FCC-hh
INJECTION AND EXTRACTION

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with many inputs from

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FCC week, 23th-27th March 2015

Outline

- FCC injection
  - Machine protection consideration
  - Kicker rise time specification
  - Septum strength
  - Optics and overall insertion length
- FCC dump system
  - Extraction locations and link with collimation
  - Insertion overview and alternative concepts
  - Dump block limitations
- Summary
  - Challenges
  - Study directions and R&D programs
  - Timeline

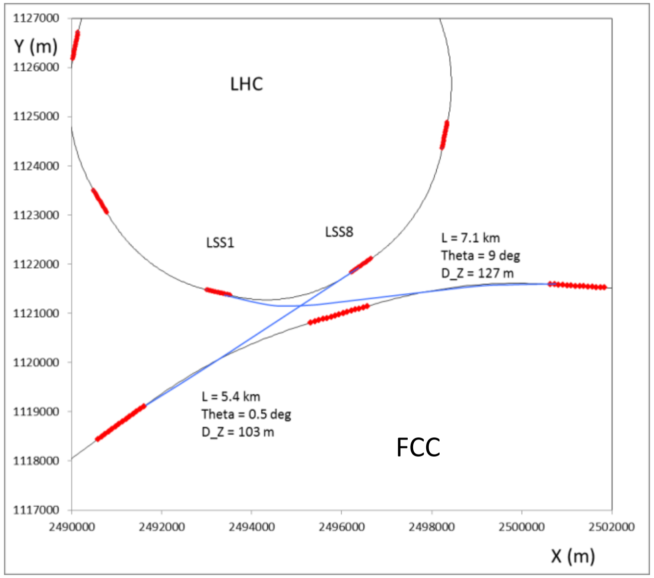
FCC-hh parameters

Beam parameters	Unit	Injection	Extraction
Kinetic energy	TeV	3.3	50
β_{rel}		$\approx$1	$\approx$1
γ_{rel}		3518	53290
Revolution period	μs	333	333
Magnetic rigidity	T.m	11011	166785
# bunches		10600	10600
Transverse emittances	μm	2.2	2.2
Total beam energy	GJ	0.65	8.5

Table 1: Beam parameters at FCC injection and extraction.

