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Status of a radio-frequency-based streak camera with subpicosecond time resolution

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Abstract

Usage of a cavity with a high quality factor in a streak camera (SC) allows us to increase the energy of electrons up to 100 keV and therefore to reduce the influence of some of the effects that limit the SC time resolution. Time resolution up to 1.4 ps on a prototype of a radio-frequency-based SC (RFC) with circular scanning was demonstrated earlier. Following this, the new RFC was produced. The possibility of achieving a time resolution of 0.6 ps for a 350-ps single light signal is demonstrated. Preparation for experiments with spiral scanning (sub-ps time resolution for 10-ns process duration) is in progress.

1. INTRODUCTION

The appearance of the first electron-optical chronography at the end of 40 s allowed us to achieve the time resolution of about 10^{-12} s. Nowadays, the sub-ps domain is being explored with the aim of reaching a time resolution as low as 100 fs. In early investigations, the limitations on the ultimate time resolution were studied (Zavoisky & Fanchenko, 1965). The major contributions were given by chromatic aberration and space-charge effect. The former consists of the lengthening of the electron bunch due to longitudinal velocity spread ΔV of the electrons emitted at the photocathode:

$$\Delta t = \frac{m\Delta V}{eE},$$

where E is the accelerating electric field at the fotocathode. Secondly, space charge affects the bunch length by

$$\Delta t \propto \frac{1}{E^{3/2}}.$$

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The accelerating voltage of the conventional streak cameras (SCs), that is, when beam deflection is driven by an electric field, is usually no higher than 20 kV.

2. CIRCULAR SCANNING

Instead of applying a voltage ramp linearly increasing with time, we used the transverse magnetic field of a TM_{001} mode with circular polarization in a cylindrical cavity (Fig. 1) for beam bending. The other components of a streak camera stay unchanged (Guidi & Novokhatsky, 1995). For such a radio-frequency-based streak camera, the use of a cavity at a high quality factor (higher than 10^4) allows one to increase the energy of electrons up to 100 keV. In this way, one may weaken the effects of both space charge and chromatic aberration.

The deflecting cavity is axially symmetric, made of OFHC copper and is fed by two orthogonal TM_{001} modes, resulting in a rotating magnetic field orthogonal to the cavity axis. Each mode is excited by a separate magnetic loop. Two loops are geometrically at right angles and fed by two RF amplifiers, reciprocally shifted by $\pi/2$ rad in phase. The resonant frequency of each mode can be separately adjusted by means of two piston tuners. Some of the parameters of the RF cavity are summarized in Table 1.

Such a radio-frequency-based streak camera (RFC) exhibits the following advantages (Aleksandrov *et al.*, 1999*a*):

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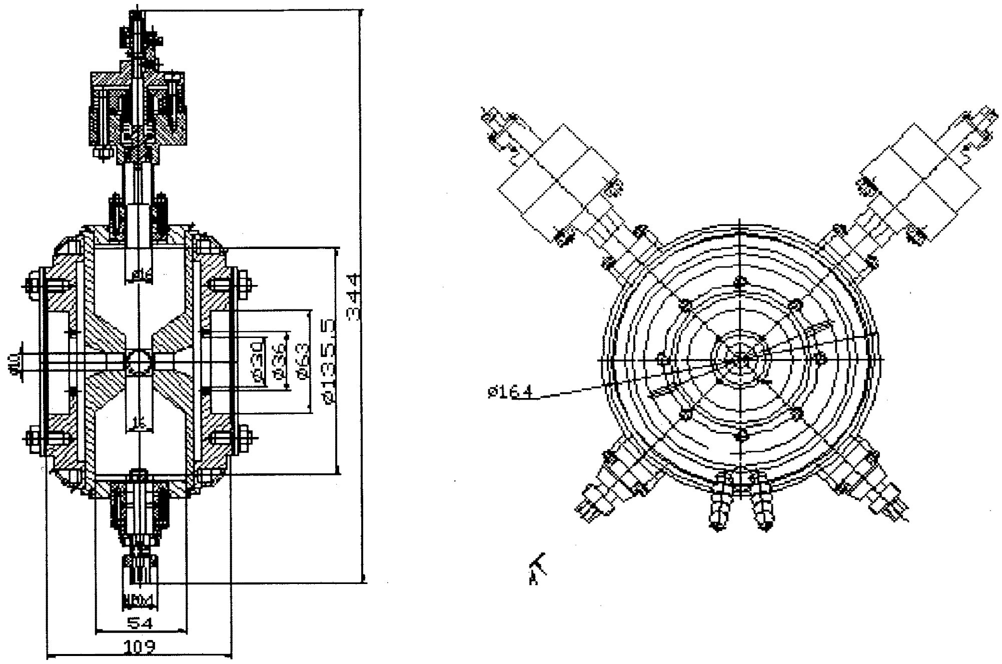

Fig. 1. The cavity for circular scanning.

