Strong-strong beam-beam simulation

Alexander Valishev

Budker Institute of Nuclear Physics, Novosibirsk, Russia

Strong-strong beam-beam simulation

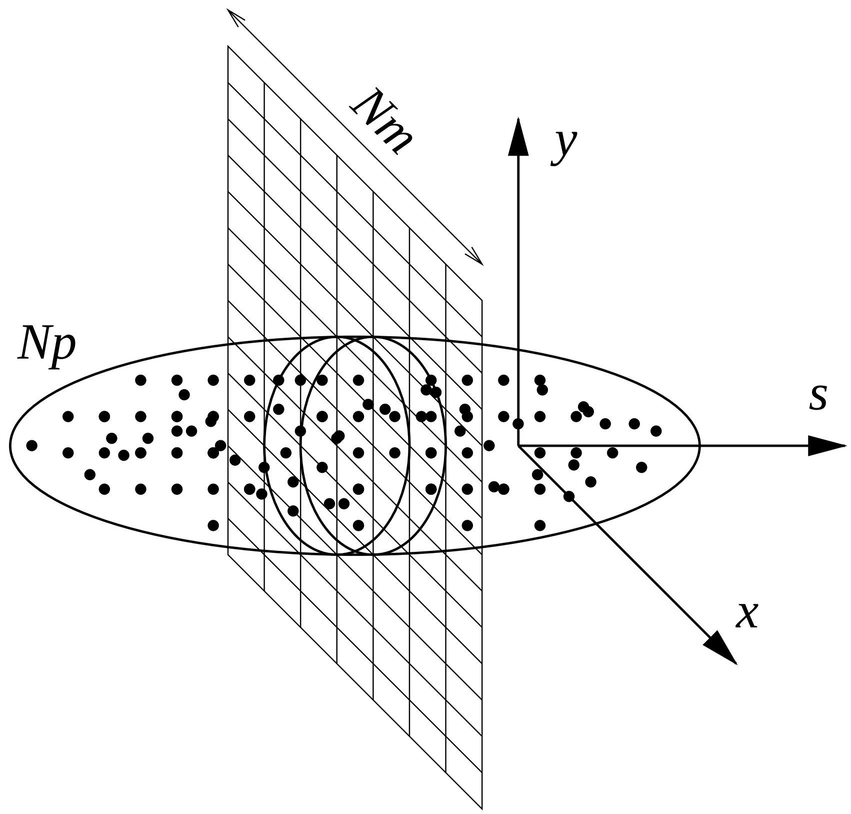
1. **Beam-beam force: Particle-In-Cell. Field calculated via the 2D Poisson equation**[a]**. Typically** 10^5 **macro-particles per bunch,** 128×128 **transverse coordinate mesh.**

2. **Arc transformation of the 6D particle phase-space coordinates, includes sextupoles.**

3. **Radiation damping and quantum excitation applied once per turn.**

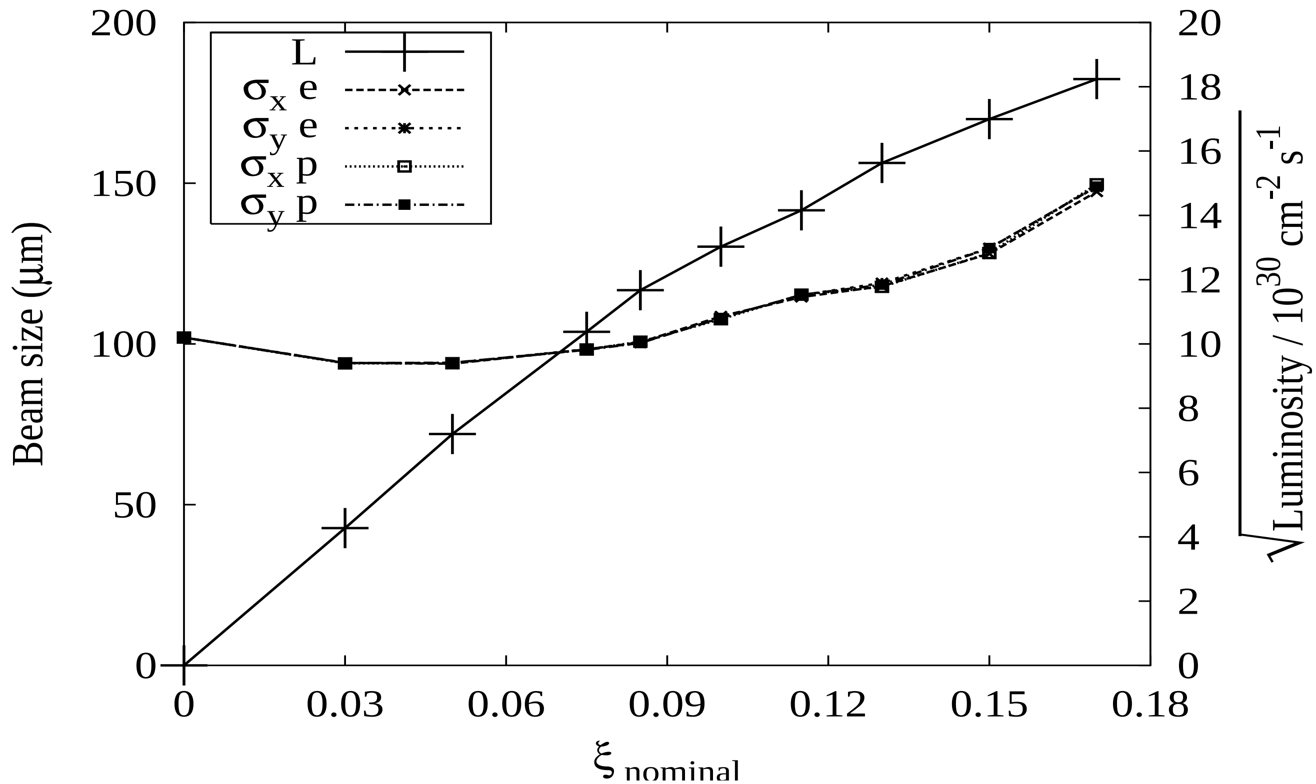
[a] K. Ohmi, Phys. Rev. E **62**, 7287 (2000)

Beam-beam force calculation: model



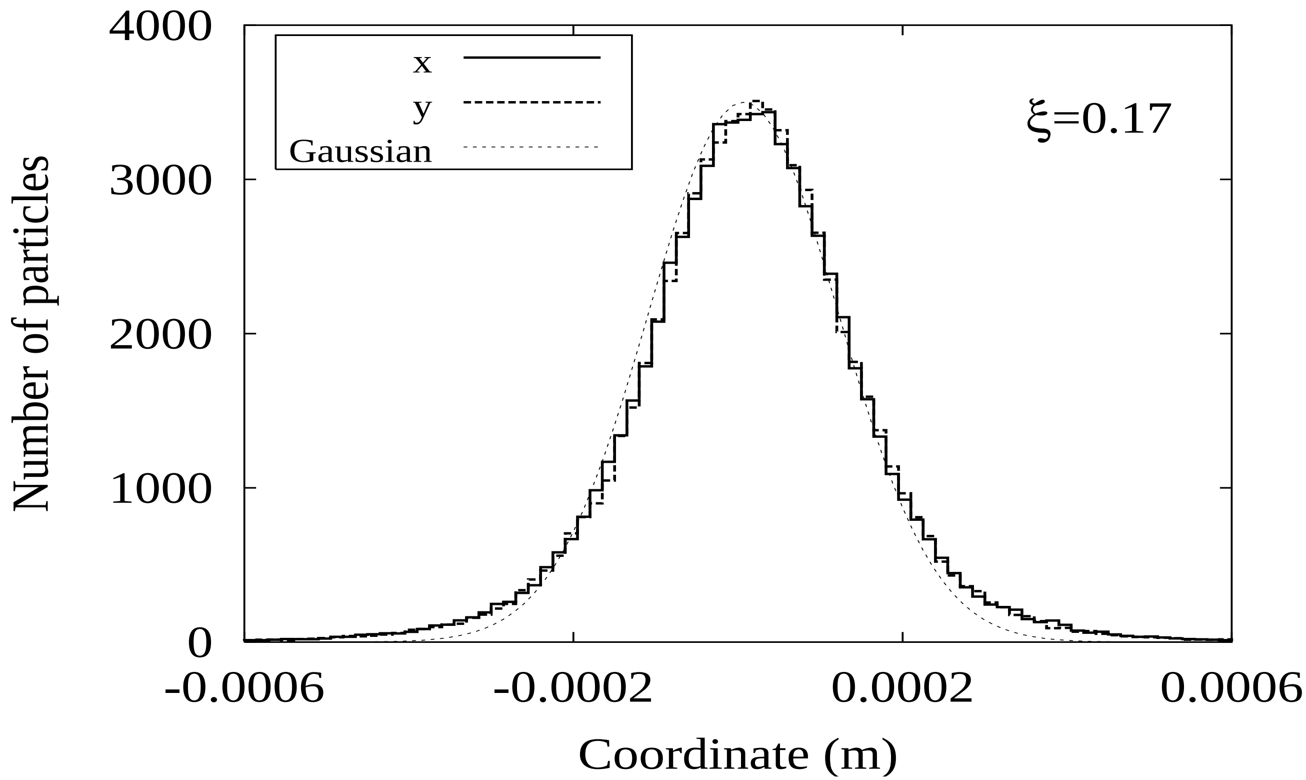
Macroparticles/bunch $N_p = 50000$**, transverse mesh** $N_m \times N_m$**,** $N_m = 128$

Simulation for round beam without sextupoles: 1



Beam size and $\sqrt{L}$ vs. the beam-beam parameter.
VEPP-2000 $E = 900$ MeV

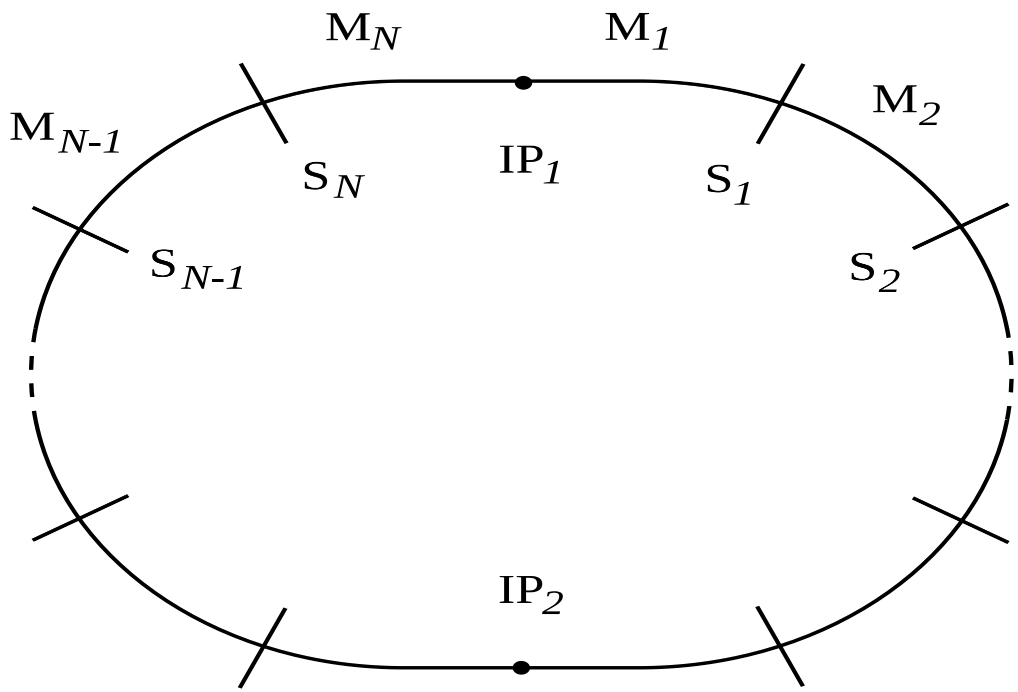
Simulation for round beam without sextupoles: 2



