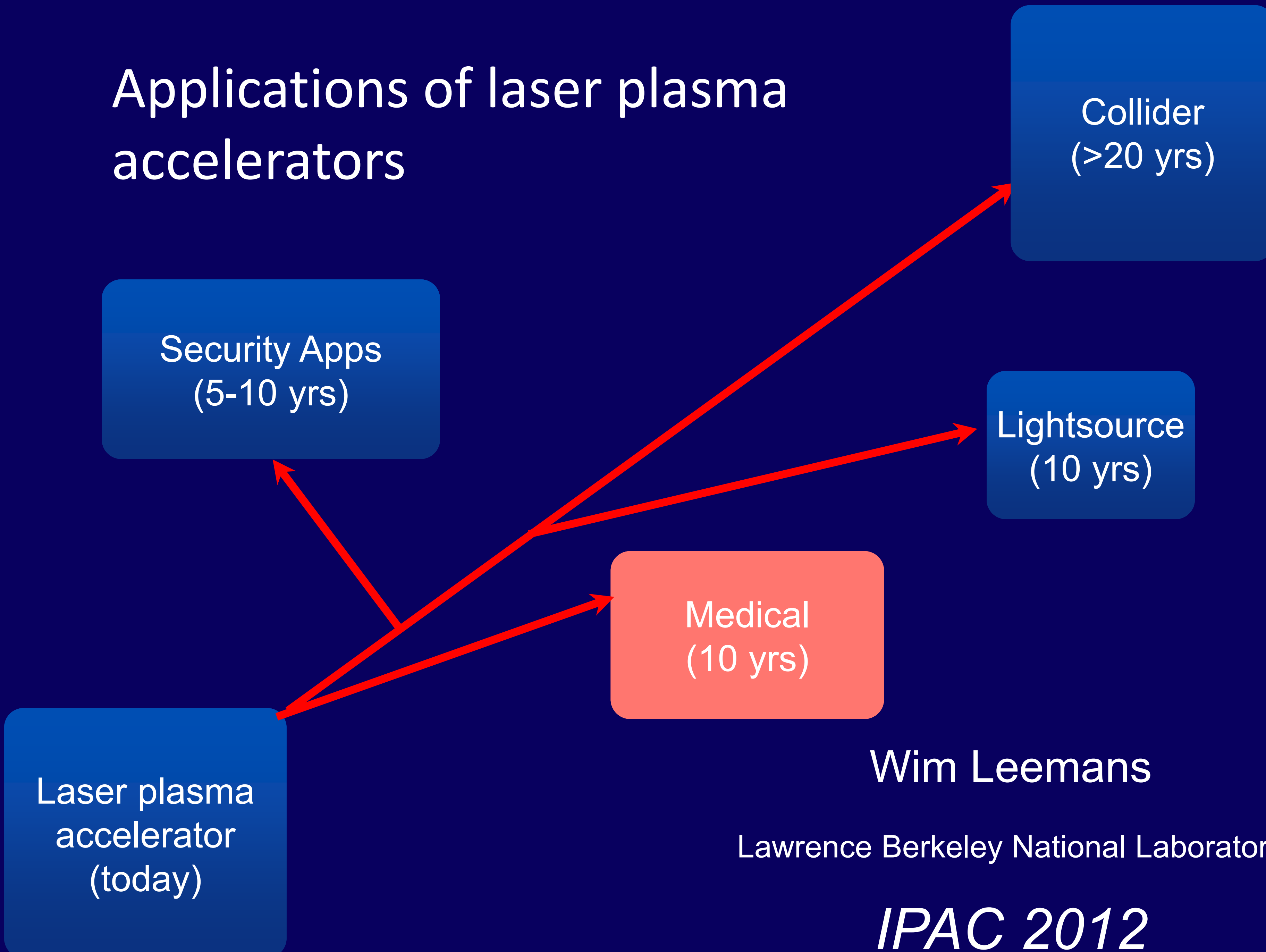
Applications of laser plasma accelerators



