Design of the Interaction Chamber for ACHIP at PSI

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Nicole Hiller, PSI
Direct Laser Acceleration (DLA)

Fig. 1. Schematic diagram of an electron linear accelerator by optical maser.

Koichi Shimoda
New acceleration techniques

The **direct laser accelerator** (DLA) in which the accelerating field is driven by a short laser pulse in a dielectric structure.

The **dielectric wakefield accelerator** (DWA) in which wakefields are driven in a dielectric tube by a high current particle bunch.

The **plasma wakefield accelerator** (PWFA) in which a plasma wave is driven in the wake of a high current particle bunch.

The **laser wakefield accelerator** (LWFA) in which a plasma wave is driven in the wake of an intense laser.
What has been done: Part 1

Acceleration Experiments with a Dielectric Structure

Electron beam >> structure

Peralta et al., Nature 503, 91 (2013)
What has been done: Part 2

Acceleration of “occasional single electrons”

Breuer et al.,
PRST-AB 17, 021301 (2014)
ACHIP - Work on all individual aspects and build a full miniature accelerator
Goal: Put the entire electron beam into the dielectric structure and accelerate it by 1 MeV.
ACHIP Chamber in the Injector

- Possibility to insert samples into 300 MeV electron beam
- Load-Lock chamber for easy exchange of samples
So what kind of experiments can you do with the injector chamber?

- **Currently on-going**
  - Radiation hardness testing of dielectric structures & materials
    (ACHIP collaboration)
  - Processional magnetisation reversal of ferromagnets
    (PSI internal research)
  - Beam-double pillar structure interaction
    (ACHIP collaboration)
  - Test of wire scanners with sub-µm resolution
    (PSI internal research)
- **Got any ideas for other experiments?**
Radiation hardness testing of dielectric structures & materials

Team at FAU: Josh McNeur, Peter Hommelhoff

Sapphire sample
Sub-Micrometer Resolution, Nanotechnology Based Wire Scanners for Beam Profile Measurements at SwissFEL

On-going master thesis of Simona Borrelli

- **Idea:** Use nanofabrication of sub-micrometer metallic stripes on a membrane via e-beam lithography

First results presented right now at: 38th International Free Electron Laser Conference 20-25 August, 2017, Santa Fe, NM, USA
The ACHIP experimental chambers at PSI have been designed to perform proof-of-principle experiments that demonstrate the potential of laser-driven electron accelerators. The chambers are equipped with state-of-the-art diagnostics and control systems to monitor and optimize the performance of the electron beams. The primary goal of the ACHIP project is to demonstrate that laser-driven electron accelerators can achieve significant energy gains, which could revolutionize various fields such as materials science, energy, and healthcare.

**Key Features**
- **Laser System:**
  - Power: 100 µJ
  - Duration: 500 fs
  - Focus: Sub-micrometre dimensions
- **Electron Beam:**
  - Energy: 3 GeV
  - Interaction: Laser-electron beam interaction
- **Diagnosis:**
  - Real-time monitoring of beam quality and interactions
- **Magnets:**
  - Permanent magnet quadrupoles
  - Flexible configurations for various experiments

**Project Background**
ACHIP is an international collaboration, funded by the Gordon and Betty Moore Foundation, whose goal is to demonstrate the feasibility of laser-driven electron accelerators. The project involves a multidisciplinary team from PSI and other institutions, focusing on the development of advanced diagnostics and control systems.

**Experimental Setup**
In this contribution, we will describe the two interaction chambers installed on SwissFEL to perform the proof-of-principle experiments. The chambers are designed to test various dielectric and magnetic materials under high-energy electron beams, aiming to understand the effects of laser excitation on different materials.

