Overview of Laser Plasma Accelerator Development & BELLA Project

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and members and collaborators
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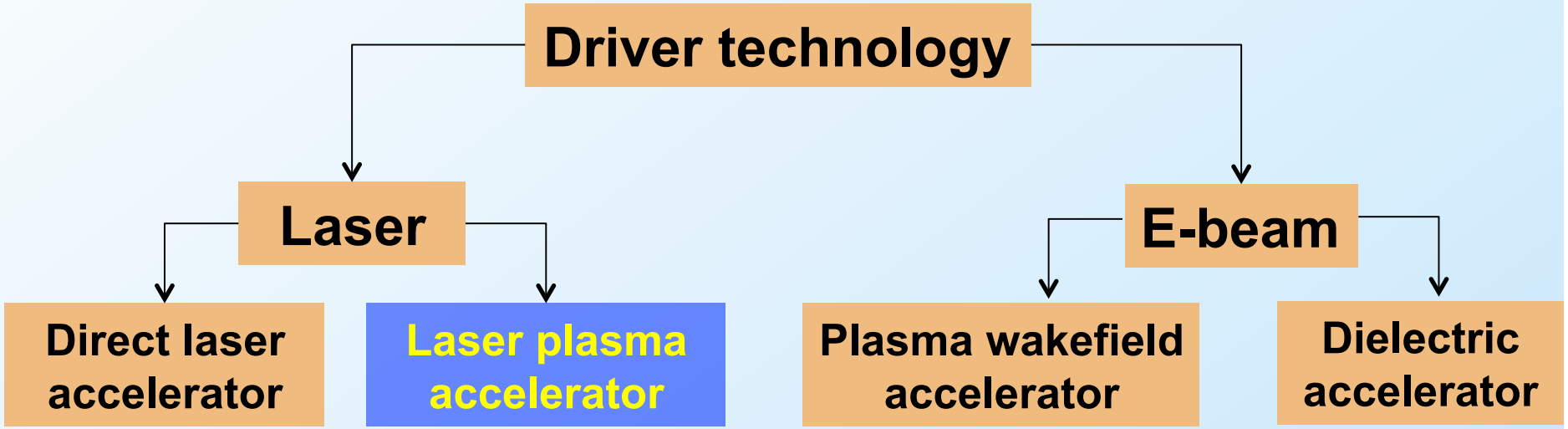
Lawrence Berkeley National Laboratory

RPM Physics Division
December 17, 2009

http://loasis.lbl.gov/

R&D for Ultra-High Gradient Accelerators

>25 year investment from DoE-HEP



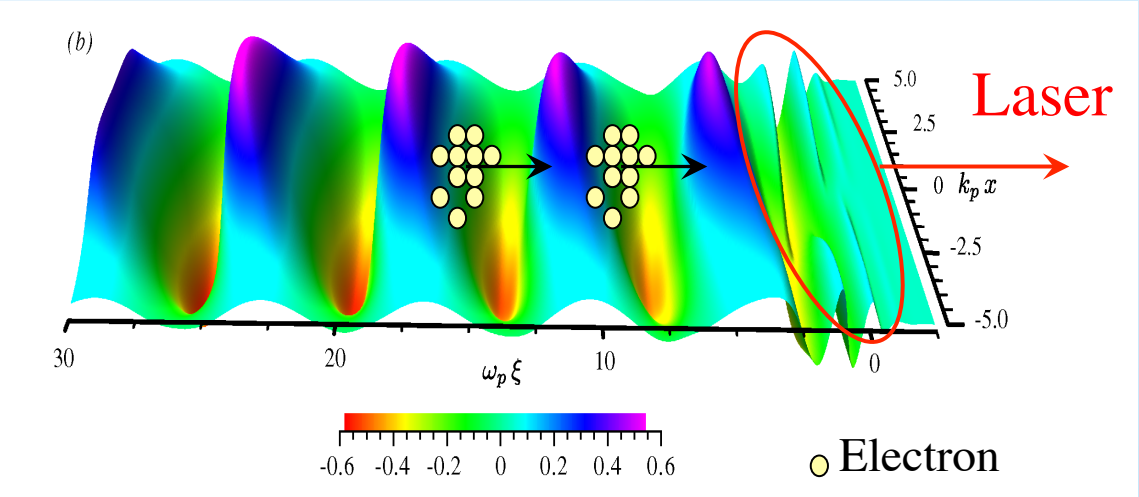
BELLA BERKELEY LAB LASER ACCELERATOR

FACET

OUTLINE

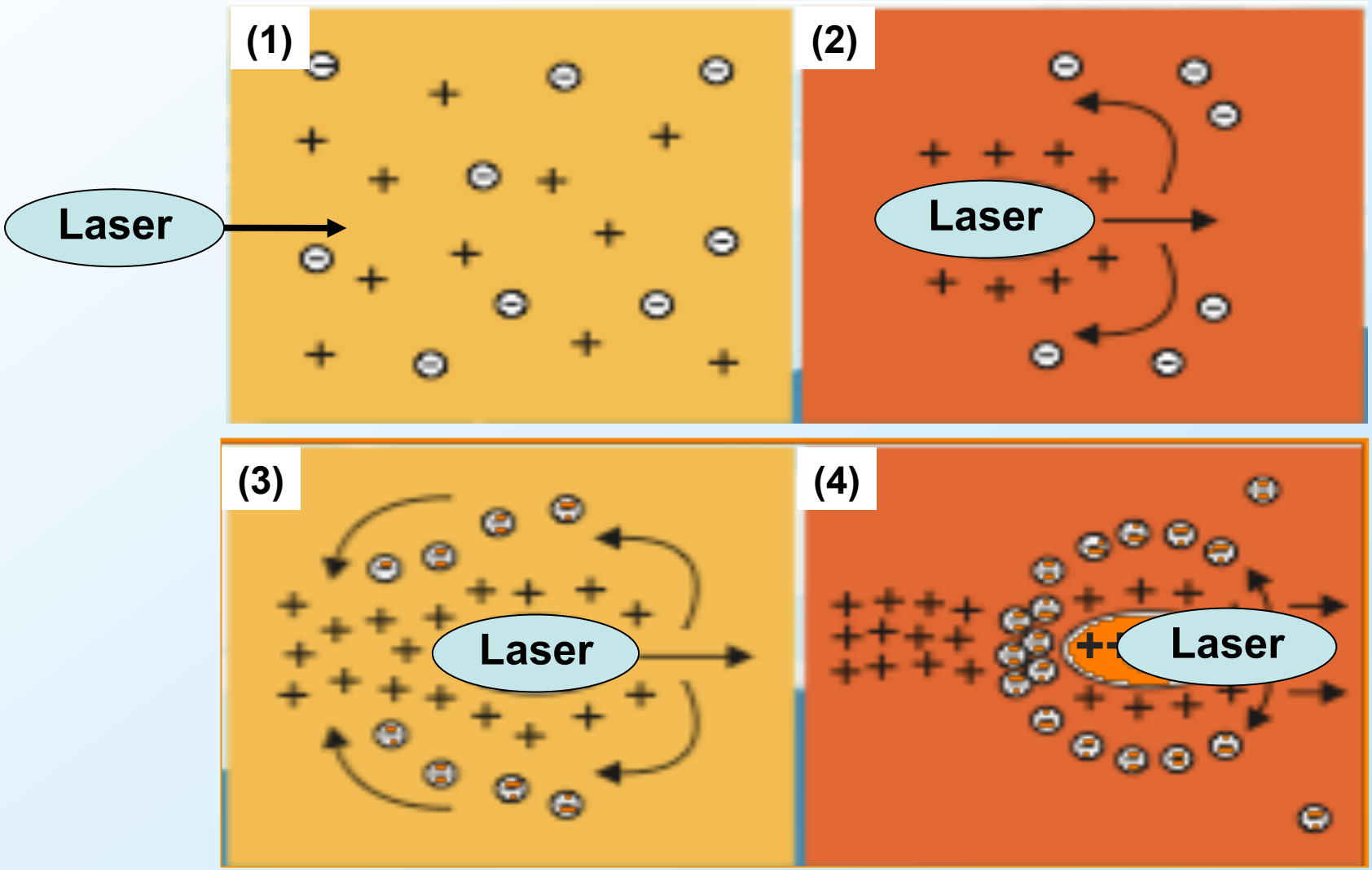
- Introduction: basic concept of laser plasma accelerator
- Transverse density control: 2004 and 2006 experiments
- Longitudinal density tailoring:
  - Injection control
  - Enhancing efficiency
- Radiation sources
- Colliders
  - Staging of modules
  - 10 GeV module with BELLA laser
- BELLA Project and ideas for experiments with 10 GeV
- Conclusion

Laser plasma accelerator: basic concept

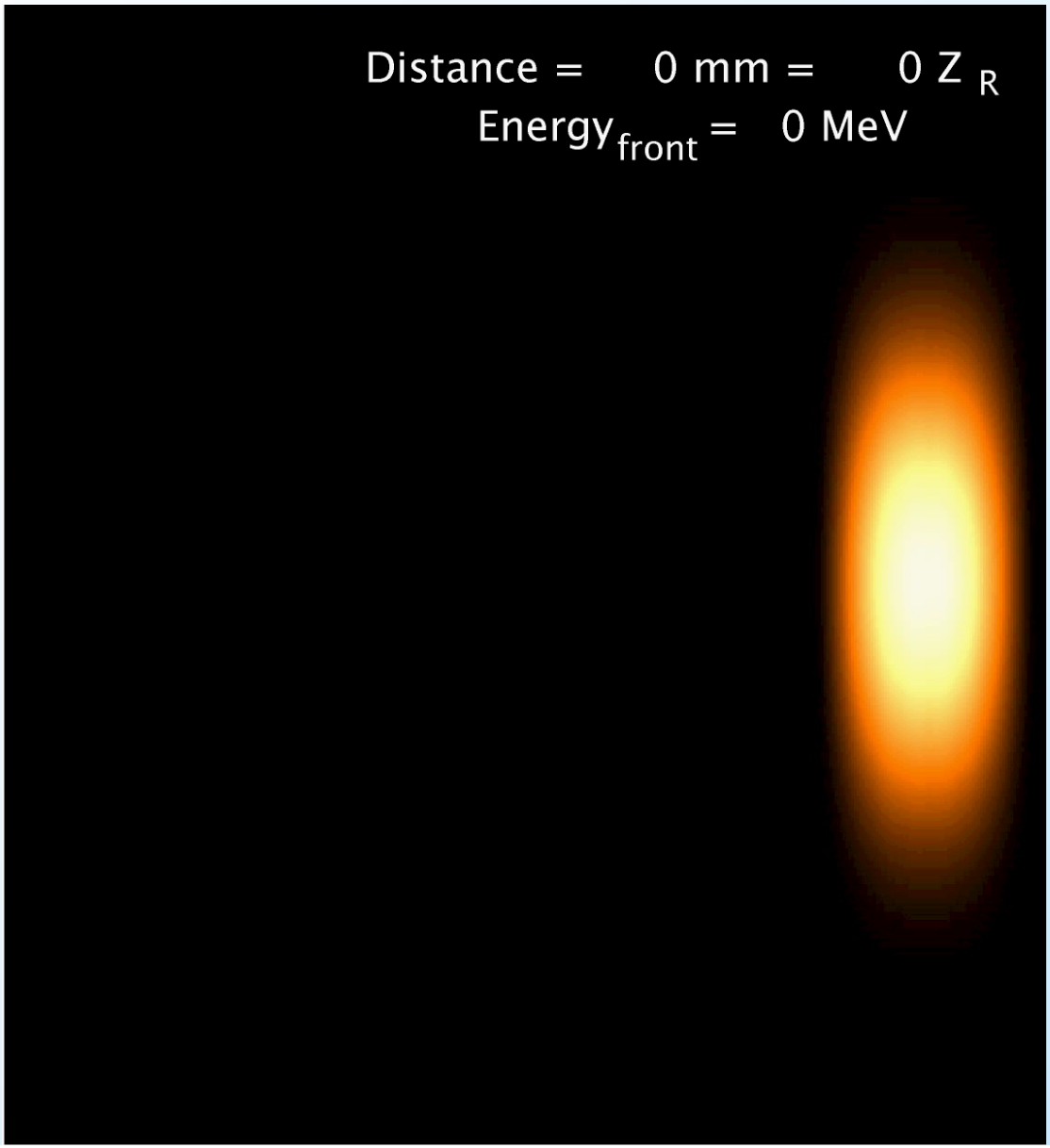


T. Tajima and J.M. Dawson, PRL 1979

Blow-out or bubble regime: the highly non-linear regime



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



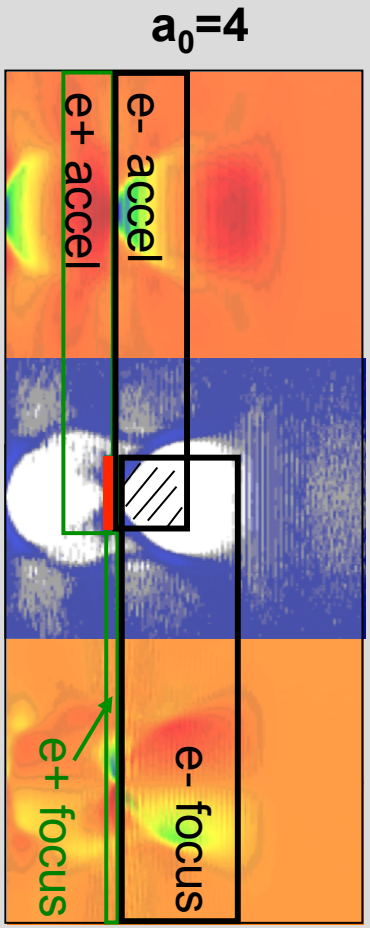
- High gradients
- Can produce narrow energy spread beams

BUT

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

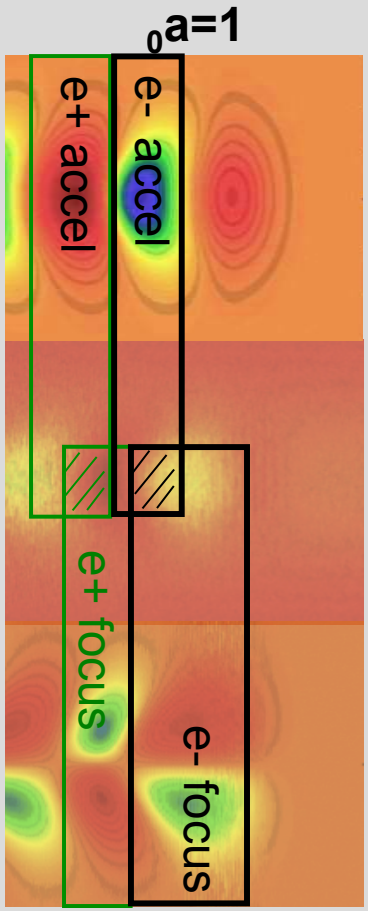
Courtesy of W. Mori, UCLA

Linear & blowout regimes: e+/e- acceleration

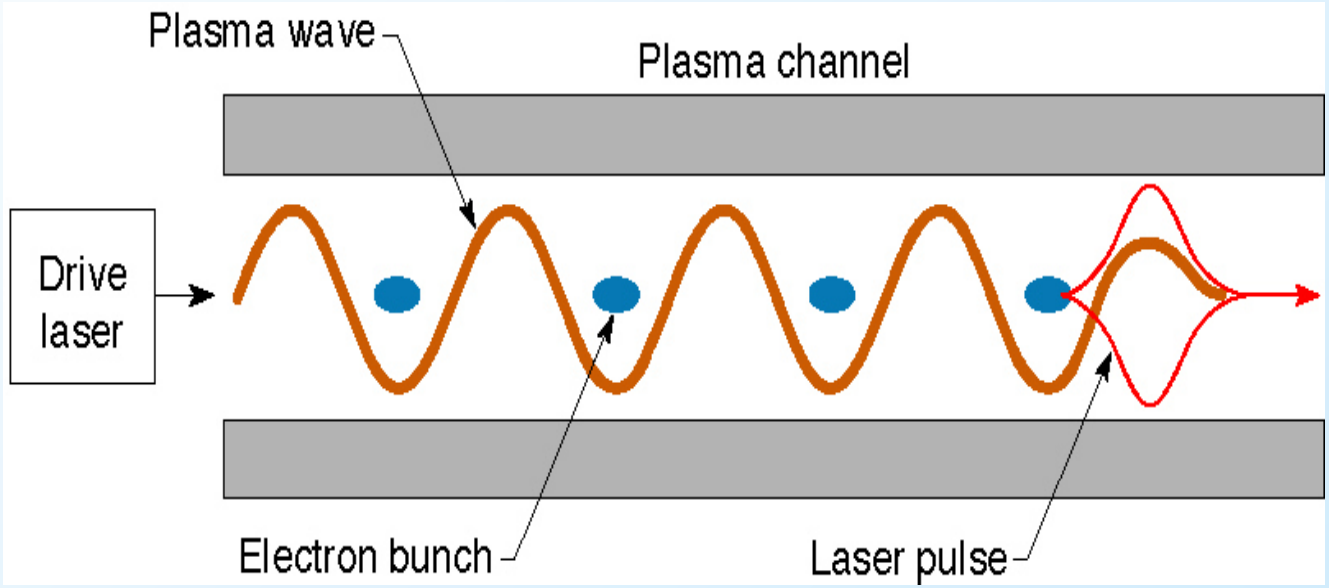


- Blowout regime
  - high field
  - very asymmetric
    - focuses e-
    - defocuses e+

- Quasi-linear regime
  - linear: symmetric e+/e-
  - high a0 desired for gradient
    - too high enters bubble: e+
  - a_0 ~1-2 good compromise



Building a laser wakefield accelerator using conventional accelerator paradigm

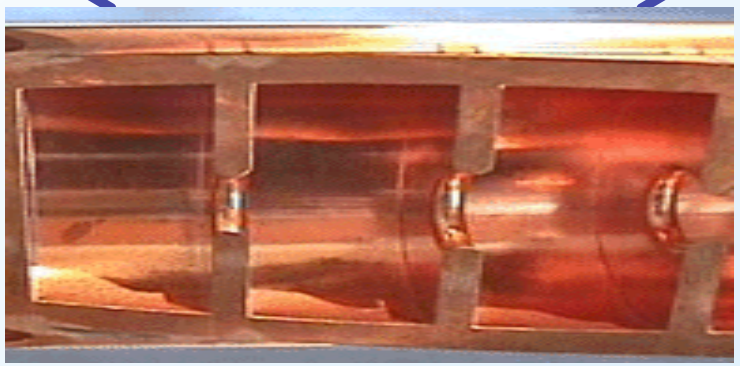


- Drive laser: Ti-sapphire (chirped amplification technology)
- Structure: plasma fiber
- Injection: self-trapped, triggered

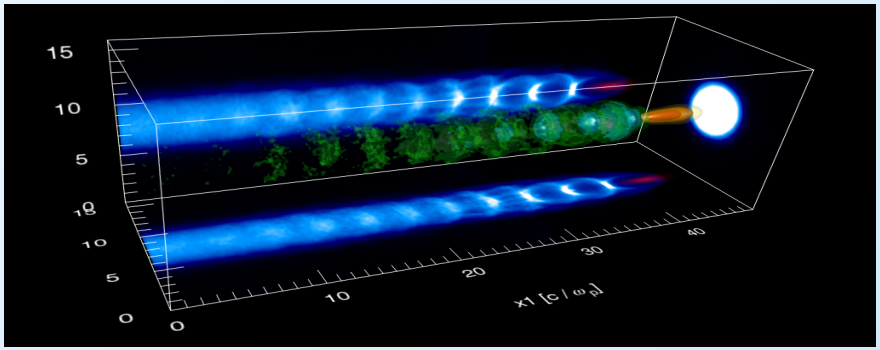
W.P. Leemans et al., IEEE Trans. Plasma Science (1996); Phys. Plasmas (1998)
W. Leemans and E. Esarey, Physics Today, March 2009;
E. Esarey, C.B. Schroeder and W.P. Leemans, Reviews of Modern Physics (2009)

Just like RF accelerators, we need to "machine" our cavities

10's of cm-scale

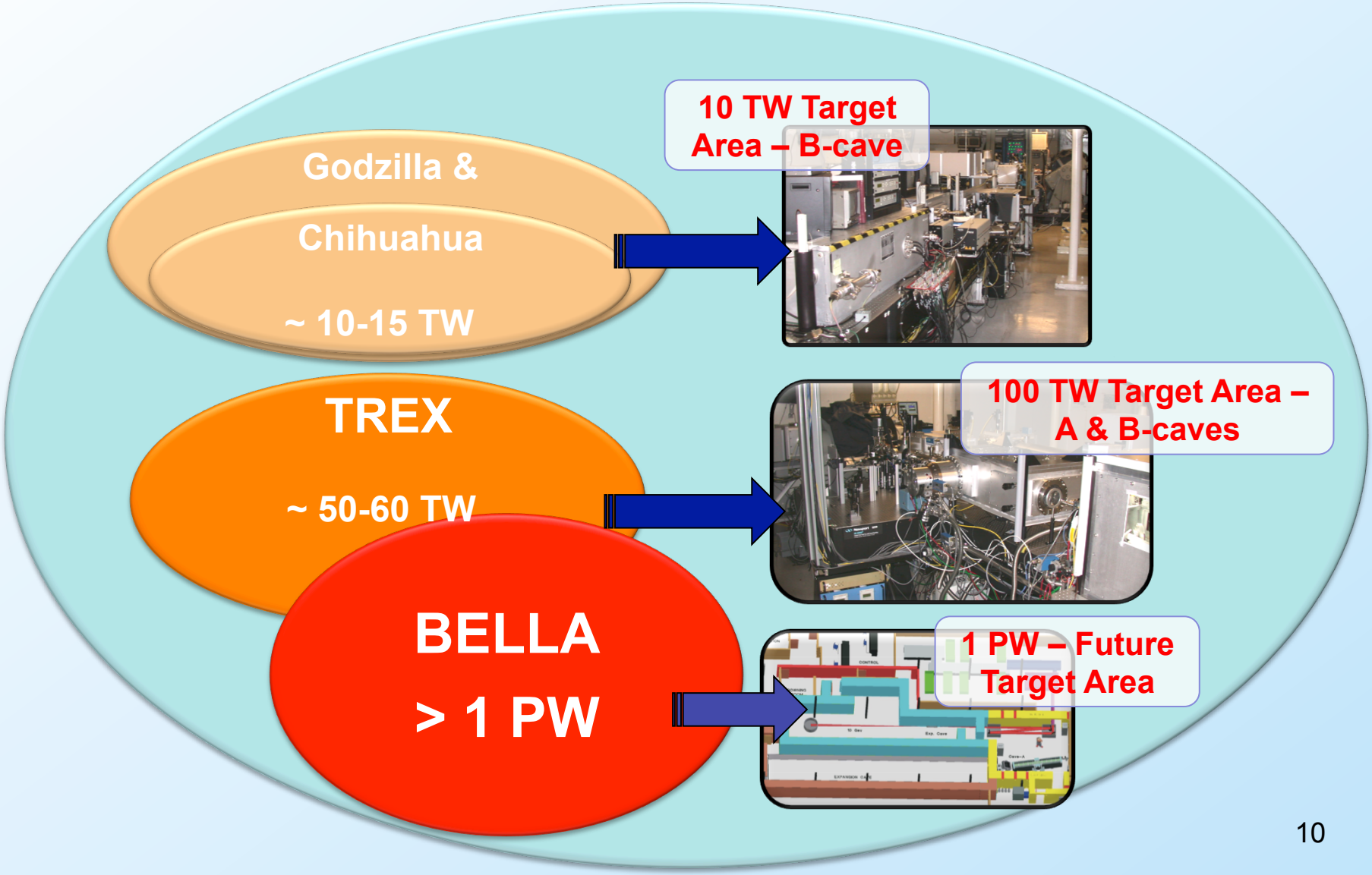


100 micron-scale

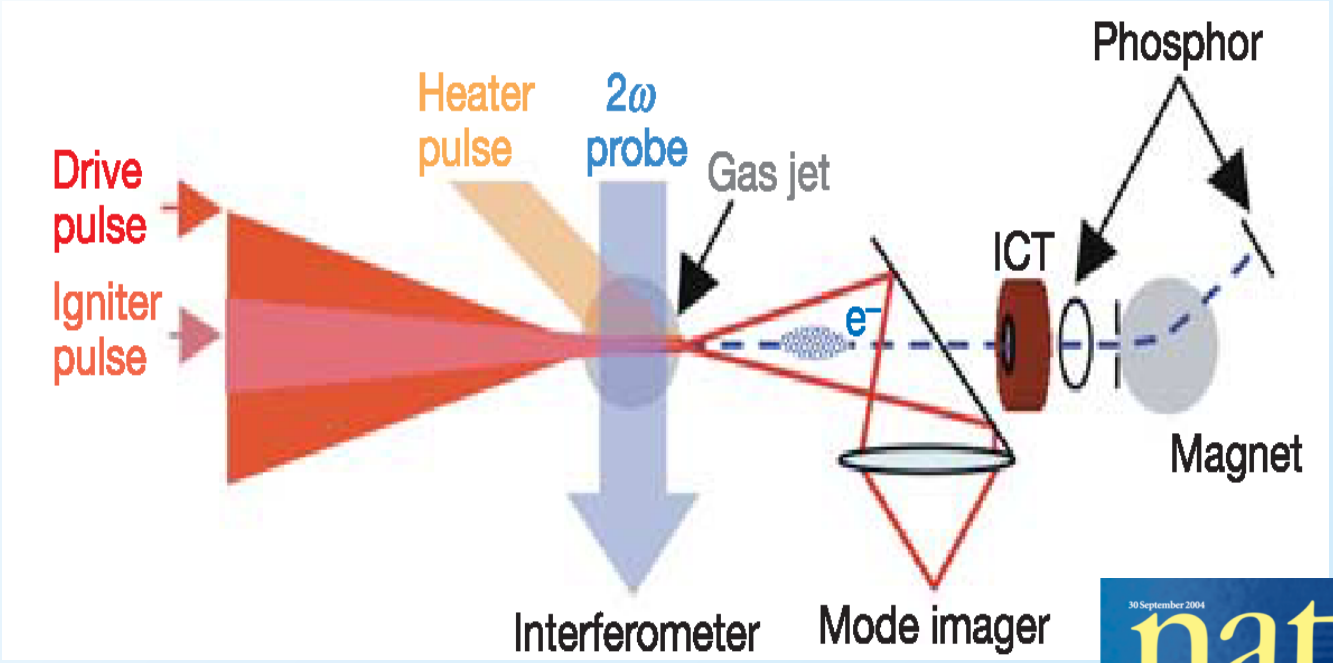


- Transverse plasma density profile:
  - Guiding the laser driver: making a high power "optical fiber"
  - Shaping the accelerating and focusing fields
- Longitudinal tailoring:
  - Injection control
  - Phase locking particle and wave: enhanced efficiency

