LOCAL BEAM LOSS AND BEAM PROFILE MONITORING WITH OPTICAL FIBERS

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1. Introduction
2. Properties of optical fibers
3. Classification of beam loss monitor systems

3.1 **Slow beam loss monitor** systems (dosimeter system)

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3.1.2 Local dosimeter system for high dose environment (Fiber Bragg Gratings)

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3.2.2 Beam profile monitor (BPM)

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Motivation

How can in general the beam loss of large linear accelerator (TESLA /ILC/ FLASH) or storage rings be continuously monitored?

Is it possible to measure the **total ionization dose** along a beam line of 30 km length with a position resolution a meter or potentially of some centimeter?

Is it possible to measure the **beam loss** along the entire beam line in less than millisecond with a time resolution of some nanosecond and a position resolution of centimeter?

YES, WE CAN

by using **optical fibers** as **radiation sensor** to measure the

total ionization dose (mGy-kGy up to MGy)

and

using the generated Cerenkov light to assess the

position and dynamic of the beam loss

Radiation effects in optical fibers:

- Generation of color center and other defect centers in SiO_2 structure increases the attenuation of the optical fiber
- At high dose values also the refractive index might also be changed
- Shift of the Bragg wavelength of Fiber Bragg Gratings

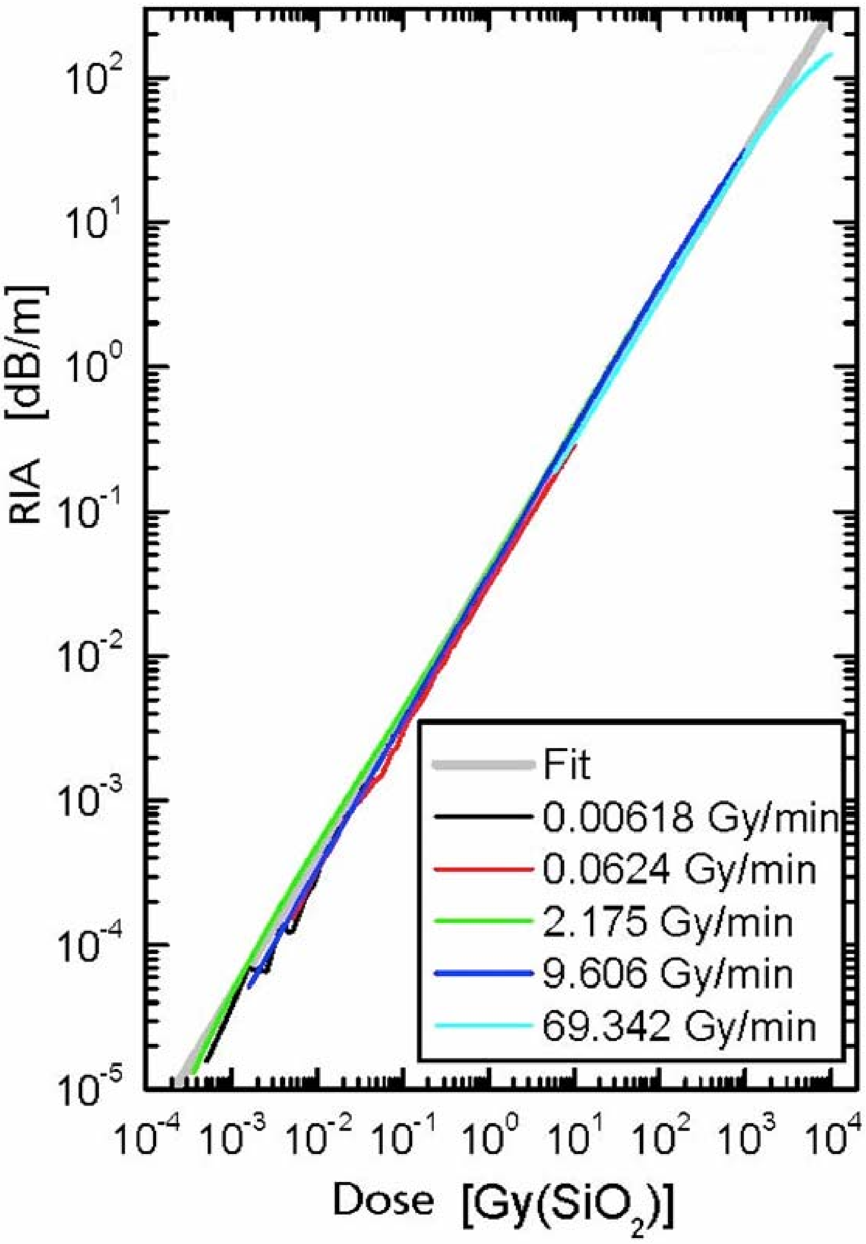
Influence of the Process parameters on the radiation sensitivity:

- Fiber type (single mode, graded index, step index)
- **Doping** of core, doping of cladding
- Preform manufacturer and used technology
- Core material manufacturer
- OH content
- Cladding core diameter ratio (CCDR)
- Coating material
- Drawing conditions: speed, temperature, ambient conditions

Parameter dependence on the radiation effect during exposure:

- Total ionizing dose (TID)
- Dose rate
- Irradiation type
- Temperature
- Annealing behavior (fading)
- Wavelength
- Light power

2. Properties of Optical Fibers (RIA)



Increase of **radiation induced attenuation (RIA)** with radiation dose of the (Ge+P)-doped GI fibre selected for TTF1. The measurements were made with varying dose rate (in Gy/min) at λ = 678 nm and λ = 829 nm at room temperature.

$$\mathrm{RIA}\ [\mathrm{dB/m}] = c(\lambda) \cdot D^{\mathbf{f(\lambda)}}$$

The constant **c** expresses the radiation sensitivity and the exponent **f** is nearly 1 for well-suited fibers (small annealing effects).

A fit to the curves measured at:

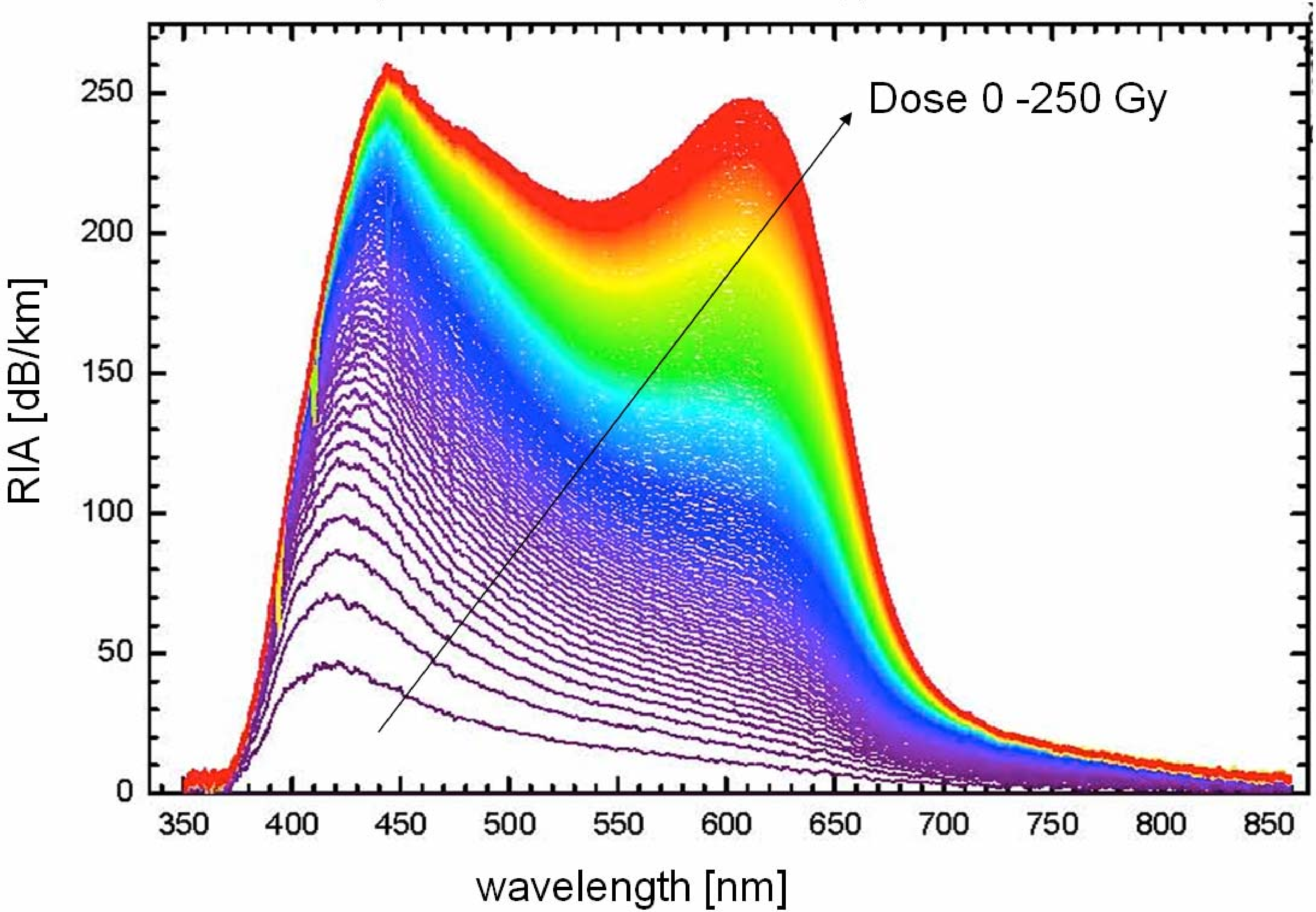
λ= **678 nm**: c = 0.0369 dB/m Gy, f = 0.972

and for

λ= **829 nm**: c = 0.0042 dB/m Gy, f = 1.025

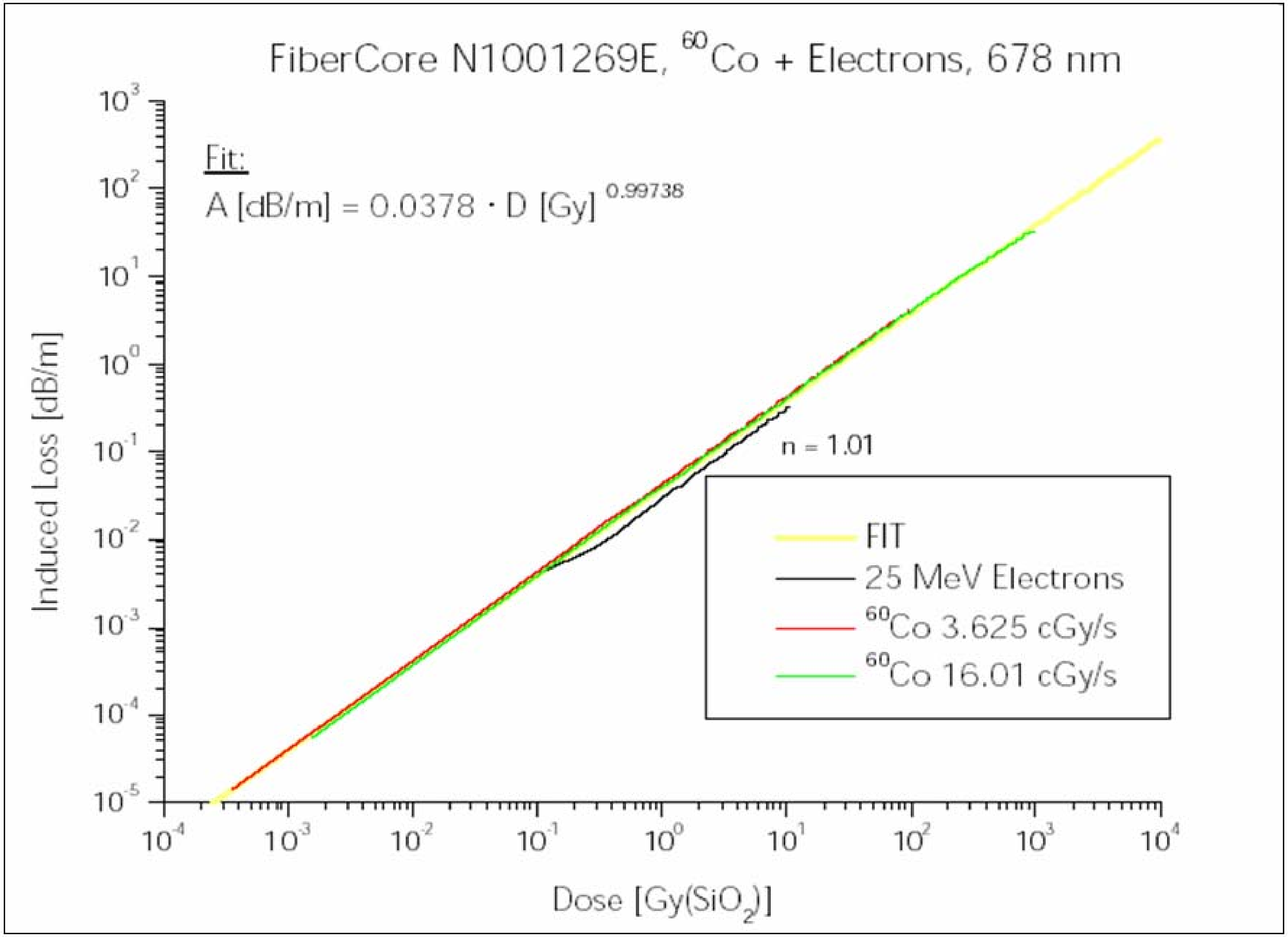
2. Properties of Optical Fibers (wavelength)

Spectral attenuation of a typical fiber



2. Properties of Optical Fibers (radiation type)

Optical fibers show (wavelength-dependent) a nearly linear increase of attenuation after irradiation with ionizing radiation independent from dose-rate and -source



3. Classification of beam loss monitor systems

Slow BLM Systems

Radiation induced attenuation or bragg wavelength shift

- local and distributed Systems
- measurement time: *tens of ms up to minutes*
- long term monitoring
- dosimetry system

Fast BLM Systems

Radiation induced Cerenkov or luminescence light

- distributed systems
- measurement time: *millisecond with time resolution of nanoseconds*
- loss trace monitoring; emergency shutdown

Radiation Induced Attenuation (RIA)

Low Dose Radiation Senor

- Optical Power Meter (OPM)
- Optical Time Domain Reflectormeter (OTDR)

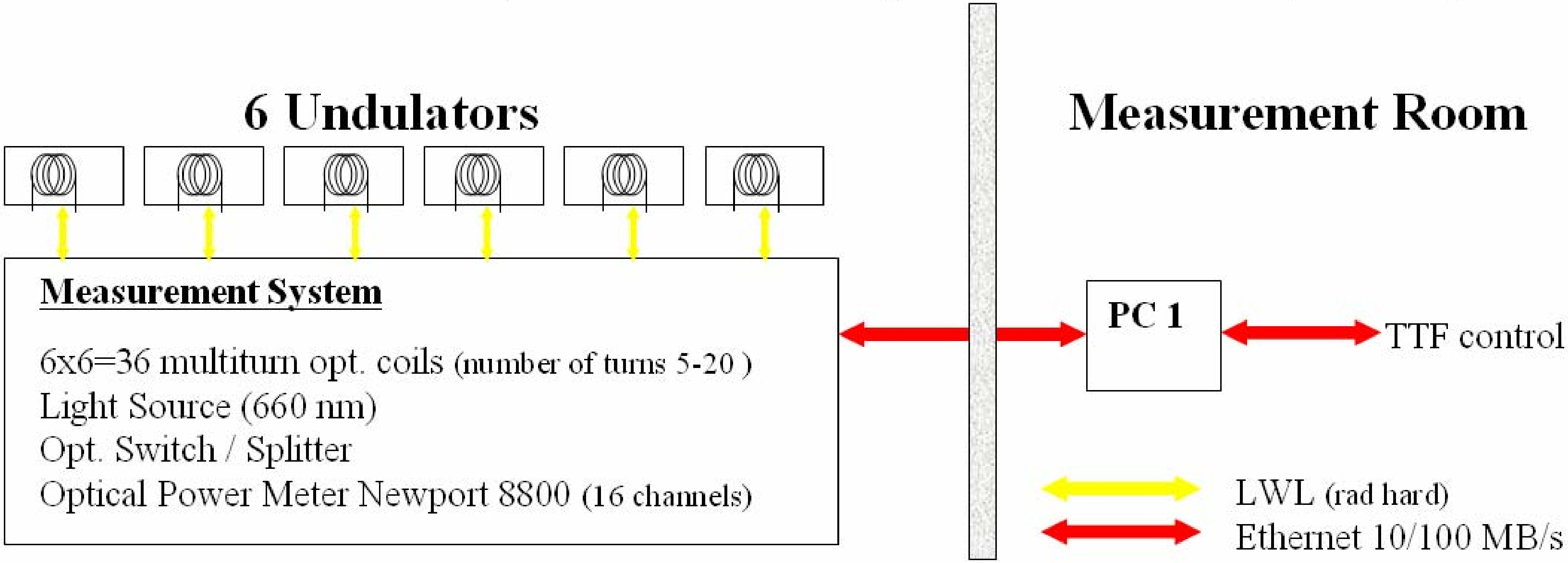
Bragg Wavelength Shift (BWS)

High Dose Radiation Sensor

- BWS measurement

3.1.1 Local dosimeter system (Optical Power Meter)

Schematic Set Up for the OPM System at FLASH (DESY)



