Advanced Undulator Concepts for Future Free-electron Lasers

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CERN Accelerator School
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Historic context: from particle physics to light sources, ***instruments*** open paths

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

Galileo Galilei with the Doge of Venice

Or we to see the very small can utilize a *microscope* (generalized!)

With *accelerators*, microscope sees infinistesimal distances <10^{-18} m. Exceed Hooke by factor of trillion…

$\lambda \sim hc/U$ ***U* = quantum energy**

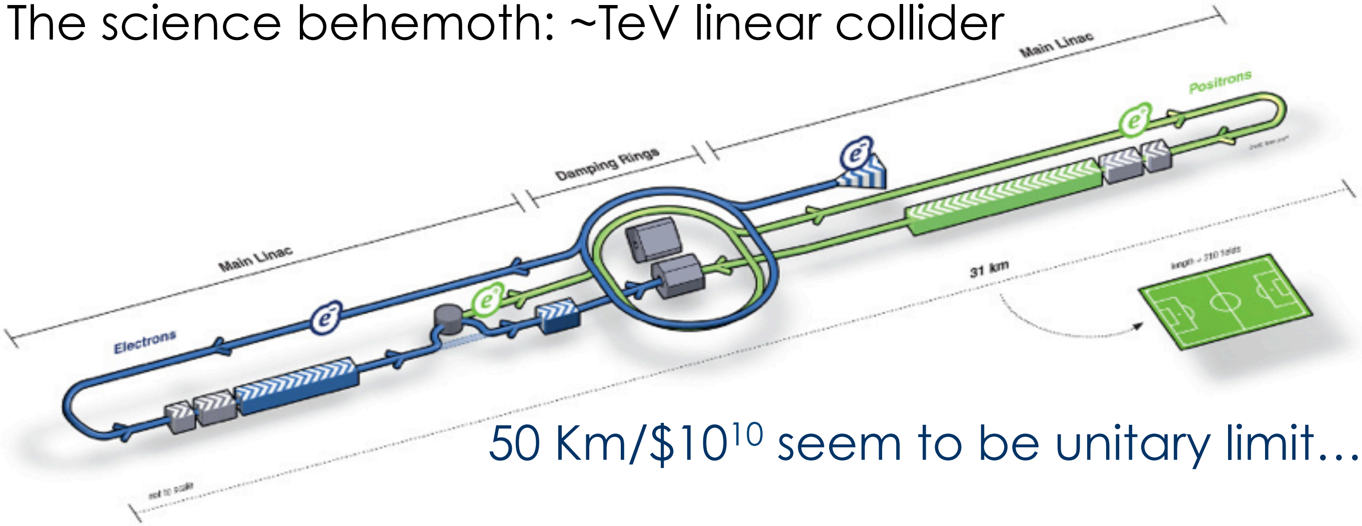
Accelerators are microscopes with up to TeV energy

Accelerator energy, size limits

- *Fatal effect in circular accelerators: <u>synchrotron radiation</u> power loss*
    - Future e+e- colliders foreseen *linear* (ILC)
    - *Large R* circular machines (e.g. FCC)
- Scaling in size/cost prohibitive
    - Acceleration < 35 MeV/m (SC)
- ***Big $cience should shrink to live***

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

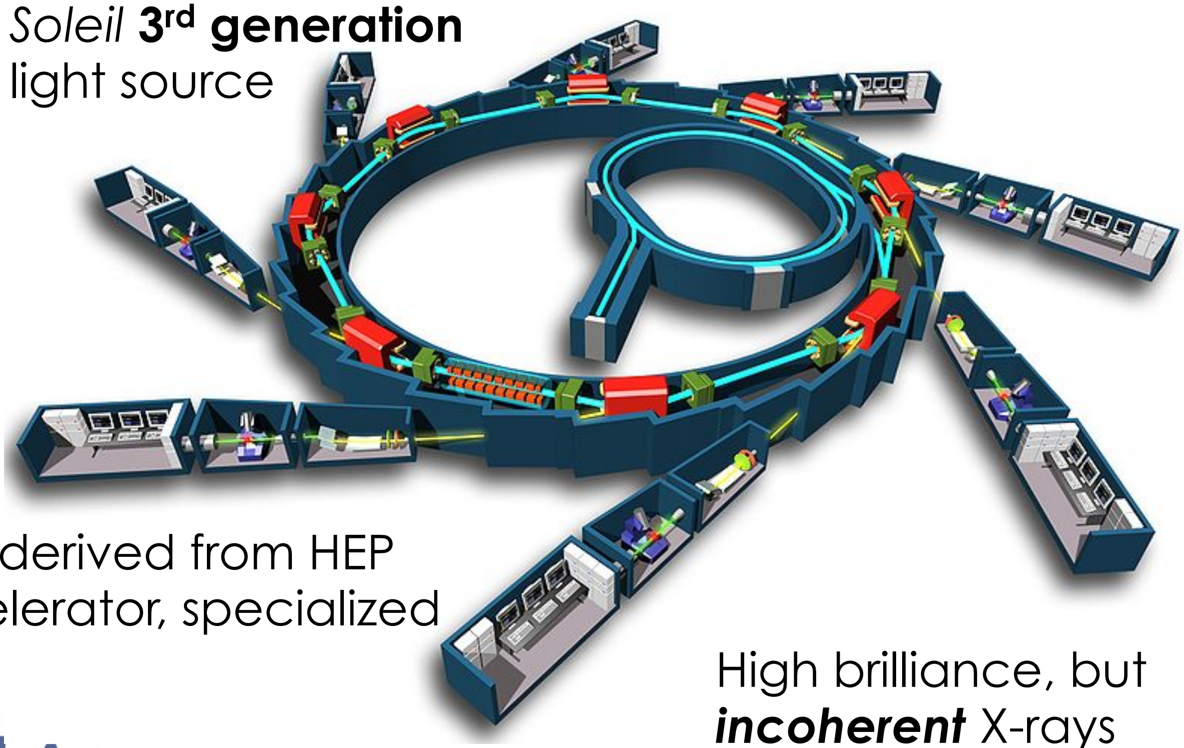
The science behemoth: ~TeV linear collider



50 Km/$$10^{10}$ seem to be unitary limit…

The **light source**: from particle physics “parasite” to essential tool

- Accelerators used as ***synchrotron light sources*** for >40 years
- HEP vice (1st generation) becomes *imaging* virtue. Dozens of *X-ray* facilities worldwide, many-E9€’s invested
- Workhorse of biology, materials, nanoscience



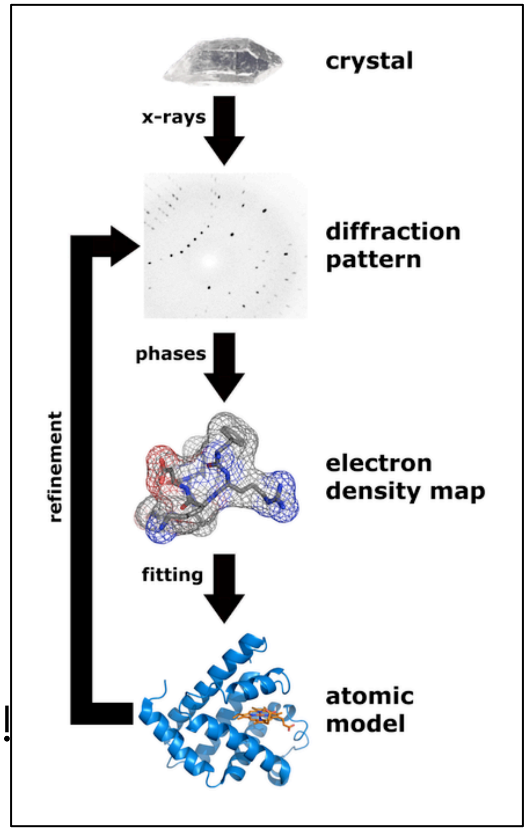
Soleil **3rd generation** light source

Ring derived from HEP accelerator, specialized

High brilliance, but ***incoherent*** X-rays

f

c!

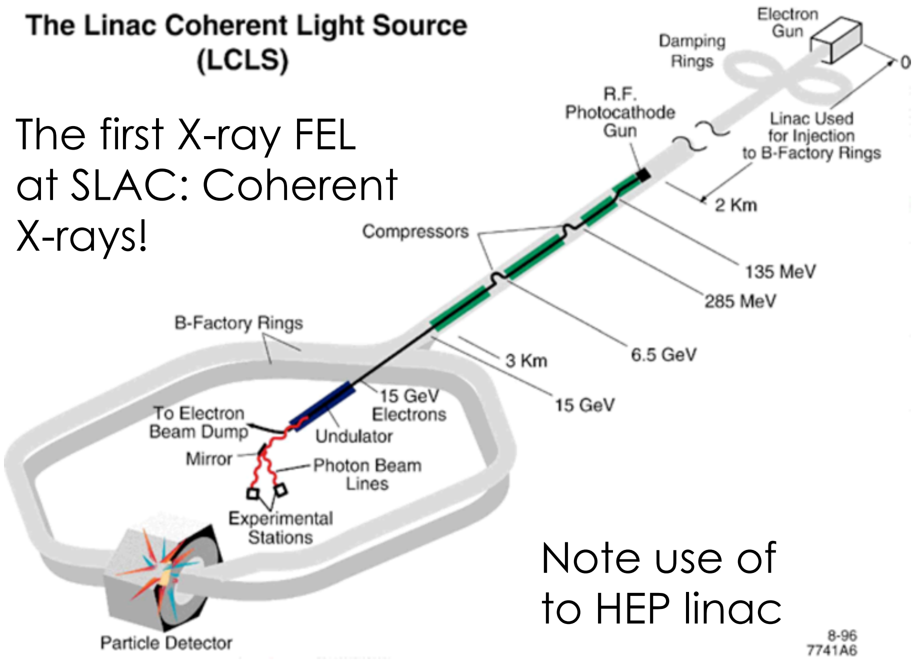


Example: X-ray protein crystallography

The 4^{th} **generation** light source: the **X-ray Free-Electron Laser**

- Also large linear accelerator (km, E=15 GeV)
- Now: coherence, *brightness,* and *fs resolution*

SLAC <2000: Dedicated to HEP



The first X-ray FEL at SLAC: Coherent X-rays!

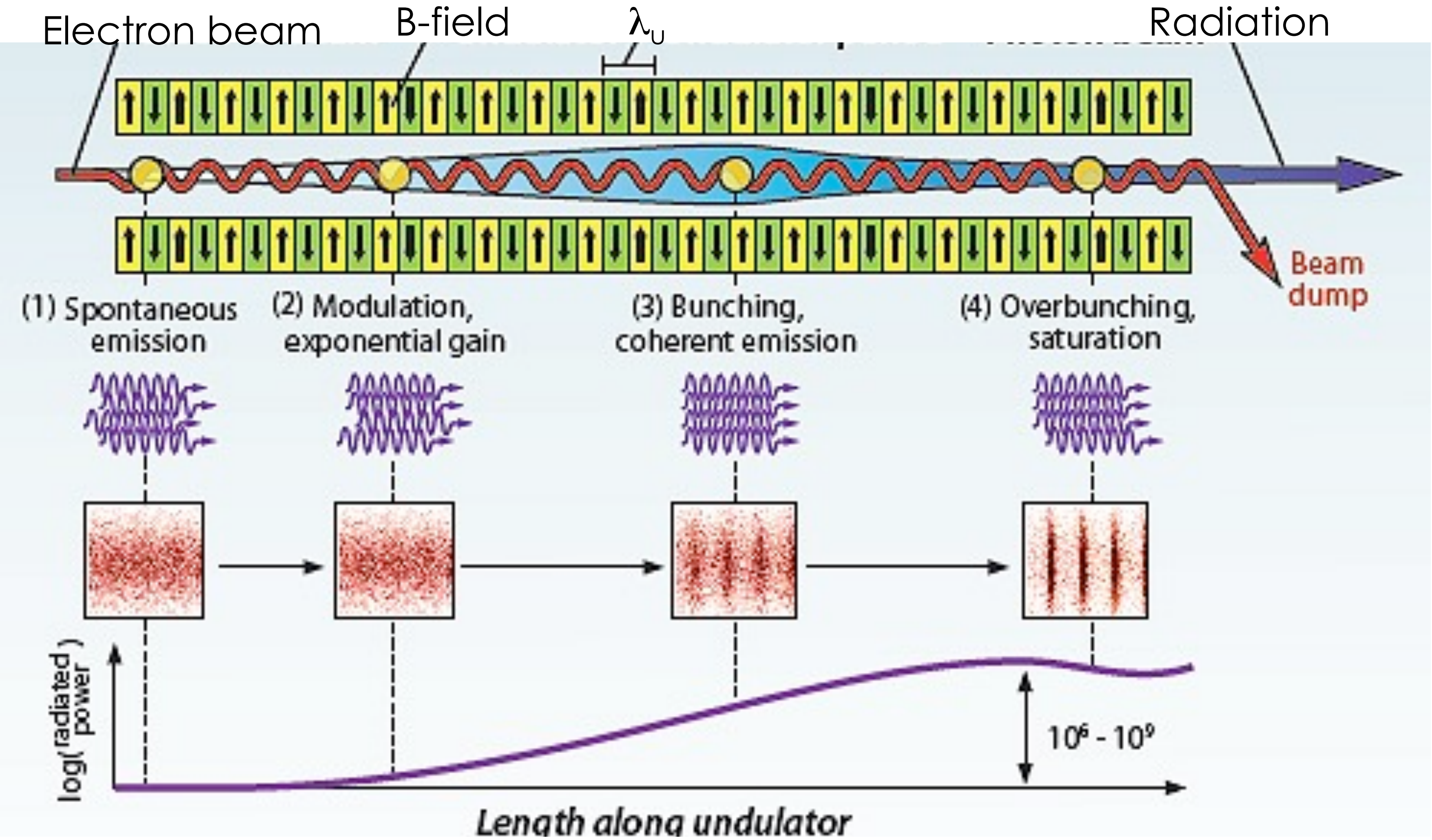
Note use of to HEP linac

SLAC >2010: Dedicated to FEL

Light sources — before: HEP spin-off, now big science (>$1B).

XFEL Provides much motivation for accelerator research

Inside the X-ray FEL



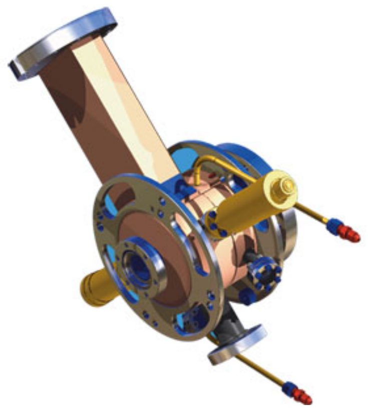
Undulator period ~ few cm, through 3-wave (B_U,E_r,I) instability gives Doppler shifted **coherent** light, **hard X-rays and beyond**

Exponential gain length L_g Approx. 20L_g to saturation

Essential ingredient of FEL: high brightness electron beam

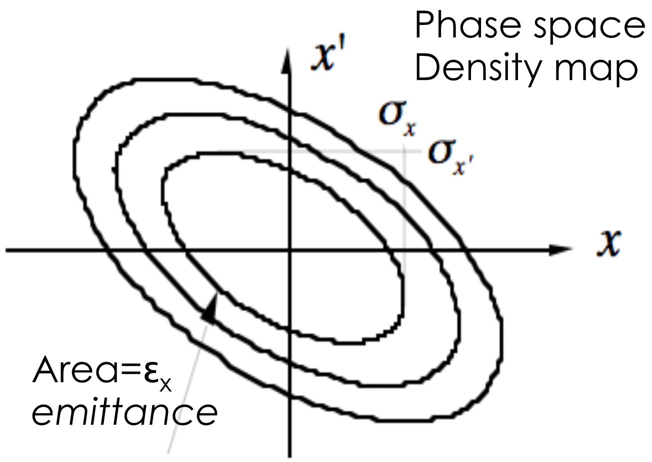
- High phase space density (**cold, focusable, intense**)
- Measure: **beam brightness**

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

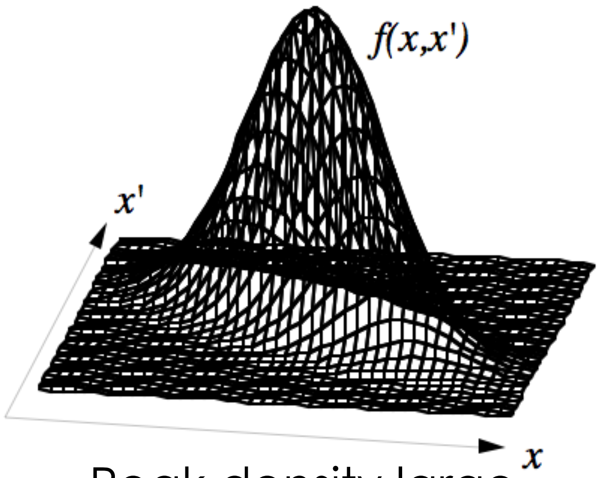


The secret:
RF photoinjector
(UCLA expertise)

- Space-charge (*plasma*) effects strong
in high brightness beams, challenging physics



Area (temperature) small



Peak density large

NB: needs shared with HEP linear collider (very high high B_e)

High brightness *electrons* beget high brightness *photons*

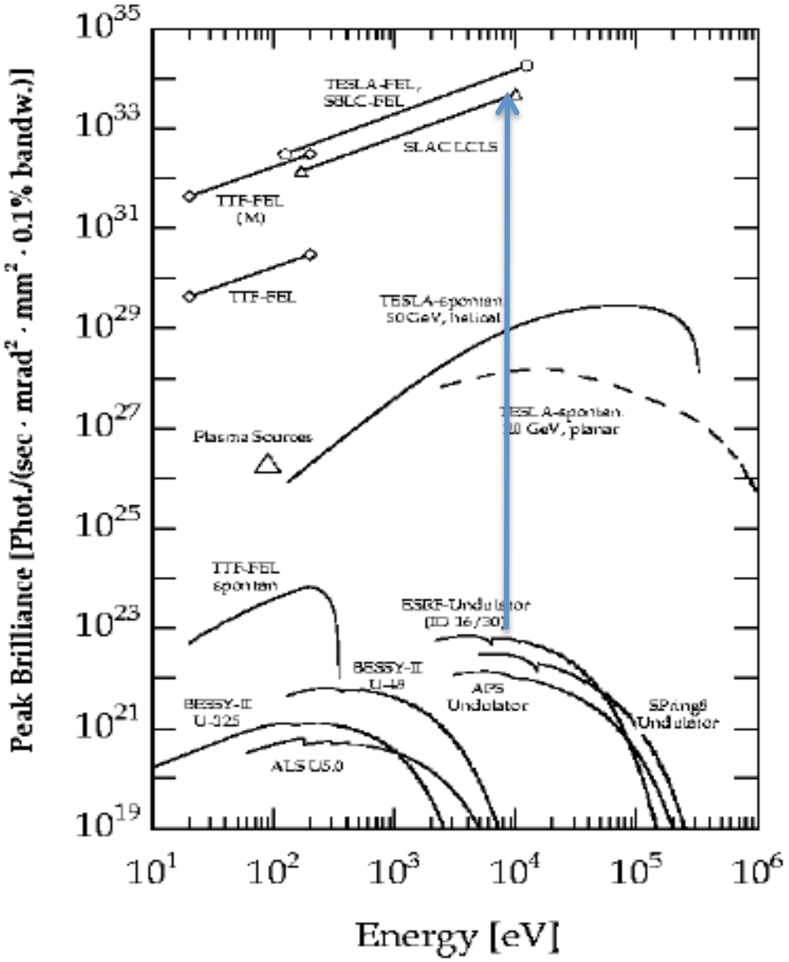
- FEL is cold beam **instability**
- Growth rate from B_e

$$L_{g,1D} = \frac{\lambda_u}{4\pi\sqrt{3}\rho_{1D}} \qquad \rho_{1D} \propto B_e^{1/3}$$

- High *I* (short pulse), small ε_x gives **dense lasing medium**

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

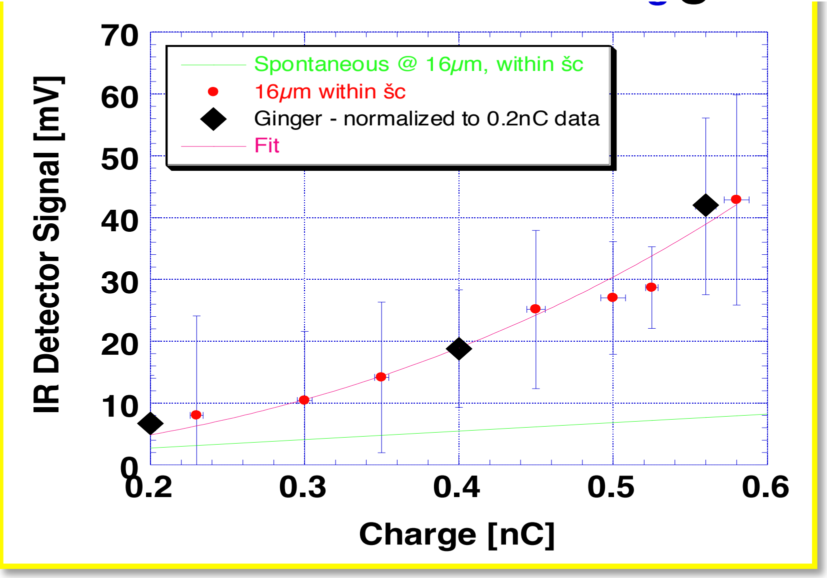
- **λ_u and ρ set length scale**
- Gives +8 *orders of magnitude* photon brightness: ***femtosecond coherent* X-rays,** a revolution in "4D" spatial/temporal imaging



UCLA

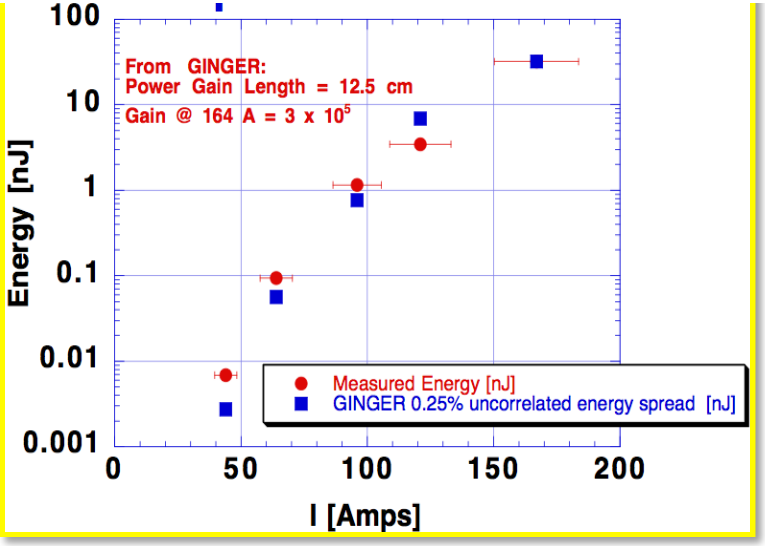
Parochial UCLA perspective: 4 generations of FEL