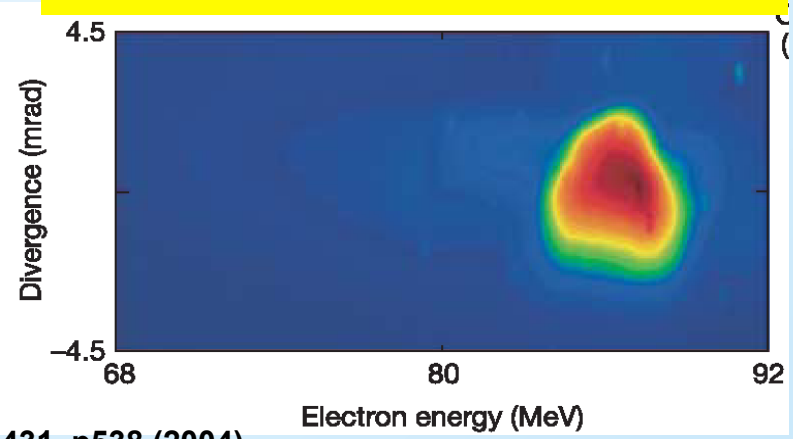
LOASIS lasers and target areas



Channel Guided Laser Plasma Accelerators – 2004 result

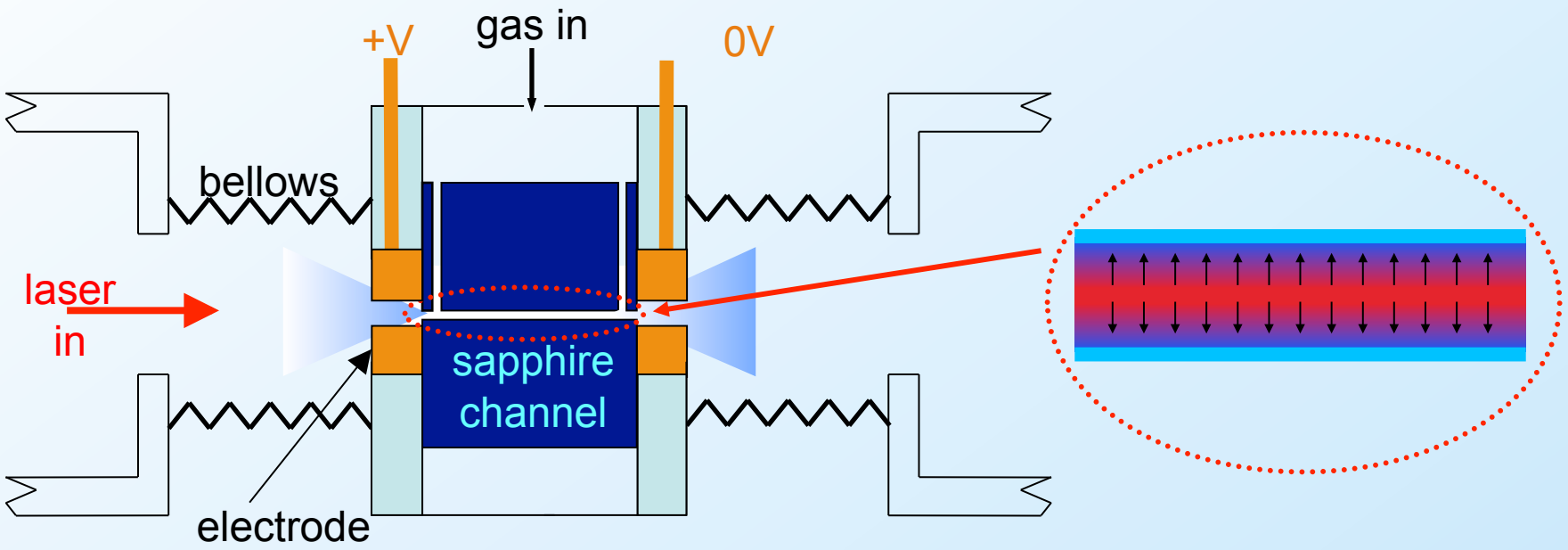


10 TW laser => 100 MeV e-beam

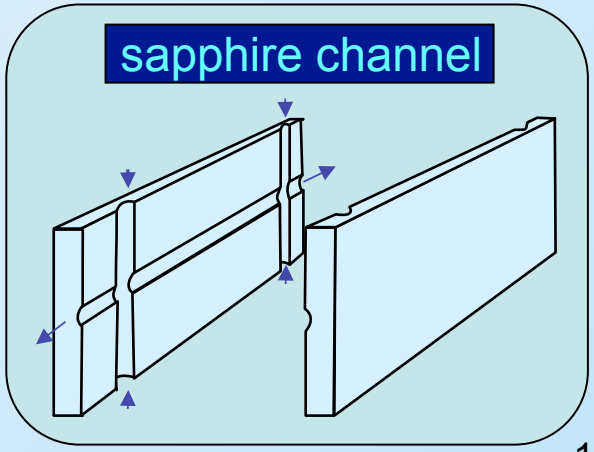


C. G. R. Geddes et al, Nature,431, p538 (2004)

Going to higher beam energy

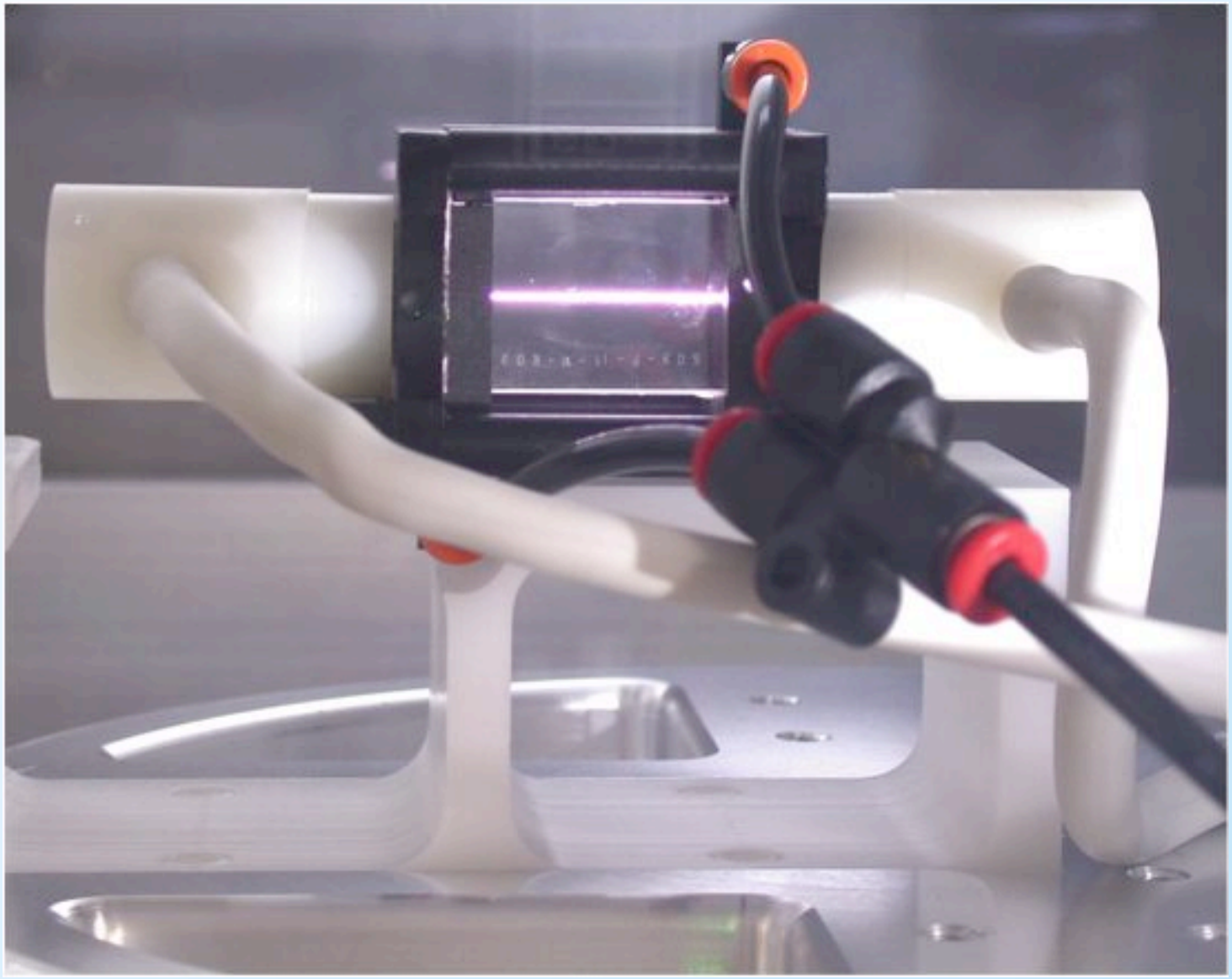


- Gas ionized by pulsed discharge
  - Peak current 200 - 500 A
    - Rise-time 50 - 100 ns



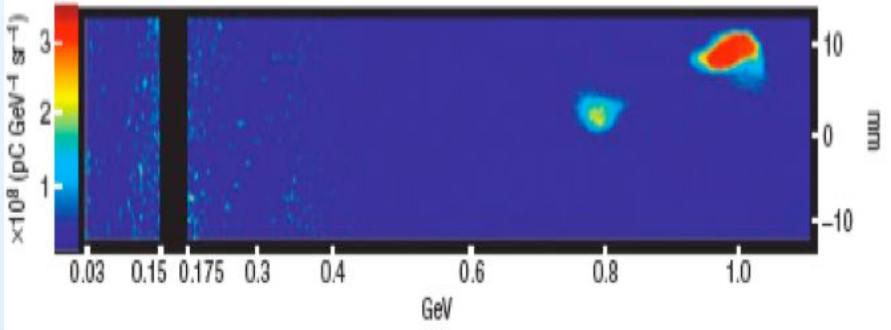
D. J. Spence & S. M. Hooker Phys. Rev. E 63 (2001) 015401 R; A. Butler et al. Phys. Rev. Lett. 89 (2002) 185003.

A GeV module…



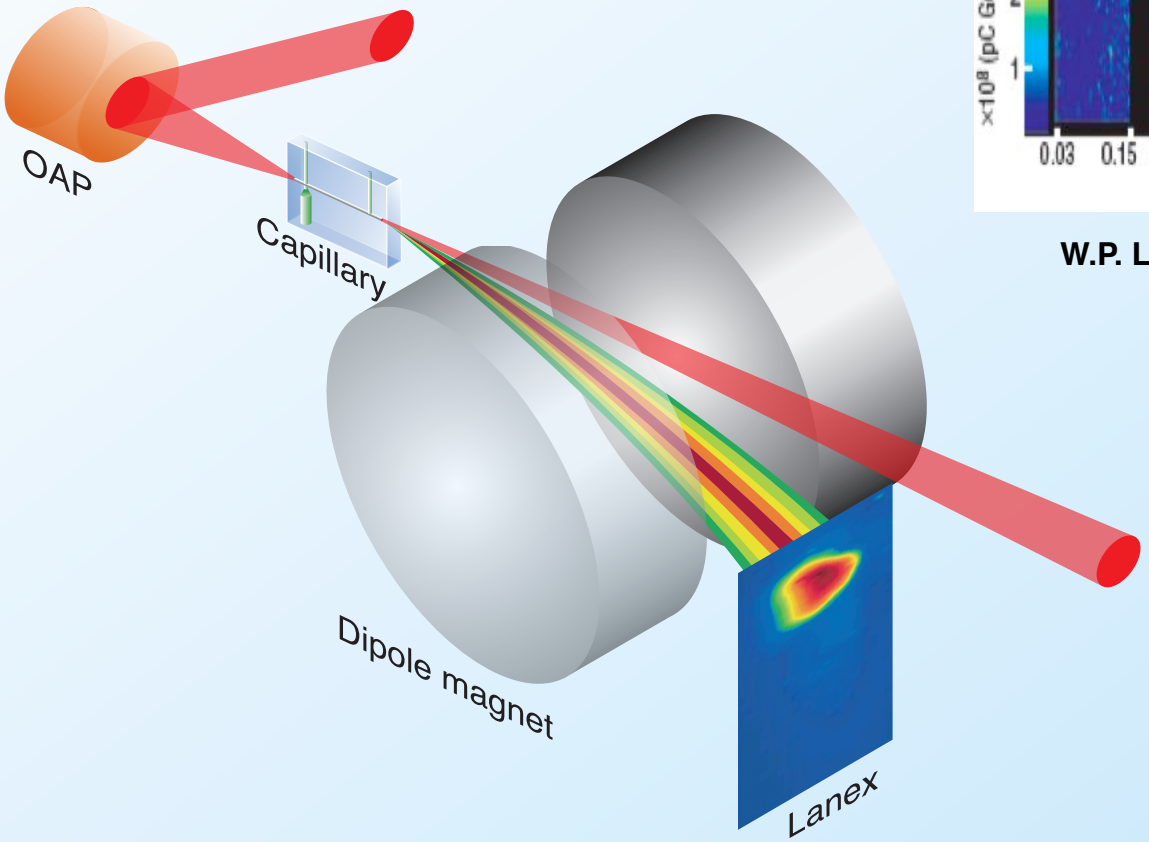
Channel Guided Laser Plasma Accelerators – 2006 result

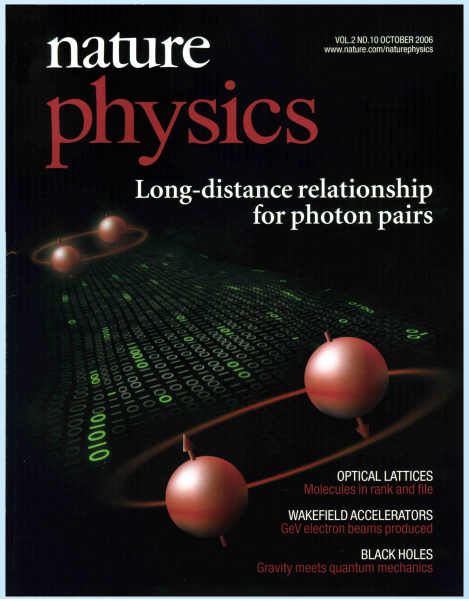
40 TW laser => 1 GeV e-beam



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

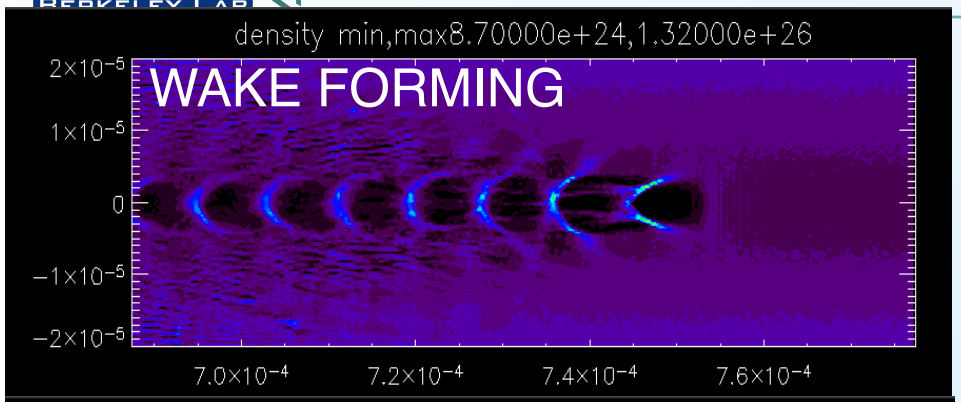
Experimental set-up

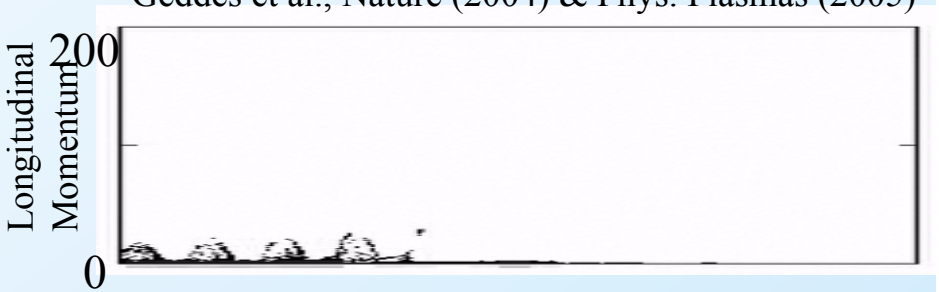


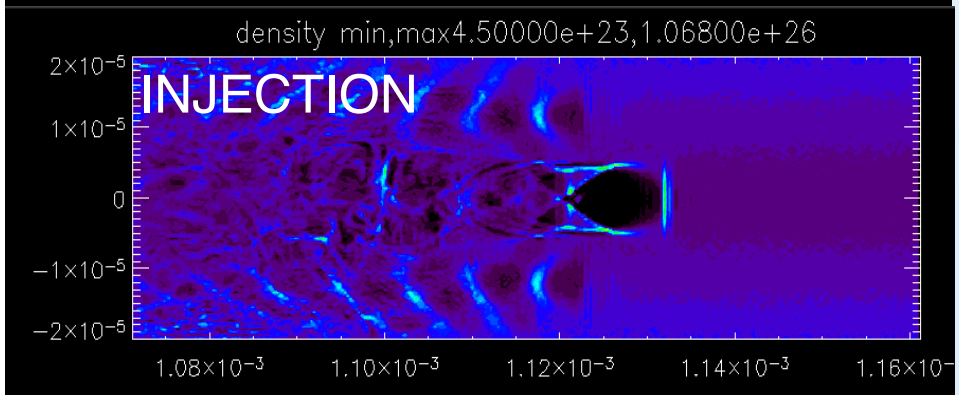


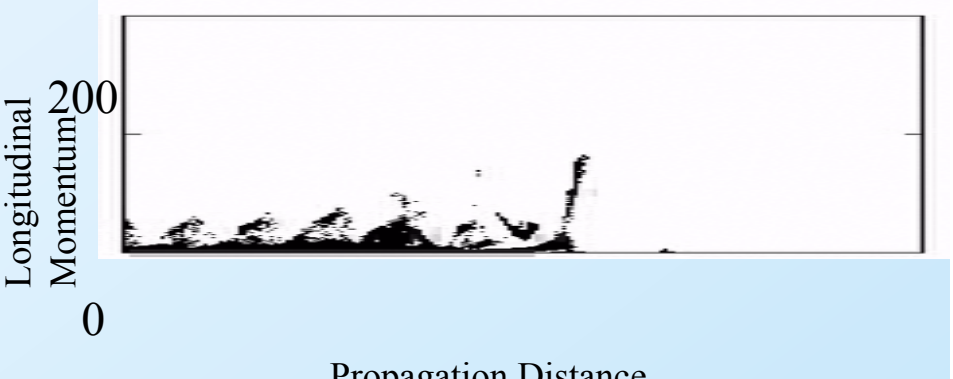
Wake Evolution and Dephasing Yield Low Energy Spread Beams in PIC Simulations

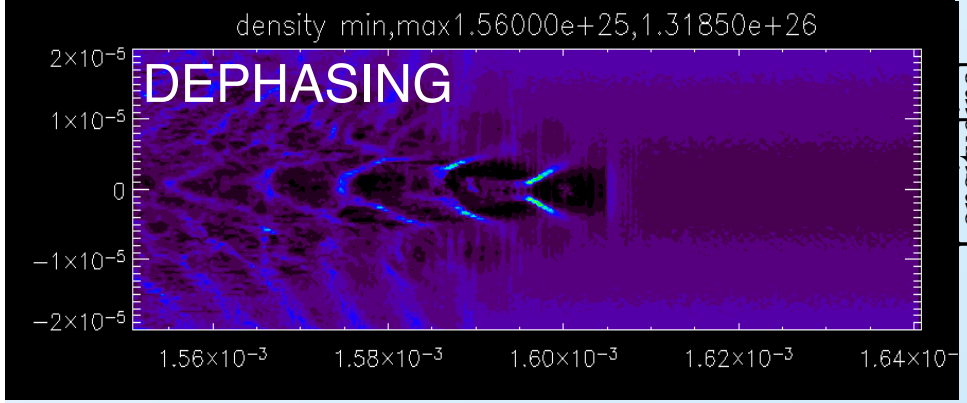
Geddes et al., Nature (2004) & Phys. Plasmas (2005)