Transverse density distribution of the electron beam at

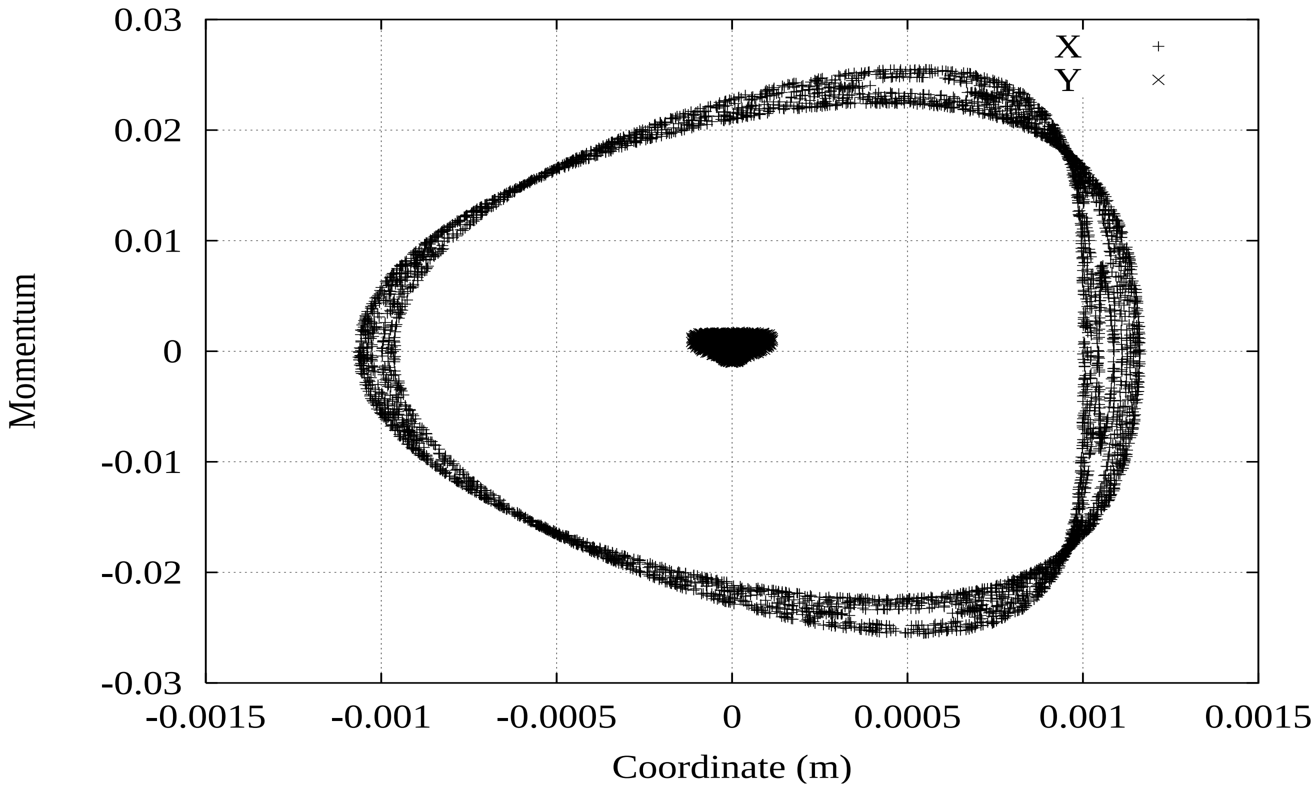
$$\xi = 0.17$$

Arc with sextupoles: 1



1. **Linear mapping with matrix** M_i
2. **Thin sextupole** S_i

Arc with sextupoles: 2



Phase portrait of the single particle tracking

Simulation of the beam emittance excitation: 1

Simulation of the beam envelope in collision includes two effects:

- **Deformation of the optical functions due to additional focusing (dynamic beta).**
- **Change of the beam emittance.**

Simulation of the beam emittance excitation: 2

Coordinate transformation:

$$X = \lambda X_0 + \sqrt{(1-\lambda^2)\epsilon} M_d \hat{F} \ ,$$

X, X_0 are normal mode 2-vectors, $\lambda = e^{-\delta}$, $\hat{F}$ is random Gaussian 2-vector.

$$M_d = \begin{pmatrix} a+d & b \\ b & a-d \end{pmatrix} \ , \quad \tilde{Q} = 2\delta\epsilon \begin{pmatrix} 1+c & -s \\ -s & 1-c \end{pmatrix} \ .$$

with $\tilde{Q}$ the diffusion matrix[a] and coefficients [b]

$$a = \pm\sqrt{\frac{1}{2} \pm \frac{1}{2}\sqrt{1-c^2-s^2}}, \ \ d = c/2a, \ \ b = -s/2a.$$

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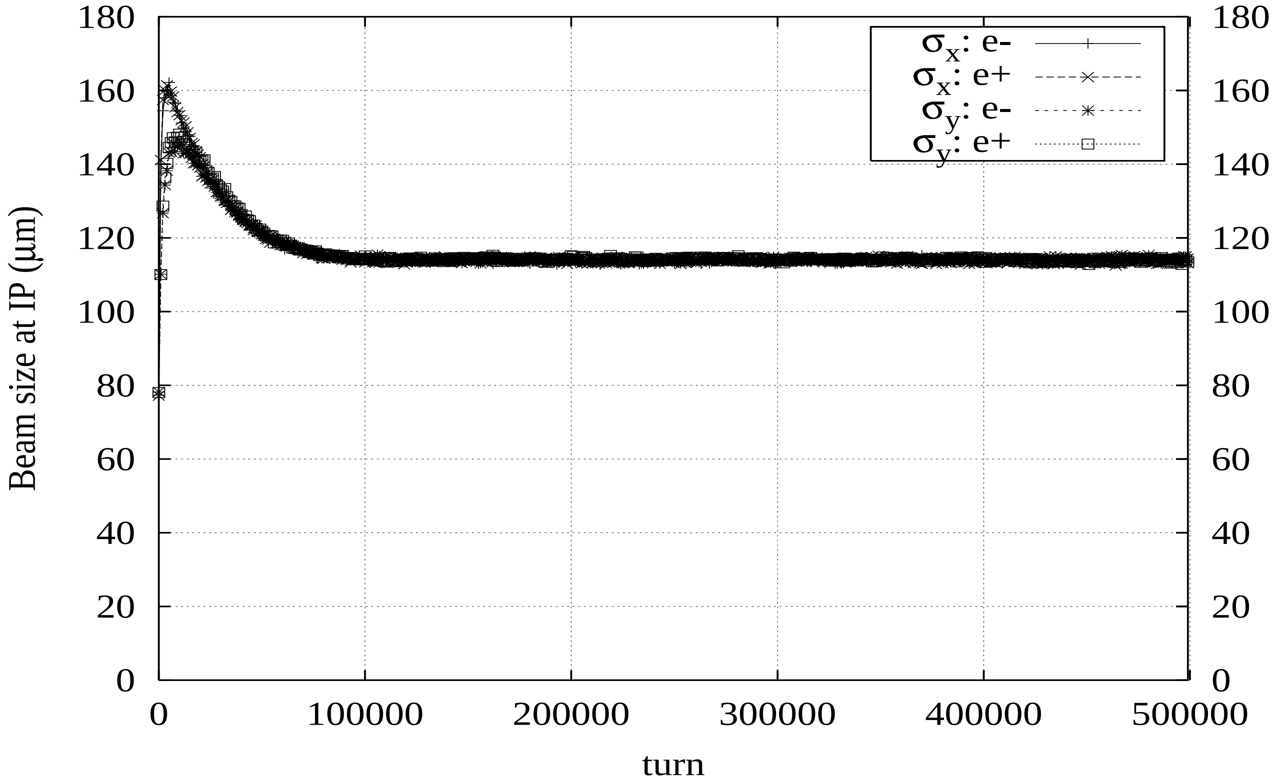
[a] K.Ohmi, K.Hirata, K.Oide, Phys. Rev. E **49**, 751 (1994)

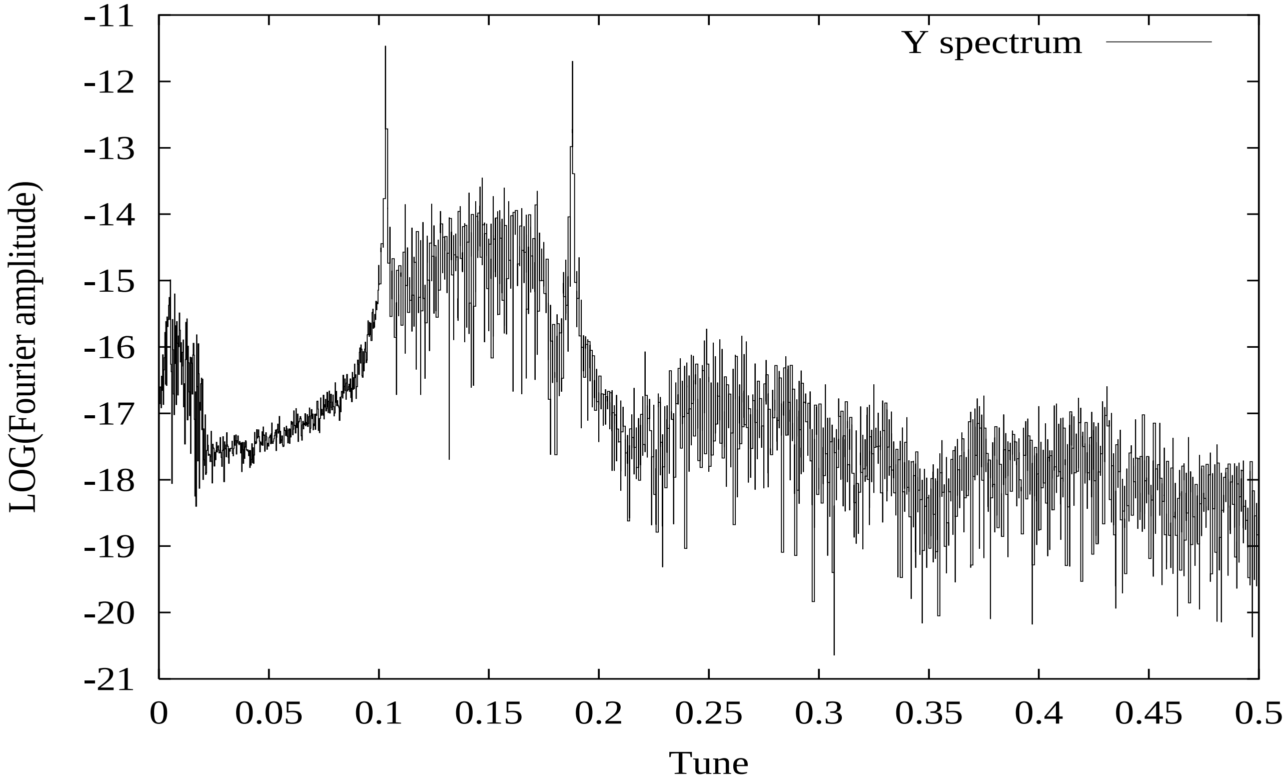
[b] E. Perevedentsev, private communication

Beam size evolution at $\xi = 0.09$



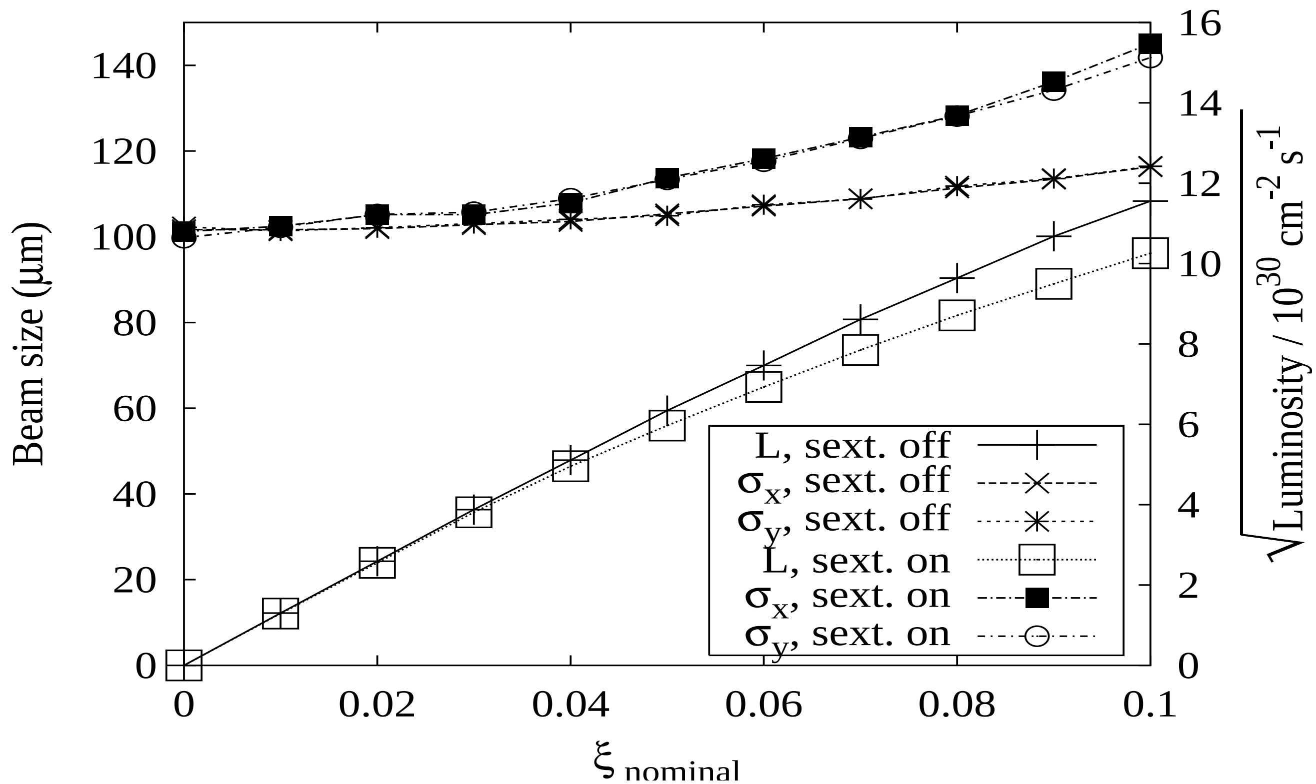
VEPP-2000 $E = 900$ **MeV**

Round beam, complete model



Fourier spectrum of the dipole signal, $\xi = 0.06$.

