Injection Options for a e+e- Higgs Factory

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Topics for Injection for an e+e- Higgs Factory

Required injection parameters for a Circular Higgs Factory

Summary of the initial injector parameters

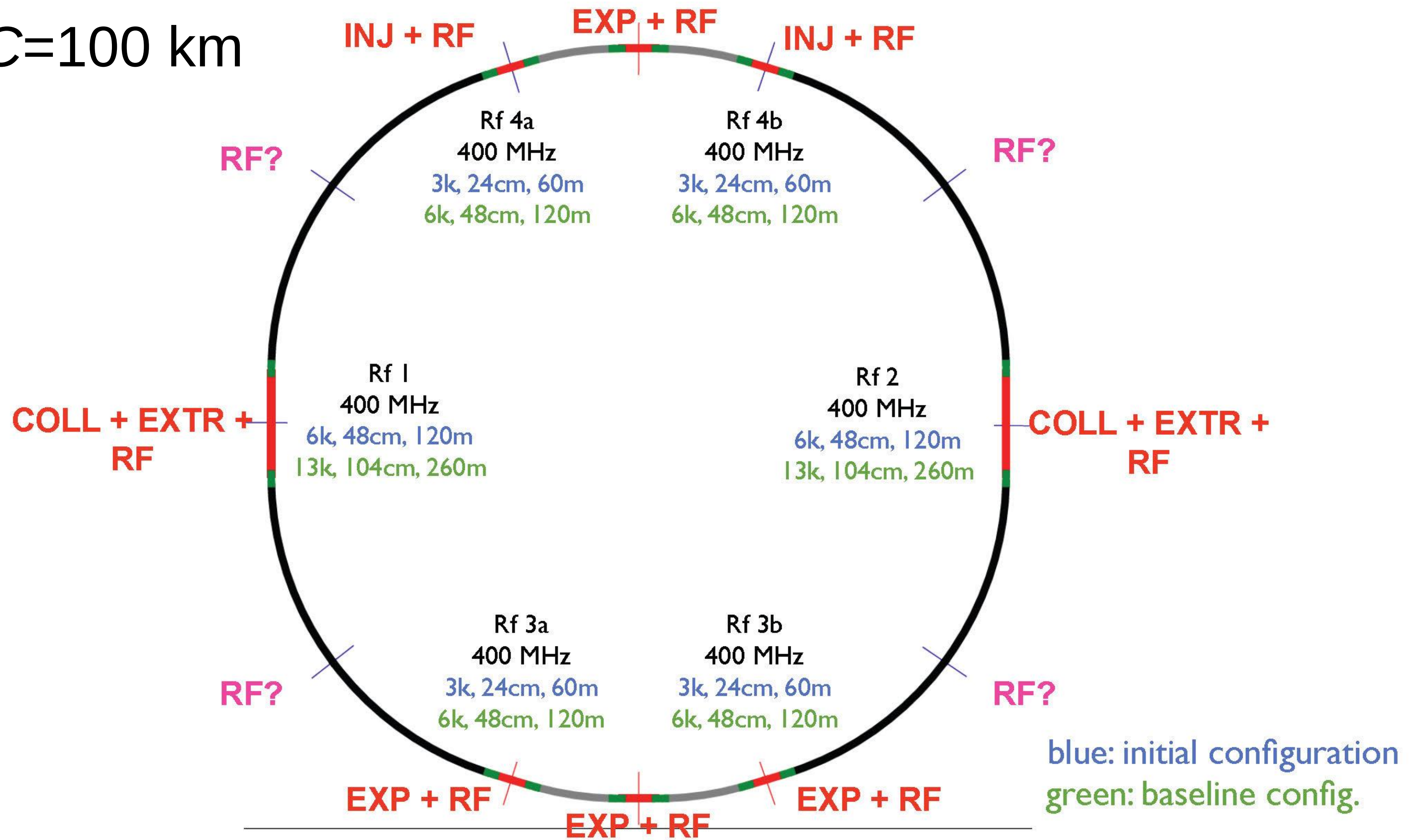
“Storage ring style” injector

“Fast cycling synchrotron” injector

Detector masking

FCC-ee preliminary layout

C=100 km



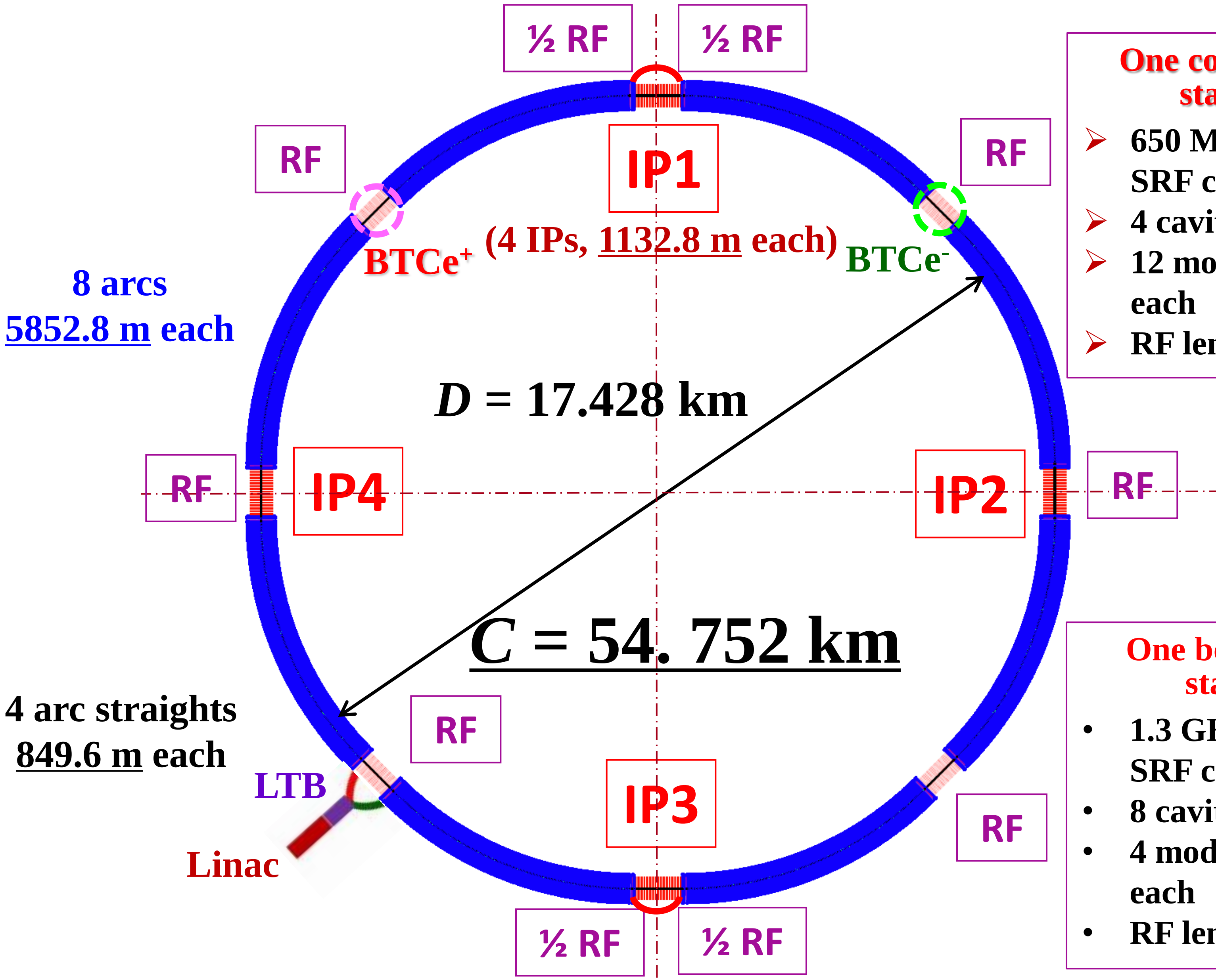
- ✓ consistent with *FCC-hh* layout
- ✓ RF staging scenario defined

preliminary FCC-ee parameters

parameter	FCC-ee	LEP2
energy/beam	45 – 175 GeV	105 GeV
bunches/beam	**50 – 60000**	4
beam current	**6.6 – 1450 mA**	3 mA
hor. emittance	**~2 nm**	~22 nm
emittance ratio $\varepsilon_y/\varepsilon_y$	**0.1%**	1%
vert. IP beta function β_y^*	**1 mm**	50 mm
luminosity/IP	**1.5-280** x 10^{34} $cm^{-2}s^{-1}$	0.0012 x 10^{34} $cm^{-2}s^{-1}$
energy loss/turn	0.03-7.55 GeV	3.34 GeV
synchrotron radiation power	**100 MW**	23 MW
RF voltage	0.3 – **11 GV**	3.5 GV

- Large number of bunches at Z and WW and H requires **2 rings**.
- High luminosity means short beam lifetime (few mins) and requires continuous injection (**top up**).