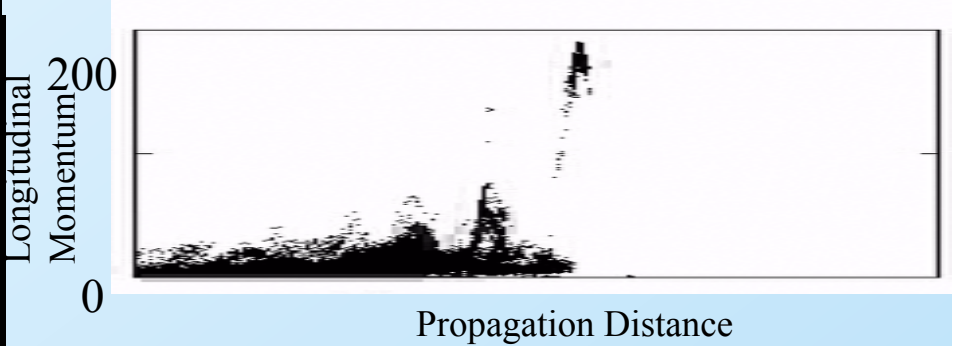






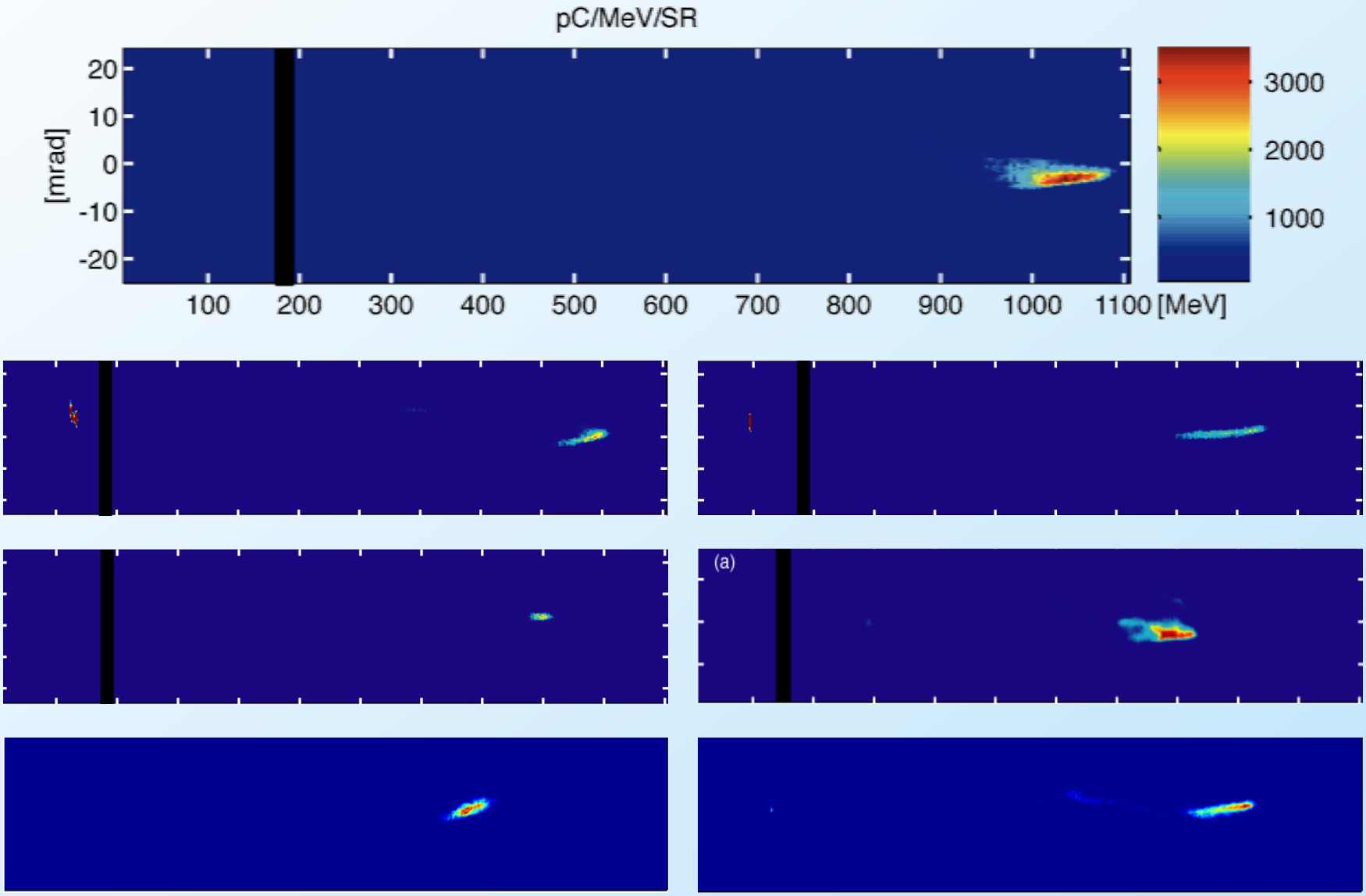




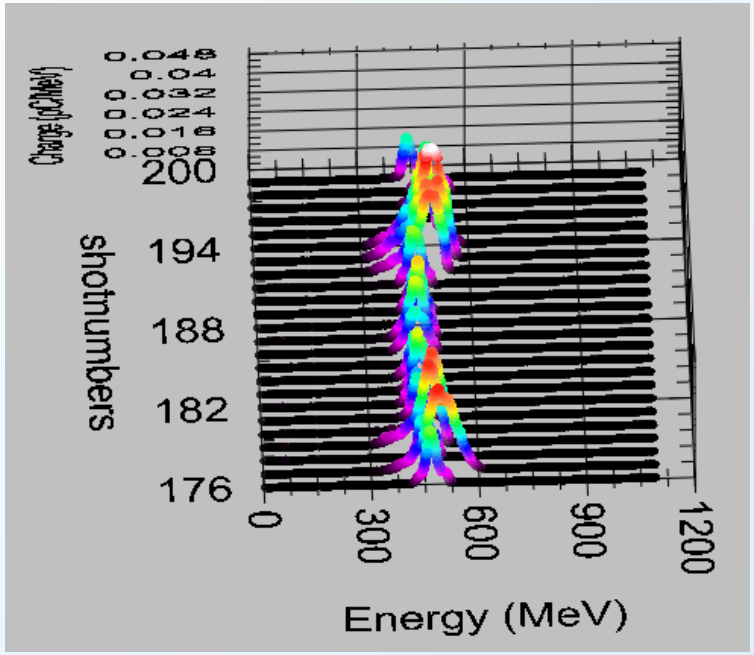


INCITE Proposal: 3 D simulation

GeV-class beams parameters not (yet) stable

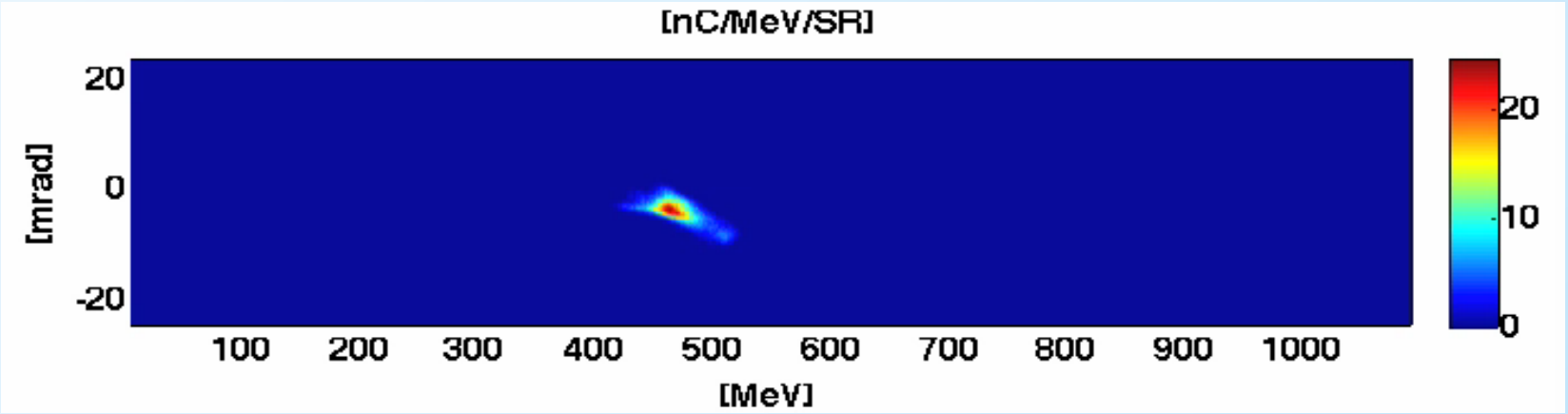


Regimes found where narrow energy spread beams are obtained without controlled injection

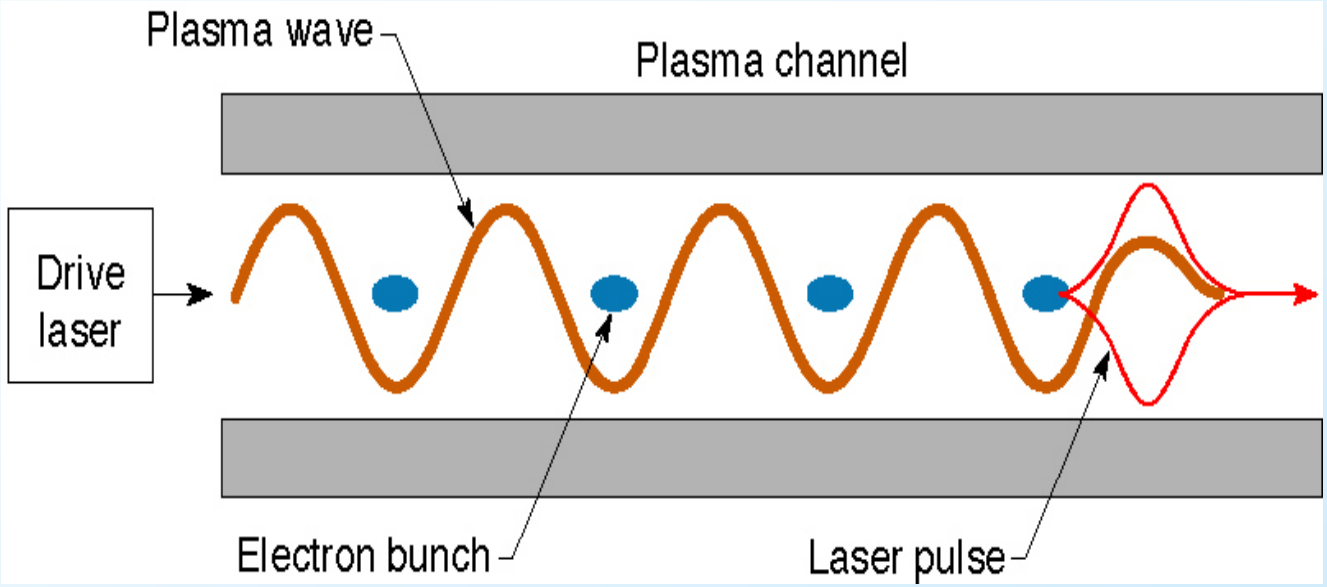


Subsequent shots during pressure scan

- **Density: $5 \times 10^{18} cm^{-3}$**
- **Laser intensity: a_0=1.2 to 1.3**
- **Laser Pulse Length 45fs**



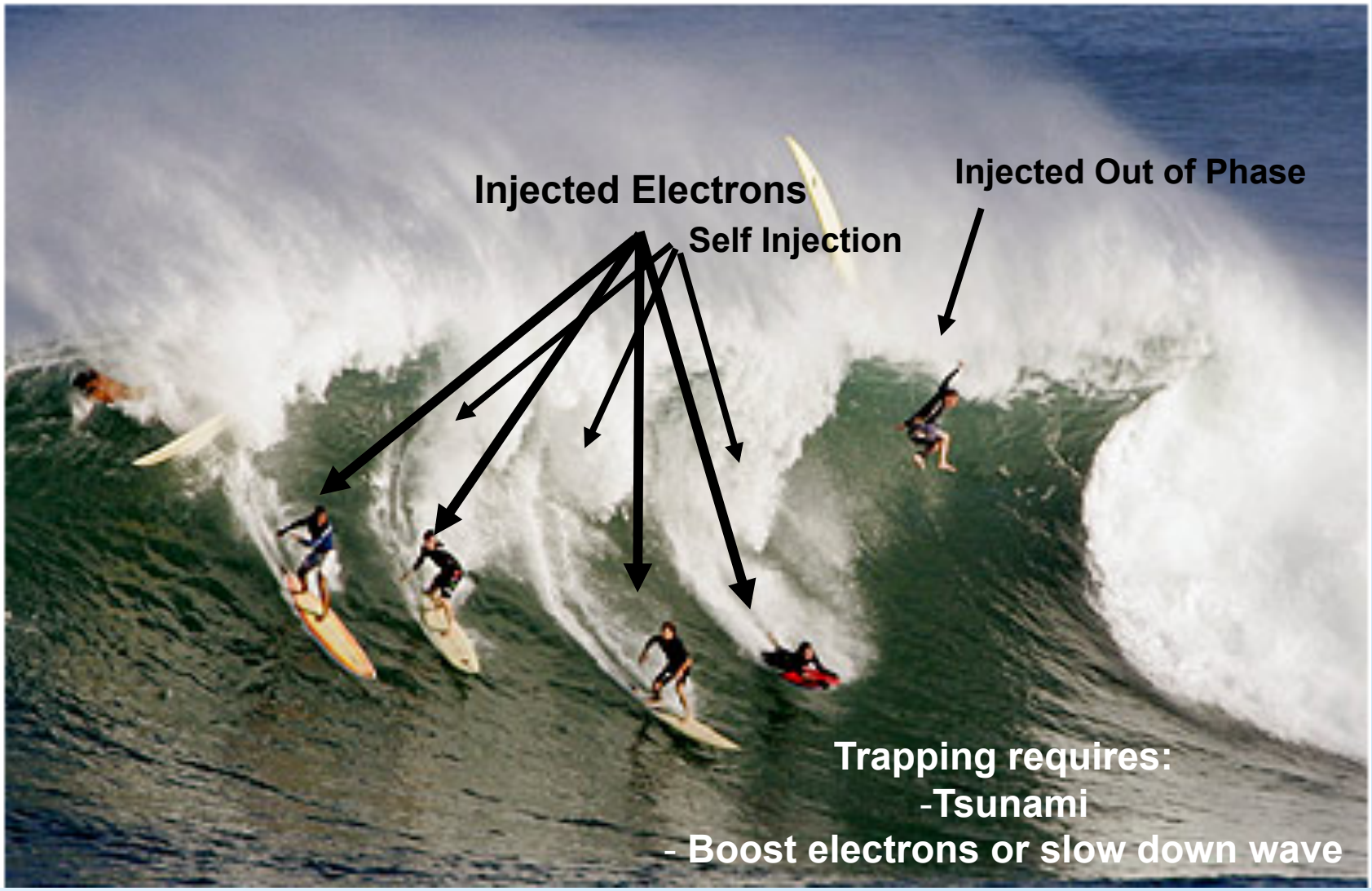
Building a laser wakefield accelerator using conventional accelerator paradigm



- Drive laser: Ti-sapphire (chirped amplification technology)
- Structure: plasma fiber
- Injection: source of electrons, controlled

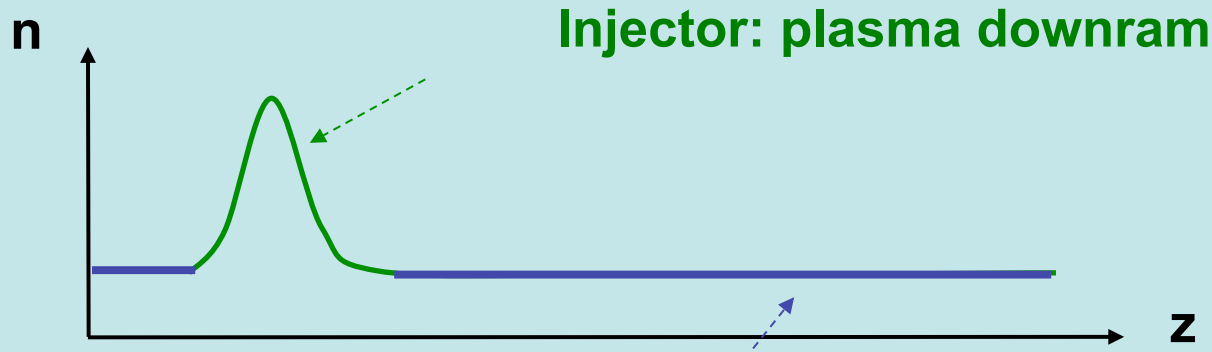
W.P. Leemans et al., IEEE Trans. Plasma Science (1996); Phys. Plasmas (1998)

“Electrons” accelerating on a wave: controlled injection



Separating injection from acceleration to produce high energy, quality beams

Solution to separate injection and acceleration



Injector: plasma downramp

Accelerator:
3 to >50 cm; n~10^{17} -10^{18} cm^{-3}

- Longitudinal tailoring of density
  - High density:
    - low phase velocity – easy to trap
  - Density downramp:
    - further reduce phase velocity

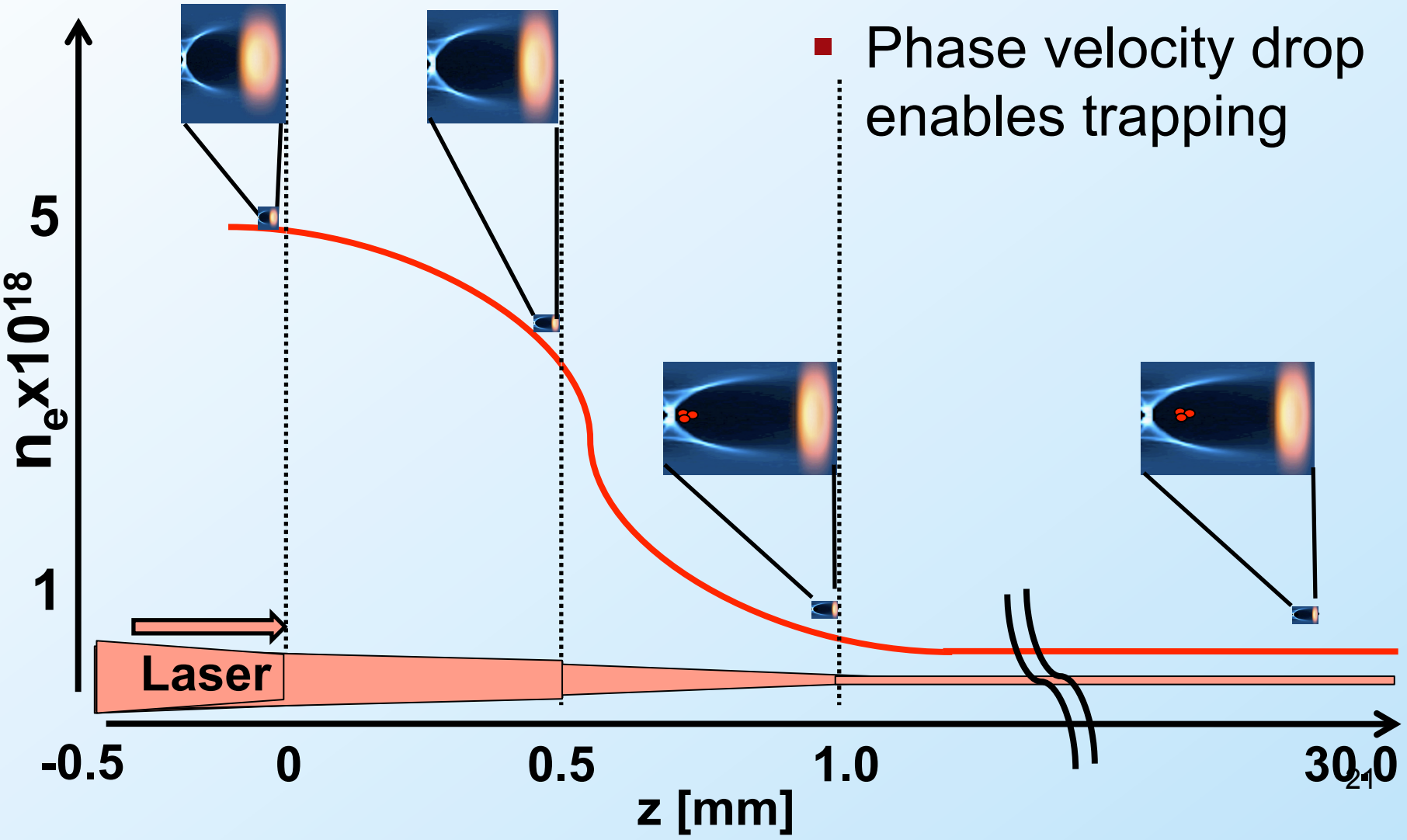
- Reduce energy spread by injecting low ΔE:
  - Simulations* show ΔE conserved during acceleration:
    - As E ↑, ΔE/E ↓

Reitsma et al., Phys. Rev. ST Accel. Beams 5, 051301 (2002)
S.V. Bulanov et al., *PRL* 78 (1997)Geddes et al., PRL 100 (2008)

*** B. Shadwick et al DPP 2005**

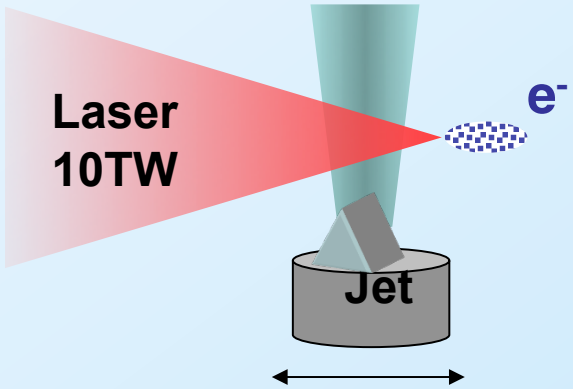
Basic physics of downramp injection

- Bucket length ~ $1/\sqrt{n}$
- Phase velocity drop enables trapping

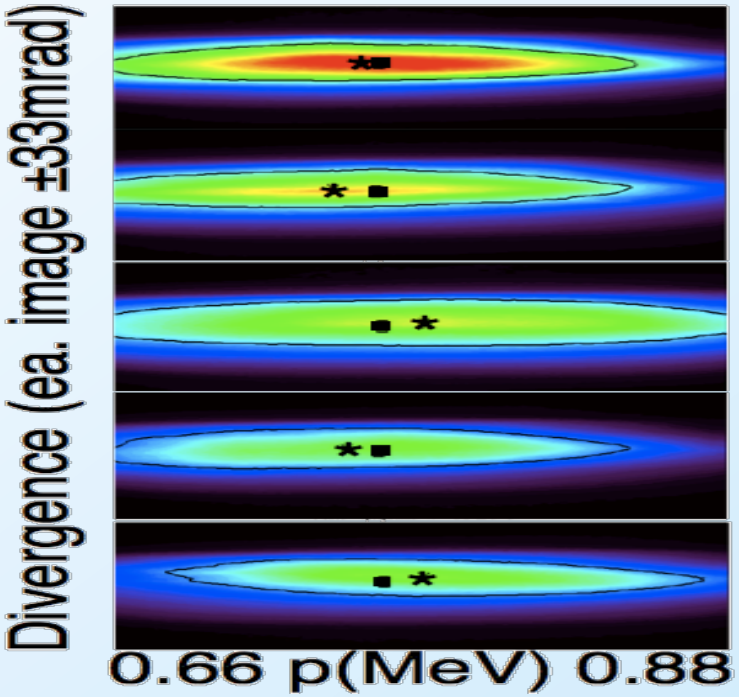


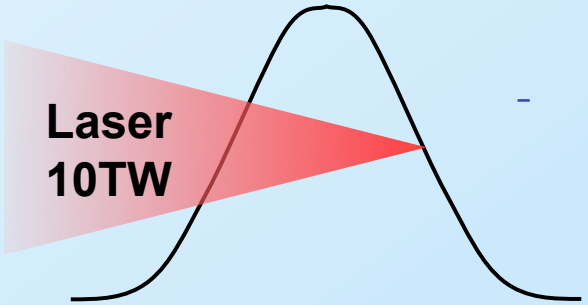
E-beam quality: reduce energy spread from ~2% to < 0.25%

- Approach:
  - Produce MeV beam with <20% ΔE/E
  - Accelerate to GeV: ΔE/E<0.2%



Sequential spectra
***centroid, avg**

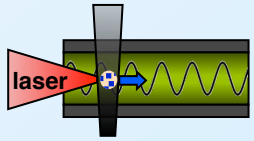




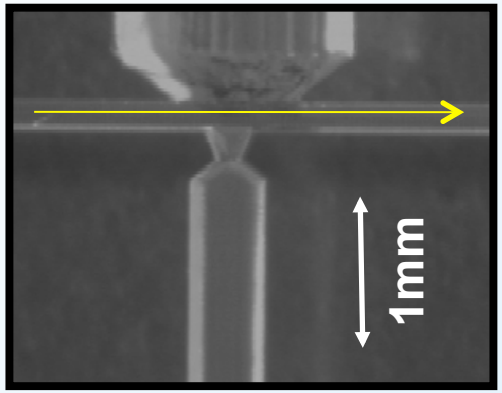
- **Stable MeV beam produced with**
  - **Low absolute energy spread (170keV)**

