Advanced Accelerator R&D:

FACET and BELLA

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Lawrence Berkeley National Laboratory

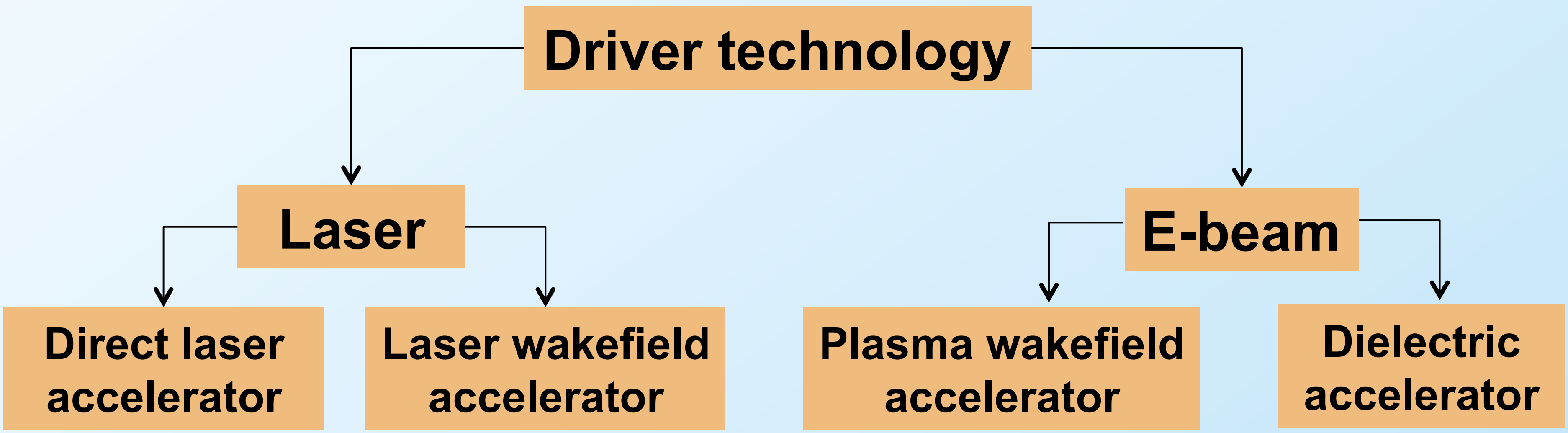
HEPAP Meeting

May 21-22, 2009

Thanks to Tor Raubenheimer &
Mark Hogan for FACET material

Motivation and overview

- Collider size set by maximum particle energy and maximum achievable gradient limited by breakdown
- Motivates R&D for ultra-high gradient technology



BELLA BERKELEY LAB LASER ACCELERATOR

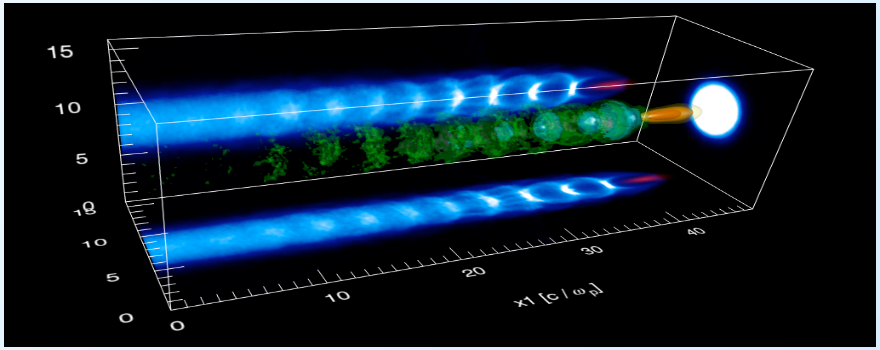
FACET

Ultra-high gradients could result in smaller accelerators

m-scale

10 – 40 MV/m

100 micron-scale



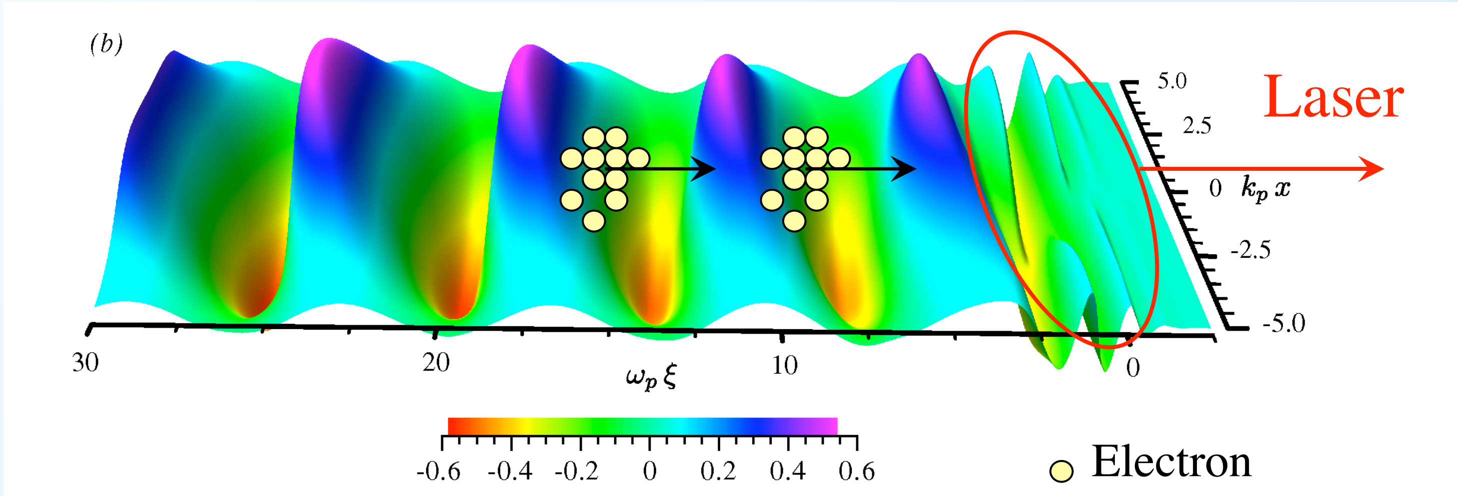
10 – 100 GV/m

Plasmas sustain extreme fields => compact accelerators

Summer – somewhere on California Coast

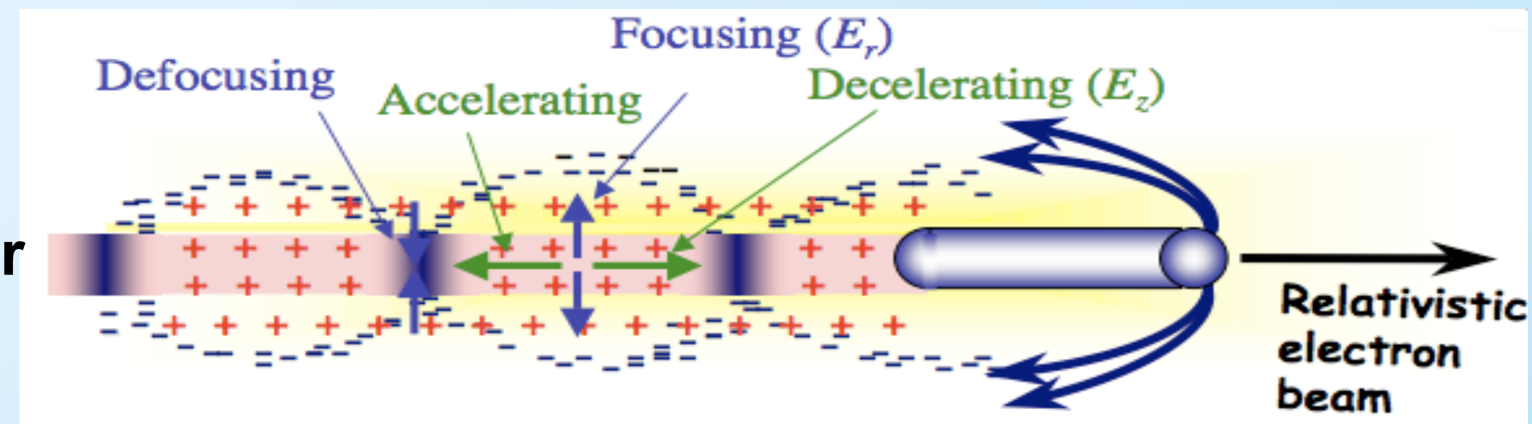
Principle of laser/plasma wakefield accelerators

Linear

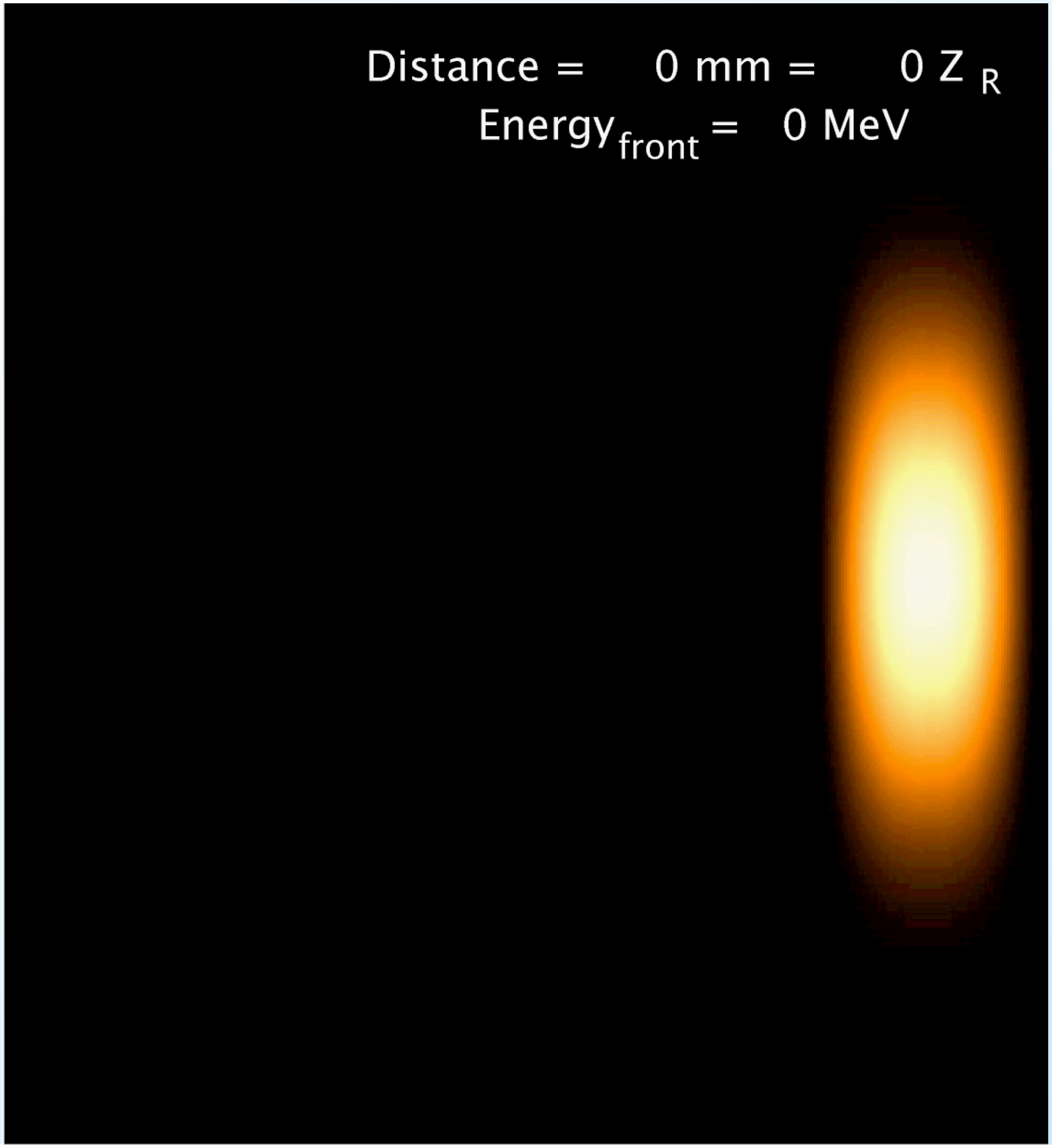


- Laser driver--Tajima&Dawson, PRL'79
- Beam driver--P. Chen et al., PRL'85
- E-fields: 10 – 100 GV/m
- Phase velocity wake=Group velocity driver

Non-Linear



Operation in bubble or blow-out non-linear regime: most experiments to date



- High gradients
- Can produce narrow energy spread beams

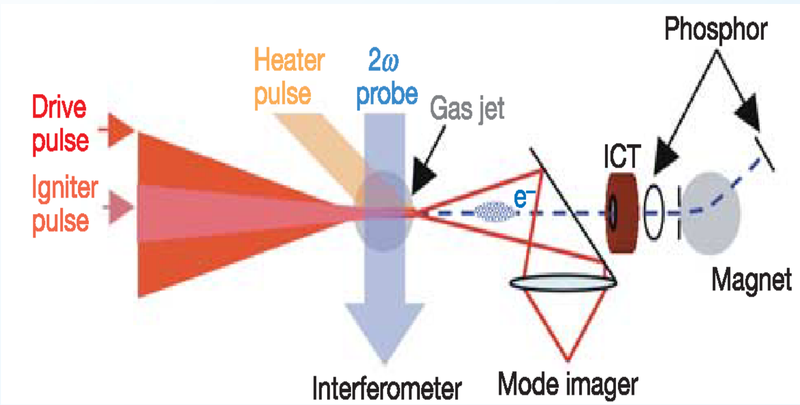
BUT

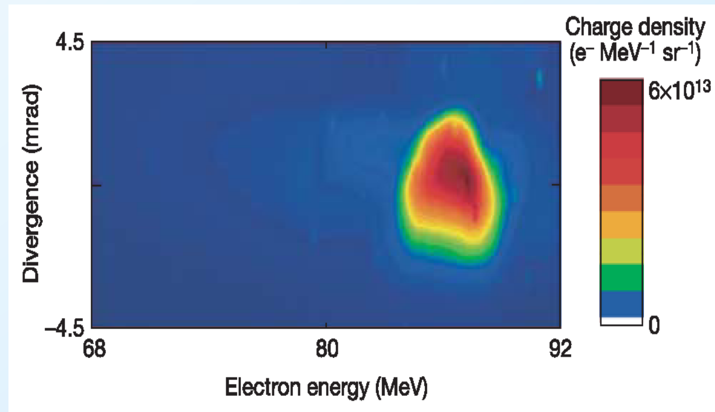
- Limited control
- Self-trapping (dark current)
- Can easily go unstable
- Does not work well for positrons

Courtesy of W. Mori, UCLA

Channel guided laser plasma accelerators achieve high quality, up to GeV beams

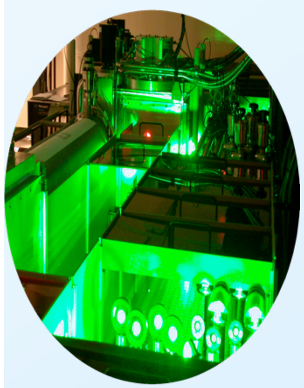
2004 result

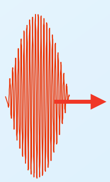


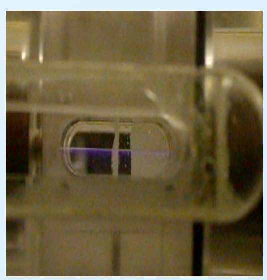


C. G. R. Geddes,et al, Nature,**431**, p538 (2004)
S. Mangles et al., Nature **431**, p535 (2004)
J. Faure et al., Nature **431**, p541 (2004)

