Optical Intensity Interferometer to Measure Short Bunch Length in SPEAR3

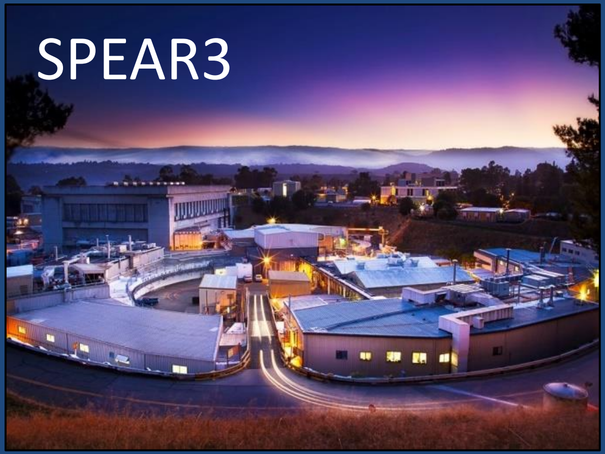
J. Corbett (SLAC)
T. Mitsuhashi (KEK)

København, 15 May, 2017

Outline

- Motivation
- Intensity Correlation and Interferometers
- Experimental setup
- Conclusion

Motivation – measure short bunch length

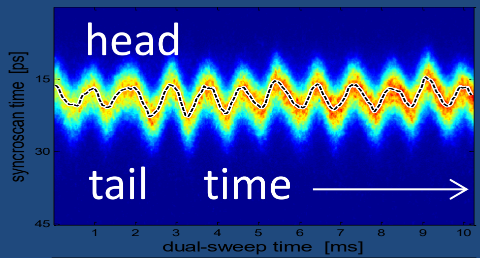


Streak camera result

~ 3 ps resolution

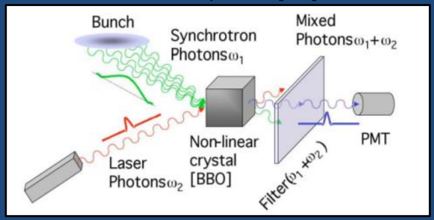
low light levels

Bunch measurement Techniques



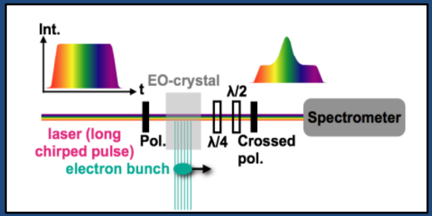
Streak camera

many authors



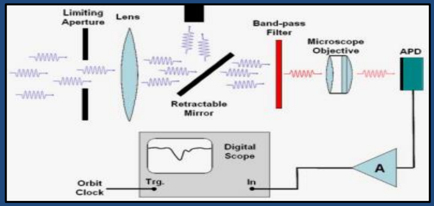
Laser/SR cross-correlation

M. Zolotorev, PAC 2003



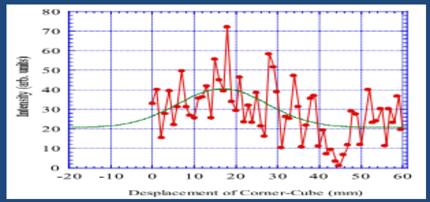
EO cross-correlation

N. Hiller, IPAC 2013



Fluctuation analysis

F. Sannibale, IPAC 2013



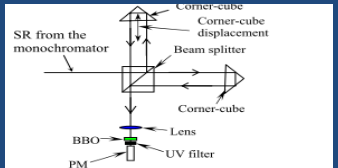


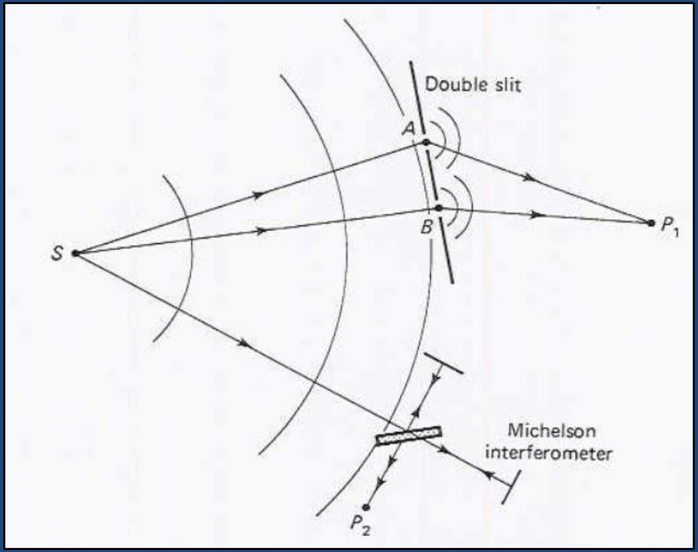
Figure 1: Measurement scheme.

Auto-correlation

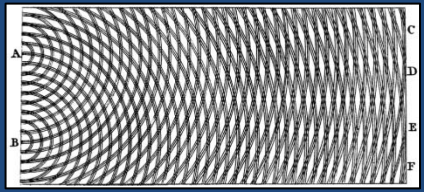
T. Mitsuhashi, EPAC 2002

Interferometery – correlation of fields

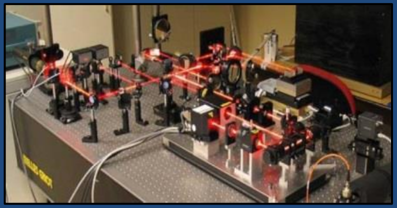
Second order interferometry



spatial coherence

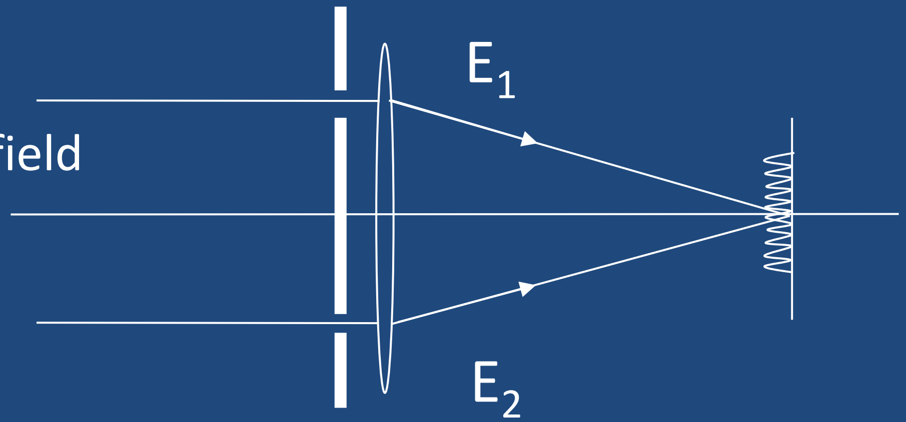


temporal coherence



Spatial Interferometers

Incident field



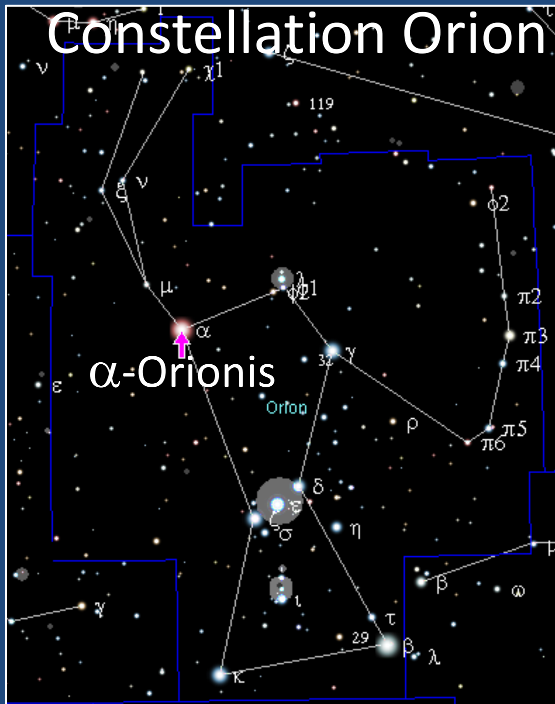
$$I = (E_1 + E_2) \cdot (E_1 + E_2)^*$$

$$I = E_1^2 + E_2^2 + 2\langle E_1 E_2 \rangle$$

2nd order field correlation (coherence)

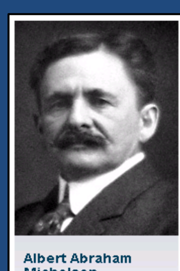
Contrast yields source size

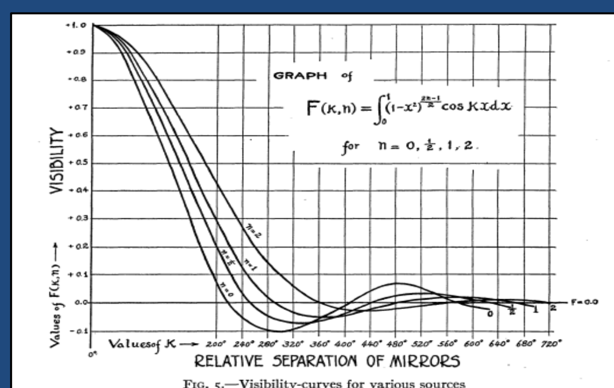
Michelson's measurement of α-Orionis

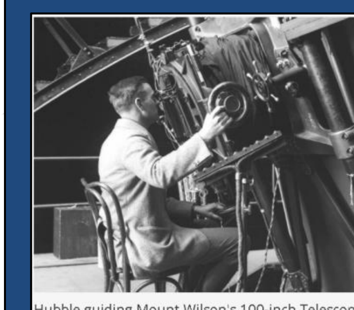


Telescope at Mt. Wilson

few meter baseline

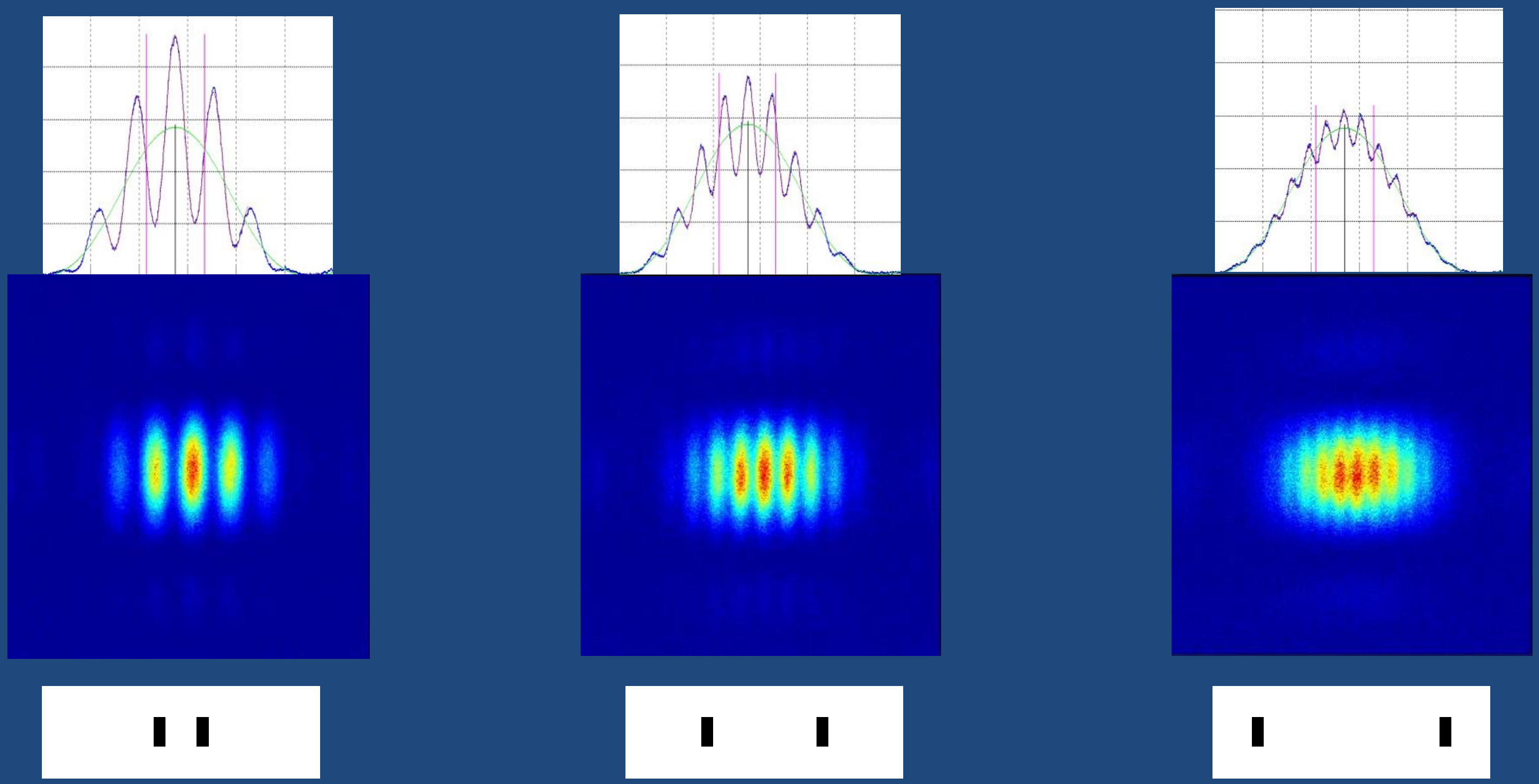


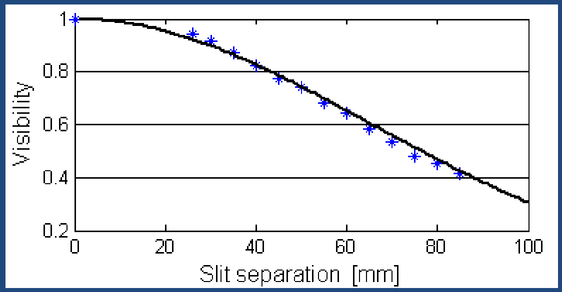




'Measurement of the Diameter of α-Orionis' (1921)