**Key Experiments**
- **Material Hardness Testing:**
  - Using 350 MeV electron beams to study the radiation hardness of materials
  - Material: Al₂O₃, SiC, Si
  - Technique: Electron beam exposure, subsequent measurement
- **Magnetic Excitations:**
  - Studying processional magnetization reversal of ferromagnets
  - High-energy electron beam through small apertures
  - Technique: X-ray microscopy, X-ray magnetic circular dichroism

**Conclusion**
The ACHIP project represents a significant step towards the realization of high-energy, laser-driven electron accelerators. The successful demonstration of these technologies could lead to advancements in various scientific and technological fields, including medical imaging, materials science, and energy production.
What’s next?

• Build and install the main chamber
• In parallel: laser room
• Initial experiments are scheduled for 2018, after installation
• **Final goal:** 1 MeV net acceleration of the full electron beam
Beam-double pillar structure interaction

To consider dielectric structures as the basis for a linear electron accelerator of significant interest, an understanding of electron beam transport through micron-scale apertures is essential. This requires a detailed study of the effects of wakefields and Coulomb repulsion on the beam, as well as the beam-induced damage on the dielectric material itself. The challenge is to fully understand the transmission of an electron beam through the small aperture of the double pillar structure, and to test the ability of dielectric structures to transmit the beam through it. As wakefield effects could potentially seriously degrade the electron beam quality, we will evaluate the electron beam through low dielectric structures proposed for the ACHIP project.

Therefore, the 350 MeV electron beam at the SwissFEL injector chamber has been used to study the radiation hardness of the materials proposed to be the components of DLAs, such as Al2O3, SiC, and Si. By placing these materials directly in the path of the electron beam, we can assess their ability to withstand the radiation exposure while maintaining their structural integrity.

Experiments in the injector chamber

In this contribution, we will describe the two interaction chambers installed on SwissFEL to perform the proof-of-principle experiments. In particular, we will present the positioning system for the samples, the magnets needed to focus the beam to sub-micrometre dimensions, and the diagnostics to measure beam properties at the interaction point. Different bunch charges and electron beam lengths will be considered to study the effects of the interaction on the beam properties.

Modern magnetic recording technology demands operational speeds far beyond the nanosecond regime, which require the investigation of processional magnetization reversal of ferromagnets. X-ray microscopy (STXM) and X-ray magnetic circular dichroism (XMCD) have been used to study the magnetic properties of magnetic excitations on a time scale much shorter than the spin lattice relaxation time (~100 ps). The experiment would provide a visual demonstration of switching on picosecond timescales for in-plane and out-of-plane magnetic nanostructures, by using the electron beam as the magnetic pulse excitation. After exposure to the electron beam, the samples will be measured using scanning transmission X-ray microscopy (STXM) and X-ray magnetic circular dichroism (XMCD) to examine for signs of structural damage under an optical microscope and an SEM.

Stripe samples were inserted in the SwissFEL electron beam for the ACHIP demonstration. The samples were 25 nm thick in-plane magnetized Ni80Fe20 Py islands of length 500 nm and width 250 nm. To test the ability to fully transmit the electron beam through the aperture of the double pillar structure, a combination of Fe based permanent magnets has been used to focus the beam to sub-micrometre dimensions. The electron beam has also been used to perform a 2D probe of the sample. X-ray microscopy (STXM) and X-ray magnetic circular dichroism (XMCD) have been used to study the magnetic properties of magnetic excitations on a time scale much shorter than the spin lattice relaxation time (~100 ps). The experiment would provide a visual demonstration of switching on picosecond timescales for in-plane and out-of-plane magnetic nanostructures, by using the electron beam as the magnetic pulse excitation. After exposure to the electron beam, the samples will be measured using scanning transmission X-ray microscopy (STXM) and X-ray magnetic circular dichroism (XMCD) to examine for signs of structural damage under an optical microscope and an SEM.

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Backup Slides
The challenge

Accelerate an electron beam using a laser, “mediated” by a dielectric structure (net accelerating field)

The dimensions of the structure are determinate by the wavelength of the laser

The electron beam must have transverse dimensions smaller than the dielectric structure.

The electron beam of SwissFEL is the ideal candidate to perform experiments at relativistic energies

The whole beam could pass through the structure (without losses) thanks to the small transverse emittance (~100 nm or less) and higher energy.

