Juliane Rönsch
Universität Hamburg / DESY

Investigations on the electron bunch distribution in the longitudinal phase space at a laser driven RF-electron source for the European X-FEL

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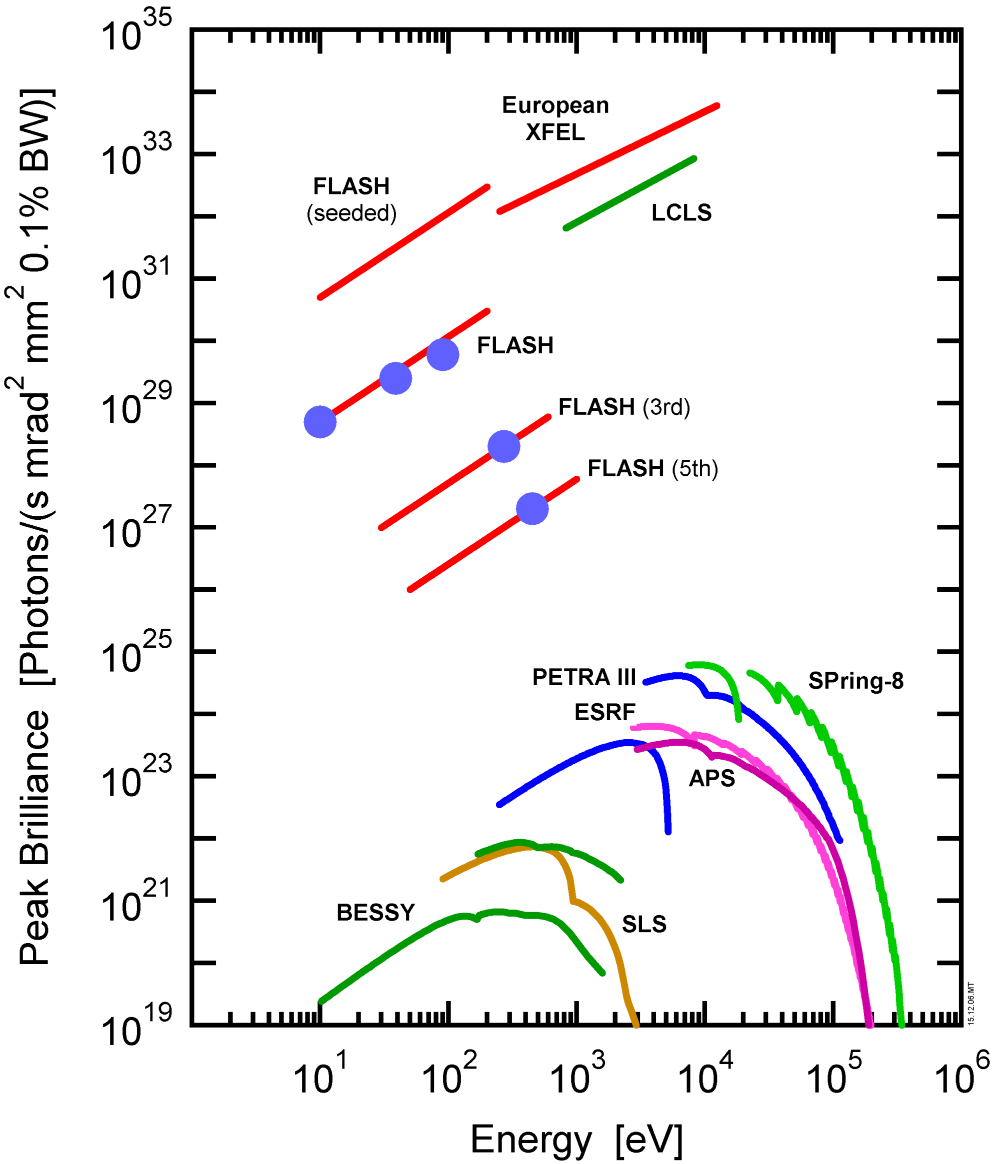
- **Measurements and simulations of longitudinal phase space at PITZ**
- Summary

Introduction

Free Electron Laser produces light with the following properties:

- **short wavelength** (XFEL: down to 0.1 nm, FLASH: down to 6 nm) **->** small structures
- **coherent ->** holography, imaging of single nanoscale objects
- **short pulses** (≤ 100 fs) **->** fast processes
- **high peak brightness ->** investigate matter under extreme conditions

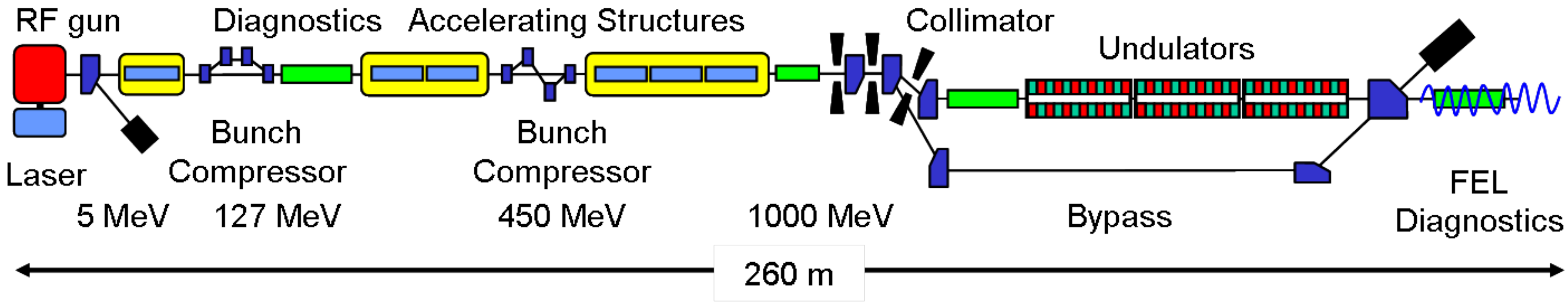


Introduction

To obtain a highly brilliant light pulse a high energy electron beam with the following properties is required:

- a high peak current, means a high charge within a short bunch length (in the range of 100 fs)
- a small energy spread
- a small transverse emittance

FLASH layout



Motivation

To obtain a highly brilliant light pulse a high energy electron beam with the following properties is required:

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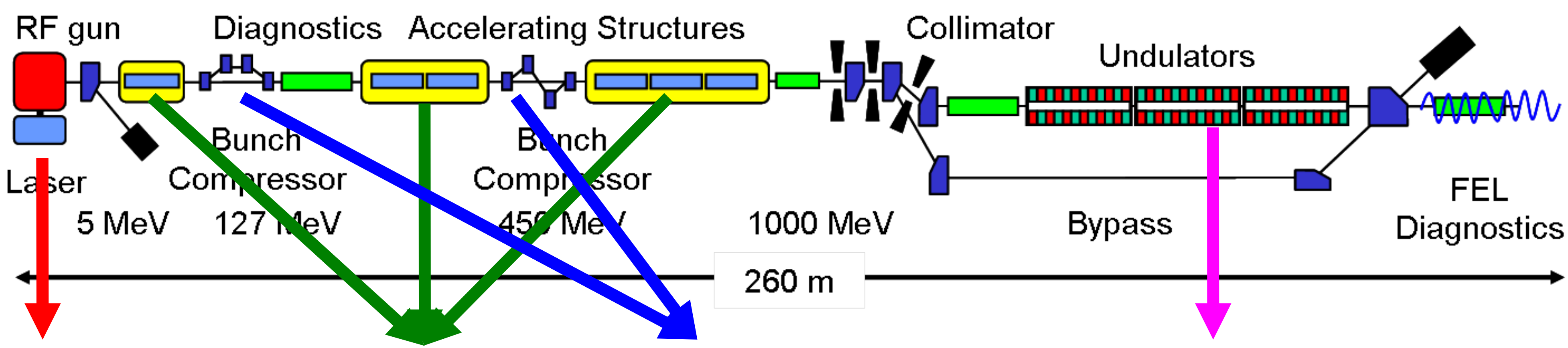
FLASH layout



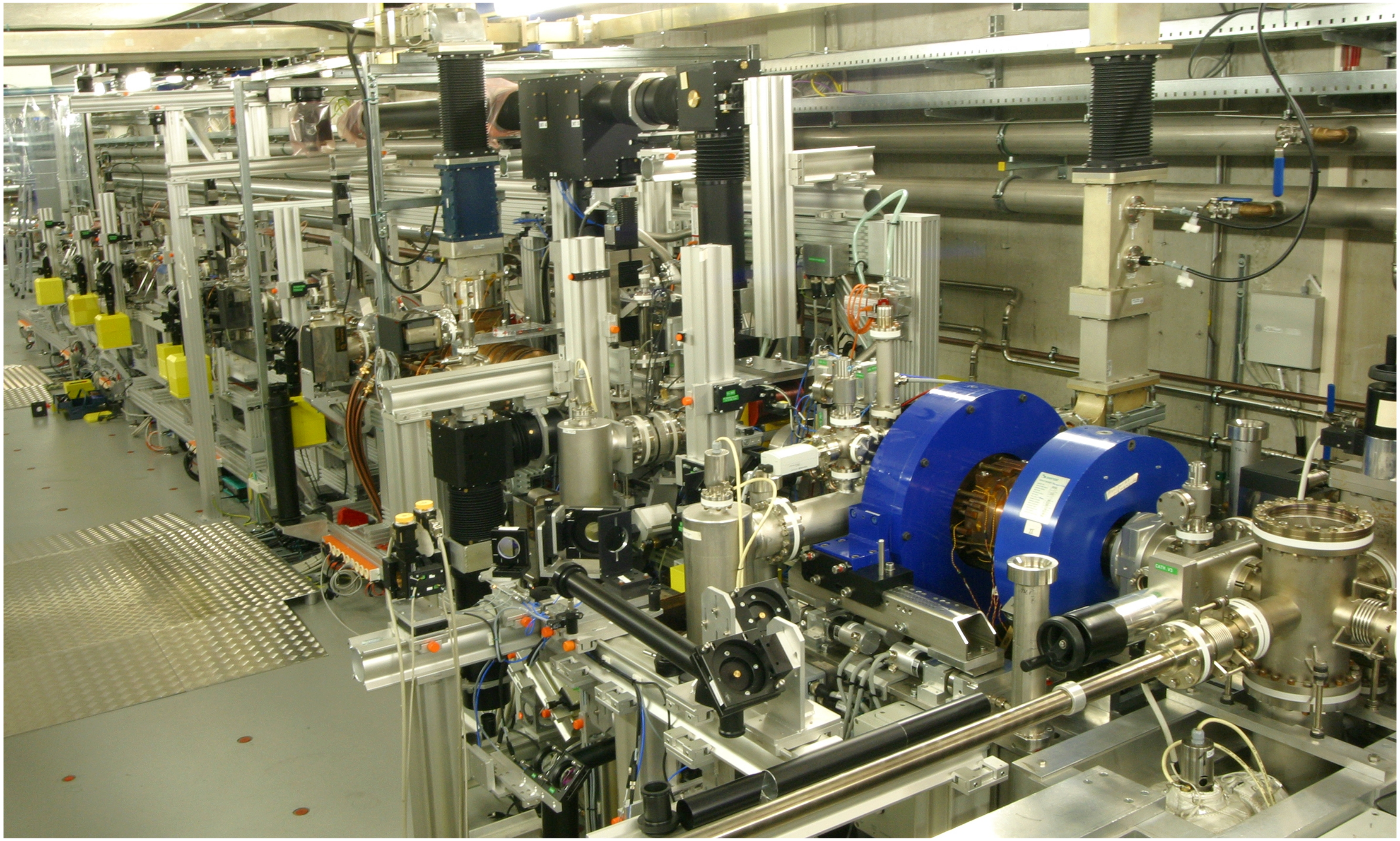
production of bunches with high charge (1nC), **medium bunch duration (20ps), small energy spread** and small transverse emittance

acceleration of electron bunches and conservation of transverse emittance

compression of the bunches to reach a high peak current **→ compression: requires the knowledge of long. phase space distribution**

generation of brilliant light pulse by the SASE (Self amplified spontanious emission) process

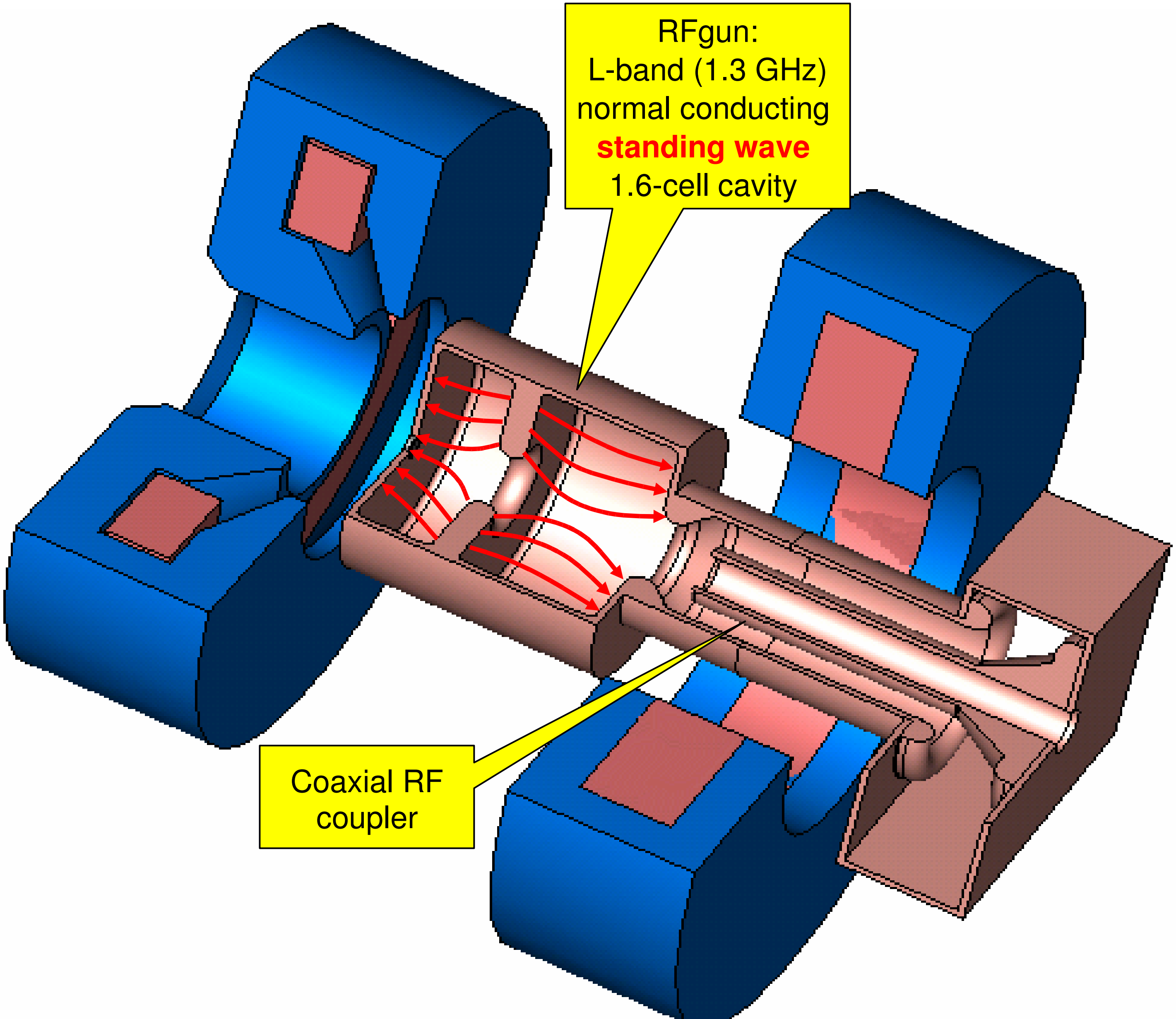
PITZ: Photo**i**njector **t**est facility at DESY, **Z**euthen site



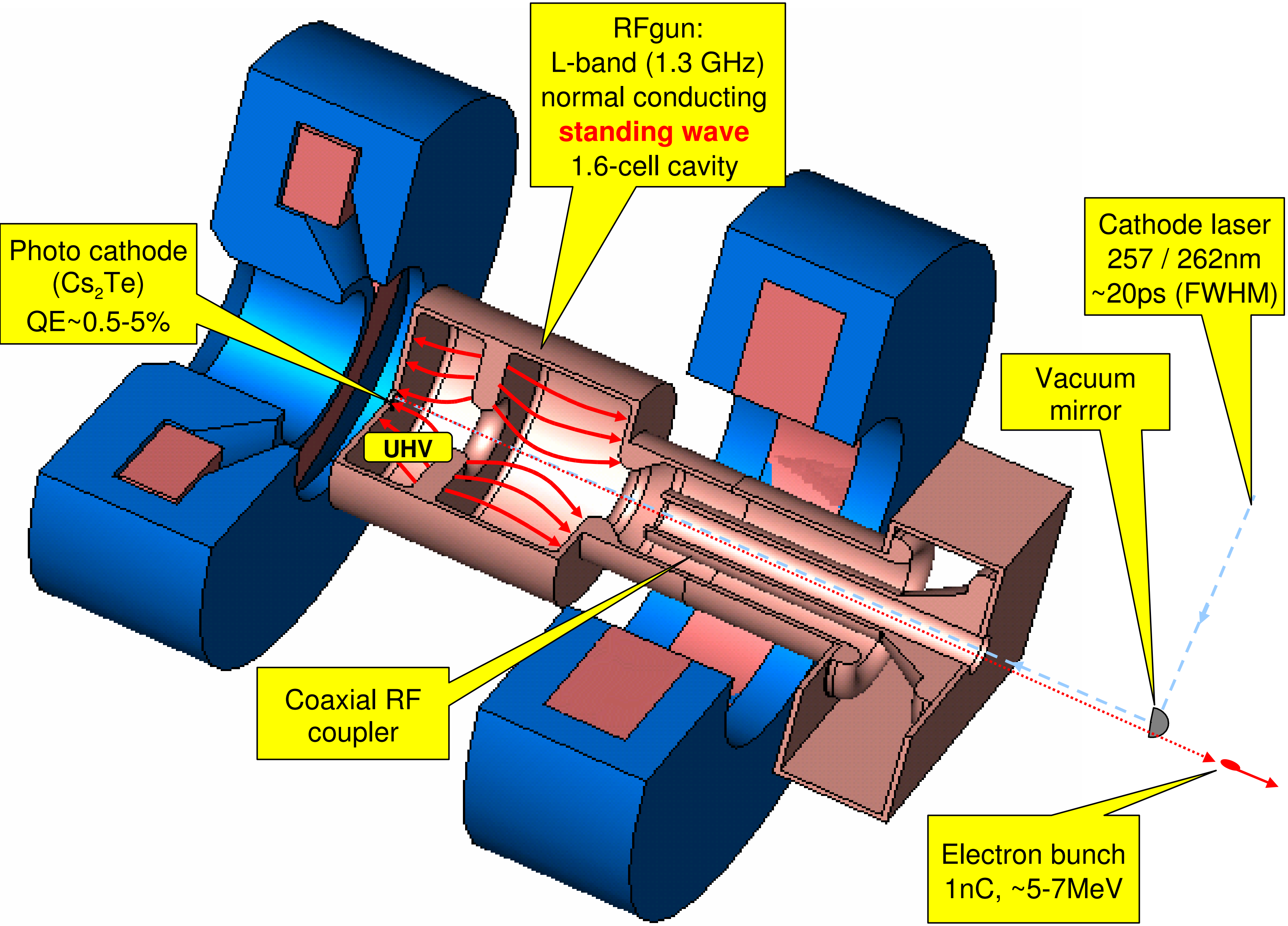
Goals:

- Test, analyse and optimize electron sources for FELs
- Development of diagnostics to analyse the electron bunch properties
- Comparison of measurements and simulations to prove the understanding of the beam dynamics in the photoinjector

