Speed of light anisotropy

Bogdan Wojtsekhowski, Jefferson Lab

- ~150 years of experiments
- Basic of special relativity

Speed of light

Bogdan Wojtsekhowski, Jefferson Lab

- 400 years of experiments
- One-way speed without a clock
- Concept of a new experiment

Speed of light

Bogdan Wojtsekhowski, Jefferson Lab

- 4000 years of experiments
- One-way speed without a clock
- Concept of a new experiment

History of the measurements

1638 Galilei: at least 10 times faster than sound

1675 Roemer: 200,000 km/sec (Jupiter's moons)

1728 Bradley: 301,000 km/s (Stellar aberration)

1849 Fizeau: 313,300 km/s (toothed wheel)

1862 Foucault: 299,796 km/s (rotating mirror)

Today: 299,792.458 km/s

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"A human controlled pulse light source" – Modern day experiment!
The idea is to have two people far away from each other, with covered lanterns. One uncovers his lantern, then the other immediately uncovers his on seeing the light from the first. This routine is to be practised with the two close together, so they will get used to the reaction times involved, then they are to do it two or three miles apart, or even further using telescopes, to see if the time interval is perceptibly lengthened. Galileo tried the experiment at distances less than a mile, and couldn't detect a time lag.

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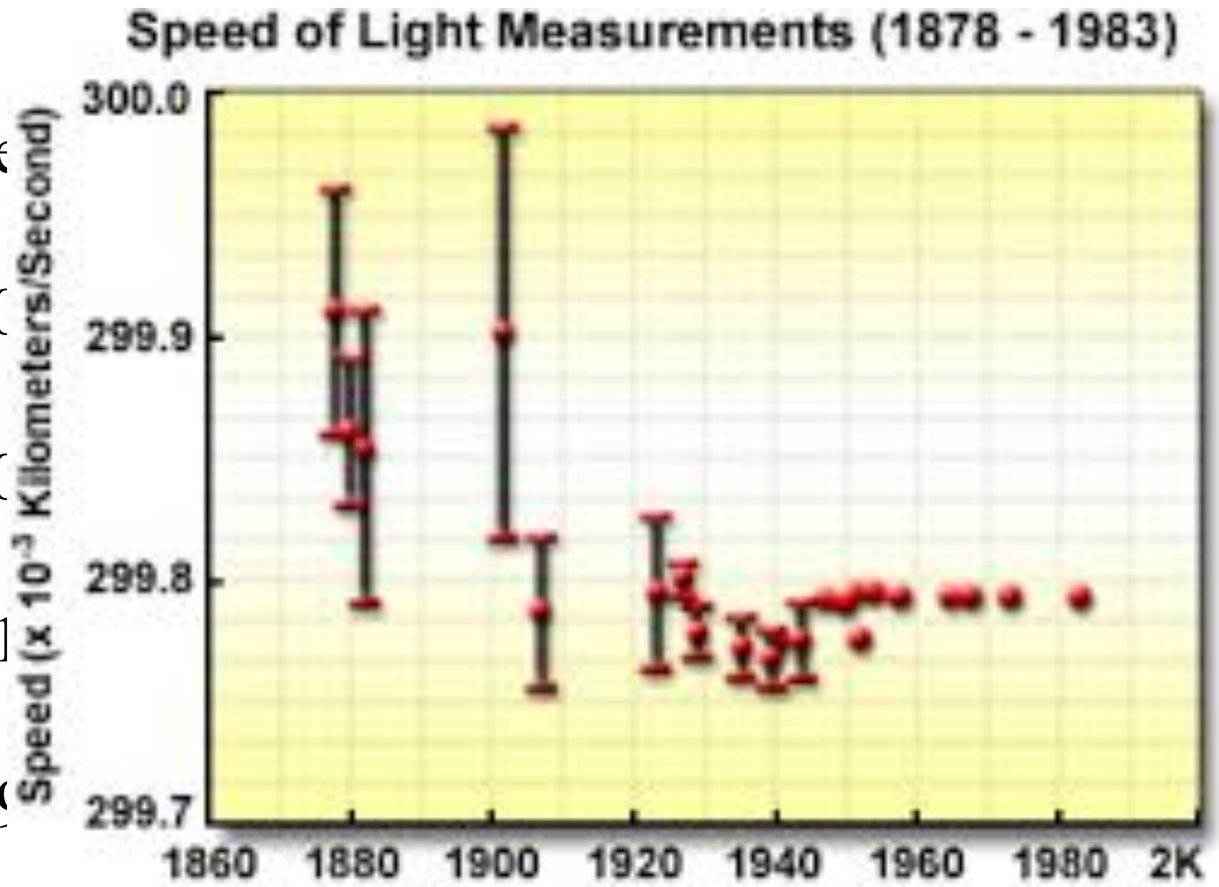

Today: 299,792.458 km/s

Einstein's postulates of physics

The laws by which the states of physical systems undergo change are not affected, whether these changes of state be referred to the one or the other of two systems of coordinates in uniform translatory motion.

Any ray of light moves in the "stationary" system of coordinates with determined velocity ***c***, whether the ray be emitted by a stationary or by a moving body.

*Einstein, Ann. d. Physik **17** (1905)*

The speed of light measurement

The speed of light is said to be *isotropic* if it has the same value when measured in any/every direction.
The constancy of the one-way speed in any given inertial frame is the basis of the special theory of relativity.

How do we measure the speed?

one-way: $v_1 = d_{AB}/t_{AB}$

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Require high precision synchronized clocks

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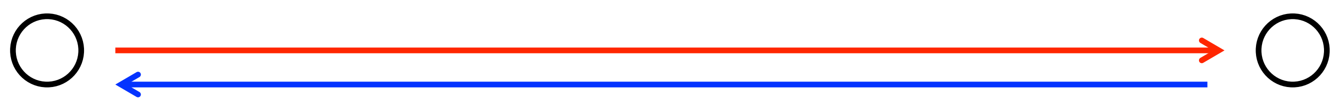

A

round-trip:
$v_2 = (d_{AB}+d_{BA})/(t_{AB}+t_{AB})$

B

The speed of light

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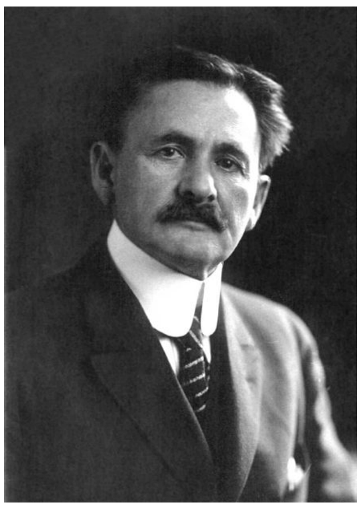
One-way speed and two-way speed: What is the difference?

What is experimentally investigated most often is the **round-trip speed** (or **"two-way" speed of light**) from the source to the detector and back.

Michelson-Morley experiment

Search for the media of light in the 1850s:
Motion relative to the Earth could be a signature!
Ether movement: v = 30 km/s = c/10,000



The v/c is "large", but without a pair of clocks the direct measurement is not possible.

The round trip speed measurement does not require two clocks but is sensitive only to $(v/c)^2$.

Michelson: Interference pattern provides a very high sensitivity for the round trip arrangement.

Michelson-Morley experiment

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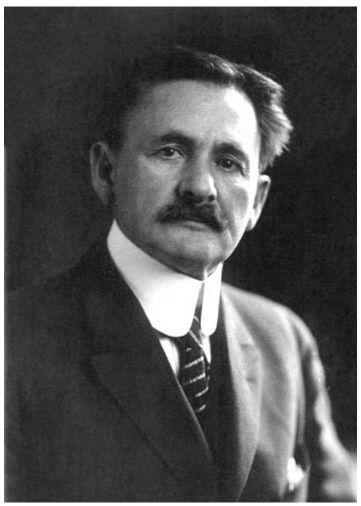

