TV/m plasma wakefield accelerator using low charge, ultra-short beam

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Background

- UCLA proposal for ultra-short beams in FEL
  - Single spike operation
  - Breaching attosecond frontier
  - Ultra-high brightness electron beams
- Coherent radiation from ultra-short beams
- Scaling the PWFA to short wavelength
- TV/m PWFA experiment at the LCLS

Ultra-short XFEL pulses: motivation

- Investigations at atomic *electron* spatio-temporal scales
  - Angstroms-nanometers (~Bohr radius)
  - Femtoseconds (electronic motion, Bohr period)
    - Femtochemistry, etc.
- 100 fs accessible using standard techniques
- Many methods proposed for the fsec frontier
  - Slotted spoiler; ESASE; two stage chirped pulse
  - Unsatisfactory (noise pedestal, low flux, etc.)
  - Still unproven
- Use “clean” ultra-short electron beam
  - Myriad of advantages in FEL *and* beam physics
  - Robust in application: XFEL, coherent optical source, PWAFA…

The “clean” path:
ultra-low charge electron beam

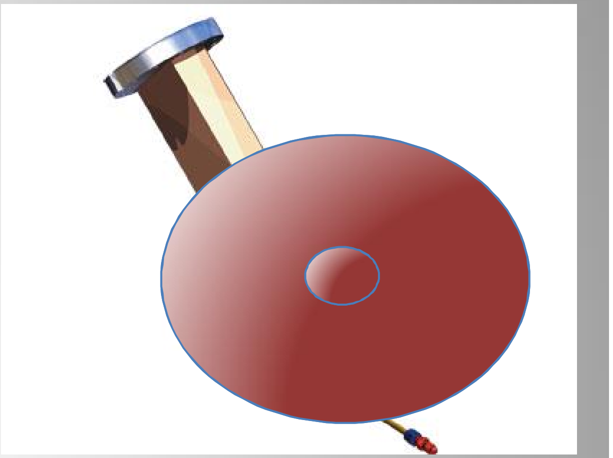
- Excellent *phase space* quality (⊥ and ||)
  - Very low emittance
  - Highly compressible
  - *Unprecedented high brightness*
- Ultra-short high brightnss beam in FEL
  - Bunch ~ cooperation length; *single spike operation*
  - *Short* cooperation length; sub-*femtosecond pulse*
  - Pedestal free, ultra-short X-ray pulse
- Mitigate collective effects dramatically
  - Coherent synchrotron radiation instability (chicane)
  - Undulator beam-pipe wakes

Ultra-high brightness beams: How?

- Brightness $B = \frac{2I}{\varepsilon_n^2} \propto \frac{Q}{\sigma_t \varepsilon_n^2}$
- Low *Q* in injector: shorter σ_t, smaller ε
- Velocity bunching at low energy, recover *I*
- Chicane bunching (1 or 2 stages)
- The rules change much in our favor
  - Low charge makes all manipulations easier
  - Higher brightness gives new possibilities, design application with open imagination…
- Illustrate 1st with original example: SPARX

Photoinjector scaling

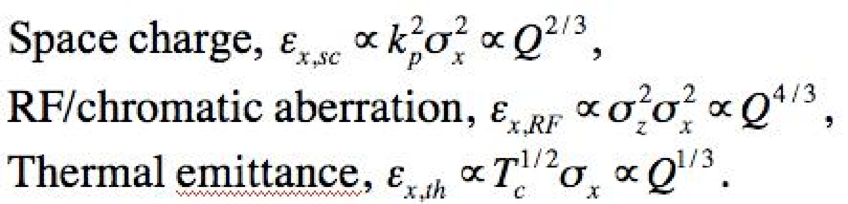
J.B. Rosenzweig and E. Colby, *Advanced Accelerator Concepts* p. 724 (AIP Conf. Proc. 335, 1995).



- Beam at lower energy is single component relativistic plasma
- Preserve optimized dynamics: change *Q*, keeping plasma frequency (*n*, aspect ratio) same
- Dimensions scale
  - Shorter beam…

$$\sigma_i \propto Q^{1/3}$$

- Emittances:



Space charge, $\varepsilon_{x,sc} \propto k_p^2 \sigma_x^2 \propto Q^{2/3}$,

RF/chromatic aberration, $\varepsilon_{x,RF} \propto \sigma_z^2 \sigma_x^2 \propto Q^{4/3}$,

Thermal emittance, $\varepsilon_{x,th} \propto T_c^{1/2} \sigma_x \propto Q^{1/3}$.

- At low *Q*, $\varepsilon_{x,th}$ dominates (Ferrario WP, SPARC/LCLS)

$$\varepsilon_n(\text{mm-mrad}) = \sqrt{a_1 Q(\text{nC})^{2/3} + a_2 Q(\text{nC})^{4/3} + a_3 Q(\text{nC})^{8/3}} \propto 0.33 \cdot Q(\text{nC})^{1/3} (\text{mm-mrad})$$

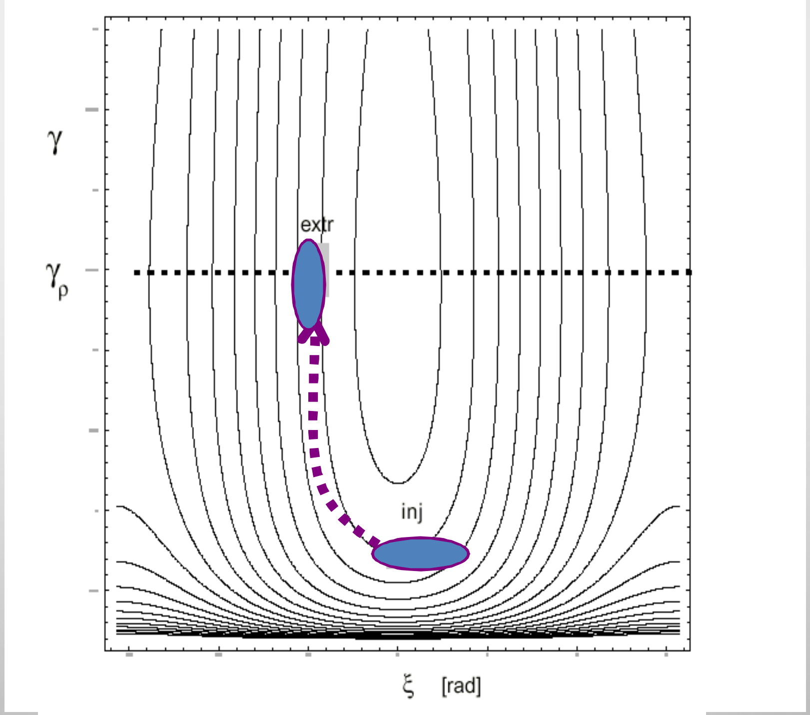
$a_1 = 0.11$

$a_2 = 0.18$

$a_3 = 0.23$

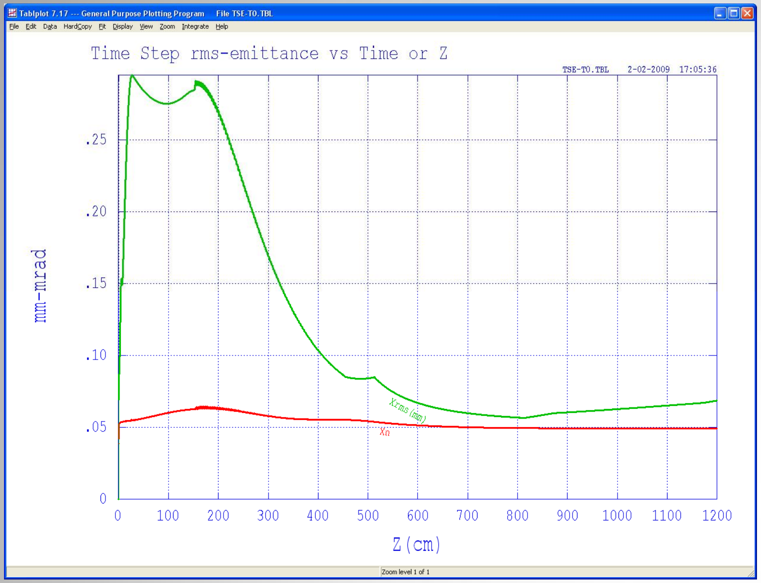
Velocity bunching

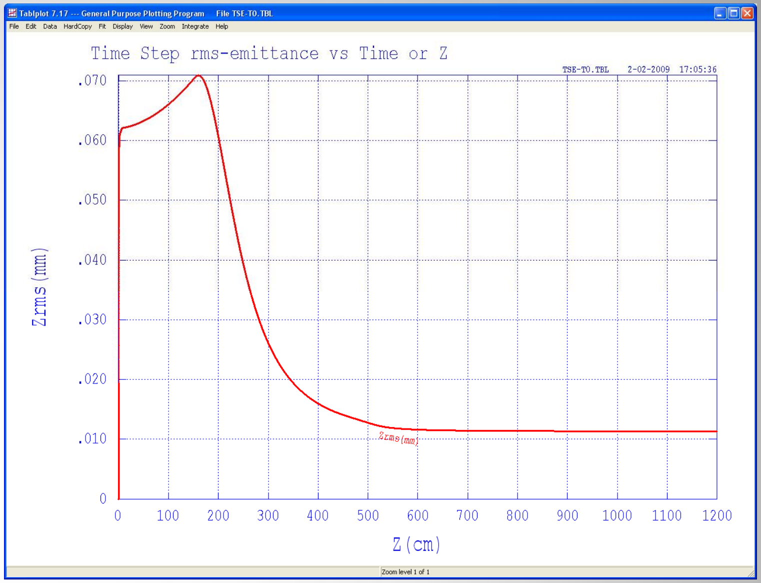
- Enhance current at low energy, avoid bending
- Inject near zero crossing
- Apply optimized focusing, manage ε evolution



