

The Birth of the 5th Generation Light Source

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CERN Seminar

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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 high brightness and temporal scales down to the attosecond level. These attributes 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 utilized a microscope



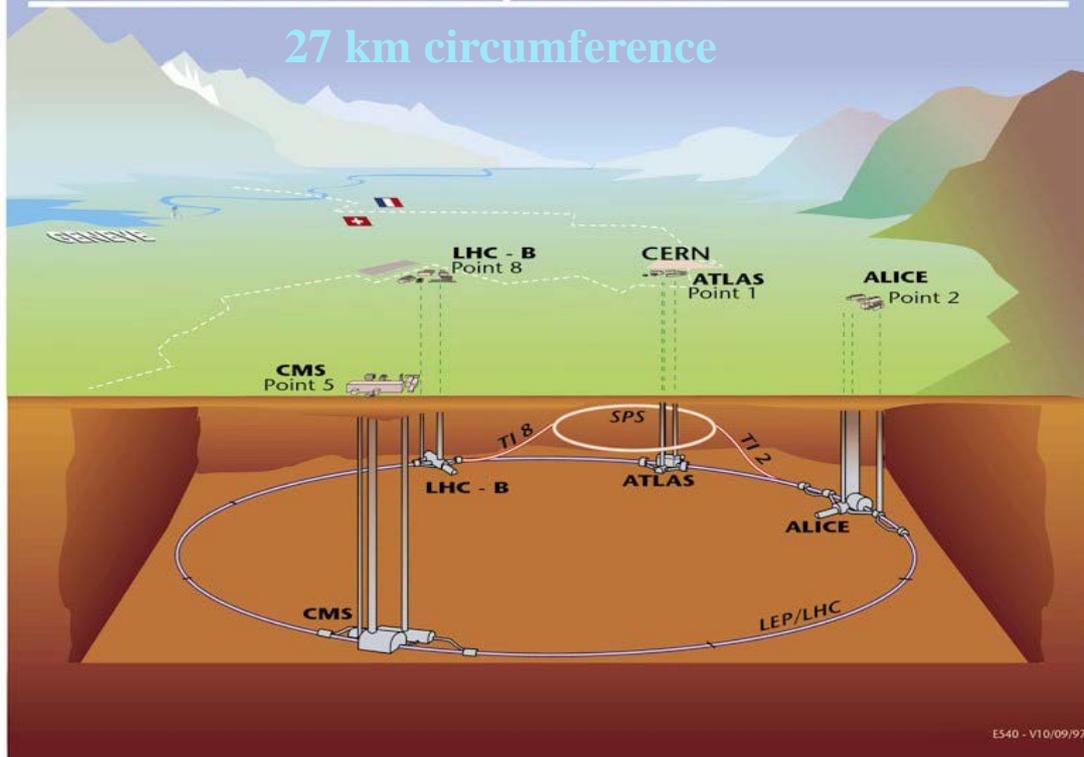
Galileo Galilei with the Doge of Venice

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

$$\lambda \sim hc/E$$

Overall view of the LHC experiments.

27 km circumference



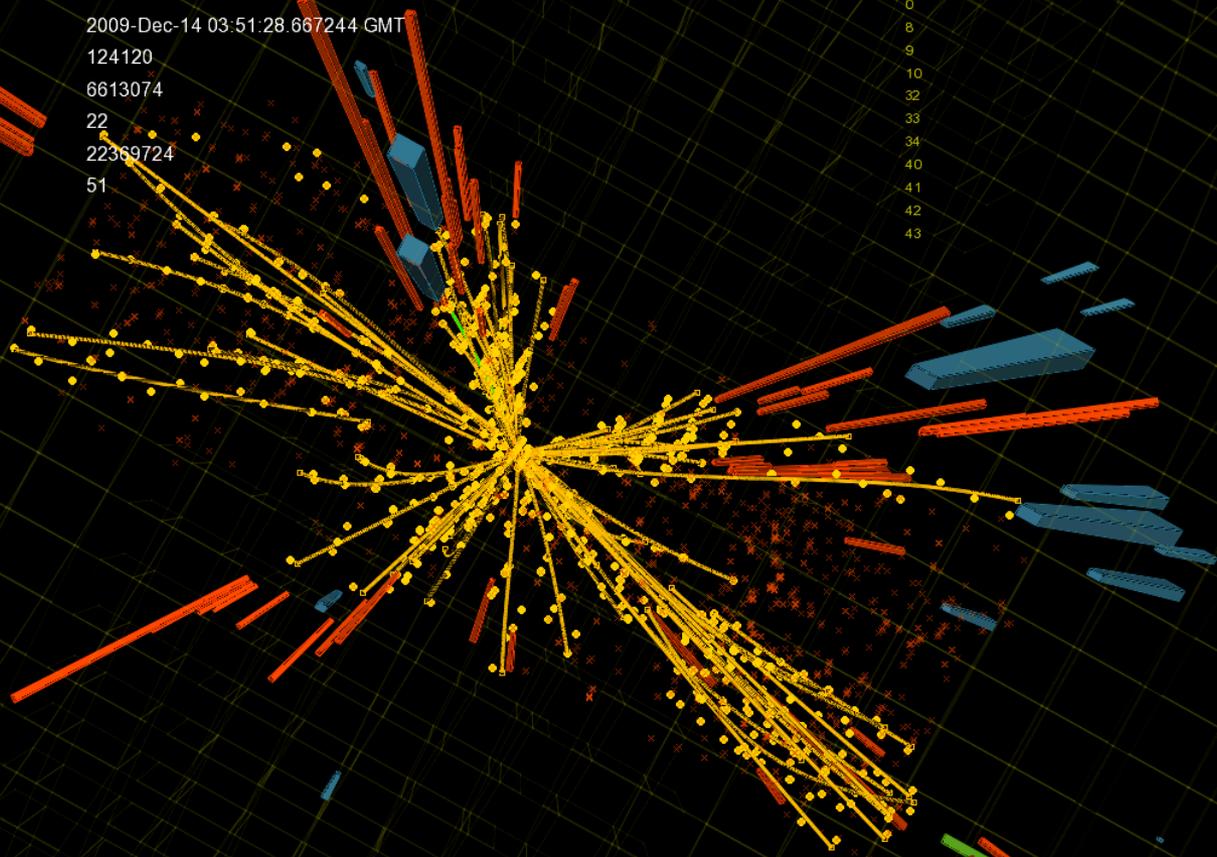


CMS Experiment at the LHC, CERN

Hot conditions of early universe (10^{16} K) produced

Data recorded: 2009-Dec-14 03:51:28.667244 GMT
Run: 124120
Event: 6613074
Lumi section: 22
Orbit: 22369724
Crossing: 51

True Triggers
0
6
9
10
32
33
34
40
41
42
43



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

The challenge of the energy frontier: colliders

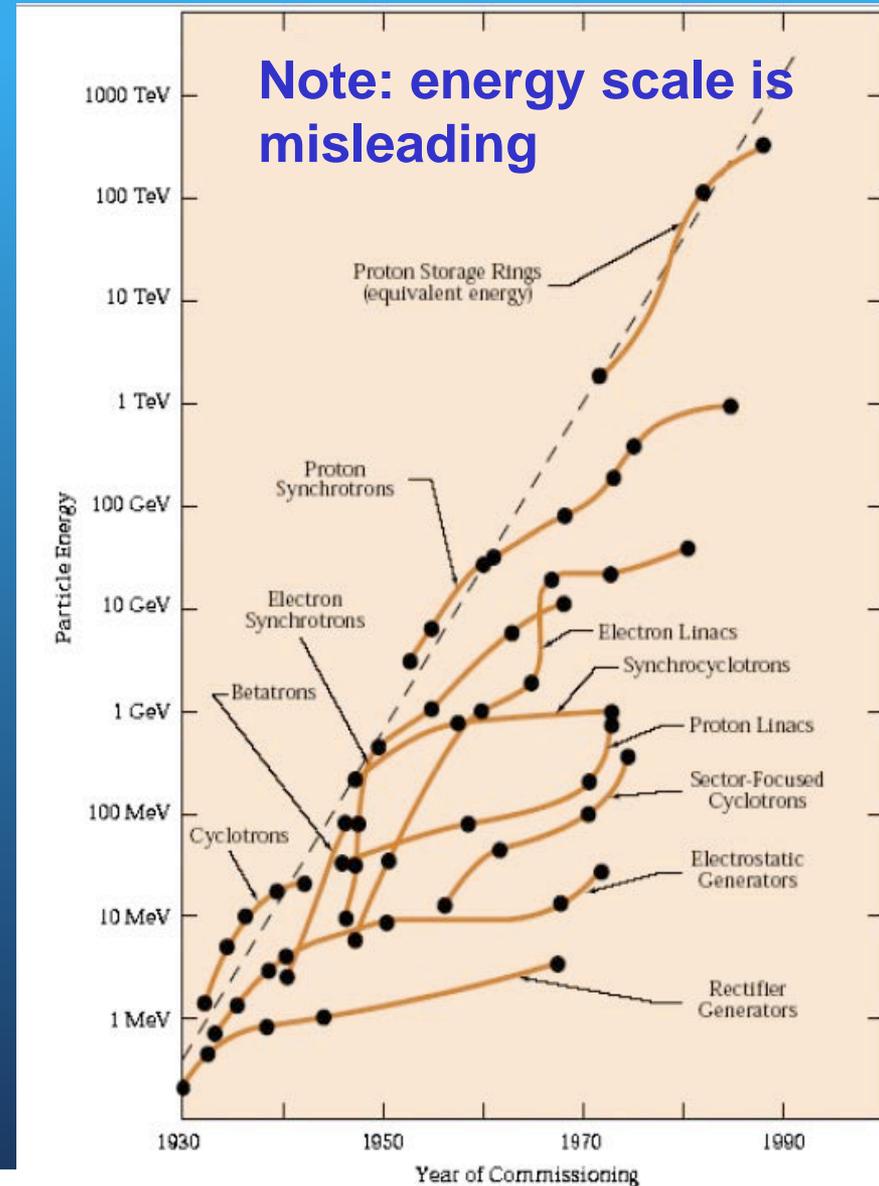
- ⊕ Fixed target energy for particle creation

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

- ⊕ 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...beam quality* as well
 - ⊕ Giant accelerators (*synch radiation*)
 - ⊕ Tiny phase spaces



Limitations of collider energy

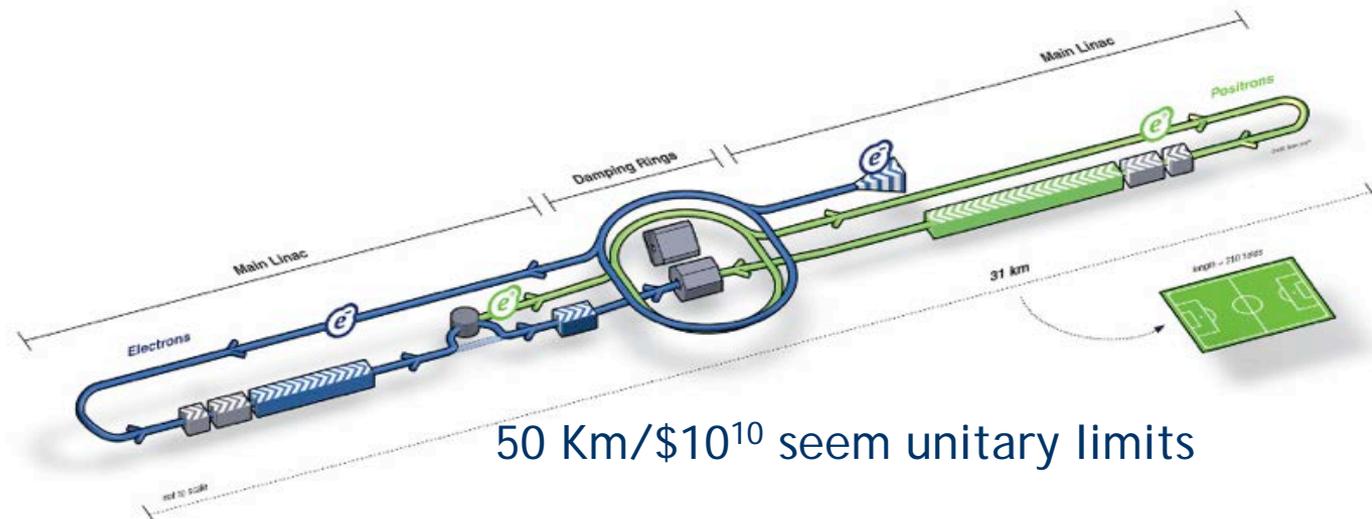
- Synchrotron radiation power loss
 - Future e^+e^- colliders foreseen *linear*
 - LEP (<207 GeV COM) was last of breed?
 - Muons?
 - *Large* circular machines for hadrons
- Scaling in size/cost prohibitive
 - Acceleration < 35 MeV/m
- Big \$science should *shrink*

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

Tevatron complex at FNAL



The science behemoth: ~TeV linear collider



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

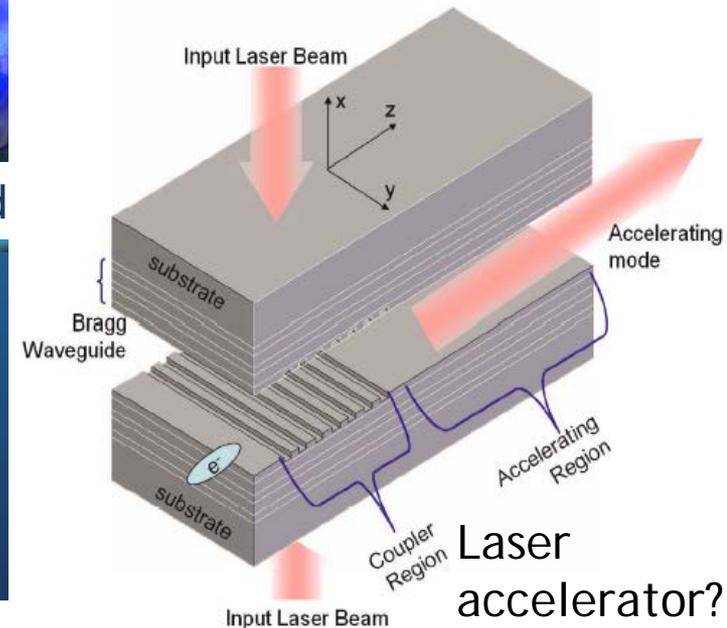
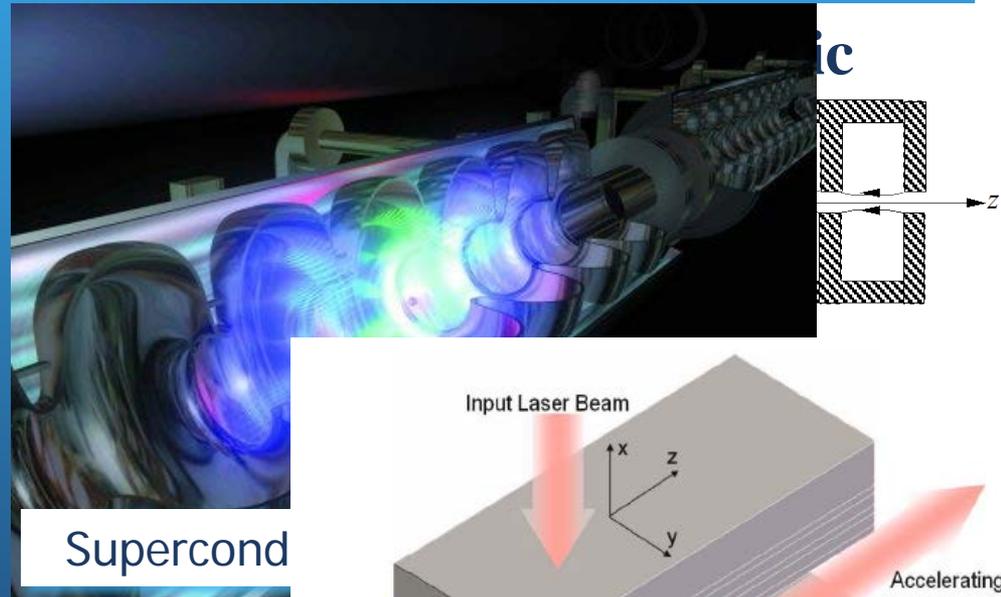
- Keeping stored EM energy, final beam energy constant,

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

- Relativistic dynamics (HED)

$$eE / mc\omega \sim 1$$

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



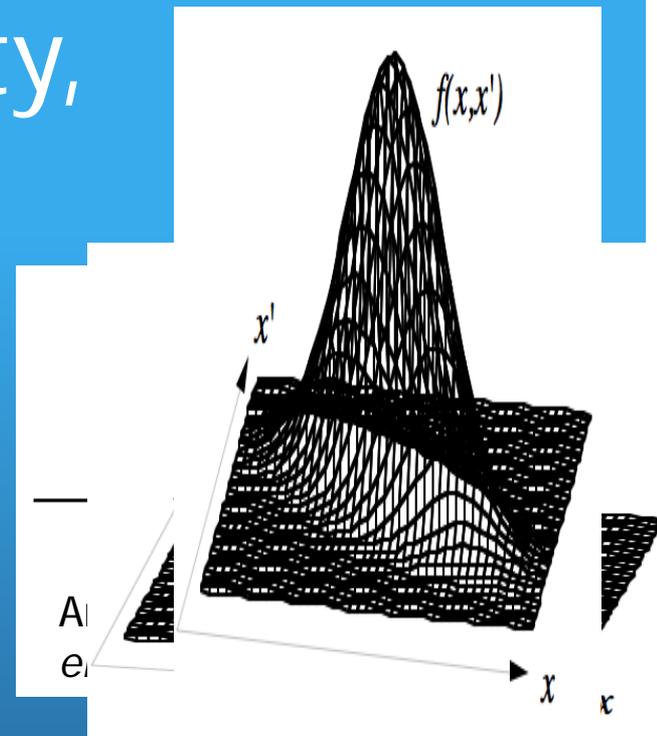
High phase space density, collective effects

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

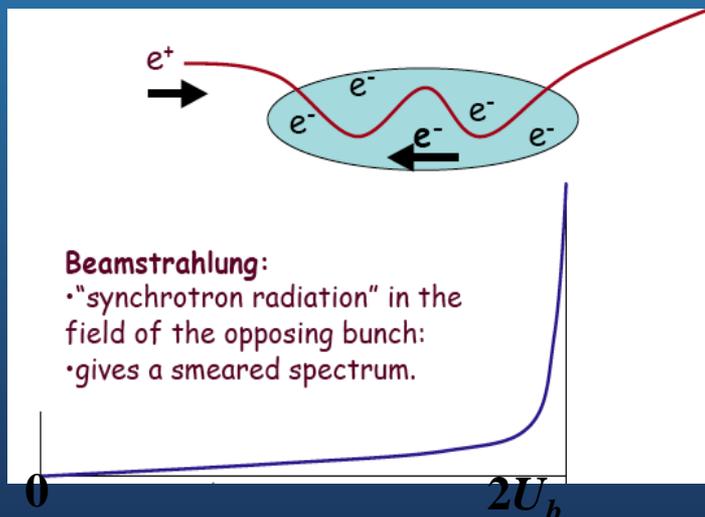
High brightness needed for next generation light sources as well.