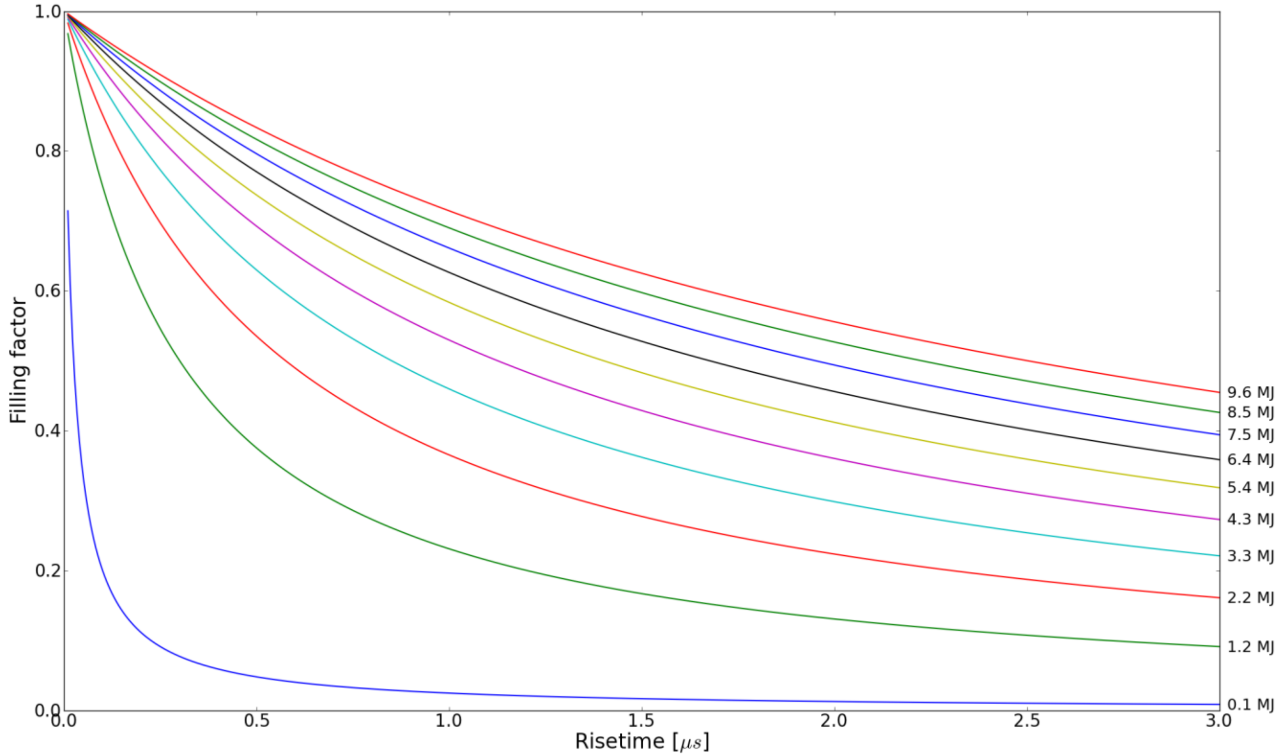
Injection concept

- Fast bunch-to-bucket transfer
- A total of 650 MJ beam energy to transfer
- For HL-LHC with an injected beam energy of ~**5 MJ** reach **limit of injection protection devices**
- **Transfer beam from HEB to FCC in stages**
- 50 – 70 bunches per transfer
  - Gives a total of ~200 injections to fill FCC
  - ~60 injections to transfer a full LHC bunch train
- Time required for the injection process
  - Have to wait for re-synchronisation between machines (~10 ms for LHC-FCC case)
  - Total time required to inject one LHC bunch train ~0.5 s
  - Would need 3 - 4 LHC trains to fill FCC