Electron beam cross-section





contrast ⟸ F ⟹ intensity

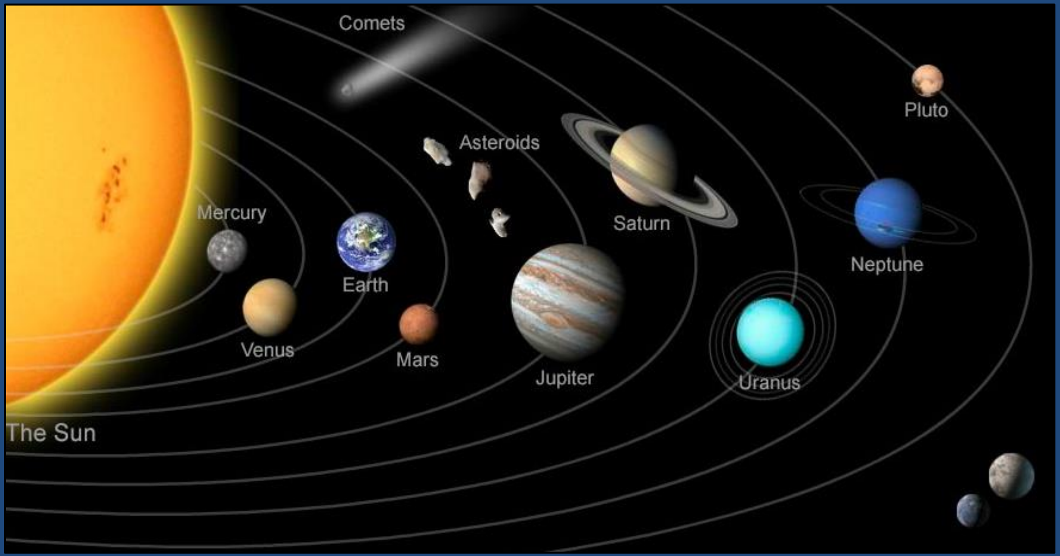
Van Cittert – Zernike theorem

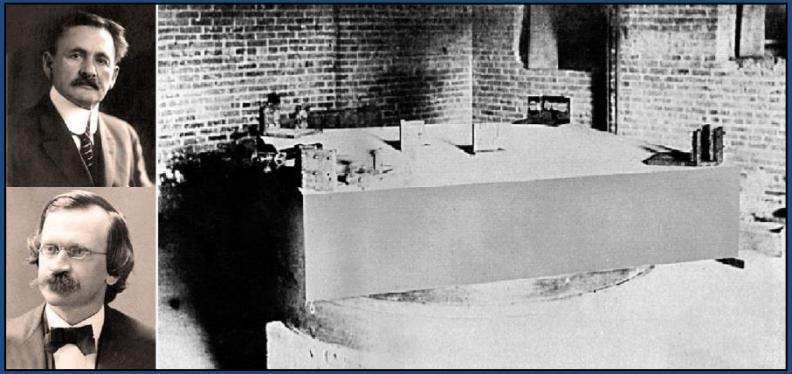
Toshiyuki Mitsuhashi

KEK (1999)

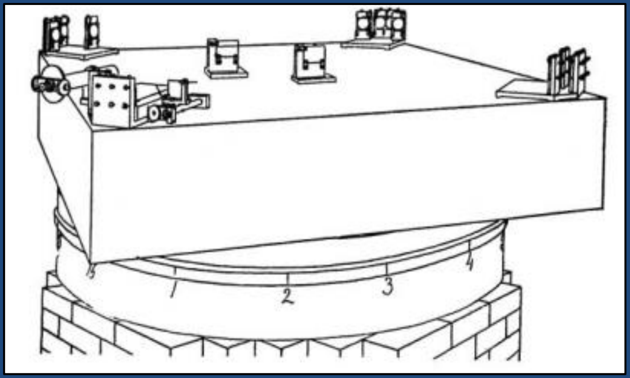
Temporal Interferometers

'Relative motion of the Earth and the Luminous Ether' (1887)





2nd order field correlation



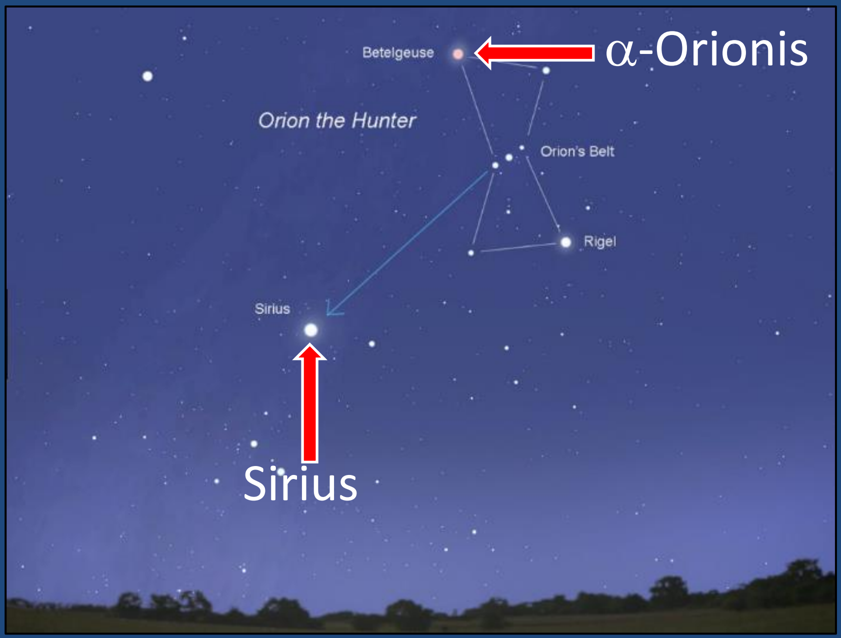
Correlation of higher order

$\langle E_1 E_2^* \rangle$ $\quad 2^{nd} - order\ field\ correlation$

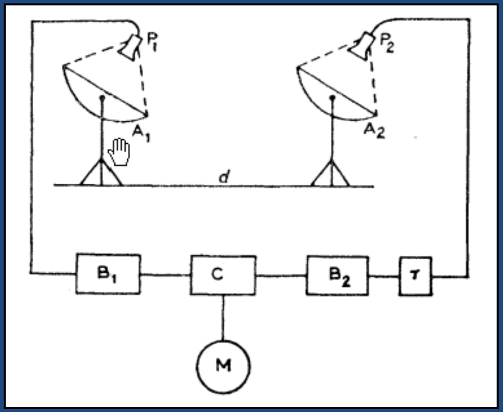
$\langle E_1 E_1^* E_2 E_2^* \rangle \sim \langle I_1 I_2 \rangle$ $\quad 4^{\text{th}} - order\ field\ correlation$

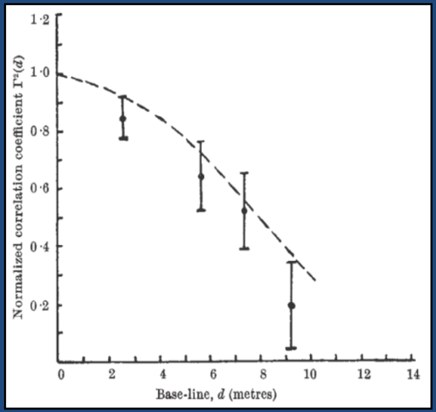
$2^{nd} - order\ intensity\ correlation$

Intensity correlation – spatial domain



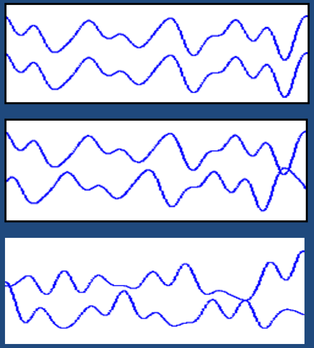
Hanbury Brown & Twiss 1954





Correlate intensity fluctuations about the mean

- Second order in intensity
- Fourth order in field
- Much longer baselines



Intensity correlation – time domain

492 | *12 Quantum Theory of Coherence*

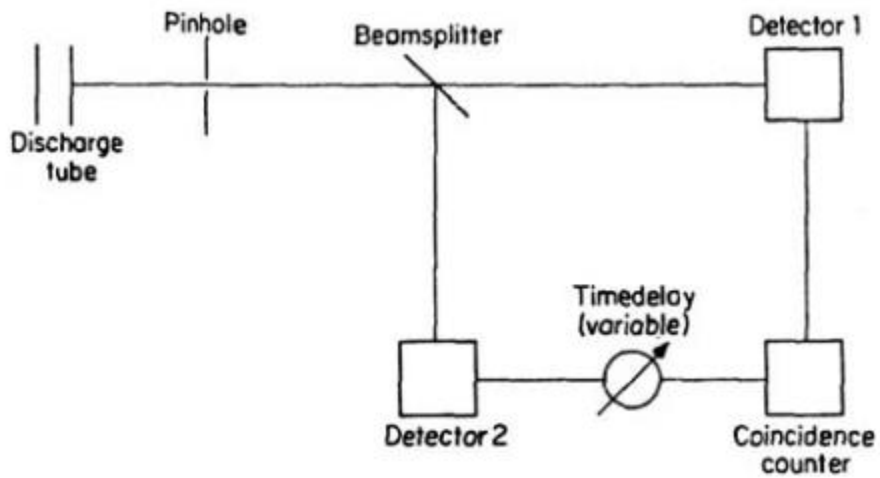


Figure 4 Hanbury Brown–Twiss experiment.

Same principle -

Count rate$= \int_{-T/2}^{T/2} < I_1\ (t) I_2(t+\tau) > dt$

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Y. Miyamoto, T. Kuga,* M. Baba, and M. Matsuoka

Institute for Solid State Physics, The University of Tokyo, 7-22-1 Roppongi, Minato-ku, Tokyo 106, Japan

Received March 1, 1993

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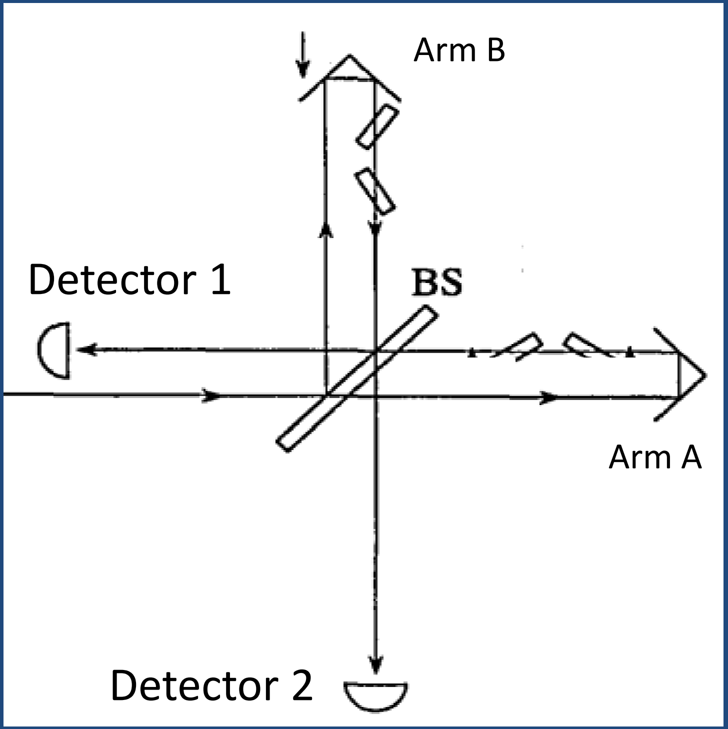

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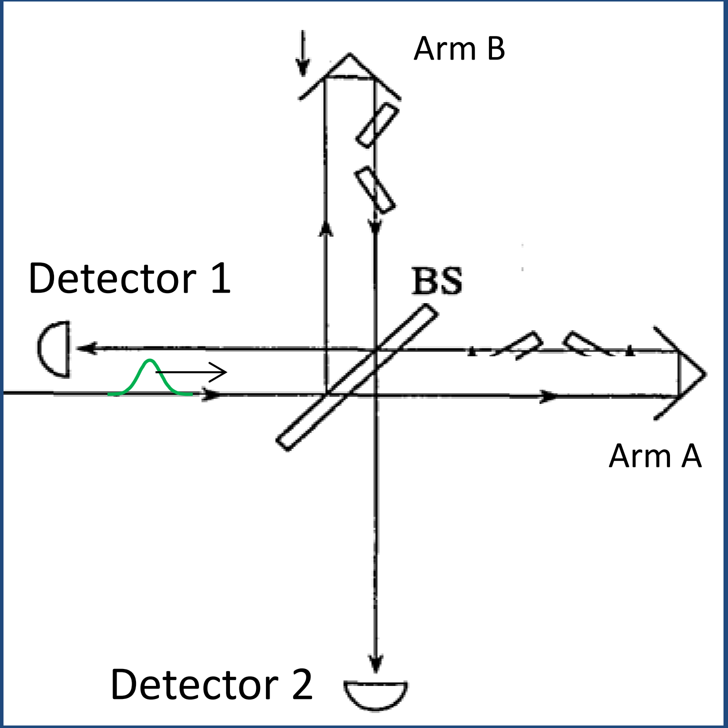

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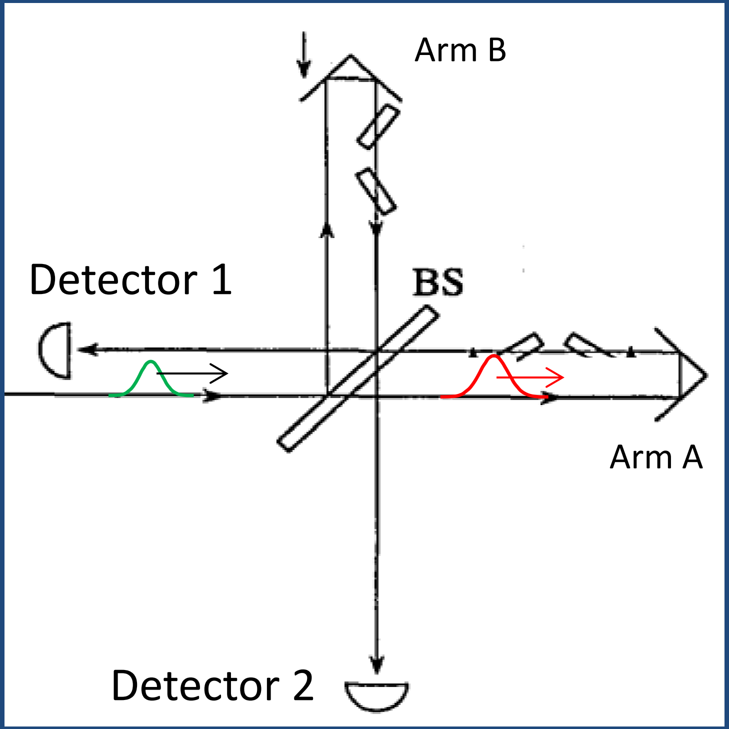