Wim Leemans

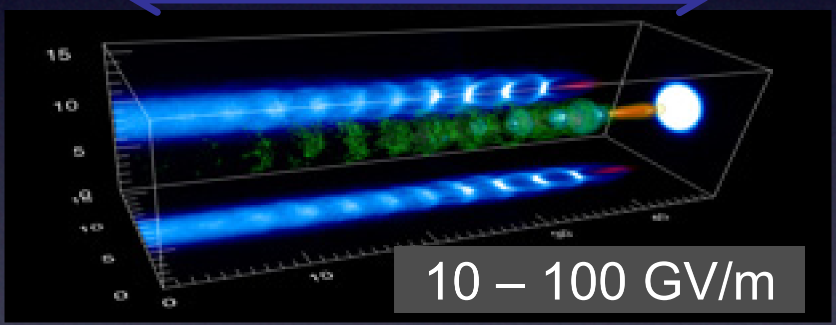
Lawrence Berkeley National Laboratory

IPAC 2012

Laser plasma acceleration enables development of “compact” accelerators

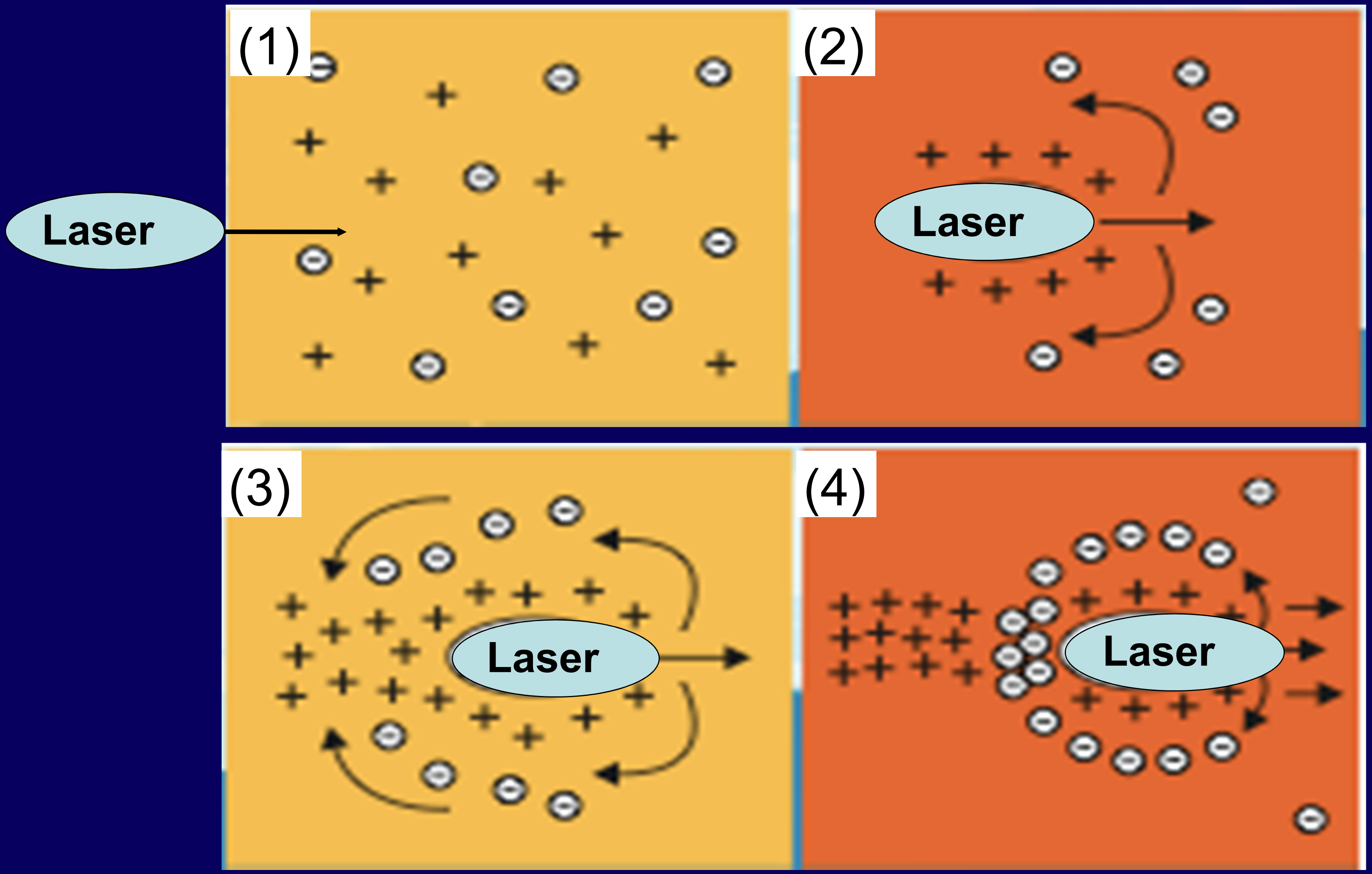
meter-scale

100 micron-scale

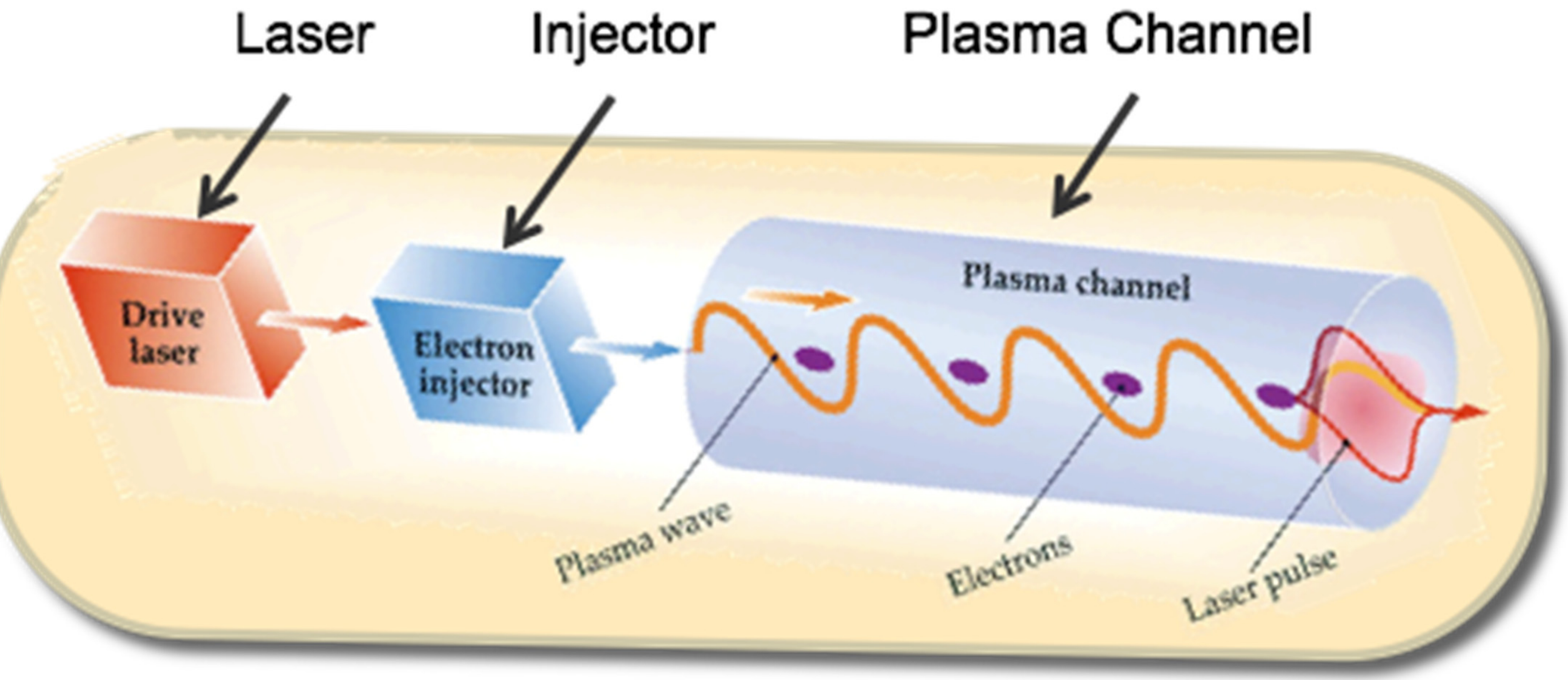


- Can this technology be developed for colliders, light sources, medical or homeland security applications?

Intense laser causes charge separation leading to extremely high fields in plasma



Building a laser plasma accelerator following the conventional linac paradigm

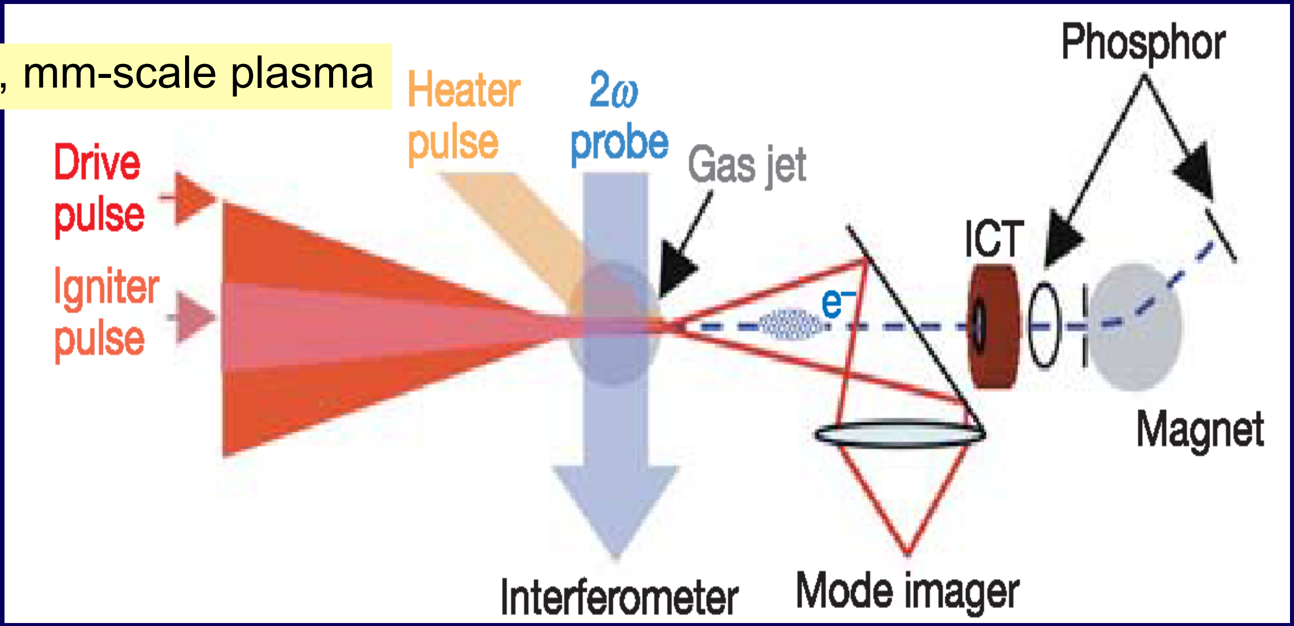


Leemans et al., IEEE Trans. Plasma Science (1996), Phys. Plasmas (1998)
Leemans and Esarey, Physics Today, March 2009
Esarey, Schroeder and Leemans, Rev. Mod. Phys (2009)

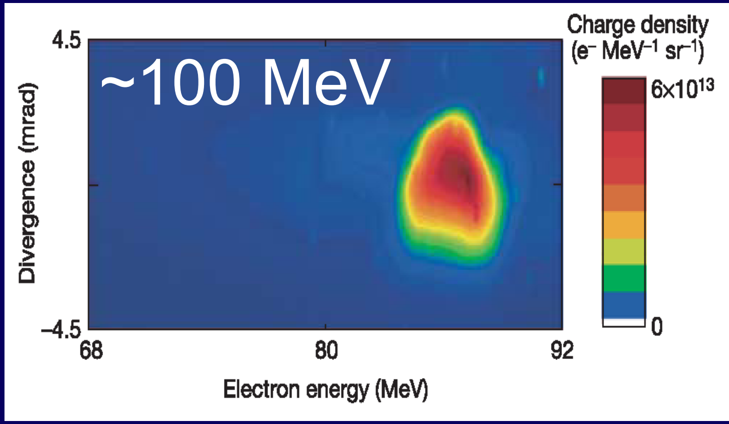
In 2004, laser guiding and dephasing control resulted in 100 MeV beams with %-level energy spread

10 TW laser, mm-scale plasma

- Guiding

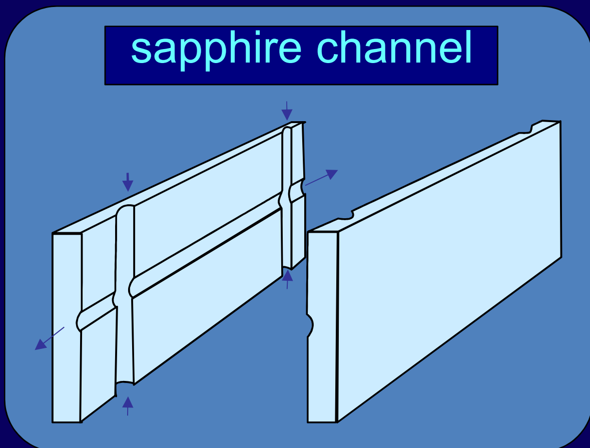


- Dephasing control
- Beam loading



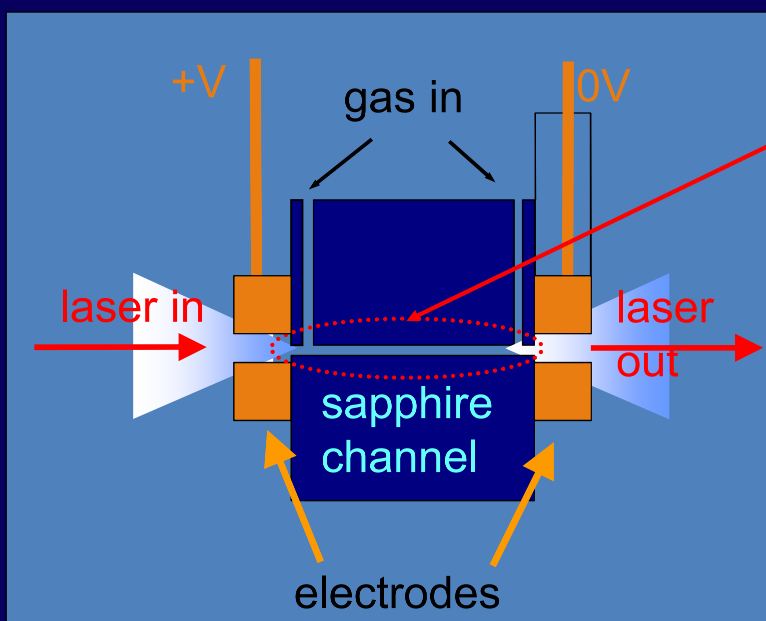
C. G. R. Geddes,et al, Nature,431, p538 (2004)
S. Mangles et al., Nature 431, p535 (2004)
J. Faure et al., Nature 431, p541 (2004)

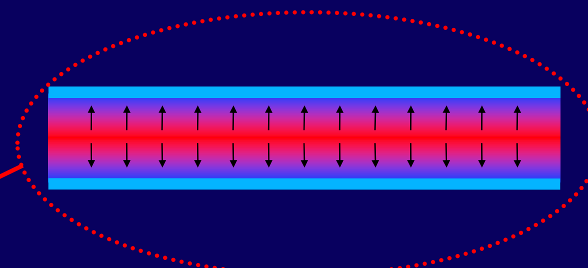
Capillary discharge waveguides are used as building block for laser plasma accelerators



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

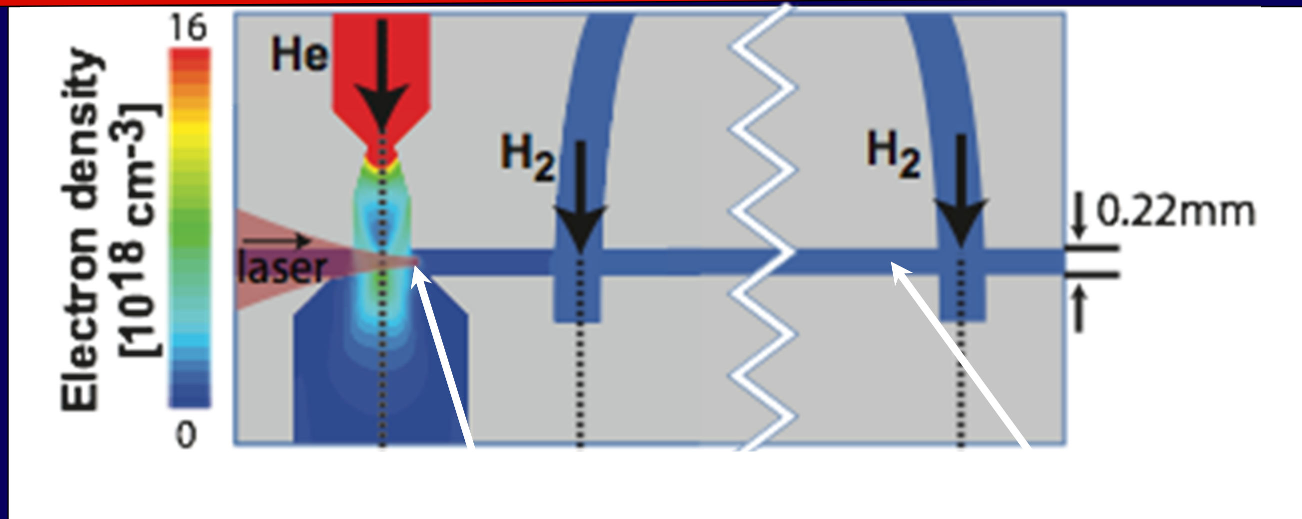
D. J. Spence & S. M. Hooker Phys. Rev. E 63 (2001) 015401 R; A. Butler et al. Phys. Rev. Lett. 89 (2002) 185003.





