Summary of COTR Effects.

Stephan Wesch

Deutsches Elektronen-Synchrotron, Hamburg

10th European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators

Standard transverse diagnostic for e-linacs

Transverse beam profiling through Optical Transition Radiation (OTR)

- ★ Full transverse information
- ★ Single shot measurement
- ★ Broad selection of available detectors
- ★ Simple and robust setup geometry

▶ **Standard method for emittance measurement, beam matching, etc.**

Breakdown of OTR beam profiling

OTR method relies on incoherent radiation of individual bunch particles

- Incoherent superposition of point spread function

→ Reflects transverse charge distribution

Origin for coherent radiation

1. Overall bunch length $\sigma_\mathrm{t} \sim 1\,fs$
2. Microstructures inside bunch $\lambda_\mathrm{MS} \sim 1\,fs$

→ Superposition of fields (interference effects)

→ Enhancement of emitted intensity

Coherent intensity

$$\frac{I_\mathrm{coh}}{I_\mathrm{incoh}} \approx N \cdot |F(\lambda, \Omega)|^2 \quad \text{with} \quad F(\vec{k}) = \int \rho_\mathrm{norm}(\vec{x})\ \exp(-\mathrm{i}\,\vec{k} \cdot \vec{x})\, d\vec{x}$$

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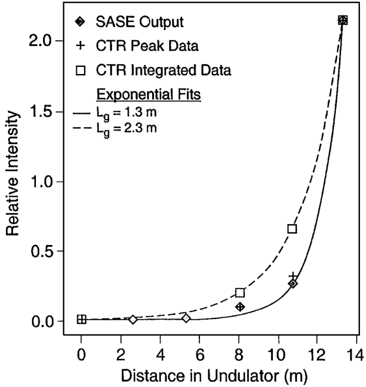
Number of electrons N large ($\sim 10^9$) → Only small fraction has to participate!

Does NOT image the beam profile!

COTR on purpose @ APS

A.H. Lumpkin et al., Phys. Rev. Lett. **86**, 79 (2001)



Machine info

- SASE FEL Experiment
- $\lambda_u = 537\,nm$
- $\sigma_t = 200 - 1000\,fs$
- 5 undulator segments
- Each equiped with OTR station
- Separation of SASE light and OTR

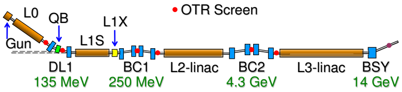
SASE microbunching formation

$\Downarrow$

growth of OTR intensity

Unexpected COTR observations @ LCLS

R. Akre et al., Phys. Rev. ST Accel. Beams **11**, 030703 (2008)
H. Loos et al., FEL2008 Proc., Gyeongju, Korea, p. 485



Setup

- RF photoinjector
- Injection into main linac via DL1
- BC1 off
- $\sigma_t = 2.4\,ps$ (rms)
- OTR screen behind BC1

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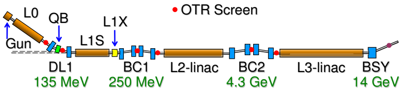

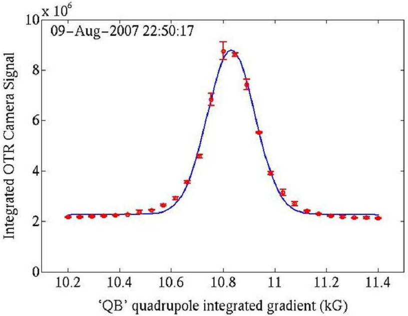

Setup

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- BC1 off
- $\sigma_t = 2.4\,ps$ (rms)
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Scan of dogleg quadrupole QD

$\rightarrow$ OTR intensity varies by factor 4

$\rightarrow$ Max. intensity - DL1 tuned to $R_{51} = R_{52} = 0$, $R_{56} \neq 0$

$\rightarrow$ $\sigma_{x,y}$ increased by 25%

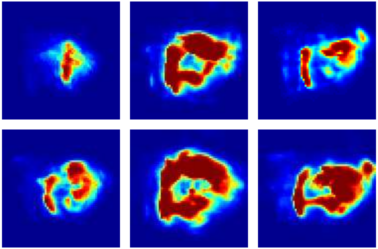
Comparison with incoherent level

$\Downarrow$

bunch fraction $3 \cdot 10^{-5}$!

