Measurements of CSR and its impact on the LCLS beam

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Stanford Linear Accelerator Center

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Zeuthen Workshop on High-brightness beams

Outline

- Introduction
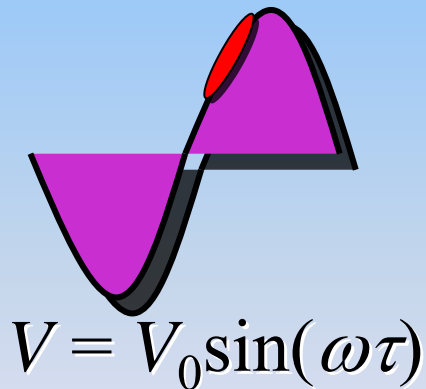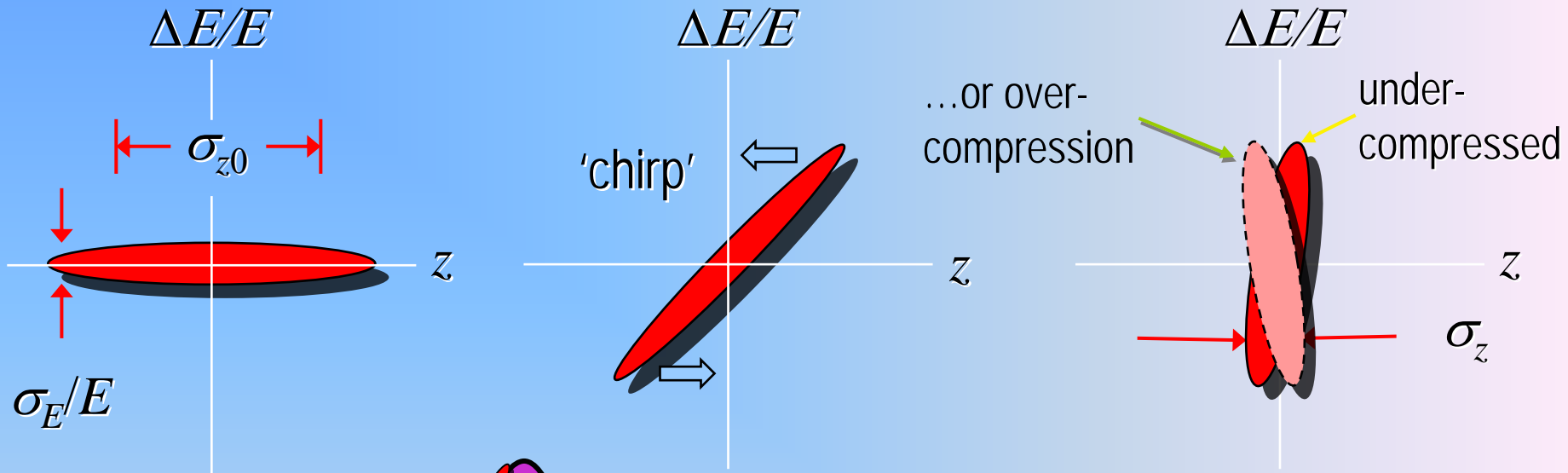
- CSR studies at BC1
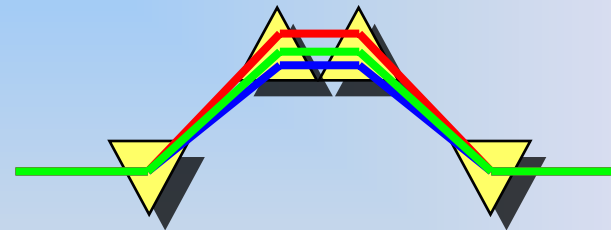   @250 pC
    @ 1 nC

- CSR studies at BC2
    @ 250 pC
    Direct observation of CSR at optical wavelengths

- Summary

Magnetic Bunch Compression

$\Delta E/E$

σ_{z0}

z

σ_E/E

$\Delta E/E$

'chirp'

z

$\Delta E/E$

…or over-compression

under-compressed

z

σ_z

$$V = V_0 \sin(\omega\tau)$$

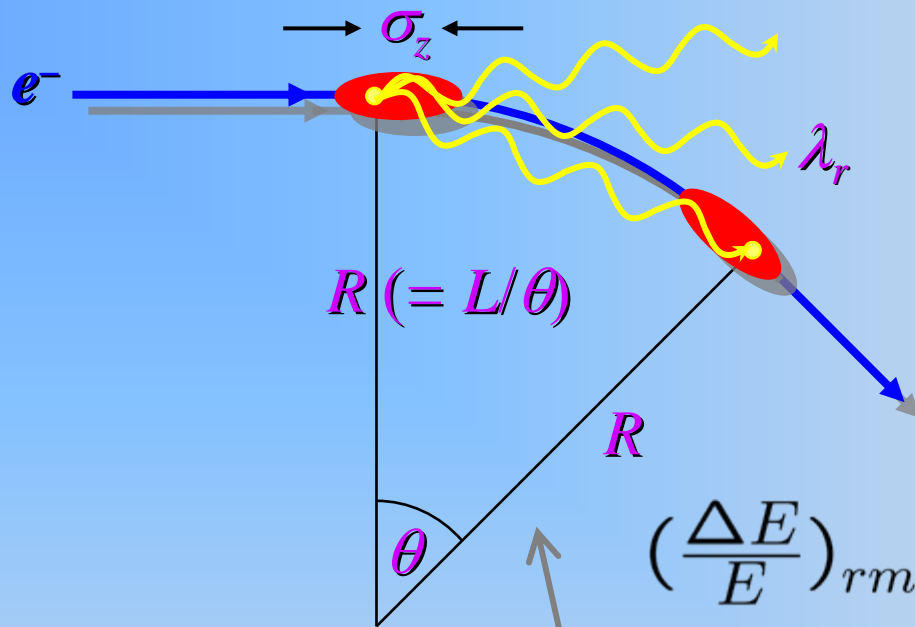$$\Delta z = R_{56}\Delta E/E \quad (\gamma \gg 1)$$

