THE STUDY OF THE BEAM DYNAMICS AT THE VEPP-2000 COLLIDER USING A GATED CAMERA

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ABSTRACT

The Nanogate-38 gated camera with a temporal resolution of 60 nanoseconds was used to measure the transverse beam dimensions in the BEP booster and the VEPP-2000 electron-positron collider. The camera was used in combination with a double-slit interferometer to measure the vertical beam size and with projection optics to construct a transverse beam profile in single-turn mode. Some beam characteristics were measured, such as decoherence time, radiation damping time and fast attenuation time. The purpose of these experiments was to investigate the possibility of using this camera to measure the transverse dimensions of the beam and its emittance, as well as to conduct experiments on accelerator physics at the SKIF synchrotron radiation source.

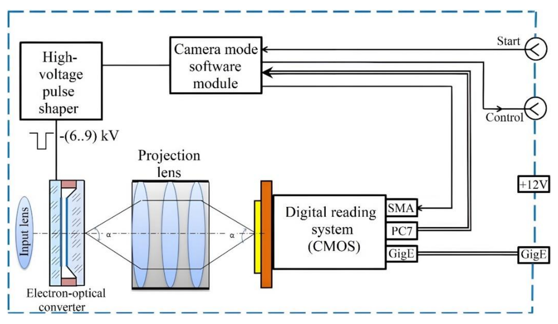
NANOGATE-38 GATED CAMERA

Camera specifications

Parameter	Value
Resolution	2048 × 2048
Sensor full size	22.5 × 22.5 mm²
Pixel size	11 µm × 11 µm
Dark noise	1.5 e−
Full pixel charge	91000 e−
Dynamic range	1400
Nonlinearity	⩽ 1 %
Exposure time	**60 ns** – 1200 µs
Jitter	⩽ 20 ns
Minimum delay	100 ns

Pulsed (gated) electron-optical cameras (EOC) of the new generation Nanogate-38 are produced by *NANOSCAN Scientific and Production Enterprise LLC* [9]. Their main purpose of these cameras is a detailed precision study of the space-time and energy characteristics of fast-moving processes in the nano- and microsecond time domains.

The image of the fast-moving process under study is focused on the EOC photocathode. The camera had an S20 type photocathode, but a version of the Camera with a sun-blind photocathode is also possible.



INTRODUCTION

The largest scientific project carried out by the Budker Institute of Nuclear Physics of Siberian Branch Russian Academy of Sciences (BINP) in recent years is the construction of a synchrotron radiation source of generation 4+ named Siberian Ring Photon Source (SKIF) [1].

The calculated emittance of the electron beam in SKIF is ε_x = 75 nm × rad. One of the important tasks in beam diagnostics at a storage rings is to measure the record-low emittance. To do this it is assumed to use the traditional method of measuring the transverse horizontal beam size σ_x [2, 3].

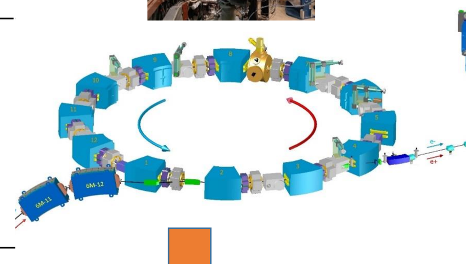
To measure the transverse beam size it is planned to use a double-slit interferometer [4, 5] which registers synchrotron radiation (SR) emitted from a dipole magnet in the ultraviolet (UV) part of the spectrum. Transverse beam oscillations which can be caused by various factors and also mechanical vibrations of optical diagnostic components, can lead to a deterioration in the visibility of the interference pattern and overestimation of the actual beam size. Recent experiments on the KISI storage ring [6] have demonstrated that it is preferable to keep exposure time during interference pattern recording below 1 ms.