Longitudinal phase space schematic for velocity bunching

VB example: SPARX (2008), 1 pC

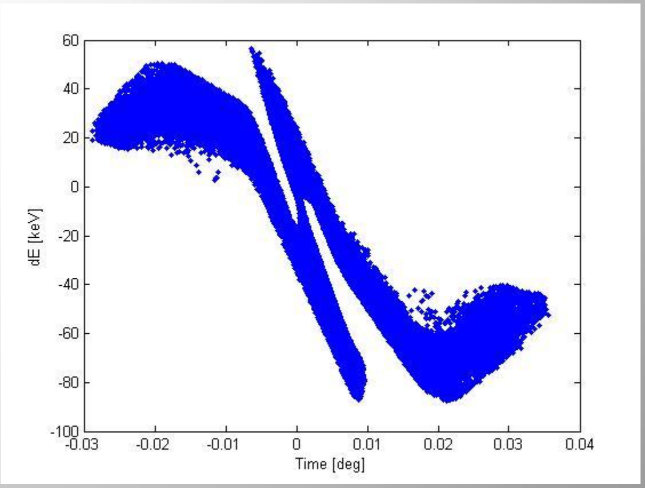




– ε growth manageable

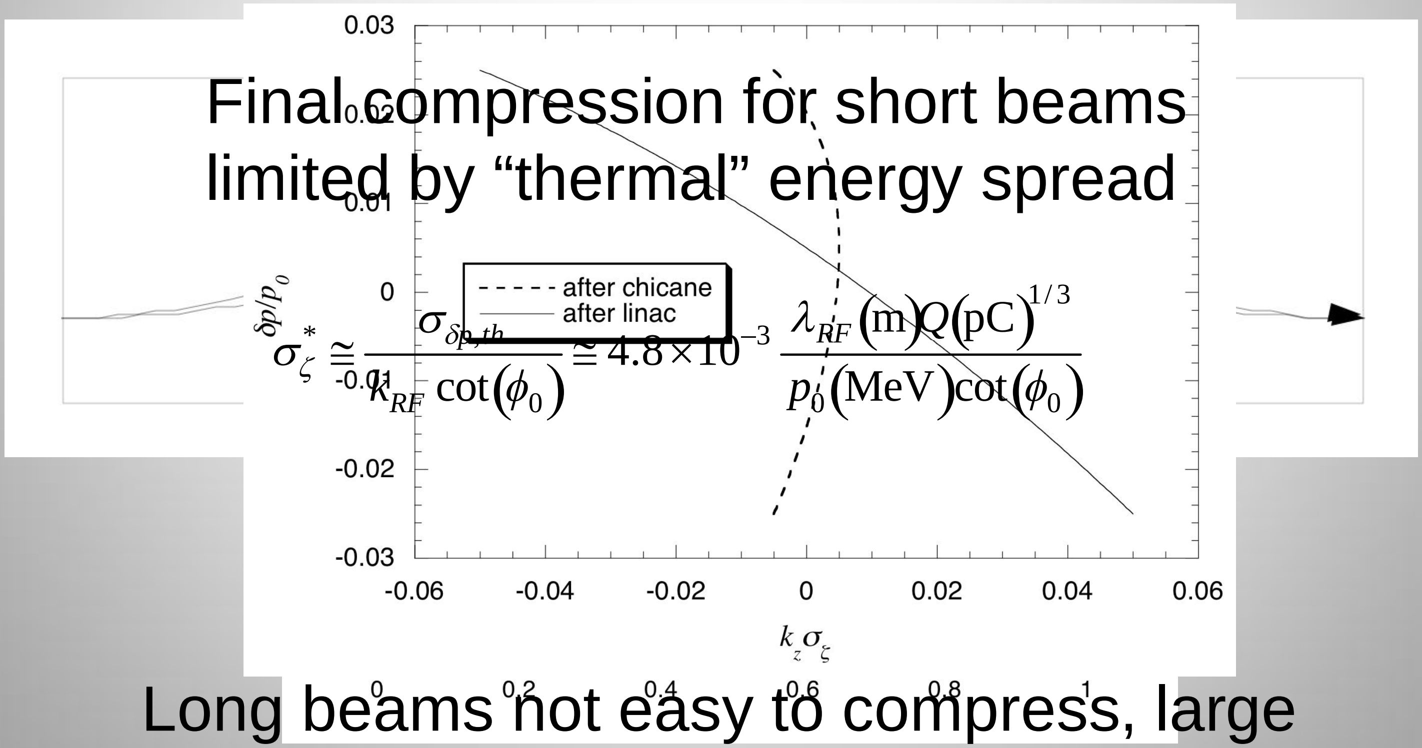
- 1 order of magnitude compression

-“Thermalized longitudinal phase space;
limits subsequent compression



Chicane Compression

- Run off-crest in linac, “chirp” longitudinal PS
- Remove chirp with chicane compressor
  - Complicated by thermal energy spread, CSR



Final compression for short beams limited by “thermal” energy spread

$$\sigma_\zeta^* \cong \frac{\sigma_{\delta p,th}}{k_{RF}\cot(\phi_0)} \cong 4.8\times10^{-3}\,\frac{\lambda_{RF}(\mathrm{m})Q(\mathrm{pC})^{1/3}}{p_0(\mathrm{MeV})\cot(\phi_0)}$$

Long beams not easy to compress, large longitudinal ε due to RF curvature

$$\varepsilon_{\zeta,\mathrm{rms}} = \frac{k_{RF}^2\sigma_z^3}{\sqrt{2}}$$

Original goal:
single spike XFEL operation

- 1D dimensionless gain parameter

$$\rho_{1D} = \left[\frac{JJ(K_{rms}) K_{rms} k_p}{4 k_u} \right]^{2/3}$$

- 1D gain length $L_{g,1D} = \frac{\lambda_u}{4\pi\sqrt{3}\rho_{1D}}$
- Cooperation length $L_{c,1D} = \frac{\lambda_r}{4\pi\sqrt{3}\rho_{1D}}$
- Single spike operation

$$\sigma_{b,SS} < 2\pi L_{c,1D} = \frac{\lambda_r}{2\sqrt{3}\rho_{1D}}$$

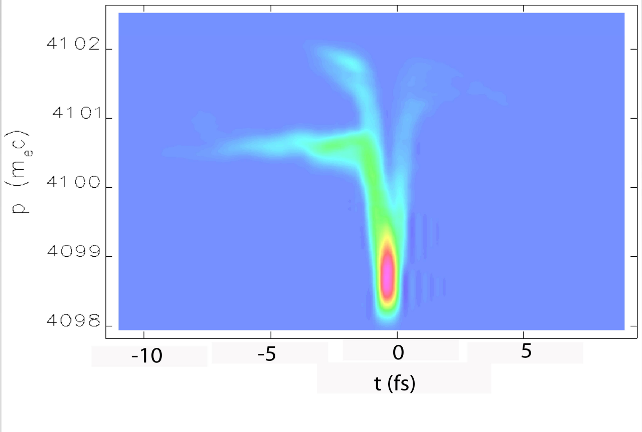
Numerical example: SPARX @ INFN-LNF

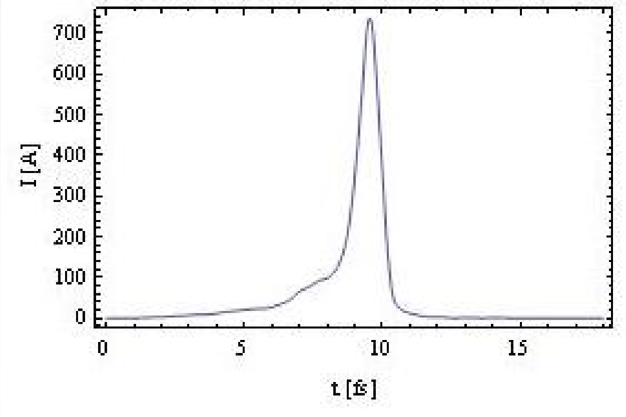
- Take 2 GeV operation, “standard SPARC undulator”, λ_u=2.8 cm
- Peak current *I*=2 kA, $\rho_{1D} = 1.8 \times 10^{-3}$
- Estimate single spike threshold:

$$\boxed{\sigma_{b,SS} < 0.48\ \mu\text{m (1.6 fsec)}}$$

- Note: with ultra-small *Q*, ρ is enhanced
  - – Spike is a bit shorter…
  - – FEL gain better

Ultra-short pulses at SPARX

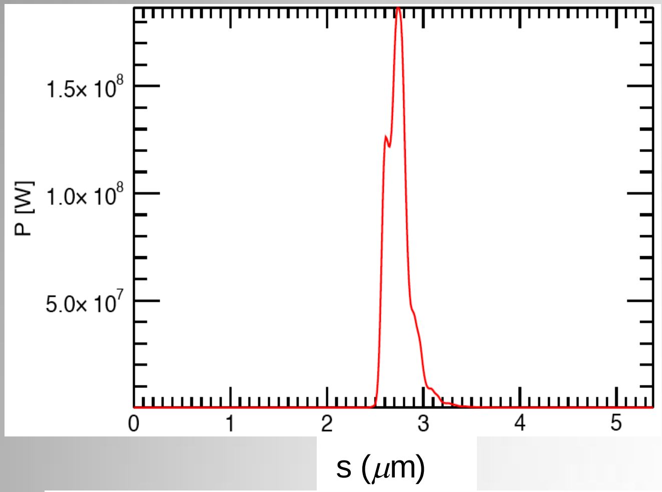


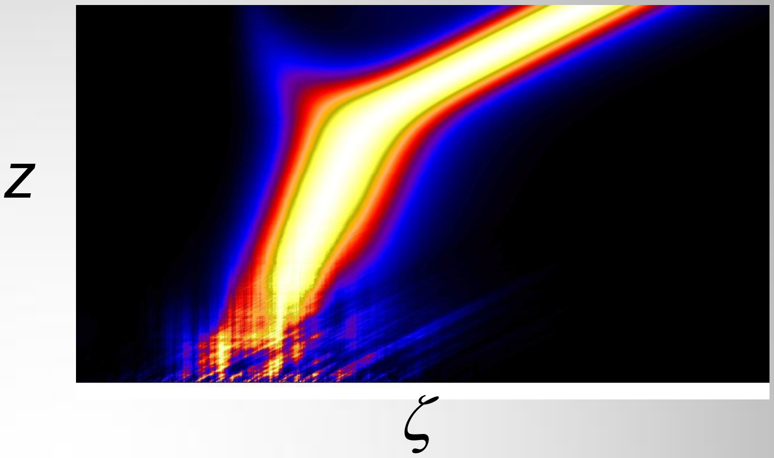


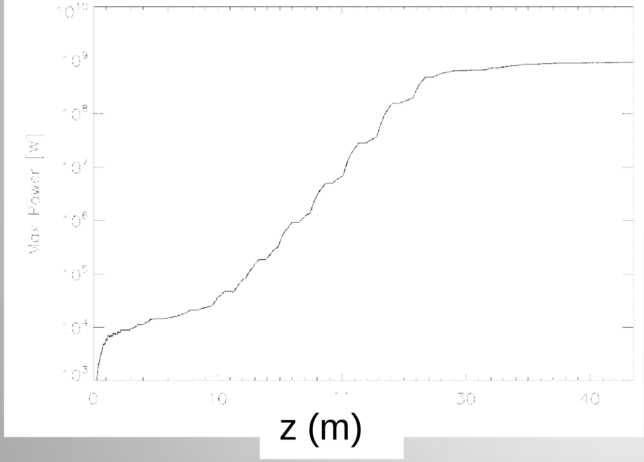
- Scaling indicates use of ~1 pC beam for single spike
- For 1 pC, σ_z only 4.7 μm after velocity bunching
- Use June 2008 version of SPARX lattice
  - compression no longer at end, at 1.2 GeV (Final 2.1 GeV)
- *Very* high final currents,
  - some CSR emittance growth, for 1 pC $\varepsilon_{nx} \cong 7.5 \times 10^{-8}$ m-rad
  - Longitudinal tails, higher peak brightness (2 orders of magnitude!)

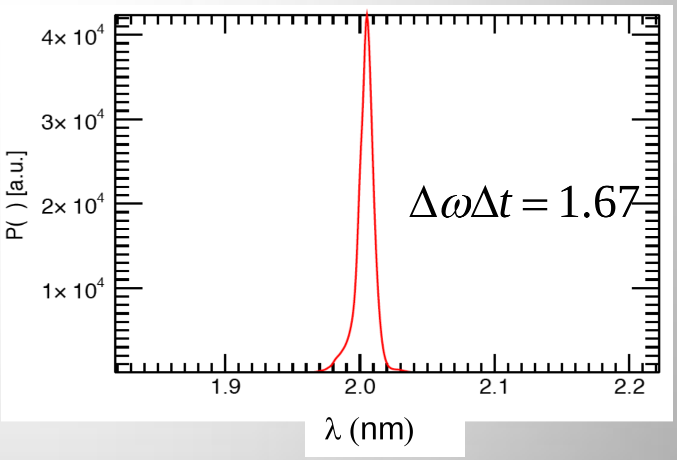
$$B = 2 \times 10^{17} \text{ A/m}^2$$

FEL performance: 1 pC



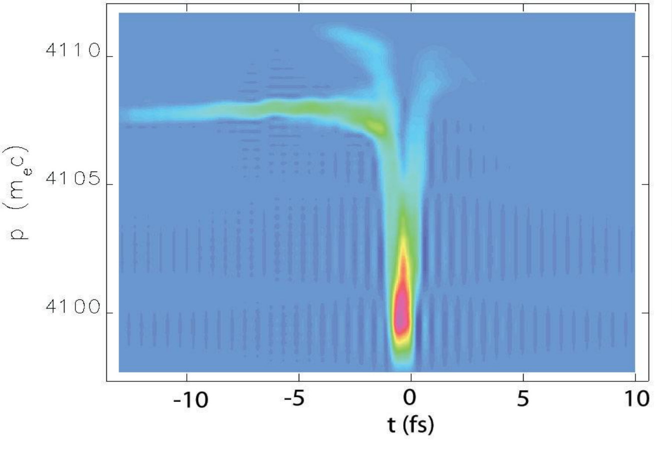




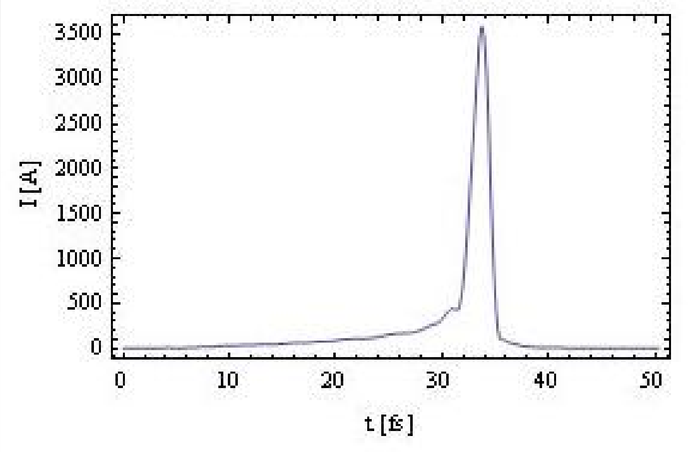


- Single spike with some structure
- > 1 GW peak power at saturation (30 m)
- 480 *attosecond* rms pulse at 2 nm

Higher Q SPARX case: 10 pC



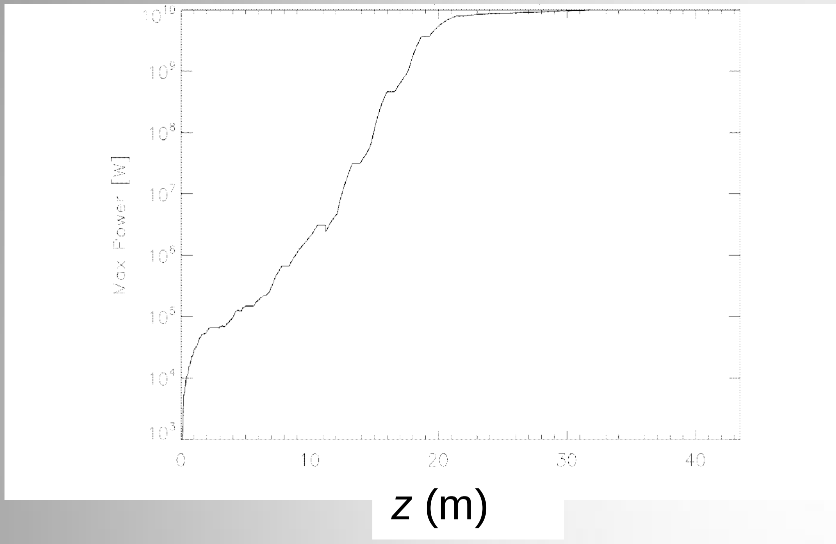
Longitudinal phase space, 10 pC

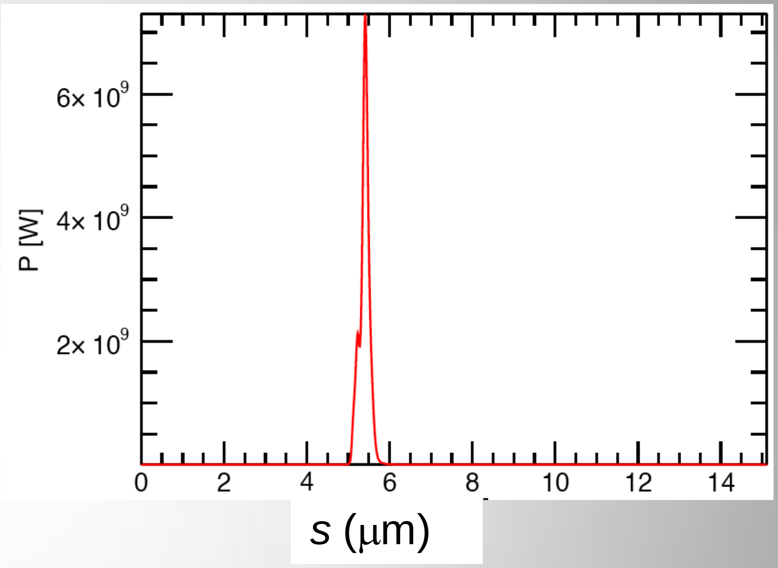


Current profile; some pedestal visible

- Put back beam power, X-ray photons
- Velocity bunch to 10.3 μm rms
  - Still space dominated charge scaling ~$Q^{1/3}$
- 1 fs pulse
- Large emittance growth $\varepsilon_n = 7.6\times10^{-7}$ m-rad

