Operational experience with the Sub-Picosecond Particle Source (SPPS)

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- Project overview
- Measurements of the bunch length
- Wake fields studies
- CSR measurements
- Bunch length measurements FFTB

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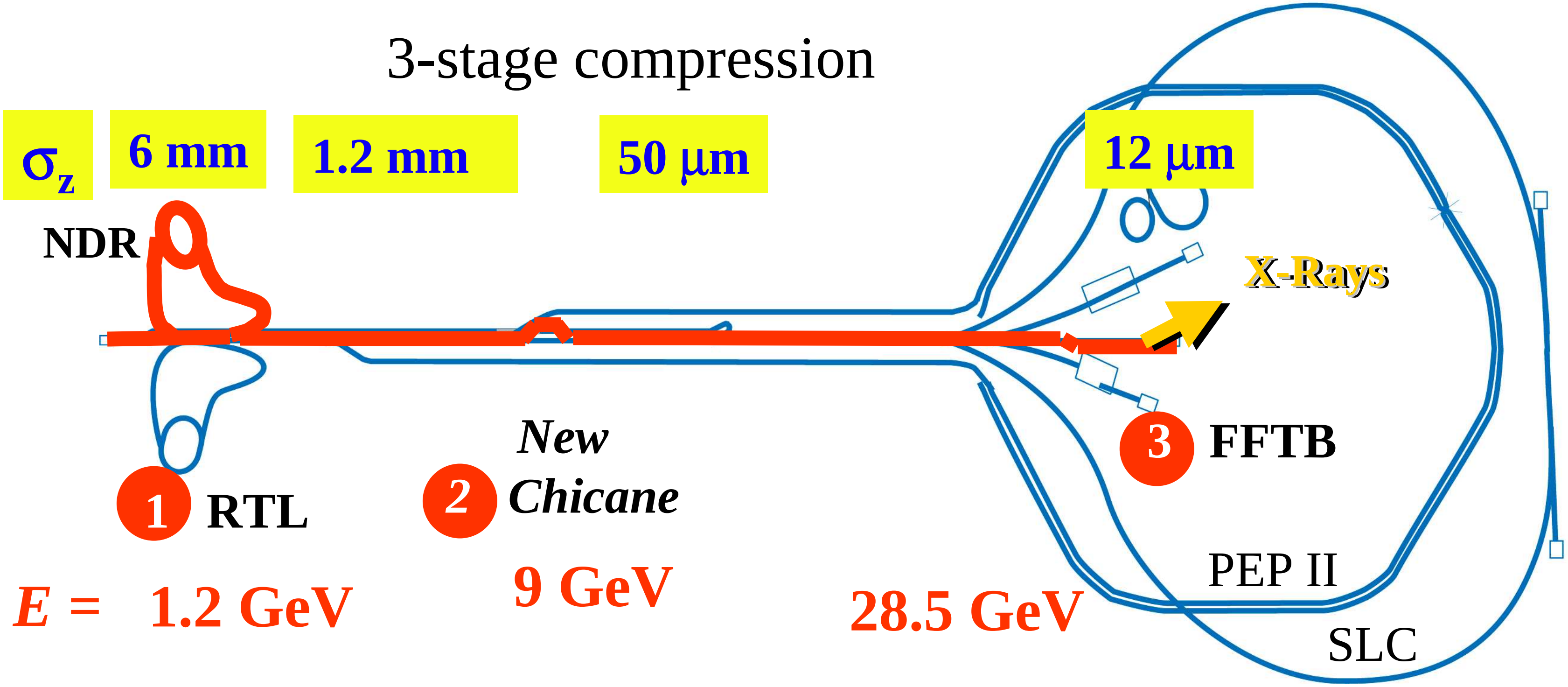
Motivation of the Chicane Bunch Compressor

- X-ray experiments at 80 femtosecond FWHM spontaneous undulator radiation at 1.5 Å
- Accelerator R&D for X-ray FELs

  - Instrumentation for electron and photon beam
  - Study beam dynamics for ultra-short bunch length
- Short electron bunches for plasma wake field experiments (E164 & E164x)

Design: High Energy Density Beams, 28.5 GeV, $2 \cdot 10^{10}$ electrons/bunch, 30 kA peak, 10 Hz, $\gamma\varepsilon_x$=40 μm, $\gamma\varepsilon_y$= 4 μm

Layout of Bunch Compressor in the SLAC Linac



$2.1\ 10^{10}\ e^-$/bunch

I_{pk}=30 kA

$\gamma\varepsilon_x$=40 μm

$\gamma\varepsilon_y$= 4 μm

Repetition rate 10 Hz/1 Hz ⇒ **Sharing linac cycles with PEP II injection**

Installations for SPPS operation

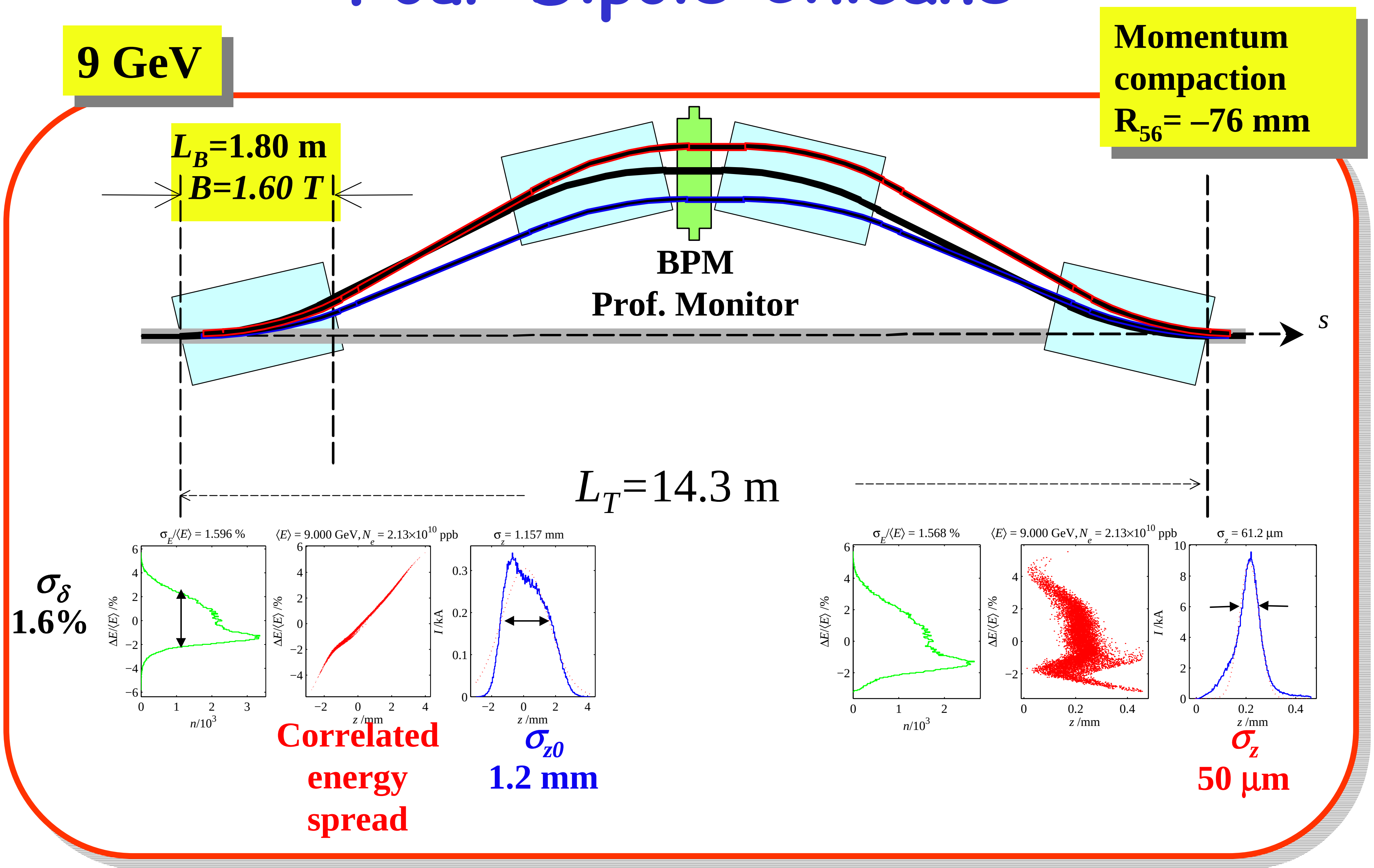
Electron beam line:

- **Linac bunch compressor chicane (LBCC)**
- **Transverse deflecting cavity (diagnostics)**
- **2 sextupoles in FFTB beam line (sec. order disp.)**
- **2.4 m long undulator with λ = 8.6 cm**
- **two quadrupoles are shifted in position (beam dump)**
- **vacuum chamber with electro-optic crystal**