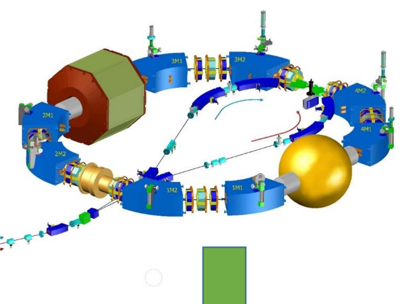
An equally important task is to tune the beam "top up" injection into the main SKIF storage ring. In this regard, efforts have been made to investigate the possibility of detecting the transverse profile of an electron beam using a Nanogate-38 gated electron-optical camera with an image brightness amplifier instead of the traditionally used digital CMOS cameras.

The experimental measurements were conducted at the VEPP-2000 complex using the Nanogate-38 camera to test its potential ability for these purpose. VEPP-2000 is a compact electron-positron collider operating in a 1×1 bunch mode and it is equipped with an electron-positron booster called BEP. Whole complex operates over a wide energy range of 160–1000 MeV. The vertical beam size in the BEP is close to the calculated diffraction limit of $\sigma^d_z \approx 0.08$ mm at a wavelength of $\lambda = 550$ nm. A double-slit interferometer allows measuring beam sizes smaller than this limit.

BEP parameters (at 430 MeV)

Parameter	Symbol	Value
Circumference	C_i	2235 cm
Bending magnet radius	r_0	128 cm
Revolution frequency	f_0	13,415 MHz
Revolution period	T	74,54 ns
Betatron tunes	ν_x, ; ν_z	3,4; 2,4
Synchrotron frequency	ν_s	0,0039
Momentum compaction coefficient	α_p	0,058
Energy spread (at "null" beam current)	σ_E/E	3.2×10^{-4}
Emittance (at "null" beam current)	ε	$1.6 * 10^{-6}$ cm × rad





VEPP-2000 parameters (at 1 GeV)

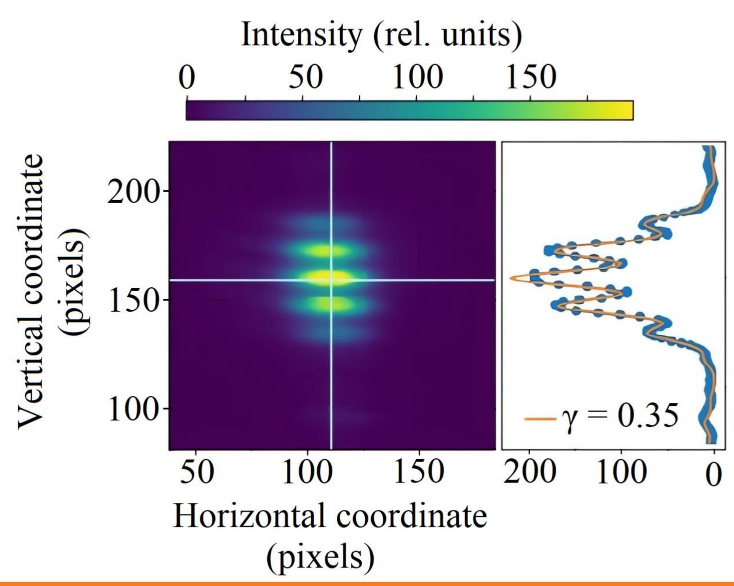
Parameter	Symbol	Value
Circumference	C_i	2439 cm
Bending magnet radius	r_0	140 cm
Revolution frequency	f_0	12,2925 MHz
Revolution period	T	81.35 ns
Betatron tunes	ν_x, ; ν_z	4.178; 2.178
Synchrotron frequency	ν_s	0,0025
Momentum compaction coefficient	α_p	0,036
Energy spread (at "null" beam current)	σ_E/E	7.1×10^{-4}
Emittance (at "null" beam current)	ε	$1.58 * 10^{-5}$ cm × rad