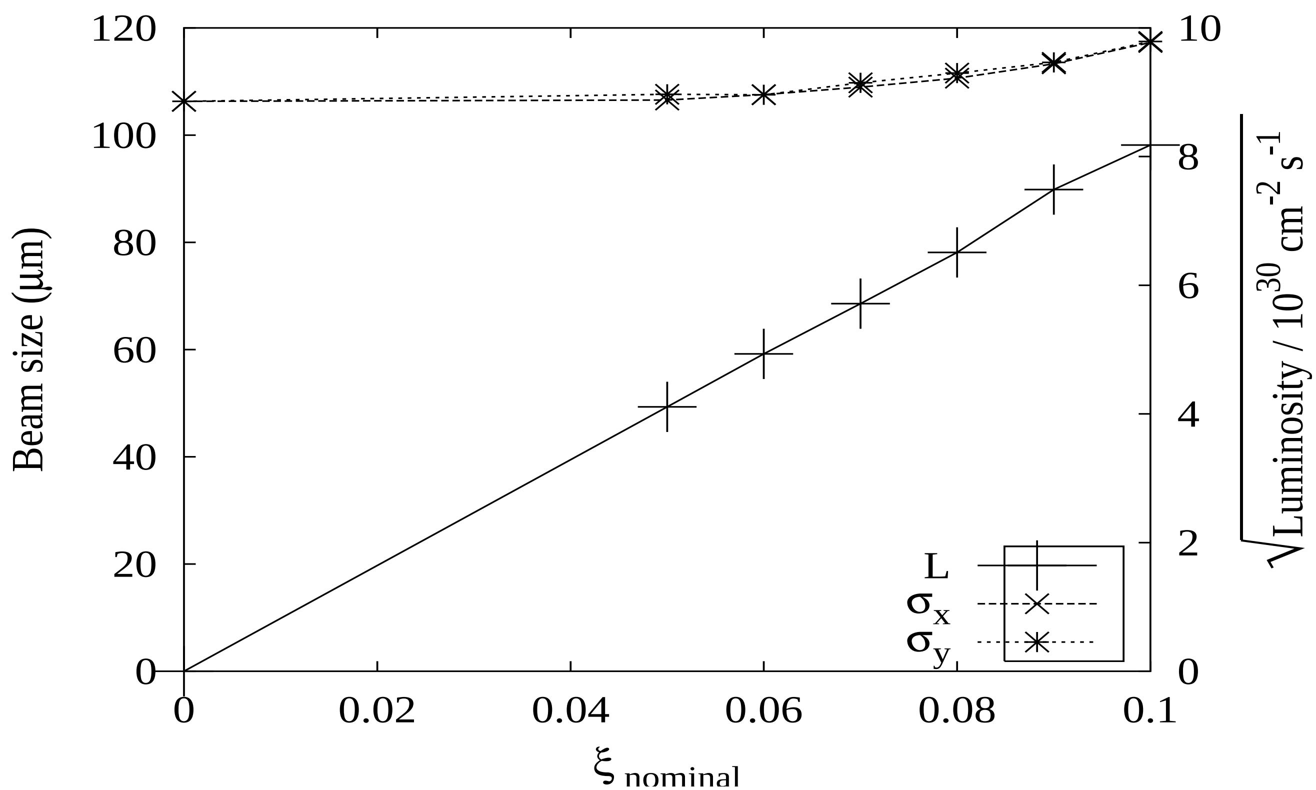
Strong-strong simulation for VEPP-2000: $\beta^* = 6$ cm



Comparison of the sextupoles on and off options.

$E = 900$ **MeV**

Strong-strong simulation for VEPP-2000: $\beta^* = 10$ cm

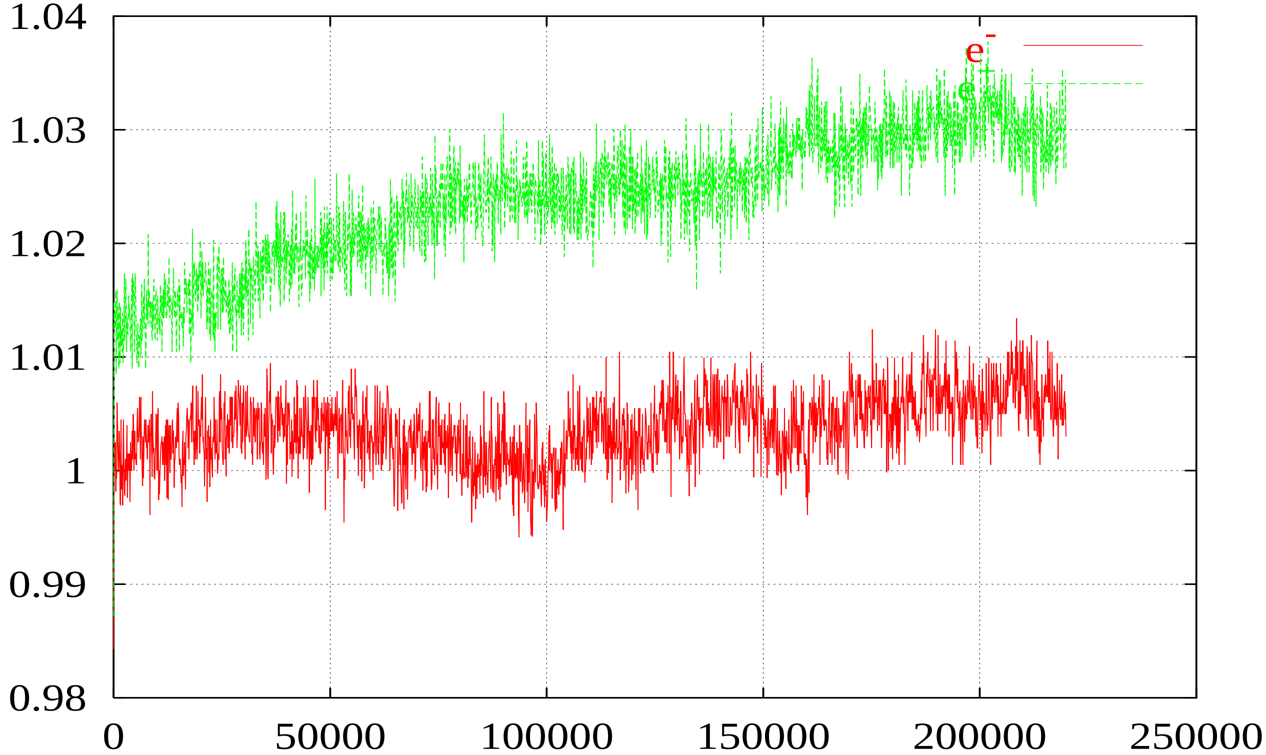


$E = 900$ **MeV**

Strong-strong simulation for DAΦNE #1, parameters

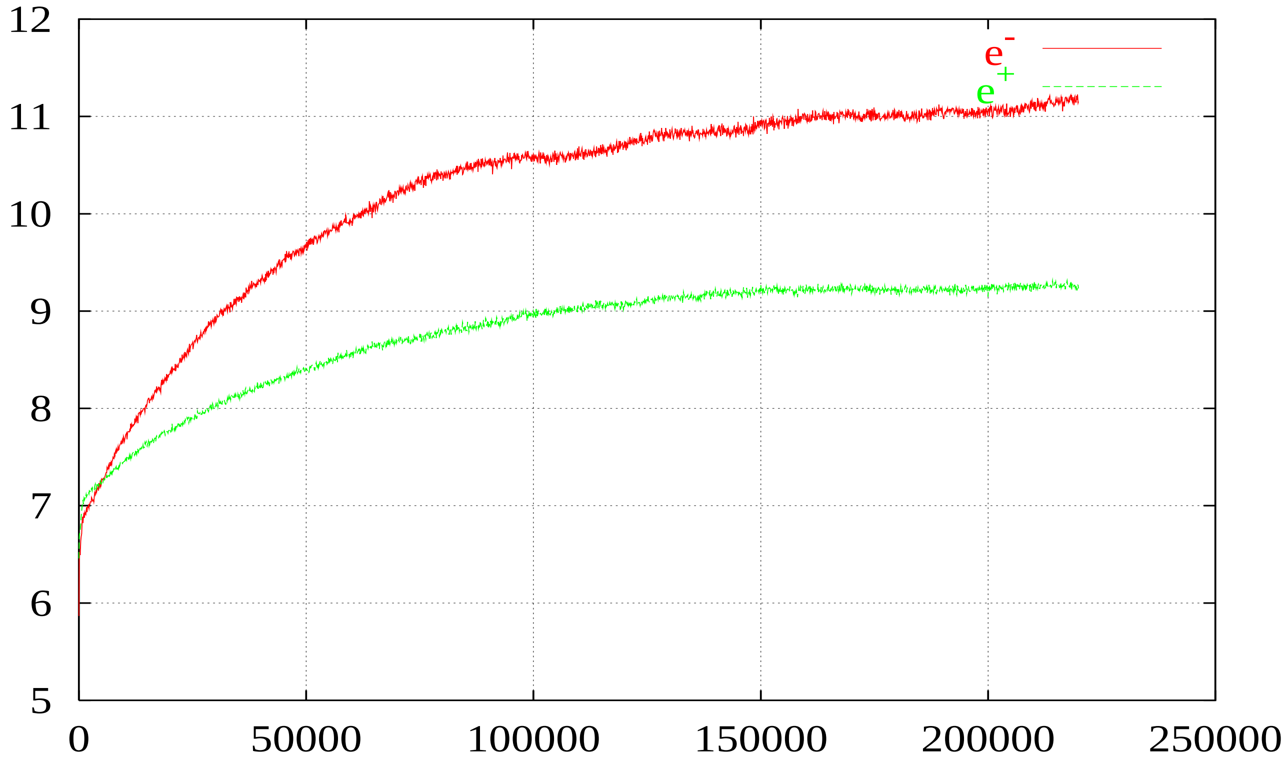
Parameter		e^-	e^+
Horizontal tune		5.107	5.154
Vertical tune		5.148	5.212
Synchrotron tune		0.008	0.008
Horizontal emittance	(m)	$0.62 \cdot 10^{-6}$	$0.62 \cdot 10^{-6}$
Vertical emittance	(m)	$0.124 \cdot 10^{-8}$	$0.124 \cdot 10^{-8}$
Energy spread		$4 \cdot 10^{-4}$	$4 \cdot 10^{-4}$
Damping decrement (turns)	horizontal	110,000	110,000
	vertical	110,000	110,000
	longitudinal	56,000	56,000
Beta function at IP (m)	horizontal	1.7	1.7
	vertical	0.035	0.035
Number of particles per bunch		$2 \cdot 10^{10}$	$2 \cdot 10^{10}$