COTR @ LCLS after compression

H. Loos et al., FEL2008 Proc., Gyeongju, Korea, p. 485



After BC1

- $\sigma_t \sim 120\,fs$ (rms) @ $I_{peak} \sim 900\,A$

→ Enhancement factor up to **100**

After BC2

- $\sigma_t \sim 30\,fs$ (rms) @ $I_{peak} > 3\,kA$

→ Enhancement factor up to $\mathbf{10}^5$

Bunch images

- Strong shot-to-shot fluctuation
- Ring structures
- Changing spectral content
  (current spikes in head & tail)

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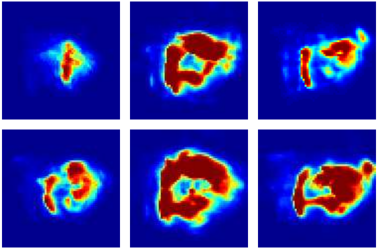

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Bunch images

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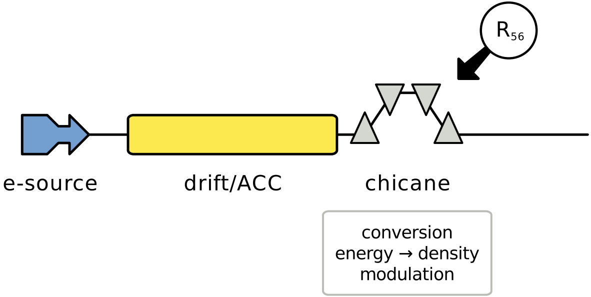
- Changing spectral content
  (current spikes in head & tail)

★ **No OTR measurements possible between dogleg and dump dipole!**

Microbunching Instability

E.L. Saldin et al., Nucl. Instrum. Methods Phys. Res., Sect. A **483**, 516 (2002)
Z. Huang et al., Phys. Rev. ST Accel. Beams **5**, 074401 (2002)



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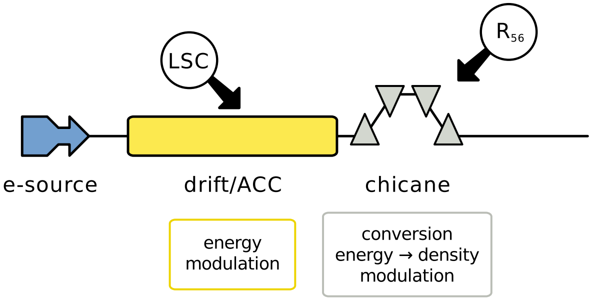

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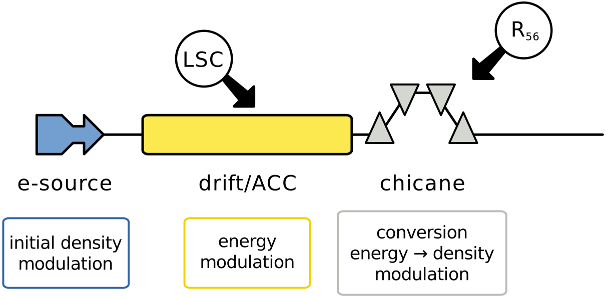

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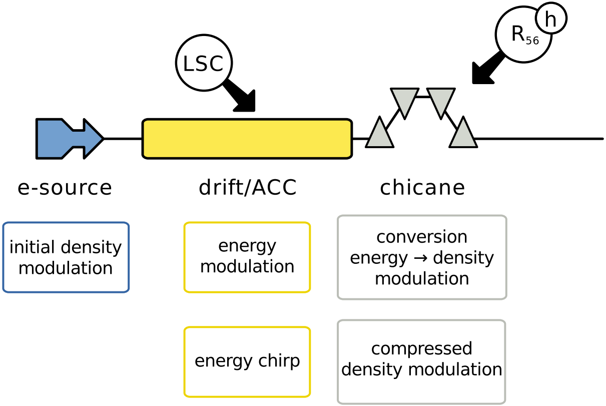