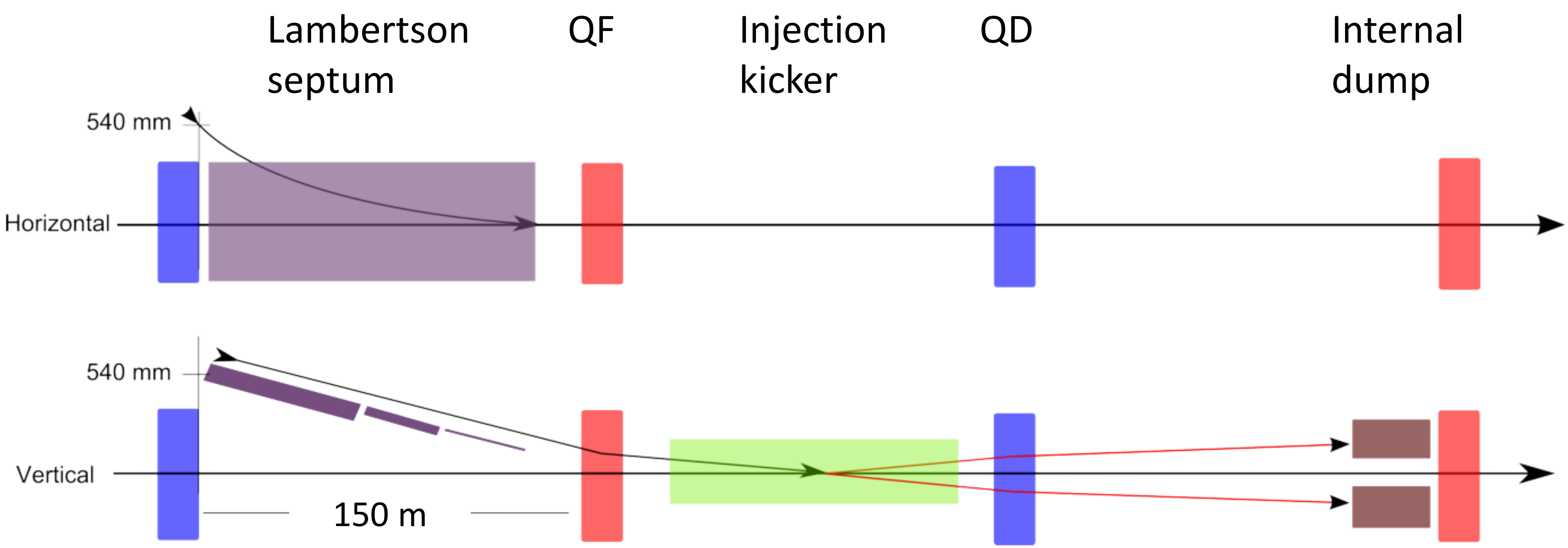


Constraints for FCC filling scheme

- Beam transfer from HEB to FCC is machine protection limited
- Aim to fill 80% of FCC
- Assume about 3 us for abort gap
- 280 ns rise time for injection kicker rise time



FCC Injection Schematic



Massless septum as active injection protection?

