Some Considerations on CSR Microbunching Instability (SASE in a Bunch Compressor?)

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Introduction

- Bunch Compressor (BC) is design to be a very effective buncher ($\sigma_s \to \frac{\sigma_s}{10}$)

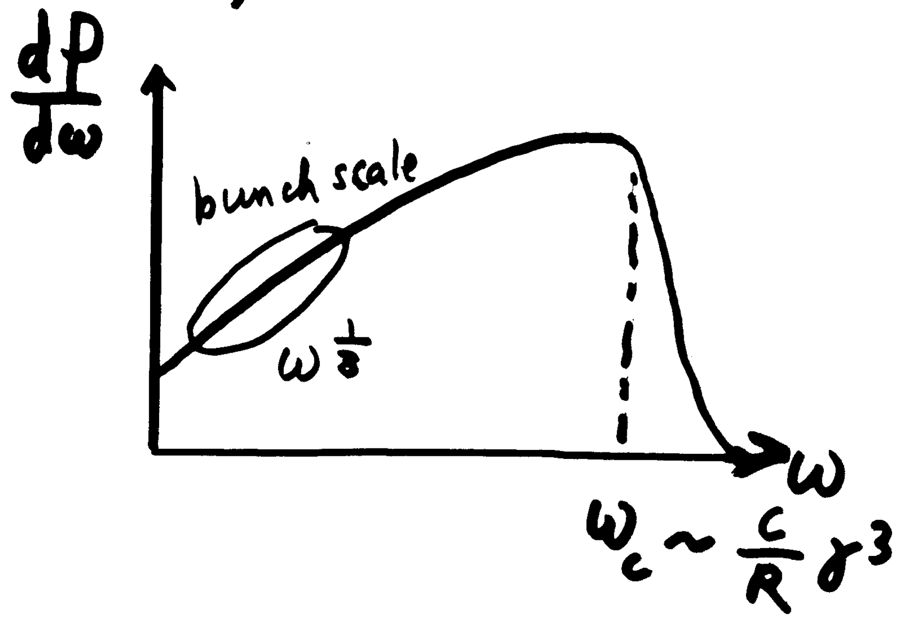
$\Rightarrow$ also very effective to grow microbunching!

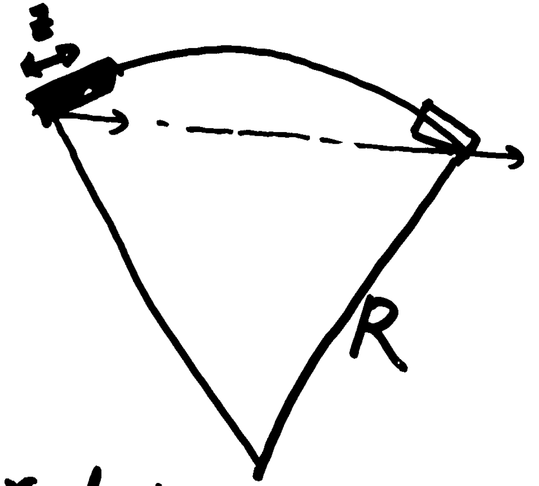
due to synchrotron radiation "wake"

- Radiative interaction in a BC is similar to FEL interaction

$$\begin{cases} \text{start up from noise (SASE)} \\ \text{high gain} \\ \text{saturation} \end{cases}$$

Synchrotron Radiation Impedance/Wake





radiative interaction within the bunch

$\Rightarrow$ impedance $Z_{\parallel} \sim \omega^{\frac{1}{3}}$

CSR "wake" $W \sim \left(-\frac{1}{z^{1/3}} \frac{\partial}{\partial z}\right)$ z: bunch coordinate

(Murphy, Derbenev at el. 1995)

- Steady state, no shielding, 1D line charge

Microbunching

- BC (chicane): energy modulation → density modulation
  "optical klystron", "HGHG"

$$\frac{dz}{ds} = R_{56}'(s)\,\delta \quad \left(R_{56}' \equiv \frac{dR_{56}}{ds} \right)$$

- SR impedance/wake: density mod. → energy mod.

$$\frac{d\delta}{ds} \propto \int_{-\infty}^{z} \frac{1}{(z-z')^{1/3}} \frac{dn_b}{dz}$$

<u>loop for instability</u> (Borland/Emma, {Schneidmiller, Heifets/Stupakov})

- Stability criterion (~Boussard's microwave stability)

$$\left|\frac{Z_{\parallel}}{n}\right| \sim \left(\frac{\omega R}{c}\right)^{-2/3} < \frac{I_A \gamma}{I |\eta|} \sigma^2$$

CSR $Z_{\parallel} \sim n^{1/3}$

$|R_{56}'|$

What's the source of modulation?