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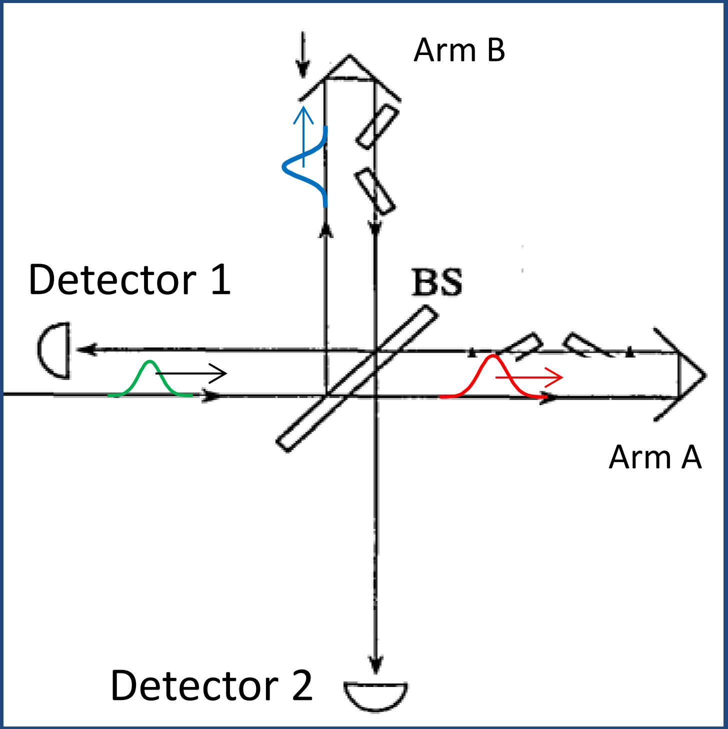

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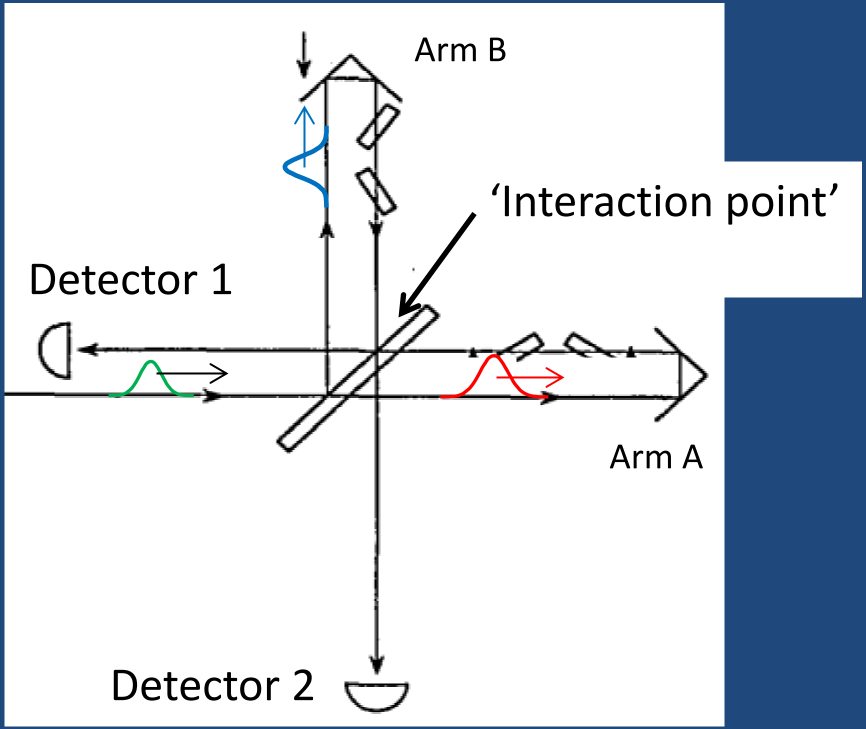

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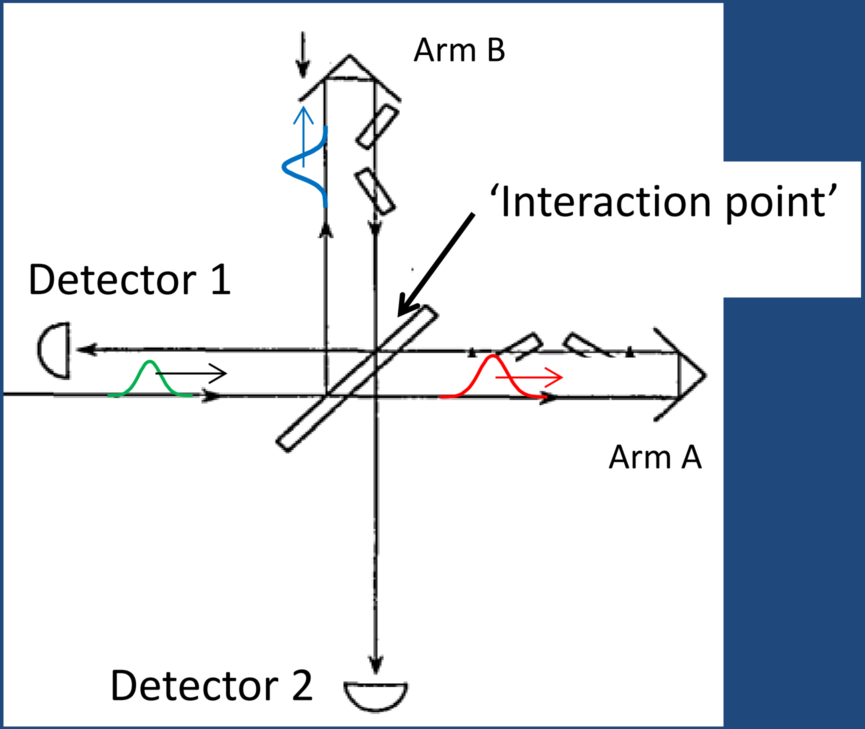
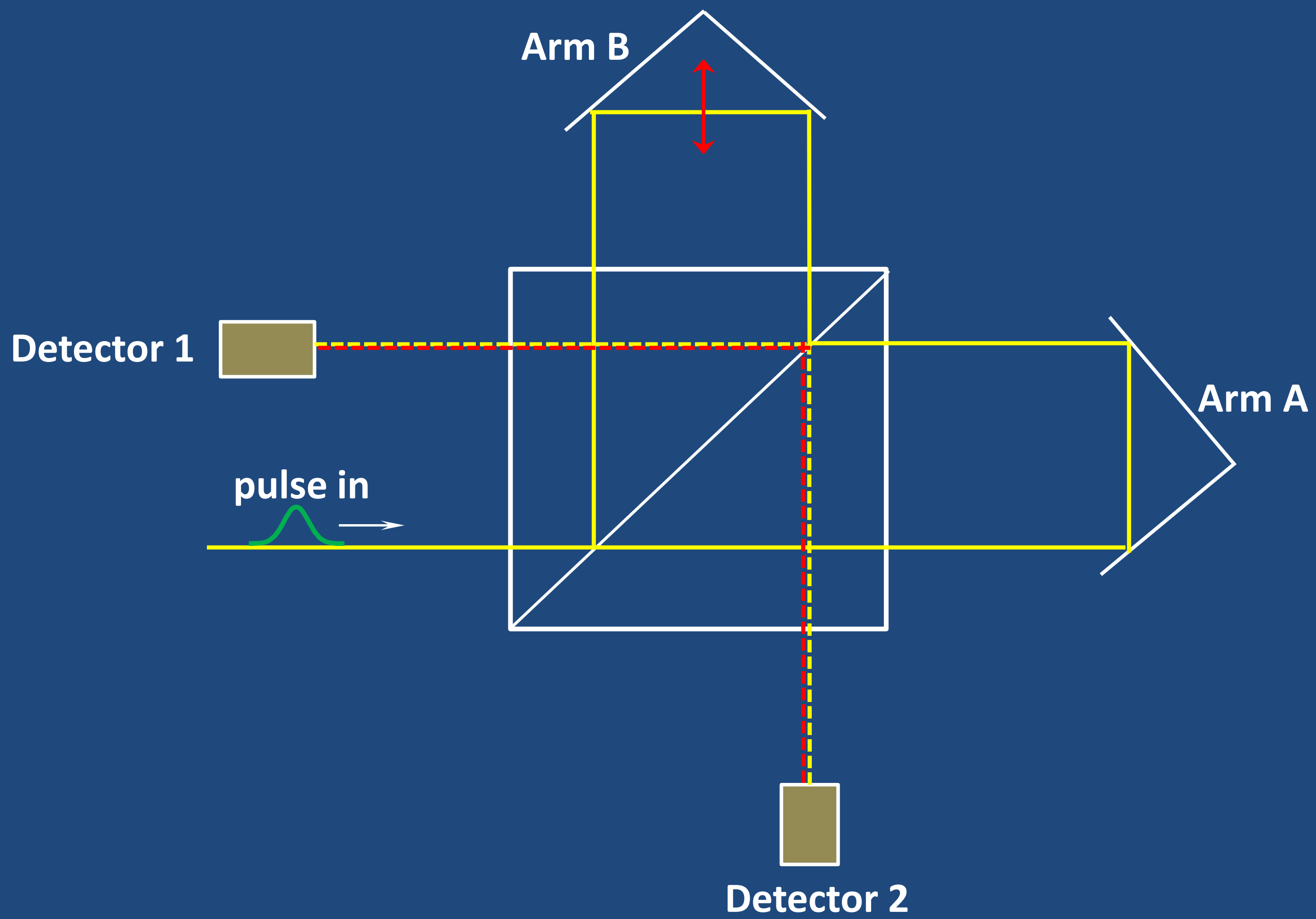


'measurement is made at photon-counting intensity levels'

Intensity Interferometer – classical field approach



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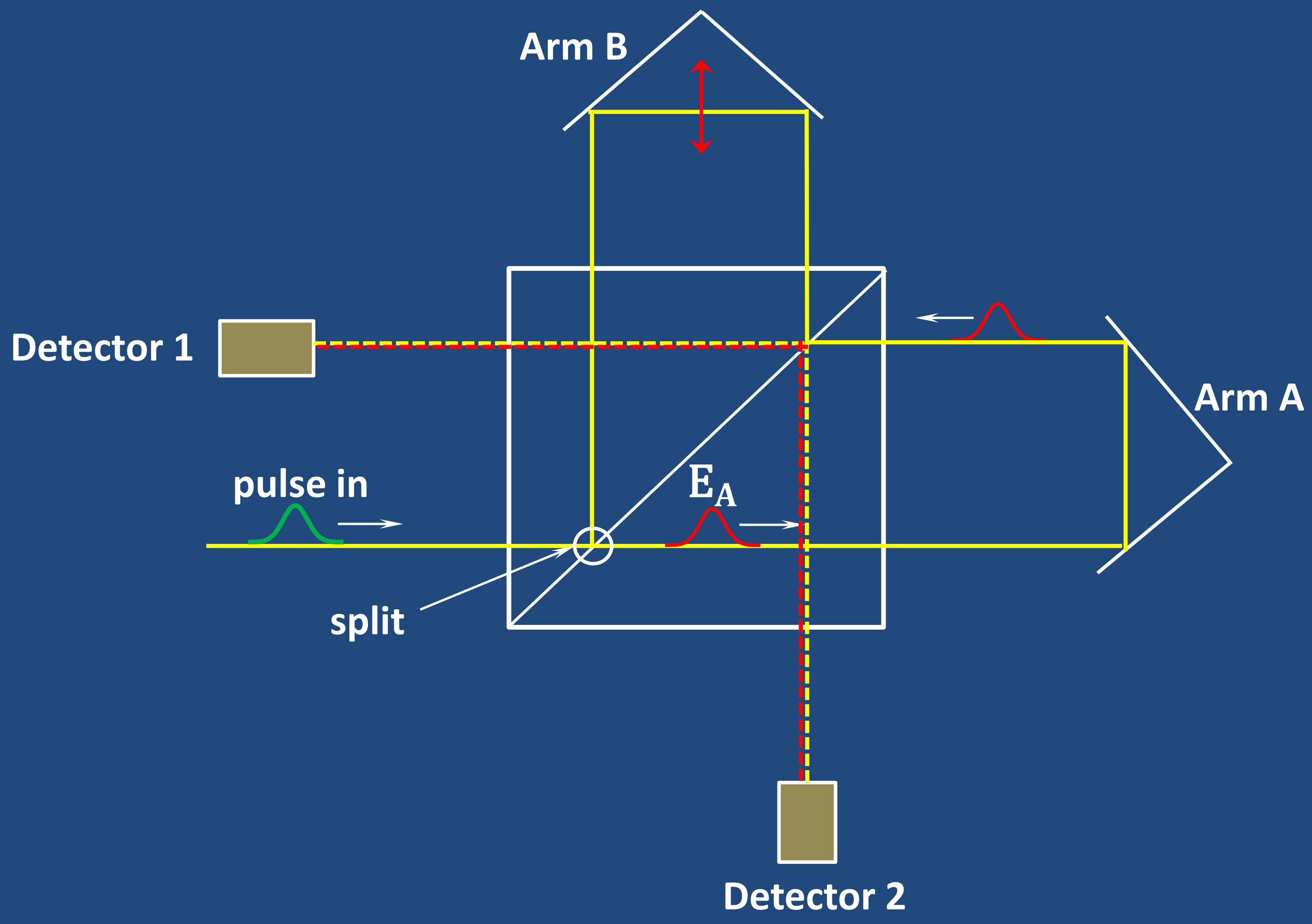

