Velocity Bunching Studies at FLASH

Bolko Beutner, DESY

XFEL Beam Dynamics Meeting 4.6.2007

Contents

- Introduction
- ASTRA simulations
- Semi-Analytic Model
- CSR microbunch instability studies
- Experiments at FLASH
- Summary and Outlook

Introduction

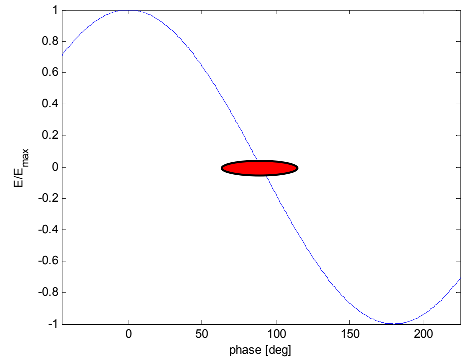
At low beam energies ~5 MeV electron velocities are not independent of the particle energy

⇒ correlated energy spread ⇔ velocity spread

⇒ bunch compression without chicanes

First cavity of ACC1 is operated at the zero crossing (-90deg off-crest)

⇒ linear correlated energy spread



L. Serafini, M. Ferrario,
``Velocity Bunching in Photo-Injectors'',
AIP Conference Proceedings 581, 87 (2001)

Velocity Bunching in Photo-Injectors

L. Serafini and M. Ferrario*

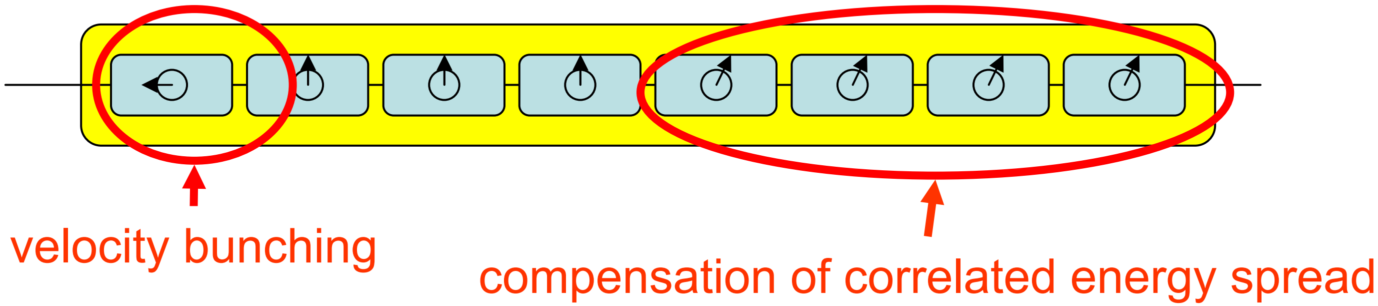
University of Milan and INFN-Milan
** INFN-Frascati*

Abstract. We describe here a new method to increase the peak current of high brightness electron beams as those required to drive X-ray SASE FEL's, that is based on a rectilinear compressor scheme utilizing the bunching properties of slow waves. It is shown that whenever a beam, slower than the synchronous velocity, is injected into a RF wave at the zero acceleration phase and slips back in phase up to the peak acceleration phase, it can be compressed as far as the extraction happens at the synchronous velocity. In fact, the bunch undergoes a quarter of synchrotron oscillation that induces a net compression (i.e. a bunch length reduction) up to a factor of 20 when proper care is taken to preserve the longitudinal emittance. A few examples are presented to demonstrate the potentialities of this method, by which multi-kA beams at very low emittance can be generated at moderate energies (about 100 MeV).

Introduction

Bunching stops in the second cavity since the energy increases and relativistic velocities are reached.

The last cavities in the module can be used to compensate the correlated energy spread.

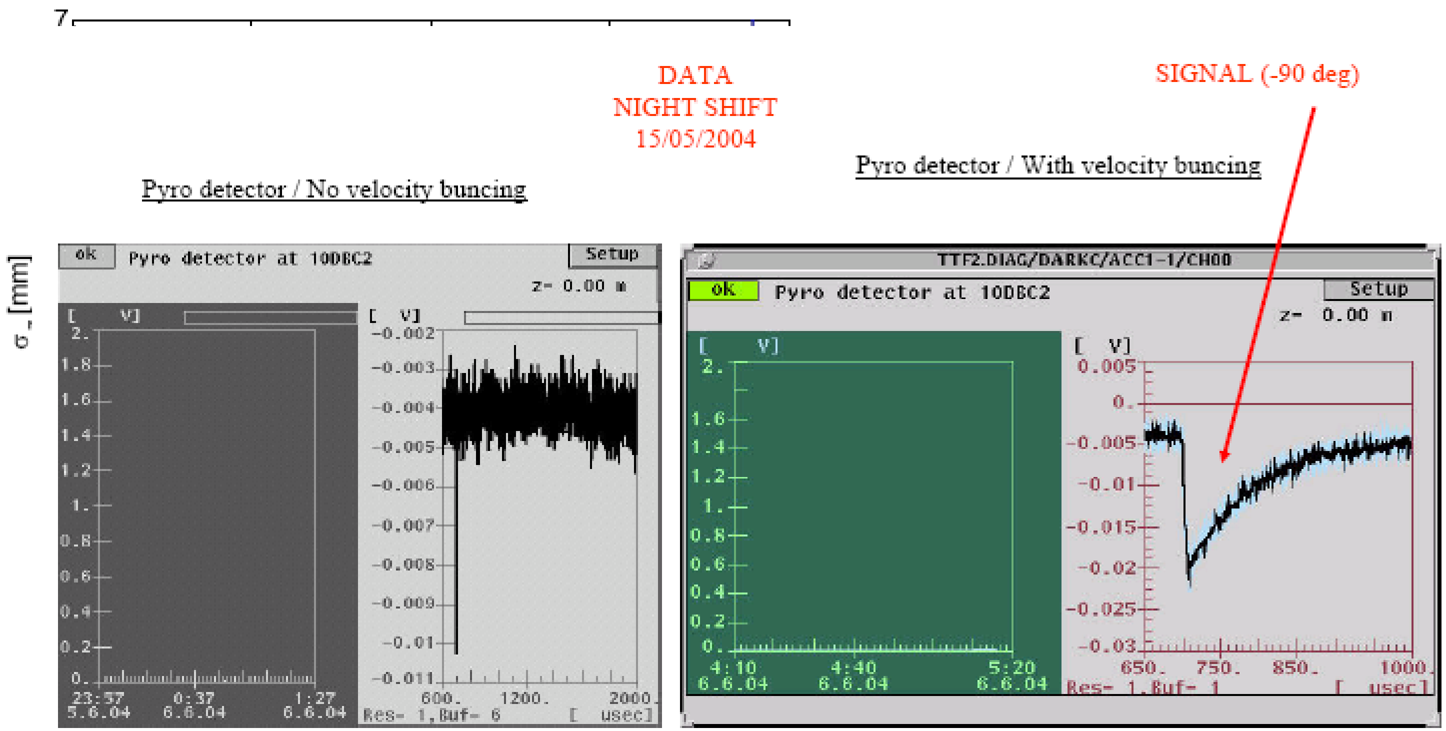


Velocity bunching is an additional “knob” to optimise the bunch compression system.

Introduction

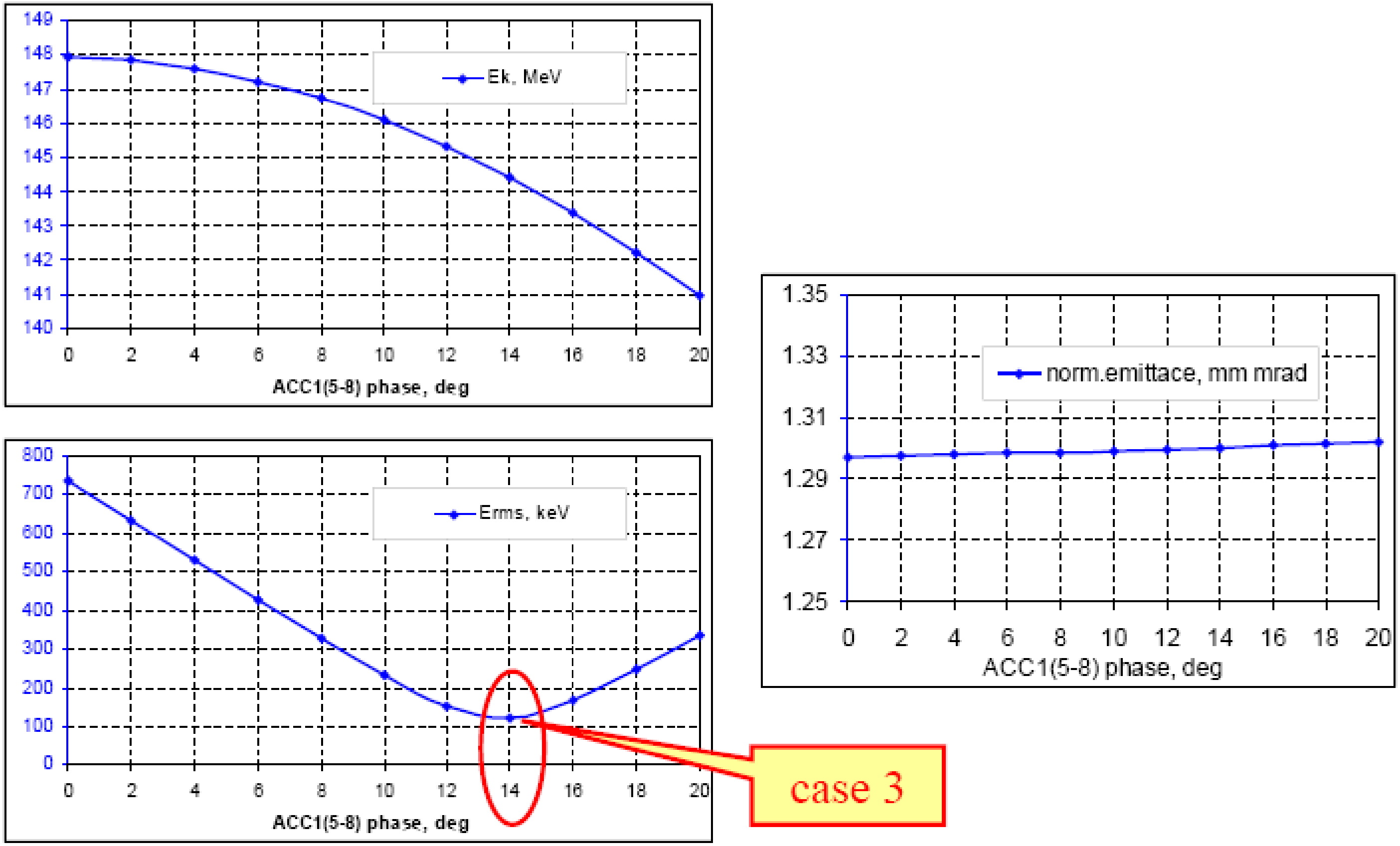
J.P. Carniero (2004) : FLASH simulations and first experiments