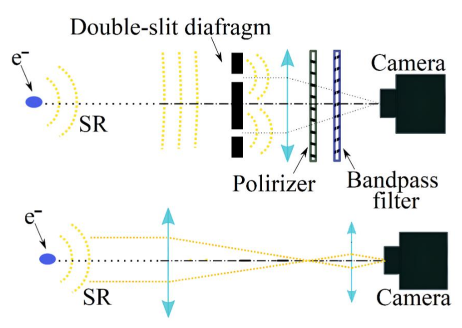
BEP

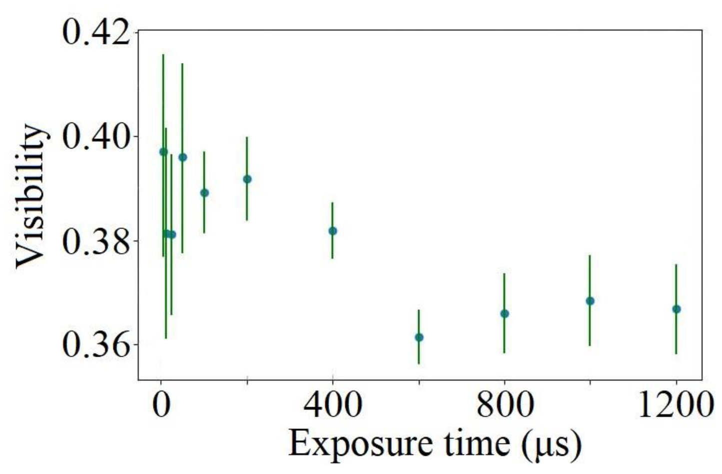
VEPP-2000

INTERFEROMETER

Figure shows the typical interference pattern from bunch SR at the vertical plane recorded using the Nanogate-38 camera. The figure also shows a cross-section of the interferogram.







To check the linearity of the camera and the correctness of the visibility measurements, the exposure time of the camera was varied at a constant beam current of $Ib \approx 100$ mA. The registered visibility value at an exposure time of less than 200 ms corresponds to a vertical beam size of σ_z = 0.055 ± 0.05 mm. The luminous flux transmitted by the interferometer is significantly limited by the aperture of the slits and the bandpass filter.

TURN-BY-TURN MEASUREMENTS

Despite the fact that the transverse dimensions of the electron beam in modern SR sources including SKIF are so small that they cannot be measured using conventional projection optics in the optical wavelength range, this beam observation tool has not lost its relevance. It still allows us to qualitatively observe the dynamics of the beam in the accelerator. The registration of the transverse beam profile using projection optics can be useful in the booster and main SKIF storage ring when tuning injection. The sensitivity and time resolution of the Nanogate-38 makes it possible to obtain transverse beam profile in BEP with high spatial resolution and single-turn time resolution when constructing a beam image using a lens on the camera's photocathode. It is interesting to observe not single but several the first turns after exciting bunch oscillation. Figure 6 shows the dynamics of the bunch in the BEP.