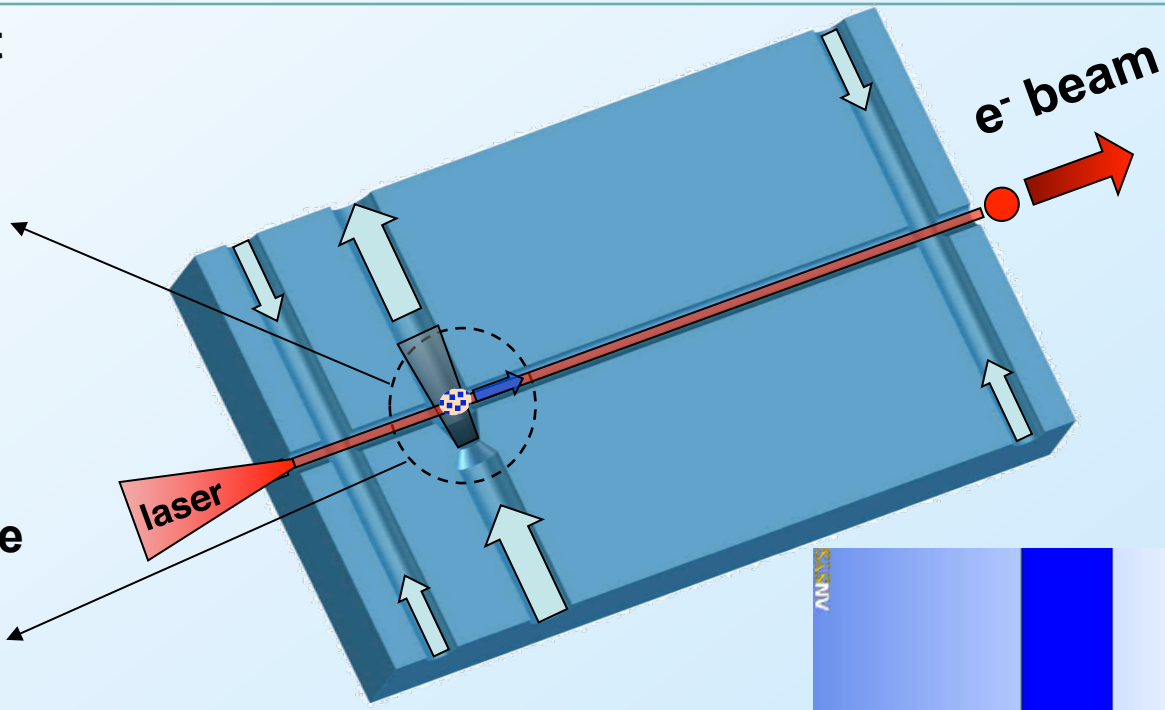
C.G.R. Geddes et al., PRL2008

Gas Jet Nozzle Machined Into Capillary Can Provide Local Density Perturbation

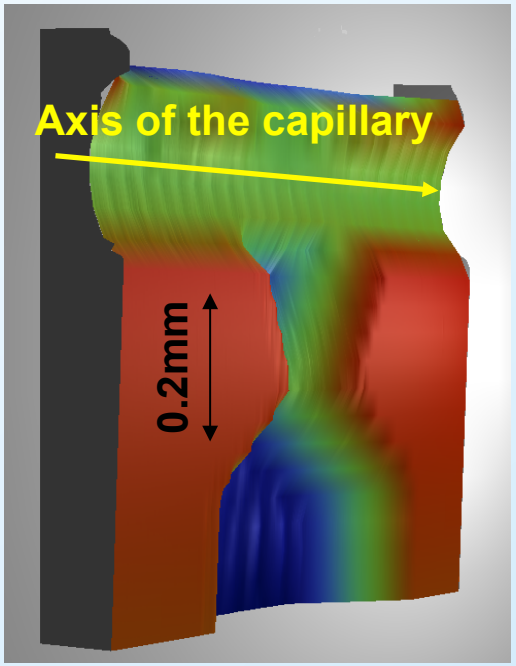


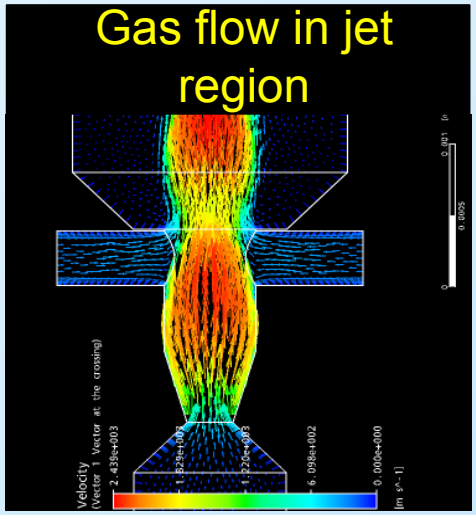
Laser-machined gas jet

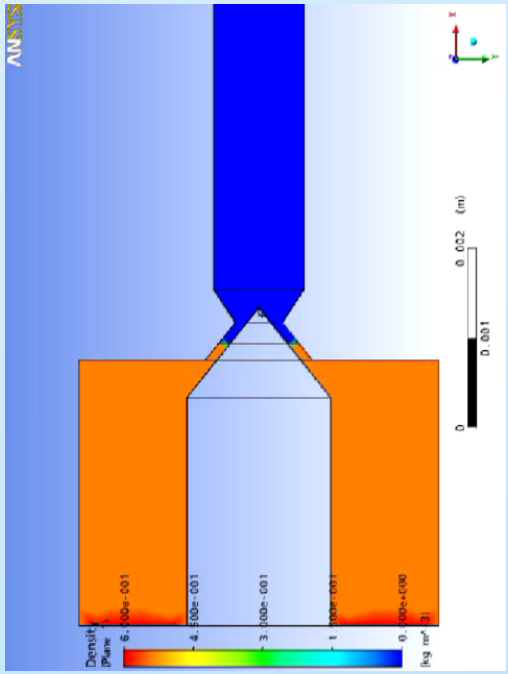




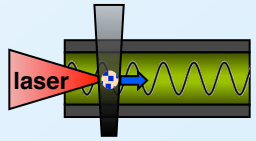
Measured surface profile



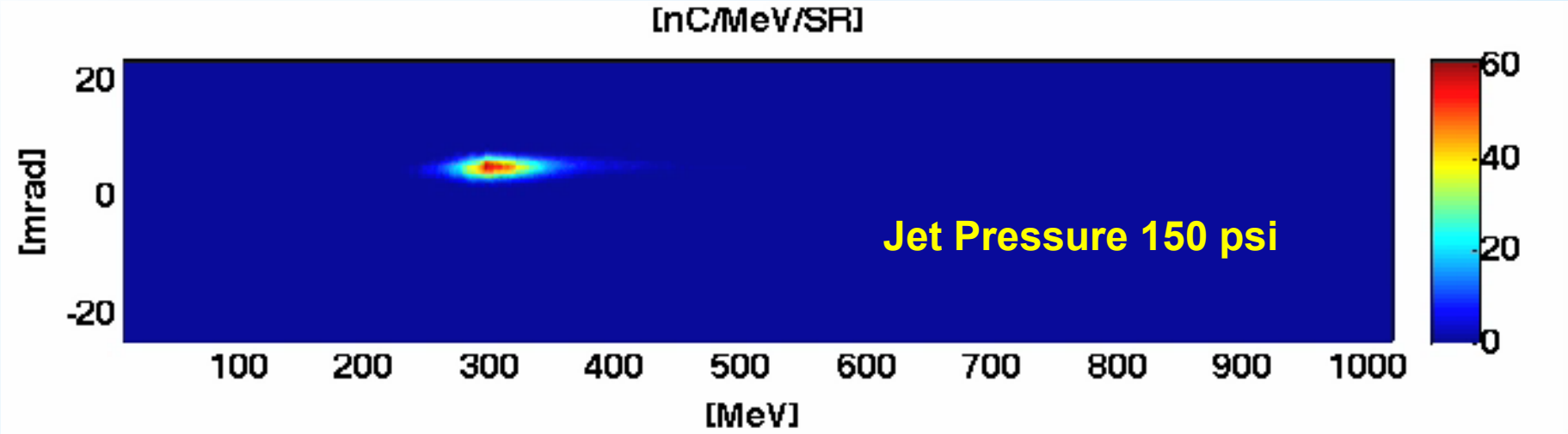




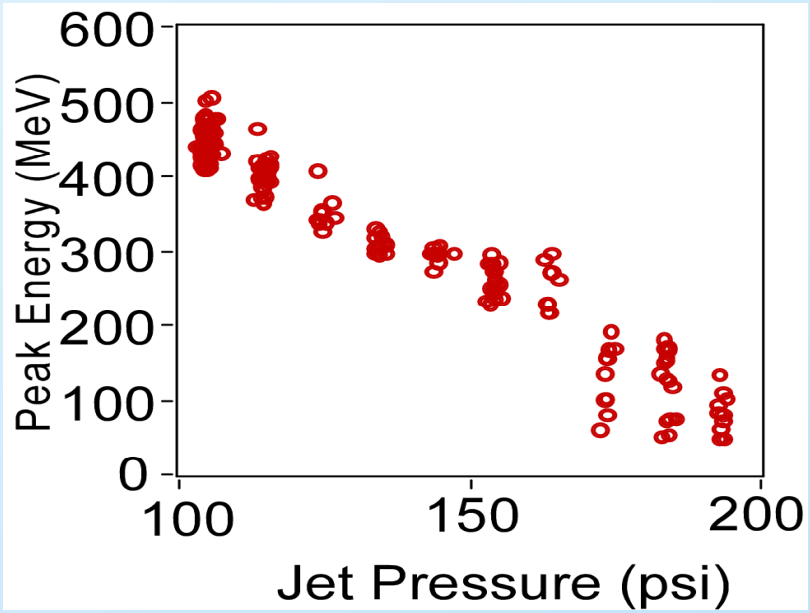
Gas jet triggered injections provides for enhanced stability & tuning



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

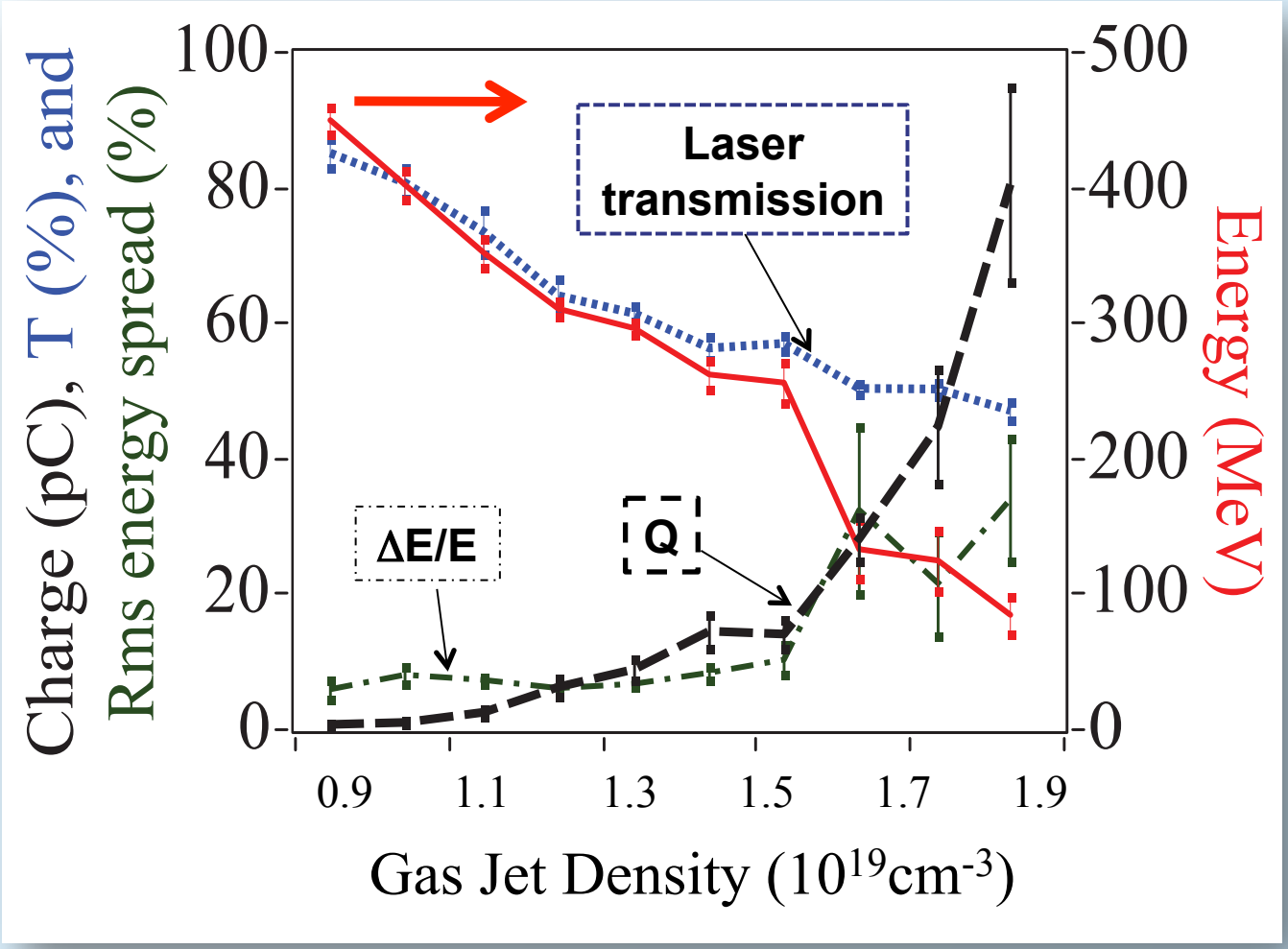


- Pointing ± 0.8 mrad
- Divergence <3mrad
- Peak energy 300MeV ± 7MeV
- Energy spread ~ 5-6%



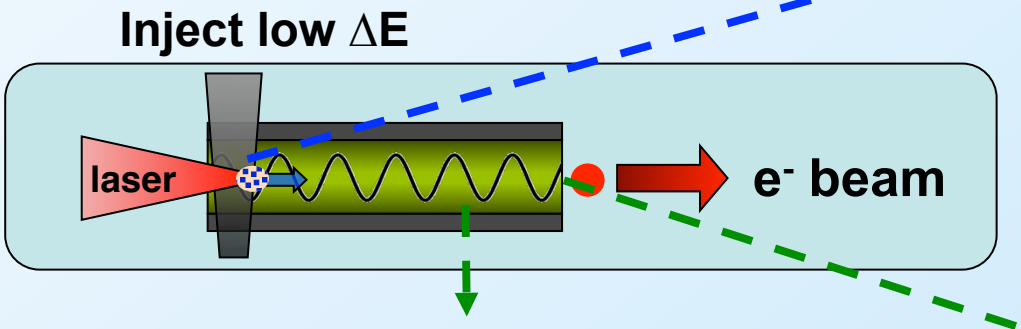
Energy Control by Varying Jet Pressure

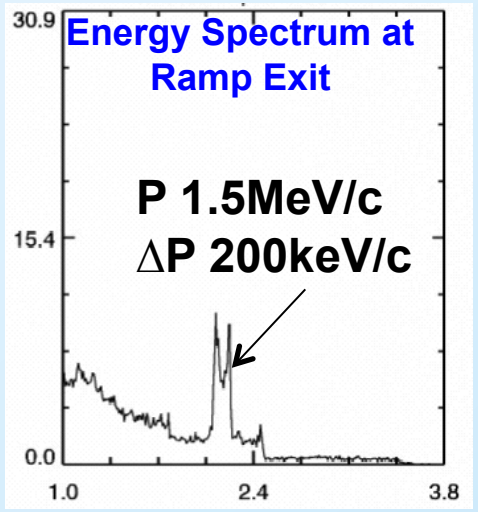
- Energy of the beam tuned without significant increase in energy spread
  - B*eam loading effects result in energy spread increase*

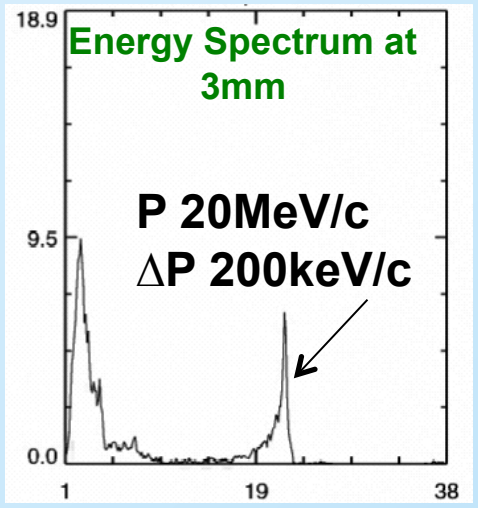


Optimization of capillary and gas jet is underway, guided by simulations

- Simulations indicate <0.25 % can be reached
  - 2D simulation done in VORPAL* of injector + accelerator up to 3mm
  - Injector peak density 2×10^{19} cm^{-3}, FWHM 900μm
  - Accelerator density 3×10^{17} cm^{-3}







Geddes et al., PRL V 100, 215004 (2008) *Nieter et al., JCP 2004

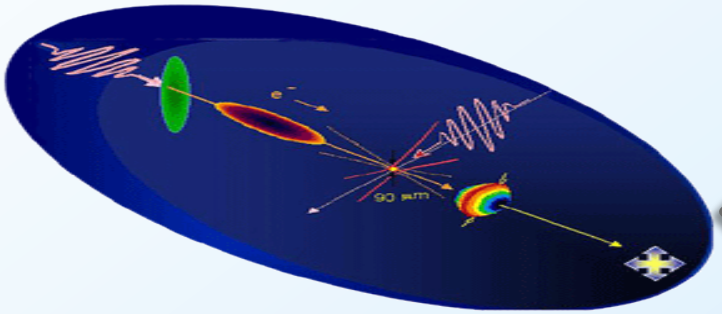
Areas of improvement in LPA performance for various applications

	THz	X-rays (betatron)	FEL (XUV)	Gamma-rays	FEL (X-rays)	Collider
Energy	✓	✓	✓	✓	↑	↑↑
ΔE/E	✓	✓	↓	↓	↓↓	↓↓
ε	✓	✓	✓	✓	↓	↓↓
Charge	✓	✓	✓	↑	✓	↑
Bunch duration	✓	✓	✓	✓	✓	✓
Avg. power	↑	↑	↑	↑	↑	↑↑

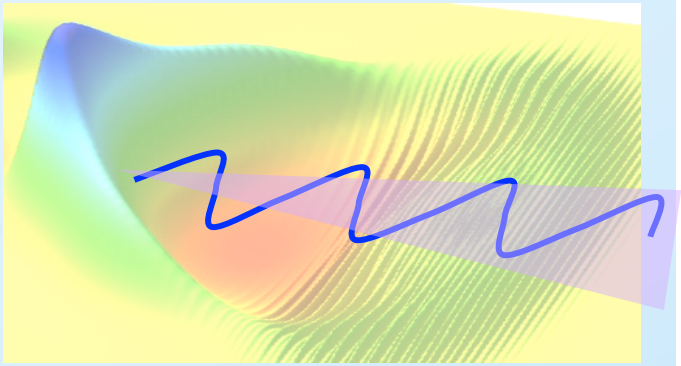
✓: OK as is
↑: increase needed
↓: decrease needed

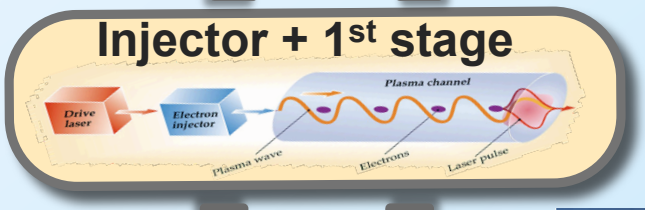
Radiation from THz to Gamma Ray – synchronized and ultra-short

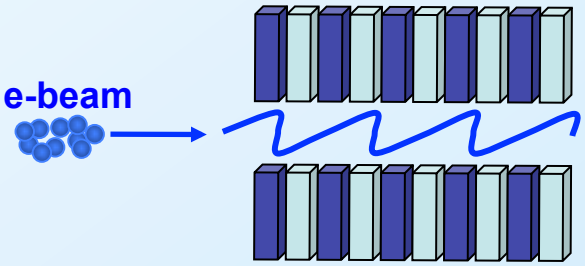
Thomson Scattering – Multi keV/ MeV x-ray/gamma ray



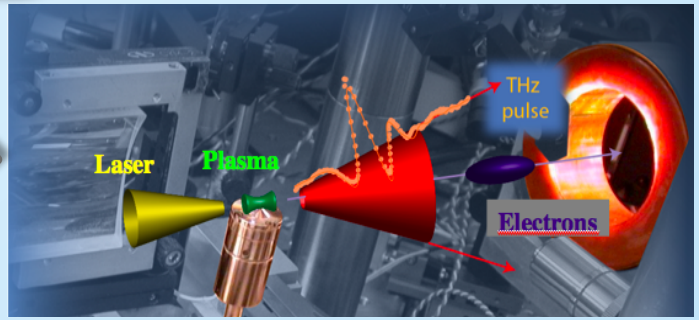
Betatron radiation during acceleration – Multi keV







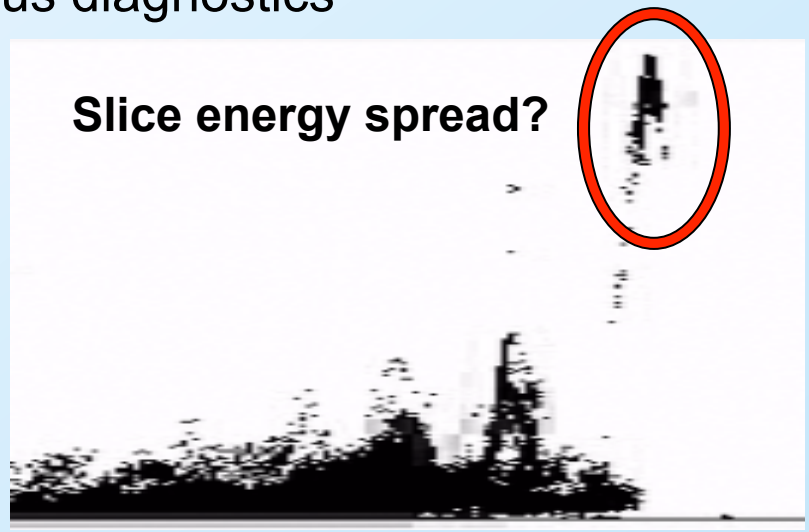
Free Electron Laser-> XUV, x-ray



Transition radiation from beam exiting plasma – MV/cm THz

Beam brightness studies are underway

- Charge:
  - Phosphor screen calibration vs. ICT at storage ring (up to 1.5 GeV)
  - Activation studies
  - %-level agreement between various diagnostics
- Emittance & energy spread:
  - Source size and divergence
  - OTR (COTR) experiments
  - Undulator based diagnostic
- Bunch duration:
  - Fluctuational interferometry (P. Catravas et al., PRL 1999)
  - THz radiation -- upper bound

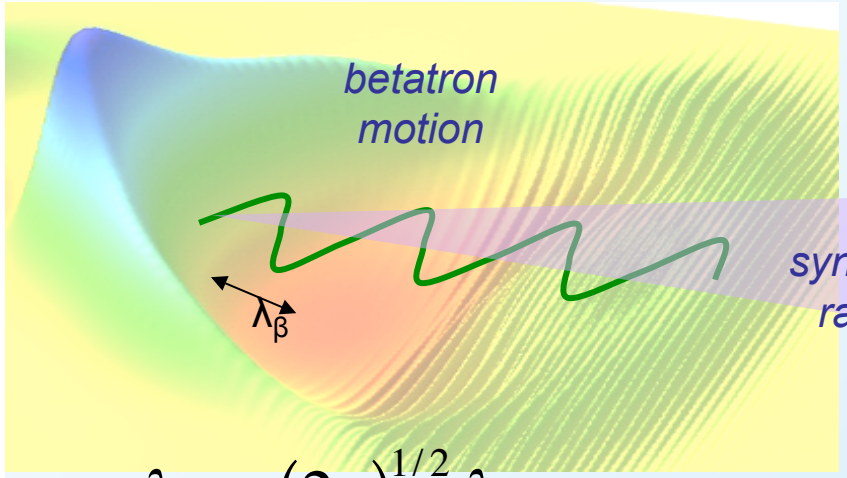


Coherent THz is emitted at plasma-vacuum boundary: diagnostic and source

- 'Traditional' laser based sources deliver < 100 kV/cm
- We achieved > 5 μJ in a single pulse
- Fields near 1 MV/cm
- Ready for expts using intense THz

Leemans et al. PRL 2003; POP2004; IEEE2005 Schroeder et al., PRE 2004;
van Tilborg et al., Laser Part. Beams2004; PRL2006; POP2006; Optics Lett. 2006

Betatron experiment provides upper bound for e-beam source size

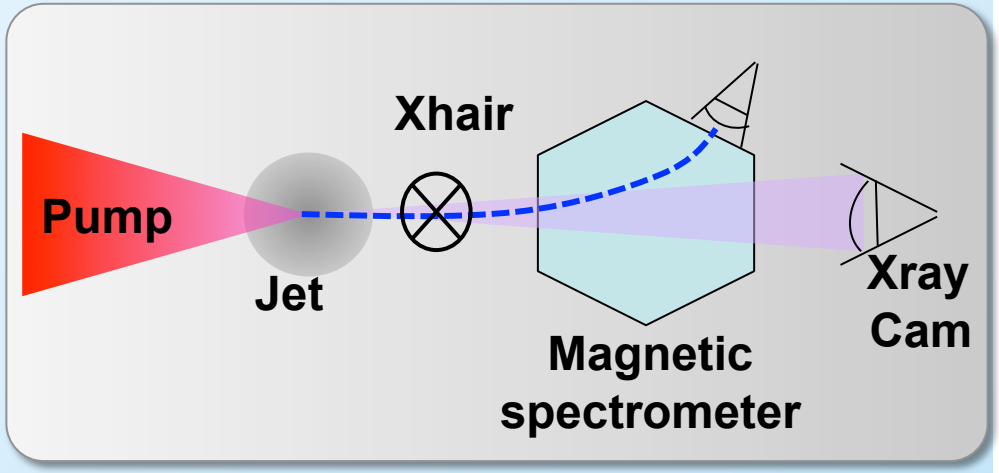


$$\theta \sim a_\beta / \gamma$$

$$\lambda_\beta = (2\gamma)^{1/2} \lambda_p$$

Esarey et al., Phys. Rev. E (2002); Rousse et al., PRL 2004; Ta Phuoc et al. PoP 2005; Leemans et al. TPS 2005, others