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

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



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



Beamstrahlung:

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

Disruption:

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

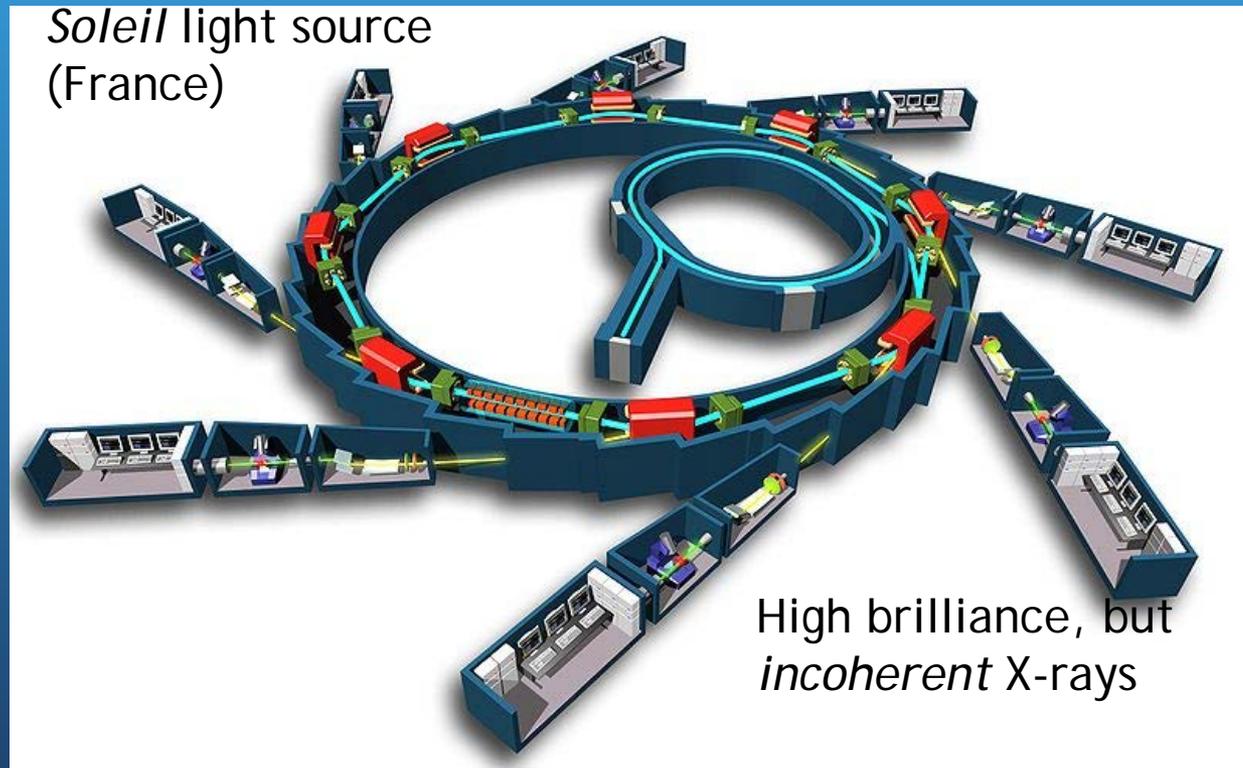
Pair Production:

- incoming beam particles scatter from the beamstrahlung photons



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

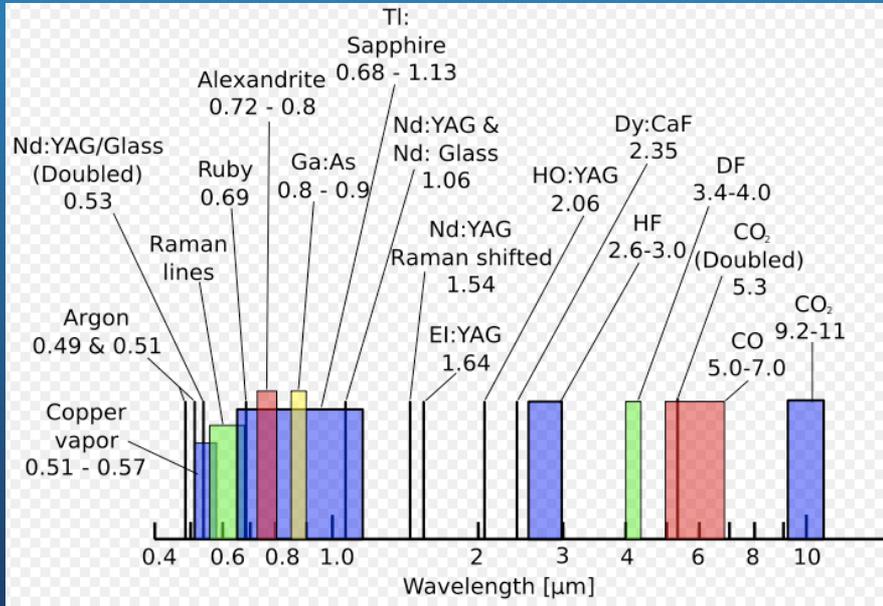
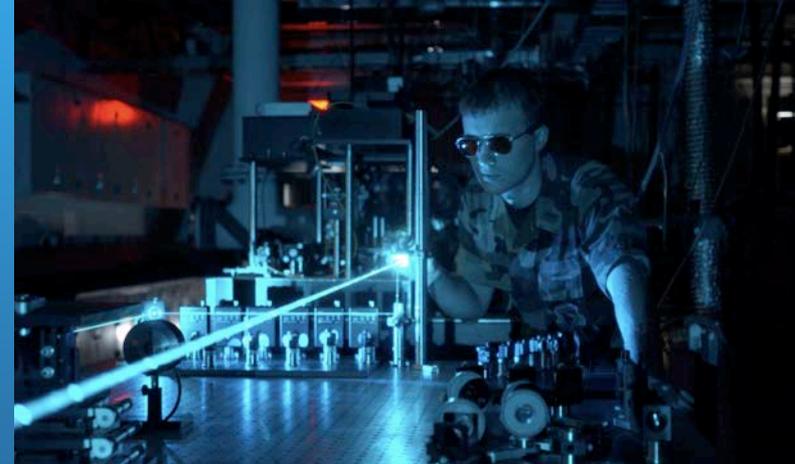
- Accelerators used as *synchrotron light sources* for >40 years
- High energy physics vice turns to an imaging virtue...



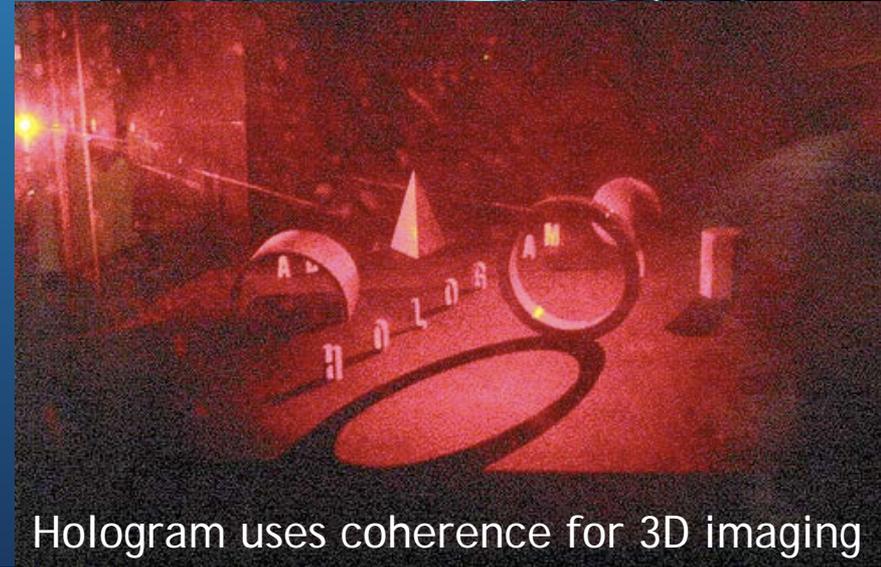
Light sources — before: spin-off, now: stepping stone

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

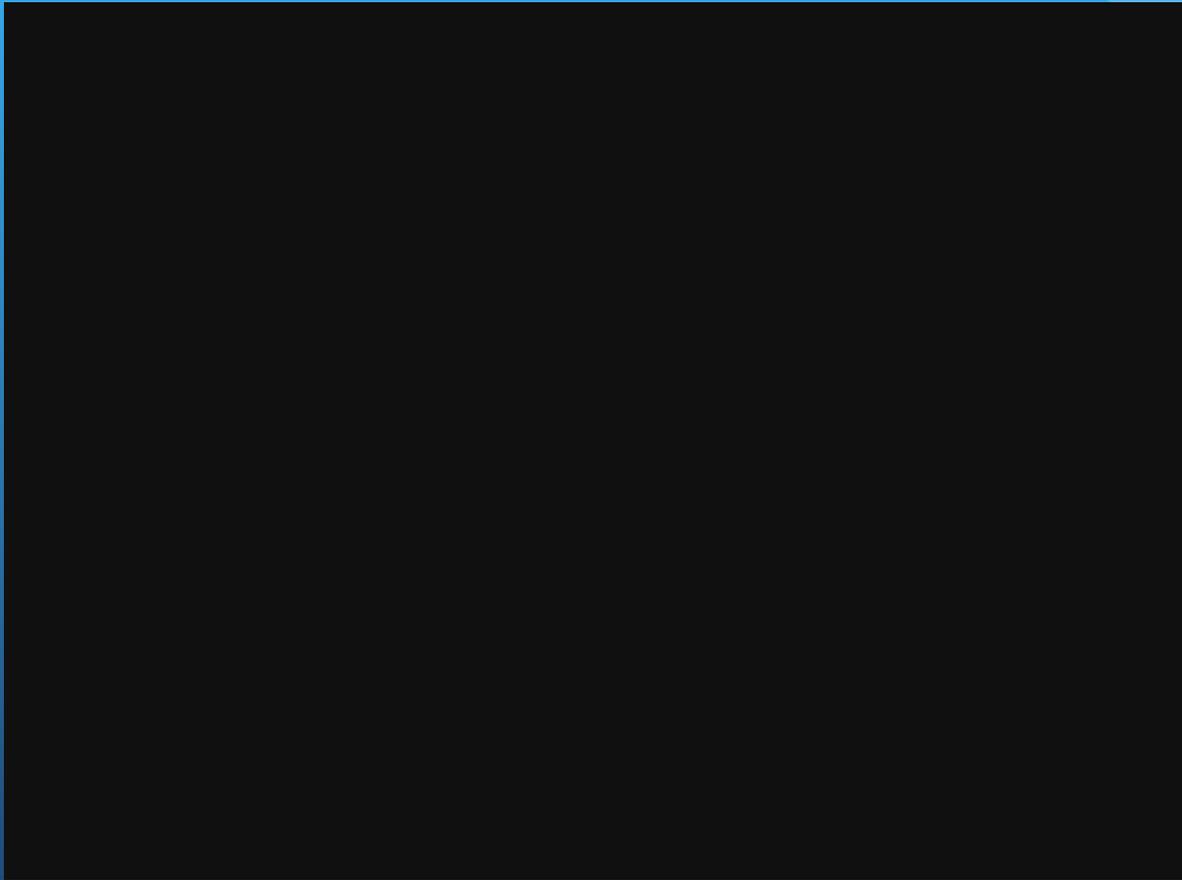


Common in optical-IR. No X-rays!



Hologram uses coherence for 3D imaging

The X-ray FEL: a dramatization



Courtesy: S. Reiche (PSI)

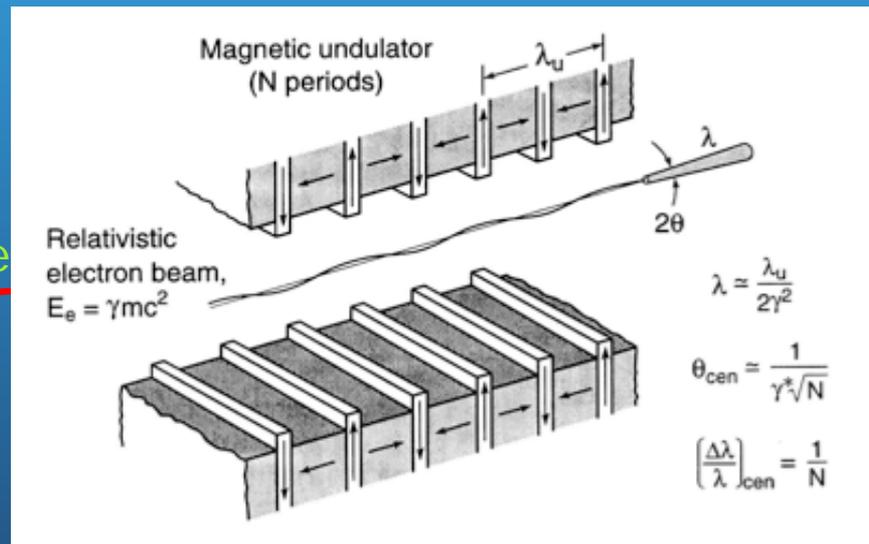
Relativistic electrons can produce coherent short λ light: the X-ray FEL

- Relativistic Doppler shift

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

- Radiating electric dipole; “wiggling” electron beam

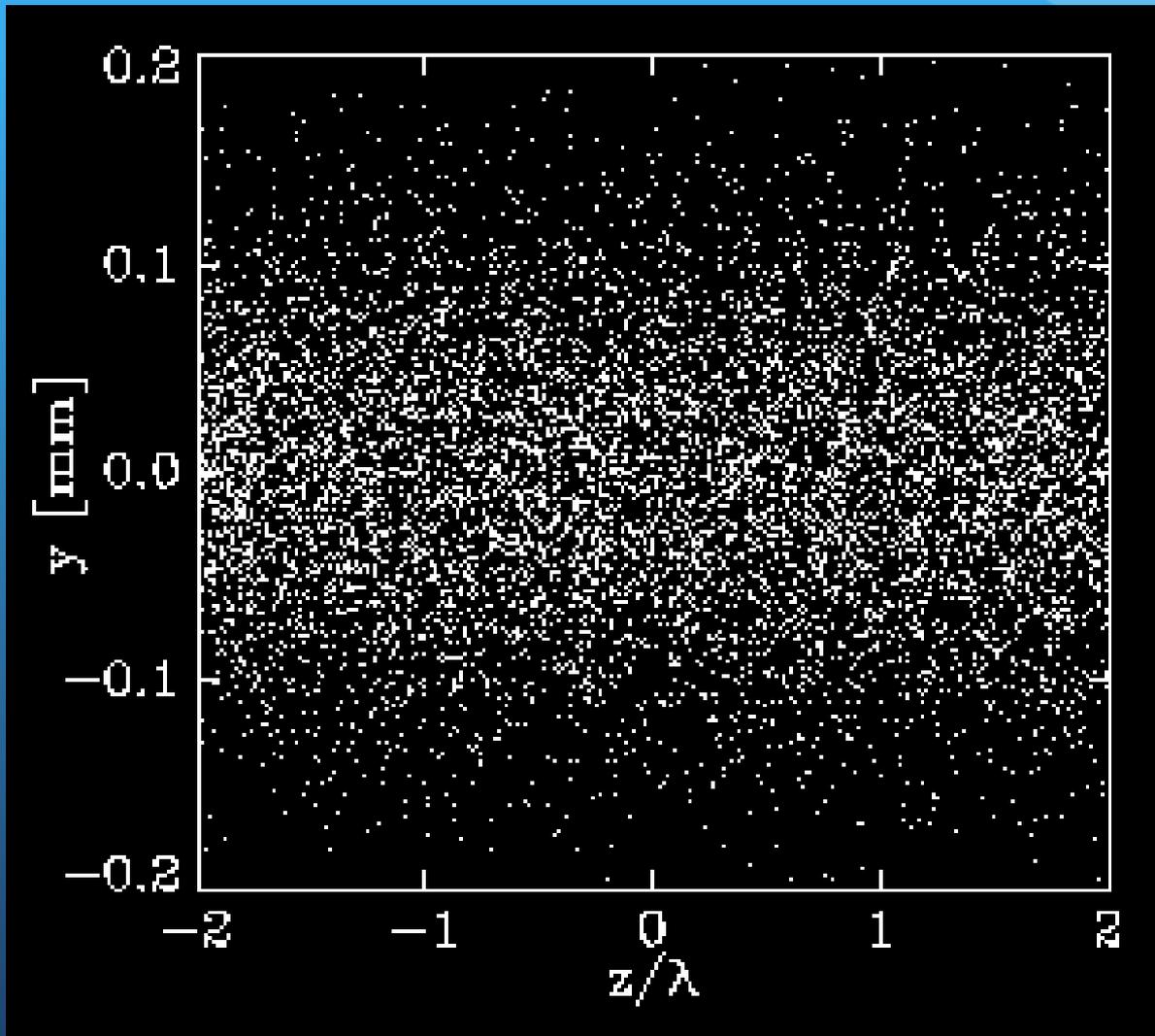
Laboratory of be
Frame



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

- 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

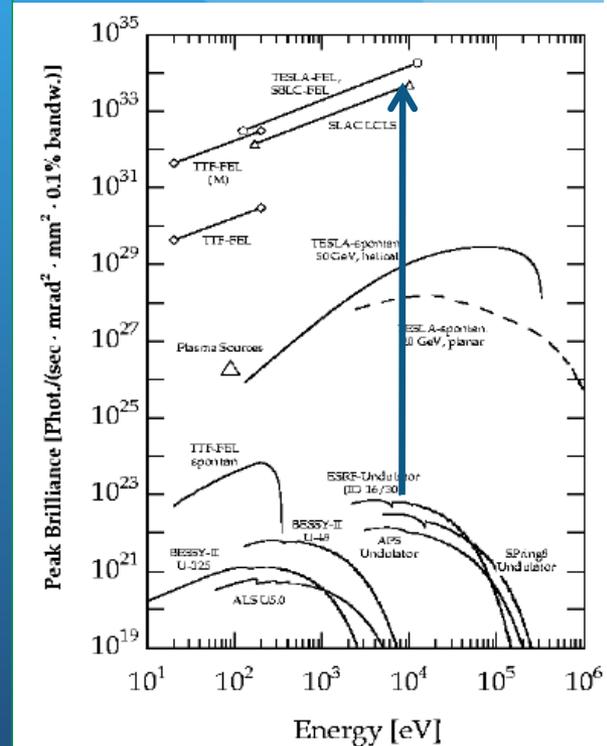
$$L_{g1D} = \frac{\lambda_u}{4\pi\sqrt{3}\rho_{1D}} \quad \rho_{1D} = \left[\frac{JJ(K_{rms})K_{rms}k_p}{4k_u} \right]^{2/3} \propto B_e^{1/3}$$