- **Velocity Bunching Principle : Adjust Phase First Cavity ACC1 / All other cavities on crest.**



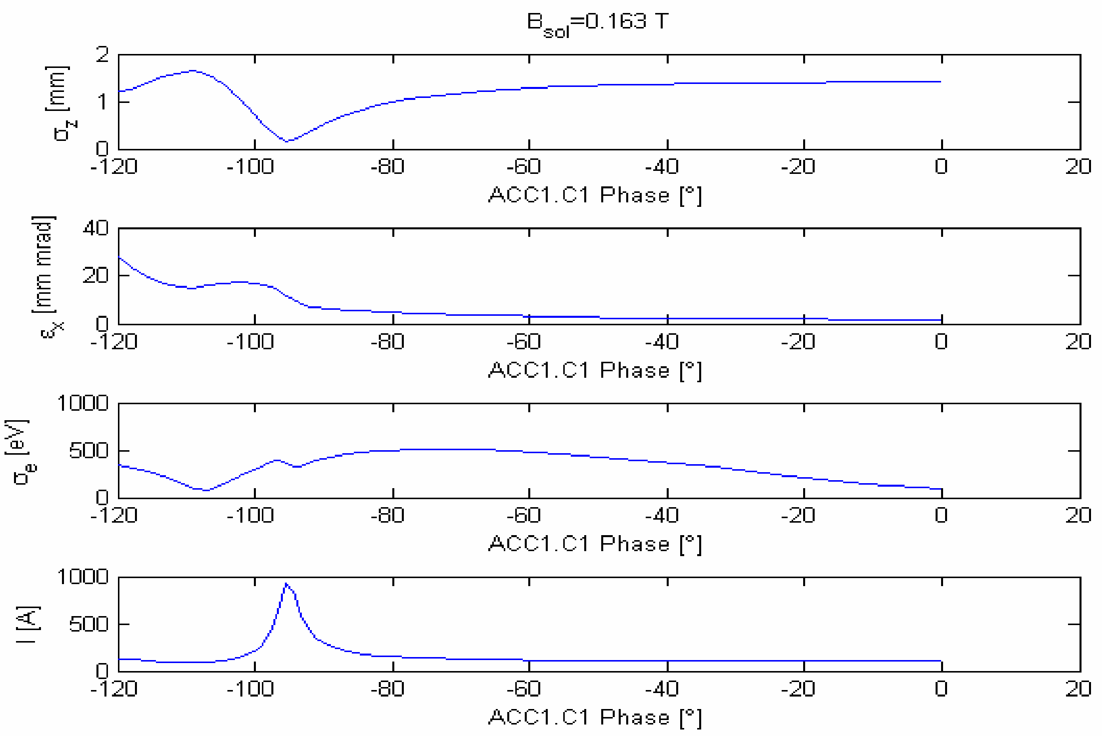
Introduction

M. Krasilnikov (2007) : XFEL studies including compensation of correlated energy spread

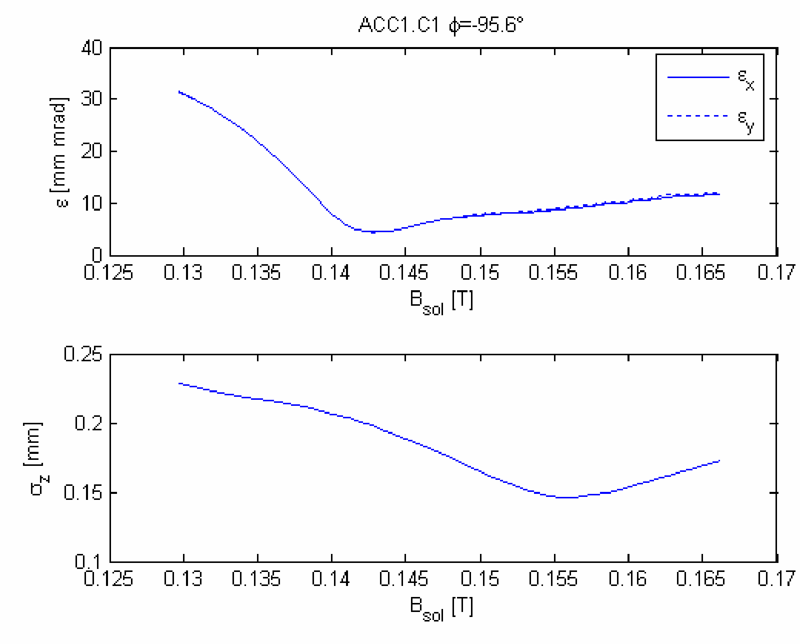


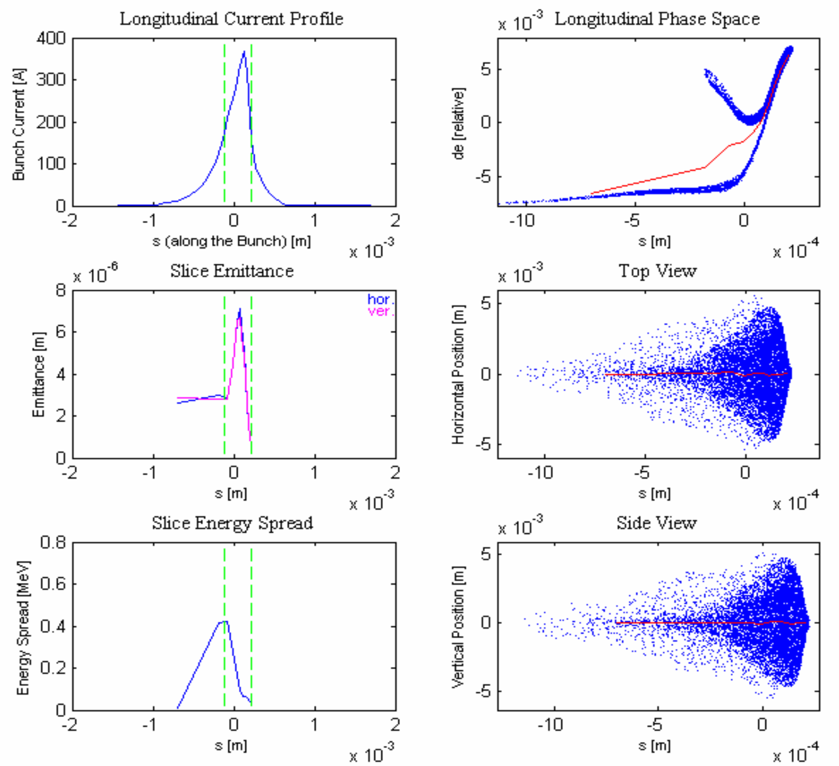
ASTRA Simulations

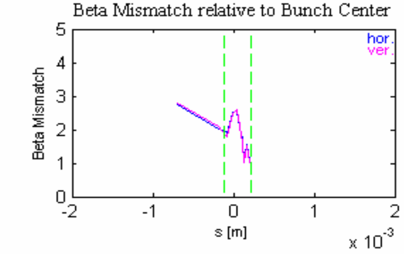
ASTRA simulations based on J.P. Carnieros files (q=0.5nC; 10k particles)



ASTRA Simulations







Number of Particles: 9999 Charge: 0.5 nC
Position: 13.635 m Beam Energy: 111.36 MeV

FWHM (distance between green bars): 341 μm (1.14 ps)
Charge within FWHM: 81.2 %
Projected Emittance: $\gamma\varepsilon_x$ = 4.55e-006 m $\gamma\varepsilon_y$ = 4.47e-006 m
Optics @ I_{peak}: α_x = -22.5 β_x = 268m α_y = -22.3 β_y = 265m

RMS Values for all Particles:
x = 1.89e-003 m x' = 1.62e-004
y = 1.86e-003 m y' = 1.60e-004
z = 1.98e-004 m δ = 4.32e-003

RMS Values within FWHM:
x = 2.01e-003 m x' = 1.73e-004
y = 1.98e-003 m y' = 1.71e-004
z = 8.69e-005 m δ = 3.48e-003

