Institute of Plasma Physics and Laser Microfusion
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Diagnostic Team

High-Speed Photography in UV-VIS-NIR Spectral Ranges for Plasma Investigations

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High-Speed Photography for Plasma Investigations

Motto:

Seeing is Believing

Diagnostic Team
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High-Speed Photography for Plasma Investigations

Nowadays,
High-Speed Photography Techniques
that can be applied
for Plasma Investigations

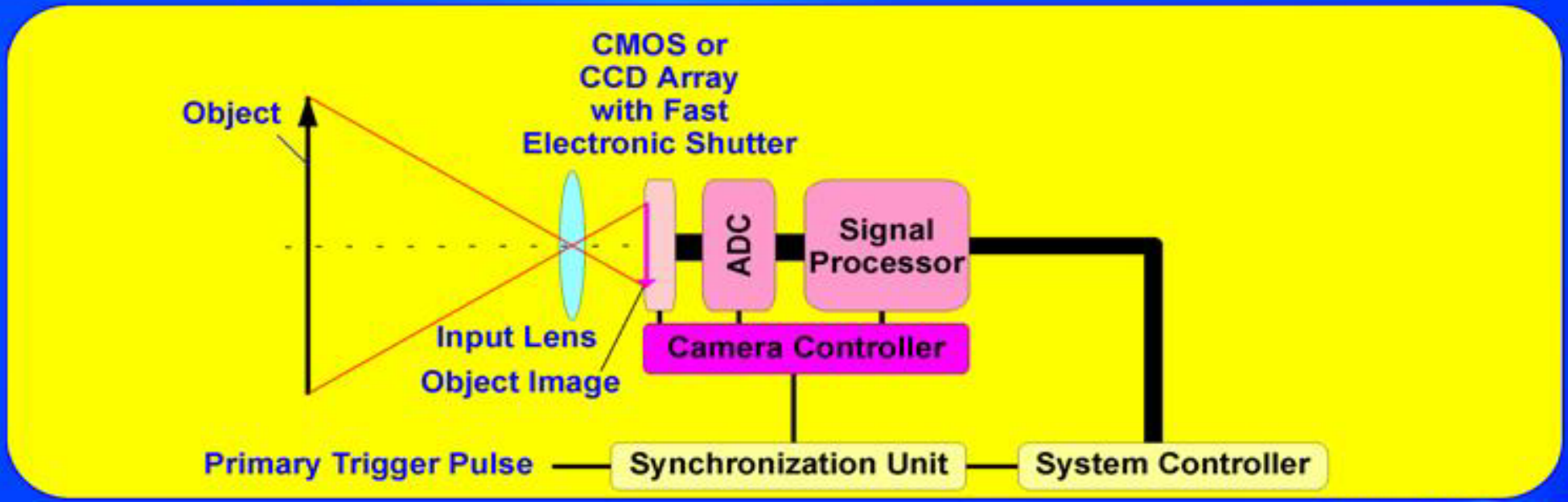
High-Speed Photography for Plasma Investigations

Nowadays, High-Speed Photography Techniques

High-Speed Video Technique (HSVT)

CCD or CMOS arrays are used, both as a main shutter and as final image detector

General layout:



High-Speed Photography for Plasma Investigations

Nowadays, High-Speed Photography Techniques

High-Speed Video Technique (HSVT)

CCD or CMOS arrays are used, both as a main shutter and as final image detector

- Very convenient and elegant solution gathers more and more popularity
- A number of cameras are commercially offered

High-Speed Photography for Plasma Investigations

Nowadays, High-Speed Photography Techniques

High-Speed Video Technique (HSVT)

Advantages:

- High frame rate

  Recently reported CMOS Camera frame rate – 100 000 frames per second

- Relative large number of the consecutive taken frames

  From a few tens to a few thousands – depends on actual frame rate and capacity of frame buffer it

- Frames are immediately stored in digital form

- These systems are frequently equipped with user-friendly software packages enable to perform on-line data processing

High-Speed Photography for Plasma Investigations

Nowadays, High-Speed Photography Techniques

High-Speed Video Technique (HSVT)

Disadvantages:

- Minimal exposure time in range of a few microseconds

  Shortest reported exposure time – 2 microseconds, typical 10 – 12 microseconds

- It is dedicated to capturing event frames only within the UV-VIS-NIR spectral ranges, with no possibility to amplify the light it receives

- Low system throughput – spatial resolution is strongly decreased with the increasing frame rate and number of consecutive frames recorded

High-Speed Photography for Plasma Investigations

Nowadays, High-Speed Photography Techniques

High-Speed Video Technique (HSVT)

Application of HSVT to the plasma studies – brief remarks:

- **Due to ultimate exposure time HSVT is able to record sequences of frames for events with characteristic velocities is in the range of tens meters per second to 1 kilometer per second**

  The main criterion is the time it takes for an object to move its own length

- **Due to impossibility to amplify the light, the capturing of event frames within narrow band of spectrum (interference filters) is not practicable**

- **Due to limited spatial resolution, the wide angle field of vision of HSVT is in practice impossible**

  The typical values of spatial resolution (at high frame rate) are: 160x80 or 1280x50 pixels

- **Rather long exposure time and insufficient spatial resolution can cause image blur**

  The small and very fast traveling objects can be invisible or lost

High-Speed Photography for Plasma Investigations

Nowadays, High-Speed Photography Techniques

Electro-Optical High-Speed Photography

High vacuum tubes (so-called image intensifiers) play the role of a primary image detector, radiation amplifier and fast or ultra-fast shutter

whereas CCD cameras are applied only as final image detectors, allowing the storage (in digital form) of the images of the investigated object appearing on luminescent screens of the gated primary image detectors

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High-Speed Electro-Optical Frame Photography in UV-VIS-NIR Spectral Ranges

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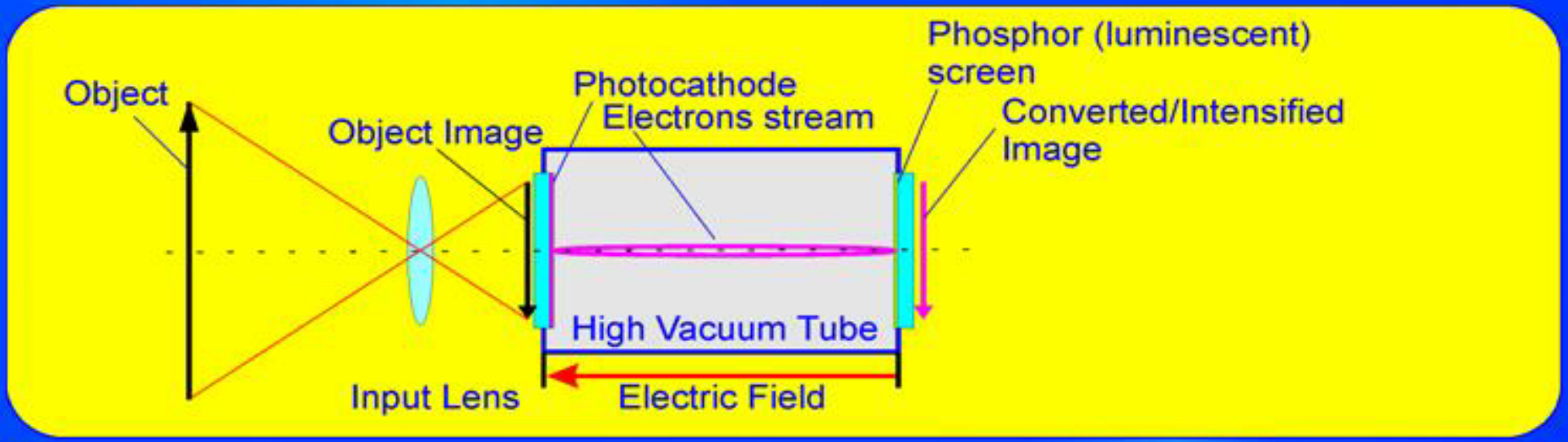
The Basic Principle of Image Conversion/Intensification

High-Speed Photography for Plasma Investigations

The Basic Principle of Image Conversion/Intensification

The operation is based on:

- Light impinges upon the photocathode through the input window. Due to the photoelectric effect, electrons are produced that escape from photocathode with very little energy.



- The electrons are accelerated by electrical field between photocathode and phosphor screen,
- The electrons strike the phosphor screen and stimulate fluorescence.

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Image Intensifiers Components

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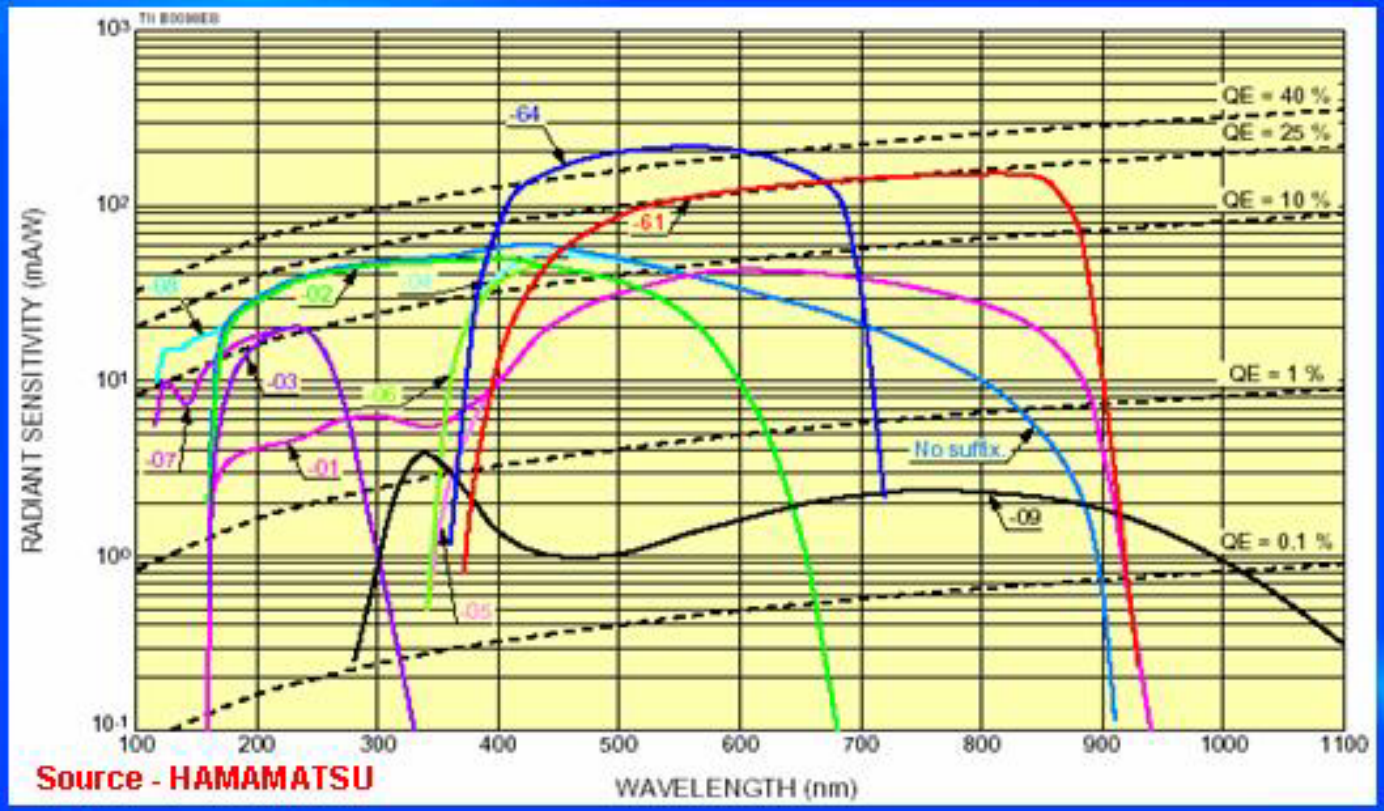
Image Intensifier Components - Photocathodes

A photocathode converts light into electrons

The relationship between the conversion efficiency and wavelength is called the spectral response characteristic



Source - HAMAMATSU

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Image Intensifier Components - Phosphor Screens

A screen converts kinetic energy of electrons into visible luminescence

Three criteria allow the choice of the most suitable phosphor type:

- Efficiency
- Emission spectrum
- Luminescence decay time

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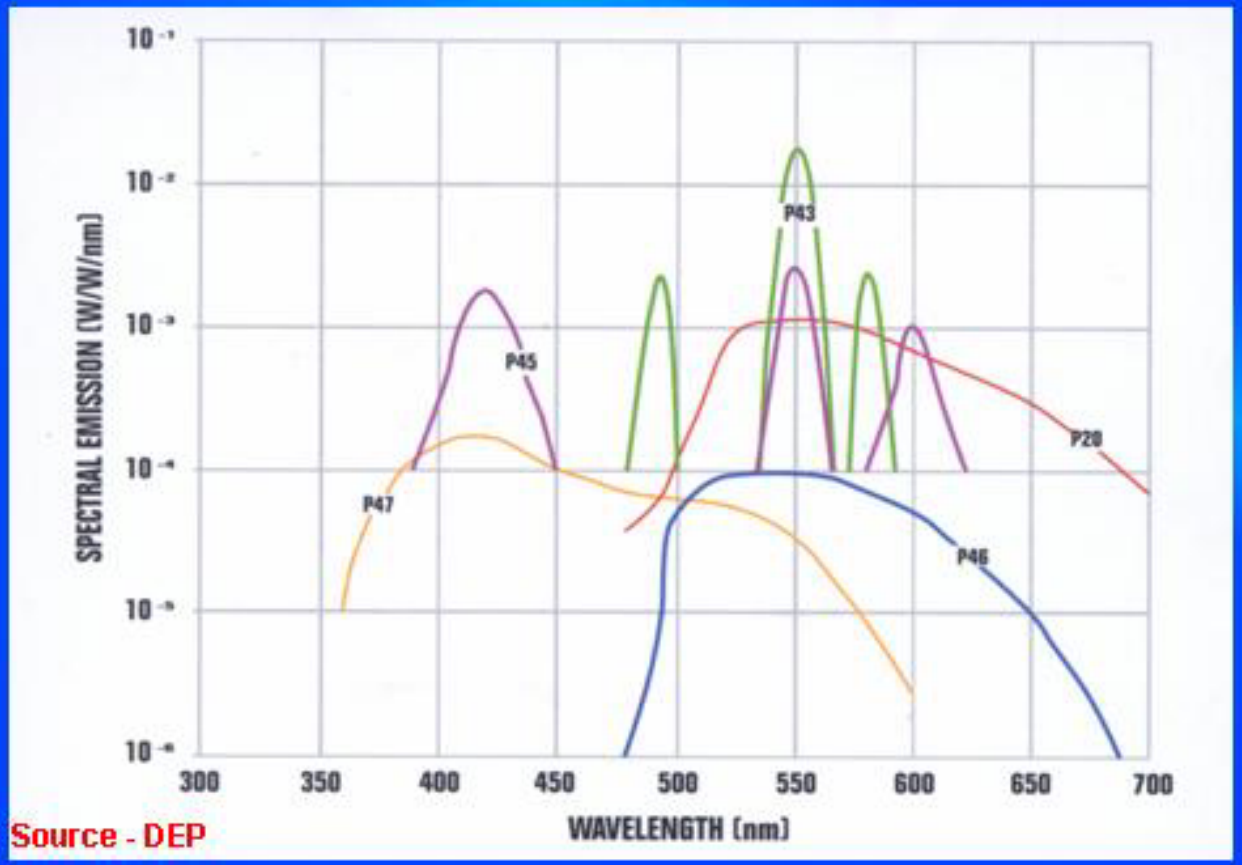
Image Intensifier Components - Phosphor Screens

The relationship between the screen efficiency and wavelength is called the spectral emission characteristics



Source - DEP

Phosphor efficiency depends on the type of phosphor but also on parameters like grain size, layer thickness, as well as on its structure

Spectral emission of a chosen phosphor should lie within spectral response of a final image detector

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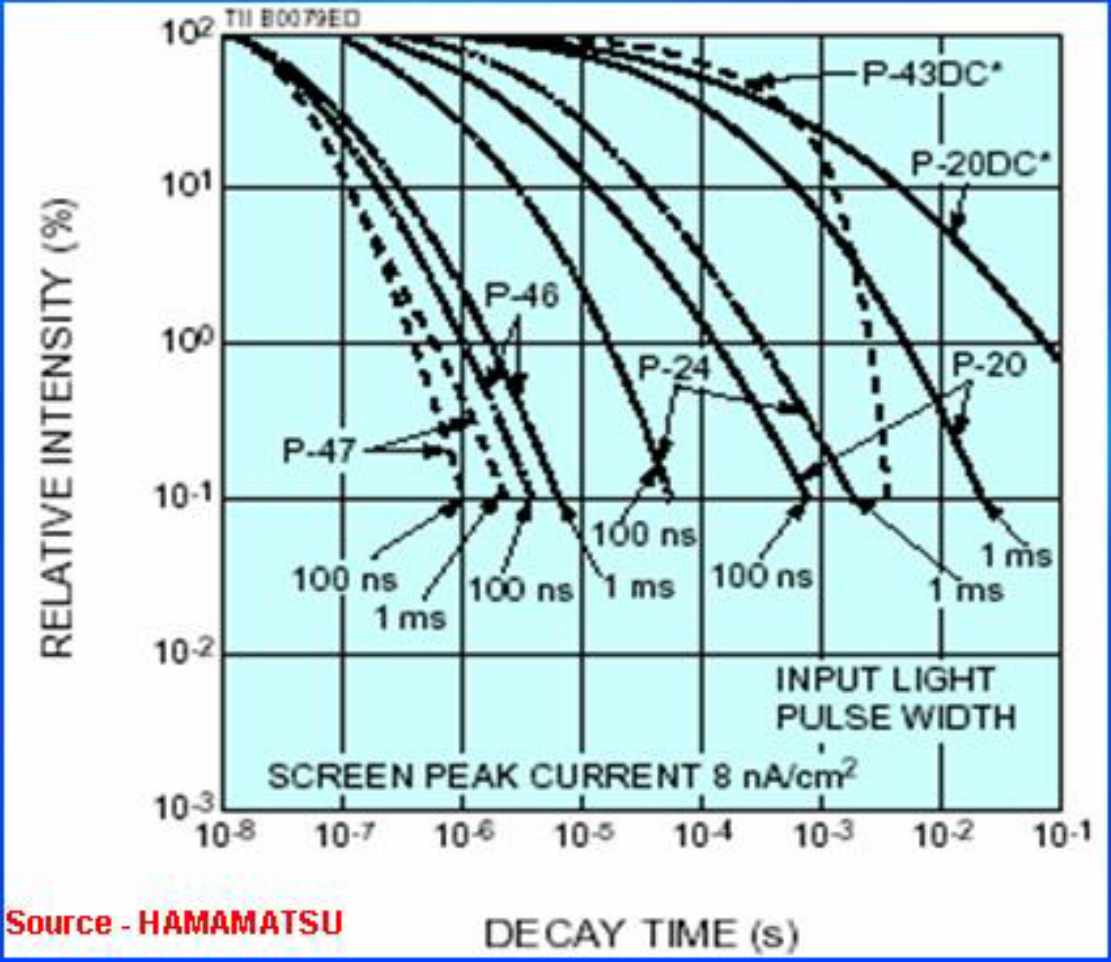
Image Intensifier Components - Phosphor Screens

Phosphor screen decay time is one of the most important factors to consider when selecting a phosphor screen type



Source - HAMAMATSU

For high repetition rate cameras, a phosphor screen with a short decay time is recommended

For another high-speed photography system, a phosphor screen with a long decay time is suggested

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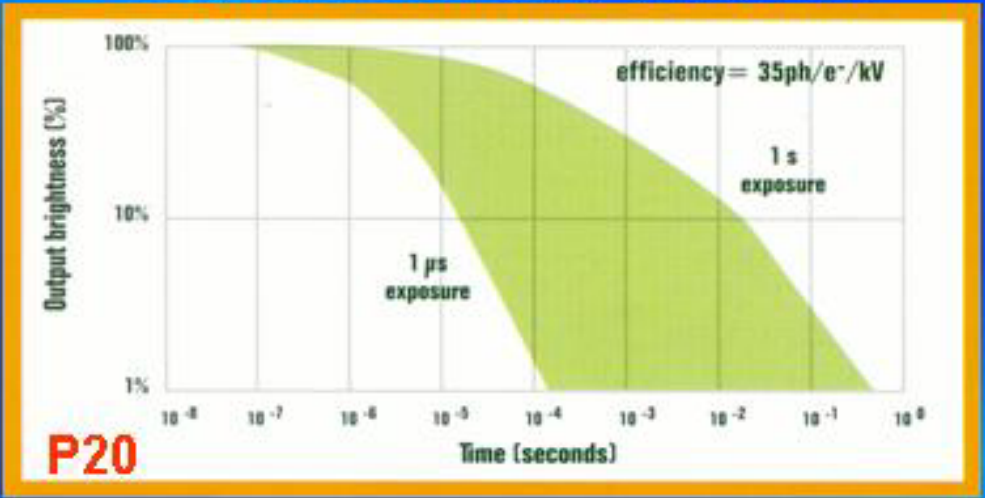
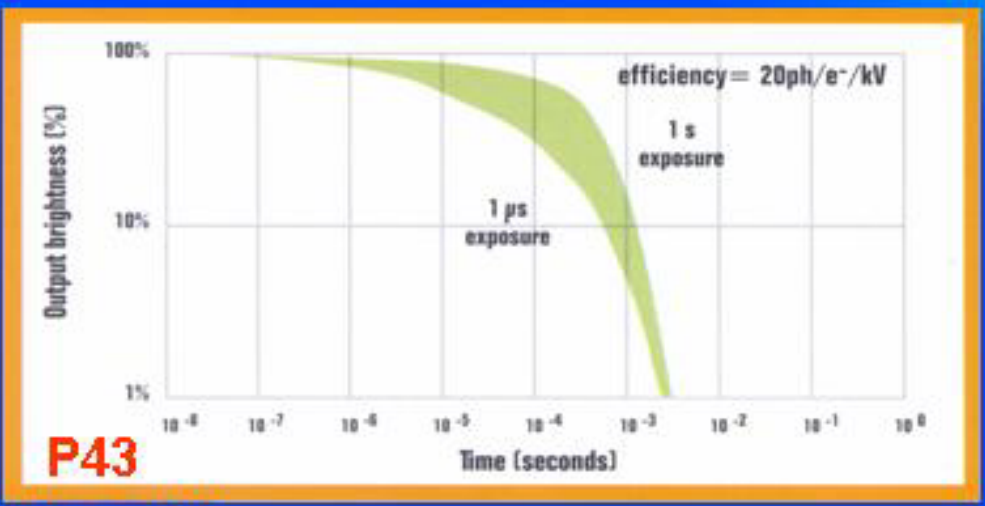
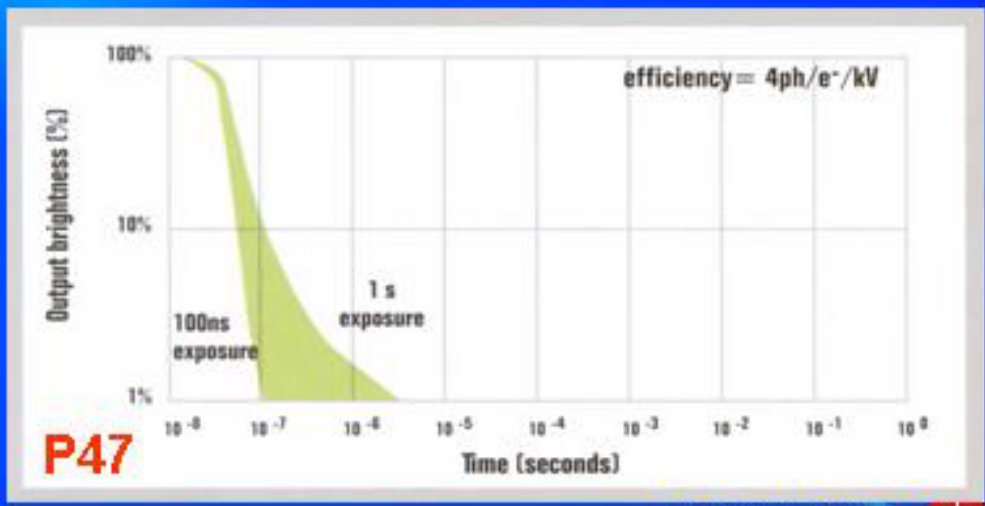
Image Intensifier Components - Phosphor Screens

Phosphors with long decay time





Phosphors with short decay time



Source - DEP

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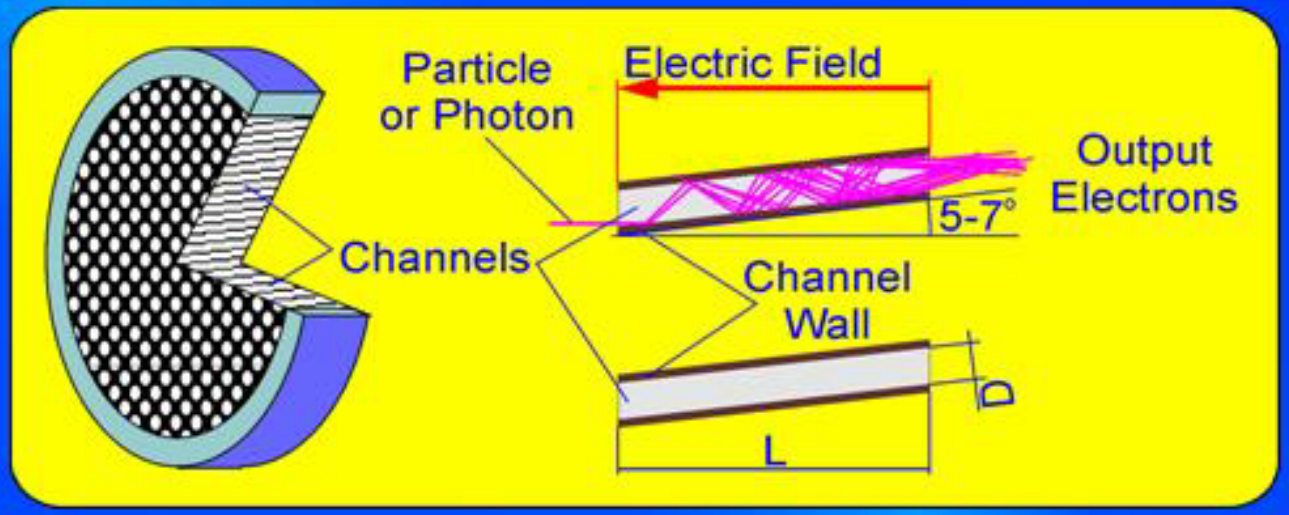
The Microchannel Plate (MCP) – Structure and Features

An MCP is a secondary electron multiplier consisting of an array of millions of very thin glass channels (glass pipes, typically 6 –10 Om diameters) bundled in parallel and sliced in the form of a disk



Each channel works as an independent electron multiplier -
when a photon or particle enters a channel and hits the inner wall,
secondary electrons are produced

This process is repeated many times along the channel wall and as a result,
a great number of electrons (multiplication factors of up to four orders of magnitude)
are output from the MCP

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The Microchannel Plate (MCP) – Structure and Features

MCP Efficiency

	Energy / Wavelength	Efficiency
Electrons	100 eV ... 500 eV 500 eV ... 4 keV 4 keV ... 100 keV	10 % ... 50 % 50 % ... 75 % ... 50 % 50 % ... 10 %
Ions	500 eV ... 3 keV 3 keV ... 10 keV 10 keV ... 50 keV 50 keV ... 200 keV	5 % ... 40 % 40 % ... 70 % 70 % ... 80 % ... 70 % 70 % ... 40 %
Soft X-ray / UV-Radiation	0.2 nm ... 30 nm 30 nm ... 115 nm 115 nm ... 150 nm	3 % ... 16 % 16 % ... 8 % 8 % ... 2 %

Source - PROXITRONIC

MCP is completely insensitive to radiation emitted in visible range

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Image Intensifiers Generations

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Image Intensifiers Generations

Types of image intensifiers are often classified by "generation"

- The first generation refers to image intensifiers that do not use MCP

Main parameters:

- Gain ~ 100
- Limiting resolution ~ 70 lp/mm
- Dynamic range ~ 10^6

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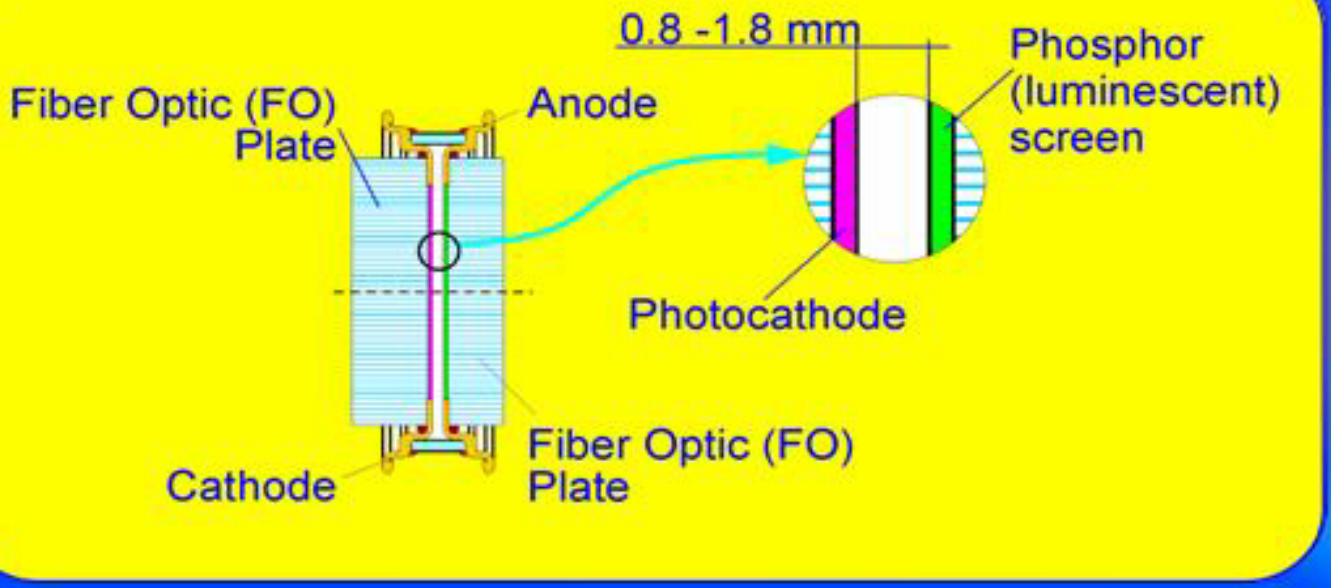
Image Intensifiers Generations

First Generation Image Intensifiers (Intensifier Diodes)

In the first generation tubes only a single potential difference is used to accelerate electrons from the photocathode to the screen

Focusing is achieved by two methods:



- by using an electron lens to focus electrons originating from the photocathode onto the screen (inverter diode)

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Image Intensifiers Generations

In the second image intensifiers generation
MCPs are applied for electron multiplication

Main parameters:

- Gain - from 10^4 to 10^{10}
- Limiting resolution - from 25 lp/mm through 5 lp/mm
- Dynamic range – from 10^4 to 10^0

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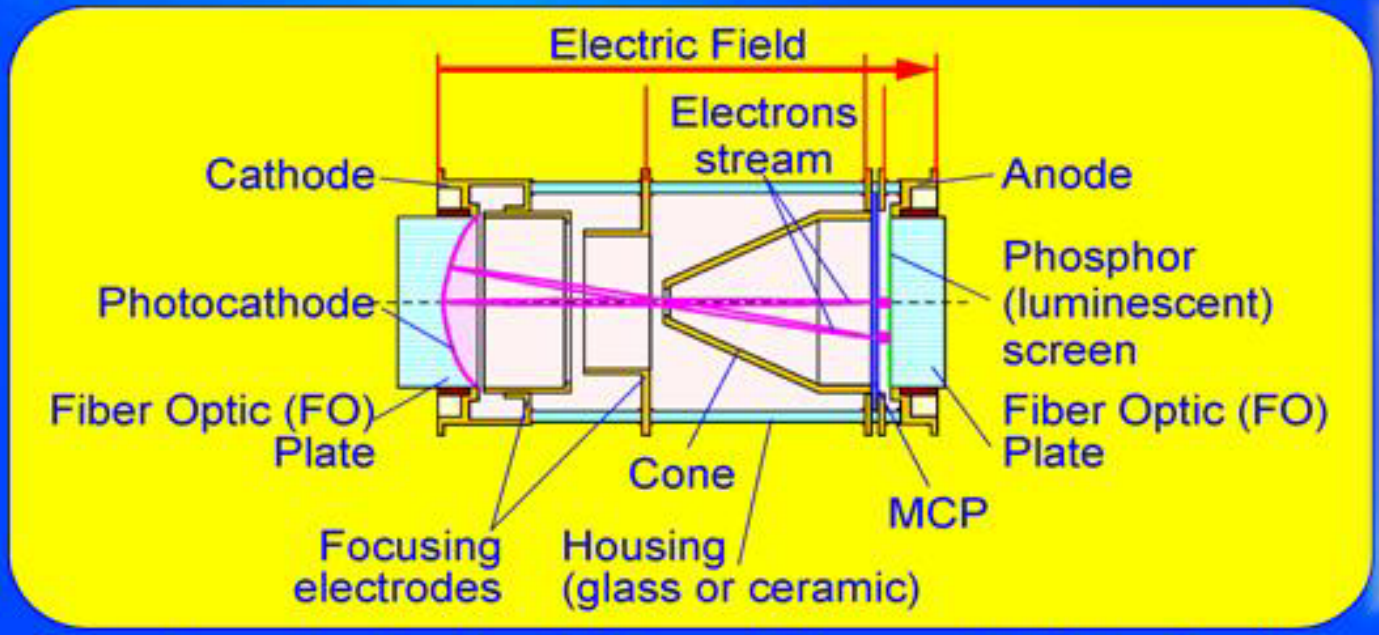
Image Intensifiers Generations

Second Generation Image Intensifiers

In the second generation tubes the three voltages must be applied to accelerate electrons from the cathode to the screen

Like in case of first generation, focusing can be achieved by two methods:



- by using an electron lens to focus electrons originating from the photocathode onto the MCP input (inverter type) and then by placing the screen in close proximity to the MCP output

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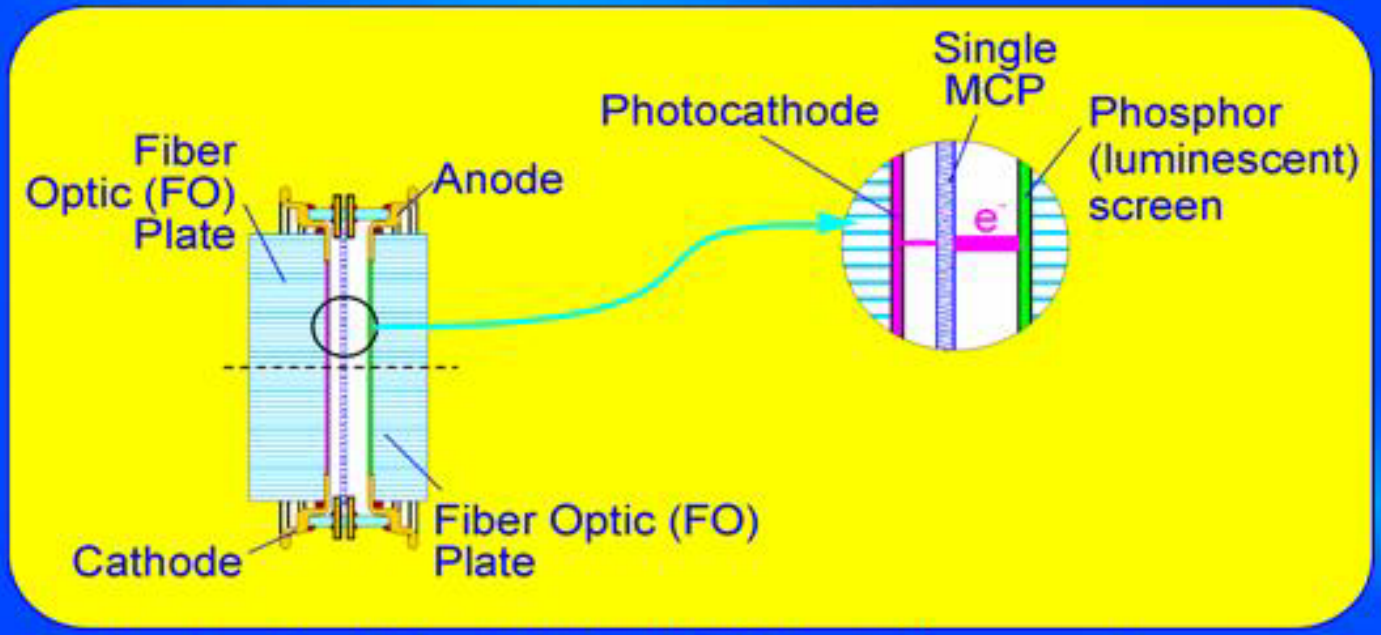
Image Intensifiers Generations

Second Generation Image Intensifiers

In the second generation tubes the three voltages must be applied to accelerate electrons from the cathode to the screen

Like in case of first generation, focusing can be achieved by two methods:



- by placing the photocathode, the MCP and the screen in close proximity (proximity type)

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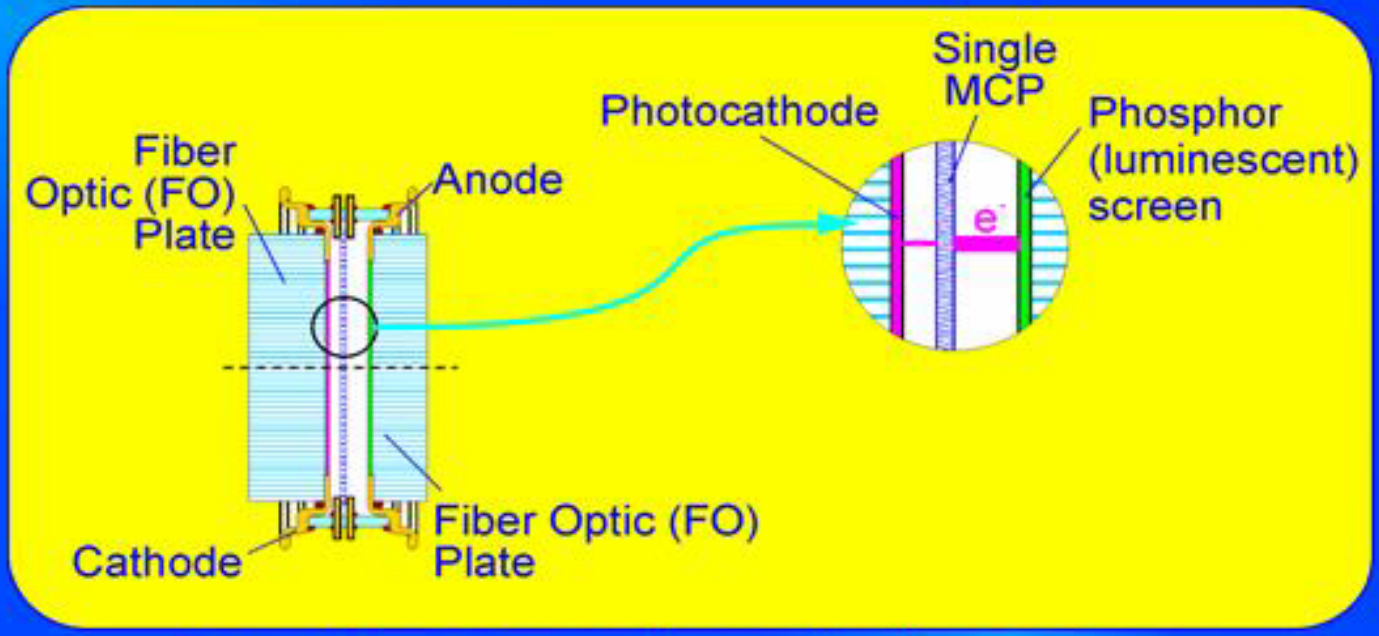
Image Intensifiers Generations

Second Generation Image Intensifiers



Regardless of a second generation image type (inverter or proximity), them operation is based on:

- Photoelectric effect in the photocathode
- Electron multiplication in a microchannel plate
- Reinforcement of the kinetic energy of the photoelectrons in an electrical acceleration field between MCP output and screen
- Production of light by fluorescence in the phosphor screen

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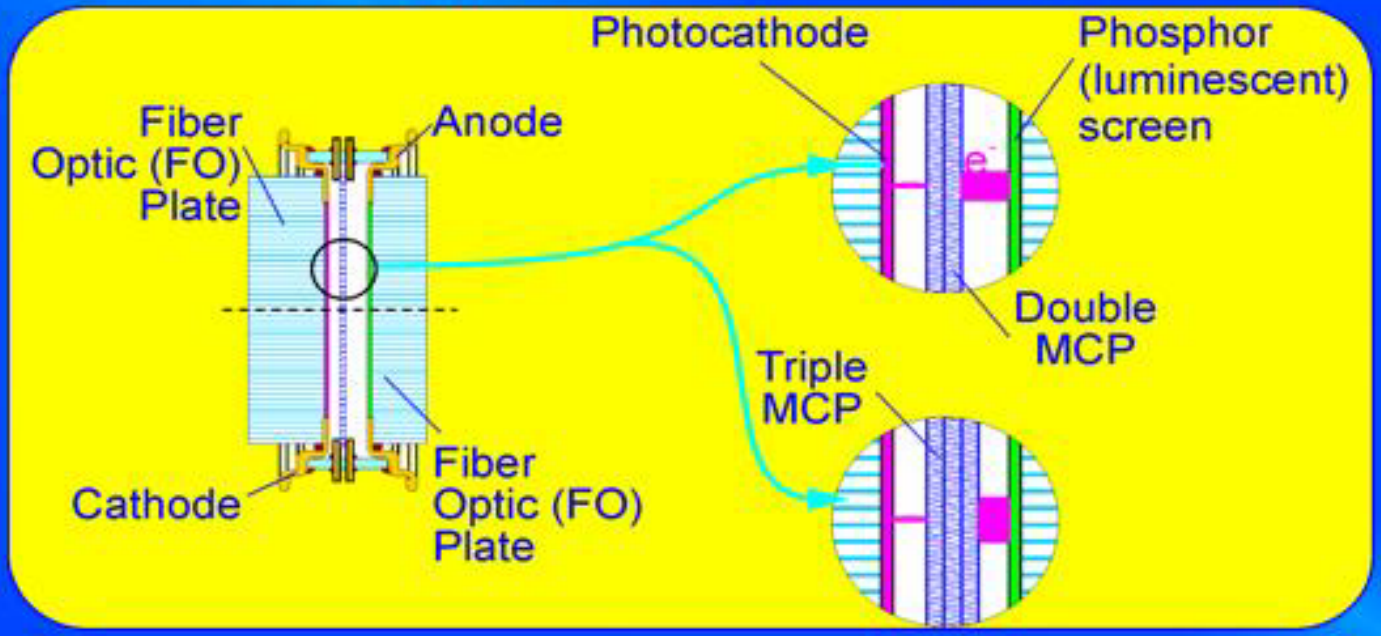
Image Intensifiers Generations

Second Generation Image Intensifiers – Modifications

Usage of a number of the MCPs instead of a single MCP



V-stack configuration – well known as CHEVRON type

Z-Stack configuration

Very high and ultra-high gain but low limiting resolution and dynamic range

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Fast and Ultra Fast Gating Manners

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Gating Manners

General Classification

- The Low Voltage Gating can be applied only for higher than First Generation Image Intensifier

  Cathode is a main gated electrode

- High Voltage Gating can be applied for all Image Intensifier Generations

Either Phosphor Screen or MCP can be a main gated electrode

In nowadays UHSP systems all electrodes can be gated

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Low Voltage Gating

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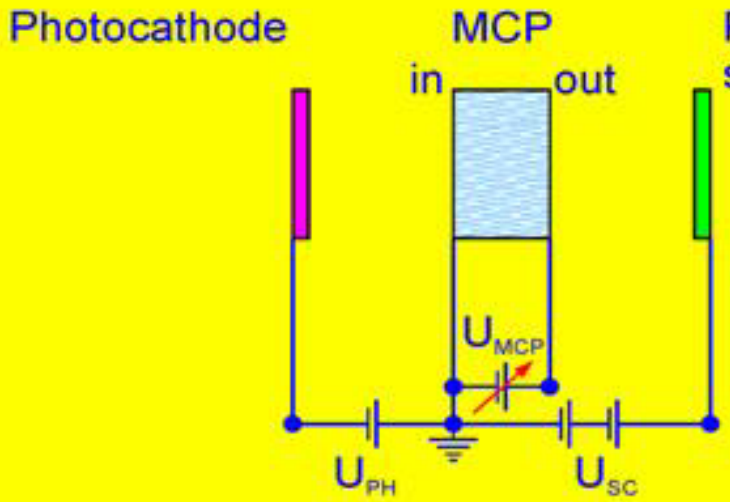
Low Voltage Gating

Principle of Operation

Static Operation



U_{PH} = -(150 -200) V
U_{MCP} = 0.5 -1 kV
U_{SC} = 5 - 6 kV

- Image intensifier gain can be controlled by adjusting of U_{MCP}

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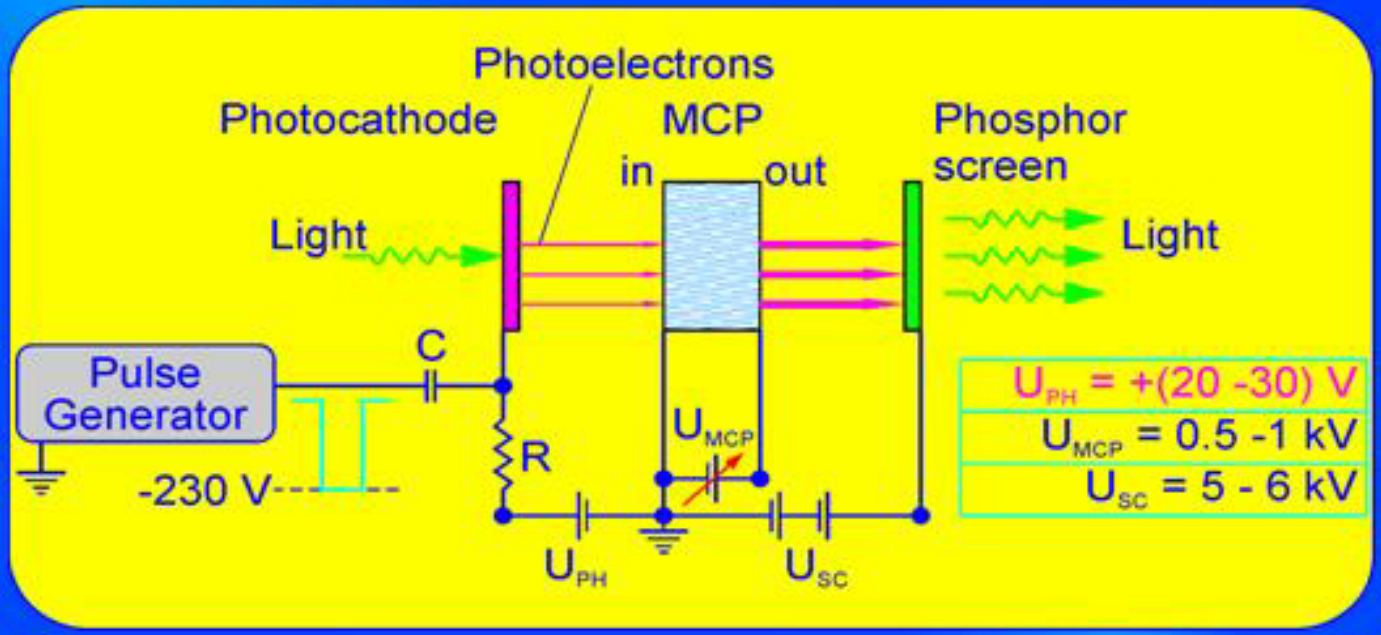
Low Voltage Gating

Gate Operation - Temporary ON Mode

Principle of Operation



- Reverse biasing, with respect to the MCP input, repels the photoelectrons emitted from photocathode
- If the gating pulse is applied, the photocathode is forward-biased for a short time; the intensifier is gated on and amplifies incoming radiation for that period of time

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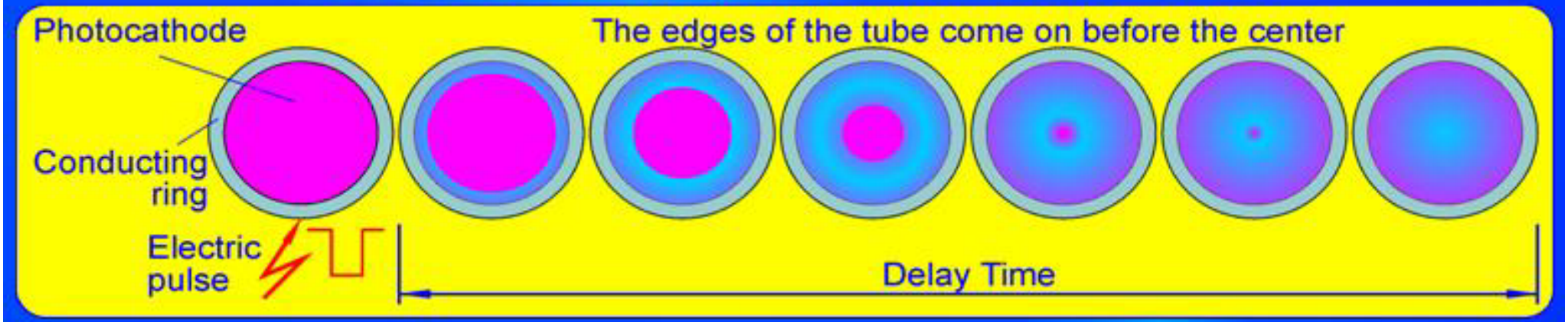
Low Voltage Gating

Main problem with the photocathode gating

"Irising Effect"

It is caused by the capacity and resistance of a cathode

When the gating pulse is applied between cathode surface and the MCP input,
the outside edge of the tube comes on first
Then this on-state propagates inward to the center of the tube



The time from applying of the gating pulse until the tube reaches
its normal operating conditions is called the irising time