PITZ : RF gun

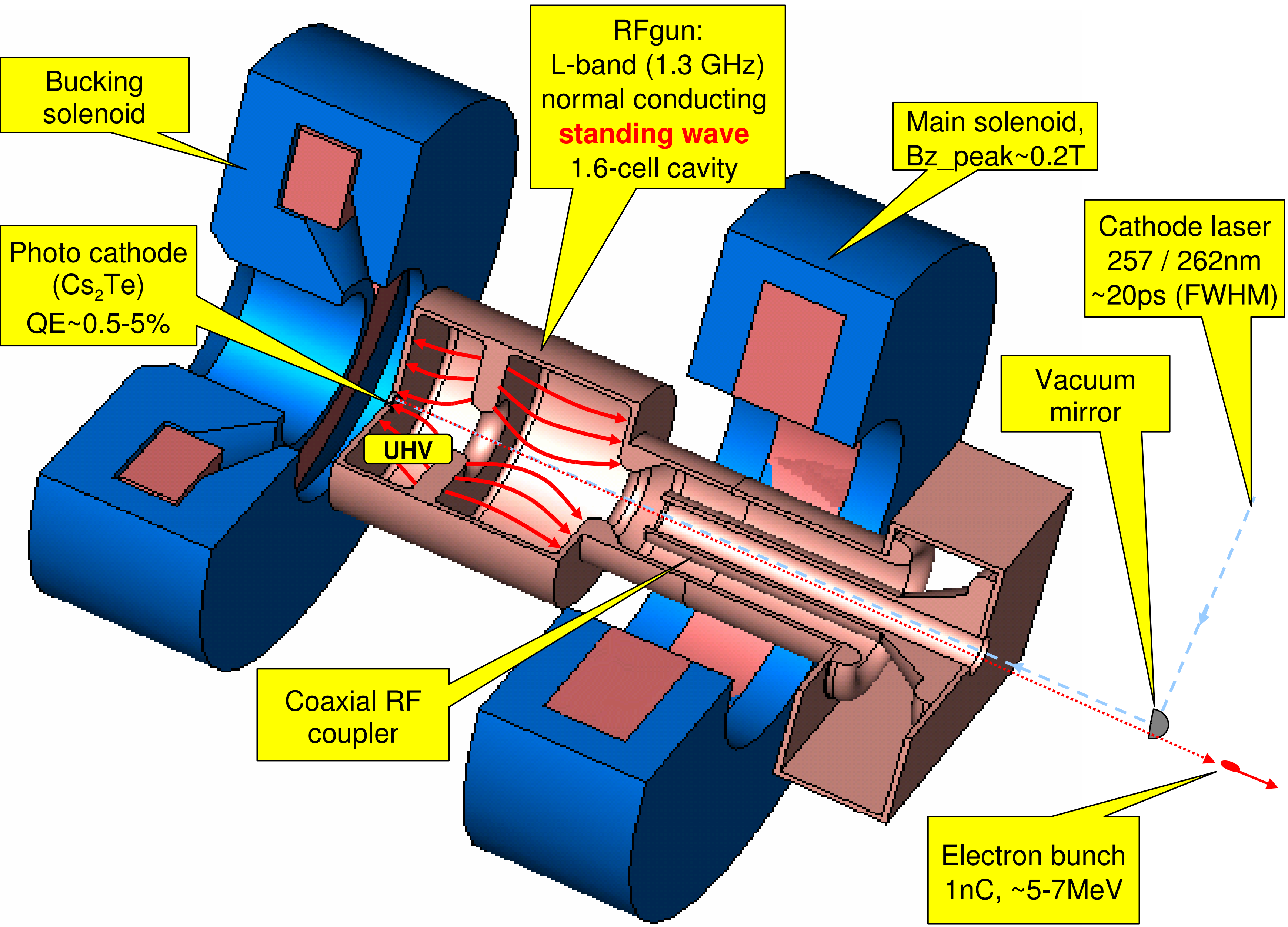

RFgun:
L-band (1.3 GHz)
normal conducting
standing wave
1.6-cell cavity
Coaxial RF
coupler

PITZ : RF gun

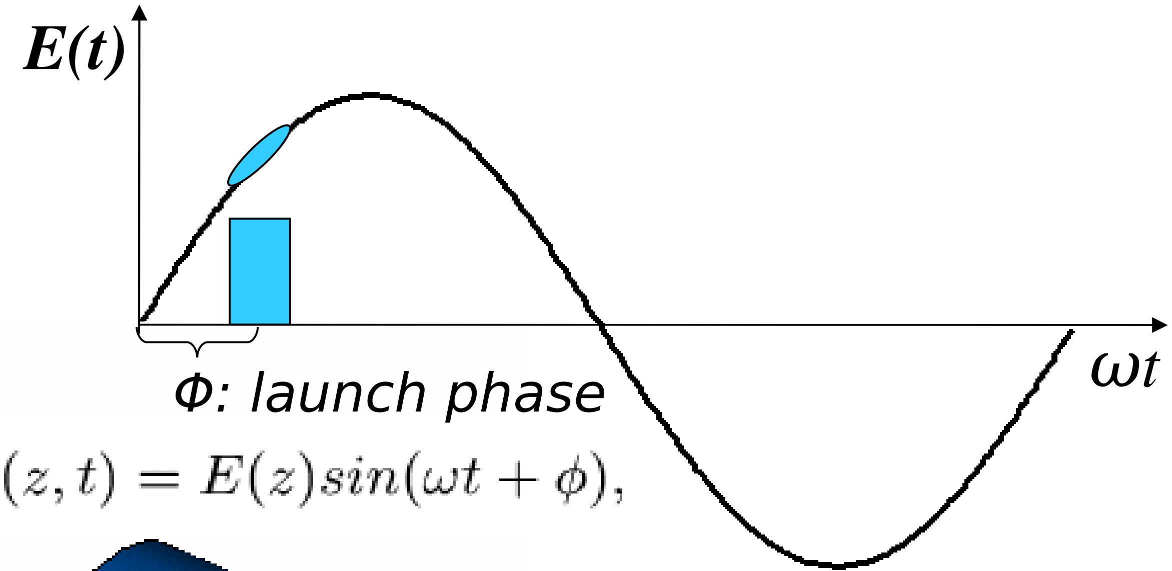


RFgun:
L-band (1.3 GHz)
normal conducting
standing wave
1.6-cell cavity
Photo cathode
(Cs_2Te)
QE~0.5-5%
UHV
Cathode laser
257 / 262nm
~20ps (FWHM)
Vacuum
mirror
Coaxial RF
coupler
Electron bunch
1nC, ~5-7MeV

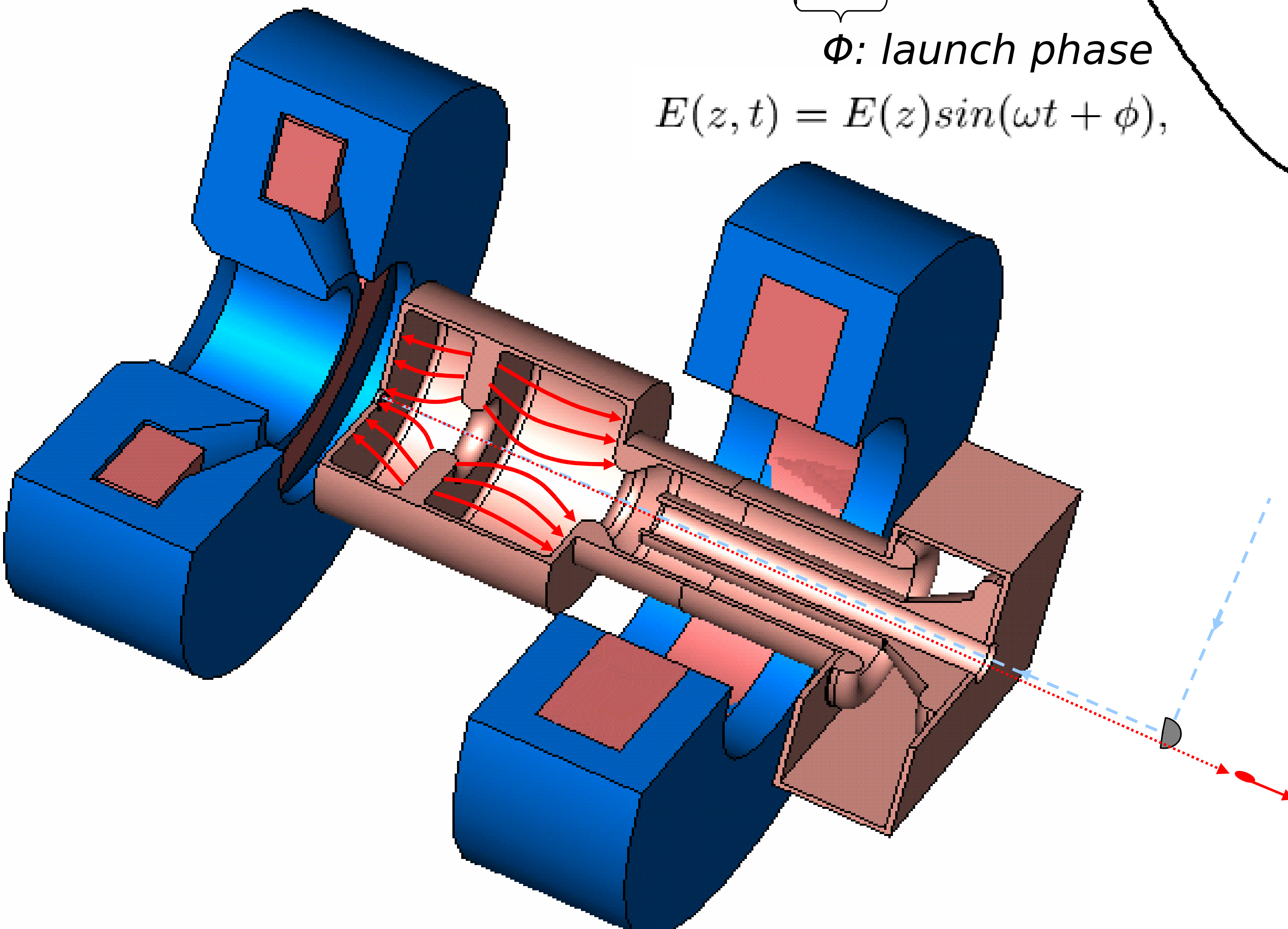
PITZ : RF gun


RFgun:
L-band (1.3 GHz)
normal conducting
standing wave
1.6-cell cavity
Bucking solenoid
Main solenoid,
Bz_peak~0.2T
Photo cathode
(Cs_2Te)
QE~0.5-5%
Cathode laser
257 / 262nm
~20ps (FWHM)
Vacuum mirror
UHV
Coaxial RF coupler
Electron bunch
1nC, ~5-7MeV

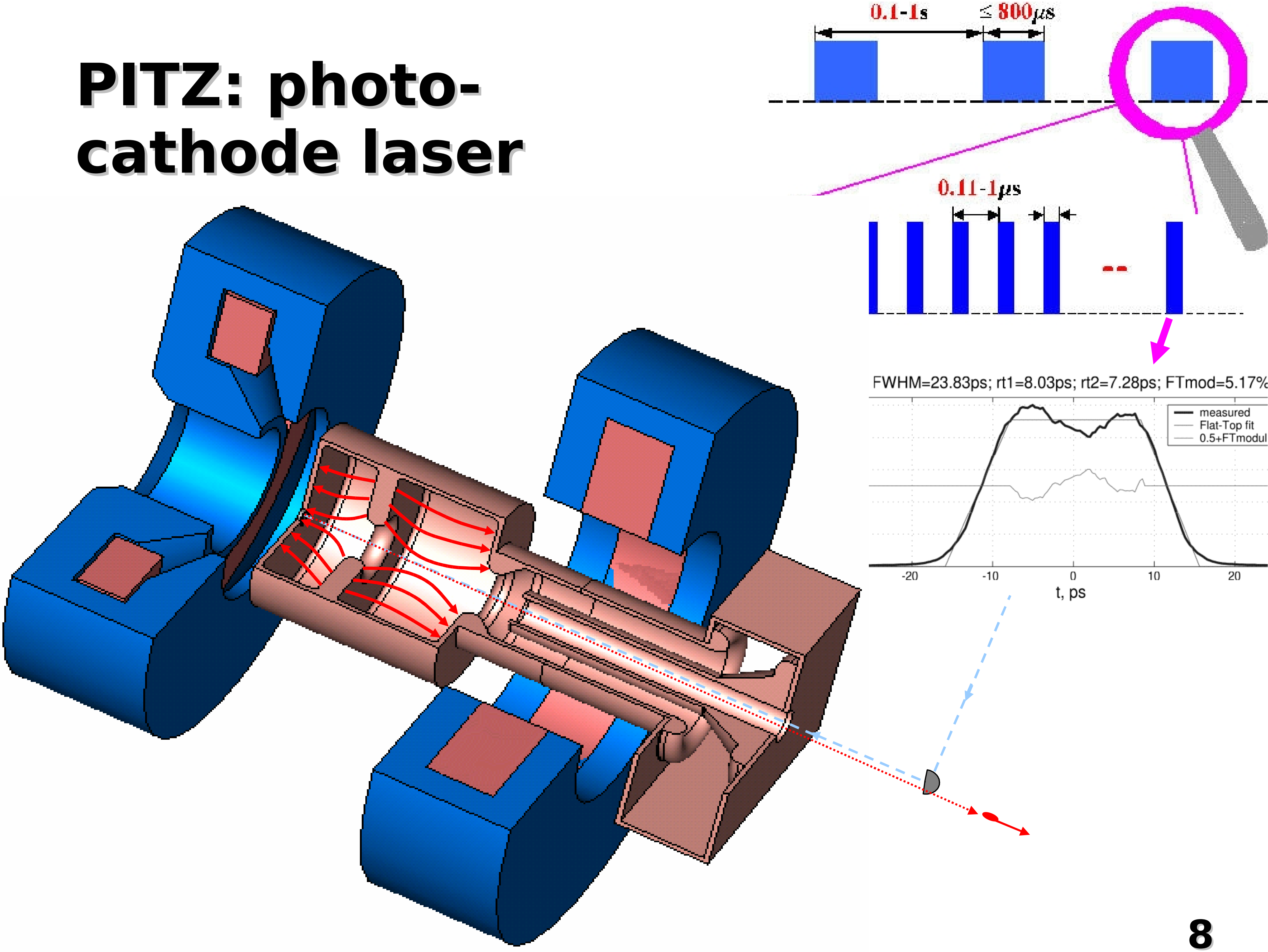
PITZ: RF gun launch phase



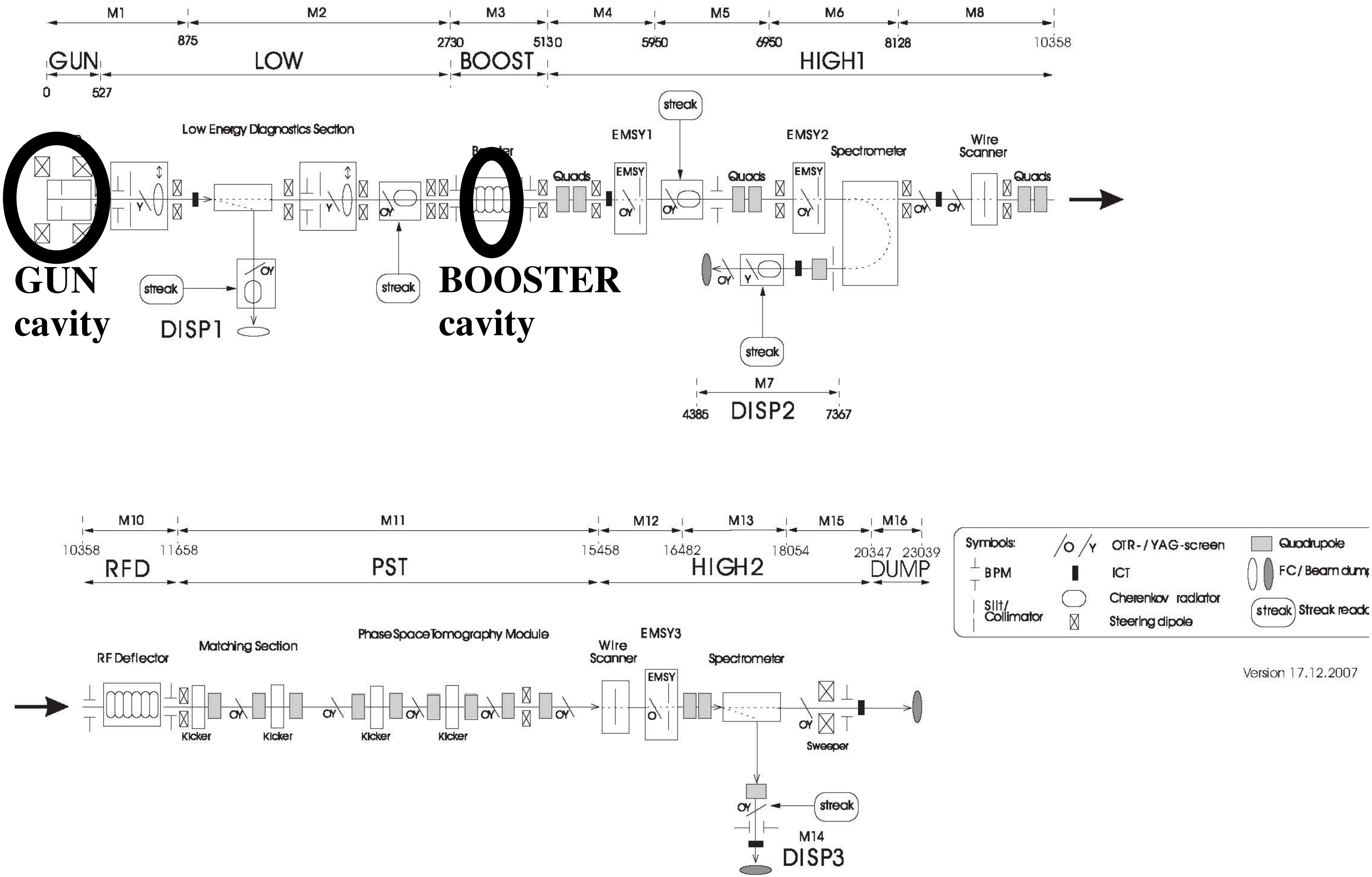
$$E(z,t) = E(z) sin(\omega t + \phi),$$



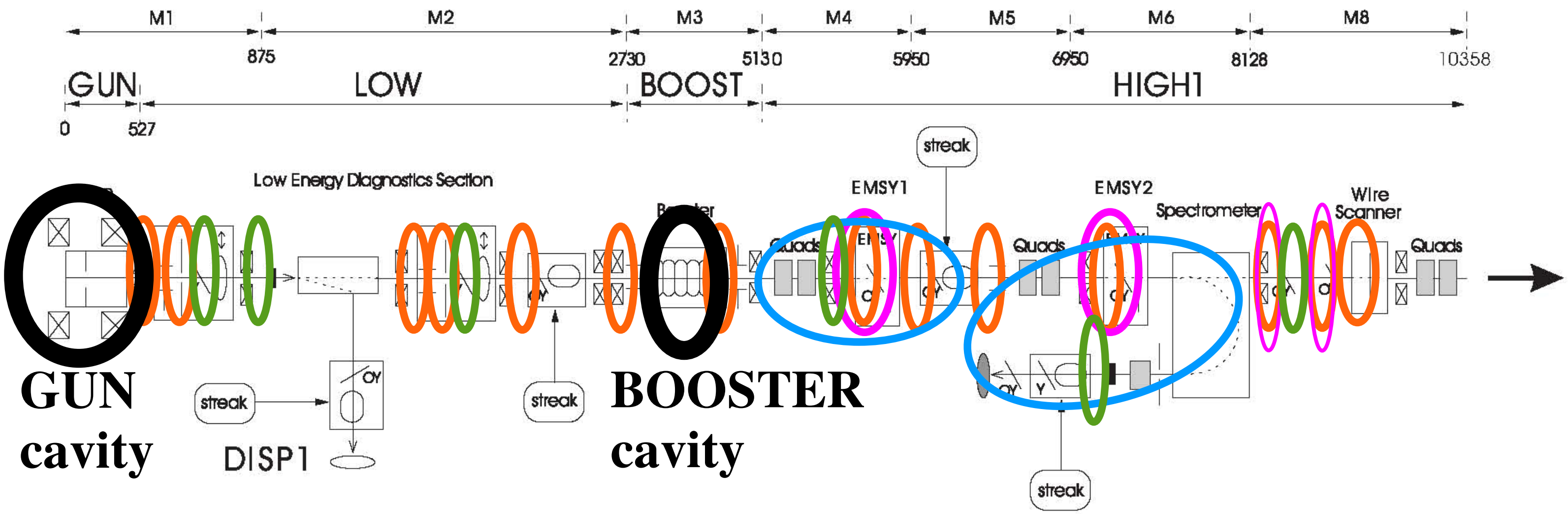
PITZ: photo-cathode laser



PITZ: electron beam line



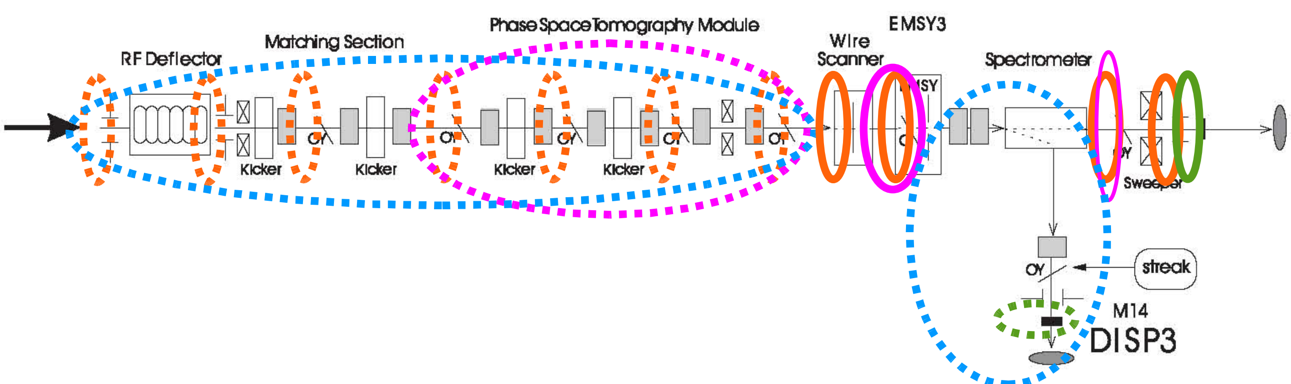
PITZ
diagnostics of electron beam properties



bunch charge:
- faraday cups
- Integrating current transformers (ICTs)

beam position & size:
- view screens and CCD cameras
- wire scanners
- BPMs

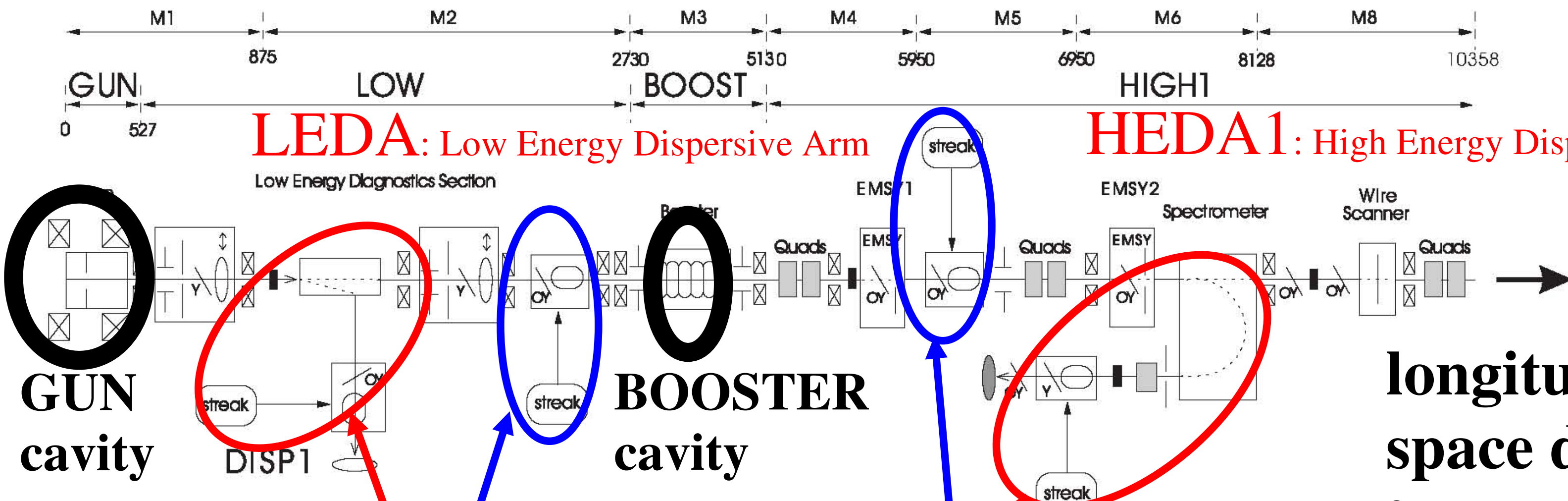
transverse phase space distribution and emittance:
- slit mask stations (slit scan method)
- tomography module



slice emittance:
- RF-deflector and tomography module
- dipole, slit, quadrupole
- quadrupole, silica aerogel and streak camera

