MATCHING OF THE INTENSIVE LASER ION SOURCE TO THE RFQ ACCELERATORS

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Abstract

One of the most promising filling scheme of modern heavy ion synchrotrons could be to generate short high current pulses in a Laser Ion Source (LIS) and to accelerate the ions first in linear resonance accelerator up to required injection energy. Short, intensive pulses from LIS give a possibility to use the most efficient single turn injection mode for the filling of the synchrotron rings. The results presented in this paper demonstrate a selfconsistent algorithm for specification of LIS parameters meeting the injection requirements of a real accelerator facility. It is shown what kind of experimentally measured characteristics of laser produced plasma and extracted beams the design of a LIS has to be based on.

1 REQUIREMENTS TO THE ION SOURCE

General design of the laser ion source is determined by the required parameters of the ion beam to be injected into a subsequent accelerators and by a number of relevant physical and technical limitations.The list of required parameters under consideration is:

- ratio of ion charge state to ion mass Z/A,
- range of required ion masses,
- ion pulse length τ_i^r,
- ion beam current for charge state Z,
- emittance of the extracted beam ε^r,
- injection energy E_{in}^r,
- energy spread $(\Delta E/E)^r$,
- repetition rate ν^r,
- number of ion source operation cycles between interventions N^r.

The necessity of repetition rate laser operation mode for considerable number of operation cycles ($\geq 10^6$) without interventions with laser output energy in order of 10 -100 J and pulse durations in oder of few tens of ns defines the choice of laser system based on TEA CO_2-laser. The experience of development and exploitation of TEA CO_2-lasers shows the possibility of its operation with resource in order of 10^7 shots for repetition rate of a few Hz with stable output parameters even for full output energy from 10 to 100 J [1].

Laser ion source consists of a target chamber, plasma expansion region between the target and the extraction system and extraction system itself [2]. Extraction system provides the extracted beam parameters meeting the injection requirements of subsequent linear accelerator.

First of all, the following basic values should be measured experimentally for the specification of laser pulse parameters and the source geometry after the chemical element to be used and its charge state is chosen:

- laser power density at the target q^0 (for fixed focal spot diameter d_f^0) corresponding to the maximum in the ion charge state distribution for required charge state Z,
- ion current density j_Z^0 for ions with charge state Z at some distance L^0 from the target and for laser power density q^0,
- velocity distribution $(\Delta N/\Delta V)^0$ of ions with charge state Z for laser power density q^0,
- emittance ε^0 of extracted ion beam for some extraction aperture D^0 and a geometry of extraction electrode system.

2 SPECIFICATION OF LASER ION SOURCE PARAMETERS

When these initial experimental data have been obtained, it becomes possible to specify the main parameters of the laser ion source by following logical steps:

1. The distance L^s from the target to extraction system providing of required value τ_i^r is defined from:

$$\tau_i^{\,r} = L^s \cdot \frac{\Delta V}{V_{min} \cdot V_{max}} \qquad (1)$$

where V_{min} , V_{max} are minimum and maximum velocities of plasma ions with charge state Z,

ΔV is absolute ion velocity spread.

2. Assuming the linear dependence of extracted beam emittance ε from extraction aperture D, the maximum extraction aperture D^s can be defined in accordance with required value of beam emittance ε^r:

$$D^s = \frac{\varepsilon^r}{\varepsilon^0} \cdot D^0 . \qquad (2)$$

3. The current of ions with charge state Z at the distance L^s from the target for aperture D^s is defined from:

$$I_z^s = j_z^s \cdot \pi \cdot \frac{(D^s)^2}{4} = j_z^0 \cdot (\frac{L^0}{L^s})^3 \cdot \pi \cdot \frac{(D^s)^2}{4} \qquad (3)$$

$$(j_z = e \cdot Z \cdot n_z \cdot V_z \sim \frac{1}{L^3}).$$

If $I_z^s \geq I_z^r$, then the main requirements to the source are fulfilled.

