Synchrotron-light detection at the IOTA/FAST D600 dipole magnet for beam diagnostics and experiments

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IOTA/FAST End-of-Run Retreat
December 21, 2017

Motivation

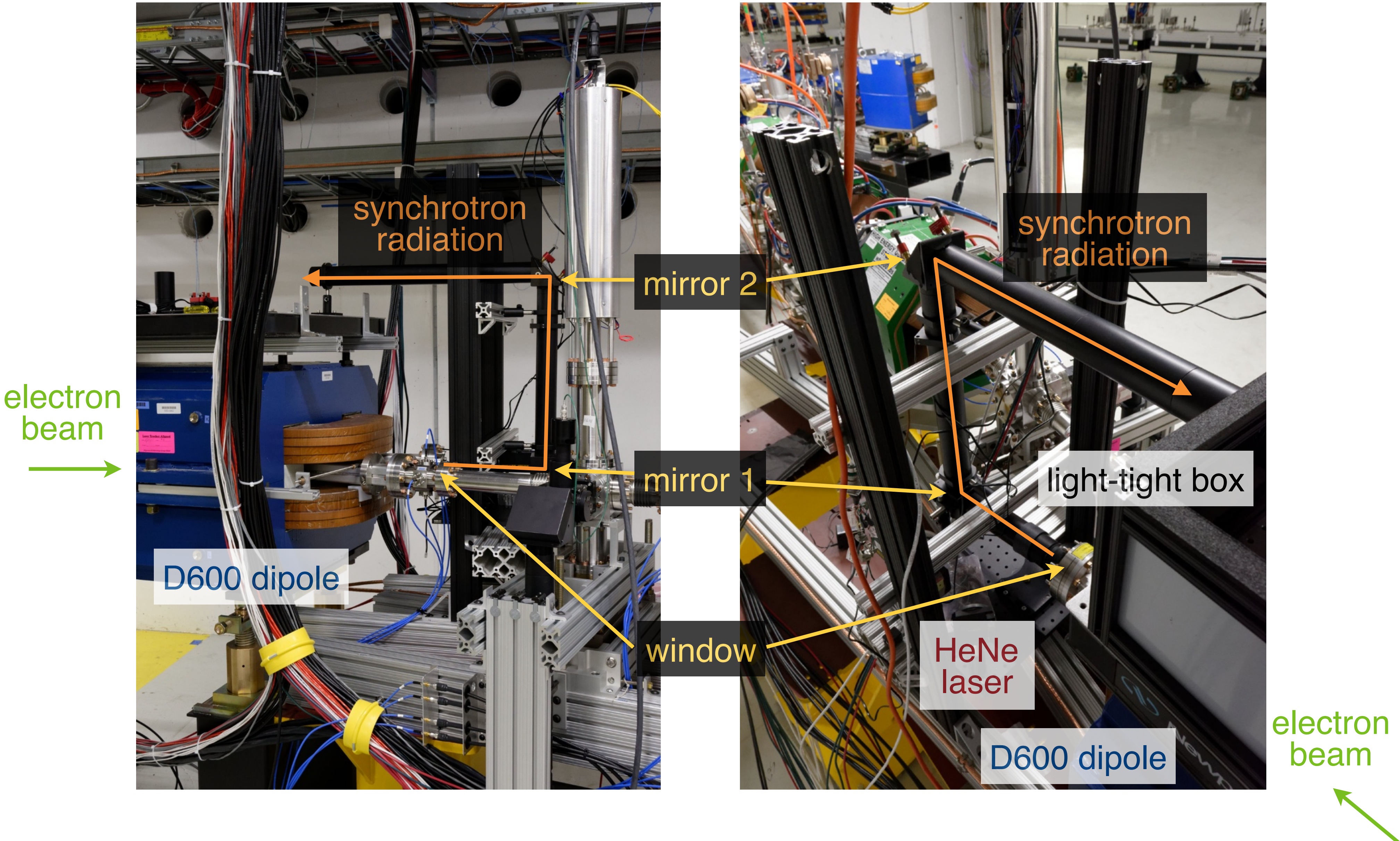
Characterize synchrotron-light signal and backgrounds in IOTA/FAST environment for

1. Beam diagnostics: bunch-by-bunch (for linac) and turn-by-turn (for IOTA) intensity monitor with wide dynamic range, from nominal intensities down to a few pC (linac) or single electrons (IOTA)

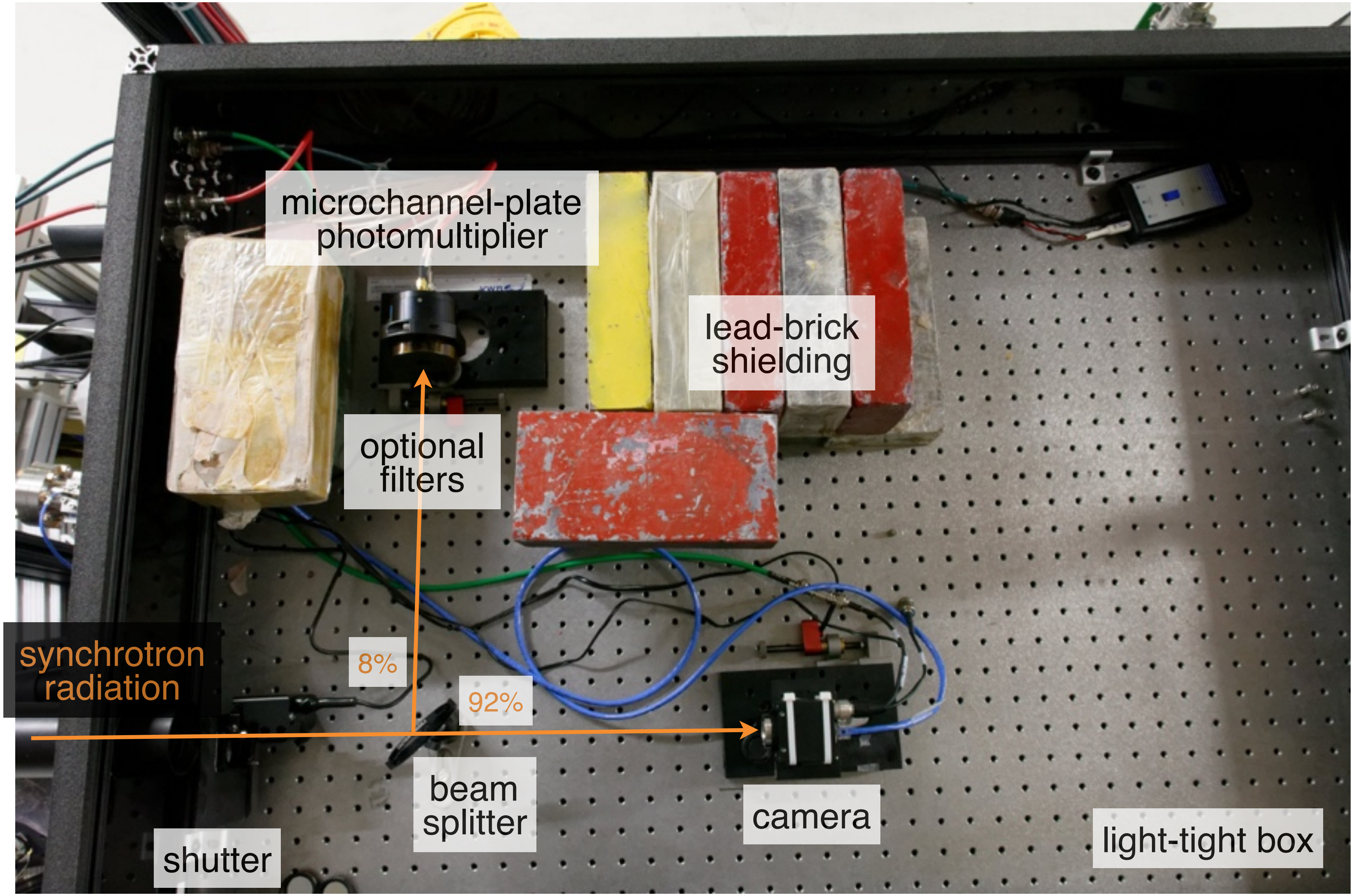
2. Scientific experiments in IOTA: e.g., direct observation of time structure of radiation emission from a single electron in a storage ring?

