SUMMARY OF WORKING GROUP 6 – INJECTORS AND INJECTION HF2014

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Abstract

We present a summary of presentations made in Working Group 6, *Injectors and Injection*, at the 55th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders – HF2014 in Beijing, China. The workshop was held October 9-12, 2014.

PAPERS PRESENTED

Contributions covered planned injectors and injection for CEPC (Chuang Zhang) and FCC-ee (Yannis Papaphilippou), polarization preservation in synchrotrons (Ivan Koop), top-up injection (John Seeman and Richard Talman), and injection with pretzels (Dave Rice).

We cover the highlights from each presentation then offer our summary of injection highlights and challenges at the end of this paper.

CEPC PLANS (IHEP)

Both CEPC and FCC-ee are planning on a full energy injector that is necessarily similar in size to the full ring, and thus sharing the same tunnel. Chuang Zhang presented a conceptual design for the CEPC full injector. Because the CEPC design anticipates building a newly constructed injector complex, the booster injection energy is 6 GeV from a linear accelerator, limited by cost considerations, though 10 GeV was mentioned as a possibility. The low energy of the injector is a primary issue for development.

An injection interval of 10 seconds, with intensity of 5% of the stored beam, simultaneously filling all 50 bunches in the collider ring will conservatively meet the needs of the predicted 25 minute collider beam lifetime, giving a factor of 3.75 combined margin for injection efficiency and beam lifetime.

A 6 GeV linac provides both electrons and positrons to the booster ring. A target at the 4 GeV point produces positrons that are accelerated to 200 MeV for return to the front end of the linac. Plans are to construct the linac on the surface with a sloped transfer line to the level of the booster.

The booster is filled with 50 bunches at 6 GeV by 50 linac pulses (operating at 100 Hz) then ramped to 120 GeV in 4 seconds. The plan presented did not include a positron damping ring, rather a booster dwell period at 120 GeV is expected to provide sufficient damping.

The beam is transferred from the booster to the storage ring 2 m below with horizontal bends and vertical Lambertson magnets. The beam is injected in the horizontal plane via a segmented septum magnet. Injection in the vertical plane is considered to ease concerns about the pretzel configuration, but this is complicated by the large β_V^* needed for local chromaticity correction in the IR.

The booster employs a 1300 MHz RF system with details still in design process.

Primary concerns are stability of the net magnetic field (30 Gauss) at injection into the booster and beam stability (125 seconds damping time), and injection into the pretzel orbits. A "wiggling-bend" layout (Figure 1) with half of the bends being bipolar to decrease damping time at 6 GeV is being considered as is higher injection energy (longer linac) and a pre-booster ring.

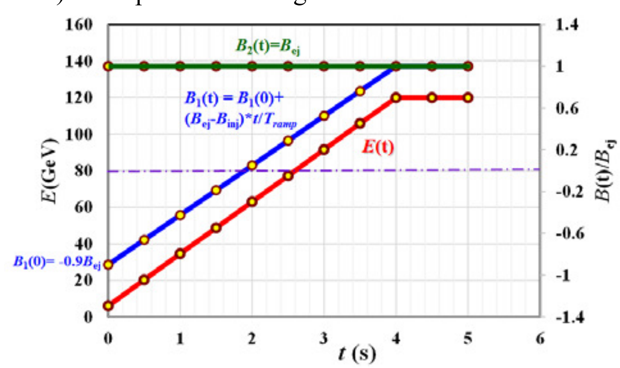

Figure 1: CEPC wiggling bend ramp program.

FCC-ee PLANS (CERN)

Yannis Papaphilippou described the FCC-ee injector, which is being designed to provide e+/e- for Z, W, Higgs, and $t\bar{t}$ (45.5 – 175 GeV) compatible with the expected 20 minute lifetime at $t\bar{t}$ energy. (Table 1) The availability of the SPS as a 20 GeV pre-booster would allow higher energy injection into the booster compared to the 6-10 GeV CEPC plans.

Following the proposed CLIC design, a new linac operated at 50Hz would accelerate 1360 bunches (in the case of the Higgs production) in a 2GHz structure. Eight linac batches are injected into a 50MHz RF system in the SPS at 10GeV to be accelerated and injected into the booster ring at 20 GeV. Five SPS accelerating cycles of 1.2 s are used providing the total 1360 bunches in the Booster flat bottom. With the addition of wigglers, the SPS can also serve as a damping ring.

Both the linac injector and booster ring are designed to provide low emittance beams (~1 nm at 120 GeV) for improved injection efficiency (~ 80%). New RF systems are needed throughout the injector chain – linac (2000 MHz, SPS (50 MHz) and booster (50 MHz).