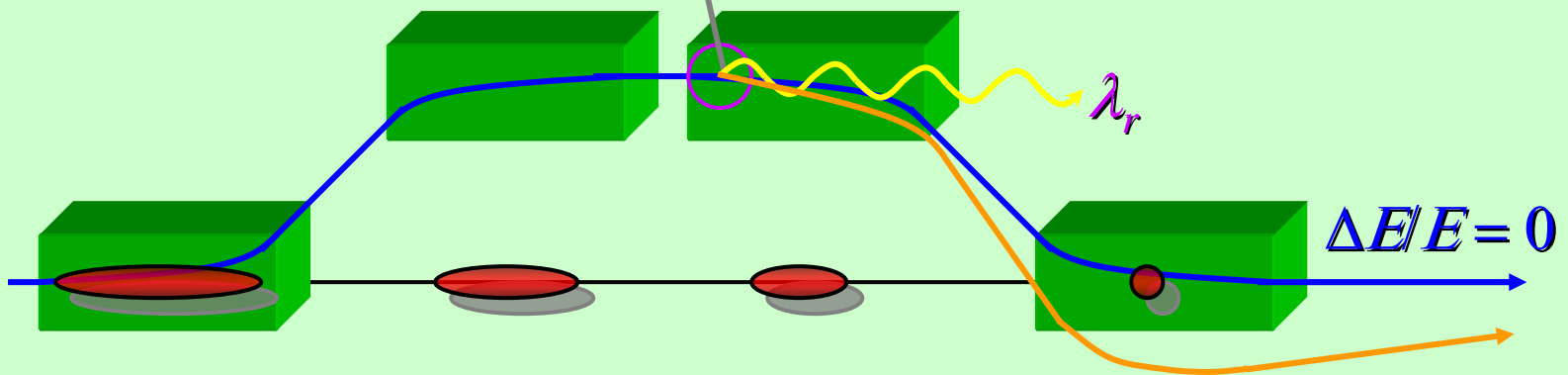RF Accelerating Voltage

Path Length-Energy Dependent Beamline
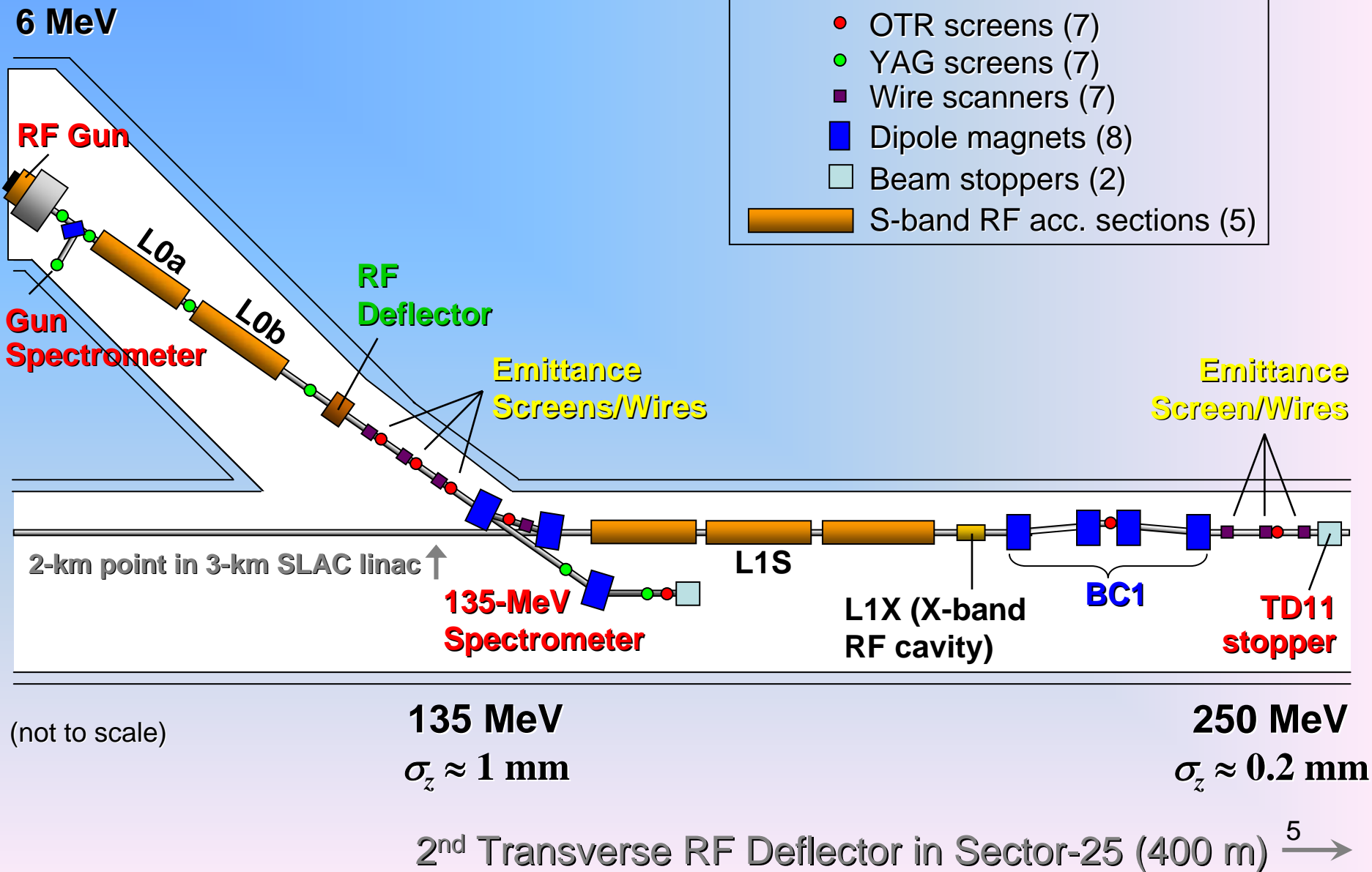
3

Coherent Synchrotron Radiation in Bends

Coherent radiation for $\lambda_r > \sigma_z$

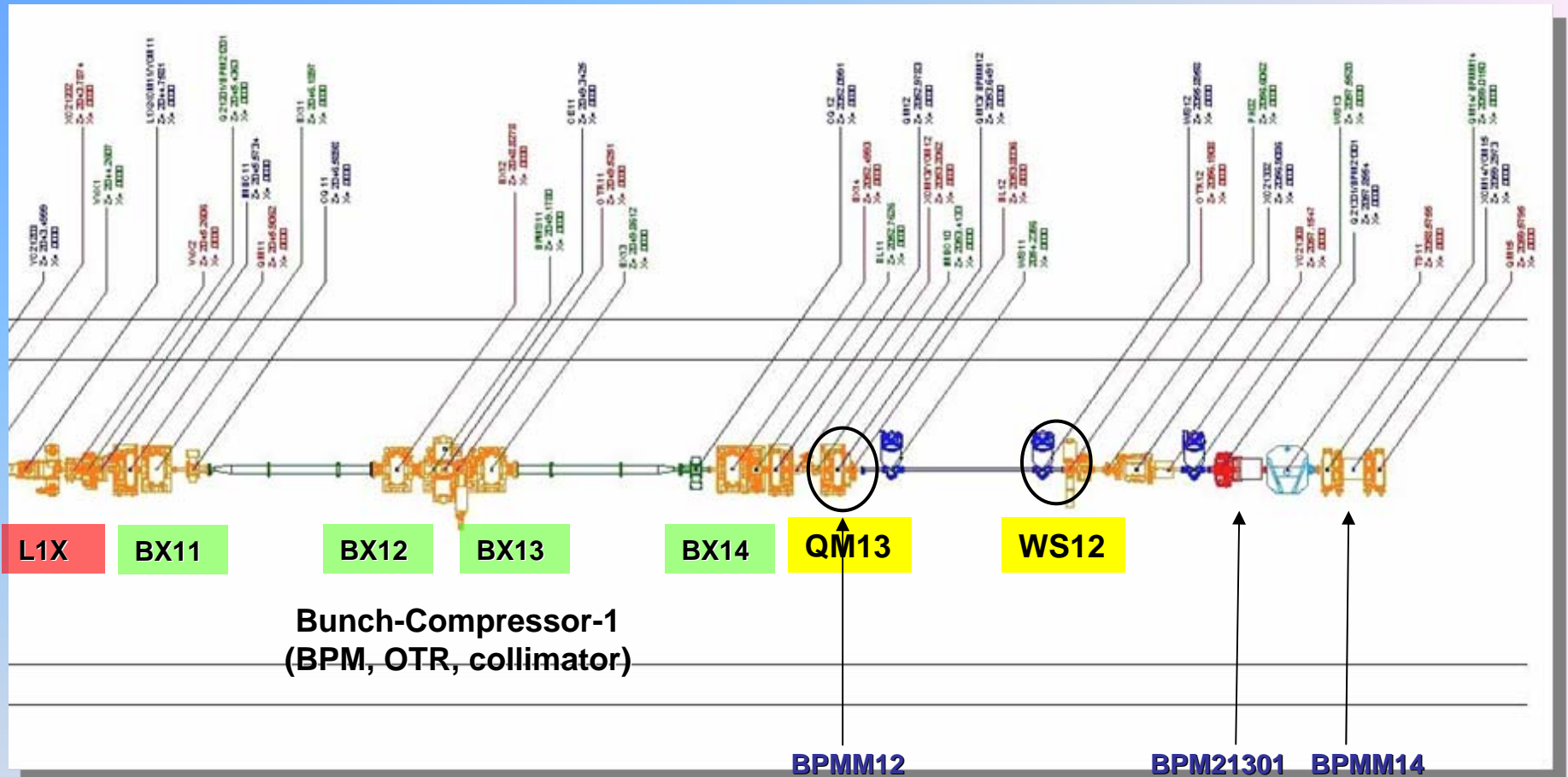$$\left(\frac{\Delta E}{E}\right)_{rms} \approx 0.22 \frac{r_e N L}{\gamma R^{2/3} \sigma_z^{4/3}}$$

$\Delta E/E = 0$

bend-plane emittance is ruined $\rightarrow$ $\Delta E/E < 0$

LCLS Injector Layout

6 MeV

RF Gun

Gun Spectrometer

L0a

L0b

RF Deflector

Emittance Screens/Wires

OTR screens (7)
YAG screens (7)
Wire scanners (7)
Dipole magnets (8)
Beam stoppers (2)
S-band RF acc. sections (5)

Emittance Screen/Wires

2-km point in 3-km SLAC linac ↑

135-MeV Spectrometer

L1S

L1X (X-band RF cavity)

BC1

TD11 stopper

(not to scale)

135 MeV
$\sigma_z \approx 1$ mm

250 MeV
$\sigma_z \approx 0.2$ mm

2nd Transverse RF Deflector in Sector-25 (400 m) $\xrightarrow{5}$

LCLS BC1 and diagnostics

L1X **BX11** **BX12** **BX13** **BX14** **QM13** **WS12**

**Bunch-Compressor-1
(BPM, OTR, collimator)**

BPMM12   BPM21301   BPMM14

➢ Bunch length monitor, deflecting cavity ➔ bunch length;

➢ QM13 + WS12 ➔ Emittance ;

➢ BPMs after BC1 ➔ energy loss.

6

BC1 CSR studies at 250 pC

- Machine setup:

  Energy = 250 MeV (held constant by E-feedback);

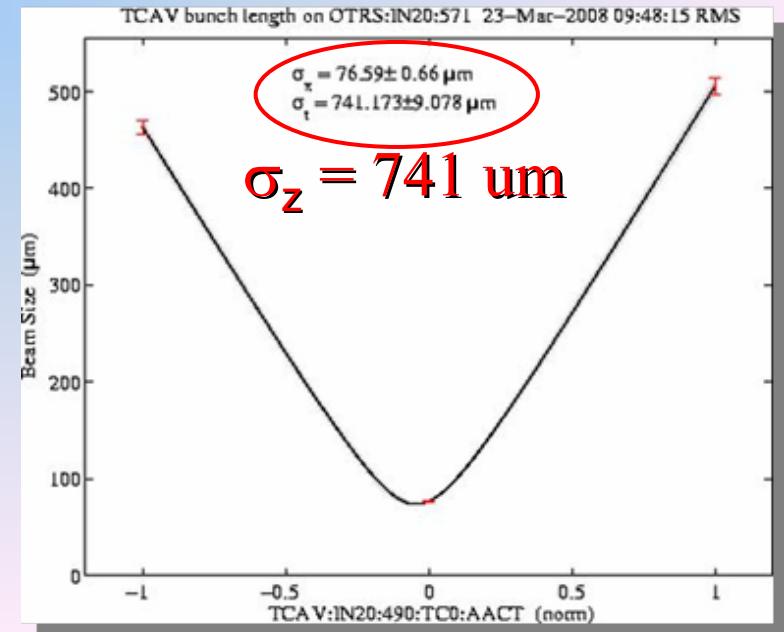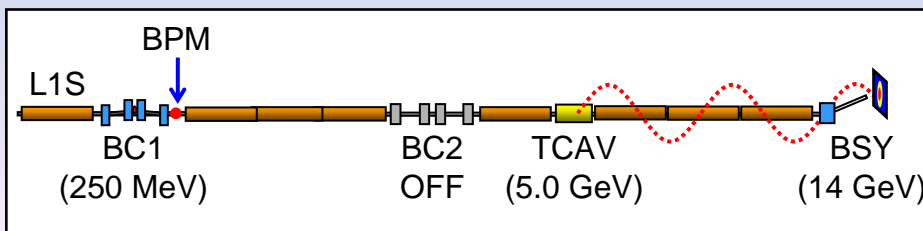 BC1 R56 = -45.5mm, dipole radius = 2.17m, $\theta \sim 5°$;

  L1X: 20MV, -160 deg;

  BC2 off

- Injector beam conditions (at 135 MeV)

  $\gamma\varepsilon_x \sim \gamma\varepsilon_y \sim 0.7$ um (WS02, asymmetric Gaussian method)

  $\sigma_z \sim 750$ um (OTR2)

- Scan L1S phase to

Control E-chirp before BC1

TCAV bunch length on OTRS:IN20:571 23–Mar–2008 09:48:15 RMS

$\sigma_x = 76.59 \pm 0.66$ μm
$\sigma_t = 741.173 \pm 9.078$ μm

$\sigma_z = 741$ um

Beam Size (μm)

TCAV:IN20:490:TC0:AACT (norm)

BPM

L1S

BC1
(250 MeV)

BC2
OFF

TCAV
(5.0 GeV)

BSY
(14 GeV)