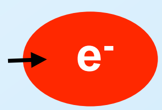
2006 result

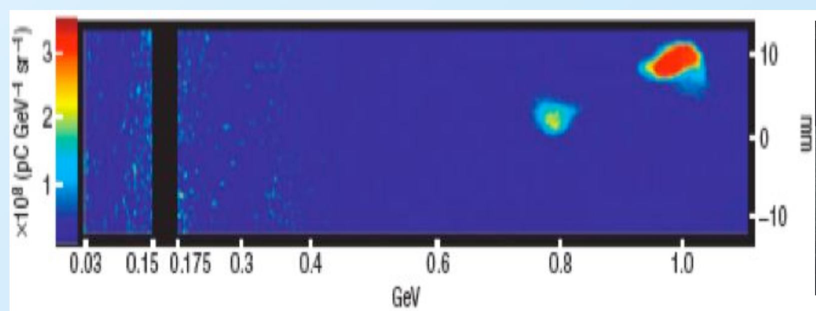


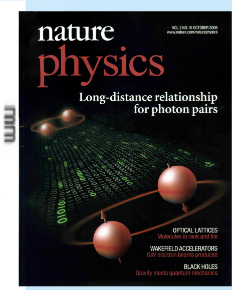




1 GeV



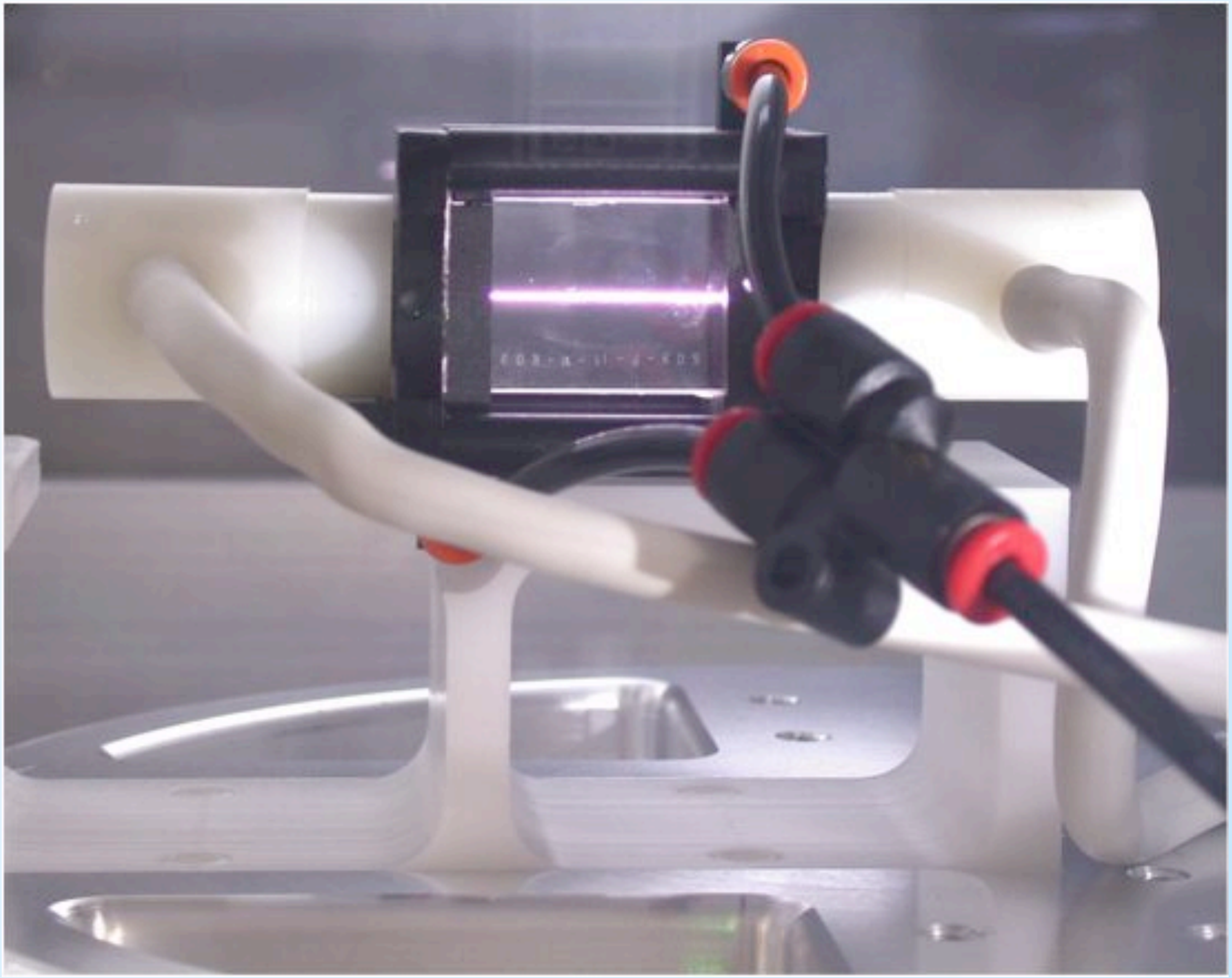




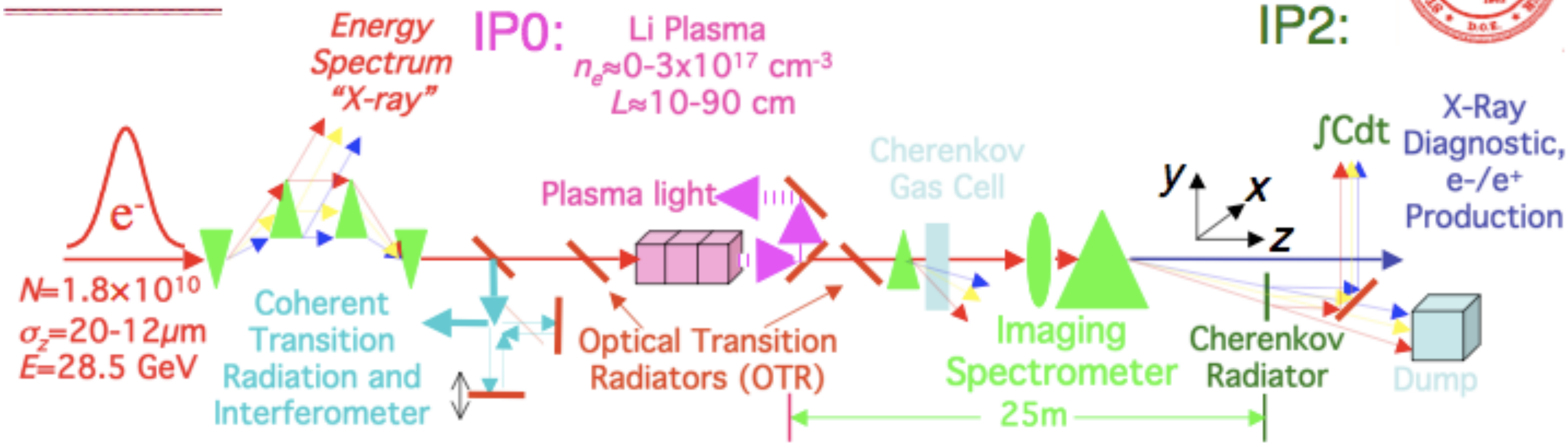
Oxford Physics

W.P. Leemans et. al, *Nature Physics* **2**, p696 (2006)

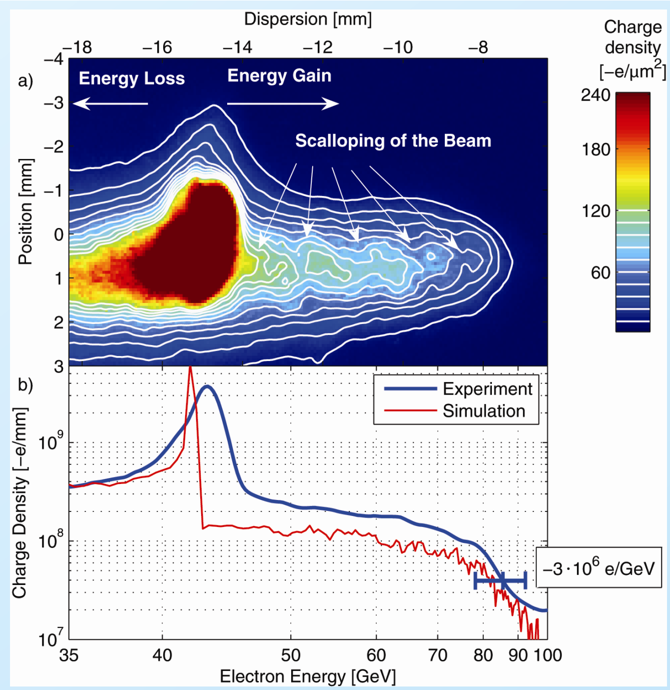
A GeV module…



Plasma wakefield accelerator expt



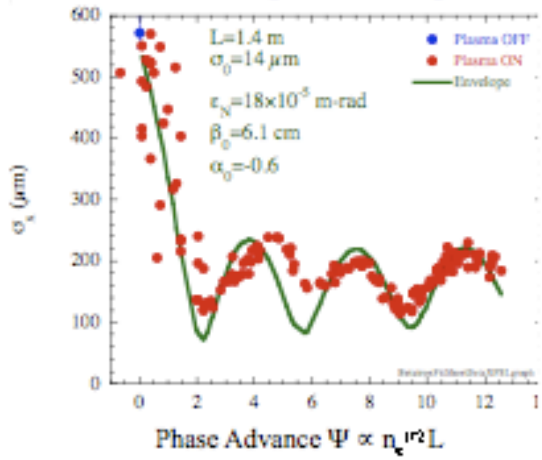
- **Used 42 GeV FFTB beam**
- **Li plasma**
- **Most electrons decelerated**
- **Few % accelerated**
- **Highest energy observed ~ 85 GeV**



Blumenfeld et al., Nature 2007

SLAC/UCLA/USC Experiments @ FFTB
Studied all aspects of beam-plasma interaction

Focusing & Matching e^-

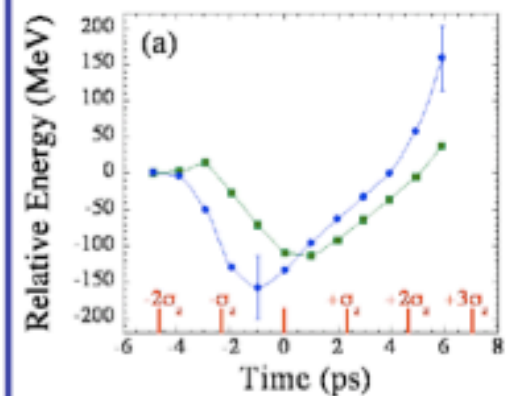


Phys. Rev. Lett. **93**, 014802 (2004)

X-ray Generation

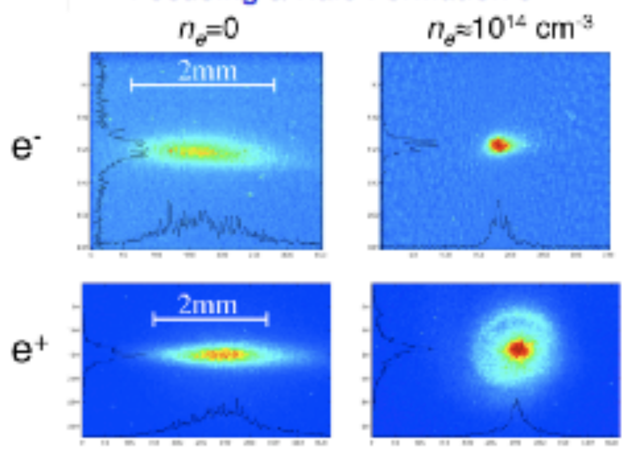
Phys. Rev. Lett. **88**, 135004 (2002)

Wakefield Acceleration e^-



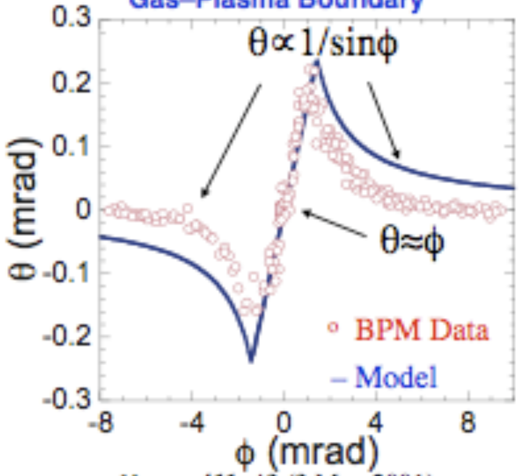
Phys. Rev. Lett. **93**, 014802 (2004)

Focusing & Halo Formation e^+



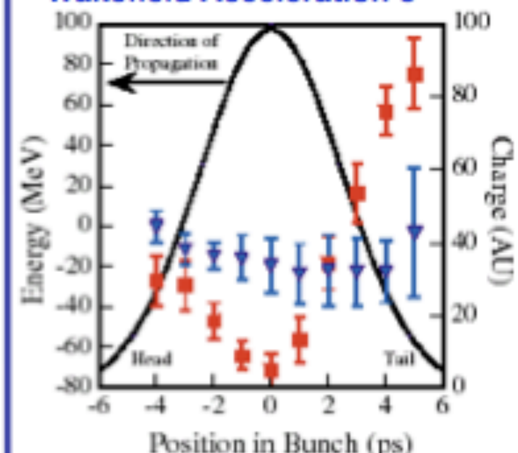
Phys. Rev. Lett. **101**, 055001 (2008)

Electron Beam Refraction at the Gas–Plasma Boundary



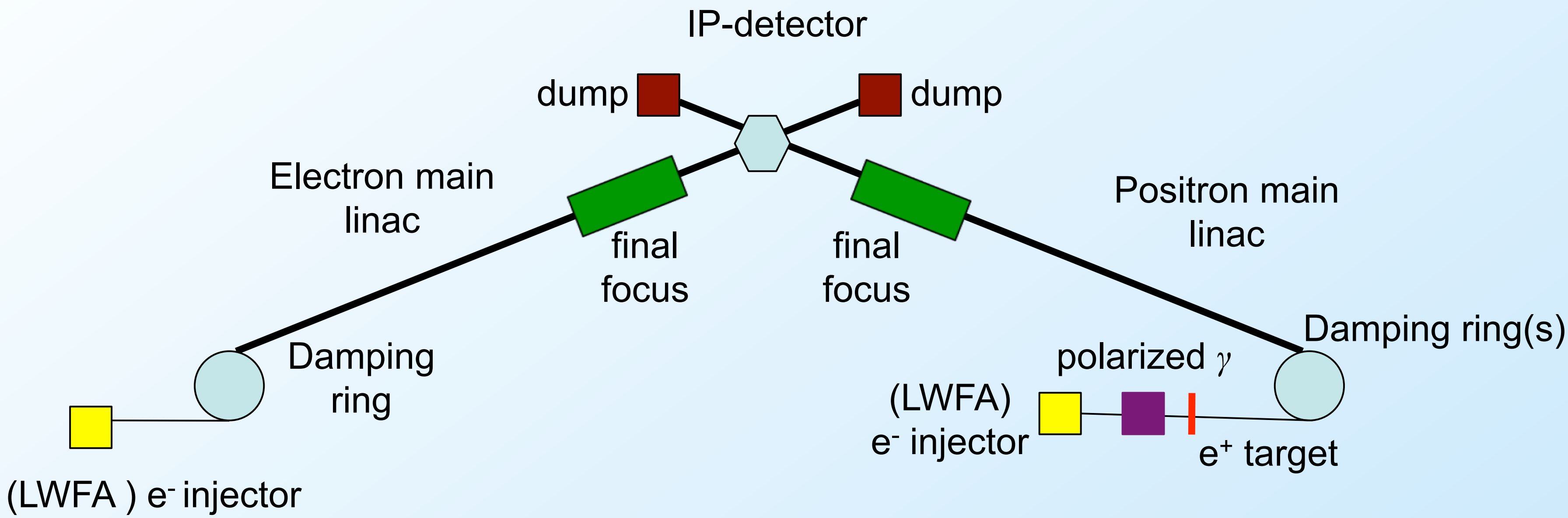
Nature **411**, 43 (3 May 2001)

Wakefield Acceleration e^+



Phys. Rev. Lett. **90**, 214801 (2003)

Electron-Positron Linear Collider



- G. Dugan, "Advanced Accelerator System Requirements for Future Linear Colliders," *in Proceedings of AAC 2004, p.29*

Conventional technology:

- Current generation of future linear collider designs based on existing technology (e.g., ILC): E_{cm}~ 0.5 TeV; gradient ~ 0.03 GV/m; ~30 km (~multi-$B).
- Higher energy collider with existing technology: 5 TeV ➔ >100 km, > tens of $B

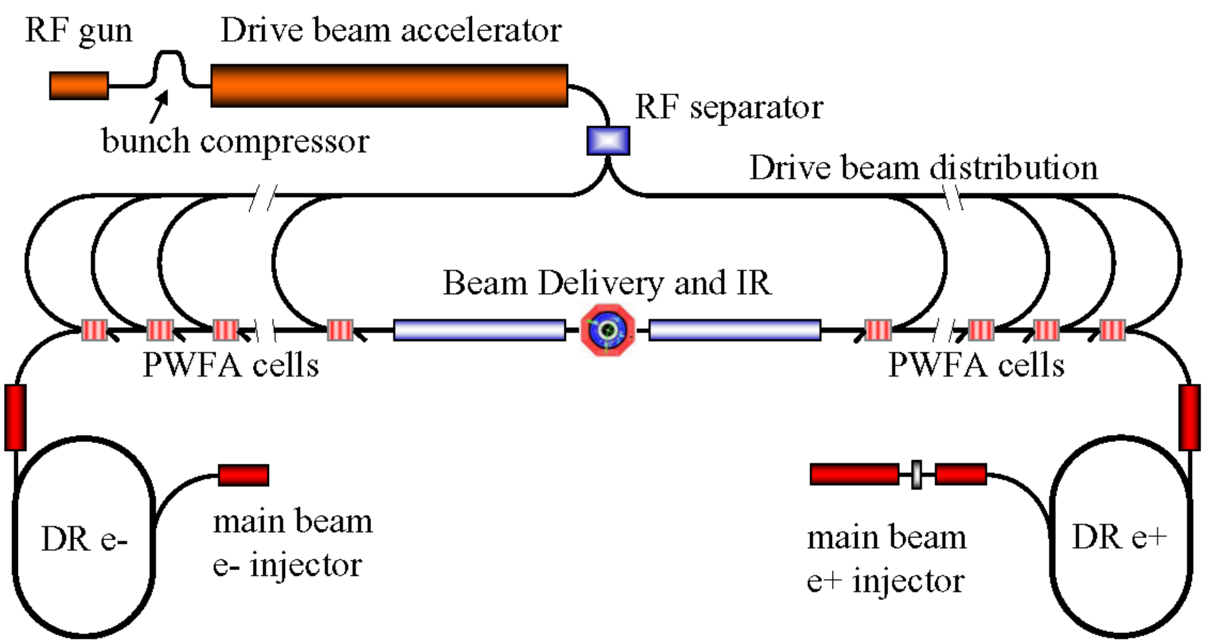
Primary Issues for any Plasma-based LC

* Need to understand acceleration of electrons & positrons
* Luminosity drives many issues:
  - High beam power (20 MW) → efficient ac-to-beam conversion
  - Well defined cms energy → small energy spread
  - Small IP spot sizes → small energy spread and small $\Delta\varepsilon$
* These translate into requirements on the plasma acceleration
  - High beam loading of e+ and e- (for efficiency)
  - Acceleration with small energy spread
  - Preservation of small transverse emittances – maybe flat beams
  - Bunch repetition rates of 10's of kHz
* Multiple stages allow better beam control and use of drive-beam
  - possible to demonstrate single stage before full system test

FACET @ SLAC

Example: PWFA-Linear Collider Concept

- Developed a concept for a 1 TeV plasma wakefield-based linear collider
  - Use conventional Linear Collider concepts for main beam and drive beam generation and focusing and PWFA for acceleration
    - Makes best use of PWFA R&D and 30 years of conventional rf R&D
  - Concept illustrates focus of PWFA R&D program
    - High efficiency
    - Emittance pres.
    - Positrons
  - PWFA concept could be used to upgrade LCLS or simply other e- acc.



