IMPROVING BEAM SET-UP USING AN ONLINE BEAM OPTICS TOOL

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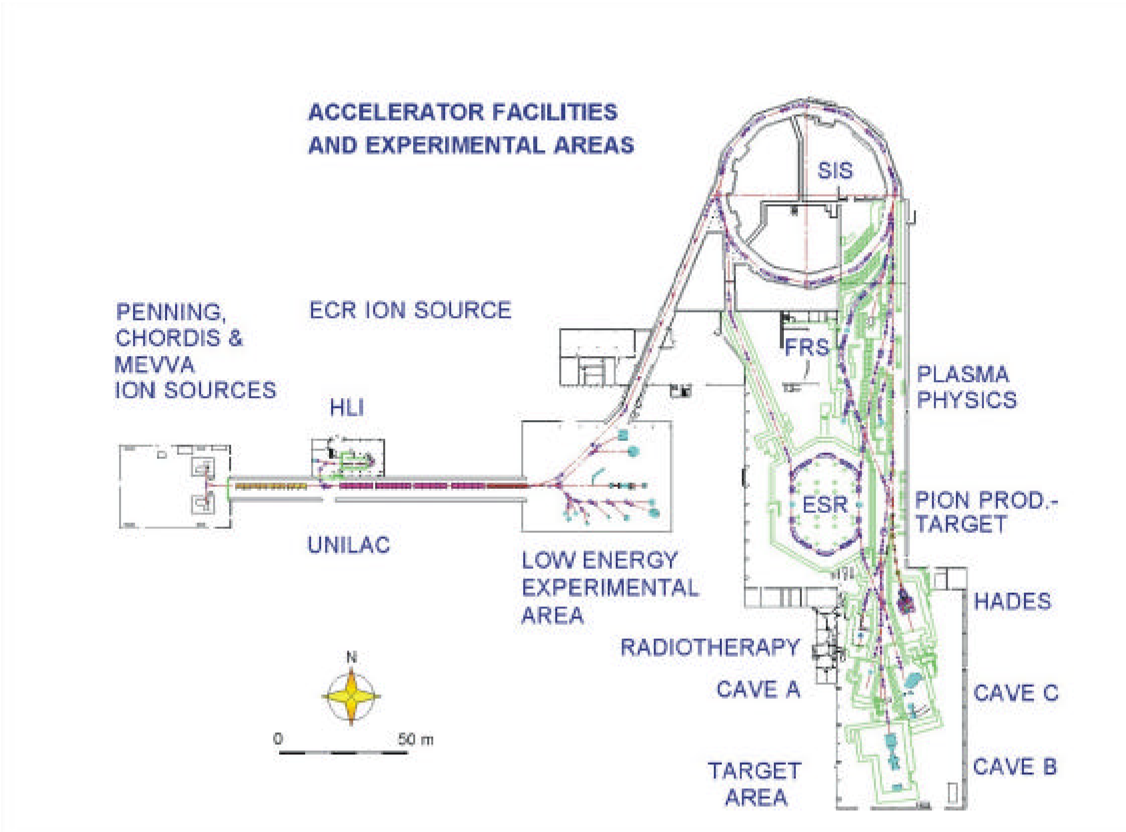

Fig. 1: Layout of the existing accelerator facility at GSI. The universal linear accelerator Unilac, the heavy ion synchrotron SIS and the Experimental Storage Ring ESR. The Unilac delivers from three sources heavy ion beams with energies of up to 13 MeV/u, the SIS accelerates ion beams to up to 2 GeV/u.

Abstract

The GSI accelerator facility [1] consists of the Universal Linear Accelerator (Unilac), the heavy ion synchrotron SIS, and the Experimental Storage Ring (ESR). Two Unilac injectors with three ion source terminals provide ion species from the lightest such as hydrogen up to uranium. The High Current Injector (HSI) for low charge state ion beams provides mostly high intense but short pulses, whereas the High Charge State Injector (HLI) supplies long pulses with a high duty factor of up to 27%. Before entering the Alvarez section of the Unilac the ion beam from the HSI is stripped in a supersonic gas jet.

