Lasers and Plasmas

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P5 Meeting @ BNL

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Office of Science

Can lasers and plasmas play a role in future high energy accelerators?

14 TeV *CM pp*, LHC at CERN

-27 km, $6 Billion+

RF: 10- 100 MV/m

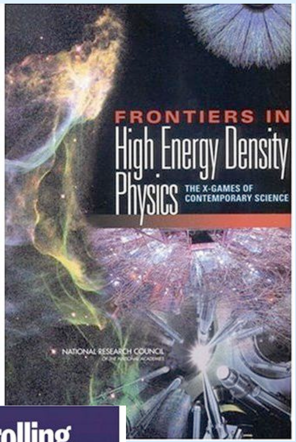
Plasma: 10-100 GV/m

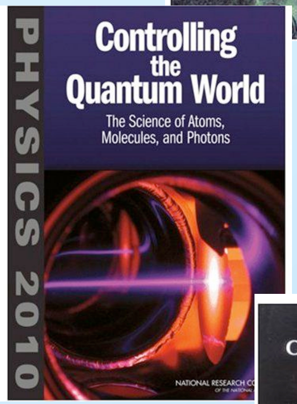
Smaller ?

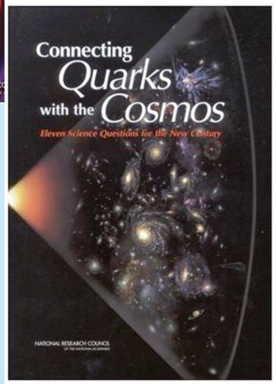
Cheaper?

AA R&D has impact on questions posed by National Academies

- *How do cosmic accelerators work and what are they accelerating?*
  - *Need better understanding of relativistic plasmas*
- *Is a new theory of matter and light needed at the highest energies?*
  - *QED well tested up to 10^5 Gauss: how about beyond critical field?*
- *Understanding the destiny of the universe*
  - *Detector development from THz to X-rays and training instrumentalists*
- *Exploring extreme physics in the laboratory*
  - *Can we use lasers to build colliders of the future?*

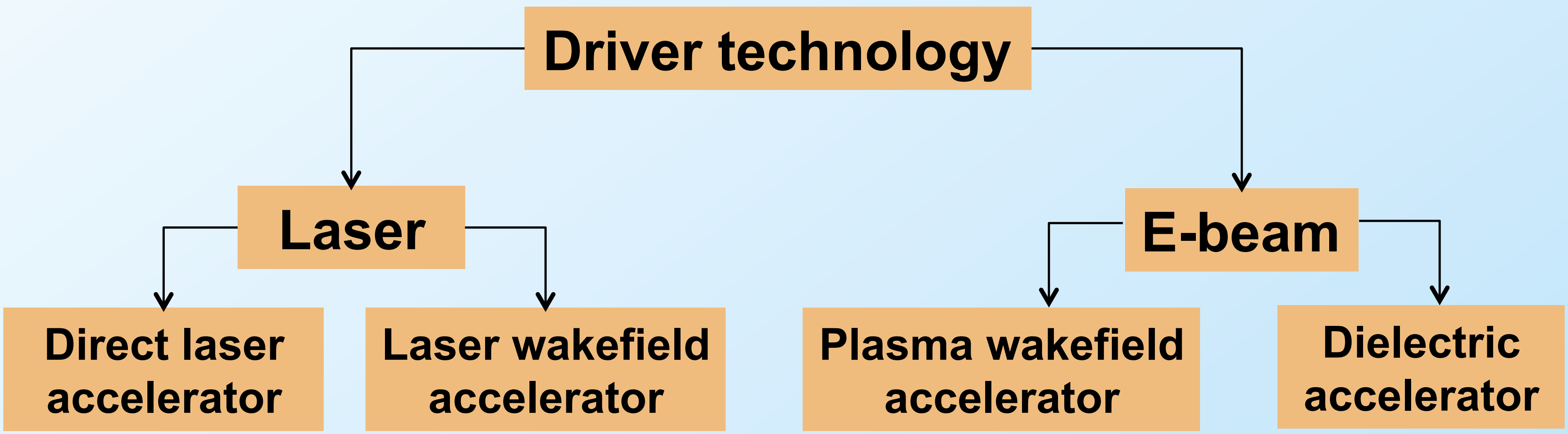






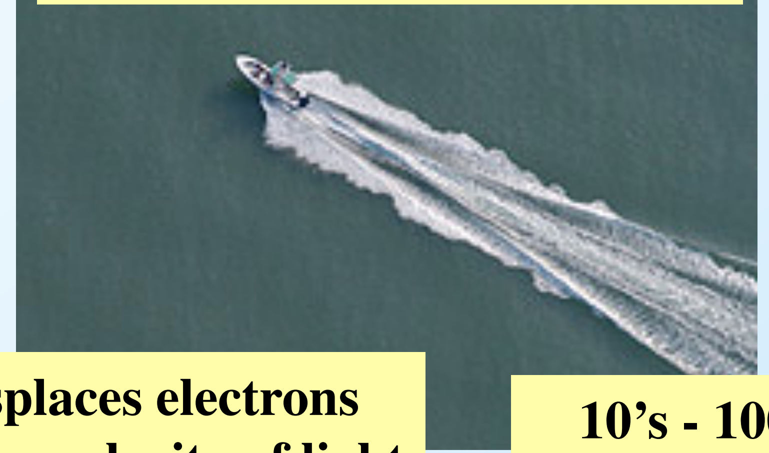
Motivation and overview

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



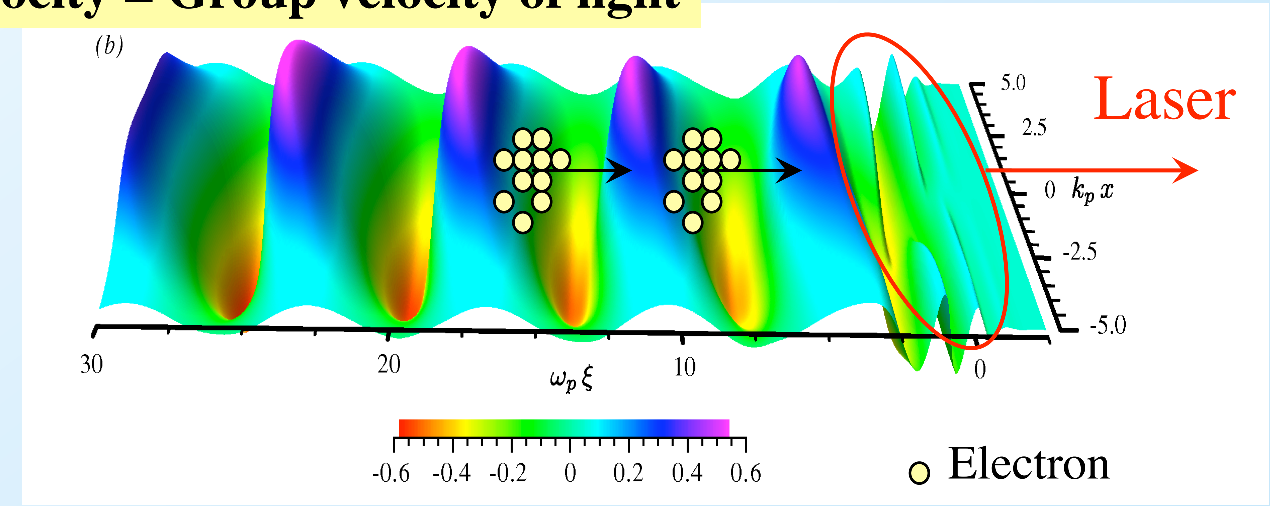
Linear laser/plasma wakefield accelerator

Boat displaces water
Wake velocity = boat velocity



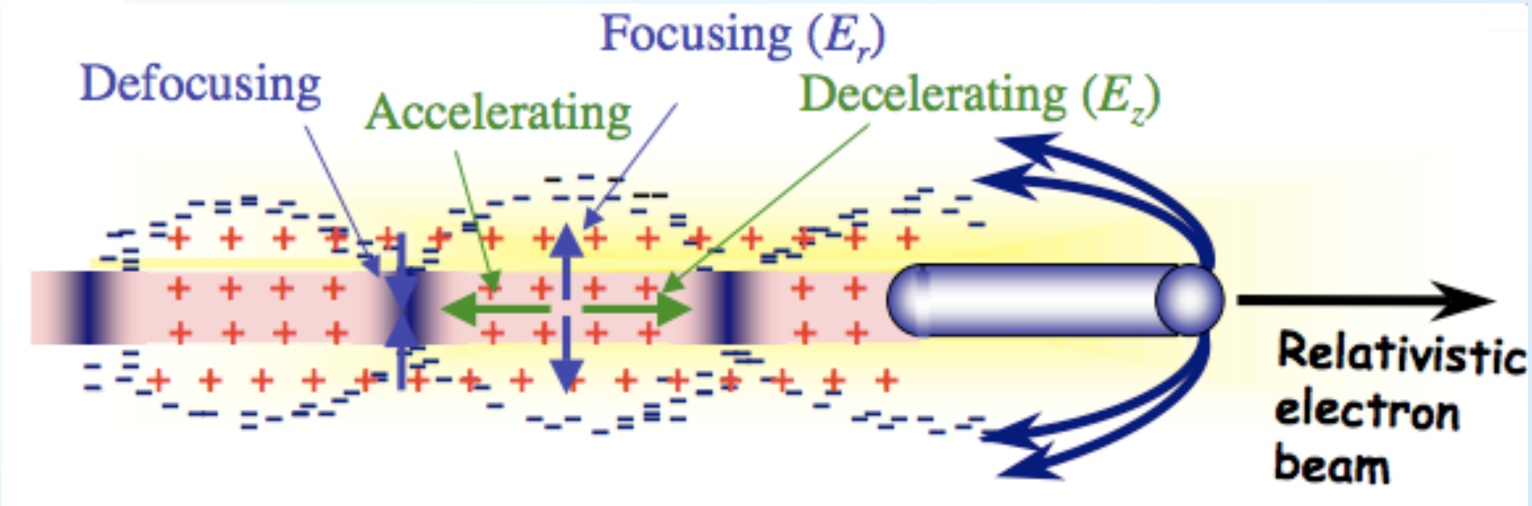
Laser in plasma displaces electrons
Wake velocity = Group velocity of light