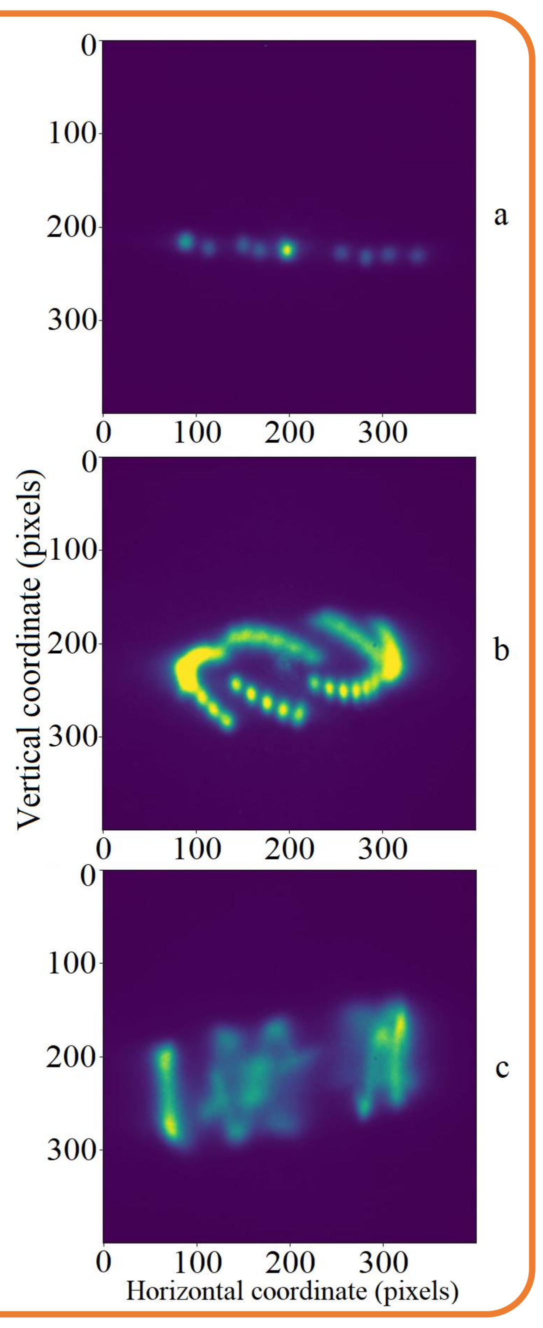
Each individual bright spot in Fig. (a) and (b) is actually composed of several hundred pixels and represents the transverse distribution of particles in the beam at an individual revolutions. In Fig. (b) and ©, the exposure time of the camera corresponds to ~40 and several hundred beam revolutions respectively at a beam current of $I_b \approx 20$ mA . The frame in Fig. (a) shows a bright spot in the center from the beam accumulated in the BEP. To the left and right of this, several revolutions of the beam making horizontal oscillations relative to the equilibrium orbit are visible.

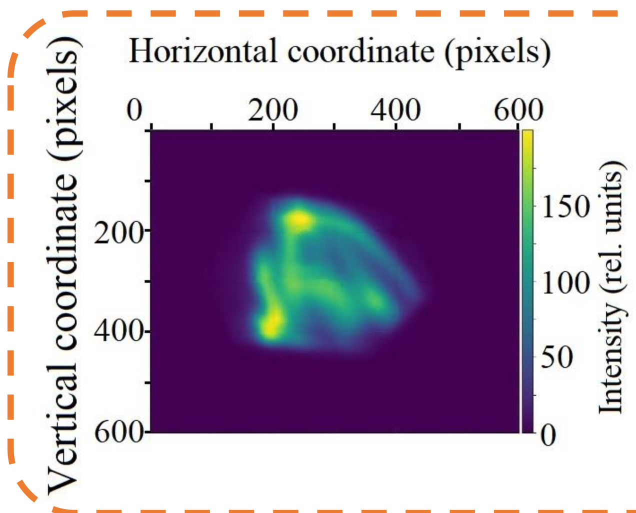
The exposure time (in turns amount):

a – general betatron oscillations of the bunch (≈10 turns);

b – phase oscillations of the bunch occur (~40 turns),

c – betatron oscillations of the bunch are excited at betatron tunes close to the betatron resonance (several hundred turns)





COMPARISON WITH GENERAL CMOS

The minimum exposure time of the MER-131-75GM digital camera [10] is 5 microseconds, which corresponds to approximately 65 revolutions of the beam in BEP. However, we were not able to obtain a clear images of the beam revolutions performing betatron oscillations with a large amplitude with this camera.