Contribution to PITZ diagnostics

diagnostics of longitudinal bunch properties



LEDA: Low Energy Dispersive Arm

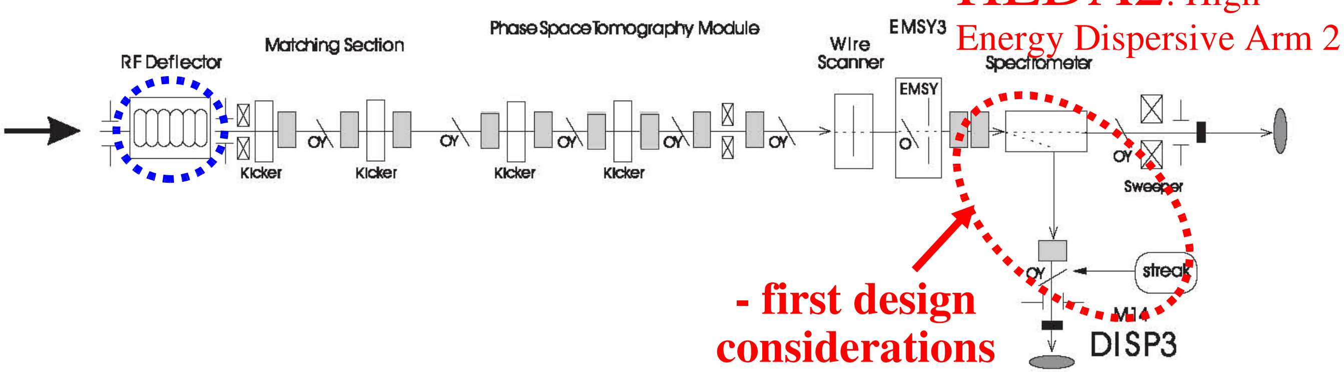
HEDA1: High Energy Dispersive Arm 1

- modified in order to adjust to higher beam energies
- first measurements performed

- designed
- commissioned
- first measurements performed

longitudinal phase space distribution:

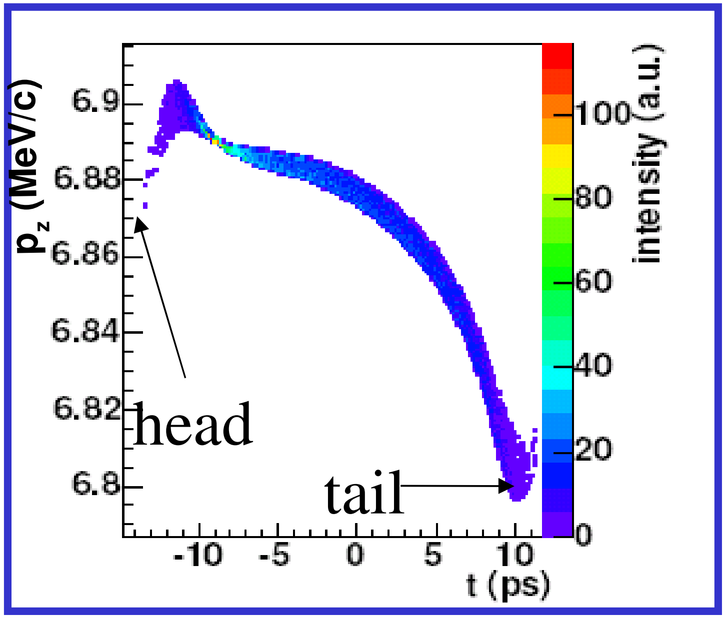
- momentum distribution
- temporal distribution
- longitudinal phase space distribution

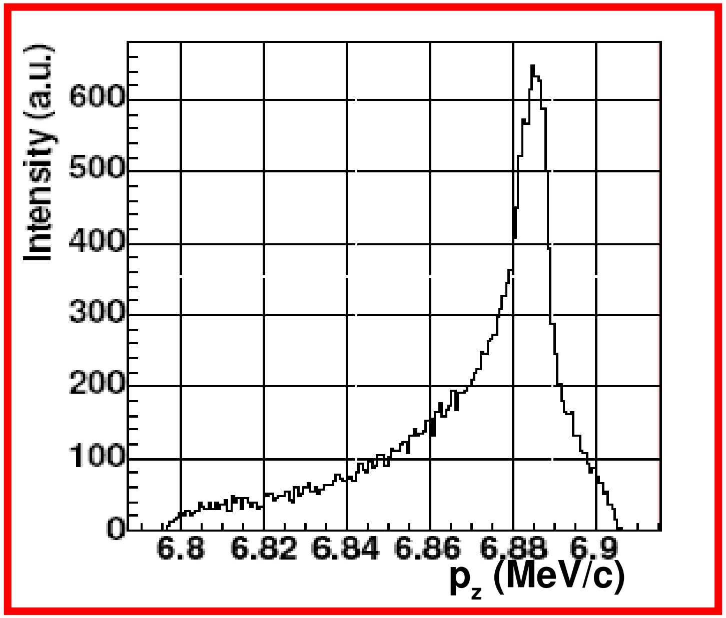


HEDA2: High Energy Dispersive Arm 2

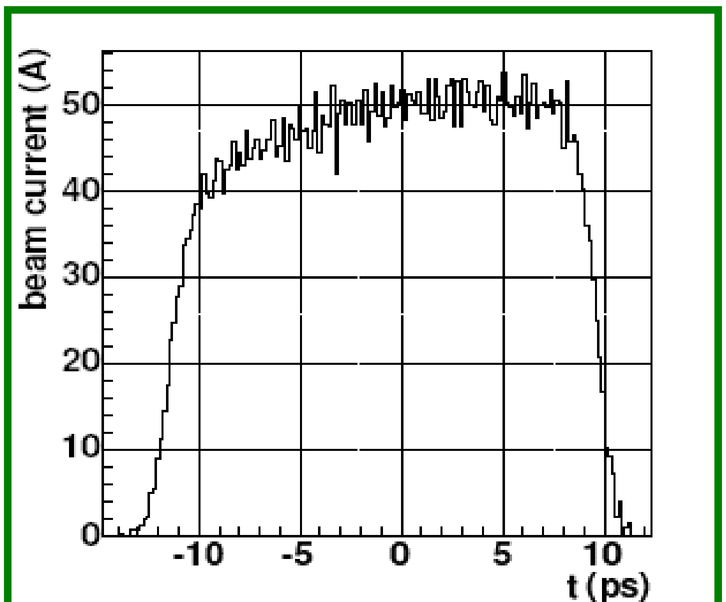
- first design considerations

Simulated longitudinal phase space distribution





- **1 nC**
- 60 MV/m
- 0.5 m after the cathode
- phase of max. momentum gain
- B_{main} = 176 mT
- cathode laser:
  - long.: flat-top FWHM : 20 ps rise time : 2 ps
  - transv.: flat-top Ø : 2 mm



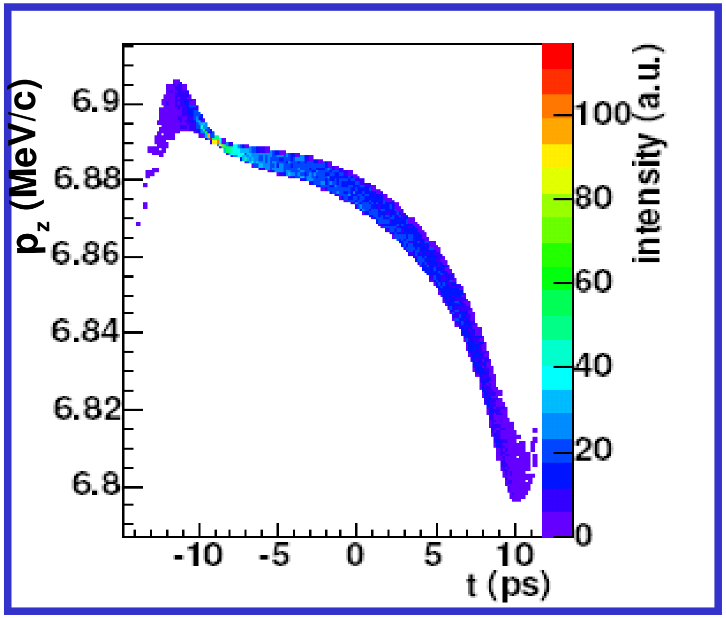
projections of longitudinal phase space distribution:

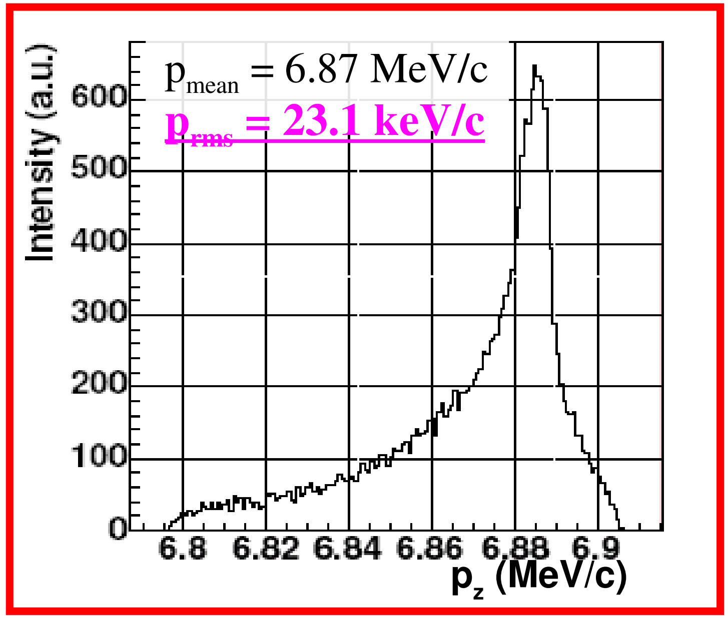
- longitudinal momentum distribution
- temporal distribution

area of longitudinal phase space: longitudinal emittance ε_z

$$\varepsilon_z = \sqrt{<(\Delta p_z)^2> <(\Delta z)^2> - <\Delta p_z \Delta z>^2}$$

Simulated longitudinal phase space distribution





- **1 nC**
- 60 MV/m
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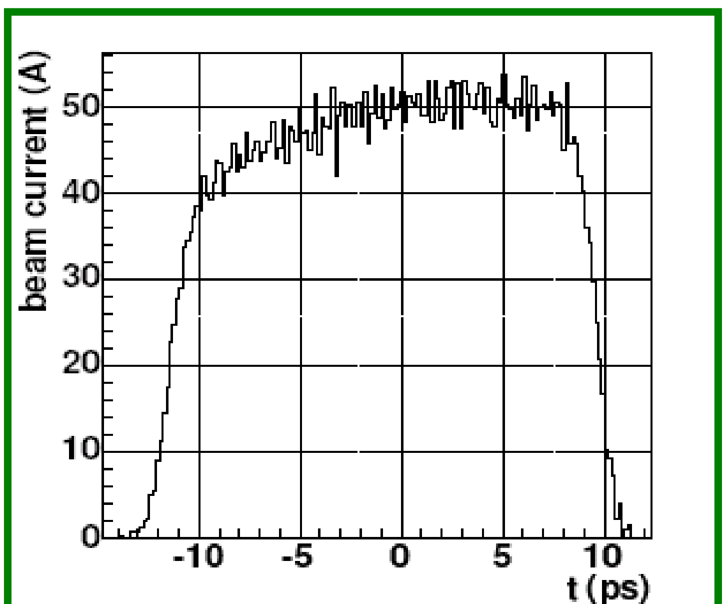
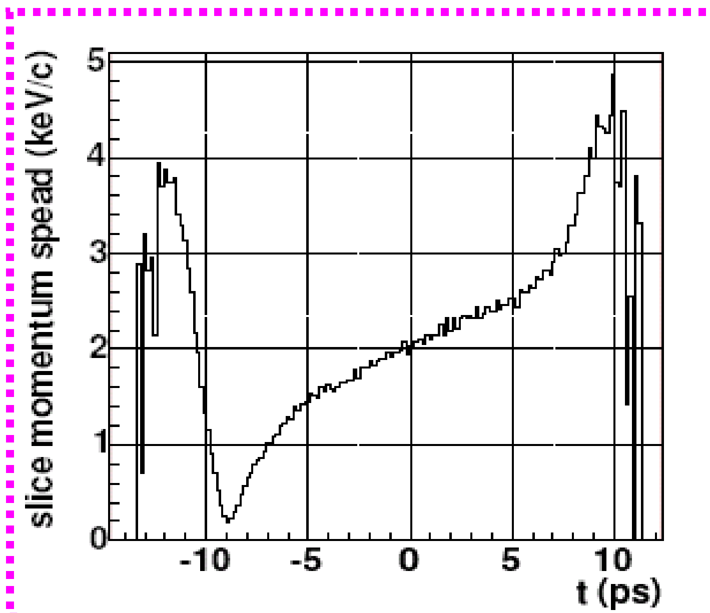
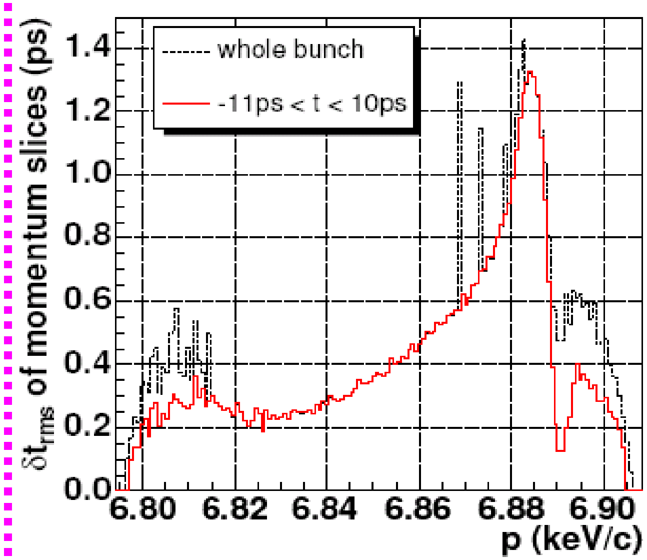
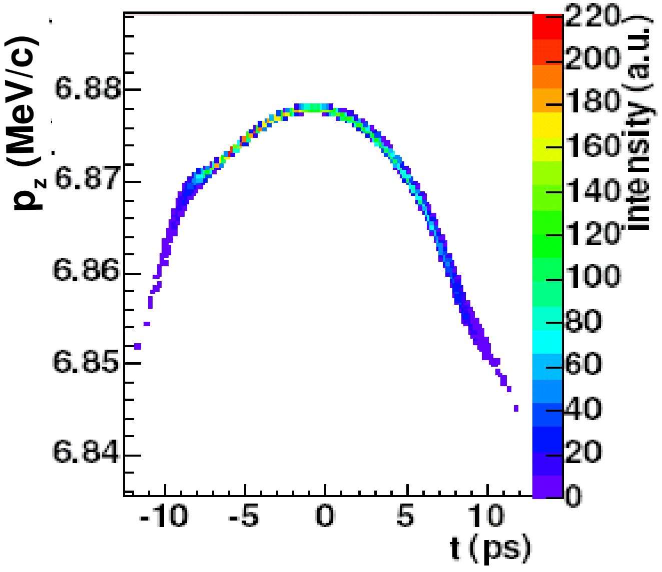
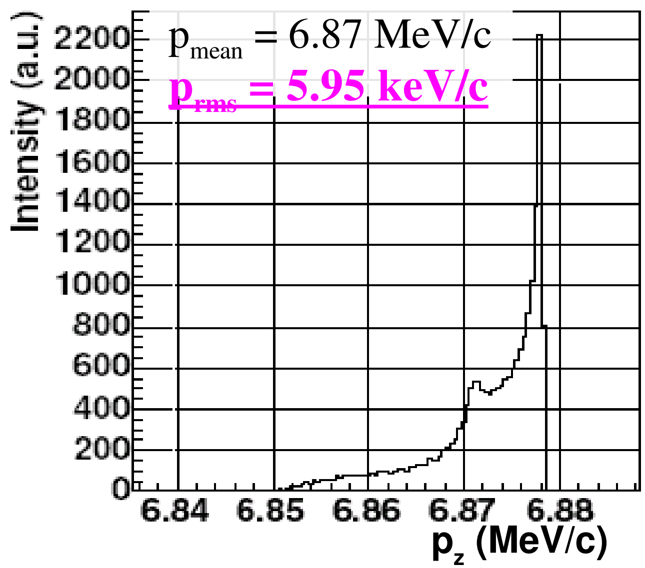




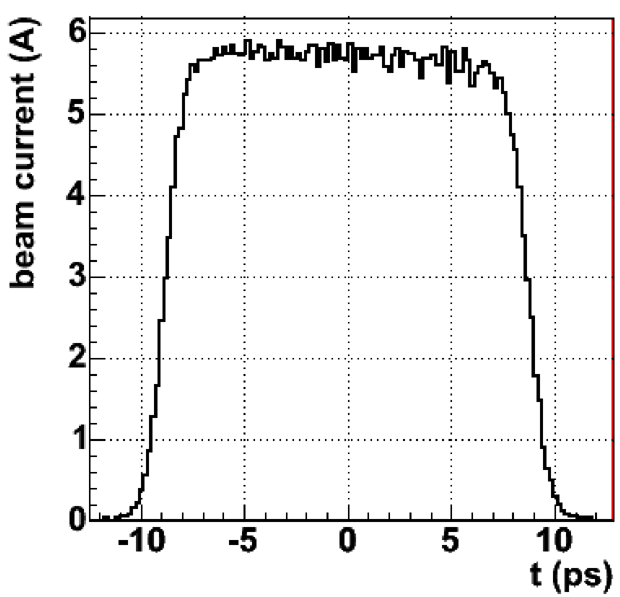


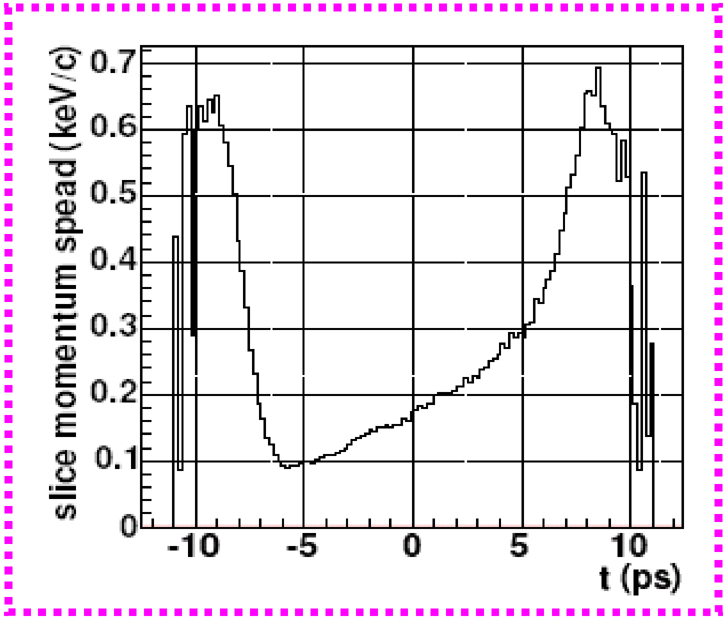
Simulated longitudinal phase space distribution