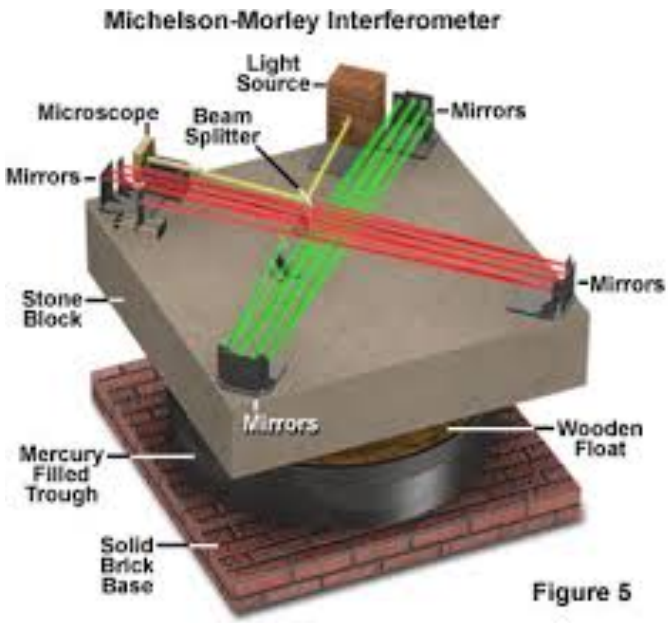

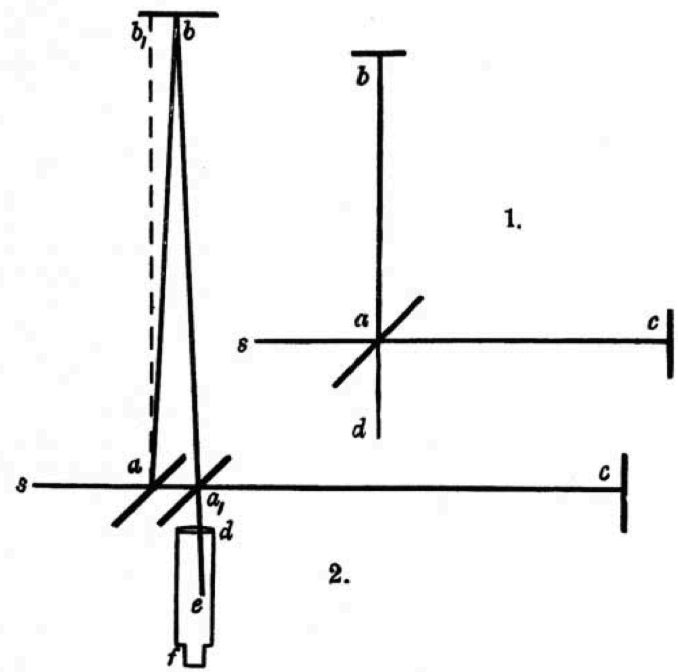

accuracy scale: 1μm / 10m ~ 10^{-7}

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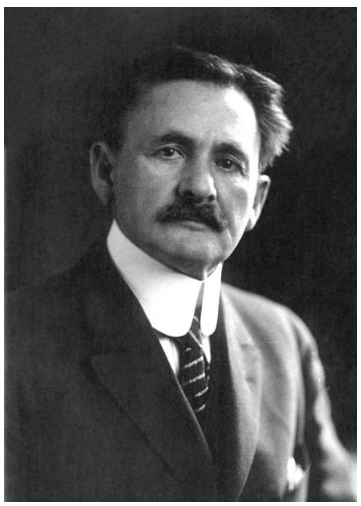
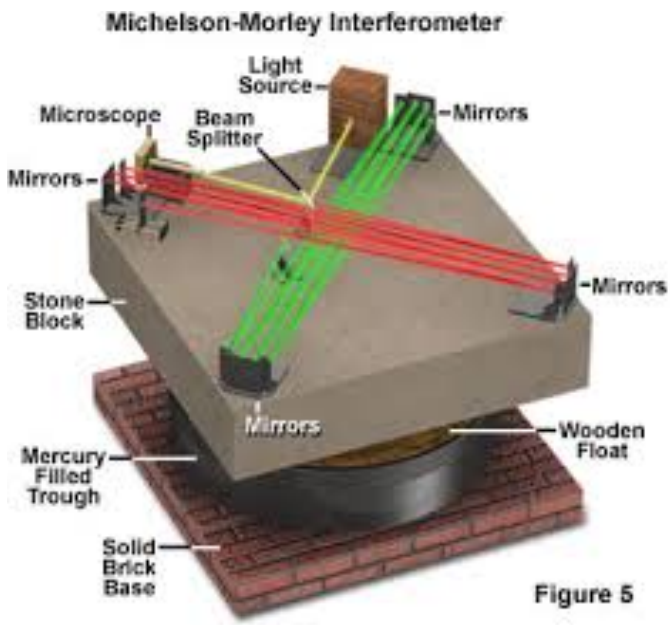
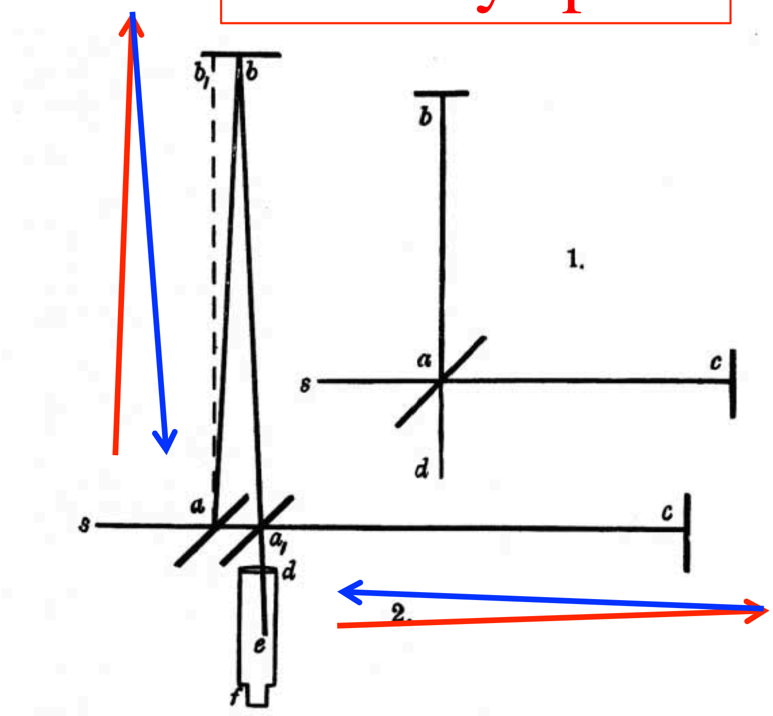
two-way speed







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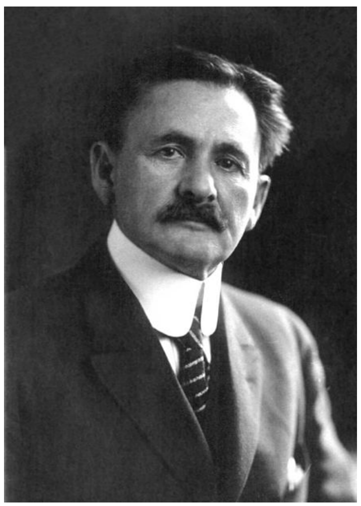


NOON OBSERVATIONS.

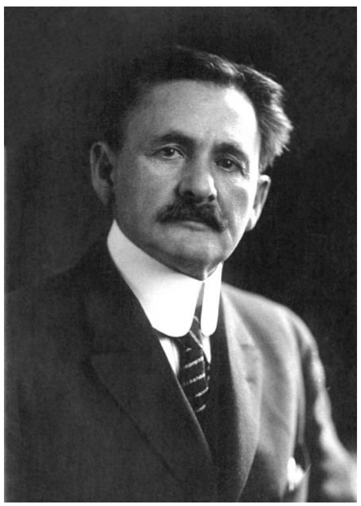
	16.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.
July 8	44·7	44·0	43·5	39·7	35·2	34·7	34·3	32·5	28·2	26·2	23·8	23·2	20·3	18·7	17·5	16·8	13·7
July 9	57·4	57·3	58·2	59·2	58·7	60·2	60·8	62·0	61·5	63·3	65·8	67·3	69·7	70·7	73·0	70·2	72·2
July 11	27·3	23·5	22·0	19·3	19·2	19·3	18·7	18·8	16·2	14·3	13·3	12·8	13·3	12·3	10·2	7·3	6·5
Mean........	43·1	41·6	41·2	39·4	37·7	38·1	37·9	37·8	35·3	34·6	34·3	34·4	34·4	33·9	33·6	31·4	30·8
Mean in w. l.	·862	·832	·824	·788	·754	·762	·758	·756	·706	·692	·686	·688	·688	·678	·672	·628	·616
	·706	·692	·686	·688	·688	·678	·672	·628	·616								
Final mean.	·784	·762	·755	·738	·721	·720	·715	·692	·661								

P. M. OBSERVATIONS.

July 8	61·2	63·3	63·3	68·2	67·7	69·3	70·3	69·8	69·0	71·3	71·3	70·5	71·2	71·2	70·5	72·5	75·7
July 9	26·0	26·0	28·2	29·2	31·5	32·0	31·3	31·7	33·0	35·8	36·5	37·3	38·8	41·0	42·7	43·7	44·0
July 12	66·8	66·5	66·0	64·3	62·2	61·0	61·3	59·7	58·2	55·7	53·7	54·7	55·0	58·2	58·5	57·0	56·0
Mean	51·3	51·9	52·5	53·9	53·8	54·1	54·3	53·7	53·4	54·3	53·8	54·2	55·0	56·8	57·2	57·7	58·6
Mean in w. l.	1·026	1·038	1·050	1·078	1·076	1·082	1·086	1·074	1·068	1·086	1·076	1·084	1·100	1·136	1·144	1·154	1·172
	1·068	1·086	1·076	1·084	1·100	1·136	1·144	1·154	1·172								
Final mean.	1·047	1·062	1·063	1·081	1·088	1·109	1·115	1·114	1·120								