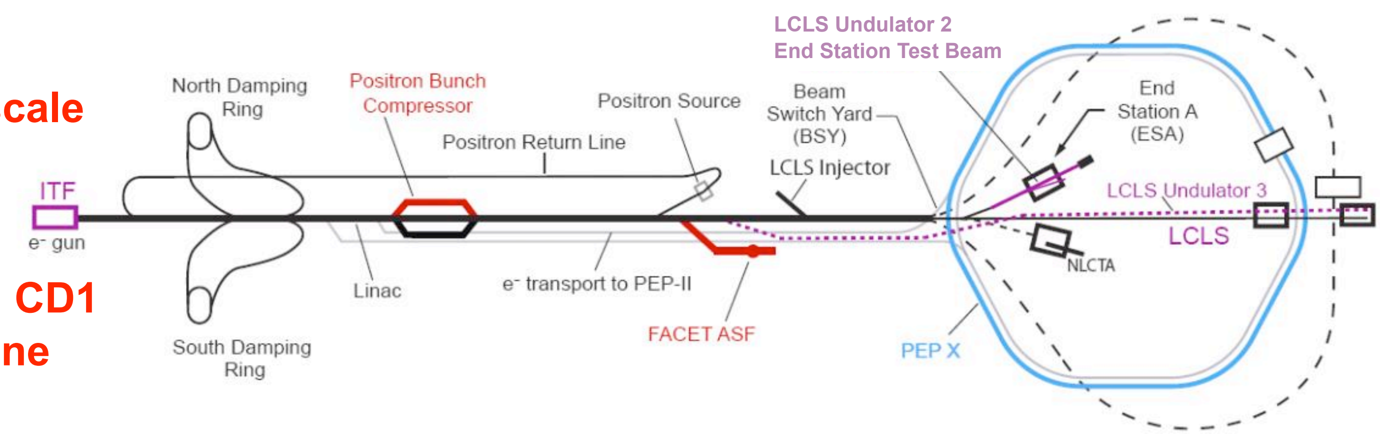
SLAC NATIONAL ACCELERATOR LABORATORY

New SLAC Experimental Facility: FACET

- New FACET facility will provide high quality 25 GeV e+ & e- beams for studies of plasma wakefield acceleration
  - Plasma wakefield acceleration could reduce cost/GeV significantly for linear colliders and could provide an easy upgrade for FEL facilities
  - FACET will also be used to develop beam-driven dielectric acceleration and plasma focusing concepts as well as other beam physics studies
    - Beams of e+ / e- at 25 GeV with 20kA and 10x10 um spot sizes

FACET timescale 2010 – 2017

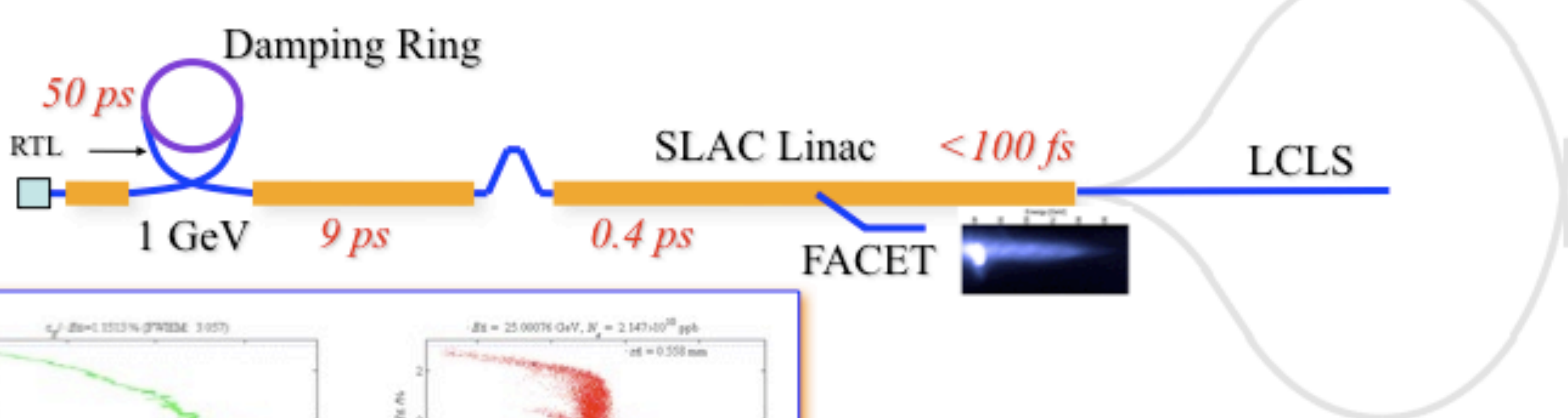
Scheduling CD1 Review in June

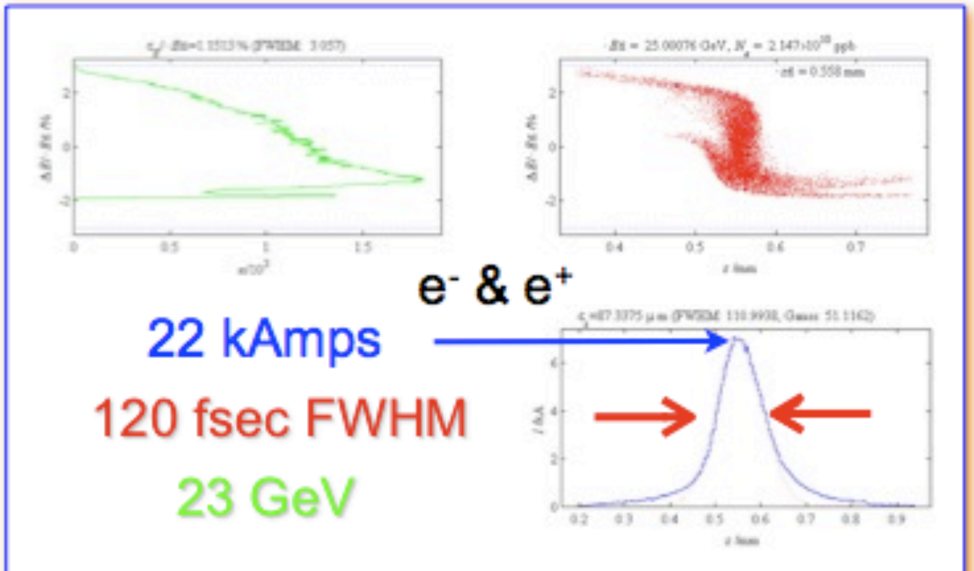


- Unique facility is only possible because of SLAC linac

SLAC NATIONAL ACCELERATOR LABORATORY

Short Bunches Bring Large Gradients and Long, Uniform High-Density Plasmas





Peak Field For A Gaussian Bunch:

$$E = 6GV/m \frac{N}{2x10^{10}} \frac{20\mu}{\sigma_r} \frac{100\mu}{\sigma_z}$$

Ionization Rate for Li:

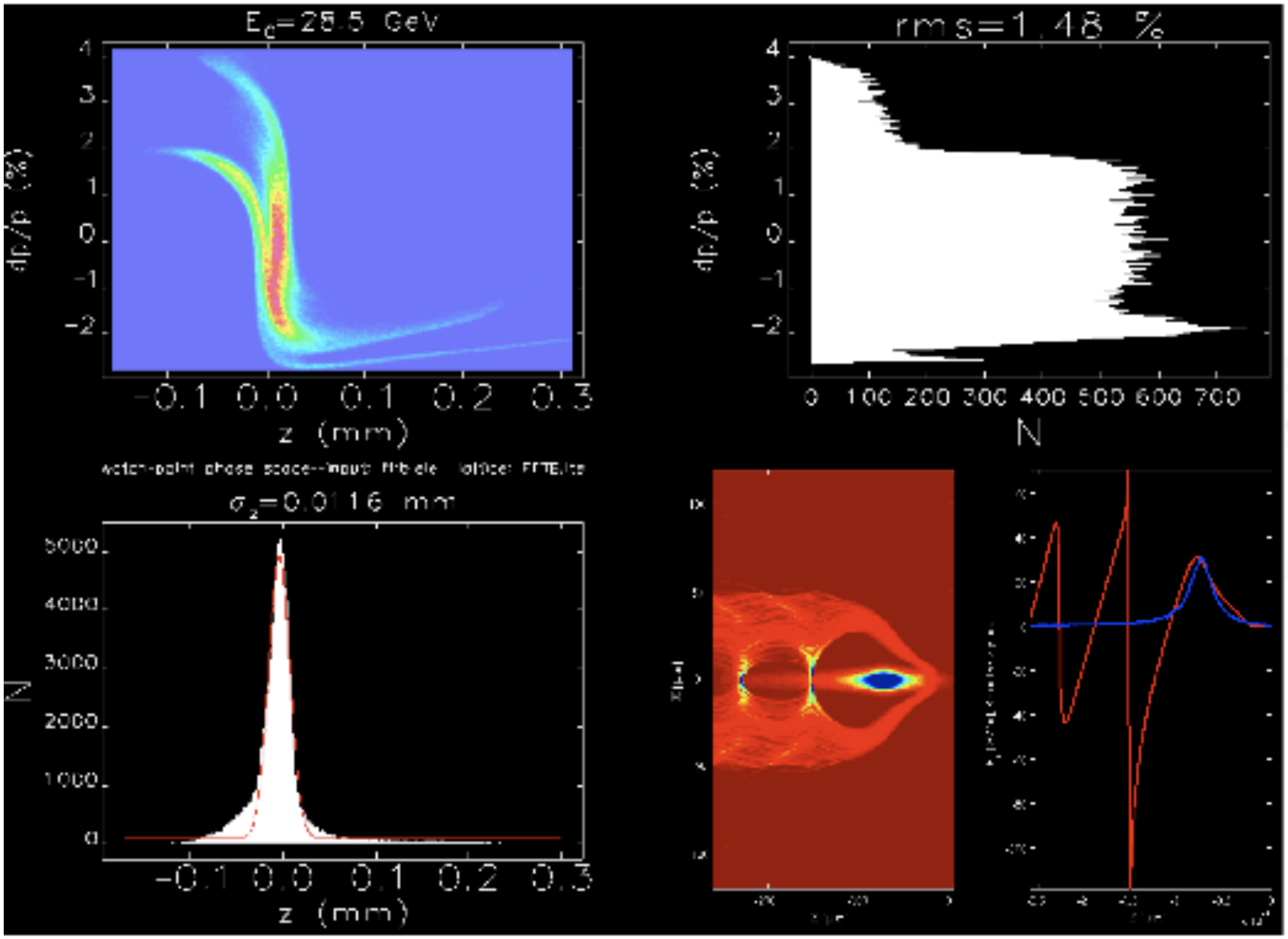
$$W_{Li}\left[s^{-1}\right] \approx \frac{3.60x10^{21}}{E^{2.18}\left[GV/m\right]} \exp\left(\frac{-85.5.}{E\left[GV/m\right]}\right)$$

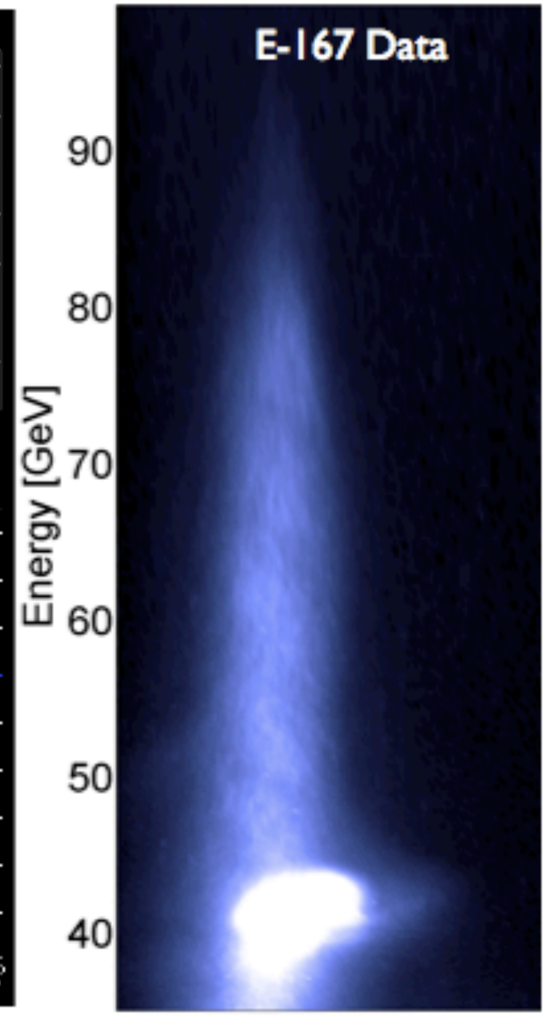
See D. Bruhwiler et al, Physics of Plasmas 2003

Space charge fields tunnel ionize the vapor!

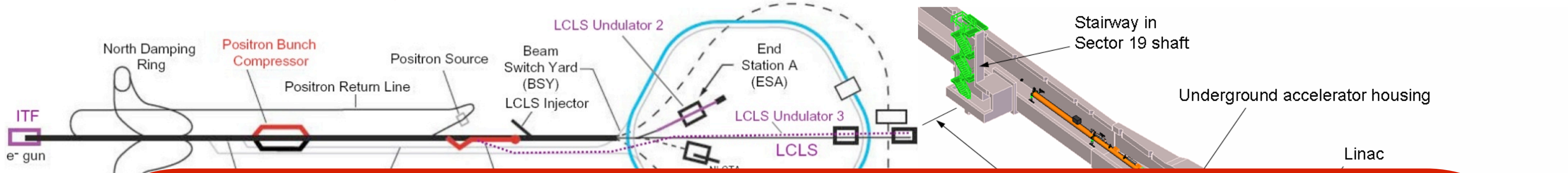
- No timing or alignment issues
- Long high-density plasmas now possible

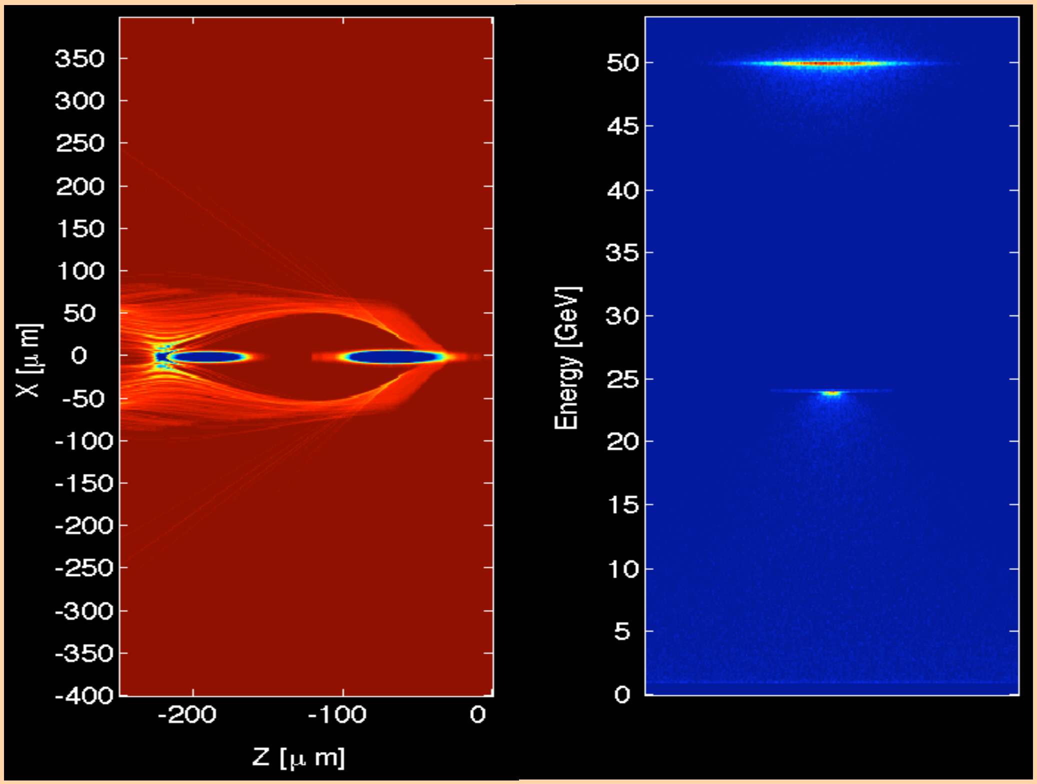
Single FFTB Bunch Sampled All Phases of the Wake Resulting in ~ 200% Energy Spread





Facility for Advanced Accelerator Experimental Tests



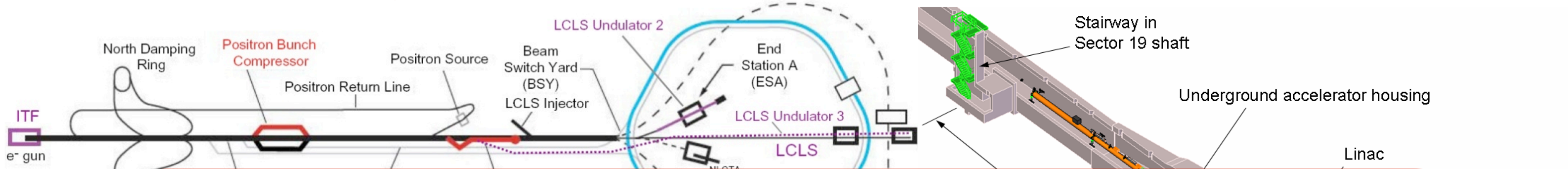


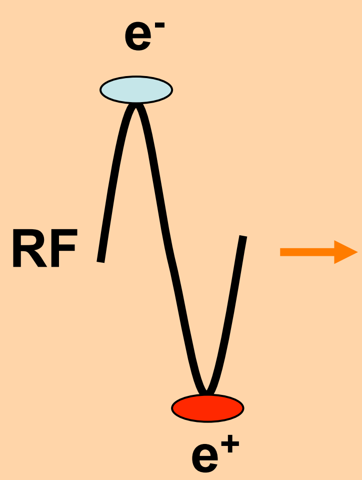
Two electron bunches formed by notch collimator will allow study energy doubling, high efficiency acceleration, emittance preservation