10's - 100's GV/m, scales as $\sqrt{n}$



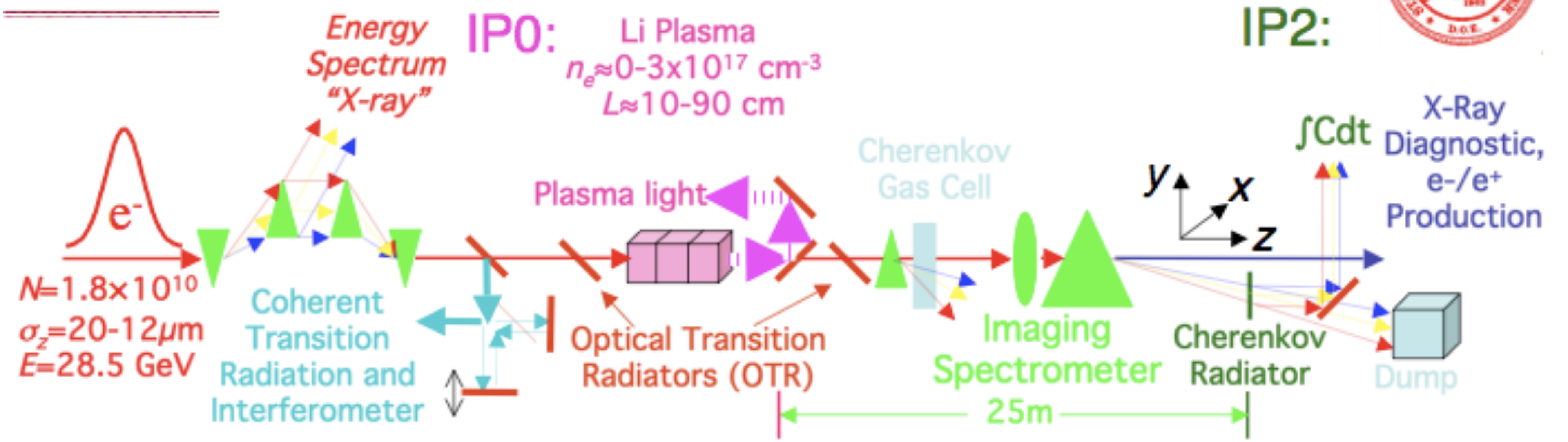
T. Tajima and J.M. Dawson, PRL 1979

Non-linear laser/plasma wakefield accelerator

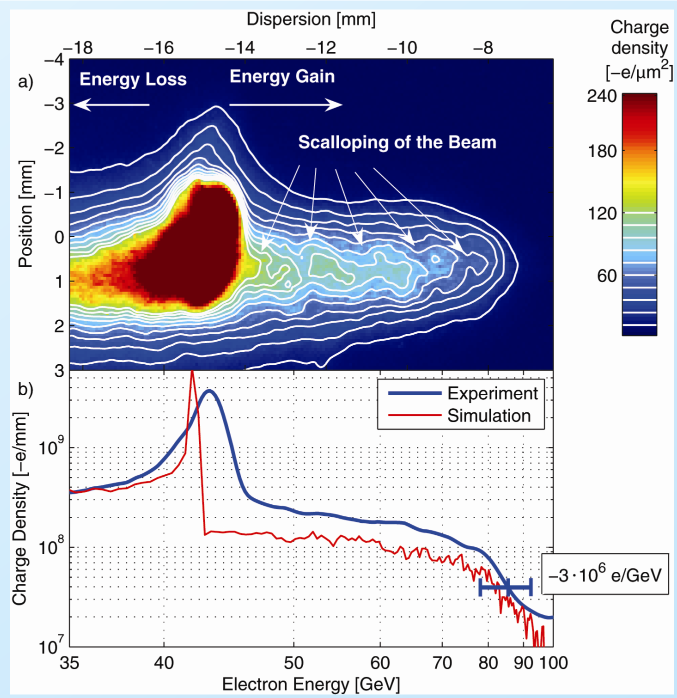


- Blow-out or bubble regime
  - Large gradients
  - Self-trapping
- Two major experimental results:
  - GeV with few % ΔE/E in 3 cm using a laser (LBNL)
  - Up to 85 GeV electrons using a 42 GeV beam (SLAC)

Plasma wakefield accelerator expt

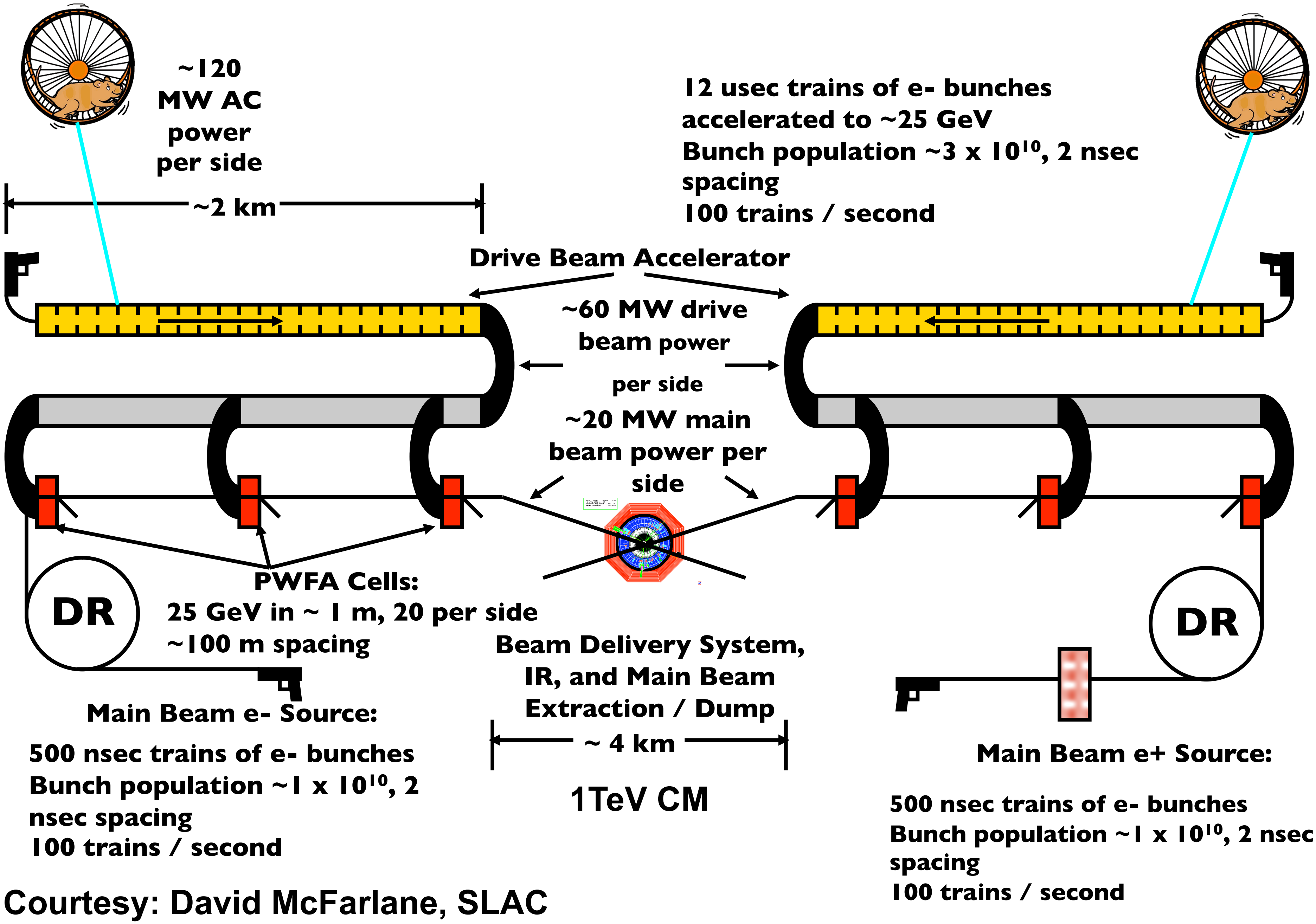


- **Used 42 GeV FFTB beam**
- **Li plasma**
- **Most electrons decelerated**
- **Few % accelerated**
- **Highest energy observed ~ 85 GeV**



Blumenfeld et al., Nature 2007

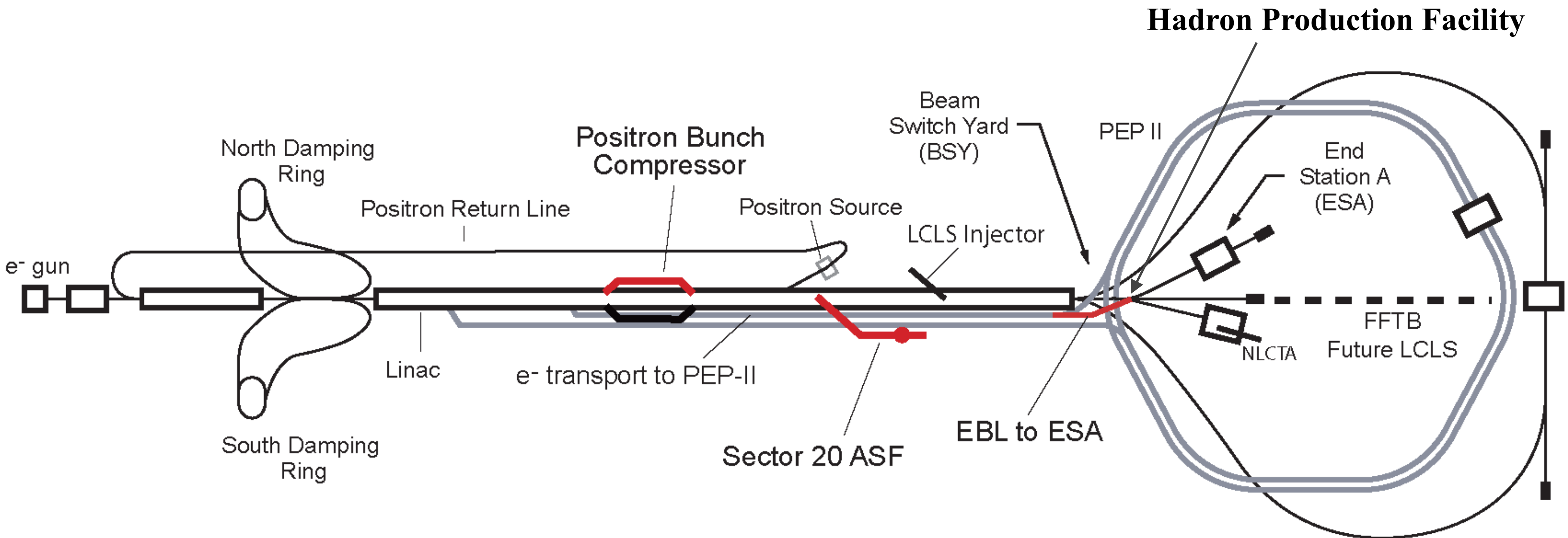
CLIC-like PWFA LC Schematic



1TeV CM

Courtesy: David McFarlane, SLAC

FACET Project



FACET project consists of four elements:

- **Accelerator Science Facility (ASF) (Sector 20)**
- **e^+ bunch compressor (Sector 10)**