- **0.1 nC**
- 60 MV/m
- 0.5 m after the cathode
- phase of max. momentum gain
- B_{main} = 176 mT
- cathode laser:
  - long.: flat-top FWHM : 20 ps rise time : 2 ps
  - transv.: flat-top Ø : 2 mm





Reduction of the charge for 1 nC to 100 pC causes a reduction of space charge forces and thus momentum spread, slice momentum spread (<1 keV/c along the whole bunch) and bunch length

Devices for measurements of longitudinal phase space distributions at PITZ

- Temporal charge distribution:
  - Silica aerogel (Cherenkov radiator) or OTR (optical transition radiator) as radiators and a streak camera
  - RF deflector
- Beam momentum distribution:
  - dipole magnet and a view screen
- Longitudinal phase space distribution:
  - dipole magnet, radiator and streak camera
  - RF deflector and dipole magnet

Devices for measurements of longitudinal phase space distributions at PITZ

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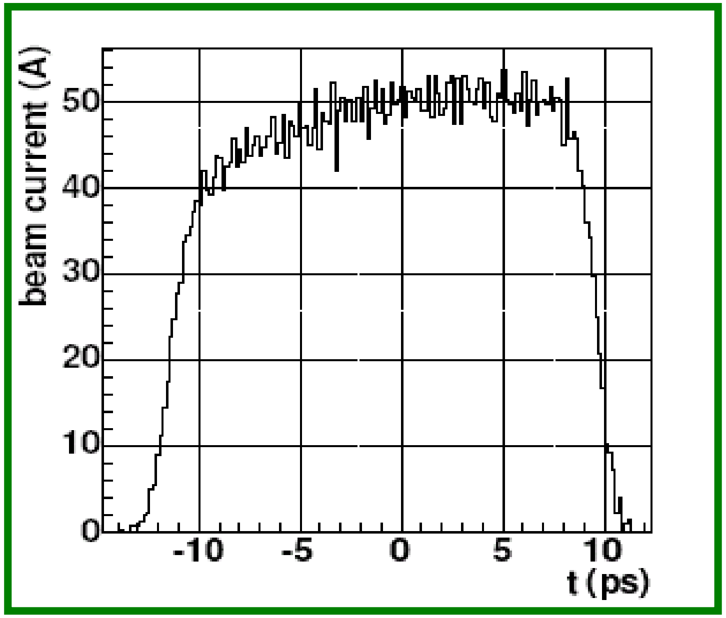
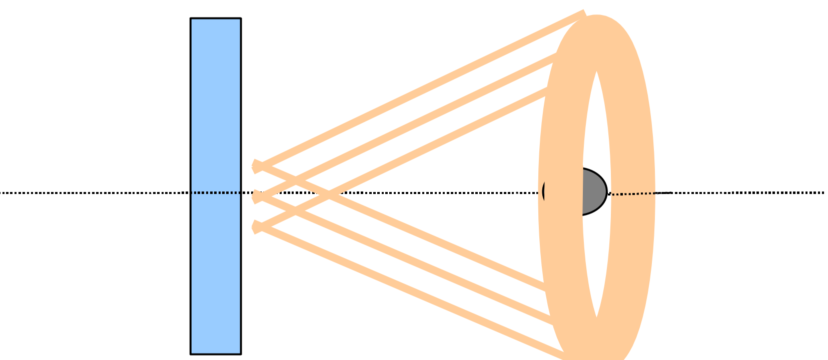


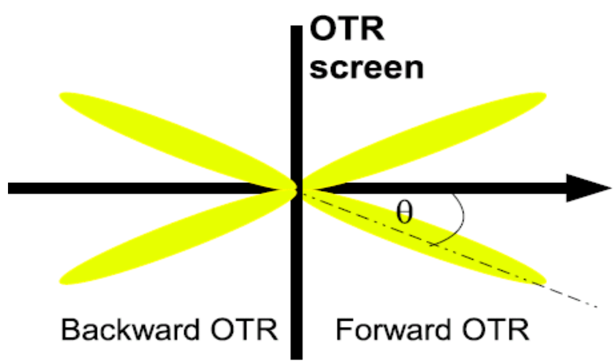
Simulated temporal charge density distribution (1 nC)

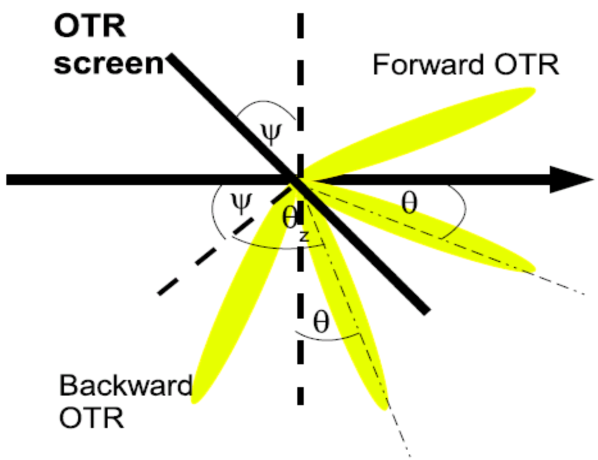
Devices for measurements of longitudinal distributions at PITZ

- Temporal charge distribution:
  - Silica aerogel or OTR as radiators and a streak camera
    - electron bunch produces a light pulse with similar temporal distribution by the Cherenkov effect or transition radiation
    - light transport
    - streak camera measurement

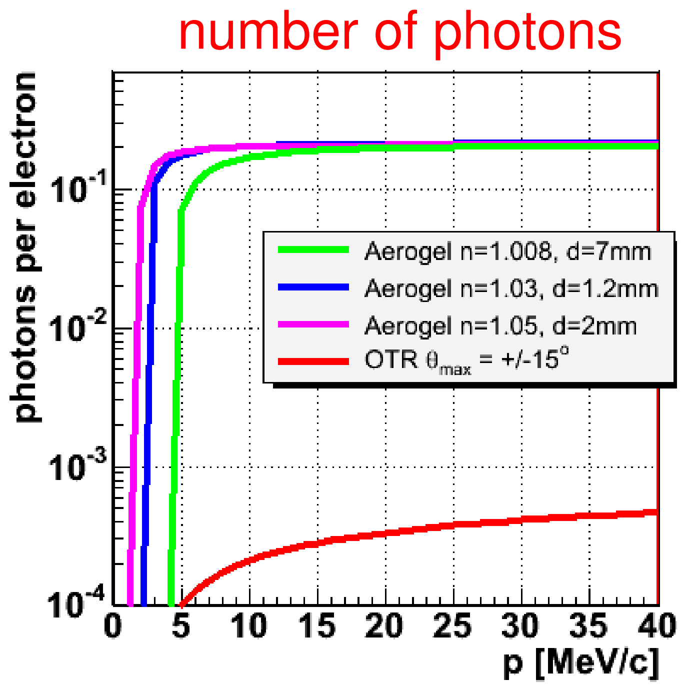


Silica aerogel
n = 1.008 – 1.05
Cherenkov radiator

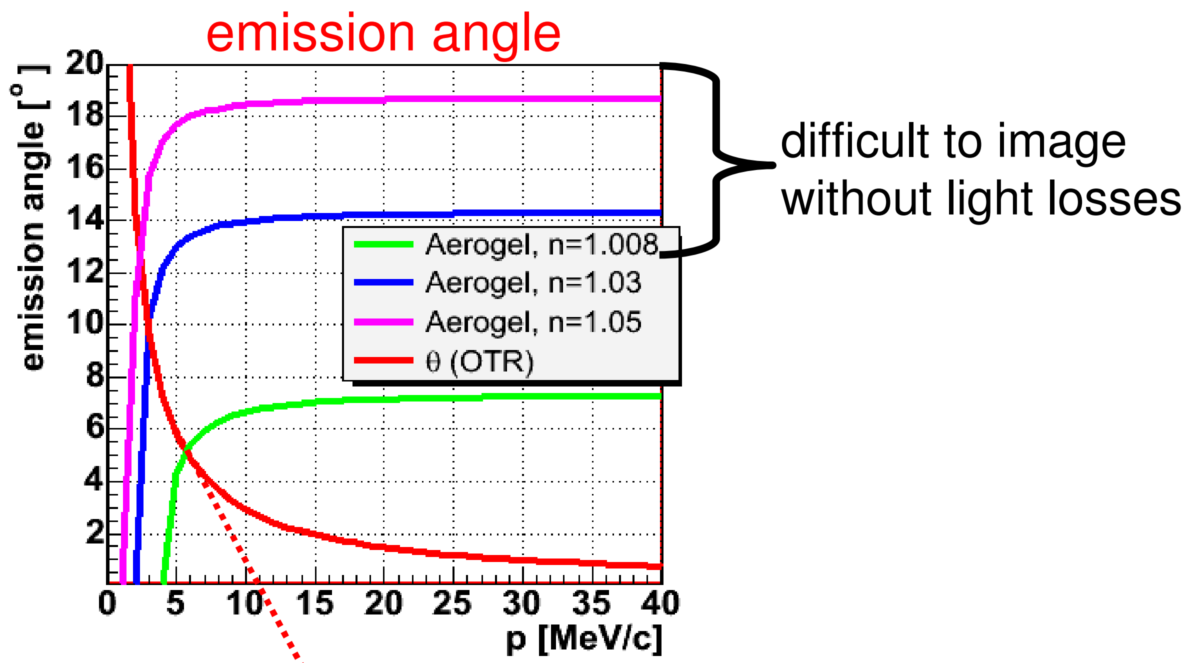


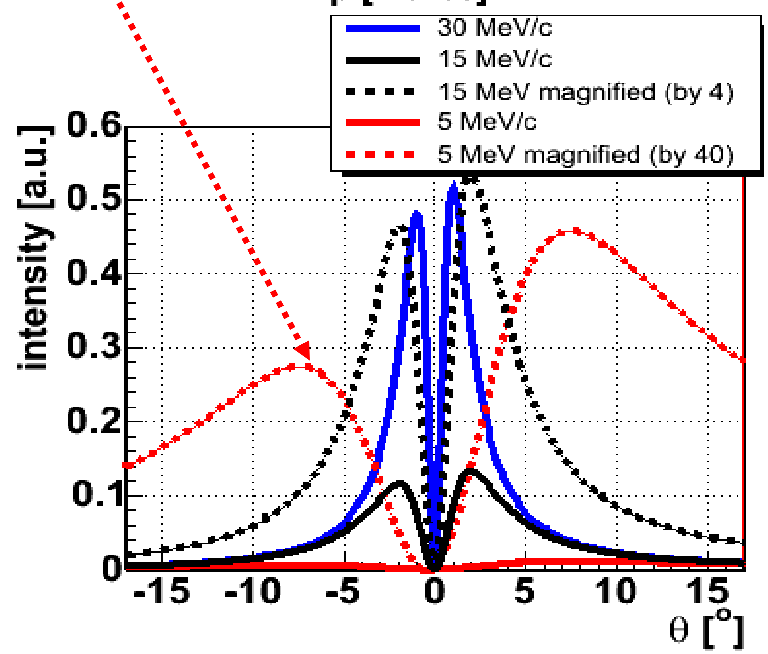


Devices for measurements of longitudinal distributions at PITZ



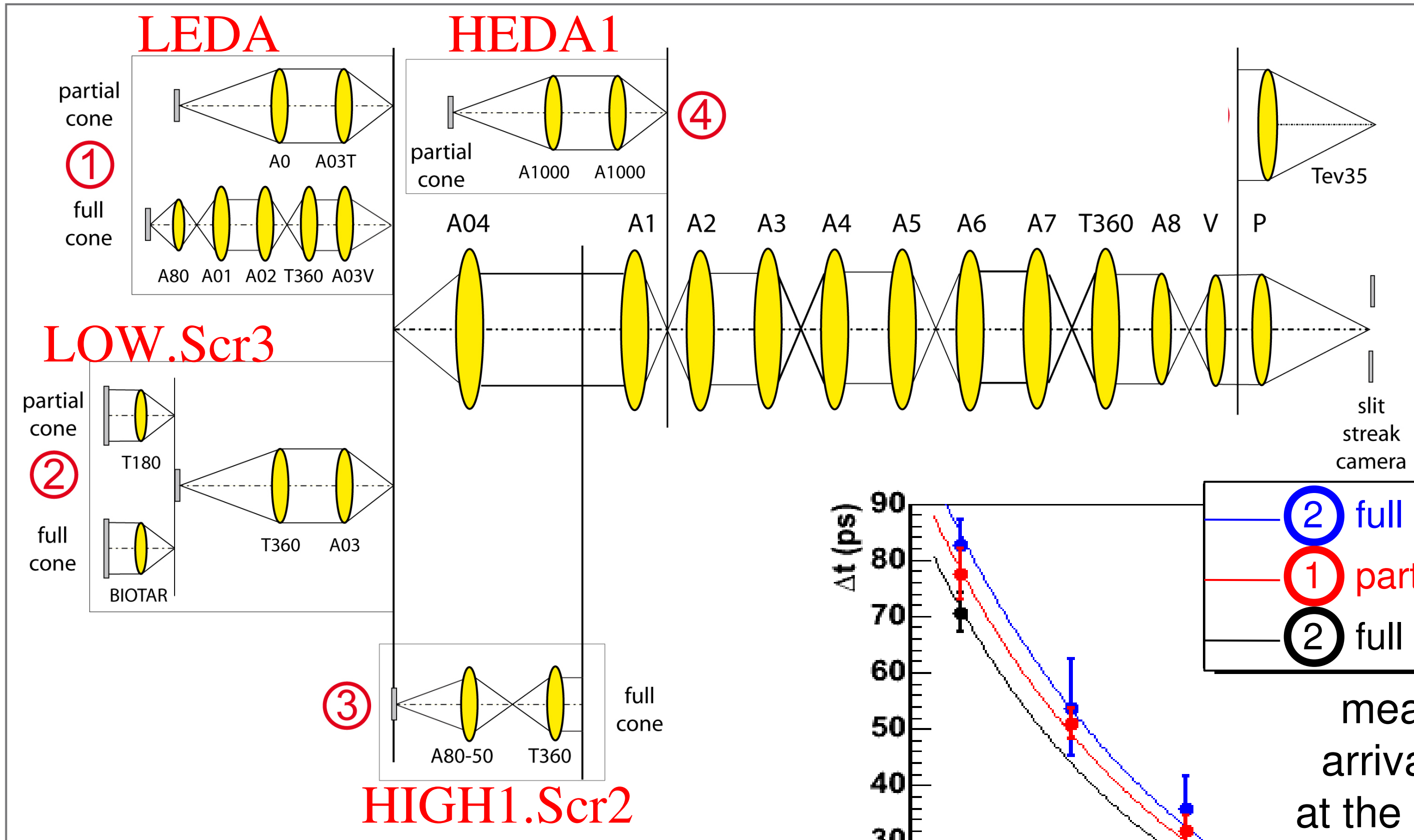
The number of photons produced by silica aerogel (up to 40 MV/m) is several orders of magnitude higher than the number of photons produced by an OTR-screen.

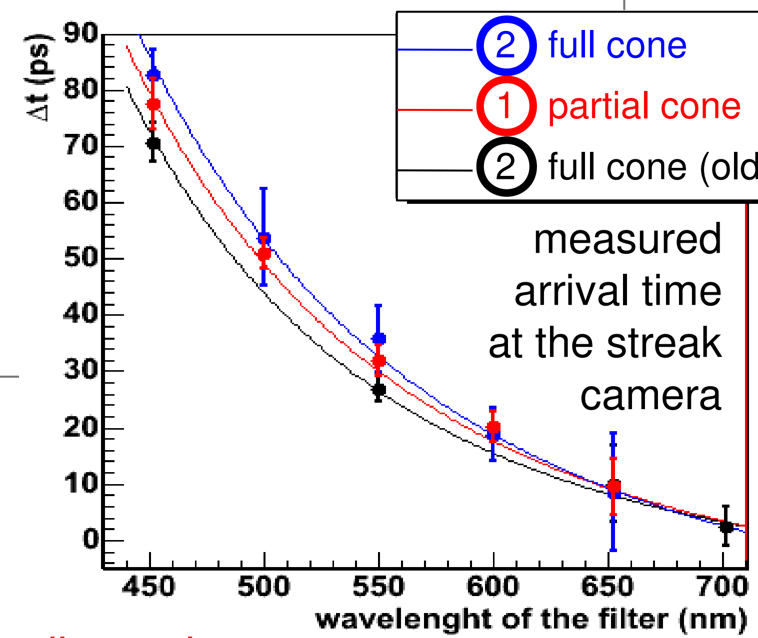




Optical transmission line

The optical system is contains telescopes consisting of achromatic lenses.



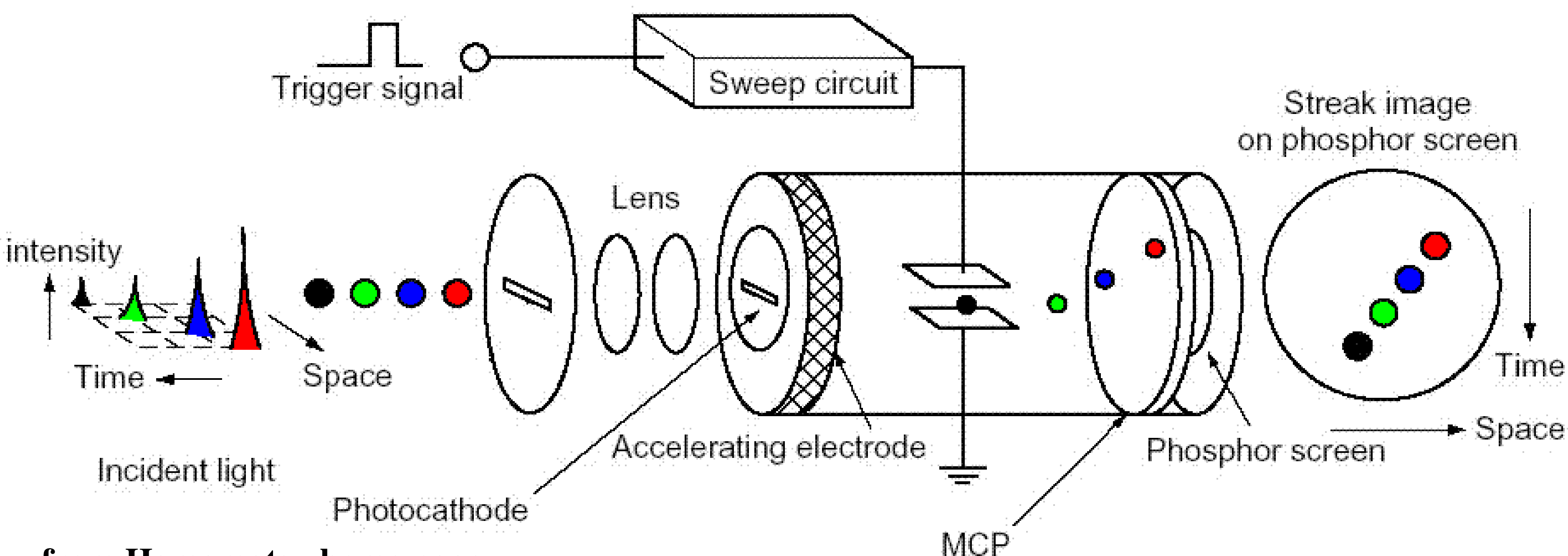


- The optical system limits the temporal resolution due to dispersion.
- The temporal resolution can be reduced by using narrow bandwidth wavelength filter, but at the expense of the reduced number of photons.
- A system consisting of reflective optics is under development.