4. If $I_z^s \leq I_z^r$ two approaches to increase the current of ions with charge state Z are possible:

- to increase the laser power density at the target,
- to increase the focal spot diameter for the fixed laser power density.

The first approach is not effective because of ion pulse length decrease with increasing of laser power density q [3]. The second approach allows to increase the current without changing of ion pulse length.

Since $I_z \sim q \cdot d_f^2$ [3}, then:

$$d_f^s = d_f^0 \sqrt{\frac{I_z^r}{I_z^s}}\,. \quad (4)$$

5. Using the defined parameters, the value of required laser pulse energy can be obtained:

$$E_1^s = q^0 \cdot \pi \cdot \frac{(d_f^s)^2}{4}\,. \quad (5)$$

6. The extraction potential U^s is defined by the required injection energy E_{in}^r and accelerated ion charge state Z:

$$U^s = \frac{E_{in}^r}{eZ}\,. \quad (6)$$

7. The energy spread of ions in a beam is defined by the expression:

$$(\frac{\Delta E}{E})^s \approx \frac{2V_{av}\Delta V}{(V_{av} + (2ZeU^s/M)^{1/2})^2} \quad (7)$$

where V_{av} is velocity of ions with charge state Z, corresponding to maximum of velocity distribution.

If :

$$(\frac{\Delta E}{E})^s \geq (\frac{\Delta E}{E})^r\,, \quad (8)$$

then considerable reduction of ion energy spread can be obtained using alternative extraction potential $U^s(t)$ [4].

The method discussed above allows to specify the laser radiation parameters and laser ion source geometry to satisfy the required parameters of the ion beam to be injected into following accelerator.

A number of technical limitations should be taken into account by developing of a selfconsistent design of a target illumination optical scheme and the laser system itself:

- Damage threshold of optical elements, measured in J/cm^2 [3], which determines the minimum diameters of optical elements to be used;
- Incident angle of the laser beam on the target defines the laser beam-plasma interaction efficiency.The efficiency of highly charged ions generation goes rapidly down for incident angles more than some critical angle (~ 5 degree) [3];
- Back coupling of the target and laser plasma with the laser cavity [5], which results a strong interaction of a complex resonator with an additional "plasma mirror" and causes a significant distortion of laser beam;
- Pumping rate should be enough to provide good vacuum conditions (~ 10^{-6} Torr) during source operation in repetition rate regime.

3 ION BEAM EXTRACTION FROM LASER PRODUCED PLASMA

External electric fields are usually used for the extraction of beams in ion sources. The extraction system consists of two or more electrodes with different potentials defining the initial distribution of electric field.

The laser produced plasma expanding in vacuum under the influence of hydrodynamic pressure gradient contains the ion flux with equivalent current density:

$$j_i(t) = e\sum_{z=1}^{z_{mzx}} Z \cdot n_z(t) \cdot V_z(t) \quad (9)$$

where $n_z(t)$, $V_z(t)$ are density and velocity of ions with different charge state Z,
Z_{max} is maximum ion charge state in the plasma,
e is elementary charge.

Under the influence of the external electric field with corresponding polarity, the ions should be extracted from plasma according to the Chailde-Lengmuire law [6]:

$$j_{3/2}(t) \approx \frac{5{,}5 \cdot 10^{-8} U_{ex}[V]\sqrt{Z_{av}}(t)}{d^2(t)[cm]\sqrt{A\,[a.m.u.]}} \quad (10)$$

where U_{ex} is extraction voltage,
A is ion mass,
d(t) is distance between surfaces with voltage U_{ex},
Z(t) is average charge state into ion flux for time t.

There exist two possibilities for ion beam extraction from nonstationary plasma flux.

In the first case the extraction system consists of two or more grids, which are under the different potentials. The idea of such scheme is to obtain an initially parallel beam. It can be done by fixation of plasma boundary on surface of the first grid, when the following requirement is fulfilled:

$$j_i(t) \leq j_{3/2}(t)\,. \quad (11)$$

However, in this case the plasma boundary inside each cell of grid differs from a plane one. In reality it spoils the ion beam emittance and leads to increase of initial beam divergence.