Bunch compression measurements

BC1 03-23-2008 measurements
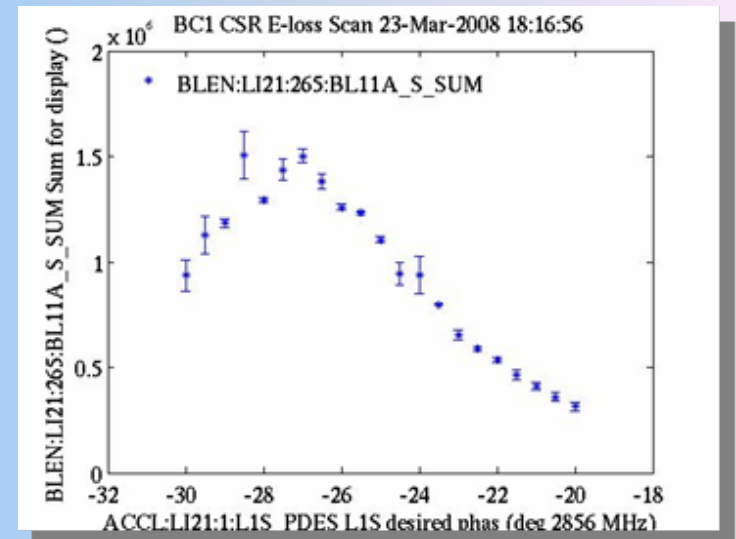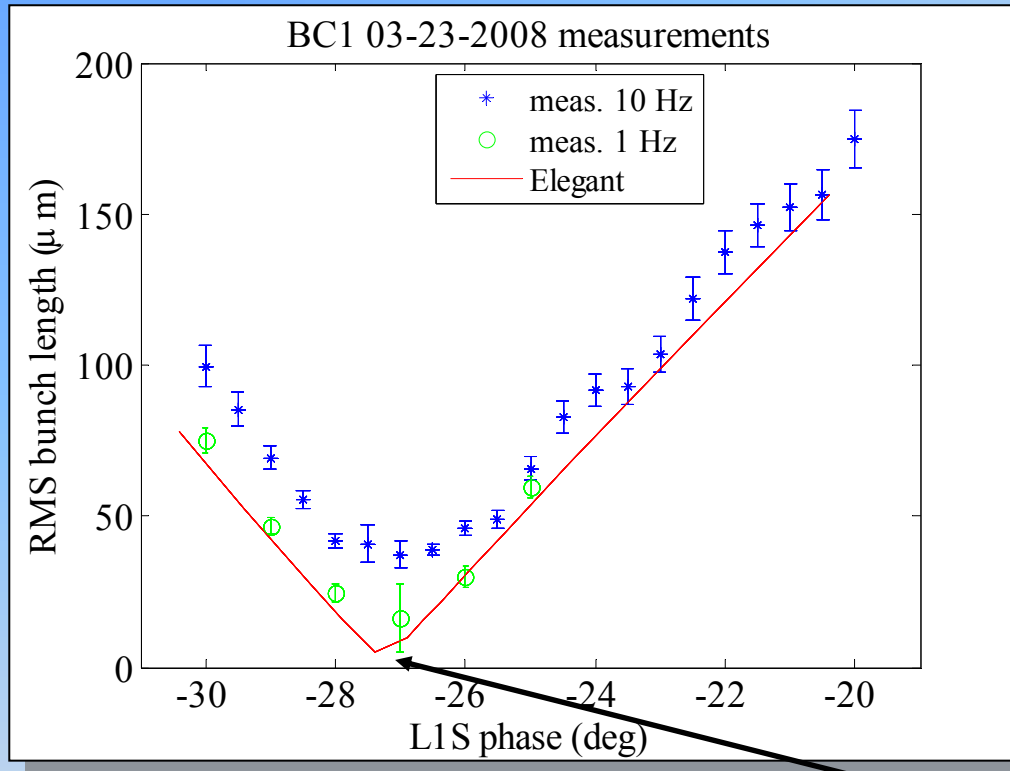
bunch length monitor (BL11A) signal

Full compression (*Elegant* simulation)
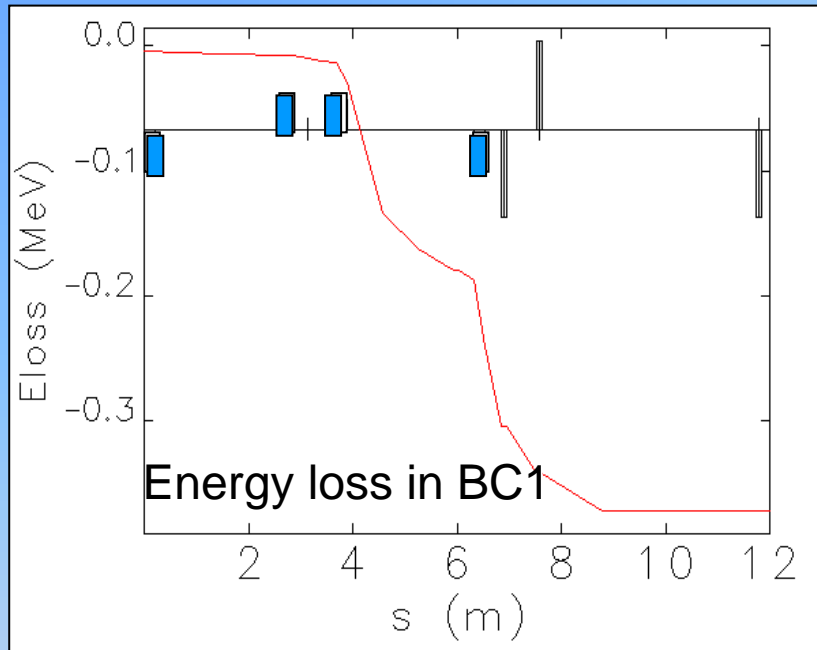
20 kA

• Absolute bunch length measured by downstream deflecting cavity

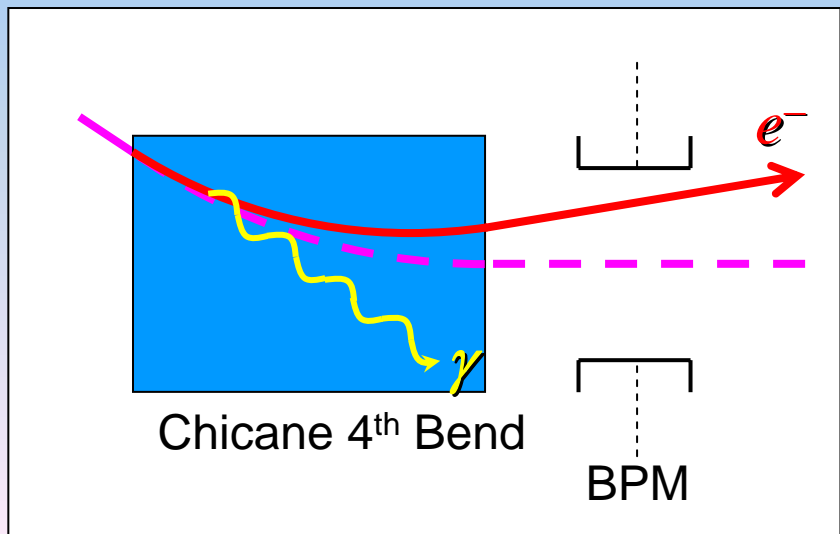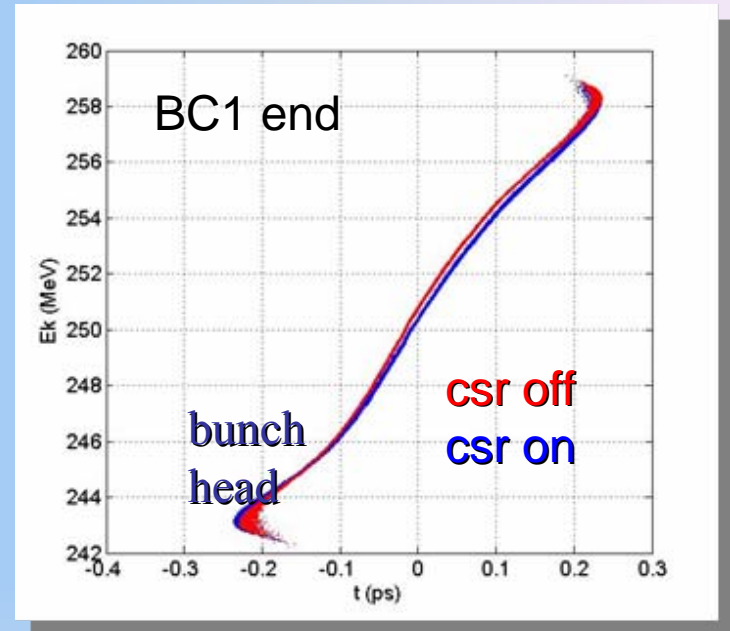• A Phase shift of -0.4 deg is added to the ***Elegant*** simulations
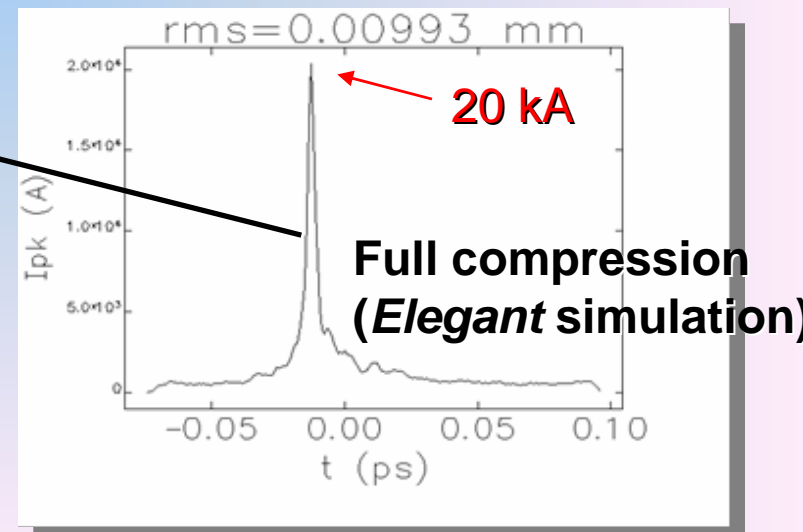
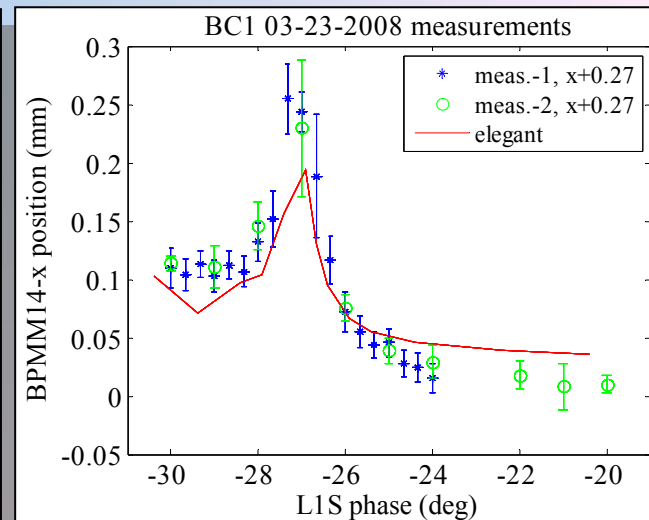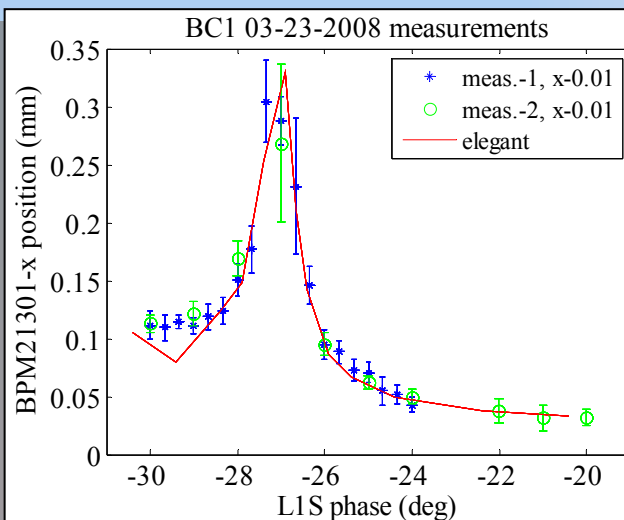# CSR energy loss

