COTR and CSR from Microbunched LCLS Beam

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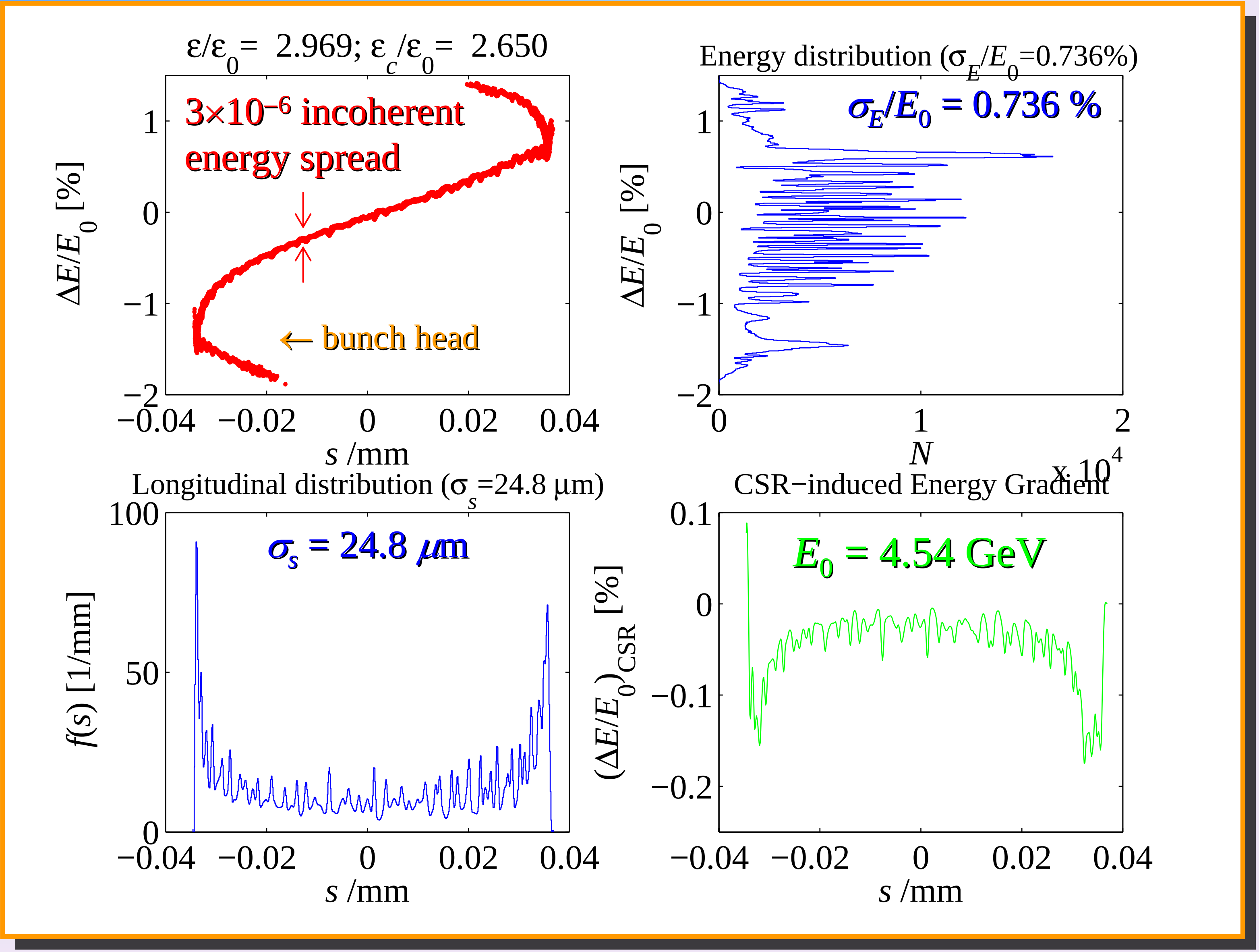
Zeuthen Workshop on High-brightness beams

Outline

- Brief review of microbunching instability
- DL1 (& BC1) observations and analysis
- BC2 observation and analysis
- Discussions

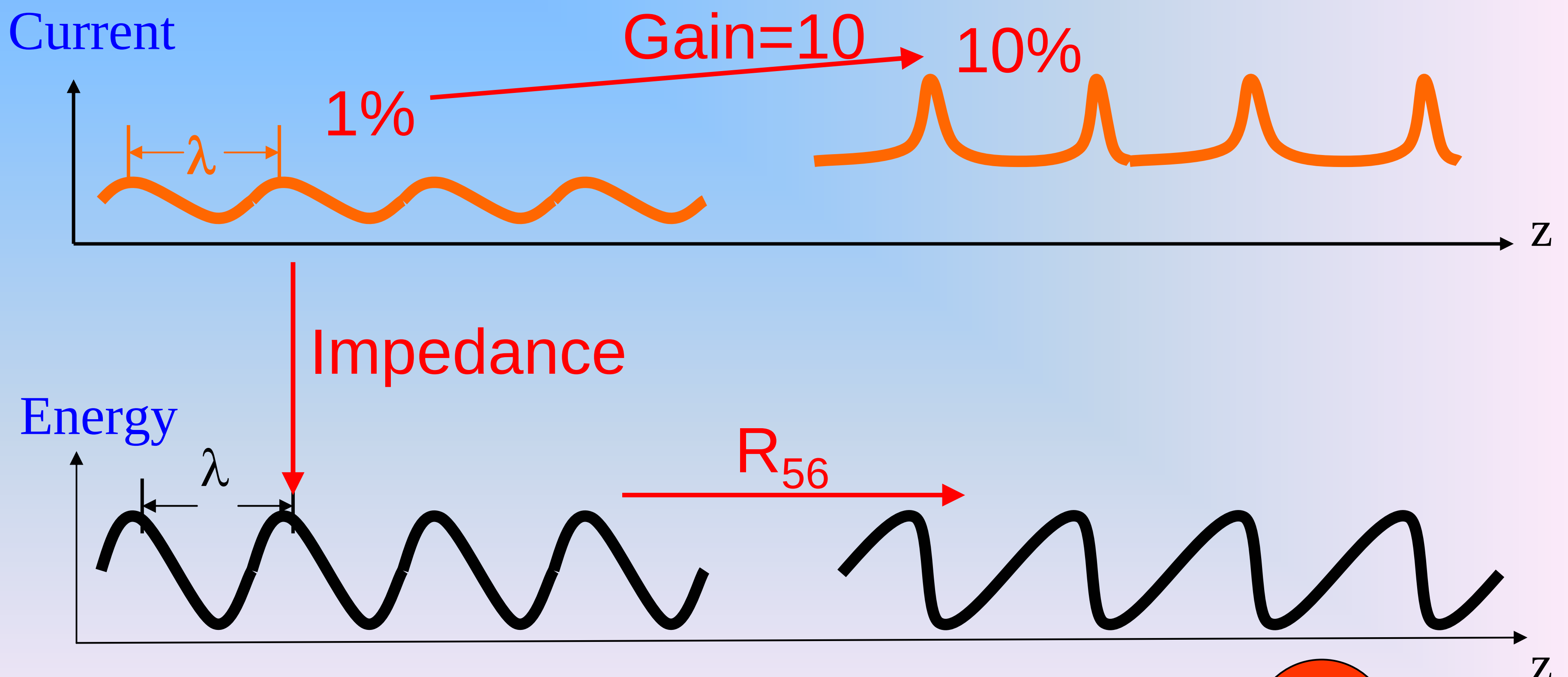
Microbunching instability in LCLS tracking



Borland, et al., NIMA 2002, ELEGANT tracking with CSR

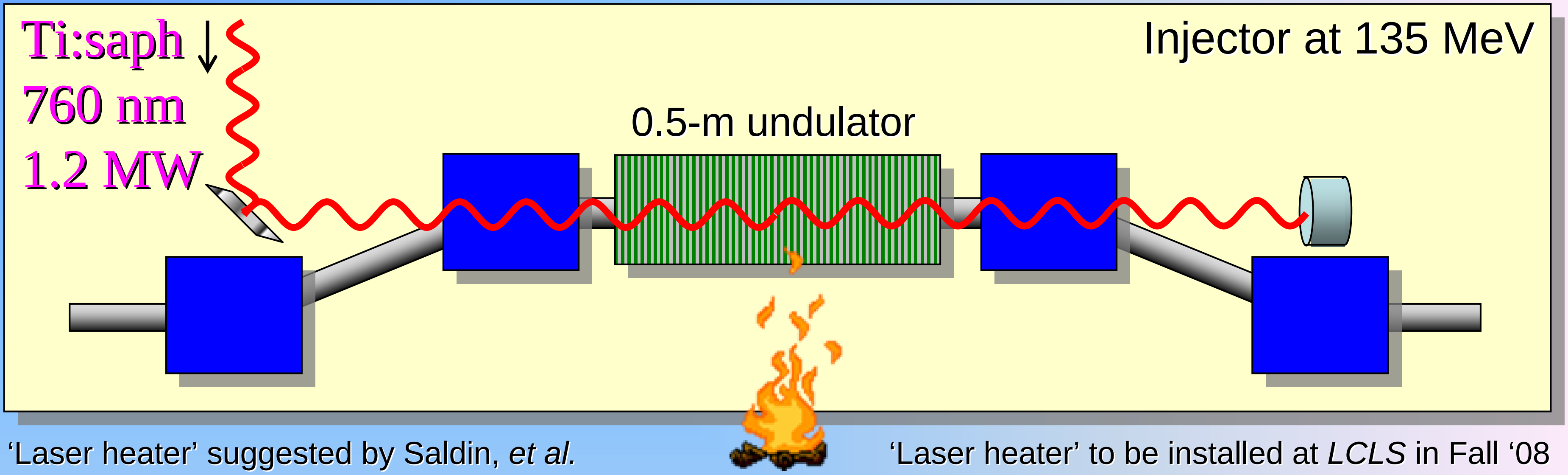
Gain mechanism

• Initial density modulation induces energy modulation through longitudinal impedance Z(k), converted to more density modulation by chicane. Space charge impedance is typically more at fault here than CSR (*Saldin, et al., NIMA 2004*)



