Test beam facilities at BINP

Presented by Viktor Bobrovnikov

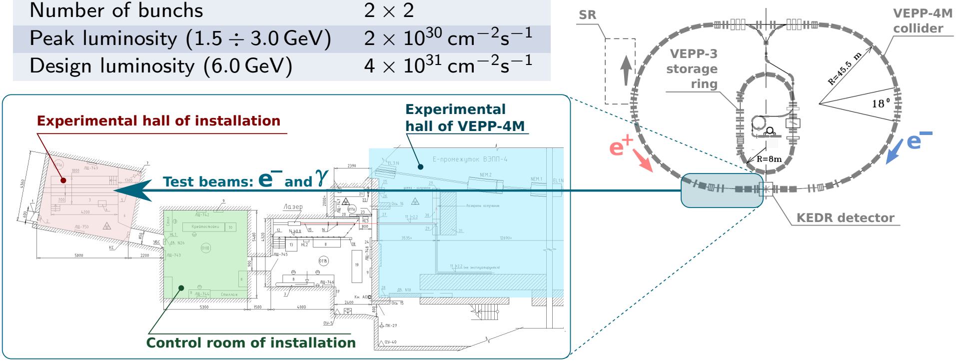
Budker Institute of Nuclear Physics SB RAS, Novosibirsk

HIEPA 2018, March 21, 2018

Introduction

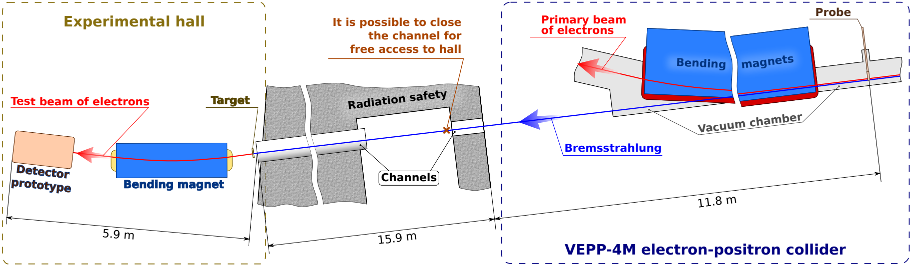
- Detectors for High Energy Physics are developed in steps, including testing of detector prototype on specialized test beams.
- For this purpose an installation for generation of test beams of electrons and gammas was designed at Budker Institute of Nuclear Physics SB RAS (BINP).
- The installation uses the infrastructure of VEPP–4M electron–positron collider.

VEPP–4M main parameters	
Perimeter	366 m
Beam energy	$1.5 \div 5.5\,\mathrm{GeV}$
Number of bunchs	2×2
Peak luminosity ($1.5 \div 3.0\,\mathrm{GeV}$)	$2 \times 10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Design luminosity ($6.0\,\mathrm{GeV}$)	$4 \times 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$



Test beam of electrons

Principle of the beam production



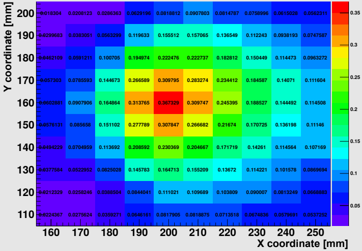
1. A special probe is moved into the halo of a primary electron beam of the VEPP–4M collider for generation of Bremsstrahlung.
2. These gammas are converted to electron – positron pairs on a lead target at the entrance to the experimental hall.
3. Electrons with a certain momentum are selected using a bending magnet.

The beam parameters	
Energy range	$0.1 \div 3.5$ GeV
Intensity	$50 \div 100$ Hz
Energy spread	7.8% for 0.1 GeV and 2.6% for 3.0 GeV

Test beam of electrons: Infrastructure

Probe and target

- The probe (thickness of 17% X_0) is positioned in the vacuum chamber of the VEPP–4M collider. Intensity of electrons is determined by a position of the probe.
- Thickness of the target is equal to 40% X_0. Position of the target is selected by special system in order to obtain maximum possible intensity of test beam.



