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Abstract

This is a brief report on LEReC recombination monitor design considerations. The recombination produced Au^{78+} ion rate is reviewed. Based on this two designs are discussed. One is to use the large dispersion lattice. It is shown that even with the large separation of the Au^{78+} beam from the Au^{79+} beam, the continued monitoring of the recombination is not possible. Accumulation of Au^{78+} ions is needed, plus collimation of the Au^{79+} beam. In another design, it is shown that the recombination monitor can be built based on the proposed scheme with the nominal lattice. From machine operation point of view, this design is preferable. Finally, possible studies and the alternative strategies with the basic goal of the monitor are discussed.

1 Recombination beam loss

The recombination caused ion beam loss, i.e., the recombination produced Au^{78+} ions in LEReC, is as [1],

$$R_i = \frac{N_i n_{eff} \alpha_r \eta}{\gamma^2}$$

where γ is the relativistic factor, N_i is the ion number of the beam, n_{eff} is the effective electron density, α_r is the recombination rate, η is the ring fraction of the electron beam, in LEReC, which is $18m$ over the ring of $3833m$.

The recombination rate α_r is obtained from the average of the relative electron velocity v and the capture cross section of the stationary Au^{79+}, which is [2]

$$\sigma_{c.s.} = A\left(\frac{h\nu_0}{E_k}\right)\left[\ln\sqrt{\frac{h\nu_0}{E_k}} + 0.1402 + 0.525\left(\frac{E_k}{h\nu_0}\right)^{1/3}\right] m^2$$

where $A = 2.11 \times 10^{-26} m^2$, E_k is the electron kinetic energy in ion beam rest frame, h is the Planck constant, $h\nu_0 = 13.6 Z^2 eV$ is the ground state binding energy, with $Z = 79$ in LEReC.

The electron kinetic energy E_k consists of two parts.

One is the inherent electron velocity characterized by the longitudinal and transverse temperature of $kT_{\parallel}$ and $kT_{\perp}$, respectively, where k is the Boltzman constant.

Another is the longitudinal electron velocity with respect to the ion beam velocity. Recombination monitor is built to evaluate it for better tuning of the cooling.

For an electron source we have $kT_{\parallel} \approx kT_{\perp}$. With the electrostatic acceleration of a DC electron beam, the transverse temperature is kept unchanged, but the longitudinal temperature is much reduced. This way, the acceleration produces the "flattened" Maxwellian distribution for electron beam at the cooling, which requires special treatment in calculating the recombination rate α_r.

In LEReC, the bunched electron beam is used for cooling, and the electron beam is accelerated by a LINAC. Therefore, the longitudinal and transverse temperature of the electron beam are comparable at the cooling, and Maxwellian distribution can be used in calculating the recombination rate.

The electron beam temperature in LEReC will be increased in the transport and the acceleration, affected by several factors, including the space charge.

In this paper, we take $kT = 0.255eV$ for LEReC electron temperature at the cooling.

Several codes, Fortran, gnuplot, and Matlab are developed for the recombination rate α_r by evaluating $\langle v\sigma_{c.s.}(v)\rangle$ from $v \approx 0$ to $v = 3 \times 10^6 m/s$.

The results from these codes are comparable to the Bell model with the Maxwellian distribution [2],

$$\alpha_r = \frac{1.92Z^2}{\sqrt{E_k}} \left(\ln \frac{5.66Z}{\sqrt{E_k}} + 0.196 (\frac{E_k}{Z^2})^{1/3} \right) \times 10^{-7} m^3/s$$

Applying

$$E_k = kT + \frac{1}{2} mc^2 \left(\frac{dp}{p} \right)^2$$

where dp/p is the electron momentum deviation from that with the same velocity of the ion beam, the recombination rate obtained from the gnuplot cross.plt and from the Bell model with the Maxwellian distribution are illustrated in Fig.1.