➔ growth of slice energy spread (and emittance)

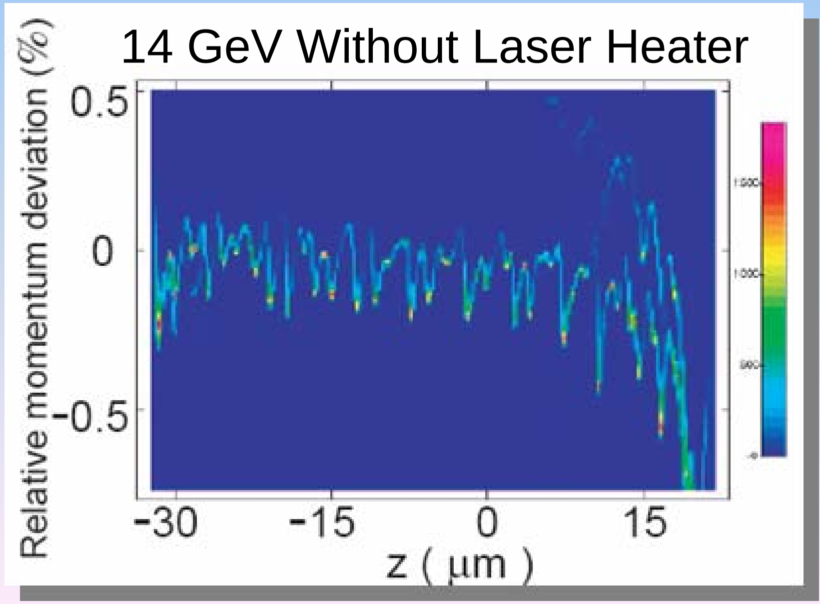
Micro-Bunching Can be Landau Damped with Laser Heater

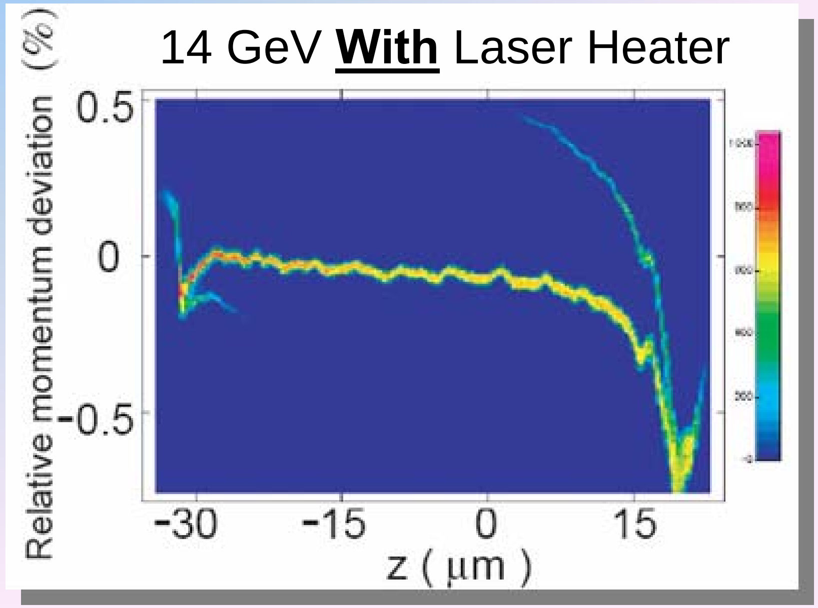


'Laser heater' suggested by Saldin, *et al.*

'Laser heater' to be installed at *LCLS* in Fall '08

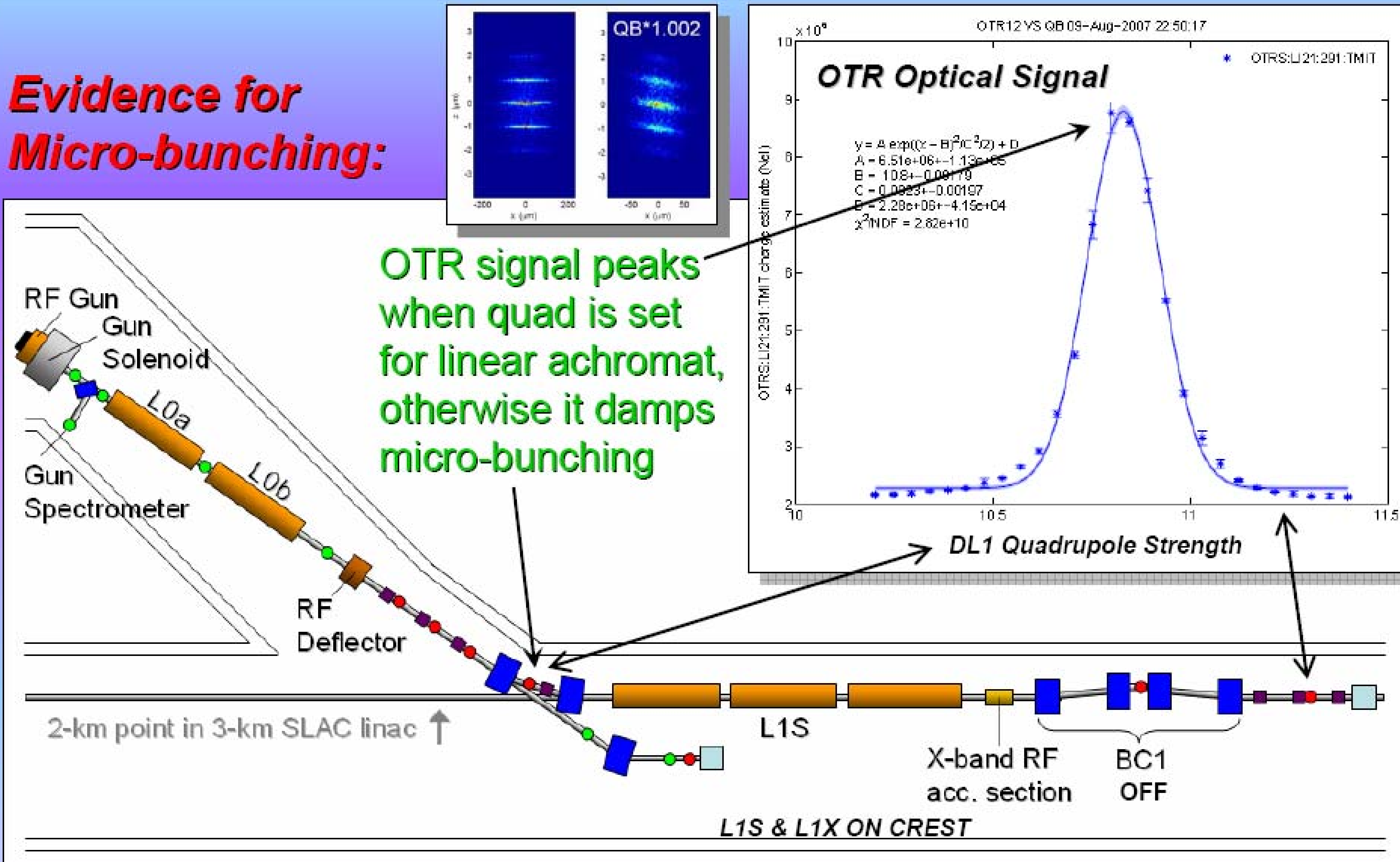
LCLS design study: *Z. Huang, et al., PRST 2004*





Unexpected Physics! *Coherent OTR after 35-degree Bend, Even With No BC1*

Evidence for Micro-bunching:



R. Akre, et al., PRST-AB 11, 030703 (2008)

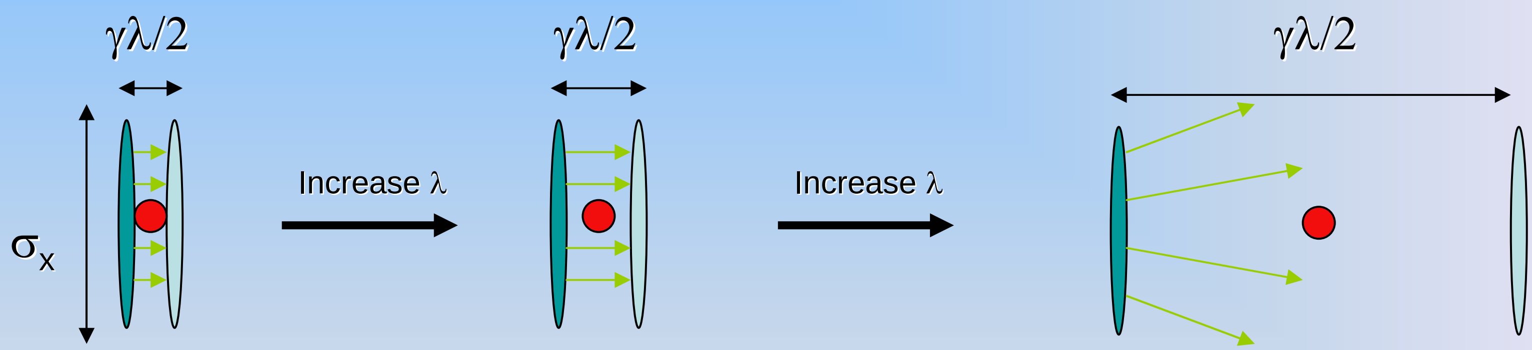
LSC instability driven by shot noise

• Statistical fluctuations in bunch longitudinal coordinate serve as initial density modulations

• At very short wavelengths, i.e. when $\sigma_x/(\bar{\lambda}\gamma) >> 1$, longitudinal space charge (LSC) has no γ dependence

High frequency/Pancake beam

Low frequency/Pencil beam



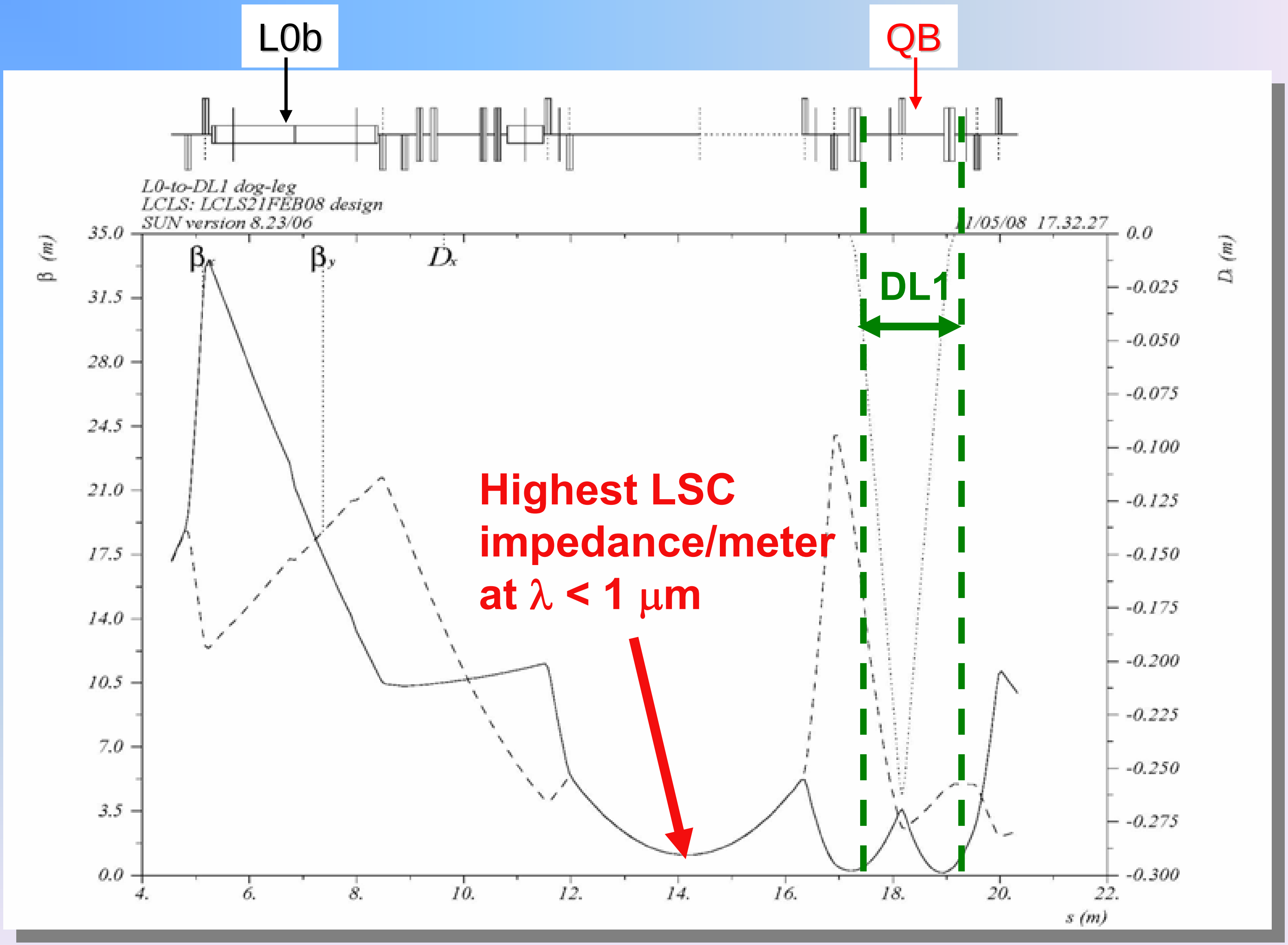
Pancake beam E-field independent of γ

Pencil beam E-field scales as γ^{-2}

➔ LSC field proportional to electron volume density

➔ must consider LSC impedance throughout injector

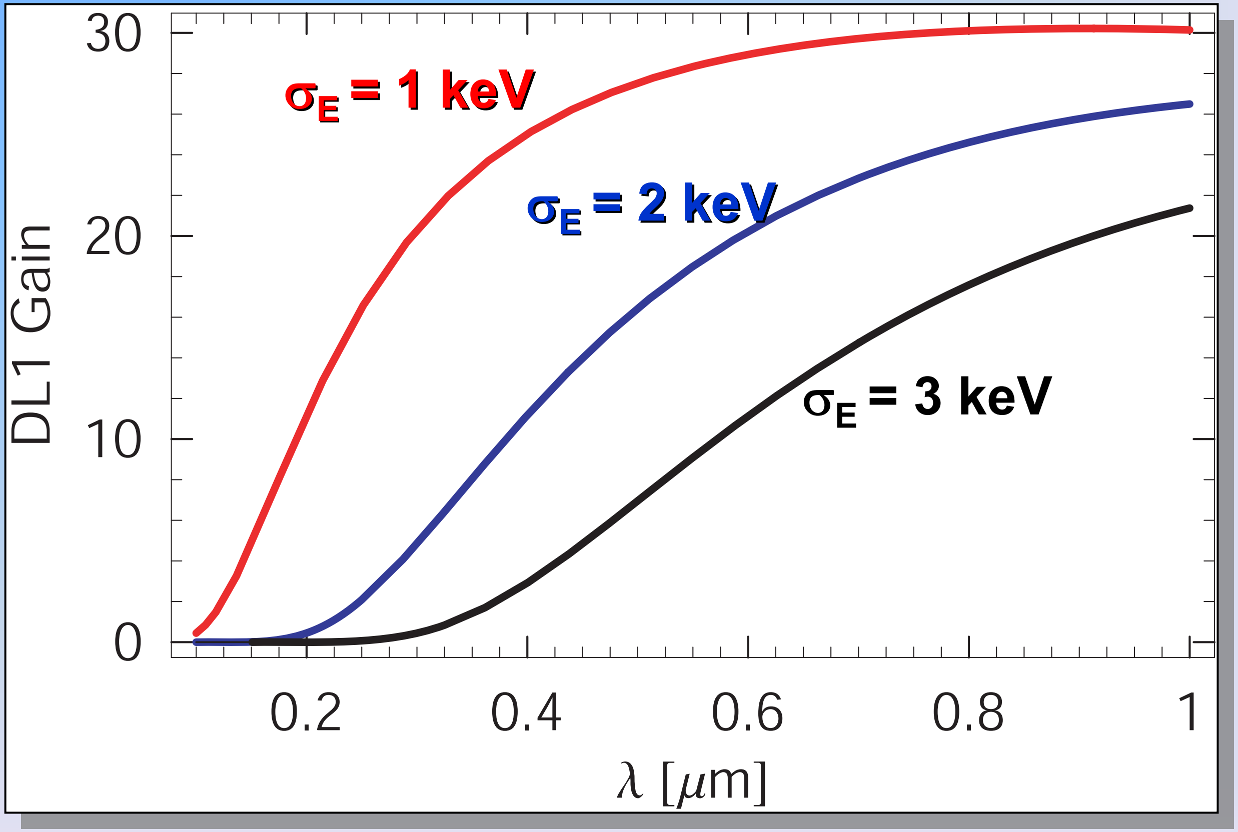
LCLS injector Optics



Other parts of beamline also contribute due to longer distance

LSC gain after DL1

LSC-induced energy modulation from 65 MeV to 135 MeV is converted to enhanced density modulation after DL1 with R_{56}=6.3 mm (assuming peak current 40 A)



$$\text{gain} = \frac{b(k)}{b_0(k)}\,, \quad b(k) = \frac{1}{N}\int dz e^{-ikz} n(z)\,, \quad k = \frac{2\pi}{\lambda}$$

OTR intensity

• OTR sees coherent (due to μ-bunching) and incoherent parts

$$\frac{d^2I}{d\omega d\Omega} = \left(\frac{d^2I}{d\omega d\Omega}\right)_1 \left[N^2|b(\boldsymbol{k})|^2 + N\right]$$

$$\left(\frac{d^2I}{d\omega d\Omega}\right)_1 \propto \frac{\gamma^4(\theta_x^2 + \theta_y^2)}{\left[1 + \gamma^2(\theta_x^2 + \theta_y^2)\right]^2}$$

$$\boldsymbol{k} \approx (k\theta_x, k\theta_y, k)$$

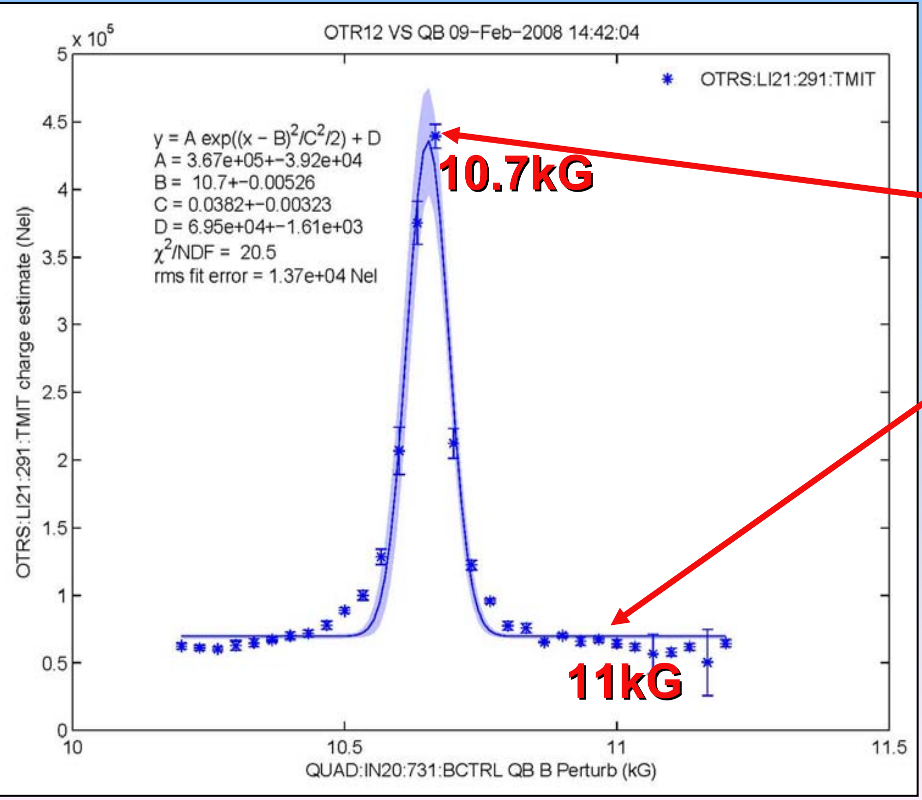
• Integrate over camera collection angle (+-75 mrad) to get OTR power spectrum and compare with OTR spectral data

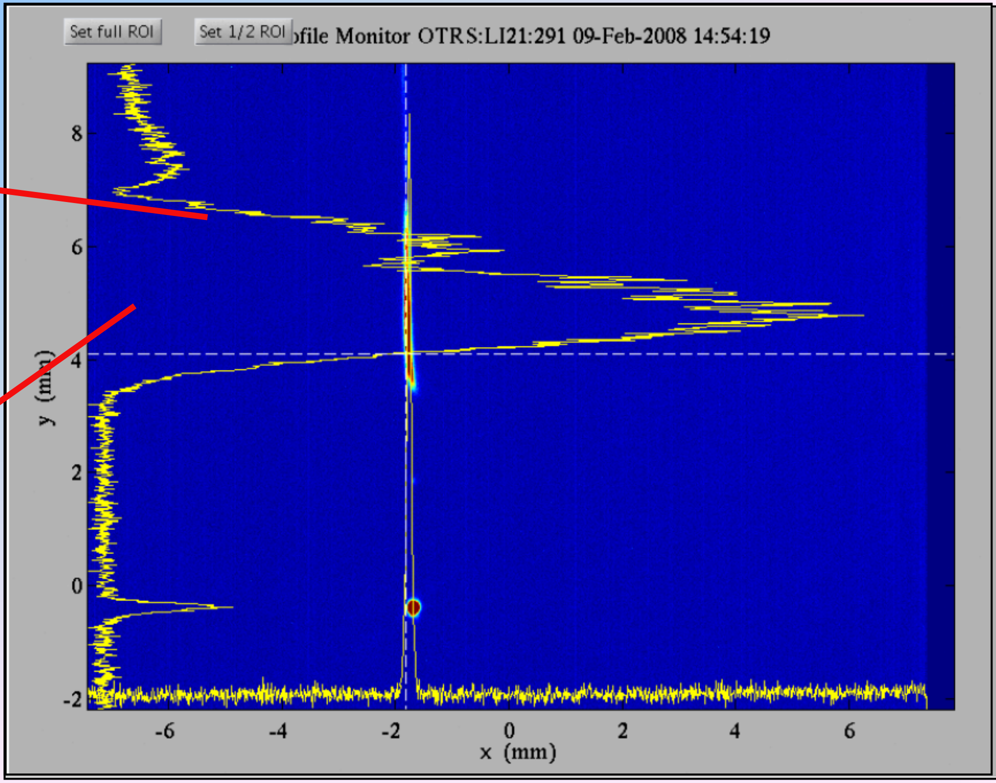
OTR12 Spectral Analysis I

- Analyzed diffraction grating spectral data on OTR12
- 2 images with BC1 off, 250pC (D. Dowell)

No COTR (QB = 11 kG, nonzero R51&R52 after DL1 suppress μ-bunching)

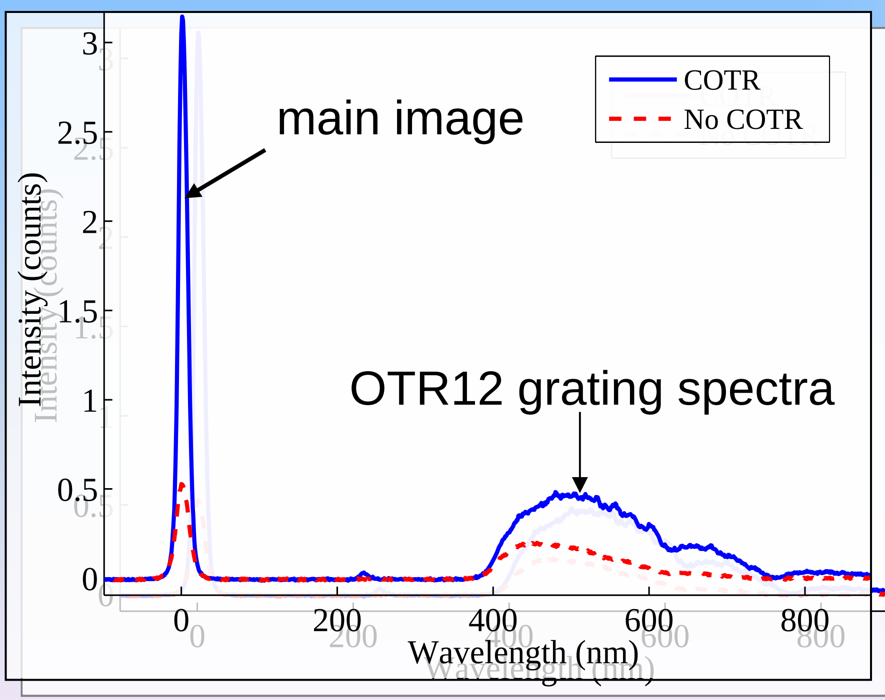
COTR (QB = 10.7 kG, DL1 is linear achromat and enhances μ-bunching)

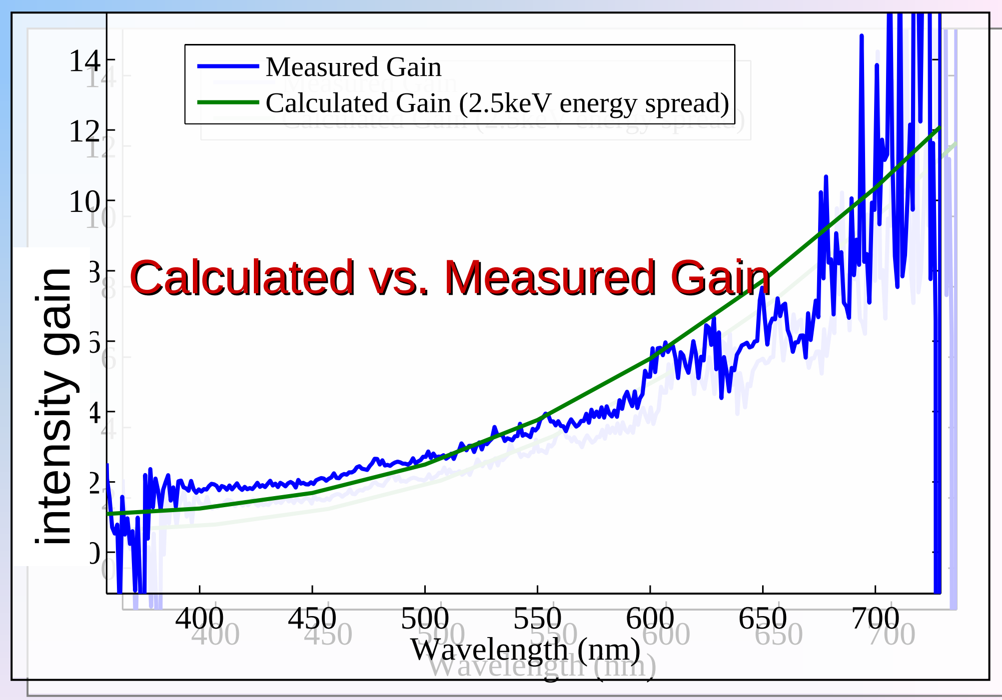




OTR12 Spectral Analysis II

- Measured intensity gain by ratio of COTR to No COTR spectra
- Calculated intensity gain with 40 A peak current (BC1 off), 1 μm norm. emittance and fit to 2.5keV slice rms energy spread)

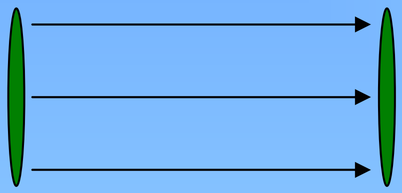




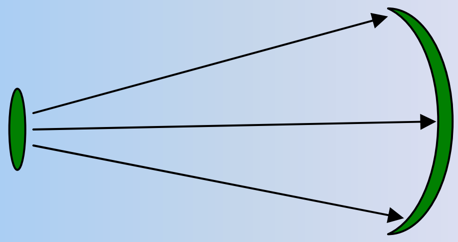
D. Ratner

Unresolved issues

• Increasing beta at pre-DL1 waist (to reduce beam density) didn’t reduce OTR12 gain. Suspect nonlinear effects at play

