GENERATION AND ACCELERATION OF LOW-EMITTANCE, HIGH-CURRENT ELECTRON BEAMS FOR SUPERKEKB

M. Yoshida#, N. Iida, S. Kazama, T. Natsui, Y. Ogawa, S. Ohsawa, H. Sugimoto, L. Zang, X. Zhou,
High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki, 305-0801, Japan
D. Sato, Tokyo Institute of Technology, 2-12-1, Ookayama, Meguro-ku, Tokyo, 152-8550, Japan

Abstract

KEK e-/e+ linac is now in a final stage of upgrade for SuperKEKB. One of the key issues is to stably generate and accelerate a low-emittance, high charge electron beam for SuperKEKB (a couple of single-bunched beams with a charge of 5 nC and a normalized emittance of 20 mm-mrad each).

REQUIREMENTS

The injector upgrade as shown in Fig. 2 is required for the SuperKEKB injection due to the small dynamic aperture and the short life time of the ring. The bunch charge must increase up to 5 times higher than KEKB and the lower normalized emittance is required around 20 mm mrad. Further the small energy spread of around 0.1 % is required in the condition of higher bunch charge for the synchrotron injection of the HER of the SuperKEKB.

Table 1: Required Parameters for SuperKEKB

	KEKB(e^+/e^-)	SuperKEKB(e^+/e^-)
Beam Energy	3.5 / 8.0 GeV	4.0 / 7.0 GeV
Bumch Charge	1.0 / 1.0 nC	4.0 / 5.0 nC
Normalized transverse Emittance (1σ)	2100 / 300 mmmrad	6 / 20 mm mrad
Energy Spread	0.1 %	0.1 %

PHOTOCATHODE RF-GUN

The initial emittance at the electron gun is determined by the space charge effect and the RF emittance. The photocathode RF-Gun is required to generate such low emittance of lower than 10 mm mrad for the high charge electron bunch of 5 nC. From the analytical calculation, the bunch length must be longer than 20 ps to obtain the charge of 5 nC and the transverse emittance of 10 mm mrad.

This requirement of the electron bunch charge for the SuperKEKB is slightly higher than the standard S-band RF-Gun. Further it is better to use same RF gun for the positron production with the primary electron bunch charge of 10 nC.

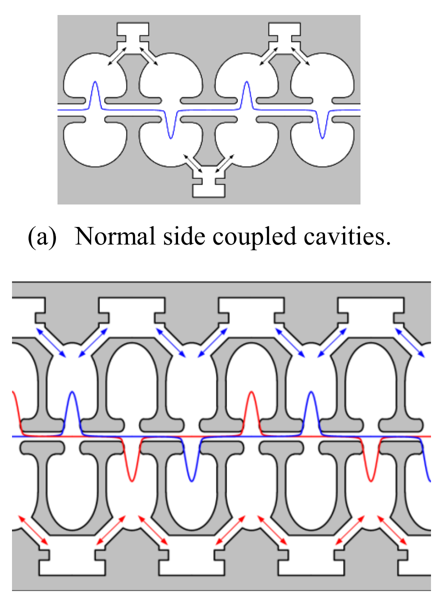
Thus we developed the new advanced RF gun with the following specifications for the long time stable operation of the SuperKEKB injection:

- The quasi-traveling wave side coupled cavities for the strong focusing electric field to keep the beam side against the space charge.
- The reasonable lower maximum surface electric field of 120 MV/m.
- The metal composite cathode (IrCe) with the long lifetime and reasonable high quantum efficiency.
- The ytterbium based laser system with the temporal manipulation to get the minimum energy spread.