Scintillation counters

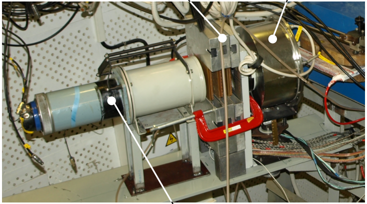
- The trigger system is made on counters with air light collection:
  - size of the scintillators are 10×10 mm^2, 15×30 mm^2 or 20×40 mm^2;
  - thickness is 1.2% X_0.
- Counters with PMMA light guides are used for organize of veto signal for background suppression, and for Bremsstrahlung intensity monitoring:
  - size of the scintillators are 100×100 mm^2 or 200×200 mm^2;
  - thickness is $(12.6 - 13.8)\%\ X_0$.

Test beam of electrons: Infrastructure

Coordinate system

- The system can be equipped with two types of coordinate detectors: wire drift chambers (DC) or detector on base gas electron multiplier (GEM).

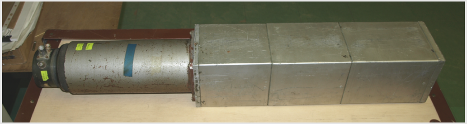
Type of detector	DC	GEM
Spatial resolution [μm]	$\sigma_x \simeq 450$	$\sigma_x \simeq 75$, $\sigma_y \simeq 250$
Don't need calibration	$x(t)$	✓
Thickness [% X_0]	0.2	0.4
Ability to register many tracks	✘	✓

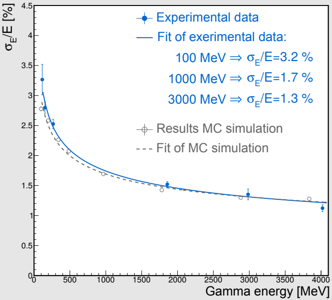


Calorimeter

- NaI–calorimeter or BGO–calorimeter are used to measure the electron energy.

Calorimeter	NaI	BGO
Length [X_0]	17.4	18.3
Width [R_M]	2.7	5.5
PMT	PMT–110	R10233 Hamamtsu

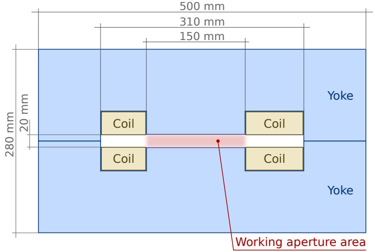




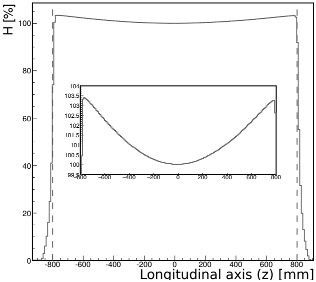
Test beam of electrons: Infrastructure

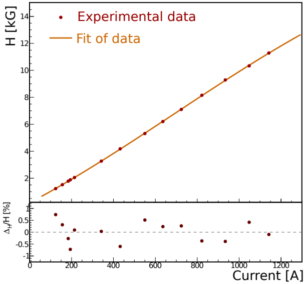
Bending magnet

Parameters	
Dimensions (L×W×H)	1600×500×280 mm
Vertical aperture	20 mm
Full width of aperture	310 mm
Working width of aperture	150 mm
Maximum field / current	15.8 kG / 1600 A
Weight	2 tons