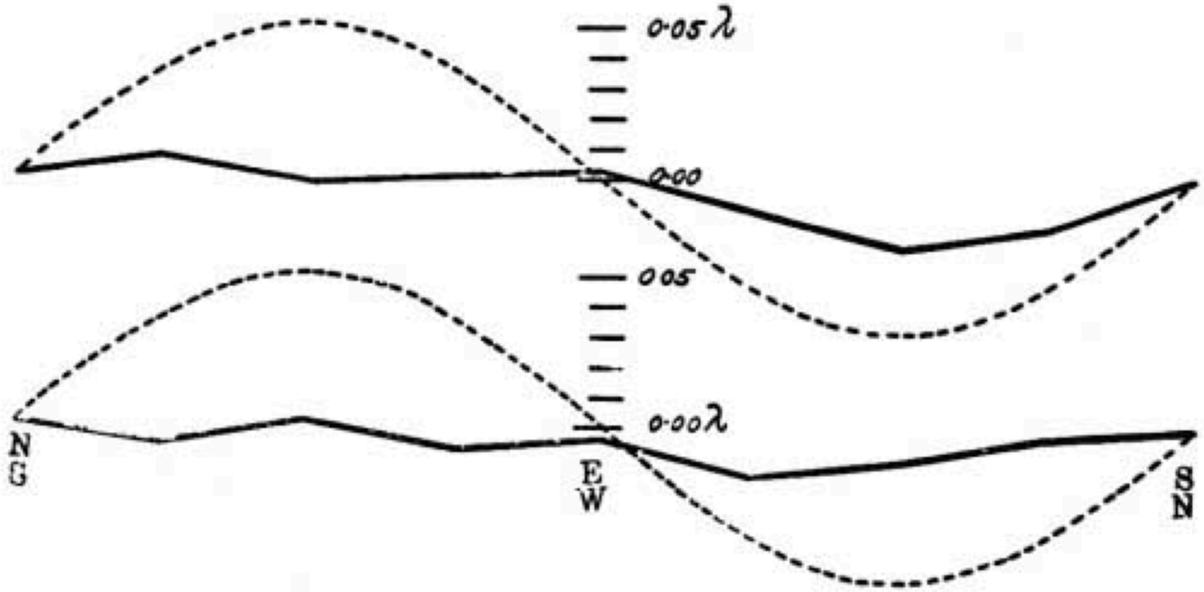
Michelson-Morley experiment

The speed of lig
value when m



The results of the observations are expressed graphically in fig. 6. The upper is the curve for the observations at noon, and the lower that for the evening observations. The dotted curves represent *one-eighth* of the theoretical displacements. It seems fair to conclude from the figure that if there is any dis-

6.



placement due to the relative motion of the earth and the luminiferous ether, this cannot be much greater than 0·01 of the distance between the fringes.

Michelson-Morley experiment

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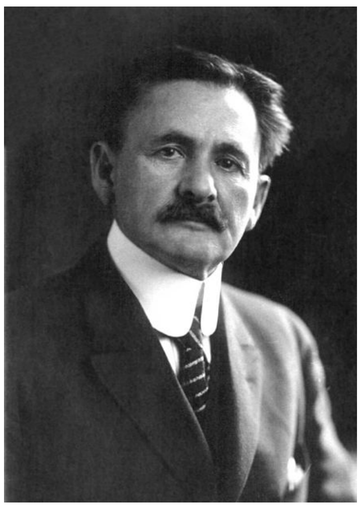

Michelson and Morley—Relative Motion of the **341**

displacement should be $2D\frac{v^2}{V^2}=2D\times10^{-8}$ The distance D was about eleven meters, or 2×10^7 wave-lengths of yellow light; hence the displacement to be expected was 0·4 fringe. The actual displacement was certainly less than the twentieth part of this, and probably less than the fortieth part. But since the displacement is proportional to the square of the velocity, the relative velocity of the earth and the ether is probably less than one sixth the earth's orbital velocity, and certainly less than one-fourth.

In what precedes, only the orbital motion of the earth is considered. If this is combined with the motion of the solar system, concerning which but little is known with certainty, the

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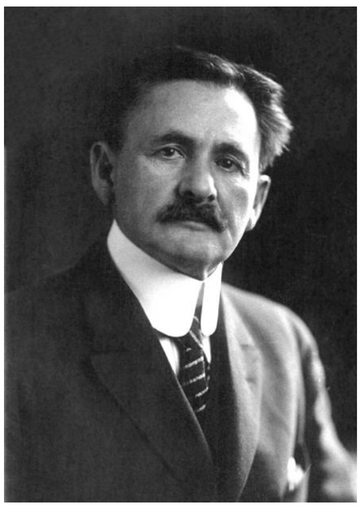

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$\frac{\Delta c}{c} < 10^{-5}$ for two-way speed

The most recent experiment

ARTICLE Communications/Nature

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Direct terrestrial test of Lorentz symmetry in electrodynamics to 10^{-18}

Moritz Nagel[1,*], Stephen R. Parker[2,*], Evgeny V. Kovalchuk[1], Paul L. Stanwix[2], John G. Hartnett[2,3], Eugene N. Ivanov[2], Achim Peters[1] & Michael E. Tobar[2]

Lorentz symmetry is a foundational property of modern physics, underlying the standard model of particles and general relativity. It is anticipated that these two theories are low-energy approximations of a single theory that is unified and consistent at the Planck scale. Many unifying proposals allow Lorentz symmetry to be broken, with observable effects appearing at Planck-suppressed levels; thus, precision tests of Lorentz invariance are needed to assess and guide theoretical efforts. Here we use ultrastable oscillator frequency sources to perform a modern Michelson–Morley experiment and make the most precise direct terrestrial test to date of Lorentz symmetry for the photon, constraining Lorentz violating

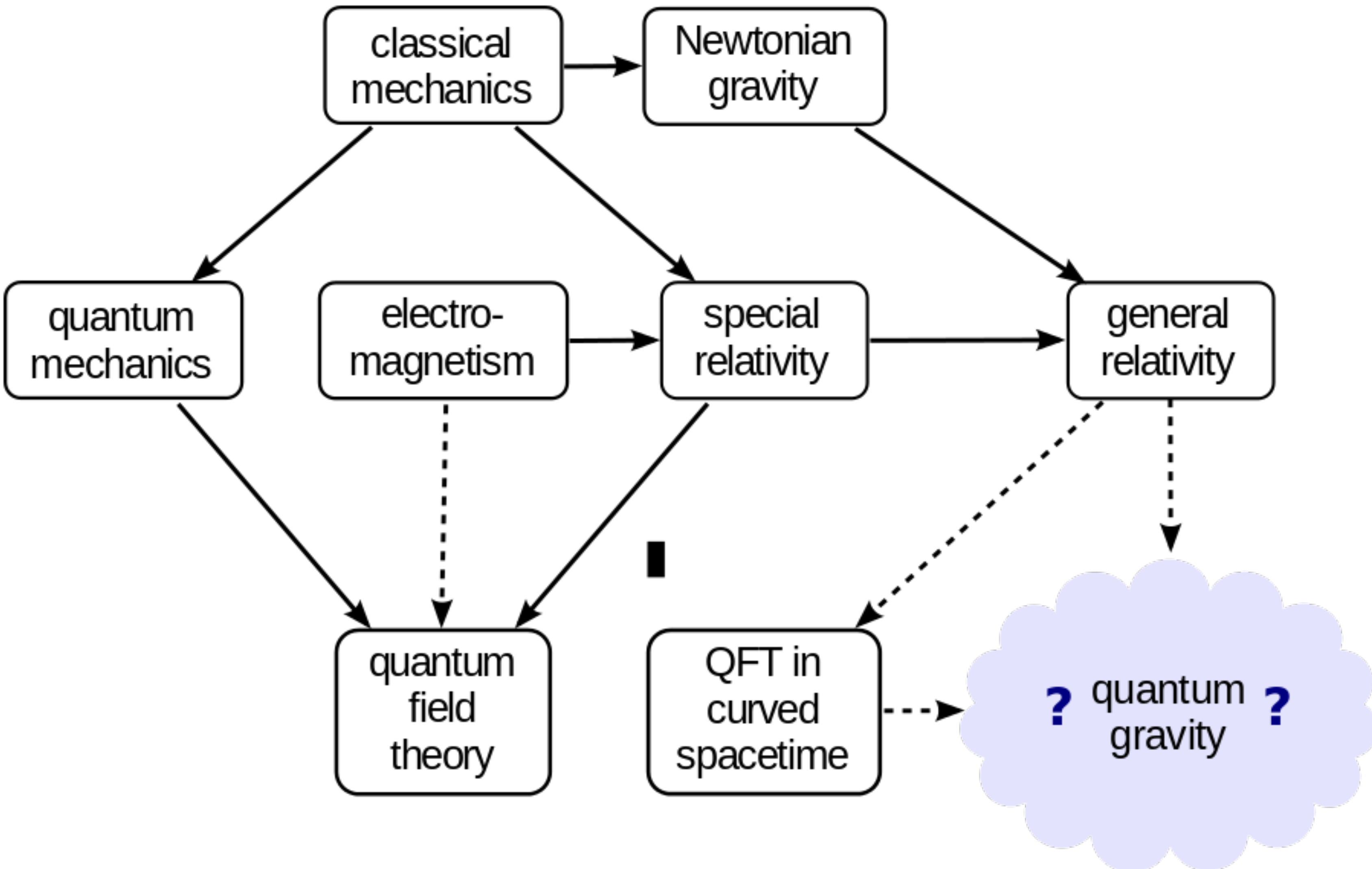
Tests of Lorentz Invariance

- Two-way speed via rotating cavities: $\Delta c_2/c < 10^{-18\ (20)}$

- One-way speed via asymmetric optical ring: $\Delta c_1/c < 10^{-14}$

At what level could we expect a Lorentz Invariance violation?

Physics


classical mechanics
Newtonian gravity
quantum mechanics
electro-magnetism
special relativity
general relativity
quantum field theory
QFT in curved spacetime
? quantum gravity ?

