The Birth of the 5 th Generation Light Source

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22 November 2013

The EuCARD-2 Enhanced European Coordination for Accelerator Research & Development project is co-funded by the partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453.

This work is part of EuCARD-2 Work Package **5: Extreme Beams (XBEAM)**.

The Birth of the 5th Generation Light Source

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CERN Seminar

22 November 2013

Geneva, Switzerland

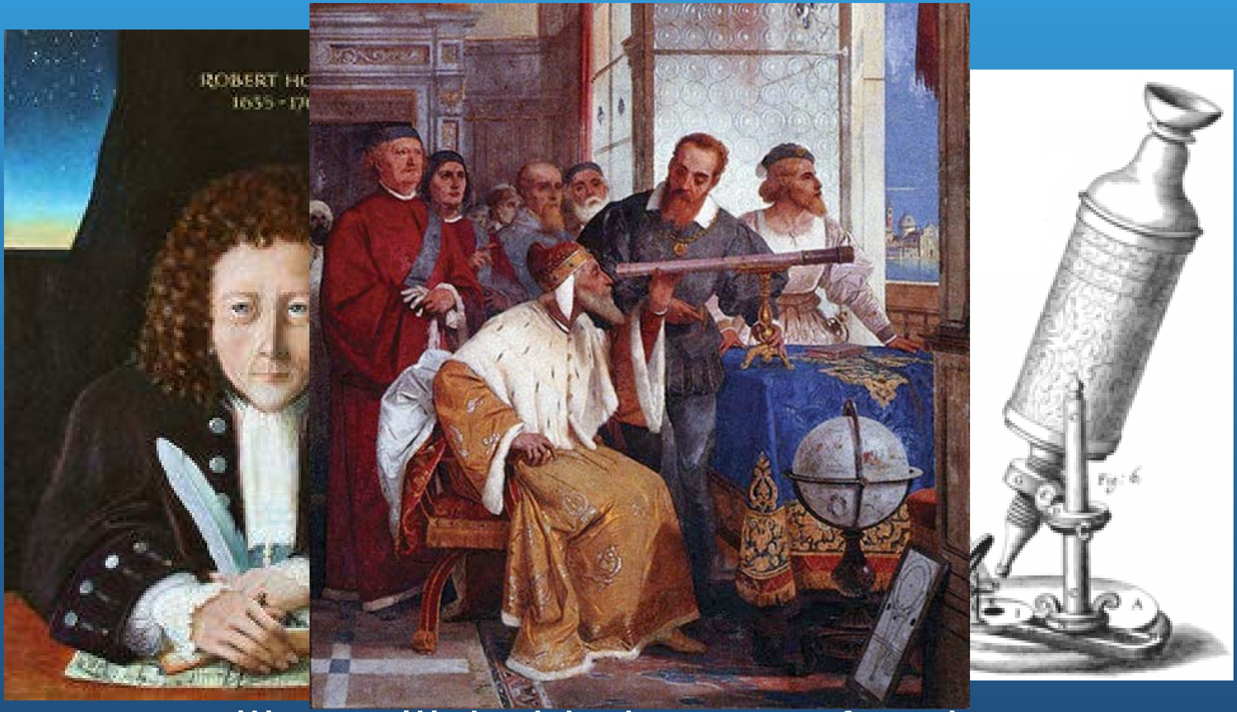
Abstract

The 4th generation light source — the X-ray free electron laser — has revolutionized the way science at the nano-to-mesoscale is done. UCLA researchers have played a key role in this development, and which is moving to a new phase: the birth of what is known as the 5th generation light source – an ultra-compact FEL or similar scheme that is driven by a beam derived from an *advanced accelerator*, a new class of accelerator based on lasers, plasmas, wakefields and exotic structures. We discuss the characteristics of such a system, beginning with an overview of FEL gain mechanisms, noting that the future will bring low charge beams with extreme hig brightness and temporal scales down to the attosecond level. These attributers also are synergistic with the characteristics of advanced accelerators which must operate at quite small accelerating wavelength, demanding small charges and short pulses. In order to fully exploit such beams, a compact FEL system must also reimagine the undulator to utilize very short periods. This in turn fundamentally changes the FEL interaction, bringing it to the threshold of the quantum regime, as well as the Raman regime, in which even for X-ray FELs the longitudinal space charge fields play a dominant role. We highlight in this talk a few of the leading 5th generation light source techniques that are currently under active development.

To see the the world more clearly… one needs a better instrument

We can look outward a *telescope*, seeing backwards in time to the Big Bang…

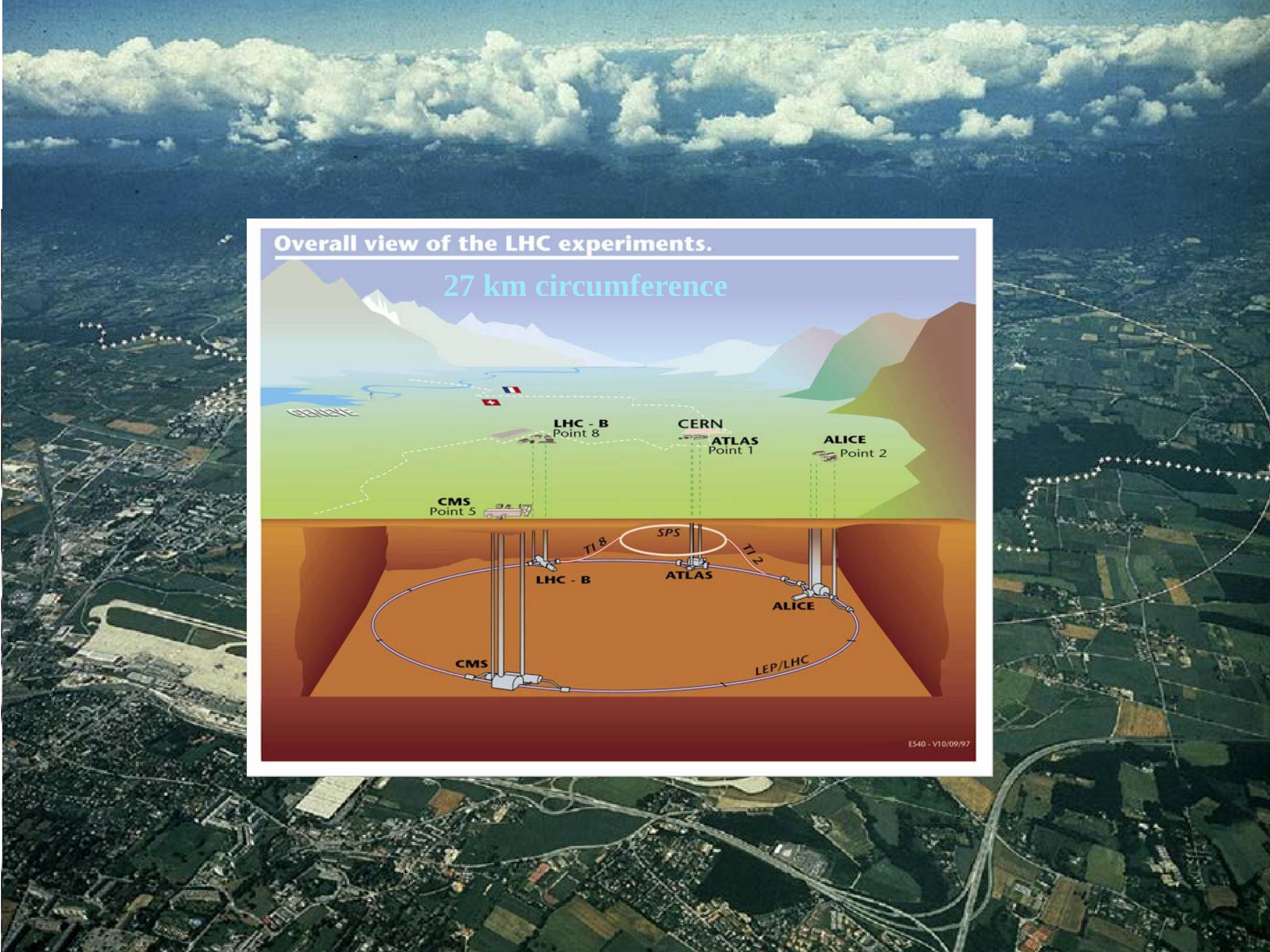
Or we can utlized a microscope



Galileo Galilei with the Doge of Venice

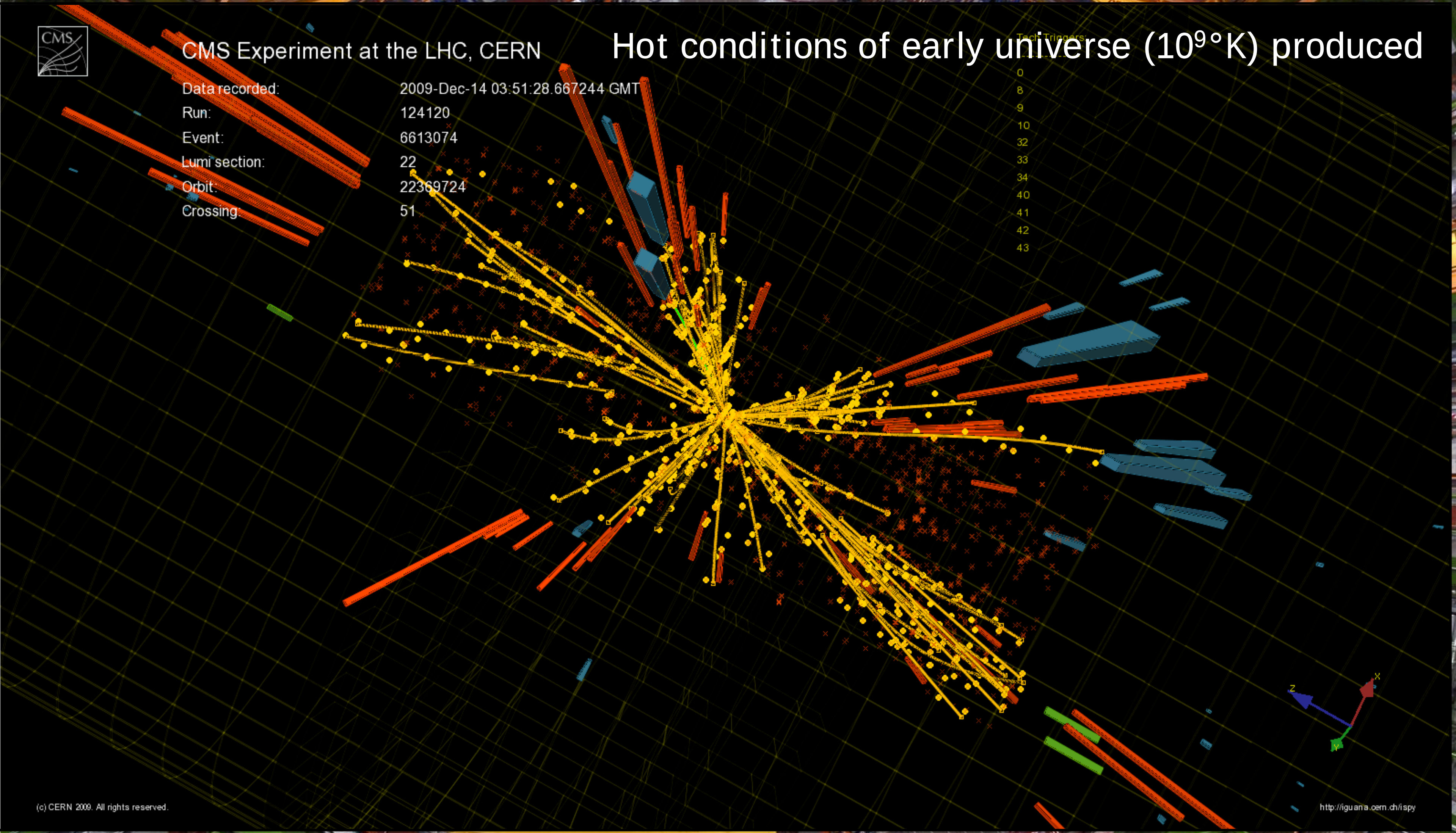
With *accelerators*, the microscope can see very small distances, $<10^{-18}$ m
Exceed Hooke by factor of trillion…

$\lambda \sim hc/E$



27 km circumference

Hot conditions of early universe (10^9 °K) produced



Detectors also enormous, complex, costly (~moon shot)

The challenge of the energy frontier: colliders

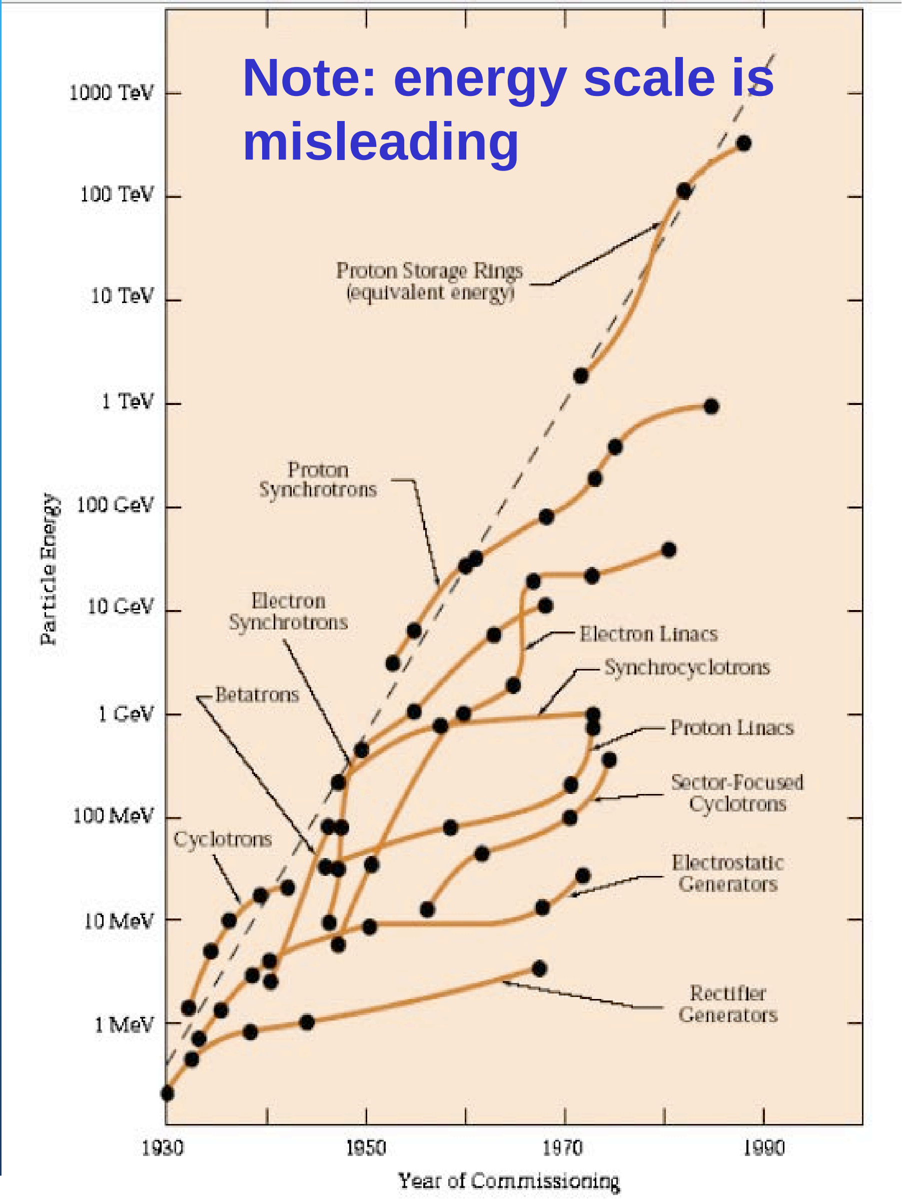
- Fixed target energy for particle creation

$$U_{PC} \cong \sqrt{2U_b m_t c^2}$$

- Colliding beams (e.g. e^+e^-) makes lab frame into COM…

$$U_{PC} = 2U_b$$

- Exp’l growth in *equivalent beam energy* w/ time
  - Livingston plot: “Moore’s Law” for accelerators
  - We are now well off plot!
- Challenge in energy, but *not only*…<u>beam quality</u> as well
  - Giant accelerators (*synch radiation*)
  - Tiny phase spaces



Note: energy scale is misleading

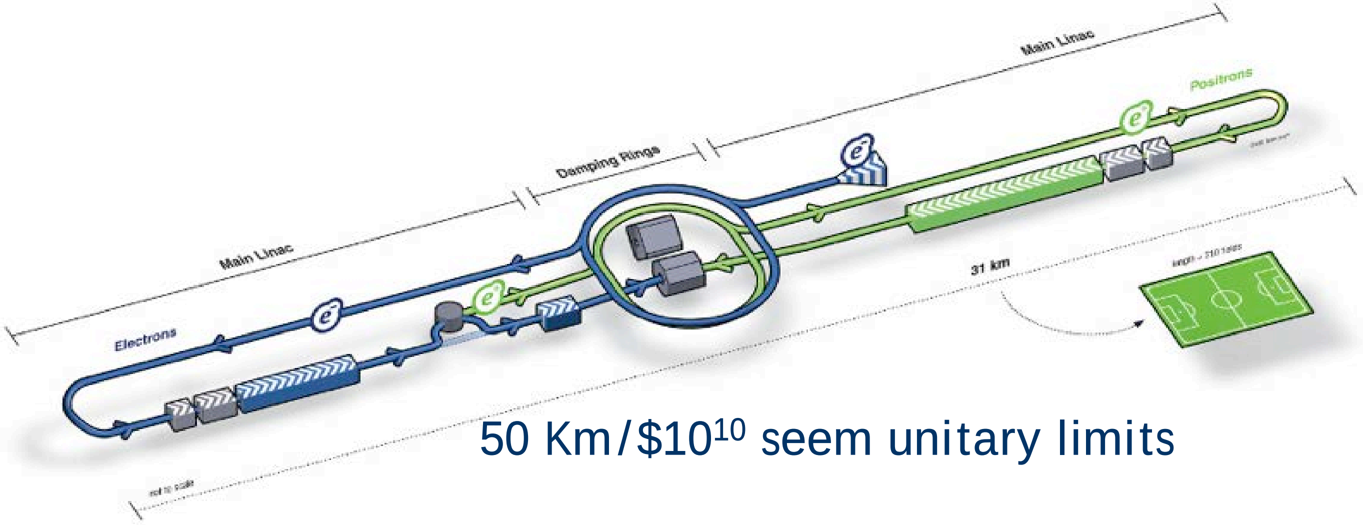
Limitations of collider energy

- Synchrotron radiation power loss
  - Future e^+-e^- colliders foreseen *linear*
    - LEP (<207 GeV COM) was last of breed?
    - Muons?
  - *Large* circular machines for hadrons
- Scaling in size/cost prohitive
  - Acceleration < 35 MeV/m
- Big $cience should *shrink*

$$P_s \propto \frac{\gamma^4}{R^2}$$


Tevatron complex at FNAL

The science behemoth: ~TeV linear collider



50 Km/$$10^{10}$ seem unitary limits

Shrinking the accelerator: ultra-high fields and *high energy density*

- Keeping stored EM energy, final beam energy constant,

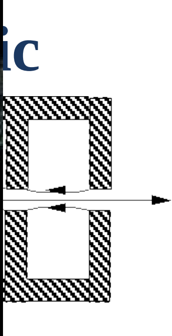
$$\boxed{E \sim \lambda_{EM}^{-1}}$$

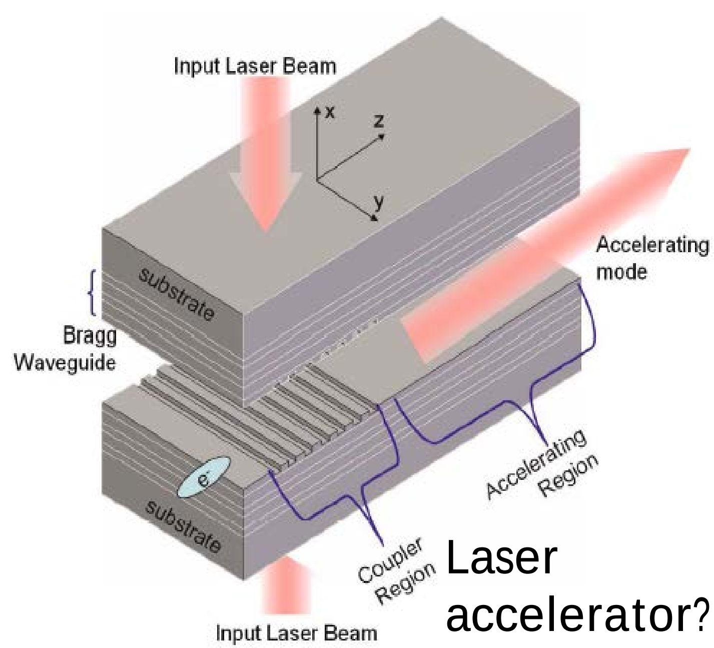
  - Relativistic dynamics (HED)

$$\boxed{eE / mc\omega \sim 1}$$

- For this scaling, need new paradigms
  - Existing laser sources?
  - New methods of creating waves?
  - New acceleration media

Supercond





Laser accelerator?