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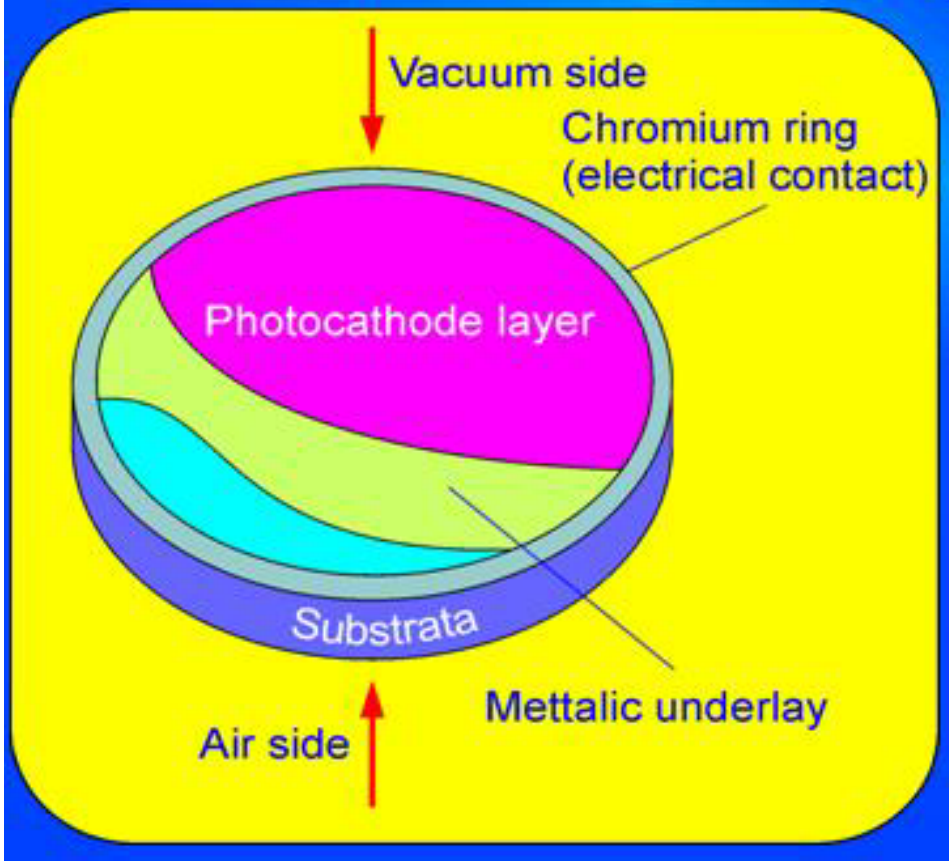
Low Voltage Gating

Counteraction Irising Effect

Decreasing of cathode resistance

An electrically conductive Nickel layer is deposited between the photocathode and substrate (5 nm average thickness)



- It allows achieving minimal gating time in range of 3 to 5 ns (for the 18 mm tube)
- It is standard solution for commercially offered gateable Image Intensifiers
- Such photocathode modification reduces QE of a photocathode by 5% to 50%

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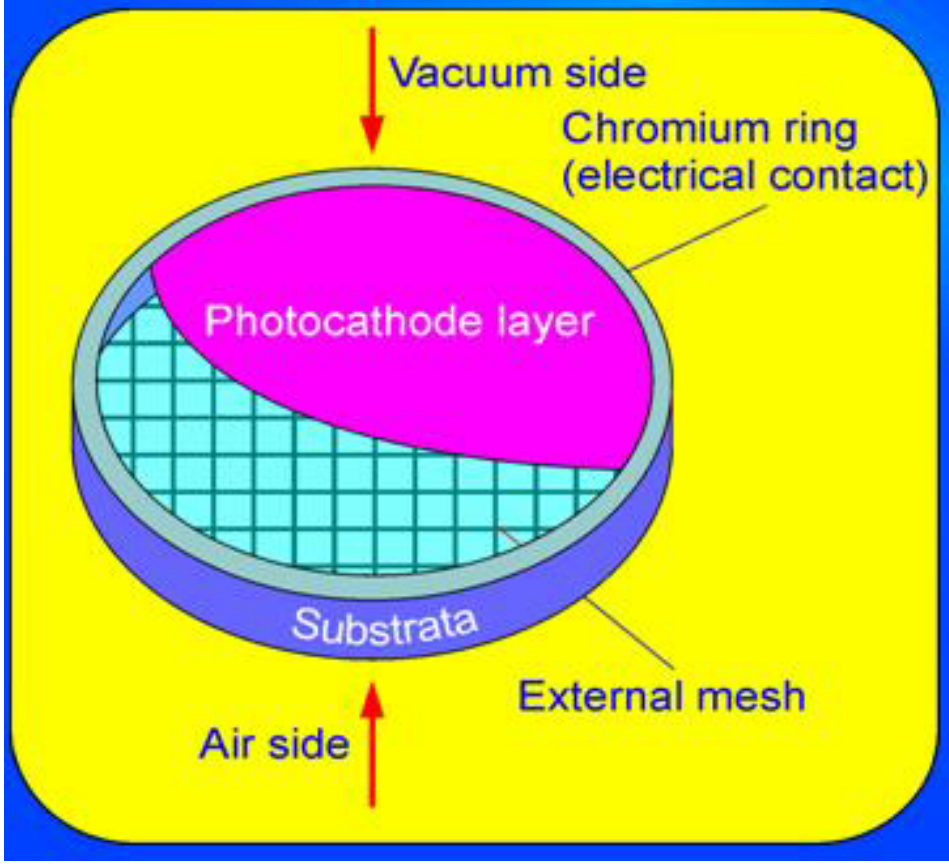
Low Voltage Gating

Counteraction Irising Effect

Decreasing of cathode resistance - other approaches

External/Internal wire mesh placed on the photocathode window



- Gating pulse is transferred from mesh to the photocathode by small capacity between them
- It allows achieving minimal gating time in range of hundreds picoseconds

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Low Voltage Gating

Counteraction Irising Effect

Decreasing of cathode resistance - other approaches

Summary

Very laborious and expensive technologies but they allow to achieving sub-nanosecond gating, limited only by the ability to generate the electrical gating pulse

However, such modification of photocathode structure can cause in any case significant changes of image intensifier parameters

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Low Voltage Gating – Brief Remarks

Low Voltage Gating
(also called "photocathode gating")

- It gains more and more popularity in most of the fast one-frame cameras, which are commercially offered at present moment
- The gating pulse generators provide precise shutter/exposure time (often adjustable in wide range) and delay
- For standard, gateable cathodes, decreasing in gating time is limited due to irising effect
- The most of gating pulse generators allow to dynamic supply for only a one high-speed photography channel (one-frame camera)
- In standard solution the gating pulse generators may be sensitive on electromagnetic noises

High-Speed Photography for Plasma Investigations

High Voltage Gating

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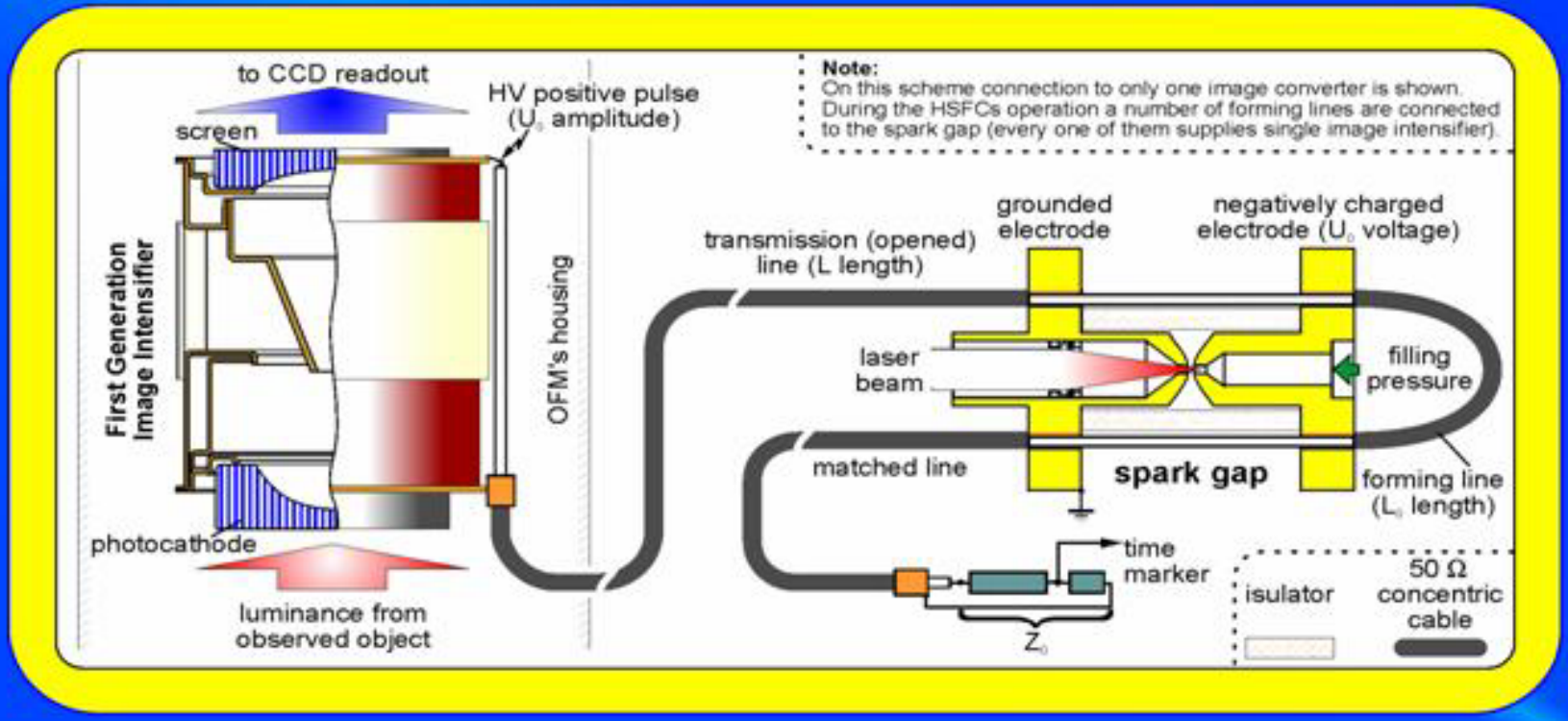
High Voltage Gating

Gating of the First Generation Image Intensifier

The high pressure, laser triggered spark-gap plays the role of the quick switch in HV gating pulse generator



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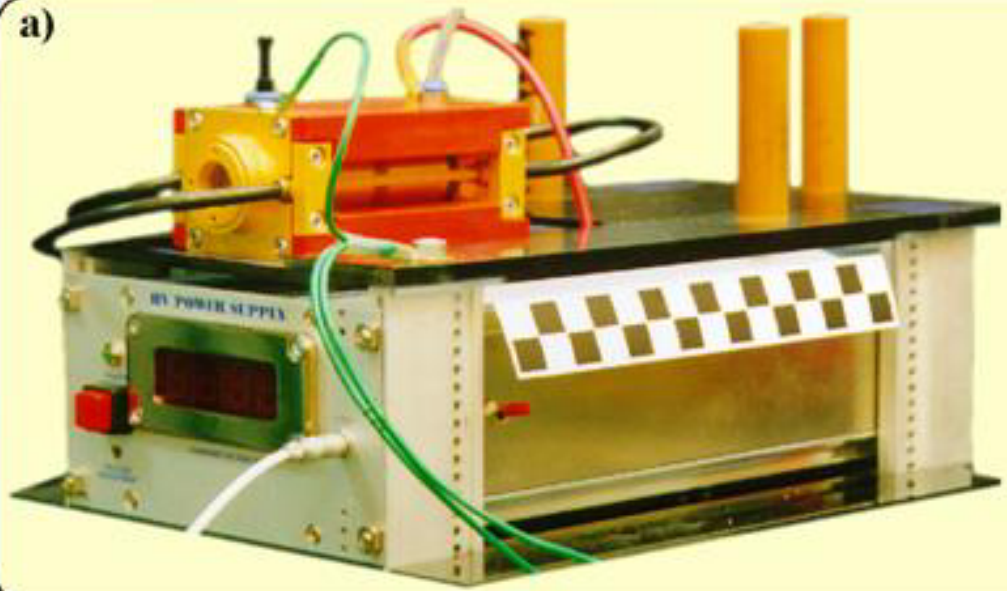
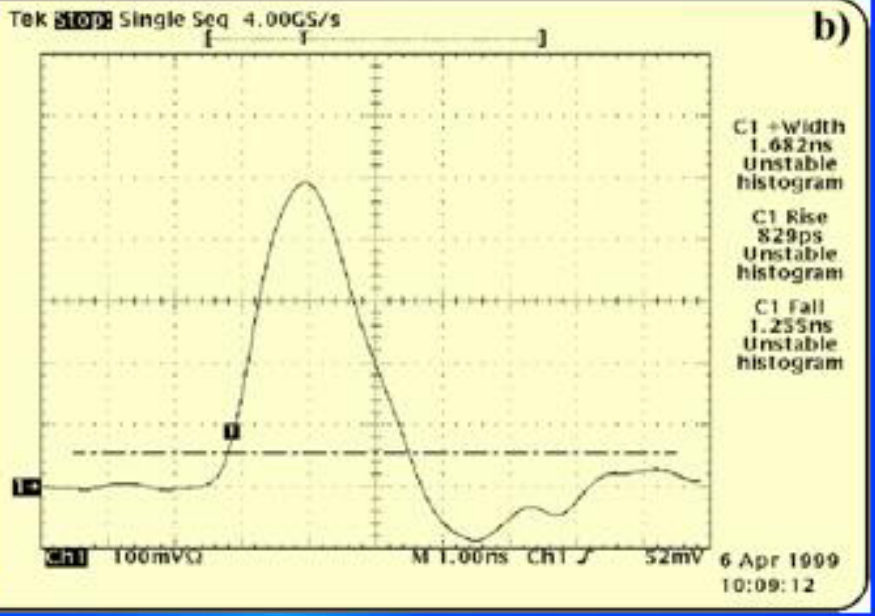
High Voltage Gating

The HV Gating Pulse Generator based on Long Line and Spark-Gap

a)



b)



The general view of the QUAD type spark gap mounted on the top of PS25 type HV power supply

The result of oscilloscope acquisition of the HV gating pulse generated by means of "forming line" switched by spark-gap

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High Voltage Gating

Gating of the Second Generation Image Intensifier

Another Approach – (introduced by Kentech Instruments Ltd. U.K.)

High-Speed Pulsers Based
on the Strings of Avalanche Transistors

- There are now capable of sub 100 ps rise time to voltages greater than 10 kV
- These pulsers can operate at high repetition rate – up to several kHz

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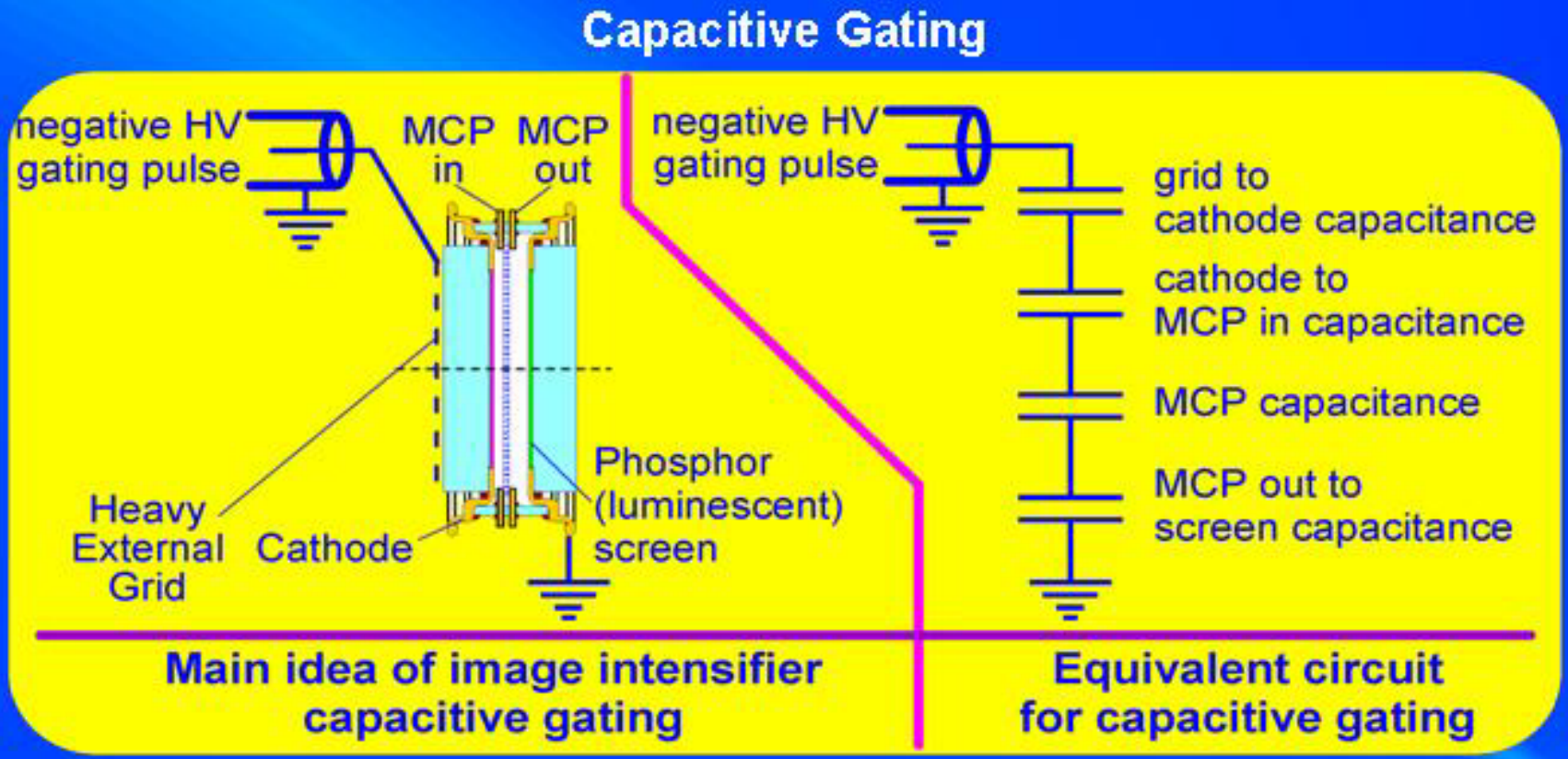
High Voltage Gating

Gating of the Second Generation Image Intensifier – Another Approach (introduced by Kentech Instruments Ltd., U.K.)



- Minimum gate width is limited by driven technology to around 50 ps

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High Voltage Gating – Brief Remarks

High Voltage Gating – Long Line Switched by Spark-Gap

- System for generation HV gating pulses has rather complex architecture and consists of many elements (pulsed laser, spark-gap, high-voltage source, gas under pressure, etc.)
- The change of the gating pulse width and delay between consecutive pulses is not easy task
- It was experimentally proven, that by means of high voltage gating manner simultaneously operation of different high-speed photography systems with sub-nanosecond accuracy is possible
- High voltage gating is completely non-disturbed by high electromagnetic interference

High-Speed Photography for Plasma Investigations

High Voltage Gating – Brief Remarks

High Voltage Gating – Avalanche Transistors Pulsers - ATP

- It gains more and more popularity in advanced laboratory – (Inertial Confinement Fusion, Laser-Mater Interaction)
- ATPs generate fastest gating pulses (about tens of picosecond)
- The ATP high repetition rate may be used to average many images and improve the signal to noise ratio

High-Speed Photography for Plasma Investigations

One-Frame Camera

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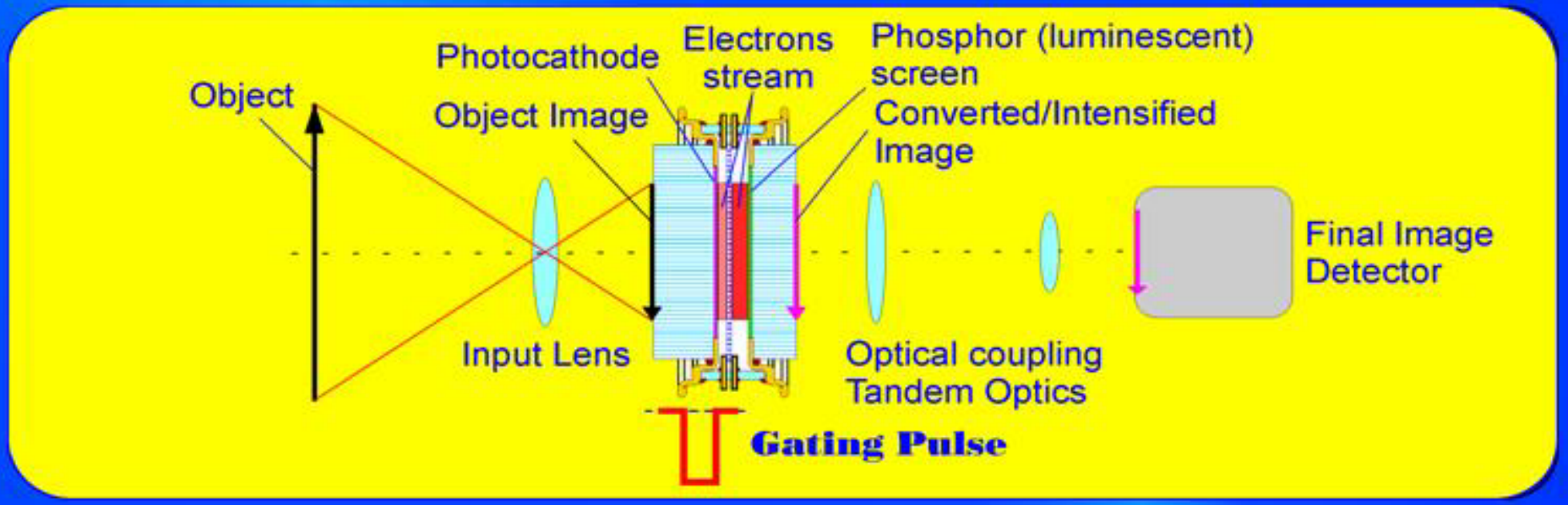
One-Frame Camera

Optical One-Fame Module - OFM



Construction of OFM allows operating as a stand alone One-Frame Camera

For multi-frame operation a number of OFMs and auxiliary equipment are necessary

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OFM

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Multi-Frame Cameras

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Multi-Frame Cameras

Preconditions for modern multi-frame camera arrangement

Each of frames is captured on independently gated image intensifiers (temporal separation), whereas the image is focused on a number of image intensifiers employed in the camera (spatial separation)

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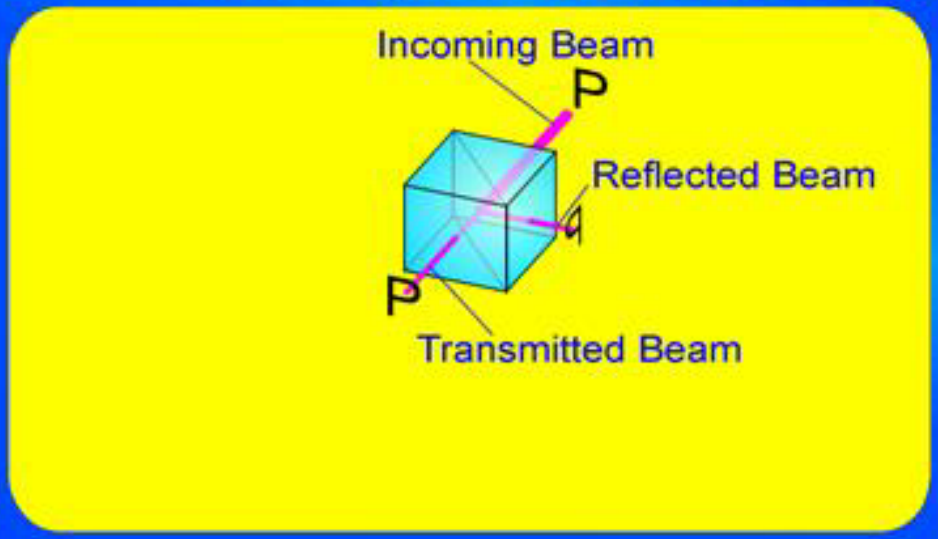
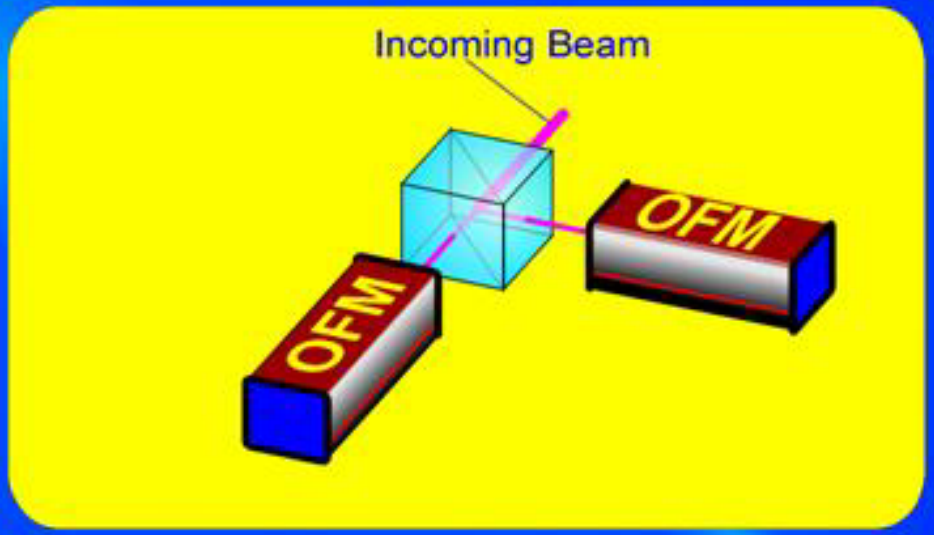
Multi-Frame Cameras

General Layout of Two-Frame Camera

Beam Splitter for Two-Frame Camera – Standard Arrangement





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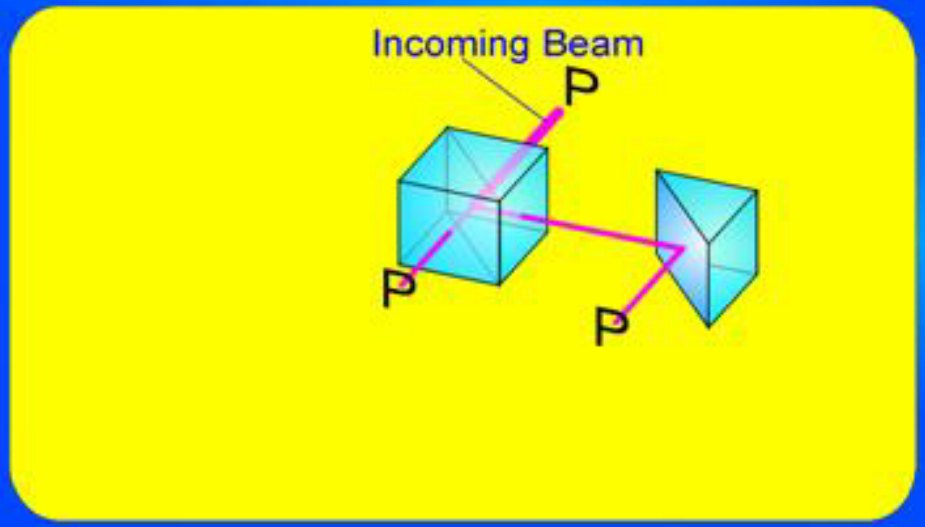
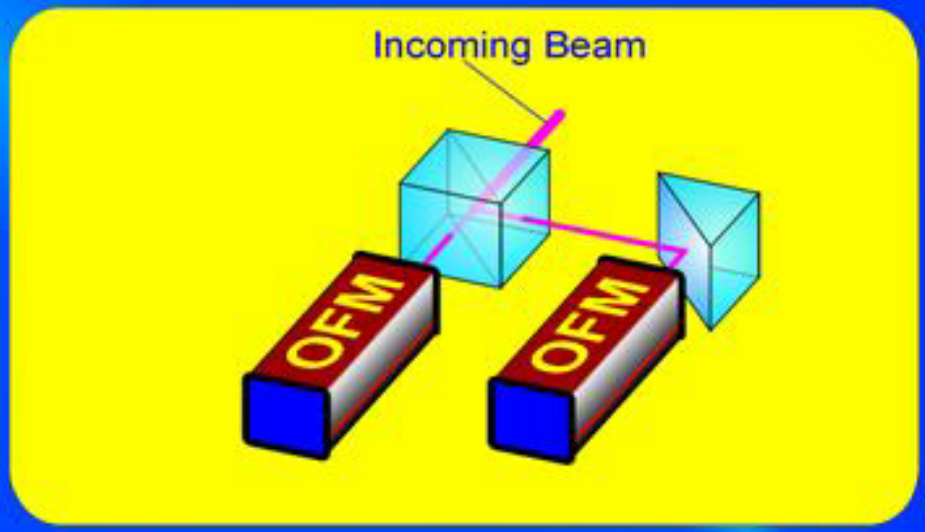
Multi-Frame Cameras

General Layout of Two-Frame Camera

Beam Splitter for Two-Frame Camera – Solution with Deflector





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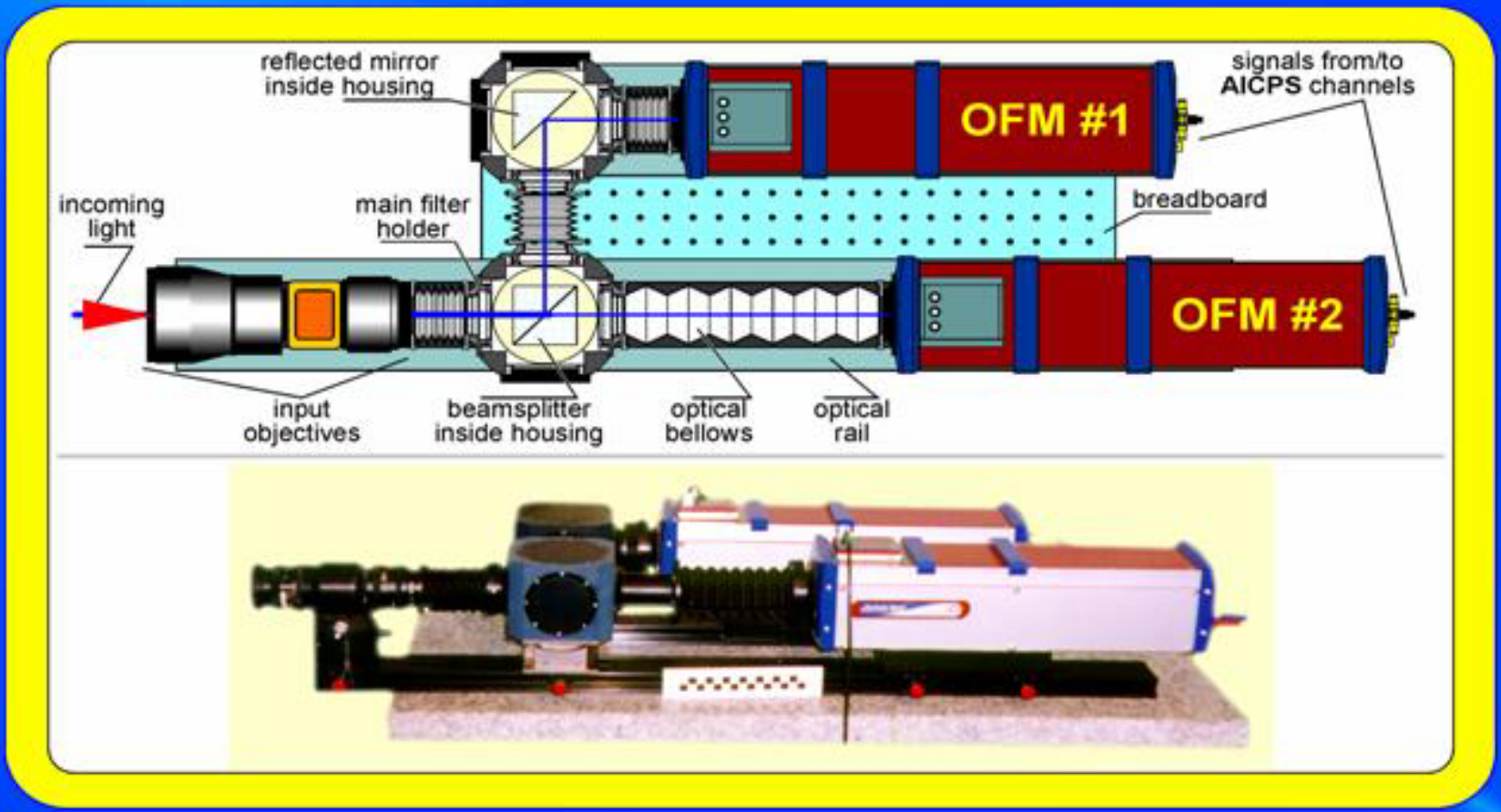
Multi-Frame Cameras – Exemplary Solution

Two-Fame DUPLO Camera



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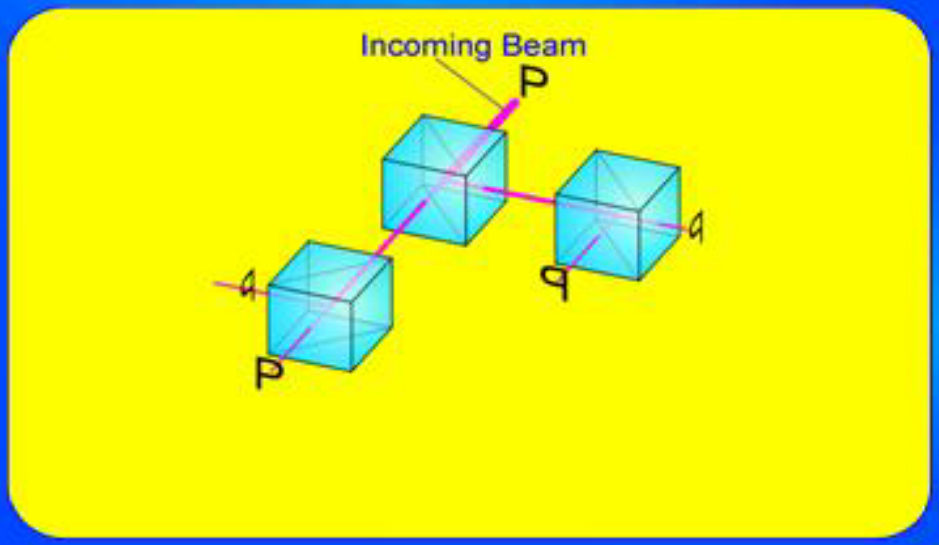
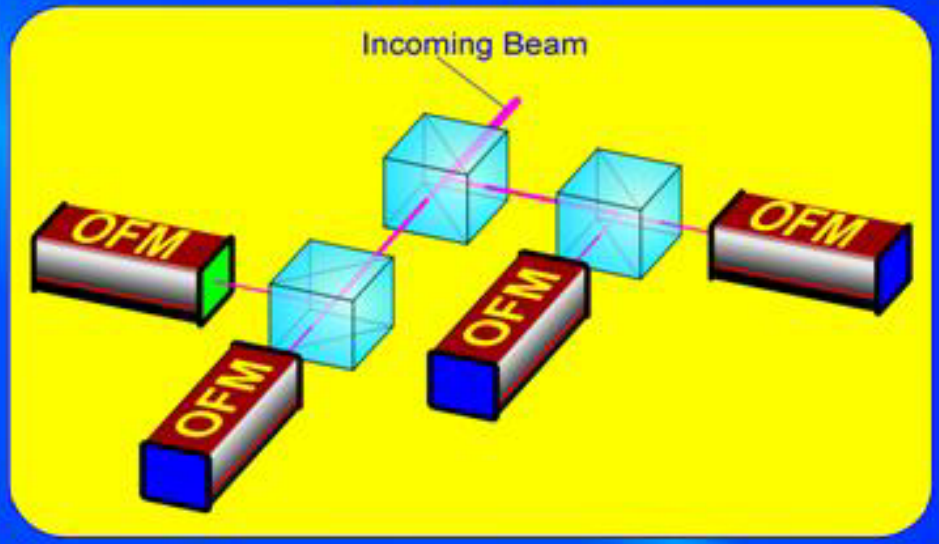
Multi-Frame Cameras

General Layout of Four-Frame Camera

Beam Splitter for Four-Frame Camera – Standard Arrangement

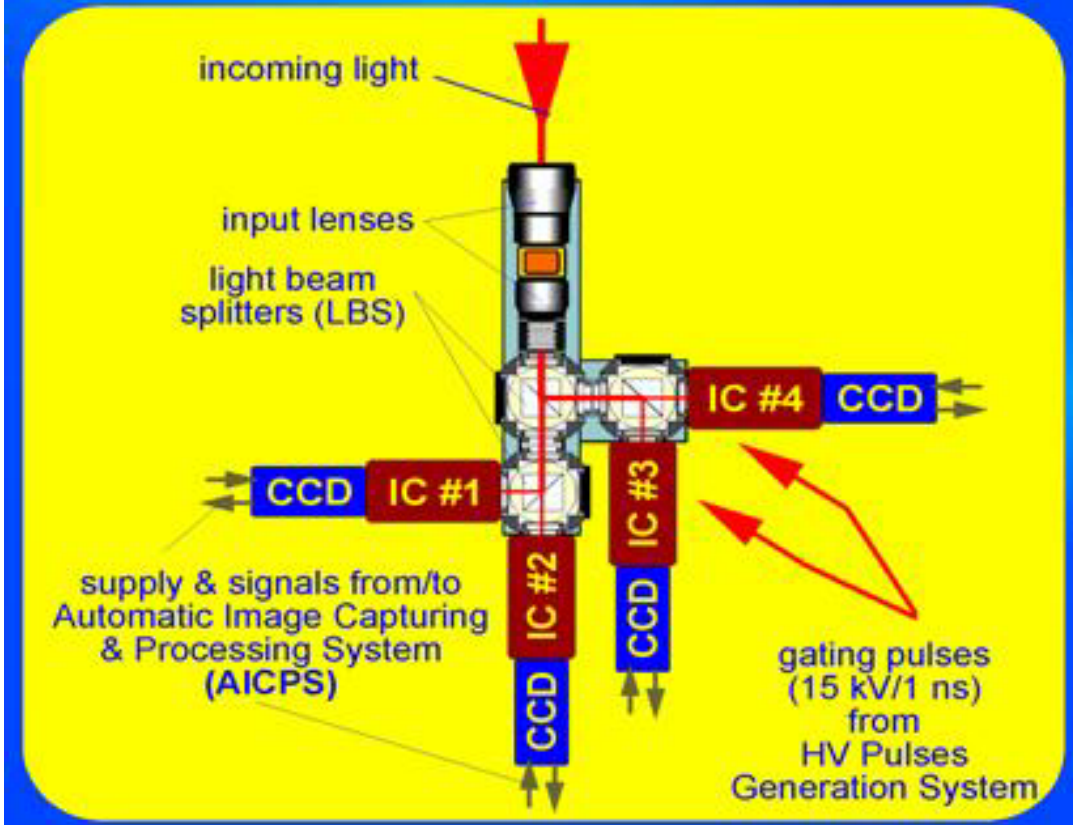




High-Speed Photography for Plasma Investigations

Multi-Frame Cameras – Exemplary Solution

Four-Fame QUADRO Camera

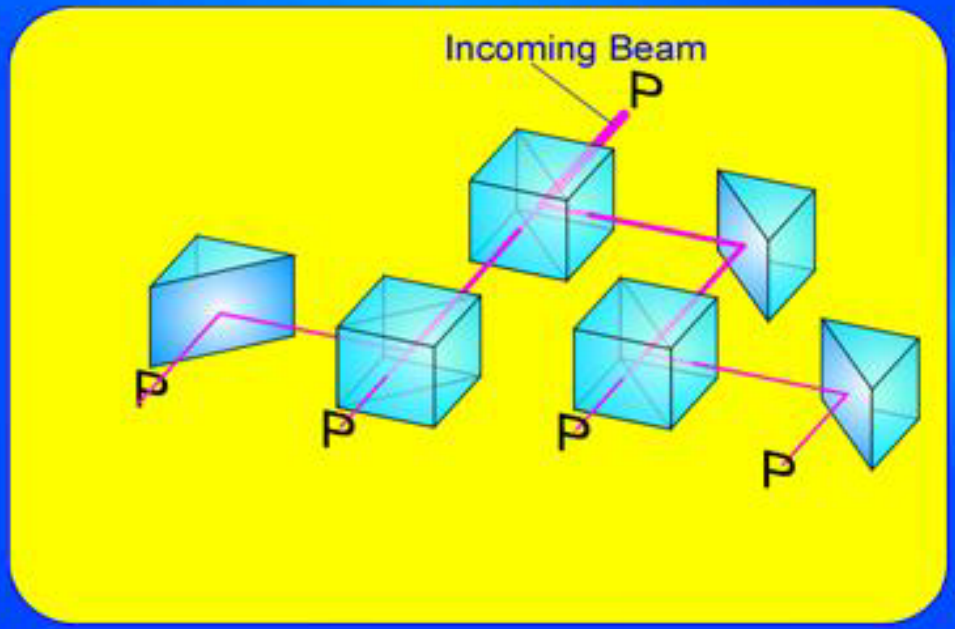


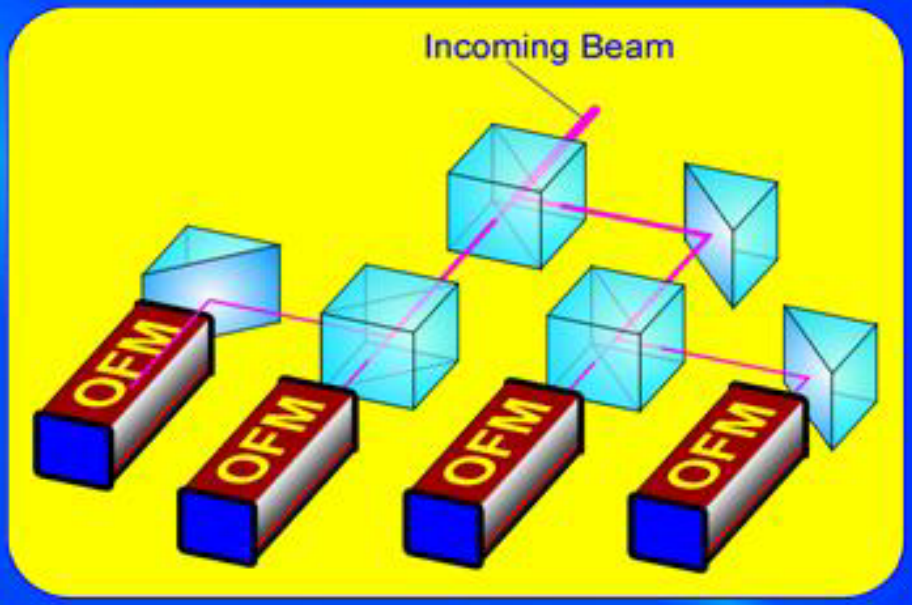
High-Speed Photography for Plasma Investigations

Multi-Frame Cameras

General Layout of Four-Frame Camera

Beam Splitter for Four-Frame Camera – Solution with Deflector





High-Speed Photography for Plasma Investigations

Multi-Frame Cameras – Exemplary Solution

hsfc pro – Four-Frame Intensified Camera

PCO Computer Optics GmbH, Kelheim, Germany, May 2000

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High-Speed Photography for Plasma Investigations

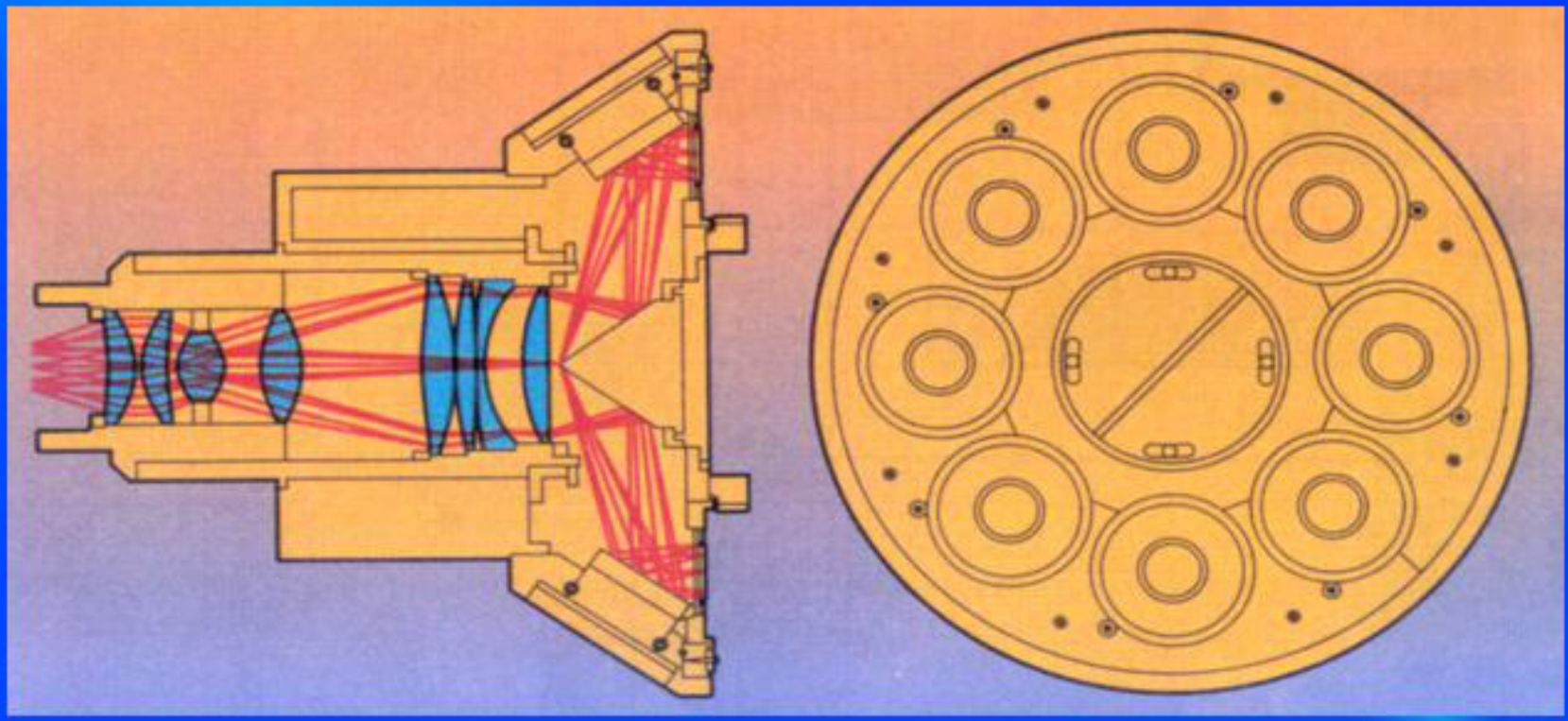
Multi-Frame Cameras - Other Solutions

High-Speed Photography for Plasma Investigations

Multi-Frame Cameras – Other Solutions

Beam Splitters Based on Reflection from Cone

Eight-Frame Camera – Another Approach



High-Speed Photography for Plasma Investigations

Multi-Frame Camera Based on Special Image Converter

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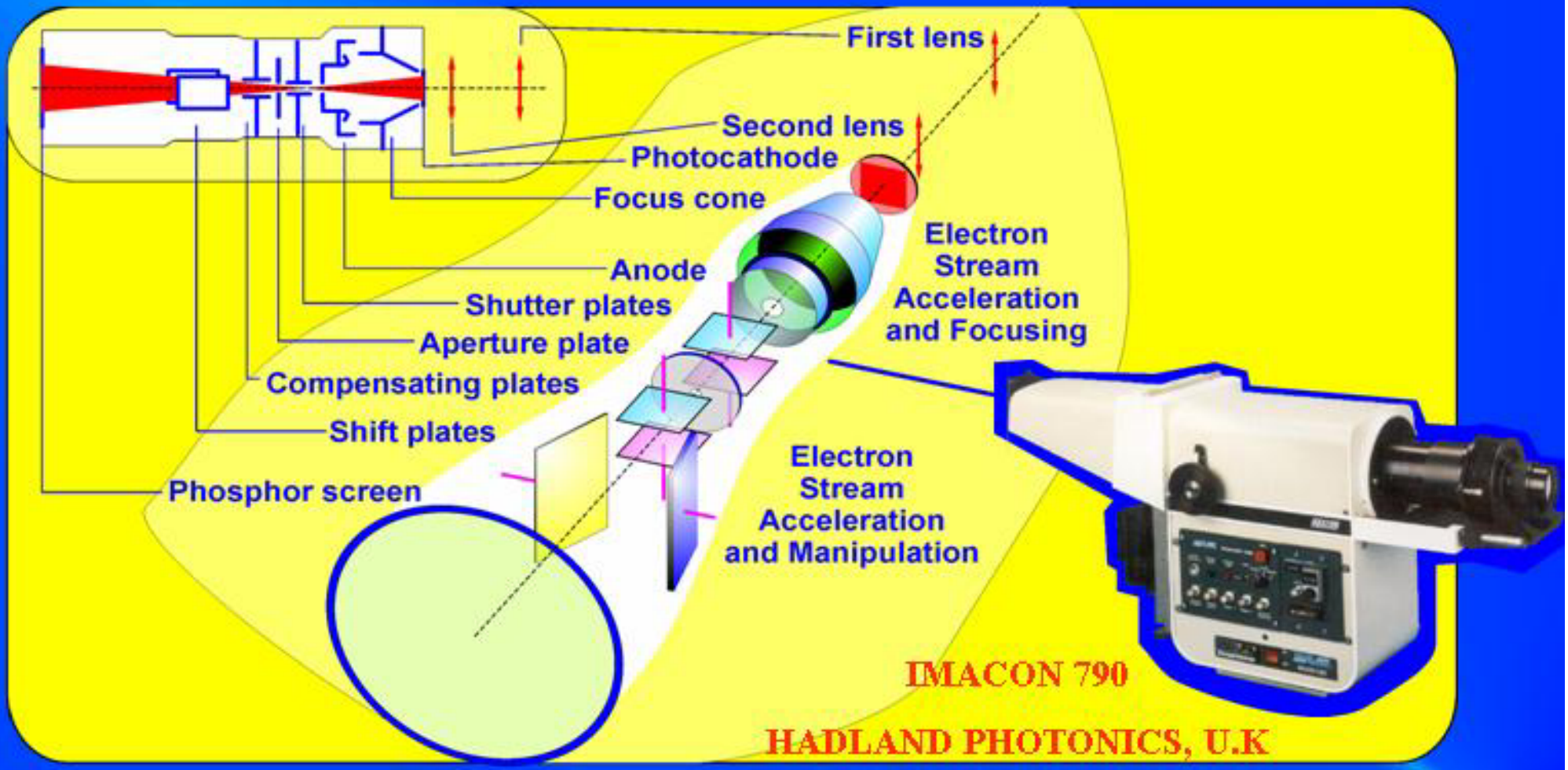
Multi-Frame Camera Based on Special Image Converter