Stancari et al., FERMILAB-FN-1043-AD-APC

Experimental apparatus at D600 dipole magnet



Experimental apparatus at D600 dipole magnet



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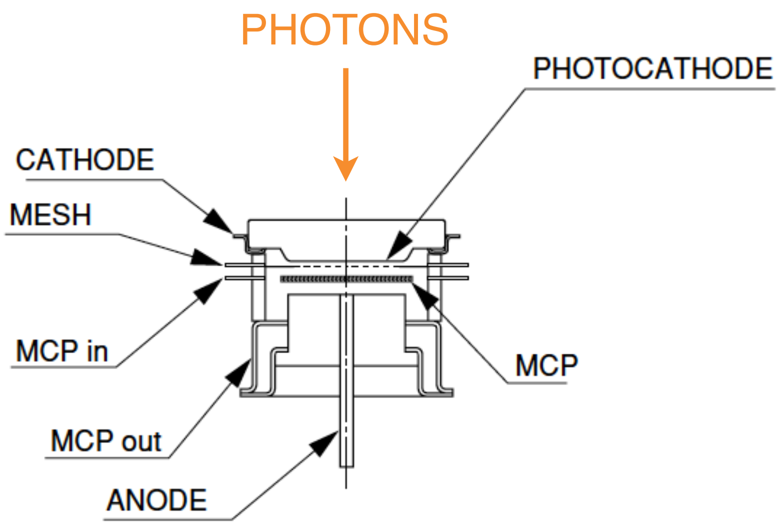
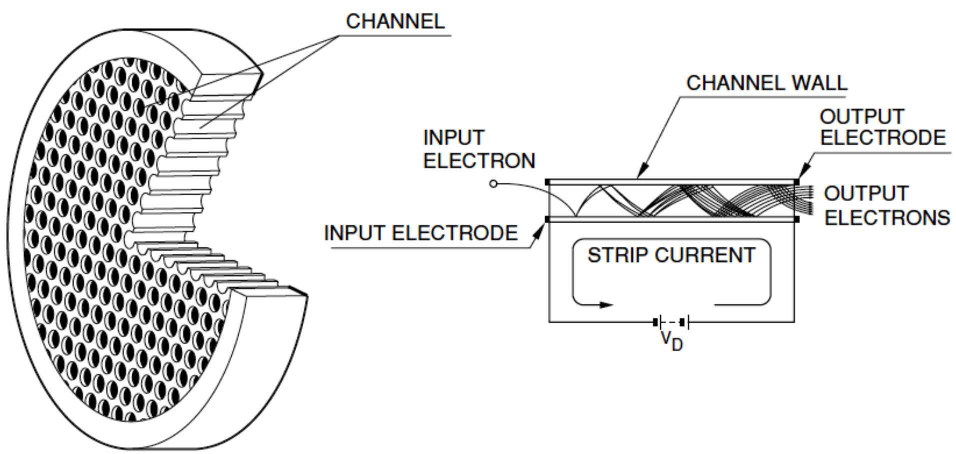
Microchannel-plate photomultiplier features

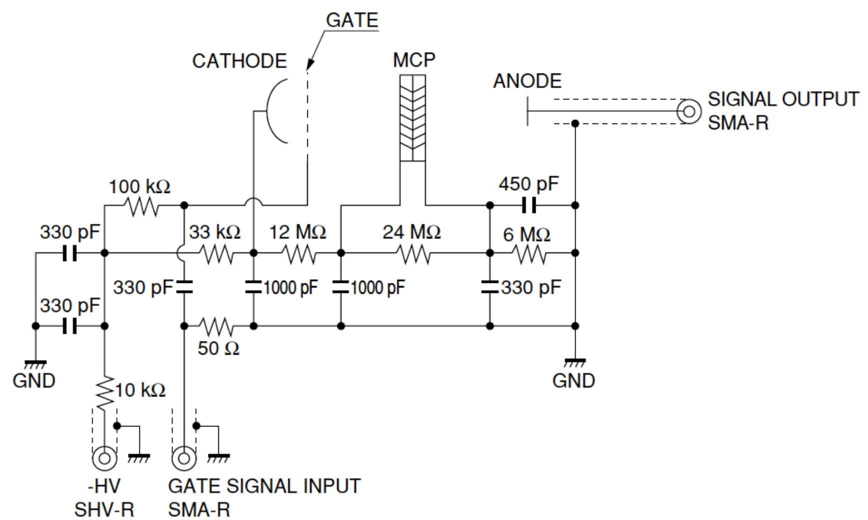
Excellent timing (sub-ns) and high gain (10^3-10^7). Can be gated.

Limited current at high rate.

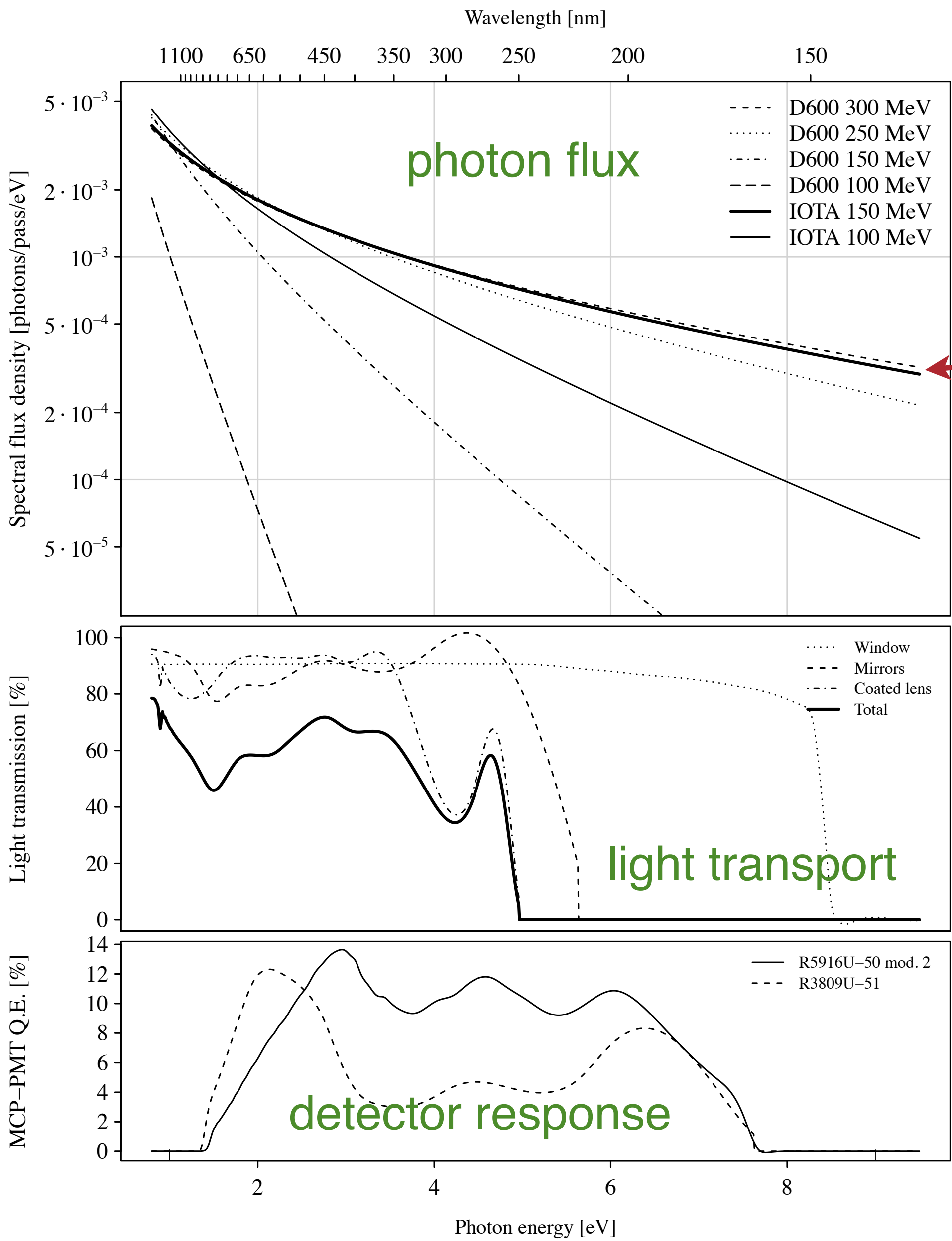
Hamamatsu R5916U-50 mod. 2 reused from Tevatron Synclite.