#mitsuhiro.yoshida@kek.jp

QTW-SIDE COUPLED RF GUN CAVITY

The strong focussing field is generated by the annular coupled cavities with the narrow acceleration gap as the disk and washer (DAW) or side coupled cavities narrow acceleration gap. Conversely the narrow gap causes a long drift space as Fig.1 (a). We solved this problem to use two staggered standing wave cavities with π/2 phase difference as shown in Fig.1 (b). This acceleration field is similar to the traveling wave from the accelerated beam. We call this cavity as the quasi-traveling wave (QTW)[1]. This quasi-traveling wave RF-Gun can realize to obtain both of the higher acceleration voltage and the strong focussing field.



(a) Normal side coupled cavities.

(b) Quasi traveling wave side coupled cavities.

Figure 1: Structure of the quasi traveling wave cavity.

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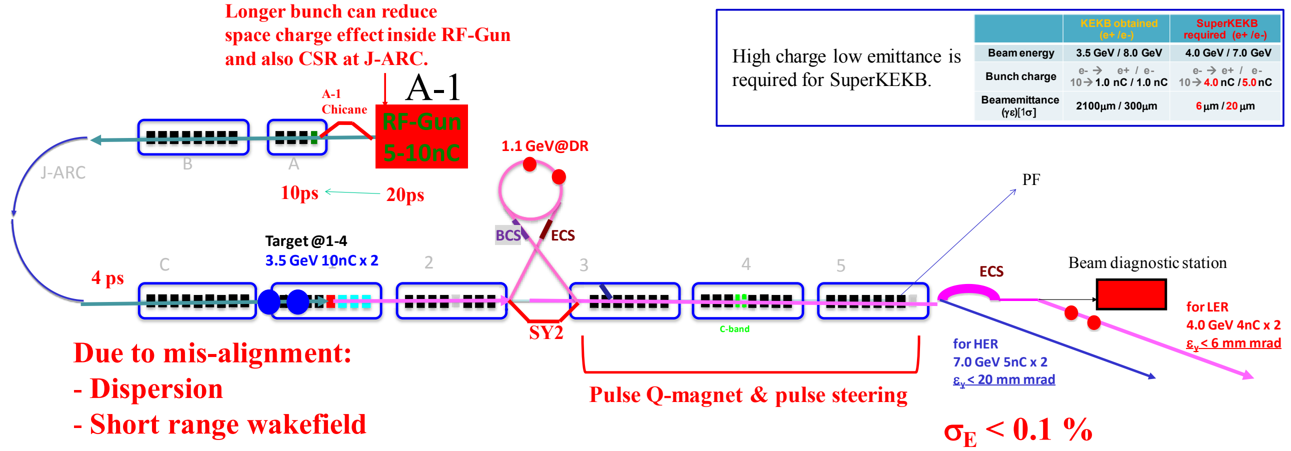


Figure 2: KEKB Injector upgrade to obtain the low emittance and the high charge for SuperKEKB injection.

The cathode cell of RF gun is most important to obtain high quality beam since the space charge affects the beam size and emittance in the low energy region. The curvature of the cathode makes the strong focussing field against the space charge effect of the high bunch charge. The electrode shape was optimized to reduce the surface electric field and to supress the non-linear component which causes the emittance growth. This RF gun consists of 7 cavities in which 3 cavities have $\pi/2$ phase difference as shown in Fig. 3. The narrow gap of those accelerating cavities makes the focusing force to keep the beam size.

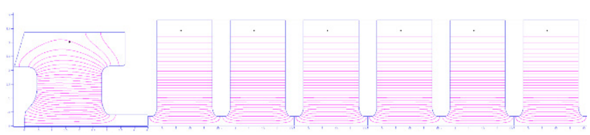


Figure 3: Designed RF gun cavities.

