TESLA

On the Microbunching Instability in TTF-2

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Abstract

- This is the first Start-To-End Simulation which considers all important impedances impacting on the microbunching instability in FEL driver linac.
- Space Charge Effects (SC), Coherent Synchrotron Radiation (CSR), Incoherent Synchrotron Radiation (ISR), and Geometric Wakefields are considered from the cathode to the end of TTF-2 Linac.
- We assumed that the modulation source are the laser beam modulation at the cathode, and their conditions are:

Modulation Period	Peak-to-Peak Amplitude	Simulation Range in TTF-2
1.0 ps, 2.0 ps, 4.0 ps	20%	Cathode-To-BC2
2.0 ps	5%, 10%, 15%, 20%	Cathode-To-ACC5
2.0 ps	20%	Cathode-To-ACC6

LSC & CSR Microbunching Instability

by longitudinal space charge force (LSC) in the drift & linac
by coherent synchrotron radiation (CSR) in the bunch compressor
by the geometric wakefields in Linac

Initial current density modulation → **Induced energy modulation**

$$dz_f = dz_i + R_{56}(dE/E)_i \text{ in BC}$$

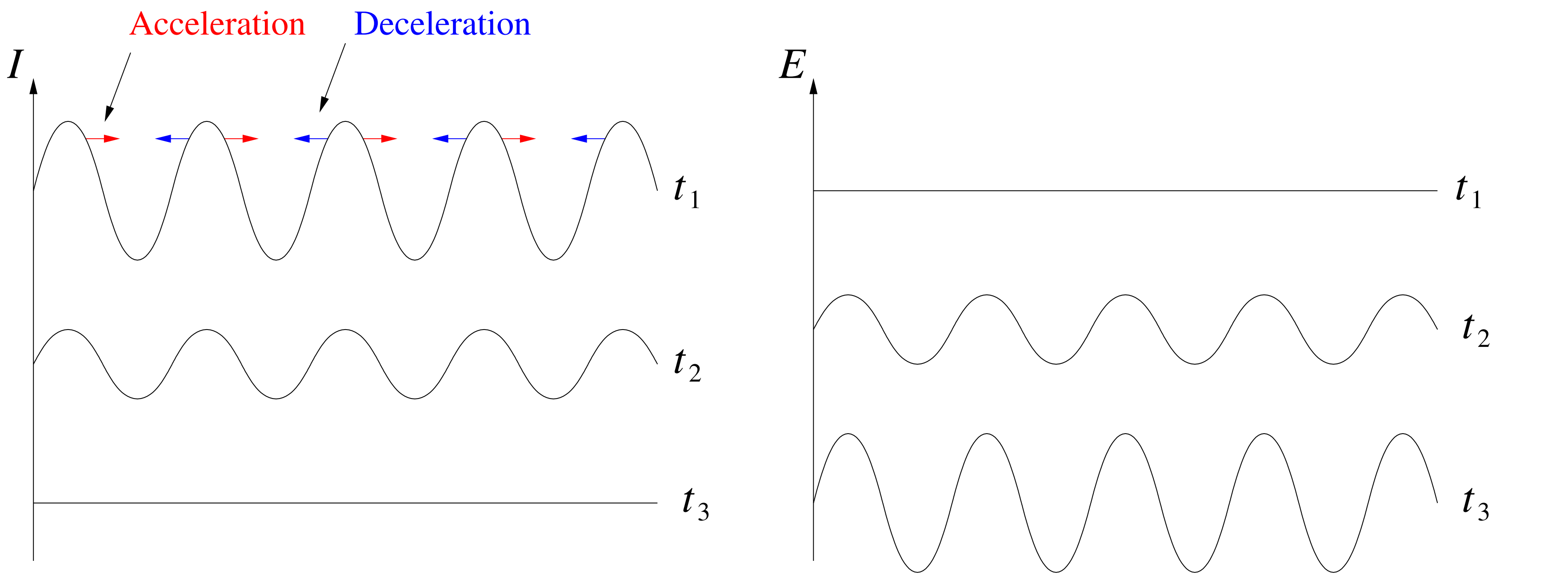
Amplified current density modulation

Slice emittance
Projected emittance
Slice energy spread
Growth !!!

$$Gain = \left| \frac{\text{Normalized amp. of current density}_2}{\text{Normalized amp. of current denisty}_1} \right|$$

Action of Longitudinal Space Charge (LSC)

If there is a density modulation, space charge pushes particles from high density to low density, creating energy modulation in the process.



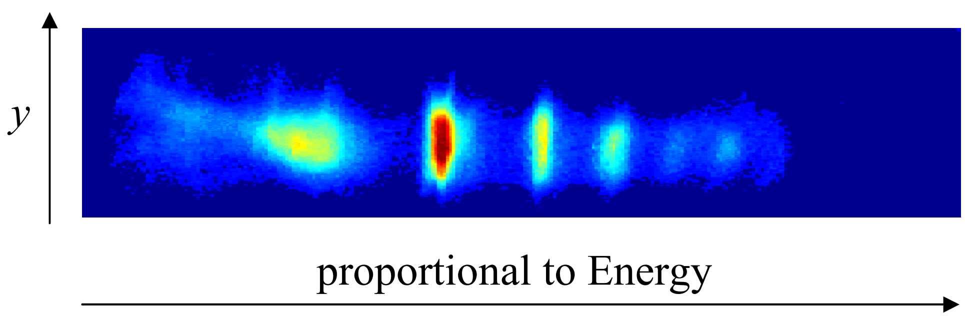
Density modulation → **Energy modulation**

Energy modulation converts back to density modulation to complete space charge oscillation with Plasma oscillation frequency (Here Landau damping is ignored)

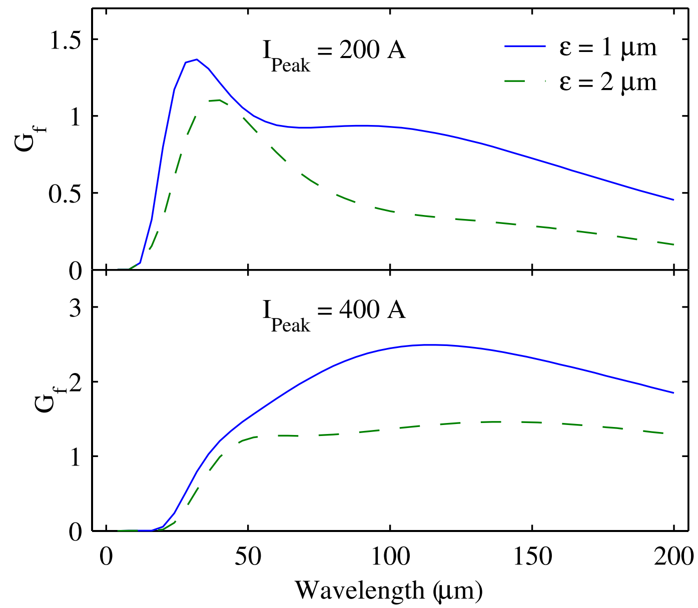
Observation at SDL

BNL friends reported a strange observation similar to the microbunching instability. For a while, we considered their observation as a CSR microbunching instability. But gain of CSR microbunching instability for the SDL chicane is small enough. Then what is source of their observation ?

Courtesy of T. Shaftan (PAC2003, TOPD005) & H. Loos (EPAC2002, TUPRI103)



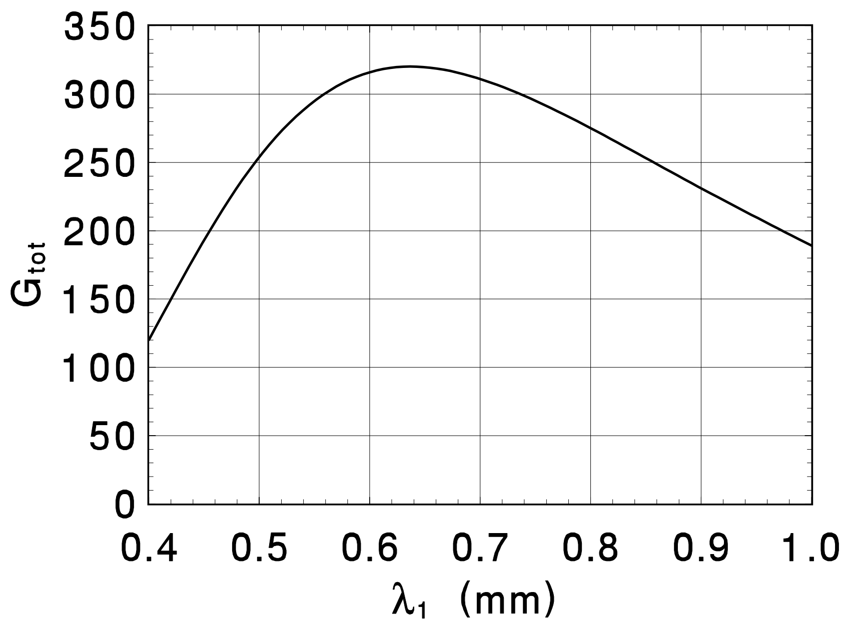
[After BC, energy profile at SDL]



[Gain of CSR Micobunching Instability]

Analytic Estimated Gain & Motivation

- **Motivation : Longitudinal Space Charge (LSC) driven Microbunching Instability TESLA-FEL-2003-02 by Dr. Schneidmiller *et al.***



Tu-P-49 at FEL2003

Maximum gain of the LSC driven microbunching instability in TTF-2 is about 320 for 2.0 ps initial density modulation.

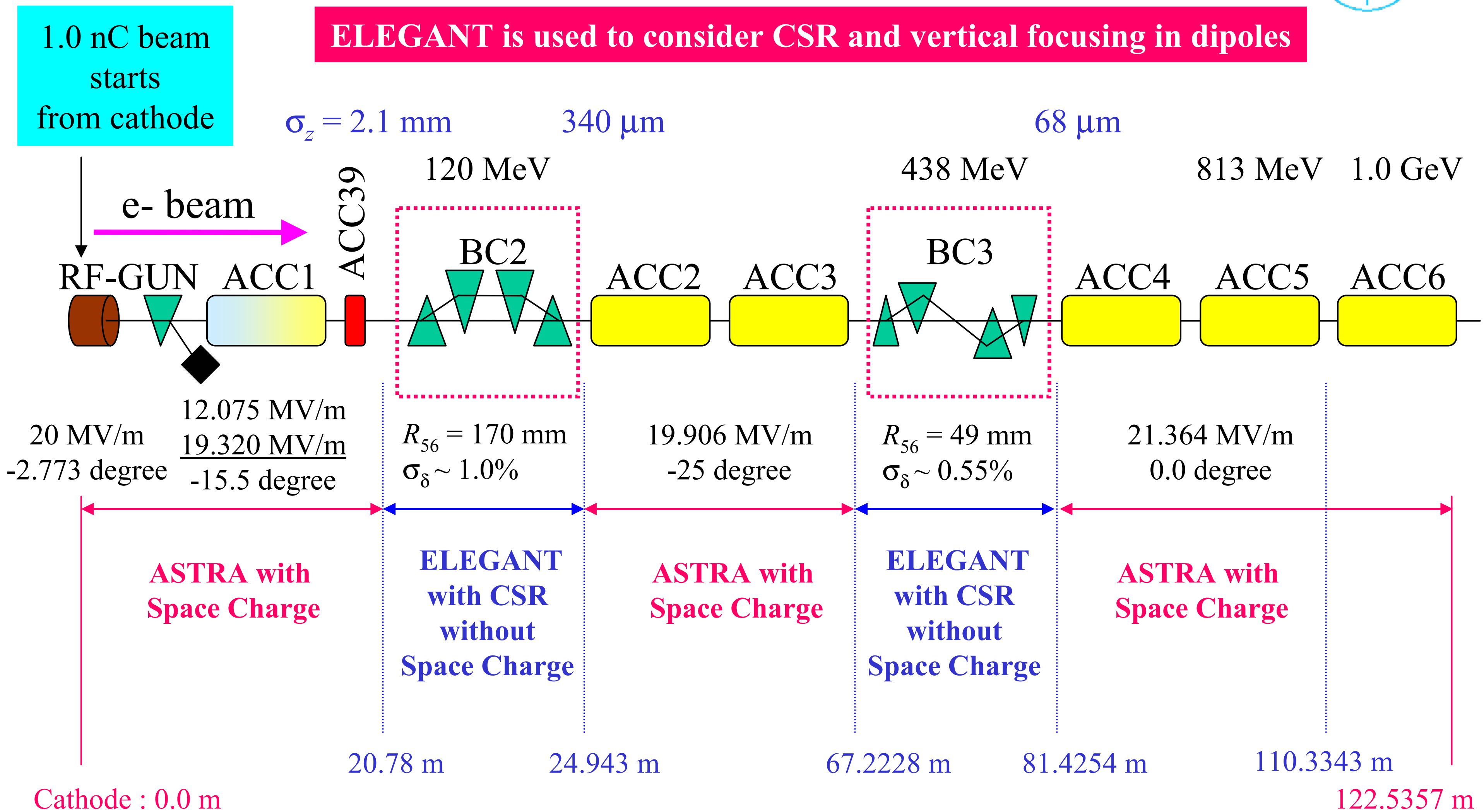
Here they assumed that Plasma oscillation and Landau damping are ignorable. Therefore the initial modulation amplitude is constant and is not damped although beams go through the linac.

$$G = Ck|R_{56}|\frac{I_0}{\gamma_0 I_A}\frac{|Z(k)|}{Z_0}\exp\left(-\frac{1}{2}C^2k^2R_{56}^2\frac{\sigma_\gamma^2}{\gamma_0^2}\right)$$

- **A S2E simulation is needed to check whether the gain is really high or not.**

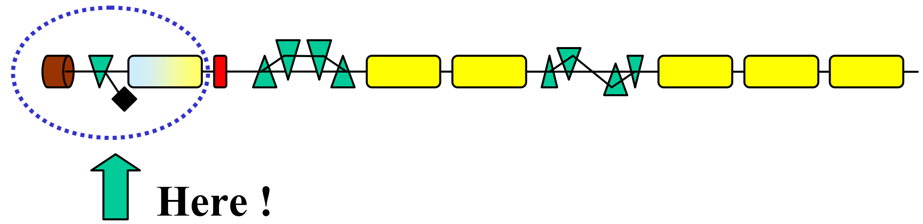
TTF-2 Linac Beamline and Tracking Methods

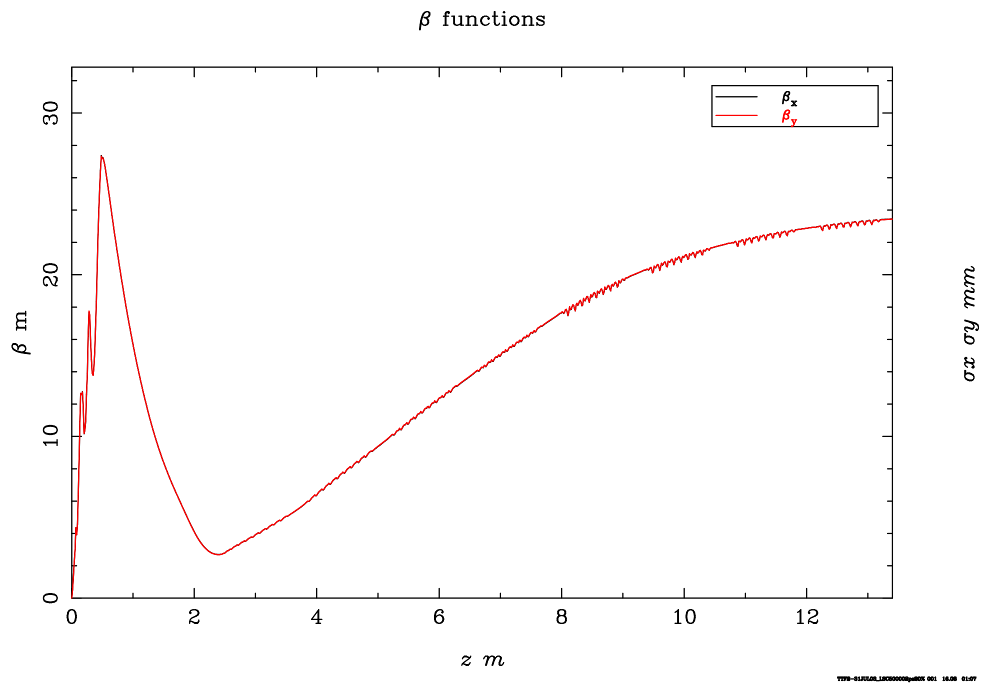
ELEGANT is used to consider CSR and vertical focusing in dipoles

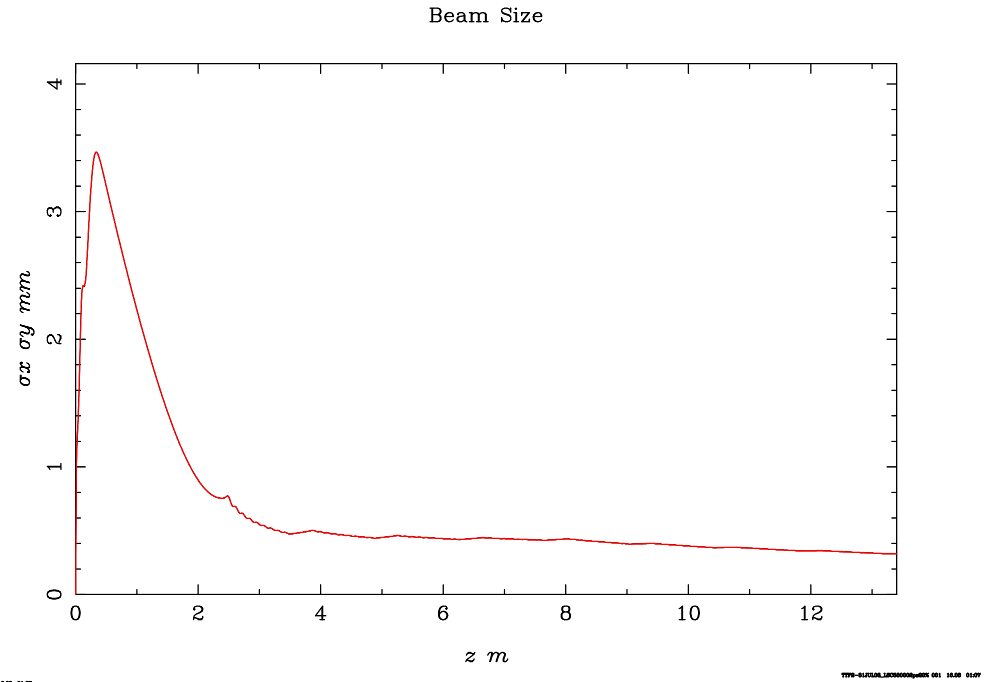


ELEGANT is called at all ends of module to apply geometric wakefields !!!