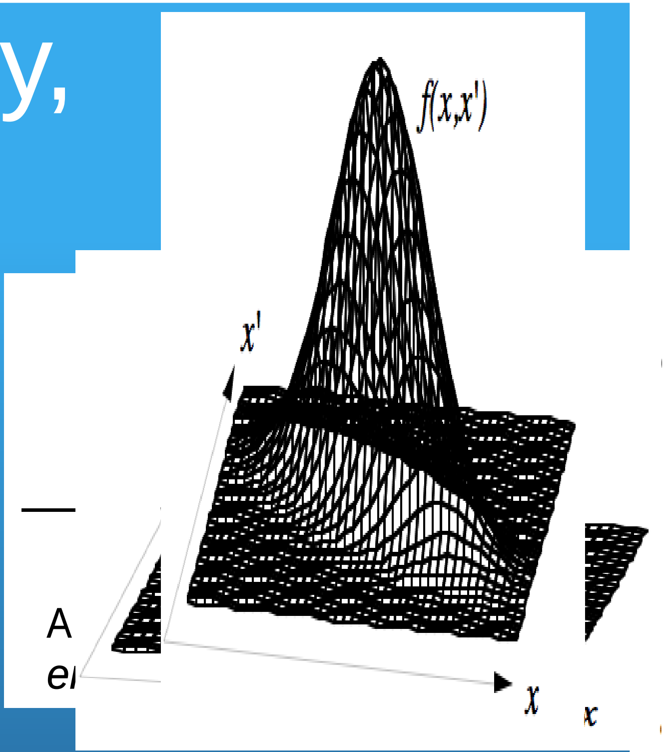
High phase space density, collective effects

- High phase space density (cold, focusable)
- Measure: high brightness

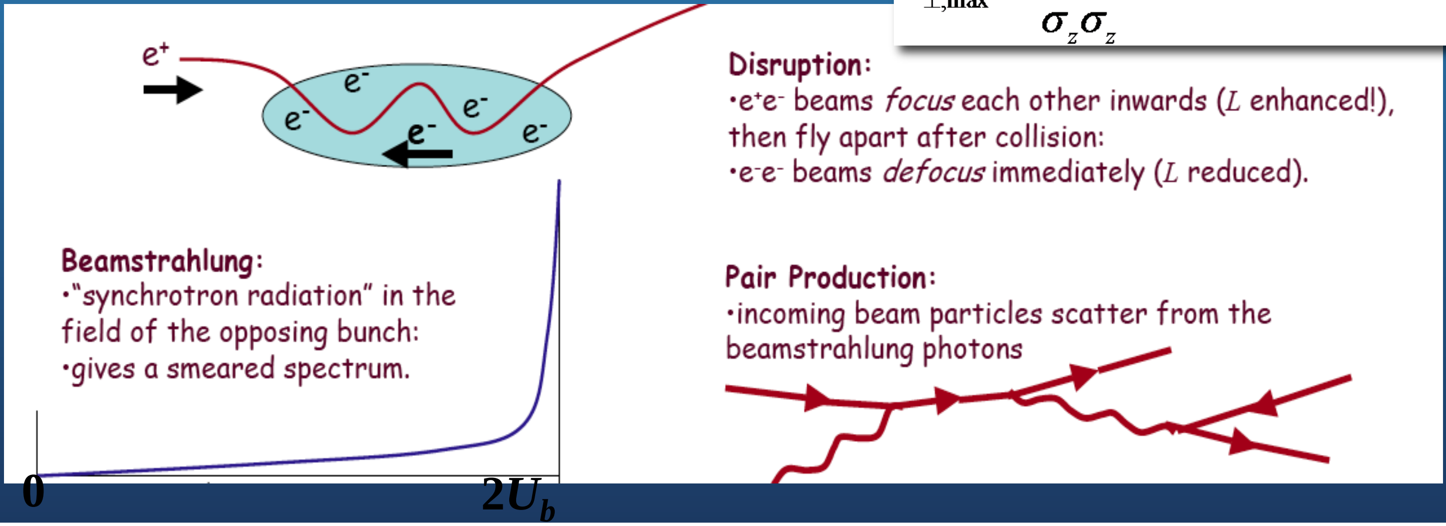
$$B_e = \frac{2I}{\varepsilon_n^2}$$

High brightness needed for next generatio light sources as well.

- *Wakefields* and space-charge (*plasma*) effects characterize high brightness beams
- *Huge collective fields* in collision



$$F_{\perp,\max} \approx \frac{N_b e^2}{\sigma_z \sigma_z} \approx 4\ \text{TeV/m in LC collision!}$$



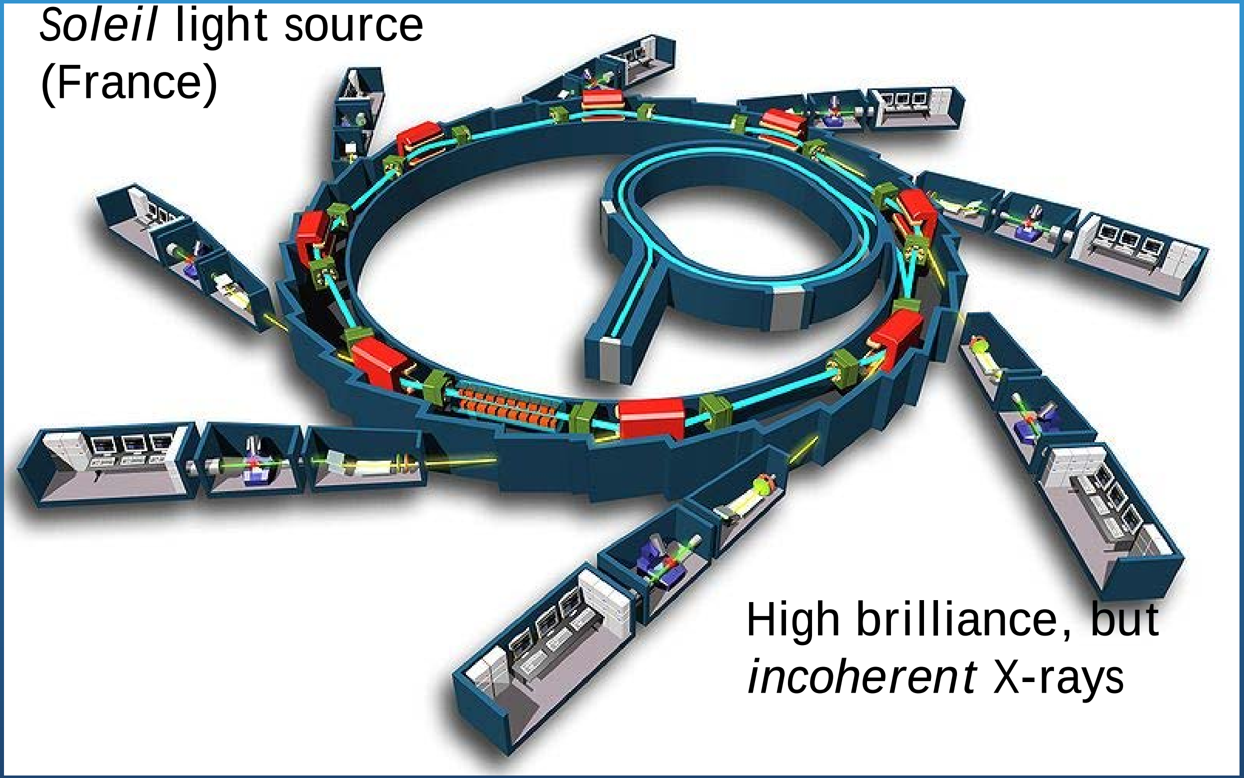
Disruption:
- e^+e^- beams *focus* each other inwards (*L* enhanced!), then fly apart after collision:
- e^-e^- beams *defocus* immediately (*L* reduced).

Beamstrahlung:
- "synchrotron radiation" in the field of the opposing bunch:
- gives a smeared spectrum.

Pair Production:
- incoming beam particles scatter from the beamstrahlung photons

4D Å-femtosecond imaging: the X-ray Free-Electron Laser (FEL)

- Accelerators used as *synchrotron light sources* for >40 years
- High energy physics vice turns to an imaging virtue...



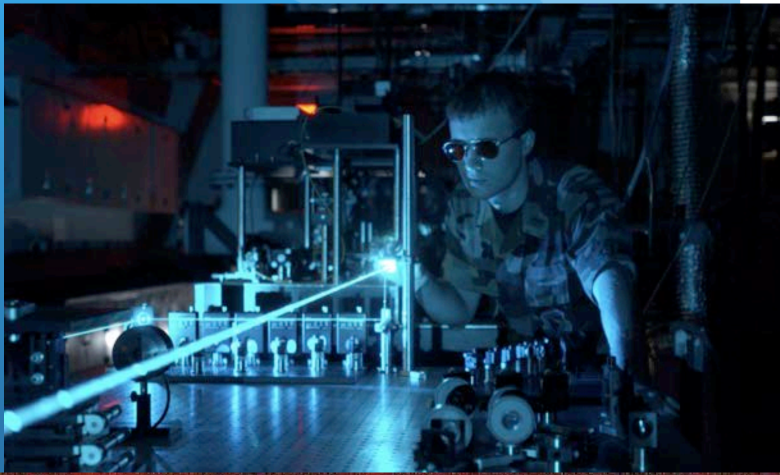
Soleil light source (France)

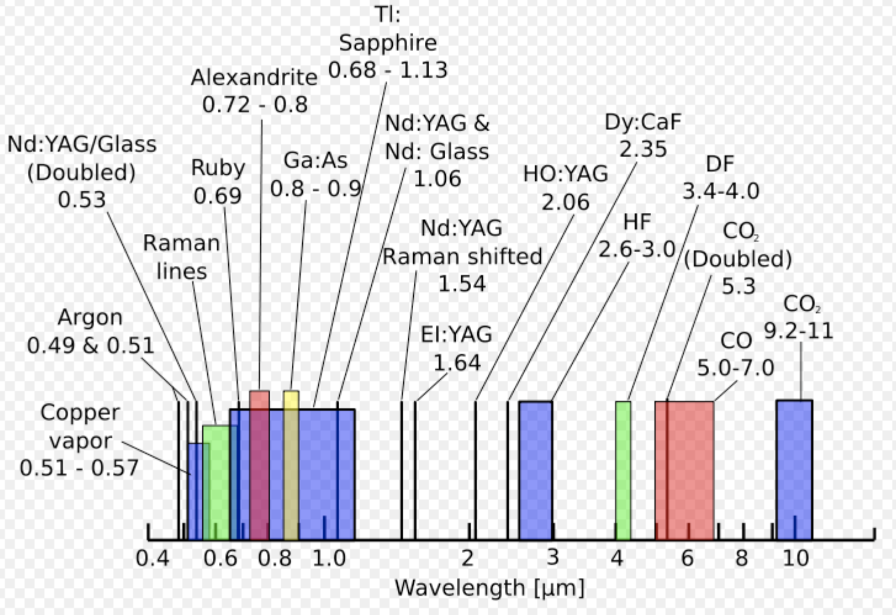
High brilliance, but *incoherent* X-rays

Light sources — before: spin-off, now: stepping stone

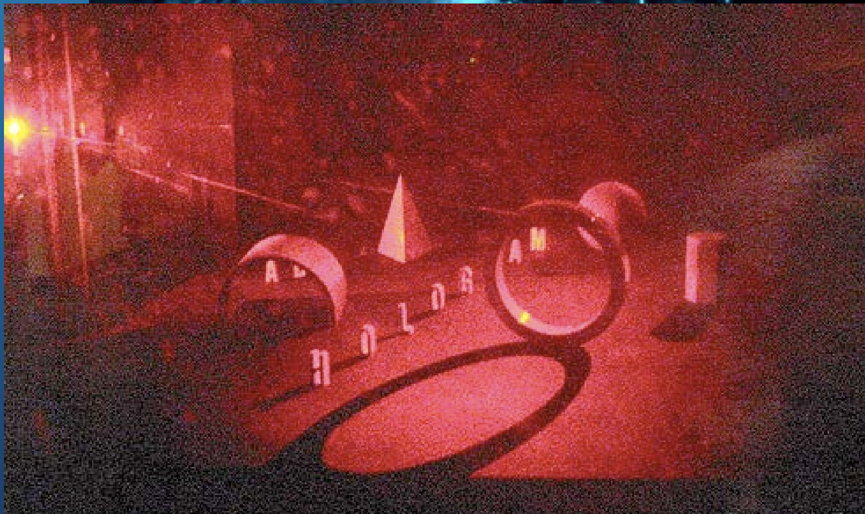
The laser: ubiquitous tool for imaging

- Lasers also provide *beams*:
  - Precise initial conditions in experiments
  - Access fs-to-as time scales: ultrafast
- *Coherent*: ~perfect wave train
  - 3D information encoded
  - Can't image atom/mol.systems





Common in optical-IR. No X-rays!



Hologram uses coherence for 3D imaging

The X-ray FEL: a dramatization

Courtesy: S. Reiche (PSI)

Relativistic electrons can produce coherent short λ light: the X-ray FEL

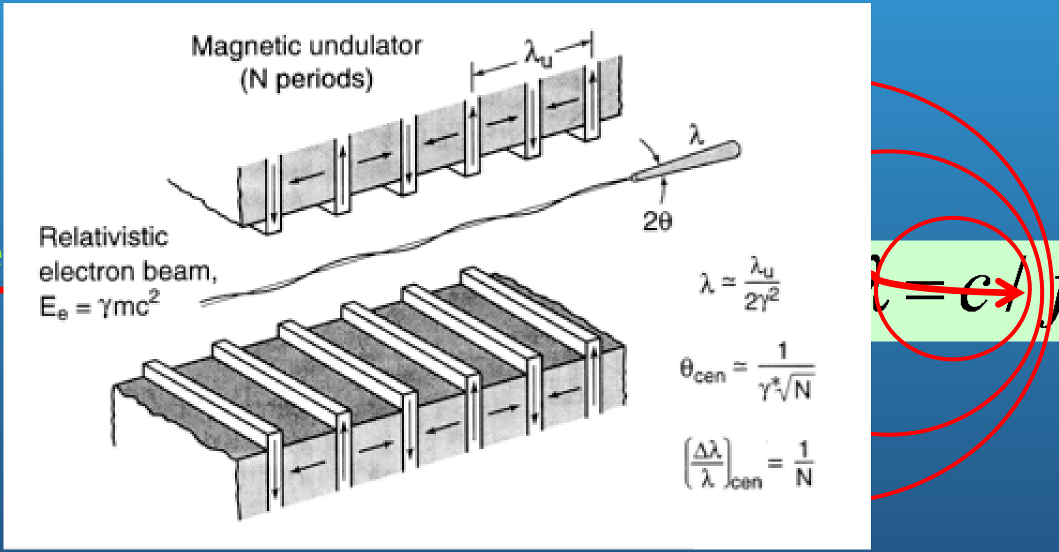
- *Relativistic* Doppler shift

$$\gamma = E / mc^2 >> 1$$

- Radiating electric dipole; “wiggling” electron beam

Rest frame of be

Laboratory Frame

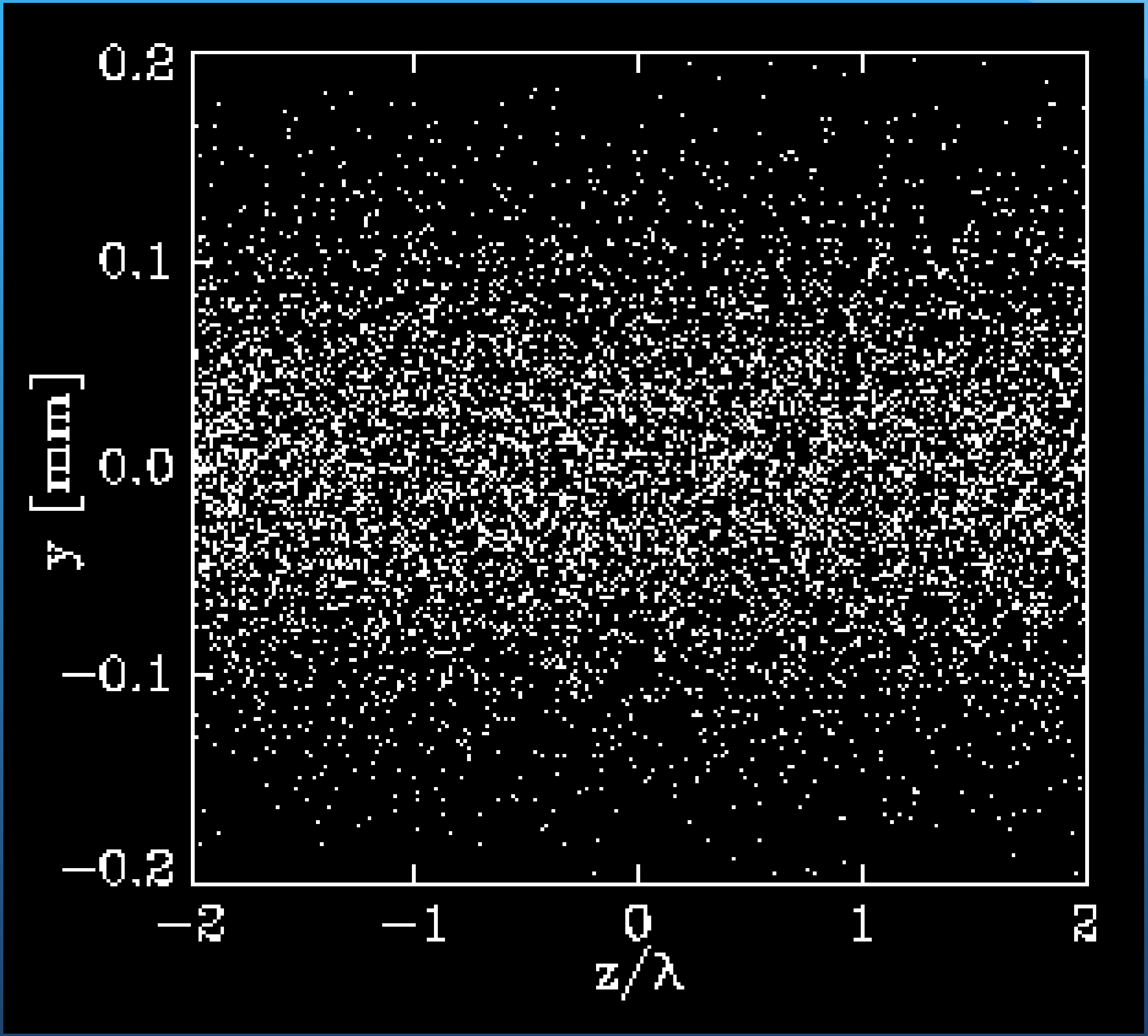


$$\lambda = c / f$$

$$\lambda = \lambda_u / 2\gamma^2$$

- Use magnets to wiggle electrons, radiate at single frequency
- “High” energy beam (2-20 GeV) => X-ray free-electron laser!
  - *Stepping stone energy*… to particle physics frontier energy

