Considerations on TLEP (top-up) injection

C.Bracco, B.Goddard
CERN TE/ABT

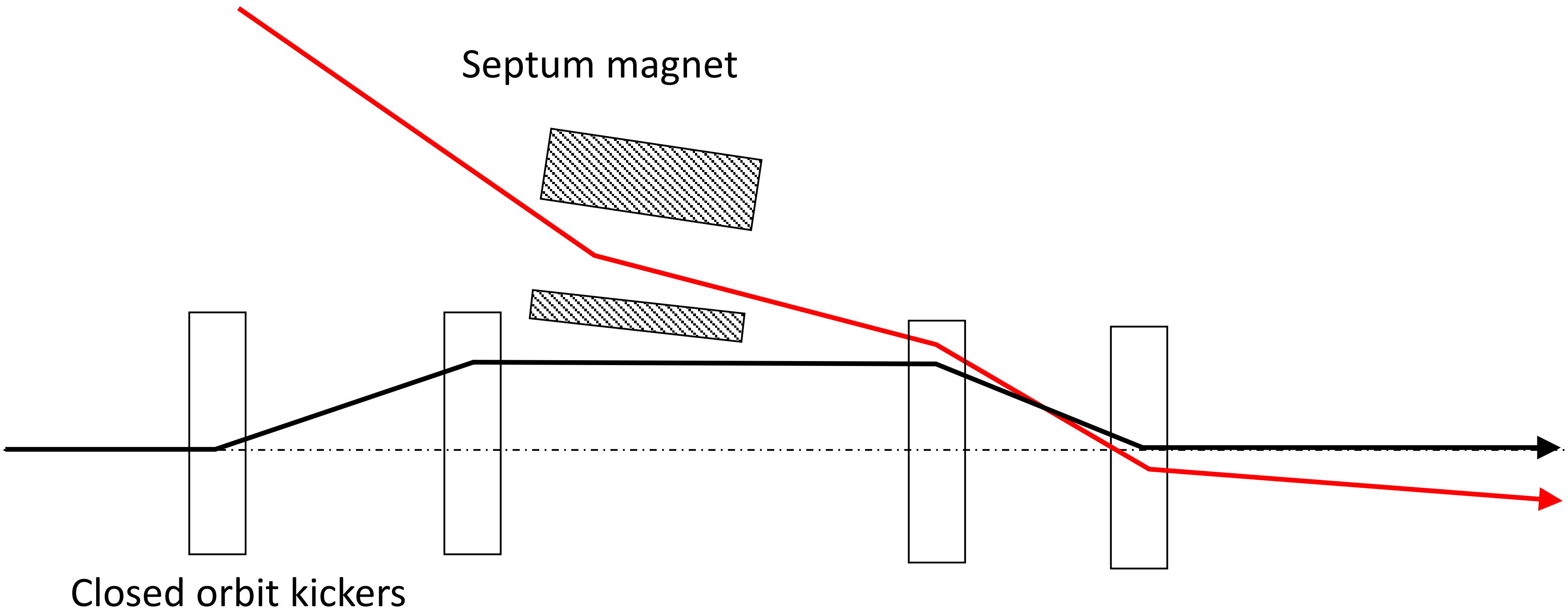
And thanks to Frank Z. for valuable input and discussion

Contents

- Injection options
- Key TLEP parameters
- Bump heights and momentum offset for synchrotron injection
- Specific features of top-up injection
- Outline component specifications
- Challenges and potential issues
- Directions for future study

Injection options

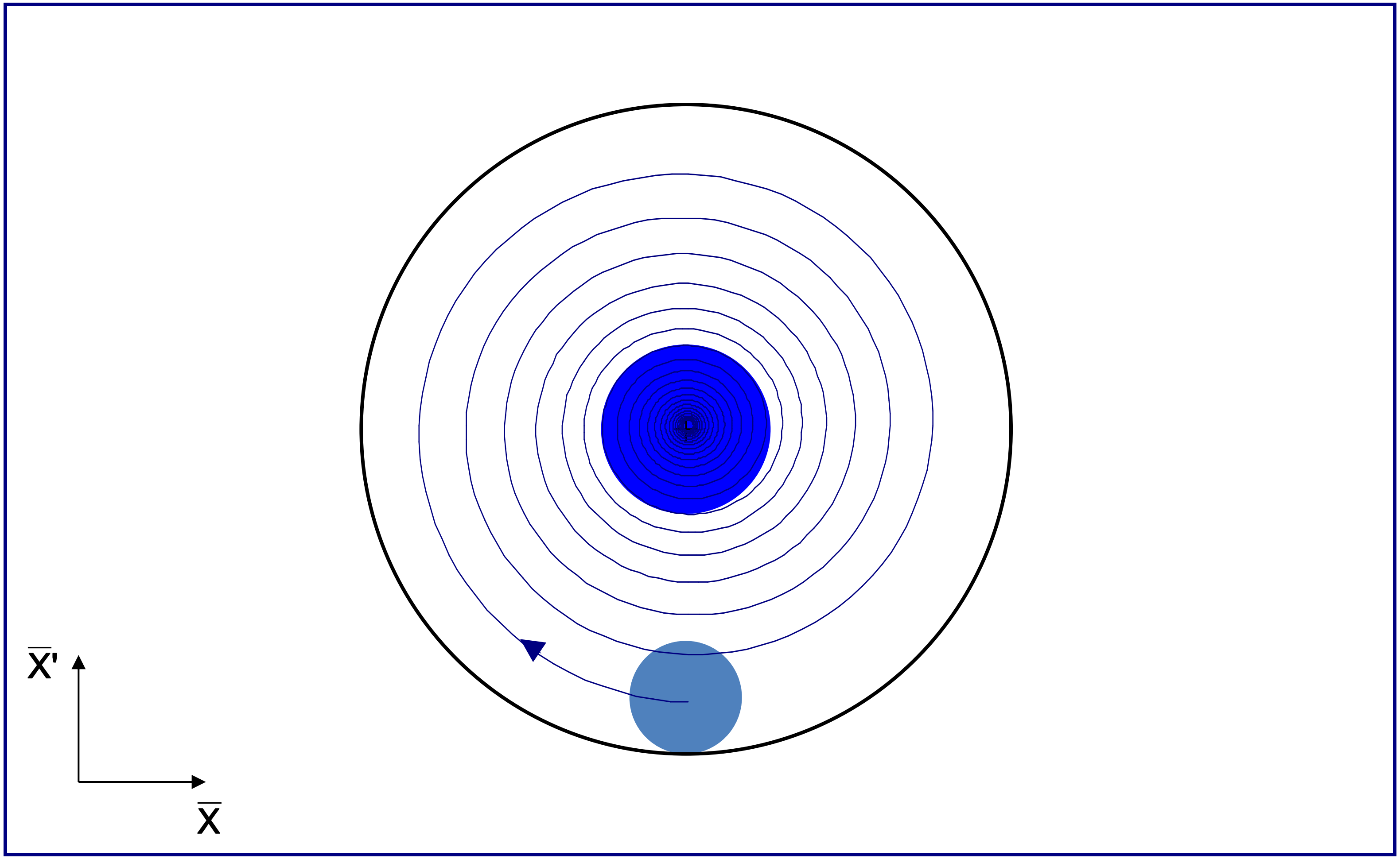
- Conventional ‘betatron’ e+e- injection