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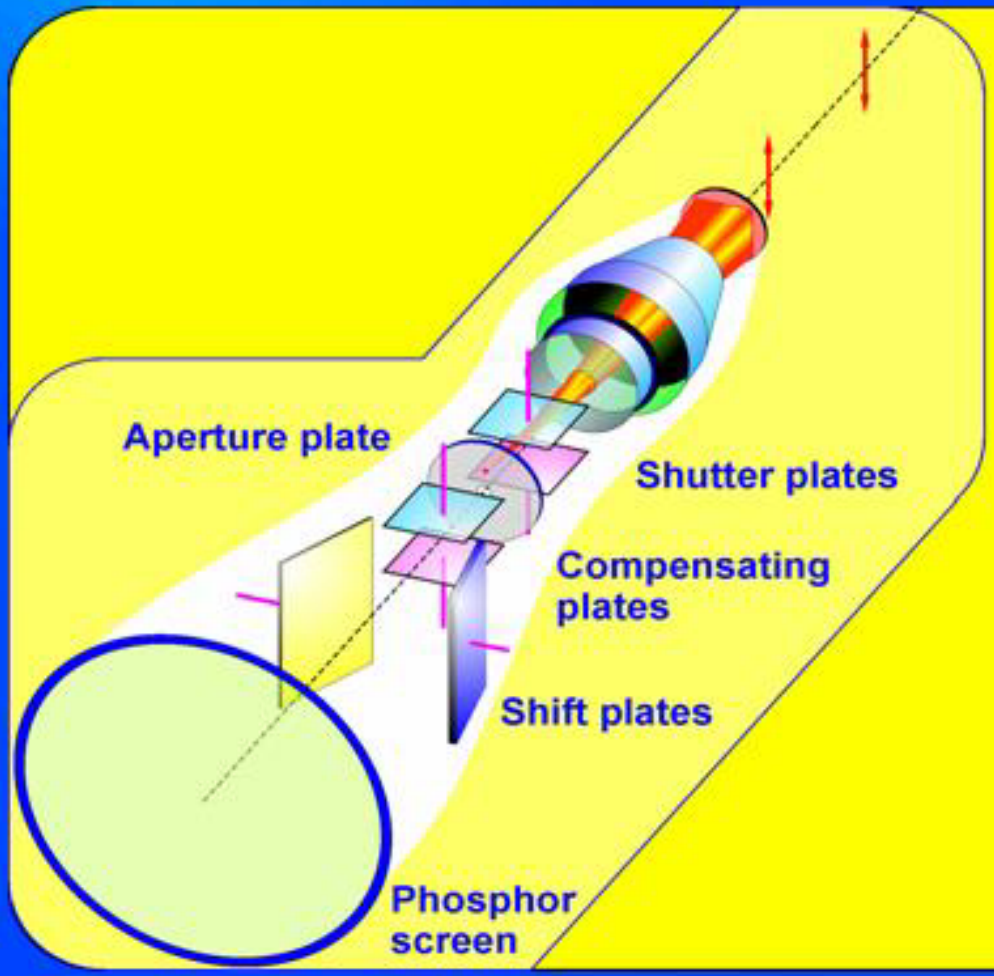
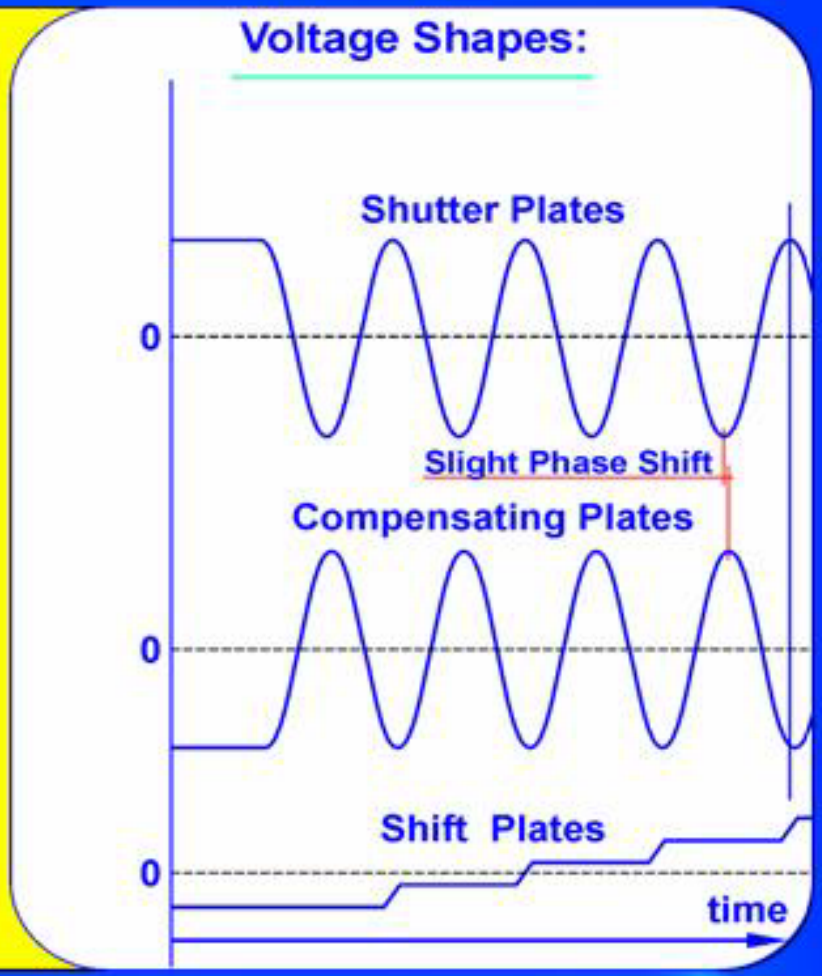
Multi-Frame Camera Based on Special Image Converter





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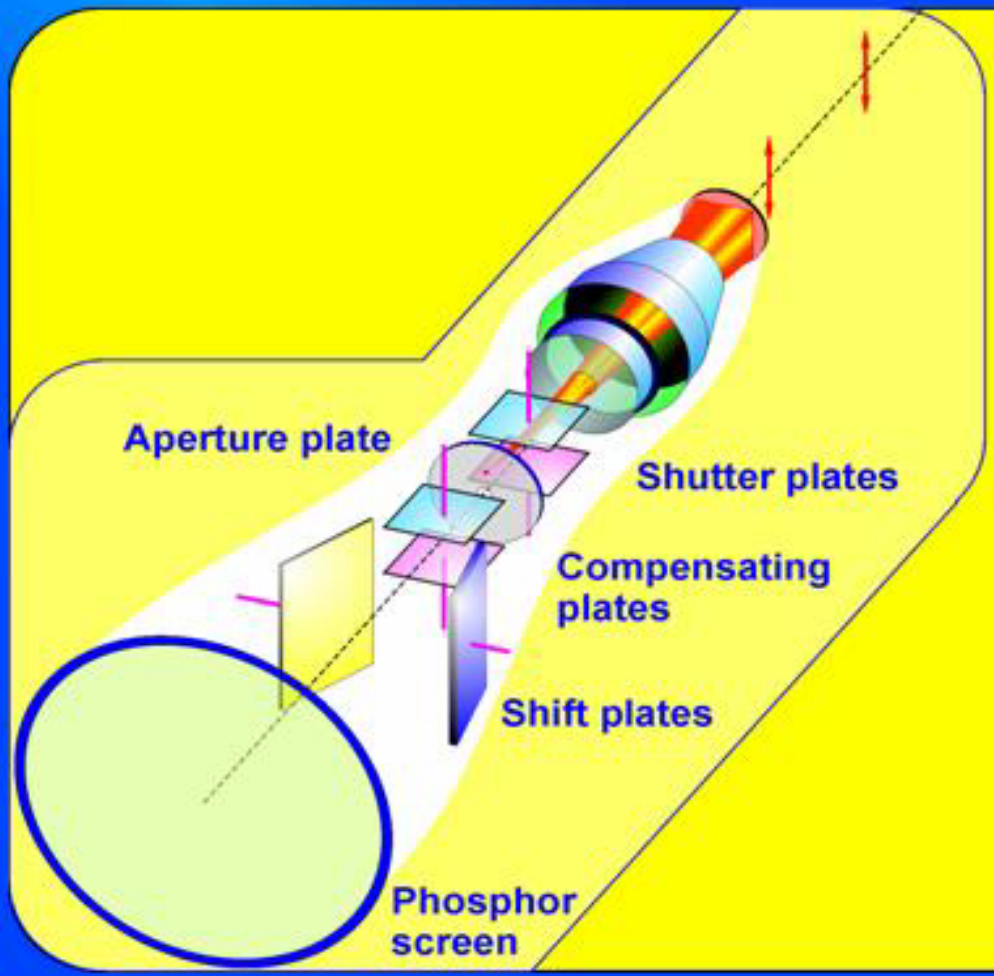
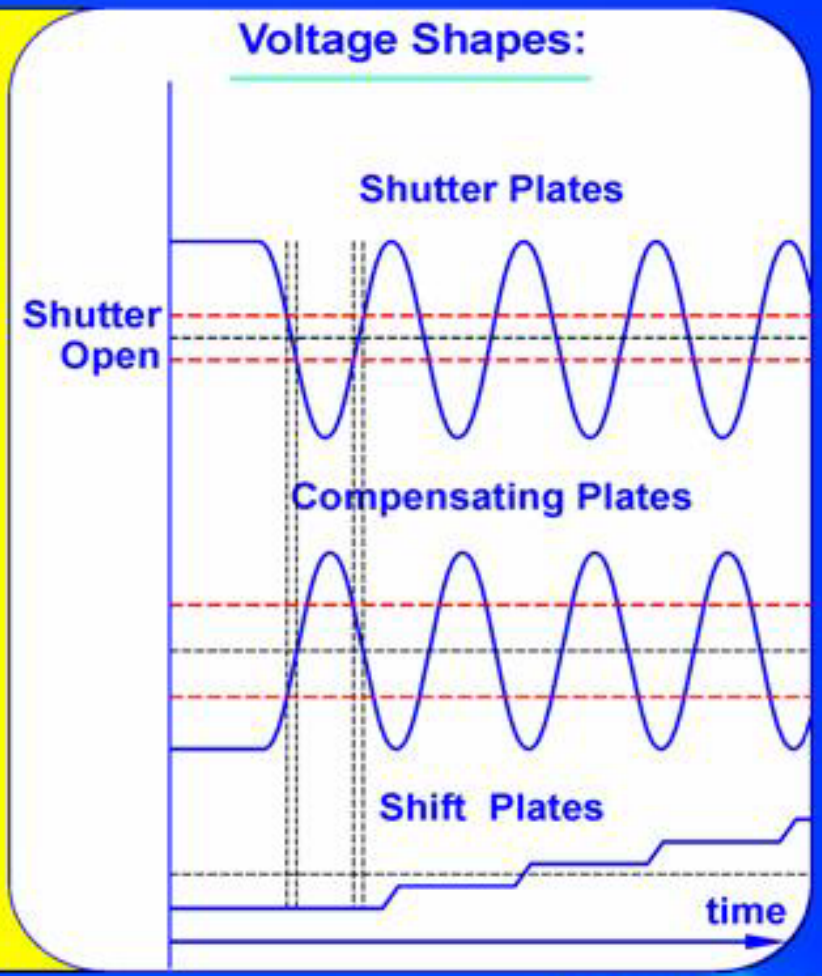
High-Speed Photography for Plasma Investigations

Multi-Frame Camera Based on Special Image Converter





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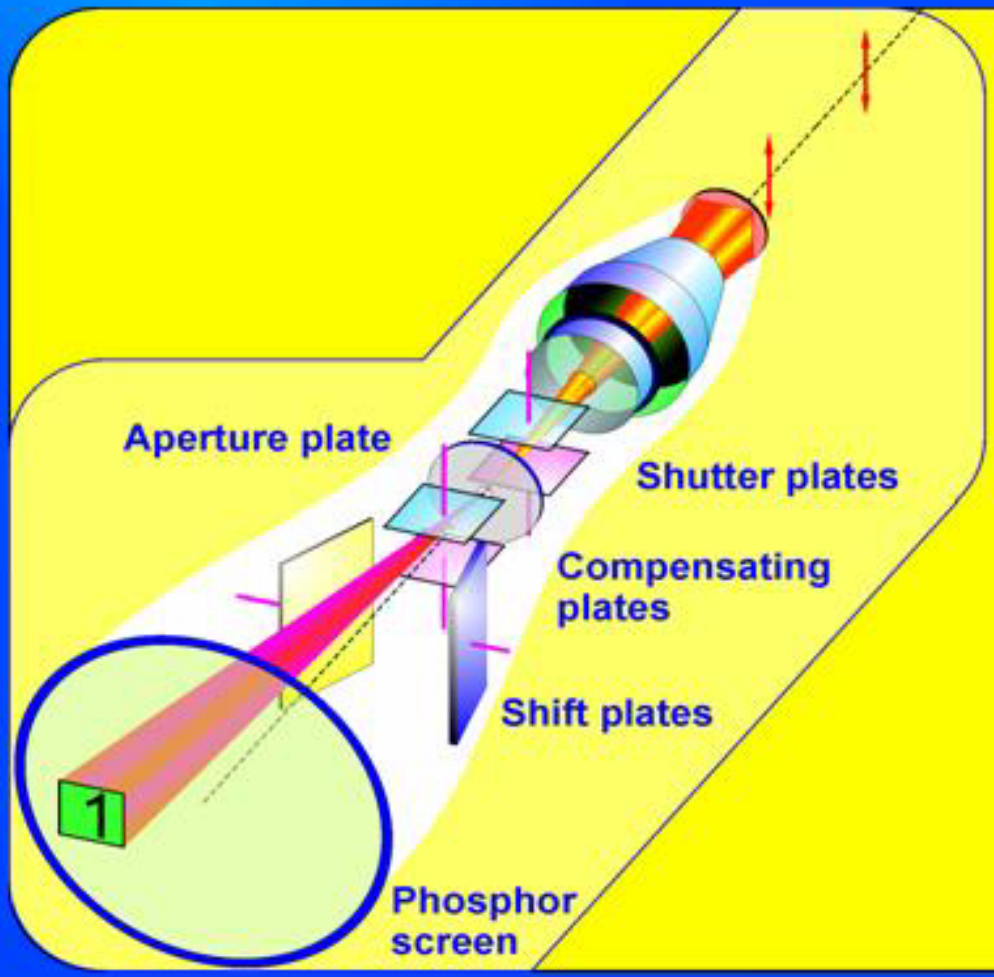
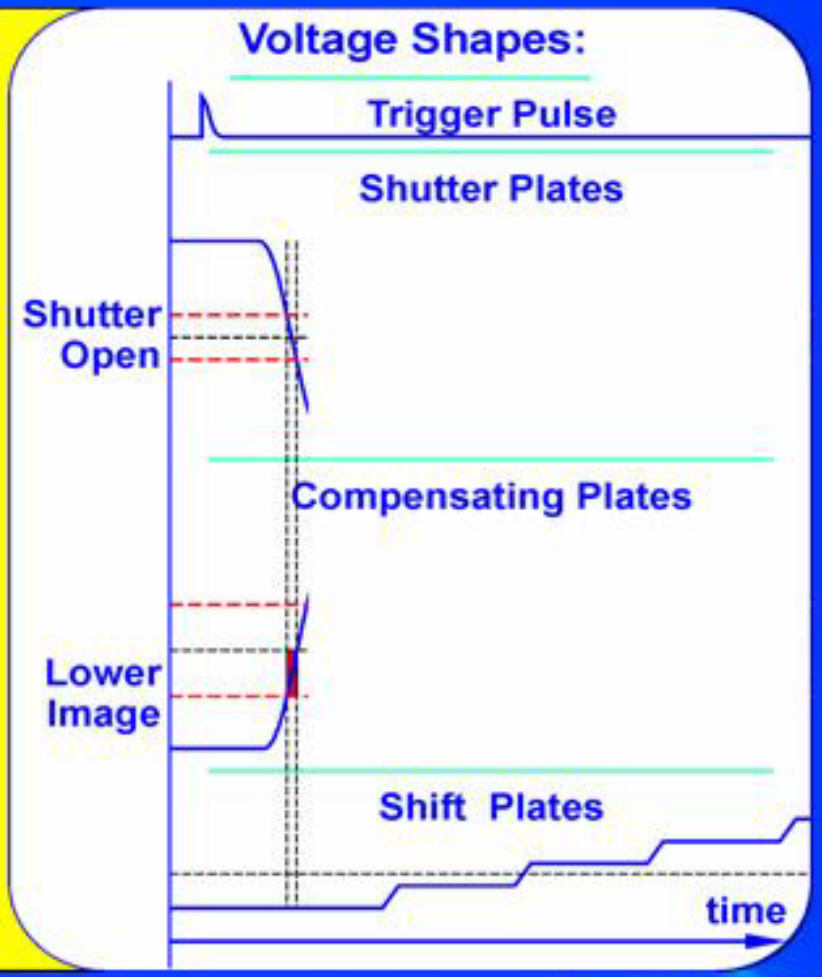
Multi-Frame Camera Based on Special Image Converter





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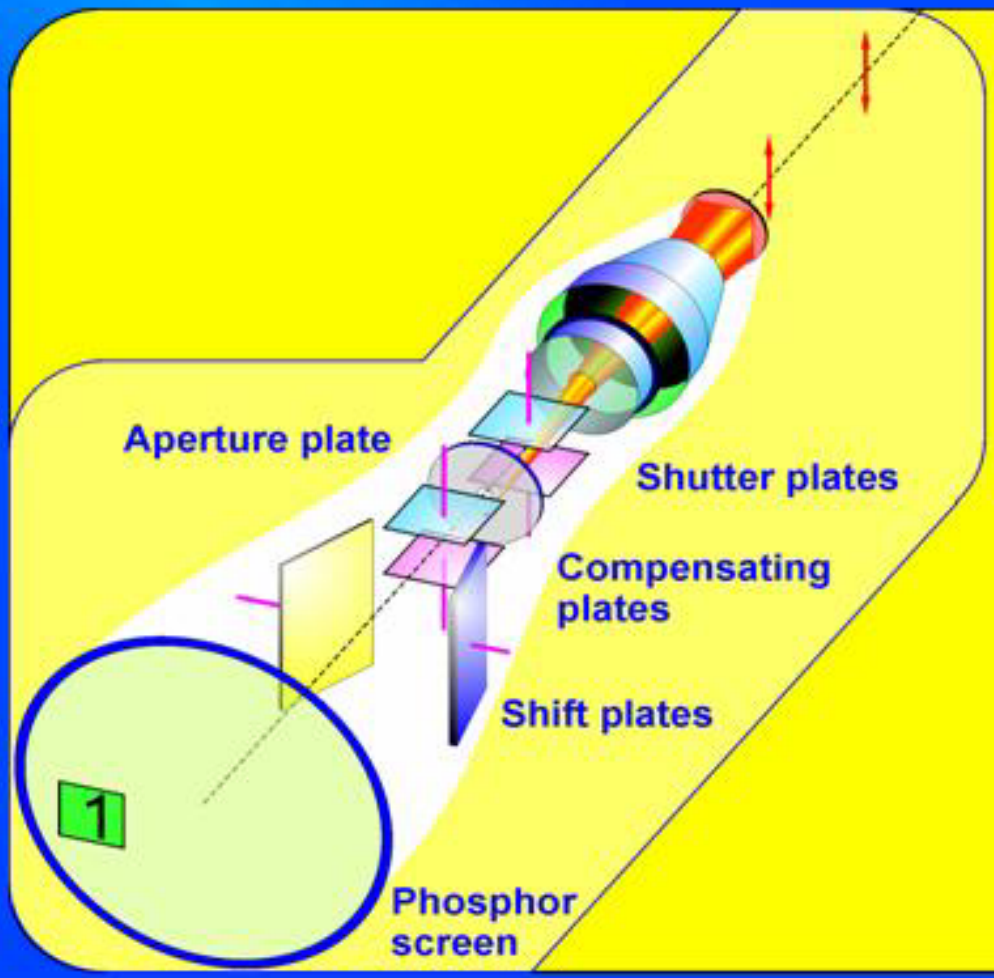
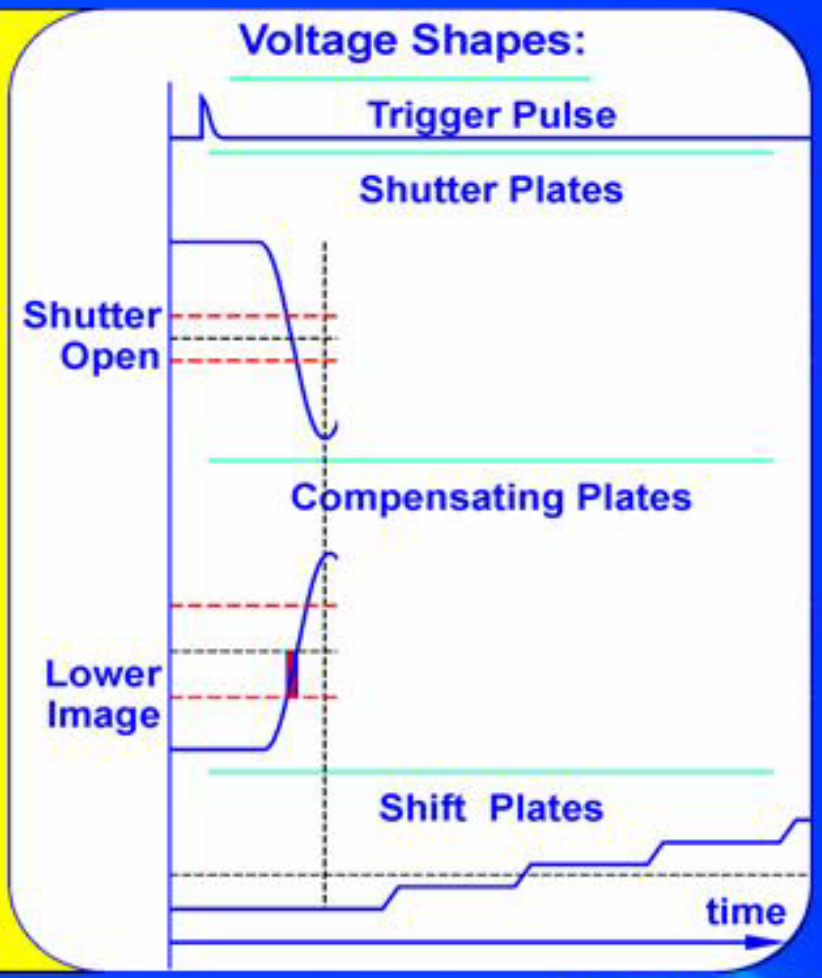
Multi-Frame Camera Based on Special Image Converter





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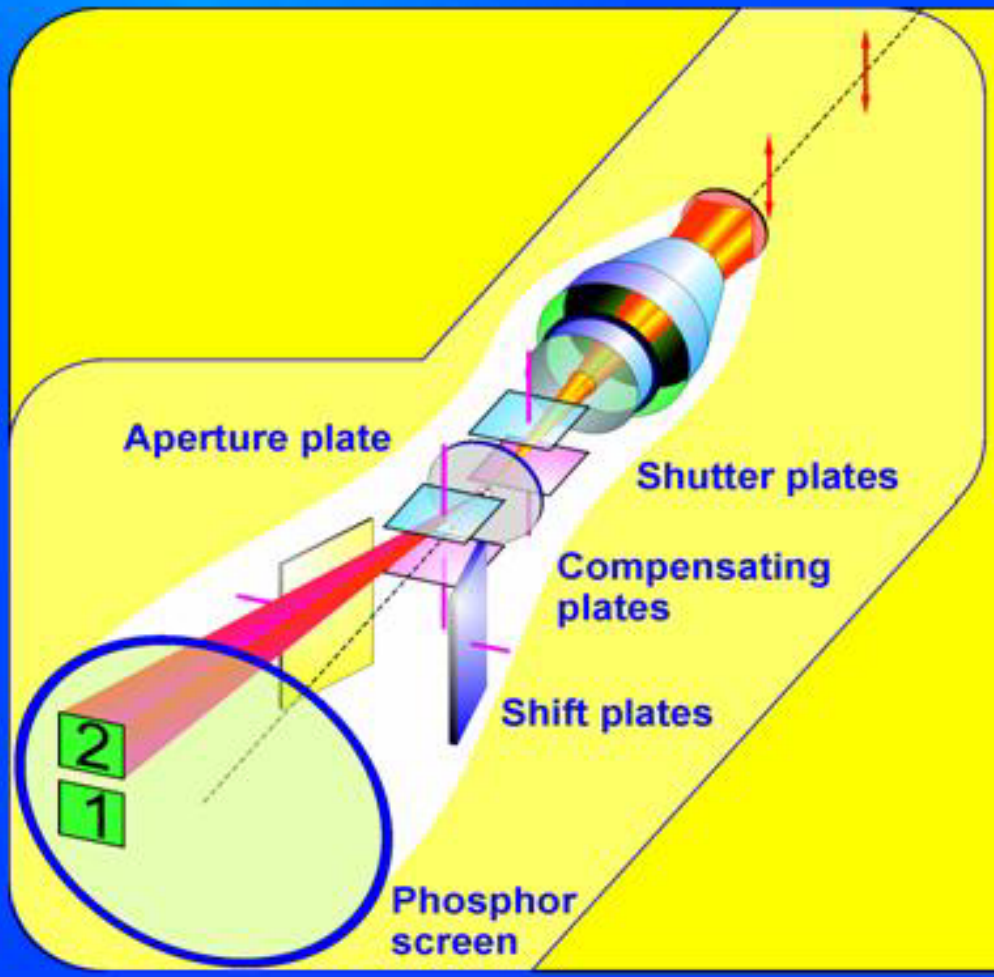
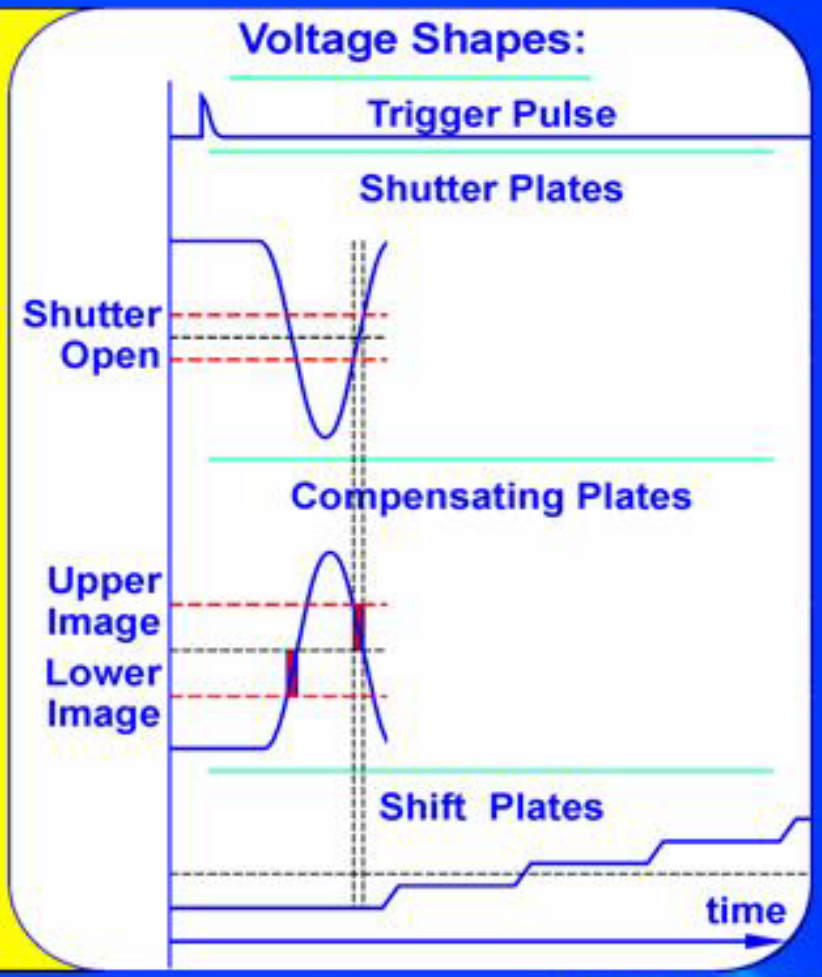
High-Speed Photography for Plasma Investigations

Multi-Frame Camera Based on Special Image Converter





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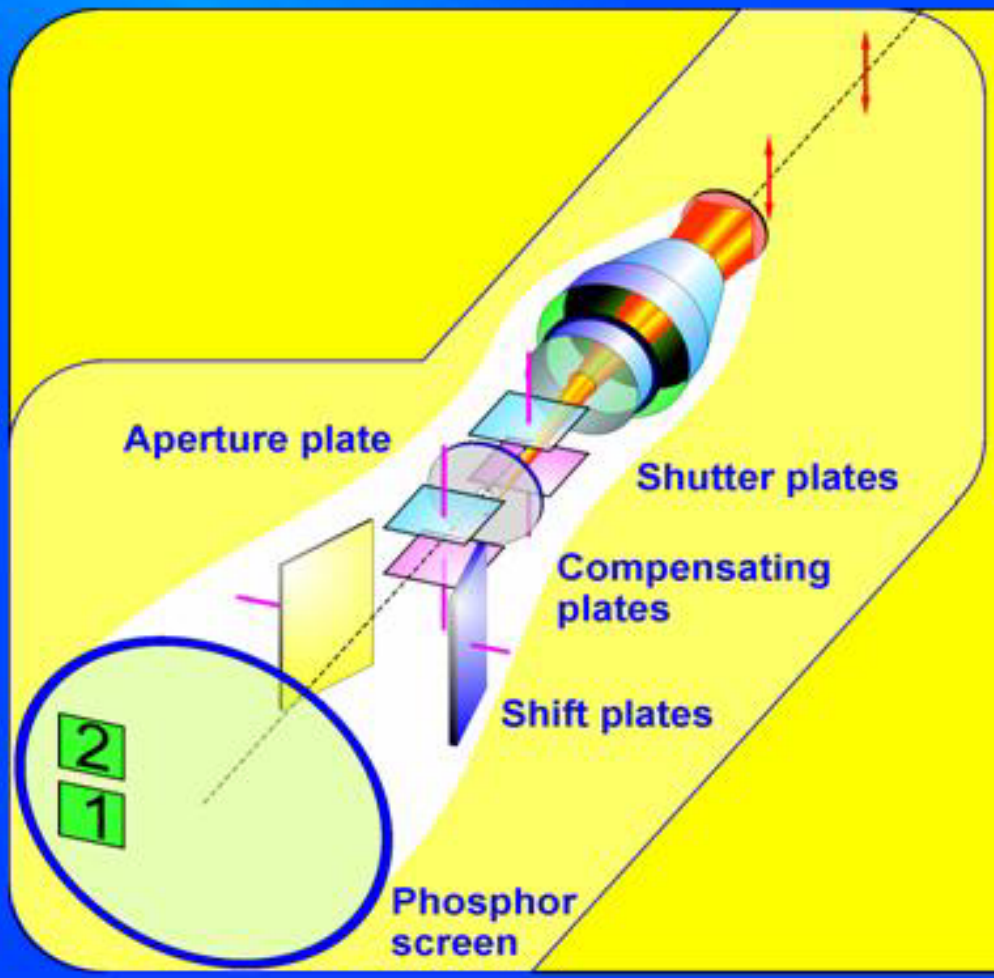
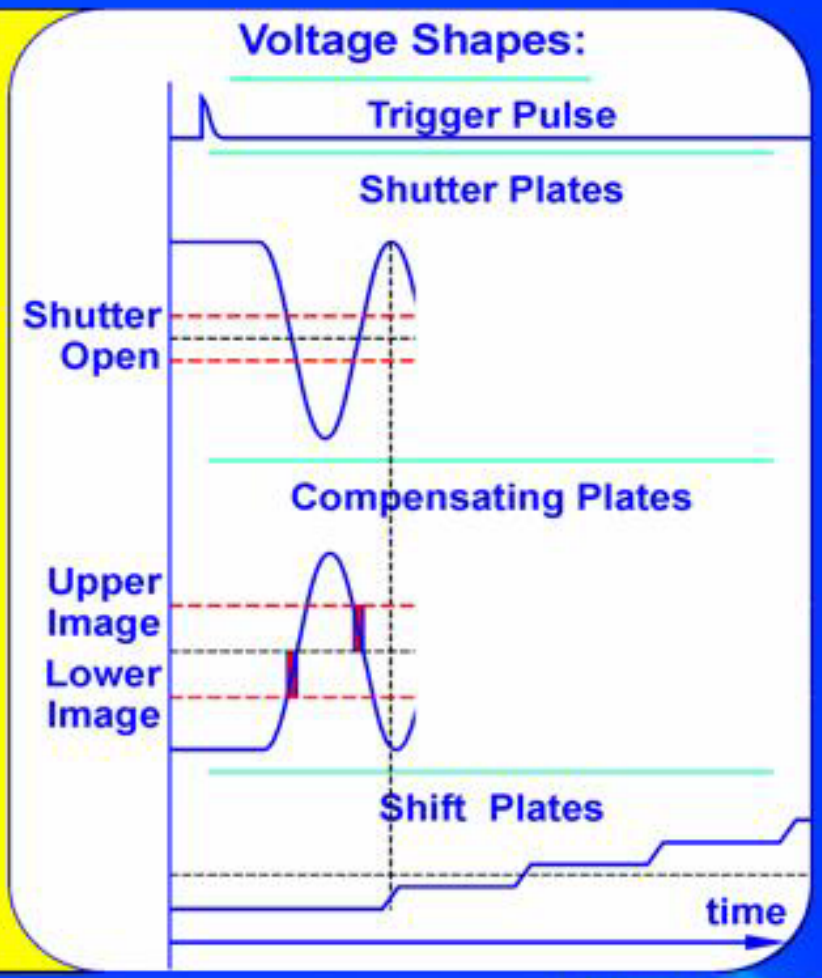
Multi-Frame Camera Based on Special Image Converter





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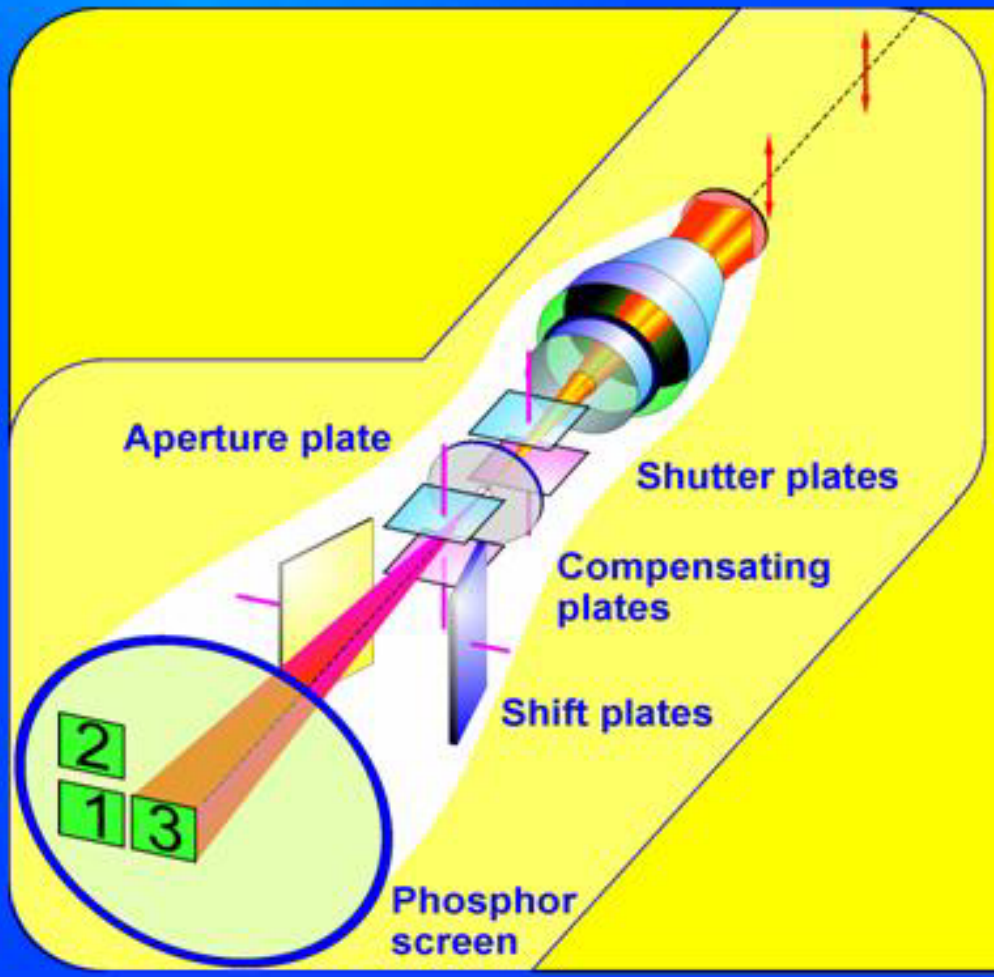
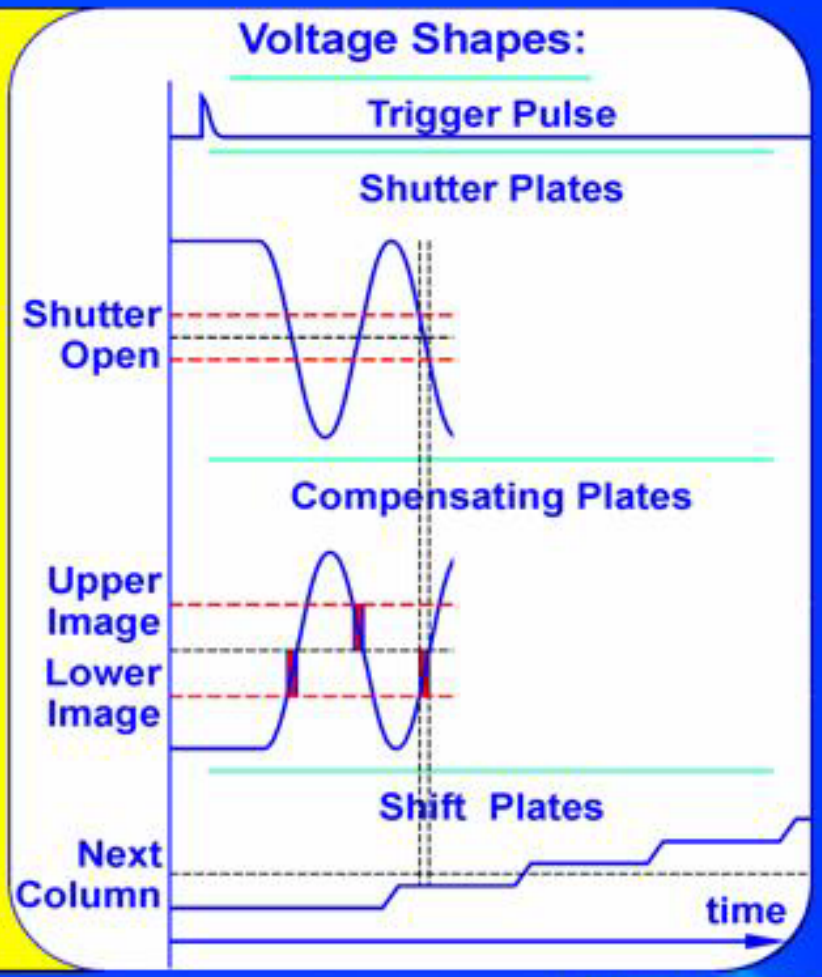
Multi-Frame Camera Based on Special Image Converter





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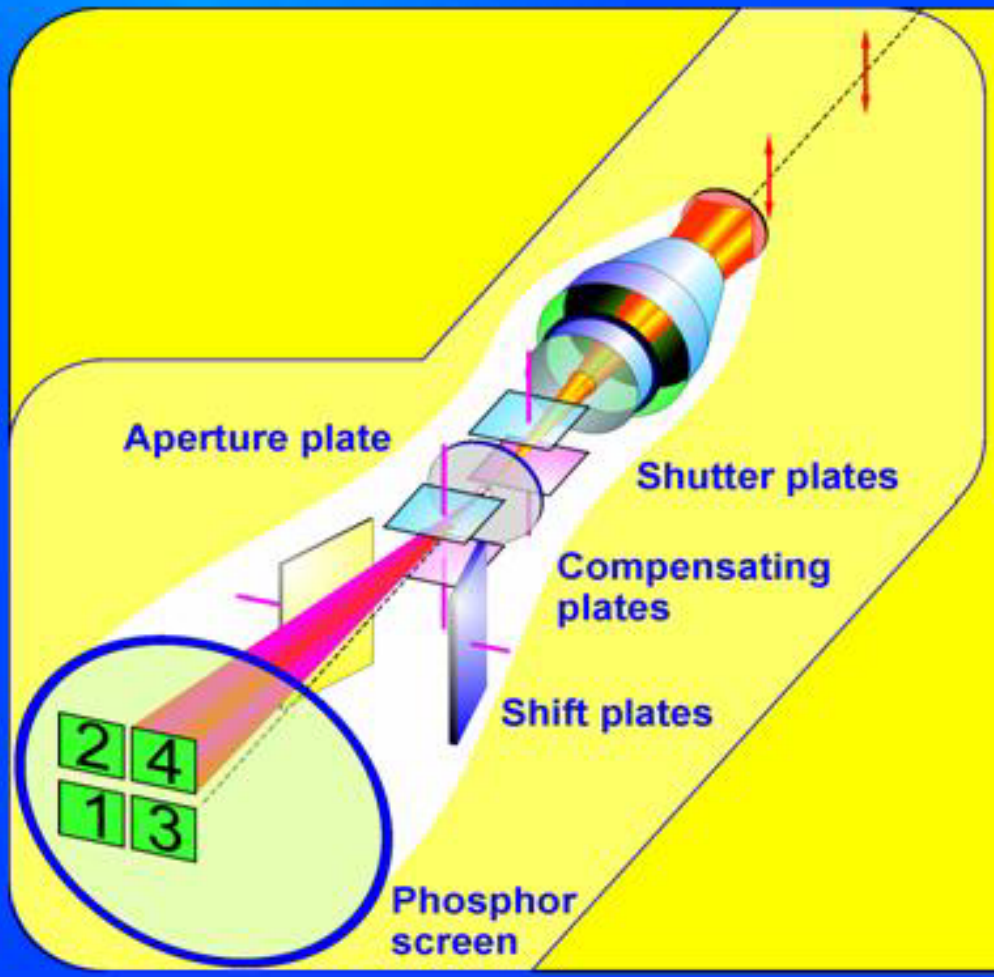
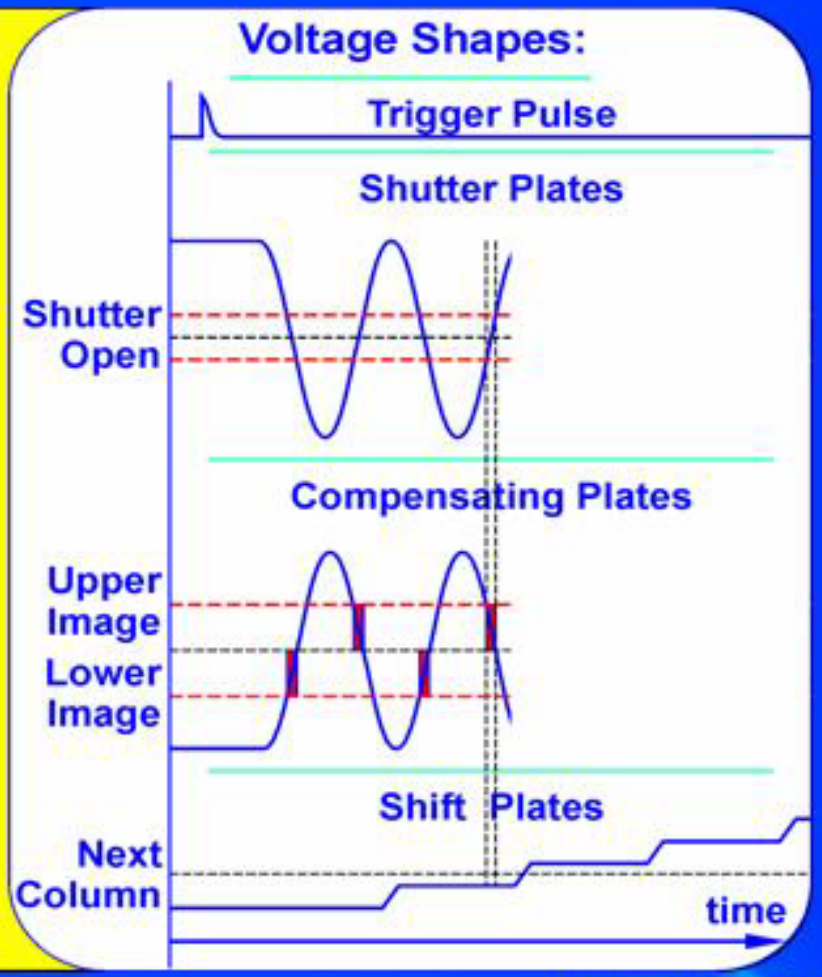
Multi-Frame Camera Based on Special Image Converter





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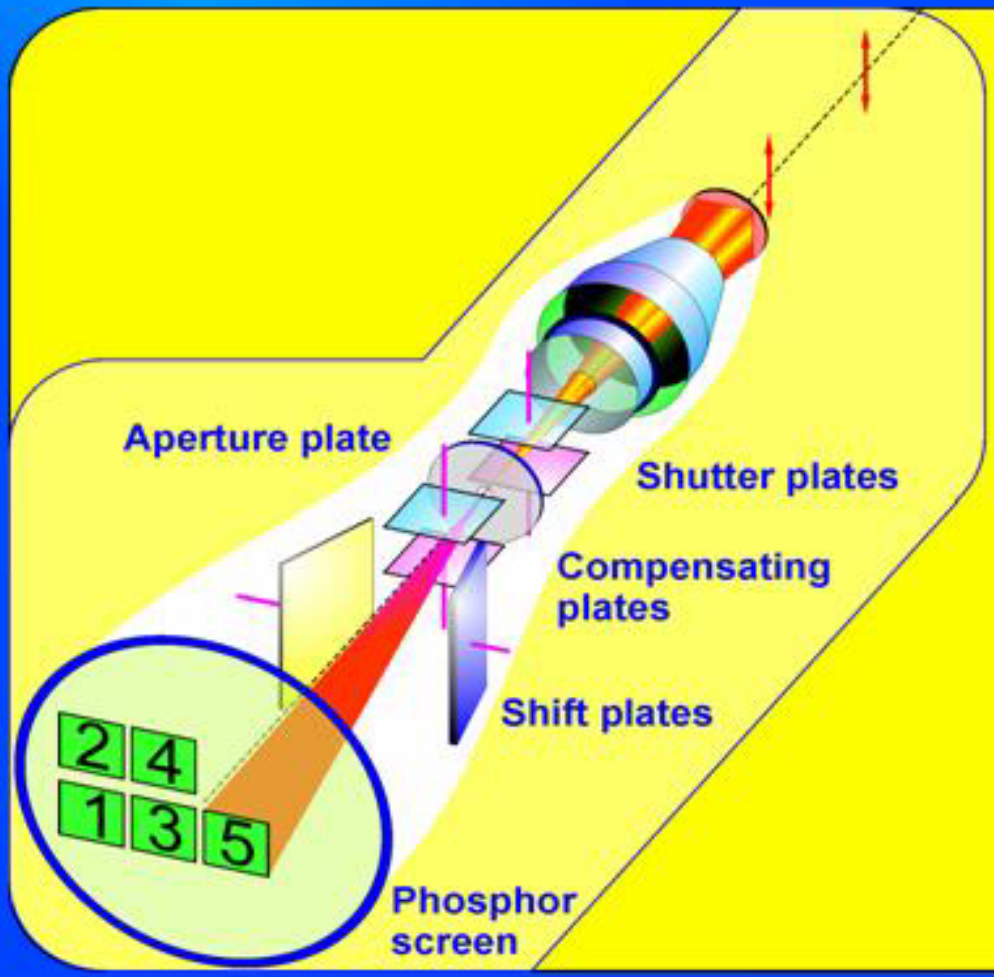
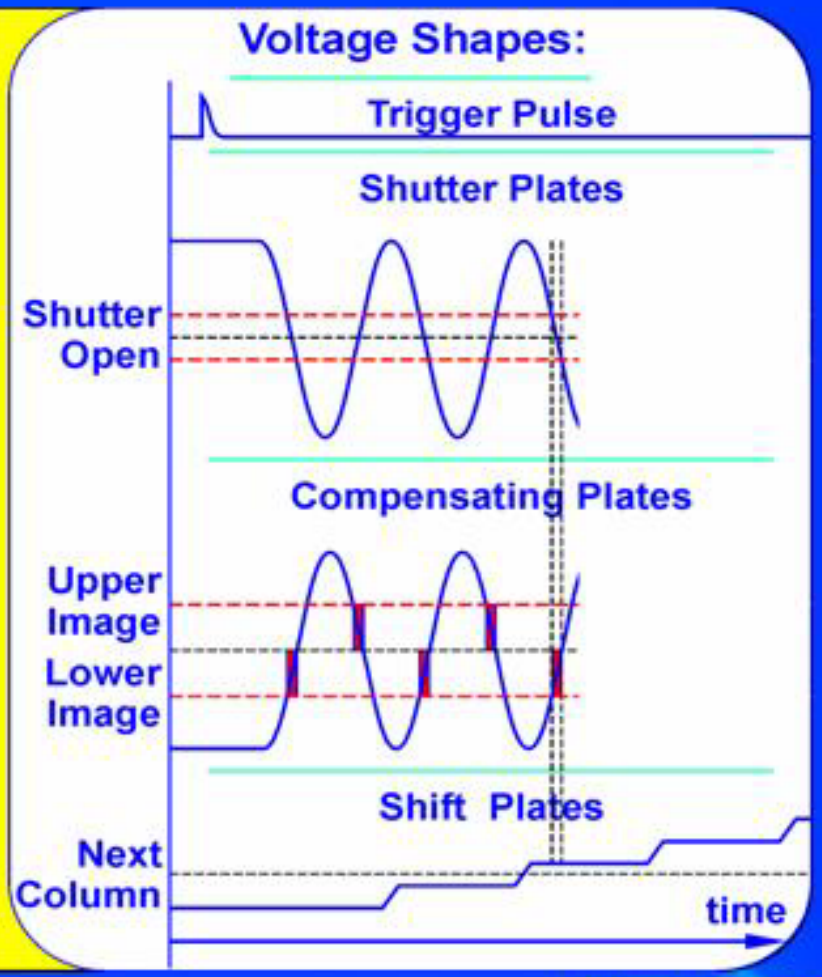
Multi-Frame Camera Based on Special Image Converter





