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ELEGANT SOFTWARE FOR INVESTIGATION OF ELECTRON TRANSPORT SYSTEMS

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Abstract: this paper presents the possibilities of the software *elegant* for the investigation of electron transport systems. The research object is the electron accelerator Photo-CATCH. It is used to study electron sources that a later further examined by the electron accelerator *S-DALINAC* (Superconducting-Darmstadt-LINear-Accelerator). For the installation of a new cryogenic electron source, which is expected to extend the lifetime of the *CsO*-coating, the setup needed to be rearranged to be able to use the existing source as well as the new cryogenic source with one beamline. The characteristics of the beam properties of both sources were obtained using *elegant*. After executing all necessary simulations and analysing the results, the beamline could be readjusted, and the source put into operation.

Keywords: *elegant* software; electron accelerator; electron beam; Photo-CATCH; photo-electrons.

I. Introduction

Photo-*CATCH* is an experimental installation, located in the Technical University of Darmstadt. It is used to research electron sources of spin polarized electrons, which are emitted by a *GaAs*-cathode with a *CsO*-coating. After investigating sources with Photo-CATCH, they are further examined using *S-DALINAC* [1].

The *CsO*-coating has in general a limited lifetime due to chemical reactions and the back bombardment effect: Emitted electrons ionize particles of the residual gas, which are accelerated towards the coating. A cryogenic source was planned, which should decrease these effects and therefore prolong the lifetime of the coating. Due to its cryogenic properties, residual gas molecules are absorbed by the chamber walls, which enhances the vacuum, decreases the influence of the back bombardment effect, and therefore increases the lifetime of the source.

To be able to use the existing source as well as the new cryogenic source with Photo-CATCH, the experimental setup had to be extended and the beam guiding elements rearranged.

Simulations were made to obtain the properties and positions of all beam guiding elements before readjusting the whole setup.

These simulations were made with the software *elegant*, which can be used to examine electron transport systems.

II. Experimental Installation

Until 2021 Photo-CATCH had only one electron source that provided spin polarized electrons with an energy of 60eV using an electrostatic field and a gallium-arsenide cathode with a caesium-oxide layer as the photo cathode.

To prolong the lifetime of the mentioned caesium-oxide layer, another source was constructed using a cryogenic chamber that enhances the vacuum by further absorbing gas molecules on the chamber walls.

Figure 1 shows the experimental installation of Photo-CATCH [2].

Photo-CATCH has two different parts: the electron source and the beamline.

The source consists of a system of chambers, which are used to prepare the gallium-arsenide cathode. A titan-sapphire-laser was used for extracting electrons out of the caesium-oxide layer. These electrons were accelerated by an electrostatic field of 30 kV or 60 kV depending on the source.

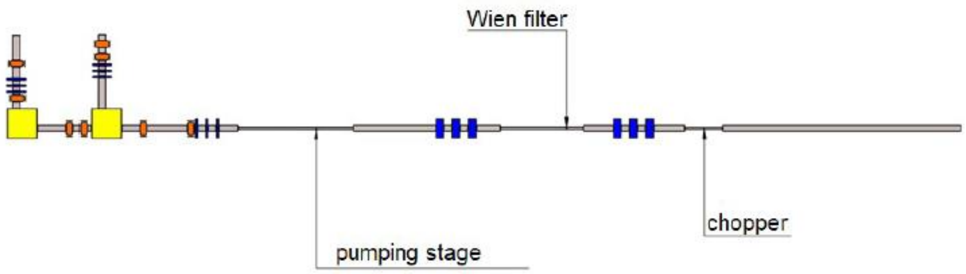

Figure 1 – Experimental installation of Photo-CATCH, where are steerer elements (orange), dipole magnets (yellow), quadrupole magnets (blue) and evacuated pipes (grey)

The electrons were accelerated into the beamline after the extraction.

The beamline consists of evacuate pipes, dipole and quadrupole magnets and steerer elements. The pipes are necessary to provide a vacuum and limit the transversal extension of the beam. Both dipole magnets are used to bend the beam into the horizontal plane. The quadrupole magnets are used only in triplet formation, which is used to focus a beam in the transversal plane. Two different configurations of quadrupole triplets with different properties were used for the whole installation. To prevent the beam and therefore electrons to interact with the pipe, steerer elements are used that change the overall angle of the beam.