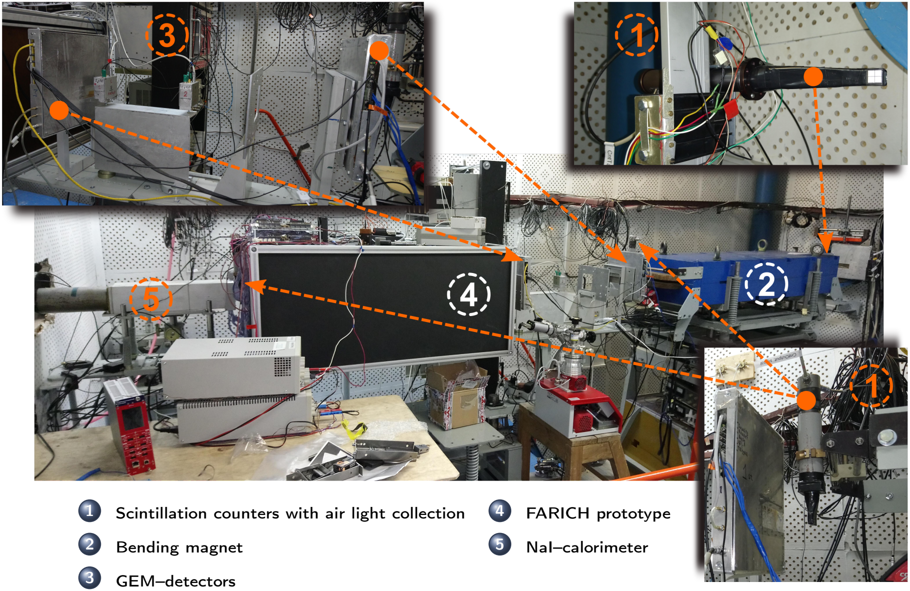
- Maximal nonuniformity of the field in the working aperture area is 1.5%.
- Accuracy of setup magnetic field is $(0.5 - 0.8)\%$.





Test beam of electrons: Infrastructure

Example disposition of equipment in experimental hall (15/03/2018)



1. Scintillation counters with air light collection
2. Bending magnet
3. GEM–detectors
4. FARICH prototype
5. NaI–calorimeter

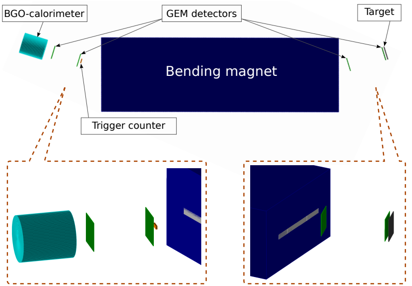
Test beam of electrons: Infrastructure

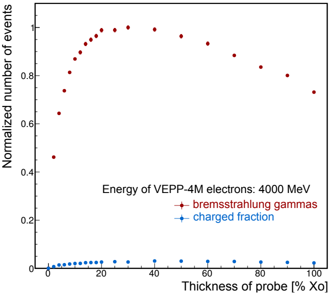
Data acquisition (DAQ)

- All DAQ applications were developed using programming languages such as C++, bash and python.
- Currently we are using CAMAC blocks (ADC, discriminators, attenuators, coincidence and etc.), but we will migrate to VME blocks in this year.
- The DAQ provides:
  - measurements of electron energy and coordinates of his track;
  - data output in ROOT TFile, which containing events with all necessary parameters (energy, coordinates, event counter, timestamp and etc.);
  - external trigger at fast NIM format.
- Synchronization of data from DAQ with data from prototype of detector can be performed in the following ways:
  - using the concept of asynchronous reading, after appearance of the trigger signal, it is blocked for a time necessary for reading prototype of detector $\Leftrightarrow$ online mode;
  - using timestamp (or/and event counter) from DAQ and prototype of detector $\Leftrightarrow$ offline mode. We are using timestamp from the GEM–detector, accuracy of it is 7 ns.

Test beam of electrons: MC simulation

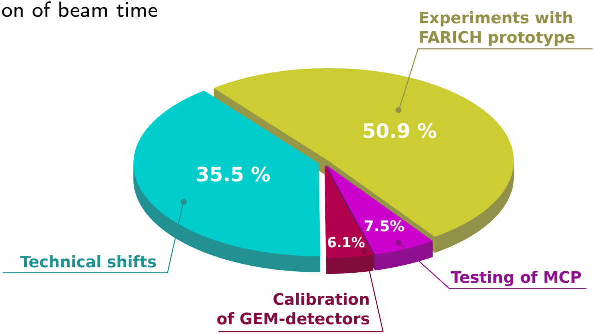
- For the simulation GEANT4 toolkit was used.
- The simulation includes:
  - A complete description of geometry of the equipment in the experimental hall: the GEM detectors, the target, the bending magnet, the trigger counters and the calorimeter. Spatial resolution of the GEM detectors and magnetic field maps in the bending magnet are corresponded experimental data.
  - Beam channels (radiation safety) and the vacuum chamber of the VEPP–4M collider are described in detail too.
- The simulation is used for: evaluation of the optimal background conditions in the place where the prototype detector is located, to determine the optimum thickness and position of the probe and the target, and for other tasks.