- High current, small ε gives dense lasing medium

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

- 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

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



Coherence: the importance of the phase information



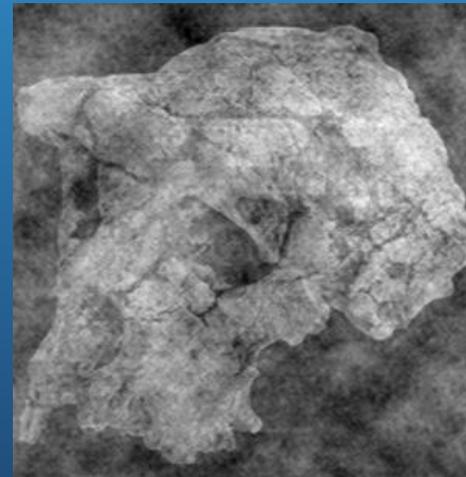
(a)



(b)



Amplitude of (a)
+ phases of (b)



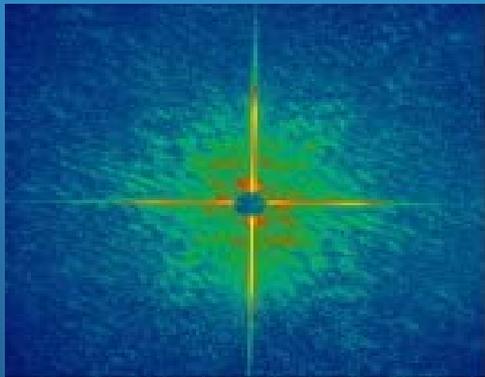
Amplitude of (b)
+ phases of (a)

XFEL: coherent imaging revolution in 4D

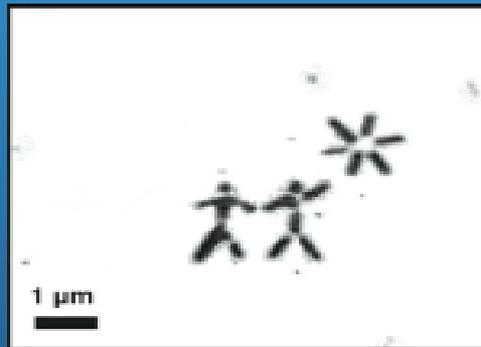
Ultrafast Coherent Imaging

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

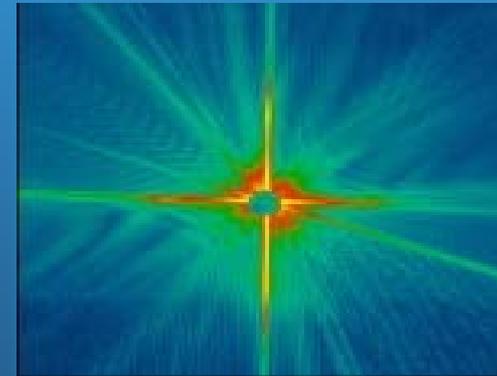
Imaging at length scale (\AA) and time scale (fs) of atomic dynamics; *4D* or *ultrafast* imaging



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 molecule 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

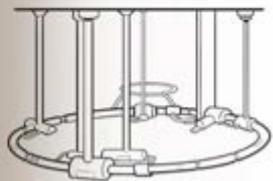
FELs are popular:

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

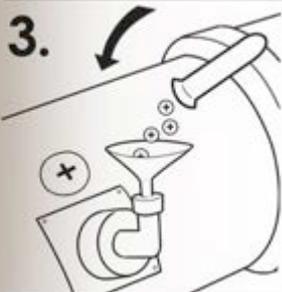
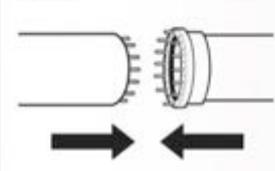
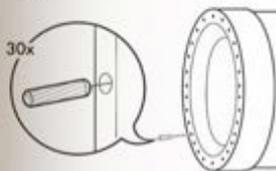
Billions \$ invested

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

HÄDRÖNN
CJÖLIDDER



The IKEA proposition:
“Miniatur Linjär Cjöllider
or Frei Eläktroen Lāzr”



Particle accelerators

Small really is beautiful

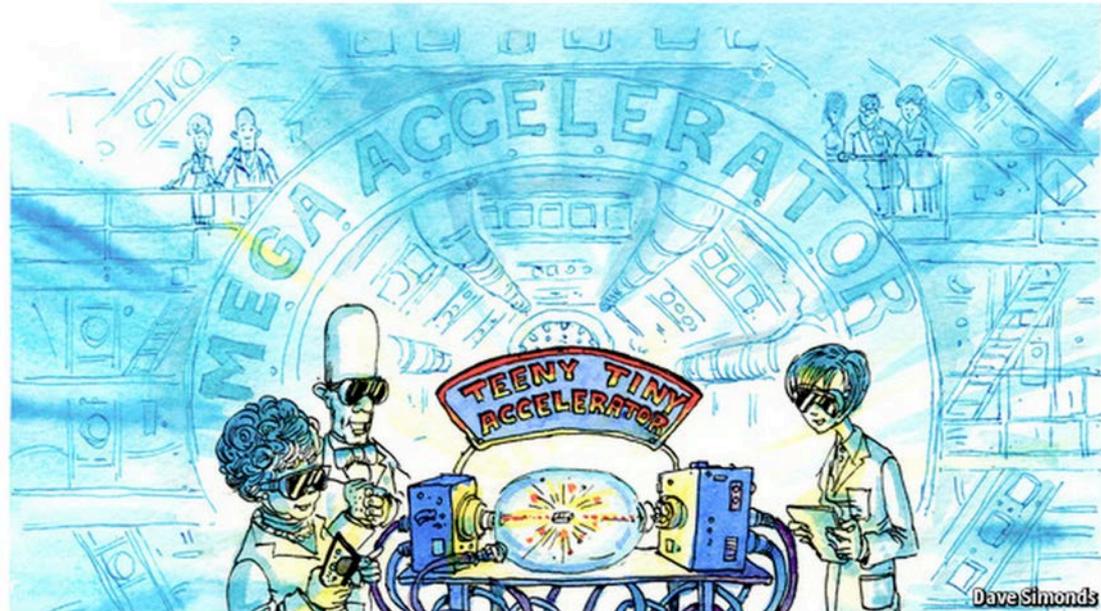
Fundamental physics seems to have an insatiable appetite for bigger, more expensive machines. There may, though, be a way to shrink them radically

Oct 19th 2013 | From the print edition

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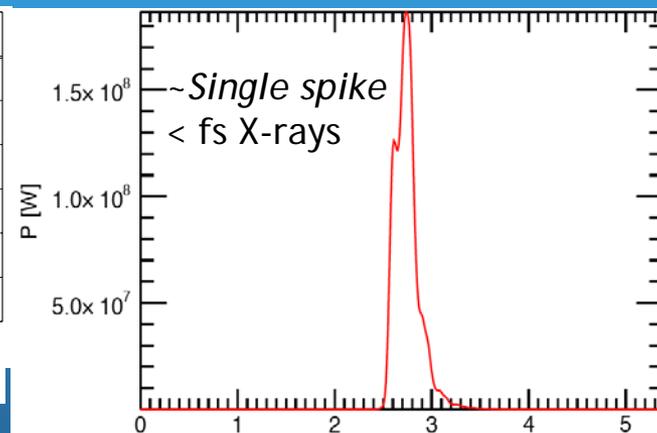
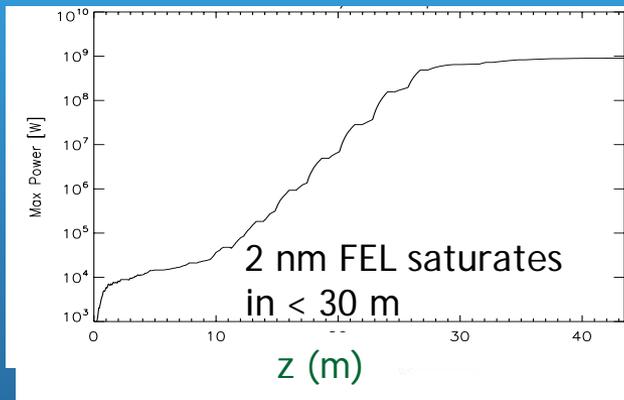
The
Economist



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 \rightarrow 1 pC (SPARX study, LNF 2007)



$$\epsilon_{mx} \cong 7.5 \times 10^{-8} \text{ m-rad}$$

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

$$B = 2 \times 10^{17} \text{ A/m}^2$$

LCLSx1000

Final longitudinal phase space

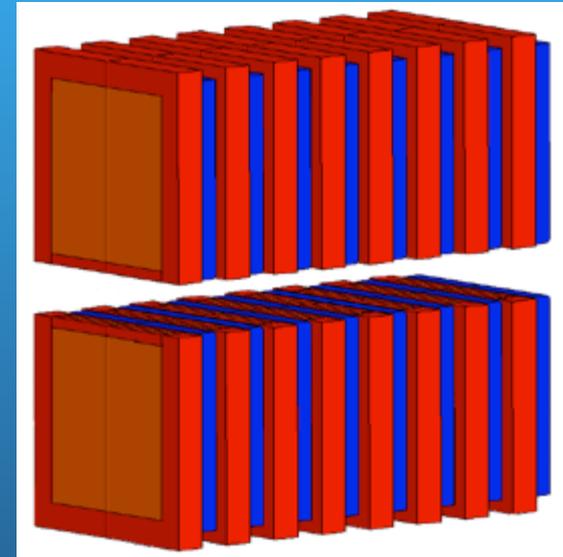
Final current profile

- 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

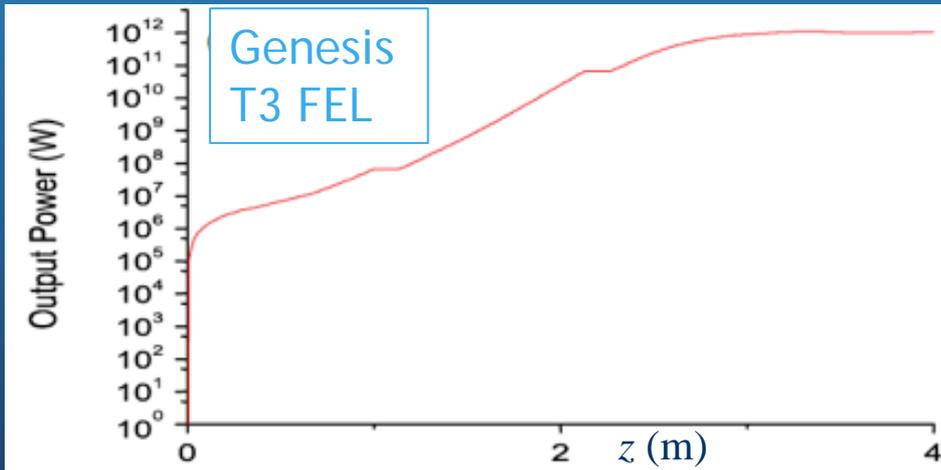
- Cryogenic , Pr-based hybrid undulator
- High field (2.2 T), short λ (9 mm)
- Can yield table-top terawatt T^3 nm FEL, assumed 1.7 GeV, 160 kA beam (from laser-plasma accelerator!)

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.)

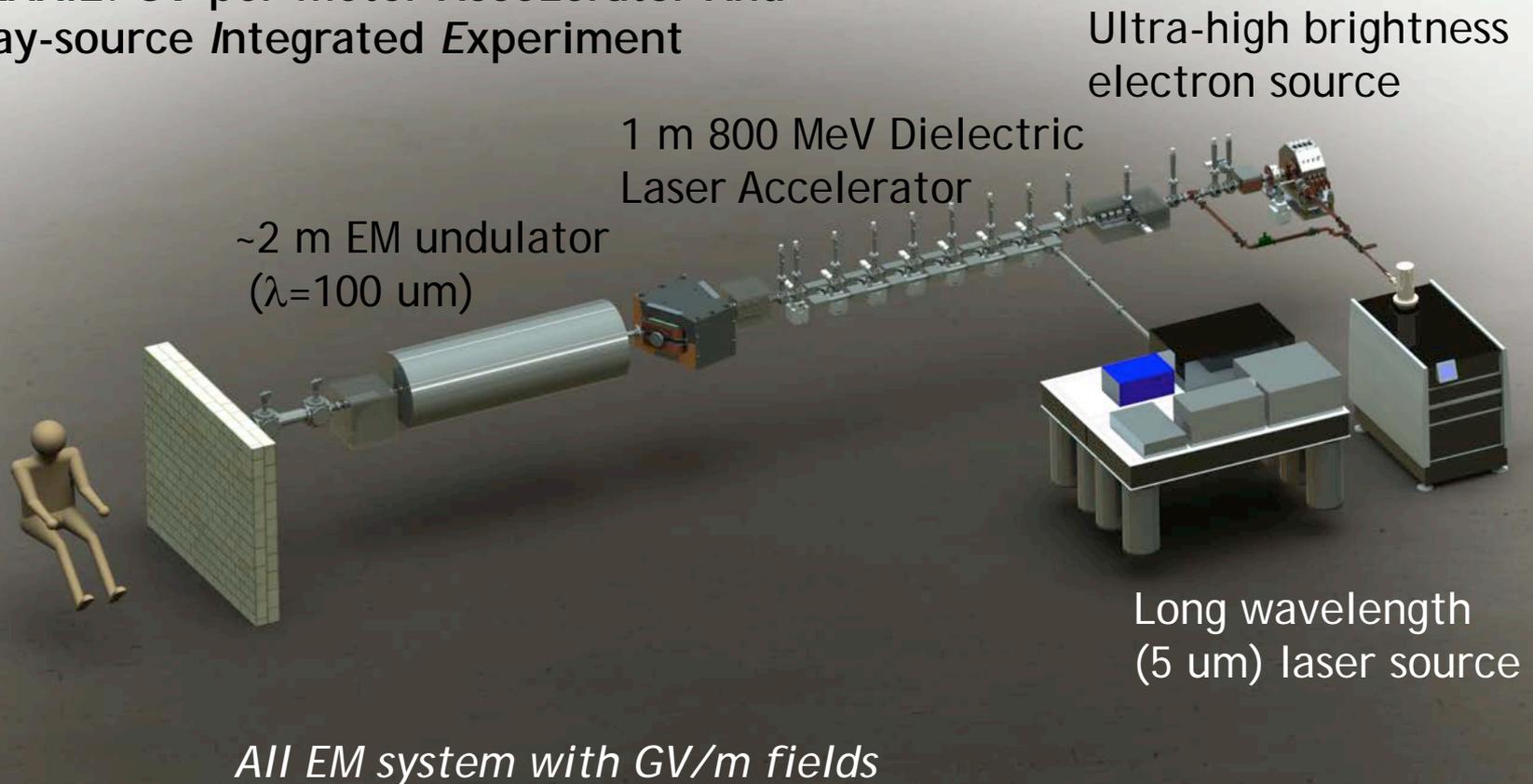


More extreme!
400 um period micromachined
Undulator (Univ. of Florida)

z (m)