III. Research Method

Elegant (**Ele**ctron **G**eneration **an**d **T**racking) is a software for simulating the beamline for different types of accelerators such as linear or circular accelerator [3].

The working principle of *elegant* is shown schematically in Figure 2.

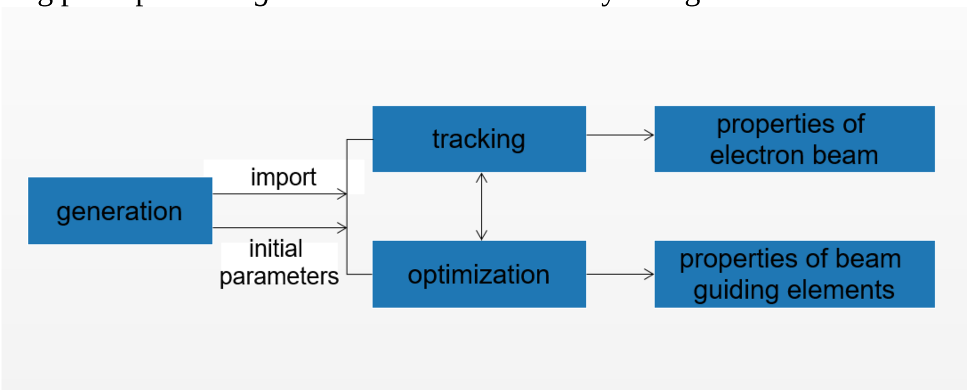

Figure 2 – Working Principle of elegant

Elegant provides the capability of generating electron beams using preset parameters or inserting complete electron bunches from other softwares, e.g. CST STUDIO SUITE. This electron bunch can then be tracked for an arbitrary beamline to obtain the properties of the beam at certain positions of the beamline.

At the same time, the properties of beam guiding elements can be optimized regarding chosen properties of the beam at selected positions of the beamline. For example, it is possible to determine the optimal position and properties of all quadrupole triplets to obtain the maximum focus in the transversal plane at the end of the beamline.

Elegant uses the matrix method for the simulation process, which means that every element in the beamline is assigned as a 6x6-matrix that fully describes it.

Figure 3 shows the basics to describe the beam and the elements of the beamline mathematically (transfer matrix).

$$R = \begin{pmatrix} R_{11} & R_{12} & 0 & 0 & 0 & R_{16} \\ R_{21} & R_{22} & 0 & 0 & 0 & R_{26} \\ 0 & 0 & R_{33} & R_{34} & 0 & 0 \\ 0 & 0 & R_{43} & R_{44} & 0 & 0 \\ R_{51} & R_{52} & 0 & 0 & 1 & R_{56} \\ 0 & 0 & 0 & 0 & 0 & R_{66} \end{pmatrix} \qquad \vec{x}(s) = \begin{pmatrix} x \text{ in mm} \\ y \text{ in mm} \\ x' \text{ in mrad} \\ y' \text{ in mrad} \\ l \text{ in mm} \\ \delta \text{ in ‰} \end{pmatrix}$$

a) *b)*

Figure 3 – Basic form of a transfer matrix (a) and of the particle vector (b)

Every electron needs to be described in the transversal and longitudinal position, angular deviation and momentum deviation so that one electron is represented by one vector.

To calculate the parameters of one particle at the end of the beamline, all matrices need to be multiplied which each other and finally multiplied with the electron vector.

Elegant provides the visualization of all relevant parameters, such as the cross section of the beam or the phase space besides of all matrix-vector multiplications.

To execute a full simulation process, three different files are needed: one file for the beamline (.lte), one file for all beam parameters (.ele) and one file with the corresponding code to start the simulation.