Supports advanced accelerator R&D

- **Electron Bypass Line (EBL) extension to ESA**
- **Hadron Production Facility in A-Line to ESA**

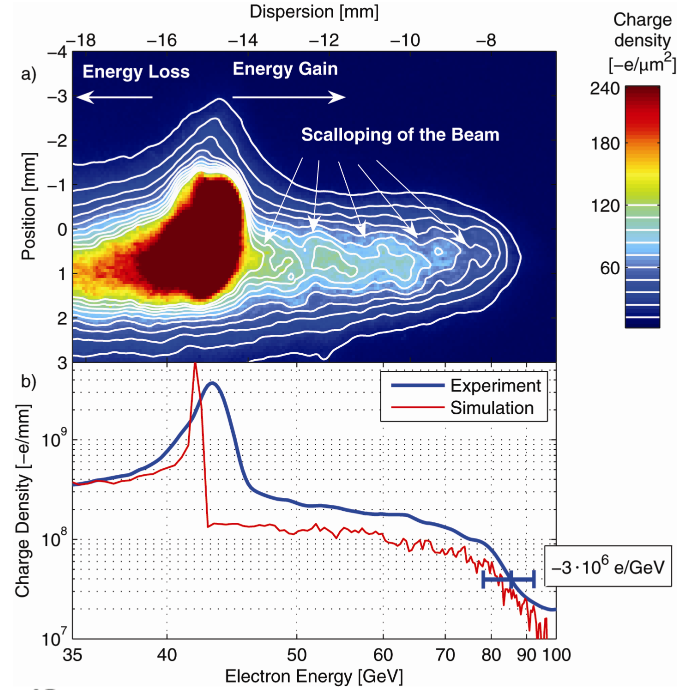
Supports detector & instrumentation R&D

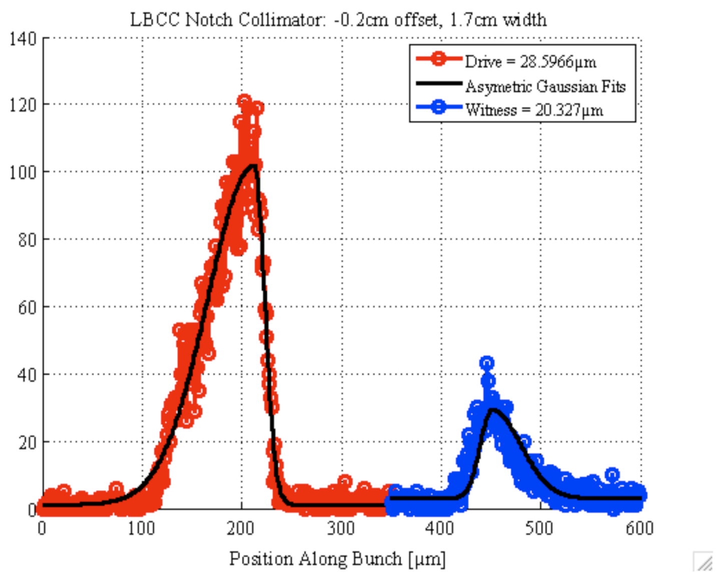
Construction: FY09-FY10 for ~$11M (ASF) & ~$17M (full project)
Operations: $7-9M for 4-6 months/year

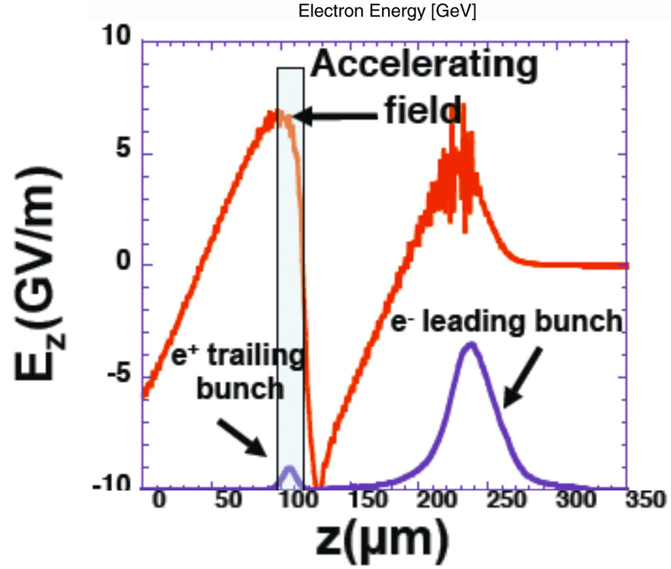
Courtesy: John Seeman/David McFarlane

Plasma Wakefield Acceleration Studies (ASF)

- Electron acceleration
  - Drive-witness bunch
  - Energy spread & efficiency optimization
  - Beam emittance preservation
- Positron acceleration
  - Acceleration mechanism (e^- or e^+ drive bunch, hollow channel)
  - Same program as for electrons

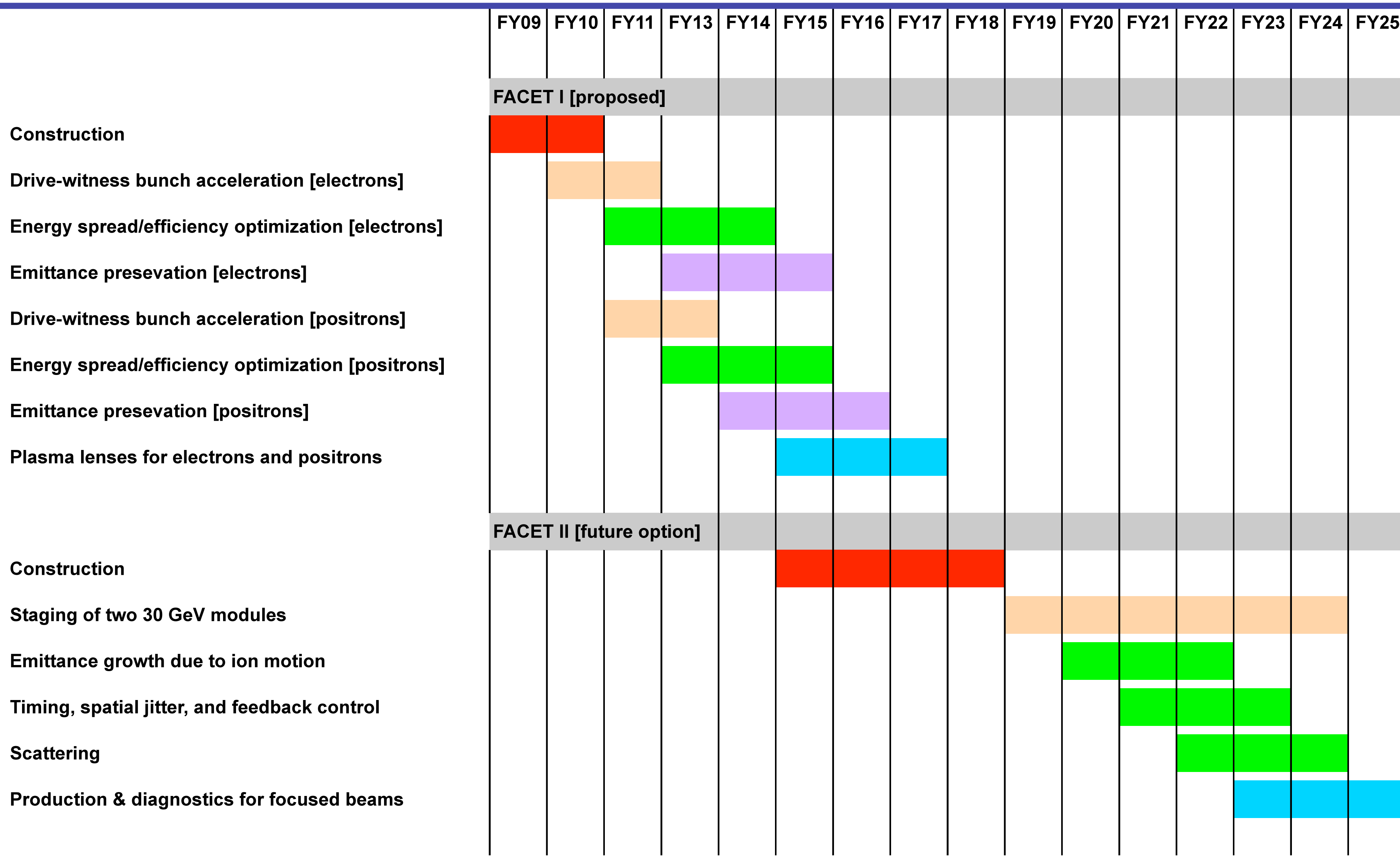






Courtesy: John Seeman/David McFarlane

Possible Timeline for PWFA R&D



Courtesy: David McFarlane

E-Beam facilities with AAR&D program

USA:

BNL-ATF: 70 MeV + CO_2 laser
FNAL-A0: 16 MeV with Supercon RF
ANL-AWA: high charge (up to 100 nC)
SLAC-NLCTA and *FACET* (proposed): up to 30 GeV e^-/e^+
UCLA-Neptune: <15 MeV, photocathode + CO_2 laser

Asia:

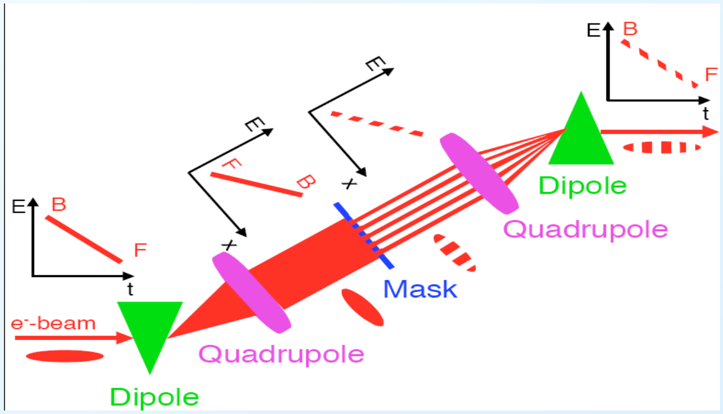
U Tokyo: twin linacs (<30 MeV)

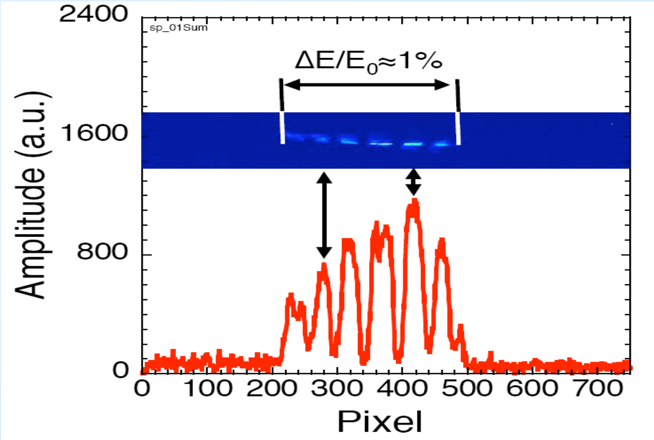
Europe:

CERN: CLIC
TU Eindhoven: photo-injector + laser + plasma

ATF: pioneering ebeam facility for users

- Example: High gradient acceleration (PWFA) – creation of witness bunch
  - New way to create beam structure suggested and tested at ATF, gradient increase with microbunch number observed. Could produce ILC baseline energy beams from SLAC scale accelerator.