Up to three different ion species can be accelerated for up to five experiments in a time-sharing mode. Frequent changes of beam energy and intensity during a single beam time period may result in time consuming set-up and tuning especially of the beam transport lines. To shorten these changeover times an online optics tool (MIRKO EXPERT) had been developed. Based on online emittance measurements at well-defined locations the beam envelopes are calculated using the actual magnet settings. With this input improved calculated magnet settings can be directly sent to the magnet power supplies. The program reads profile grid measurements, such that an automized beam alignment is established and that steering times are minimized. Experiences on this tool will be reported. At the Unilac a special focus is put on high current operation with short but intense beam pulses. Limitations like missing non-destructive beam diagnostics, insufficient longitudinal beam matching, and influence of the hard edged model for magnetic fields will be discussed. Special attention will be put on the limits due to high current effects with bunched beams.

1 GSI ACCELERATOR COMPLEX

The GSI accelerator facility (shown in Fig. 1) consists of the Unilac (Universal linear accelerator), the Heavy Ion Synchrotron SIS, the Experimental Storage Ring ESR, and various experimental set-ups for low energy experiments in the experimental hall (4 – 13 MeV/u) and in the High Energy Physics Area (100-2000 MeV/u).

The Unilac accelerates the full range of ion species from hydrogen up to uranium. With three ion source terminals (PIG , and high current operation sources MEVVA and MUCIS at the High Current Injector HSI, and the ECR ion source at the High Charge State Injector HLI) a three beam operation is accomplished. The three ion beams are further accelerated to individual energies in the Alvarez section in a pulse-switched mode, either for injection into the SIS, or for low energy experiments downstream from the Unilac. This mu lti-beam operation is shown exemplarily in Fig. 2. The administration of the different ion beams is done in so called virtual accelerators (up to 14 at Unilac and 14 at SIS). These accelerators are treated by the control system as independent accelerators.

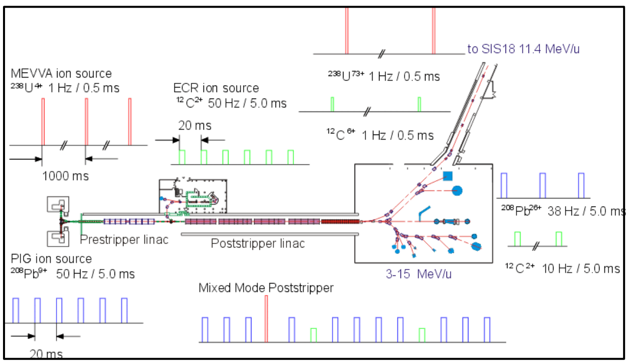

Fig. 2: Multi beam operation at the Unilac. On the left side the pulse structure of the MEVVA and the PIG ion source are indicated, running for the prestripper linac, showing different repetition frequencies and duty cycles. The ECR ion source is operated with a third ion species, carbon, which is also operated with high duty cycle. The different beams are switched into the Unilac experimental hall and into the SIS injection line following the requests of the experiments.

The SIS further accelerates the ions provided by the Unilac with an energy of 11.4 MeV/u up to 2 GeV/u. It can be operated at maximum magnetic bending power up of to 18 Tm with a ramp rate of 1,3 T/s. The beam can either be extracted fast or slow from pulse to pulse. Like at the Unilac, the energy, intensity and ion species can also be changed from pulse to pulse.

2 MIRKO -- INTRODUCTION

At GSI the program MIRKO [3] was developed originally to support beam-line-design and the analysis of 1. order beam-dynamics. The following key-features are implemented:

- Various beam transport elements
- Multipole approximation through thin lenses
- Misalignments
- Arbitrary matrices

The code is based on the matrix formalism (6x6 matrices) to describe the beam as well as the optical elements. Space charge effects can be simulated by the introduction of thin lenses which have a defocusing effect.

Alternatively the user can switch between the ellipse transformation notation and single particle tracing calculations. Up to six parameters of the optical system can be defined as variables to meet fitting constraints.