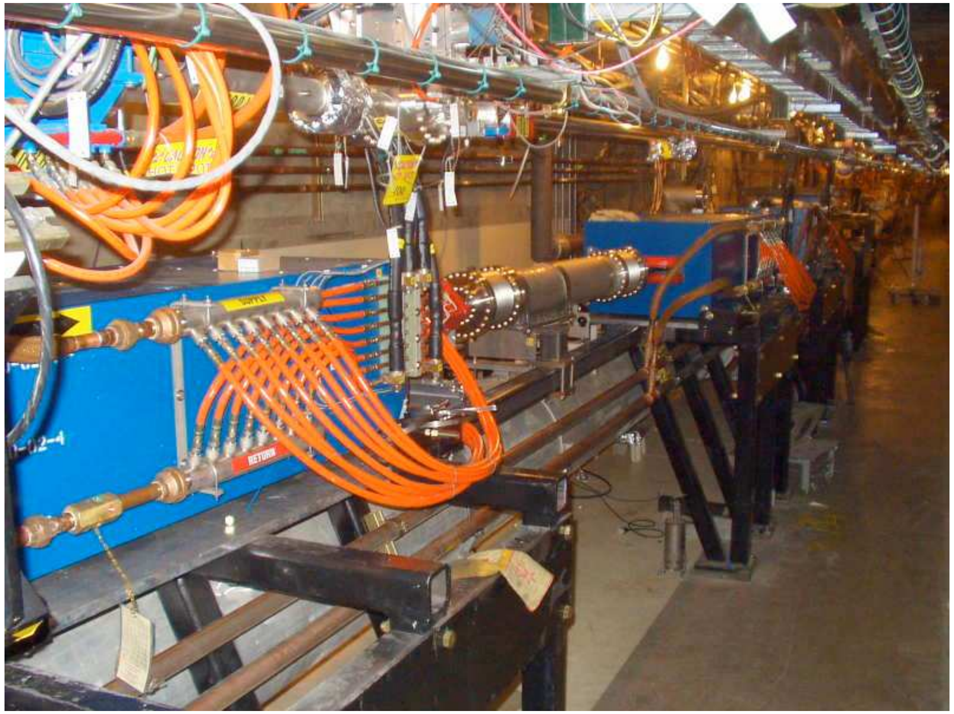
Photon beam line:

- **monochromator for x-ray beam**
- **x-ray beam transfer line**
- **x-ray experimental hutch (houses also the pump-probe laser system**

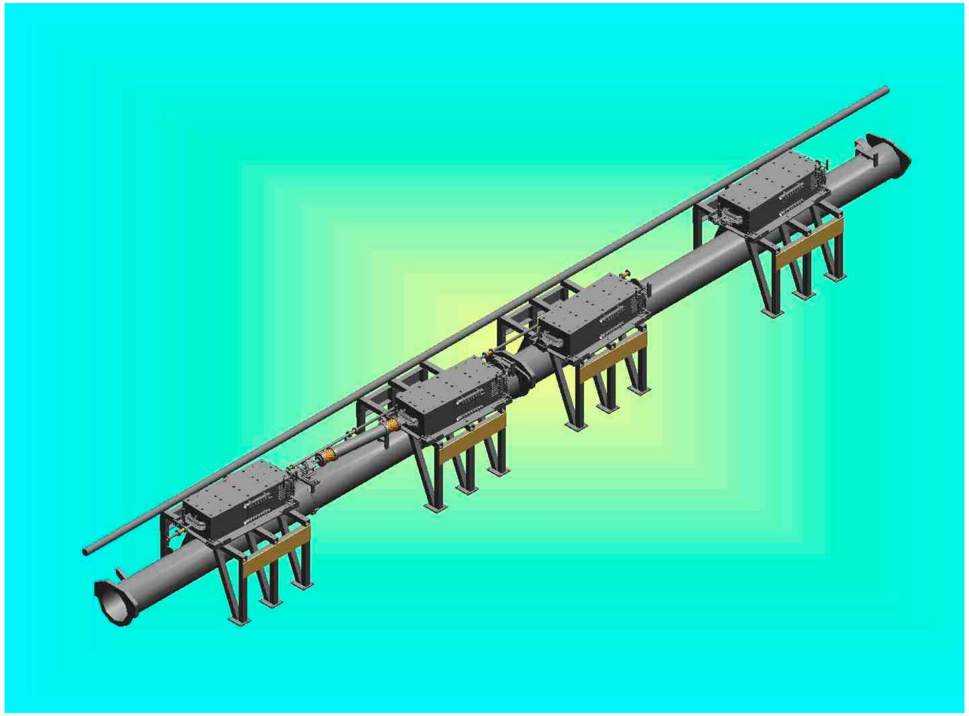
Four Dipole Chicane



Linac Bunch Compressor Chicane Installation



View in LINAC tunnel



Engineering model

Parameters of the Linac Bunch Compressor Chicane (LBCC)

Table 1: Chicane and beam parameters [2].

parameter	symbol	value	unit
e^- energy	E_0	9.0	GeV
Bunch population	N	2.1	10^{10}
rms corr. energy spread	σ_E/E_0	1.6	%
init. rms bunch length	σ_{s0}	1.16	mm
final rms bunch length	σ_{sf}	50	μm
x/y norm. emittance	$\gamma\epsilon_{x,y}$	45/5	μm
momentum compaction	R_{56}	-76	mm
bend angle per dipole	$\|\theta\|$	97	mrad
bend magnet length	L_B	1.8	m
drift from bend-1 to 2	ΔL	2.8	m
drift from bend-2 to 3	ΔL_c	1.5	m
peak dispersion	η_{pk}	450	mm
initial x beta-func.	β_x	56.3	m
initial x alpha-func.	α_x	3.29	

Energy measurement with high resolution & optimum condition for energy feedback

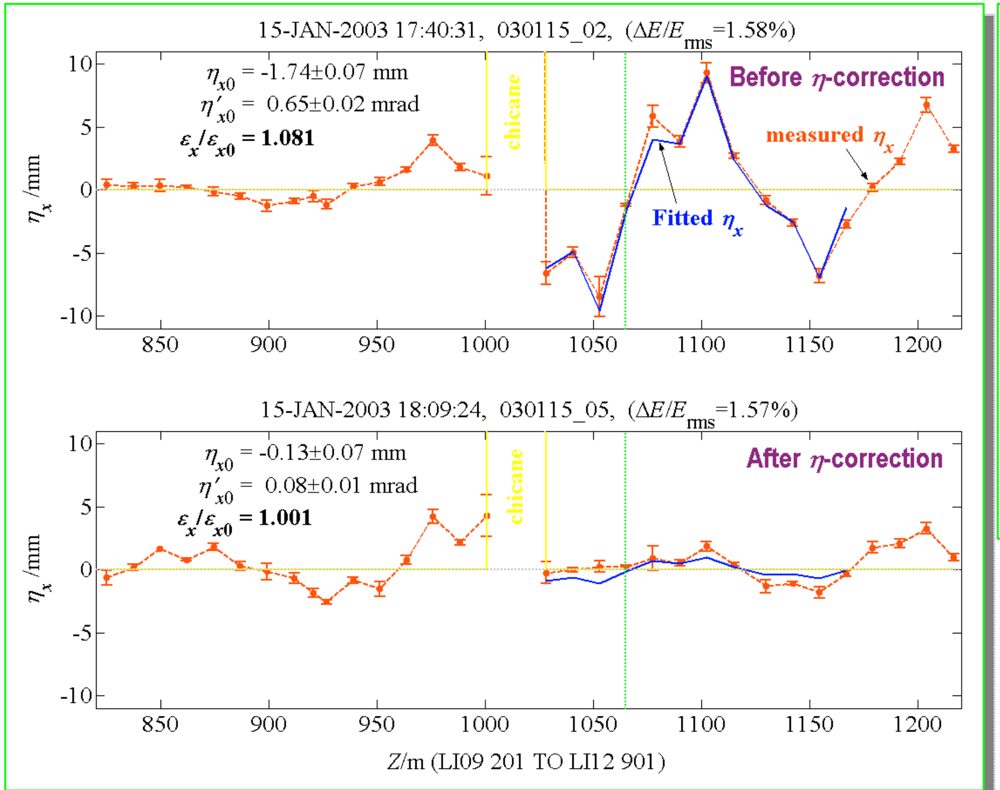
Beam waist between 3^{th} and 4^{th} dipole

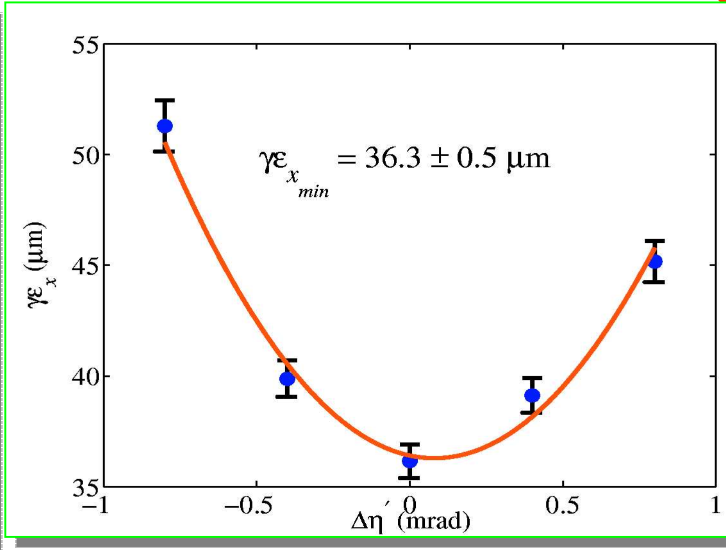
Commissioning Key Points

- Compatibility with PEP II operation
- Multi-beam energy control with feedback (LBCC)
- Dispersion correction in LBCC
- Measurement of bunch length with RF transverse deflecting cavity
- Bunch length optimization using wake energy-loss scans
- Linac tuning to minimize emittance growth
- Measurement of CSR induced emittance growth
- Beam stability