1. For a usual SC, the time resolution falls with an increase in the time duration of the light pulse under study. Therefore, some fast features inside a long pulse can be lost. Indeed for the RFC with circular scanning, sub-ps resolution is guaranteed over a single pulse as long as 350 ps.

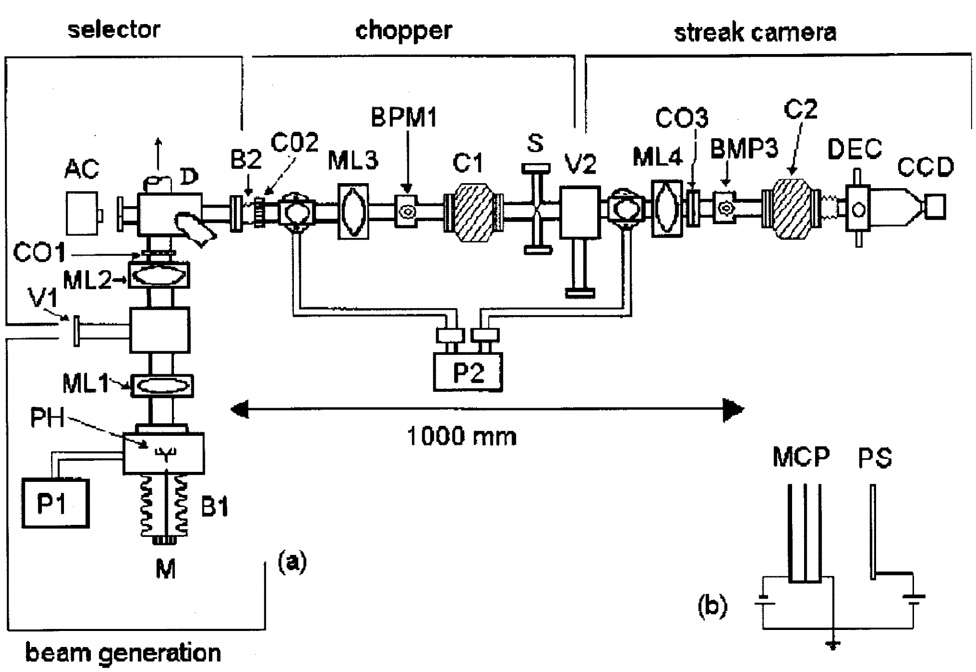

Fig. 2. Experimental setup: (a) Electron beam transportation line: AC: auxiliary camera; BPM1, BPM2: beam position monitors; B1, B2: bellows; C1, C2: rf cavities; CCD: CCD camera and focusing lens; CO1, CO2, CO3: correctors; D: deflecting dipole; DEC: detection system; ML1, ML2, ML3, ML4: magnetic lenses; M: manipulator; PH: photocathode; P1, P2: ionic pumps; S: slit; V1, V2: valves. (b) Detection system: MCP: microchannel plates; PS: phosphor screen.

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Table 1. *Parameters of the cavity*

Operating mode	TM_{001}
Resonant frequency	2856 ± 0.5 MHz
Unloaded quality factor	16,000
Deflecting efficiency at 50 kV	$1.5 \cdot 10^{-3}$ rad/W$^{1/2}$

2. Nanosecond accuracy for triggering is needed in contrast with normal SCs where triggering is often a serious problem.
3. As already mentioned, a cavity with a high quality factor damps the limiting factors to the resolution of the instrument.

3. PREVIOUS EXPERIMENT

In a preliminary experiment (Aleksandrov *et al.*, 1999*b*) the time resolution of 1.4 ps was reached (Fig. 2). An electron bunch of 60-ps time duration from GaAs fotocathode was cut by the chopper system that consists of deflecting cavity C1, drift tube, and adjustable slit S1. The bunch moved from the cavity C1 was turned in on the horizontal plane and hit the vertical slit. To increase the power in the cavity at 400 mkm slit width, it was possible to cut the bunch with time duration far less than 1 ps. A time resolution of at least 1.4 ps (FWHM) was reached (Fig. 3).