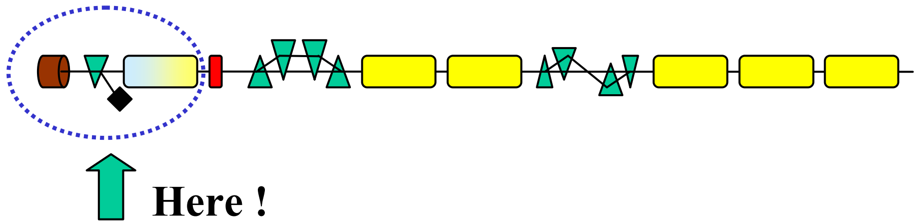
TTF-2 Injector Beamline

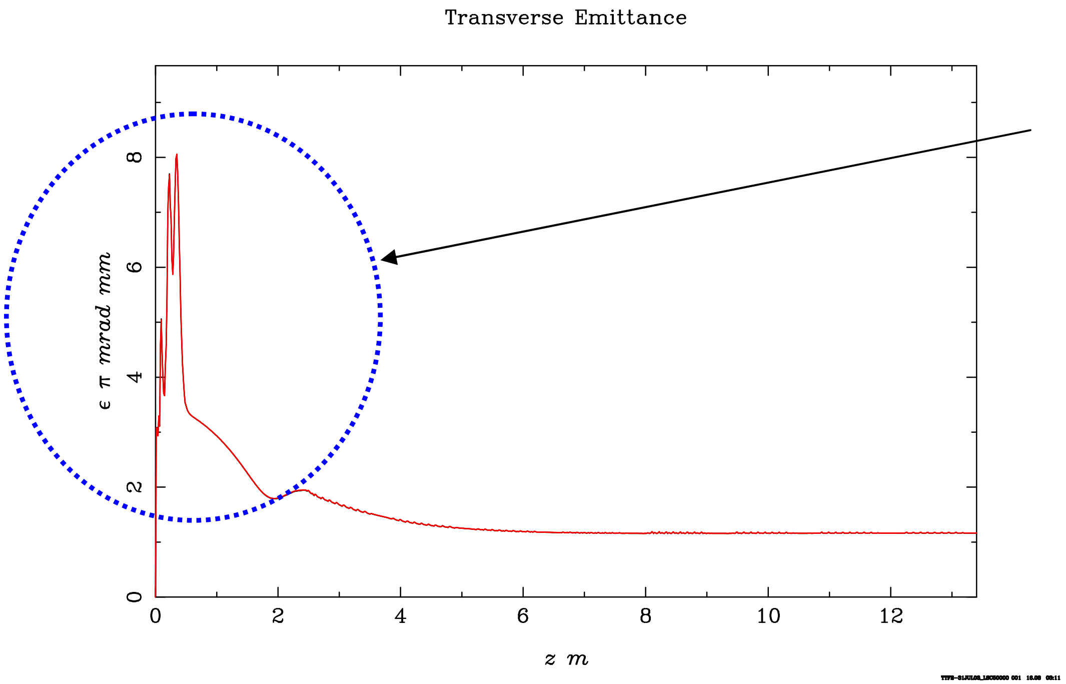






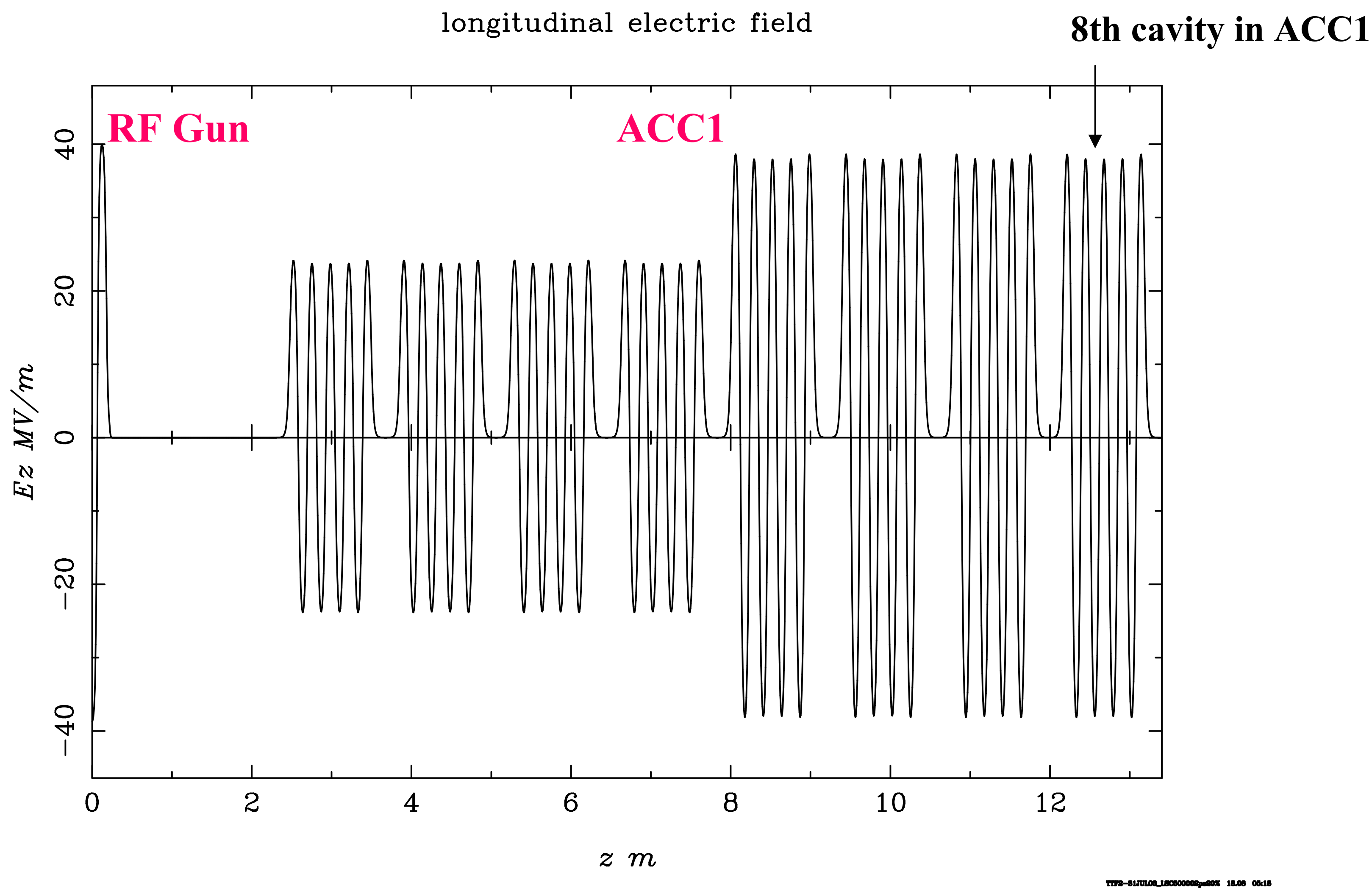
TTF-2 Injector Beamline





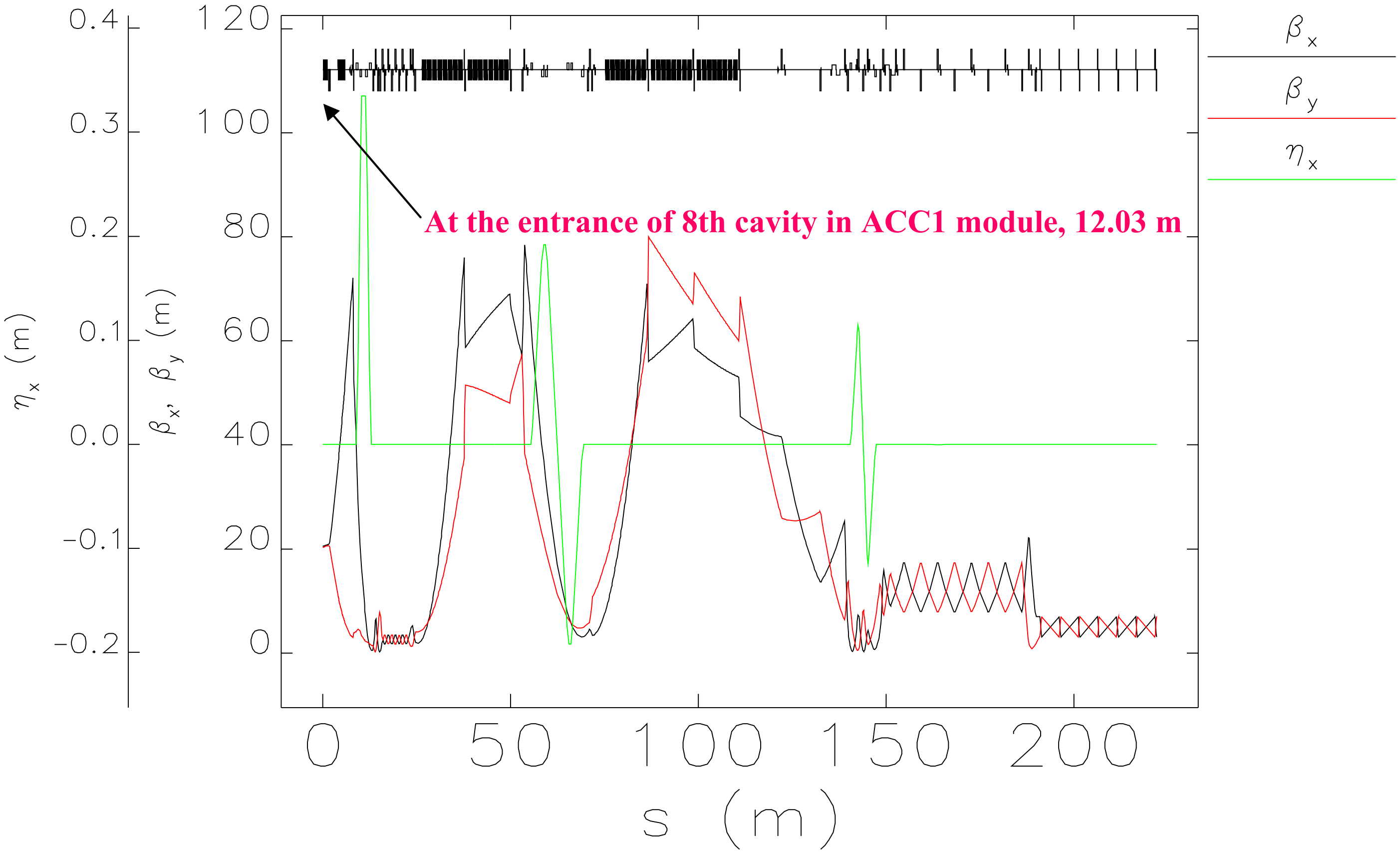
Landau damping is not ignorable at the low energy region due to the large emittance & energy spread.

TTF-2 Injector Accelerating E-Fields



TTF-2 Linac Beamline

All QM strengths and linac phases and gradients come from an optimized ELEGANT lattice !

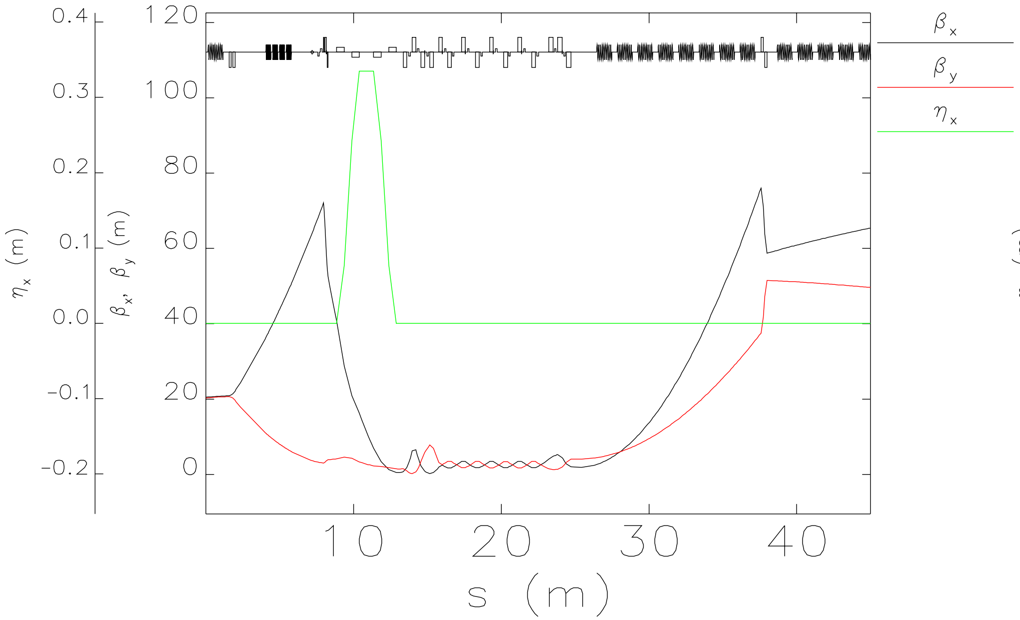


Twiss parameters of TTF-2 Nominal Operation

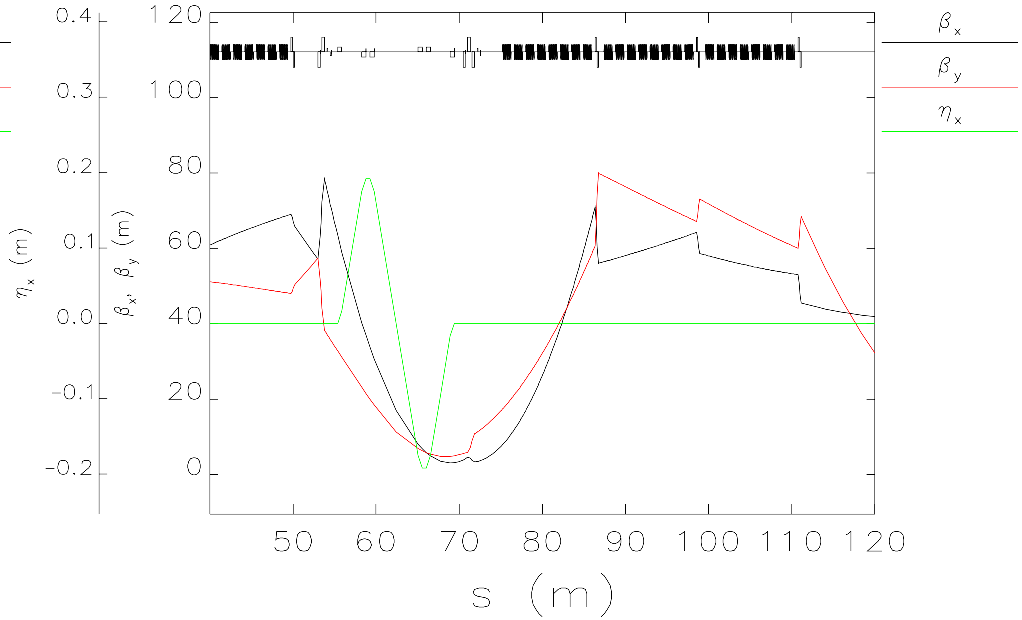
TTF-2 Linac Beamline

All QM strengths and linac phases and gradients come from an optimized ELEGANT lattice !

BC2



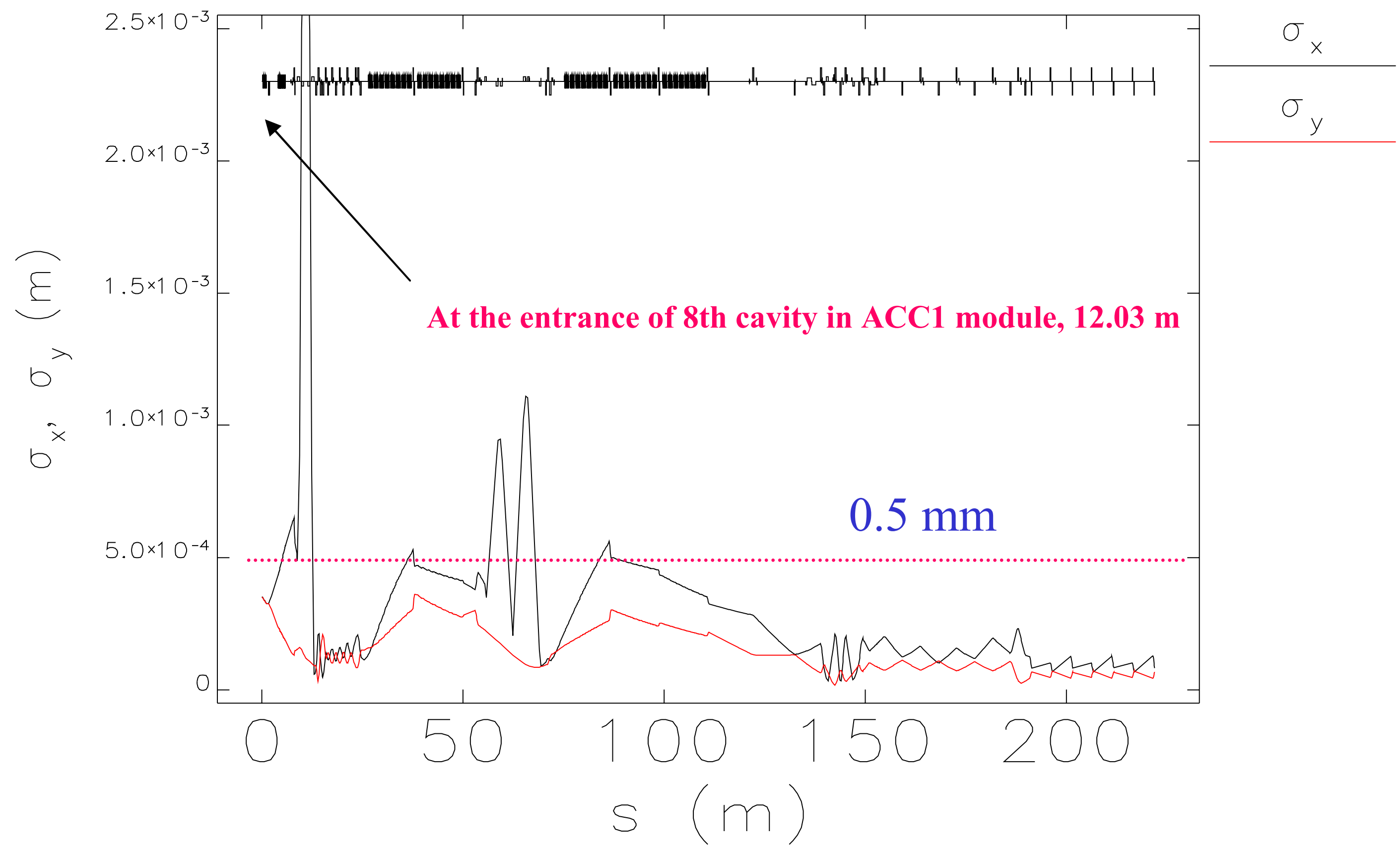
BC3



Twiss parameters around TTF-2 BC2 and BC3

TTF-2 Beamline

All QM strengths and linac phases and gradients come from an optimized ELEGANT lattice !