- a non-smooth bunch shape has high frequency content

- Shot noise → density fluctuation
  (incoherent synchrotron radiation)
  at modulation wavelength λ

  noise bunching $b \sim \frac{1}{\sqrt{N_\lambda}} \leftarrow$ # of particles in λ

  $\sim 10^{-3} - 10^{-4}$

- Similar to SASE, but broad-band v.s. narrow-band

  SASE $b_{eff} \sim \frac{1}{\sqrt{N_{\ell c}}} \leftarrow$ # of particles in coherence length $\ell_c \sim 100\lambda$

High Gain Regime

- like FEL, introduce scaling "ρ" (stability $\sigma_\delta > \rho$)

$$\rho \sim \sqrt{\frac{I}{I_A}\frac{1}{\gamma}\frac{1}{(-R_{56}')}}\left(\frac{\lambda}{R}\right)^{\frac{1}{3}} \sim 10^{-4} \quad (\lambda \sim 10 \text{ to } 1\ \mu m)$$

- PC Gun simulation : incoherent $\sigma_\delta \sim 10^{-5}$ @ 250MeV

$\Rightarrow$ $\sigma_\delta \ll \rho$ (very unstable against Microbunching)

- High-gain approximation

  instability occurs much faster than bunch compression,

  $\Rightarrow$ use the <u>instataneous I, λ</u> for the instability calculation

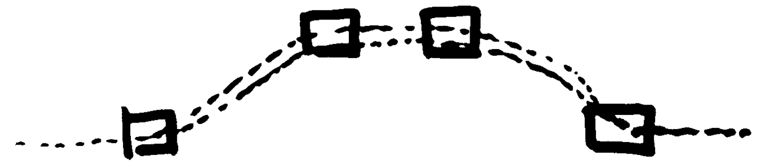
Gain length

- When $\sigma_\delta \ll \rho$, gain length $\dfrac{\lambda}{\rho(-R'_{56})} \sim \dfrac{\lambda^{2/3}}{(-R'_{56})^{1/2}}$
- Compare to FEL gain length $\dfrac{\lambda_u}{\rho} \sim \dfrac{(2\gamma^2)\lambda}{\rho}$