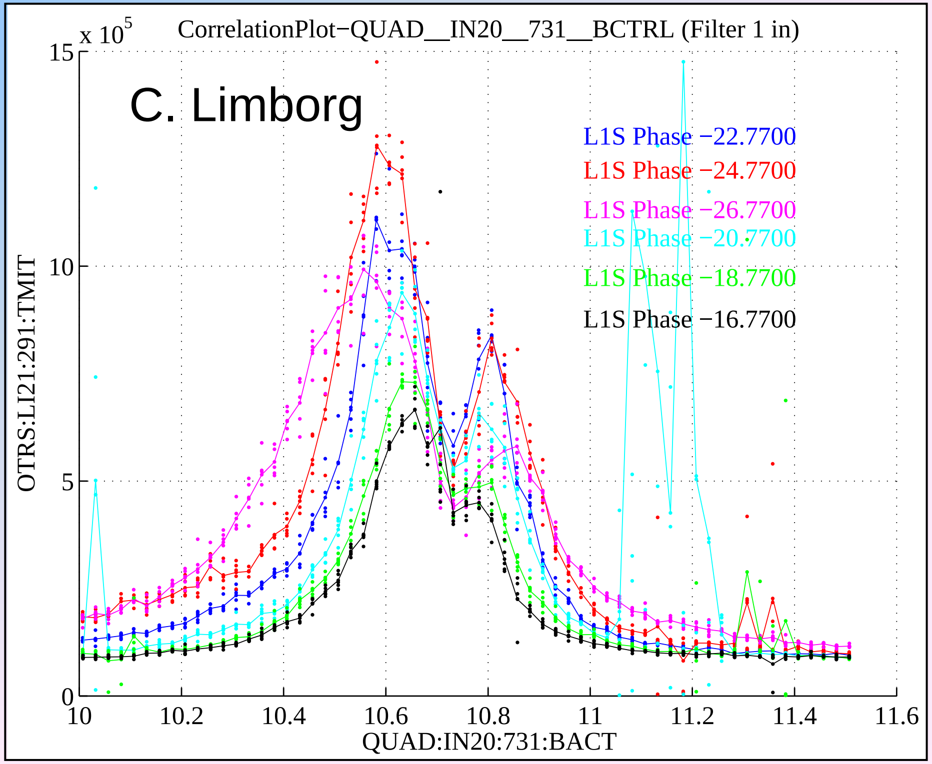


big beta

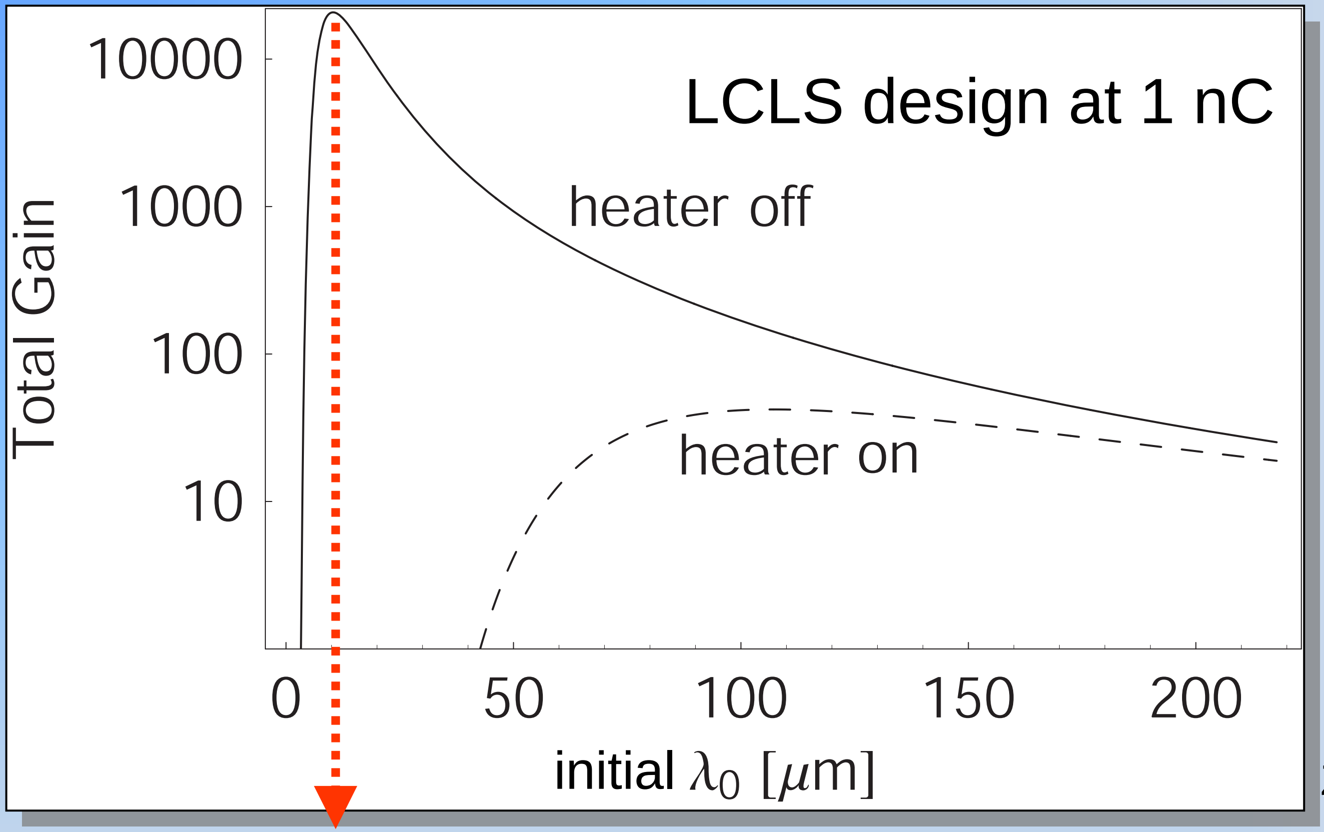


small beta

• With BC1 on, observed double peaks in QB scan



LCLS microbunching gain after BC2*

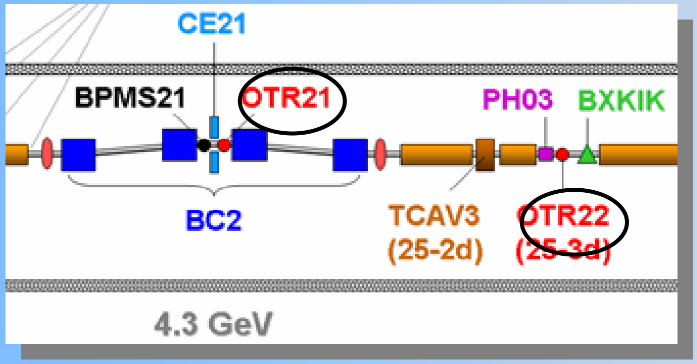


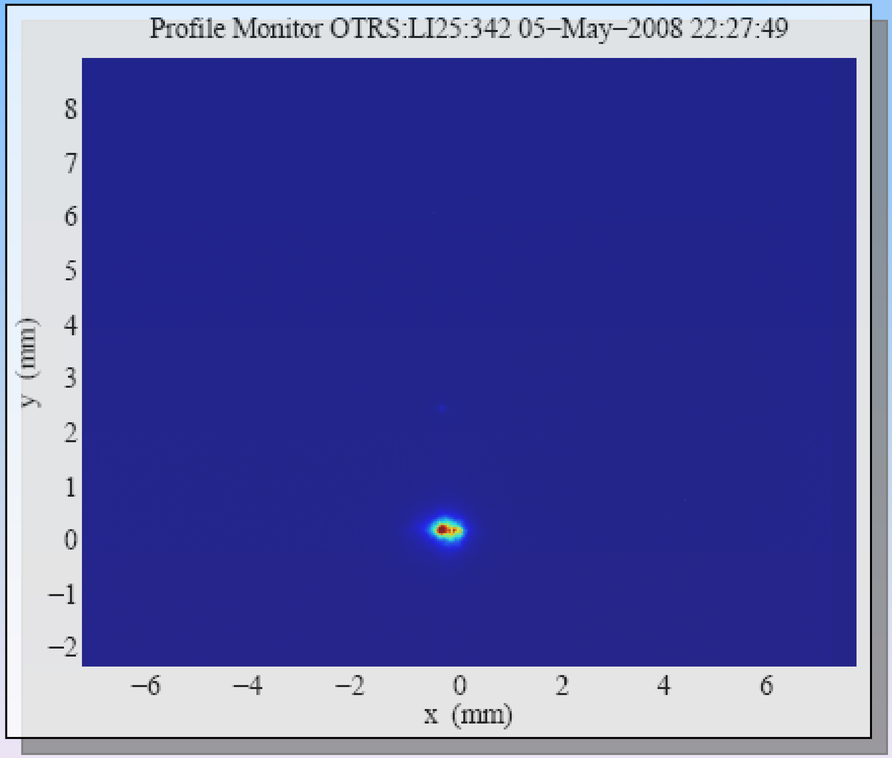
Z. Huang, *et al*., PRST 2004

Peak of gain at $\lambda_0 \approx 15\ \mu m$ from 3 keV slice energy spread

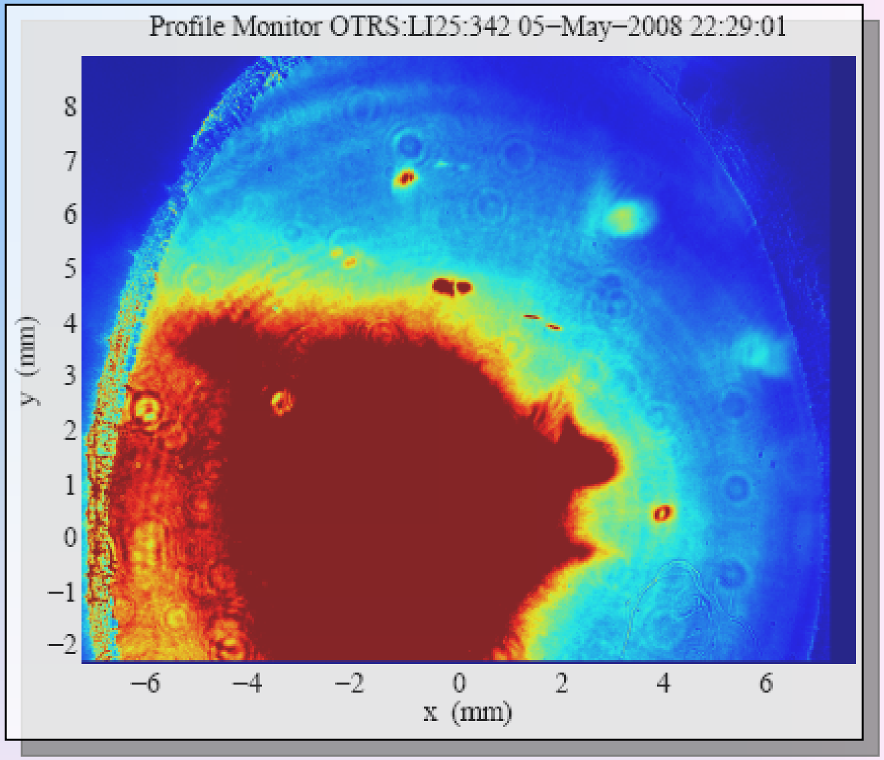
- Gain dominated by LSC in linacs
- Enough gain to amplify shot noise fluctuations to saturation
- 15 μm/30 (compression ratio) = 0.5 μm, spectacular COTR!