W.P. Leemans et al., Nature Physics 2, 696 (2006)
A.J. Gonsalves et al., Nature Physics 7, 862 (2011)

Reliable injector and acceleration stage has been developed based on longitudinal density tailoring



Supersonic gas jet embedded into capillary

Laser

0.1-1 GeV

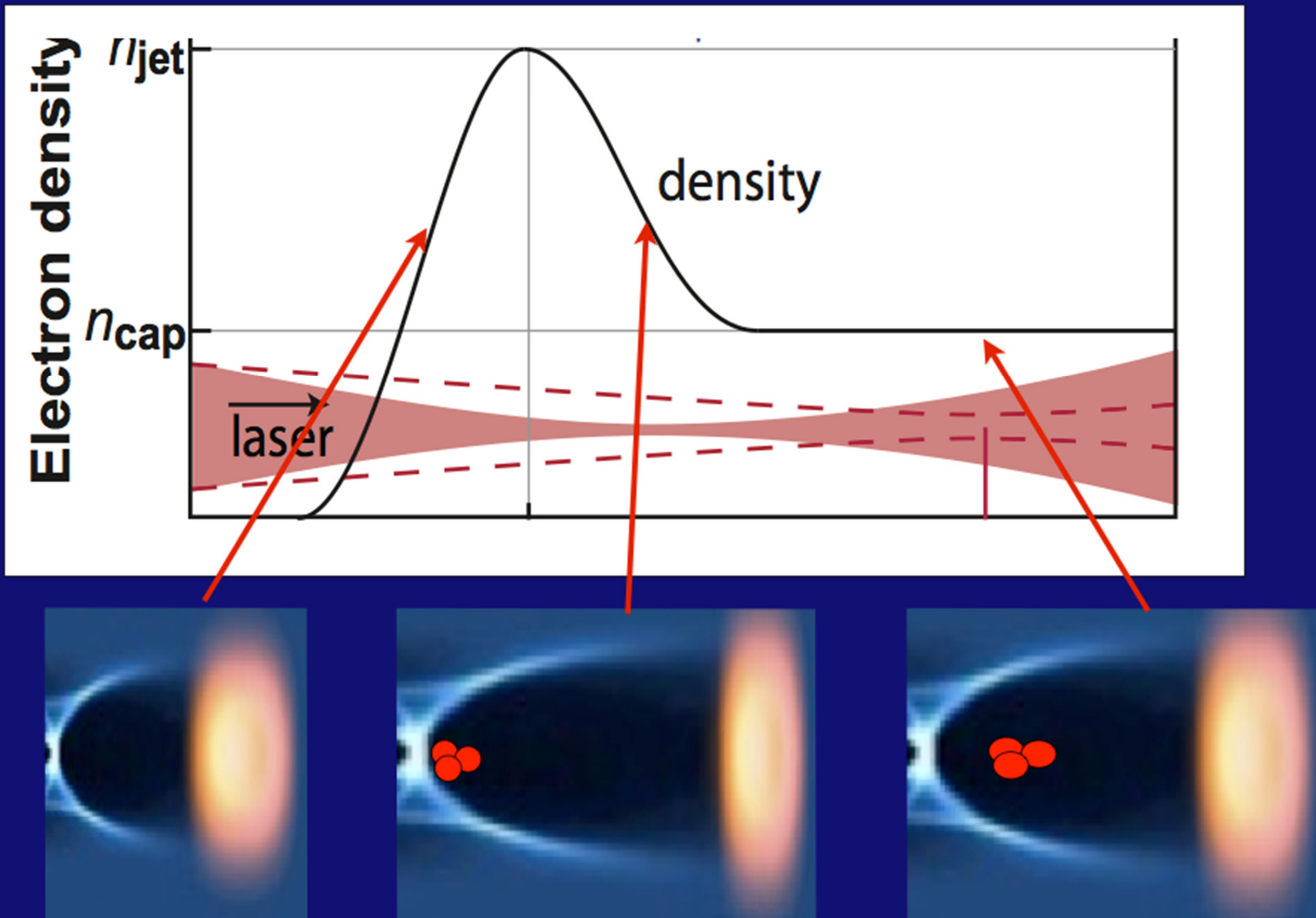
Injector

Acceleration section

3 cm

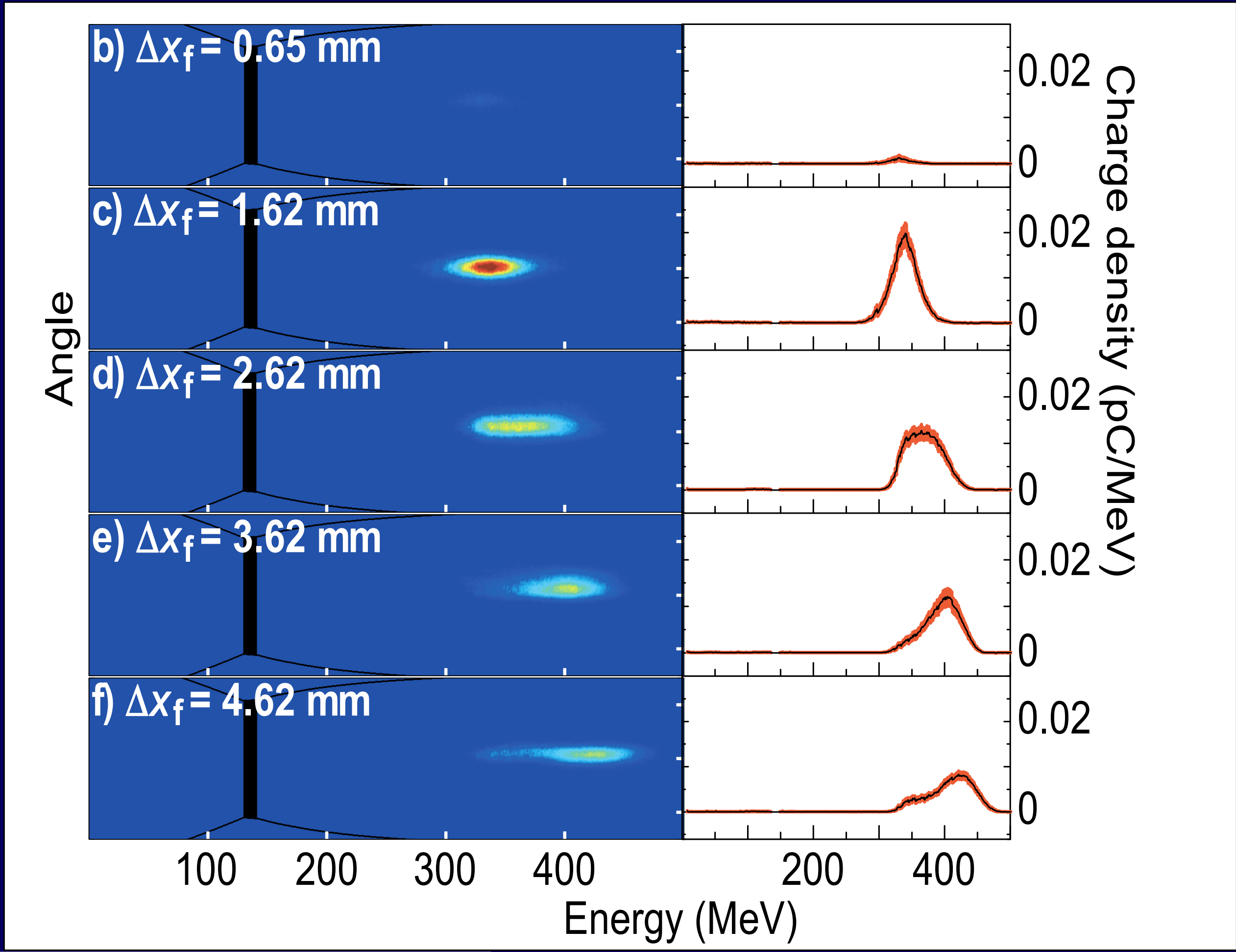
A.J. Gonsalves et al.,Nature Physics 7, 862 (2011)

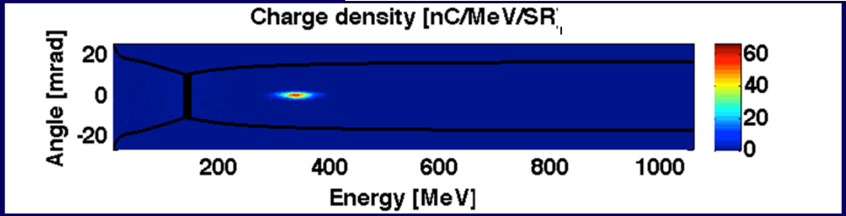
Controlled trapping in a laser plasma accelerator can be realized by longitudinally tailoring the density profile



Tunable electron beams can be produced with jet+capillary module using laser focus control

