Laser Plasma Accelerators: From Dream Towards Reality

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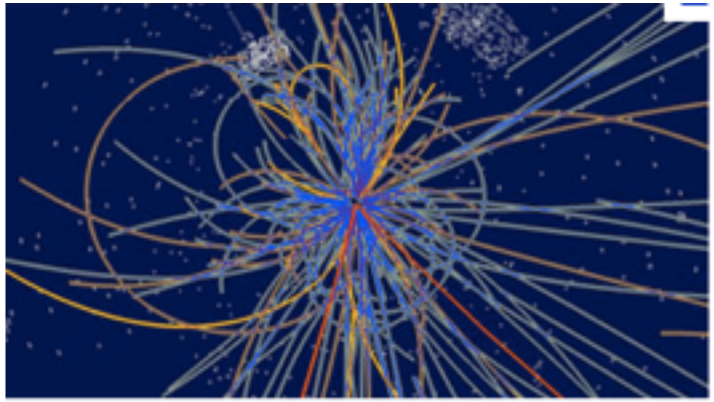
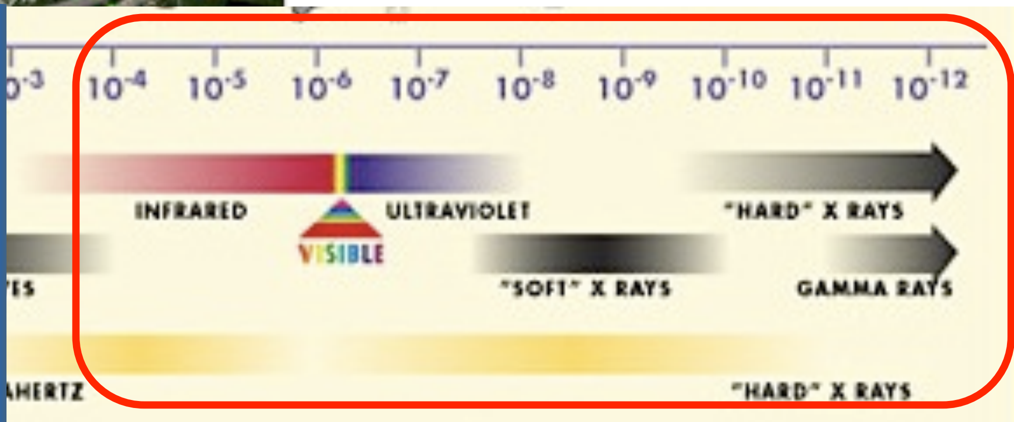
CAMOS meeting

April 5, 2011

Accelerators: drivers for science





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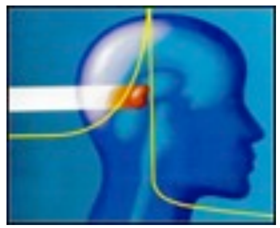
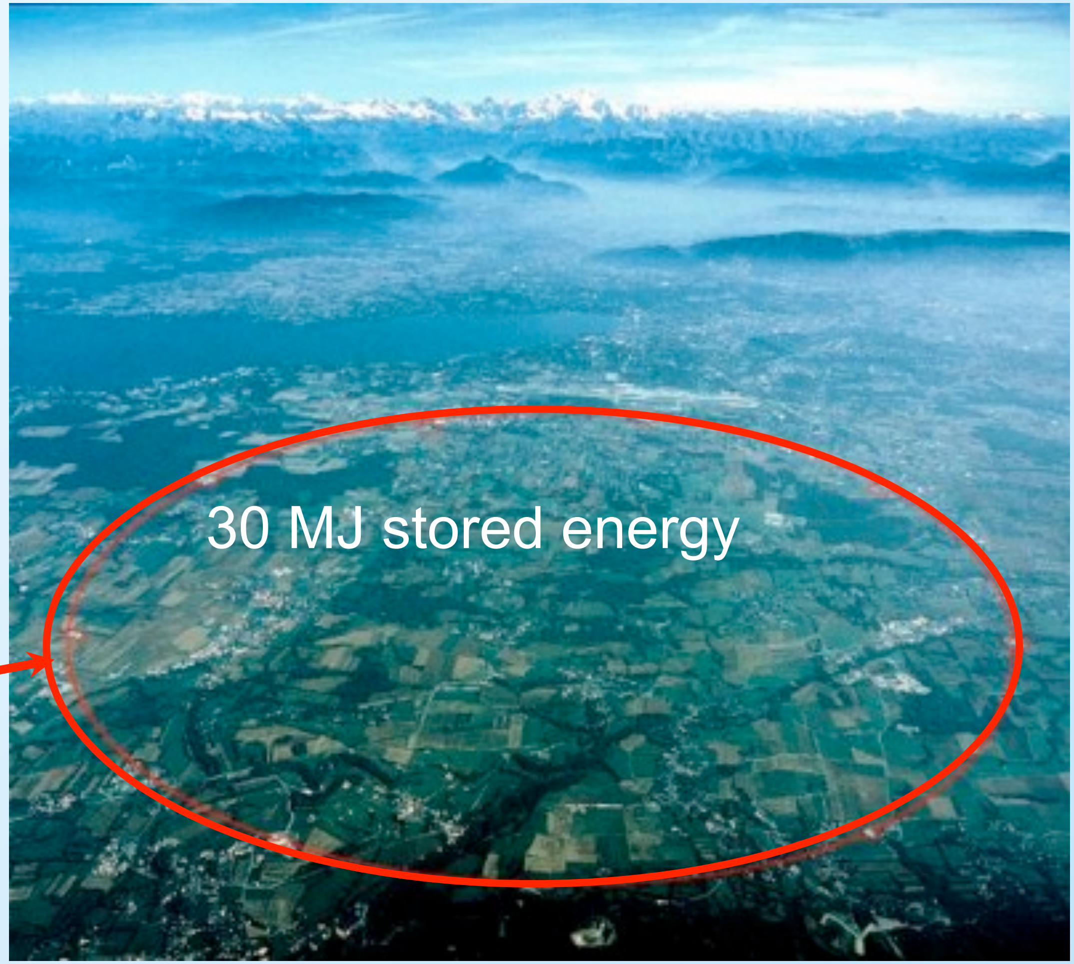


Accelerators: from handheld to size of a small country

1929

LHC, 2010



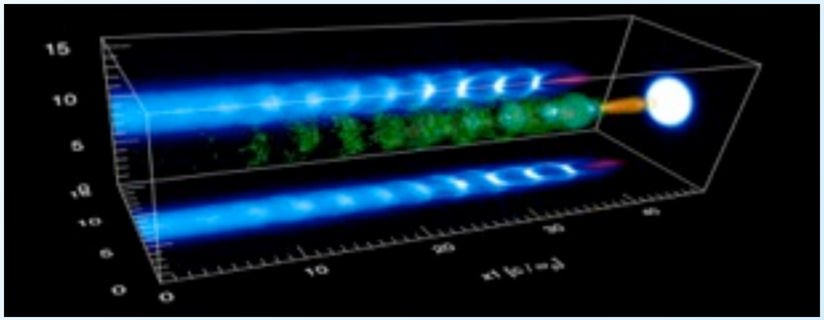
Size x 10^5 Energy x 10^9

Laser plasma acceleration enables development of "compact" accelerators

m-scale

10 – 40 MV/m

100 micron-scale



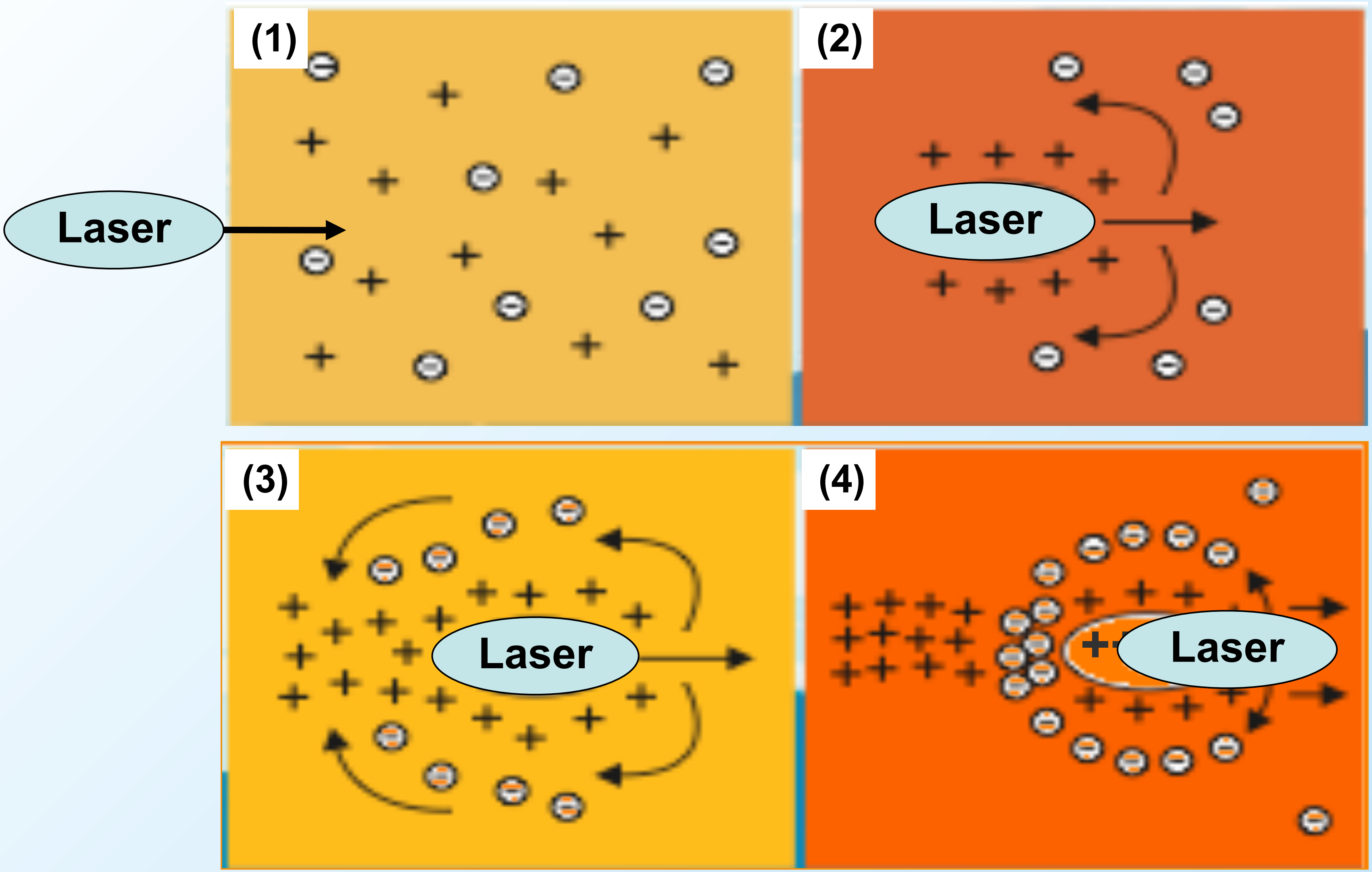
10 – 100 GV/m

Plasmas sustain extreme fields => compact accelerators
Can this technology be developed for energy frontier machines, light sources, medical or homeland security applications?

OUTLINE

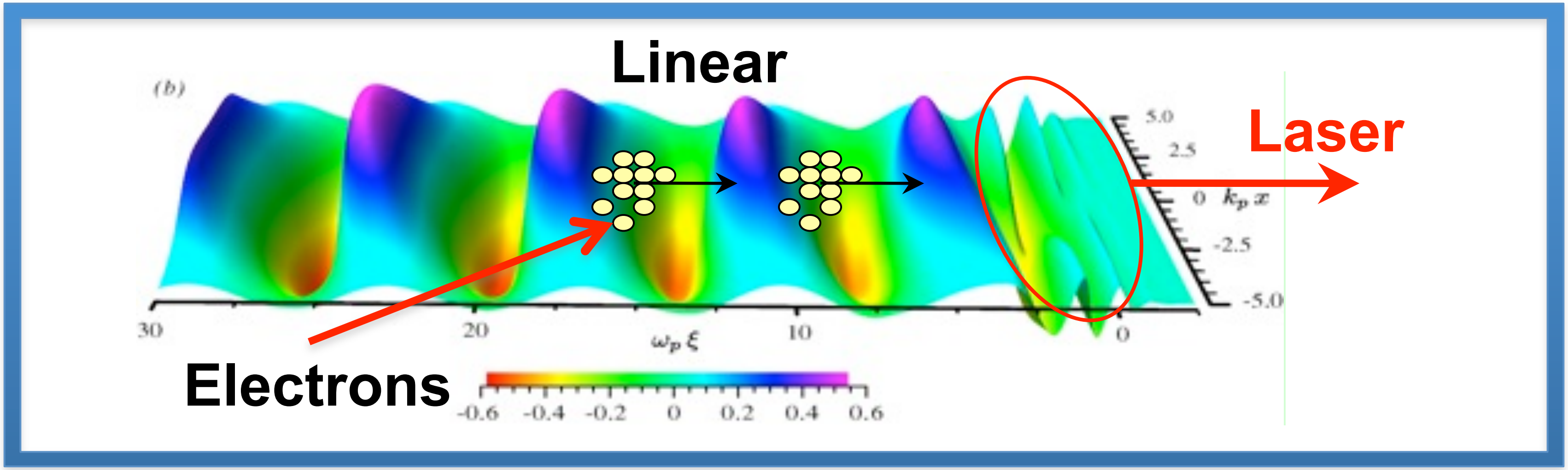
- Basic concept of laser plasma acceleration
- Controlling particle injection
- LPA as building block for a hyperspectral source
- Laser technology and investments
- Conclusion

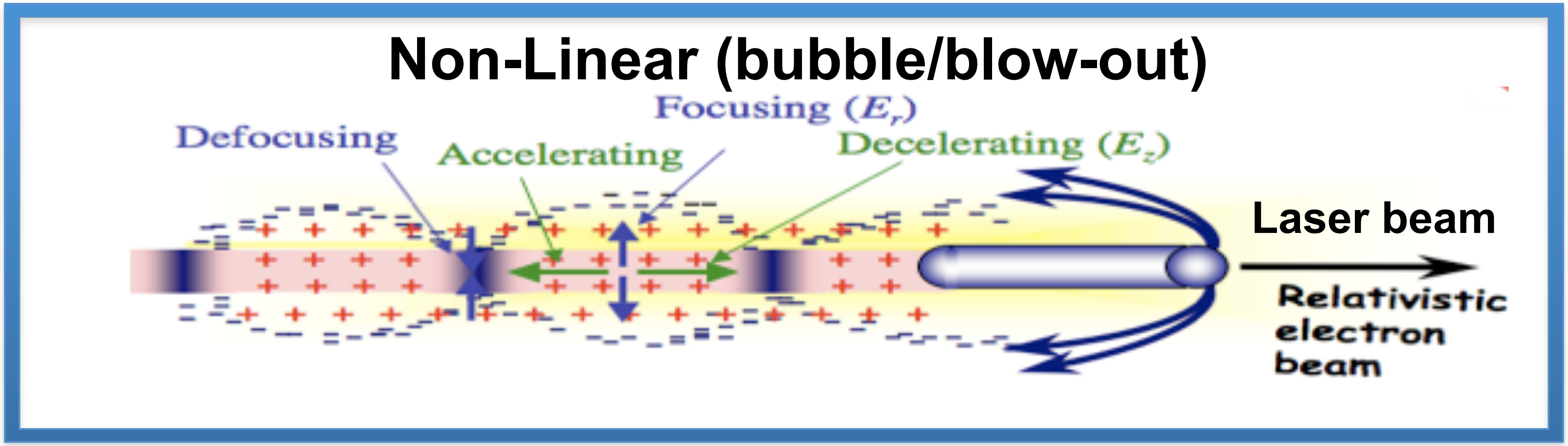
Blow-out or bubble regime: the highly non-linear regime



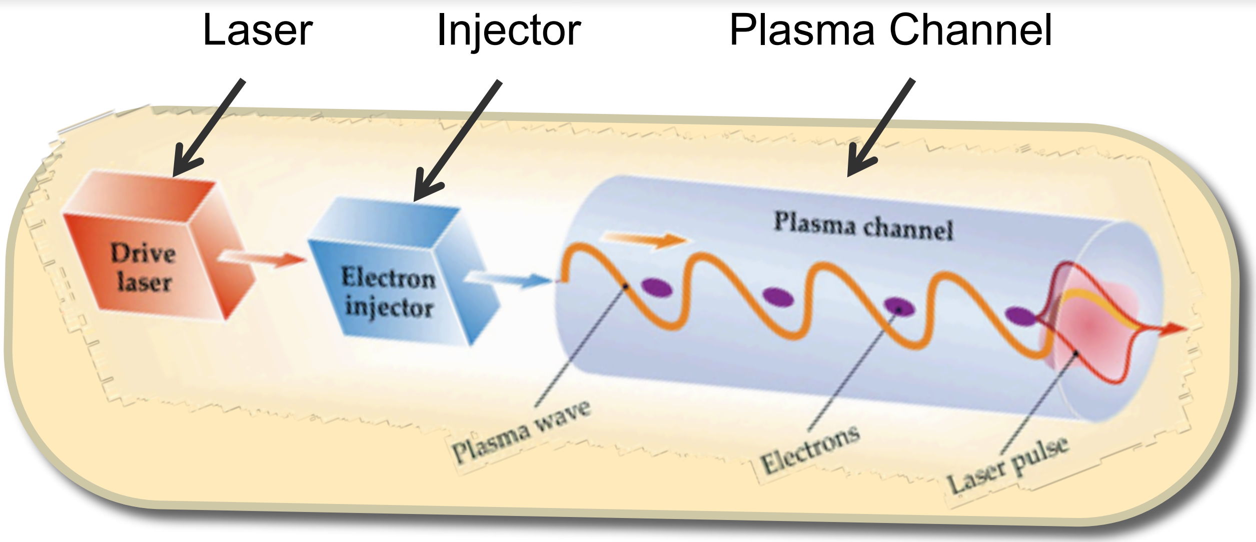
Principle of Laser-Plasma Accelerators

- E-fields: 10 – 100 GV/m => compact accelerators





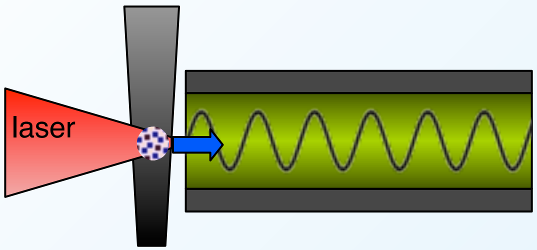
Building a laser plasma accelerator following conventional linac paradigm



