Top-up injection scheme

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Y. Papaphilippou, F. Zimmermann,
and many colleagues
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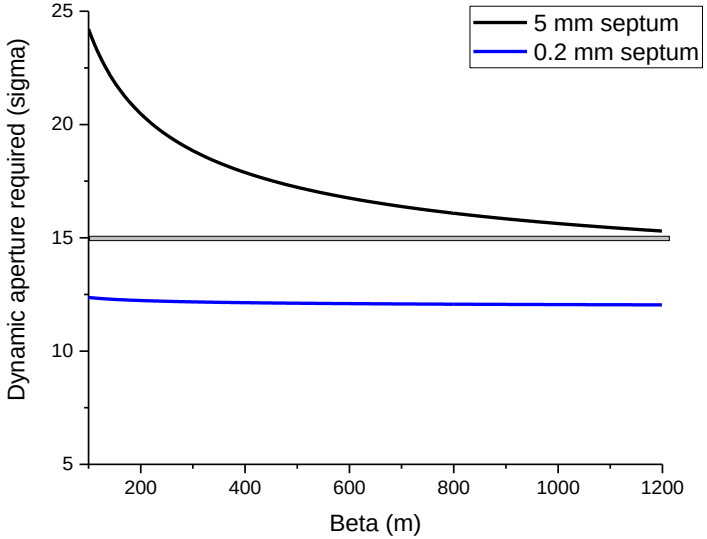
Summary from previous studies

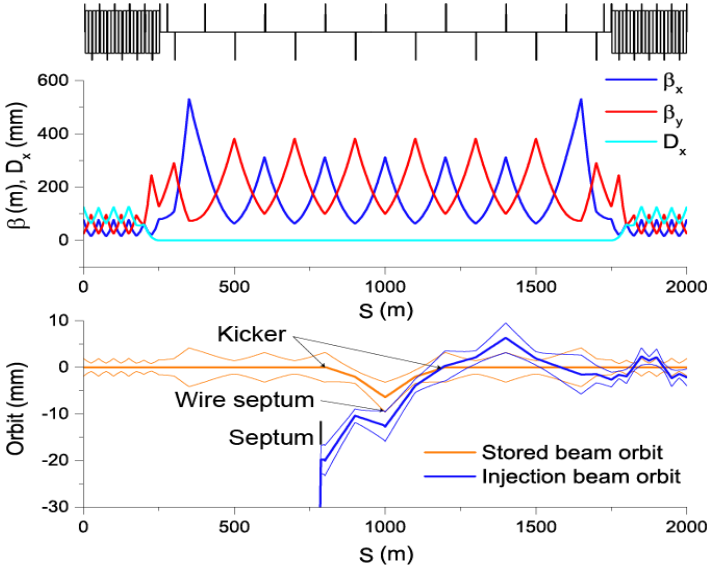
- Top-up injection is essential for FCC-ee; Beam lifetime is ~1 hour (tt)
- Previous studies focused on tt operation mode parameters
- Requirements/Assumptions for designing top-up injection system
  - Similar emittance in booster and collider (~1.3 nm @ 175 GeV)
  - ~1.5 km straight section available in collider
  - 5σ clearance for high injection efficiency
  - (Limited) dynamic aperture: ~15 sigma for on-energy, 5 sigma up to +/- 2% off-energy
    - c.f. SLS: ~15 mm dynamic aperture corresponds to ~ 100 sigma
  - Septum
    - Magnetic septum: Blade thickness of 5 mm (3 mm + mechanical margin)
    - Electrostatic septum: Wire septum of 0.2 mm (~20 um + mechanical margin)
- Two viable injection schemes found, but with some “weak points”
  - Conventional injection scheme (on-energy/off-energy)
    - Both on- and off-energy injection require a wire septum or beta function at septum >1 km
    - Beam disturbance (coherent betatron oscillation) due to a bump leakage in practice
  - Multipole kicker injection (on-energy/off-energy)
    - Nonlinear kicker may be essential to avoid strong injection beam mismatch
    - Unavoidable emittance growth up to 30% due to the limited dynamic aperture
- On-axis (off-energy) injection is preferable due to higher injection efficiency and lower detector backgrounds foreseen

