Design of a luminosity monitor for the P2 parity violating experiment at MESA

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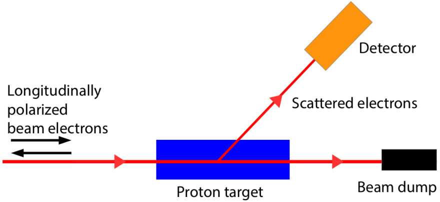
P2-experiment

- Precise determination of the electroweak mixing angle $\sin^2 \Theta_w$ in parity violating elastic electron-proton scattering A^{PV}
- By measurement of the weak charge of proton Q_W^p



$$A^{PV} = \frac{d\sigma_{eN}^{+} - d\sigma_{eN}^{-}}{d\sigma_{eN}^{+} + d\sigma_{eN}^{-}} = \frac{-G_F Q^2}{4\pi\sqrt{2}\alpha}(Q_W^p - F(Q^2))$$

$$Q_W^p = 1 - 4 \cdot \sin^2 \Theta_w$$

- $A^{PV} \approx \mathcal{O}(10^{-8})$
- For measurement time of 10^4 h $\rightarrow \frac{\Delta \sin^2 \Theta_w}{\sin^2 \Theta_w} = 0.16\%$

P2-experiment

- Parity violating asymmetry measured in experiment A_{exp} obtained from number of elastically scatterd electrons $N^{\pm}$:

$$A_{exp} = P \cdot A^{PV} + A_{false}$$

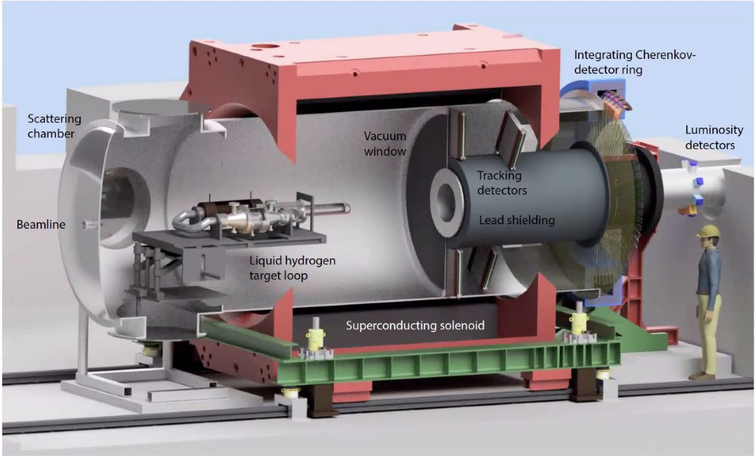
- $A_{false} \rightarrow$ helicity correlated fluctuations in beam parameters such as current I_{beam}, energy, beam position and angle and density fluctuations of the target ρ
- To achieve precision of $\frac{\Delta \sin^2 \Theta_w}{\sin^2 \Theta_w} = 0.16\%$, necessary to monitor A_{false}
- Luminosity $\mathcal{L}$:

$$\mathcal{L} = \rho \cdot L \cdot I_{beam}/e$$

- A_{exp} weighted by target density:

$$A_{exp} = \frac{(N^+/\rho^+) - (N^-/\rho^-)}{(N^+/\rho^+) + (N^-/\rho^-)} = \frac{N^+ - N^-}{N^+ + N^-} + \frac{I_e^+ - I_e^-}{I_e^+ + I_e^-} - \frac{\mathcal{L}^+ - \mathcal{L}^-}{\mathcal{L}^+ + \mathcal{L}^-}$$
$$= A^{PV} + A_{I_e} - A_L$$

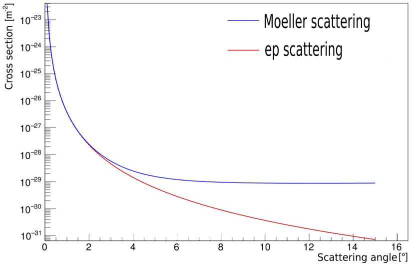
P2 set up



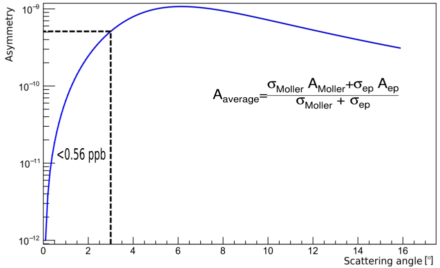
- For the detector ring consisting of 72 fused silica bars, intend to use 8 LUMI monitors
- LUMI monitors placed downstream
- Distance from target $z_{position} = 4300$ mm