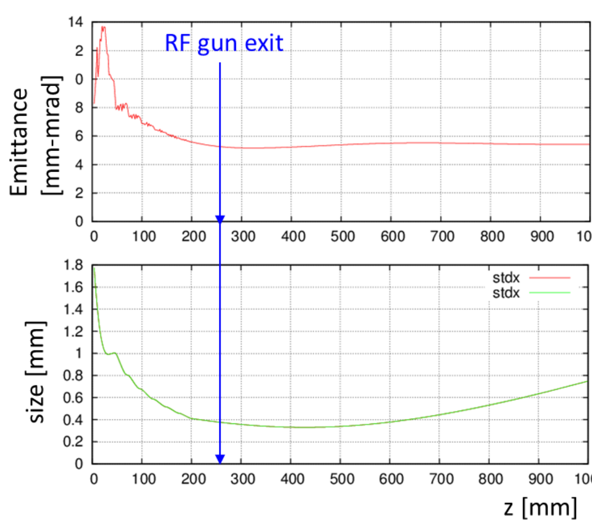
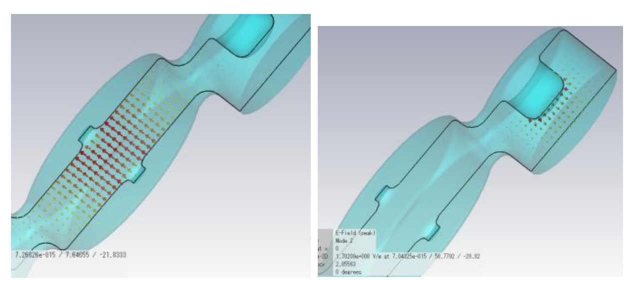


Figure 4: Beam tracking simulation result.

The Figure 4 shows the beam tracking simulation for 5 nC beam. The normalized emittance of 5.5 mm-mrad and the beam size of 0.4 mm are expected at the exit of the RF gun. This small beam size is obtained by the focusing electric field without any additional magnetic field. After the RF gun, the beam energy of 11.5 MeV is high enough to supress the space charge. The required RF power is 20 MW. Also this RF gun can generate 10 nC beam for the positron generation. The normalized emittance of 10 mm-mrad and energy spread of 1 % are expected.

Figure 5 shows the acceleration mode and the coupling mode of the regular cavity. The coupling coefficient is 3%. Those 3 and 4 side coupled cavities are mounted as 90 degrees in the azimuthal angle as shown in Fig. 6.



(a) Accelerating mode (b) Coupling mode

Figure 5: Regular cell cavity calculation result.

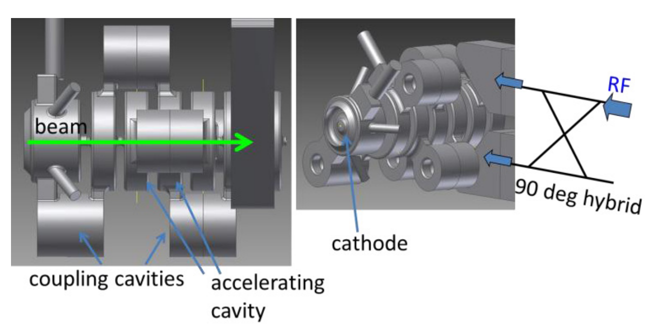


Figure 6: Whole cavity shape.

Those two standing wave cavities are fed by 90 degree hybrid. As shown in Fig. 6, the whole cavity shape is complex. Thus the sliced cavity shape was machined and stacked by brazing process as shown in Fig. 7. Also the compact 90 degree hybrid was developed. This RF gun was installed in September 2013 replaced from a thermionic cathode DC gun as shown in Fig. 8.

Figure 7: Photo of manufactured cells after brazing.

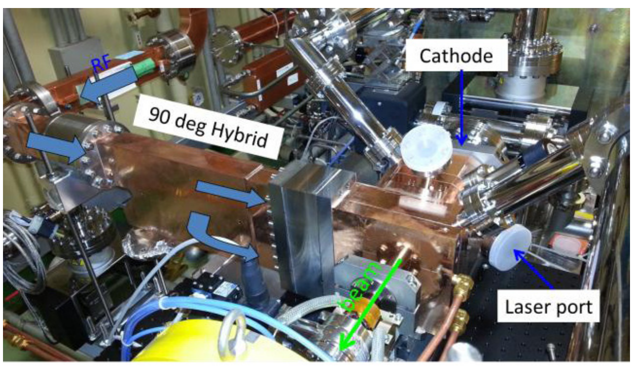


Figure 8: Installed RF gun.