Tests of Lorentz Invariance

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At what level could we expect a Lorentz Invariance violation?

$$E^2 = m^2 + p^2 + \boxed{E_{\rm Pl} f_i^{(1)} p^i} + f_{ij}^{(2)} p^i p^j + \frac{f_{ijk}^{(3)}}{E_{\rm Pl}} p^i p^j p^k + \ldots,$$

dispersion equation in some LI violation models
see, Mattingly, Living Rev. Rel. 8 (2005) 5

Tests of Lorentz Invariance

- Two-way speed via rotating cavities: $\Delta c_2/c < 10^{-18}$

- One-way speed via asymmetric optical ring: $\Delta c_1/c < 10^{-14}$

At what level could we expect a LI violation?

$$M_z/M_{Pl} \sim 10^{-17}$$

One-way speed without a clock

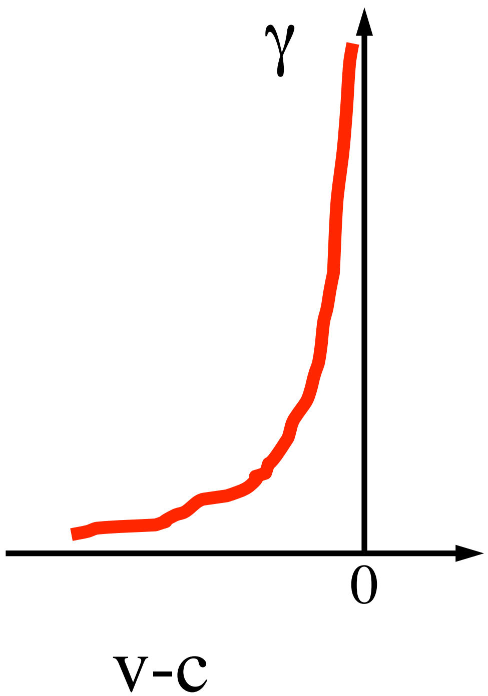
One can compare the speeds of light quanta of different energies – it was done using astrophysics data from distant objects.

One can measure directly the relative speed of a massive particle and light quanta. It could be done with high but still limited accuracy: $(v-c)/c \sim 10^{-3}$.

We propose to use a Lorentz factor γ as a measure of the $(v-c)$ because the value of γ is very sensitive to $(v-c)$ for high energy electrons and variation of the γ as a particle momentum turns around.

Speed of light variation and Lorentz factor

$$\gamma = \frac{c}{\sqrt{(c-v)\cdot(c+v)}}$$



When the value of the speed $\boldsymbol{v}$ is fixed, a tiny variation of **c** in the direction of motion leads to a large variation of **γ**, which provides a powerful enhancement of sensitivity to a possible variation of **c**.

$$\frac{\Delta\gamma}{\gamma} = \gamma^2 \cdot \frac{\Delta c}{c}$$

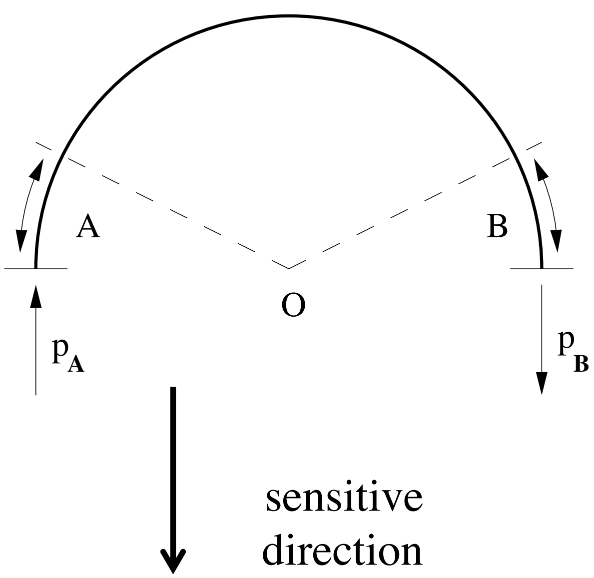
A concept of a new Lorentz Invariance test

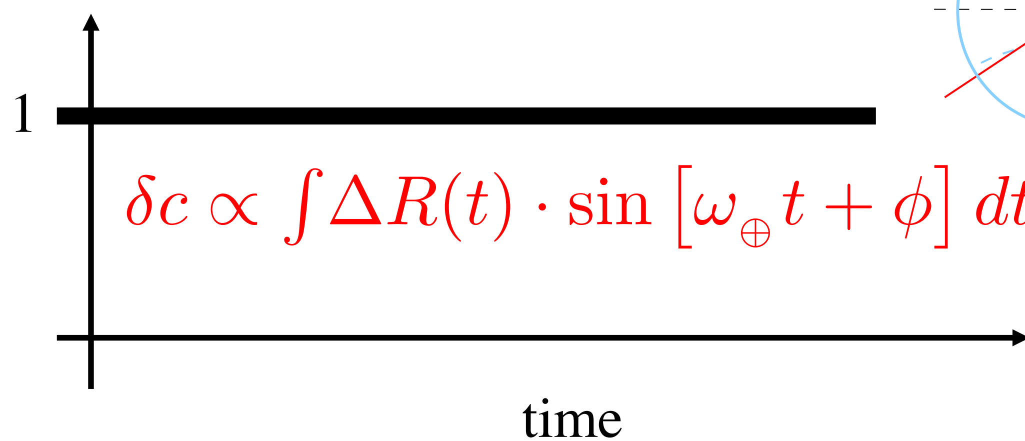
- Explore the difference of (v-c) in opposite directions of v
- Use a very small value of (v-c)/c ~ 10^{-9}, ultra relativistic electrons

<u>The method</u> (BW, EPL, 108 (2014) 31001; arXiv:150902754)

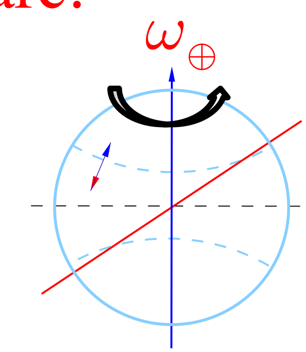
- Momentum measurements at the opposite ends of the arc:

$$R = \frac{P_A}{P_B}$$, ratio of momenta in segments A and B





$$\delta c \propto \int \Delta R(t) \cdot \sin\left[\omega_\oplus t + \phi\right] dt$$



Speed of light anisotropy and Lorentz force

Deflection of the particle trajectory in the transverse magnetic field provides both:

A: a way to measure momentum.

B: a way to turn the particle trajectory.

Conventional Lorentz force

$$S = \int_a^b (-mcds - \frac{e}{c} A_\mu dx^\mu)$$

$$L = -mc^2\sqrt{1-\beta^2} + \frac{e}{c}\vec{A}\vec{v} - e\phi$$

$$\frac{d}{dt}\frac{\partial L}{\partial \vec{v}} = \frac{\partial L}{\partial \vec{r}}$$

$$\frac{d\vec{p}}{dt} = -\frac{e}{c}\frac{\partial \vec{A}}{\partial t} - e\nabla\phi + \frac{e}{c}[\vec{v} \times rot\vec{A}]$$

Charge motion in magnetic field

The conventional Lorentz force is normal to the speed and the momentum, so the particle speed is constant.

If the speed of light has anisotropy and the particle speed is constant, then the momentum must change during movement in the arc, e.g. the form of the Lorentz force should be modified as well as the energy-momentum dispersion formula.

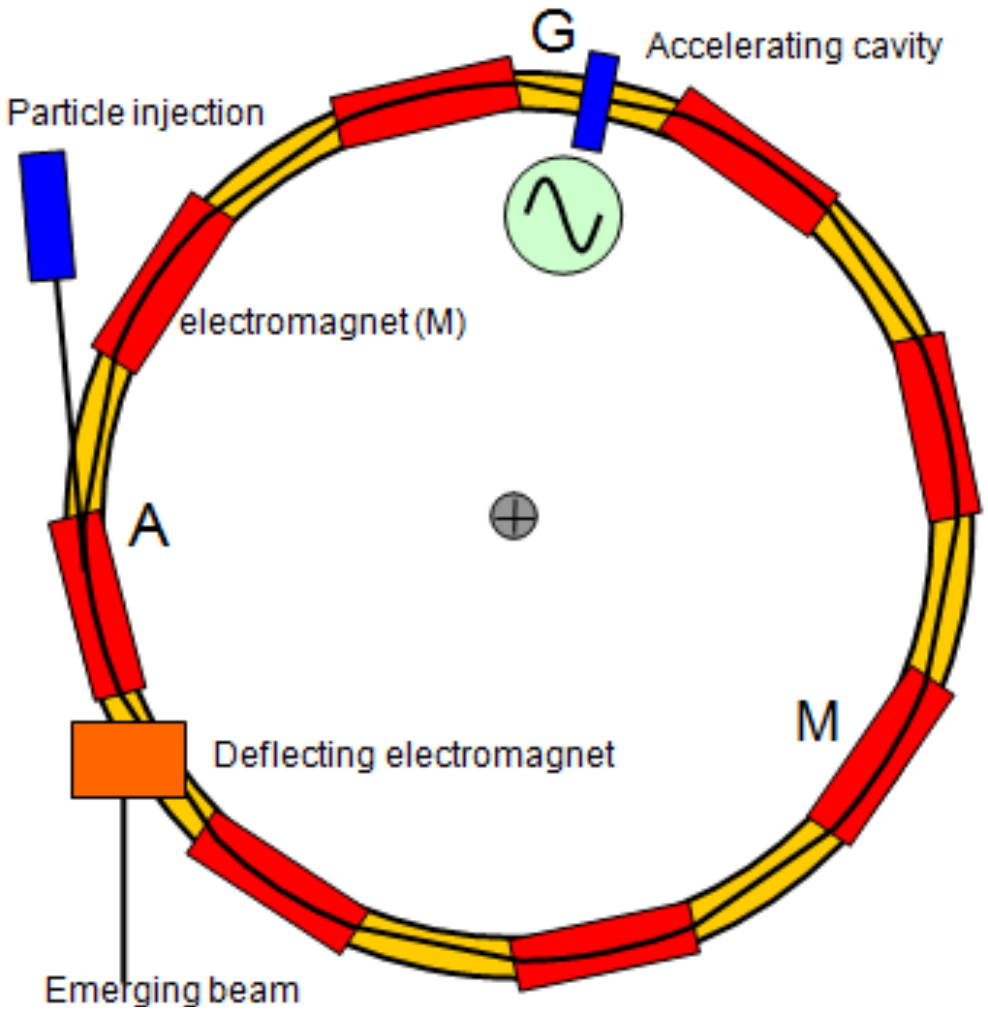
A concept of a new Lorentz Invariance test