Conventional injection

Required dynamic aperture
as a function of beta at kicker/septum

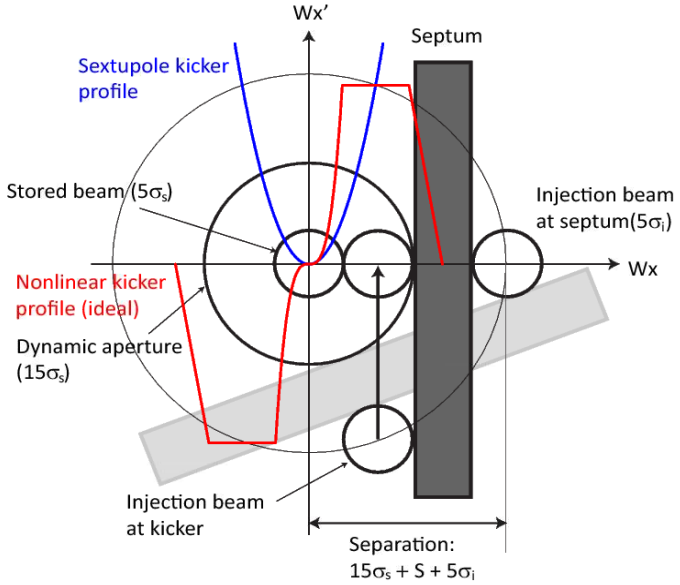


Optics and orbits, example for
on-energy injection with wire septum

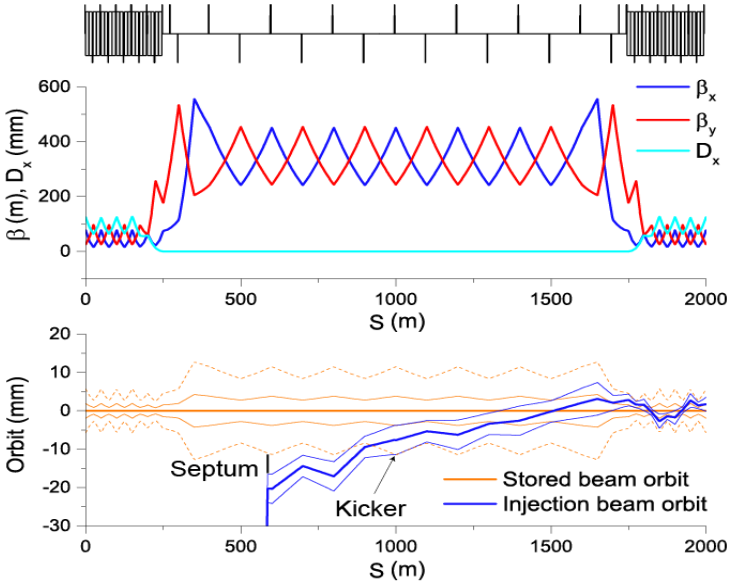


Multipole kicker injection

How the beams are “packed” into limited dynamic aperture…



Optics and orbits, example for on-energy injection with septum (5 mm)



Injection system specifications (tt)

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 septum	Wire septum or 5-mm septum	5-mm septum
Required DA, on-energy/off-energy (σ)	~15/5@-1.8%	15/5@-2%

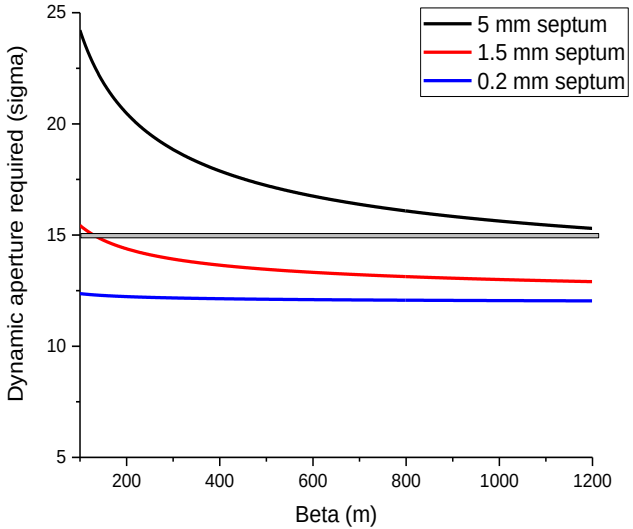
Remarks:

- Required kicker field strengths are modest values even though high beam energy (175 GeV)
- Wire septum can be avoided but it minimises the requirement of dynamic aperture in the conventional injection scheme, enabling higher injection efficiency or even lower β^*
- **Kicker and septum pulse durations are missing**
- Need to go through other operation modes; e.g. off-momentum dynamic aperture may be about ±1% in Z mode…

Possible improvements

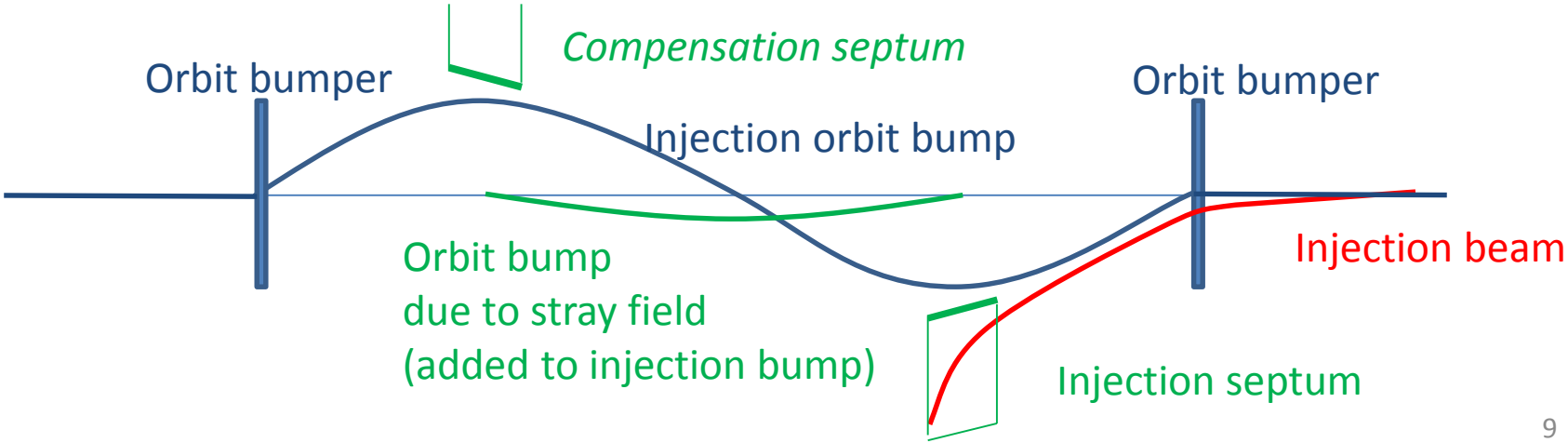
“Compensation septum” for conventional injection (1)

- Reconsideration of magnetic septum assumptions
  - Present assumption: 3 mm blade (5 mm septum thickness with margin)
    - To achieve strong enough field (>0.5 T) to inflect the injection beam
    - The blade should be thick enough to suppress stray field
  - Thinner septum?
    - Field of ~0.1 T is enough; a large ring beta and very long straight section 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
    - Ease the conventional injection scheme, still with the advantage of lowering the dynamic aperture requirement



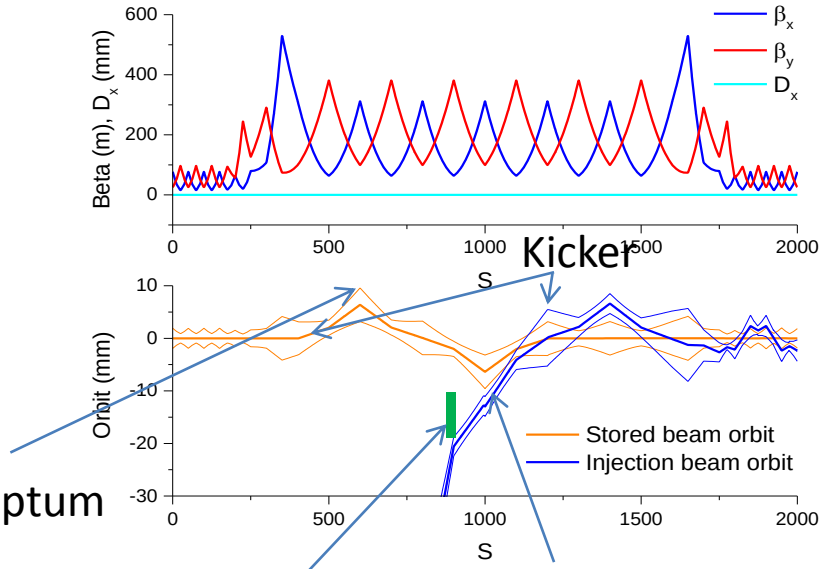
“Compensation septum” for conventional injection (2)

