Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Proton Bunch Compression

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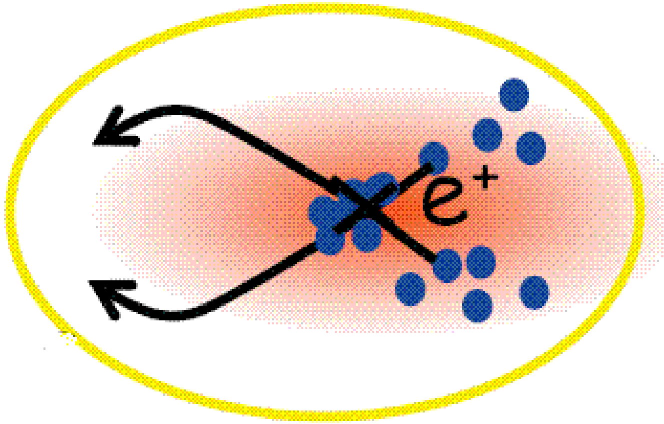
Outline

- Motivation
- Bunch compression
- Magnetic bunch compression
- Low alpha ring
- Plasma self-modulation
- Conclusion

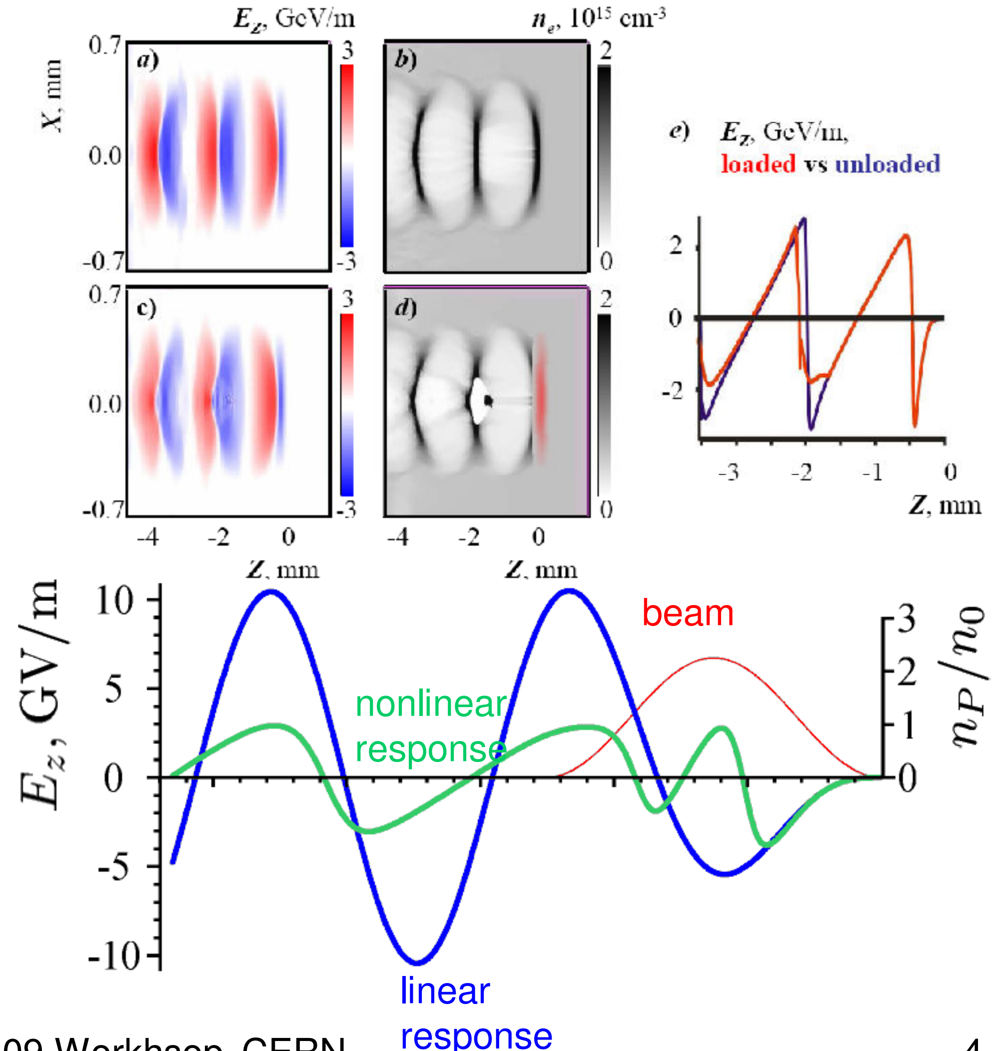
Motivation

- Short proton bunches are required in many future projects, such as neutrino factories, muon colliders, spallation neutron sources, high energy proton colliders, etc.
- Plasma wakefield acceleration (PWFA) also asks for short drivers. Linear theory of PWFA indicates that the wakefield amplitude scales inveresly as the bunch length squared.
- For the proton driven plasma wakefield acceleration (PDPWA), the plasma electrons flow in the vicinity of proton drivers and therefore enhance the local plasma density, shorter bunch length is thus required to match the optimum condition
- However, current proton synchrotrons run the p beam in bunch length of tens of centimetres, to get hundreds of microns, the compression ratio is over 1000, it seems difficult to be realized by only one stage of compression

Positively-charged particle drivers



e+ driver



Existing proton machines

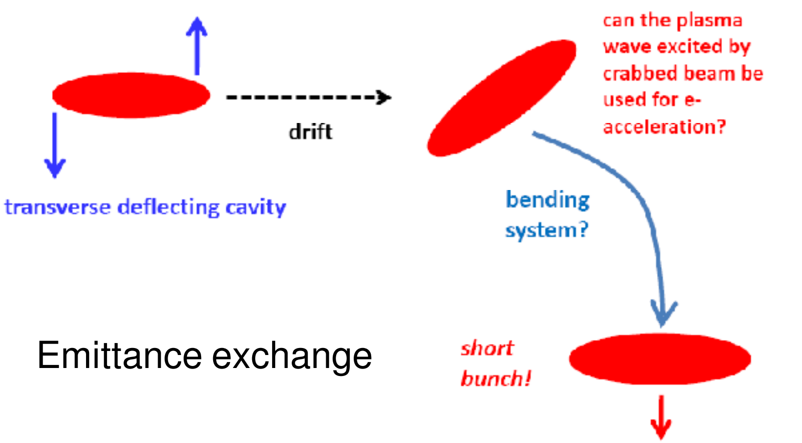
	HERA	TEVATRON	LHC
Circumference [km]	6.336	6.28	26.659
Maximum energy [TeV]	0.92	0.98	7.0
Energy spread [10^{-3}]	0.2	0.14	0.113
Bunch length [cm]	8.5	50	7.55
Transverse emittance [10^{-9} π m rad]	5	3	0.5
Particles per bunch [10^{10}]	7	26	11.5

Bunch compression*

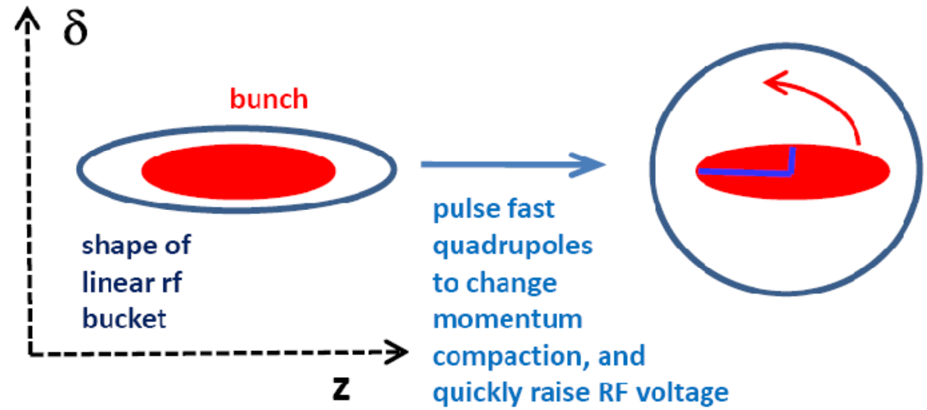
- Emittance exchange technique, exchange the horizontal emittance to longitudinal emittance, and vice versa
- Fast quads tunning for low momentum compaction factor before extraction from the ring
- Fast nanochoppers to get microbeam?
- Masks as suggested by Patric?
- Magnetic bunch compression
- Plasma wakefield self modulate the long beam

* F.Zimmermann et al., Generation of short proton bunches in the CERN accelerator complex, Proceedings of PAC09.

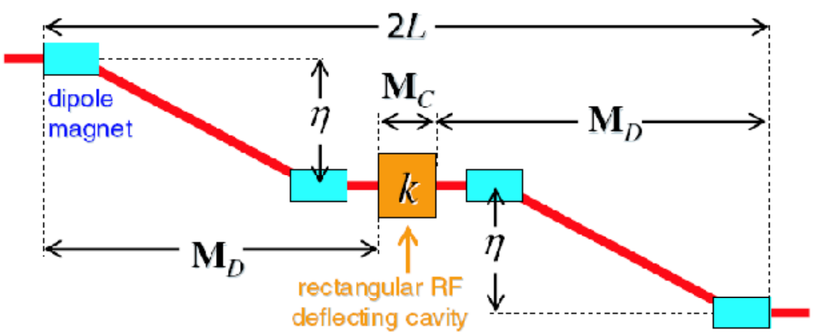
Bunch compression



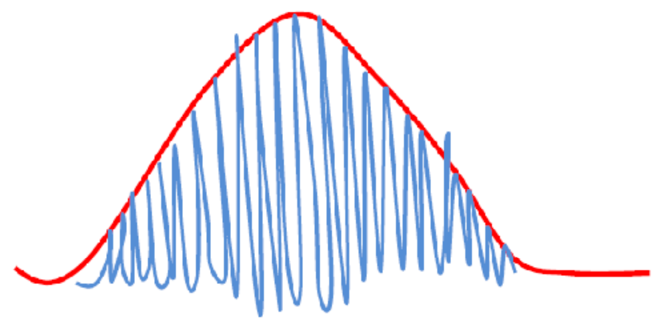
Emittance exchange



Schematics of fast bunch rotation in storage ring



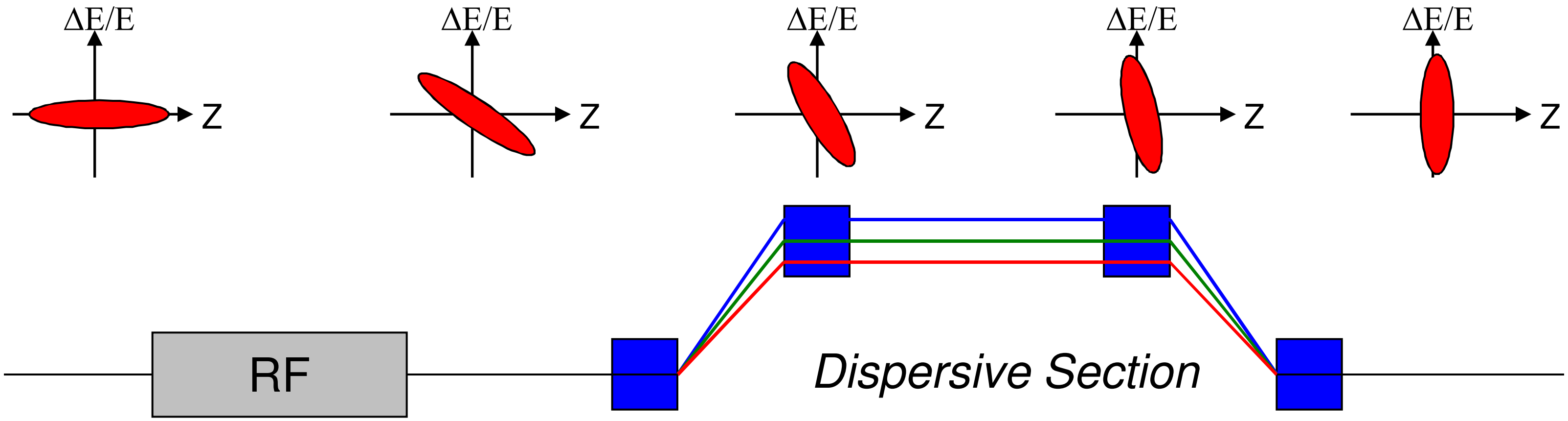
F.Zimmermann et al., Generation of short proton bunches in the CERN accelerator complex, Proceedings of PAC09.