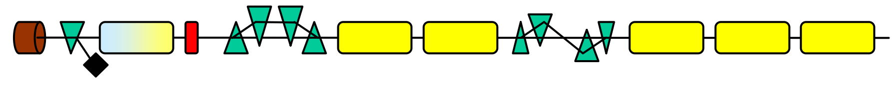


Beamsizes of TTF-2 Nominal Operation

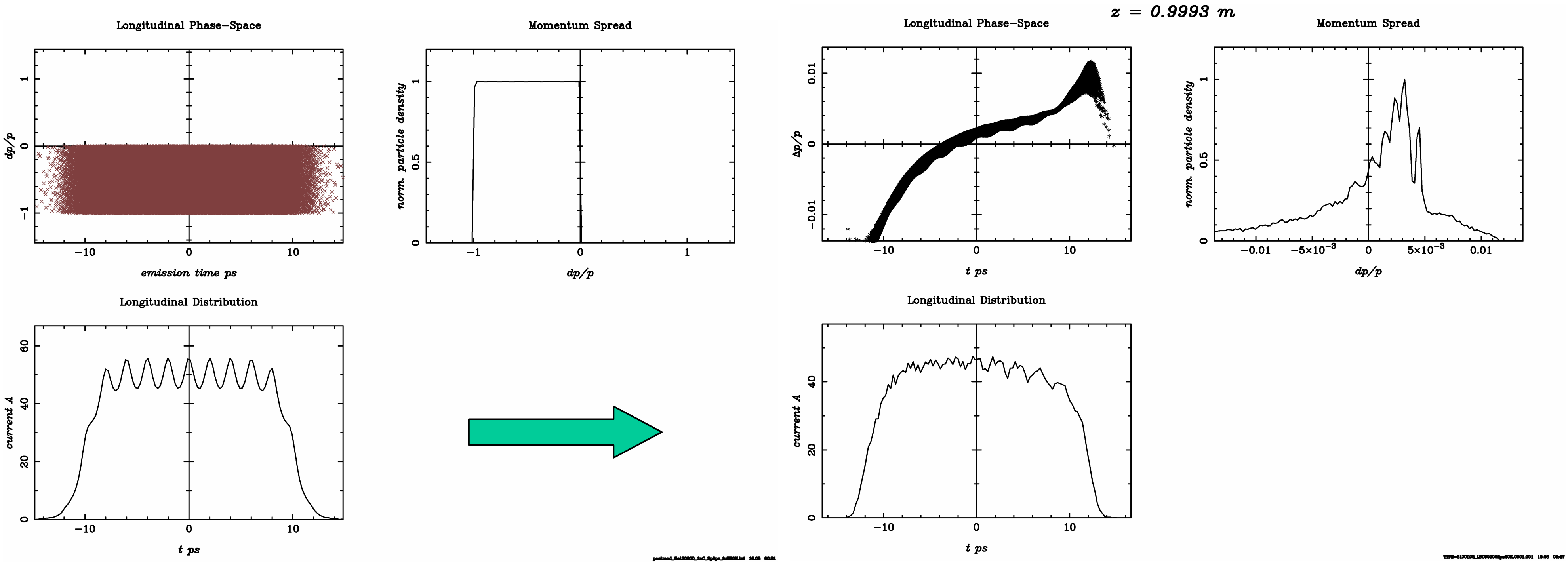
ASTRA Tracking with Laser Beam Modulation

From Cathode to Before ACC1- 1.0 m

Modulation period = 2.0 ps
Modulation Amplitude = ±10%
Postpro BIN number = 125
Simulation particles = 50,000
ASTRA Grids for space charge calculation = 10 rings × 50 cells



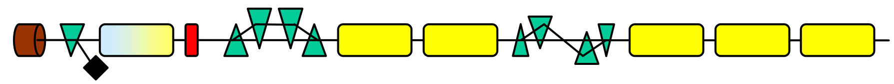
Here !



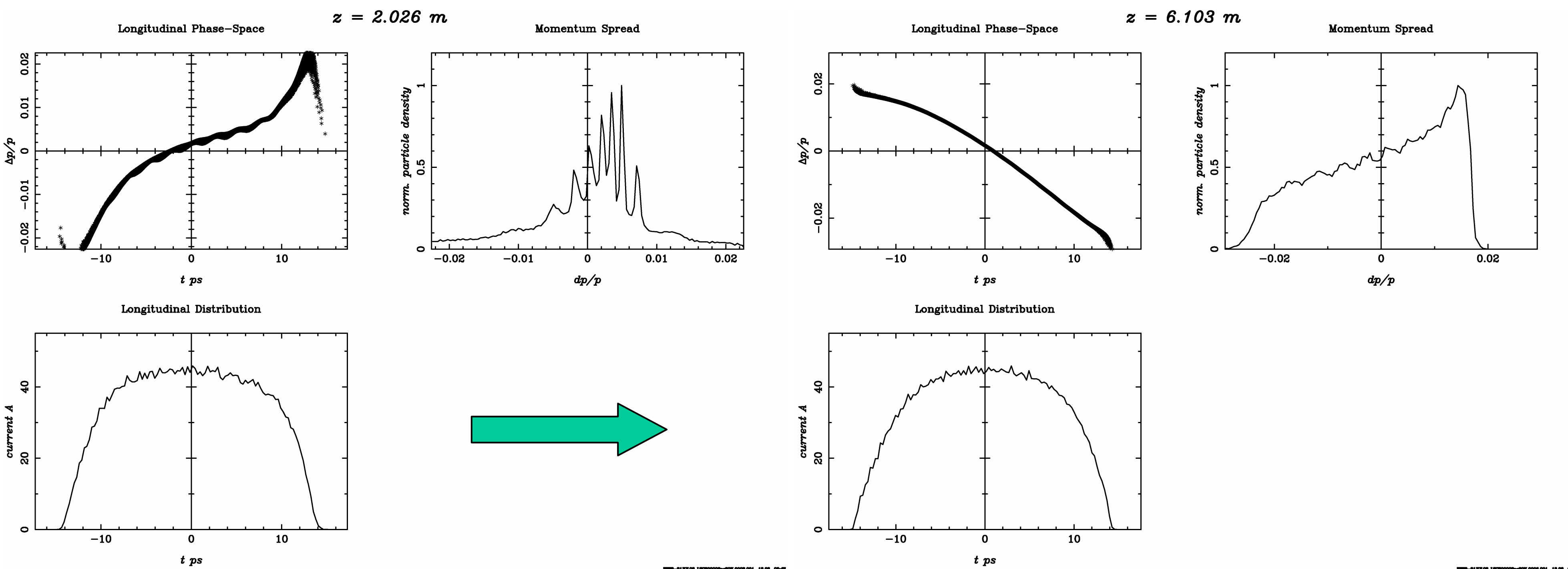
ASTRA Tracking with Laser Beam Modulation

From 2.0 m to 6.1 m

Modulation period = 2.0 ps
Modulation Amplitude = ±10%
Postpro BIN number = 125
Simulation particles = 50,000
ASTRA Grids for space charge calculation = 10 rings × 50 cells



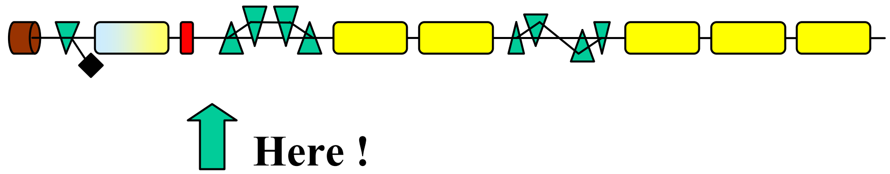
Here !

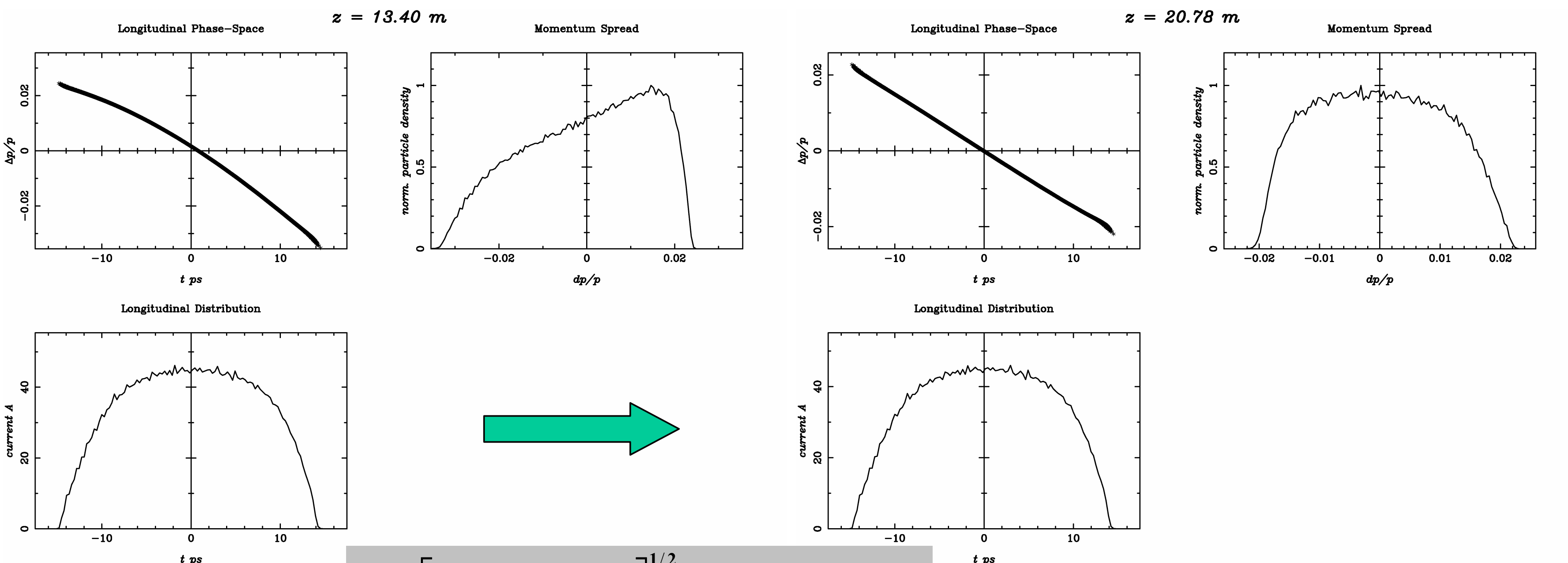


ASTRA Tracking with Laser Beam Modulation

From end of ACC1 to Upstream of BC2

Modulation period = 2.0 ps
Modulation Amplitude = $\pm 10\%$
Postpro BIN number = 125
Simulation particles = 50,000
ASTRA Grids for space charge calculation = 10 rings $\times$ 50 cells





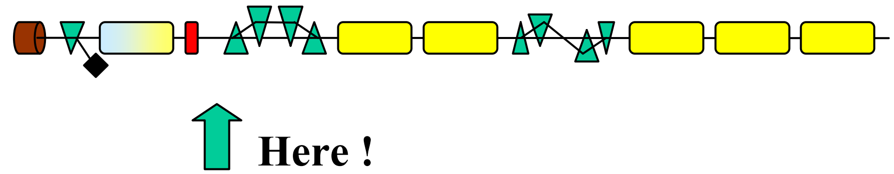
$$\omega = c\left[\frac{I_0}{\gamma^3 I_A} k \left|Z_{LSC}(k)\right|\right]^{1/2}, \text{ if } k \to \infty,\ \omega \to \omega_p$$

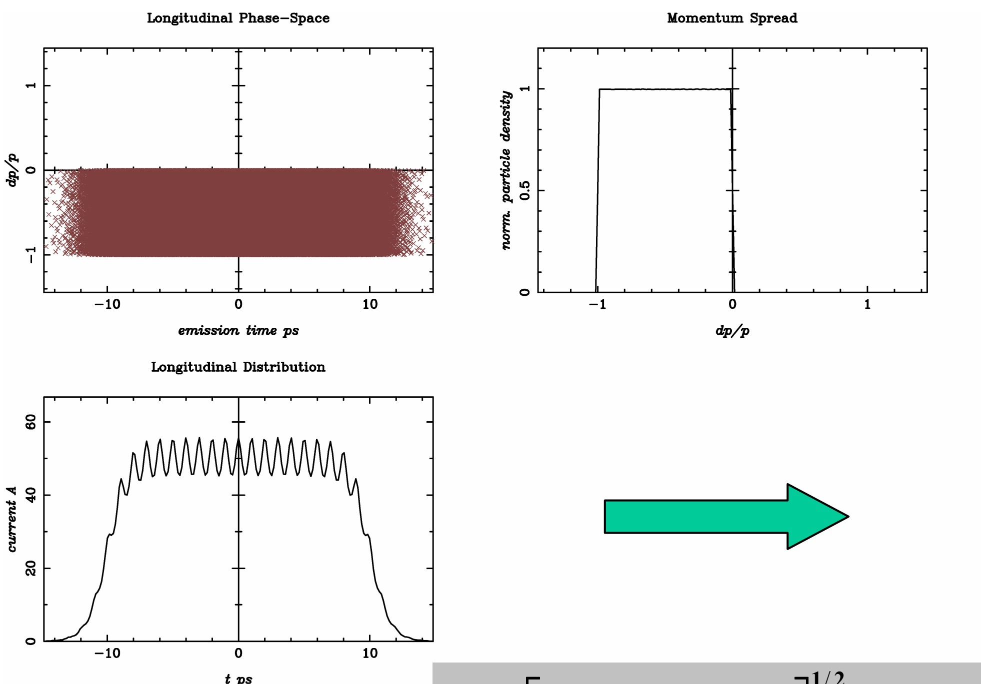
well smeared out by fast Plasma oscillation & strong Landau damping

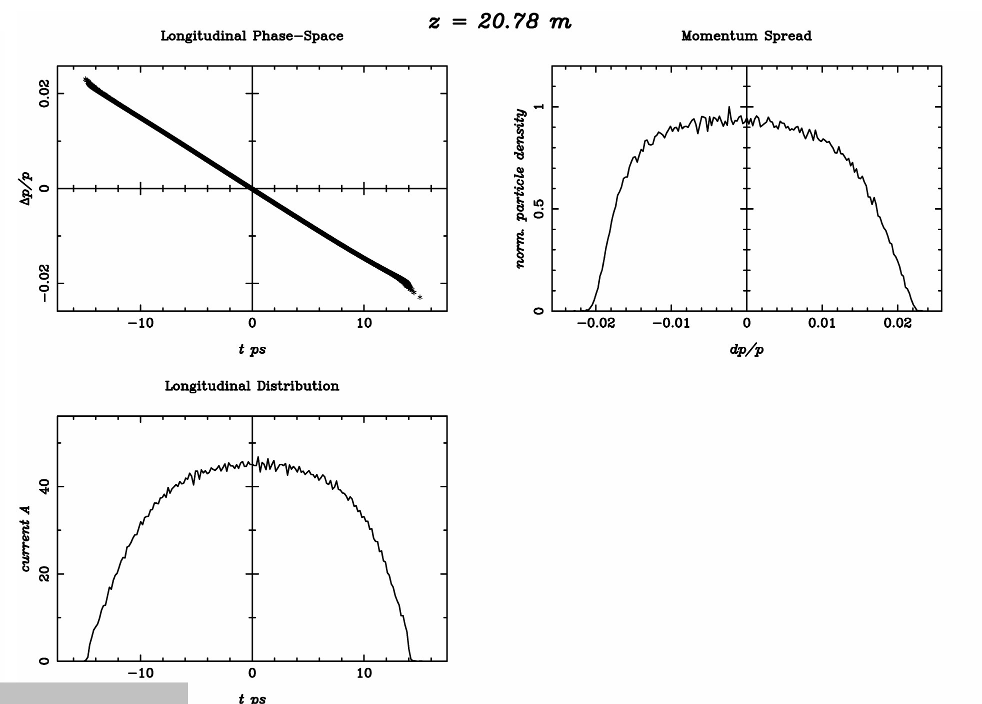
ASTRA Tracking with Laser Beam Modulation

From Cathode to Upstream of BC2

Modulation period = 1.0 ps
Modulation Amplitude = ±10%
Postpro BIN number = 200
Simulation particles = 100,000
ASTRA Grids for space charge calculation = 10 rings × 100 cells







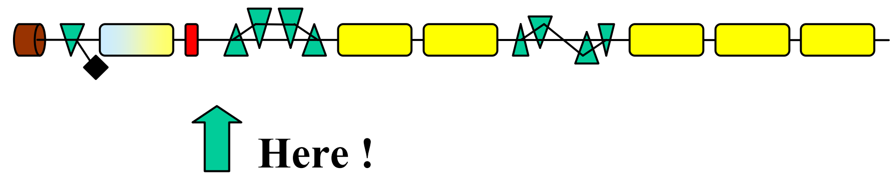
$$\omega = c\left[\frac{I_0}{\gamma^3 I_A} k \left|Z_{LSC}(k)\right|\right]^{1/2}, \text{ if } k \to \infty,\ \omega \to \omega_p$$

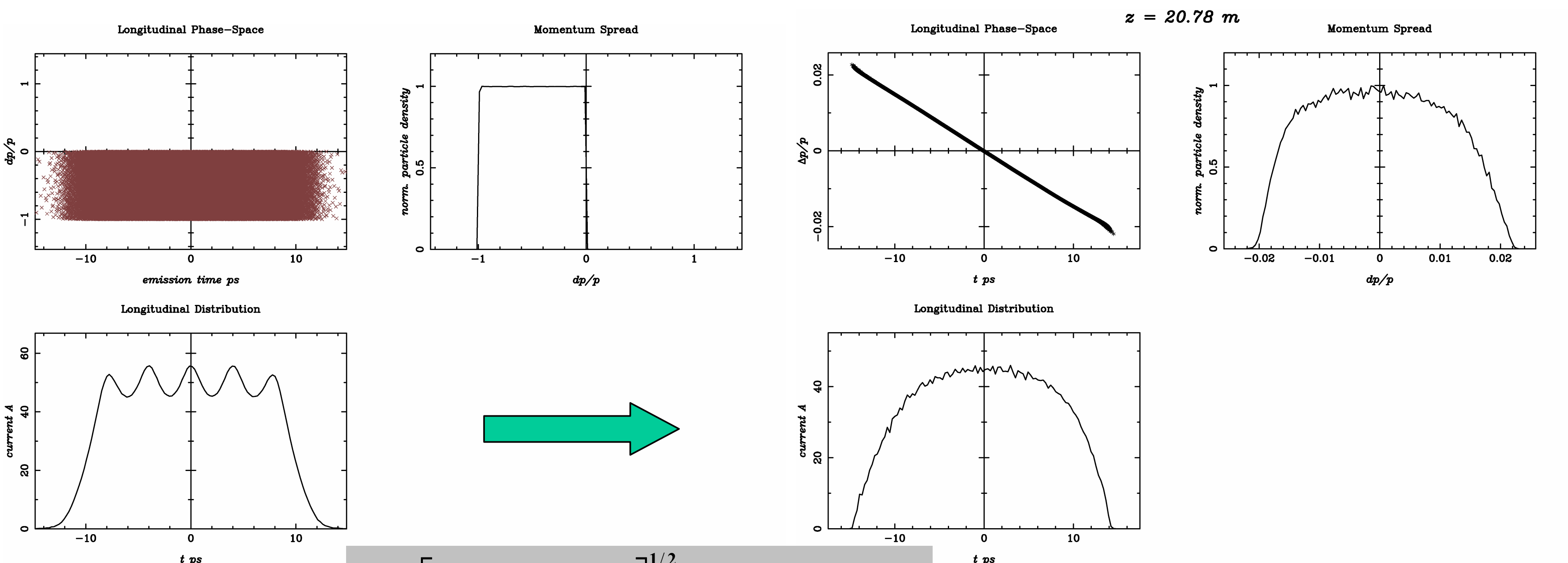
well smeared out by fast Plasma oscillation & strong Landau damping