Test beam of electrons: Experiments

- Since 2011 the installation has been used successfully for the following experiments:
  - Development of FARICH detector prototypes (FARICH – Focusing Aerogel RICH). FARICH is a promising detector for particle identification in future experiments, for example, Super Charm-Tau Factory at Novosibirsk.
  - Calibration of coordinate detectors based on GEM. These detectors are now used actively in several BINP experiments.
  - Detectors based on microchannel plates (MCPs) can be used for measurement of the time resolution and detection efficiency of charged particle. This is a new development mode for the upgrade of the endcap electromagnetic calorimeter of the CMS detector at the LHC (high luminosity).
- The distribution of beam time

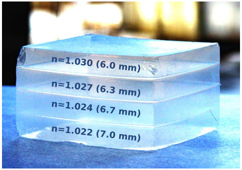


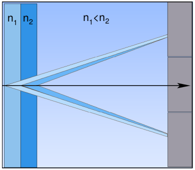
Focusing Aerogel RICH

The radiator in FARICH is composed of several aerogel layers with different refractive indices.

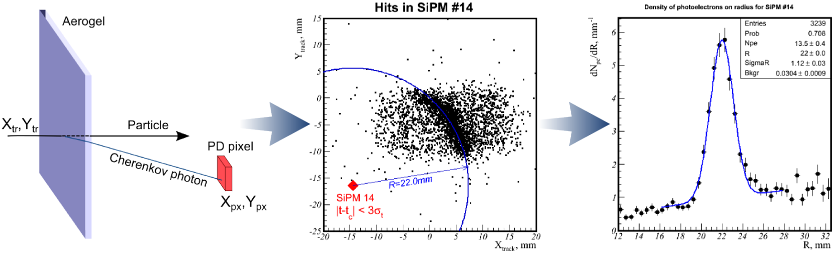
✓ Improvment of the Cherenkov angle measurement accuracy as compared to single layer is achieved by the reduction of the contribution from the thickness of the radiator in the error.

For details see report by A. Barnyakov.





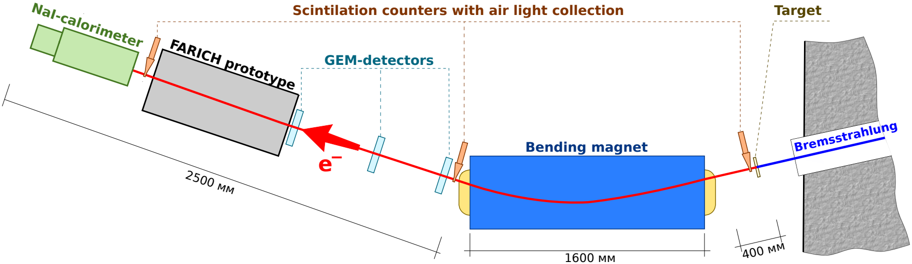
- Given a tracking system and enough particle statistics, a single PD pixel is enough to build the distribution of Cherenkov photons on R_{ch} (Θ_{ch}).



- Many pixels can be combined to improve accuracy and align the tracking system with the PD pixels.

Focusing Aerogel RICH

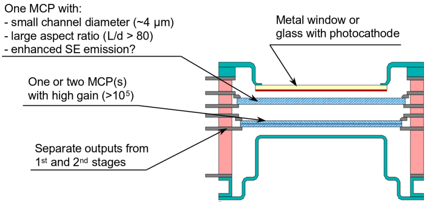
- Four FARICH prototypes were tested from 2011 to 2018.
- The electron beam facility for test the FARICH prototype.