SPARX FEL at 10 pC

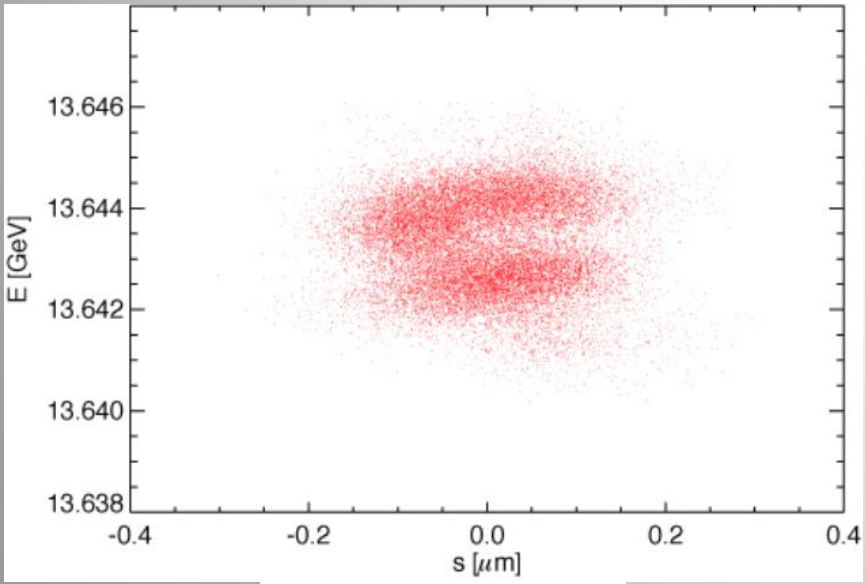




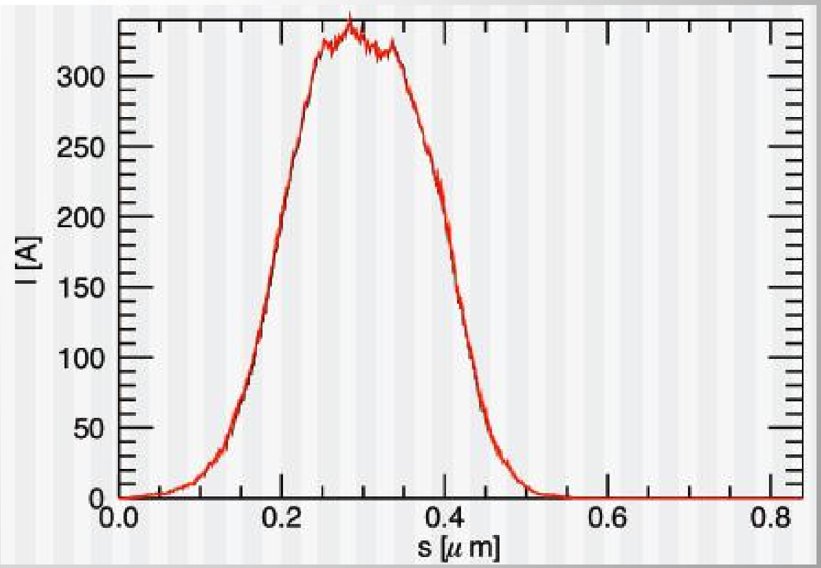
- 10 GW peak FEL power
- Saturation at 20 m (v. high brightness)
- Quasi-single spike
  - Lower brightness=longer cooperation length
  - 4×10^{11} photons, good for many applications

Extension to LCLS case

- 1 pC does not give quasi-single spike operation
  - Beam too long, need to scale with λ/ρ
- Use 0.25 pC (1.5M e$^-$), obtain ε_n=0.033 mm-mrad
- *Yet highe*r brightness; saturation expected in 60 m