The CEPC Layout



One collider RF station:

- 650 MHz five-cell SRF cavities;
- 4 cavities/module
- 12 modules, 8 m each
- RF length 120 m

One booster RF station:

- 1.3 GHz 9-cell SRF cavities;
- 8 cavities/module
- 4 modules, 12 m each
- RF length 48 m

CEPC Accelerator Parameters

Accelerator Parameters		
Beam energy [E]	GeV	120
Circumference [C]	km	53.6
Luminosity [L]	$cm^{-2}s^{-1}$	1.82E+34
SR power/beam [P]	MW	50
Bending radius [ρ]	m	6094
N_{IP}		2
n_B		50
filling factor [κ]		0.71
Lorentz factor [γ]		234834.66
Revolution period [T_0]	s	1.79E-04
Revolution frequency [f_0]	Hz	5591.66
Magnetic rigidity [Bρ]	T·m	400.27
momentum compaction factor [α_p]		4.15E-05
Energy acceptance Ring[η]		0.02
cross-section for radiative Bhabha scattering [(	cm^2	1.53E-25
lifetime due to radiative Bhabha scattering [τ_L]	min	55.42
build-up time of polarization [τ_p]	min	21
Beam Parameters		
Beam current [I]	mA	16.60
Bunch population [N_e]		3.71E+11

CEPC Injector Parameters

Parameter	Symbol	Unit	Value
Injection energy	E_{inj}	GeV	6
Ejection energy	E_{ej}	GeV	120
Circumference	C	km	52.7528
Bending radius	ρ	km	6.519
Main bending field	B_{ej}/B_{inj}	T	0.0614/0.00307
SR loss/turn	U_0	GeV	2.814
Bunch number	n_b		50
Bunch population	N_b	10^{10}	2.0
Beam current	I_{beam}	mA	0.87
SR power @ 120GeV	P_{SR}	MW	2.46
SR Power density @120GeV	P_{SR}/C	W/m	45

Electron and Positron Production

A Higgs Factory stores about 3 to 5 $x10^{13}$ e+ per ring.

HF with 10 minute lifetime needs 1 to 3 $x10^{13}$ e-/e+ every 10 min or ~5 $x10^{10}$ e+ and e- per second at full energy.

Past:

CERN: LEP injection complex delivered ~10^{11} e+ per second.

SLAC: SLC injection complex delivered ~6 x 10^{12} e+ per second.

So a HF injector particle production should be straight forward.

Summary Injection Parameters

Ring: 100 km

45 GeV: 60000 bunches at 5×10^{10} per bunch

175 GeV: 50 bunches at 2.8×10^{11} per bunch

Ring: 50 km

120 GeV: 50 bunches at 3.7×10^{11} per bunch

Injection:

50 bunches with $\sim 7 \times 10^{9}$ per bunch at 0.067 Hz (15 sec cycle)

or

1000 bunches at $\sim 10^{9}$ per bunch at 0.1 Hz (10 sec cycle)