- Explore the difference of (v-c) in opposite directions of v
- Use a very small value of $(v-c)/c \sim 10^{-9}$, ultra relativistic electrons

The method (BW, EPL, 108 (2014) 31001; arXiv:150902754)

- Momentum measurements at the opposite ends of the arc:
  - **Ratio of the momenta** provides the measure of $\Delta c/c$.
  - The momenta ratio has a double value of the signal and strongly suppresses the systematics:
    - beam energy variations,
    - magnetic field calibration and common variation,
    - Beam Position Monitors locations drift.
- Search for **a sidereal variation** of the ratio.
- Difference between **counter rotating** electron and positron beams

Synchrotron

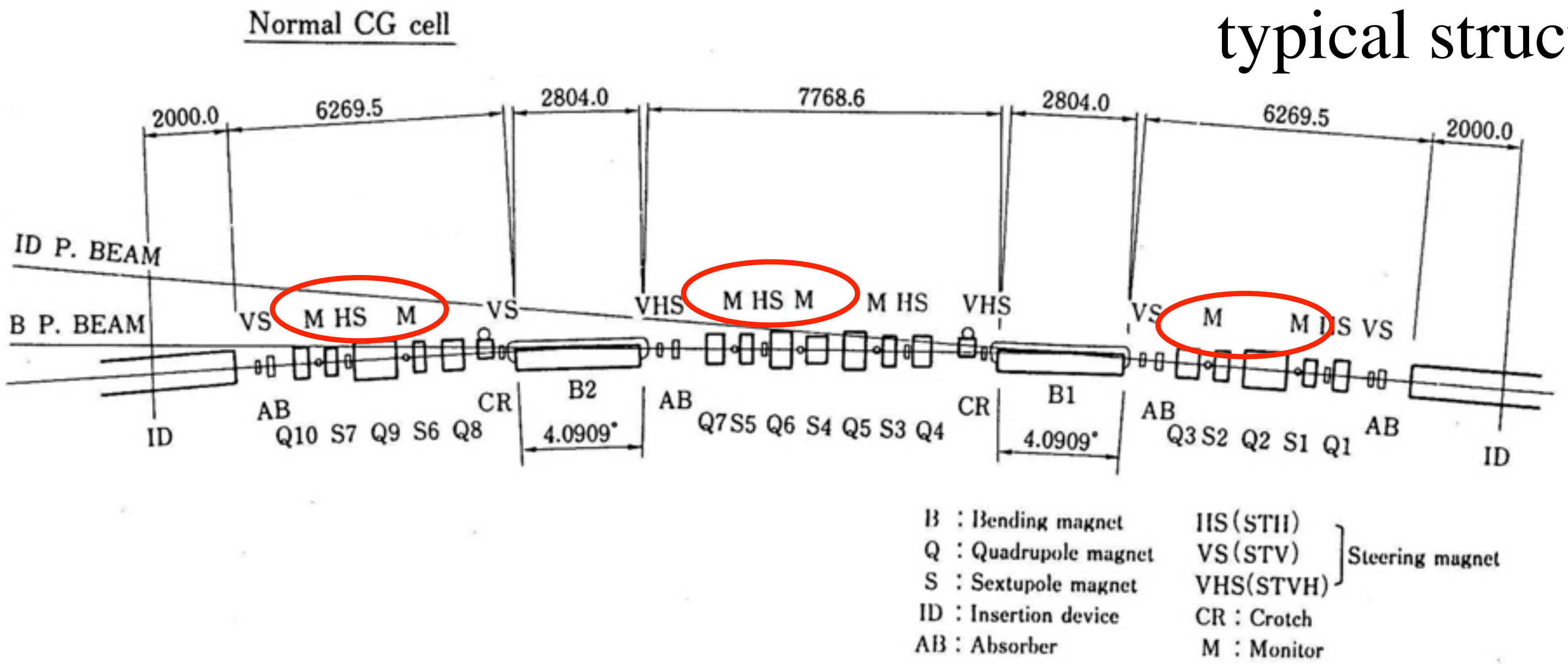


Accelerating cavity
synchronizes
the beam motion

Magnets provide
the beam focusing and
deflection

Synchrotron

typical structure



Beam position monitors provide high precision information about beam location along the path.

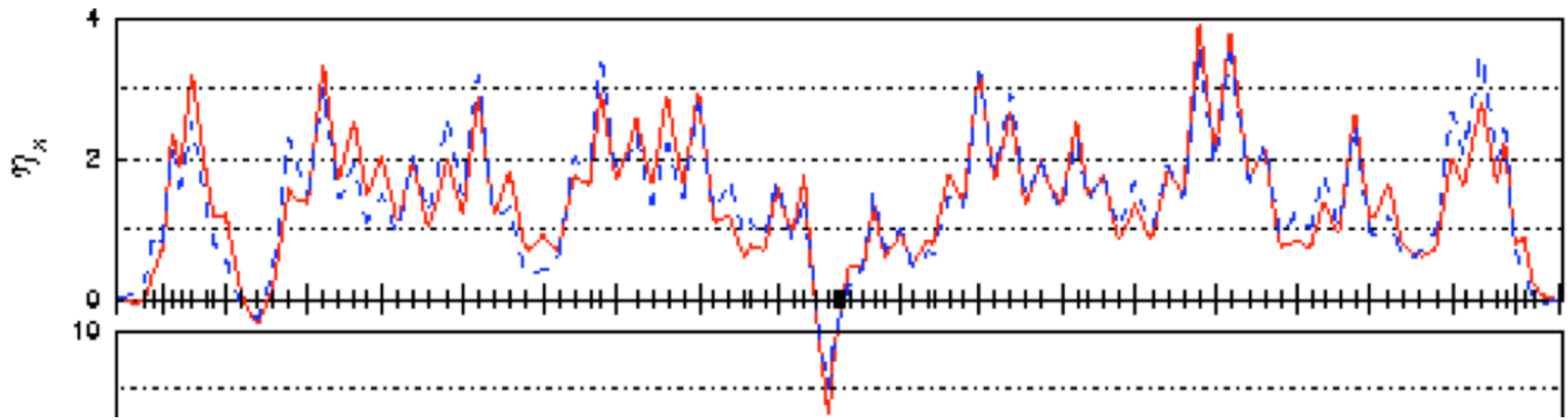
Beam dynamics in an accelerator

$$x(s) = x_{\beta}(s) + \eta(s) \times \frac{\Delta p}{p}$$

Hor. displacement = Dispersion times Momentum deviation

CESR-c Lattice Design and Optimization

D. Rubin, M.Forster



Beam dynamics in an accelerator

$$x(s) = x_\beta(s) + \eta(s) \times \frac{\Delta p}{p}$$

Hor. displacement = Dispersion times Momentum deviation

as a first-order estimate using the dispersion along the orbit:

$$\eta_{large} \sim 1.5m \; , \; \sigma_x \sim 50\mu m$$

$$\sigma\left[\frac{p_A - p_B}{p_{aver}}\right] = \sigma\left[\frac{x_A}{\eta_A}\right] \oplus \sigma\left[\frac{x_B}{\eta_B}\right] \sim 0.5 \cdot 10^{-4}$$

A large number of Beam Position Monitors could be used for higher accuracy.

