Development of a Beam Profile Monitor based on Silicon Strip Sensors for Low-Charge Electron Beams at ARES

Sonja Jaster-Merz (DESY)
Elba, 19.09.2019
Introduction

Injection into novel accelerators
• Spectrometer setup to measure energy
• Special beam profile monitor for low-charge beams

ARES parameter

<table>
<thead>
<tr>
<th>ARES parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch duration</td>
<td>fs to sub-fs</td>
</tr>
<tr>
<td>Energy</td>
<td>52 MeV – 155 MeV</td>
</tr>
<tr>
<td>Charge</td>
<td>0.3 pC – 30 pC</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>50 Hz</td>
</tr>
</tbody>
</table>

See talk: B. Marchetti “SINBAD-ARES - A Photo-Injector for external Injection Experiments in novel Accelerators at DESY”
Introduction

See talk:
**B. Marchetti** “SINBAD-ARES - A Photo-Injector for external Injection Experiments in novel Accelerators at DESY”

- Injection into novel accelerators
- Spectrometer setup to measure energy
- Special beam profile monitor for low-charge beams

**ARES parameter**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch duration</td>
<td>fs to sub-fs</td>
</tr>
<tr>
<td>Energy</td>
<td>52 MeV – 155 MeV</td>
</tr>
<tr>
<td>Charge</td>
<td>0.3 pC – 30 pC</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>50 Hz</td>
</tr>
</tbody>
</table>
Possible Electron Distribution

At spectrometer screen

- Small apertures → low charge (< 0.5 pC)
- For a possible ACHIP working point:
  Less than 7 electrons per µm²

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge</td>
<td>pC</td>
<td>0.5</td>
</tr>
<tr>
<td>Energy</td>
<td>MeV</td>
<td>52</td>
</tr>
<tr>
<td>Full Bunch Duration</td>
<td>ps</td>
<td>5.6</td>
</tr>
<tr>
<td>$\sigma_x$</td>
<td>ps</td>
<td>1.2</td>
</tr>
<tr>
<td>Full Width on Screen $\Delta x$</td>
<td>mm</td>
<td>12</td>
</tr>
<tr>
<td>$\sigma_y$</td>
<td>mm</td>
<td>3.4</td>
</tr>
<tr>
<td>Full Height on Screen $\Delta y$</td>
<td>mm</td>
<td>0.5</td>
</tr>
<tr>
<td>$\sigma_y$</td>
<td>mm</td>
<td>0.1</td>
</tr>
</tbody>
</table>

See poster: F. Mayet “Status report on the dielectric laser acceleration experiments at the SINBAD/ARES linac”

STRIDENAS
dedicated beam profile monitor for low-charge beams

Courtesy: F. Mayet (DESY)
STRIDENAS
A Silicon Strip Detector for Novel Accelerators at SINBAD
DESY Collaboration (MPY-1 and FH-ATLAS)

MPY-1
Sonja Jaster-Merz
Florian Burkart

FH-ATLAS / FLC
Marcel Stanitzki
Jan Dreyling-Escheiler, Uwe Kraemer, Lennart Huth

Further support from DESY technical groups

University of Hamburg
Detector development group of Erika Garutti
Silicon Strip Sensors

Theory

- Working principle: pn-junction
- To gain spatial resolution: segmented electrodes p-type bulk and n-type implants
- Electrons and photons interact with the sensor material and deposit energy, follows a Landau distribution for MIPs
- Production of electron-hole pairs (~80 per µm and MIP)
- Under reversed bias charge carriers drift towards the electrodes and start the signal current
- Geometric resolution: $\sigma = \frac{\text{pitch}}{\sqrt{12}}$
- Transverse signal spread due to
  - Thermal diffusion
  - Plasma effect (for high charge carrier densities)

$w \sim \sqrt{V_{\text{ext}}}$

$w$ – depletion width (asymetrically doped)
$V_{\text{ext}}$ – external potential
STRIDENAS Challenges

LOW CHARGE DENSITIES AT ARES  ➔ USE SILICON SENSORS FROM HEP EXPERIMENTS?

Challenges
• Sensors usually used for single particle detection
• At ARES an intensity $\sim 10^5$ times higher is expected
  • Regime where sensor behaviour is not well studied
  • HEP signal amplification done with an ASIC - not designed for such intensities
  • ASIC not ultra-high vacuum compatible

Approach

SENSOR from HEP experiments + READOUT ELECTRONICS for higher charges
STRIDENAS Specifications

Requirements

- Spatial resolution in the 100 µm range
- Dynamic charge range after the spectrometer dipole between ~1 fC and ~40 fC per readout channel
- Needs to withstand ~10^6 electrons per shot
- Compact and shielded from ambient light
- Remotely controllable and ultra-high vacuum compatible final setup

- First: Prototype outside vacuum + test of the components
- Then: Vacuum compatible design

ATLAS sensors
charge-to-digital converters
printed circuit board and holder
STRIDENAS