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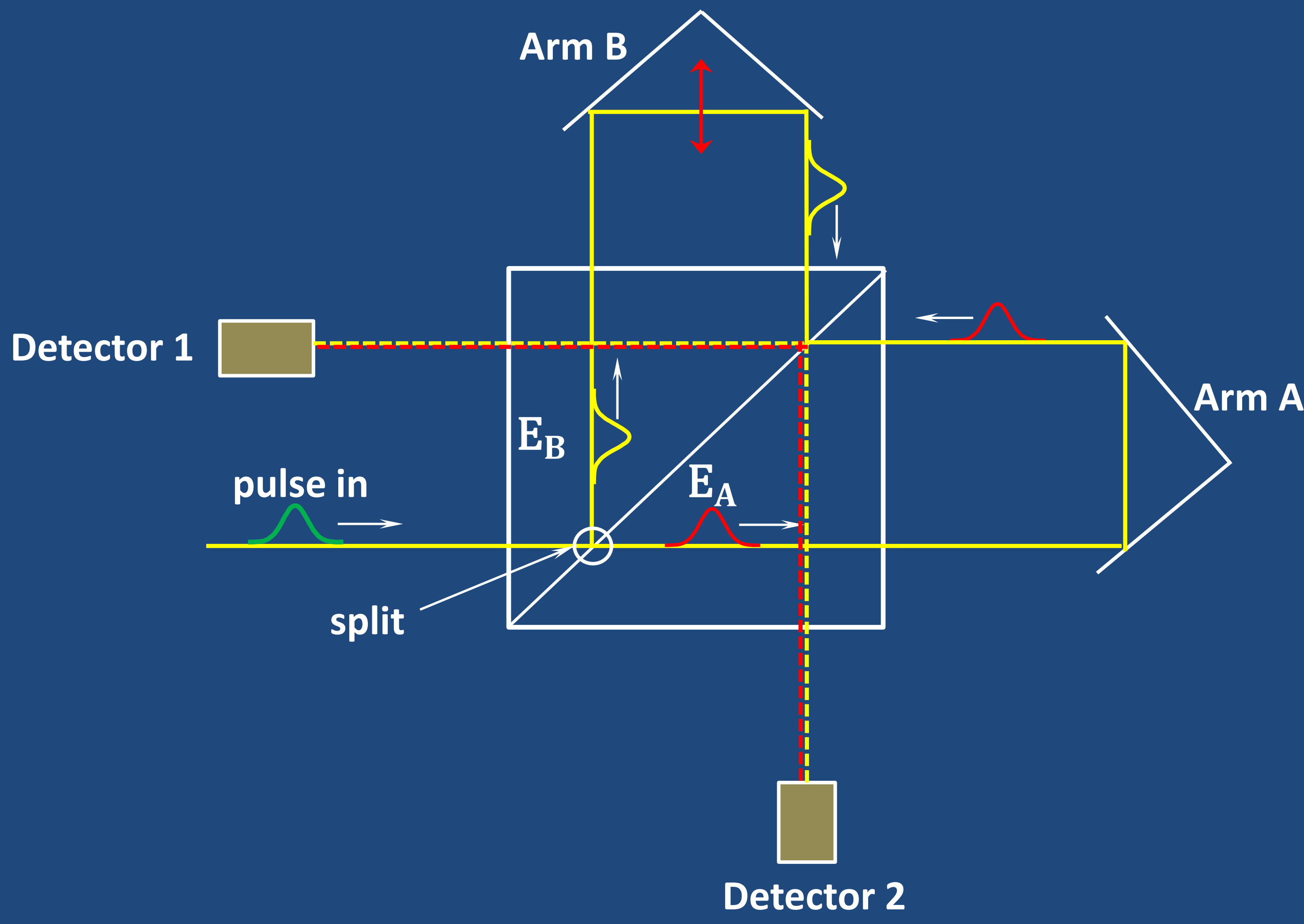

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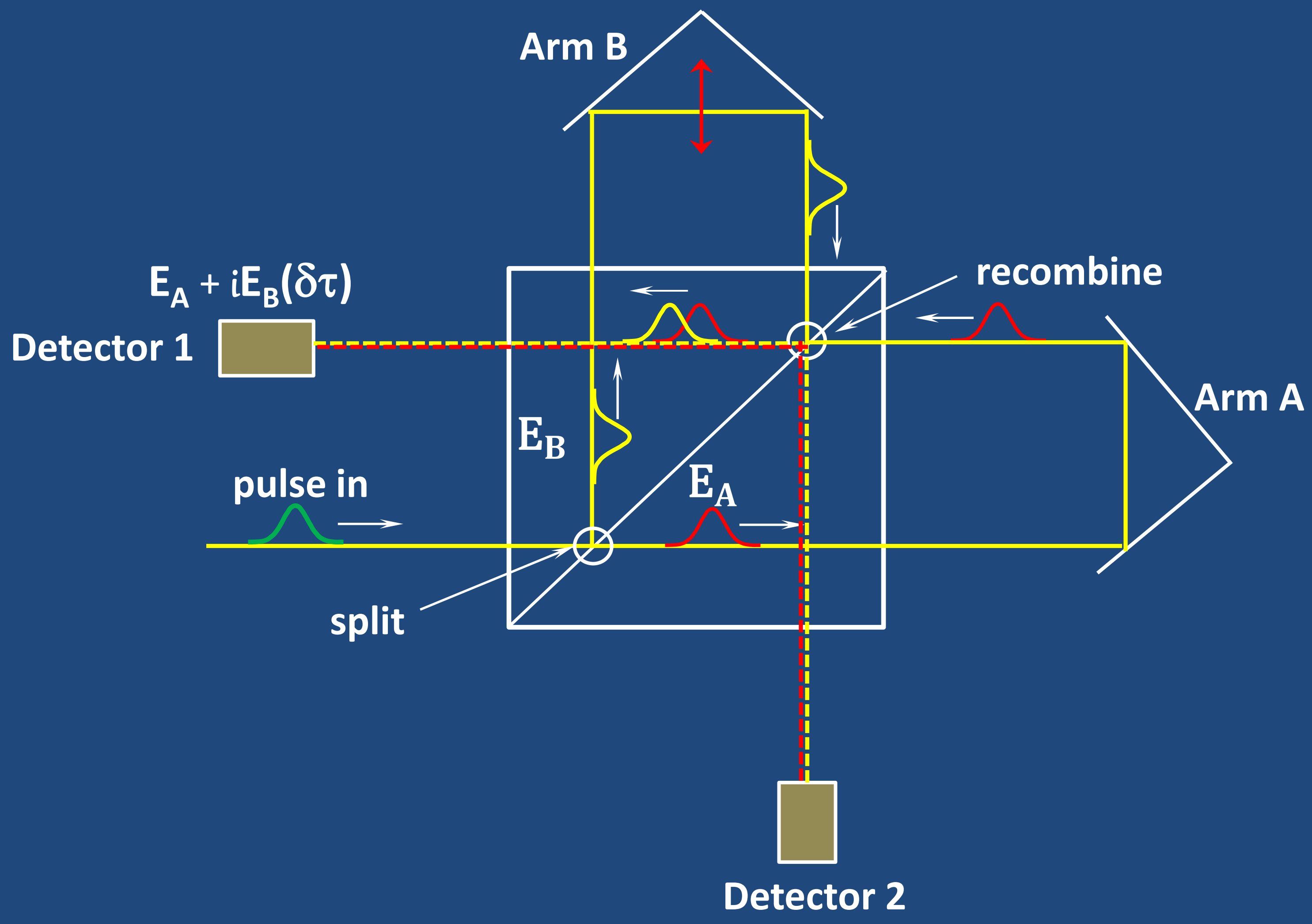

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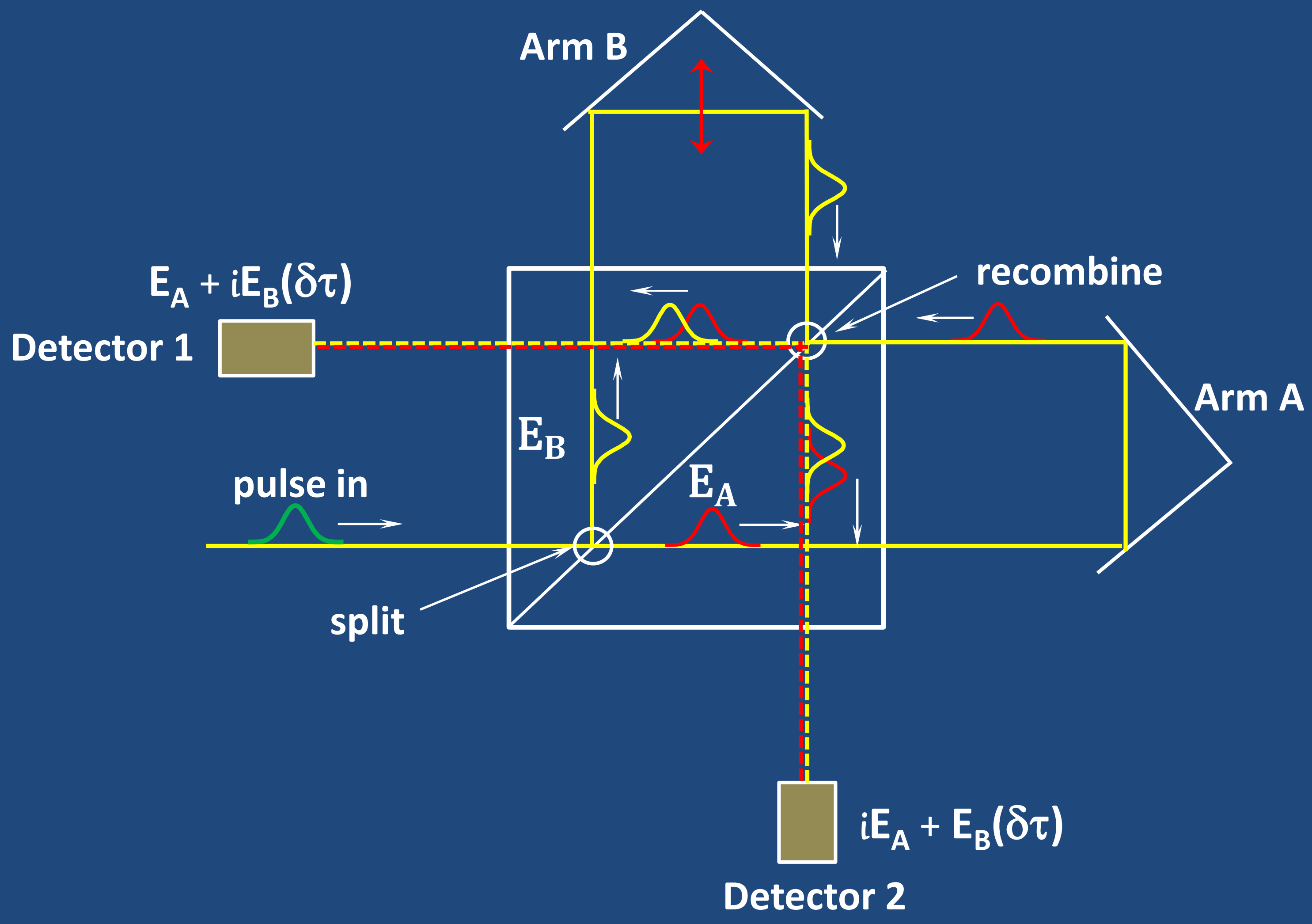
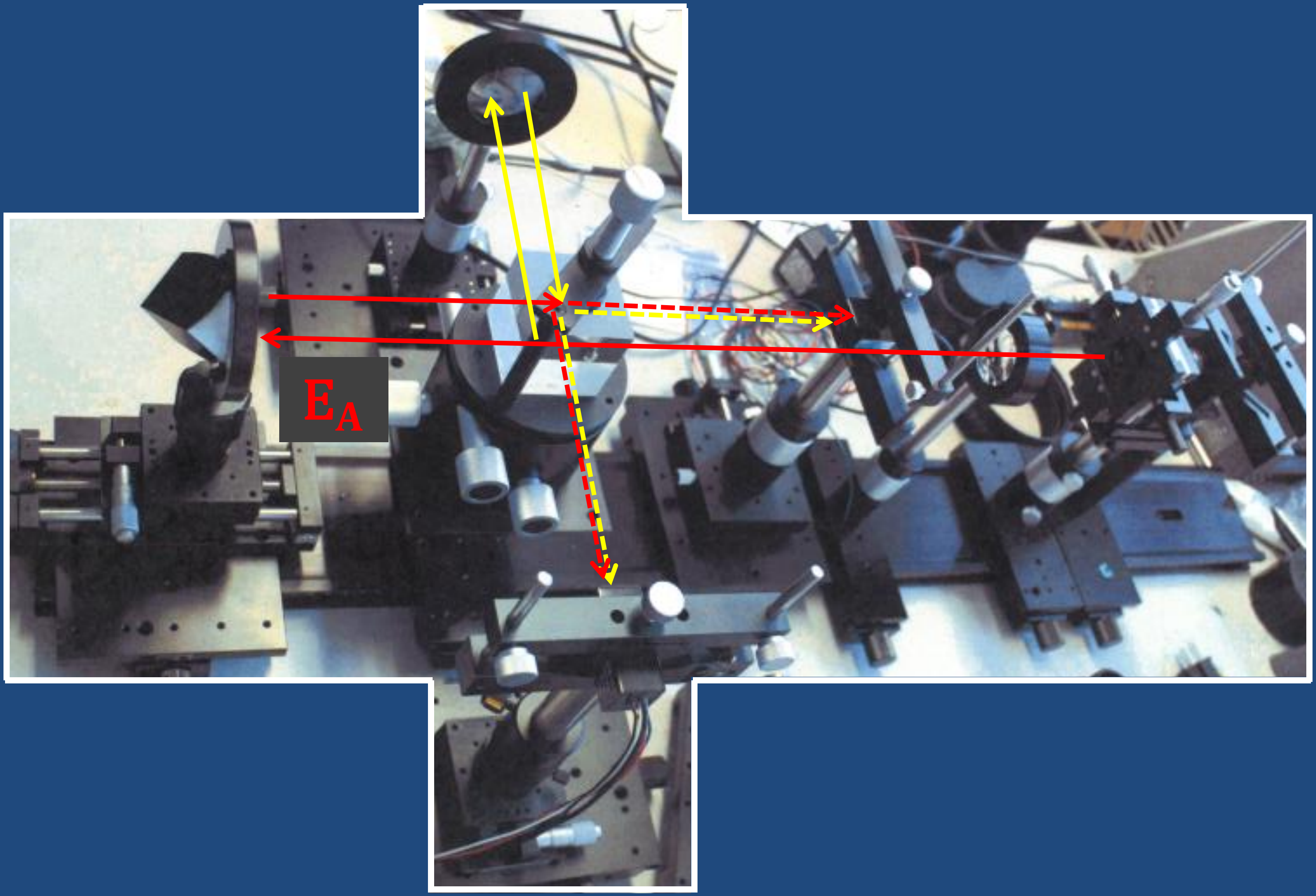


Interferometer Hardware



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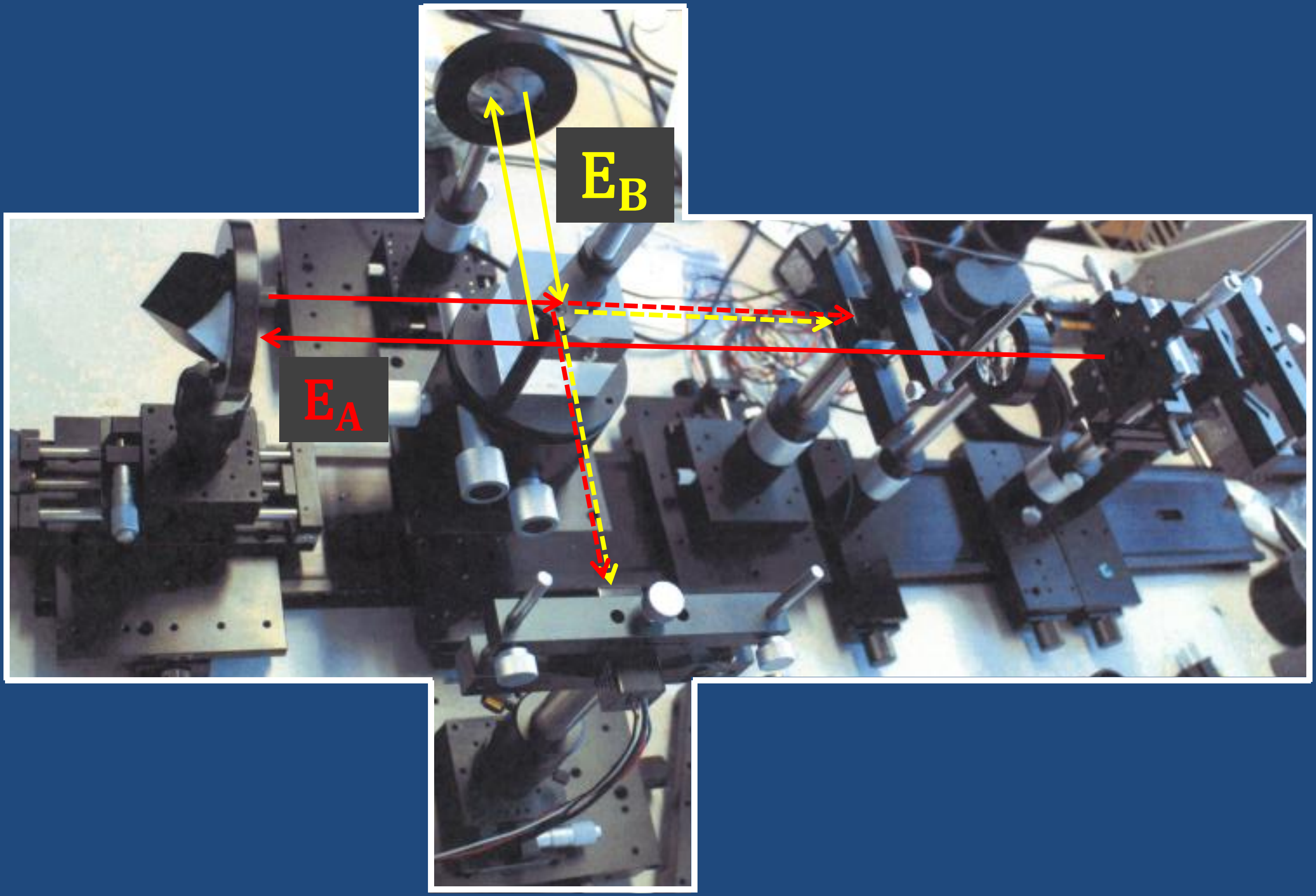

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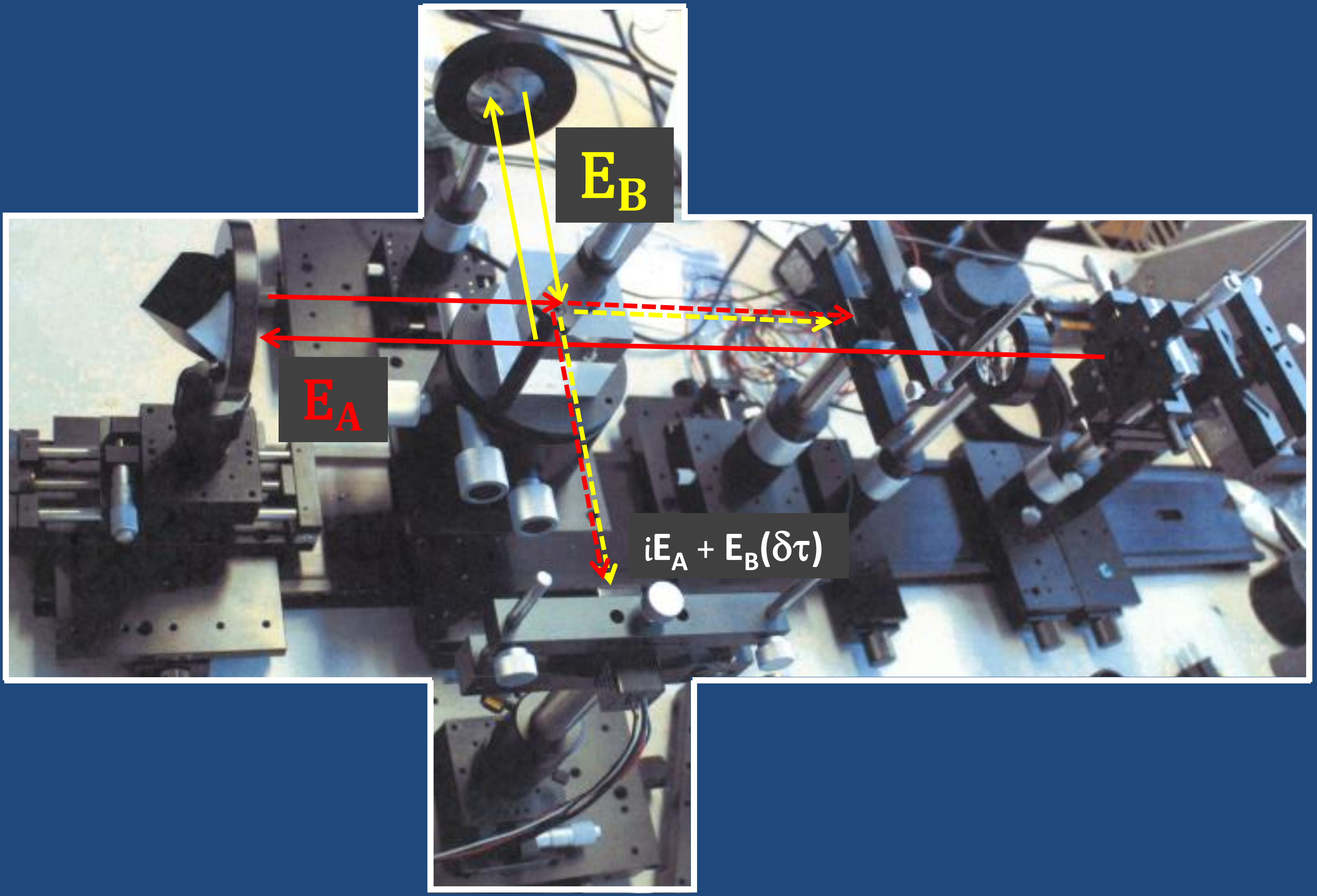

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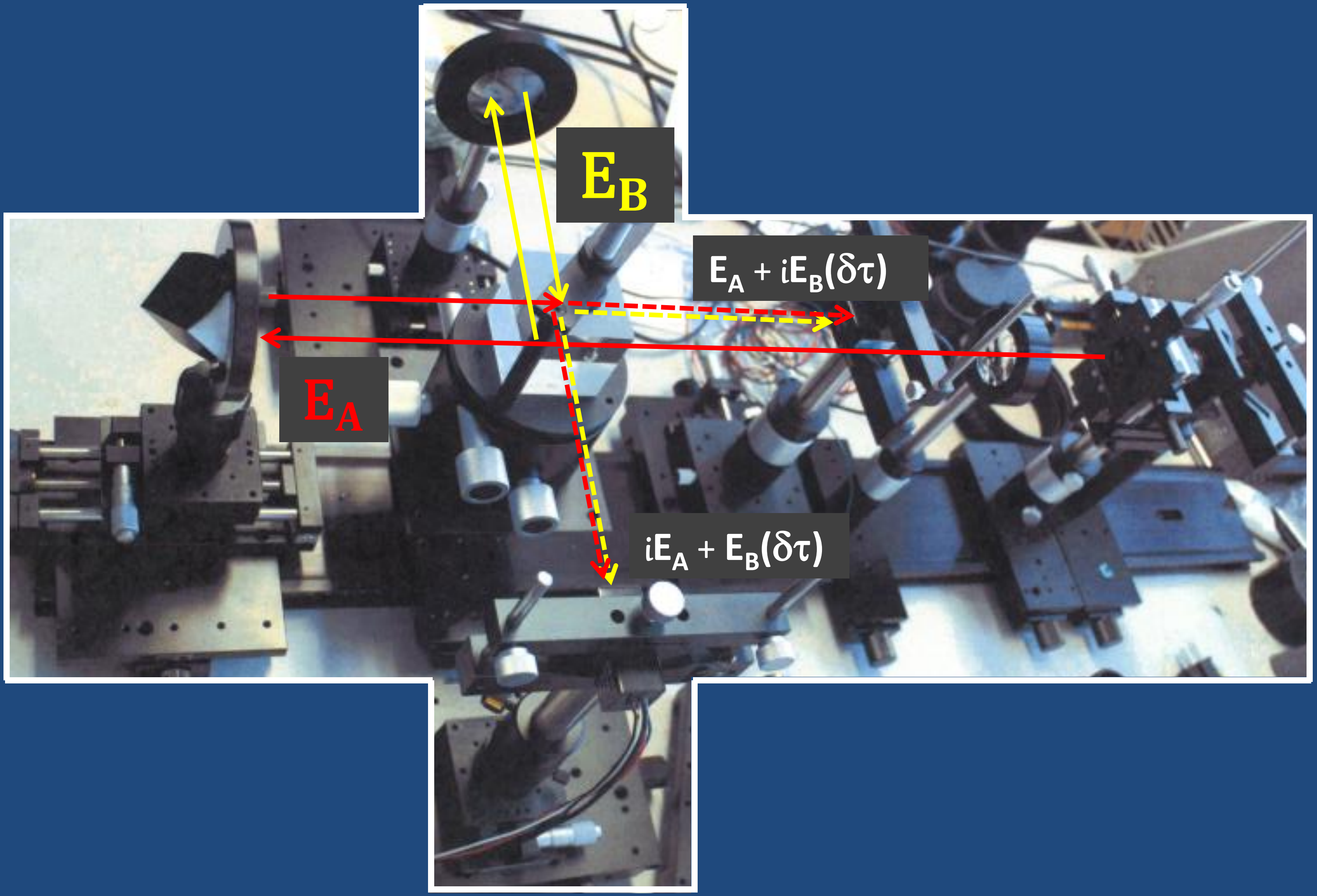
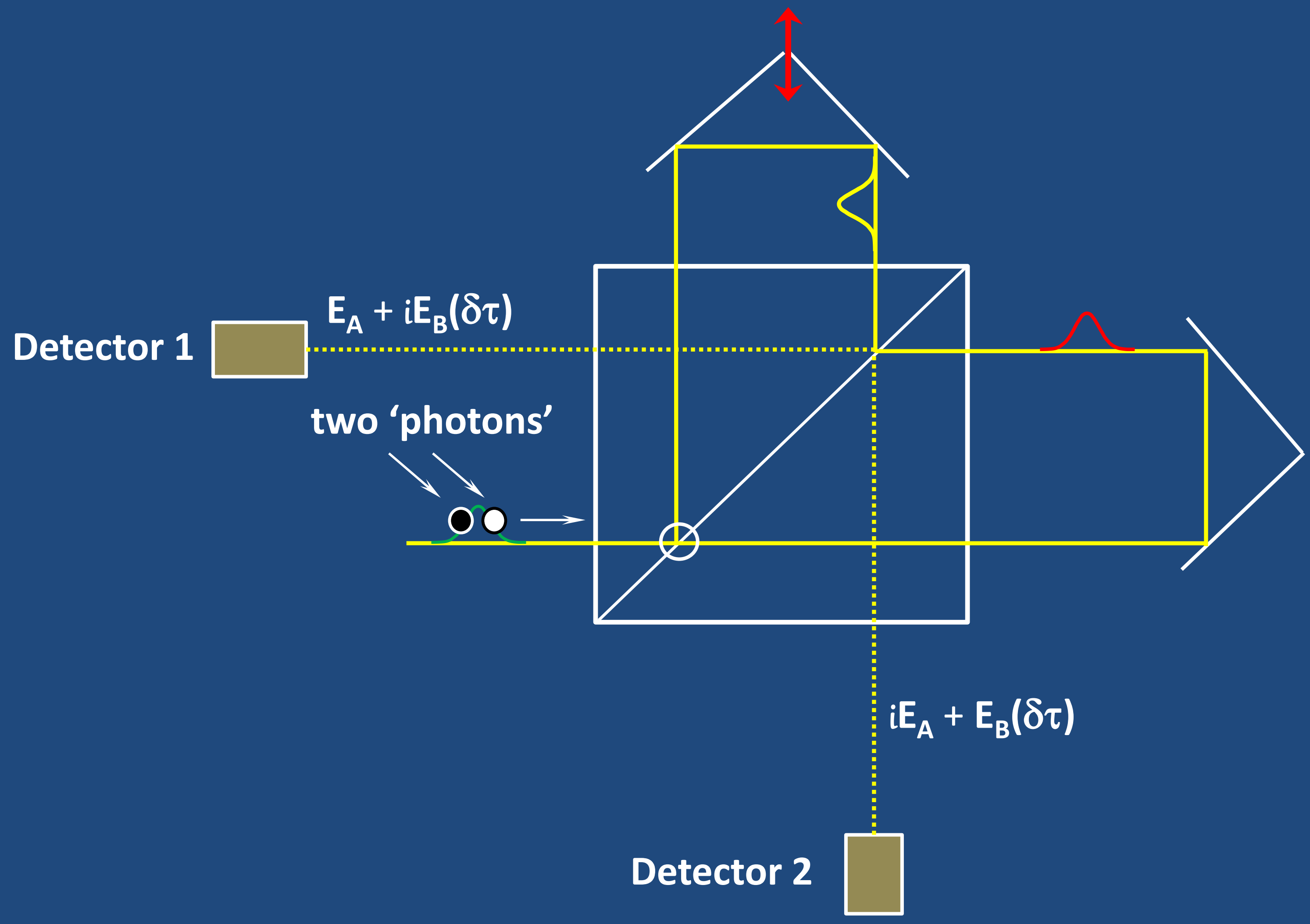


Important point – discrete 'photon' effect



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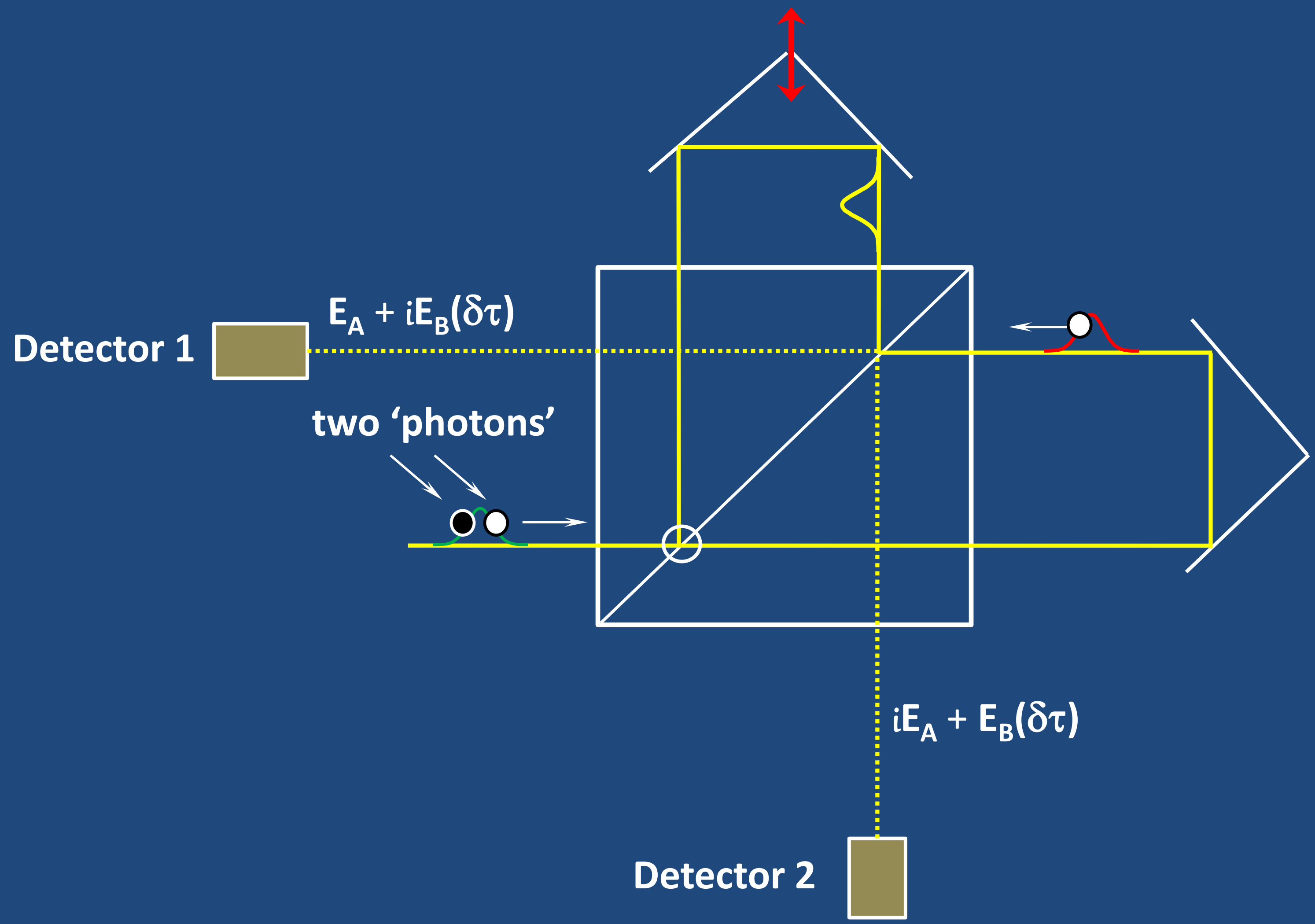

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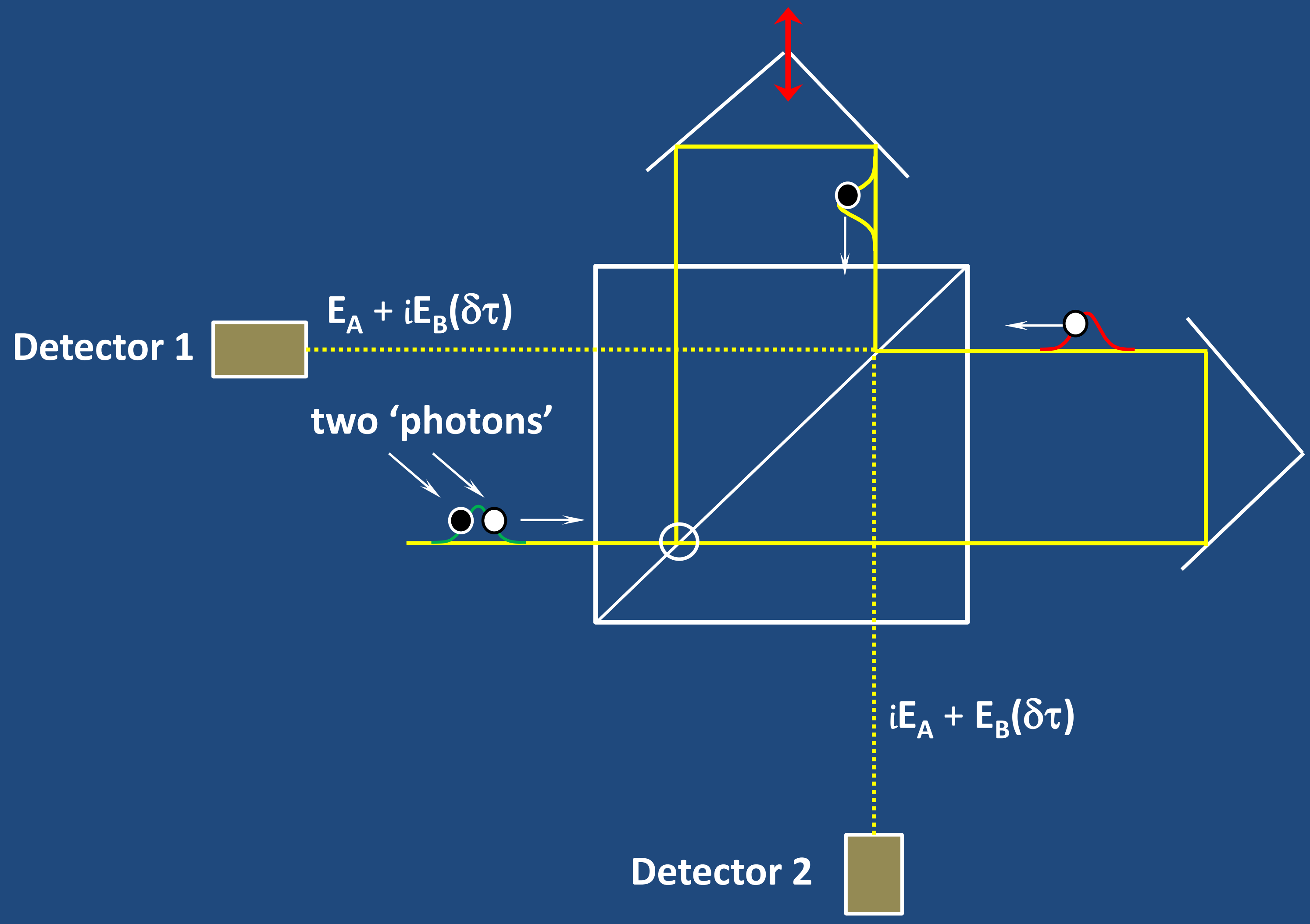

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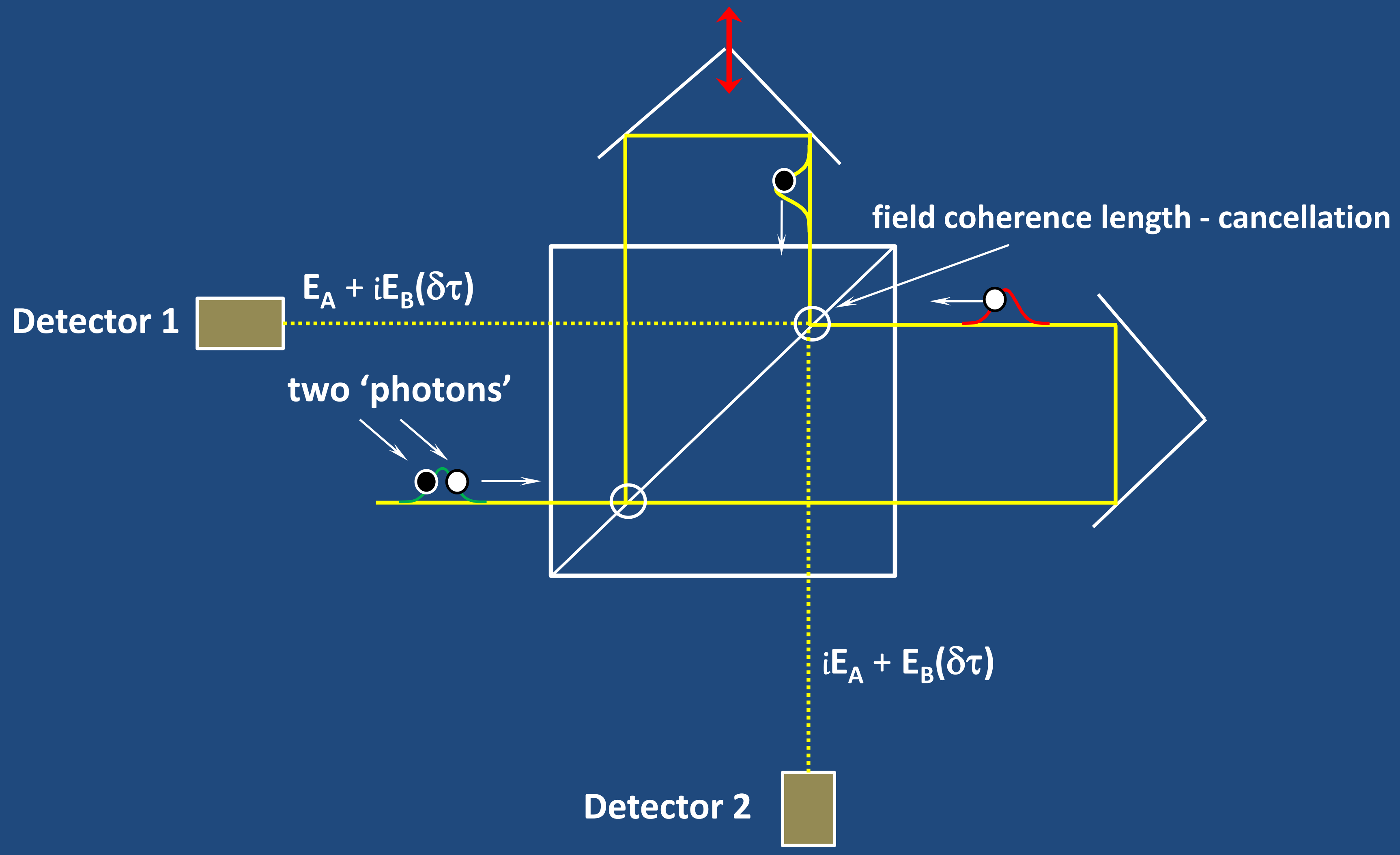