ASTRA Tracking with Laser Beam Modulation

From Cathode to Upstream of BC2

Modulation period = 4.0 ps
Modulation Amplitude = ±10%
Postpro BIN number = 125
Simulation particles = 50,000
ASTRA Grids for space charge calculation = 10 rings × 50 cells





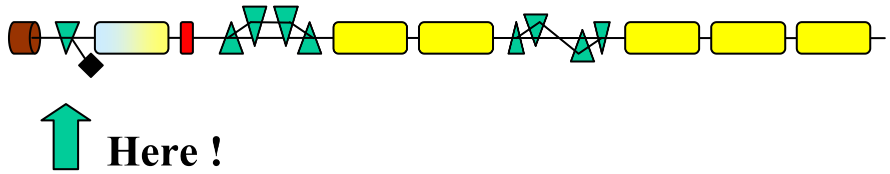
$$\omega = c\left[\frac{I_0}{\gamma^3 I_A} k \left|Z_{LSC}(k)\right|\right]^{1/2}, \text{ if } k \to \infty,\ \omega \to \omega_p$$

well smeared out by fast Plasma oscillation & strong Landau damping

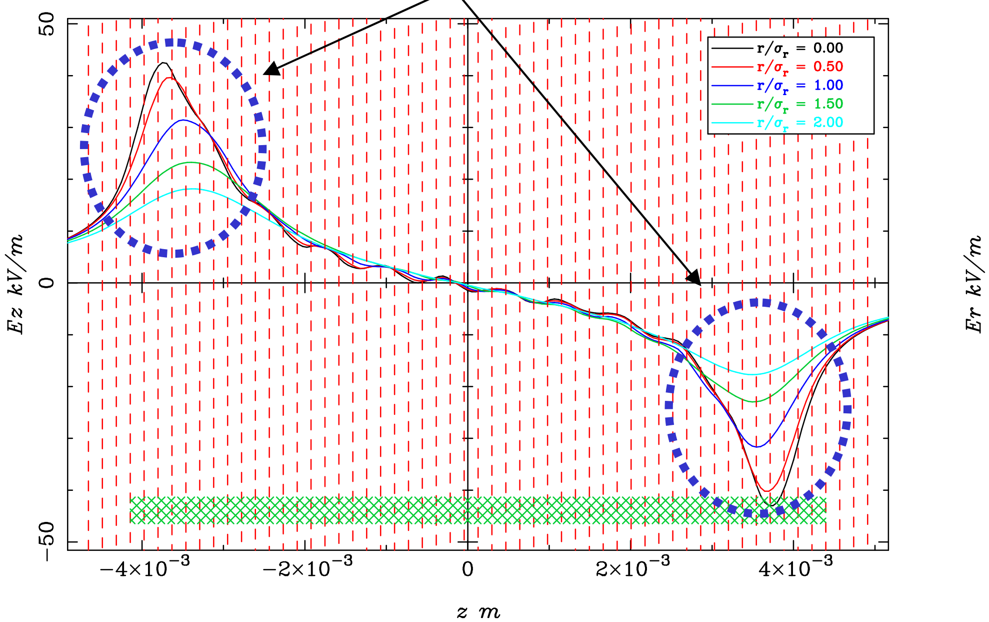
What happened in injector ?

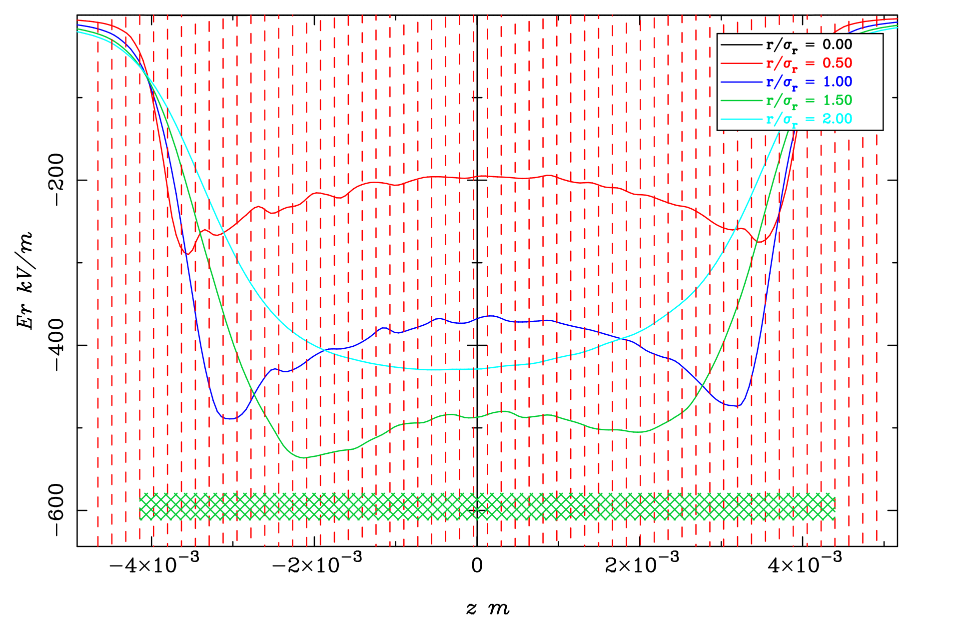
<u>E-fields due to Space Charge at 1.0 m, *E*=4.2 MeV</u>

Modulation period = 2.0 ps
Modulation Amplitude = ±10%
Postpro BIN number = 125
Simulation particles = 50,000
ASTRA Grids for space charge calculation = 10 rings × 50 cells



2D space charge force increases the local energy spread at the head & tail regions and helps in smearing of the initial density modulation





What happened in injector ?

E-fields due to Space Charge at 3.0 m, *E*=11.2 MeV

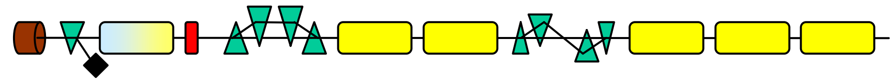
Modulation period = 2.0 ps

Modulation Amplitude = ±10%

Postpro BIN number = 125

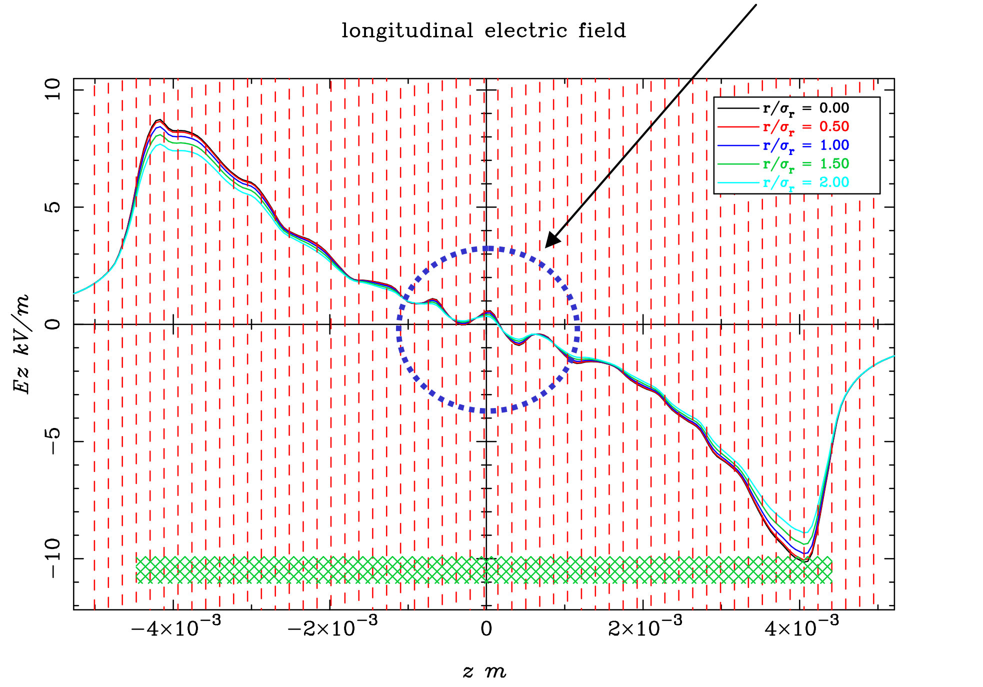
Simulation particles = 50,000

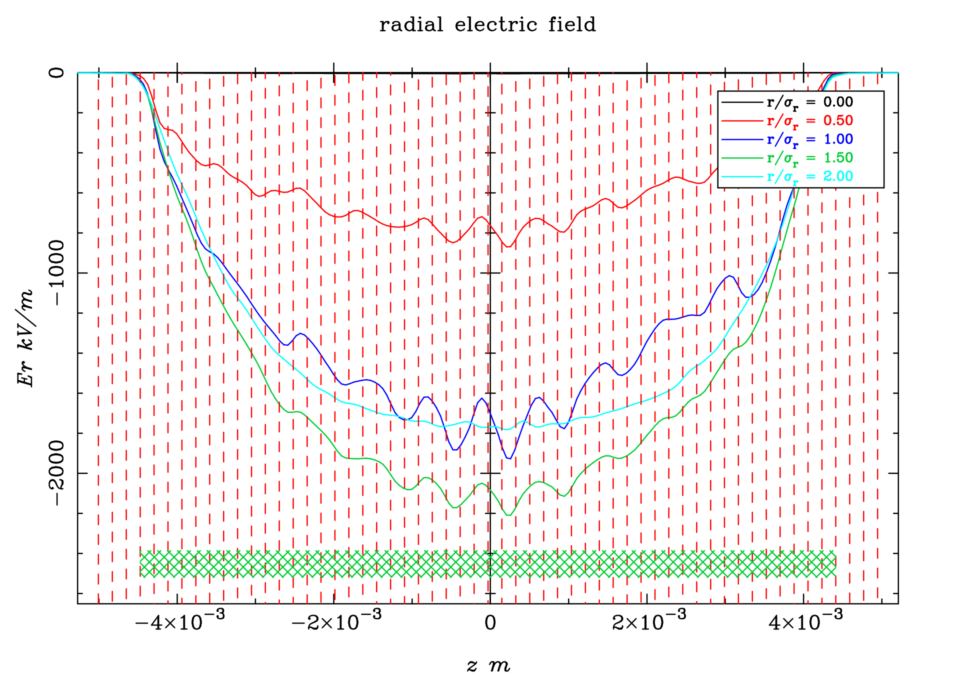
ASTRA Grids for space charge calculation = 10 rings × 50 cells



Here !

This makes eneregy modulation, but soon damped !





What happened in injector ?

E-fields due to Space Charge at 6.0 m, *E*=40.1 MeV

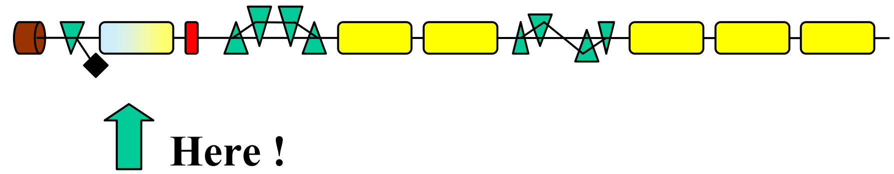
Modulation period = 2.0 ps

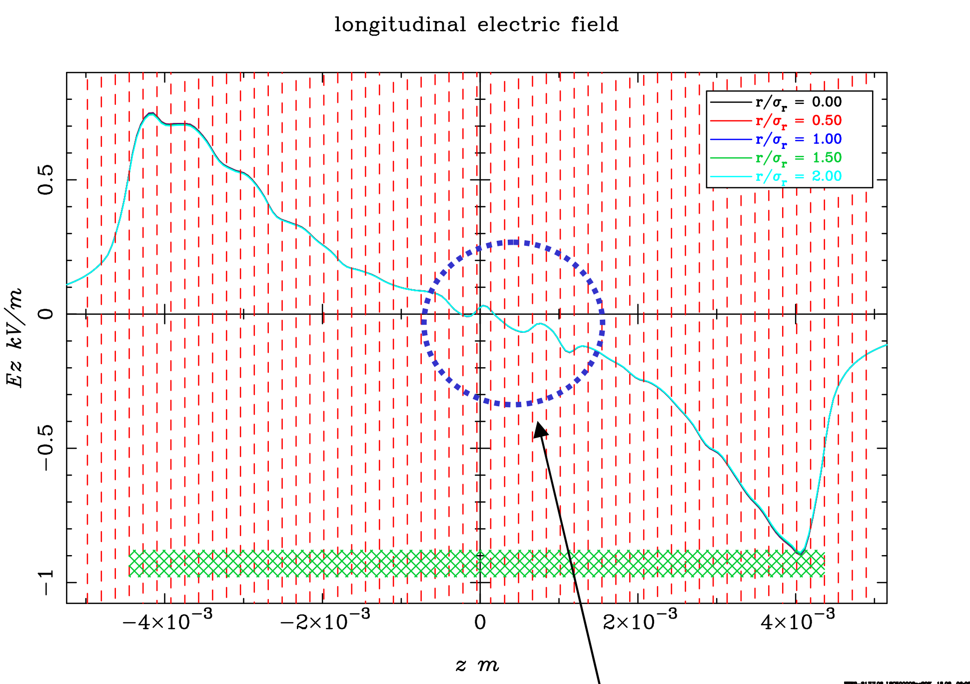
Modulation Amplitude = ±10%

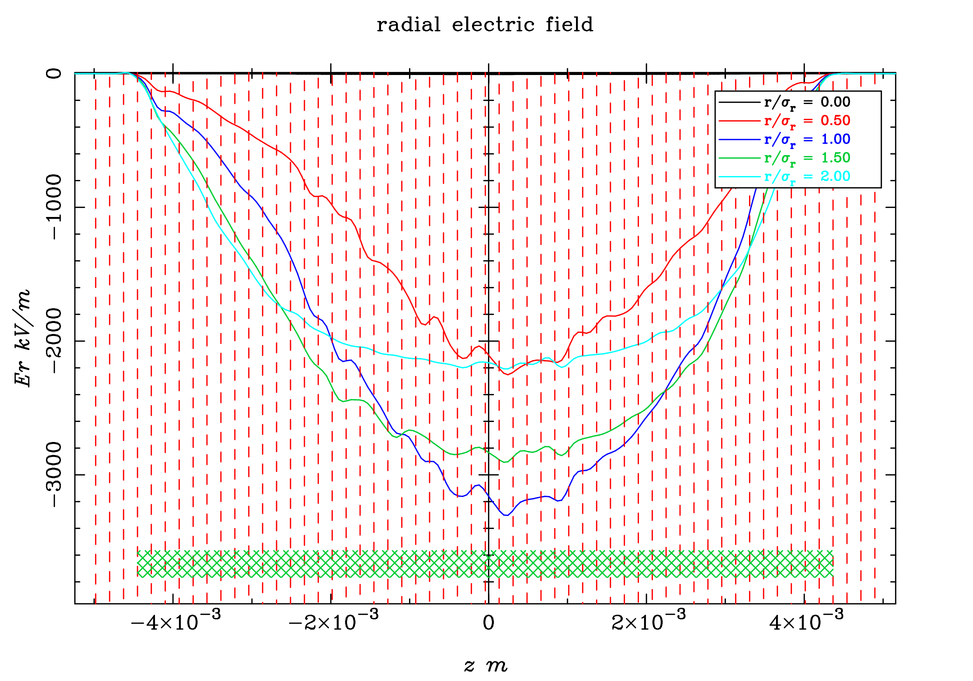
Postpro BIN number = 125

Simulation particles = 50,000

ASTRA Grids for space charge calculation = 10 rings × 50 cells





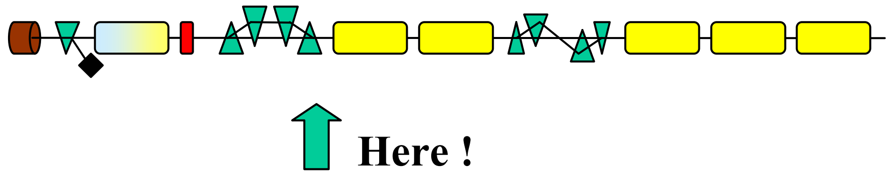


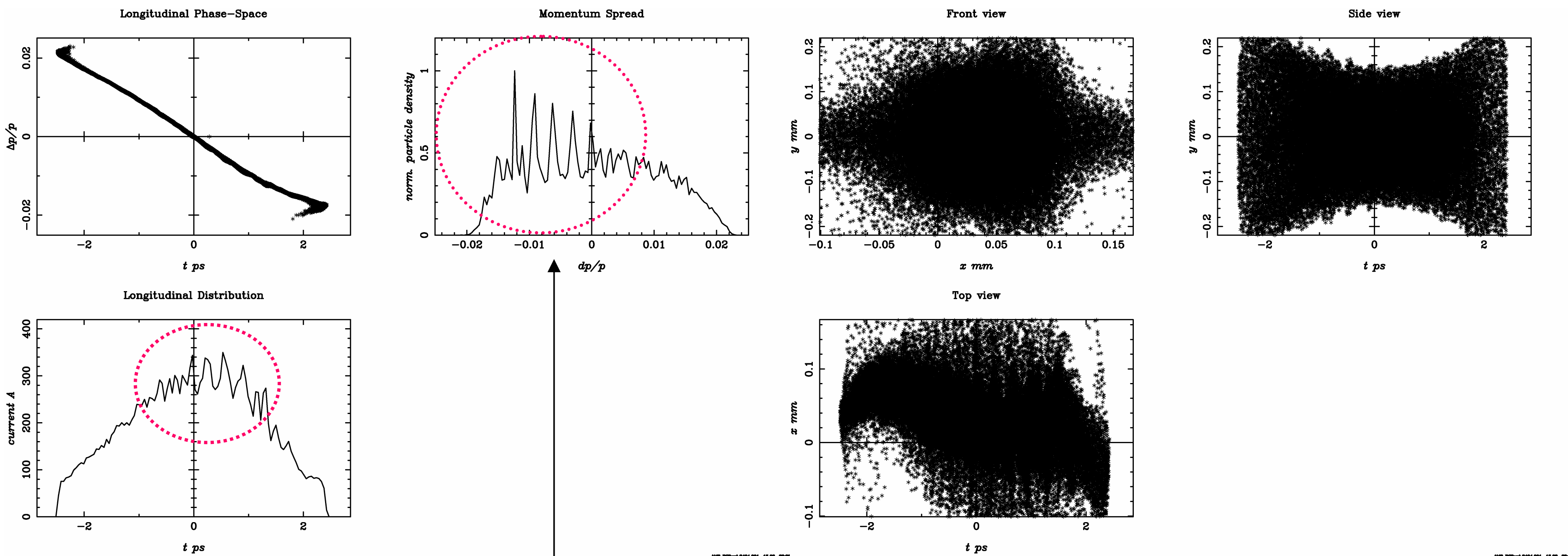
Damped space charge E_z-field and energy modulation

ASTRA Tracking with Laser Beam Modulation

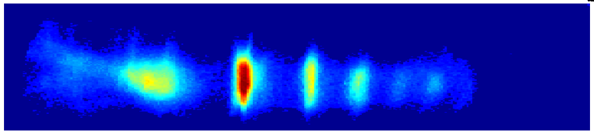
At the end of BC2 with CSR

Modulation period = 2.0 ps
Modulation Amplitude = ±10%
Postpro BIN number = 125
Simulation particles = 50,000
ASTRA Grids for space charge calculation = 10 rings × 50 cells





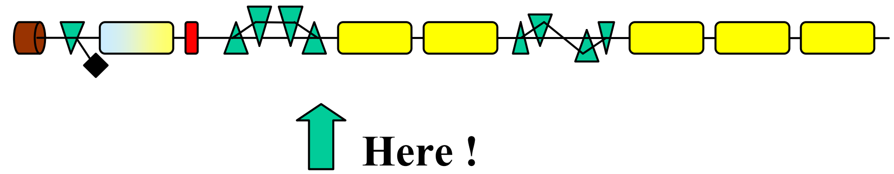
This energy modulation may be observed at SDL
We do not meet a strong density modulation yet !