L1S = -25.5 deg, *Elegant* simulations

Longitudinal phase space

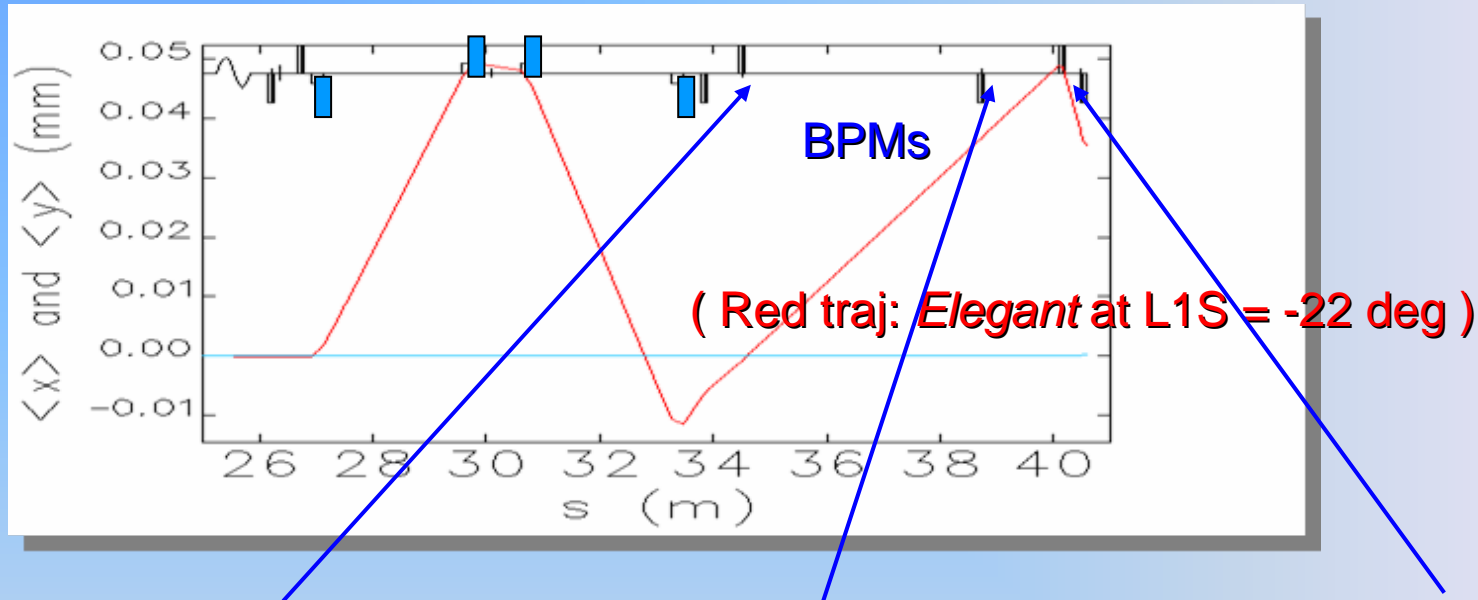Energy loss in BC1

BC1 end

csr off
csr on

bunch
head

Chicane 4th Bend

BPM

BPMs after the chicane could be used to measure this energy loss.

CSR E-loss as seen by BPMs

Trajectory change due to CSR seen by three BPMs after BC1

BPMs

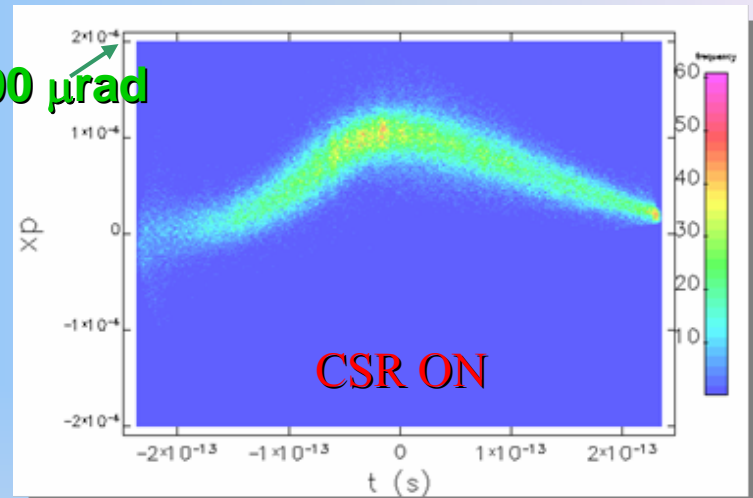(Red traj: *Elegant* at L1S = -22 deg)
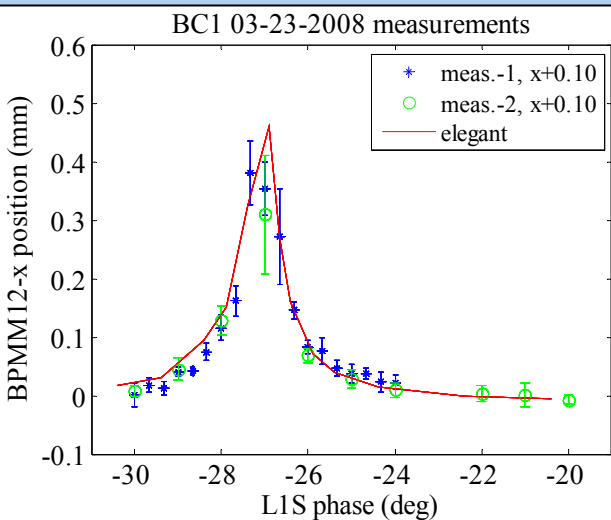
X-plane properties affected by CSR

• CSR E-loss in bends leads to transverse distortion of the bunch and emittance growth; *Elegant* BC1 simulations at L1S = -25.5 deg
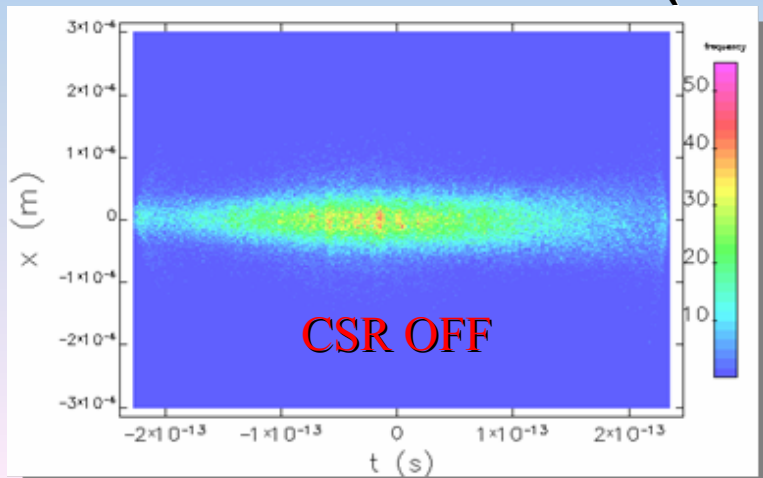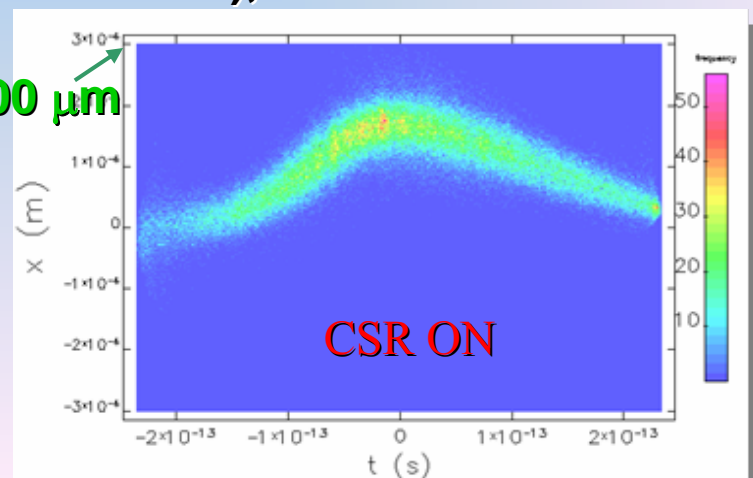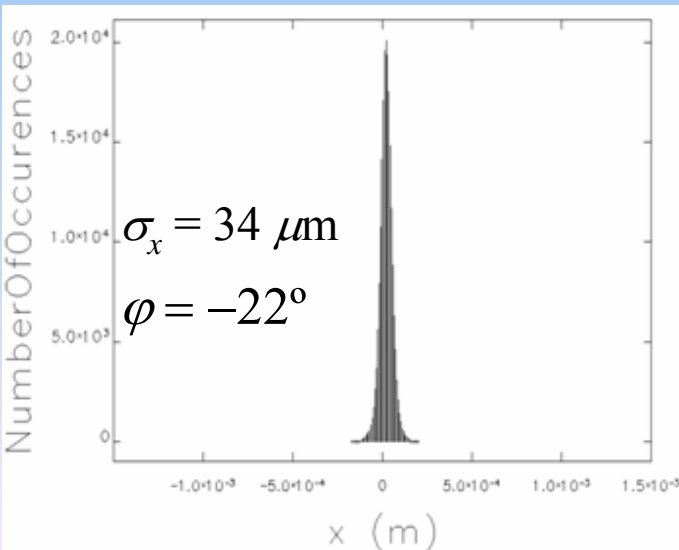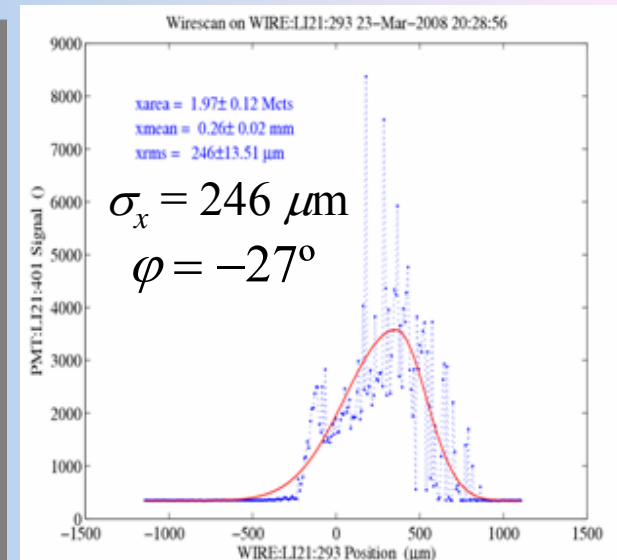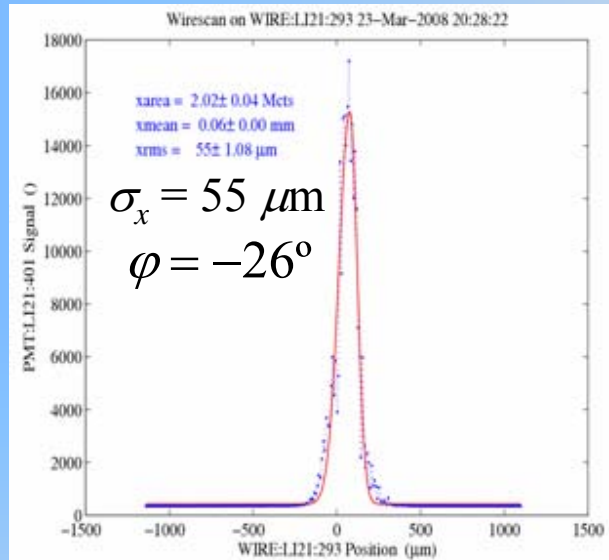
BC1 END, t – x'