- Beam is injected with a position/angle offset with respect to the closed orbit
- Injected beam performs damped betatron oscillations about the closed orbit

Betatron injection

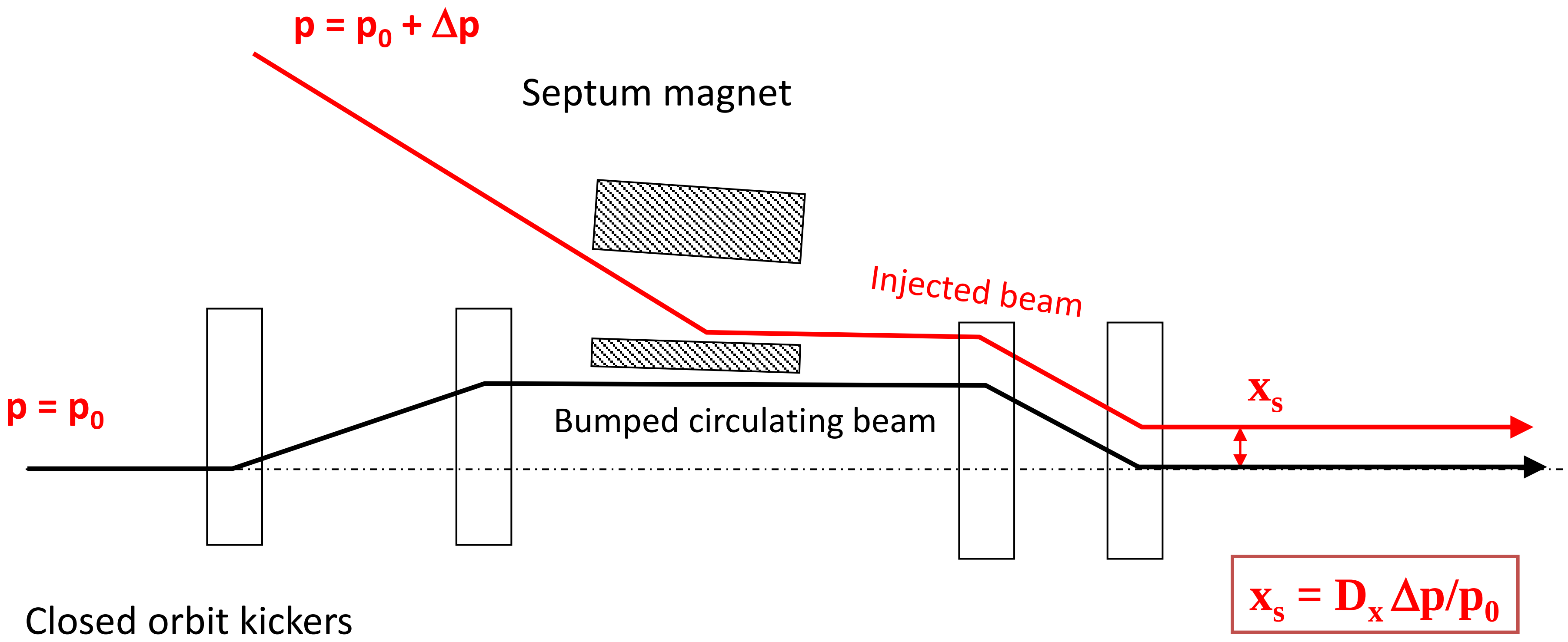
Injected bunch performs damped betatron oscillations



In LEP at 20 GeV, the damping time was about 6’000 turns (0.6 seconds)

Injection options

- 'Synchrotron' e+e- injection: inject off-momentum

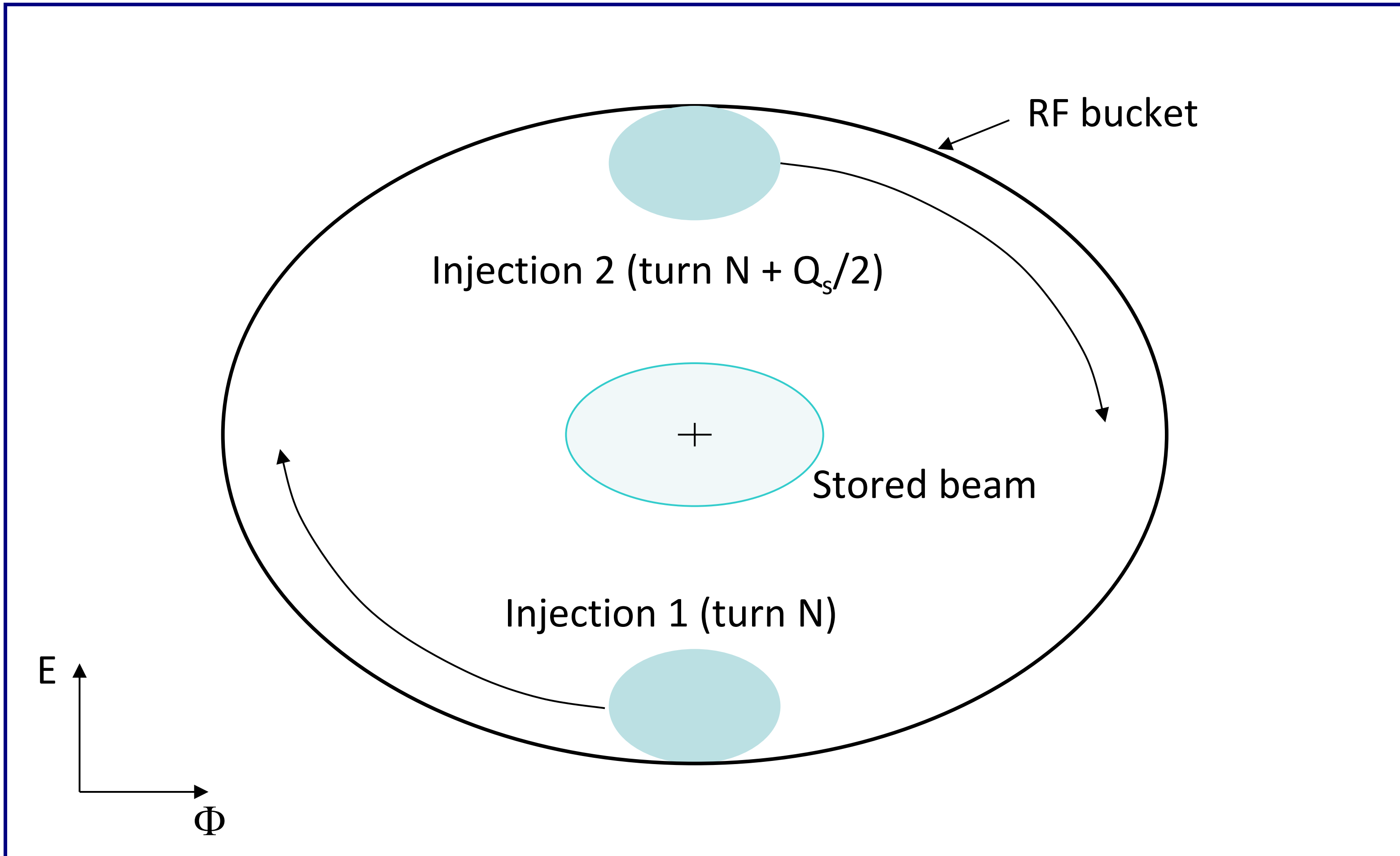


$x_s = D_x \Delta p/p_0$

- Beam injected parallel to circulating beam, onto matched dispersion orbit of a particle having the same momentum offset $\Delta p/p$.
- Injected beam makes damped *synchrotron oscillations* at Q_s but does not perform betatron oscillations.