Expected signal



D600 dipole at 300 MeV and IOTA dipoles at 150 MeV yield similar spectra

Typical photoelectron yield is ~ 10^{-4} / e^{-}

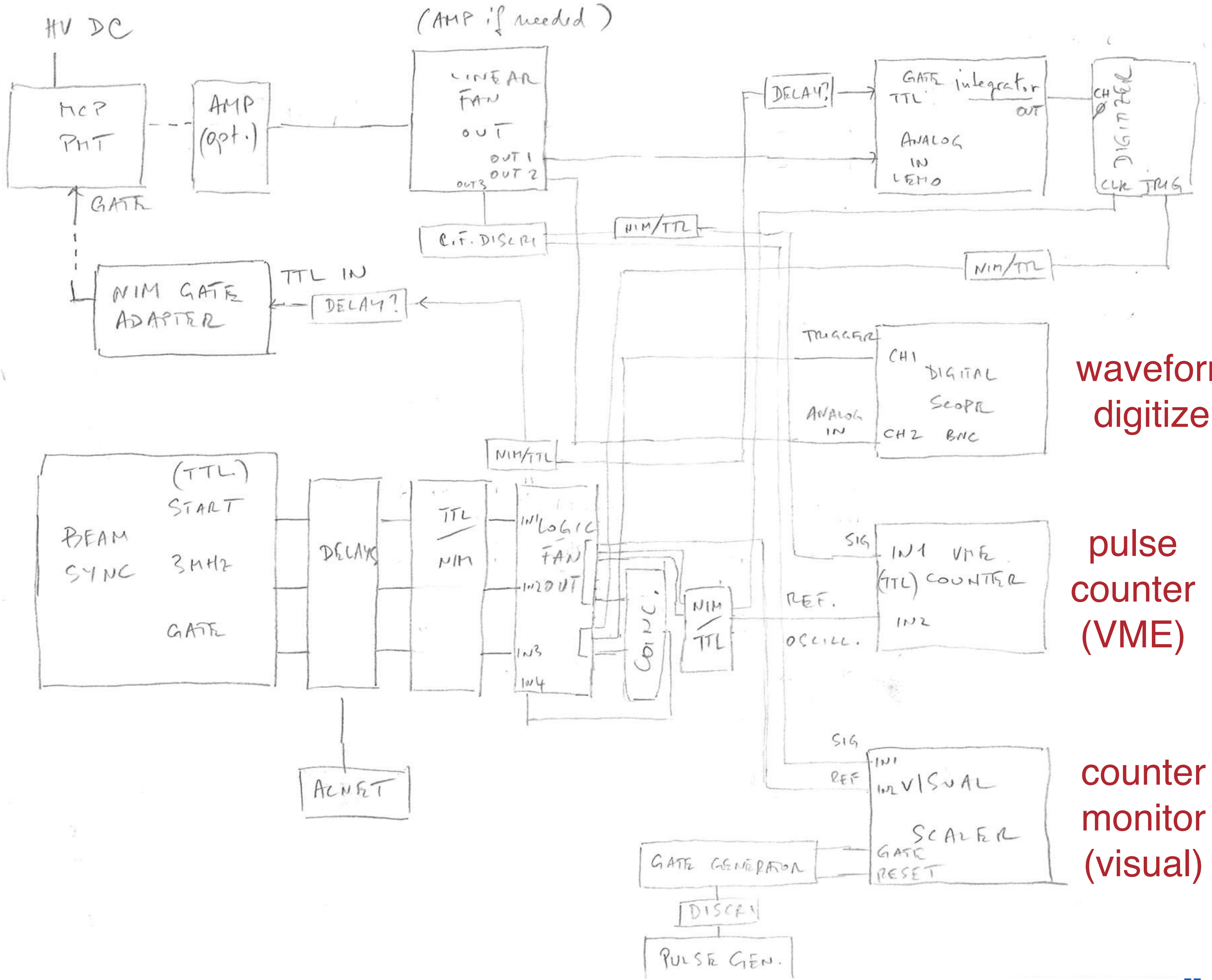
Table II. Calculation of expected photoelectron yield for each sample case.

	Avg. Q.E. $[10^{-3}]$	Error on avg. Q.E. $[10^{-5}]$	Average number of collected photoelectrons N_{pe} $[10^{-4}/e^{-}/\text{pass}]$	Integration error on N_{pe} $[10^{-6}/e^{-}/\text{pass}]$
D600 300 MeV	10.8	2.47	2.27	0.52
D600 250 MeV	10.5	2.65	2.22	0.558
D600 150 MeV	3.95	3.1	0.832	0.652
D600 100 MeV	0.151	1.58	0.0318	0.332
IOTA 150 MeV	10.8	2.52	2.28	0.531
IOTA 100 MeV	8.01	0.193	1.69	0.0407

Stancari et al., FERMILAB-FN-1043-AD-APC (updated calculation with 2 mirrors)

Data acquisition schematic

PHOTONS



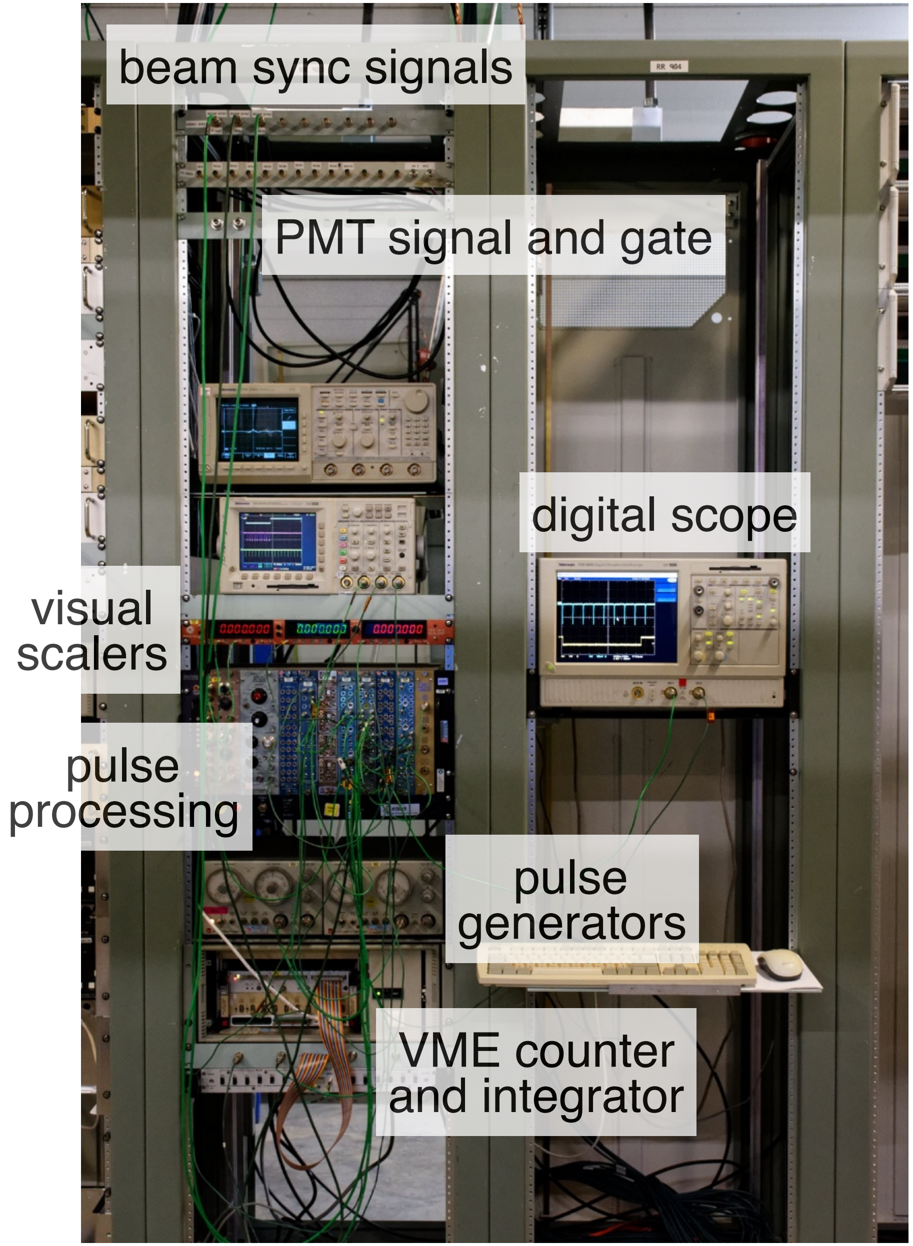
fast bunch integrator

waveform digitizer

pulse counter (VME)

counter monitor (visual)