Higgs Factory Injection Phase Space

β_x at injection septum (stored) = ~200m

β_x at injection septum (injection) = ~30m

$\varepsilon_{xstored}$ (stored) =6 nm

ε_{xinj} (injected) =40 nm

$\sigma_{xstored}$ at septum (stored) = 1.1 mm

σ_{xinj} at septum (injected) = 1.1 mm

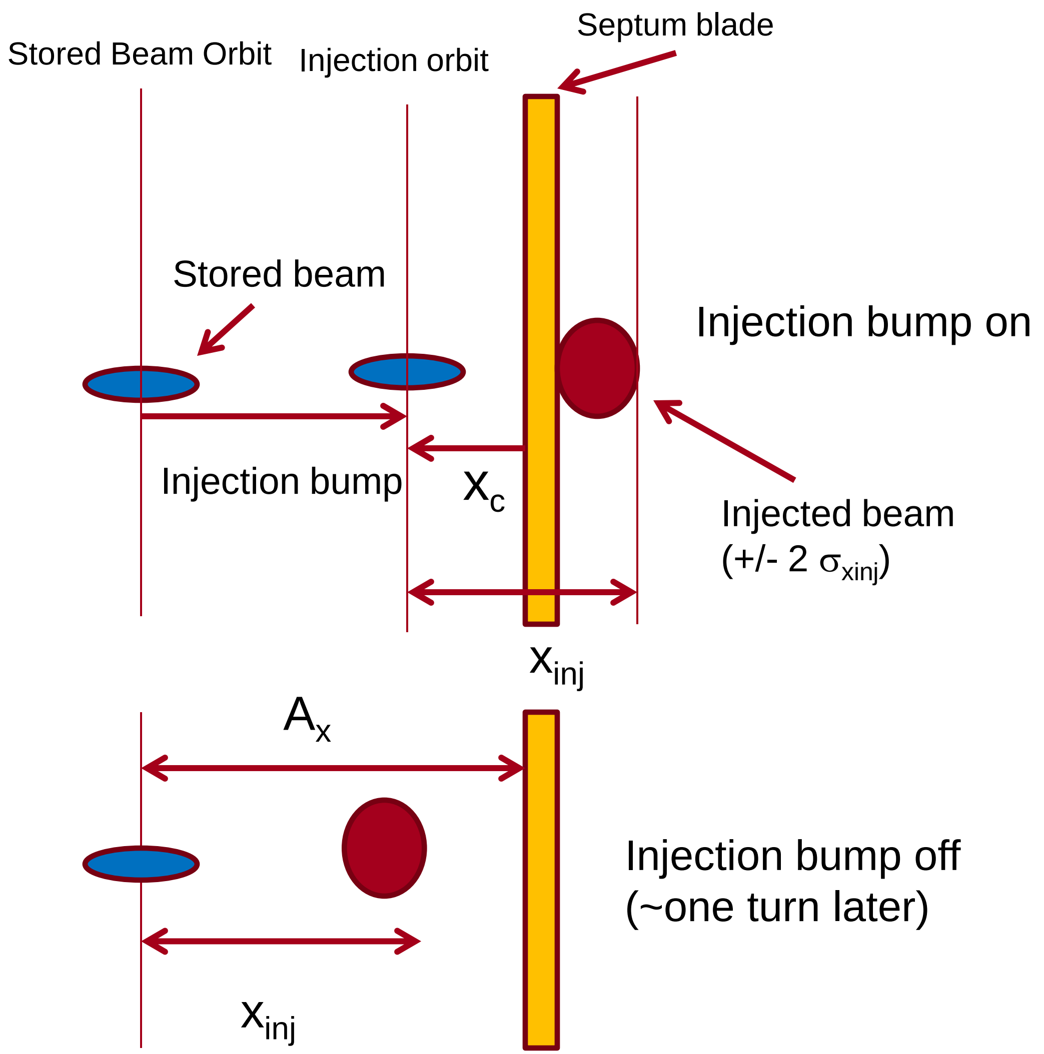
X_s = Septum blade thickness =~ 5 mm

X_c = septum clearance distance = ~6σ_x

Xinj < A_x

Xinj = 4σinj+X_s+Xc = ~16 mm

A_x = machine aperture > ~20 mm



Technical Items Needed for Full Energy Top-Up injection

1) Measure each bunch charge in real time and determine when it needs refilling.
2) In the injector, time each bunch to deliver it to the needed particular bunch (bucket) in the ring.
3) Inject the bunch(es) into the collider with very low losses.
4) Determine the injected beam backgrounds in the particle physics detector and find cures using collimation.
5) Develop methods to monitor relevant backgrounds in real time for accelerator operators to tune on.
6) Develop trigger masking for the detector physics taking by turn and with azimuthal variation.

Option 1: "Ramped Storage Ring" as a HF Injector

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Top-up injection = 50 bunches / pulse / beam

Slow ramp due to magnet laminations

Injection rate: Once every 4 minutes.

Particles per ring injection: ~10^{12} / pulse

Particles per injected bunch: 2 x 10^{10} / pulse

Bunch injection controller: Fill all bunches at once

Tailor each bunch separately.