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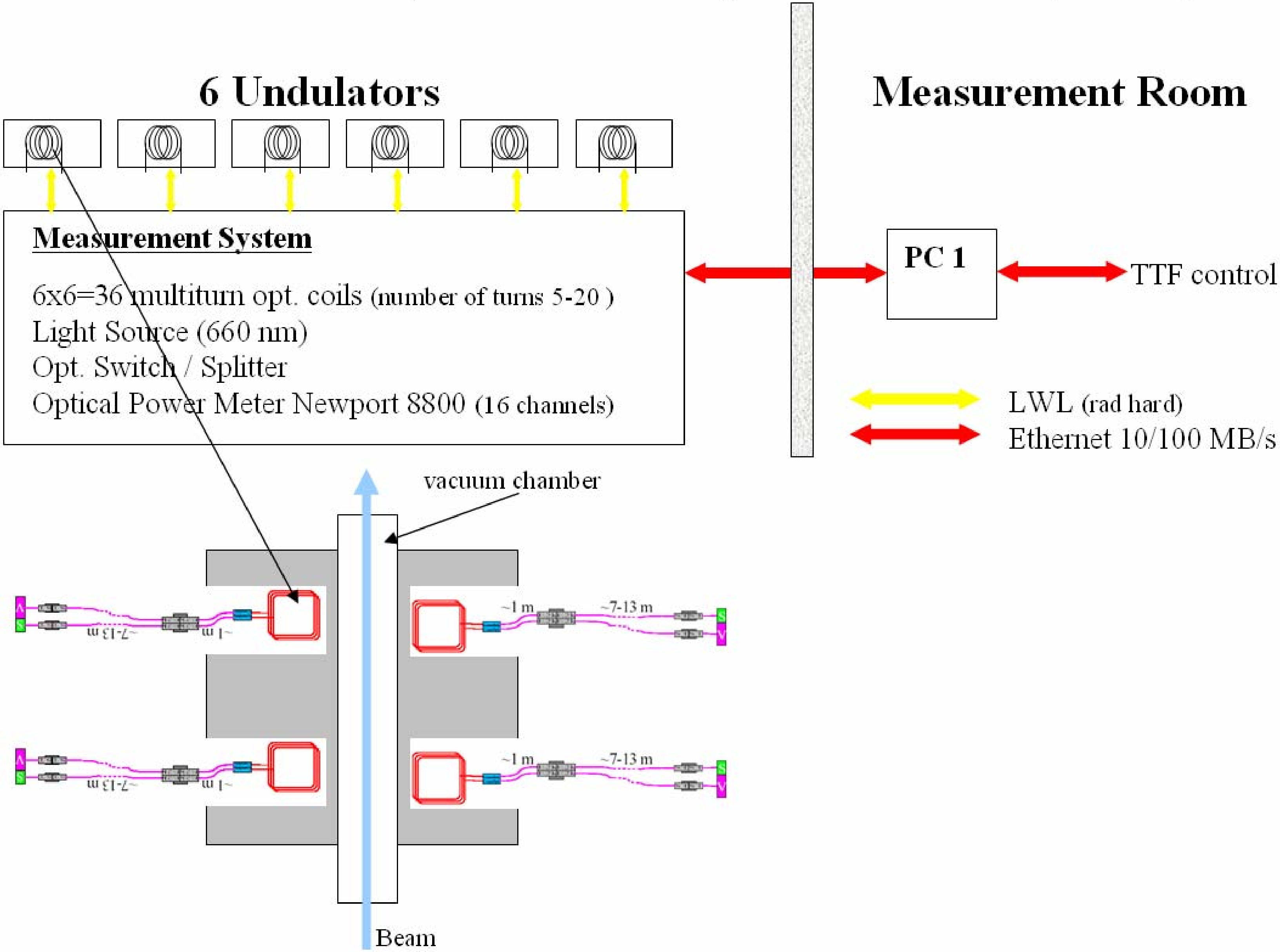

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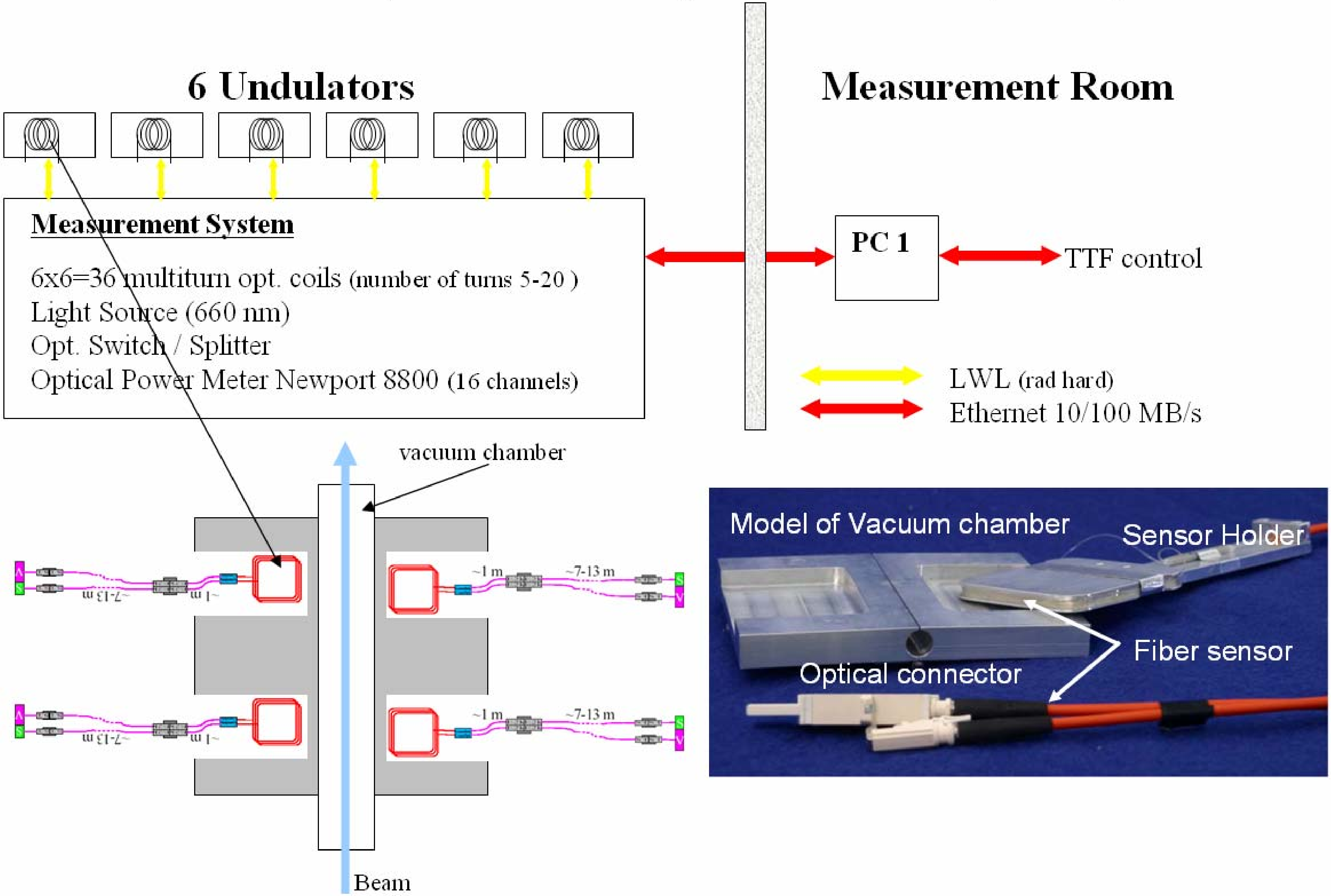

3.1.1 Local dosimeter system (Optical Power Meter)

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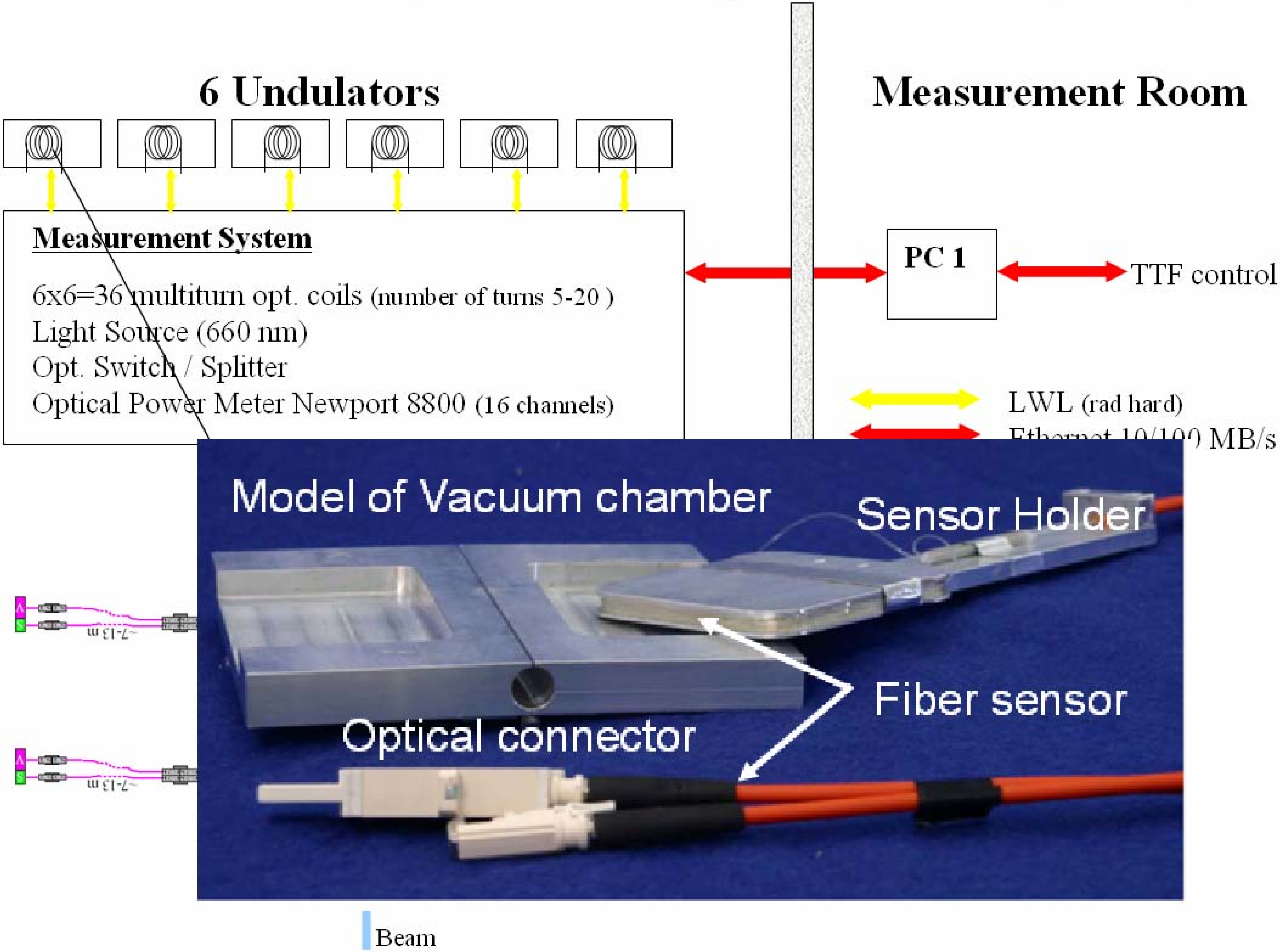

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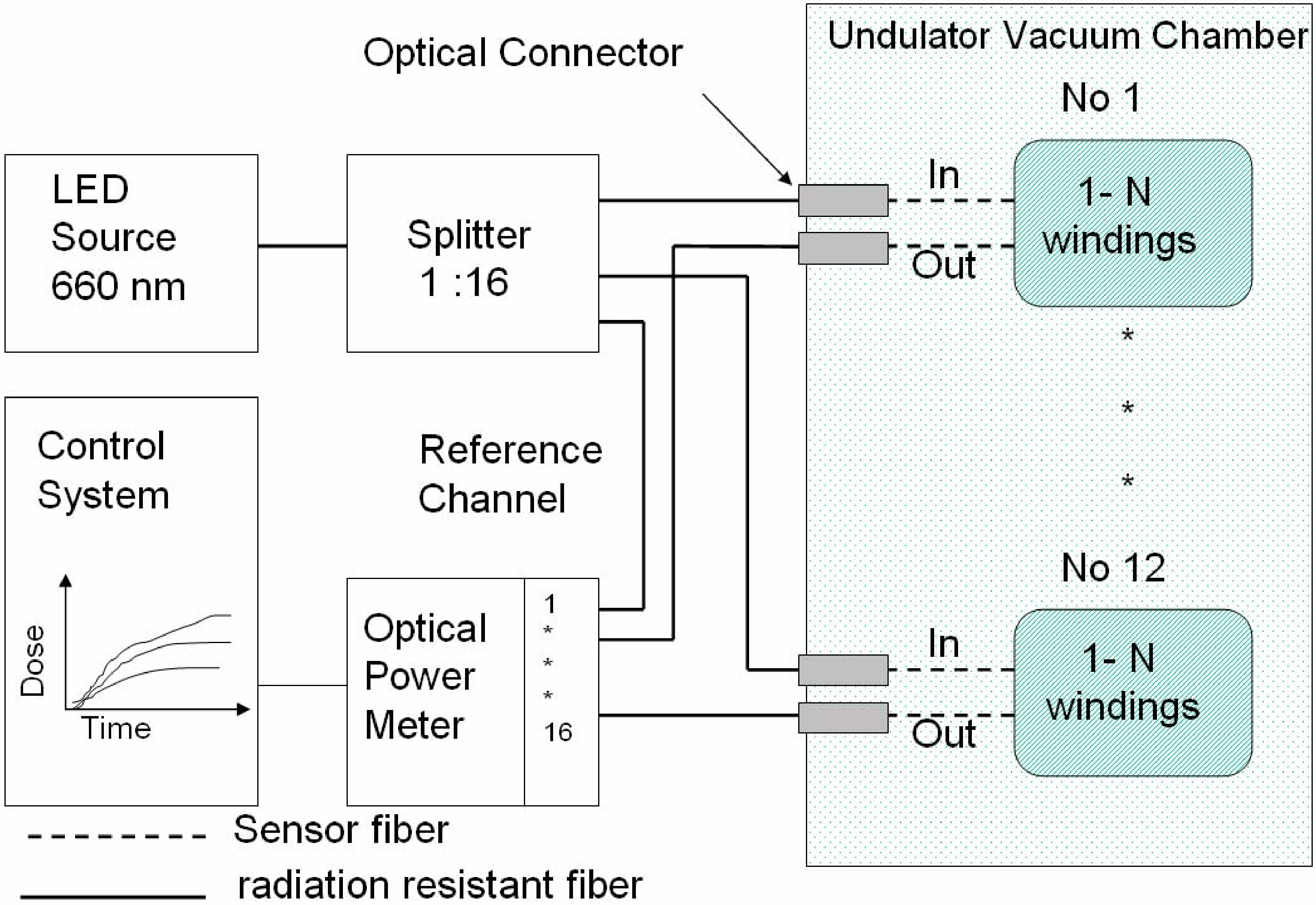
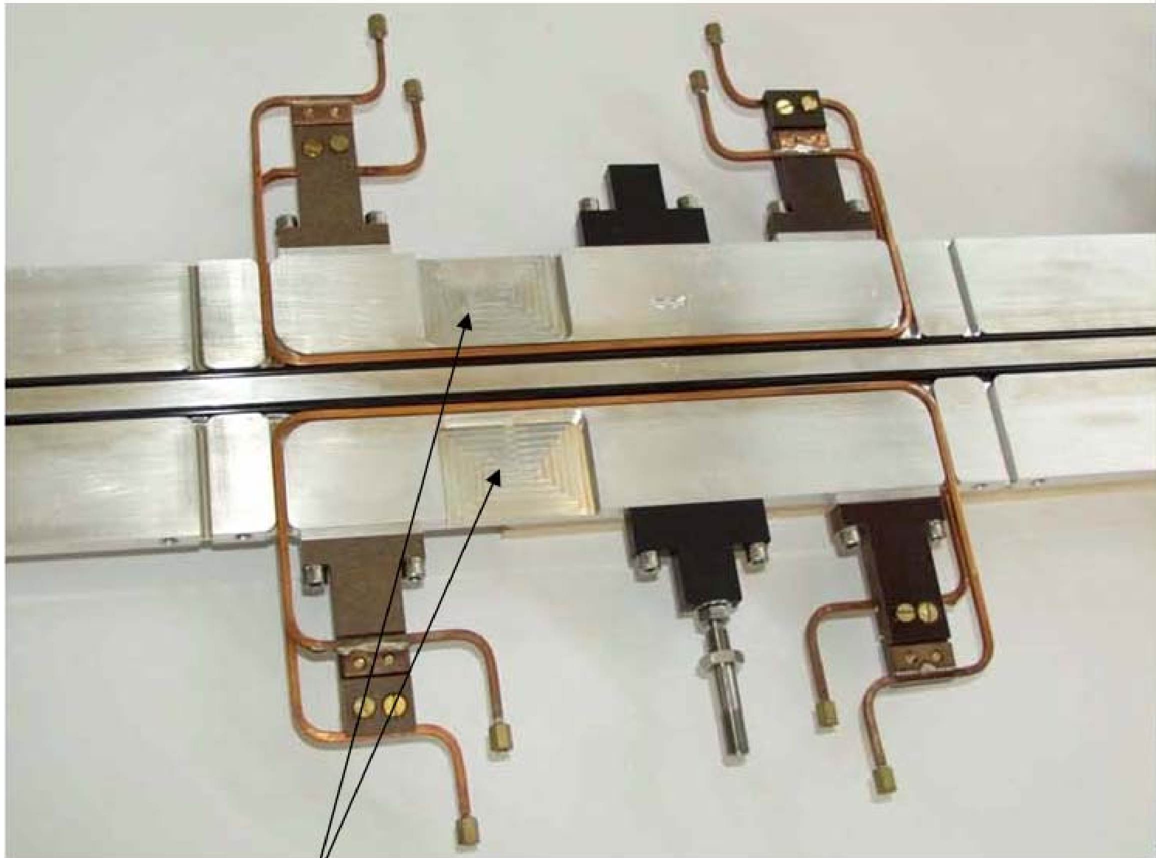
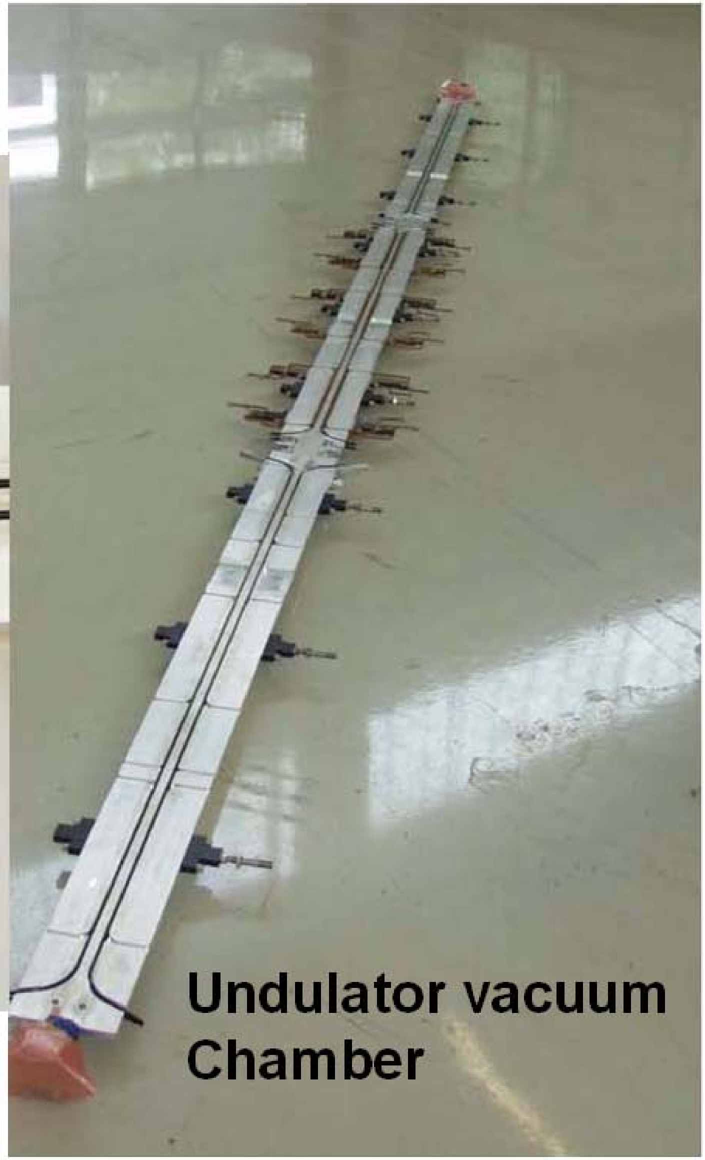