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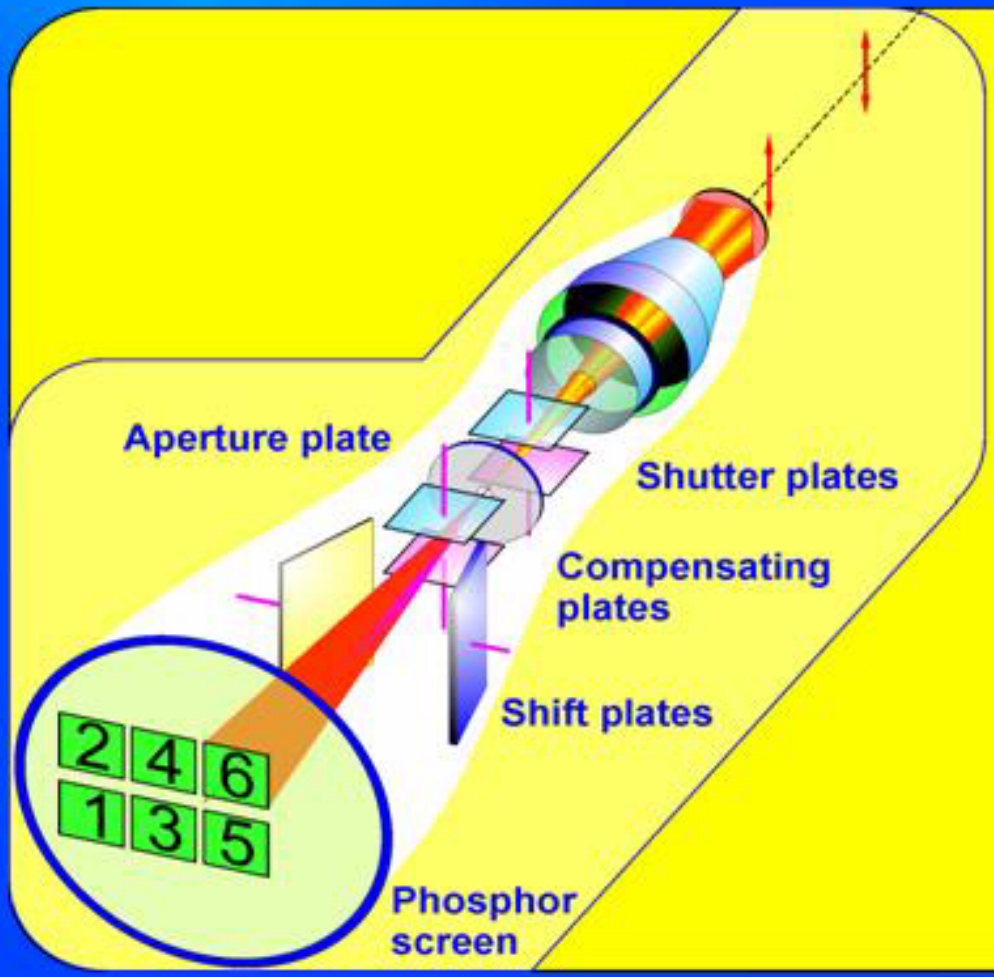
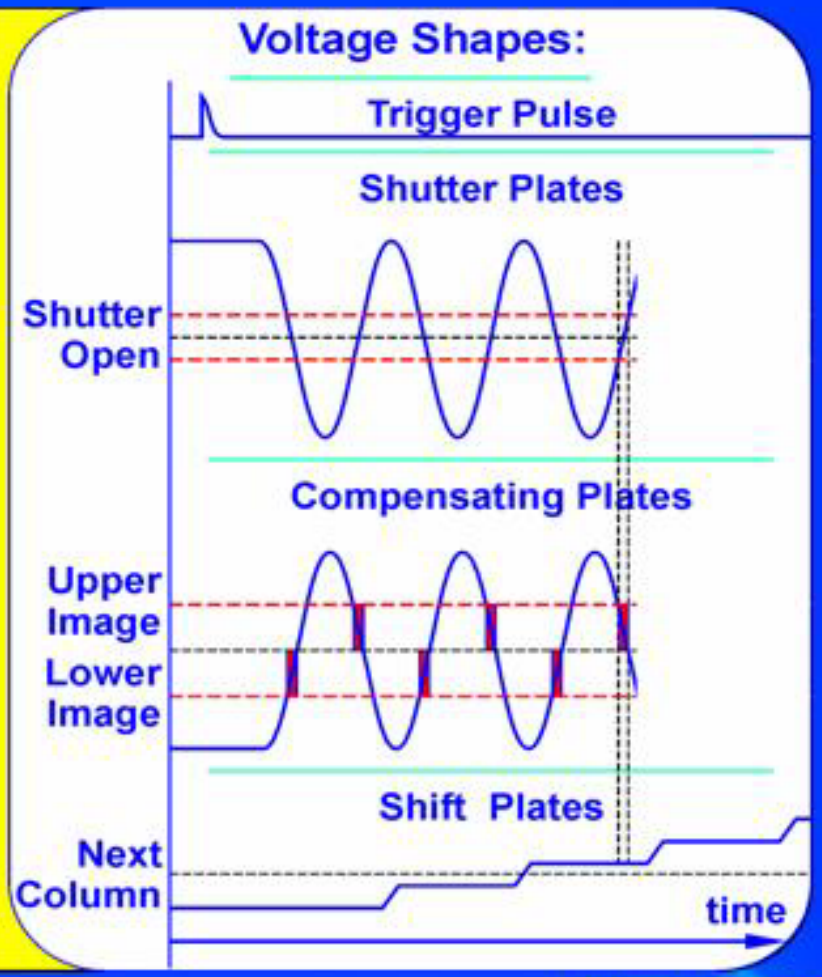
Multi-Frame Camera Based on Special Image Converter





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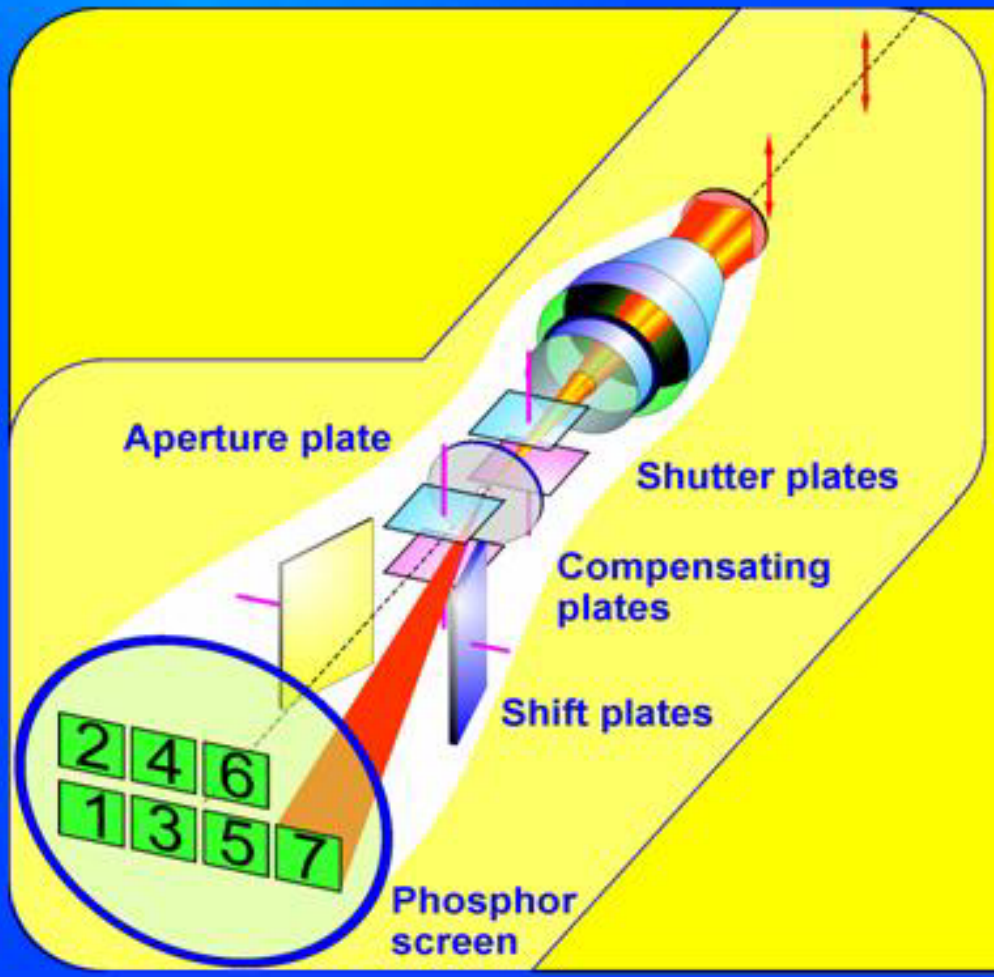
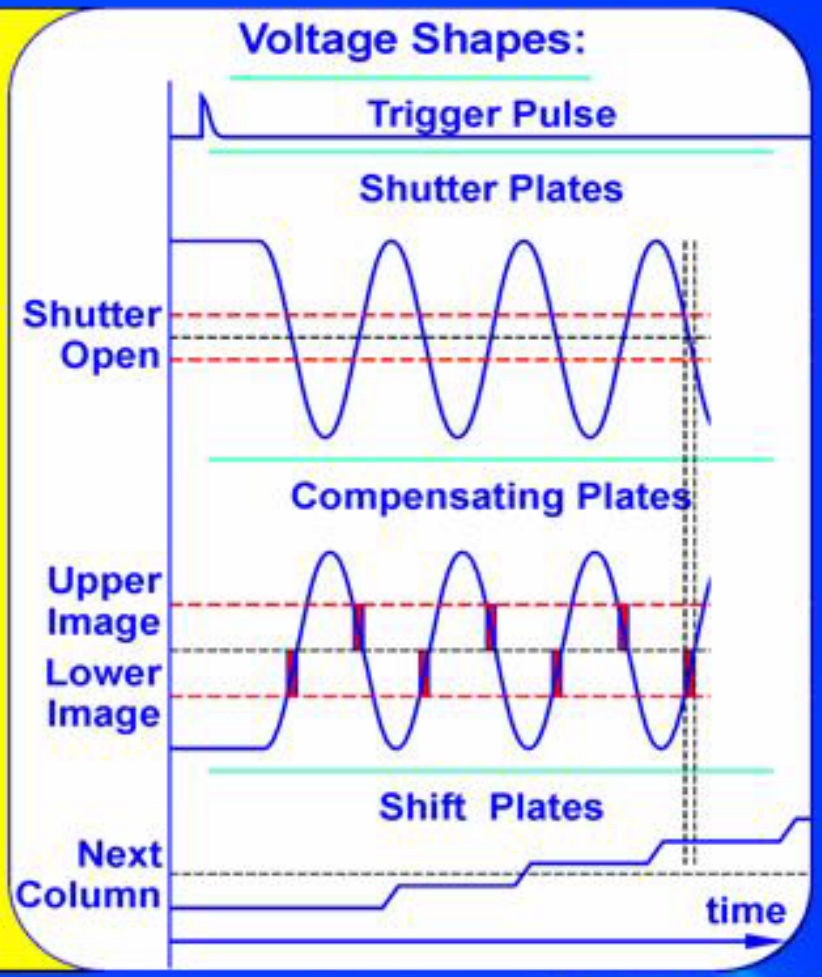
Multi-Frame Camera Based on Special Image Converter





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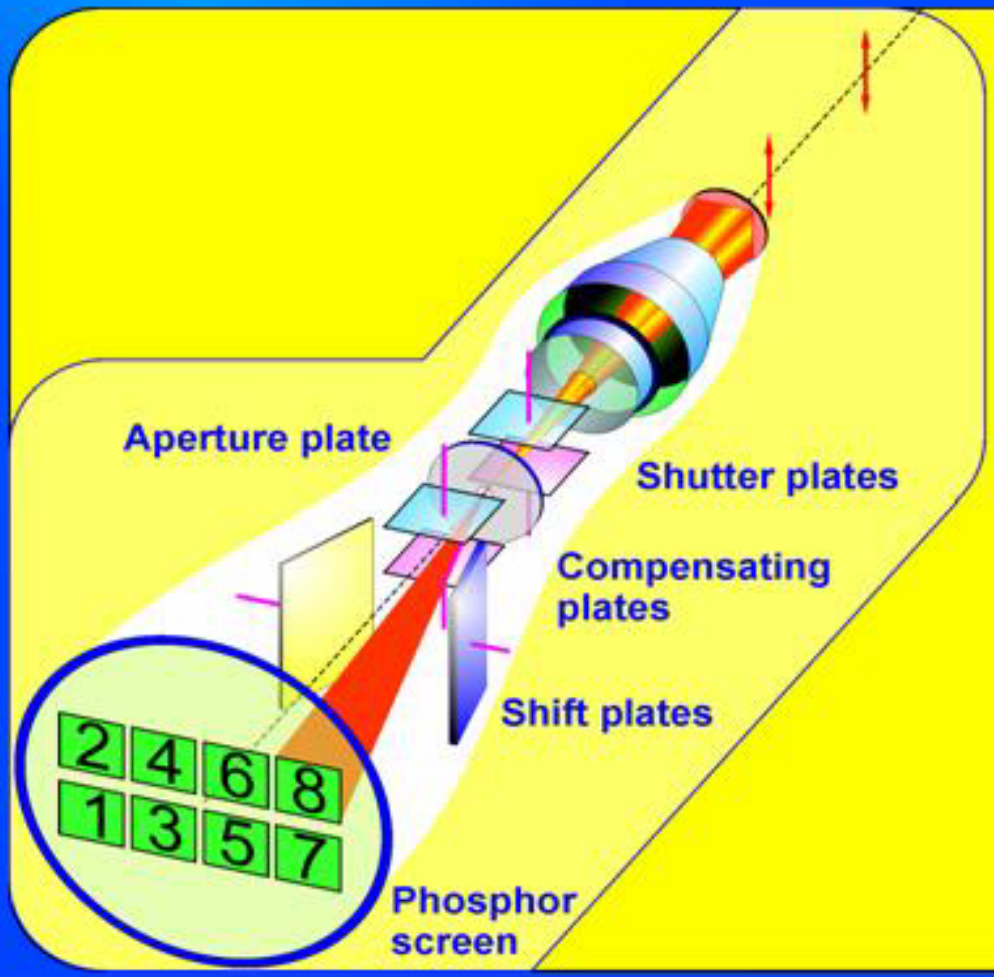
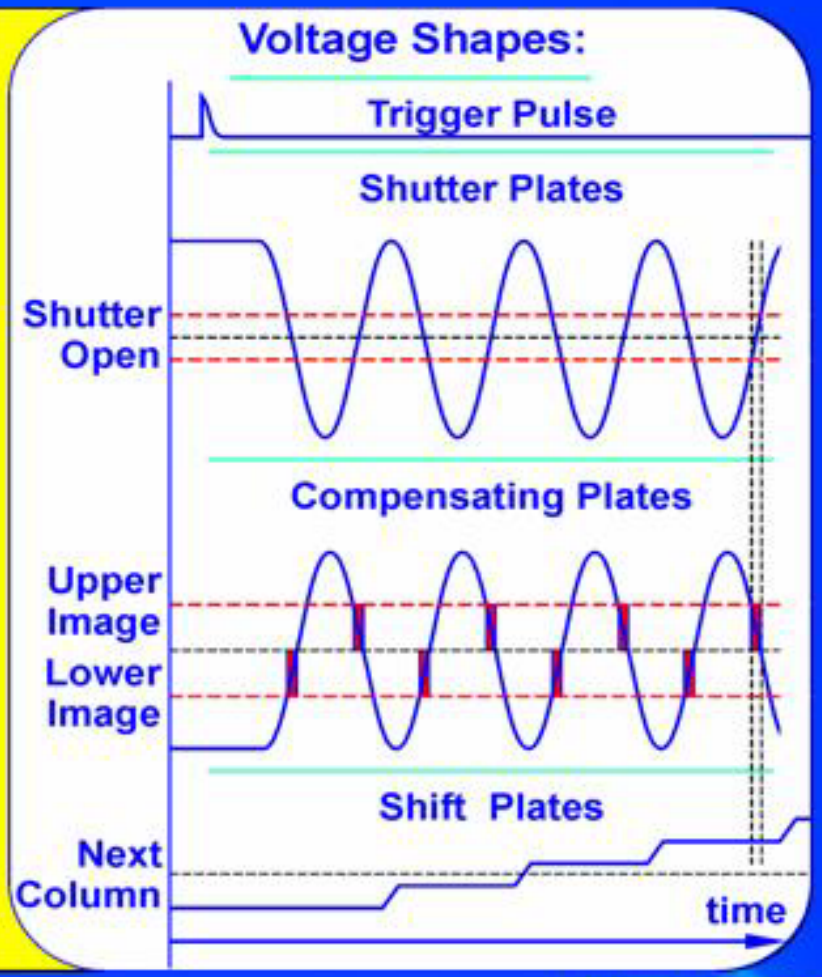
Multi-Frame Camera Based on Special Image Converter





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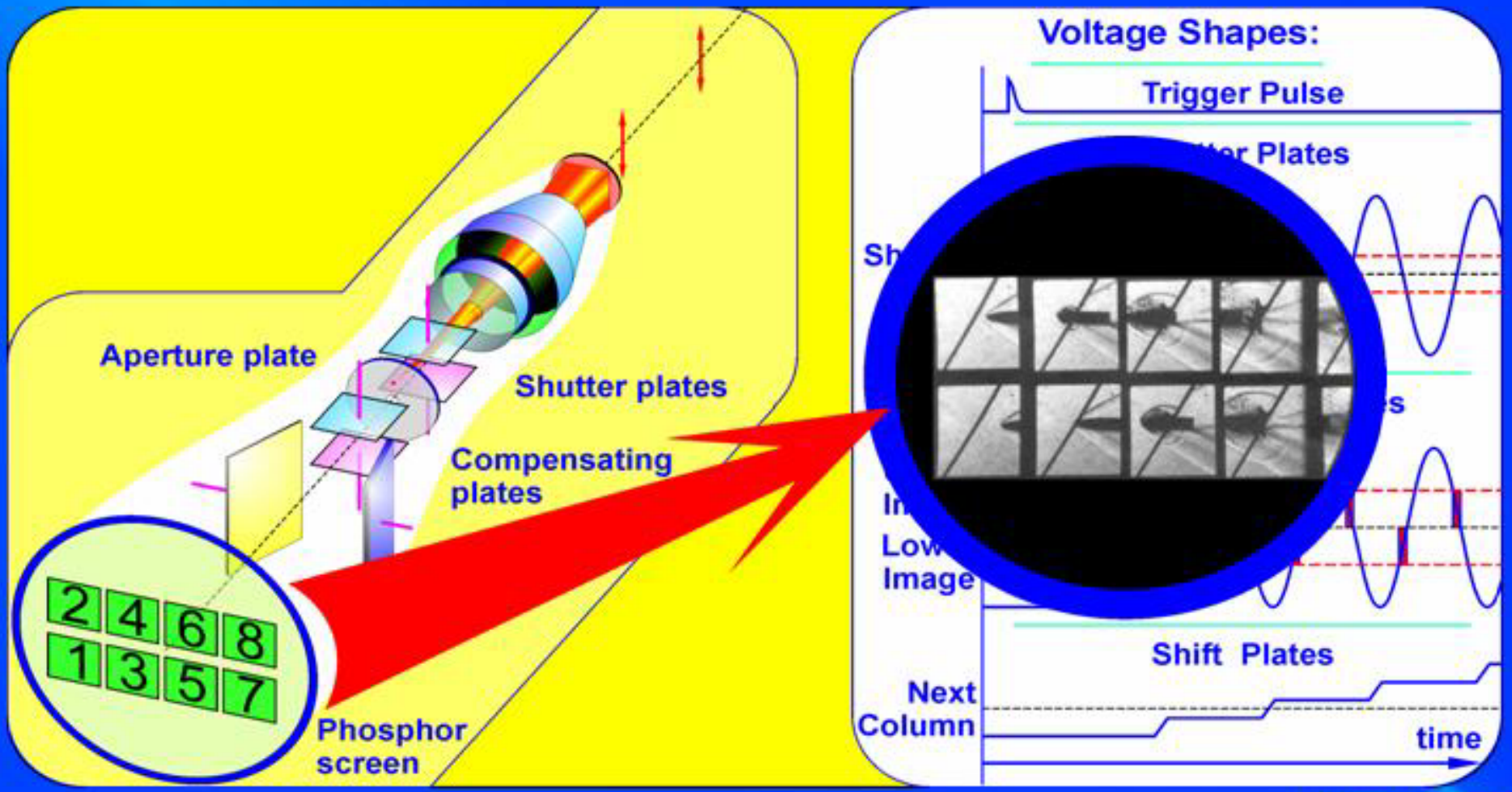
Multi-Frame Camera Based on Special Image Converter



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High-Speed Photography for Plasma Investigations

Introduction to High-Speed Streak Photography

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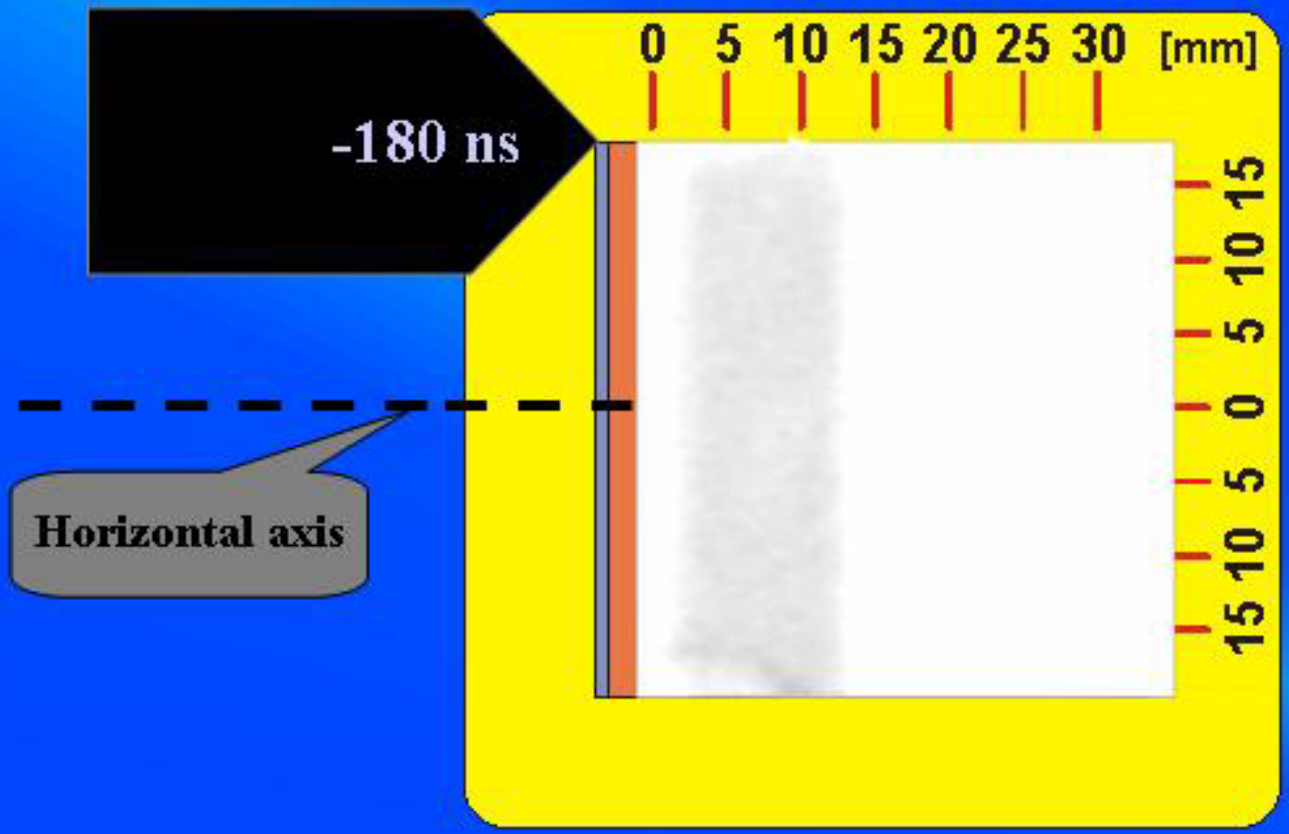
High-Speed Photography for Plasma Investigations

Subsequent Frames of Non-Cylindrically Collapsed Object



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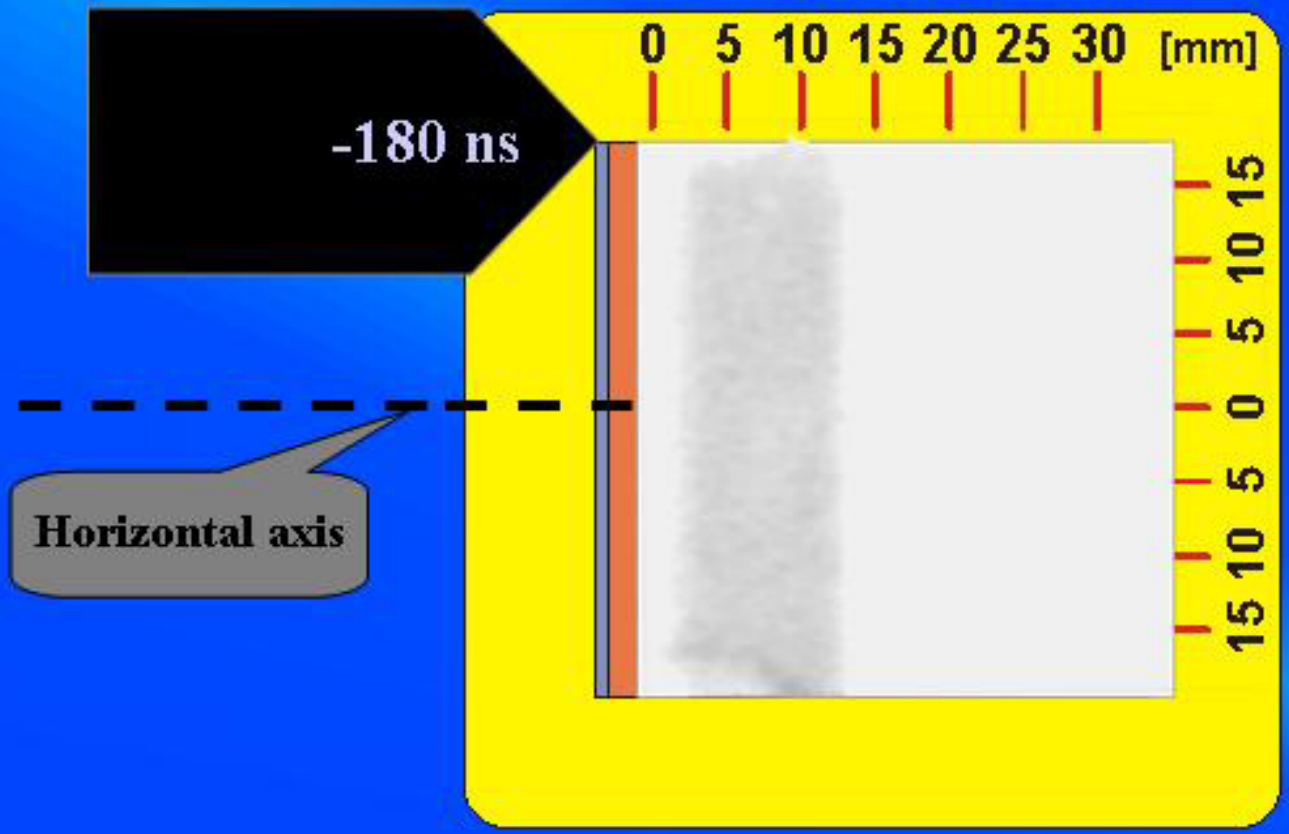
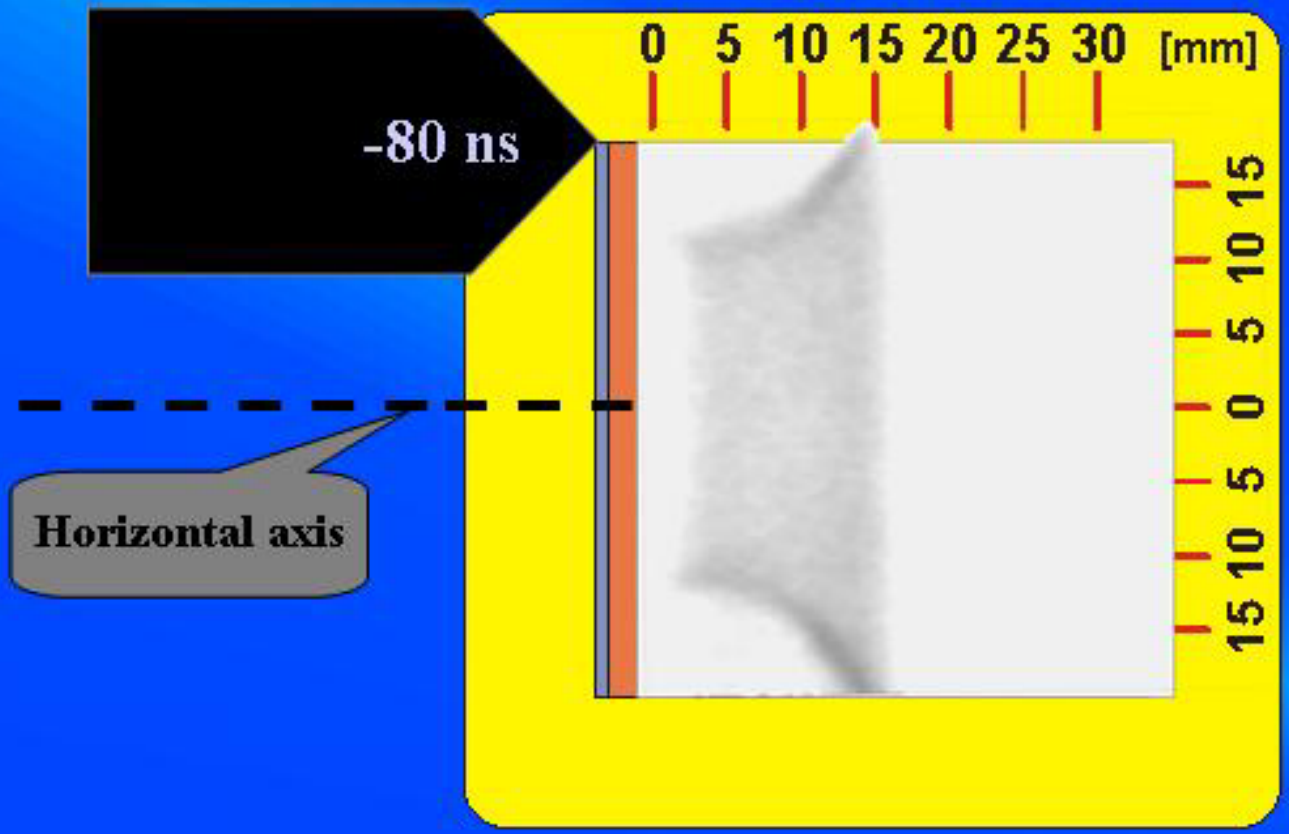
Subsequent Frames of Non-Cylindrically Collapsed Object



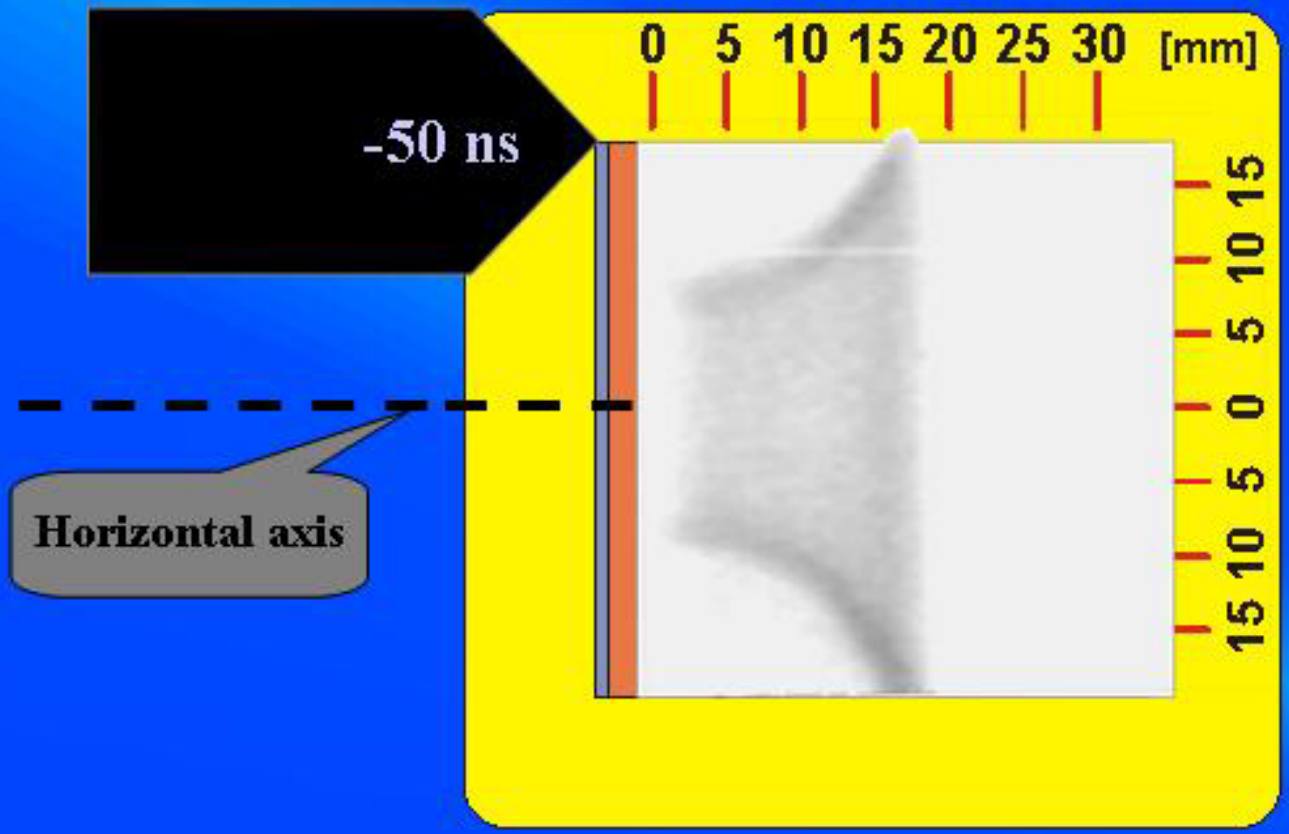
High-Speed Photography for Plasma Investigations

Subsequent Frames of Non-Cylindrically Collapsed Object



High-Speed Photography for Plasma Investigations

Subsequent Frames of Non-Cylindrically Collapsed Object



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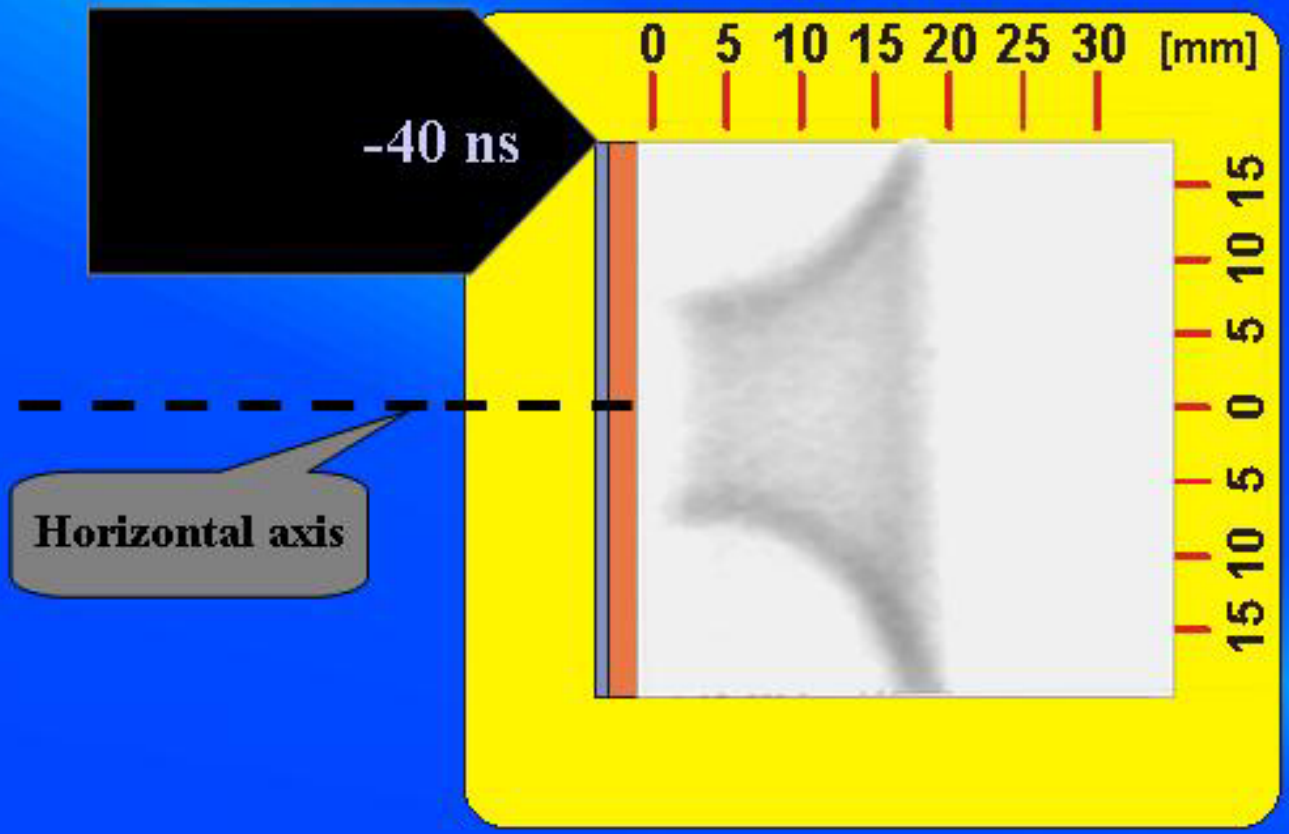
Subsequent Frames of Non-Cylindrically Collapsed Object



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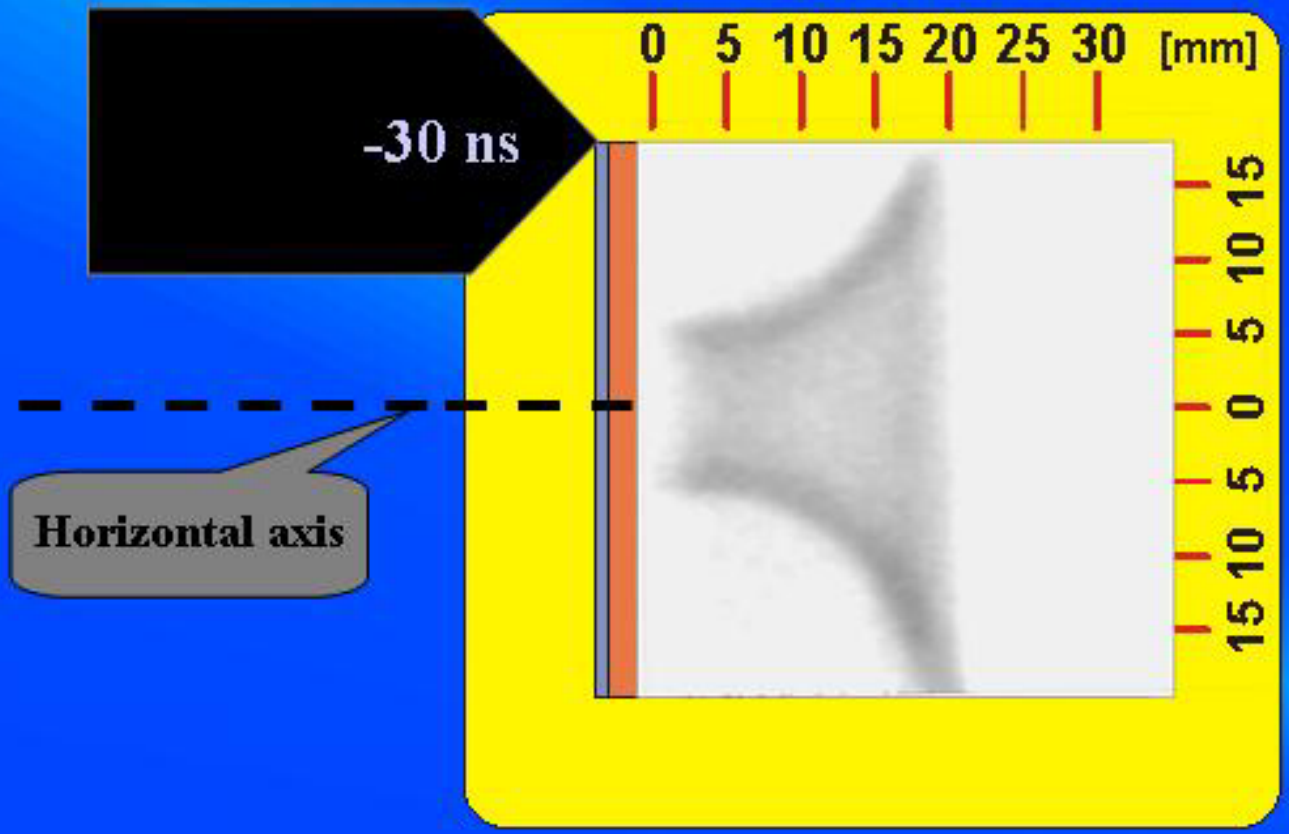
Subsequent Frames of Non-Cylindrically Collapsed Object



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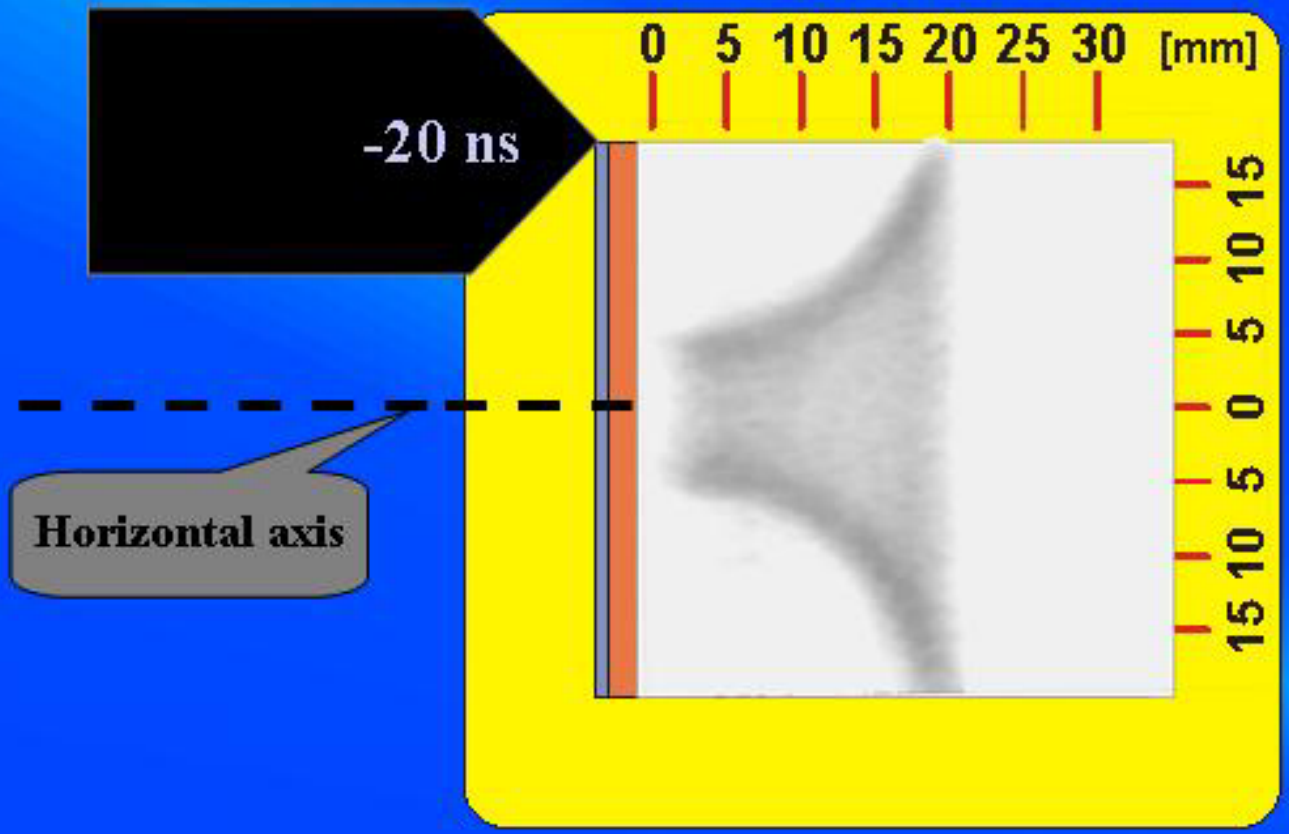
Subsequent Frames of Non-Cylindrically Collapsed Object



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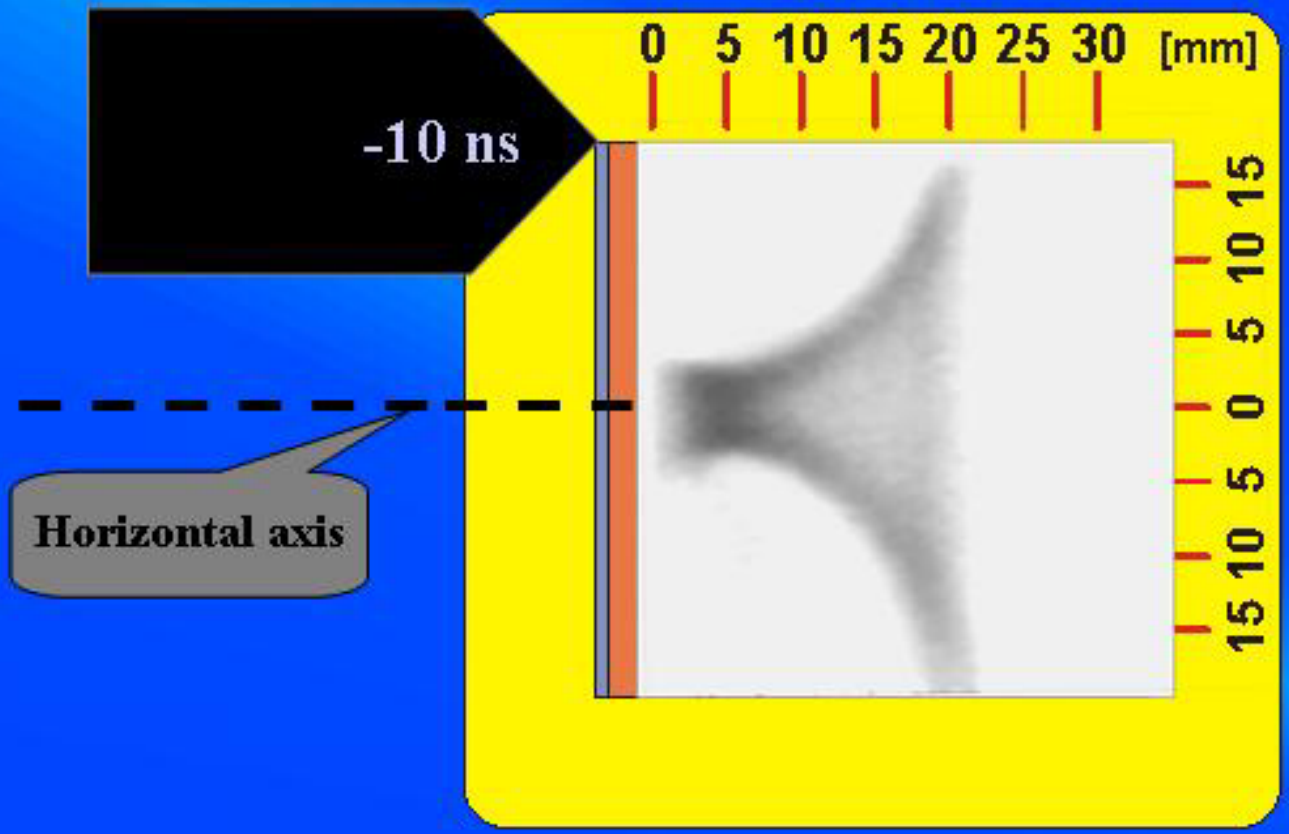
Subsequent Frames of Non-Cylindrically Collapsed Object



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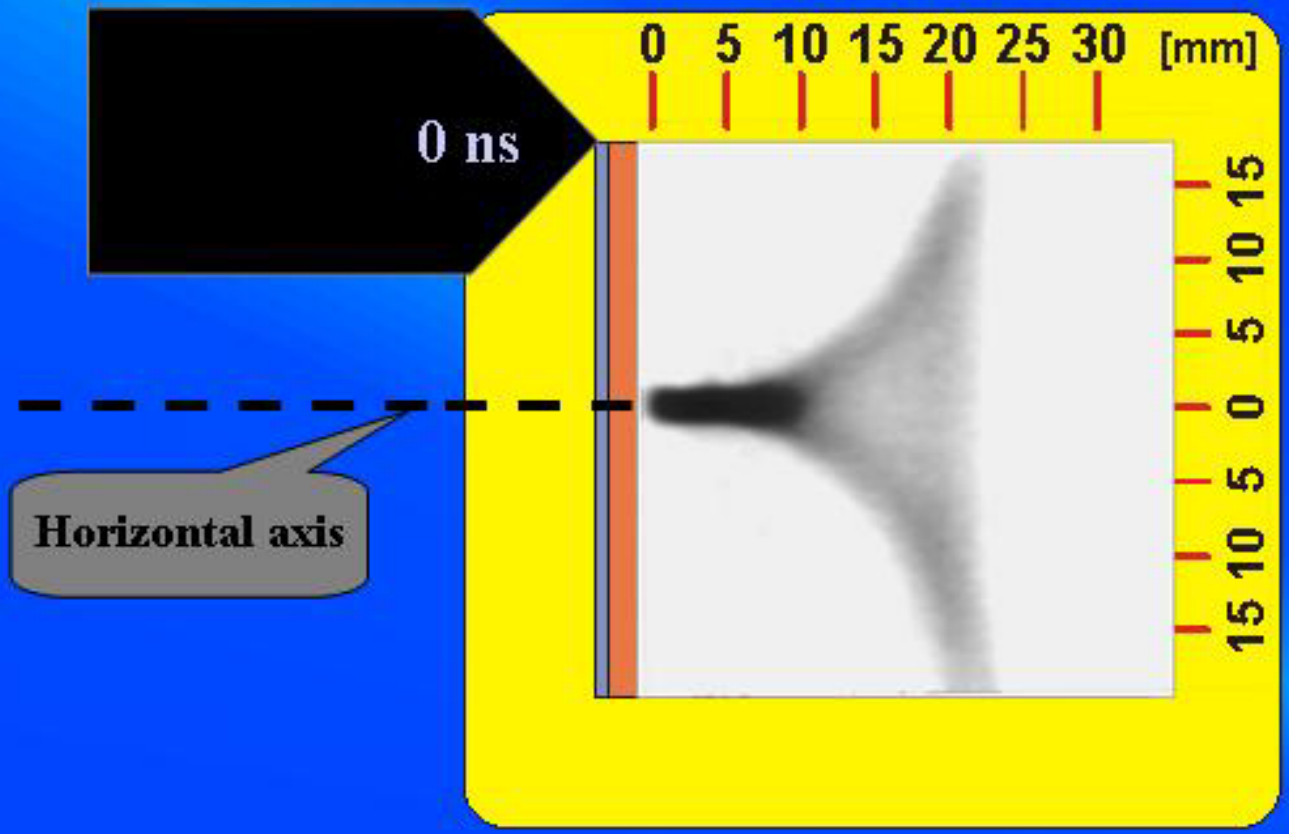
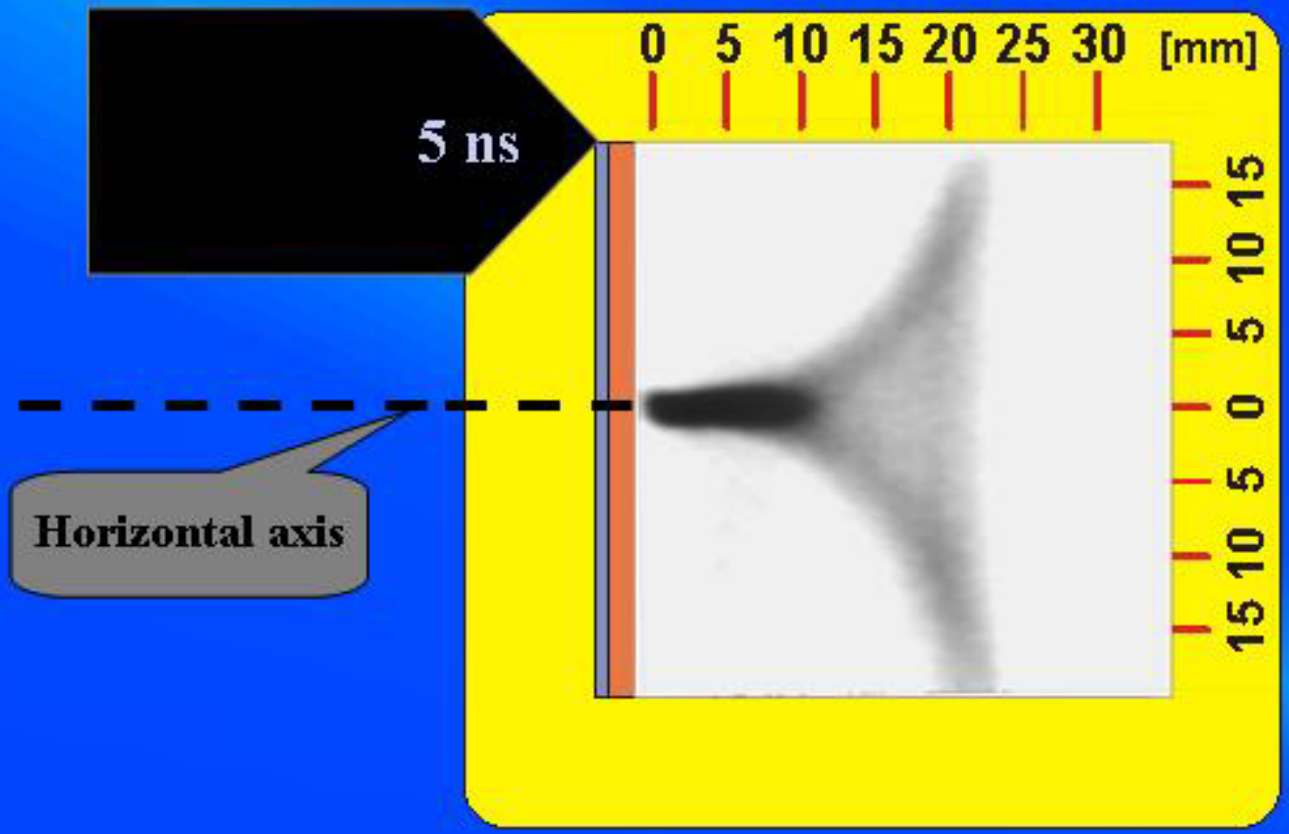
Subsequent Frames of Non-Cylindrically Collapsed Object