Nanochopper gets the microbunch

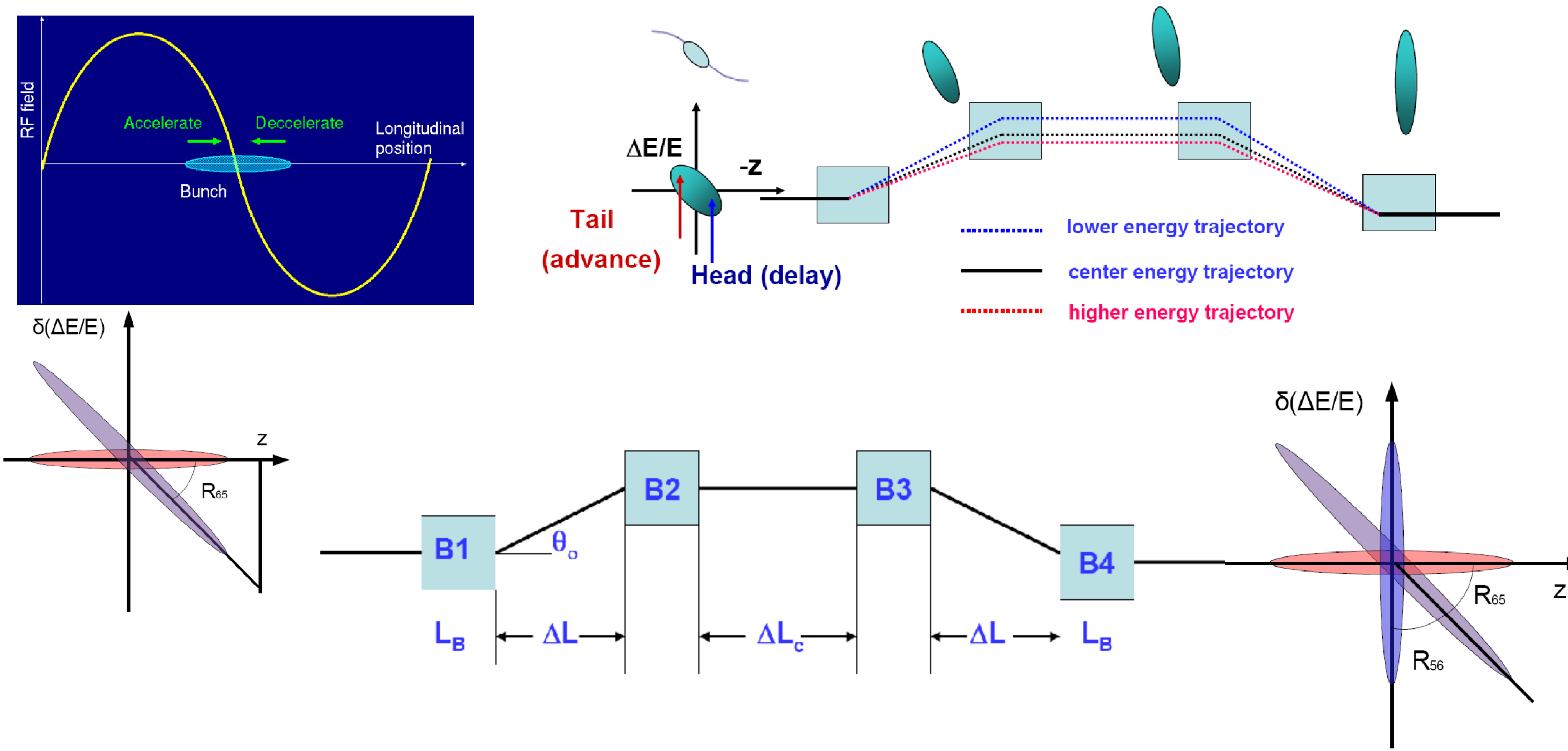
Magnetic bunch compression

- Magnetic bunch compressors are widely used in free electron laser facilities and linear colliders
- RF introduces the energy chirp along the bunch (energy modulation)
- Dipole magnets produces the dispersive path for path modulation
- The head and the tail of the bunch converge together and the short bunch is therefore produced.



Magnetic compression

- Magnetic compression principle



Magnetic compression

- Beam transport matrix

$$\begin{pmatrix} x(s) \\ x'(s) \\ y(s) \\ y'(s) \\ z(s) \\ \delta(s) \end{pmatrix} = \begin{pmatrix} R_{11} & R_{12} & R_{13} & R_{14} & R_{15} & R_{16} \\ R_{21} & R_{22} & R_{23} & R_{24} & R_{25} & R_{26} \\ R_{31} & R_{32} & R_{33} & R_{34} & R_{35} & R_{36} \\ R_{41} & R_{42} & R_{43} & R_{44} & R_{45} & R_{46} \\ R_{51} & R_{52} & R_{53} & R_{54} & R_{55} & R_{56} \\ R_{61} & R_{62} & R_{63} & R_{64} & R_{65} & R_{66} \end{pmatrix} \begin{pmatrix} x(0) \\ x'(0) \\ y(0) \\ y'(0) \\ z(0) \\ \delta(0) \end{pmatrix}$$

- Without coupling

$$\begin{pmatrix} z(s) \\ \delta(s) \end{pmatrix} = \begin{pmatrix} R_{55} & R_{56} \\ R_{65} & R_{66} \end{pmatrix} \begin{pmatrix} z(0) \\ \delta(0) \end{pmatrix}$$

Magnetic compression

- Drift space

$$\begin{pmatrix} z(s) \\ \delta(s) \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} z(0) \\ \delta(0) \end{pmatrix}$$

- Energy modulation

$$\begin{pmatrix} z(s_1) \\ \delta(s_1) \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ R_{65} & 1 \end{pmatrix} \begin{pmatrix} z(0) \\ \delta(0) \end{pmatrix}$$

- Dispersive area

$$\begin{pmatrix} z(s) \\ \delta(s) \end{pmatrix} = \begin{pmatrix} 1 & R_{56} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} z(0) \\ \delta(0) \end{pmatrix}$$

Magnetic compression

- If the beam is zero-crossing

$$R_{65} = \frac{\delta}{z} = \frac{1}{z}\frac{\Delta E}{E} = \frac{eV_0}{E}\frac{\omega}{\beta c}$$

- The total matrix for magnetic compression

$$\begin{pmatrix} z(s_2) \\ \delta(s_2) \end{pmatrix} = \begin{pmatrix} 1 & R_{56} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ R_{65} & 1 \end{pmatrix} = \begin{pmatrix} 1 + R_{56}R_{65} & R_{56} \\ R_{65} & 1 \end{pmatrix} \begin{pmatrix} z(s_0) \\ \delta(s_0) \end{pmatrix}$$

- Therefore, if $1 + R_{56}R_{65} = 0$ is satisfied, the bunch length is minimum.
- The final bunch length is

$$z_2 = R_{56}\delta_0$$

RF requirements

- Linear theory of magnetic compression indicates that the length of RF scales inversely with the RF frequency, given the limited space in the extraction regions of PS and SPS, high frequency RF is preferable.
- Current RF could be used: 201 MHz RF, 704.4 MHz RF, 11.4 GHz RF.
- Considering the bunch spacing 25 ns, harmonic cavity of frequency of 720 MHz is also investigated

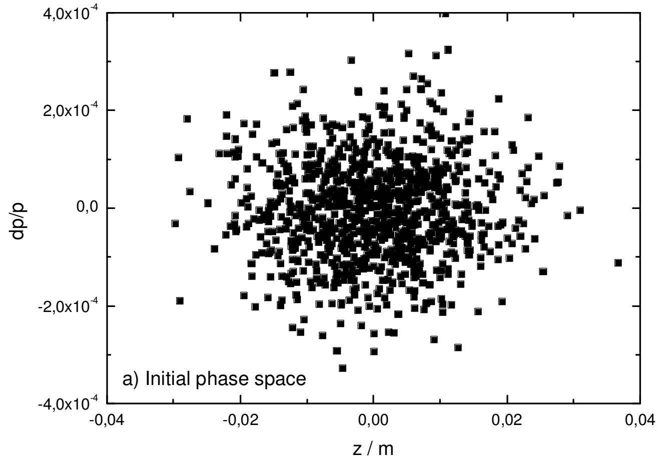
Bunch compression

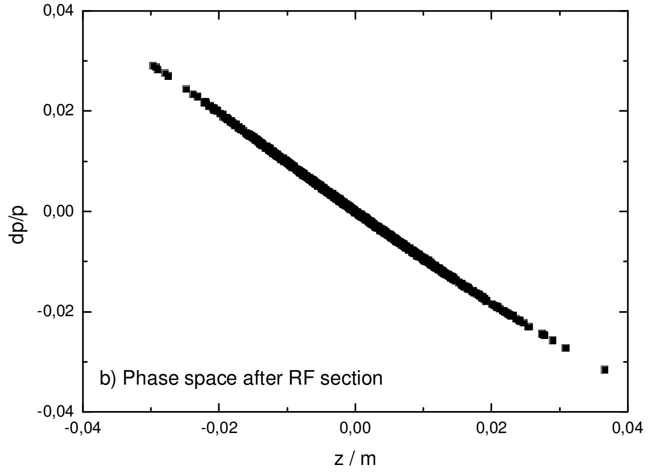
- 1 TeV beam compression
- PS beam compression
- SPS beam compression