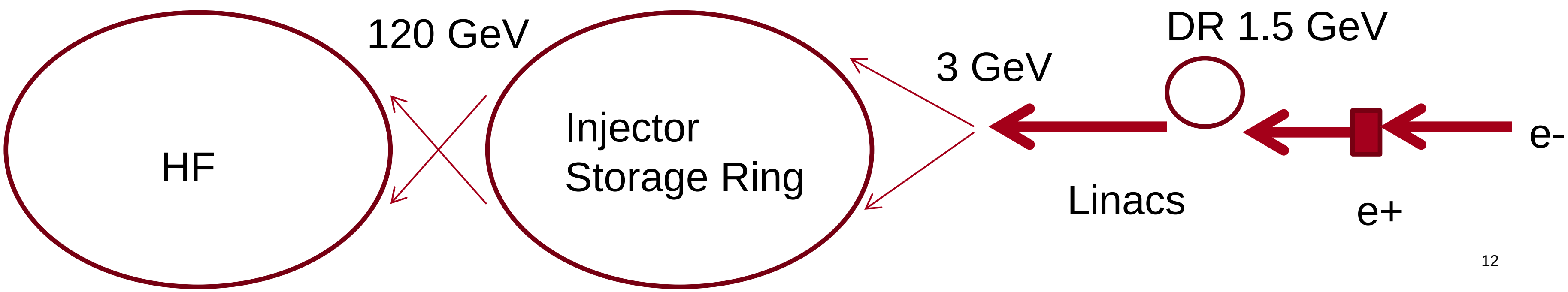
Ring path length = 182 to 333 μsec.

Injection kicker pulse length = 182 to 333 μsec.

Kickers = 13 stronger than PEP-II but long flat top

CERN LEP: 26.7 km
Ramping speed is 0.5 GeV/sec
→ 120 GeV in 4 minutes.

→ Luminosity varies from 100% to 74% over 8 minutes with 4 minutes per ring.



Option 2: "Fast Cycling Synchrotron" as a HF Injector

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For Higgs Factory Injector:

Top-up injection = 50 bunch / pulse

Cycle rate = 0.067 to 0.1 Hz

Injection rate: 0.033 or 0.05 Hz e+, 0.033 or 0.05 Hz e-

Particles per injection: 3×10^{11} / pulse over 50 bunches with 90% injection efficiency

→ ~10^{10} /bunch → means low instability effects.

Bunch injection controller: Tailor the charge of each bunch

Magnet laminations same as AC transformers.

Injection kicker pulse length = 183 to 333 μsec

Kickers = 10-20 stronger than PEP-II but 7 times slower.

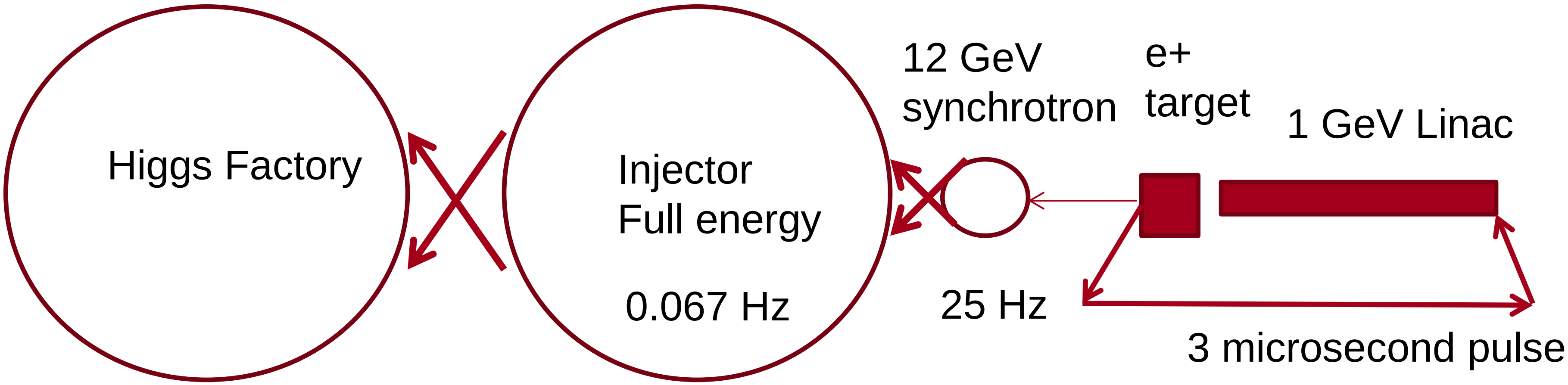
Ring path length = 183 to 333 μsec

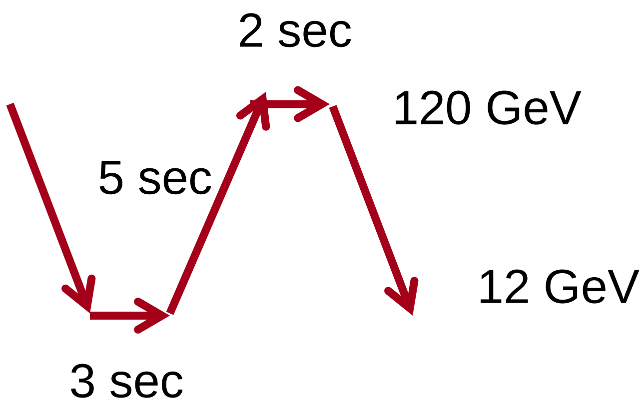
→ Luminosity stays within 1% of the peak.