Alternative injection schemes were presented, including synchrotron injection (both Δp and Δt) and pulsed sextupole injection.

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Primary concerns are the stability of the booster guide field at 20 GeV (60 g) including stray fields, finding the optimum pre-booster chain choosing from both new and existing systems, accommodating shared use, and meeting the needs of a wide range of collider energies, bunch patterns, and currents.

Table 1: FCC-ee Injector Tentative Parameters

Accelerator	FCCee-Z		FCCee-W		FCCee-H		FCCee-tt	
Energy [GeV]	45.5		80		120		175	
Type of filling	Full	Top-up	Full	Top-up	Full	Top-up	Full	Top-up
LINAC # bunches	3200				1360		280	
LINAC repetition rate [Hz]	50							
LINAC RF freq [MHz]	2000							
LINAC bunch population [10^8]	5.9	0.4	0.6	0.2	0.3	0.3	0.02	0.04
# of LINAC injections	8						7	
SPS/BR bunch spacing [MHz]	50							
SPS bunches/injection	80				34		7	
SPS bunch population [10^{10}]	2.35	0.16	0.25	0.08	0.12	0.12	0.10	0.14
SPS duty factor	0.5						0.29	
SPS / BR # of bunches	640/3200				272/1360		49/98	
SPS / BR cycle time [s]	1.2 / 12						1.2 / 8.4	
Number of BR cycles	50	15	50	3	50	1	71	1
Transfer efficiency	0.8							
Total number of bunches	16700		4490		1360		98	
Filling time (both species) [sec]	1200	360	1200	72	1200	24	1193	16.8
Injected bunch population [10^{10}]	18	0.36	7	0.14	0.46	0.092	14	0.28

POLARIZATION

While physics with longitudinally polarized beams is desirable, the high luminosity and related IR configurations will be extremely challenging. The most likely use of polarization will be in energy calibration, especially at Z and WW energies where only a few percent polarization is required. A precision of 10^{-5} or better is desired. Maintaining polarization above 80 GeV beam energy becomes difficult as the depolarization time approaches the time the beam is in the booster.

Ivan Koop showed that polarization may be maintained throughout the acceleration cycle by having a spin tune of ½. This may be accomplished with an odd number of 180º snakes (Figure 2). With three snakes, depolarization time is 320 seconds at 45.5 GeV and 6.2 s at 80 GeV. Increasing the number of snakes to 7 or 9 would preserve polarization into the 80-100 GeV range, confirmed by spin tracking simulations.

Dynamic depolarization from orbit distortions and betatron oscillations appears minimal according to simulations performed to 86 GeV. Alternating signs of the solenoid field will substantially reduce spin tune chromaticity.

In summary, polarization should be maintainable in the booster synchrotron up to 80-100 GeV given sufficient care and installation of up to 9 180º snakes. Spin tracking, including radiative effects, is required for confidence in the design.

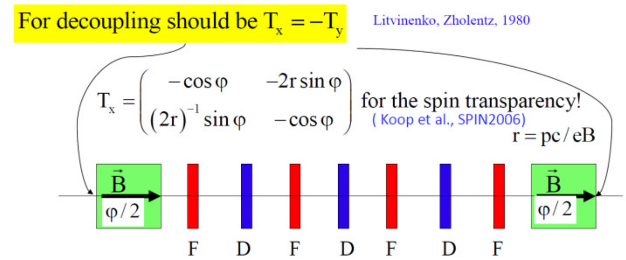

Figure 2: Spin transparent rotator for the solenoid partial snake. Two solenoids, each 40 m, 5T, provide 180º rotation at 45.5 GeV.

TOP-UP INJECTION

Top-up injection has been used at PEP-II and KEK-B, producing impressive gains in performance. In addition to the expected 15-20% gain over periodic refilling, the nearly constant currents from topping up every one or two minutes permits more focused optimization of tuning, adding another 10-20% in luminosity.

John Seeman stated that, beyond an efficient injection strategy, top-up operation requires attention to individual storage ring bunch currents, injector bunch charges and timing relationships throughout the facility. In addition, the details of particle losses near the interaction region and the characteristics of the physics detectors' systems will determine need for masking, inhibiting of trigger systems, or protection of high voltage systems.

The PEP-II top-up ("trickle-charge") injection controller was able to track the bunches with lowest charge, tailor the gun charge to match what was needed to top up to nominal current, and time the gun pulse to fill the right storage ring bunch, even after positron generation and damping ring time. Each 3 to 15 Hz injection cycle carried 3-9x10^9 particles in one bunch.