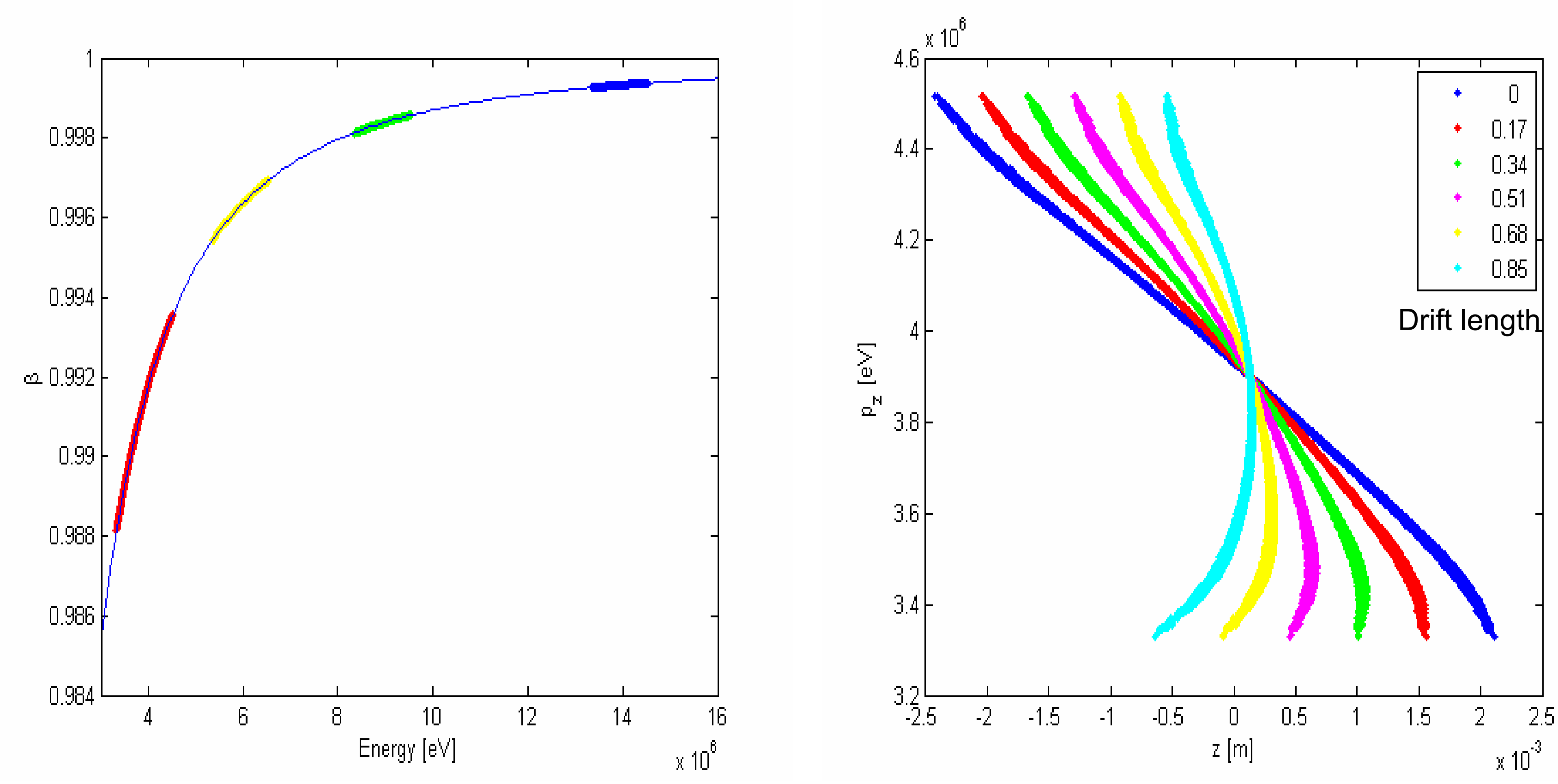
At full compression emittance after solenoid optimisation is 4.5mm mrad after ACC1.

Nonlinear compression

longitudinal SpCh forces

ASTRA simulations

Nonlinear bunch compression for a linear correlated energy spread due to a nonlinear dependence of the velocity on energy.



ASTRA Simulations

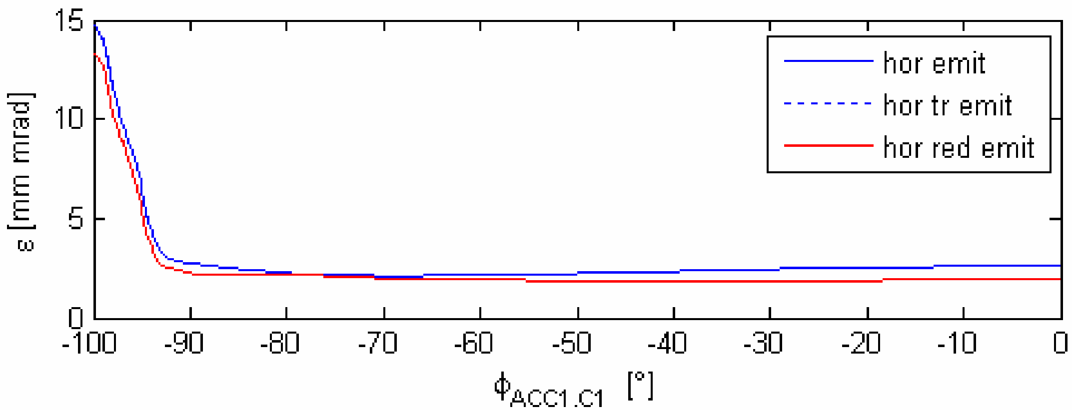
- New Gun (thanks to Jang-Hui Han)
  - 10k particles, Nrad=24, Nlong=64

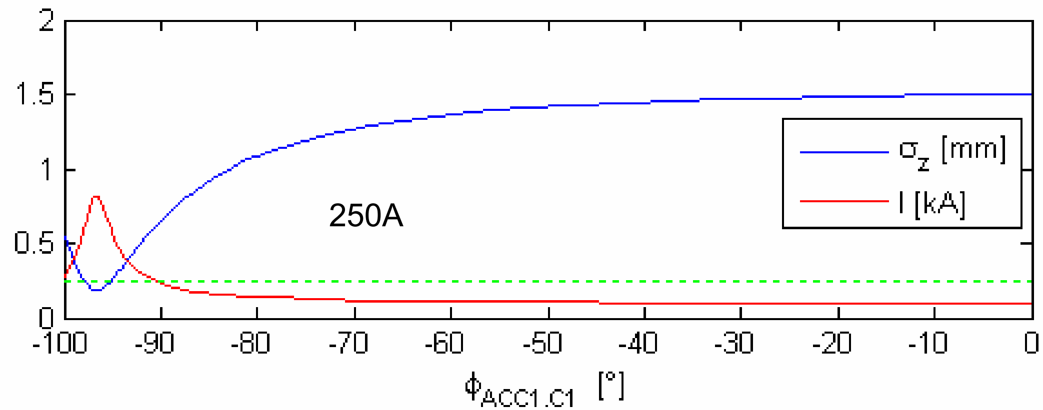
Solenoid optimsed to B=0.165T

Q=0.5nC

initial bunch length = 1.5mm

ACC1.C1 Phase [deg]	Bunch length [mm]	emmit. [mm mrad]
-80.0	1.087	2.14
-90.4	0.622	2.29
-96.3	0.183	8.04