3.1.1 Local dosimeter system (Optical Power Meter)

Installation at the undulators
included in the vacuum chamber

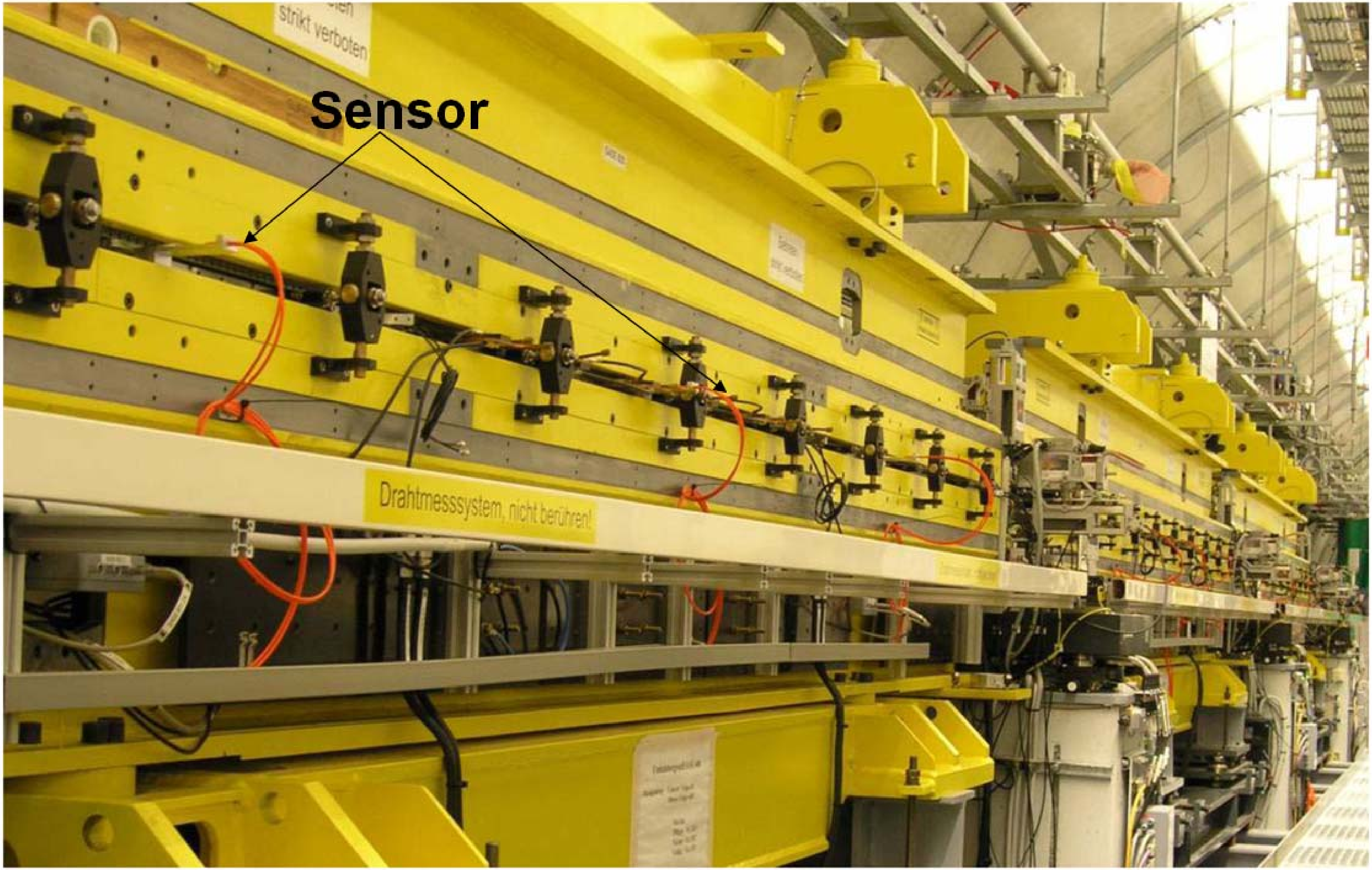


Cut out for Power Meter Sensor



3.1.1 Local dosimeter system (Optical Power Meter)

Optical Power Meter System at the Undulator at FLASH (DESY)



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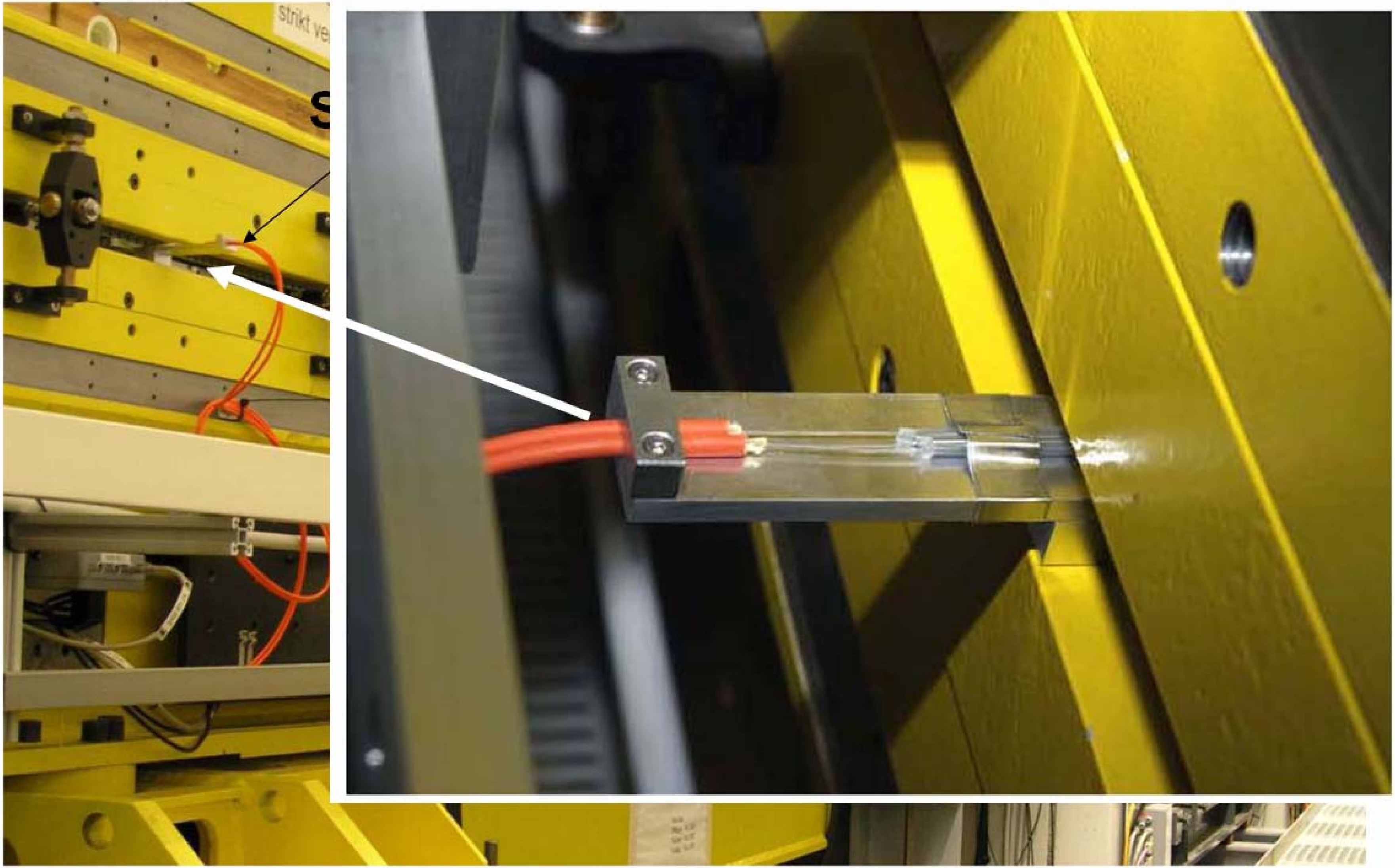
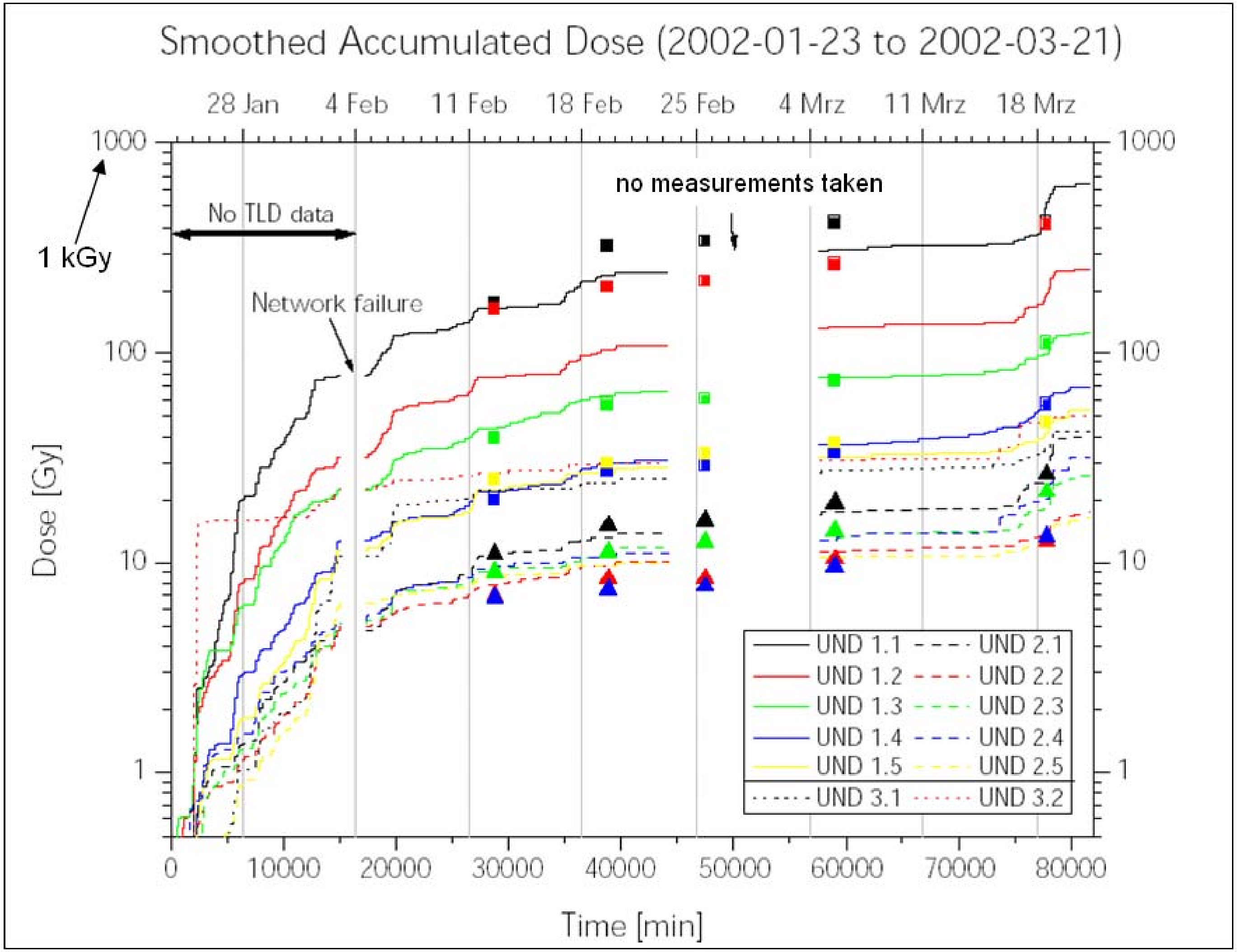


Dose measurement at the undulator compared with TLD measurements



Deviation:
< 25 %

Reasons:
- not same position
- TLD Error 10-20 %

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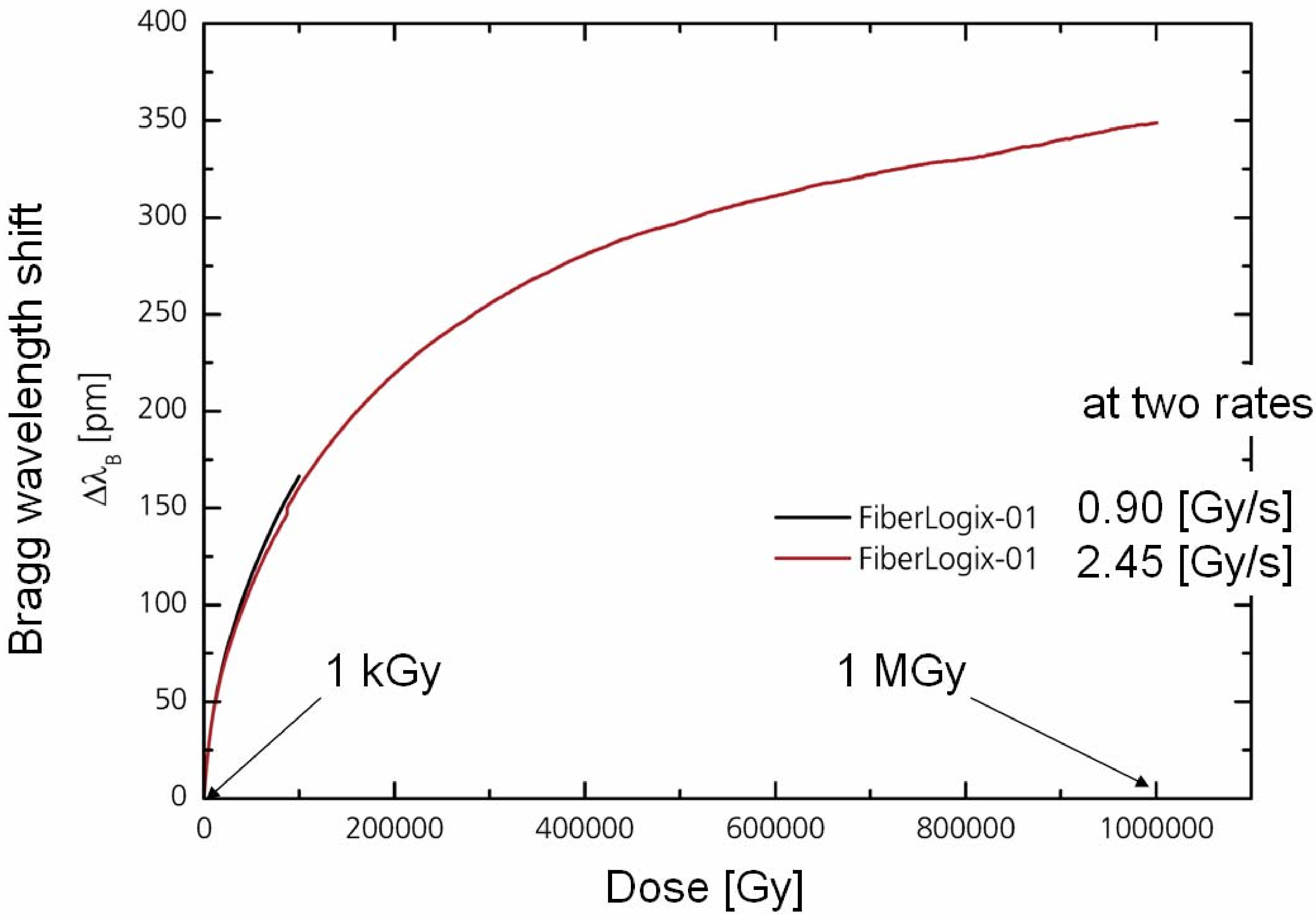
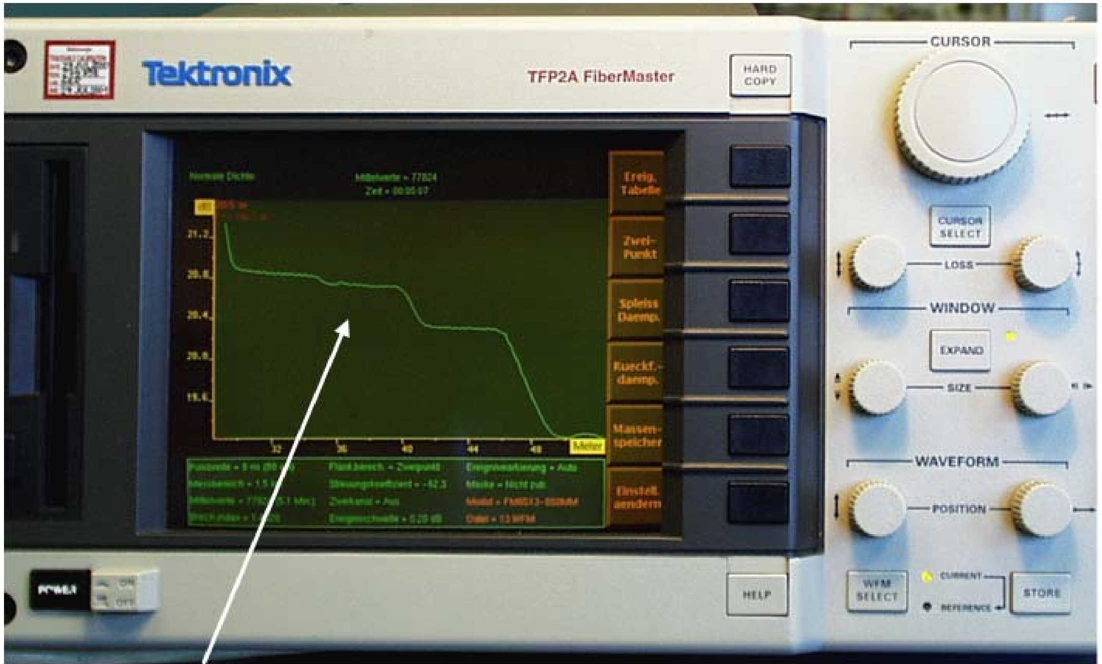
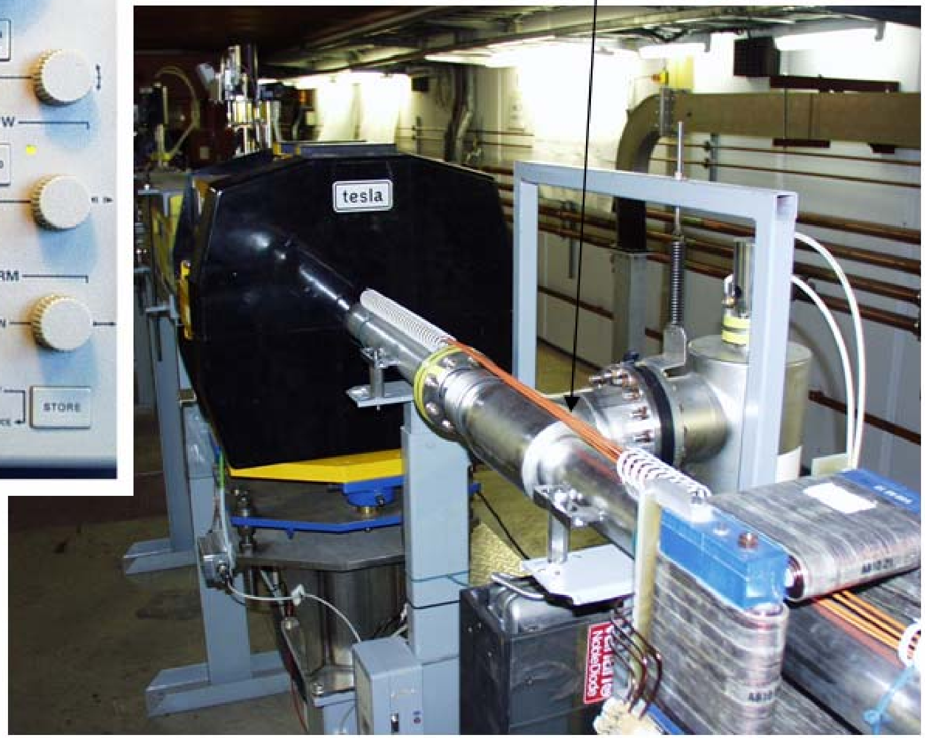
First Results with Fiber-Bragg-Gratings at FLASH