The effective electron density in the cooling can be written as

$$n_{eff} = \frac{1}{2} \frac{N_e \xi}{(2\pi)^{3/2} \sigma_{ez}^2 \sigma_{es}}$$

where N_e is the electron bunch intensity, σ_{ez} and σ_{es} are the transverse and longitudinal rms size of the electron bunches. In LEReC, 30 electron bunches are used overlapping one ion bunch for cooling, this way, the geometrical overlap of the electron bunches on an ion bunch is written as $\xi = 30\sigma_{es}/\sigma_{is}$, where σ_{is} is the longitudinal rms size of the ion bunch.

Note that if one takes Gaussian distributions with the same beam sizes for the ions and electrons, the average electron density should be a half of the peak, therefore, a factor of 1/2 is added for the effective electron density.

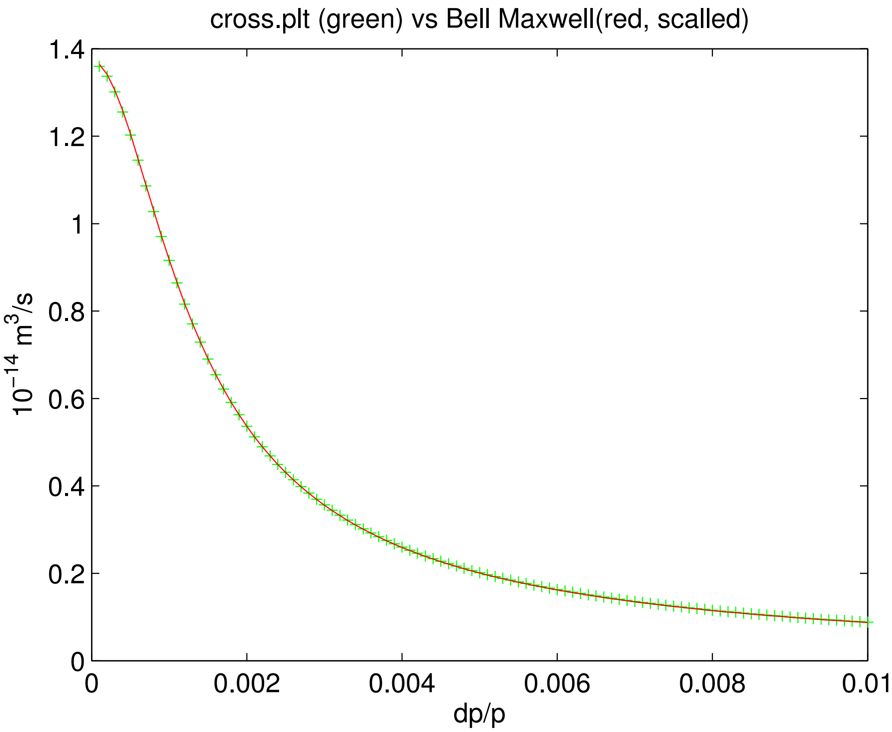

Figure 1: Recombination rate of gnuplot cross.plt by evaluating $\langle v\sigma_{c.s.}(v)\rangle$ is compared with the Bell model of the Maxwellian distribution. The Bell model at the peak is at $1.60 \times 10^{-14} m^3/s$, whereas gnuplot cross.plt gave a little lower at $1.36 \times 10^{-14} m^3/s$. Plot is scaled to the same amplitude.

Taking total $3nC$ for 30 electron bunches, the electron bunch intensity is $N_e = 6.25 \times 10^8$. With the normalized rms emittance $\epsilon_{rms} = 2.5\pi\mu m$, and the beta function $\beta_\perp = 30m$ at the cooling section, the transverse rms beam size is $\sigma_{ez} = 4.3\ mm$. Electron bunch has a full length of $\tau = 50\ ps$. Taking the longitudinal rms bunch length as 1/4 of the full length, the longitudinal rms size is $\sigma_{es} = 3.75mm$.

With the ion beam longitudinal rms bunch length at $11ns$ with the $9MHz$ RF, we have $\sigma_{is} = 3.2m$. This gives rise to the effective electron density,

$$n_{eff} = 10.1 \times 10^{12}/m^3$$

The recombination produced Au^{78+} ion rate, or the Au^{79+} beam loss, is shown in Fig.2, with $\gamma = 4.1$ and the ion bunch intensity of 0.5×10^9, total 111 bunches.