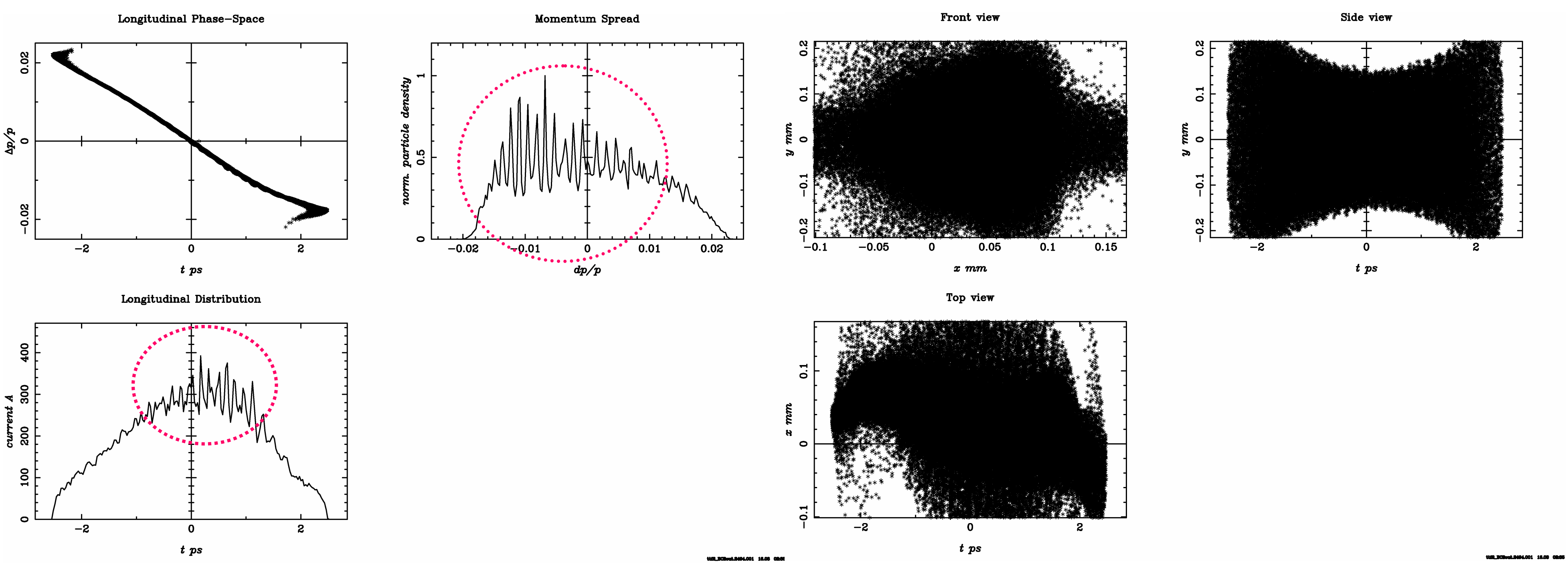


ASTRA Tracking with Laser Beam Modulation

At the end of BC2 with CSR

Modulation period = 1.0 ps
Modulation Amplitude = $\pm$10%
Postpro BIN number = 200
Simulation particles = 100,000
ASTRA Grids for space charge calculation = 10 rings $\times$ 100 cells

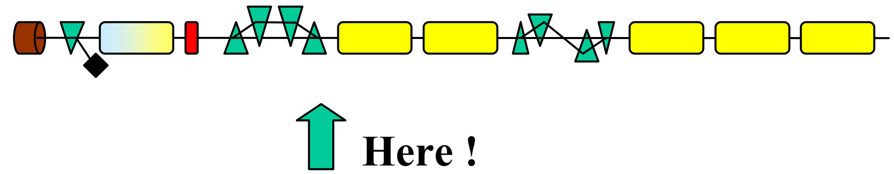


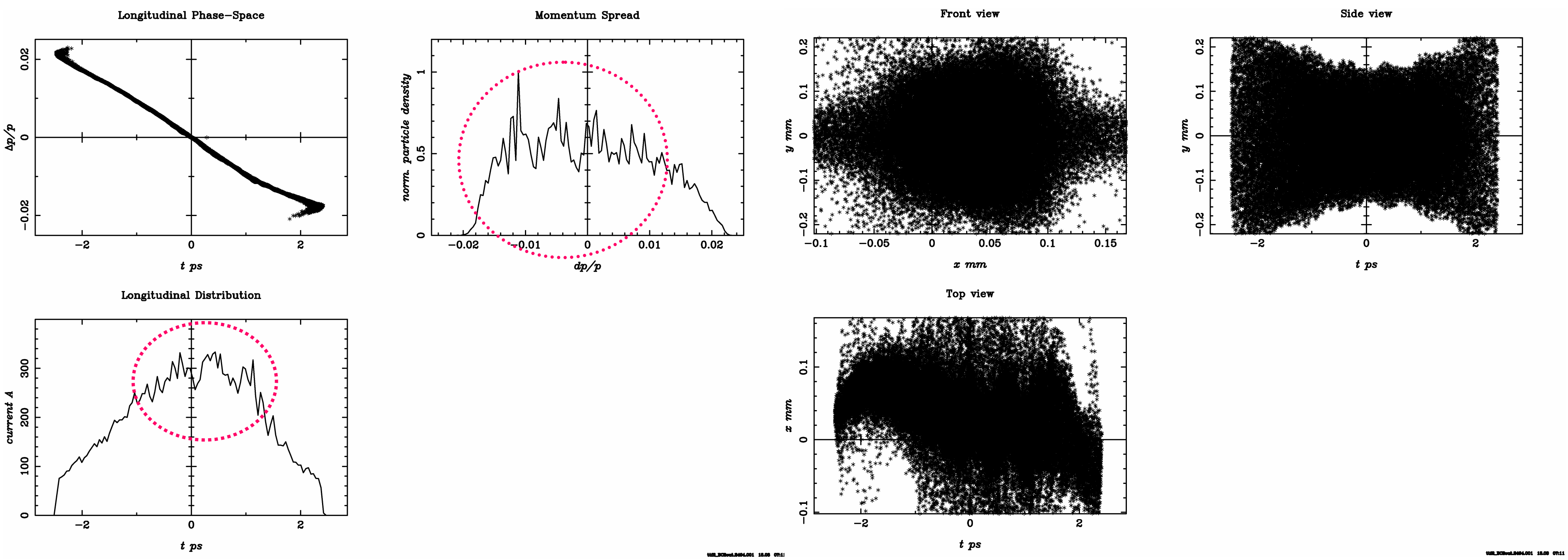


ASTRA Tracking with Laser Beam Modulation

At the end of BC2 with CSR

Modulation period = 4.0 ps
Modulation Amplitude = $\pm$10%
Postpro BIN number = 125
Simulation particles = 50,000
ASTRA Grids for space charge calculation = 10 rings $\times$ 50 cells





ASTRA Tracking with Laser Beam Modulation

From Downstream of BC2 – 26.77 m

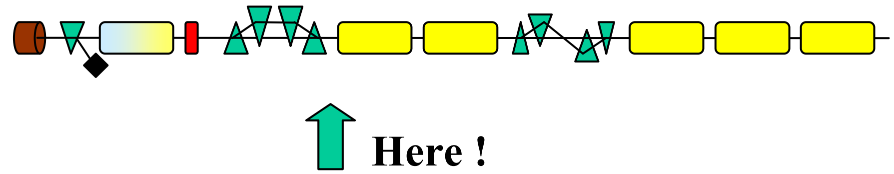
Modulation period = 2.0 ps

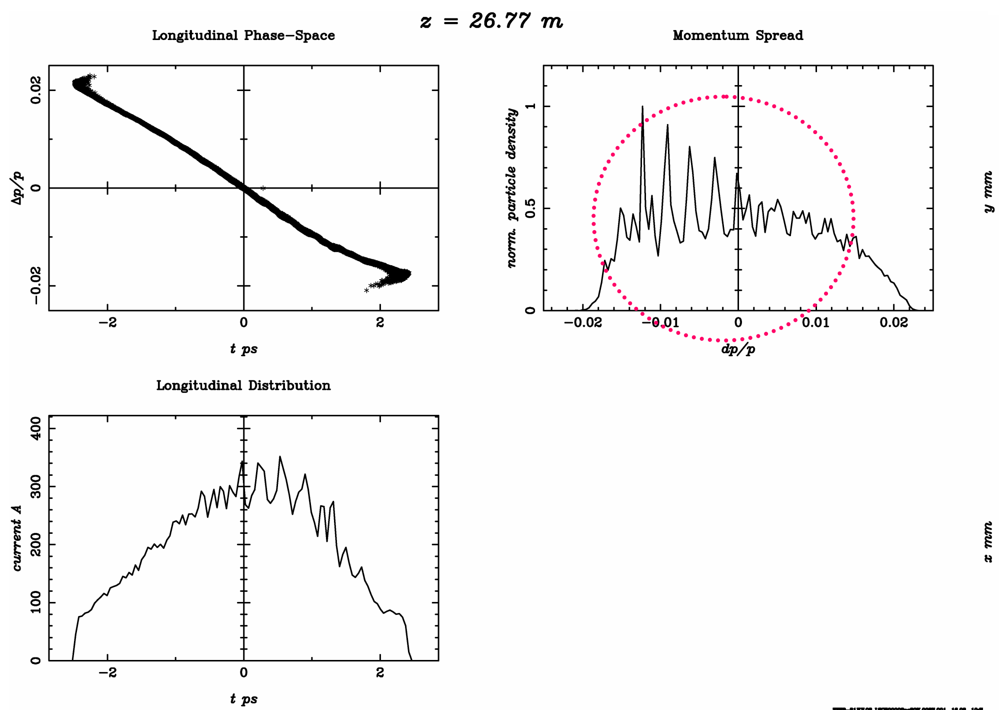
Modulation Amplitude = $\pm 10\%$

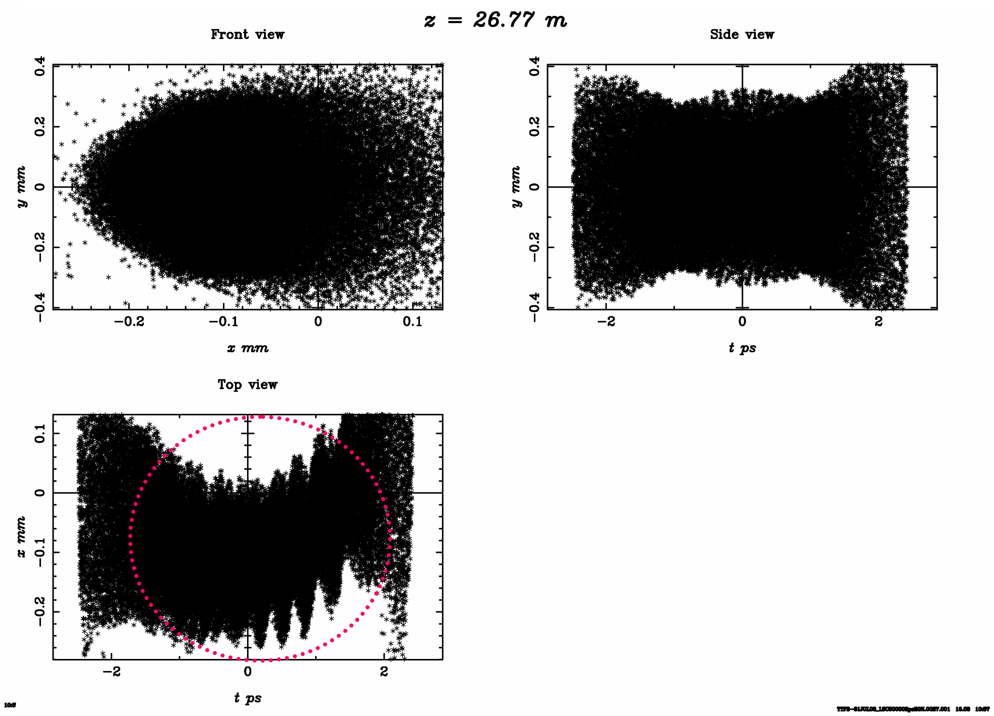
Postpro BIN number = 125

Simulation particles = 50,000

ASTRA Grids for space charge calculation = 10 rings $\times$ 50 cells



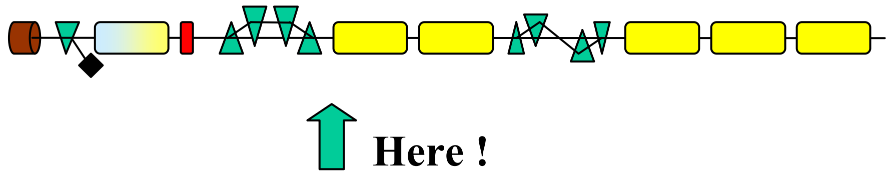


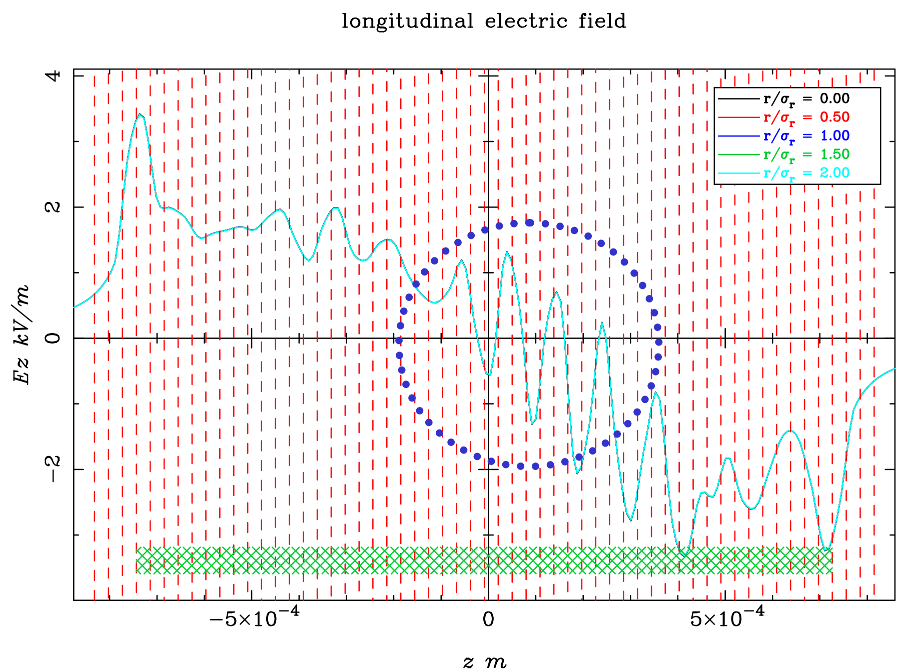


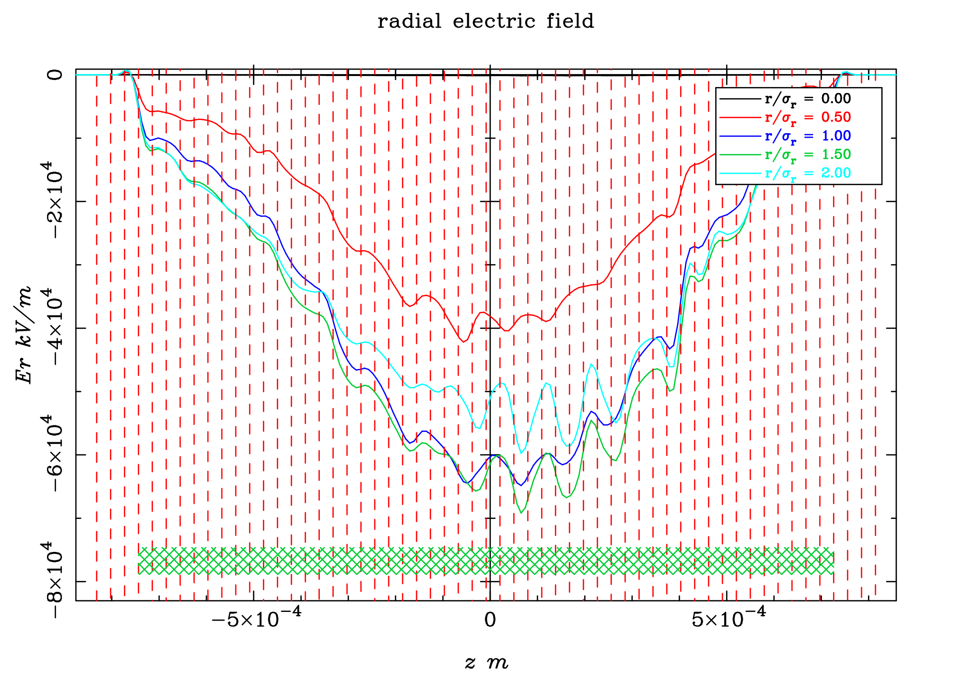
ASTRA Tracking with Laser Beam Modulation

E-fields at FODO channels - 29 m, *E*=120.8 MeV

Modulation period = 2.0 ps
Modulation Amplitude = ±10%
Postpro BIN number = 125
Simulation particles = 50,000
ASTRA Grids for space charge calculation = 10 rings × 50 cells





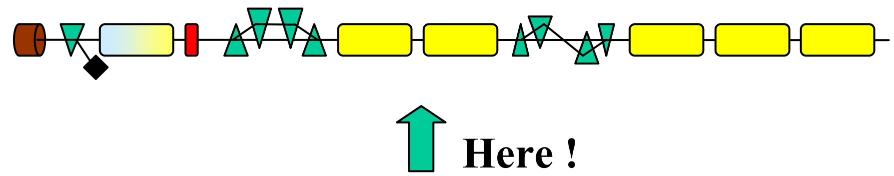


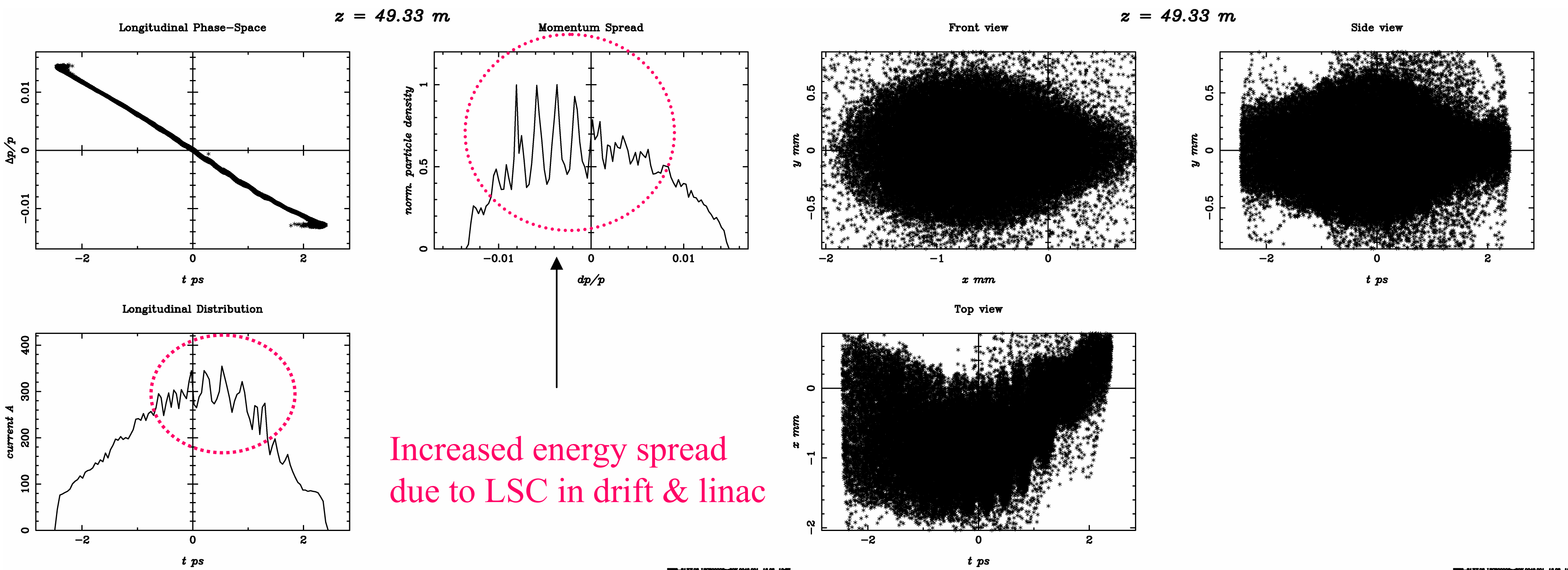
Modulation in E_z field & energy modulation is amplified after BC2
Uncorrelated energy spread is also increased in a small local region !