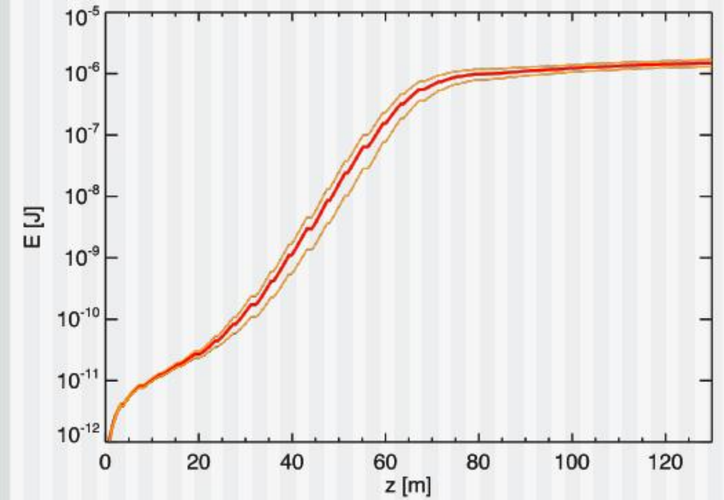


$$\sigma_E / E = 4 \times 10^{-4}$$

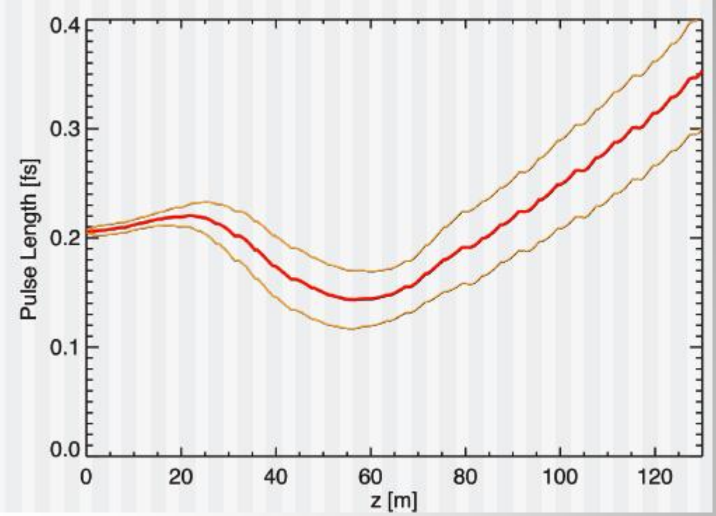


Over 350A peak

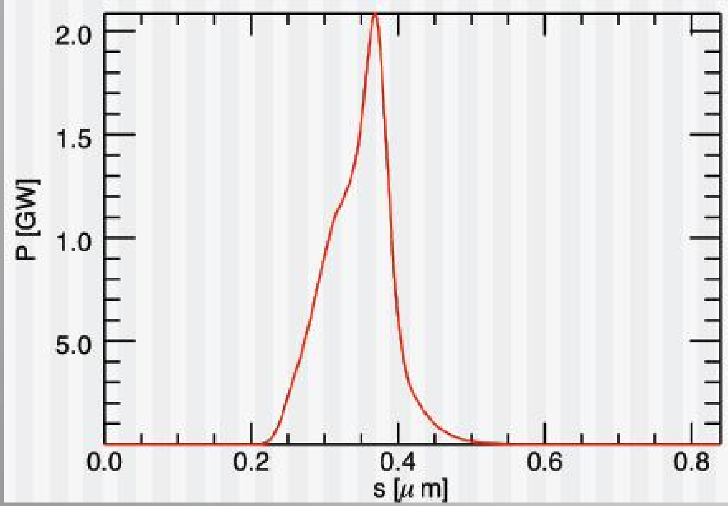
LCLS Genesis results



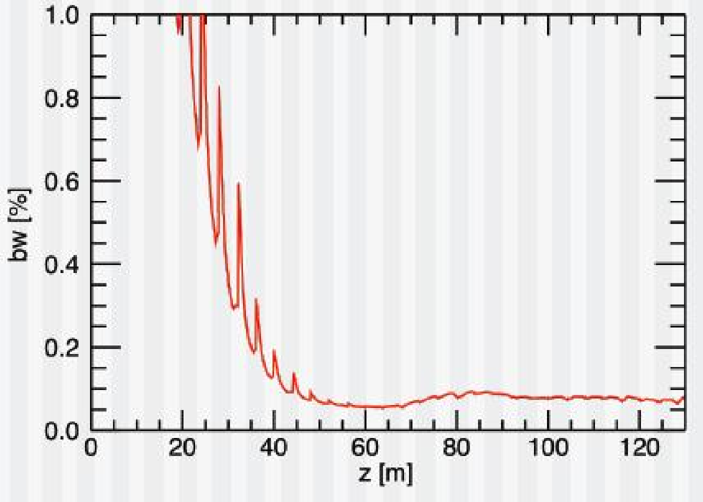
Deep saturation achieved



Minimum rms pulse: 150 attosec



Quasi-single spike, 2 GW

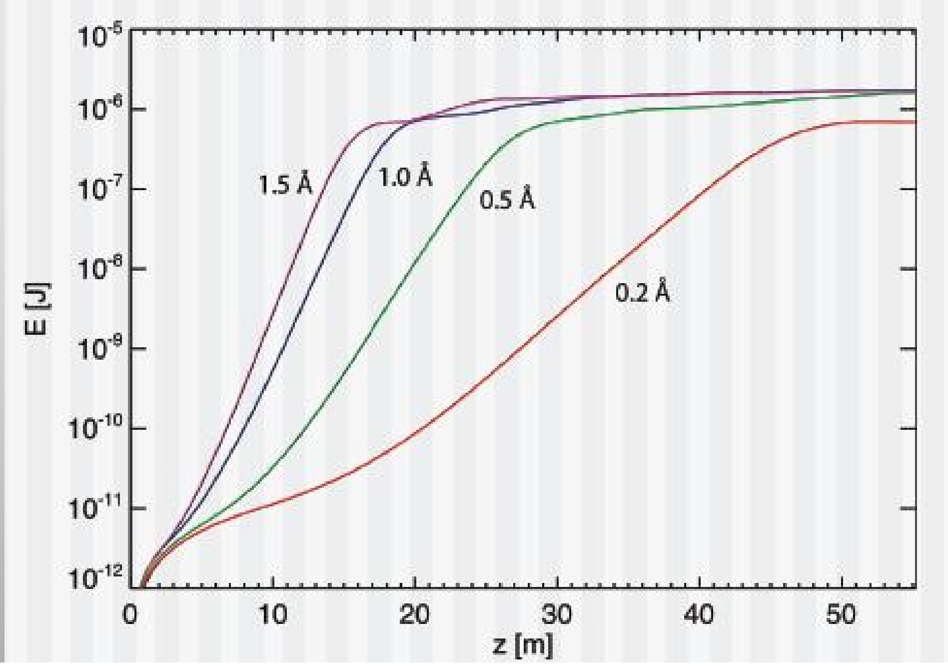


$\sigma_{\omega}\sigma_{t} \cong 1.1$

Alternative scenario: new undulator for very short λ operation

- Use high brightness beam to push to short wavelength
  - LCLS example
- Shorter period undulator
  - *Shorter still soon available…*

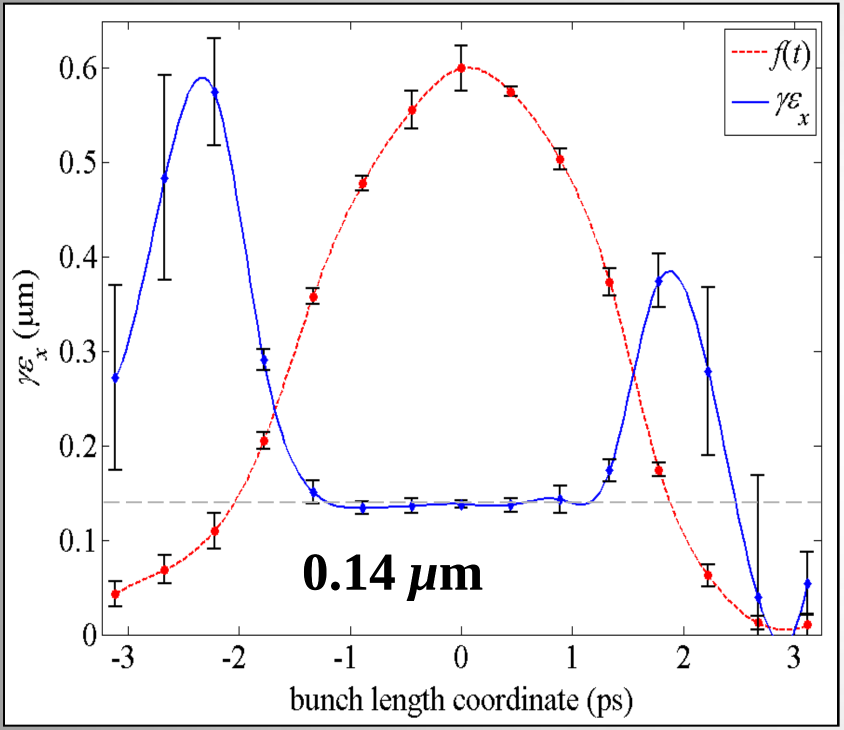
K_u	**1**
λ_u (cm)	1.5
β (m)	2-6
U (GeV)	4-14

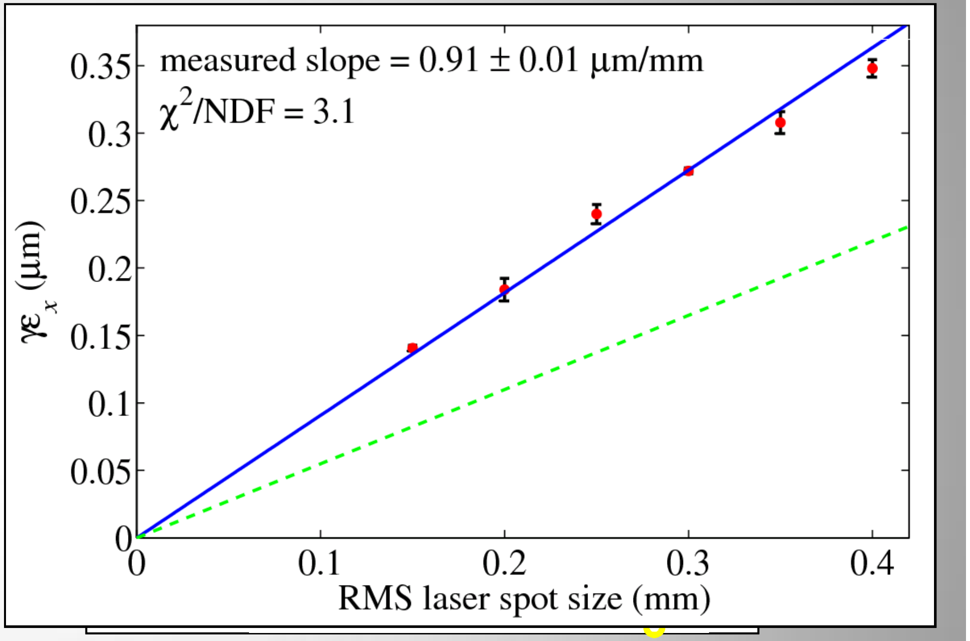


Progress at SLAC on low-*Q*, high brightness beams

- 20 pC case measured
  - *Diagnostic limitation*
- Excellent emittance after injector
  - No velocity bunching
- Chicane compression
  - As low as 2 fs rms, with some ε growth

Slice Emittance at LCLS: Low Charge Case





OTR screen with
transverse
deflector ON

Emittance near calculated thermal emittance limit,

20 pC, 135 MeV, 0.6-mm spot diameter, 400 *μ*m rms bunch length (5 A)