UCLA 16-mm FEL: 1st SASE gain

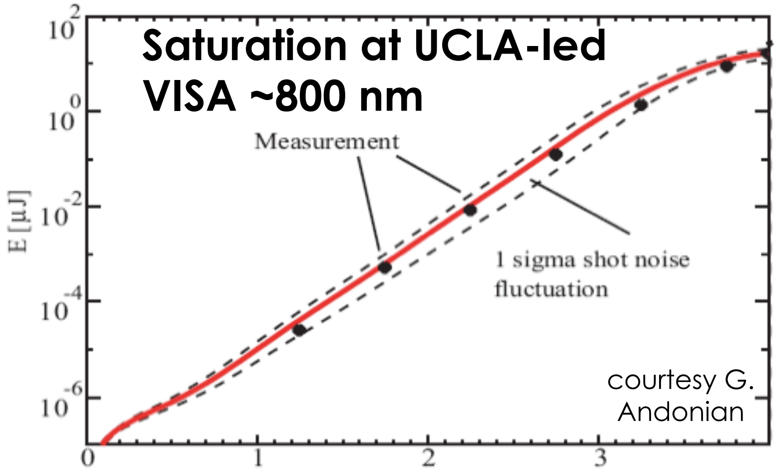


M. Hogan *et al.*, Phys. Rev. Lett., **80**, 289–292 (1998).

LANL/UCLA *1st high* gain SASE



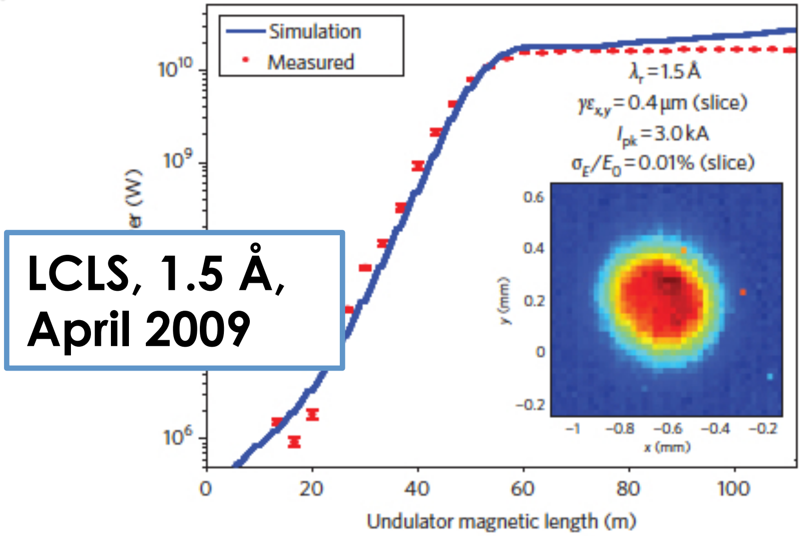
M. Hogan *et al.*, PRL, **81**, 4867–4870 (1998).



Saturation at UCLA-led VISA ~800 nm

courtesy G. Andonian

A. Murokh, et al., *Phys. Rev. E* **67**, 066501 (2003)



LCLS, 1.5 Å, April 2009

XFELs a burgeoning field: what is wrong?

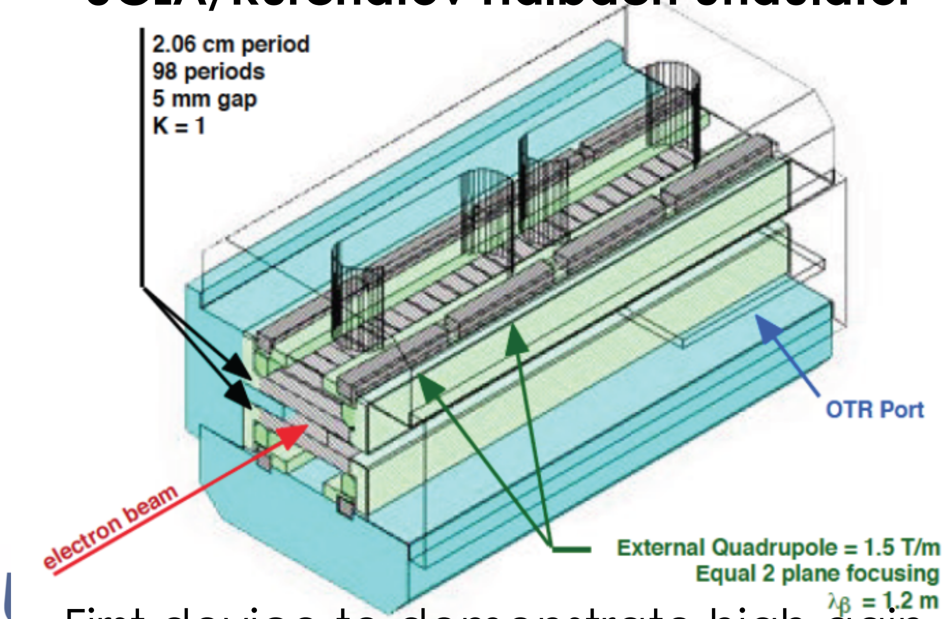
- **Existing facilities are large/expensive**
  - High-cost ➔ limited access ➔ risk to science
    - Pressure to publish in every experiment
    - Beam time precious; hard to *verify* experiments by other teams
  - Result: **Pace of science is slowed, quality hindered**

Solution: *5th Generation Light Source*:
Re-invent XFEL to fit in campus laboratory. How?

Begin with the undulator…

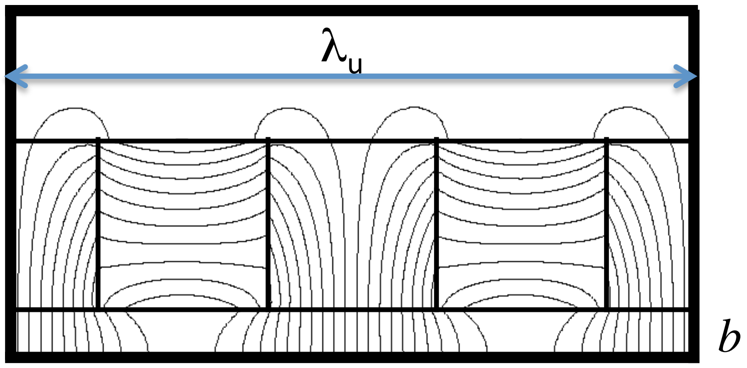
- Present undulators are typically λ_U>2 cm, Halbach or hybrid devices
- Field limits from magnetic material
- Gap (and thus λ_U) set by fabrication, wakefields
- Integrate focusing (natural focusing weak for E>20 MeV)

UCLA/Kurchatov Halbach undulator



First device to demonstrate high gain

$$\vec{B}(y=0)=\frac{8\mu_0 M}{\sqrt{2\pi}}\left(1-\exp\left(-\frac{\pi}{2}\right)\right)\exp(-k_u b)\hat{y}$$



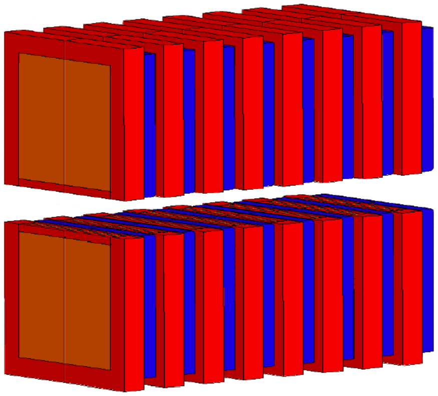
Halbach pure PM geometry and flux lines

Ultra-compact FEL based on new undulators: the recipe

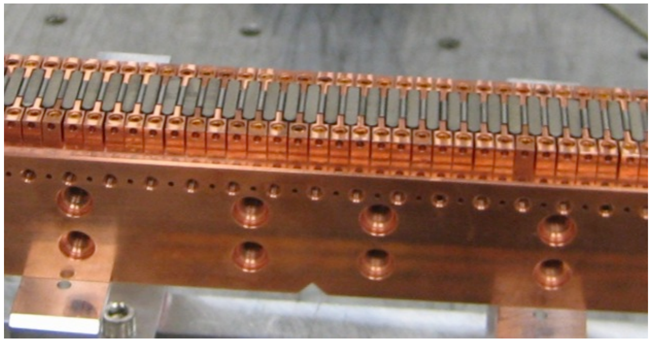
- **High brightness beam (HBB)**
  - low charge (pC), ultrashort pulses
  - Ultralow emittance, enables use of…

J.B. Rosenzweig, et al., *Nucl. Instruments Methods A,* 593, 39 (2008)

- **High field, short λ undulator**
  - **With HBB, large *ρ*, short L_g**
- **Lower e- energy needed** to reach short wavelength
  - ***Much smaller accelerator, undulator***
- ***Might also reinvent accelerator…***
  - **Another lecture; 5th generation light source based on plasma/laser accel.**



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

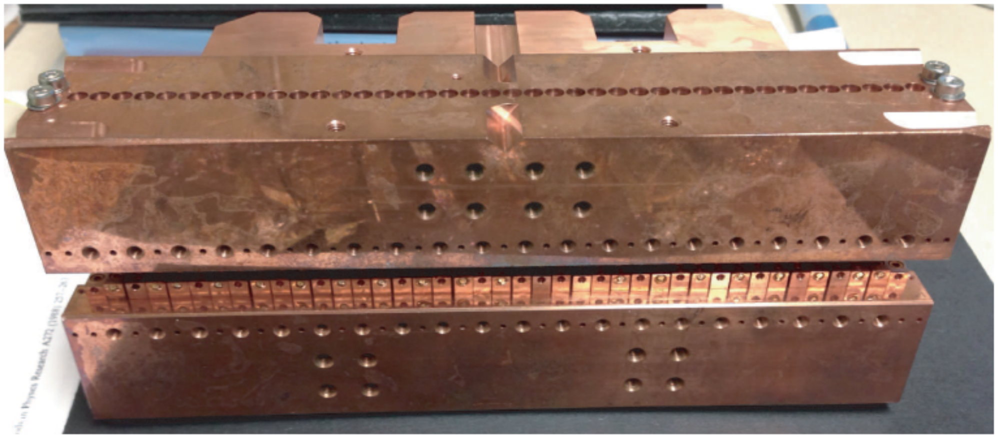


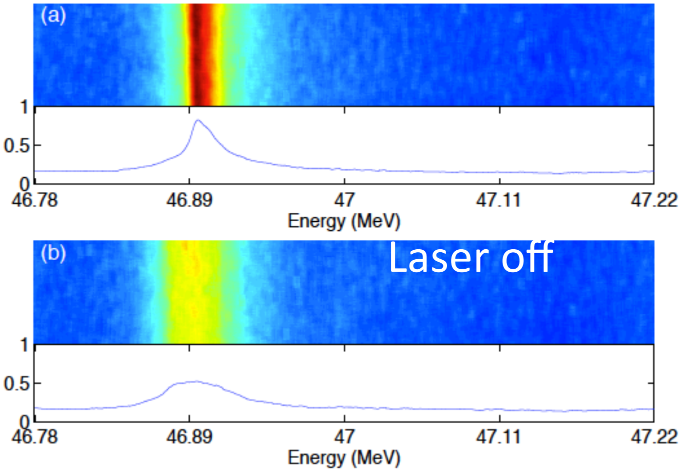
F.H. O'Shea et al, PRSTAB 13, 070702 (2010)

HZB/UCLA/MPQ Cryo-undulator

- Cryogenic, Pr-based hybrid undulator
  - Innovation in magnetic material, operating *T*
- High field (2.2 T), short λ_U (9 mm)
  - Next generation (Dysprosium)is 7 mm period.

Factor of 3 in λ_U, still have *K*~2



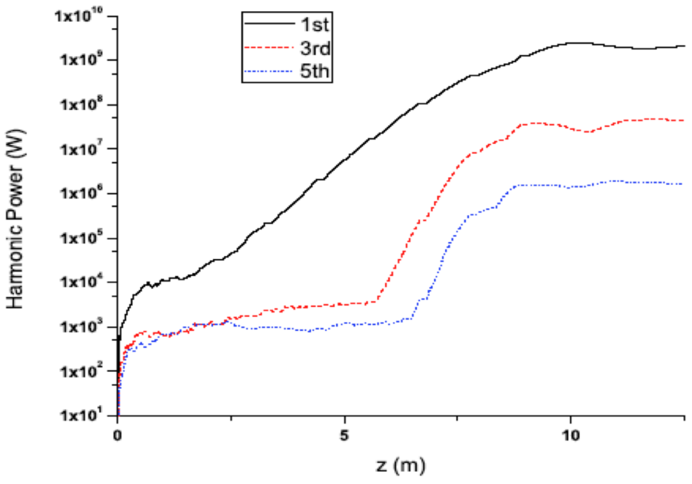


Use of cryo-undulator for IFEL energy modulation at 800 nm

F. H. O'Shea, et al., J. Phys. B: At. Mol. Opt. Phys. 47 234006 (2014)

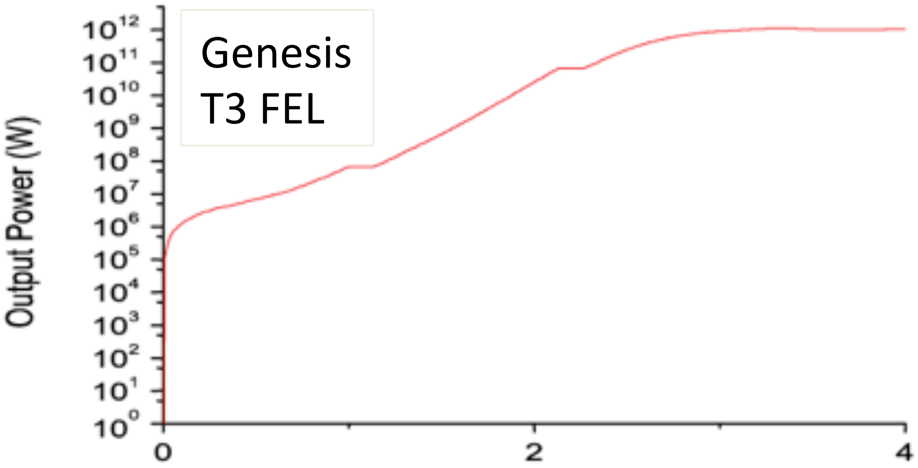
Physics possibilities with cryo-undulator

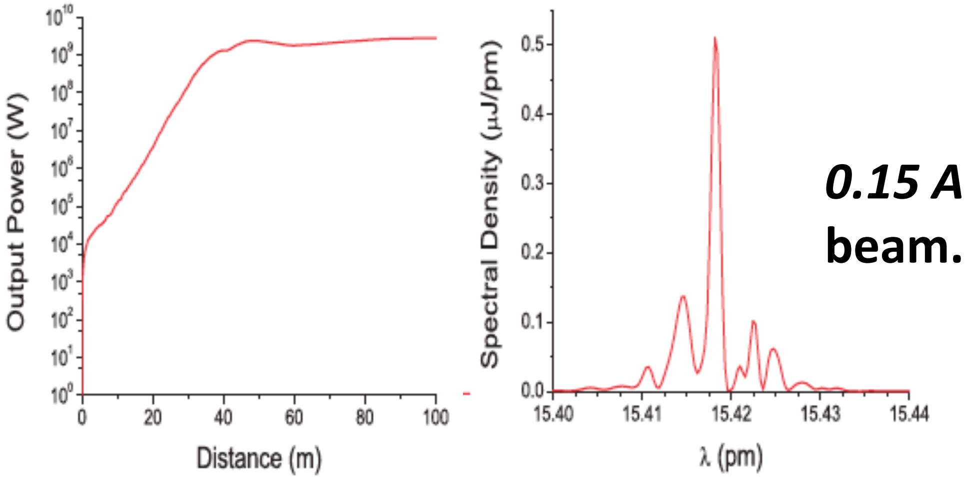
-Always pushing beam brightness!



0.75 nm FEL with 1 pC, ultra-high brightness, <2 fs beam, **2.1 GeV driver**. 5th harmonic yields LCLS-λ photons. Saturation in 10 m.

Original use : table-top terawatt *T*³, few nm FEL with 1.7 GeV, **160 kA** beam from laser-plasma accelerator. FEL saturates 10x sooner than present state-of-art.



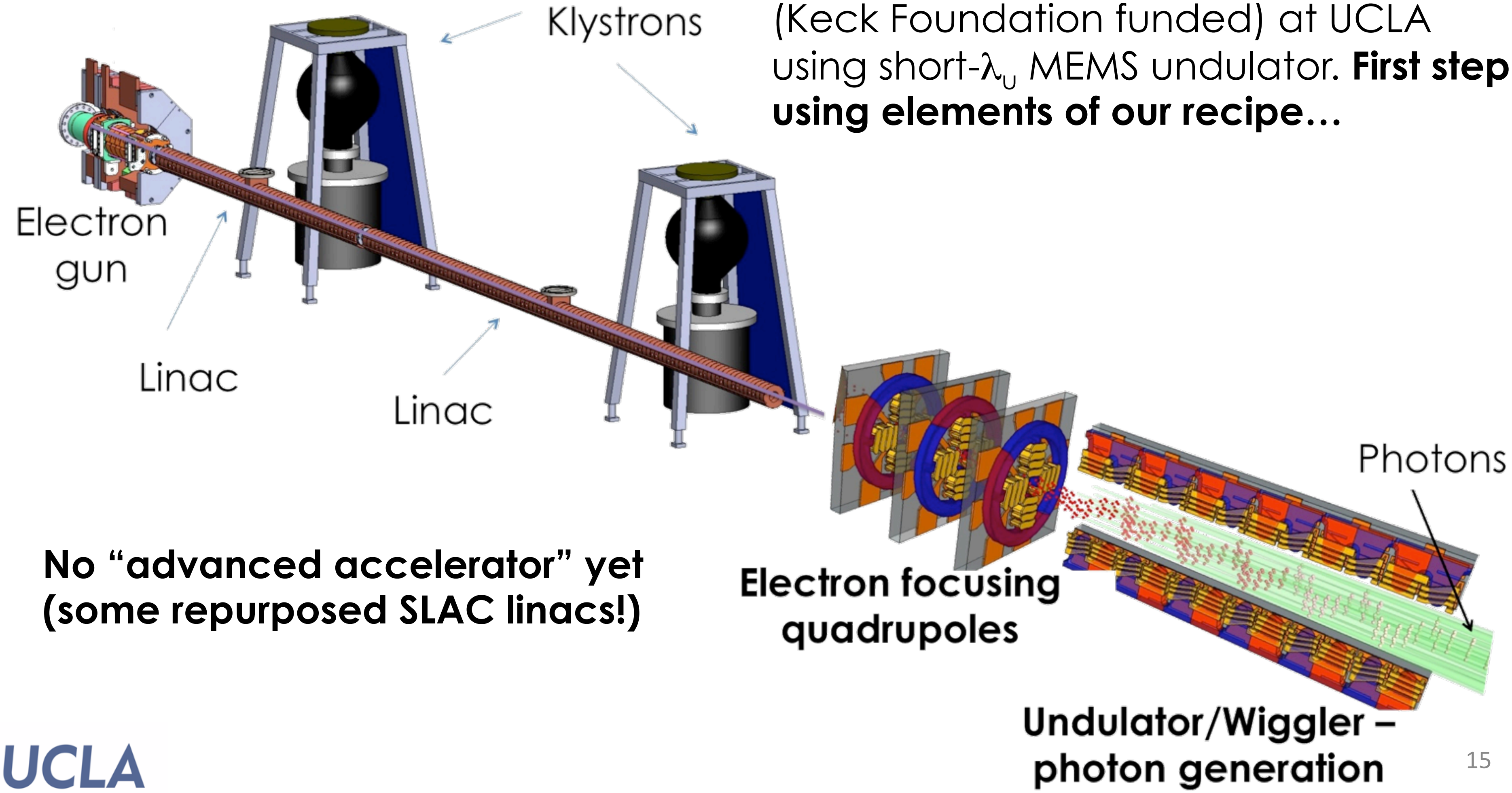


***0.15 Angstrom* SASE FEL with LCLS beam. Saturation in 40 m**

Cryo-undulator design and physics use:
F.H. O'Shea et al, *PRSTAB* 13, 070702 (2010)

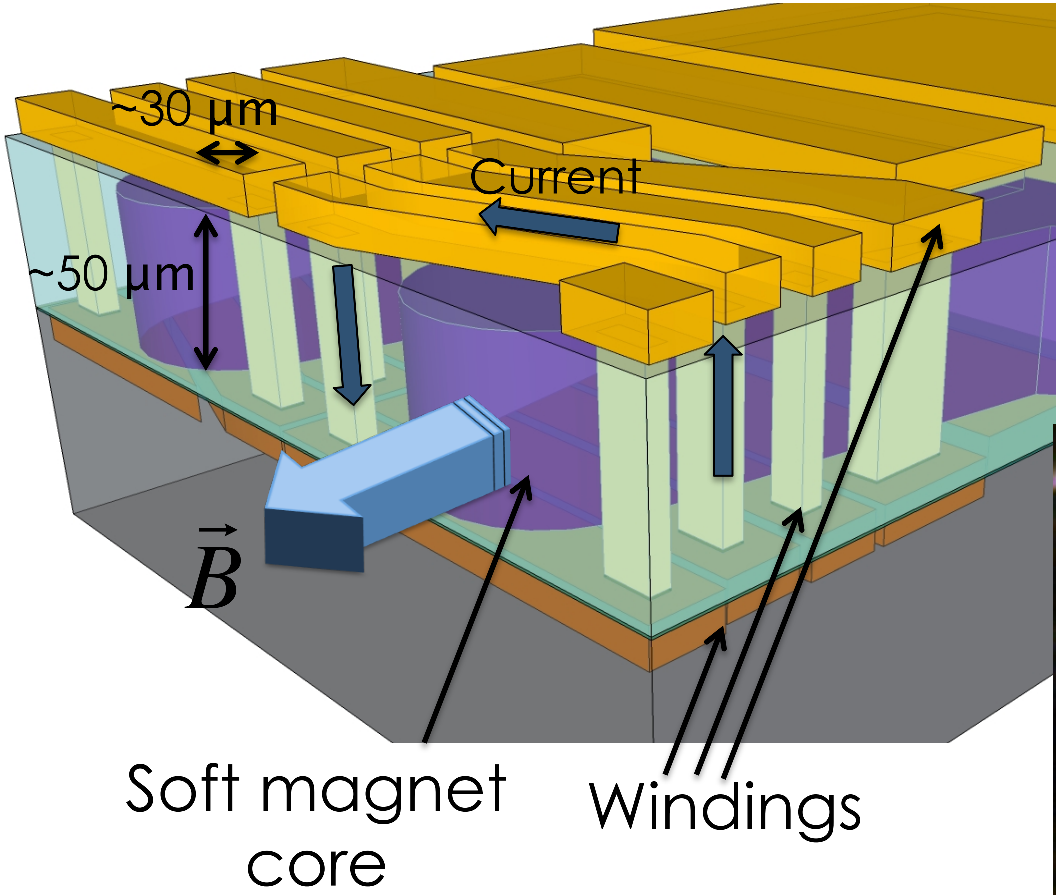
Generation 4.1: state-of-art injector and ultra-short period undulator

Goal: Enable compact soft-X-ray FEL (Keck Foundation funded) at UCLA using short-λ_u MEMS undulator. **First step using elements of our recipe…**

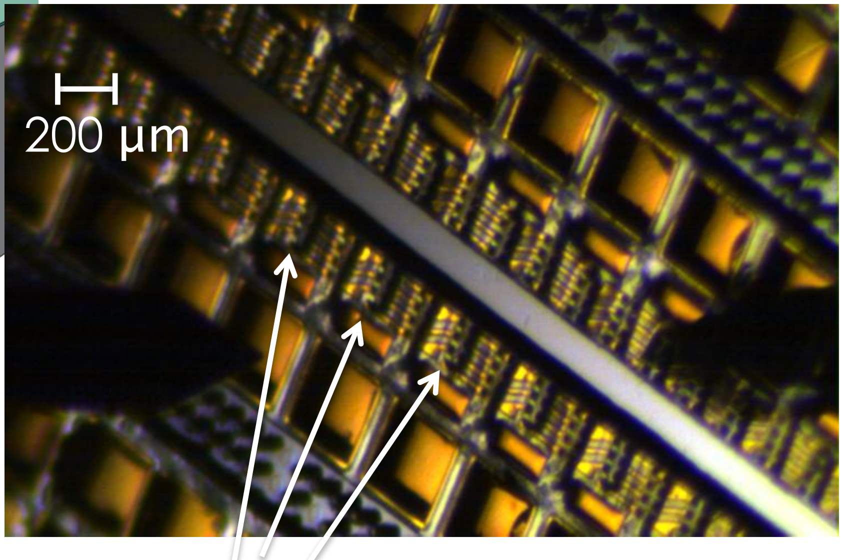


No “advanced accelerator” yet (some repurposed SLAC linacs!)