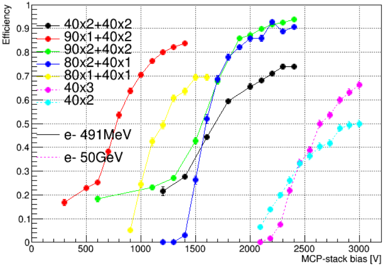
- Several single layer and focusing aerogel samples were tested at the beam.
- Focusing effect has been observed:
    - four layers aerogel (thickness 30 mm) $\Rightarrow \sigma_r = 1.1$ mm
    - single layer aerogel (thickness 20 mm) $\Rightarrow \sigma_r = 2.1$ mm

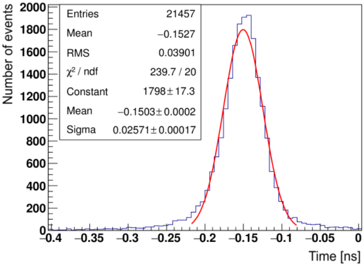
MCP based devices

- MCP devices by BINP design structure and appearance.



- For trigger and time reference two MCP PMT based Cherenkov counters are used.
- MCP based devices working in ionization mode could provide MIP detection efficiency up to 90% with time resolution better than 50 ps.

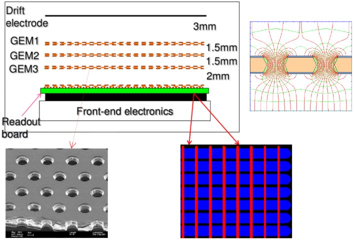


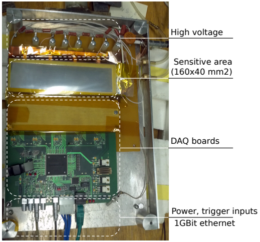


Test beam of electrons: Experiments

GEM-based detectors

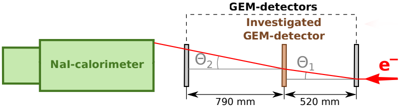
- GEM-detector structure and appearance.



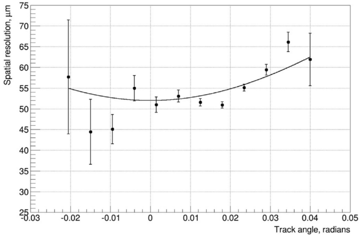


- Amount of material and spatial resolution for the GEM-detectors were measured.

- The amount of material was measured, using 100 MeV electrons. The angular distribution of the tracks after multiple scattering in the investigated detector corresponds to the amount of material: $0.203 \pm 0.003\%\ X_0 \Leftrightarrow$ estimation $0.15\%\ X_0$.

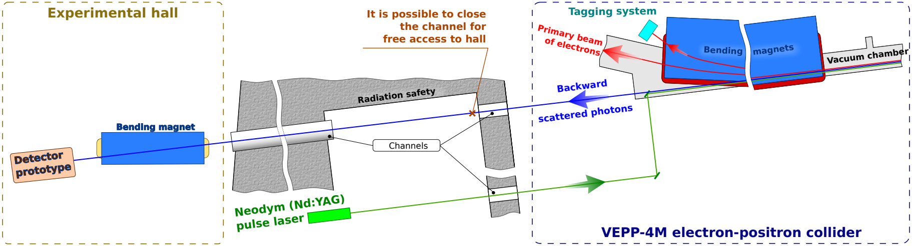


- The spatial resolution varies within about $45 - 65\ \mu$m.



Tagged photon beam

Principle of the beam production



1. A pulsed laser is used to form the photon beam. The special setup of mirrors transported the laser photons to the interaction point of VEPP–4M.
2. After interaction a photon gets part of the primary electron energy and moves along the electron beam direction mainly within a cone with an angle of $1/\gamma$.
3. To determine the photon energy the scattered electron energy is measured by the unique tagging system. This device has the energy resolution of $\sigma_E/E \sim 10^{-3}$.

The beam parameters	
Energy range	$(0.39 \div 0.97) \times$ E
Intensity	$\sim$ 1000 Hz

✓ The photon beam was used in 1998 last time for testing BELLE CsI calorimeter prototype. So, it takes some time (about 2-3 months) for its come back.