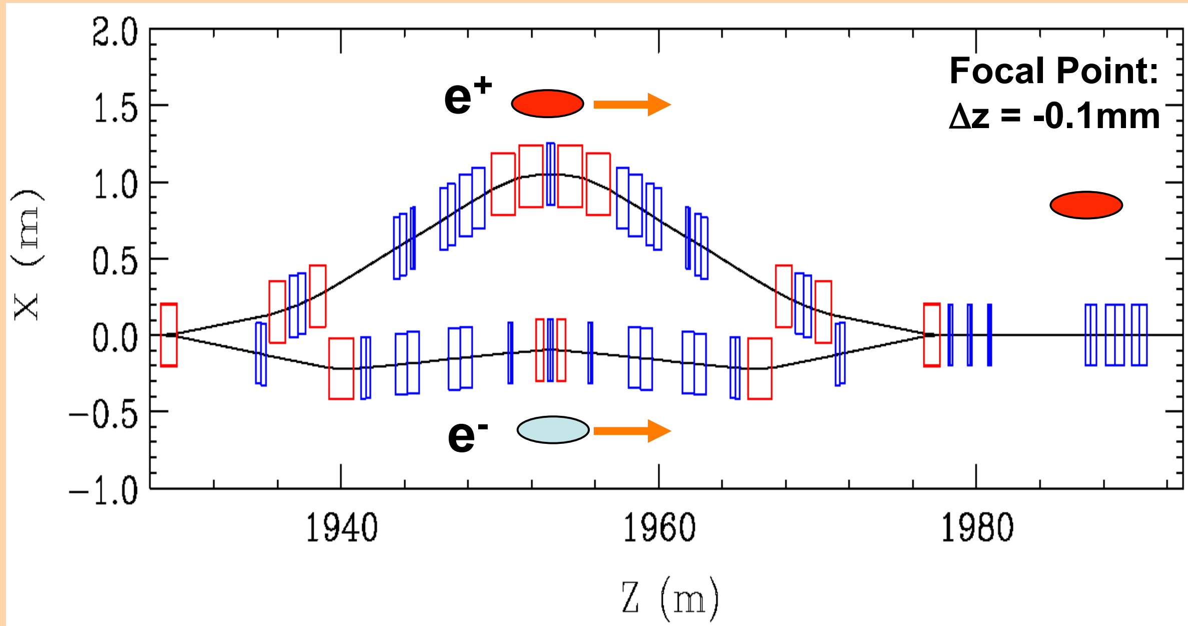
Short bunches and their Tera-Hz radiation open new possibilities to study ultrafast magnetization switching

Bent crystal for beam collimation or photon source
e+ and e- acceleration study essential for LWFA & PWFA
Dielectric wakefield acceleration
Energy-doubling for existing facilities such as FEL’s
Generation of THz radiation for materials studies

Facility for Advanced Accelerator Experimental Tests







"Sailboat" dual chicane will give unique opportunity to study acceleration of positrons by an electron bunch

Short bunches and their Tera-Hz radiation open new possibilities to study ultrafast magnetization switching

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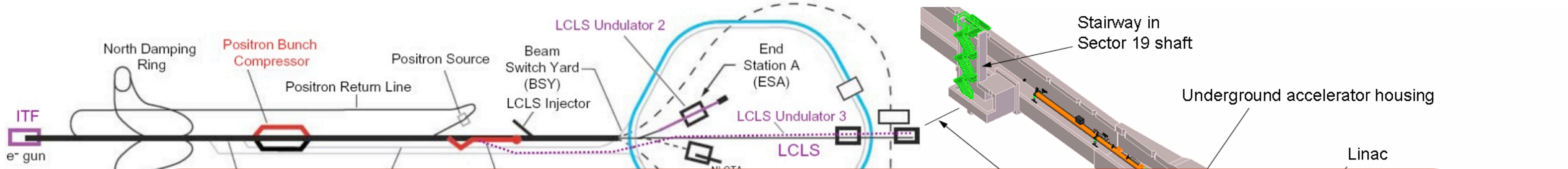

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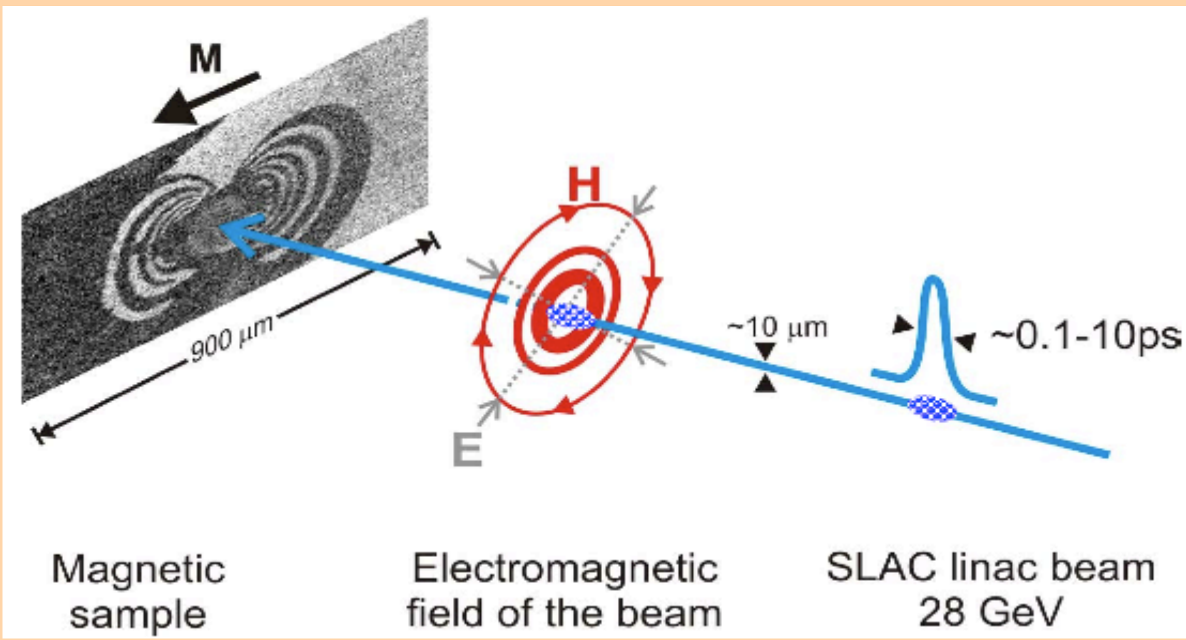

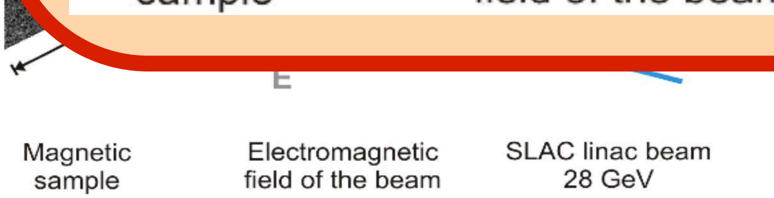

Short bunches and their Tera-Hz radiation open new possibilities to study ultrafast magnetization switching

Bent crystal for beam collimation or photon source
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Dielectric wakefield acceleration
Energy-doubling for existing facilities such as FEL's
Generation of THz radiation for materials studies

Facility for Advanced Accelerator Experimental Tests

Unique science opportunities for variety of fields:

- Plasma beam source for LC or Basic Energy Science
- Plasma lens for compact focusing
- Bent crystal for beam collimation or photon source
- e+ and e- acceleration study essential for LWFA & PWFA
- Dielectric wakefield acceleration
- Energy-doubling for existing facilities such as FEL’s
- Generation of THz radiation for materials studies

Short bunches and their Tera-Hz radiation open new possibilities to study ultrafast magnetization switching

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PWFA Experimental Program

Experimental Tasks and Milestones	FY09	FY10	FY11	FY12	FY13	FY14	FY15	FY16
Accelerate e- bunch with sufficient charge		FACET	FACET					
Accelerate e- bunch achieving low energy spread			FACET	FACET				
Accelerate e- bunch with high efficiency			FACET	FACET				
Demonstration of electron acceleration: high η, low ΔE					★			
Emittance preservation of e- bunch			FACET	FACET	FACET			
Demonstration of a single stage of an electron PWFA-LC						★		
Acceleration of e+ bunch by e+ drive			FACET	FACET	FACET			
Initial test of e+ acceleration in e- wakes				FACET	FACET			
Emittance preservation of e+ bunch				FACET	FACET		FACET	
Upgrade Sector-20 chicane					●			
Accelerate e+ by e- drive; charge, low dE/E						FACET	FACET	
Accelerate e+ by e-, high efficiency, low emittance						FACET	FACET	
Selection of optimum positron acceleration mechanism for a PWFA-LC								★
Upgrade injector with rf gun				●				
Plasma cell with jet and power removal	Study	Study	Eng.	Eng.	FACET	FACET	FACET	
Design plasma cell with needed stability and cooling								★

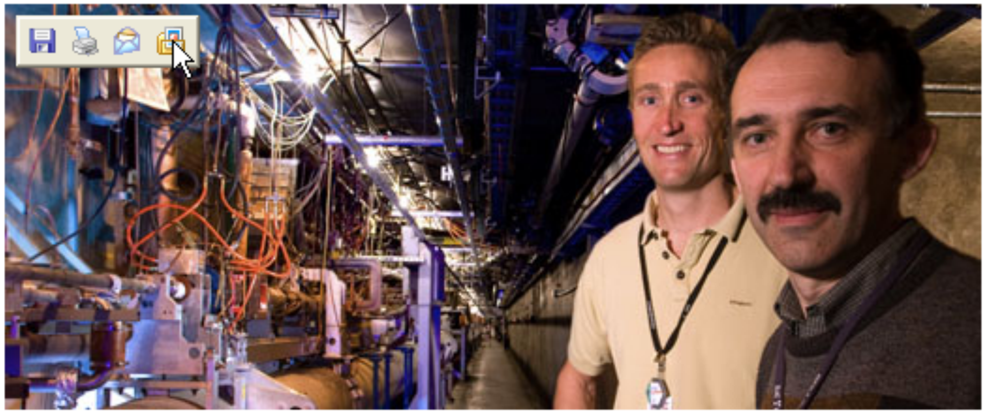
FACET FACILITY FOR ADVANCED ACCELERATOR EXPERIMENTAL TESTS

U.S. DEPARTMENT OF ENERGY

Search GO

SLAC WEB PEOPLE

SLAC NATIONAL ACCELERATOR LABORATORY



News and Events

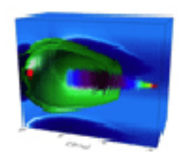
SLAC National Accelerator Laboratory to Receive $68.3 Million in Recovery Act Funding - March 23, 2009

New Accelerator Technique Doubles Particle Energy in Just One Meter - February 14, 2007

» more

What Is FACET?

Advanced accelerator research promises to improve the power and efficiency of today's particle accelerators, enhancing applications in medicine and high-energy physics, and providing potential benefits for research in materials, biological and energy science. Experiments on future acceleration techniques require high-quality, forefront facilities.



FACET—Facilities for Accelerator science and Experimental Test beams at SLAC—will study plasma acceleration, using short, intense pulses of electrons and positrons to create an acceleration source called a plasma wakefield accelerator. FACET will meet the Department of Energy Mission Need Statement for an Advanced Plasma Acceleration Facility.

» more

Research

With FACET, the SLAC linac will support a unique program concentrating on second-generation research on plasma wakefield acceleration.

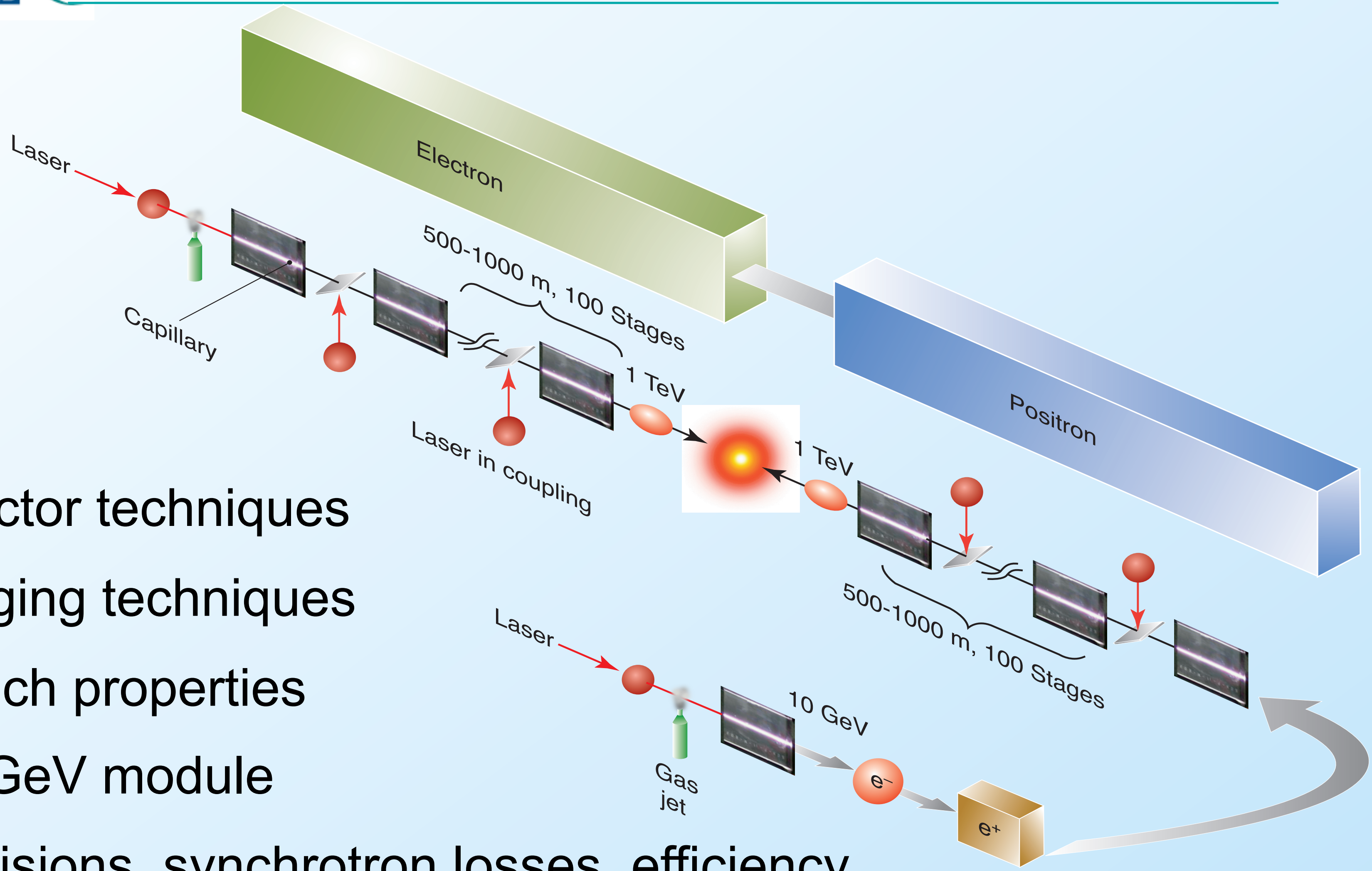
- **Plasma Wakefield Acceleration**
- **THz Radiation**
- **Plasma Focusing**
- **Dielectric Wakefield Acceleration**

» more

BELLA @ LBNL

BELLA
BERKELEY LAB
LASER ACCELERATOR

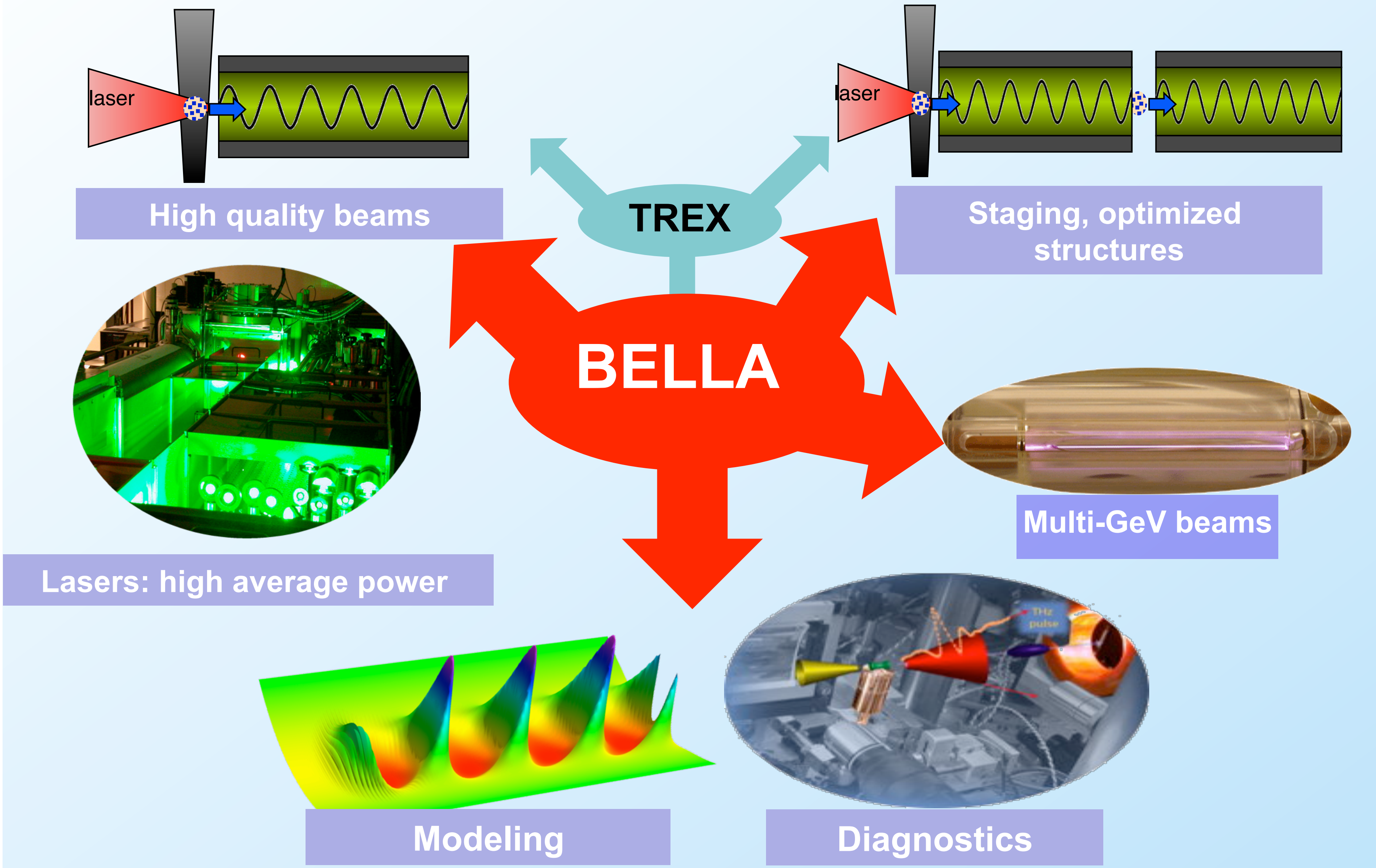
Draft concept has been developed for a Laser Plasma Linear Collider