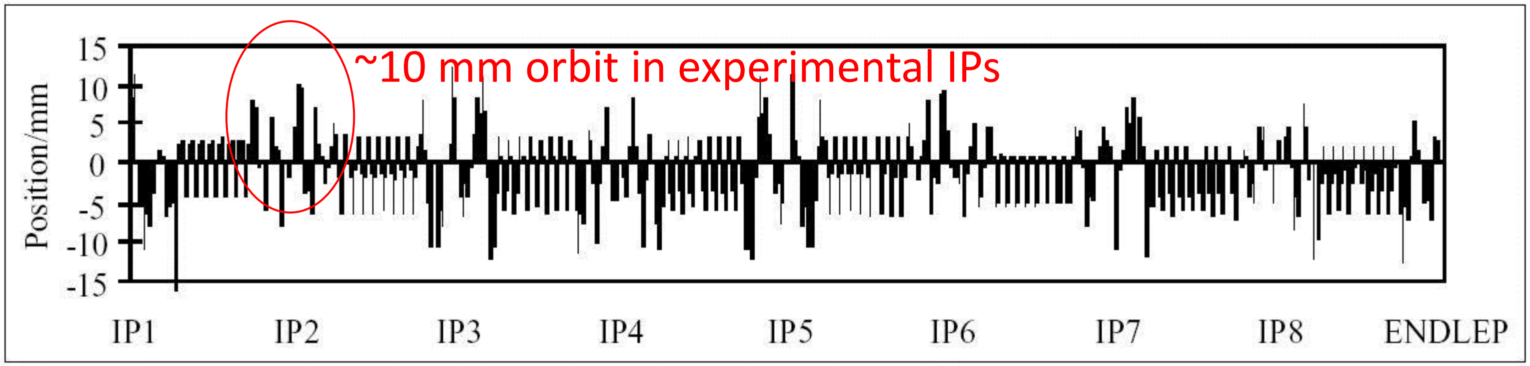
Synchrotron injection

Double batch injection possible….



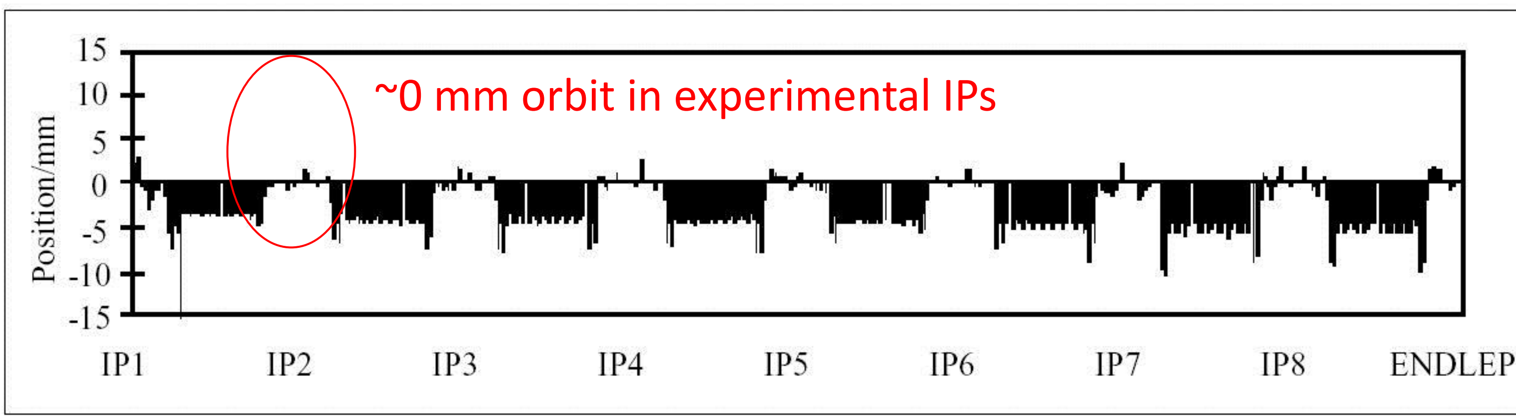
Longitudinal damping time in LEP was ~ 3' 000 turns (2 x faster than transverse)

Synchrotron injection could be big advantage for TLEP



Optimized Horizontal First Turn Trajectory for Betatron Injection of Positrons into LEP.

P.Collier et al.