200 μrad

CSR OFF

CSR ON

WS12 (3.3 m down stream), t - x

300 μm

CSR OFF

CSR ON

WS12 x-profiles

Wirescan on WIRE:LI21:293 23–Mar–2008 20:26:39

xarea = 2.03± 0.03 Mcts
xmean = −0.00± 0.00 mm
xrms = 38± 0.60 μm

$\sigma_x = 38\ \mu m$

$\varphi = -22°$

Wirescan on WIRE:LI21:293 23–Mar–2008 20:28:22

xarea = 2.02± 0.04 Mcts
xmean = 0.06± 0.00 mm
xrms = 55± 1.08 μm

$\sigma_x = 55\ \mu m$

$\varphi = -26°$

Wirescan on WIRE:LI21:293 23–Mar–2008 20:28:56

xarea = 1.97± 0.12 Mcts
xmean = 0.26± 0.02 mm
xrms = 246±13.51 μm

$\sigma_x = 246\ \mu m$

$\varphi = -27°$

$\sigma_x = 34\ \mu m$

$\varphi = -22°$
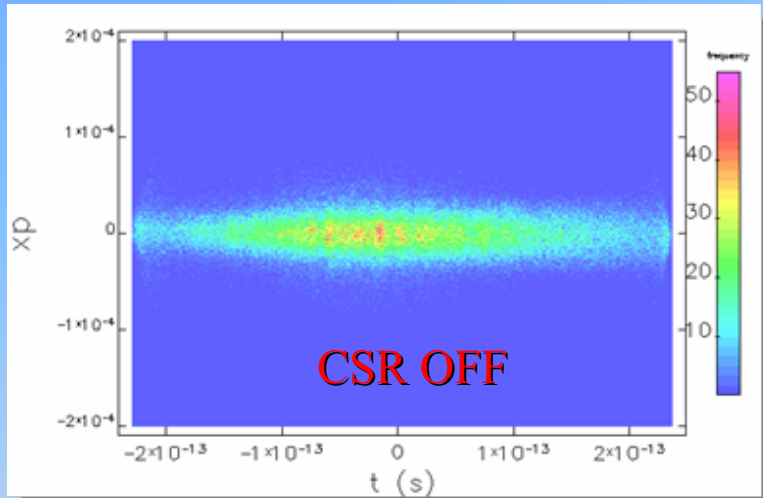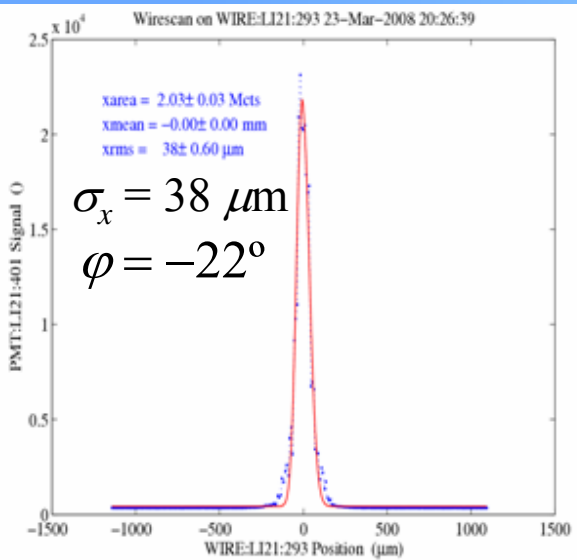
Elegant
simulated
x-profiles

$\sigma_x = 251\ \mu m$

$\varphi = -27°$
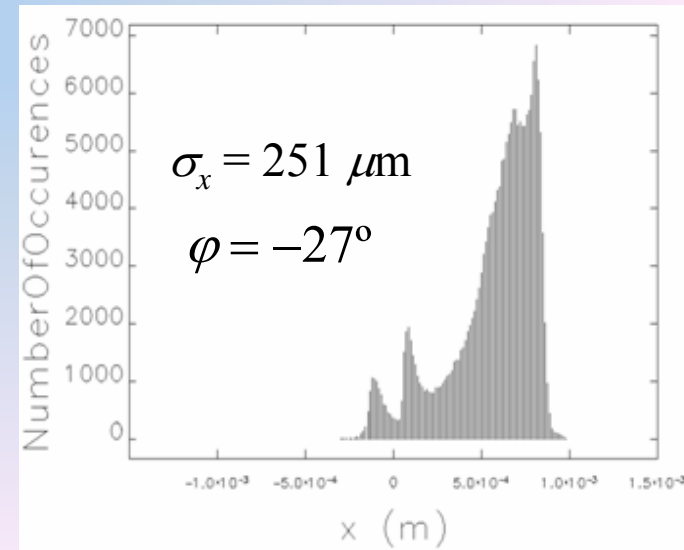
CSR Emittance growth after BC1 (250pC)

BC1 03-23-2008 measurements

meas.-1
meas.-2
elegant
CSRtrack g2m
elegant+Impact-T

operating point

$\gamma \varepsilon_x$ (µm)

L1S phase (deg)

BC1 03-23-2008 measurements

meas.
elegant
CSRtrack g2m
elegant+Impact-T

$\gamma \varepsilon_y$ (µm)

L1S phase (deg)
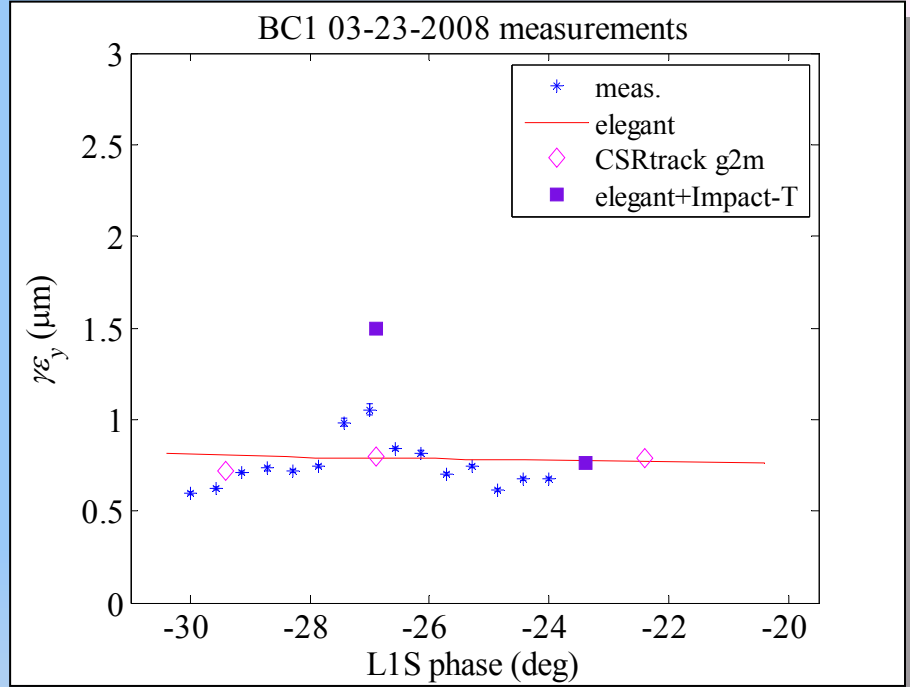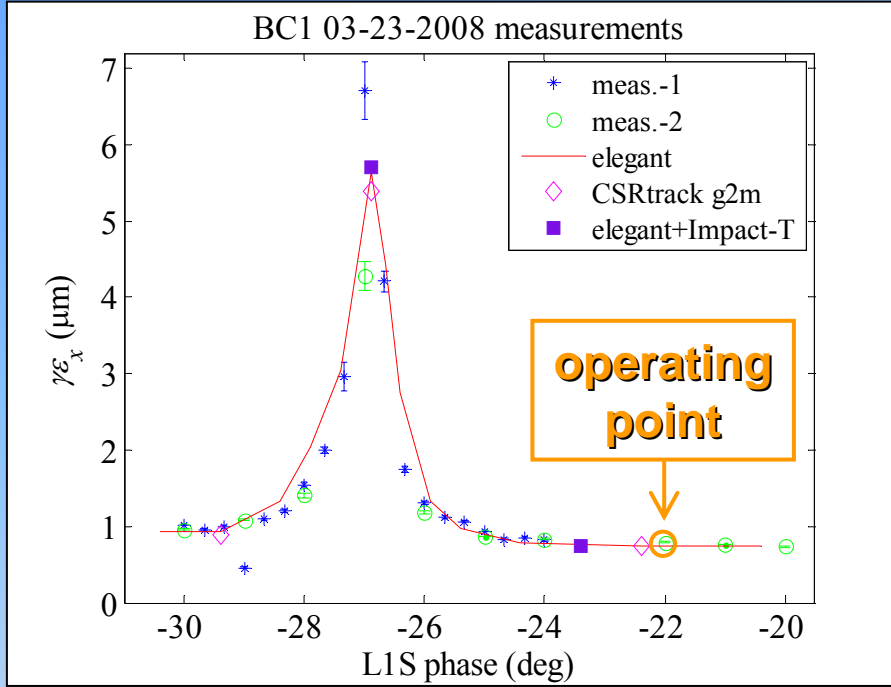
- *Elegant* (1D CSR with transient) shows good agreement with data