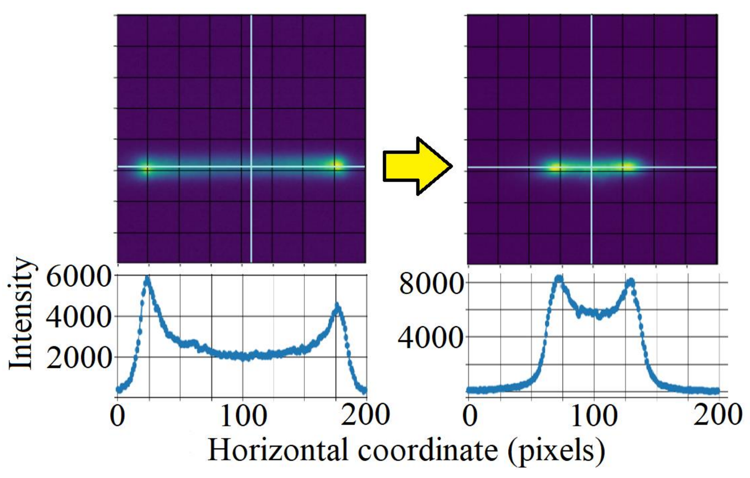
The beam oscillations were caused by kick from a deflector near one of the betatron resonances. It can be assumed that the absence of single-turn transverse beam profiles, similar to those shown in (a) and (b), is related to the features of recording and reading images by the camera's CMOS matrix.

RADIATION DAMPING

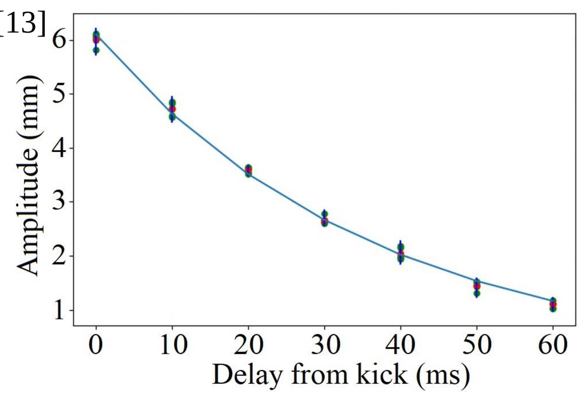
The radial (horizontal) oscillations of the beam were excited by the kick from the electrostatic deflector, and their amplitude was measured using a camera. The amplitude was defined as the distance between two opposite breakpoints of high bunch oscillations (left figure). One image was captured during ~230 bunch turns (the Nanogate-38 exposure time was 17 µs). The theoretically calculated radiation damping time [11] at bunch energy E = 430 MeV is $\tau_x \approx 32$ ms which correlates well with the measured value of 36 ms.

The measurements of the amplitude were also taken at significant values of the beam current, when collective effects took place and so-called fast damping [12] arose alongside radiation damping.

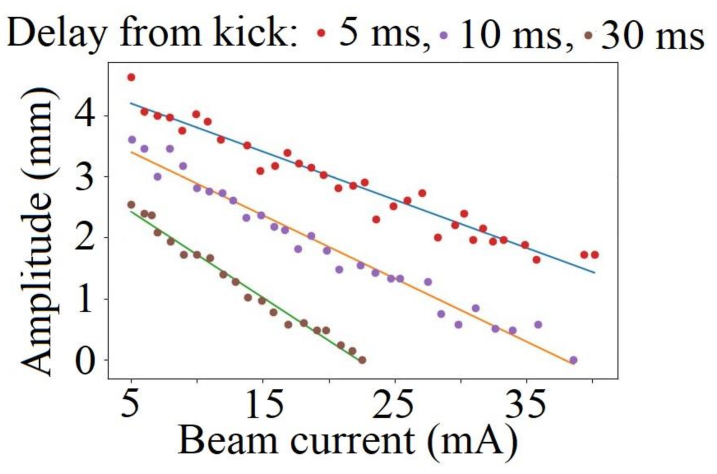
The details of the measurements on BEP can be found in [13]



The profile at two different time delays after the kick (top) and their cross-sections (bottom)



The experimentally obtained dependence of the oscillation amplitude on the beam current at various delays from the deflector kick. This measurement was carried out at a very low beam current (almost "zero") Ib = 0.7 mA .