Fig.2 shows that the recombination produced Au^{78+} is about $2.5 \times 10^6/s$ at $v \approx 0$ and about $1.65 \times 10^5/s$ at $v = 3 \times 10^6 m/s$.

To detect Au^{78+} at the lower rate about $1.65 \times 10^5/s$, therefore, is required for the recombination monitor.

It is noted that the electron beam temperature is an important parameter. This temperature directly affects the cooling factor, and the recombination rate as well, the latter

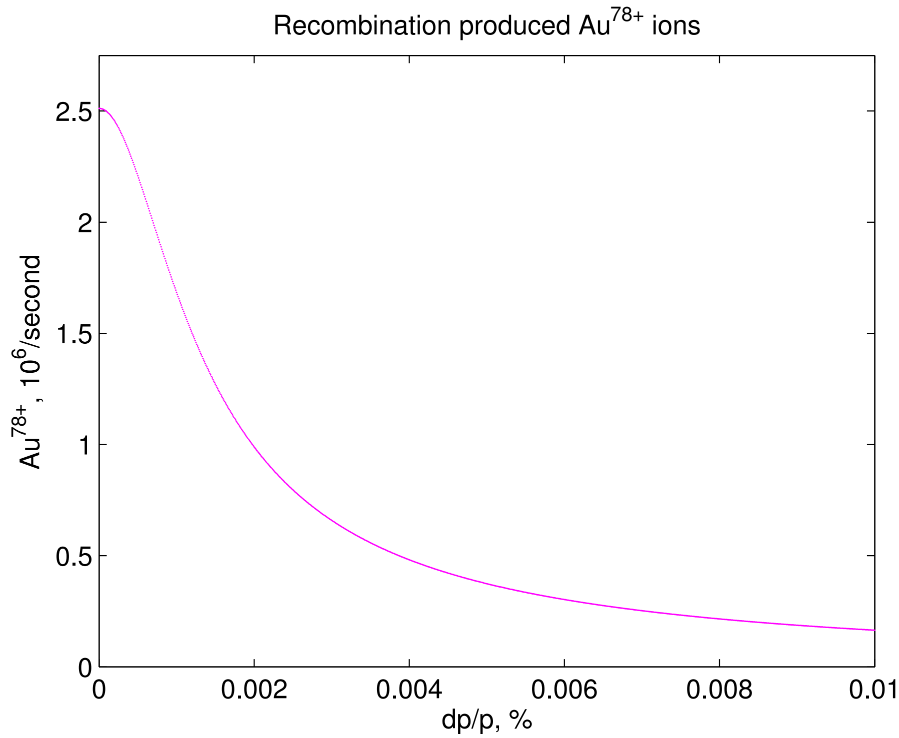

Figure 2: LEReC recombination produced Au^{78+} ions, i.e., the Au^{79+} beam loss, with $\gamma = 4.1$ and the ion bunch intensity of 0.5×10^9, total 111 bunches. This is from the relative electron velocity $v \approx 0$ to $v = 3 \times 10^6 m/s$, or the momentum deviation from $dp/p = 0$ to $dp/p = 0.01$.

in turns affects the ion beam lifetime.

Just take an example, for the parameters shown above, with the electron temperature of $kT = 0.255eV$, the ion beam at the relative electron velocity $v \approx 0$, i.e. the optimized cooling condition, has an Au^{79+} ion beam loss rate about $2.5 \times 10^6/s$. This implies that just due to the recombination, the ion beam lifetime is $6.1hour$, which is not trivial with respect to the designed luminosity lifetime of $1hour$. Given lower $kT = 0.128eV$, the Au^{79+} ion beam loss rate would be $3.8 \times 10^6/s$, i.e., the ion beam lifetime is $4.1hour$. Therefore, the electron temperature at the cooling would be of interest to watch.

2 Recombination monitor design 1

To observe the recombination Au^{78+} ions, a lattice has been developed to separate Au^{78+} beam and Au^{79+} beam by more than 7 rms beam size at an arc, where the separated Au^{78+} beam is supposed to scrape the wall alone and the secondary particles are detected outside of the cryostat, serving as the recombination monitoring [3].