- *CSRtrack* (2D self-field) uses 100k particles, g2m, reads *Elegant* output at BC1 entrance, tracks BC1 up to WS12; agrees with *Elegant*

- *Impact-T* (3D space charge, no CSR) reads *Elegant* output at BC1 exit, compute to WS12 (3.3 m downstream) ➔ suggests that small vertical emittance growth due to space charge at full compression (need to rule out instrumental effects)

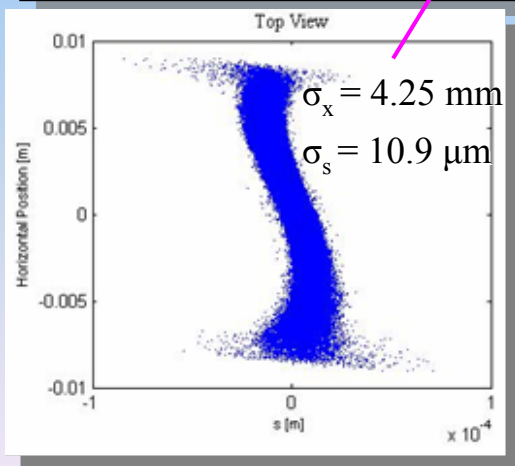# Emittance still gold when over-compressed
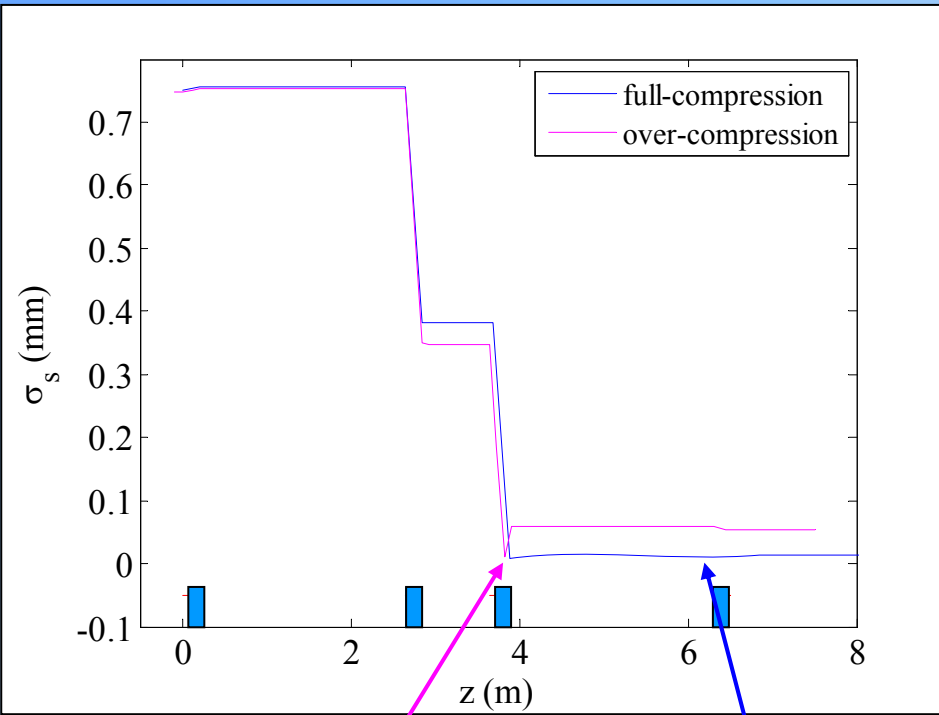
- Very short interaction length at minimum bunch length (in the 3rd dipole) when over compressed

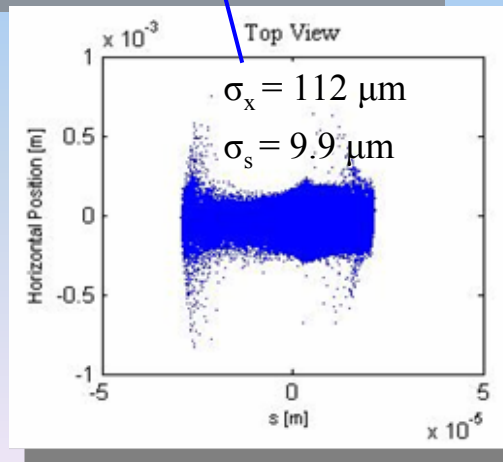- Dispersion at 3rd dipole makes horizontal beam size large

At over-compression minimum bunch length:

$$\frac{\sigma_x}{\sigma_s} >> \left(\frac{\rho}{\sigma_s}\right)^{1/3}$$

3D CSR may further reduce 1D estimation

$\sigma_x = 4.25$ mm

$\sigma_s = 10.9$ μm

$\sigma_x = 112$ μm

$\sigma_s = 9.9$ μm

Over compression

Full compression

14

BC1 CSR studies at 1 nC

- Machine setup:
  Energy = 250 MeV;
  BC1 R56 = -45.5mm;
  L1X: 20MV, -160 deg;
  BC2 off.

- Injector beam conditions (at 135 MeV)

  $\gamma\varepsilon_x \sim \gamma\varepsilon_y \sim 0.9$ um (WS02, asymmetric Gaussian method)

  $\sigma_z \sim 1.1$ mm (OTR2)

CSR E-loss and emittance growth at 1 nC
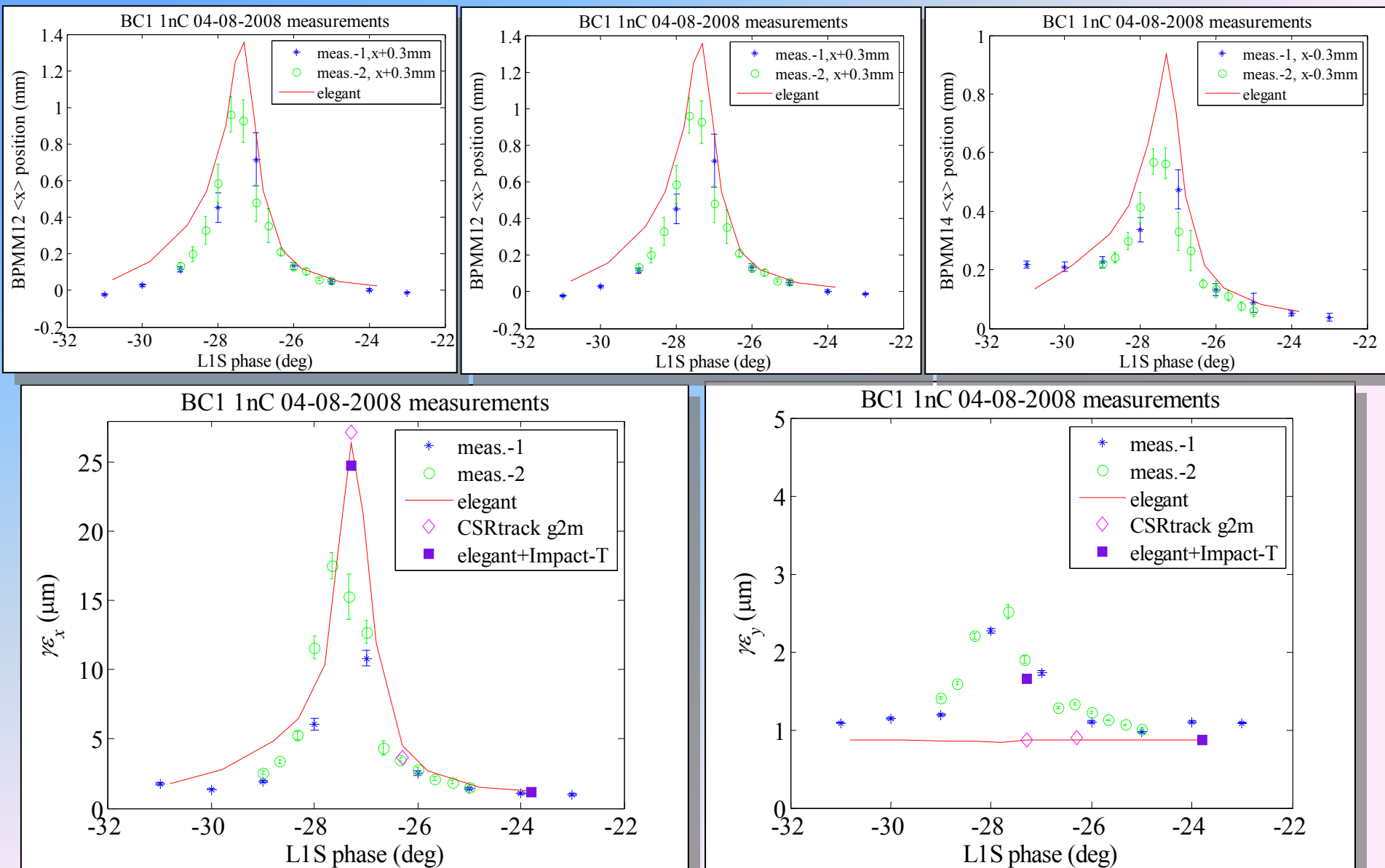
A Phase shift of −0.8 deg is added to the *Elegant* curves

BC2 CSR studies at 250 pC

- Machine setup:

  L1S: -22 deg; L1X: 20MV, -160 deg;

  BC1 R56 = -45.5 mm; Energy = 250 MeV;

  BC2 R56 = -24.7 mm; Energy = 4.3 GeV.