Investigation of the dominant electron scattering processes at small scattering angles

1. Møller scattering
2. Electron proton scattering



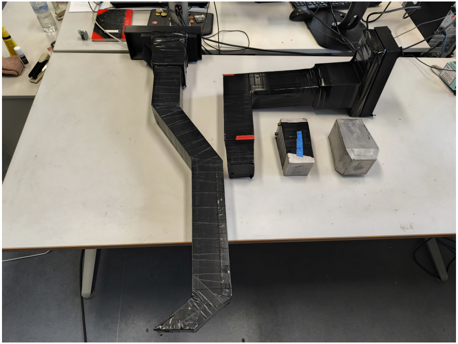
- Moeller scattering dominating



- $A_L \leq \Delta A^{PV} = 5.6 \cdot 10^{-10}$
- Condition met for $\theta \leq 3^\circ$

Luminosity monitor prototype

- High event rate $\mathcal{O}(10^{13}\ \mathrm{s}^{-1})$ at detector $\rightarrow$ challenges in signal readout, lifespan of electronics and radiation resistance
- Current idea for luminosity monitor: analog integrating air Cherenkov detector

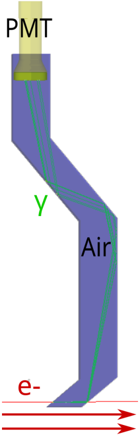


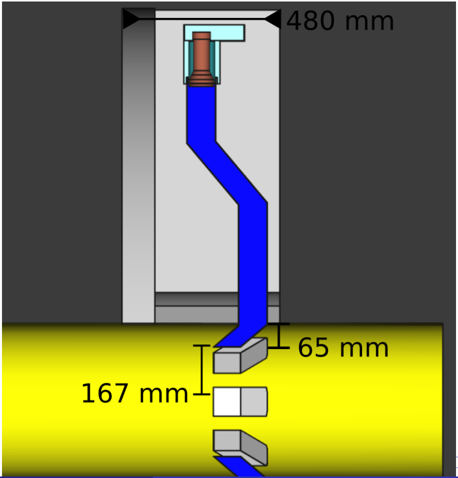
Different versions of LUMI monitors

- 4 LUMI prototypes tested
- Right side one can see the oldest version of the prototype and on the far left is the newest one

Luminosity monitor prototype

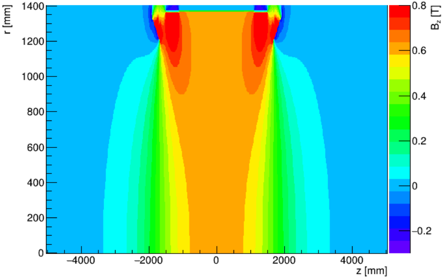
- Air (cherenkov material) stored in a funnel
- Cherenkov light is reflected on the walls, covered by special aluminium reflector from Alanod
- Detector consists of two parts: an "active part" within exit beamline and light guide protected by lead shield
- PMT placed at the end of light guide

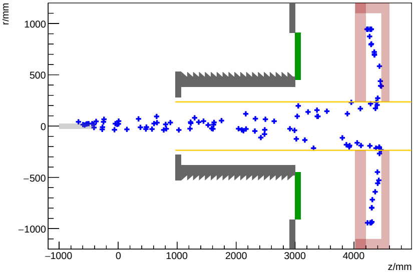




LUMI and P2 magnetic field

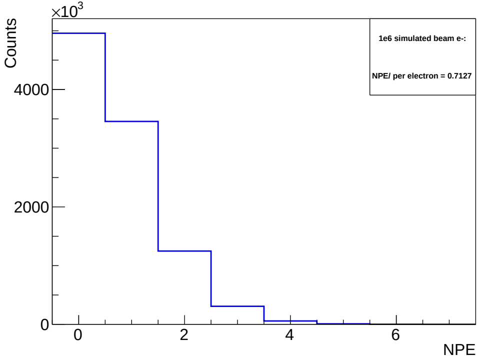
- LUMI positioned (z=4300 mm) at the edge of P2 magnetic field
- Some electrons deflected by the magnetic field so that they scattered in the LUMI
- Shape chosen so that scattered particles from the target that reach the PMT-readout electronics are suppressed