A.J. Gonsalves et al.,Nature Physics 2011

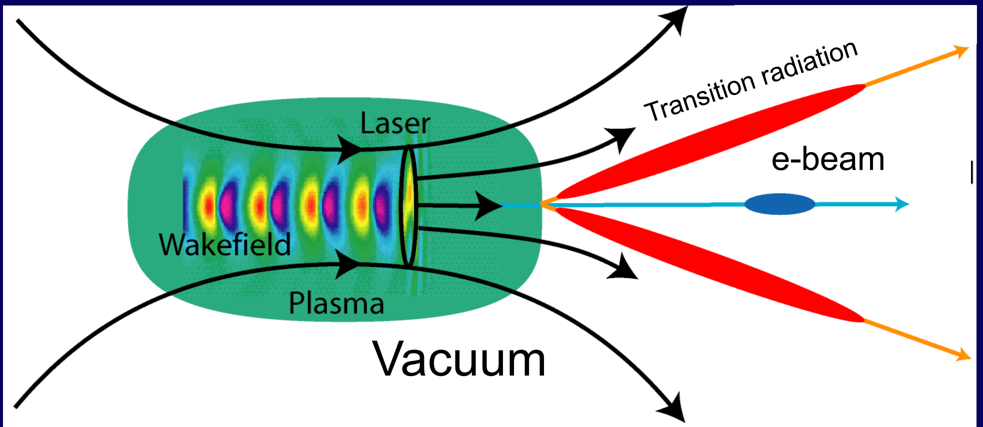




Energy variation < 2 % rms
Charge variation < 6 % rms
Divergence change < 0.57 mrad rms

LPAs can produce femtosecond hyperspectral radiation as an integral part of the laser-plasma interaction

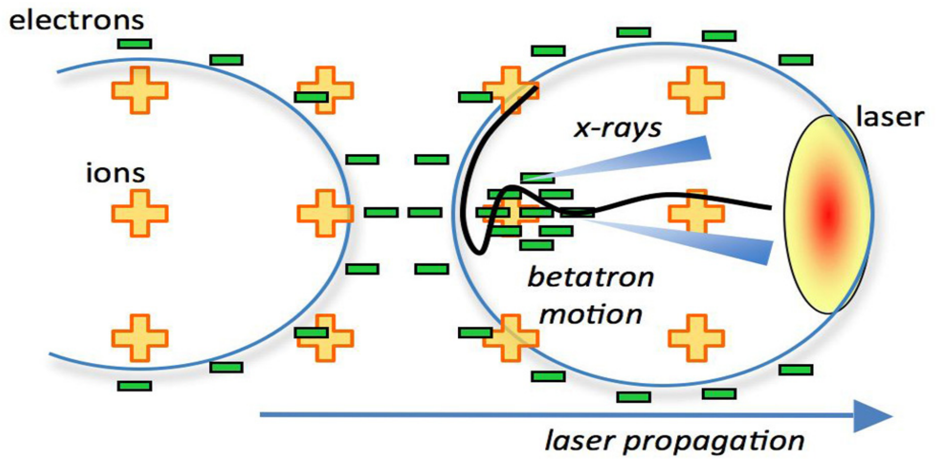
- THz:



W.P. Leemans et al., PRL 2003
C.B. Schroeder et al., PRE2004
J. van Tilborg et al., PRL 2006

- Coherent, multi microJoule single cycle pulses, 1-10 THz

- X-rays:



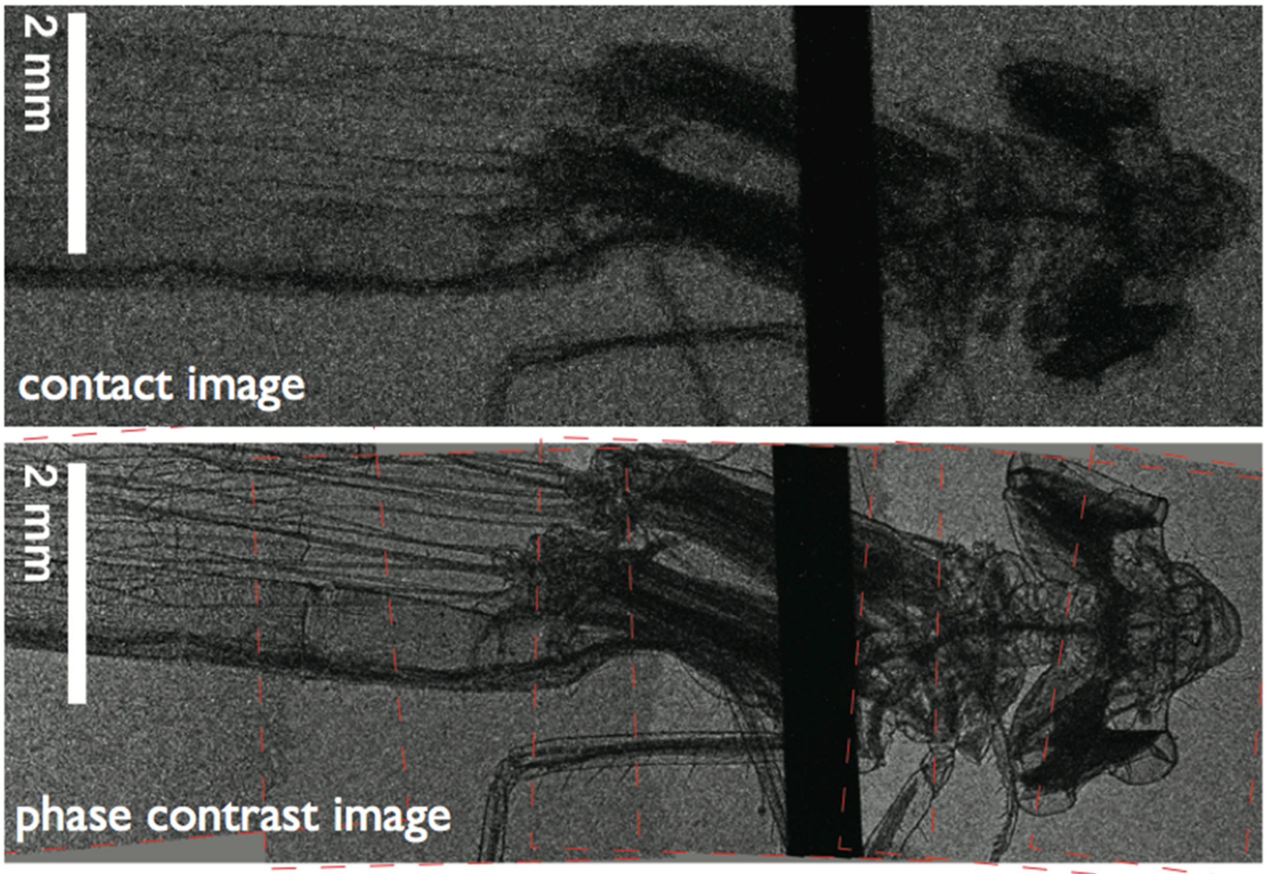
E. Esarey et al., PRE 2002
A. Rousse et al., PRL2004
S. Kneip et al., Nat. Phys. 2010

- Incoherent broadband keV X-rays, 10^6-10^8/shot

Betatron radiation from LPA has been used for biological imaging

Imperial College London

Imaging of Biological Specimens



- specimen and camera ~3m from source
- specimen ~0.5m and camera ~1.8m from source

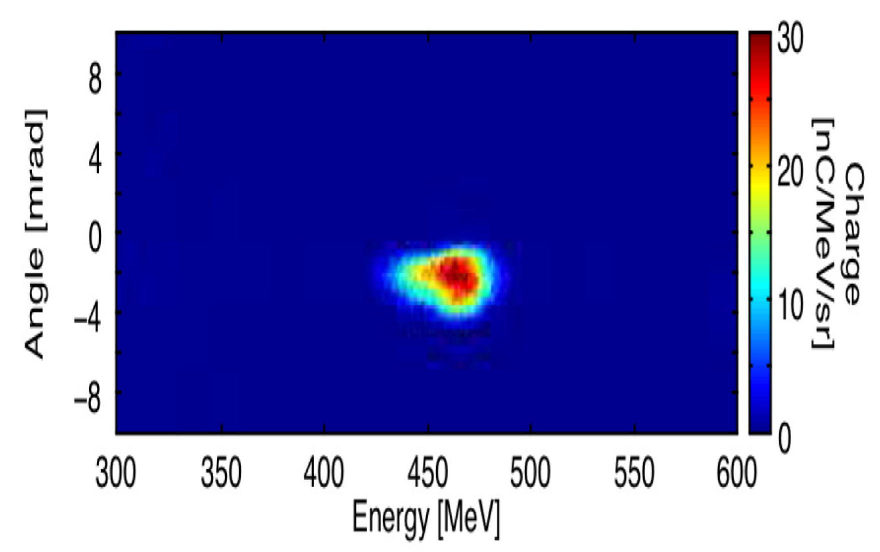
MichiganEngineering

S Kneip et al., Nat. Phys. **10**, 980 (2010)
S Kneip et al., arXiv 1105.2517v1 (2011)
S Kneip et al., APL, accepted (2011)

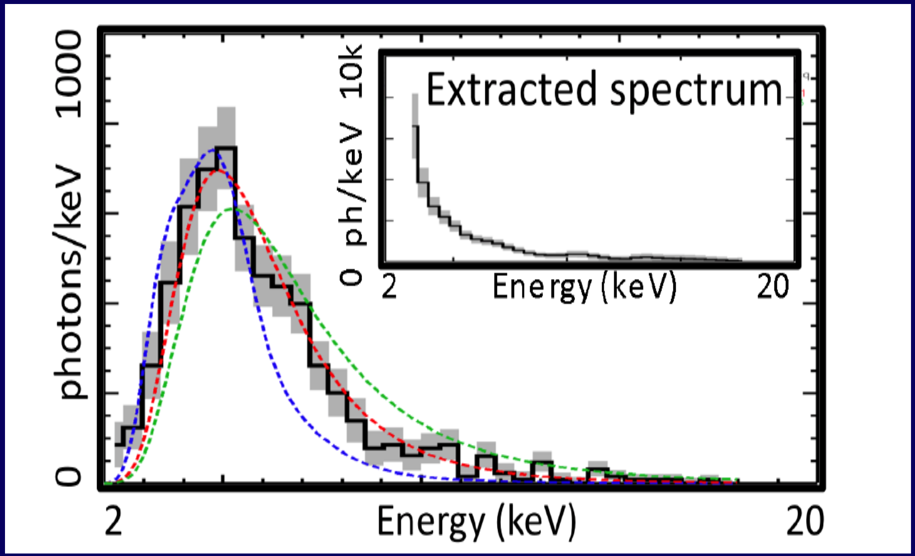
2

Betatron spectroscopy indicates LPA beams can have sub-micron normalized emittance