In a brief review, one may identify some problems with this scheme.

Problem 1.

The amplitude of the Au^{78+} beam produced from the recombination is much below the typical halo level, which is around 10^{-5} of the peak intensity of the ion beam. Therefore, the continued monitoring of the recombination is not possible. Some Au^{78+} beam accumulation is needed.

Problem 2.

With the large dispersion lattice separating Au^{78+} and Au^{79+} beams by more than 7 rms beam size, a clear accumulation is difficult. A possibly reduced beam size may help, nevertheless, to this end, both the beta function at the arc and the beam transverse emittance are difficult to reduce. On the other hand, a collimation on the Au^{79+} beam should help.

We therefore suggest the following in dealing with these problems.

1. With about 3 second of Au^{78+} accumulation, the Au^{78+} beam's amplitude for $dp/p = 0.01$ is just comparable with the halos. More accumulation, say by 30 second, is needed to lift the Au^{78+} beam level above the halos.

2. To use the dispersion lattice with 6, not more than 7, rms beam size separation. This way, the accumulation is less difficult. Meanwhile, the demand on large dispersion can be eased a little.

3. To use collimation for the Au^{79+} ion beams. This way, the size of the Au^{78+} beam is also reduced.

In Fig.3, a possible scheme is presented, where the beam pipe diameter is $69.1mm$, and the beam amplitude is normalized with Au^{79+} to unity. Note that, therefore, the amplitude of Au^{78+} beam vs. Au^{79+} beam is not dependent on Au^{79+} beam intensity.

The Au^{78+} beam shown in Fig.3 represents the recombination created Au^{78+} at the relative electron velocity of $v = 3 \times 10^6 m/s$, i.e., the electron beam momentum deviation is $dp/p = 0.01$. The sensitivity of the recombination monitor is required to detect clearly there.

A brief description of the key issues are as follows:

1. A lattice with 6 rms beam size separation of Au^{78+} beam from Au^{79+} beam is applied, where the Au^{78+} beam accumulation looks acceptable, with minimum scraping on the wall.

2. A collimation with 3 rms beam size on the Au^{79+} ion beam is used, which still left 99% of the Au^{79+} beam intensity, therefore, the operation is not affected.

3. There is a 30 second Au^{78+} beam accumulation. For the recombination produced Au^{78+} ions at $dp/p = 0.01$, which is required by the monitor to detect, the relative level of Au^{78+} is at 9.0×10^{-5} of the Au^{79+} beam, above the halo level.

A tracking study suggested that at $\gamma = 4.1$, the Au^{78+} beam may circulating about 2×10^6 turns, i.e., about 25 seconds [4]. Therefore, the Au^{78+} accumulation should be possible to raise the Au^{78+} intensity level above the halo level.