B C (Chicane) | undulator

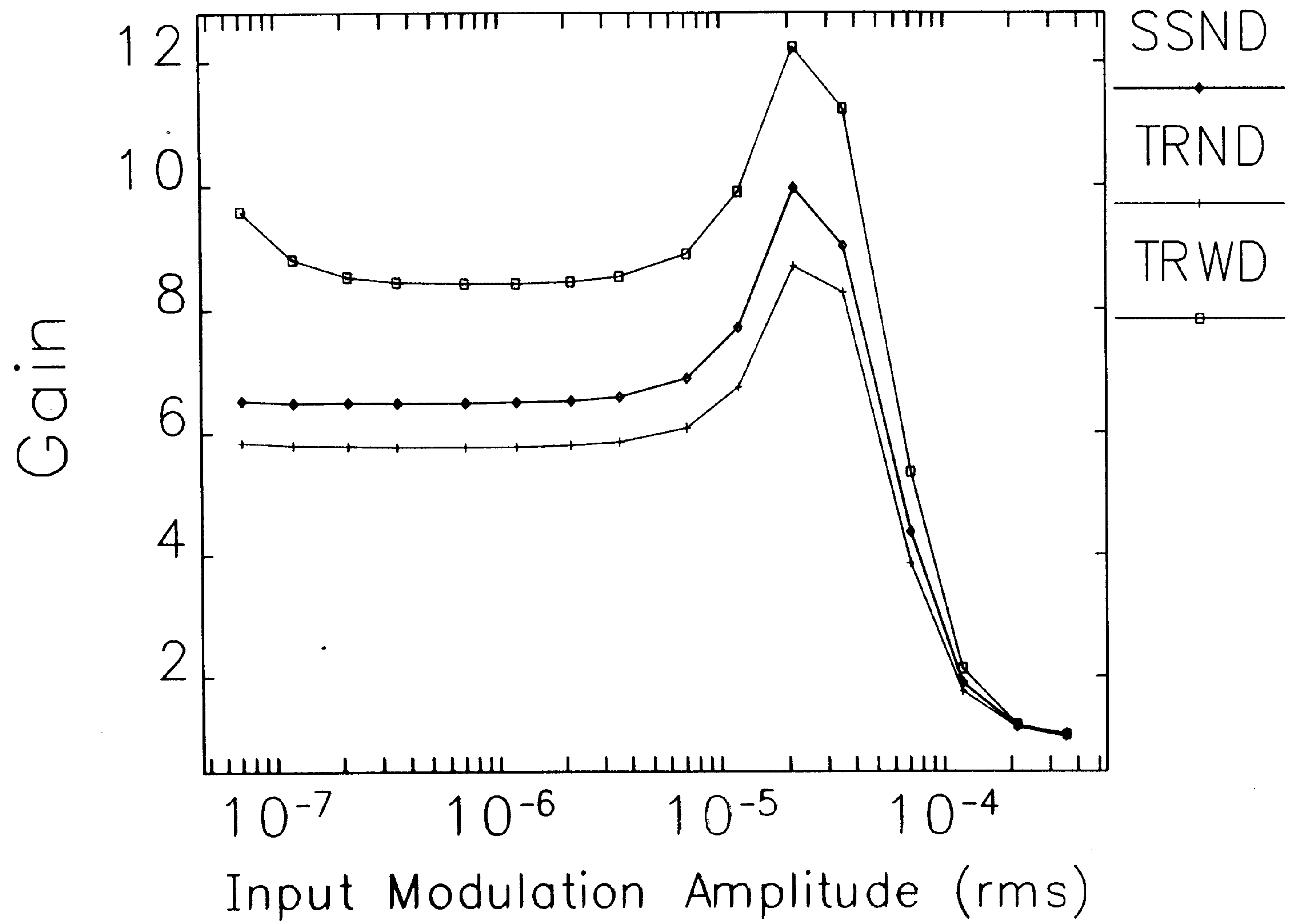
$(-R'_{56}) \sim \dfrac{\eta}{R} \gg \dfrac{1}{\gamma^2}$

Bunching: path length difference | velocity difference

much more effective when $\sigma_\delta < \rho$ (micros) | FEL instability can occur even at 1 Å

Elegant Simulations (M. Borland), no compression



Group bc1-07Nov01

LCLS BC1, $\lambda = 10\,\mu m$, $G_{theory} = 6$

Numerical Calculations

initial

	LEUTL	LCLS BC1	BC2	Test-chicane
energy [GeV]	0.15	0.25	4.5	5
charge [nC]	0.5	1	1	1
σ_s [μm]	540	830	190	200
incoherent σ	6e-5	1.2e-5	3e-5	2e-6
chirp [m^{-1}]	12	21.4	40	36
bending R [m]	0.8	2.5	12.2	10.35
length per bend [m]	0.192	0.203	0.4	0.5
R_{56} [mm]	65	36	22	25
$(1+hR_{56})^{-1}$	4.4	4.4	8.4	10
$-R'_{56}$	0.17	0.089	0.0275	0.025
wavelength λ [μm]	10/1	10/1	3	1
scaling ρ (at s=0)	1.9e-4/8.6e-5	1.5e-4/7.2e-5	5.3e-5	3.8e-5
relative Gain	500/1	150/1e11	~ 1	2e6
saturation σ		3.8e-4/1.9e-4		1.3e-4
$\Delta\varepsilon_n$ [μm]		~ 0.1		~ 1

