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CERN SECONDARY BEAM LINES SOFTWARE MIGRATION PROJECT

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Abstract

The Experimental Areas group of the CERN Engineering department operates a number of beam lines for fixed target experiments, irradiation facilities and test beams. The software currently used for the layout of the beam lines (BEATCH), beam optics (TRANSPORT), particle tracking (TURTLE) and muon halo calculation (HALO) has been developed in Fortran in the 1970's and 1980's and requires renovation in order to ensure long-term continuity. The on-going Software Migration Project transfers the beam line description to a set of newer commonly used software tools, such as MADX, FLUKA, G4Beamline, BDSIM and others. This contribution summarizes the goals and the scope of the project. It discusses the implementation of the beam lines in the new codes, their integration within the CERN layout database and the interfaces to the software codes used by other CERN groups. This includes the CERN secondary beam line control system CESAR, which is used for the control of the beam via setting of the magnets, collimators, filters etcetera, as well as readout of the beam instrumentation. The proposed interface is designed to allow a comparison between the measured beam parameters and the ones calculated with beam optics software.

INTRODUCTION

Beam Lines Managed by the Group

The Experimental Areas group of the Engineering department is responsible for the management of the fixed target experimental areas and test beams at CERN. This includes the so-called secondary beam lines, their associated facilities, beam line elements and infrastructure. The group is also ensuring the support in regards to the operation, design and physics studies of secondary beams and the technical and engineering support.

Figure 1 illustrates the CERN accelerator complex layout. The areas and beam lines managed by the EA group include three categories:

1. The **fixed target experiments**, including COMPASS, NA61, NA62, NA63, NA64, CLOUD, UA9 and several others. These are often designed to perform precision studies in the fields of the Standard Model (e.g. quantum chromodynamics) and Beyond Standard Model physics. They require stable beam conditions for prolonged periods of time.
2. The **irradiation facilities** such as HiRadMat, CHARM, IRRAD and GIF++, which are used for measurements of irradiation hardness of different types of materials, electronics or detectors.
3. The **test beams,** used for prototype tests and calibration of detectors, e.g. for LHC, linear colliders, space & balloon experiments. These are also utilized for outreach purposes (e.g. within the Beamlines for Schools programme). Users of the test beams usually require a large spectrum of beam conditions within a few days.

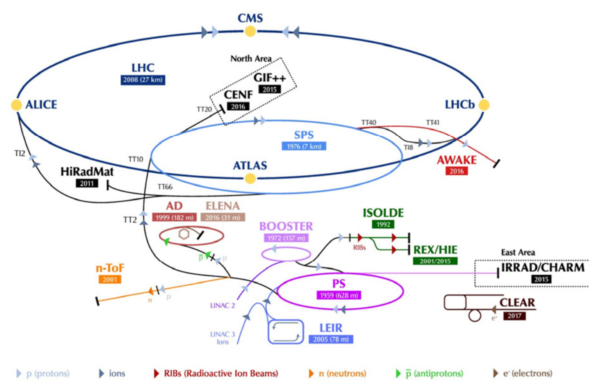

Figure 1: CERN accelerator complex scheme.

Requirements on the Software for the Beam Simulation and Beam Line Control

The group is responsible for a wide spectrum of beam lines mentioned above, which sets broad requirements on the software which is used to describe the beam lines, simulate beams, control beam line elements and read out beam instrumentation data. The ideal set of software has to be able to provide its users with the computation of the particle production at the targets and be able to simulate the beam optics properties (such as momentum selection, transverse beam parameters, beam intensity, particle type etc.) along the beam line. In addition it must provide input (if necessary, via a suitable interface) for other groups at CERN dealing with e.g. radiation protection, civil engineering, ventilation, survey and metrology and material survival studies. Finally, it has to be able to control the beam line elements with the aim that the envisaged beam properties can be achieved, measured and verified.