Single shot e-beam spectrum



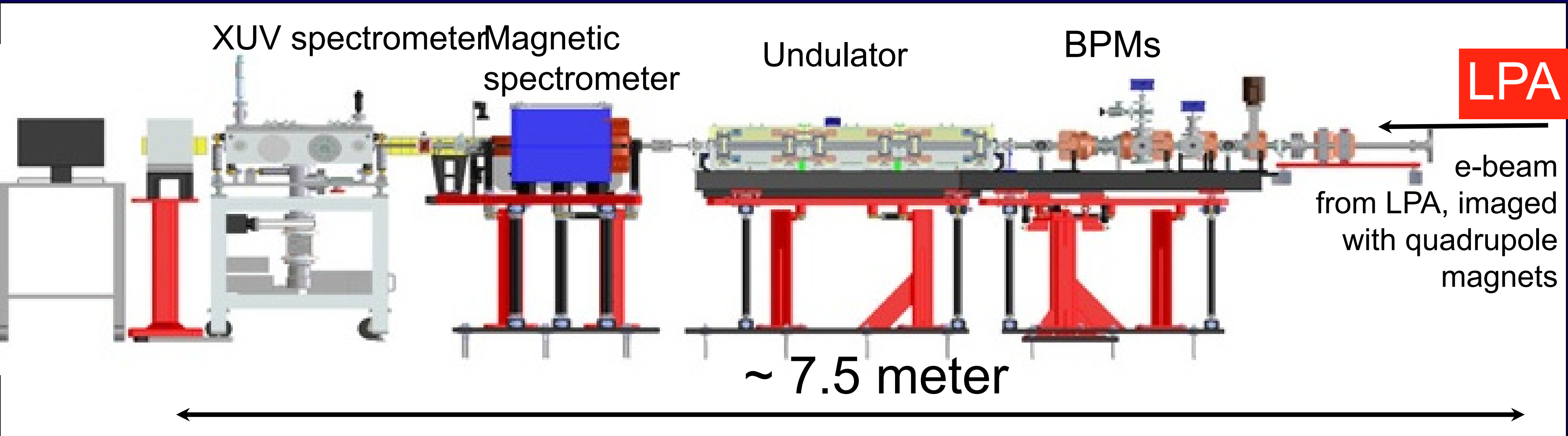
Single shot x-ray spectrum



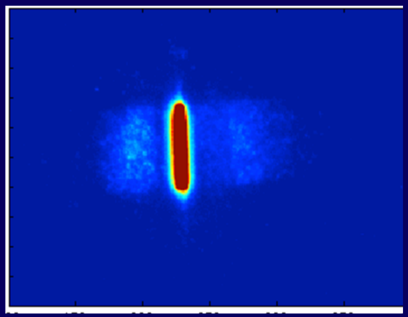
- Normalized emittance ~ 0.1 - 0.2 micron
- Necessary condition for FEL based on LPA
- Important for applications/beam transport

G. Plateau et al., submitted to PRL

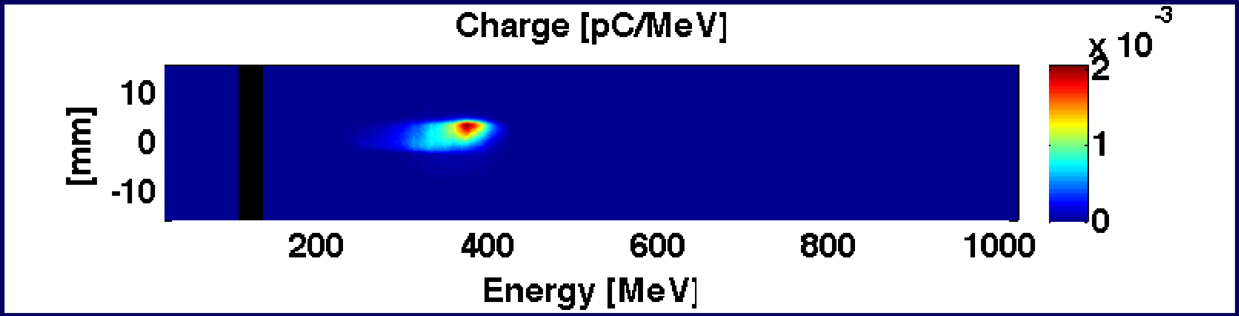
XUV light (36-100 eV) seen from LPA produced beam propagating through undulator: step towards FEL



XUV light



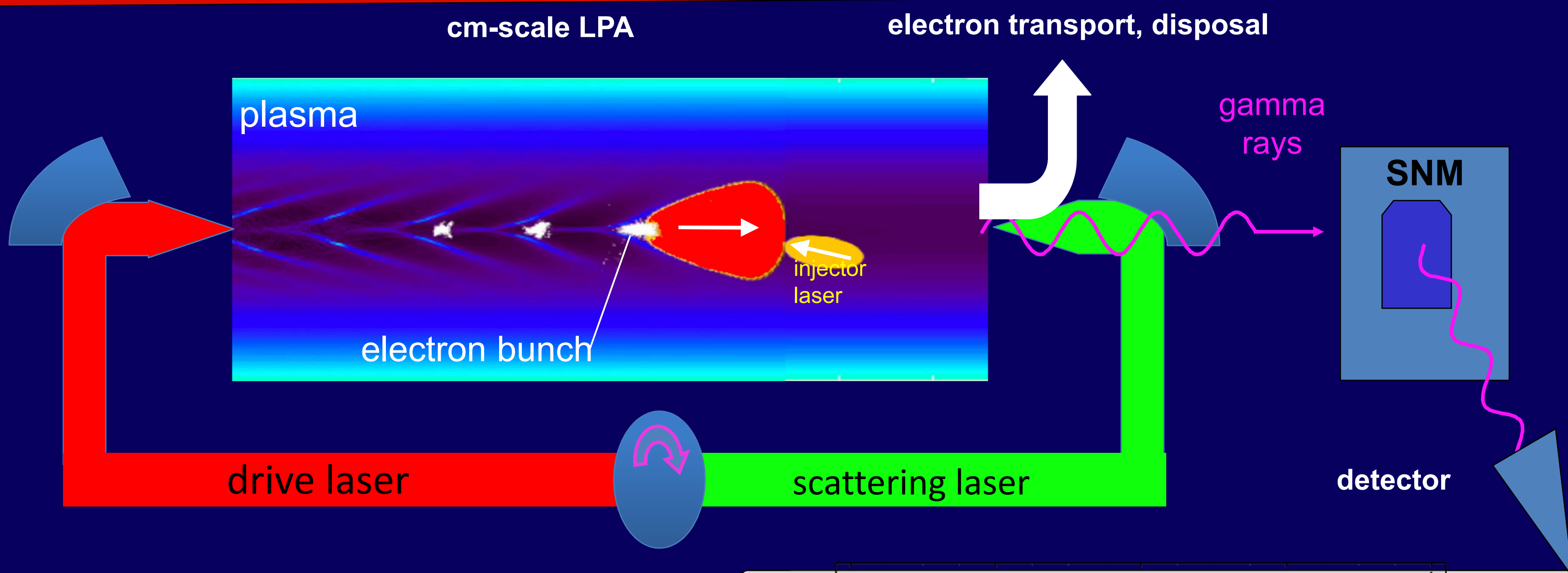
Electron beam spectra



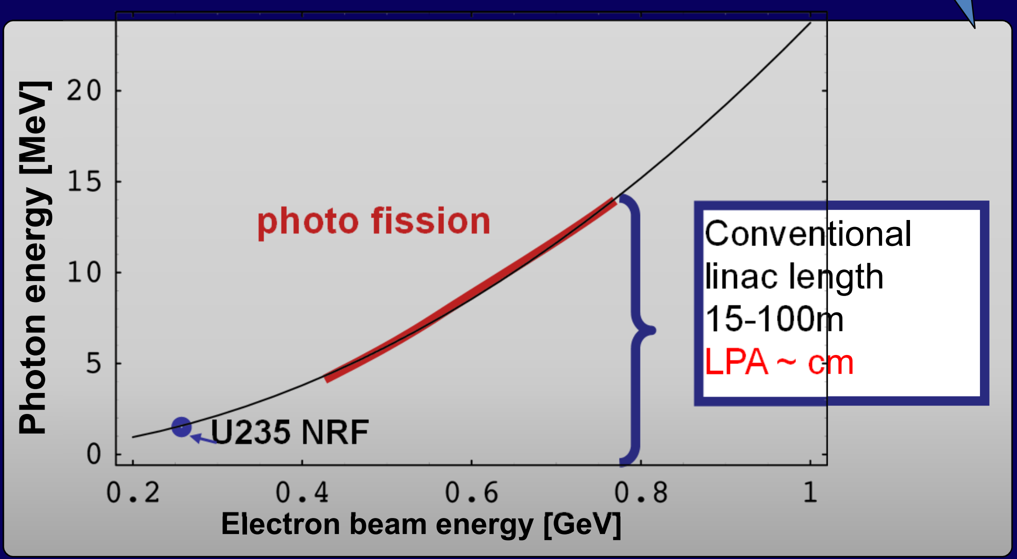
also:
Schlenvoigt et al., Nature Physics 2008
Fuchs et al., Nature Physics 2009

- Main challenge is energy spread control
- COTR observation indicates slice energy spread can be small (C. Lin et al., PRL 2012)

Multi-MeV gamma rays can be obtained from compact system by Thomson scattering LPA beam against laser