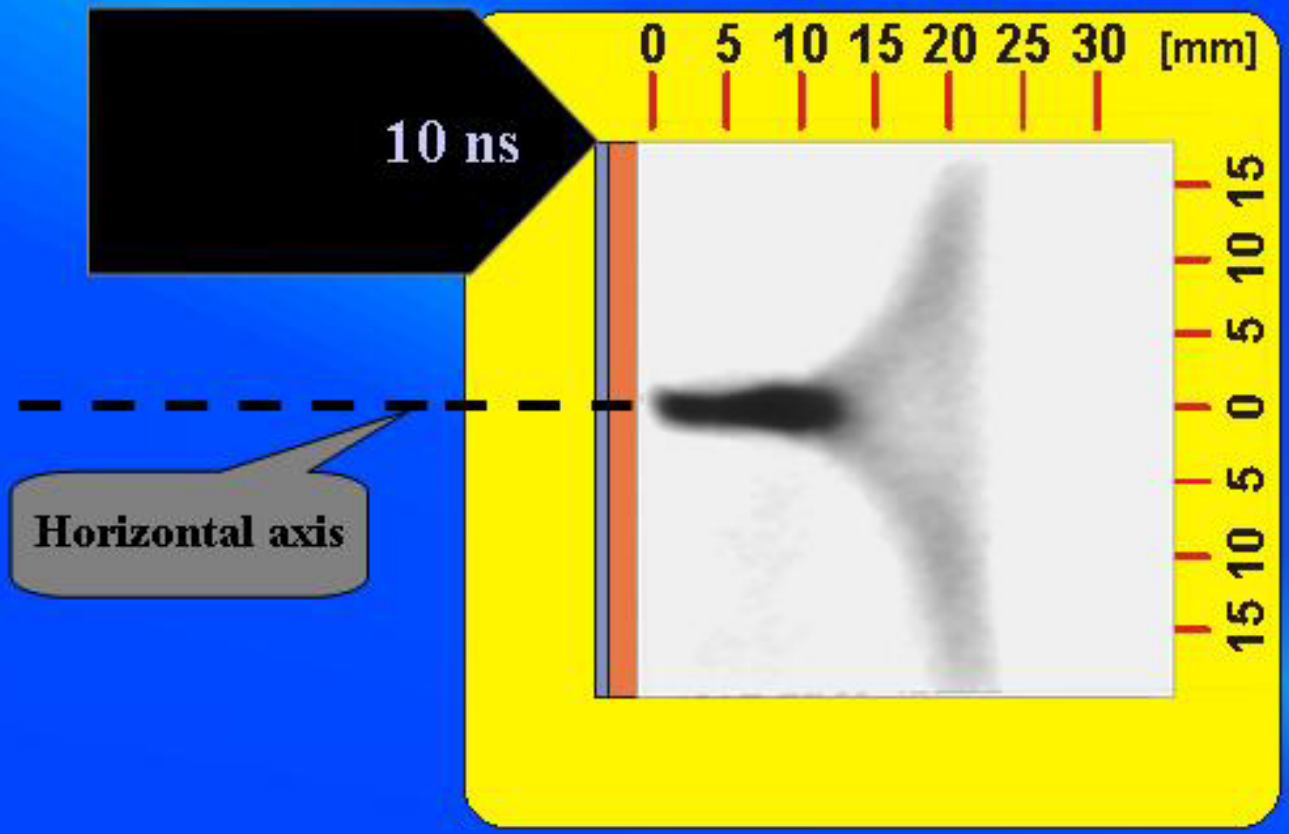
High-Speed Photography for Plasma Investigations

Subsequent Frames of Non-Cylindrically Collapsed Object



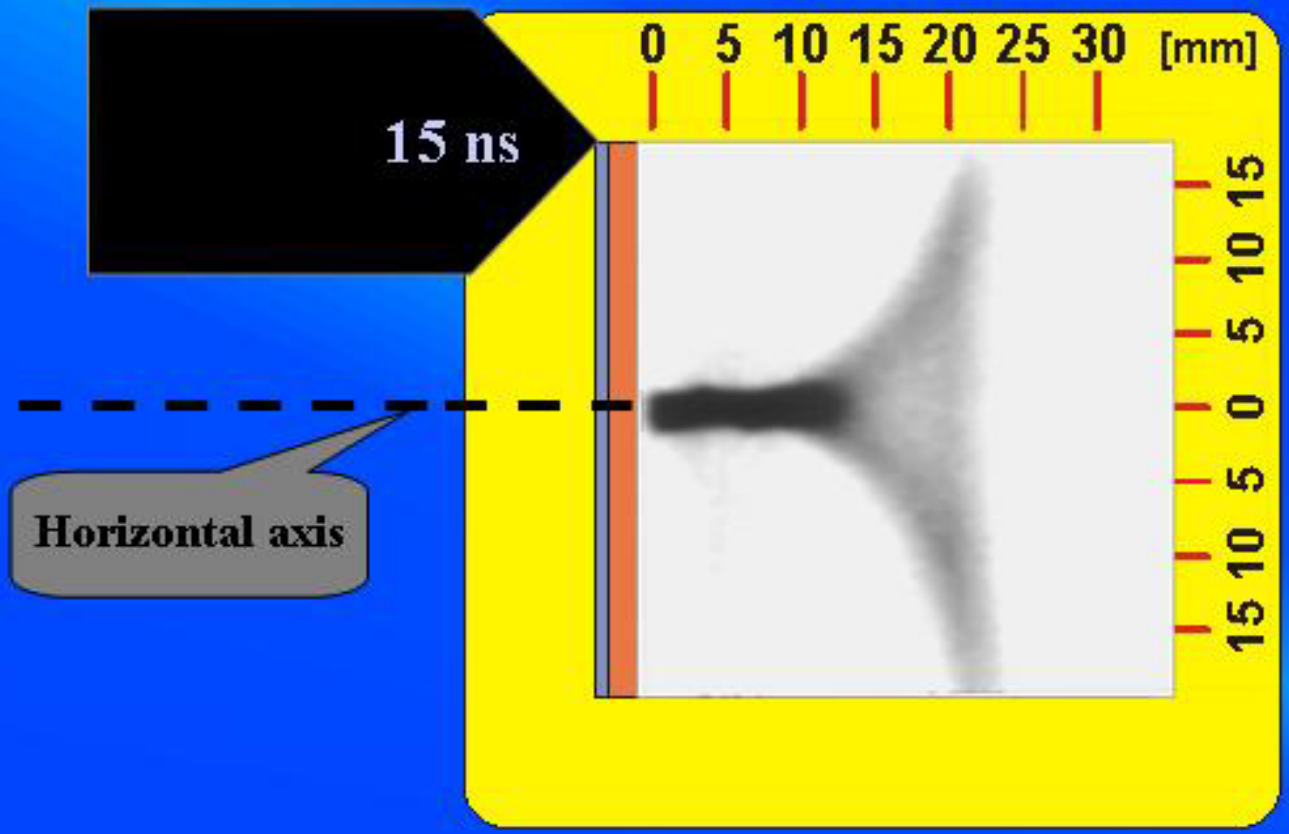
High-Speed Photography for Plasma Investigations

Subsequent Frames of Non-Cylindrically Collapsed Object



High-Speed Photography for Plasma Investigations

Subsequent Frames of Non-Cylindrically Collapsed Object



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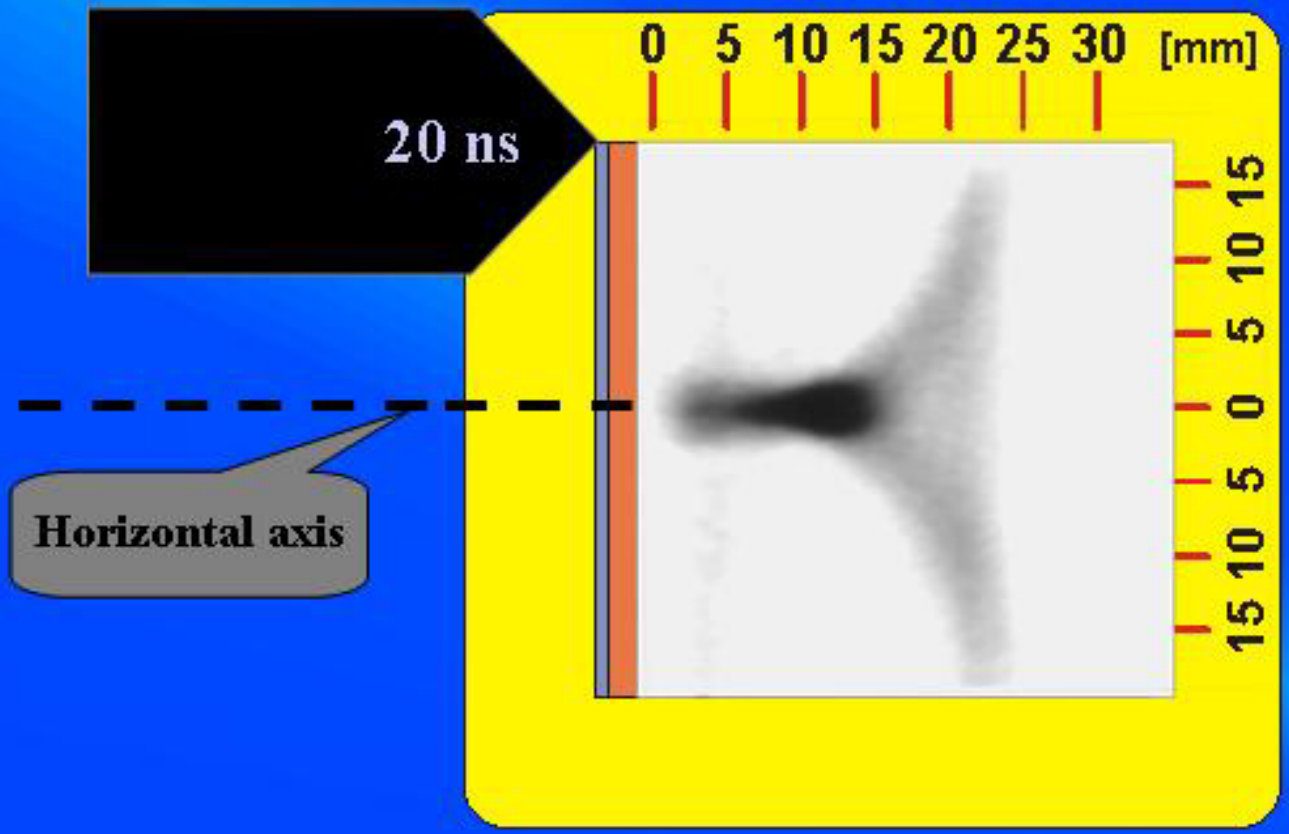
Subsequent Frames of Non-Cylindrically Collapsed Object



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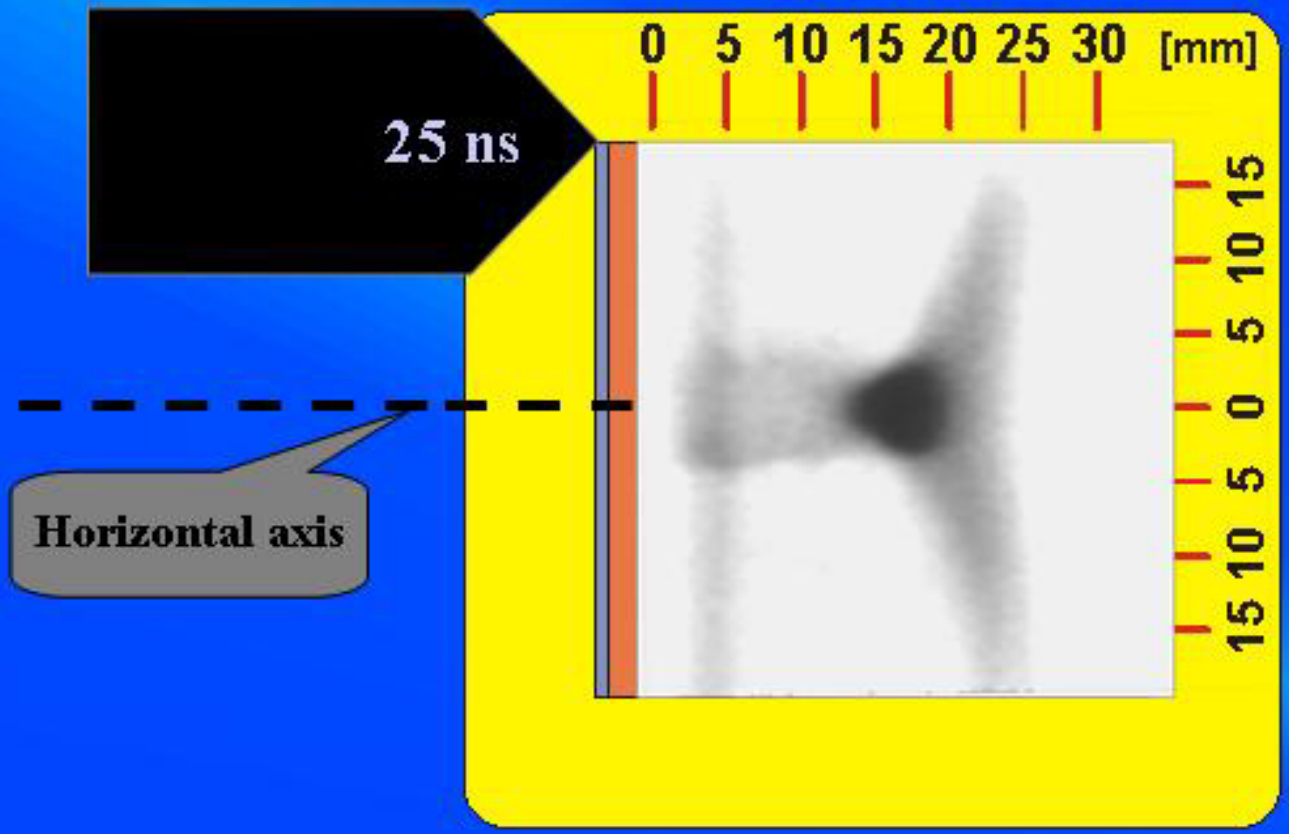
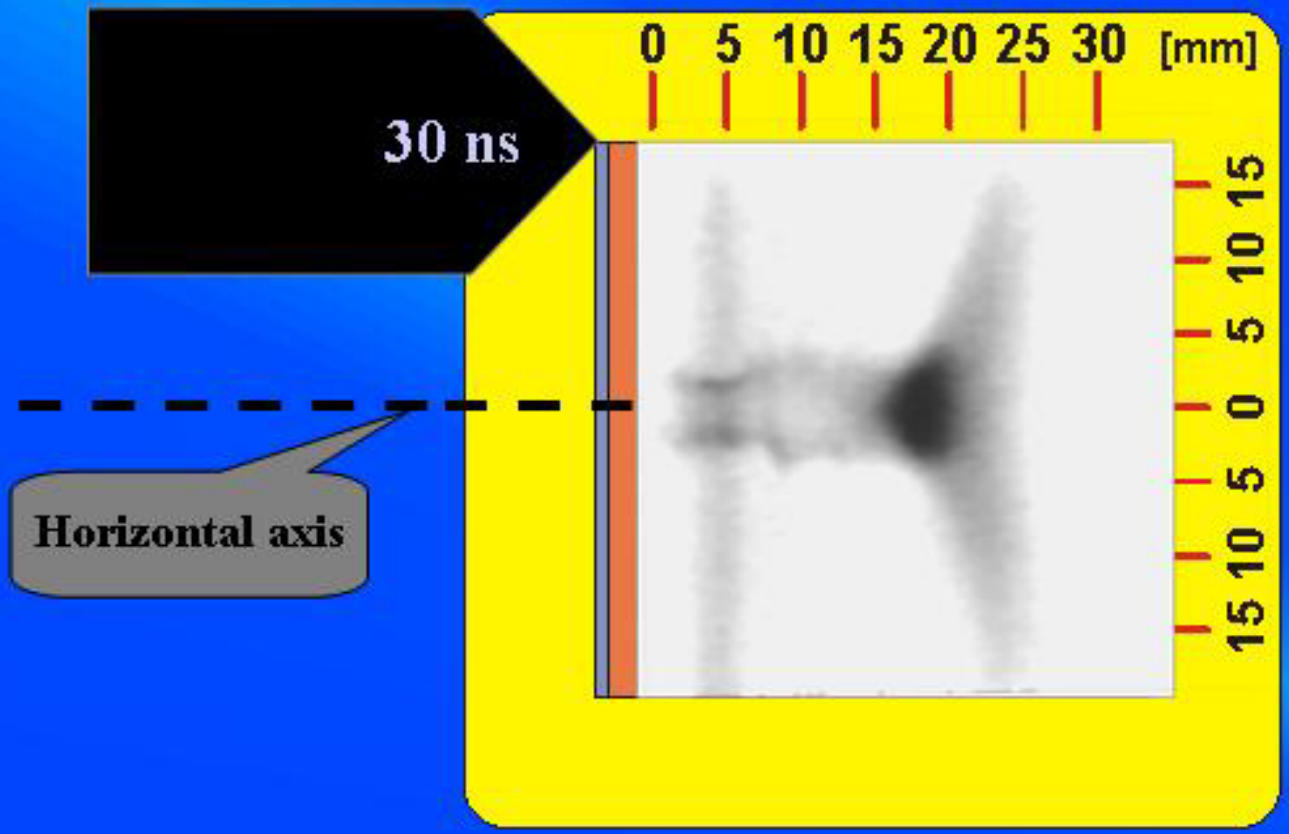
Subsequent Frames of Non-Cylindrically Collapsed Object



High-Speed Photography for Plasma Investigations

Subsequent Frames of Non-Cylindrically Collapsed Object



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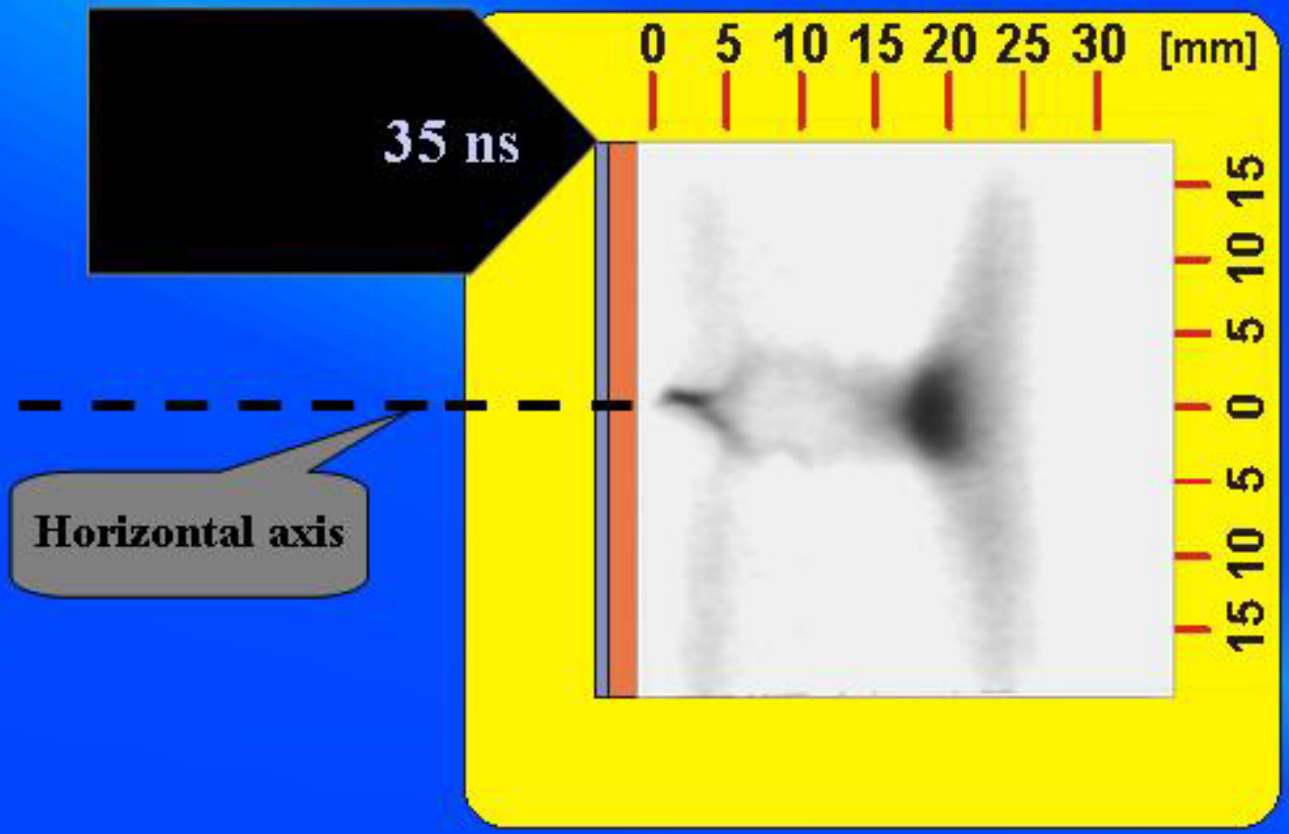
Subsequent Frames of Non-Cylindrically Collapsed Object



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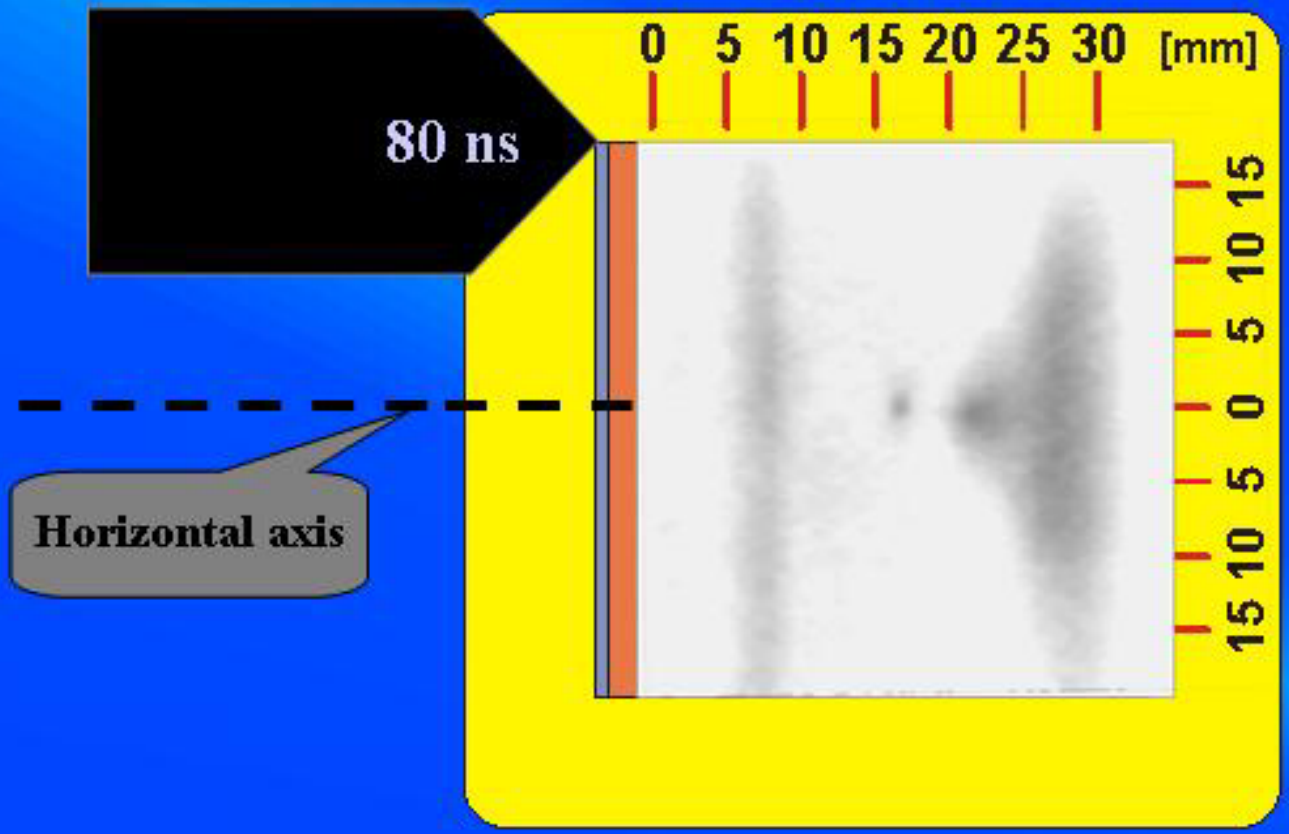
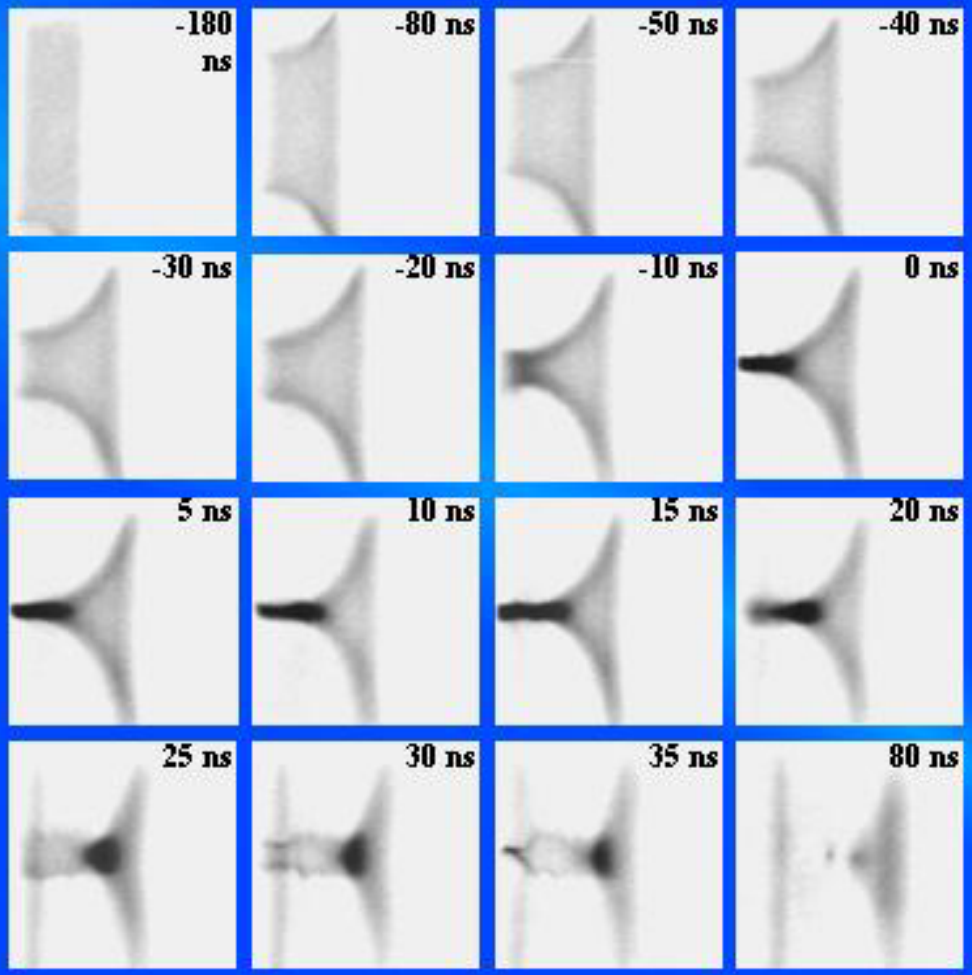
Subsequent Frames of Non-Cylindrically Collapsed Object



High-Speed Photography for Plasma Investigations

Subsequent Frames of Non-Cylindrically Collapsed Object



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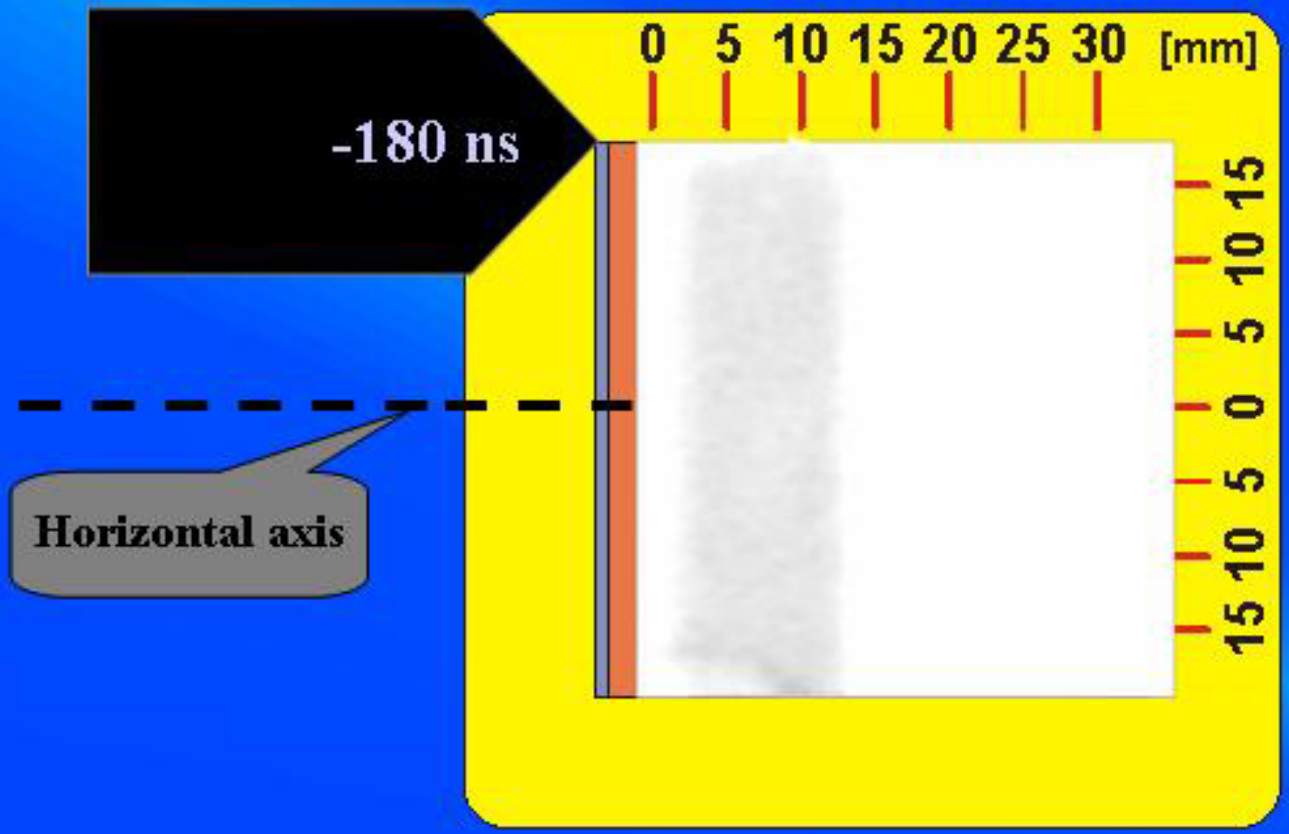
High-Speed Photography for Plasma Investigations

Subsequent Frames of Non-Cylindrically Collapsed Object



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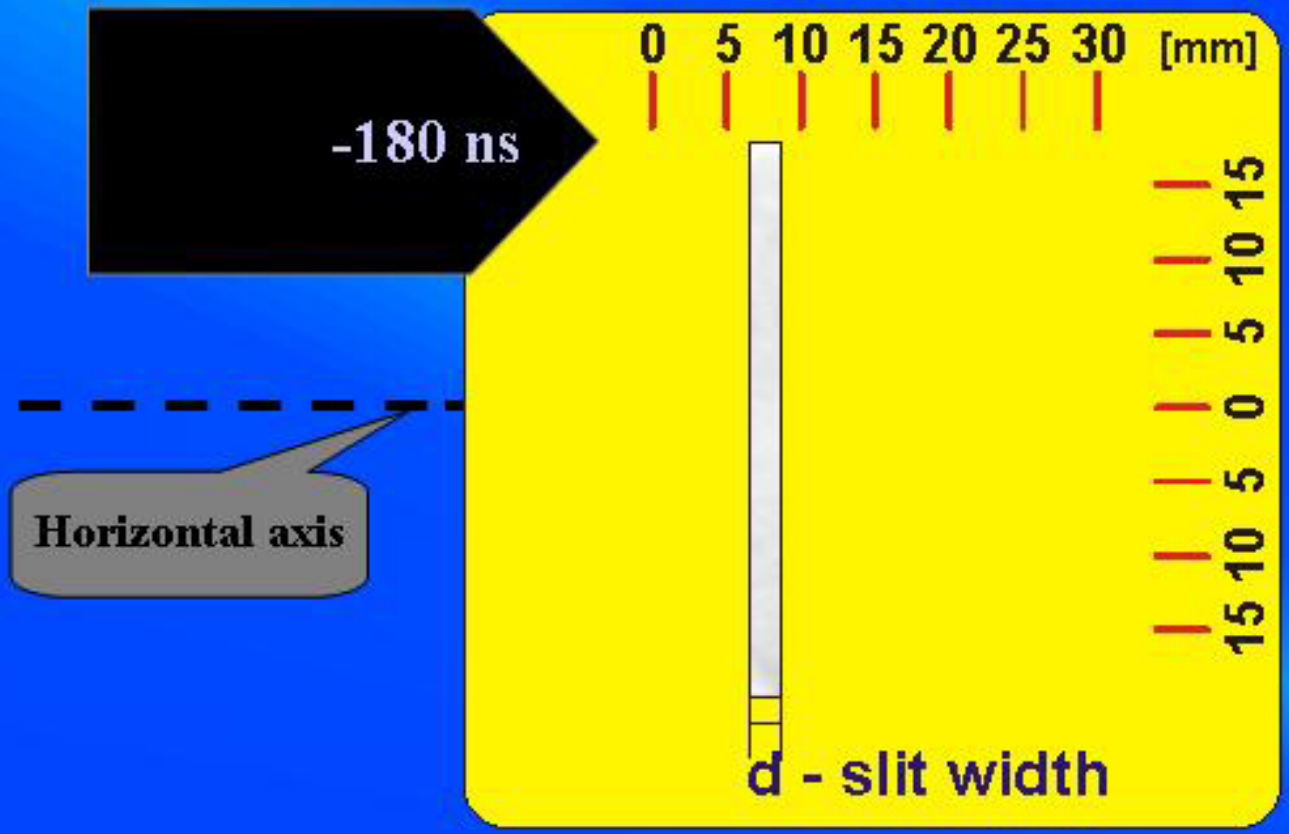
Subsequent Frames of Non-Cylindrically Collapsed Object



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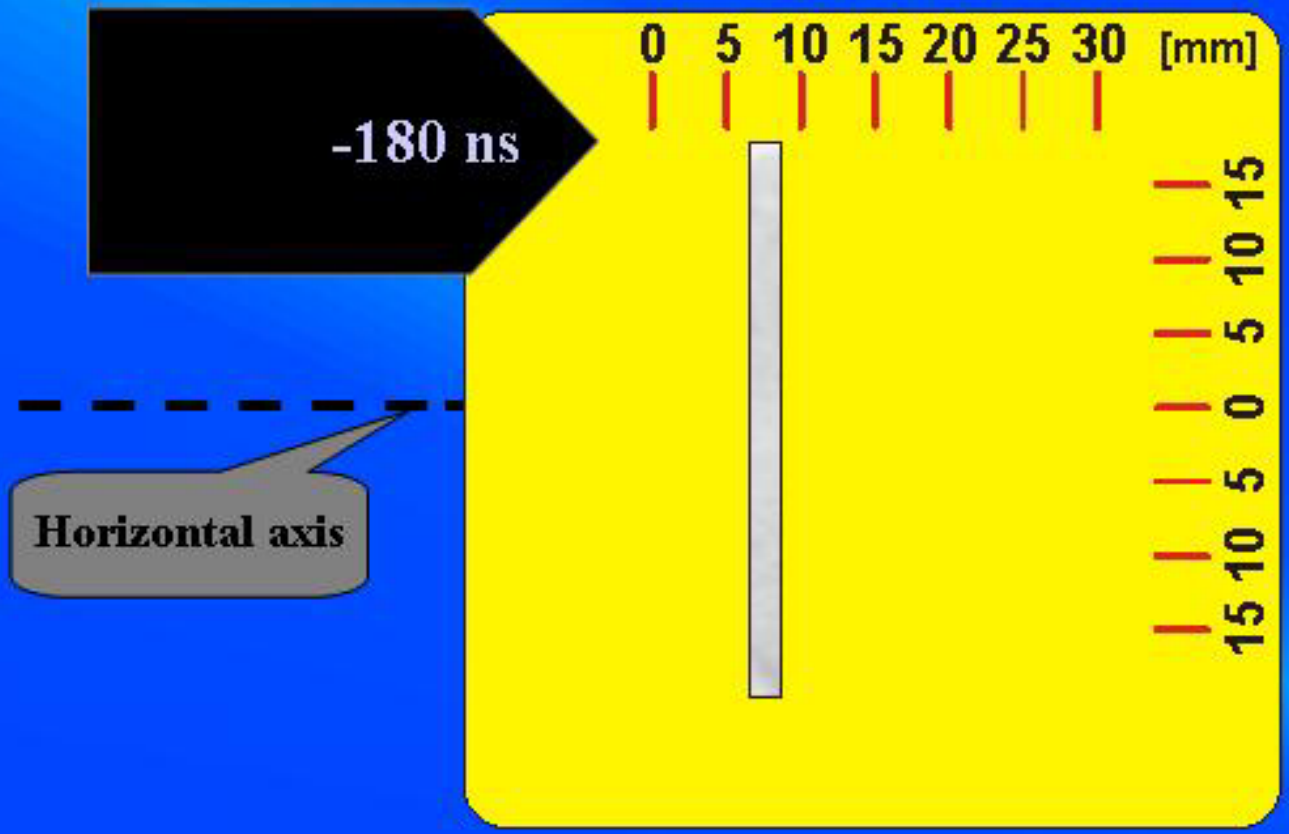
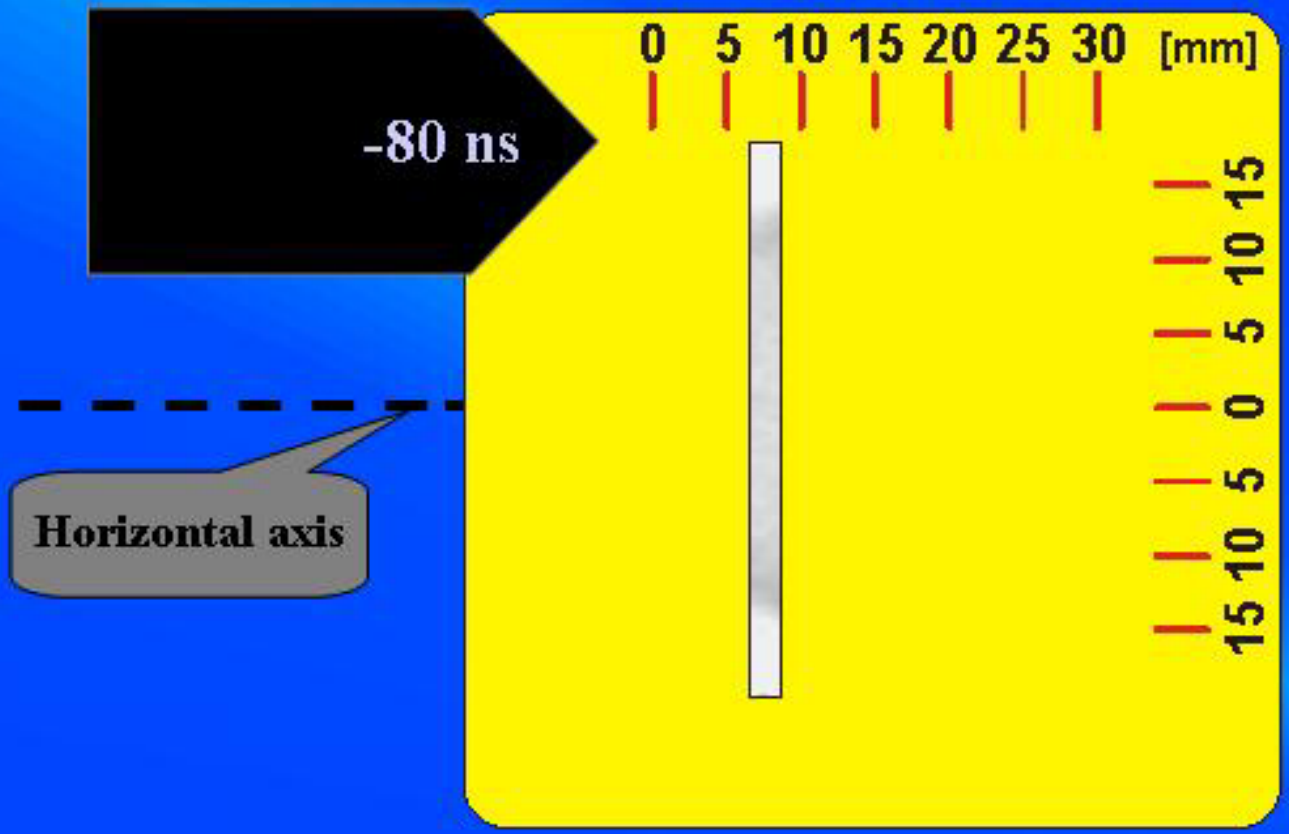
Subsequent Frames of Non-Cylindrically Collapsed Object



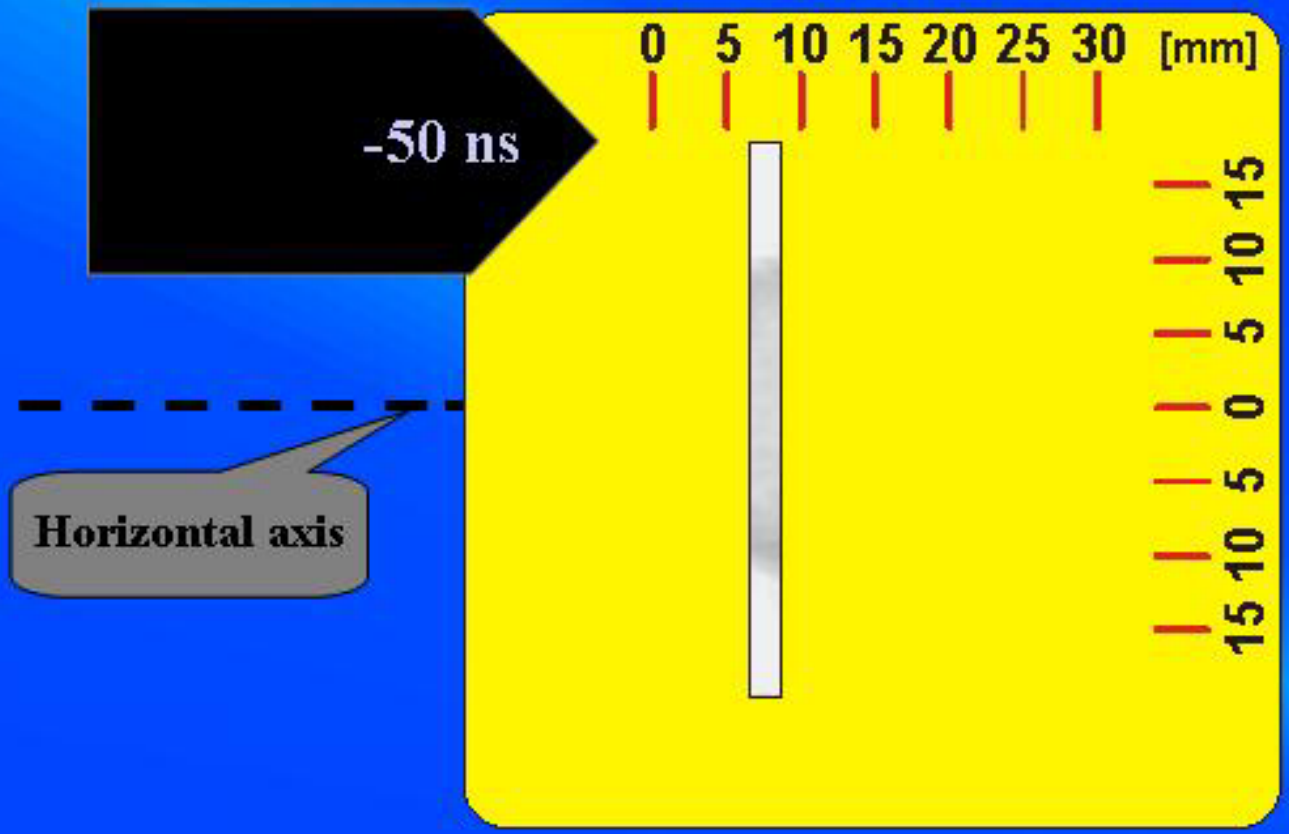
High-Speed Photography for Plasma Investigations

Subsequent Frames of Non-Cylindrically Collapsed Object



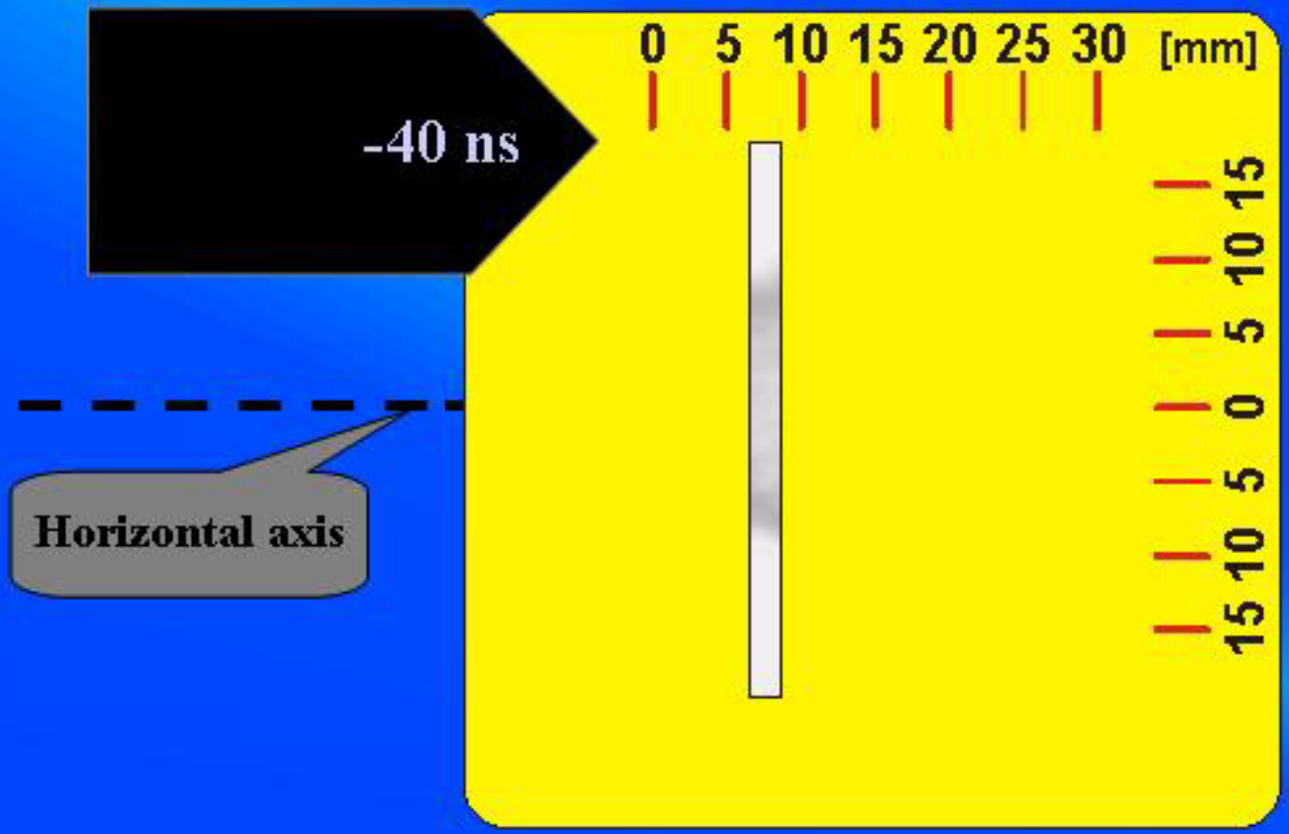
High-Speed Photography for Plasma Investigations

Subsequent Frames of Non-Cylindrically Collapsed Object



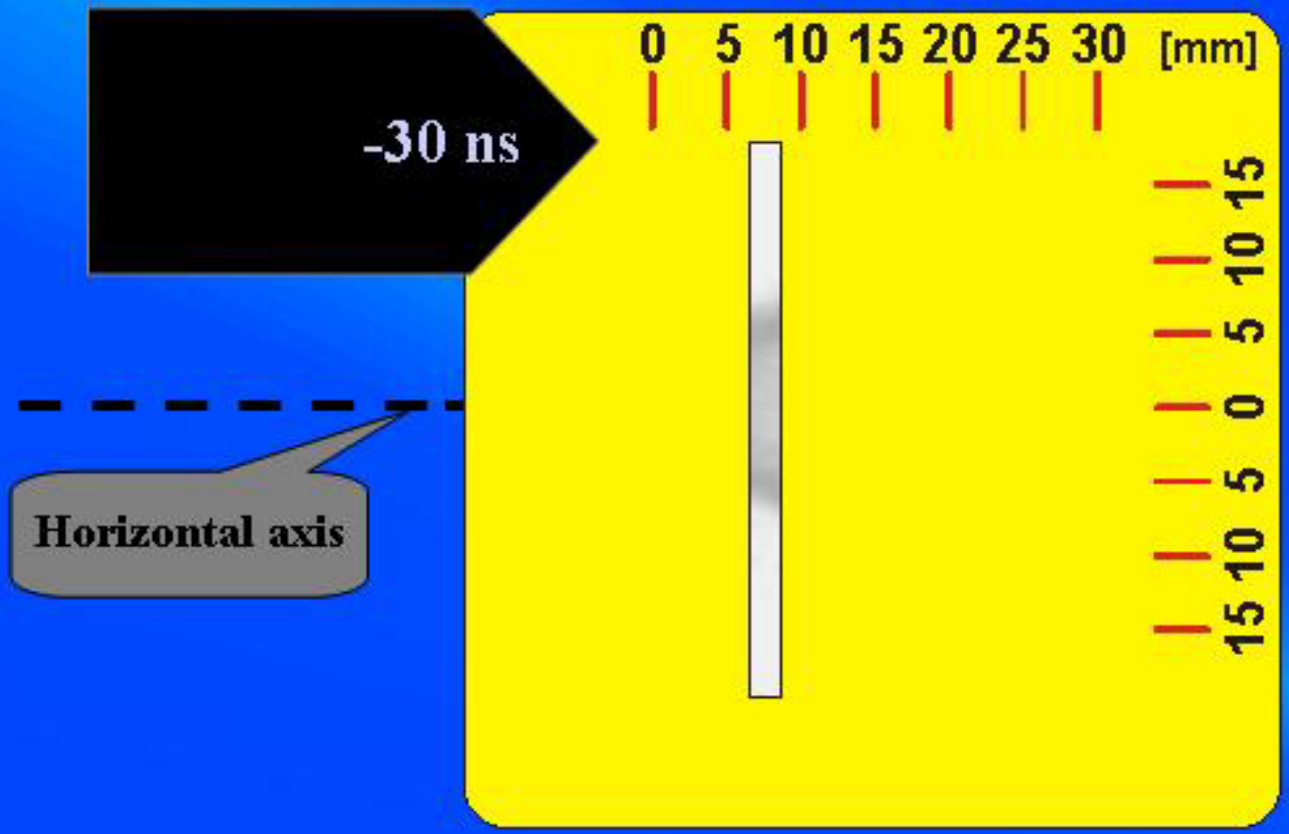
High-Speed Photography for Plasma Investigations