OTR22 after BC2



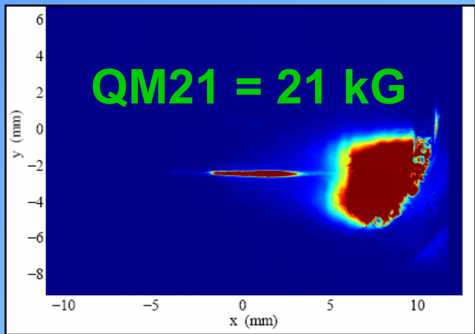


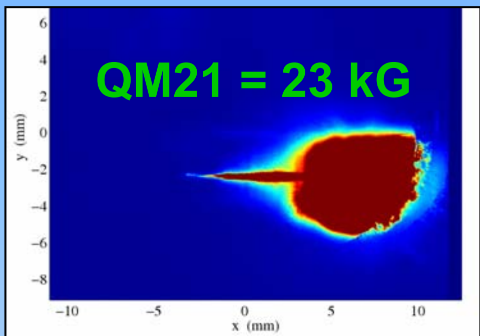
with OTR21 screen inserted
(smoothes μ-bunching)

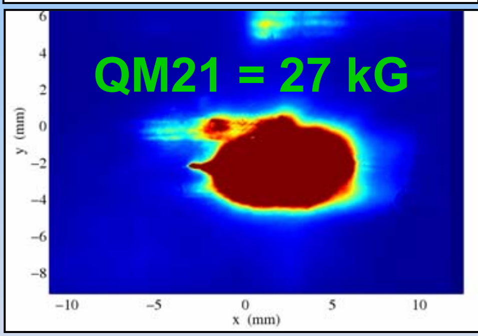


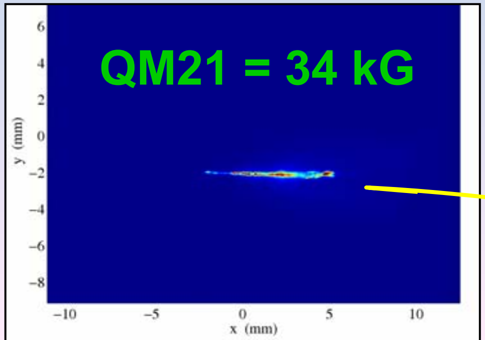
with OTR21 screen OUT
(μ-bunching present – COTR!)