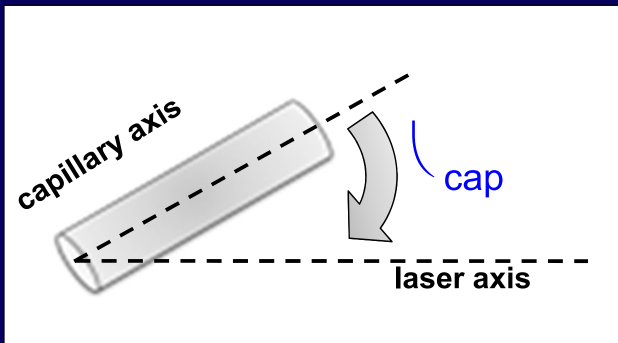


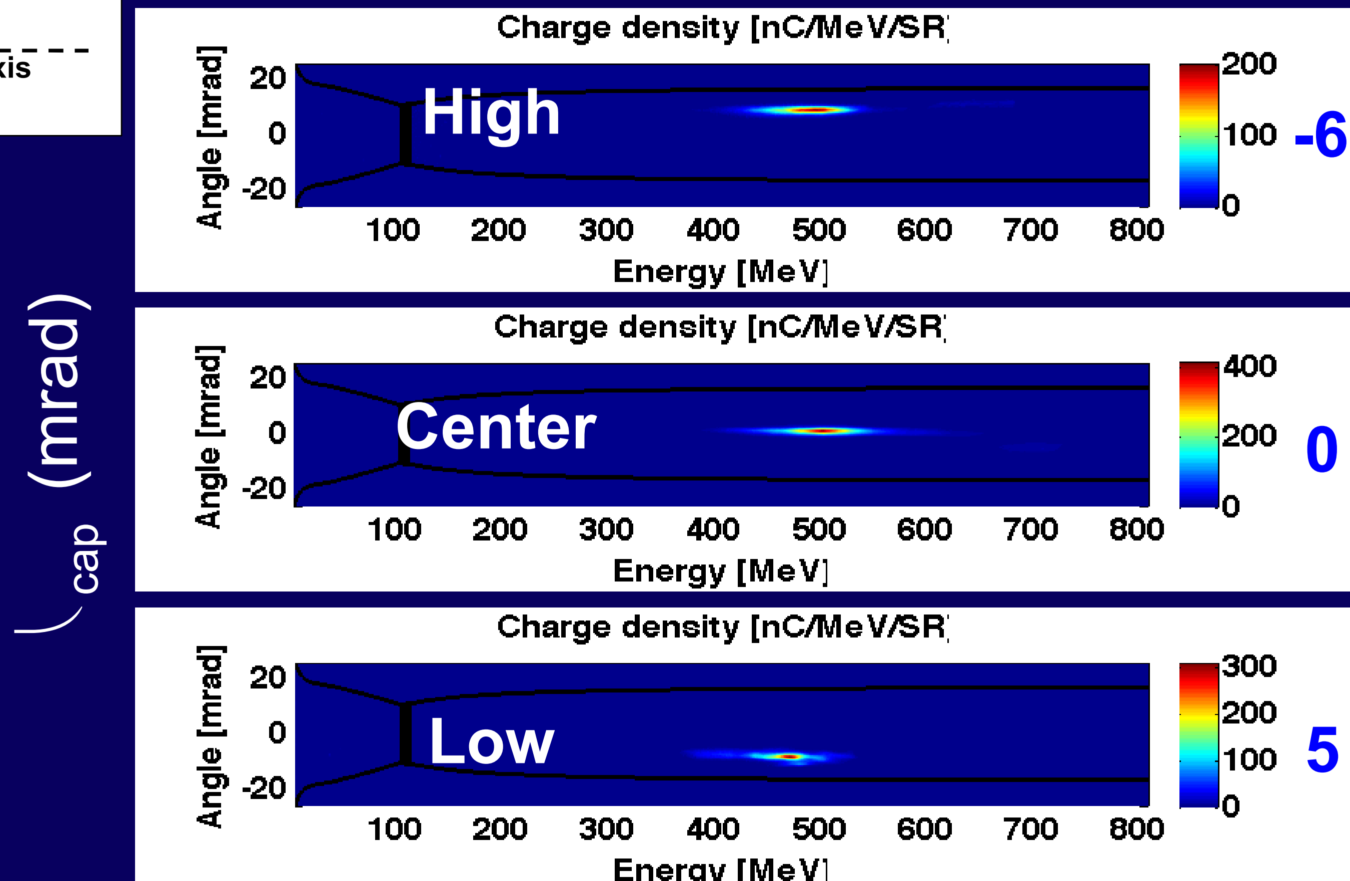
- 10-40 TW laser:
  - can produce up to GeV beam
  - fits on 4 m x 1.5 m optical table



NNSA National Nuclear Security Administration

Electron beam can be steered using tip-tilt of capillary





feature article

Laser-driven plasma-wave electron accelerators

Wim Leemans and Eric Esarey

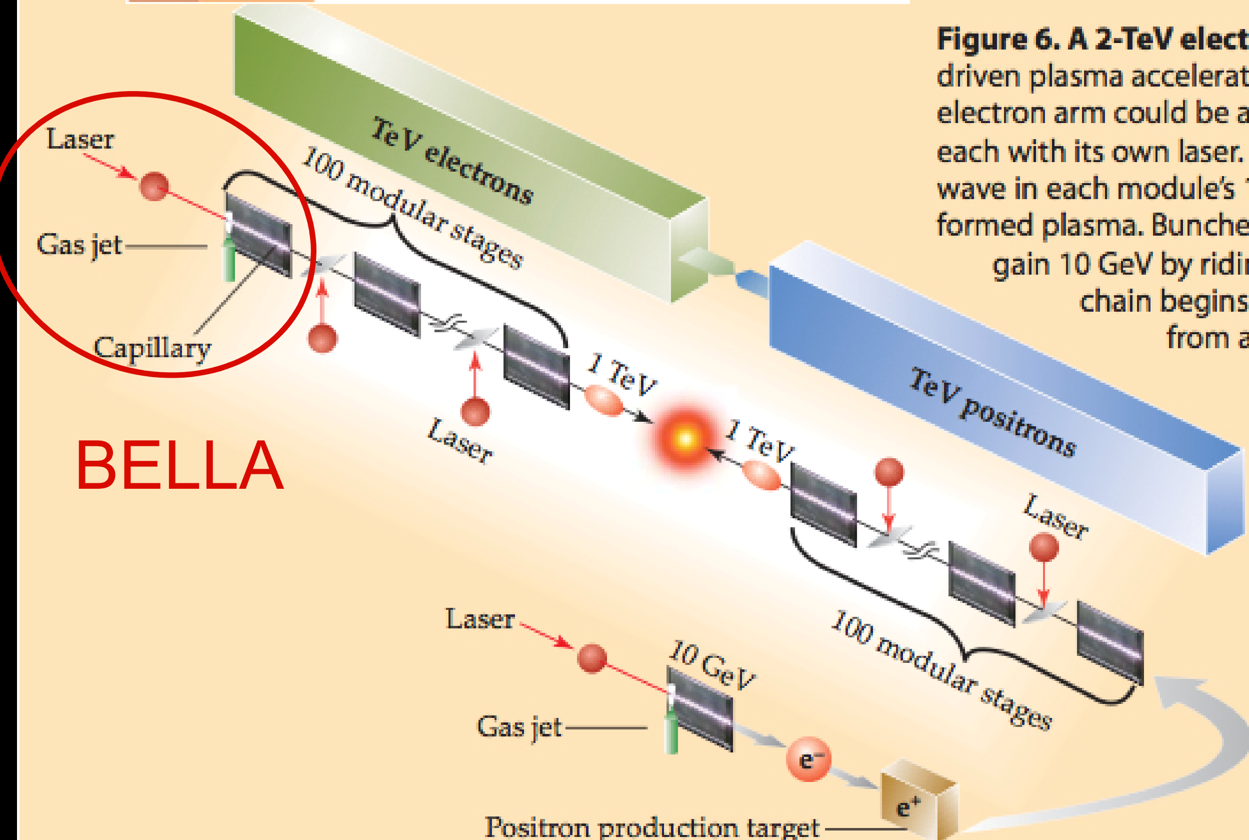


Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed 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.

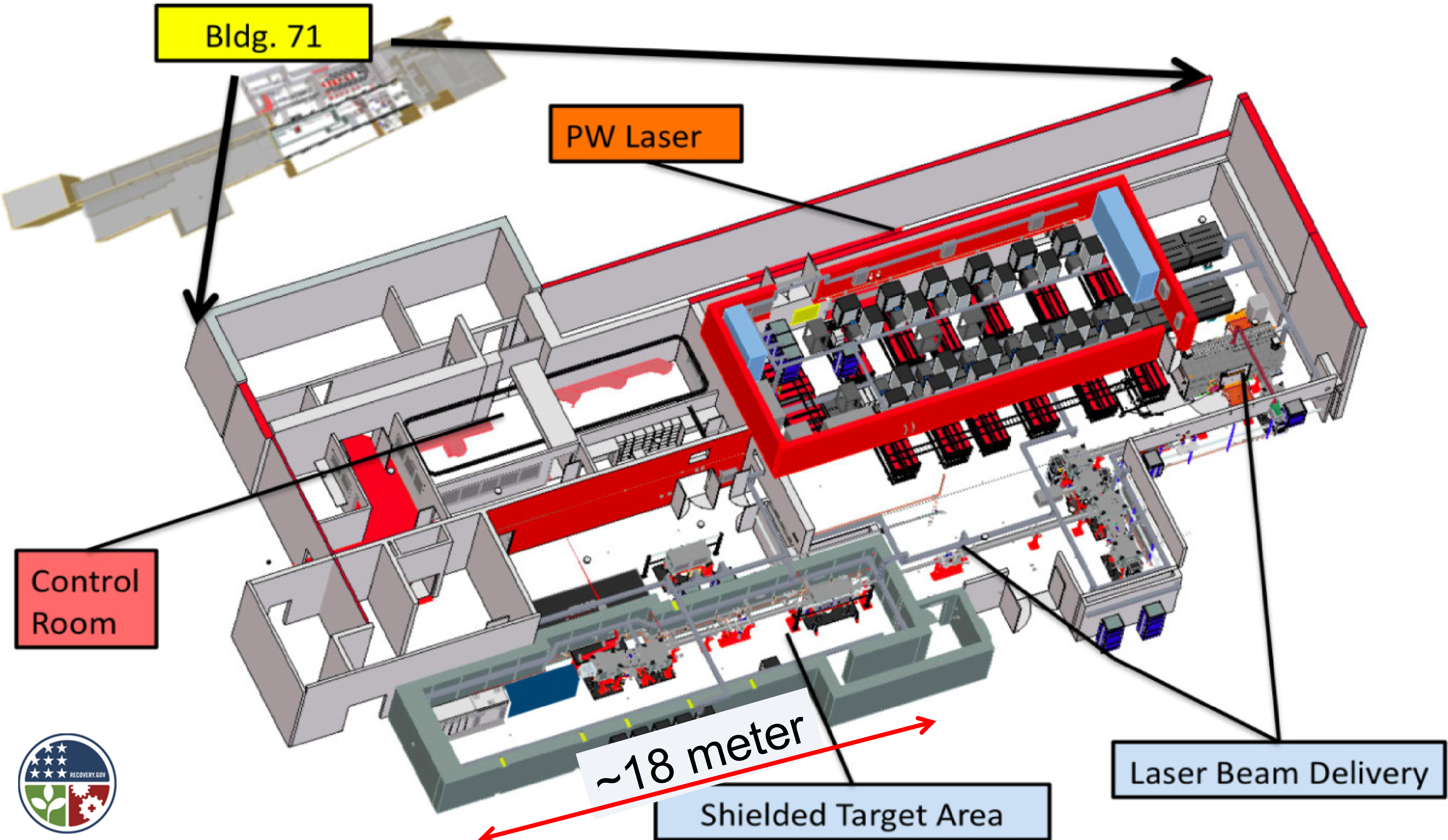
March 2009 Physics Today

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

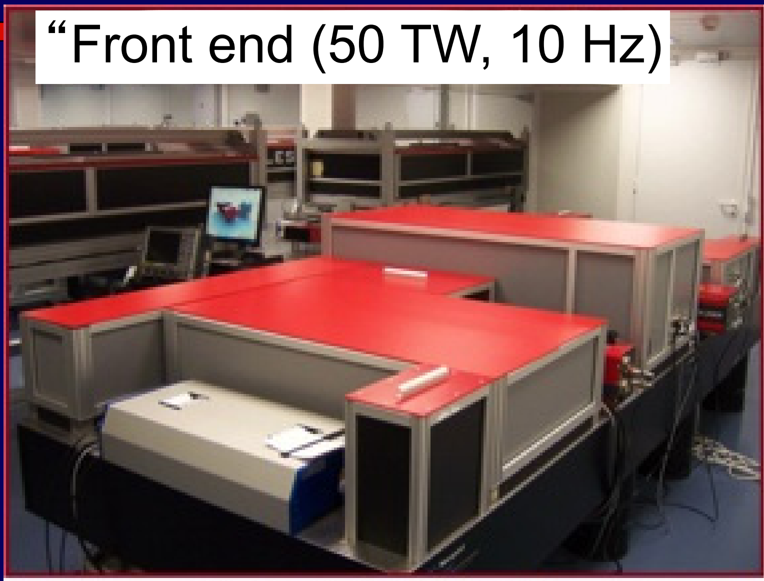
Physics considerations for laser-plasma linear colliders