Figure 4 shows the parts of the code that is needed to execute a simulation.

```
&bunched_beam
    bunch = %s.bun
    n_particles_per_bunch = 100000
    Po = 0.34590872
    emit_x  = 1.822172027e-7
    emit_y  = 1.821255512e-7
    sigma_s = 0.03920130376
    sigma_dp= 0
    one_random_bunch = 1
    distribution_type[0] = "gaussian"
    distribution_type[1] = "gaussian"
    distribution_cutoff[0] = 4
    distribution_cutoff[1] = 4
&end
```

(a)

```
V2Q1: KQUAD, l=0.012, k1=700

V2Q2: KQUAD, l=0.012, k1=-1000

V2Q3: KQUAD, l=0.012, k1=700

V2DQ: DRIFT, l=0.019

V2QT: LINE=(V2Q1,V2DQ,V2Q2,V2DQ,V2Q3)

V2QTD: DRIFT, l=0.074
```

(b)

Figure 4 – Configuration of the initial beam (a) and implementation of quadrupole triplet in elegant (b)

Figure 4a shows the initial parameters for the beam. The number of particles does not change the final results, but just provide a higher resolution. *Po* describes the initial momentum as the multiplication of the average velocity times the Lorentz factor divided by the speed of light. *emit_x* and *emit_y* represent the transversal emittance in m*rad and *sigma_s* provides information about the longitudinal extension of the beam. The parameters *distribution_type* and *distribution_cutoff* determine the shape of the beam in all three dimensions.

Figure 4b shows a part of the code that was used to model a quadrupole triplet. *KQUAD* is the term of one of many kinds of quadrupole magnets that can be used in *elegant*. *l* states the length of each magnet and *k1* defines the strength of the focus. *DRIFT* is a function, which defines a part of a beamline without any elements besides the drift tube. The length is again stated by *l*. To combine all different elements, the *LINE* function can be used. This function consists of names of all elements that should be entailed in the beamline.

IV. Experimental Results

The main goal of the simulations made with *elegant* for Photo-CATCH was to find all relevant properties of the beam guiding elements to provide the maximum transmission of the electrons.

Figure 5 was obtained and shows transversal σ-matrices as a function of the position in the beamline, using *elegant* and the visualization properties of Python [4].

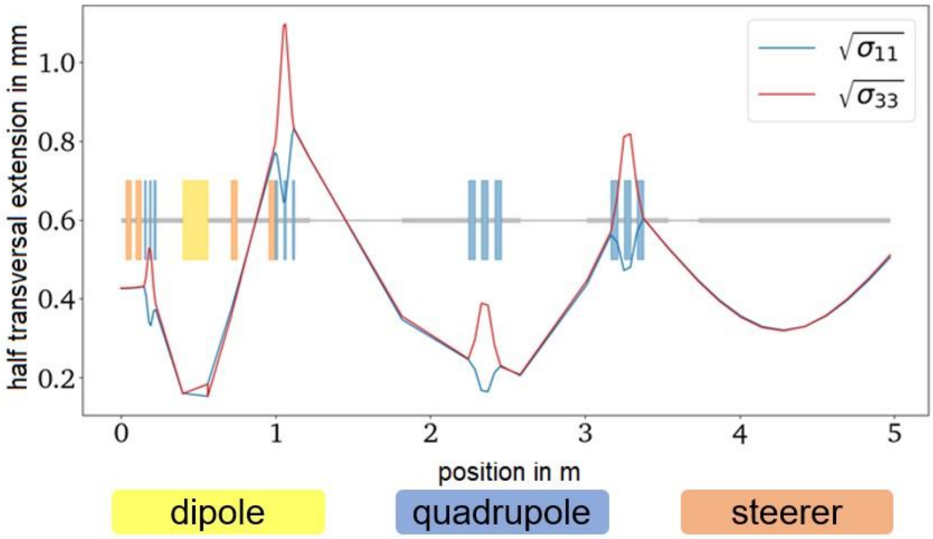

Figure 5 – Half transversal extension as a function of the length of the beamline with steerer elements (orange), quadrupole magnets (blue) and one dipole magnet (yellow)

It is easily possible to extract information about the transversal extension of the beam as well as the positions of the quadrupole triplets that were used to focus the beam, using this graph.

The extension increases linear in the beginning of the beamline due to the drift section. The extension of the beam decreases to a minimum after the first quadrupole triplet; as a result, the angle of each electron towards the symmetry axis of the tube increases. This leads to an increase of the extension over the following drift section. For the rest of the beamline, the beam is focused by quadrupole triplets and defocused by drift sections. At the end of the beamline, the beam shows almost the same extension as in the beginning.

Conclusion

The results provided by *elegant* were used to rearrange the experimental installation; the cryogenic source could be examined.

Simulations always deviate from real experiments, but it is not possible to determine the magnitude of the deviations before the cryogenic source was put into operation.

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