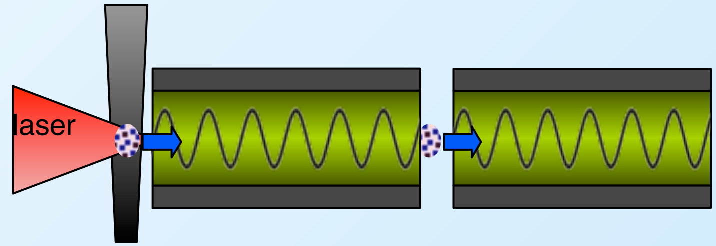
- Field excitation
- Accelerator structure and length
- Electron injection
- Laser

Leemans et al., IEEE Trans. Plasma Science (1996), Phys. Plasmas (1998)
Leemans and E. Esarey, Physics Today, March 2009
Esarey, Schroeder and Leemans, Rev. Mod. Phys (2009)

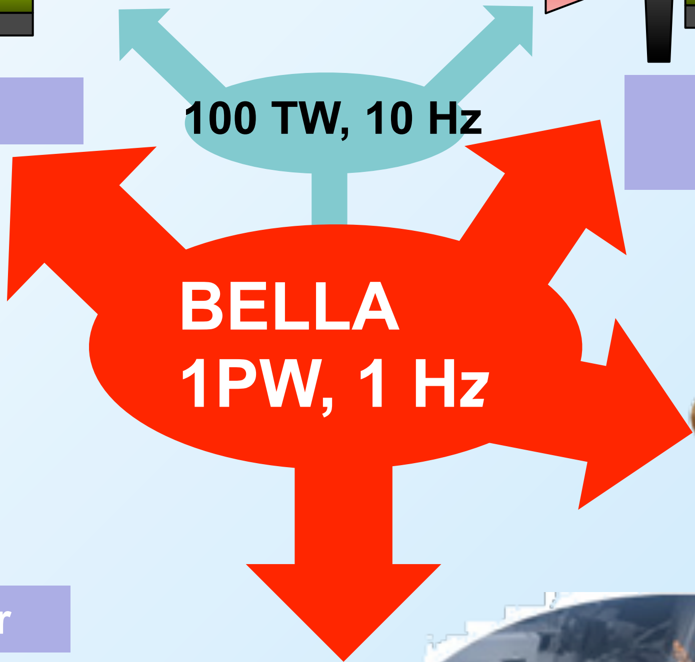
Technical challenges in next 10 years

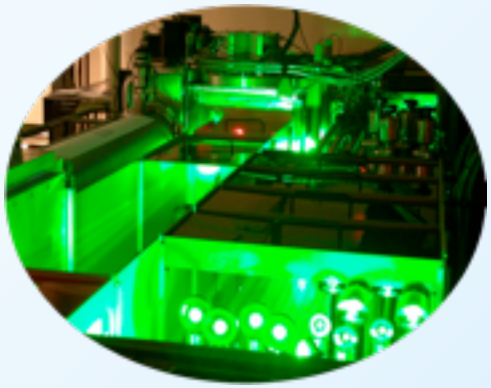


High quality beams



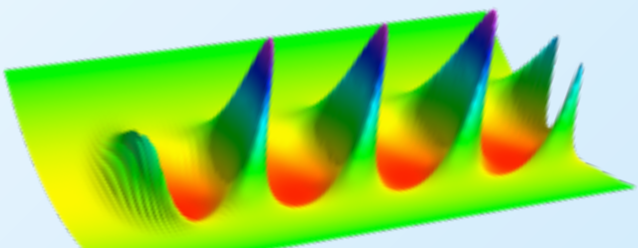
Staging, optimized structures



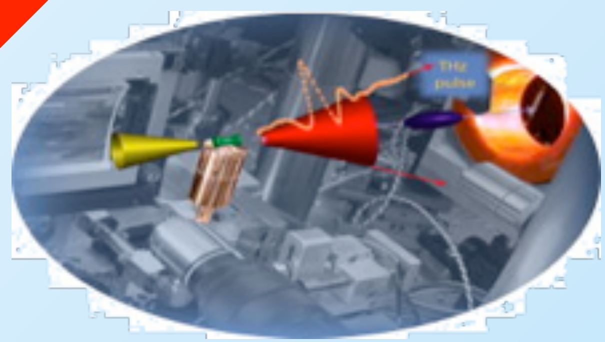


Lasers: high average power

Multi-GeV beams

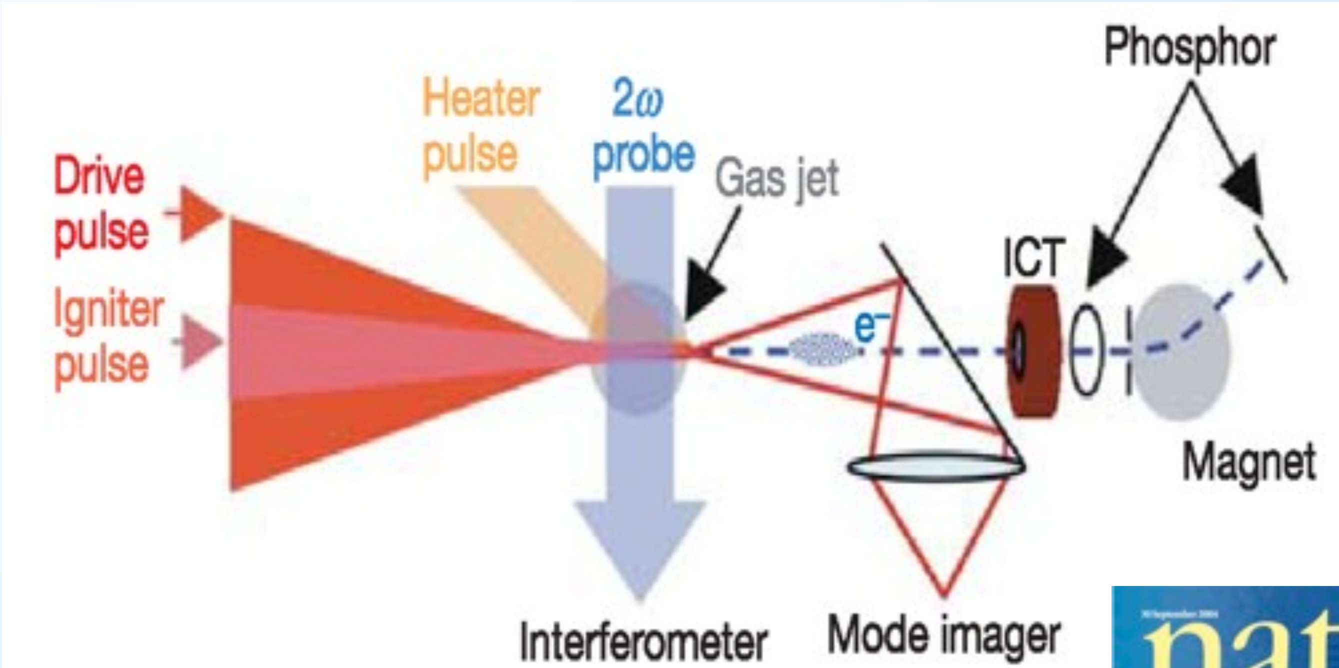


Modeling

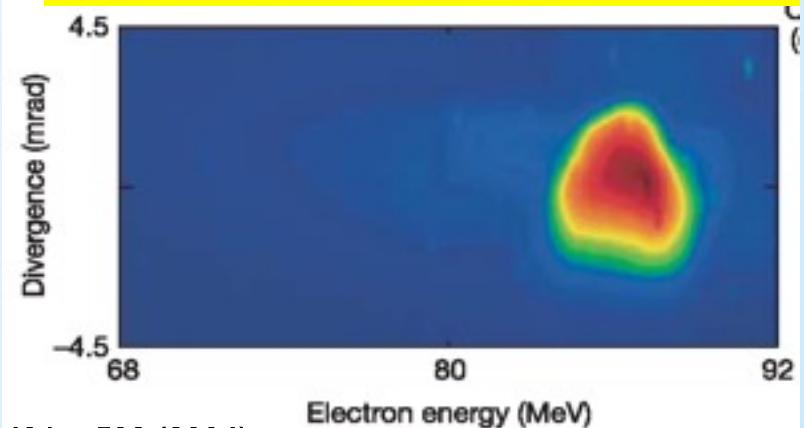


Diagnostics/Radiation sources

Channel Guided Laser Plasma Accelerators – 2004 result

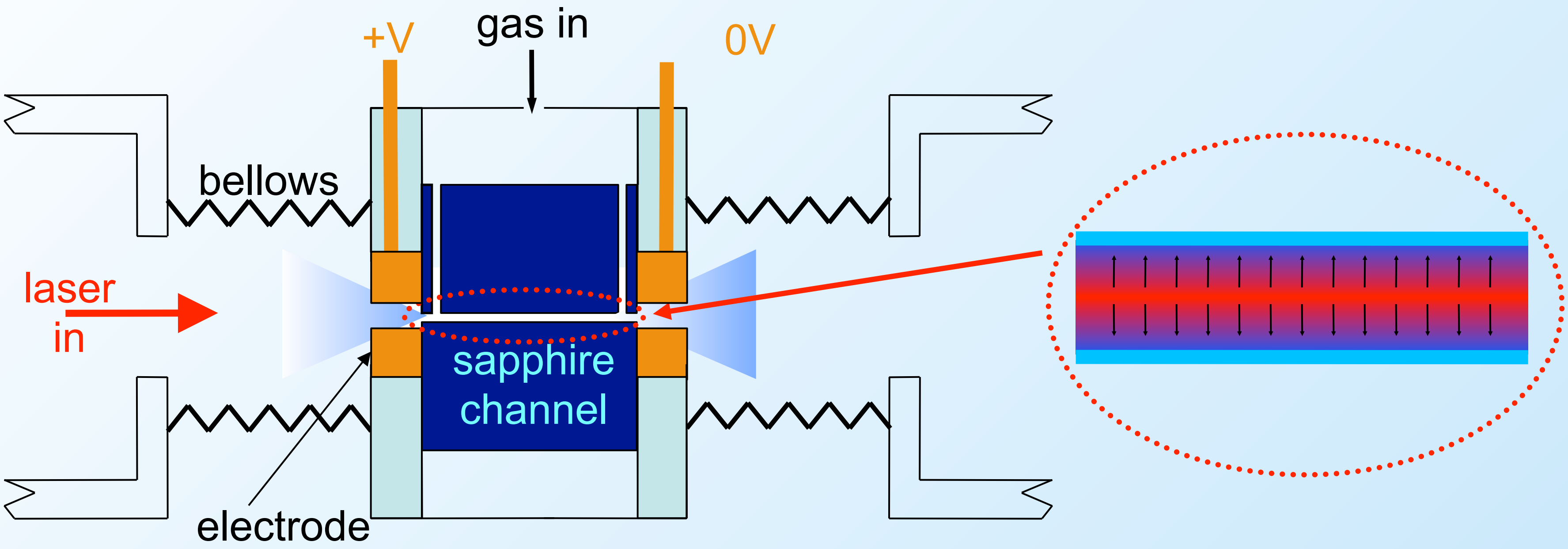


10 TW laser => 100 MeV e-beam



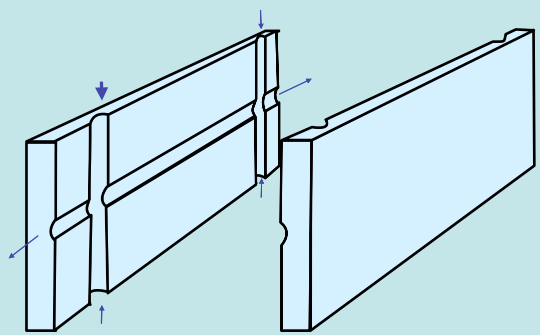
C. G. R. Geddes et al, Nature,431, p538 (2004)

Going to higher beam energy



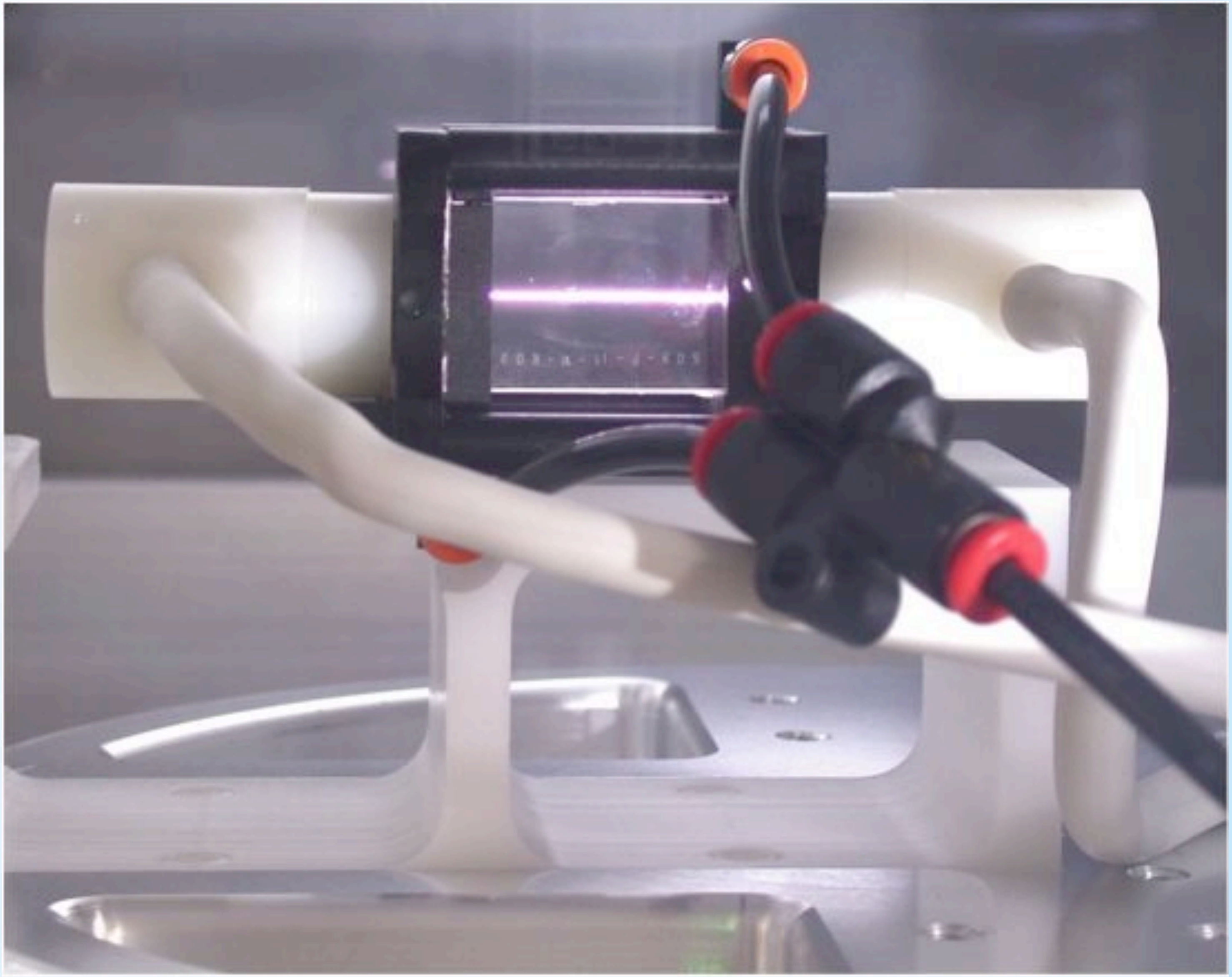
- Gas ionized by pulsed discharge
  - Peak current 200 - 500 A
  - Rise-time 50 - 100 ns

sapphire channel



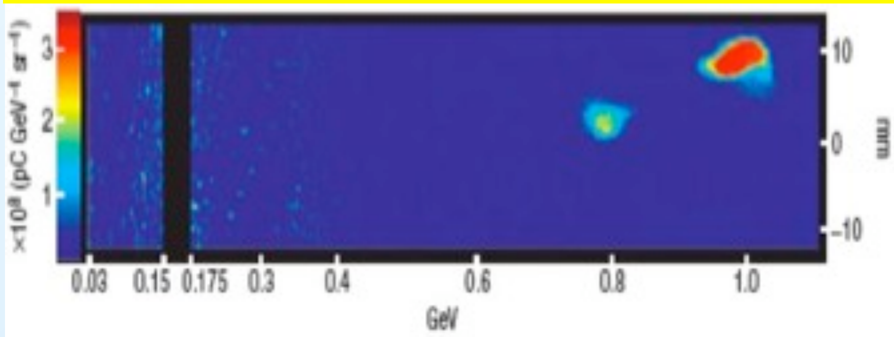
D. J. Spence & S. M. Hooker Phys. Rev. E 63 (2001) 015401 R; A. Butler et al. Phys. Rev. Lett. 89 (2002) 185003.