Air Cherenkov prototype in simulation

- Geant4 simulation: Electrons 155 MeV shot directly at detector
- Determining number of Cherenkov photons → number of photoelectrons (NPE) at PMT cathode

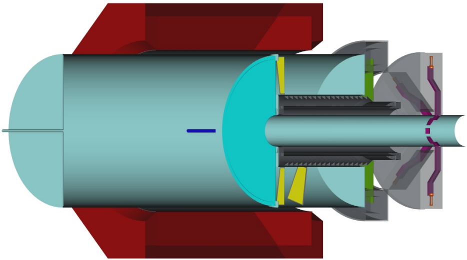
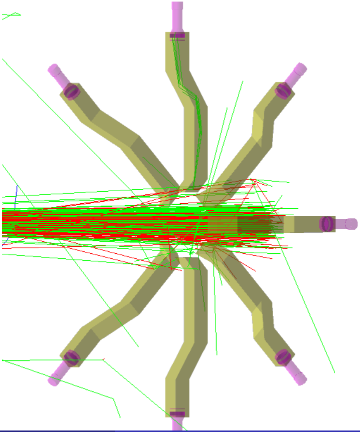


NPE distribution

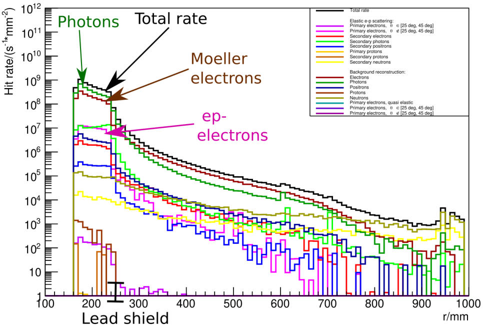
- Average NPE per beam electron 0.7127
- Small refractive index → small number of cherenkov photons

Simulation of physical processes within LUMI in the P2 experiment

- Geant4 simulation to test 8-LUMI detector ring:
- Real energy loss in target
- Multiple scattering
- Secondary particles
- Full experiment set-up
- Lead shield (10 t) around LUMI monitors

Geant4 rate distribution for LUMI monitors



Simulated rate distribution of physical processes hitting luminosity monitor at $z_{position}$, r distance from beam axis, with complete P2 setup and magnetic field of solenoid

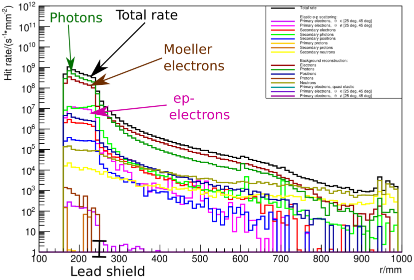
Largest particle contributions:

- Background photons 4.0913e+13 1/s
- Møller electrons 1.2002e+13 1/s

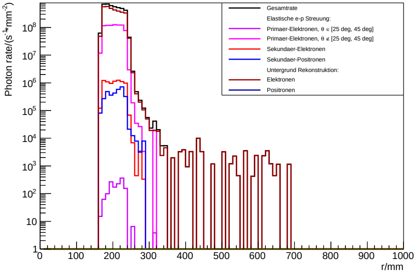
Largest signal contributions:

- Cherenkov threshold air $E_{min} = 20.87$ MeV
- Møller electrons 3.6504e+12 1/s

Geant4 Cherenkov photon rate



Rate distribution of physical processes as a function of the distance r from the beam axis



Rate distribution of Cherenkov photons as a function of the distance r from the beam axis

- Rate distribution of Cherenkov photons generated in the air volume is displayed with its corresponding parent particle
- Majority of Cherenkov photons are emitted in the designated "active area" of the LUMI

Simulated cathode current

- With the number of photons at the PMT, as well as the quantum efficiency: $\rightarrow$ cathode current is determined