- “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 generates a *closed* π bump → Bump leakage due septum stray field is suppressed
  - 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



Compensation septum

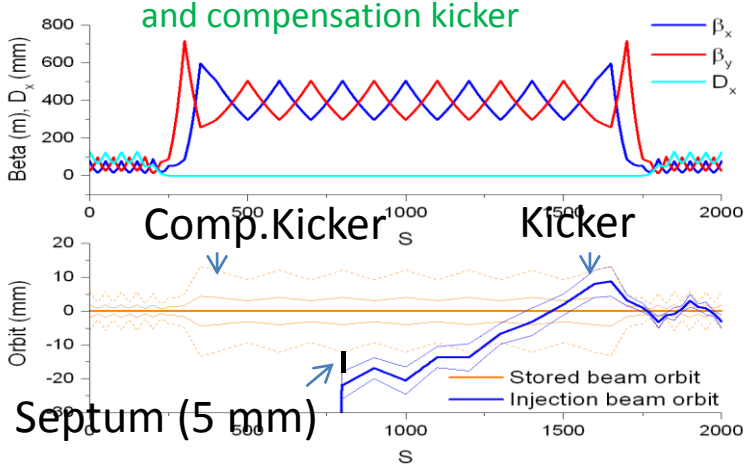
Thick septum
(Can be DC magnet)

Injection septum (1.5 mm)
Integrated field = 0.1 Tm

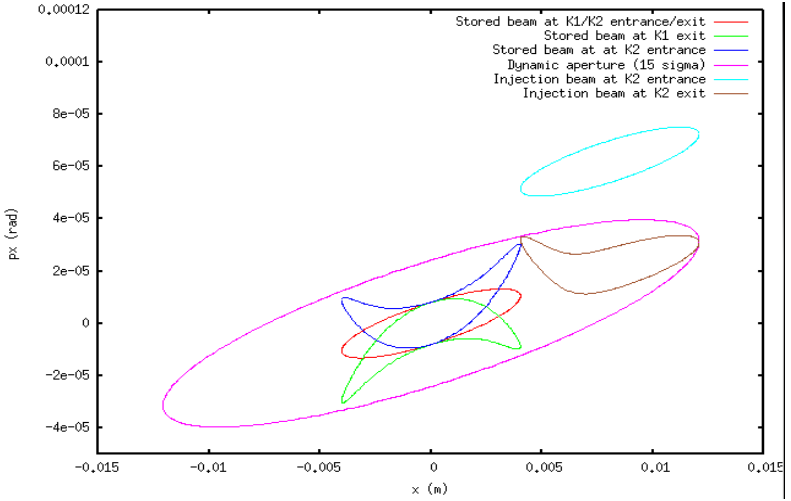
“Compensation kicker” for multipole kicker injection

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

Optics and orbits for on-energy injection with sextupole-like kicker and compensation kicker



Beams in phase space



Kicker/septum pulse duration (1)

FCC-ee injector parameters (new)