Measurements and Simulations for 20-pC Bunch at 14 GeV

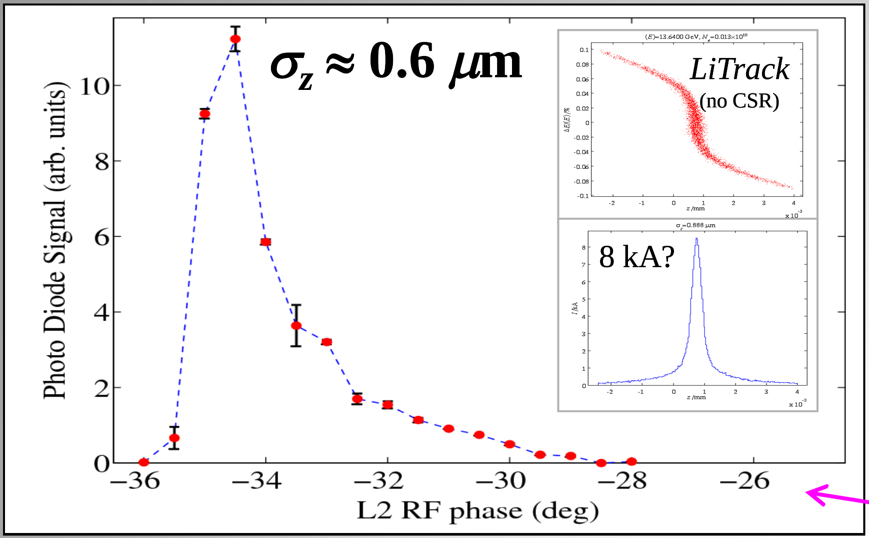
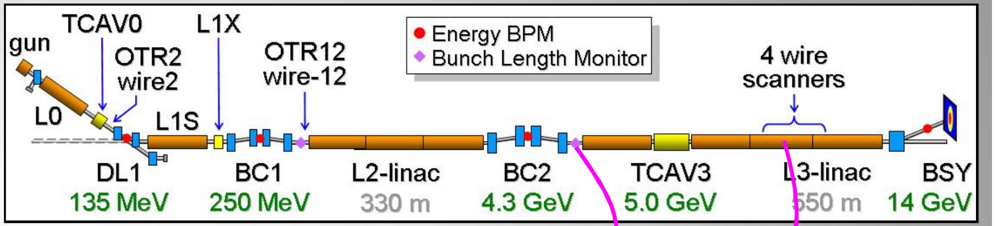
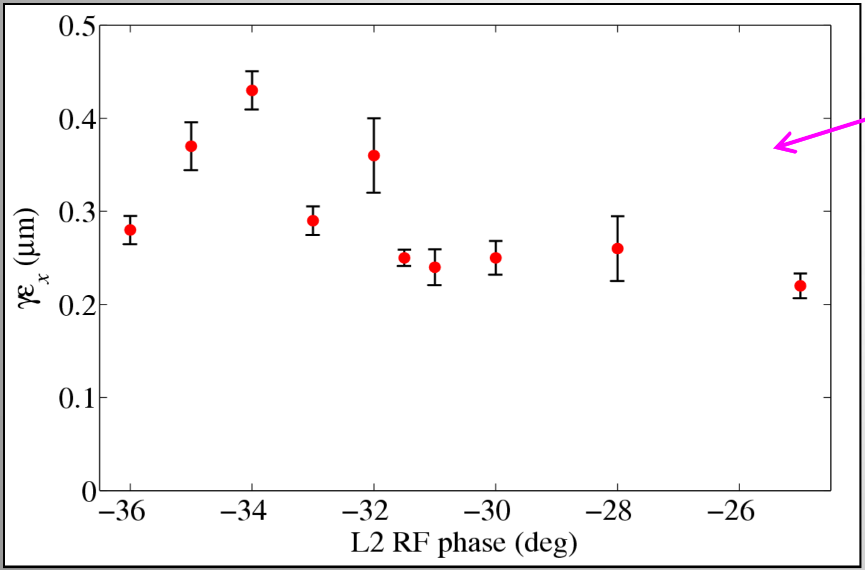
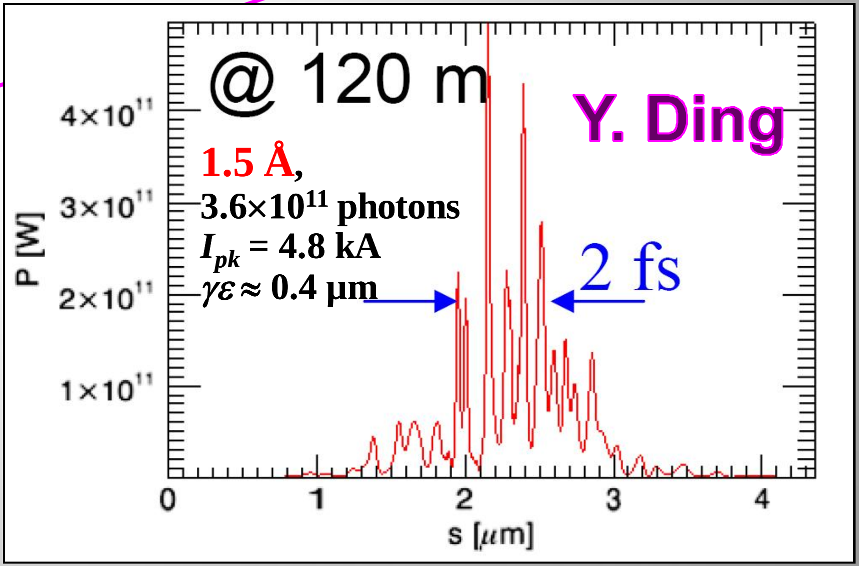


Photo-diode signal on OTR screen after BC2 shows minimum compression at L2-linac phase of -34.5 deg.





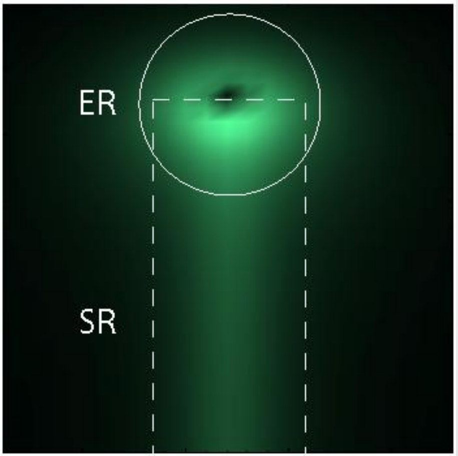
Horizontal projected emittance **measured** at 10 GeV, after BC2, using 4 wire-scanners.



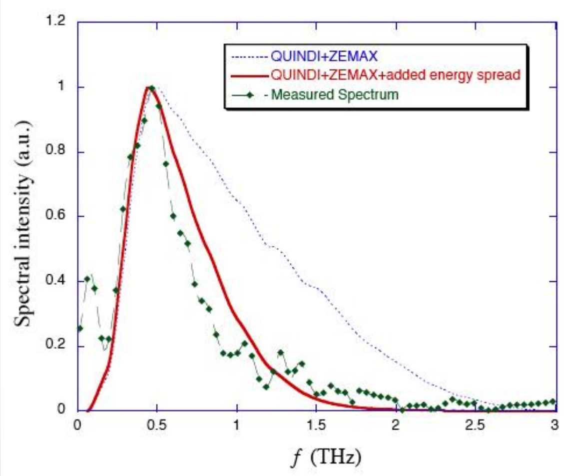
LCLS FEL **simulation** at 1.5 Å based on measured injector beam and *Elegant* tracking, with CSR, at 20 pC.

Ultra-short beam application: coherent, sub-cycle radiation

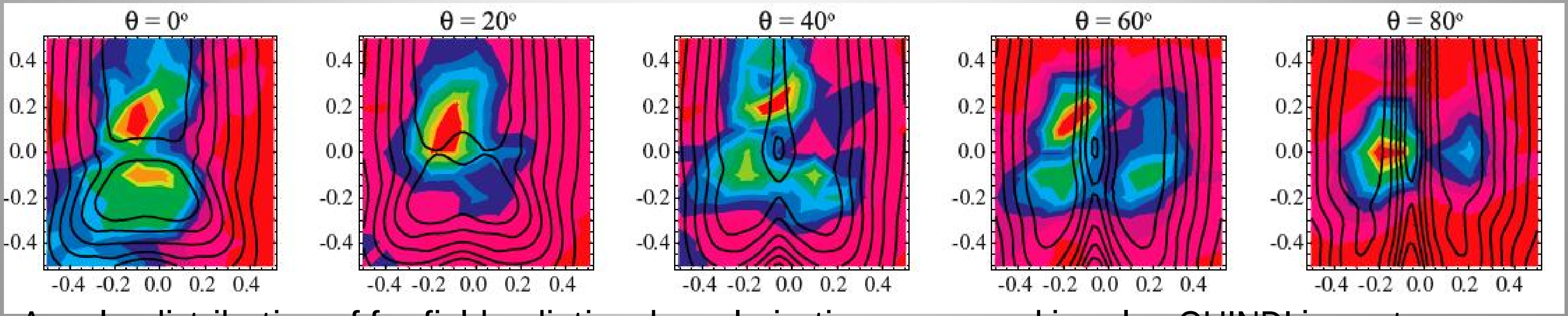
- Coherent transition radiation
- Non-destructive: coherent edge radiation (CER)



Combined ER and SR



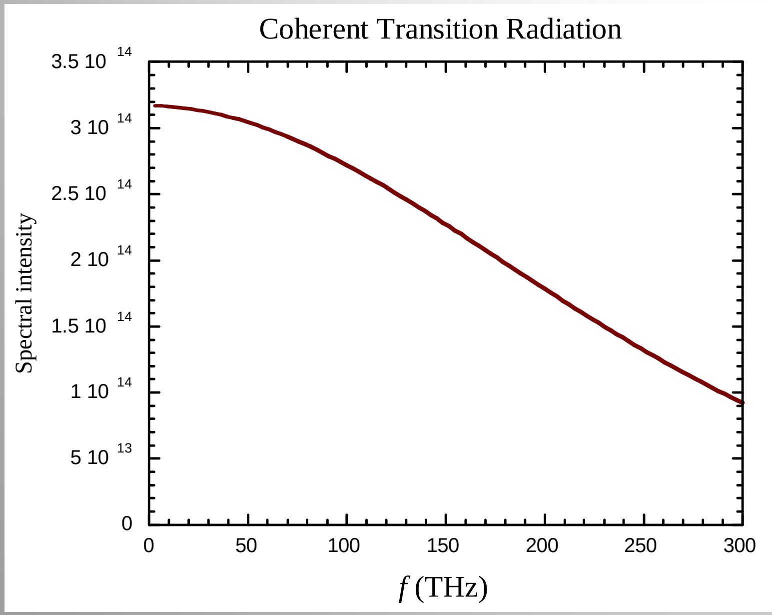
Total emitted CER spectrum (BNL ATF, UCLA compressor), measured compared to QUINDI. Coherent THz pulses…

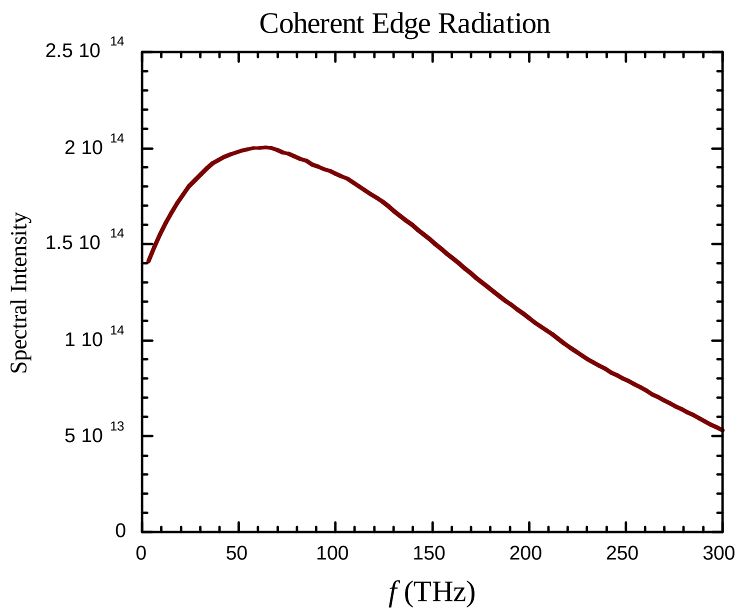


Angular distribution of far-field radiation, by polarization: measured in color, QUINDI in contours

Coherent optical-IR sub-cycle pulse

- CER and CTR cases simulated with QUINDI
  - Coherent *IR*, sub-cycle pulse (SPARX 1 pC case)
  - Unique source at these wavelengths (~30 MW, peak)
  - Use in tandem w/X-rays in pump-probe
  - Would like to try this at LCLS...

