AN OPTIMIZER FOR HIGH-CURRENT BEAMLINES

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Abstract

A novel approach to the problem of beamlines development for high-current electron beam is put forward. Transient electron beam is considered as a set of independent stationary beams with different currents, energies, and initial conditions. In such a way, the overall acceptance of a beamline can be maximized effectively on some conditions and the loss can be predicted well. The simulation code implemented this approach is described. Some examples of existing and designed beamlines are presented.

THE GOAL

The optimizer is intended for designing or adjustment of a beamline carrying high-current transient electron beam. Additional conditions, such as η, η' [1], rms-size and divergence at the exit can be set. Although a number of numerical simulators already exist, no one fits to the problem set. The matter is (i) it seems to be impossible to optimize anything manually if the number of controlled parameters exceeds, say, five, and (ii) the parameters of the beam at the entrance are usually known only very inaccurately. Thus, an optimizer is to minimize the loss of beam in a beamline, be very time-efficient, take into account main effects, but mustn't be very precise.

THE METHOD

Let's find an appropriate model for the problem. It should take into account main effects in high-current beam and be computation conserving. It mustn't be too accurate, as the initial conditions aren't known well.

Basic Parametric Models

An uncharged linear model [1] considers sin- and cos-like trajectories of particles in a beamline

$$\begin{Bmatrix} C & S & D \\ C' & S' & D' \\ 0 & 0 & 1 \end{Bmatrix}, \qquad \frac{C''}{S''} = -\frac{e}{p} G \frac{C}{S}, \quad D'' = \frac{1}{\rho} - \frac{e}{p} GD, \tag{1}$$

where second derivative is taken by the longitudinal coordinate z. Twiss parameters of the beam are converted with the obtained matrix. There is no way to take into account space charge force in this case.

KV-approach [2] considers charged beam with special distribution in phase space. Due to that, the type of distribution is preserved, and one can derive ordinary differential equations (ODE) for its parameters (for rms-values here):

$$\begin{cases} x'' = \dfrac{\varepsilon_x^2}{x^3} + \dfrac{I}{I_0(\beta\gamma)^3}\dfrac{1}{x+y} - \dfrac{e}{p} G_x x, \\ y'' = \dfrac{\varepsilon_y^2}{y^3} + \dfrac{I}{I_0(\beta\gamma)^3}\dfrac{1}{x+y} - \dfrac{e}{p} G_y y, \end{cases} \tag{2}$$

where x and y mean horizontal and vertical coordinates respectively. Emittance is ever preserved and included as a "force-like" term in each right part. The ratio of the second term to the first one gives a criterion of high-current beam. Only if it's << 1, space charge effect can be neglected. Really, another criterion is typically much stronger (something like betatron phase):

$$\int_L \sqrt{\frac{I}{I_0(\beta\gamma)^3}\frac{1}{(x+y)(x \text{ or } y)}}\,dz << 1, \tag{3}$$

where L is the total length of the beamline. If only the second criterion is not valid, space charge effect can be considered as a small tare.

Proposed Model

Transient charged beam is considered as a set of independent stationary charged beams (partial beams) with different currents and initial conditions, including energies. Each one has zero emittance and uniform distribution of charge within some ellipse in *xy*-plane. In *xx*' and *yy*' phase spaces it looks as a line segment with the middle at the point of origin. The rms-sizes of each one are given by KV equations (2) without the emittance term.

Passing through a limited aperture each partial beam can loose some part of particles depending on the oversize, that is the ratio of its current diameter to the aperture. The final oversize at the end is the maximum of local oversize values. The total loss is approximated as

$$Loss = \sum_i Weight_i \left(1 - 1/Oversize_i\right), \tag{4}$$

where $Weight_i$ and $Ovrsize_i$ are the weight coefficient (proportional to the carrying current) and the final oversize of a partial beam respectively, independently for x and y.

The goal function to be minimized is taken as

$$\sum_i \cosh\sqrt{2}\,\frac{\xi_i - \xi_0^i}{\Delta\xi_i} \tag{5}$$

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where ξ_i is the obtained parameter, ξ^i_0 is the desirable one, and $\Delta\xi_i$ is the admitted accuracy. Thus, the strongest effect in transient beam is considered, while others are neglected. The latter are microscopic emittance and non-uniform distribution of particles in each cross-section.