OTR21 in BC2

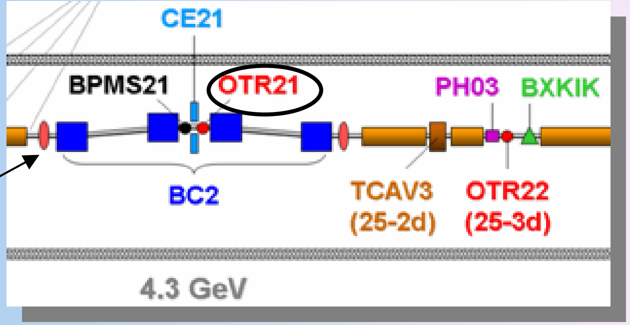


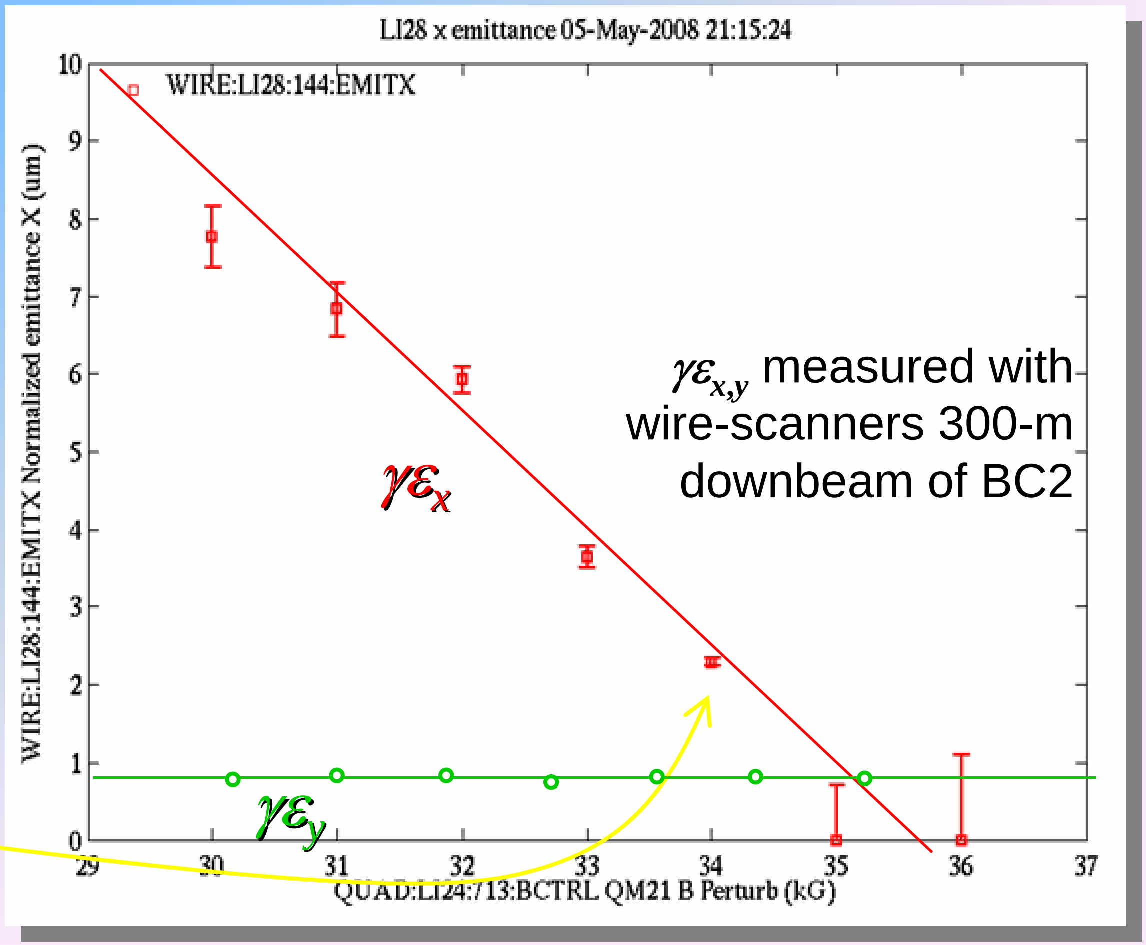




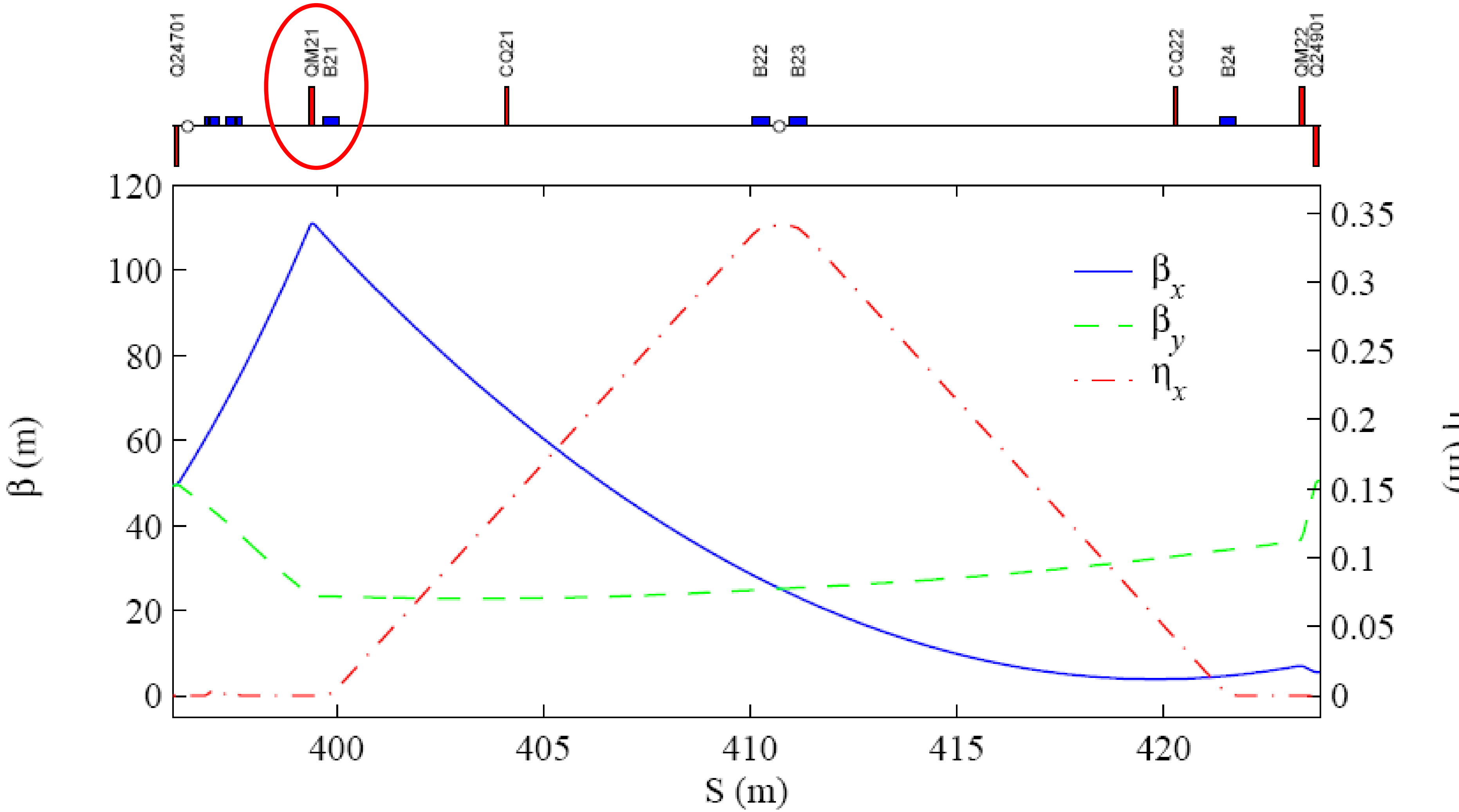


Scan QM21



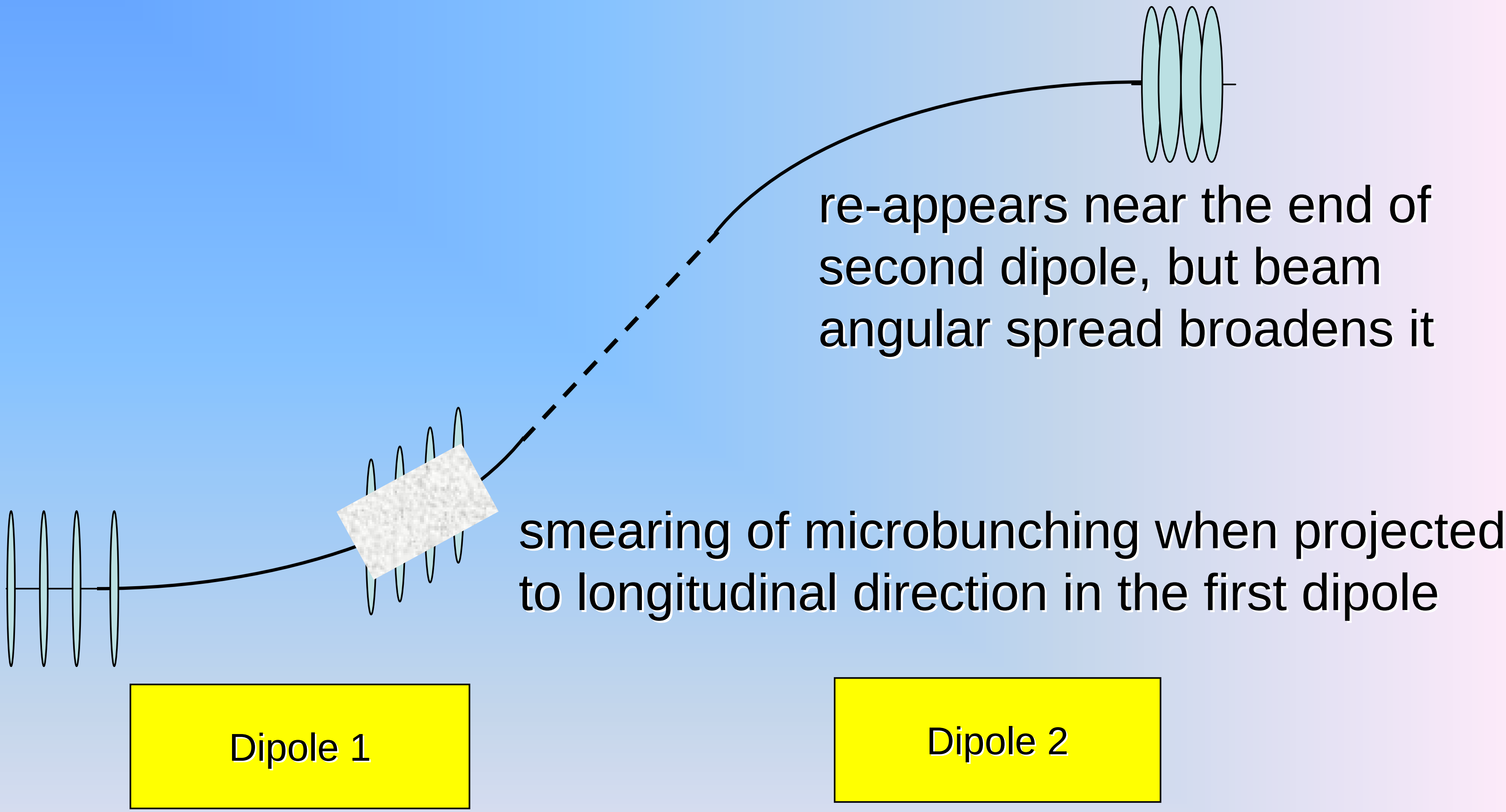


BC2 design optics



- QM21 changes beam divergence at BC2 entrance, not much effect on transverse size there

Microbunching evolution in a Chicane



- Varying pre-BC2 beam divergence (by QM21) changes sharpness of microbunching and sharpest location of microbunching in the second dipole

Theory

- Ignore further CSR amplification of microbunching in BC2 (BC2 gain is low <3, see *Heifets/Stupakov/Krinsky, PRST 2002*; also see *Huang/Kim, PRST 2002*)

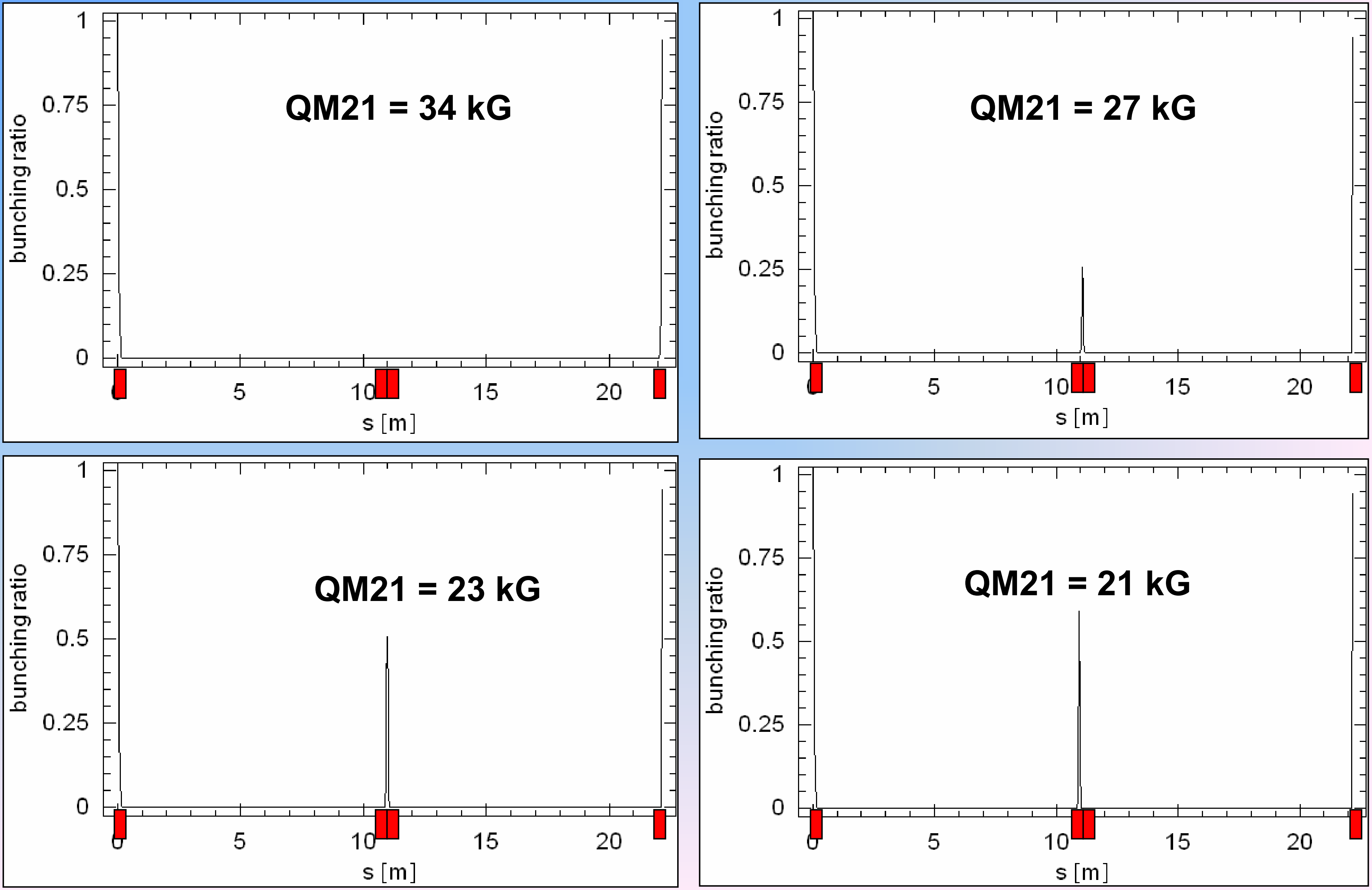
- Bunching evolution in a chicane is approximately

$$b_0[k(s);s] = b_0[k_0;0]e^{-k^2(s)R_{56}^2(s)\sigma_\delta^2/2} \times \exp\left[-\frac{k^2(s)\varepsilon_0\beta_0}{2}\left(R_{51}(s) - \frac{\alpha_0}{\beta_0}R_{52}(s)\right)^2 - \frac{k^2(s)\varepsilon_0}{2\beta_0}R_{52}^2(s)\right] \quad (26)$$