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)

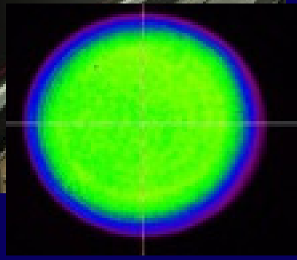
BELLA Project has built a new lab to house a state-of-the-art PW-laser operating at 1 Hz for LPA science

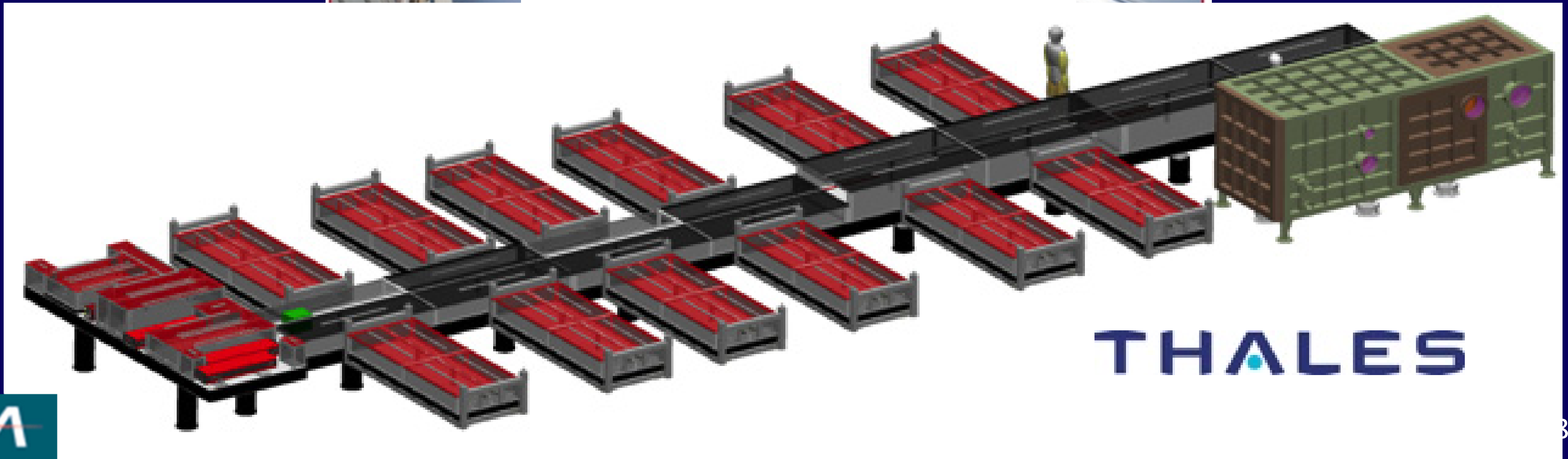


BELLA laser is commercial and will be available for experiments by summer 2012 -- 1.3 PW at 1 Hz



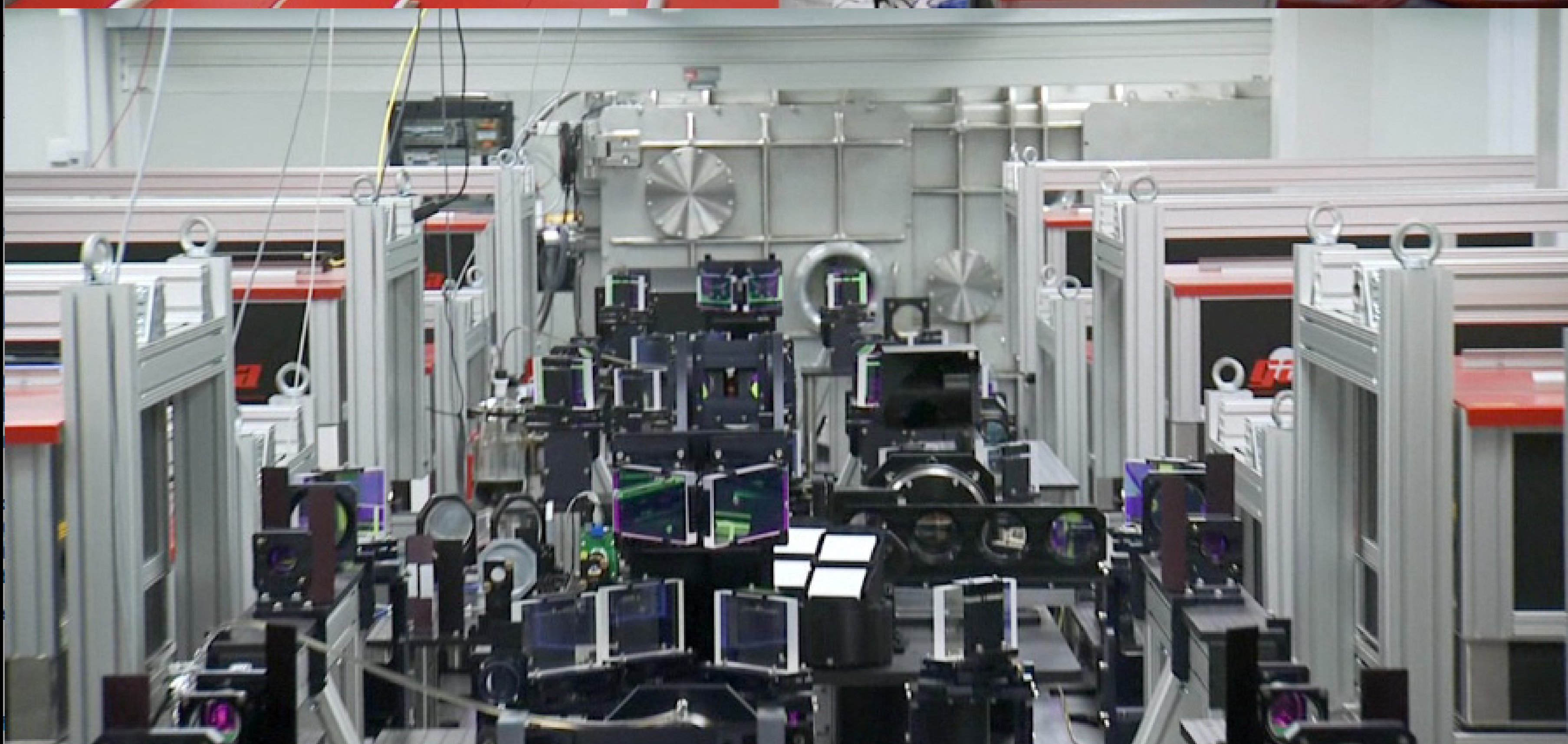
BELLA Front End within the BELLA laser room