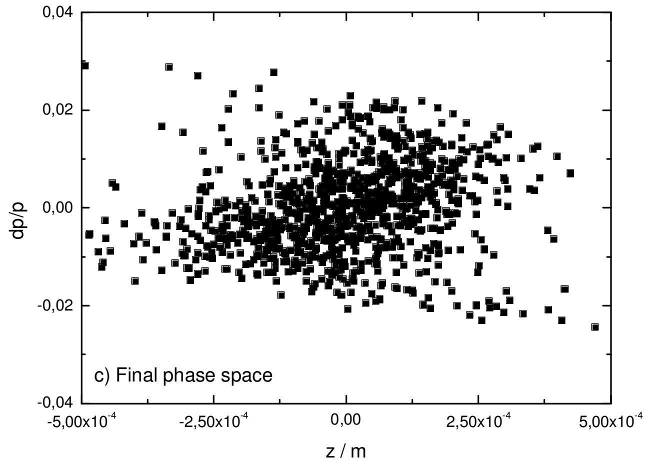
1 TeV beam compression

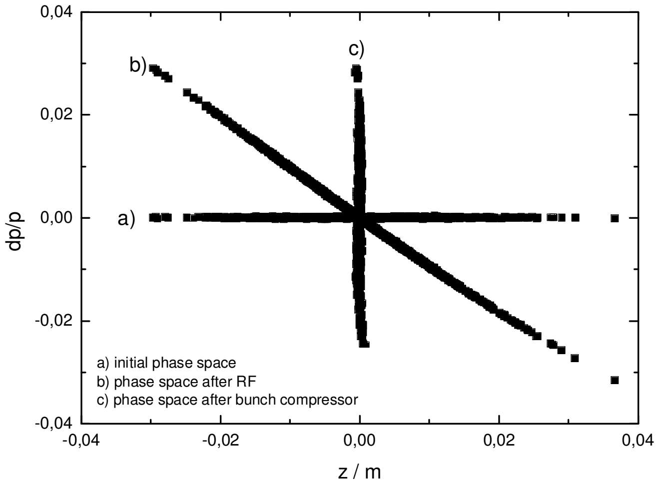
Bunch charge	10^{11}
Proton energy [TeV]	1
Initial energy spread [%]	0.01
Initial bunch length [cm]	1.0
Final bunch length [μm]	164
RF frequency [MHz]	704.4
Average gradient of RF [MV/m]	25
Required RF voltage [MV]	6.5×10^{4}
Length of RF section [km]	3.6
RF phase [degree]	-102
Compression ratio	~60
Momentum compaction (MC) [m]	-1.0
Second order of MC [m]	1.5
Bending angle of dipole [rad.]	0.05
Length of dipole [m]	14.3
Drift space between dipoles [m]	190.6
Total BC length [m]	4131
Final beam energy [GeV]	986.5
Final energy spread [%]	0.93

1 TeV beam compression

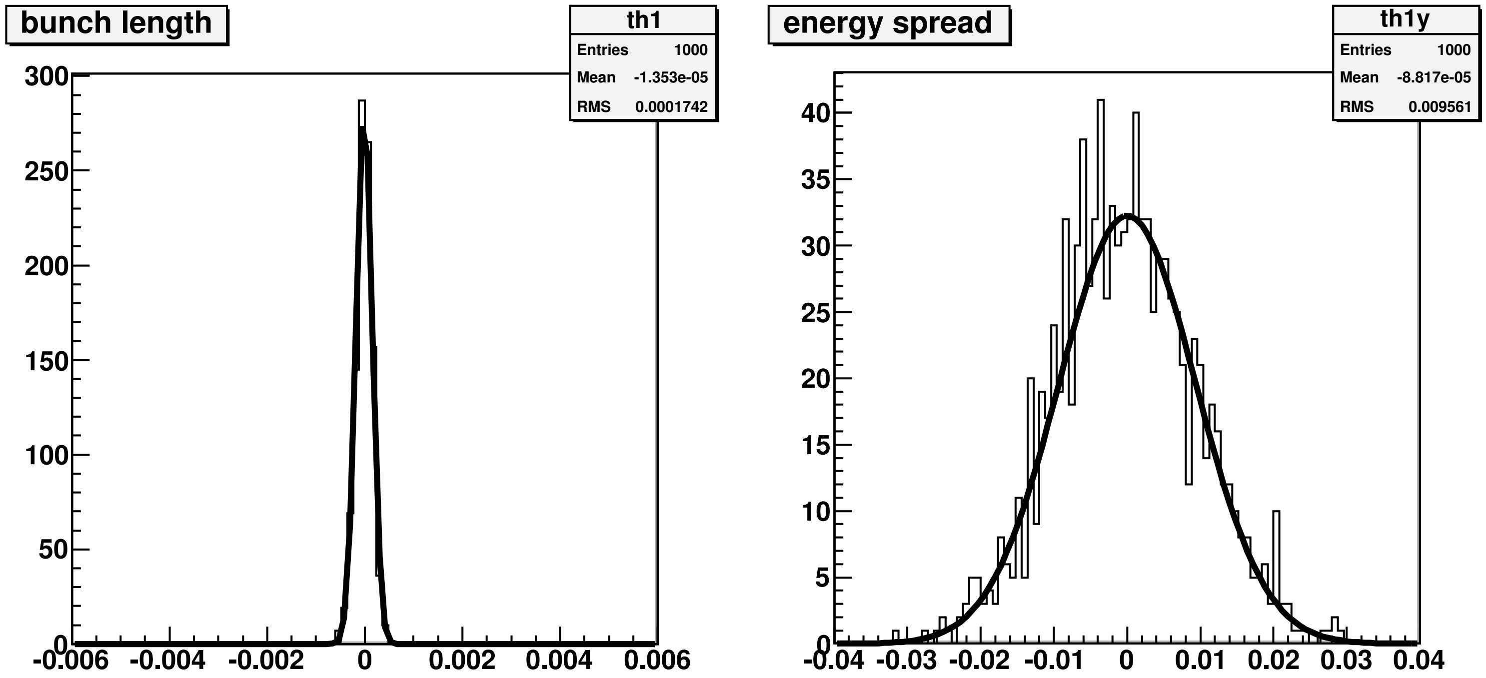








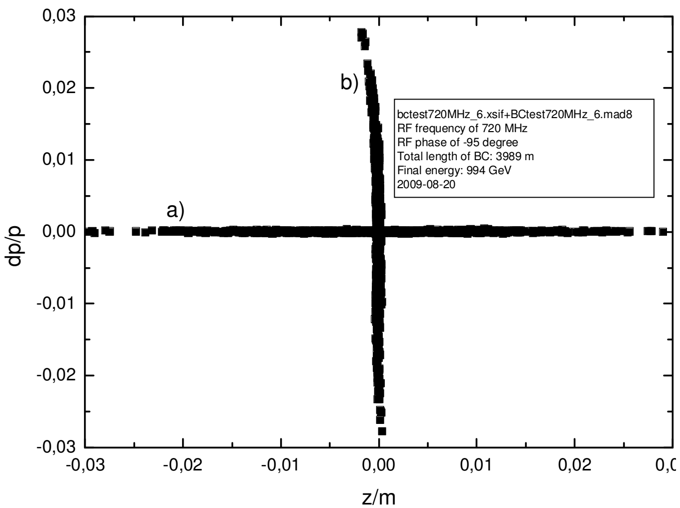
1 TeV beam compression



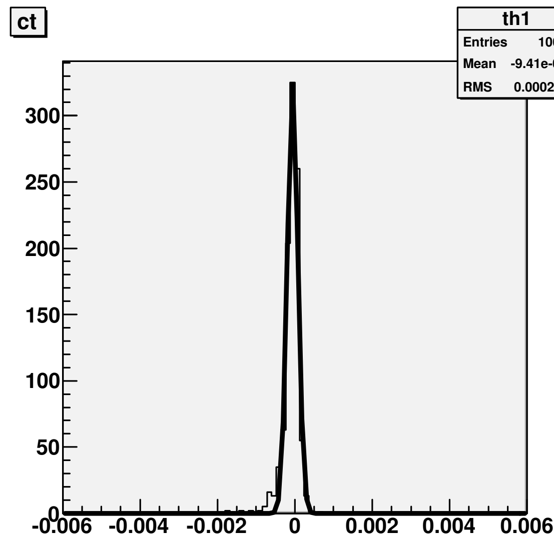
Bunch length and the energy spread after bunch compression.

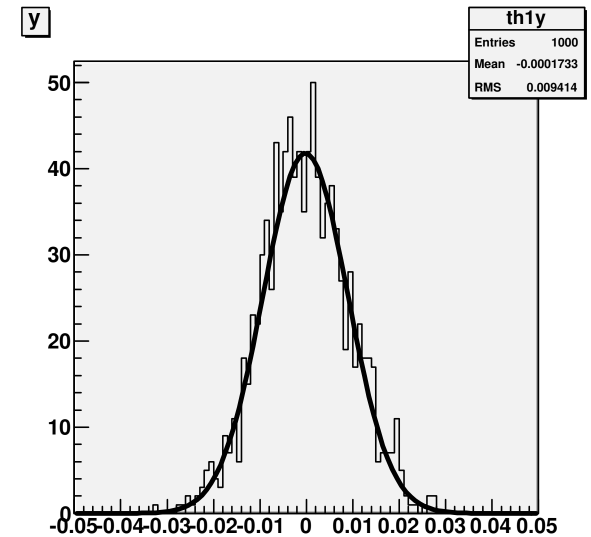
Results show one sigma bunch length of 164 µm and the relative energy spread of 9.3e-3.

1 TeV beam compression



a) initial phase space and b) phase space after bunch compression (720 MHz RF).

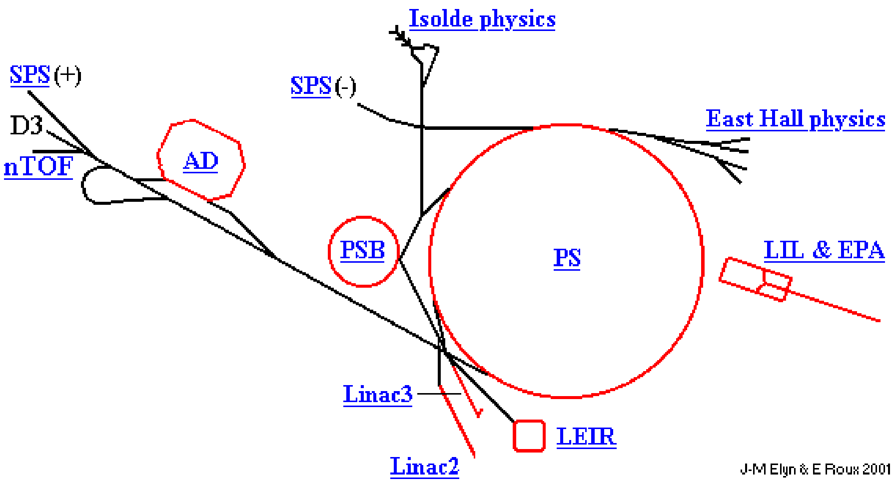




Bunch length & energy spread after the bunch compressor; (720 MHz RF).

The fitting data of bunch length (one sigma) is around 130 microns and the corresponding energy spread is about 9.1e-3

PS beam as a driver



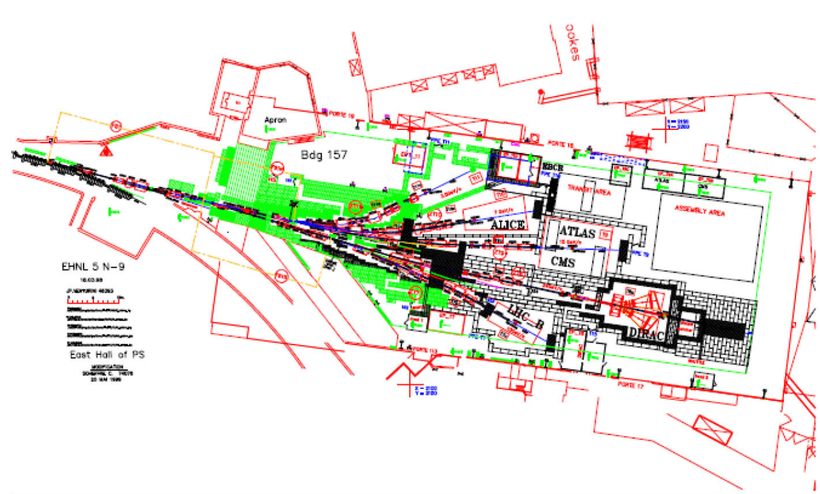
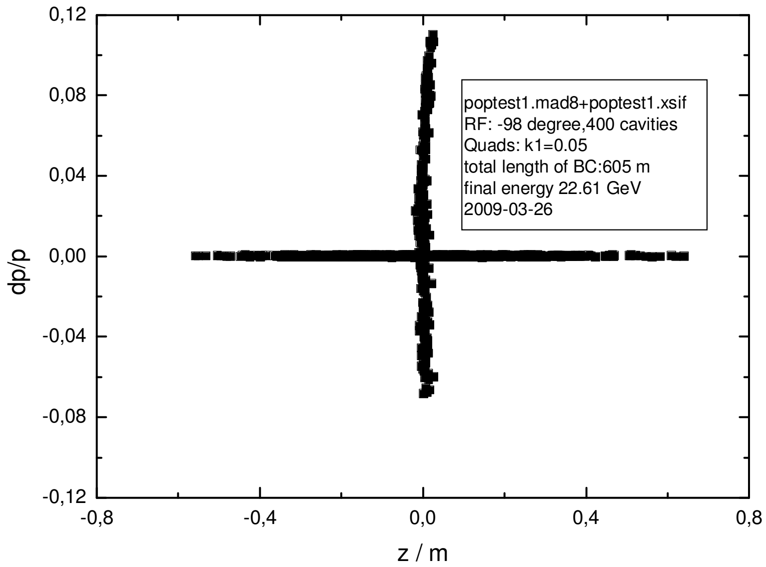


Figure: Beam lines in the PS East Hall. T7 and T8 are near the bottom. The maximum length is below 100 m.

PS beam extraction lines at East Hall

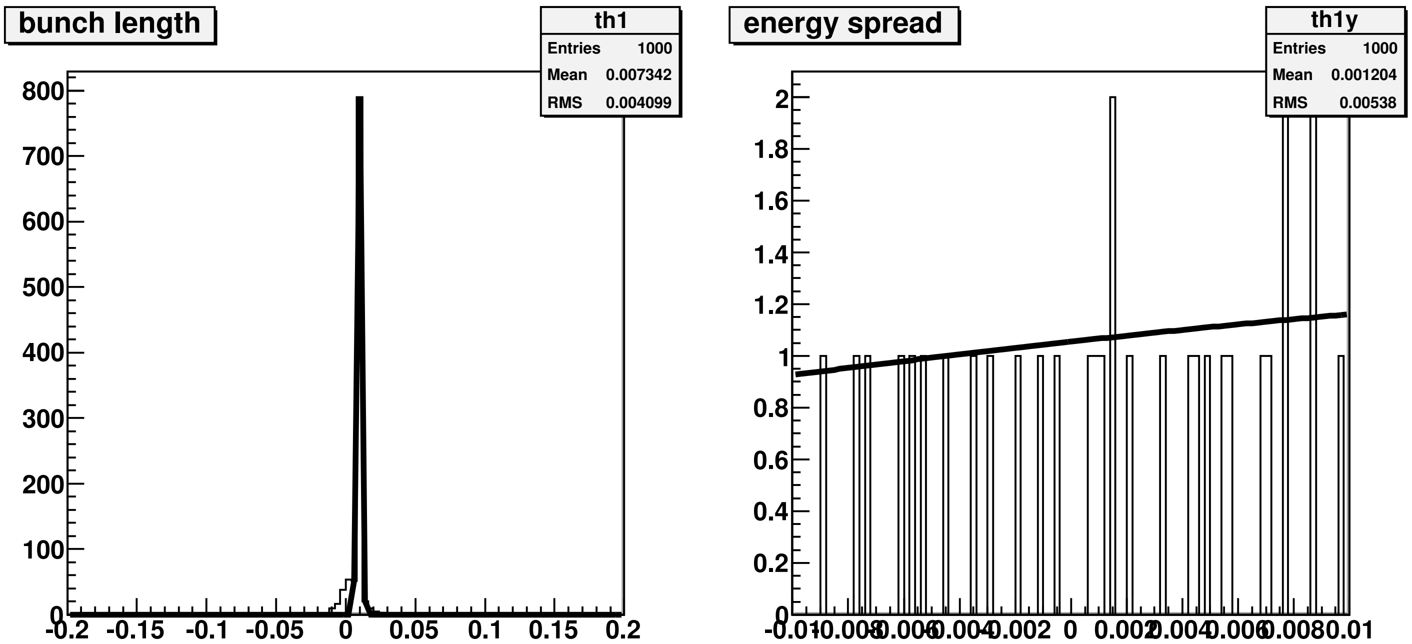
PS beam compression

PS beam parameters	
Momentum [GeV/c]	24
Protons/bunch [10^{11}]	1.3
rms longitudinal emittance [eVs]	0.03
rms bunch length [cm]	20
Relative rms energy spread [10^{-4}]	5
rms transverse emittance [mm]	3.0
Bunch spacing [ns]	25
# bunches / cycle	72
Cycle time [s]	3.6



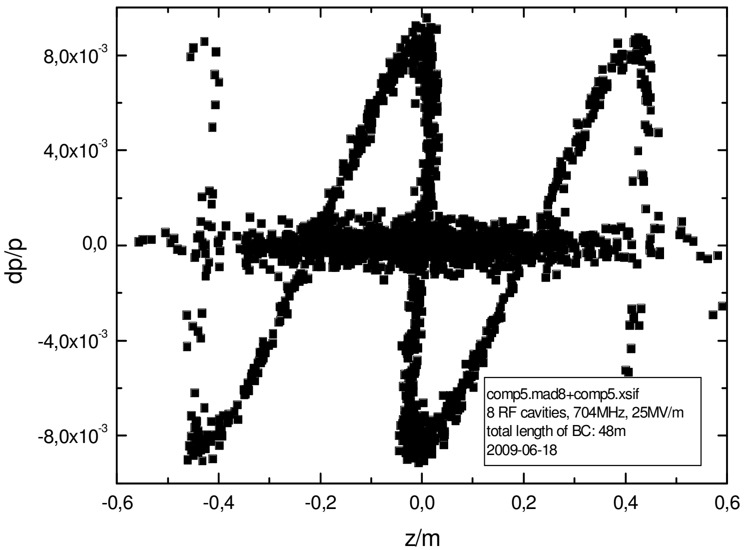
Magnetic bunch compressor (RF: 201 MHz).

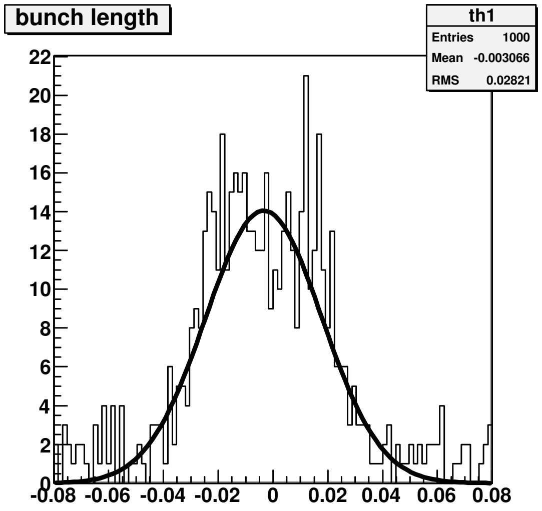
PS beam compression

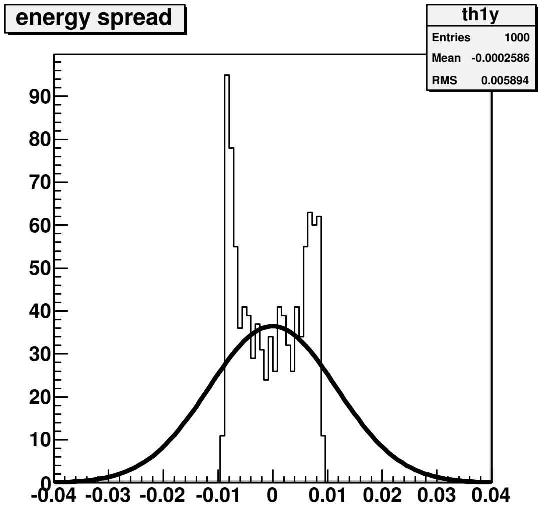


Bunch length and energy spread after the magnetic compression (RF: 201 MHz).
Fitting data show that the bunch length is 1.58 mm and energy spread is 5.39e-3.

PS beam compression







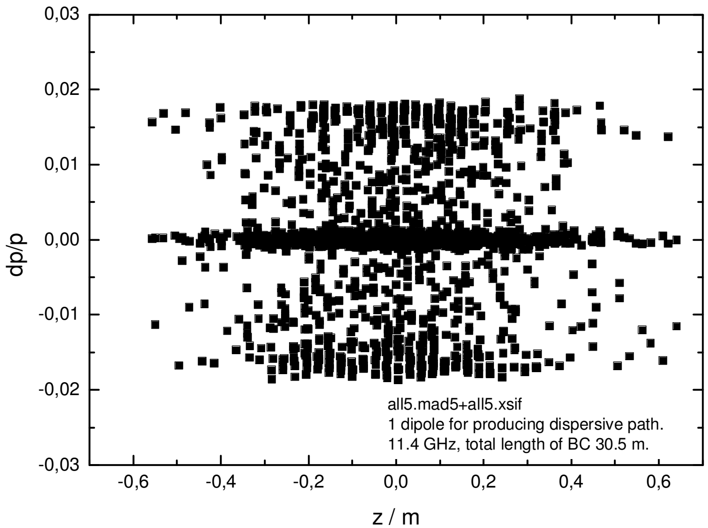
Phase space of the PS beam before and after the magnetic compression

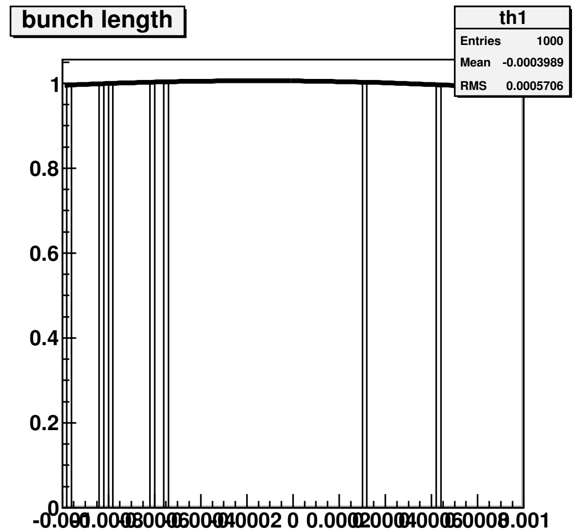
(RF: 704 MHz)

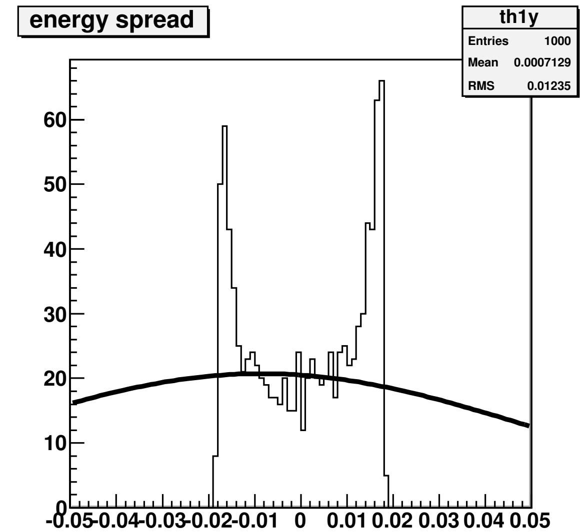
Bunch length & energy spread after the magnetic compression.

Fitting data show that the bunch length is 2.1 cm and energy spread is 6.6e-3.

PS beam compression







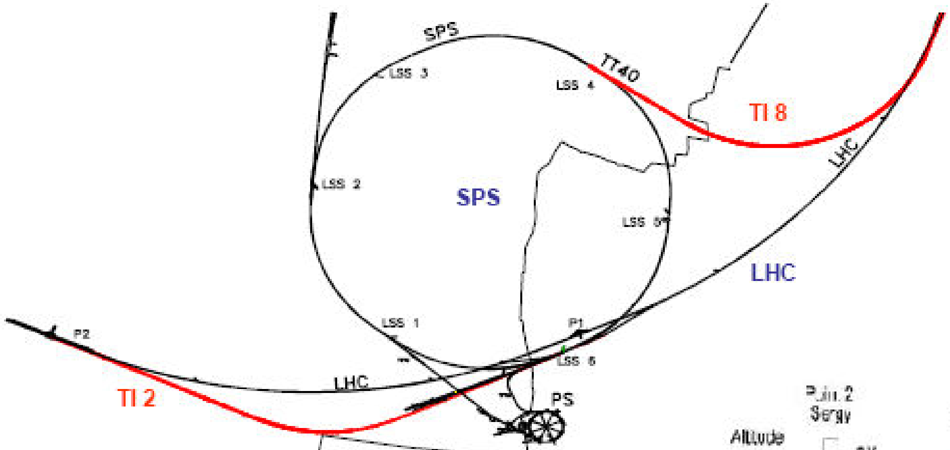
phase space of the PS beam before and after the magnetic compression

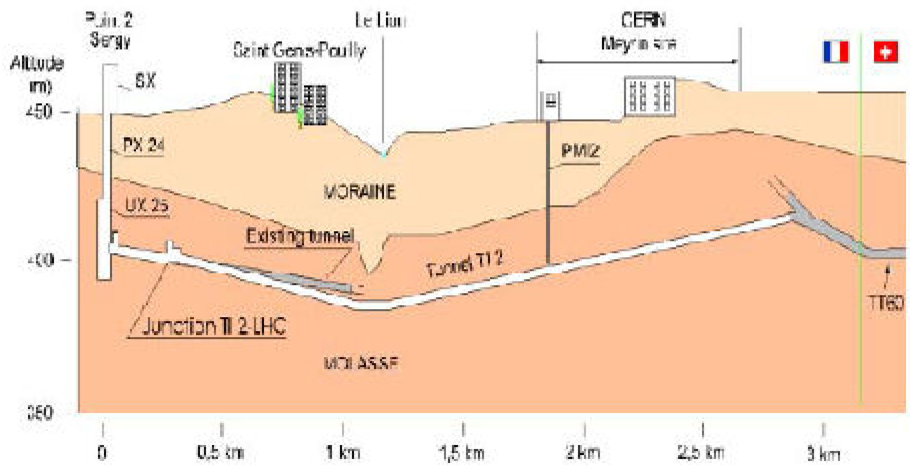
(RF: 11.4 GHz)

Bunch length & energy spread after the magnetic compression.

The fitting data shows that the bunch length of 200 micron and the energy spread is 5.8e-2.

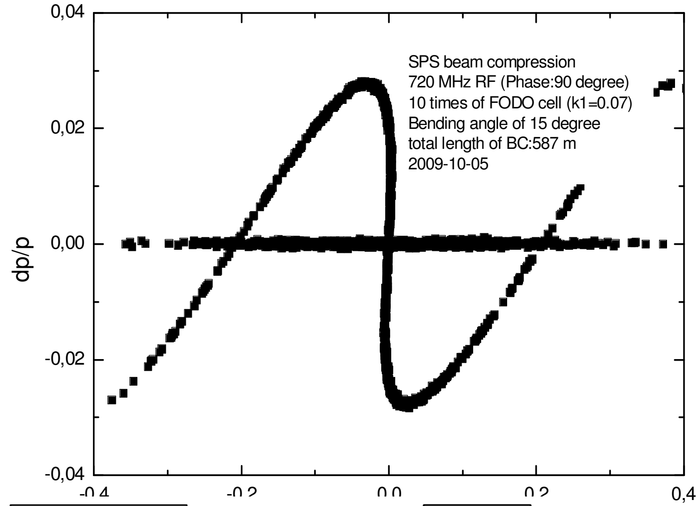
SPS beam as a driver

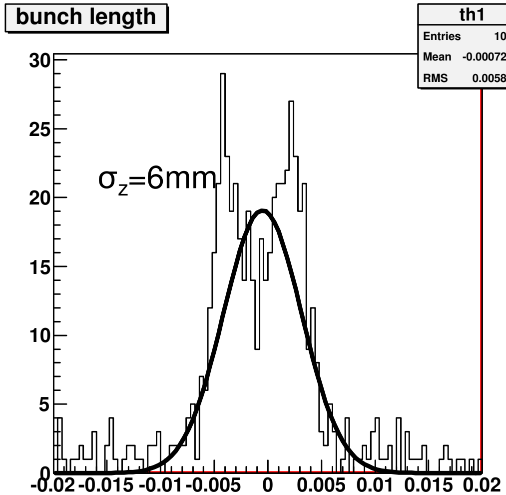


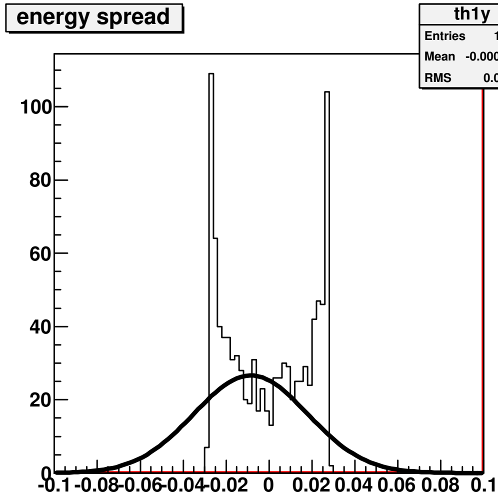


SPS beam compression

Super Proton Synchrotron-SPS	
Momentum [GeV/c]	450
Maximum protons/bunch [10^{11}]	1.15
rms bunch length [cm]	12
Relative rms energy spread [10^{-4}]	2.8
rms transverse emittance [μm]	3.5
Bunch spacing [ns]	25

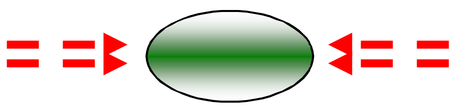






Bunch length (low current)

The equilibrium bunch length is due to the quantum nature of the emission of synchrotron radiation and is the result of the competition between quantum excitation and radiation damping. If high current effects are negligible the bunch length is



$$\sigma_z = \frac{\alpha\, c}{2\pi\, f_s}\sigma_\varepsilon \propto \sqrt{\frac{\alpha\,\gamma^3}{d\,V_{RF}/dz}}$$

We can modify the optics to reduce α

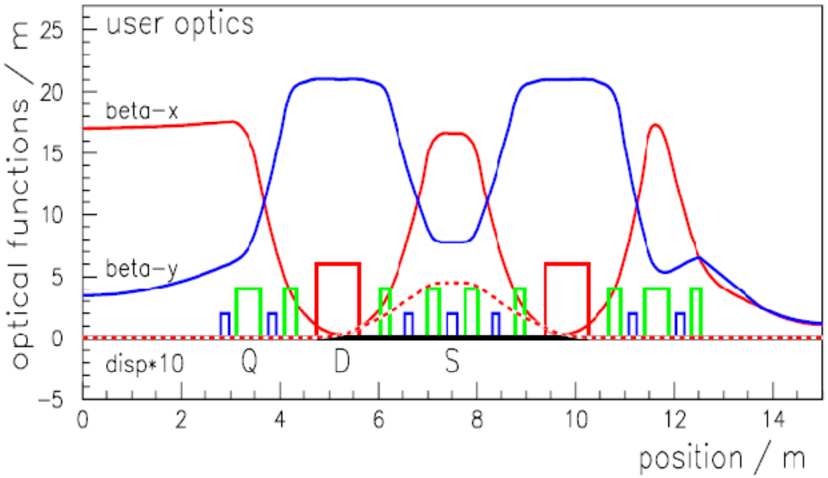
$$\alpha = \frac{1}{L}\oint\frac{D_x}{\rho}ds \approx 10^{-6}$$