Measurements in the range 50 - 100 μm

Dispersion Correction of the Chicane with Quadrupoles

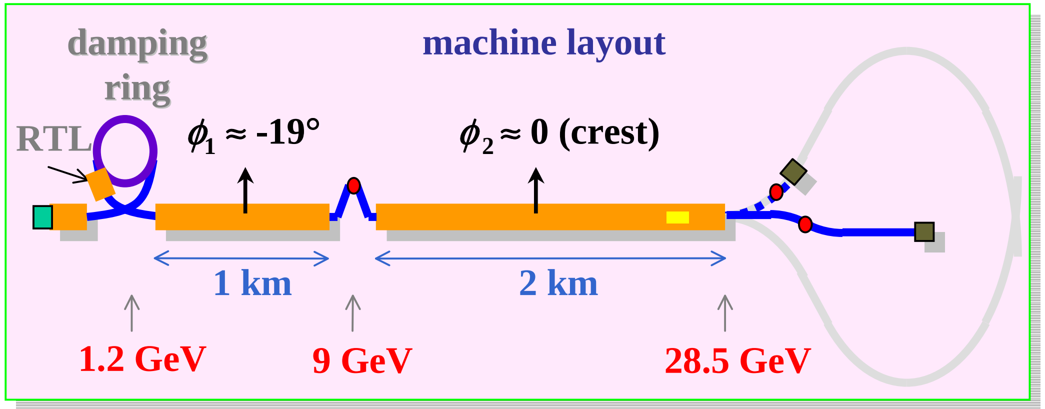




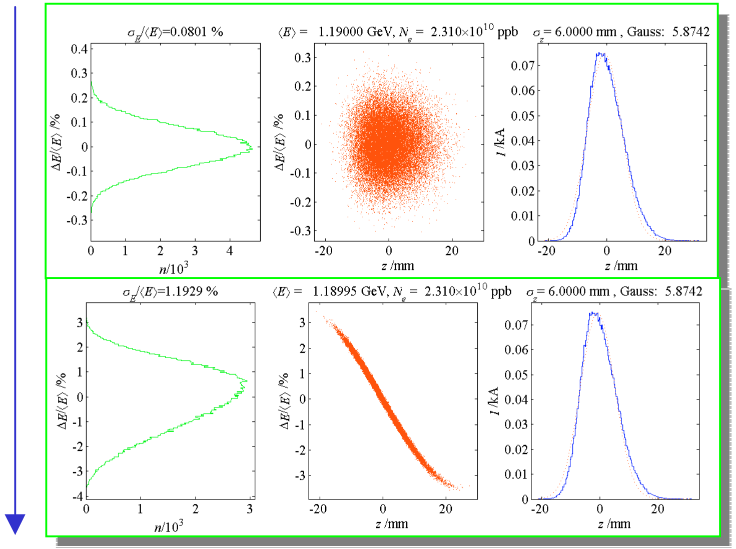
Residual *x*-dispersion and its angle after chicane minimized using quads in chicane.

- roll error of chicane dipoles has been corrected by survey group

Evolution of Particle Distribution in long. Phase Space



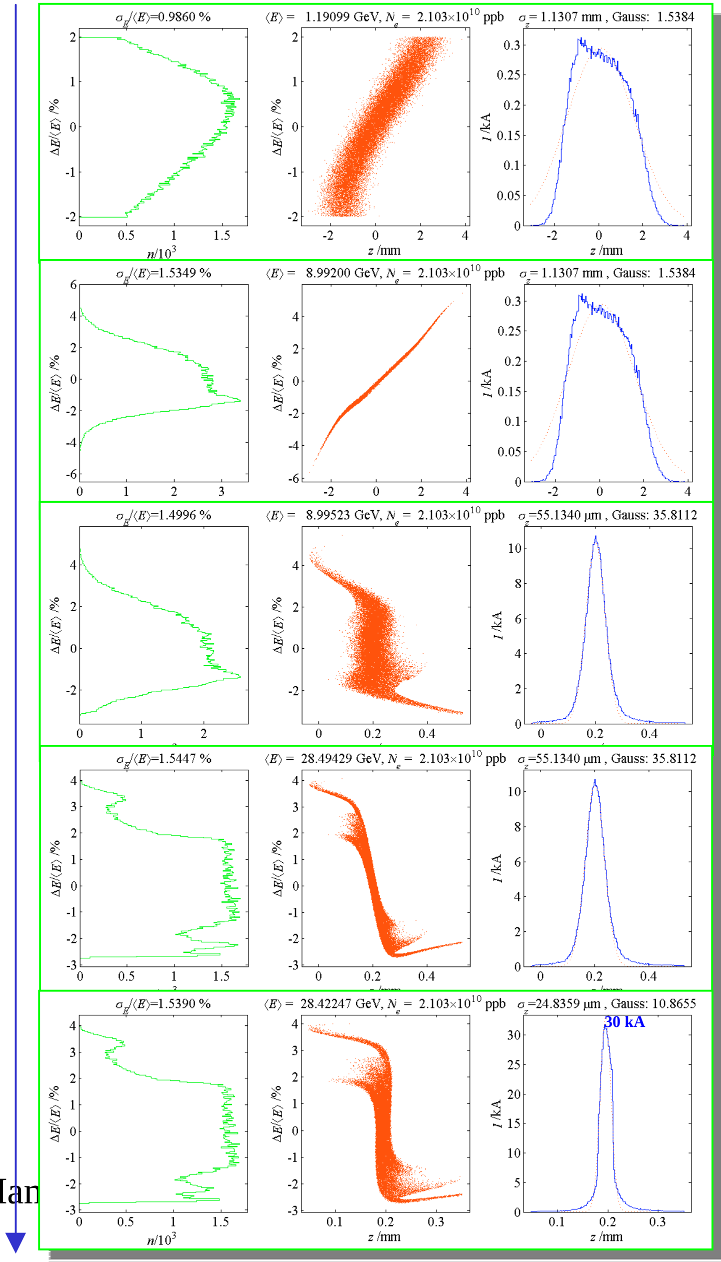
dp/p z-dp/p z



exit of damping ring

after compressor cavity ~40 MV

Head Tail



RTL R_{56}= 590mm

before LBCC

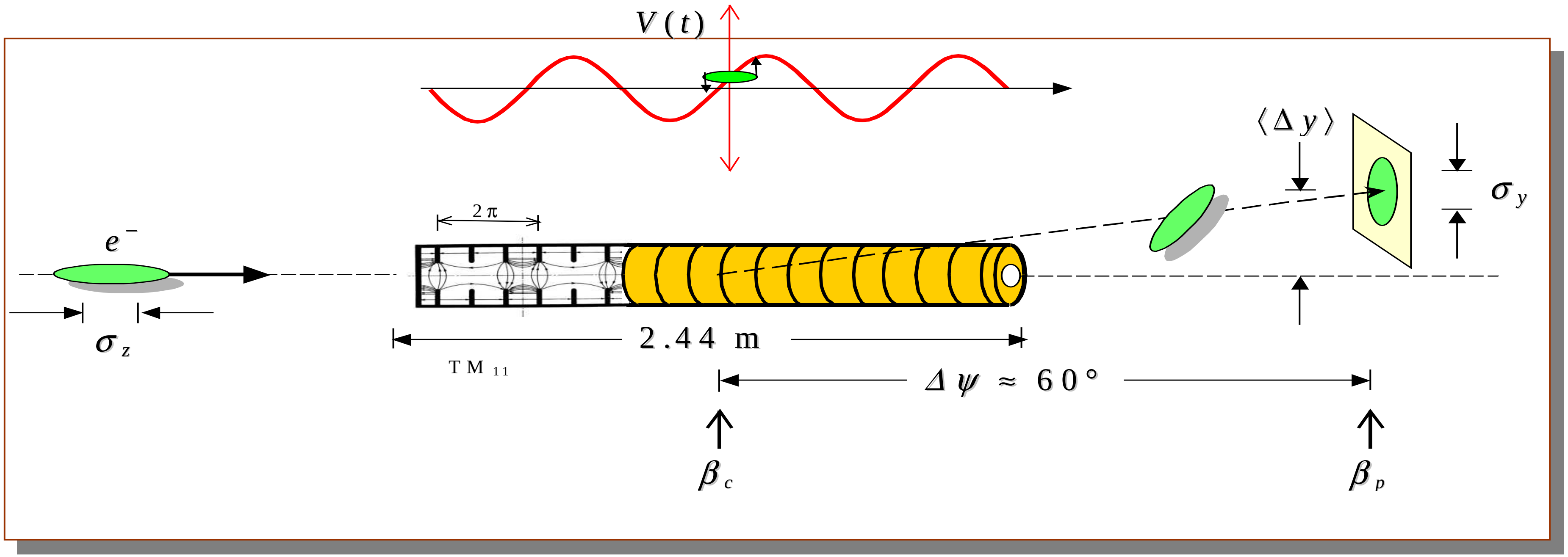
after LBCC R_{56}= -76mm

end of Linac

after dogleg R_{56}= 2mm

RF Transverse Deflecting Cavity

- "LOLA" S-band cavity installed at end of linac
- 25 MW klystron power to "streak" the 28.5 GeV linac beam
- Measurement with beam profile monitor