IRIDIUM CERIUM CATHODE

A photocathode material is a key component to obtain the high charge electron beams using a photocathode RF gun. Generally, multi-alkali photocathodes (e.g. Cs_2Te, K_2CsSb) have been used as photocathode material since they have low work function (< 3eV) and high quantum efficiency (QE ~ 0.1). These photocathodes, however, are not suitable for SuperKEKB injector since the lifetime of these photocathodes is not enough for a long-term continuous operation. On the other hand, the metallic photocathodes (e.g. Mg, Cu) have a long lifetime (<1 year) which is enough to operate a RF injector for a year without cathode maintenance. It is, however, difficult for these photocathodes to generate the high charge electron beams since they have too low QE as shown in Fig. 9.

We have tried to develop a new metal compound as a photocathode which has reasonably high quantum efficiency (> 10^{-4}) and high laser durability to generate high charge electron beams for a long-term (> 1 year).

The iridium cerium (Ir_5Ce) photocathode has a reasonably high quantum efficiency (QE = 1.54 × 10^{-4} @266nm) and a long lifetime (>> lanthanum hexaboride : LaB6). Moreover, the Ir_5Ce photocathode showed a high resistance to poisoning and it can be easily activated by the laser irradiation (laser cleaning) as shown in Fig. 10 left. Futher the quantum efficiency can be increased by shorter wavelength laser or the heat treatment as shown in Fig. 10 right.

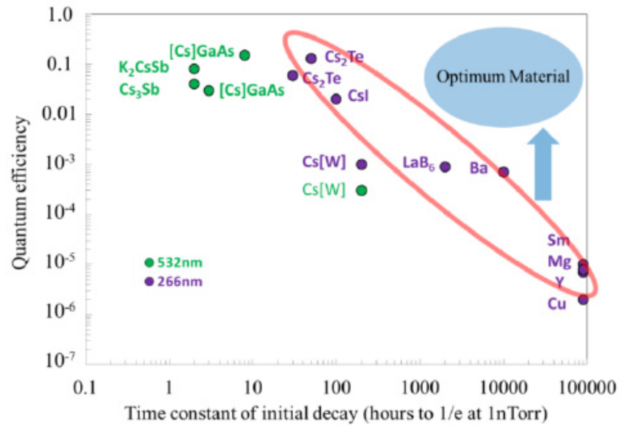


Figure 9: Quantum efficiency vs cathode lifetime.

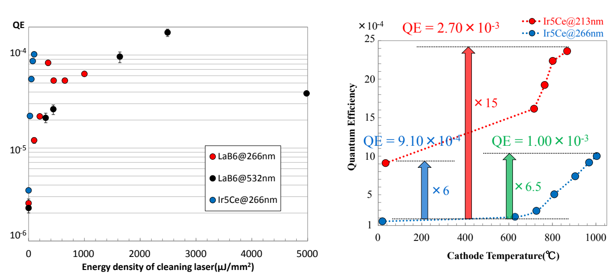


Figure 10: Laser activation and quantum efficiency.

Yb-DOPED HYBRID LASER SYSTEM

The required energy spread of 0.1 % was achieved for the bunch charge of 1 nC at the previous KEKB operation. However the required bunch charge becomes 5 nC for SuperKEKB and it induces the stronger longitudinal wakefield. Further the shorter bunch is preferred to supress the emittance dilution due to the transverse wakefield from the mis-alignment of the accelerating structure. This stronger longitudinal wakefield induced by the shorter bunch causes the larger energy spread. Fortunately the energy spread at the optimum RF phase dramatically decreases in case of the uniform charge density as shown in Fig 11.