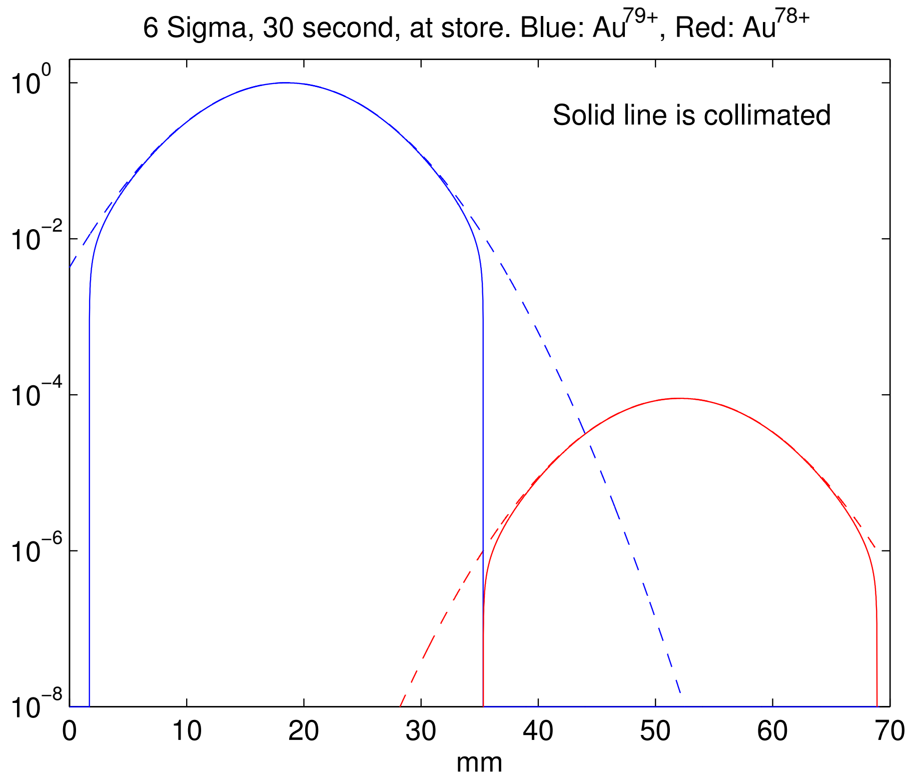

Figure 3: Beam profiles in the arc, where the Au^{79+} beam and Au^{78+} beam are separated by 6 rms beam size. Beam amplitudes are normalized with Au^{79+} beam at the unity. The Au^{78+} beam intensity is after 30 second accumulation, with no scraping loss at the wall.

In the measurement, we propose to use the RF controlled CO (closed orbit) shift to move the beam toward outside chamber wall, then the secondary particles are detected outside the cryostat, which is used to determine the recombination rate.

To shift the CO by using the RF control means to move the entire beam in the ring. In specific, in the arc with the beta function of $50m$, this move is about $30mm$, which is too large with respect to the concerns of the possible beam loss in the ring.

We propose to shift the beam by a half of Au^{78+} beam in horizontal direction to scrape for the measurement, the rest particles in other side of the beam would be scraped due to the betatron motion. With the fractional tune of 0.2, some 5 turns of the betatron oscillation will help to scrape the ions of the entire beam.

With the beam rms size around $5.6mm$ at the beta function of $50m$, a $15mm$ of CO shift at the arcs by RF manipulation is required to move the Au^{78+} beam shown in Fig.3 to scrape for the measurement.

With this CO shift, and $\triangle f/f \approx 1.5 \times 10^{-6}$, the RF frequency change is about $14Hz$.

3 Recombination monitor design 2

The large dispersion lattice requires a new powering scheme for the transition gamma jump quadrupoles, as well as for some focusing quadrupoles in both insertion regions enclosing the arc [3]. This scheme will be tested later.

A possible design of the recombination monitor required no change at the arc is also of interest to study.

With the nominal lattice, at the dispersion function of $2m$, the Au^{79+} and Au^{78+} are separated by about 4.6 rms beam size.

With this scheme, the Au^{78+} beam can be easily set not touching the wall, therefore no loss in accumulation.

Once the accumulation finished, or at the accumulation, a 3-bump can be used to push Au^{78+} beam in barely touching the wall. Then, an RF controlled CO shift will be used to push the Au^{78+} beam scraping for measurement.

The use of 3-bump push is in order to reduce the RF CO push as much as possible.