- Initial beam for simulations (at 135 MeV):

  $\gamma\varepsilon_x \sim \gamma\varepsilon_y \sim 0.7$ um (WS02)
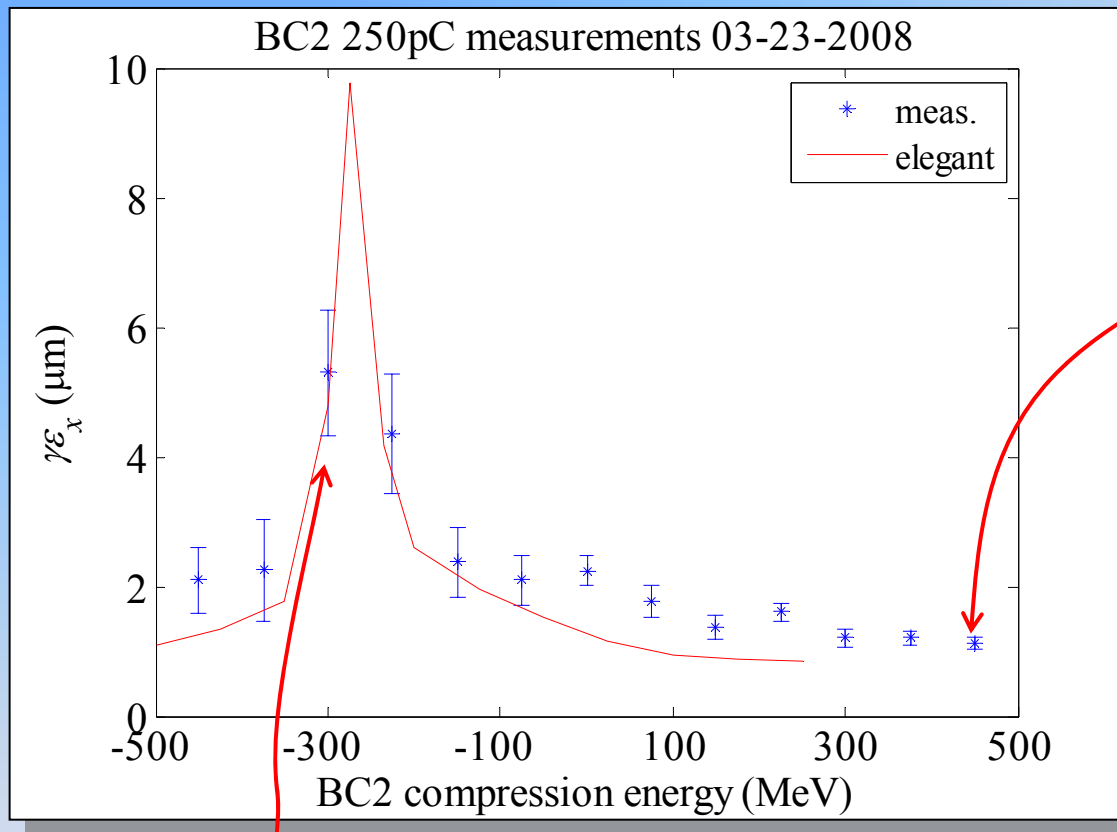
  $\sigma_z \sim 750$ um (OTR2)

- Scan BC2 chirp control instead of whole L2 linac phase
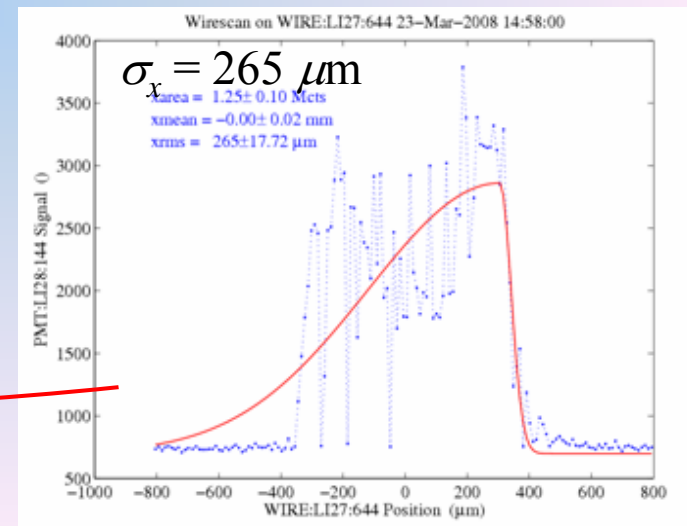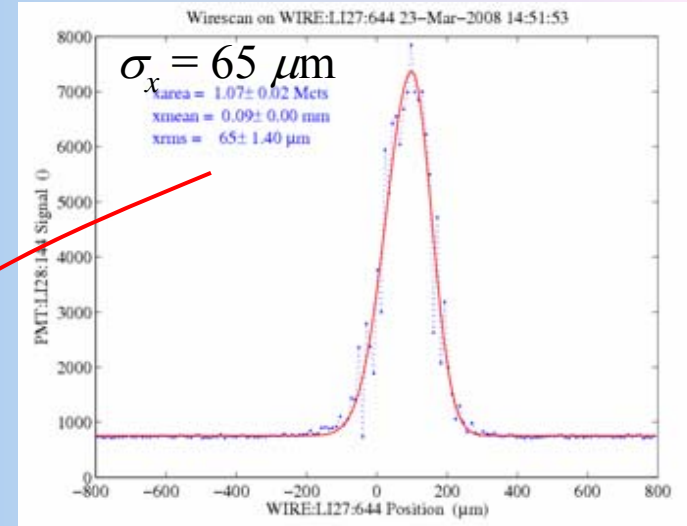
RMS bunch length and CSR energy loss vs. BC2 compression
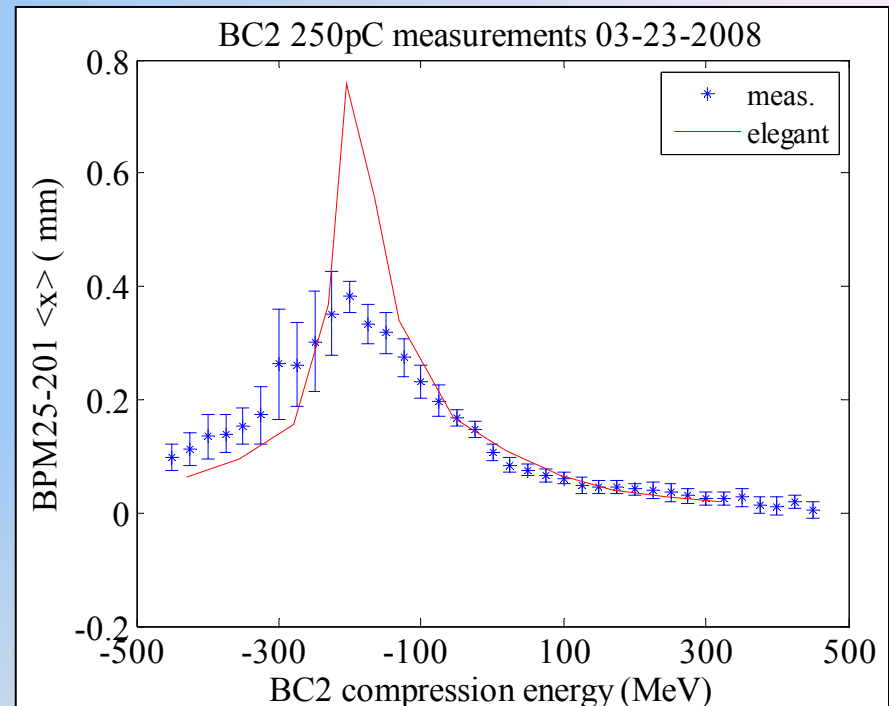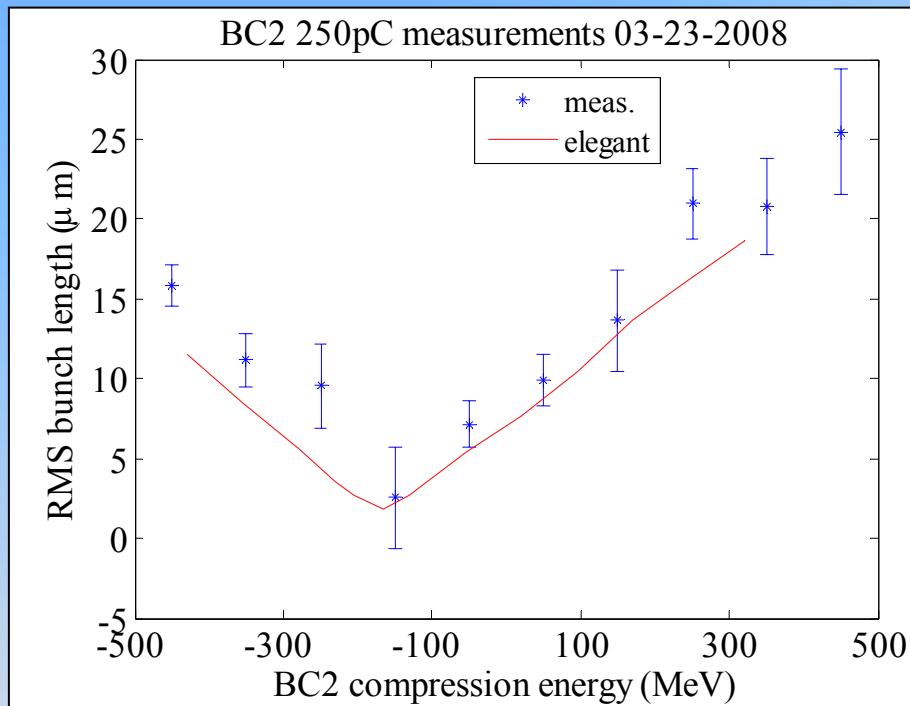
A shift -130 MeV is added to *Elegant* simulations
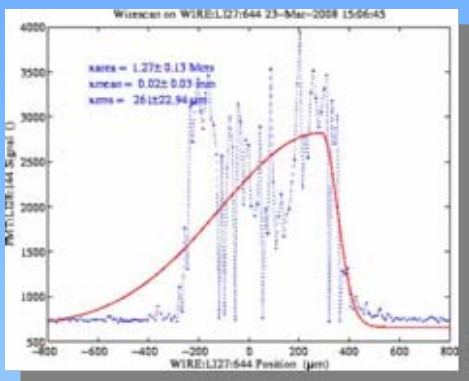
X-Emittance vs BC2 compression