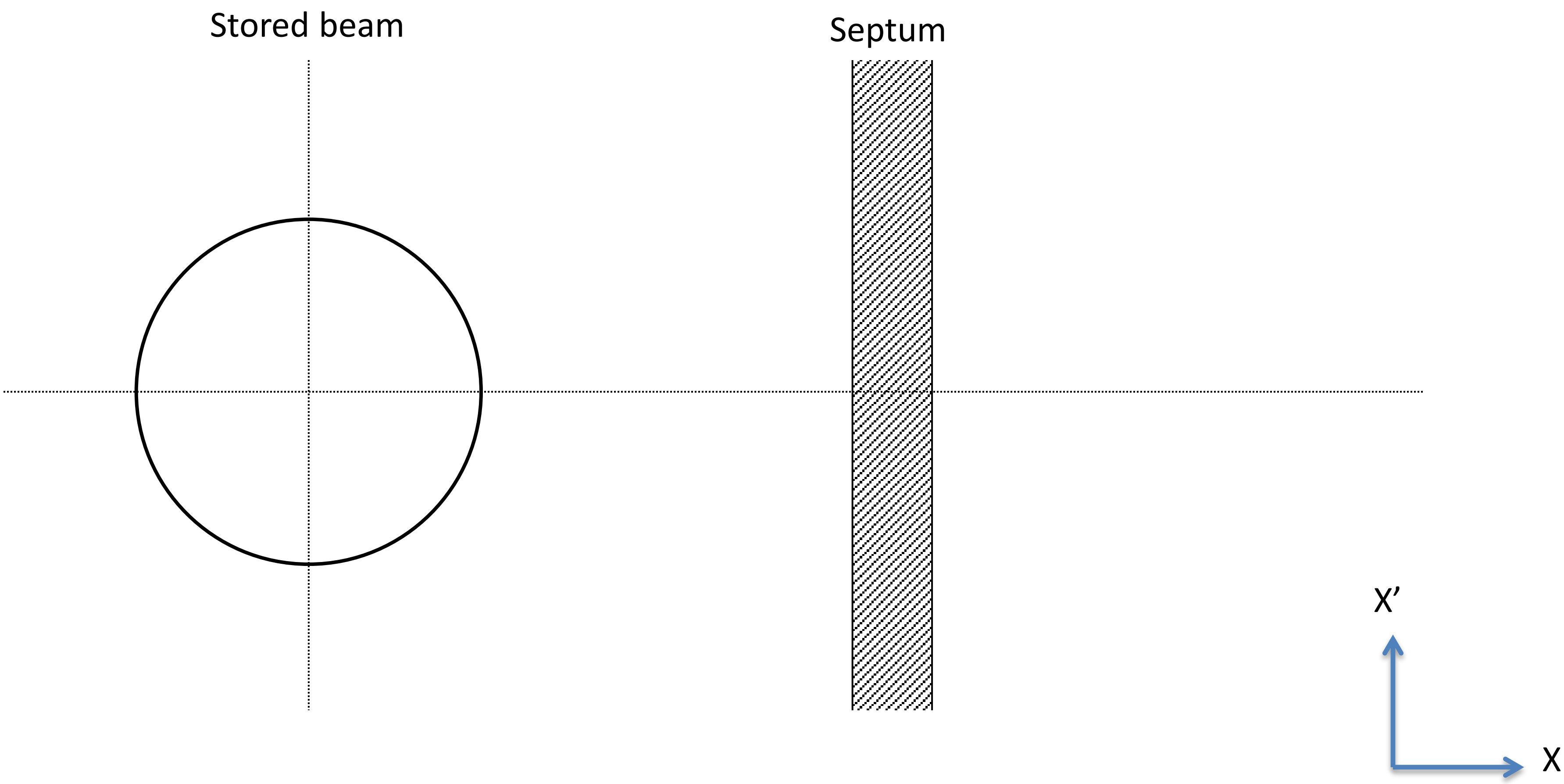


Optimized Horizontal First Turn Trajectory for Synchrotron Injection of Positrons with $\Delta P/P$ at -0.6%

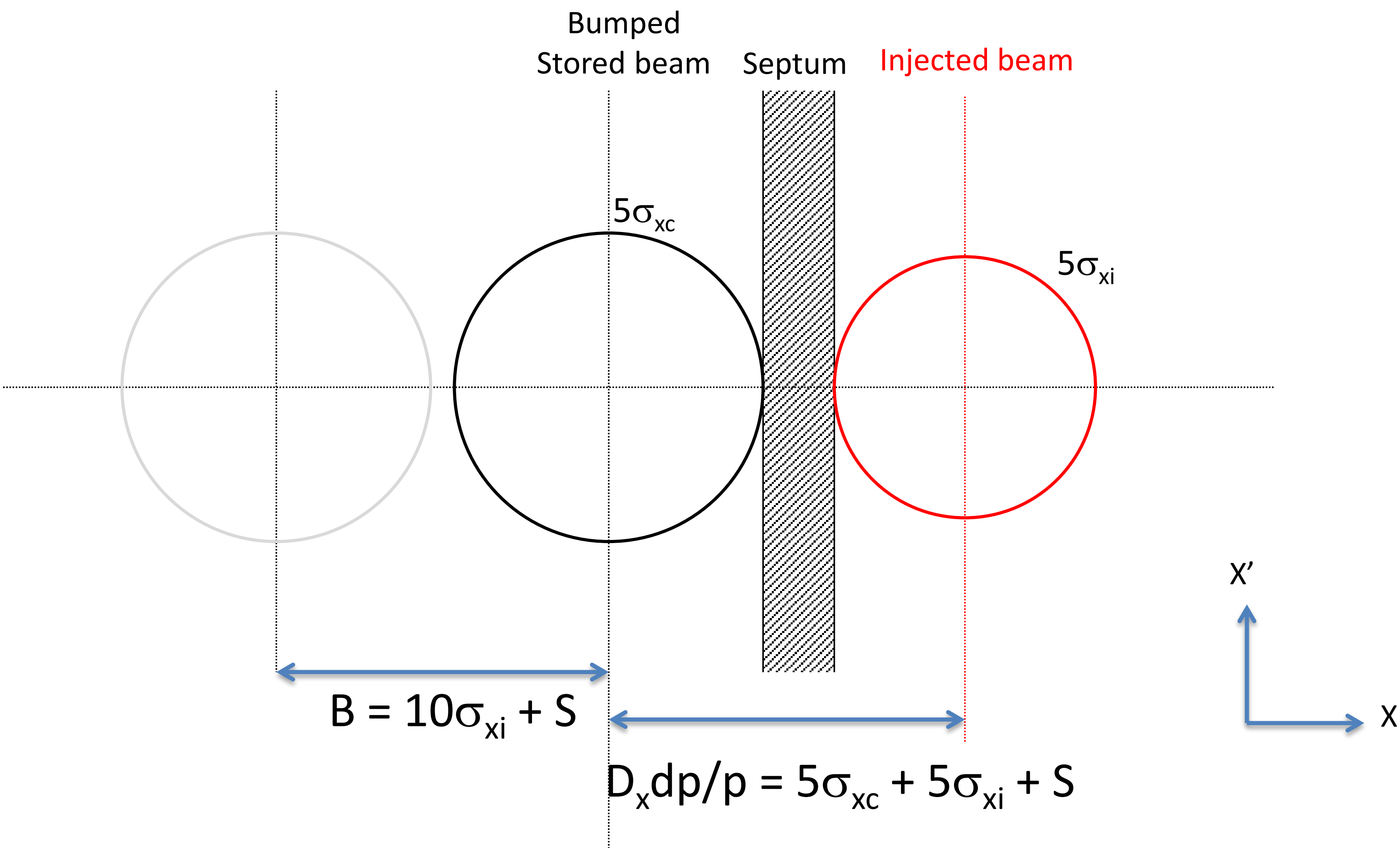
Synchrotron Injection in LEP gave improved background for LEP experiments due to small orbit offsets in zero dispersion straight sections