DAΦNE #1: 1



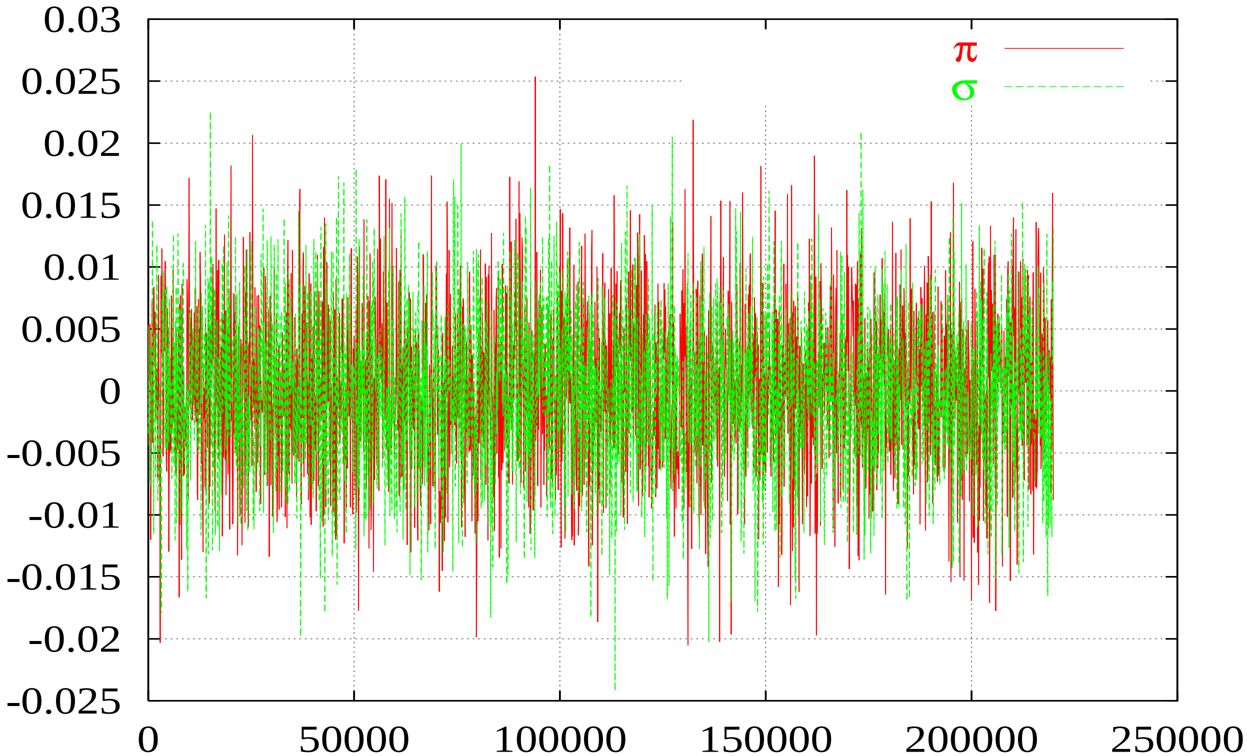
Horizontal beam size (mm) vs. turns

DAΦNE #1: 2



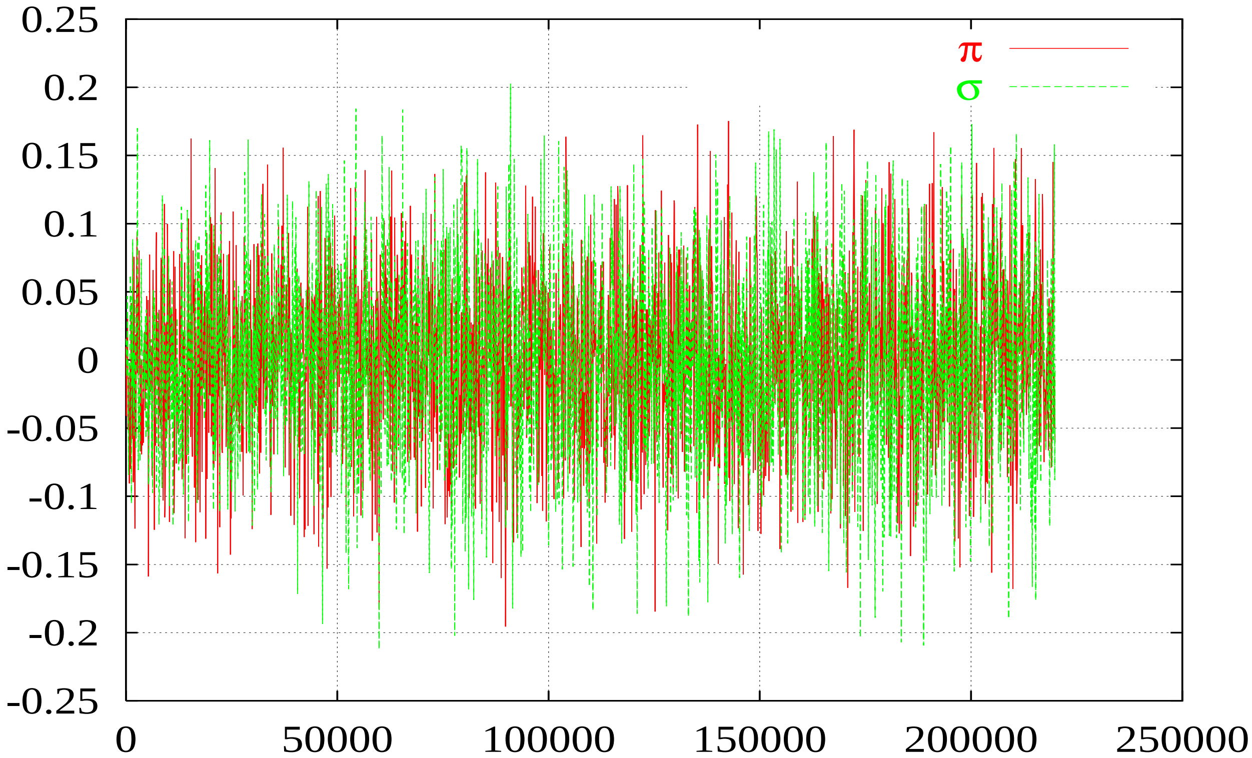
Vertical beam size (μm) vs. turns

DAΦNE #1: 3



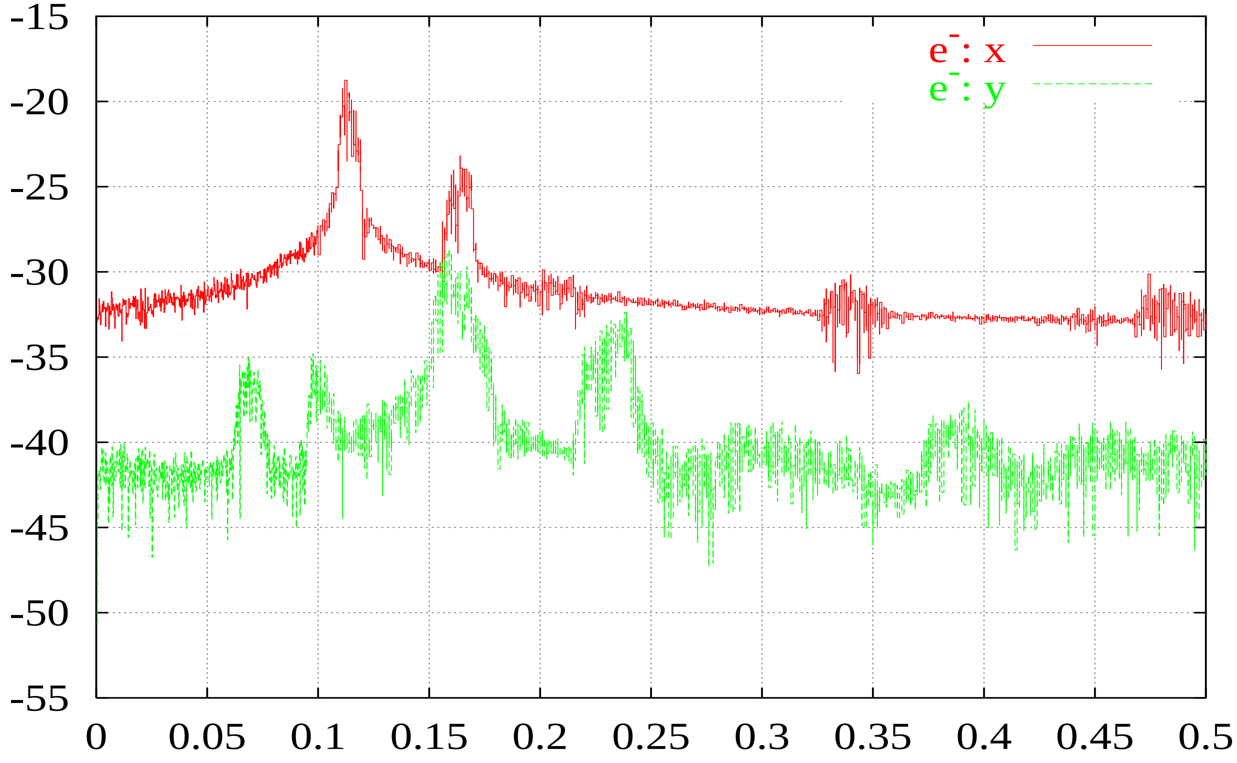
Horizontal coherent beam-beam modes (mm) vs. turns

DAΦNE #1: 4



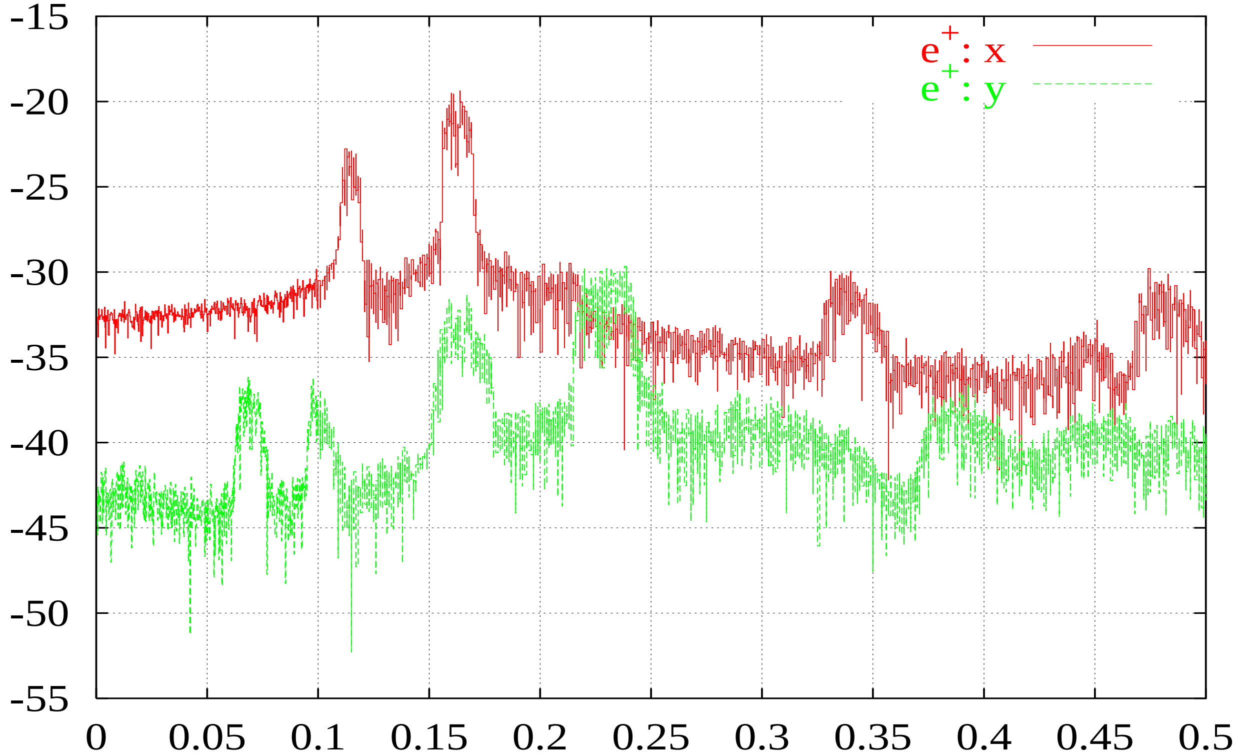
Vertical coherent beam-beam modes (μm) vs. turns