FEL lasing dynamics



Microbunching yields
-coherent emission
-high power

High brightness electrons beget high brightness photons

- FEL is 3-wave interaction instability
- Growth rate depends on e- beam brightness

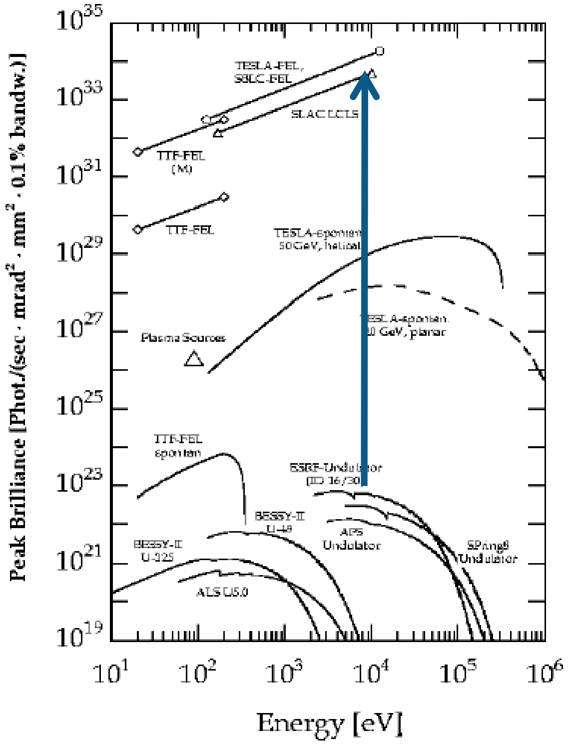
$$L_{g\,1D} = \frac{\lambda_u}{4\pi\sqrt{3}\rho_{1D}} \qquad \rho_{1D} = \left[\frac{JJ(K_{rms})K_{rms}k_p}{4k_u}\right]^{2/3} \propto B_e^{1/3}$$

- High current, small ε gives dense lasing medium

$$\boxed{E_{rad} \propto \exp\left(z/L_g\right);\ L_g \propto B_e^{-1/3}}$$

- Gives +8 *orders of magnitude* photon brightness: fs, *coherent* X-rays
- Both X-ray FEL and linear collider need high energy, very high quality electron beams
- Brightness enhanced at low charge

$$\boxed{B_e \propto Q^{-2/3}}$$

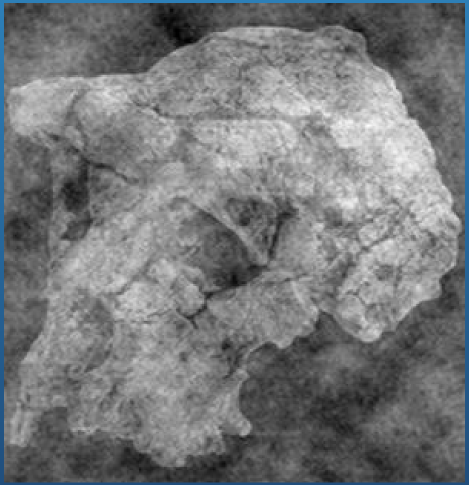


Coherence: the importance of the phase information

(a)

(b)

Amplitude of (a)
+ phases of (b)



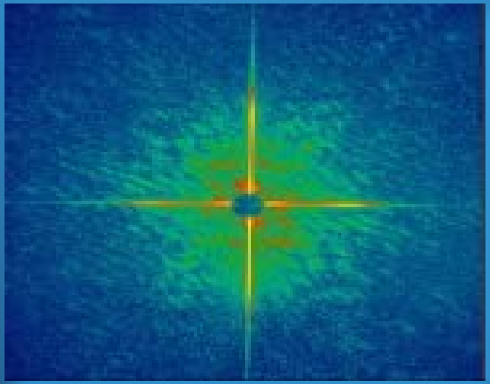
Amplitude of (b)
+ phases of (a)

XFEL: coherent imaging revolution in 4D

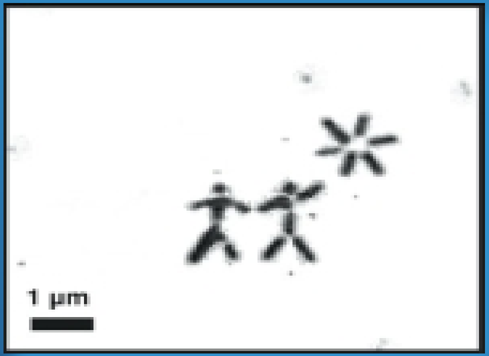
Ultrafast Coherent Imaging

Intense FEL pulse gives coherent diffraction pattern of object before it moves or is destroyed

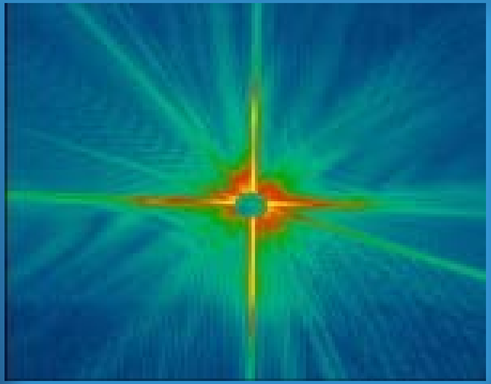
Imaging at length scale (Å) and time scale (fs) of atomic dynamics; *4D* or *ultrafast* imaging



Coherent single 25 fs shot diffraction pattern at FLASH X-FEL (DESY)



Reconstructed X-ray image, no evidence of damage due to X-ray pulse.



Coherent diffraction pattern for the subsequent pulse, sample destroyed

Holy grail: single moletule imaging

Generations of Synchrotron Light Sources

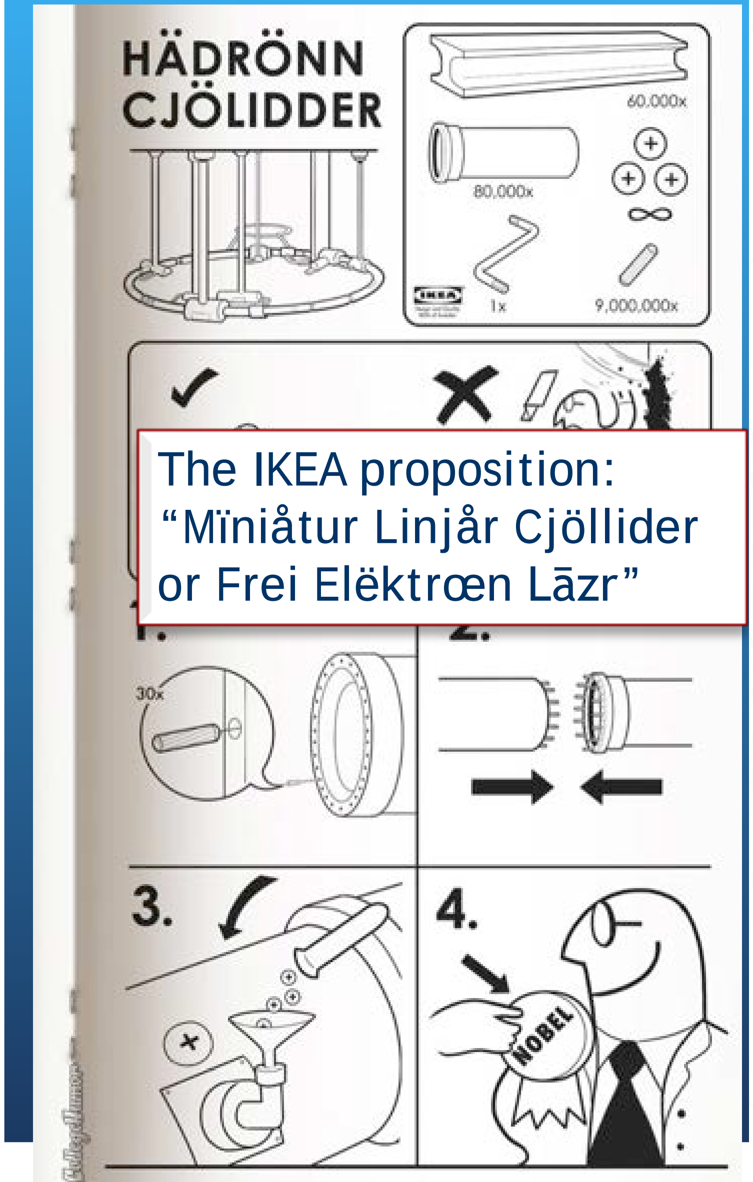
- 1st: bend magnets in HEP rings
- 2nd : dedicated undulator
- 3rd : optimized rings
- 4th : short wavelength FEL
  - Revolution in imaging
- 5th : FEL from adv. Accelerators
  - Enable FEL in smaller labs

FELs are popular:

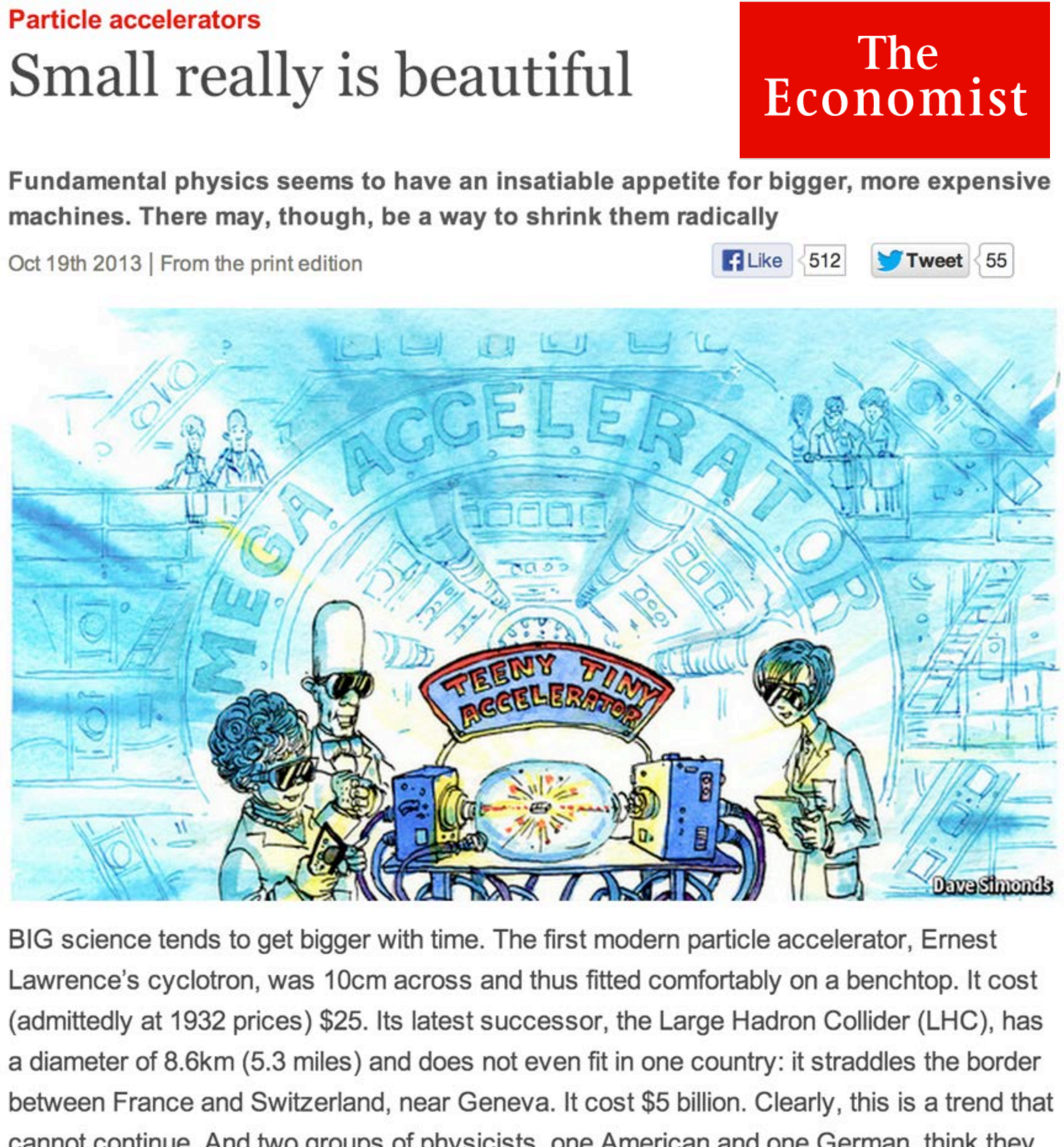
FLASH/XFEL (Hamburg)
LCLS/LCLSII (SLAC)
SACLA (Japan)
PAL FEL (Pohang)
Swiss FEL (PSI)
FERMI (Trieste)
SPARC (LNF)
Etc.

Billions $ invested

Miniaturizing the collider and FEL: some popular views...



The IKEA proposition: "Mïniåtur Linjår Cjöllider or Frei Elëktrœn Lāzr"



Particle accelerators

Small really is beautiful

The Economist

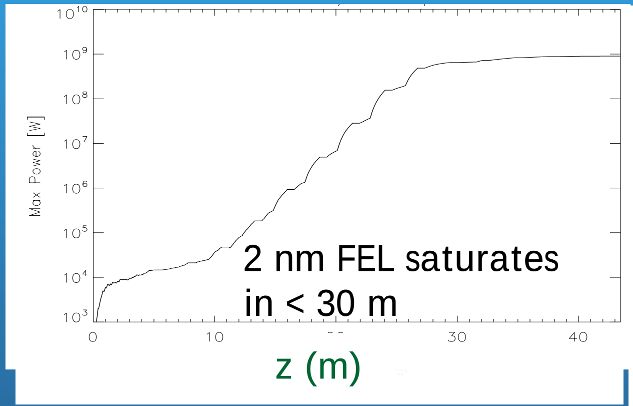
Fundamental physics seems to have an insatiable appetite for bigger, more expensive machines. There may, though, be a way to shrink them radically

Oct 19th 2013 | From the print edition

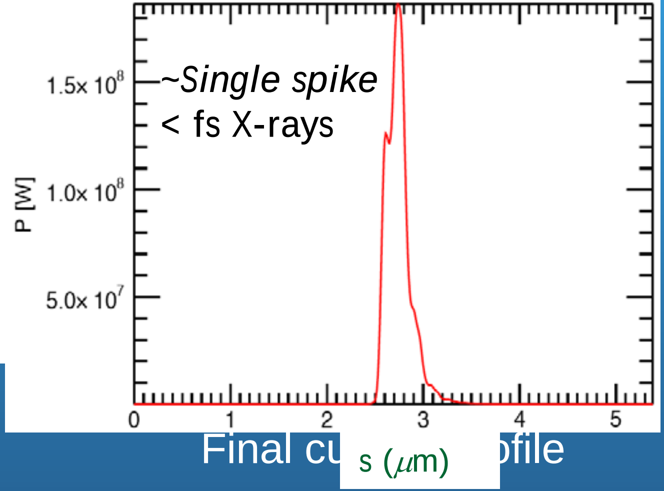
BIG science tends to get bigger with time. The first modern particle accelerator, Ernest Lawrence's cyclotron, was 10cm across and thus fitted comfortably on a benchtop. It cost (admittedly at 1932 prices) $25. Its latest successor, the Large Hadron Collider (LHC), has a diameter of 8.6km (5.3 miles) and does not even fit in one country: it straddles the border between France and Switzerland, near Geneva. It cost $5 billion. Clearly, this is a trend that cannot continue. And two groups of physicists, one American and one German, think they

Honey, I shrunk the X-ray FEL: a physics-driven recipe

- Necessary ingredients
    - Shrink the charge, *Q*=1 nC -> 1 pC (SPARX study, LNF 2007)



Final longitudinal phase space



Final cu ofile

$\varepsilon_{nx} \cong 7.5\times10^{-8}\ \mathrm{m\text{-}rad}$

$\sigma_t \cong 600\ \text{attoseconds(!)}$

$B = 2\times10^{17}\ \mathrm{A/m^2}$

LCLSx1000

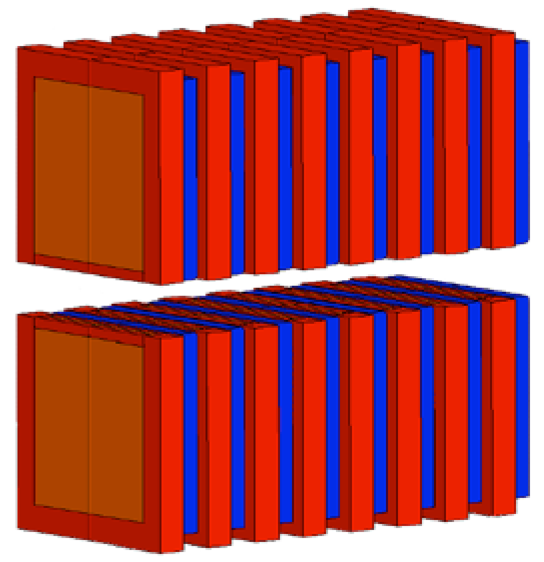
- Shrink the *phase space*; sub-fs! Freeze atomic e- dynamics
- Shrink the undulator (currently >100 m)
- *Shrink the accelerator* (currently km)

- Lets examine potential *ingredients*

Example: next generation undulator, LWFA source

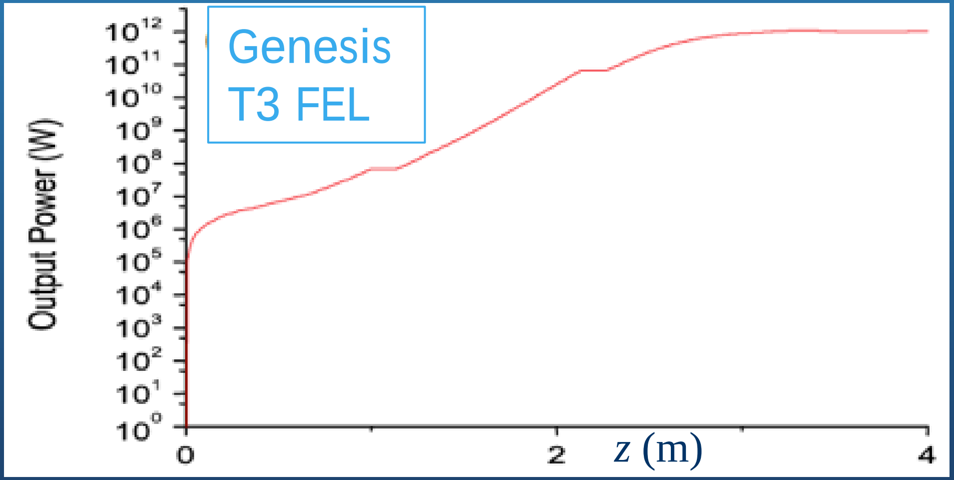
- Cryogenic , Pr-based hybrid undulator
- High field (2.2 T), short λ (9 mm)
- Can yield table-top terawatt *T*^{3} nm FEL, assumed 1.7 GeV, 160 kA beam (from laser-plasma accelerator!)