Synchrotron injection: Defining bump height, dispersion and dp

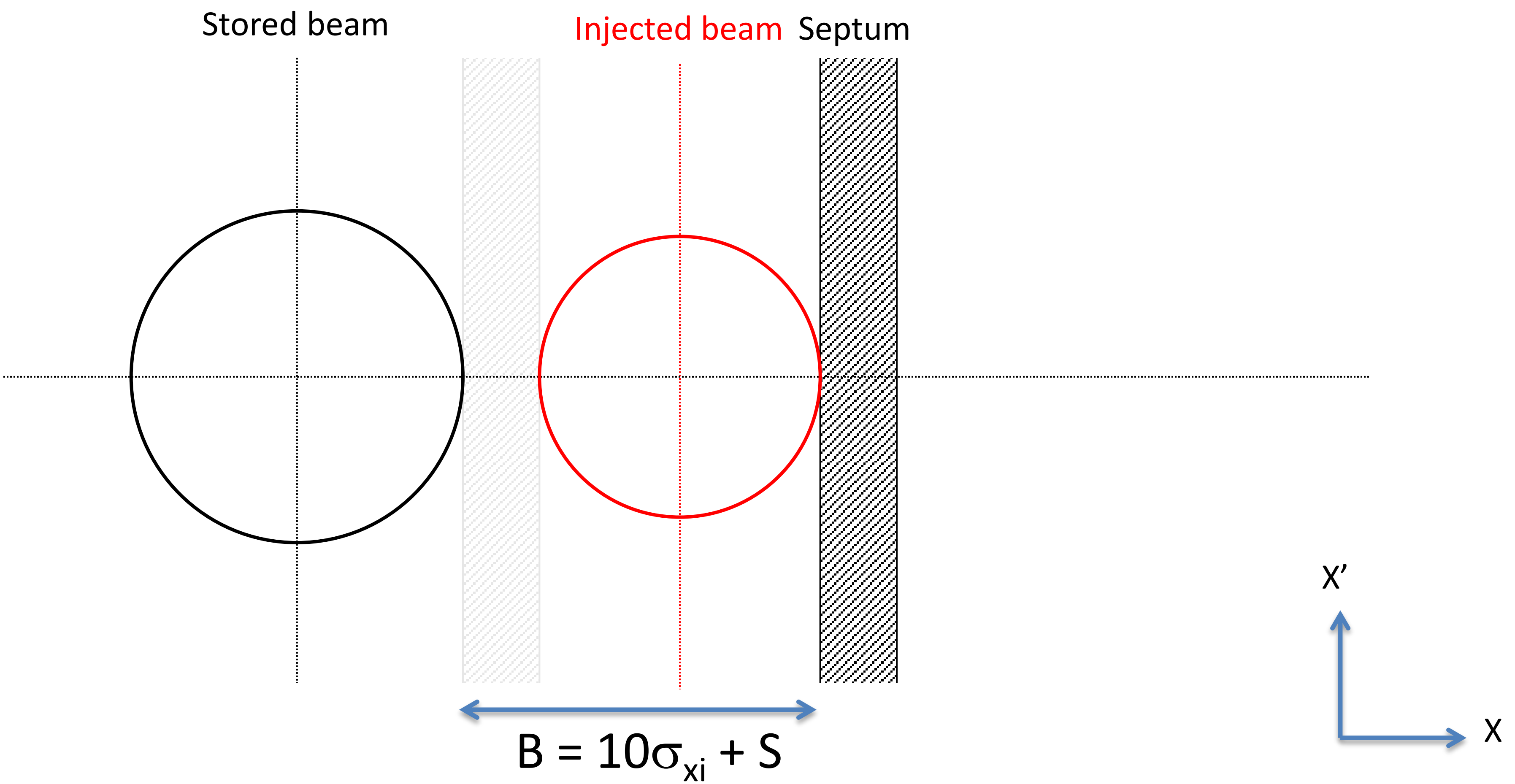
Before injection process



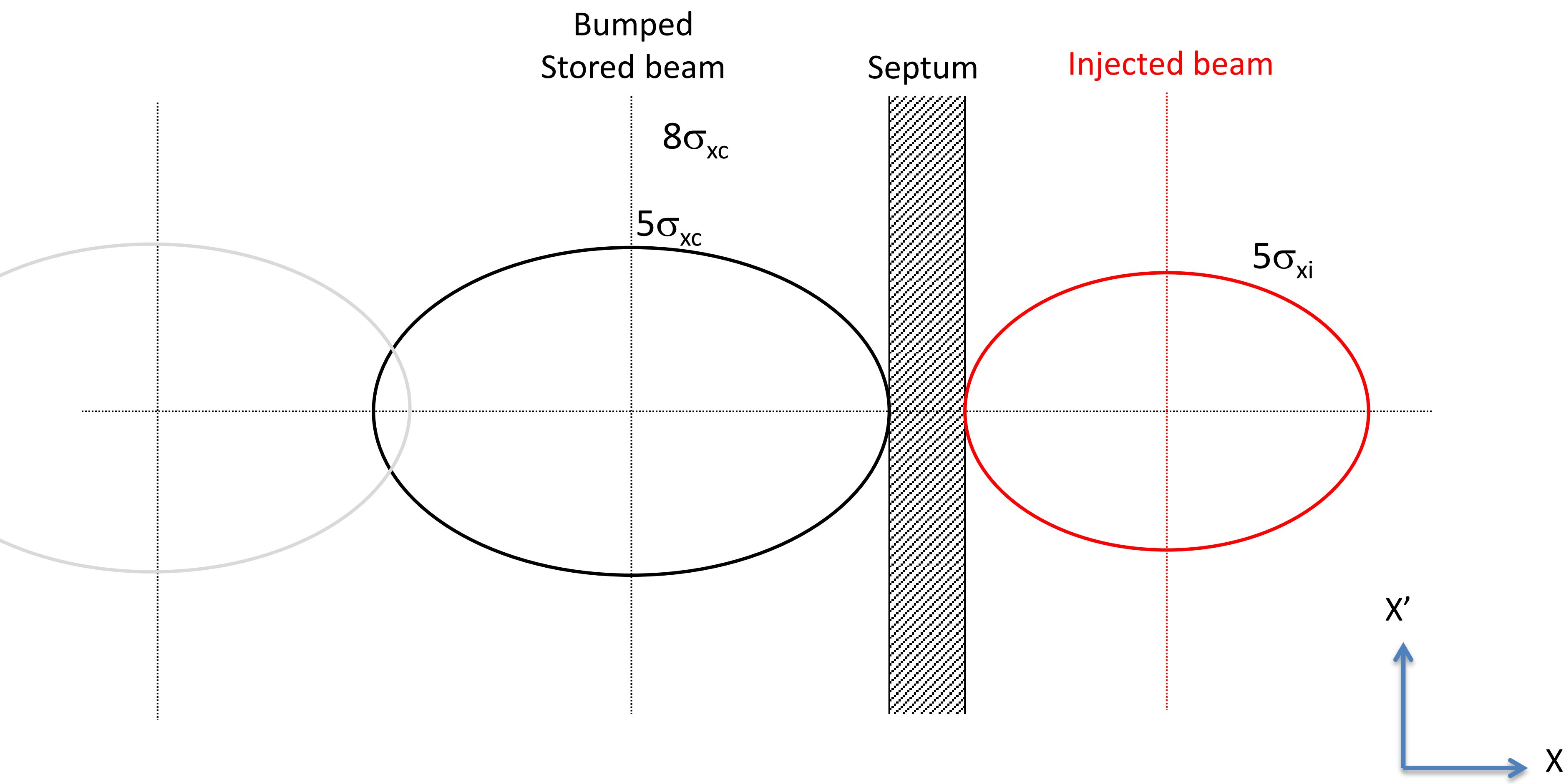
At moment of injection (bump at full amplitude)



Next turn (bump off)