New enabling technology: MEMS electromagnetic undulator



MEMS=
Micro-
Electro-
Mechanical
Systems



Batch-fabricated electromagnets
First generation

Very short period **possible:**
20-800 microns

Inclusion of focusing still critical…

Micromachined *undulator*

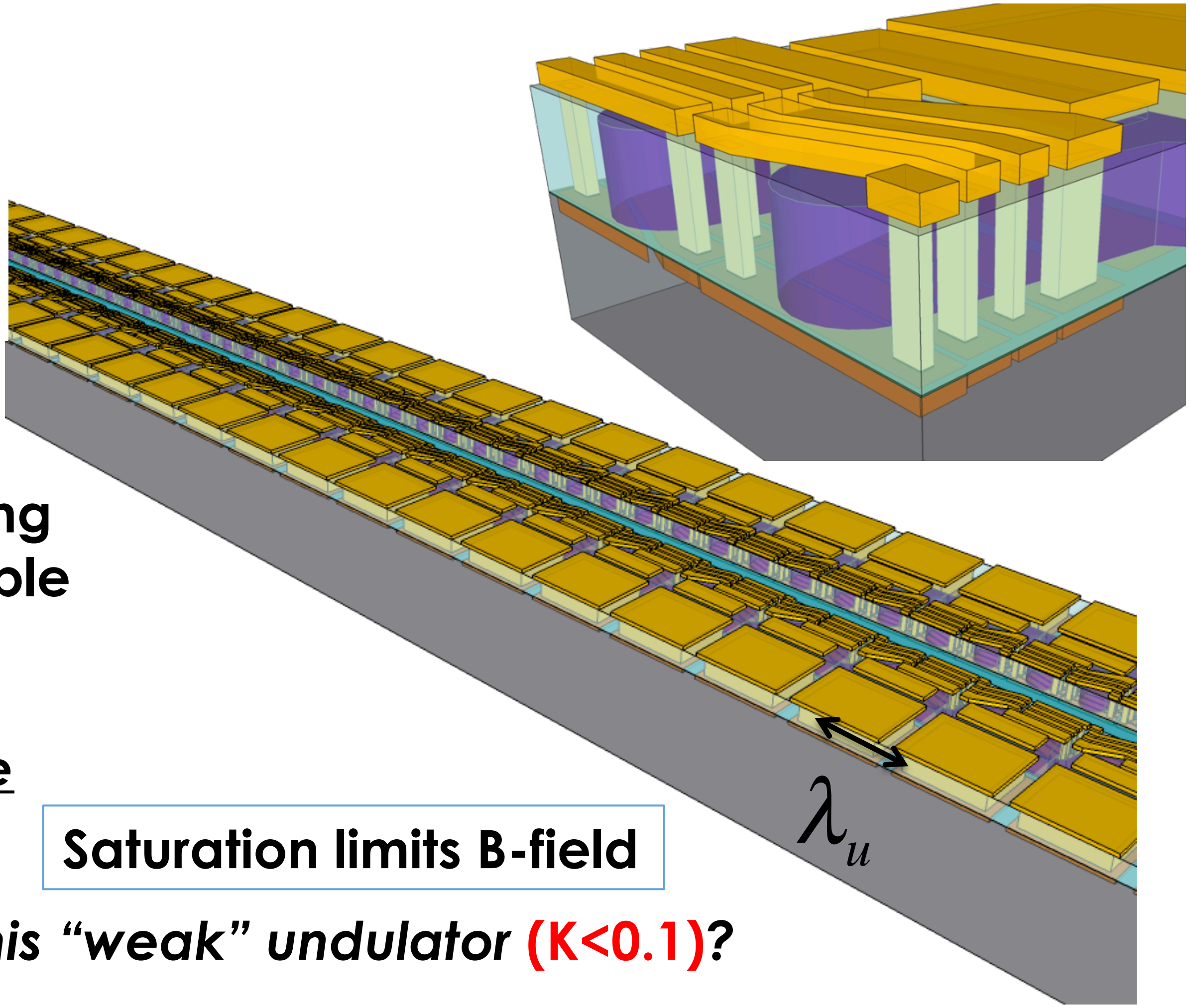
- Both advantages and challenges with new technology

$$\lambda_r = \frac{\boxed{\lambda_u}(1+K^2/2)}{2\gamma^2}$$

λ scaling favorable

$$K = \frac{qB_0\boxed{\lambda_u}}{2\sqrt{2}\pi m_0 c}$$

Scaling a *challenge*



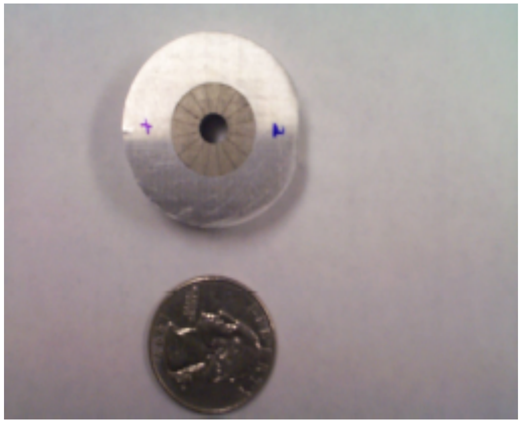
Saturation limits B-field

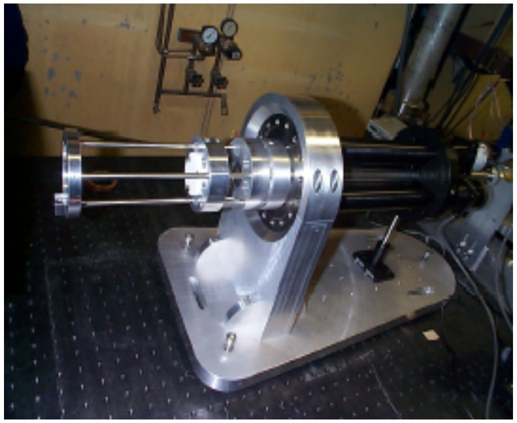
***How do we use this “weak” undulator* (K<0.1)?**

Should provide higher gain medium: *focus beam harder*

(Aside: later we can abandon magnetic materials…)

How to achieve focusing?





- Until now, permanent magnet focusing quads
- Very short focal length (1 cm at 60 MeV)
- Field gradient 600 T/m
  - Strongest ever in use
- Tunable by longitudinal motion
- Physics and engineering challenge; not easy to integrate with FEL undulator
  - Used at UCLA for inverse Compton scattering, PWFA final foci
- **New solution: MEMS!**

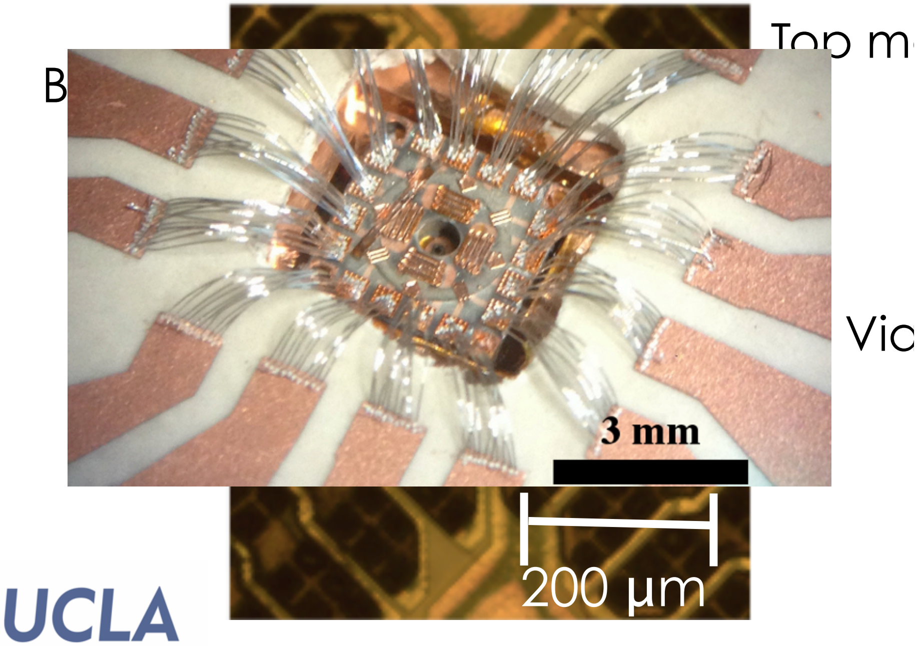
J. K. Lim, et al., *Phys. Rev. ST Accel. Beams* **8**, 072401 (2005)

MEMS electromagnetic *quadrupoles*

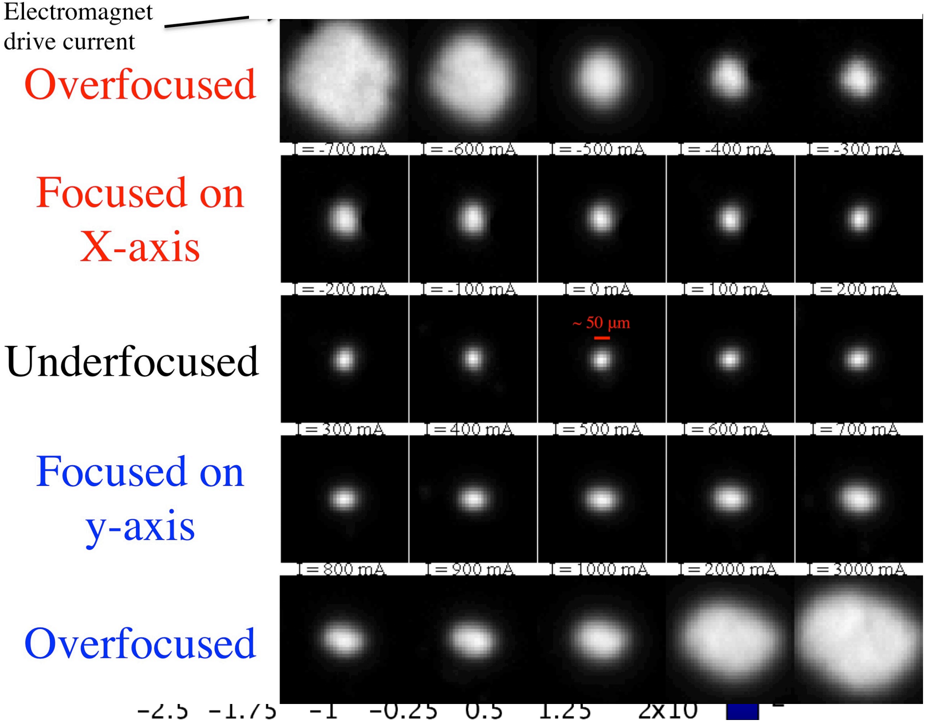
J. Harrison, Y. Hwang, O. Paydar, J. Wu, E. Threlkeld, J. Rosenzweig, and R. Candler,
Phys. Rev. ST Accel. Beams **18**, 023501

	Currently Available	Future
Technology	Permanent magnet quadrupole	Machined electromagnets
∇B	560 T/m	**>3,000 T/m**
Inner diameter	5 mm	200 µm
Tuning	Axial translation of magnets	Electromagnet

Top View

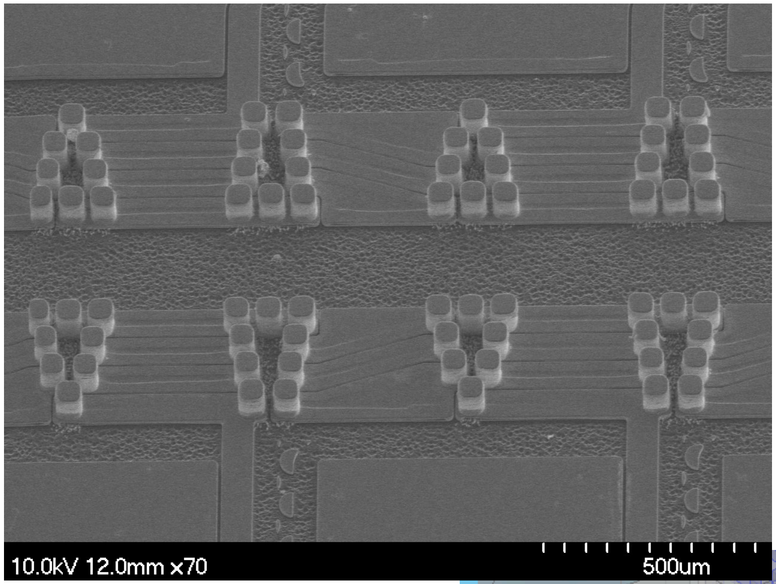


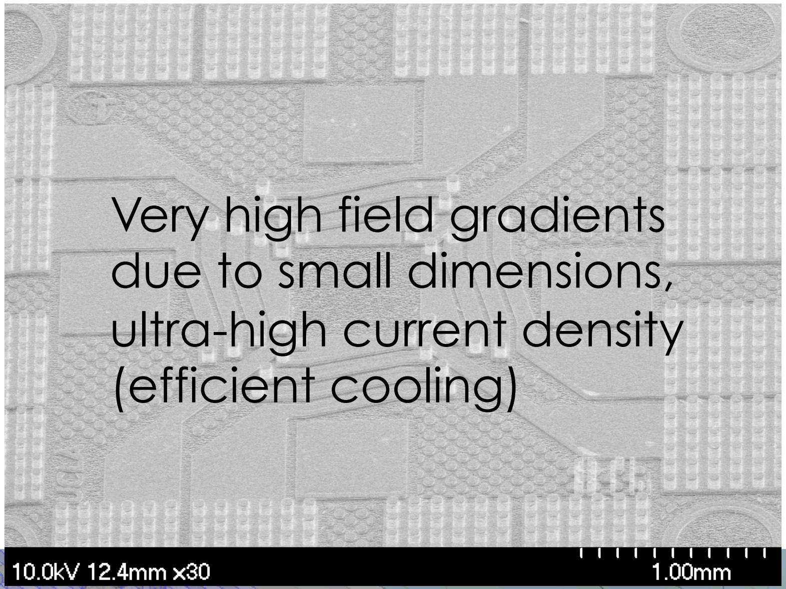
POP beams measurements



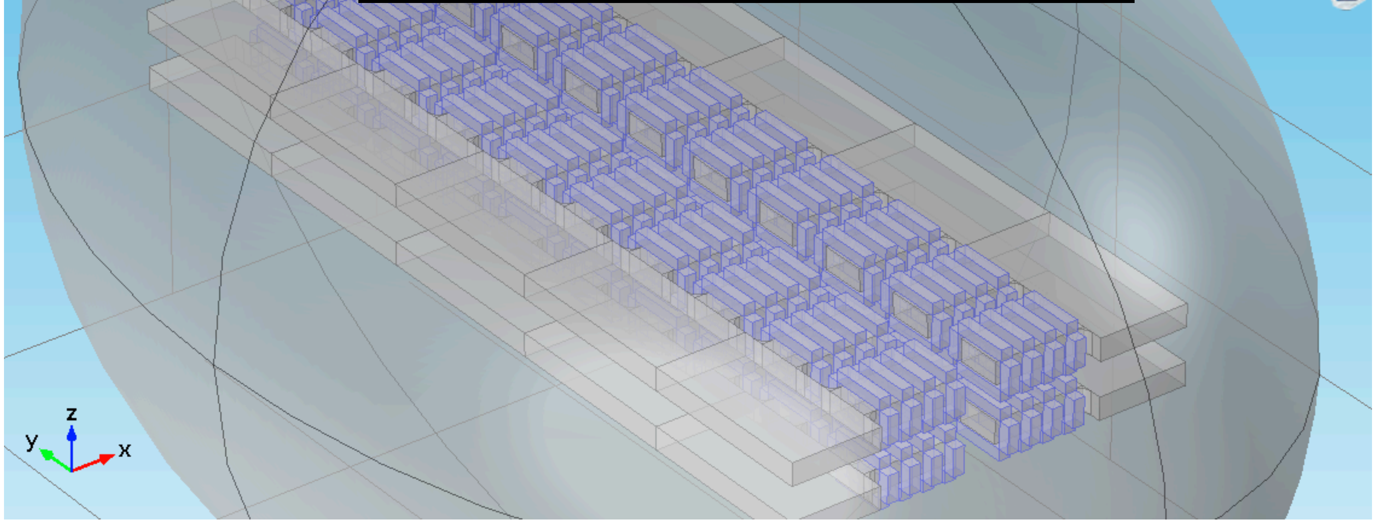
Assembly line of *high current* EM quadrupoles

Fabrication in course at UCLA Nanolab and industrial partner



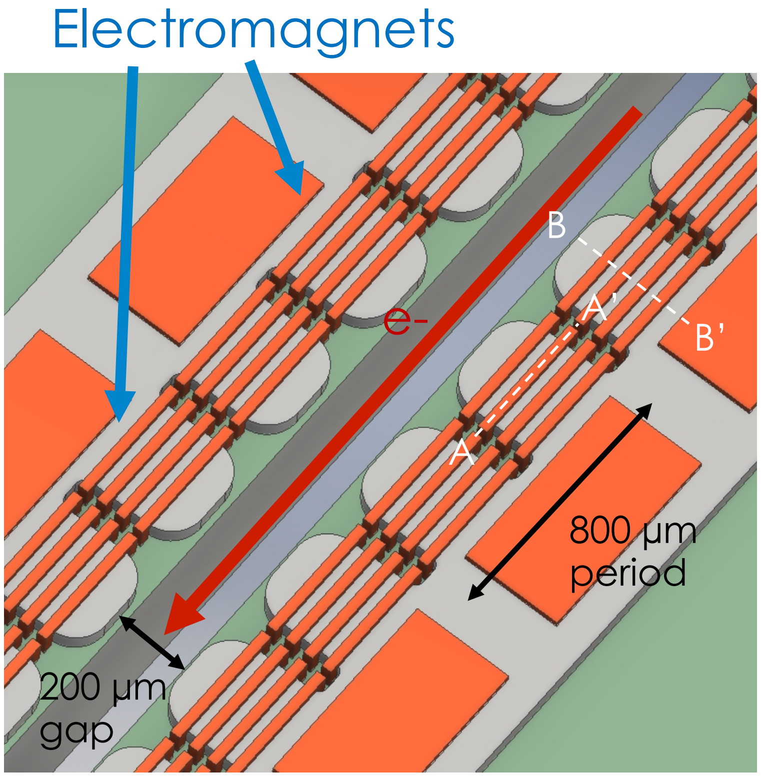


Very high field gradients due to small dimensions, ultra-high current density (efficient cooling)



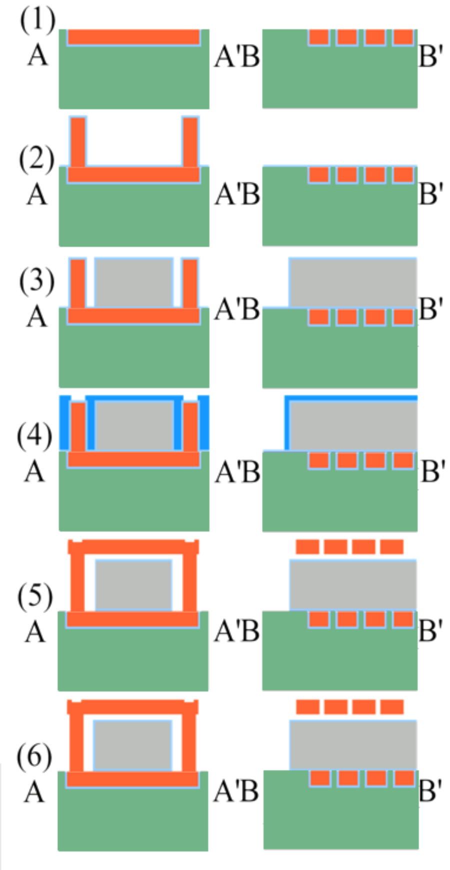
MEMS Undulator Fabrication

Process highlights
- Fully 3D solenoidal electromagnets
- 20μm-thick copper windings for coils
- >50μm-thick Permalloy magnet yoke
- $Ni_{80}Fe_{20}$ with B_{sat} = 1.1 T and μ_r > 8000