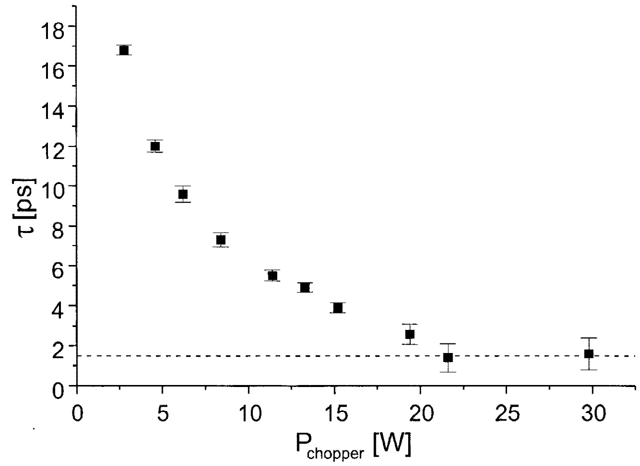

Fig. 3. Measurements of electron bunch length as a function of power on the chopper cavity.

4. THE LAST EXPERIMENT

After this experiment, the GaAs photogun and chopper system was changed to a photogun with transparent multialkali photocathode. The other components of a RFC stayed unchanged. Thus a compact device—an RFC for analysis of the light signal with a duration of one RF period (350 ps)—was created (Bak *et al.*, 2000*a*). The evidence of time resolution better than 0.6 ps was demonstrated. A scheme of the RFC is given in Fig. 4. It consists of the photogun, drift tube, corrector, magnetic lens, RF cavity, detection system, and two ionic pumps. The general layout of the RFC is given in Figure 5.

For a circular scanning with radius R, period of RF $T = 1/f$ the scanning, the beam velocity is

$$V = \frac{2\pi R}{T}.$$

Then the possible time resolution is defined as

$$t_R = x/V,$$

where x is the FWHM of a focused beam on the screen. In our case at $x = 140$ μm, $f = 2.856$ GHz, $2R = 27$ mm, the scanning velocity is 0.8 light velocity times, and the possible time resolution is 600 ps (Bak *et al.*, 2000*b*).

The amplitude of the high voltage is up to 35 kV. Further raising the photogun high voltage requires further improvement in the photogun design. A new RFC has recently been assembled with an improved 80-kV gun, which will be

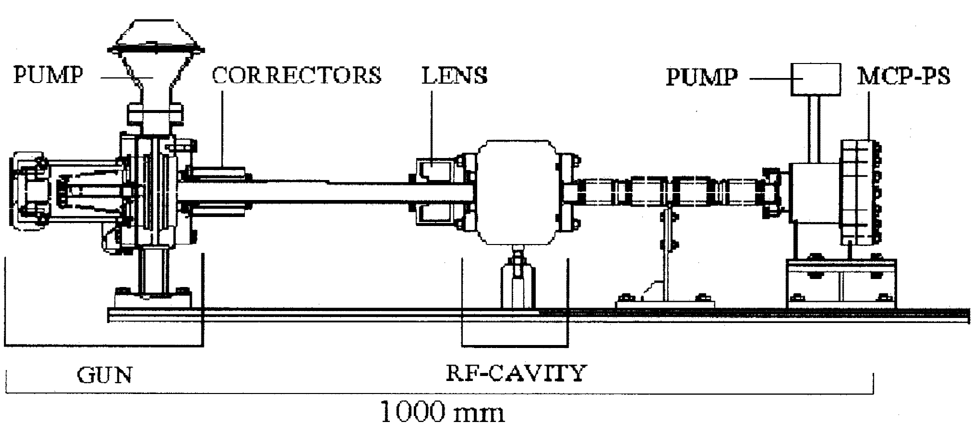

Fig. 4. The new RF streak camera.