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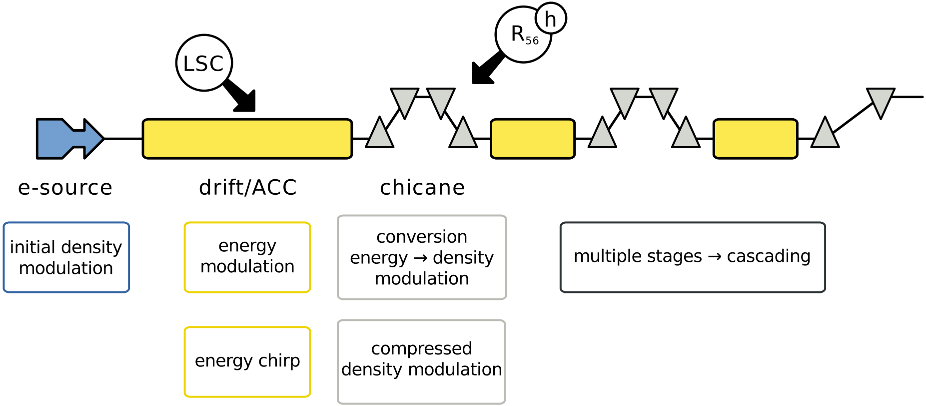

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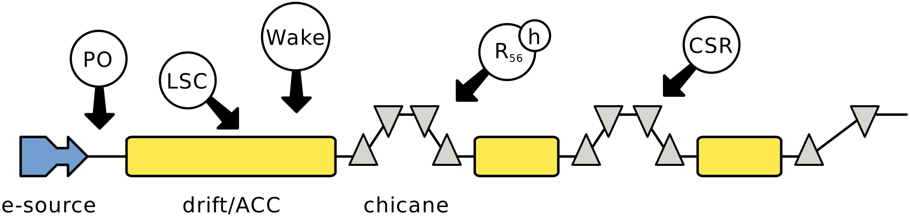


initial density modulation

energy modulation

conversion energy → density modulation

multiple stages → cascading

energy chirp

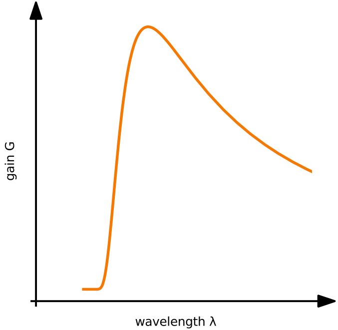
compressed density modulation

coherent synchrotron radiation
plasma oscillation
geometric wakefields

Microbunching Gain

1-dim theory (one chicane)

$$G = \frac{\rho_\mathrm{f}}{\rho_\mathrm{i}} \sim C\,k\;|R_{56}|\;|Z_\mathrm{LSC}(k)|\;\exp(-\frac{1}{2}\,C^2\,k^2\,R_{56}^2\,\delta_\mathrm{E}^2)$$



Characteristic behavior

- Position and value of G_max critical!

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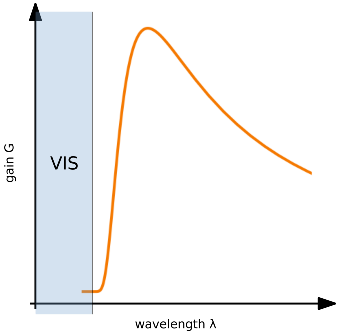

Characteristic behavior

- Position and value of G_max critical!
- $G \ll 1$ in visible regime

$\rightarrow$ **Incoherent radiation**

Microbunching Gain

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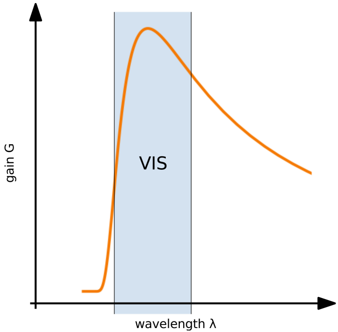
$$G = \frac{\rho_\mathrm{f}}{\rho_\mathrm{i}} \sim C\,k\,|R_{56}|\,|Z_\mathrm{LSC}(k)|\,\exp(-\frac{1}{2}\,C^2\,k^2\,R_{56}^2\,\delta_\mathrm{E}^2)$$