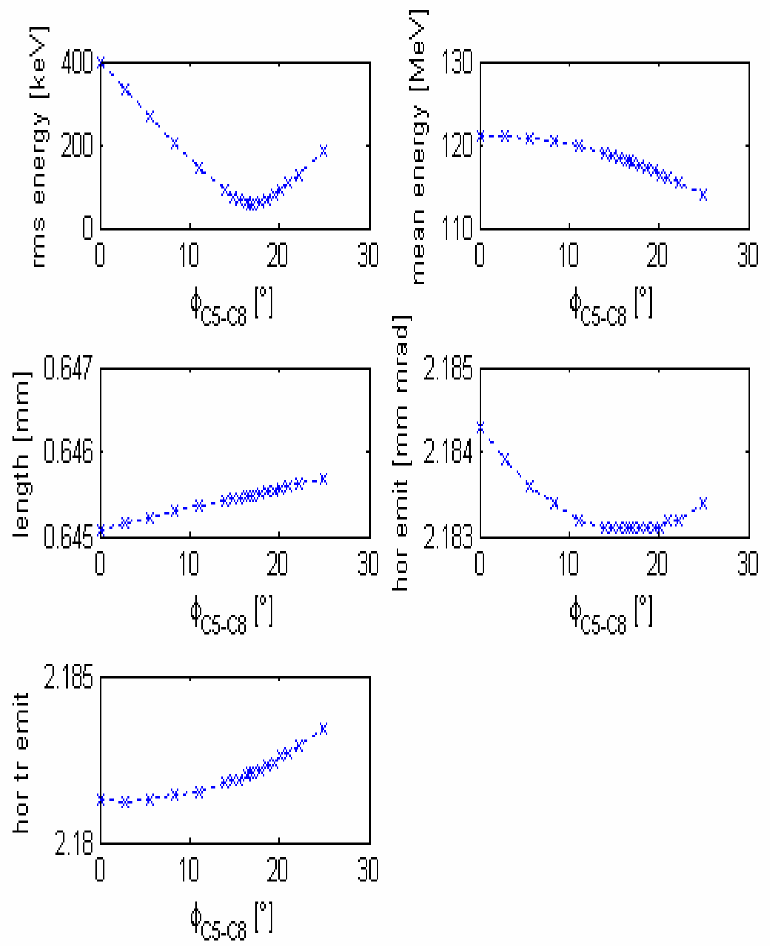
ASTRA Simulations

Compensation of the correlated energy spread with ACC1.C5-C8

ACC1.C1 phase = -90 deg

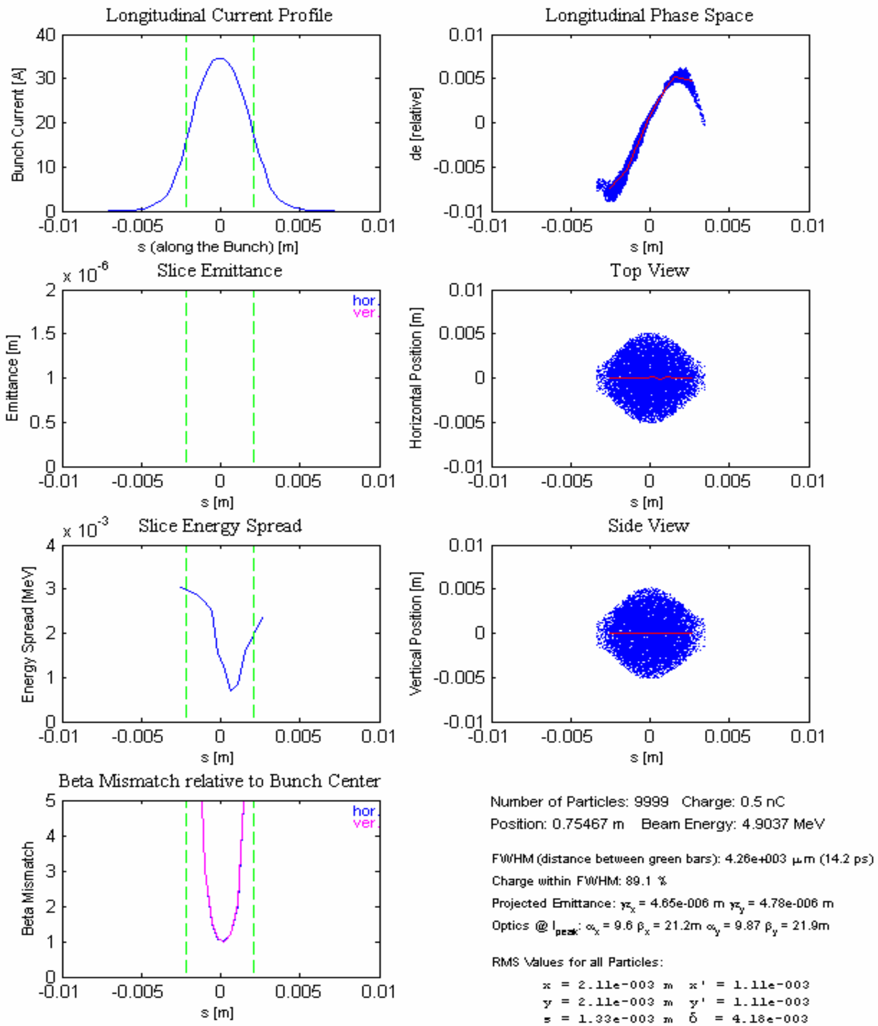
B solenoid = 0.165T

Minimal energy spread (58.2 keV) at ACC1.C5-C8 phase = 17.11deg



ASTRA Simulations

0.75m



Number of Particles: 9999   Charge: 0.5 nC
Position: 0.75467 m   Beam Energy: 4.9037 MeV

FWHM (distance between green bars): 4.26e+003 μm (14.2 ps)
Charge within FWHM: 89.1 %
Projected Emittance: $\gamma\varepsilon_x$ = 4.65e-006 m $\gamma\varepsilon_y$ = 4.78e-006 m
Optics @ I_{peak}: α_x = 9.6 β_x = 21.2m α_y = 9.87 β_y = 21.9m

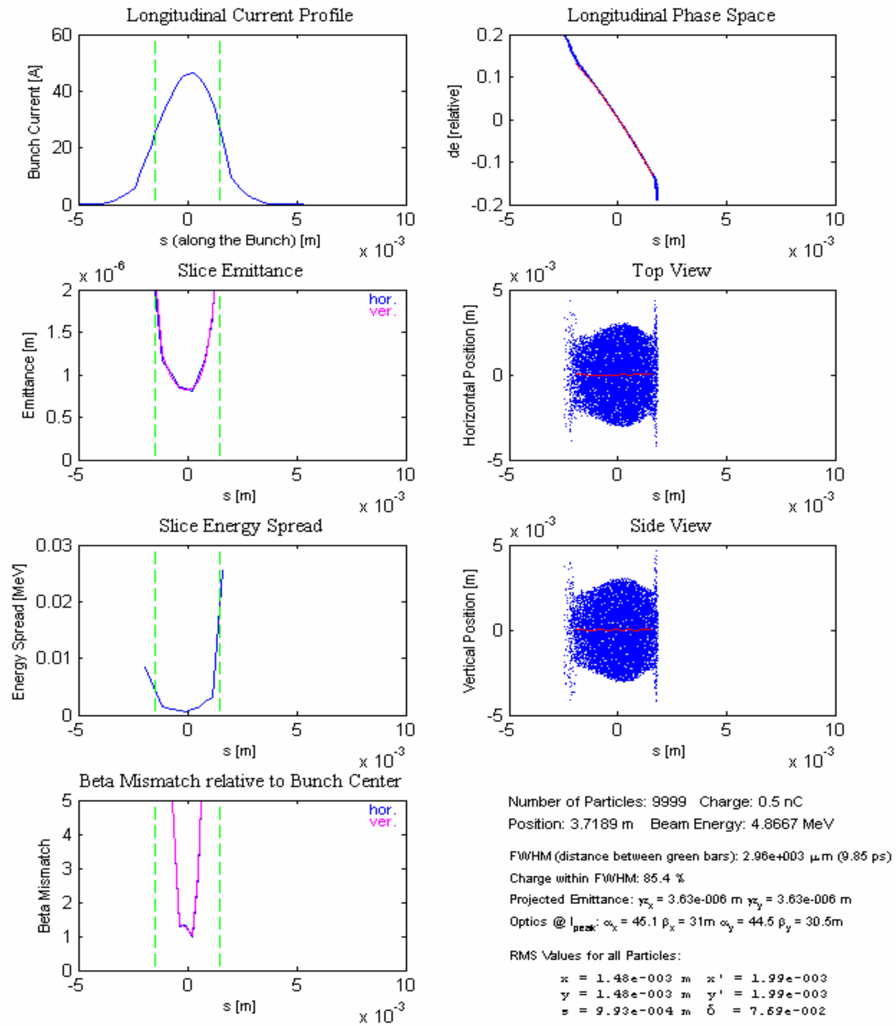
RMS Values for all Particles:

```
x = 2.11e-003 m  x' = 1.11e-003
y = 2.11e-003 m  y' = 1.11e-003
s = 1.33e-003 m  δ  = 4.18e-003
```

RMS Values within FWHM:

```
x = 2.20e-003 m  x' = 1.11e-003
y = 2.18e-003 m  y' = 1.10e-003
s = 1.10e-003 m  δ  = 3.85e-003
```

3.72m



Number of Particles: 9999   Charge: 0.5 nC
Position: 3.7189 m   Beam Energy: 4.8667 MeV

FWHM (distance between green bars): 2.96e+003 μm (9.85 ps)
Charge within FWHM: 85.4 %
Projected Emittance: $\gamma\varepsilon_x$ = 3.63e-006 m $\gamma\varepsilon_y$ = 3.63e-006 m
Optics @ I_{peak}: α_x = 45.1 β_x = 31m α_y = 44.5 β_y = 30.5m

RMS Values for all Particles:

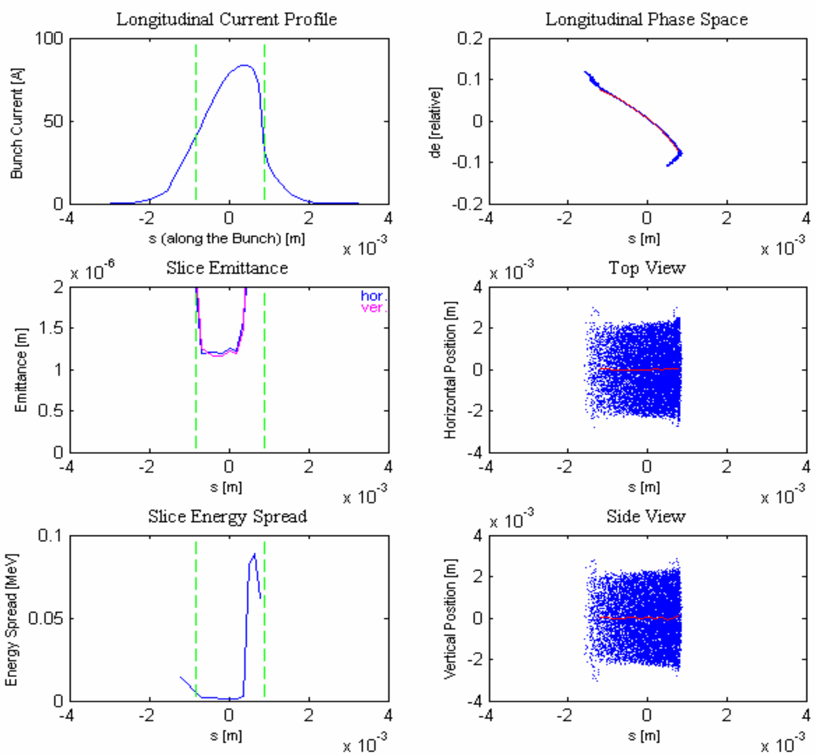
```
x = 1.48e-003 m  x' = 1.99e-003
y = 1.48e-003 m  y' = 1.99e-003
s = 9.93e-004 m  δ  = 7.69e-002
```

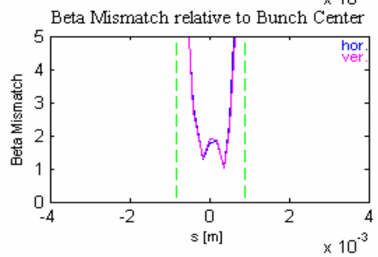
RMS Values within FWHM:

```
x = 1.50e-003 m  x' = 2.06e-003
y = 1.49e-003 m  y' = 2.04e-003
s = 7.86e-004 m  δ  = 6.05e-002
```

ASTRA Simulations

4.56m





Number of Particles: 9999 Charge: 0.5 nC
Position: 4.4588 m Beam Energy: 8.9036 MeV