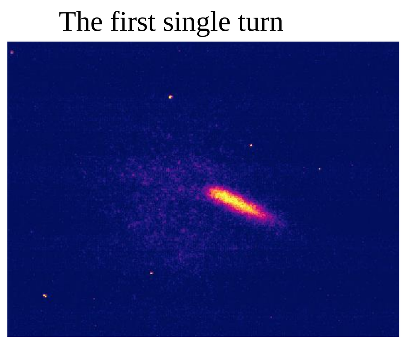


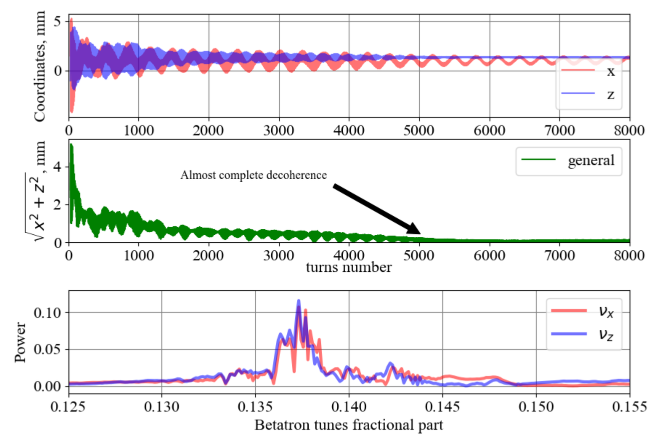
As can be seen, as the beam current increases, the oscillation amplitudes decrease at the same delays relative to the impact, which means a decrease in the damping time. The strength of the deflector kick was the same in all cases.

OSCILLATIONS DECOHERENCE

There is decoherence phenomenon [2, 14, 15] during the injection of the bunches in the VEPP-2000 collider, which is caused by the nonlinearity of the magnetic fields and chromaticity. This effect can be observed by electrostatic BPM. Almost complete decoherence occurs in the 5000-th turn when the radiation damping time is around 246000 turns (~20 ms) for VEPP-2000 at a energy of experiment of E = 511 Mev.