Subsequent Frames of Non-Cylindrically Collapsed Object



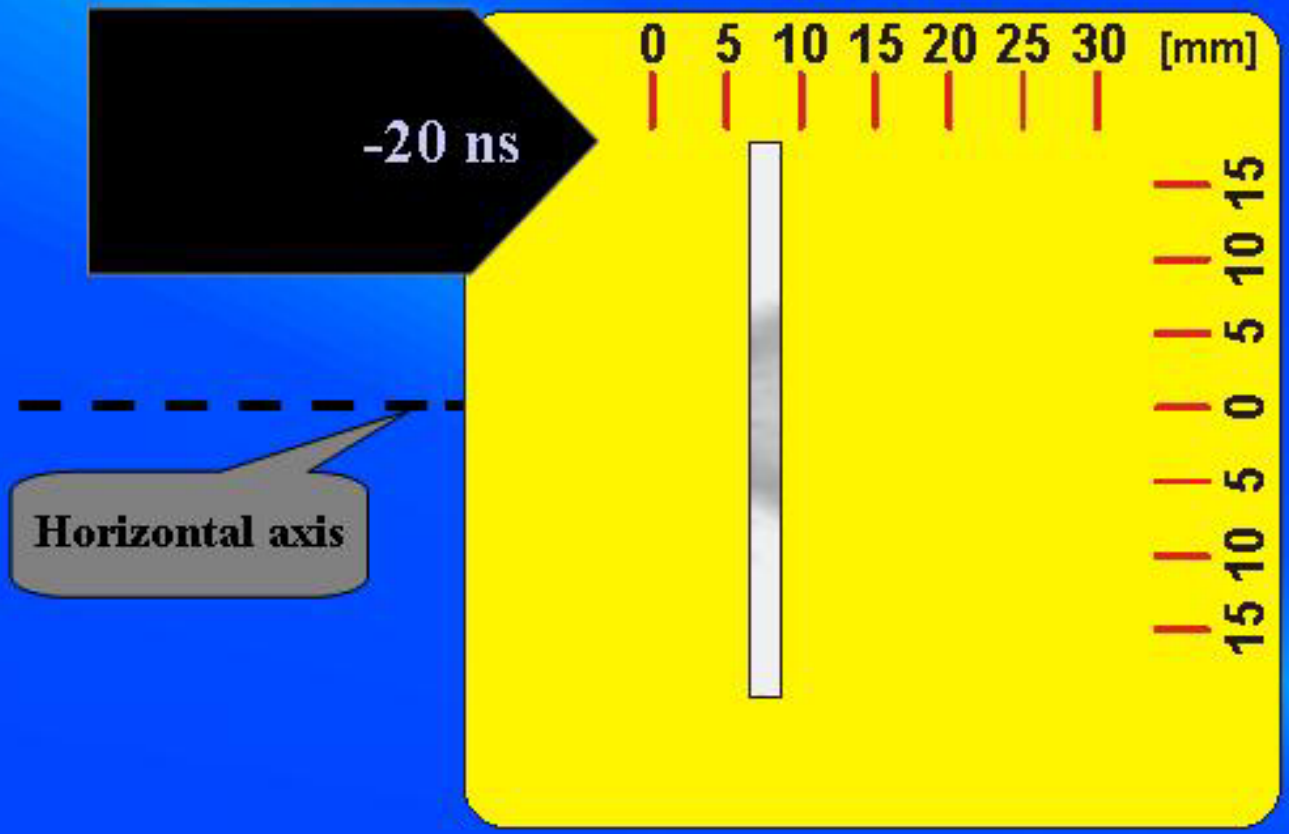
High-Speed Photography for Plasma Investigations

Subsequent Frames of Non-Cylindrically Collapsed Object



High-Speed Photography for Plasma Investigations

Subsequent Frames of Non-Cylindrically Collapsed Object



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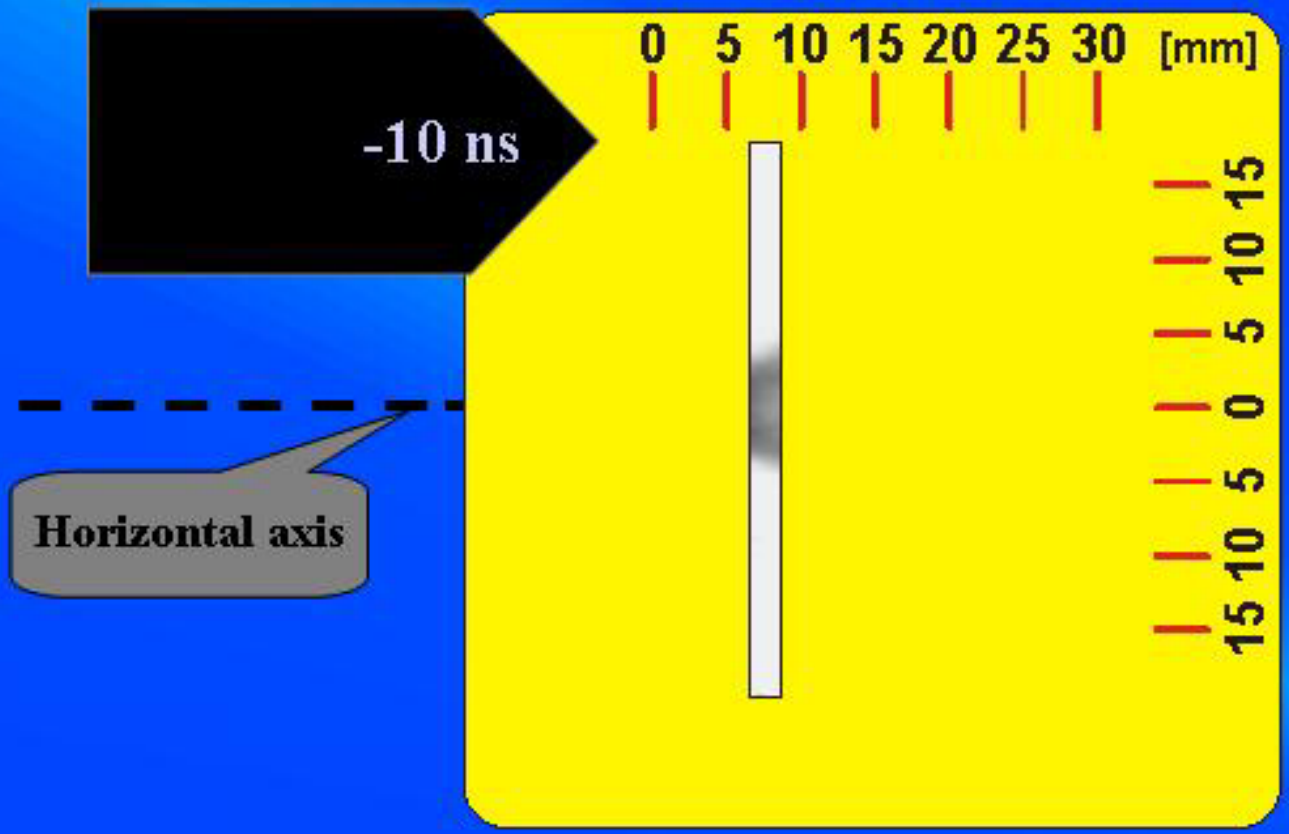
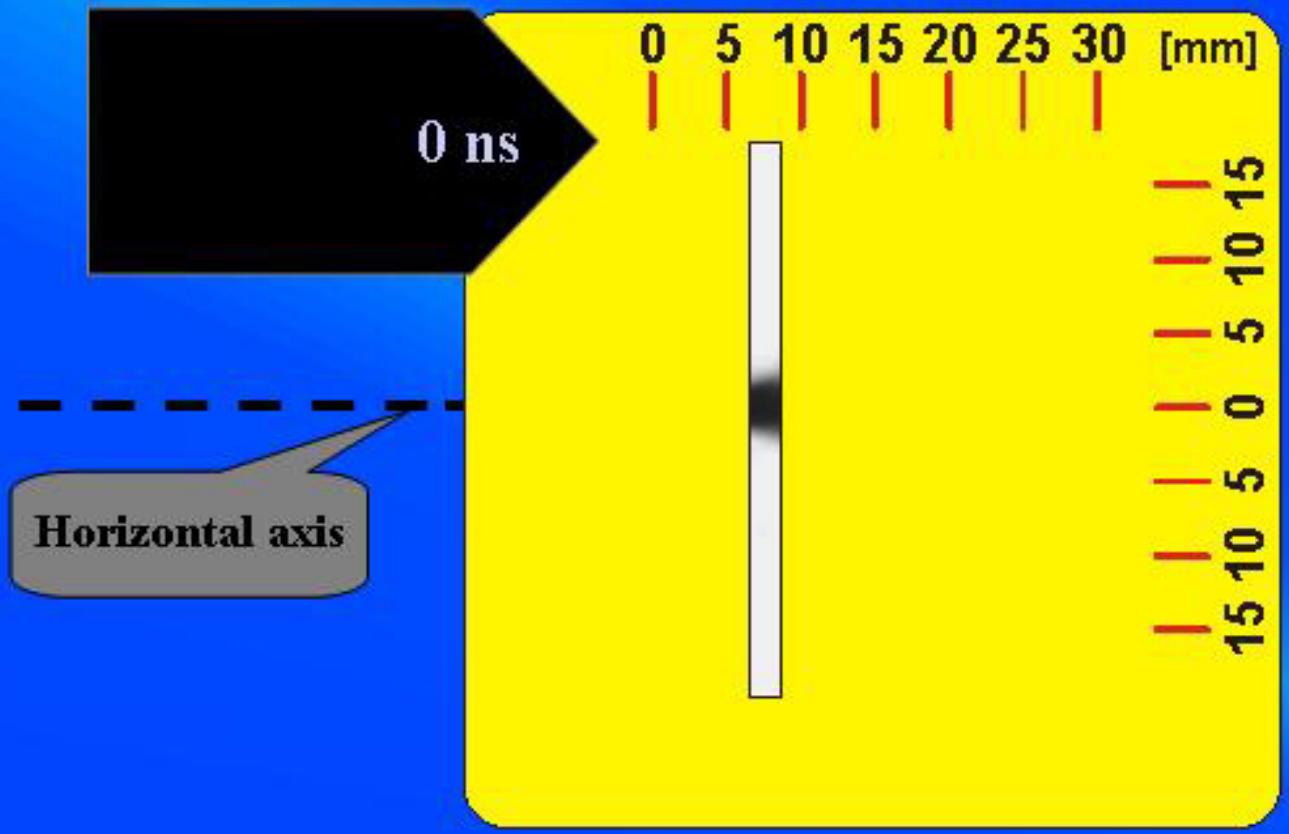
Subsequent Frames of Non-Cylindrically Collapsed Object



High-Speed Photography for Plasma Investigations

Subsequent Frames of Non-Cylindrically Collapsed Object



High-Speed Photography for Plasma Investigations

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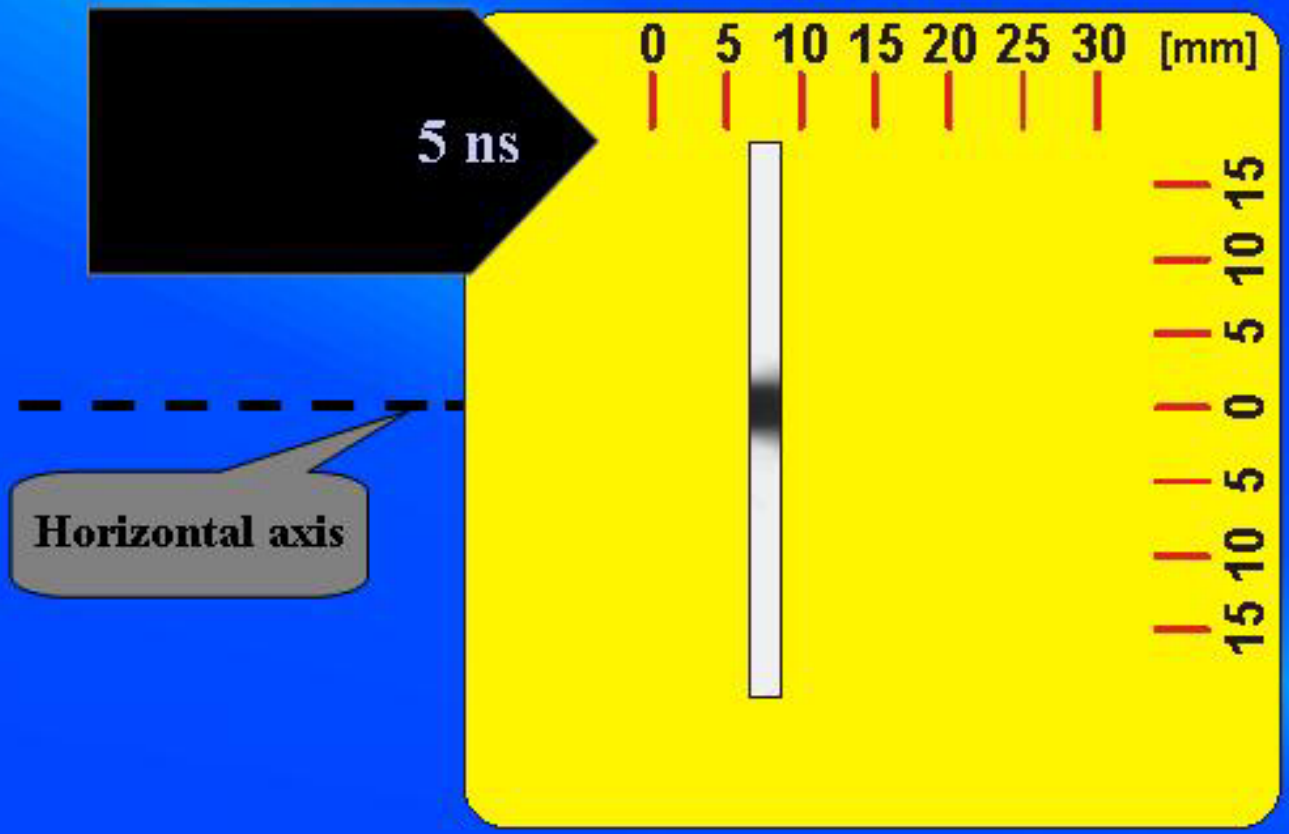
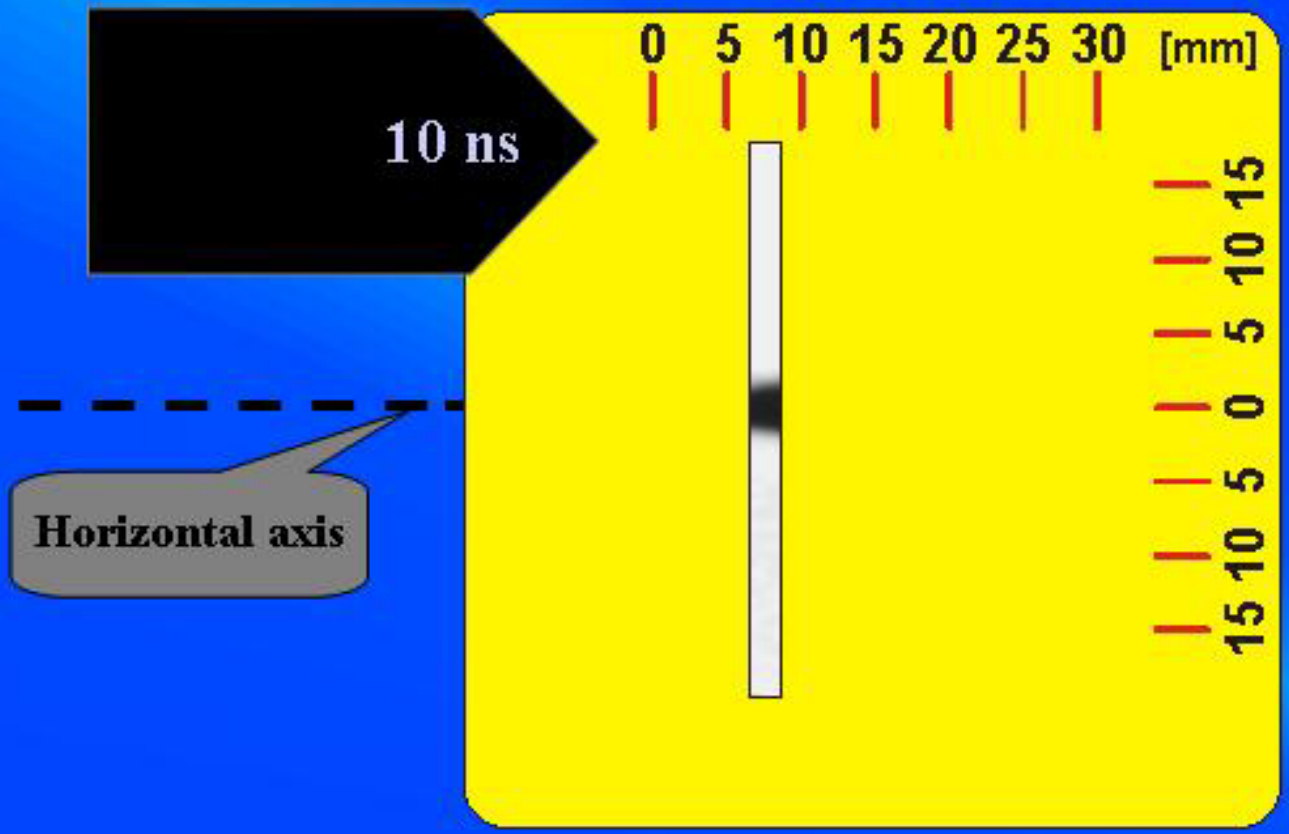


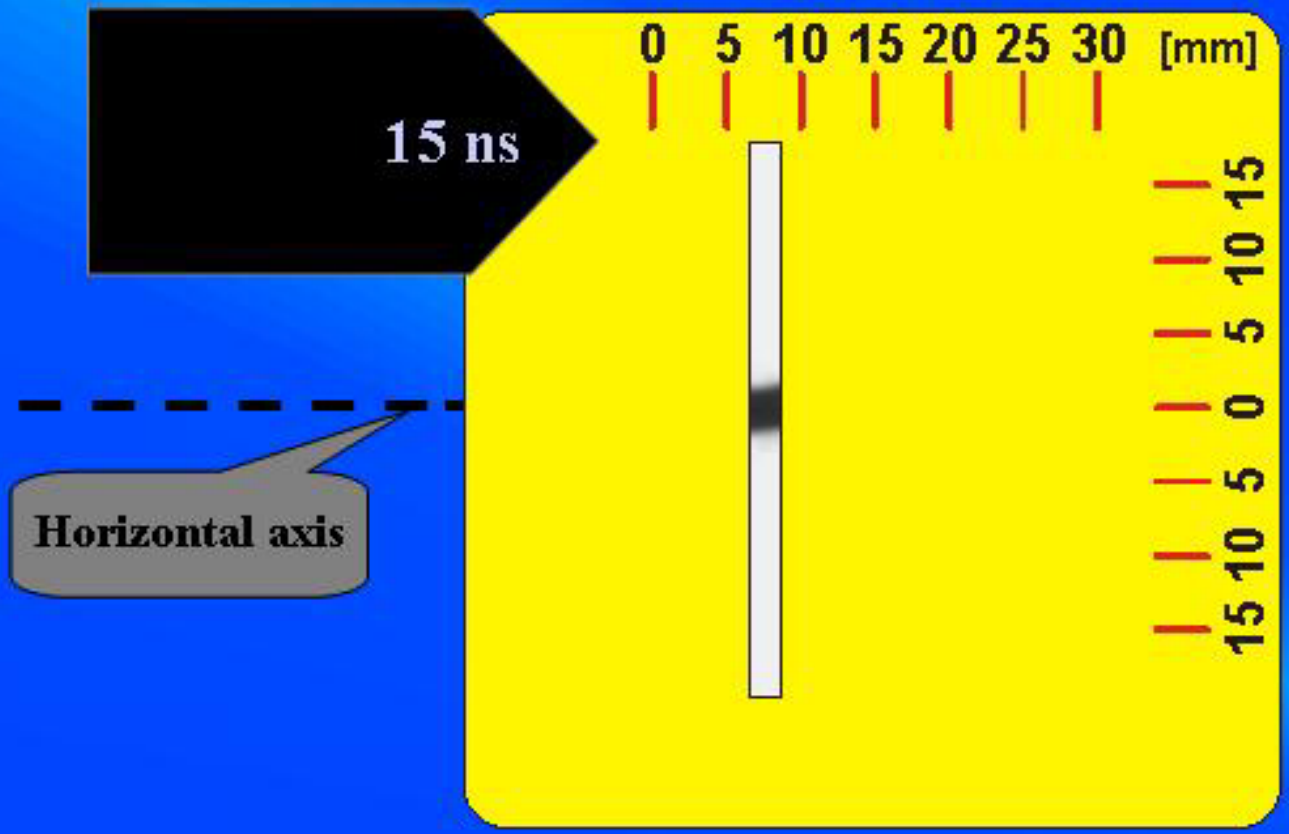
High-Speed Photography for Plasma Investigations

Subsequent Frames of Non-Cylindrically Collapsed Object



High-Speed Photography for Plasma Investigations

Subsequent Frames of Non-Cylindrically Collapsed Object



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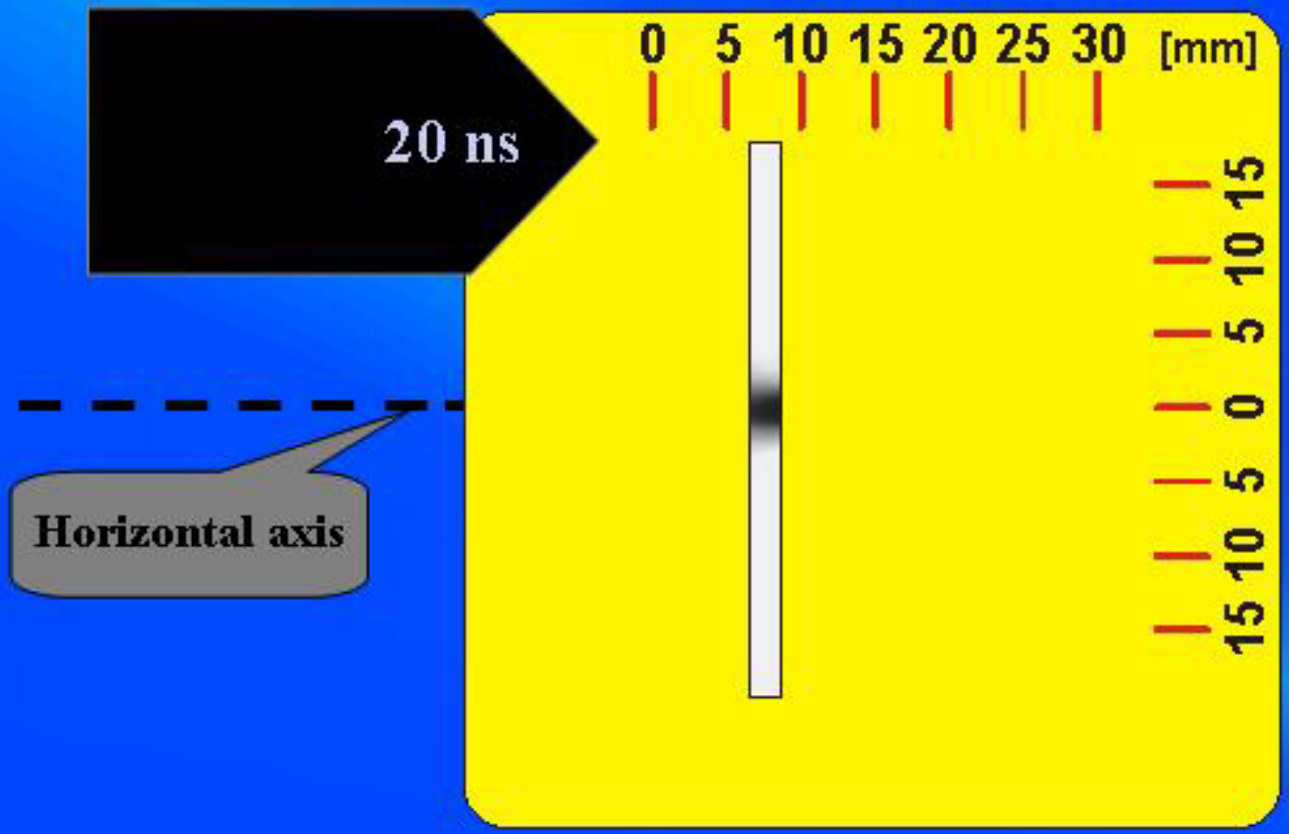
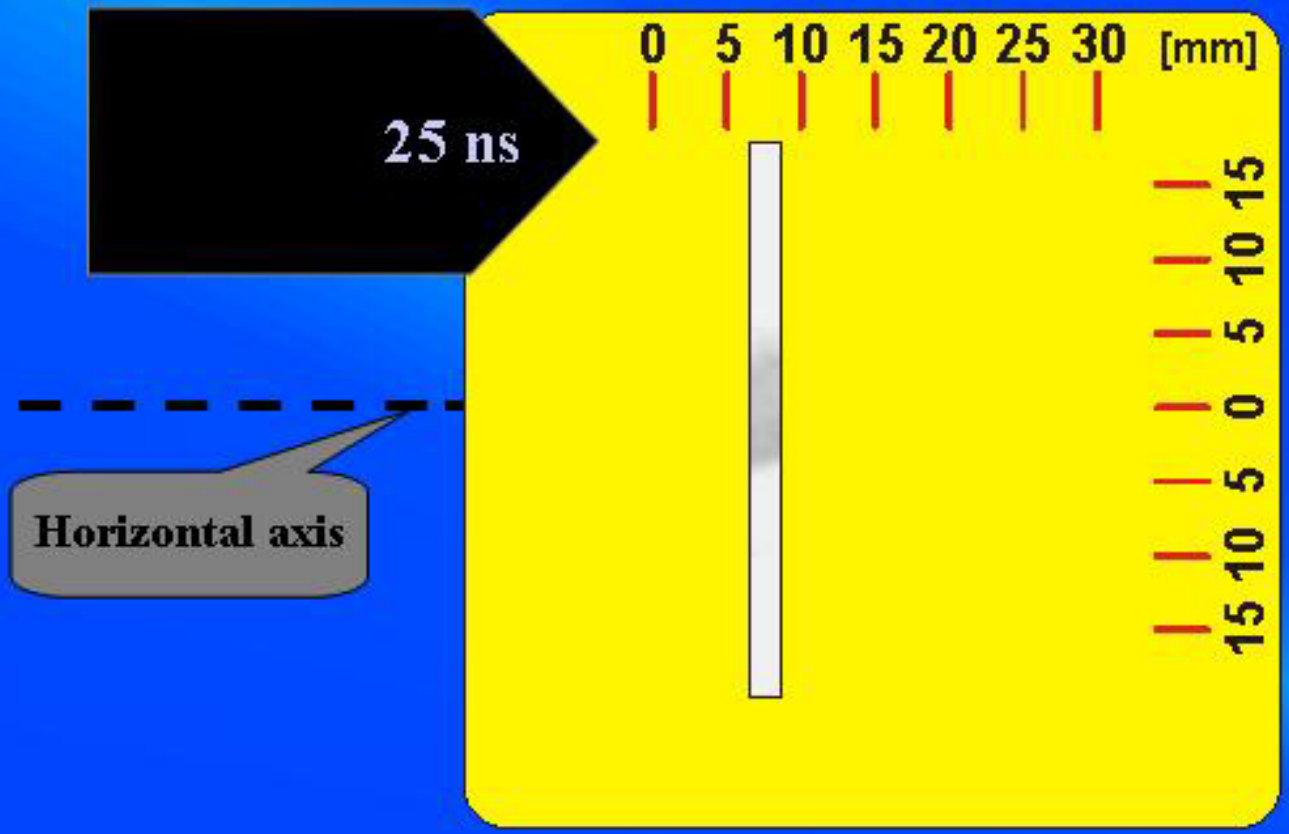
Subsequent Frames of Non-Cylindrically Collapsed Object



High-Speed Photography for Plasma Investigations

Subsequent Frames of Non-Cylindrically Collapsed Object



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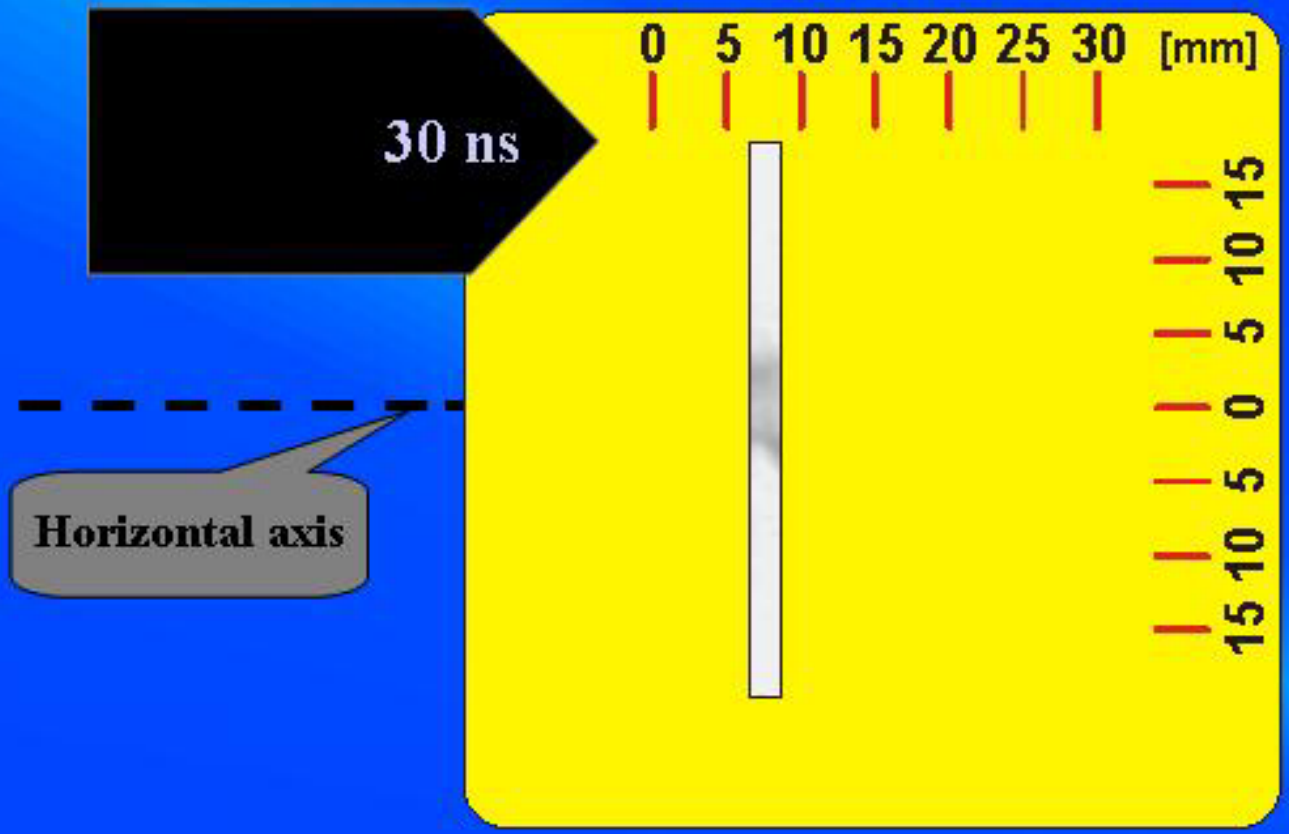
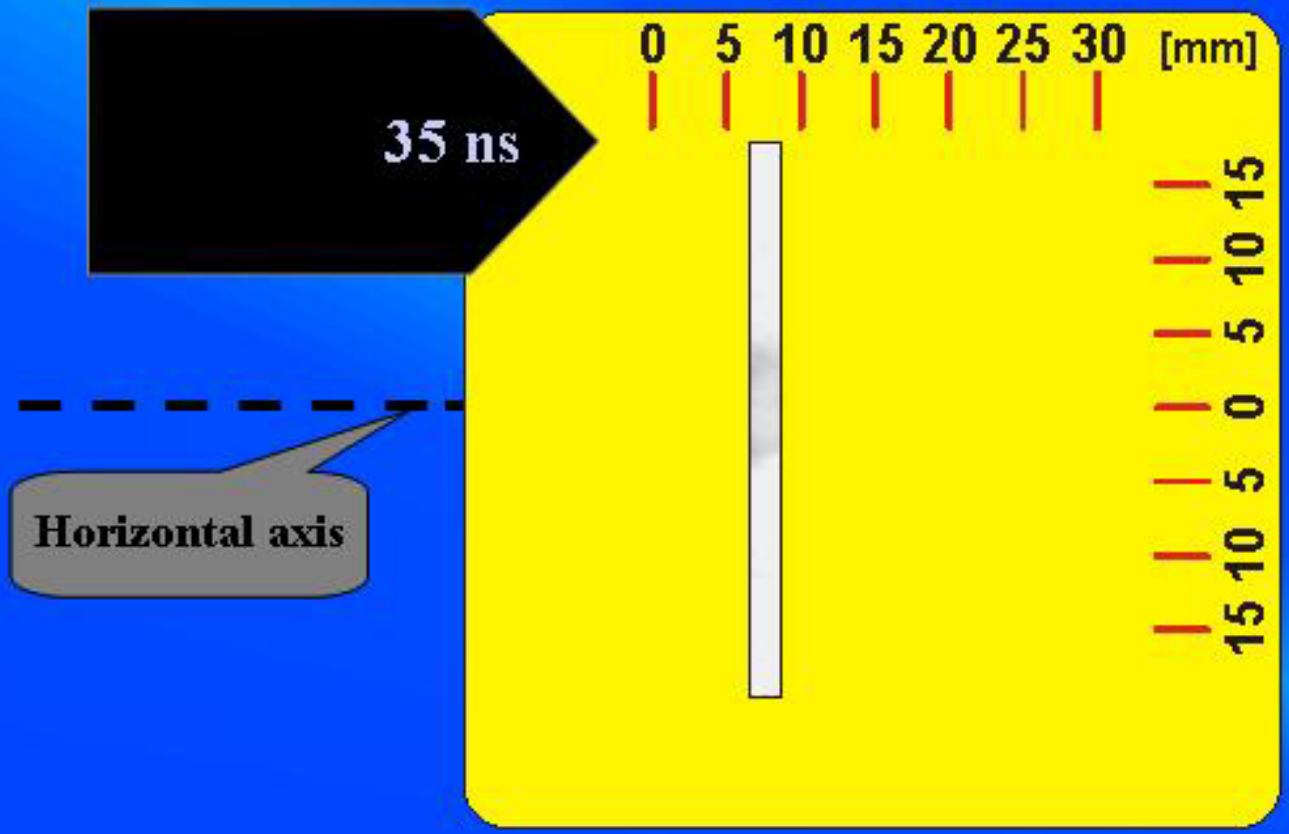


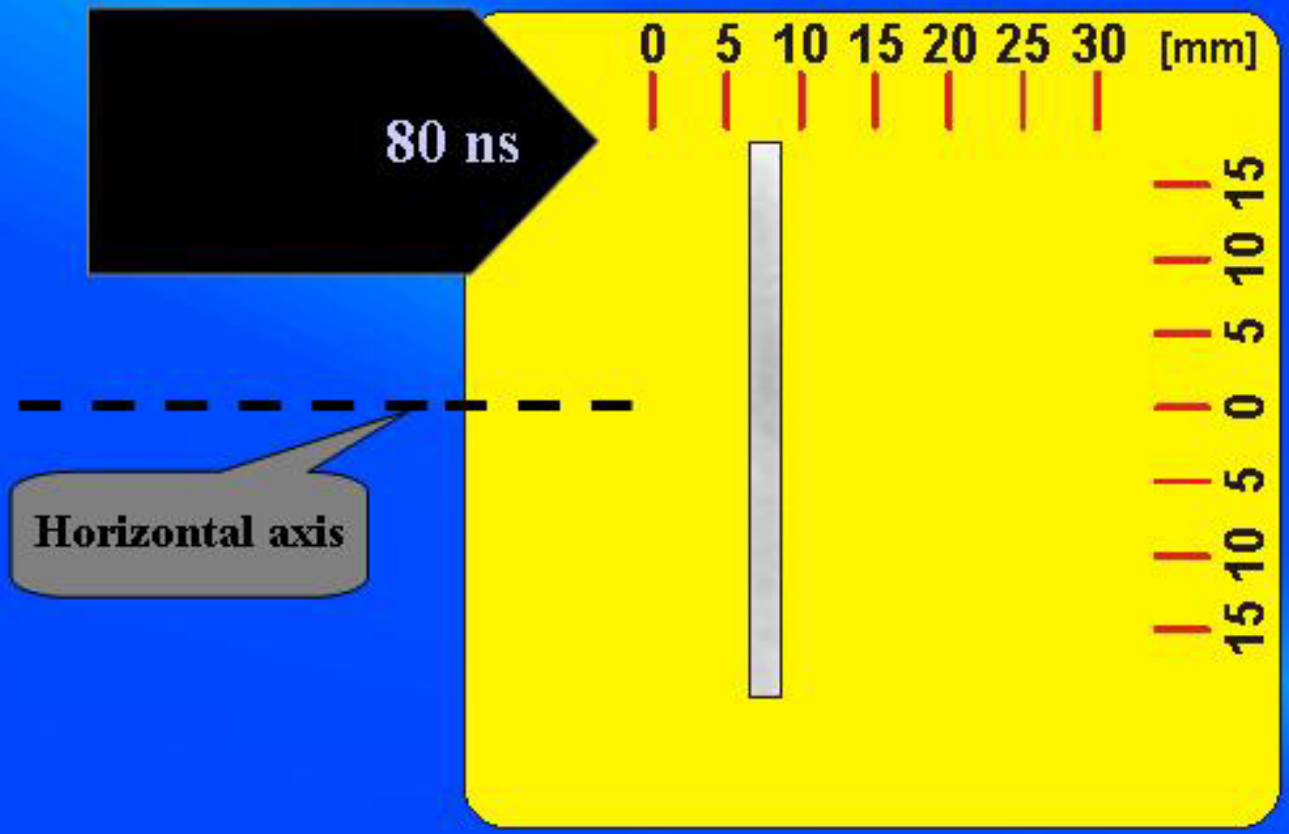
High-Speed Photography for Plasma Investigations

Subsequent Frames of Non-Cylindrically Collapsed Object



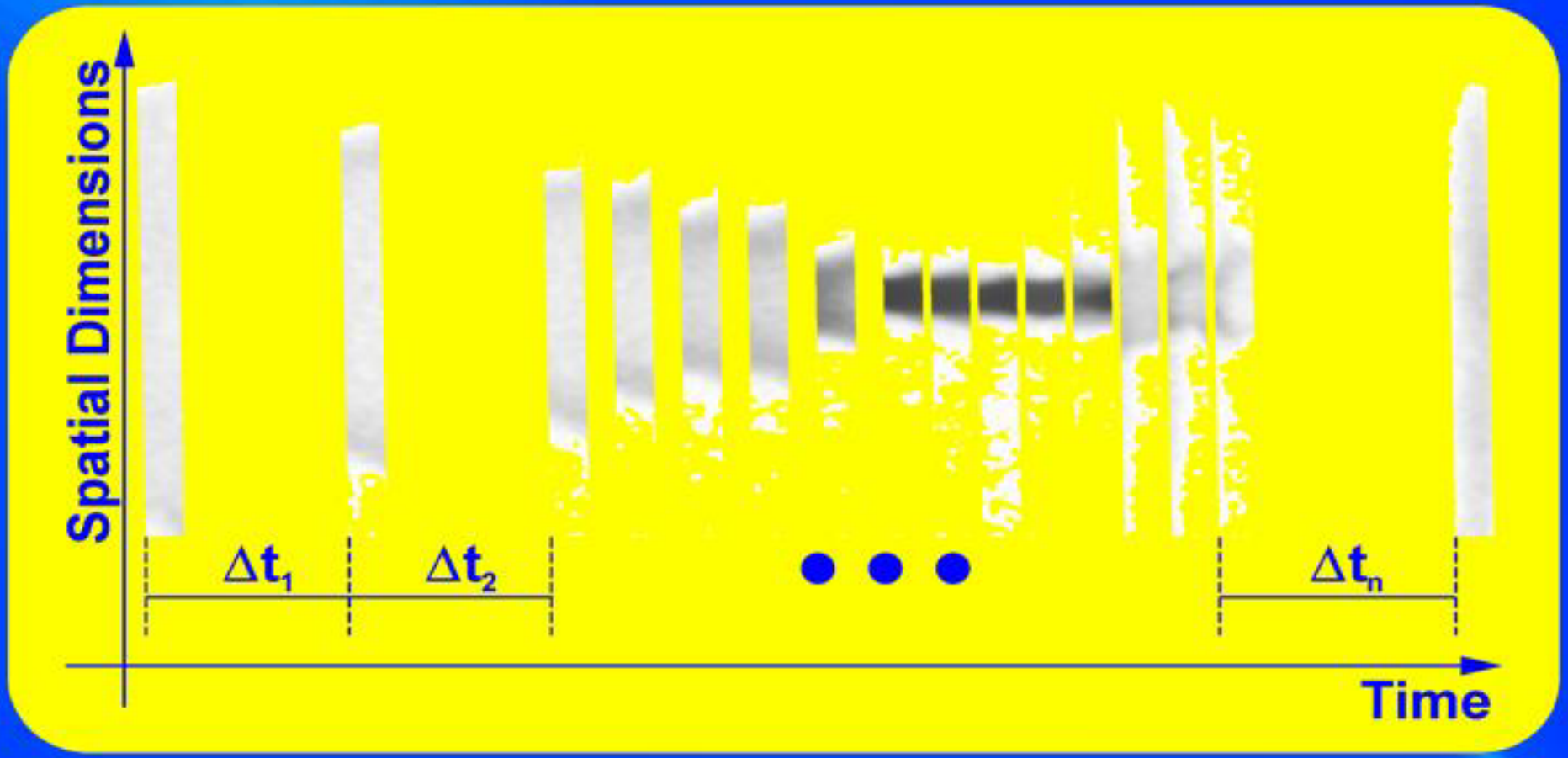
High-Speed Photography for Plasma Investigations

Subsequent Frames of Non-Cylindrically Collapsed Object



High-Speed Photography for Plasma Investigations

Subsequent Frames of Non-Cylindrically Collapsed Object



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High-Speed Photography for Plasma Investigations

Subsequent Frames of Non-Cylindrically Collapsed Object

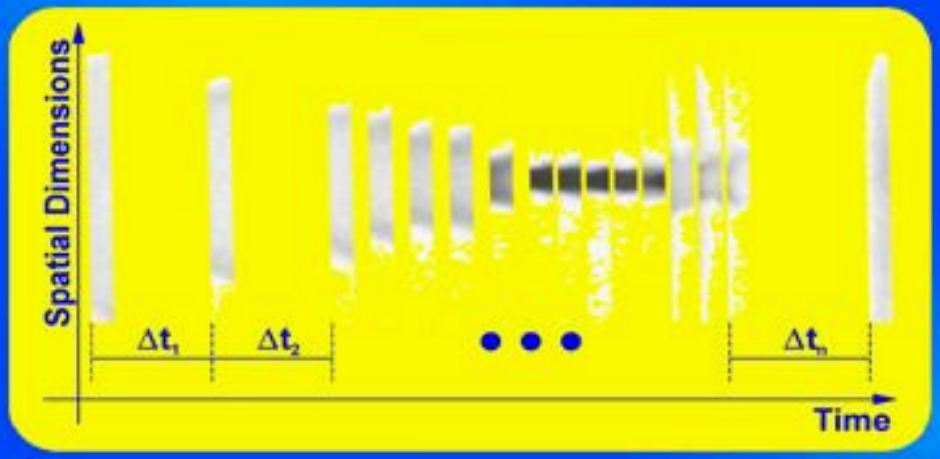
If

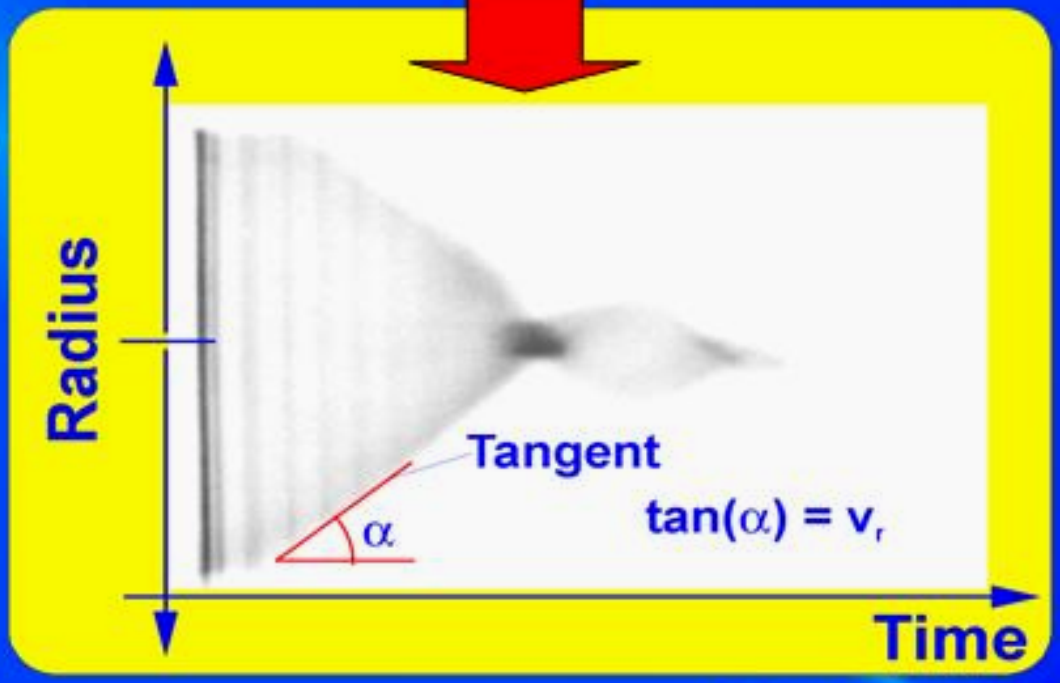
Slit width will be narrowed,

$(\delta t_1, \delta t_2, \delta t_3 \ldots\ldots \delta t_n) \downarrow 0$

and frame number (n) $\uparrow \infty$

then:





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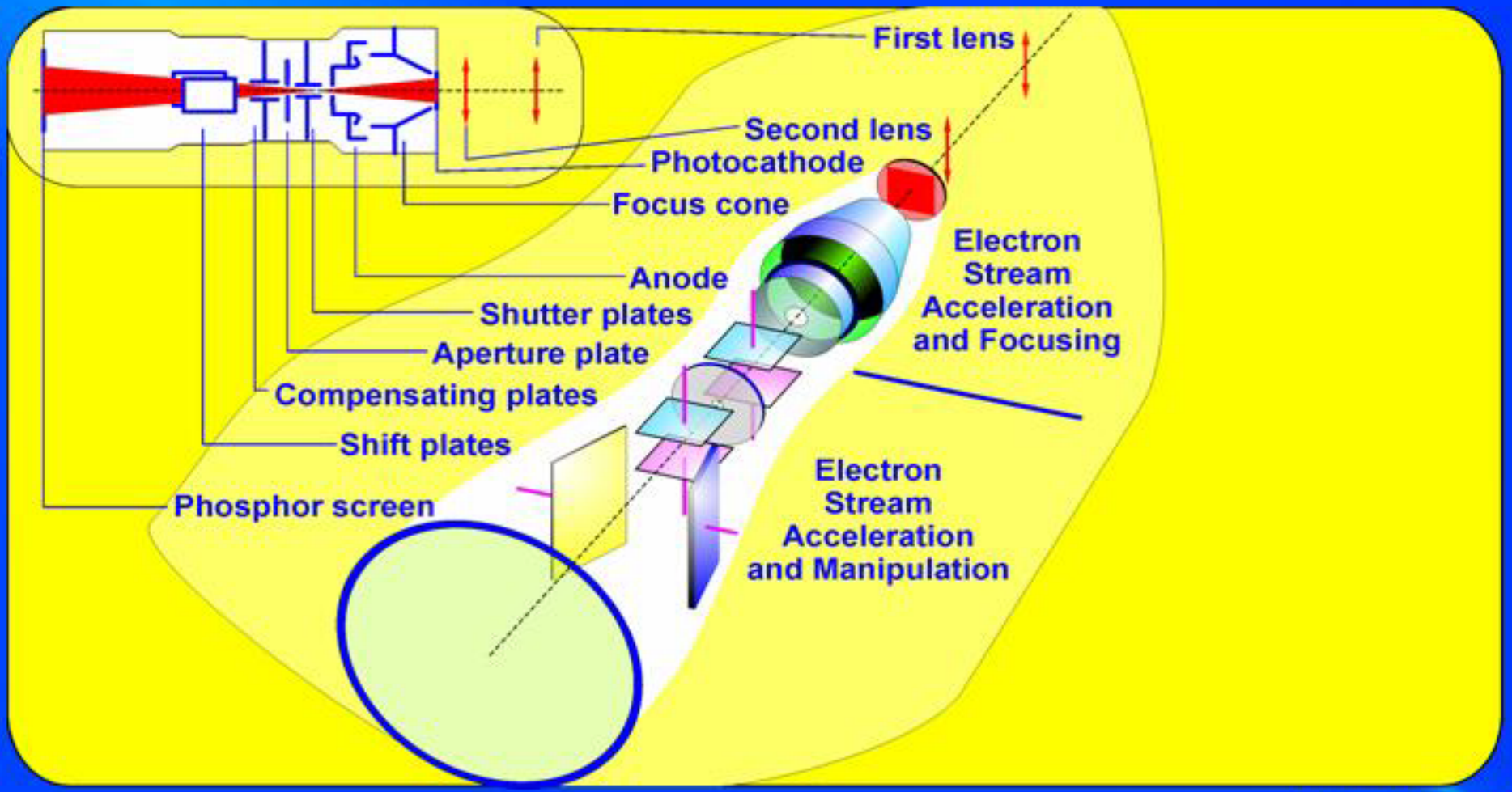
High-Speed Photography for Plasma Investigations