Problem comes with large momentum spread…as will be seen

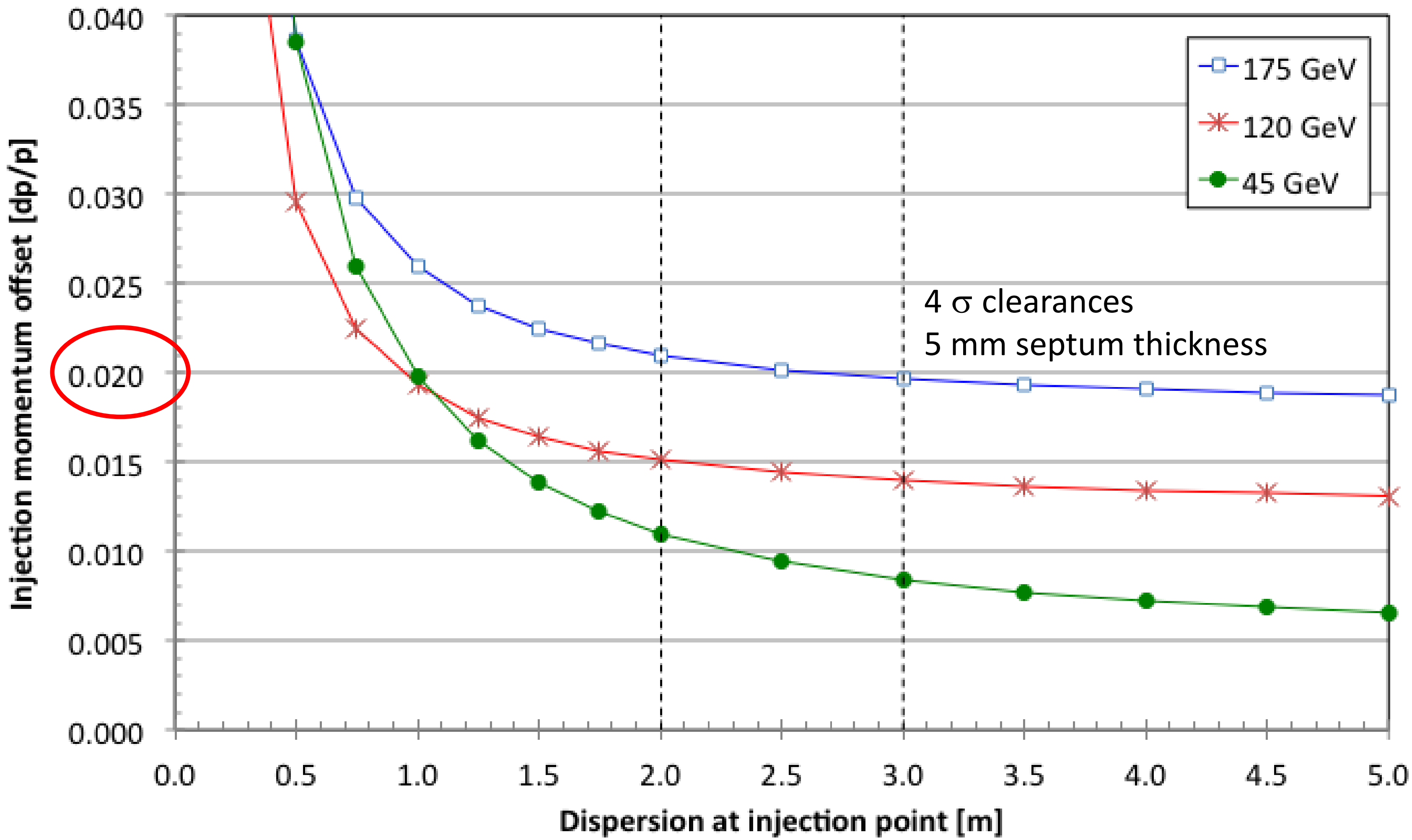


Key parameters for TLEP injection

	LEP2	LHeC	LEP3	TLEP-Z	TLEP-H	TLEP-t
beam energy E_b [GeV]	104.5	60	120	45.5	120	175
circumference [km]	26.7	26.7	26.7	80	80	80
beam current [mA]	4	100	7.2	1180	24.3	5.4
#bunches/beam	4	2808	4	2625	80	12
#e-/beam [10^{12}]	2.3	56	4.0	2000	40.5	9.0
horizontal emittance [nm]	48	5	25	30.8	9.4	20
vertical emittance [nm]	0.25	2.5	0.10	0.15	0.05	0.1
bending radius [km]	3.1	2.6	2.6	9.0	9.0	9.0
partition number J_ε	1.1	1.5	1.5	1.0	1.0	1.0
δ^{SR}_{rms} [%]	0.22	0.12	0.23	0.06	0.15	0.22
$\sigma^{SR}_{z,rms}$ [cm]	1.61	0.69	0.31	0.19	0.17	0.25
L/IP[$10^{32}cm^{-2}s^{-1}$]	1.25	N/A	94	10335	490	65
number of IPs	4	1	2	2	2	2
Rad.Bhabha b.lifetime [min]	360	N/A	18	37	16	27
Υ_{BS} [10^{-4}]	0.2	0.05	9	4	15	15
n_γ/collision	0.08	0.16	0.60	0.41	0.50	0.51
$\Delta\delta^{BS}$/collision [MeV]	0.1	0.02	31	3.6	42	61
$\Delta\delta^{BS}_{max}$/collision [MeV]	0.3	0.07	44	6.2	65	95

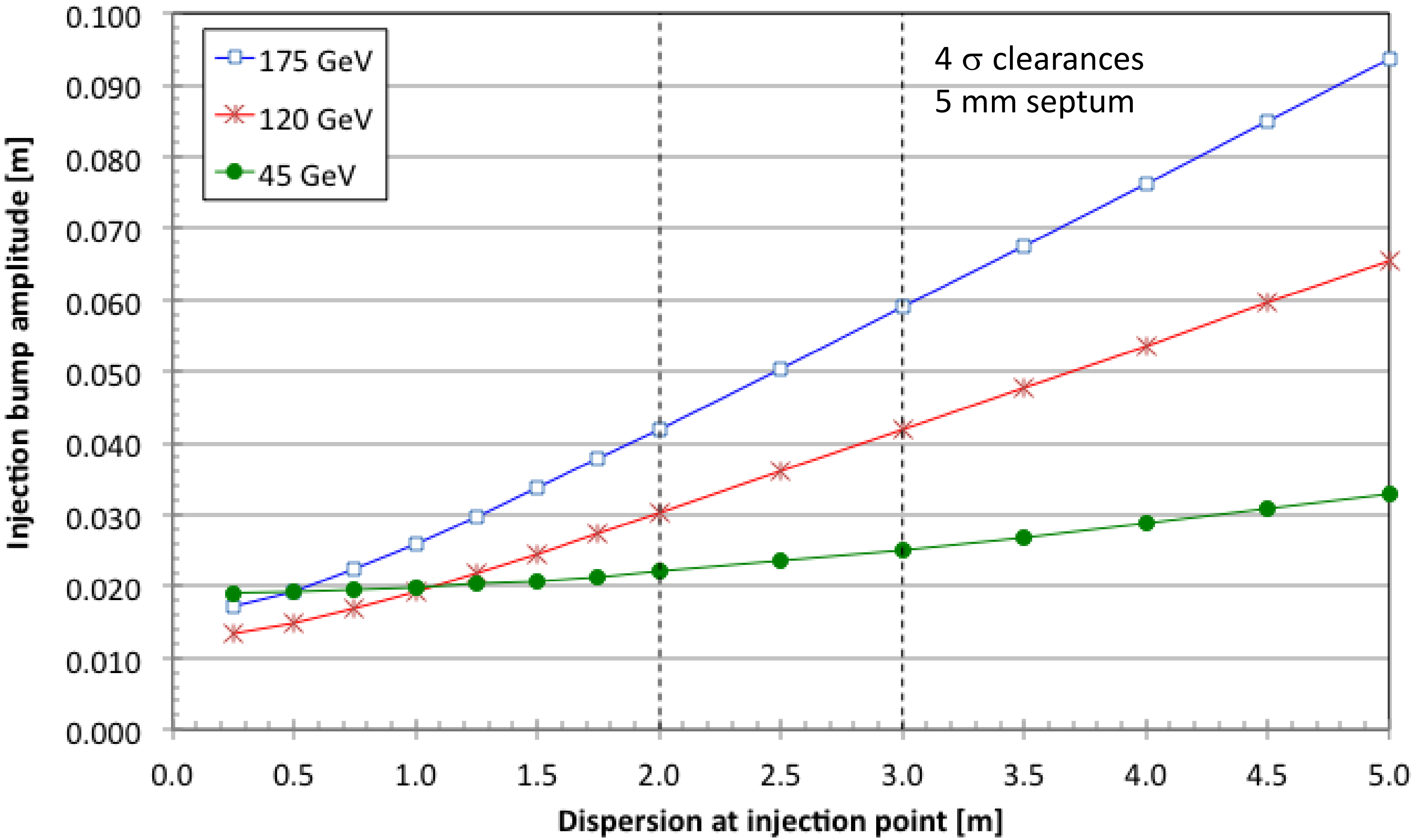
Synchrotron injection gets difficult for higher energies due to momentum spread δp/p!