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

GALAXIE: GV-per-meter Accelerator And X-ray-source Integrated Experiment

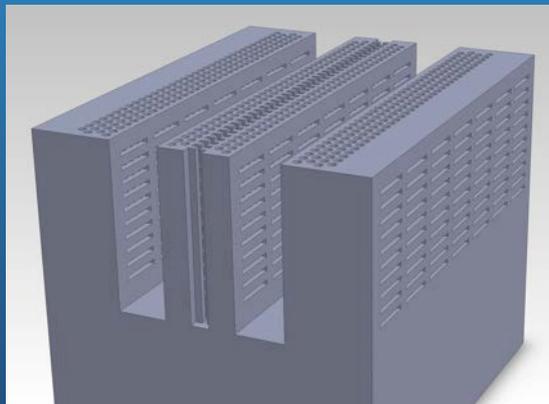
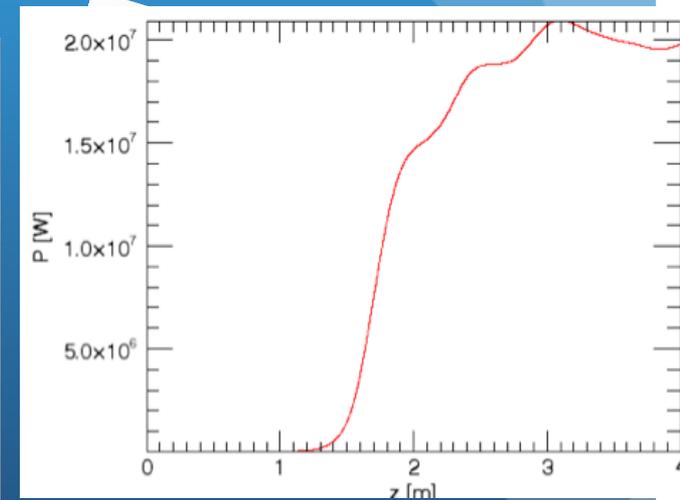
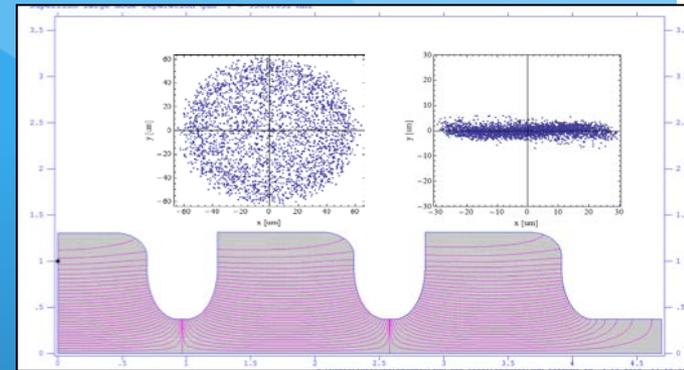


Supported by DARPA AXiS Program

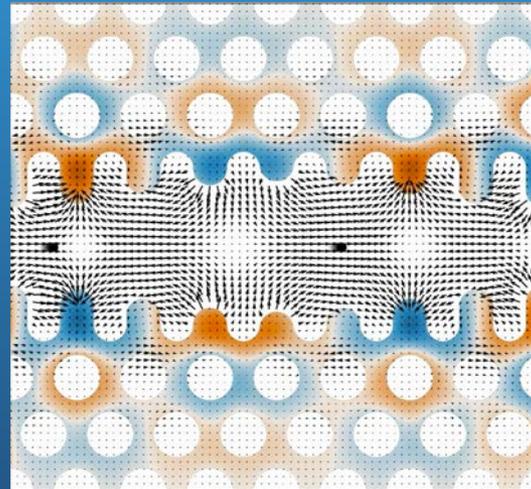
Inside of GALAXIE

- 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



Traveling wave dielectric laser accelerator

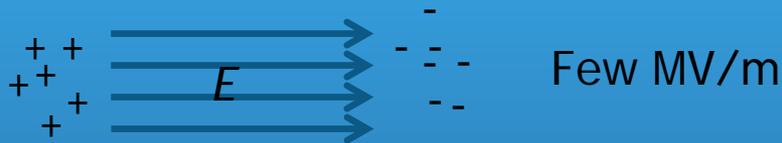


Photonic defect mode bi-harmonic structure with 2nd order focusing and acceleration on high spatial harmonic

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

Particle acceleration in electromagnetic waves: history

- Originally electrostatic



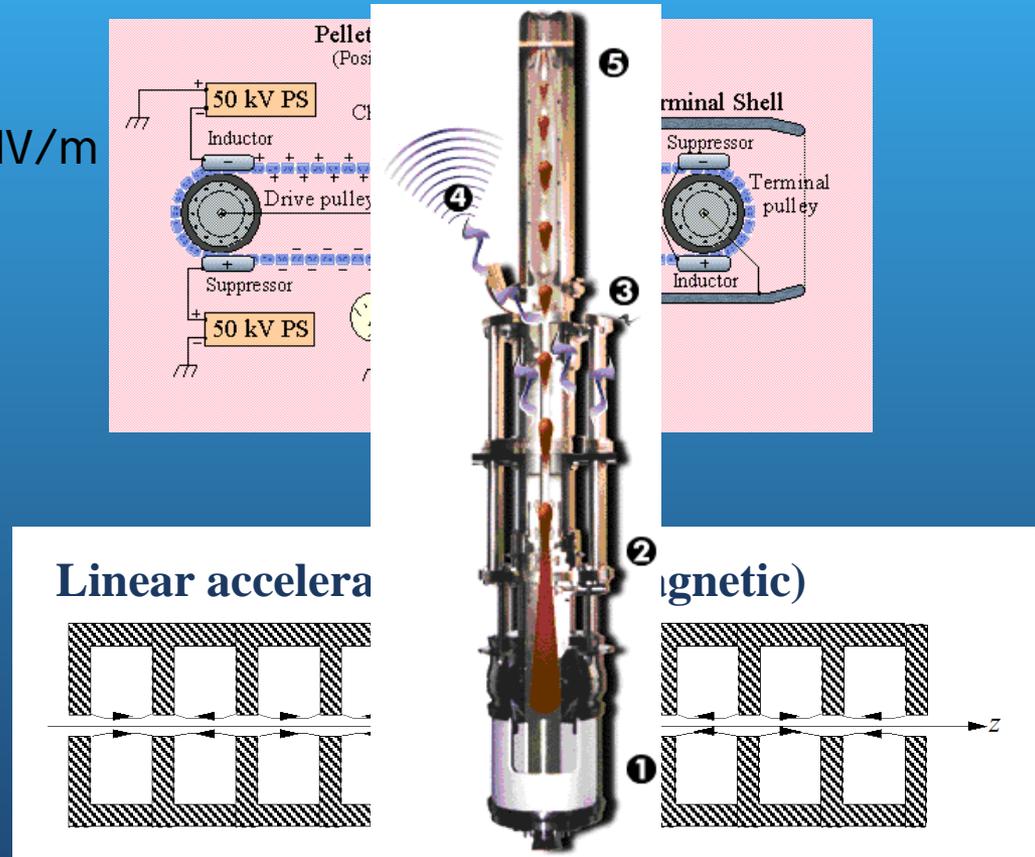
- Later electromagnetic

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



- In microwave linacs, source is a klystron

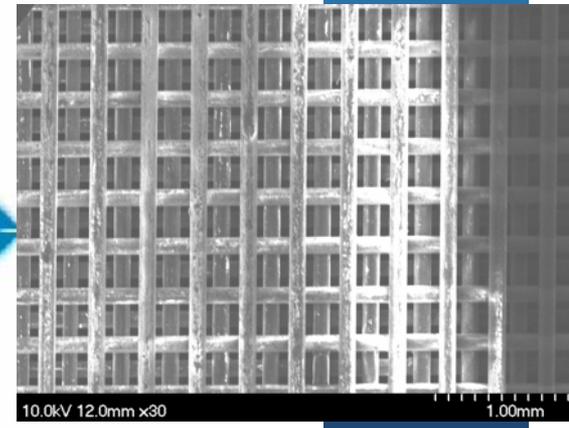
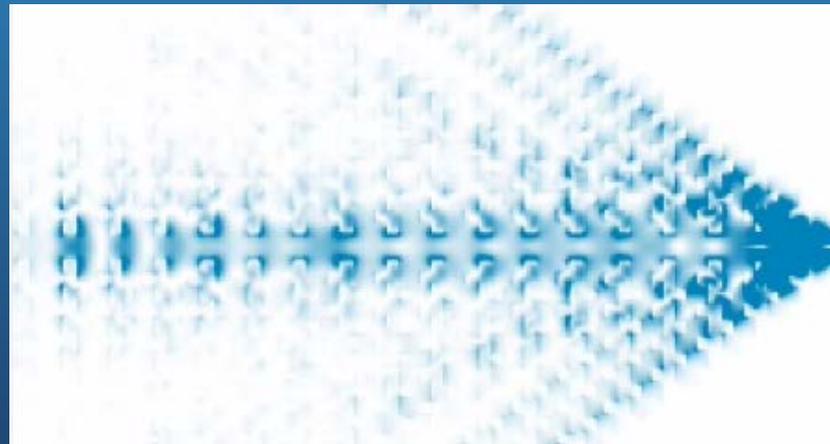
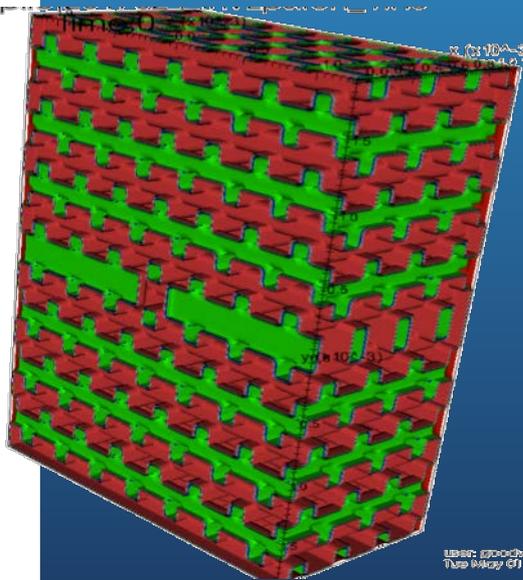
- Need ~100 MW
- Restrict to $\lambda > cm$



The klystron

Shrinking the *accelerator*

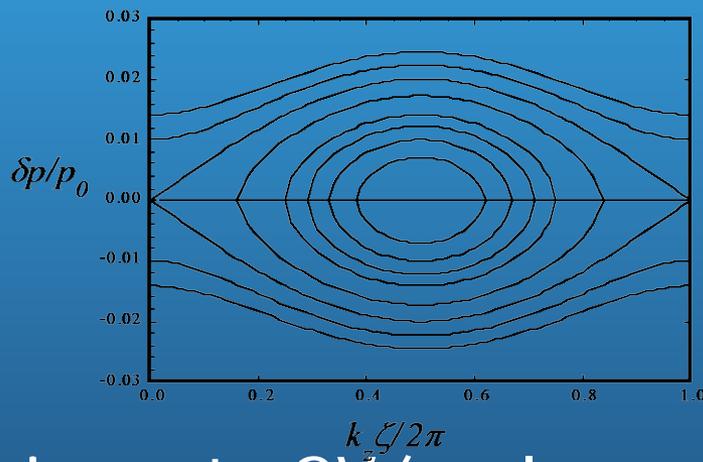
- Higher E ($>GV/m$): shorter λ ($E \sim \lambda^{-1}$); THz down to IR
 - Need much smaller ε
 - Small Q (beam loading/eff. $Q \sim \lambda^2 E \sim \lambda$). Synergy with brightness, FEL
 - Losses \rightarrow dielectric at short $\lambda \rightarrow$ photonics
 - Breakdown considerations \rightarrow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



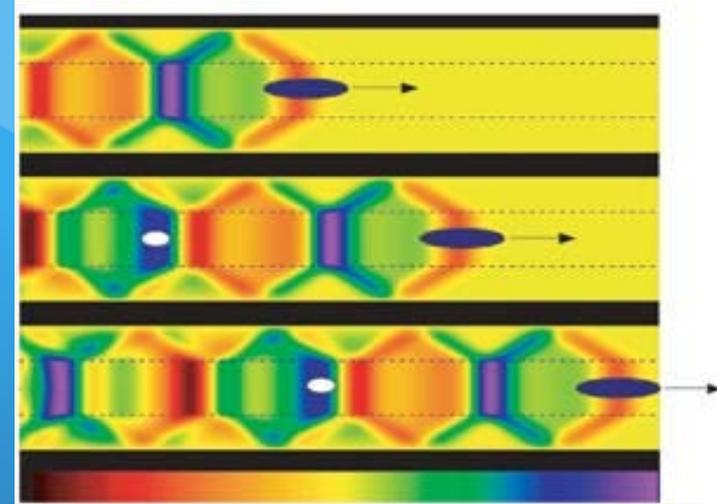
Laser wavelength accelerator
longitudinal dynamics: few % $\delta p/p$ stability range...

$$\alpha_{EM} \equiv \frac{qE_0}{k_z m_0 c^2} \propto \lambda_{EM} \quad \frac{\delta p_{\max}}{p_0} = \sqrt{\frac{4\alpha_{EM}\gamma_0}{\beta_0^2}}$$

$$\alpha_{EM} \ll 1$$

- 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...

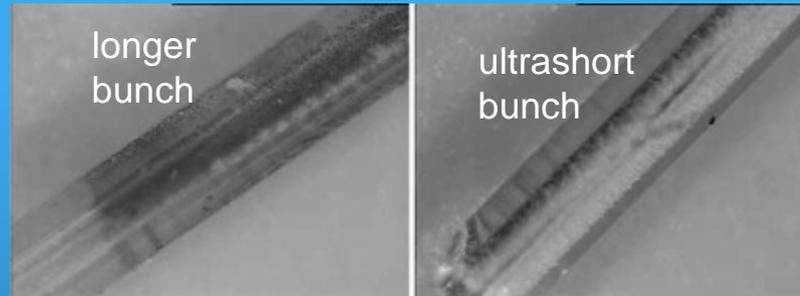
New paradigm for high field acceleration: *wakefields*



Wakefields in dielectric tube
Driving & accelerating beams

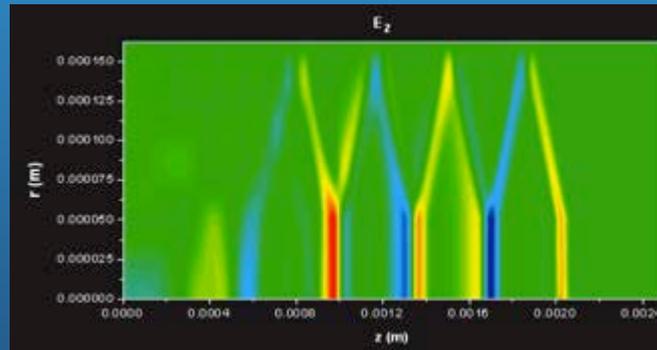
- *Coherent* radiation from *bunched*, $v \sim c$, e^- beam
 - Any *slow-wave* environment (metal, dielectric, plasma)
 - Resonant or *short pulse* operation
 - THz within reach
- *High average power beams* can be produced
 - Tens of MW, can beat lasers
 - Motivates CLIC-like schemes

Breakdown threshold: many GV/m



Post mortem images (1st vaporize Al coating, next damage SiO₂)

Breakdown determined by benchmarked simulations (OOPIC)



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

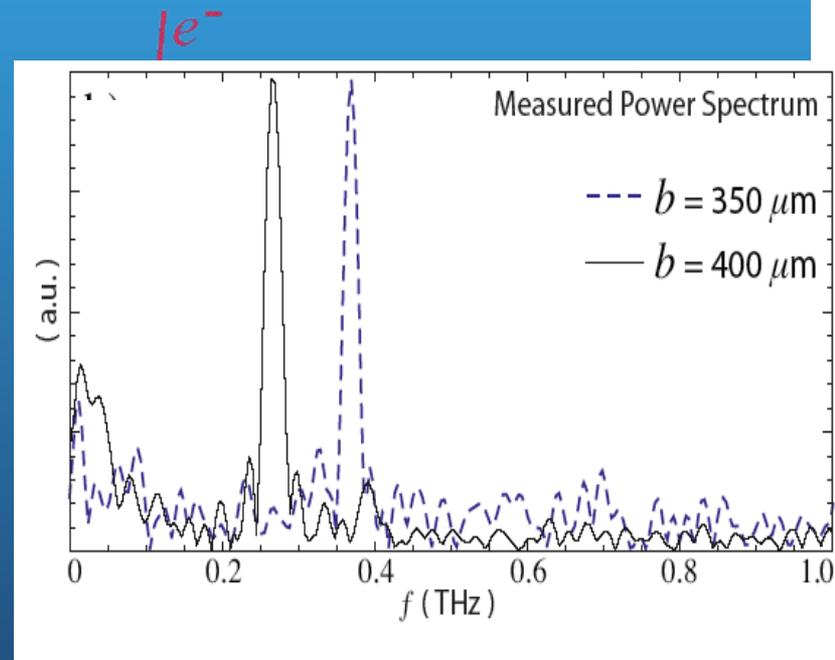
Multi-mode excitation - 100 fs, pulses separated by ps
— gives better breakdown dynamics

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 ($\sigma_z < 200 \mu\text{m}$), $Q=0.3 \text{ nC}$ beam @ Neptune
 - PMQ focuses to $\sigma_r \sim 100 \mu\text{m}$ ($a=250 \mu\text{m}$)
- 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