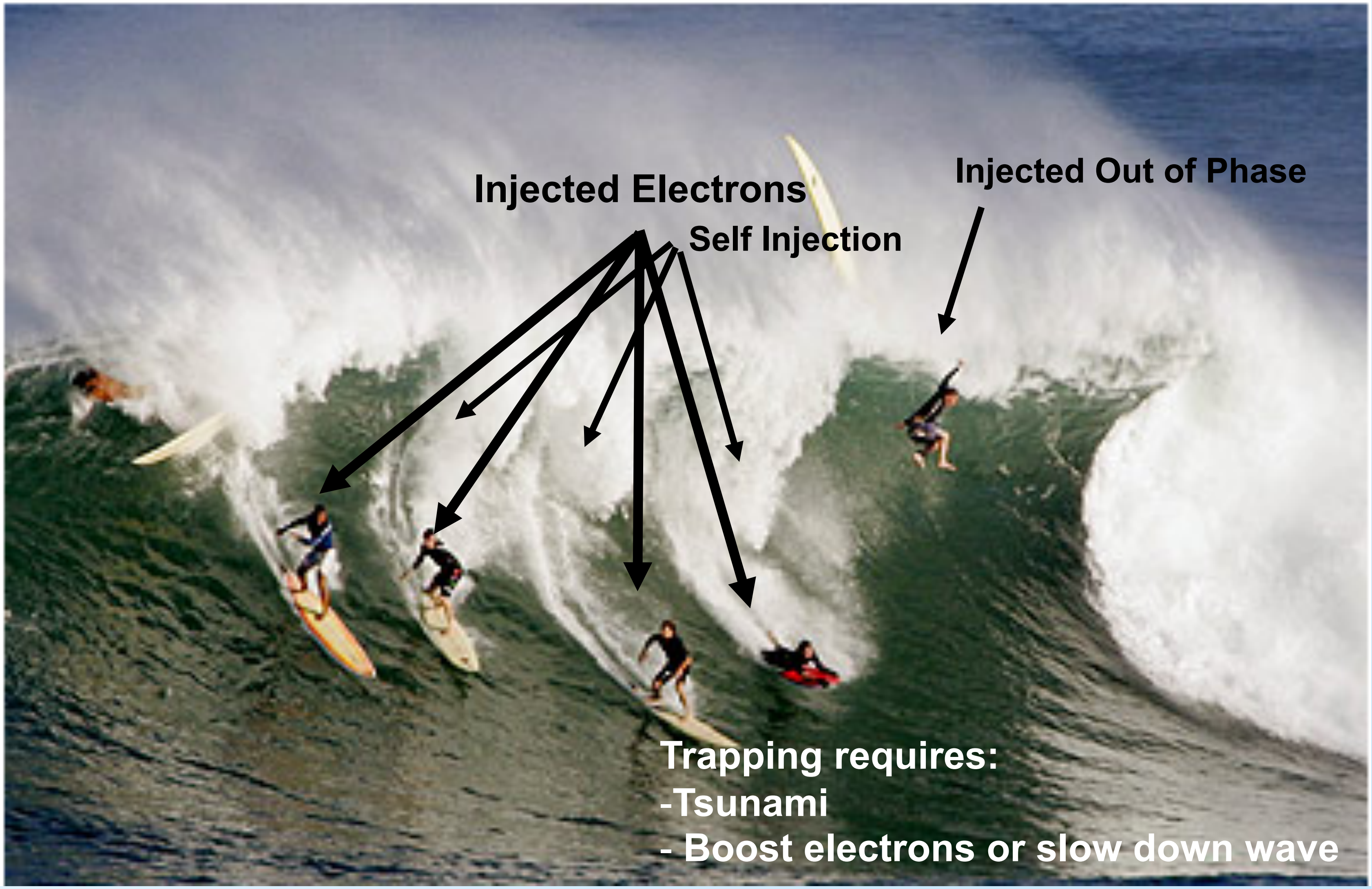
- Injector techniques
- Staging techniques
- Bunch properties
- 10 GeV module
- Collisions, synchrotron losses, efficiency

C.B. Schroeder et al., AAC Proceedings 2008

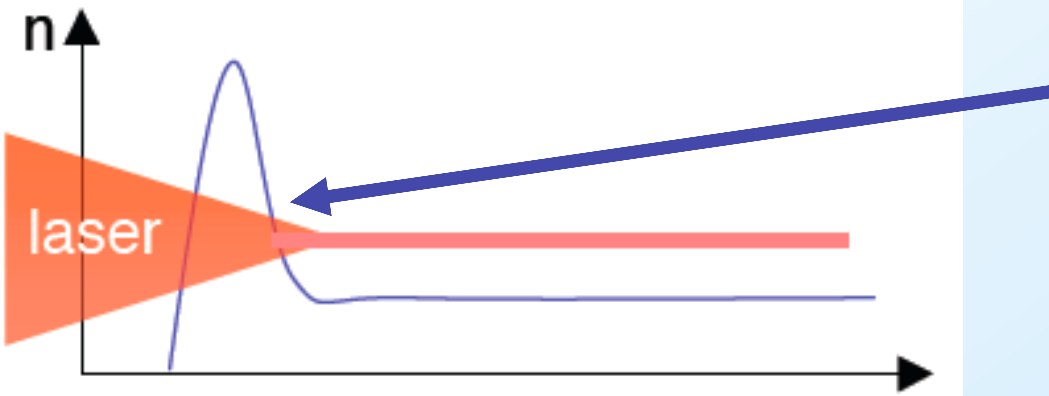
Technical challenges in next 10 years

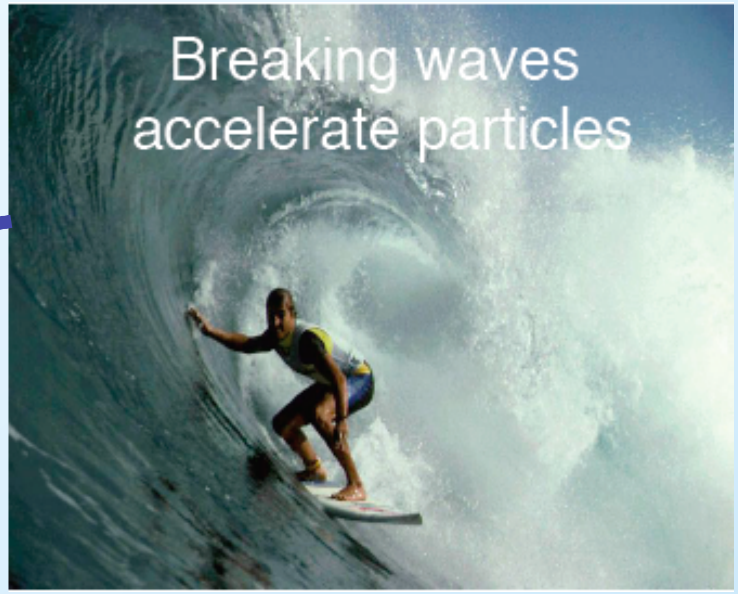


"Electrons" accelerating on a wave: controlled injection



Longitudinal density tailoring allows trapping control

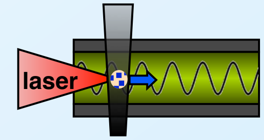




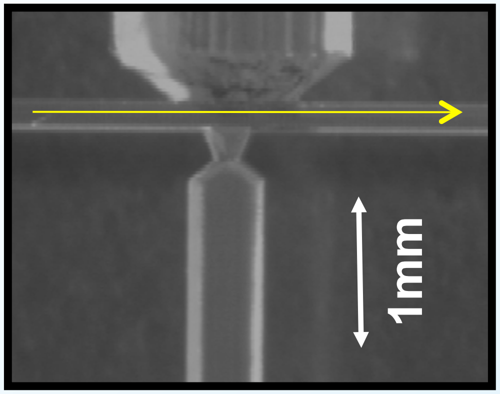
- **As laser propagates through down-ramp**
  - **Plasma wavelength increases so wave period and laser period match leading to**
    - **Efficient wave generation**
    - **Slower phase velocity that enables trapping**

Geddes et al., PRL V 100, 215004 (2008); S.V. Bulanov et al., *PRL* 78, (1997)

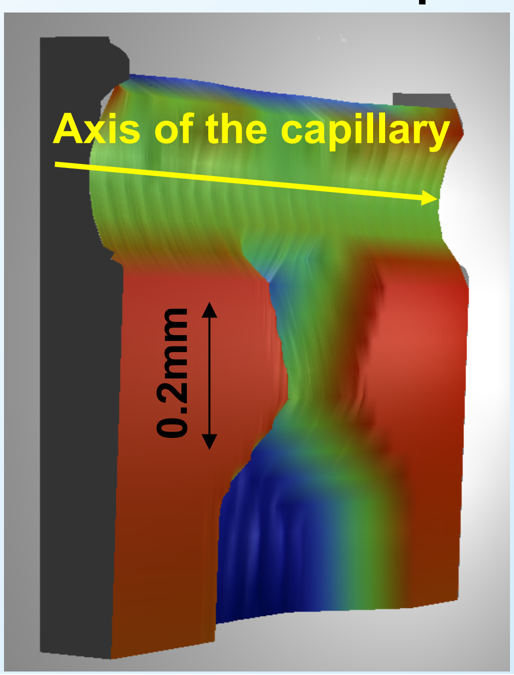
Gas Jet Nozzle Machined Into Capillary Can Provide Local Density Perturbation

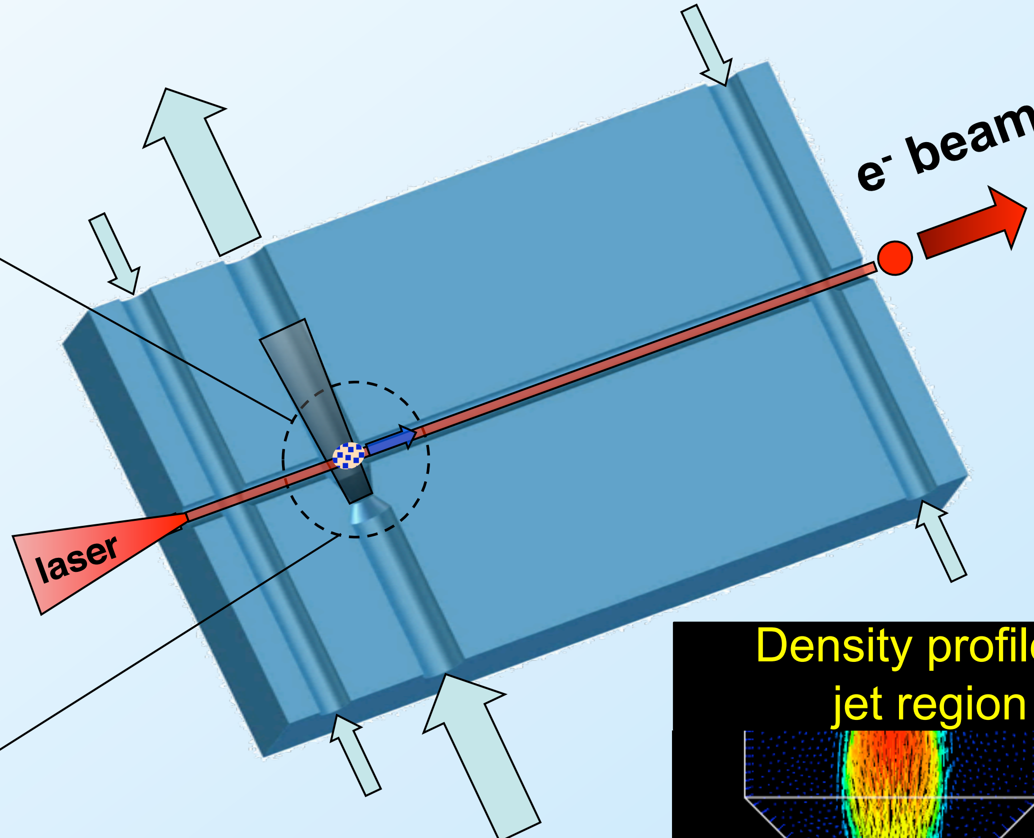


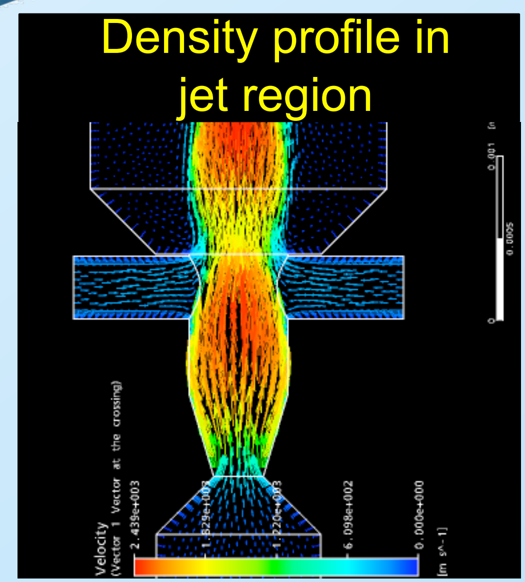
Laser-machined gas jet



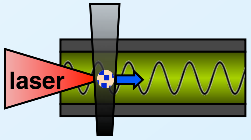
Measured surface profile



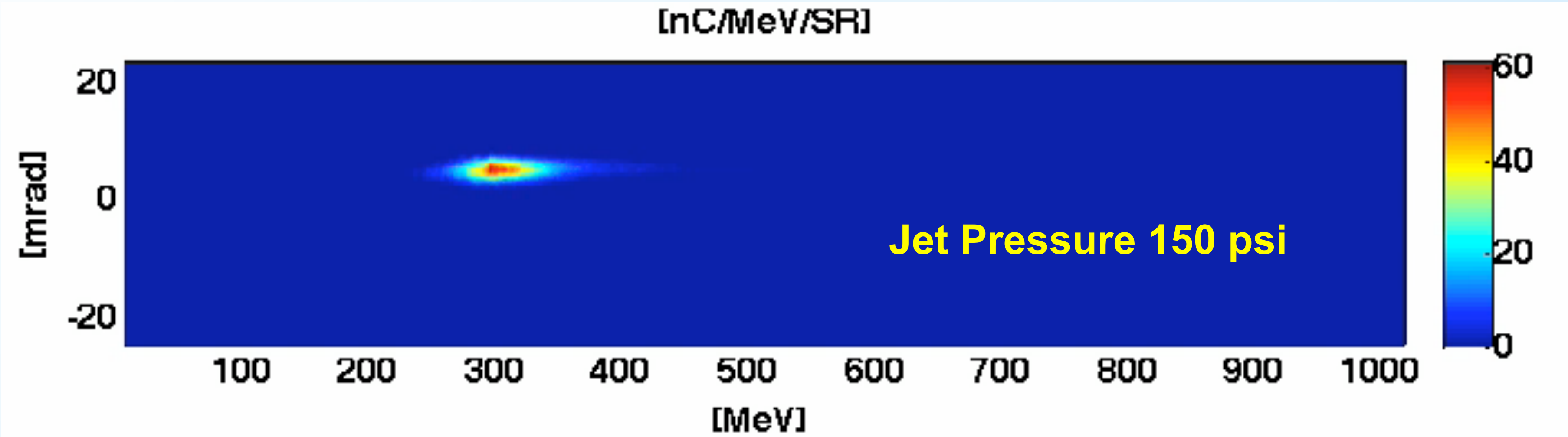




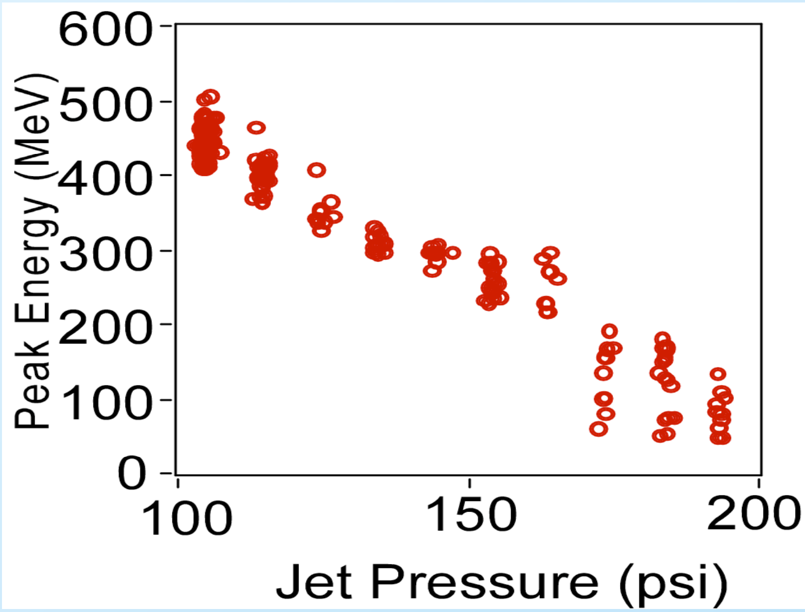
Gas jet triggered injections provides for enhanced stability & tuning