Measurement set up at FLASH

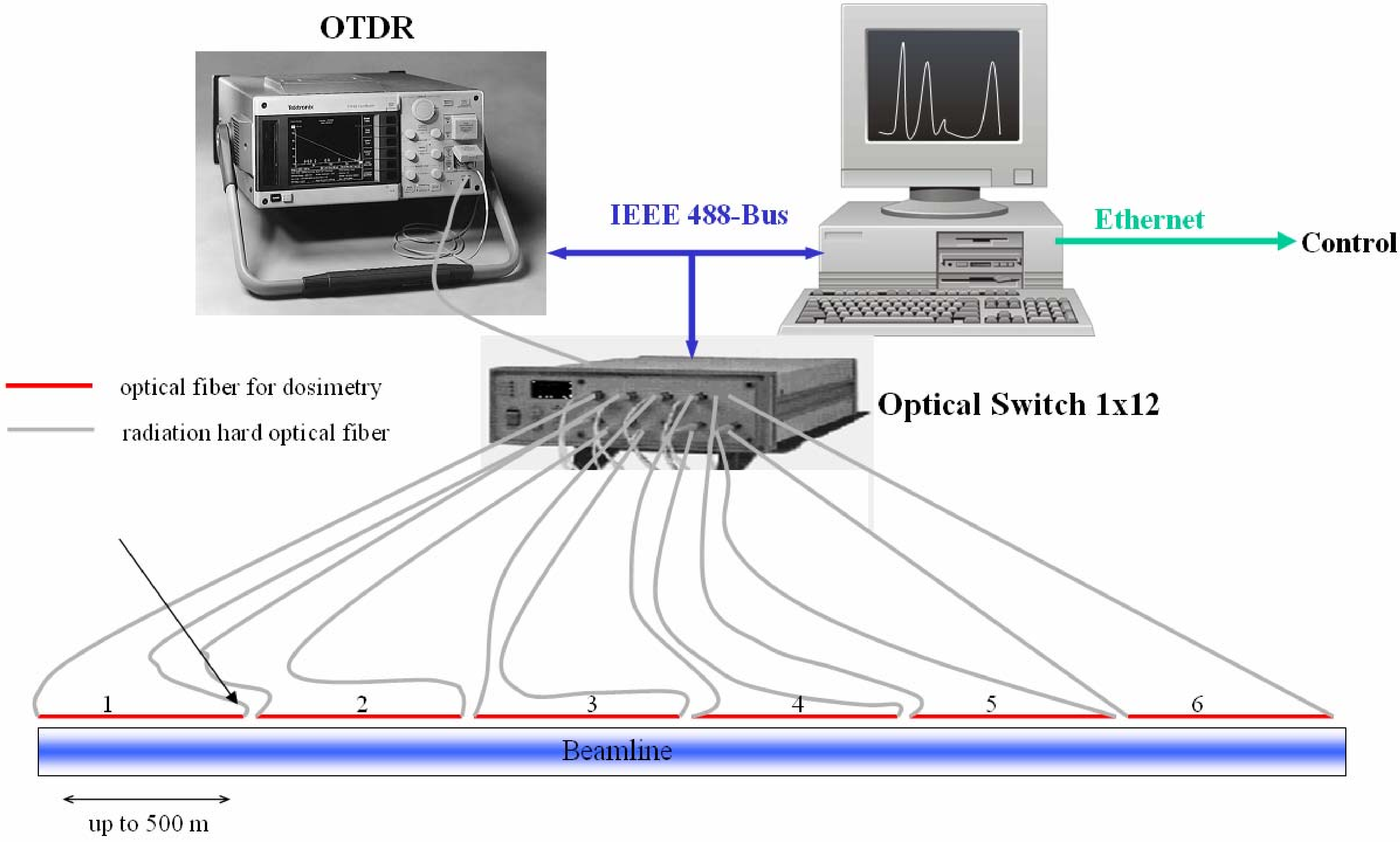




OTDR fiber

RIA along the beam line

Schematic of a set up for long distance OTDR measurement



3.1.3 Distributed dosimeter system (OTDR)

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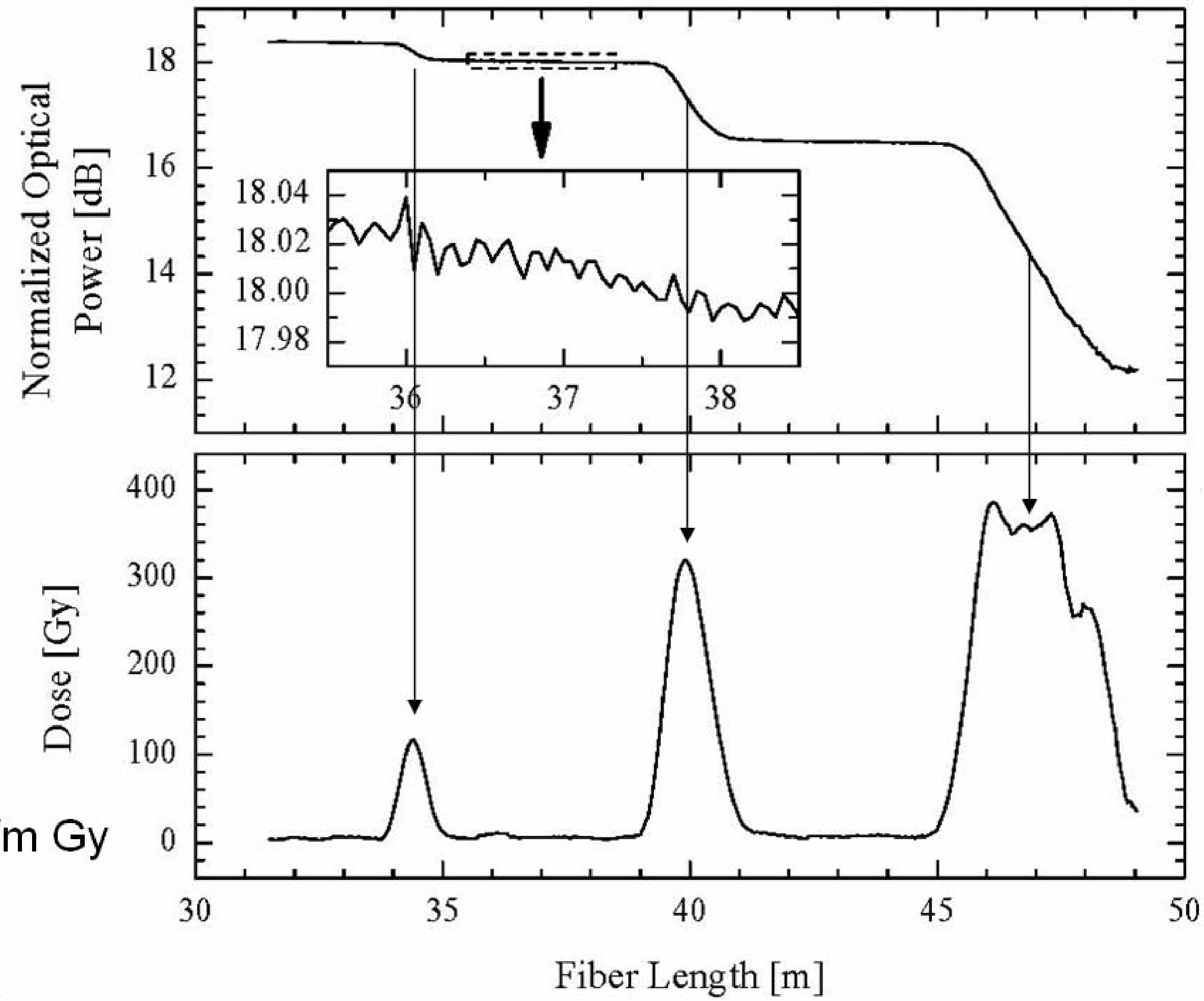
$$c(\lambda) \cdot D^{f(\lambda)} = \frac{dI}{dl}$$

for f = 1

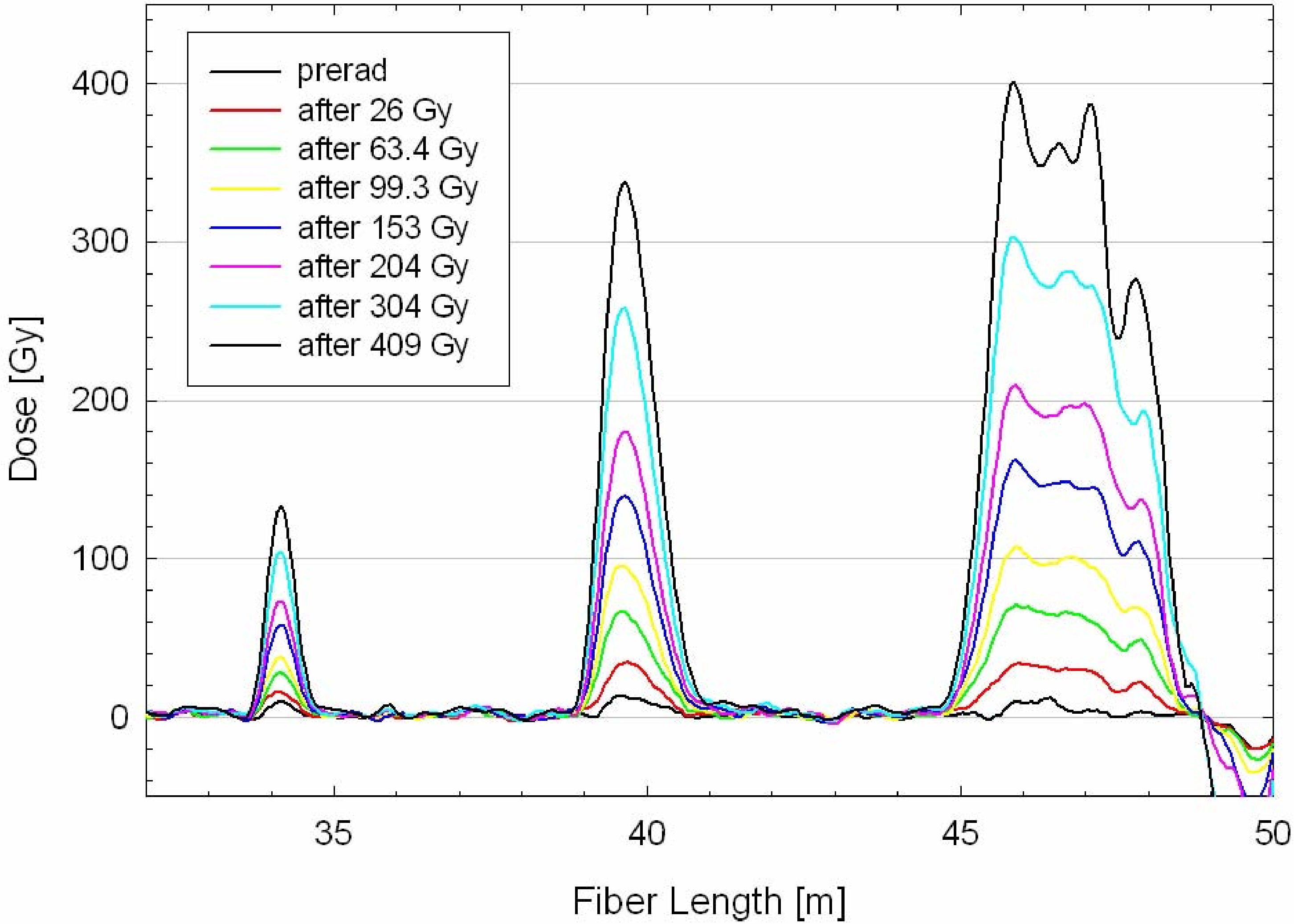
$$D = \frac{1}{c(\lambda)} \cdot \frac{dI}{dl}$$



typical values:

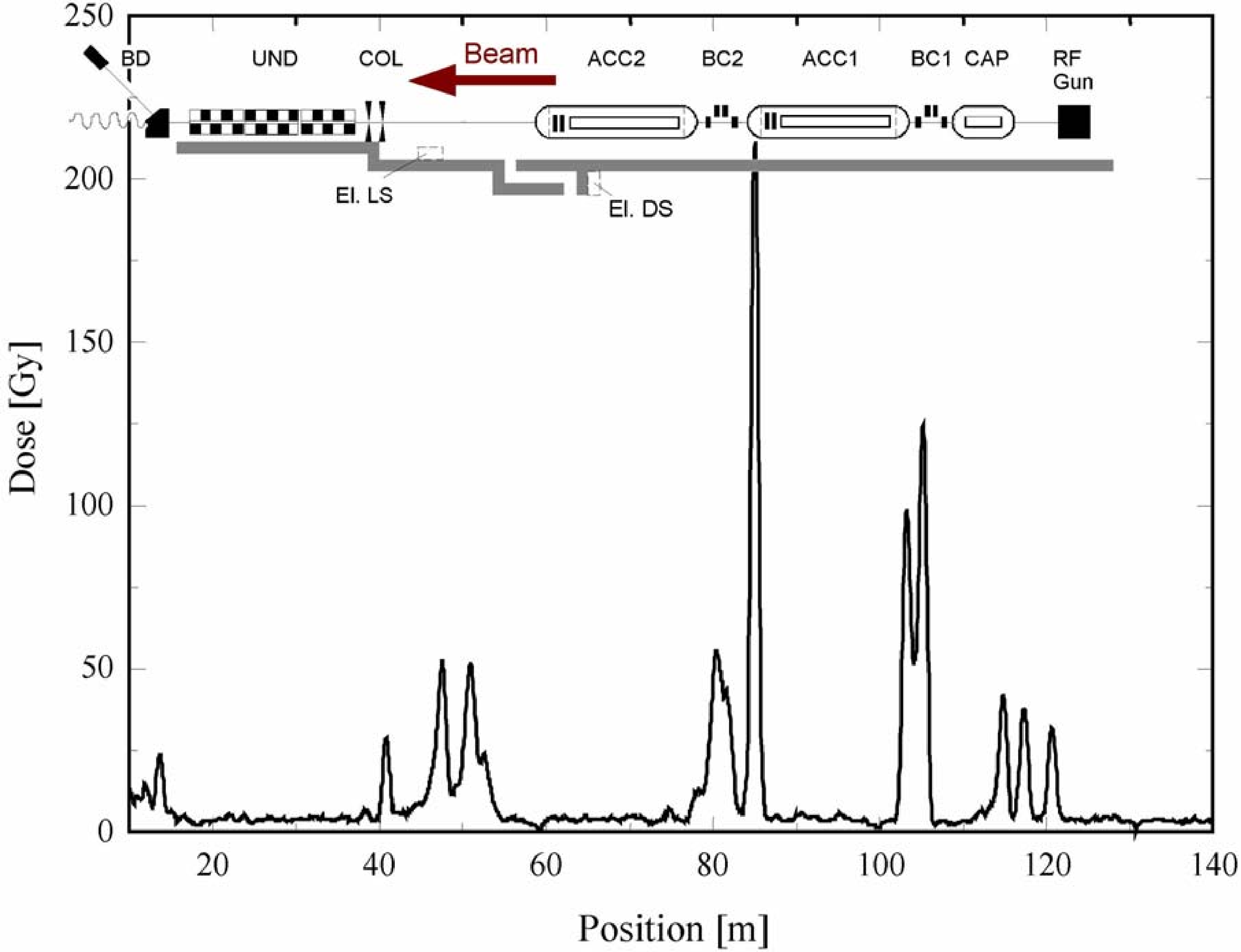
λ= 829 nm, c = 0.0042 dB/m Gy
ODTR: pulse width: 3 ns
Minimum Dose: 3 Gy
local resolution: 1,5 m