- Proposal-driven, advisory committee reviewed USER FACILITY for long-term R&D
- ATF features:
  - High brightness electron gun (World record in beam brightness)
  - 75 MeV Linac
  - High power lasers (including terawatt CO2 laser at 10.6 mm), beam-synchronized at the picosec level
  - 4 beam lines + controls

Material courtesy of V. Yakimenko, BNL

Advanced Accelerator R&D Activities at the Argonne Wakefield Accelerator (AWA)—Mission and Research Program

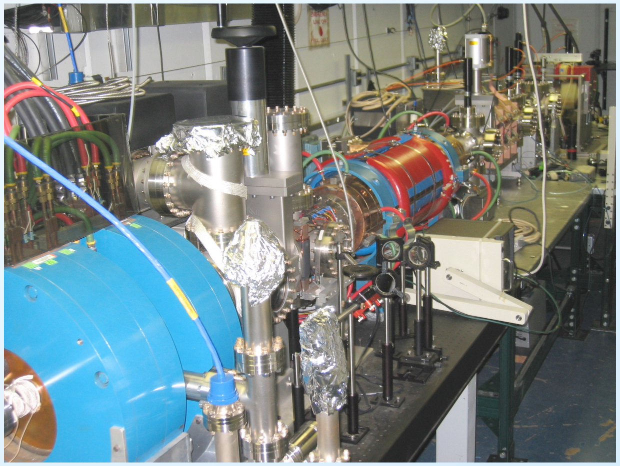
Argonne Wakefield Accelerator (AWA) Facility

- 1.3 GHz RF Photoinjector based facility for the production of high-current and high-brightness electron beams (0.1 – 150 nC/bunch, 15 MeV, 10 Hz).
- 100 MV/m generated, 30 MW in 10 ns RF

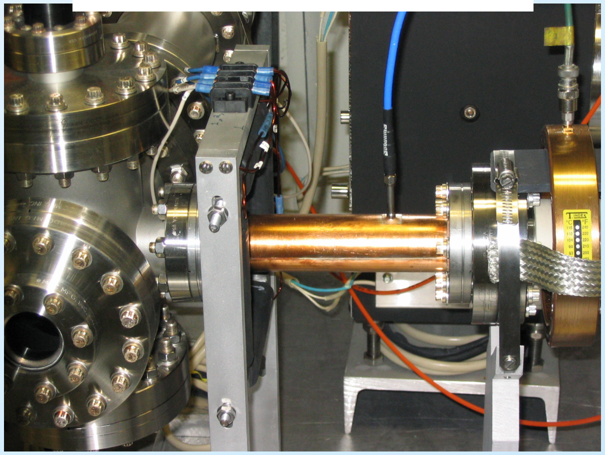
Support of external programs

- Positron source for ILC; Lab Astrophysics; Equipment Testing.
- Providing facilities for collaborator/user's research program (~ 10 Universities and Institutes) and student training (10 Ph.D. students graduated.)

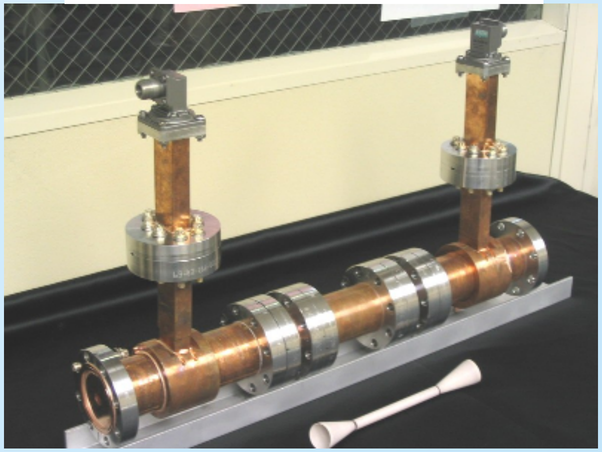
AWA Facility



Dielectric: Structure Under Test



Dielectric Loaded Accelerator



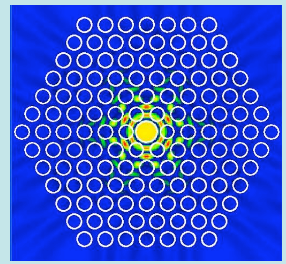
Advanced Accelerator Research: Direct Laser Acceleration (LEAP & E163)

Motivation

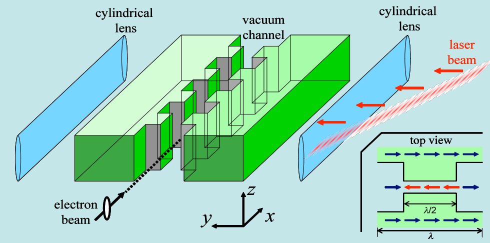
* **All solid-state** – no plasmas, no klystrons → easier to simulate, more reliable to operate
* **High gradient** (>0.5 GeV/m) possible with silicon and fused silica structures
* **High Efficiency** (40% optical-to-beam efficiency structures have been designed, >20% efficient lasers are commercially available
* **Modest laser requirements:** microJoules, not kiloJoules are required due to the high coupling efficiency.
* **Inexpensive --** leveraging of commercially available technologies reduces R&D costs; accelerator and its power source can be fully integrated on a single silicon chip making mass production possible

Structure Candidates for High-Gradient Accelerators

Maximum gradients based on measured material damage threshold data



Photonic Crystal Fiber
Silica, λ=1053nm,
E_z=790 MV/m



Transmission Grating Structure
Silica, λ=800nm,
E_z=830 MV/m

These structures are being simulated and experimentally tested at SLAC.

Strawman parameters for a DLA-based e+e- collider

Luminosity from a laser-driven linear collider must come from **high bunch repetition rate** and **smaller spot sizes,** which naturally follow from the small emittances required

E_{CM} = 500 GeV	Laser	JLC/NLC
N	5×10^6	9.5×10^9
f_c	50MHz	11.4kHz
P_b (MW)	10	4.5
σ_x/σ_y (nm)	0.5/0.5	330/5
$N\gamma$	0.22	1.1
σ_z (μm)	120	300
σ_z/c (psec)	0.4	1
ξ_1	0.045	0.11
L	1×10^{34}	5.1×10^{33}

Beam pulse format is

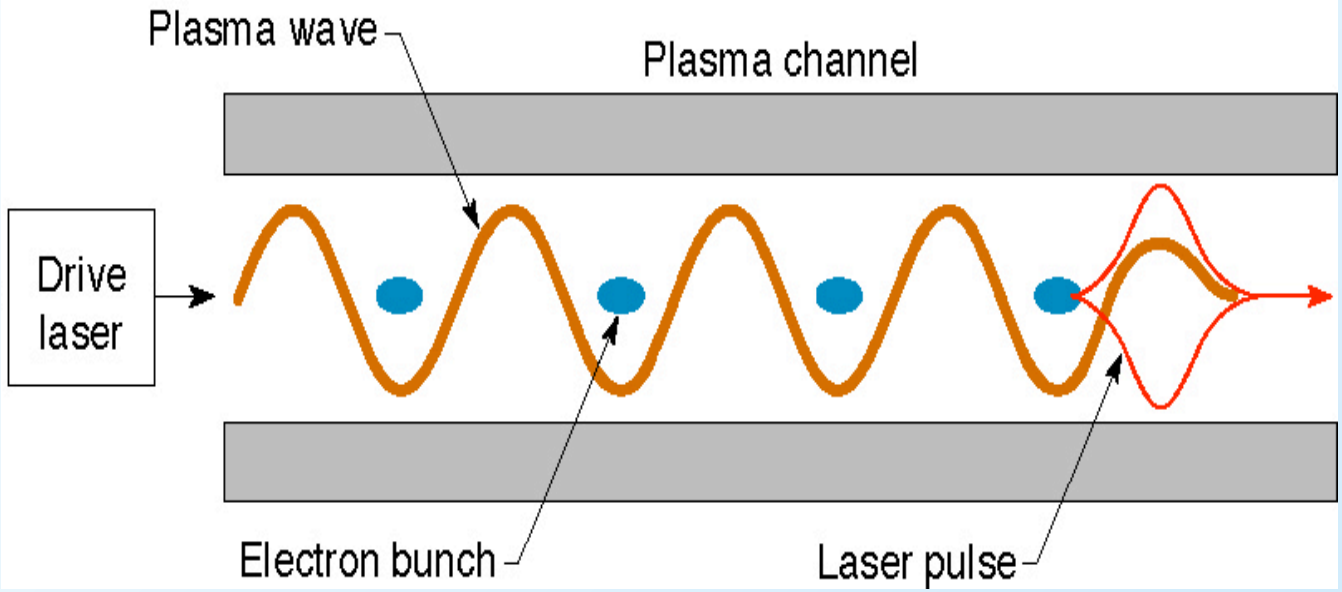
(160 microbunches of 3×10^4 e^- in 1 psec) x 50MHz

→ Storage-ring like beam format → *reduced event pileup*

→ High beam rep rate=> *high bandwidth position stabilization is possible*

Courtesy:Eric Colby, SLAC

Building a laser wakefield accelerator using conventional accelerator paradigm

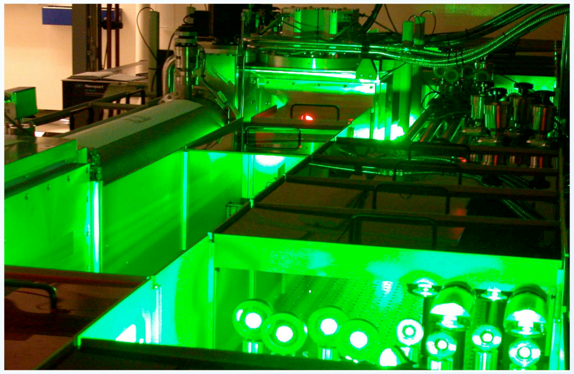


- Drive laser: Ti-sapphire (chirped amplification technology)
- Structure: plasma fiber
- Injection: self-trapped, triggered

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

Laser accelerator: 1 GeV with 40 TW laser pulse in 3 cm plasma capillary structure