FWHM (distance between green bars): 1.71e+003 μm (5.7 ps)
Charge within FWHM: 89.1 %
Projected Emittance: $\gamma\epsilon_x$ = 3.17e-006 m $\gamma\epsilon_y$ = 3.23e-006 m
Optics @ I_{peak}: α_x = 14 β_x = 16.6m α_y = 13.6 β_y = 16.2m

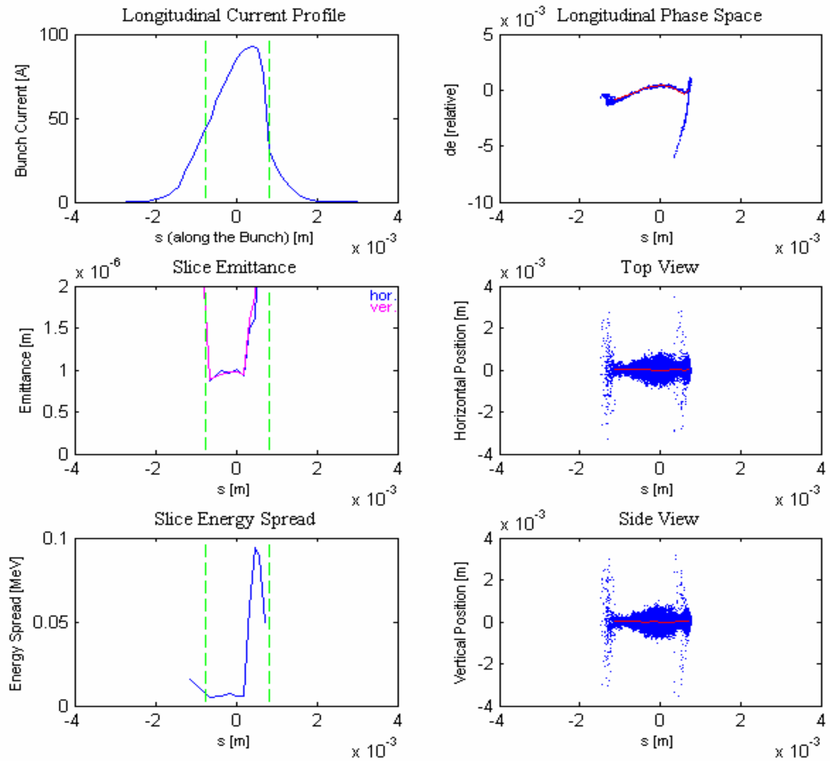
RMS Values for all Particles:

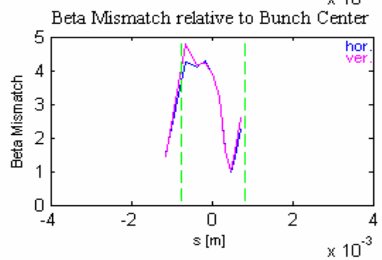
```
x = 1.19e-003 m  x' = 9.33e-004
y = 1.19e-003 m  y' = 9.31e-004
s = 5.75e-004 m  δ  = 4.44e-002
```

RMS Values within FWHM:

```
x = 1.20e-003 m  x' = 9.50e-004
y = 1.19e-003 m  y' = 9.46e-004
s = 4.51e-004 m  δ  = 3.75e-002
```

14.00m





Number of Particles: 9999 Charge: 0.5 nC
Position: 14.04 m Beam Energy: 118.32 MeV

FWHM (distance between green bars): 1.58e+003 μm (5.27 ps)
Charge within FWHM: 89.1 %
Projected Emittance: $\gamma\epsilon_x$ = 2.2e-006 m $\gamma\epsilon_y$ = 2.29e-006 m
Optics @ I_{peak}: α_x = -0.988 β_x = 10.8m α_y = -1.15 β_y = 12.3m

RMS Values for all Particles:

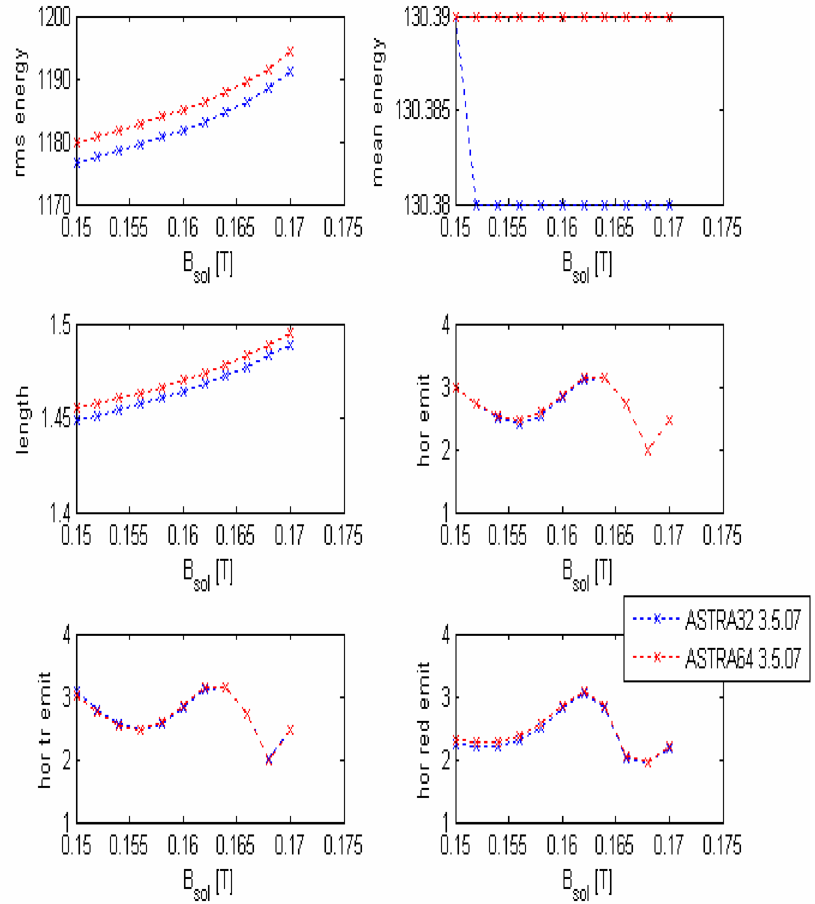
```
x = 3.12e-004 m  x' = 5.07e-005
y = 3.24e-004 m  y' = 5.14e-005
s = 5.29e-004 m  δ  = 5.56e-004
```

RMS Values within FWHM:

```
x = 2.88e-004 m  x' = 4.79e-005
y = 2.97e-004 m  y' = 4.84e-005
s = 4.11e-004 m  δ  = 5.06e-004
```

ASTRA Simulations

Comparison between the 32bit and 64bit paralell version of ASTRA gives an agreement better than a percent.



Bolko Beutner, DESY

Semi-Analytic Model

Scans with ASTRA to find a reasonable gradient and phase settings of the modules are time consuming

=> preliminary optimisation is done in an semi-analytic model

longitudinal position after a low energy drift space:

$$l_f = l_i + c\beta(\delta)\frac{d}{c\beta(0)}$$

$$l_f = l_i + d\frac{\beta(\delta)}{\beta(0)} \Rightarrow l_i + R_{56}\delta + T_{566}\delta^2 + \cdots$$

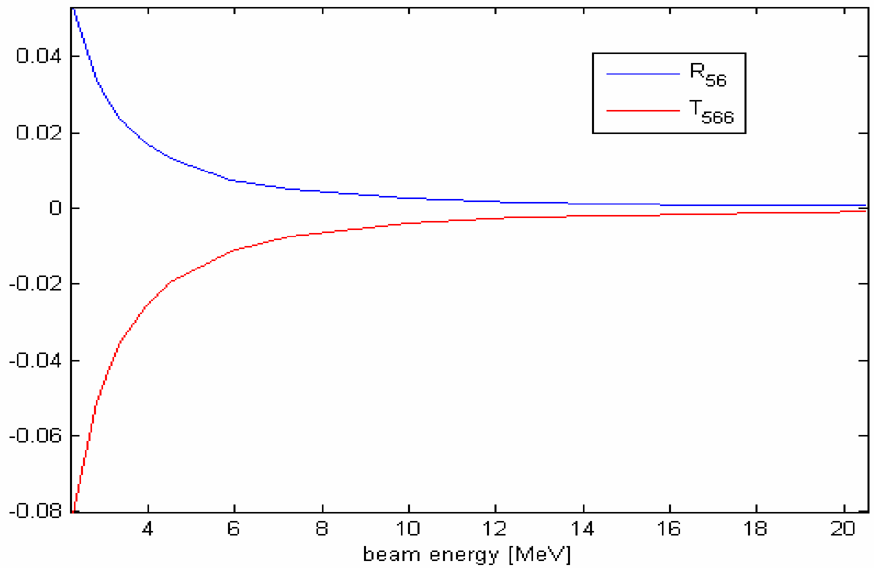
with drift length d and velocity $\beta(\delta) = \sqrt{1 - \left(\frac{1}{\frac{E_0 + \delta E_0}{m_0}}\right)^2}$

Semi-Analytic Model

¯(±) is expressed in a Taylor-series around zero in ±:

$$) \quad R_{56} = \frac{{}_{3}\, d m_0^2 \; ´}{E_0^2 \left(1 ¡ \frac{m_0^2}{E_0^2}\right)}$$

$$T_{566} = ¡ \frac{{}_{3}\, d m_0^4 \; ´}{2E_0^4 \left(1 ¡ \frac{m_0^2}{E_0^2}\right)^2} ¡ \frac{{}_{3}\, 3 d m_0^2 \; ´}{2E_0^2 \left(1 ¡ \frac{m_0^2}{E_0^2}\right)}$$