Components

- PCB with 64 readout channels
- Sensors glued and bonded to PCB
- PCB can be placed in a dedicated holder
- CAEN charge-to-digital converters
  - Dynamic range: 0 – 900 pC
  - Dual range: 25 fC and 200 fC resolution
STRIDENAS

ATLAS12EC Silicon Sensors

- Test structures developed for the High Luminosity LHC ATLAS inner tracker upgrade
- 1 x 1 cm², 310 µm thick, 103 strips, 74.5 µm pitch
- Punch through protection

- **IV measurement:**
  - Determine leakage current
  - Check breakdown of sensors

- **CV measurement:**
  - Determine the depletion voltage
  - Uniform behaviour of all sensors
  - Agree with measurements performed by ATLAS
Simulation of Charge Sharing

- Estimate the behaviour of the sensor for a 0.5 pC ACHIP working point
- ROOT simulation
  - Assuming incoming particles are MIPs
  - Sensor thickness: 310 µm
  - 64 readout channels with 223.5 µm pitch
  - Gaussian transverse spread with a σ of 300 µm
- Beam features of interest well resolved
Sensor Characterization

Transient-Current Technique Measurements

- Transient-current technique uses laser light instead of electrons
- Also production of electron-hole pairs
- Investigate signal length, transverse spread, plasma effect, correlation between applied bias voltage and produced charge in the sensor
- Measurements with red and infrared light
Sensor Characterization

Transient-Current Technique Measurements

- Position scan to investigate signal spread
- For maximum charge: no problems expected (7298 ± 691 MIPs)
STRIDENAS Functionality Tests

DESY II Test Beam Facility

- DESY II Test Beam facility generates particles with a double conversion setup
- Electron energies: 1 – 6 GeV
- Single electrons needed for detector tests
- Particle rate up to ~ 40 kHz
- Provides infrastructure for experiments
- Due to single electrons: Individual tests of the STRIDENAS components
  - Readout electronics tests with a photomultiplier signal from the test beam telescope
  - Tests of the STRIDENAS detector
  - Tests with the sensor bonded for the TCT measurements
STRIDENAS Functionality Tests

Readout Electronics Test with Photomultiplier Signals

- Different charge integration gates
- Use of iron plates to produce particle showers and increase the number of incoming particles
- Example measurements with a 15 µs gate signal
STRIDENAS Functionality Tests
Readout Electronics Test with Photomultiplier Signals

- Different charge integration gates
- Use of iron plates to produce particle showers and increase the number of incoming particles
- Example measurements with a 15 µs gate signal

- Triple Landau fit
  - Equally spaced peak-to-peak distance corresponding to ~15 pC
  - Agrees well with expected value from photomultiplier
STRIDENAS Functionality Tests

Test Measurements with the STRIDENAS detector

- Different test measurements with STRIDENAS detector
  - Measurements unsuccessful due to early breakdown of the sensors

- Investigate with new sensor if it is in principle possible to observe single electrons

- No visible signal from the Test Beam (single electrons)
  - Produced signals were too small to be detected
  - **Higher charge carrier density** or **amplification** is needed
STRIDENAS Functionality Tests

Sensor Tests with Amplifier

- Measurements with sensor from the TCT measurements and a 40 dB amplifier
- Signal connected to an oscilloscope
- Area under the signal is proportional to the produced charge inside the sensor
- Varies according to the Landau distribution
STRIDENAS Functionality Tests

Sensor Tests with Amplifier

- Measurements with sensor from the TCT measurements and a 40 dB amplifier
- Signal connected to an oscilloscope
- Area under the signal is proportional to the produced charge inside the sensor
- Varies according to the Landau distribution

\[ Q = \frac{L_C}{A R} \int_{t_s}^{t_f} Ud t \sim \frac{L_C}{A R} I_M \Delta t \]

- Histogram of waveform integrals with Landau fit

\[ L_C = \text{signal loss compensation} \]
\[ A = \text{amplification factor} \]
\[ R = \text{impedance of system} \]
\[ U = \text{measured voltage} \]
\[ t_s, t_f = \text{starting and final time boundaries} \]
\[ I_M = \text{MATLAB integral} \]
\[ \Delta t = \text{actual data spacing} \]

Most probable produced charge:
\[ (1.14 \pm 0.14) \times 10^{-14} \text{ C} \]
\[ 229 \pm 34 \text{ eh pairs per } \mu \text{m} \]
Conclusion

✓ Successfully detected single electrons
✓ Successful sensor tests with a high electron intensity simulated with laser beam
✓ Readout electronics tested successfully for high intensities with signals from photomultipliers
✓ Amplifier needed to reduce noise introduced by meter long cables
Outlook

- Repeat high intensity measurements with incoming electrons
- Development of suited signal amplification
- Build vacuum compatible setup
  - First discussions with the DESY vacuum group are ongoing
- Implementation at the ARES spectrometer
MADE POSSIBLE WITH THE HELP OF: