Berkeley
January 24, 2018

Letter from Wim Leemans

Dear Toshi,

Let me start by wishing you a happy birthday and many more years to go. As I mentioned to Gerard in December, I unfortunately cannot attend the celebration of your 70th birthday due to the imminent birth of my first grandchild. Both your birthday and the birth of my oldest daughter's first child are special moments but I hope you understand that I chose to be with family.

In your honor, I did want to share a few personal thoughts. In 1984, my Professor in plasma physics at the University of Brussels made me aware of your and the late John Dawson's groundbreaking paper and the exciting experimental and theoretical work that it had triggered at UCLA. This inspired me to apply to UCLA and I had the good fortune of being accepted into this wonderful group headed by Frank Chen and from 1986 onwards with Chan Joshi, and benefit from the teachings of John Dawson. You had already left in 1985 but your foundational paper created a new field where plasmas become accelerator structures with unprecedented field gradients. The Department of Energy became an early adopter of the pursuit of this concept and it has led to major successes that continue today. This new field at the intersection of plasma physics and accelerator science and technology was underpinned of course also by the revolution in laser technology that was started by Gerard's and Donna Strickland's paper in 1985 on chirped pulse amplification.

Much has happened since the 1979 PRL and the first CPA paper in 1985. From just one group pursuing this exciting new science and technology of laser plasma acceleration in the early nineteen eighties, we move forward nearly 40 years. Our field is now blossoming with many groups and labs all over the world exploring the science behind the coupling of intense short pulse lasers and plasmas and how to build the devices that produce better and better beams with energy ranging from the MeV towards the 10 GeV class and higher. As a testimony for how far we have come, many of the major accelerator labs around the world have strongly embraced the exploration of this new technology, with significant investments and creation of vibrant research groups. Many students and postdocs gravitate to our field as it is intellectually challenging and stimulating, and could lead to many new applications with significant impact to society. Major investments (billion dollar level) have been made in small and large scale facilities, with ELI being the most prominent of this new class of labs that will advance the field significantly. You and Gerard were the major drivers behind the initial spawning of the Extreme Light Infrastructure concept and launch of the projects.

I did have the pleasure to work closely with you during your leadership in the community of laser aficionados in your role of chair of the International Committee of Ultra-Intense Lasers (ICUIL). You initiated connections with the International Committee for Future Accelerators (ICFA) and asked us within ICUIL for ideas on topics that the laser and accelerator communities could jointly work on. I proposed the formation of a special joint task force between ICFA and ICUIL on exploring "lasers for accelerators". You wholeheartedly embraced this and we organized several productive workshops that brought the communities closer together. This eventually led to better coordination and advocacy of advanced laser driven accelerators within the traditional accelerator community, a motivation for the laser community to build better and better lasers and which also has had real impact on how funding agencies are supporting our field. I thank you for your vision for wanting more formal links between ICFA and ICUIL and for being extremely supportive and taking an active role in shaping the long term vision for the field. Gerard of course deserves a lot of credit but he is not being celebrated today. Sorry Gerard!

In closing, I wish you a happy birthday and many more years of enjoyment in contributing to and seeing how the field that the famous Tajima and Dawson paper launched is growing and is having a real positive impact on society. I also wish all the attendees a wonderful two day celebration.

Happy birthday Toshi!

Wim

A Path to Laser Wakefield Accelerators

Eric Esarey

BELLA Program
Accelerator Technology and Applied Physics Division
Lawrence Berkeley National Laboratory

Tajima Symposium, UC Irvine
25 Jan 2018

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

BERKELEY LAB

My Path to Laser Wakefield Accelerators: Fusion and Confusion

- U. Michigan (1978-1981): Plasma physics, fusion
- MIT (1981-1986): Plasma physics, fusion, tokamaks
  - Advisor: Kim Molvig
- First APS Division of Plasma Physics Meeting: New Orleans 1982
  - Dinner with Kim Molvig and Toshi Tajima
  - Both were PhD students of Norman Rostoker
- Prof. Larry Lidsky (MIT): The Trouble with Fusion 1983

The Trouble With Fusion

Long touted as an inexhaustible energy source for the next century, fusion as it is now being developed will almost certainly be too expensive and unreliable for commercial use.

By Lawrence M. Lidsky

MIT Technology Review, October 1983

My Path to Laser Wakefield Accelerators: Star Wars and Laser-Plasmas

- Ron Davidson (MIT): Suggests NRL
  - Phil Sprangle: PhD Student of Norman Rostoker
- Naval Research Lab, Plasma Physics Division (1986-1998)
  - SDI: High power FELs
  - Small contract on laser accelerators: David Sutter, DoE
- Active Program at UCLA
  - Plasma Beat Wave Accelerator: Long pulse CO2 laser
- If only all that laser energy could be put in a single, short pulse…

Generation of Ultrahigh Peak Power Pulses by Chirped Pulse Amplification

P. MAINE, D. STRICKLAND, P. BADO, M. PESSOT, AND G. MOUROU

(*Invited Paper*)

***Abstract*—Single picosecond pulses have been amplified to the terawatt level by a table-top size Nd:glass amplifier by using the technique of chirped pulse amplification (CPA). The divergence of the beam is twice the diffraction limit, making the brightness of this source equal to ~2 × 10^{+18} W/(cm · sr), which is the highest brightness ever reported. The technique of chirped pulse amplification allows the efficient energy extraction from extremely compact amplifier systems. Amplification of chirped pulses over nine orders of magnitude, i.e., from nanojoule to the joule level, has been demonstrated. By using a large-scale Nd:glass amplifier system, it should be possible to extend the technique of CPA to the amplification of 1 ps pulse to the kilojoule level leading to petawatt power pulses. These pulses, once focused, could produce intensity in the range of 10^{23} W/cm², five orders of magnitude over the present state of the art.**

spatial filtering. In the case of dyes and solid-state media, this leads to a critical intensity on the order of 10 GW/cm².

Typically, dye and excimer systems are used to amplify short pulses. These media have broad bandwidths on the order of 20 nm which can support pulsewidths as short as 30 fs. However, these media have low saturation fluence levels of millijoules per square centimeter. 100 fs pulses can be amplified to the saturation level without reaching prohibited peak powers and generating unwanted nonlinear effects. Dye amplifiers are therefore well suited for amplification of short pulses to the millijoule level. Fur-

2146 Appl. Phys. Lett. 53 (22), 28 November 1988 0003-6951/88/482146-03$01.00 2146

Laser wakefield acceleration and relativistic optical guiding

P. Sprangle, E. Esarey,[a)] A. Ting,[a)] and G. Joyce
Plasma Theory Branch, Plasma Physics Division, Naval Research Laboratory, Washington, DC 20375-5000

(Received 8 July 1988; accepted for publication 20 September 1988)

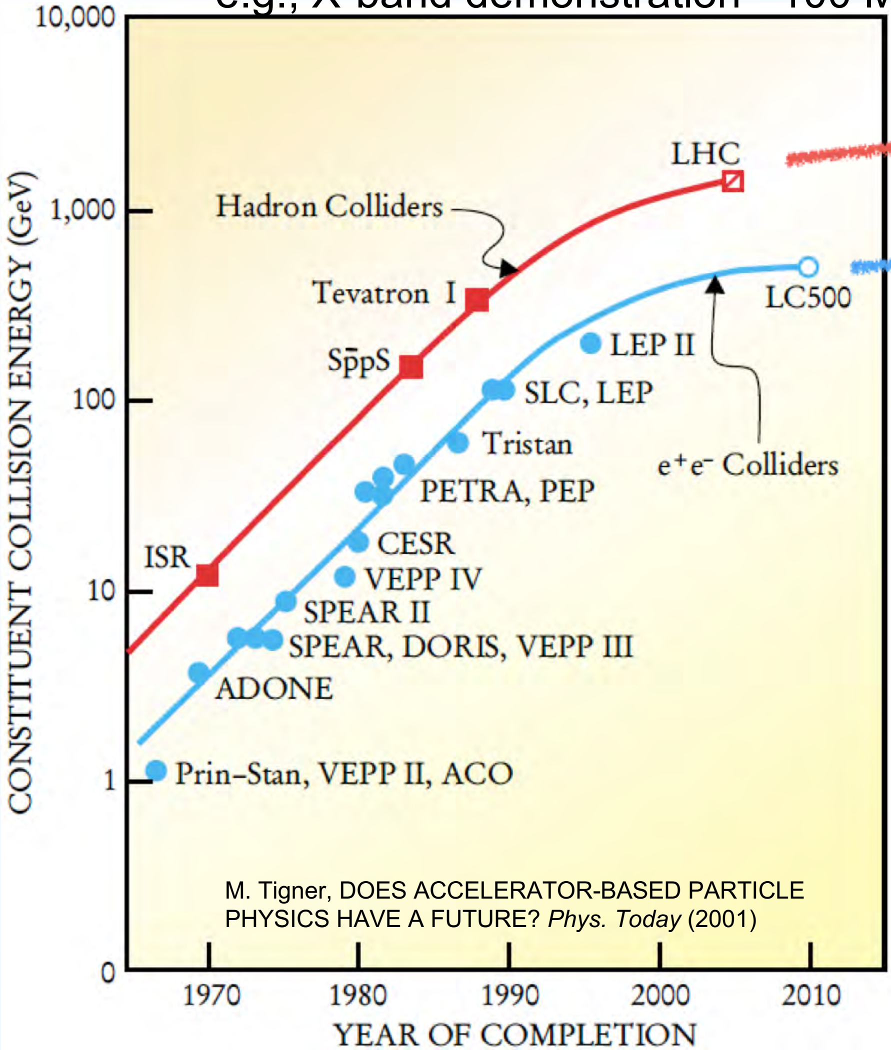
An electron acceleration method is investigated which employs a short ($\tau_L \sim 2\pi\omega_p^{-1} \sim 1$ ps), high-power ($P \geqslant 10^{15}$ W), single frequency laser pulse to generate large amplitude ($E \geqslant 1$ GeV/m) plasma waves (wakefields). At sufficiently high laser powers [$P \geqslant 17(\omega/\omega_p)^2$ GW], relativistic optical guiding may be used to prevent the pulse from diffracting within the plasma.

My Path to Laser Wakefield Accelerators: From NRL to LBNL

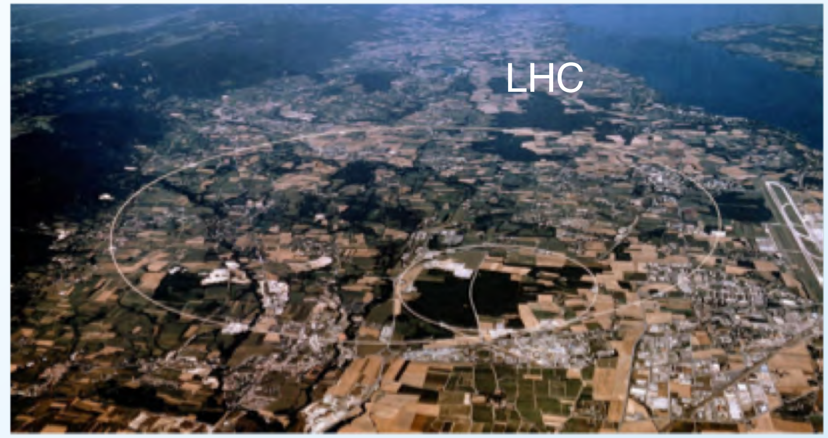
- If only all that laser energy could be put in a single, short pulse…
- Chirped Pulse Amplification: Gerard Mourou et al (1985-1988)
- "Laser Wakefield Accelerator'': Sprangle, Esarey et al (1988)
- Don Umstadter (Michigan) contacts me regarding LWFA (1989)
  - Visits to U. Michigan
- First Advanced Accelerator Concepts Workshop:
  - Lake Arrowhead CA (1989)
  - Met C. Joshi, J. Dawson, Wim Leemans….
- NRL acquires TW laser from Positive Light (early 1990s)
- Self-modulated LWFA experiments (mid 1990s)
  - Many electrons, Many labs
- LBNL Accelerator Division (1998-Present)
  - Collaboration with Wim Leemans

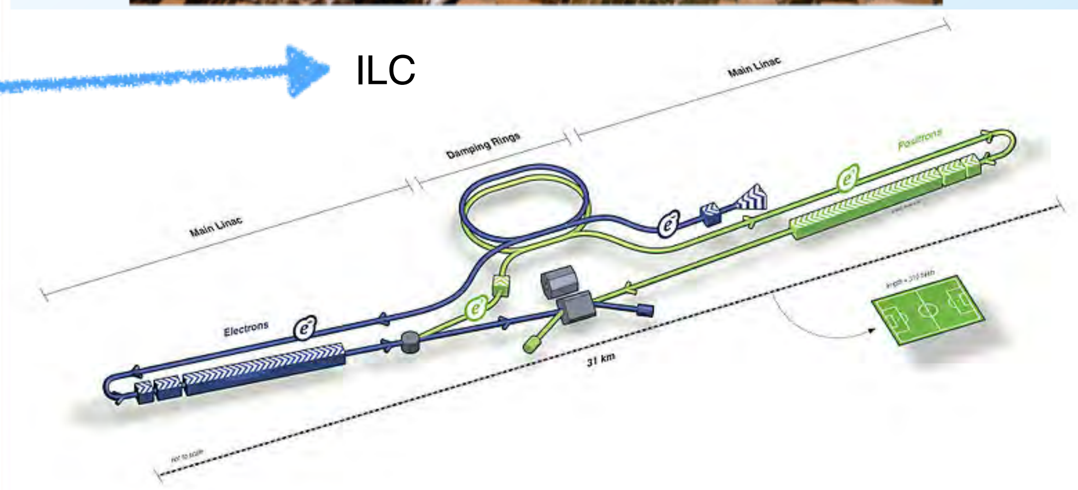
High-energy physics application of LPAs

- "Livingston Plot" Saturation of accelerator tech.
  - Practical limit reached for conventional RF accelerator technology
  - Gradient limited by material breakdown
    - e.g., X-band demonstration ~100 MV/m



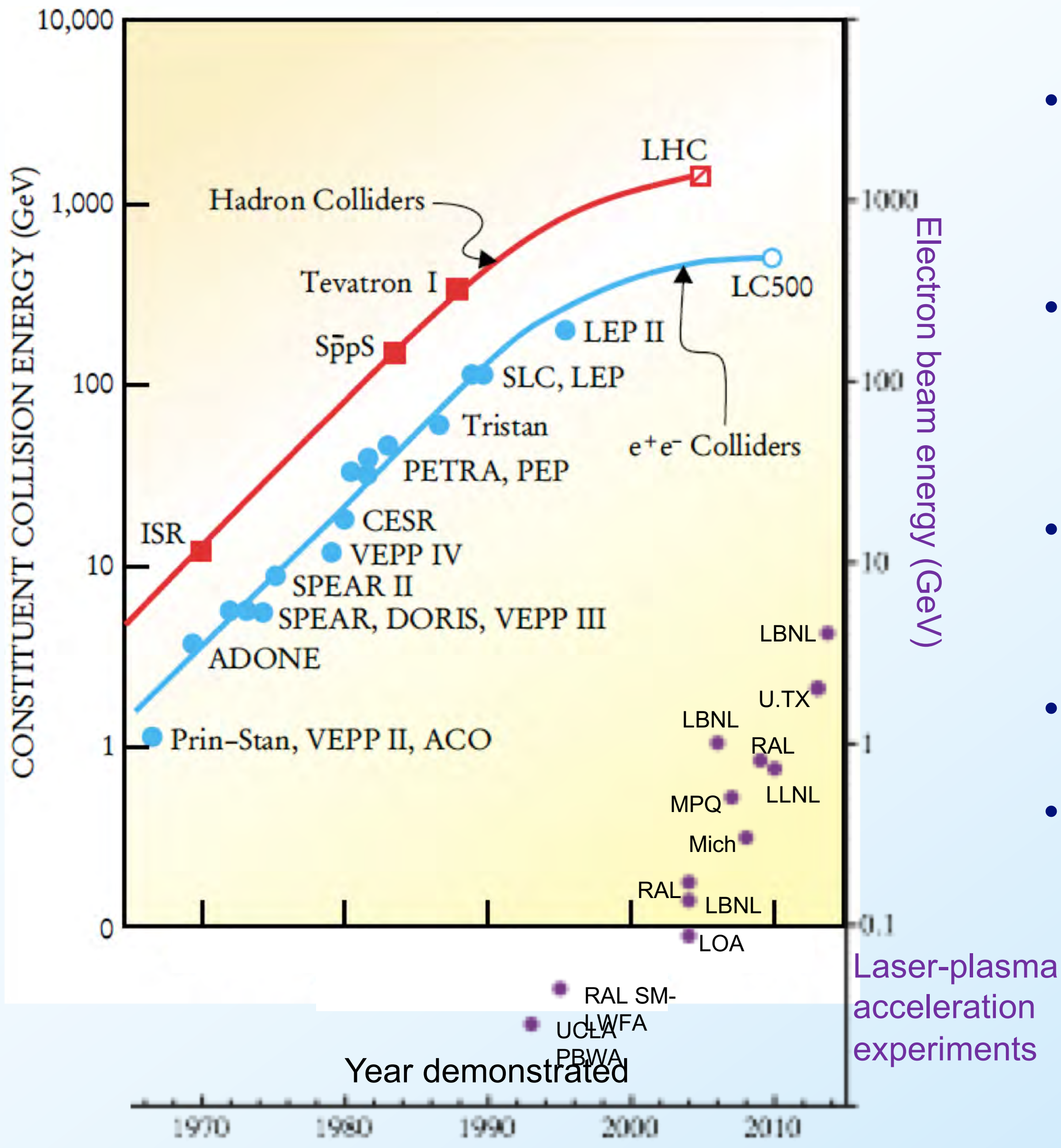
M. Tigner, DOES ACCELERATOR-BASED PARTICLE PHYSICS HAVE A FUTURE? *Phys. Today* (2001)



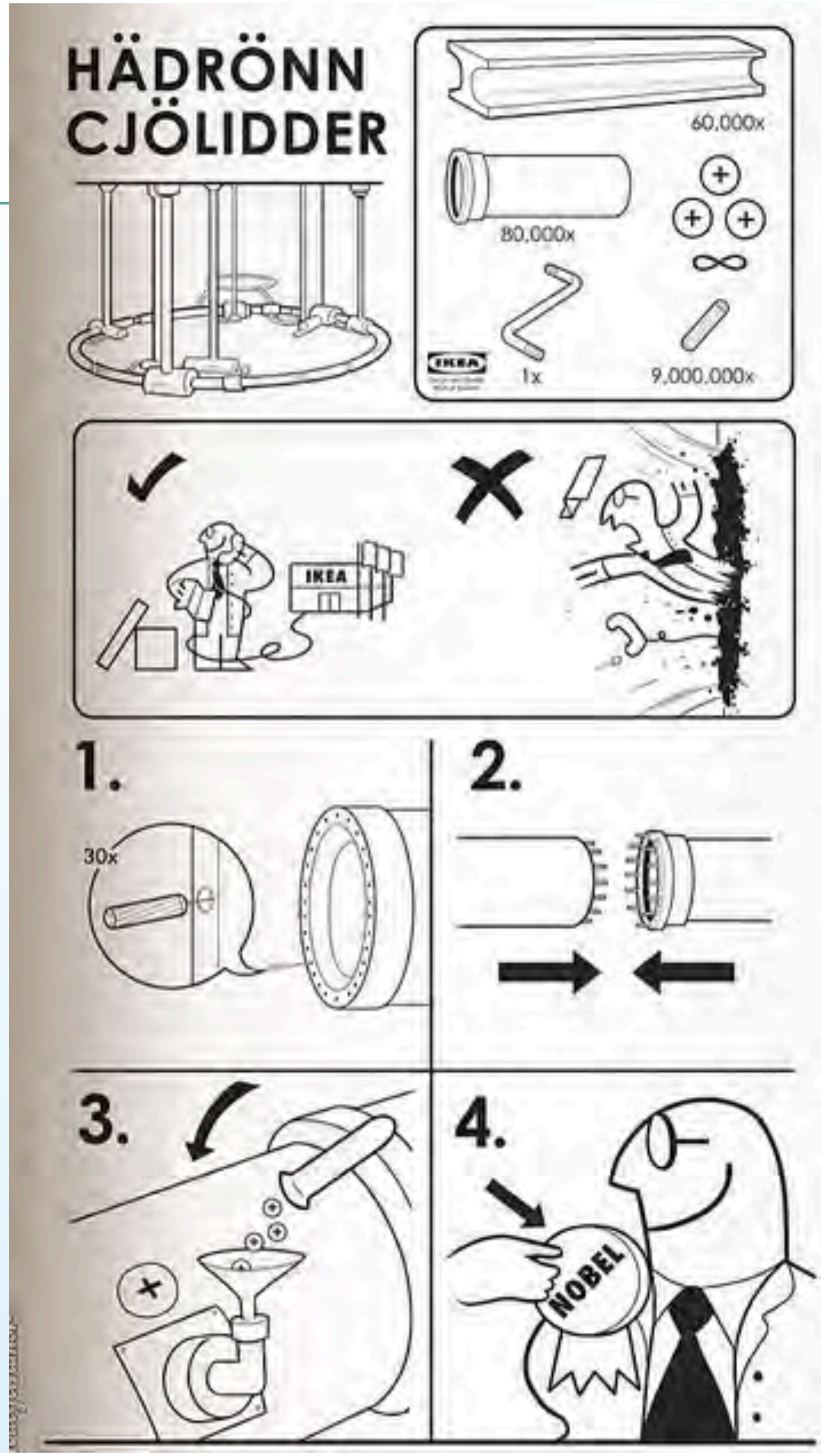


- Largest cost driver is acceleration
  - ~50 MV/m implies ~20 km/TeV
  - Facility costs scale roughly with facility size (and power consumption)
  - >50% cost in main linacs (e.g., ILC)

LPA application: Lepton Collider



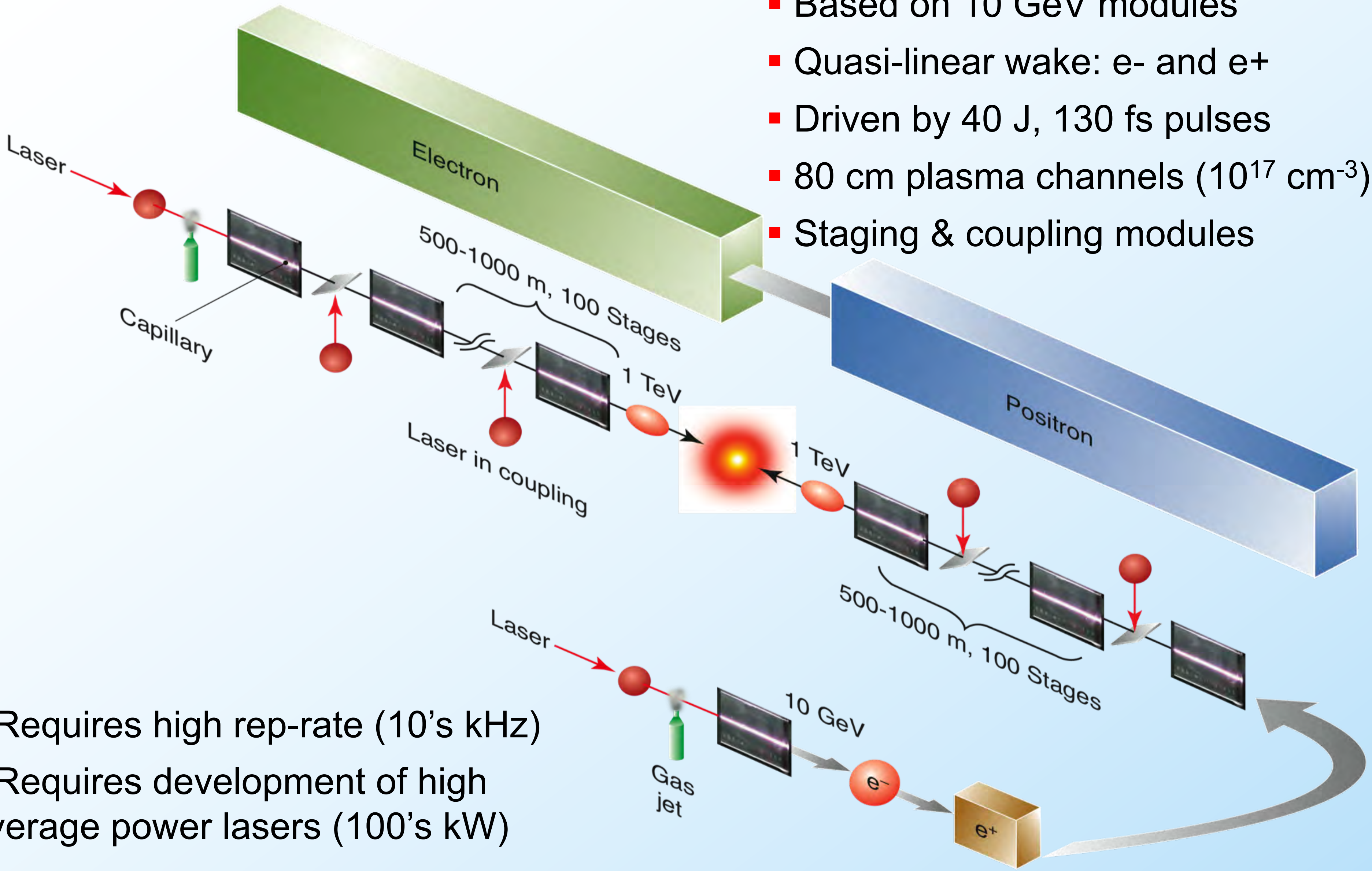
- Any future linear TeV (>TeV) collider is a massive (ultra-massive) project
  - require >order of magnitude increase in acceleration gradient
- Ultra-high gradient requires structures to sustain high fields:
  - Dielectric structures: ~1 GV/m
  - Plasmas: ~10 GV/m
- High gradients require high peak power:
  - Beam driven
  - Laser driven
- Significant progress worldwide in LPAs in the last 20+ years
- Critical developments:
  - Better understanding of LPA physics
  - Development of laser technology (CPA) for high peak power delivery



HÄDRÖNN
CJÖLIDDER
60,000x
80,000x
1x
9,000,000x
IKEA
1.
30x
2.
3.
4.
NOBEL

Conceptual LPA Collider

- Based on 10 GeV modules
- Quasi-linear wake: e- and e+
- Driven by 40 J, 130 fs pulses
- 80 cm plasma channels (10^{17} cm^{-3})
- Staging & coupling modules



- Requires high rep-rate (10's kHz)
- Requires development of high average power lasers (100's kW)

Leemans & Esarey, Physics Today (2009); Esarey et al, Rev. Mod. Phys. (2009)

Laser-plasma accelerators (LPAs)

Tajima & Dawson, Phys. Rev. Lett. (1979); Esarey, Schroeder, Leemans, Rev. Mod. Phys. (2009)

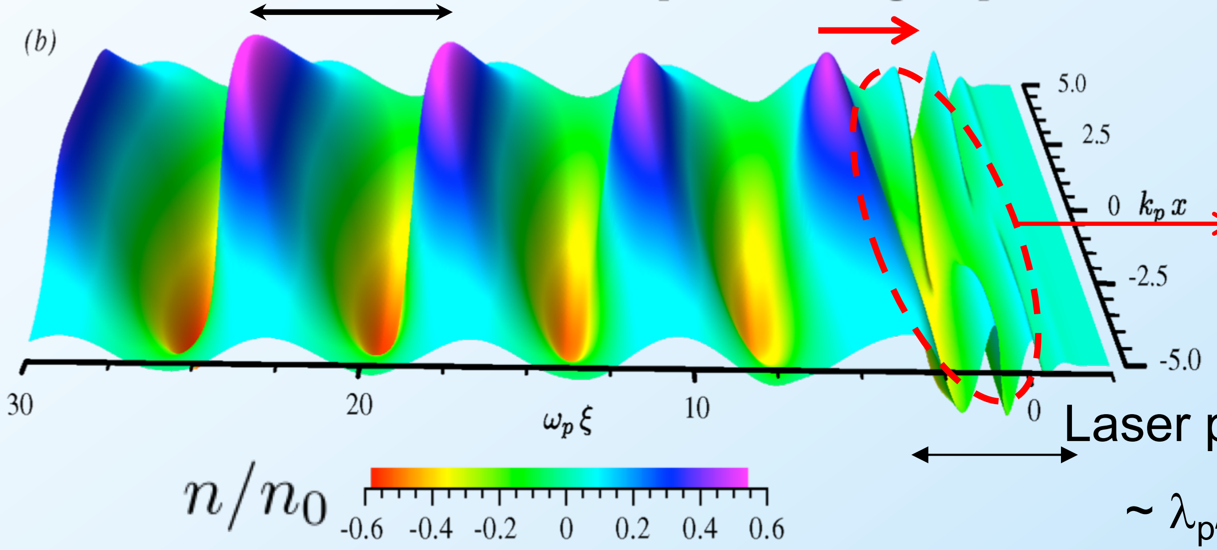
$$\left(\frac{\partial^2}{\partial t^2} + \omega_p^2\right)\frac{n}{n_0} = c^2\nabla^2\frac{1}{4}\left(\frac{eE_{\text{laser}}}{mc^2\omega}\right)^2$$

Plasma wave: electron density perturbation

Laser ponderomotive force (radiation pressure)

$\lambda_p = 2\pi c/\omega_p \sim n_p^{-1/2} \sim 30\ \mu m$

$v_{\text{phase}} \simeq v_{\text{group}} \simeq c$



short pulse, ultra-intense laser: I~10[18] W/cm[2]

Laser pulse duration

~ λ_p/c ~ tens fs

electron plasma density perturbation

Laser-plasma accelerators: >10 GV/m accelerating gradient

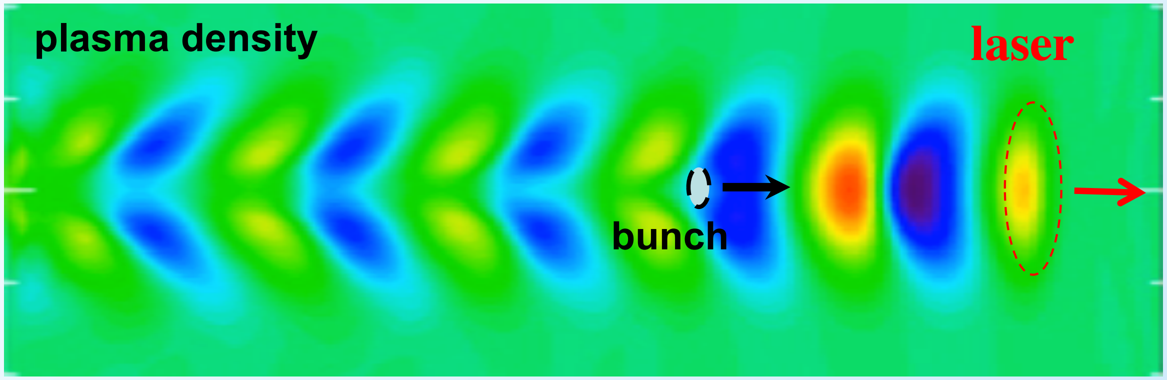
$$E \sim \left(\frac{mc\omega_p}{e}\right) \approx (96\ \mathrm{V/m})\sqrt{n_0[\mathrm{cm}^{-3}]}$$

plasma wave (wakefield) E ~100 GV/m (for $n \sim 10^{18}$ cm^{-3})

>10^3 larger than conventional RF accelerators: ">km to <m"

Accelerating bucket ~ plasma wavelength

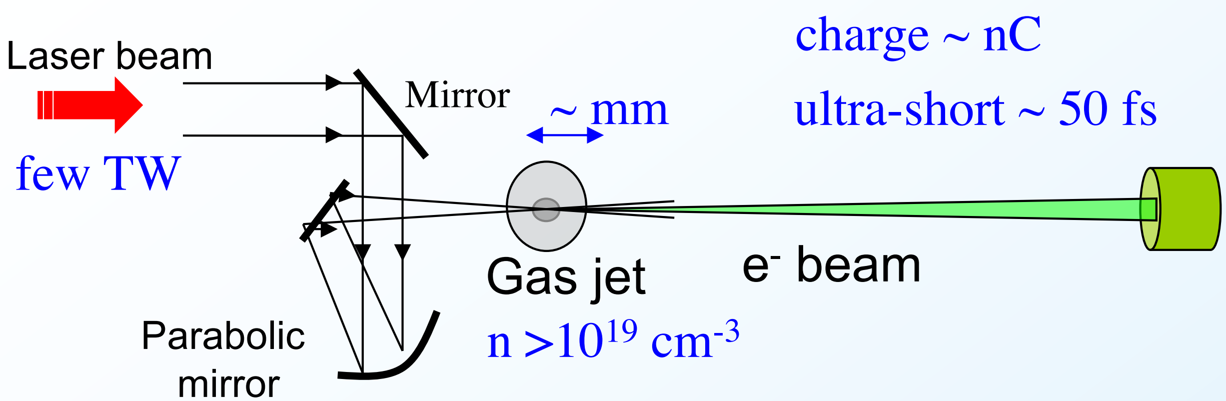
➔ **ultrashort (fs) bunches (<λ_p /4)**



- beam charge (set by beam loading): ~100 pC (for $n \sim 10^{18}$ cm^{-3})
- beam duration (set by trapping physics): <10 fs

➔ **high peak current** $\gtrsim 10$ kA

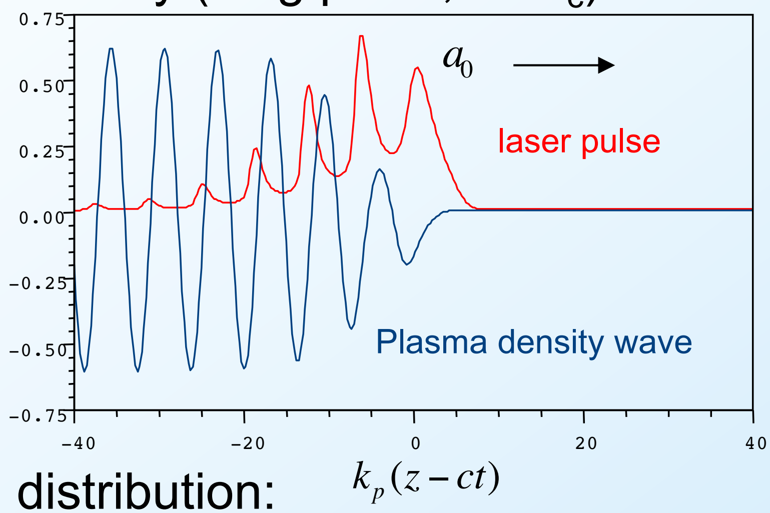
Prior to 2004: Self-modulated laser-plasma accelerator experiments



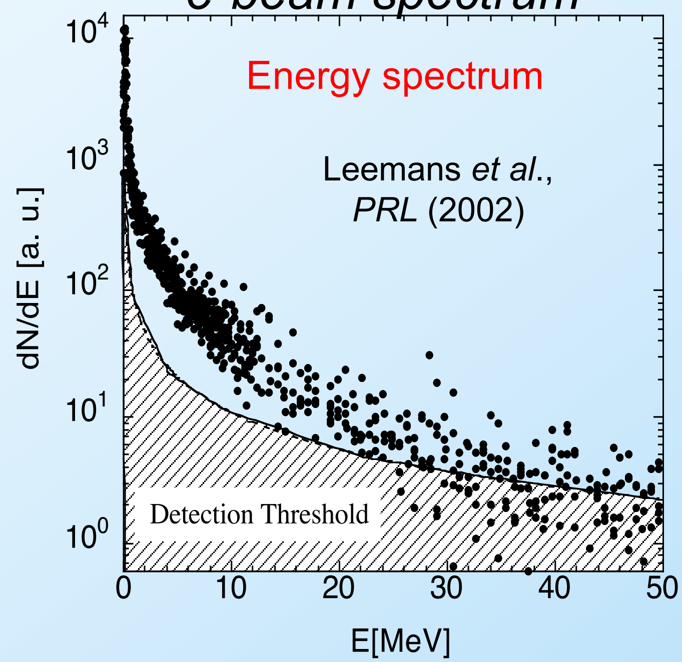
Experiments:
Japan (Nakajima et al, 1995)
LLNL (Coverdale et al, 1995)
UK (Modena et al, 1995)
Michigan (Wagner et al, 1997)
NRL (Moore et al, 1997)
Many others…

- Plasma wave generated via self-modulation instability (long pulse, $P>P_c$)

Schroeder *et al.*, *Phys. Plasmas* (2003)



e-beam spectrum



Exponential distribution:

(1) Instability results in continued electron trapping

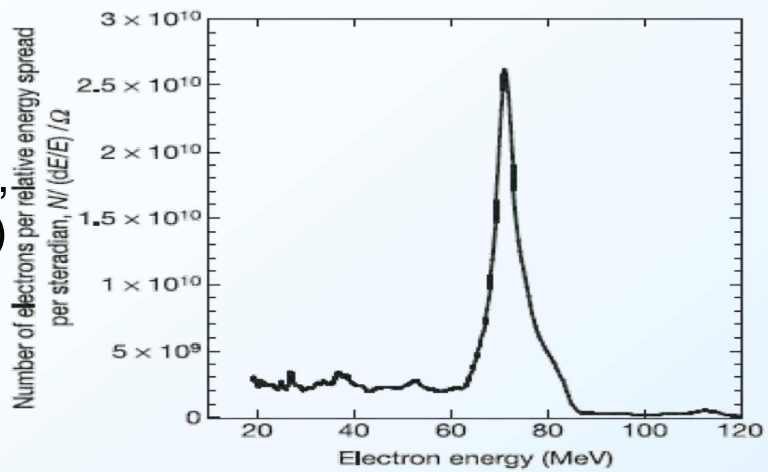
(2) High density $\Rightarrow$ $L_{dephase} << L_{gas\text{-}jet} \Rightarrow$ electrons accelerated and deccelerated

2004 Experimental Results: High-quality 100 MeV beams

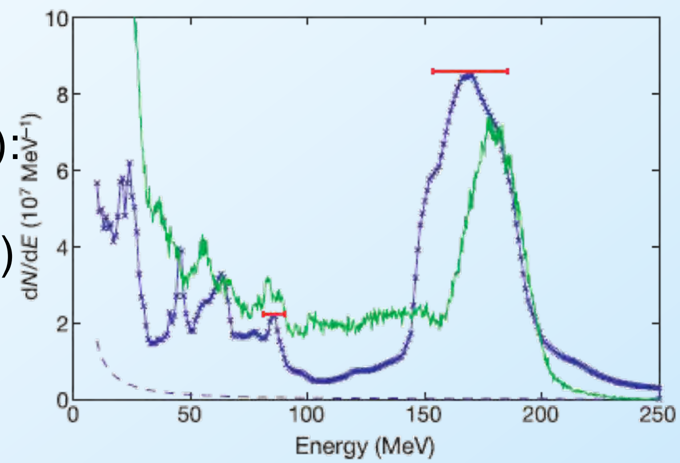
Extend interaction length and lower plasma density to match interaction length to dephasing length: $L_{\text{int}} \sim L_{\text{dephase}} \sim L_{\text{deplete}}$

- Approach 1: bigger laser spot (more laser energy)

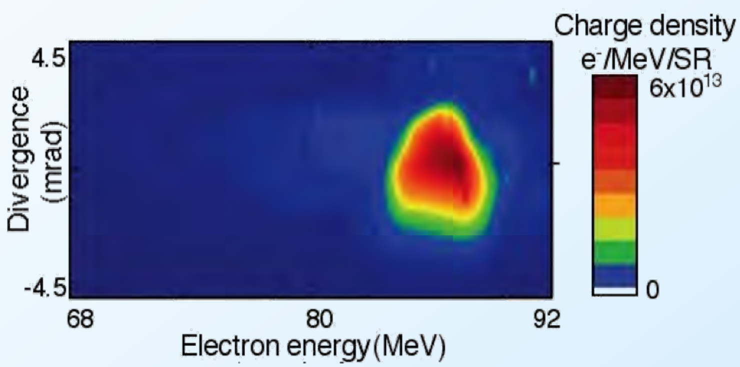
RAL (UK): Mangles et al, Nature (2004)



LOA (France): Faure et al, Nature (2004)



- Approach 2: preformed channel guided: LBNL expt.



Geddes et al, Nature 431 (2004)

PIC Simulation of LBNL Expt.

LWFA: Production of a Monoenergetic Beam

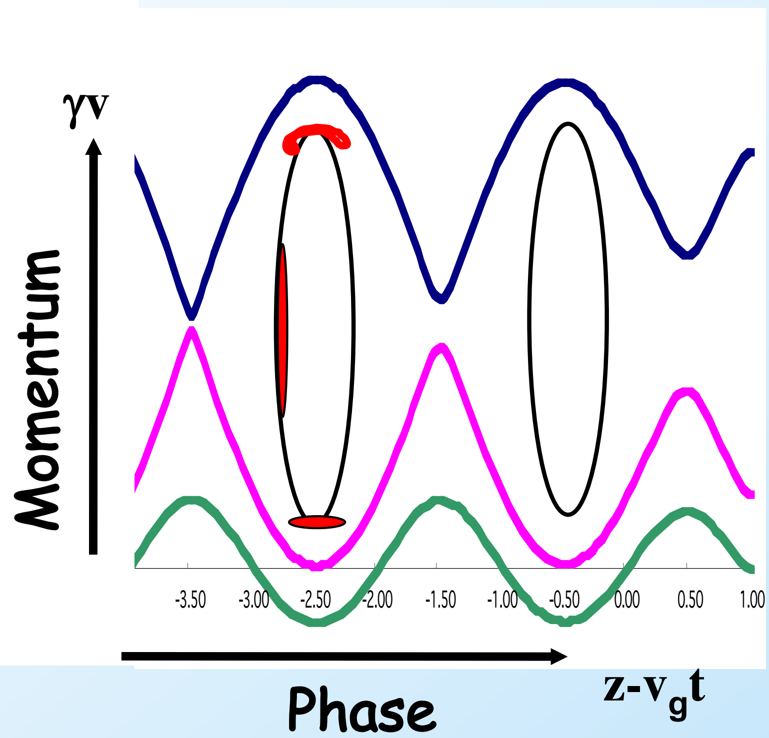
1. Excitation of wake (e.g., self-modulation of laser)
2. Onset of self-trapping (e.g., wavebreaking)
3. Termination of trapping (e.g., beam loading)
4. Acceleration length

   If > dephasing length: large energy spread

   If ≈ dephasing length: monoenergetic

- **Dephasing distance:**

$$L_{dph} \approx \left(\lambda_p^3 / \lambda^2\right) \propto n_e^{-3/2}$$

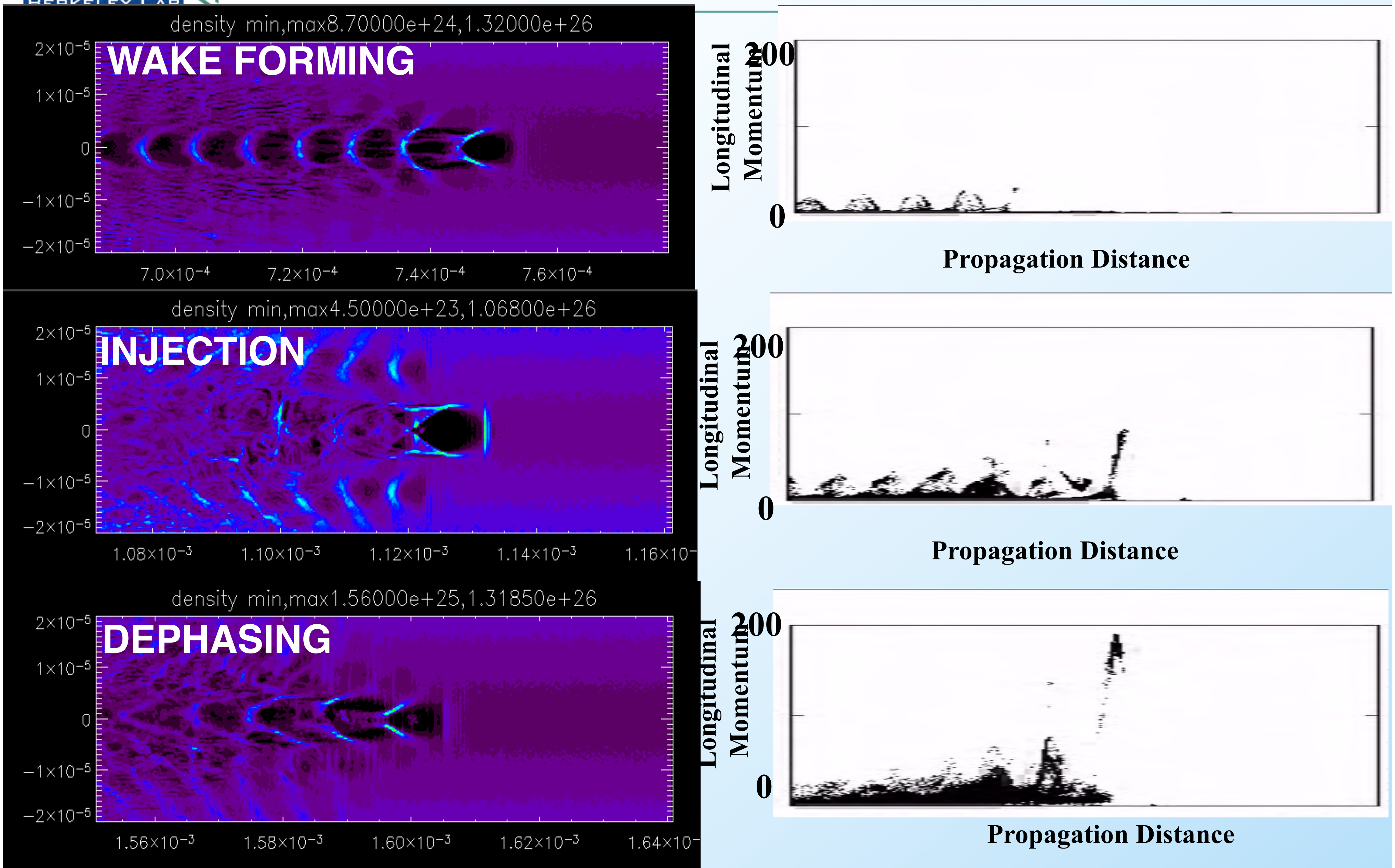


1 — **Wake Excitation**

2-3 — **Trapping**

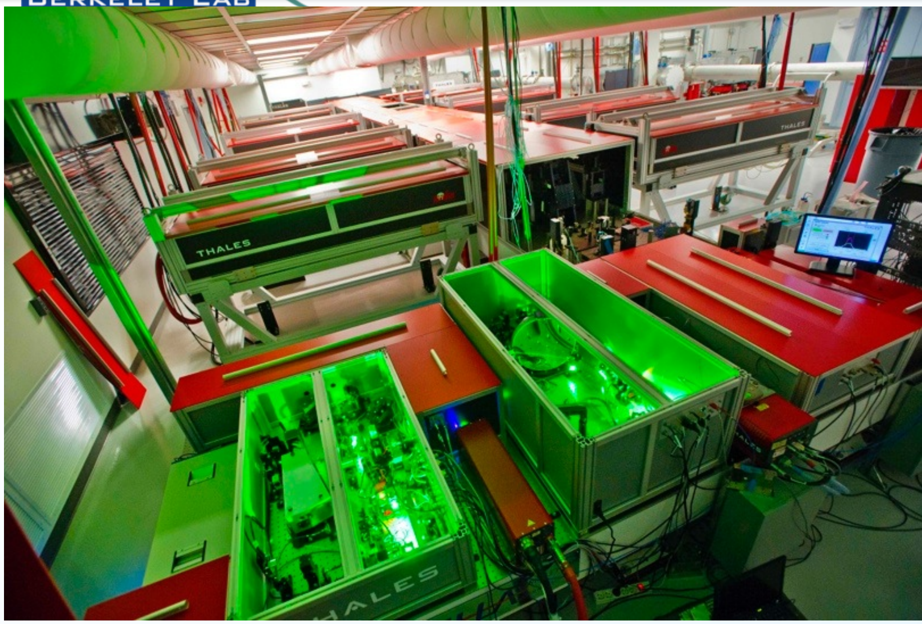
4 — **Acceleration: $L_{accel} \sim L_{dephase}$**

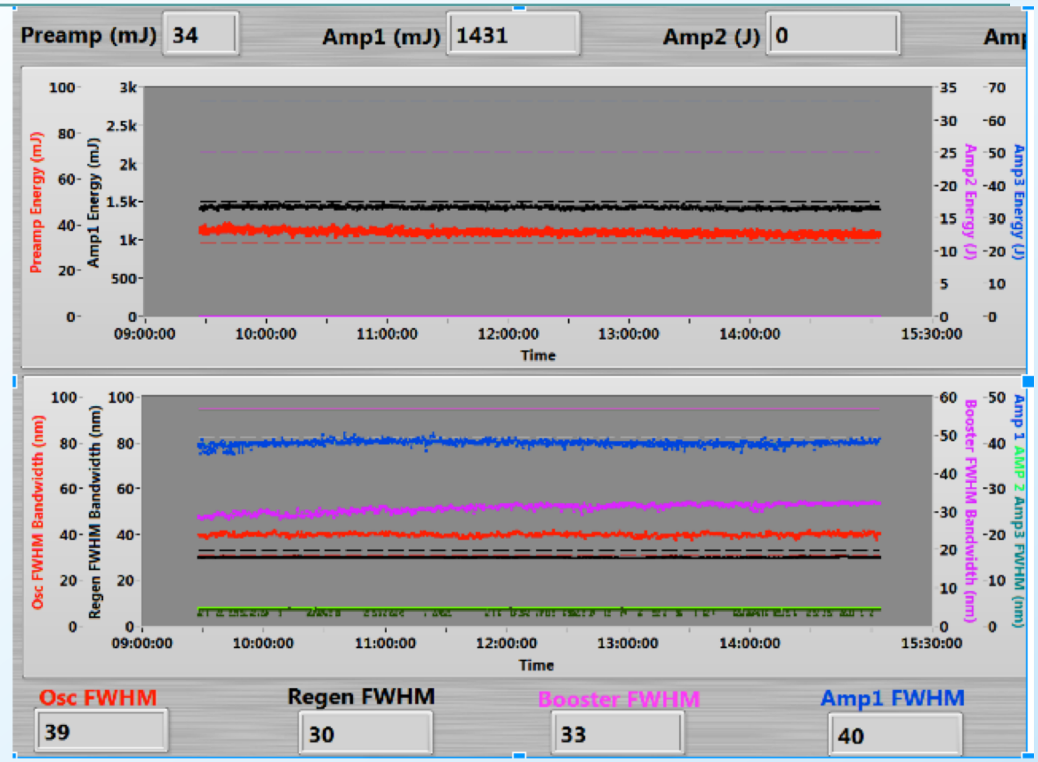
Wake Evolution and Dephasing Yield Low Energy Spread Beams in PIC Simulations



Geddes et al., Nature (2004) & Phys. Plasmas (2005)

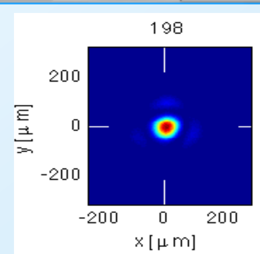
BELLA laser: (still) **highest rep rate PW-laser for high intensity LPA experiments**

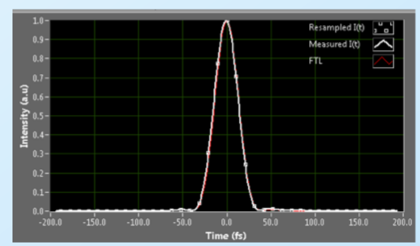




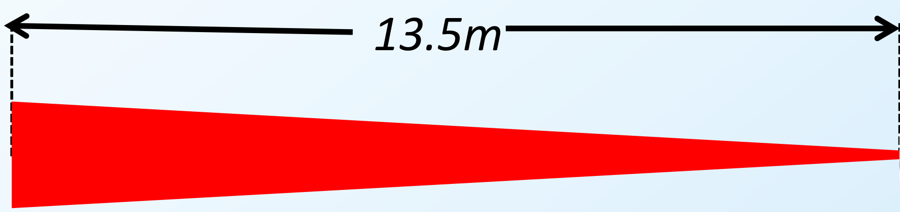
- Petawatt laser operating at up to 42 J in ~30 fs at 1 Hz

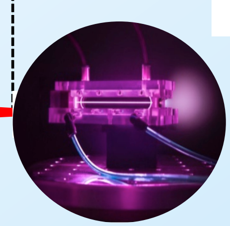
~ 55 micron spot





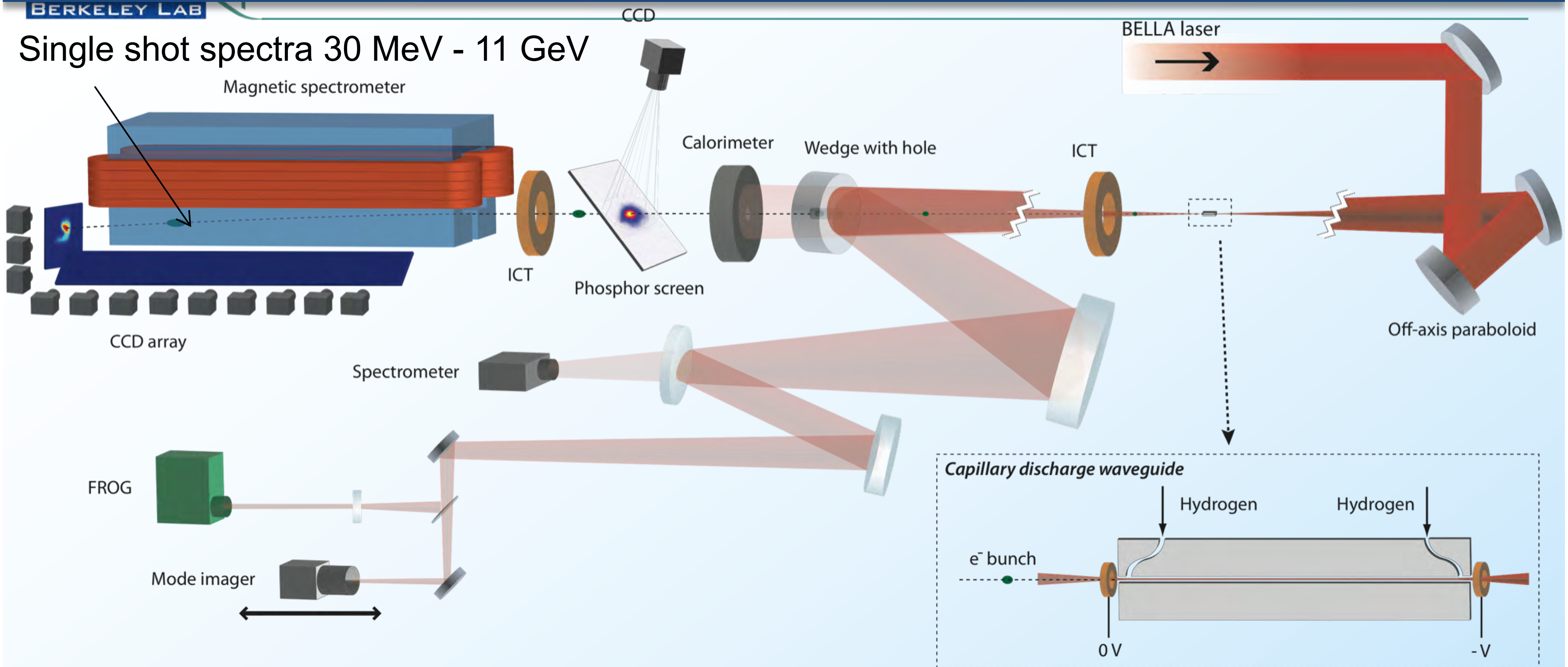
~30 fs



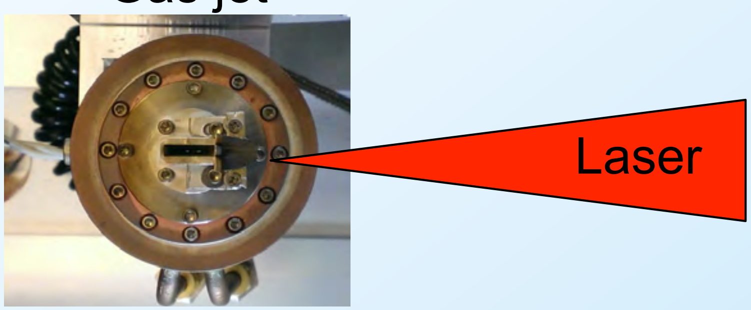


Intensity ~1.5x10^{19} Wcm^{-2}
Acc. fields ~10-50GV/m

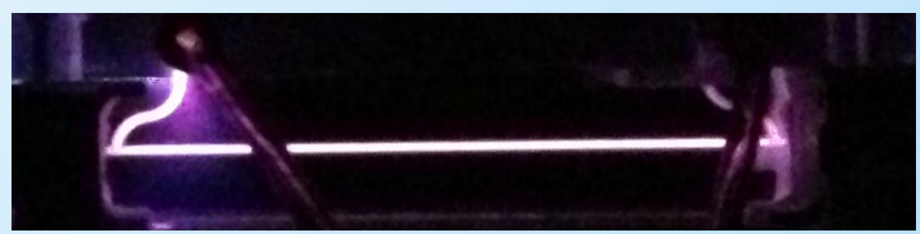
Experiments at LBNL use the BELLA laser focused by a 14 m focal length off-axis paraboloid onto gas jet or capillary discharge targets

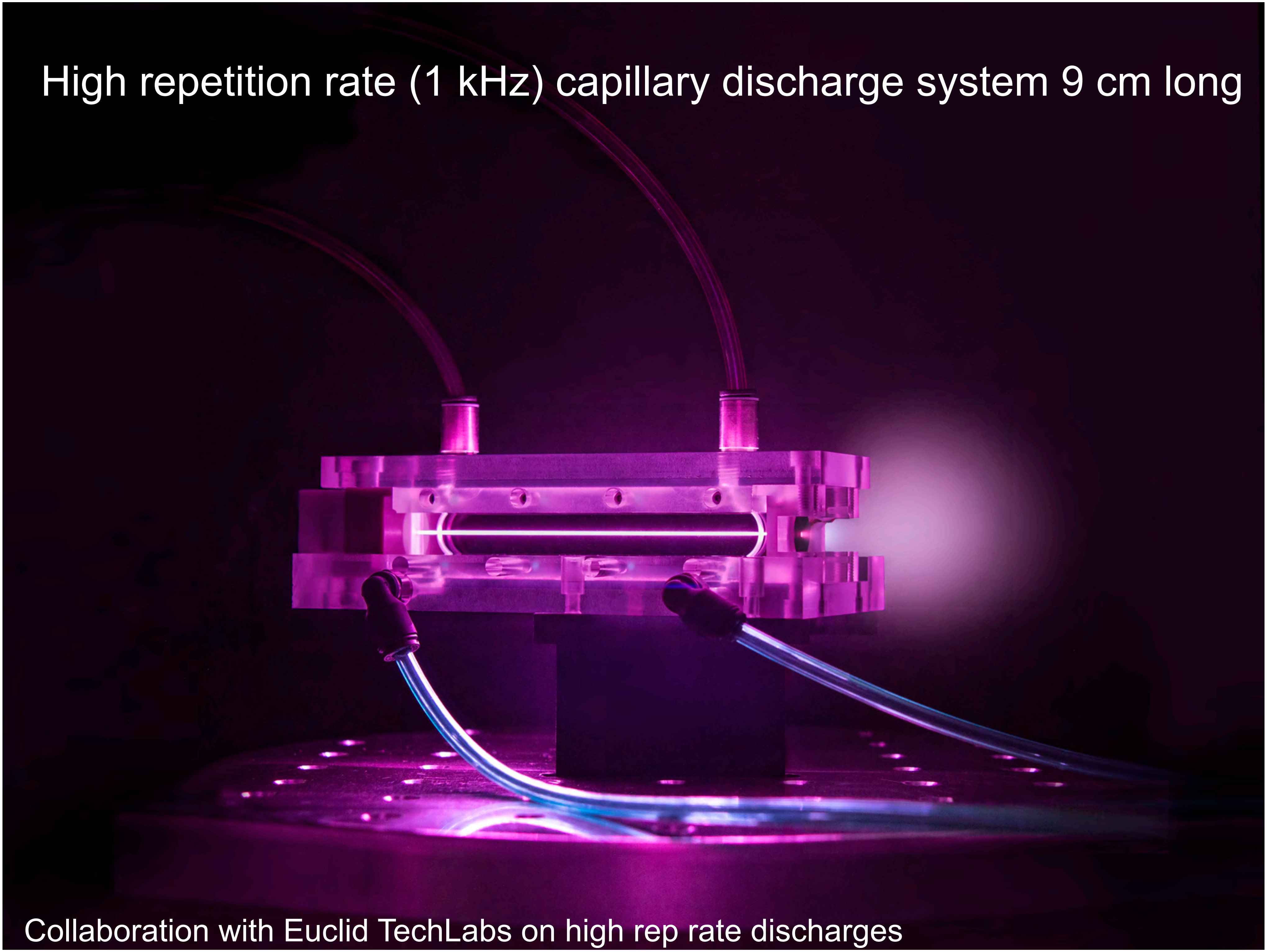


Gas jet

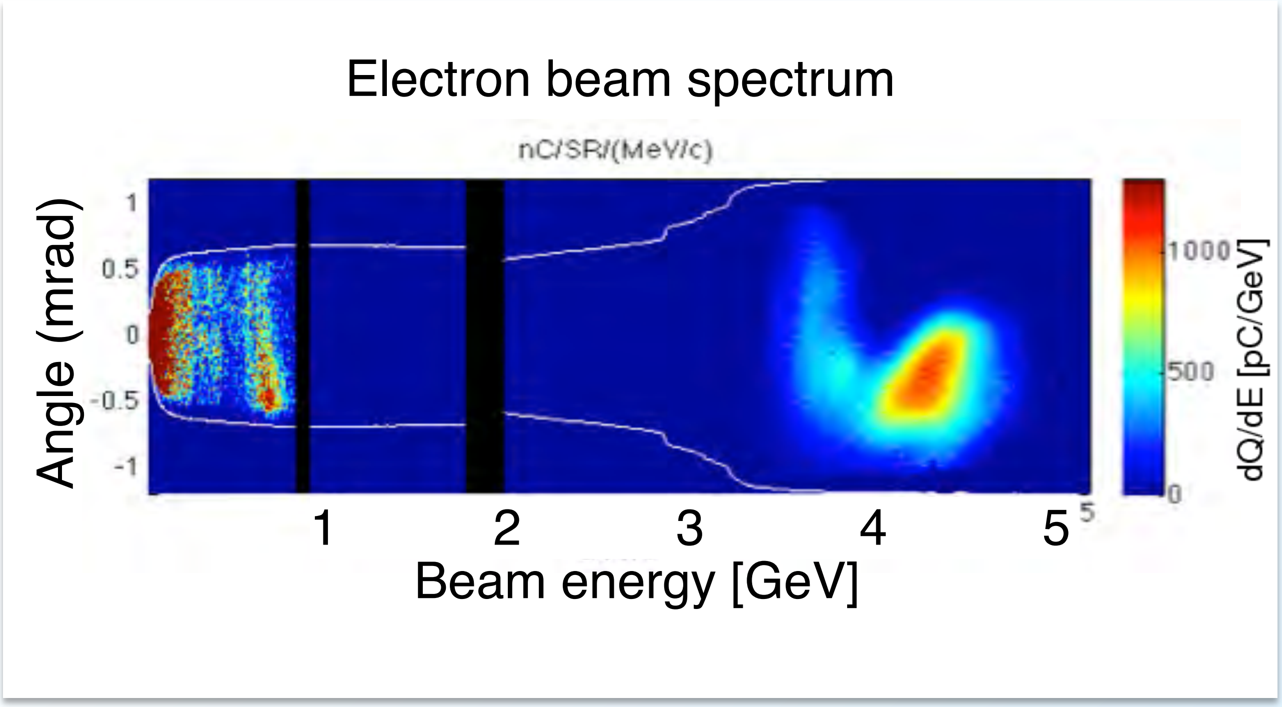


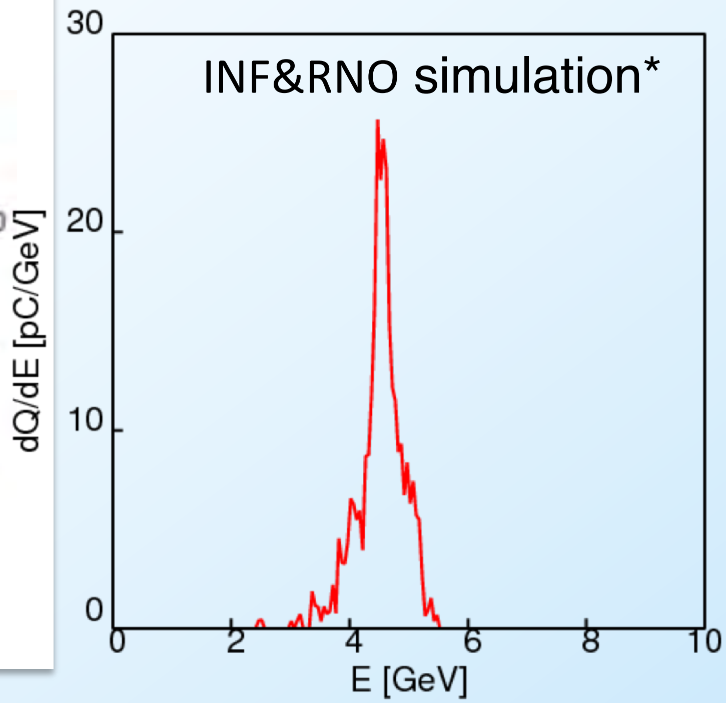
Capillary discharge




High repetition rate (1 kHz) capillary discharge system 9 cm long
Collaboration with Euclid TechLabs on high rep rate discharges

4.25 GeV beams have been obtained from 9 cm plasma channel powered by 310 TW laser pulses (15 J)





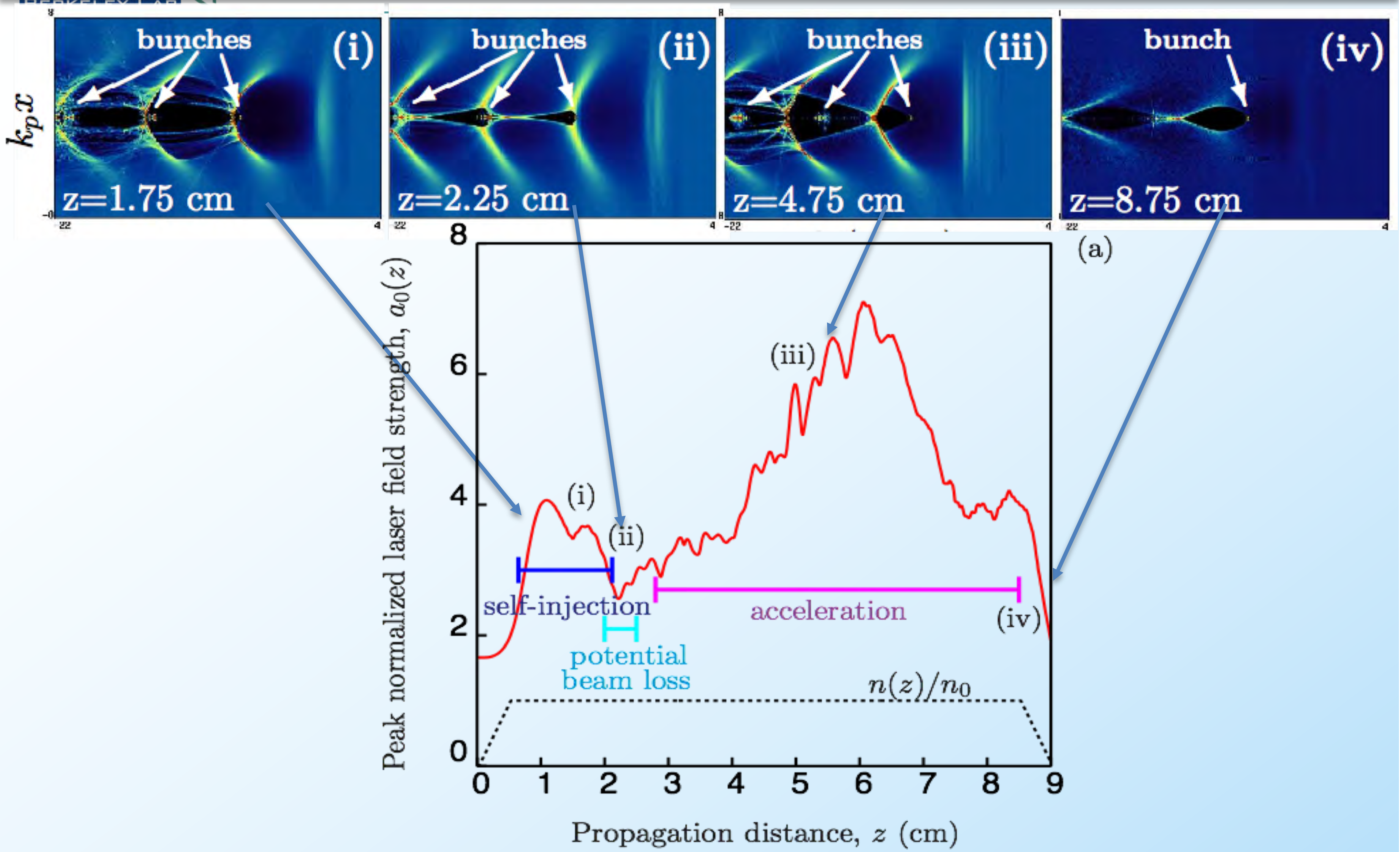
	Exp.	Sim.
Energy	4.25 GeV	4.5 GeV
ΔE/E	5%	3.2%
Charge	~20 pC	23 pC
Divergence	0.3 mrad	0.6 mrad