The Code

The optimizer code consists of three parts: a beamline editor, a line geometry builder, and an optimizer itself. The beamline editor is destined to insert a beamline element by element and edit it. It supports quadrupoles, solenoids, and bending magnets including distributed ones. Step-like and linearly changed apertures are available. The geometry builder shows the trajectory in the inserted beamline and all the elements and apertures along it.

The optimizer receives the inserted beamline and optimizes the chosen elements to minimize the goal function. One is to set the optimized elements, the initial parameters, and the goal ones. The latter can include emittance and current at the entrance, η, η', rms-size and divergence at the exit, and ever includes loss. The initial parameters are current, energy, energy spread, η, η', rms-size and divergence at the entrance.

BEAMLINES OPTIMIZED

Injection Beamline at KAERI

The beamline [3] is intended to transport electron beam from an injector to a superconducting RF-cavity. Its regular aperture is 100 mm. Its basic parameters are placed in Table 1. The operation mode is continuous.

Table 1: Beamline at KAERI

Kinetic energy of electrons, MeV	1.5
Peak current, A	20
Average current, mA	up to 10
Initial emittance, π mm·mrad	10
Energy spread, relative	$3 \cdot 10^{-3}$
Acceptance at 4% loss, π mm·mrad	15.5

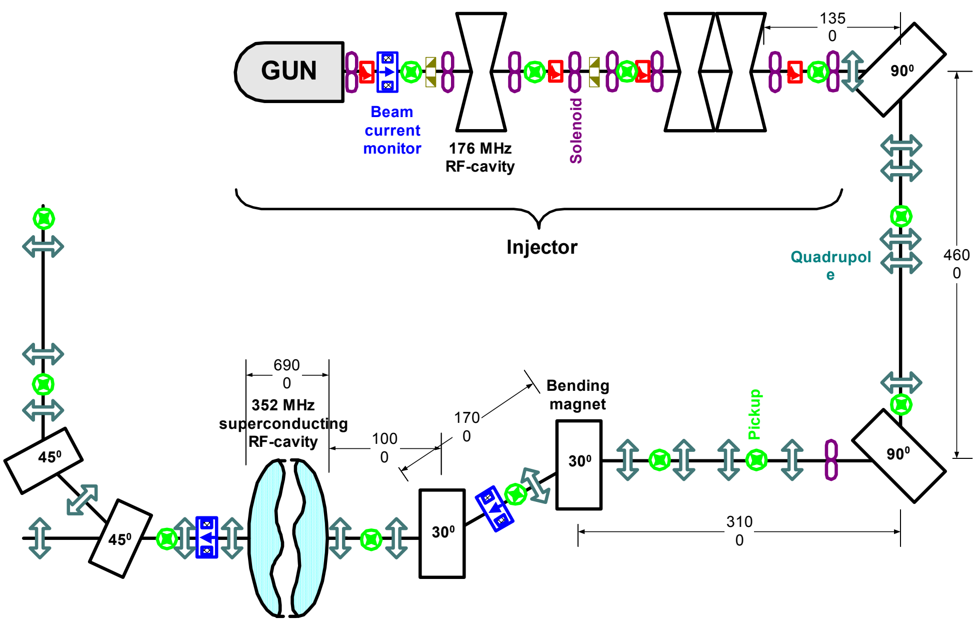

Figure 1: Injection beamline at KAERI.

Originally it was designed using the uncharged linear model. During its commissioning, it turned out that none of found in such a way regimes could be used due to great loss in the beamline. It is not surprising as for typical radius 3 mm, both terms in (2) are $\sim 3\cdot10^{-3}$ m^{-1}. Simulations according to KV-approach permitted to find manually new regimes that could be used as initial approximation. After lengthy manual adjustment, acceptable loss was obtained. Nevertheless, significant discrepancy between the regimes installed and ones after manual adjustment ever occurred. After that, the beamline was optimized with the described code, the regime found was installed, and further adjustment included only the first three lenses and the last two, that is only ones laying outside the bends. Thus they didn't affect the chromatism of the beamline. The total loss ≈ 3% was easily obtained.