- 1-10 keV x-rays
- Directional source
- Image crosshair → size



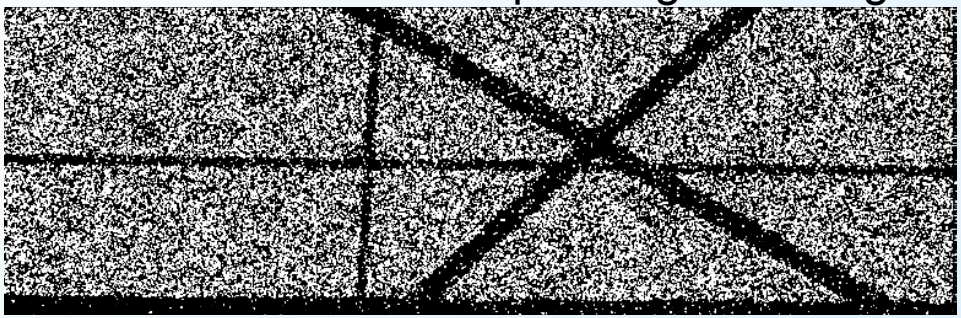
- Single beam experiment
- Pump = 0.45J, 45fs, 7μm
- n_e= 3x10^{19}/cc
- Image crosshair → size

Experiment in collaboration with Stoehlker, Thorn et al., GSI Battaglia, Denes et al., LBNL

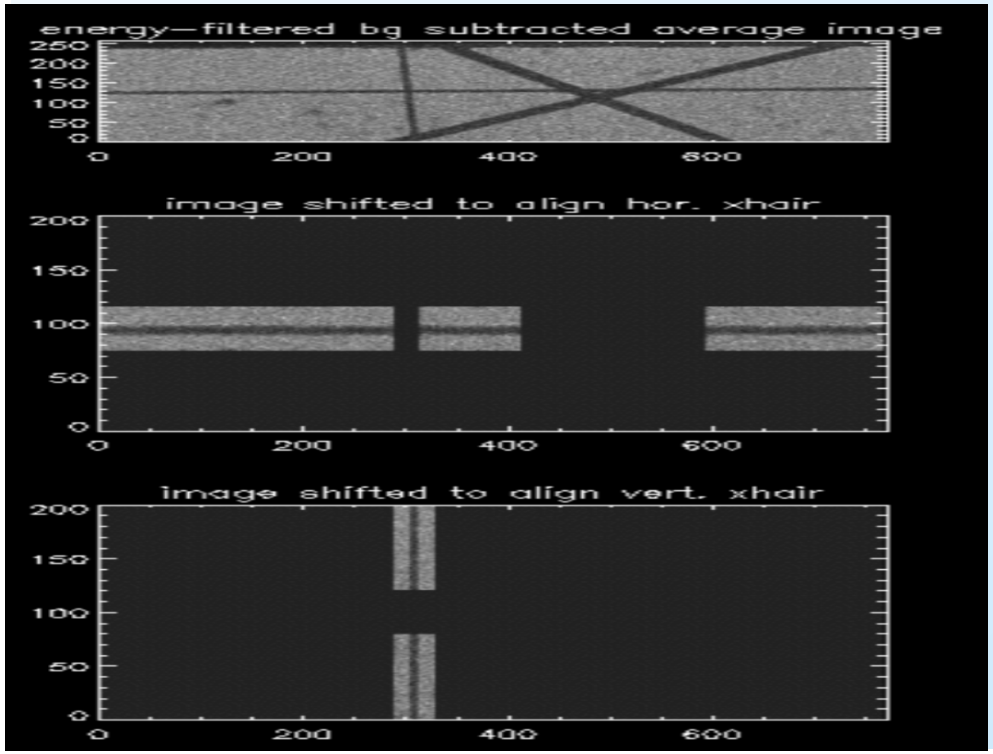
Single shot and integrated crosshair image: Beam stability and emittance

Single shot image ~2e5 photons on cam.

est. order 1e7 total depending on diverg.

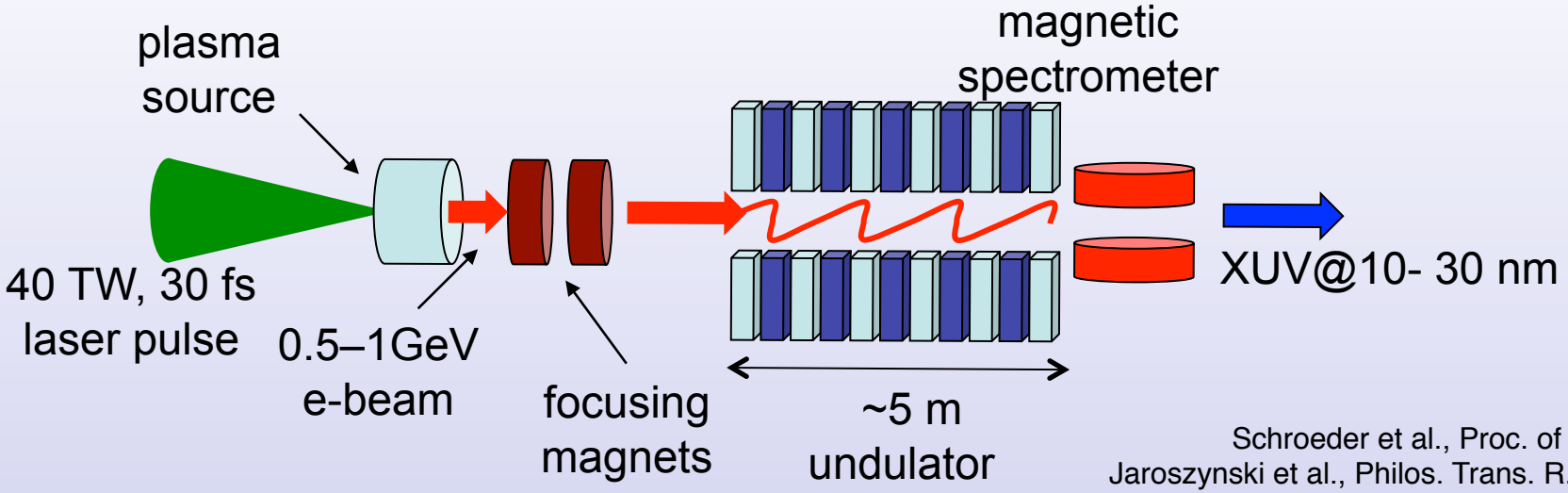


Integrated image



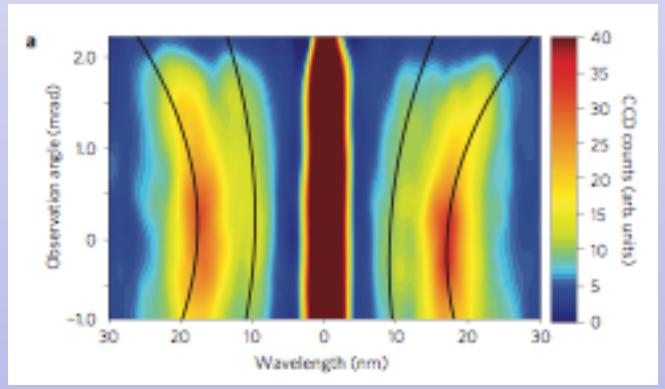
- crosshair imaged at 10:1
- Integrated source size / fluctuation ~ 6 μm – stable beam
  - Important for TS source
  - Automated correction not used for this run
- Simulations indicate < 2 μm
- Divergence ~1 mrad
- “Geometric emittance”:
  - < 1 mrad x 6 μm = 6 nm
  - Could be < 2 nm

Proof-of-principle experiments of Free Electron Laser driven by LPA-beam underway



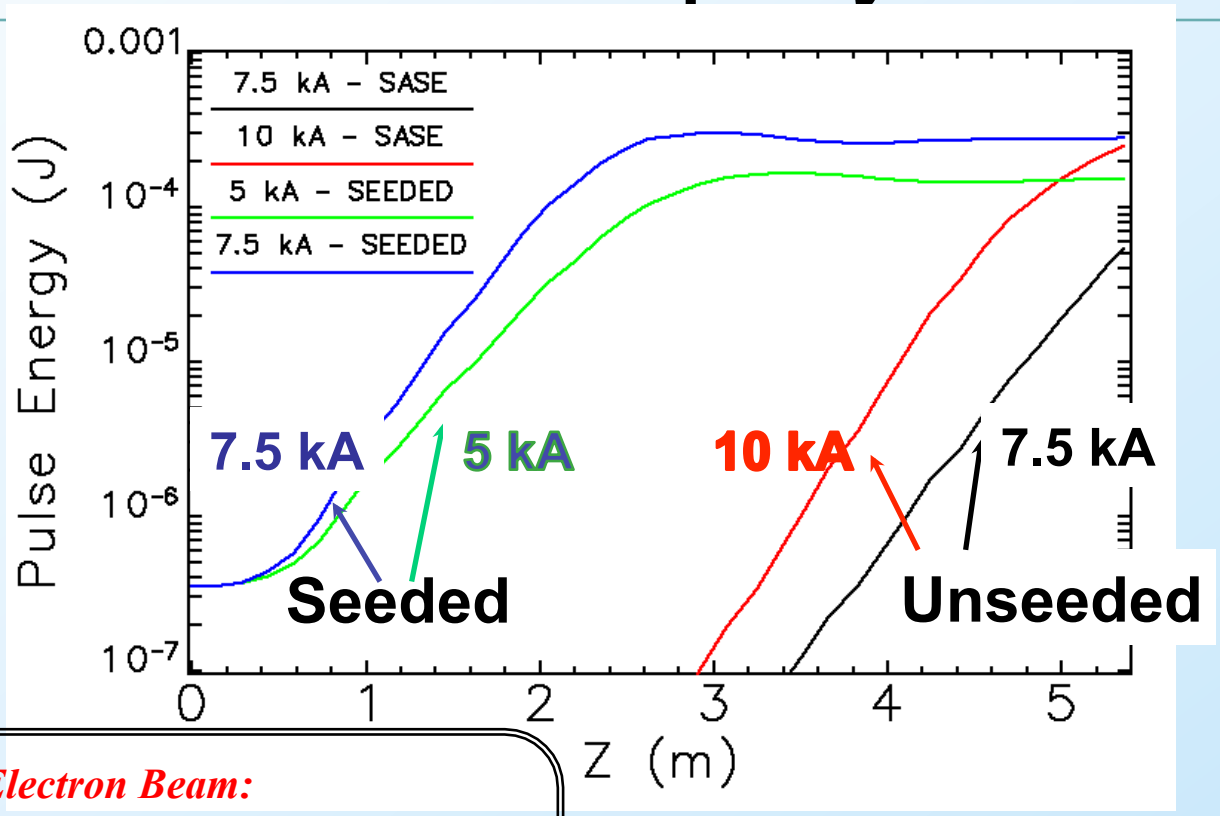
Schroeder et al., Proc. of FEL06 (2006)
Jaroszynski et al., Philos. Trans. R. Soc. A (2006)
Grüner, et al., Appl. Phys. B (2007)

- First step achieved:
  - Spontaneous emission of LPA beam through undulator at 17 nm (@ MPQ-Garching)
- Next step: FEL (with high harmonic seeding)



Fuchs et al.,Nature Physics (2009)

FEL places tight constraints on e-beam quality



LWFA Electron Beam:

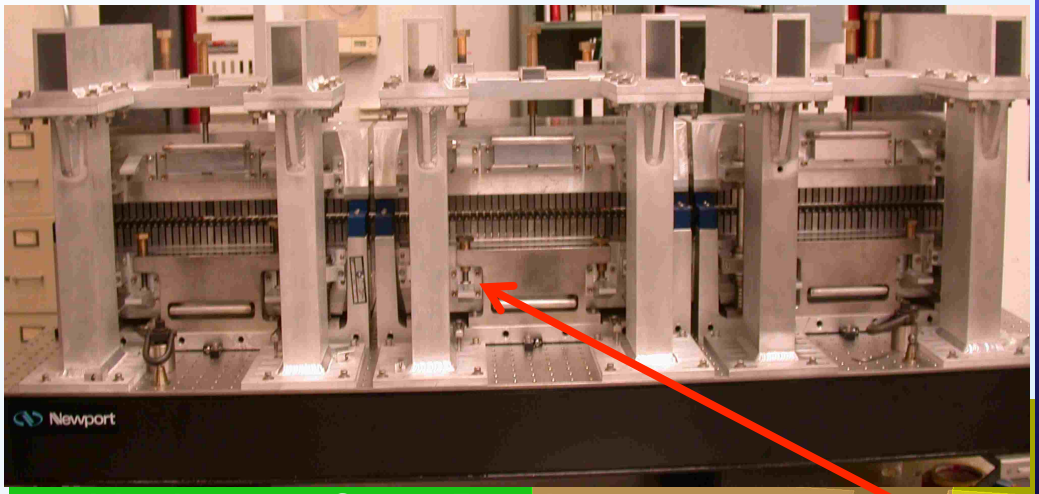
Beam Energy	0.5 GeV
Peak current	10 kA
Charge	0.2 nC
Bunch duration, FWHM	20 fs
Energy spread (slice)	0.25 %
Norm. Emittance	1 mm-mrad

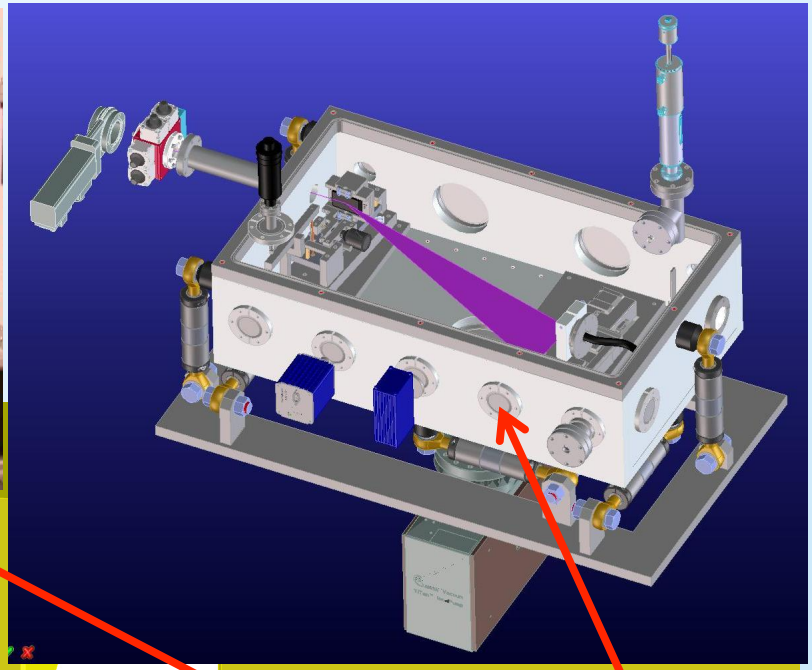
Photon beam:

λ=31 nm

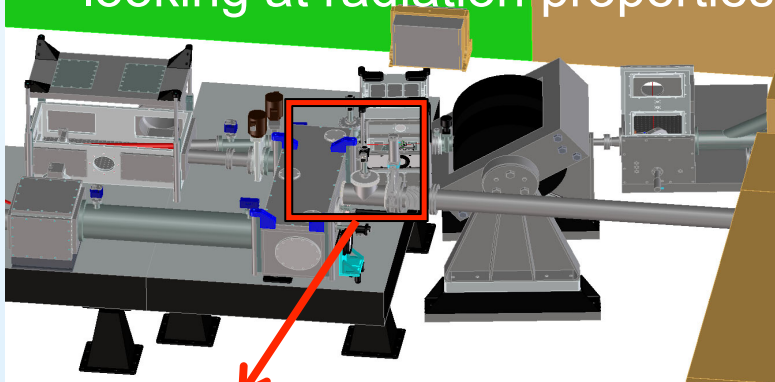
10^{13} photons/pulse in 5 fs

Undulator based diagnostic under development

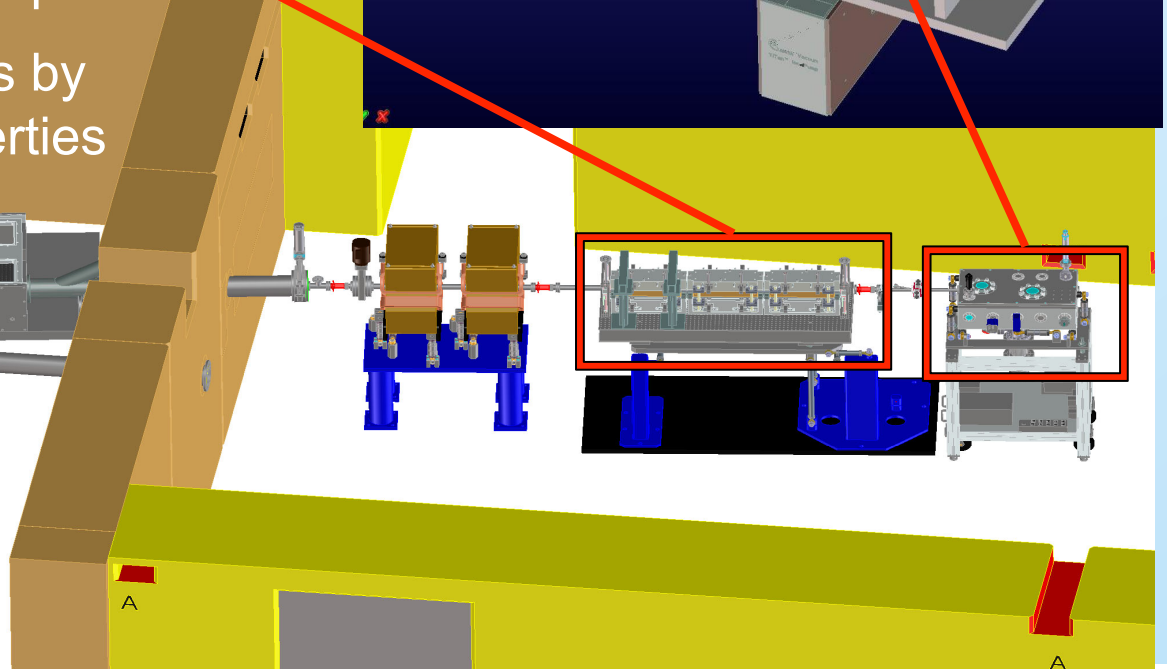




- Undulator from Boeing corp.
- Measure beam properties by looking at radiation properties