At 175 GeV would need to inject with 2% momentum offset…



…and basically no gain with larger dispersion

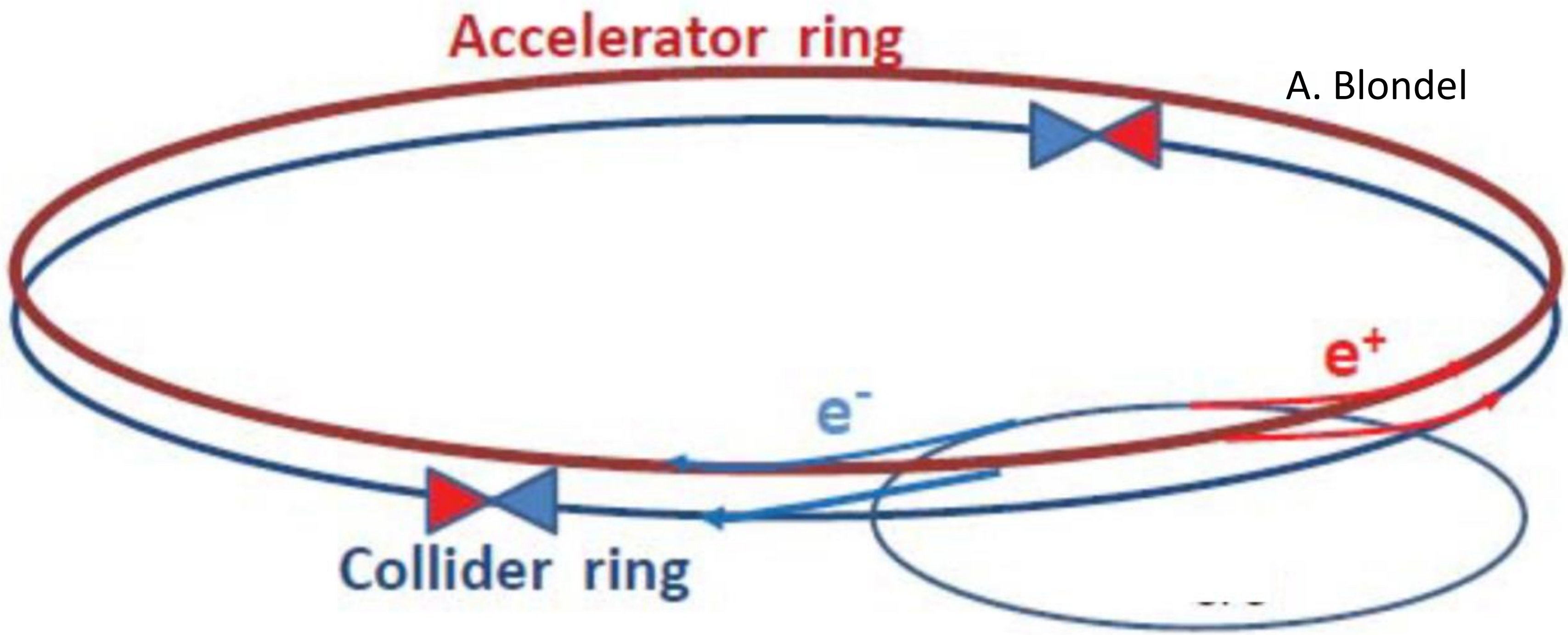
Injection bump amplitude increases with Dx



circular HFs – top-up injection

double ring with top-up injection

supports short lifetime & high luminosity



top-up experience: PEP-II, KEKB, light sources

Top-up injection: 'standard' for light sources, PEP-II and KEKB

Two Operating Modes

		Stability	Number of shots	Time between injection	
Injection at fixed Delta I	SPring 8	0.03 %	One	≈ 2 to 3 mn *Hybrid 10 to 30 sec*	One shot
	Bessy	0.13 %	One	≈ 20 to 30 sec	
	Soleil	0.5 %	One	≈ 2 to 5 mn	
	Elettra	0.3 %	20 shots	*≈ 6 mn at 2 GeV* *25 mn at 2.5 GeV*	Few shots
	SLS	0.5 %	10 shots	≈ 1 to 2 mn	
	Petra	1 %	40-50 low charge shots	≈ 8 mn *1 mn (timing mode)*	
Injection at fixed Delta Time	APS	≈ 0.5 %	One	1 and 2 mn	One shot
	Diamond	≈ 0.8 %	Few	10 mn	Few shots
	ESRF	≈ 20%	400	12 hours	

Adapted from J.L.Revol, ESRF

Top-up injection assumptions (for starting point)

- SPS accelerates to ~20 GeV
- 8 bunches of 2.5e10 per injection into SPS, 1.2 sec SPS cycle, gives 1.6e11 leptons per sec
  - Alternating e+ and e- cycles
- 1,2,… n SPS injections into AR
- 6 s AR ramp up/down period (faster? – especially for lower energy?)
- 100% injection efficiency…

Top-up injection - Imax

- Peak achievable CR current limited by throughput of injectors
- Need to accelerate and inject at a rate of at least $I_{inj} = I_{tot} / \tau$ (loss rate of e+/e- at t=0)
- Need to fill both e- and e+…lose a factor 2
- Issue for TLEP-z, since I_{max} = 2e15 e+e-!!
  - 1e11 e+/sec implies τ = 5.5 *hours*
  - Need τ = 11 hours if filling both beams!

TLEP-t injection scenario

- CR: 12 bunches, ~20 us spacing, Itot 9e12 e+/e-
- Fill AR with 24 bunches
- 24x AR->CR single bunch injections (into 12 bunches) per top-up
- AR extraction and CR injection kicker rise/fall time can be many us, flat-top maybe 10 ns (depends on synchronisation and stability)?
  - 3 SPS cycles, 3.6 sec, 24 bunches in AR, double-batch synchrotron injection
  - Imax = 1e14 e+/e- (filling either e+ or e-)
  - Imax/Itot = 5.6 (filling both e+ and e-). Good margin
  - Blind-out time for experiments 3% of data taking time, assuming 100 turns blind-out per injection, every ~10 sec. Could maybe improve by 'burst mode' for kickers?
- Looks comfortable with 12x (or 24x) single bunch transfer AR->CR per ~10 s

TLEP-h injection scenario

- CR: 80 bunches, ~3 us spacing, Itot 4e13 e+/e-
- 20 AR-CR injections of 4 bunches each per top-up: AR extraction and CR injection kicker rise/fall time <3 us, flat-top around ~10 us
  - Imax/Itot of 1.3 – little margin
  - 3% of data taking time lost, again assuming 100 turns blind-out per injection, every 18 sec. Again would improve with burst mode kicker
- Alternative to make 80x single bunch transfers
  - Advantage of short kicker flat top
  - Would rely on kicker in burst mode (otherwise 12% of data taking lost)
- At the limit with ~20x AR->CR transfers of ~8 bunches every ~20 sec – very little margin for lower CR lifetime
  - Need to push Ib or nb up in SPS – RF power?