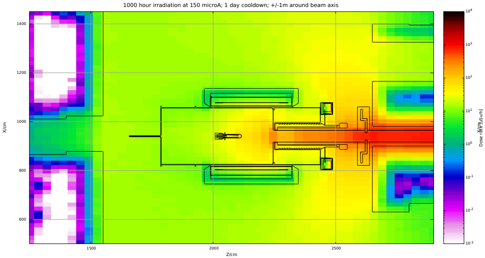
Cathode current

Contribution	LUMI-Sickle [nA]
Background reconstructions	
Møller electrons	14.88
Elastic electron-proton scattering	
Primary electrons $\theta \notin$[25 deg, 45 deg]	5.1528
Secondary electrons	0.0319
Secondary positrons	0.0129

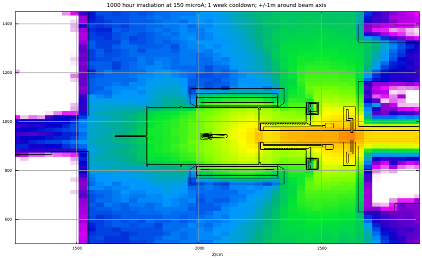
- Cathode current per PMT = 20.0776 nA
- Anode current (dynode gain=10^3)= 20.0776 μA
- One fused silica detector (1 GHz event rate) anode current = 8 μA
- After 2767 h active run time LUMI-PMT output will typically reduce by a factor of 50 %

FLUKA simulation LUMI

- Lead shield (10 t) and LUMI-detector in Fluka simulation (radiation protection assessment)
- Equivalent radiation dose rate after 1000 h irradiation
- Spectrum directly after turning of beam



1 day cooldown

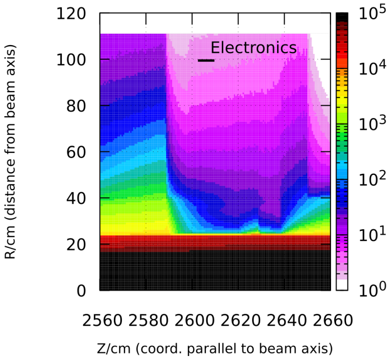


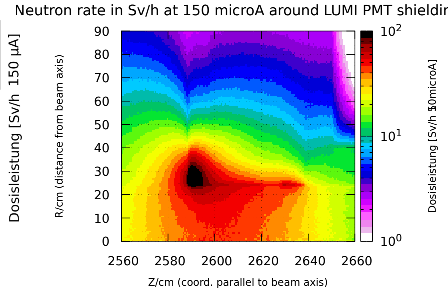
1 week cooldown

- Around beam axis $\approx$ 1 mSv/h
- "" $\approx$ 0.1 mSv/h

FLUKA simulation LUMI

Total dose rate in Sv/h at 150 microA around LUMI PMT shielding

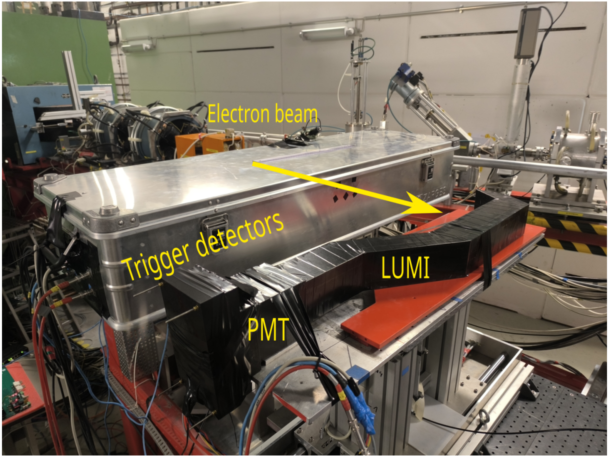




- Radiation around PMT and readout electronics < 10 Sv/h

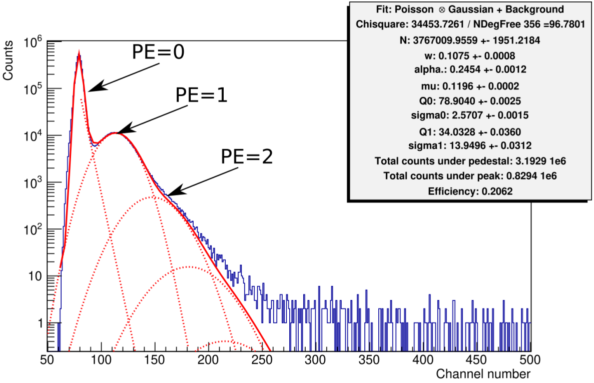
Characterization of LUMI spectra in beam tests at MAMI