Compton and Bremsstrahlung spectra (photon beam)

- Energy spread of the primary electron beam in the VEPP–4M is $\sigma_E/E = 3 \times 10^{-4}$.
- The energy scale and resolution of the NaI and BGO calorimeters were calibrated using the edges of the Compton (by laser) and Bremsstrahlung (by residual gas) spectra.
- The edge (maximum energy) of the Compton spectra is defined as:

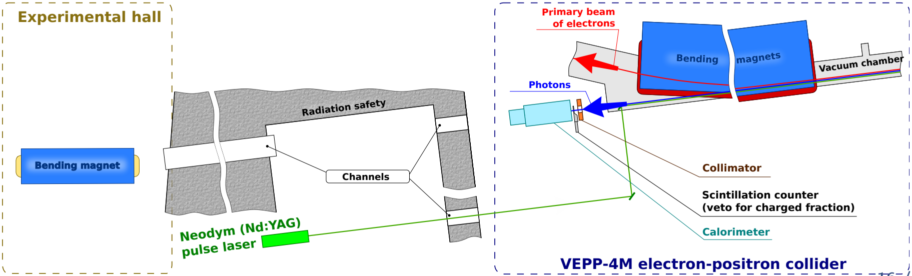
$$w_{max} = E\frac{x}{1+x},$$

where: E – energy of the primary electron beam in the VEPP–4M, $x = 4\omega_0 E/m_e^2c^4$, ω_0 is the laser photon energy (1.165 eV and 2.33 eV for I and II harmonics, respectively)

- List of possible calibration points at VEPP–4M collider

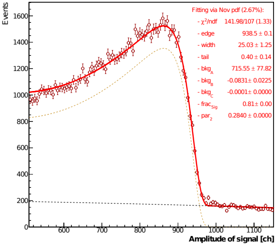
VEPP–4M energy [MeV]	Bremsstrahlung edge [MeV]	Compton edge I harmonic [MeV]	Compton edge II harmonic [MeV]
1850	1850	59	115
3000	3000	152	290
4000	4000	267	500

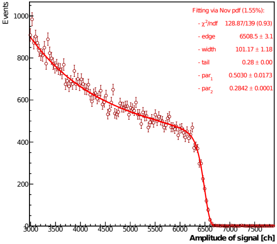
- Calorimeters were located next to the output window of the vacuum chamber.



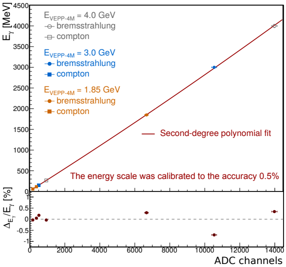
Compton and Bremsstrahlung spectra (photon beam)

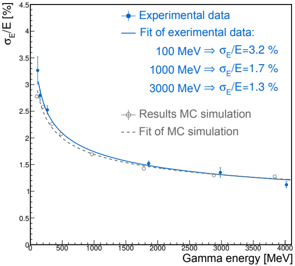
- Examples of fit of Compton spectrum near edge (left) and of Bremsstrahlung spectrum near edge (right).

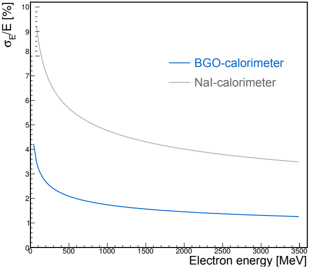




- The calibration results of energy scale (left) and energy resolution (middle) for the BGO–calorimeter. Comparison of energy resolution of calorimeters (right).







Summary

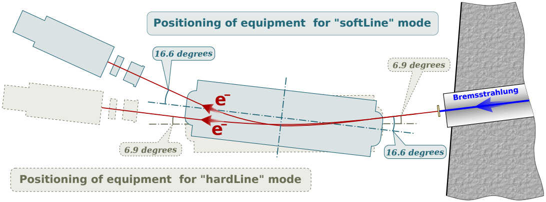
- The test electron beam facility is fully operational since 2011.
- The parameters of the test electron beam:
  - energy range: 100 – 3500 MeV
  - energy spread: 7.8% (100 MeV) – 2.6% (3000 MeV)
  - itensity: 50÷100 Hz
- A series of experiments with FARICH prototype detectors, MCP-based devices and GEM–detectors were successfully performed on the electron beam.
- The tagged photon beam was used in 1998 last time for testing BELLE CsI calorimeter prototype. It takes some time (about 2-3 months) for its come back, if we will have tasks for it.
- Calibration energy resolution of calorimeters can be performed using the edges of the Compton and Bremsstrahlung spectra of the VEPP–4M collider.