40 TW laser pulse

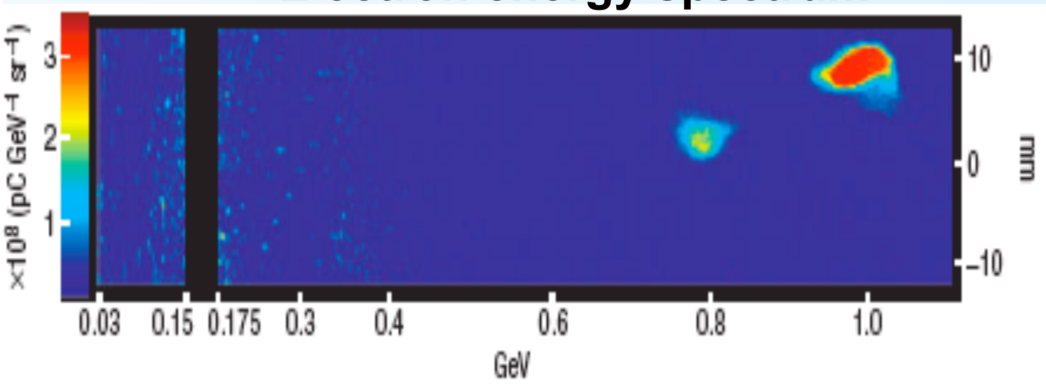


3 cm capillary

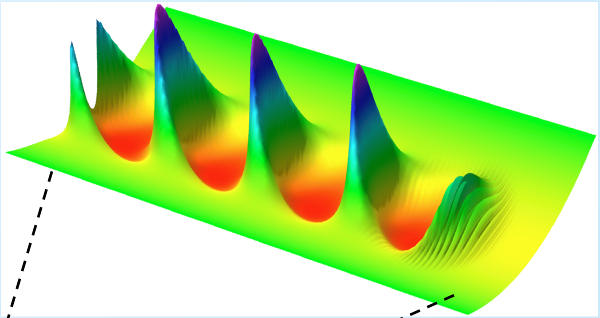
Leemans et al., Nature Physics 2006

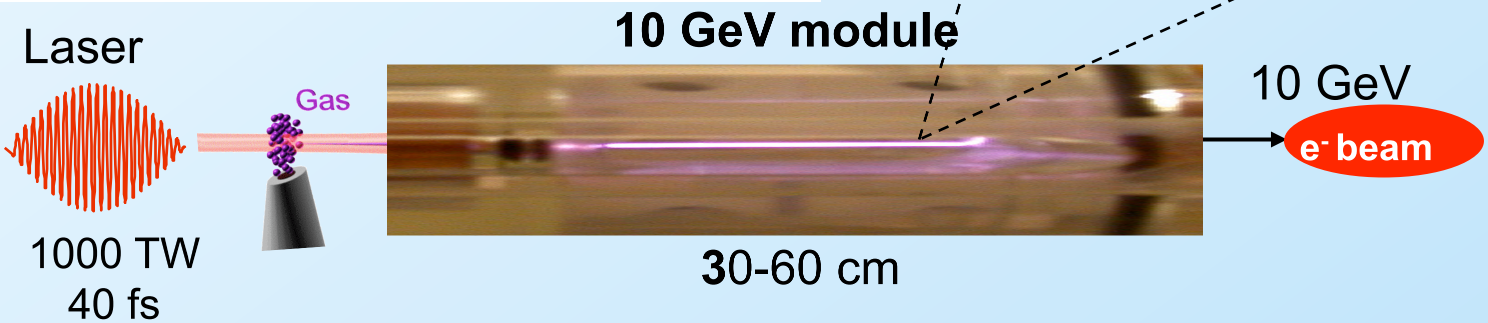
- **LBNL/Oxford team**
- **Self-trapped electrons**
- **Few % energy spread**
- **Step towards 10 GeV**

Electron energy spectrum

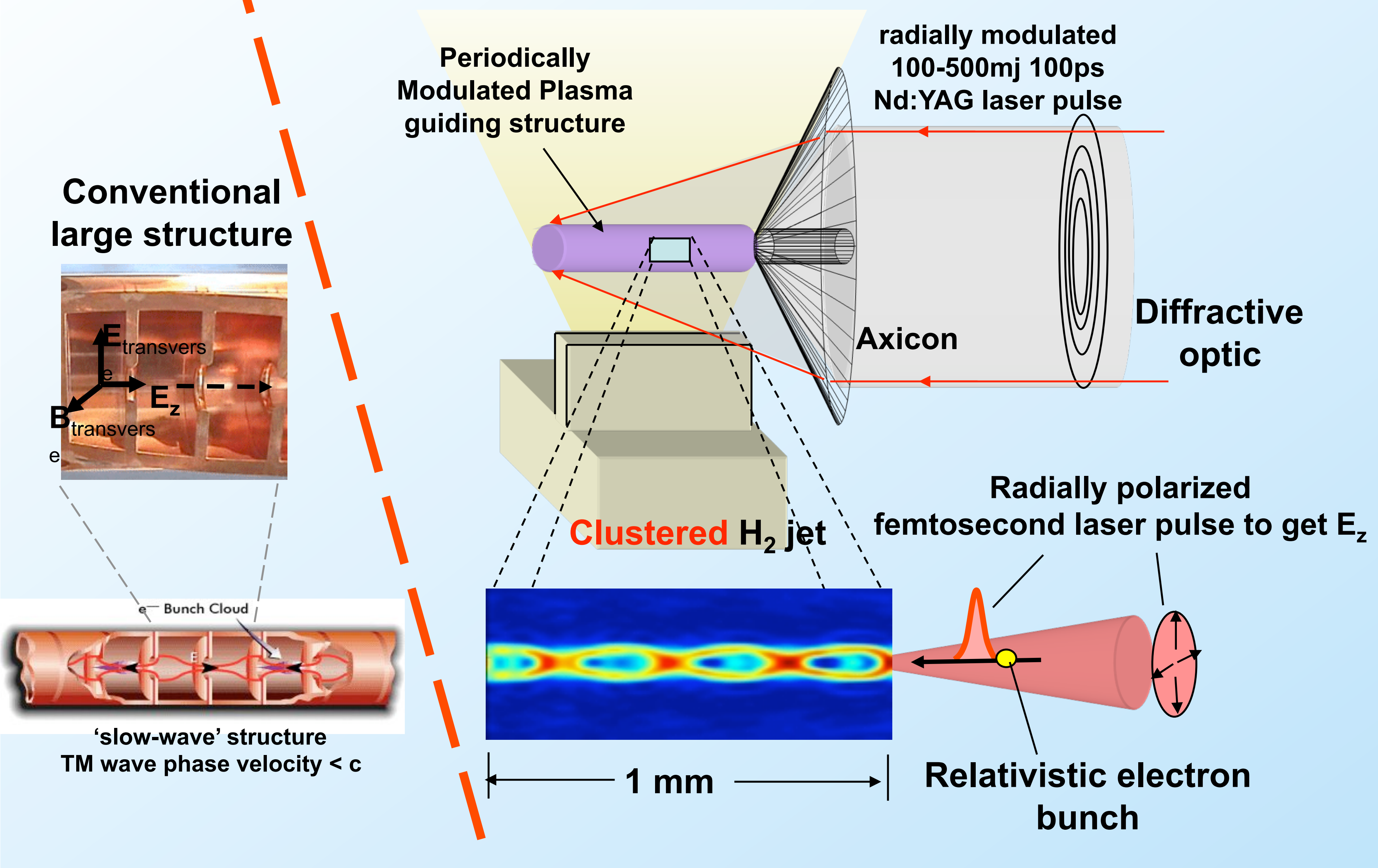


Wakefield simulation





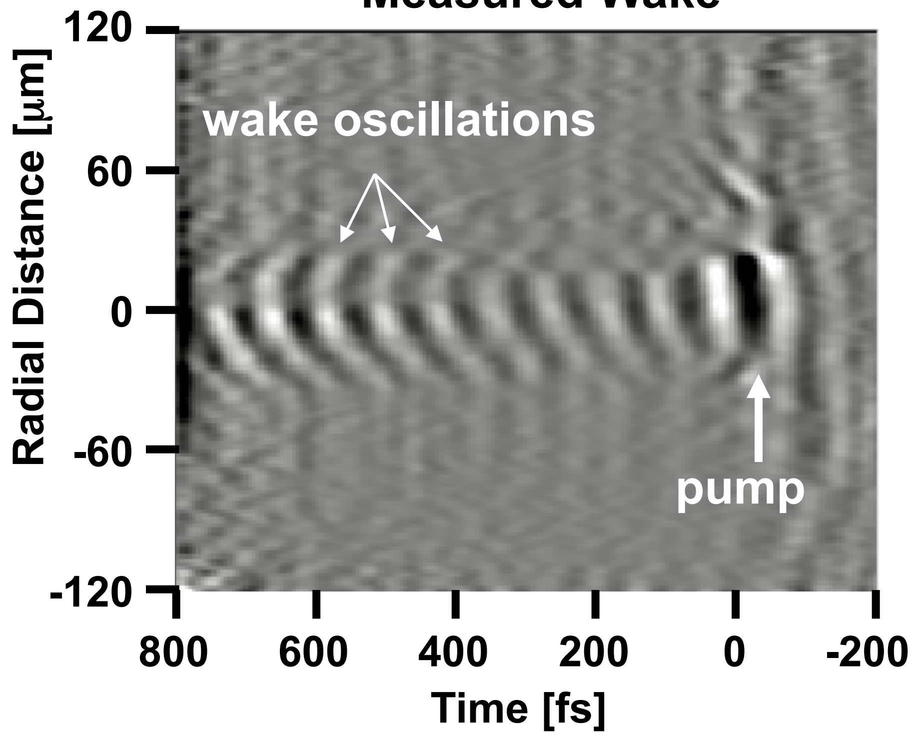
Direct laser acceleration in plasma slow wave structures



Wakefield Snapshots using Frequency Domain Holography enrich experiment-theory dialog