MPQ-UCLA-HZB collaboration



Hybrid cryo-undulator: Pr-based, SmCo sheath 9 mm λ, up to 2.2 T

F.H. O'Shea et al, PRSTAB 13, 070702 (2010)

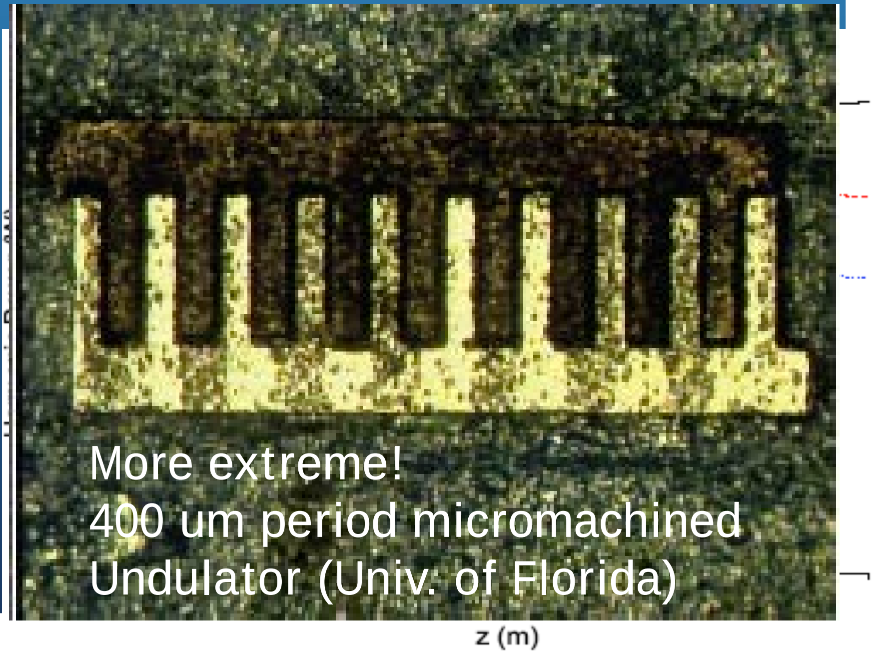


Soft-X-ray FEL saturates 10 x sooner!

Thus… a compact FEL

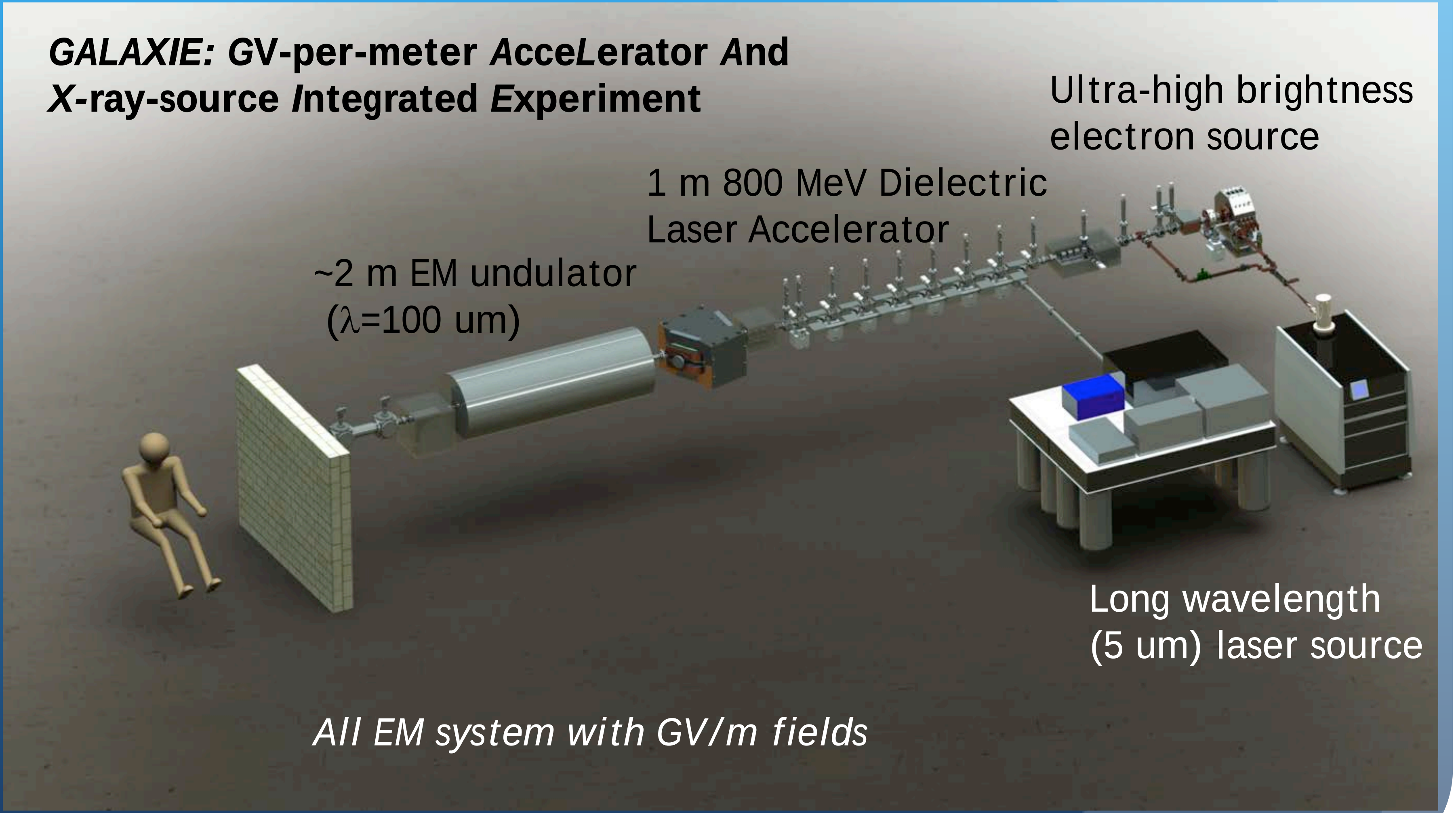
- High brightness beam
  - pC beam, *attosecond* pulse, few 10^{-8} emittance
- High field, short λ_u undulator
  - With *high brightness beam*, $>\rho$, $<L_g$: *short undulator*
- Dramatically lowers e- energy needed
  - *~2 GeV* (or less) X-ray FEL
  - Compact accelerator helps!
  - Push further? Why not?

Hard X-ray FEL in 10 m
w/1 pC driver at 2.1 GeV
("LCLS" photons on 5th harm.)


More extreme!
400 um period micromachined
Undulator (Univ. of Florida)

GALAXIE: An Illustrative Example of *Integrated* Table-top X-ray SASE FEL

GALAXIE: GV-per-meter _AcceL_erator _And_
_X_-ray-source _I_ntegrated _E_xperiment



Ultra-high brightness
electron source

1 m 800 MeV Dielectric
Laser Accelerator

~2 m EM undulator
(λ=100 um)

Long wavelength
(5 um) laser source

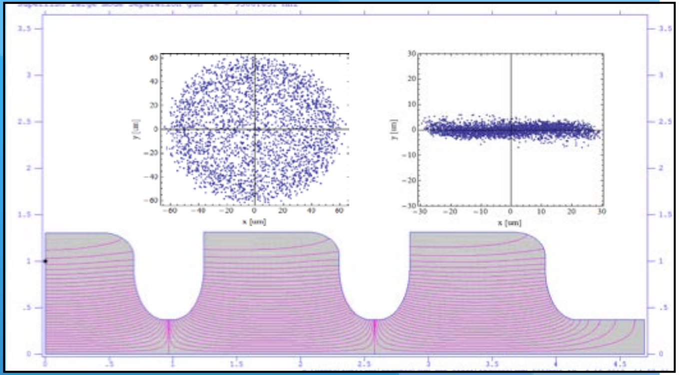
All EM system with GV/m fields

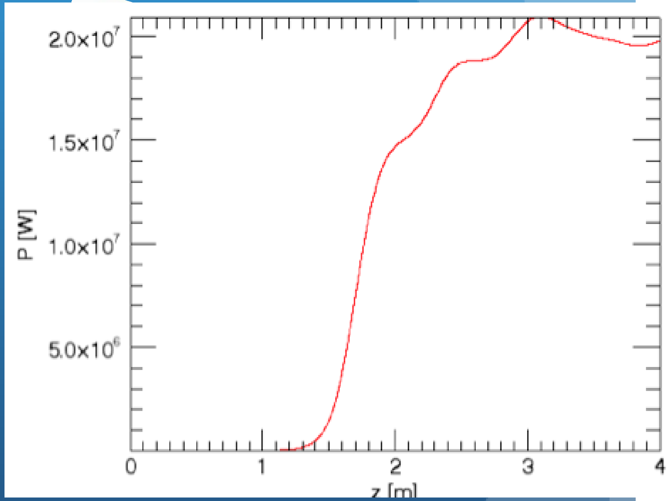
Supported by DARPA AXiS Program

Inside of GALAXIE

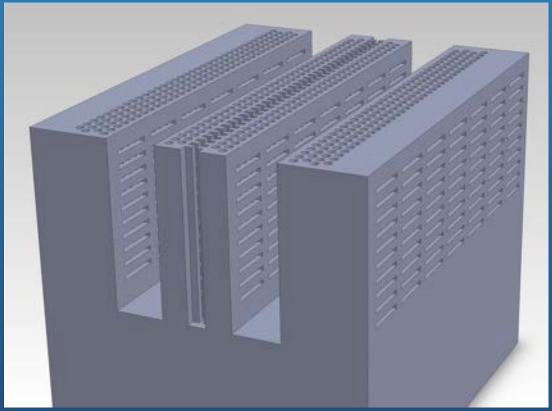
- Ultra-low emittance, optically gated electron source (*magnetized beam*)
- Relativistic photonic dielectric accelerators
- Electromagnetic high field undulator, QFEL
- New mid IR laser source: 5 microns
- New optics/diagnostics!

200 MV/m X-band RF gun w/ flat beam converter

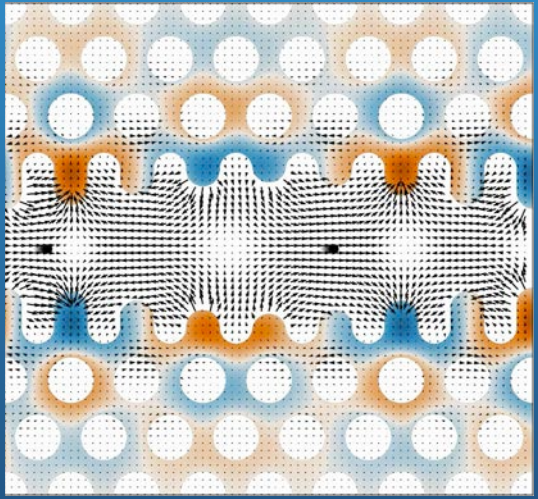




20 MW SASE
X-ray FEL in 2 m
(40 keV photons)



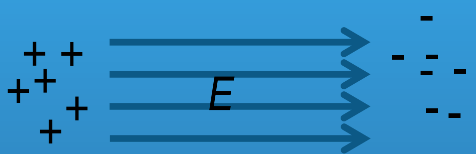
Traveling wave dielectric laser accelerator



Photonic defect mode bi-harmonic structure with 2nd order focusing and acceleration on high spatial harmonic

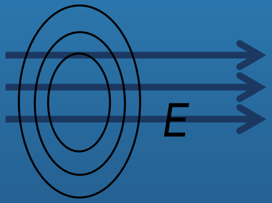
Particle acceleration in electromagnetic waves: history

- Originally electrostatic



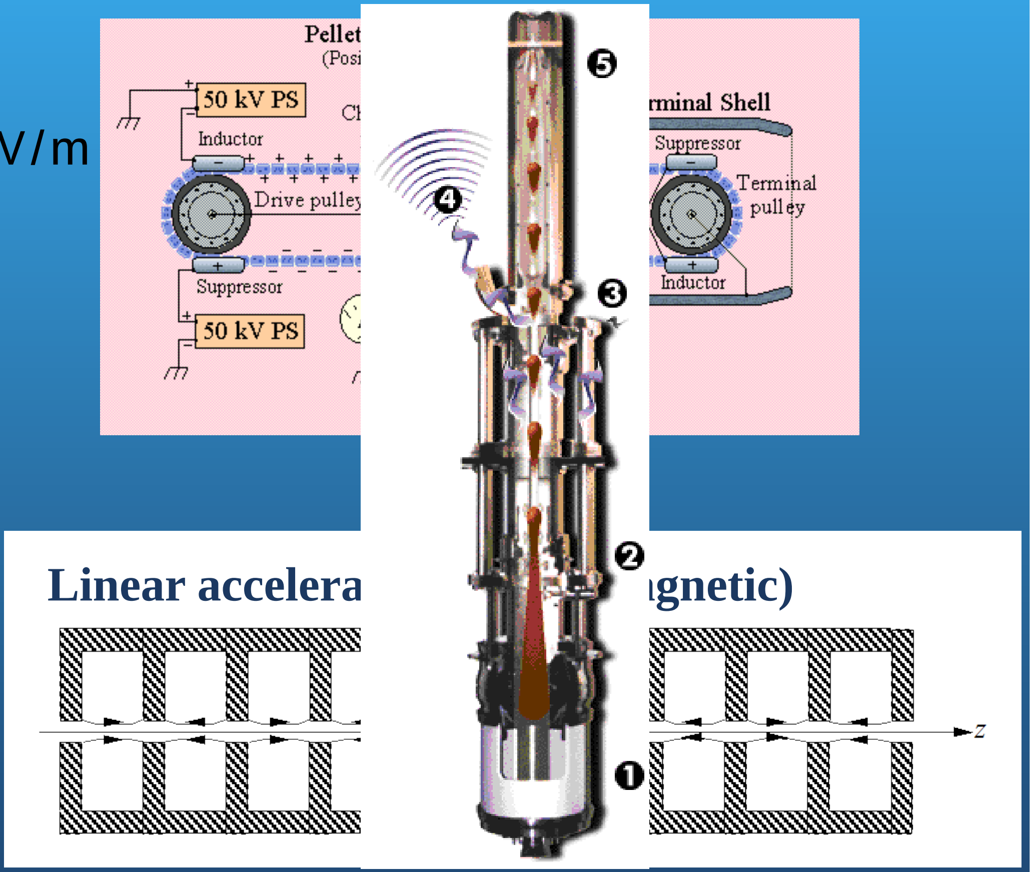
Few MV/m

- Later electromagnetic
  - Need metal structure for longitudinal E-field, $v_\phi < c$



10’s MV/m

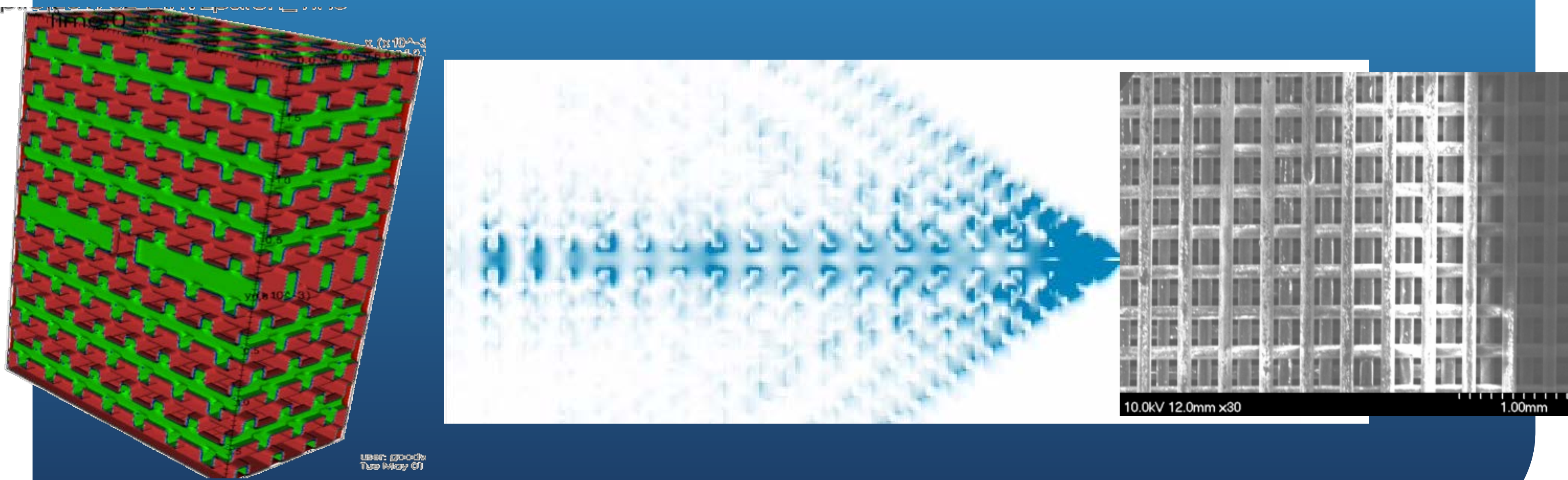
- In microwave linacs, source is a klystron
  - Need ~100 MW
  - Restrict to λ>cm



The klystron

Shrinking the *accelerator*

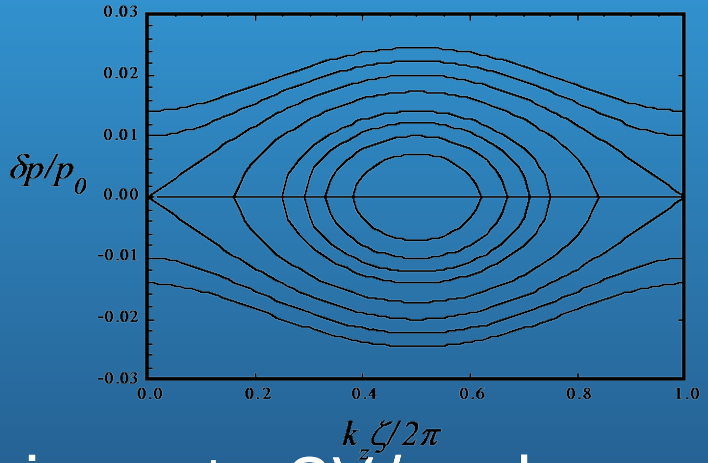
- Higher E (>GV/m): shorter λ ($E \sim \lambda^{-1}$); THz down to IR
  - *Need* much smaller ε
  - Small Q (beam loading/eff. $Q \sim \lambda^2 E \sim \lambda$). *Synergy with brightness, FEL*
  - Losses -> dielectric at short λ -> photonics
  - Breakdown considerations -> dielectric -> plasma
  - Sources? Laser (to mid IR). THz? From wakefields…



Photonic structure (woodpile) wakes; as constructed at UCLA (left)

What is optimum scaling of λ_{EM}?