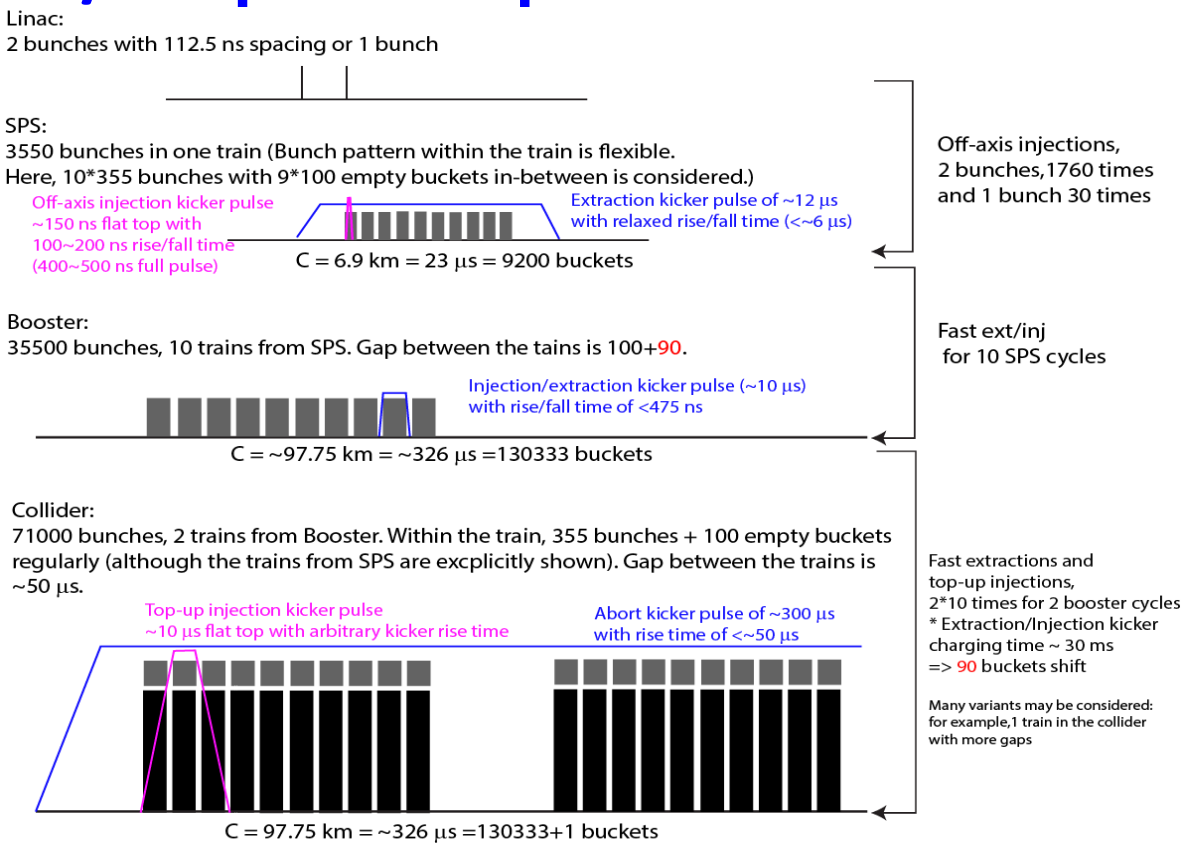
Accelerator	FCCee-Z		FCCee-W		FCCee-H		FCCee-tt	
Energy [GeV]	45.6		80		120		175	
Type of filling	Full	Top-up	Full	Top-up	Full	Top-up	Full	Top-up
LINAC # bunches, with 2.8 GHz RF	2		1					
LINAC repetition rate [Hz]	200		100					
LINAC/SPS bunch population [10^{10}]	2.66	0.27	1.88	0.15	0.77	0.20	2.77	0.55
# of LINAC injections	355	1775	263		60		62	
SPS bunch spacing [ns]	2.5		50		380		280	
# SPS cycles	10		20		13		1	
SPS # of bunches	710	3550	263		60		62	
SPS cycle time [s]	2.28	9.38	3.13		1.10		1.12	
SPS duty factor	0.79	0.94	0.91		0.15	0.70	0.16	
BR # of bunches	7100	35500	5260		780		62	
BR cycle time [s]	26.75	97.75	68.6		7.1	20.3	7.12	
#of BR cycles	20	2	4	1	13	1	10	1
# of injections/collider bucket	2	1	4	1	13	1	10	1
Total number of bunches	71000		5260		780		62	
Filling time (both species) [sec]	1070	391	548.8	84.6	184.6	40.6	142.4	14.2
Injected bunch population [10^{10}]	4.3	0.21	6.0	0.12	8.0	0.16	22.1	0.44

- Table by Y. Papaphilippou
- Talks for injector complex Thursday morning

To determine the collider injection kicker/septum pulse length, start-to-end filling scheme should be defined