Undulator

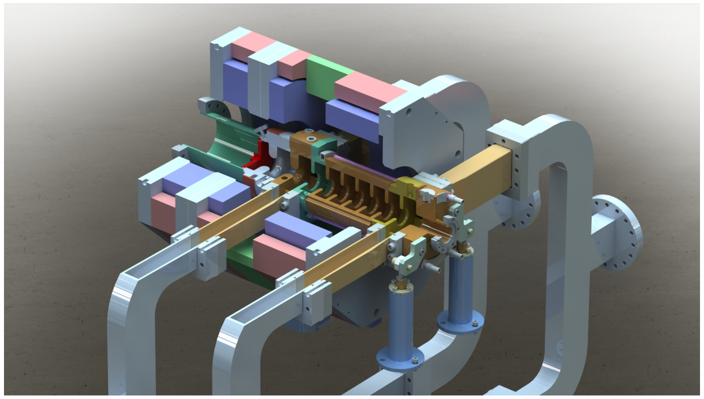
8 cm long section to be:
- Magnet tests at UCLA August 2015
- Beam tests at BNL ATF in Oct. 2016

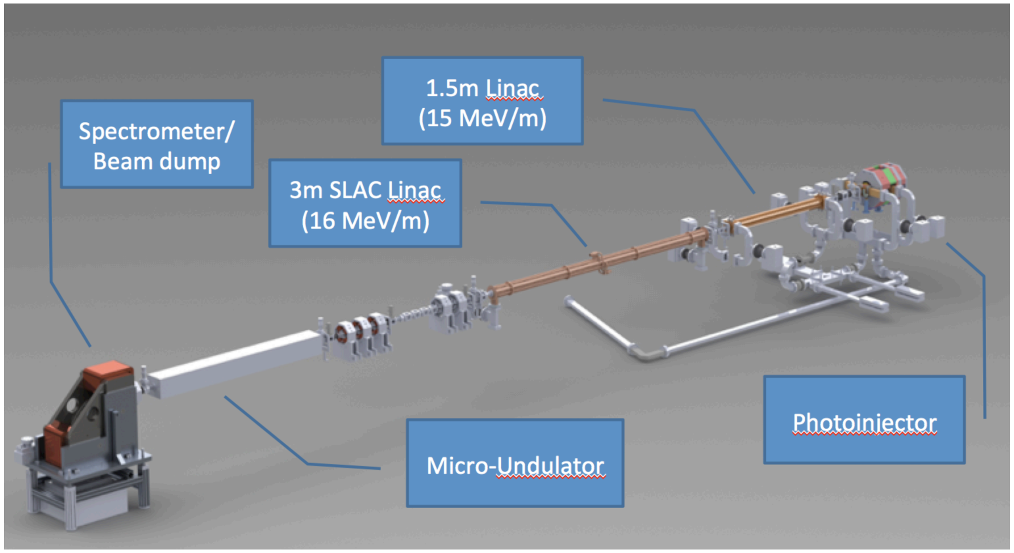


Legend
- Silicon nitride
- Permalloy
- Structural photoresist
- Copper
- Substrate

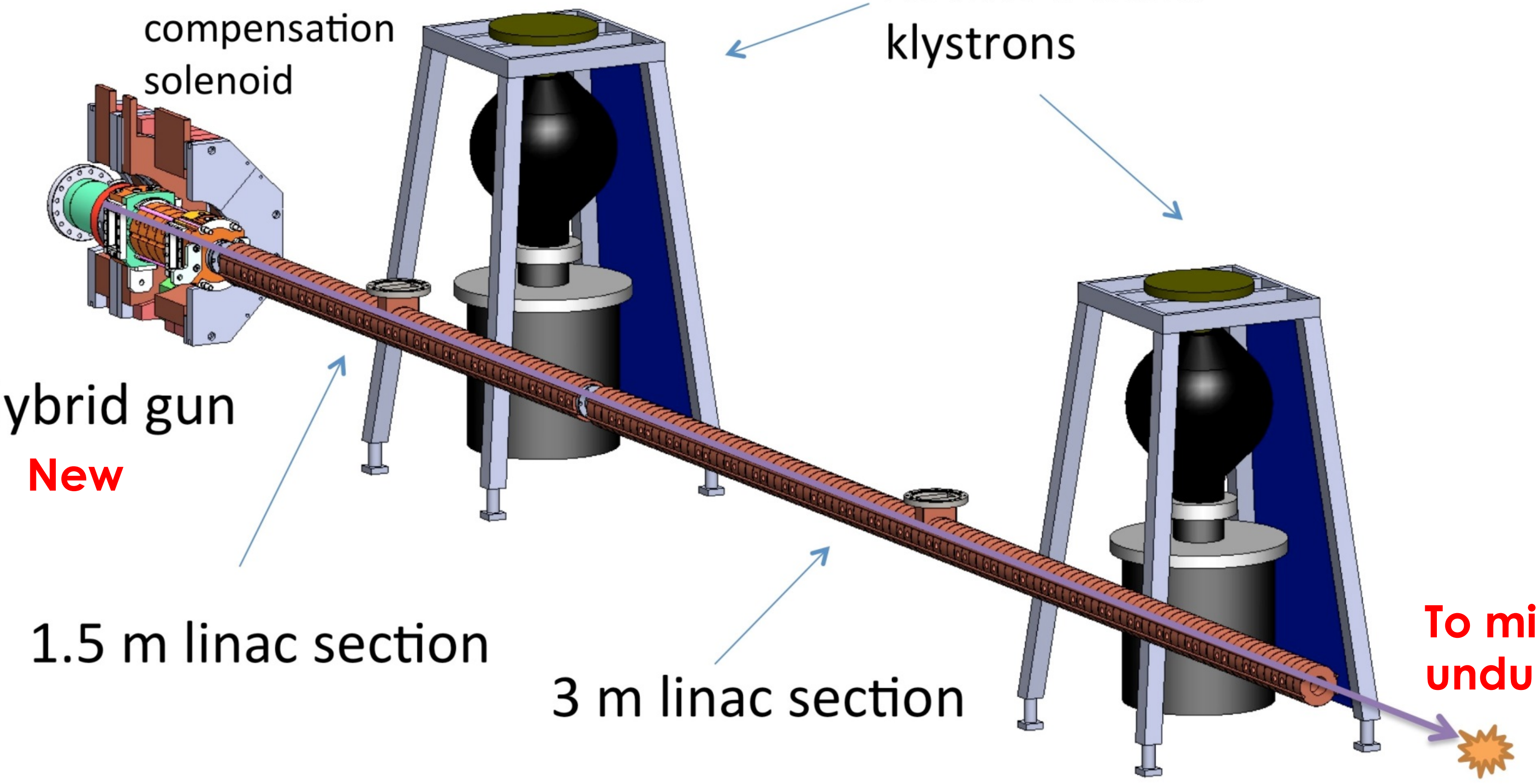
SAMURAI: **S**pontaneous **A**mplified **M**icro**U**ndulator **R**adiation **I**nteractions

- >63 MeV beamline
- “Hybrid” photoinjector
- 2 TW Ti: Sapphire laser
- Mission: compact FEL, other light sources and new accelerators





UCLA Keck-SAMURAI FEL : High brightness electron injector



Emittance compensation solenoid

25 MW S-band klystrons

Hybrid gun

New

1.5 m linac section

3 m linac section

To micro undulator

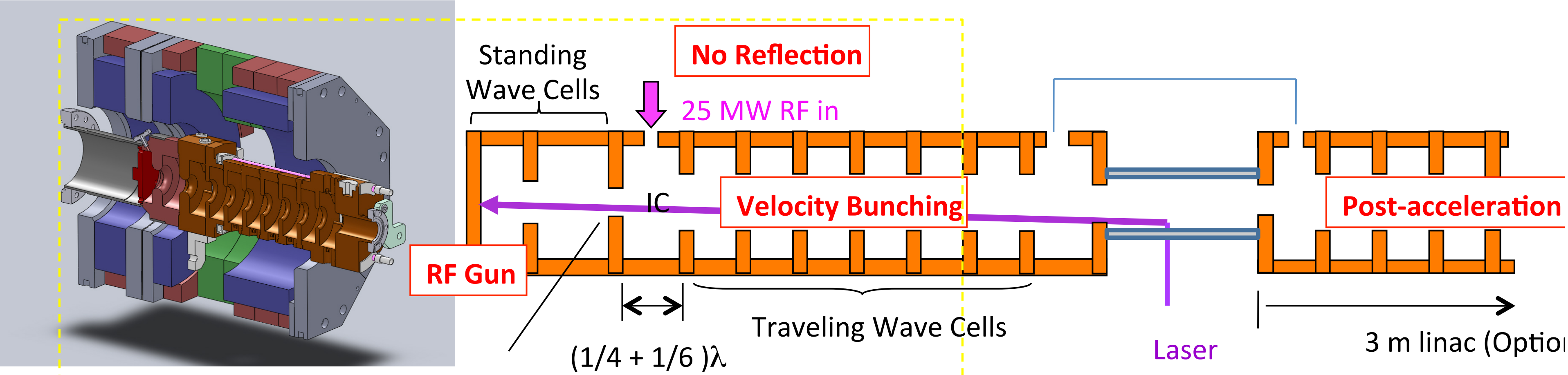
High brightness 63 MeV e-beam

Beam parameters for injection into Keck FEL micro-undulator

Beam energy	63 MeV
Beam charge	*20 pC*
Beam emittance	*0.2 mm-mrad*
Energy spread	*0.1 %*
Pulse length (FWHM)	*70 fs*
Peak current	~300 Amp

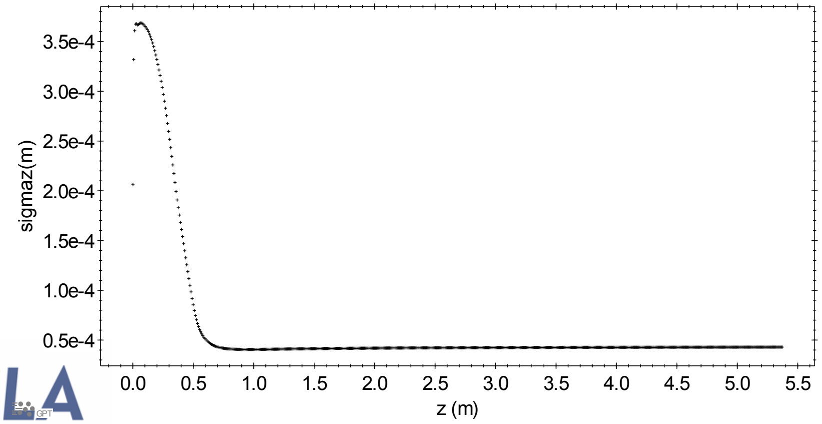
Present state of the art:
<20 A peak current at 0.2 mm-mrad

Compact solution for high brightness beam: Hybrid SW/TW Hybrid Photoinjector

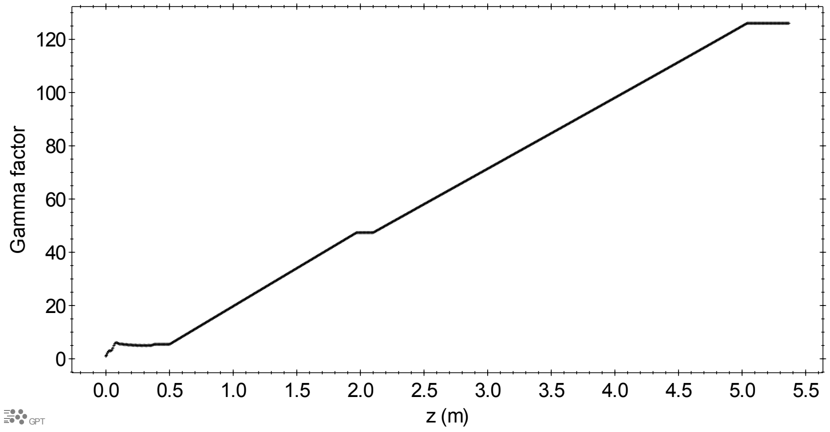


- Compact high brightness beam source integrated with RF gun (low emittance) + *velocity buncher* (high peak current)
- TW post-acceleration for high current, moderate energy beam
- Remove RF reflection from the cavity, simpler waveguide system

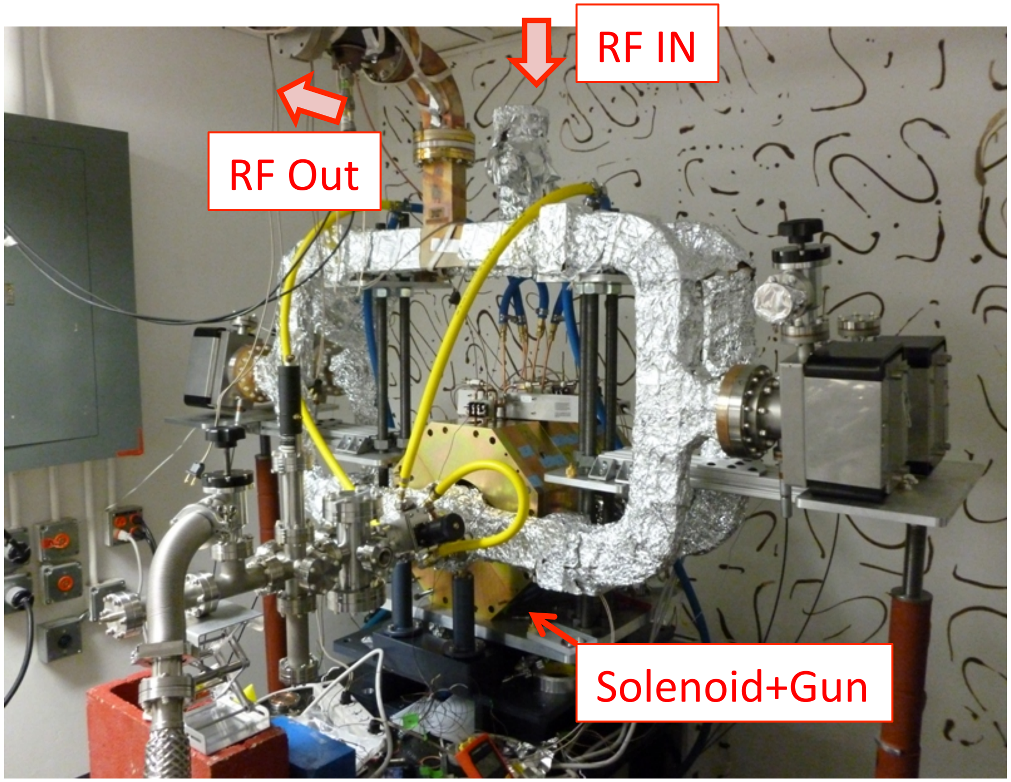
Bunch length



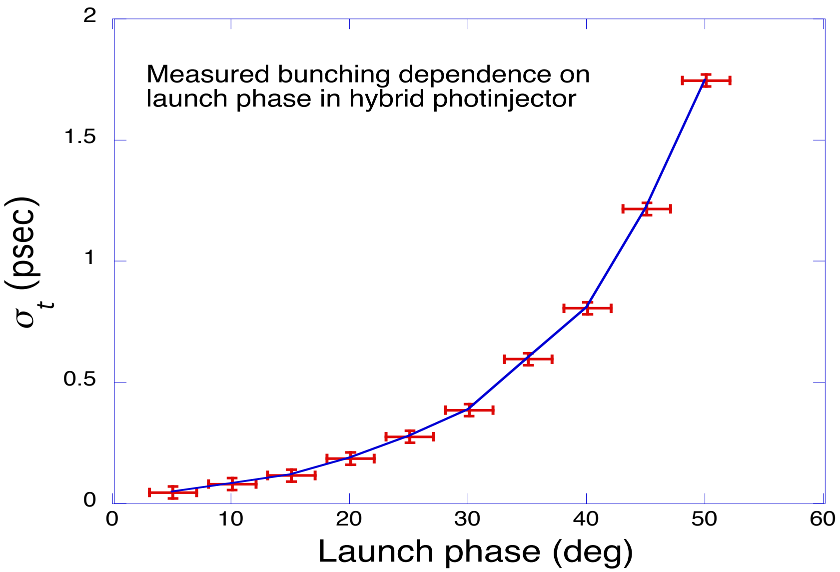
Energy



First beam measurements at UCLA



Tests at Pegasus Lab, UCLA.



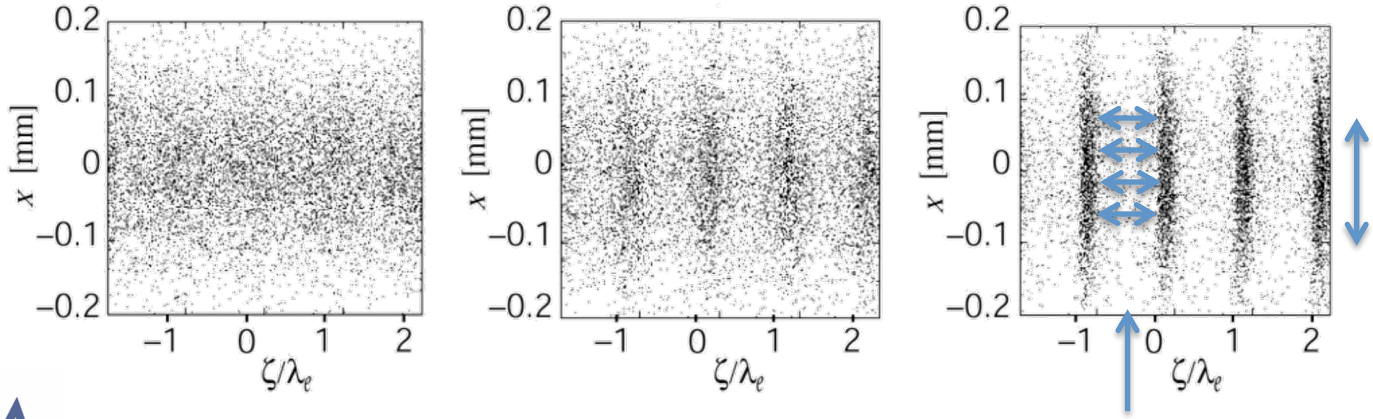
2 ps laser in-> 100 fs beam out

- Measured beam dynamics at low power P_{RF}=11.5 MW
- **Strong velocity bunching observed**
- Validate model, hybrid characteristics
- Moving to KECK SAMURAI Lab

UCLA

Space charge effects in FELs

- With 0.8-mm period undulator, soft X-ray machine is in ~100 MeV range (not few GeV)
- Dense beam gives space charge response: measured by "*plasma skin depth*" $k_p^{-1} \sim \gamma^{3/2}$
- Approaches relevant scale lengths $k_p = \sqrt{4\pi r_e n_b / \gamma^3}$
  - Transverse $k_p^{-1} \sim \beta$, **must focus stronger (microquads)**
  - Longitudinal $k_p^{-1} \sim L_{1D}$, longer L_g (also an advantage!)