- *Lasers* produce copious power (~J, >TW)
  - Scale in λ_{EM} by *~5 orders* of magnitude
  - GV/m fields possible, “only” *two orders of magnitude* greater
    - Avalanche breakdown limited… quantum energy is large



Laser wavelength accelerator longitudinal dynamics: few % δp/p stability range…

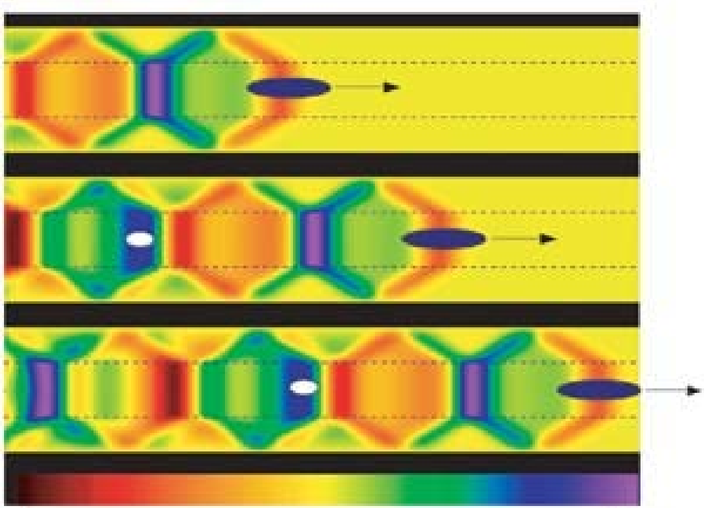
$$\alpha_{EM} \equiv \frac{qE_0}{k_z m_0 c^2} \propto \lambda_{EM}$$

$$\alpha_{EM} << 1$$

$$\frac{\delta p_{\max}}{p_0} = \sqrt{\frac{4\alpha_{EM}\gamma_0}{\beta_0^2}}$$

- To jump to GV/m, longer λ_{EM} may be better:
  - Beam dynamics(!), breakdown scaling
  - Need *new power sources* for THz spectral range
    - OPA lasers (mid-IR),
    - *Wakefields*: start discussion here…

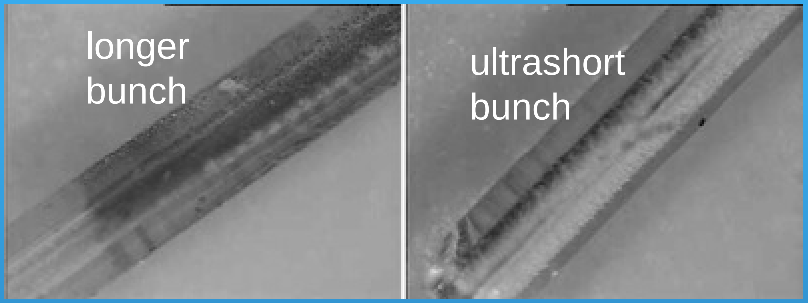
New paradigm for high field acceleration: *wakefields*



Wakefields in dielectric tube
Driving & accelerrating beams

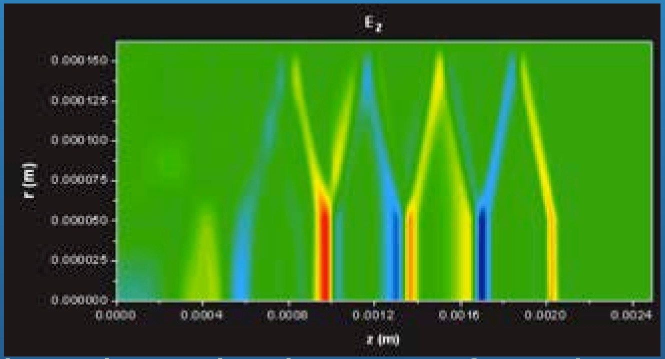
- *Coherent* radiation from *bunched*, *v~c,* e$^-$ beam
  - *Any slow-wave* environment (metal, dielectric, plasma)
  - Resonant or *short pulse* operation
  - THz within reach
- *High average power beams* can be produced
  - Tens of MW, can beat lasers
  - Motivates CLIC-like schemes

Breakdown threshold: many GV/m



Post mortem images (1^{st} vaporize Al coating, next damage SiO_2)

Breakdown determined by benchmarked simulations (OOPIC)



Breakdown limit:
5.5 GV/m decel. field
(10 GV/m accel.?)

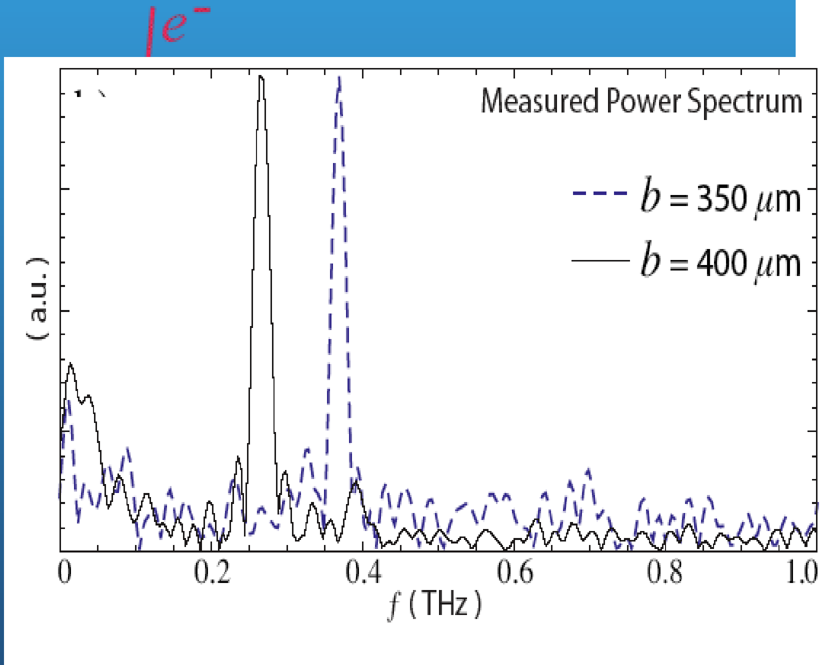
Multi-mode excitation – 100 fs, pulses separated by ps — gives better breakdown dynamics

Multi-GV/m in the sights for laser accelerator and DWA

M. Thompson, et al., *PRL* 100, 214801 (2008)

THz Coherent Cerenkov Radiation (CCR) from DWA

- FFTB gone … move expt to UCLA
- Chicane-compressed (σ_z<200 μm), *Q*=0.3 nC beam @ Neptune
  - PMQ focuses to σ_r~100 μm (*a*=250 μm)
- Autocorrelation of CCR pulse
- Single mode operation
  - Two tubes (diff. *b*), *2* THz frequencies
  - Extremely narrow line width in THz
    - Long wave trains from low v_g

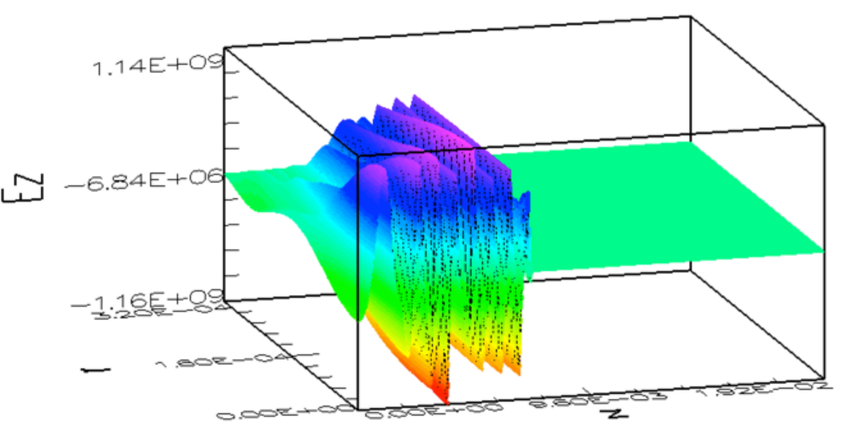


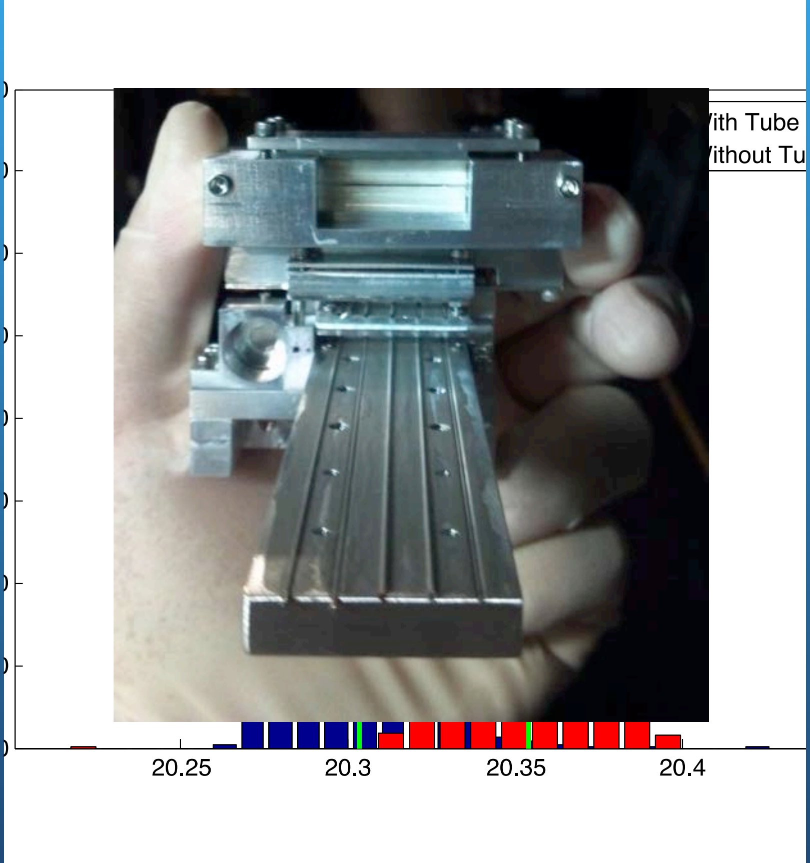
A. Cook, et al., Phys. Rev. Lett. **103**, 095003 (2009)

Spin-off: Higher power, lower bandwidth than THz FEL

FACET now online: 20 GeV wakefied facility at SLAC

- 3 nC, 20x20 um beams
- 10 cm long structures
- GV/m sustained acceleration (June 2013)!



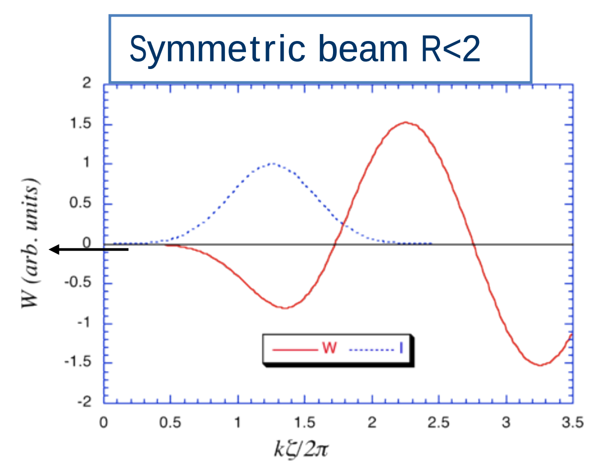


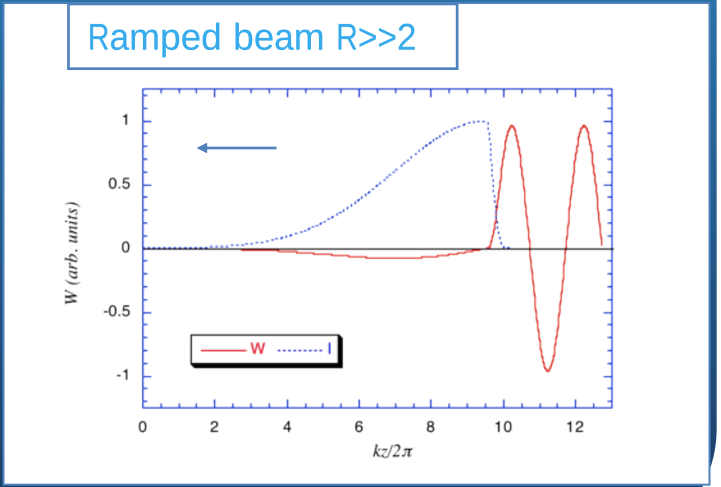
Pulse shaping: reaching *high transformer ratios*

- How to make wakefield acceleration more powerful
- Reach high (FEL) energy with single DWA module?
- Enhanced transformer ratio with *ramped beam*

$$R \equiv \frac{\left\|E_{acc,witness}\right\|}{\left\|E_{dec,driver}\right\|}$$

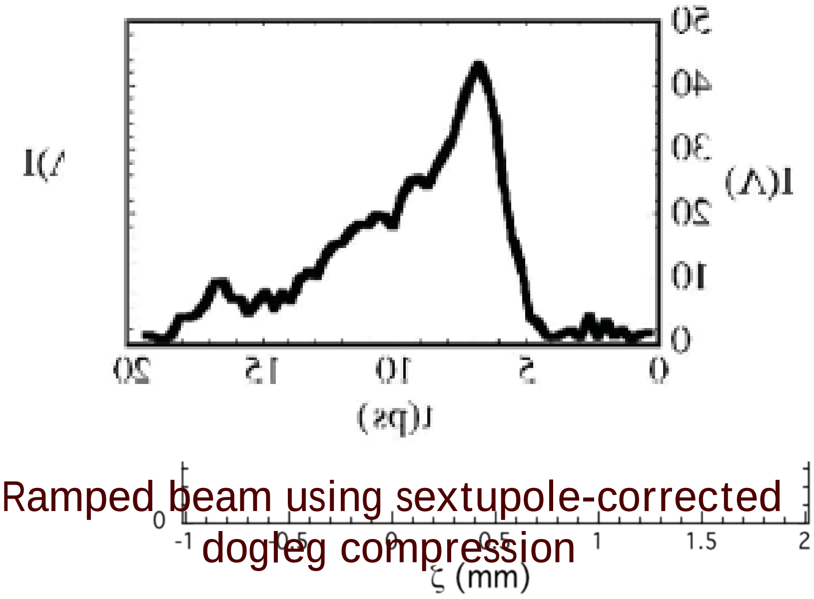
- FEL scenario: 0.5-1 GeV ramped driver; 5-10 GeV X-ray FEL injector in <10 m
  - Matches length of advanced undulator


Symmetric beam R<2


Ramped beam R>>2

Example: DWA-driven 5th generation light source

- Beam parameters: *Q*=3 nC, ramp *L*=2.5 mm, *U*=1 GeV
  Possible at SLAC FACET
- Structure: *a*,*b*=100,150 µm, *ε*=3.8; fundamental @ *f*=0.74 THz
- Performance: E_z>GV/m, *R*=9-10
- Ramp achieved at UCLA, BNL
- Enables hard X-ray source w/high average power, small footprint?
- Ongoing work at FACET, BNL
  - Advanced slab structures
  - Photonics
  - New materials



Ramped beam using sextupole-corrected dogleg compression

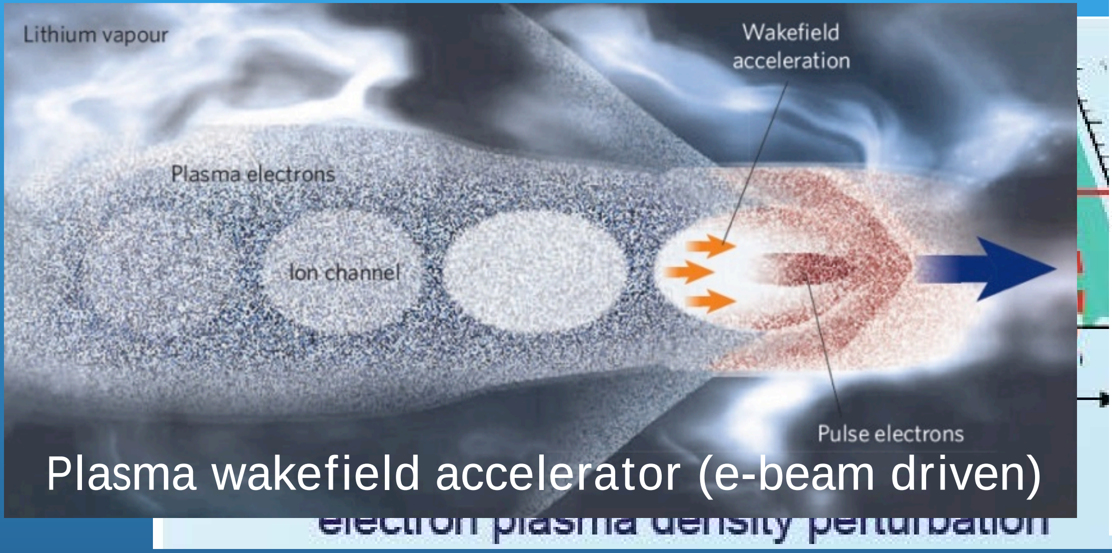
Longitudinal phase space after 1.3 m DWA (OOPIC)

R. J. England, J. B. Rosenzweig, and G. Travish, PRL 100, 214802 (2008)

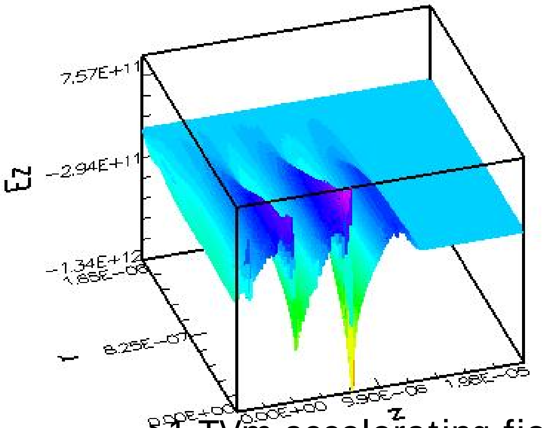
Longitudinal wakefields with ramped beam

Past Breakdown: Plasma Accelerators

- Intense laser *or* relativistic e- beam excites wake plasma waves



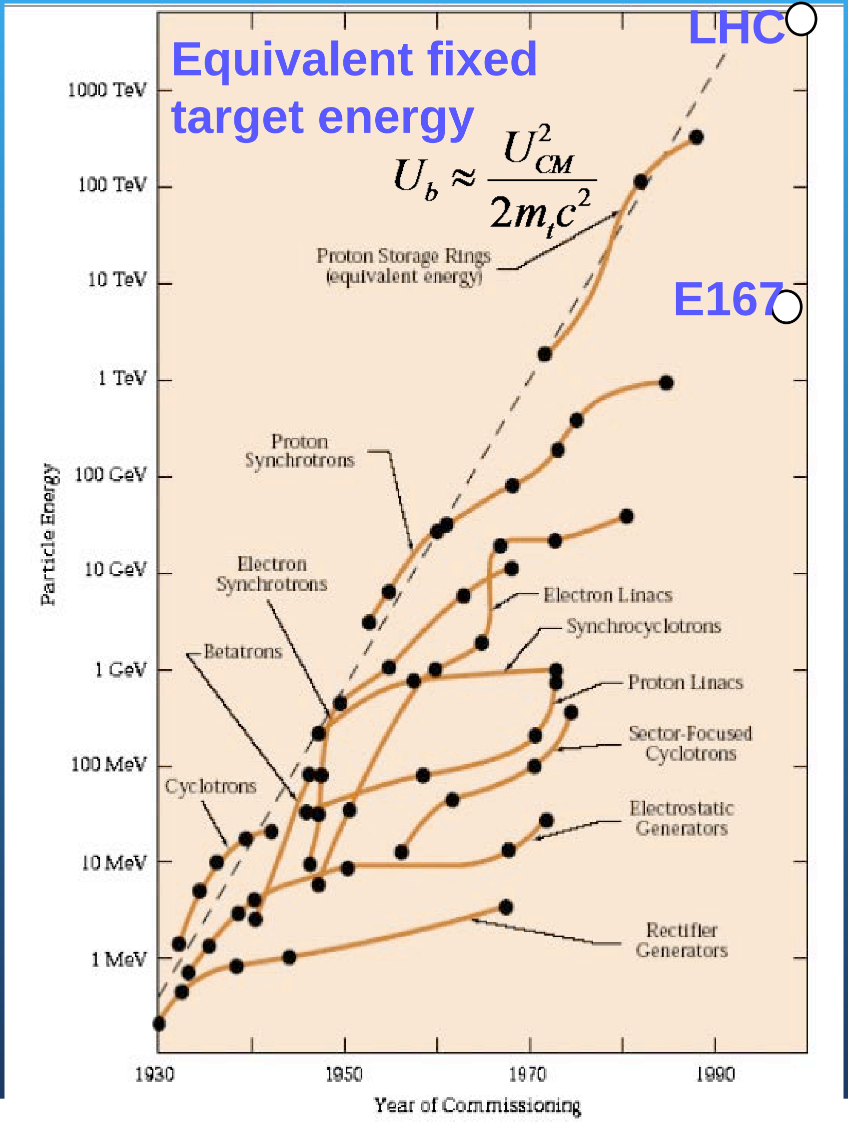
Plasma wakefield accelerator (e-beam driven)