Characteristic behavior

- Position and value of G_max critical!
- $G \ll 1$ in visible regime

→ **Incoherent radiation**

- Other parameters
- Compression of modulation

→ $G \gg 1$ in visible regime

→ **Coherent radiation**

Microbunching Gain

1-dim theory (one chicane)

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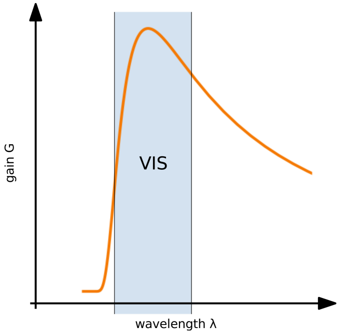

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- $G \ll 1$ in visible regime

$\rightarrow$ **Incoherent radiation**

- Other parameters
- Compression of modulation

$\rightarrow$ $G \gg 1$ in visible regime

$\rightarrow$ **Coherent radiation**

$\frac{\lambda}{2\pi}\,\gamma_0 < \sigma_\mathrm{x,y} \rightarrow$ **3-dim treatment necessary!**

$(F_\mathrm{3D}(\lambda,\Omega),\,\epsilon_\mathrm{n},\,\beta,\,R_{51},\,R_{52})$

Initial modulation for RF photoinjectors

Potential sources:

Non-smooth temporal laser profile

- Finite bandwidth of drive laser

$\rightarrow$ $\Delta\lambda_{\text{laser}} \approx 1\,nm$ @ UV $\lambda_{\text{i}} > 50\mu m$

$\rightarrow$ Visible for compressed bunches

Inhomogenity of photocathode

- Irregularities of surface

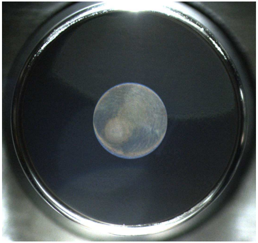
$\rightarrow$ Small variation in QE

Shot noise

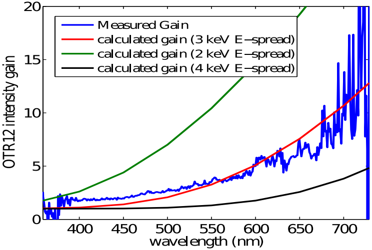
- Pointlike electrons
- White spectrum in modulation

$\rightarrow$ 3-dim treatment

$\rightarrow$ $\delta_{\text{E}} = 3\,keV$



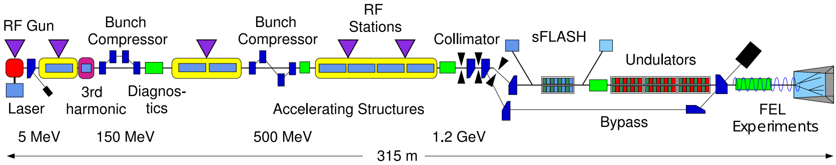
Courtesy S. Lederer



D. Ratner et al., FEL2008, Gyeongju, Korea, p. 338

Microbunching instability @ FLASH

Overview 2011



Setup till Sep. 2009

- roll-over compression
- $Q \approx 1\,nC$

Gun $\sigma_t \approx 5\,ps$ (rms) @ $I_{peak} \approx 40\,A$

BC1 $\sigma_{t,spike} \approx 200\,fs$ @ $I_{peak} \approx 0.3\,kA$

BC2 $\sigma_{t,spike} < 50\,fs$ @ $I_{peak} > 1\,kA$

Setup since spring 2010

- linearized phase space
- $Q = 150\,pC - 1\,nC$

Gun $\sigma_t \approx 5\,ps$

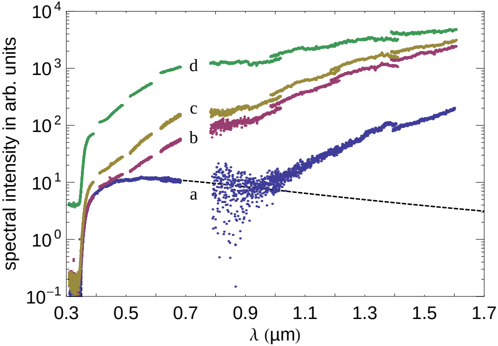
BC1 $\sigma_t > 500\,fs$

BC2 $\sigma_t > 50\,fs$

Spectral measurements VIS and NIR

S. Wesch et al., FEL2009 Proc., Liverpool, UK, p. 619

In front of dogleg w/o 3rd harmonic (roll-over compression)



Compressed beam (a)

- no COTR
- coherent fraction starts @ $1\ \mu m$

Microbunching not obvious
$\rightarrow$ Could be related to short spike ...