A GeV module…



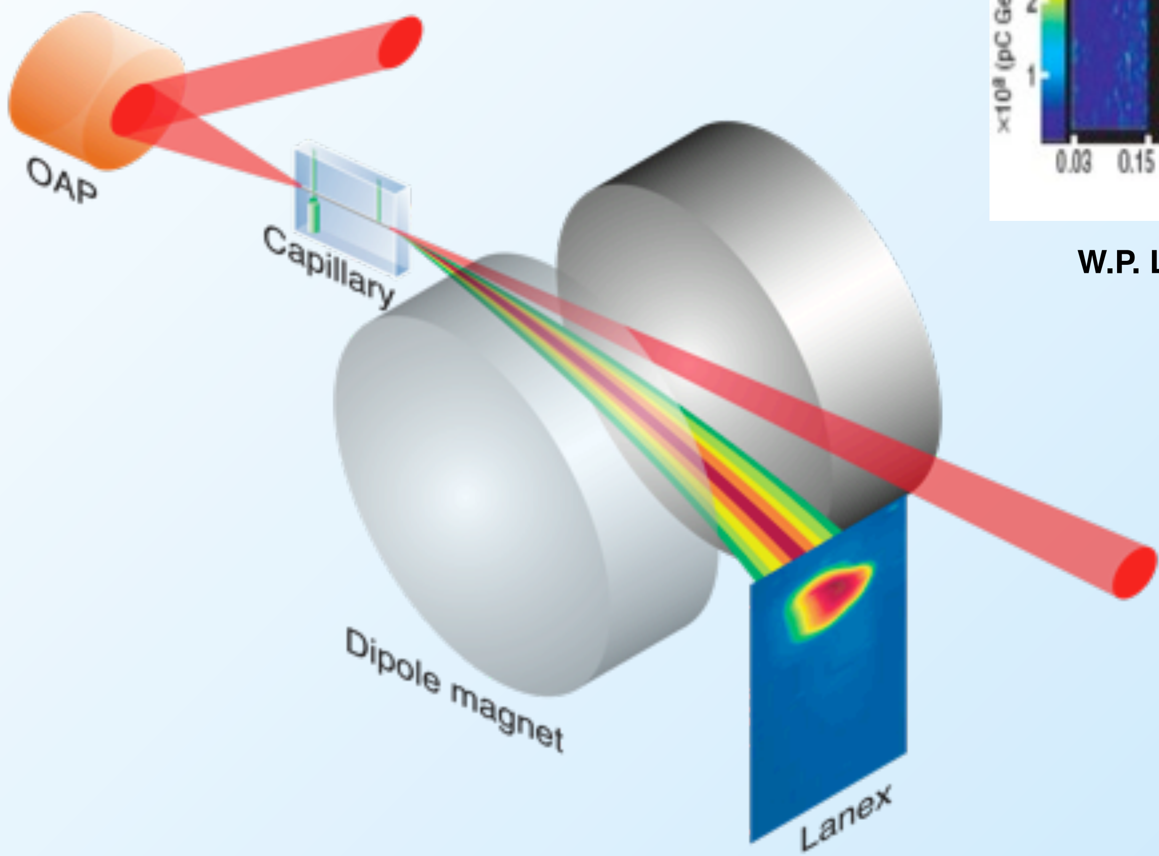
Channel Guided Laser Plasma Accelerators – 2006 result

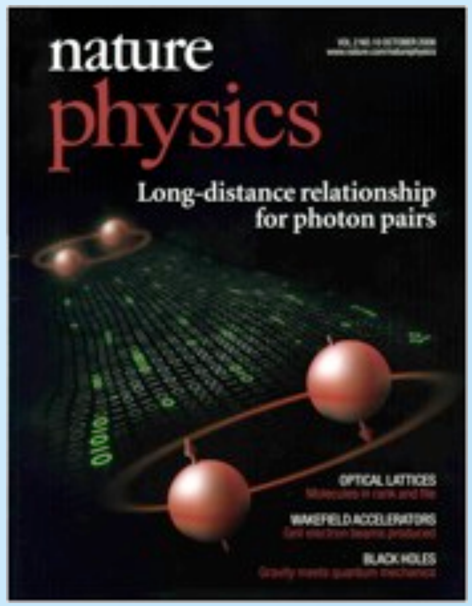
40 TW laser => 1 GeV e-beam



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

Experimental set-up





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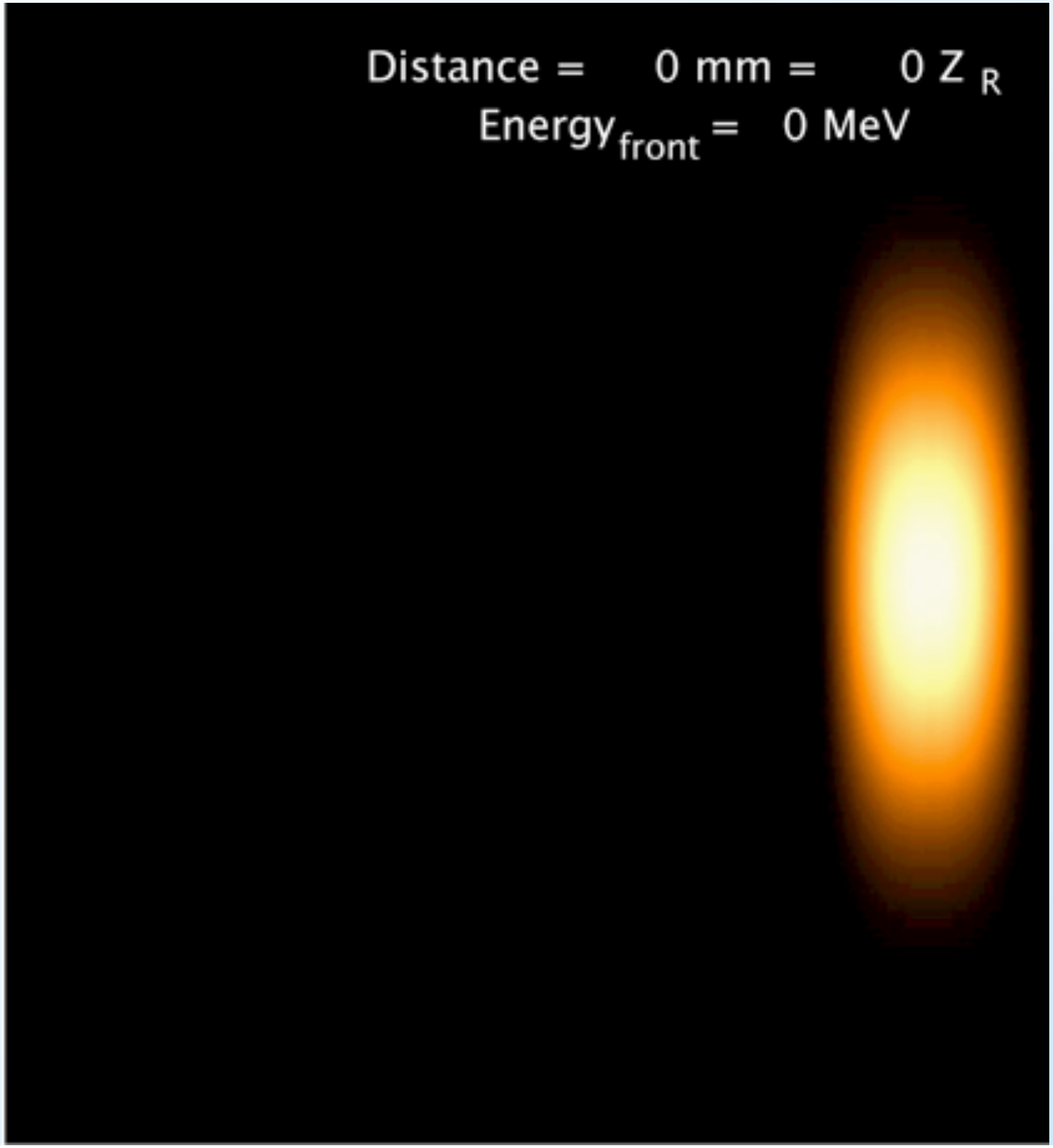
Operation in bubble non-linear regime: limited control



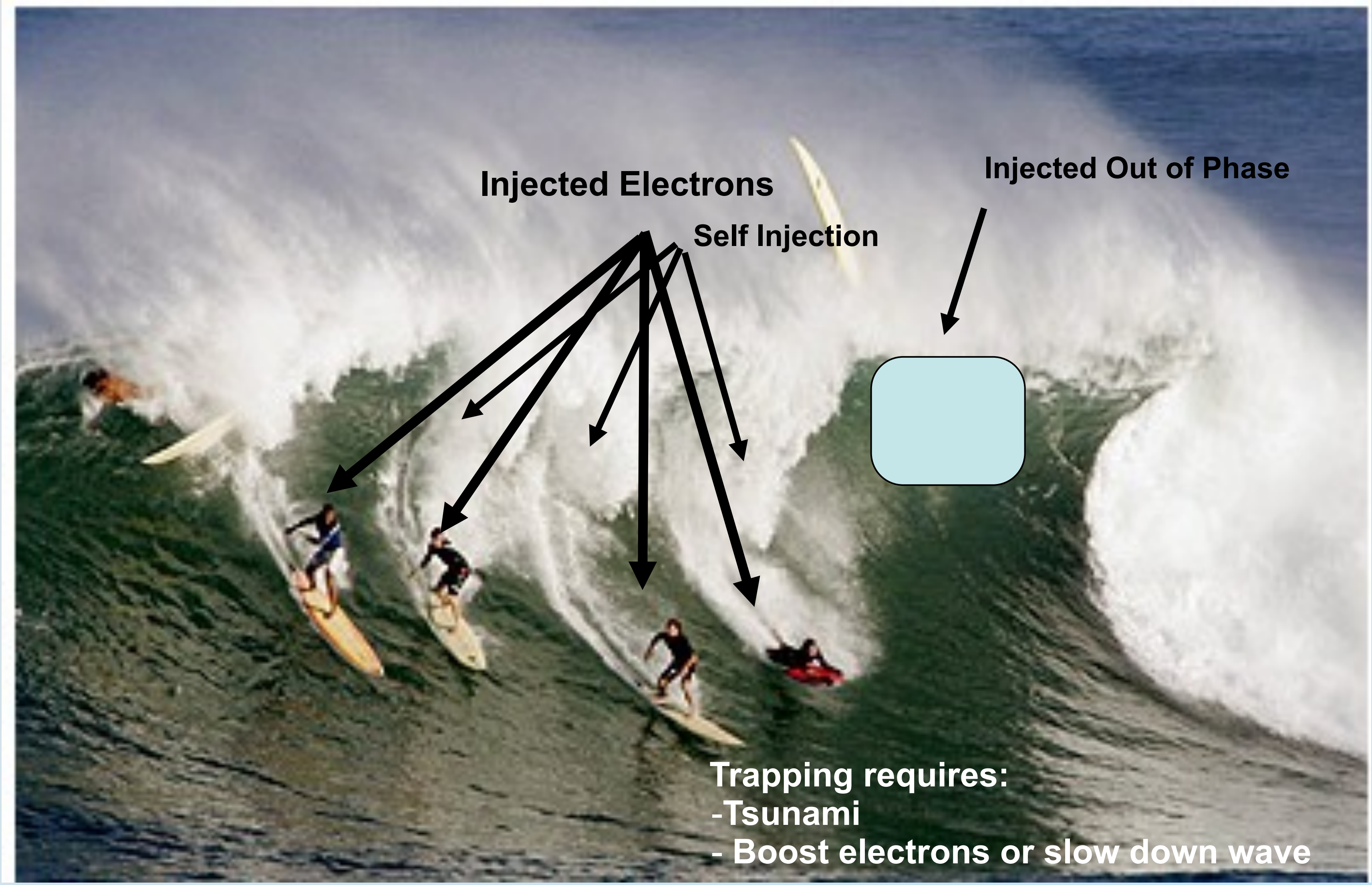
- High gradients
- Can produce narrow energy spread beams

BUT

- Limited control
- Self-trapping (dark current)
- Can easily go unstable

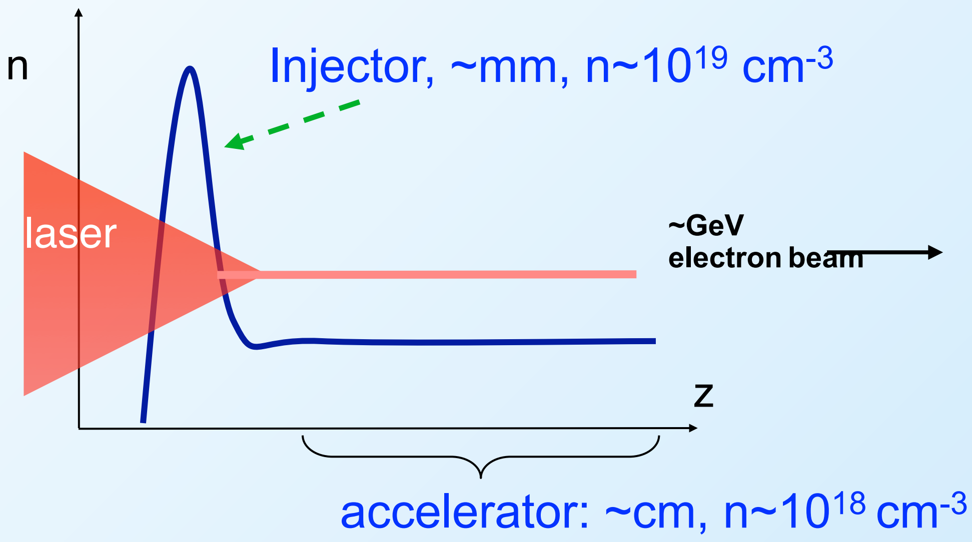
Courtesy of W. Mori, UCLA

Electrons surfing on a wave: controlled injection



Integrated injector and accelerator for stability, improved beam quality

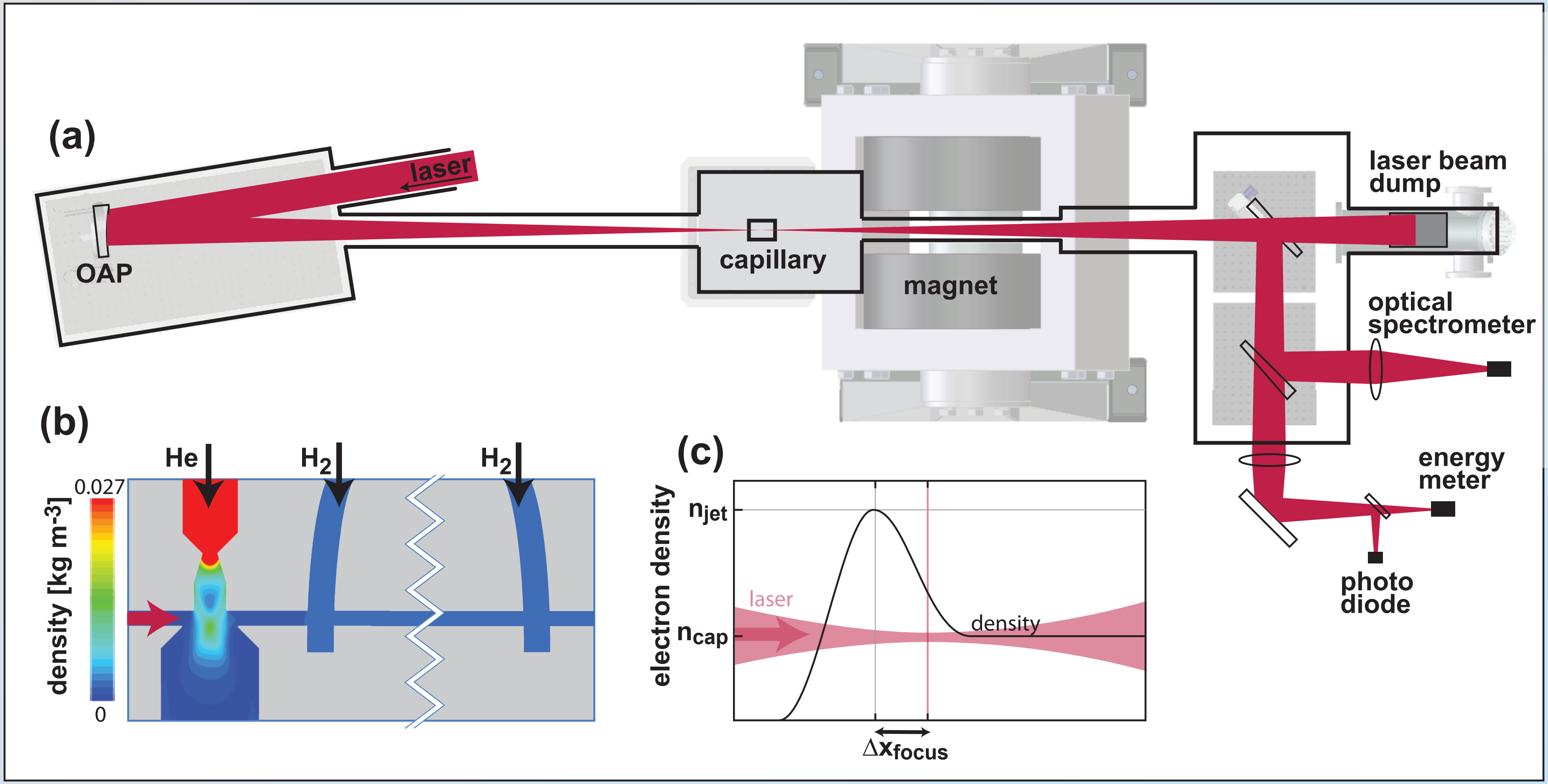
- Couple (short, high plasma density) injector to (long, low density) plasma channel:



- Two effects control wave's phase velocity:
  - Negative density gradient -> plasma wavelength increases
  - Laser focus -> relativistic self-focusing results in plasma wavelength increase (decrease) before (after) focus

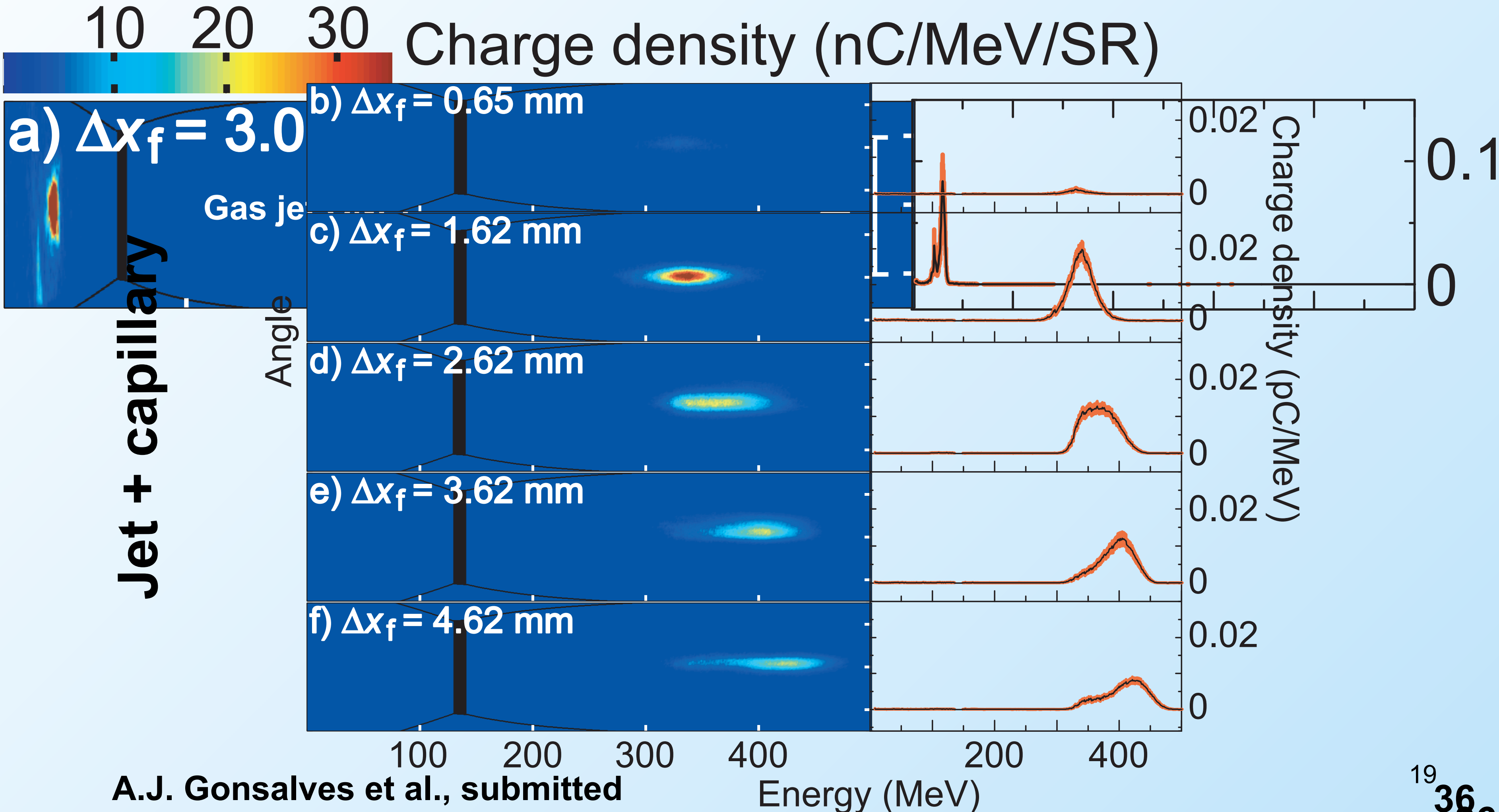
A.J. Gonsalves et al., submitted

Practical implementation of combined injector and acceleration stage



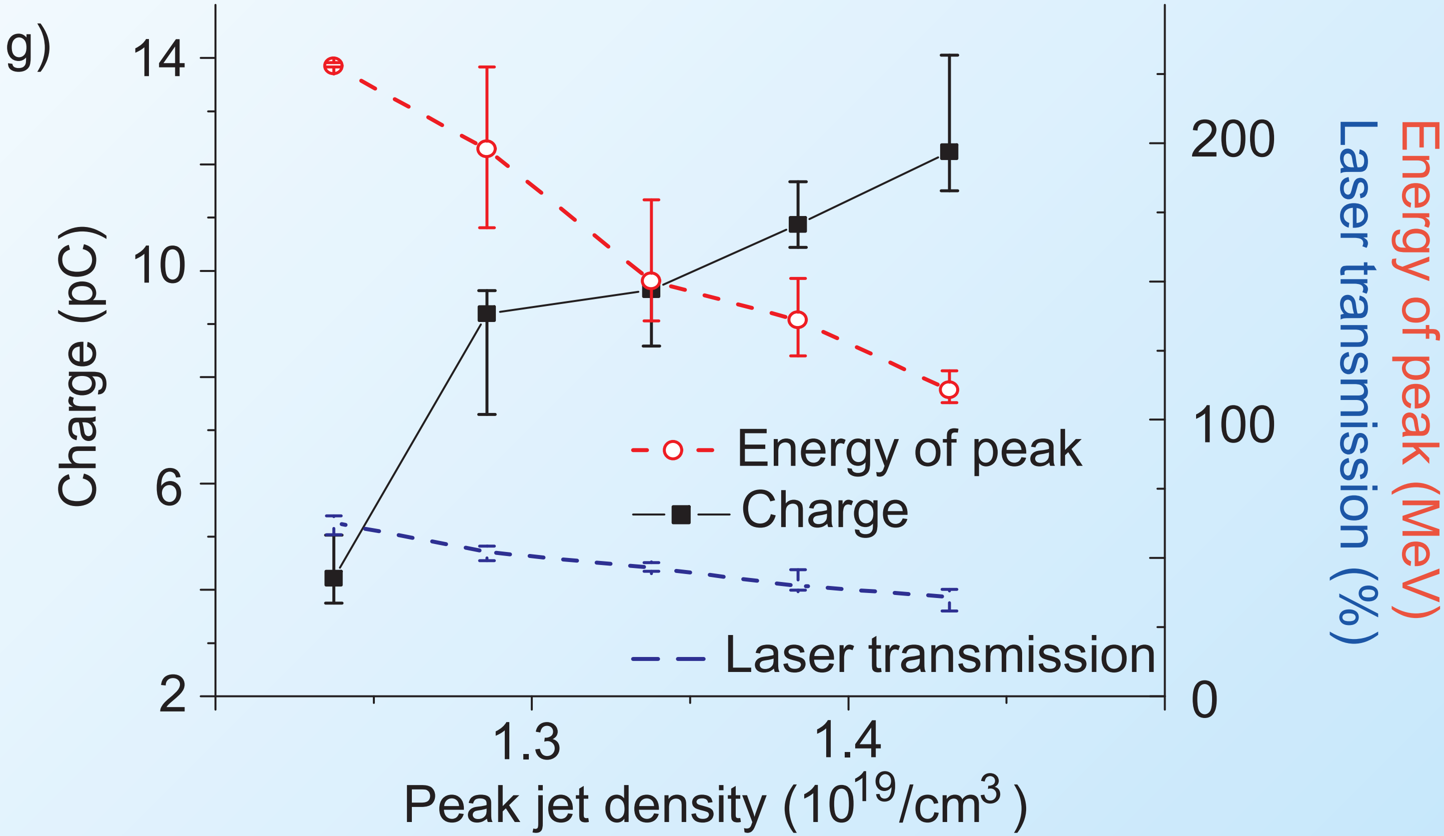
Tunable electron beams produced via laser focus control using jet+capillary module

Energy variation <1.9 % rms
Charge variation < 4% rms
Divergence change < 0.57 mrad rms



A.J. Gonsalves et al., submitted

Tunable electron beams produced via gas jet pressure control in integrated structure



A.J. Gonsalves et al., submitted

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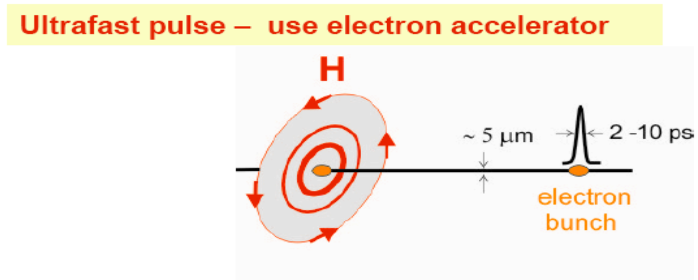
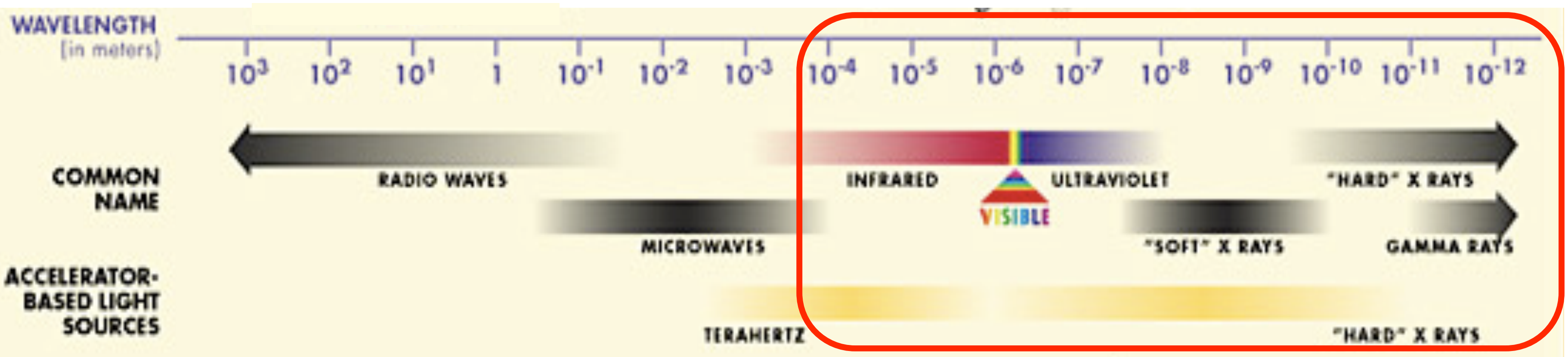
Unique bunch parameters enable wide range of forefront applications

- Bunch properties:
  - Ultra-short electron bunches, high peak current (multi-kA)
  - **Intrinsic synchronization with laser pulse**
- Direct use of e-bunches:
  - **< 10 fs intense magnetic field**
  - **< 10 fs intense electric field**
- Radiation sources:
  - **Coherent terahertz emission**
  - XUV generation
  - X-rays and gamma rays

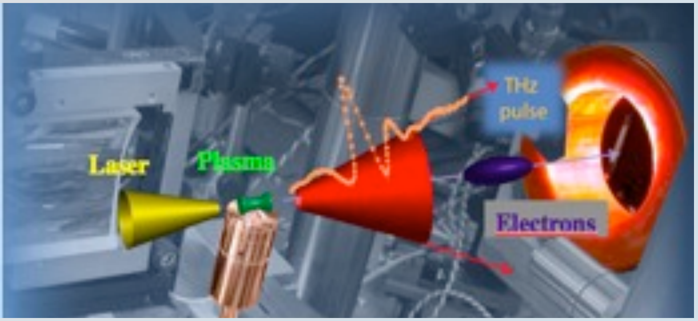


C. H. Back et al., *Science* **285**, 864 (1999)

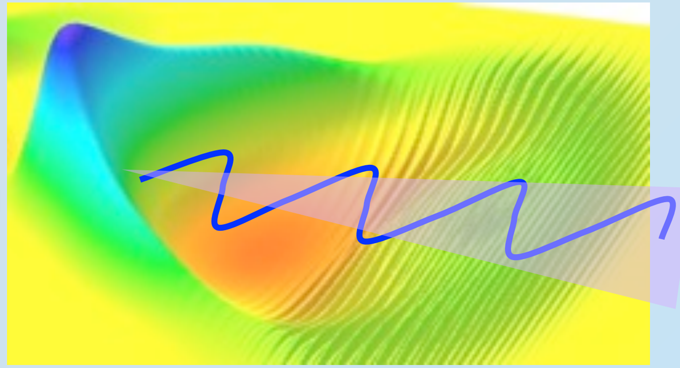


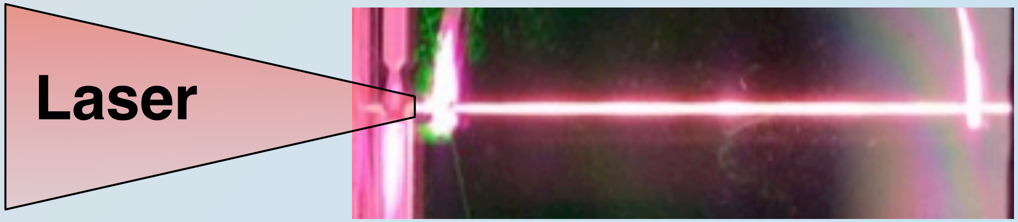
Radiation from THz to Gamma Ray – synchronized and ultra-short

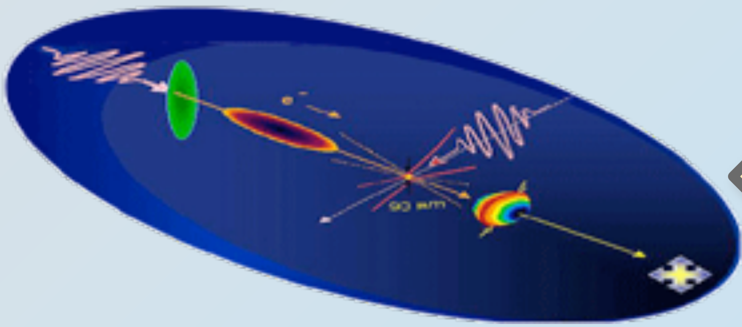
Transition radiation from beam exiting plasma – MV/cm THz



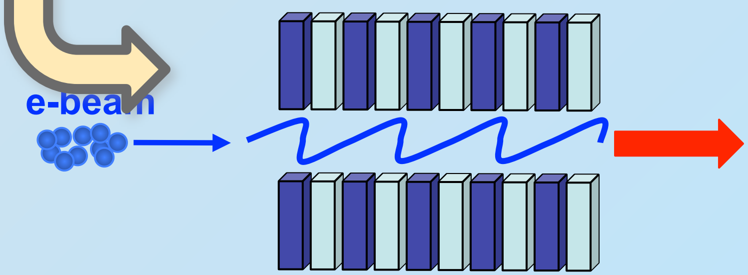
Betatron radiation during acceleration – Multi keV