Beamline for Beam Splitting into Three Targets

The beamline is destined to split a short train of electron bunches (≈ 200 ns) into three shorter ones and transport them to three separate bremsstrahlung converters. Thus one obtains three X-ray sources flashing almost simultaneously. This is a prototype of a future diagnostic device. Its operation mode is one pulse for a long time. The injector of BINP FEL [4] is used as a beam source. It's very similar to one at KAERI.

The beamline was designed using the described code. The regular aperture was chosen as 40 mm. Additional conditions were (i) achromatism of each branch and (ii) small sizes of the spots on the converters. It's found, that this beamline has ≈ 1.2 times worse acceptance than one at KAERI, or 1.5 times greater loss for the same beam. At the same time, it proved that the acceptance can't be improved significantly nor the beamline can't be simplified by extension of the aperture. The matter is that it's always limited in the kickers and the septum magnets, so there's almost no sense to increase the aperture in other parts. Any way, < 10% loss is acceptable for this rare pulse machine.

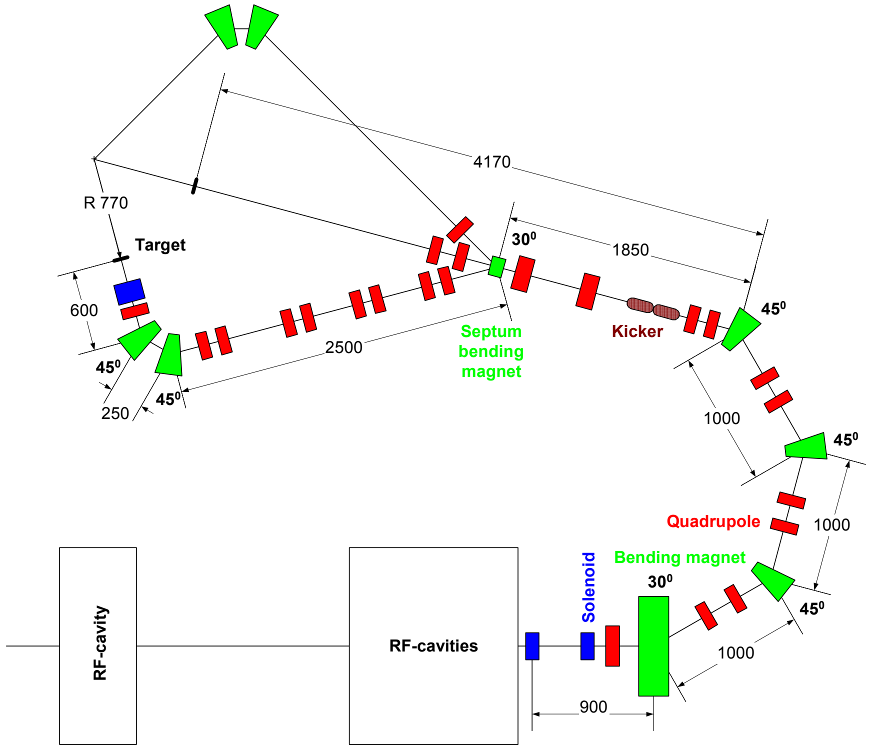

Figure 2: Beamline for beam splitting into three targets at BINP.

Injection Beamline of BINP FEL

The beamline is intended to transport electron beam from the injector to a set of accelerating RF-cavities of BINP high-power FEL [4]. It contains four 30° bends and is to conduct 45 mA beam in continuous mode. The total length is ≈ 8.5 m. The regular aperture is 100 mm. An additional condition is achromatism.

The beamline was designed originally using the uncharged linear model. Later it was analysed with the described code. No achromatic regime with acceptable loss was found, while in the absence of this condition, its acceptance is greater than one of KAERI beamline. In situ, acceptable loss was obtained only by manual adjustment of all the lenses in the beamline, so the regime is not achromatic.

It turned out that an achromatic regime with acceptable loss is possible if four additional quadrupole lenses are added, and some others are shifted. In this case the acceptance is the same as in the original beamline with no achromatism condition. This modification proposed is being considered now.

CONCLUSIONS

- A novel method of optimization of beamlines carrying transient high-current electron beam was proposed.
- A code implementing this method was developed.
- A number of beamlines was designed and analysed with the code.
- Successful operation of the beamline at KAERI with the predicted regime verifies reasonableness of the method.

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