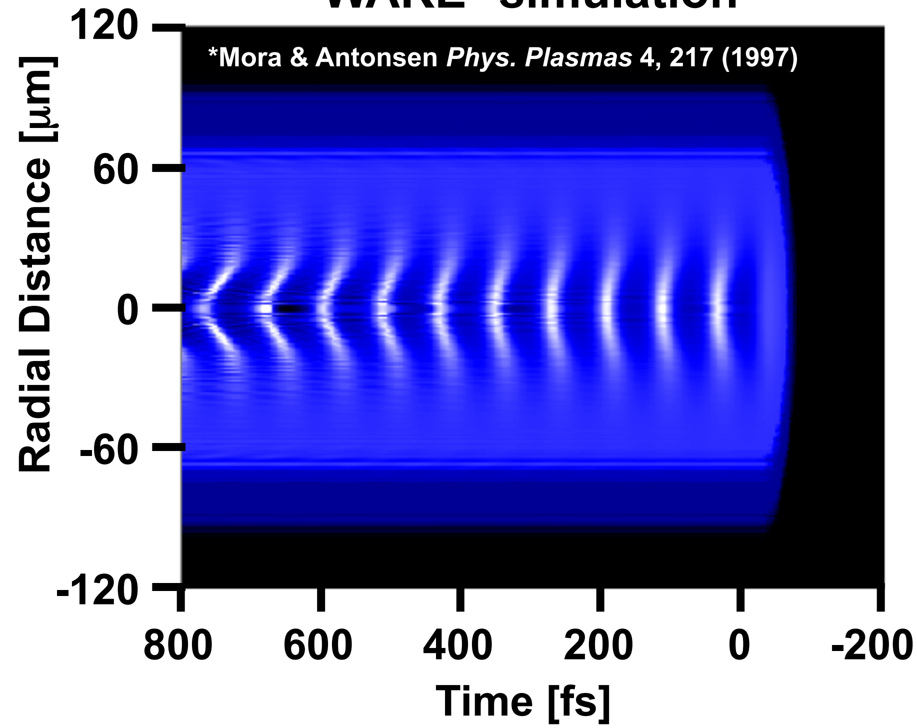
N. Matlis *et al.*, *Nature Physics* 2, 749 (2006)

Measured Wake



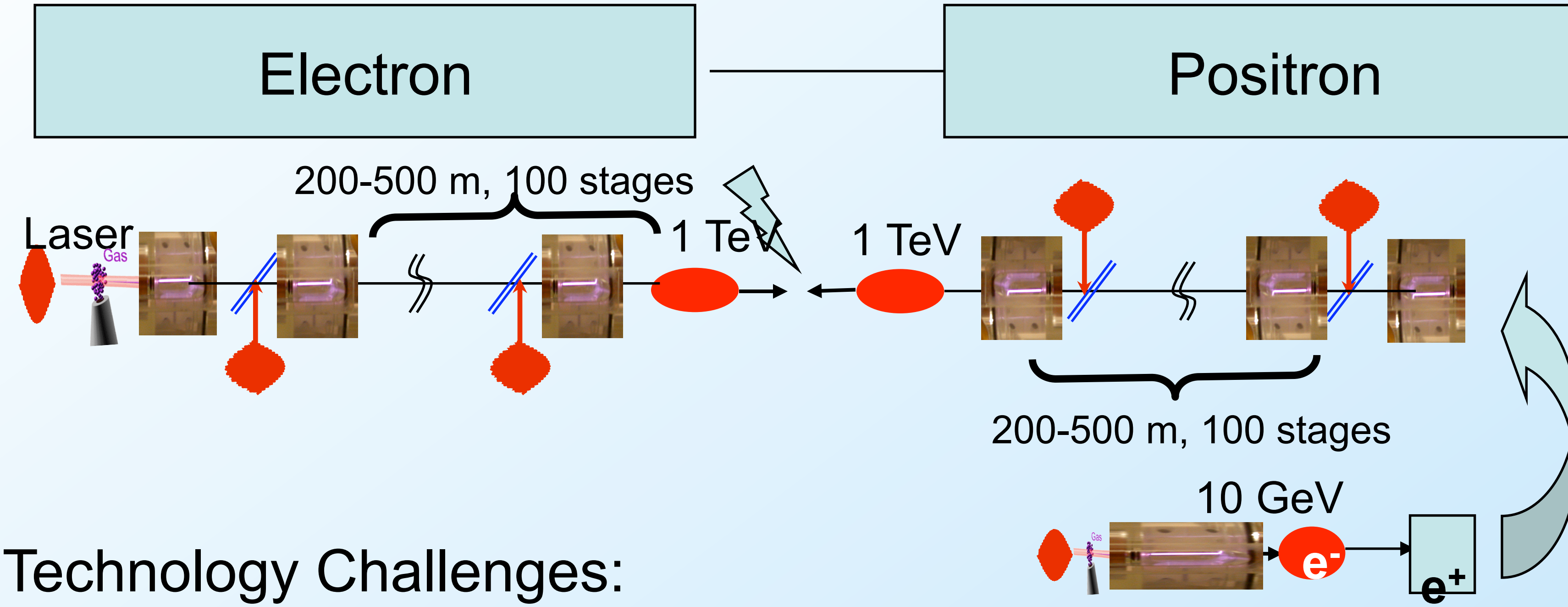
slide courtesy Mike Downer, U. Texas-Austin

WAKE* simulation



simulation by S. Kalmykov, G. Shvets

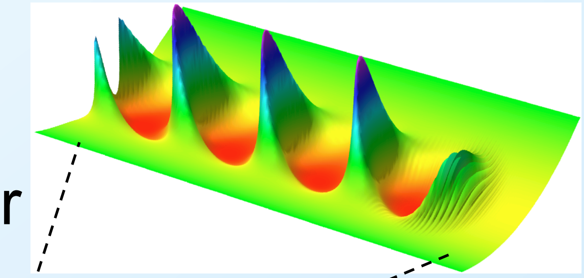
Conceptual (strawman) collider lay-out

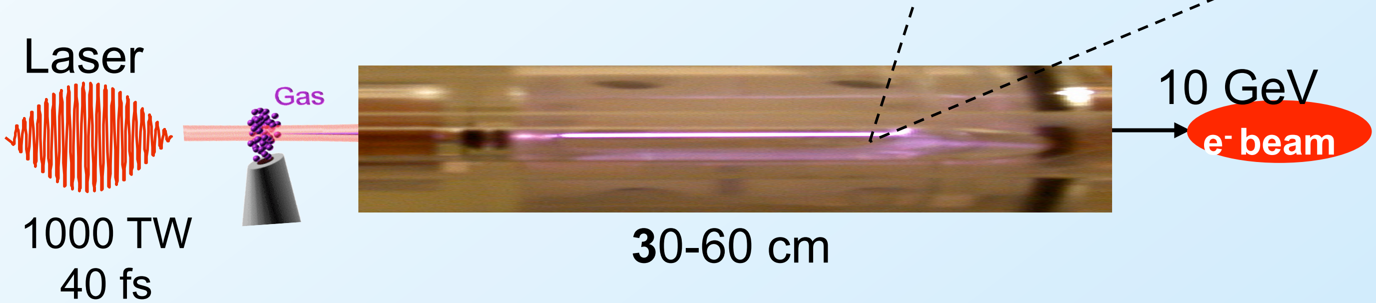


- Technology Challenges:
  - Staging technology
  - Diagnostics -- control
  - Positron and polarized electron sources compatible with laser accelerators
  - Emittance and energy spread control (collisions in plasma)
  - High average power, high peak power lasers

BELLA = **BE**rkeley **L**ab **L**aser **A**ccelerator

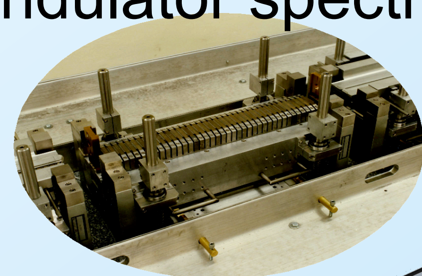
- BELLA Project: 1 PW, 1 Hz laser

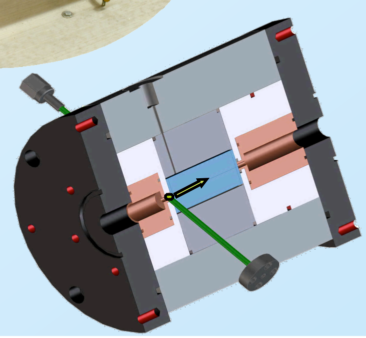




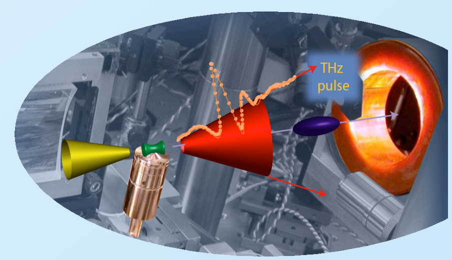
- BELLA R&D:
  - Diagnostics
  - Staged Accelerators