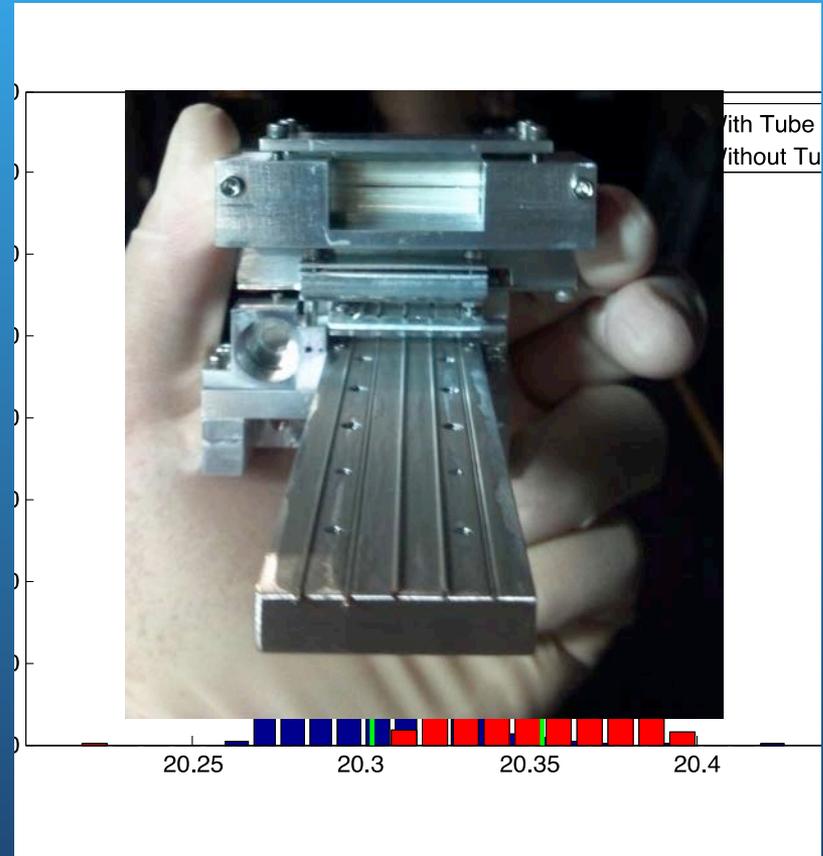
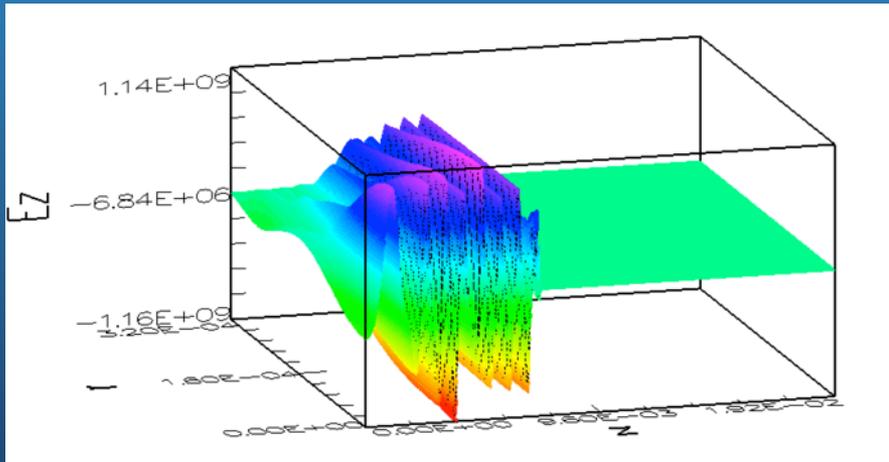


A. Cook, et al., *Phys. Rev. Lett.*
103, 095003 (2009)

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

FACET now online: 20 GeV wakefield facility at SLAC

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

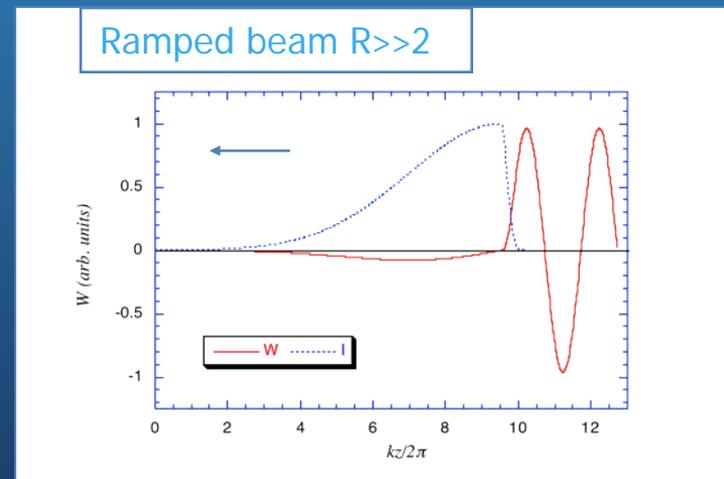
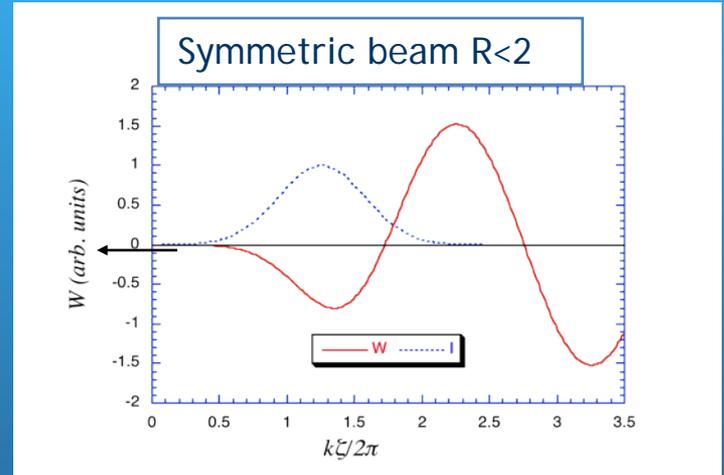


Pulse shaping: reaching *high transformer ratios*

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

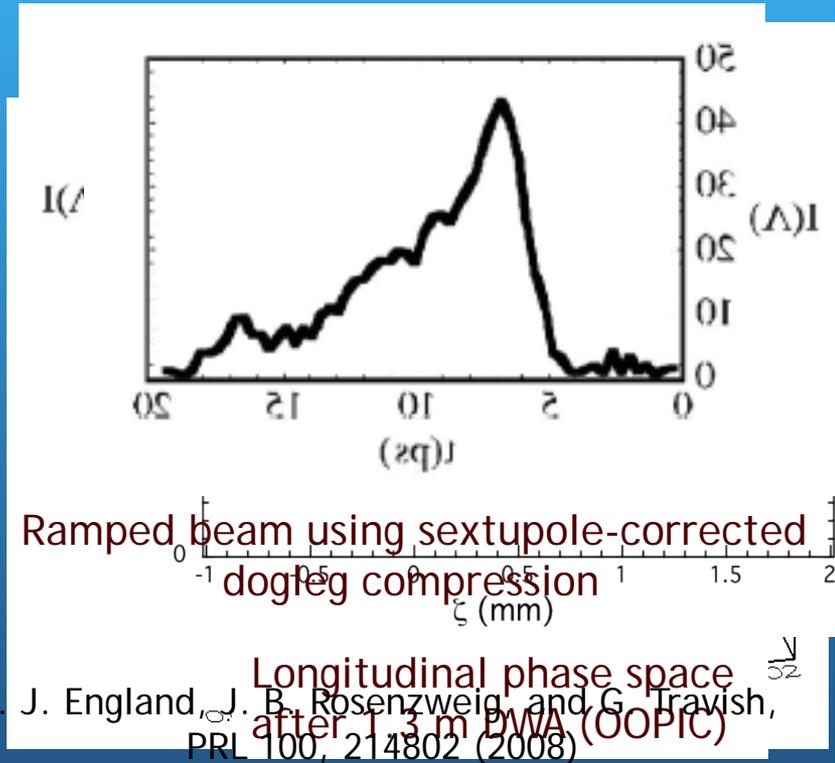
$$R \equiv \frac{\|E_{acc,witness}\|}{\|E_{dec,driver}\|}$$

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



Example: DWA-driven 5th generation light source

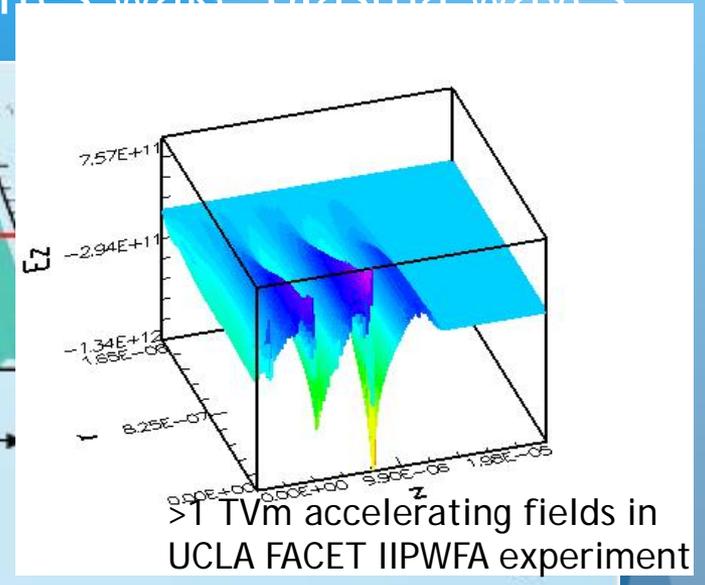
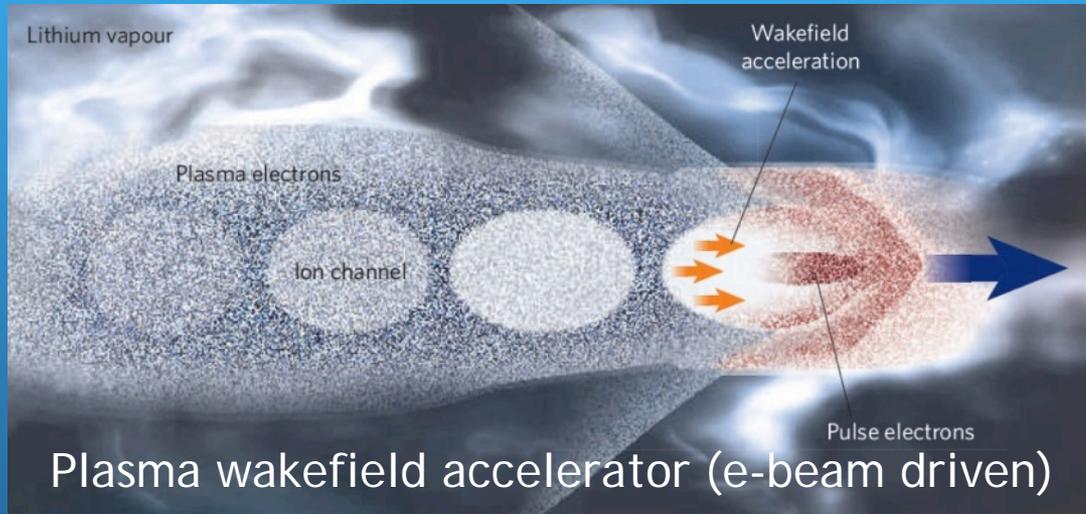
- Beam parameters: $Q=3$ nC, ramp $L=2.5$ mm, $U=1$ GeV
Possible at SLAC FACET
- Structure: $a, b=100, 150$ μm , $\epsilon=3.8$; fundamental @ $f=0.74$ THz
- Performance: $E_z > \text{GV/m}$, $R=9-10$
- Ramp achieved at UCLA, BNL
- Enables hard X-ray source w/high average power, small footprint?
- Ongoing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



Longitudinal wakefields with ramped beam

Past Breakdown: Plasma Accelerators

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



- ⊕ Extremely high fields possible:

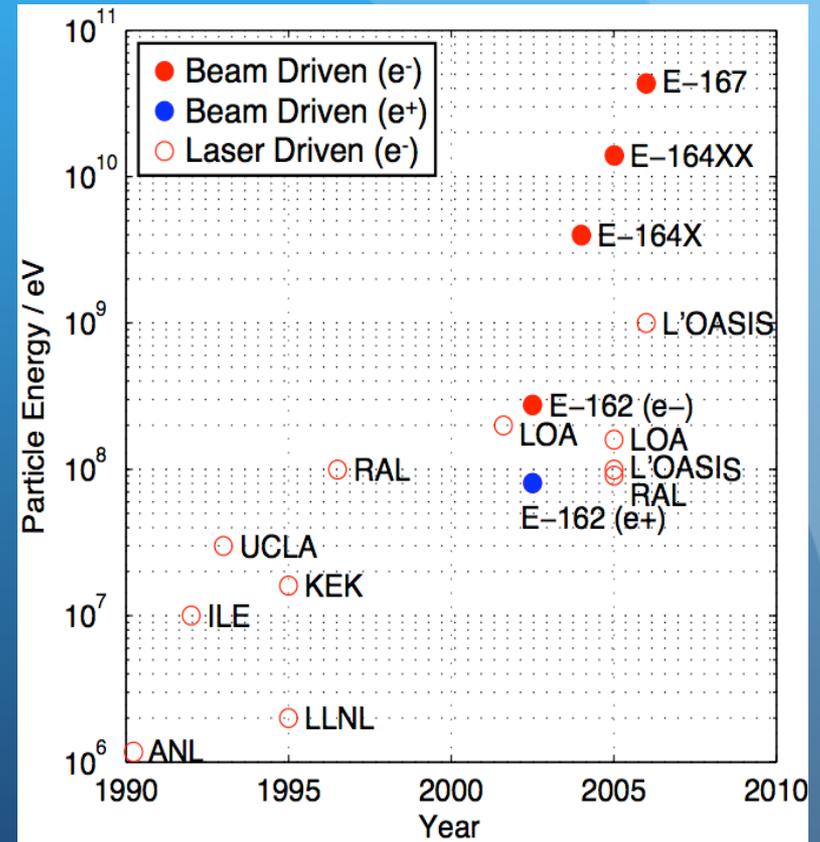
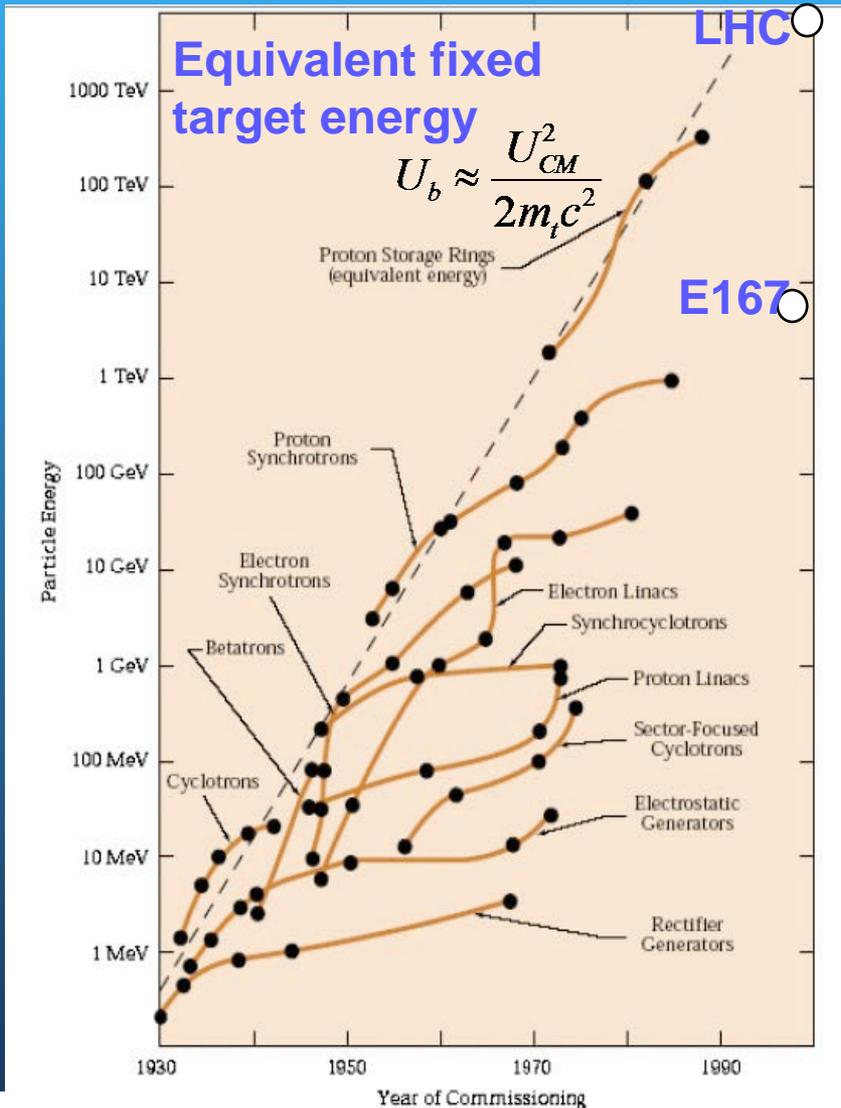
$$E(\text{V/cm}) \propto \sqrt{n_e (\text{cm}^{-3})}$$

- ⊕ Ex: atmospheric gas density

$$E \propto 1 \text{ TV/m, for } n_e = 10^{20} \text{ cm}^{-3}$$

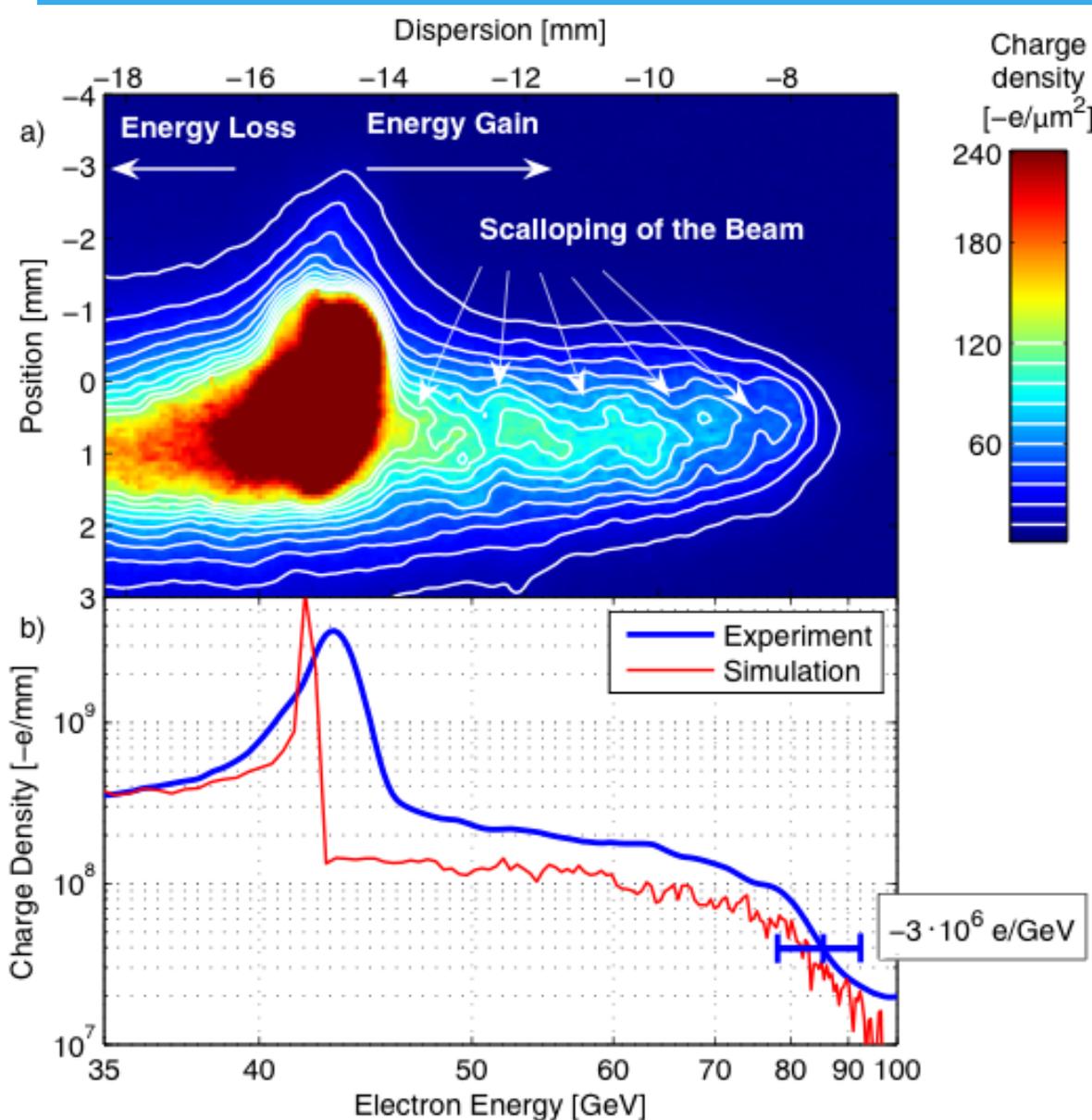
- ⊕ LHC-class energies in the length of an automobile?

Plasma Accelerators History: Livingston Plots Old and New



**Plasma accelerators
(actual, not “equivalent”)**

PWFA doubles highest energy linac

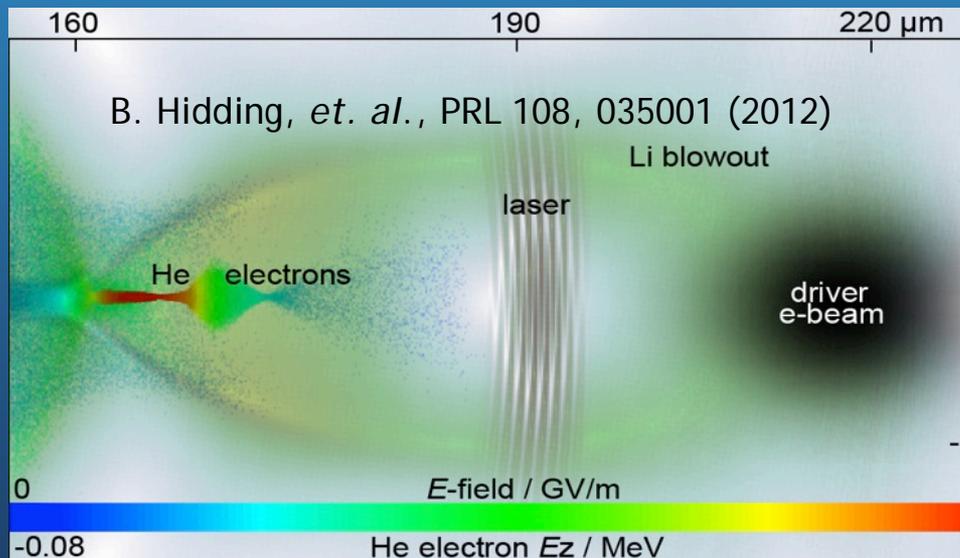


- Acceleration gradients of $\sim 50 \text{ GV/m}$ ($3000 \times$ SLAC linac)
- Doubled 45 GeV beam energy in 1 m plasma
- Required enormous infrastructure at SLAC
- Still not yet a "beam"

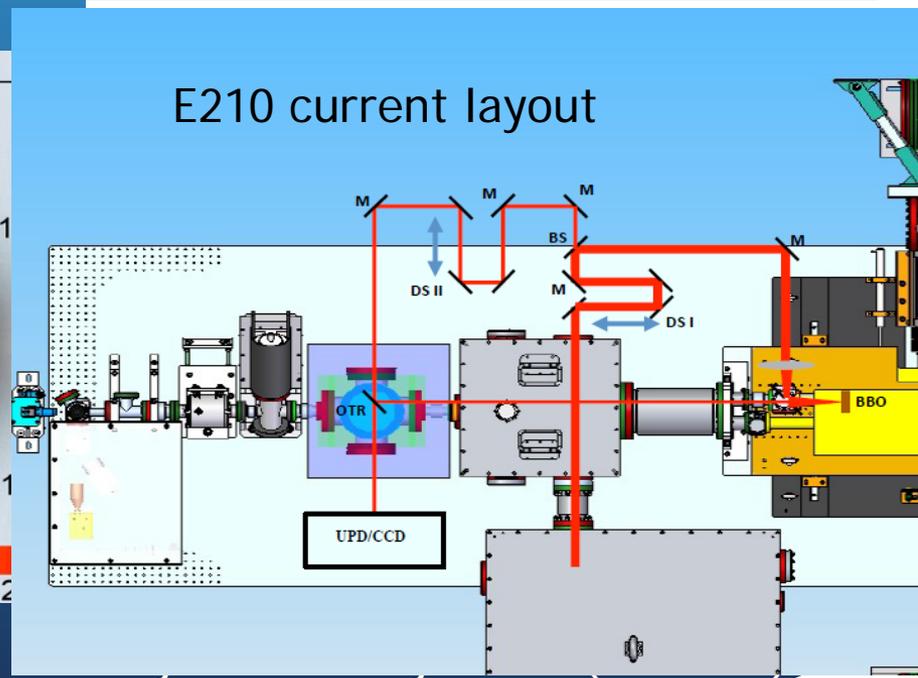
I Blumenthal et al., Nature
445 741 15-Feb-2007

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

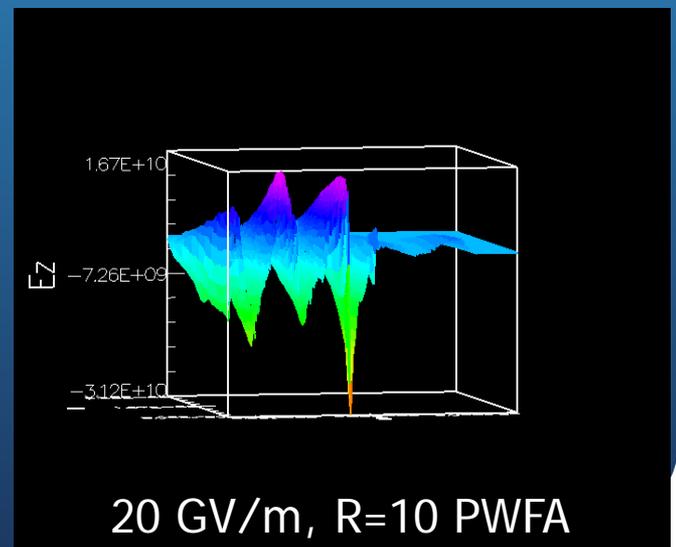
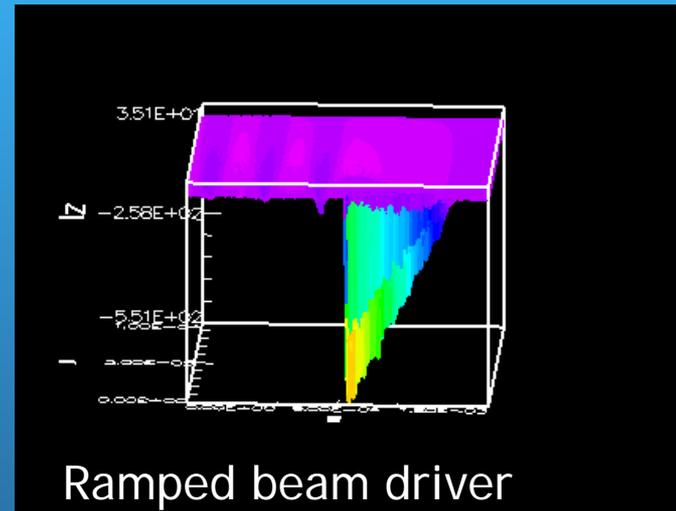


Trojan Horse Injection (Hidding *et al.*)

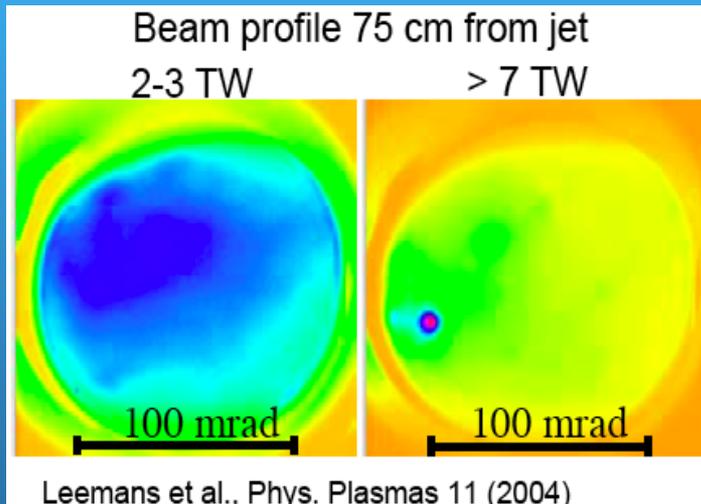


Pulse shaped PWFA driver for low energy X-ray FEL

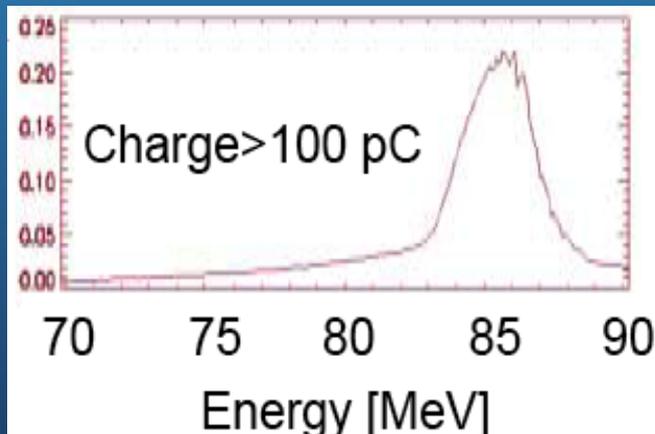
- Inject with Trojan scheme
 - Ultra-high brightness beam
- FEL scenario: ramped driver
 - 5-10 GeV X-ray FEL injector in <10 m
 - SLAC-UCLA-Strathclyde collaboration
 - FACET context; FEL goal
 - Example: 500 MeV driver, 9 mm period undulator gives nm X-rays



Laser wakefields (LWFA) already create high quality electron beam



- 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...

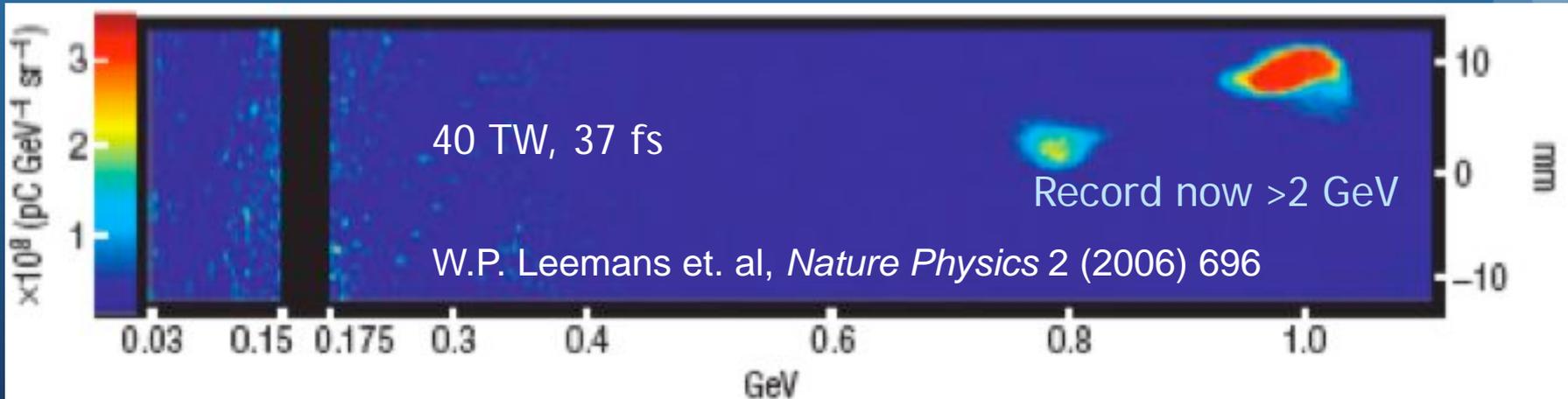
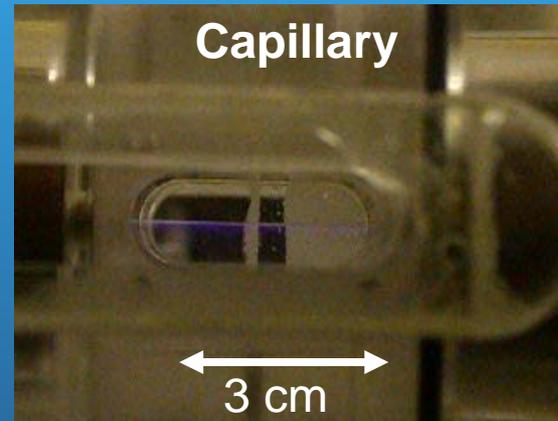
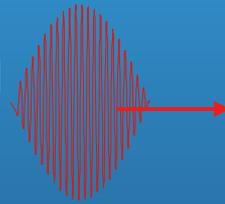
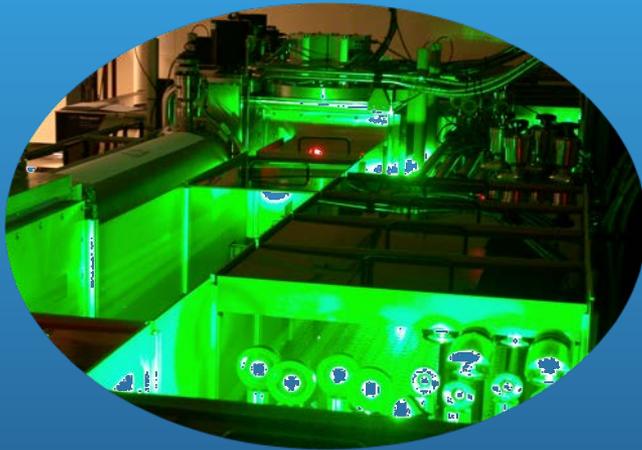


Early LWFA beams

Channel guided LWFA can produce *multi-GeV beams*

- Higher power laser
- Lower density, longer plasma

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



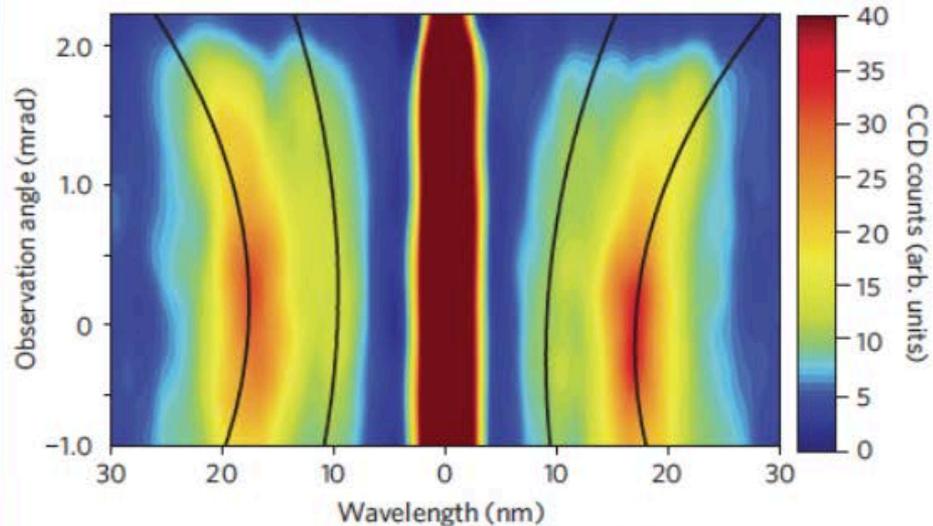
5th generation XFEL light source based on LWFA

MPQ-centered (Uni. Hamburg) collab.