Masking of the detector trigger was tailored around the lost particle pattern, covering the full azimuthal distribution of bunches for several turns, then limited to 100-200 bunches around the azimuth of the bunch just filled for over 1000 turns. (Figure 3)

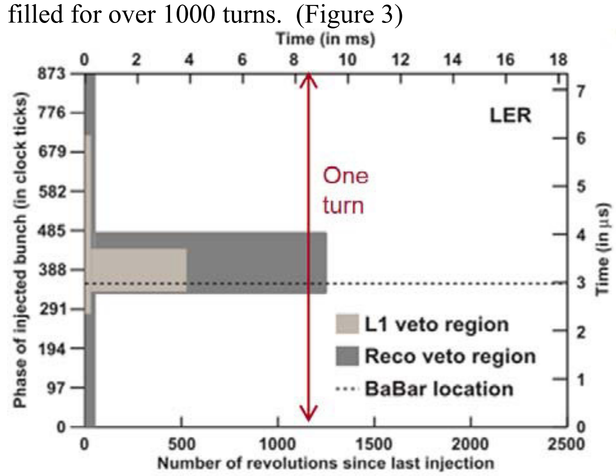

Figure 3: Regions of azimuth-time masked in BaBar detector at PEP-II for level-1 triggers and reconstruction triggers.

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There should be no fundamental barriers for top-up operation in a Higgs factory, but attention will be required to control particle losses, background, and track bunch-by-bunch charges and timing. Close work with detector designers will be essential. A rapidly (2-4 seconds) ramped booster ring should be adequate to keep collider currents within a few percent of peak.

INJECTION WITH PRETZELS

Dave Rice suggested that the major issue for injection with pretzels is the passage of the injected bunch near the core of the opposing beam. Economical design and optics considerations limit separation of the beams at parasitic crossing points to around 10 σ. (Figure 4) When stacking is done in betatron phase space, limiting the amplitude of the injected bunch core around the equilibrium orbit to much less than 10 σ (stored beam wall clearance, injected beam clearance, septum thickness) is challenging. If the pretzel and injection are in the same plane (typically horizontal) injection efficiency plummets. With flat beams, the beam dynamics at PC's impact vertical motion more than horizontal, placing a premium on good vertical apertures, physical and dynamic.

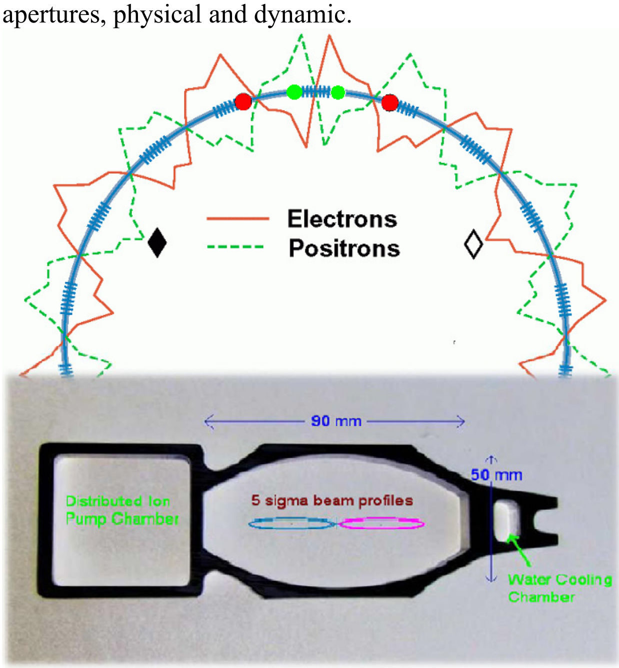

Figure 4: CESR pretzel orbits and beam profiles.

Beam-beam tune shift from parasitic crossings further complicate injection since, depending on distribution of bunch currents and optics functions at PC's, each bunch may have variation in betatron tunes.

These effects can bring the injection efficiency from a single-beam value of ~80% down to 10-30%. Simulations, either tracking or beam envelope analysis, can be useful to identify particularly bad crossing points.

Several mitigating steps used at CESR were presented, including: optics design for maximum separation at PC's; using special sextupole families to control the tunes of the two beams; increase the vertical emittance of the "strong" beam by coupling to reduce the vertical gradient for BBI;.a short kicker pulse may be used to decrease the amplitude of the injected bunch at the expense of small excitation of the previously stored bunch; keeping bunch populations even is usually beneficial.

The experience at LEP may offer guidance closer to the HF experience – in addition to the higher energy LEP had less (but still significant) flexibility in optics.