Transverse Deflecting Cavity Bunch Length Reconstruction

Beam size RF off

Bunch Length

Beta fn at cavity & screen

Cavity voltage and beam energy

Phase adv cavity to screen

Beam size on screen

$$\sigma_y = \sqrt{\sigma_{y0}^2 + \sigma_z^2 \beta_c \beta_p \left(\frac{2\pi e V_0}{\lambda E_0} \sin \Delta\psi \cos\varphi \right)^2}$$

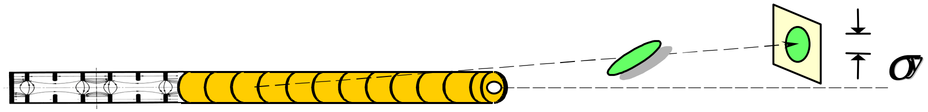
RF phase

Net deflection

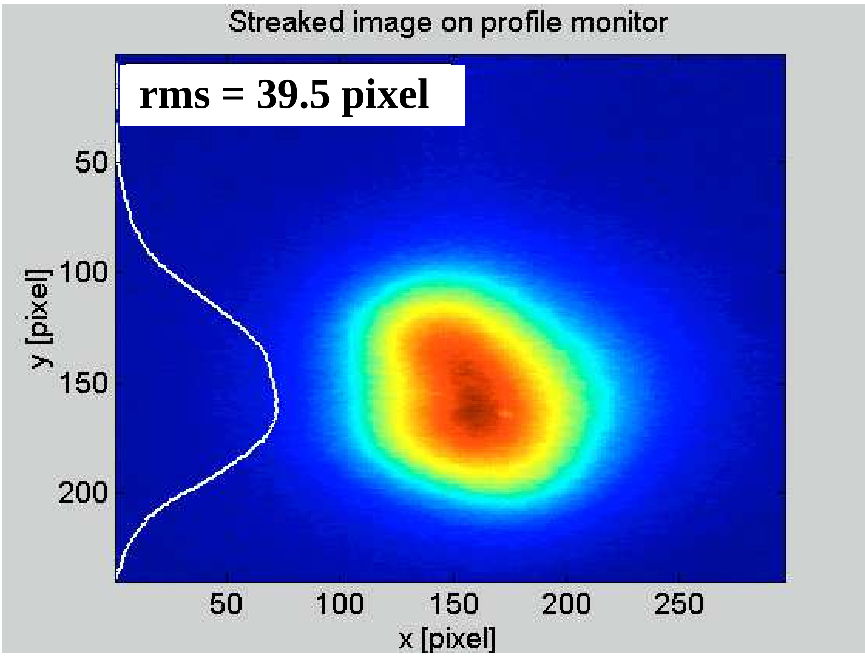
SLAC cavity shunt impedance

$$\langle \Delta y \rangle = \frac{eV}{E_0} \sqrt{\beta_c \beta_p} \sin \Delta\psi \sin\varphi , \qquad V_0 \approx \left(1.6 \text{ MV/m/MW}^{1/2} \right) L \sqrt{P_0}$$

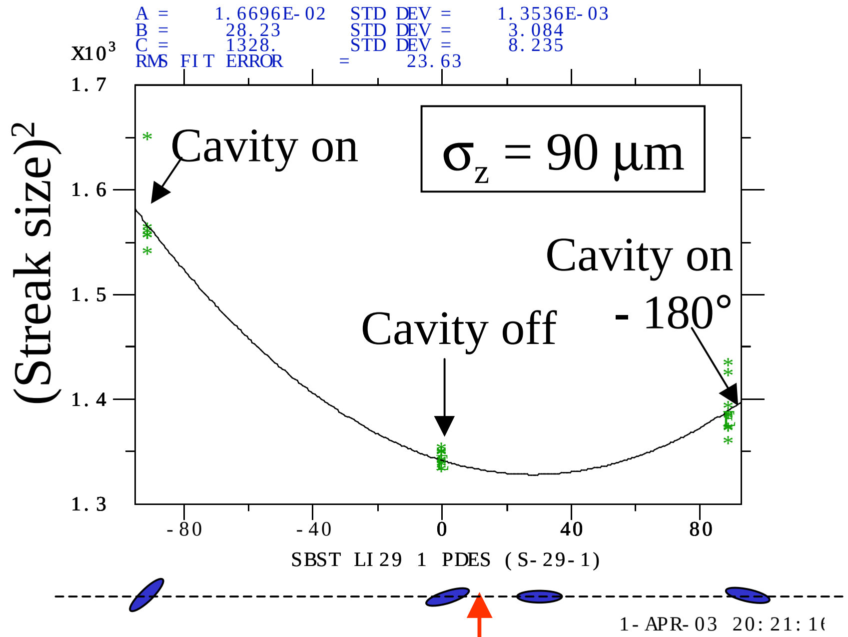
Bunch Length Measurements with the RF Transverse Deflecting Cavity

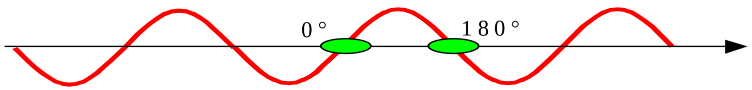


Bunch length reconstruction
Measure streak at 3 different phases



$$\sigma_y^2 = A\phi_{rf}^2 + B, \quad \sigma_z = \frac{\lambda_{rf}\sqrt{A}}{4C}$$





Asymmetric parabola indicates incoming tilt to beam

Challenges of the Transverse Deflecting Cavity

- Parasitic operation desirable

  ⇒ horizontal kicker (1 Hz) deflects on screen ✓
- Timing drifts

  ⇒ feedback system regulates cavity phase (slow drifts are removed, operates up to 10 Hz) ✓
- Small vertical beam size required

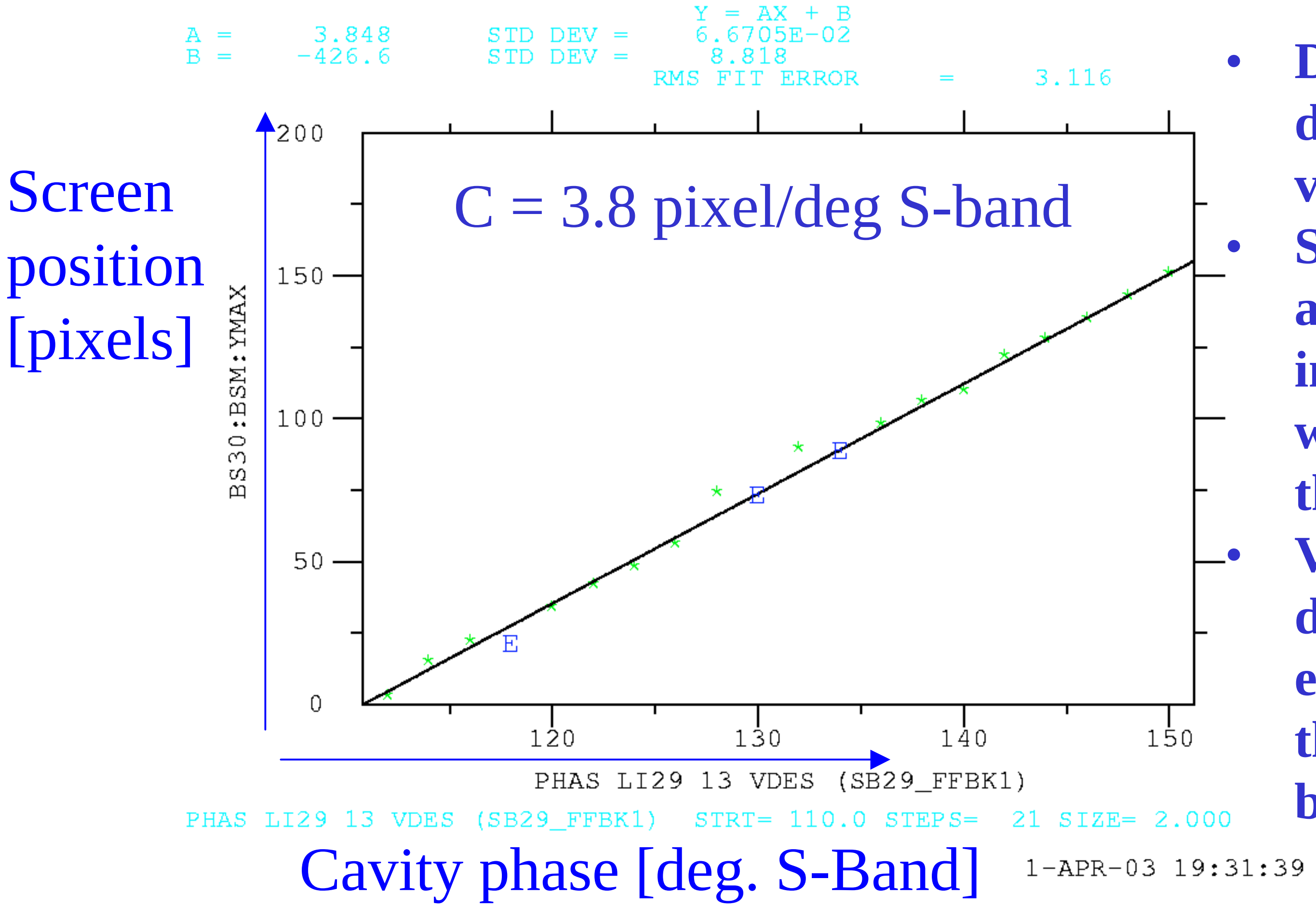
  ⇒ emittance tuning ✓
- Profile monitor setup is not optimized

  ⇒ used better optics and camera (✘)
- Tails in beam profile

  ⇒ different fitting routines applied (✘)
- Calibration of deflecting cavity gradient + screen

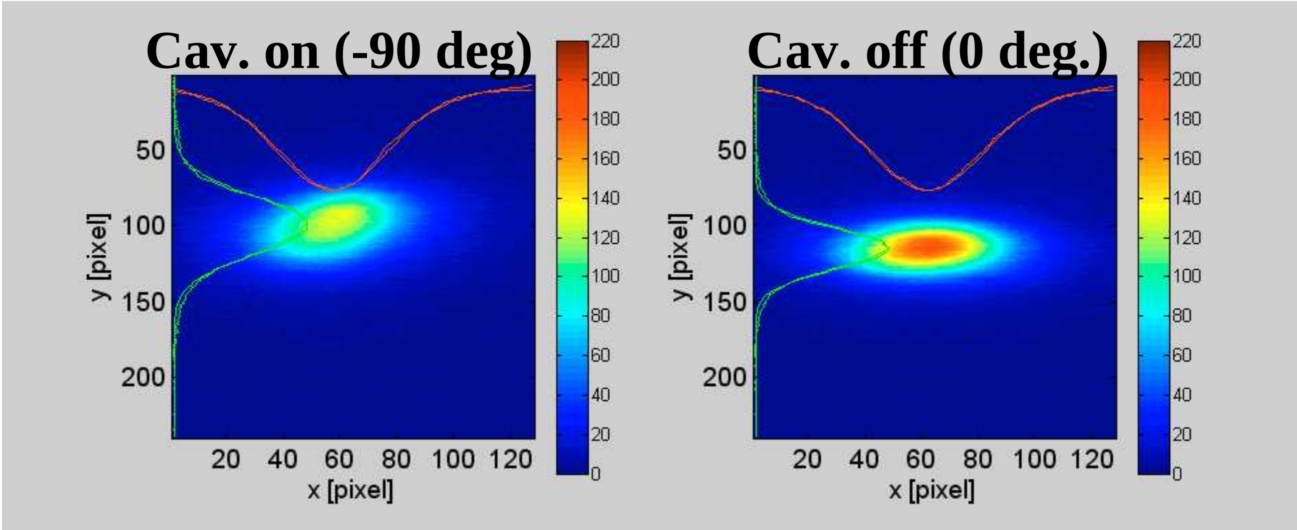
  ⇒ special calibration procedure developed ✓

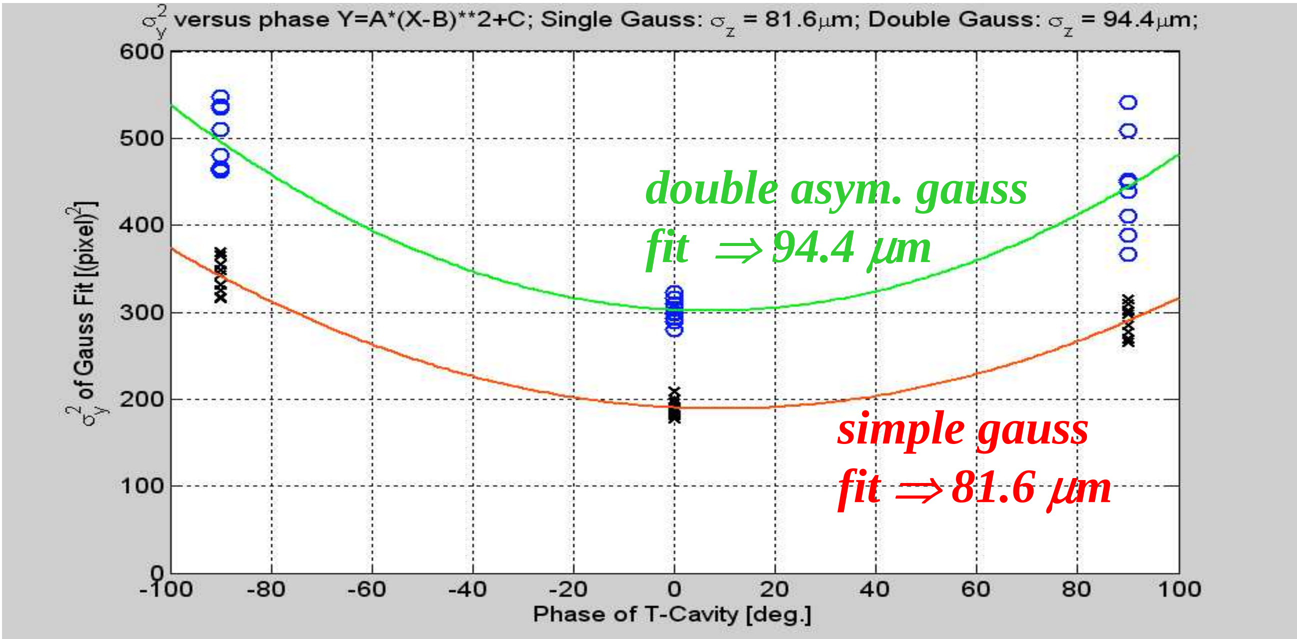
Calibration Scan for RF Transverse Deflecting Cavity



- **Decrease deflecting RF voltage (~1/10)**
- **Screen pixels are calibrated in units of the wavelength of the S-band RF**
- **Vertical deflection is extracted from the peak of the beam profile**

Example for Bunch Length Measurement





Energy Loss due to Wake Fields in the SLAC Linac

- Short-range approximation for the point-charge wake field (for SLAC S-band $s_0 \approx 1.47$ mm, $a \approx 11.6$ mm, $s < 5$ mm):

$$W(s) = \frac{Z_0 c}{\pi a^2} H(s)\, e^{-\sqrt{s/s_0}}$$

- Loss-factor (V/C/m) for gaussian bunch distribution with rms length s_z:

$$\kappa(\sigma_z) = \frac{1}{2\sqrt{\pi}\,\sigma_z} \int_0^\infty W(s)\, e^{-(s/\sigma_z)^2/4}\, ds$$

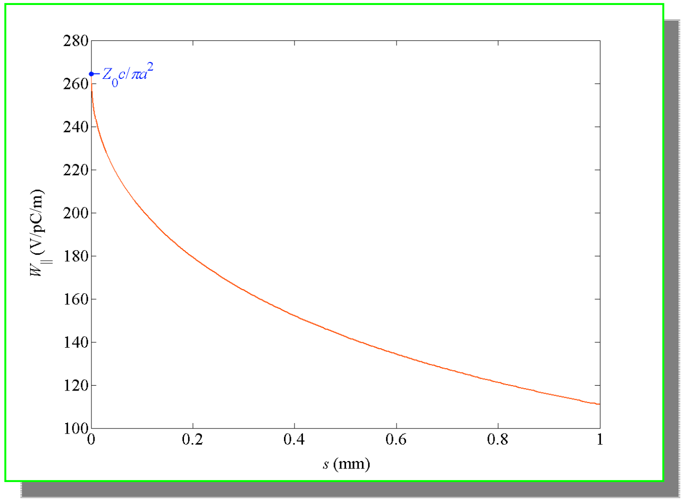
- Approximation for loss-factor (2% accuracy for $s_z \leq s_0$):

$$\kappa(\sigma_z) \approx \frac{Z_0 c}{2\pi a^2}\, e^{-0.88\sqrt{\sigma_z/s_0}}$$

- Energy change of bunch due to rf shape and wake field loss, where E_{acc} is rf voltage (19.5 MV), f is phase w.r.t. crest (= 0), k_{rf} is wavenumber, eN is charge (3.4 nC), and L is linac length (1870 m).

$$\Delta E = \hat{E}_{acc} \cos\phi\, e^{-k_{rf}^2 \sigma_z^2/2} - eNL\kappa(\sigma_z)$$

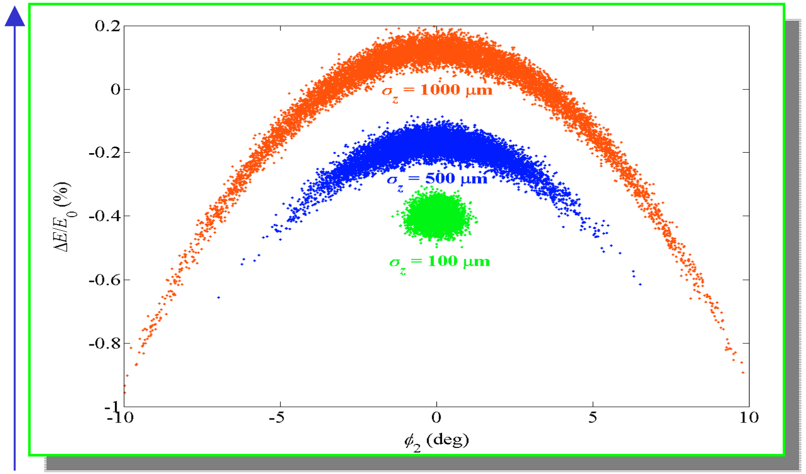
RF effect — Wake field



Effect of Linac Wake Fields on Beam

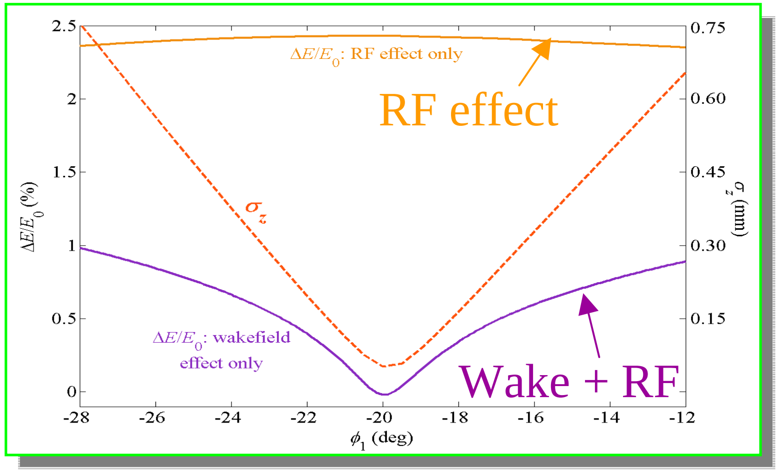
- Energy loss due to RF curvature

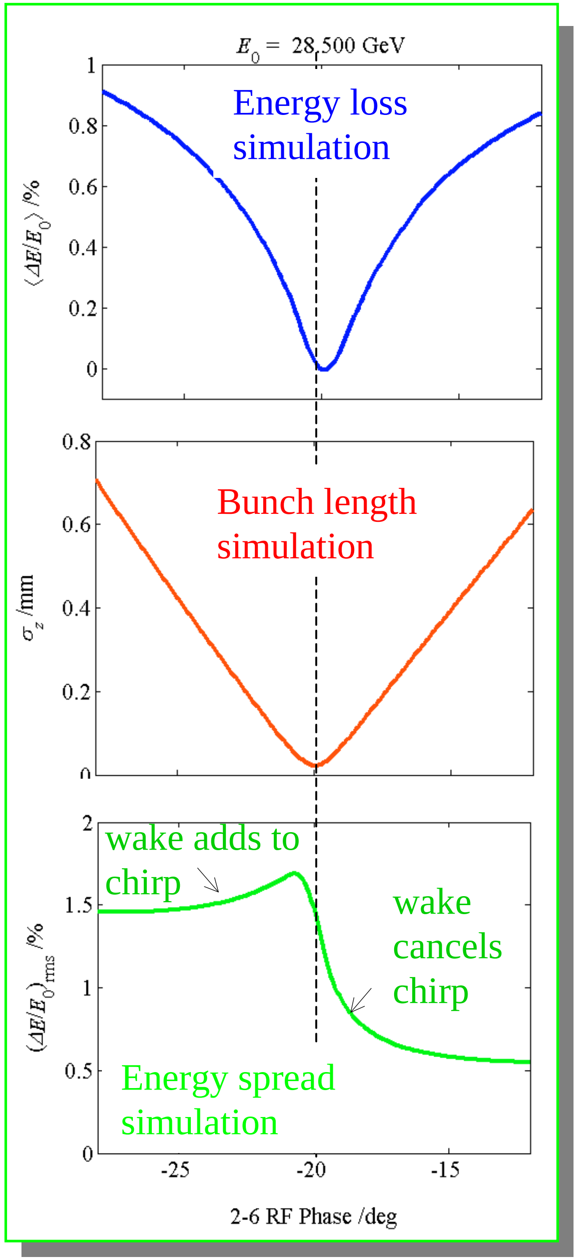
dE/E [%]



Phase of 1 km linac

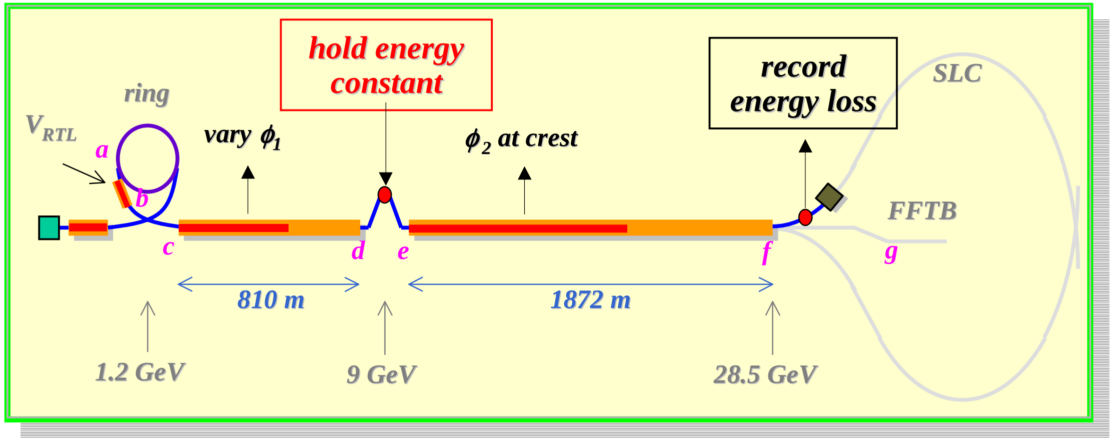
- Energy loss Wake + RF





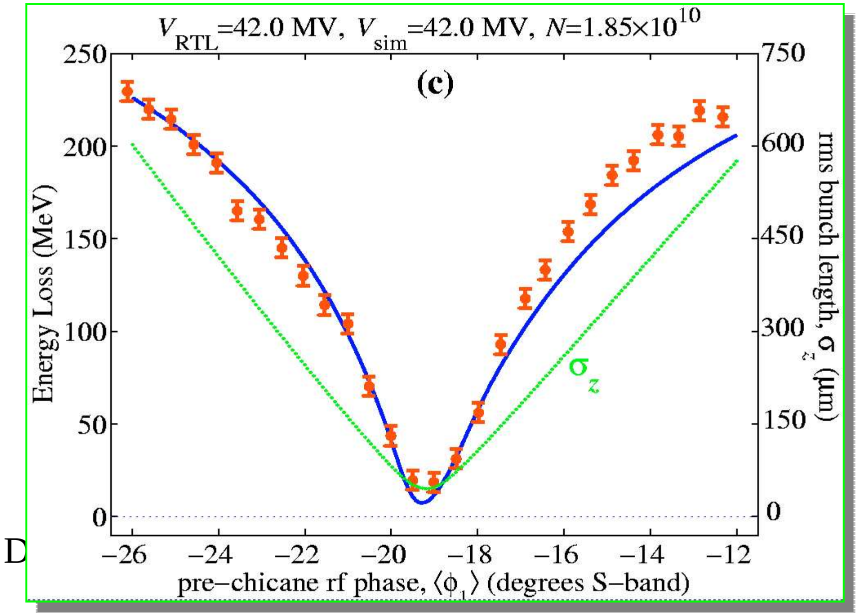
Wake Energy Loss are used to Minimize the Bunch Length

- Energy feedback holds beam energy constant at chicane

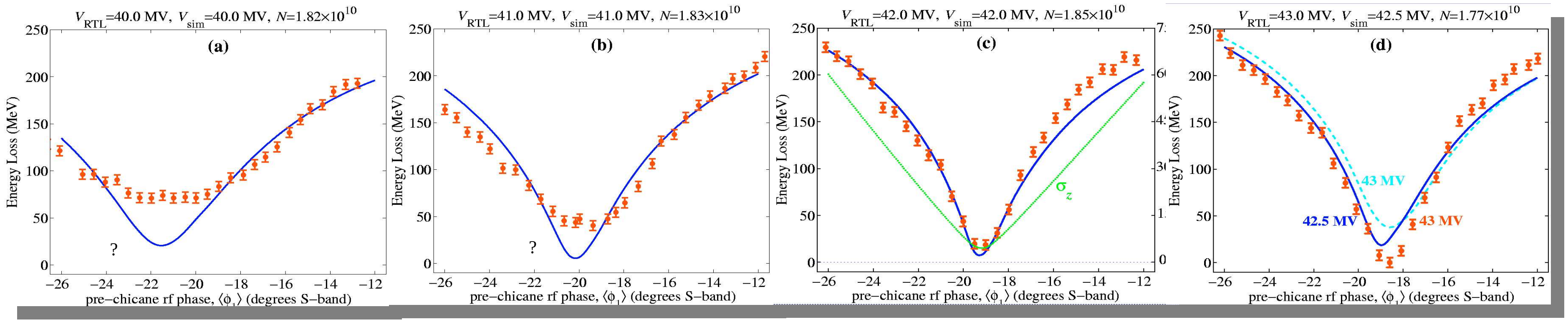


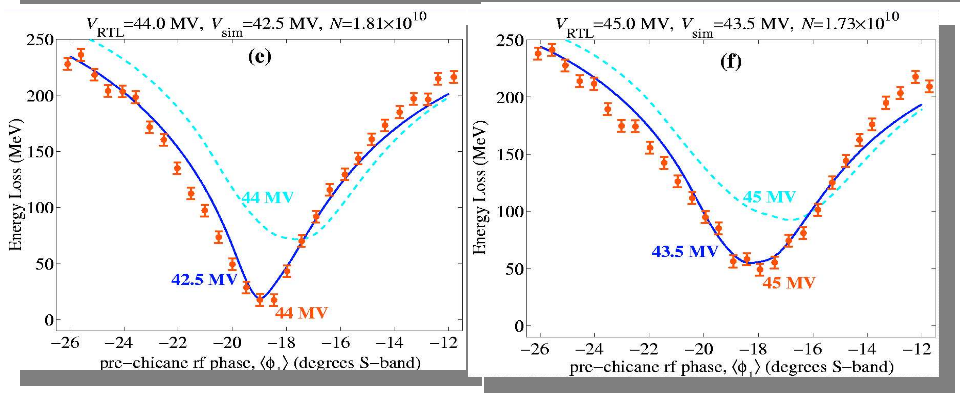
1) Uncouples the energy losses up- and downstream chicane
2) Beam arrival time (phase) in second part of linac is constant