Data acquisition system at ESB



Shift summary 1/3

- **Nov. 16, 2017 (4 h)**
  - equipment installation
  - tests with HeNe laser
- **Nov. 17, 2017 (6 h)**
  - experiments with beam at 150 MeV, 150 pC/bunch
  - observed difference before/after PMT gate
  - increased energy to 200 MeV, 160 pC/bunch
  - signal vs. PMT gain
  - signal vs. bunch charge
  - pulse shape
  - signal fluctuations
- **Nov. 22, 2017 (2 h, parasitic)**
  - 150 MeV, 200 pC/bunch
  - replaced discriminator
  - fluctuations of first pulse (background)
  - waveforms of whole train
  - observed 1:10 difference in before/after gate with defocused or blocked electron beam

Shift summary 2/3

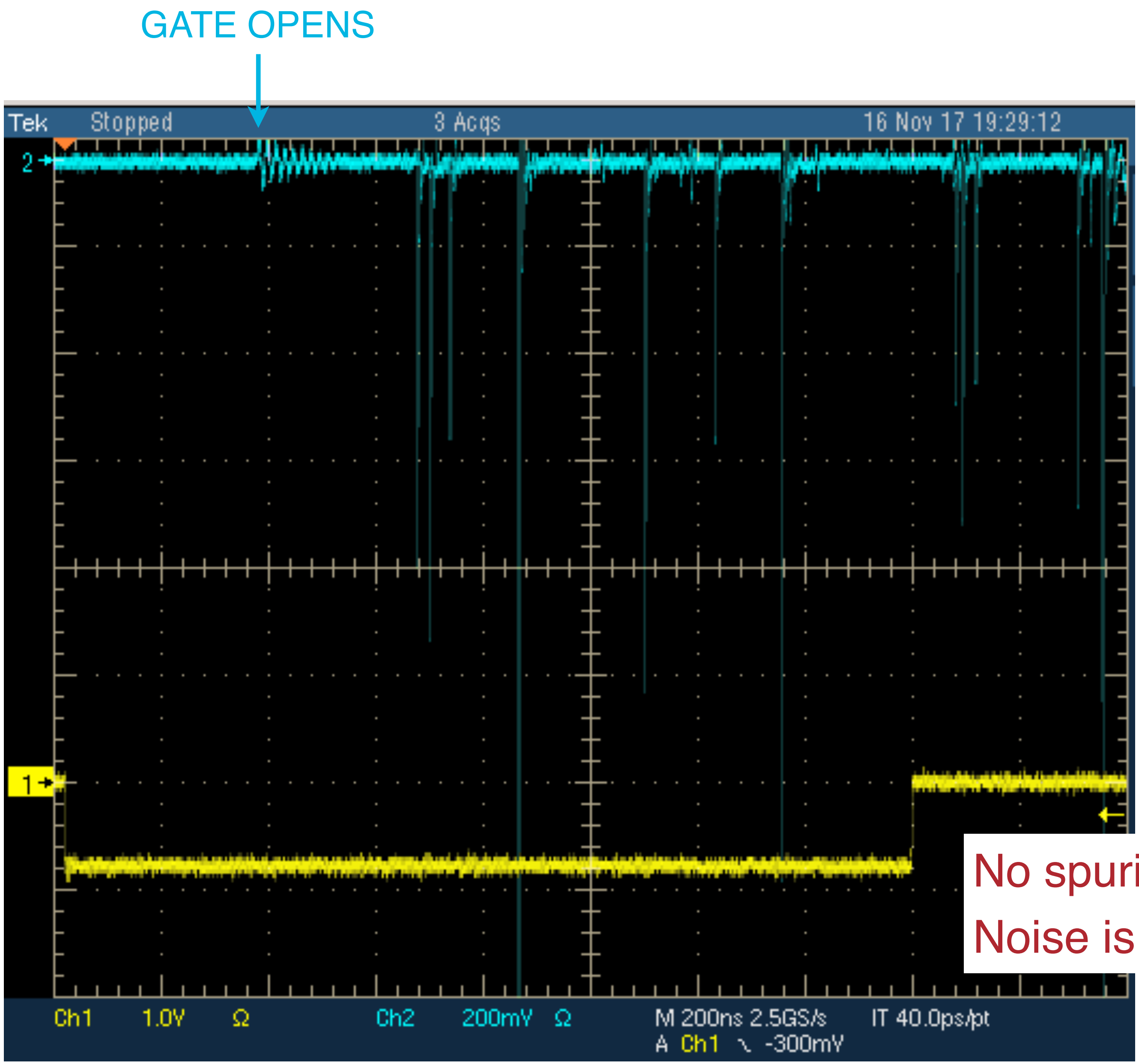
- **Nov. 27, 2017 (8 h)**
    - 150 MeV, 200 pC/bunch
    - steered e- beam to see signal on both camera and PMT
    - set up timing signals for integrator/digitizer
    - controlled access: black paper at D600 port to block light
    - signal is similar: all background?
    - controlled access
        - removed OD2 filter; no filters in front of PMT
        - added lead bricks for shielding
        - removed black paper from D600 port
    - beam-induced background is much smaller
    - issues with PMT gate level translator; temporary fix: use TTL signal as gate (5 V instead of 15 V)
    - not enough time to verify signal by blocking light
    - tested digitizer in "IOTA-like" configuration with test pulses

Shift summary 3/3

- **Nov. 30, 2017 (9 h)**
  - controlled access:
    - installed shutter at entrance of light-tight box
    - installed horizontal motorized stand for PMT
    - installed picomotors on top mirror
  - using pulse generator for PMT gate (8.2 V instead of 15 V)
  - 150 MeV, 250 pC/bunch
  - recorded signal with shutter open/closed
  - scanned mirror position, following beam spot on camera and PMT signal
  - sync-light signal and beam-induced background vs. PMT gain
  - sync-light signal and beam-induced background vs. bunch charge
  - recorded 100 frames to study fluctuations of individual bunch
  - recorded 10 frames of whole bunch train
  - investigated variations of signal vs. bunch number at different gains and bunch charges
- **Dec. 2, 2017 (6 h)**
  - 150 MeV, 250 pC/bunch
  - tuned spot size at TPM601 with cryomodule phase
  - larger signal and smaller background compared to Nov. 30
  - 250 MeV, 250 pC/bunch
  - signal vs. bunch charge
  - 100 MeV, 250 pC/bunch
  - signal and background vs. bunch number
  - signal vs. bunch charge
  - searched for detection limit by reducing signal to level of random pulses
  - measured signal dependence on PMT gate voltage, 8.2 V vs. 15 V

Observations with HeNe laser (no linac beam)