Influence of the streak camera (C5680)

resolution is limited by:

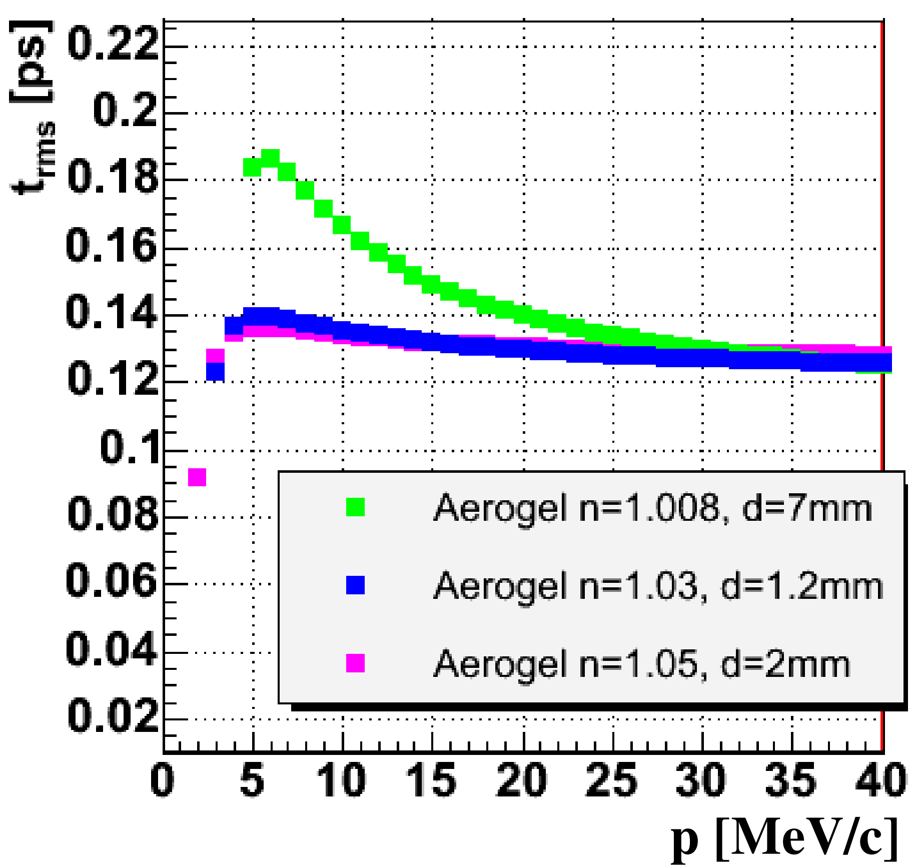
- **streak camera slit width and space charge**
  - **slit width of 100 µm: Δt = 1.75 ps**
  - correction: deconvolution (signal without RF-field)
- **RF jitter and jitter of signal arrival time**
  (due to the overlap of several measurements)
- **diff. momentum of photo electrons for diff. wavelength**



from Hamamatsu home page,
C5680 series (www.hama-comp.com)

Temporal resolution

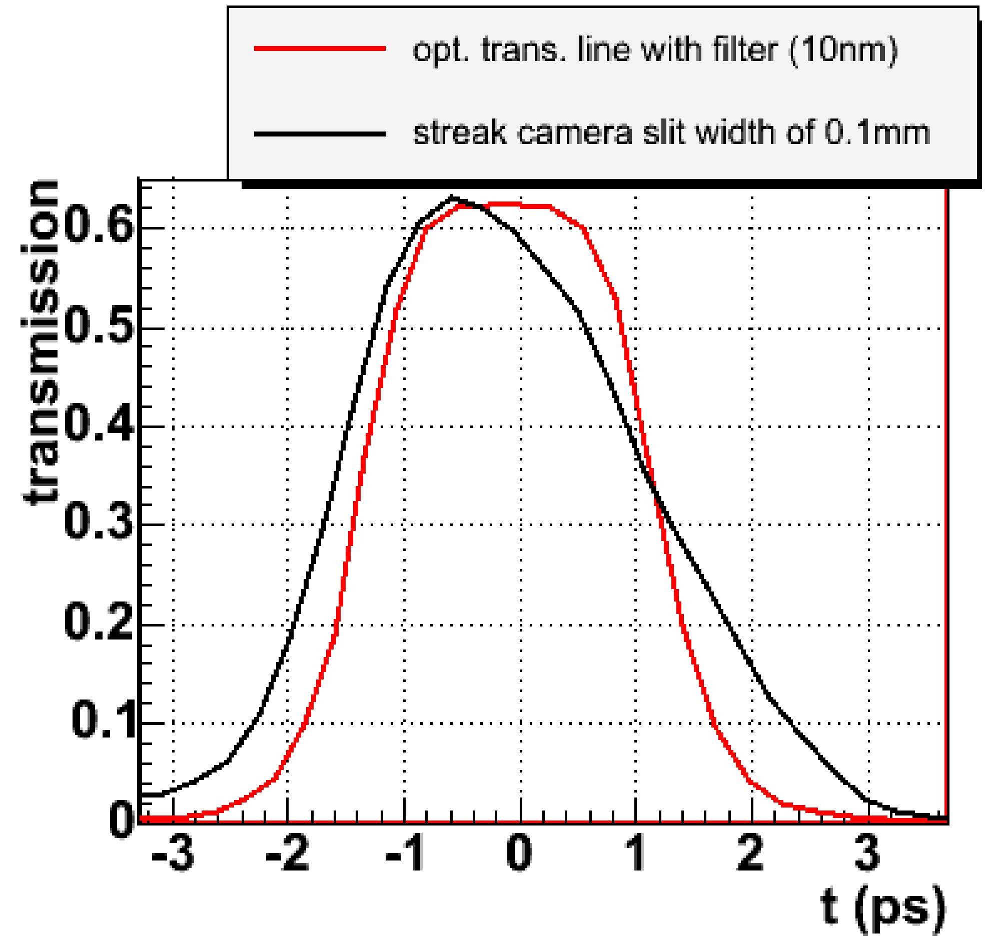
Limitation of the temporal resolution by the different Cherenkov radiators



n : index of refraction

d : thickness

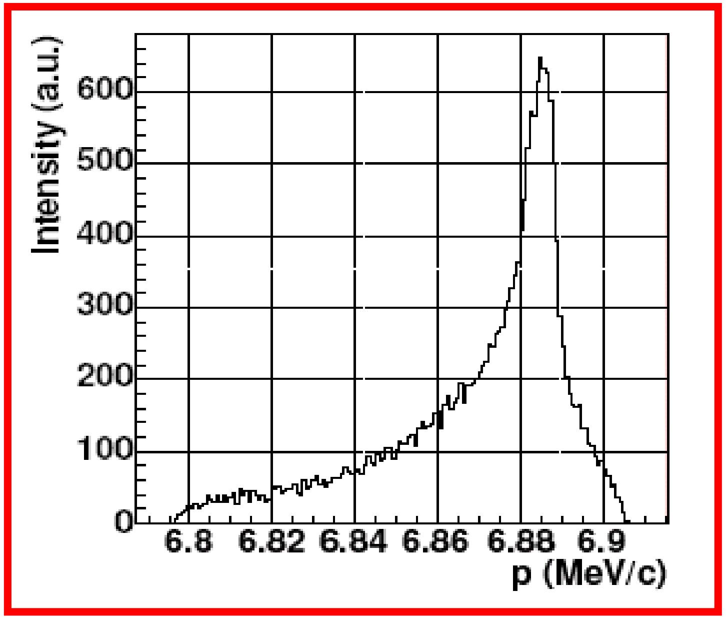
Limitation of the temporal resolution by the optical system using an optical transmission filter of 550 nm with 10 nm bandwidth and a streak camera slit width of 0.1 mm



temporal resolution by the optical system and the streak camera (0.1 mm slit width) is about 4 ps FWHM

Devices for the measurement of the longitudinal phase space distribution at PITZ

- Beam momentum distribution:
  - dipole magnet and a view screen



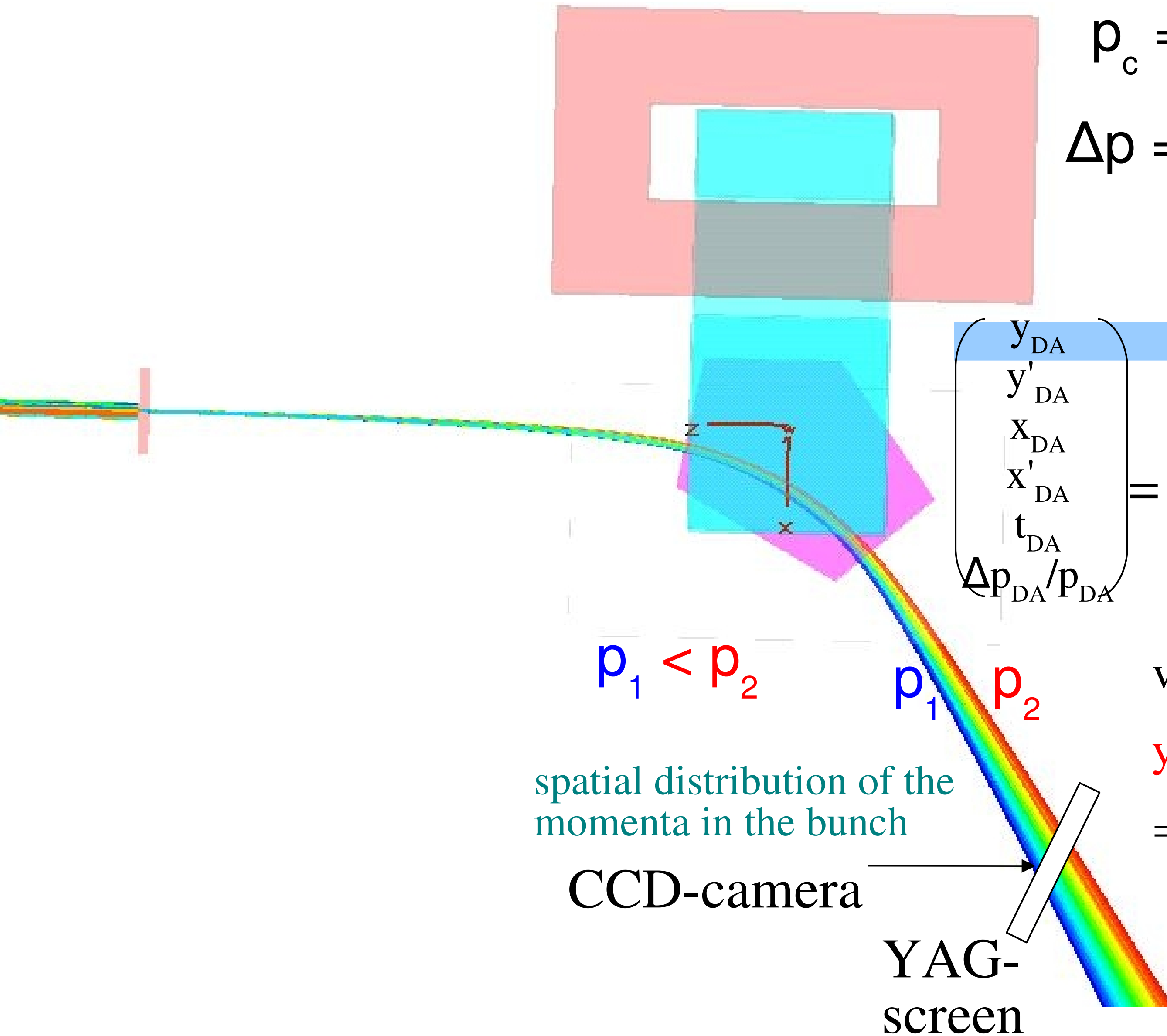
simulated longitudinal
momentum distribution (1 nC)

Devices for the measurement of the momentum distribution at PITZ

$$p = e / \alpha \int B_{dipole}(l)\, dl$$

$$p_c = \left| e\, B_{dipole}\, l_{eff} / \alpha \right|$$

$$\Delta p = p_c\, \Delta y / R_{16}$$



$$\begin{pmatrix} y_{DA} \\ y'_{DA} \\ x_{DA} \\ x'_{DA} \\ t_{DA} \\ \Delta p_{DA}/p_{DA} \end{pmatrix} = \begin{pmatrix} R_{11} & R_{12} & 0 & 0 & 0 & R_{16} \\ R_{21} & R_{22} & 0 & 0 & 0 & R_{26} \\ 0 & 0 & R_{33} & R_{34} & 0 & 0 \\ 0 & 0 & R_{43} & R_{44} & 0 & 0 \\ R_{51} & R_{52} & 0 & 0 & 1 & R_{56} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} y_0 \\ y'_0 \\ x_0 \\ x'_0 \\ t_0 \\ \Delta p_0/p_0 \end{pmatrix}$$

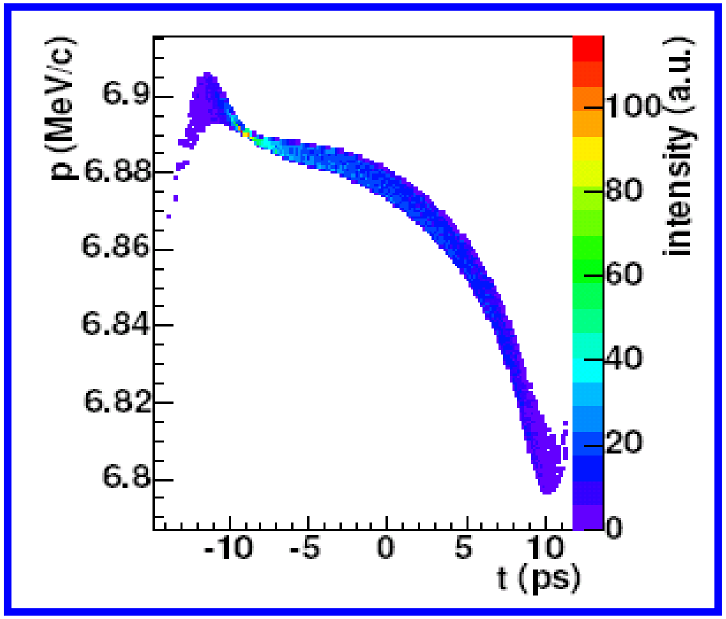
vertical position of a particle:

$$y = R_{11}\, y_0 + R_{12}\, y'_0 + R_{16}\, \Delta p_0/p_0$$

$$\Rightarrow R_{16}\, \Delta p_0/p_0 \gg R_{11}\, y_0 + R_{12}\, y'_0$$

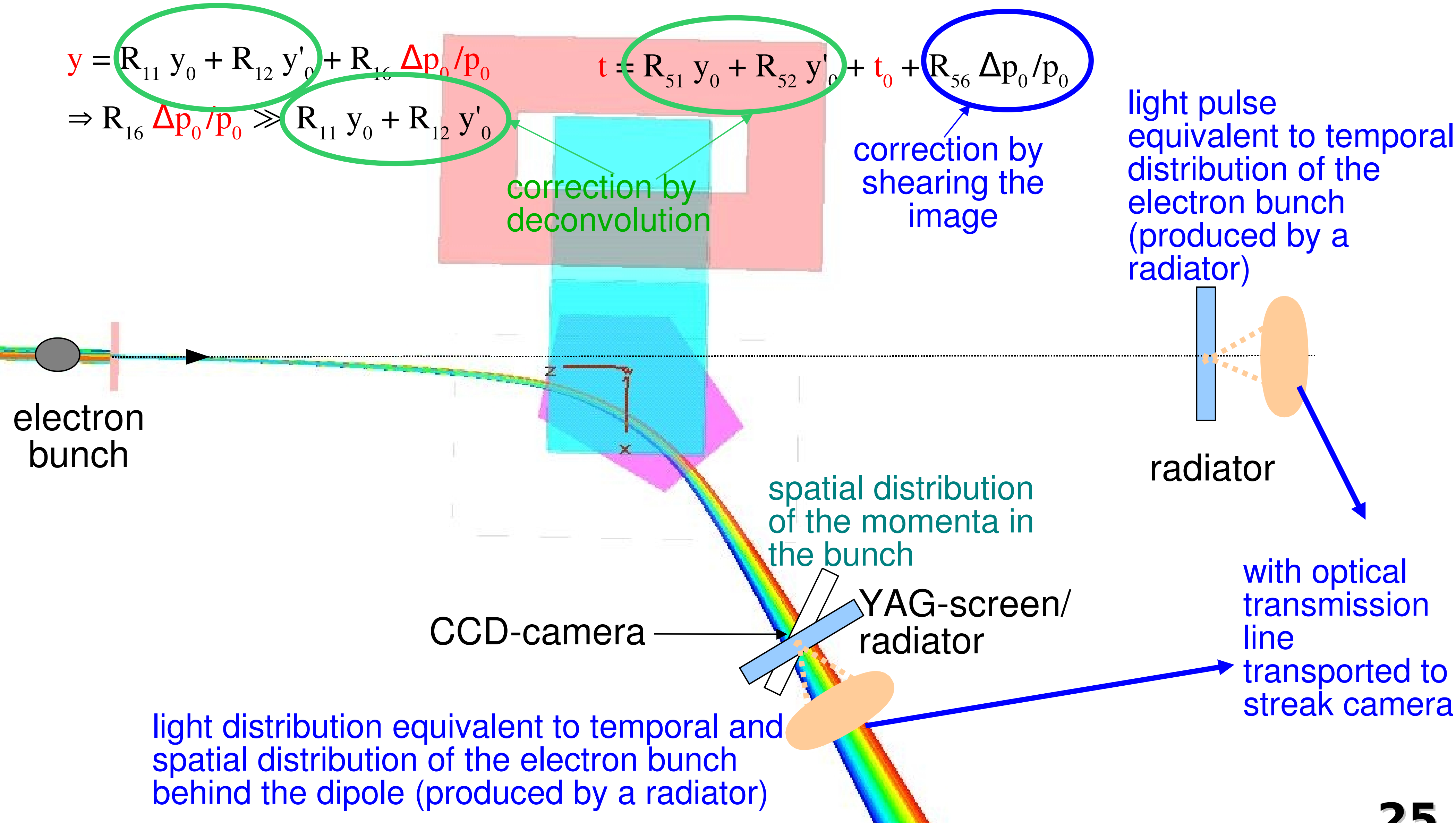
Devices for the measurement of the longitudinal phase space distribution at PITZ

- Longitudinal phase space distribution:
  - dipole magnet, radiator and streak camera

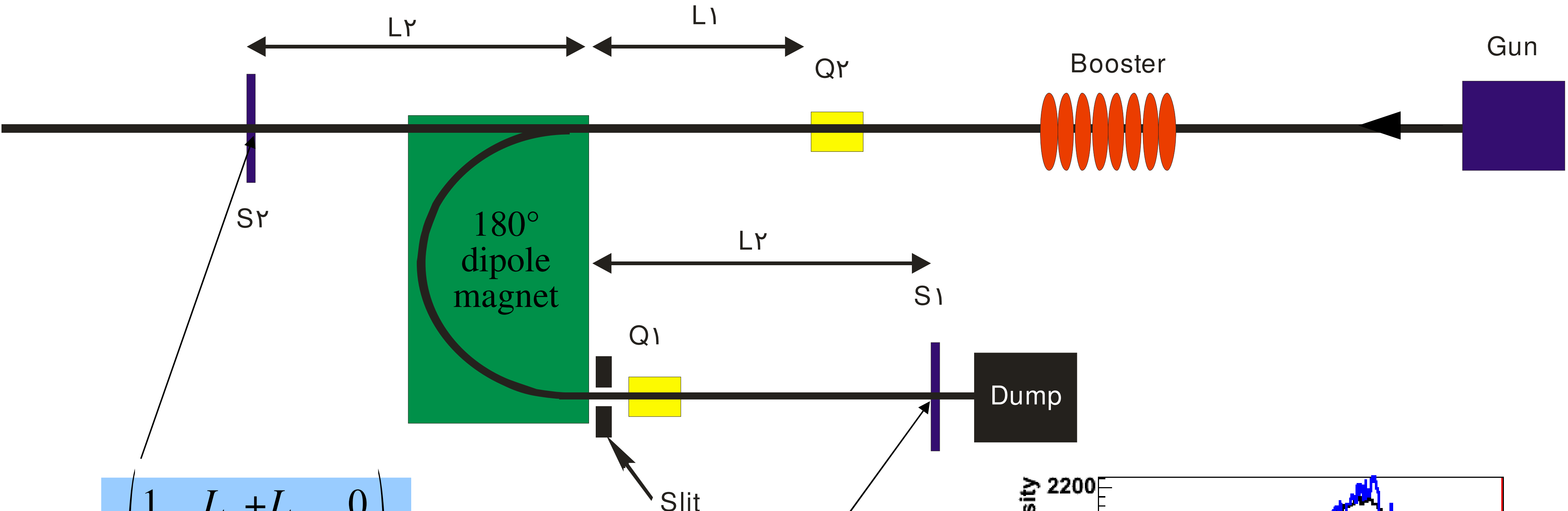


simulated longitudinal phase space distribution (1 nC)

Devices for the measurement of the longitudinal phase space distribution at PITZ

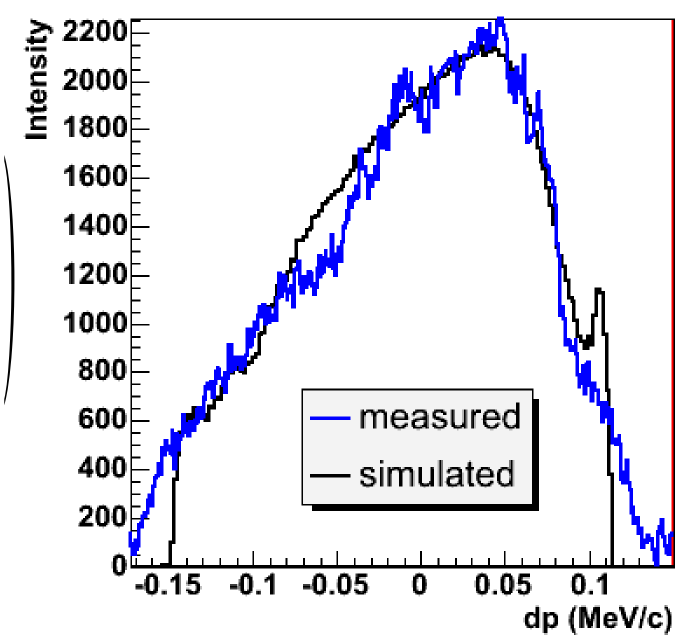


Example for a spectrometer magnet (first high energy dispersive arm - HEDA1)



$$M_S = \begin{pmatrix} 1 & L_1+L_2 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$M_D = \begin{pmatrix} -1 & -L_1-L_2 & 2\rho \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