3.1.3 Distributed dosimeter system (OTDR)



smoothing procedure Savitzky-Golay algorithm

Beam loss measurements at
TESLA Test Facility of DESY Hamburg



Classification of beam loss monitor systems

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Fast BLM Systems

Radiation induced Cerenkov or luminescence light

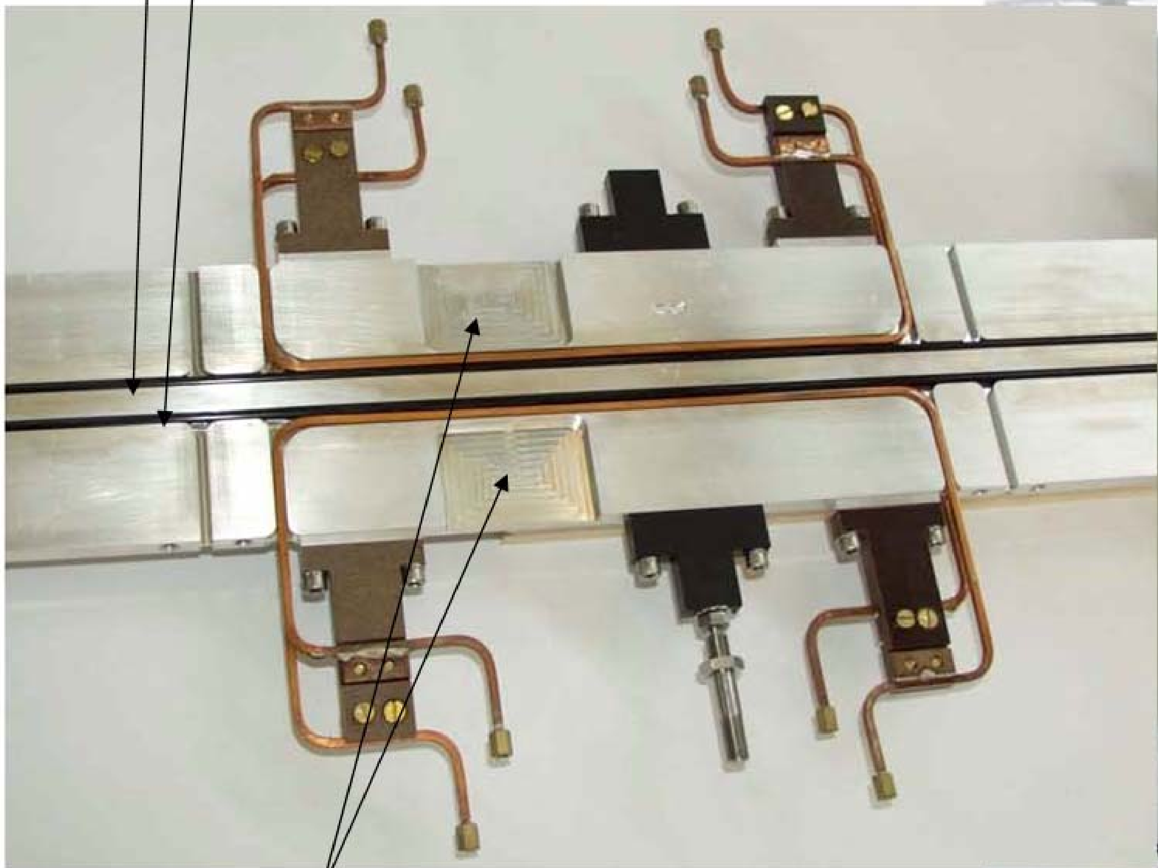
- distributed systems
- measurement time: *millisecond with time resolution of nanoseconds*
- loss trace monitoring; emergency shutdown

Cerenkov Light | Scintillation

Light Detection Systems
- Photomultiplier
- Fast Data Acquisition (DAQ)

Installation at the undulator

Dosimetrie- and Cerenkov Fiber



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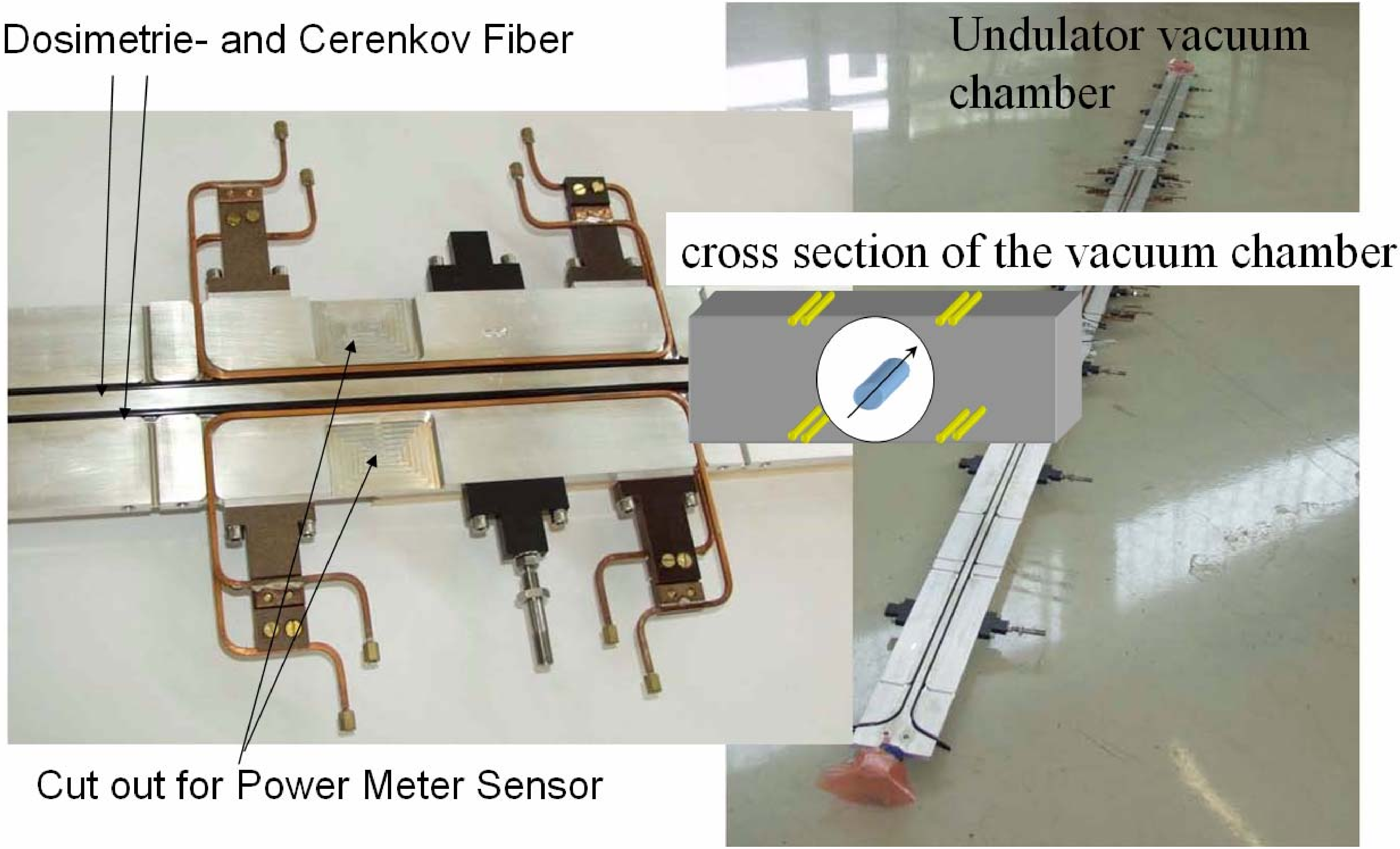
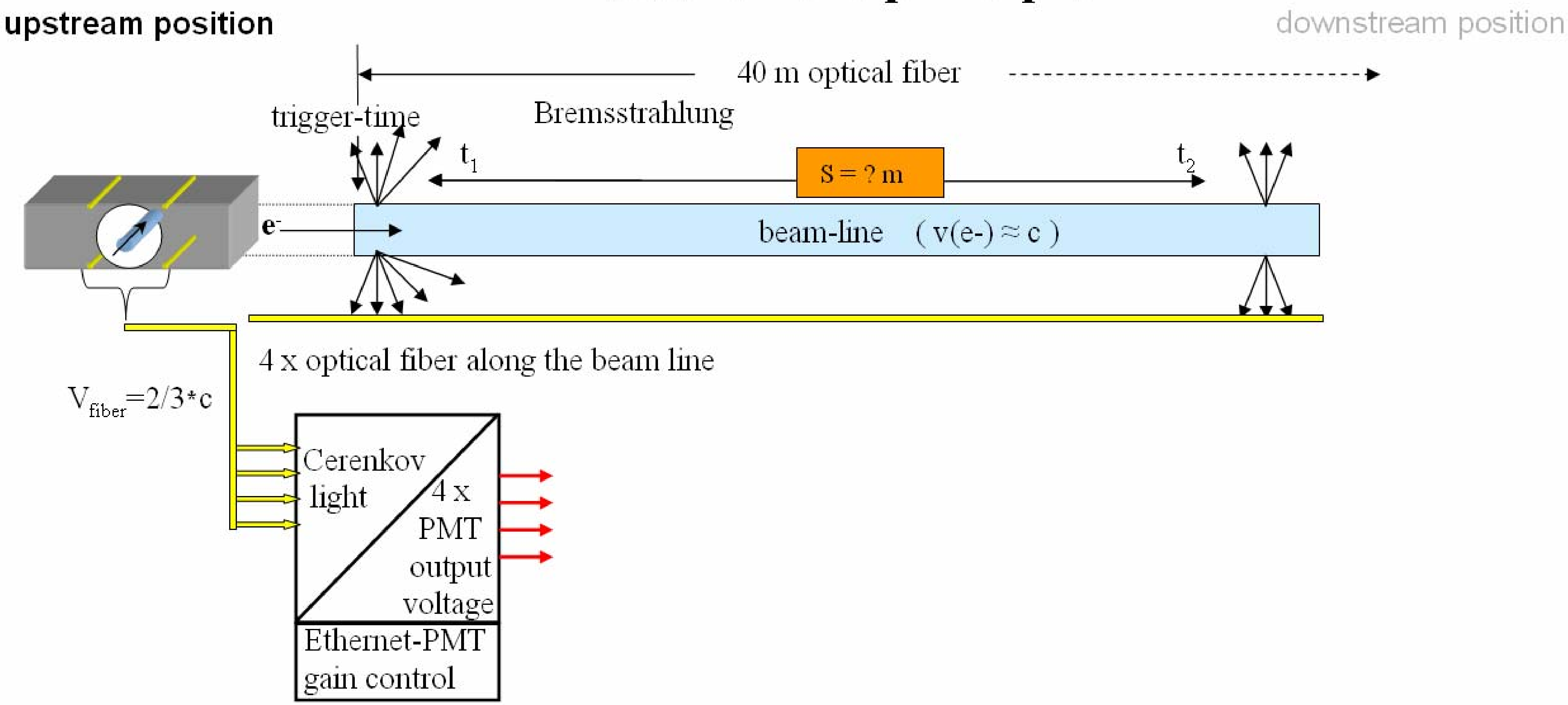
Installation at the undulator

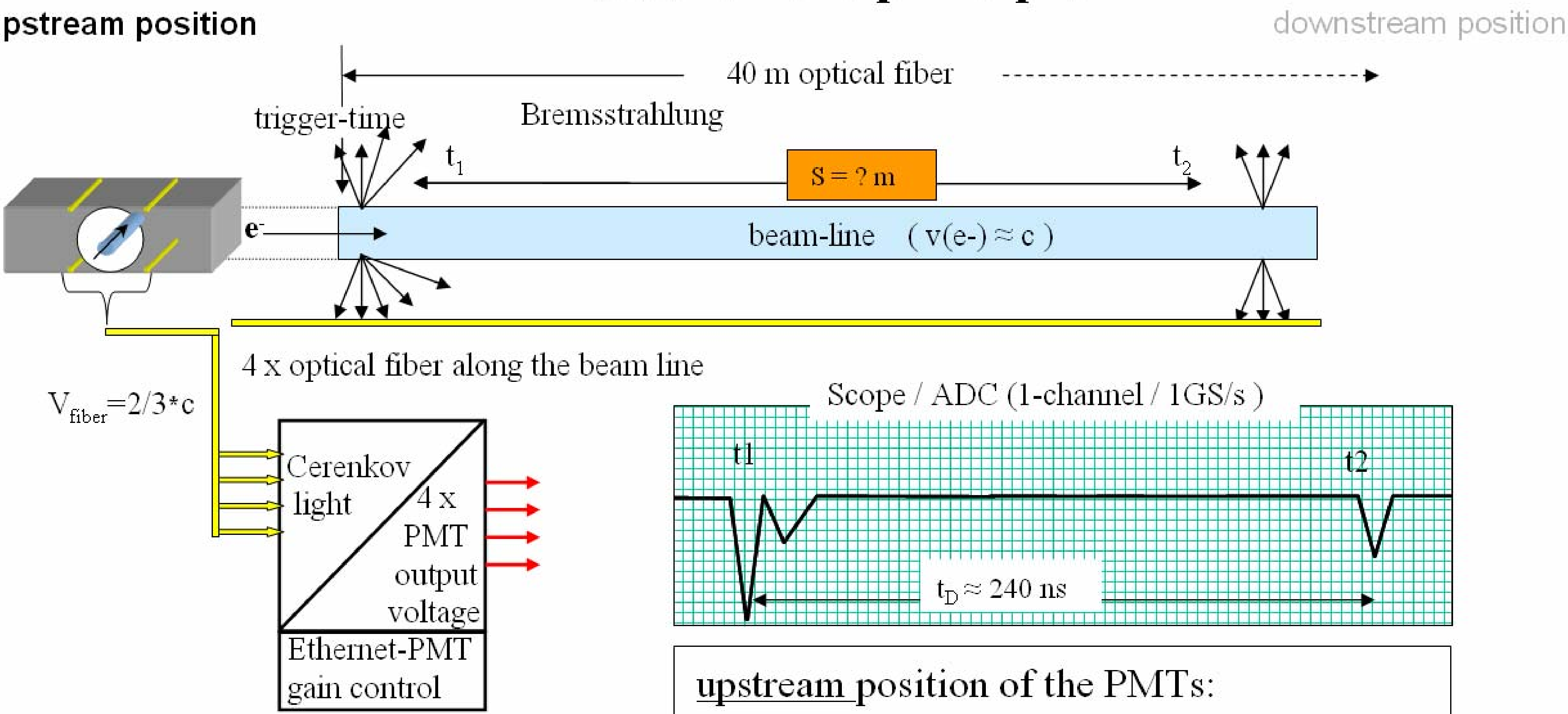


Measurement principle

Measurement principle



Measurement principle



v_{vac}	≈	**c**	(≈ 3.3 ns/m)
v_{fiber}	≈	**0,66*c**	(≈ 5.0 ns/m)
v_{meas}	≈	**2/5*c**	(≈ 8.3 ns/m)

upstream position of the PMTs:

$\mathbf{S = t_D * 2/5 * c}$

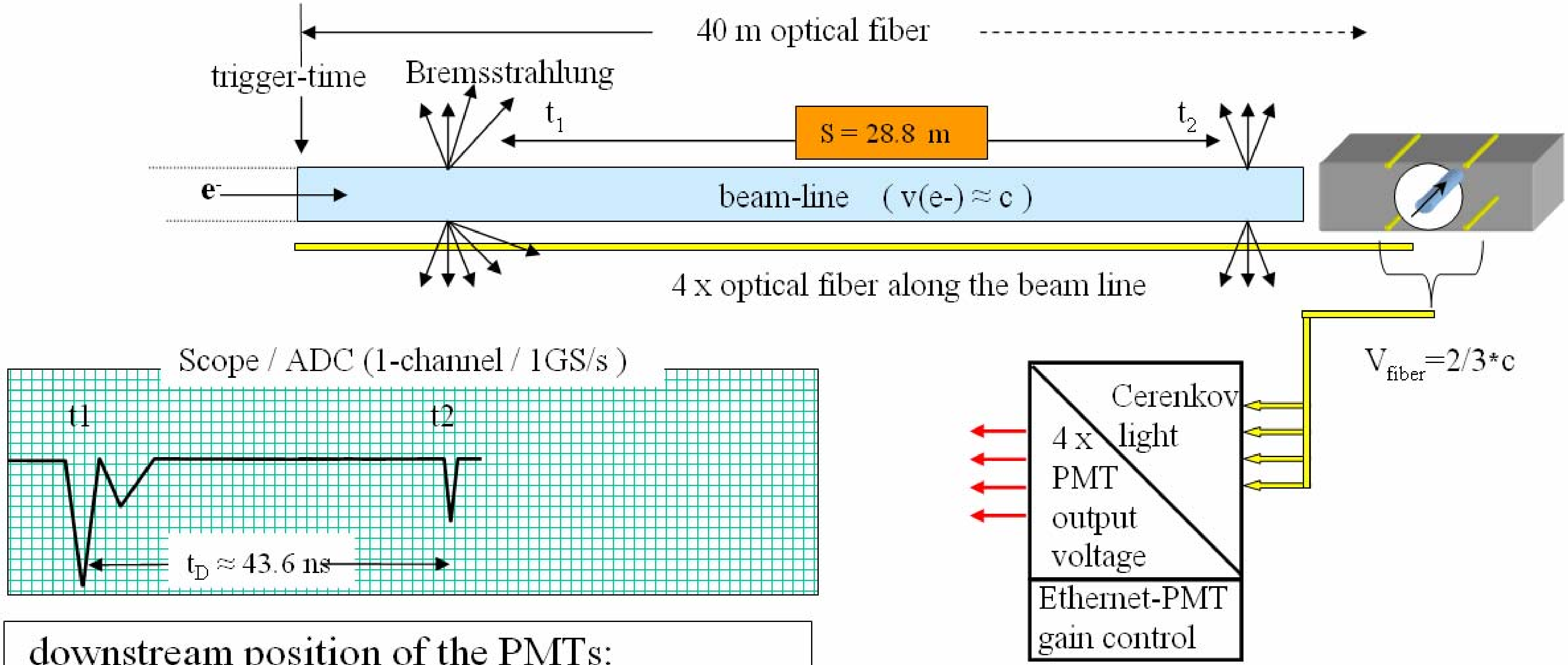
$t_D = t_2 - t_1 = 240$ ns ⟹ $S = 28.8$ m

expansion factor of 2.5

Measurement principle

upstream position

downstream position



downstream position of the PMTs:

$\mathbf{S = t_D * 2 * c}$

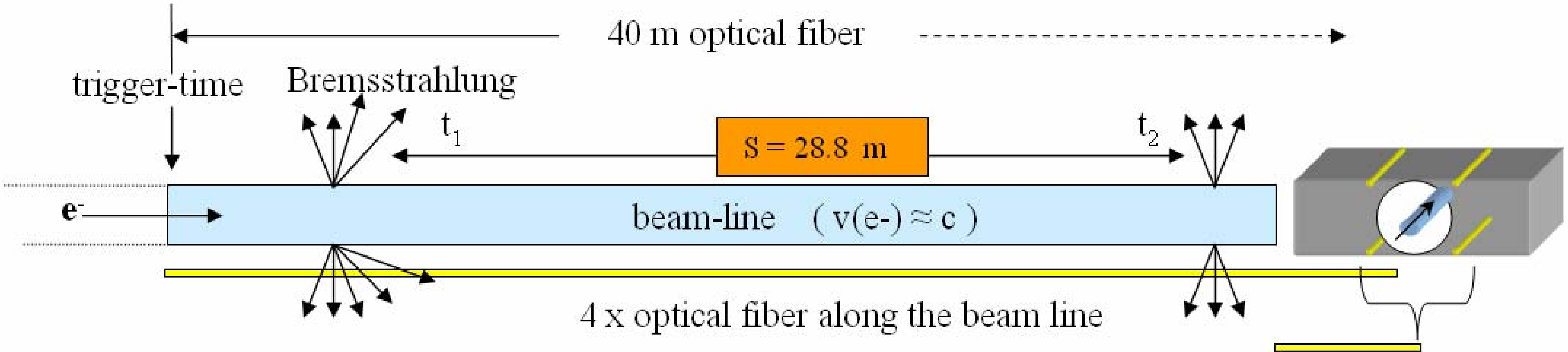
$t_D = t_1 - t_2 = 48$ ns $\Longrightarrow$ S = 28.8 m

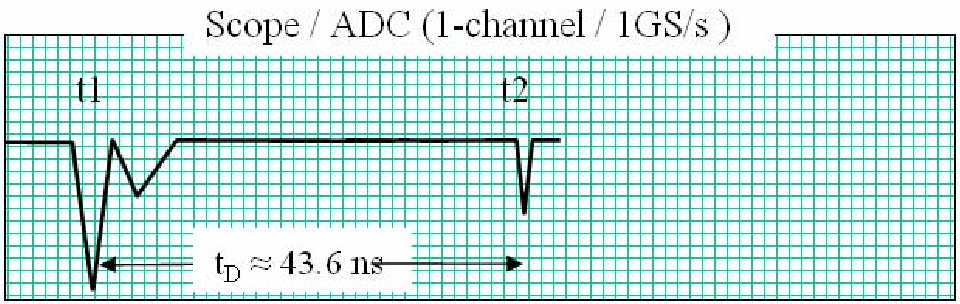
compression factor of 2

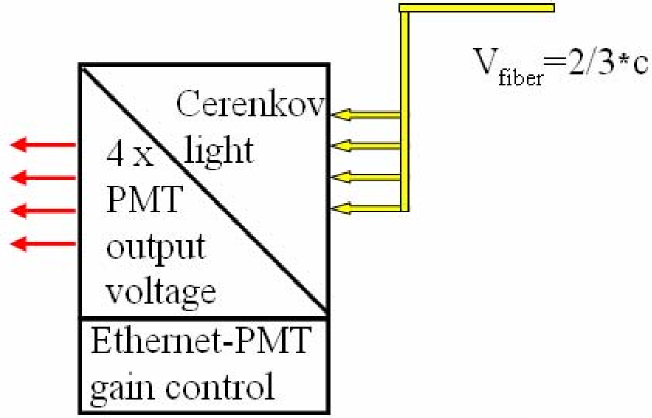
Measurement principle

upstream position

downstream position







downstream position of the PMTs:

$\mathbf{S = t_D * 2 * c}$

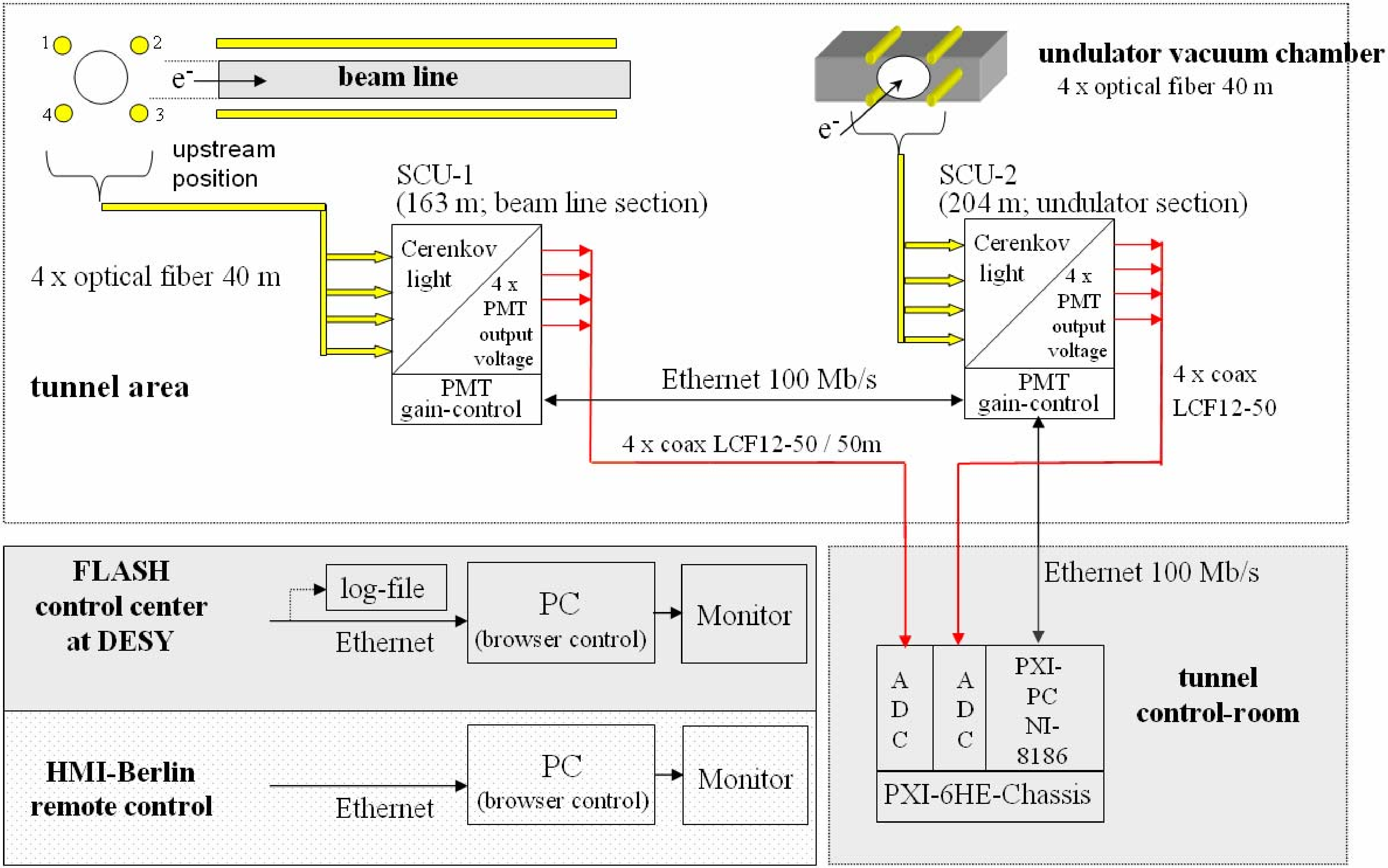
$t_D = t_1 - t_2 = 48$ ns $\Longrightarrow$ S = 28.8 m

compression factor of 2

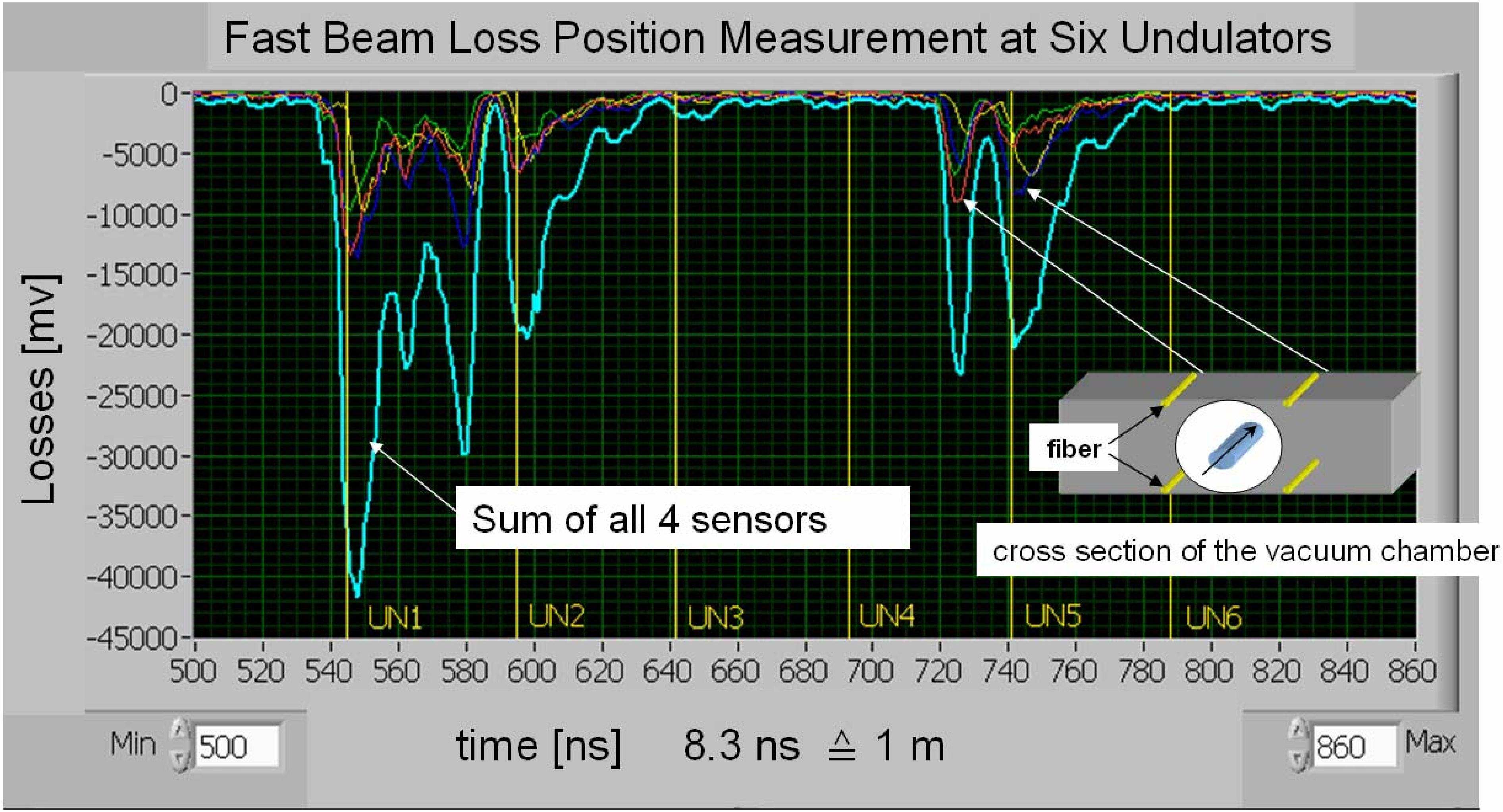
The required **observation window** at downstream position compared to the upstream position is 5 times shorter. The position resolution at same bandwidth and sample rate is worse

Measurement set up at FLASH

Measurement set up at FLASH



Screen shot at FLASH
Measurement over the length of six undulators



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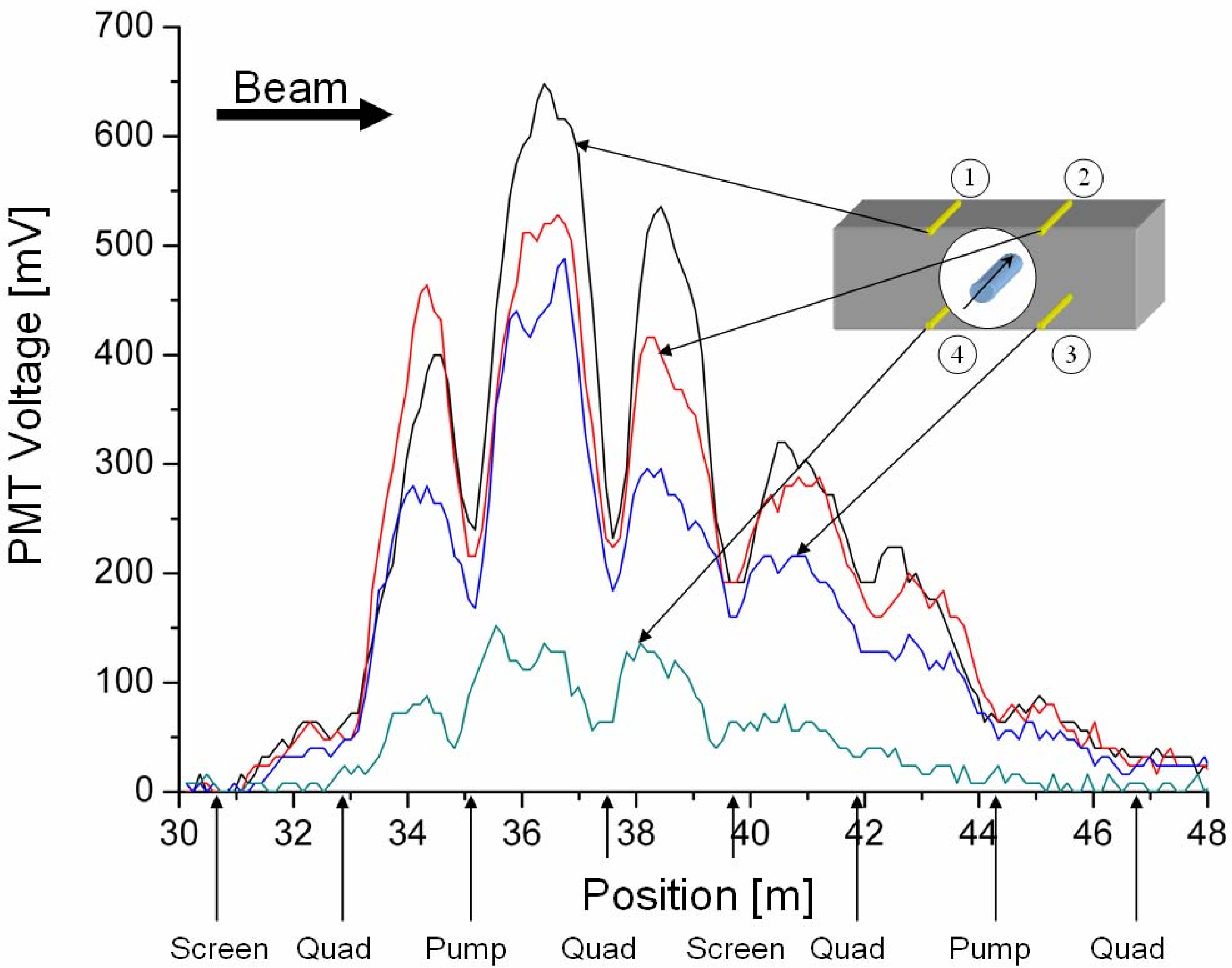
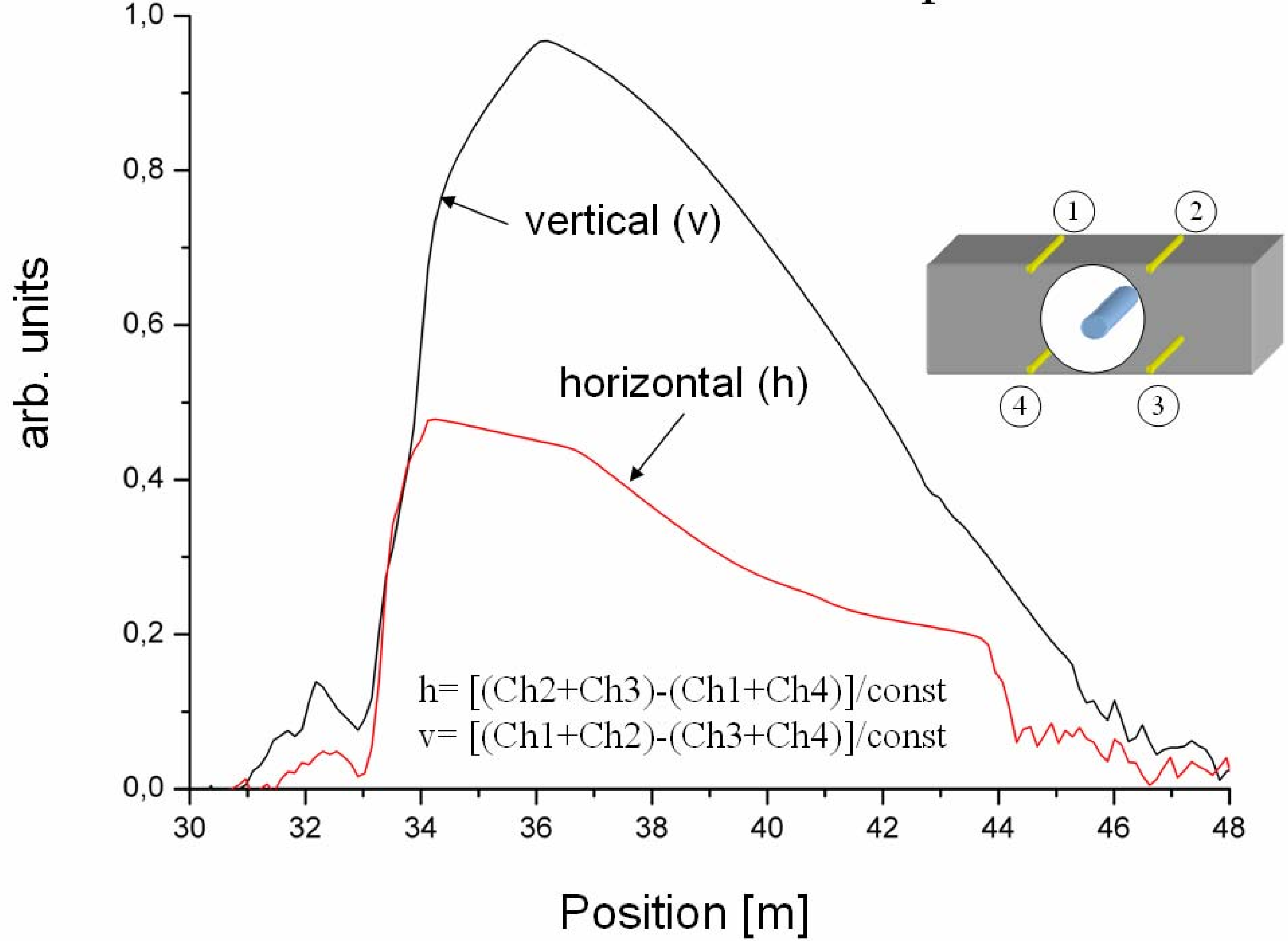
Cerenkov signals at an interesting section of the beam line