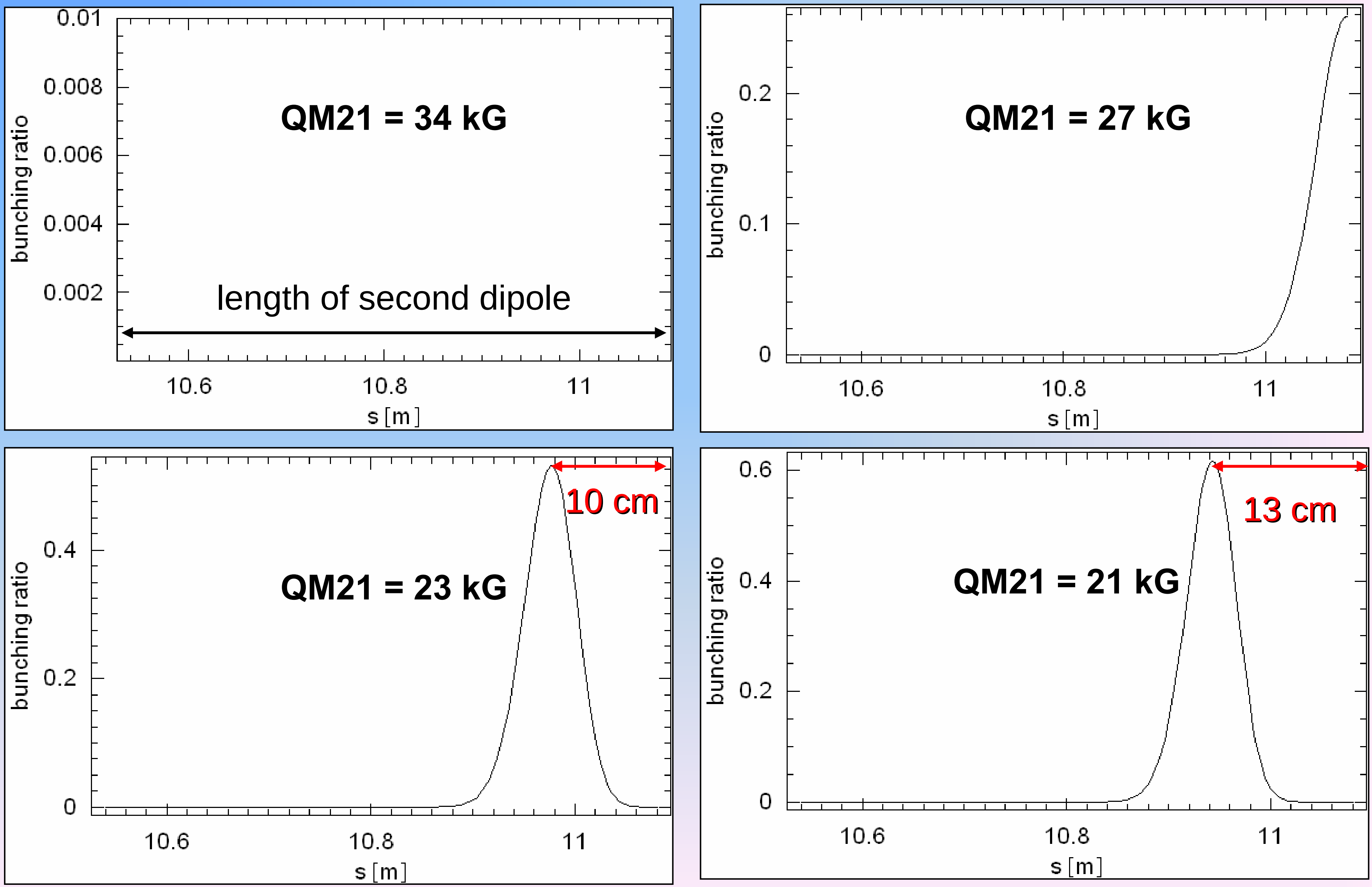
Initial bunching (+energy modulation) due to LSC instability in linac+DL1+BC1

Controlled by QM21

• Assume pre-BC2 microbunching at 2 μm, compressed to 1 μm after second dipole, observed by OTR21



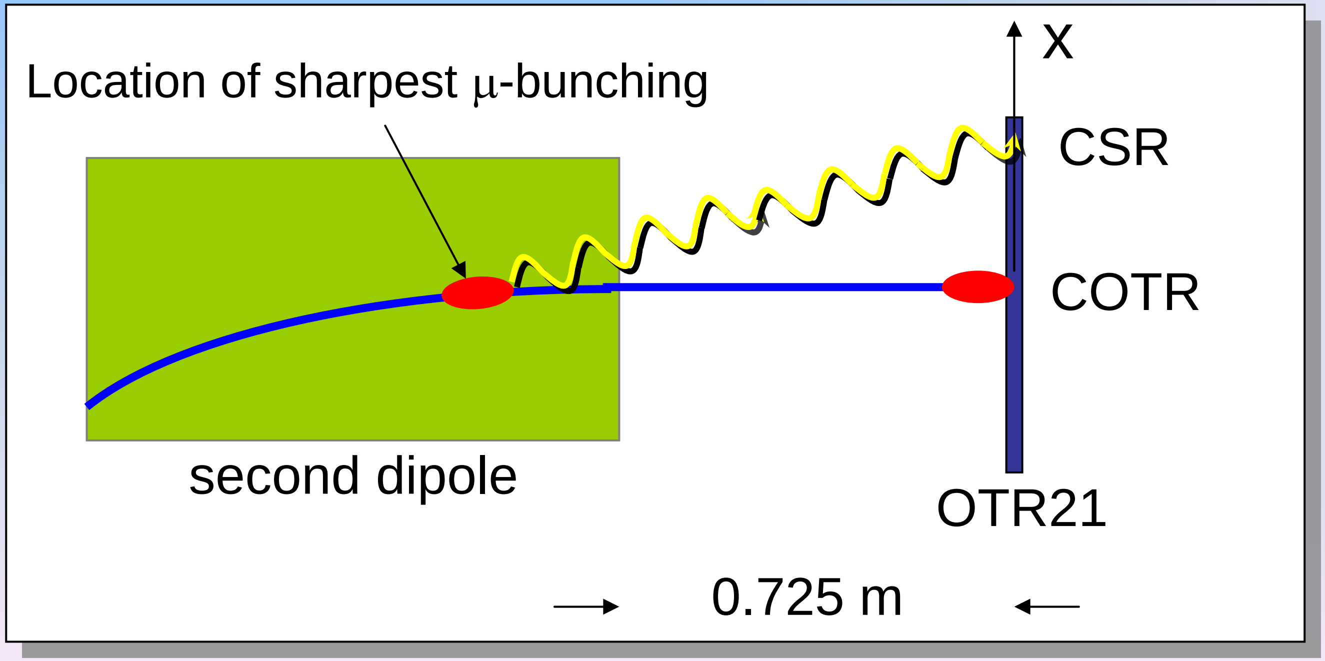
Zoom in to the second dipole



Effects on OTR21

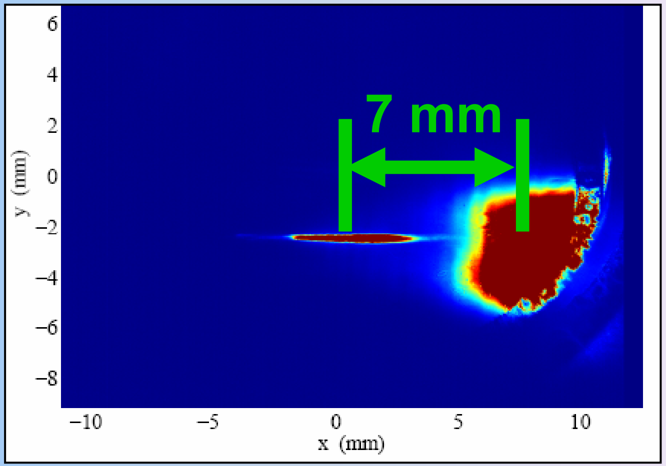
• COTR+CSR intensity changes drastically with QM21 (QB-like effect)

• Intense CSR radiation is emitted near the bunching maximum (determined by QM21) inside second dipole
➔ separation of COTR and CSR on OTR21

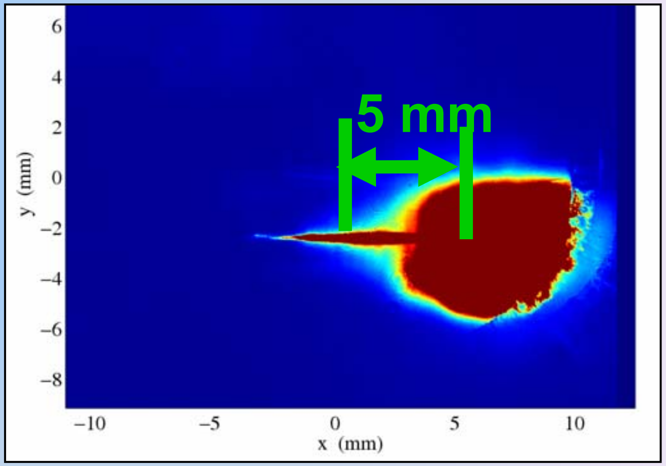


Shift of CSR from COTR

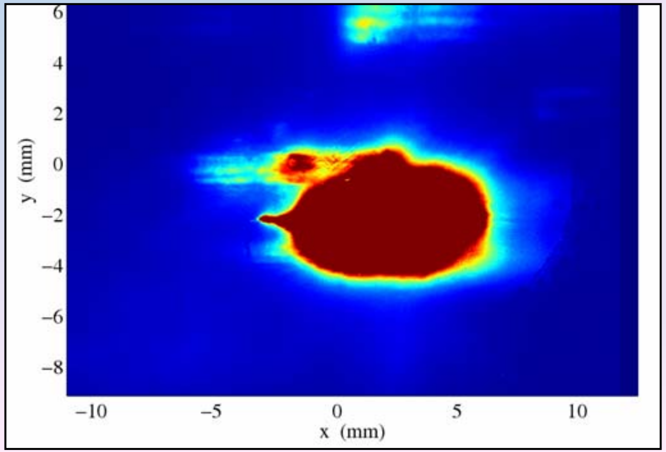
QM21 = 21 kG
Calculated shift ~ 7 mm



QM21 = 23 kG
Calculated shift ~ 5 mm



QM21 = 27 kG
Calculated shift ~ 0 mm



Summary

- A high-brightness beam such as generated by LCLS tends to microbunch itself in a bend system with nonzero R_{56} (Shot noise can naturally start the process).
- Strong COTR and CSR emissions at optical wavelengths are clear evidences of beam microbunching.
- Studies are ongoing: some effects are understood, some details are still missing.
- Laser heater (to be commissioned in early 2009) will mitigate microbunching and (hopefully) get rid of COTR. We look forward to how it works out.

Thanks for your attention!

Acknowledgements

* LCLS commissioning team

* Gain analysis with D. Ratner, A. Chao

* Useful discussions with Y. Ding, D. Dowell, P. Emma, J. Frisch, C. Limborg, H. Loos, G. Stupakov, J. Wu, M. Venturini, A. Zholents