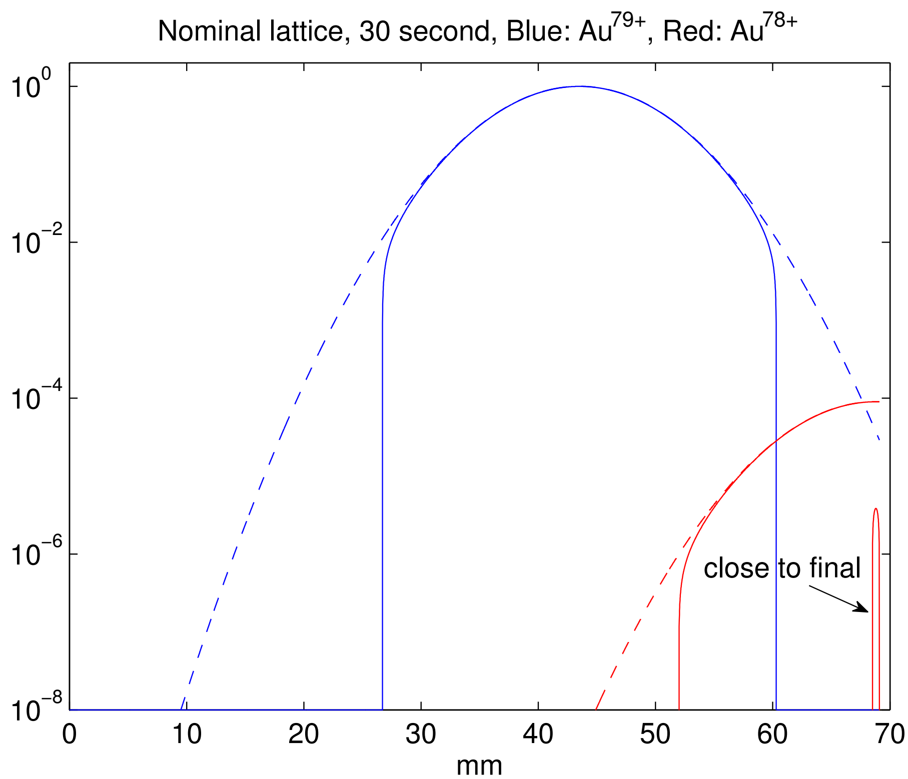

Figure 4: Beam profiles in the arc with the nominal lattice, where the Au^{79+} beam and Au^{78+} beam are separated by 4.6 rms beam size. Beam amplitudes are normalized with Au^{79+} beam at the unity. The Au^{78+} beam intensity is after 30 second accumulation. The beam position is at a Au^{78+} beam scraping for the recombination measurement. An Au^{78+} beam profile at very close to the end of the measurement is also shown.

In Fig.4, this operation is illustrated for the beam position at the measurement.

Similarly, a 30 second Au^{78+} accumulation, together with the 3 rms beam size collimation on the Au^{79+} beam, are applied.