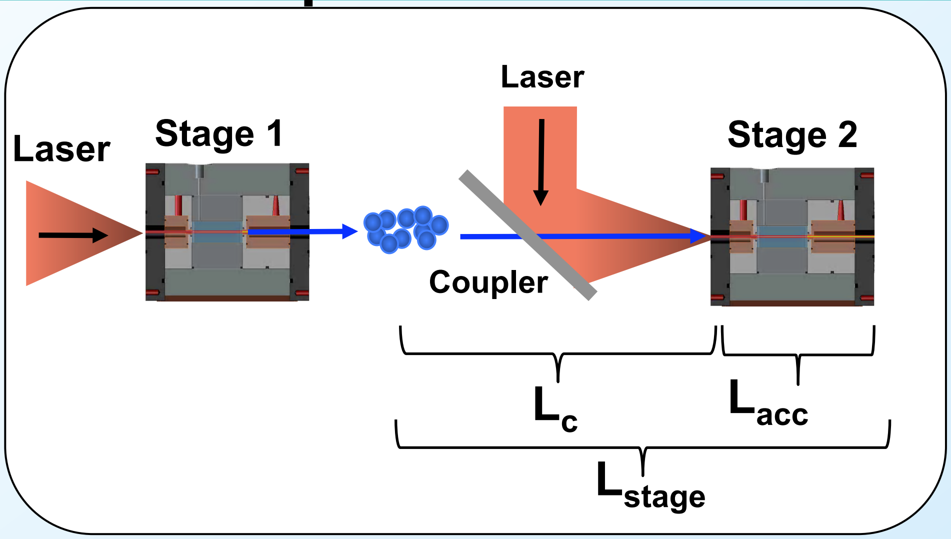
Input Parameters: $N_e \approx 2 \times 10^{18}$ cm^{-3}, $a_0 \approx 1$ (25TW), Laser pulse length ≈ 45 fs



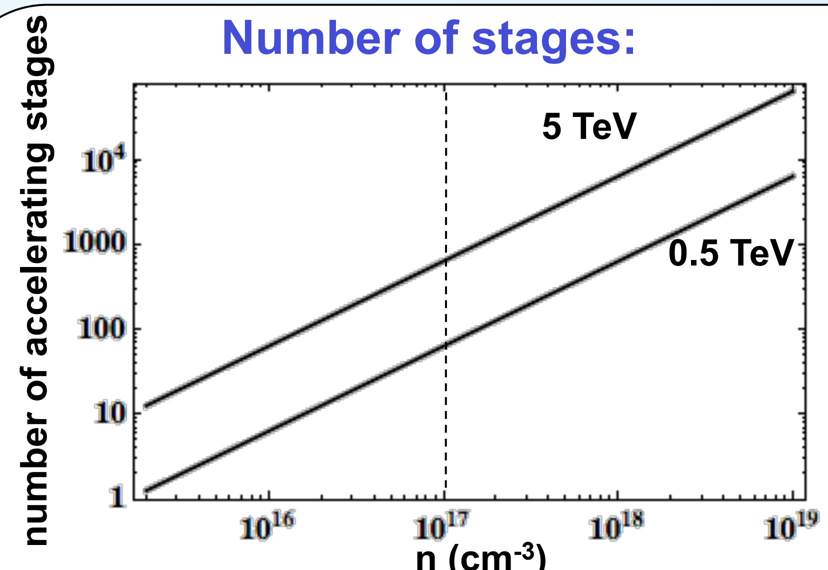
- Pointing ± 0.8 mrad
- Divergence <3mrad
- Peak energy 300MeV ± 7MeV

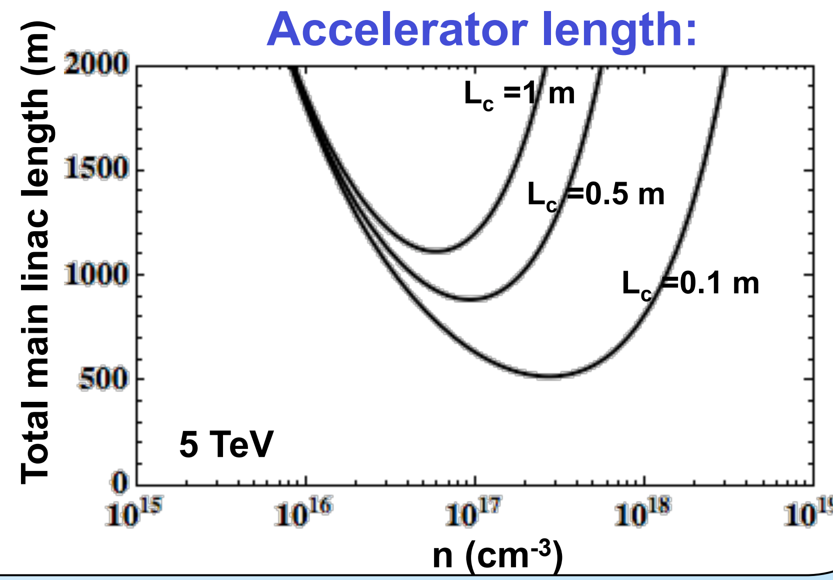


Staging laser accelerators is required to reach TeV

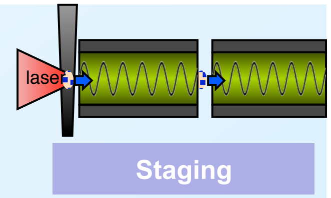


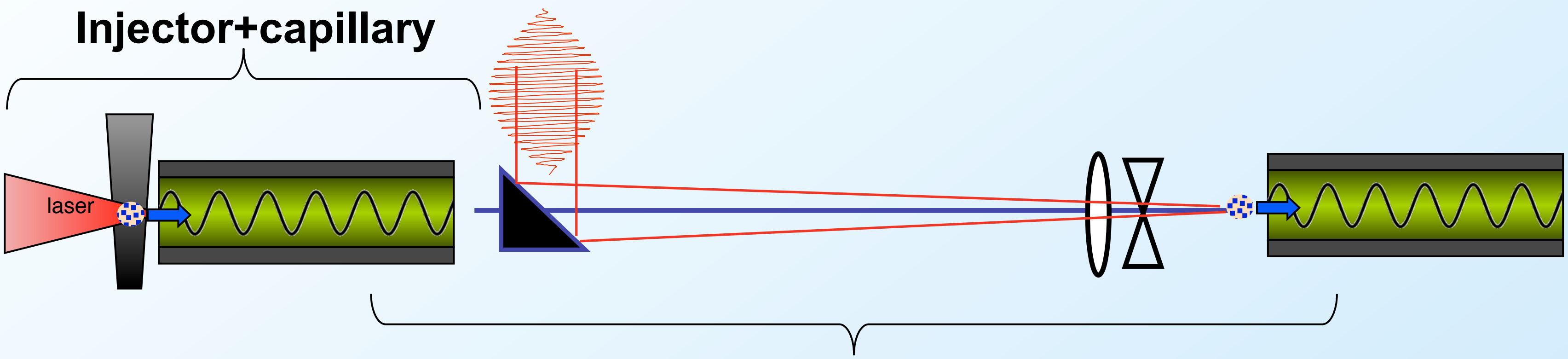
Accelerator length will be determined by staging technology:



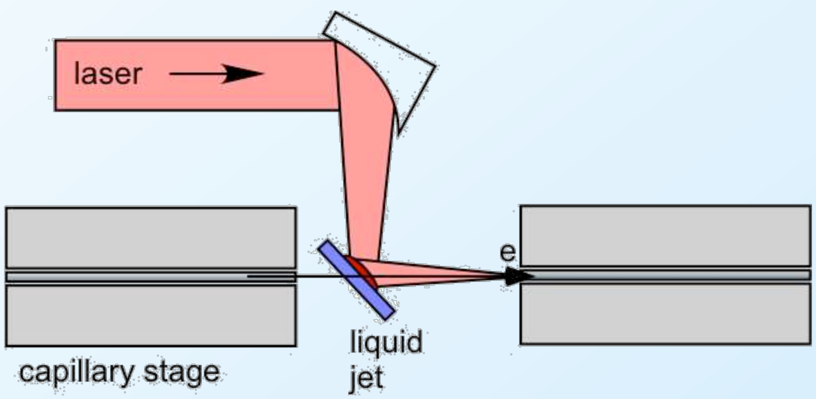


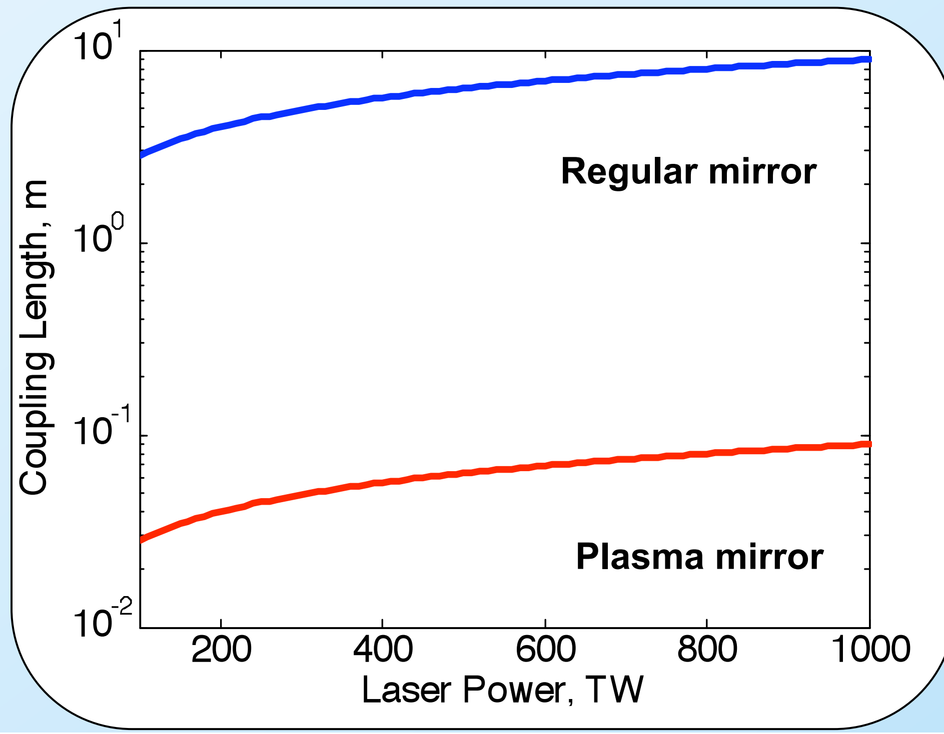
Staging: solving the issue of depletion of laser energy





Renewable mirrors **Structure-to-structure**

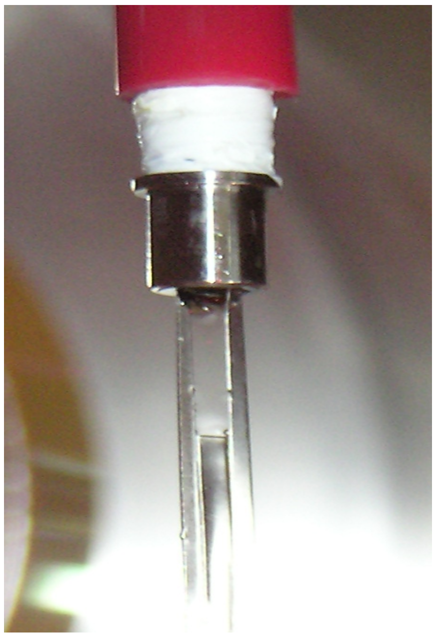


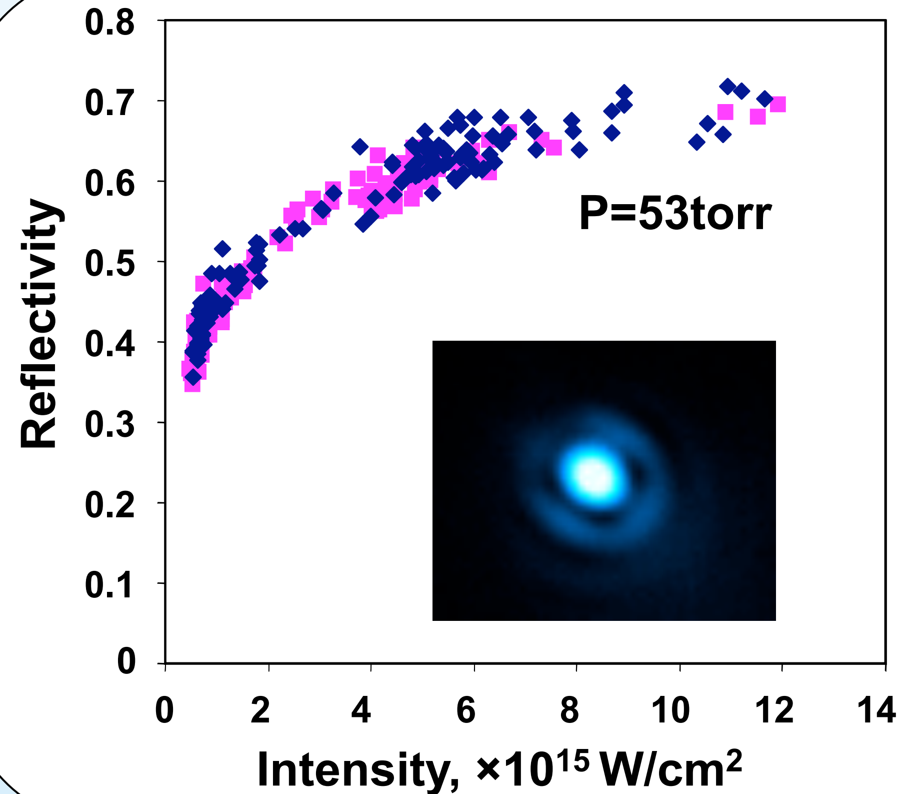


- Reflectivity and flatness
- Preserve quality of electron beam
- Non-contaminating, renewable

Prototype water jet plasma mirror is being tested in vacuum

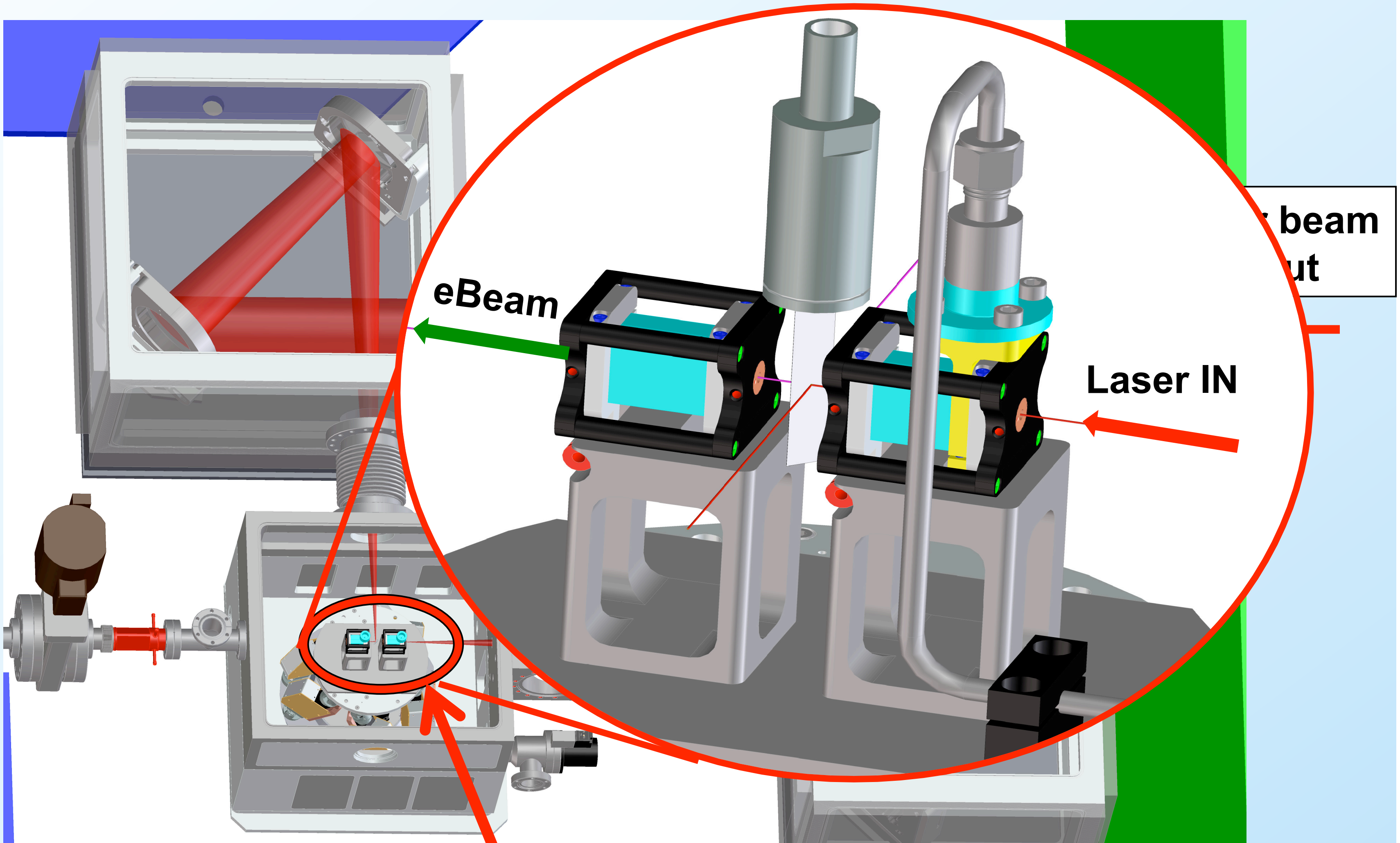
LOASIS Jet with a guiding structure





- 70% maximum reflectivity
- Pressure in the chamber limited by water vapor sat. pressure (~20 torr)