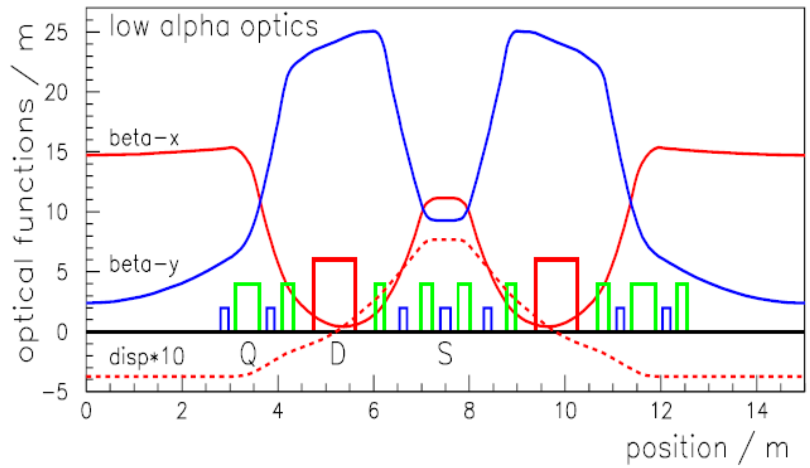
α (low_alpha_optics) $\approx$ α (nominal) /100 ➔ **σ_z (low alpha optics) $\approx$ σ_z(nominal)/10**

$$\frac{\sigma_{zf}}{\sigma_{zi}} \propto \sqrt{\frac{(dV_{RF}/dz)_i\,\alpha_f}{(dV_{RF}/dz)_f\,\alpha_i}}$$

Bessy-II, ANKA, ELETTRA and SPEAR3 have successfully demonstrated low-alpha operation with few ps bunches for Coherent THz radiation or short X-ray pulses

Low alpha optics: BESSY-II





$\alpha = 7 \cdot 10^{-4} \rightarrow 10^{-6}$

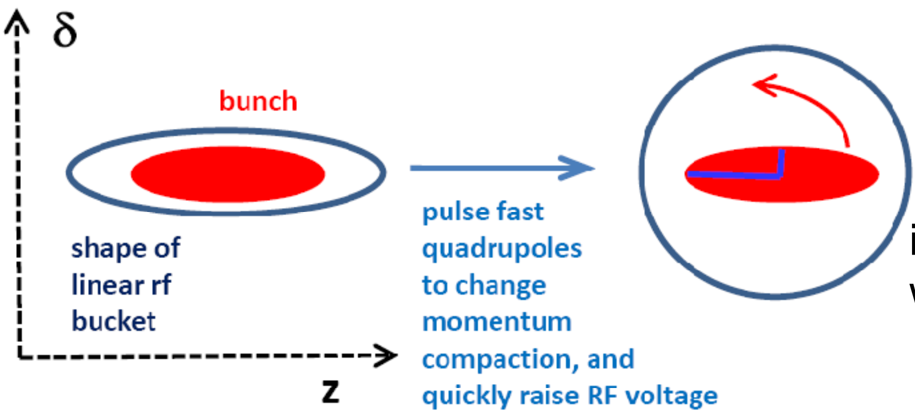
σ_z = 12 ps (rms) $\rightarrow$ 0.7 ps

ε_x = 6 nm $\rightarrow$ 30 nm

When the bunch is too short CSR generates chaotic bursts of THZ radiation

Courtesy: BESSY-II

SPS low-alpha mode?



initial momentum compaction a_c,initial ~ 0.01
we may hope for a_c(new) ~ 10^{-6}

initial RF voltage ~ few MV
we may hope for final RF voltage ~ 10x higher

→ expect compression by factor
2×10^{-2} /Sqrt(10) ~ 0.006 ~ 1/160

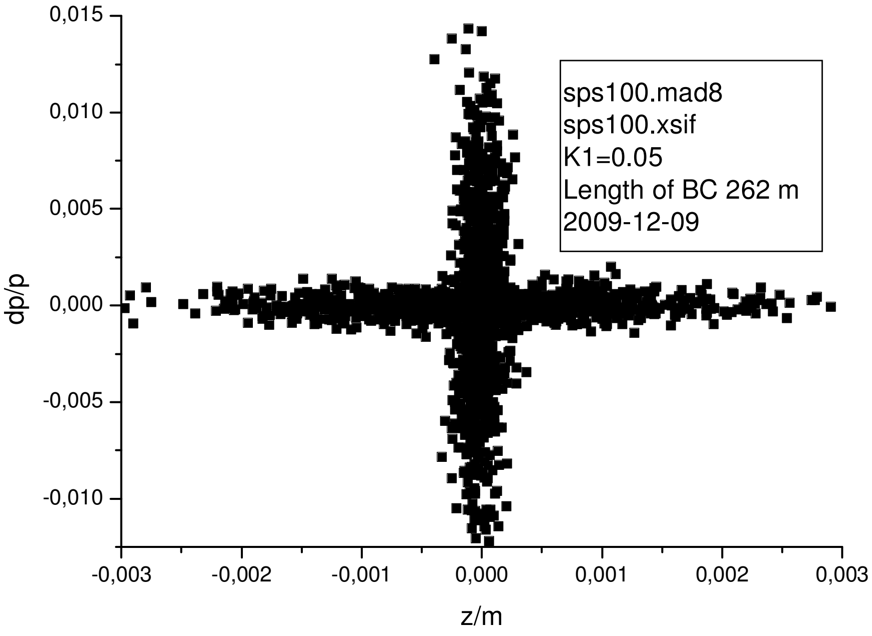
Before extraction of beam, pulse fast quadrupoles to change the momentum compaction factor of the ring, and simultaneously quickly raise the RF voltage

Question: Can momentum compaction factor be changed in SPS lattice by a factor of 100?

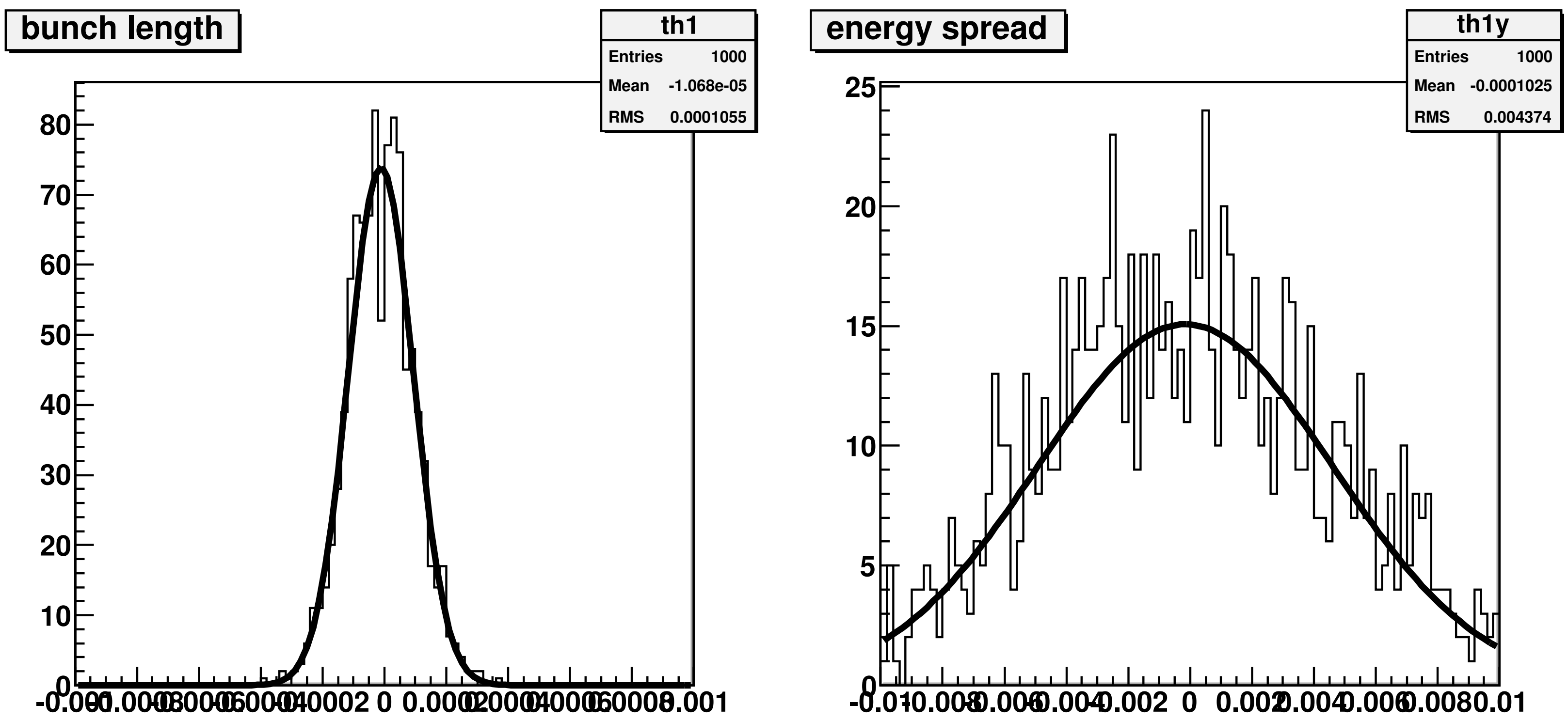
F. Zimmermann, talk at PDPWA08 meeting

SPS beam compression

- If SPS ring can compress the beam by a factor of 100, then X-band RF (11.4 GHz) can be used.
- The initial 1 mm beam can be compressed down to 100 microns within 300 meters

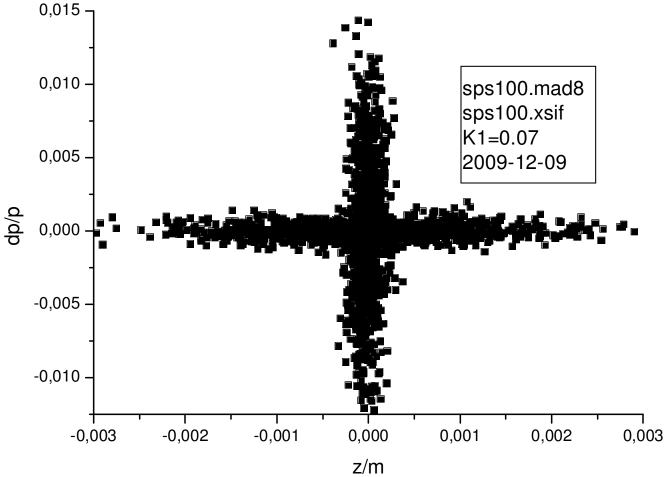


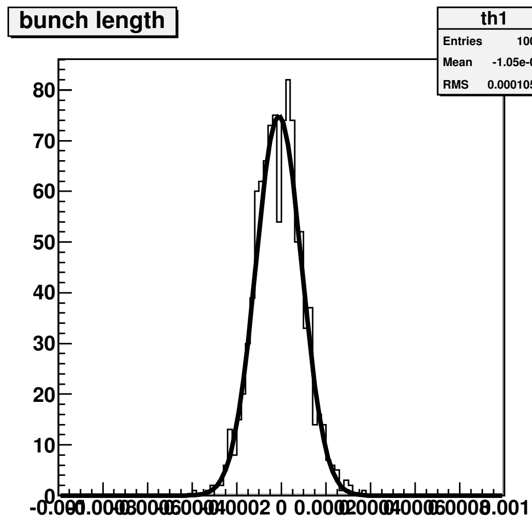
SPS beam compression

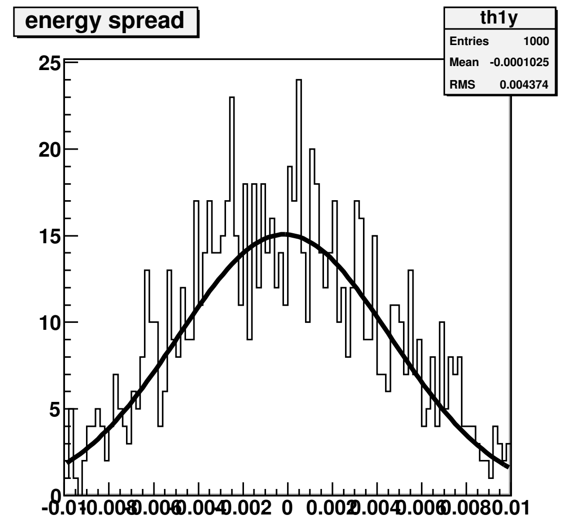


Bunch length and energy spread after the magnetic compression (RF: 11.4 GHz). Fitting data show that the bunch length is 100 μm and energy spread is 4.3e-3.