ASTRA Tracking with Laser Beam Modulation

At the end of ACC2

Modulation period = 2.0 ps
Modulation Amplitude = ±10%
Postpro BIN number = 125
Simulation particles = 50,000
ASTRA Grids for space charge calculation = 10 rings × 50 cells



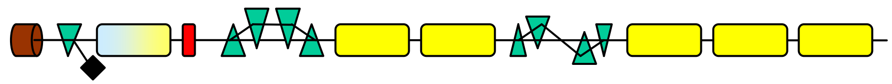


Increased energy spread
due to LSC in drift & linac

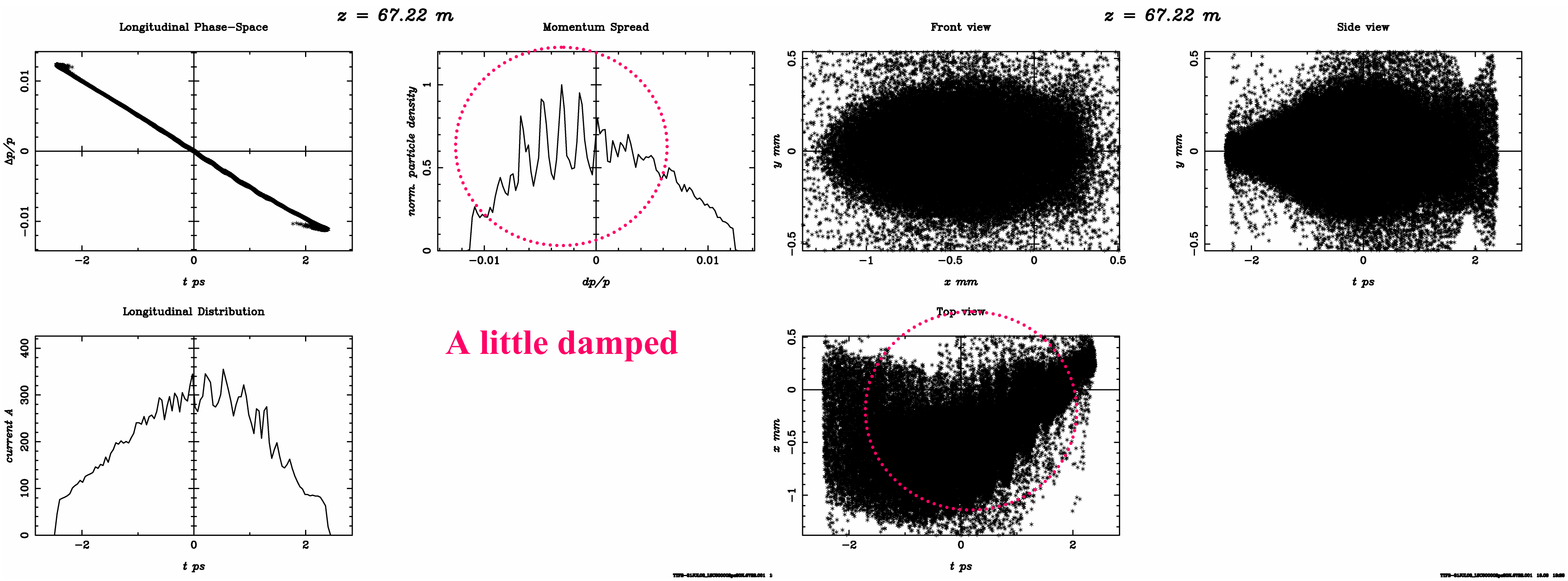
ASTRA Tracking with Laser Beam Modulation

At the upstream of BC3

Modulation period = 2.0 ps
Modulation Amplitude = $\pm$10%
Postpro BIN number = 125
Simulation particles = 50,000
ASTRA Grids for space charge calculation = 10 rings $\times$ 50 cells



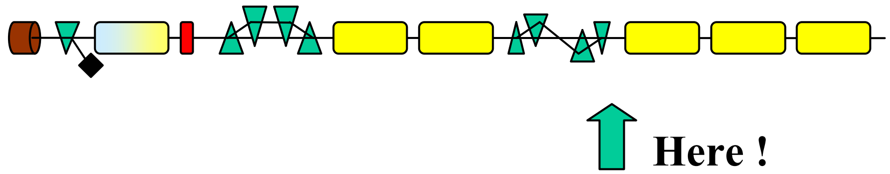
Here !



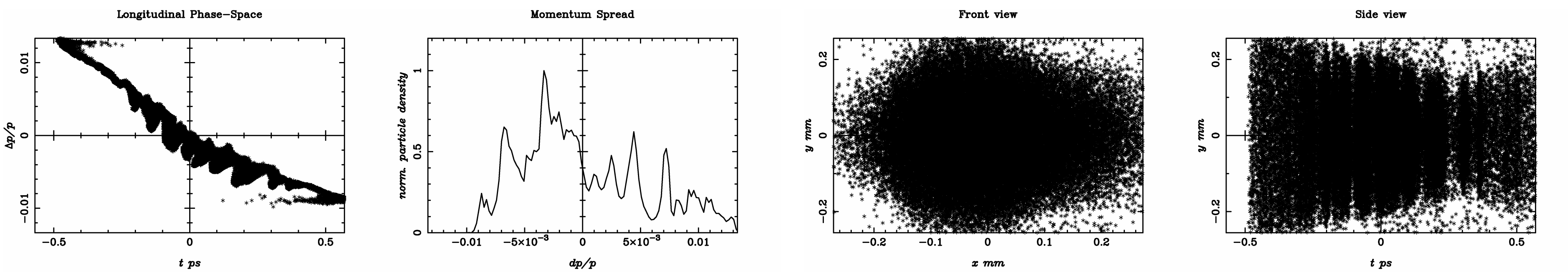
ASTRA Tracking with Laser Beam Modulation

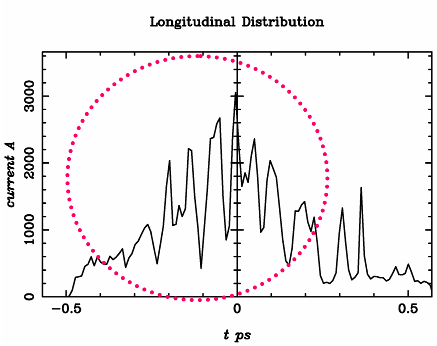
At the end of BC3

Modulation period = 2.0 ps
Modulation Amplitude = ±10%
Postpro BIN number = 125
Simulation particles = 50,000
ASTRA Grids for space charge calculation = 10 rings × 50 cells

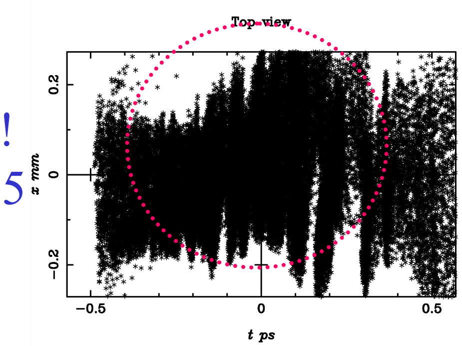


Here !





±50% density modulation !
Total gain from cathode ~ 5

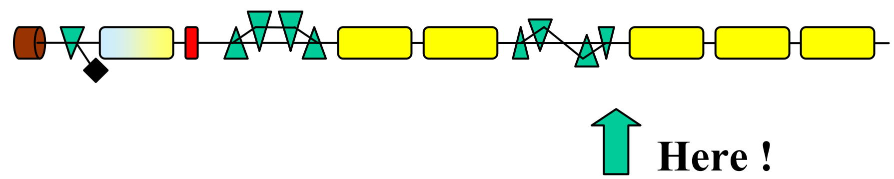


Unfortunately, we meet a density modulation !

ASTRA Tracking with Laser Beam Modulation

Beam Parameters at the end of BC3

Modulation period = 2.0 ps
Modulation Amplitude = ±10%
Postpro BIN number = 125
Simulation particles = 50,000
ASTRA Grids for space charge calculation = 10 rings × 50 cells

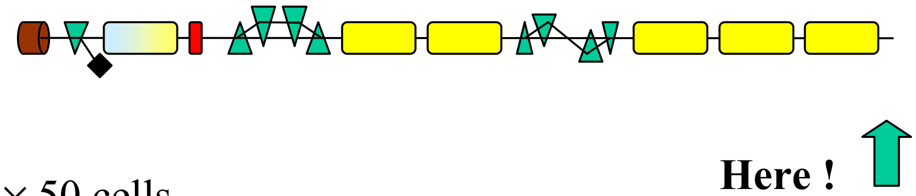


total charge	Q = -1.000 nC	
horizontal beam position	x = 7.9004E-04 mm	
vertical beam position	y = 1.3362E-05 mm	
longitudinal beam position	z = 81.43 m	
horizontal beam size	sig x = 0.1088 mm	
vertical beam size	sig y = 0.1021 mm	
longitudinal beam size	sig z = 6.7587E-02 mm	
average kinetic energy	E = 436.2 MeV	
energy spread	dE = 2334. keV	
transverse beam emittance	eps x = 4.994 pi mrad mm	
average slice emittance	eps x slice = 2.8 pi mrad mm	> 2.0 pi mrad mm
correlated divergence	cor x = 1.5377E-02 mrad	
transverse beam emittance	eps y = 1.289 pi mrad mm	
longitudinal beam emittance	eps z = 170.3 pi keV mm	
correlated energy spread	cor z = -1551. keV	

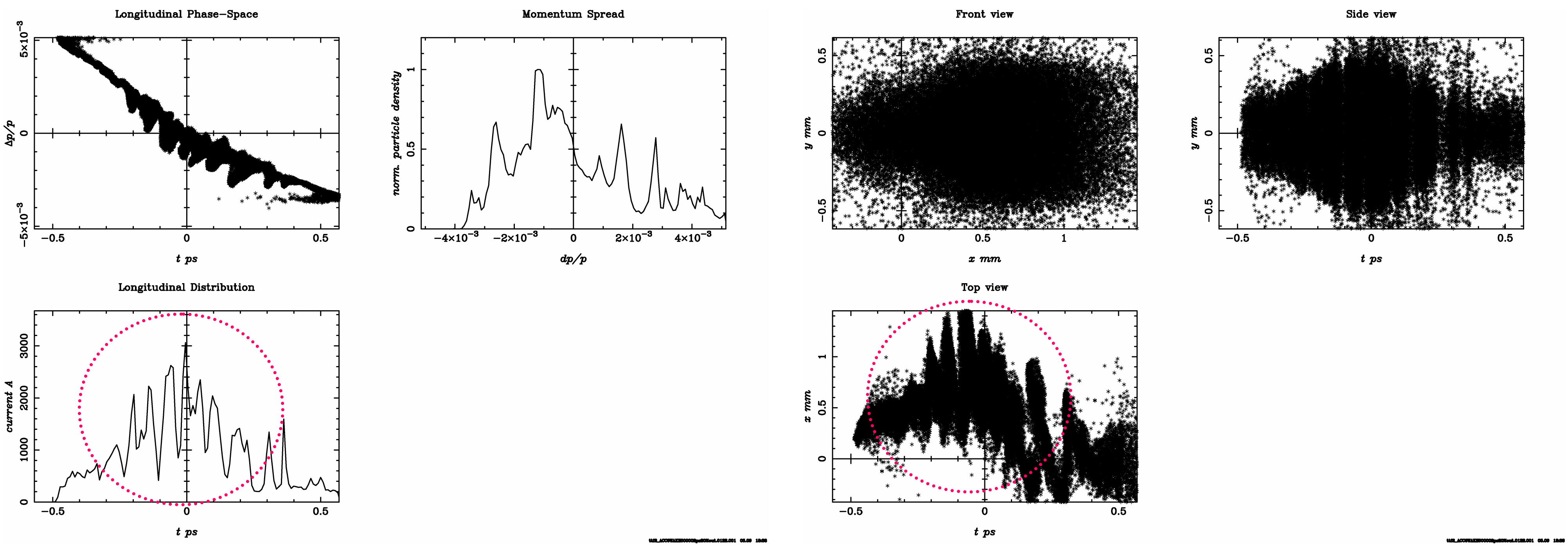
ASTRA Tracking with Laser Beam Modulation

At the end of Linac, ACC6

Modulation period = 2.0 ps
Modulation Amplitude = ±10%
Postpro BIN number = 125
Simulation particles = 50,000
ASTRA Grids for space charge calculation = 10 rings × 50 cells



Here !

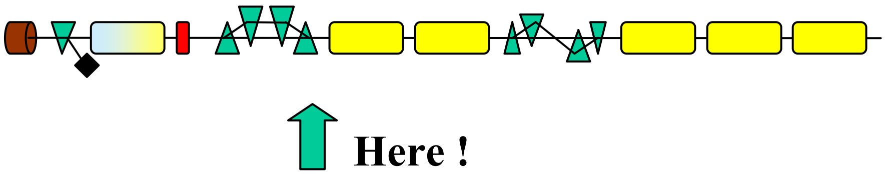


modulation is somewhat amplified,
but not so strong due to increased energy & higher gradient

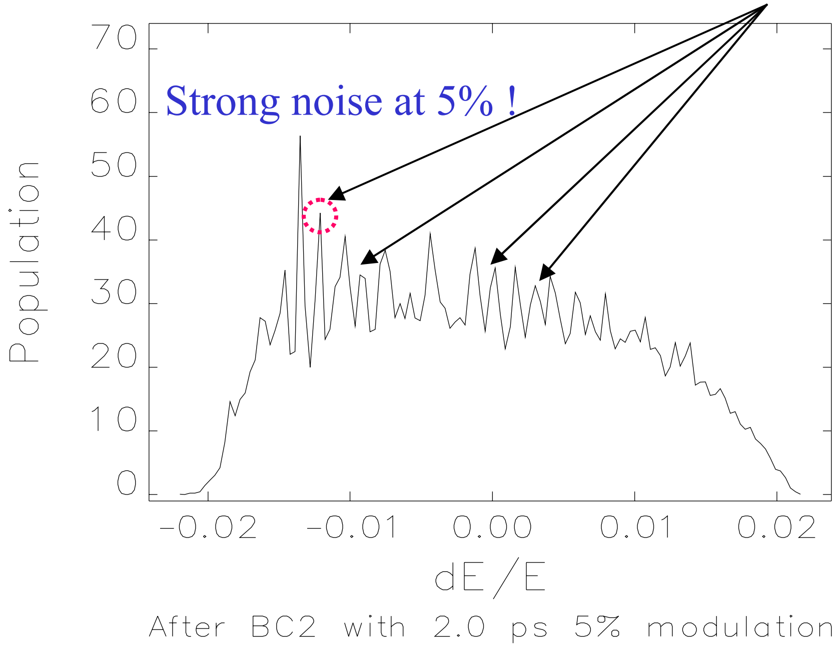
Noise Level Investigation

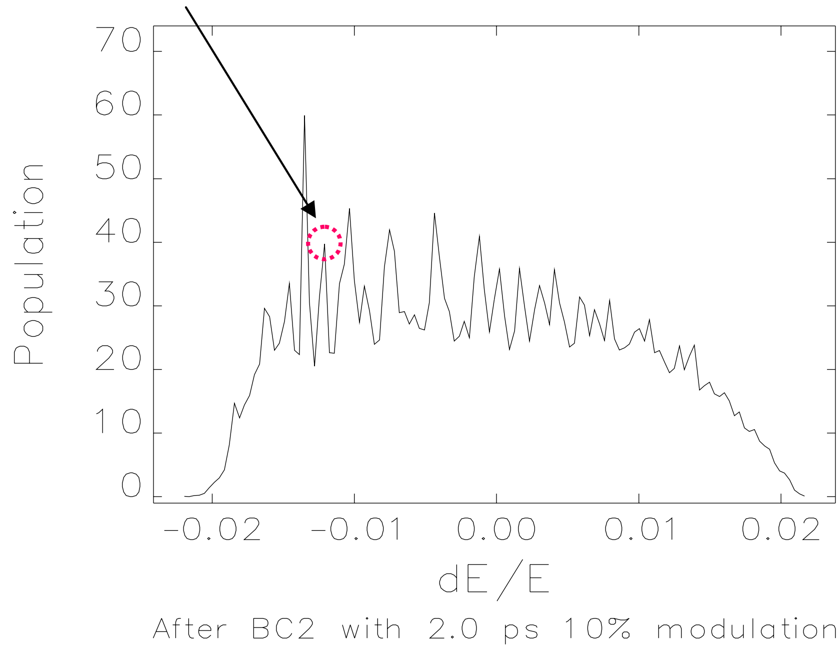
At the end of BC2 with CSR

Modulation period = 2.0 ps
Modulation Amplitude = 5% (left) & 10% (right)
Postpro BIN number = 125
Simulation particles = 50,000
ASTRA Grids for space charge calculation = 10 rings × 50 cells