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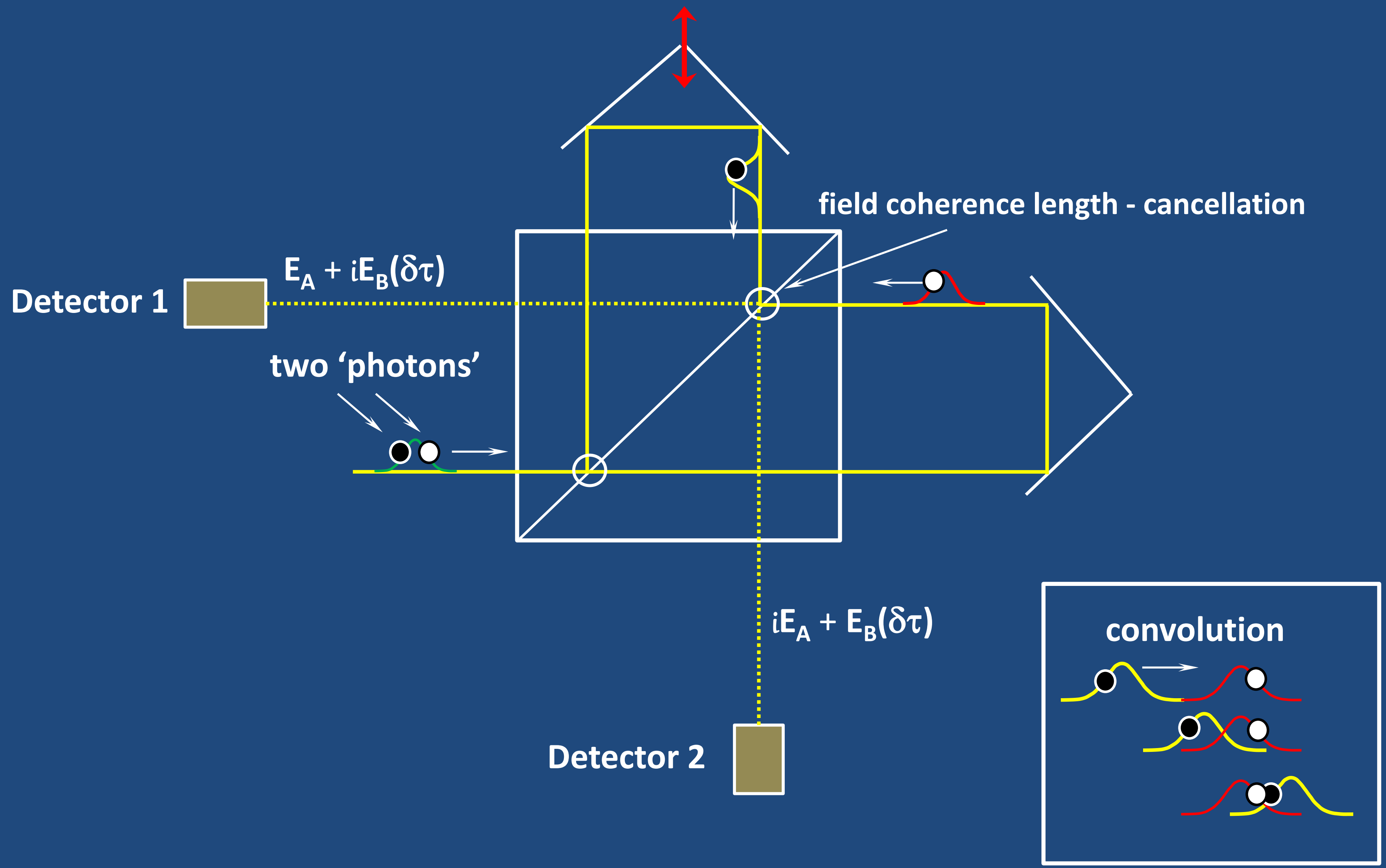
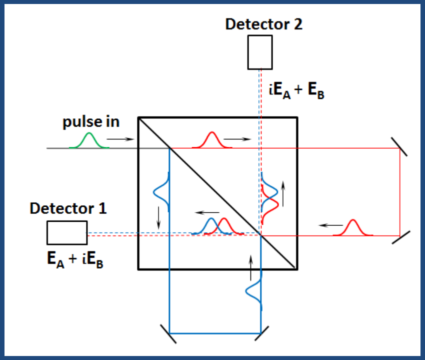
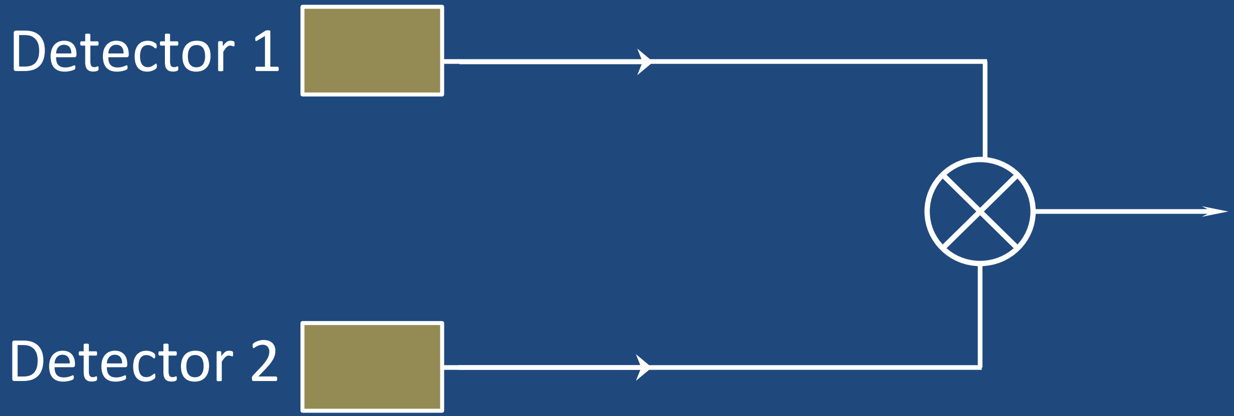


Coincidence detector
- model in terms of fields





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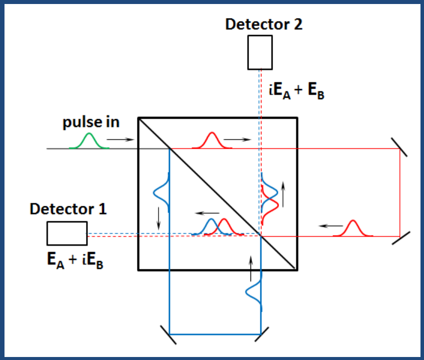
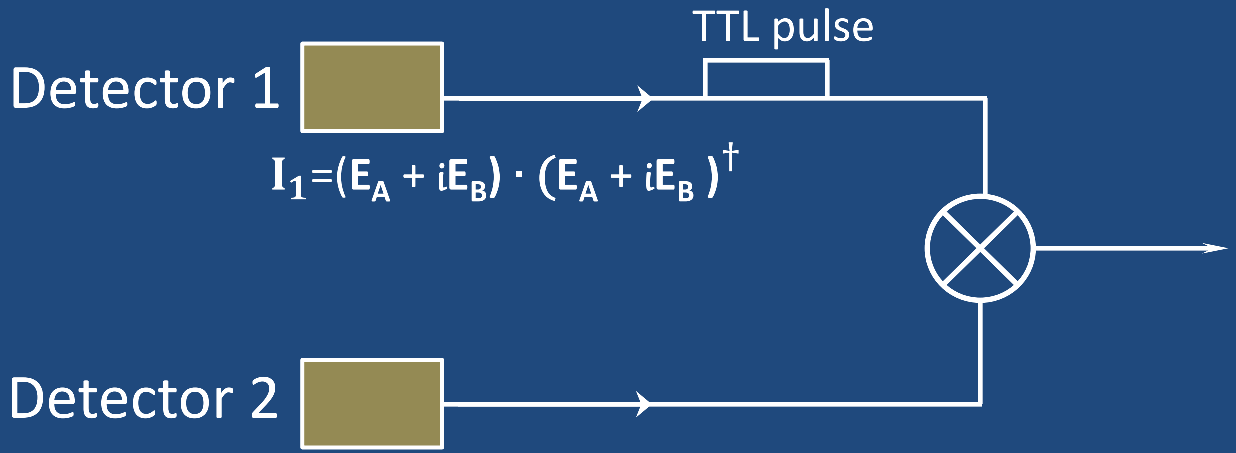
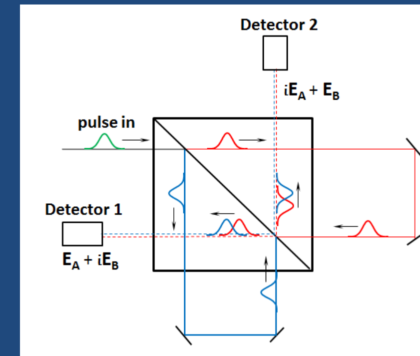


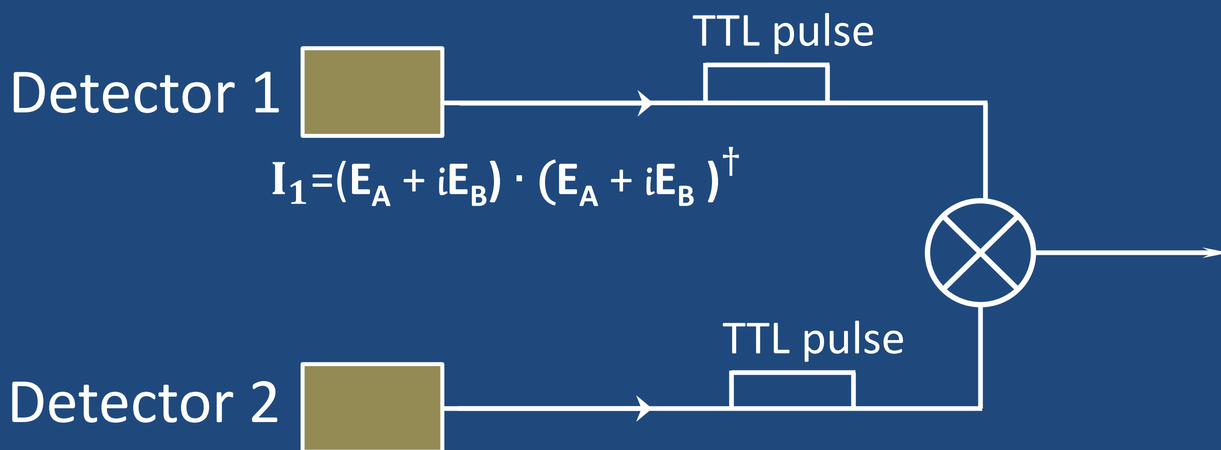


$I_1 = (E_A + iE_B) \cdot (E_A + iE_B)^\dagger$

Coincidence detector

- model in terms of fields





$$I_1 = (E_A + iE_B) \cdot (E_A + iE_B)^\dagger$$

$$I_2 = (iE_A + E_B) \cdot (iE_A + E_B)^\dagger$$

Coincidence detector

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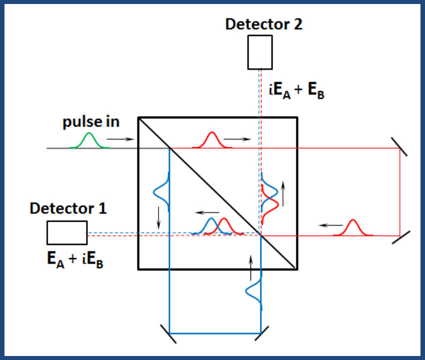
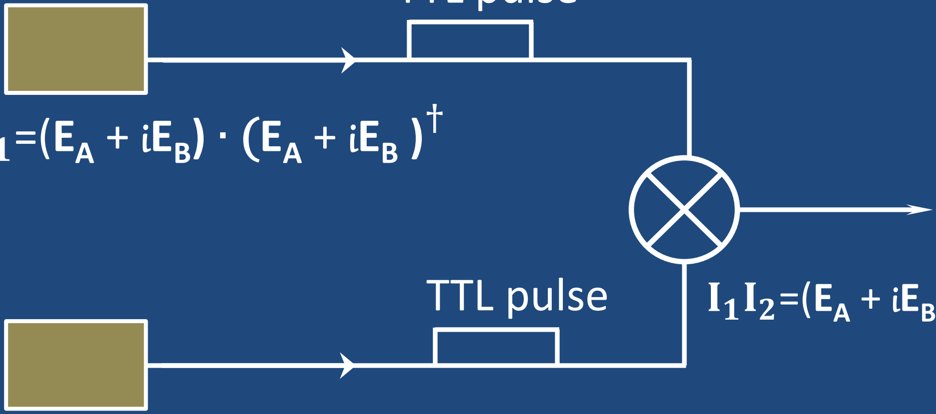




$I_1 = (E_A + iE_B) \cdot (E_A + iE_B)^\dagger$

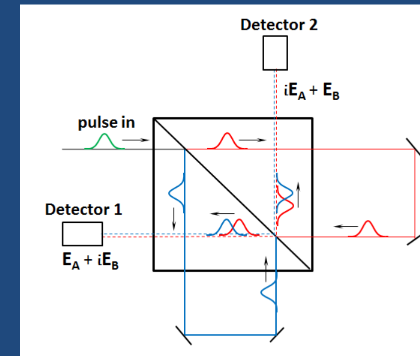
$\langle I_1 \cdot I_2 \rangle$

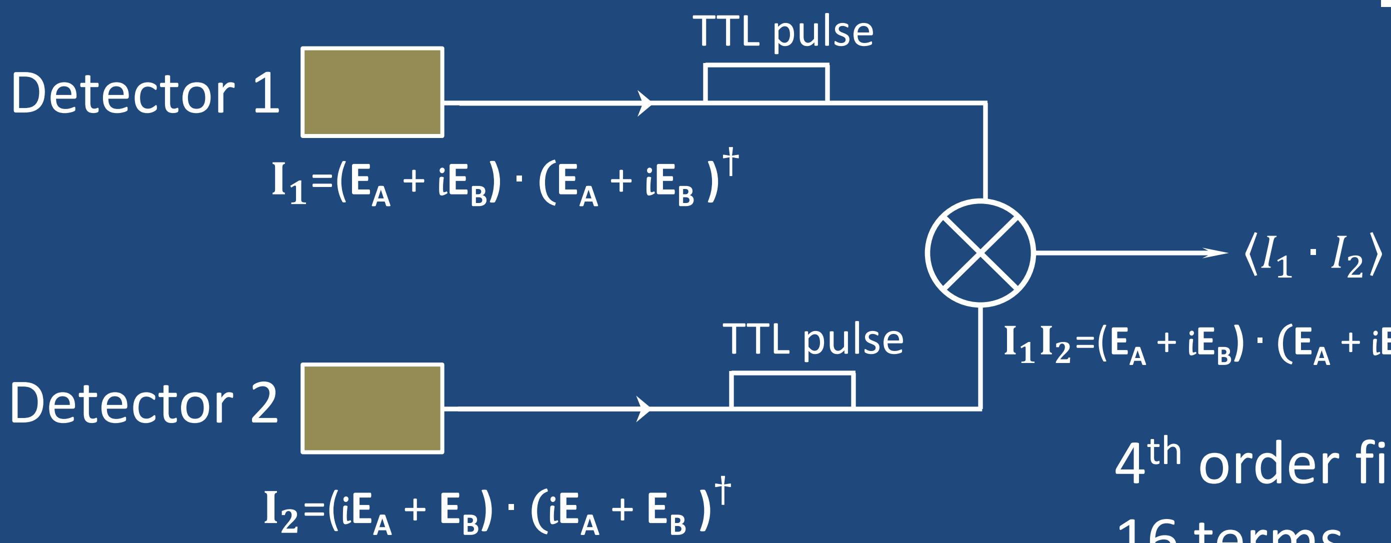
$I_1 I_2 = (E_A + iE_B) \cdot (E_A + iE_B)^\dagger \, (iE_A + E_B) \cdot (iE_A + E_B)^\dagger$

$I_2 = (iE_A + E_B) \cdot (iE_A + E_B)^\dagger$

Coincidence detector

- model in terms of fields





$$I_1 I_2 = (E_A + iE_B) \cdot (E_A + iE_B)^\dagger \, (iE_A + E_B) \cdot (iE_A + E_B)^\dagger$$