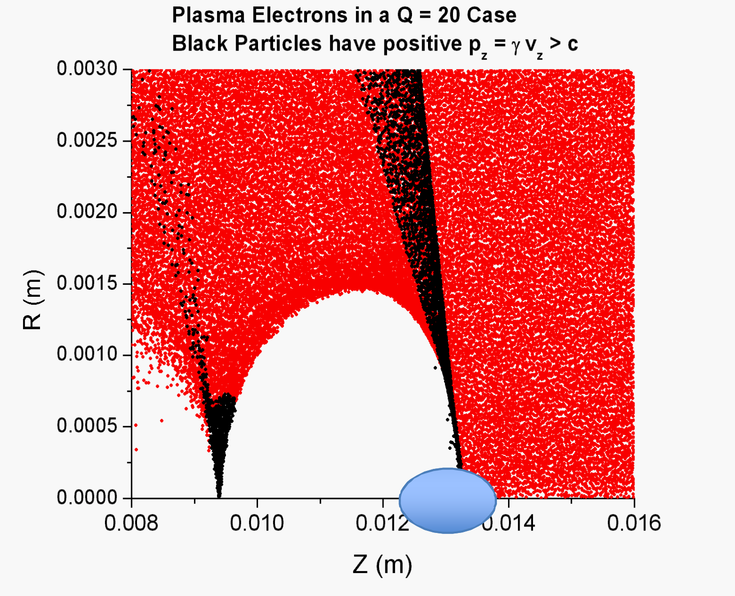




Ultra-short beam application: IR wavelength PWFA

- Ultra-high brightness, fs beams impact HEP also!
- Use 20 pC LCLS beam in high *n* plasma
- In “blowout” regime: total rarefaction of plasma e$^-$s
  - Beam denser than plasma
  - Very nonlinear plasma dynamics
  - Pure ion column focusing for e-s
  - Linac-style EM acceleration
  - General measure of nonlinearity:

$$\tilde{Q} \equiv \frac{N_b k_p^3}{n_0} = 4\pi k_p r_e N_b \begin{cases} \ll 1, & \text{linear regime} \\ > 1, & \text{nonlinear "blowout"} \end{cases}$$

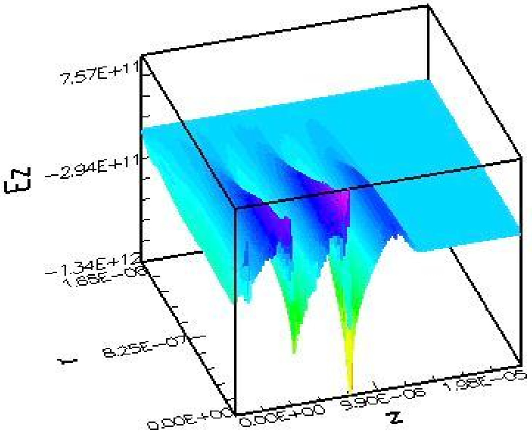


MAGIC simulation of blowout PWFA case

Optimized excitation

- Beam must be short and narrow compared to plasma skin depth $\sigma_r < k_p^{-1}$ $\sigma_z < k_p^{-1}$
- In this case $\tilde{Q} > 1$ implies $n_b > n_0$, blowout
- With 2 fs LCLS beam we should choose $n_0 = 7 \times 10^{19}\ \text{cm}^{-3}$
- For 20 pC beam, we have $\tilde{Q} = 7$
- *1 TV/m fields* (!)
- Forming collaboration
  - UCLA-SLAC-USC-DESY

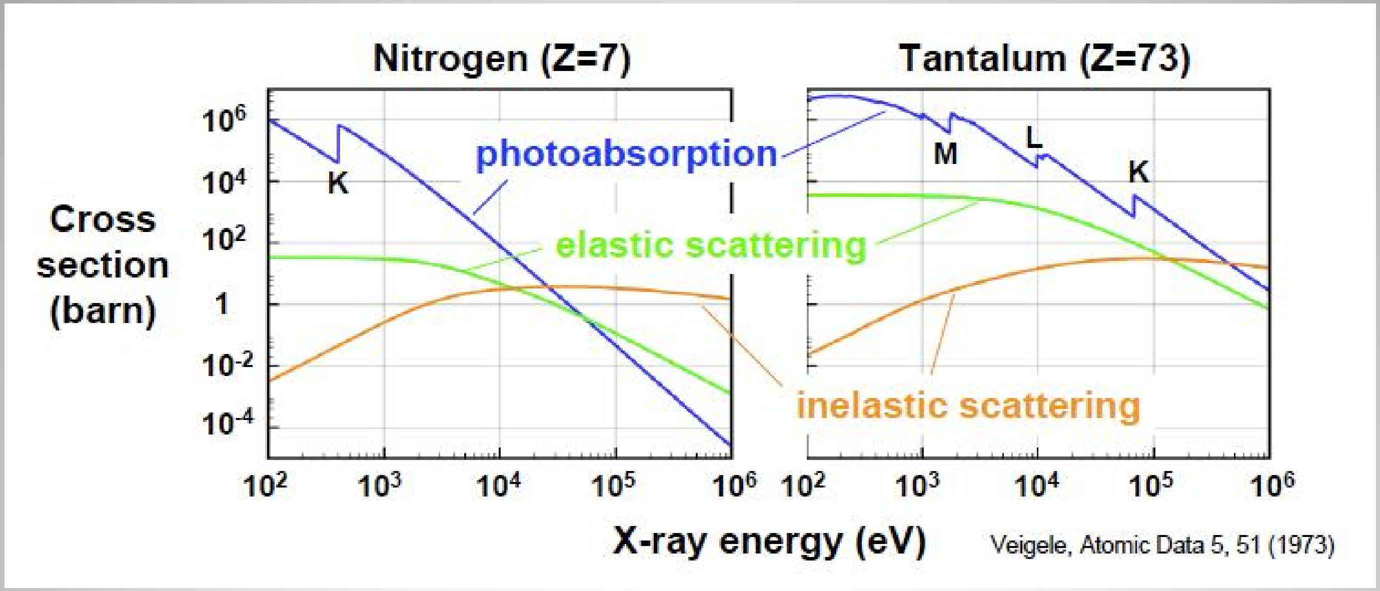
OOPIC simulation of LCLS case



What are the experimental issues?

- Length of plasma: ~1 mm
  - 1 GeV energy change, perturbative at beginning
  - Straightforward diagnosis
- Plasma formation
  - 3 atm gas jet
  - Ionization via LCLS X-rays…
  - Beam-induced ionization
- Beam focusing
  - Need sub-μm beam
  - Use strong-field mini-beta insertion

X-ray ionization

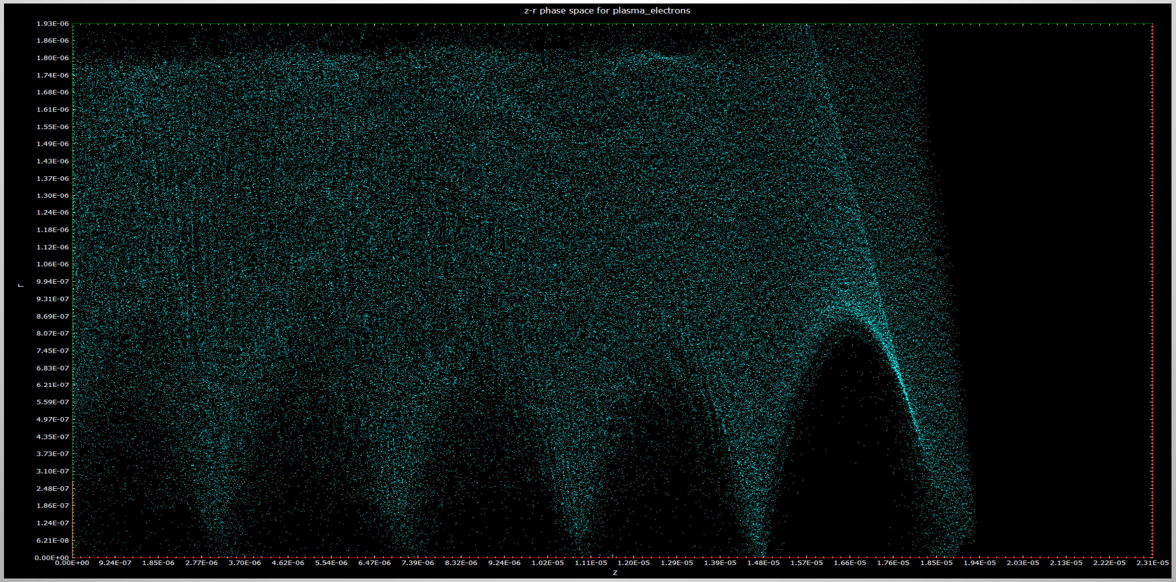


Veigele, Atomic Data 5, 51 (1973)