>1 TVm accelerating fields in UCLA FACET IIPWFA experiment

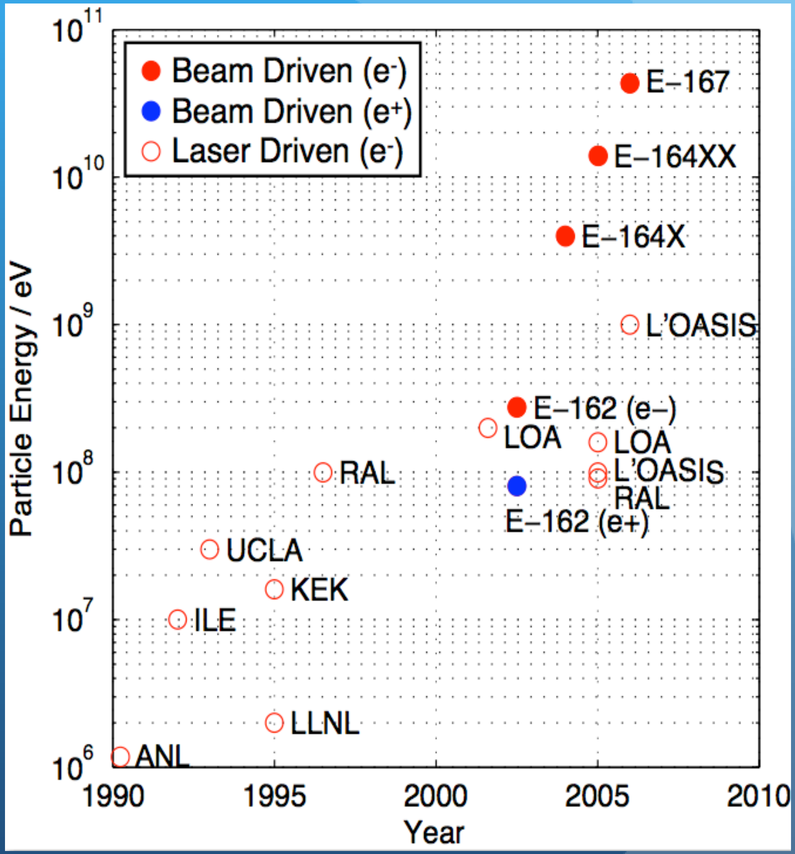
- Extremely high fields possible: $E(\text{V/cm}) \propto \sqrt{n_e(\text{cm}^{-3})}$
- Ex: atmospheric gas density $E \propto 1\ \text{TV/m, for } n_e = 10^{20}\,\text{cm}^{-3}$
- LHC-class energies in the length of an automobile?

Plasma Accelerators History: Livingston Plots Old and New



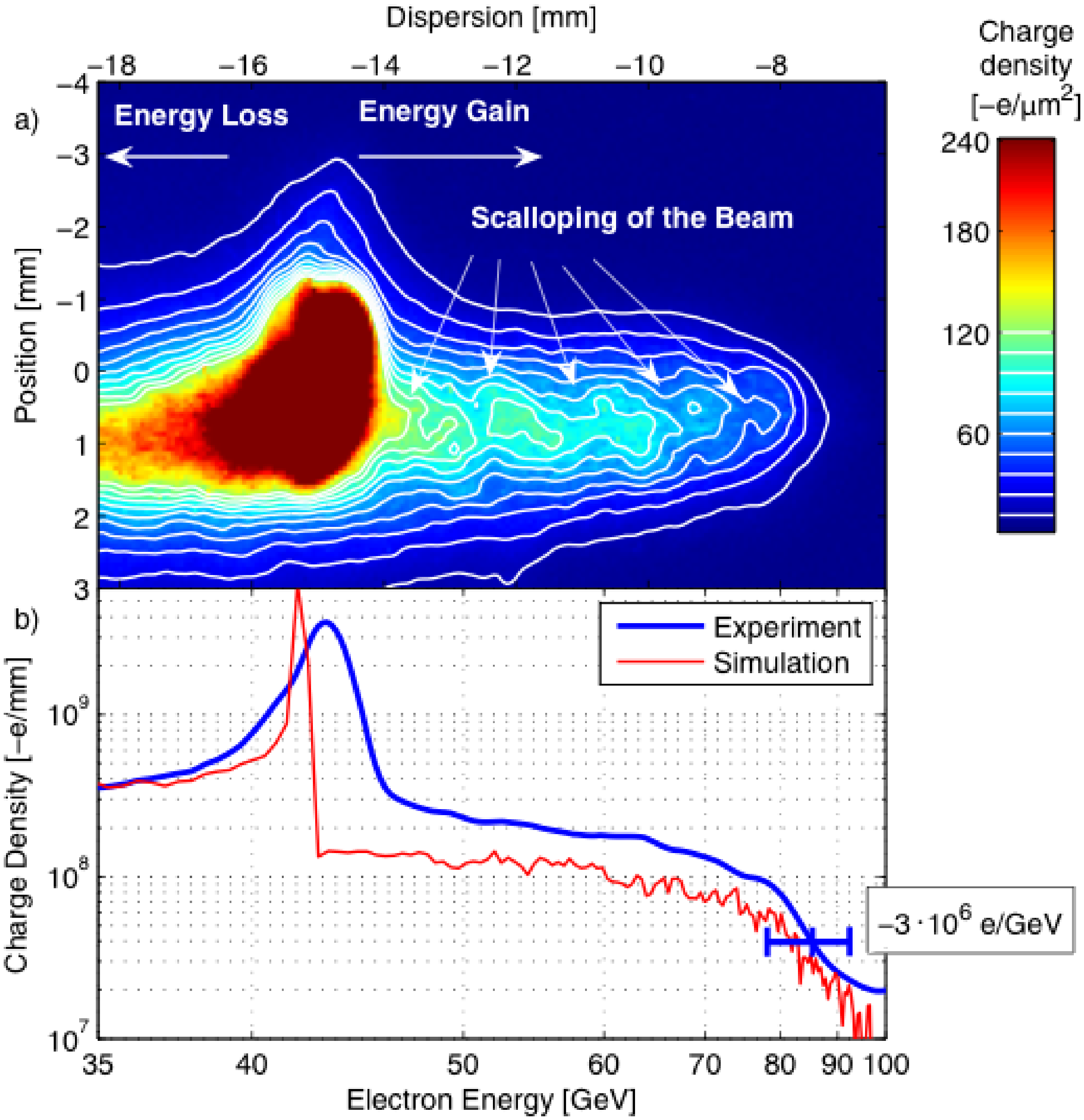
Equivalent fixed target energy

$$U_b \approx \frac{U_{CM}^2}{2m_t c^2}$$



Plasma accelerators (actual, not "equivalent")

PWFA doubles highest energy linac



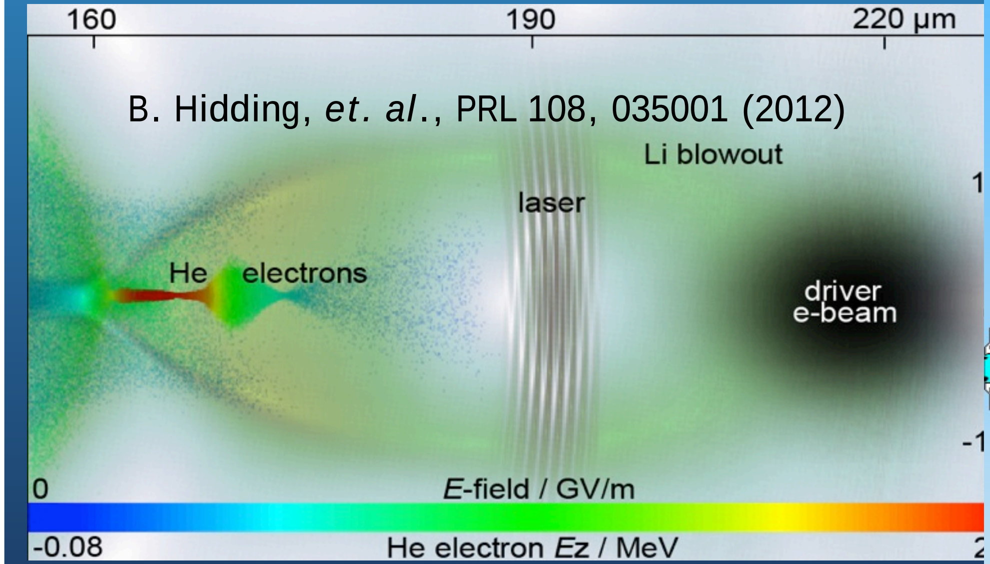
- Acceleration gradients of ~50 GV/m

  (*3000 x* SLAC linac)
- Doubled 45 GeV beam energy in *1 m plasma*
- Required enormous infrastructure at SLAC
- Still not yet a “beam”

I Blumenthal et al., Nature 445 741 15-Feb-2007

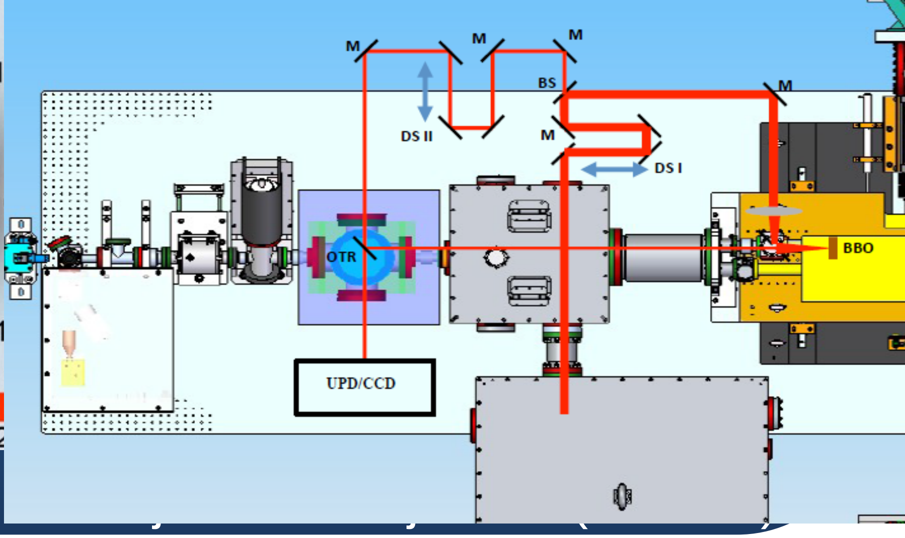
5th generation injector based on PWFA

- To $\varepsilon < 10^{-8}$ m for low energy XFEL; new approaches needed
- Very high field at beam birth, use PWFA in *controlled* fashion
- “Trojan Horse” injection
  - Load e- only in narrow *r,z,t* window with laser, selective ionization
  - E210 at FACET underway


B. Hidding, *et. al*., PRL 108, 035001 (2012)

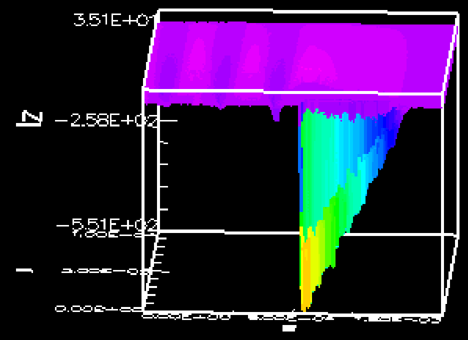
Trojan Horse Injection (Hidding et al.)

E210 current layout

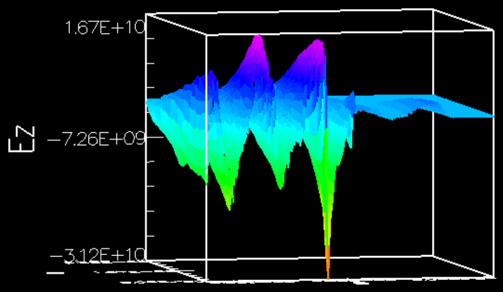


Pulse shaped PWFA driver for low energy X-ray FEL

- Inject with Trojan scheme
  - Ultra-high brightness beam
- FEL scenario: ramped driver
  - 5-10 GeV X-ray FEL injector in <10 m
  - SLAC-UCLA-Strathclyde collaboration
  - FACET context; FEL goal
  - Example: 500 MeV driver, 9 mm period undulator gives nm X-rays

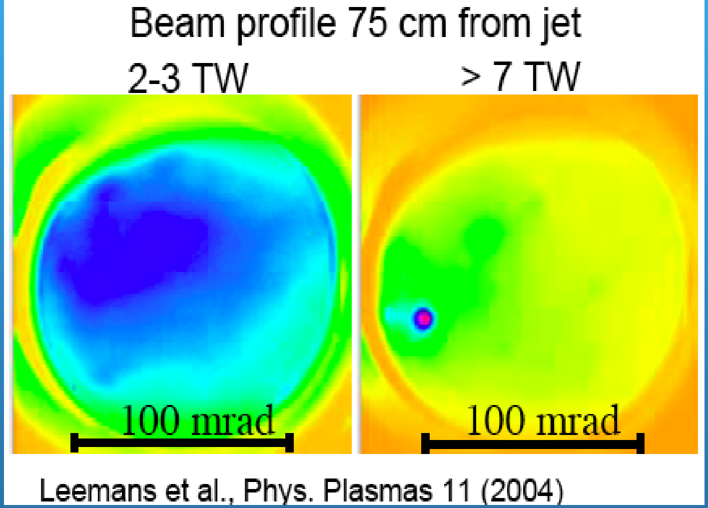


Ramped beam driver

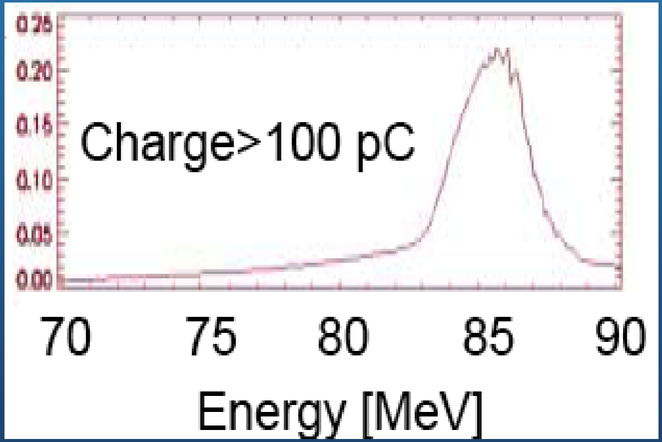


20 GV/m, R=10 PWFA

Laser wakefields (LWFA) already create high quality electron beam



Leemans et al., Phys. Plasmas 11 (2004)



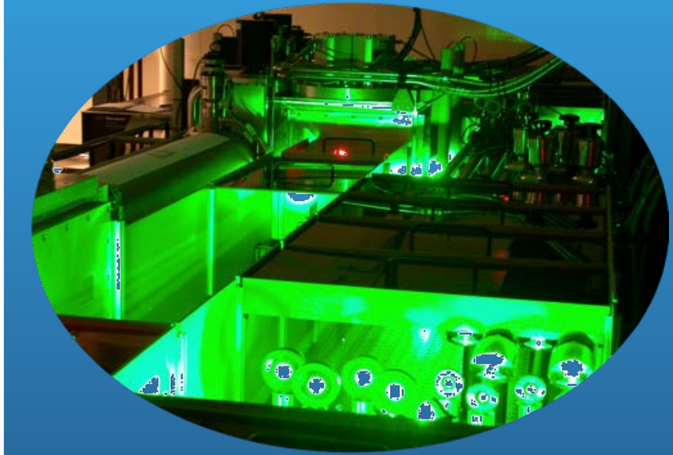
Early LWFA beams

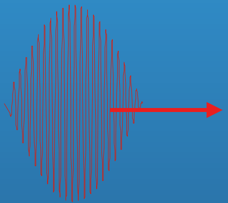
- Trapped plasma e-'s in LWFA
  - Gives $\varepsilon_n \sim 1\text{E-}6$ m-rad at $N_b \sim 10^9$
- Narrow $\delta E/E$ spread produced
  - accelerating in *plasma channels*
- Looks like a beam!
  - Applications to FEL
  - Betatron radiation
  - Less expensive than e-beam wakefields...