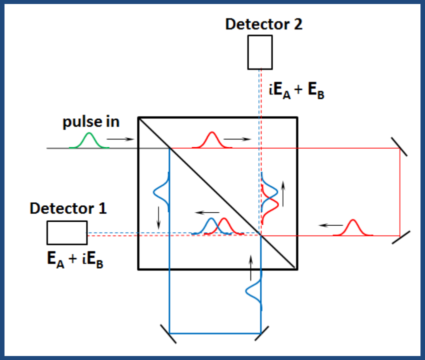
4th order field correlation

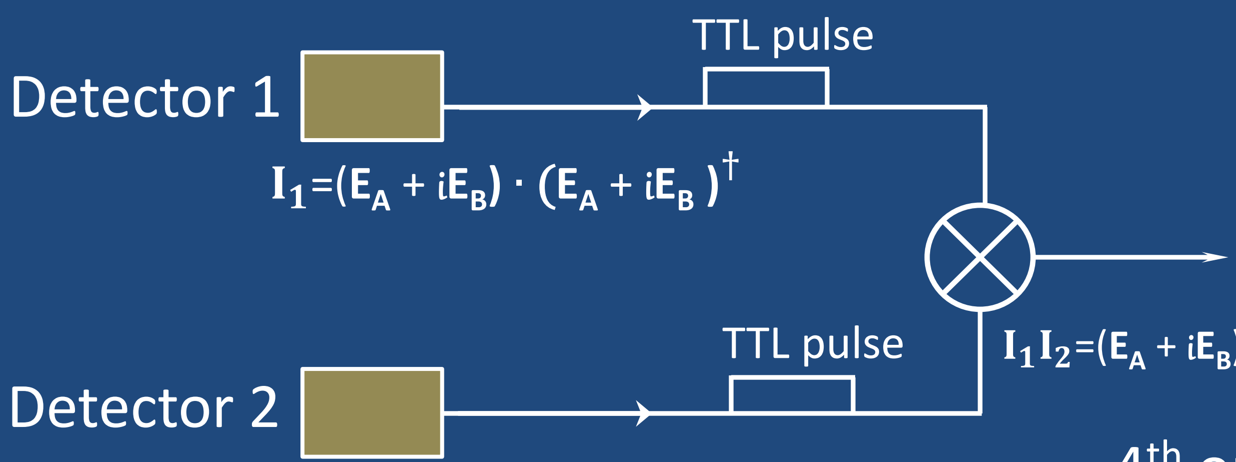
16 terms

- 8 complex terms
- four positive real terms
- four negative real terms

Coincidence detector

- model in terms of fields





$\mathbf{I_1 = (E_A + \imath E_B) \cdot (E_A + \imath E_B)^\dagger}$

$\mathbf{I_2 = (\imath E_A + E_B) \cdot (\imath E_A + E_B)^\dagger}$

$\langle I_1 \cdot I_2 \rangle$

$\mathbf{I_1 I_2 = (E_A + \imath E_B) \cdot (E_A + \imath E_B)^\dagger (\imath E_A + E_B) \cdot (\imath E_A + E_B)^\dagger}$

4th order field correlation

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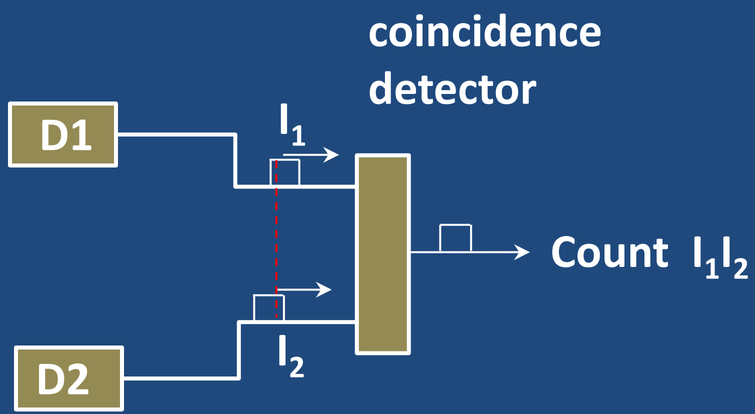
Interference effect

'dip' in signal as a function of overlap



$$I_1 I_2 = (E_A + iE_B)\cdot(E_A + iE_B)^\dagger\,(iE_A + E_B)\cdot(iE_A + E_B)^\dagger$$

$= \langle T^2 E_A^{(-)}(t)\, E_B^{(-)}(t+\tau)\, E_B^{(+)}(t+\tau)\, E_A^{(+)}(t)$ 1

$+\, i\, T\sqrt{T}\sqrt{R}\; E_A^{(-)}(t)\, E_B^{(-)}(t+\tau)\, E_B^{(+)}(t+\tau)\, E_B^{(+)}(t+dt)$ 2

$+\, i\, T\sqrt{T}\sqrt{R}\; E_A^{(-)}(t)\, E_B^{(-)}(t+\tau)\, E_A^{(+)}(t+\tau+d\tau)\, E_A^{(+)}(t)$ 3

$-\, T\cdot R\; E_A^{(-)}(t)\, E_B^{(-)}(t+\tau)\, E_A^{(+)}(t+\tau+d\tau)\, E_B^{(+)}(t+dt)$ 4

$+\, i\, T\sqrt{T}\sqrt{R}\; E_A^{(-)}(t)\, E_A^{(-)}(t+\tau+d\tau)\, E_B^{(+)}(t+\tau)\, E_A^{(+)}(t)$ 5

$-\, RT\; E_A^{(-)}(t)\, E_A^{(-)}(t+\tau+d\tau)\, E_B^{(+)}(t+\tau)\, E_B^{(+)}(t+dt)$ 6

$-\, RT\; E_A^{(-)}(t)\, E_A^{(-)}(t+\tau+d\tau)\, E_A^{(+)}(t+\tau+d\tau)\, E_A^{+}(t)$ 7

$-\, i\, R\sqrt{R}\sqrt{T}\; E_A^{(-)}(t)\, E_A^{(-)}(t+\tau+d\tau)\, E_A^{(+)}(t+\tau+d\tau)\, E_B^{(+)}(t+dt)$ 8

以上の16項をとる、

$+\, i\, T\sqrt{T}\sqrt{R}\; E_B^{(-)}(t+d\tau)\, E_B^{(-)}(t+\tau)\, E_B^{(+)}(t+\tau)\, E_A^{(+)}(t)$ 9

$-\, TR\; E_B^{(-)}(t+d\tau)\, E_B^{(-)}(t+\tau)\, E_B^{(+)}(t+\tau)\, E_B^{(+)}(t+dt)$ 10

$-\, TR\; E_B^{(-)}(t+d\tau)\, E_B^{(-)}(t+\tau)\, E_A^{(+)}(t+\tau+d\tau)\, E_A^{(+)}(t)$ 11

$-\, i\, R\sqrt{R}\sqrt{T}\; E_B^{(-)}(t+d\tau)\, E_B^{(-)}(t+\tau)\, E_A^{(+)}(t+d\tau)\, E_B^{(+)}(t+dt)$ 12

$-\, TR\; E_B^{(-)}(t+d\tau)\, E_A^{(-)}(t+\tau+d\tau)\, E_B^{(+)}(t+\tau)\, E_A^{(+)}(t)$ 13

$-\, i\, R\sqrt{R}\sqrt{T}\; E_B^{(-)}(t+d\tau)\, E_A^{(-)}(t+\tau+d\tau)\, E_B^{(+)}(t+\tau)\, E_B^{(+)}(t+dt)$ 14

$-\, i\, R\sqrt{R}\sqrt{T}\; E_B^{(-)}(t+d\tau)\, E_A^{(-)}(t+\tau+d\tau)\, E_A^{(+)}(t+\tau+d\tau)\, E_A^{(+)}(t)$ 15

$+\, R^2\; E_B^{(-)}(t+d\tau)\, E_A^{(-)}(t+\tau+d\tau)\, E_A^{(+)}(t+\tau+d\tau)\, E_B^{(+)}(t+dt)$ 16

T. Mitsuhashi

$$\mathbf{I_1 I_2} = (E_A + iE_B) \cdot (E_A + iE_B)^\dagger \, (iE_A + E_B) \cdot (iE_A + E_B)^\dagger$$

Integrate $\mathbf{I_1 I_2}$ over detector time and sample time

Answer:

$$C_{12}(\delta\tau) = K\left\{1 + \frac{\tau_c}{\tau_p}\left[1 - \frac{1}{2} exp\left(-\frac{\delta\tau^2}{4\tau_p^2}\right)\right]\right\}$$

$$\mathbf{I}_1\mathbf{I}_2 = (\mathbf{E}_A + i\mathbf{E}_B) \cdot (\mathbf{E}_A + i\mathbf{E}_B)^\dagger \, (i\mathbf{E}_A + \mathbf{E}_B) \cdot (i\mathbf{E}_A + \mathbf{E}_B)^\dagger$$

Integrate $\mathbf{I}_1\mathbf{I}_2$ over detector time and sample time

Answer:

$$C_{12}(\delta\tau) = K\left\{1 + \frac{\tau_c}{\tau_p}\left[1 - \frac{1}{2} exp\left(-\frac{\delta\tau^2}{4\tau_p^2}\right)\right]\right\}$$

Pulse length

$$\mathbf{I_1 I_2} = (E_A + iE_B)\cdot(E_A + iE_B)^\dagger\,(iE_A + E_B)\cdot(iE_A + E_B)^\dagger$$

Integrate $\mathbf{I_1 I_2}$ over detector time and sample time

Coherence time

Answer:

$$C_{12}(\delta\tau) = K\left\{1 + \frac{\tau_c}{\tau_p}\left[1 - \frac{1}{2}exp\left(-\frac{\delta\tau^2}{4\tau_p^2}\right)\right]\right\}$$

Pulse length

$$\mathbf{I_1 I_2} = (E_A + iE_B)\cdot(E_A + iE_B)^\dagger\,(iE_A + E_B)\cdot(iE_A + E_B)^\dagger$$

Integrate $\mathbf{I_1 I_2}$ over detector time and sample time

Coherence time

Stage delay

Answer:

$$C_{12}(\delta\tau) = K\left\{1 + \frac{\tau_c}{\tau_p}\left[1 - \frac{1}{2}exp\left(-\frac{\delta\tau^2}{4\tau_p^2}\right)\right]\right\}$$

Pulse length

$$\mathbf{I_1 I_2} = (E_A + iE_B)\cdot(E_A + iE_B)^{\dagger}\,(iE_A + E_B)\cdot(iE_A + E_B)^{\dagger}$$

Integrate $\mathbf{I_1 I_2}$ over detector time and sample time

Coherence time

Stage delay

Answer:

$$C_{12}(\delta\tau) = K\left\{1 + \frac{\tau_c}{\tau_p}\left[1 - \frac{1}{2}exp\left(-\frac{\delta\tau^2}{4\tau_p^2}\right)\right]\right\}$$

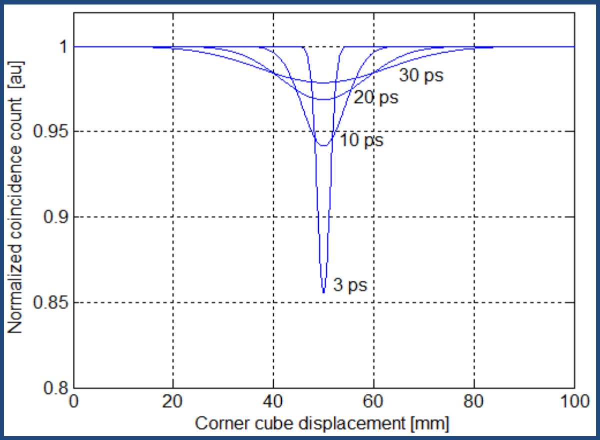
Pulse length

signal reduction (interference)

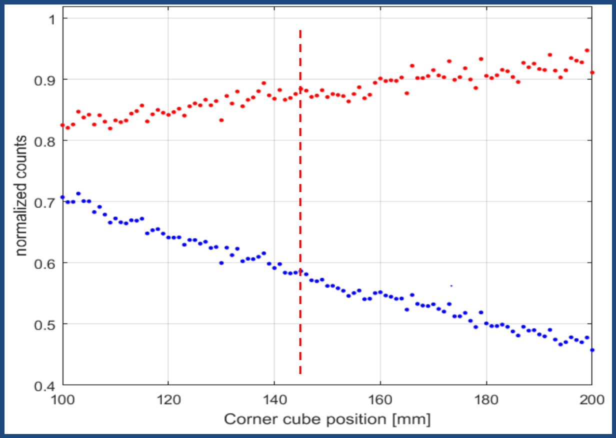
$\tau_c/\tau_p \sim$ 5-10%

Experimental results

expected value



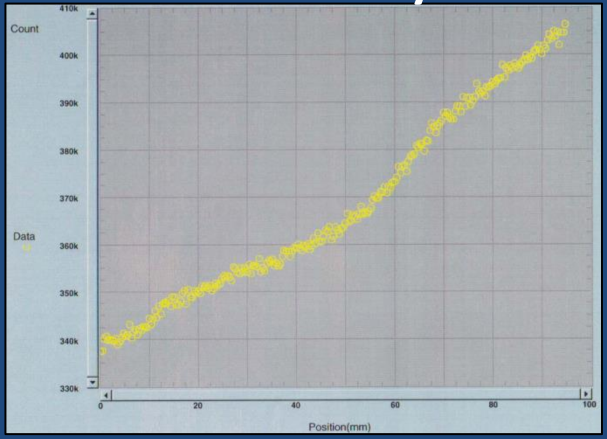
last SPEAR3 scan



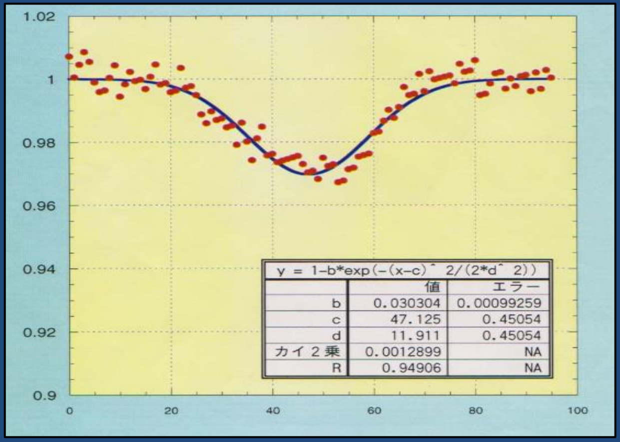
normalized

raw data

Photon Factory scan



PF data 'flattened'



$$C_{12}(\delta\tau) = K\left\{1 + \frac{\tau_c}{\tau_p}\left[1 - \frac{1}{2}exp\left(-\frac{\delta\tau^2}{4\tau_p^2}\right)\right]\right\}$$

Conclusion

Intensity interferometer approach:

- good for weak, incoherent light (single photon)
- insensitive to synchrotron oscillations
- best for short bunches
- relatively low cost
- fascinating physics

Thank you, enjoy IPAC17 !