DAΦNE #1: 5



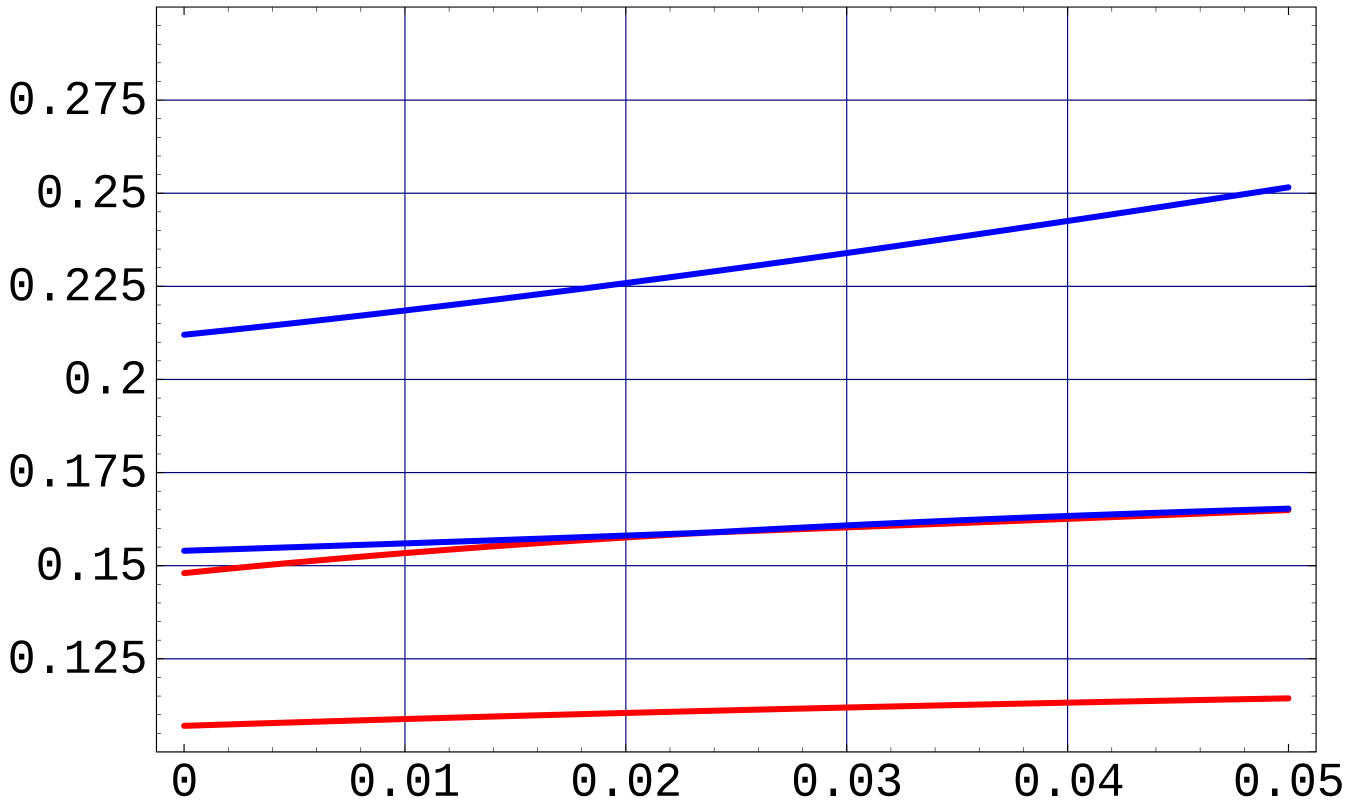
Coherent spectra of the electron beam.

DAΦNE #1: 6



Coherent spectra of the positron beam.

DAΦNE #1: 7

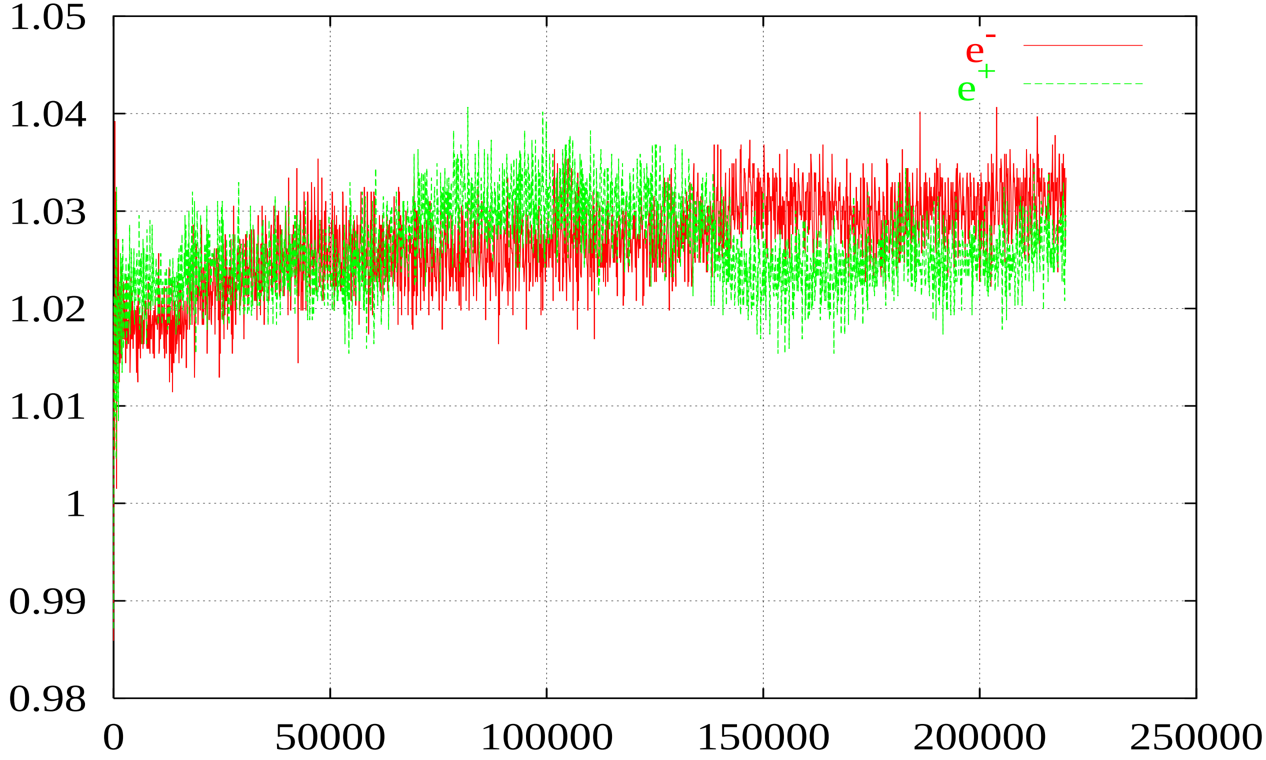


Coherent beam-beam mode tunes vs. ξ (linear model).

Strong-strong simulation for DAΦNE #2, parameters

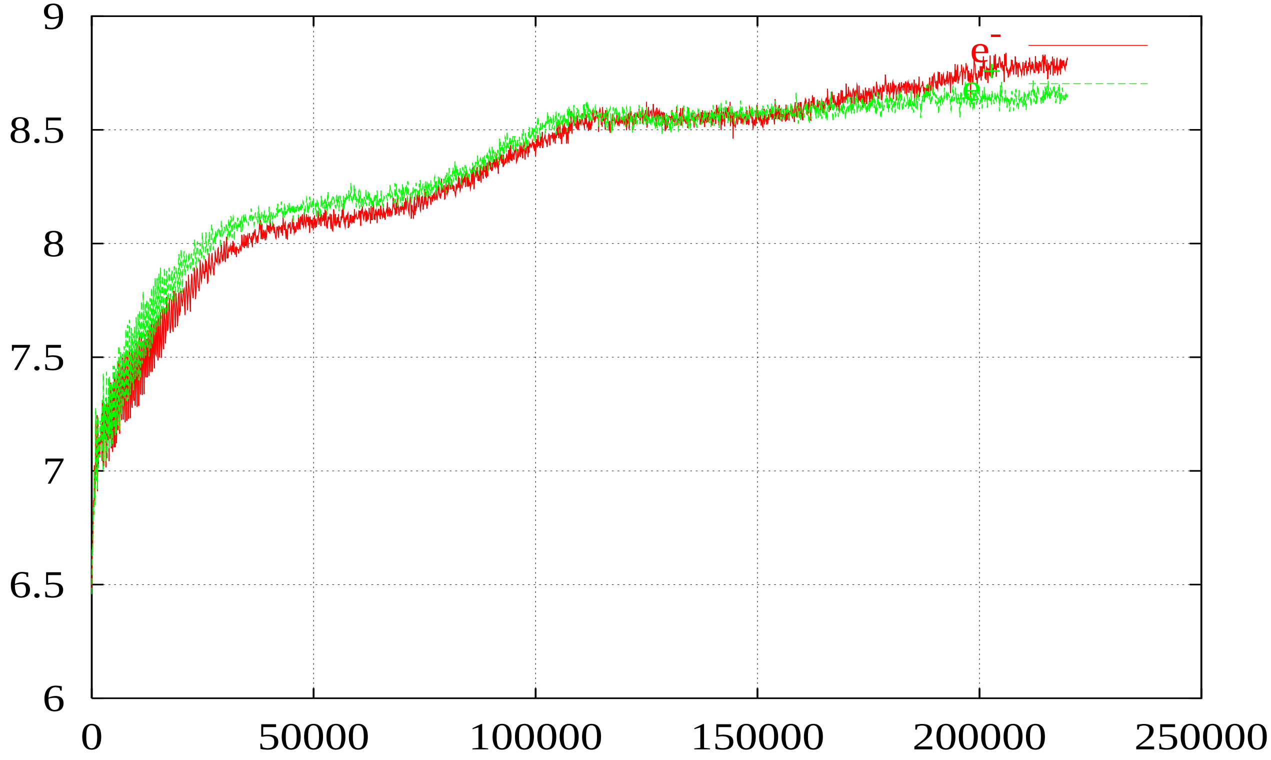
Parameter		e^-	e^+
Horizontal tune		5.154	5.154
Vertical tune		5.212	5.212
Synchrotron tune		0.008	0.008
Horizontal emittance	(m)	$0.62 \cdot 10^{-6}$	$0.62 \cdot 10^{-6}$
Vertical emittance	(m)	$0.124 \cdot 10^{-8}$	$0.124 \cdot 10^{-8}$
Energy spread		$4 \cdot 10^{-4}$	$4 \cdot 10^{-4}$
Damping decrement (turns)	horizontal	110,000	110,000
	vertical	110,000	110,000
	longitudinal	56,000	56,000
Beta function at IP (m)	horizontal	1.7	1.7
	vertical	0.035	0.035
Number of particles per bunch		$2 \cdot 10^{10}$	$2 \cdot 10^{10}$