Emittance measured with four wire scanners ~300 m downstream of BC2
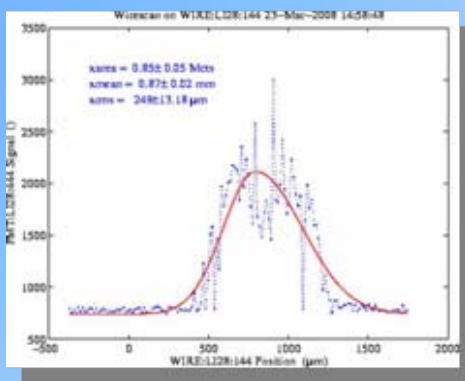
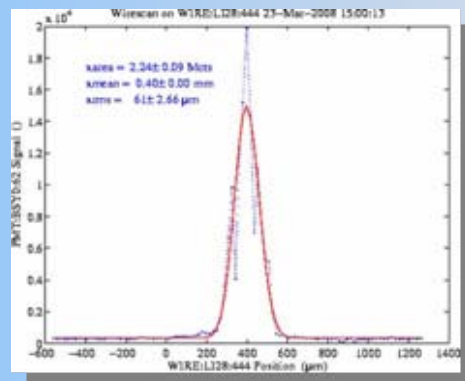Shift of -200 MeV added to *Elegant*

X-profiles at BC2 full compression
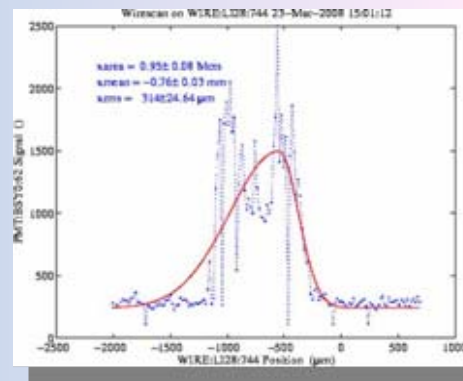
4 wire scanners at 9 GeV
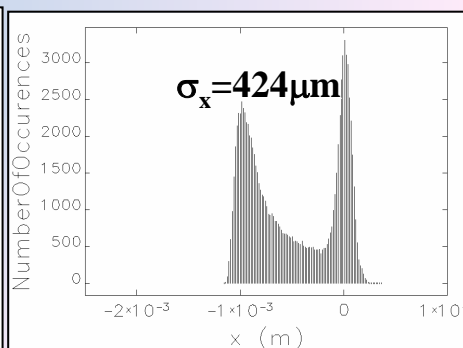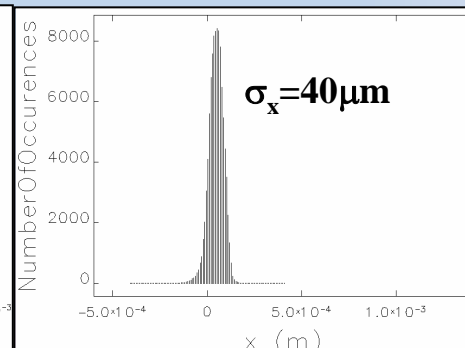

WS27644   WS28144   WS28444   WS28744

Elegant simulations

$\sigma_x = 414\mu m$ $\sigma_x = 470\mu m$ $\sigma_x = 40\mu m$ $\sigma_x = 424\mu m$
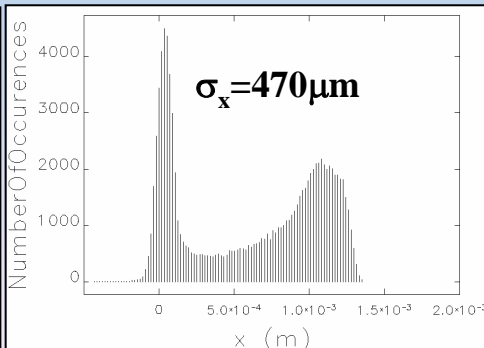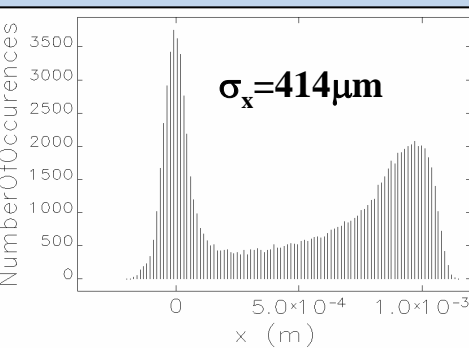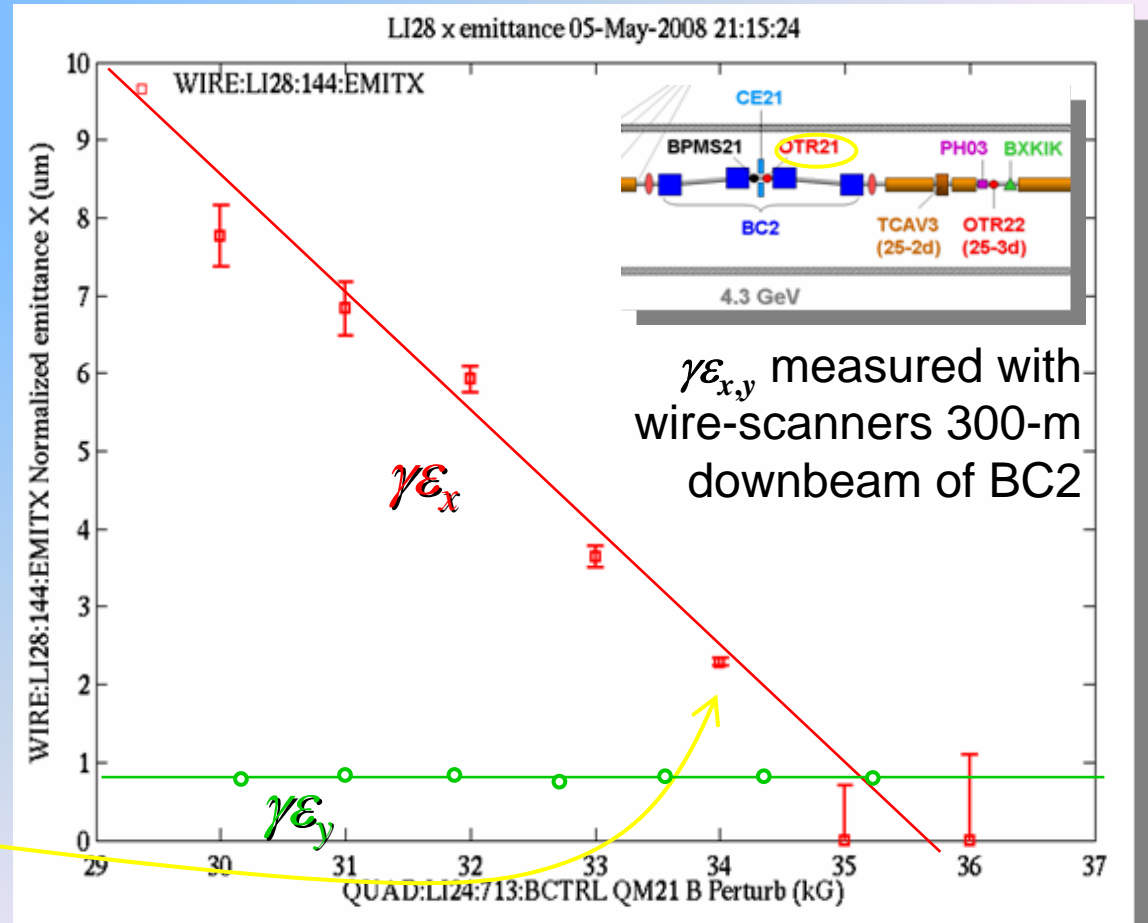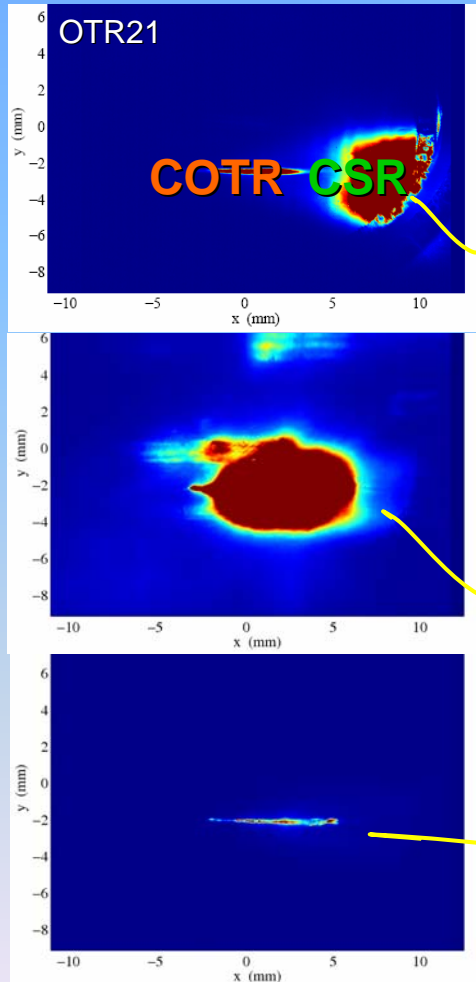
Direct observation of CSR at optical wavelength due to μ-Bunching at BC2

OTR screen in BC2

More on this and μ-Bunching tomorrow…

Summary

- We presented measurements of CSR-induced energy loss and related transverse emittance growth in both compressors

- Measurements are in good agreement with codes. BC1 normally operates away from CSR problems.

- BC2 emittance measurements are still tricky (wires ~300 m downstream, μ-Bunching may complicate things here), we hope to get improved data soon.

- No 'slice' emittance data yet available after compression (FEL is impacted by 'slice' emittance and not so much 'projected')

Thanks for your attention!

Acknowledgements

* P. Emma for leading LCLS commissioning and CSR studies

* Y. Ding for providing CSR simulations and many slides