The input parameters are the beam-line (the optics system), and the characteristics of the ion beam, such as mass number, charge, beam energy and emittance.

Additionally to the output of beam parameters at any desired position in the beam transport system, MIRKO also delivers graphical output. The beam envelopes in the transverse or longitudinal plane can be displayed as well as the phase space ellipse or the acceptance of the system. To simulate the behavior of a particle distribution through a non-linear system, different particle distributions can be generated and transported through the system in the single particle mode.

3 MIRKO EXPERT

With frequent changes of ion species and energy – sometimes several times a week – the beam-line set-up and tuning is elaborate (not possible) without a qualified operating tool assisting these tasks. Since the design and tuning of a beam–line comprise many features in common, the transition and development from MIRKO as a standalone design tool towards an operating tool - MIRKO EXPERT - was the consequent step (Fig. 3).

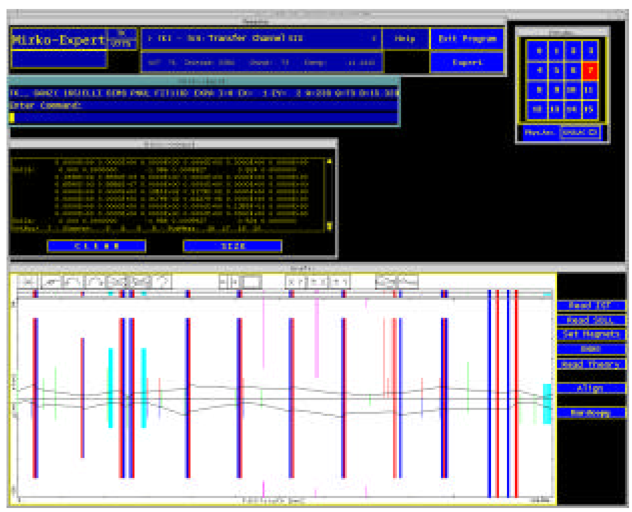

Fig. 3: Screenshot of MIRKO EXPERT. The selection of the accelerator (Unilac or SIS), the virtual accelerator number and the beam-line part is needed to start with MIRKO EXPERT. A graphical output window starts up, where the beam-line together with the transverse beam envelope is displayed.

This tool is integrated into the control system of the GSI accelerator complex. The operators can access MIRKO EXPERT out of their console environment. When it starts the *operation mode* is default. There is no command line interface present. All required input parameters are accessible via mouse clicks. To make use of the full complexity of MIRKO EXPERT an *expert mode* with an additional command line interface is accessible. MIRKO EXPERT can be used to tune any of the virtual accelerators independently.

3.1 Integration into the Control System

MIRKO EXPERT has access to different components of the controls. When a virtual accelerator is selected, the program has read access to the database that administrates the different virtual accelerators and gets the information about the ion species, charge state, energy and source and respectively target of the beam. To get the missing beam-line data from the actual setting, the values of the magnet settings are read out. To set the changed values resulting from calculation, MIRKO EXPERT also has write access to any magnet in the selected beam-line. The translation between the physical values – focusing values (focal values) – and the manipulated variables which a power supply can process is supported by function calls the control system supplies. Additionally, read access to profile grid measurements is granted. Implemented as console program, no authorization mechanisms are included.

3.2 Scope of MIRKO EXPERT

To assist the operators in beam-line set-up and tuning, MIRKO EXPERT is used in beam transport lines such as the transport lines into the experimental hall, the Transfer Channel to the SIS and the high energy transport lines.

It gives support to tune the beam-lines and to achieve certain conditions at well defined positions (e.g. focus on target). In the Unilac accelerating sections semi-empirical settings are used for the periodic focusing in the rf tanks, since MIRKO EXPERT does not yet cover sufficiently the various accelerating elements in a linac. To tune the synchrotron, MIRKO (as beam optics tool) is implemented in the optics model for the data supply, so that there is no need to use MIRKO EXPERT for that task.

Unilac

The use of MIRKO EXPERT at the Unilac is limited to beam transport sections in the experimental hall and the Transfer Channel. As input for the calculations the information about the emittance size and orientation is needed. This data is obtained either by emittance measurements with slit-grid devices or by the measurement of at least three profile grids.