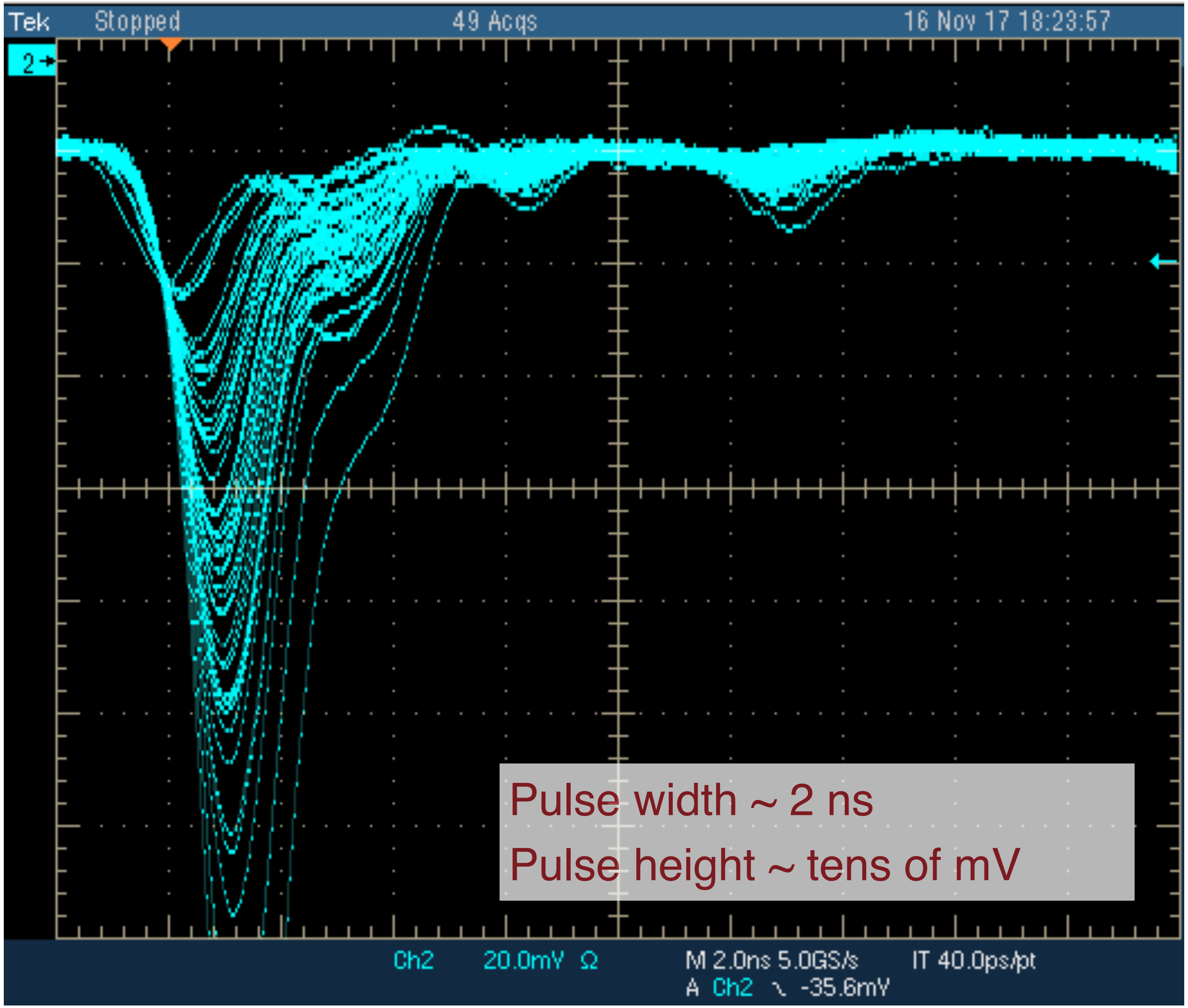
MCP-PMT signal with HeNe laser light



No spurious pulses with gate off

Noise is ~ 2 mV

MCP-PMT pulse-height distribution with HeNe laser



Expected photon flux with HeNe laser

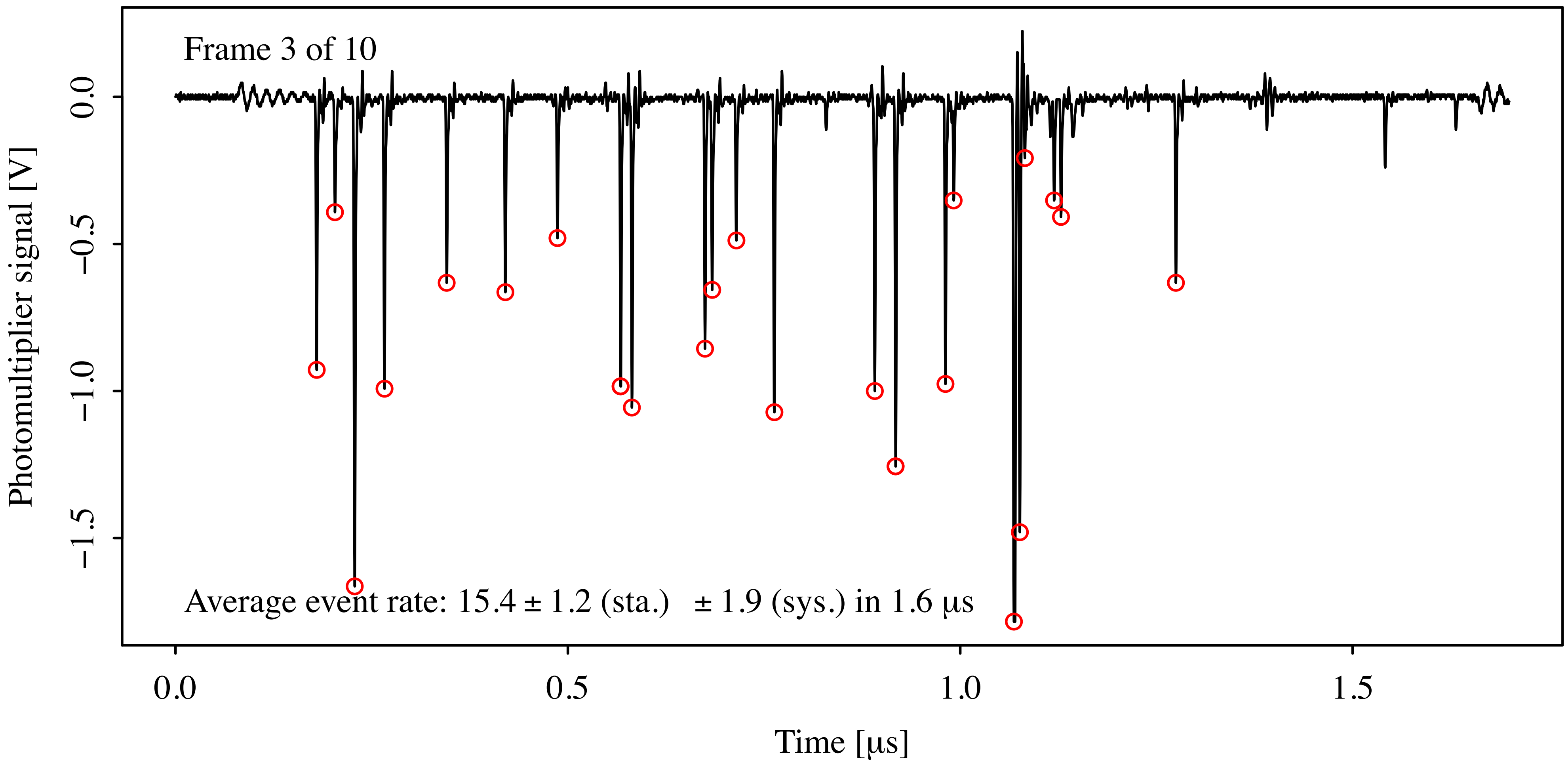
Approximate number of events within MCP-PMT gate:

$$(1\ \mathrm{mW}) \cdot \frac{(632.8\ \mathrm{nm})}{2\pi\hbar c} \cdot (40\%) \cdot (8\%) \cdot (10^{-5}) \cdot (4\%) \cdot (1.6\ \mu\mathrm{s}) = 64$$

laser power	convert to photon flux	light transport efficiency	beam splitter	filter	quantum efficiency	gate width

(Laser power was not calibrated.)

Measured event rate with HeNe laser



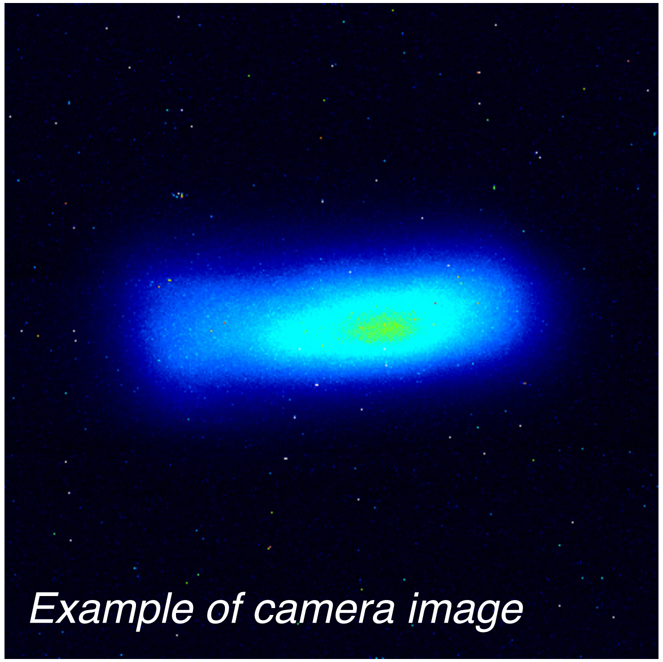
Observed flux is ~ 4 times lower than approximate prediction