The first single turn



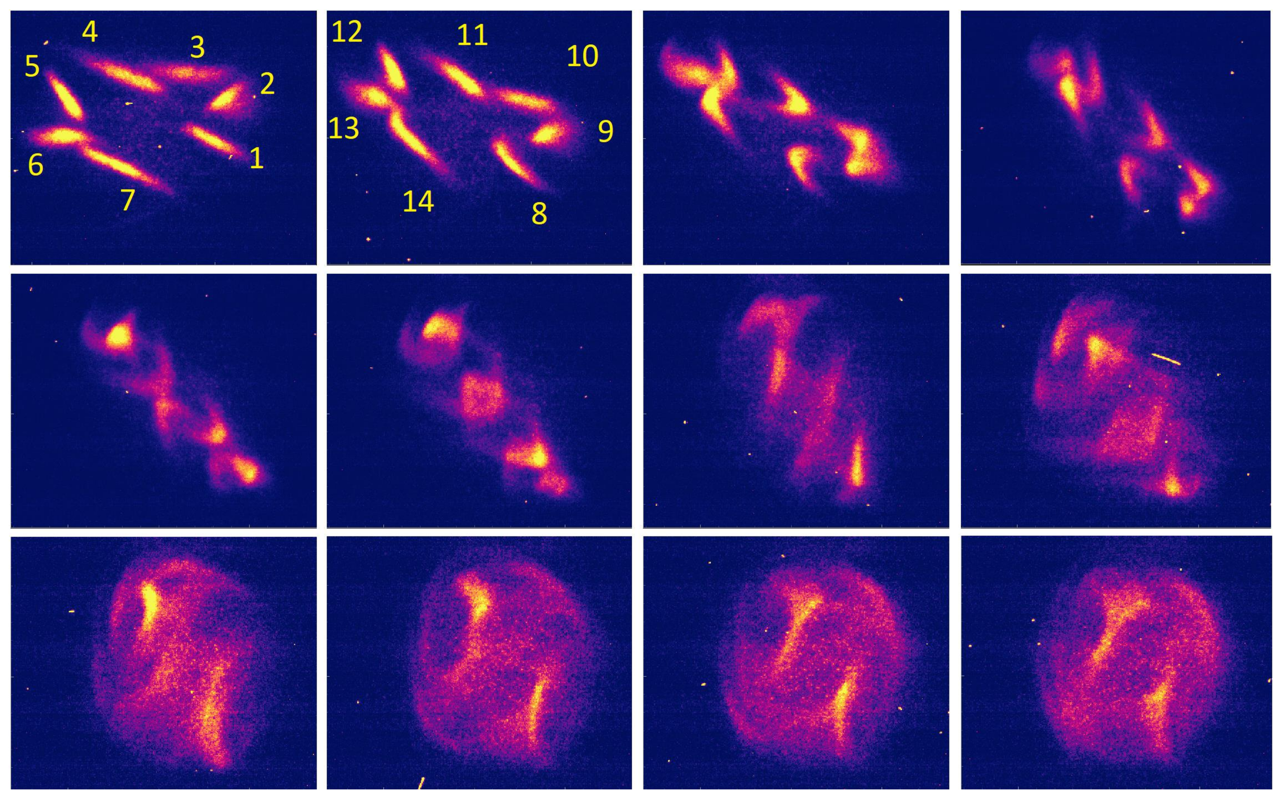


BPM signals during injection.
The arrow indicates when decoherence is nearly complete; the *general* curve was calculated after oscillations high-pass filtering using FFT.

The beginning of the decoherence was captured by the Nanogate-38. Typical operating conditions in VEPP-2000 is operating at the betatron coupling resonance with fractional parts of both betatron oscillation tunes $\nu_x = \nu_z \approx 1/7$.

It would be more interesting to set the exposure time to ~7 turns to obtain a sequence of 7-turn series, which demonstrate decoherence process until the 84-th turn.

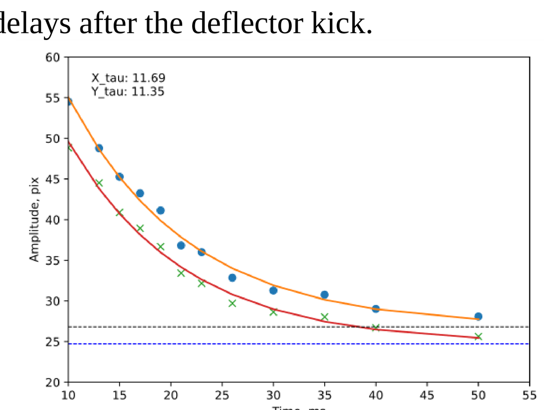
Note that the **figure shows seven consecutive turns (bunch profiles in X–Z space) rather than a single instantaneous bunch profile or phase portrait.**

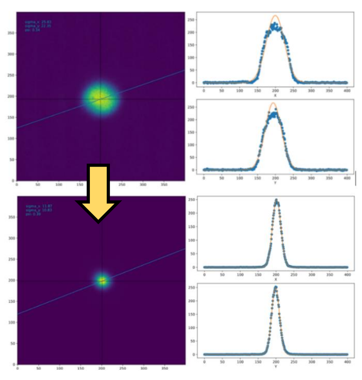


RADIATION DAMPING

Whereas the BEP had a flat beam the VEPP-2000 operated with a almost round beam at the observation point with almost 100% betatron couple also the decoherence took place. Instead of using the term "amplitude", we have the standard deviations, or sizes, of a two-dimensional normal distribution, which we use to approximate the beam profile.

The method of measurement is similar to that used in BEP, which is to obtain sizes at different time delays after the deflector kick.





CONCLUSION

The Nanogate-38 gated electron-optical camera was used at the electron-positron BEP booster and VEPP-2000 collider to measure the vertical beam size with the optical scheme of a double-slit interferometer and to register the transverse beam profile using conventional projection optics. Experiments have shown that the Nanogate-38 has a significantly lower sensitivity compared to the MER-131-75 GM CMOS camera. However, the CMOS camera is not able to obtain single-turn profiles of the beam undergoing betatron oscillations with a large amplitude, which is possible using the Nanogate-38.Based on these findings, it can be concluded that the Nanogate-38's potential in accelerator physics experiments for studying the beam dynamics are promising.

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