In the second case the extraction system consists of two or more apertures, which are under different potentials. In such scheme the plasma boundary is not stable in time and boundary position and its form are defined by the value of ion flux $j_i(t)$ and by the distribution of electric field. The problem of ion beam extraction in this case is more complicated and it is usually solved by numerical simulation [7].

The geometrical parameters of the extraction system and potential distribution are defined for fixed initial distributions of ion densities $n_z(t)$ and velocities $V_z(t)$ to optimize beam parameters taking into account a following transport line. Examples of such numerical simulations can be found in [1].

In the most cases the extraction system consists of three electrodes (so-called "accel-decel" system). The intermediate electrode is under a negative potential relatively to the exit electrode. This electrode:

- prevents the penetration of secondary electrons inside of extraction system and, therefore, decreases the possibility of discharges;
- promotes the capturing of secondary electrons by the field of ion beam space charge.

The last point leads to decreasing of influence of ion beam space charge during the beam transport [8].

Emittance, measured for three electrode extraction system, is usually less than 100 π mm·mrad (D_0 = 3 cm) [9].

Energy spread in extracted ion beam for fixed extraction voltage is defined by the initial energy spread of ions in plasma. Applying to extraction system arising in time extraction voltage, it can be obtained decreasing of ion beam energy spread [4], because the arrival time of ions to extraction system is defined by its energy and ions with lower energy are extracted from plasma later. The rise time and additional extraction voltage are defined by the ion pulse length and initial energy spread of ions with required charge state in plasma.

During the course of powerful laser interaction with plasma an intensive pulse of UV and x-ray radiation is produced. This pulse can cause a breakdown of the extraction gap. Therefore some special efforts should be done to avoid breakdowns.

4 CONCLUSIONS

The results detailed in this paper have demonstrated a clear sequence of the steps by designing of real LIS for given injection parameters of the accelerator facility. It has been shown the charge state distribution of laser produced plasma by variations of laser power density on the target, ions velocity spread in expanding plasma stream, ion current density for defined laser power level and extracted beam emittance to be the basic experimental information, determing the LIS parameters specification.

The LIS parameters specification method developed can be applied for matching of the Laser Ion Source with any accelerator facility adapted for acceleration of intensive heavy ion beams.

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REFERENCES

[1] Dubenkov V.P. et.al. Acceleration of Ta^{10+} ions produced by laser ion source in RFQ “Maxilac”. 1995 Technical Report GSI-95-02, Darmstadt, Germany.

[2] Sharkov B.Yu. et. al. Laser ion source for heavy ion accelerators. 1992 Rev. Sci. Instrum. 63(4), pp. 2841-2843.

[3] Sharkov B.Yu. et. al. 1995 Final Report of Annex to Memorandum of Understanding between CERN and the Institute for Laser Physics (ILP), Moscow region, Troitsk.

[4] Hall G. et. al. Modulated extraction voltage experiments on the CERN Laser Ion Source study. 1995 PS/HI Note 95-08 (Tech.), CERN.

[5] Kozochkin S.M. et. al. High-charge state lead ions generation in CO_2-laser produced plasma. Experiments and numerical simulations. 1993 Preprint of Kurchatov Intitute IAE-5635/7, Moscow.

[6] Gabovich M.D. 1972 Physics and Technology of Plasma Ion Sources. 1972 Energoizdat, Moscow.

[7] Becker R. and Herrmannsfeldt W.B. IGUN-a program for the simulation of positive ion extraction including magnetic fields. 1992 Rev. Sci. Instrum. 63(4), pp. 2756-2758.

[8] Kondrashev S.A. et. al. Highly charged ion beam transport with space charge compensation. 1994 Preprint ITEP 73, Moscow.

[9] Collier J. et.al. Emittance measurements on the CERN Laser Ion Source. 1995 PS/HI Note 95-07 (Tech.), CERN.