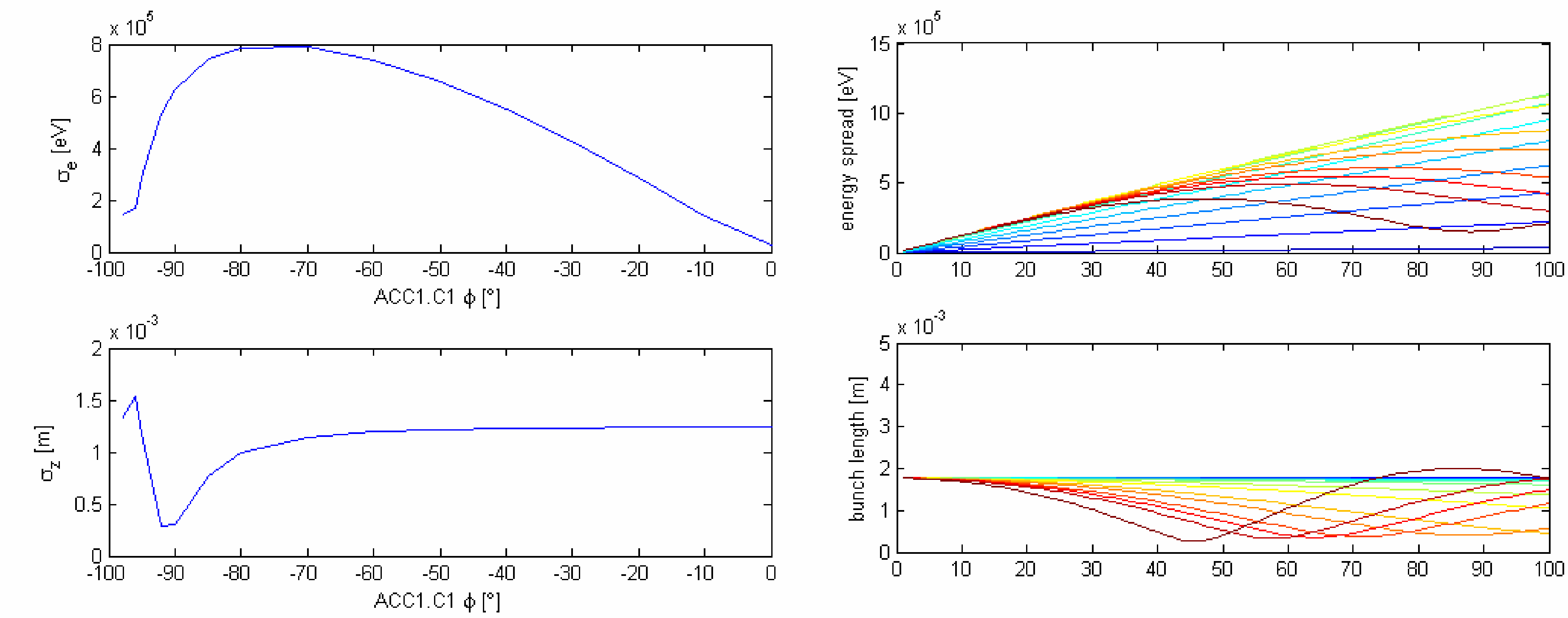
Semi-Analytic Model

- Beam from the ASTRA simulations at the entrance of ACC1
- The cavities are divided into subintervals in which the effective longitudinal dispersion is applied
- Fraction of RF-voltage is applied at the intersections

Semi-Analytic Model

ACC1.C1 divided into 100 segments

initial rms bunch length = 1.2mm ; GUN energy gain = 4.7MeV



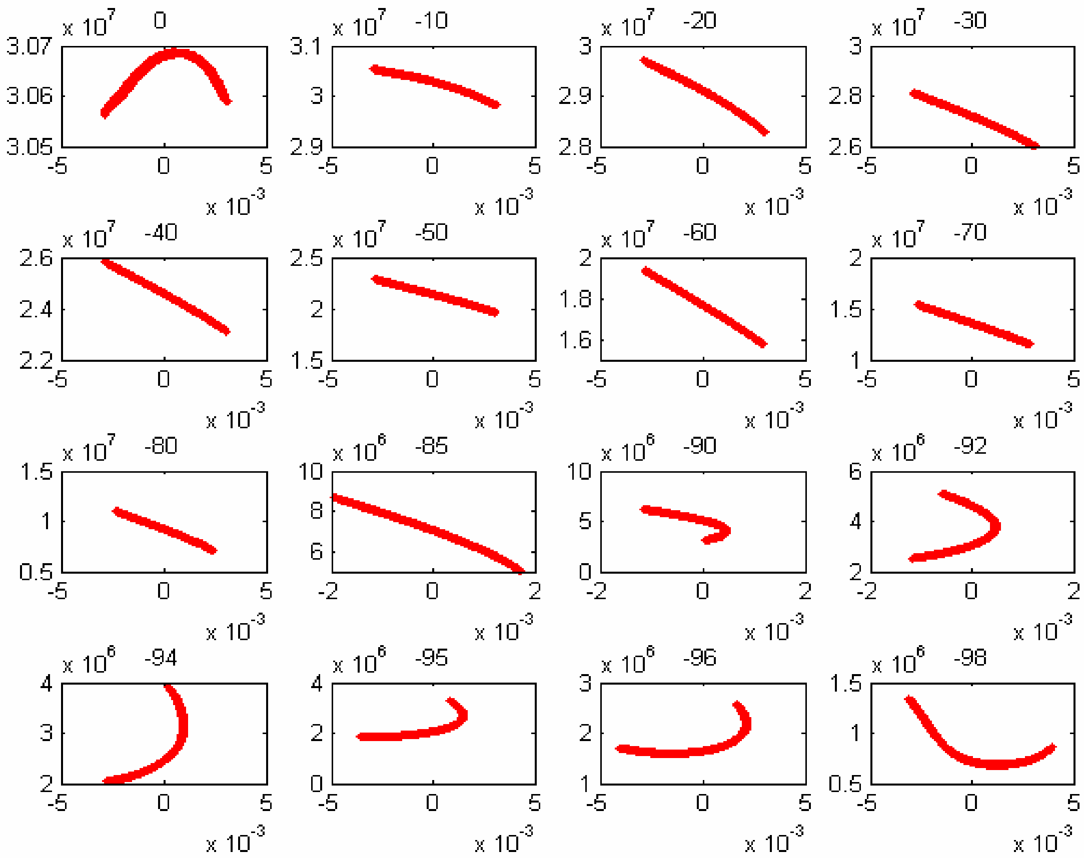
ACC1.C1 gradient = 26MV/m

0deg (blue) -> -100deg (dark read)

Semi-Analytic Model

Longitudinal phase space

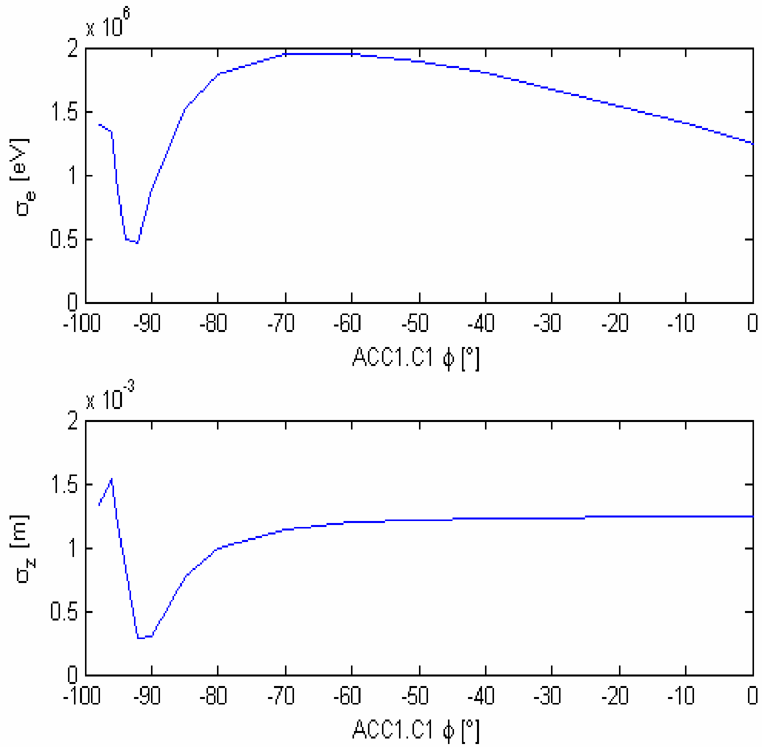
(energy [MeV] vs. longitudinal position [mm])