Streak Camera
-Design and Principle of Operation

Diagnostic Team
IPP&LM, Warsaw, Poland

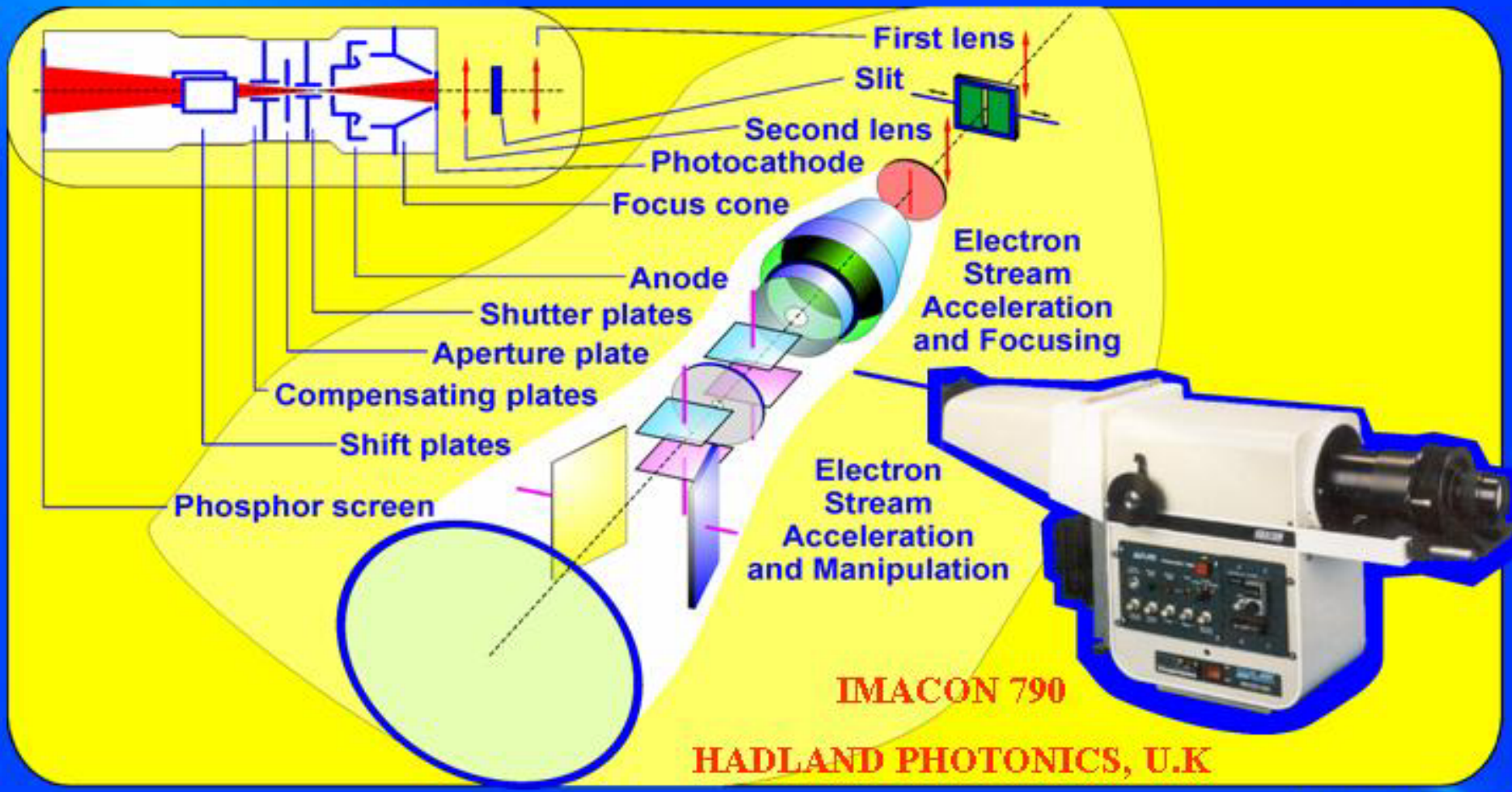
High-Speed Photography for Plasma Investigations

Streak Camera – Design and Principle of Operation



High-Speed Photography for Plasma Investigations

Streak Camera – Design and Principle of Operation



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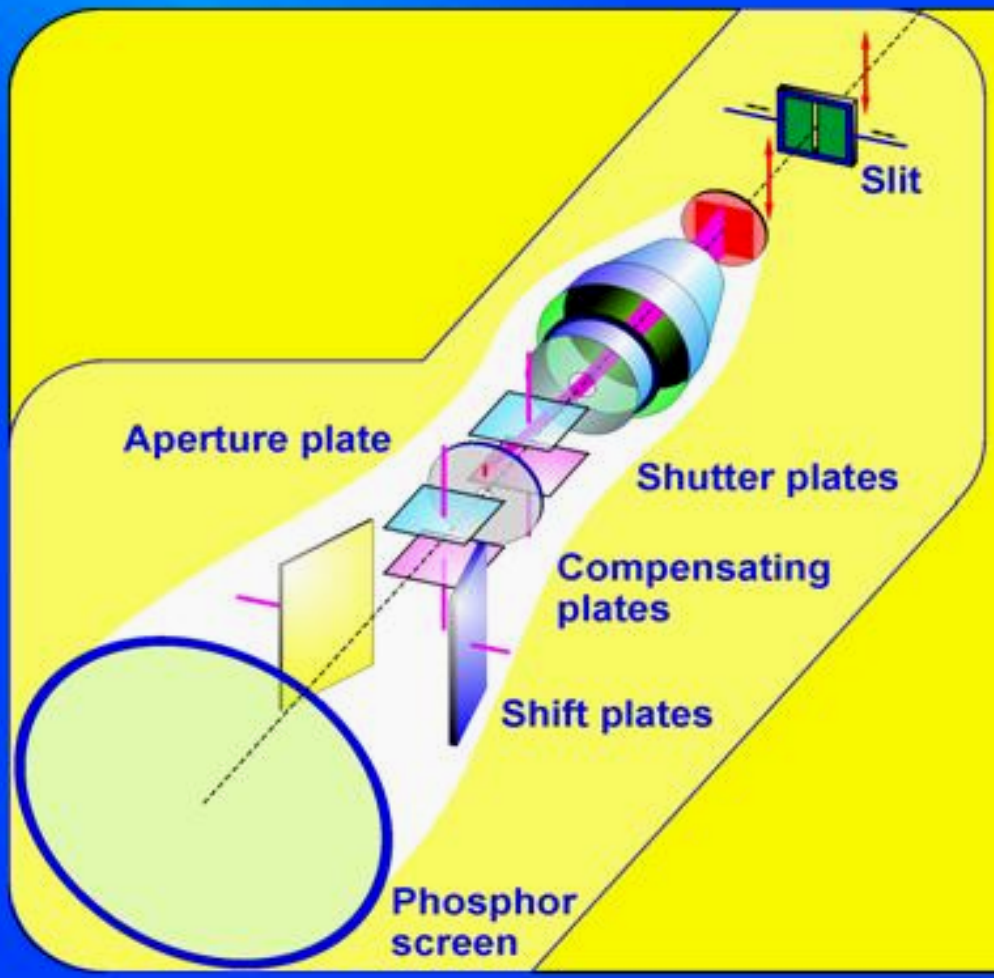
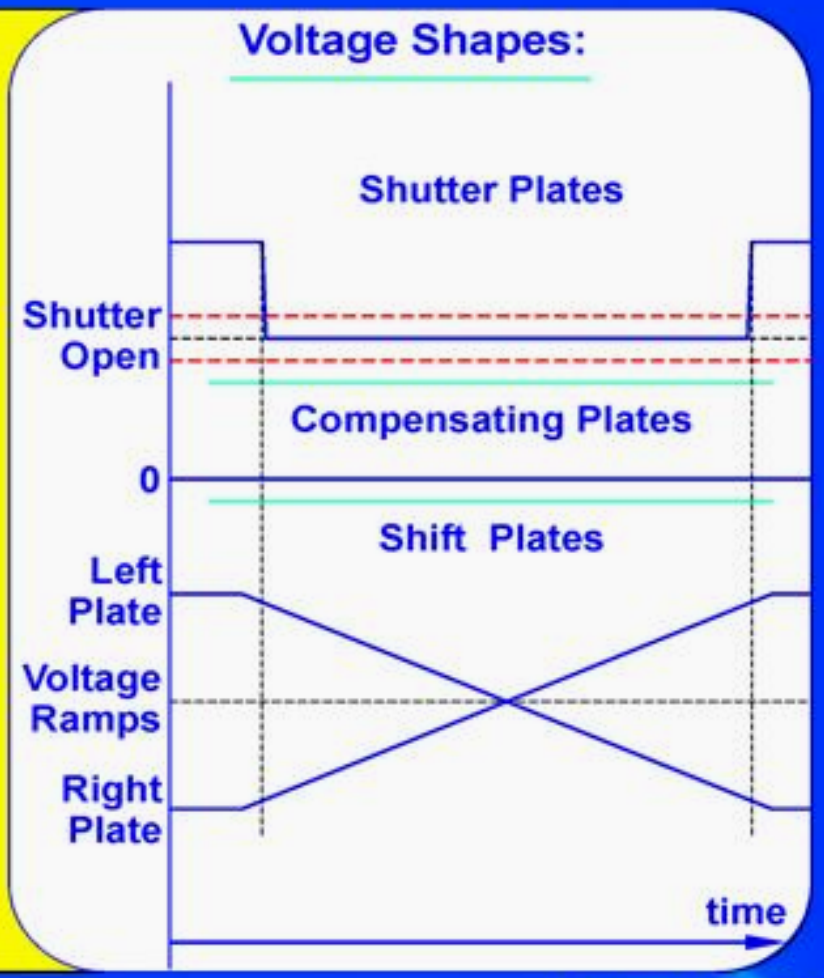
Streak Camera – Design and Principle of Operation





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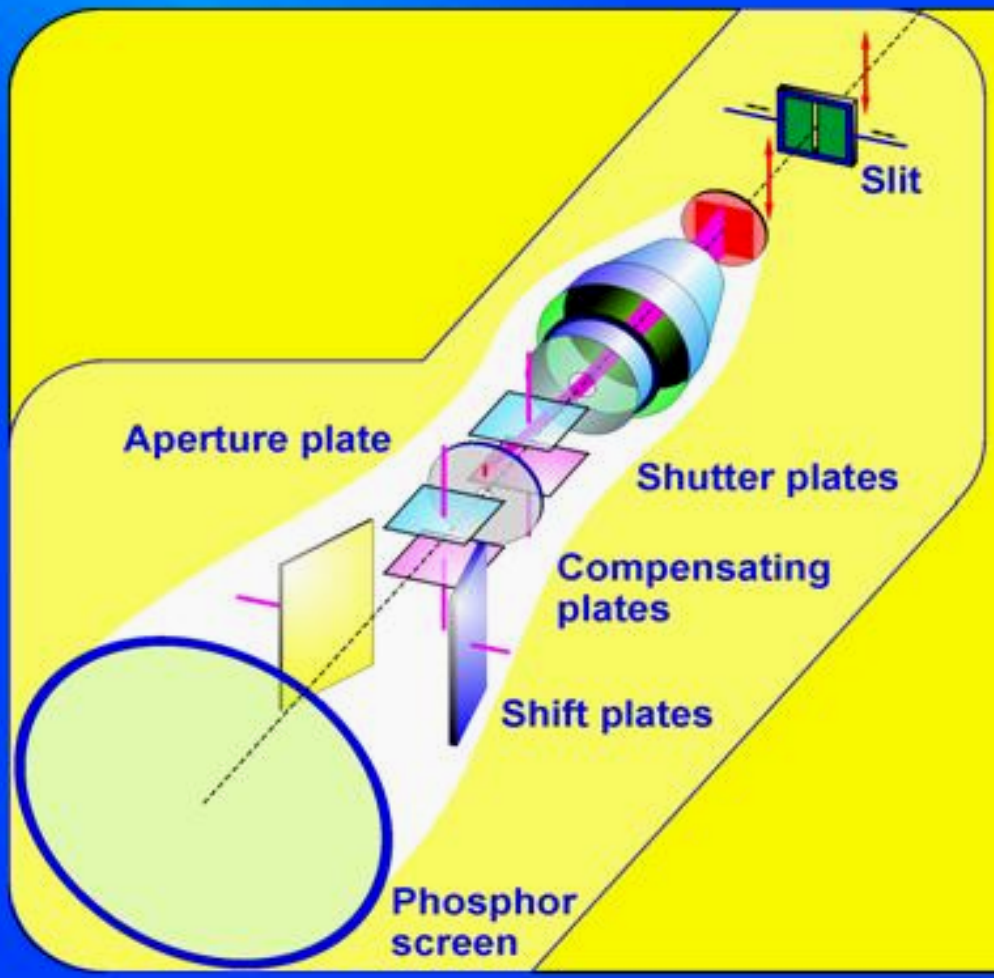
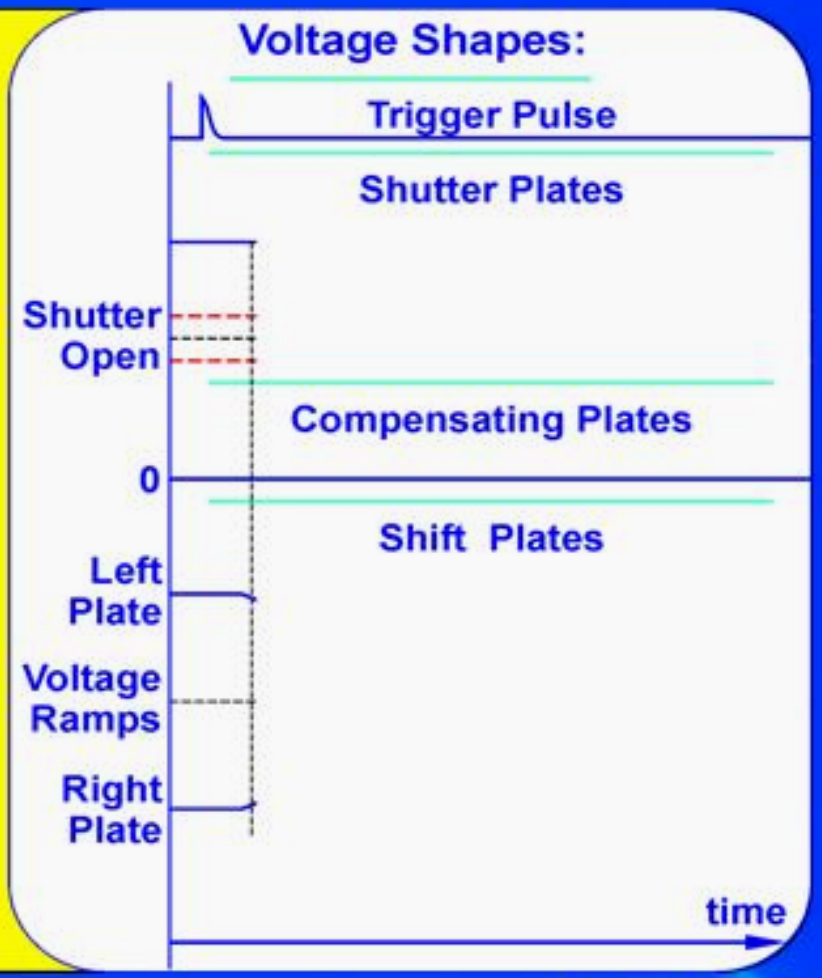
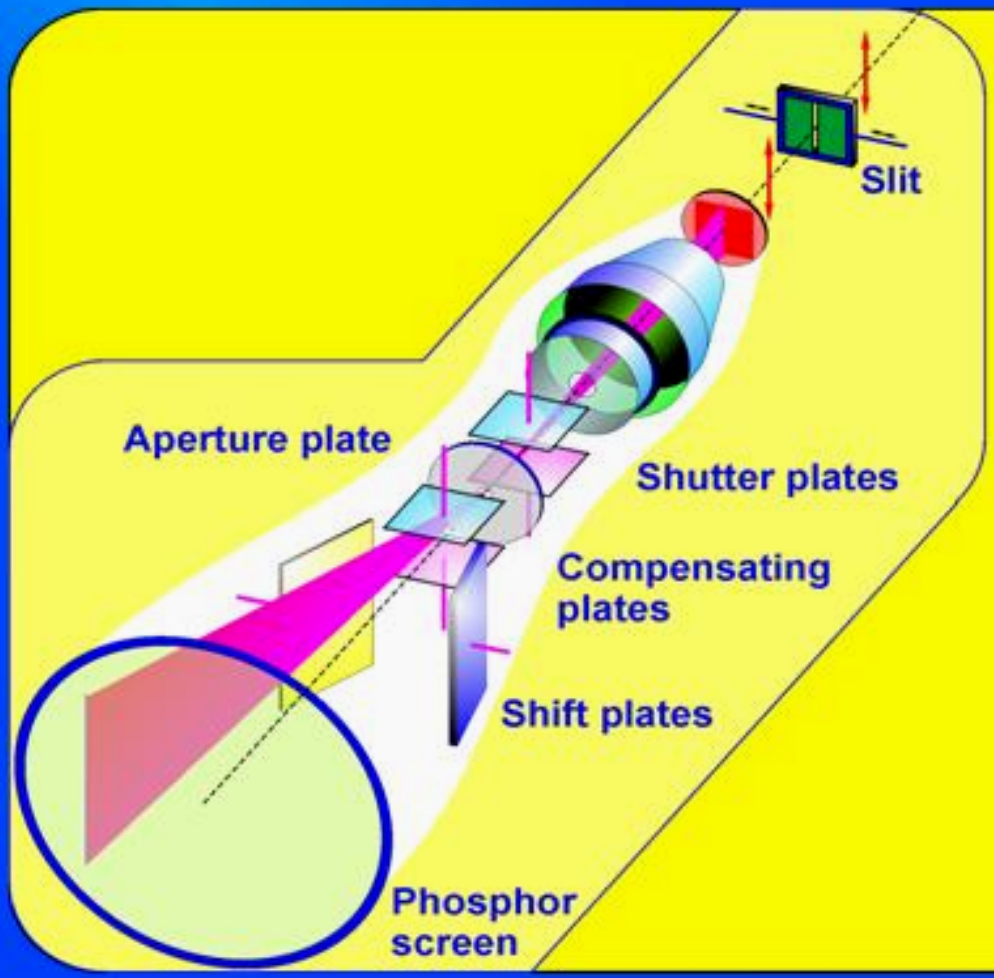
Streak Camera – Design and Principle of Operation

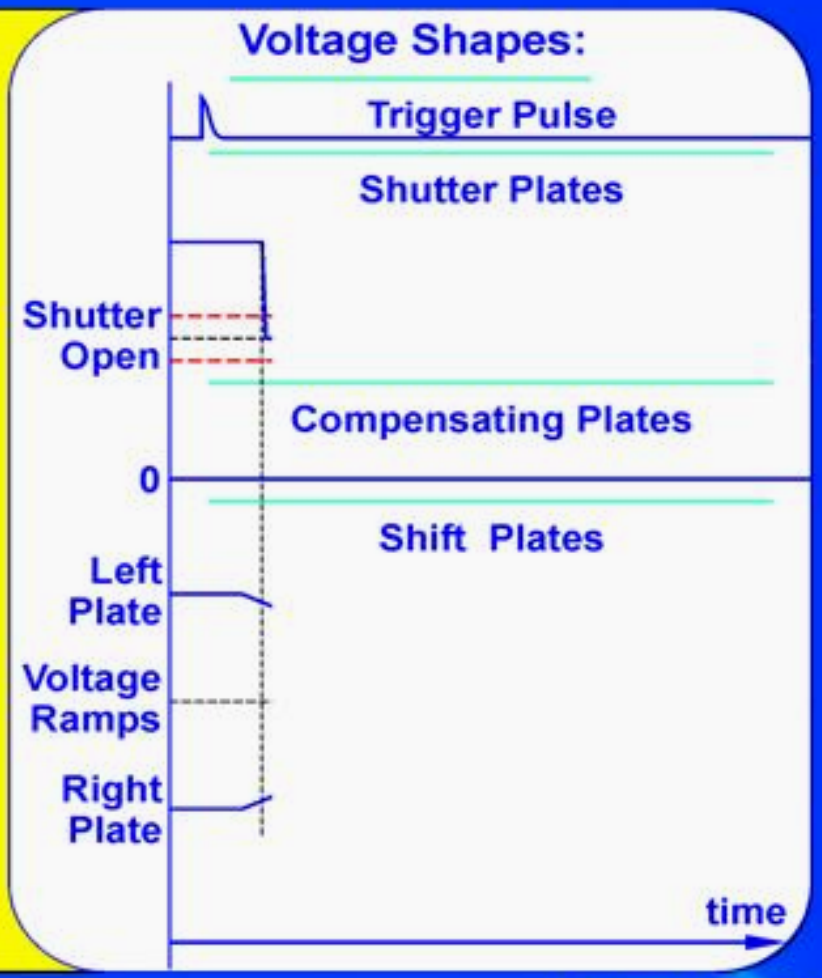




High-Speed Photography for Plasma Investigations

Streak Camera – Design and Principle of Operation





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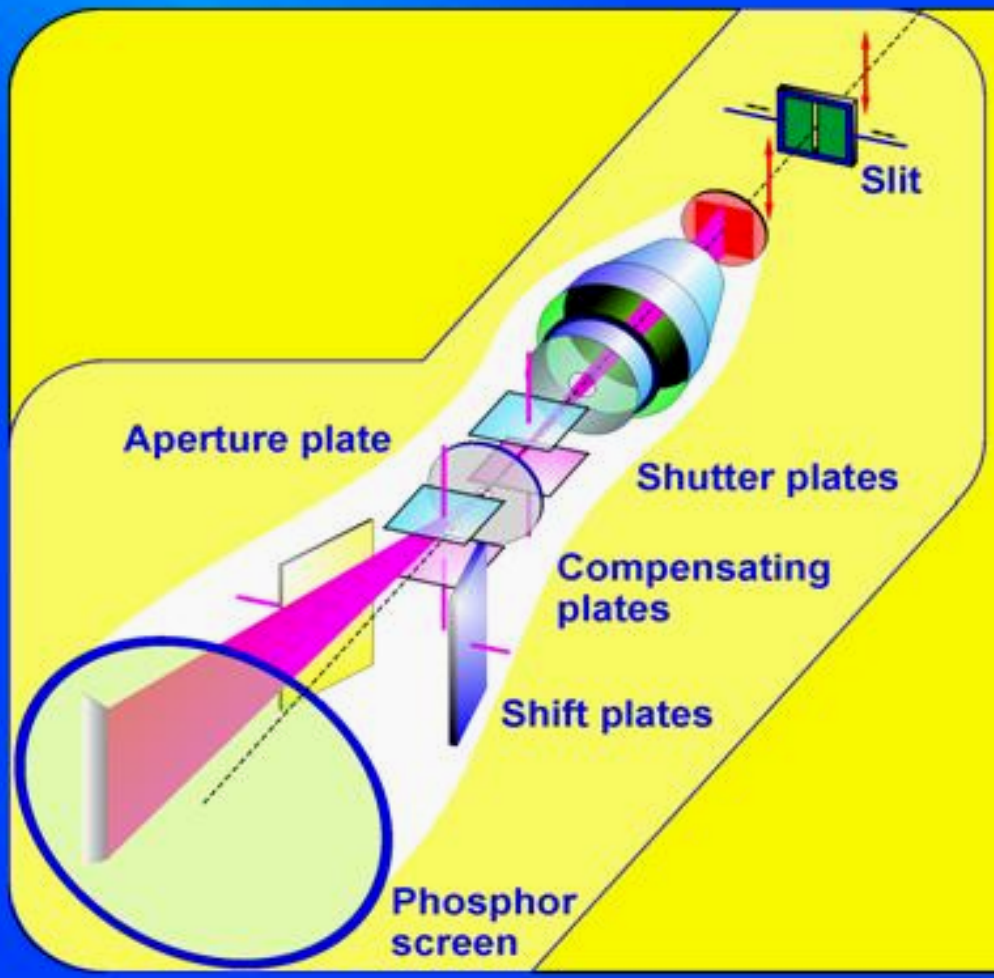
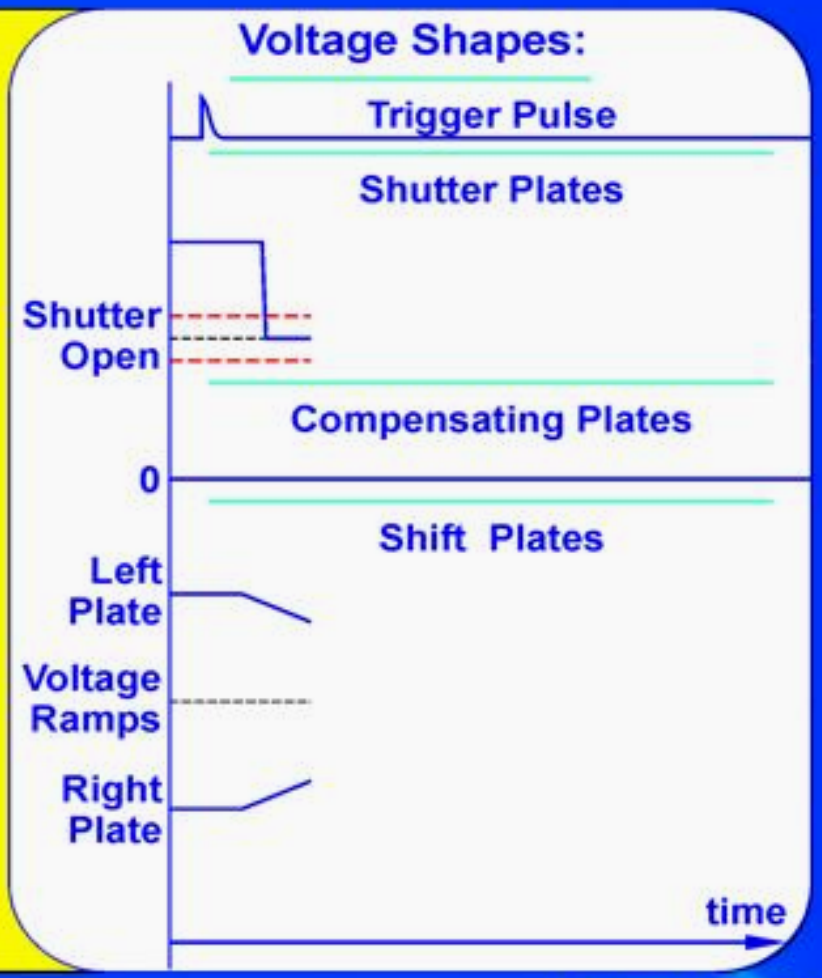
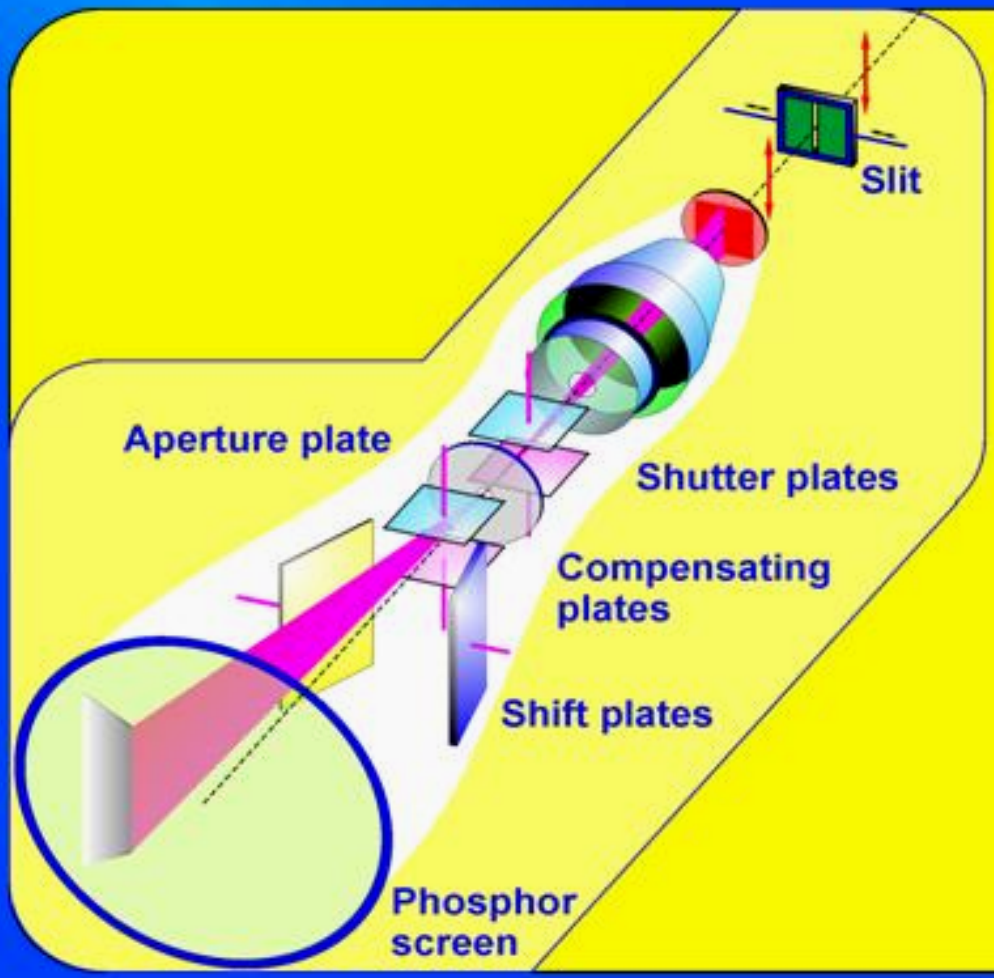
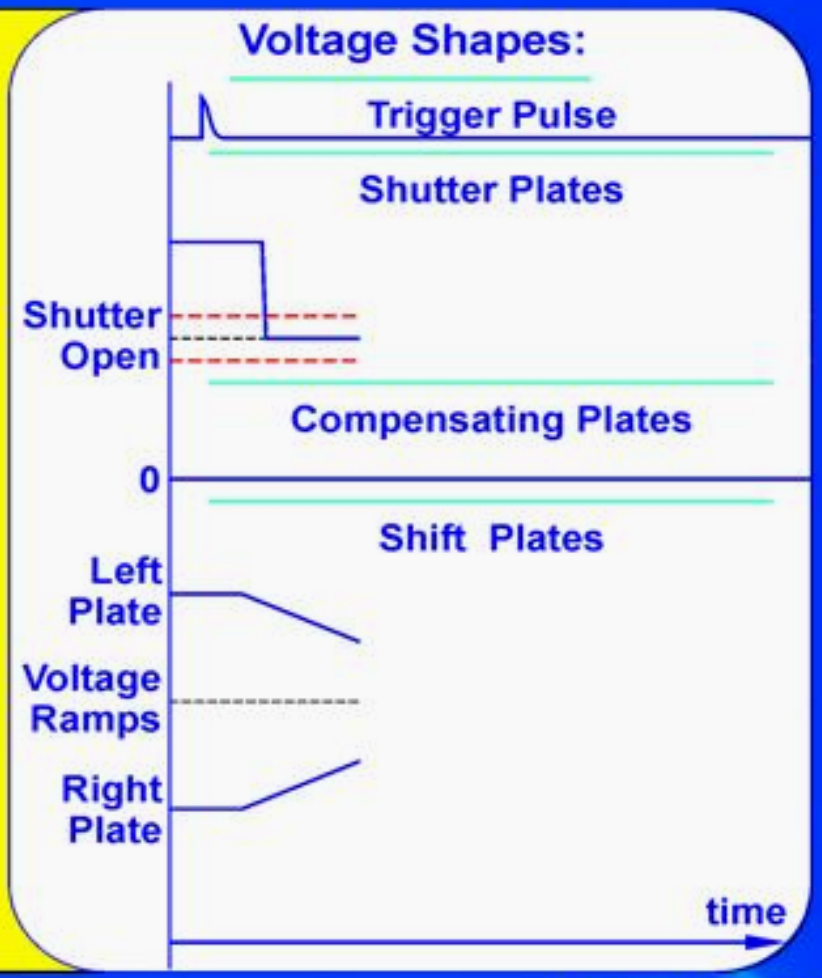




High-Speed Photography for Plasma Investigations

Streak Camera – Design and Principle of Operation





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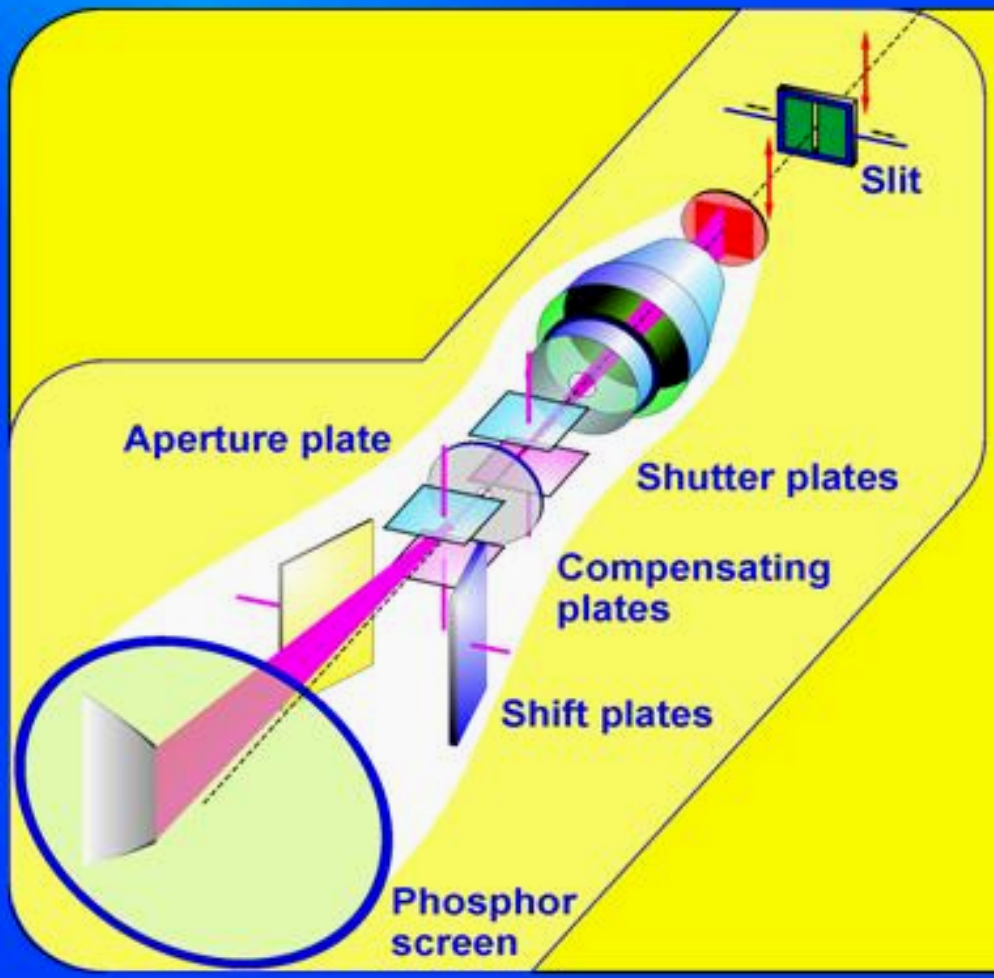

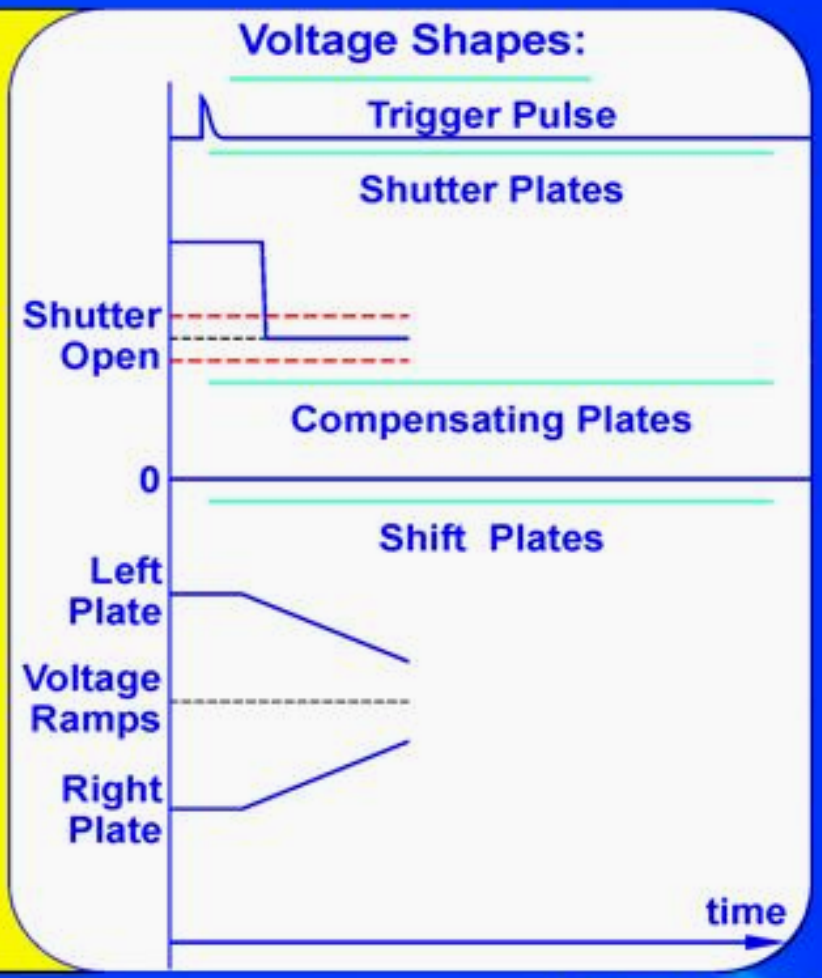

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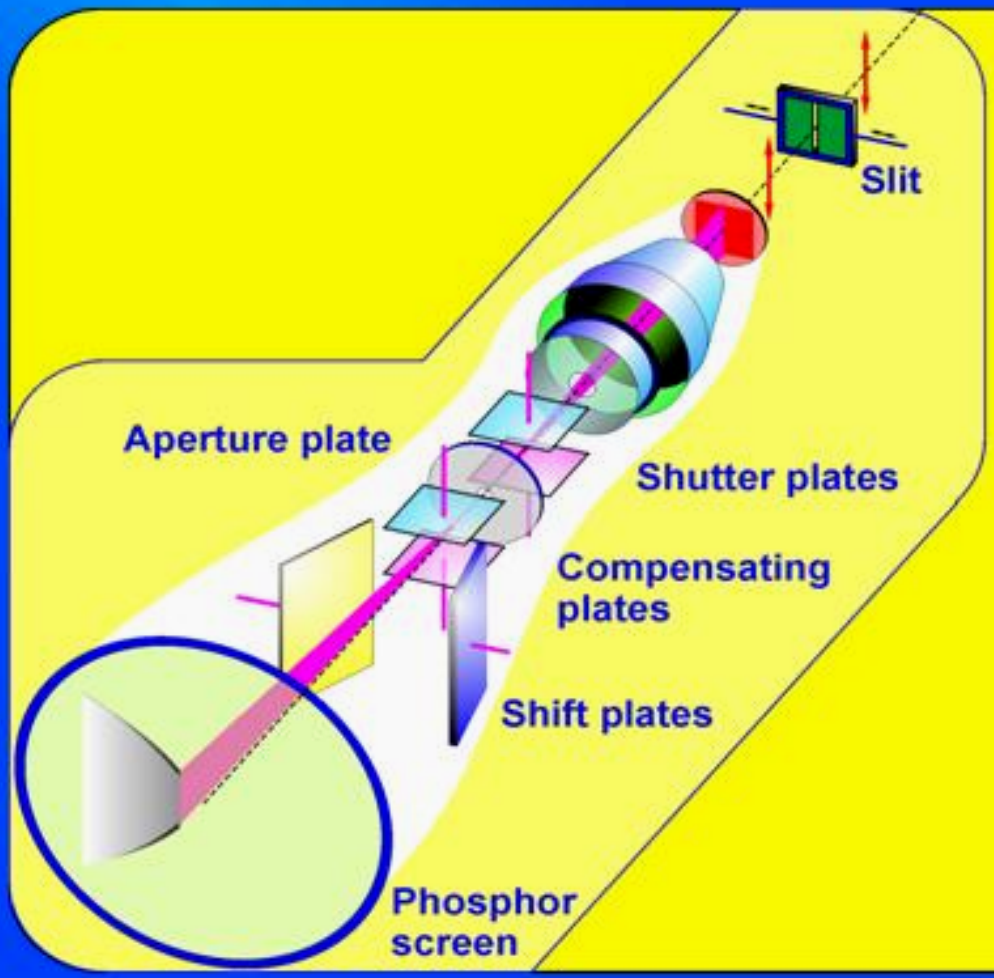

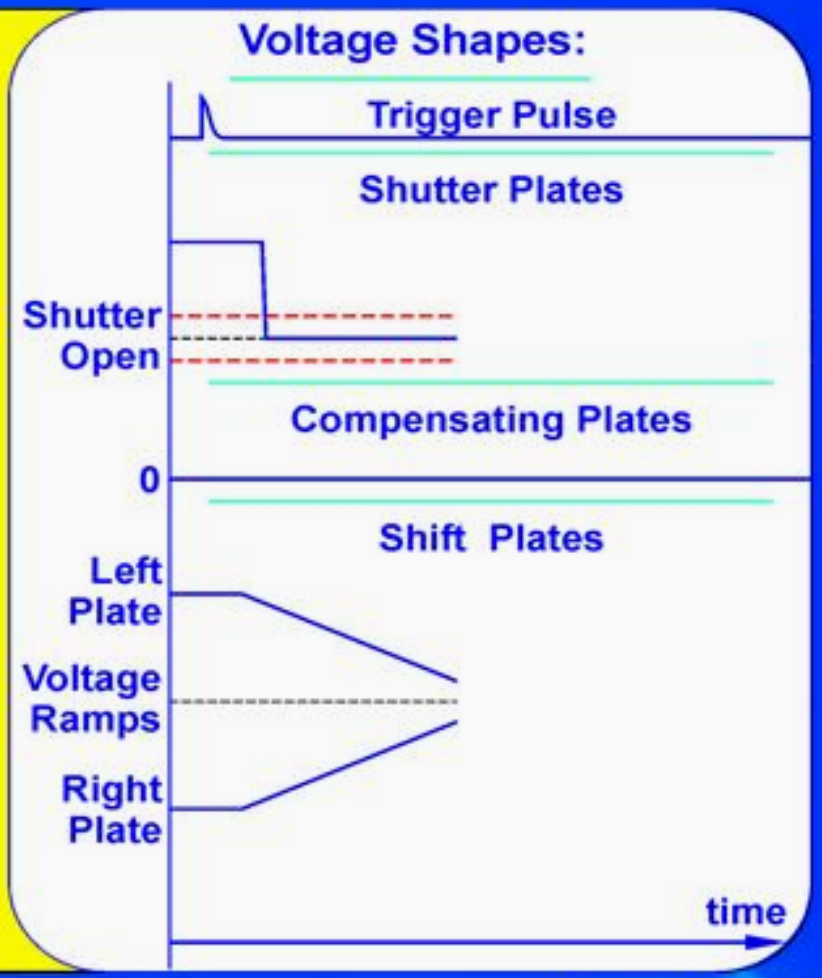

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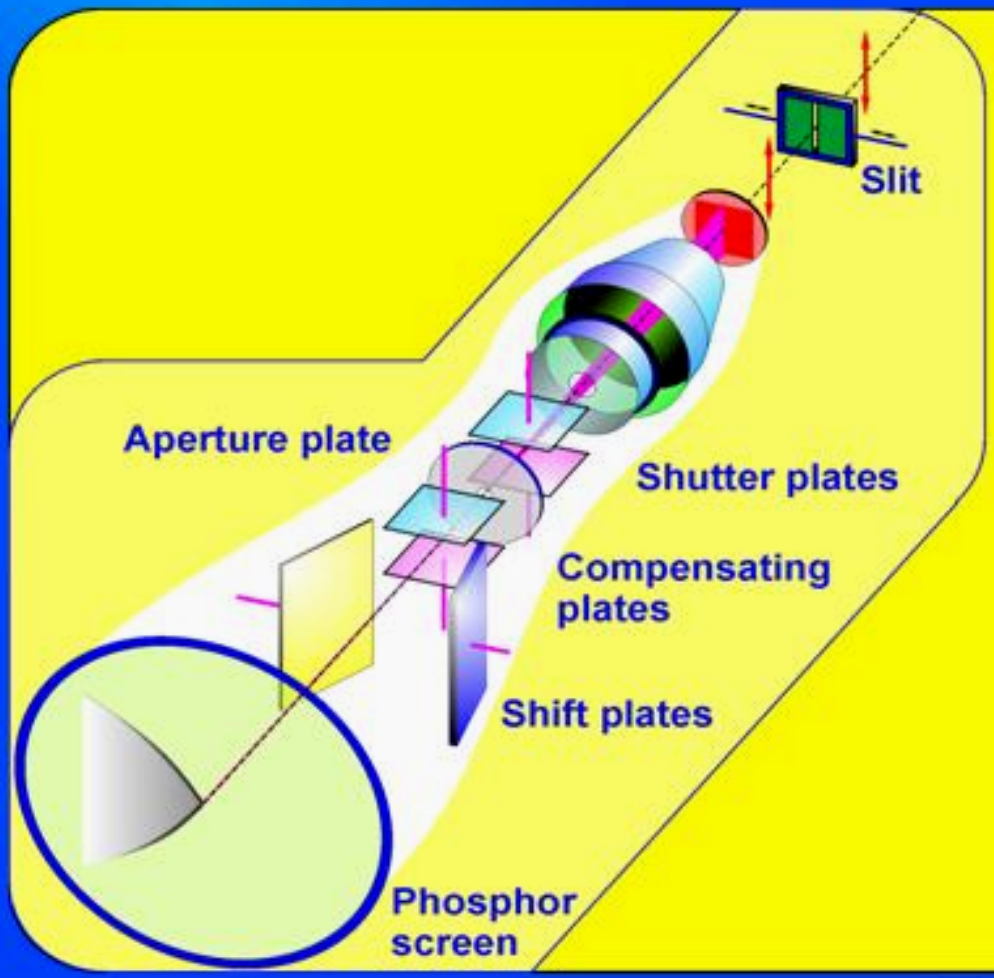

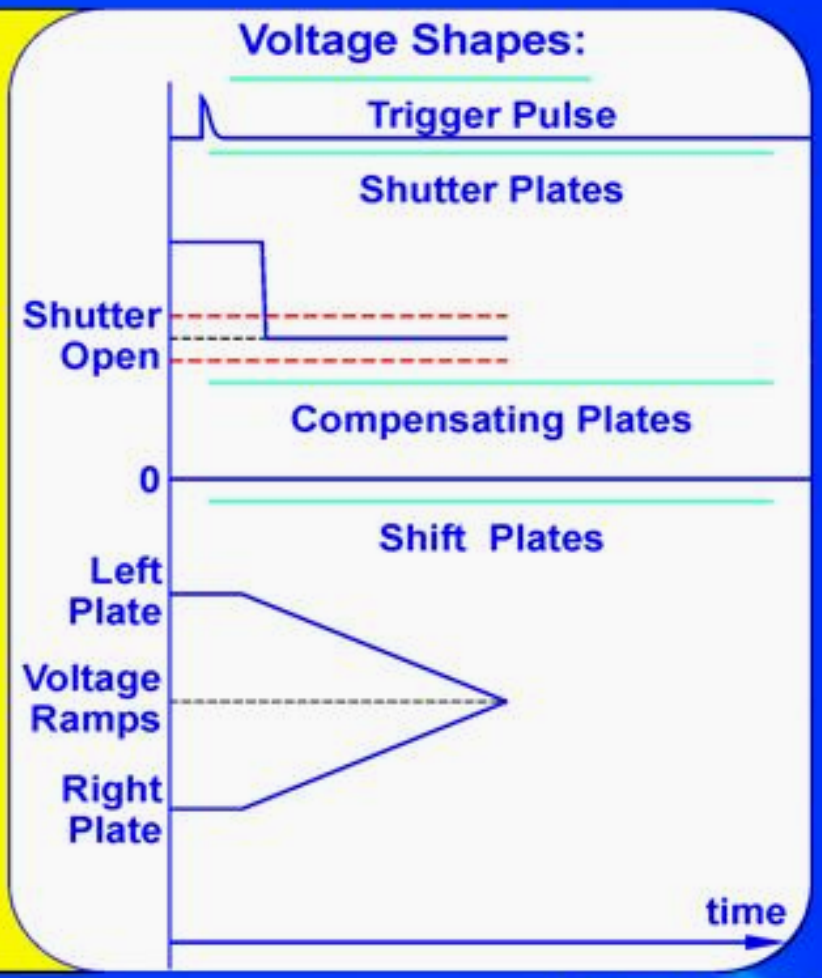

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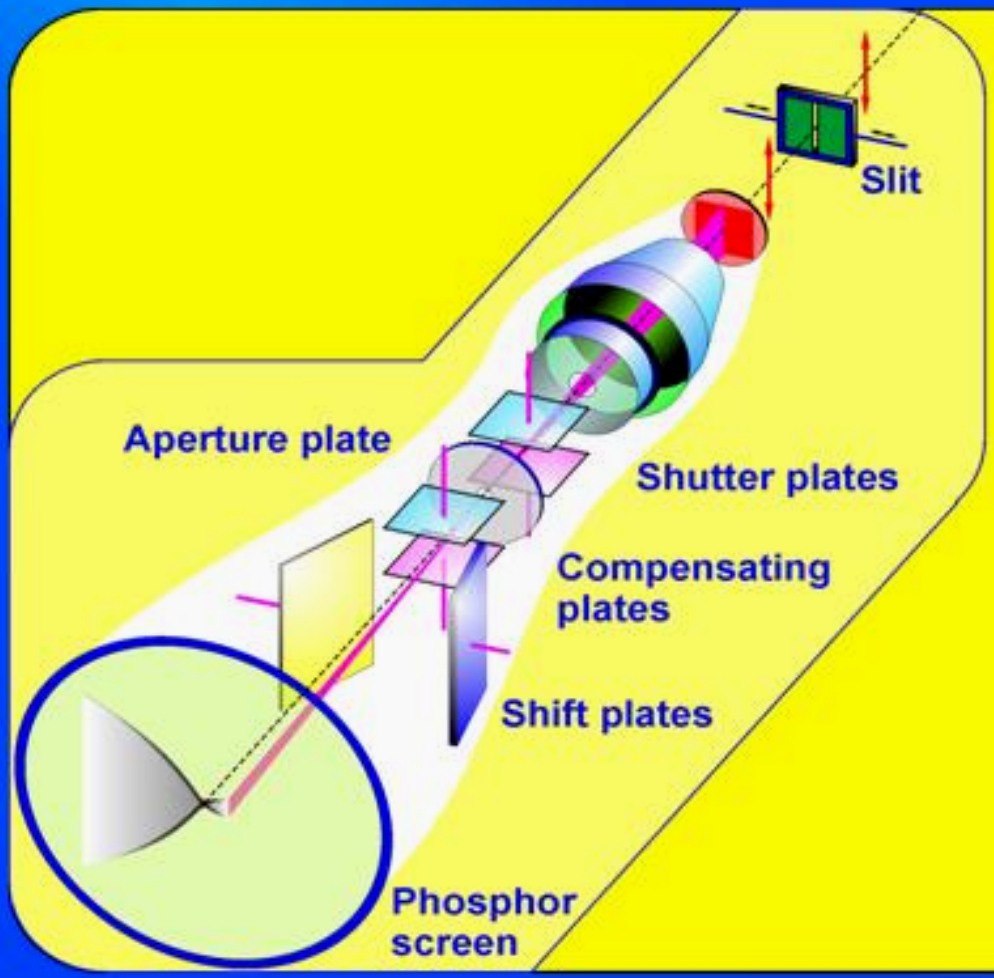