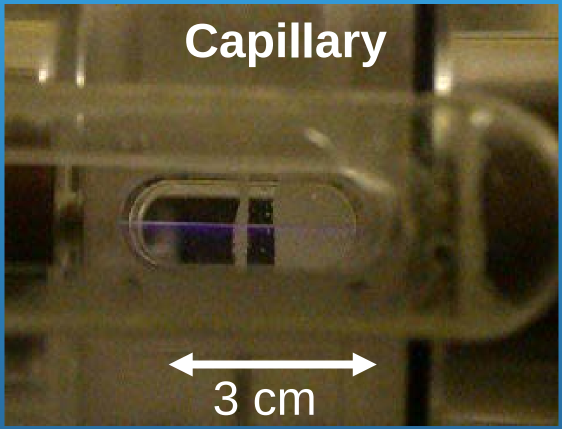
Channel guided LWFA can produce *multi-GeV beams*

- Higher power laser
- Lower density, longer plasma

$$\Delta W[\mathrm{GeV}] \sim I[\mathrm{W/cm^2}]/n[\mathrm{cm^{-3}}]$$

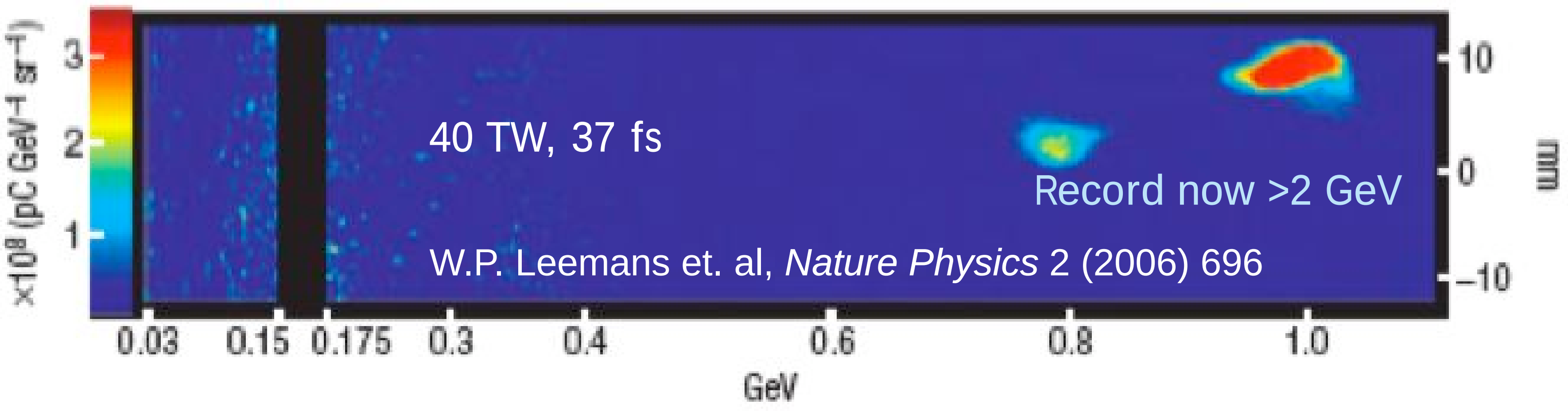






1 GeV

e^- beam



40 TW, 37 fs

Record now >2 GeV

W.P. Leemans et. al, *Nature Physics* 2 (2006) 696

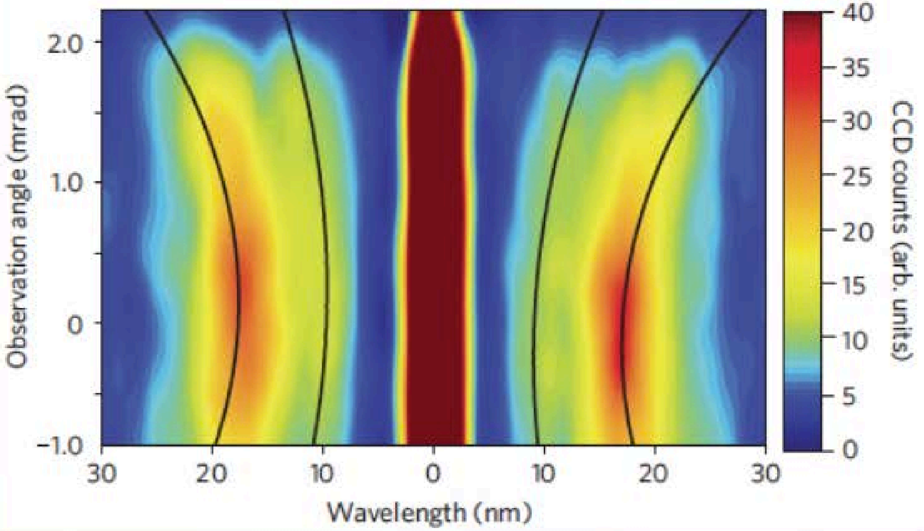
5th generation XFEL light source based on LWFA

MPQ-centered (Uni. Hamburg) collab.

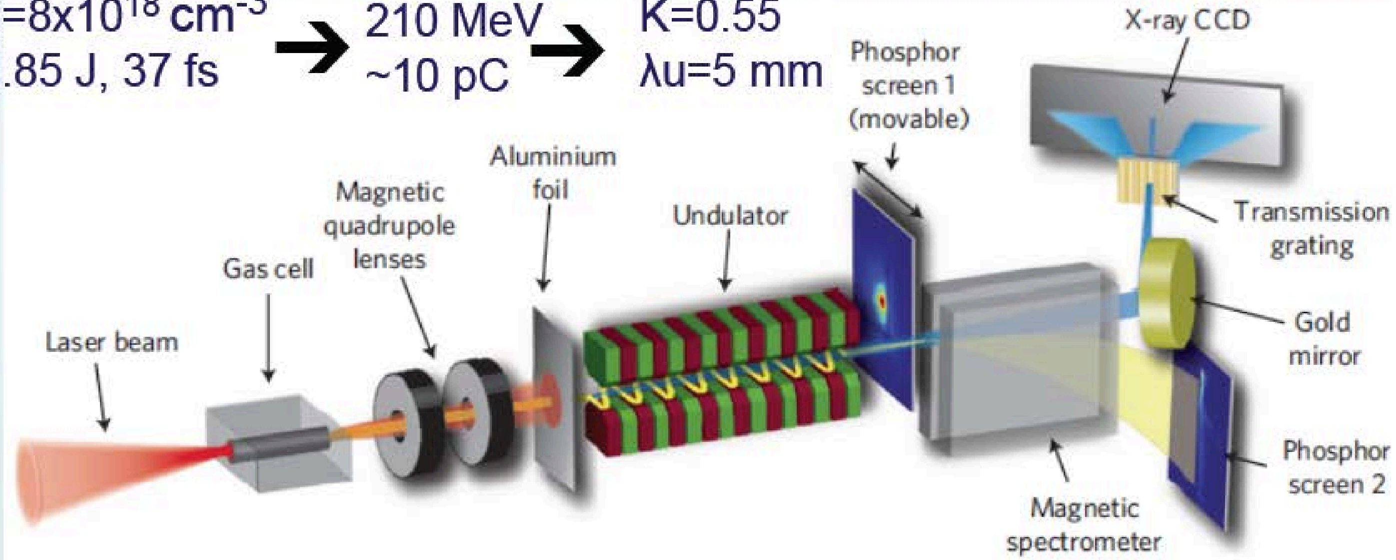
M. Fuchs et al., Nature Physics (2009)

- Measured 1st and 2nd harmonic:

$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

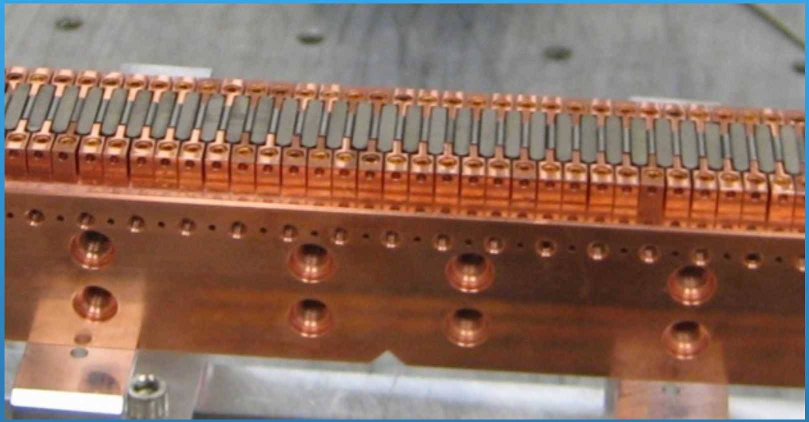


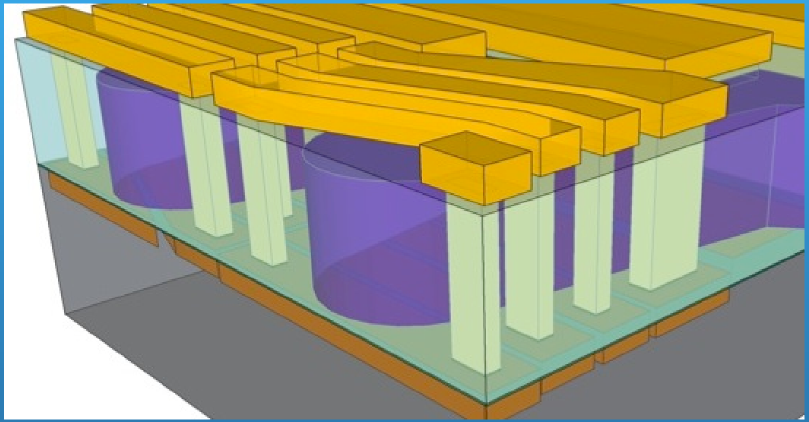
$n=8\times10^{18}$ cm^{-3} 0.85 J, 37 fs → 210 MeV ~10 pC → K=0.55 λ_u=5 mm



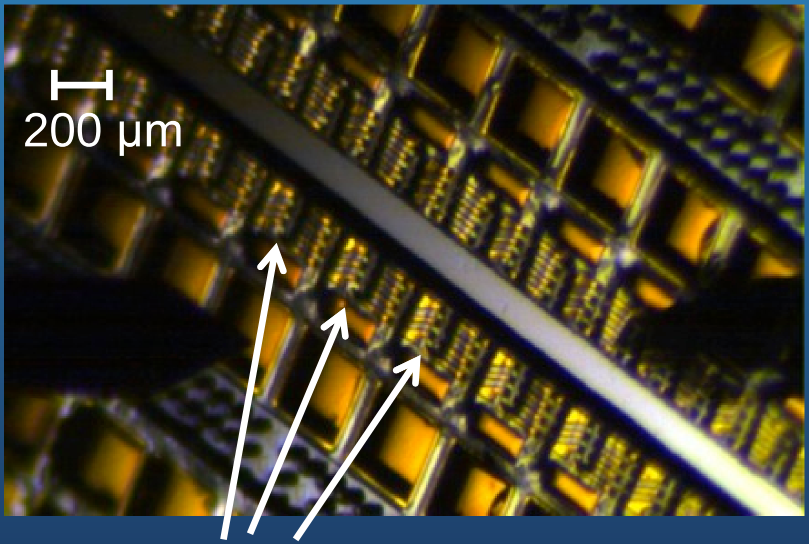
Pushes R&D for short λ cryoundulator

Mini-to-micro-undulators

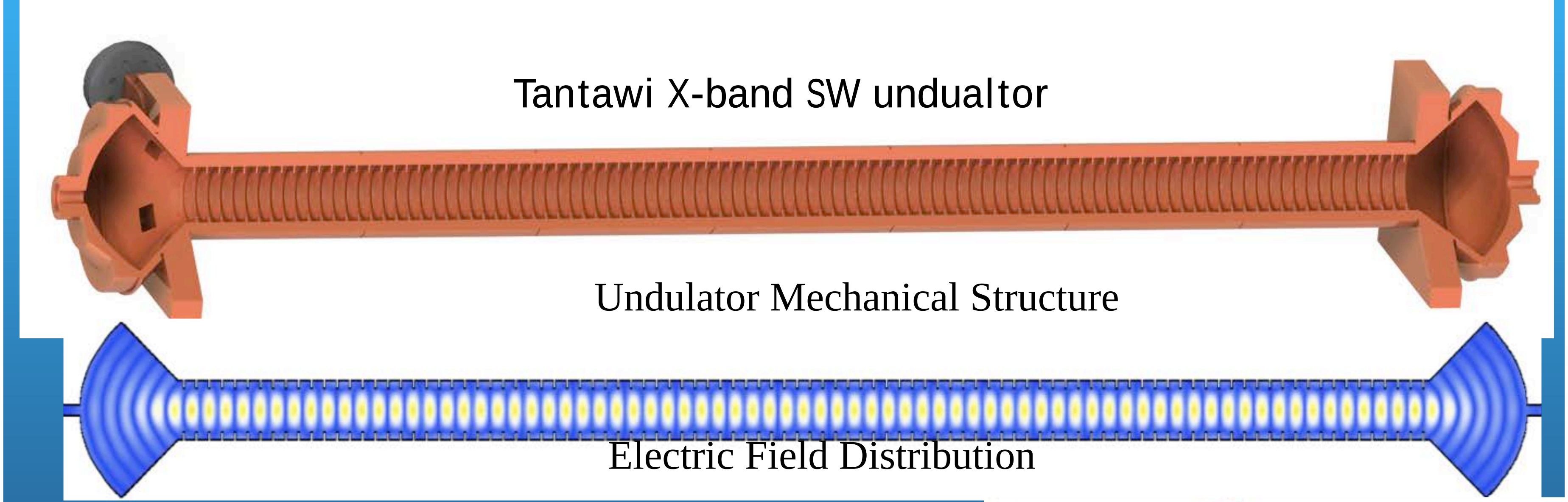




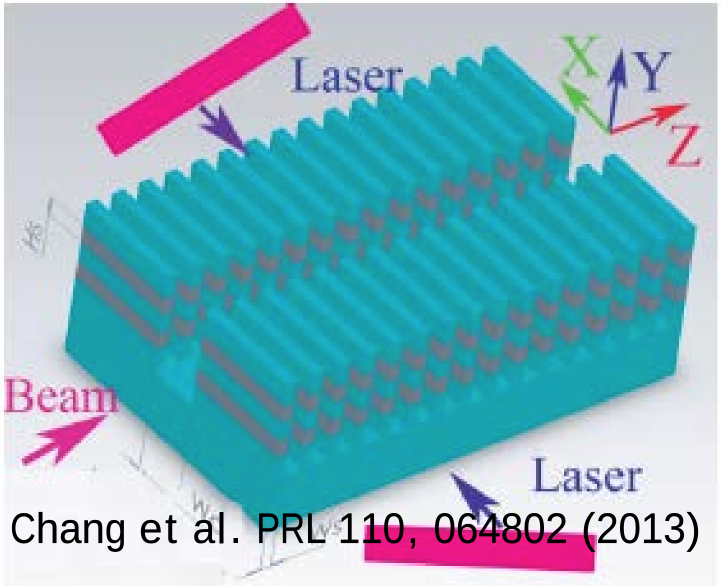
- 9 mm period, 2 T peak field cryoundulator
- MEMS-based 100-800 um(!) period current-driven undulator (*K* is low)
  - Need EM solution to go beyond 1T level…



The next generation undulator: The electromagnetic era



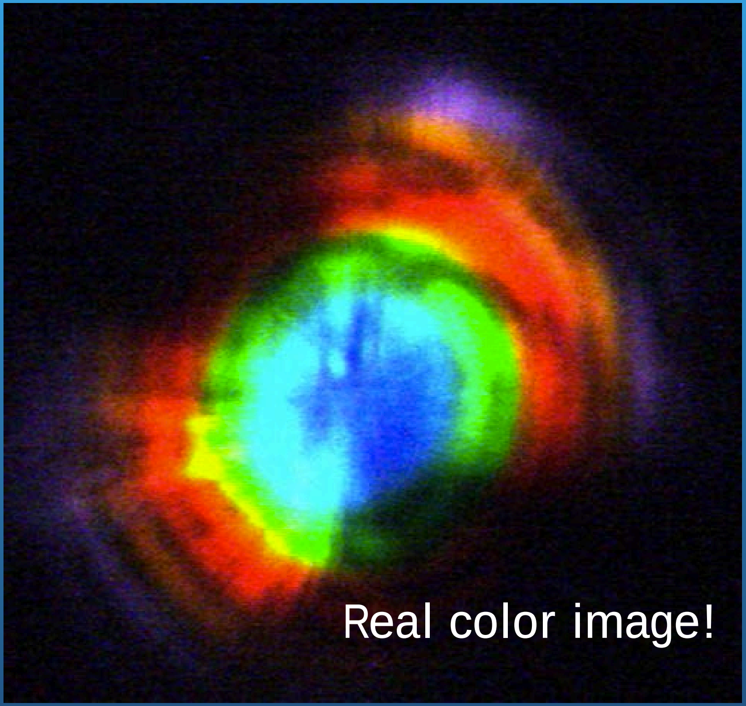
- To use <1 GeV in XFEL, need λ=100 um undulator
- *K*~0.1 or above means *T*-level B_0 inadequate
- On to *EM undulators*: THz SW structures, IR TW guides, free-space Thompson



Chang et al. PRL 110, 064802 (2013)

The EM era has dawned
(Tantawi, et al., 2012, GALAXIE collaboration)

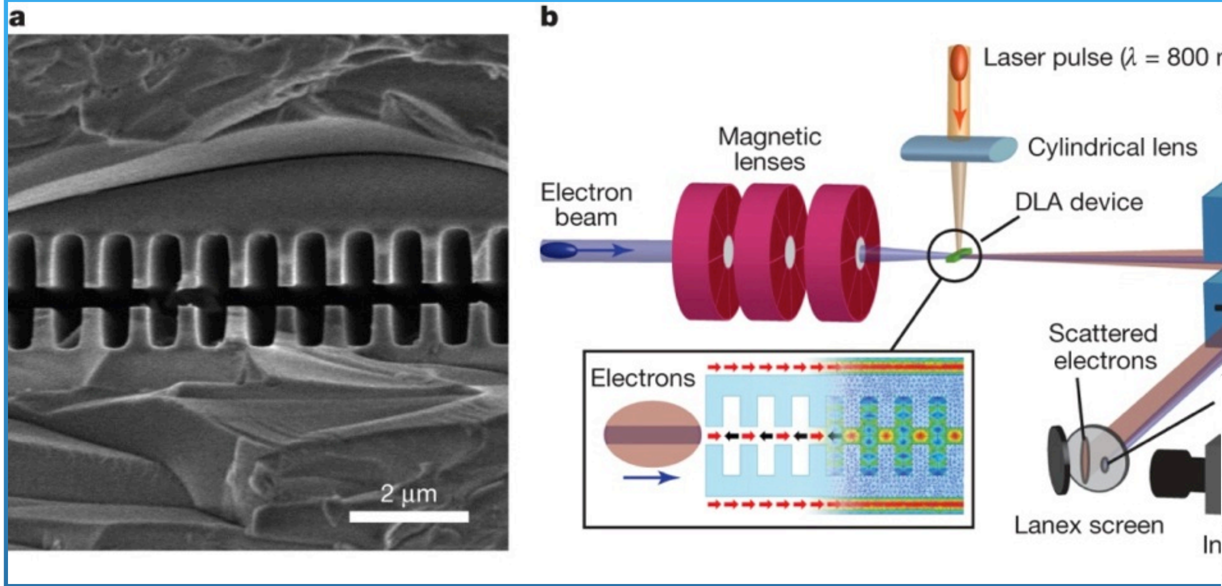
- Second harmonic, w/off-axis red-shifting

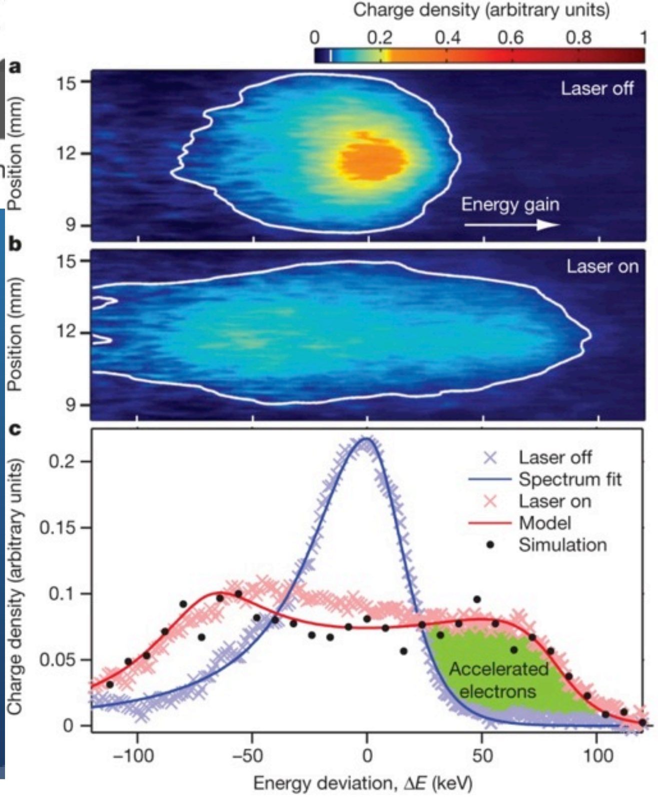


NLCTA prebunched beam radiation

- Scale to THz for GALAXIE

The dielectric laser accelerator (DLA)