Beam dynamics in an accelerator

$$x(s) = x_\beta(s) + \eta(s) \times \frac{\Delta p}{p}$$

$$\frac{\sigma_{\Delta p}}{p} = \sigma\left[\Delta \frac{x}{\eta}\right] \oplus \frac{x}{\eta} \cdot \frac{\sigma_\eta^{time}}{\eta}$$

consider the first term statistics over 100 seconds:

$$\frac{\sigma_{\Delta p}}{p} = 0.5 \cdot 10^{-4} \times \sqrt{\frac{2.5 \cdot 10^{-6}}{100}} \sim 10^{-8}$$

Beam dynamics in an accelerator

$$x(s) = x_\beta(s) + \eta(s) \times \frac{\Delta p}{p}$$

Hor. displacement = Dispersion times Momentum deviation

Back to statistical estimations:

$$\frac{\sigma_{\Delta p}}{p} = 10^{-8}$$

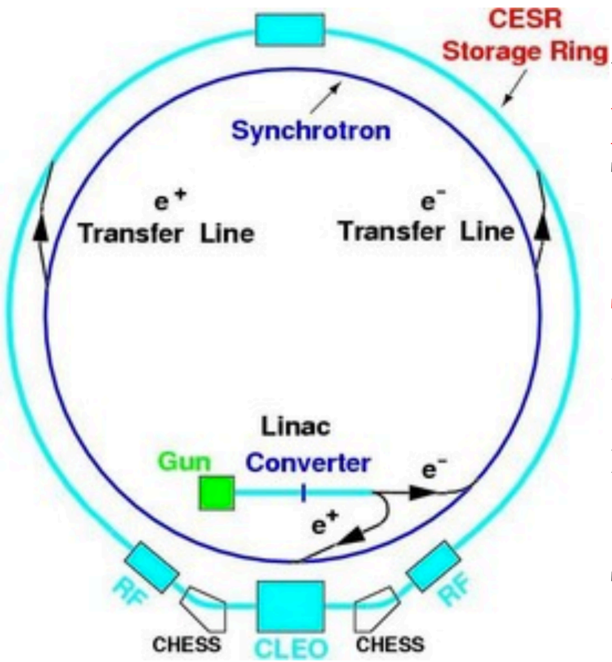
a short time ~100 s

A measurement over 24 hours => $\frac{\sigma_{\Delta\gamma}}{\gamma} = 3 \cdot 10^{-10}$

a few days' experiment: $\delta c/c \sim 10^{-18}$

It would be 10,000 times better than the current limit
for the one-way $\delta c/c$

Cornell ring based experiment



An important feature of CESR is that the electron and positron beams are in the same magnetic arc.
The RF cavities are localized: A long arc could be used!

The e+, e- beam orbits could be made almost identical, which would allow a cross calibration of the momentum measurement.

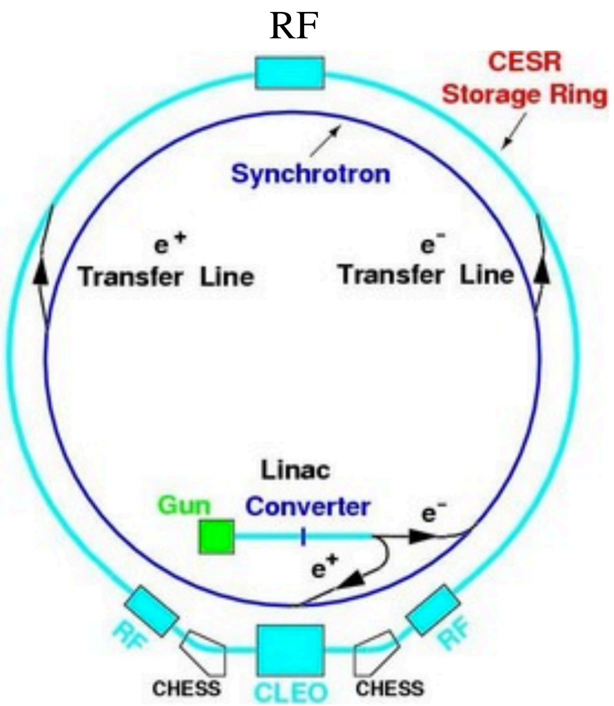
The drift of the dispersion (in 0.1 second) is << 10^{-10}

Required beam time (for the production run):
2 x 120s x 24 times per day x100 days ~ 80 hours

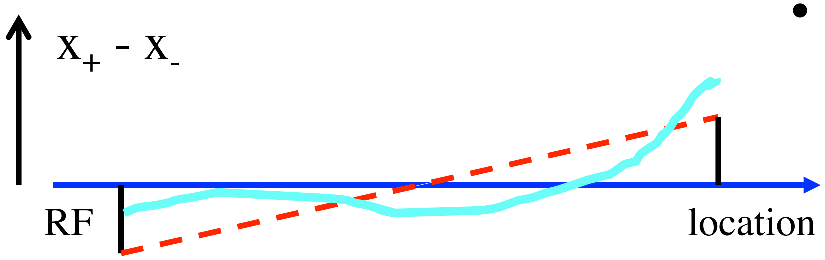
The sensitivity would be $\Delta c_1/c \sim 10^{-18}$

The difference is 25 microns after a day of travel

Cornell ring based experiment



- We will measure the position of the beam at 98 points along the orbit
- It will be done for both an electron and a positron bunch rotating in the ring at the same time in opposite directions.
- The differences in those positions reflect energy changes along the orbit due to synchrotron radiation.
- It is close to a "saw" line with a slope of 10^{-4}.



- Sidereal phase variation of the fit to the residual will be fitted to the shape of the signal:

$$A \sin(2\pi s/L + \omega_E t + \phi_\Sigma)$$

Potential sensitivity to $A \sim 1 \cdot 10^{-10}$

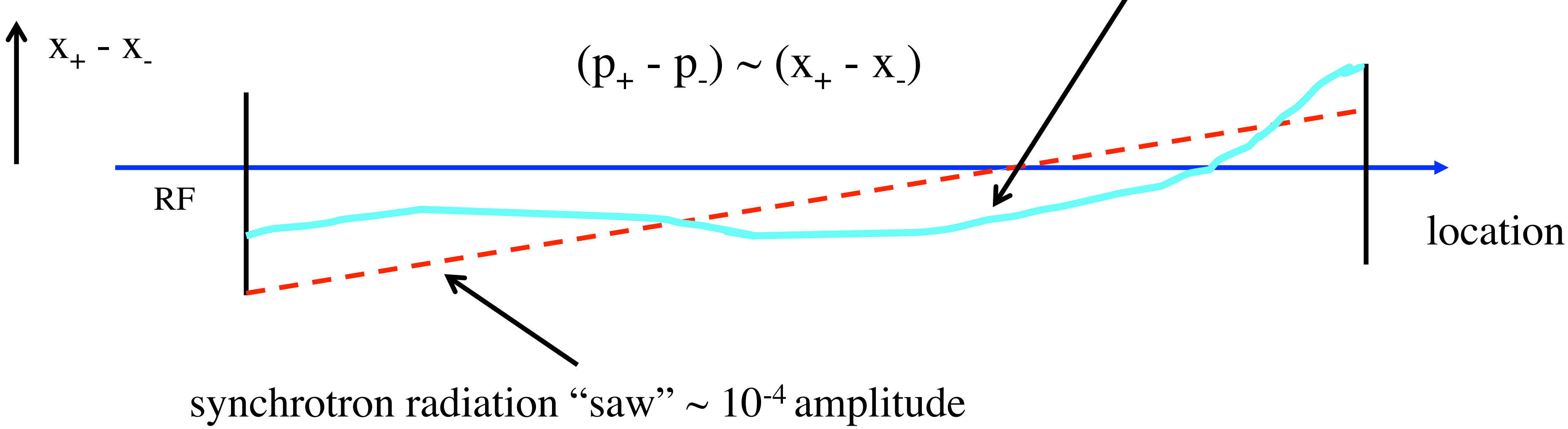
resulting in $\Delta c_1/c \sim 10^{-18}$

What will be measured?

The difference between momenta of an electron and a positron along the orbit.

Search for a sliding sine wave with a moving phase: $A \sin(2\pi s/L + \omega_E t + \phi_\Sigma)$

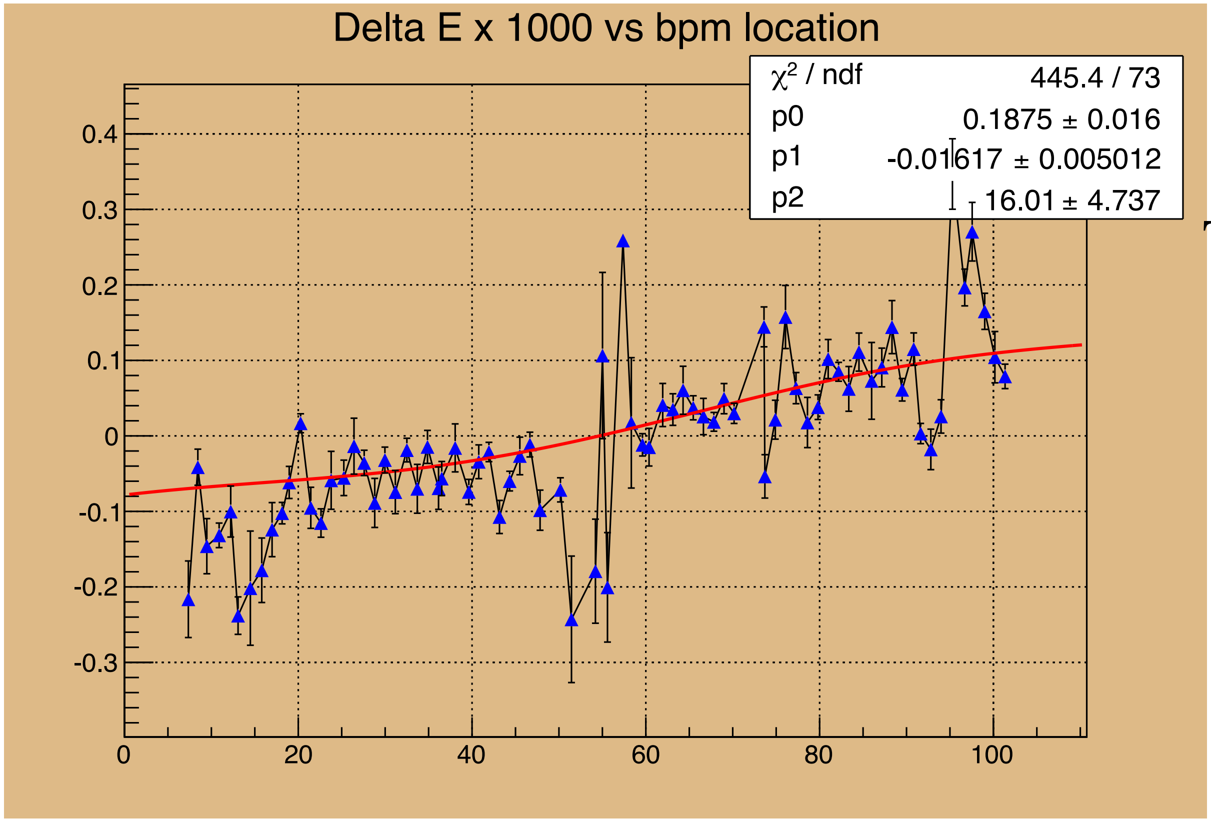
The observed noise of the beam position monitors allows an estimate: potential sensitivity to A is $\sim 1 \cdot 10^{-10}$, which results in $\Delta c_1/c \sim 10^{-18}$



A first test measurement

The difference between momenta of an electron and a positron along the orbit.