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SOFTWARE MIGRATION

Current Status

Since no single existing software program is capable of covering the full range of requirements listed above, the description and control over the beam lines can only be achieved by a set of several software codes. Currently, four major programs are used for this purpose. These have been developed in the 1980's in Fortran and use card based input (see the example in Fig. 2).

```
"P42 TRANSPORT FROM T4 TO T10"
100
15.0  1.0 "MM" 0.1   ;
15.0  9.0 "KG" 0.994 ;
13.0  18.0 ;
13.0  19.0 ;
13.0  41.0  ;
1.0  1.0  0.6  1.0  0.6  0.0  0.2  447.3  ;
3.0  0.0  "T4"  ;
3.0  1.35   ;
2.0  0.000 ;  4.0  3.6  2.919  0.0  "B1" ;  2.0  0.040 ;
3.0  0.6 ;
2.0 -0.040 ;  4.0  3.6  2.919  0.0  "B1" ;  2.0  0.080 ;
3.0  8.05    ;
3.0  1.615  "TAX7" ;
3.0  0.01  ;
3.0  1.615  "TAX8" ;
3.0  0.41   ;
2.0 -0.040 ;  4.0  3.2  -6.567  0.0  "B2" ;  2.0 -0.040 ;
3.0  3.78 ;
2.0 -0.080 ;  4.0  3.2 -13.134  0.0  "B3" ;  2.0 -0.080 ;
3.0  0.39   ;
```

Figure 2: Card based input illustrated from the example of the Transport input code for the P42 beam line in the CERN North Area.

They now are compiled for a Linux operating system and are executed on the CERN LXPLUS cluster.

- BEATCH [1] is used to generate coordinates of beam line elements for their installation and alignment. The EN-EA group is now the last active user of this code at CERN.
- TRANSPORT [2] is a matrix based tool for beam optics calculations. It performs calculations of the transfer matrix parameters and beam size up to third order and can also perform matching (which only reliably delivers useful results for first order calculations).
- TURTLE [3] is a particle-tracking tool, which includes total absorption at collimators and at magnet apertures, particle decay, calculate transmission and particle distributions (X, X', Y, Y', $\Delta p/p$). It is convenient to use in parallel with TRANSPORT, since these two codes have almost identical input formats.
- HALO [4] is a Monte-Carlo simulation software for muon tracking, which tracks parent particles (π, K) and their decay products (μ, ν).

There is also a set of auxiliary tools made specifically by the EN-EA group, such as

- Beamplt, which produces a simple graphical output of the optics, based on Transport output.
- Beamopt, a more sophisticated version of Beamplt, which compares output of TRANSPORT and BEATCH, produces the graphical output of the beam line with the correct apertures and element names as well as calculates the maximal transverse and longitudinal beam line acceptance.
- BLI, which is used to calculate the electrical current needed in a specific magnet to achieve a given integrated magnetic field or integrated gradient.

These software codes are, however, limited in their functionality, have small user communities and currently have to be maintained within the EN-EA group, requiring dedicated time, effort and know-how.

New Software Codes for Beam Simulations

The purpose of the software migration project is to change the set of routinely used software programs to the new ones, fulfilling following conditions:

- The new set of software programs covers at least the same functionality as the previous set.
- There is a support team (outside of EA group) responsible for maintenance and upgrades of the new software, preferably based at CERN.
- There is a large user community for the software, preferably also at CERN.
- The software can serve as (or must have an) interface to other groups at CERN. One has to consider that:
    - The most common tool used for the description of beam optics at the PS and SPS rings (including their extracted primary lines) is MADX [5].
    - The most common tool used by the radiation protection group as well as for target and collimator material studies is FLUKA [6] [7].

Software Infrastructure

The **Layout database** is a CERN-wide database **[8]**, designed to contain for all CERN beam lines the integration and installation drawings, a naming portal, photographs of the beam lines, tunnels, areas, as well as tables with all parameters relevant for the beam line description (see Fig. 3). The beam lines managed by the Experimental Areas group will be included in the database in the framework of the software migration project. It is foreseen to import beam line parameters such as magnet names, magnetic lengths, apertures, B→I curves and others from the CESAR database (see next chapter) into the layout database. It is also planned to use the already existing function of automatic generation of MADX input files from the layout database. This application takes various parameters from the database, which are required to construct the MADX input and creates the sequence file for any beam line.

In order to have advanced flexibility, the GitLab **[9]** platform is used to store the strength parameters for each magnet. These two separated information sources (Layout database and GitLab repository) allow the user to select a beam line and if necessary to create several MADX input files with distinct beam optics settings.

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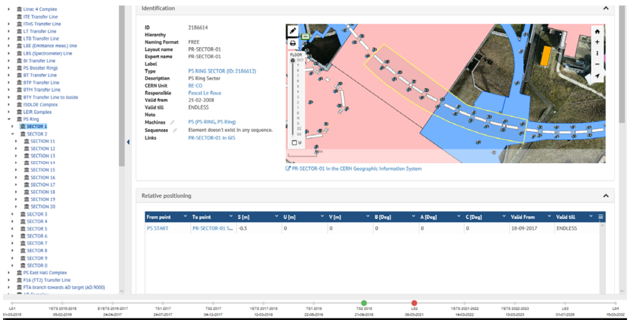

Figure 3: Example of the layout database website open in an internet browser.