SPS beam compression



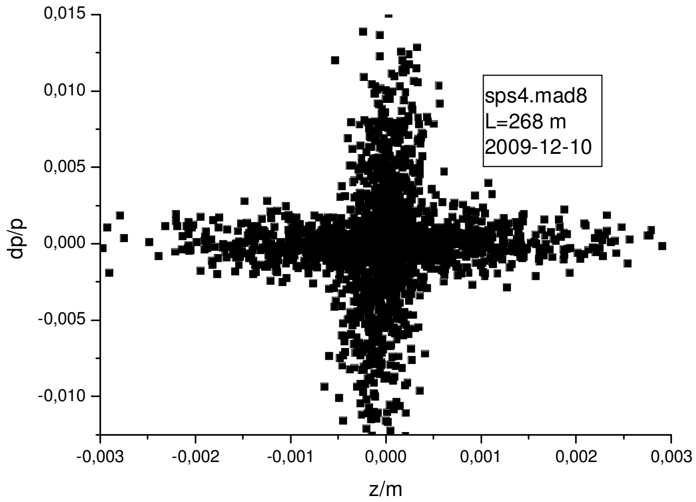


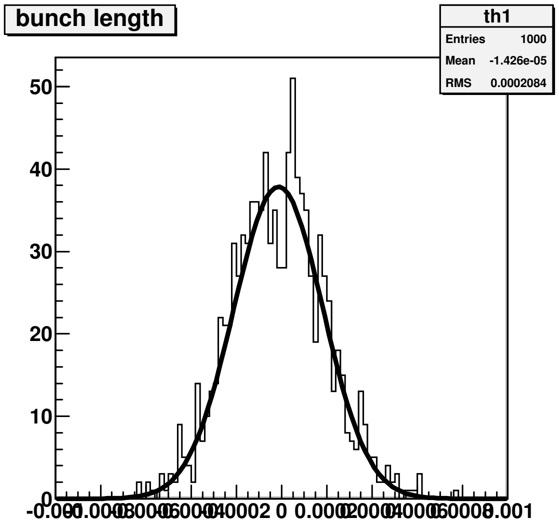


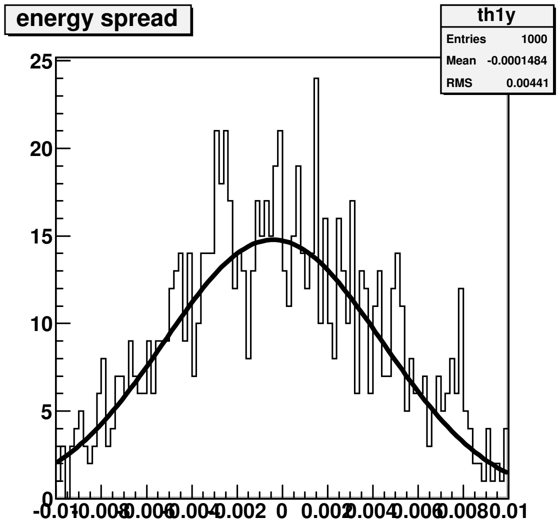
Change the strength of quads a bit

K1=0.07

SPS beam compression



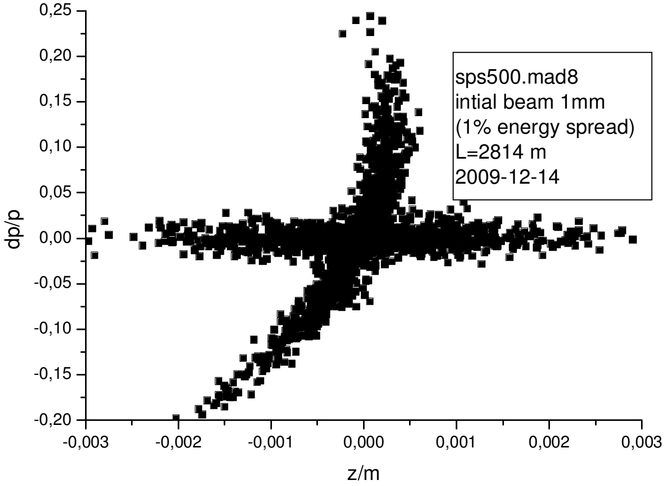


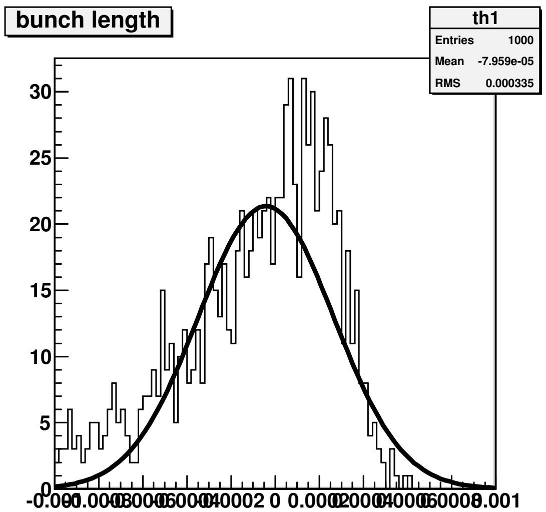


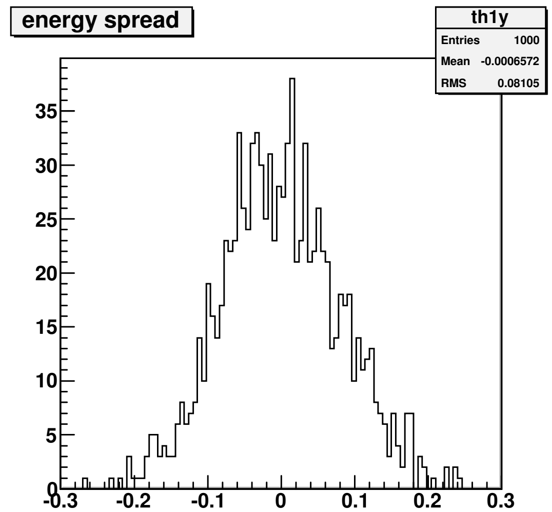
Initial beam energy spread 1e-3

sigma z=190 microns after 270 m compressor

SPS beam compression





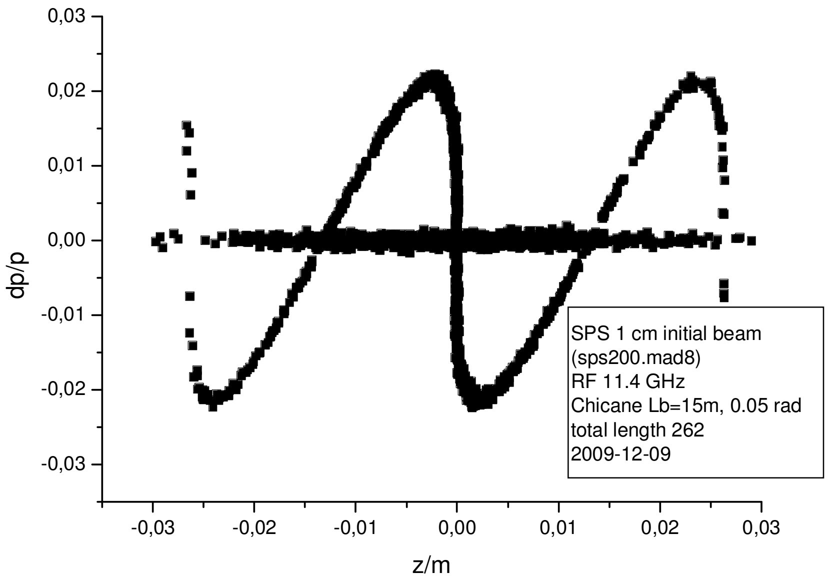


Initial beam 1mm, dp/p=1%

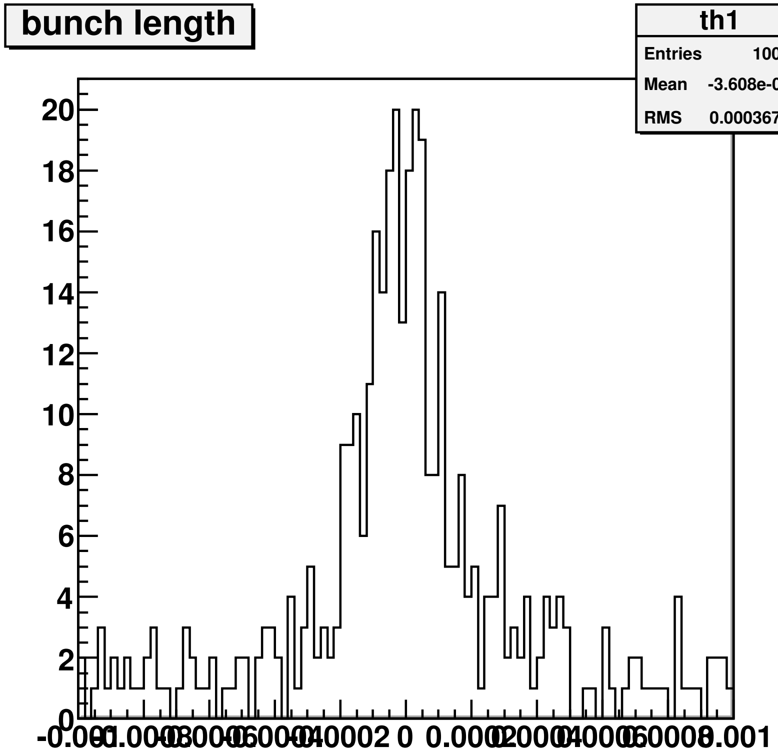
difficult to apply correlated energy along the bunch !