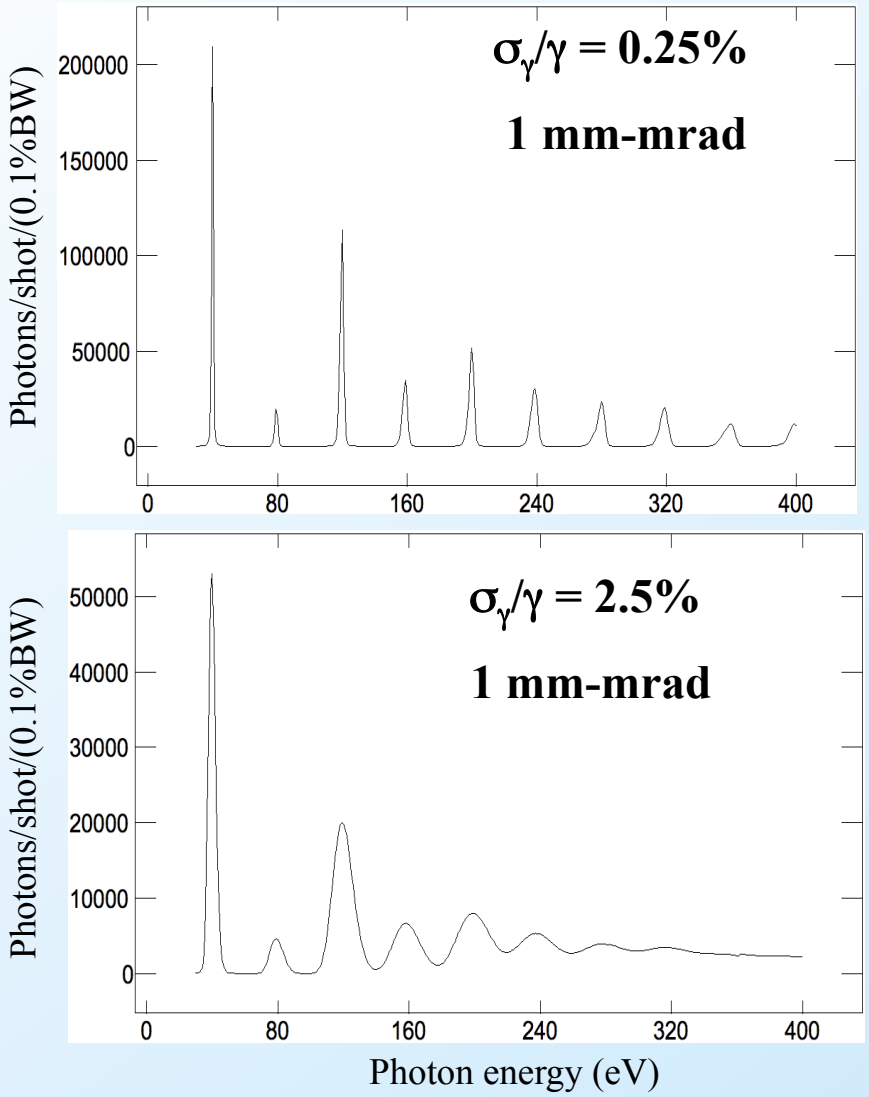


GeV module

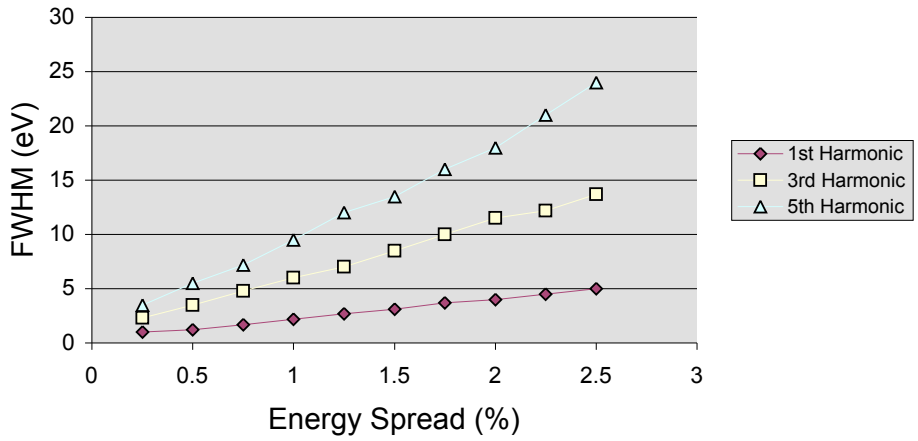


Undulator based diagnostic: single shot ΔE/E and ε

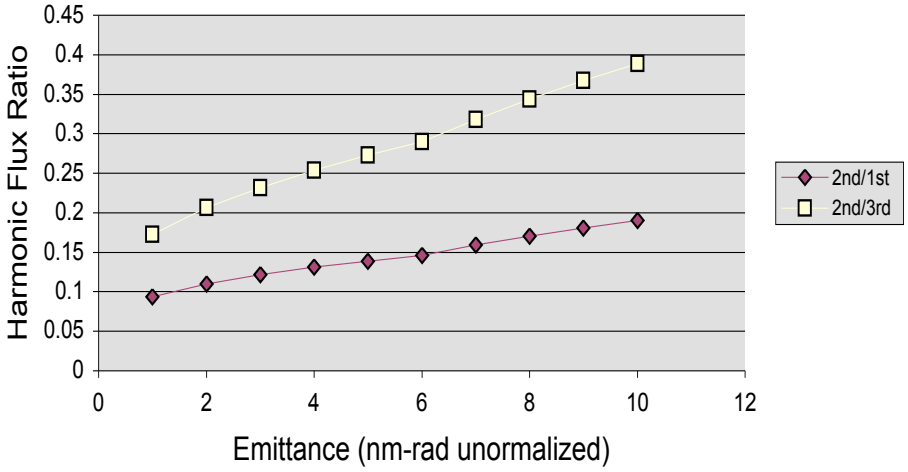
Changing energy spread



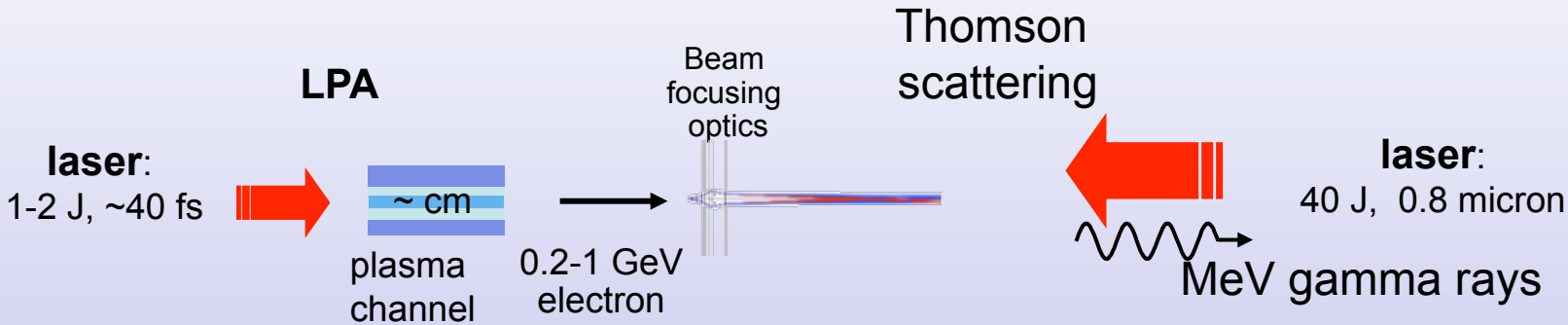
Line Width vs. Energy Spread



Flux Ratio vs. Emittance

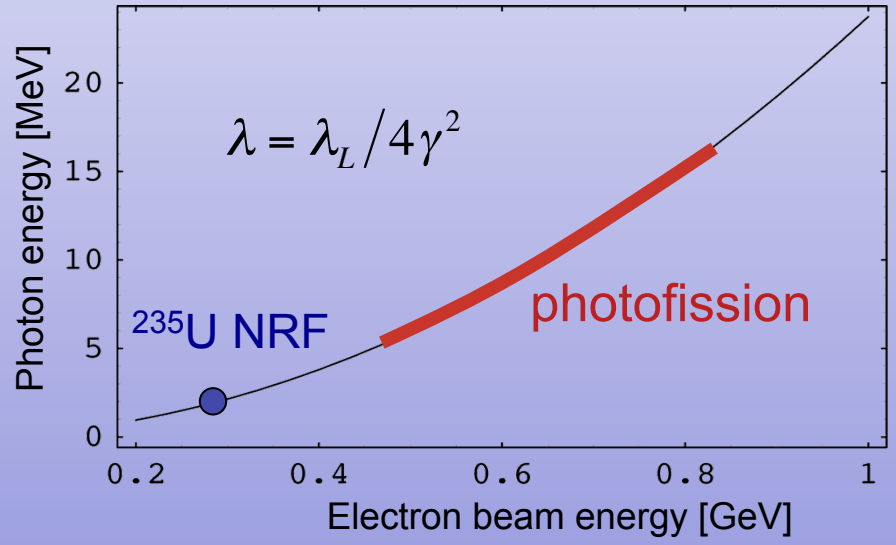


Compact Thomson scattering gamma-ray source using LPA



$$N_\gamma = \frac{\pi}{3}\alpha_f N_w N_e a_L^2 \approx 1.7\times10^9 \text{ ph/pulse}$$

compact gamma-ray source



⇒ Compact source of tunable, narrow energy spread, small divergence, MeV photons: active stand-off interrogation of special nuclear material (SNM)

Leemans et al., IEEE Trans. PS (2005); Geddes et al., Proc. CAARI (2009)

How about a collider ?

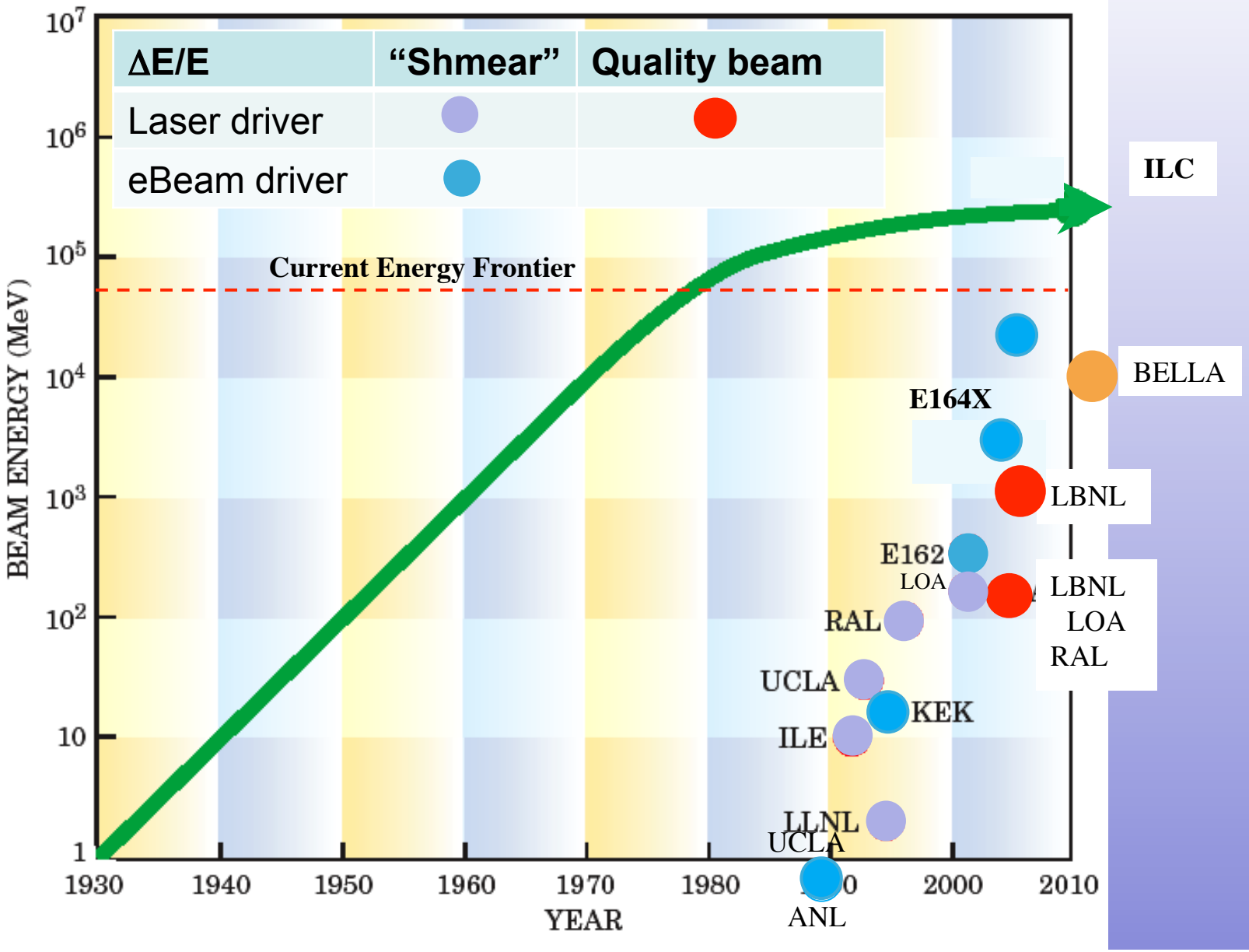
Case study: e^+-e^-

Alternative:

- **gamma-gamma (no positrons or polarized particle beams needed)**
- **muon beams – beginning to think about it**

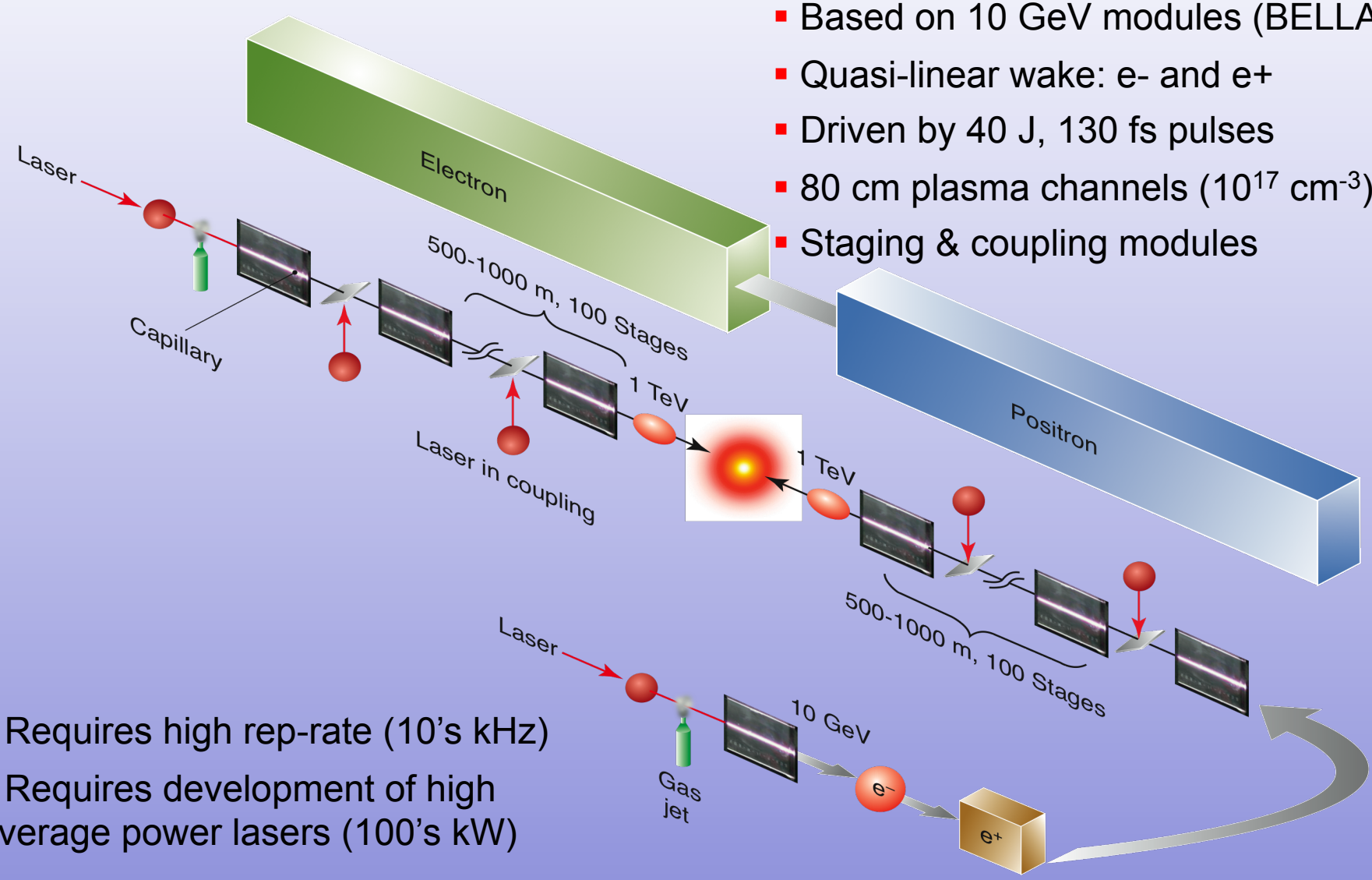
Plasma Accelerator Progress

"Accelerator Moore's Law"



Conceptual LPA Collider

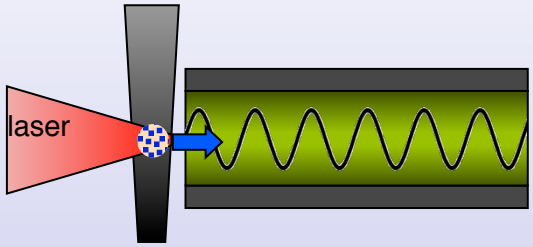
- Based on 10 GeV modules (BELLA)
- Quasi-linear wake: e- and e+
- Driven by 40 J, 130 fs pulses
- 80 cm plasma channels (10^{17} cm^{-3})
- Staging & coupling modules



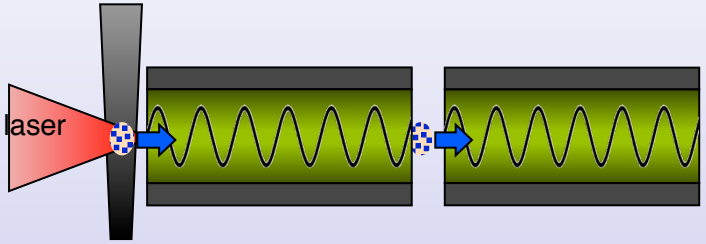
- Requires high rep-rate (10's kHz)
- Requires development of high average power lasers (100's kW)

Leemans & Esarey, Physics Today, March 2009

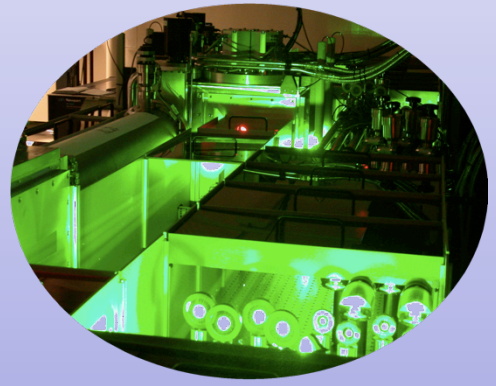
Technical challenges in next 10 years



High quality beams



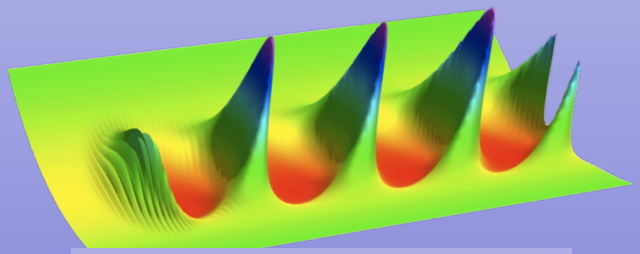
Staging, optimized structures



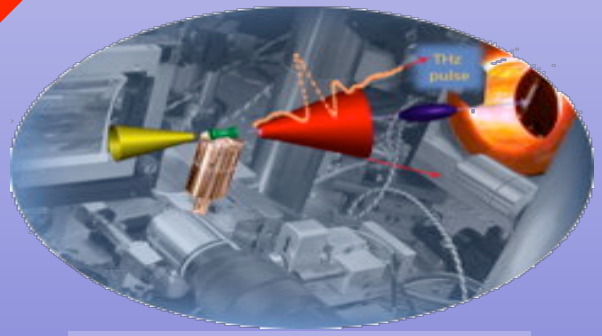
Lasers: high average power

BELLA

Multi-GeV beams



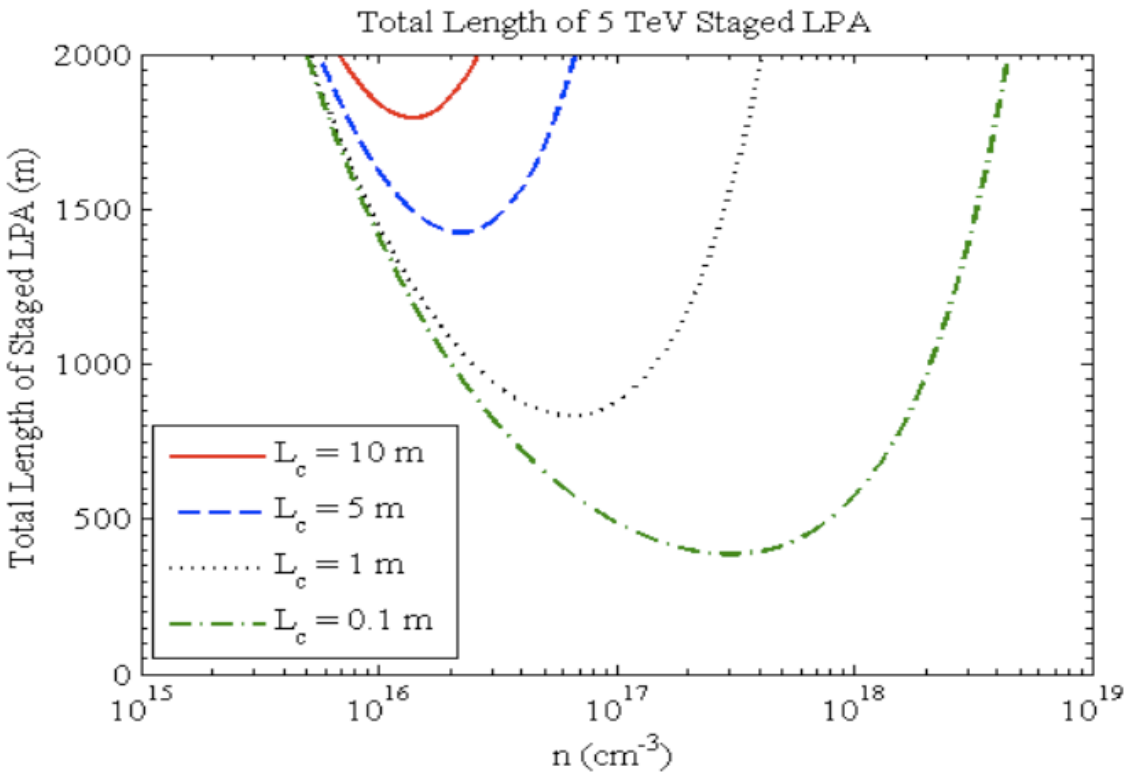
Modeling



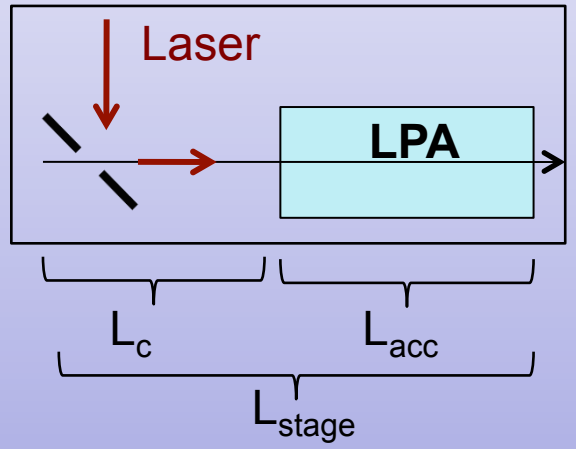
Diagnostics

Proper choice of plasma density and staging minimizes main linac length

- Number of stages: $N_{\text{stage}} \propto n$

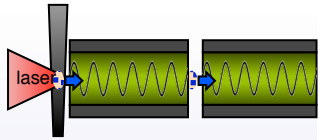


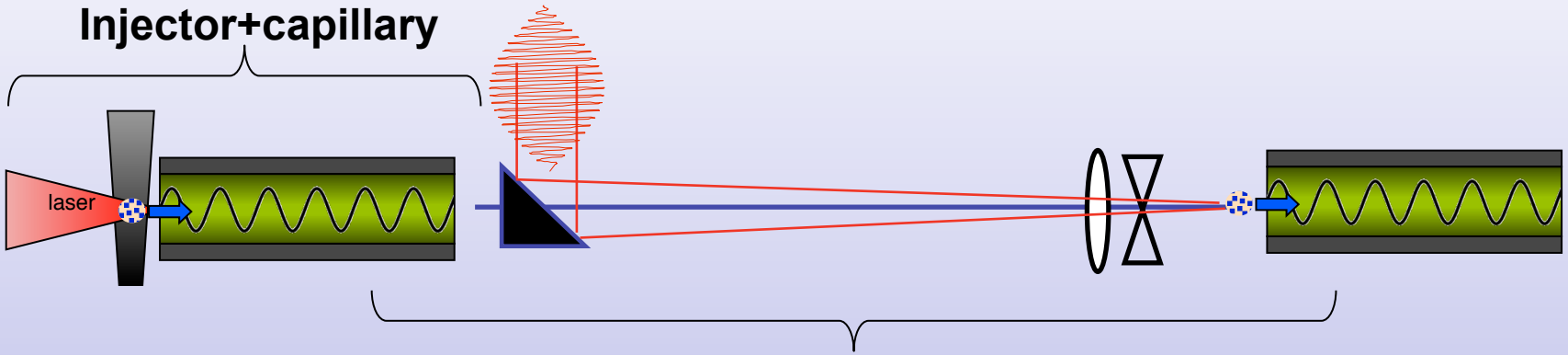
- Linac length will be determined by staging technology



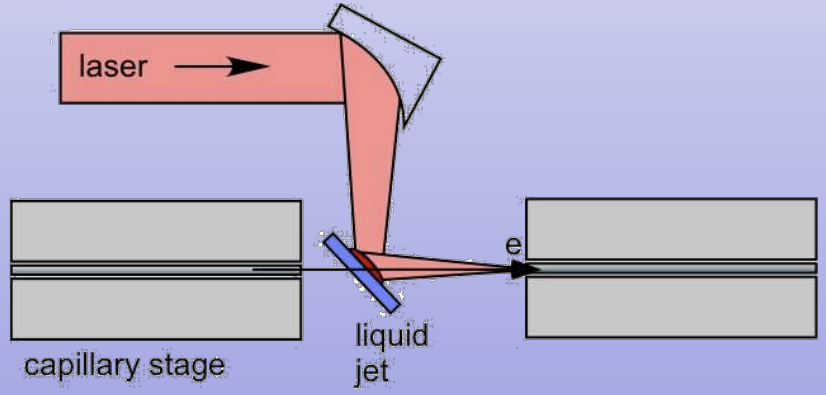
- Conventional optics (~10 m)
- **Plasma mirror (~10 cm)**