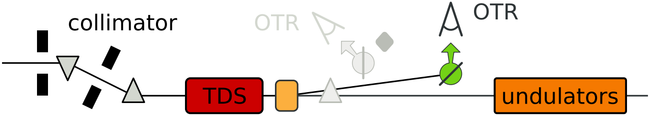
Uncompressed beam

b.) Shift of coherent cut-off to shorter wavelength ($C \rightarrow 0$)

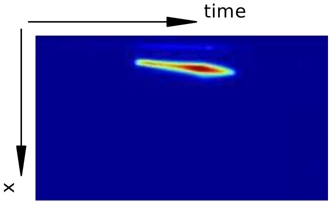
c+d.) Reduced R_{56} $\rightarrow$ shift cut-off into UV region

Spectral content is very broadband

Time resolved measurements @ FLASH



C. Behrens et al., FEL2010 Proc., Malmö, Sweden, p. 131



x - t - plane

- Vertical time streak (shearing of slices)

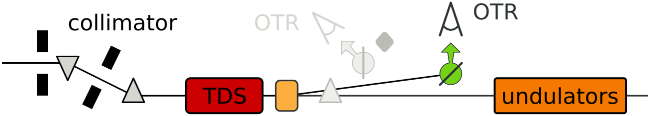
→ Conserving transverse coherence!

Compression dependence

- moderate compressed bunch

→ apparently incoherent OTR

Time resolved measurements @ FLASH



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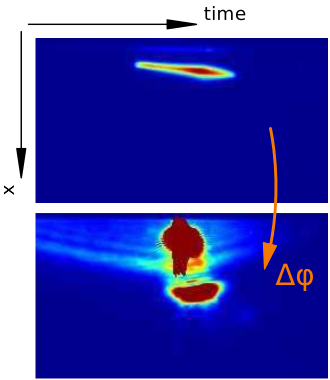

x - t - plane

- Vertical time streak (shearing of slices)

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Compression dependence

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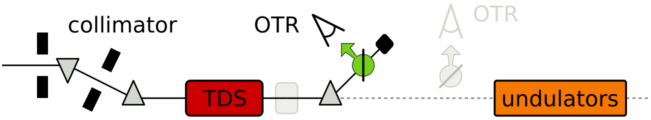
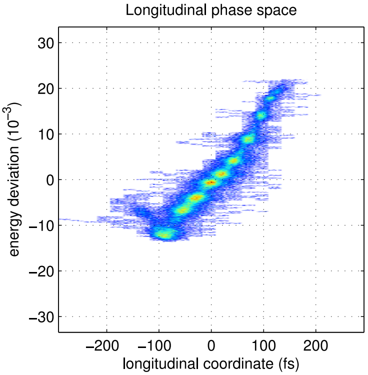
→ apparently incoherent OTR

- $\Delta\varphi_{\mathrm{ACC1}} = +0.5\,deg$

→ COTR

Time resolved measurements @ FLASH





∆E/E - t - plane

- Vertical time streak
- Horizontal energy dispersion (R_{16})

→ Destroying transverse coherence (R_{5i})!

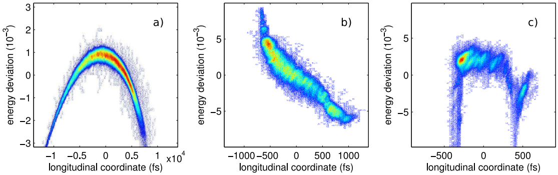
→ Phase space measurements possible!

