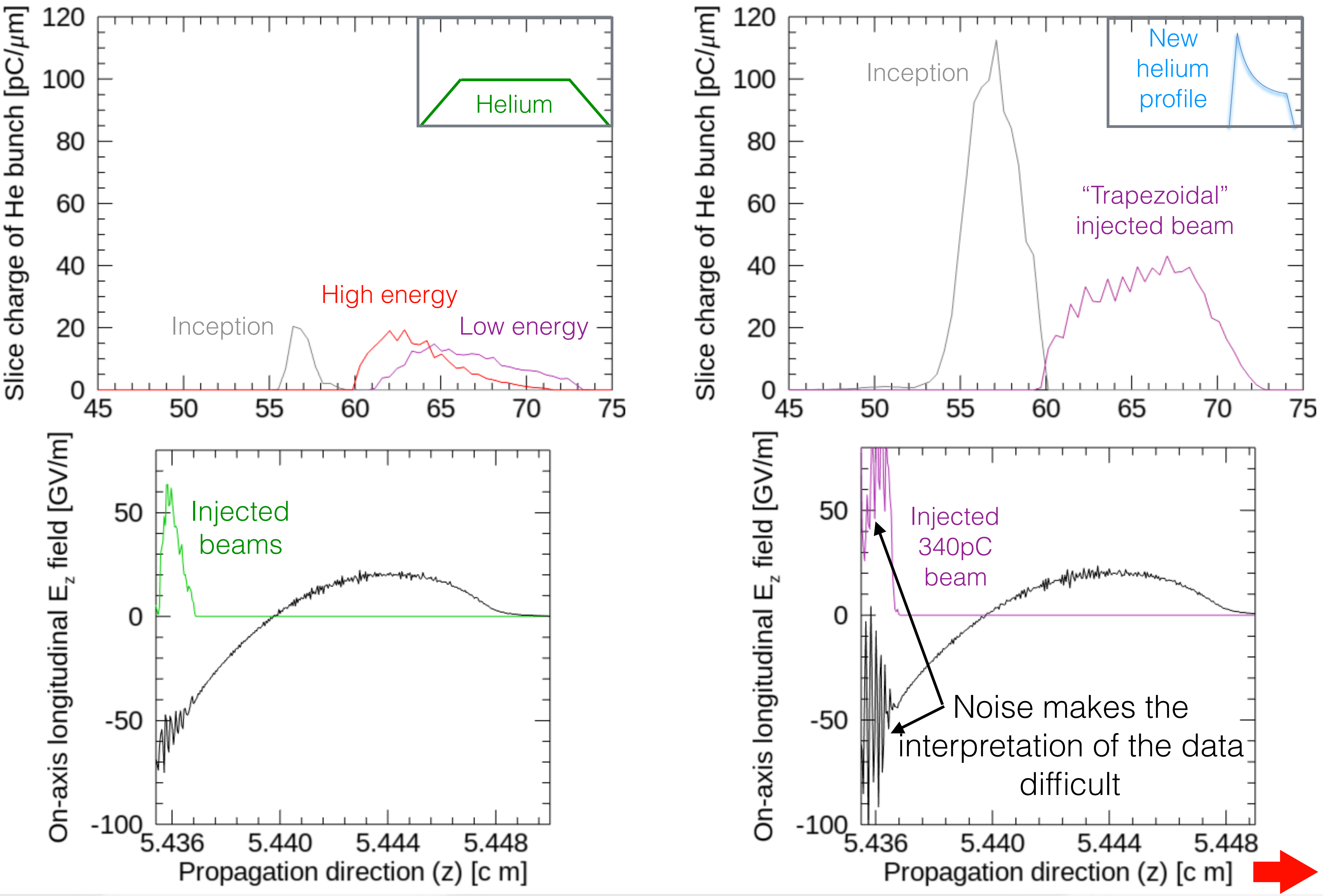






By controlling the concentration of impurity in each pinching location we can control the final beam density profile

Beam Profiles Injected with Different Density Regions



FACET Collaboration

N. Vafaei-Najafabadi

C.E. Clayton, K.A. Marsh, W. An, W. Lu, F. Tsung, W.B. Mori, C.Joshi

S. Corde, A. Doche

E. Adli, C. Lindtrom

J. Allen, C.I. Clarke, J.P. Delahaye, R.J. England, A.S. Fisher, J. Frederico, S. Gessner, S.Z. Green, N. Lipkowitz, G. White, J. Yocky , M.J. Hogan, V. Yakimenko

M. Litos

ATF **AE-71** Collaboration

J.Yan, P. Iapozzuto, P. Kaur, P. Kumar, L. Diana Amorim, R. Samulyak, V. N. Litvinenko and N. Vafaei-Najafabadi	@ Stony Brook University, US
I. V. Pogorelsky, M. Babzien, Y. Jing, K. Kusche, M. Polyanskiy, M. Fedurin, M. Palmer	@ Brookhaven National Laboratory, US
J. Welch, R. Zgadzaj, M. Downer	@ University of Texas at Austin, US
W. B. Mori and C. Joshi	@ University of California Los Angeles, US

Acknowledging funding from DOE Grant No. 215125

CORI@NERSC facility, operated under Contract No. DE-AC02-05CH11231

The End