Injection septum strength

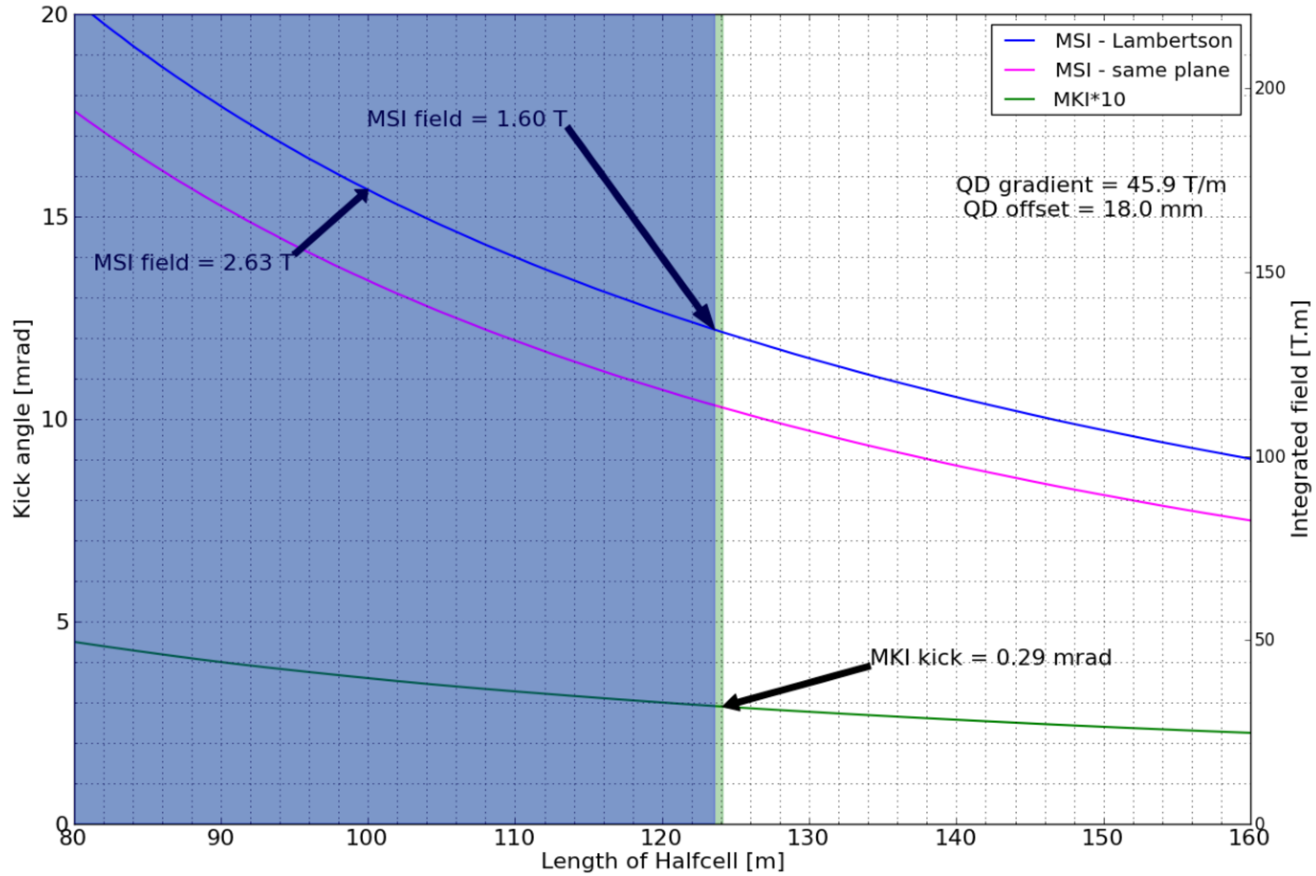
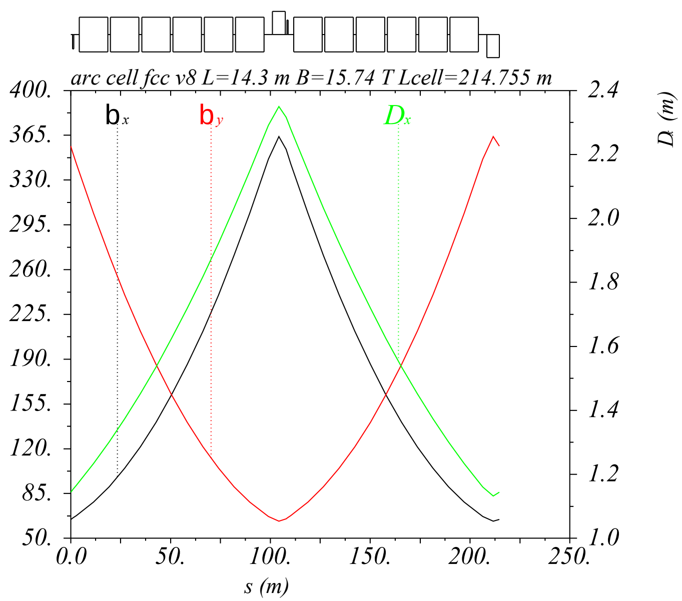
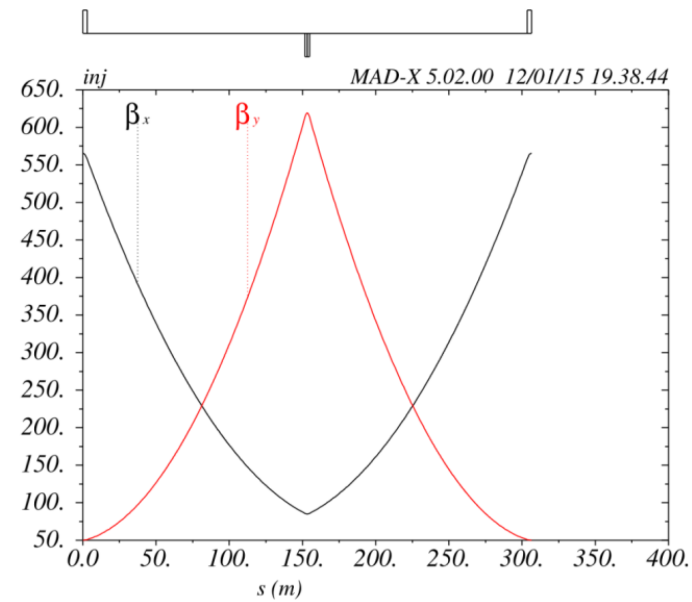


Figure 3: Kick angle and integrated field of septum and kicker as a function of the half cell length.