Search for a sliding sine wave with a moving phase: $A \sin(2\pi s/L + \omega_E t + \phi_\Sigma)$

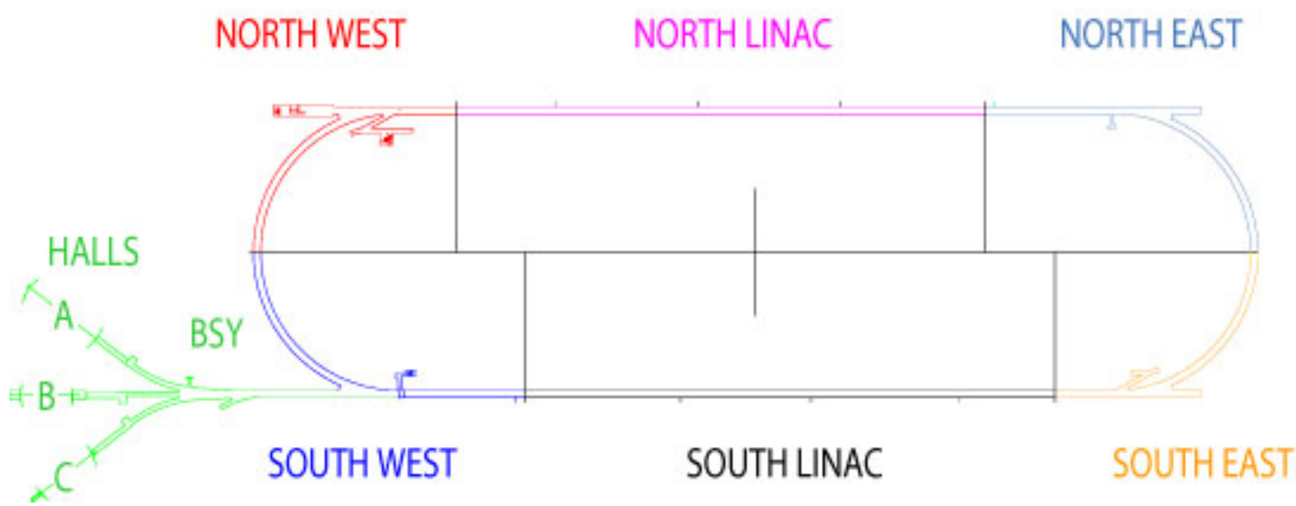


Data from two 2.5 ms runs
The electron run "few" minutes after the positron run
Uncertainty of the sine wave amplitude is 5×10^{-6}

JLab machine based experiment

12GeV

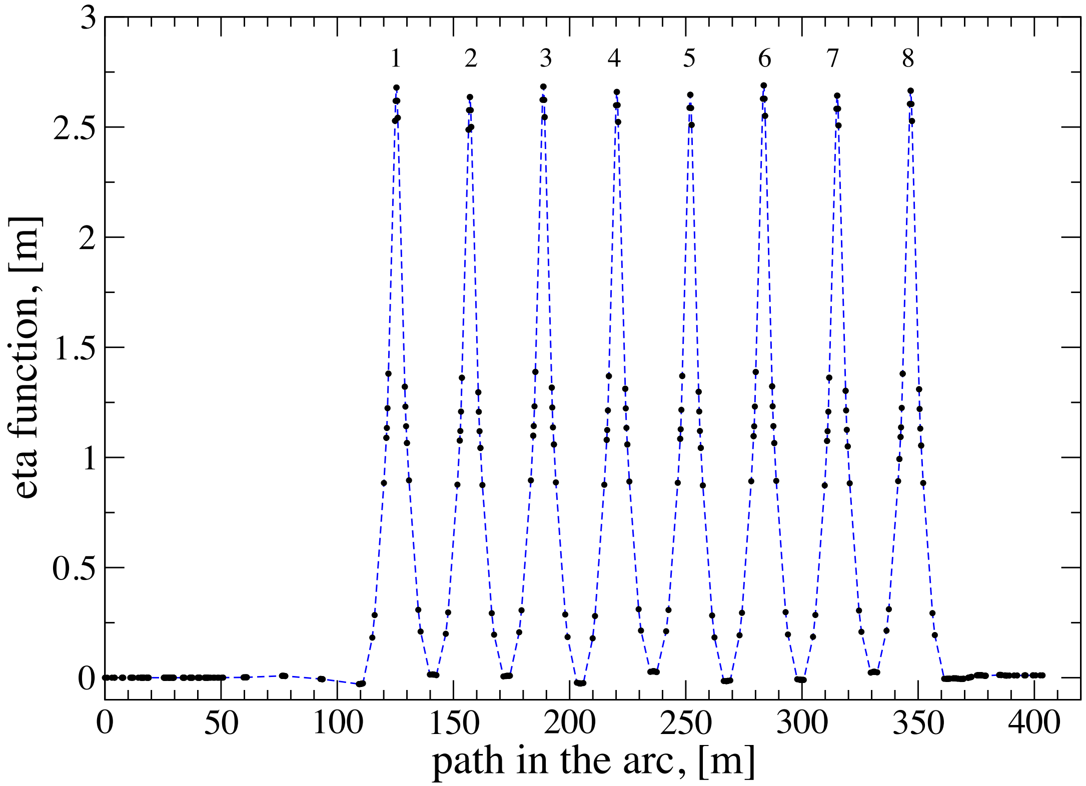
ACCELERATOR



How to measure the momentum?

$$x(s) = x_{\beta}(s) + \eta(s) \times \frac{\Delta p}{p}$$

Hor. displacement = Dispersion times Momentum deviation



Projected precision of the search

$$x(s) = x_\beta(s) + \eta(s) \times \frac{\Delta p}{p}$$

Now, consider the statistics over 1 month (parasitic)
(data archived every time that the beam is ON)
with the existing readout (one per sec), 10 GeV arc,
2.5 m dispersion, precision shown for $\delta R/R$ in arc#1:

$$\frac{\delta c}{c} = \frac{1}{\gamma^2} \times \frac{\delta R}{R}\Big|_{1hr,arc\#1} \cdot \frac{\eta_1}{\eta_{10}} \times \frac{1}{\sqrt{N_{hr}}} =$$

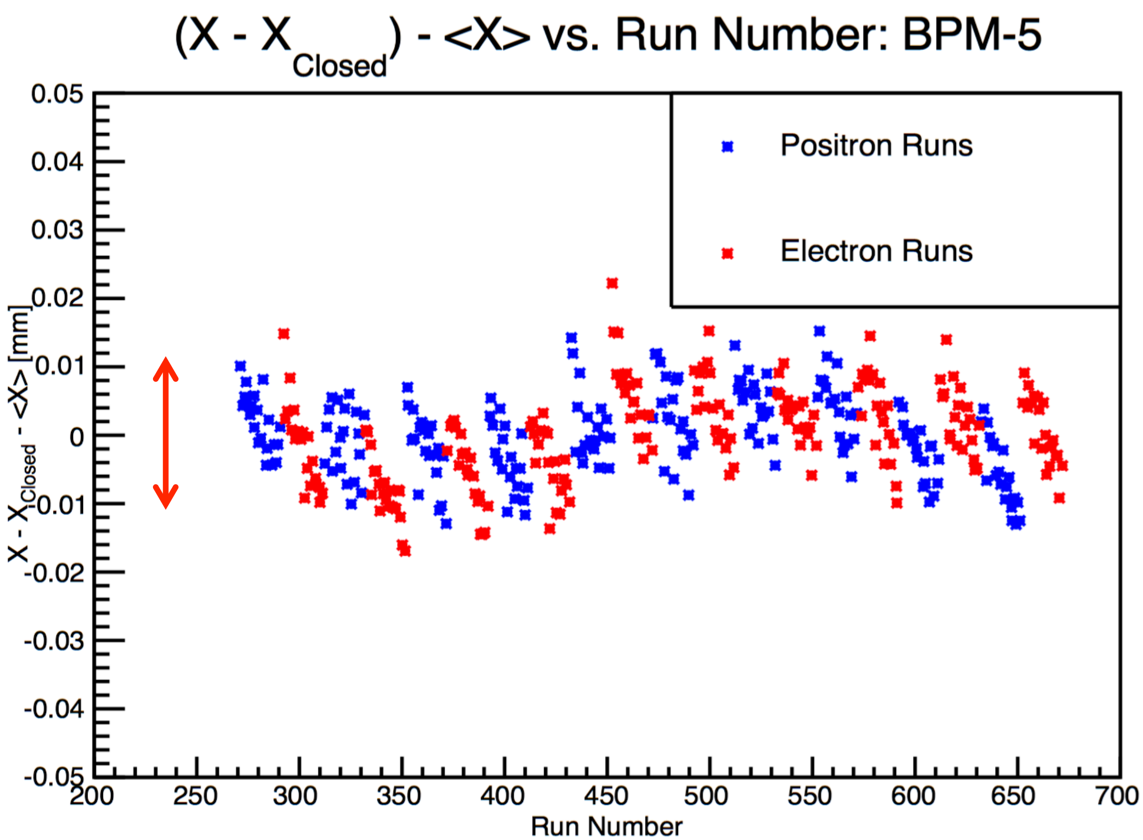
$$2.6 \cdot 10^{-9} \times 1 \cdot 10^{-6} \times \frac{8}{2.5} \times \frac{1}{\sqrt{24 \cdot 30}} \approx 3 \cdot 10^{-16}$$

Optimization of the beam optics should allow us to reach
$1 \mathrm{x} 10^{-16}$ (100 times better than the currently best limit).