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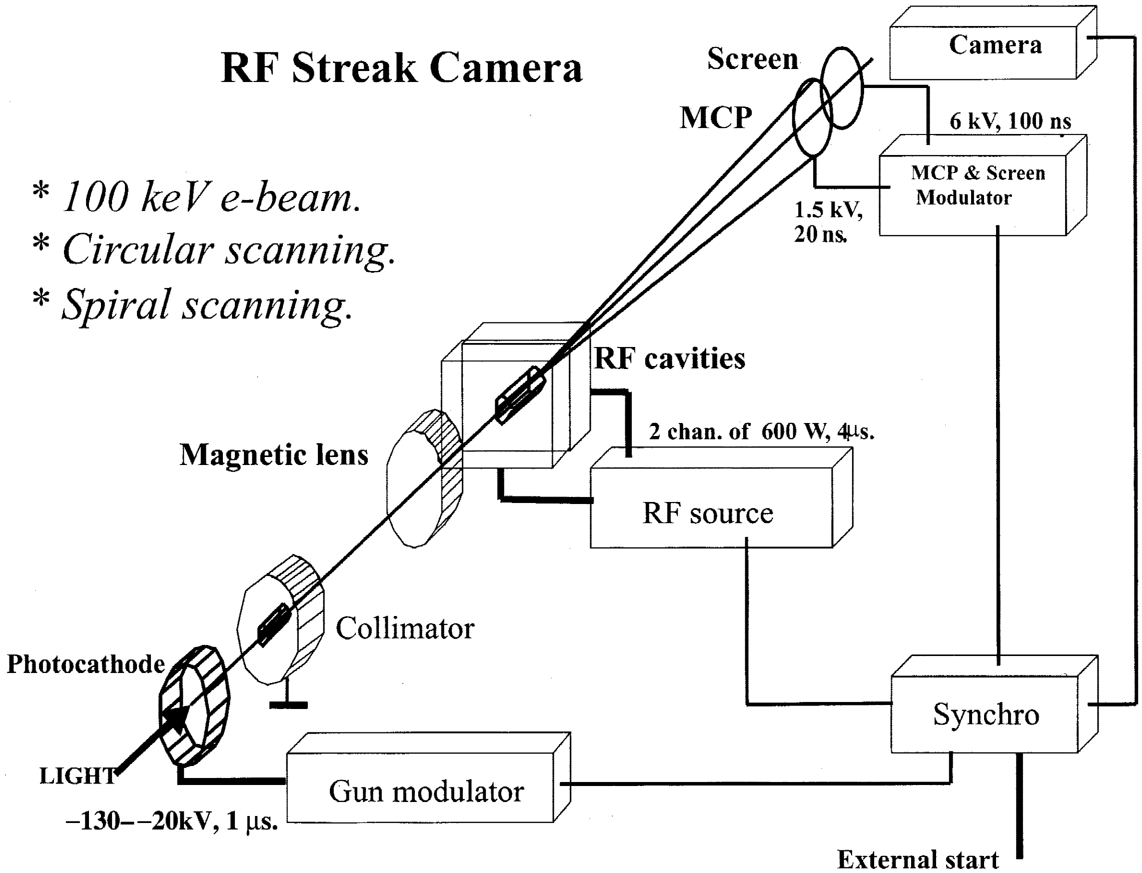

Fig. 5. The general layout.

probed by a 140-fs light pulse from a Ti:Sa laser. Experiments will be done shortly and we expect to reach a better time resolution.

5. SPIRAL SCANNING

In the previous scheme, the measurable pulse length must necessarily be shorter than one RF period (350 ps in the last experiment). Otherwise, there would be a superposition of the trace drawn by electrons over themselves on the screen.

The idea of a "RFC with spiral scanning," that is, allowing it to keep the sub-ps time resolution over a wide time interval, was proposed by Chernousov (2000). This regime is provided by an appropriate decrease in amplitude for the RF field in the cavities of the camera, resulting in a spiral-like pattern of the beam onto the screen.

Due to the high Q-value of the cavity, it is not an easy job to carry out a sufficiently fast RF-amplitude decrease. Certainly, it is not possible to await the natural decay of the RF power in the cavity; therefore it was suggested to replace the previously used one-cavity configuration by two deflecting-cavity assemblies. Each of the two assemblies is formed by two coupled pill-box cavities (Fig. 6). Strictly speaking, only the first cavity deflects the beam while the second cavity is for loading of the RF power into the deflecting cavity.