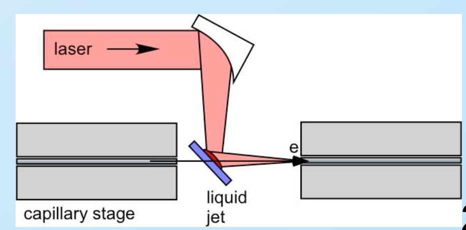
Undulator spectrum



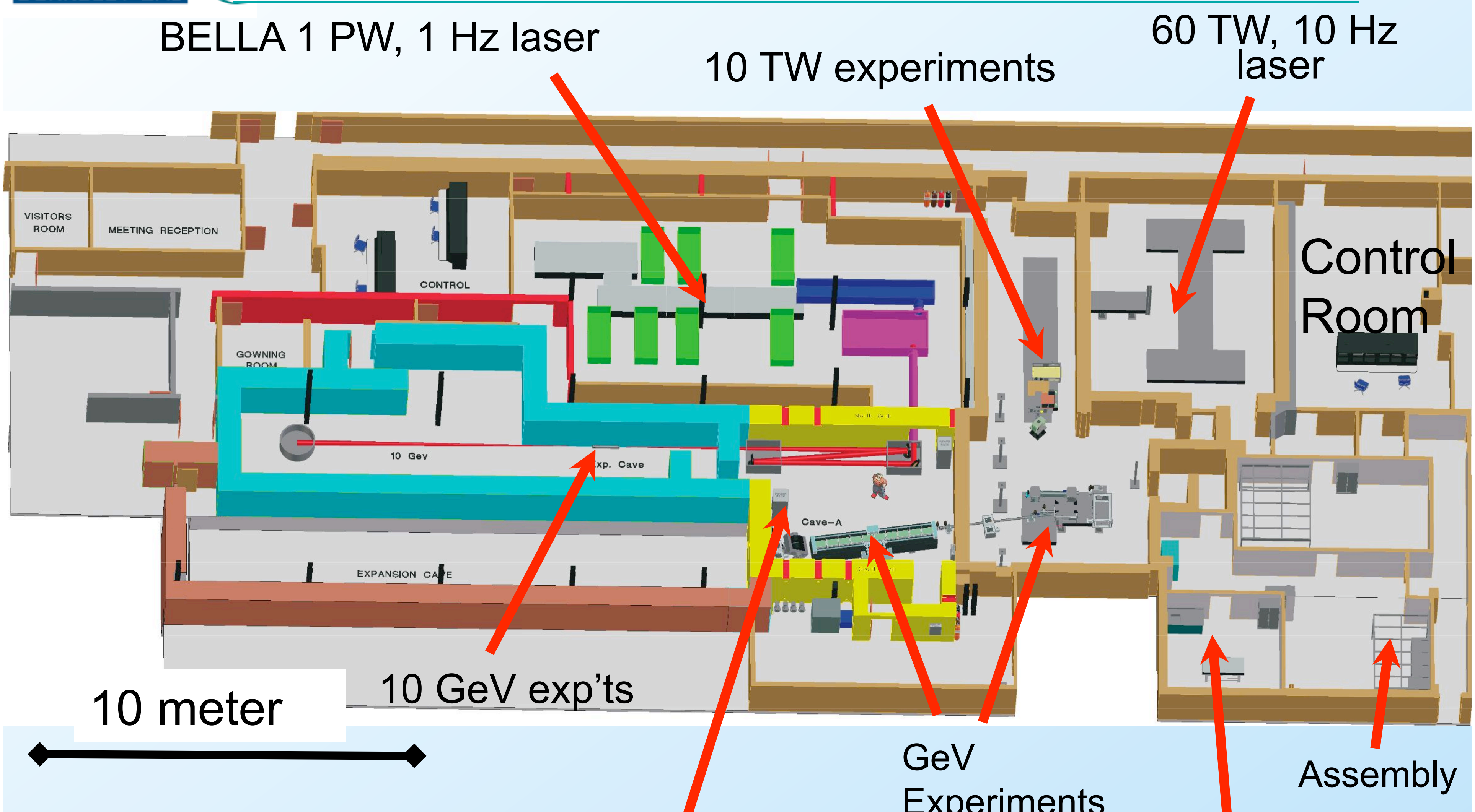


THz



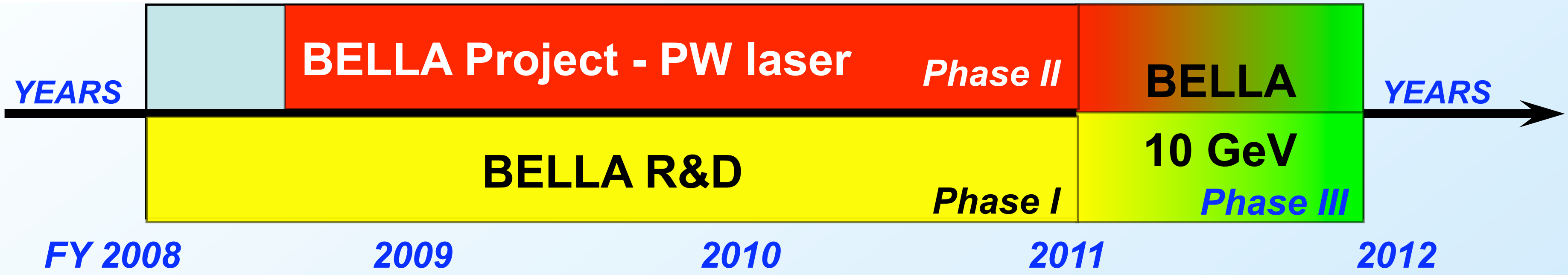


BELLA laser will enable 10 GeV expt's



LOASIS Facilities
(Ground Floor, Bldg. 71)

BELLA time lines and budget estimates



- **BELLA Project (2008 – 2011): Commercial 40 J, 40 fs laser at 1 Hz**

  Facility to house laser and beamline + laser diagnostics

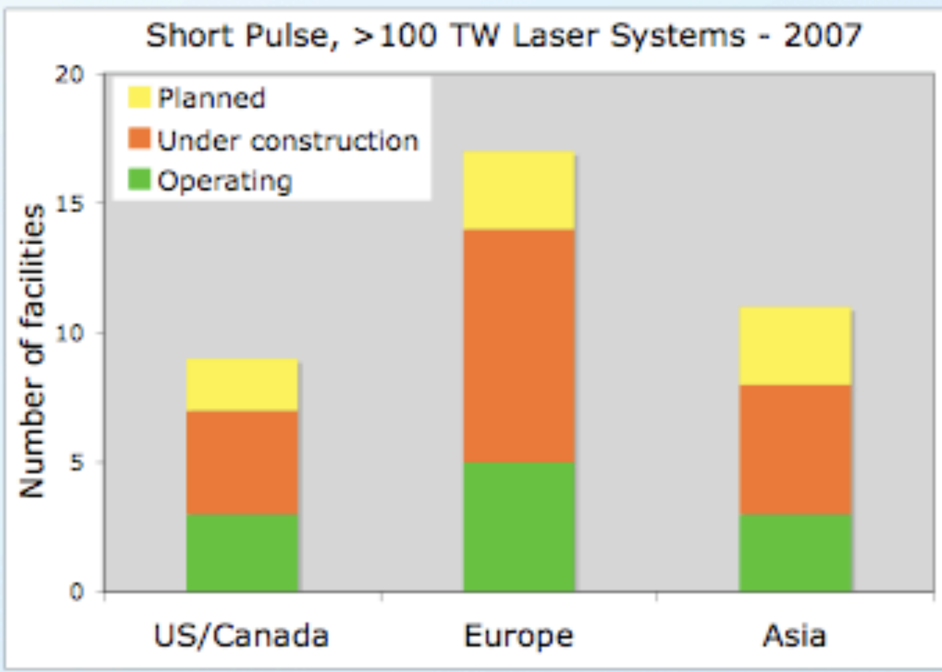
  Total Project Cost: 23-26 M$

- **BELLA R&D (2008 – 2015):**
  - **BELLA OPS: ~ 2M$/yr**
  - **Phase space diagnostics**
  - **Wakefield diagnostics**
  - **Injection techniques**
  - **Staging techniques**
  - **Emittance control**
  - **Acceleration efficiency**
  - **10 GeV stage**
  - **THz to gamma rays**
  - **Detector testing**

High power lasers for AA R&D

USA

BNL & UCLA: CO_2, single shot, < 1 TW
LBNL: 60TW @ 10 Hz + BELLA (planned)
Michigan: 500 TW @ 1/min
Nebraska: 150 TW@ 10 Hz, upgrade 1 PW
UNR: 100 TW@10 Hz
UT Austin: 40 TW @ 10 Hz
UMaryland: 20 TW @ 10 Hz
UCLA: 10 TW @ 10 Hz



Asia

China: > 500 TW + 1 PW in progress
India: 10 TW @ 10 Hz
Japan: 10-100TW @ 10 Hz + 1 PW @ 0.1 Hz
Korea: 200 TW @ 10 Hz

Canada

ALLS: 200 TW @ 10 Hz – commercial

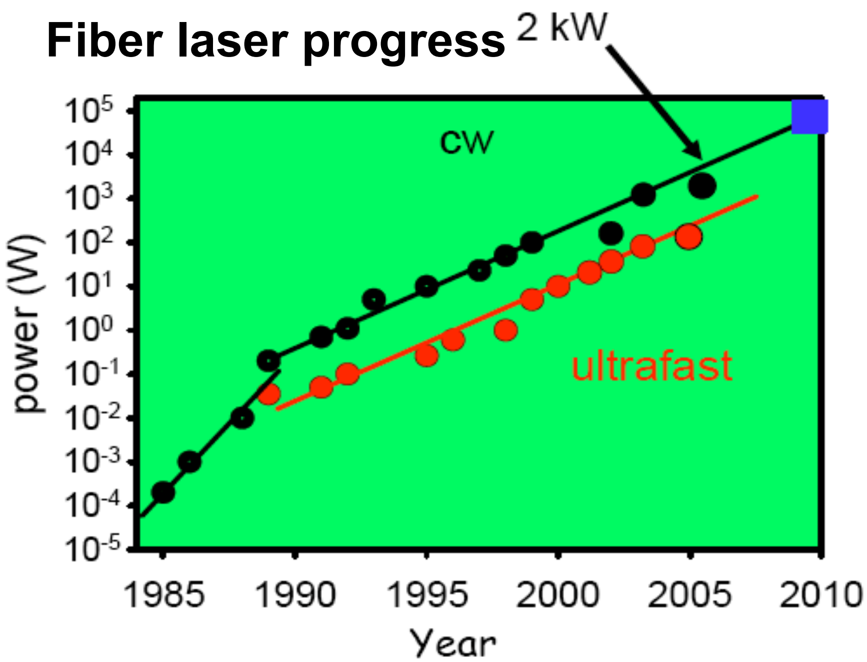
Europe

France: LIXAM: 1 PW @ 0.1 Hz
ILE (in progress): 25 PW @ 1/10 min
ELI (planned): 250 PW, single shot
LOA: 60TW @ 10 Hz
Germany: MPQ: 1 PW@ 0.1 Hz
Dusseldorf: 40 TW @ 10 Hz
Rossendorf: 100 TW@ 10 Hz
Italy: INFN: 20 TW @ 10 Hz
Portugal: 100 TW @ 10 Hz
Spain: 100 TW @ 10 Hz
Sweden: Lund: 30 TW@10 Hz
UK: RAL/IC/Oxford: 500 TW x 2 @ 0.1 Hz
Strathclyde: 50 TW @ 10 Hz

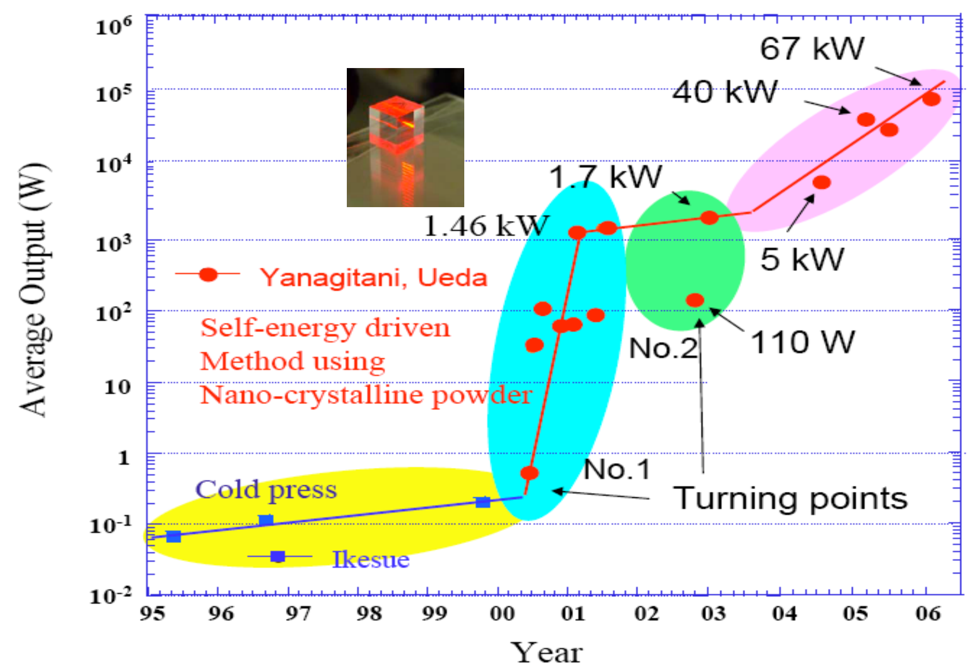
Critical Technology: High average power, high peak power lasers, high wall plug efficiency

