FCC-ee top-up injection

Masamitsu Aiba, PSI
Thanks to B. Goddard, K. Oide,
Y. Papaphilippou and F. Zimmermann
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Injection and Injection Systems,
Berlin, Germany

Introduction (1)

- Future Circular Collider (FCC)
  - 100-km-scale collider for physics beyond LHC (27 km, 14 TeV c.m.)
  - FCC-ee as a possible first step for Z/W/H/ttbar (up to 350 GeV c.m.)
  - FCC-hh aiming at high energy frontier (100 TeV c.m.)
  - FCC-he as an upgrade option

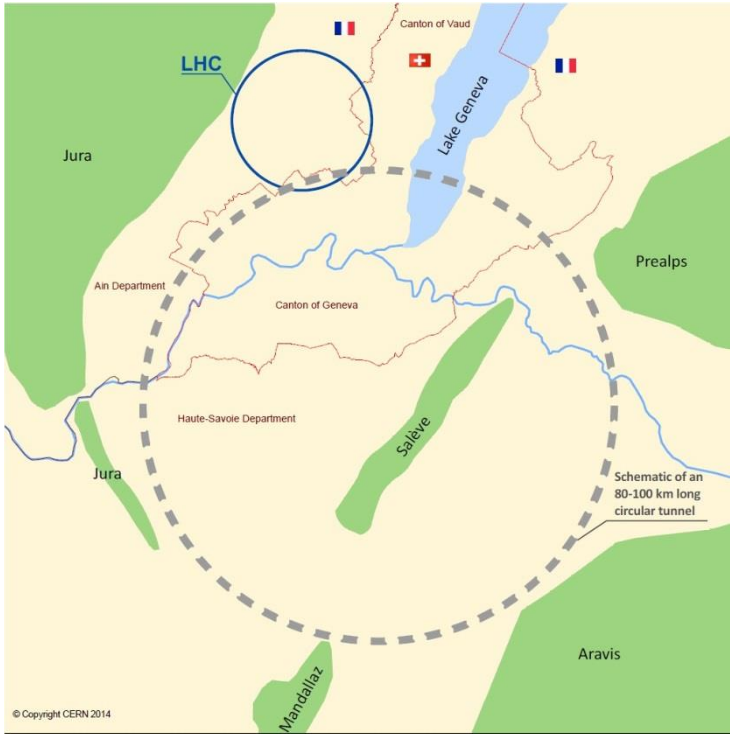

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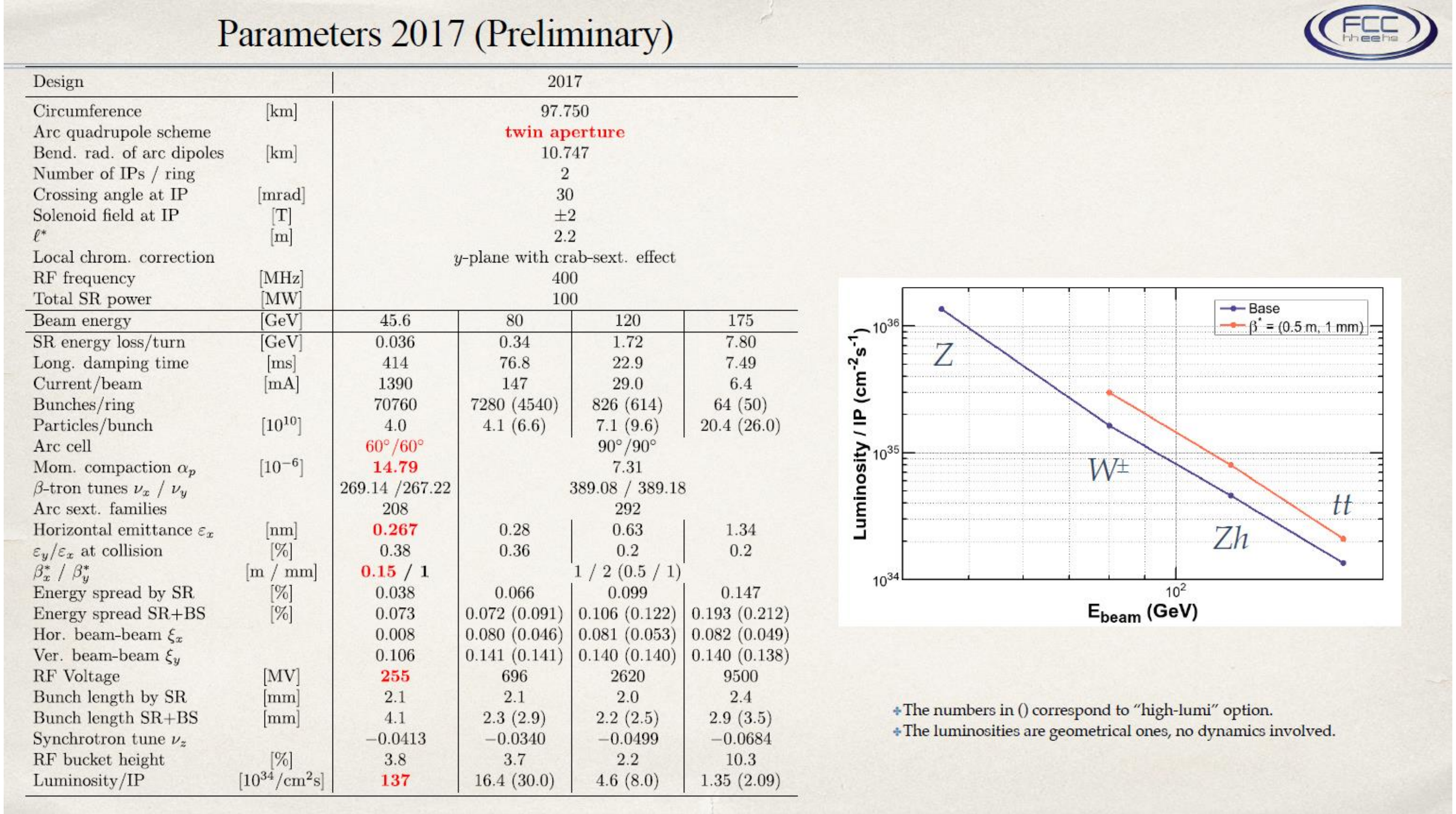
Figure taken from FCC-ee design study homepage: http://tlep.web.cern.ch/
See also https://fcc.web.cern.ch/

This presentation is about top-up injection into FCC-ee.
Two more talks by T. Tydecks and B. Harer
on the injector chain and FCC-ee collider optics tomorrow.