One beam-line in the experimental hall is equipped with octupoles [4] which require a careful preparation of the beam to show the desired effect. MIRKO EXPERT is essential to set-up this beam-line. In the Transfer Channel beam-line MIRKO EXPERT supports the use of collimators to cut off the emittance to adjust the beam for SIS injection.

High Energy Beam-Lines

The assistance of MIRKO EXPERT in the High Energy Beam-Lines is widely used by operators and by the experimentalists. The assumption that the orientation of the phase space ellipse is well known after SIS extraction is used to deduce standard input parameters for calculations. The emittance size is not measured directly, since the information obtained about the beam size (read-out from profile-grids) is sufficient to have an adequate description of the beam in MIRKO EXPERT being very close to the actual beam size in the machine.

3.3 Beam Alignment

Beam alignment is a typical example for the application of MIRKO EXPERT. The following figure displays in a sequence the different steps, the operator has to perform in order to align the beam as best as possible.

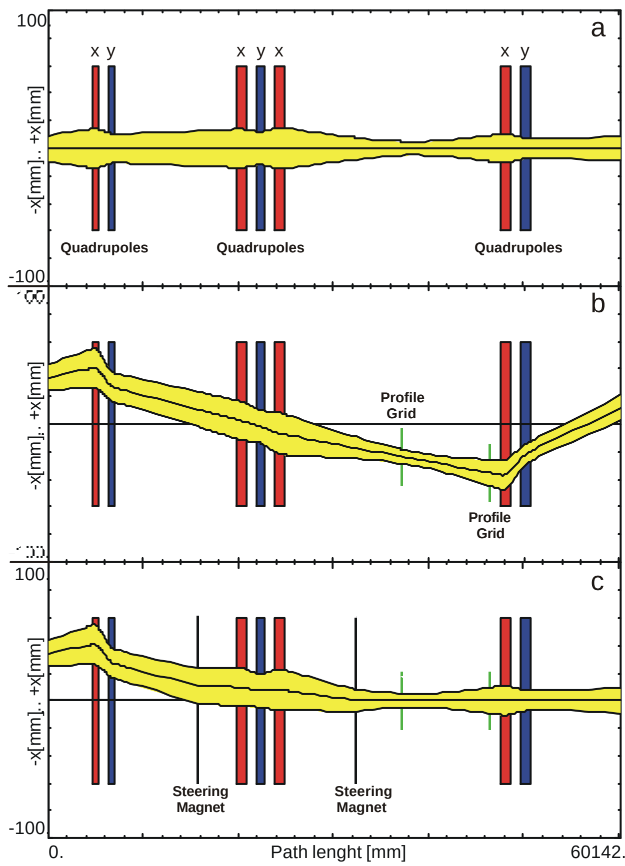

Fig. 4: Screenshots taken during the beam alignment procedure. Only the graphical output for the horizontal beam envelope is shown. See text for explanation.

Part (a) shows the result of the envelope determination with actual magnet settings. No information about eventual misalignment is included yet. Measurements with profile grids provide the information about the misalignment. Then MIRKO EXPERT calculates the actual beam envelopes and beam steering (b). An automized beam alignment can be used now. A predefined correlation between profile grids and steering magnets is used to calculate the steering magnet settings and to align the beam. An example of this correlation is shown in the following figure.

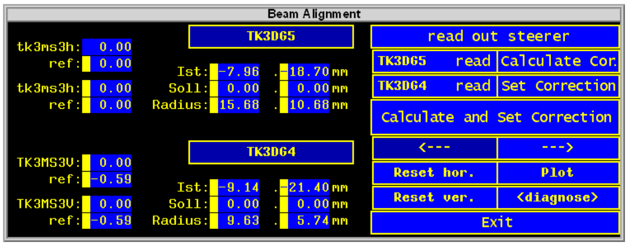

Fig. 5: Screenshot of the beam alignment window.