Apply more focusing to overcome trans. repulsion

Longitudinal repulsive self forces oppose microbunching

Space charge effects can give *enhanced FEL efficiency*

- Gain length increased

$$L_{g,R} / L_{g,1D} \cong \sqrt{2.6 k_p L_{g,1D}}$$

G. Marcus E. Hemsing, J. Rosenzweig, *Phys. Rev. ST Accel. Beams* **14**, 080702 (2011)

- Efficiency ***η*** also increased
  - A. Gover and P. Sprangle, IEEE J. Quantum Electron. 17, 1196 (1981)
  - I. Gadjev, et al., submitted to *NIM*

More E-field demanded for bunching

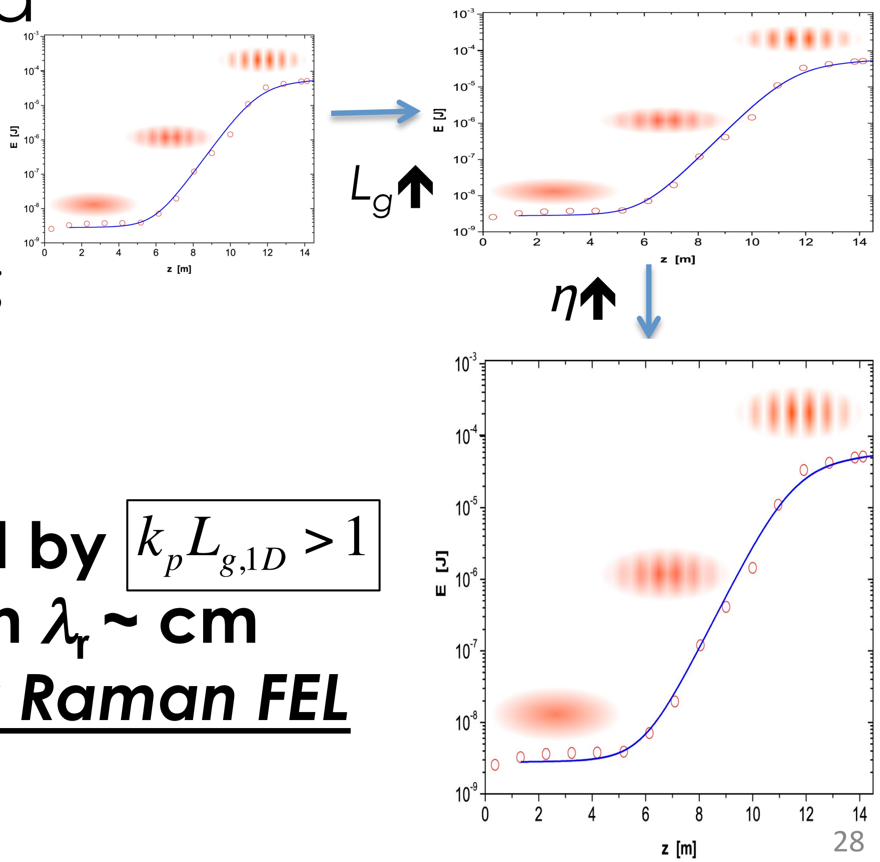
Large efficiency increase possible

$$\eta_R / \eta_{1D} \cong 3.46 k_p L_{g,1D}$$

Termed *Raman regime*, defined by $\boxed{k_p L_{g,1D} > 1}$

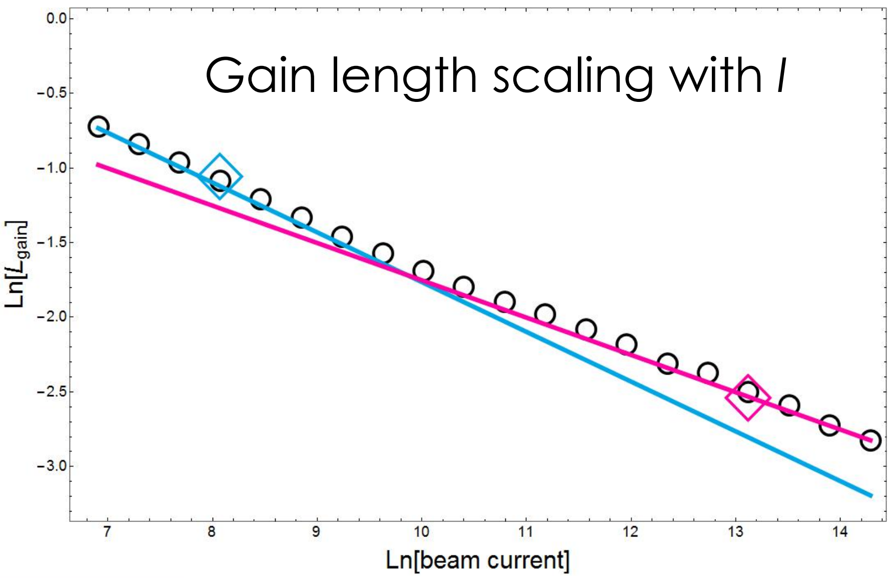
Typical in past of μwave FEL with λ_r ~ cm

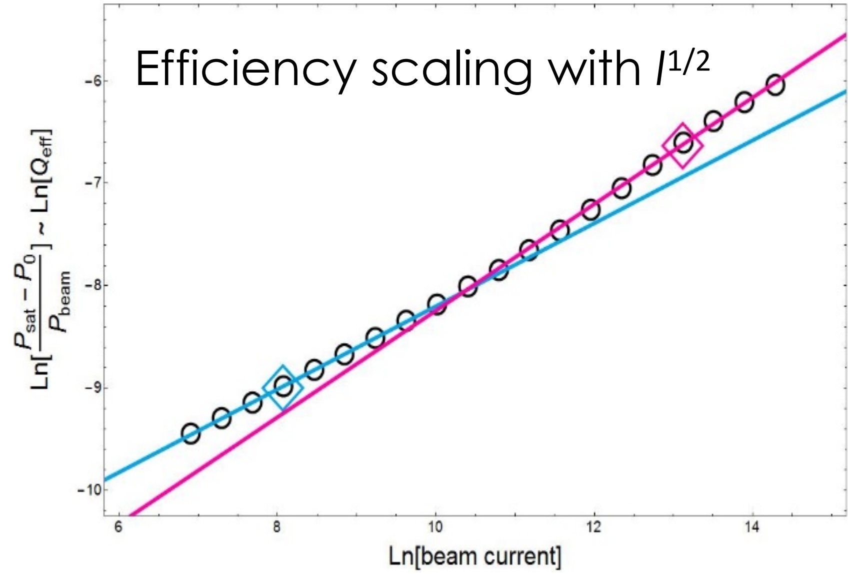
Microundulator gives *<u>soft-X-ray Raman FEL</u>*



Scaling: Compton-to-Raman Transition

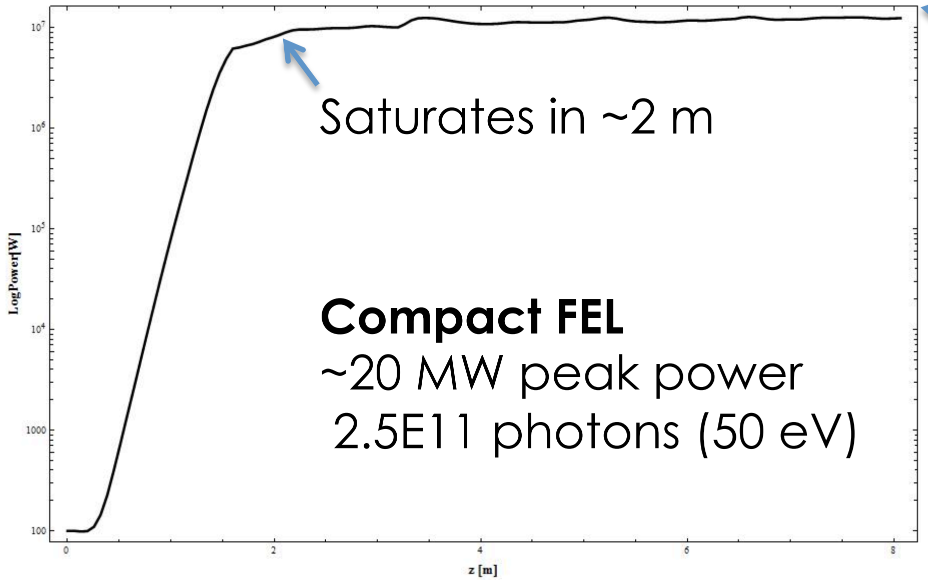
- In Compton (standard, no space-charge) regime, the L_g scales as $I^{-1/3}$
- In the Raman regime, $L_g \sim k_p^{-1} \sim I^{-1/2}$
- Efficiencies: Compton $I^{1/3}$ ➡ **Raman $I^{1/2}$**





UCLA KecK EUV FEL

- With the Keck proposal and compact accelerator, we can reach **λ_r=26 nm**
  - FEL similar to Fermi or FLASH in small UCLA lab



Saturates in ~2 m

Compact FEL
~20 MW peak power
2.5E11 photons (50 eV)

Saturation length *without* μquads
- focusing critical

k_p^{-1}~β~6 cm; Raman!
(very strong focus)
$L_{g,1D}$~ 6 cm

Competitor for the university scale is HHG
***EUV Raman FEL*, despite low charge, gives *three orders of magnitude* > HHG**

HHG: see T. Popmintchev, et al., *Science* 336, 1287 (2012)

Future plans:
Water window Raman regime FEL

- Parameter list for *highly focused micro-undulator based* SASE FEL

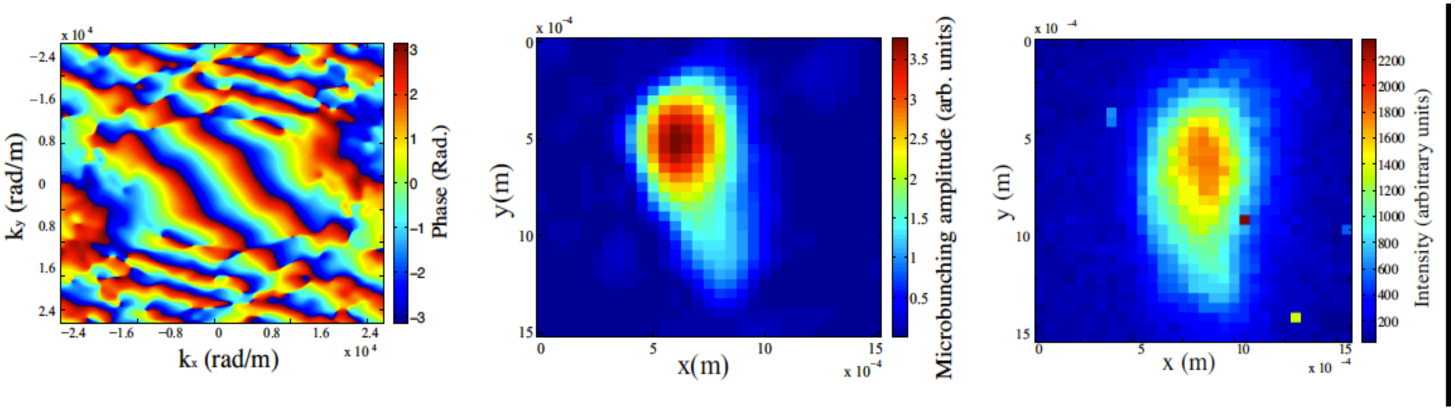
Parameter	*Value*	
Undulator Period	800 μm	Small!
Undulator Peak Field	1 T (K=0.074)	
Beam Energy	175 MeV	Small!
FEL Radiation Wavelength	3.5 nm	Small!
Beam Current (charge)	300 A (10 pC)	
Beam Emittance (normalized)	0.02 mm-mrad	
Beam Energy Spread (normalized, slice)	1E-4	
Beam Size (average)	3 μm	Small!
1D Gain Length (Compton limit, $L_{g,1D}$)	5.6 cm	Small!
Beam Plasma Wavelength (Normalized, k_p^{-1})	6 cm	Small!
3D Gain Length (Space Charge)	11.2 cm	
Saturation Length	2.25 m	

- **Firmly in Raman regime**
- **Less diffraction than EUV FEL**
- **Challenging beam sizes, 3 μm!**

UCLA

Example: μm beam manipulation and diagnostics

- Manipulating sub-μm beams: ultra-short focal length optics with microquads and dipoles (like undulator)



Reconstructed phase

Reconstructed profile

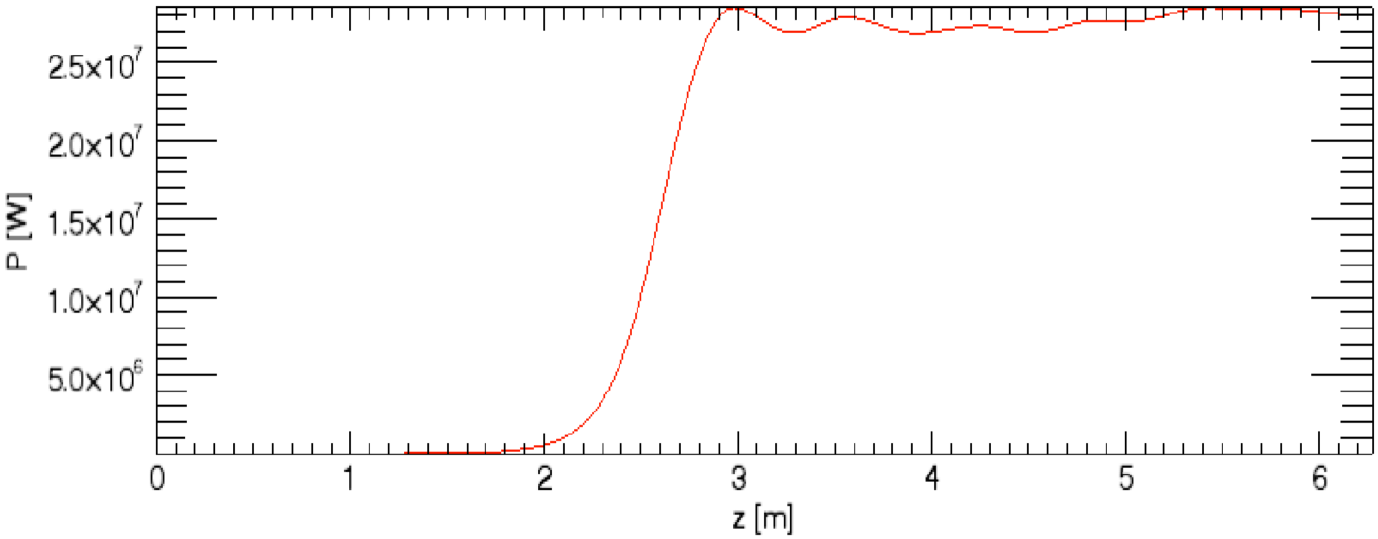
Incoherent (detuned) OTR

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

- How to measure sub-μm beam sizes? Coherent imaging (borrowed from XFEL!)
  - At Keck, can radiate TR coherently at 26 nm

Soft X-ray FEL simulation

- Saturation length increased as expected, but…



- 30 MW peak power, effective efficiency ρ=5x10^{-4}; **3x expected by Compton scaling**

Very compact, soft X-ray FEL for biology enabled

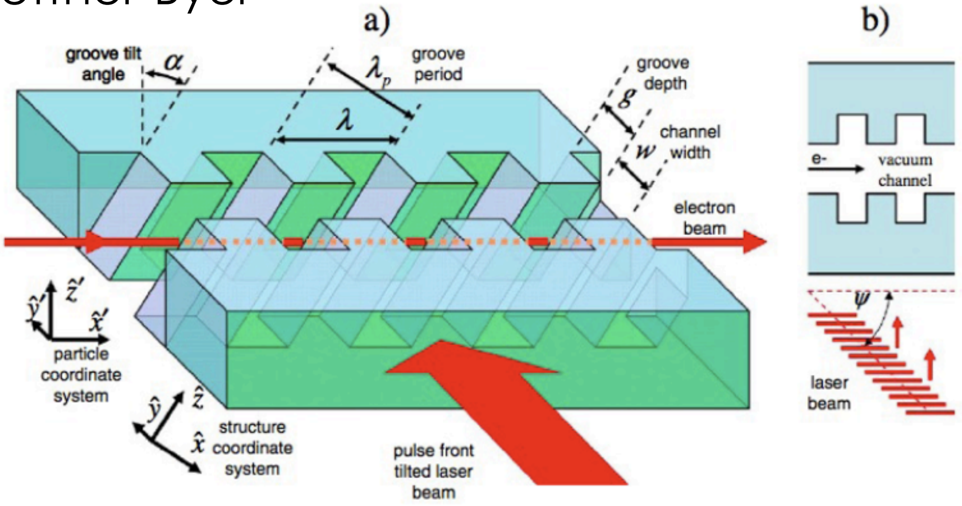
Evading magnetic material limits

- We would like to have short period undulators, but with high *K* (above 0.1)
- Need B-fields higher than 1 T (equivalent to 300 MV/m E-field)
- Possible directions:
  - Electromagnetic waves, confined
  - Electromagnetic waves, free- space
  - Plasma fields

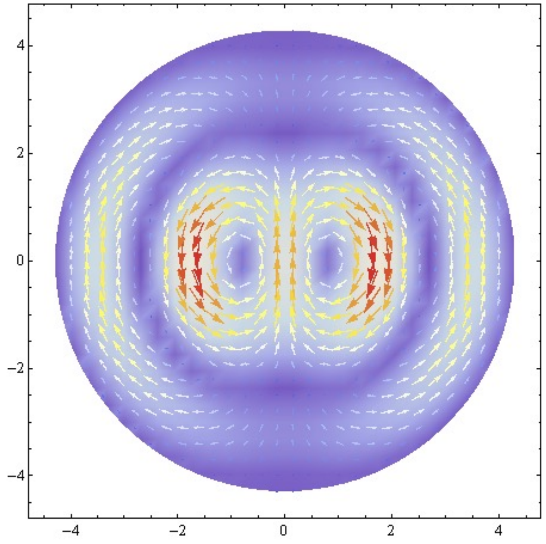
Electromagnetic Undulators

- Plettner-Byer scheme (optical-IR)
  - Slippage ($v>v_\phi$) allows choice of λ_U by stretching
  - Problem: cancellation of E,B deflection for co-propagating e- and mode [$F \sim eE(1-\beta_\phi \beta)$]
  - Still have material limits (~GV/m)

Plettner-Byer

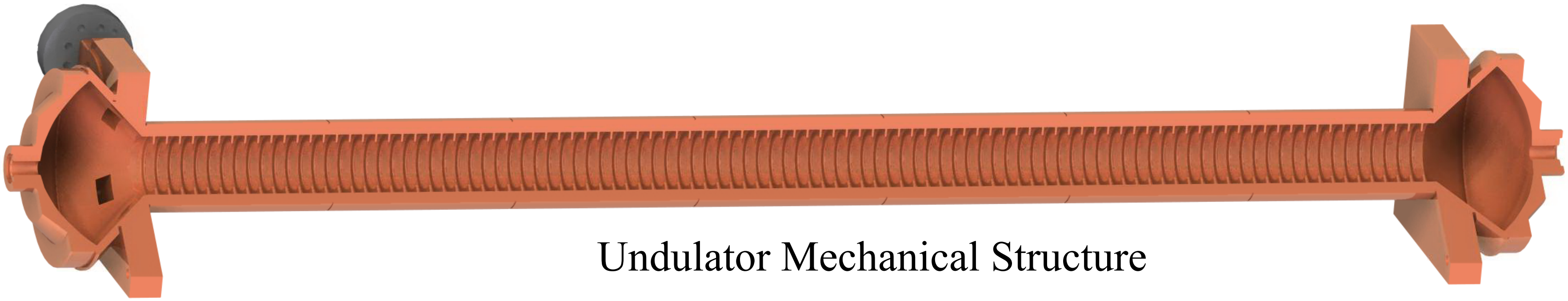


Overmoded cylindrical structure

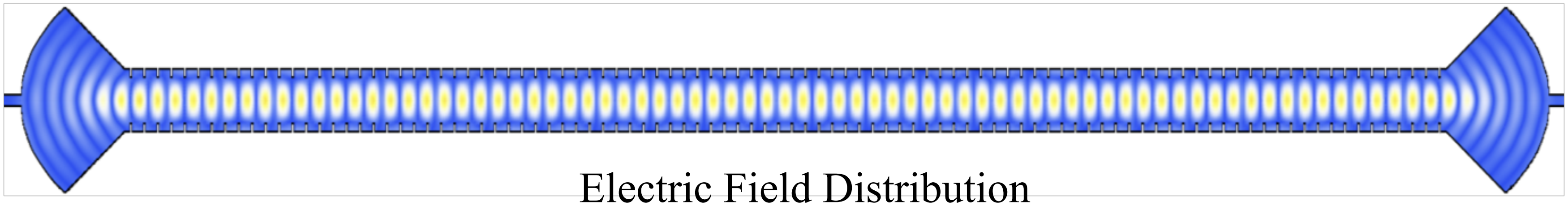


EM first step: *microwave* undulator

Tantawi (SLAC), with UCLA collaboration on 5th generation light source
Standing wave: negative v_ϕ component provides efficient wiggling ($E + B$ add)



Undulator Mechanical Structure



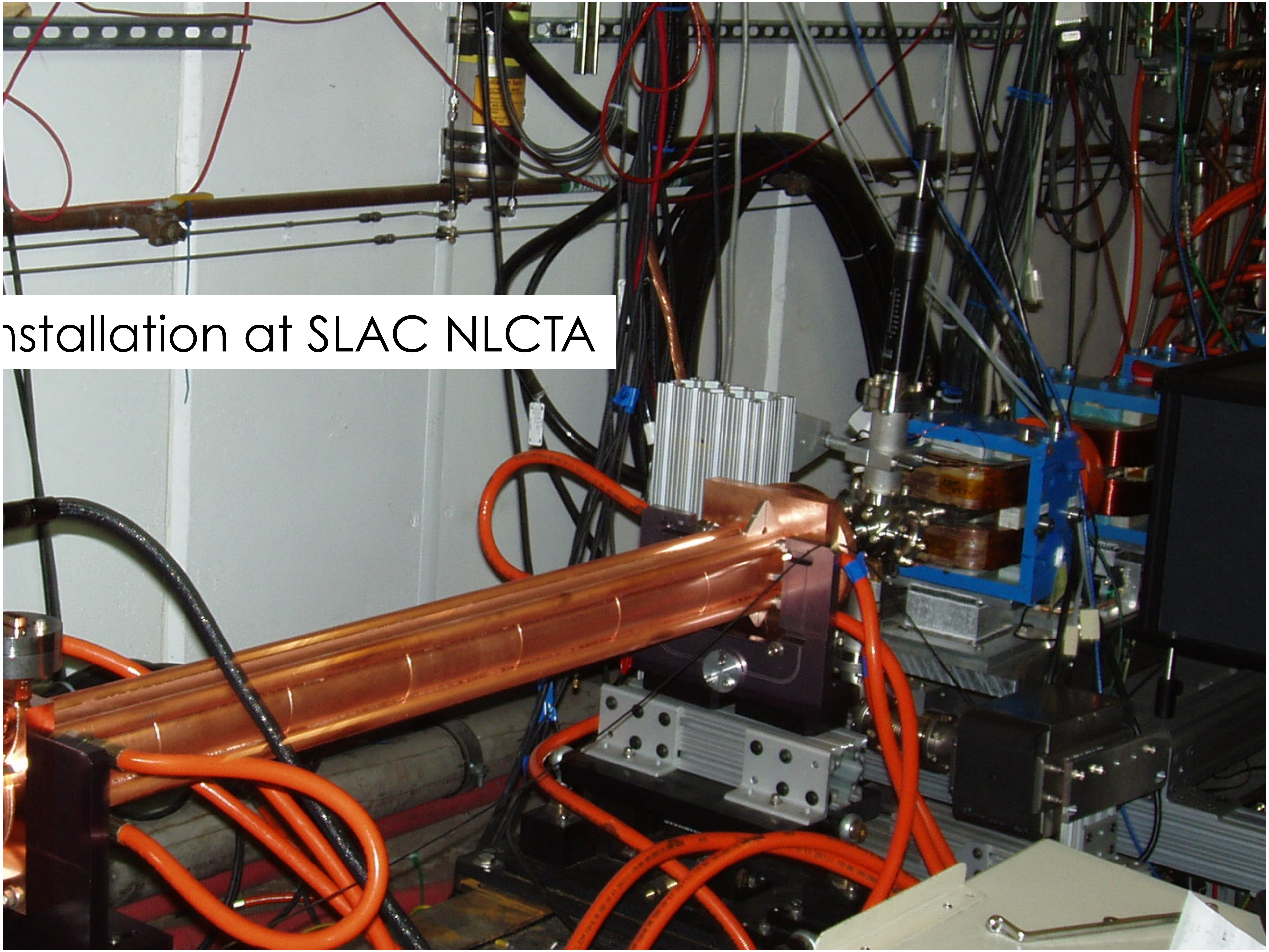
Electric Field Distribution

Corrugation Period=0.4254 λ
Inner Radius=0.75 λ
Outer radius= 1.01293 λ
Corrugation Thickness= $\lambda/16$
Number of periods =98