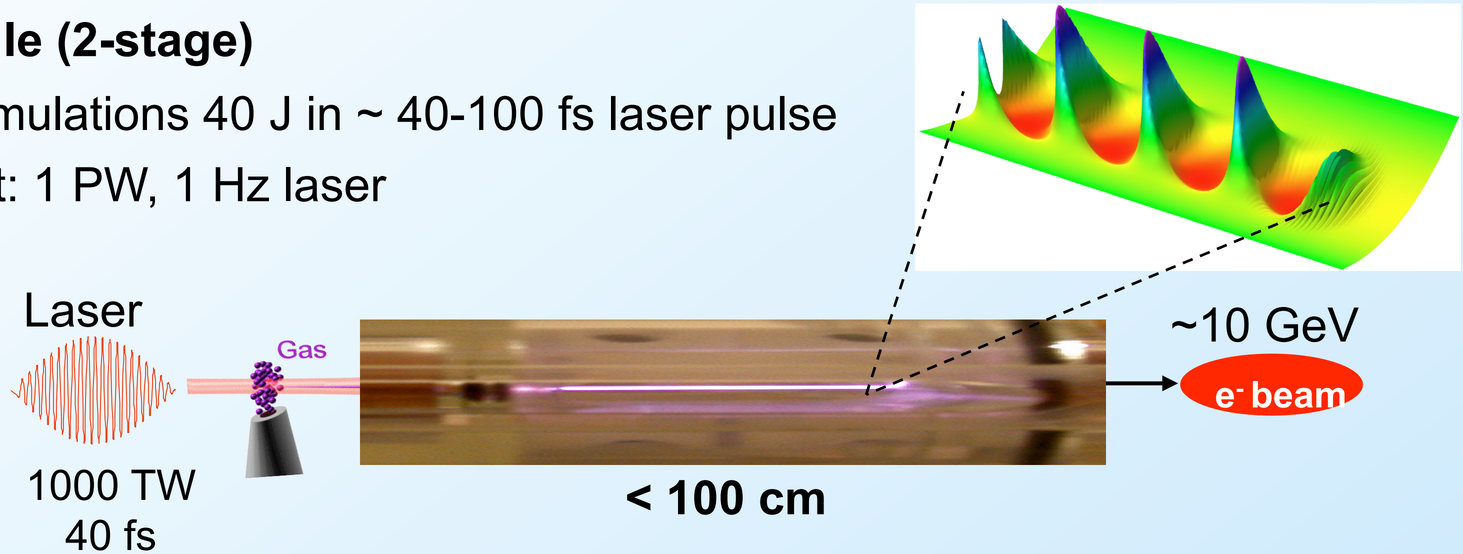
Lay-out for proof-of-principle staging experiments



Double capillary

BELLA laser will enable 10 GeV module and high energy staging experiments

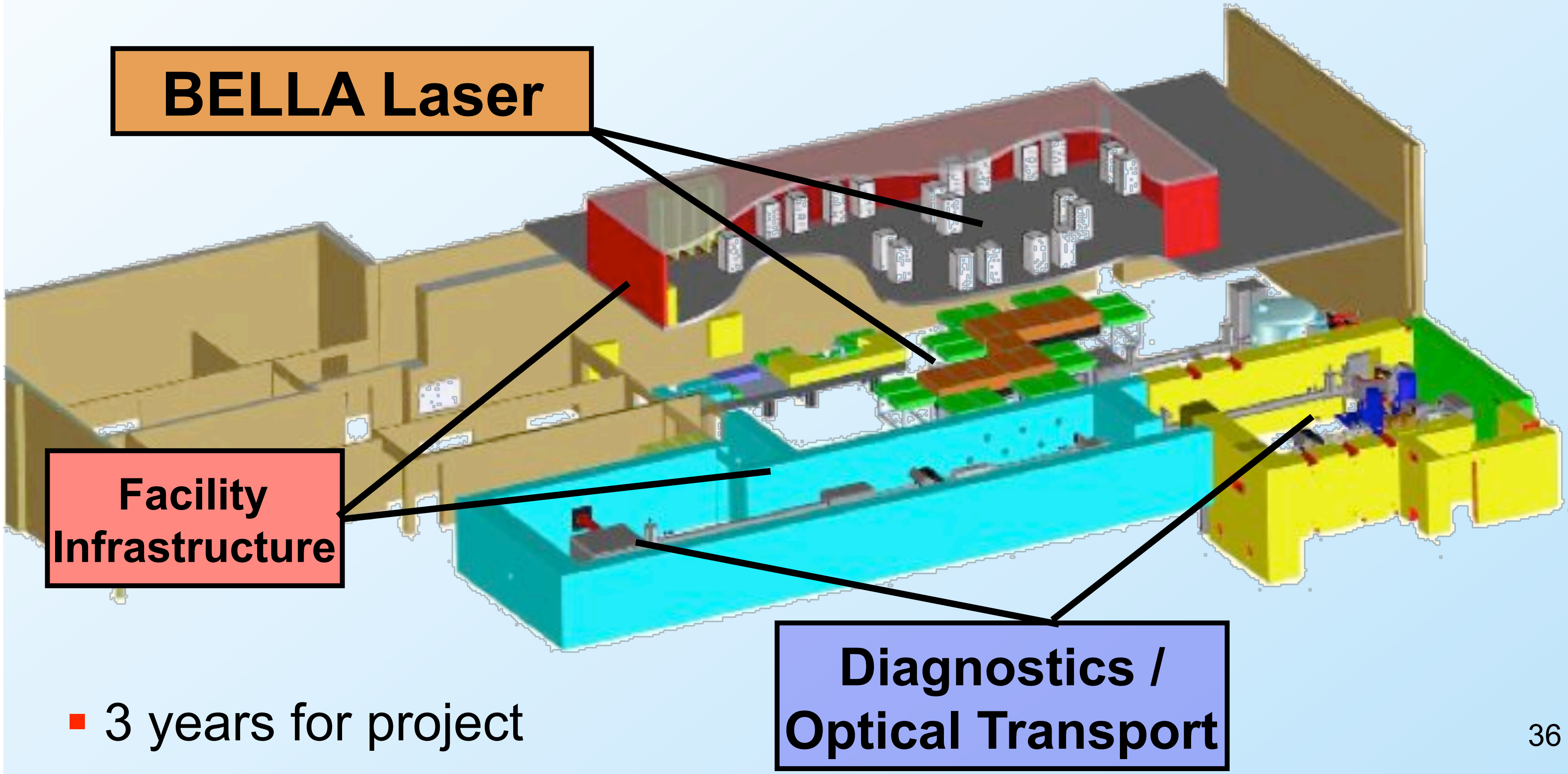
- **10 GeV module (2-stage)**
- Theory and simulations 40 J in ~ 40-100 fs laser pulse
- BELLA Project: 1 PW, 1 Hz laser



- Long scale length plasma channels
- Energy spread and emittance studies; pump depletion
- Tapered channels to optimize laser to e-beam efficiency
- Higher order laser mode drivers for emittance control
- X-ray FEL driver; coherent THz; ultra-fast magnetic switching; gamma-rays
- Positron production; plasma wakefield acceleration
- Detector testing

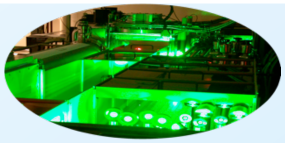
BELLA Project underway: state-of-the-art facility for laser based accelerator science

- High rep rate (1 Hz), Petawatt class laser (>40 J in < 40 fs)
- Laser bay and target area
- Laser diagnostics

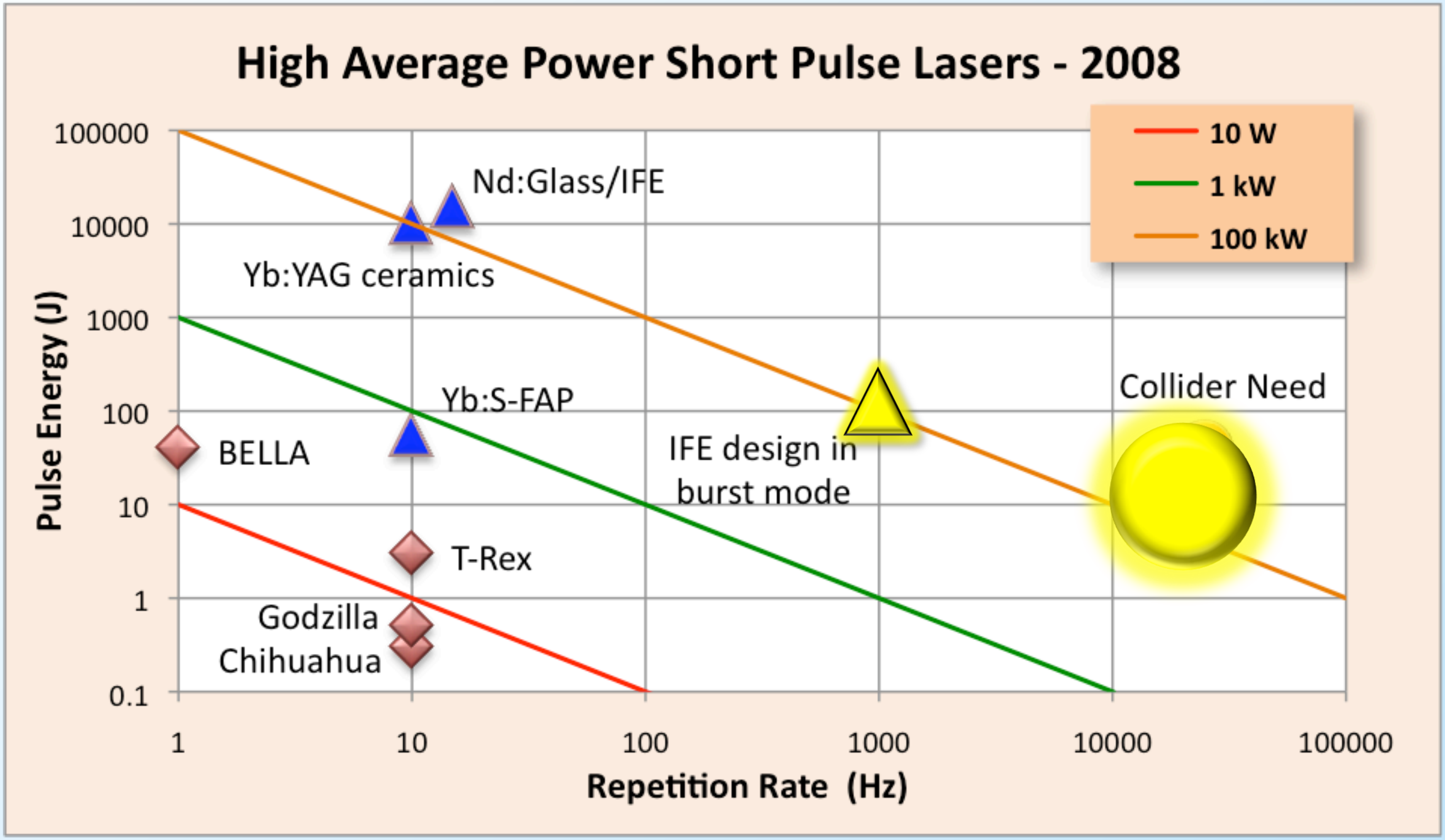


- 3 years for project

Lasers approach 100 kW average power
Pulses need to be shortened below ps



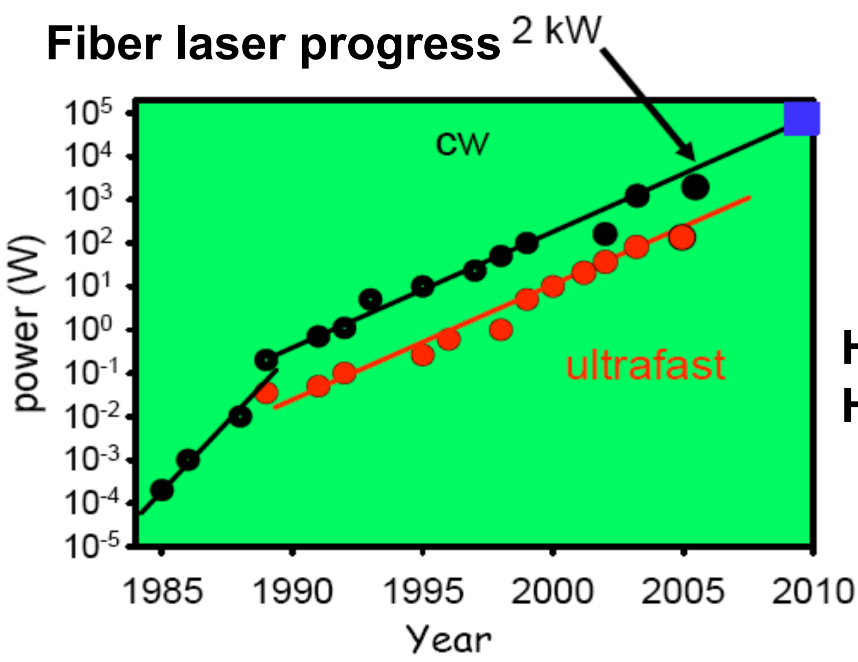
Lasers: high average power

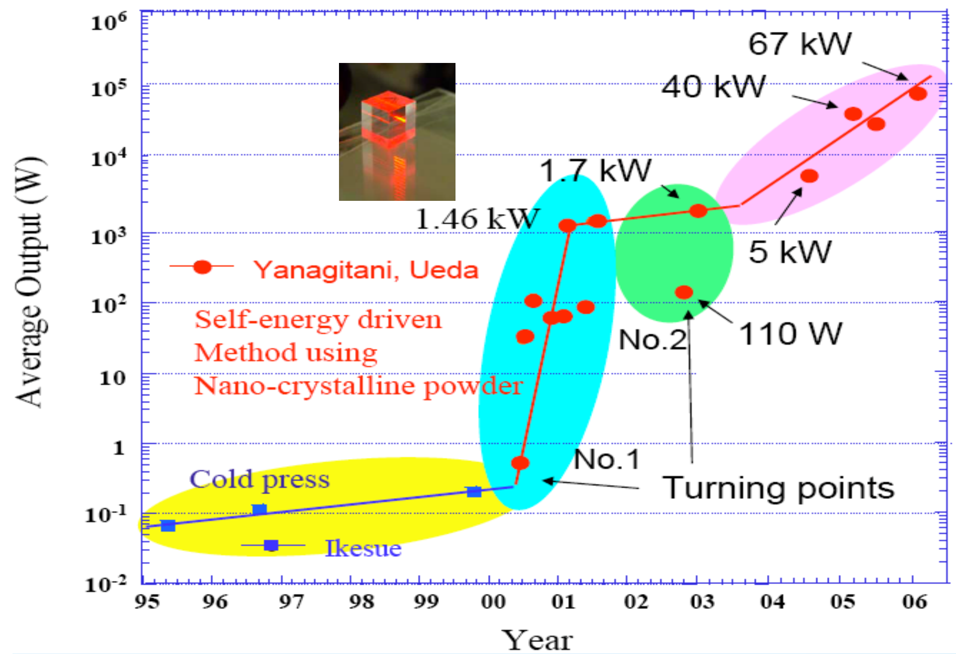


Critical Technology: High average power, high peak power lasers, high wall plug efficiency

- Large core single mode fibers
- Multiplexing, coherent addition
- Ceramic materials

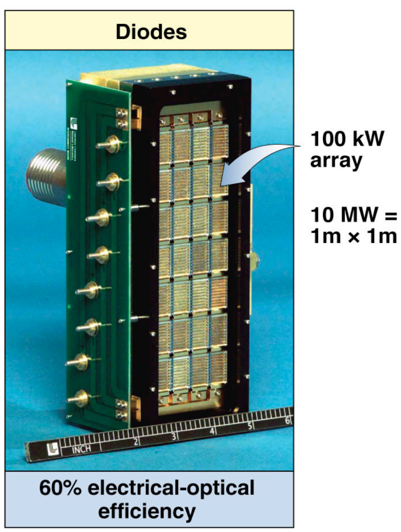
Fiber laser progress





High power diodes
High efficiency pumping

Prospect for kJ, picosecond, multi-kHz systems at 30-50 % wallplug seems possible