Thus the uniform pulse shaping is required for the laser system. It means that the chirped pulse and spectrum shaping is required using the broadband crystal. The Ti:Sapphire and Ytterbium(Yb)-doped crystal is the candidate for such a broadband crystal. We adopted the Yb-doped crystal to obtain the higher efficiency using the diode pumped laser since our operation repetition rate of 50 Hz is slightly high for the another crystal.

In more recent years, both fiber lasers and thin-disk lasers are expected to show significant further progress.

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The fiber laser offers high efficiency, good stability, low cost and simple configuration. And the thin-disk laser optimizes heat removal which makes possible the high energy pulse amplifier. We employed a hybrid system which includes an Yb-doped fiber oscillator, amplifiers and thin-disk Yb:YAG amplifiers.

A schematic diagram of the laser system is shown in Fig.12. The seed pulse was generated by an Yb-doped fiber ring oscillator with the repetition rate of 51.9 MHz which is required to synchronize with our S-band LINAC and the RF frequency of SuperKEKB ring. Then the pulse repetition is reduced to 10.38 MHz by an EO fiber pulse picker. After an Yb fiber pre amplifier to compensate for the power loss in EO system, the pulse was chirped to ~30 ps by a transmission grating stretcher with variable slit. An Yb-doped large-mode-area polarizing double-clad photonic crystal fiber was employed to the first amplification stage. Then, the pulse repetition rate was separated with an EO modulator pockels cell. To increase the pulse energy, another Yb-doped LMA PCF was used. To obtain the mJ-class pulse energy, three stages of the multi-pass Yb thin-disk amplifier were employed as shown in Fig. 13. Deep UV pulses for the photocathode are generated by using two frequency-doubling stages. Figure 14 shows the current pulse profile. This profile is much better than the normal Gaussian pulse shape. The dazzler will be installed to obtain the flat top.

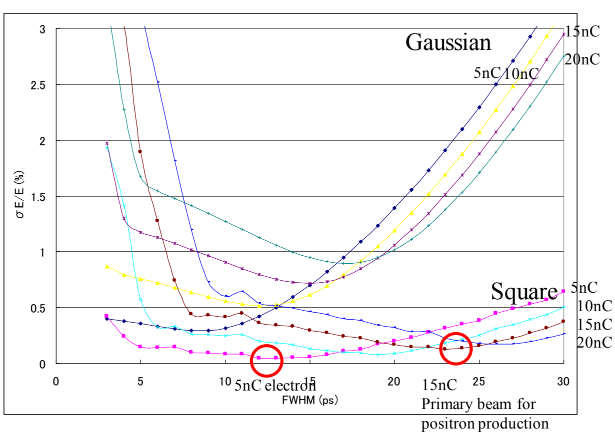

Figure 11: Energy spread vs bunch length.

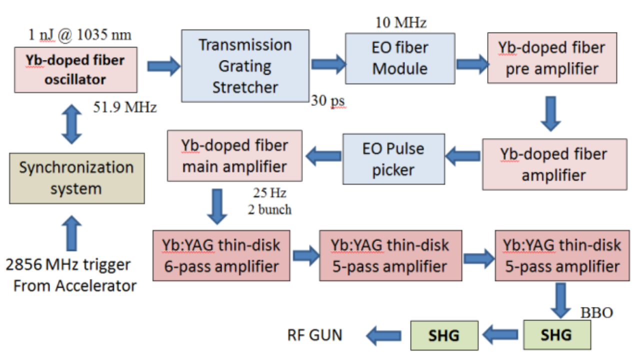

Figure 12: Layout of laser system.