DAΦNE #2: 1



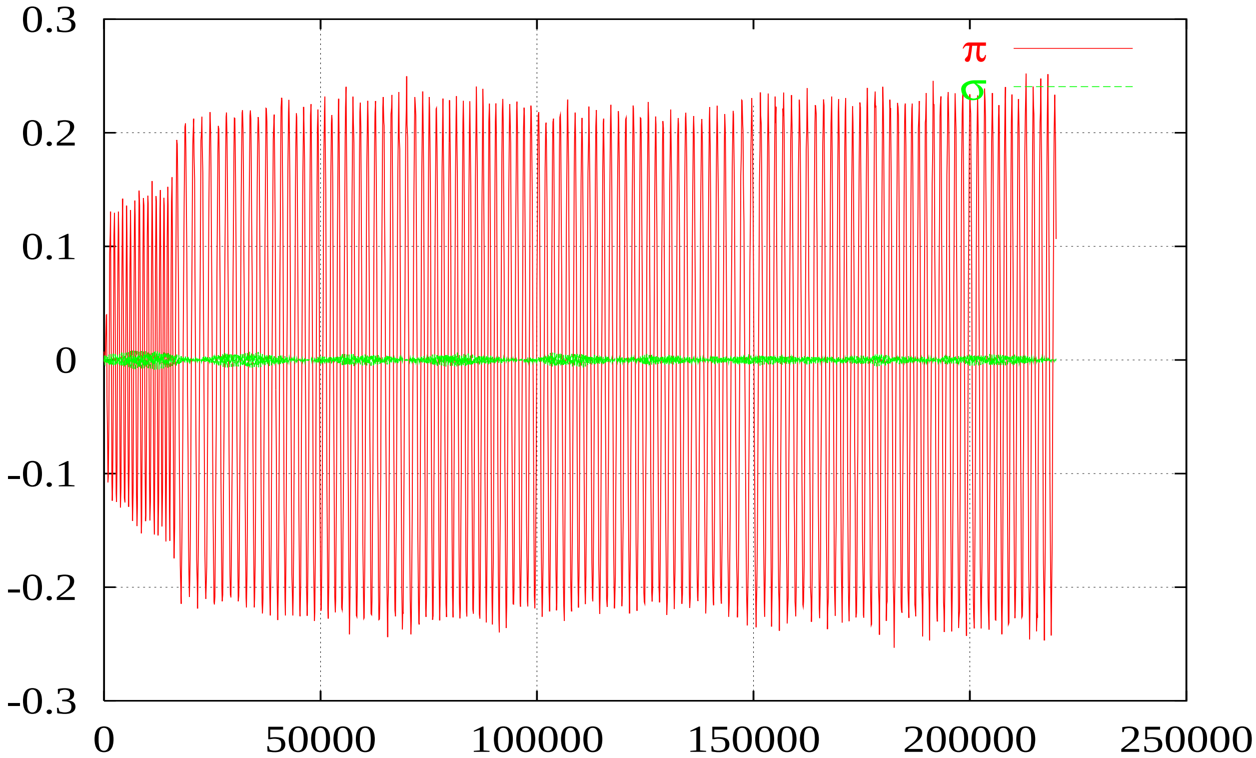
Horizontal beam size (mm) vs. turns

DAΦNE #2: 2



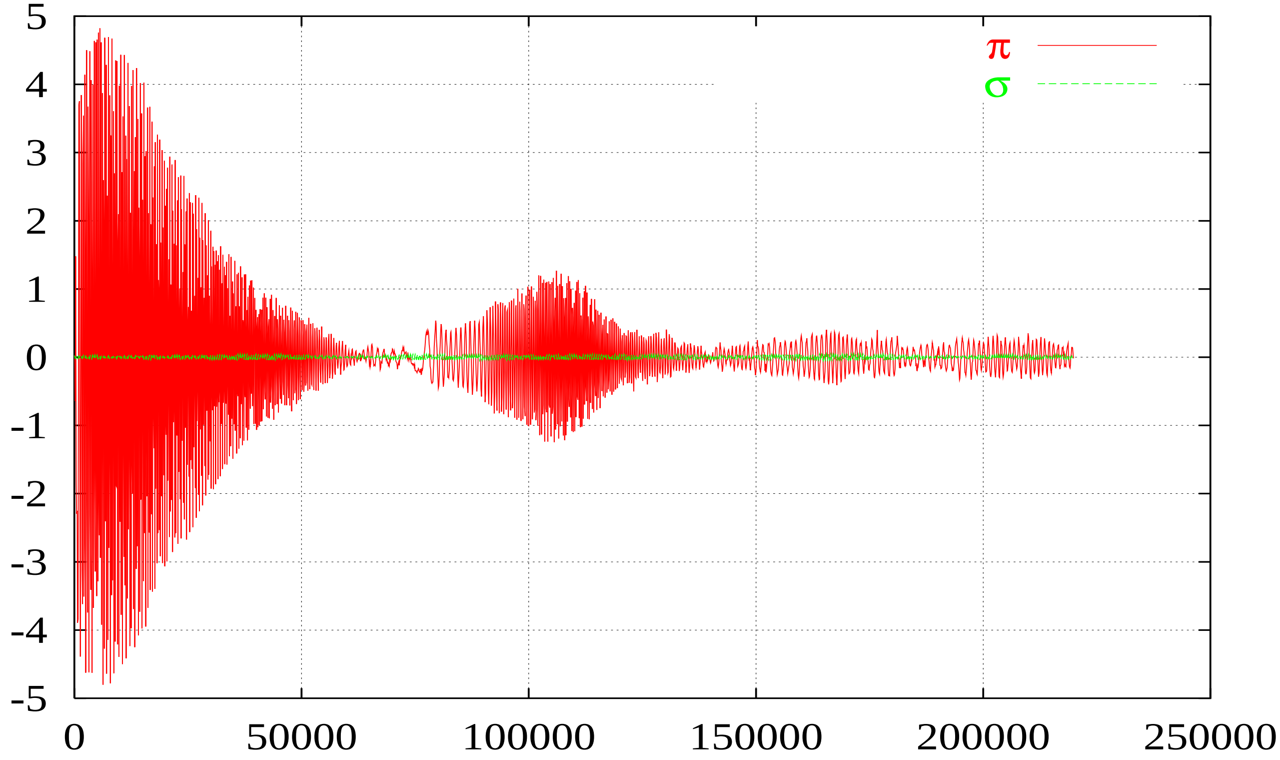
Vertical beam size (μm) vs. turns

DAΦNE #2: 3



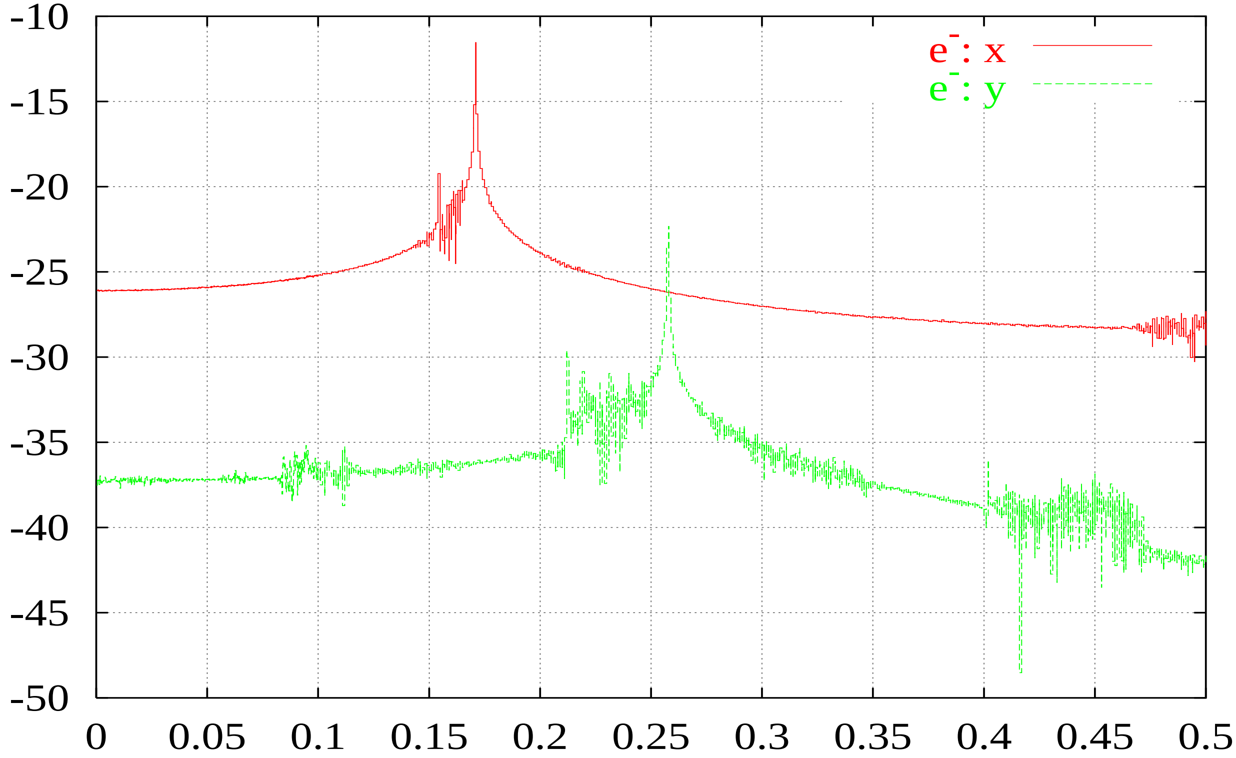
Horizontal coherent beam-beam modes (mm) vs. turns

DAΦNE #2: 4



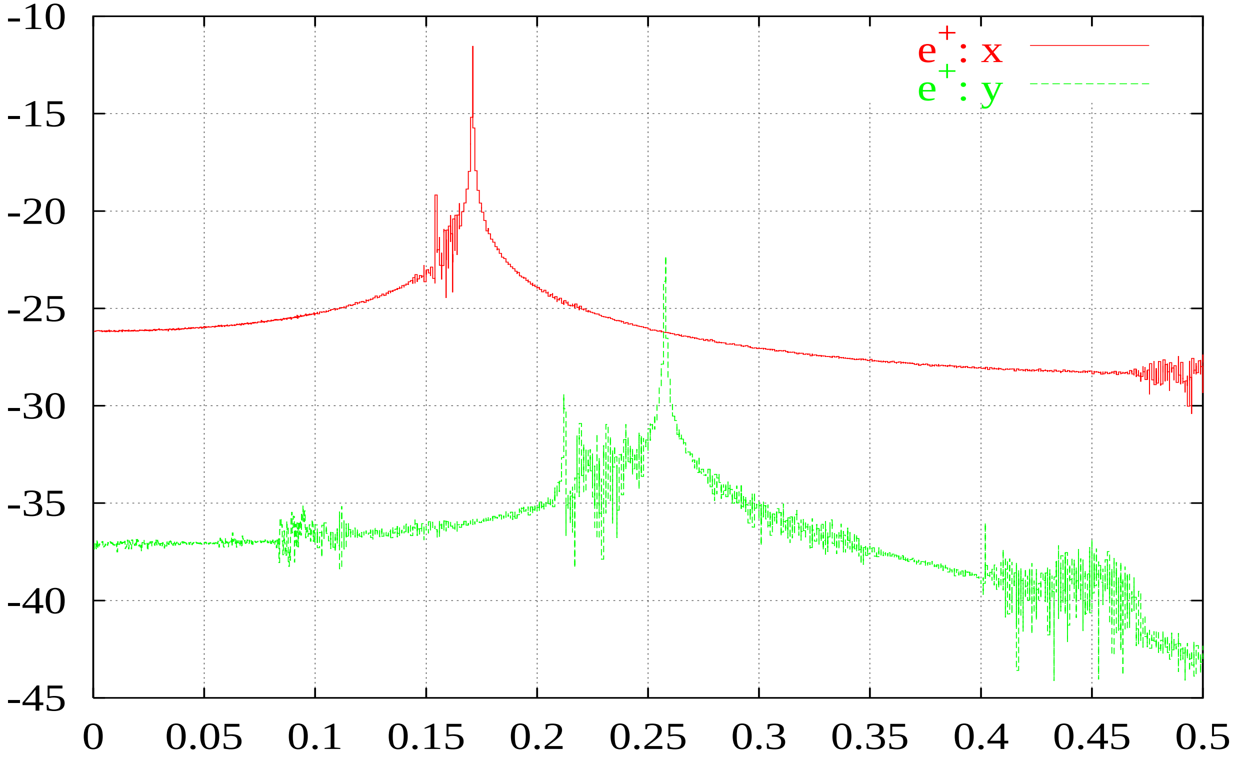
Vertical coherent beam-beam modes (μm) vs. turns

DAΦNE #2: 5



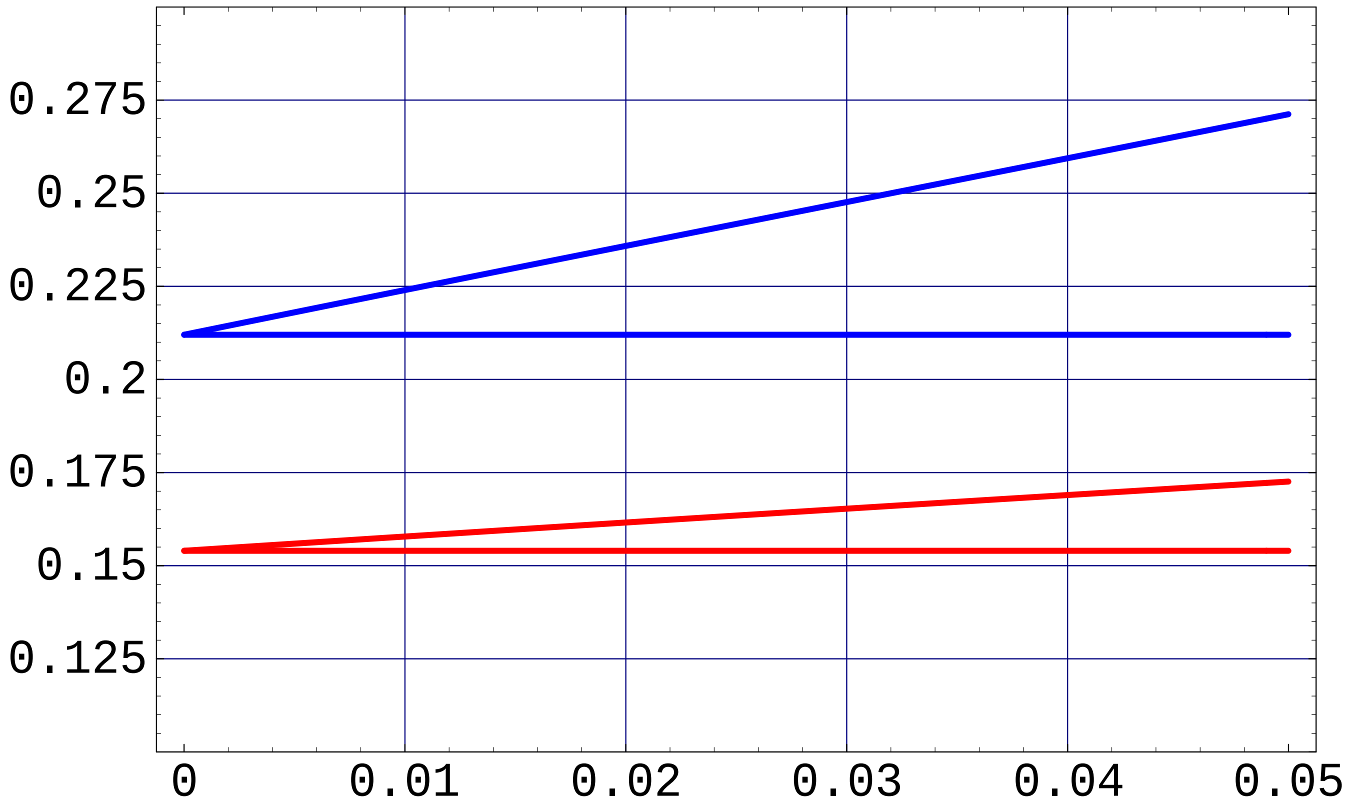
Coherent spectra of the electron beam.