A dedicated vacuum chamber is needed to perform such experiments

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron beam energy</td>
<td>3 GeV</td>
</tr>
<tr>
<td>Electron bunch charge</td>
<td>1 pC</td>
</tr>
<tr>
<td>Energy gain (goal)</td>
<td>1 MeV</td>
</tr>
<tr>
<td>Structure type</td>
<td>Double pillar</td>
</tr>
<tr>
<td>Accelerating length</td>
<td>1 mm</td>
</tr>
<tr>
<td>Accelerating gradient (goal)</td>
<td>1 GV/m</td>
</tr>
<tr>
<td>Structure diameter</td>
<td>1.2 μm (x) – 7.0 μm (y)</td>
</tr>
<tr>
<td>Laser wavelength</td>
<td>2 μm</td>
</tr>
<tr>
<td>Laser pulse energy</td>
<td>500 μJ</td>
</tr>
<tr>
<td>Laser pulse length (FWHM)</td>
<td>100 fs</td>
</tr>
</tbody>
</table>
## ACHIP Chamber - Specs

<table>
<thead>
<tr>
<th>Electron beam</th>
<th>Chamber in injector</th>
<th>Chamber in Athos</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>&lt; 350 MeV</td>
<td>3.0 GeV</td>
</tr>
<tr>
<td>Goal: energy gain</td>
<td></td>
<td>1 MeV</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>0.5 pC - 200 pC</td>
<td>1 pC</td>
</tr>
<tr>
<td>Diameter</td>
<td>1.4 μm rms / 25 μm rms</td>
<td>&lt; 1 μm rms</td>
</tr>
</tbody>
</table>

| Laser                                             |                     |                  |
| Wavelength                                        | N.A.                | 2 μm             |
| Pulse energy                                      | 100 μJ              |                  |
| Pulse length                                      | 500 fs              |                  |

| Accelerating Structure                            |                     |                  |
| Length                                            | 3 mm                | 1 mm             |
| Accelerating gradient                             | 0.75 GV/m           | 1 GV/m           |
| Opening                                           | 90 μm x 500 μm      | 1.2 μm x 7 μm    |

Reference to Eugenio’s FEL paper
Beam-double pillar structure interaction

Transmitting an electron beam through the small aperture of the dielectric structures proposed for the ACHIP project is an experiment in itself. We will use a suitably expanded structure and low energy electrons to test the ability to fully transmit the electron beam through it. As wakefields could potentially seriously degrade the electron beam quality, we will evaluate the effect of the interaction of the electron beam with the double pillar structure, by measuring the emittance and energy distribution after the interaction, for different bunch charges and electron beam lengths.
Modern magnetic recording technology demands operational speeds far beyond the nanosecond regime, which require the investigation of magnetic excitations on a time scale much shorter than the spin lattice relaxation time (~100 ps). The experiment would provide a visual demonstration of switching on picosecond timescales for in-plane and out of plane magnetic nanostructures, by using the electron beam field as the magnetic pulse excitation. After exposure to the electron beam, the samples will be measured using scanning transmission X-ray microscopy (STXM) and X-ray magnetic circular dichroism (XMCD). The samples inserted in the SwissFEL electron beam were 25 nm thick in-plane magnetized Ni80Fe20 Py islands of length 500 nm and width 250 nm.
Radiation hardness testing of dielectrics

To consider dielectric structures as the basis for a linear electron accelerator of significant current, the effect of sending a high-power electron beam through the micron-scale apertures typical in optical scale dielectric accelerators must be fully understood. In addition to the effects of wakefields and Coulomb repulsion on the beam, the beam-induced damage on the dielectric material itself needs to be studied. Therefore, the 350 MeV electron beam at the SwissFEL injector chamber has been used to study the radiation hardness of the materials proposed to be the components of DLAs, e.g. Al2O3, SiC, and Si, by placing directly in the path of the electron beam. The materials have been examined for signs of structural damage under an optical microscope and an SEM.