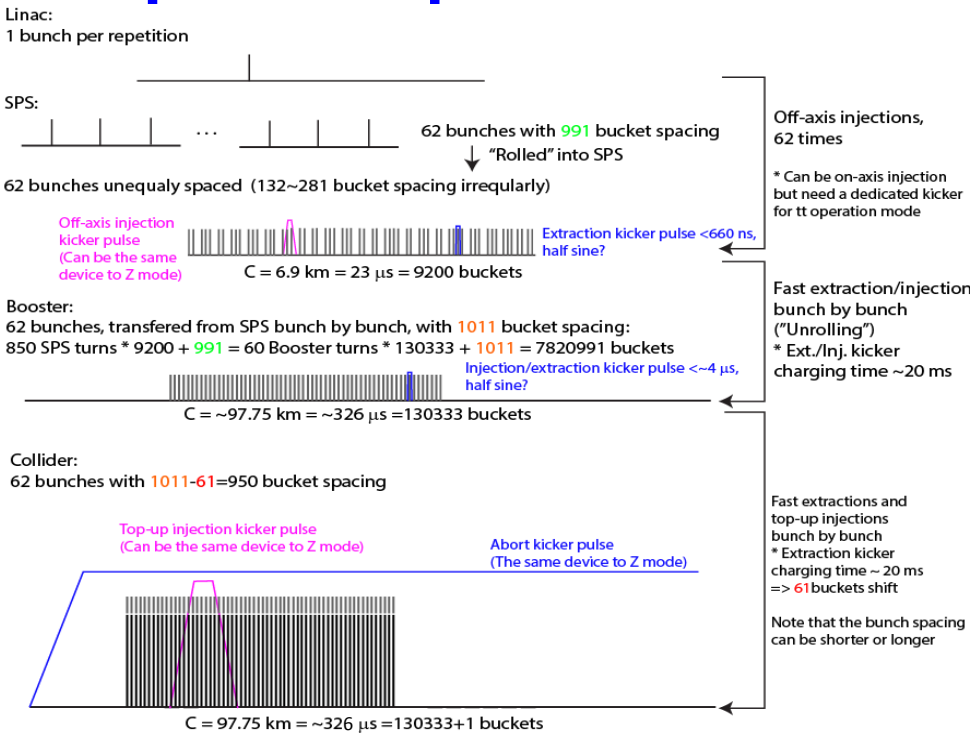
Kicker/septum pulse duration (2)

Possible scenario for Z top-up



Kicker/septum pulse duration (3)

Possible scenario for tt top-up / full



Two extreme cases are studied, and a collider injection kicker/septum with 10 μs flat top works for both.

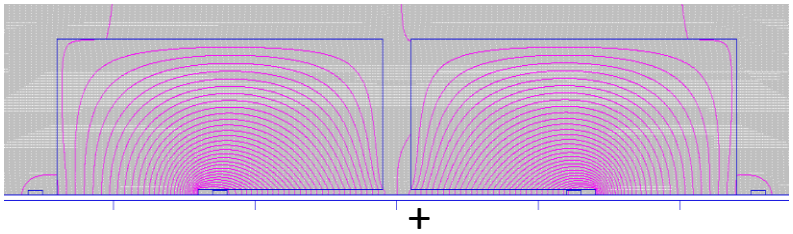
Summary and next steps

- Two viable injection schemes identified (from previous studies)
- Possible improvements in these schemes are under investigation
- First investigation of collider ring injection kicker/septum pulse duration: a flat top of 10 μs is a candidate. (Need to go through all the operation modes.)
- Next steps towards CDR
  - Failure scenario to be discussed; Stored beam energy is >20 MJ in Z operation mode
  - Further tracking studies to evaluate/improve dynamic aperture and injection efficiencies (T. Tydecks et al.)
  - Select ‘Plan A’: Conventional injection or Multipole injection
  - Hardware consideration/design

Idea for nonlinear kicker

- Sextupole-like nonlinear kicker:

Two C-shape kickers



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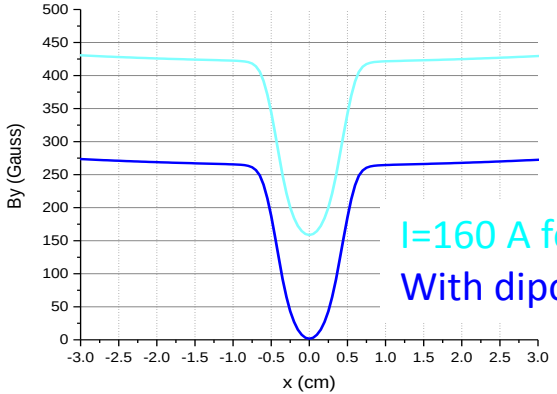
Dipole kicker to cancel
the dipole component at the centre

Field profile expected for on-energy inj.
(Poisson computation for static field)



I=160 A for 4 mm full gap
With dipole kicker attached