The underlying basic calculation algorithm is the solution of two differential equations. The matrix elements from the beginning of the system to the first resp. second profile grid are known. With the information about the misalignment a backward calculation is performed.

$$X_1 = A_1 x_0 + B_1 x_0'$$
$$X_2 = A_2 x_0 + B_2 x_0'$$

After that automatic procedure of which the result is shown in part (c) of Fig. 4, the beam is aligned. Sometimes this procedure must be repeated once or twice. This is due to the inaccuracy of the profile grid measurements. If the beam is far off axis the beam center can not be determined with adequate accuracy. This uncertainty can be due to the fact that the beam may be wider than the profile grid or the calculation of the center of mass is inaccurate because the wire distance of the outer wires is larger. The measurement gets more accurate if the beam is near the axis.

4 LIMITATIONS OF MIRKO EXPERT

This paragraph focuses on the limitations of MIRKO EXPERT in daily operation and in the high current operation for the future project.

4.1 Operation at the Unilac

As the transverse emittance size and - orientation of UNILAC beams cannot be treated as a constant as after SIS extraction, a measurement must precede all calculations. These measurements are beam destructive, that do not just disturb one beam in one virtual accelerator but also the beam in all other virtual accelerators. For a machine that is characterized by its high grade of parallel operation, this condition should be avoided.

Since emittance growth is not covered in MIRKO, its use is limited to support the beam matching between the pre- and the poststripper section. The HSI operates with a frequency of 36 MHz whereas the Alvarez with 108 MHz. This source of emittance growth due to bunch compression cannot be handled adequately for the time being. As a partly solution to that problem an insert of a matrix that blows up the emittance by a fixed factor could be seen as a workaround.

4.2 High intensity operation at the Unilac

The Unilac was not originally designed as an injector for a synchrotron, filling the SIS up to the space charge limit even for the highest mass numbers. The HSI commissioned in 1999 was designed to provide an intensity increase by 2.5 orders of magnitude. Table 1 summarizes the design parameters for high intense uranium operation [5].

With the introduction of high current operation, the way and the means how to operate and to handle those beams had to be modified compared to the operation with low and medium intense beams. Beam destructive diagnostics cannot be used under these conditions. With the immense power that is stored in the beam, the diagnostics elements could be destroyed within a macro pulse of 150 µs with full intensity. To avoid destruction, the pulse is shortened. Providing incomplete information about the beam being not representative for the whole beam.

Table 1: Specified beam parameters at UNILAC and SIS injection, exemplary for a uranium beam.

	HSI entrance	HSI exit	Alvarez entrance	SIS injection
Ion species	$^{238}U^{4+}$	$^{238}U^{4+}$	$^{238}U^{28+}$	$^{238}U^{73+}$
El. Current [mA]	16.5	15	12.5	4.6
Part. per 100µs pulse	$2.6\cdot10^{12}$	$2.3\cdot10^{12}$	$2.8\cdot10^{11}$	$4.2\cdot10^{10}$
Energy [MeV/u]	0.0022	1.4	1.4	11.4
$\Delta W/W$	-	$\pm4\cdot10^{-3}$	$\pm2\cdot10^{-3}$	$\pm2\cdot10^{-3}$
$\varepsilon_{n,x}$ [mm mrad]	0.3	0.5	0.75	0.8
$\varepsilon_{n,y}$ [mm mrad]	0.3	0.5	0.75	2.5

Additionally the handling of space charge effects is not considered as adequate any more, the assumption of faultless magnetic fields must be dropped. If the envisaged high intensities are reached, the physics model behind MIRKO with its linear space charge model has to be revised in order to provide the required accuracy to serve as an online tool or if multi-particle tracking codes have to be used instead.

5 CONCLUSION AND OUTLOOK

MIRKO EXPERT has proven to be a valuable tool for beam-line set-up and tuning in many transport sections of the GSI accelerator facility. This time consuming task was reduced significantly employing the code. For the standard high current operation envisaged for the future project, the use of MIRKO EXPERT has to be revised. The use of a complementary multi-particle code must be considered. If such a tracking program will be developed as an operations tool or if it will be an offline tuning aid, must still be discussed.

6 ACKNOWLEDGEMENTS

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