GitLab is an online repository for code and files, which is frequently used for software development **[9]**. It includes version management, allowing several project participants to edit files, which can be later merged by the folder owner. It provides access to the released (stable) versions of the software as well as to the working versions. Older versions can be viewed and recovered if necessary, which also secures a convenient back-up for files and code. Within the EA group, it is envisaged to store and edit on GitLab beam optics and other simulation input/output files for all currently existing and also proposed future beam lines. The descriptions of the beam lines will include the lists of responsible persons (beam physicists, engineers in charge, etc.), important links, user guides, tuning procedures etc.

MADX

MADX is a commonly used optics software, at CERN and worldwide [5]. It has a C++ style input, which as opposed to the TRANSPORT code described above allows calculations to be included in the definition of the variables. Its functionality includes calculations, matching and output of the transfer matrix along the beam, which is usually used for the description of the secondary beam lines. It also provides basic tracking possibilities similar to the TURTLE code, in which beam-matter interaction is not simulated, but the particles are simply absorbed when they reach a collimator yoke or a magnet aperture.

MADX is also capable of generating survey file output [10], which can be later used by the metrology team at CERN for the alignment of the beam line elements.

The functionality described above makes MADX a feasible substitute for BEATCH, TRANSPORT and TURTLE at the same time.

To complement the standard MADX graphical output, a dedicated graphical output tool is under development within the EA group. It is designed to use the MADX Twiss file output to produce a figure with the relevant optics parameters along the beam line. The figure includes information on magnet apertures, collimators and vacuum pipes and displays the beam line element names (see Fig. 4).

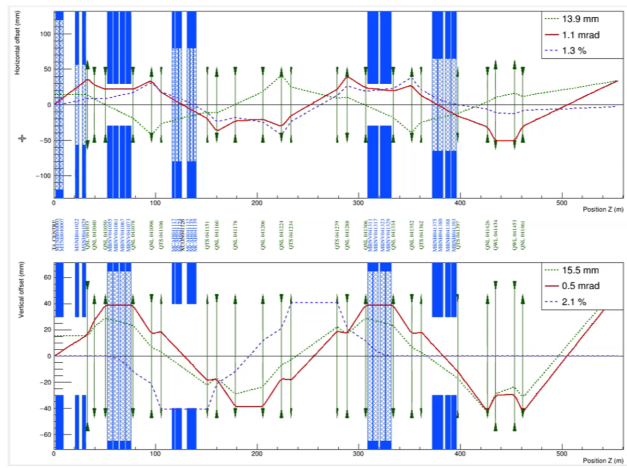

Figure 4: Output of the graphical tool on the example of the H6 beam line of CERN North Area. The trajectories of the particles with a particular position offset (green), angle offset (red) and momentum offset (blue) is represented as a function of the location along the beam line.

The tool is also capable of calculating the maximal transverse and longitudinal beam line acceptance and of performing matching of the quadrupole settings in order to achieve the required beam parameters. It also performs tracking, similarly to MADX, and can calculate the beam transmission through any segment of the beam line. Currently the tool is being rewritten from C++ code into Python in order to make it platform and operating system independent. It is the only tool envisaged for use after migration, which has been developed within the group and will have to be maintained locally.

Simulation of the Beam-matter Interaction

FLUKA is a FORTRAN based tool for the beam matter interaction with a large user community and strong support at CERN [6] [7]. The software has been used for decades and is well calibrated, using existing measured data. A graphical user interface, named Flair, makes the input definition more convenient for the users. FLUKA also has a specific Line Builder tool for beam line design, which was initially developed for the studies of losses in the LHC accelerator and its collimation, but can be also used for the design of other beam lines.

