Limits and Possibilities of Laser Plasma Accelerators

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News & Comment > News > Q&A > 2015 > December > Article

NATURE | NEWS: Q&A

CERN's next director-general on the LHC and her hopes for international particle physics

Fabiola Gianotti talks to *Nature* ahead of taking the helm at Europe's particle-physics laboratory on 1 January.

Elizabeth Gibney

22 December 2015

Maximilien Brice/CERN

Fabiola Gianotti is the incoming director-general of CERN.

Some people think that future governments will be unwilling to fund larger and more expensive facilities. Do you think a collider bigger than the LHC will ever be built? And will it depend on the LHC finding something new?

The outstanding questions in physics are important and complex and difficult, and they require the deployment of all the approaches the discipline has developed, from high-energy colliders to precision experiments and cosmic surveys. High-energy accelerators have been our most powerful tools of exploration in particle physics, so we cannot abandon them. What we have to do is push the research and development in accelerator technology, so that we will be able to reach higher energy with compact accelerators.

The U.S. Particle Physics Project Prioritization Panel (P5) provided strong support for accelerator R&D

Recommendation 26: Pursue accelerator R&D with high priority at levels consistent with budget constraints. Align the present R&D program with the P5 priorities and long-term vision, with an appropriate balance among general R&D, directed R&D, and accelerator test facilities and among short-, medium-, and long- term efforts. Focus on outcomes and capabilities that will dramatically improve cost effectiveness for mid-term and far-term accelerators.

Recommendation 10. Convene the university and laboratory proponents of advanced acceleration concepts to develop R&D roadmaps with a series of milestones and common down-selection criteria towards the goal of constructing a multi-TeV e+e- collider.

The U.S. Particle Physics Project Prioritization Panel (P5) provided strong support for accelerator R&D

Building for Discovery
Strategic Plan for U.S. Particle Physics in the Global Context

Recommendation 26: Pursue accelerator R&D with high priority at levels consistent with budget constraints. Align the present R&D program with the P5 priorities

Workshop on Concepts for Future Plasma Based Colliders
Lawrence Berkeley National Laboratory, Jan. 6-8, 2016

Laser-plasma collider requirements to guide R&D roadmap

Charge for M. Peskin: Identify colliders parameters that are interesting for particle physics – including lower energy “entry” machines

> The goals of particle physics have been shaped by the 2012 discovery of the Higgs boson.
>
> The particle content of the Standard Model is now complete. Tests of this model — especially, of the electroweak sector at high energy — will continue at the LHC.
>
> To believe that the next accelerator is worth building, we must believe that there are new interactions of physics beyond the SM that this accelerator will make accessible.

Performance Goals for a Future Linear Collider (M. E. Peskin)

- Multi-TeV (~1-3 TeV) desired for beyond SM exploration
- Acceleration mechanism must produce high *average* gradient for compact linacs: >1 GV/m (average or geometric) implies <1 km/TeV

Laser-plasma collider requirements to guide R&D roadmap

> Luminosity is at a premium when we go above 1 TeV.
>
> Beam polarization is not a luxury. It is an important diagnostic, and it has a qualitative effect on rates.

(M. E. Peskin)

- Achieve high luminosity: $\mathcal{L} \propto \mathcal{E}_{\mathrm{cm}}^2$
- Accelerator must be compatible with reasonable (wall-plug) power: high-efficiency, small emittance, high charge/bunch

$$P_{\mathrm{wall}} \propto \eta^{-1} P_{\mathrm{beam}} = \eta^{-1} \frac{4\pi\sigma_*^2}{N} \mathcal{L}\mathcal{E}_{\mathrm{cm}}$$

- Acceleration of *polarized* electron and positron beams

> e-e- seems best applied as a basis for a γγ collider.

(M. E. Peskin)

- A γγ collider requires a high-efficiency, high-average power laser system for Compton scattering. At TeV energy, optical wavelengths are required (1-2 micron); same laser system used to drive the LPAs could be employed as Compton source.

Laser-plasma collider requirements to guide R&D roadmap

Performance Goals for a Future Linear Collider (M. E. Peskin)

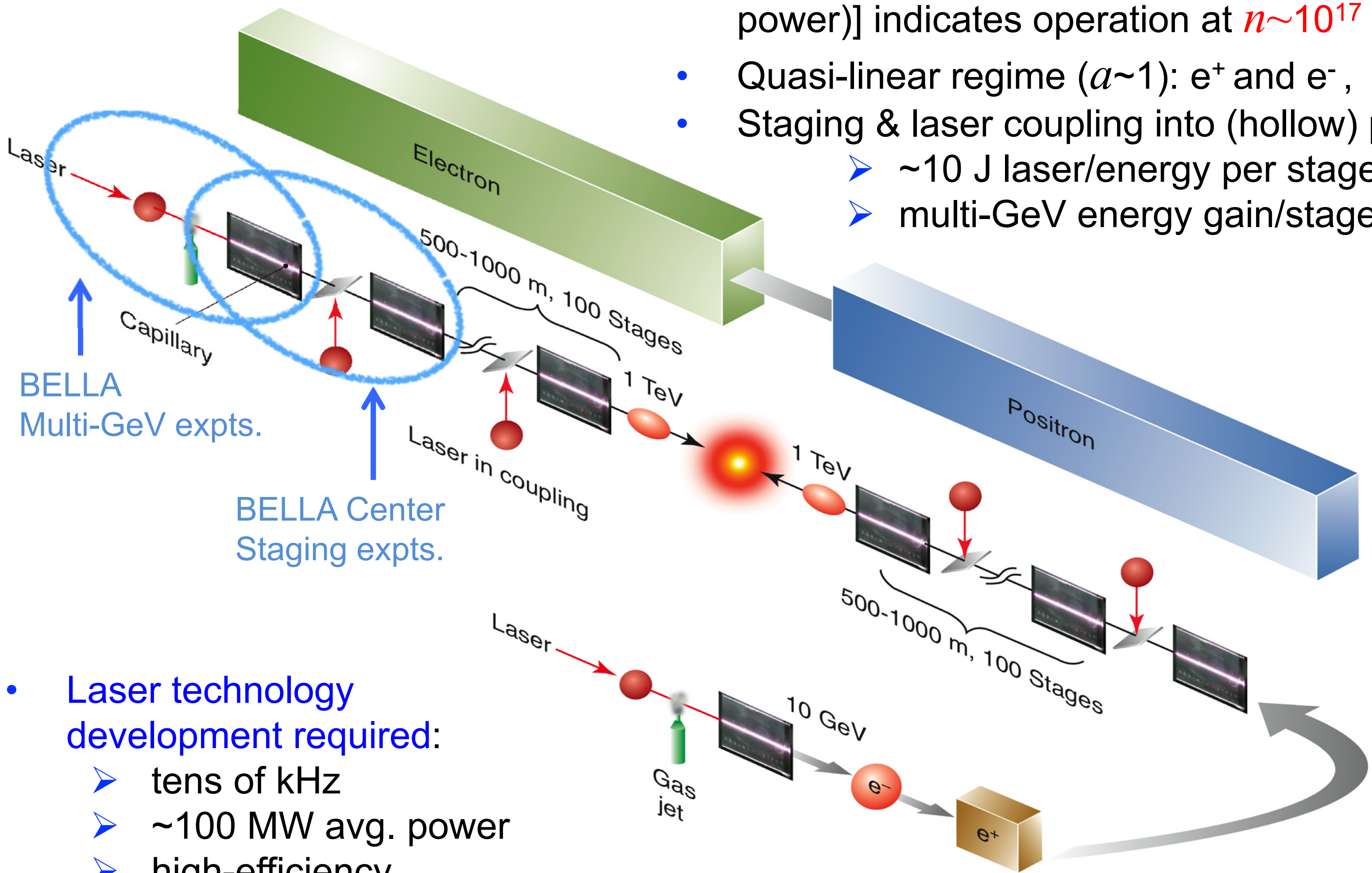
> The era is in view where new accelerator technologies must take over from the current ones.
>
> This makes it very important to take the first steps toward practical plasma accelerators, proving their robustness for few-GeV electron accelerator applications such as FELs.
>
> This is only the beginning of a long road, but that road leads to the future of particle physics.

- Development of near-term (non-HEP) LPA applications (FEL, medical, radiation sources, etc.) are important part of collider roadmap

Laser-plasma accelerator (LPA) linear collider concept

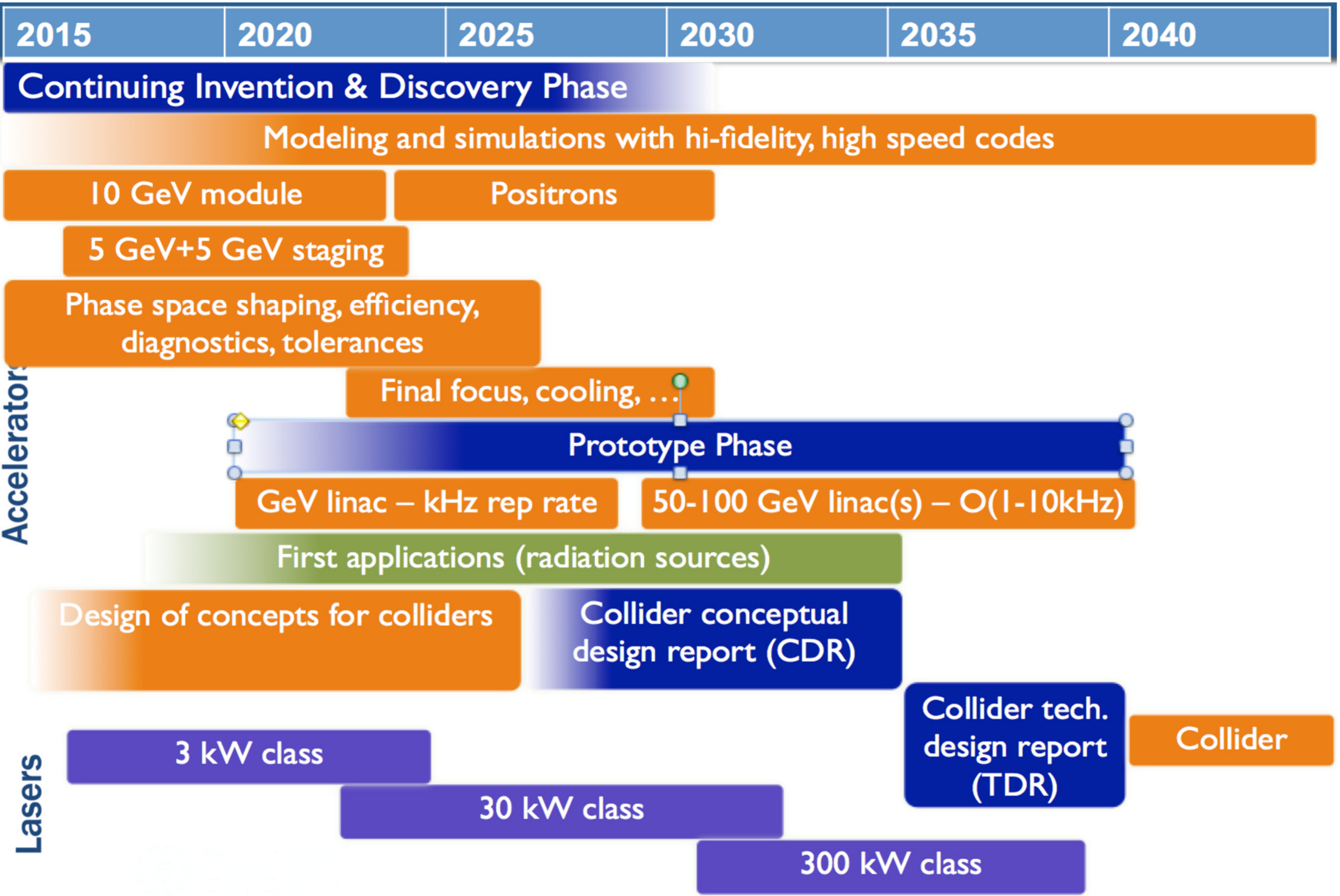
Leemans & Esarey, Phys Today (2009)