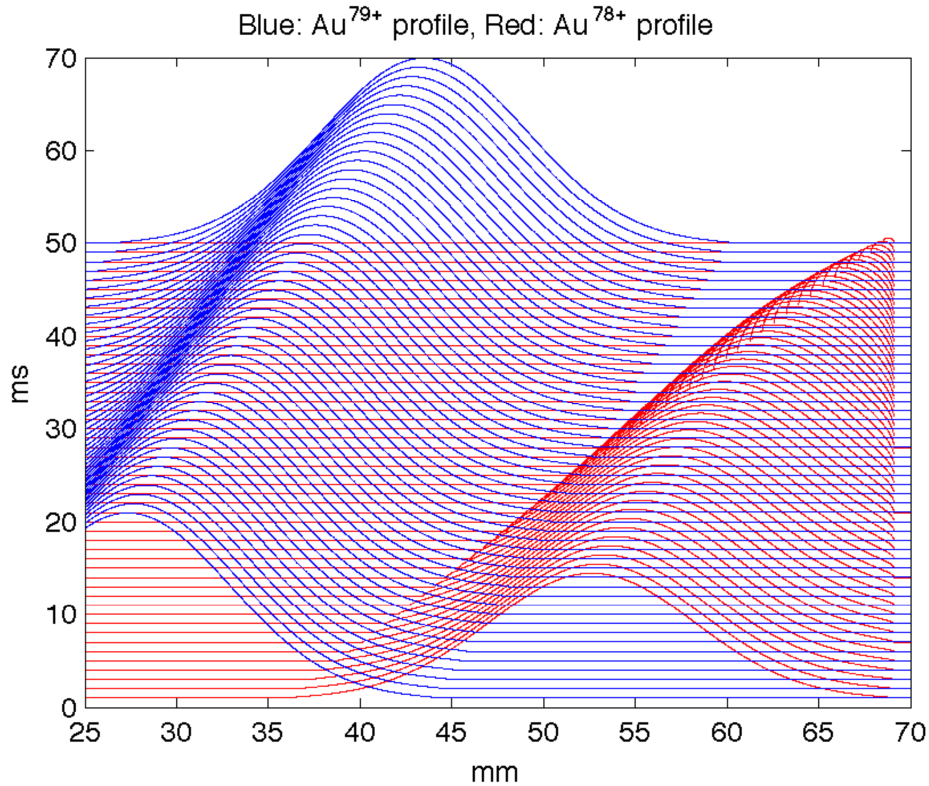

Figure 5: A possible measurement procedure, where the red lines are for Au^{78+} beam and Blue lines are for Au^{79+} beam from the beginning to the end of the measurement. The amplitude of the Au^{79+} beam is reduced 10,000 times for ease to illustrate. Started from the beginning, the RF controlled CO push moves the beam toward the wall, and at the end, all Au^{78+} particles are scraped.

In Fig.5, a possible measurement procedure according to this scheme is presented. Just as an example, the RF controlled CO pushes the beams to the wall, with the rate of $0.3mm$ per ms. At $50ms$, both Au^{79+} beam and Au^{78+} beam are moved $15mm$, which is about a half of the beam size.

The 5 turns of the betatron oscillation took only $0.65\mu s$, therefore, each step of $1ms$ is more than sufficient to scrape the Au^{78+} particles on the other side in the horizontal direction. Therefore, the Au^{78+} beam profiles shown in Fig.5 should be accurate.

In overall, by scraping $15mm$ of the Au^{78+} beam in $50ms$, one step of the the measurement is completed. After that, the accumulation would be started again for the next step of the measurement.

4 Detector sensitivity

APEX study of 6/15/2016 has shown that the scintillator's sensitivity is better than the pin-diodes. For detailed study results and analysis, see [5].

In Fig.6, typical beam loss excited by the ARTUS kicks are shown together with the scintillator's readings. With a beam loss of 5×10^7 ions, the combined readings from the two scintillators are about 5,000. During the study, there are comparable beam loss in other location in the ring, therefore, this reading account should be solid.