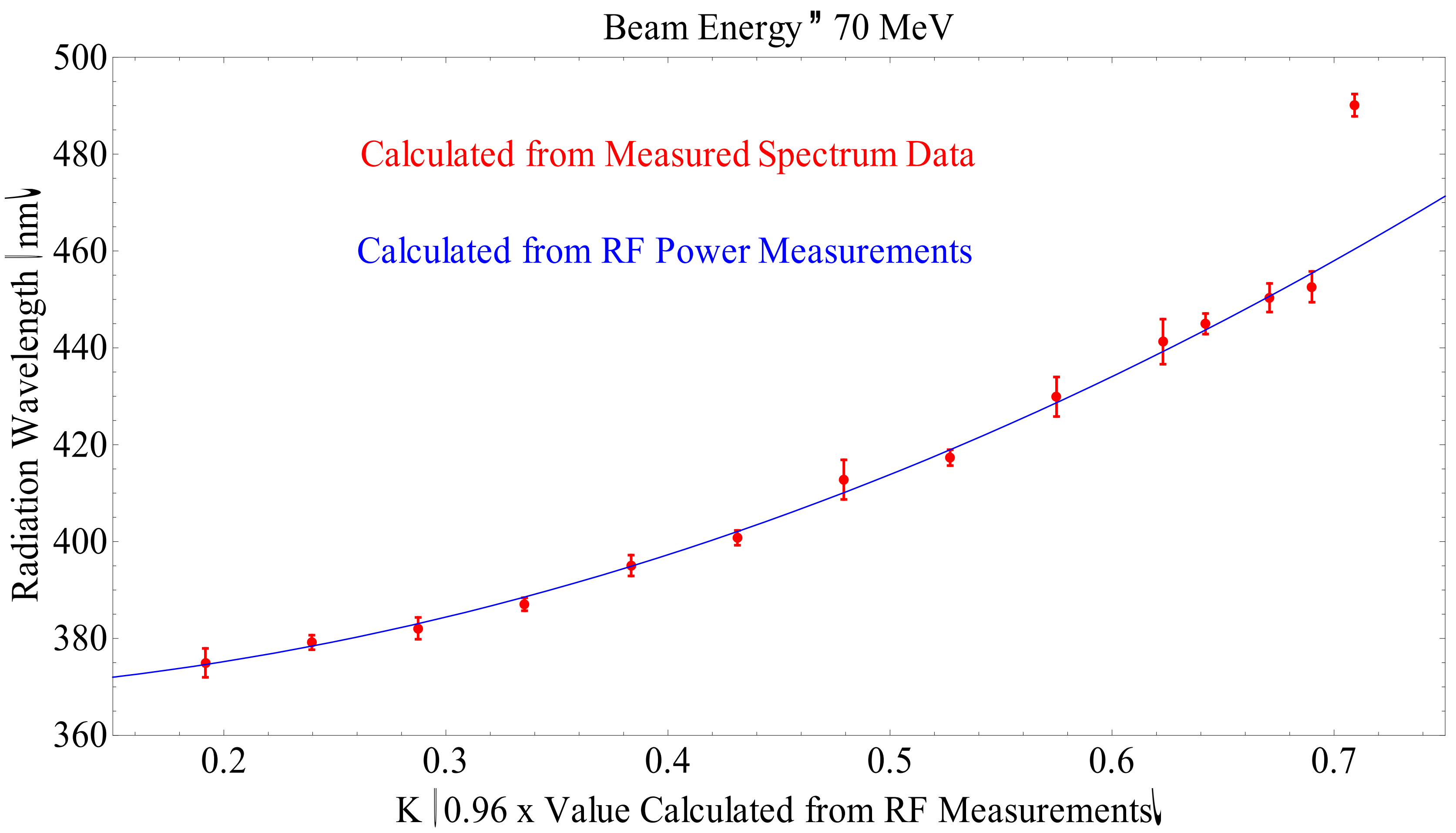
λ=2.625 cm (SLAC X-band)
Undulator Wavelength=1.393 cm
Power required (linearly polarized, K=1)=48.8 MW
Q_0=94,000

High power; *K~1* reachable at 14 mm λ_u

nstallation at SLAC NLCTA

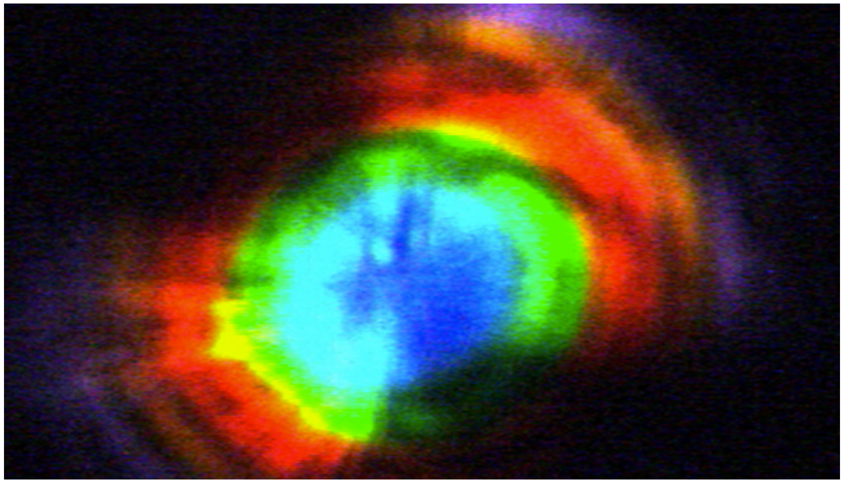


Measurement of undulator K parameter



RF undulator test spectra

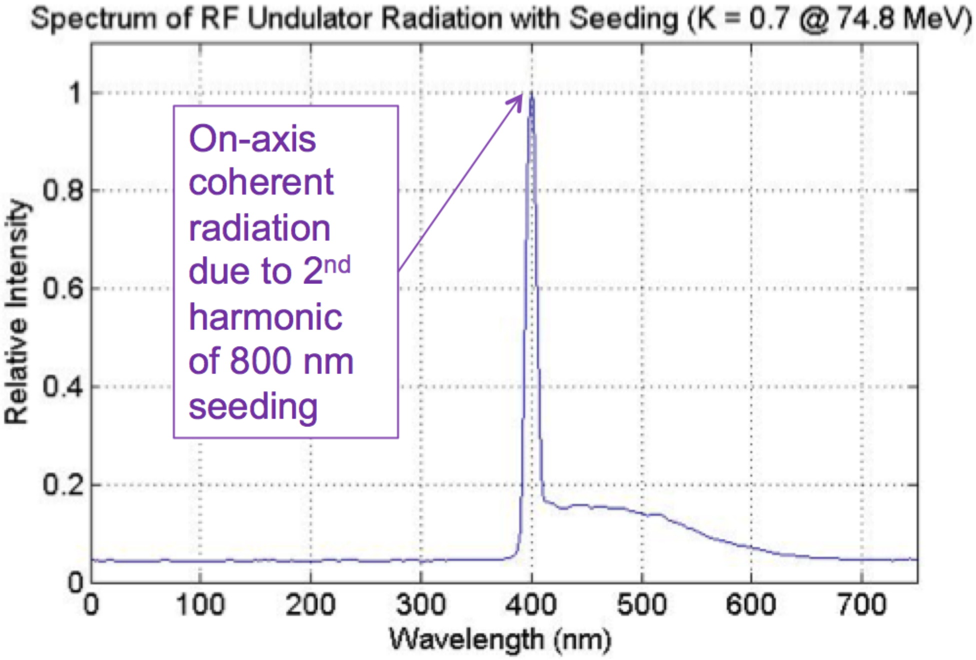
Color camera image of far-field undulator radiation!



UCLA-μbunching-induced super-radiance exp’t, with S.Tantawi’s RF undulator

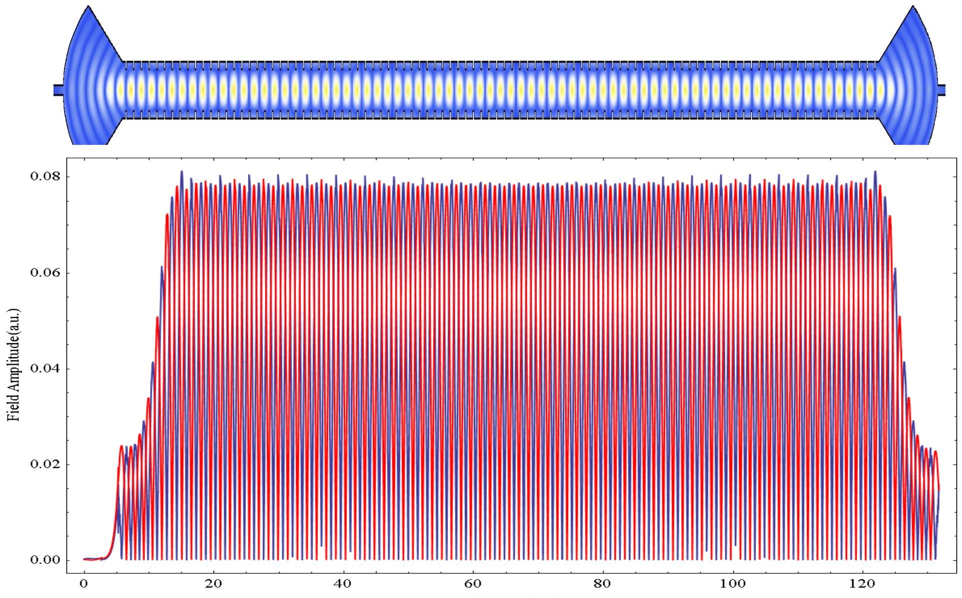
- Note off axis red shift
- Note also off-axis harmonic (violet)

- Seeded experiments show undulator utility
- 2nd harmonic seeding shown
- Off-axis red-shifting, harmonics



Next Step:THz (200-300 μm) Undulator

- *Balanced hybrid mode* in corrugated guide creates ultra-high field in the center, small surface fields
- Excellent field flatness expected, beam dynamics display slight *defocusing*
- Extrapolates from X-band device
- THz structure mechanical and RF design complete; THz source at Univ. Maryland has been tested up to 80 KW with a pulse length of 7 usec



Field flatness good for FEL (large coupling)

Parameters for 221 um undulator (from available 680 GHz source; with pulse compression to few MW)

$P(MW) \approx \frac{0.24K^2L^{2/3}}{\lambda_u^{7/6}}$ **900 kW for K=0.03, 10 MW for K=0.1 (5.5 T)**

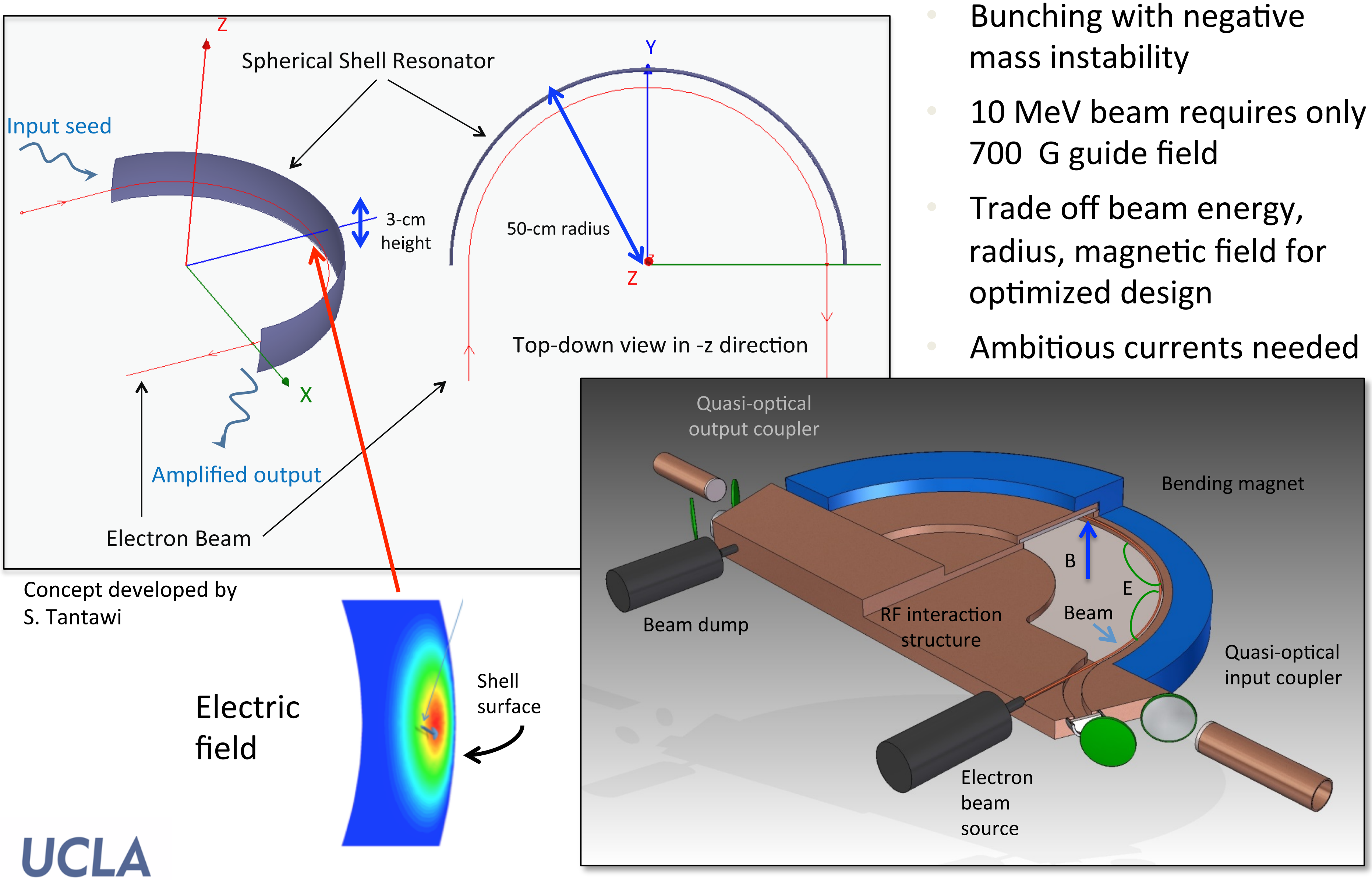
$t_{filling}(\mu s) = 32.8L\sqrt{\lambda_u}$ **48 ns filling time**

$a(m) = 0.41\lambda_u^{2/3}\sqrt[3]{L}$ **1.4 mm diameter aperture**

Challenge: need 1 GW for K~1

CSR-maser for high power THz

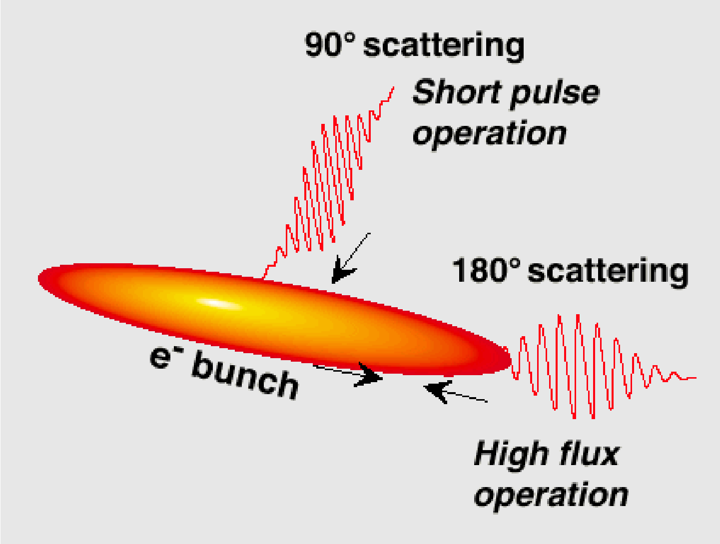
- Bunching with negative mass instability
- 10 MeV beam requires only 700 G guide field
- Trade off beam energy, radius, magnetic field for optimized design
- Ambitious currents needed

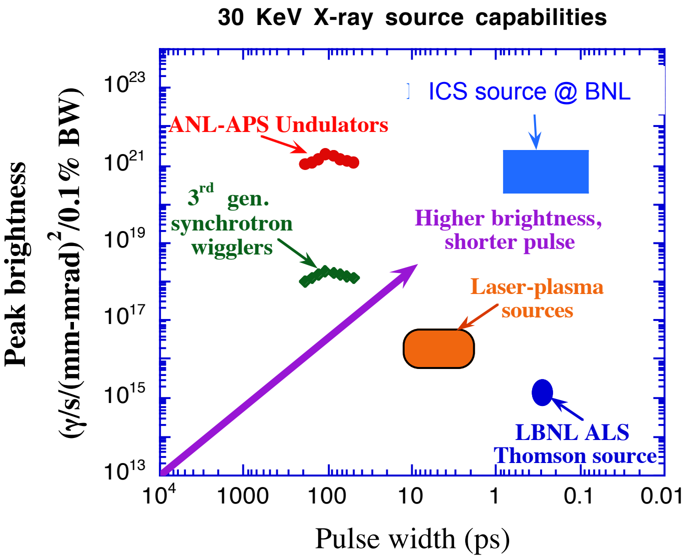


Concept developed by
S. Tantawi

Free-space undulator

- Head on collision with laser gives very short period undulator ($\lambda_L/2$) $\lambda_{sc} \approx \lambda_L / 4\gamma^2$
- Termed *inverse Compton scattering* (ICS)
- Counter-propating wave: E and B *add*

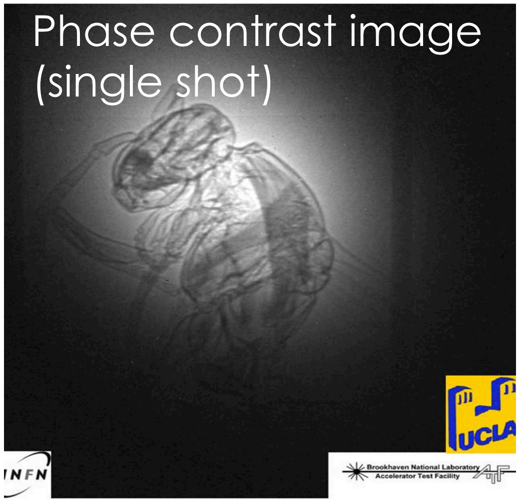




- **Incoherent, but high brightness, ultra-fast process**
- **Very large photon energies reachable (to GeV)**

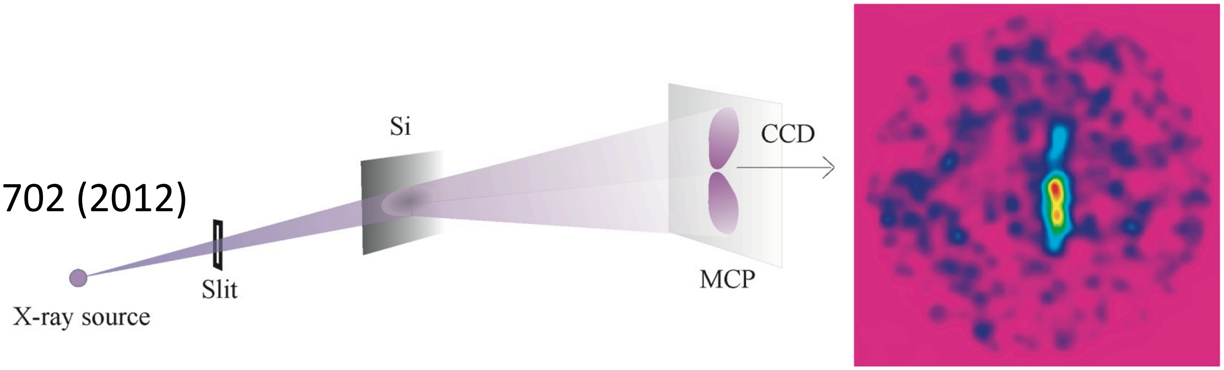
Applications of monochromatic ICS photons span wide spectral range

- Ultra-fast materials characterization
  - X-rays (keV) for penetrating metals
  - X-ray probe, (sub)ps resolution
- Biology and medicine
  - Phase contrast imaging, Auger
  - Photon activation therapy
- Intermediate energy (MeV)
  - Nuclear materials detection
  - Slow positrons (for materials)
- High energy physics (GeV)
  - $\gamma\gamma$ collider, polarized e+


Phase contrast image (single shot)

P. Oliva, et al., *Appl. Phys. Letters* **97,** 134104 (2010)

Single shot X-ray ps diffraction
F.H. O'Shea, et al.,
Phys. Rev. ST-Accel Beams **15**, 020702 (2012)



Physics of ICS collisions

- Free-space EM undulator, *or* Thomson scattering of dense electron-photon beams

$$N_\gamma = \sigma_T L = \sigma_T N_e N_L / 4\pi\sigma_x^2 \approx 10^{10}$$

- Focus laser tightly for efficient production

$$N_\gamma = 0.6\alpha\left(k_L\sigma_z\right)a_L^2 N_{e-} \propto a_L^2$$

$$a_L = \frac{eE_L\lambda_L}{2\pi m_e c^2}$$

- As a_L (norm. vector potential) is equivalent to *K* in undulator, there is a spectral spread

$$\lambda_{sc} \approx \frac{\lambda_L}{4\gamma^2}\left[1+\frac{a_L^2}{2}+\left(\gamma\theta\right)^2\right]$$

Large flux=large BW
"Nonlinear" scattering

Nonlinear ICS: Microscopic Electrodynamics

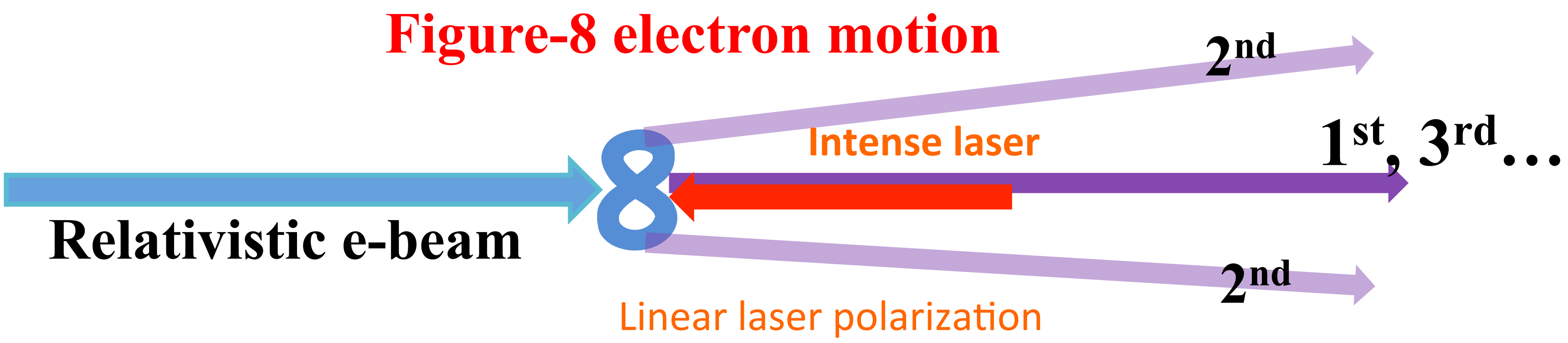


Figure-8 electron motion

Relativistic e-beam

Intense laser

Linear laser polarization

2nd

1st, 3rd…

2nd

Nonlinear ICS: a_L~1, transverse motion relativistic, with longitudinal oscillation