- Plasma density scalings [minimize construction (max. average gradient)] and operational cost (min. wall power)] indicates operation at $n\sim10^{17}$ cm^{-3}
- Quasi-linear regime (a~1): e$^+$ and e$^-$, focusing control
- Staging & laser coupling into (hollow) plasma channels
  - ~10 J laser/energy per stage
  - multi-GeV energy gain/stage



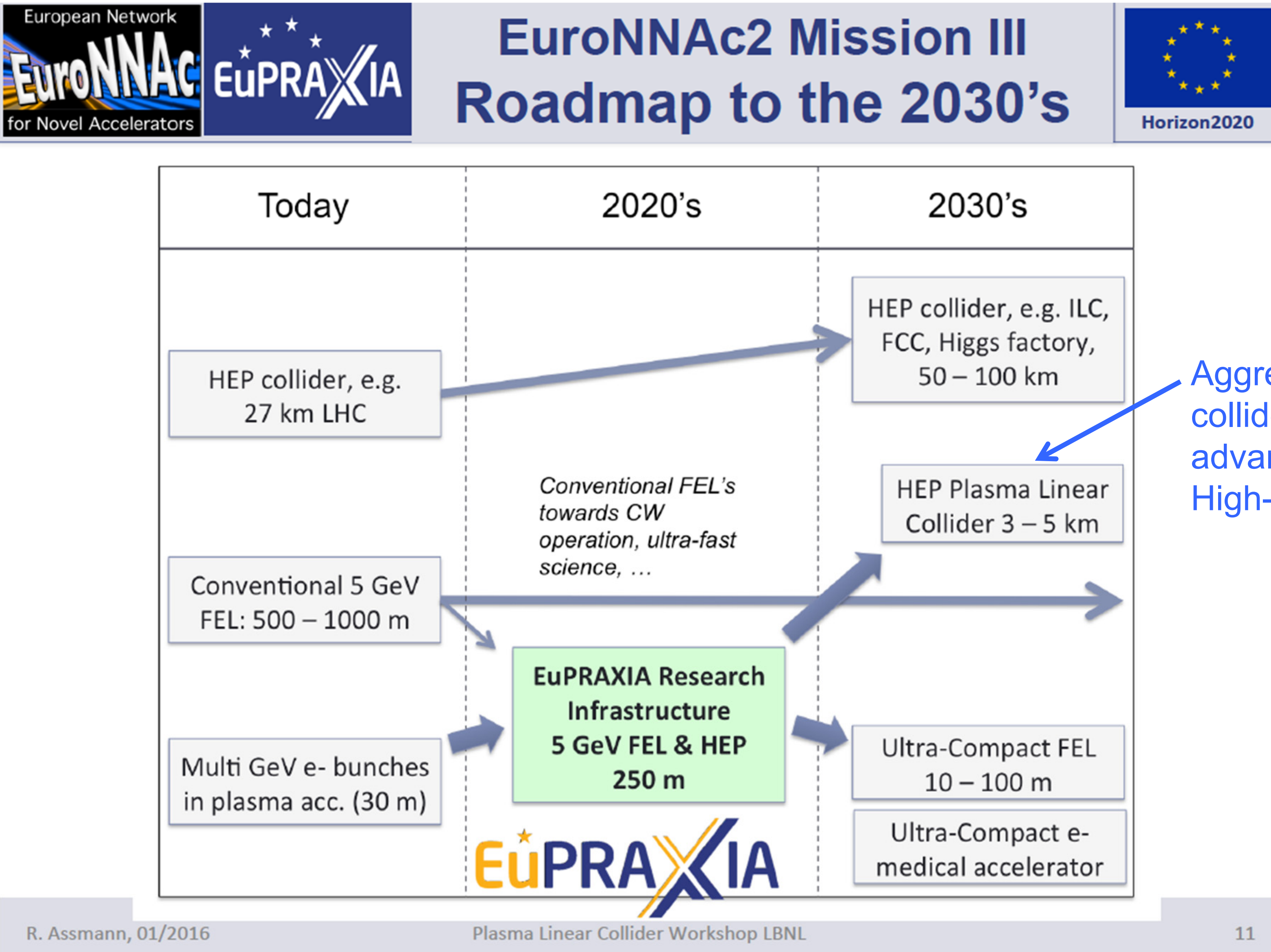
- Laser technology development required:
  - tens of kHz
  - ~100 MW avg. power
  - high-efficiency

A community roadmap for plasma based concepts for future plasma based collider is being developed



Nominal European roadmap was presented

Report from Europe Ralph Assmann (DESY)



Aggressive ~2035 collider target to take advantage of end of High-Lumi LHC

Report from Europe: organization of R&D efforts

Report from Europe Ralph Assmann (DESY)

European Network EuroNNAc for Novel Accelerators | EuPRAXIA

Plasma Acc. R&D in Europe

Horizon2020

National novel accelerator projects with European network

Independent national projects*, funded by national states. About 16 major facilities for novel plasma acceleration R&D.

Funded by EU FP7 through EuCARD2

European Network EuroNNAc for Novel Accelerators

European novel accelerator projects with international involvement

AWAKE

CERN experiment collaboration under leadership of MPI

** See note on ELI*

EuPRAXIA

Funded by EU Horizon2020 as EU Design Study feature article

Laser-driven plasma-wave electron accelerators

Wim Leemans and Eric Esarey

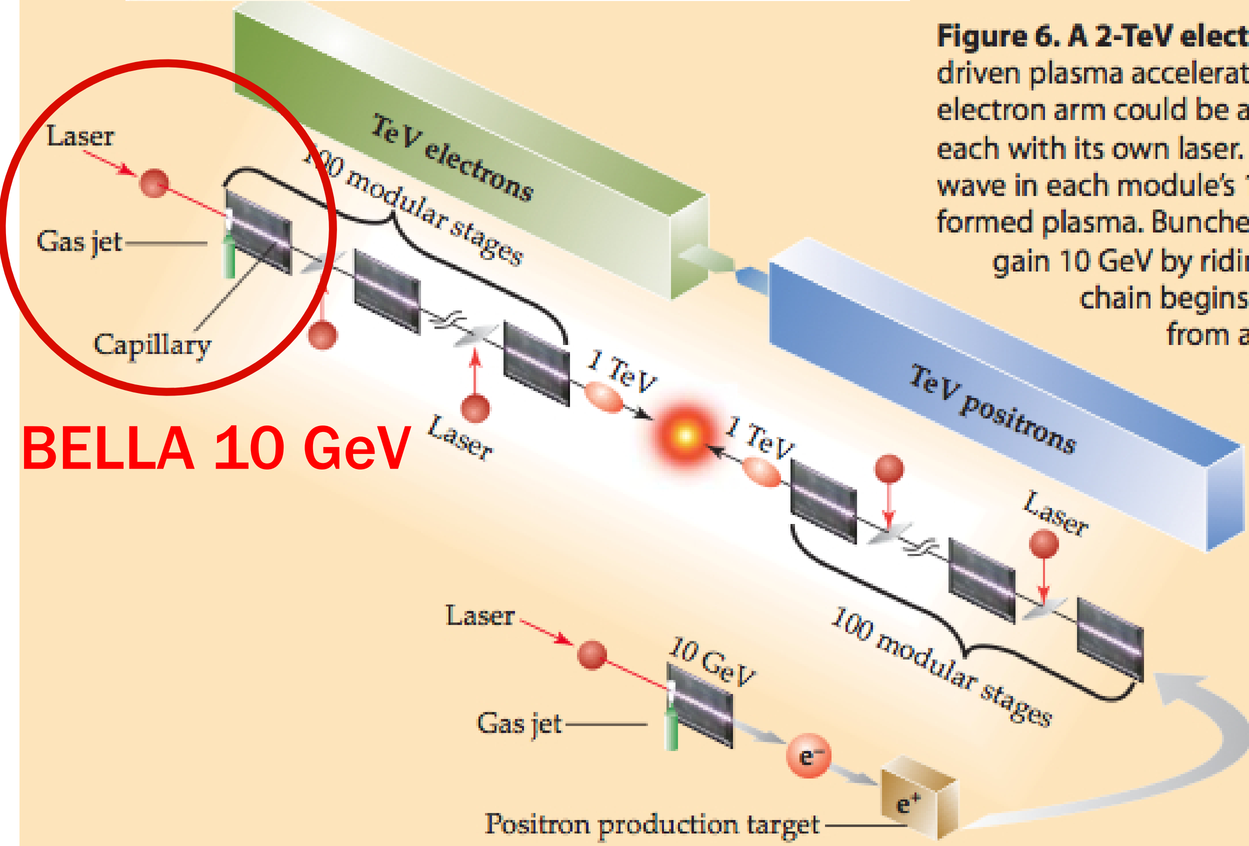


Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

March 2009 Physics Today

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 13, 101301 (2010)

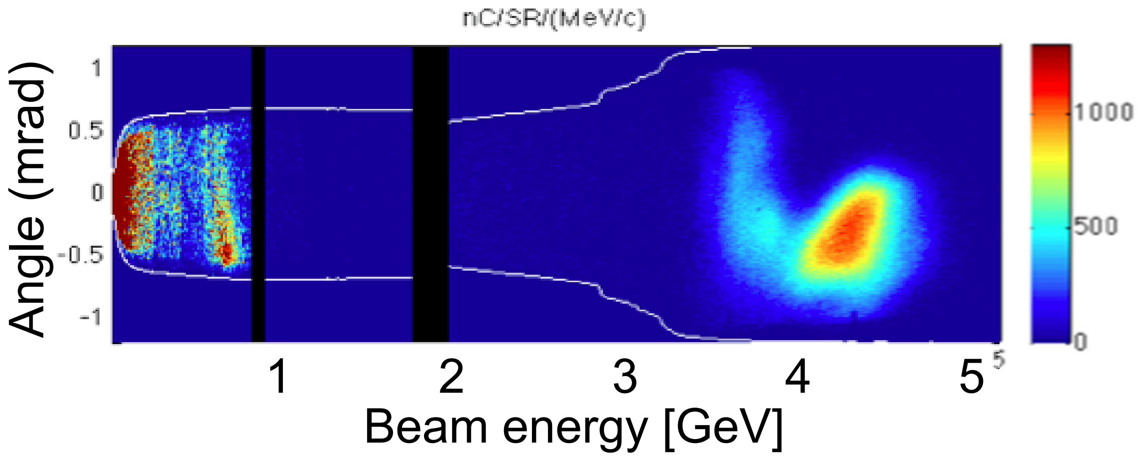
Physics considerations for laser-plasma linear colliders