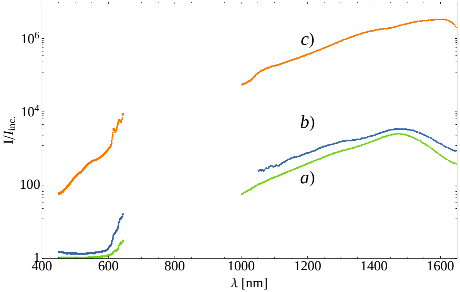
Macroscopic modulations

- Shot-to-shot variation
- scale $20\,fs$
- Resolution limited ($14\,fs$)

Spectral measurements VIS and NIR

Behind dogleg with 3rd harmonic





Mean COTR spectra

- COTR for all compressions
- Intensity increasing with C

$\rightarrow$ OTR diagnostic impeded

- Cut-off $\lambda_{coh,min} \approx 600\,nm$

$\rightarrow$ Dominated by dogleg

- Weaker cut-off for **c)**

$\rightarrow$ CSR effects from upstream (current spikes)

Other RF photoinjector linacs

Operation: APS (Argonne, USA)

- positive COTR
- identified to uB Instability

A.H. Lumpkin et al., Phys. Rev. ST Accel. Beams **12**, 080702 (2009)

Operation: NLCTA (SLAC, USA)

- positive COTR
- identified to uB Instability

S. Weathersby et al., PAC2011 Proc., New York, USA, p. 1

Commissioning: FERMI (Elettra, Italy)

- positive COTR
- not clearly indentified to uB Instability
- generation of short spike
- analysis ongoing . . .

private communications S. Di Mitri

Thermionic cathode based linacs

Operation: APS (Argonne, USA)

- no indication for COTR
- same accelerator structure for RF gun!

A.H. Lumpkin et al., Phys. Rev. ST Accel. Beams **12**, 080702 (2009)

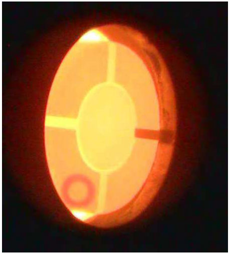
Operation: SCSS (SPring-8, Japan)

- no indication for COTR

Commissioning: SACLA (SPring-8, Japan)

- positive COTR
- probably generation of short electron bunch
- analysis ongoing . . .

private communications T. Shintake



Courtesy Shintake

Are thermionic cathode based linacs less prone to microbunching instability?

Strategies for beam profiling

Alternative techniques

- Wire scanners (e.g. LCSL)

  Talk by H. Loos on e-beam diagnostic

  ★ Projective measurement

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Suppression of Microbunching Instability

- Special magnet optics
  → Minimizing LSC and CSR effects
- Laser heater
  → Increasing δ_{E}

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Rescue screen methods

- Shorter wavelengths for TR measurements!
  → Well below usual uB regime
  Talk by L.G. Sukhikh on EUVTR @ $\sim 20\,nm$

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- Laser heater

  → Increasing δ_{E}

Rescue screen methods

- Shorter wavelengths for TR measurements!

  → Well below usual uB regime

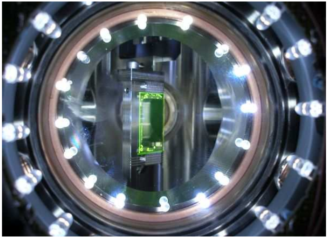
  Talk by L.G. Sukhikh on EUVTR @ $\sim 20\,nm$
- Use scintillator material as screen

  → Ionisation based radiation process!

  → Not sensitive to temporal structures!

  Talk by B. Walasek-Höhne on applications
  Talk by O.I. Meshkov on various materials

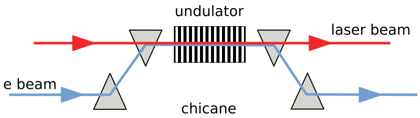
  ★ Crystal vacuum boundary source for OTR

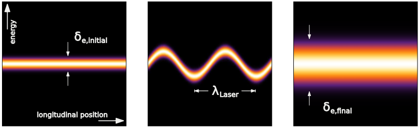


Courtesy C. Behrens

Laser heater

E.L. Saldin et al., Nucl. Instrum. Methods A **528**, 355 (2004)
Z. Huang et al., Phys. Rev. ST Accel. Beams **7**, 074401 (2004)





Idea

- Overlapping laser pulse with bunches
  - Wavelength λ_{laser}
  - $\sigma_{\mathrm{t,laser}} \geq \sigma_{\mathrm{t,bunch}}$
- Energy modulation inside undulator
- Longitudinal smearing by half chicane
  - Finite R_{52}
  - Angular spread $\sigma_{\mathrm{x}'}$

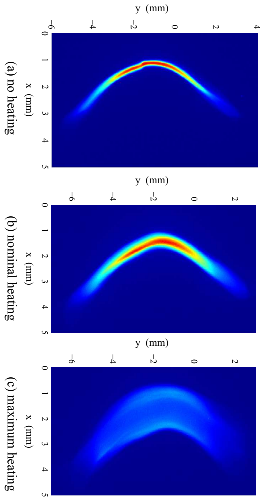
$\rightarrow$ Effective increase of energy spread

Suppress microbunching instability downstream of linac!

