A.2 : Particle source part I (9, December, 2013) by Masao KURIKI

Answer the following questions.

Q.A2.1 According to several technical limitations, the size of the cathode active area is 8.0mm (6.0mm in the problem was my mistake. I am sorry.) in radius. The laser is illuminated on the cathode with the same area and the intensity is flat. To extract the beam, 250kV bias voltage is applied between the cathode and anode with 100mm gap. To extract the required bunch charge (3.2nC), how much is the appropriate laser bunch length? Please assume that the extractable current density from the gun is limited by space charge effect.

(Answer) The emission density limited by the space charge effect is

$$J = 2.33 \times 10^{-6} \frac{(2.5 \times 10^5)^{3/2}}{0.1^2} = 2.91 \times 10^4 A/m^2, \tag{1}$$

The current from the cathode is then

$$2.91 \times 10^4 \times \pi \times 0.008^2 = 5.85A. \tag{2}$$

Then, the time to extract the 3.2nC bunch charge is

$$t_t = 3.2 \times 10^{-9}/5.85 = 5.47 \times 10^{-10} \tag{3}$$

The answer is 547ps.

Q.A2.2 How much energy spread ($\Delta E/E$) is expected if we inject directly the bunch to 1.3 GHz RF accelerator? Please assume that the bunch centre is on crest and ignore beam-loading effect of the accelerator and space charge effect.

(Answer) The period of 1.3GHz RF is 770ps. The bunch length obtained in Q.A2.1 is larger than the half of the period, 385ps. Then, we will get 100% energy spread if we inject the beam directly to accelerator.

Q.A2.3 The energy spread of calculated in Q.A2.2. is likely to be larger than DR acceptance in energy (1.5% full width). We need bunching prior to the RF acceleration. As the bunching RF cavity, we employ a 650MHz RF cavity. The shunt impedance of the cavity is $2.0 \times 10^6$ohm and input RF power is 5.0 kW. What is the distance from the cavity to the first accelerator? Please assume only the linear term in the bunching.

(Answer) The voltage of the bunching RF is

$$V_0 = \sqrt{2.0 \times 10^6 \times 5.0 \times 10^3} = 1.0 \times 10^5 V. \tag{4}$$

$\gamma$ and $\beta$ of the beam is

$$\gamma = \frac{250 + 511}{511} = 1.49, \tag{5}$$

$$\beta = \sqrt{1 - \frac{1}{\gamma^2}} = 0.741. \tag{6}$$

According to the bunching condition (in linear approximation)

$$L = \frac{c\beta^2\gamma^2 E_0}{eV_0\omega} = \frac{3.00 \times 10^8 \times 0.741^3 \times 1.49^2 \times 761}{100 \times 2\pi \times 650 \times 10^6} = 0.504. \tag{7}$$

The answer is 0.504m.

Q.A2.4 How much bunch length is expected after the bunching? Please assume only the linear term. Laser wavelength for the beam generation is 700nm and the band gap of the GaAs crystal is 1.4 eV. The cathode temperature is 300 K.
(Answer) The energy spread after the emission is dominated by the laser energy and thermal energy as explained in our lecture. Because the energy is equally distributed among the degree of freedom, the longitudinal energy spread ($E_z$) is same as $E_x$ and $E_y$. The photon energy is

$$h\nu = \frac{1.05 \times 10^{-34} \times 2\pi 2.99 \times 10^8}{700 \times 10^{-9} \times 1.60 \times 10^{-19}} = 1.76eV. \tag{8}$$

The thermal energy is

$$\frac{kT}{2} = \frac{1.38 \times 10^{-23} \times 300}{2 \times 1.60 \times 10^{-19}} = 1.29 \times 10^{-2}eV. \tag{9}$$

$E_z$ is then

$$E_Z = \frac{1.76 - 1.40}{6} + 1.29 \times 10^{-2} = 7.29 \times 10^{-2}eV \tag{10}$$

$R_{56}$ is

$$R_{56} = \frac{0.504}{\gamma^2\beta^2} = 0.413, \tag{11}$$

gives the bunch length after the bunching as

$$z = 0.413 \times \frac{7.29 \times 10^{-2}}{756 \times 10^3} = 4.00 \times 10^{-8}, \tag{12}$$

The answer is 40 nm.

Q.A2.5 By considering the next higher order on the energy modulation, the bunching performance is not good as expected obtained in Q.A2.4. How much extra bunch length is expected by this non-linearity?
(Answer) Energy spread by the third order term is

$$\delta_3 = \frac{100}{761}\frac{(2\pi \times 650 \times 10^6 \times 547 \times 10^{-12}/2)^3}{6} = 3.05 \times 10^{-2}. \tag{13}$$

giving the extra bunch length (in half length) is

$$R_{56} \times 3.05 \times 10^{-2} = 1.26 \times 10^2. \tag{14}$$

The answer is 1.26 cm.

Q.A2.6 By assuming the bunch length obtained in Q.A2.5, how much energy spread is expected at 5.0 GeV when we employ 2.6 GHz RF accelerator? Is this acceptable by DR (70mm z, 1.5% energy spread)?
(Answer) The expected energy spread by 2.6 GHz RF accelerator is

$$1 - cos\left(2\pi \times 2.6 \times 10^9 \frac{1.26 \times 10^{-2}}{2.99 \times 10^8}\right) = 0.228 \tag{15}$$

where we assume particle position in the bunch does not change during acceleration. Then, the energy spread is 22.8% which is still larger than DR acceptance.