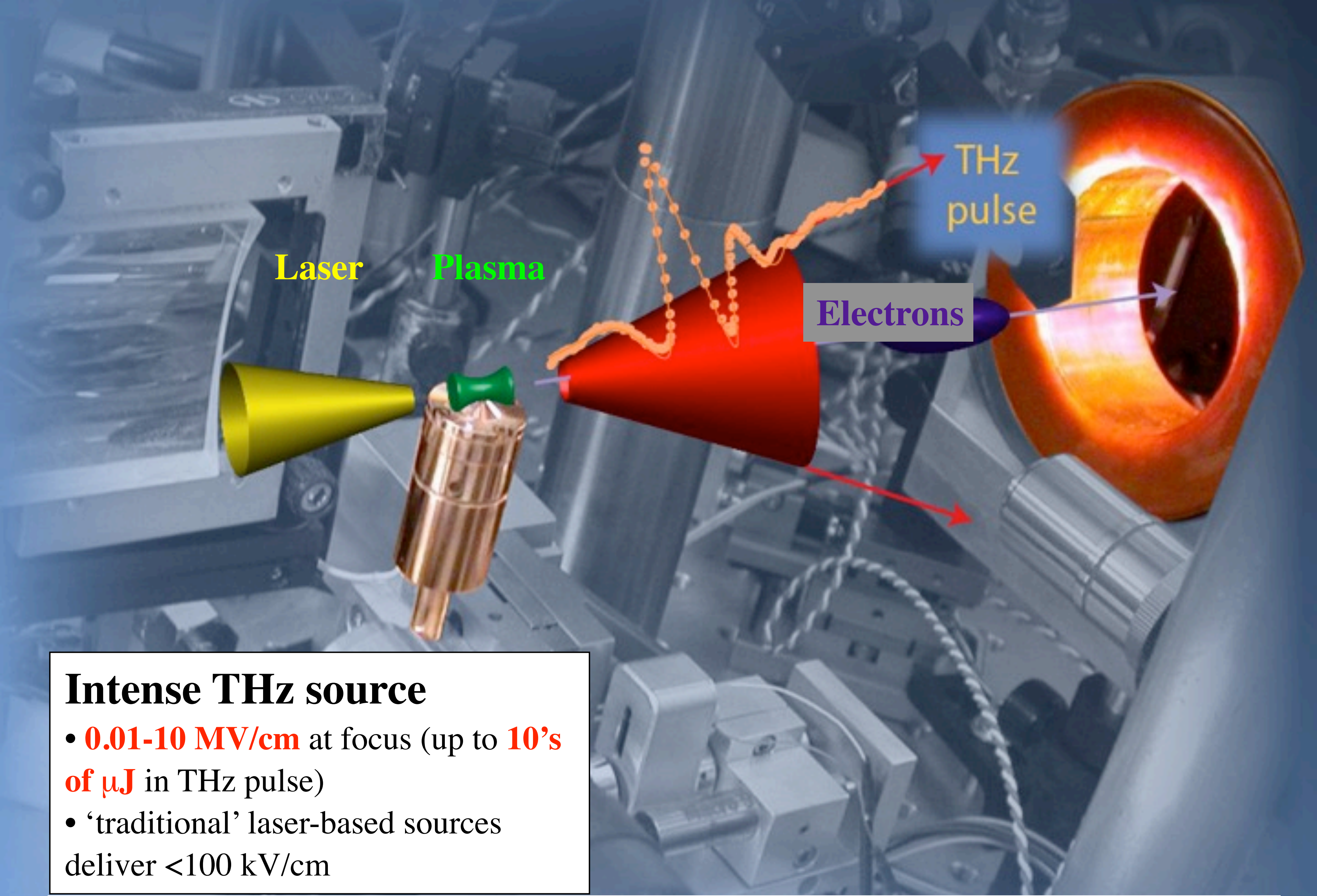




Thomson Scattering – Multi keV/ MeV x-ray/gamma ray



Free Electron Laser-> XUV, x-ray



Intense THz source

- **0.01-10 MV/cm** at focus (up to **10's of μJ** in THz pulse)
- 'traditional' laser-based sources deliver <100 kV/cm

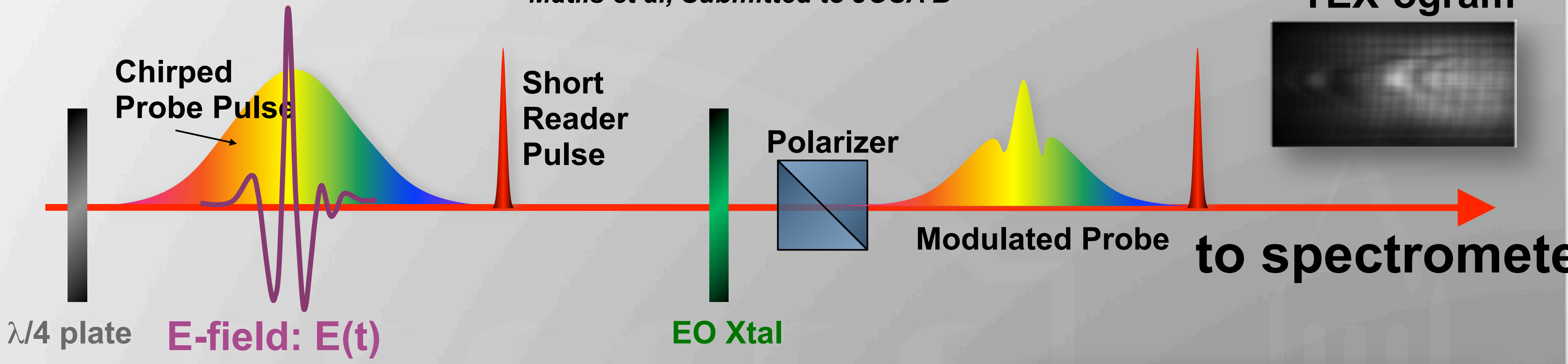
Leemans *et al*. PRL 2003; POP2004; IEEE2005 Schroeder *et al*., PRE 2004;
van Tilborg *et al*., Laser Part. Beams2004; PRL2006; POP2006; Optics Lett. 2006

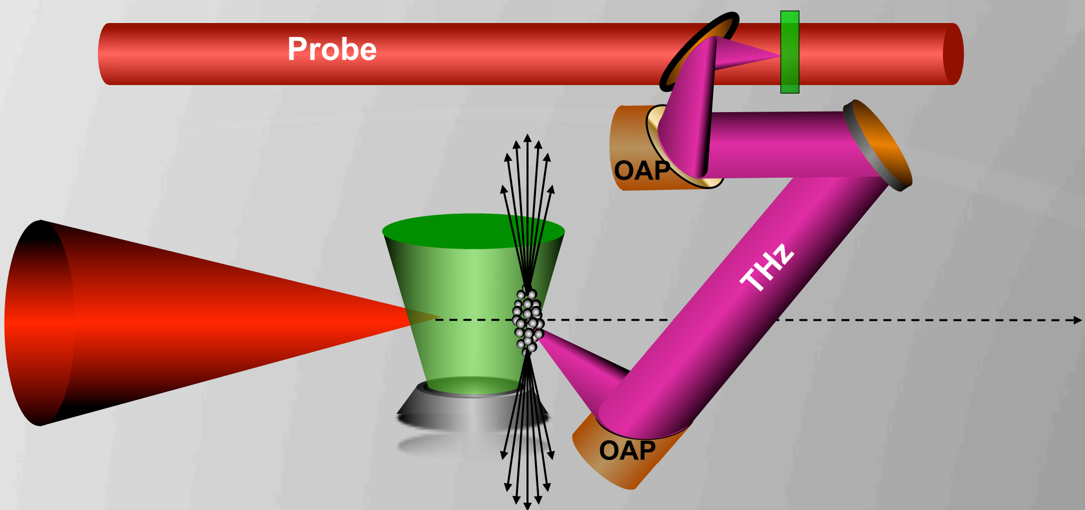
Single shot THz detection technique developed

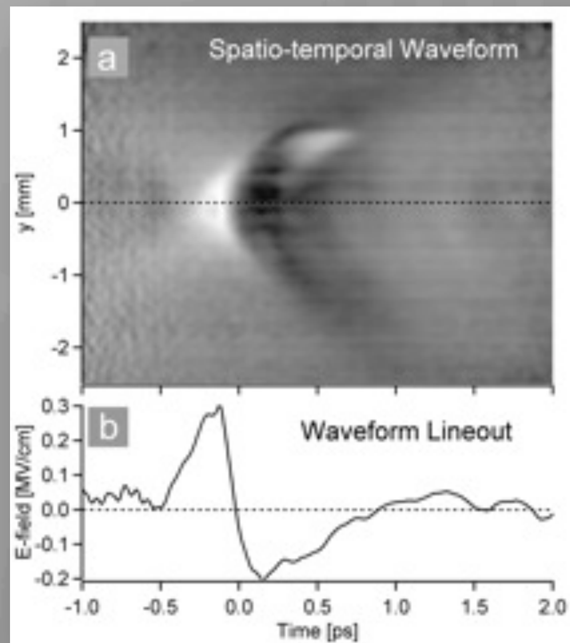
Temporal Electric-field Cross-correlation (TEX)

Matlis et al, Submitted to JOSA B

TEX-ogram



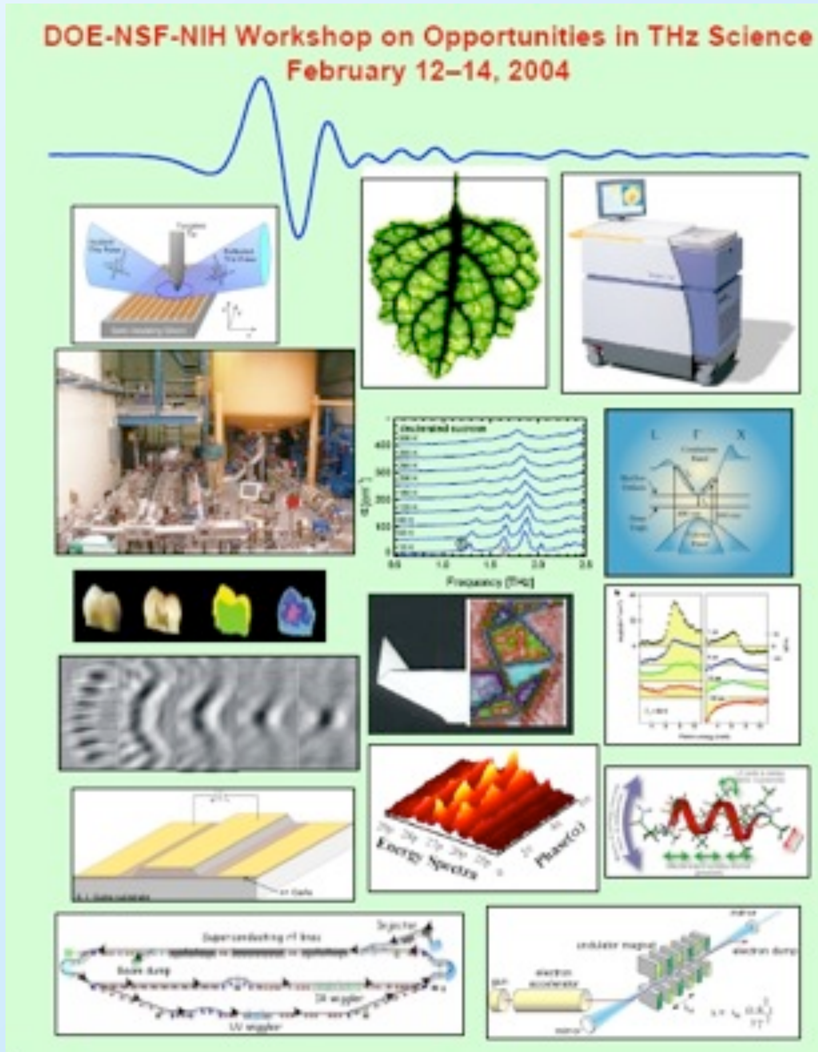




Leemans *et al*., Phys. Rev. Lett. 91(7) 074802 (2003)
Schroeder *et al*., Phys. Rev. E 69, 016501 (2004)
van Tilborg *et al*., Phys. Rev. Lett. 96, 014801 (2006)

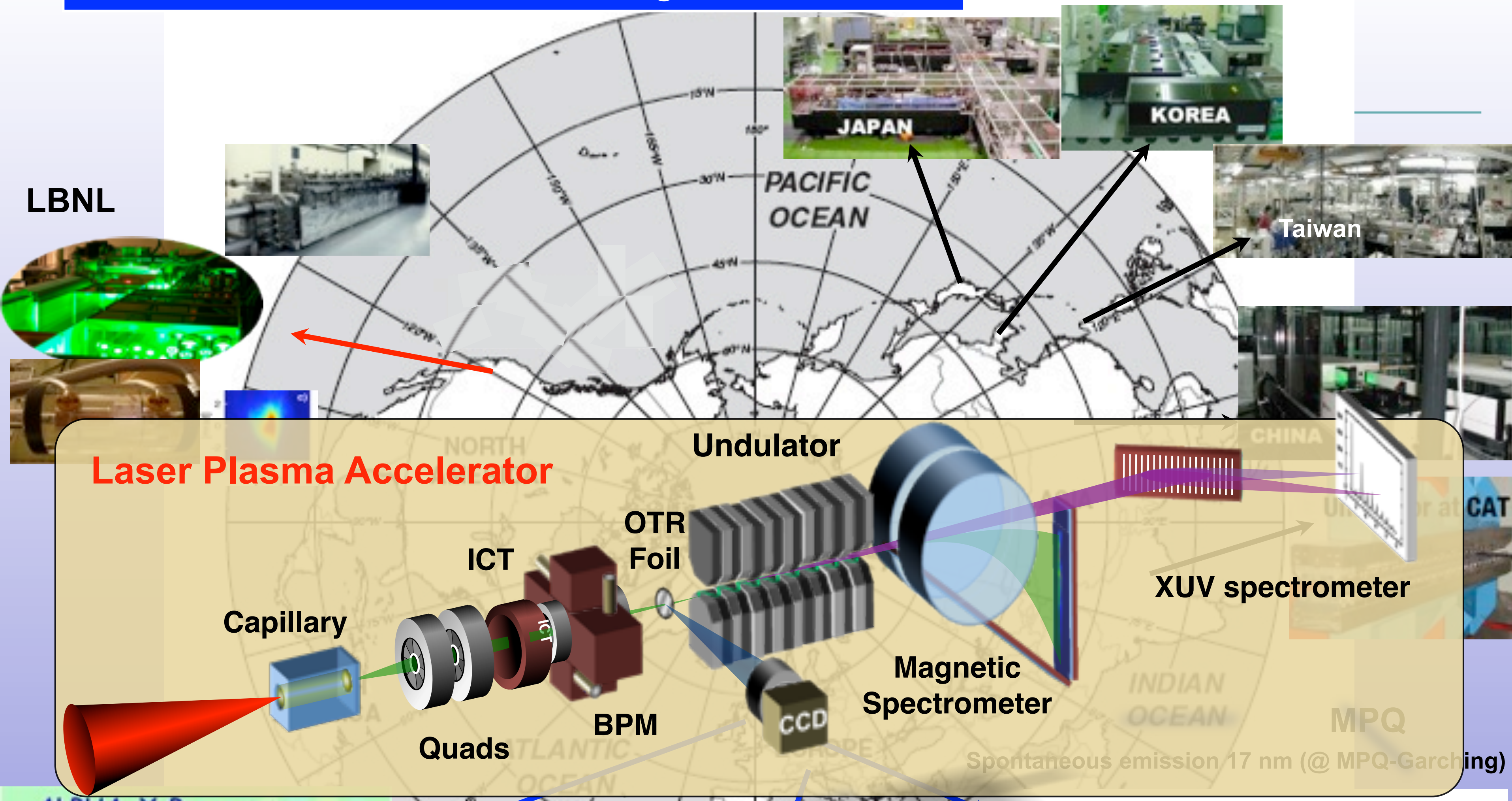
THz from Laser Accelerated Bunches ready for “user” experiments

- THz source properties
  - E_{THz} ~ 1-5 MV/cm
  - High frequency 0.5-10 THz
  - Intrinsic synchronization with laser, electrons, x-rays, etc.
  - Single shot time-space resolved THz waveform measurement*
- Pump-probe experiments:
  - Superconducting material studies (e.g., breaking of Cooper pairs)
  - Non-linear carrier dynamics in semi-conductors



* N.H. Matlis et al., JOSA-B 2011

World-wide effort aimed at FEL using laser accelerator



Main challenges:

➡ Beam quality:

➡ Energy spread, emittance, peak current

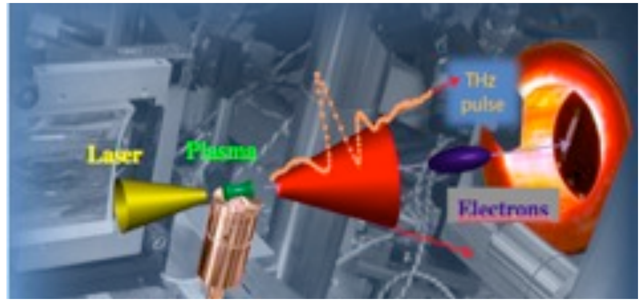
➡ Seeding for temporal coherence

Beam brightness studies are underway

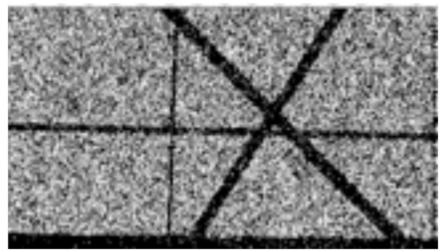
- Bunch duration:
  - Fluctuational interferometry (Catravas et al., PRL 1999)
  - THz radiation -- upper bound (van Tilborg et al., PRL2006)
  - Coherent OTR -- mm scale distance from LPA (Glinec et al., PRL2007, Lundh et al., NP 2011)

- Emittance & energy spread:
  - Betatron source size and e-beam divergence (Plateau et al., in preparation)
  - Slice energy spread via coherent OTR (COTR) -- meter scale distance from LPA (Lin et al., submitted)
  - Undulator based diagnostic

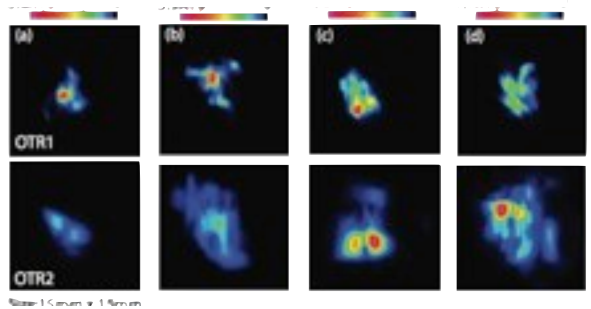
Transition radiation from beam exiting plasma – coherent THz