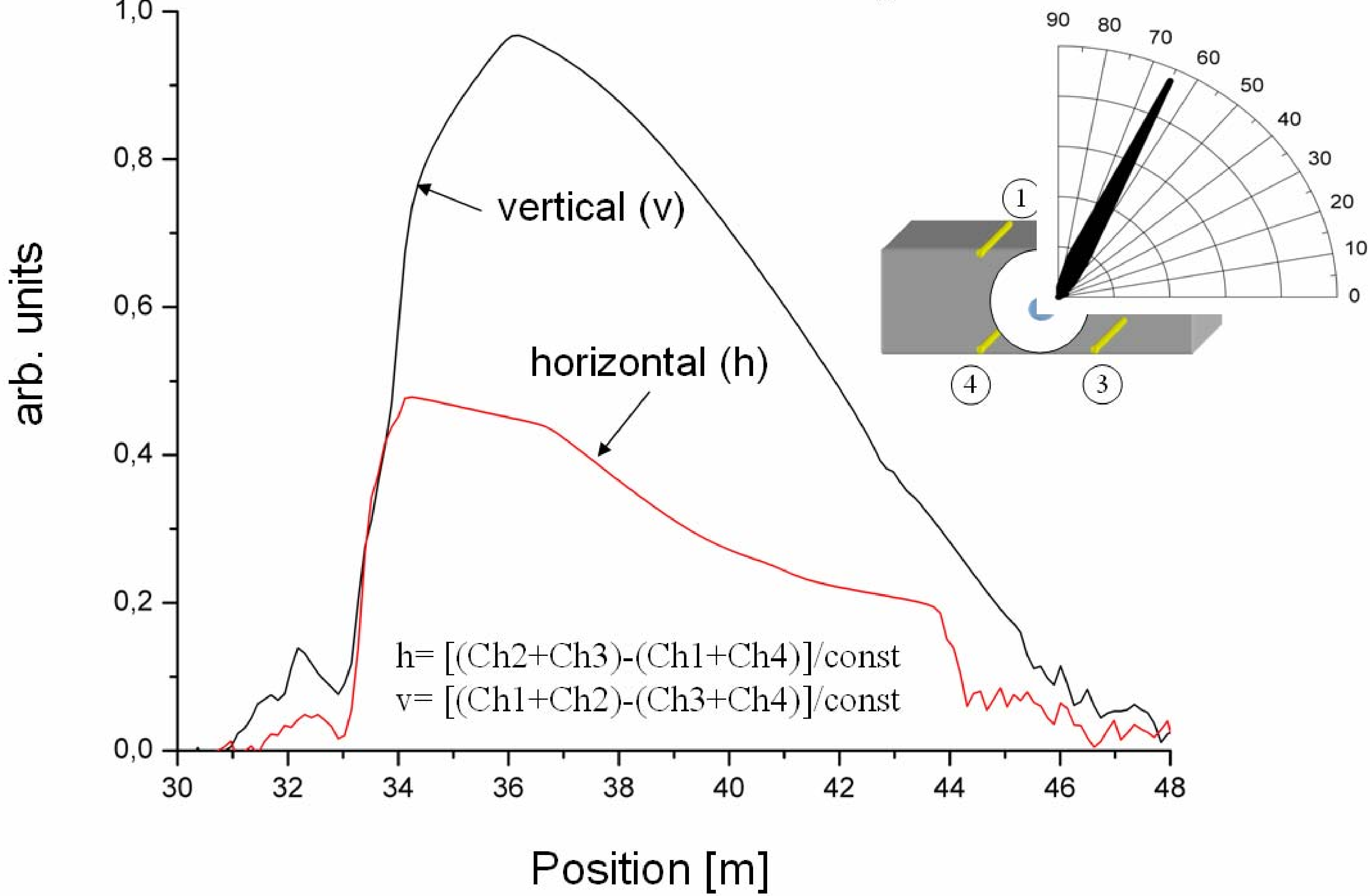


Enveloped function of the Bremsstrahlung along the beam line and the direction of the radiation pattern



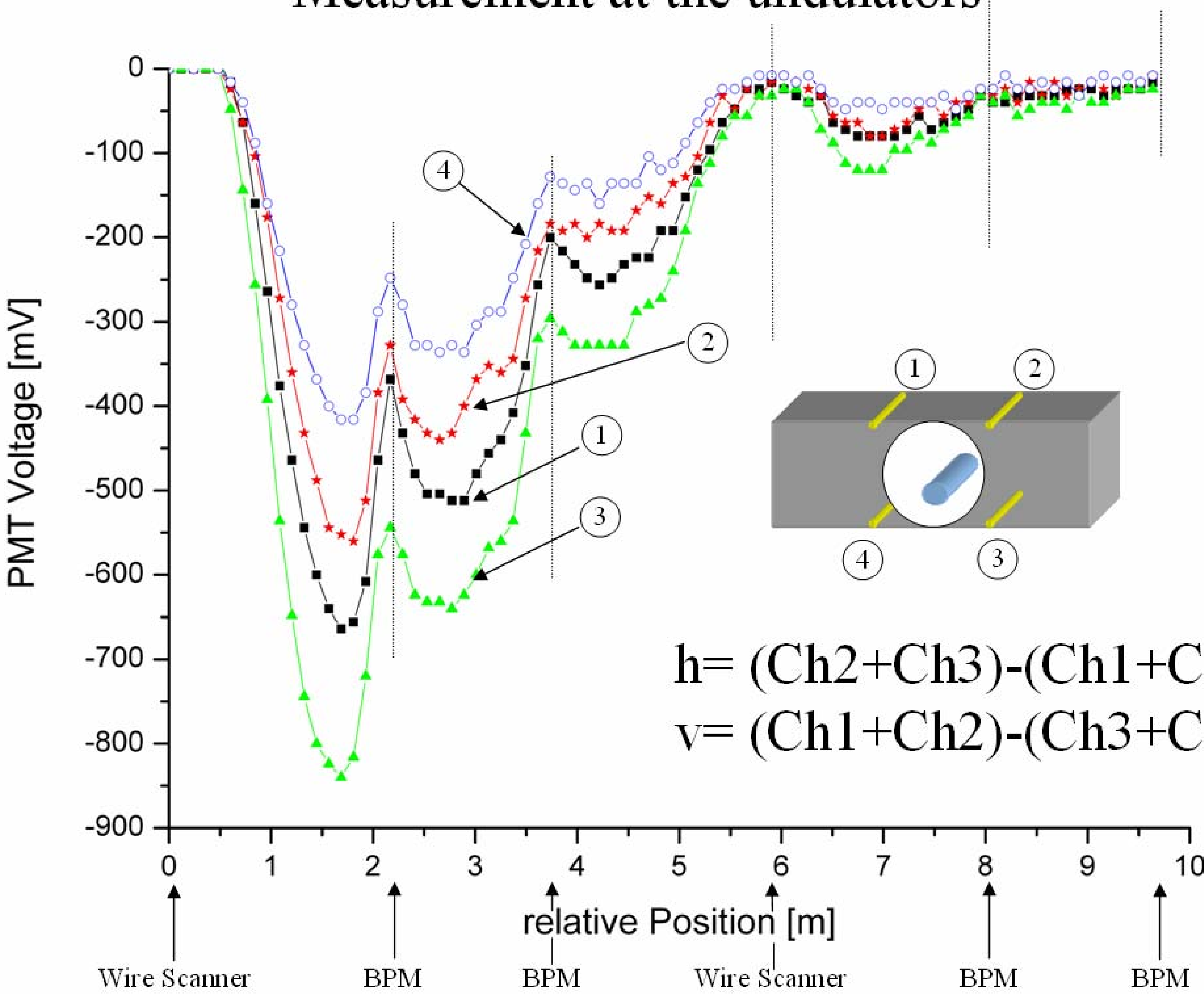
3.2.1 Beam loss position monitor

Enveloped function of the Bremsstrahlung along the beam line and the direction of the radiation pattern



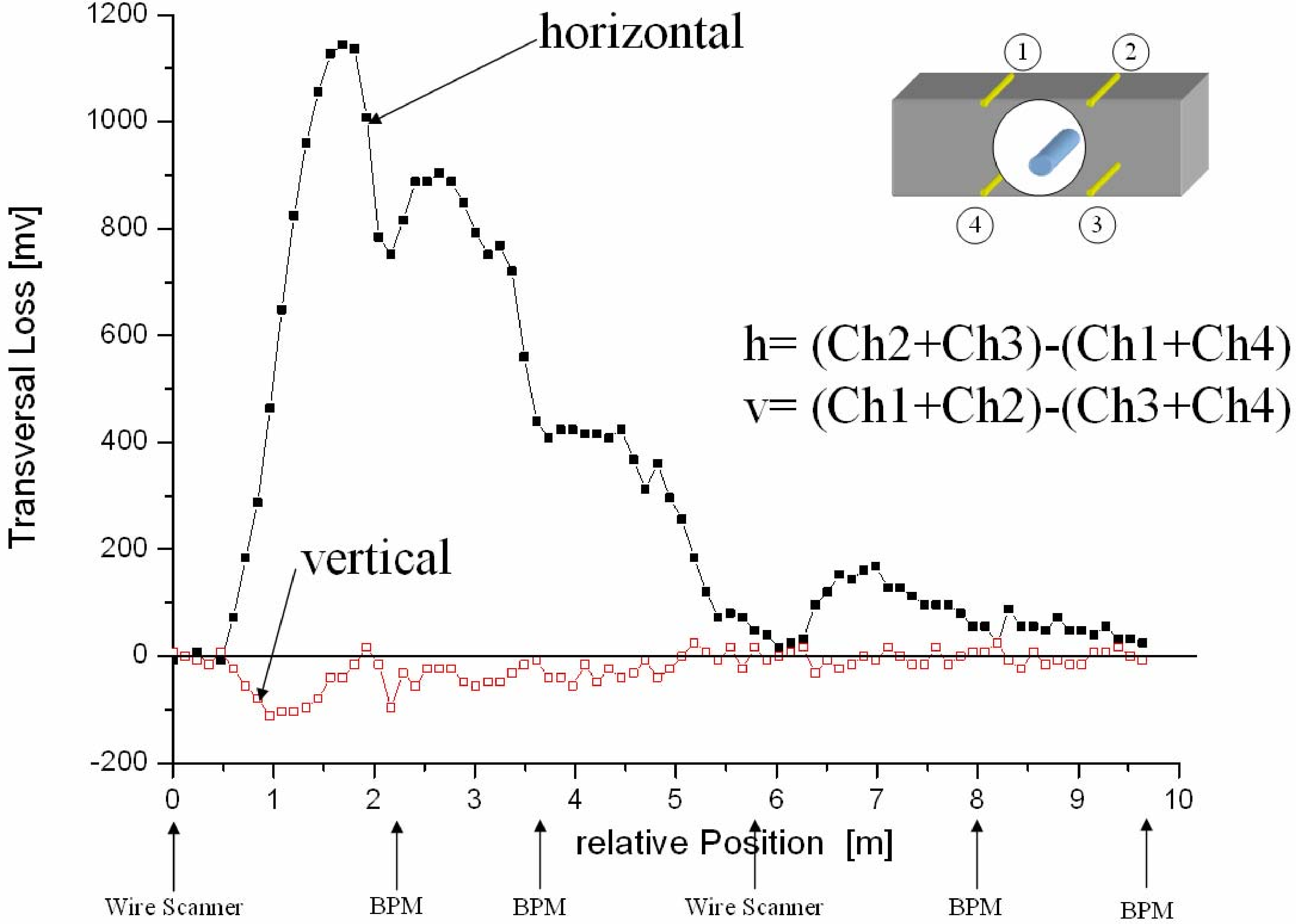
Measurement at the undulators

Measurement at the undulators

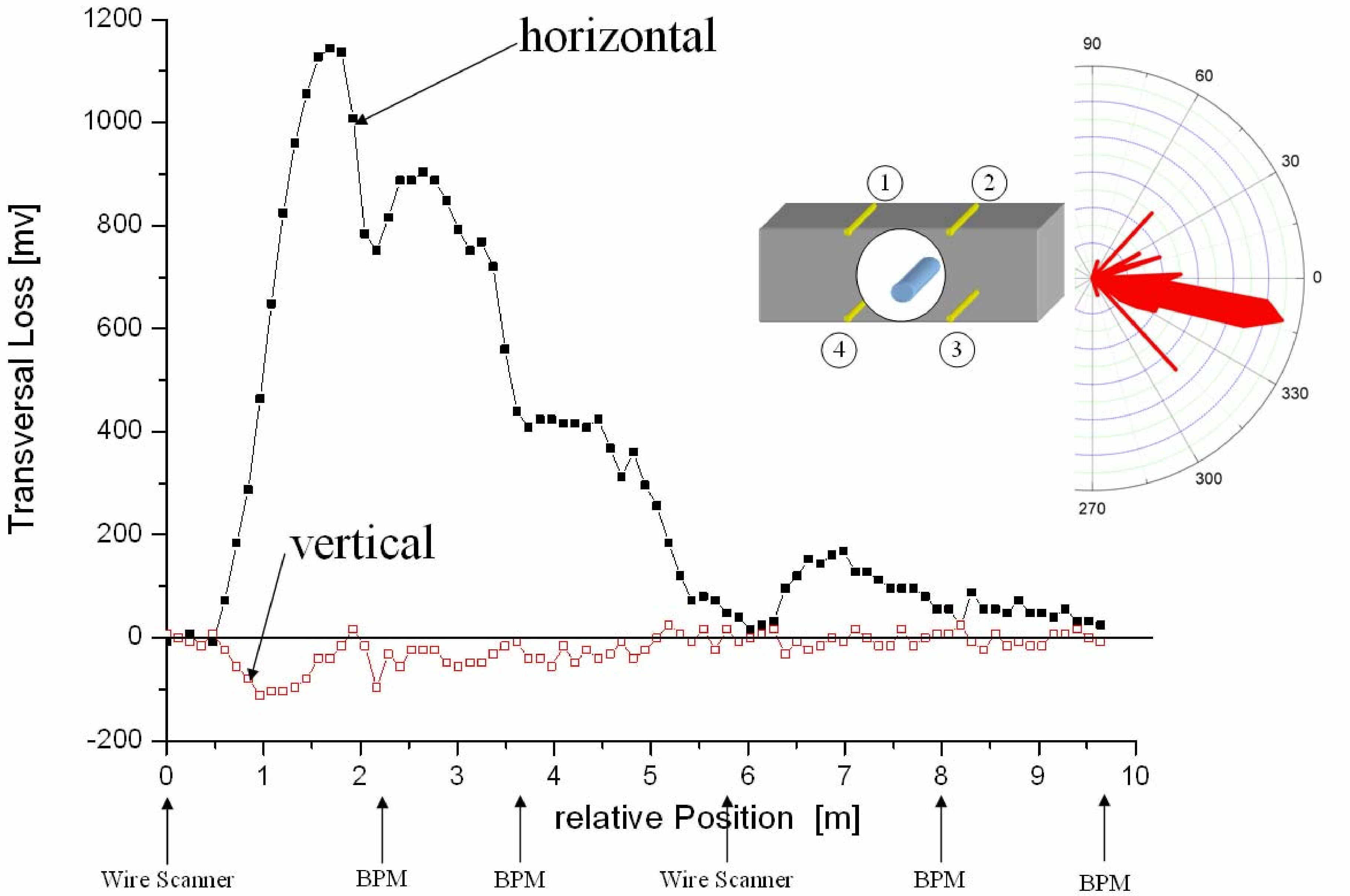


h= (Ch2+Ch3)-(Ch1+Ch4)

v= (Ch1+Ch2)-(Ch3+Ch4)

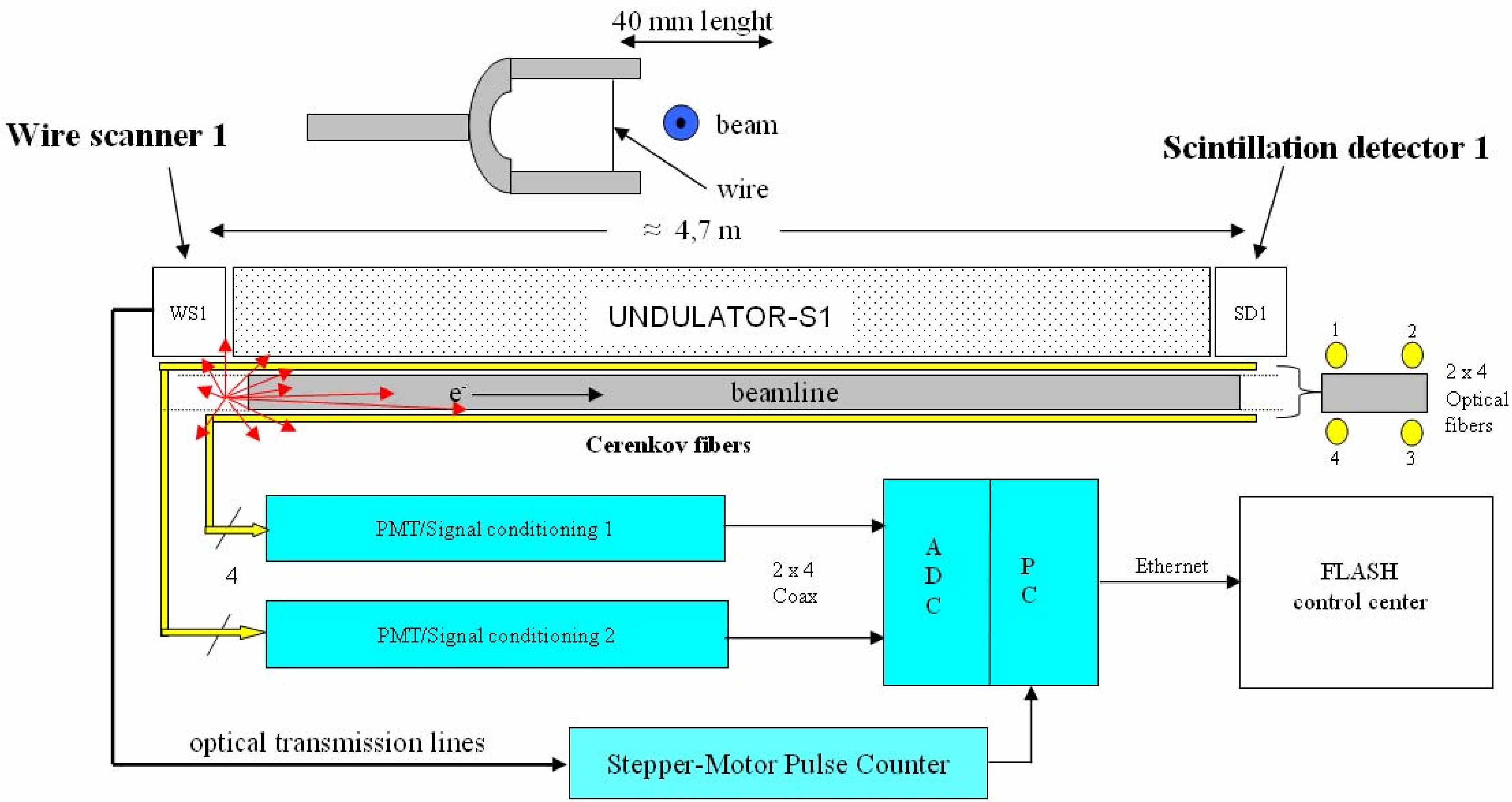

horizontal
vertical
1
2
3
4
h= (Ch2+Ch3)-(Ch1+Ch4)
v= (Ch1+Ch2)-(Ch3+Ch4)
Transversal Loss [mv]
1200
1000
800
600
400
200
0
-200
0
1
2
3
4
5
6
7
8
9
10
relative Position [m]
Wire Scanner
BPM
BPM
Wire Scanner
BPM
BPM