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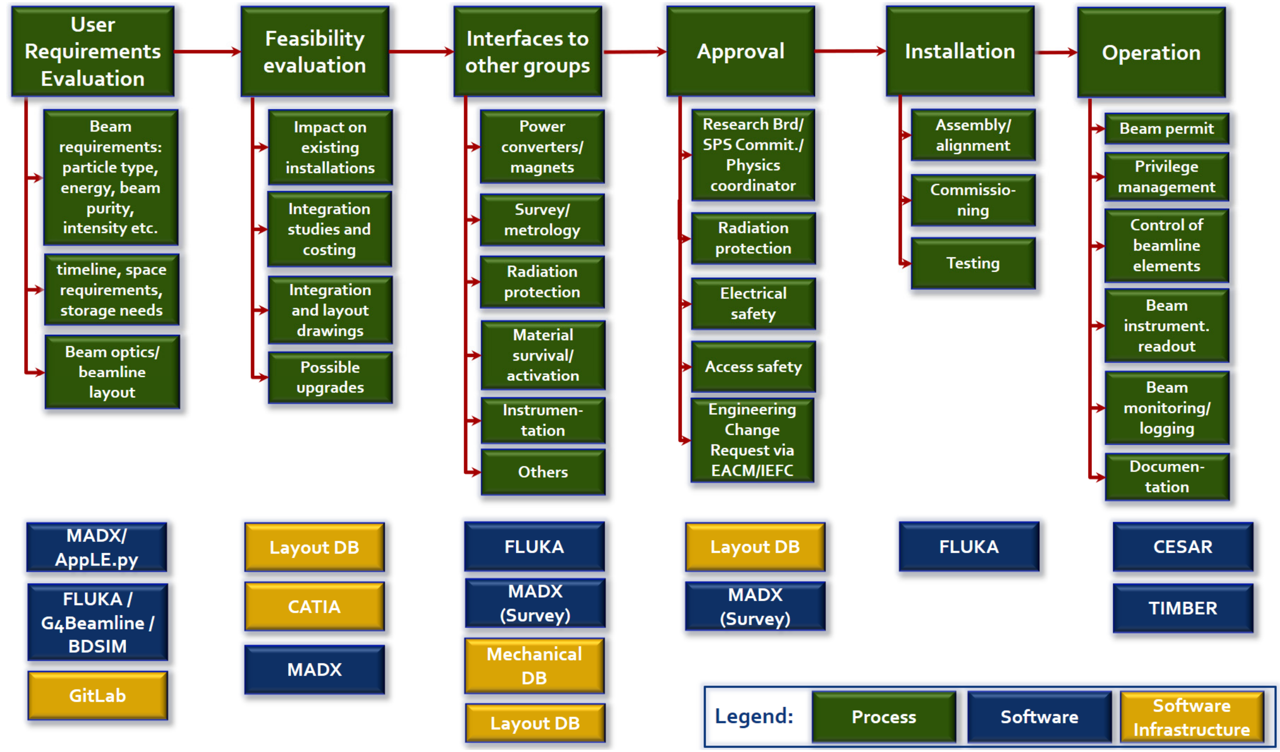

Figure 5: Workflow diagram for the activities of the Experimental Areas group and the respective software codes used in these activities.

G4Beamline [11] is a software code for the beam line design, based on Geant4 **[12]**, to simulate beam-matter interaction. Geant4 is a popular open source software, heavily used mainly in the detector development community.

BDSIM [13] is another Geant4-based software for beam line design. While having a smaller world-wide user community than G4Beamline, it has a local support at CERN and has the technical advantage of being able to use the use MADX Twiss output files for a comparably easy generation of the BDSIM input files.

Fig. 5 depicts the typical workflow of Experimental Areas group for the set-up and operation of a new experiment. The software codes and infrastructure envisaged to be utilized of the workflow are displayed below the respective steps.

CONTROL SYSTEM SOFTWARE

CESAR

CESAR is a client-server control system for the beam lines of the PS and SPS experimental areas, used by beam physicists, operators and user teams of the experimental areas [14] [15]. Apart from controlling 30 different types of hardware, CESAR is used for viewing, controlling and managing the beam line settings (magnets, collimators, scintillators, obstacles, etc.).

Technically, CESAR is a three-tier application with many GUIs, a J2EE server and front-end computers (see Fig. 6). CESAR communicates with the different types of hardware by subscribing to the corresponding FESA (Front-End Software Architecture) class [16]. FESA classes are developed by equipment experts to control most of the elements in the beam lines. The equipment addresses are stored in the CESAR Data Base, which is designed for convenient modification of its elements in order to keep up with the frequent physical changes of the beam line elements in the secondary beam lines.

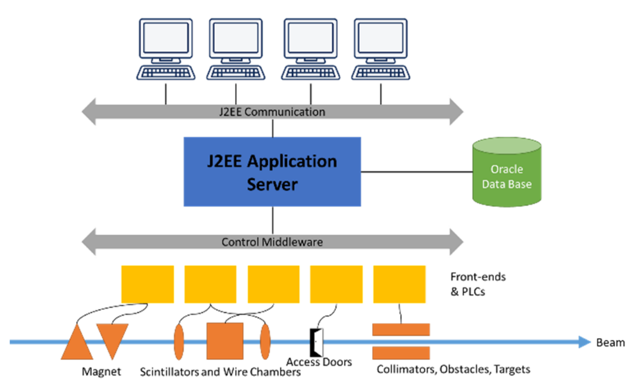

Figure 6: Schematic representation of CESAR functionality

Via the CESAR GUI (see Fig. 7) the physicists and operators can view equipment readings and control the beam line elements from the CERN control centre and user control rooms. Beams can be tuned by controlling magnets, collimators and other equipment. There is also the possibility to view the beam profile and intensity with help of beam instrumentation devices, such as wire chambers, scintillating counters and ionisation chambers. The aforementioned

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elements are of several different types, and hence have different FESA classes for data acquisition and control. However, as an example, in CESAR a regrouping of the different profile types in a single window has been implemented. These are ordered along the beam path in the beam line.