- Ionization cross section for 8 keV X-rays in gas is in the kBarn range
- Mean free path of few cm
- With 1E12 photons and 50 μm X-ray beam, ionization fraction <1E-4…

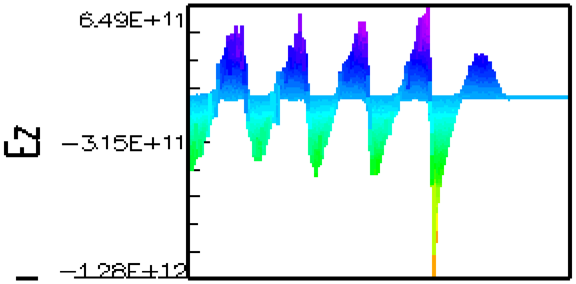
Beam-field induced ionizaton

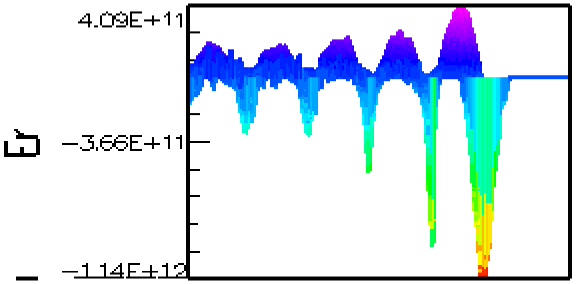
- Need to focus beam to < 1 μm rms (later...)
- Radial E-field > TV/m
- Ionization studied in hydrogen gas



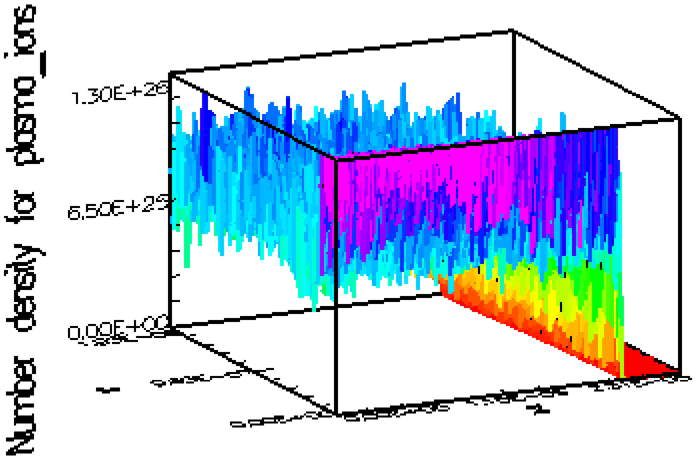
OOPIC study, 3 atm hydrogen ionized by beam

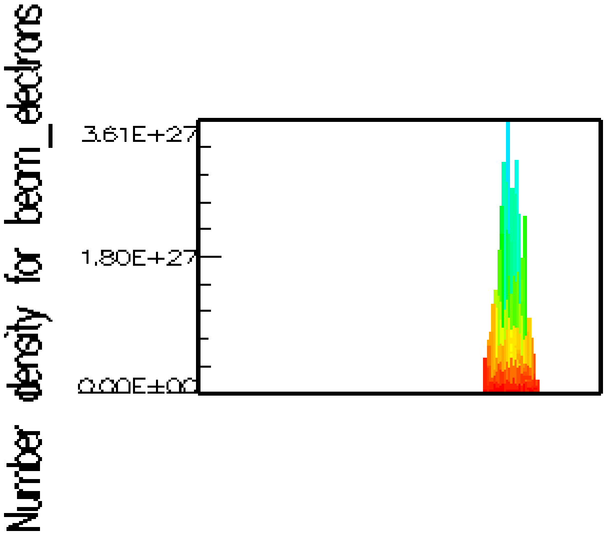
OOPIC predictions for 3 atm case





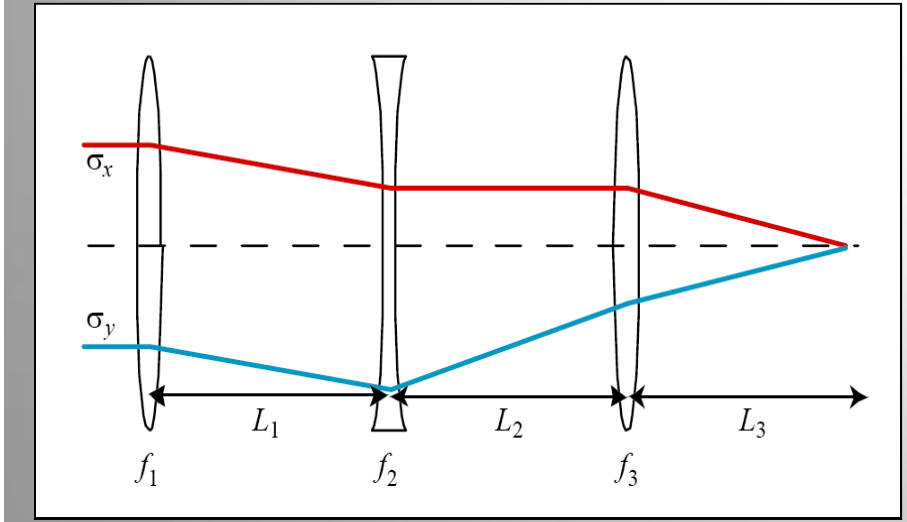
~7E19/cc plasma, >TV/m peak wakefield!

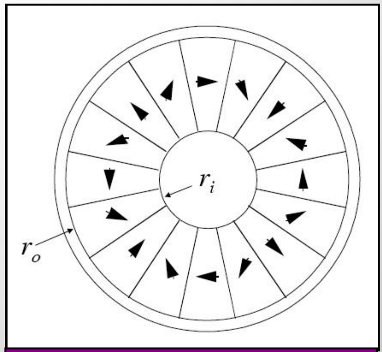




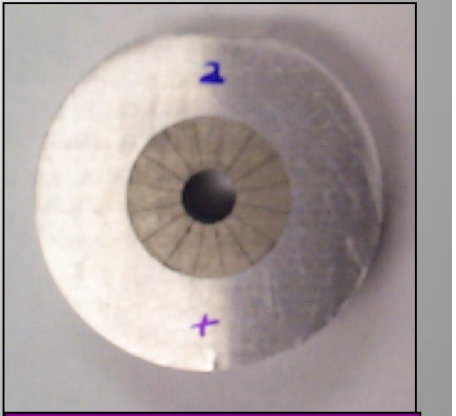
Final focusing system

- Need few mm β-function at plasma
- Use ultra-high field permanent magnet quads
  - – mitigate chromatic aberration limits
  - – FF-DD-F triplet, adjustable through quad motion
- Developed 570 T/m (!) PMQ fields





Small aperture PMQ B'=570 T/m



Halbach PMQ as built

Where and when

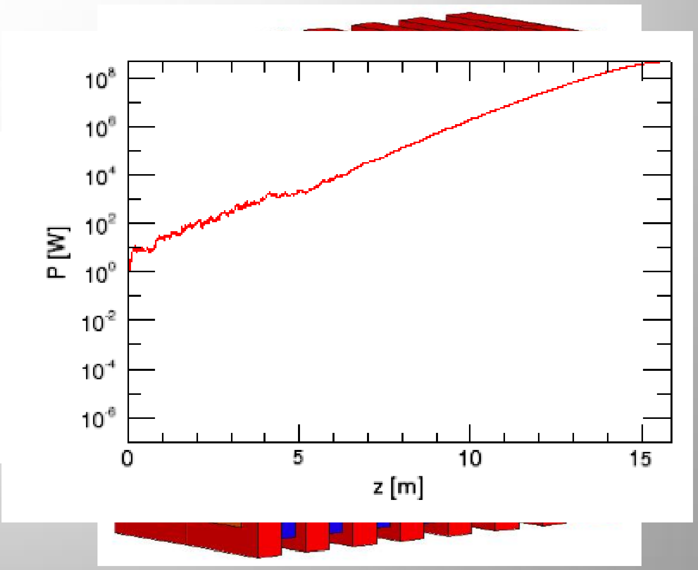
- Option 1: LCLS beam time proposal
  - Downstream of undulator
  - Competitive
  - Disruptive due to mini-β insert
- Option 2: LCLS bypass line
  - Proposal for test beam (HEP)
  - Possible addition of undulator (BES)
  - Under consideration now, could be fast track
- Option 3: FACET *after upgrade*
  - Need RF photoinjector
  - Optics not yet established
  - *Long* lead time…

Use Table-top XFEL undulator?

- LMU MPQ (Garching)-centered collaboration (BESSY, LBNL, UCLA, etc.)
- UCLA collaboration on beam transport and advanced undulator (Pr-based)
- Need short λ_u high field undulator for X-rays @1 GeV – important for linac-based sources too…

Examine use of undulator at SPARX
Lase at 6.5 Å (smaller by almost 5)
Saturation at 500 MW (5E9 γ's)
Gain length shortened by 2

Apply with LCLS energy… 0.1 Å?



Lets organize

- Collaboration
  - Based on E169
- Initial explorations with SLAC stake-holders
  - Accelerator people
  - Director
  - Bucksbaum, Stohr
- First experiments in 2011?