Numerical Noise

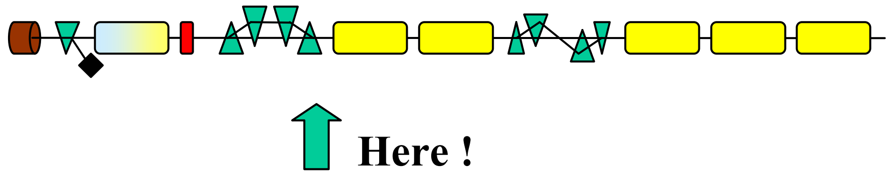




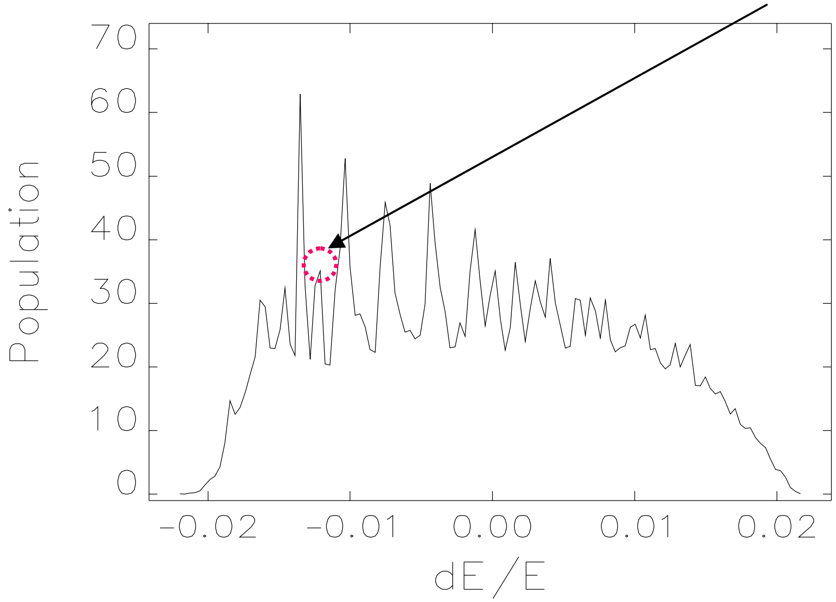
Noise Level Investigation

At the end of BC2 with CSR

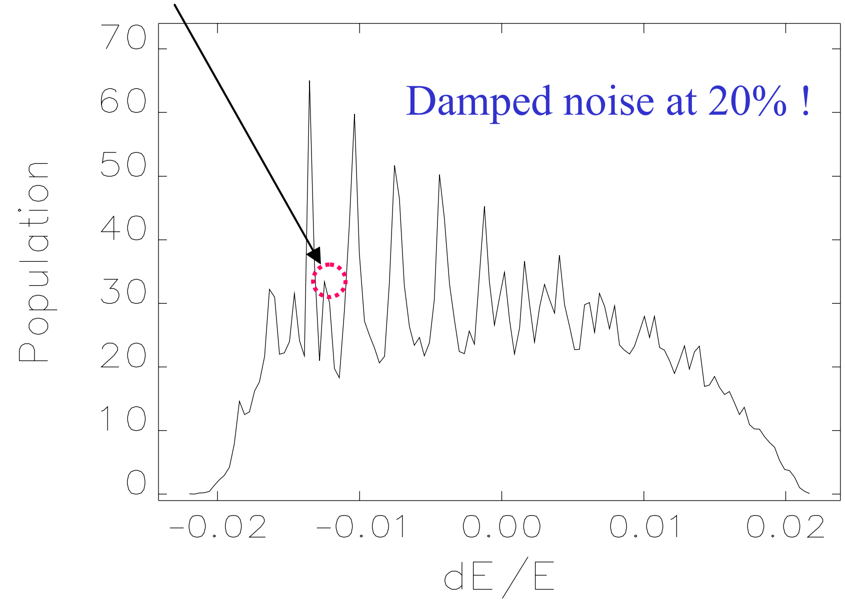
Modulation period = 2.0 ps
Modulation Amplitude = 15% (left) & 20% (right)
Postpro BIN number = 125
Simulation particles = 50,000
ASTRA Grids for space charge calculation = 10 rings × 50 cells



Numerical Noise



After BC2 with 2.0 ps 15% modulation

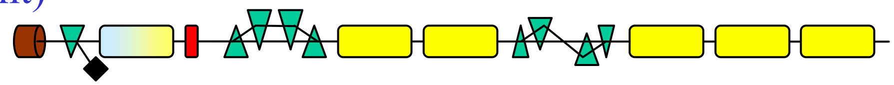


After BC2 with 2.0 ps 20% modulation

Noise Level & Smearing Investigation

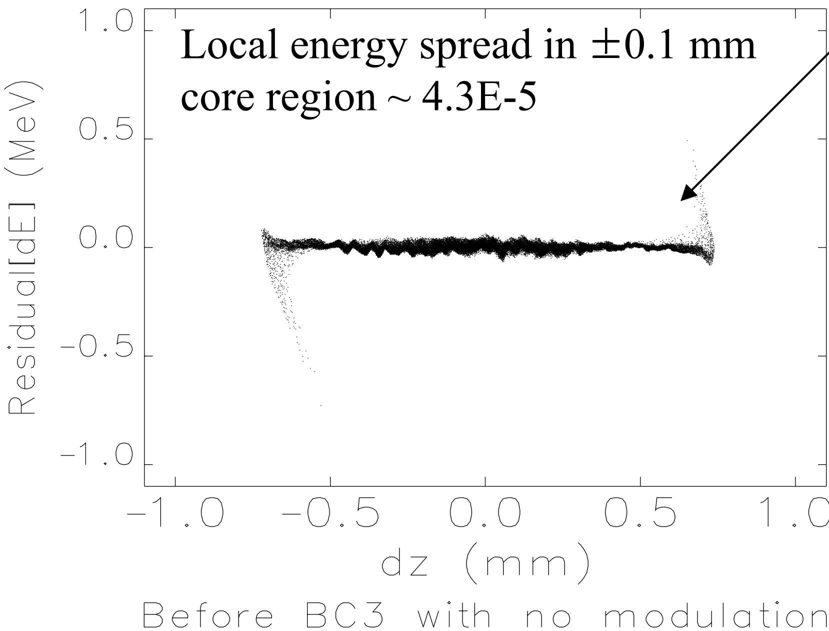
At the upstream of BC3

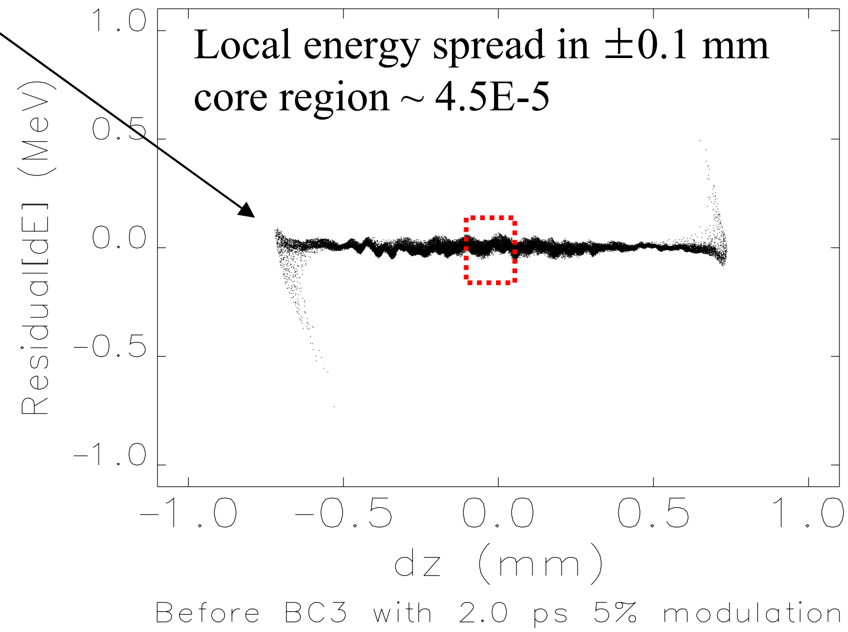
Modulation period = nomodulation (left) & 2.0 ps (right)
Modulation Amplitude = 0% (left) & 5% (right)
Postpro BIN number = 125
Simulation particles = 50,000
ASTRA Grids for space charge calculation = 10 rings × 50 cells



Here !

There is no big different between two due to noise !

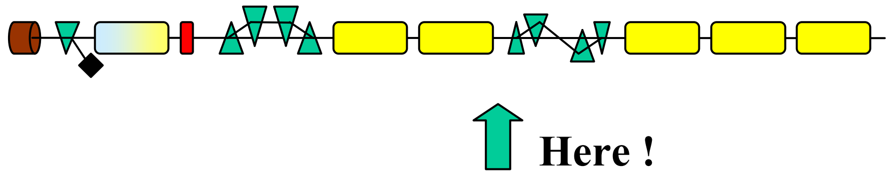




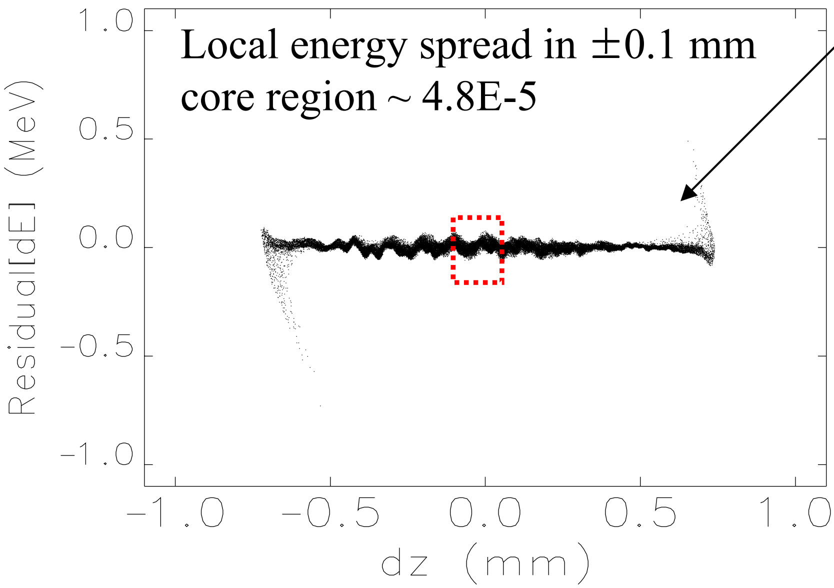
Noise Level & Smearing Investigation

At the upstream of BC3

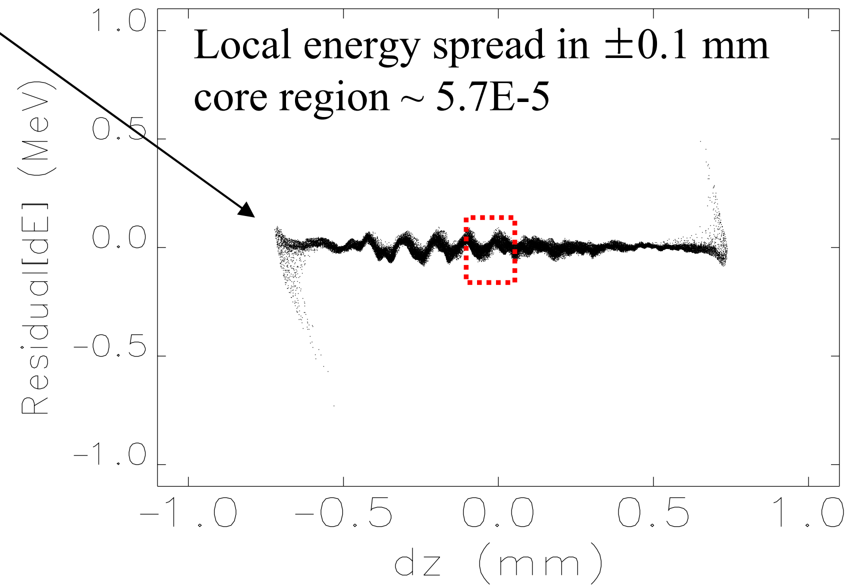
Modulation period = 2.0 ps
Modulation Amplitude = 10% (left) & 20% (right)
Postpro BIN number = 125
Simulation particles = 50,000
ASTRA Grids for space charge calculation = 10 rings × 50 cells



Increased local energy spread before BC3 due to LSC induced modulated E_z will help in smearing the microbunching instability in BC3



Before BC3 with 2.0 ps 10% modulation

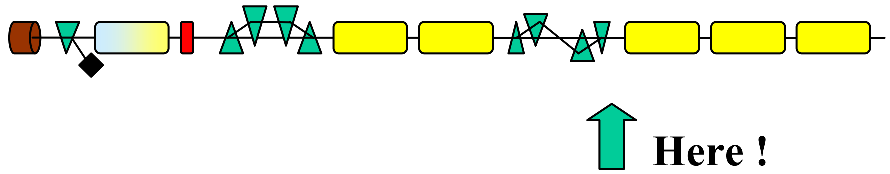


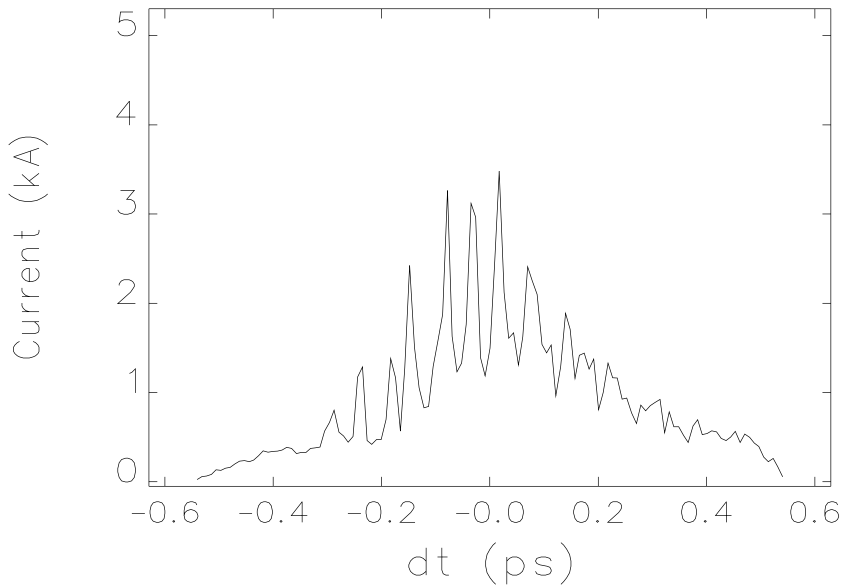
Before BC3 with 2.0 ps 20% modulation

CSR & Smearing Investigation

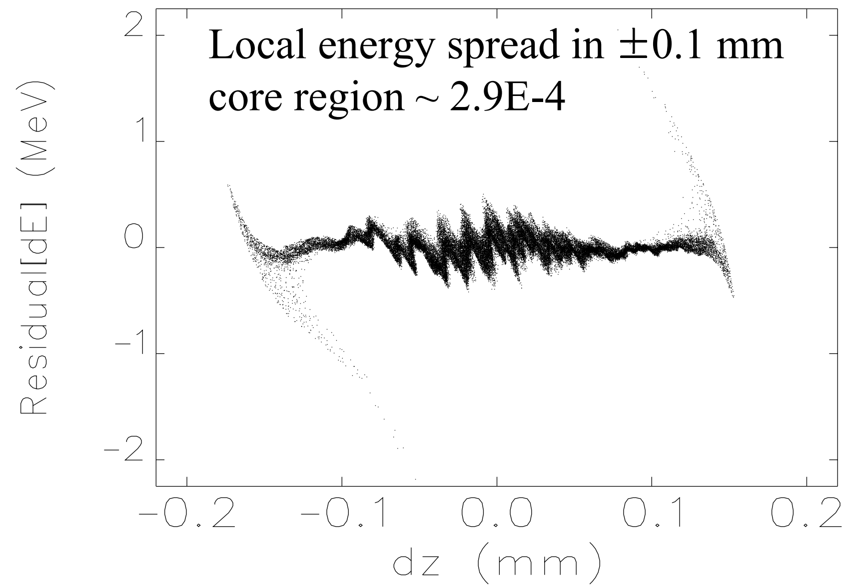
At the end of BC3 without CSR at BC3

Modulation period = 2.0 ps
Modulation Amplitude = 10%
Postpro BIN number = 125
Simulation particles = 50,000
ASTRA Grids for space charge calculation = 10 rings × 50 cells





After BC3 with 2.0 ps 10% modulation & without CSR

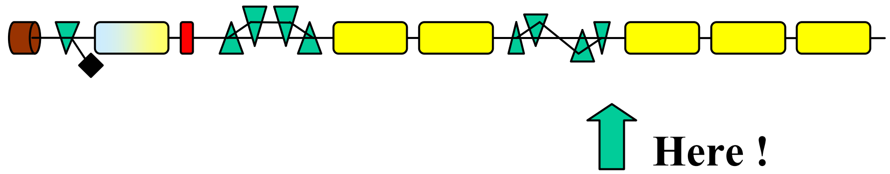


After BC3 with 2.0 ps 10% modulation & without CSR

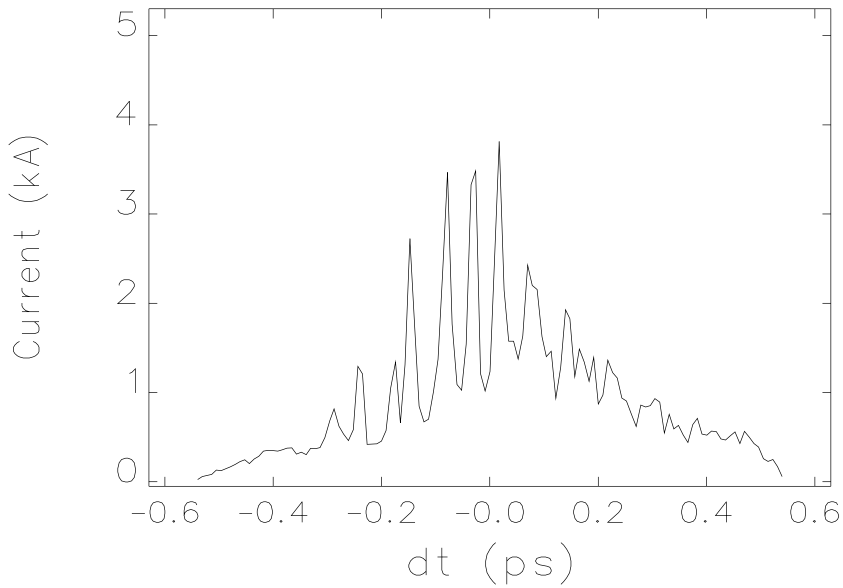
CSR & Smearing Investigation

At the end of BC3 without CSR at BC3

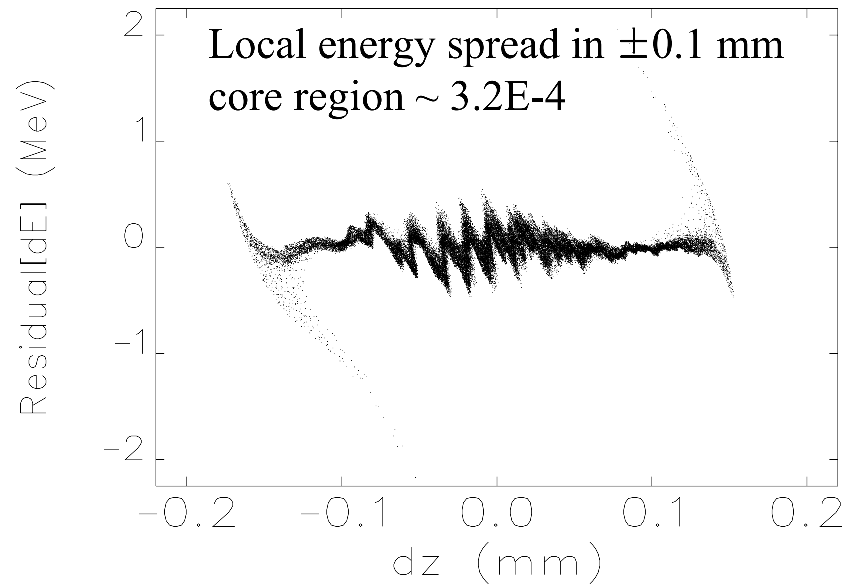
Modulation period = 2.0 ps
Modulation Amplitude = 15%
Postpro BIN number = 125
Simulation particles = 50,000
ASTRA Grids for space charge calculation = 10 rings × 50 cells



Increased modulation amplitude than that of 10% means
no saturation by LSC driven microbunching instability at 15% amplitude !