The pilot studies in 2016 by CESR collaboration

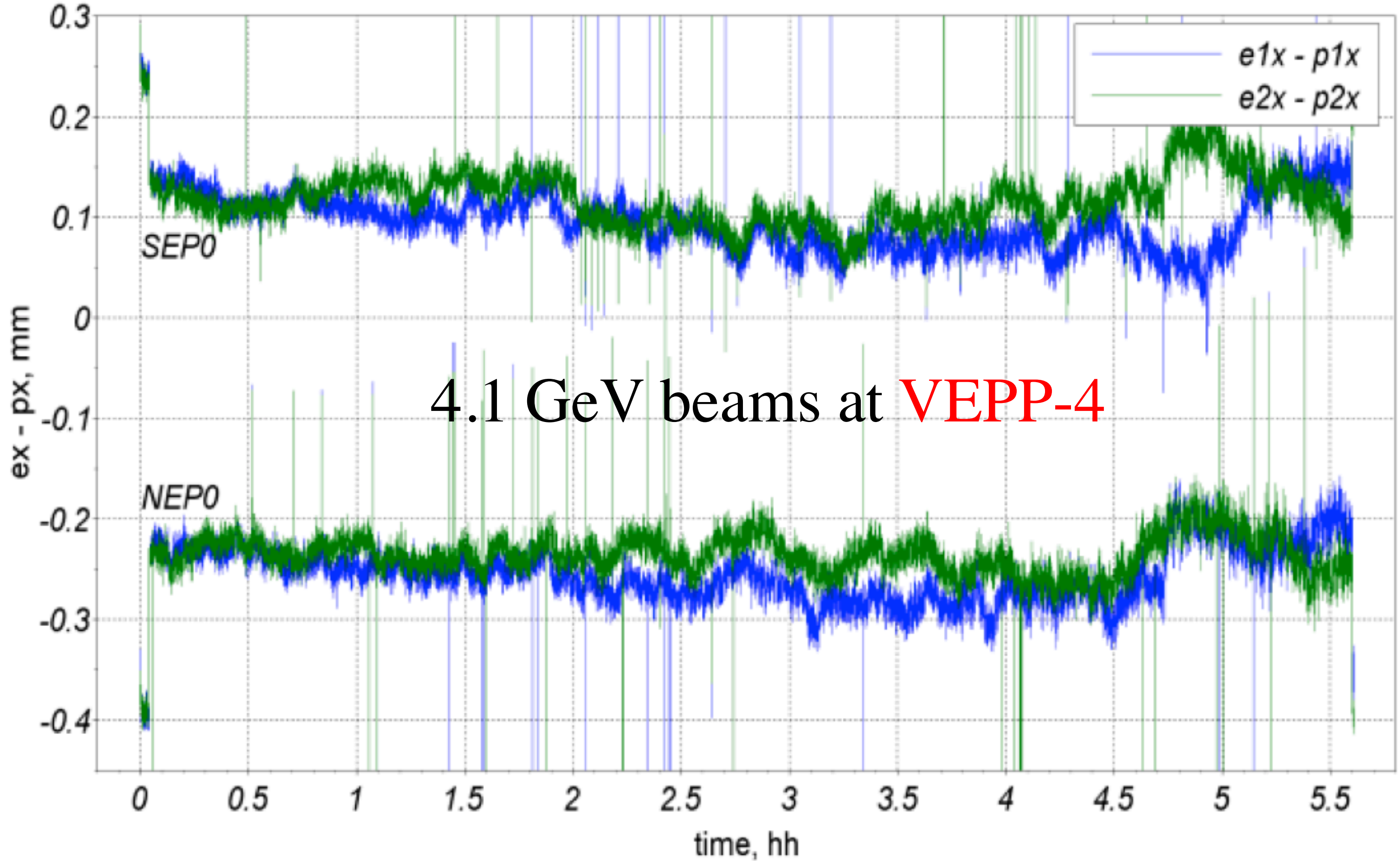
10^{-5}

20 μm

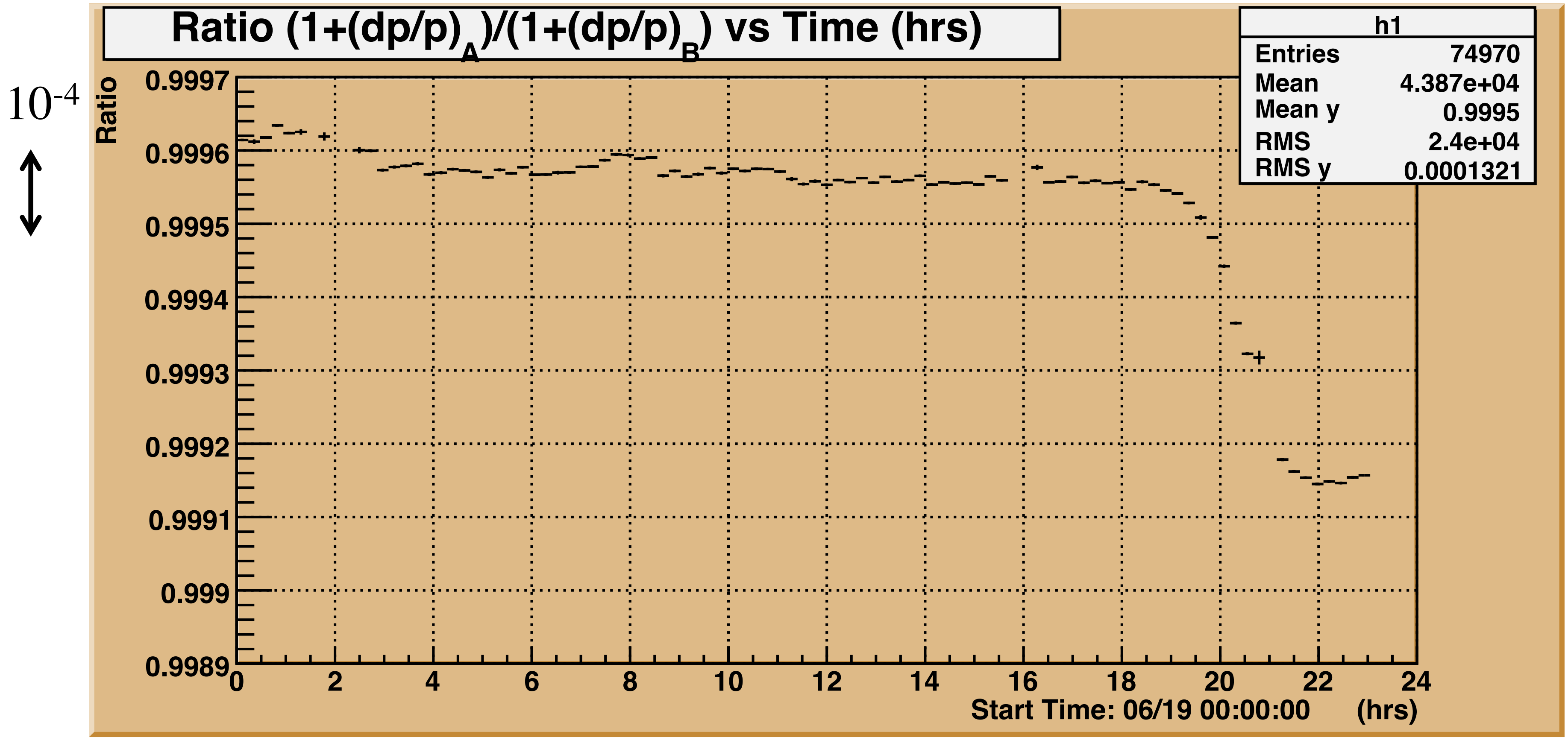


2.1 GeV beams at CESR, 2 hours

The pilot studies in 2016 by BINP collaboration



The pilot studies in 2016 by JLab collaboration



1.1 GeV beam at CEBAF arc #1; 16 hours

Summary

- A search for possible anisotropy of the maximum attainable speed is proposed using high energy electron (and/or positron) beam deflections in a magnetic arc.

- The CESR as well as VEPP-4 positron/electron beam combination provides a natural way to improve effective stability of the magnetic arc. It would open the way to an accuracy of 10^{-18} (the onset of the quantum gravity effect could potentially be observed).

- The CEBAF 11 GeV beam with its exceptional quality and the world's largest Lorentz factor allows a far-reaching experiment independent of an assumption CPT for e-/e+.