- Single photoelectron measurement at mainzer accelerator
- Intensive testing of two measuring mods: Single event mode (kHz), integration mode (GHz)



Characterization of LUMI spectra by single photoelectron response function

- Single photoelectron measurement, electron rate ≈5 kHz

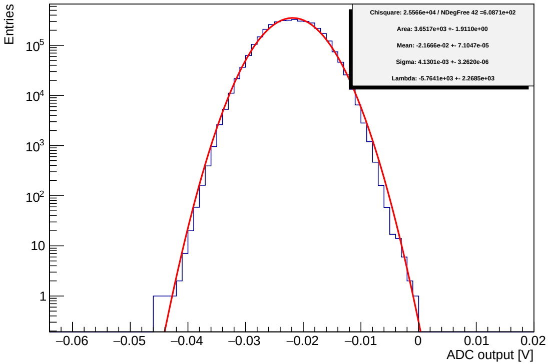


- Response function of PMT signal:

$$P(n;\mu) \otimes G(x) + noise = \sum_{n=o}^{\infty} \frac{\mu^n e^{-\mu}}{n!} \frac{1}{\sigma_n \sqrt{2\pi n}} exp\left(\frac{(x-nQ_n)^2}{2n\sigma_n^2}\right) + noise$$

LUMI spectra for high electron rate in integration mode

- Verficiation of single photoelectron spectra in integration mode
- Electron rate 3 GHz
- Special 18-Bit-Analog-Digital-Wandler
- Sampling rate: $15 \cdot 10^6$ samples per second

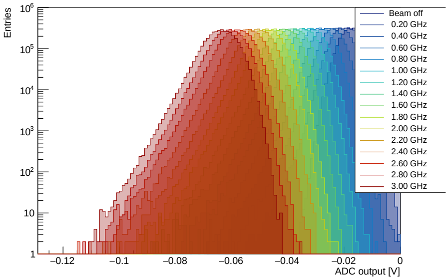


$$Measured\ mean(offset\ correc.) = 5.631 \cdot 10^{-3}\,V$$

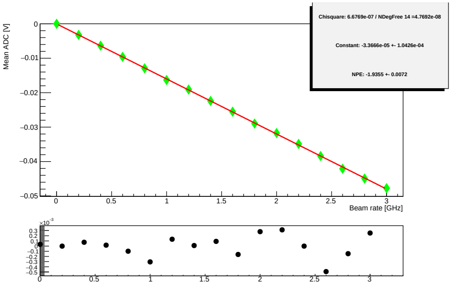
$$Theo.\ value[NPE..] = 5.024 \cdot 10^{-3}\,V$$

LUMI spectra for high electron rate in integration mode

- Linearity test of LUMI for electron rate 0-3 GHz
- Plot mean of spectra against electron rate



Rate scan 0-3 GHz



Mean vs beam rate

- No significant fluctuation in the spectra

Summary and outlook

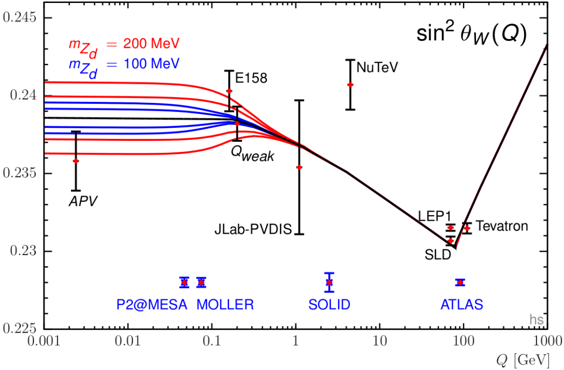
- Luminosity monitor to observe helicity correlated fluctuations in beam parameters and density fluctuations of the target tem
- Optimized detector design for high beam current → long run time readout electronics and protection against radiation damage
- Geant4 simulations confirm feasibility of LUMI prototype
- Prototype measurements with MAMI electron beam
- Experimental results agree with theoretical predictions

Outlook:

- Development of a concrete prototype
- Support structure for lead shield and realistic attachment to the exit beamline

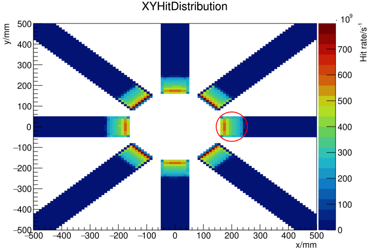
Thank you for your attention!