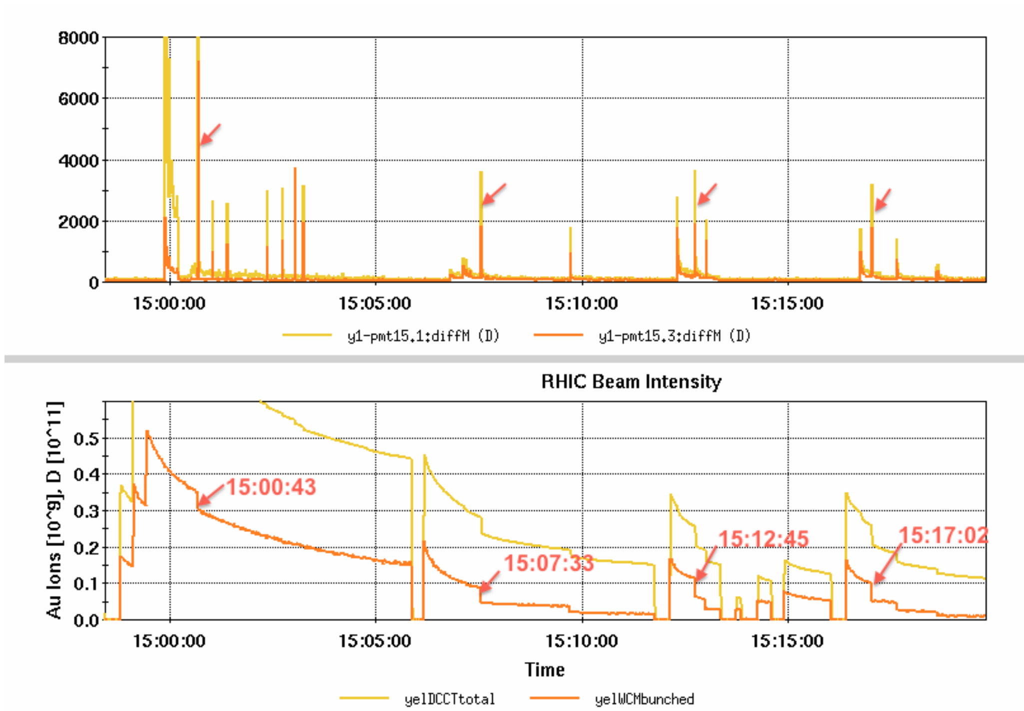

Figure 6: APEX study of 6/15/2016, with bumps at Q14 then Q12. Typical cases with a beam loss of 5×10^7 ions are shown together with the two scintillators' readings

6/15/2016	15:00:43	15:07:33	15:12:45	15:17:02
Bumps at	Q14	Q12	Q12	Q12
Beam loss, 10^9	0.05	0.044	0.05	0.05
y1-pmt-15.1	12300	3619	3668	3191
y1-pmt-15.3	7200	1816	1906	1776

Table 1: Beam loss vs. scintillators' reading in 6/15/2016 APEX beam study

In Table 1, the details of this measurement study are shown. Only 4 typical cases with beam loss about 5×10^7 ions are listed.

Regarding the sensitivity of the scintillators, the beam loss rate is a relevant factor. The beam loss time in the study is not very clear. To be conservative, we take it the same as the scintillators' sampling time in the study, which is 1 second.

With the recombination monitor sensitivity requirement that to detect the beam loss with $1.65 \times 10^5/s$ at $v = 3 \times 10^6 m/s$, considering the 30 second accumulation, the beam loss rate is $5 \times 10^6/s$.

If one takes the scintillators' reading of 5,000 at the loss of $5 \times 10^7/s$ according to the APEX study, then the current scintillators should be able to provide a reading of 500 counts for the loss rate of $5 \times 10^6/s$.

Consider the background and noise, the scintillators' sensitivity is a little short, nevertheless, it is not too far away from the required.

To improve the sensitivity, consider that the beam loss area covers more than $10m$ in the location, to extend the scintillator's cover area could be considered.

Also, it is suggested that moving the loss location closer to the monitor would increase the yield up to two orders of magnitude [5].

Since the scintillators may respond very fast, if the RF controlled Au^{78+} scraping takes only a portion of a second, then the scintillator sensitivity requirement is reduced.

For example, if the CO shift time is reduced from 1 second to $50ms$, which is the example shown in Fig.5, then the beam loss rate is increased from $5 \times 10^6/s$ to $1 \times 10^8/s$, and the scintillator counting will be improved by a factor of 20, as well.

5 Summary and discussion

It has been suggested to use the recombination generated Au^{78+} ion detection for LEReC cooling velocity matching [6].

In this note, the recombination produced Au^{78+} ion rate is presented. Beam parameters are preliminary, therefore, this report may need to be tracked and updated.

Even with the large dispersion lattice, continuous monitoring of the recombination rate is not possible, and some accumulation of the Au^{78+} is needed. Also the Au^{79+} ion beam's collimation is suggested.

In addition to the design consideration based on the large dispersion lattice, a design with the nominal lattice is of interest, where the scheme shown in Fig.5 looks feasible. From machine operation point of view, this design is preferable.

Some studies are proposed at below.

1. For RF controlled CO shift, the beam loss around the ring needs to be studied. Associated with this study, an optimization of the beam orbit with less beam loss is of interest.

2. For Au^{79+} ion collimation, the primary collimator created fragments with a wide range of Z/A rations may not be intercepted by the secondary collimators. This may need a study.

3. Other parameters, such as the 3-bump setting, the time period of the RF controlled CO shift, the degree of the collimation, are all open for study and test.

Finally, to achieve the eventual goal of the recombination monitoring for cooling tuning, only a relative change of the recombination rate is needed to measure.

To this end, all available means are up to play, these include: the time of the Au^{78+} accumulation; the degree of the Au^{79+} collimation; the part of the Au^{78+} in horizontal direction to scrape, i.e., the extent of the CO push; and the time of the RF controlled CO push.

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