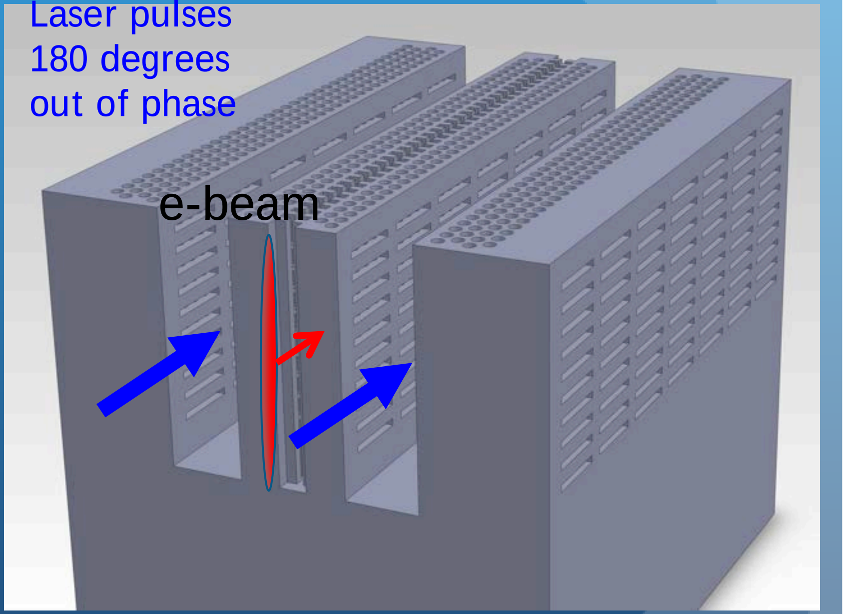




- Dedicated DARPA program last 2 years (AXiS)
- SLAC experiments make a splash in *Nature*
- Uses 800 nm laser, simple structure
    - *Non-optimized*
- Demonstrated >300 MV/m fields

The DLA Design Philosophy

- Why dielectrics for laser?
  - *Dissipation and breakdown* in metals
- Why *photonic* structures?
  - Natural in dielectric (confinement)
  - Advantages of burgeoning field
    - design possibilities
    - fabrication
- Why slab-type geometries?
  - Highly asymmetric (power available!)
  - Longitudinal wakes, Q limits
  - Transverse wakes
- Dynamics concerns
- External coupling schemes



Schematic of GALAXIE monolithic photonic DLA

Example:GALAXIE accelerator structure

Hole ID=800 nm

e-beam propagation

2 um

Close up of beam channel in GALAXIE traveling wave DLA

- *Single material* (Si, Al_2O_3) *photonic* structure, easier fabrication
- Rich spatial harmonic spectrum for 2nd order transverse focusing (resonant TW *defocusing*)

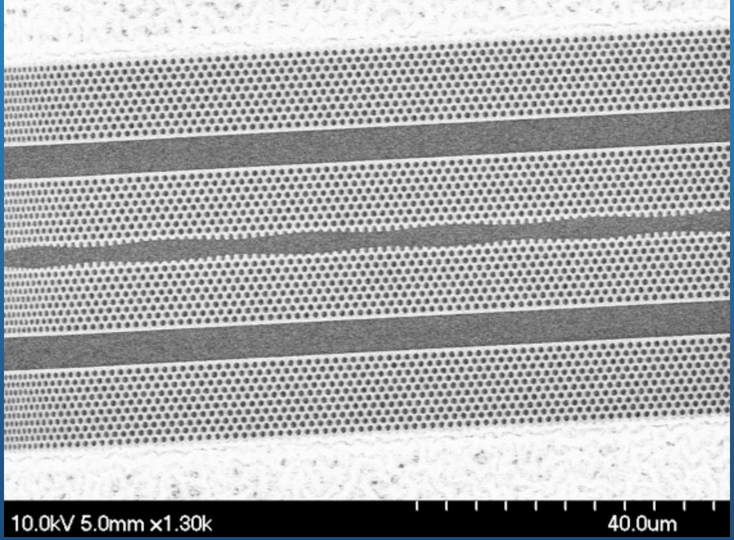
  B. Naranjo, A. Valloni, S. Putterman, J.B. Rosenzweig, *PRL* **109**, 164803 (2012)
- Fully 3D photonic structure (mode control)
- Optimized E-field w/ “teeth”; small E in dielectric

New beam dynamics in DLA: 2nd order focusing and *adiabatic compression*

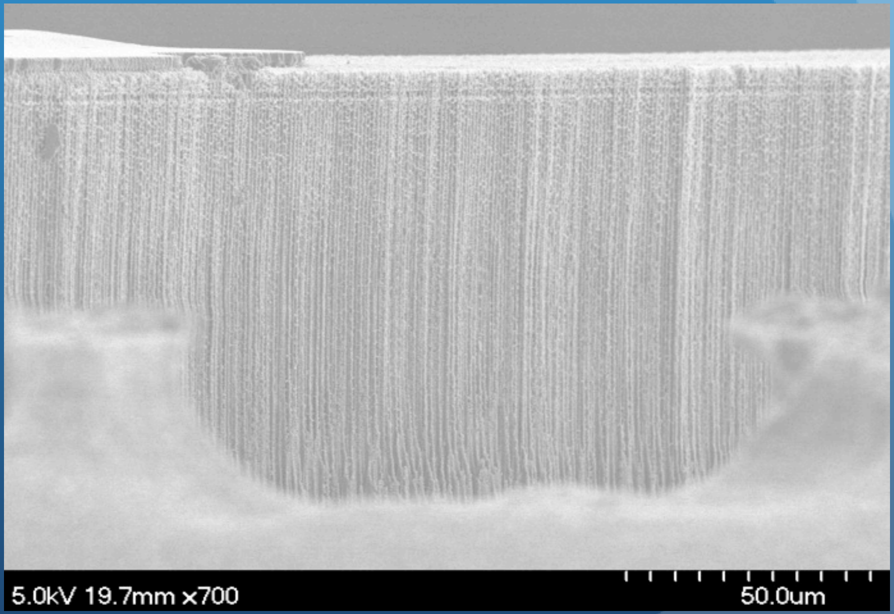
GALAXIE example: Adiabatic: (1) focusing (2) capture (3) compression (x1000!)

DLA fabrication is *challenging*

- Very high aspect ratio features (e.g. 0.8 x 200 um holes) for photonics, wide beams
- Utilize *macroporous silicon etching*



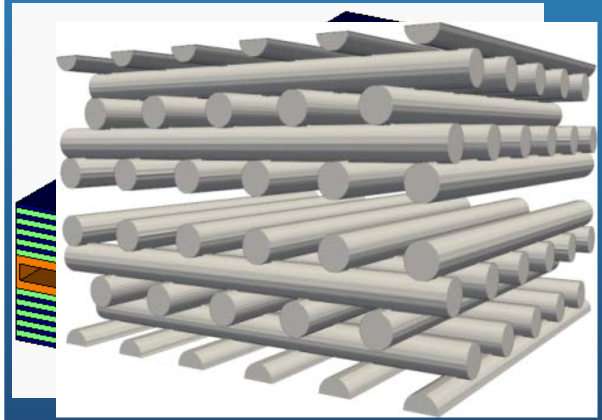
Mask for etching



Cross-section of photonic array

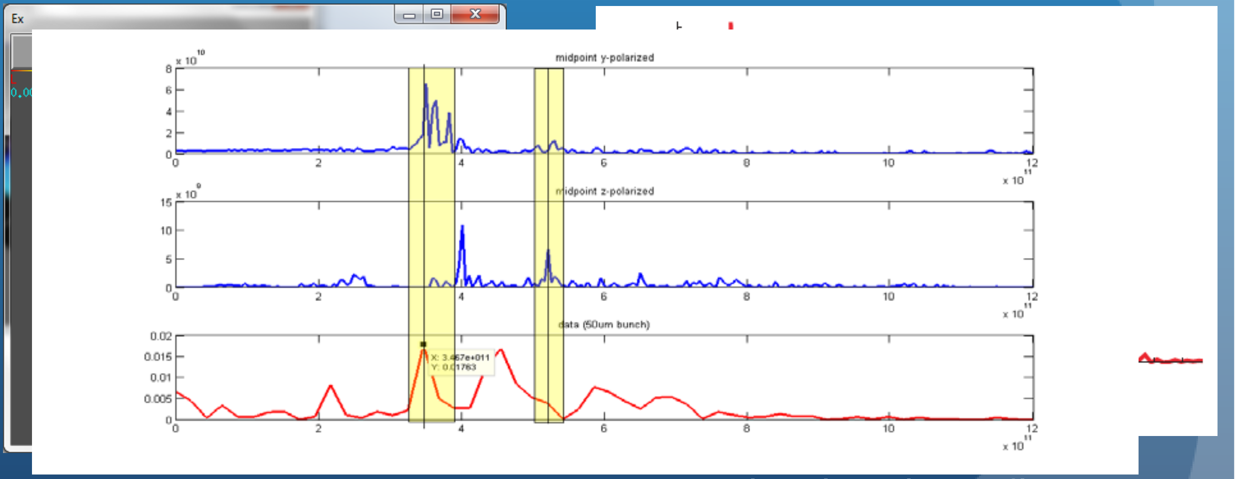
Collective effects: wakes in photonic DLAs

- Scaled experiments in THz at BNL ATF
- Bragg (1D photonic slab structure)
- Woodpile (3D photonic structure)



Bragg structure

Woodpile schematic



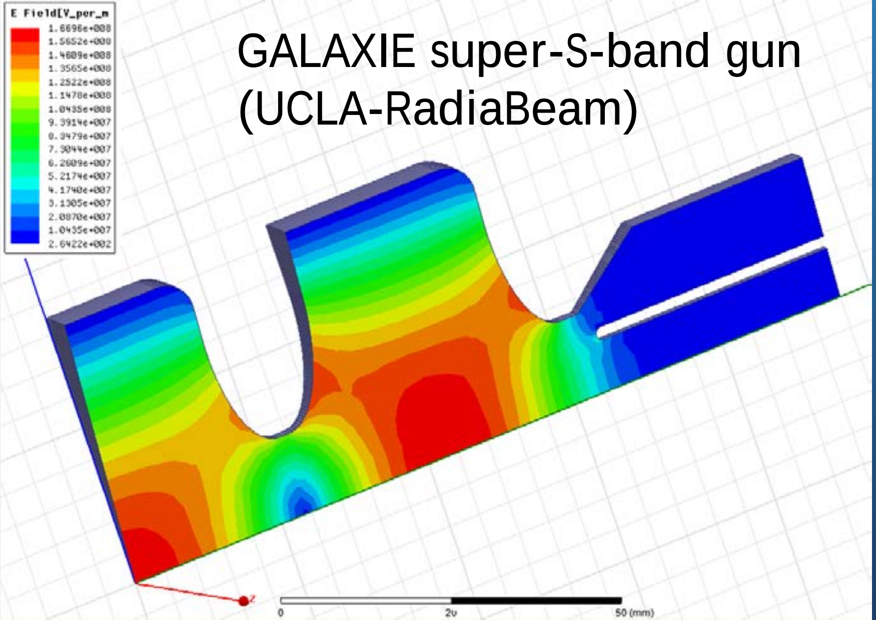
Simulated wakes (side view)

Narrow-band mode confinement

Measured emitted spectrum: modes in pass-bands

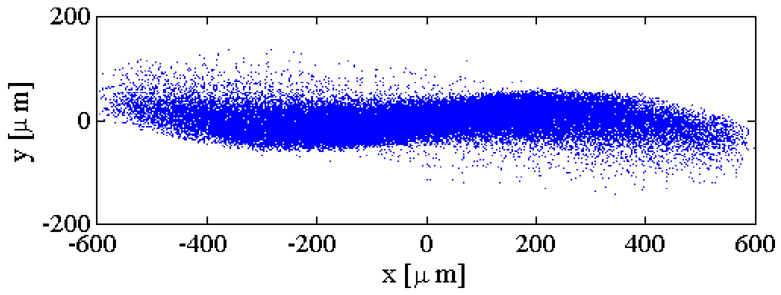
The front-end: generating very high brightness electron beams

- Photoinjector at *extreme* high field (>175 MV/m), short RF pulse
- Very low charge (1 pC for GALAXIE)
- New phase space manipulations
  - magnetized beam emittance splitting



GALAXIE super-S-band gun (UCLA-RadiaBeam)

From Valloni et al.

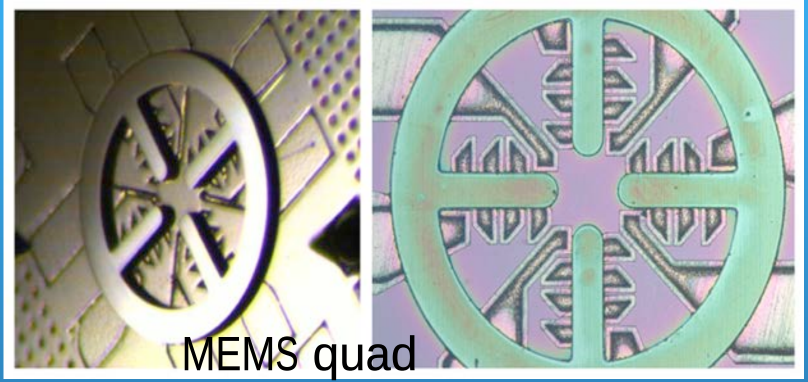


Beam after emittance splitting

Normalized Emittance

$\varepsilon_{n-},\varepsilon_{n+}$=2.9×10-9, 2.6×10-7 m-rad

Microbeam optics and diagnostics



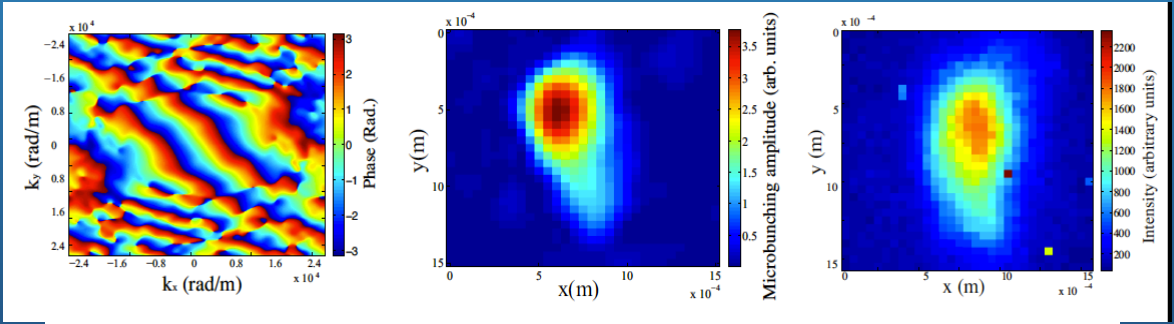
MEMS quad

Linear Field Region

Field Gradient in aperture is 3.3 T/mm = 3,300 T/m!!

Candler group/RBT

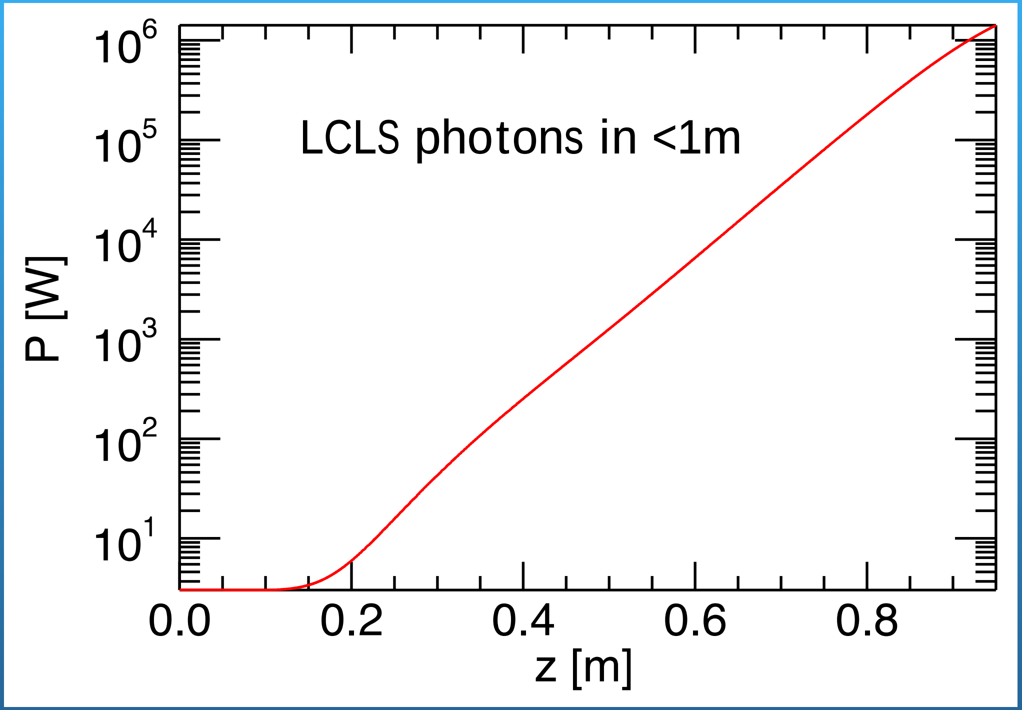
- Manipulating sub-um beams: ultra-short focal length optics



Coherent transition radiation imaging reconstruction expt., Marinelli et al., PRL 110, 094802 (2013)

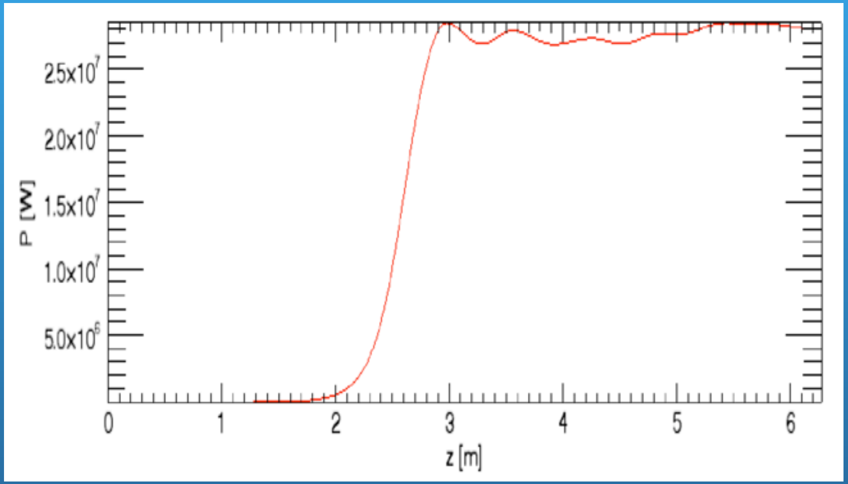
- Measure sub-um beam sizes? Coherent imaging (borrowed from XFEL!)

GALAXIE FEL physics are also new



- GALAXIE is a quantum FEL: less than one (very hard) photon emitted per electron
- Spectrum changes radically; theory still in flux

Spin-off idea: new regime, *soft X-ray Raman FEL*



Undulator Period	**800 μm**
Beam Energy	175 MeV
FEL Radiation Wavelength	3.5 nm
1D Gain Length (Compton)	5.6 cm
Beam Plasma $\lambda/2\pi$	6 cm

- MEMS undulator with MEMS quad array: 3 um rms beam
- Gain length expanded, but…
- Much more efficient (compensates low energy in beam)
- Proposed for UCLA on-campus FEL

Conclusions

- Advanced accelerator concepts are accelerating
- High quality beams can be produced
- Promising application: the 5th generation light source
- Many paths to 5th generation — wakefields, lasers, etc.
- New projects are intellectually vigorous
  - Very exciting, many interested
- New techniques are also vulnerable
  - AXIS now on chopping block (sequester)
  - Mainstream agencies concerned with present projects
- HEP still the long-term goal