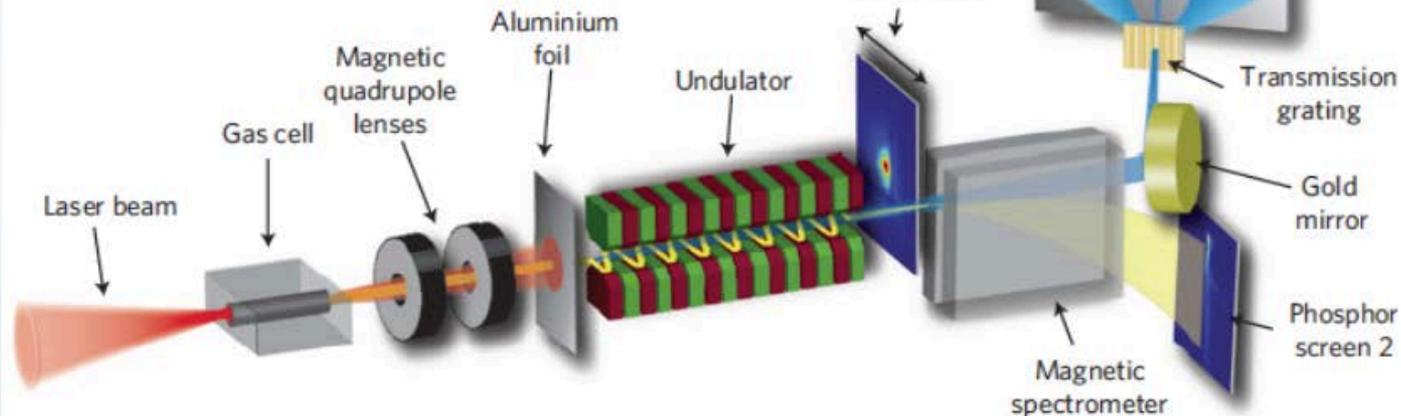
M. Fuchs et al., Nature Physics (2009)

- Measured 1st and 2nd harmonic:

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

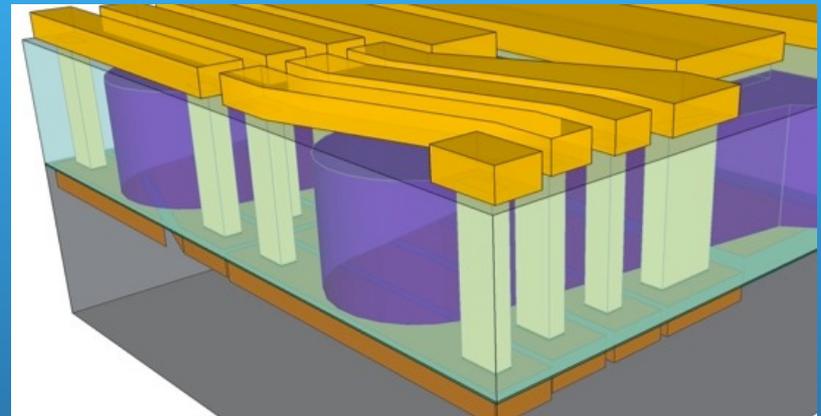
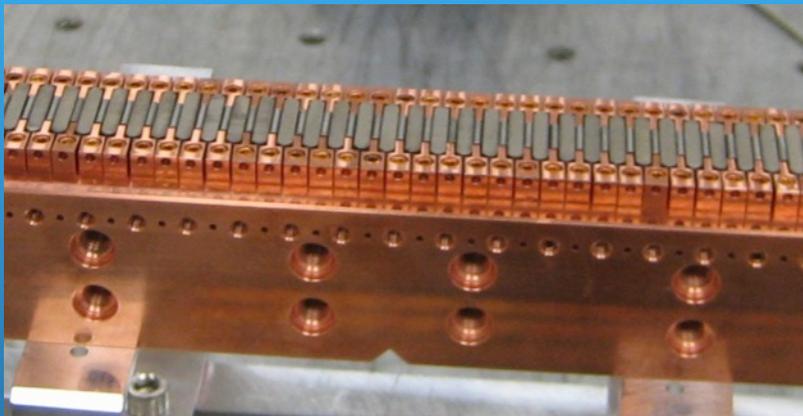


$n=8 \times 10^{18} \text{ cm}^{-3}$ → 210 MeV → $K=0.55$
 0.85 J, 37 fs → ~10 pC → $\lambda_u=5 \text{ mm}$

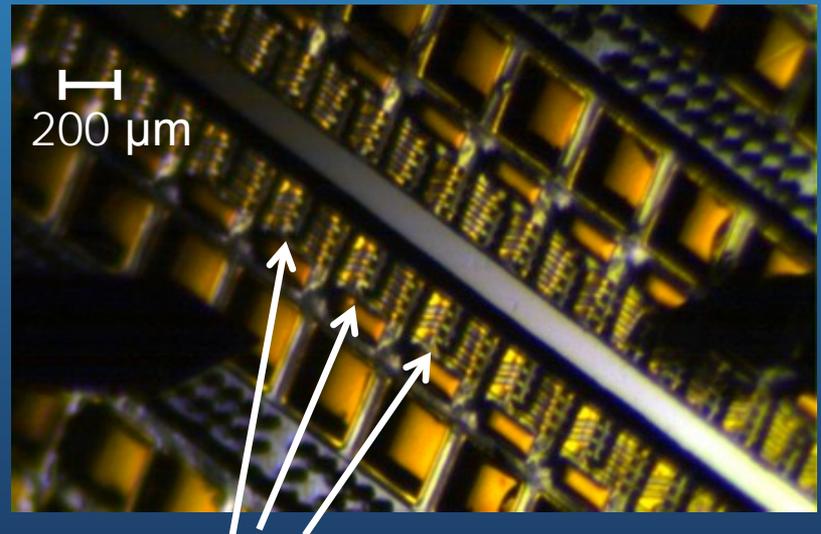


Pushes R&D
for short λ
cryundulato
r

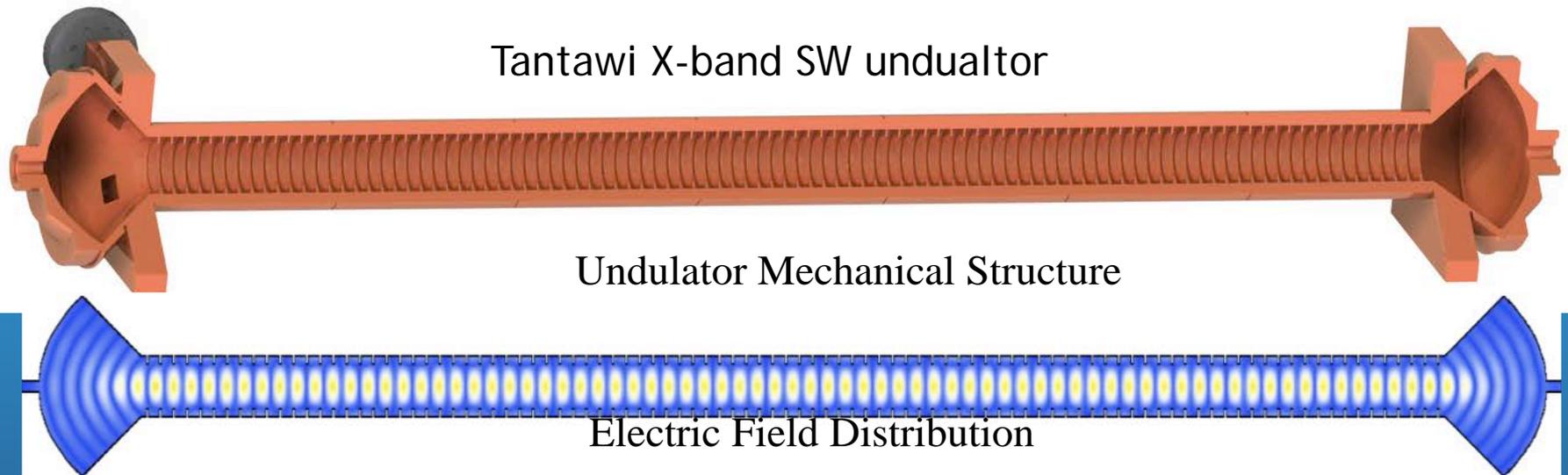
Mini-to-micro-undulators



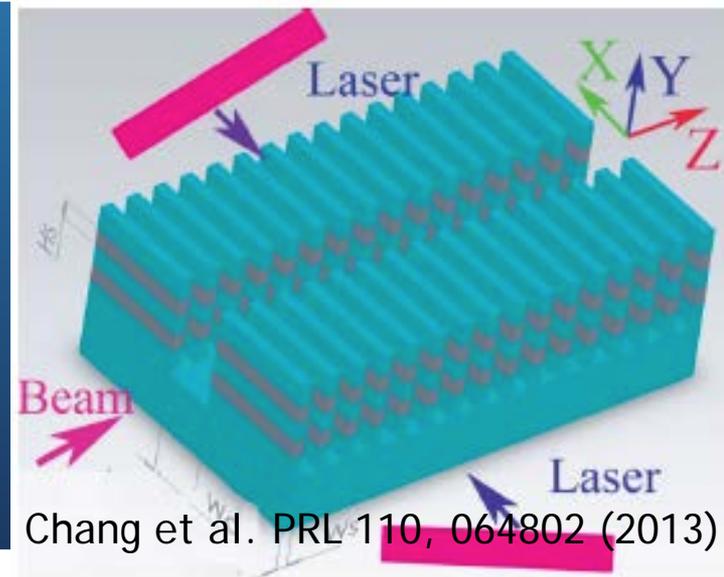
- 9 mm period, 2 T peak field cryo-undulator
- MEMS-based 100-800 μm (!) period current-driven undulator (K is low)
 - Need EM solution to go beyond 1T level...



The next generation undulator: The electromagnetic era



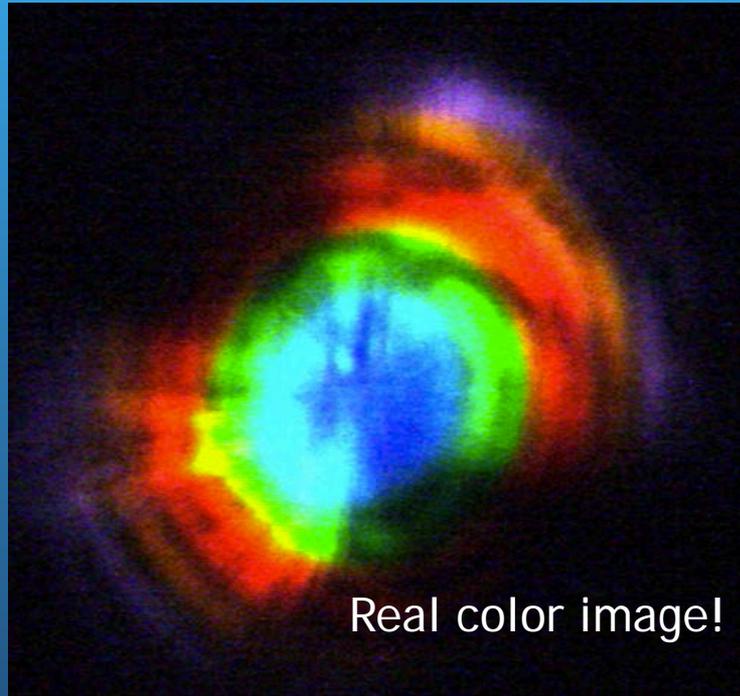
- To use <1 GeV in XFEL, need $\lambda=100$ μm undulator
- $K \sim 0.1$ or above means T -level B_0 inadequate
- On to *EM undulators*: THz SW structures, IR TW guides, free-space Thompson



The EM era has dawned

(Tantawi, et al., 2012, GALAXIE collaboration)

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

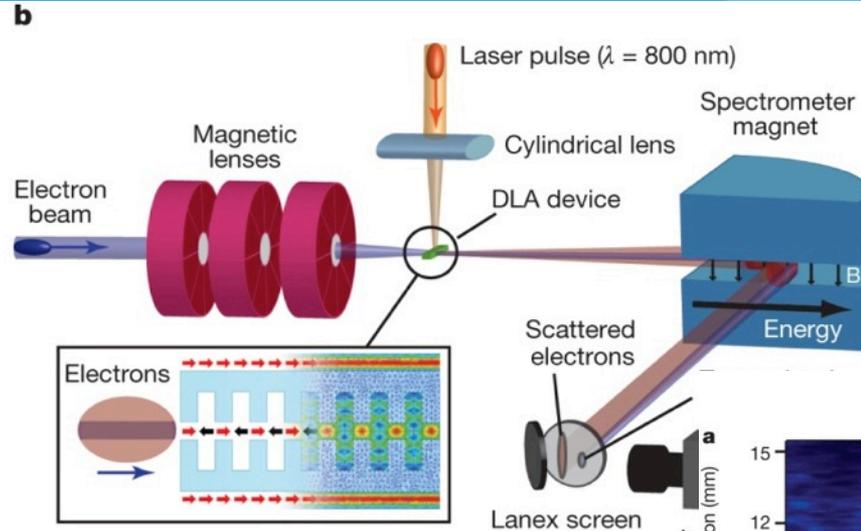
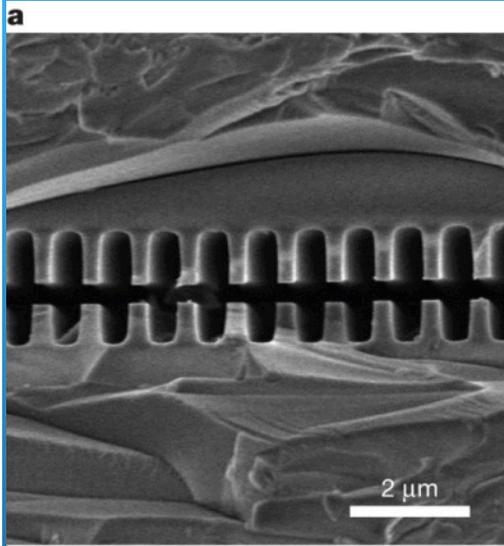


Real color image!

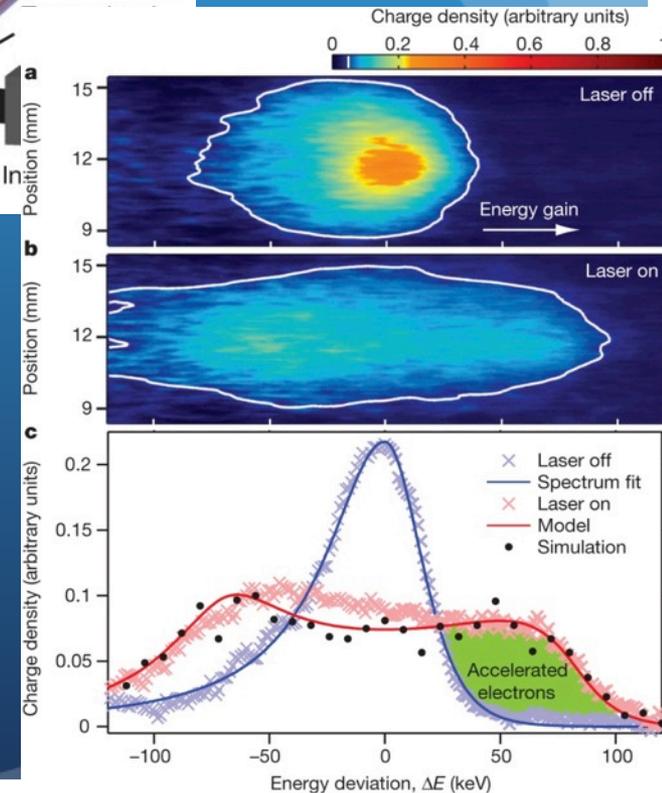
NLCTA prebunched beam radiation

- Scale to THz for GALAXIE

The dielectric laser accelerator (DLA)

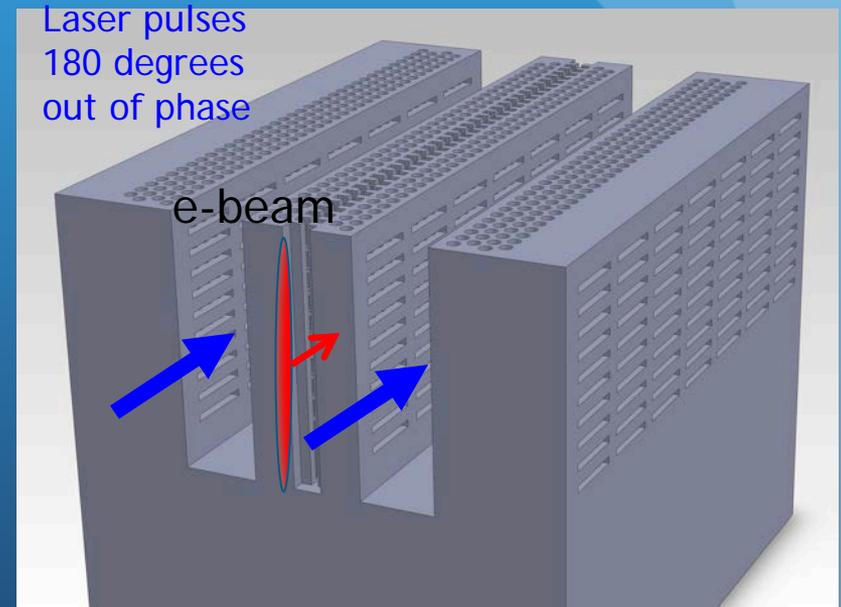


- Dedicated DARPA program last 2 years (AXiS)
- SLAC experiments make a splash in *Nature*
- Uses 800 nm laser, simple structure
 - *Non-optimized*
- Demonstrated $>300 \text{ MV/m}$ fields