Other injection schemes such as vertical and longitudinal phase space stacking may be preferred if other factors are favorable (though the restriction of vertical acceptance by the IR configuration will challenge vertical injection designs). In determining an injection scheme, one may assume that any particles passing within 2 σ of the opposing beam are at risk. A program of detailed modelling and simulation must be part of any design effort where injection with pretzels is planned.

LATTICE OPTIMIZATION FOR TOP-OFF INJECTION

Richard Talman stressed the critical role of efficient injection in a high-energy circular collider and presented several design strategies to meet this need.

Scaling parameters from LEP values, keeping dispersion constant will help in controlling chromaticity. This leads to cell length, L_c, scaling as $R^{1/2}$ as a reference point. Following through with the scaling of related parameters one reaches the conclusion that horizontal dynamic aperture $x_{d.a.}/\sigma_x \propto R^{1/2}$.

Designing the injector with smaller emittance than the storage ring would facilitate efficient injection and enable the kickerless injection described later. Talman suggests the cell length L to scale as $R^{1/4}$ for the injector and $R^{3/4}$ for the collider ring, varying about the central value mentioned above.

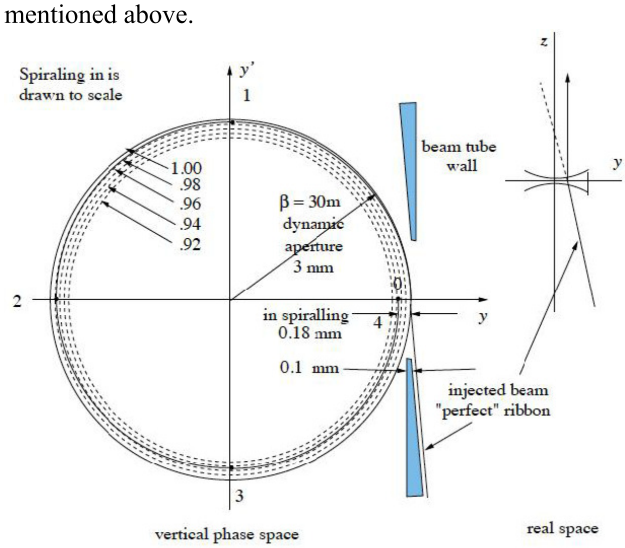

Figure 5: Schematic view of kicker-free vertical injection.

The fast damping in a Higgs factory might be exploited along with a thin (0.1 mm) septum and small vertical emittance to inject vertically without the need of kicker magnets. (Figure 5) Should this prove too challenging, a small pulsed closed-orbit bump would provide sufficient margin. As previously discussed, the IR designs to

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implement a 1 mm β_y^* will likely restrict vertical acceptance.

SUMMARY

The short lifetimes and high energy inherent in high luminosity Higgs factories place new demands on the injector. Full energy, multiple-bunch topping off requires a booster ring similar in size to the collider ring, bringing the injector cost to a similar scale as the collider ring.

The relatively low B field of the booster ring at injection requires attention to power supply stability, stray currents from transient and ground capacitance effects, and shielding of ambient magnetic fields. Using ramped negative bends in a wiggler-ring configuration could mitigate some of these issues. Both projects consider low energy a primary booster ring design challenge.

Collective effects have not been studied in any depth. High frequency, multi-cell cavities exacerbate this concern, especially for the lower energy operation with optimum bunch numbers well over 1000. This concern ranks close to low B field in priority.

Maintaining polarization in the booster, at least up to 80 GeV, seems feasible with an odd number of 180º snakes. No design has yet made provision for these. Using polarization for energy calibration for Z and W operation is feasible, but beyond is more difficult. Longitudinal polarization for physics does not sound practical at this stage of machine design, nor does production of polarized positrons in sufficient quantity.

Proposals for reduction of positron emittance include adding damping wigglers to a pre-booster (SPS) and to the booster ring (CEPC), avoiding construction of a smaller, dedicated ring, although a dedicated ring may relax aperture requirements for the booster, thereby significantly reducing cost.

Top-up/trickle-charge operation is feasible with either 2 or 1 ring configuration. Careful thought must be given to instrumentation (bunch measurement and timing) and to detector backgrounds and having minimum dead-time from trigger masks and other detector protection measures.

Single ring / pretzel operation adds challenges to avoid “collisions” between injected bunches and opposing-beam bunches. CESR has had partial success mitigating these effects a variety of techniques. Pretzels and bunch trains were both used at LEP where the optics and beam energy were closer to the HF values. The critical issues with pretzel operation must be understood before finalizing a single-ring design.

Alternative injection schemes – vertical or longitudinal injection and optimization at every opportunity, such as reduction of emittance of the booster beam, will be key to successful operation of a Higgs factory.

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