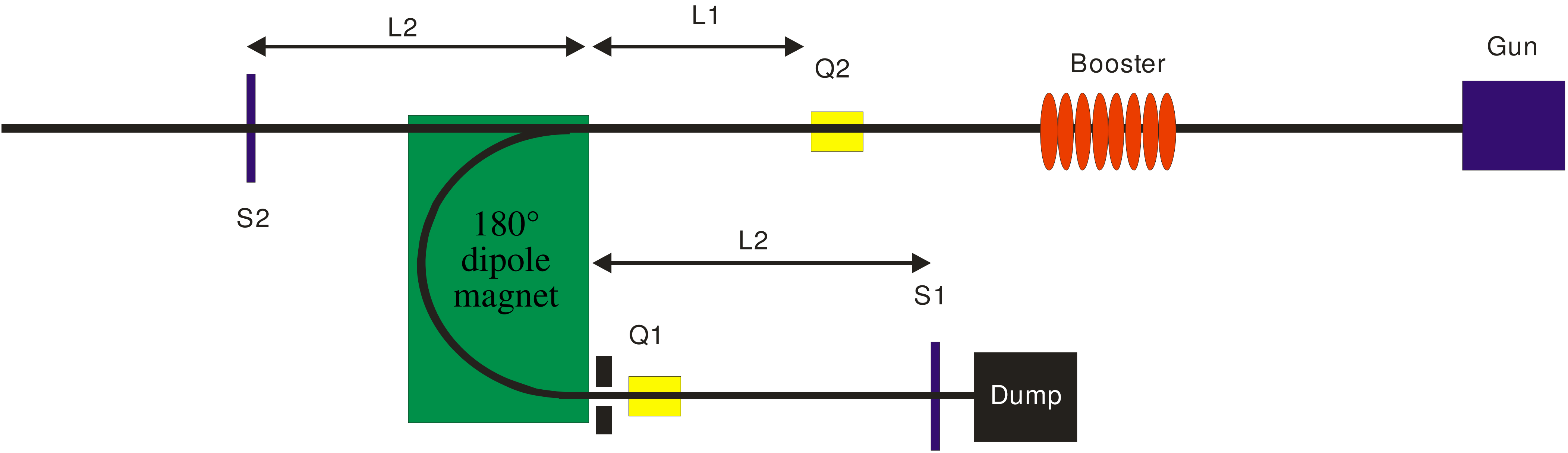


vertical distribution

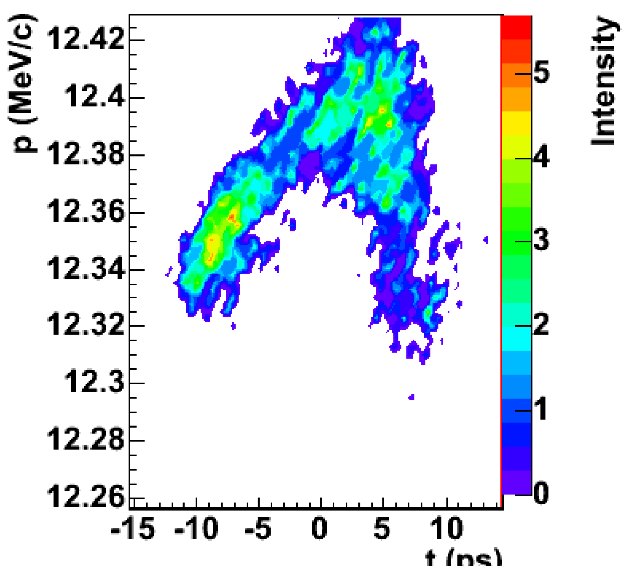
$$y = R_{11}\, y_0 + R_{12}\, y'_0 + R_{16}\, \Delta p_0/p_0$$

$$\Rightarrow R_{16}\, \Delta p_0/p_0 \gg R_{11}\, y_0 + R_{12}\, y'_0$$

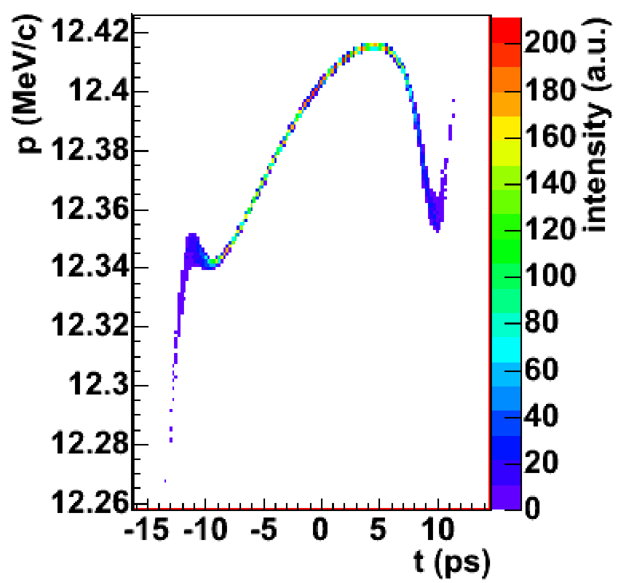
Example for a spectrometer magnet (first high energy dispersive arm - HEDA1)



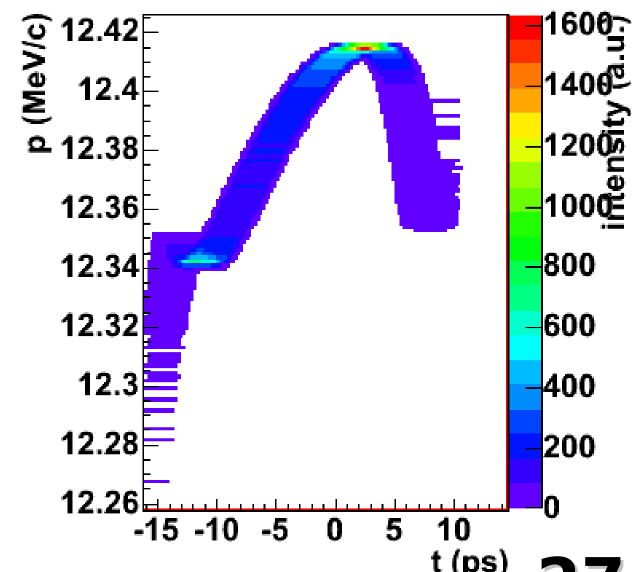
Measurement



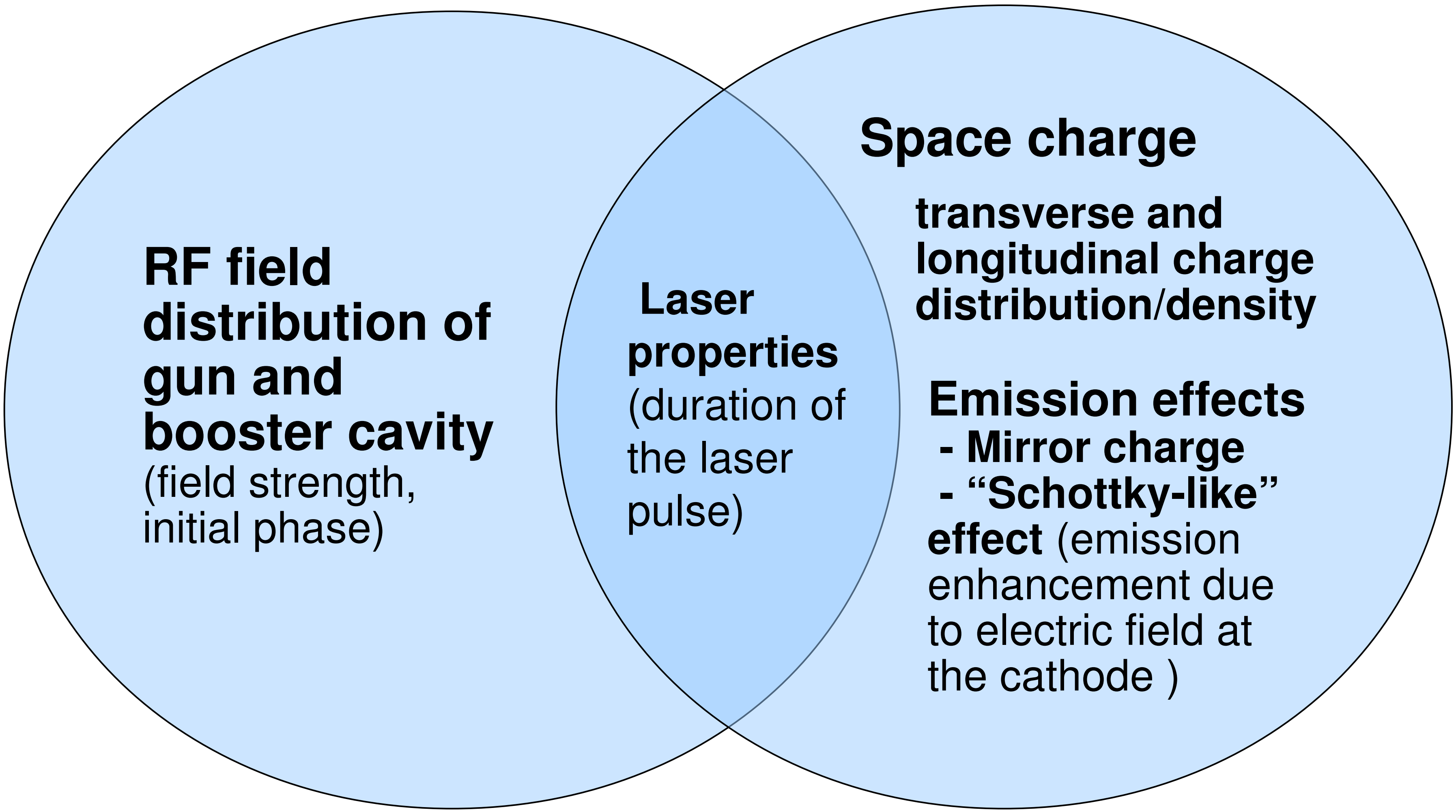
ASTRA Simulation



Simulation convoluted with resolution of streak beam line



The longitudinal phase space distribution is affected by:

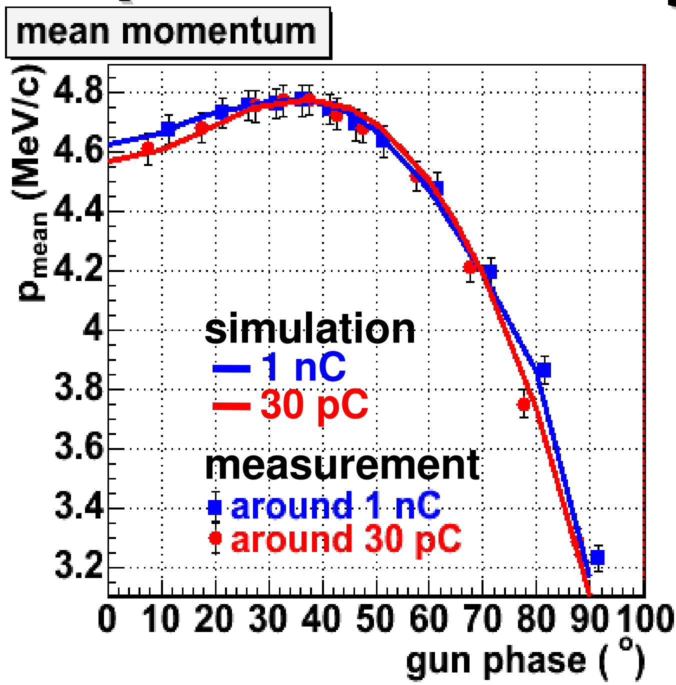


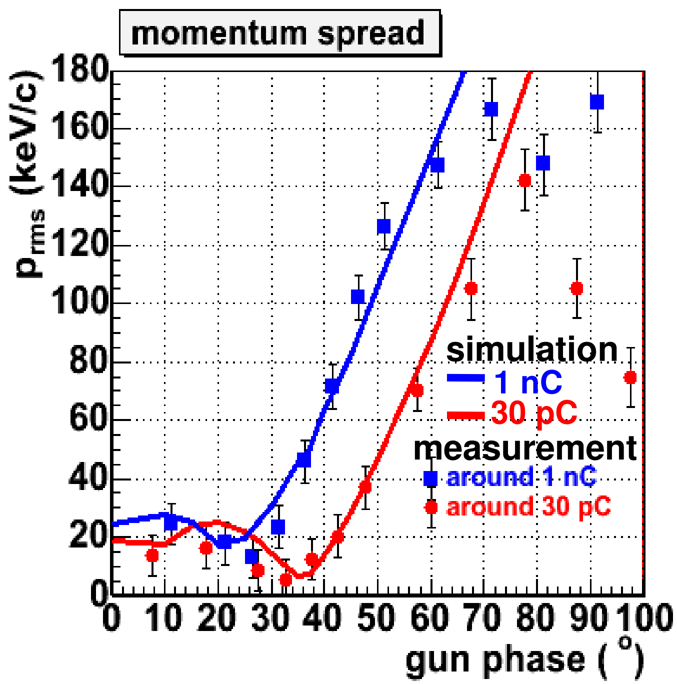
→ These properties and effects are coupled.

Measurements of longitudinal phase space distribution

- **Dependence on bunch charge:**
  - p_z & p_{rms} for different gun phases after the gun
  - σ_z after the gun
  - longitudinal phase space distribution after the gun
- **Dependence on increased beam energy**
  - p_z vs. gun gradient
  - p_z vs. booster gradient
  - p_z & σ_z vs. gun and booster phase
- **Dependence on laser properties**
  - σ_z vs. $\sigma_{xy\text{-}laser}$
  - long. phase space distribution for diff. temp. laser distribution

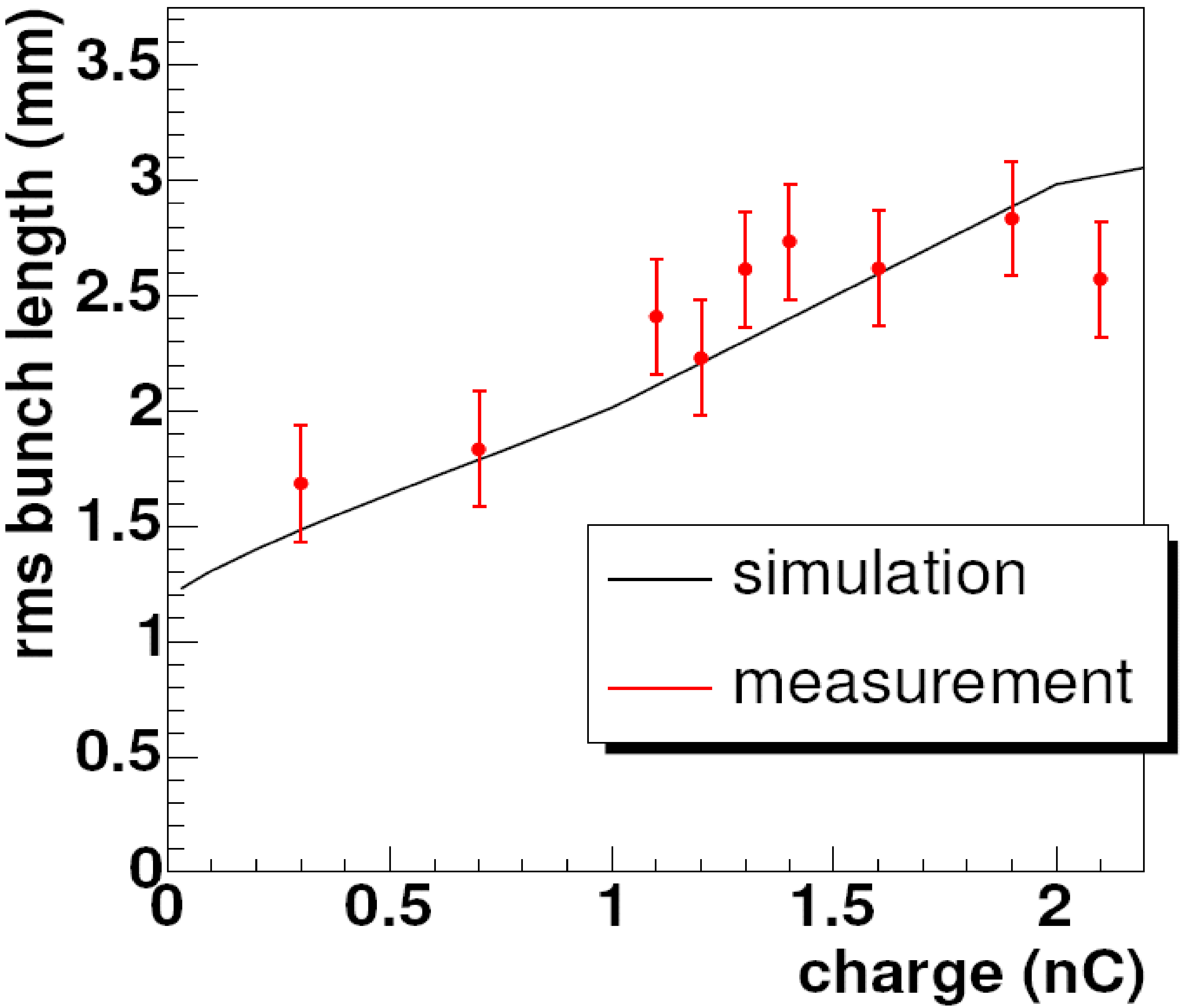
Momentum measurement
(influence of gun phase and bunch charge)





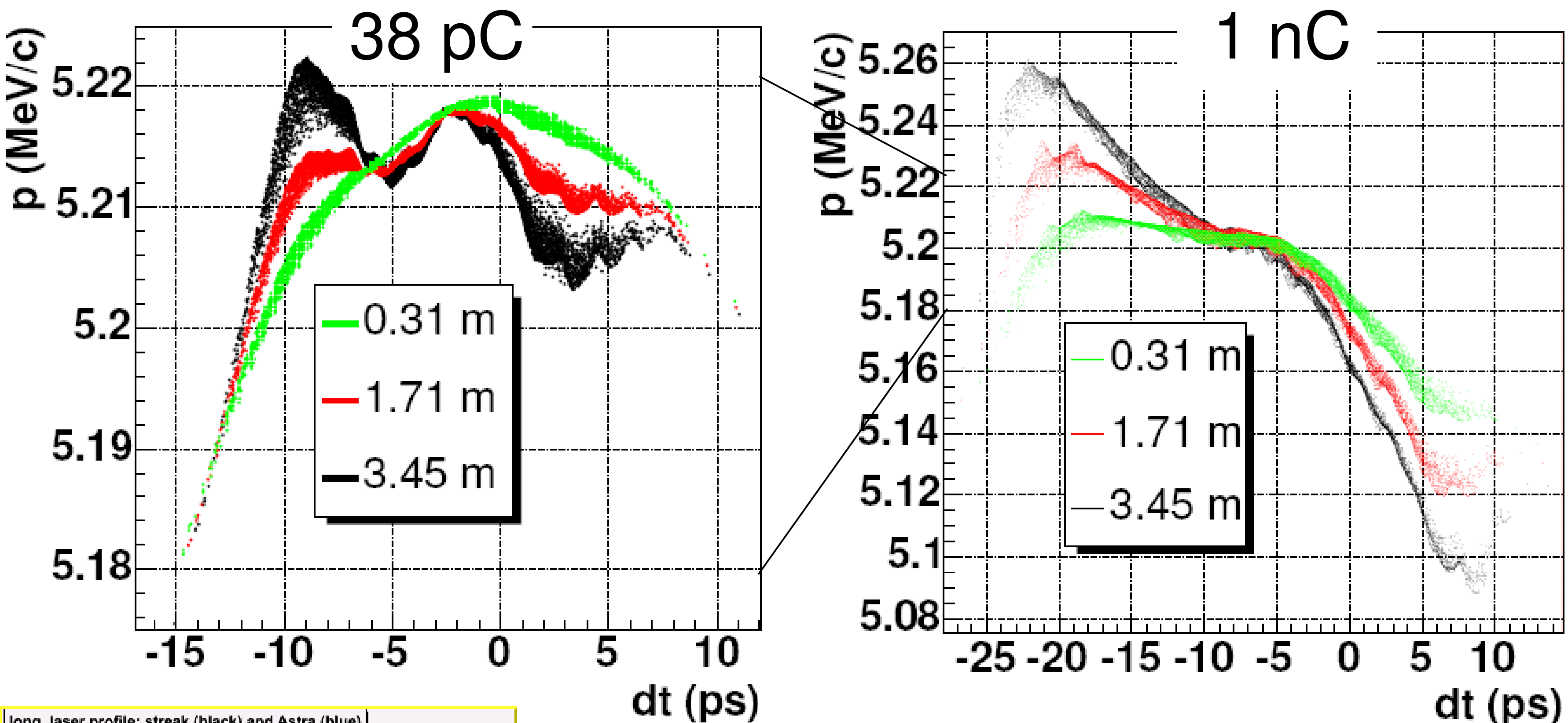
- Gun gradient: ~40MV/m
- The dependence of the mean momentum on the launch phase is similar for different charge
- highest mean momentum: 4.8 MeV/c
  at launch phase: of about 37°
- minimum momentum spread:
  30 pC: 5 keV/c at launch phase: of about 35°
  1 nC: 13 keV/c at launch phase: of about 30°
- for phase from 80° to 100° the momentum distribution is cut by the screen
- 1nC: space charge increases momentum spread
- 30 pC: phase of max. momentum gain is close to phase of min. momentum spread
  → space charge forces small