Observations with linac beam

Experiments with linac beam, 100-250 MeV

We chose to align light transport with linac axis, not with tangent through center of magnet

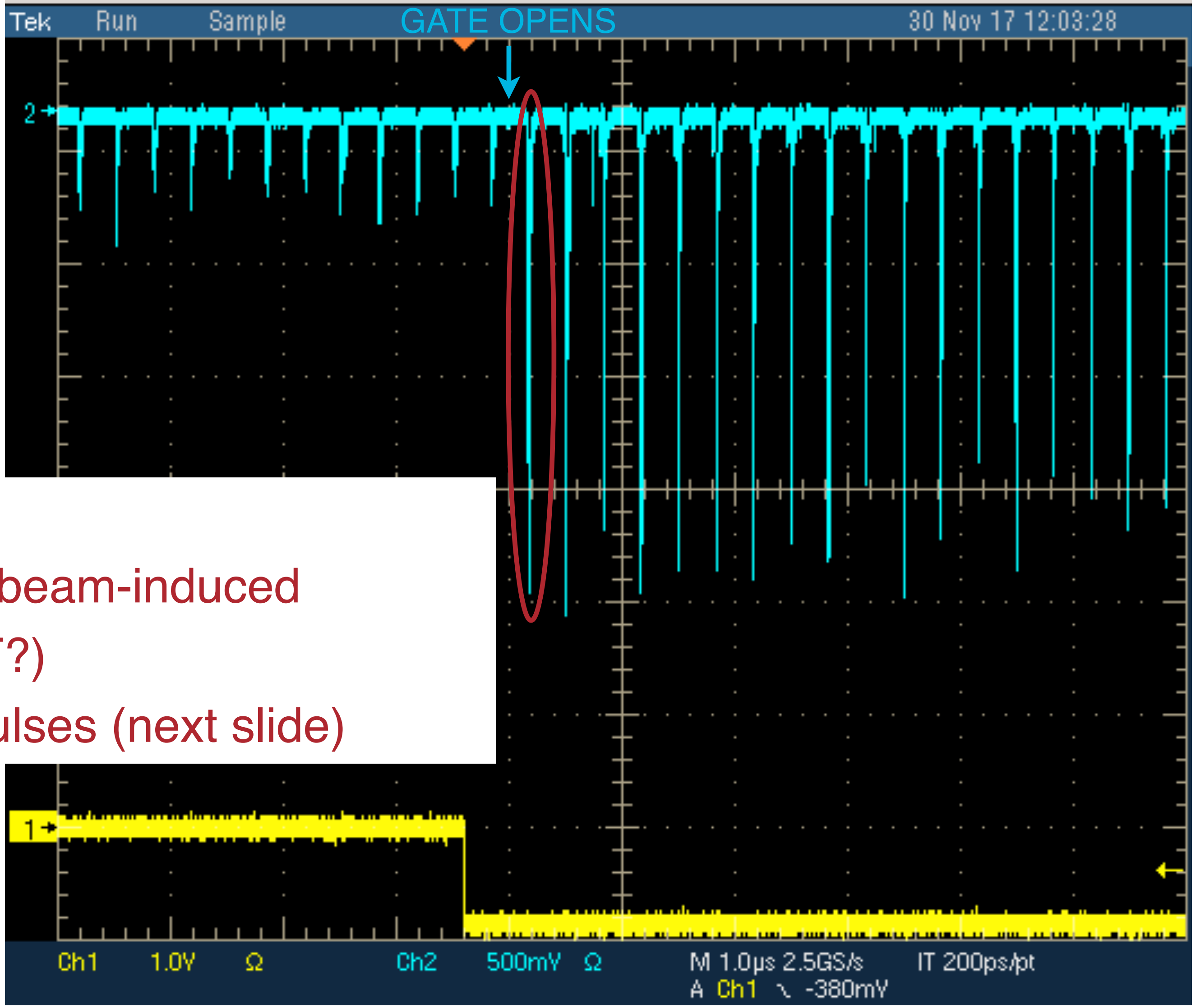
Linac beam needed to be slightly mis-steered to see synchrotron light in both camera and photomultiplier



Example of camera image

Photomultiplier signal with linac beam

150 MeV, 250 pC/bunch, 30 bunches (12 before gate, 18 after)
PMT HV = 3.8 kV, PMT gate = 8.2 V, no filters

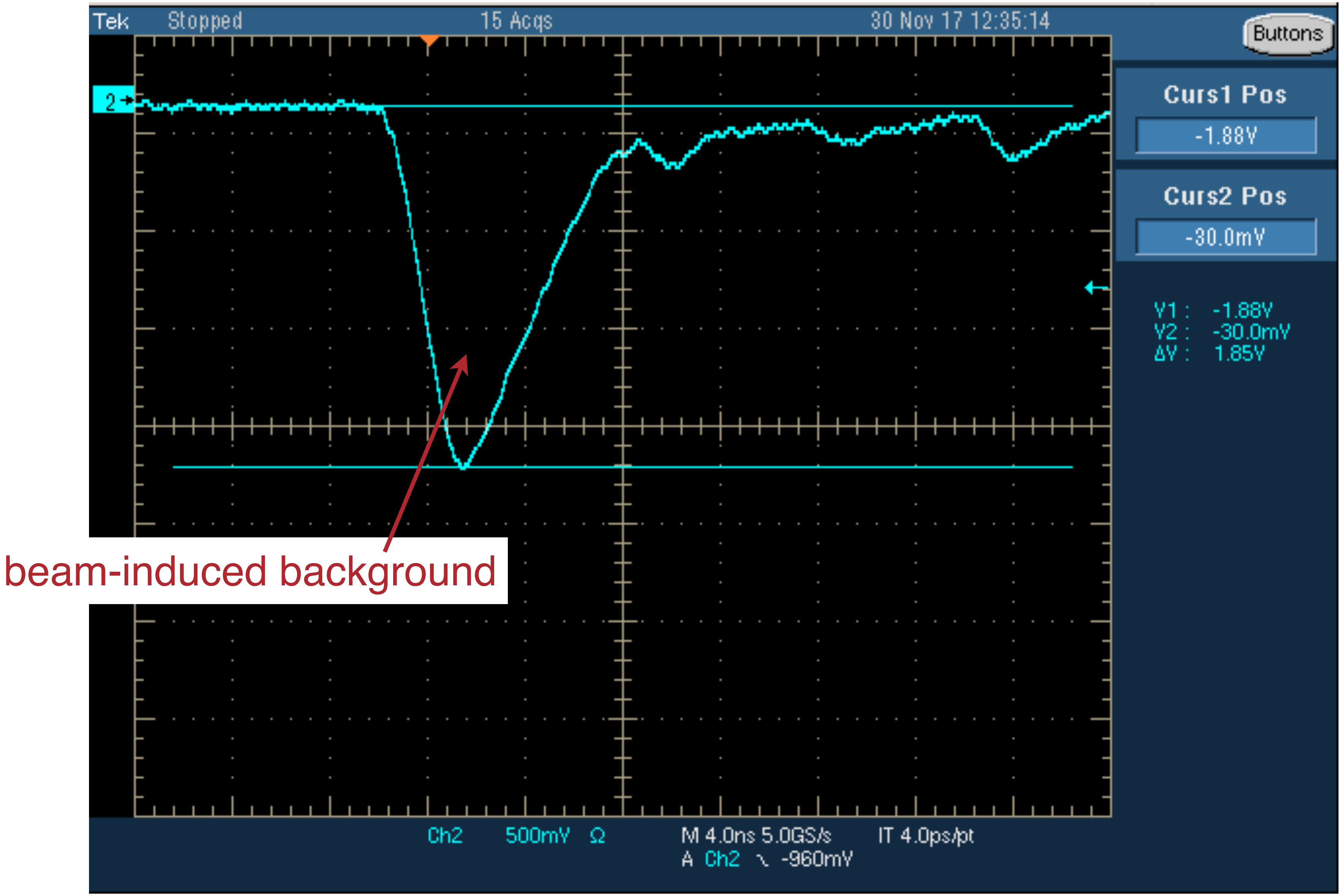


Large signal ~ volts

Non-zero signal before gate (beam-induced background hitting MCP-PMT?)