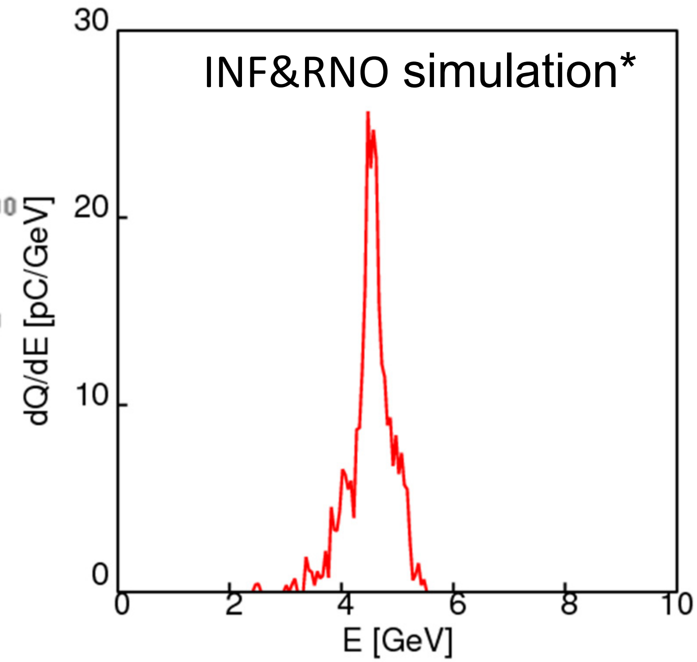
C. B. Schroeder, E. Esarey, C. G. R. Geddes, C. Benedetti, and W. P. Leemans
Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
(Received 11 June 2010; published 4 October 2010)

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

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

Electron beam spectrum



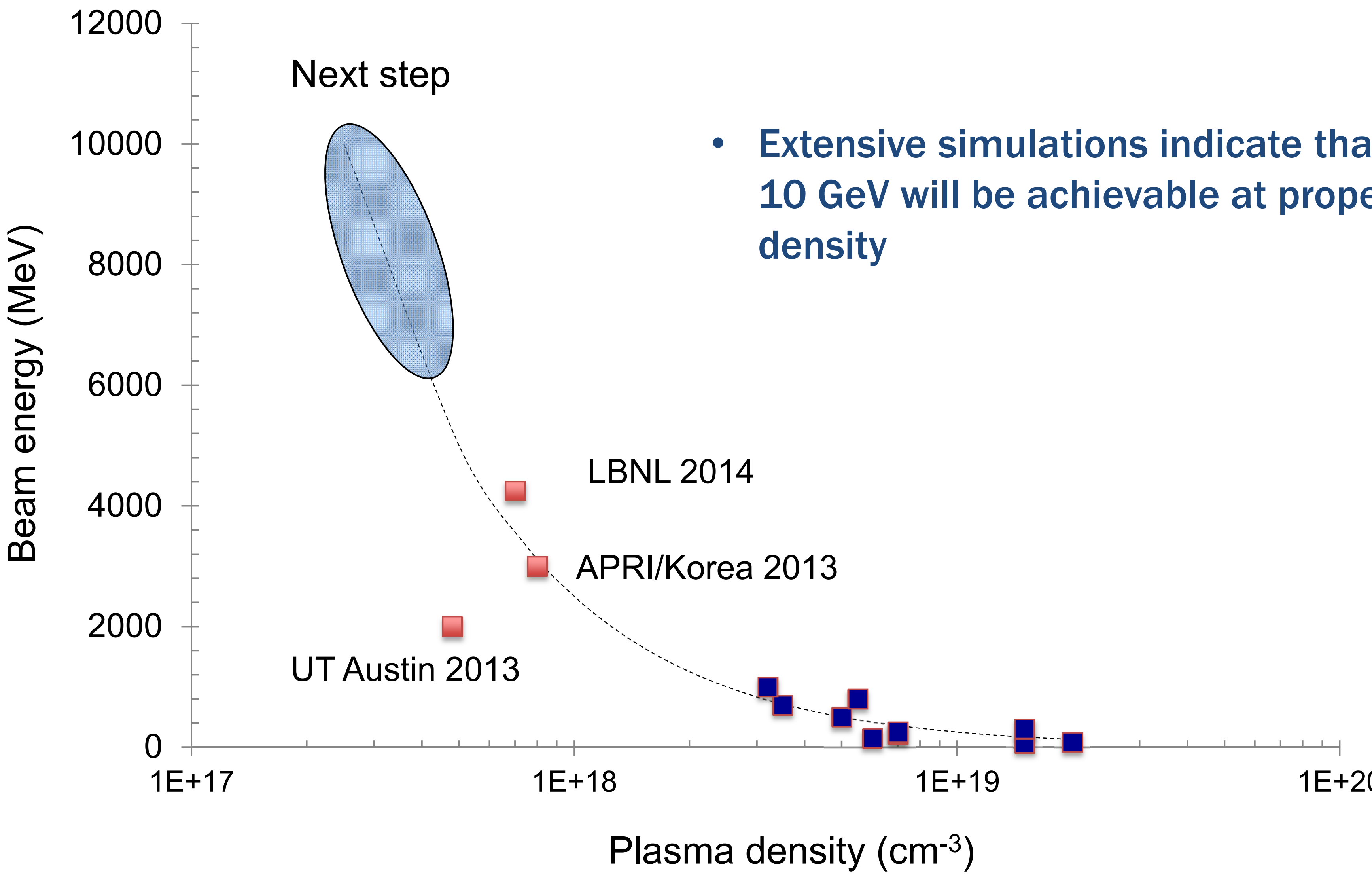


- **Laser** (E=15 J):
  - Measured) longitudinal profile (T_0= 40 fs)
  - Measured far field mode (w_0=53 μm)
- **Plasma:** parabolic plasma channel (length 9 cm, n_0~6-7x10^{17} cm^{-3})

	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

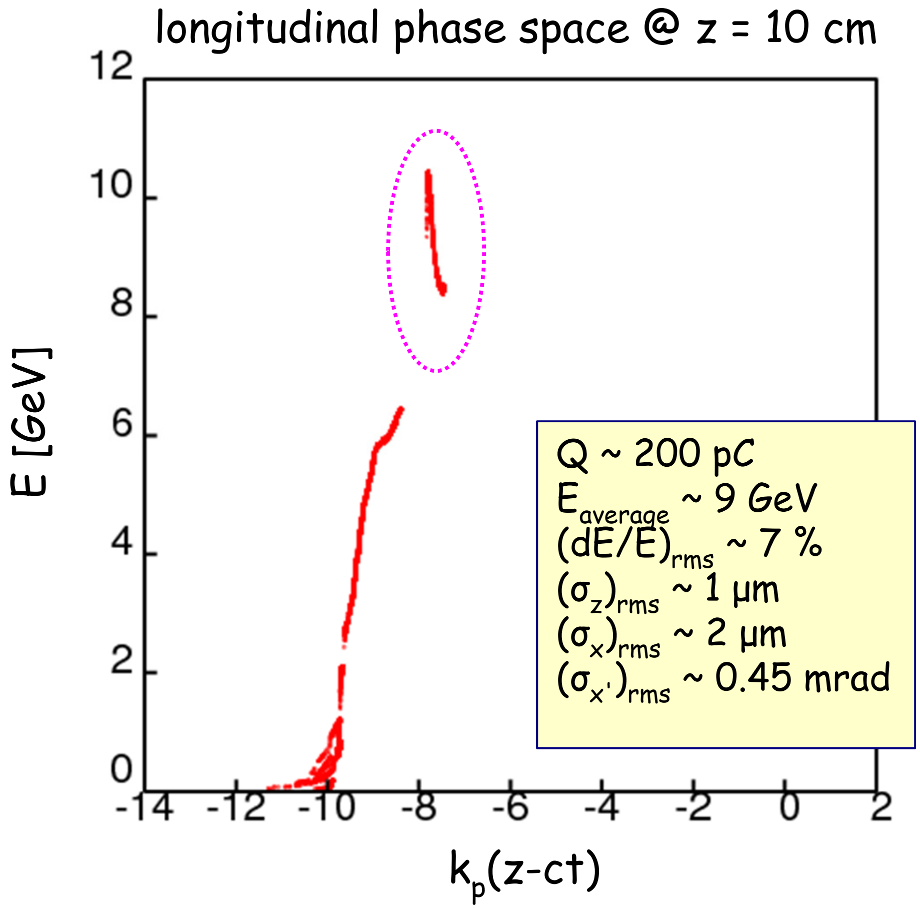
W.P. Leemans et al.,PRL 2014

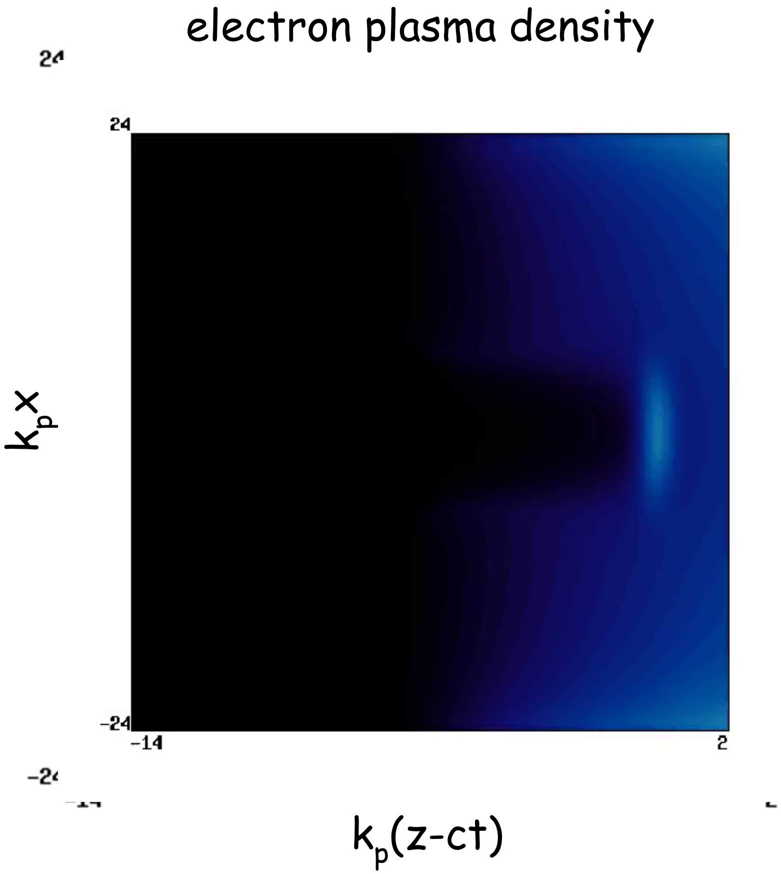
Operating in the Right Plasma Density Regime is Key for 10 GeV BELLA Experiments



- **Extensive simulations indicate that 10 GeV will be achievable at proper density**

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

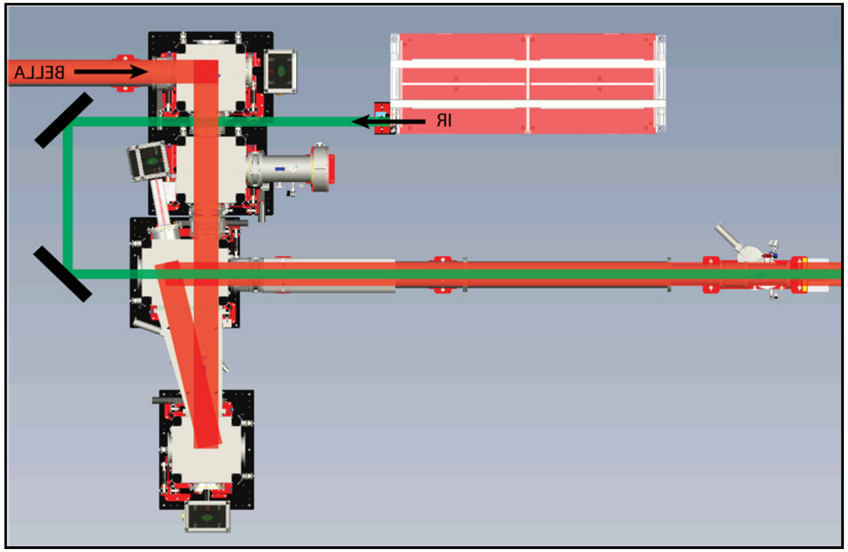




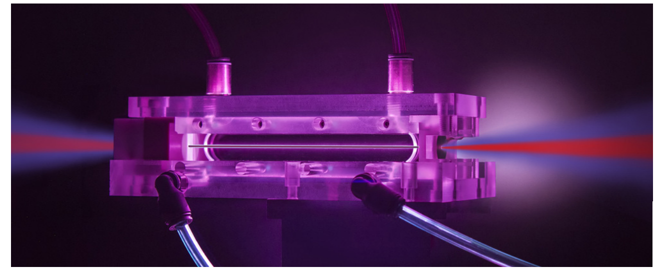
Initial a0~3.5-4.0
Plasma density ~ 3 x 10^{17} cm^{-3}

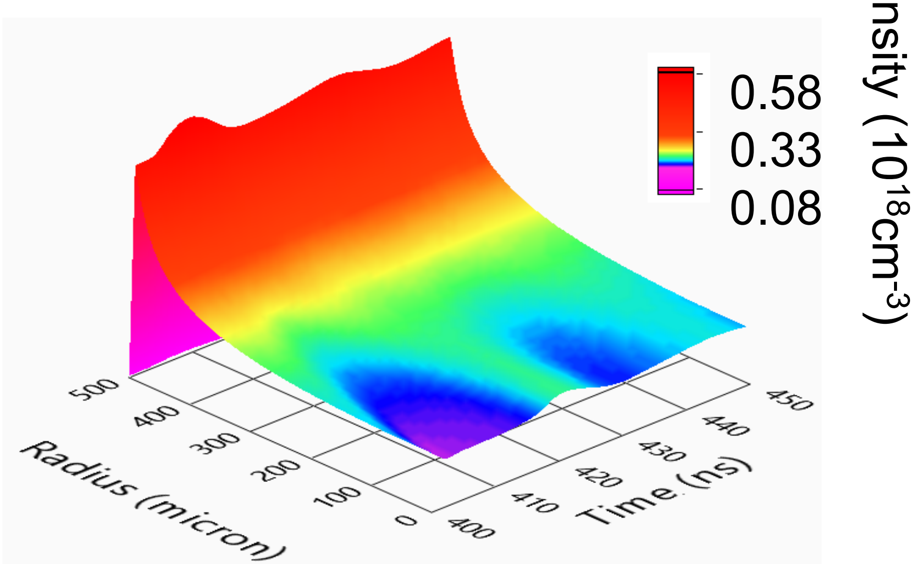
Laser heater required to deepen channel

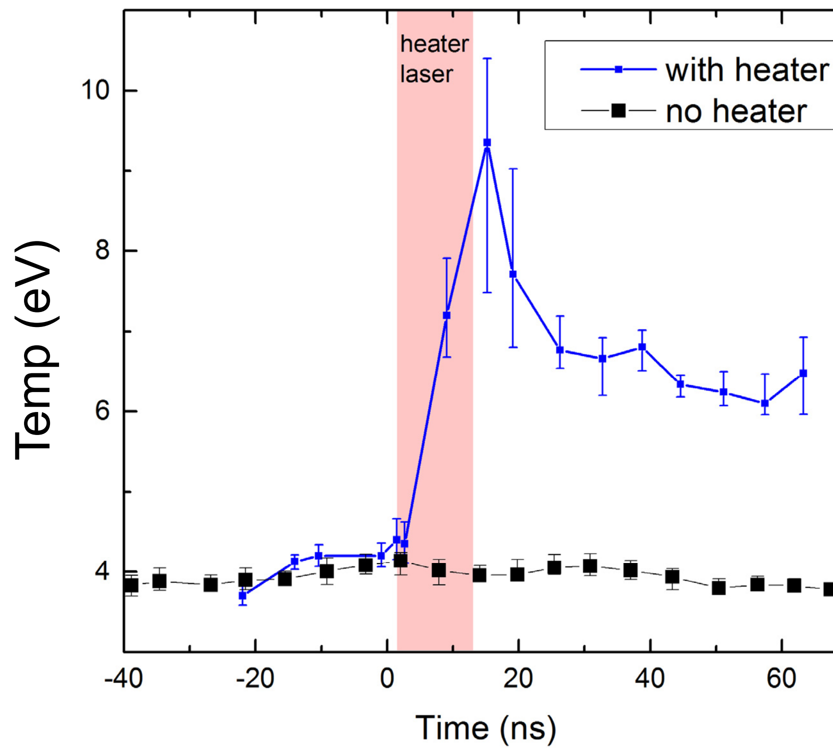
ns-scale Heater Pulse helps Shape Plasma; Near-term Implementation on BELLA Underway



Ph.D. thesis J. Daniels





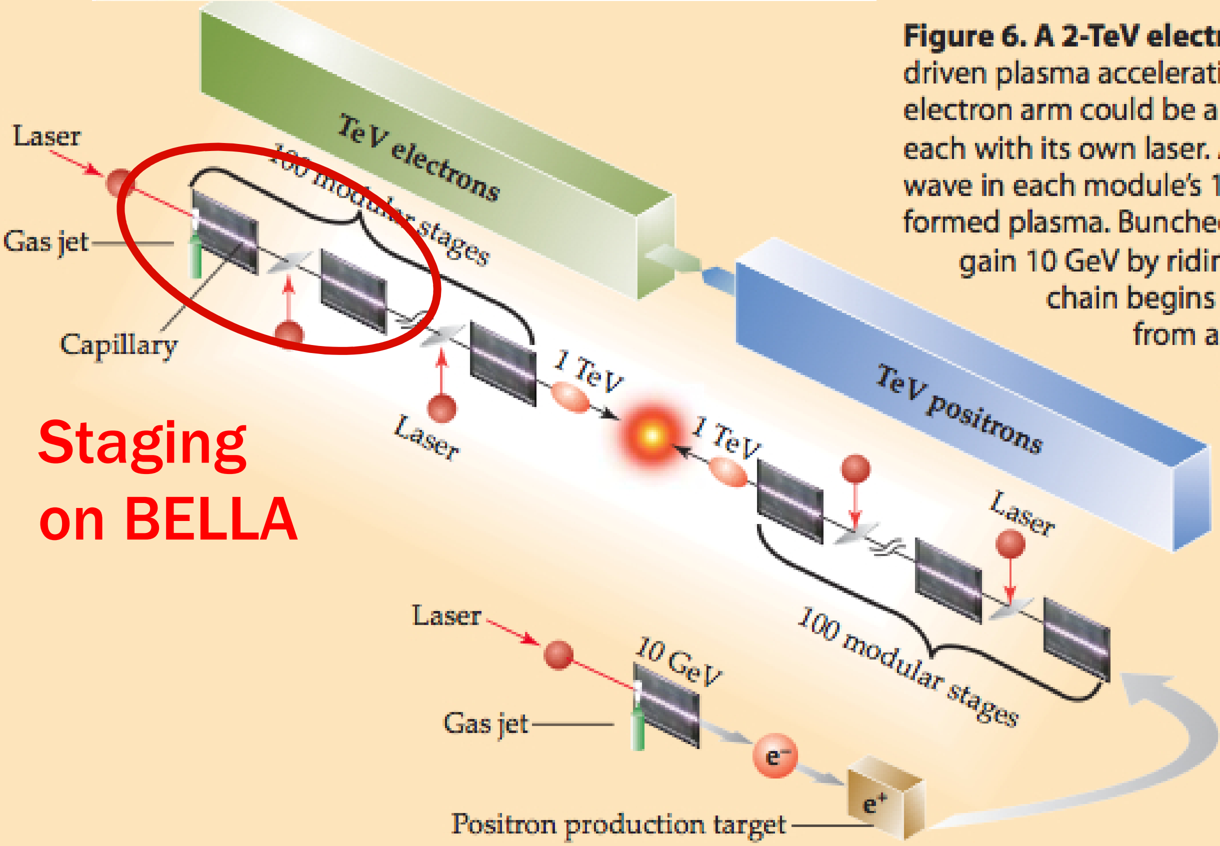


N.A. Bobrova, P.V. Sasorov, C. Benedetti, S.S. Bulanov, C.G.R. Geddes, C.B. Schroeder, E. Esarey and W.P. Leemans, "Laser-heater assisted plasma channel formation in capillary discharge waveguides", Phys. Plasmas 20, 020703 (2013).

feature article

Laser-driven plasma-wave electron accelerators

Wim Leemans and Eric Esarey



Staging on BELLA

Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

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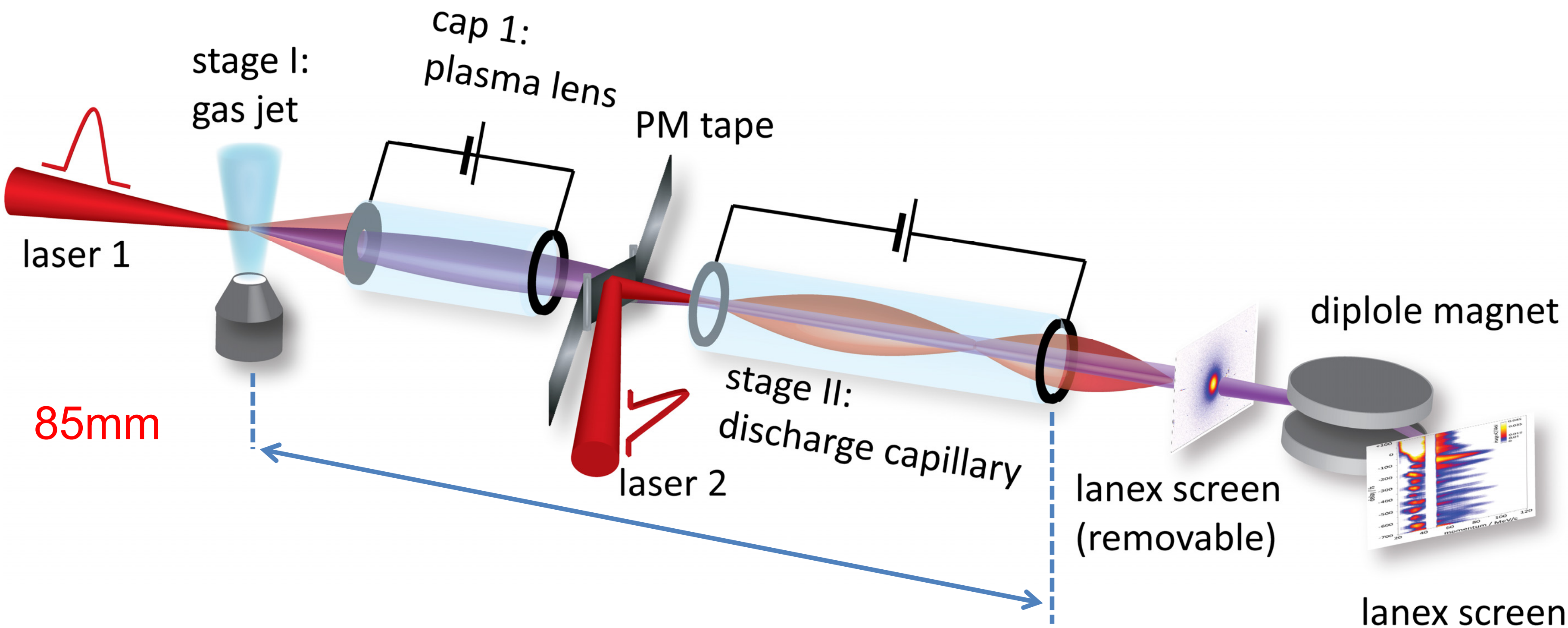
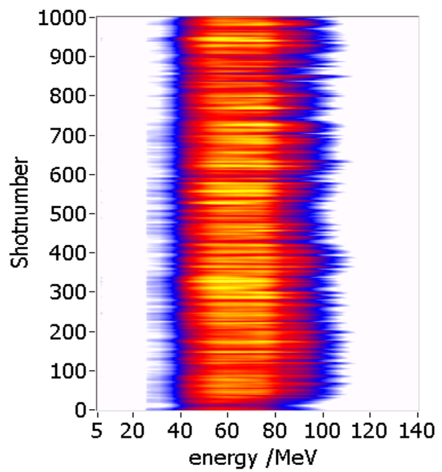
BERKELEY LAB

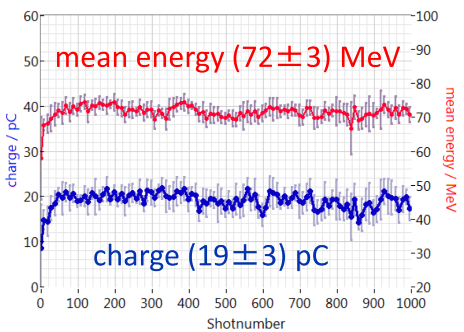
We have succesfully achieved acceleration in a second independently powered laser plasma accelerator



We have succesfully achieved acceleration in a second independently powered laser plasma accelerator

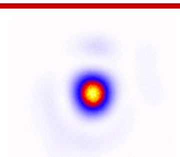
Stage I: gas jet

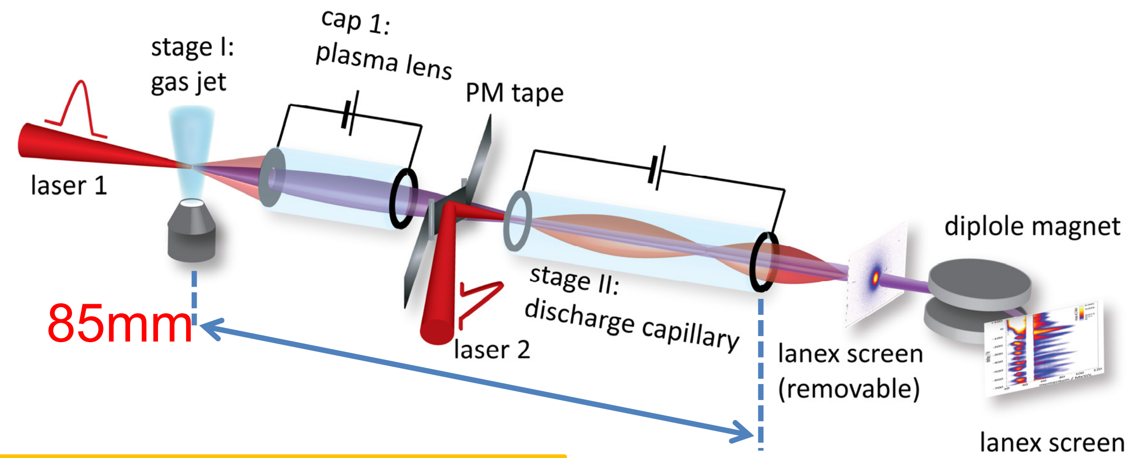




Steinke *et al.*, Nature 2016

PM





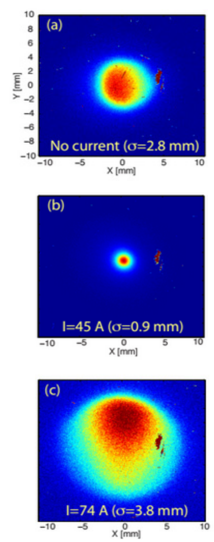
Active plasma lens

1.5 cm, up to 3,000 T/m

I = 0 A

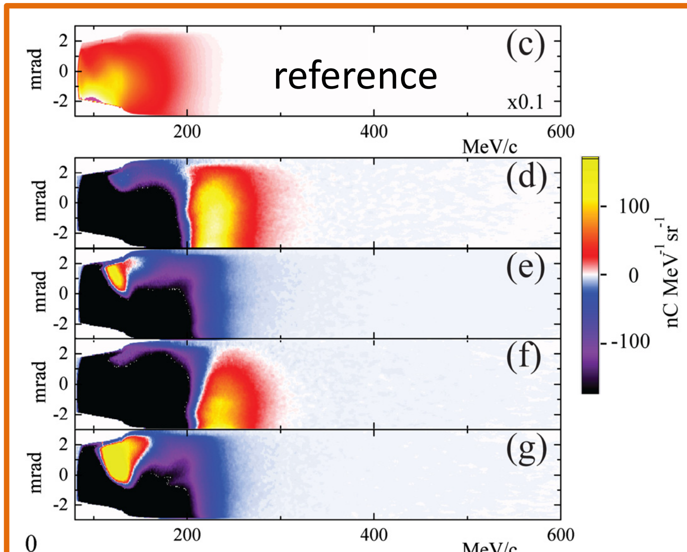
I = 45 A

I = 74 A



van Tilborg *et al.*, PRL 2015

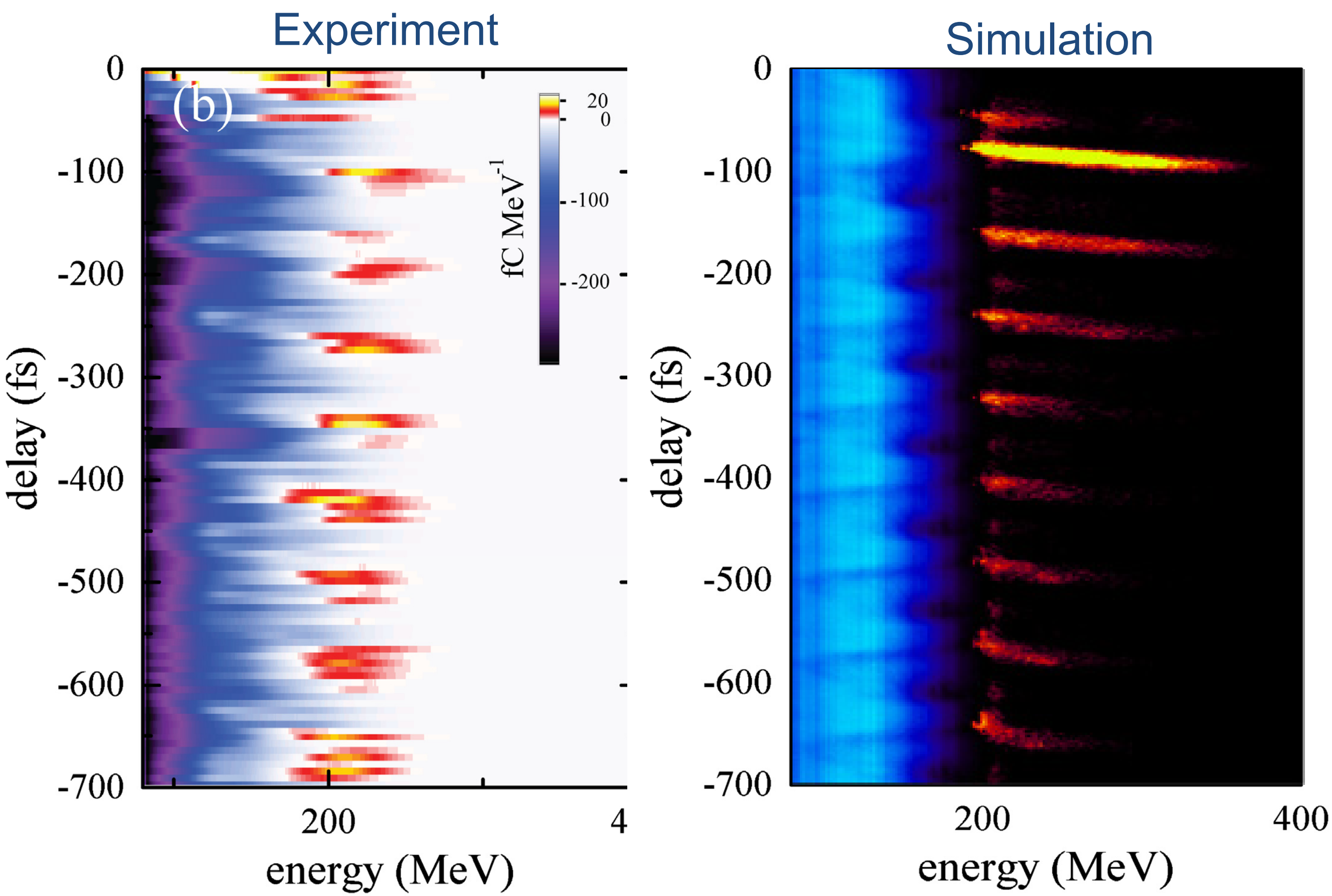
Stage I + II



Steinke *et al.*, Nature 2016

Simulations reproduce staging signatures at correct magnitude

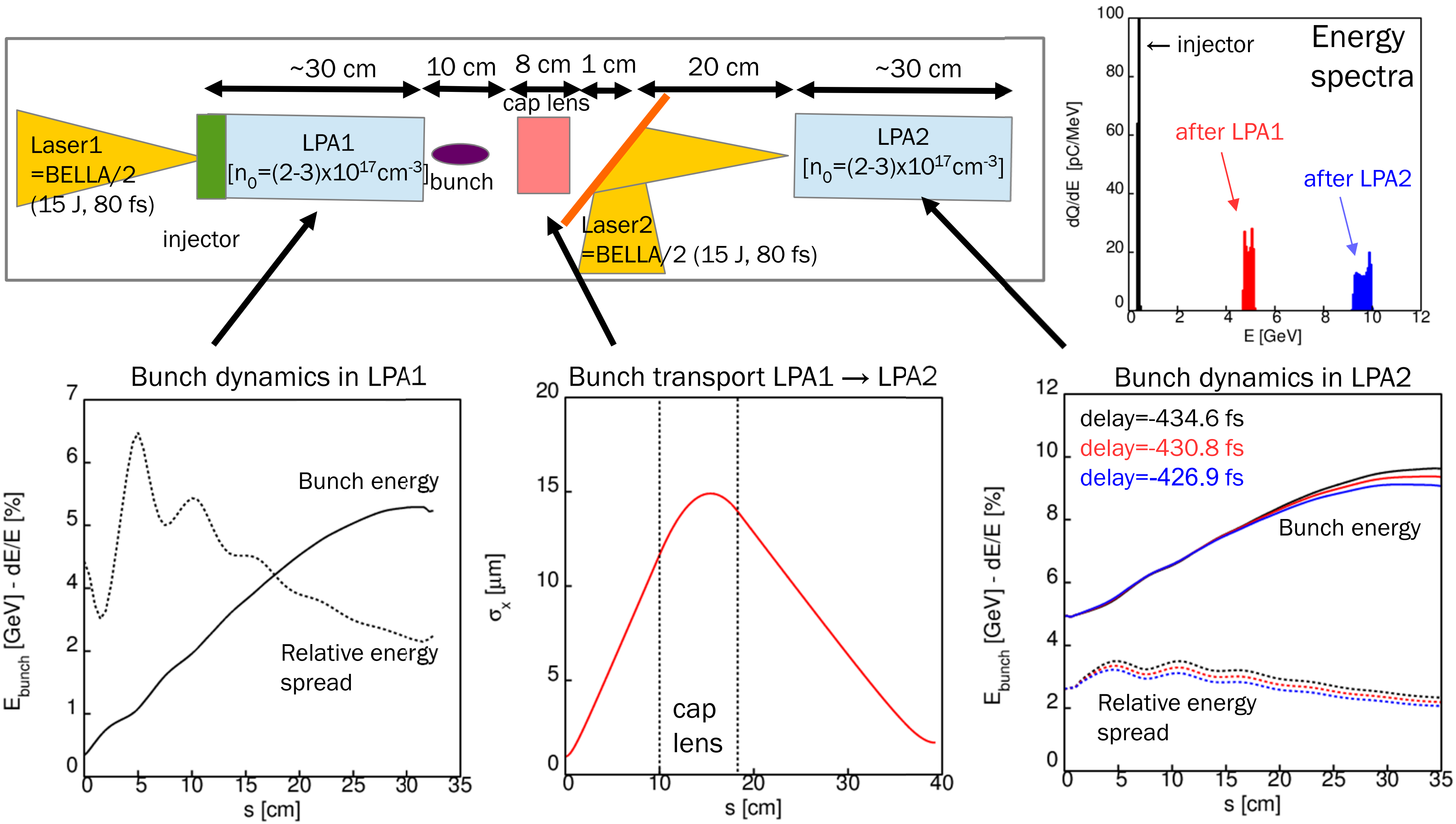
- Timing scans reveal multiple accelerating buckets