Staging: solving the issue of depletion of laser energy

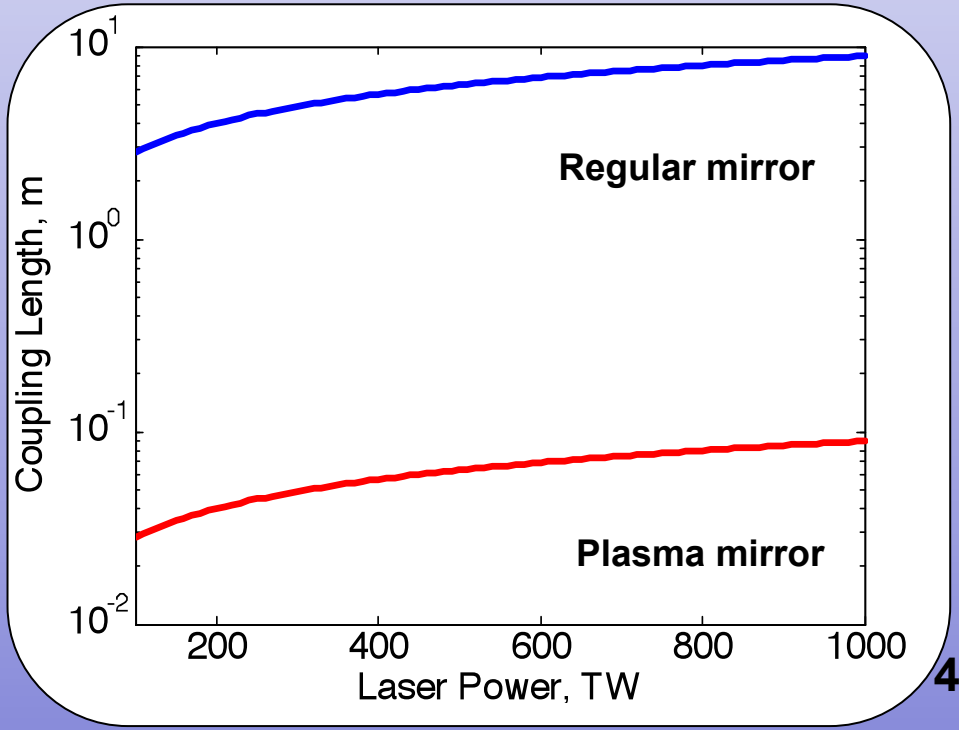




Renewable mirrors

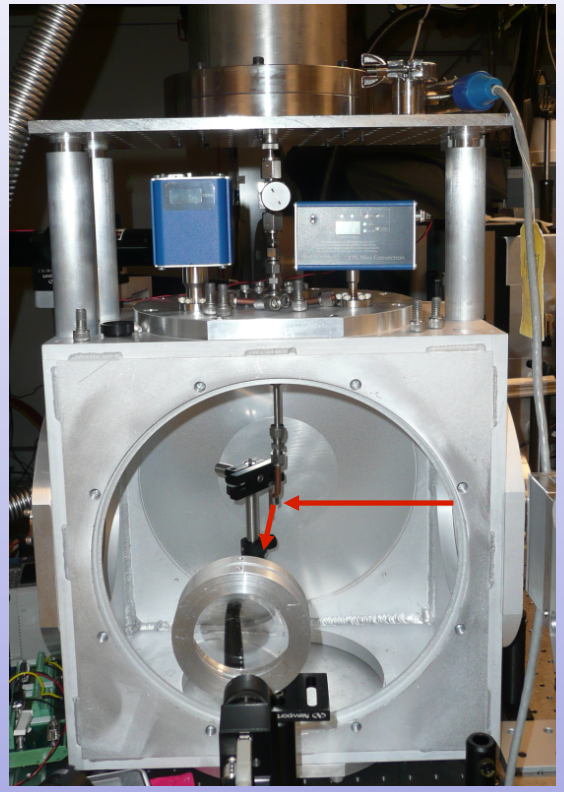


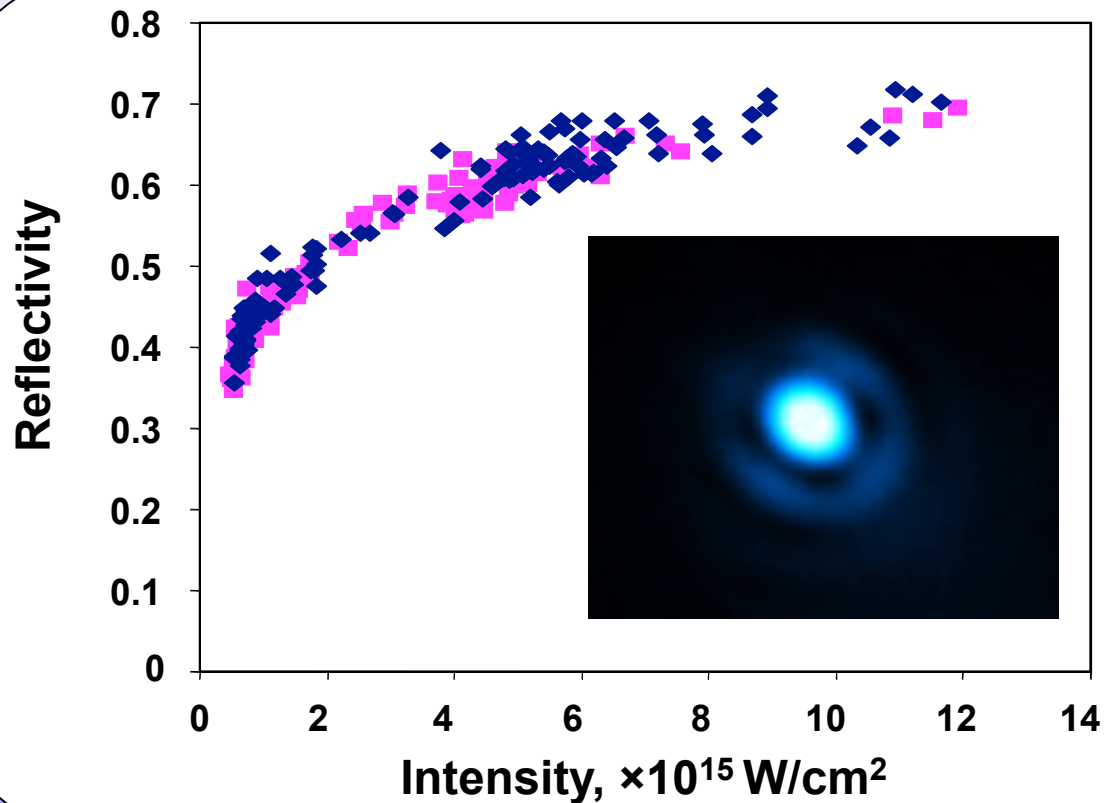
Structure-to-structure



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

Prototype plasma mirrors are being tested

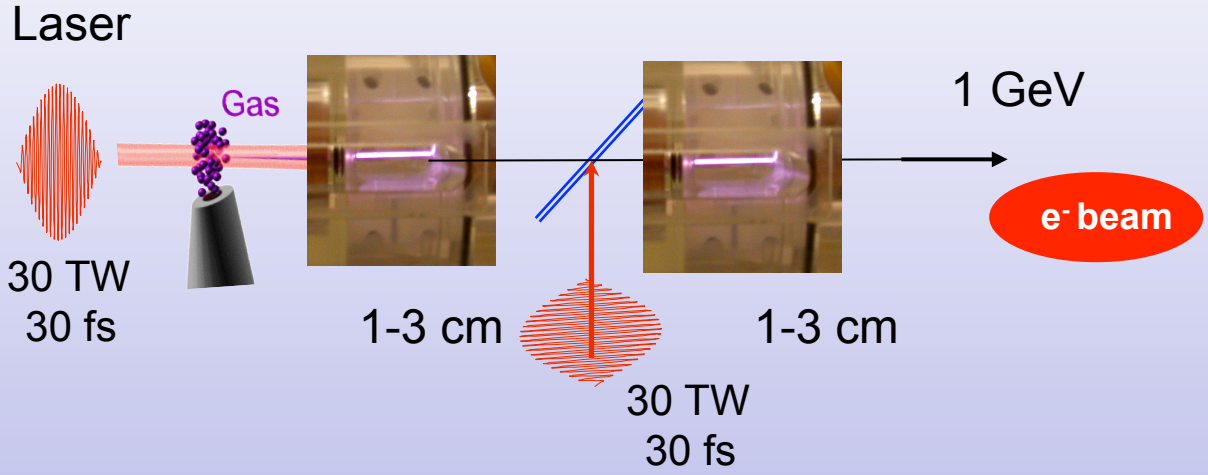




- Water jet based:
  - Pressure in the chamber limited by water vapor sat. pressure (~20 torr)
  - Differential pumping system with limited volume kept at high pressure required
- Ultra-thin (micron) foils: limited debris, will test tape drive (from SLAC)

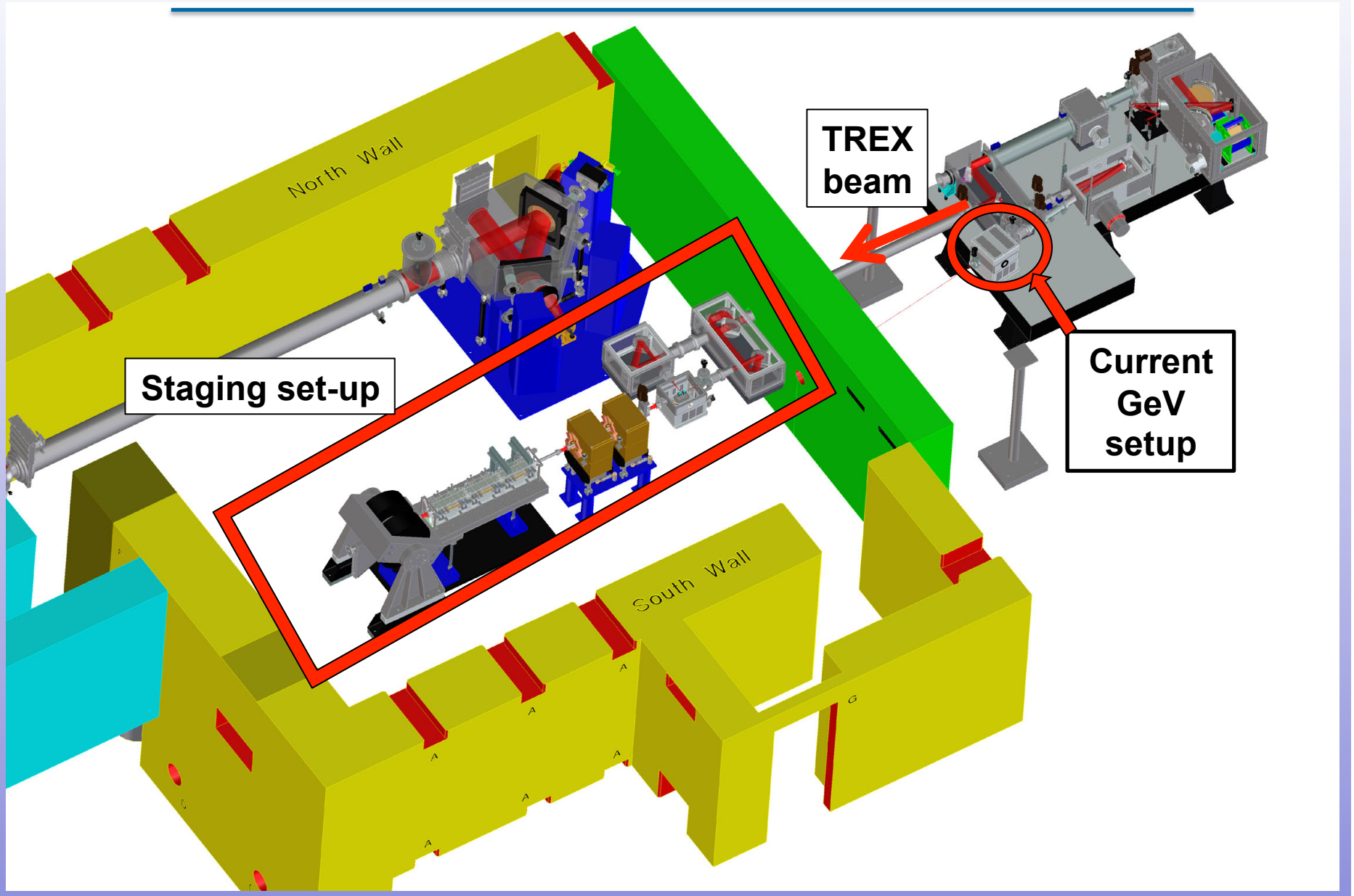
Staging experiments will start with TREX in A-cave

- Three stages (injector + cap + cap) – driven by TREX

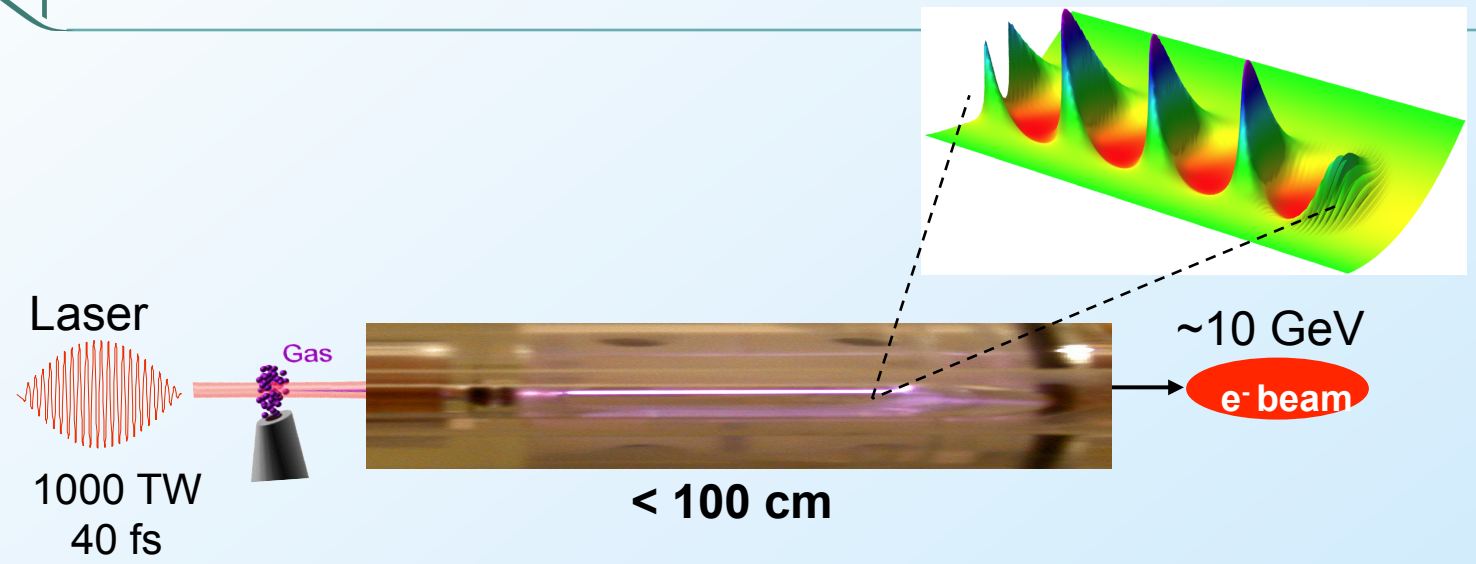


- Current concept relies on water jet based in-coupling
- Powered by TREX: x GeV + y GeV ~ O(1 GeV)
- Witness beam experiments with arbitrary delay (electron beam intrinsically synchronized with laser driver)
  - Wakefield mapping
  - Injection phase studies

Lay-out for staging in A-cave



BELLA laser will enable forefront accelerator and radiation science



- 10 GeV compact linac:
  - Collider module
  - X-ray FEL driver with seeding, coherent THz, gamma rays
  - Ultra-fast magnetic switching
  - Positron production and acceleration
  - Access to non-linear QED

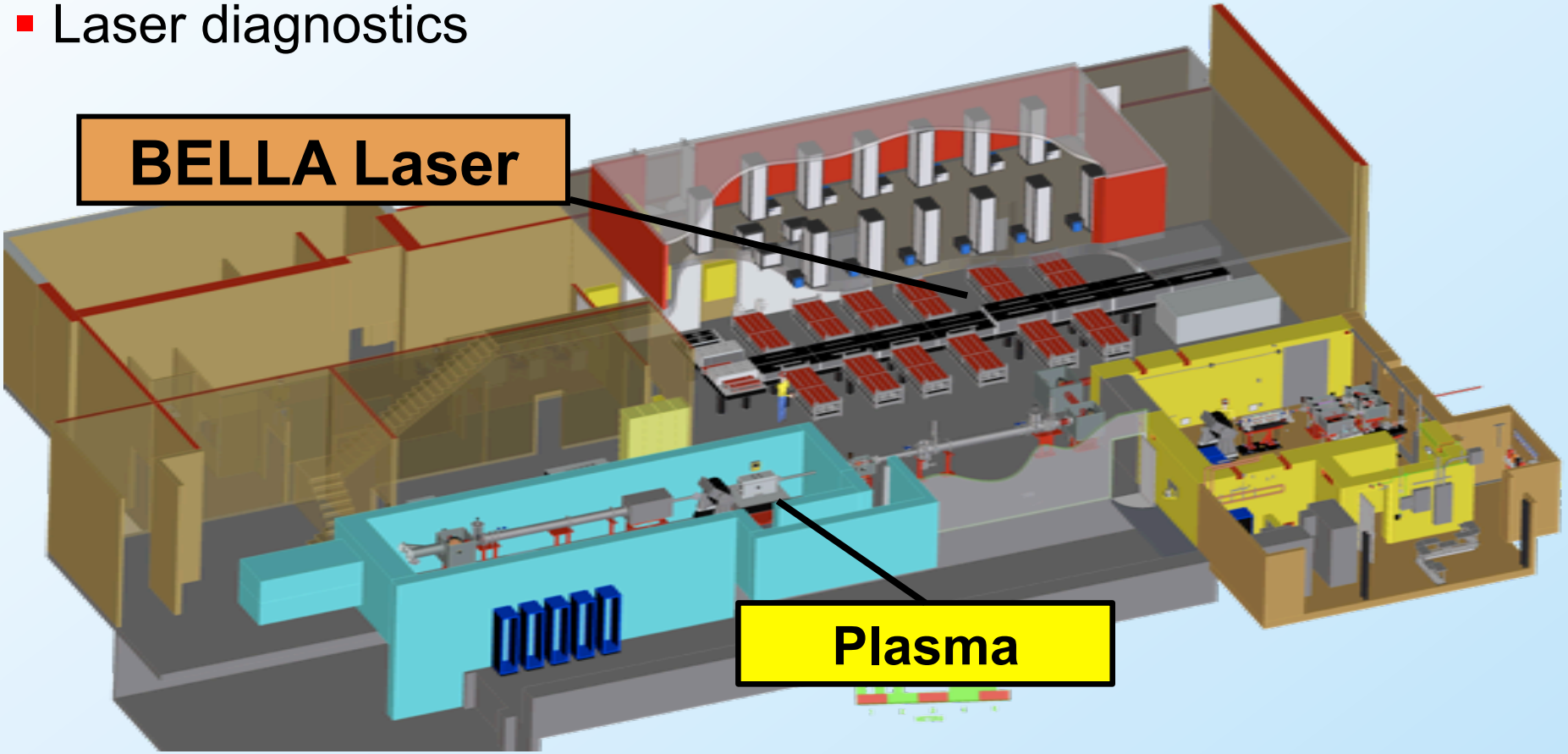
Point designs: 10 and 100 GeV

a_0	P/P_c	P(PW)	W_L	t_0(fs)	r_0(μm)	λ_p(μm)	n_0(cm^{-3})	L_{dp}	W_e (GeV)
2	2.2	0.38	40 J	98	53	80	1.7×10^{17}	38 cm	10
1.5	1.1	0.30	40 J	130	63	99	1.1×10^{17}	79 cm	10
1	0.45	0.22	40 J	170	82	140	6.0×10^{16}	2.4 m	10
2	2.2	3.8	1.3 kJ	310	170	250	1.7×10^{16}	12 m	100
1.5	1.1	3.0	1.3 kJ	390	200	310	1.1×10^{16}	25 m	100
1	0.45	2.2	1.3 kJ	550	260	430	6.0×10^{15}	78 m	100

Laser power: $P[GW] = 21.5(a_0 r_0/\lambda)^2$, Critical power: $P_c[GW] = 17(k/k_p)^2$, $P/P_c = (a_0 k_p r_0)^2/32$.
All assume: $k_p L_0 = 2$, $\lambda = 0.8\ \mu m$

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



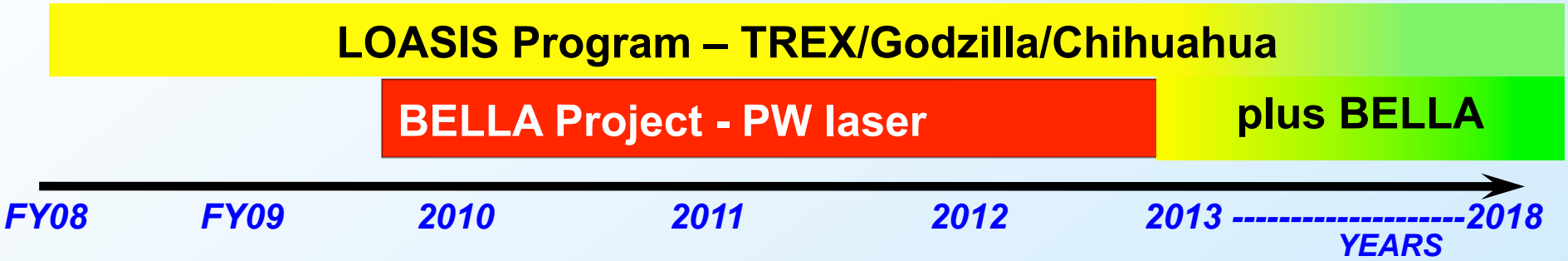
- 3 years for project

BELLA – Project details from 30,000 ft

- Scope:
  - Provide a 1 PW, 1 Hz laser system with diagnostics, optical transport and facility infrastructure to support reliable operation for an extensive laser plasma wake-field accelerator development program
  - Project completion CD-4 is meeting laser performance specs
- Funds:
  - DOE-HEP funding: ARRA (~ $20.7 M) and Program (~$8M)
- Schedule
  - Three and a half year project: 30 Months to build laser
- Aspects
  - Will ensure US competitiveness in this important technological area for next decade

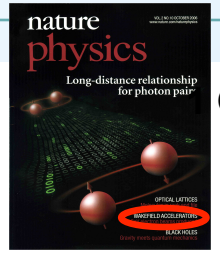
BELLA Team:
experienced in science and projects

BELLA Project & Integration with LOASIS Program



- FY09-FY12: LOASIS Program – current (Godzilla/Chihuahua/ TREX) + development of meter-scale plasma and diagnostics
- FY09-12: BELLA Project: concurrent with LOASIS program activities
- FY13-18 LOASIS Program – augmented with BELLA

Progress in laser accelerator science quickly follows after increasing laser power



Beam "Brightness" [arb. Units]

10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}

1995 2000 2005 2010

Year

LOASIS starts

Ignitor/Heater Channels

Electrons! 11/8/99

Radio-isotope POP exp't 2001

"Dream Beam" 2004

GeV Beam 2006

10 GeV beam

Chihuahua on-line

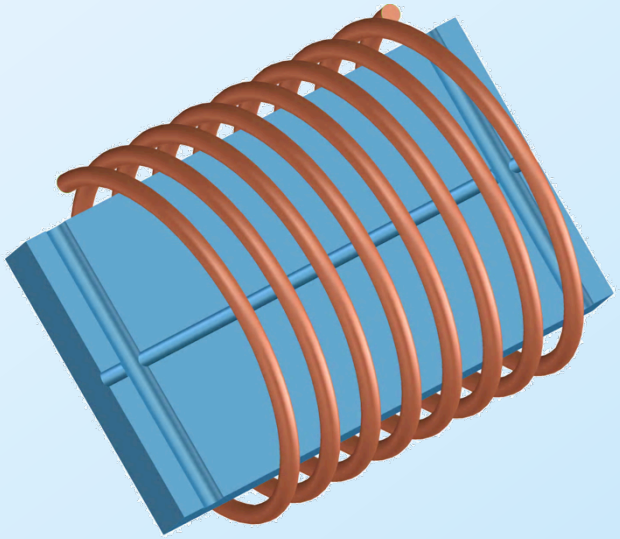
Godzilla on-line

TREX on-line

BELLA on-line

Capillary discharge technology and diagnostics will be refined for the 10 GeV module

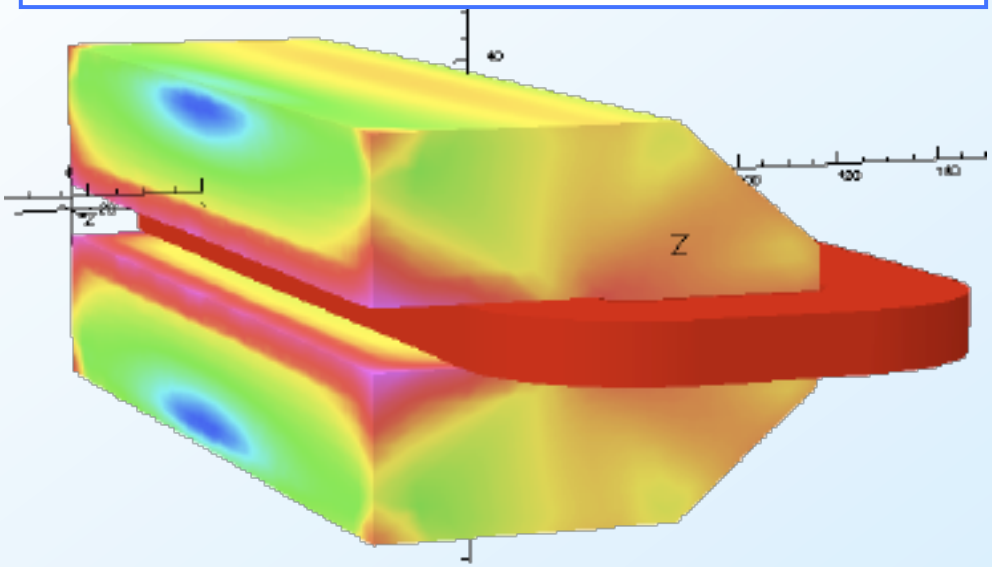
- Integrated injector+cap
- Capillary discharge:
  - Longer capillary discharges
  - Radial density shaping
    - Deep, shallow or hollow channels
  - Longitudinally tapered channels
  - Wall ablation issues: magnetic confinement
- Beam diagnostics:
  - Building on B&A-cave experience:
    - Present spectrometer covers 0.03 -1.1 GeV
    - New 0.1 - 11 GeV spectrometer will be built
    - Undulator based diagnostic will be implemented on BELLA beam line