Example:
Cornell synchrotron: 768 m
Sine wave-magnet excitation
0.2 GeV to 12 GeV in
8.3 msec at 60 Hz.
Does not affect CESR storage ring operation just 1.3 m away.

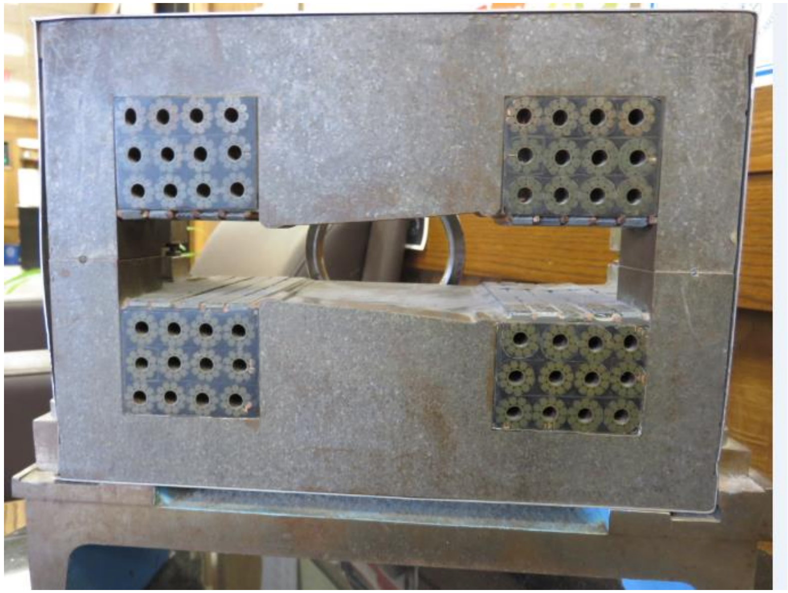
e-

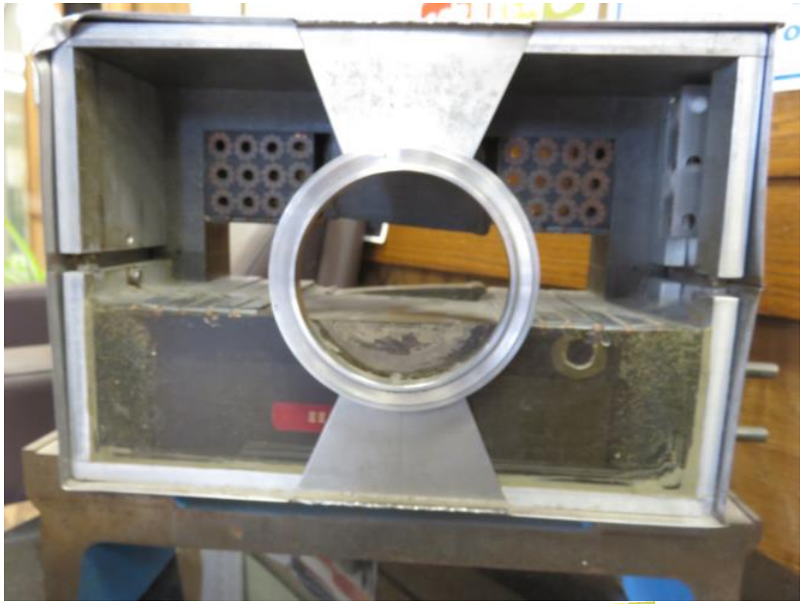
Synchrotron Injector Layout

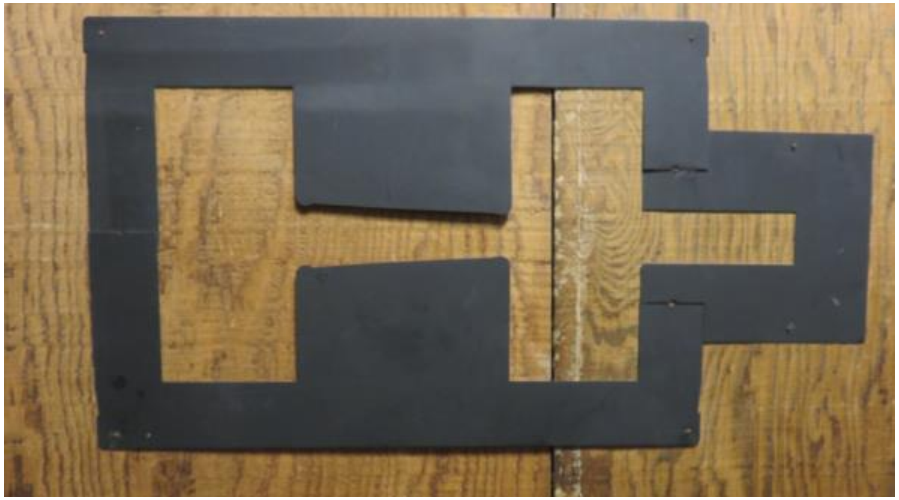




Cornell Synchrotron Combined Function Magnets (60 Hz)







Cornell Synchrotron Parameters

Energy range 10-20 GeV, ran up to 12 GeV

Circumference = 757 m

T0 = 2.53 microseconds

Number of magnets = 192

Length of magnets = 3.23 m

Magnetic field at 10 GeV = 3.3 kG (4 kG at 12 GeV)

Gap height (vert focusing) = 38 mm

Gap height (horiz focusing) = 26 mm

Current at 10 GeV = 424 Amp (508 Amp at 12 GeV)

Inductance = 8.7 or 5.8 mH (h or v)

Capacitance per magnet = 1.94 mF

Phase advance per cell = 75.4 degrees

RF frequency = 714 MHz

Vacuum pressure = 10^{-6} torr.

Total power at 10 GeV = 360 kW (D.C.) + 180 kW (A.C.) + 230 kW (misc) = 770 kW.

Reference:

R. R. Wilson, “The 10 to 20 GeV Cornell Electron Synchrotron” CS-33 May 1, 1967.

How to modify the 12 GeV Cornell Synchrotron for HF injector at 120 GeV (54 km)

1) Build 10 x number of Cornell magnets (620 m to 6200 m) to get to 120 GeV.
2) Space each lamination by a factor of 7 (6200 m to 46,000 m) with same beam energy.
3) The bending radius is 7325 m so loss per turn is 2.4 GeV.
4) The magnets are combined function so no extra quadrupoles are needed.
5) Need to check anti-damping.
6) The field is reduced from 4000 gauss to 500 Gauss at 120 GeV.
7) Magnetic field at injection (12 GeV) is 50 gauss.
8) Residual field in Cornell magnets is 2 gauss at minimum energy. Lower for HF with spaced laminations.