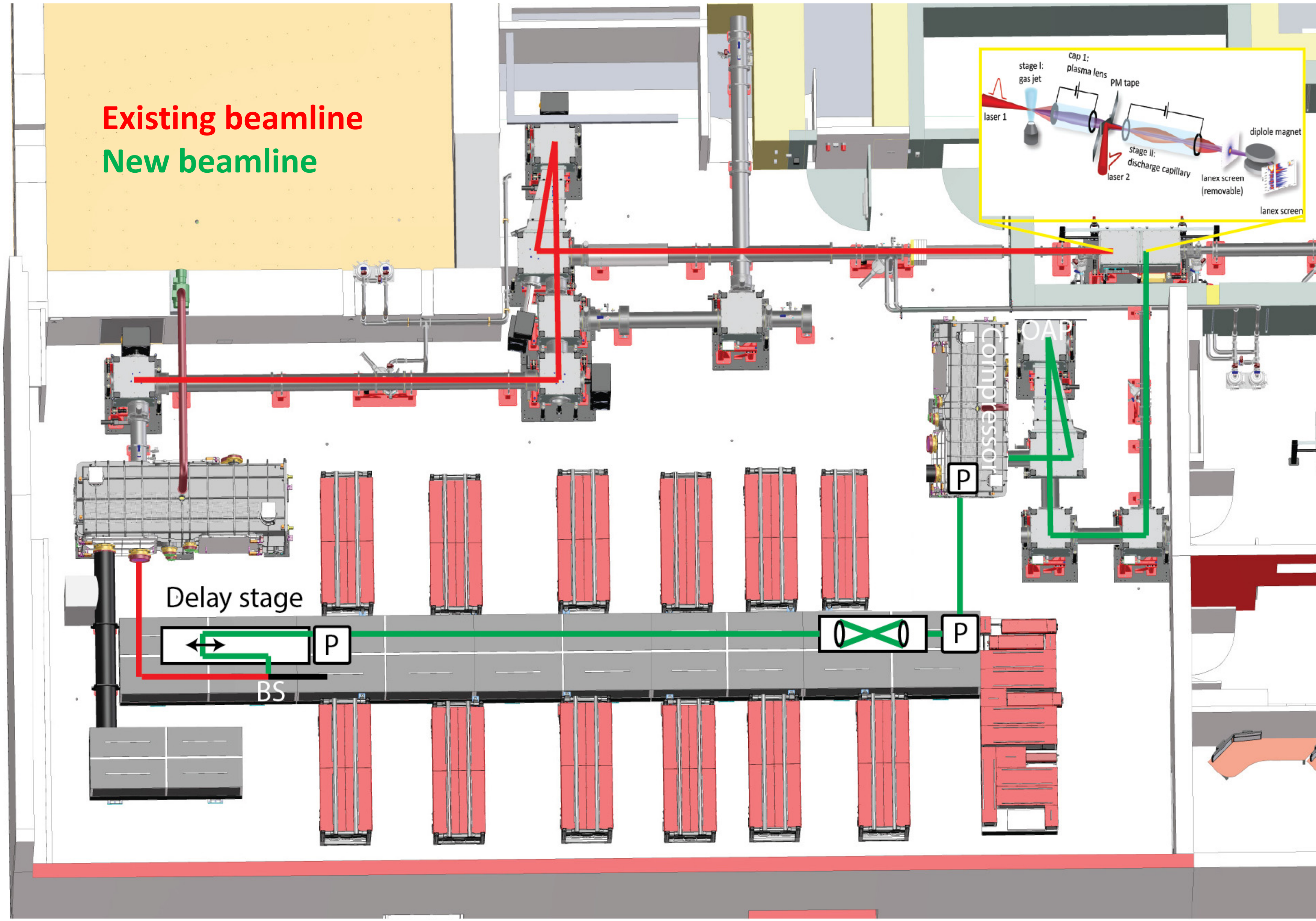
INFERNO simulation by C. Benedetti

- Further improvements underway to improve capture fraction
- Planning 5 GeV boost on 5 GeV beam using BELLA

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



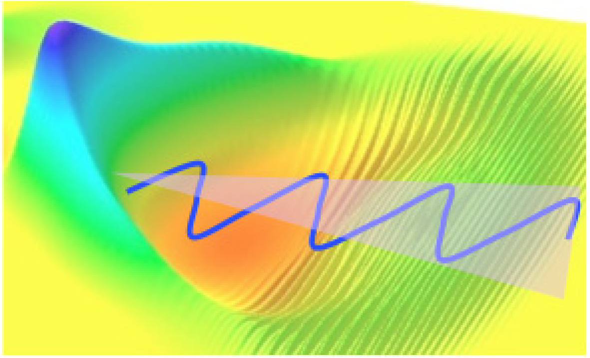
Upgrade BELLA experimental area with second beamline to prototype the first two stages of an LPA based collider at 5 GeV + 5 GeV



Laser plasma accelerators are also being developed for compact ultrafast radiation sources

Wenz et al., Nature Comm. 2015

keV Betatron radiation

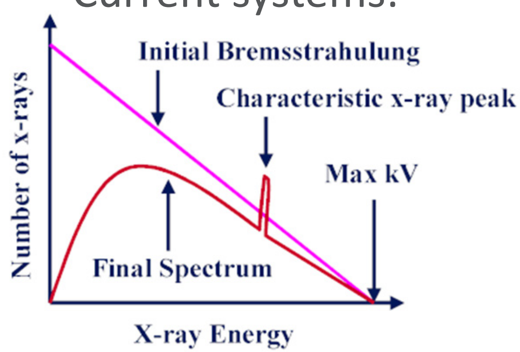


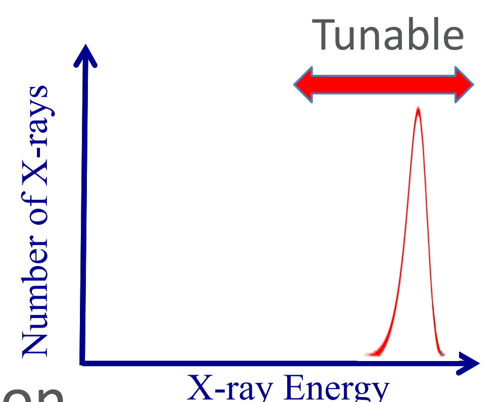
Also ultrafast electron diffraction (U. Michigan and LOA, France)

Example: replacing bremsstrahlung based cargo scanners with compact source

Monoenergetic: reduce dose & noise
Narrow angle beam at ≥kHz: target dose

Current systems:





Next steps:

- Experiments underway including active beam dumps
- kHz high peak power lasers
- Accelerator brightness
- Tunability, stability
- Detectors
- Signal processing
- Detection of SNM

Improve: radiography, photofission, nuclear resonance fluorescence

FEL application: LPA 6D electron beam brightness comparable to conventional sources

Beam brightness: $$B_{6D} = \frac{N}{\epsilon_{nx}\epsilon_{ny}\epsilon_{nz}} \approx \frac{(I/I_A)}{r_e \epsilon_n^2 \sigma_\gamma} = b_6 \lambda_c^{-3}$$

LPA (~cm)

ε_N = 0.1 micron
1 GeV
3% energy spread
I = 3 kA (~10 fs)

$b_6 \sim 10^{-12}$

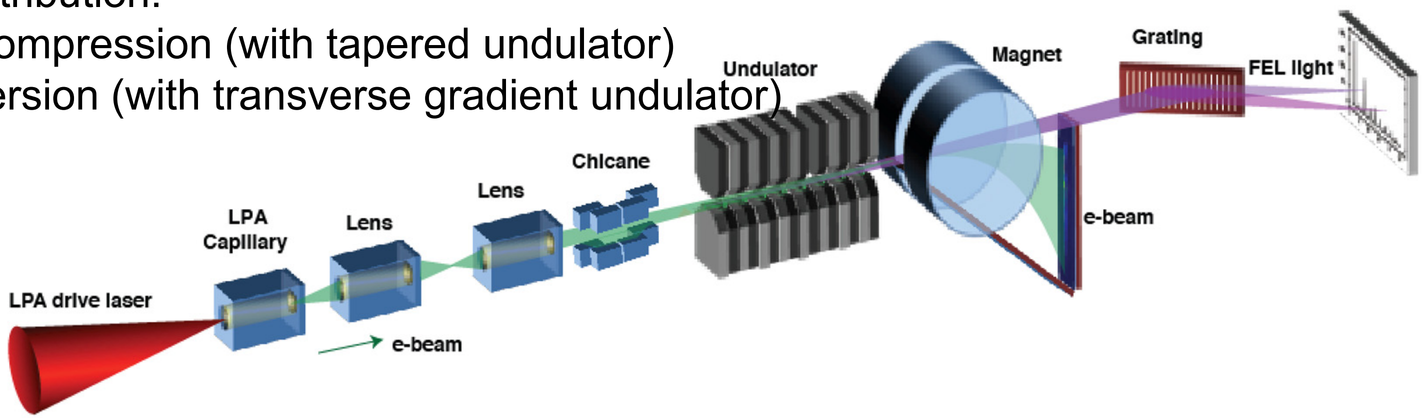
LCLS (~km)

$b_6 \sim 10^{-12}$

ε_N = 0.4 micron
13.6 GeV
0.01% energy spread
I = 3 kA

- FEL application realized with post-LPA e-beam phase-space manipulation (redistribution)
  - Emittance exchange
  - Phase-space redistribution:
    - Longitudinal decompression (with tapered undulator)
    - Transverse dispersion (with transverse gradient undulator)