Courtesy: B. Byer and C. Barty

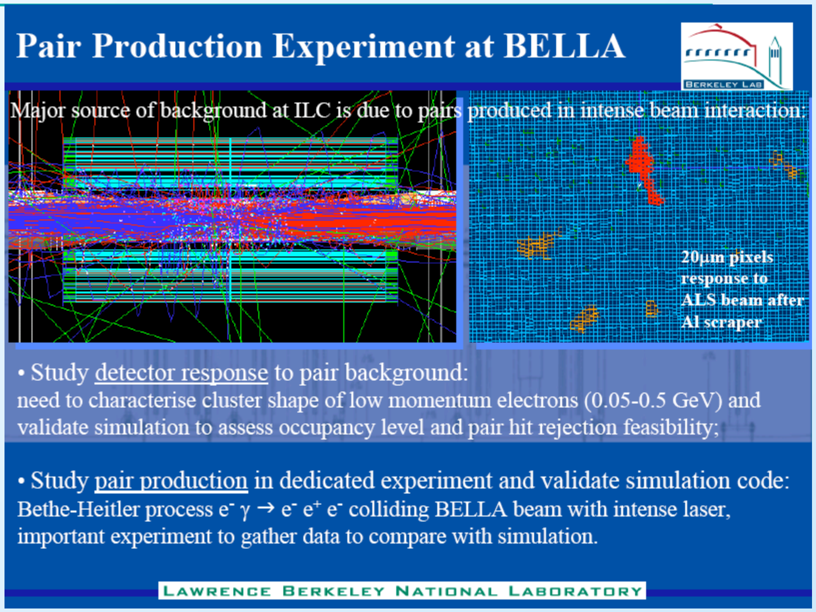
Summary

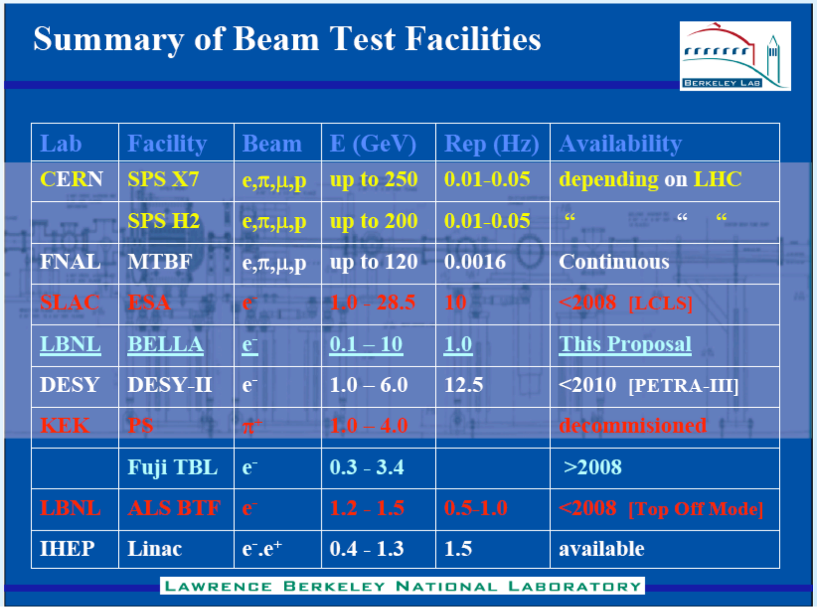
- TeV collider is extremely challenging (for any technology), let alone multi-TeV
- Steady, phased approach is needed to address major technological challenges
- BELLA and FACET now launched: cornerstone facilities for AA R&D
  - Address key technological challenges for collider designs
  - Will keep plasma based accelerator R&D in US competitive with rest of world
  - Train students and postdocs
  - Important spin-off applications
- Workshop on laser technology for driving future accelerators planned with ICFA and ICUIL blessing

- Backup material on BELLA/LOASIS

Detector test facility at BELLA: one stop shopping for 0.1 – 10 GeV electrons

- Battaglia gave talk at CD-0 review:
  - Need for Test Facilities
  - Pair production expt's on BELLA
  - See CD-0 talks

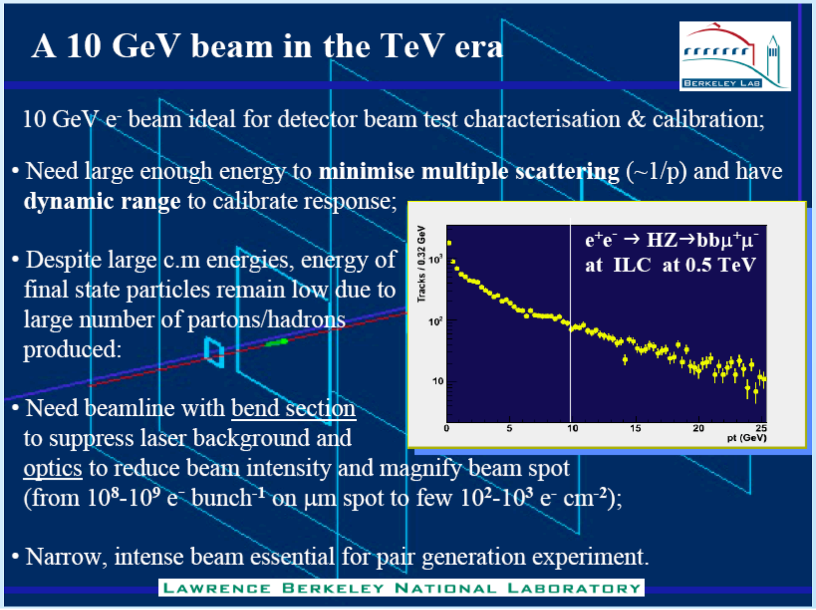




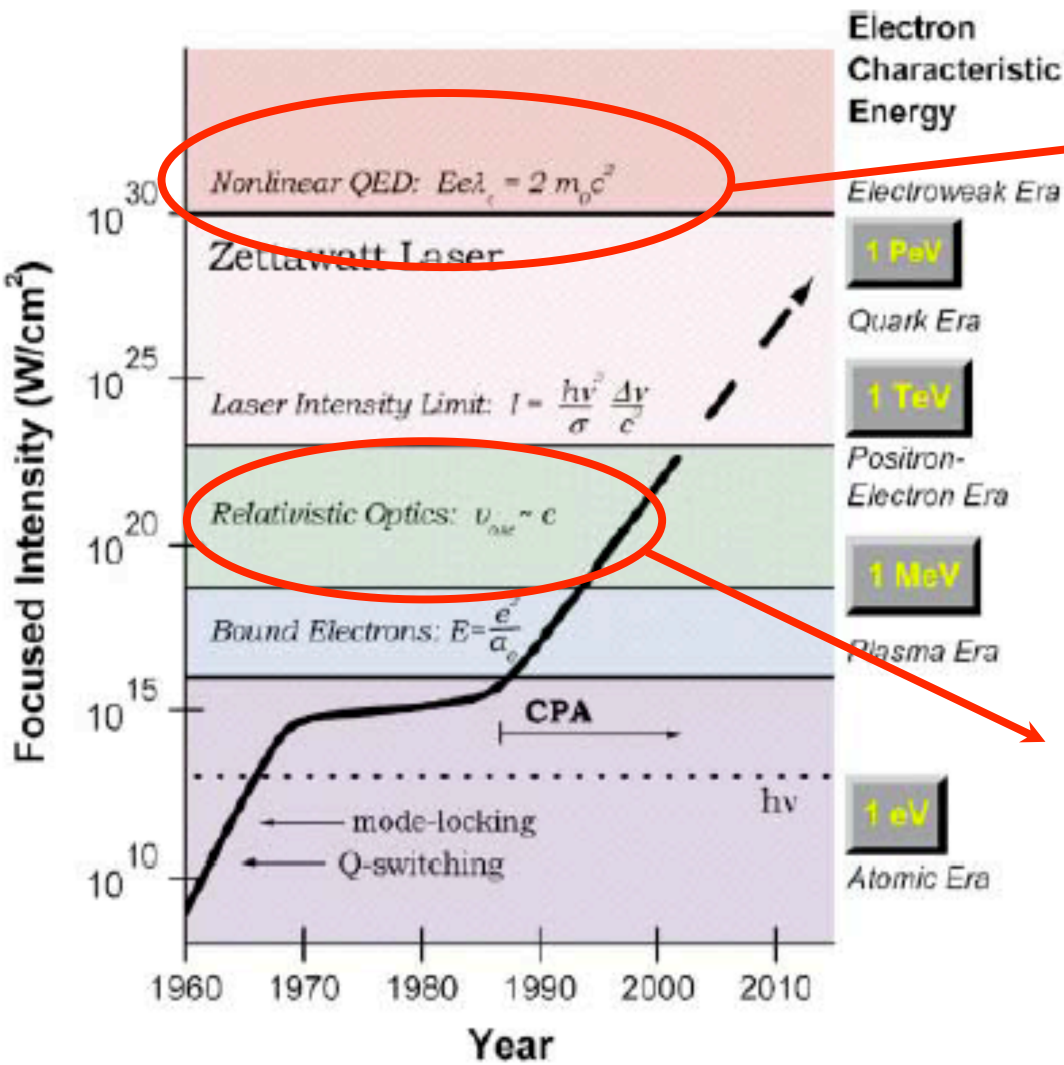
Summary of Beam Test Facilities

Lab	Facility	Beam	E (GeV)	Rep (Hz)	Availability
CERN	SPS X7	e,π,μ,p	up to 250	0.01-0.05	depending on LHC
	SPS H2	e,π,μ,p	up to 200	0.01-0.05	" " "
FNAL	MTBF	e,π,μ,p	up to 120	0.0016	Continuous
SLAC	ESA	e^-	1.0 – 28.5	10	<2008 [LCLS]
LBNL	BELLA	e^-	0.1 – 10	1.0	This Proposal
DESY	DESY-II	e^-	1.0 – 6.0	12.5	<2010 [PETRA-III]
KEK	PS	π^+	1.0 – 4.0		decommisioned
	Fuji TBL	e^-	0.3 - 3.4		>2008
LBNL	ALS BTF	e^-	1.2 – 1.5	0.5-1.0	<2008 [Top Off Mode]
IHEP	Linac	$e^-.e^+$	0.4 - 1.3	1.5	available

LAWRENCE BERKELEY NATIONAL LABORATORY



BELLA laser will provide access to ultra-relativistic physics



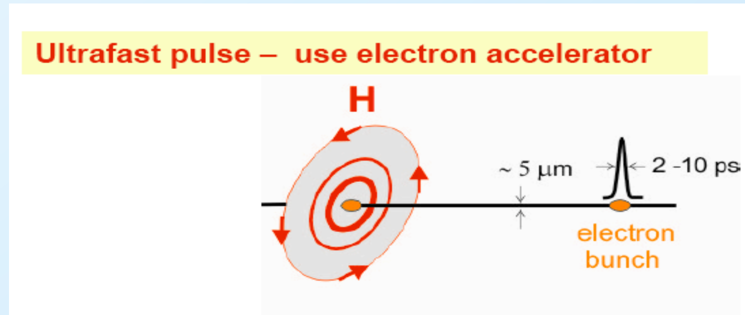
Focused Intensity vs. Year
(after T. Tajima and G. Mourou, PRSTAB2002)

- Schwinger critical field
- Vacuum breakdown
- Non-linear QED
- Accessible by Compton scattering part of BELLA beam against 10 GeV beam

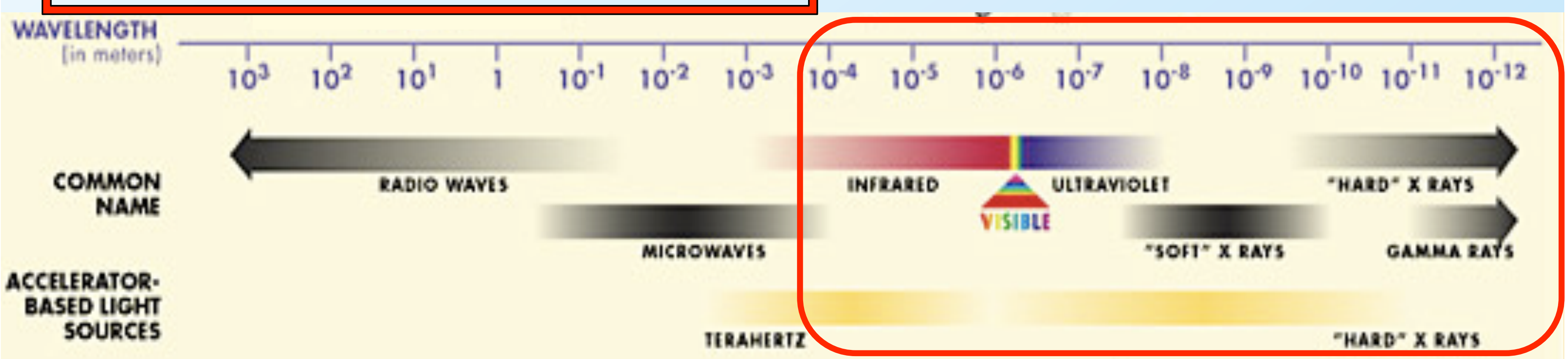
- Ultra-high gradient acceleration
- Photon and Particle Foundry
- AMO science
- HEDP
- Pathway to Ultra-relativistic physics

Unique bunch parameters enable wide range of forefront applications

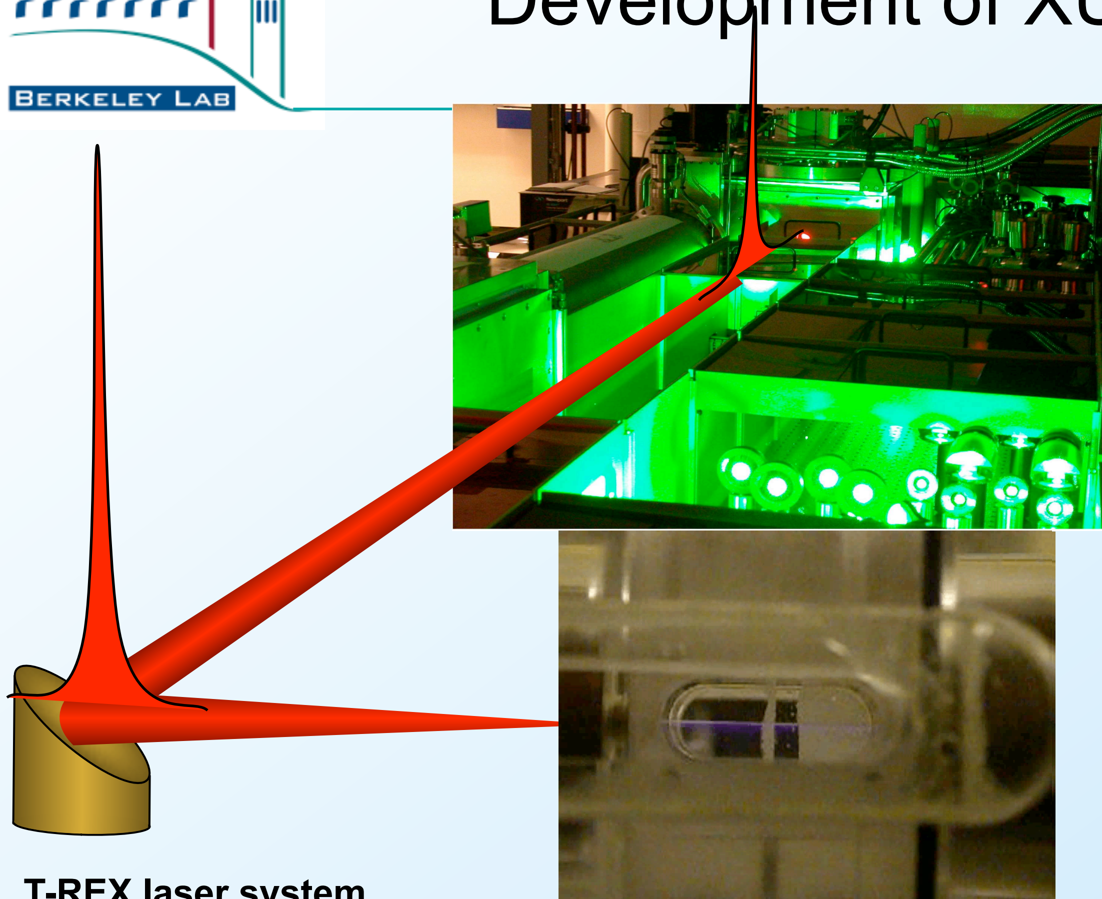
- Bunch properties:
  - Ultra-short electron bunches, high peak current (multi-kA)
  - Intrinsic synchronization with laser pulse
- Direct use of e-bunches:
  - Domain switching in ferromagnets
- Radiation sources:
  - Coherent terahertz emission
  - XUV generation
  - X-rays and gamma rays



C. H. Back et al., *Science* **285**, 864 (1999)



Development of XUV/soft x-ray FEL

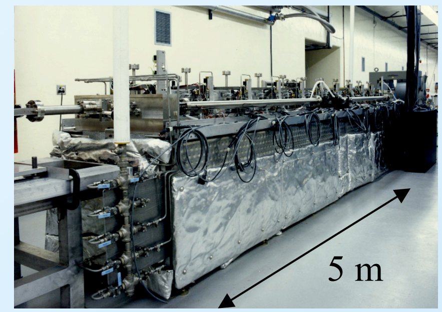


T-REX laser system

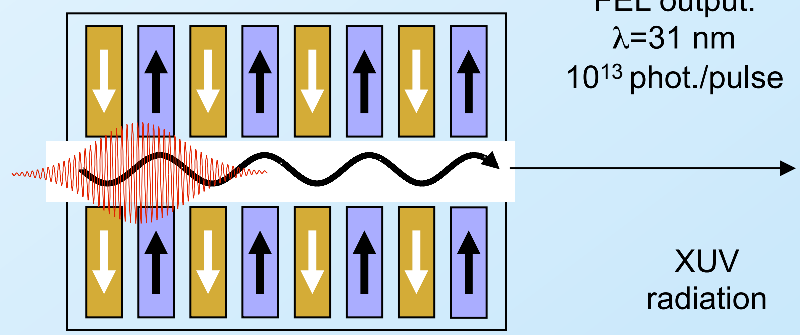
I_{pk} ~ 10^{18} W/cm^2

40 TW, 40 fs

Plasma capillary technology

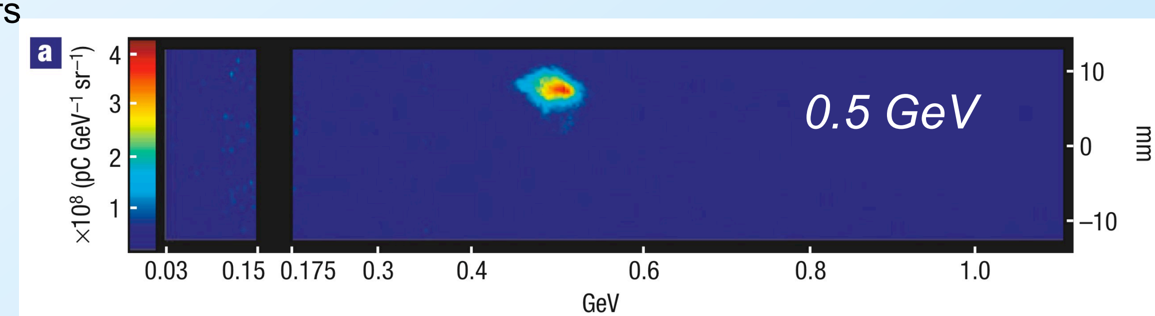


Undulator



FEL output:
λ=31 nm
10^{13} phot./pulse

XUV
radiation



World-wide effort aimed at FEL using laser accelerator