Table 1: CSR microbunching instability in bunch compressors

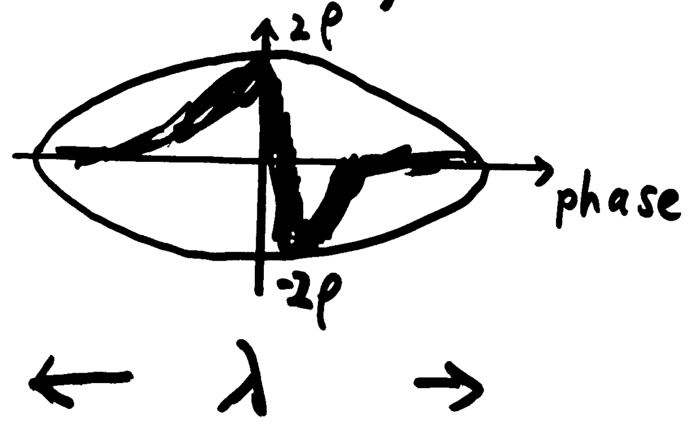
Saturation

- Microbunching instability saturates when $|b| \sim 1$

  noise $|b| \sim \frac{1}{10^3 \sim 10^4}$

- All it takes a gain of $10^3 \sim 10^4$

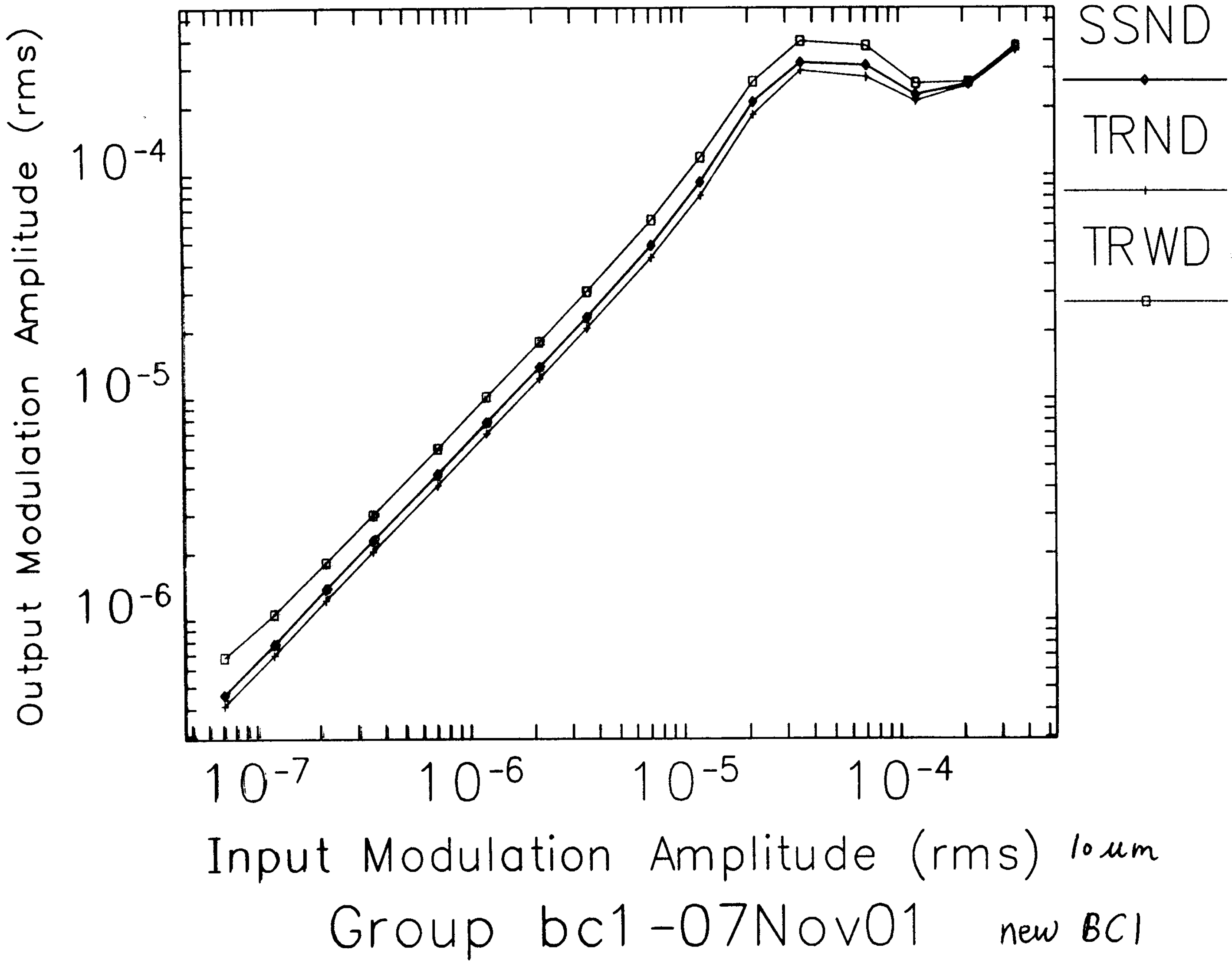
- At saturation, electrons trapped in bucket