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

Fiber laser progress



Courtesy: B. Byer



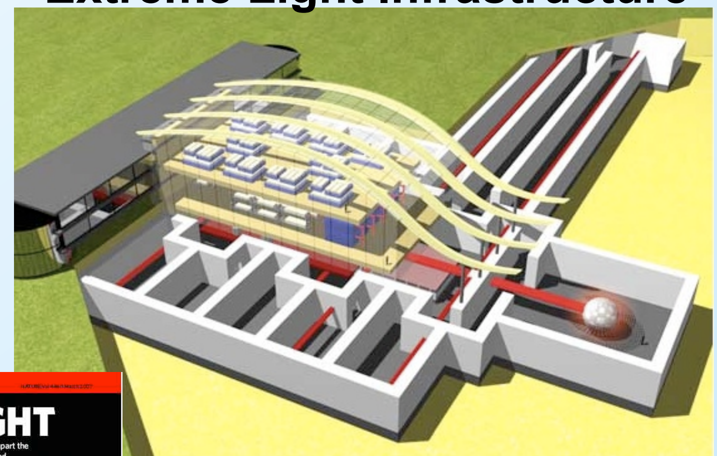
- Emerging market: LED Street lights
  - 50 million lamps in US alone
  - Volume drives down price

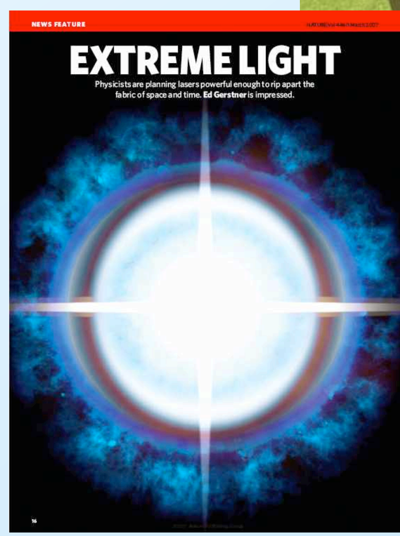
Prospect for kJ, picosecond, multi-kHz systems at 30-50 % wallplug seems possible

Large scale ultra-short pulse facilities are planned outside US

- Example: ELI in France -- 25 PW
- High field science:
  - Photon-photon scattering
  - Gamma ray generation
  - Electron-positron pairs
  - Schwinger field limit
- AMO science:
  - Relativistic High Harmonics
  - Coherent X-rays
- Medical science
  - Phase contrast imaging
  - FEL's

Extreme Light Infrastructure

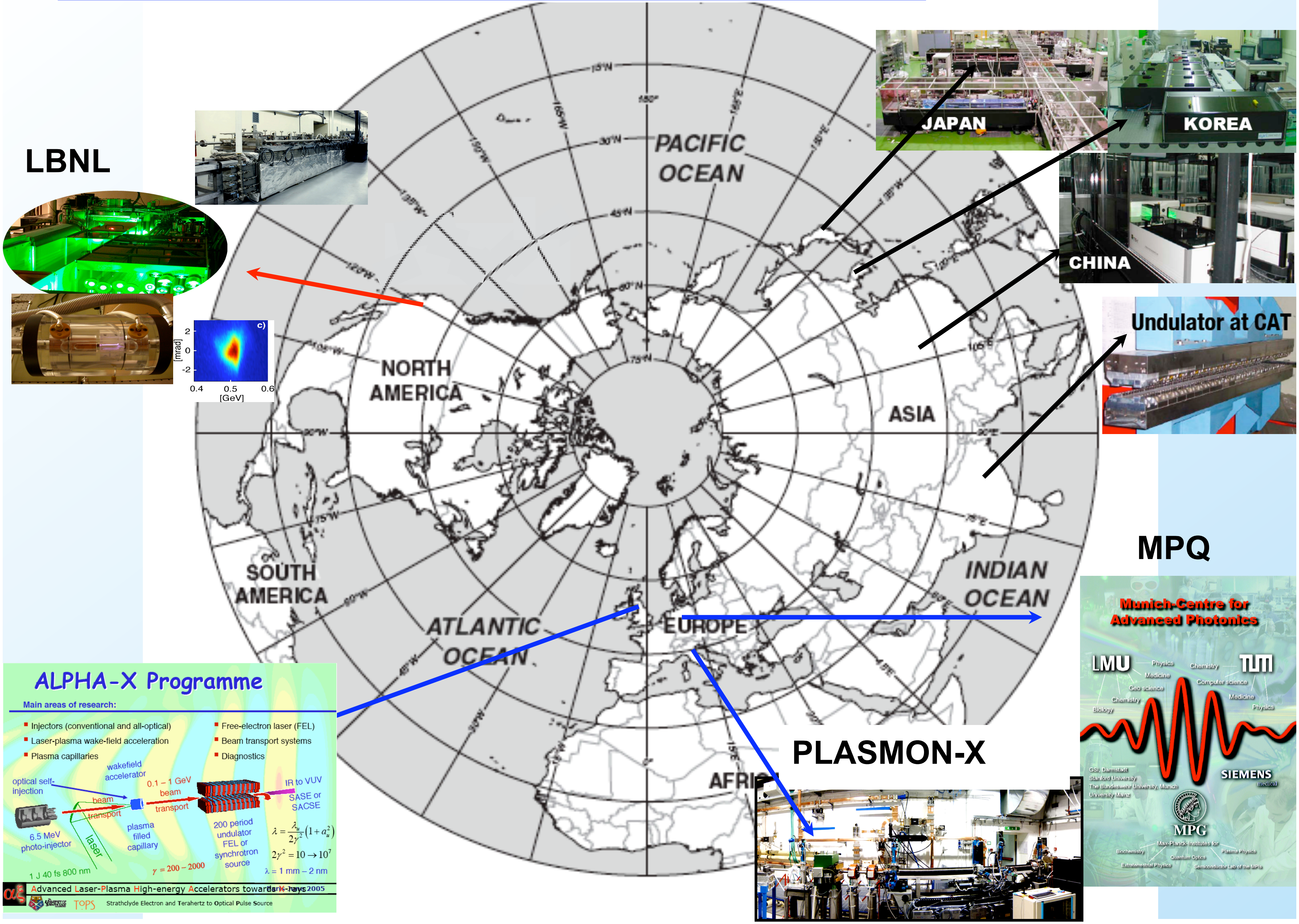




E. Gerstner, Nature 446 (2007)

Excerpt from Jay Marx report (p.82): "ELI has been called a "science integrator" that will bring many frontiers of contemporary physics, i.e. relativistic plasma physics, particle physics,nuclear physics, gravitational physics, nonlinear field theory, ultrahigh pressure physics, and cosmology together."

World-wide effort aimed at FEL using laser accelerator



Summary

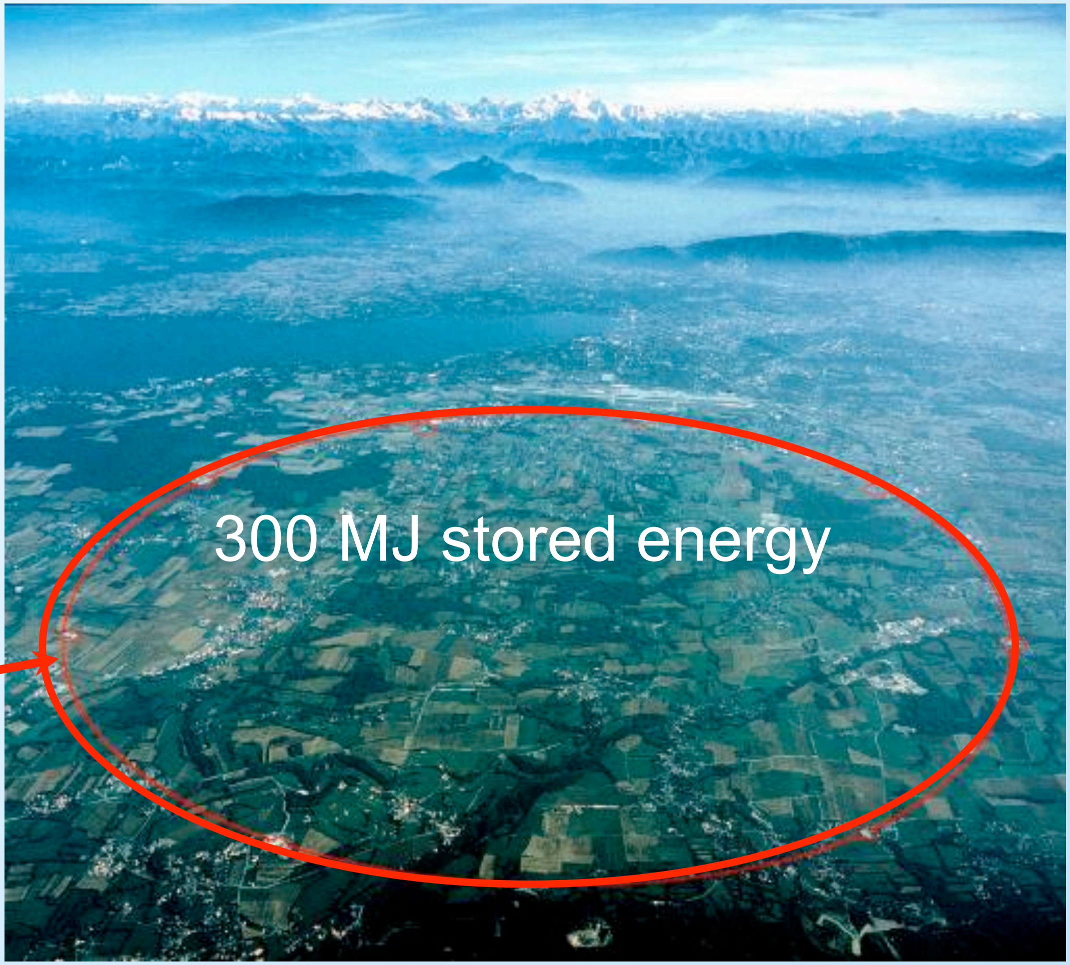
- TeV collider is extremely challenging (for any technology), let alone multi-TeV
- Steady, phased approach is needed to address major technological challenges
- Community as a whole will need to become engaged to tackle the challenges
- BELLA and FACET proposed: cornerstone facilities for AA R&D
- Laser and plasma based accelerator technology continues to show promise:
  - GeV beams (~% $\Delta E/E$) demonstrated and 10 GeV is feasible with PW laser
  - Up to 85 GeV electrons obtained in PWFA expt with 45 GeV driver
  - Laser performance continues to improve but a long way still to go

People who say it cannot be done should not interrupt those who are doing it.

George Bernard Shaw

1929

LHC, 2008



Size x 10^5 Energy x 10^9