3.2.1 Beam loss position monitor

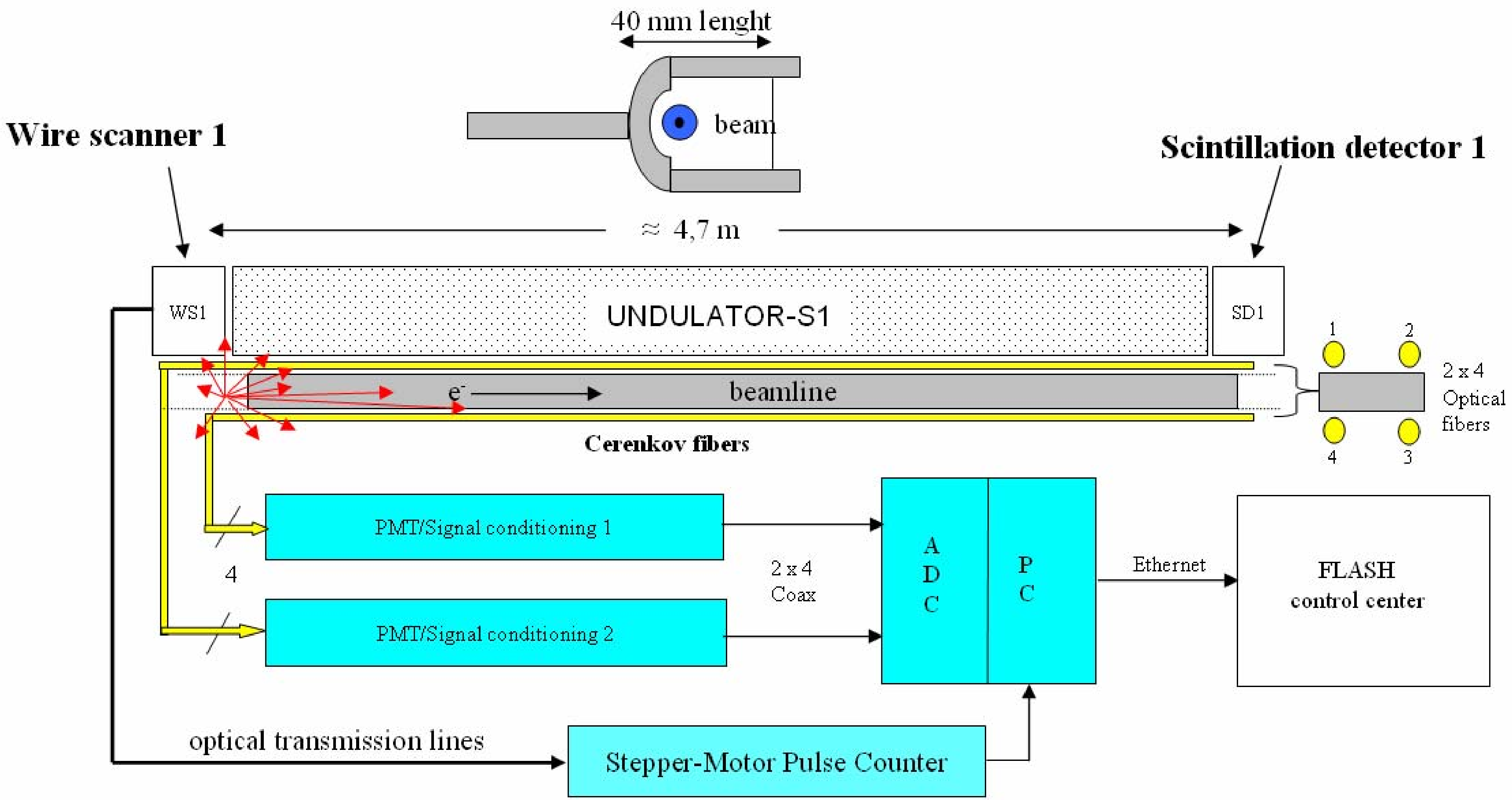


Wire scanner in combination with fiber sensors from the BLPM system used as beam profile monitor

Wire scanner in combination with fiber sensors



Wire scanner in combination with fiber sensors



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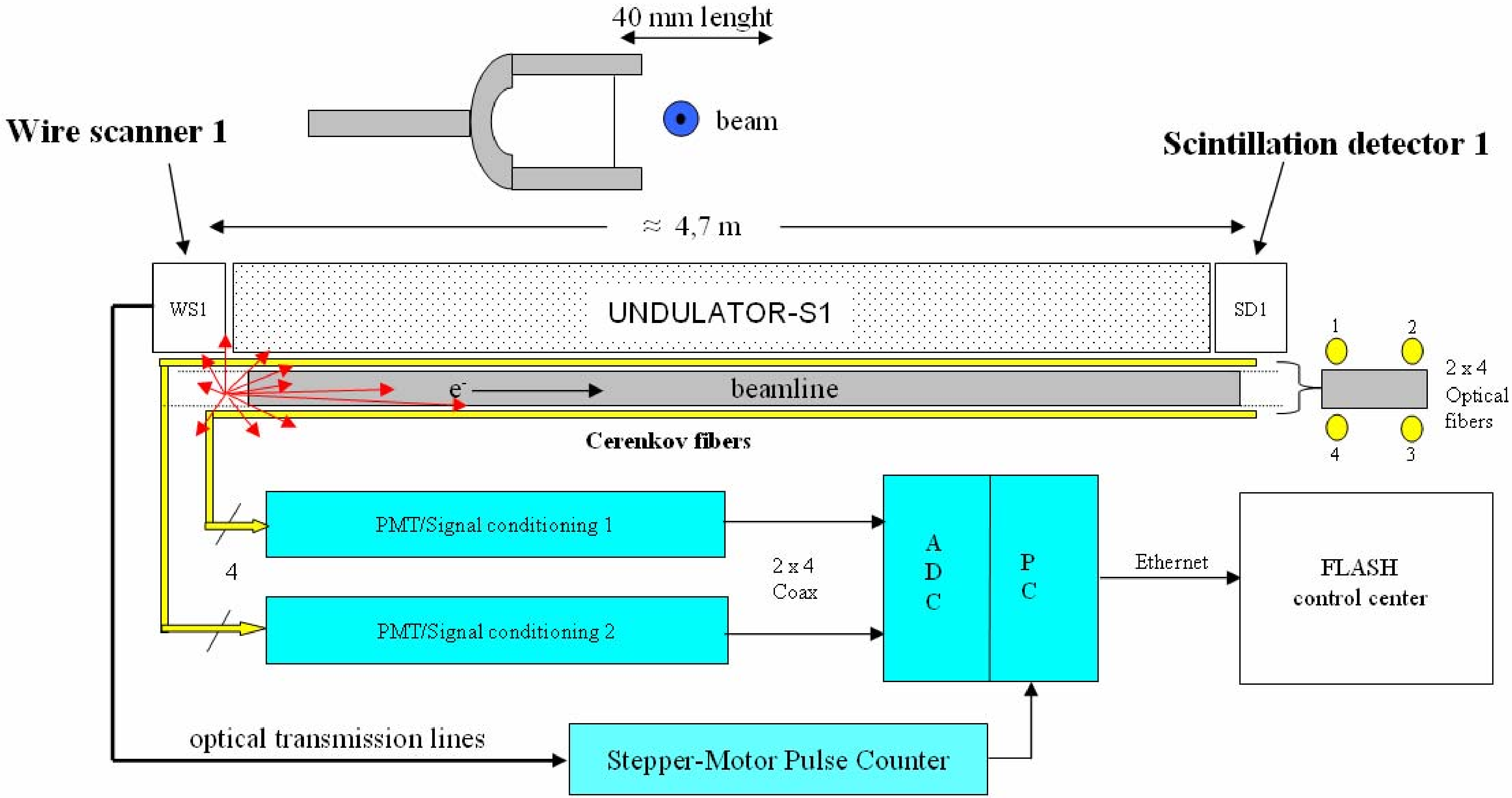

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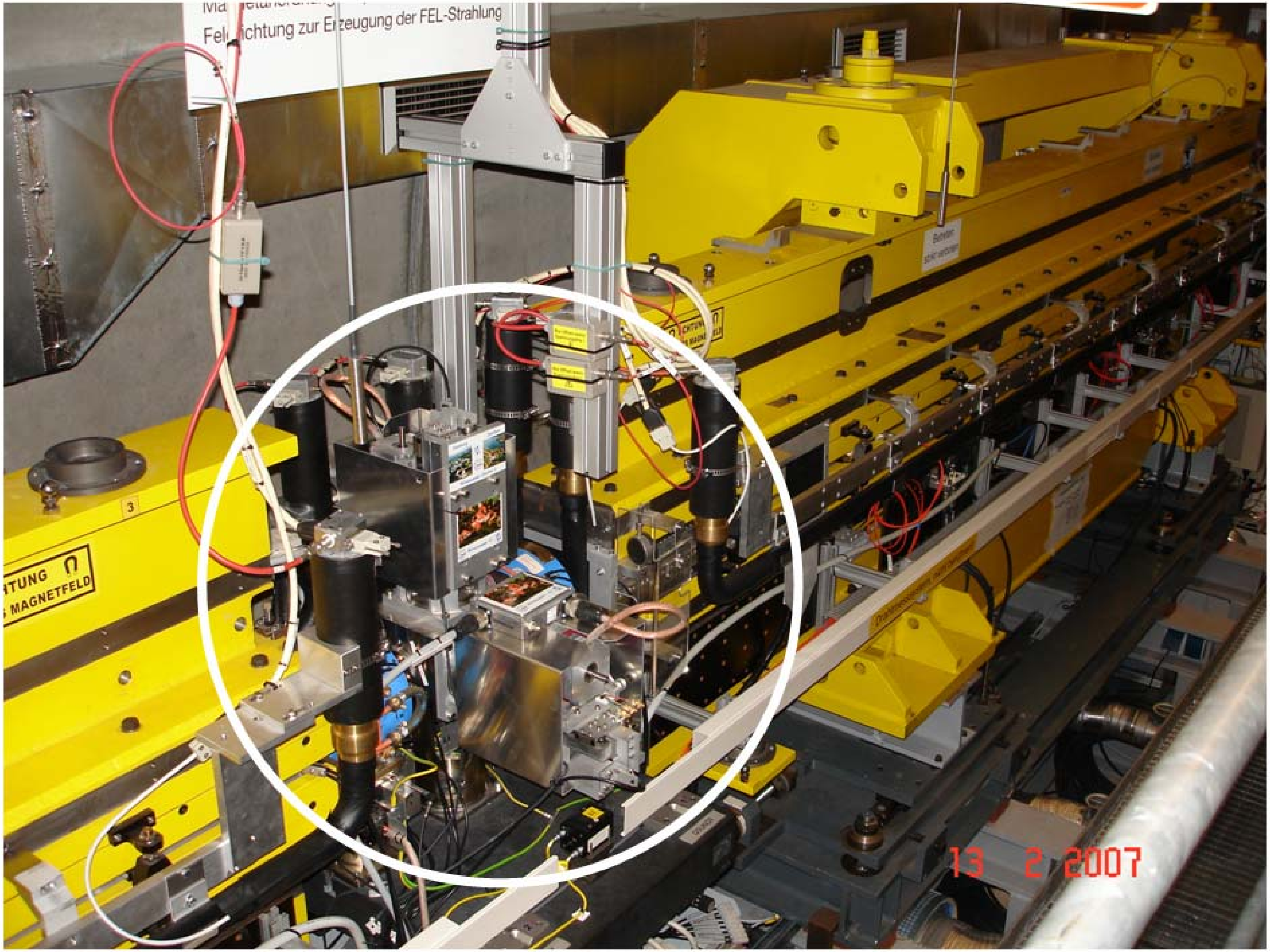
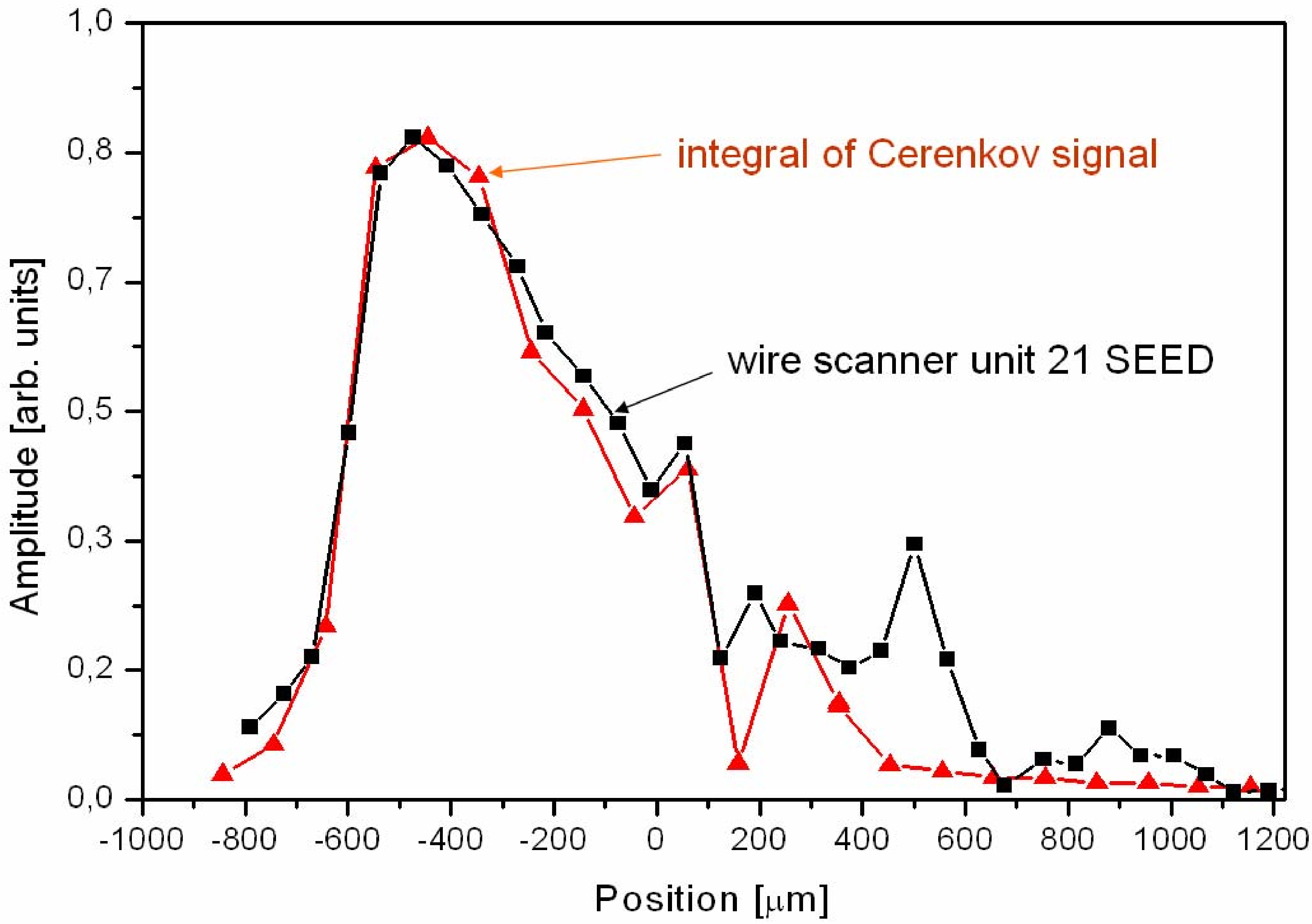
A complete wire scanner system positioned in the gap between two undulator segments



Horizontal beam profile measurement



4. Conclusion

Application	Slow BLM Systems			Fast BLM Systems
	Distributed Dosimeter System	Local Dosimeter System	Local Dosimeter System (High Dose)	Beam Loss Position Monitor and Beam Profile Monitor
Measurement principle:	Optical Time Domain Reflectometer	Optical Power Meter	Bragg Wavelength shifting (Δ BWS)	Cerenkov Light
Bunch resoltution	No	No	No	YES, with in one train
Measurement time (detection response)	minutes	ms to minutes	ms to sec	$\leq$ ms with time resolution of 1 ns
Range of maximum dose TID [Gy]	3 – 450 limited by OTDR	0.06- 2000 limited by fiber type	$2 * 10^3 - 10^6$ limited by fiber type	only a rough estimation possible, fiber can used until $1*10^5$
wavelength range	850 - 1330 nm	860 nm	820 nm - 1,55 µm $\Delta \lambda_B = 5\text{-}350$ pm	200 - 850 nm
Position resolution	1.5 m	0.05 m	0,5 m	0.25 m
reasonable Fiber length*	$\leq$ 5 km typical $\leq$100 m sections	-	-	$\leq$ 1 km typical 50 - 100 m sections

* Depending on max. Dose and required position resolution

4. Conclusion

Installed measurement systems:

- FLASH, beam line and undulator, BPM system
- PITZ Injector beam line
- MAX-LAB undulator
- BESSY II, beam line
- DELTA storage ring Dortmund
- SLS (PSI)

ACKNOWLEDGEMENT

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O. Köhn[2] R. Awwad[3]
H.-J. Grabosch[4] M. Sachwitz[4]

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Thank you for your attention