When a potential is applied to the pin diode, the transmission coefficient at the pin-diode diaphragm becomes close to one and the influence of the loading cavity on the deflecting one is negligible; in this way, we have stable oscillations in the deflecting cavity. Indeed, when direct current is

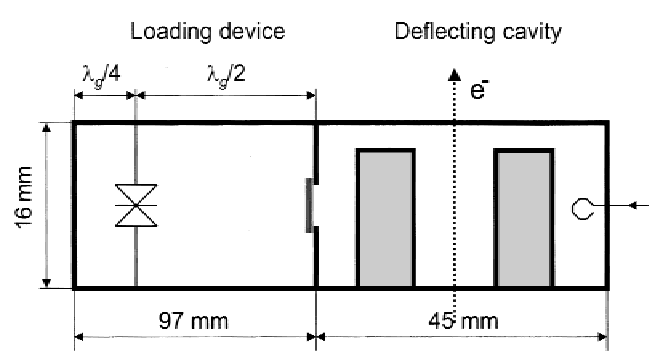

Fig. 6. The cavity for spiral scanning.

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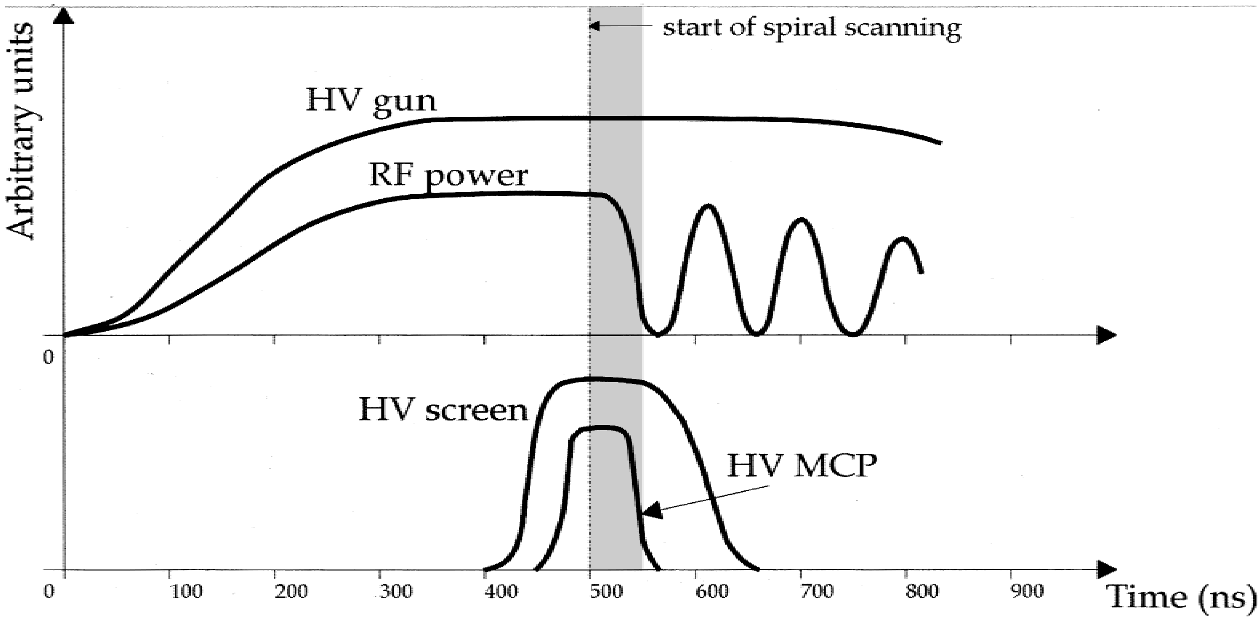

Fig. 7. The synchronization of different signals.

applied to the pin diode, the resonance diaphragm acts as a perfect reflector and the effective length of the cavity decreases to $\lambda_g/2$. Due to proper coupling, energy starts oscillating back and forth from the deflecting cavity to the loading one. The total time to void the energy out of the deflecting cavity can be significantly less than the filling time of the cavity, $\tau_s = 2Q_D/\omega_0$. The pulsed HV power supply of the MCP is able to gate the best time-resolution part of the spiral. A sketch for a possible scheme of synchronization of signals is depicted in Figure 7.

In this way, it would be possible to reach approximately sub-ps resolution over an extraordinarily long time interval (at least 10 ns) for a single light pulse.

Presently, a prototype for a RFC with spiral scanning is underway and first measurements are planned for the autumn.

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