9) Mount the laminations on a strong back to keep the magnet straight. No concrete.
10) The ramp rate is low (5 sec) so an extruded aluminum vacuum chamber can be used using NEG strip pumping and holding ion pumps similar to PETRA-4.
11) The coil current is still 508 A at 24 turns. Due to lower eddy currents, a new coil configuration can likely use solid bus bars with cooling holes to reduce power losses.

How to modify the 12 GeV Cornell Synchrotron for HF injector at 120 GeV (100 km)

1) Build 10 x number of Cornell magnets (620 m to 6200 m) to get to 120 GeV.
2) Space each lamination by a factor of 14 (6200 m to 87,000 m) with same beam energy.
3) The bending radius is 13,850 m so loss per turn is 1.4 GeV.
4) The magnets are combined function so no extra quadrupoles are needed.
5) Need to check anti-damping.
6) The field is reduced from 4000 gauss to 256 Gauss at 120 GeV.
7) Magnetic field at injection (12 GeV) is 26 gauss.
8) Residual field in Cornell magnets is 2 gauss at minimum energy. Lower for HF with spaced laminations.
9) Mount the laminations on a strong back to keep the magnet straight. No concrete.
10) The ramp rate is low (5 sec) so an extruded aluminum vacuum chamber can be used using NEG strip pumping and holding ion pumps similar to PETRA-4.
11) The coil current is still 508 A at 24 turns. Due to lower eddy currents, a new coil configuration can likely use solid bus bars with cooling holes to reduce power losses.

Required RF System for a 15 second ramp time

For the rapid cycling synchrotron:

Synchrotron radiation loss per turn is 1.3 to 2.4 GeV at 120 GeV.