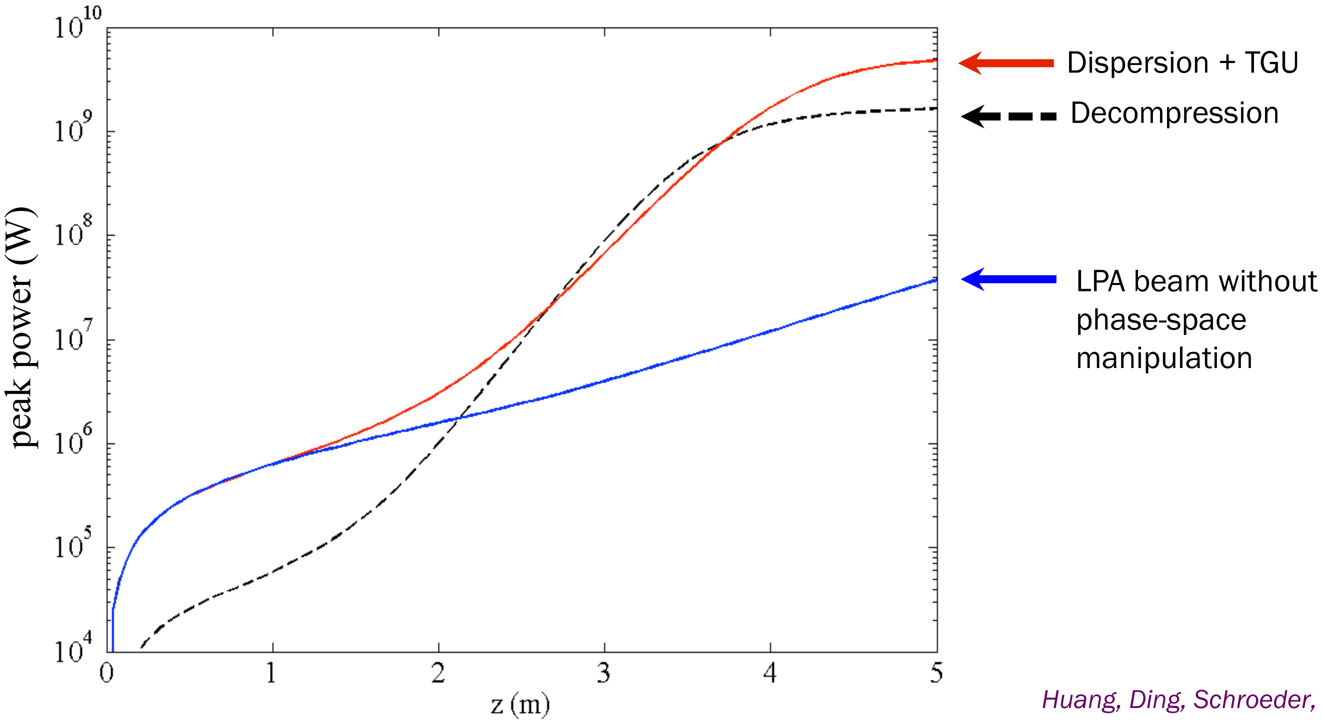
Schroeder et al., FEL Proc (2013)



Compact LPA-driven soft-x-ray FEL using e-beam phase-space manipulation

- 1 GeV, 10 kA, 1% rms energy spread
- 0.1 um emittance; 5 fs (50 pC)
- 5-m (SC) undulator: λ_u = 1 cm, K = 2
- Fundamental wavelength **λ_r = 3.9 nm**

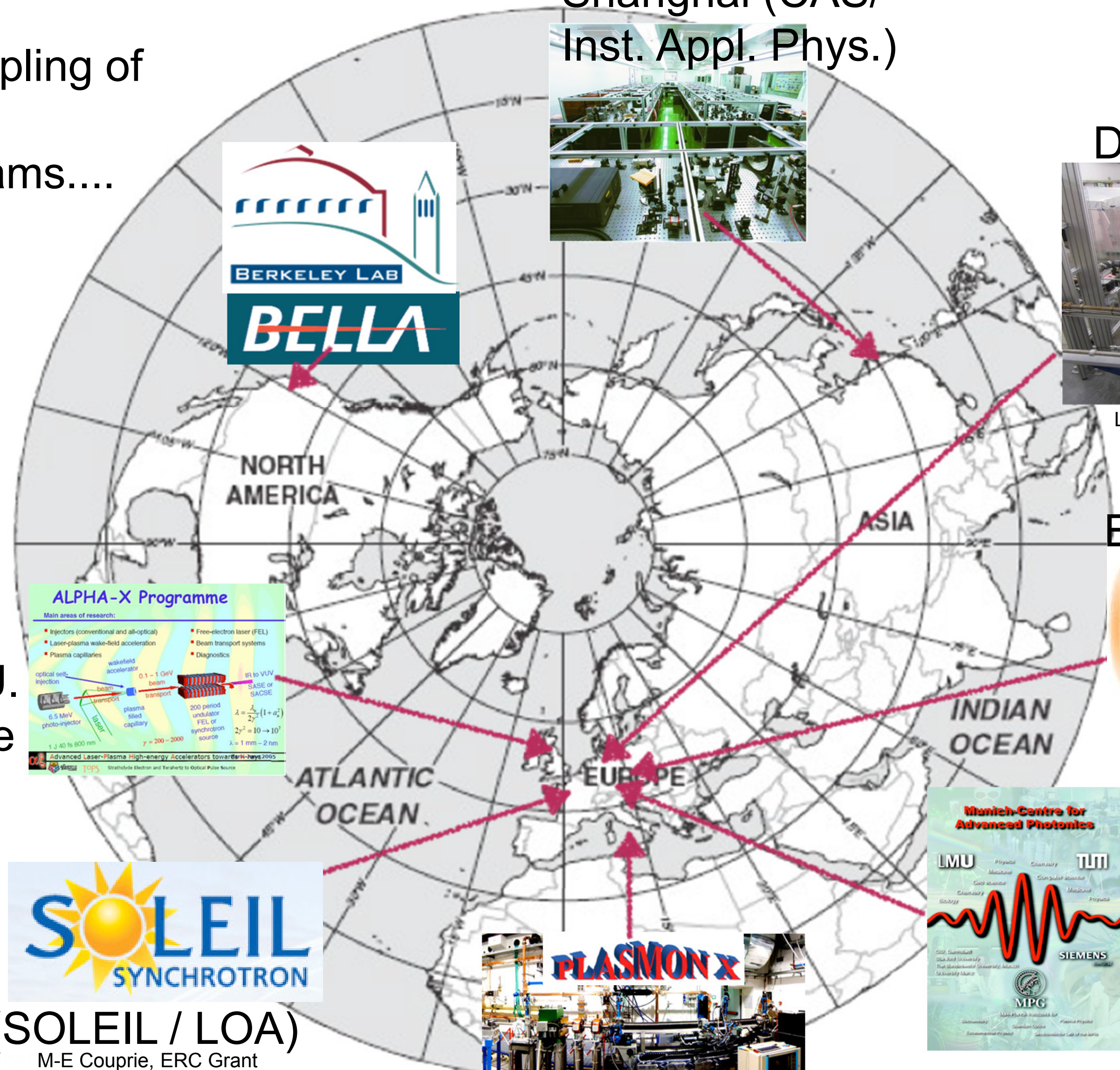
100 TW laser system: ~few J, ~50 fs, ~10^{19} W/cm^2
10 Hz (~kHz available in next few years)



Huang, Ding, Schroeder, PRL (2012)

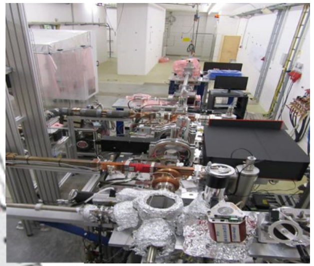
World-wide interest in LPA-driven FEL development

a sampling of active programs....



Shanghai (CAS/ Inst. Appl. Phys.)

DESY / LAOLA



LUX: LPA-driven FEL

ELI - Beamlines

eXtreme light infrastructure

~300M-euro Project (user facility) laser-driven XFEL

Alpha-X: U. Strathclyde

SOLEIL SYNCHROTRON

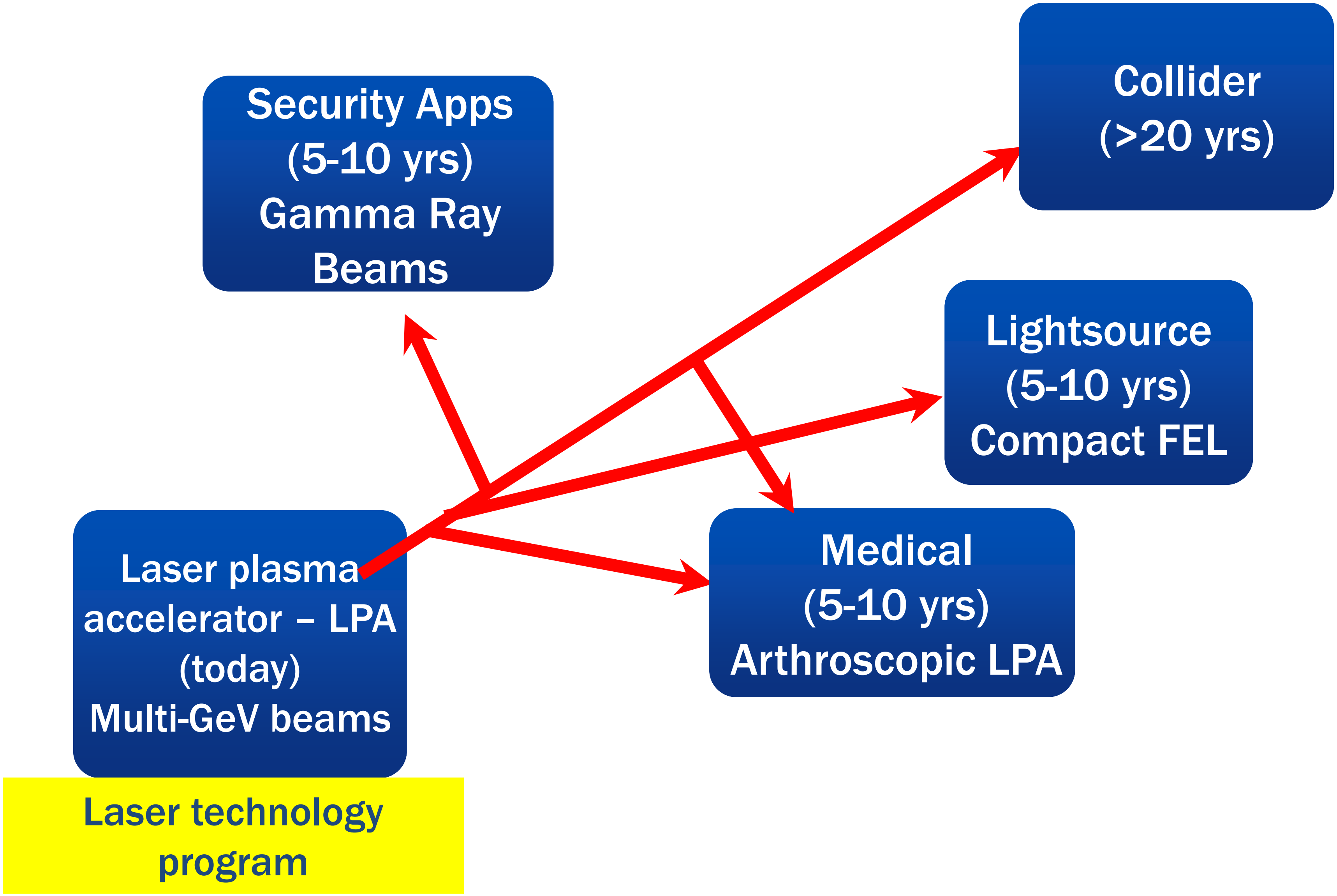
LUNEX5 (SOLEIL / LOA)

M-E Couprie, ERC Grant
V. Malka, ERC Grant

INFN: SPARC / FLAME

MPQ / MAP

Laser technology needs to be developed to enable higher average power operation for applications