$\sigma_\delta \sim 2\rho \sim 10^{-4}$

↑ sliced energy spread

Elegant Saturation Simulation (M. Borland)



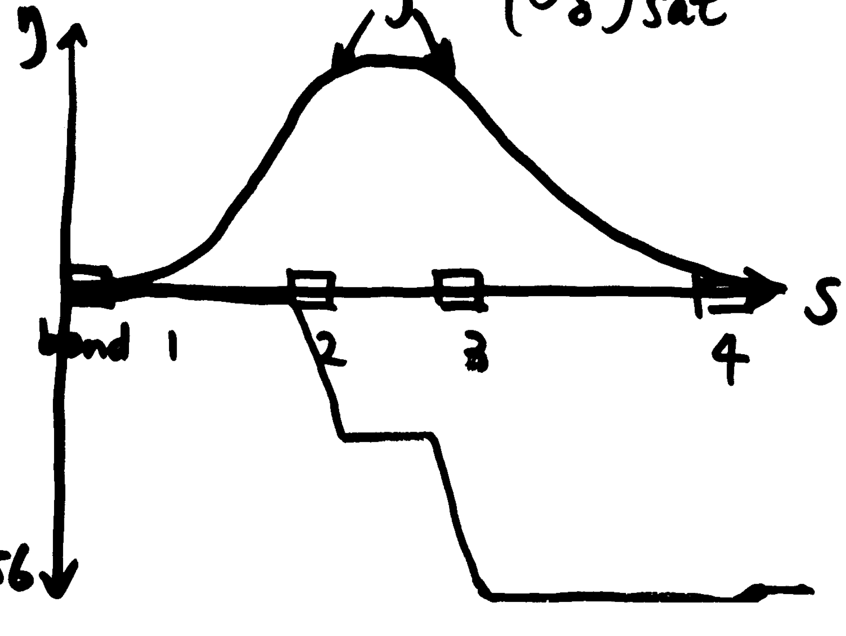
Emittance Growth

- Energy loss in the bend $\xrightarrow{\text{dispersion}}$ emittance growth

- RMS size change (Emma/Brinkmann, PAC 97)

$$\langle \Delta X \rangle_{rms} = \int R_{16} \frac{d\sigma_\delta}{dS}\, dS$$

$$= \eta \cdot (\sigma_\delta)_{sat} \sim \eta \cdot (2\rho)$$



$$-\int \frac{\eta}{R}\, dS = R_{56}$$

$$\frac{\varepsilon_n}{\varepsilon_0} = \sqrt{1 + \frac{\gamma(1+\alpha)}{\varepsilon_0 \beta} \langle \Delta x \rangle^2}$$

Possible Cures

- Unlike FELs, don't want CSR microbunching
- Stability requires

$$\underbrace{\frac{\gamma_f}{\gamma_{BC}}\rho_{FEL}}_{10^{-3}} > \underbrace{\frac{\sigma_\delta}{(1+hR_{56})}}_{\text{increase}} > \underbrace{\rho_{BC} \sim \sqrt{\frac{I}{I_A}\frac{1}{\gamma_{BC}}\frac{1}{(-R'_{56})}}\left(\frac{\lambda}{R}\right)^{\frac{1}{3}}}_{\text{decrease}}$$

wiggler before BC2	faster compression helps
what about BC1?	less bends to grow instab.
(a laser wiggler)?	but how effective