- $\sin^2(\theta_w)$ central parameter of SM
- Deviation from SM prediction $\rightarrow$ hints for new physics
- Sensitivity to hypothetical new particle/interaction

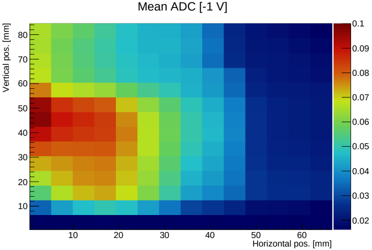


- Dark Z-Boson
  - New vector Boson
  - Kinematic mass mixing with $\frac{\gamma}{Z}$

- To analyse beam position deviations $\Delta X = 1\ mm$ combine simulation and beam time results
- Initial assumption was point of entry of the beam onto the detector would have a strong influence
- Simulation = particle rate, beam time = ADC value depending on beam position
- Beam time rate $3 \cdot 10^9 1/s$, $\rightarrow$ ADC value per signal electron



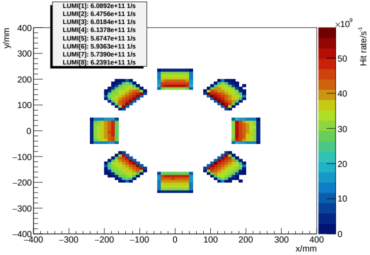
X-Y hit distribution Geant4 simulation



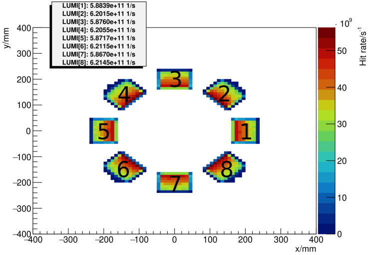
Beam time integration position scan results

$$LUMI_{ADC}\ signal(x, y)[V] = Rate(x, y) \cdot ADC(x, y)/3 \cdot 10^9$$

- Compare particle rate for $\Delta X = 1$ and $\Delta X = 0$
- Only particles with energy ≤ 21 MeV, air Cherenkov threshold
- Margin of error $1/\sqrt{N}$, N number of simulated entries, statistic error



$\Delta X = 1$ *mm*



$\Delta X = 0$ *mm*

$$Asym.(1) = 1.7147 \cdot 10^{-2} \pm 4.7225 \cdot 10^{-4}$$
$$Asym.(2) = 2.1622 \cdot 10^{-2} \pm 4.5881 \cdot 10^{-4}$$
$$Asym.(3) = 1.1972 \cdot 10^{-2} \pm 4.7392 \cdot 10^{-4}$$
$$Asym.(8) = 1.9753 \cdot 10^{-3} \pm 4.6286 \cdot 10^{-4}$$

$$Asym.(4) = -5.4848 \cdot 10^{-3} \pm 4.6489 \cdot 10^{-4}$$
$$Asym.(5) = -1.7062 \cdot 10^{-2} \pm 4.809 \cdot 10^{-4}$$
$$Asym.(6) = -2.2654 \cdot 10^{-2} \pm 4.6677 \cdot 10^{-4}$$
$$Asym.(7) = -1.1029 \cdot 10^{-2} \pm 4.7974 \cdot 10^{-4}$$

False asymmetries from beam position deviations

- MESA max. beam location difference at target 1 nm
- Asymmetry calculation (1 nm) estimation from fit parameters

$$Asym.(1) = 1.718 \cdot 10^{-8} \qquad Asym.(4) = -5.5271 \cdot 10^{-9}$$
$$Asym.(2) = 2.1725 \cdot 10^{-8} \qquad Asym.(5) = -1.7092 \cdot 10^{-8}$$
$$Asym.(3) = 1.1993 \cdot 10^{-8} \qquad Asym.(6) = -2.2656 \cdot 10^{-8}$$
$$Asym.(8) = 1.9669 \cdot 10^{-9} \qquad Asym.(7) = -1.1003 \cdot 10^{-8}$$