- Linac phase before chicane is varied
- Wake energy loss depend on bunch charge and the compressor voltage
- Standard procedure for adjusting injection phase

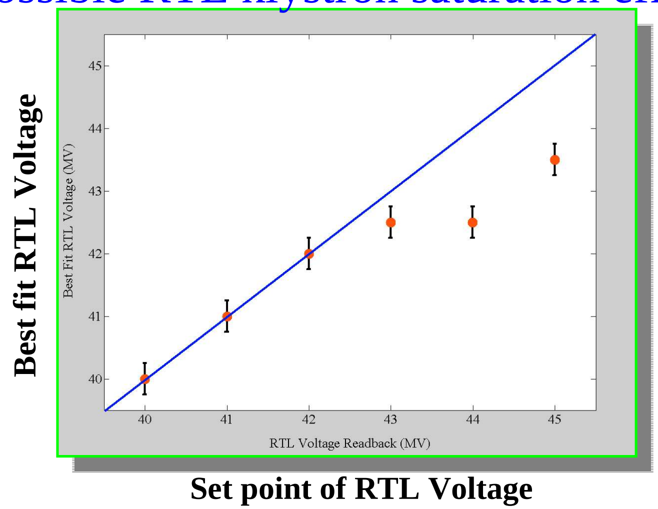


Wake Energy Loss for Various RTL Compressors Settings





•Possible RTL klystron saturation effect

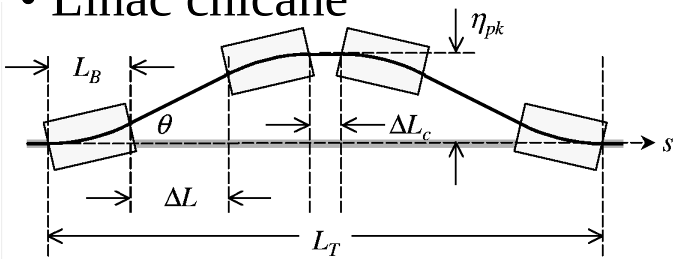


- ***Measured energy loss deviate from simulation if V_{RTL} is varied***
- ***particular towards smaller voltage***

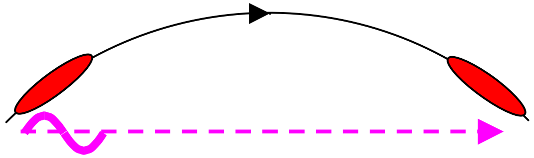
RTL klystron appears to saturate at V > 42 MV.
But this was not independently confirmed.

CSR Induced Emittance Growth

- Linac chicane

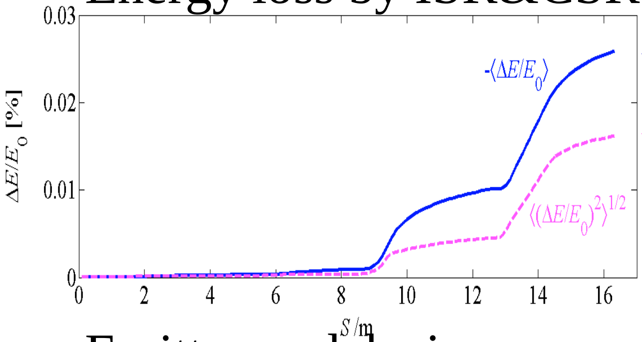


- Radiation from tail can catch up with head



- At $\lambda \approx \sigma_z$ synchrotron radiation is coherent

- Energy loss by ISR&CSR



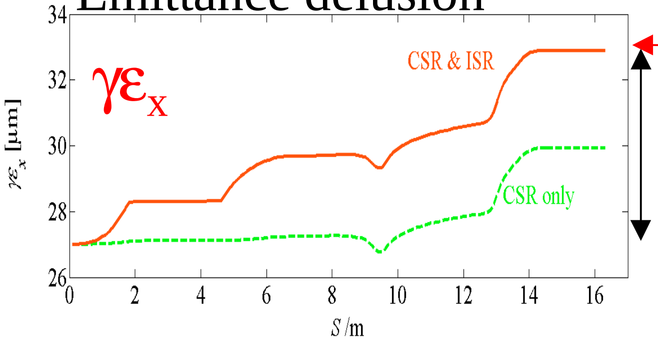
induced energy loss (can be corrected)

induced energy spread

in dispersion section

caused emittance growth

- Emittance delusion



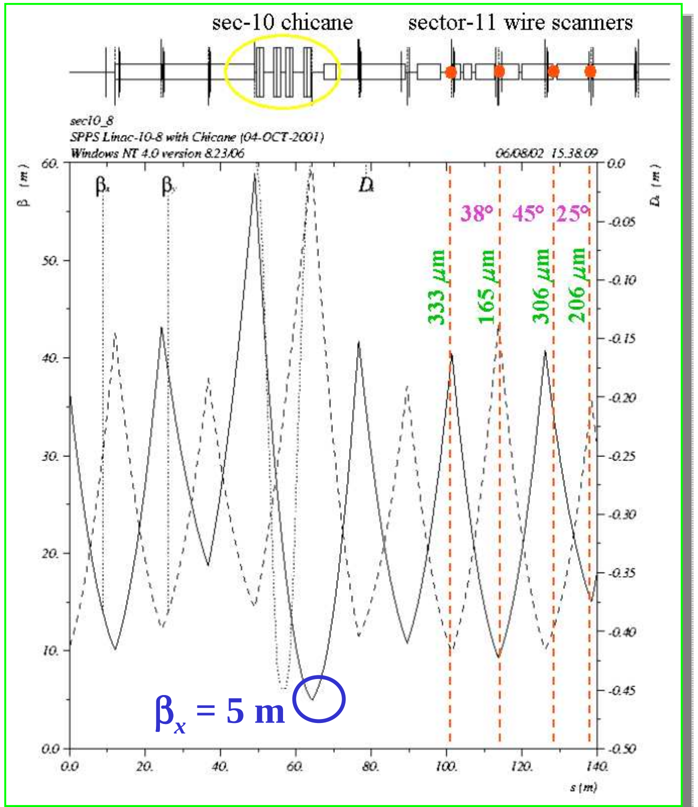
22%

Simulation: with 1D (*Elegant*) and 3D (*TraFiC⁴*) codes

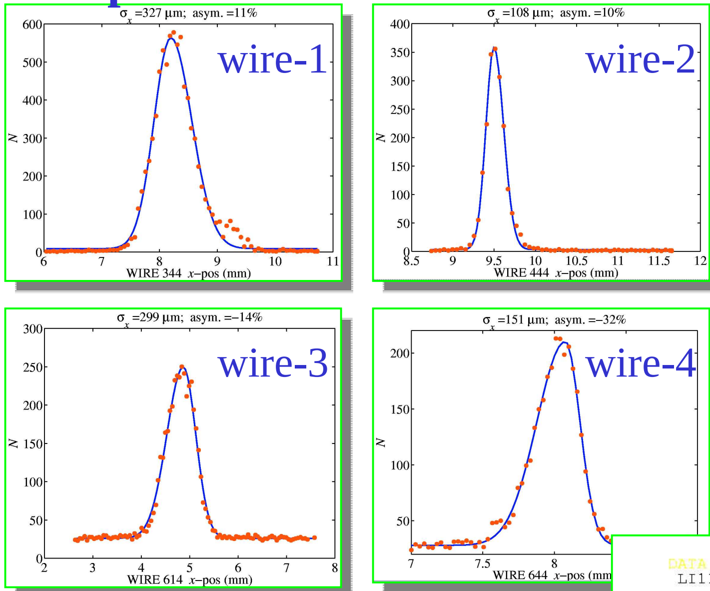
Ref: PAC03, P. Emma et al
"Measurements of Transverse Emittance Growth due to Coherent Synchrotron Radiation in the SLAC SPPS Bunch Compressor Chicane"