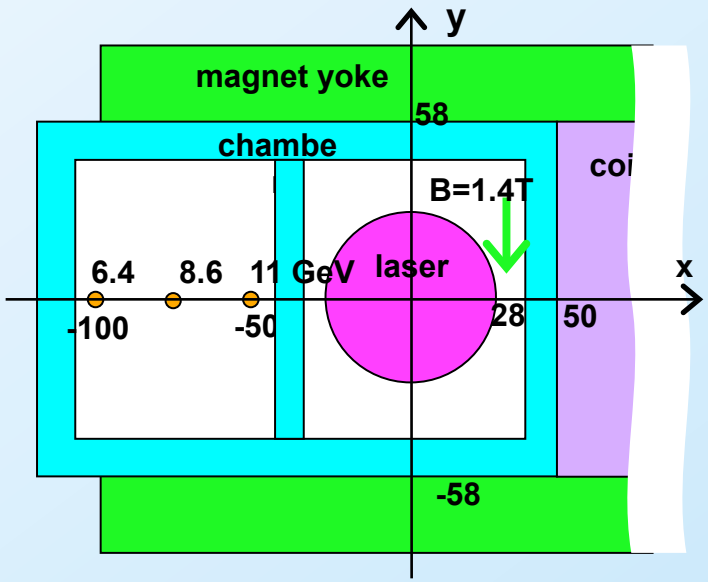
Single-Shot 0.1-11 GeV Electron Spectrometer

Large gap dipole magnet*

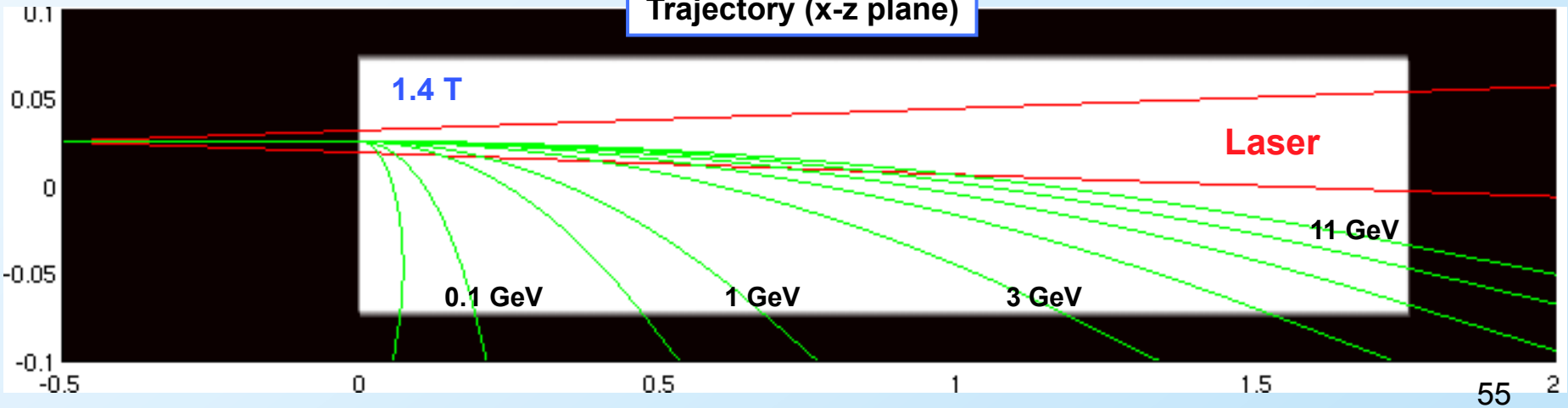
B = 1.4 T, L = 1.75 m, width = 150 mm, gap = 116 mm



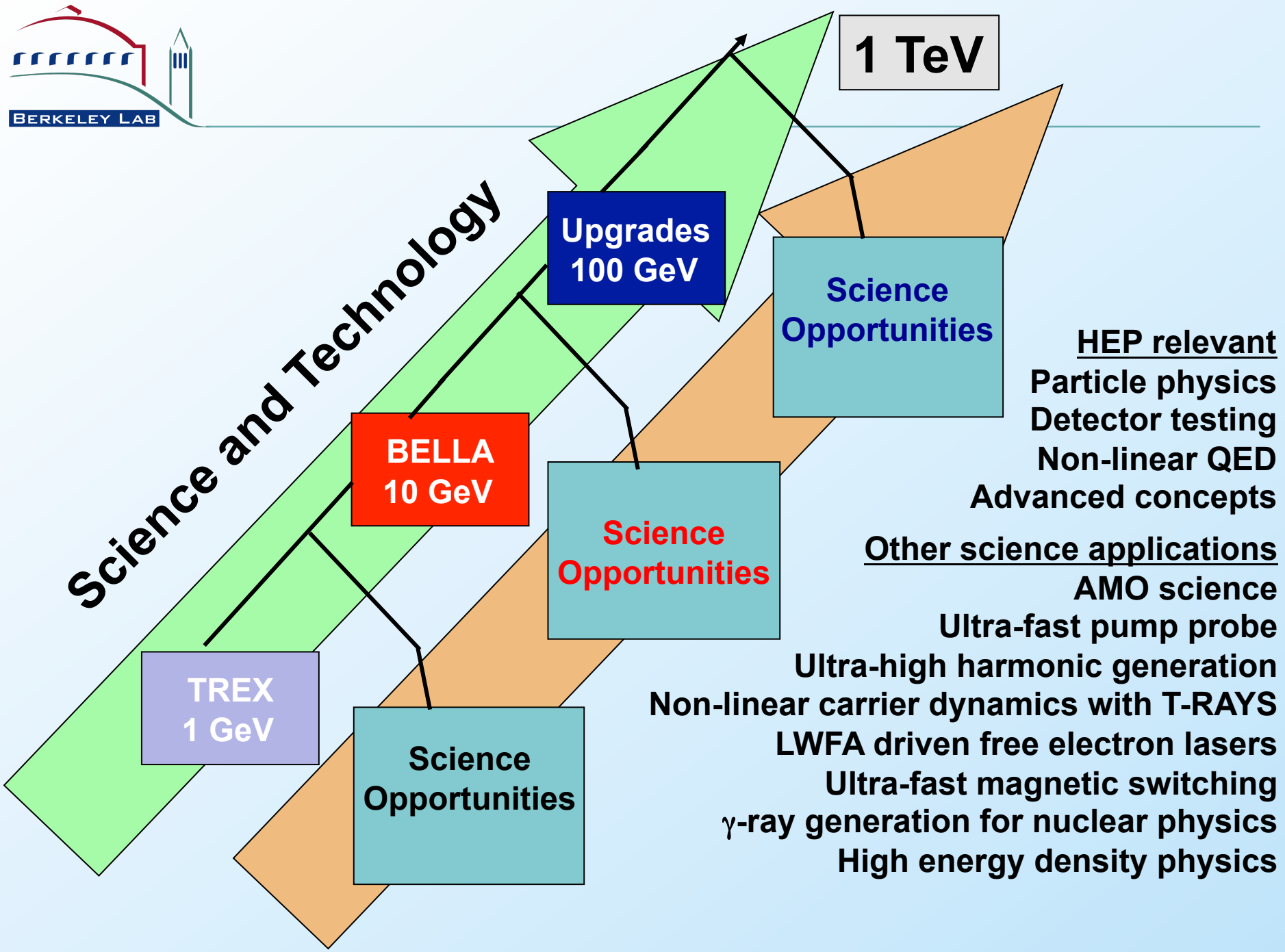
Trajectory (x-y plane)



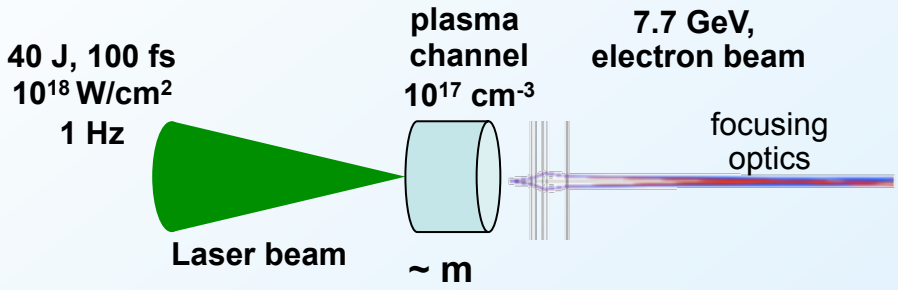
Trajectory (x-z plane)

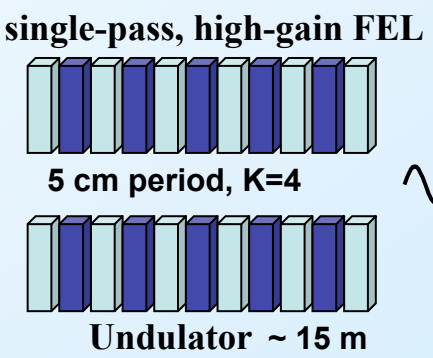


*S. Prestemon, and R. Schlueter, LBNL


1 TeV
Science and Technology
Upgrades
100 GeV
Science
Opportunities
BELLA
10 GeV
Science
Opportunities
TREX
1 GeV
Science
Opportunities
HEP relevant
Particle physics
Detector testing
Non-linear QED
Advanced concepts
Other science applications
AMO science
Ultra-fast pump probe
Ultra-high harmonic generation
Non-linear carrier dynamics with T-RAYS
LWFA driven free electron lasers
Ultra-fast magnetic switching
γ-ray generation for nuclear physics
High energy density physics

Laser-plasma accelerator driven soft x-ray FEL





FEL output:
λ=1 nm
~10^{13} photons/pulse

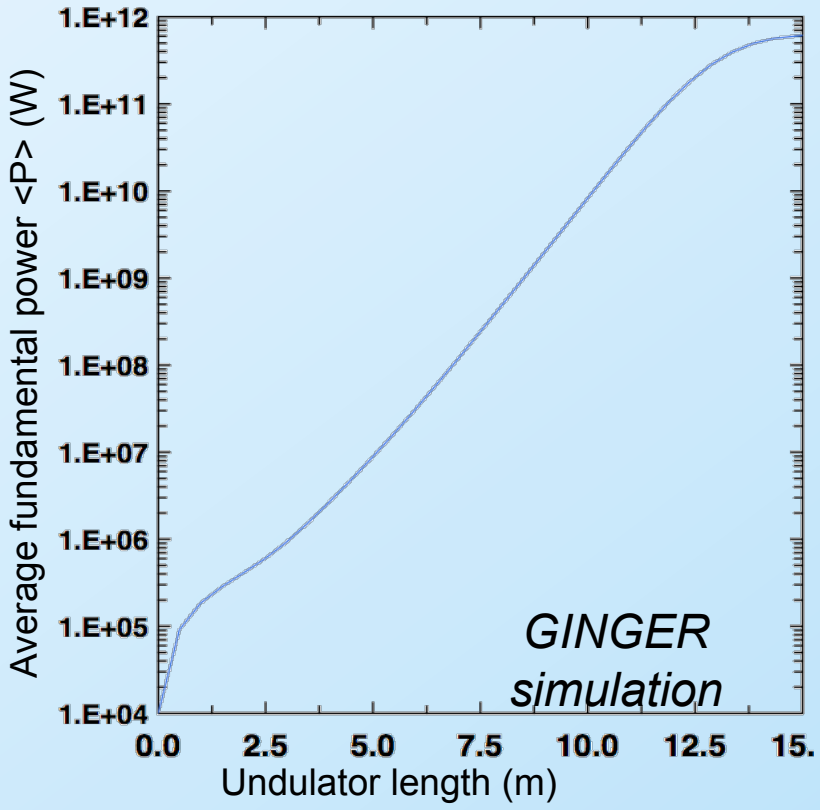
Coherent soft x-ray radiation

LPA electron beam:

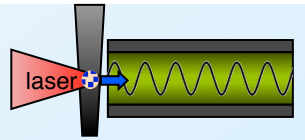
Beam energy	7.7 GeV
Peak current	30 kA
Relative energy spread	10^{-3}
Normalized emittance	1 micron

FEL Radiation:

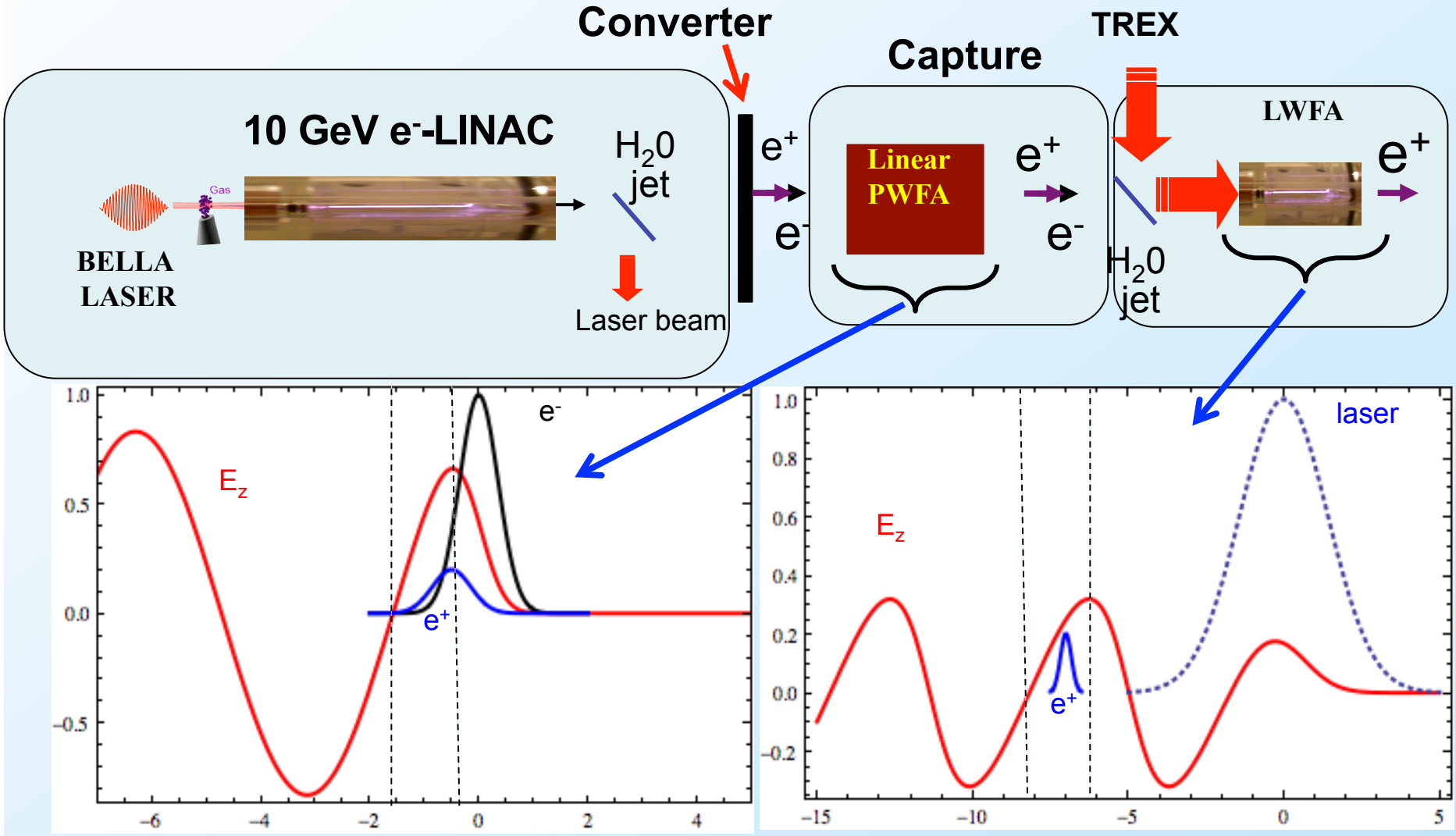
Resonant fundamental wavelength	1 nm
Photon energy	1.2 keV
Bandwidth at saturation	7 eV
FEL parameter	5×10^{-3}
1D gain length	0.4 m
3D gain length	0.6 m
Saturation length	13 m
Cooperation length	8 nm
Slippage length	0.3 mircon
Energy/pulse (fundamental)	8 mJ



R&D with BELLA: Proof-of-principle positron acceleration experiment



High quality beams



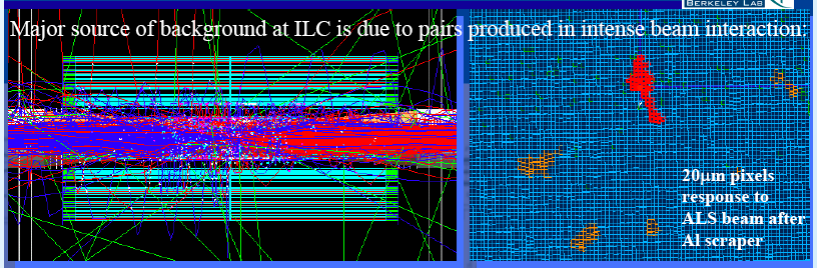
BELLA laser will enable basic collider components to be developed

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

Pair Production Experiment at BELLA

Major source of background at ILC is due to pairs produced in intense beam interaction:



• Study detector response to pair background:
need to characterise cluster shape of low momentum electrons (0.05-0.5 GeV) and validate simulation to assess occupancy level and pair hit rejection feasibility;

• Study pair production in dedicated experiment and validate simulation code:
Bethe-Heitler process $e^- \gamma \rightarrow e^- e^+ e^-$ colliding BELLA beam with intense laser, important experiment to gather data to compare with simulation.

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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

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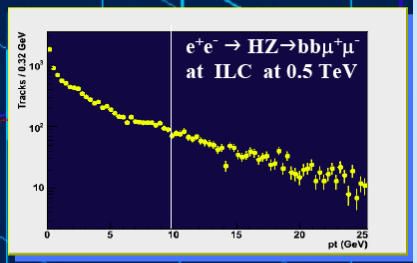
A 10 GeV beam in the TeV era

10 GeV e^- beam ideal for detector beam test characterisation & calibration;

• Need large enough energy to **minimise multiple scattering** (~1/p) and have **dynamic range** to calibrate response;

• Despite large c.m energies, energy of final state particles remain low due to large number of partons/hadrons produced:



• Need beamline with bend section to suppress laser background and optics to reduce beam intensity and magnify beam spot (from 10^8-10^9 e^- bunch^{-1} on μm spot to few 10^2-10^3 e^- cm^{-2});

• Narrow, intense beam essential for pair generation experiment.

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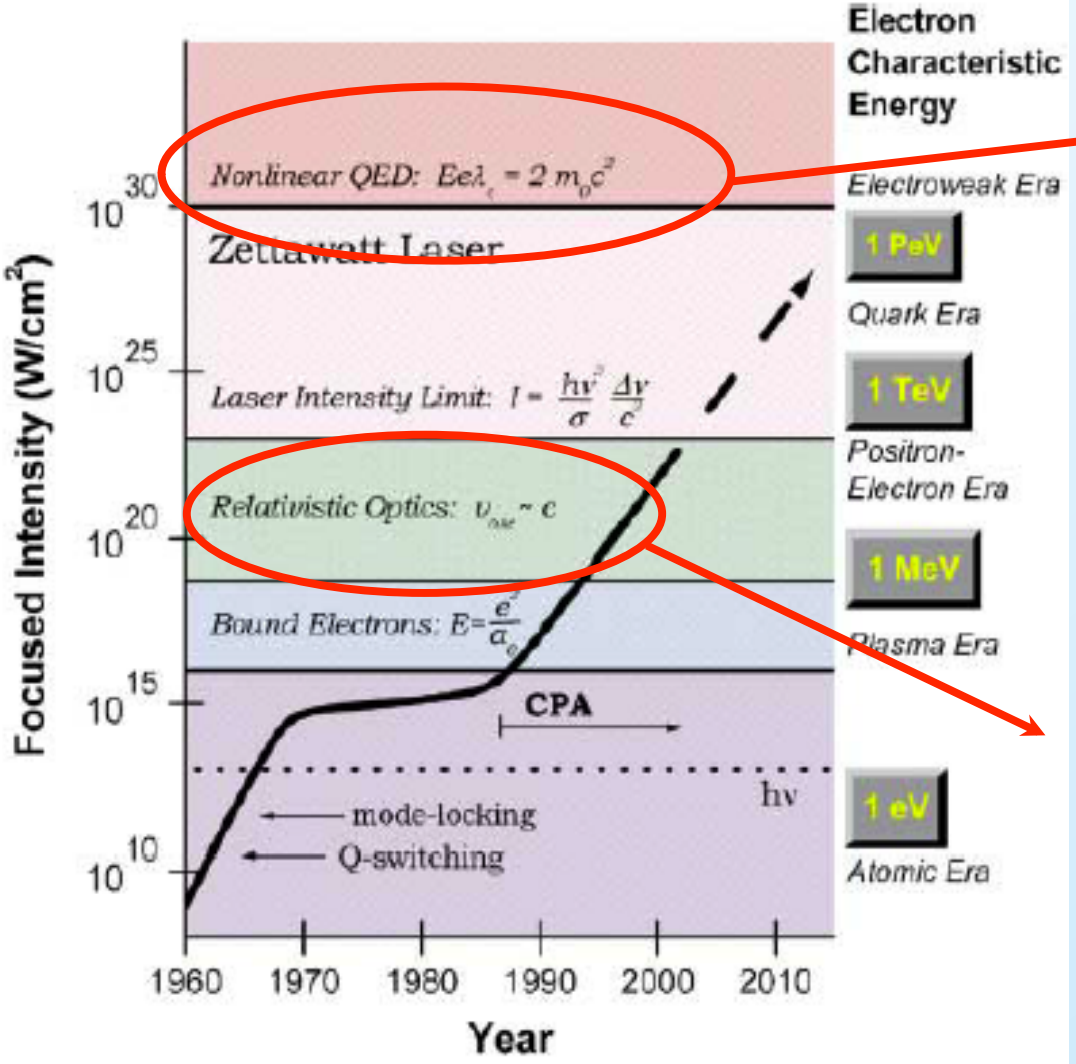
BELLA laser will provide access to ultra-relativistic physics



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

Intensity Frontier: reaching non-linear QED

- Schwinger critical field: $E_{crit}=1.3\times10^{18}$ V/m
  - Requires $>2\times10^{29}$ W/cm^2 with laser…
- Lorentz boost: scatter on 1-10 GeV beam
  - Requires $>6\times10^{20}$ - 6×10^{22} W/cm^2
  - Doable with 0.2 - 1 PW laser !
- Scattering intense laser off laser accelerated GeV e-beam opens ultra-relativistic intensity regime
  - Vacuum breakdown
  - Intense positron production via e-beam/laser scattering
- What can we learn from this?

Conclusion

- Laser-plasma accelerators have produced GeV beams (~% $\Delta E/E$)
  - Key LBNL technology: guiding structures and controlled injection
  - Could potentially be used for DUSEL Cerenkov calibration work (R. Kadel et al.)
- Demonstration experiments underway at LOASIS:
  - Beam control, plasma structure control for improved beam quality – foundation for LPAs
  - LPA driven FEL at 30 nm – foundation for novel light source
  - Staging technology – foundation for a collider
- BELLA: will allow 10 GeV module development
  - Detector calibration – need to develop diagnostics for measuring 10 GeV beam
  - Positron production
  - X-FEL
  - Non-linear QED, muon production

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- TechX-Corp: J. Cary, D. Bruhwiler, et al.
- SciDAC team
- Oxford Univ.: S. Hooker et al.
- MPQ: F. Krausz, F. Gruener et al.
- LOA: O. Albert, L. Canova
- GSI: T. Stoehlker, D. Thorn

Collider power and efficiency requirements: ~ 400 kW average power laser

- Beam power: $P_b = fNE_{cm}$

$$\left.\begin{array}{l} N \sim 3\text{x}10^9 \\ f \sim 15\ \text{kHz} \\ E_{cm} \sim 1\ \text{TeV} \end{array}\right\} \quad P_b \sim 4\ \text{MW}$$

- AC wall-plug power: ~ 200 MW ➔ 2% efficiency

- Laser to plasma wave efficiency: ~50%
- Plasma wave to beam efficiency: ~20%

➔ ~10% laser to beam efficiency
➔ ~20% wall-plug to laser efficiency

- Collider based on 10-GeV stages:
  - (total beam energy ~240 J)/(50 stages) = ~4 J/stage
  - ~40 J/laser at 10 kHz = ~400 kW average power laser

beyond state-of-the-art laser technology

➔ Laser technology development required

- Task force for roadmap on laser technology:
  - Proposed as core activity of ICUIL with ICFA panel as partner
  - Workshop planning underway for April 2010
    - Invite international panel of experts on laser and accelerator technology
    - Develop science and technology strategies towards multi-kW lasers for light sources, colliders

ICUIL = International Committee for Ultra-Intense Lasers
ICFA = International Committee for Future Accelerators