Laser technology needs to be developed to enable higher average power operation for applications

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yrs)

e

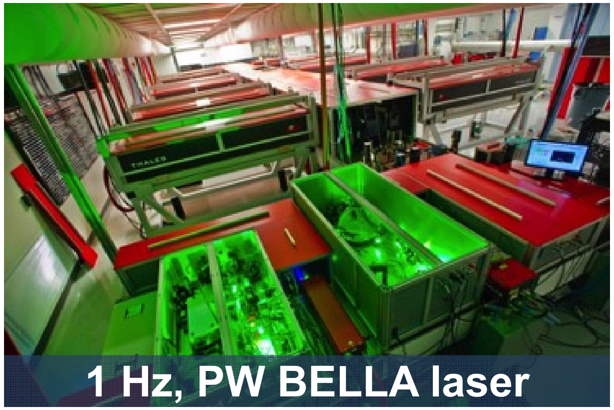
EL

Laser plasma
accelerator – L
(today)
Multi-GeV bea

Laser technolo
program

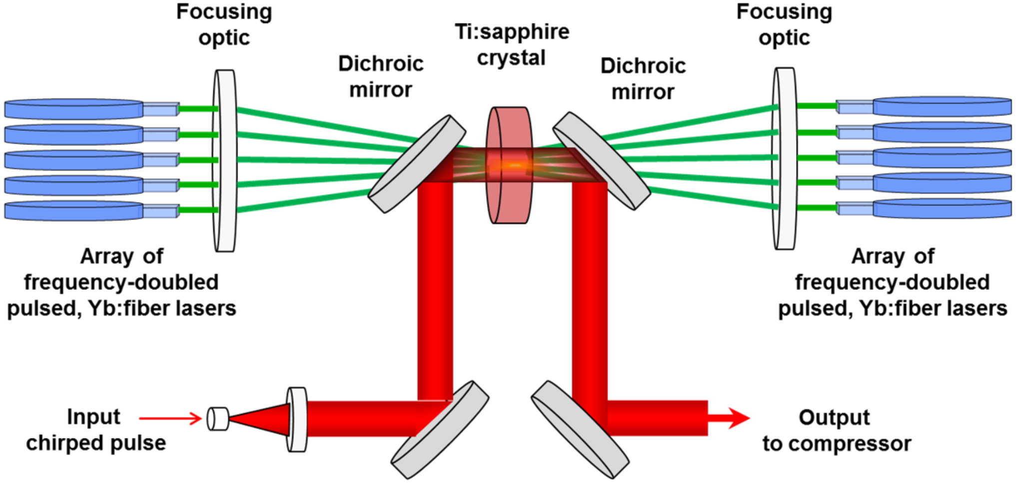
High average and high peak laser power is becoming available

High **peak** power,
low average power



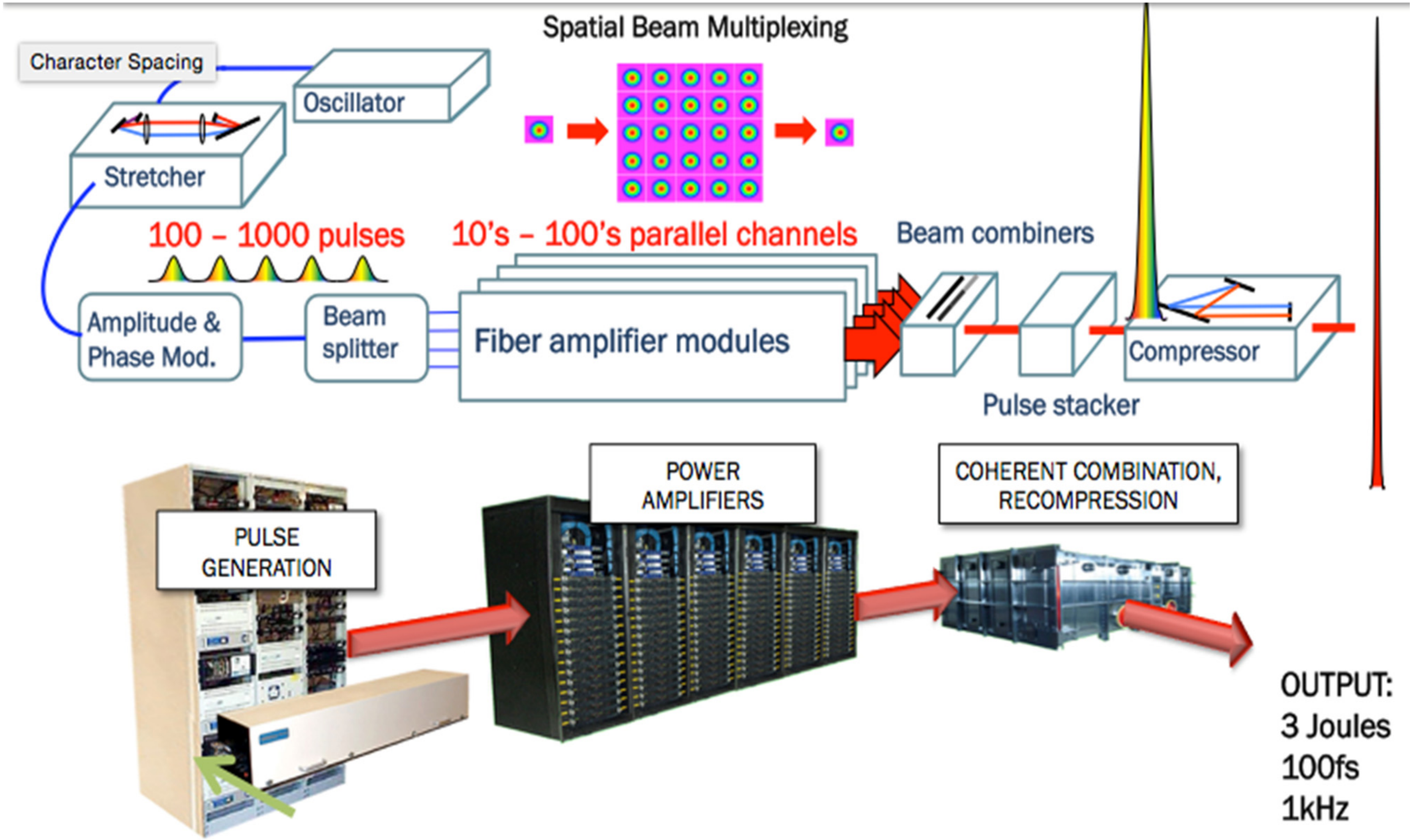
High **average** power,
low peak power

High average and peak power lasers



- Coherent combining schemes also possible
- $B-level investments overseas in lasers and laser-powered accelerators

Innovative laser concepts using coherent pulse stacking, spectral combining and beam combining are pursued



LBNL, LLNL, U Michigan partnership
Funded through DOE Stewardship

Also: A. Tunnerman/J. Limpert et al.;
U. Keller et al., and several other groups

Summary

- Development of plasma based collider concepts
  - Towards 10 GeV on BELLA
  - First demonstration of staged laser plasma accelerators
  - Many challenges to be overcome
- Compact radiation sources – near term applications
  - Betatron x-ray phase contrast imaging source
  - Gamma rays based on Thomson scattering
  - XUV FEL demo experiments are underway
- Applications require higher rep rate devices:
  - Laser technology is rapidly moving towards multi-kW 100 TW class lasers for first applications with high average power

Example set of LPA stage parameters for collider (target parameter set)

Plasma density (wall), $n_0[\mathrm{cm}^{-3}]$	10^{17}
Laser wavelength, $\lambda[\mu\mathrm{m}]$	1
Normalized laser strength, a_0	1
Plasma wavelength, $\lambda_p[\mathrm{mm}]$	0.1
Channel radius, $r_c[\mu\mathrm{m}]$	22
Peak laser power, $P_L[\mathrm{TW}]$	34
Laser pulse duration (FWHM), $\tau_L[\mathrm{fs}]$	130
Laser energy, $U_L[\mathrm{J}]$	4.5
Normalized accelerating field, E_L/E_0	0.2
Peak accelerating field, $E_L[\mathrm{GV/m}]$	6
Laser depletion length, $L_{pd}[\mathrm{m}]$	5.7
Plasma channel length, $L_c[\mathrm{m}]$	1.62
Laser depletion, η_{pd}	29%
Bunch phase (relative to peak field), φ	$\pi/3$
Loaded gradient, $E_z[\mathrm{GV/m}]$	3
Beam beam current, $I[\mathrm{kA}]$	3.2
Charge/bunch, $eN_b = Q[\mathrm{nC}]$	0.19
Length (triangular shape), $L_b[\mu\mathrm{m}]$	36
RMS beam length, $\sigma_z[\mu\mathrm{m}]$	14.5
Efficiency (wake-to-beam), η_b	75%
e^-/e^+ energy gain per stage	5 GeV
Beam energy gain per stage	0.95 J

- LPA stage density and wavelength scalings:

$$E_z \propto n^{1/2}$$

$$L_{\mathrm{stage}} \propto n^{-3/2}\lambda^{-2}$$

$$U_{\mathrm{stage}} \propto n^{-1}\lambda^{-2}$$

$$\tau_{\mathrm{laser}} \propto n^{-1/2}$$

$$U_{\mathrm{laser}} \propto n^{-3/2}\lambda^{-2}$$

$$P_{\mathrm{laser}} \propto n^{-1}\lambda^{-2}$$

$$\sigma_z \propto n^{-1/2}$$

$$N_b \propto n^{-1/2}$$

Example parameters for 1 TeV and 3 TeV CM colliders (target parameter sets)

Energy, center-of-mass, U_{cm}[TeV]	1	3
Beam energy, $\gamma mc^2 = U_b$[TeV]	0.5	1.5
Beam power, P_b[MW]	4.3	23
Luminosity, $\mathcal{L}[10^{34}\ \mathrm{s}^{-1}\mathrm{cm}^{-2}]$	1	10
Laser repetition rate, f_L[kHz]	45	80
Horiz. beam size at IP, σ_x^*[nm]	50	18
Vert. beam size at IP, σ_y^*[nm]	1	0.5
Beamstrahlung parameter, Υ	1.4	11
Beamstrahlung photons, n_γ	0.7	1.1
Beamstrahlung energy spread, δ_γ	0.10	0.27
Number of stages (1 linac), N_{stage}	100	300
Distance between stages [m]	0.5	0.5
Linac length (1 beam), L_{total}[km]	0.21	0.64
Average laser power, P_{avg}[MW]	0.20	0.36
Efficiency (wall-to-beam)[%]	11	16
Wall power (linacs), P_{wall}[MW]	74	282

Assumed η_{laser} = 0.4 and $\eta_{recovery}$=0.9

- Density and wavelength scalings (fixed Luminosity and laser efficiency):

$$N_{\rm stages} \propto n\lambda^2$$

$$L_{\rm linac} \propto n^{-1/2}$$

$$f_{\rm rep} \propto n$$

$$P_b \propto n^{1/2}$$

$$P_{\rm avg\ laser} \propto n^{-1/2}\lambda^{-2}$$

$$P_{\rm wall} \propto n^{1/2}$$

$$n_\gamma \propto n^{-1/2}$$

- Total efficiency:

$$\eta_{\rm total} = \frac{\eta_{\rm beam}\eta_{\rm pd}}{[1/\eta_{\rm laser} - (1-\eta_{\rm pd})\eta_{\rm recovery}]}$$

- Electrical-to-optical of diode-pumped lasers = 55%
- Optical-to-optical of fibers = 90%
- Combining/stacking fibers = 80%