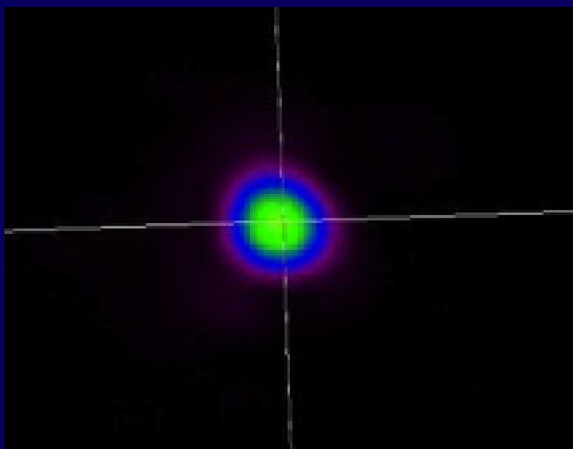
BELLA


gaia
gaia

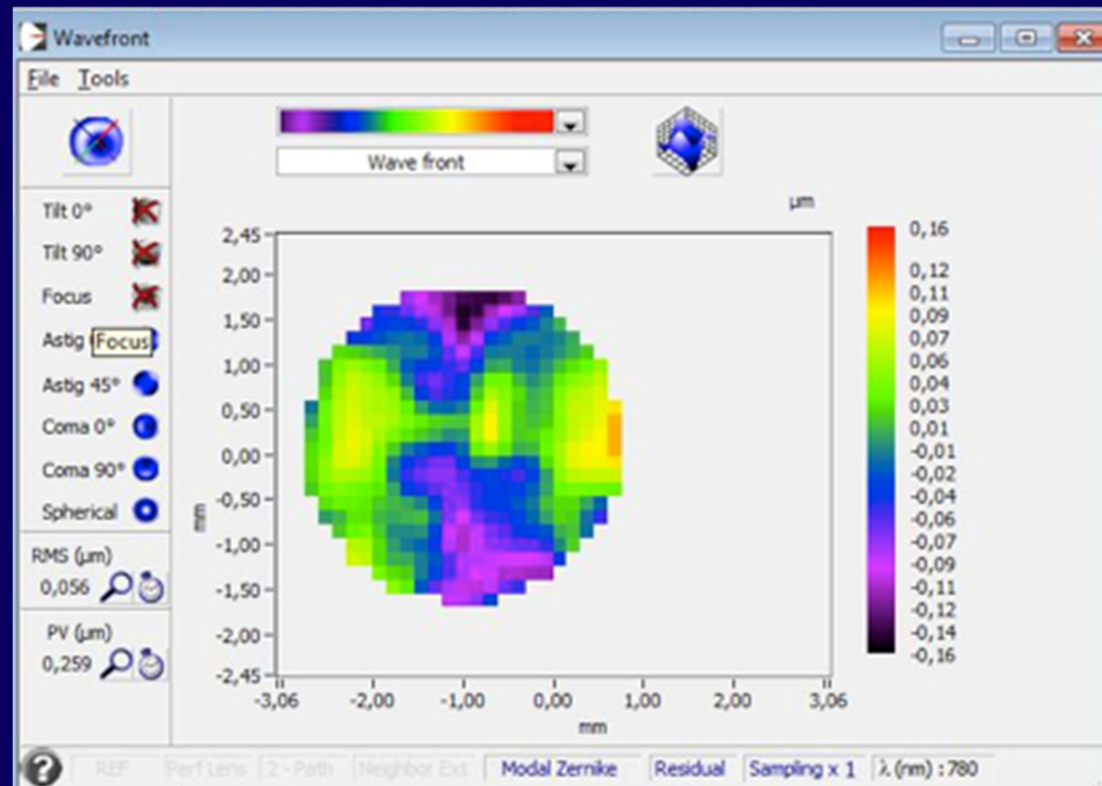

gaia

Focused beam is of high quality and has good pointing stability

Wavefront rms error = 0.056 ⌠m



FWHM = 58 micron
using 10 m focal length lens
Measured at ~500 TW



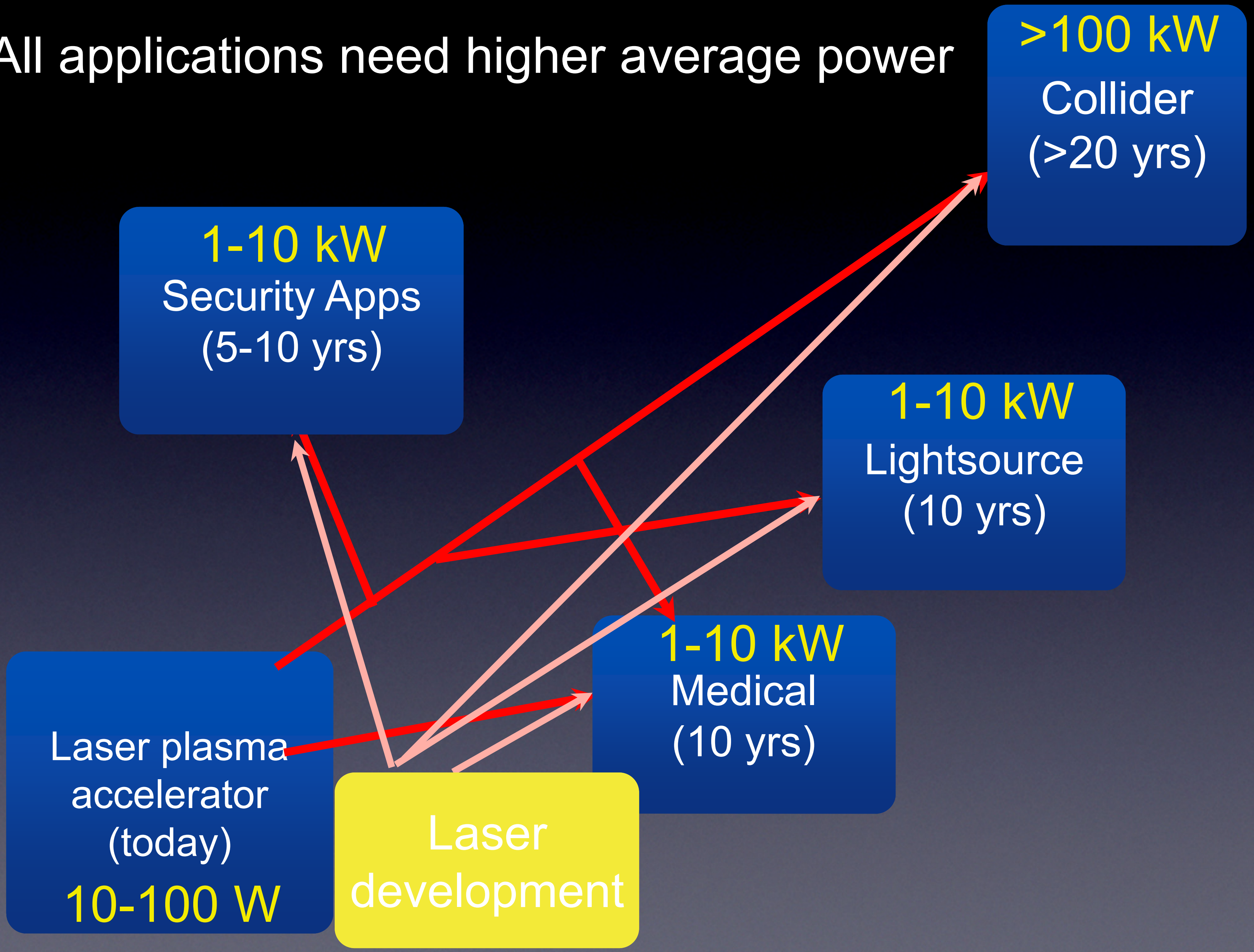
- 150 mm diameter deformable mirror with wavefront sensor integrated into diagnostic system
- ~ 1-2 microrad pointing fluctuation

BELLA

Our simulations indicate 10 GeV beams with several 100's of pC in charge can be produced using BELLA

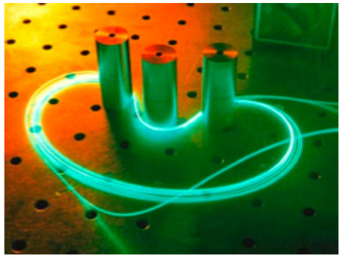
- Provided beam quality is good:
  - Driver for short wavelength FEL
  - Positron production
  - Ultra-high intensity particle-photon interactions
- BELLA can also be used for ion acceleration

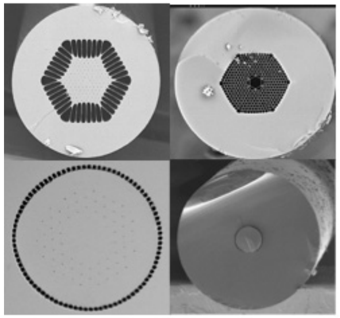
All applications need higher average power



Novel lasers and materials are being developed

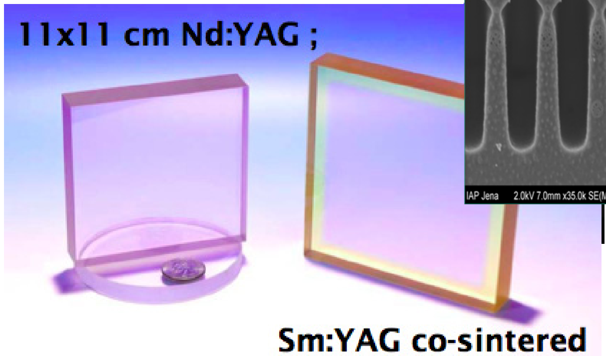
- Amplifiers
  - Rods, slabs, discs and fibers

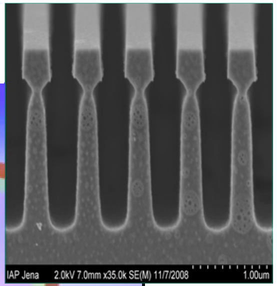


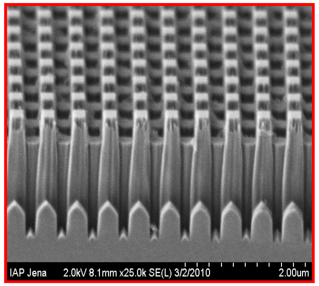


Novel fiber designs, PCF

- Materials for amplifiers, mirrors and compressor gratings
  - Ceramics and diamond
  - Nano-fabricated structures

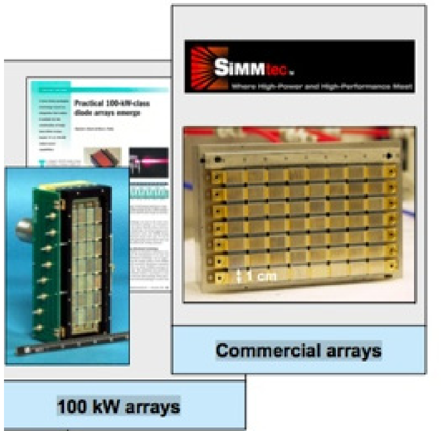






- Diodes and small quantum defect materials

Talk on Friday by
Andreas Tünnerman



Roadmap effort between accelerator and laser communities has resulted in defining challenges ahead for laser technology

Launched joint ICFA-ICUIL taskforce in 2010

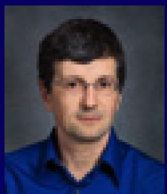
White paper published:
ICFA Beam Dynamics Newsletter #56 of December 2011

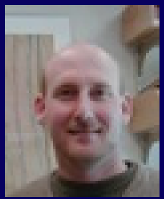
Conclusion

- Applications center on key advantages of LPAs:
  - Compact high (and low) energy accelerators based on ultra-high gradient
  - Hyperspectral radiation
- Revolution in laser technology is key for continued success:
  - The better the laser, the better the accelerator
    - Development of high peak power, high average power lasers with high efficiency
      - Industry to get involved with Nat'l labs and Universities
  - PW-lasers rep rated lasers coming on-line and many exciting results for LPA science and applications are forthcoming

LOASIS/BELLA staff includes experimentalists, theoreticians, students, postdocs, technicians, engineers and admins (FY12)

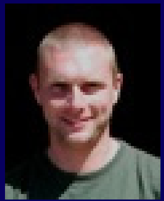
Scientific Staff:

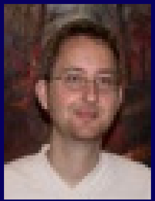

Wim Leemans


Eric Esarey


Csaba Toth

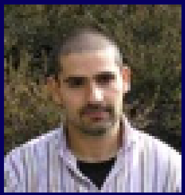

Carl Schroeder


Cameron Geddes


Anthony Gonsalves


Nicholas Matlis


Jeroen van Tilborg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Guest Researchers:


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Dave Evans


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Mark Kirkpatrick


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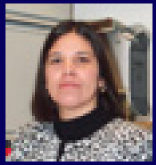
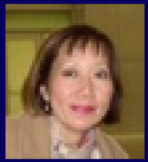
Nathan Ybarrolaza

Administrative Support:


Martha Condon


Olivia Wong