DAΦNE #2: 6



Coherent spectra of the positron beam.

DAΦNE #2: 7



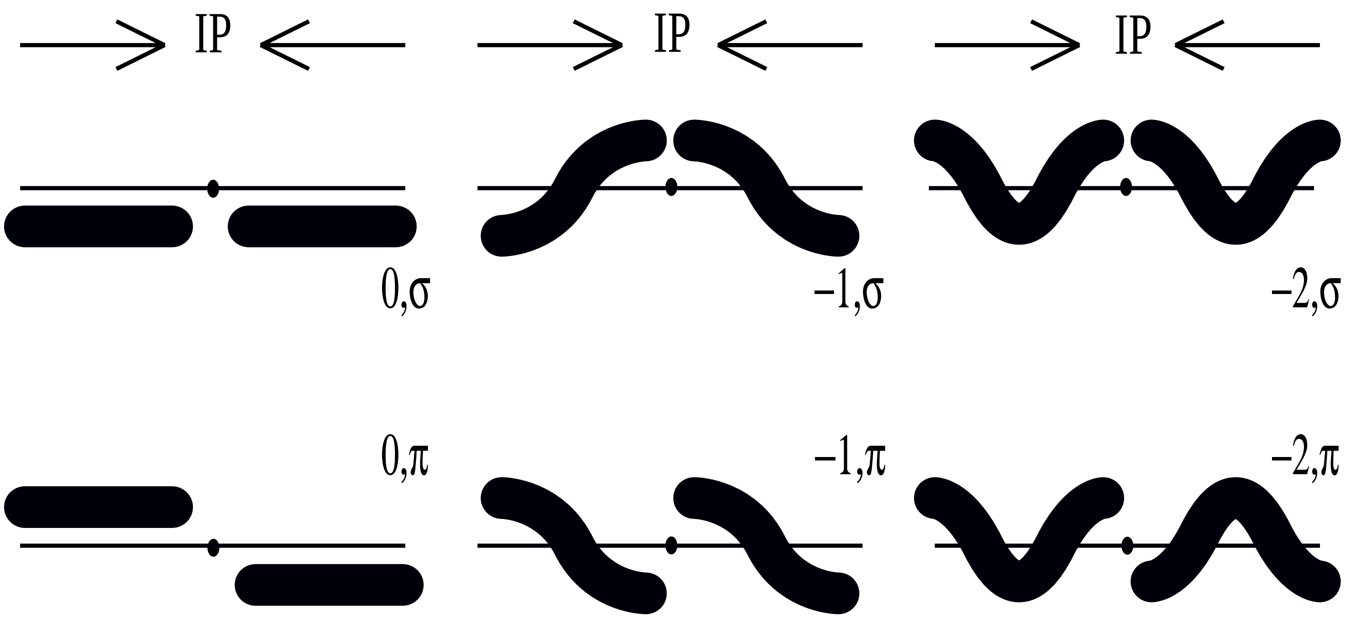
Coherent beam-beam mode tunes vs. ξ (linear model).

Coherent synchrobetatron beam-beam modes

- **We study the coherent dipole oscillations of colliding bunches in a circular collider**
- **The bunch length σ_s is comparable with β^*, and the beams are being bent during the collision**
- **Linearized beam-beam force (small oscillation amplitudes and the bunches are rigid in transverse direction)**
- **One transverse degree of freedom (small betatron coupling), no radiative effects**

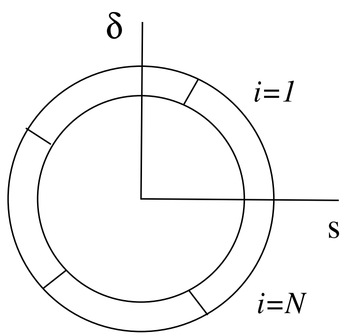
E.A.Perevedentsev and A.A.Valishev, Phys. Rev. ST Accel. Beams 4, 024403 (2001)

Mode naming convention



Calculation methods

1. **Circulant matrix → eigenvalue problem**



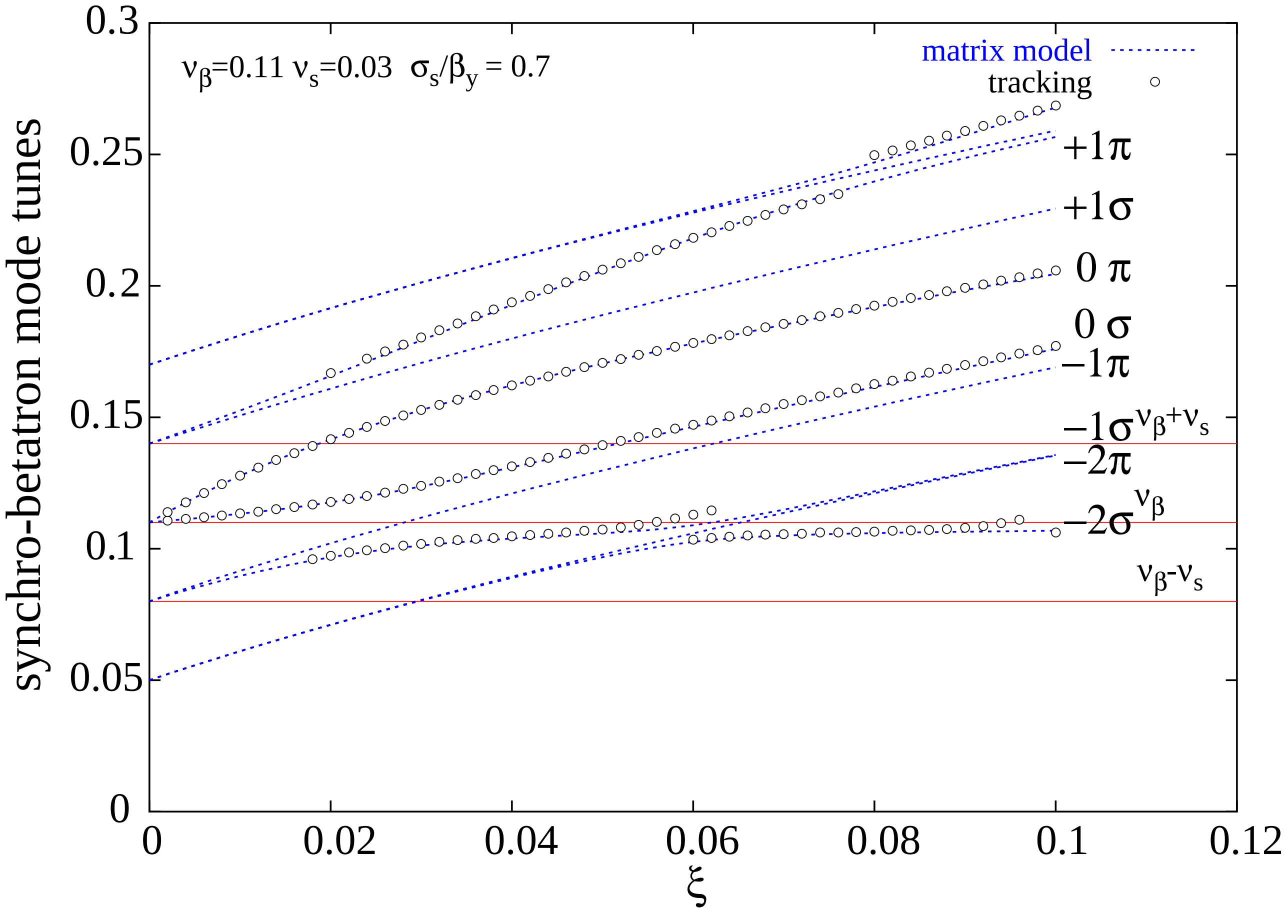
$$\longrightarrow M_{sb} \begin{pmatrix} x_1 \\ p_1 \\ \dots \\ x_N \\ p_N \end{pmatrix}$$

$$M_{sb} = C \otimes B$$

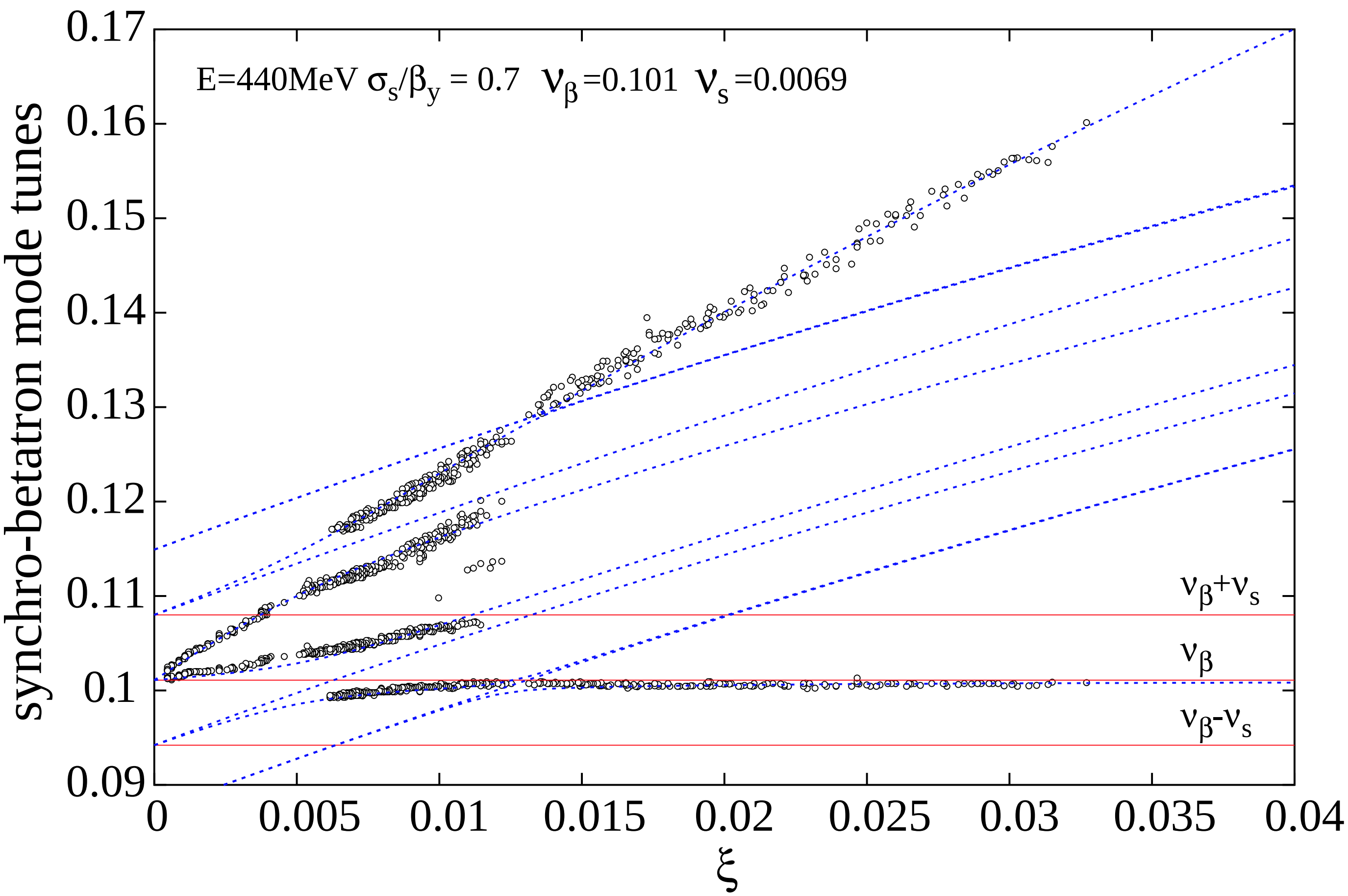
$$M_2 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \otimes M_{sb}$$