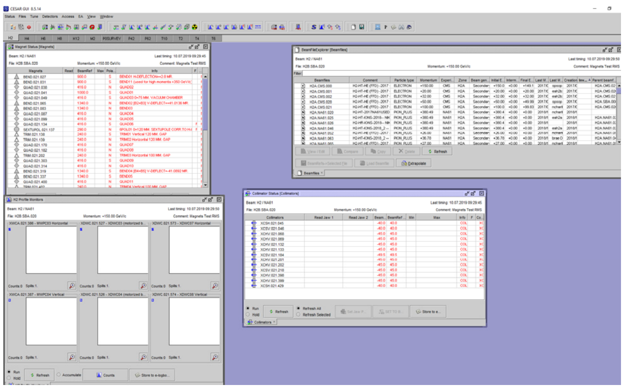

Figure 7: Window with CESAR GUI.

At the end of the tuning, the expert or user can save the configuration into a beam file. If the users prefer to use different beam configurations (energy, particles, intensity...) than the one currently loaded, they can do so with help of a control computer in the counting room by loading the corresponding beam file. The users have also the possibility to modify most of the settings for their beam line and can request to access the experimental zone in which their experiment is installed. When they initiate the procedure to open the zone, CESAR communicates with the access safety elements and switches them into safe position. Once the procedure is finished, CESAR verifies with the access system that the conditions for access have been granted.

In summary, CESAR is a highly integrated tool that allows its users to have full information and control of the beam. In long term several new applications can be included into it, which would make the use of CESAR software even more convenient for the beam physicists, operators and the users.

Coupling of CESAR with MADX

It is foreseen to couple the CESAR control system with the MADX software described above. With a comparably limited effort an application will be developed that creates a beam file directly from a MADX Twiss output file. CESAR will read the Twiss file and find inside its own database (to be updated on a weekly basis from the central CERN layout database) the corresponding magnet and the associated currents for setting up the required beam optics in the beam line. CESAR would also need to check if there is no missing information and if all the elements from the MADX output file are present in the CESAR database. It is also possible to implement for every beam file a display of its MADX graphical output within the CESAR GUI window.

In the longer term an application for creating the MADX input files using the CESAR database can be developed. The database contains a table, in which most of the magnet types used for beam line are listed. The beam physicist can add magnets and other beam elements one by one, enter the position, the magnet strength ("k-values") and other relevant parameters for each magnet (see Fig. 8). New magnet types can be created within this application in case they are not yet available in the table. At the end the beam physicist can save the generated beam line as an input file for MADX software.

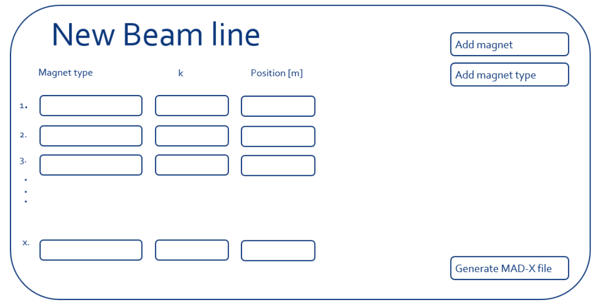

Figure 8: Simplified proposal for the window of beam line generator application.

SUMMARY AND OUTLOOK

The software codes currently used by the EA group for the description of the beam lines are obsolete and it is difficult and resource consuming to secure a long term support for those. Hence, a migration to new software codes is currently undertaken.

The functional requirements for new software codes have been defined and a set of software suites fulfilling these requirements has been identified. The project of the EA software migration is well under way and is scheduled to finish before the end of LS2, i.e. early in 2021.

The CESAR control system will continue to be the control system of choice for the experimental area beam lines. A link between the CESAR control software and the beam optics code MADX will allow for many useful tools and applications, e.g. the possibility to compile MADX files from CESAR or to construct/modify the beam lines, as well as for creating a live beam optics display or automated beam tuning within the same control system window.

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