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

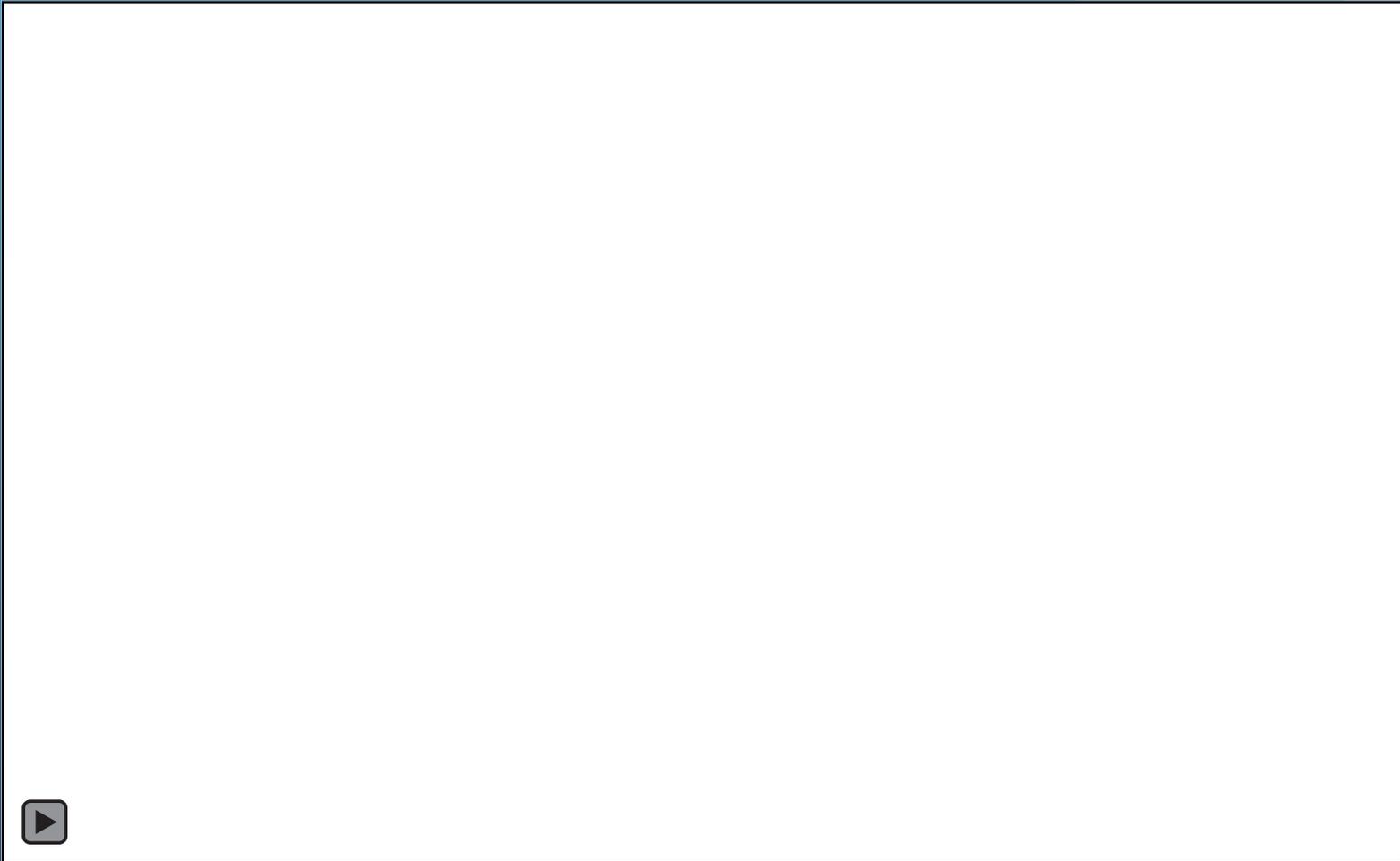


2 μm

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

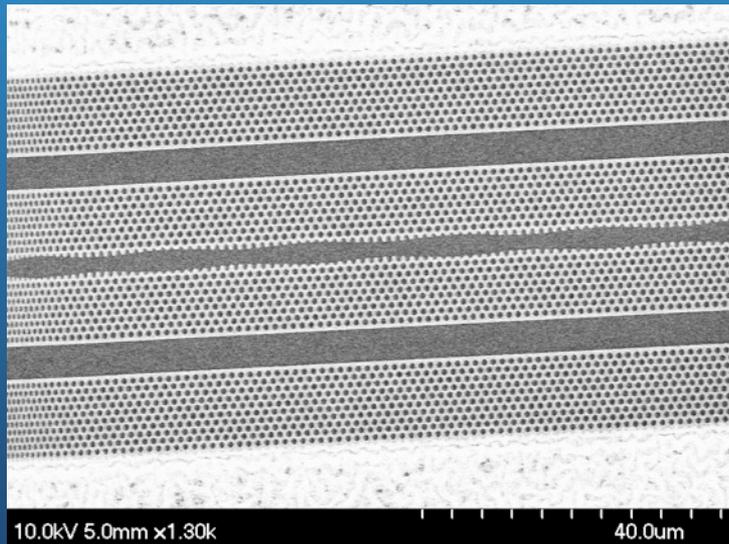
New beam dynamics in DLA: 2nd order focusing and *adiabatic compression*



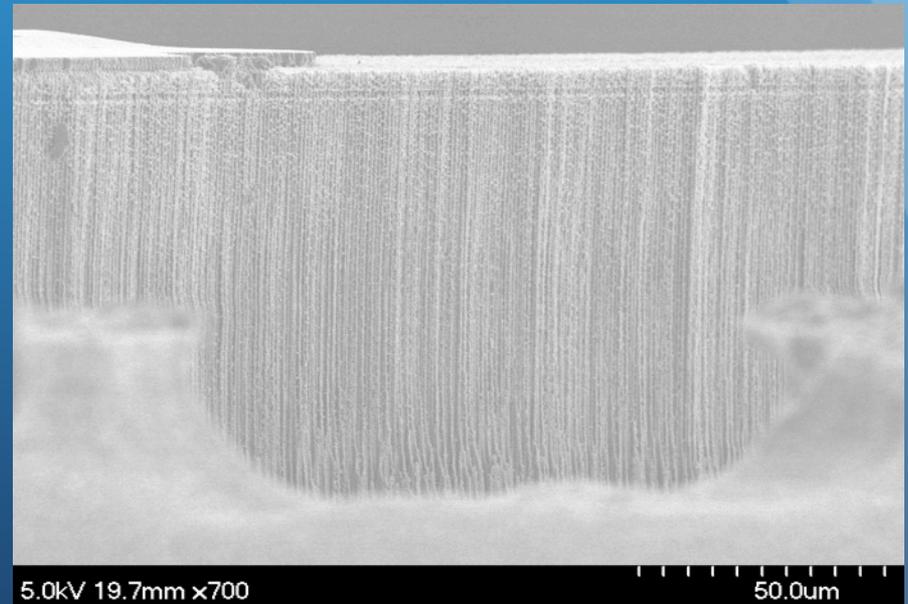
GALAXIE example: Adiabatic: (1) focusing (2) capture
(3) compression (x1000!)

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*



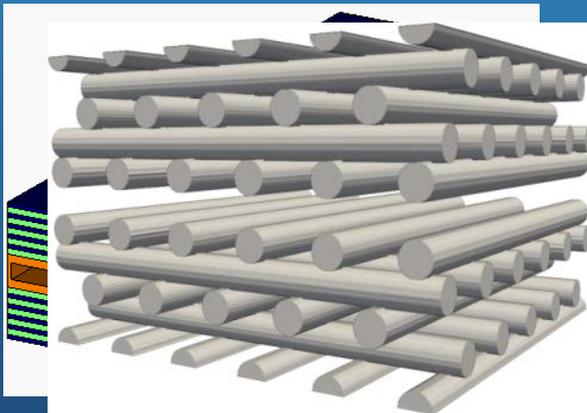
Mask for etching



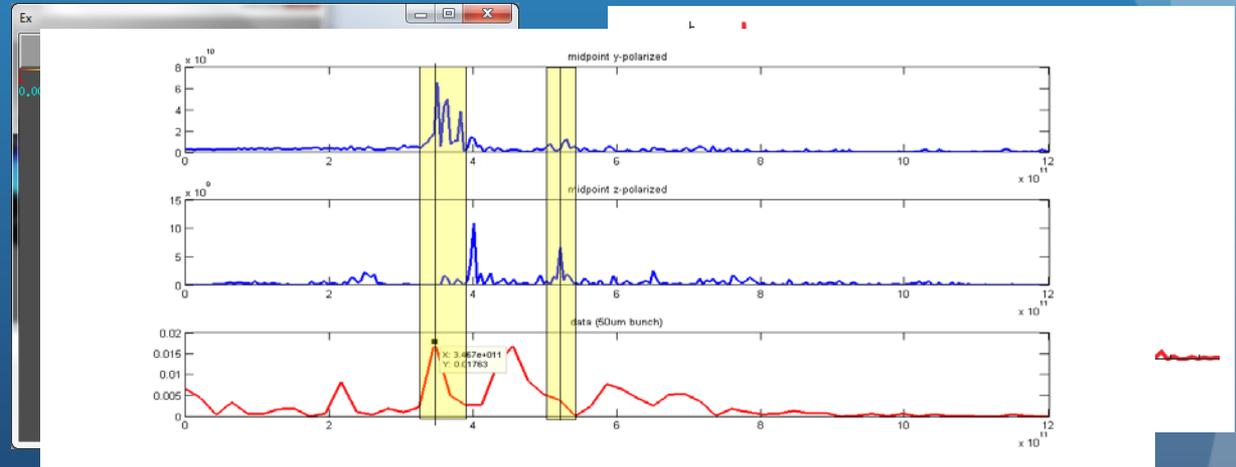
Cross-section of photonic array

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



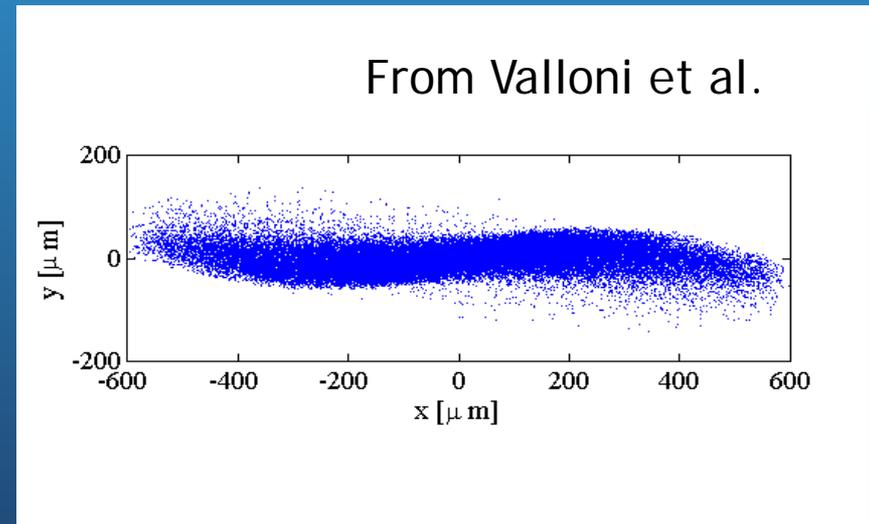
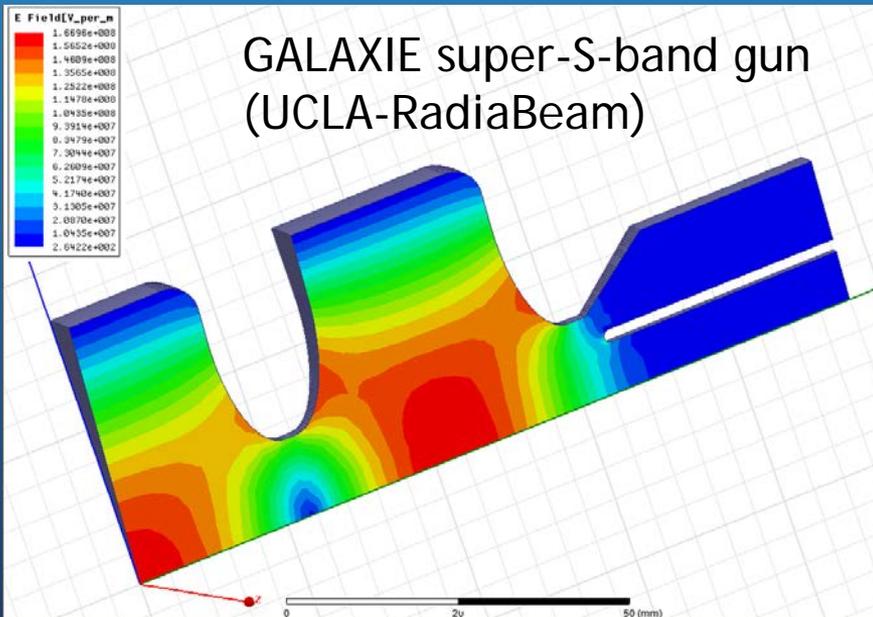
Simulated wakes (side view)

Narrow-band mode confinement

Measured emitted spectrum: modes in pass-bands

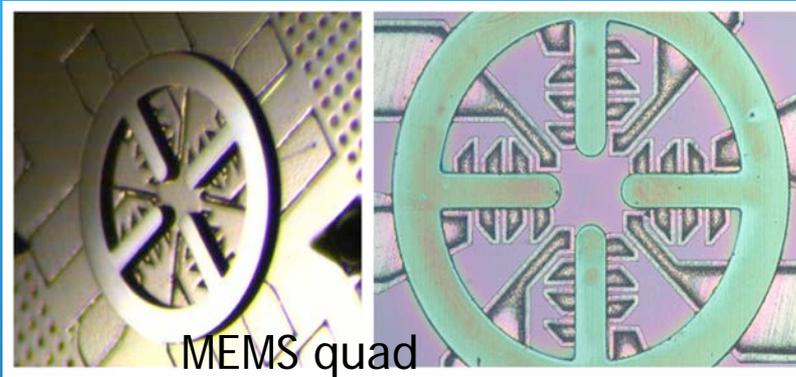
The front-end: generating very high brightness electron beams

- 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

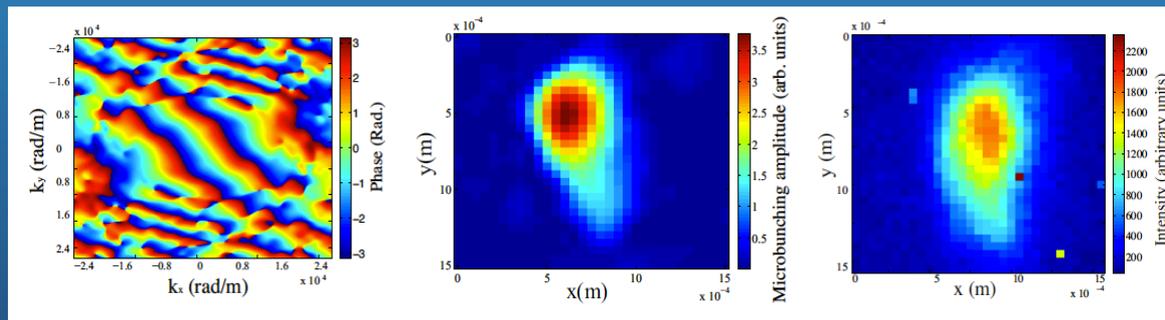


Beam after emittance splitting
Normalized Emittance
 $\varepsilon_{n-}, \varepsilon_{n+} = 2.9 \times 10^{-9}, 2.6 \times 10^{-7}$ m-rad

Microbeam optics and diagnostics



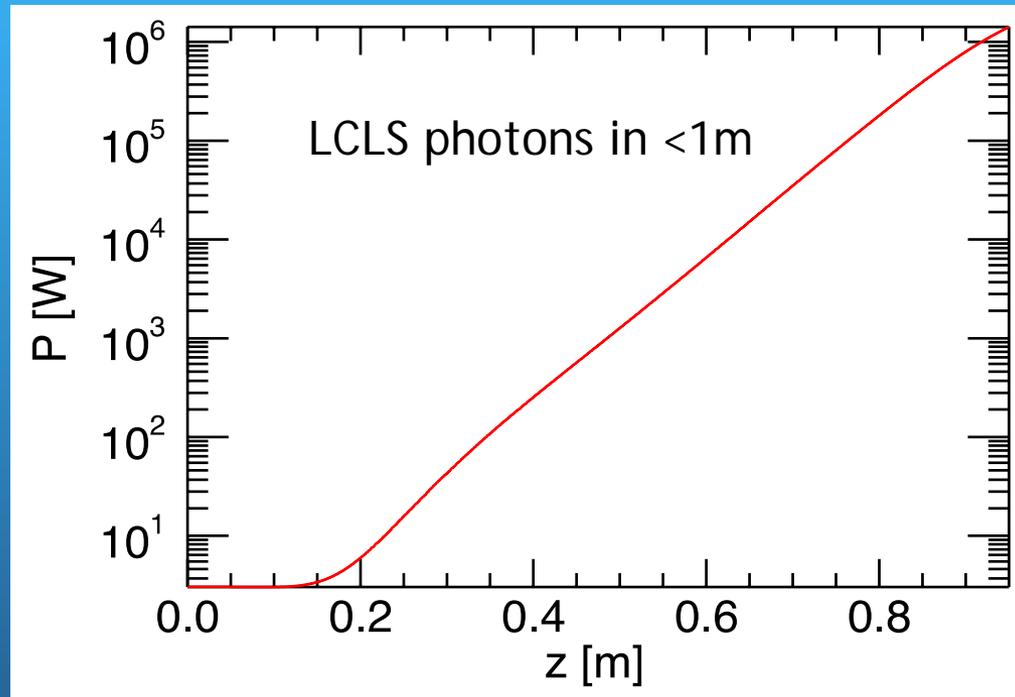
- Manipulating sub-um beams: ultra-short focal length optics



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

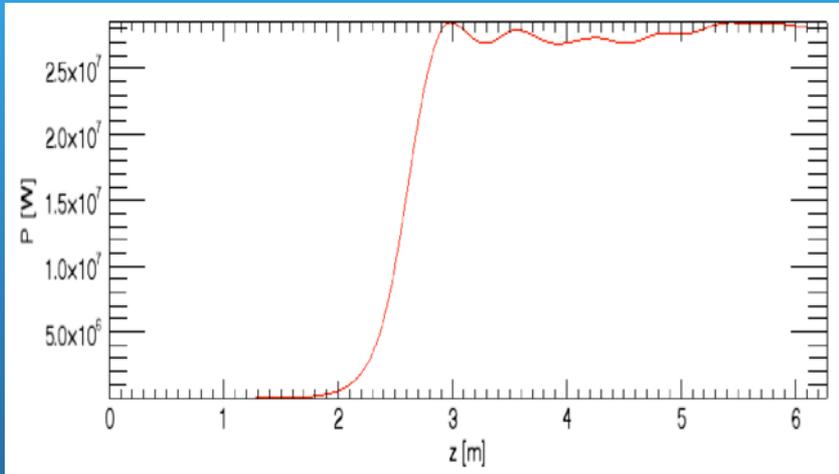
- Measure sub-um beam sizes? Coherent imaging (borrowed from XFEL!)

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 μm 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