Microstructure of individual pulses (next slide)

Individual pulse, shutter closed



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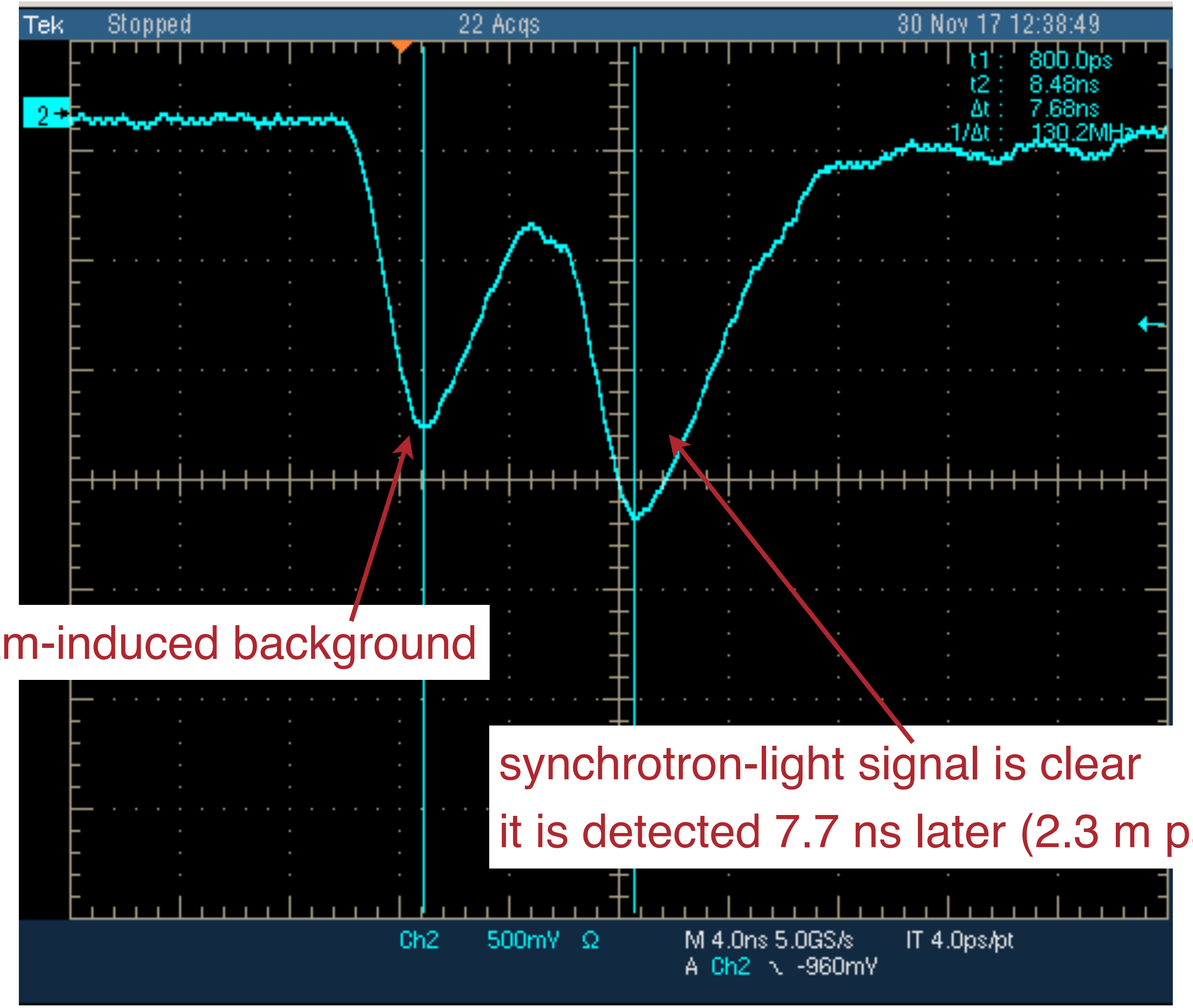
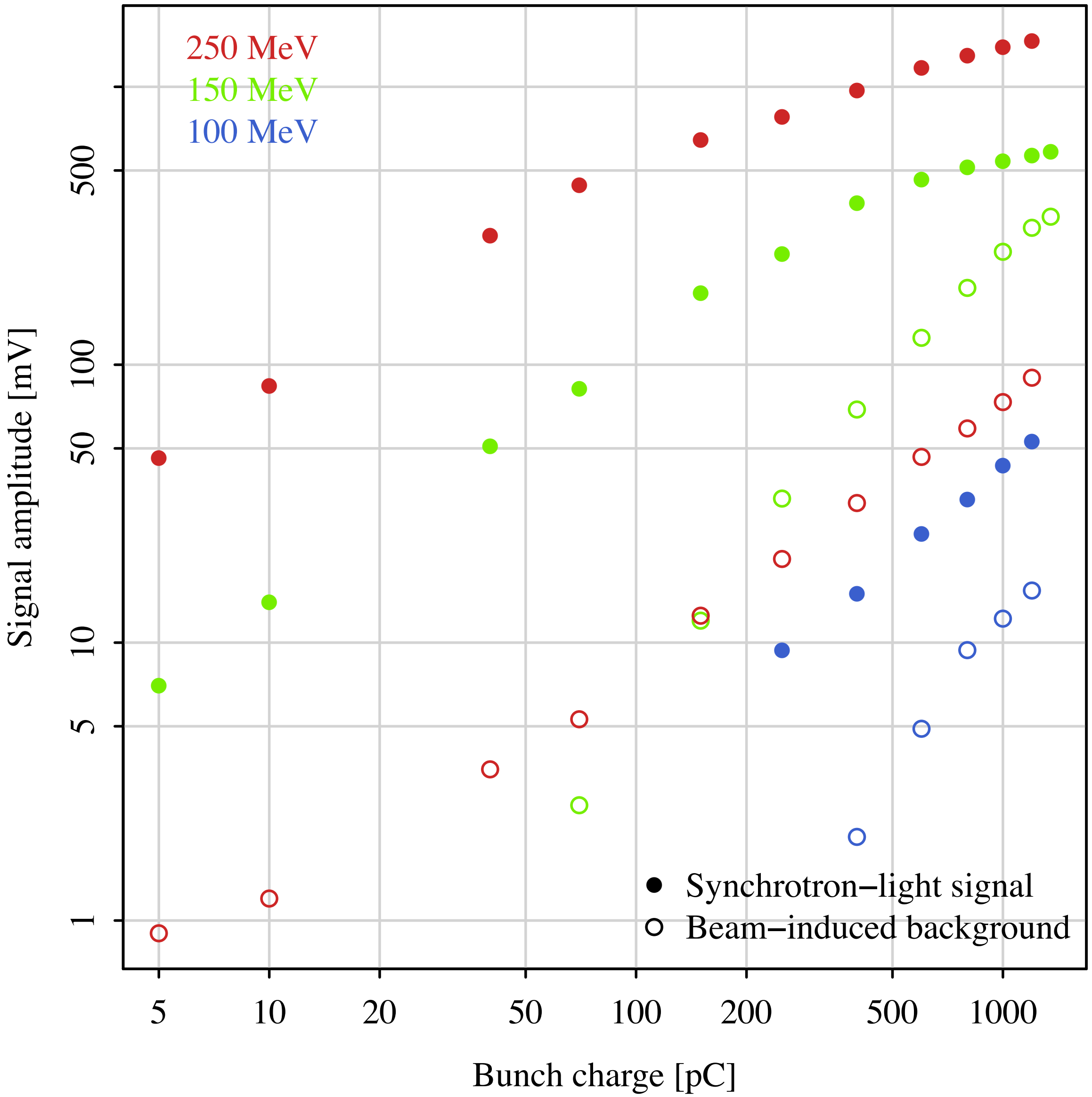
Individual pulse, shutter open



beam-induced background

synchrotron-light signal is clear
it is detected 7.7 ns later (2.3 m path)

Synch-light and background vs charge and energy



Measured linearity, energy dependence, and signal/background ratios

(Data at 150 MeV was taken before optimizing cryomodule phases to minimize spot at TPM601)