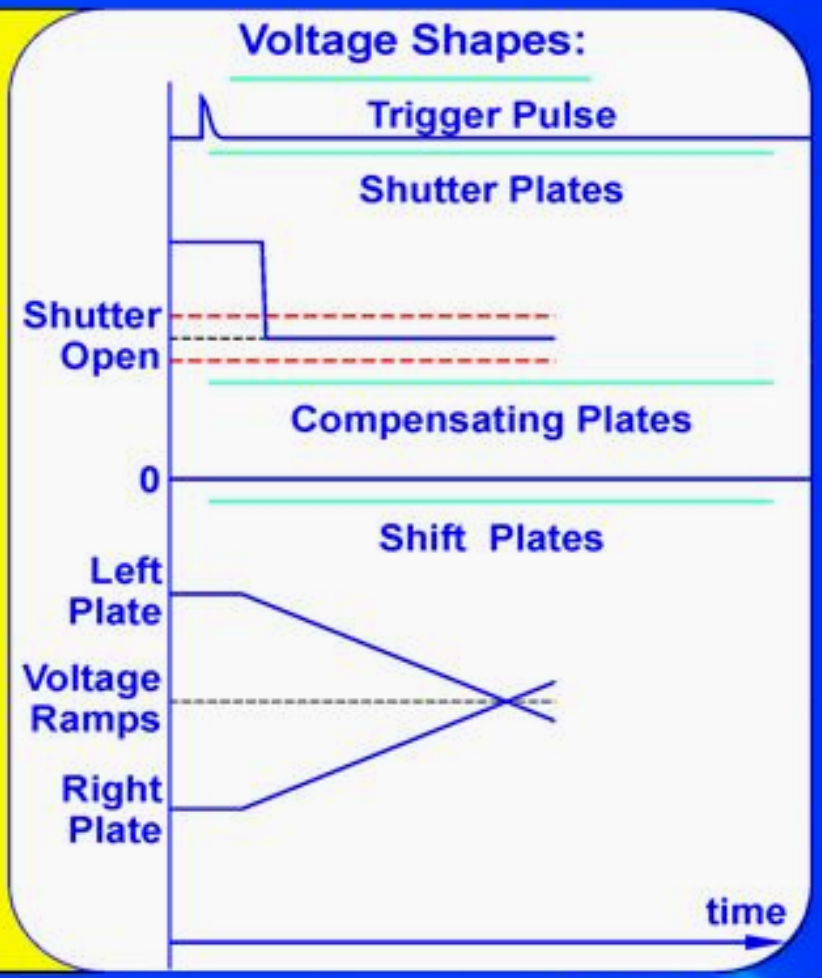

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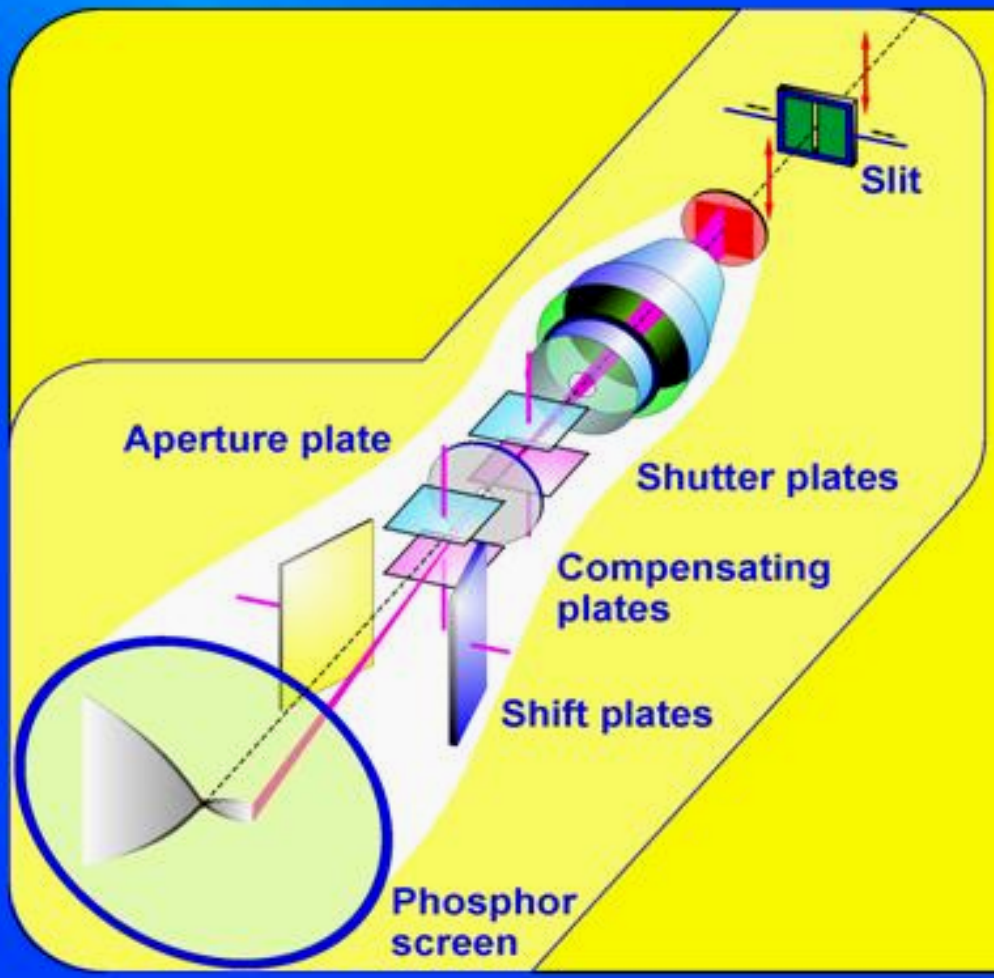
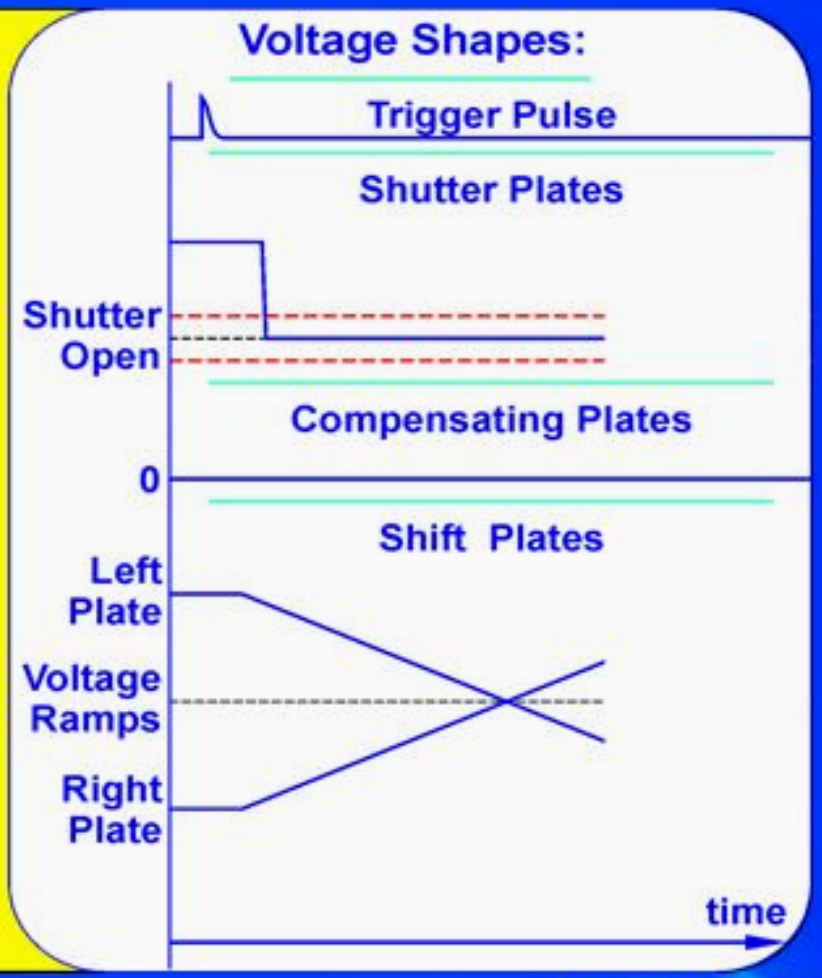
Streak Camera – Design and Principle of Operation





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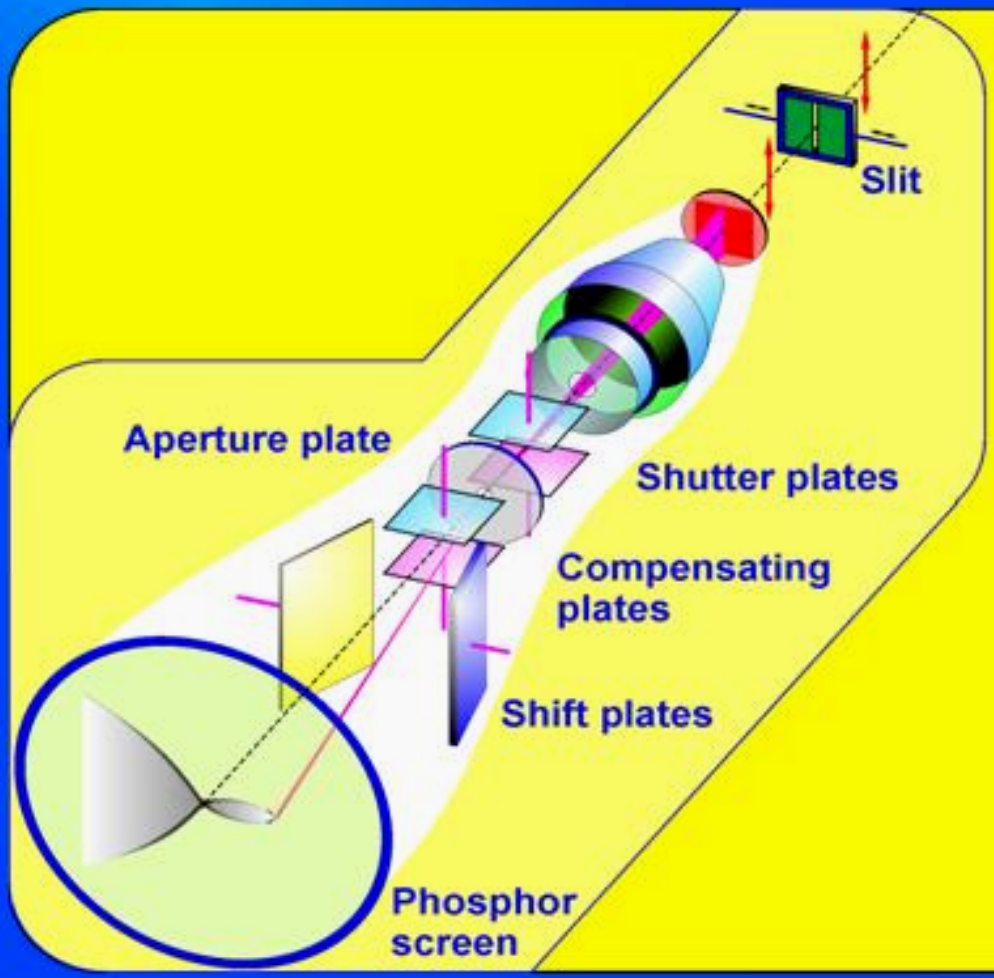
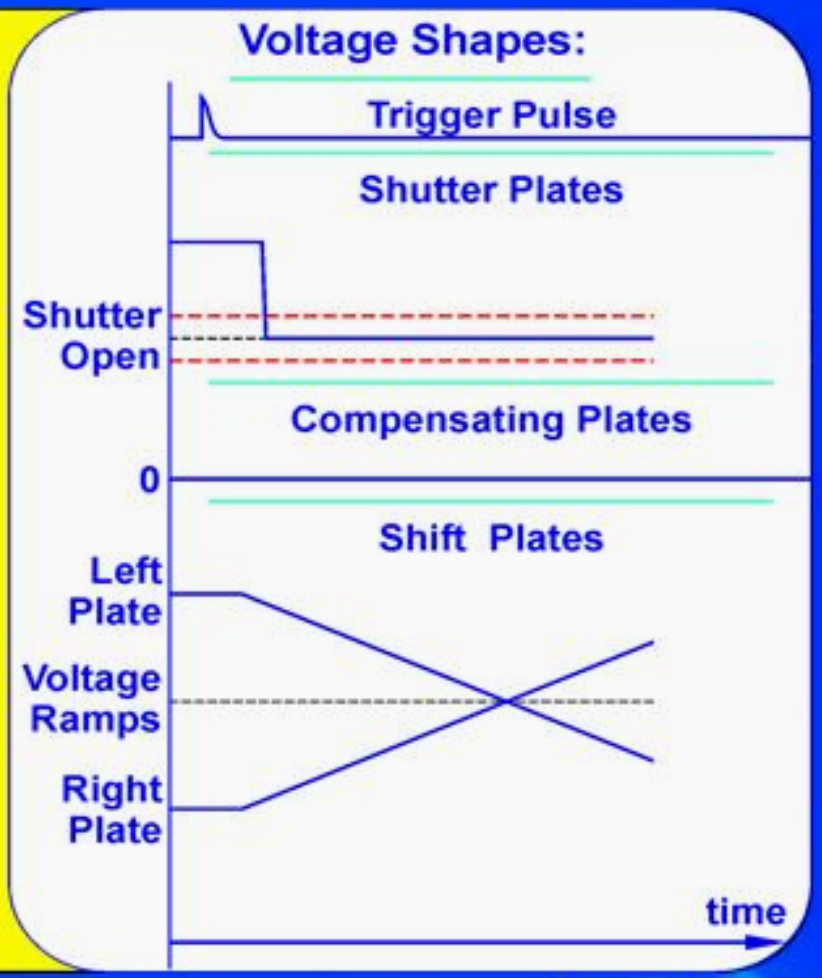
Streak Camera – Design and Principle of Operation





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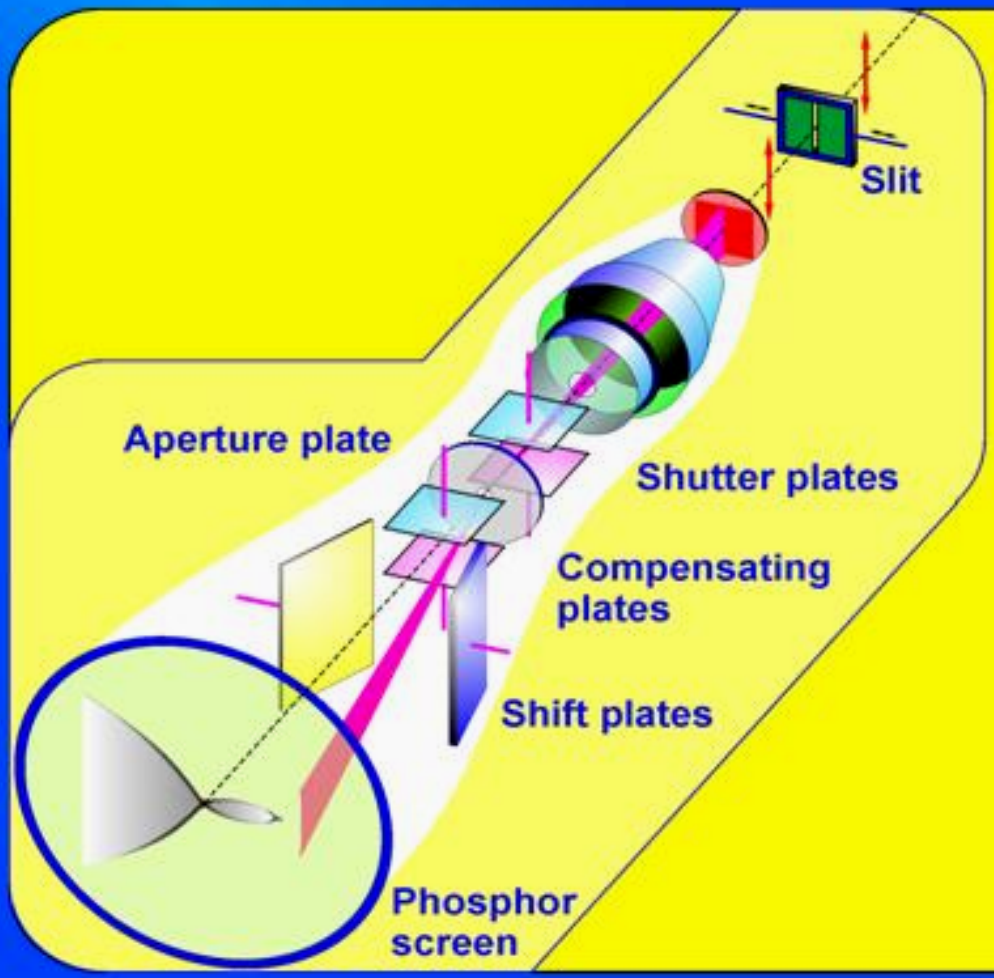
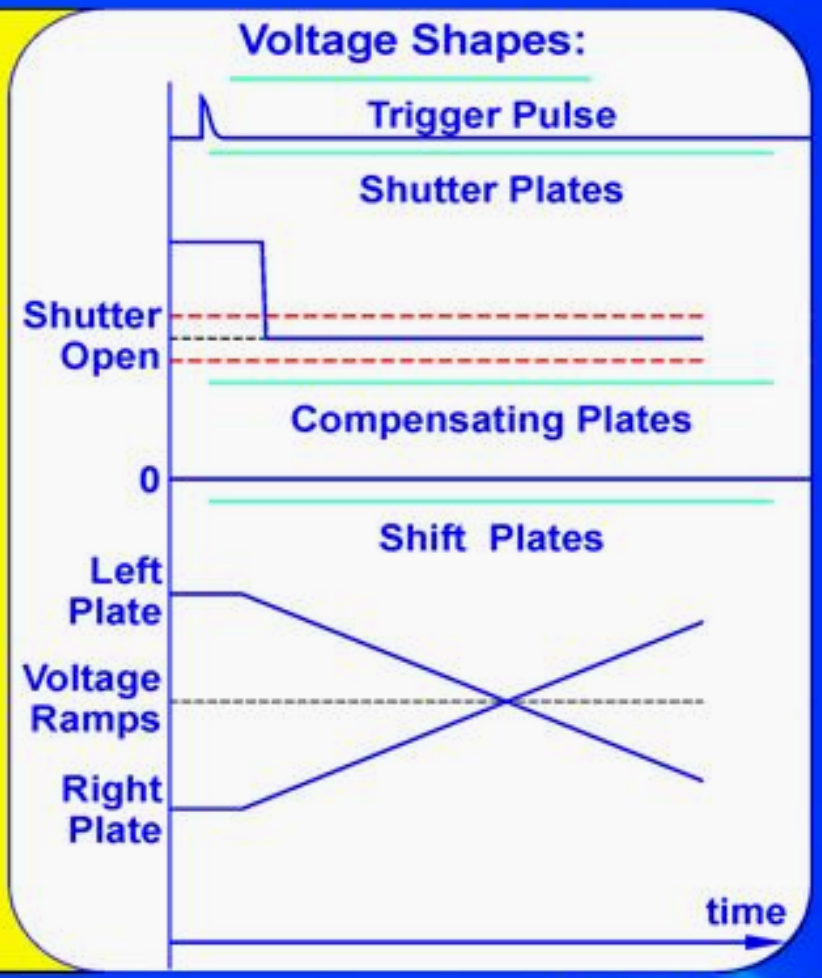
Streak Camera – Design and Principle of Operation





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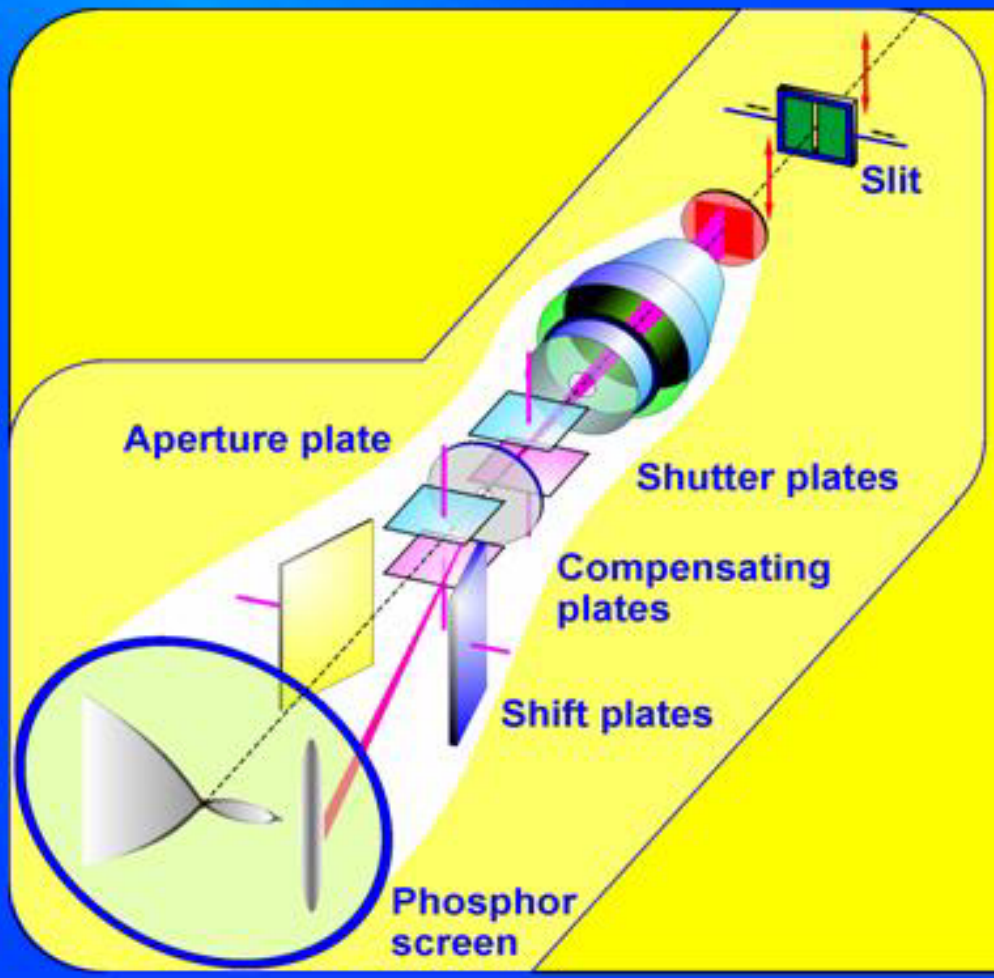

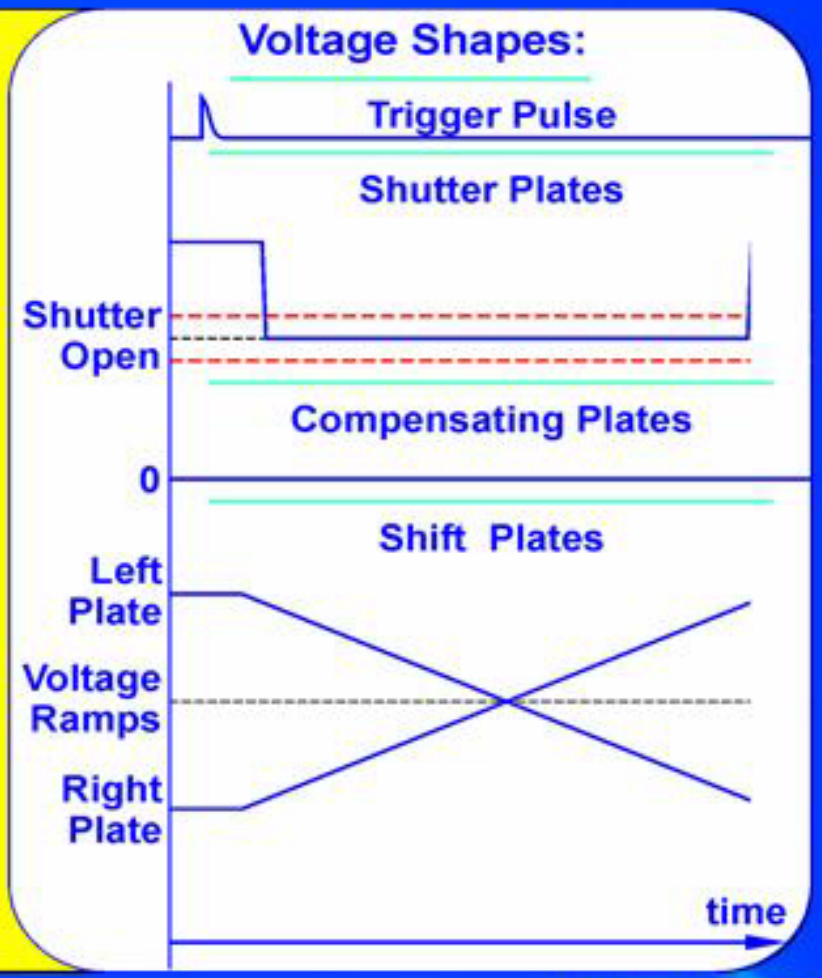

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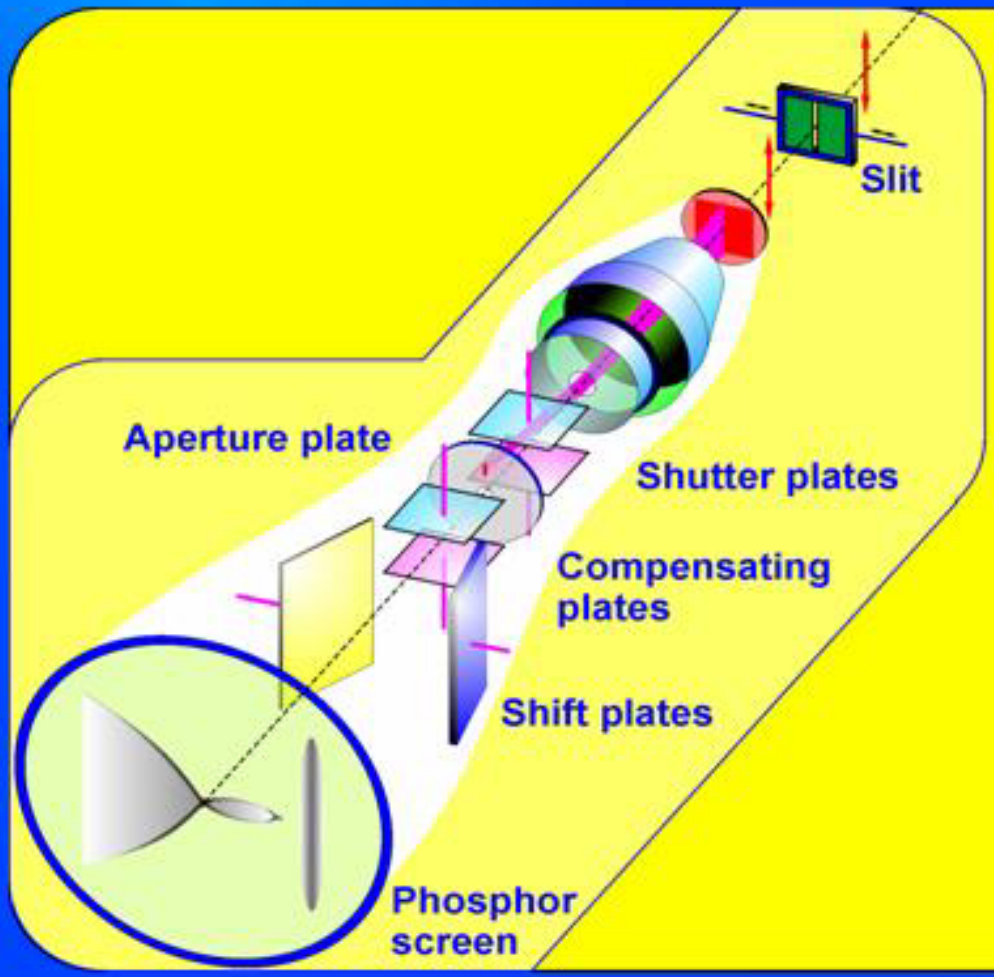

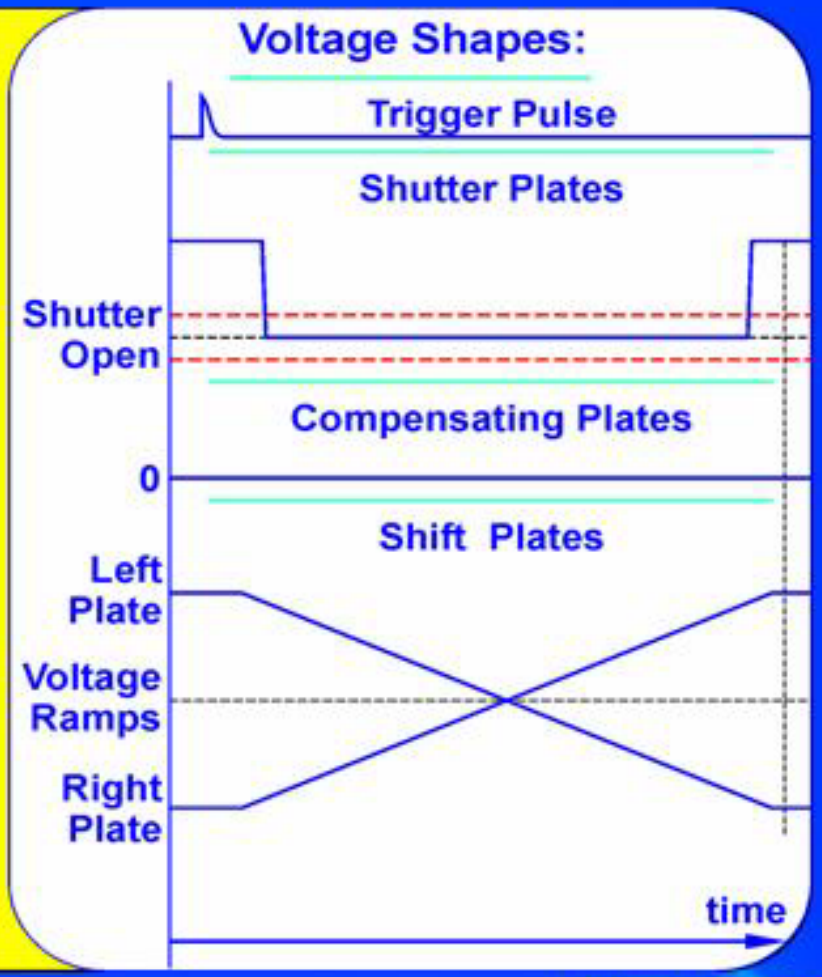

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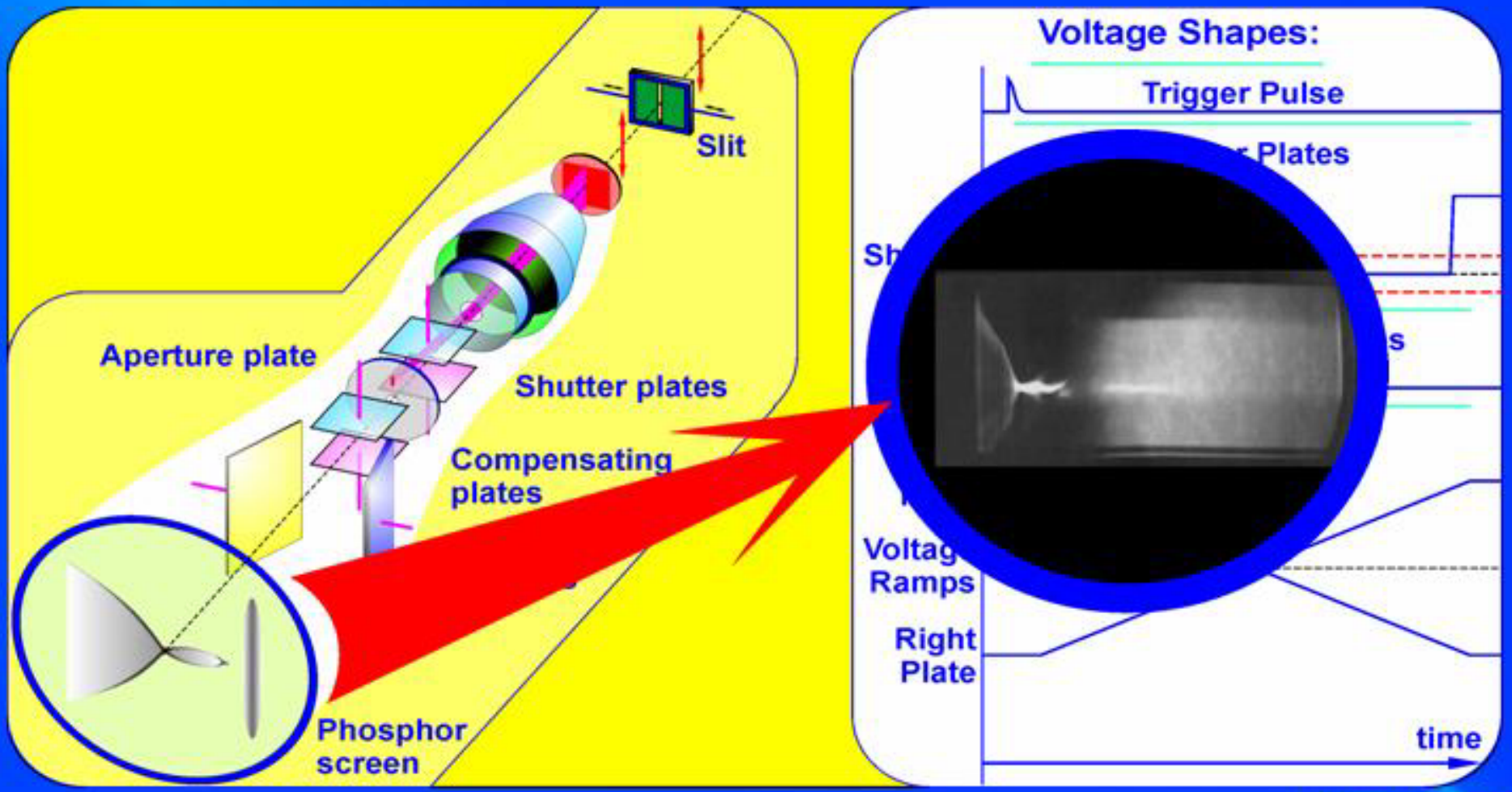
Streak Camera – Design and Principle of Operation



High-Speed Photography for Plasma Investigations

Exemplary Results

High-Speed Photography for Plasma Investigations

Z-Pinch Investigation

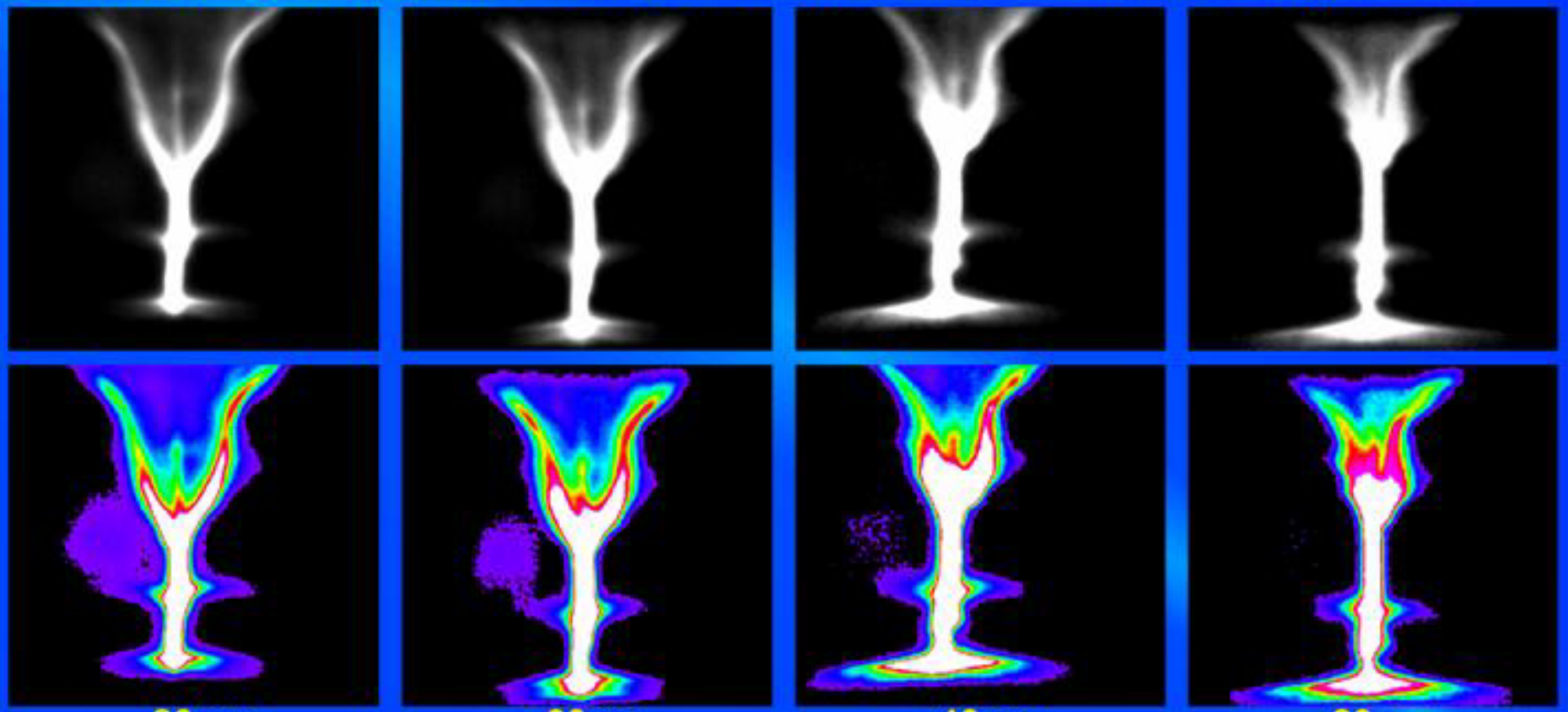
Diagnostic Team
IPP&LM, Warsaw, Poland

High-Speed Photography for Plasma Investigations

Gas-Puff Z-Pinch Investigation

Zipper Effect at the Implosion Phase

- Four-frame images taken with 1 ns exposure time; t = 0 refers to maximum compression



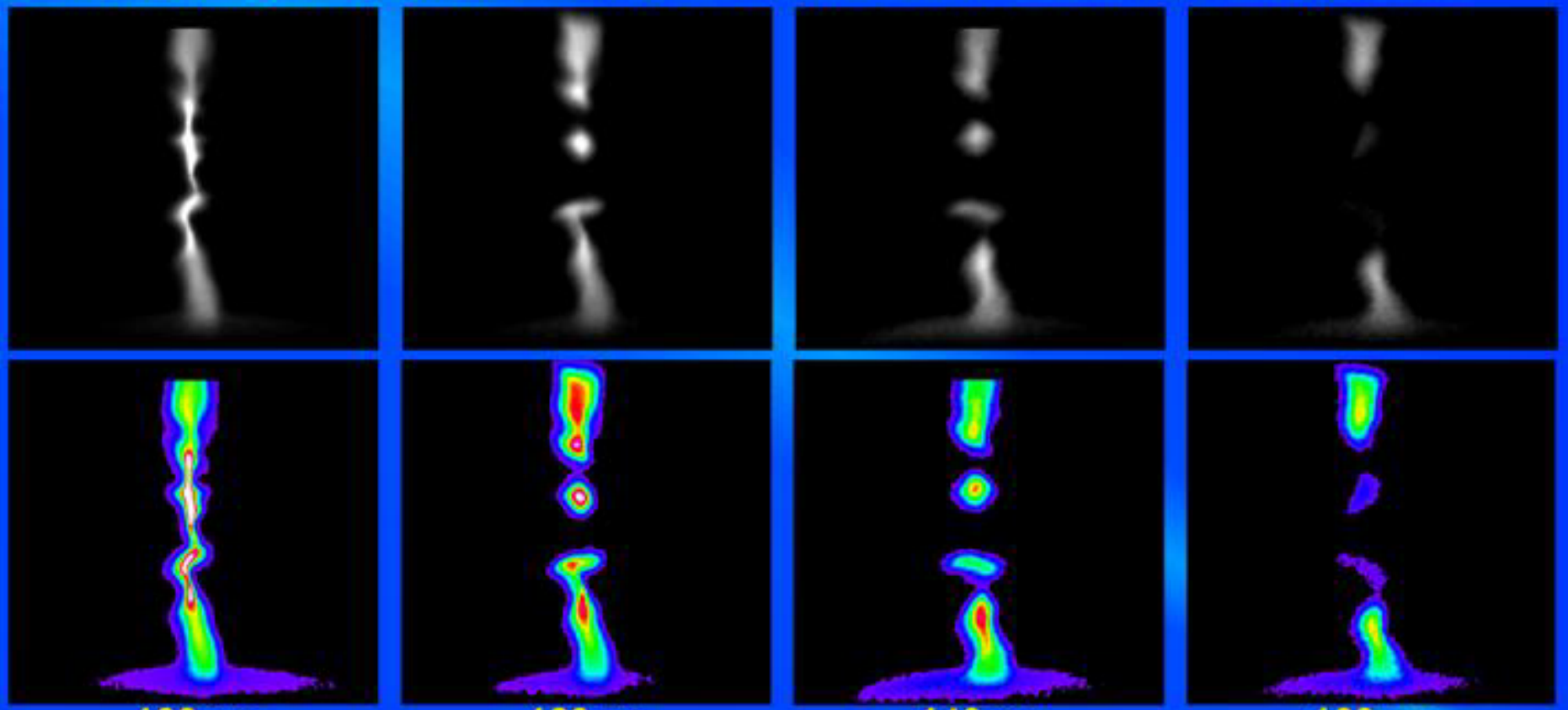
- *Experiment was carried out in June 1995, at Institute of Plasma Physics, Czech Academy of Science, Prague, Czech Republic*

High-Speed Photography for Plasma Investigations

Gas-Puff Z-Pinch Investigation

Evolution of Early Stage of Plasma Column Collapse

- Four-frame images taken with 1 ns exposure time; t = 0 refers to maximum compression



- *Experiment was carried out in June 1995, at Institute of Plasma Physics, Czech Academy of Science, Prague, Czech Republic*

Diagnostic Team
IPPLM, Warsaw, Poland

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Plasma-Focus (PF) Investigation

Diagnostic Team
IPP&LM, Warsaw, Poland

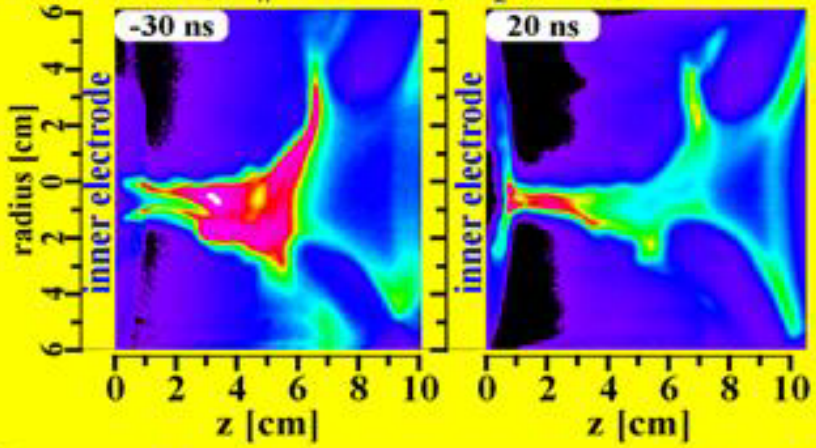
High-Speed Photography for Plasma Investigations

Exemplary Results – Final Stages of Plasma Evolution

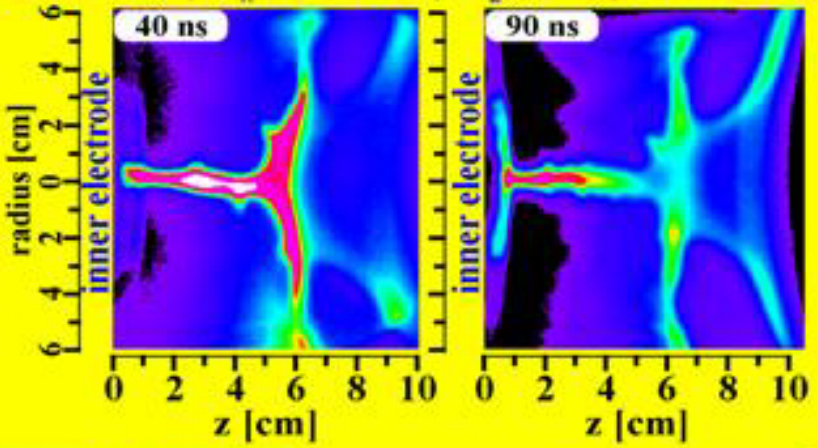
PF1000 Device (September, 2000)

- Multi-frame images taken with 1 ns exposure time; side-on direction of observation
- t = 0 refers to start of soft X-ray radiation

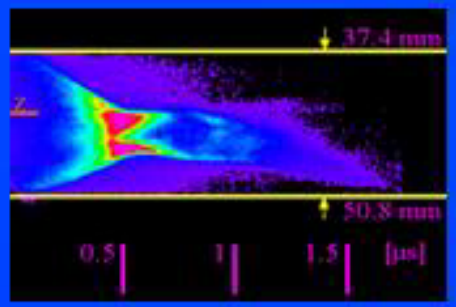
Bad shot; $Y_n = 3.1 \cdot 10^8$; D_2- 4 Tr; E=973 kJ



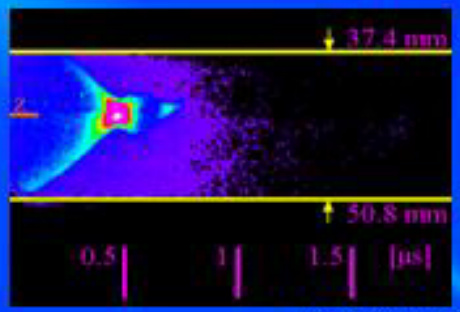
Good shot; $Y_n = 8.1 \cdot 10^{10}$; D_2- 4 Tr; E=922 kJ



Two-frames sequences obtained in shots with completely different neutron yield



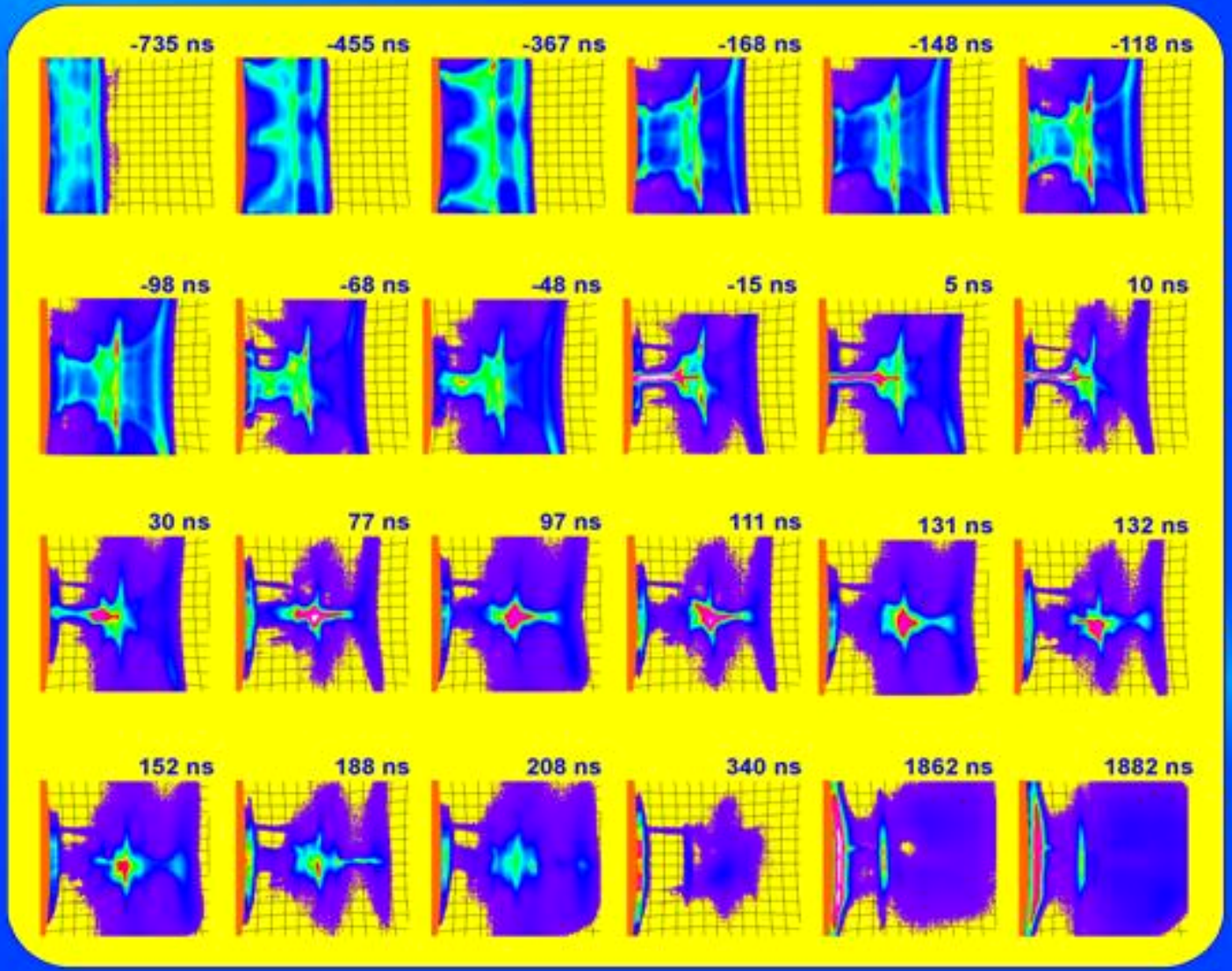
Related streak images



Diagnostic Team
IPPLM, Warsaw, Poland

High-Speed Photography for Plasma Investigations

PF1000 – Large-Scale PF Device – Exemplary Results



PF1000 Device (April, 2002)

- E = 730 kJ
- p = 400 Pa (D_2)
- Average $Y_n = 1.5 \times 10^{11}$
- Multi-frame images taken with 1 ns exposure time; side-on direction of observation
- t = 0 refers to the first maximum of soft X-ray radiation
- Dimension of grid is equal to 10x10 mm

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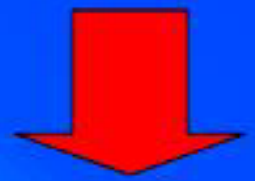
High-Speed Photography for Plasma Investigations

Summary

High-Speed Photography for Plasma Investigations

Summary

Electro-Optical High-Speed Photography



- **Extremely short exposure time – down to nanosecond range**

  Typical (standard solution) from 5 to 10 ns, in ultra HSPS 50 ps can be achieved

- **Frames are immediately stored in digital form**

  Vertical resolution of 10 bits is standard

- **High and very high ultimate spatial resolution**

  768x512 pixels (video rate CCD camera), 2048x2048 pixels (high resolution ILT CCD array)