$$M = M_{beam-beam} \cdot M_2$$

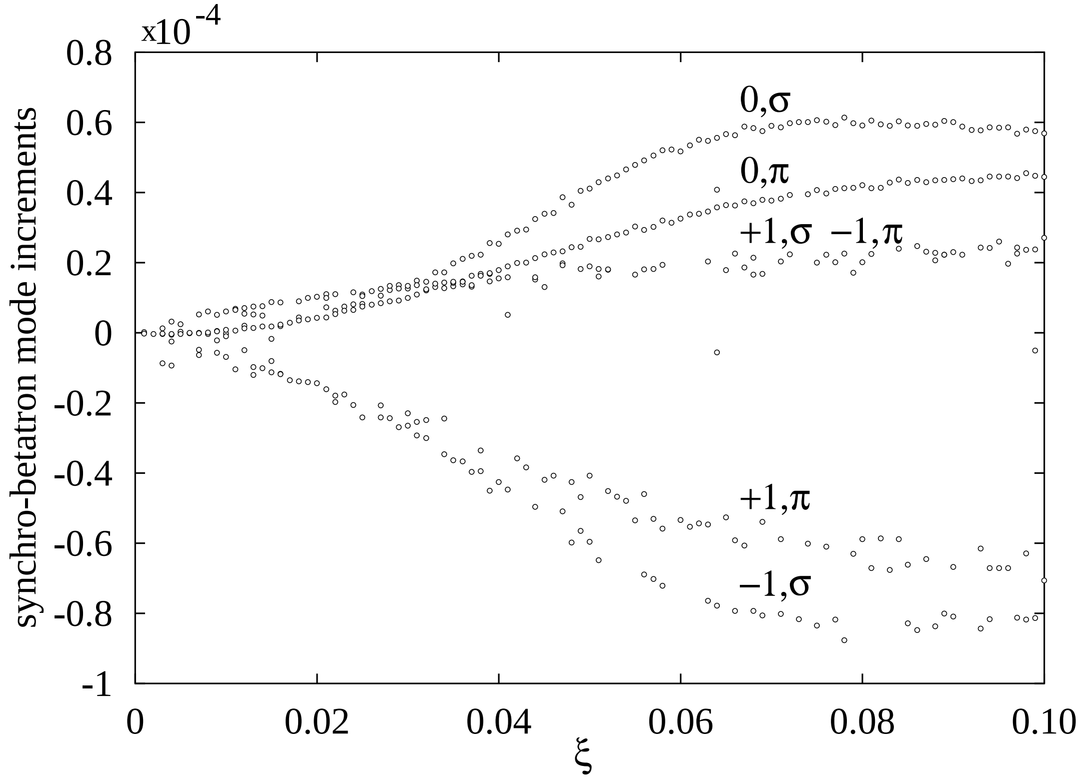
2. **Numerical tracking → Fourier transform of the turn-by turn dipole moment**



Synchrobetatron mode tunes vs. the beam-beam parameter ξ. Comparison of the circulant matrix hollow beam model (lines) with tracking of the Gaussian distribution (circles; number of particles in tracking was 1000).



Synchrobetatron beam-beam mode tunes vs. ξ.
Comparison of measured (circles) and calculated (lines) data.



Synchrobetatron beam-beam mode increments vs. ξ for combined action of the beam-beam interaction and machine impedance (tracking).

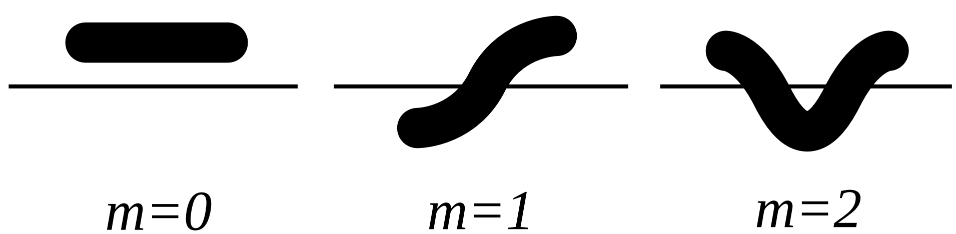
Equal bunch intensities, $\nu_\beta = 0.11$, $\nu_s = 0.03$, and the bunch length is $0.7\beta^*$.

The constant wake, $Q = 0.005$, corresponds to the $m = 0$ mode tuneshift of $-3 \cdot 10^{-5} = -10^{-3}\nu_s$.

Observation of coherent synchrobetatron modes

- **Turn-by-turn high accuracy measurement of the vertical (or horizontal) dipole moment of a selected bunch.**
- **Direct observation of the transverse head-tail modes.**

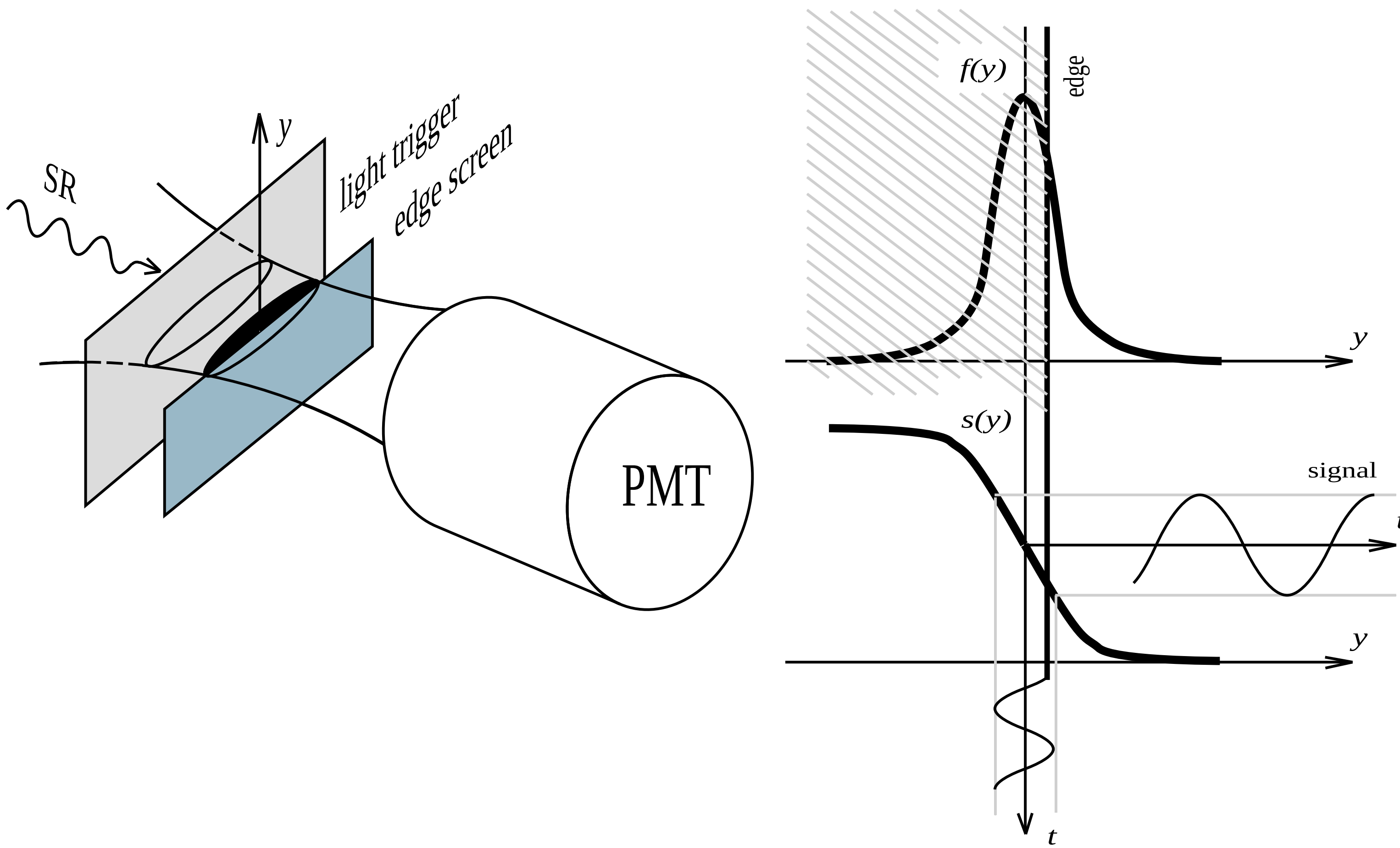
$$D = \sum_m D_m e^{i\omega_m t}$$



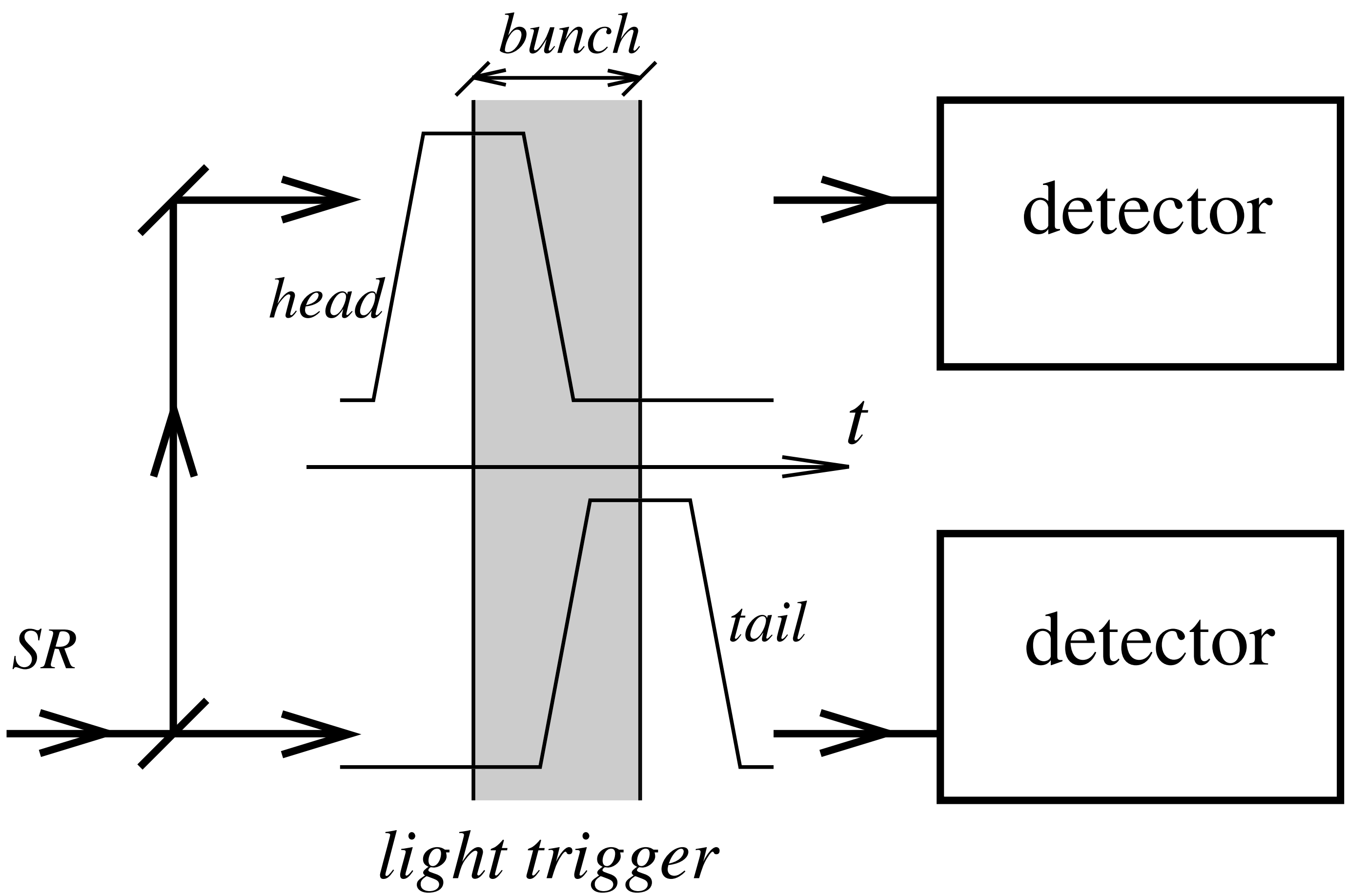
Instrumentation

- The system utilizes SR from the beam
- The light is gated turn-by-turn by a fast switch (e.g. Pockels cell) to separate single bunch or its part
- The beam image is focused into the plane of a movable screen
- The light which passed the screen is detected with a photomultiplier tube (PMT)
- The PMT signal is sampled with an ADC
- The stored array of data is Fourier-analyzed

Scheme of the detector



Direct observation of the head-tail oscillation (proposal)



Possible applications

- Measurement of the betatron tune of the selected bunch without external excitation of the beam motion
- Detection of the dipole synchrobetatron modes
- Detection of the quadrupole coherent modes
- Evaluation of the beam-beam σ and π modes tune split