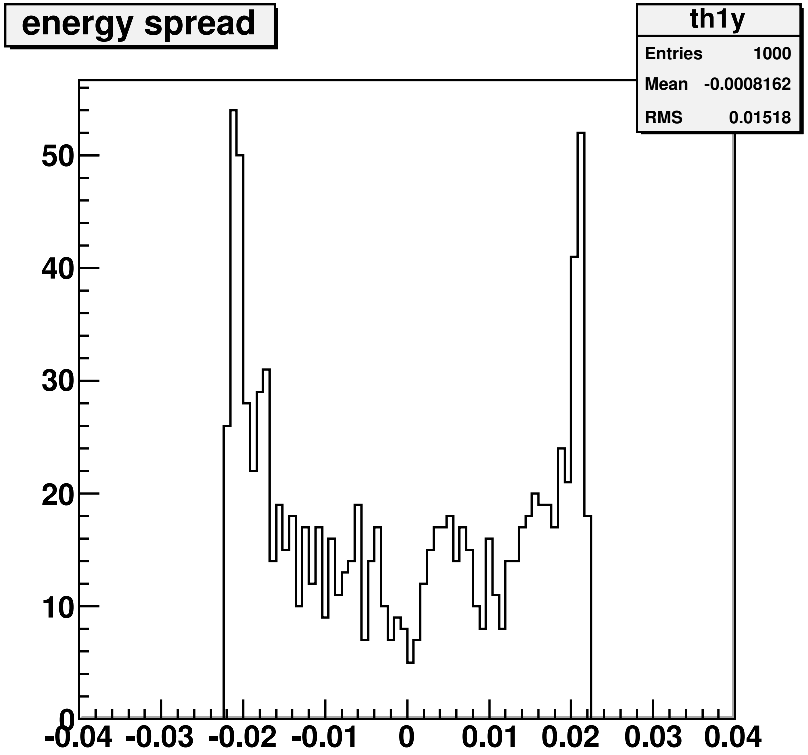
SPS beam compression

- If SPS ring can compress the beam by a factor of 10, then X-band RF (11.4 GHz) can be used.
- The initial 1 cm beam can be compressed down within 300 meters



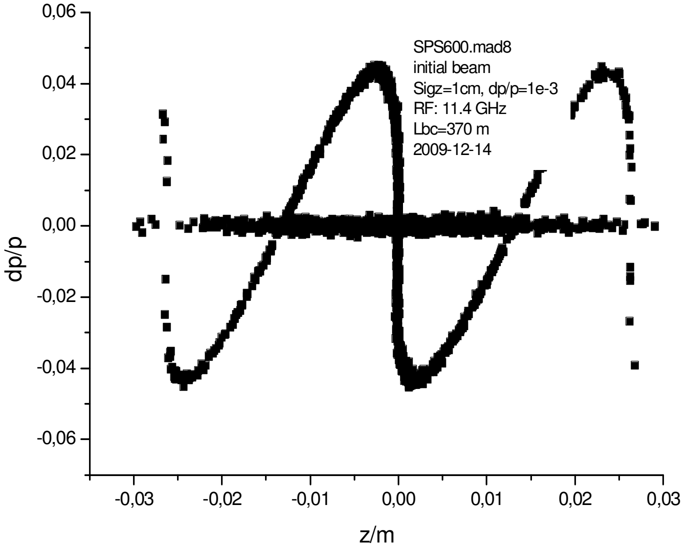
SPS beam compression

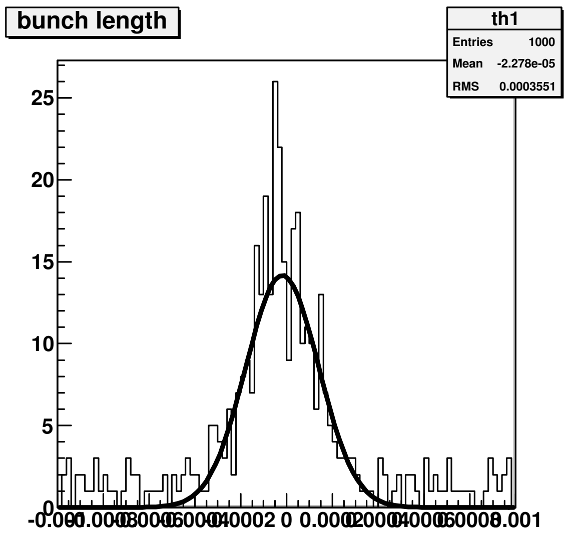


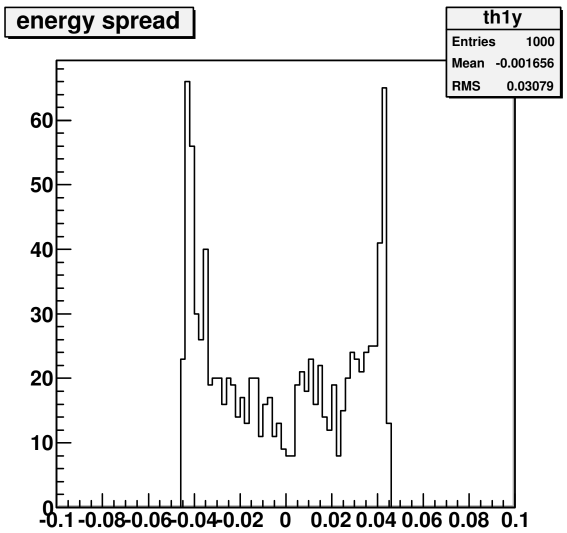


Bunch length & energy spread after the magnetic compression (RF: 11.4 GHz). Fitting data show that the bunch length is 360 μm and energy spread is 1.5e-2.

SPS beam compression







Bunch length & energy spread after the magnetic compression (RF: 11.4 GHz). Fitting data show that the bunch length is 350 μm and energy spread is 3.0e-2.

Plasma self-modulate a long beam

- When the bunch length is much longer than the plasma wavelength, the transverse two-stream (TTS) instability occurs and modulate the beam into small slices *
- The distance between each slice is equal to the plasma wavelength
- For our very first experiment, we will investigate the self modulation effect in the plasma and measure it

* D.H. Whittum, Phys. Plasmas 4, 1154 (1997); K. Lotov, EPAC98.

Plasma self-modulate a long beam

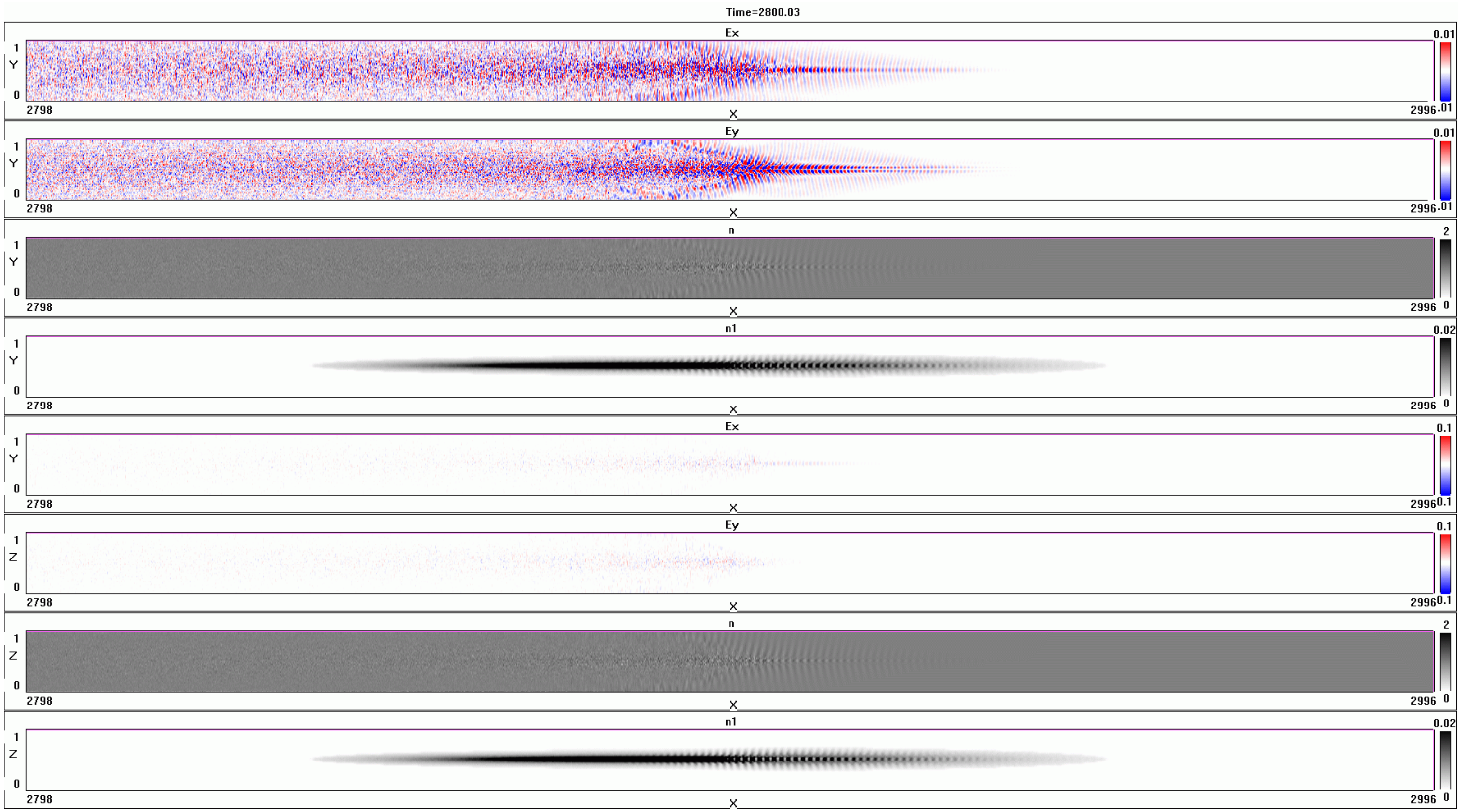
VLPL3D simulation

PS-beam:

10cm,10e11 p

Plasma: 10e13 1/cc

Plasma self-modulate a long beam



r_b=1 mm, n_p=1e11, σ_z=12 cm, E_p=450 GeV, n_0= 1e14cm-3 (λ_p=3mm)

Length of simulation=8.4 meters

Conclusion

- Short proton bunch is critical to the proton driven plasma wakefield acceleration
- Multi-stage beam compressions can achieve the bunch length in the range of 100 microns
- For 1 TeV proton beam, it needs very long RF for providing the energy chirp. The length of bunch compressor is over 4 km.
- For compression of SPS beam, if the ring can compress it a bit, by a factor of 10 to 100, we could make further compression via the designed magnetic compressors.
- Plasma self-modulation can produce the short beam slices as well

Thanks for your attention!