With 5 sec ramp, need 3.8 MeV gain per turn to accelerate the beam.

Small compared to the SR losses.

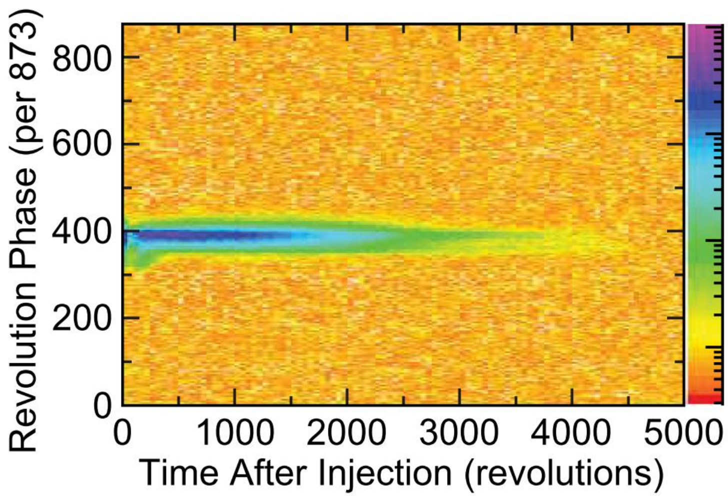
To have quantum lifetime the RF needs about 2.0 to 3.4 GeV total.

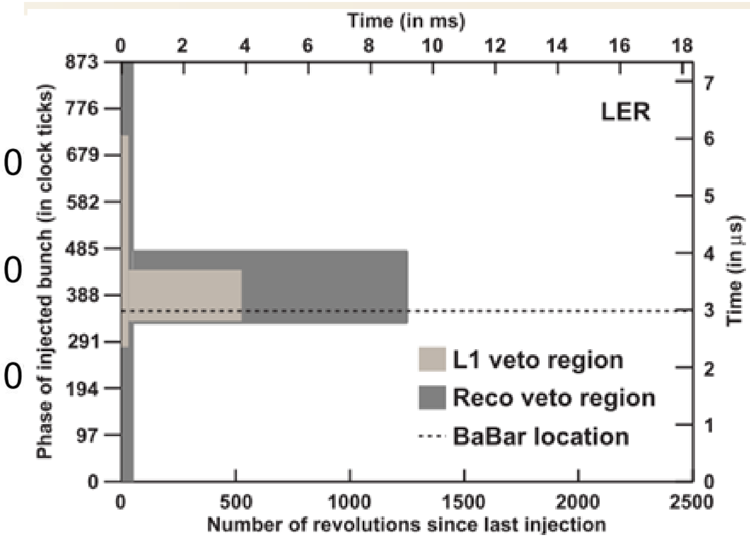
Relative to the collider, the beam loading is small as the current is 10 times smaller (and only one beam).

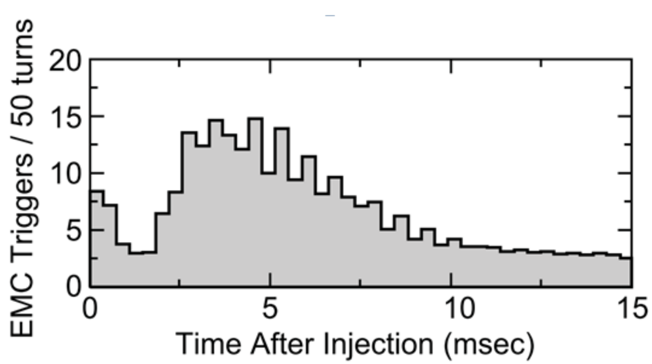
RF system similar to the LCLS one in length but simpler and high power beam only 3 seconds out of 15 for a 20% duty cycle.

Detector Masking: PEP-II/BaBar Top-Up Injection and Detector Trigger Masking

One turn







BaBar trigger masking:
Mask all of ring a few tens of turns.
Mask injected bunch area for 1250 turns or about 0.9 msec.

Similar for HF detector.

Conclusions

A full energy injector is needed because of beam lifetime.

A synchrotron injector will work the best as it easily meets what is needed (cycle time 15 sec). The luminosity is constant to better than 1%. RF system is smaller and needs much less power than the collider ring.

However, a slowly ramped storage ring injector (minutes) does work but doesn’t really make the luminosity constant enough.

The detectors will need to mask out the buckets with damping injected bunches during data taking.