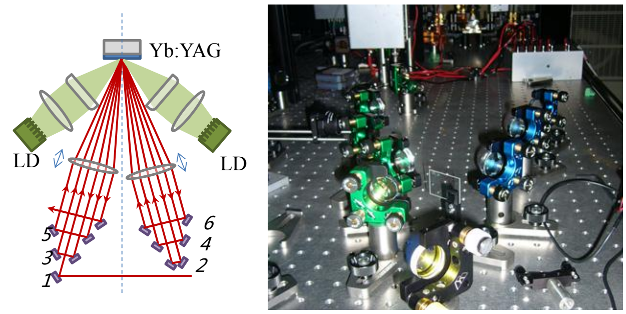

Figure 13: Thin-disk multi-pass amplifier.

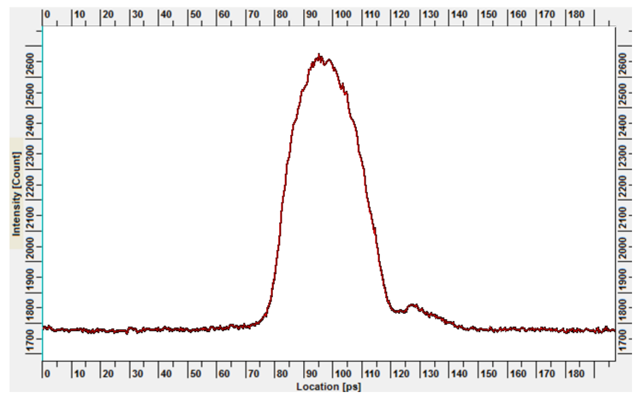

Figure 14: Laser pulse profile.

RF GUN COMISSIONING

The RF gun beam commissioning was started autumn 2013. The bunch charge of 5.6 nC has been observed. The Q-scan emittance measurements were performed using a 30 μm thickness alumina fluorescent plate. Beam size was measured as shown in Fig.15. Beam energy was 25 MeV at the plate. As a result, normalized emittance is 10.7 (±1.4) mm-mrad in vertical at beam charge of 1 nC.

We have to improve the Yb laser system for the future stable and high charge operation for the continuous SuperKEKB injection.

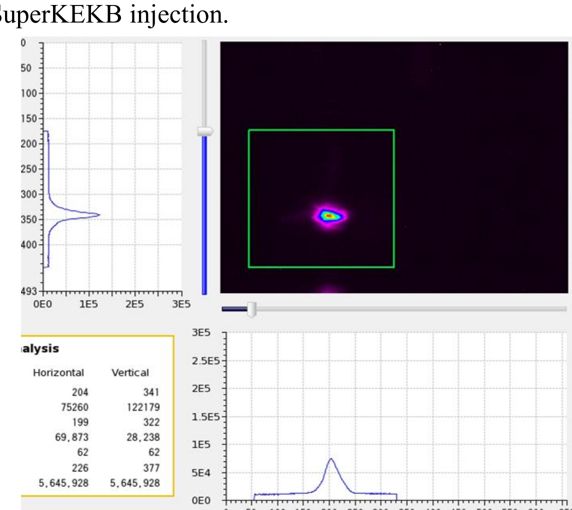

Figure 15: Emittance measurement by Q-scan method.

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EMITTANCE PRESERVATION

The transverse wakefield is main source of the emittance dilution for the high bunch charge of 5 nC after the beam orbit is well corrected in the LINAC beam optics. And the energy spread is determined by the longitudinal wakefield strength. The smaller alignment tolerance and the shorter bunch length can reduce the transverse wakefield strength. However the shorter bunch length causes the stronger longitudinal wakefield.

Figure 16 shows the analytical calculation of the projected emittance in several cases of the bunch length and the alignment error. The bunch length of 4 ps and 10 ps are required for the alignment error of 0.3 mm and 0.1 mm respectively from Fig. 16. Since our normal bunch length is 10 ps, we are working to reach the alighment error of 0.1 mm for each local section which consists of 8 units. However it seems very hard to keep this small alignment error in our old support structure and the frequent earthquake. Thus we have to consider the 4 ps option for the alignment error of 0.3 mm.