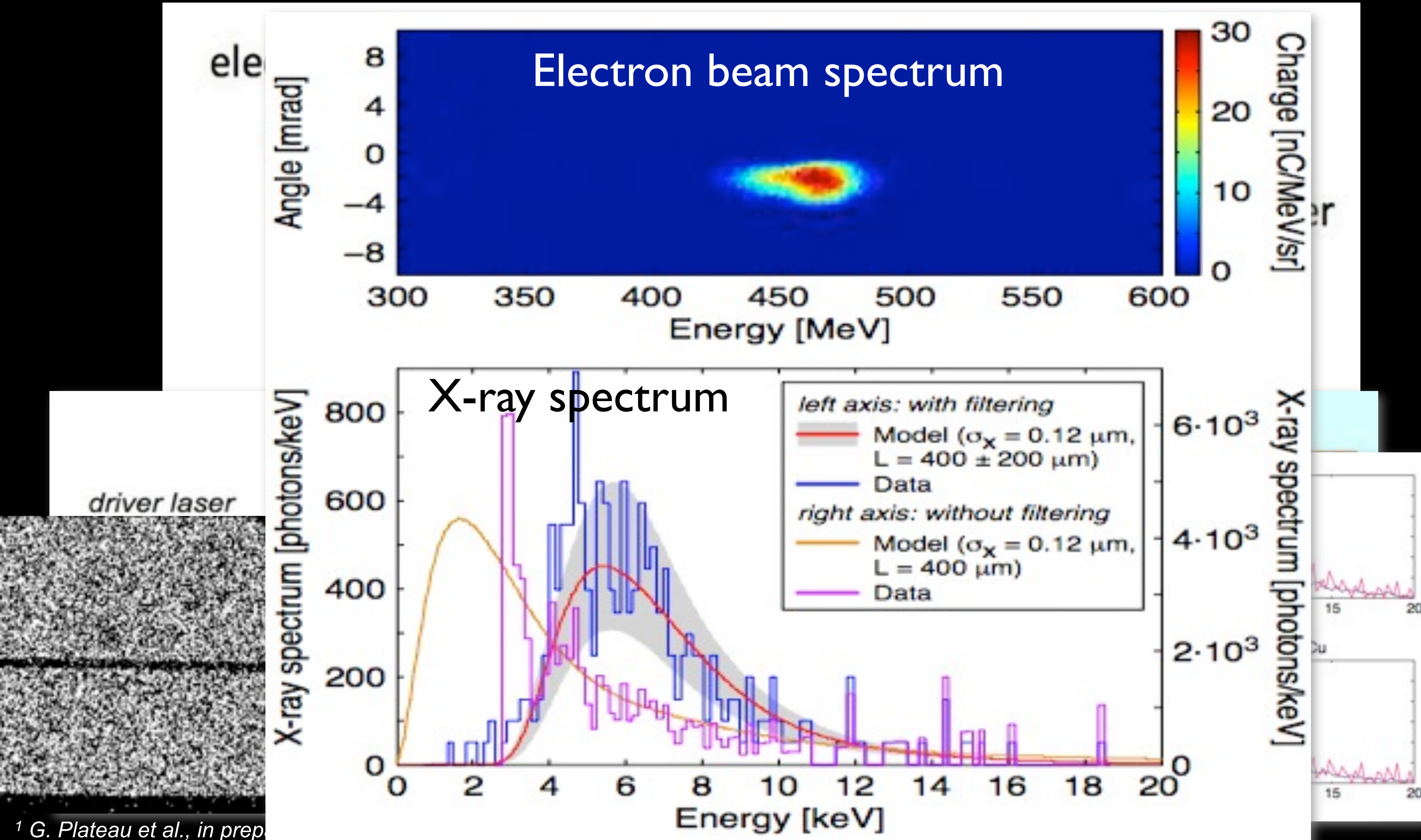
Single shot X-Ray Image



Coherent optical radiation



Ultra-low emittance of electron beam is deduced from x-rays produced by electrons inside LPA



[1] G. Plateau et al., in prep

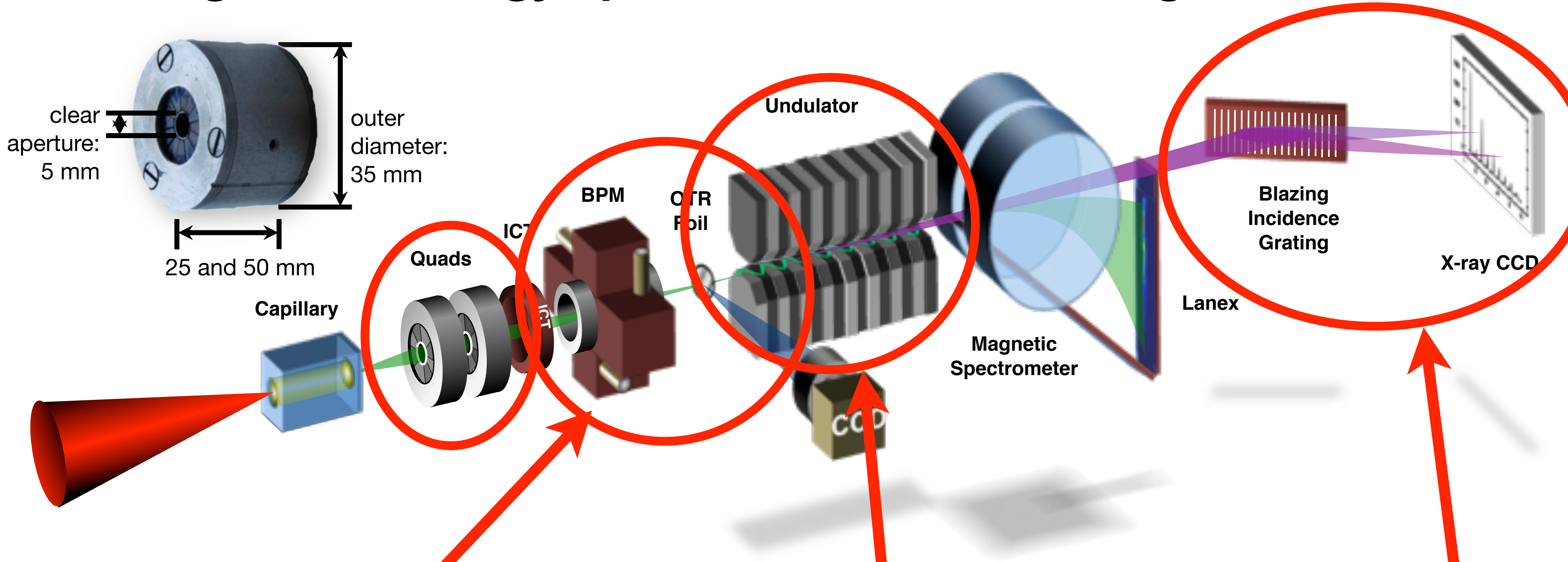
[2] E. Esarey et al., PRE **65** 056505 (2002)

[3] M. Chen et al., In preparation (2011)

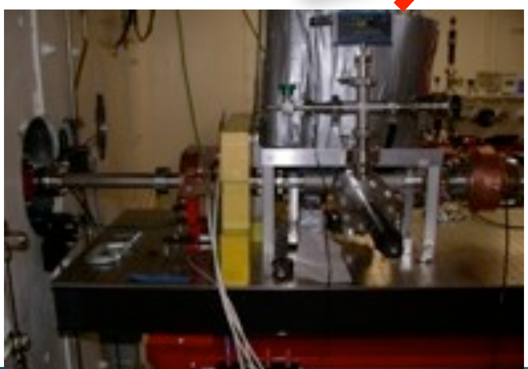
Normalized emittance < 0.2 micron

Undulator radiation experiment: towards an FEL powered by LPA

Single shot energy spread and emittance diagnostic

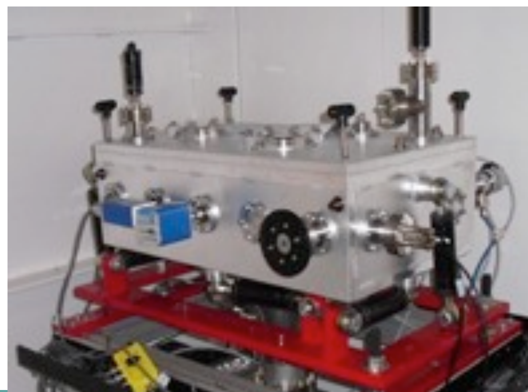


BPM & OTR

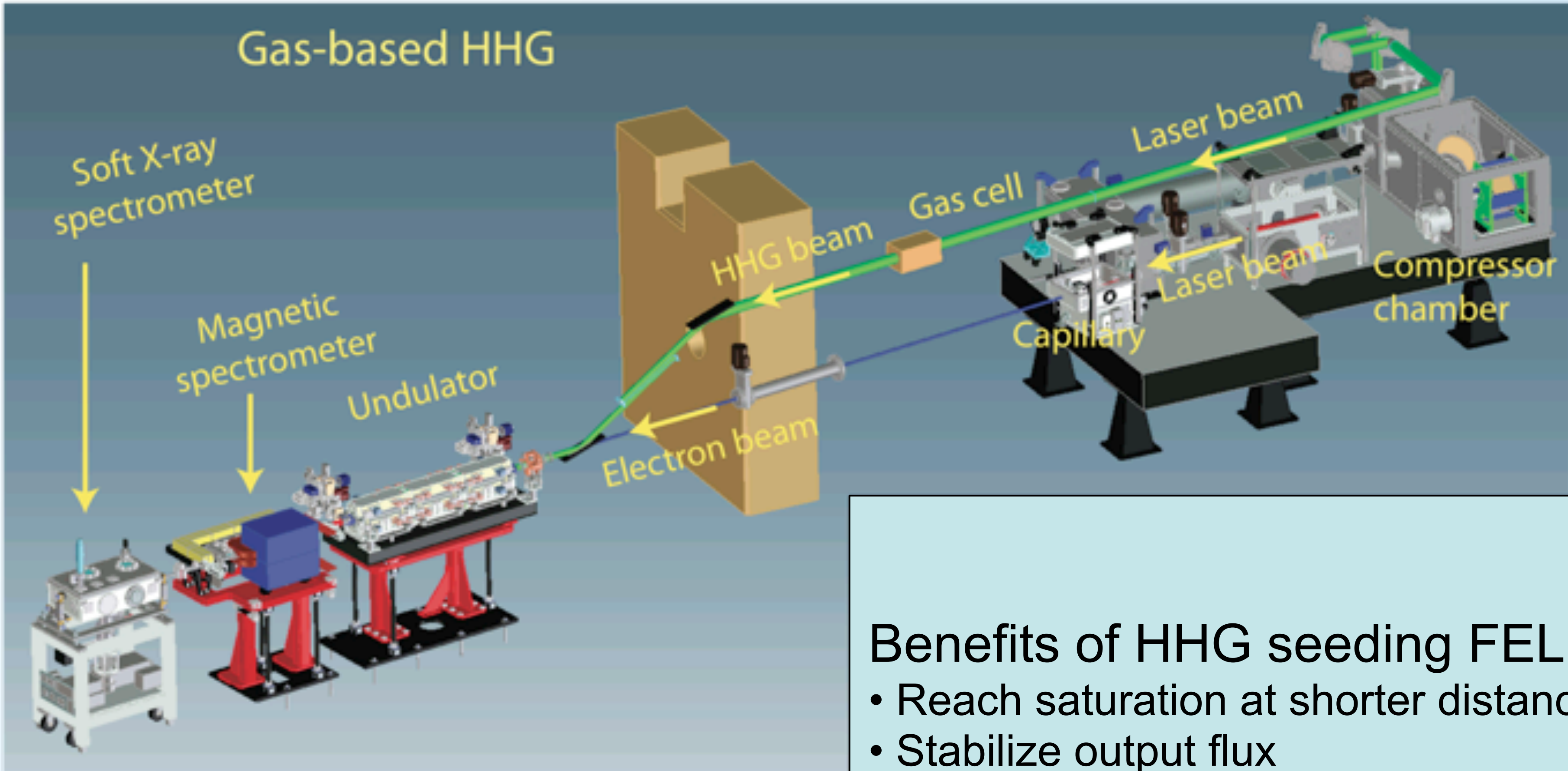


THUNDER Undulator

Single-shot XUV Spectrometer



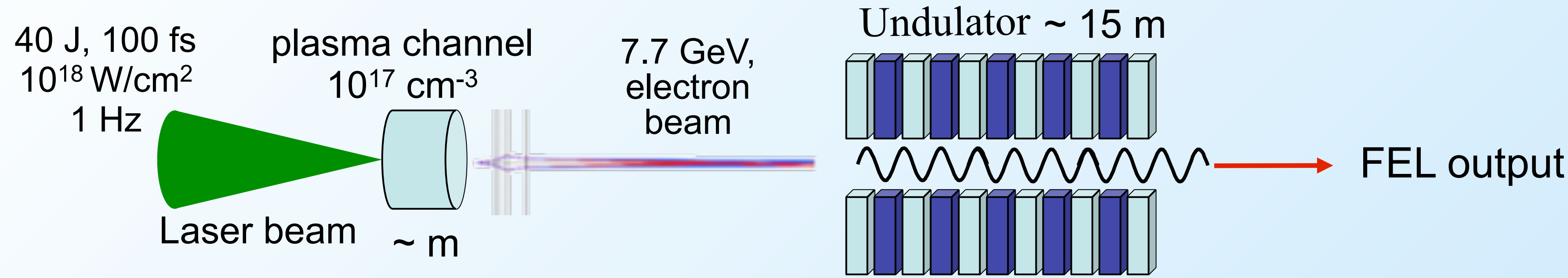
Experiments on seeding the FEL being planned



Benefits of HHG seeding FEL

- Reach saturation at shorter distance
- Stabilize output flux
- Improve temporal coherence

Laser-plasma accelerator driven soft x-ray FEL at 1 nm

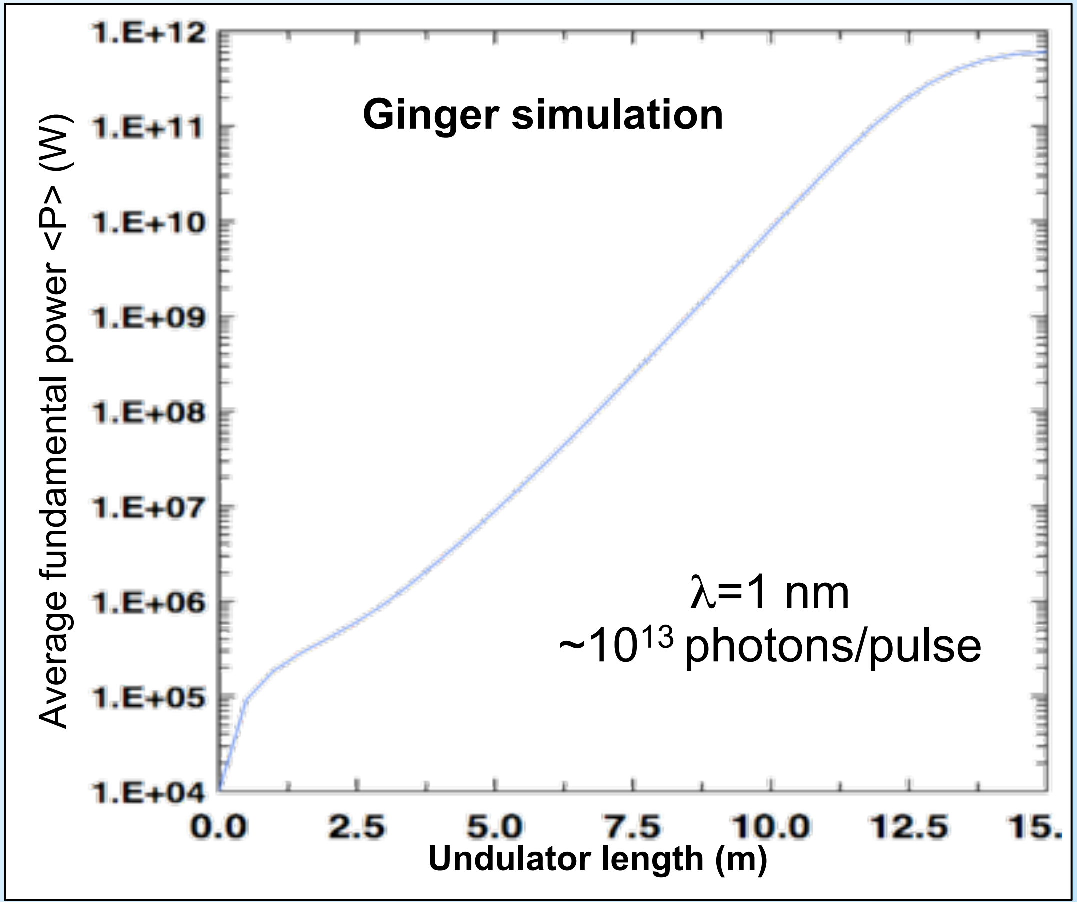


LPA electron beam:

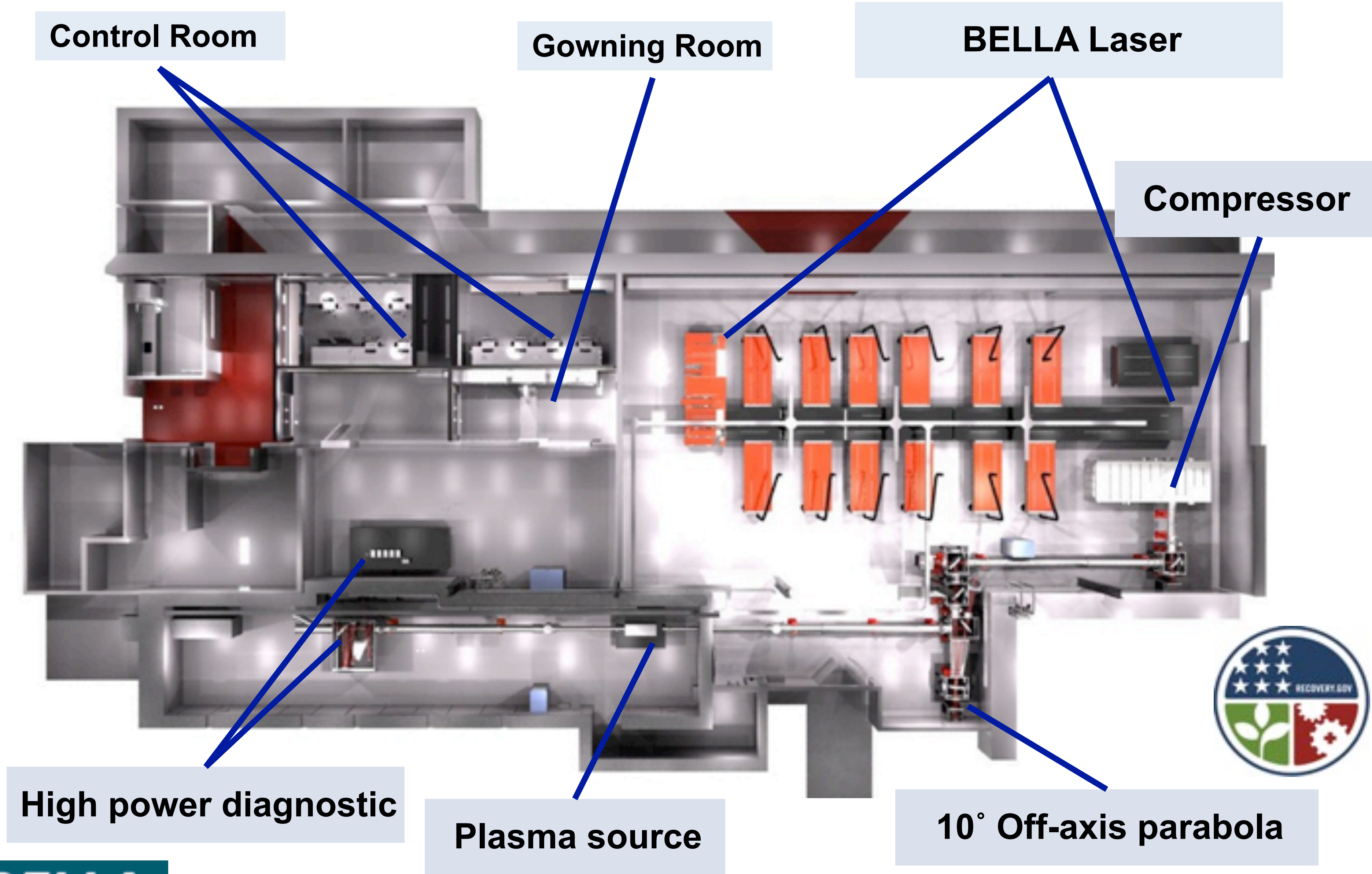
Beam energy	7.7 GeV
Peak current	30 kA
Bunch length	20 fs
Relative energy spread	10^{-3}
Normalized emittance	1 micron

Requires nominal

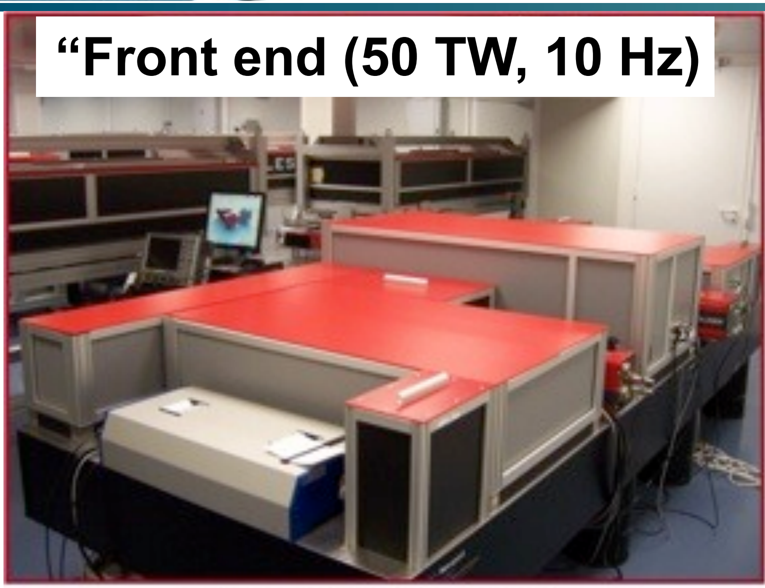
10 GeV LPA



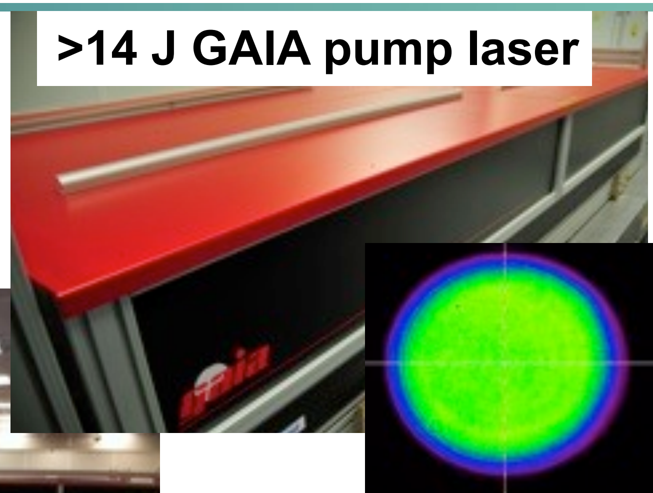
BELLA Facility: state-of-the-art PW-laser for laser accelerator science

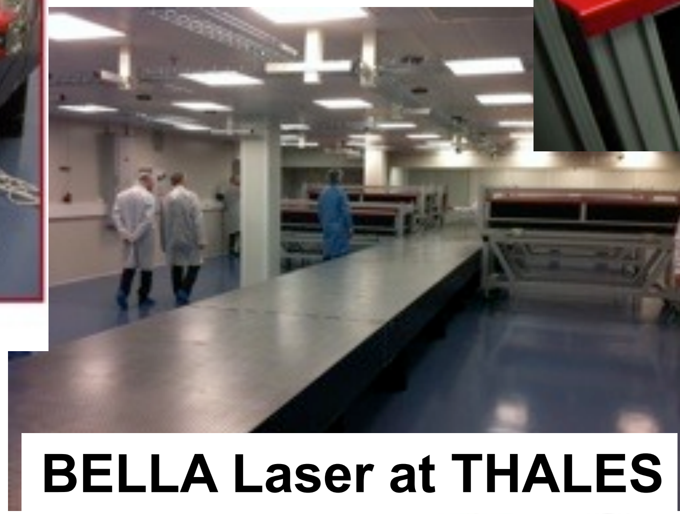


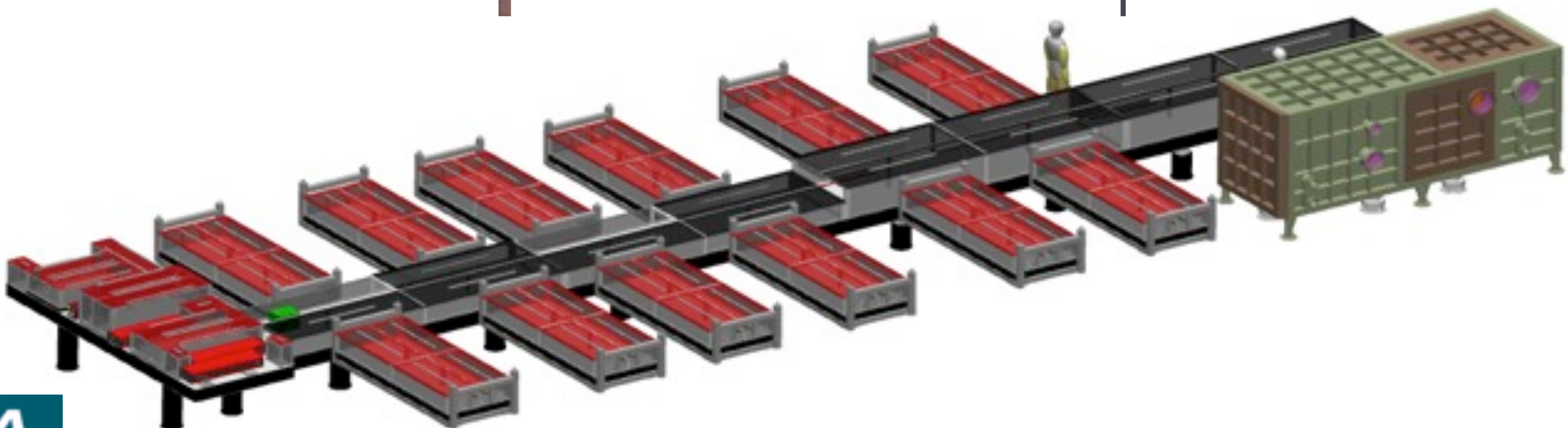
BELLA is expected to be available by summer 2012



BELLA Front End within the BELLA laser room







BELLA laser opens significant opportunities

Lorentz boosted frame simulation
Full 1 m BELLA stage -- major advance
Courtesy of J.-L. Vay

2013 Experiments

Laser

~10 GeV

1000 TW
40 fs

< 100 cm

- Light source development
  - 10 GeV Module as driver for 1 nm seeded soft x-ray FEL

W. Leemans et al., AAC2010 Proceedings

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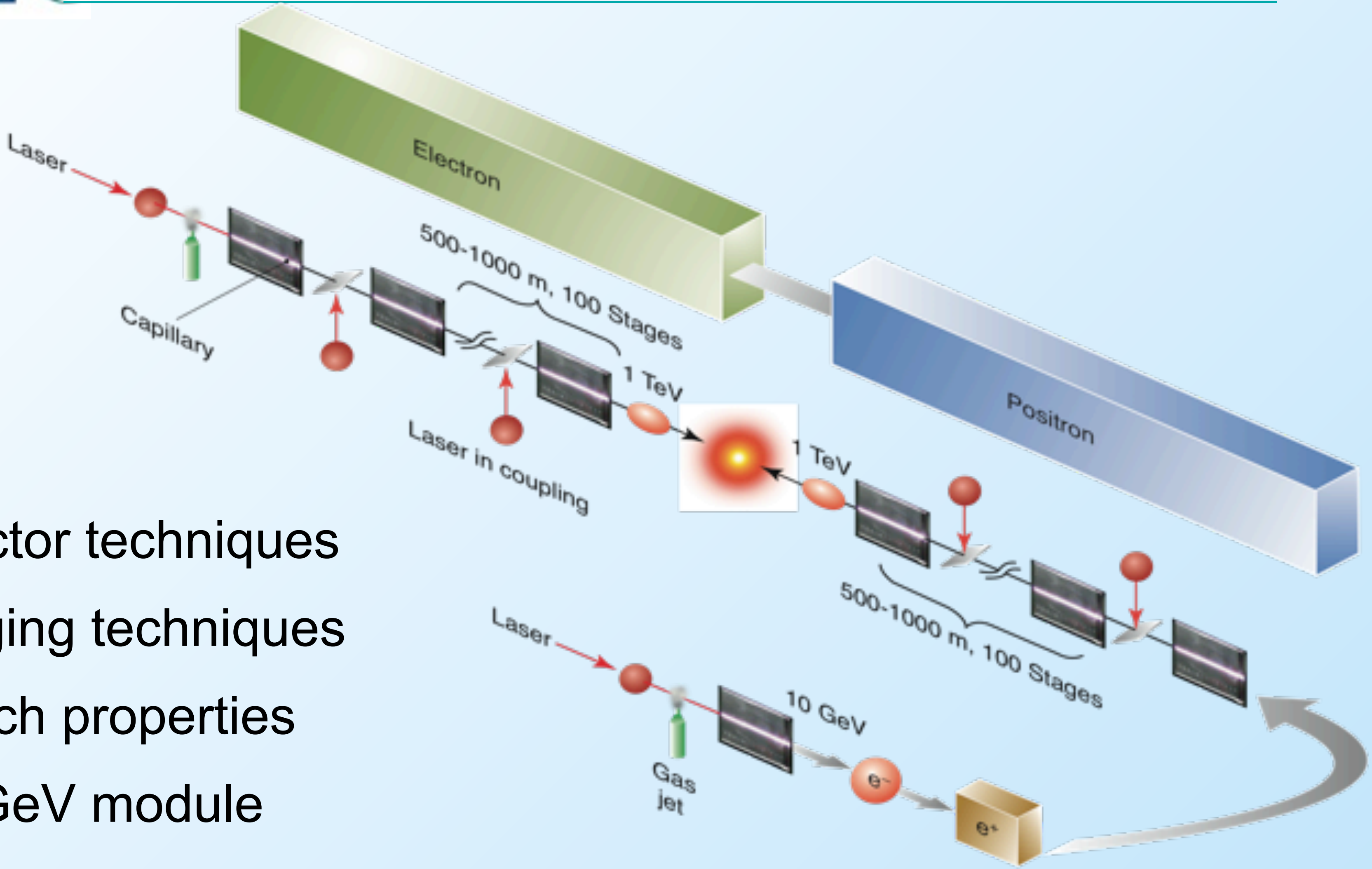
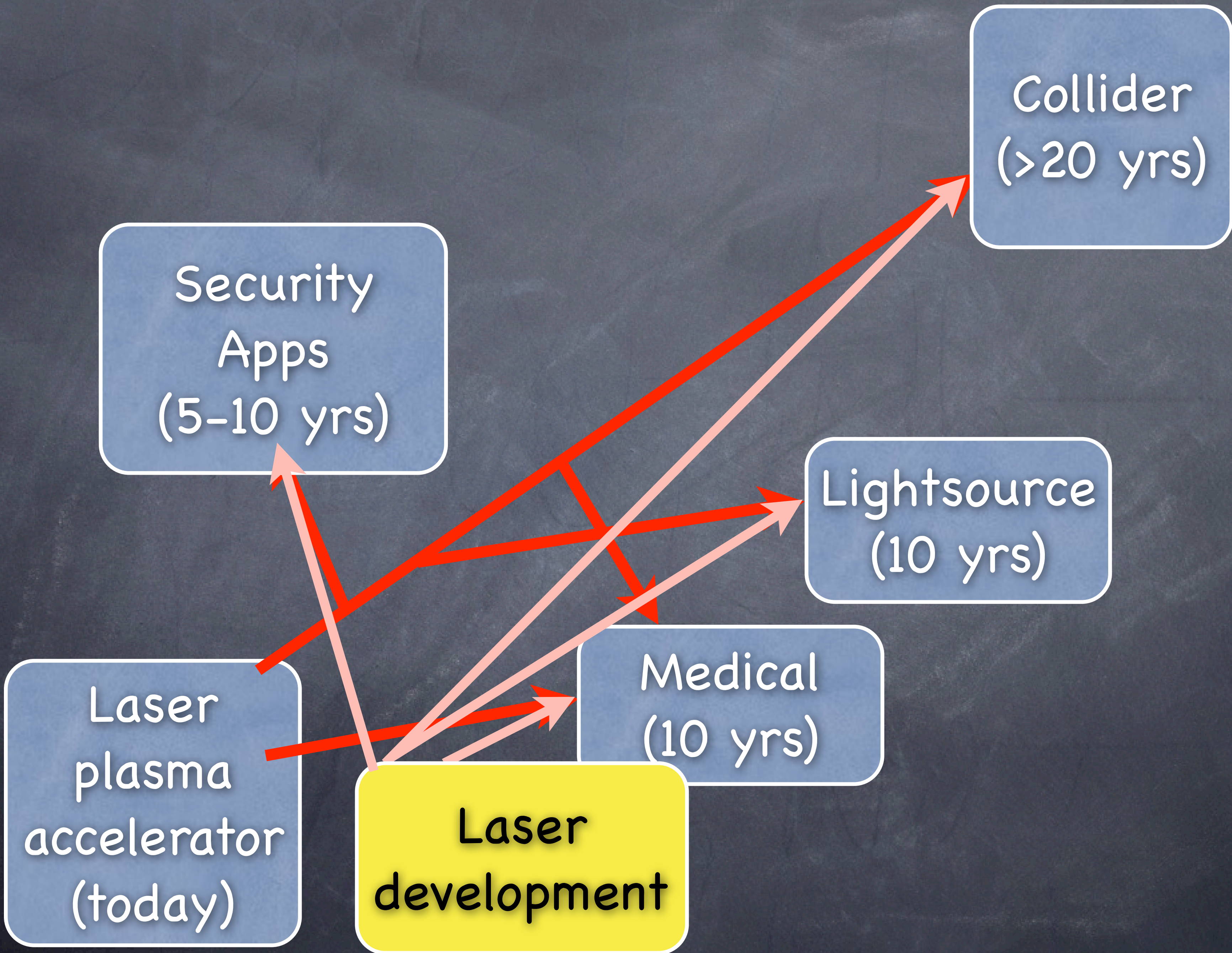
- Conclusion