TLEP-z injection scenario

- CR: 2625 bunches, ~100 ns spacing, Itot 2e15 e+/e-
- Maybe fill ~100 bunches per AR cycle (12 SPS injections) and then 1 injection per top-up:
- AR extraction and CR injection kicker rise/fall time few hundred ns, flat-top around ~20 us
  - Imax = 2.6e14 e+/e- (filling either e+ or e-)
  - Imax/Inom = 0.07 (filling both e+ and e-)
- Not feasible with SPS as injector (8b of 2.4e10 every 1.2 sec)
- Need about a factor 18-20 increase somewhere in the lepton injection

Injection kicker strengths/rise times

- Arrange main kickers at ±90 deg from septum
  - 4 kickers forseen for angle/position control
- Take 100 m βx at kickers and septa (more would be better)
- Bump heights taken for 2.5 m Dx
- Kick strengths then 0.3 – 0.5 mrad per magnet
- Rise times: few hundred ns for 45 GeV, otherwise anything below a few us.

CR Injection requirements

	45 GeV	120 GeV	175 GeV
Bunches	2625	80	12
Bunch spacing (us)	0.1	~3	~20
Lifetime (min)	37	16	27
I_{tot} (e+e-)	2e15	4e13	9e12
I_{tot} / τ (e+e-/sec)	9e11	4.2e10	5.6e9
Rigidity (Tm)	151	400	583
Kicker Rise time (us)	0.5 ?	<3	<20
Kicker Flat-top (us)	20 ?	0.01 /10?	0.01
Bump height (mm)	24	36	50
Kicker strength (mrad)	0.3	0.4	0.5
Dx at injection (m)	2.5	2.5	2.5
dp/p offset (injected)	0.020	0.015	0.009

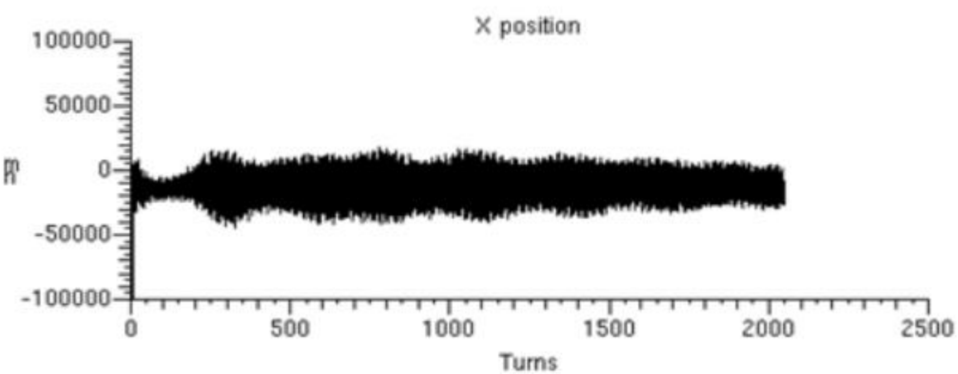
Possible kicker parameters…?

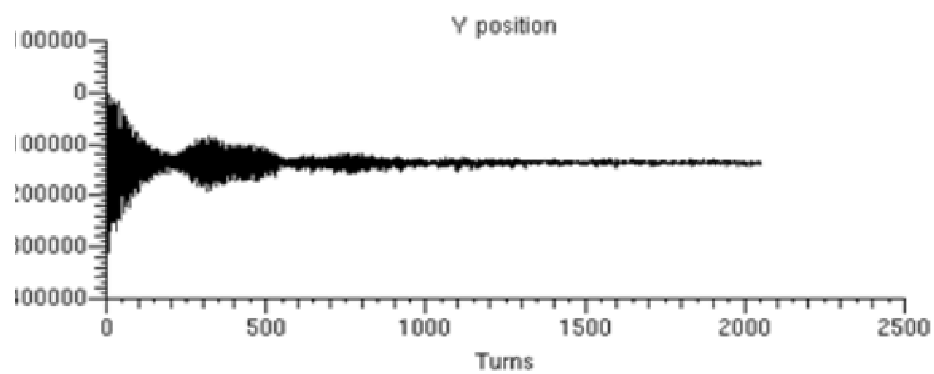
TLEP version		175 GeV	120 GeV	45 GeV
Rigidity	Tm	583	400	151
Impedance	Ohm	5	5	5
Type		SC	SC	Terminated
Aperture height	mm	61	61	61
Aperture width	mm	100	100	100
Chosen magnet length	m	3.6	1.8	0.9
Filling time per magnet	ns	3909	1954	489
Unit -length inductance	µH/m	2.7	2.7	2.7
Magnet inductance	nH	9.6	4.8	2.4
Current	kA	5	5	2.5
Mag. Flux Density	mT	103	103	51.5
B.dl per magnet	Tm	370.8	185.4	46.35
Deflection per magnet	mrad	0.636	0.464	0.307
Number of magnets required		1	1	1
Total deflection	mrad	0.64	0.46	0.31
Total magnetic length	m	3.6	1.8	0.9
Voltage	kV	25	25	25

Not yet optimised, especially vertical gap!

Challenges - stability

- Stability perturbations from injection process
  - Kicker bump non-closure
  - Septum stray fields
  - AR ramping
  - Thermal drifts
- Example from Diamond
  - Stored beam moves ±250 um H, ±150 um V, for ~10 ms (~5000 turns)





Other challenges

- Stray fields from injection septum
  - Difficult to model/measure for eddy-current septum
- Protection of experiments during injection
  - "Blind-out" during injection (100 turns?)
  - Effect of chromaticity, residual steering errors, damper, …
  - Failures of injection system elements (kickers, settings, …)
- Systematics in filling patterns
  - More important for many bunches
  - Any issue for colliding beam dynamics?
- Issues for instrumentation, orbit feedback, damper, etc?

Conclusions

- Top-up based on LEP injection chain with SPS as pre-injector:
  - Looks feasible for TLEP-t (x6 margin)
  - At the limit for TLEP-h (x1.3 margin)
  - Seems impossible for TLEP-z (factor 18-20 too few e+/e-)
- Synchrotron injection attractive as baseline
  - Avoid large betatron oscillations at experiments
  - Need to generate 2-3 m dispersion at injection point
  - But dp/p of injected beam maybe 0.8 – 2%...feasible?
  - Kicker strengths of about 0.3 – 0.5 mrad needed (at 150 – 580 Tm)
- Blind-out time of 100 turns per injection will lose about 3% of data-taking time, if kicker shots widely spaced
  - Kicker flat-top of 20 us probably possible
  - Look at 'burst mode' to fire kicker repeatedly in few turns…?
- Kicker strengths and rise times
  - First parameter outlines look reasonable for ~0.5 – 3 us rise time – could used different numbers of same type of kicker for the 3 energies – 3.5 m magnetic needed *per kicker* for 175 GeV
  - Effect of impedance shielding still to take into account in rise time!

Some directions for future study

- Construct detailed injection insertion
  - Kickers, septa, phase advances, dispersion, injection channel, apertures
- Detailed kicker parameter set, kicker impedance shielding requirements and technical possibilities
- Evaluation of injection accuracy required
  - Betatron mismatch, dipole steering mismatch, kicker strength and timing matching
- Look at limitations in e+/e- Ib and nb from injector chain
  - Especially for TLEP-z