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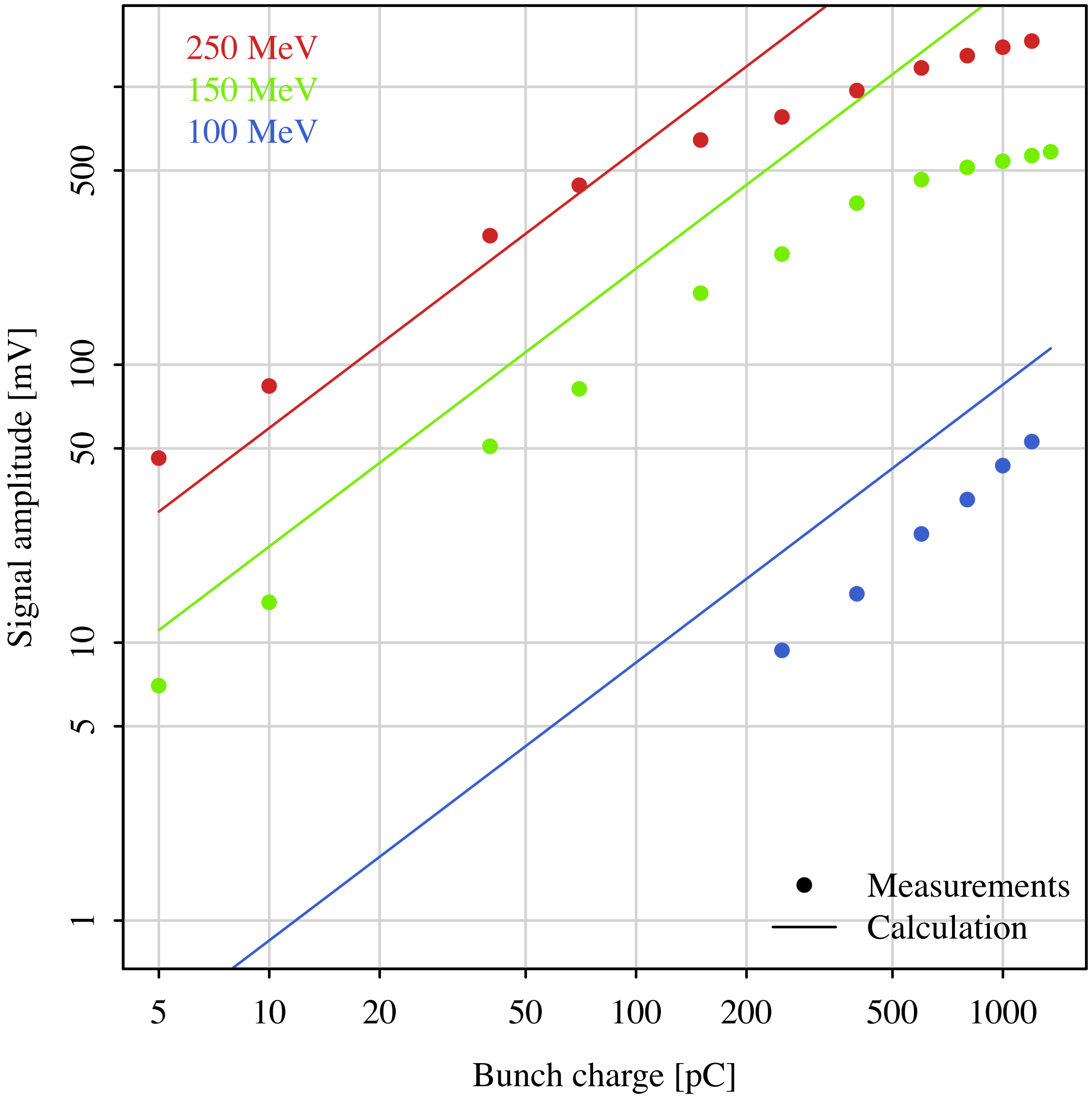
Measured sync-light signal and calculation



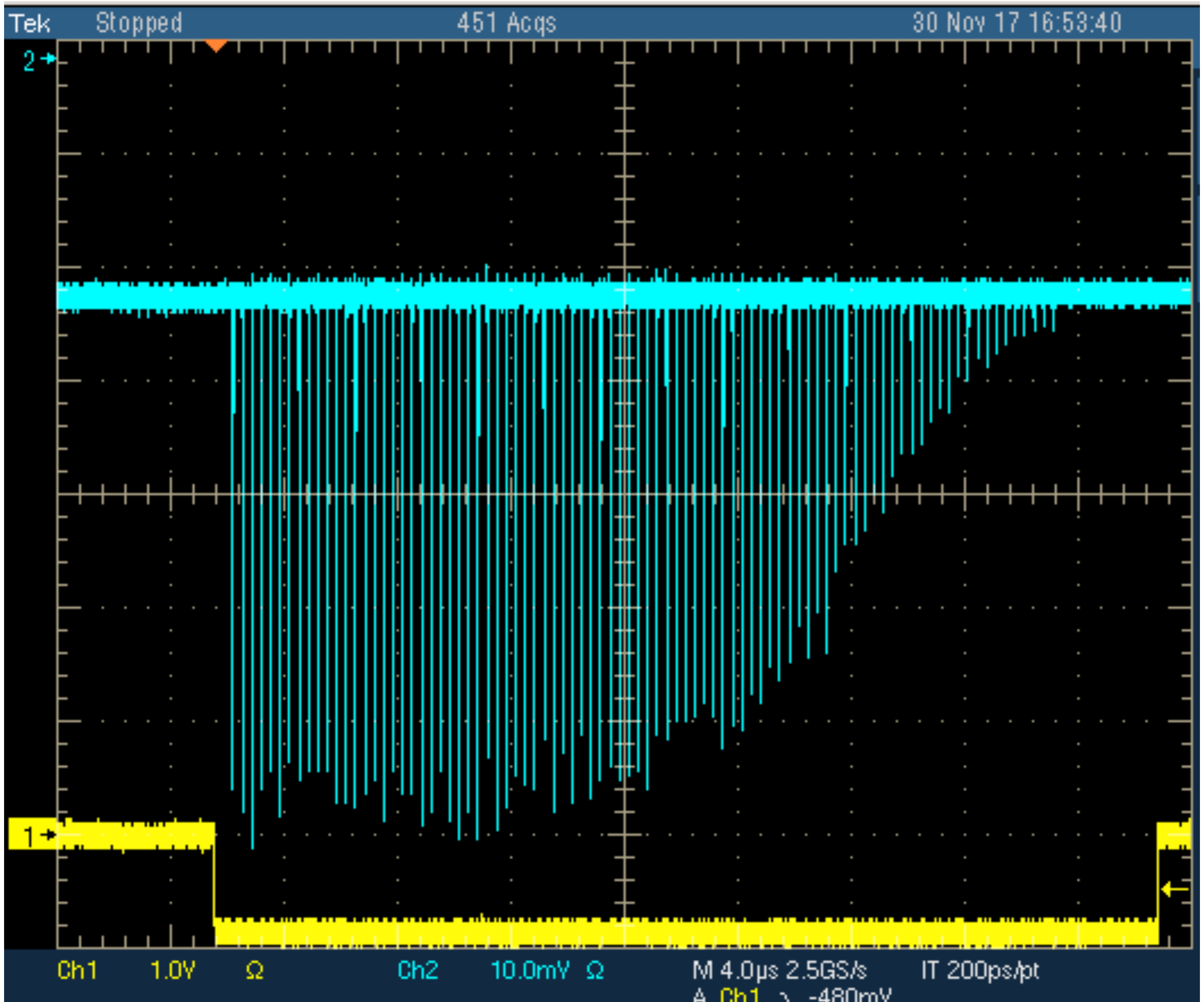
Measured signal is ~ 2 times smaller than expected at lower energies; larger at 250 MeV

Typical MCP-PMT saturation is visible at high charge or gain

250 pC/bunch at 100 MeV can be clearly detected

Signal drooping with long bunch trains

150 MeV, 400 pC/bunch, 100 bunches (12 before gate, 88 after)
PMT HV = 2.9 kV, PMT gate = 8.2 V, no filters



At high repetition rates, gain of MCP-PMT sags due to charge accumulation

This is a problem for measuring many consecutive turns in IOTA at high charge

Observations and conclusions

Observed and studied synchrotron-radiation signal and beam-induced backgrounds

Good scheduling overall. Some shift time required for installation and cave access. Minor equipment failures.

“Zero-budget” experiment: MCP-PMT from Tev Synclite, optics from laser lab, electronics and scope from PREP, etc. New apparatus suitable for IOTA will be needed.

Gathered experience on PMT choice for IOTA. Laser tests of different options at high rep. rate are possible.

Further analysis planned on signal timing, fluctuations, detection limits

Thank you to the whole IOTA/FAST team for your dedication!