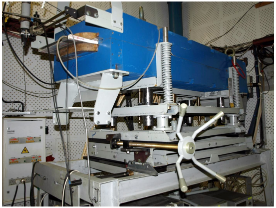
Thank you for your attention !

Additional slides

Test beam of electrons: Two operating modes

- The experimental equipment of the installation is located on a specific trajectory of electrons, which is called the central trajectory.
- The momenta of the electrons have the spread $\Delta p = p_{max} - p_{min}$ around the "mean" momentum p_{mean}. The trajectory of an electron with the momentum p_{mean} corresponds to the central trajectory.
- The installation can generate electrons in two basic modes, conventionally called $hardLine$ and $softLine$. The difference between these modes is in the location of the experimental equipment of the installation relative to Bremsstrahlung.

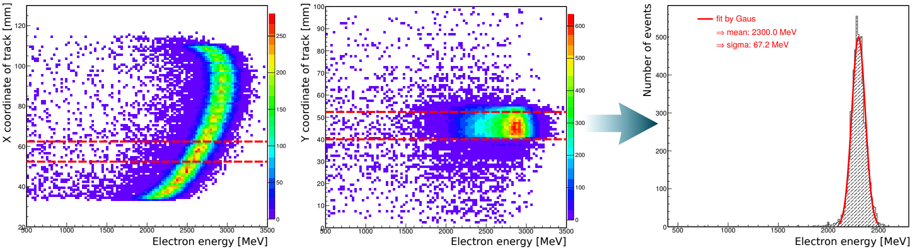




- The working modes are switched via a turn and shift of the bending magnet and the equipment located after it. An advanced positioning system enables doing this in 10–15 minutes.
- A large rotation angle decreases the range of the momenta of the generated electrons ($\Delta p/p$), but results in an electron intensity $1.5 \div 2.0$ times reduced because of the smaller acceptance of the system.

Test beam of electrons: Two operating modes

- The electron energy is limited from above by the maximum value of the magnetic field and is equal to 1300 MeV and 3500 MeV for the $softLine$ and $hardLine$ modes, correspondingly.
- The measured energy spread of electrons Δ_E/E was done.

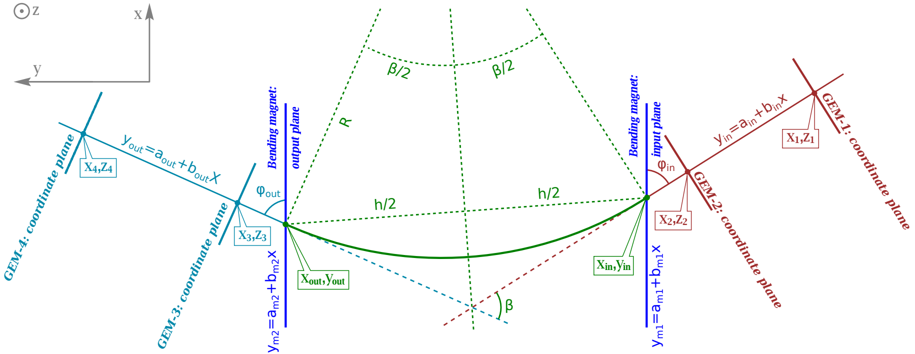


- Δ_E/E for electron beam with trigger area of ± 5 mm horizontally and ± 5 mm vertically relative to the central trajectory.