- ❖ **Harmonic generation/angular dependence:** (*Multi-photon process in dense photon field*)

$$h\nu_{sc} = 4\gamma^2 h\nu_L n$$

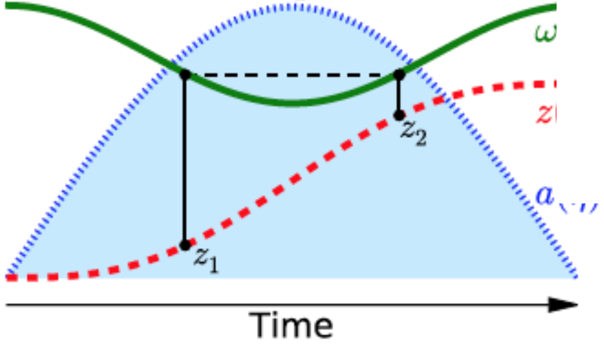
- ❖ **Red-shifting *and* BW increase even on axis:**

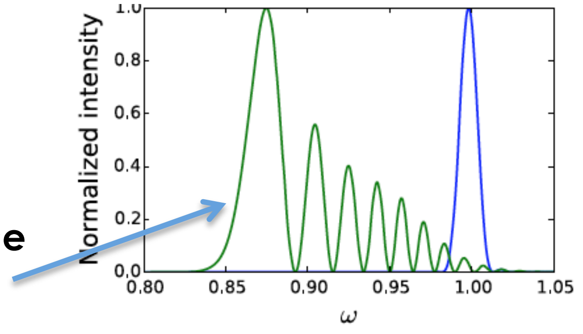
$$h\nu_{sc} \Rightarrow h\nu_{sc} / (1+a_L^2/2),$$

a_L *not* constant *during interaction*

No field flatness…

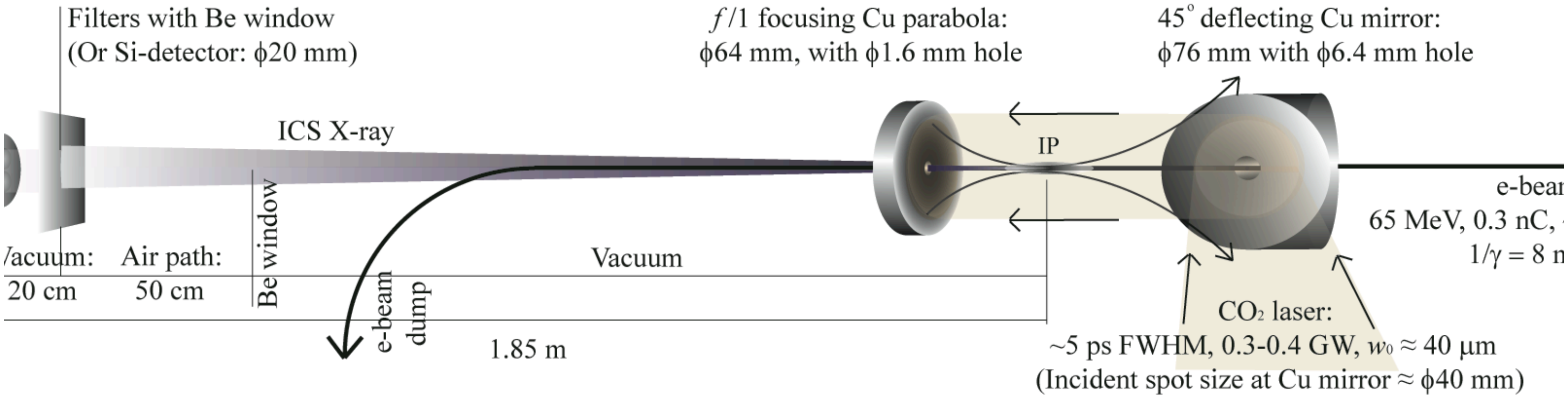
Variation of a_L during pulse





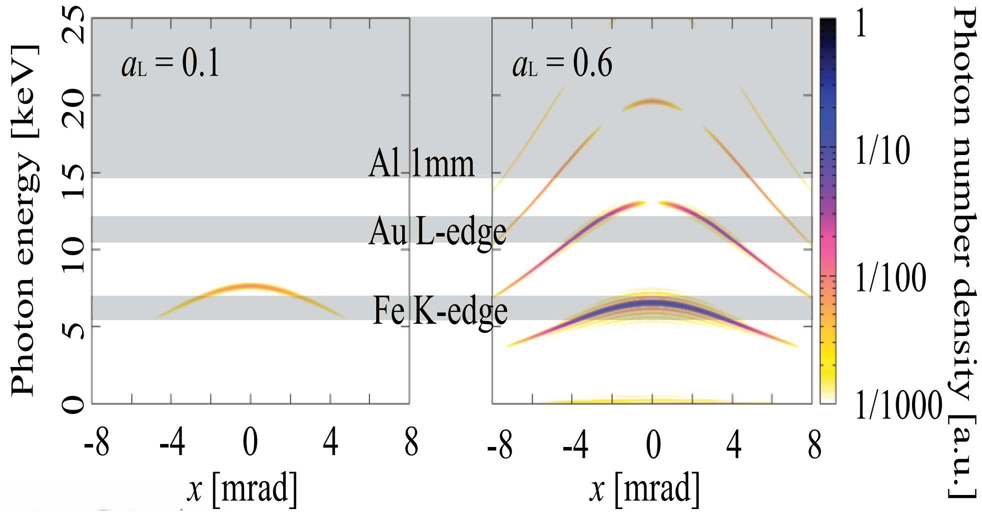
Resultant interference
a_L=0.4

Nonlinear ICS Experiments

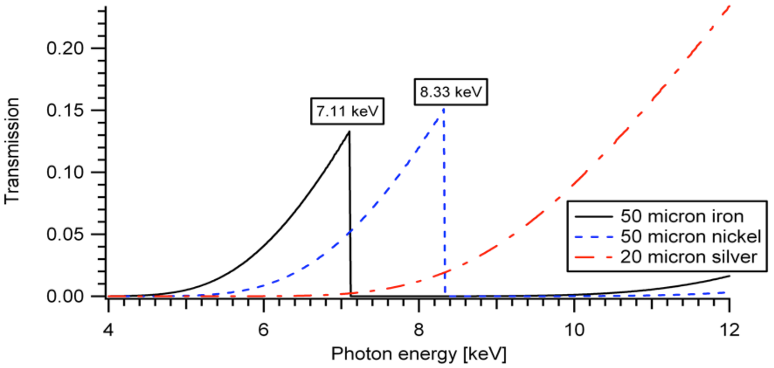


CO_2 laser: $a_L \approx 0.1\text{-}1.0$

Electron beam: $Q \approx 0.3$ nC, $\sigma_z \approx 300\ \mu m$, $\sigma_x \approx 30\ \mu m$, $E=65$ MeV



Harmonic/redshifted spectra, filtering



Metal foils near K and L edges: poor man's band-pass filter

K-edge filtering for hard x-ray harmonics

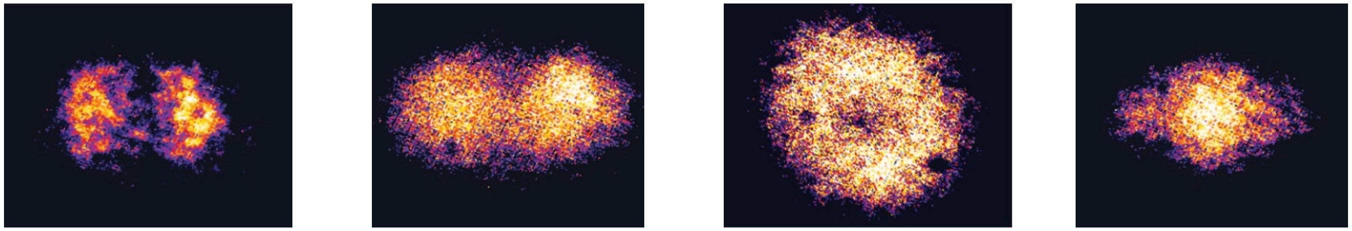
2^{nd} harmonic
Al 750 μm

Superposition
2^{nd} and 3^{rd} harmonic
250 μm Al foil

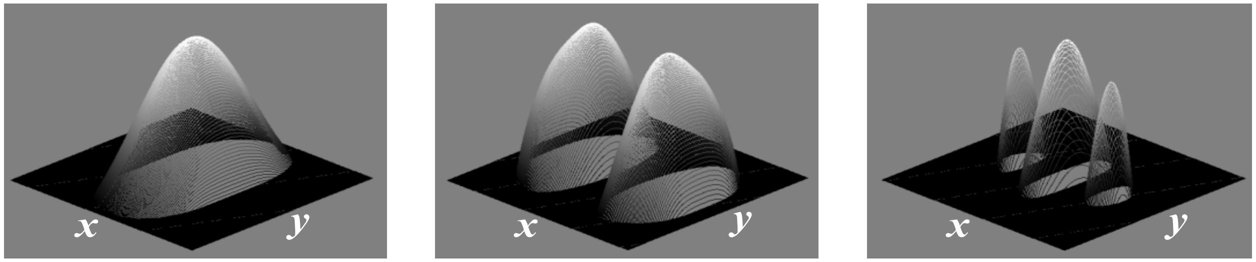
2^{nd} harmonics
Al 750 μm
circular
polarization

3^{rd}+ …
Al 1000 μm

Experiments



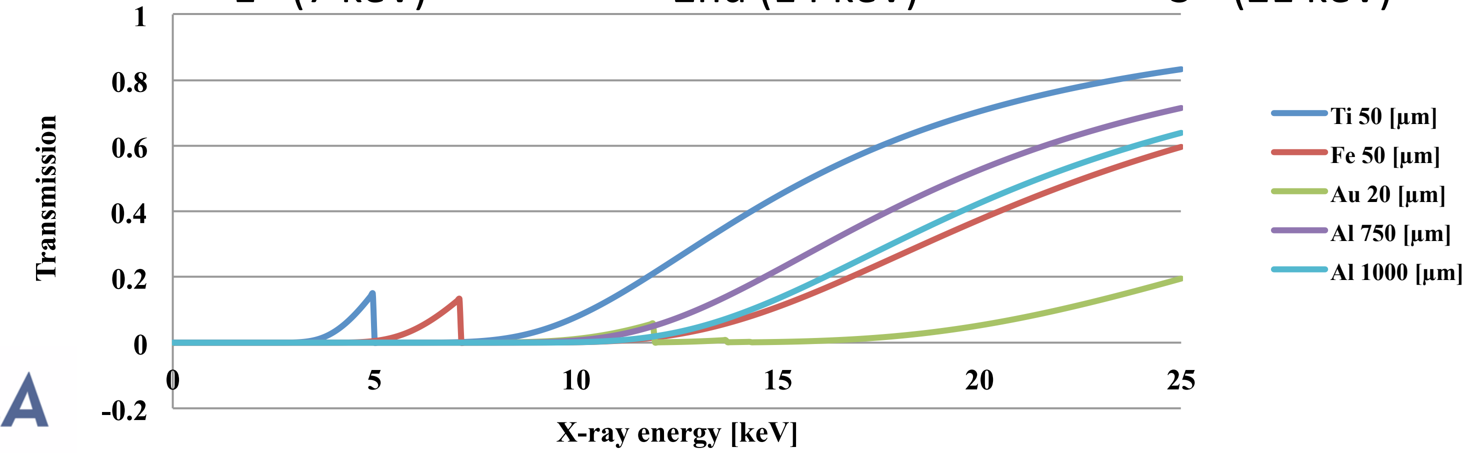
LW simulation



1^{st} (7 keV)

2nd (14 keV)

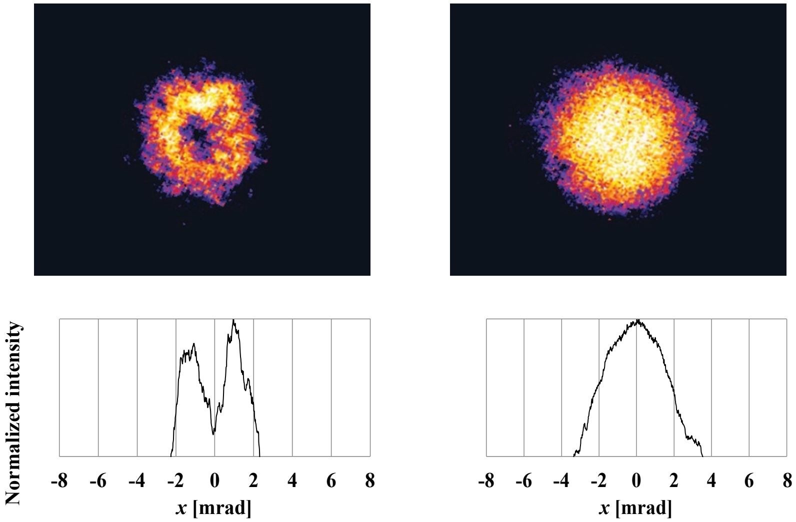
3^{rd} (21 keV)



Observation of strong nonlinear redshift

"Mass shift" effect unequivocally detected

- Demonstration of red-shifting in ICS *fundamental* using 7.2 keV Fe K-edge



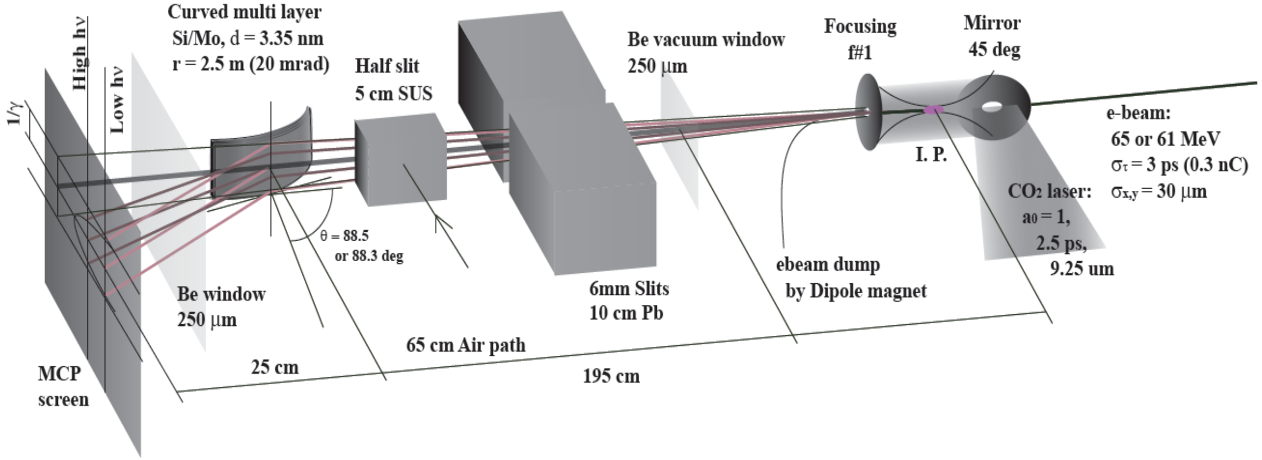
Shift below K-edge, no attenuation of center

$a_0^2<0.06$ $a_0^2\sim0.4$

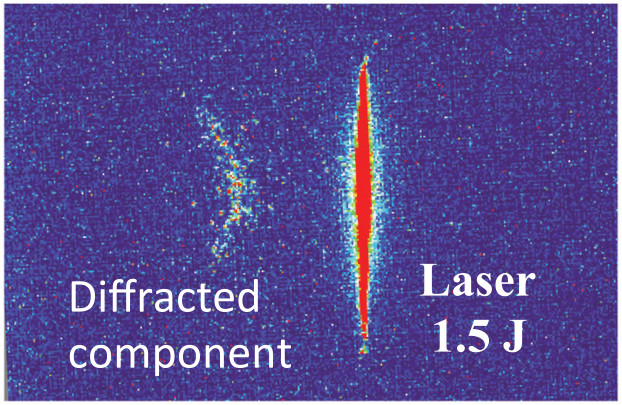
Shows, along with harmonics angular distribution, radiation from nonlinear figure-8 motion

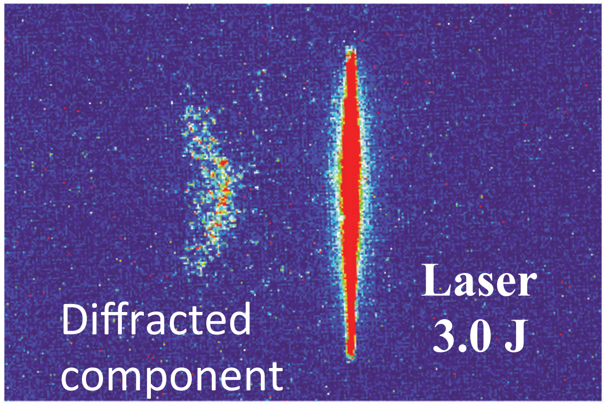
Y. Sakai, et al., *Phys. Rev. ST Accel. Beams*, 18, 060702 (2015)

Beyond filters: single shot spectrum measurement



✡ Mo-Si *bent multi-layer* thickness: *d* ≈ 3.3 nm, Bragg angle ~ 25 mrad @ *hv* = 7.6 keV
✡ Viewing angle of curved layer ~ 50 mrad (observation range of many keV)
✡ Multi-layer reflectivity of ~ 15% @ NSLS X15A





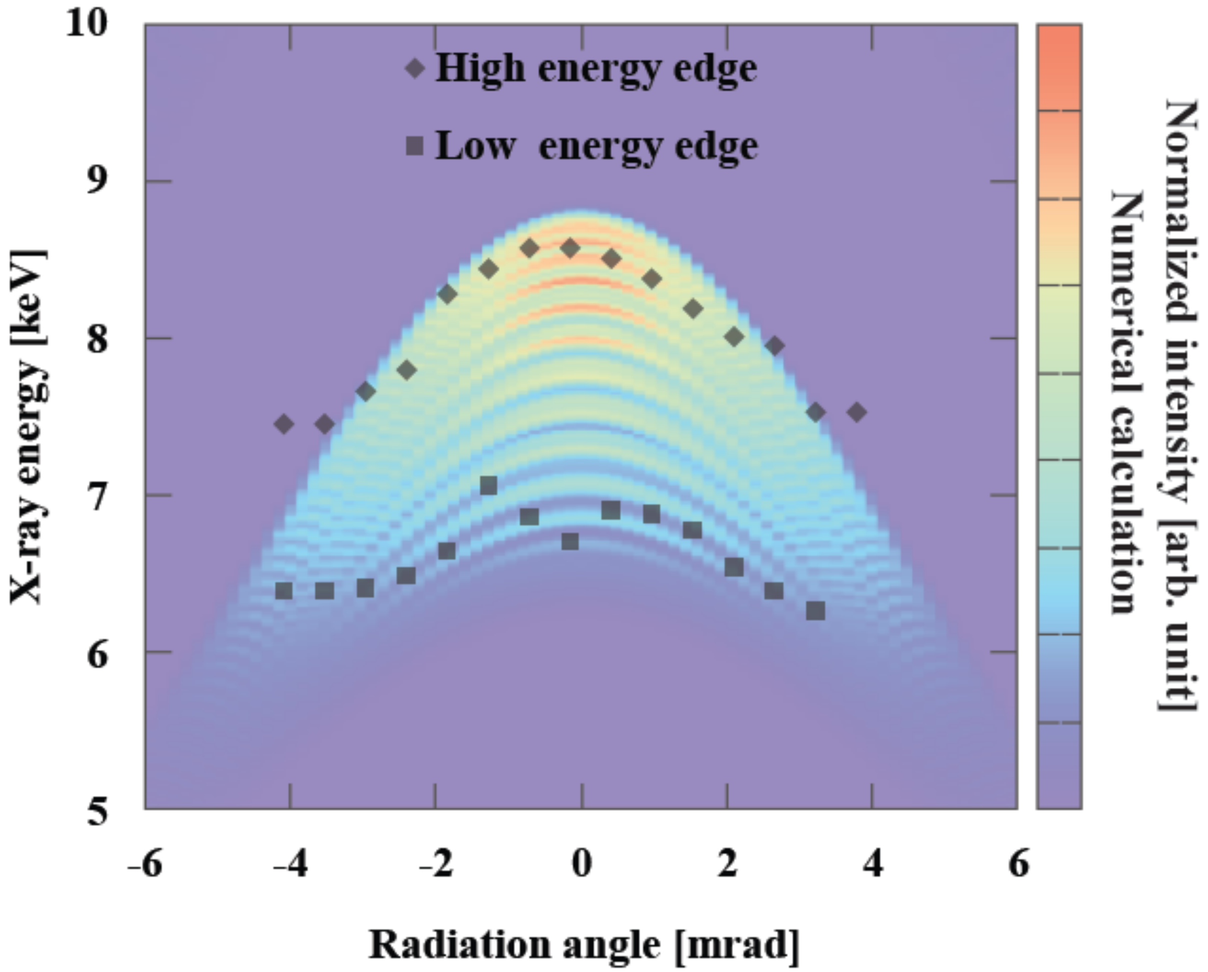
Double
Differential
Spectrum
observed!

Projection of

[5] Y. Kamiya, T. Kumita and P. Siddons et al., X-ray spectrometer for observation of nonlinear Compton scattering, Proc. Joint 28th Workshop on Quantum Aspects of Beam Physics (World Scientific), 103 (2003)

Double differential spectrum

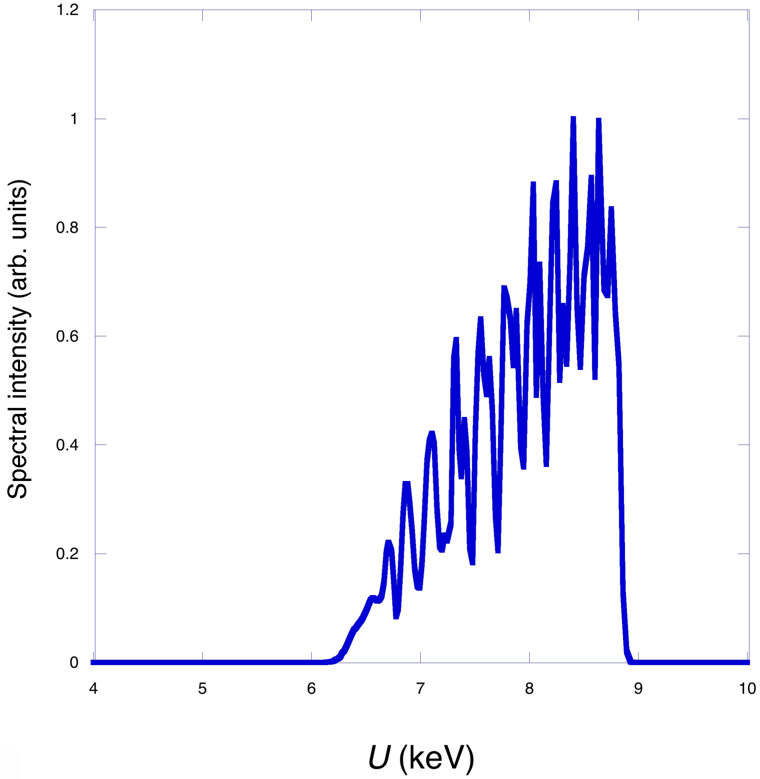
- Data overlaid on simulation (Lenard-Wiechert)

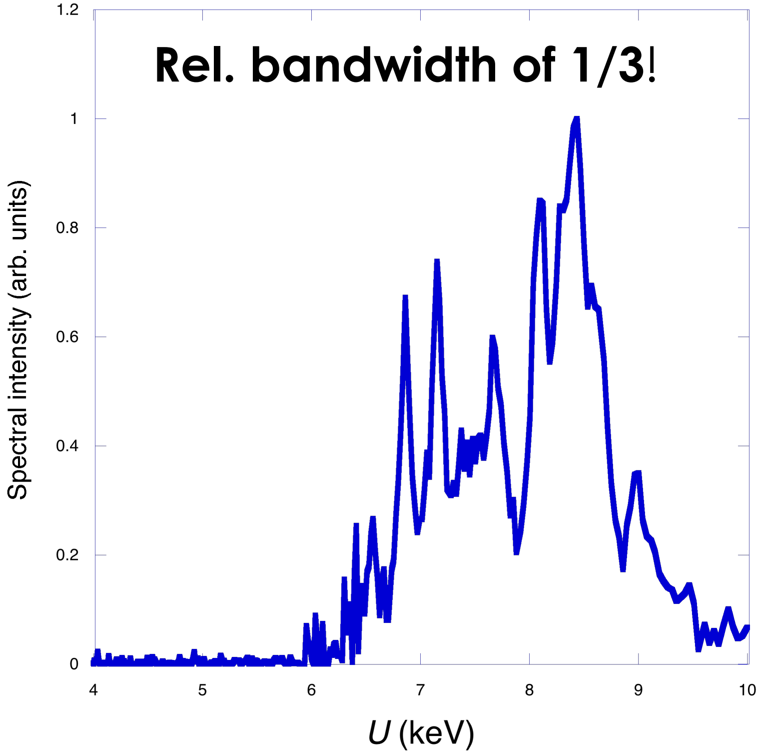


UCLA

Near axis spectrum reveals nonlinear spectral spread

- Interesting self-interference effect in simulations, experiment cannot resolve (spectrometer limit)

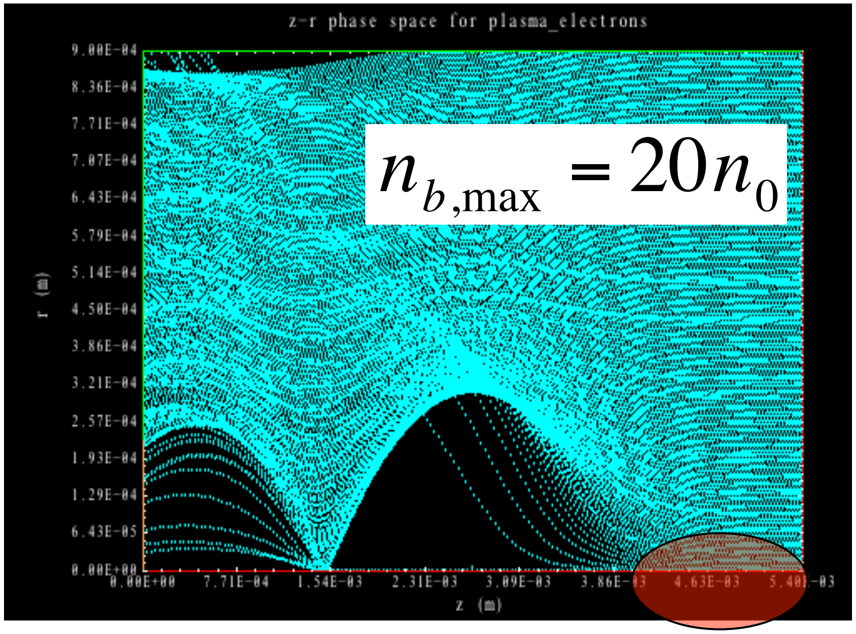

Simulated spectrum (L-W code, a_{lL} =1


Experimental Spectrum

Rel. bandwidth of 1/3!

Laser undulators will be challenging for FEL!

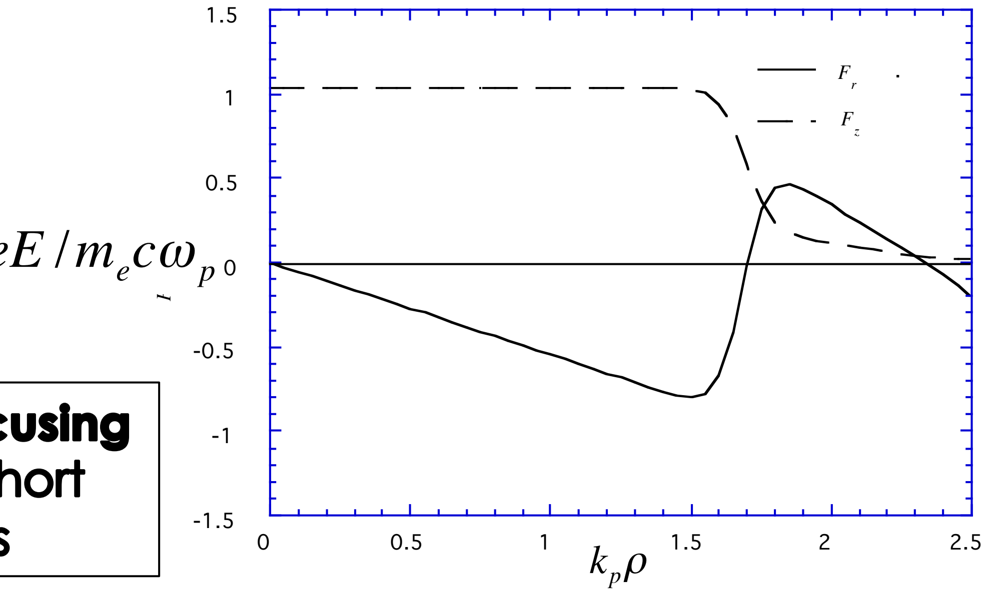
New undulator from plasma wakefields in the “blowout” regime



Plasma electron distribution (*ρ,z*) blowout regime

Complete electron rarefaction achieved by “blow-out”, beam denser than plasma *$n_b > n_0$*

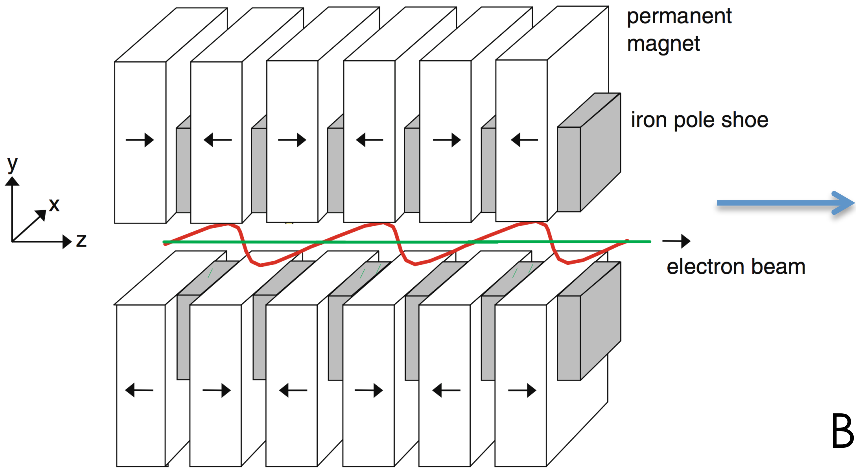
- **Fields due to electrons are EM (like linac cavity)**
- **Ions form a uniform charge column, *give linear focusing***

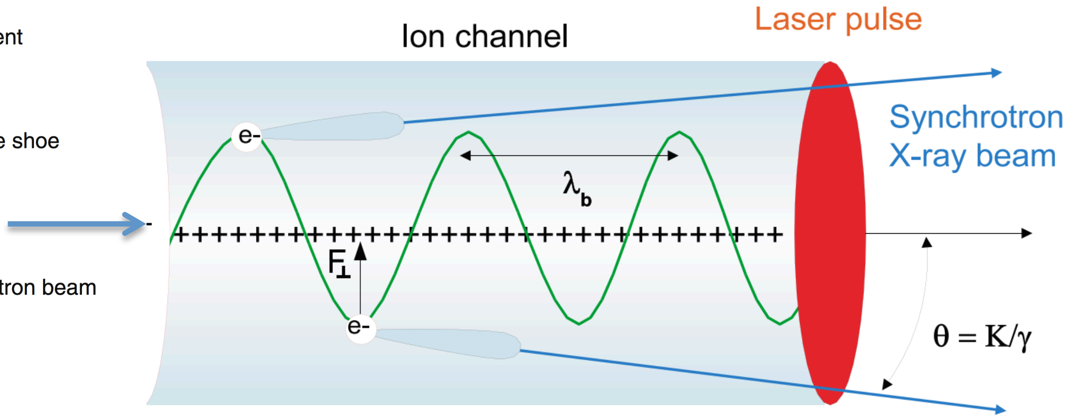


Fields inside plasma electron rarefaction region. $E_{\max} > E_{WB}$

Use linear very strong (MT/m) **focusing fields** to create undulator from short wavelength betatron oscillations

Plasma wiggler: undulator from strong betatron motion





Betatron oscillation $k_\beta = \sqrt{2\pi r_e n_0/\gamma} = k_p/\sqrt{2\gamma}$

A. Rousse *et al.,* Phys. Rev. Lett. **93**, 135005 (2004).

$$K = \frac{2\pi\gamma x_0}{\lambda_\beta} \simeq 1.33 \times 10^{-10}\,\gamma^{0.5}\,n_e^{0.5}[\mathrm{cm}^{-3}]\,x_0[\mu\mathrm{m}]$$

<u>Amplitude dependent</u>

K can reach ~100 (Requires large offset, $k_p x_0$ ~1)

$$E_c[\mathrm{eV}] = 5\times10^{-21}\,\gamma^2\,n_e[\mathrm{cm}^{-3}]\,x_0[\mu\mathrm{m}]$$

Photon energy up to

Can reach up to 100 MeV with dense plasma.

Plasma wigglers can give magnet field equivalent B_u>100 T with sub-cm wavelength

S. Kiselev, *et al.*, Phys. Rev. Lett. 93 135004 (2004)

Proposal: resonant excitation with *magnetic undulator!*

- Undamped simple harmonic oscillator (ion focusing) driven (undulator) on resonance. Similar to cavity drive with RF…
- Mathematics:

$$x'' + k_\beta^2 x = \frac{k_u K}{\gamma}\exp(ik_u z), \quad \underset{k_u = k_\beta}{K} = \frac{eB_0}{k_u m_e c}$$

With resonance

$$x = -i\frac{K}{2\gamma}z\exp(ik_u z)$$

Response

$$x_u = \frac{K}{k_u \gamma}$$

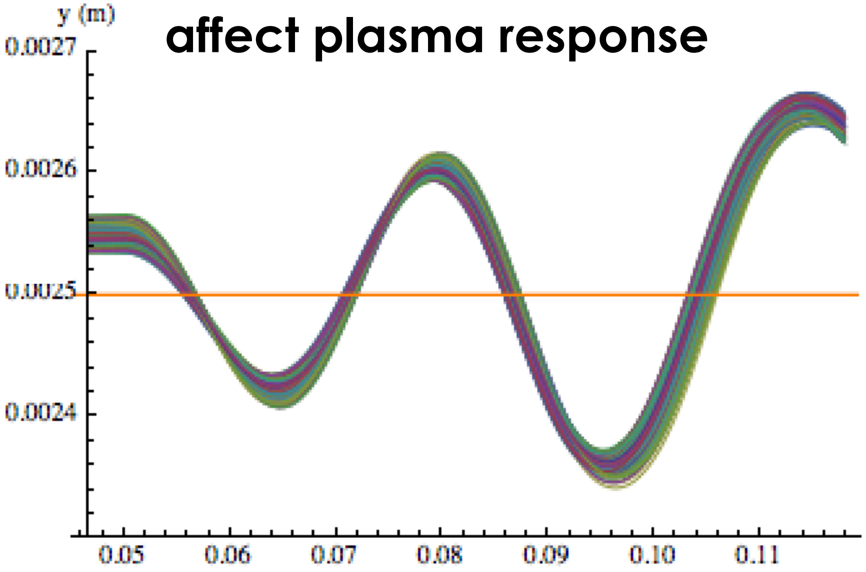
Define "natural" amplitude of undulator

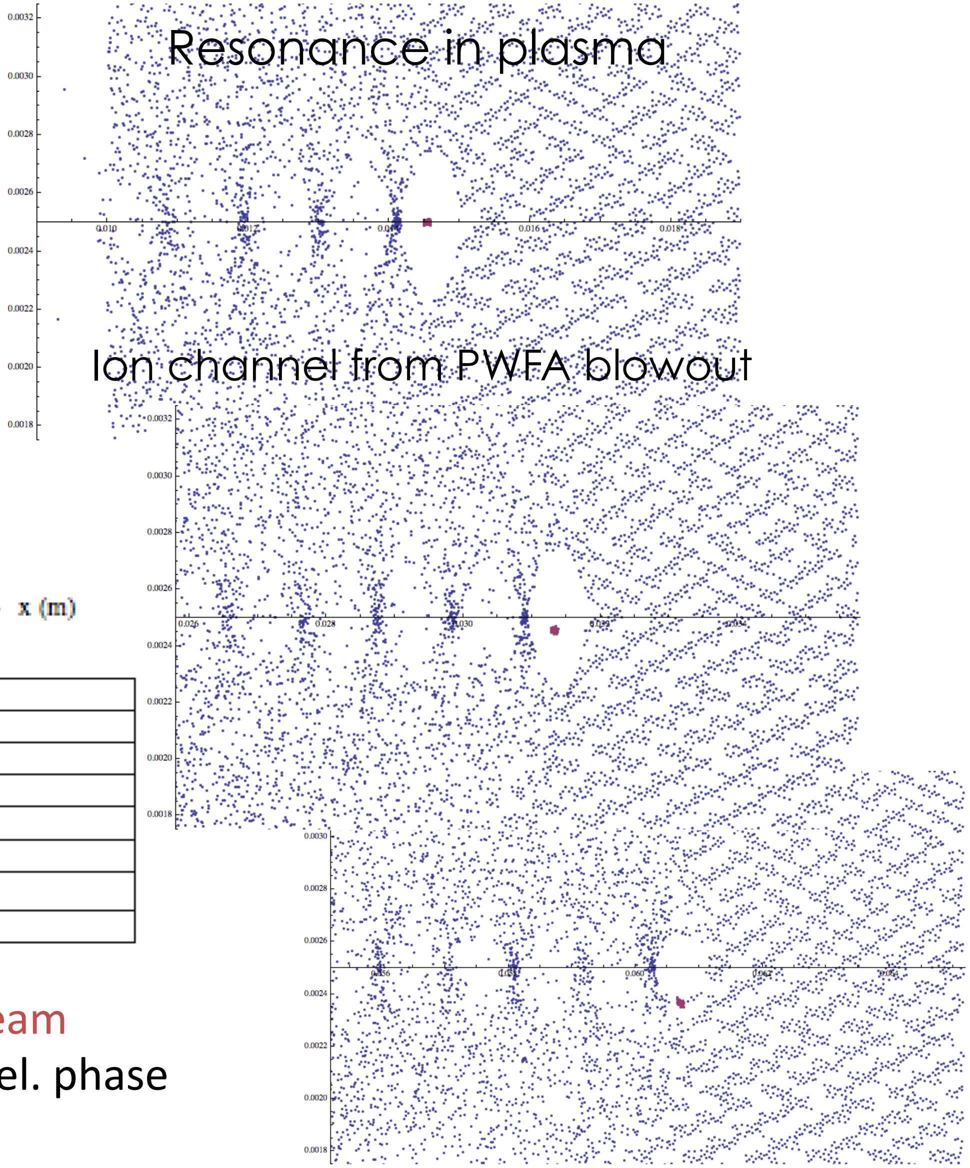
$$x = -ix_u(k_u z)\exp(ik_u z)$$

- Multiplies one undulator amplitude per radian of undulator

Resonant betatron: simulation

Existence of B-field does not affect plasma response





Resonance in plasma

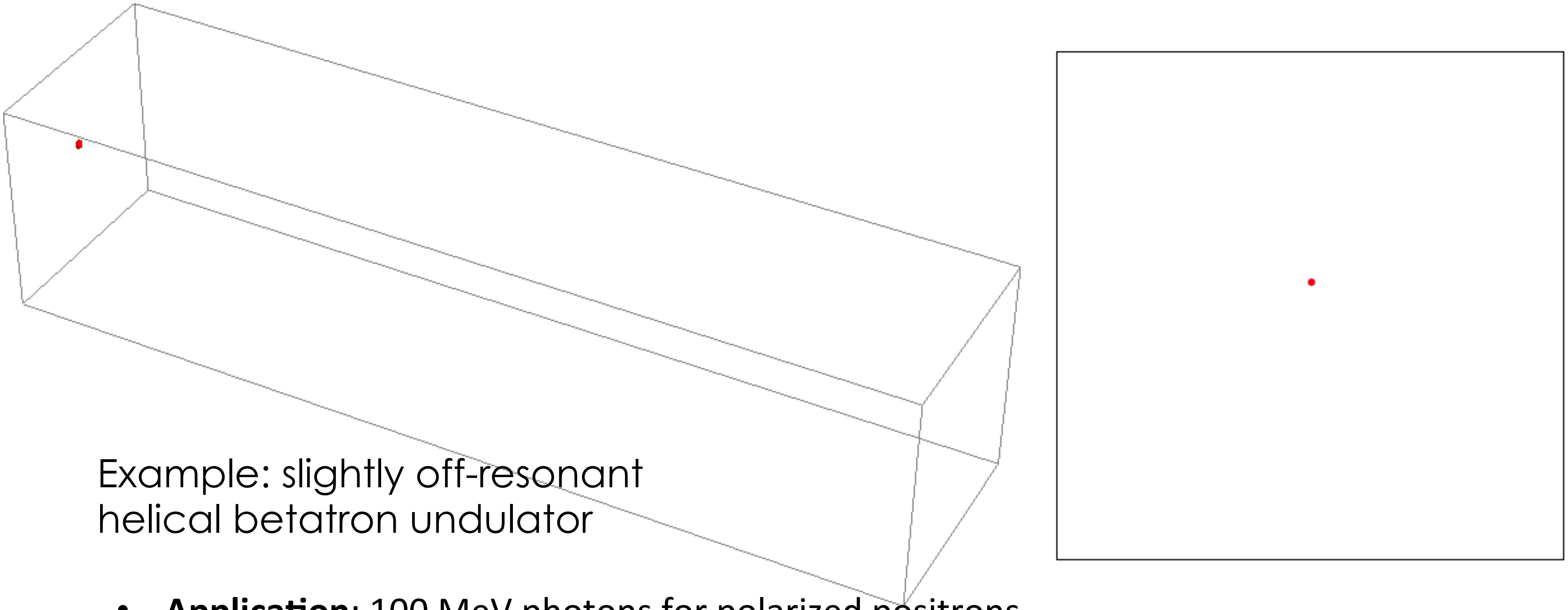
Ion channel from PWFA blowout

Plasma ion species	Ar+
Plasma density	10^{15} cm^{-3}
Undulator magnetic field amplitude	1 T
Undulator period	3 cm
Drive beam energy	20 GeV
Drive beam charge	3.2 nC
Drive beam dimensions σ_x, σ_z	30 μm, 30 μm
Witness beam energy (negligible charge)	250 MeV

VORPAL simulation: low energy beam particles in red, placed at zero accel. phase x_u=27 um, bubble edge ~175 um

UCLA

Unique mechanism for helical betatron undulator



Example: slightly off-resonant
helical betatron undulator

- **Application**: 100 MeV photons for polarized positrons
- Pair helical undulator with PWFA over ~meter length scales
- Recent results from FACET are encouraging, showing formation of >1 m narrow **wakeless** preformed plasma channels with 10 TW laser and axicon lenses
- Experimental outlook: highly promising for FACET2 at SLAC

Conclusions

- **Compact XFELs are intriguing new instruments for revolutionizing wide swaths of science**
  - **Nanoscience, biology, fs chemistry, EUV lithography, etc.**
- **Opportunities to bring cutting-edge FEL tools to wide use**
- **Convergence of advanced concepts**
  - **Frontiers of bright electron beams**
  - **Very short period undulators**
  - **Enables new FEL regimes, and first *5th generation light source***
- **Various options, from**
  - **advanced cm-period undulators**
  - **EM undulators (mm-wave to optical)**
  - **Plasma undulators**
- **New vistas opened up in radiation sources…**