Further the initial offset can compensate the transverse wakefield to recover the emittance dilution. The initial offset is taken as the two steering magnets with 90 degree phase difference of the betafunction for each axis. Figure 17 shows the emittance optimization using the initial offset scan. It is realized using the RF deflector to observe the longitudinally sliced bunch shape.

The shorter bunch can suppress the emittance dilution due to the transverse wakefield. However it causes the stronger longitudinal wakefield. The RF phase becomes deeper and deeper corresponding to the longitudinal wakefield strength to suppress the energy spread. Thus the bunch length was chosen by those balances.

The initial bunch length of 20 ps generated by the photocathode RF-Gun will be compressed to 10 ps using the chicane at the low energy section. And the J-ARC section is place at the energy of 1.6 GeV. We can change this optics design to the achromatic condition from original isochronous design to obtain certain R56 to compress the bunch as shown in Fig. 18.

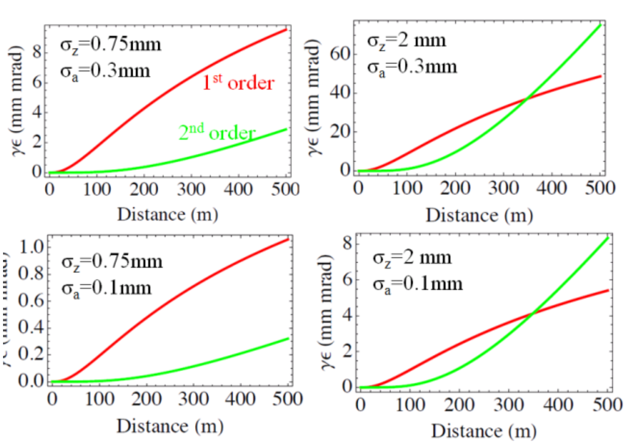

Figure 16: Analytical emittance growth due to mis-alignment.

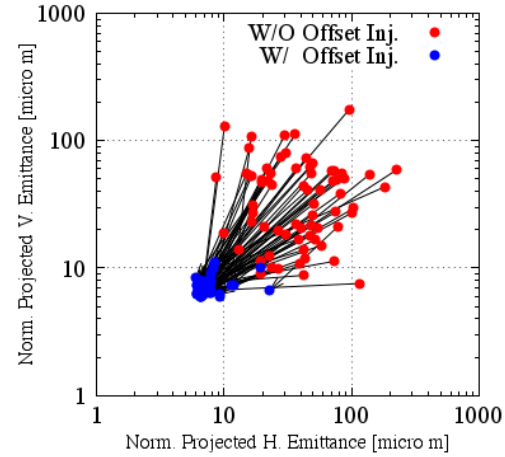

Figure 17: Initial offset to optimise the projected emittance.

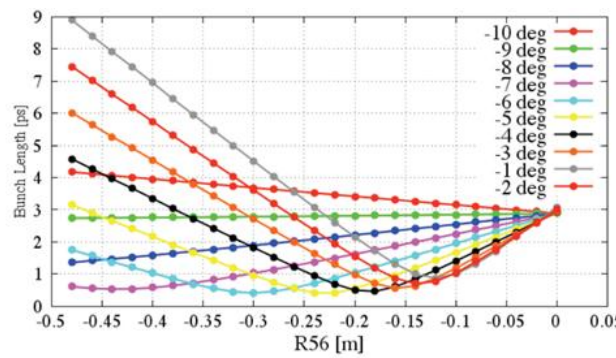

Figure 18: Possible R_{56} by achromatic design of J-ARC.

CONCLUSION

An advanced quasi-travelling wave side couple RF gun with special metal composite cathode was installed to generate the high charge and low emittance beam for SuperKEKB. The charge density was controlled by new Yb fiber and thin-disk hybrid laser system to obtain the required energy spread. Further the emittance preservation is another important issue to inject the high quality beam for SuperKEKB ring.

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