Injection straight optics

- Increase regular half cell length from 100 m to 150 m in injection insertion
  - Relax magnet strengts, make space for instrumentation and protection devices
- Maximum betas of 620 m – why not go higher?
- Total injection insertion requires about 500 m for septum, kicker and internal dump
- Further protection downstream is required





Injection HW

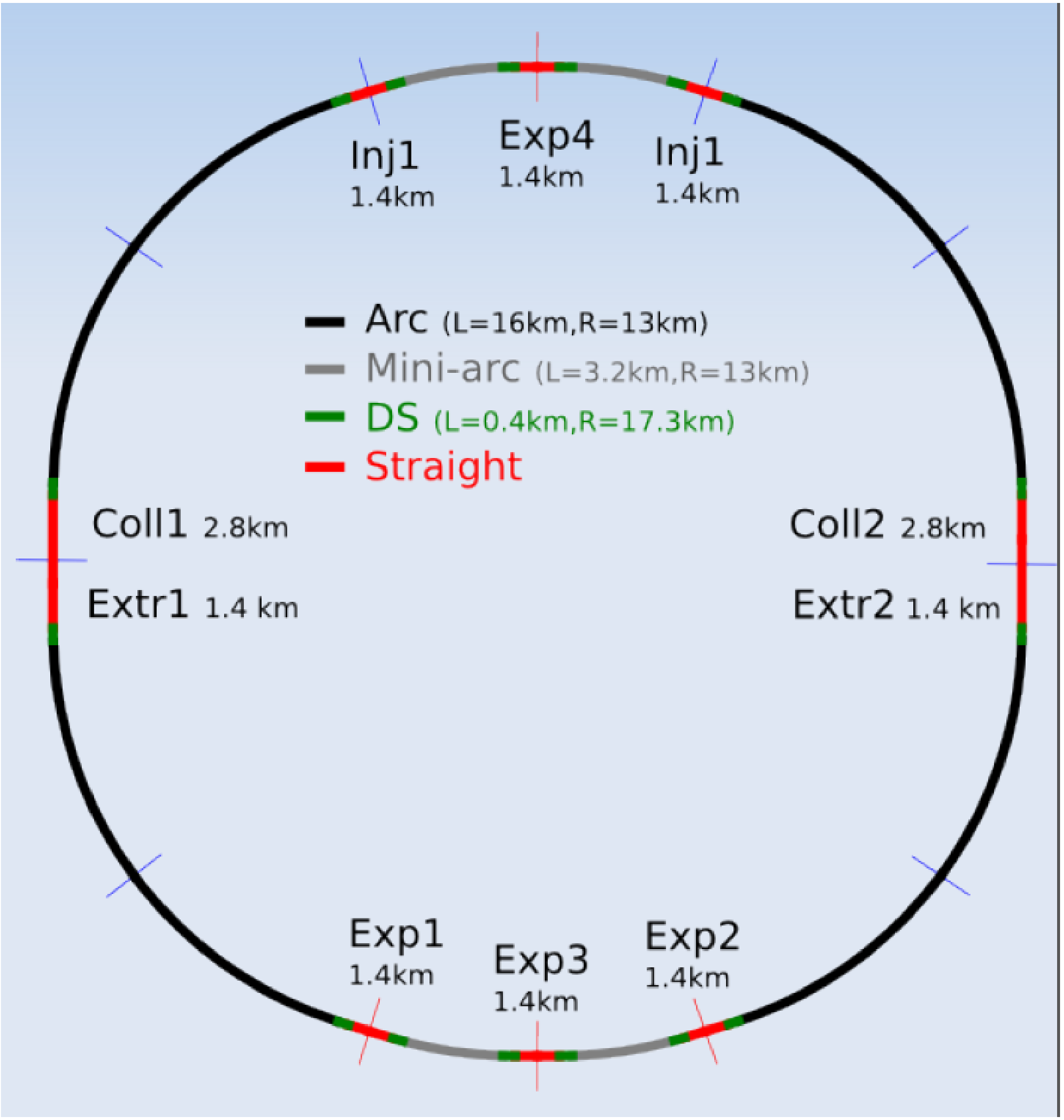
Hardware parameters	Unit	Kicker	Septum
Deflection	mrad	0.29	12.3
Integrated field	T.m	3.2	134
Available system length	m	120	90
Rise time	μs	0.28	-
Flattop length	μs	2.25	$\geq$2.25
Flattop stability	%	$\pm$0.5	$\pm$0.5
GFR h/v	mm	18/18	18/18