- **Laser** (E=15 J):
  - Measured) longitudinal profile (T_0= 40 fs)
  - Measured far field mode (w_0=53 μm)
- **Plasma:** parabolic plasma channel (length 9 cm, n_0~6-7x10^{17} cm^{-3})

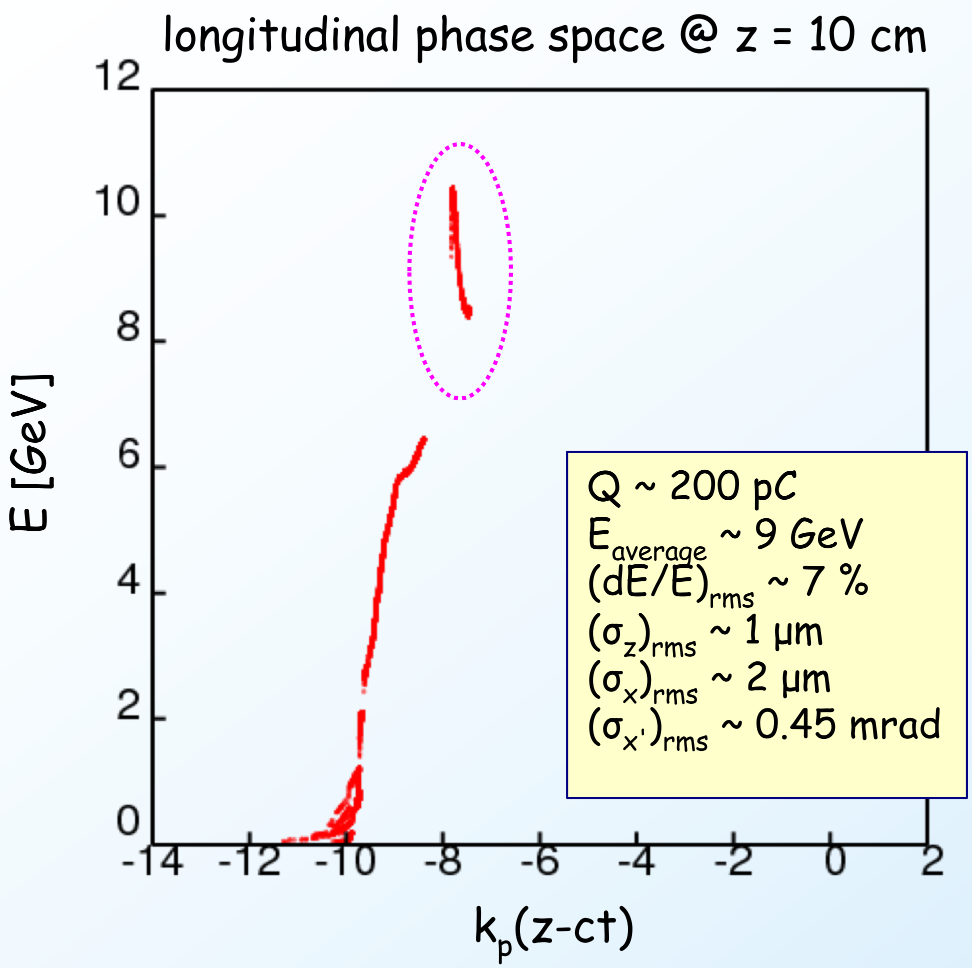
W.P. Leemans et al., PRL 2014

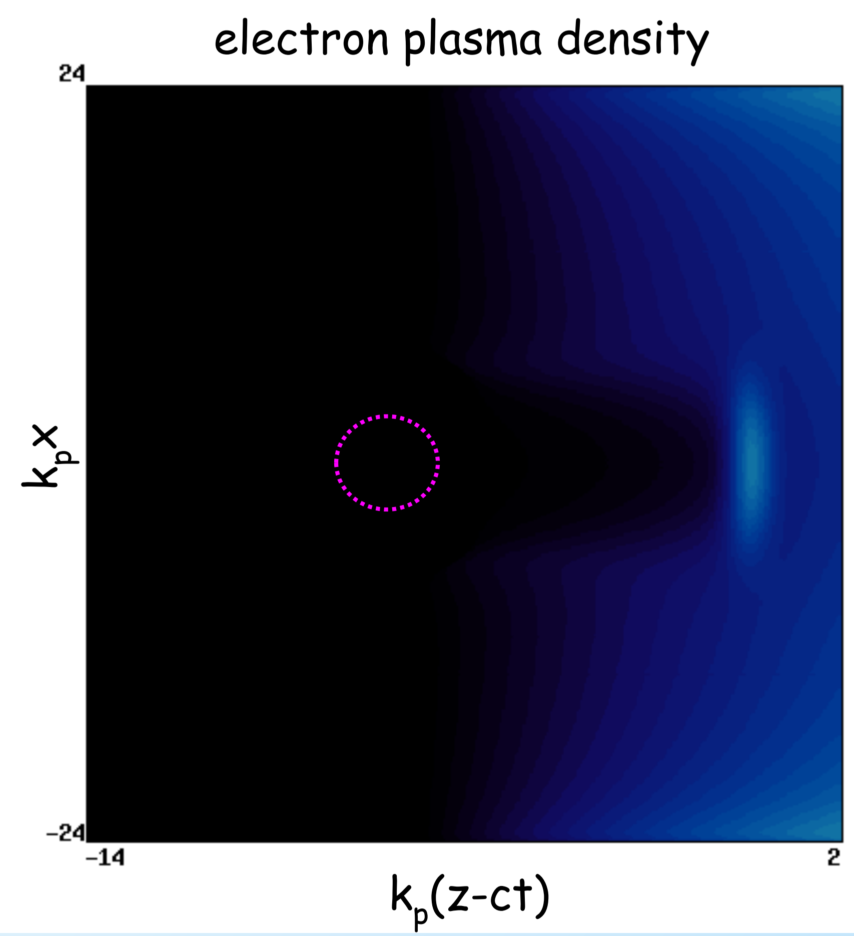
**C. Benedetti et al., proceedings of AAC2010, proceedings of ICAP2012*

Electron trapping and acceleration is complex in this regime: Simulations based on measured input parameters



Simulations indicate 10 GeV quasi-monoenergetic beams can be obtained in ~ 10 cm capillary in non-linear regime





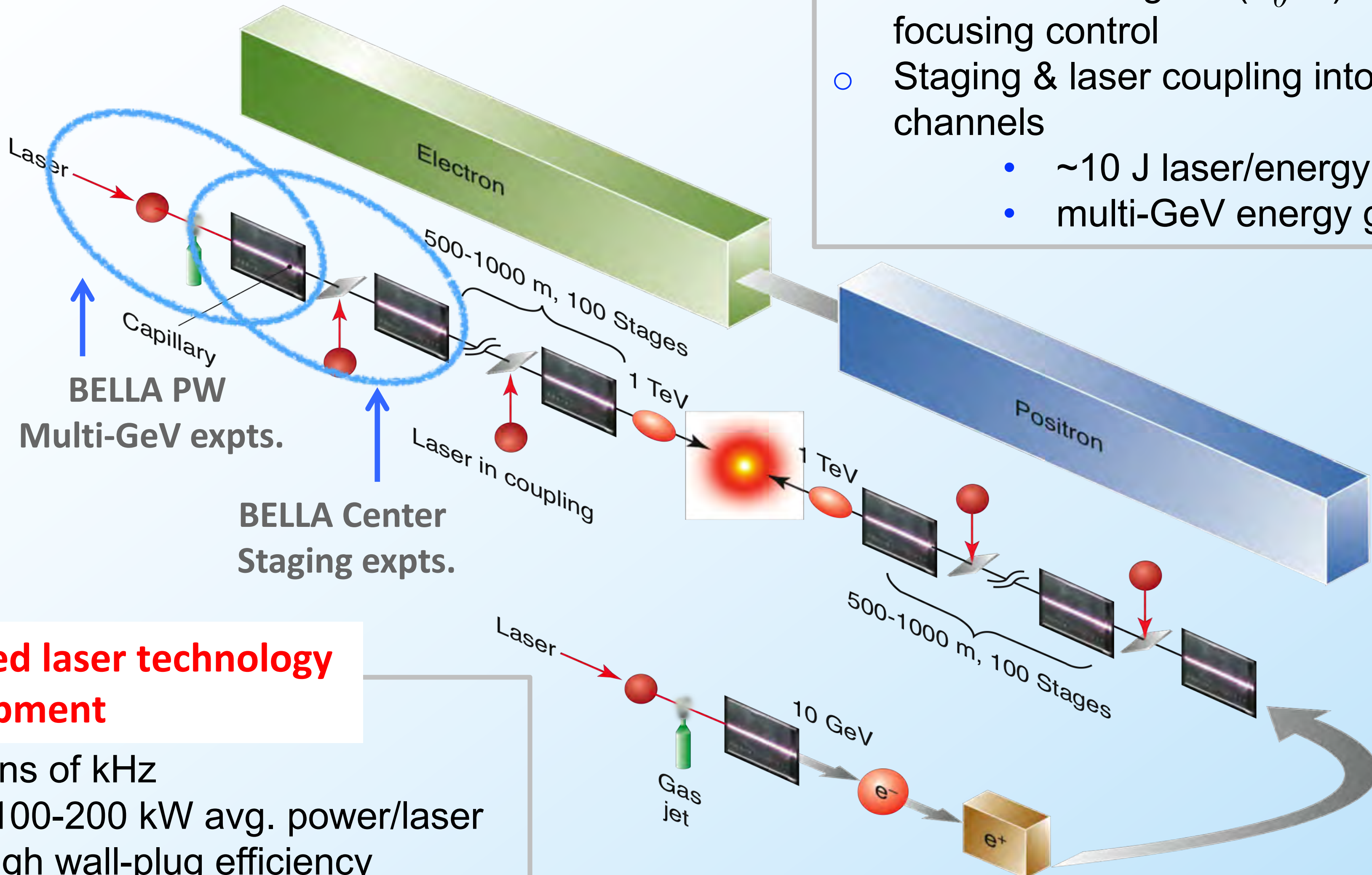
Initial a_0~3.5-4.0
Plasma density ~ 3 x 10^{17} cm^{-3}

Laser heater required to deepen channel

Vision: LPA linear collider concept

Scaling laws indicate

- operation at n_e~10^{17} cm^{-3}
- Quasi-linear regime (a_0~1): e^+ and e^-, focusing control
- Staging & laser coupling into plasma channels
  - ~10 J laser/energy per stage
  - multi-GeV energy gain/stage



Leemans & Esarey, Phys Today (2009)

Required laser technology development

- tens of kHz
- ~100-200 kW avg. power/laser
- High wall-plug efficiency

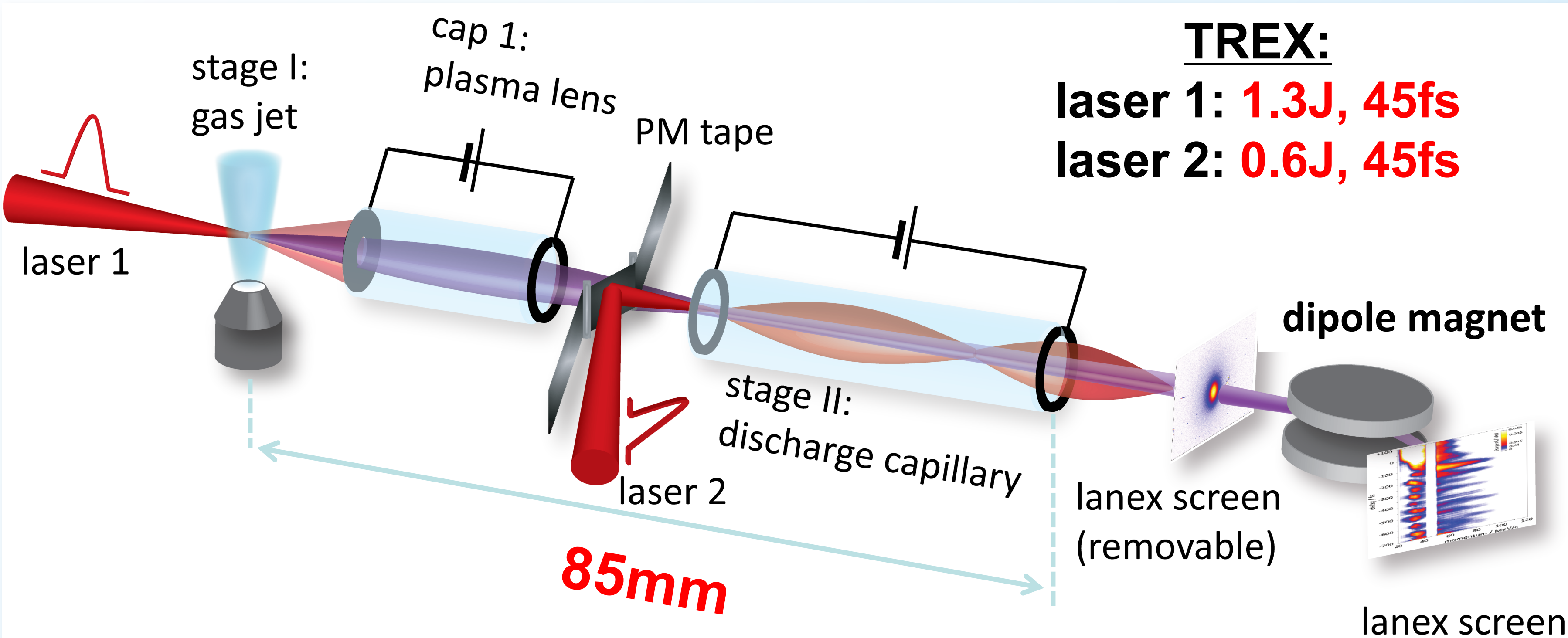
Multistage Coupling of two independent LPAs