Bunch length measurement (influence of charge)

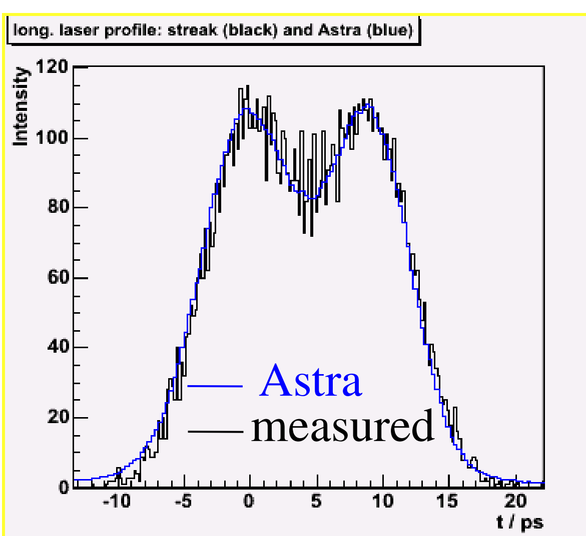


- 40 MV/m
- phase of max. momentum gain
- laser:
  - long.: flat-top
    FWHM : 20 ps
    risetime : 7 ps
  - transv.: flat-top
    Ø : 2 mm

Simulations of the longitudinal phase space at different long. positions and charges

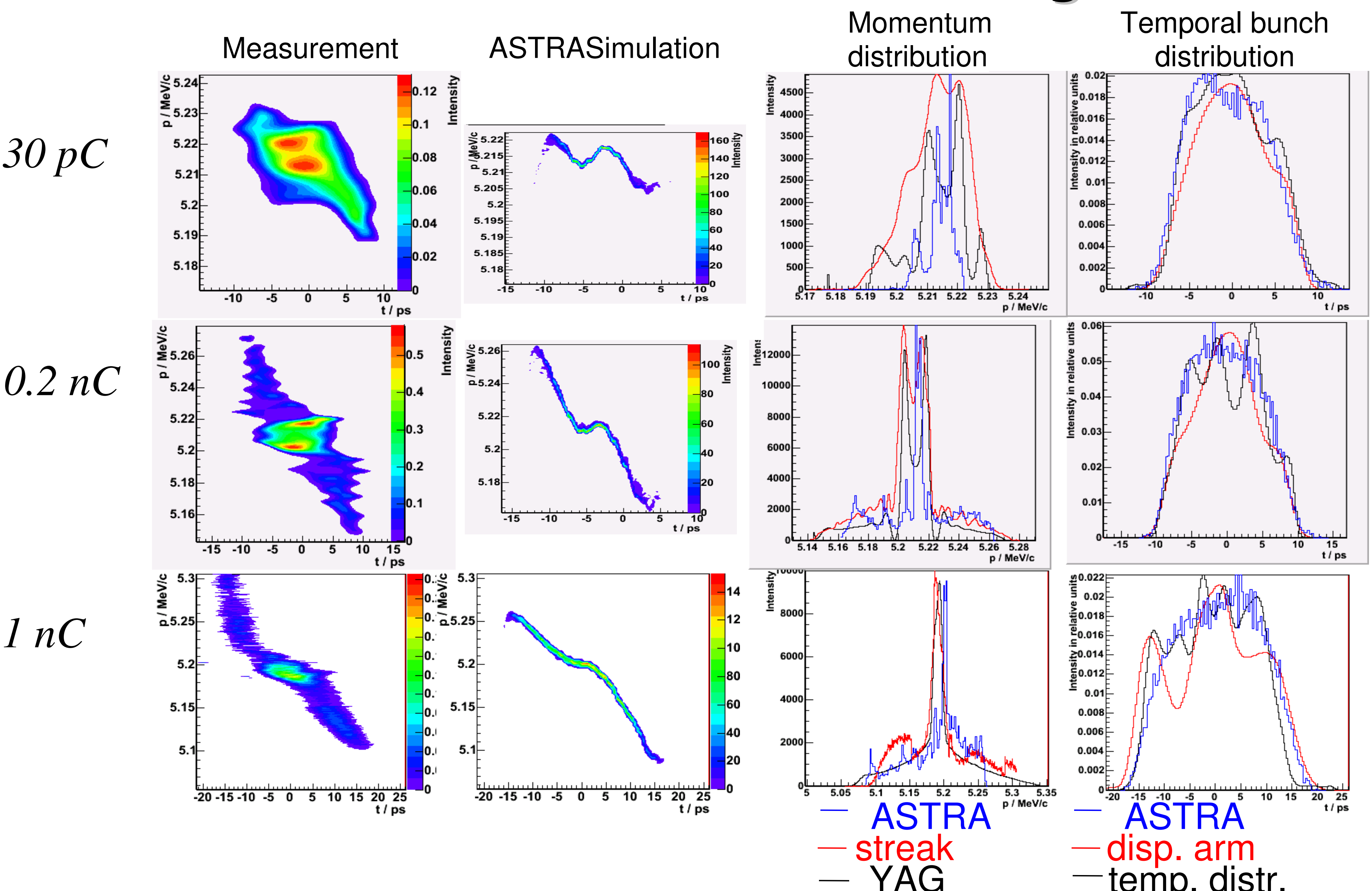


- 45 MV/m,
- flat-top temporal and transverse laser distribution,
- phase of max. momentum gain

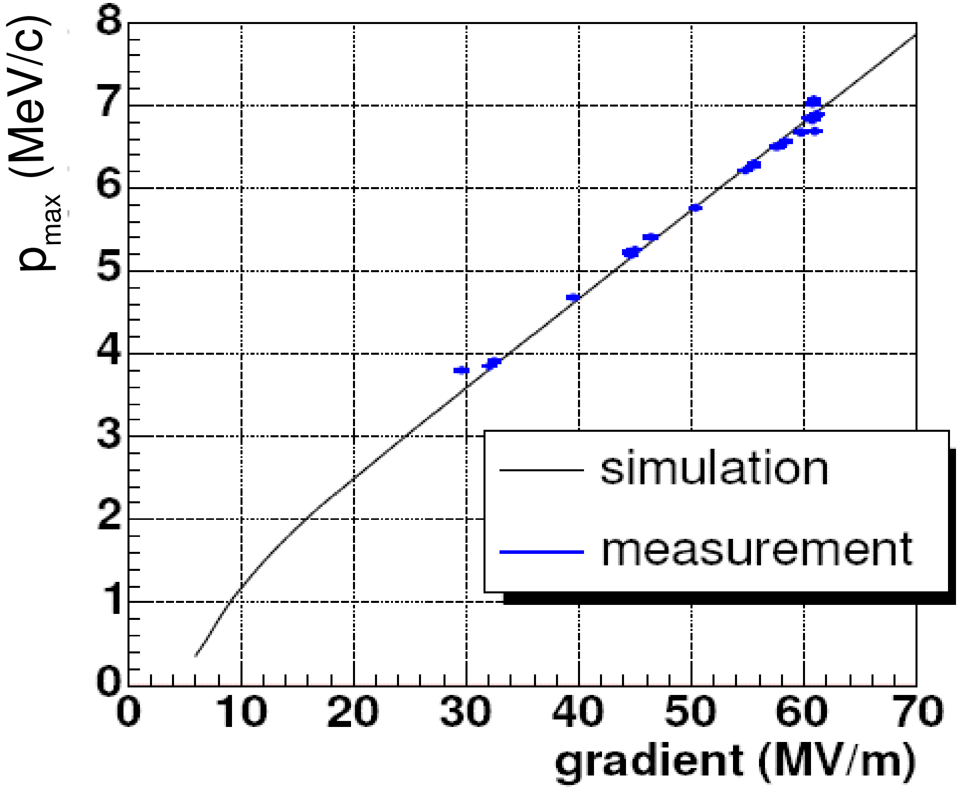


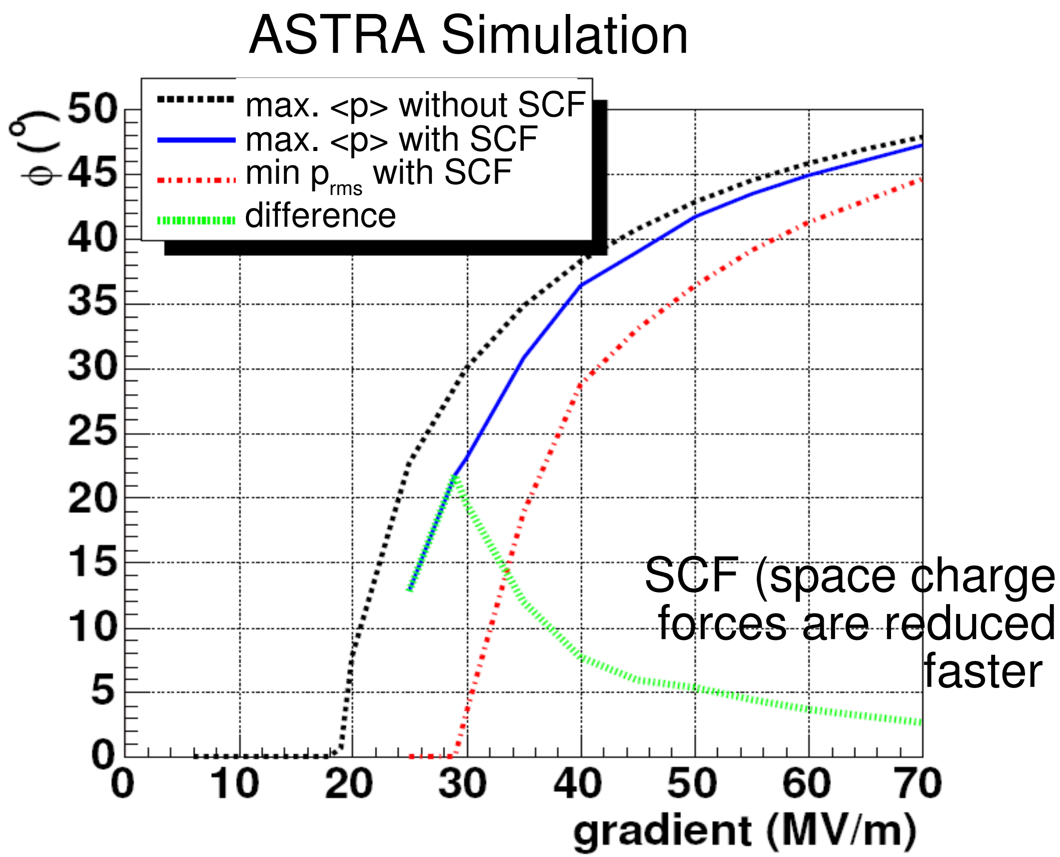
• modulation in the initial laser distribution cause modulations in the longitudinal phase space distribution
• small charges: strong modulations appear in the longitinal phase space distribution

Measurements of the longitudinal phase space distribution at different charges



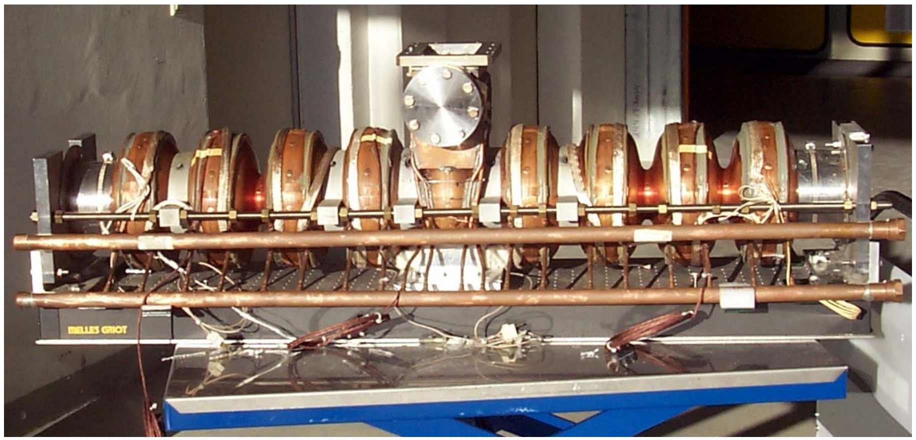
Momentum measurement (influence of gun gradient)





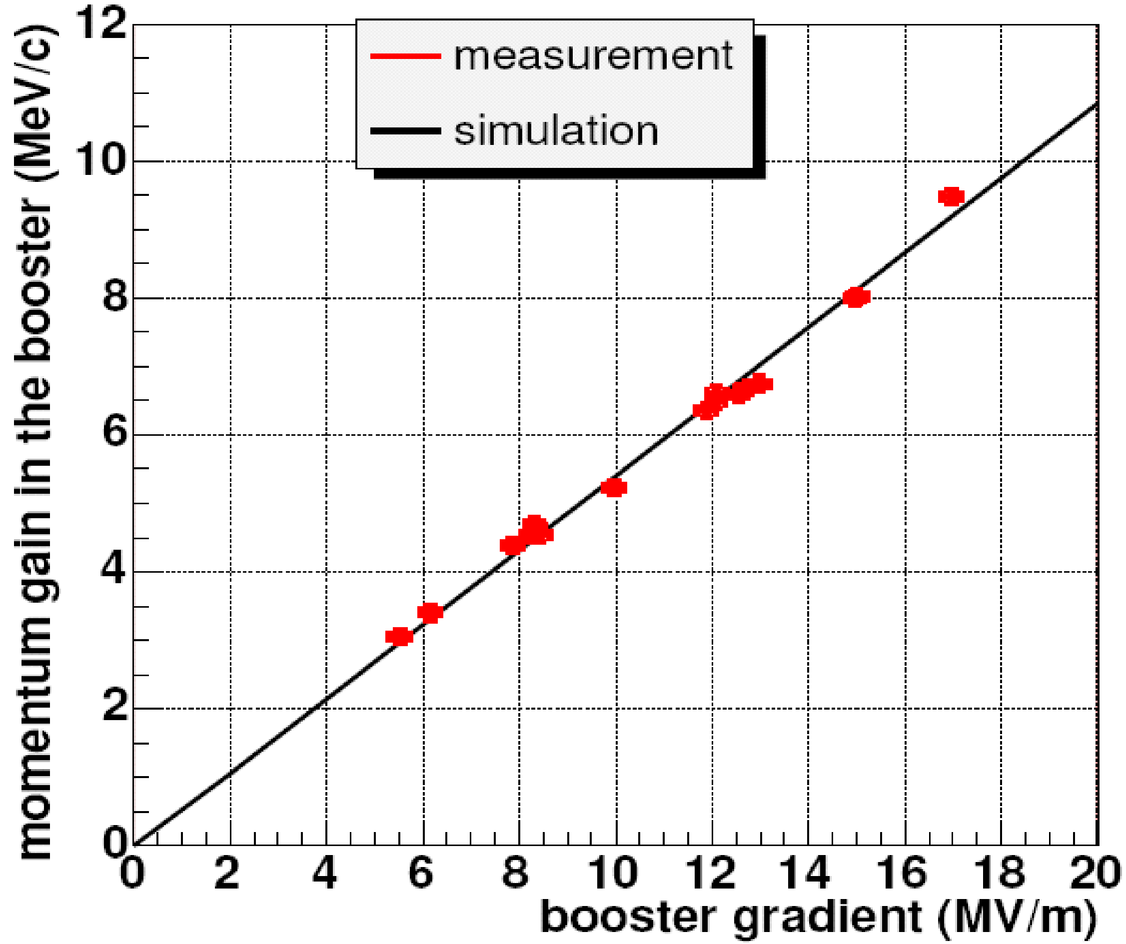
- max. mean momentum scales linear with the gradient (for E_{cath} > 20 MV/m)
- for E < 18 MV/m: phase of max. mean momentum gain = 0°
- for E < 6 MV/m: no acceleration

Momentum measurement (influence of booster gradient)



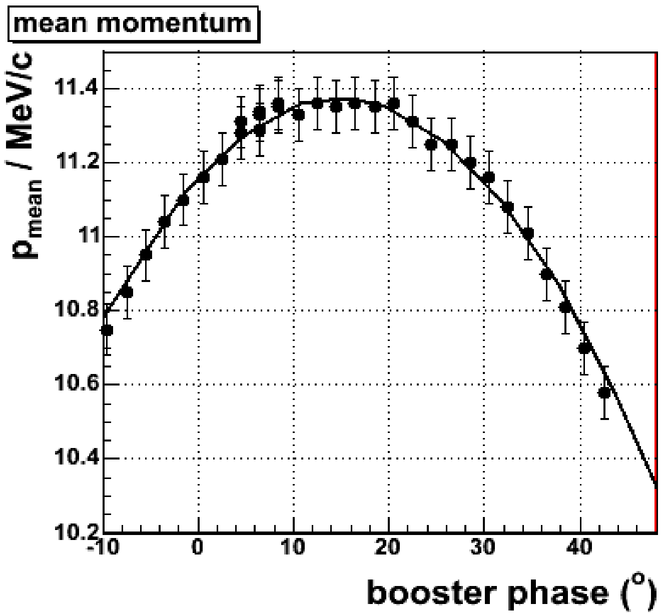
TESLA booster
(9 cell copper cavity)

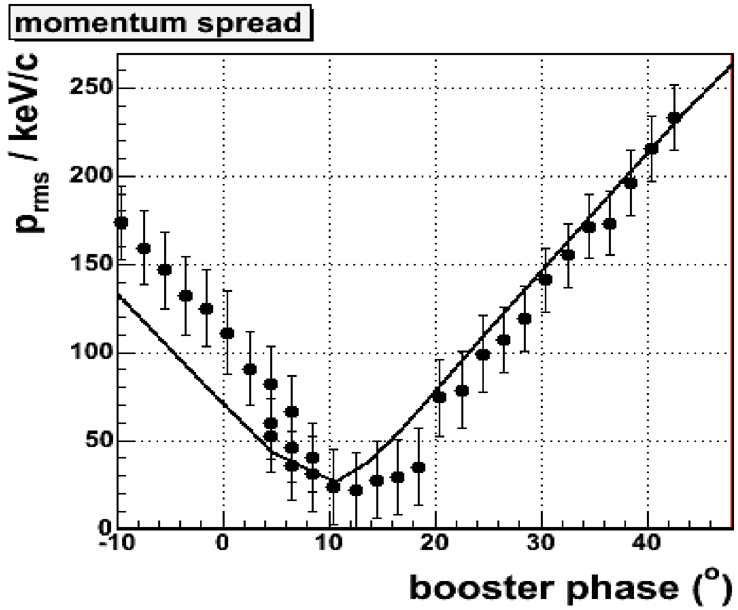
- field distribution is only roughly known
- the average power is limited by the cavity cooling



The points display measurementon different days during an measurement periode for:
- gun and booster phase of max. momentum gain

Momentum measurement (influence of gun & booster phase)

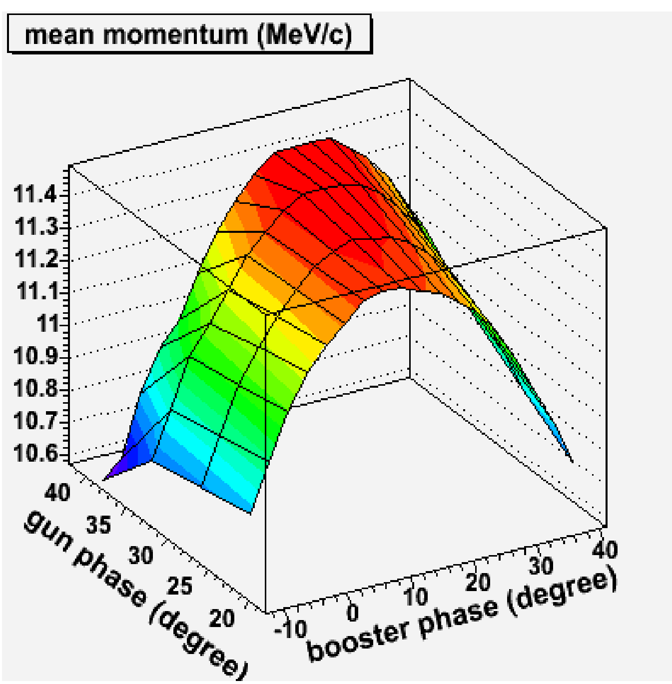


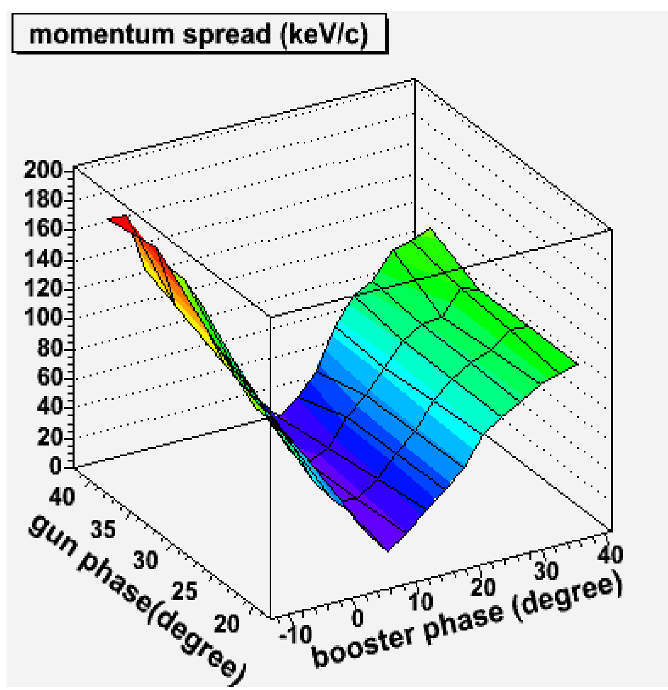


- 1 nC
- gun gradient: 40 MV/m
- gun phase of max. momentum gain (top)
- booster gradient: 12.5 MV/m