After BC3 with 2.0 ps 15% modulation & without CSR

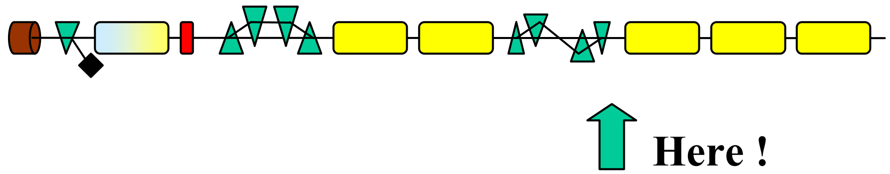


After BC3 with 2.0 ps 15% modulation & without CSR

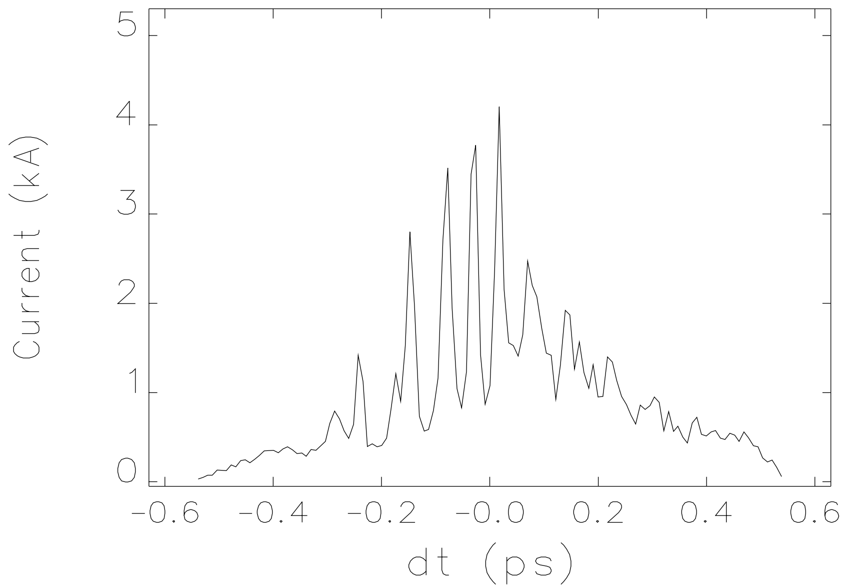
CSR & Smearing Investigation

At the end of BC3 without CSR at BC3

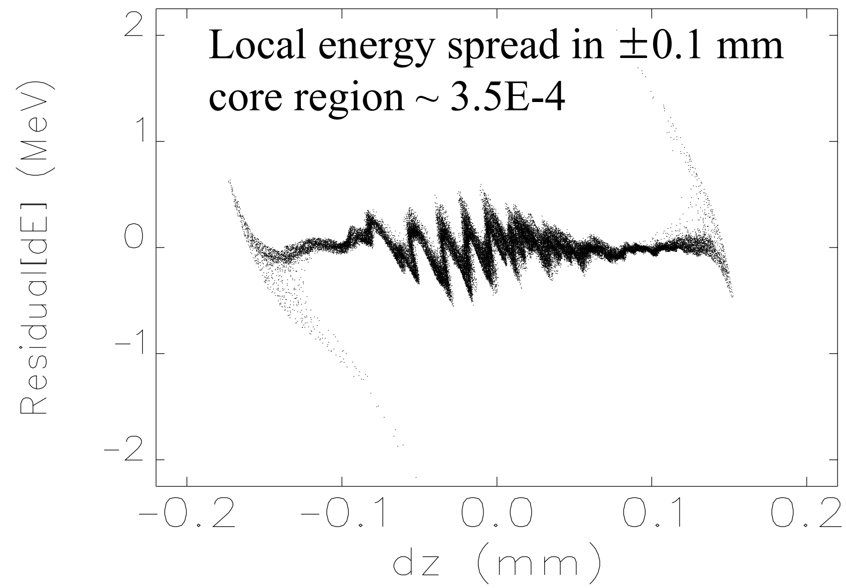
Modulation period = 2.0 ps
Modulation Amplitude = 20%
Postpro BIN number = 125
Simulation particles = 50,000
ASTRA Grids for space charge calculation = 10 rings × 50 cells



Increased modulation amplitude than those of 10% and 15% means
no saturation by LSC driven microbunching instability at 20% amplitude !



After BC3 with 2.0 ps 20% modulation & without CSR

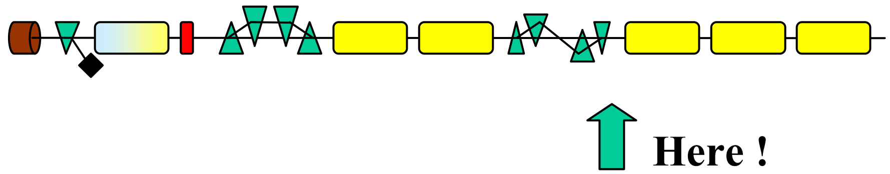


After BC3 with 2.0 ps 20% modulation & without CSR

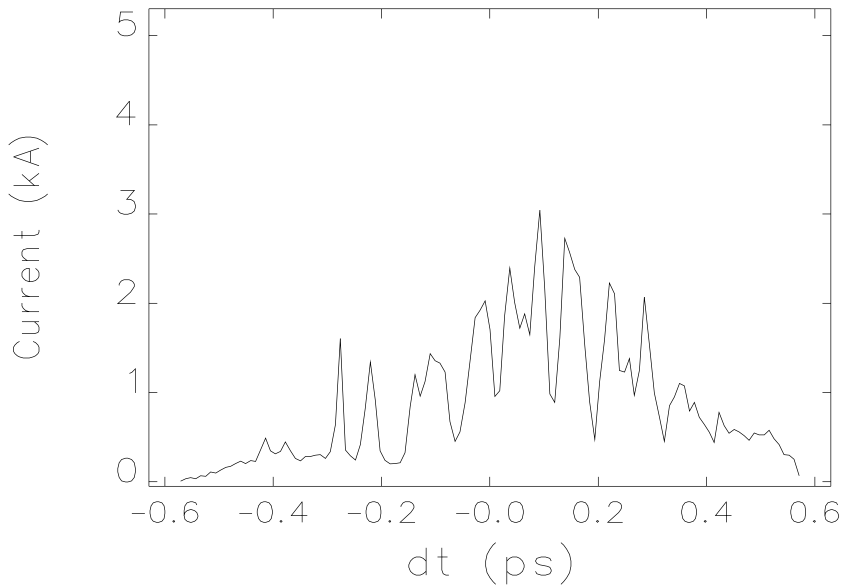
CSR & Smearing Investigation

At the end of BC3 with CSR at BC3

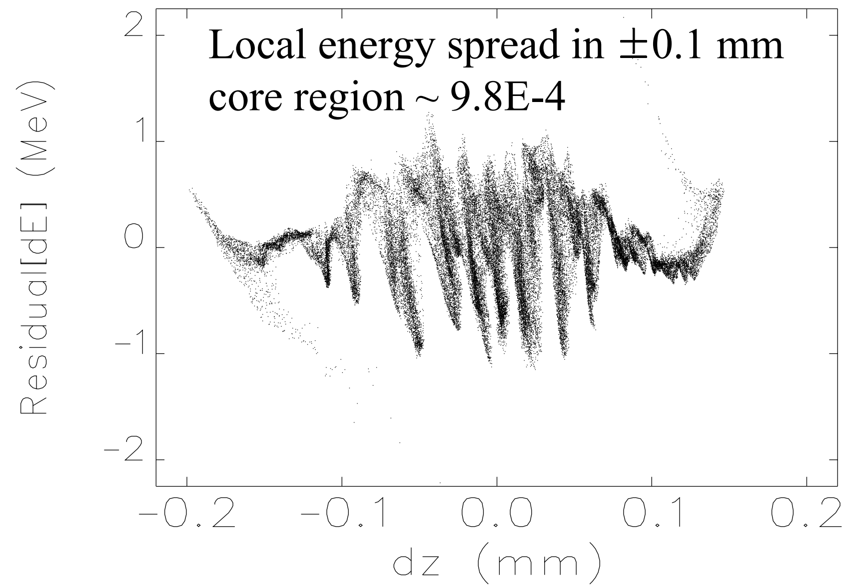
Modulation period = 2.0 ps
Modulation Amplitude = 20%
Postpro BIN number = 125
Simulation particles = 50,000
ASTRA Grids for space charge calculation = 10 rings × 50 cells



LSC microbunching instability is somewhat smeared
by the increased local energy spread under CSR wakefield !



After BC3 with 2.0 ps 20% modulation and with CSR

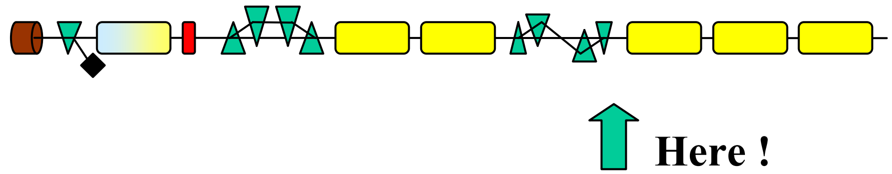


After BC3 with 2.0 ps 20% modulation and with CSR

Gain after BC3

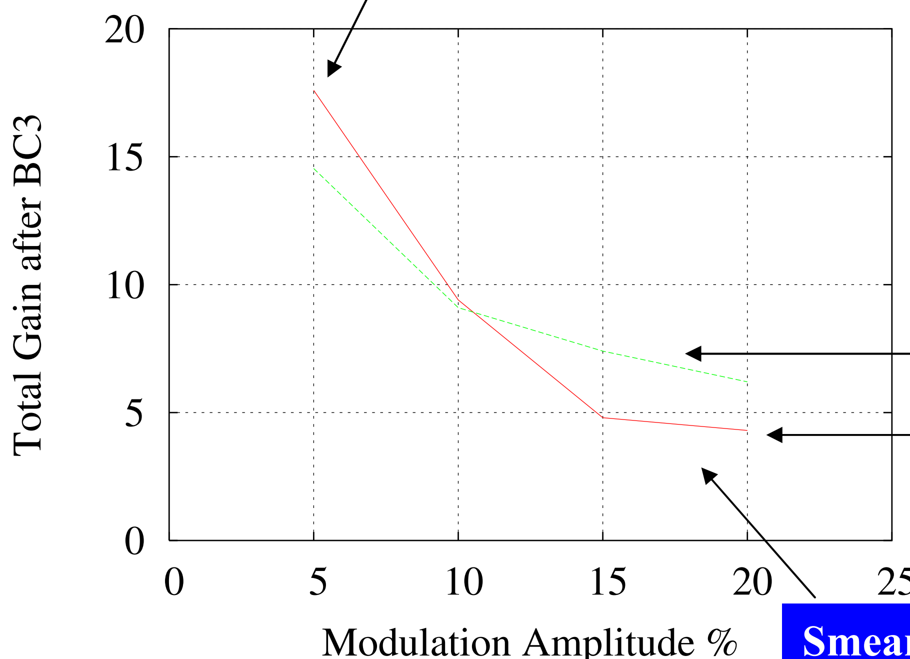
At the end of BC3

Modulation period = 2.0 ps
Modulation Amplitude = 5%, 10%, 15%, 20%
Postpro BIN number = 125
Simulation particles = 50,000
ASTRA Grids for space charge calculation = 10 rings × 50 cells



Here !

Gain is overestimated at small amplitude due to numerical noise



CSR effects becomes strong due to the increased non-uniformity in the current density profile when the modulation amplitude is increased.

Gain ~ 7 without CSR at BC3

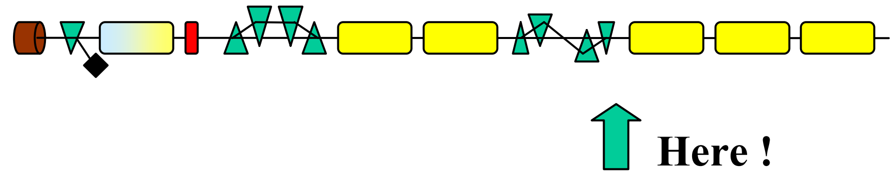
Gain ~ 5 with CSR at BC3

Smeared by the increased local energy spread due to CSR wakefield

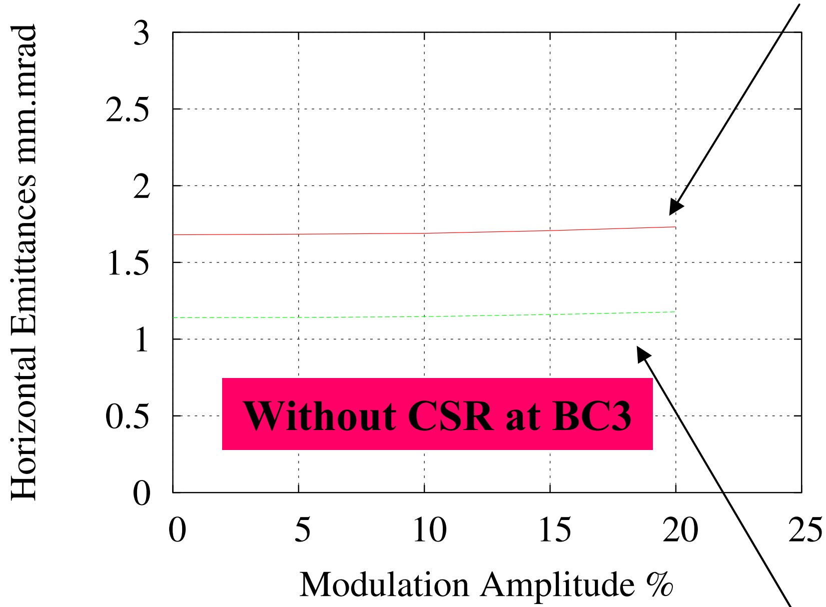
Slice & Projected Emittances after BC3

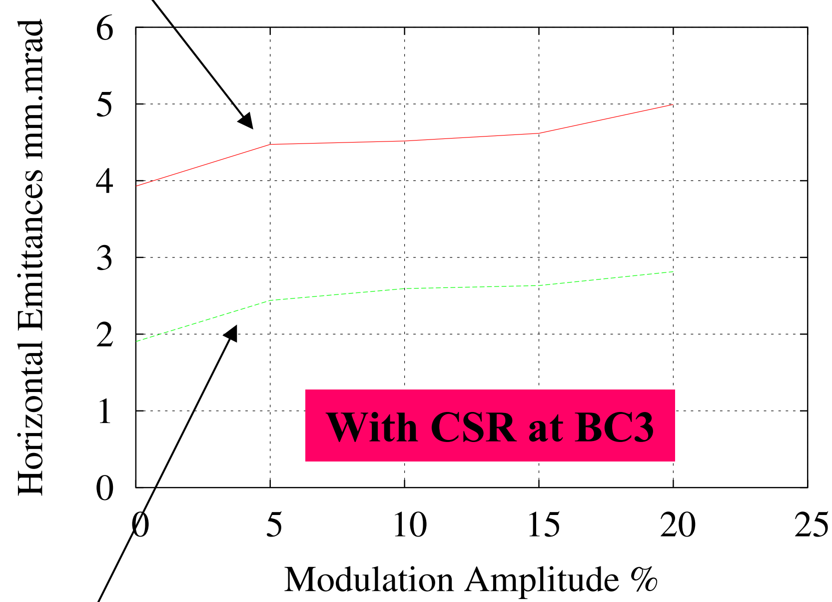
At the end of BC3

Modulation period = 2.0 ps
Modulation Amplitude = 5%, 10%, 15%, 20%
Postpro BIN number = 125
Simulation particles = 50,000
ASTRA Grids for space charge calculation = 10 rings × 50 cells



Normalized projected emittance





Normalized slice emittance

Summary

We have investigated the microbunching instability in the TTF-2 under all important impedances, LSC, CSR, and the geometric wakefields.

Certainly LSC induced microbunching instability is much stronger than that of CSR induced microbunching instabilty.

The initial density modulation is smeared out by several unconsidered smearing effects in the analytical formulae: fast Plasma oscillation & strong Landau damping at the low energy region, local energy spread growth in linac & in drift by modulated E_z, and local energy spread growth in BC by CSR.

Estimated total gain after BC3 is smaller than 10 for 2 ps laser modulation.

Only one BC, we meet only an strong energy modulation and the current density modulation is not strong (This is observed at SDL). But after second BC, we meet strong density modulation.

We will check chicane type & these microbunching experimentally in TTF-2.

Acknowledgments

Y. Kim sincerely thanks K. Flöttmann, S. Schreiber, Z. Huang, E. A. Schneidmiller, M. Dohlus, T. Limberg, P. Emma, Prof. J. Rossbach, Prof. K.-J. Kim, and Prof. W. Namkung for their encouragements of this work and many useful comments and discussions.

Dr. Schneidmiller's Assumption Reviews

Following Assumptions should be reviewed in TESLA-FEL-2003-02

- **Amplitude of an initial density modulation is not constant and damped at low energy region, specially at RF gun.**

  Confirmed by ASTRA and PARMELA simulations
  Confirmed by experimentally (Journal of Applied Physics, Vol 86, No 3, p 1699)
  Specially, at short-wavelength region, dispersion effects is strong.

$$\text{under } \lambda \le \text{circumference of beam pipe}$$
$$\text{dispersion effects damp the initial modulation.}$$
$$\text{dispersion effects} \propto \frac{1}{\lambda^2}$$

- **CSR effect can not be ignored at BC3:** $\boldsymbol{k\sqrt{\varepsilon\beta}\theta_d >> 1}$ to ignore CSR

$$\boldsymbol{k\sqrt{\varepsilon\beta}\theta_d = 0.1 \sim 0.3} \text{ at BC3}$$

Dr. Schneidmiller's Assumption Reviews

Following Assumptions should be reviewed in TESLA-FEL-2003-02

- **1-D space charge model of a pencil like beam can not be applied at the low energy region, specially Gun region.**
- **2-D space charge model gives an additional local energy spread.**

$$p = \gamma/(k\sigma_\perp) >> 1 \ \text{ for } \ 1-\text{D space charge model}$$

$$\gamma = 0 \sim 2000$$

$$\mathrm{k} = 10471.97 \ \text{ for } \ 2.0\,\mathrm{ps}$$

$$\sigma_\perp = \sim 5.0\mathrm{E}-4 \ \ \mathrm{m}$$

- **Influence of vacuum chamber should be considered at BC2 and BC3 with 8 mm gap**