Concepts are being explored towards a Laser Plasma Linear Collider



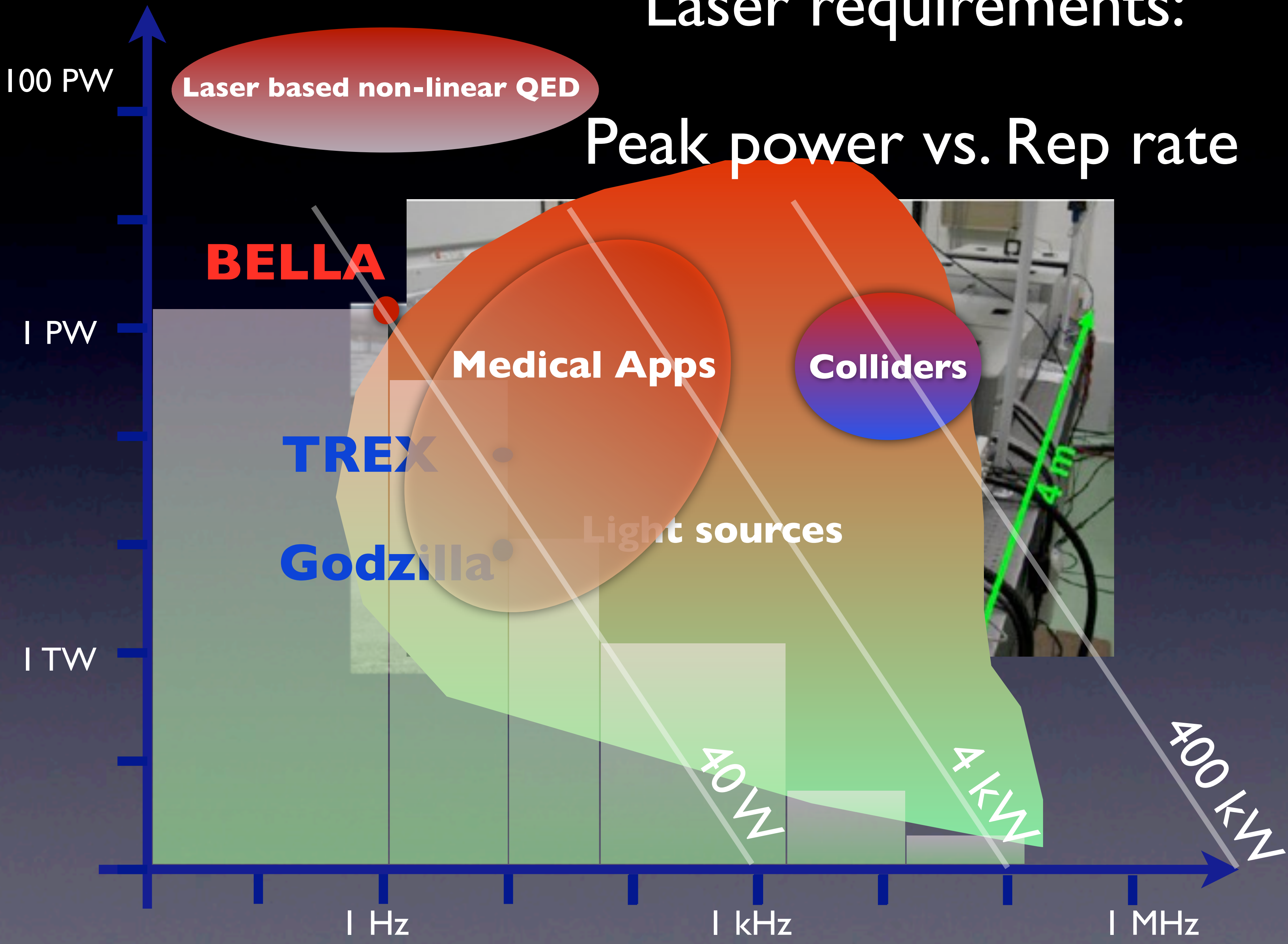
- Injector techniques
- Staging techniques
- Bunch properties
- 10 GeV module
- Collisions, synchrotron losses, efficiency, etc

W. Leemans and E. Esarey, Physics Today (2009); C.B. Schroeder et al., PRST-AB 2010


Collider
(>20 yrs)
Security
Apps
(5-10 yrs)
Lightsource
(10 yrs)
Medical
(10 yrs)
Laser
plasma
accelerator
(today)
Laser
development

Laser requirements:

Peak power vs. Rep rate



Novel lasers and materials are being developed

- Amp
  -
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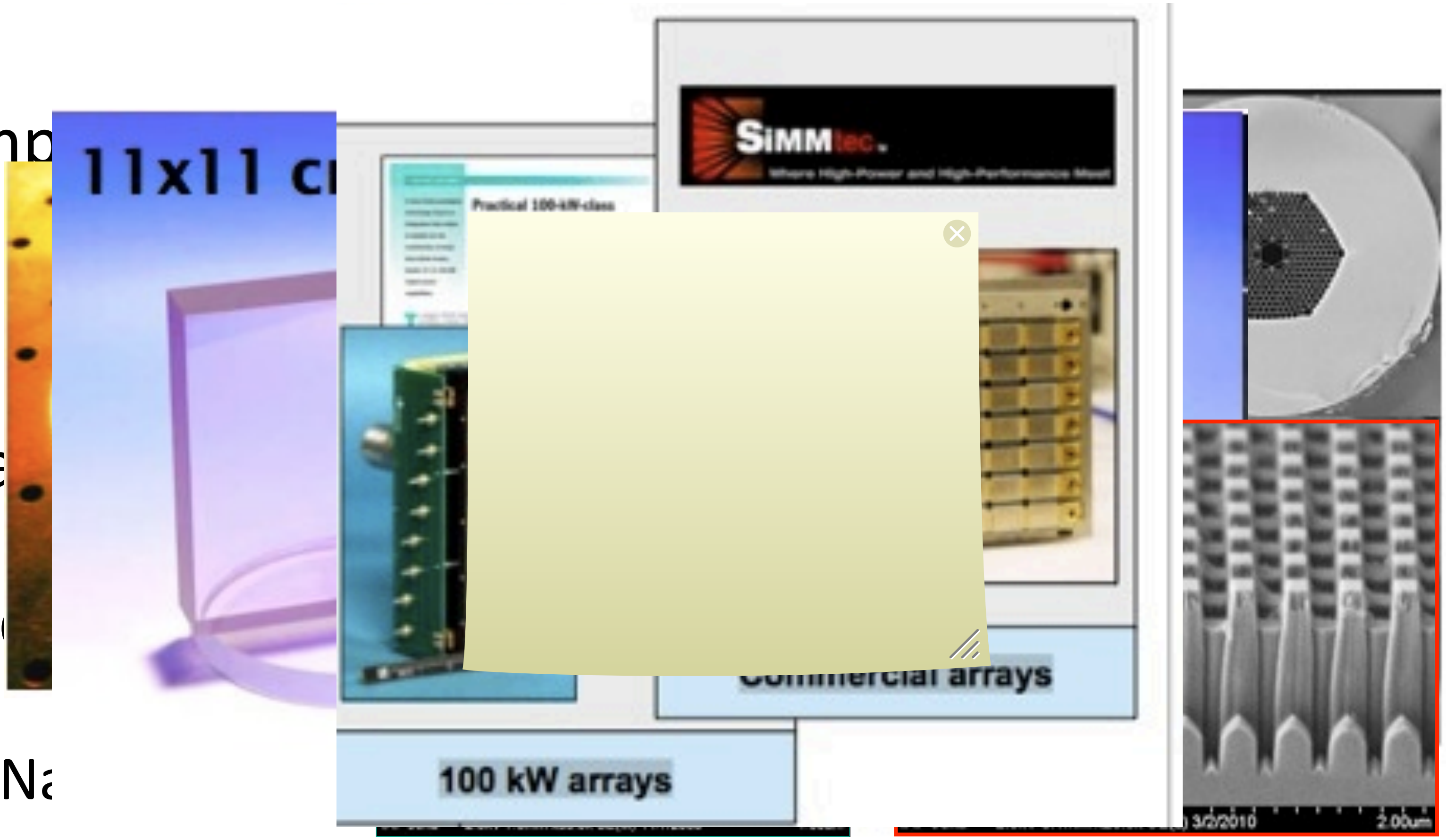


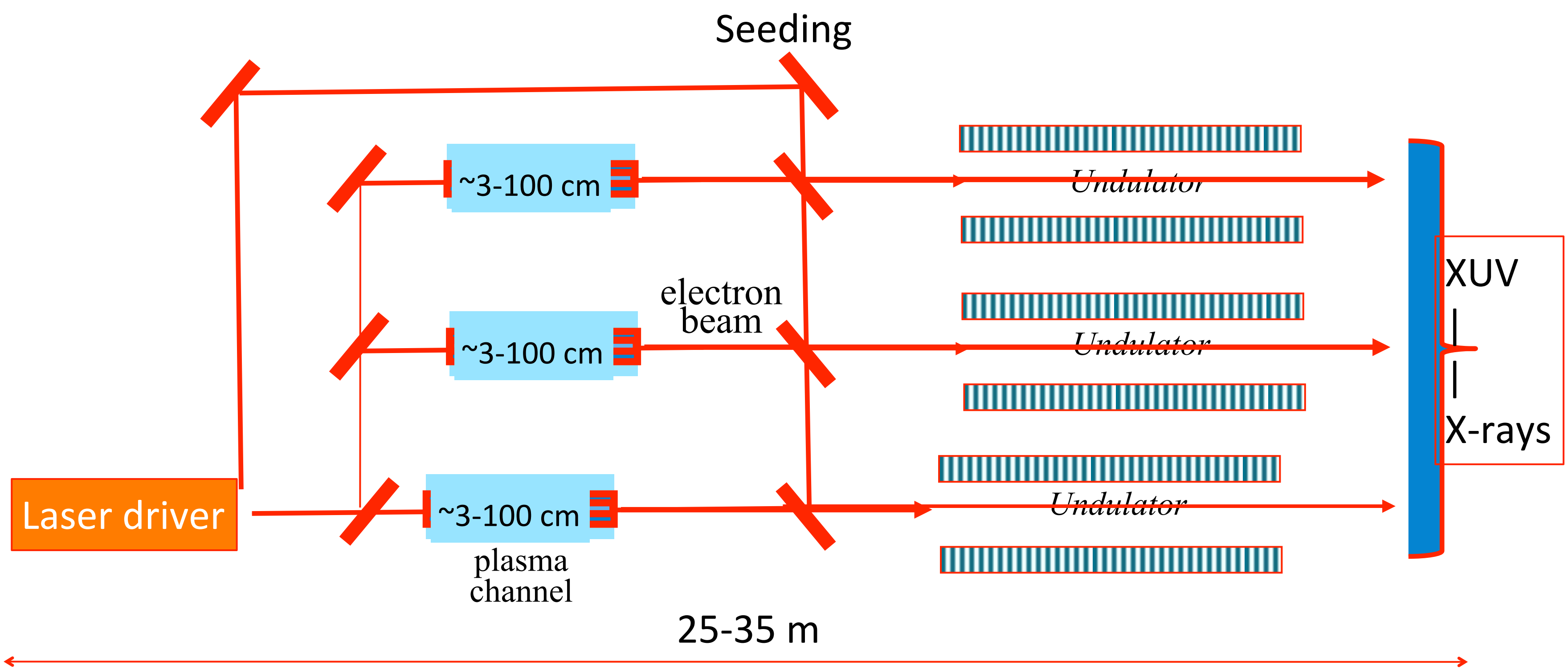
- Diodes and small quantum defect materials

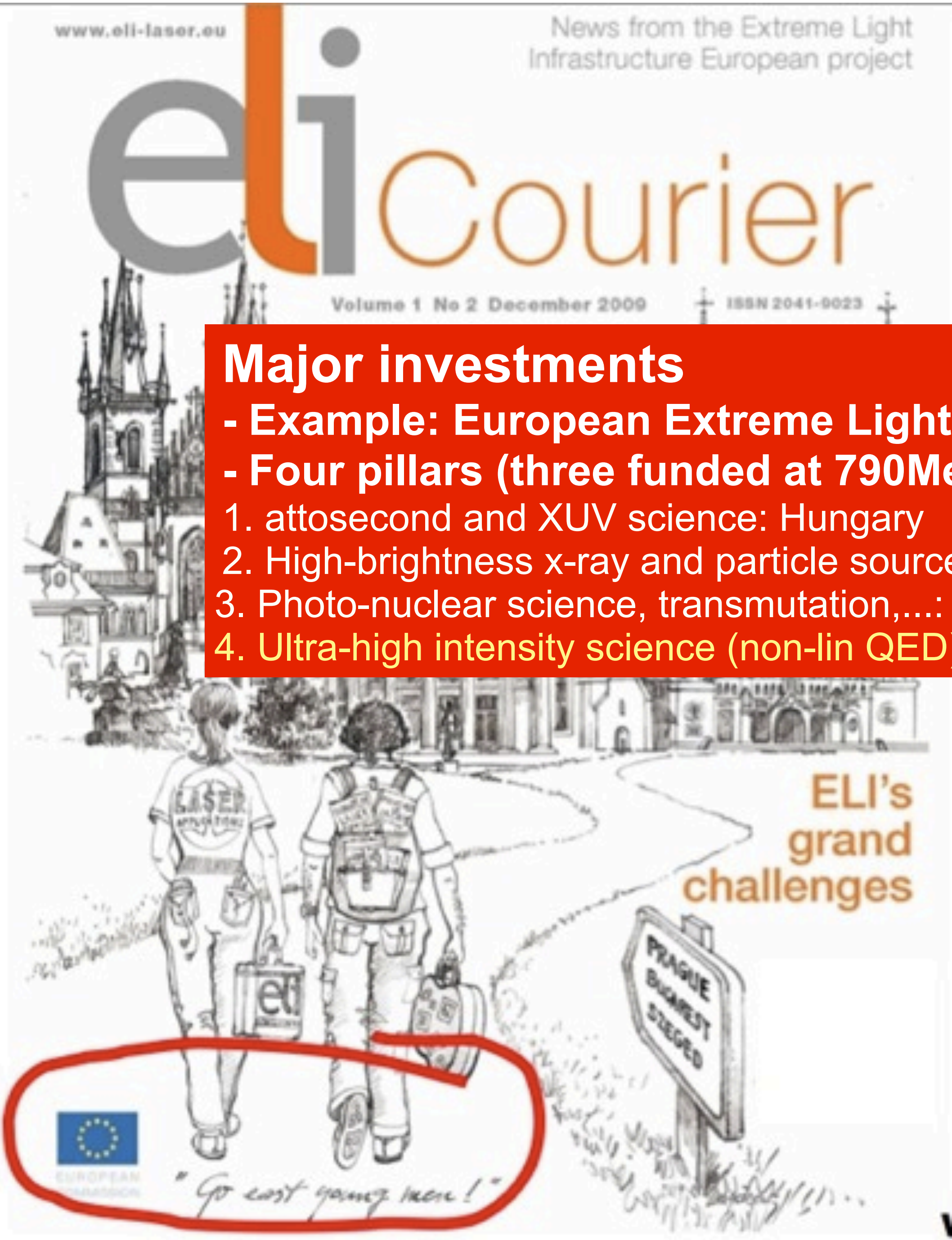
Tuesday, April 5, 2011

Laser-plasma accelerator based hyperspectral user facility

Compact, intrinsically synchronized hyperspectral source covering THz to gamma rays using laser based sources and laser plasma accelerators (LPA)

- Builds on know-how and technology for new accelerators
- New paradigm: single laser system driving multiple tunable compact LPAs





Major investments

- Example: European Extreme Light Infrastructure

- Four pillars (three funded at 790Meuro):

1. attosecond and XUV science: Hungary
2. High-brightness x-ray and particle sources: Czech Republic
3. Photo-nuclear science, transmutation,...: Romania
4. Ultra-high intensity science (non-lin QED): ???

www.eli-laser.eu

Research Facilities of ELI

Attosecond Facility → [Attosecond XUV/X-ray physics](#)
Applications in material sciences and biology
Szeged HU

Beamlines Facility → [High-brightness sources of X-rays & particles](#)
Particle acceleration, dense plasma physics, exotic physics
Prague CZ

Nuclear Physics Facility → [Laser-induced nuclear physics](#)
Photonuclear science and applications
Magurele RO

Funded at 790 Meuro

Extreme-intensity development → [Exawatt-class laser technology](#)
High-intensity laser technologies for frontier physical research

Technology & site are to be determined after 2012

Courtesy of K. Osvay

Conclusion

- Laser plasma accelerators are reaching AMO relevant performance
  - High peak field THz for non-linear carrier dynamics, superconducting R&D
  - Direct e-beam based magnetic switching
  - FEL proof-of-principle experiments, including seeding + user experiments
- In 5-10 years: BELLA style technology based user facility for peak power hyperspectral source apps
- User apps will require investment in high average power laser technology
  - Multi-kW 100 TW to Petawatt-class lasers
  - Sustained, long range R&D needed with major investment in high peak power lasers, novel materials and fiber timing technology & partner with universities, labs and industry
  - Major investments being made overseas
- Exciting times to work on accelerator and laser driven science

Team, collaborators and funding

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- Oxford Univ.: S. Hooker et al.
- DESY: F. Gruener, J. Osterhoff et al.
- LOA: O. Albert
- GSI: T. Stoehlker, D. Thorn
- Trieste: F. Parmigiani

THALES

NSF

NNSA National Nuclear Security Administration

U.S. DEPARTMENT OF ENERGY Office of Science