CSR Induced Emittance Growth
- optics and emittance measurement -

- **Four wire-scanners within 60 m of chicane, are used to measure emittance.**

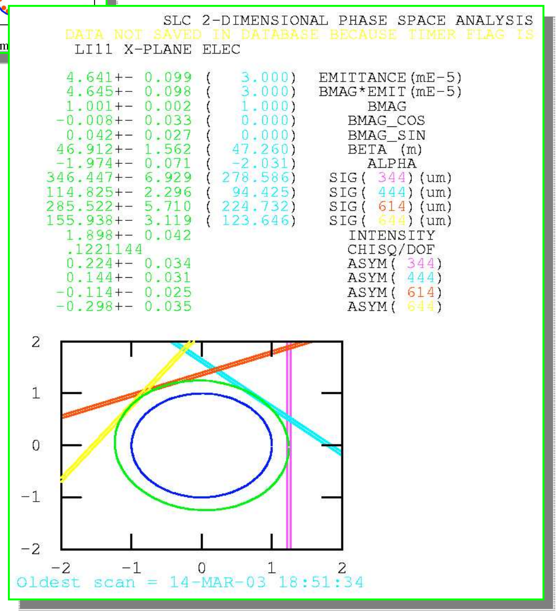


- **bend-plane emittance measurements**



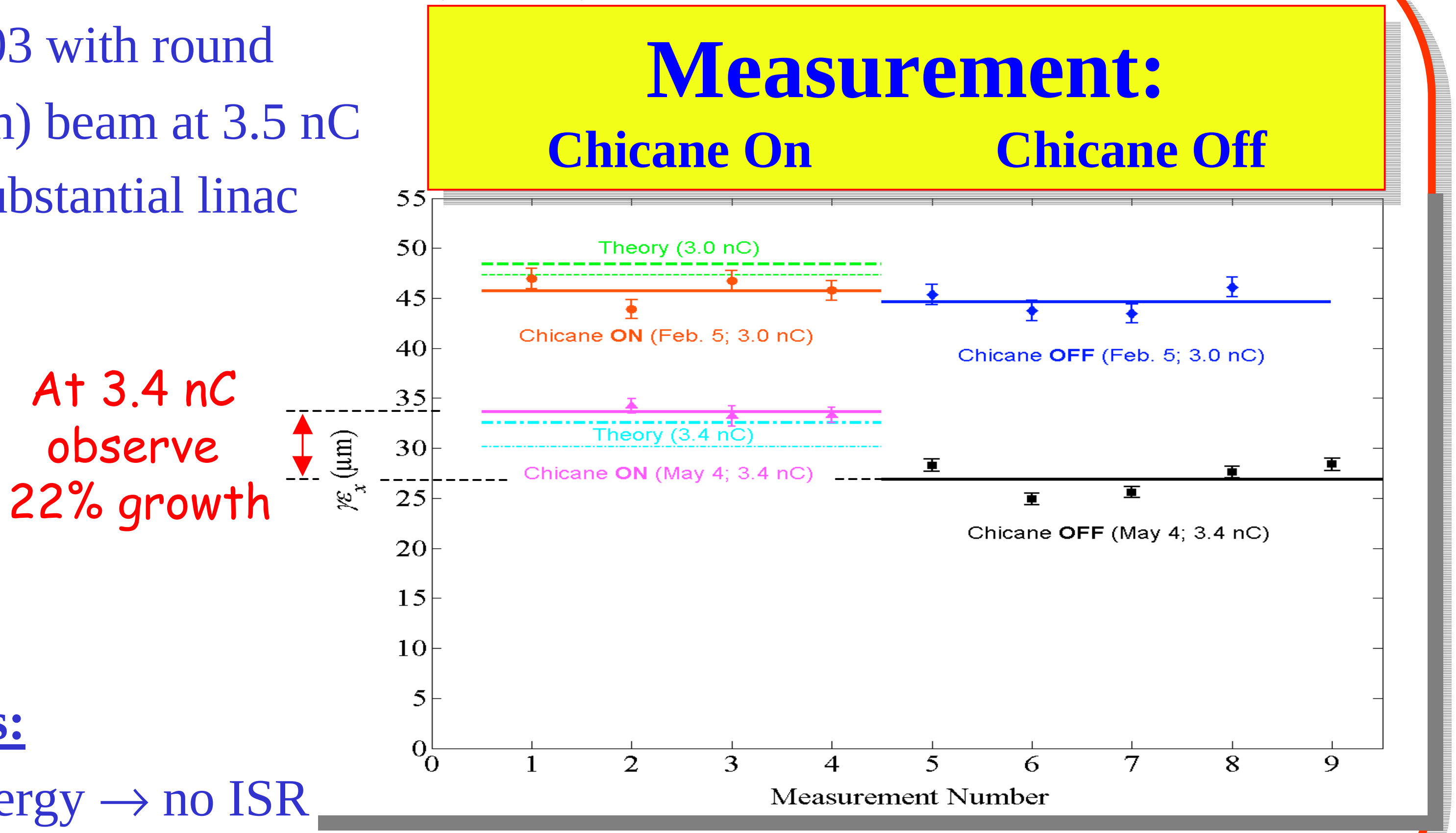
Individual beam size fits with asymmetric-gaussian.

Wire-scanners measure emittance with precision of 2-4%.



CSR Induced Emittance Growth
- two measurements sofar-

- Feb. 6 2003 with flat beam (50µm× 3µm) at 3.0 nC
- May 4 2003 with round (20µm× 10µm) beam at 3.5 nC
- requires substantial linac tuning



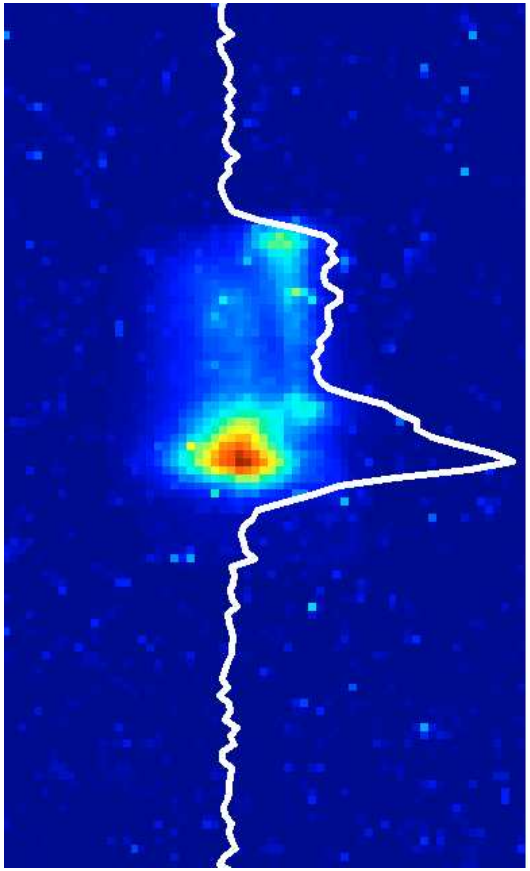
- **<u>Next steps:</u>**

  - lower energy → no ISR
  - special optics → enhanced CSR

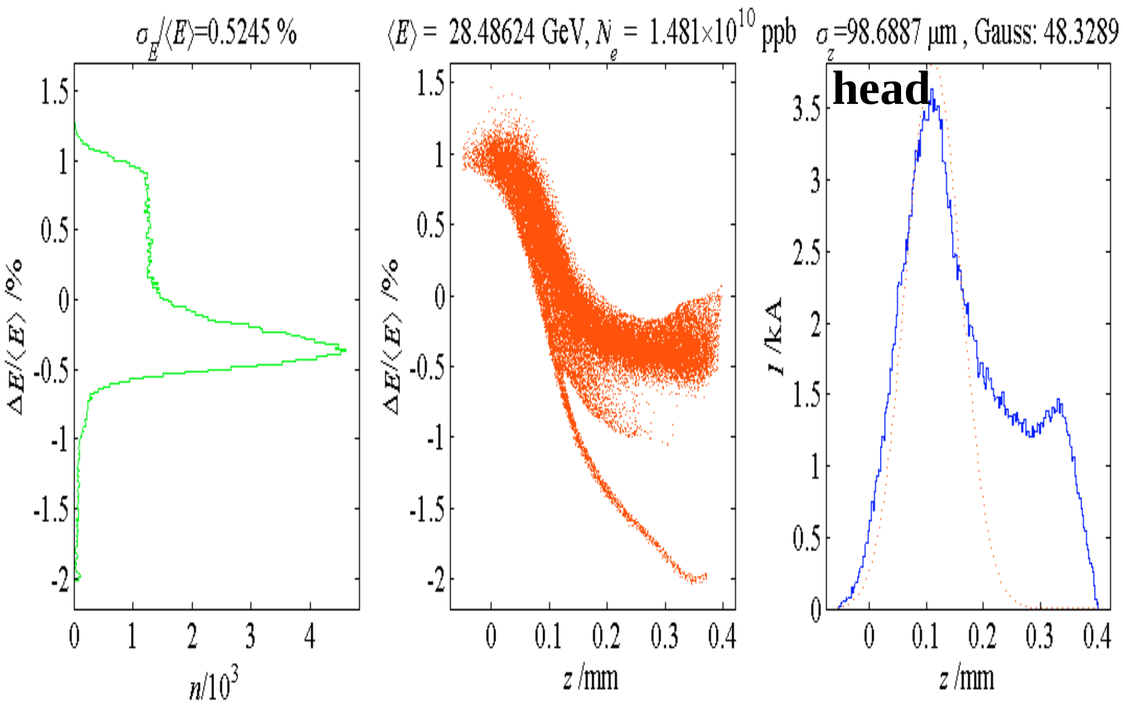
Measurements in FFTB Beam Line

- Wake loss scan had to adapted to FFTB operation
- Opportunity to measure the energy profile more accurate
- Problem: for ultra-short bunches bunch length diagnostics more difficult (even not available)
  $\Rightarrow$ Electro-Optic Sampling experiment in preparation
  $\Rightarrow$ Use THz detector to optimize bunch length

Measured and Predicted Energy Spread of a Compressed Bunch



Special setup to give 100 mm bunch length with more charge at the head of the bunch



Measured at the end of FFTB