E [MeV]	100	120	500	1000	1500	2000	2300	3000
Δ_E/E ($softLine$) [%]	7.8	7.0	3.3	2.7	—	—	—	—
Δ_E/E ($hardLine$) [%]	14.1	—	6.6	4.2	3.6	3.2	2.9	2.6

Test beam of electrons: Alternative way to beam energy measurement

- After the passage of the detector prototype, the energy of the electrons is measured with a calorimeter.
- If detector prototypes have a large amount of material, as in case of calorimeter prototype, the energy of the electrons is measured very roughly.
- For the determination of the energy of electrons with an accuracy of $1 \div 2\%$ it was suggested to use coordinate detectors placed before and after the magnet.



$$pc = 300HR,$$

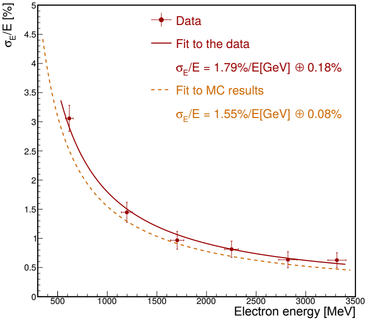
p is the electron momentum [eV/c],
H is the magnetic induction [G],
R is the curve radius of the electron track in the magnetic field [cm]

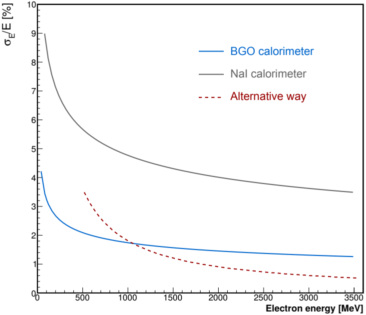
$$R = \frac{h}{2\sin\beta/2},$$

β is the angle of electron rotation in the magnetic field,
h is the length of the chord corresponding to the angle β

Test beam of electrons: Alternative way to beam energy measurement

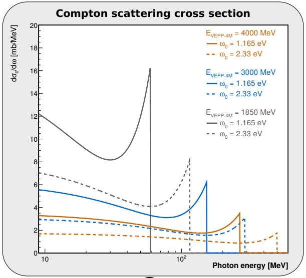
- The simulation showed that we could expect an energy resolution of about 1.5% for electrons with energies above 1000 MeV for the $hardLine$ operation mode.
- In the $softLine$ operation mode, to achieve an energy resolution of about 2% at an energy of 100 MeV, it is necessary to use coordinate detectors with a thickness less than 0.2% X_0.
- Since we had no such detectors, we decided to perform an experiment only for high energies in the $hardLine$ mode.
- Comparison of $\sigma_\mathrm{E}/\mathrm{E}$ obtained from: experimental data with simulation for $hardLine$ mode (left) and different measurements of electron beam energy (right).



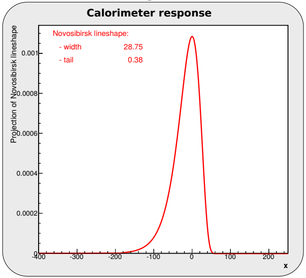


- Currently we are developing new coordinate GEM detectors that will take into account the specifics of our installation.

Procedure for fit of the Compton edge

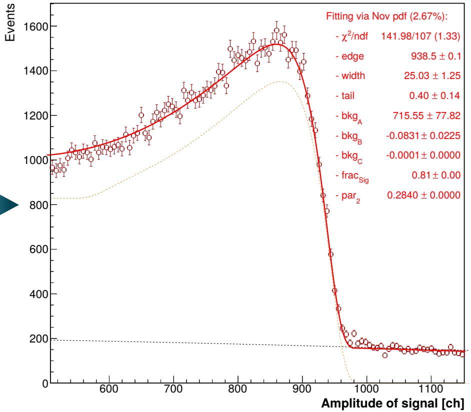


$\otimes$

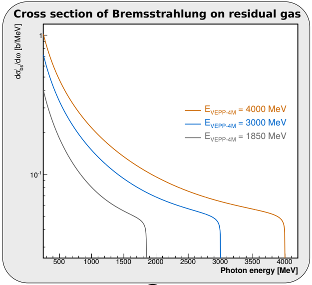


$+$

Background



Procedure for fit of the Bremsstrahlung edge



$\otimes$