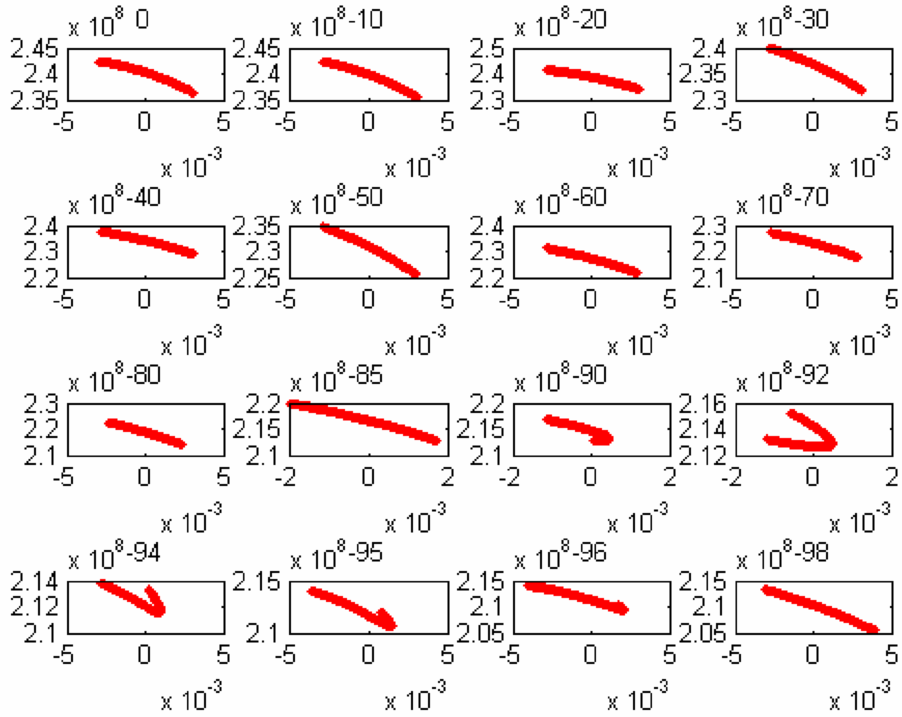


Bolko Beutner, DESY

ACC1.C2-C4 on-crest

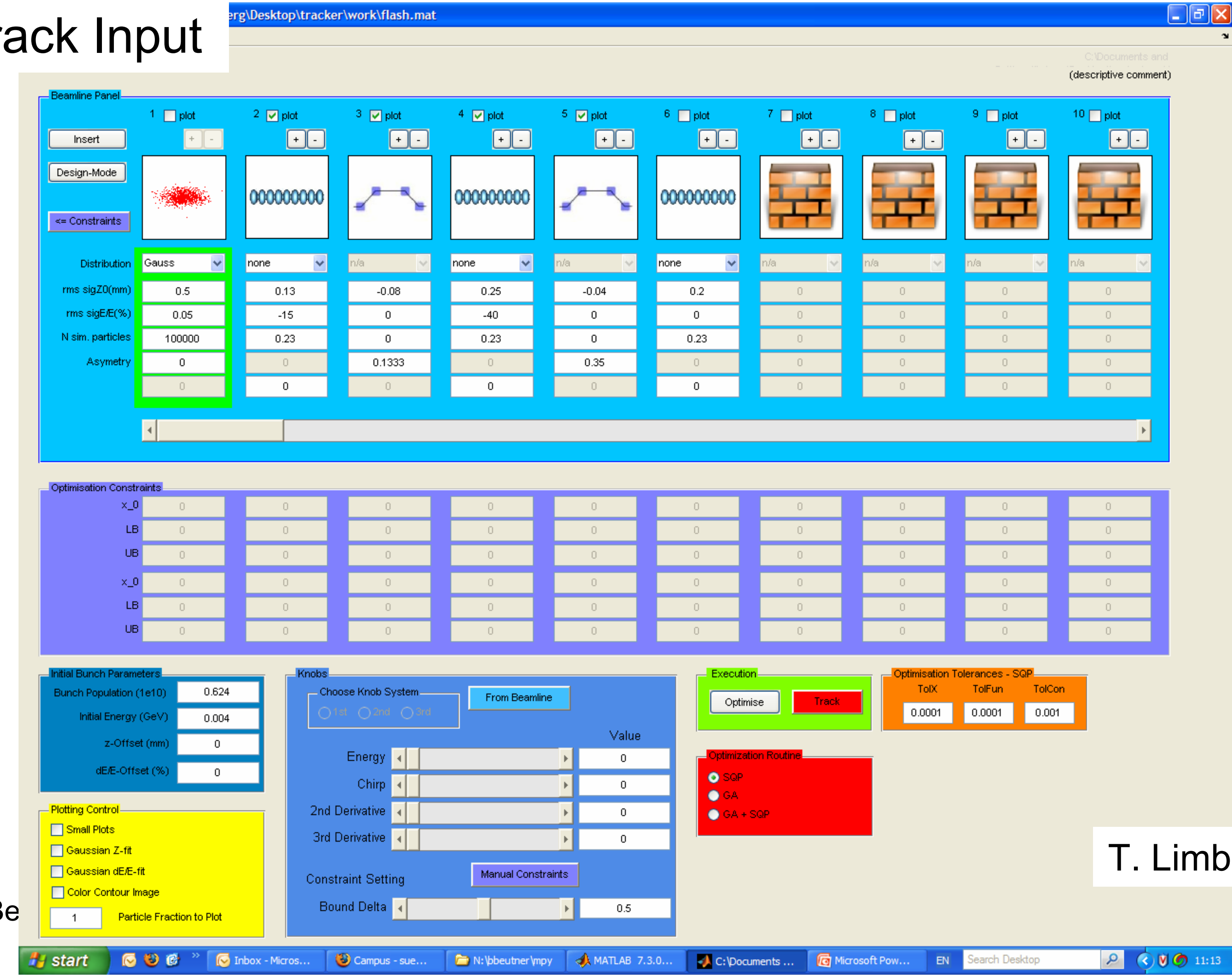
ACC1.C5-C8 -10deg off-crest => bunch length is mapped to correlated energy spread