Laser:

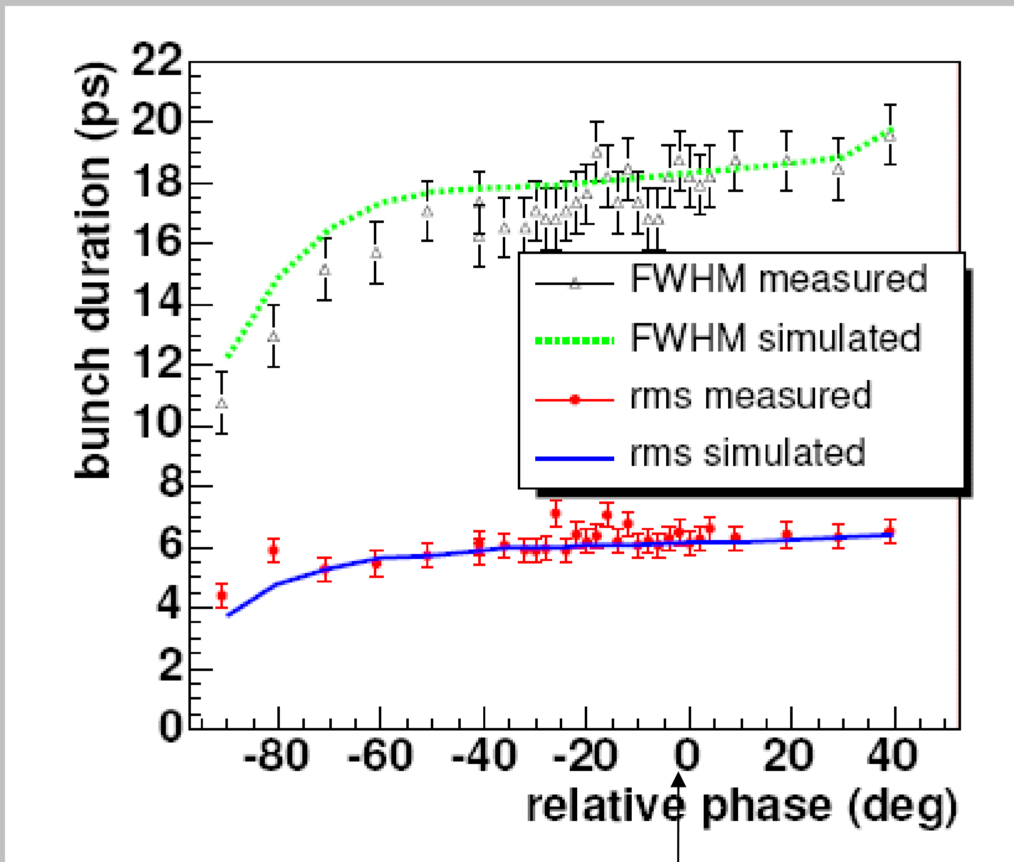
- long.: flat-top
  FWHM : 20 ps
  rise : 7 ps
- transv.: flat-top
  Ø : 2 mm



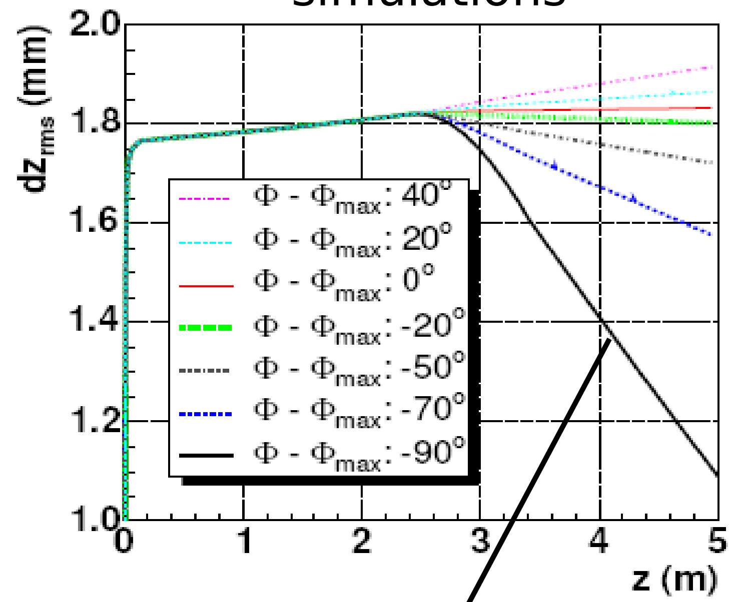


Bunch length downstream the booster cavity

Bunch duration vs. the booster phase



simulations

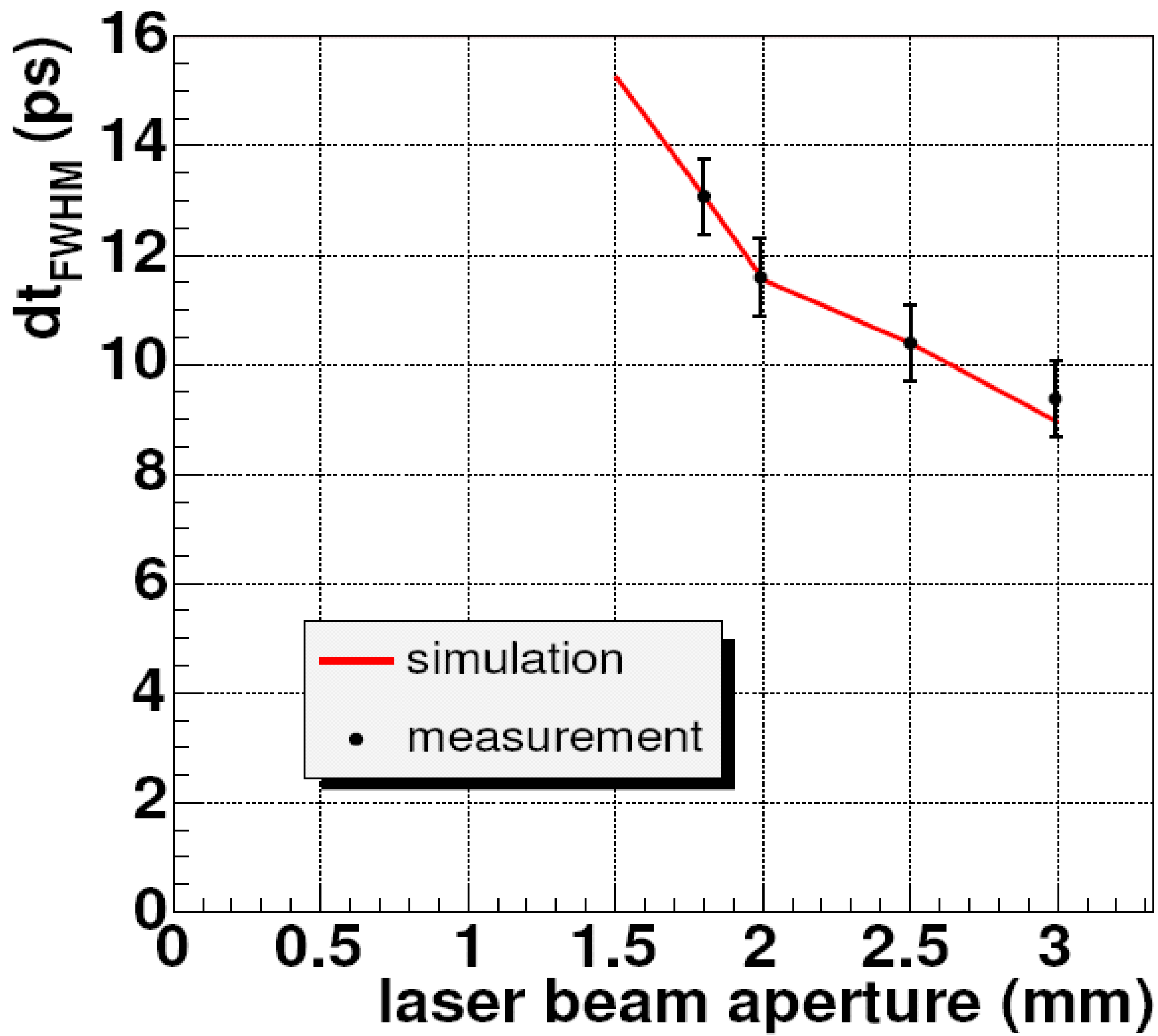


strong off-crest operation:
- balistic bunching
- low beam energy → space charge → transverse emittance growth

p_z^{mean} = 15.9 MeV/c

Parameter:
- 800 pC
- transv. laser diameter = 1.5mm
- Flat-top laser

Bunch length measurements

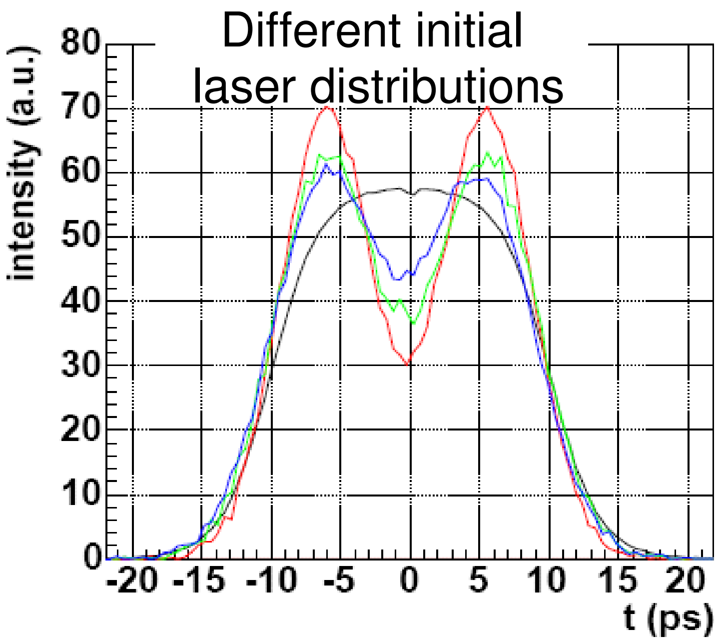


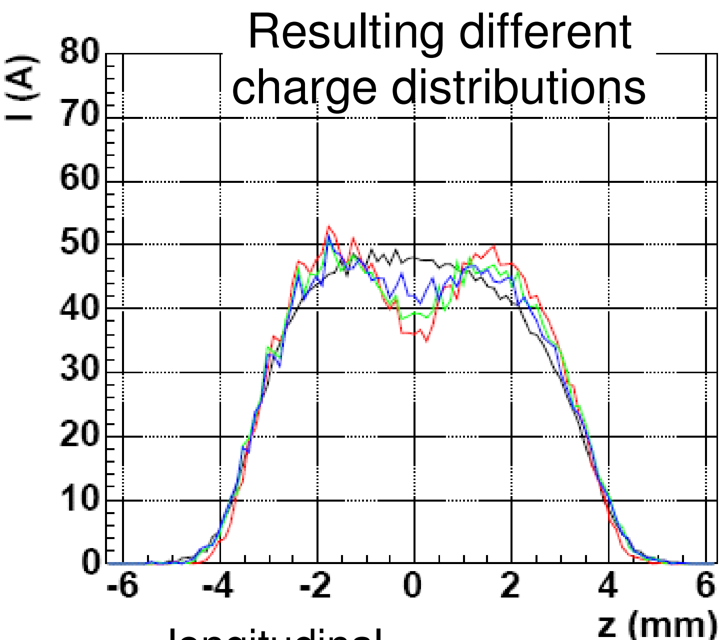
- 1 nC
- 60 MV/m
- laser:
  - long.: gaussian FWHM : 2 ps
  - transv.: flat-top Ø : variable

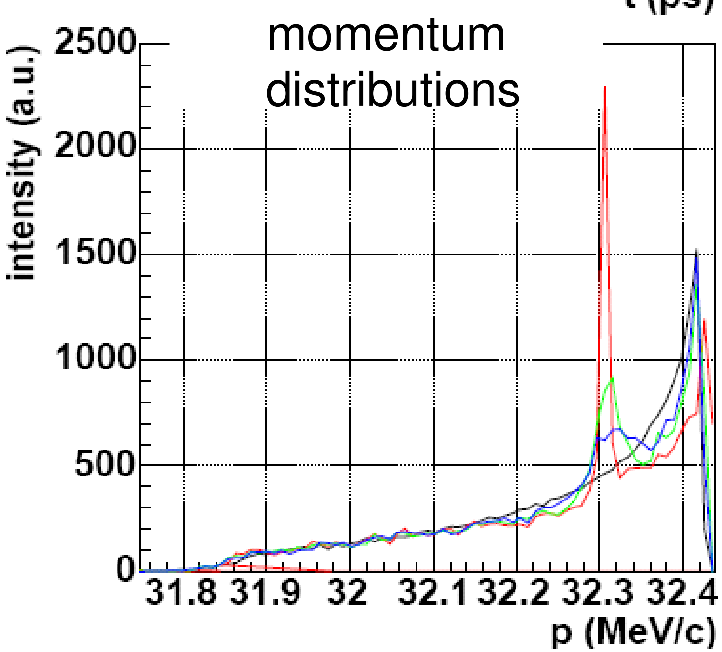
space charge dominated beam

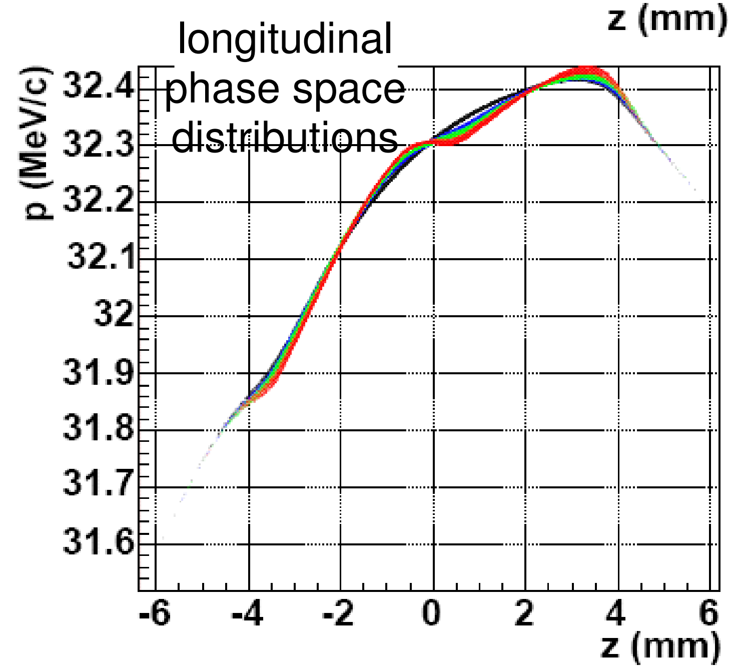
coupling of the transverse beam size and the longitudinal bunch properties

Influence of laser temporal modulations on longitudinal phase space distribution
(simulations for old cathode laser system)









- 1 nC
- z = 8 m
- gun gradient: 60 MV/m
- gun & booster phase of max. momentum gain
- booster gradient (CDS): 28.85 MV/m

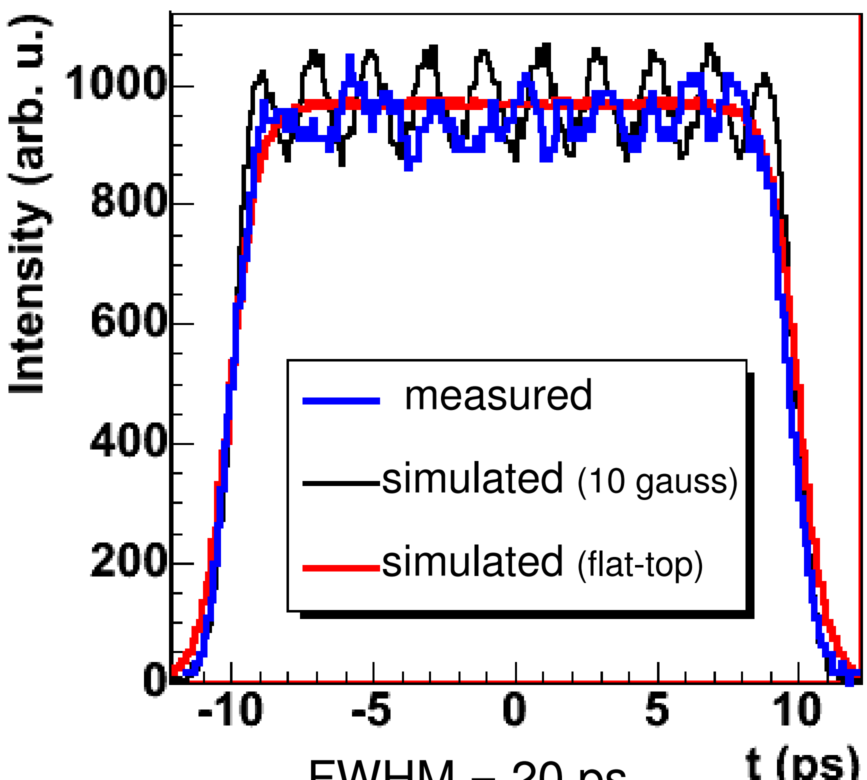
Laser:

- transv.: flat-top
  Ø : 2 mm

The modulations in the temporal laser distribution introduce modulations in the longitudinal phase space and momentum distribution.

Influence of laser temporal modulations on longitudinal phase space distribution
(new cathode laser system)

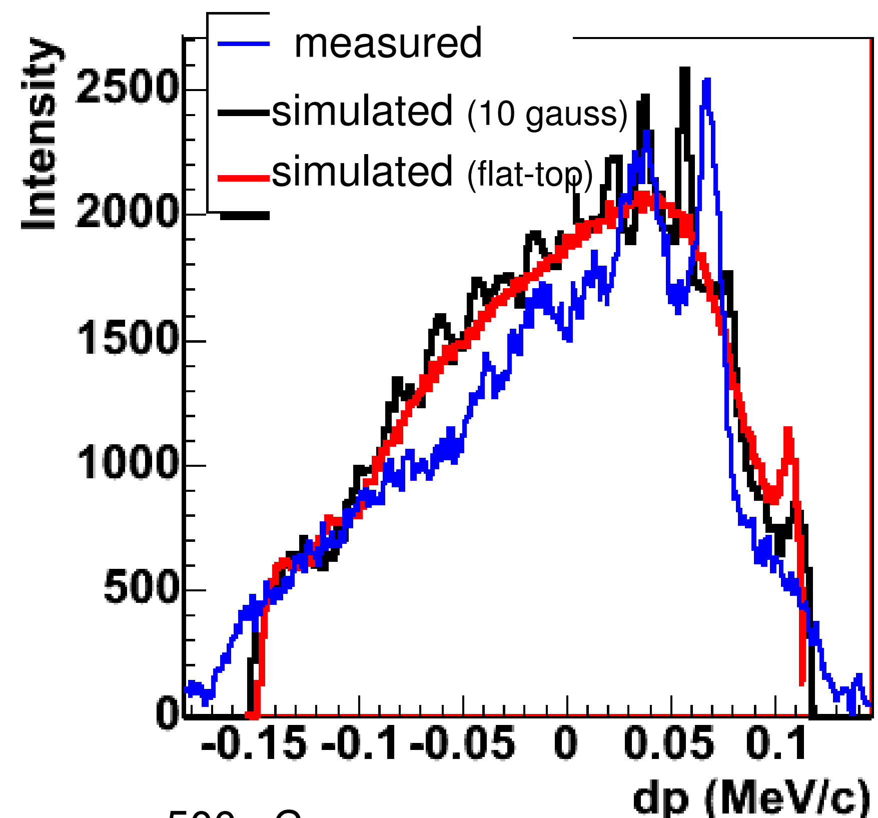
Different initial laser distributions



FWHM = 20 ps
rise time = 2 ps

modulations in the temporal laser distribution translate into modulations in themomentum distribution

Resulting different momentum distributions



- 500 pC
- gun gradient: 60 MV/m
- gun phase of max. momentum gain - 10°

Laser:

- transv.: flat-top
  Ø : 1.5 mm

Summary

- A method to measure the longitudinal phase space distribution and its projection used at PITZ was presented.
- The limit of the resolution of this method was analysed:
  - the major limitation of the temporal resolution is the optical system.
  - an optical system of reflective optics is under development.
- The spectrometer dipole magnets were optimized for high momentum resolution.
- The influence of space charge force on the longitudinal phase space distribution was studied in dependence on the bunch charge
- The impact of the increased gun gradient onto the longitudinal phase space distribution has been investigated. Bunch length dependence by off-crest booster operation was studied.
- A transformation of longitudinal modulations of the laser into momentum modulations has been experimentally observed and can be generally reproduced by simulations.
- Space charge density increase causes strong coupling between transverse and longitudinal bunch properties.

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