Laser heater @ LCLS

Z. Huang et al., Phys. Rev. ST AB **13**, 020703 (2010)

Experience

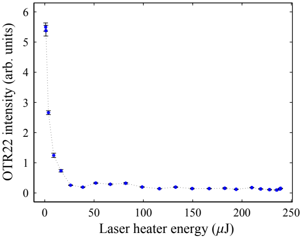


Parameters

- Position in front of DL1
- Increasing of δ_e from few keV to

$\rightarrow$ 20 keV @ normal operation

$\rightarrow$ $>$ 100 keV @ max. heating



★ Laser Heater suppresses COTR!

★ Remaining enhancement factor of 5!

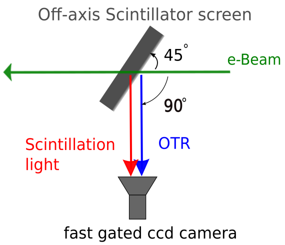
Gating of OTR

M. Yan et al., TUPD59, poster on Tuesday

Idea

- Standard OTR diagnostic setup with scintillator screen
- Fast OTR process $< 1\,ps$ (depends on bunch length)
- Slow scintillation process with $\tau > 50\,ns$

Delayed imaging with fast gated camera!

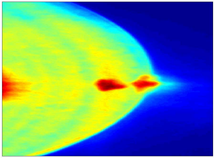


Setup

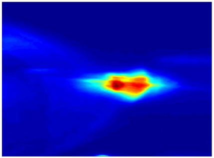
- Scintillator LuAG
  - $\tau = 70\,ns$
  - $\lambda = 500 - 600\,nm$
- PCO DicamPro
  - Intensified CCD camera
  - exposure time $\sim 100\,ns$
- OTR screen in addition for reference

Gating of OTR @ FLASH

Experience



(a) OTR screen



(b) LuAG screen

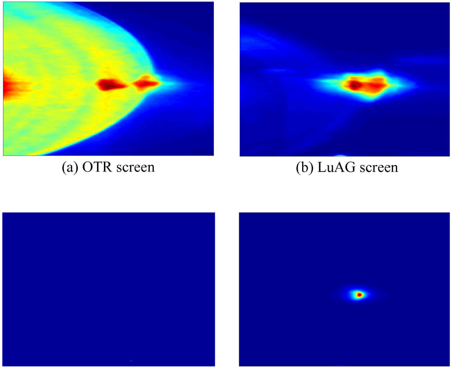
0 ns gate delay

OTR Mixture of (C)OTR + (C)SR

LuAG Coherent radiation NOT eliminated!

Gating of OTR @ FLASH

Experience


(a) OTR screen (b) LuAG screen
(c) OTR screen, +100ns delay (d) LuAG screen, +100ns delay

0 ns gate delay

- OTR Mixture of (C)OTR + (C)SR
- LuAG Coherent radiation NOT eliminated!

100 ns gate delay

- OTR Masking of ALL radiation
- LuAG Scintilator afterglow

- ★ Blocking COTR/CSR completely
- ★ Improving detection geometry

- ★ Camera very expensive
- ★ Photoluminescence ?

Summary

COTR: problem for 2-dim beam profiling

Different origins

- Short bunches (good)
- Microbunching instability (very bad)

Serious problem for RF photoinjector linacs

- Compressed and uncompressed bunches
- Visible tail of more general uB instability

Problem for thermionic cathode linacs?

Remedies

- Modifying beam phase space (not good enough)
- Profiling at shorter wavelength below coherent cut-off
- Use of scintillators + special geometries
- New ideas

Thanks for your attention!

Online CTR spectrometer @ FLASH