CSR microbunch instability studies

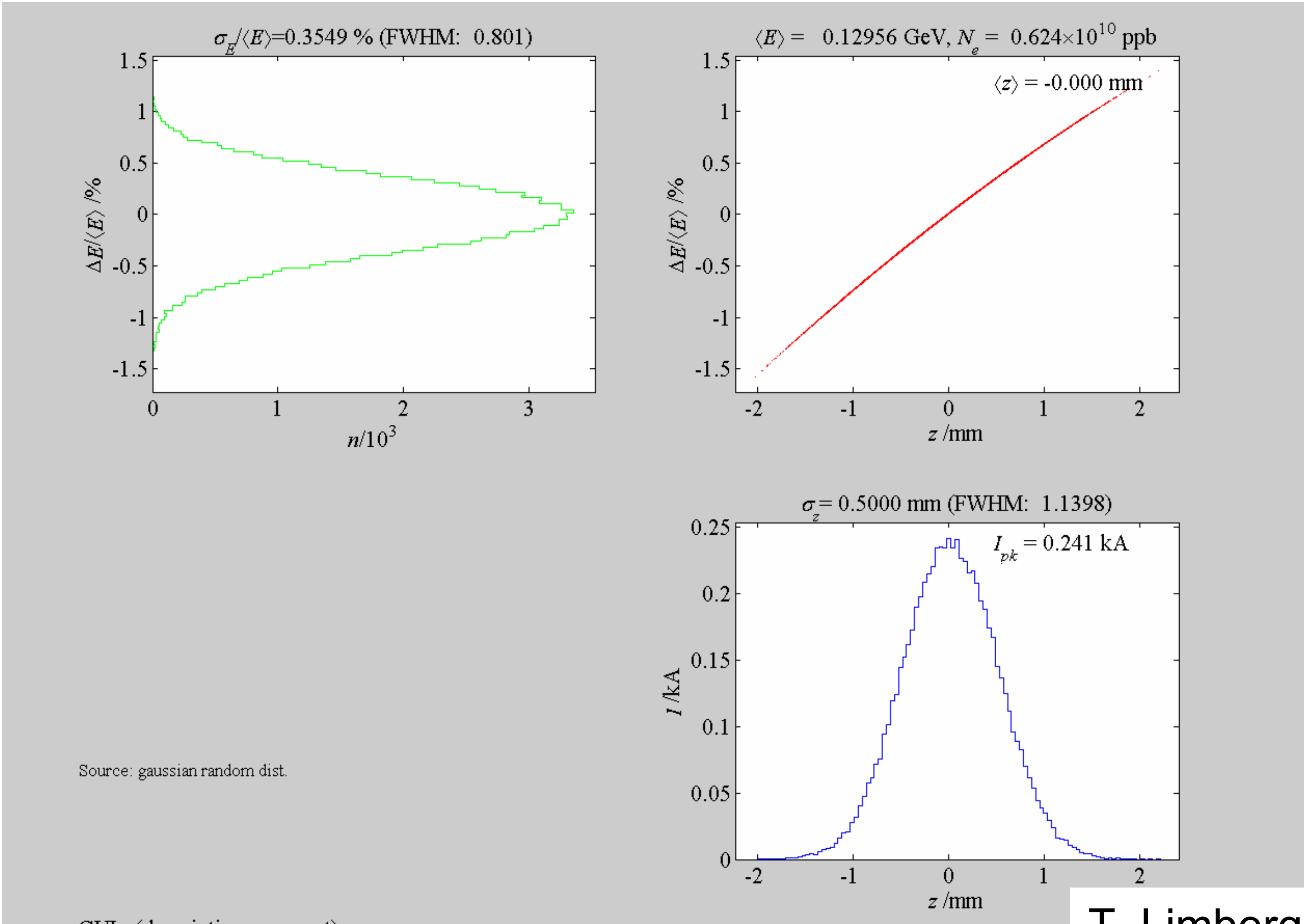
LiTrack Input



T. Limberg

CSR microbunch instability studies

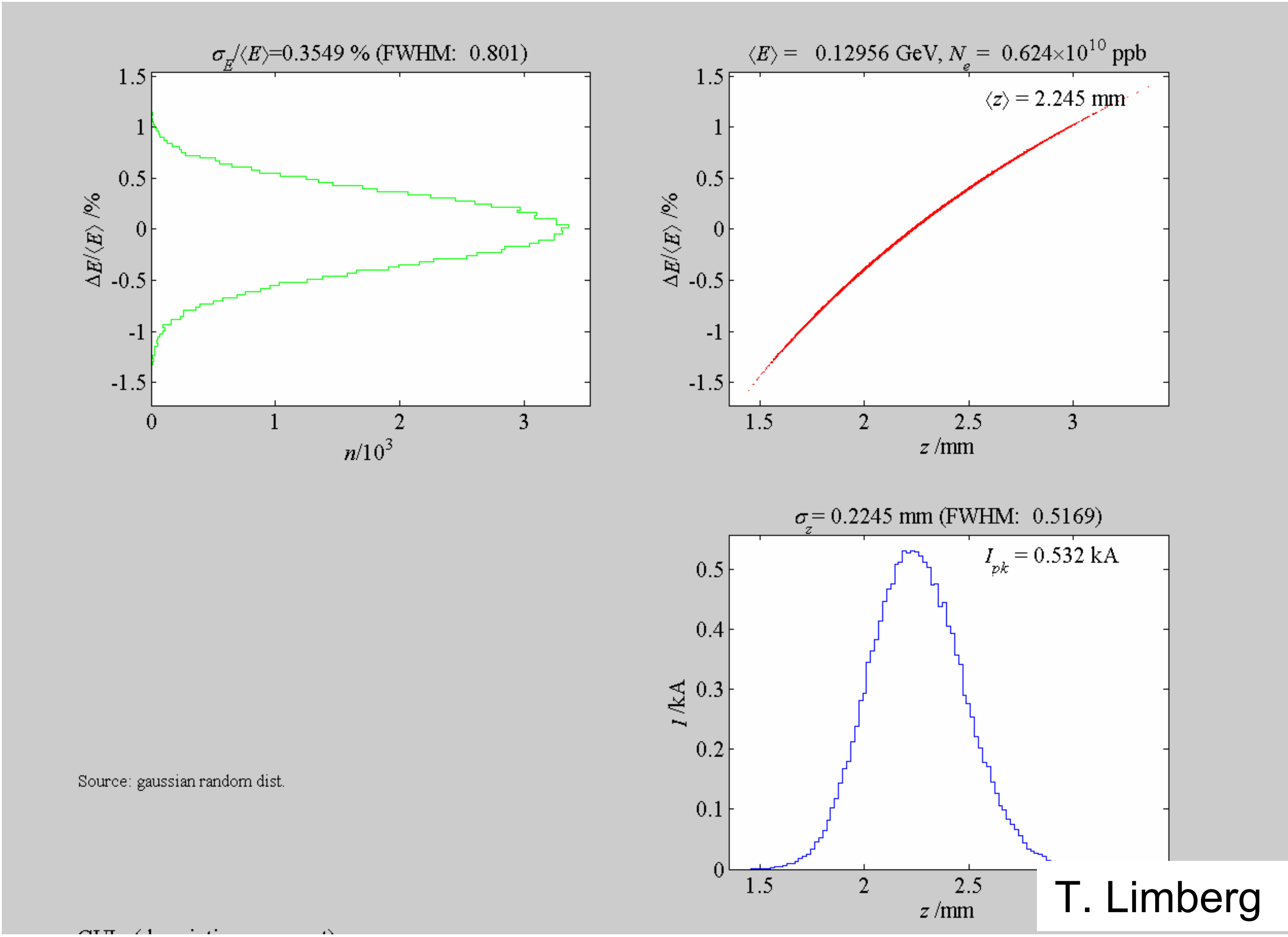
Longitudinal Phase Space @ End ACC1



T. Limberg

CSR microbunch instability studies

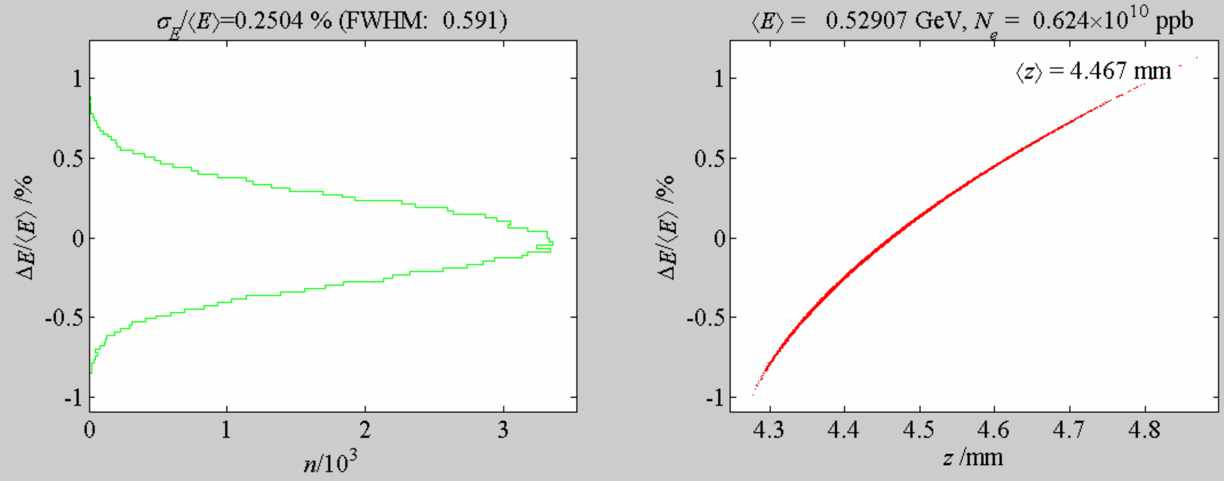
Longitudinal Phase Space @ End BC2



T. Limberg

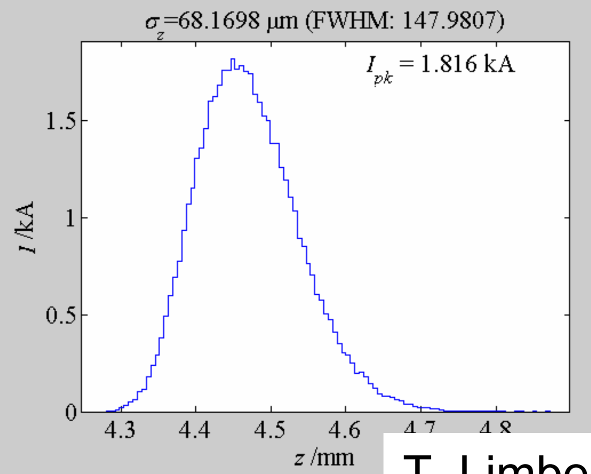
CSR microbunch instability studies

Longitudinal Phase Space @ LOLA



1.8kA in BC3 with a linear energy chirp lead to a strong microbunch instability gain

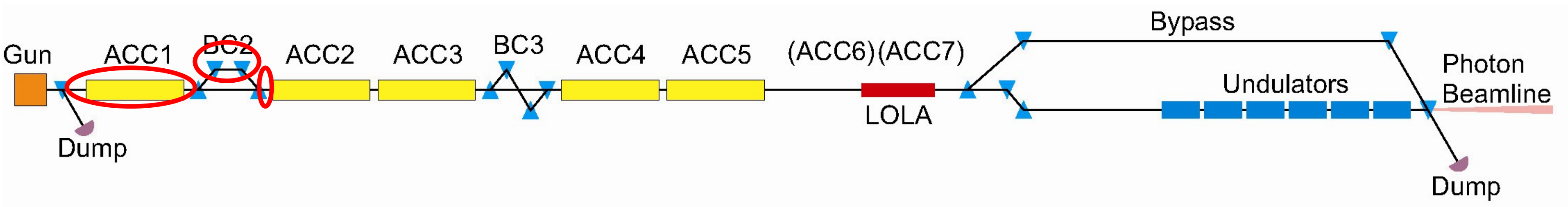
Corresponding slice emittance growth should be observable at LOLA



T. Limberg

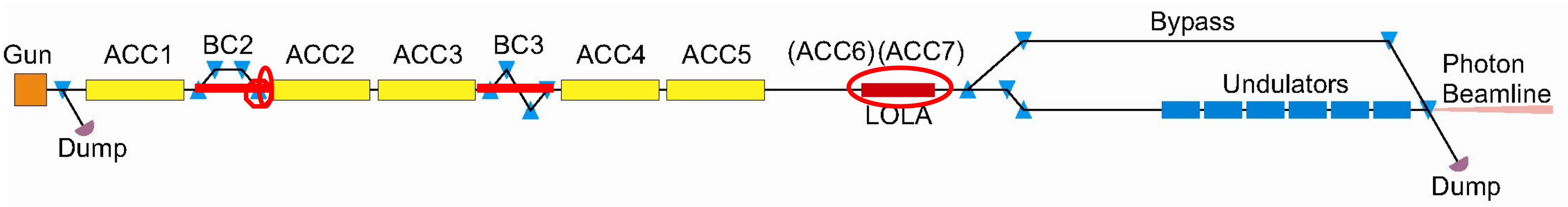
Experiments at FLASH

- Modifications of the ACC1.C1 phase offset and the phase offset between ACC1.C1-C4 (up to about 100deg) and ACC1.C5-C8 (up to about 90deg) (Huening)
- Indirect measurements of compression using the energy spread in BC2 with ACC1.C5-C8 off-crest
- Pyro detector compression measurements ot the DBC2 diffraction radiator or TOSYLAB



Experiments at FLASH

- Measurements of bunch length vs. ACC1.C1 phase with the streak camera at TOSYLAB using synchrotron radiation from BC2 (Grimm)
- Setup of beam transport to LOLA with chicanes off
- Measurements of the emittance in DBC2 FODO section
- Bunch length measurements at LOLA
- CSR microbunch instability studies



Experiments at FLASH

Requirements:

- For the measurements of emittance the BC2 dipoles should be switched off to prevent further compression and CSR effects
- Streak camera measurements require the minimisation of the correlated energy spread to avoid additional compression in BC2
- Bunch length measurements with LOLA require transport with proper optics to LOLA while the bunch compressors are switched off (lower total energy and different phase advance)

Summary and Outlook

- Velocity bunching operation is possible at FLASH
- Compression process is analysed with ASTRA and an semi-analytic model
- Beam time is requested for measurements

Next Steps:

- further preparations of Measurements (setup of streak camera, RF-manipulations etc.)
- Detailed simulations on CSR microbunch instability studies
- Measurements
- Testing and optimising of different VB setups (ACC1 gradients and phase offsets)
- Development of an optimised compression scheme for FLASH and XFEL including VB

Thank You