Introduction (2)

- FCC-ee parameters



Parameters 2017 (Preliminary)

Design		2017			
Circumference	[km]	97.750			
Arc quadrupole scheme		**twin aperture**			
Bend. rad. of arc dipoles	[km]	10.747			
Number of IPs / ring		2			
Crossing angle at IP	[mrad]	30			
Solenoid field at IP	[T]	±2			
ℓ^*	[m]	2.2			
Local chrom. correction		y-plane with crab-sext. effect			
RF frequency	[MHz]	400			
Total SR power	[MW]	100			
Beam energy	[GeV]	45.6	80	120	175
SR energy loss/turn	[GeV]	0.036	0.34	1.72	7.80
Long. damping time	[ms]	414	76.8	22.9	7.49
Current/beam	[mA]	1390	147	29.0	6.4
Bunches/ring		70760	7280 (4540)	826 (614)	64 (50)
Particles/bunch	[10^{10}]	4.0	4.1 (6.6)	7.1 (9.6)	20.4 (26.0)
Arc cell		**60°/60°**	90°/90°		
Mom. compaction α_p	[10^{-6}]	**14.79**	7.31		
β-tron tunes ν_x / ν_y		269.14 /267.22	389.08 / 389.18		
Arc sext. families		208	292		
Horizontal emittance ε_x	[nm]	**0.267**	0.28	0.63	1.34
$\varepsilon_y/\varepsilon_x$ at collision	[%]	0.38	0.36	0.2	0.2
β^*_x / β^*_y	[m / mm]	**0.15 / 1**	1 / 2 (0.5 / 1)		
Energy spread by SR	[%]	0.038	0.066	0.099	0.147
Energy spread SR+BS	[%]	0.073	0.072 (0.091)	0.106 (0.122)	0.193 (0.212)
Hor. beam-beam ξ_x		0.008	0.080 (0.046)	0.081 (0.053)	0.082 (0.049)
Ver. beam-beam ξ_y		0.106	0.141 (0.141)	0.140 (0.140)	0.140 (0.138)
RF Voltage	[MV]	**255**	696	2620	9500
Bunch length by SR	[mm]	2.1	2.1	2.0	2.4
Bunch length SR+BS	[mm]	4.1	2.3 (2.9)	2.2 (2.5)	2.9 (3.5)
Synchrotron tune ν_z		−0.0413	−0.0340	−0.0499	−0.0684
RF bucket height	[%]	3.8	3.7	2.2	10.3
Luminosity/IP	[10^{34}/cm^{2}s]	**137**	16.4 (30.0)	4.6 (8.0)	1.35 (2.09)

- The numbers in () correspond to "high-lumi" option.
- The luminosities are geometrical ones, no dynamics involved.

Slide taken from K. Oide's presentation at FCC Week 2017: https://indico.cern.ch/event/556692/

Introduction (3)

- Challenges in FCC-ee top-up injection
  - Collider ring optics is designed/optimised for achieving high luminosity
  - Luminosity lifetime of ~1 hour at 175 GeV

  → Top-up injection is essential and should be robust
  - Very squeezed β^* to maximise the luminosity → Strong nonlinear elements required → Limited dynamic aperture

Requirements/Assumptions

- To start design, the following requirements and assumptions were set:
  - Similar emittance in booster and collider (1.3 nm @ 175 GeV)
  - ~1.5 km straight section available in collider
  - 5σ clearance for high injection efficiency
  - Dynamic aperture: ~15σ for on-energy, 5σ up to +/-2% off-energy
    - cf. SLS: ~15 mm dynamic aperture corresponds to ~ 100σ
  - Septum thickness
    - 5 mm (3 mm + mechanical margin) or
    - Wire septum ~0.2 mm (~20 um + mechanical margin)
      - Widely used in hadron machine but never used for lepton beams (?)

Off-axis or On-axis?

- Collider prefers residual synchrotron oscillation (on-axis injection) because lower background signal is expected
- Higher injection efficiency was observed at LEP with on-axis injection (Synchrotron phase space injection)

First turn injection beam trajectory,
off-axis (top) and on-axis (bottom) at LEP

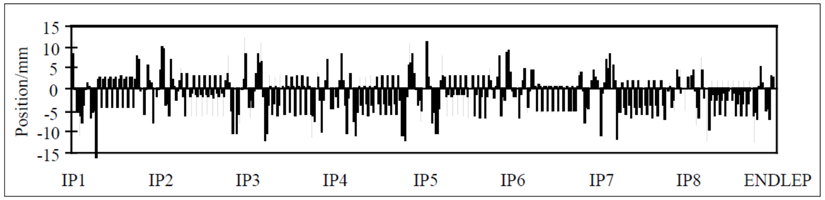


Figure 3: Optimized Horizontal First Turn Trajectory for Betatron Injection of Positrons into LEP.

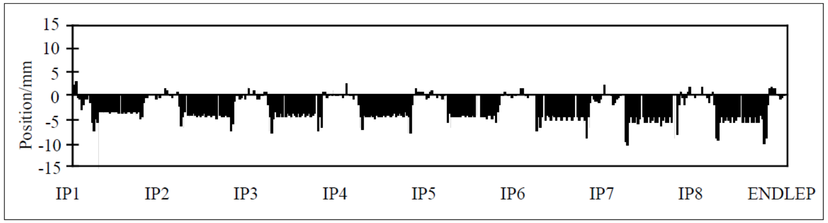
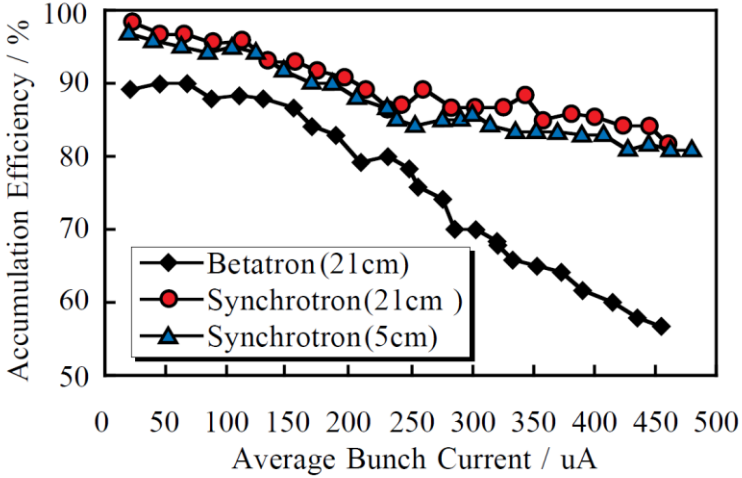


Figure 4 : Optimized Horizontal First Turn Trajectory for Synchrotron Injection of Positrons with ΔP/P at -0.6%

Injection efficiency
for off-axis and on-axis injection

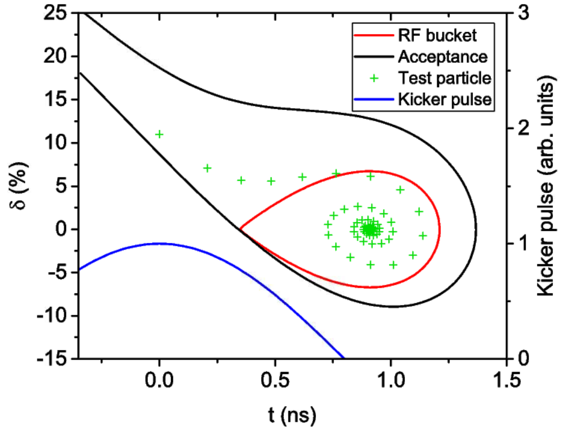


Figures taken from P. Collier, “Synchrotron phase space injection into LEP”, PAC 1995

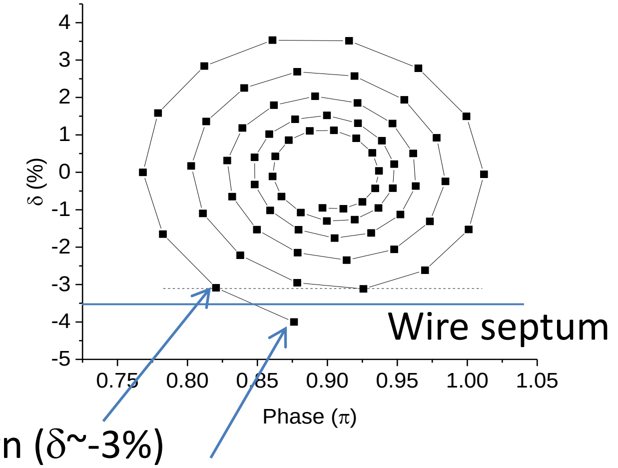
Selection of injection schemes

- Applicable schemes
  - Conventional scheme (with kicker bump), both off-axis and on-axis
  - Multipole kicker injection, both off-axis and on-axis
- Discarded schemes
  - Swap-out injection
    - Discarded(?) due to practical difficulties: preparing full current bunches, swapping several MJ beams…
  - Longitudinal injection
    - High radiation loss (7.8 GeV at 175 GeV!) → Discarded due to too high RF bucket exceeding the off-momentum dynamic aperture
  - Kickerless injection
    - Injection without kicker like in Cyclotron
    - Discarded due to limited off-momentum dynamic aperture
    - Also only applicable to high energy operation modes

Longitudinal injection (discarded)



Kickerless injection in long. phase space, 175 GeV(discarded)



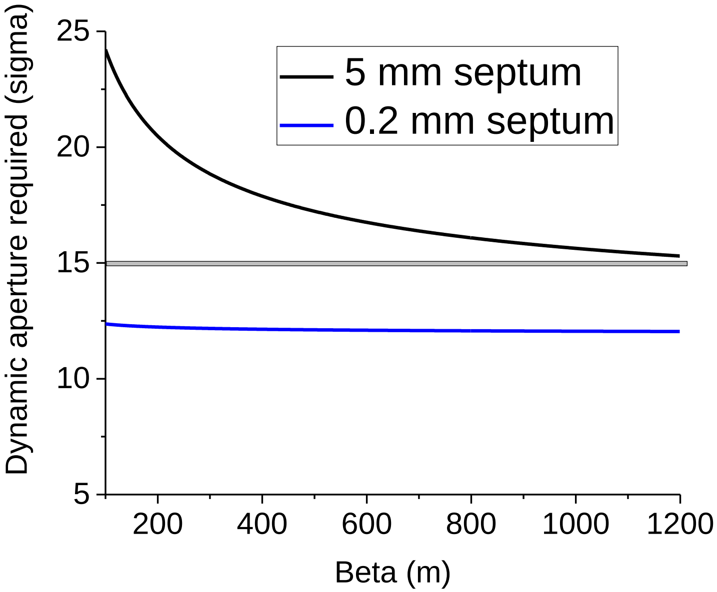
Wire septum

2nd turn (δ~-3%)

Injection point (δ=-4%)

Conventional injection (1)

- Dynamic aperture required vs. beta function at septum
  - Plot for clearance of 5σ
  - Optimum injection beam matching is assumed

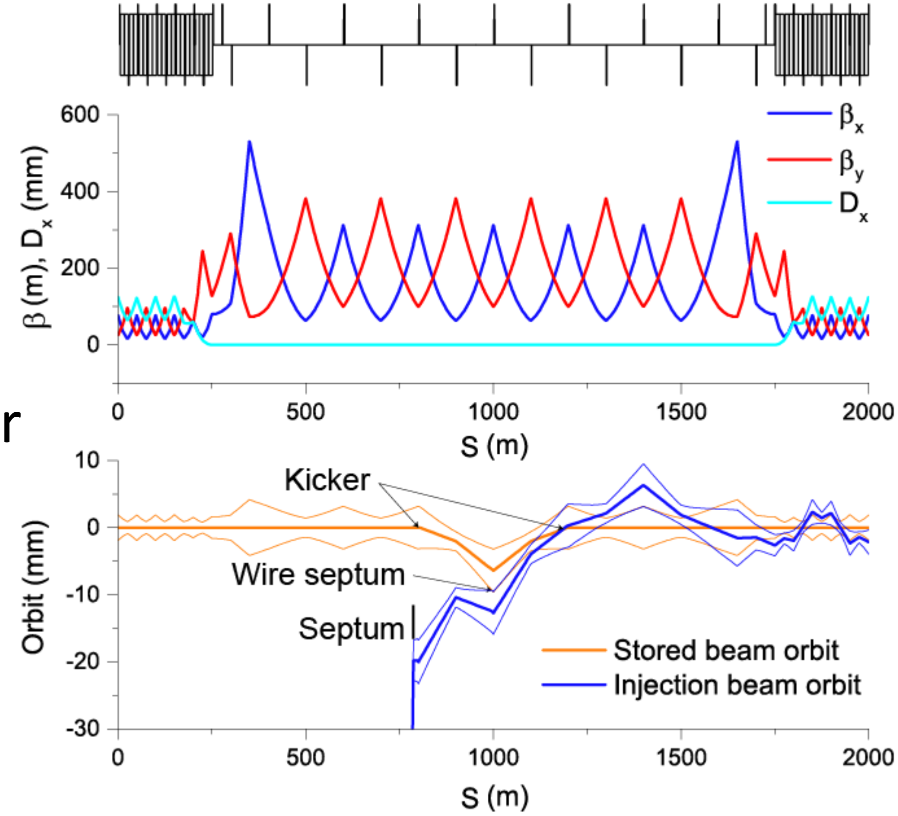


Conventional injection (2)

- Off-axis injection
- FODO cell
  - 200 m cell length
  - 90 deg/cell, Beta ~312 m
  - With dispersion suppressor
- Bump kicker field

  ~0.012 Tm @ 175 GeV
- Wire septum, Vint=11 MV

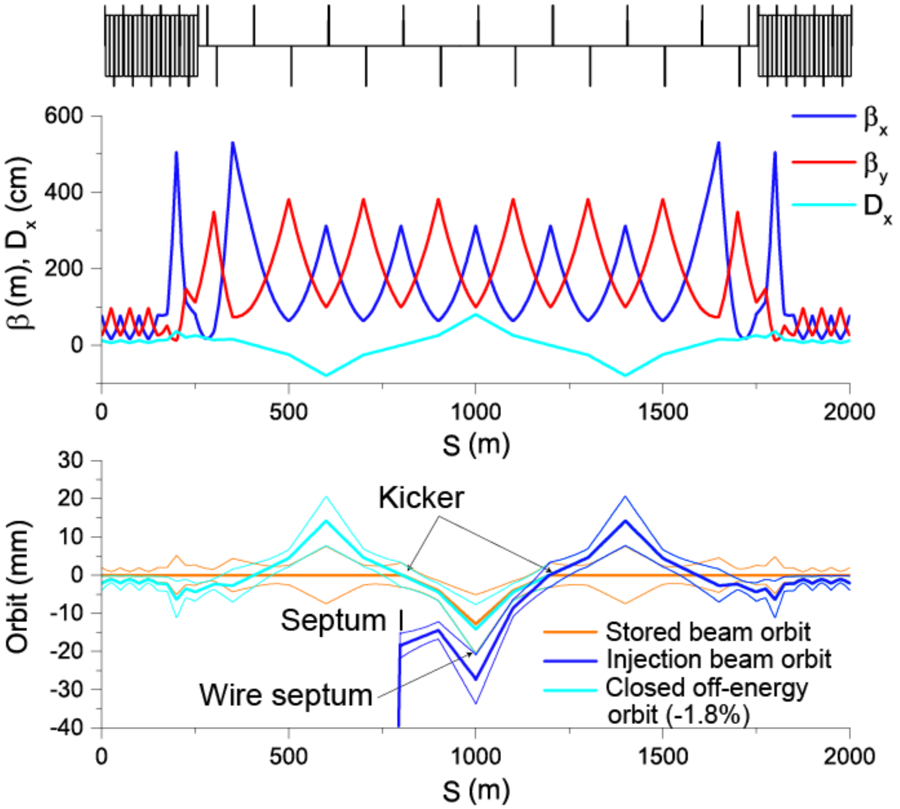
Optics and orbits



Conventional injection (3)

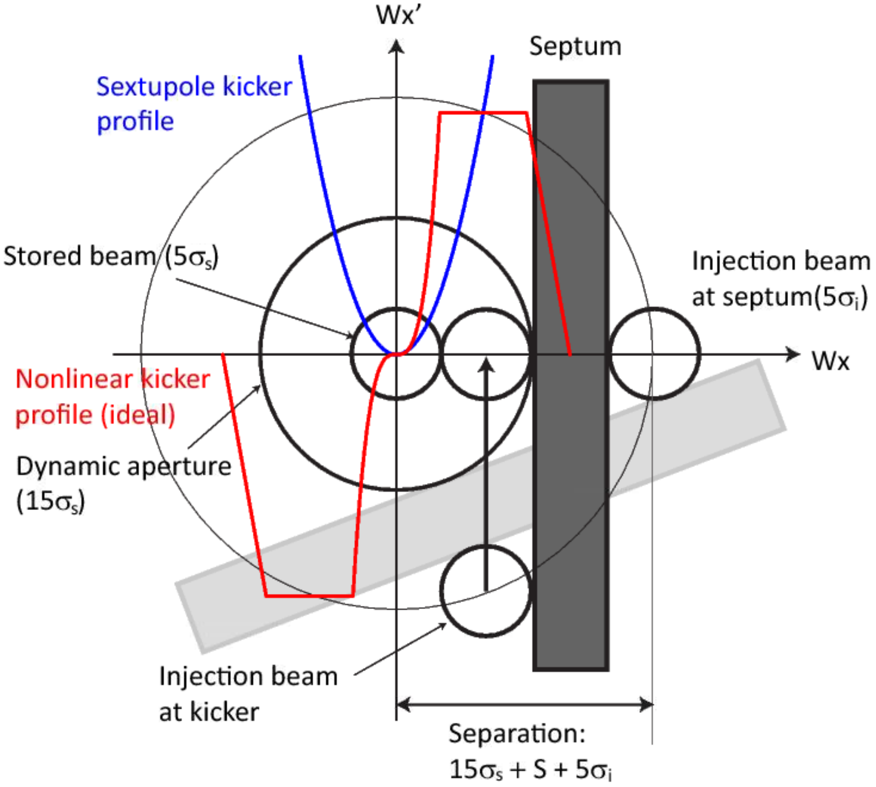
- On-axis injection
- FODO cell
  - 200 m cell length
  - 90 deg/cell, Beta ~312 m
  - Dx=0.8 m at septum
- Bump kicker field
  ~0.025 Tm @ 175 GeV
- Wire septum, Vint=11 MV

Optics and orbits



Multipole kicker injection (1)

- Beams "packed" in phase space

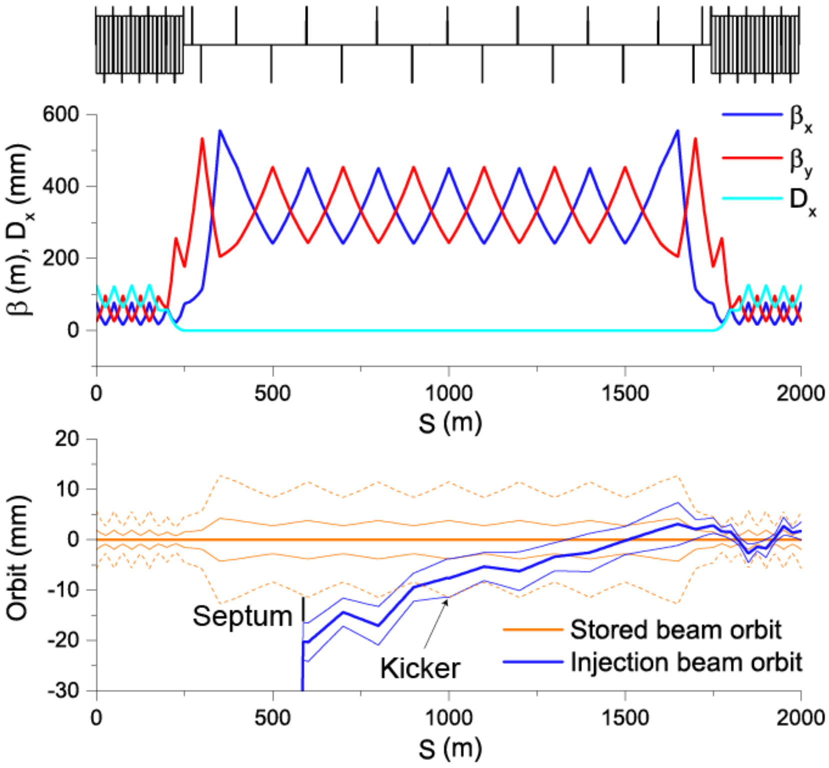


Stored beam emittance is increased by the kicker field…

Multipole kicker injection (2)

- Off-axis injection
- FODO cell
  - 200 m cell length
  - ~70 deg/cell, Beta ~450 m
  - With dispersion suppressor
- Nonlinear kicker, 0.025 Tm on plateau

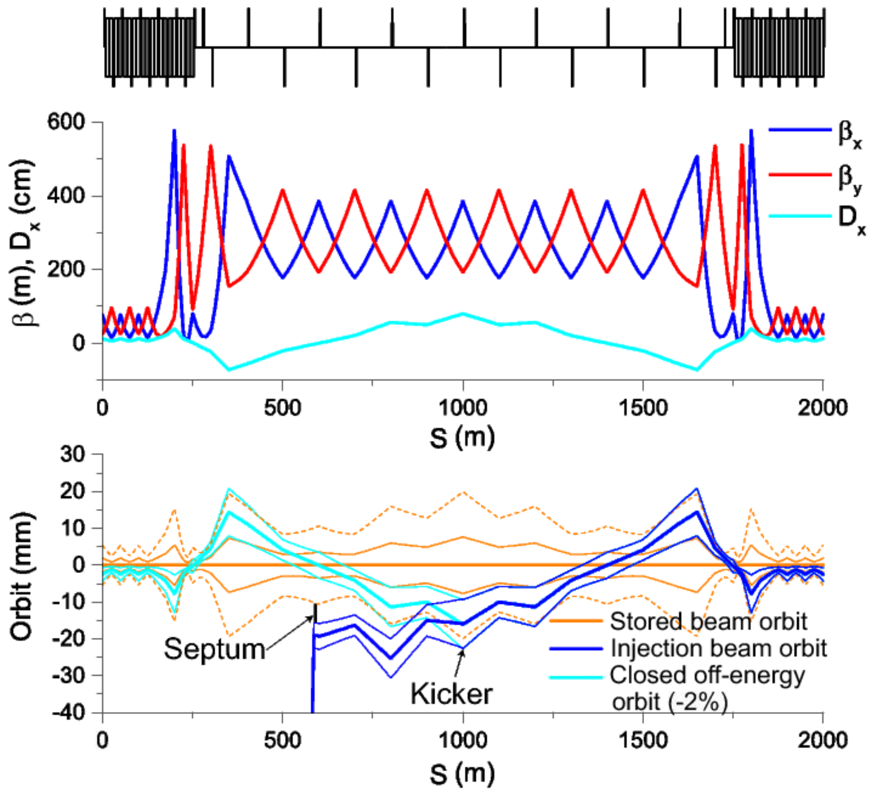
Optics and orbits



Multipole kicker injection (3)

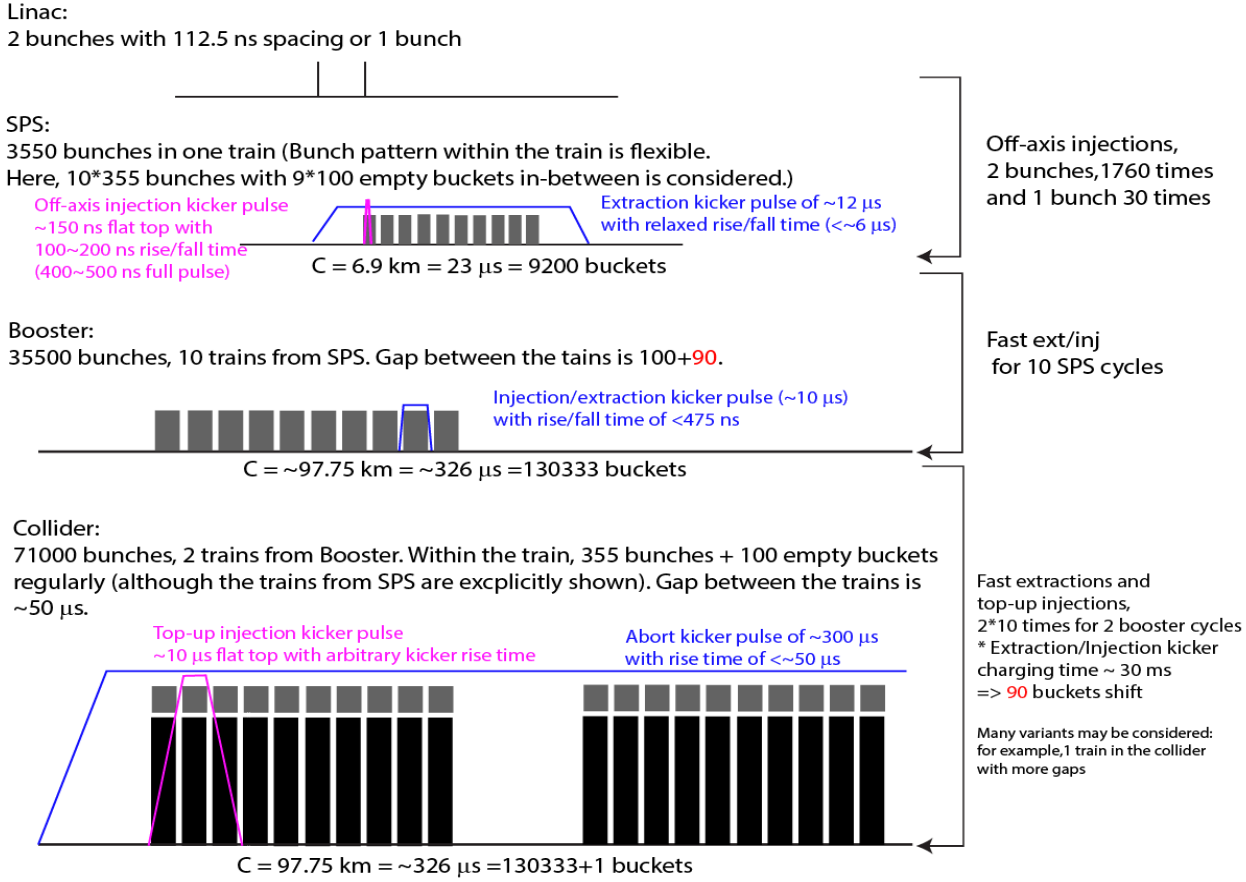
- On-axis injection
- FODO cell
  - 200 m cell length
  - 90 deg/cell, Beta ~380 m
  - Dx=0.8 m
- Nonlinear kicker, 0.03 Tm on plateau

Optics and orbits



Injection kicker/septum pulse length

How to fill the collider ring with ~70k bunches (Z, 45 GeV)!



Linac:
2 bunches with 112.5 ns spacing or 1 bunch

SPS:
3550 bunches in one train (Bunch pattern within the train is flexible.
Here, 10*355 bunches with 9*100 empty buckets in-between is considered.)

Off-axis injection kicker pulse
~150 ns flat top with
100~200 ns rise/fall time
(400~500 ns full pulse)

Extraction kicker pulse of ~12 μs
with relaxed rise/fall time (<~6 μs)

C = 6.9 km = 23 μs = 9200 buckets

Off-axis injections,
2 bunches,1760 times
and 1 bunch 30 times

Booster:
35500 bunches, 10 trains from SPS. Gap between the tains is 100+90.

Injection/extraction kicker pulse (~10 μs)
with rise/fall time of <475 ns

C = ~97.75 km = ~326 μs =130333 buckets

Fast ext/inj
for 10 SPS cycles

Collider:
71000 bunches, 2 trains from Booster. Within the train, 355 bunches + 100 empty buckets regularly (although the trains from SPS are excplicitly shown). Gap between the trains is ~50 μs.

Top-up injection kicker pulse
~10 μs flat top with arbitrary kicker rise time

Abort kicker pulse of ~300 μs
with rise time of <~50 μs

C = 97.75 km = ~326 μs =130333+1 buckets

Fast extractions and
top-up injections,
2*10 times for 2 booster cycles
* Extraction/Injection kicker
charging time ~ 30 ms
=> 90 buckets shift

Many variants may be considered:
for example,1 train in the collider
with more gaps

Although the collider ring is large (~100 km), kicker/septum pulse length of ~10 μs is enough with multiple beam transfers

Injection specifications (ttbar)

Parameters	Conventional injection (on-/off-energy)	Multipole kicker injection (on-/off-energy)
Minimum beta function at septum and kicker (m)	310/310 or 1200/1800	~400 m
Type of kicker	Dipole kickers	Nonlinear kicker
Integrated kicker field (Tm)	0.012/0.025 or weaker	0.025/0.03 (Plateau)
Type of (last) septum	Wire septum or 5-mm septum	5-mm septum
Kicker/septum flat-top (μs)	~10	
Required DA (σ)	<~15/5@-1.8%	15/5@-2%

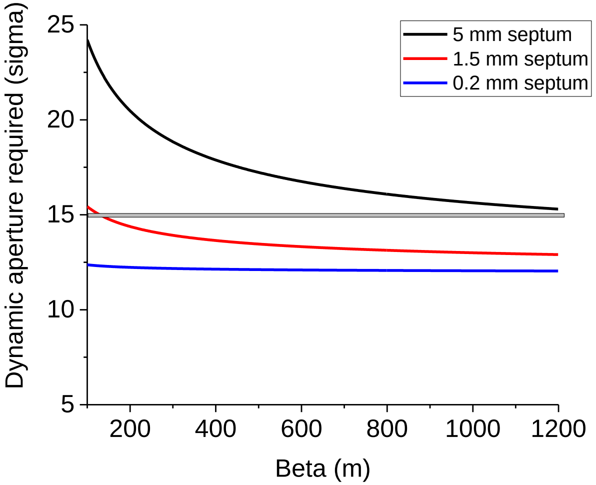
Remarks:

- Required kicker field strengths are modest values even though high beam energy (175 GeV)
- Wire septum can be avoided, but it minimises dynamic aperture required in the off-axis conventional injection, thus supporting low β^* optics
- Need to go through other operation modes; Off momentum dynamic aperture does not reach to ±2% in Z mode…

Some ideas

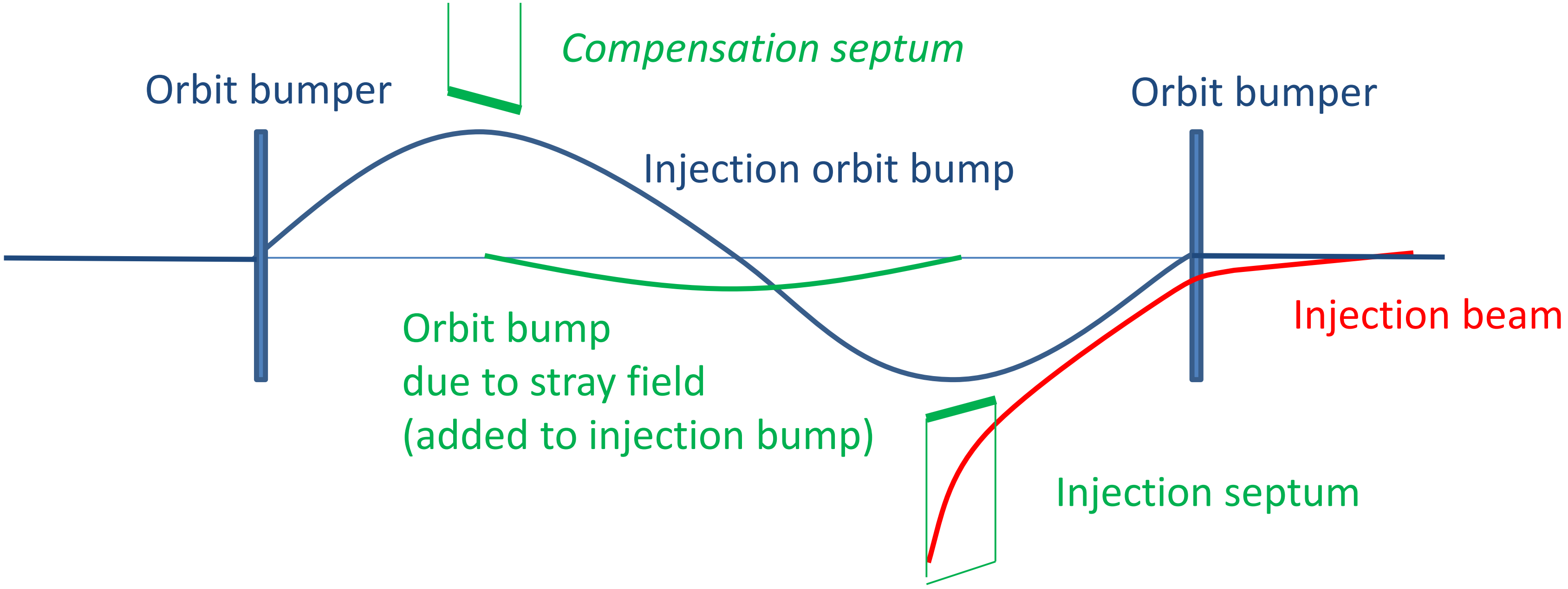
“Compensation septum” for conventional injection (1)

- Reconsideration of magnetic septum assumptions
  - Present assumption: 3 mm blade (5 mm septum thickness with margin)
    - To achieve strong enough (~0.5 T) field to inflect the injection beam
    - The blade should be thick enough to suppress stray field
  - Thinner septum?
    - Field of ~0.1 T is enough because of a large beta function available
    - **Allow (some) stray field but compensate for by *other means* rather than by thick blade**
    - With a lower field and a less stringent stray field criterion, the thickness can be thinner
  - Possible revised assumption: 1.5 mm including mechanical margin
    - Easy for conventional injection scheme (e.g. no wire septum and easy-handling beta)



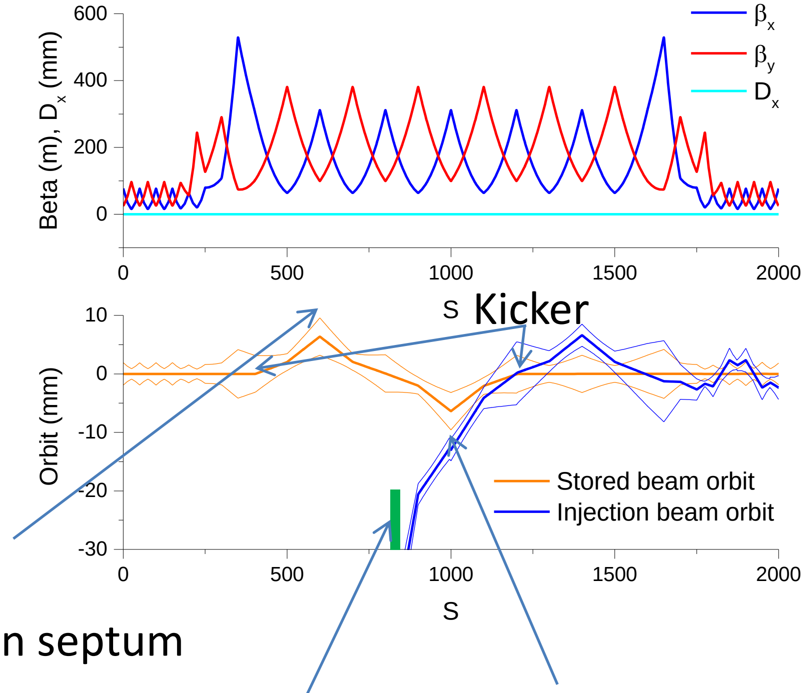
“Compensation septum” for conventional injection (2)

- “Compensation septum” (or “Dummy septum”)
  - Put another septum to compensate for the stray field disturbance
  - 2π injection orbit bump with Compensation and Injection septa at the peak of bump with a π phase advance in-between
  - Stray field generate a *closed* π bump → No bump leakage in principle when the two septa are identical
  - Orbit bumpers and septa do not necessarily have same pulse duration/shape



“Compensation septum” for conventional injection (3)

Optics and orbits for on-energy injection with thin septum and compensation septum



Kicker

Compensation septum

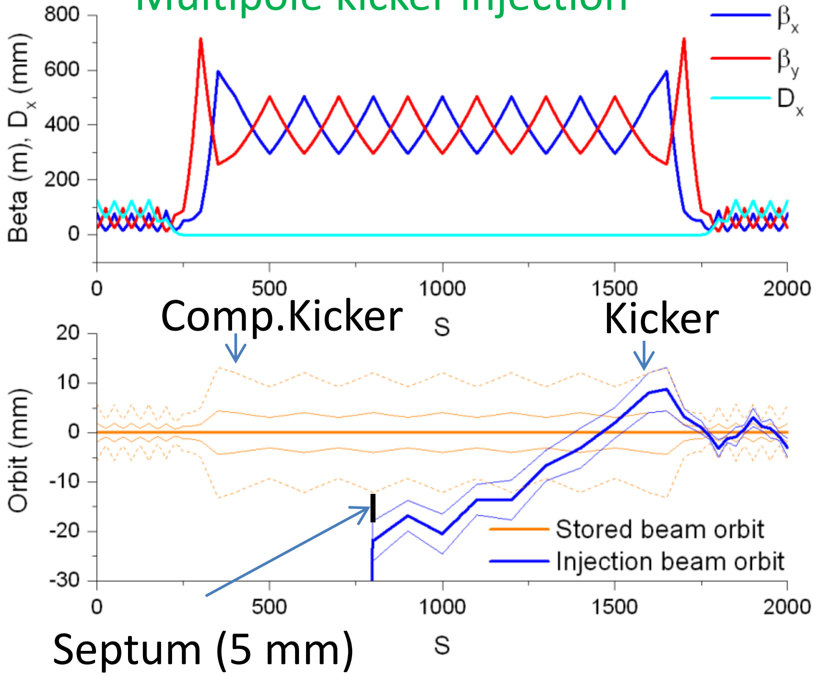
Thick septum
(Can be DC magnet)

Injection septum (1.5 mm)
Integrated field = 0.1 Tm

“Compensation kicker” for multipole kicker injection

- Similar approach to “Compensation septum”
  - With π phase advance between two kickers, the disturbance to the beam is compensated for (up to any high multipole)

Optics and orbits for on-energy Multipole kicker injection

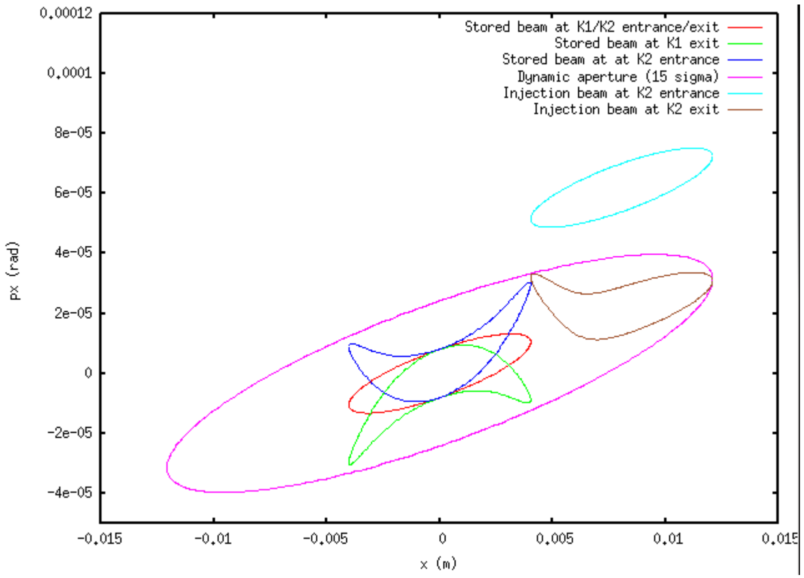


Comp.Kicker

Kicker

Septum (5 mm)

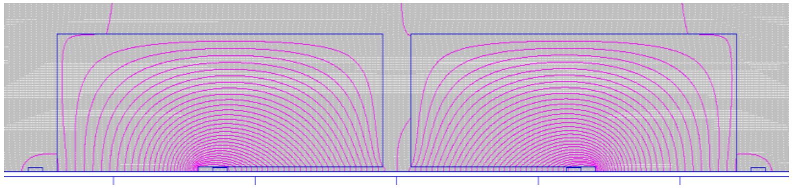
Beams in phase space



Nonlinear kicker with magnetic material?

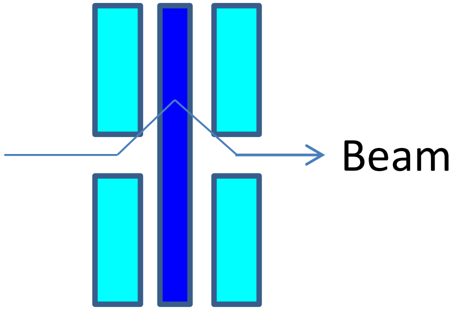
- Possible nonlinear kicker with two C-shape dipole kickers:

Two C-shape kickers



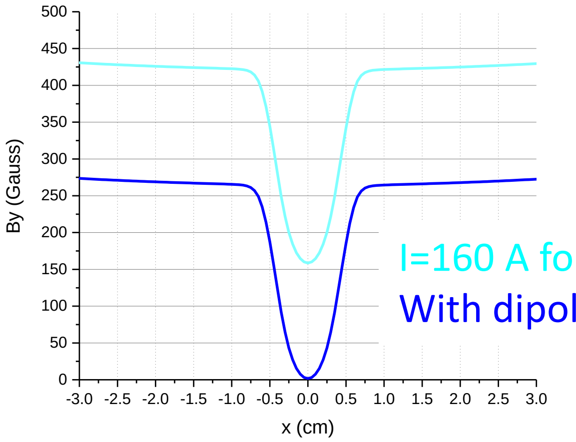
+

Dipole kicker to cancel
the dipole component at the centre



Field profile

(Poisson computation for static field)



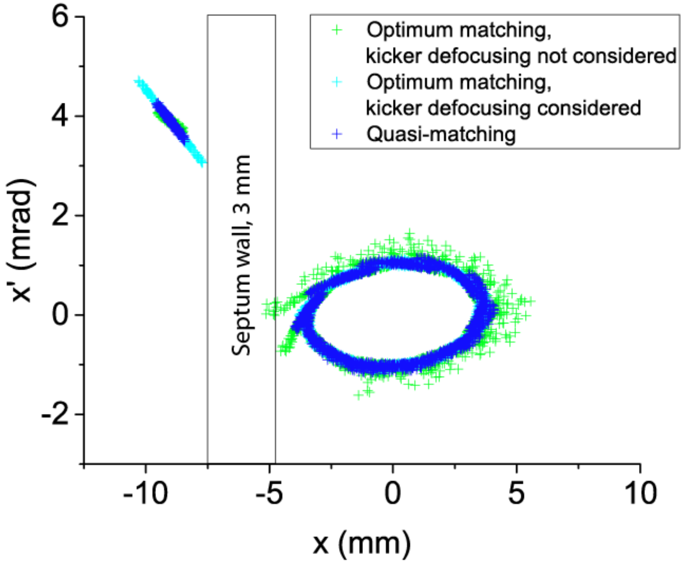
I=160 A for 4 mm full gap

With dipole kicker attached

“Quasi-matching”

- Multipole kicker gives strong defocusing to the injection beam
  - Nonlinear kicker is one of solutions
  - Another solution may be matching the injection beam, considering the defocusing
  - However, matching to cancel the defocusing is difficult, if not impossible
  - “Quasi-matching”: i.e. approximate matching, keeping the beam orientation (α/β) in phase space
  - Example from SLS-2 injection:

	Paramters at Septum	
	Beta (m)	Alpha
Optimum if no defocusing	8.7	2.94
Optimum with defocusing	65.3	33.3
"Quasi matching"	13.1	6.67



Multipole kicker injection with quasi-matching might be applicable to FCC-ee injection? To be studied.

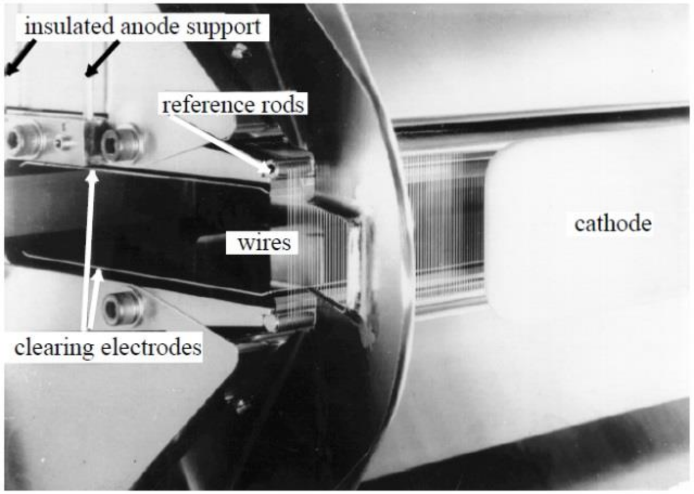
Summary

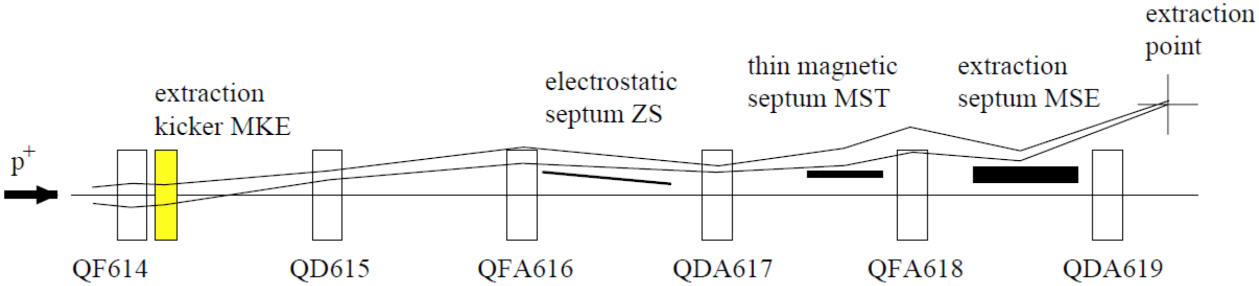
- Conventional scheme and Multipole kicker injection are applicable to FCC-ee top-up injection
  - On-axis injection is preferable in colliders
    - Applicable to higher beam energy operation modes
    - Off-energy dynamic aperture is not enough for lower beam energy operation modes
  - In spite of very high beam energy, injection kicker specifications are modest thanks to the large beta function available
  - Possible improvements of these schemes are under investigation

Backup slides

SPS ZS septum

- 25 um wires
- Field 100 kV/cm
- 3 m * 5 units
- Integrated Volt. 150 MV
- Used for 450 GeV p-beam extraction





* Figures taken from B. Goddard and P Knaus, Proc. of EPAC 2000, p.2255