Stage I: gas jet - injector

Coupling II (laser): tape-driven plasma mirror

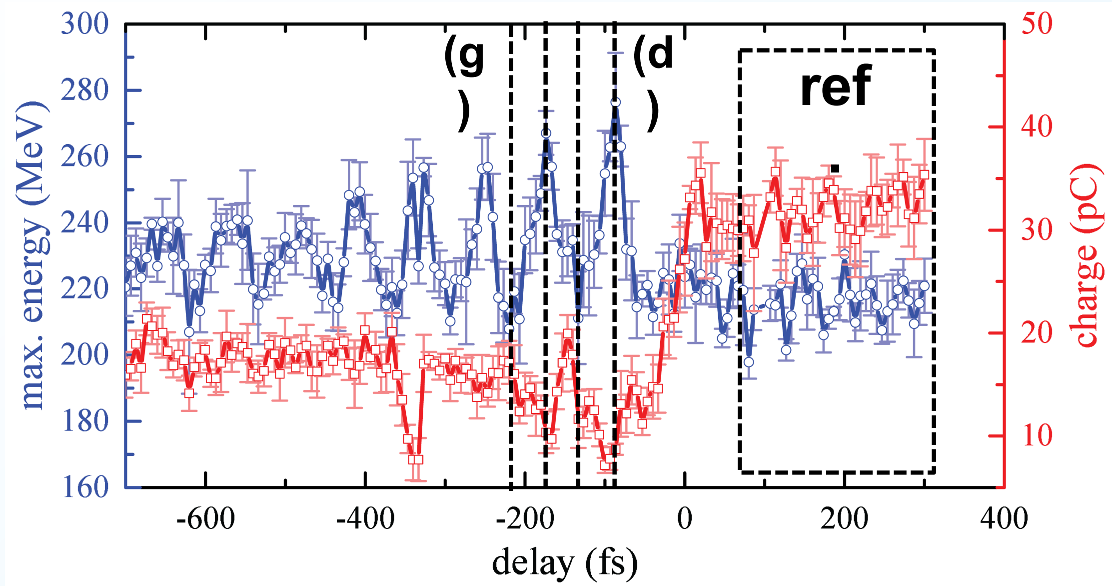
Coupling I (e-beam): active plasma lens

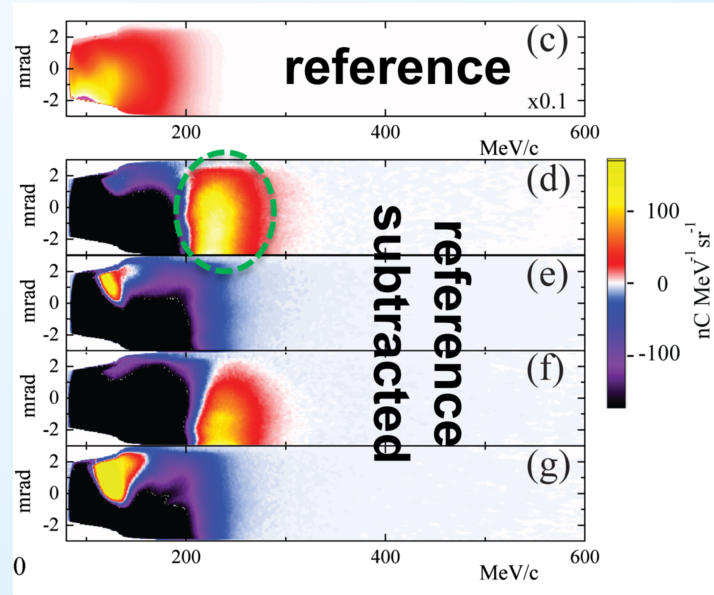
Stage II: discharge capillary - accelerator



Staging Experiment: Energy gain of witness beam by timing of second laser (wake phase)

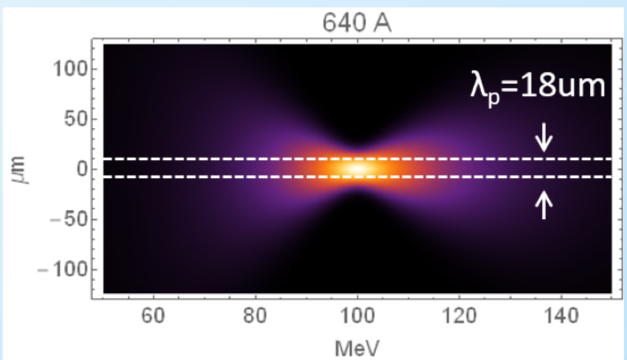
Modulation period of 80 fs consistent with a plasma frequency at a density of 2×10^{18} cm^{-3}





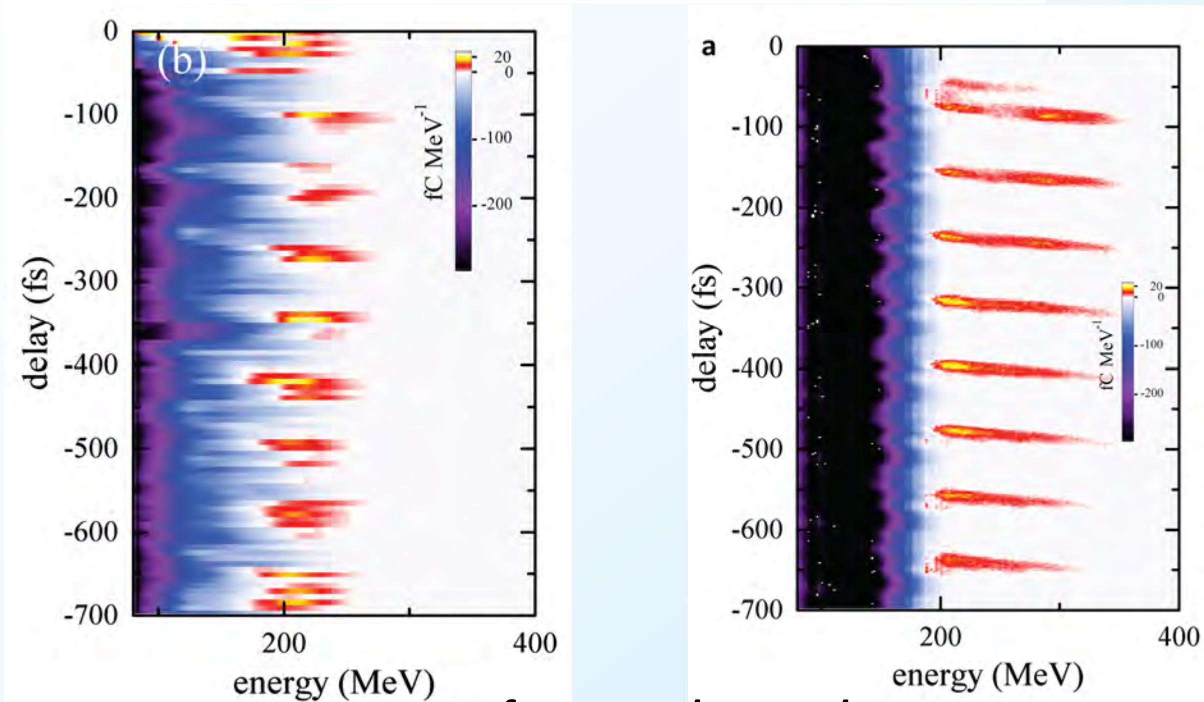
S. Steinke et al., Nature 530, 190 (2016)

Previous plasma lens calculation suggest that 1.2pC of trapped charge corresponds to a wake trapping efficiency of 30%, but it's not that easy (unfortunately)



Simulation reproduce staging signatures at correct magnitude

Comparison of experiment and simulation

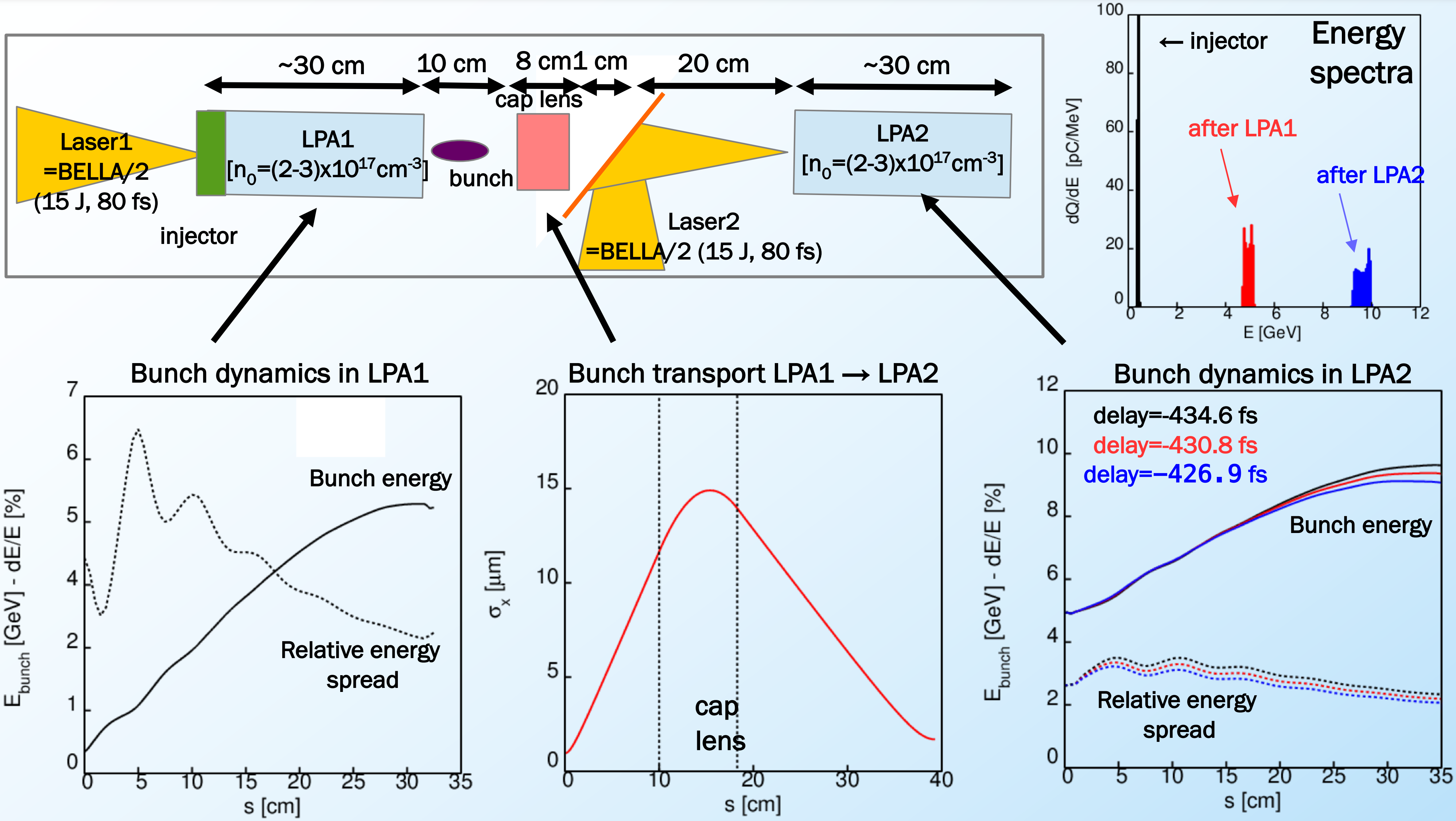


reference subtracted

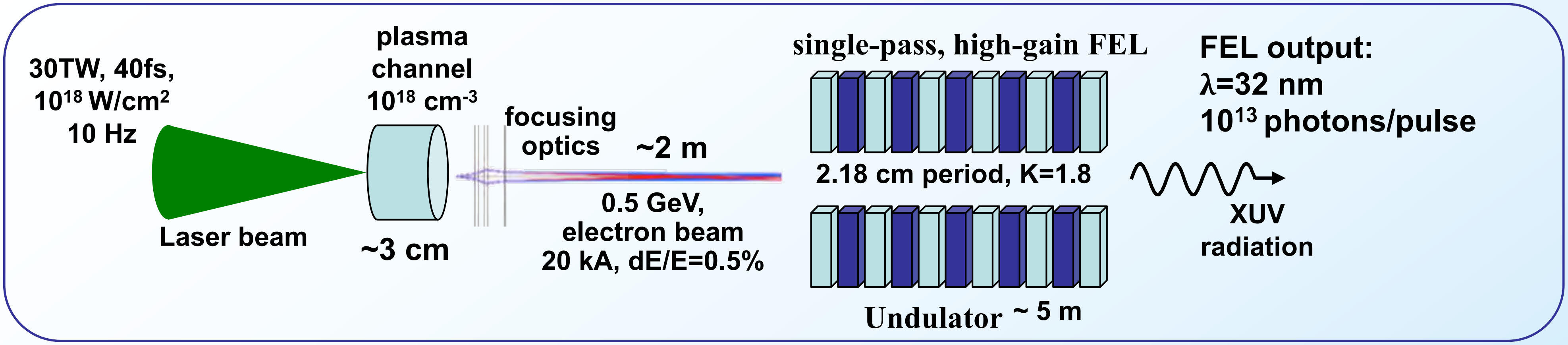
S. Steinke et al., Nature 530, 190 (2016)

- Recurring post acceleration (100 MeV) at the plasma frequency
- ~ 1 pC of charge at energies > 200 MeV
- Analysis of simulation results unravels details of the acceleration/ deceleration

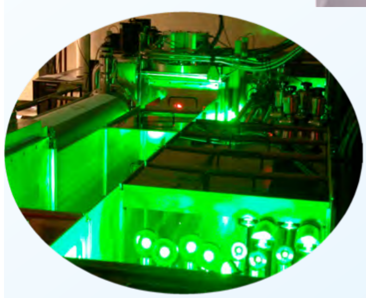
~10 GeV electron beams from STAGING experiment using BELLA: simulations show high efficiency capturing and acceleration in LPA2 of the bunch produced by LPA1

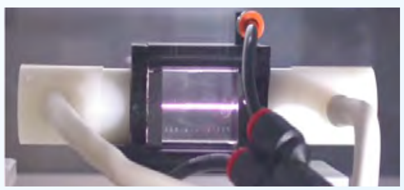


Laser-plasma accelerator driven XUV FEL at LBNL



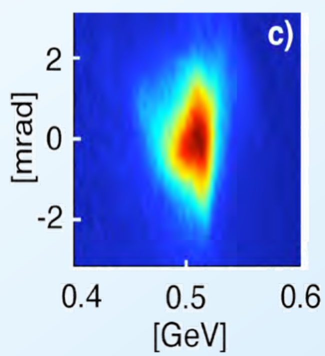
$Ti:Al_2O_3$
laser system





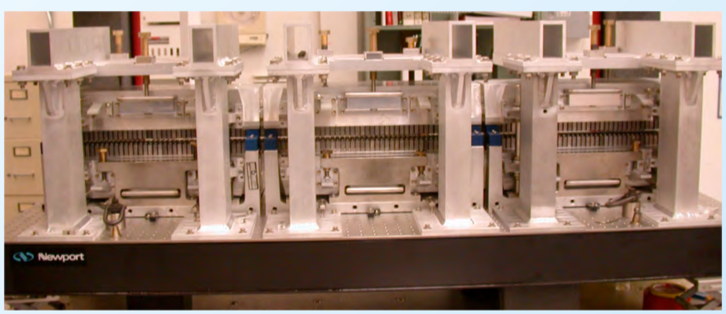
Plasma
capillary
technology

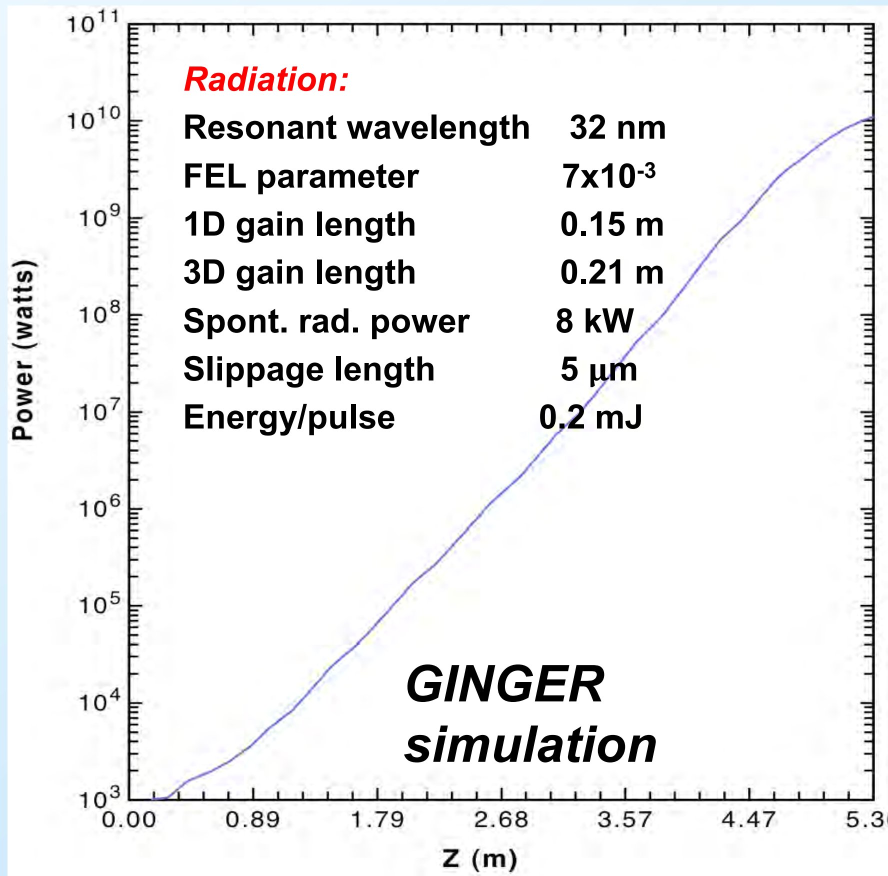
LPA electron
beam



conventional
undulator
(THUNDER)

K. Robinson et al.,
IEEE QE (1987)

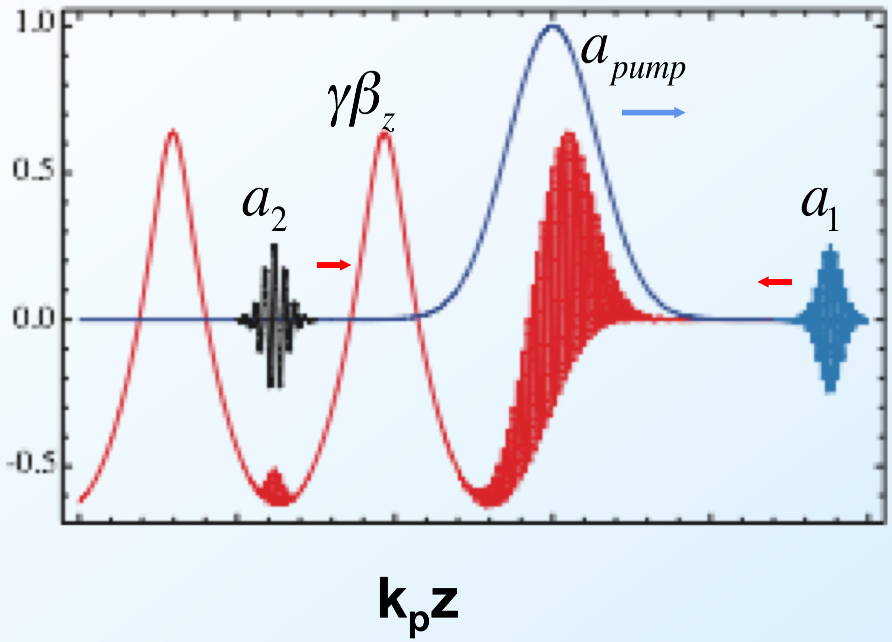


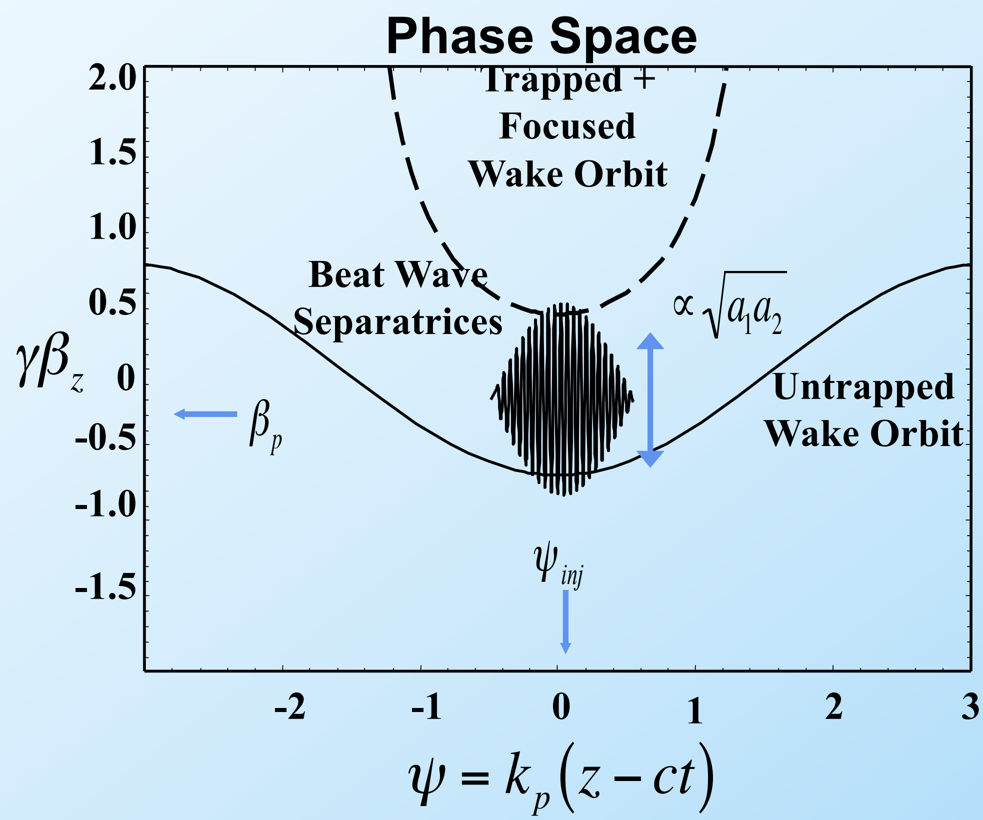


Controlled pulse injection enables detailed control of injection phase space via laser

Room for improvement:

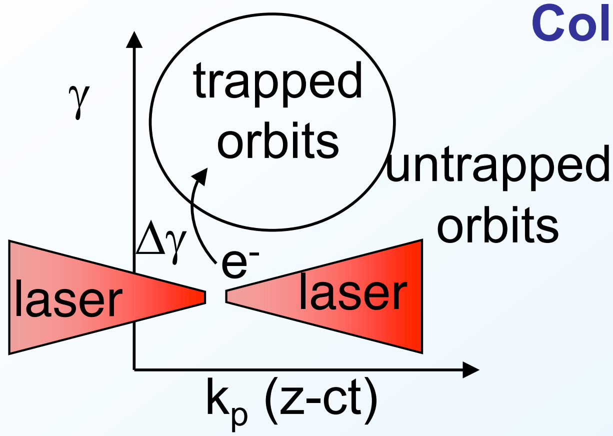
- *3-pulse* colliding pulse:
  1. control of injection position (by delay between pump and trailing pulses)
  2. lower colliding laser pulse intensity (less wake distrubiton)
- Phase velocity of beat separatrices controlled by using different frequency laser pulses





Controlled injection via colliding laser pulses improves beam quality

Theoretical development:

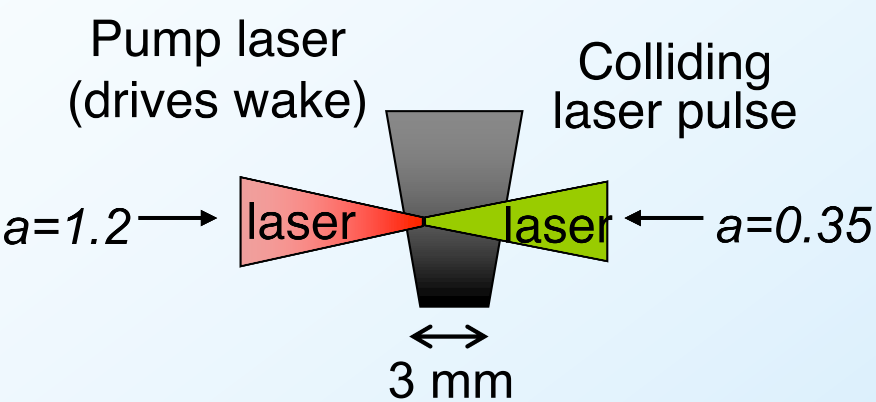


Colliding pulse injection:

Esarey et al. PRL (1997);
Schroeder et al. PRE (1999);
Fubiani et al. PRE (2004)

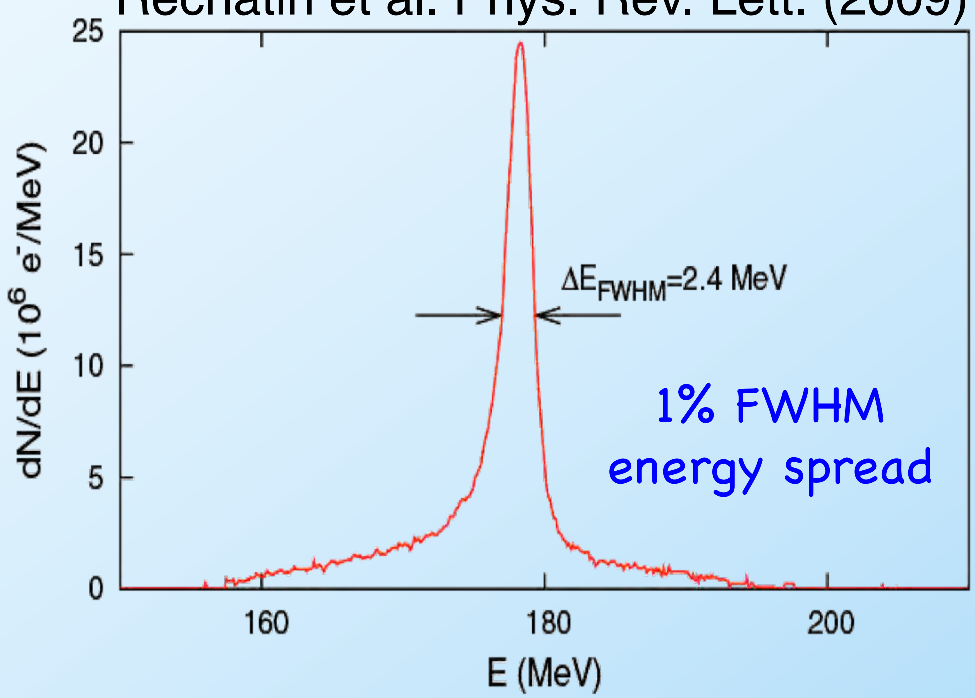
Experimental demonstration:

LOA (France): Faure et al., Nature (2006)



Gas jet: 7×10^{18} cm^{-3}

Rechatin et al. Phys. Rev. Lett. (2009)



My Path to Laser Wakefield Accelerators: Not Possible Without…

- Norman Rostoker
  - Toshi Tajima, Phillip Sgrangle, Kim Molvig
    - Eric Esarey (Grandstudent)
- UCLA laser-plasma accelerator program
  - John Dawson
    - Toshi Tajima, Warren Mori…
  - Chan Joshi
    - Don Umstadter, Wim Leemans …
- Gerard Mourou et al – CPA lasers
- David Sutter – DoE Support
- My many collaborators and colleagues
  - LBNL, UCLA, Texas, Michigan, Nebraska, Maryland, NRL, world-wide…

Summary

- Laser plasma accelerators:
  - 1 GeV in < 3 cm
  - BELLA Project will allow 10 GeV in < 1 m
  - Developing techniques for beam control and staging
  - Laser technology maturing rapidly
- Applications:
  - Compact accelerator for basic science
    - Collider based on 10 GeV LPA stages
  - Medical, homeland security
  - Compact light source based on Berkeley's LPA technology
    - 5^{th} generation light source: LPA-FEL
- Many LPA research programs all over the world