Table 2: Parameters of kicker and Lambertson septum at FCC injection for a halfcell length of 125 m.

FCC Extraction

FCC Extraction

- Two separated extraction insertions
- Sequence of collimation and extraction systems
  - If betatron cleaning is separated would be ideal to have collimation downstream extraction
  - Protection of downstream machine and experiments in case of asynchronous dump



Dump insertion – LHC scaled

Extraction kicker:

- 0.13 mrad, **22 T.m**
- 110 m drift

Enlarged quadrupole:

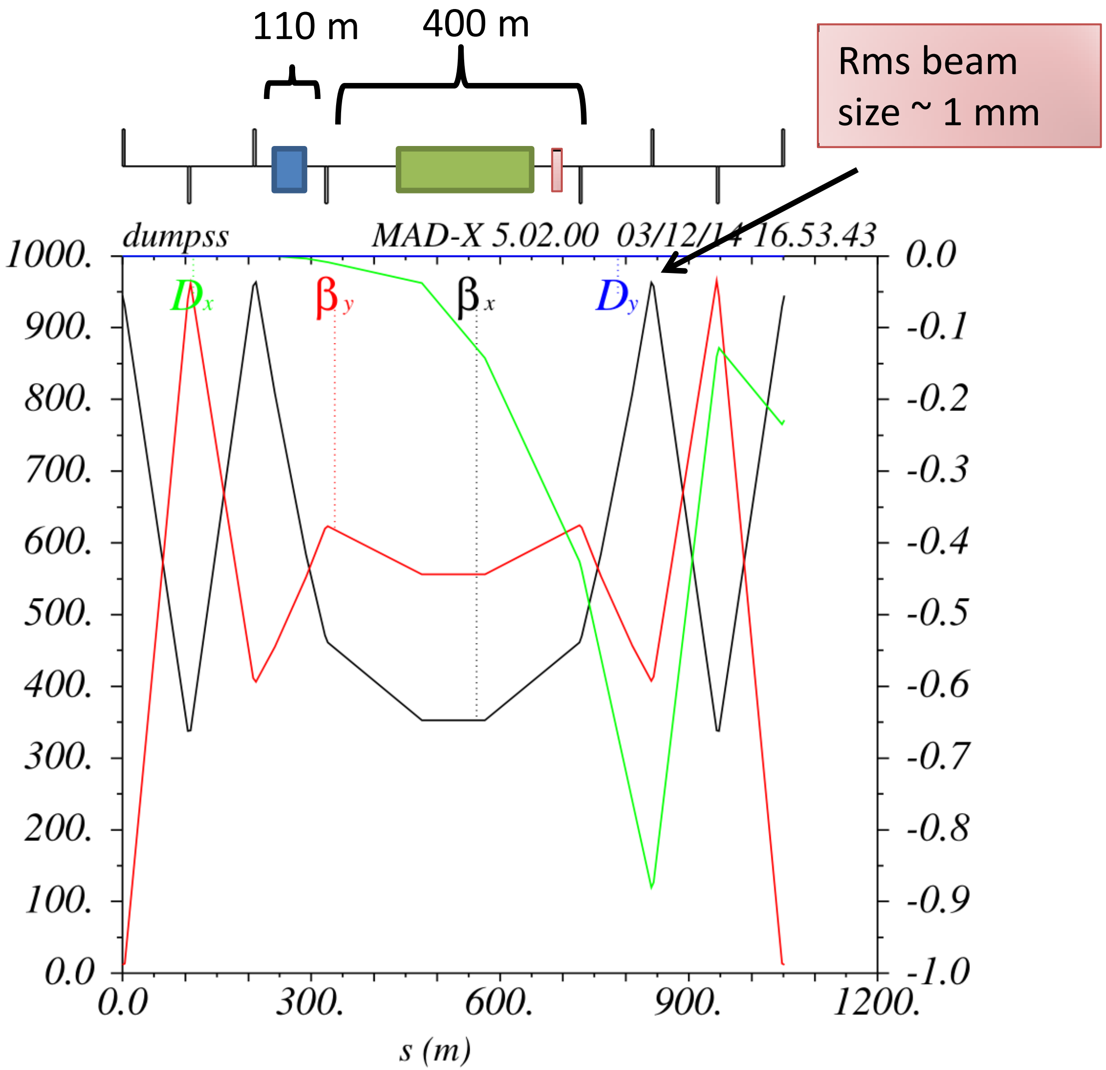
- 9 mm offset

Bump (not in LHC):

- 9 mm
- 0.3 mrad, **50 T.m**

Extraction septum:

- 17 mm septum width
- 150 m drift to clear blade
- 50 m for protection devices +2 bumpers
- **200 m available length**
- 1.7 mrad, **284 T.m, 1.42 T**



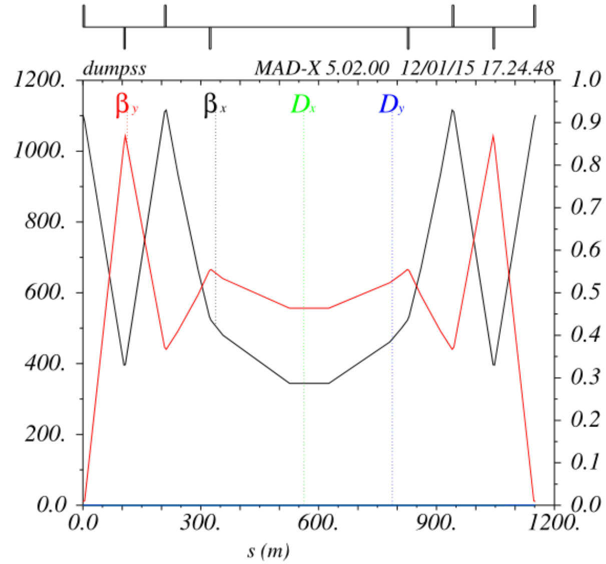
Dump insertion alternatives

SSC like

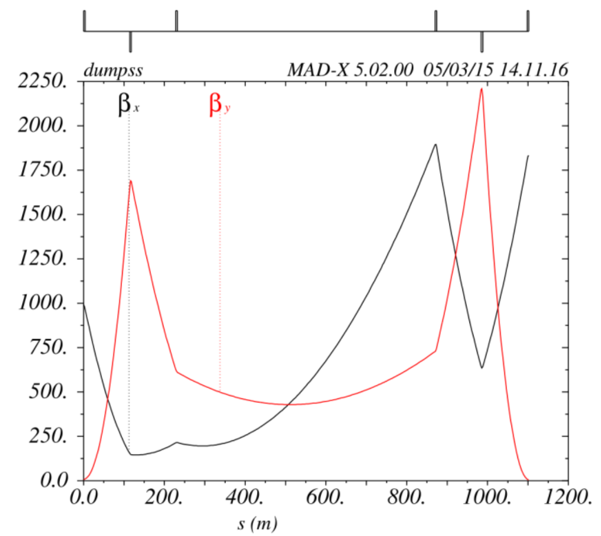
Septum is part of extraction bump

Use field free channel of septum to extract

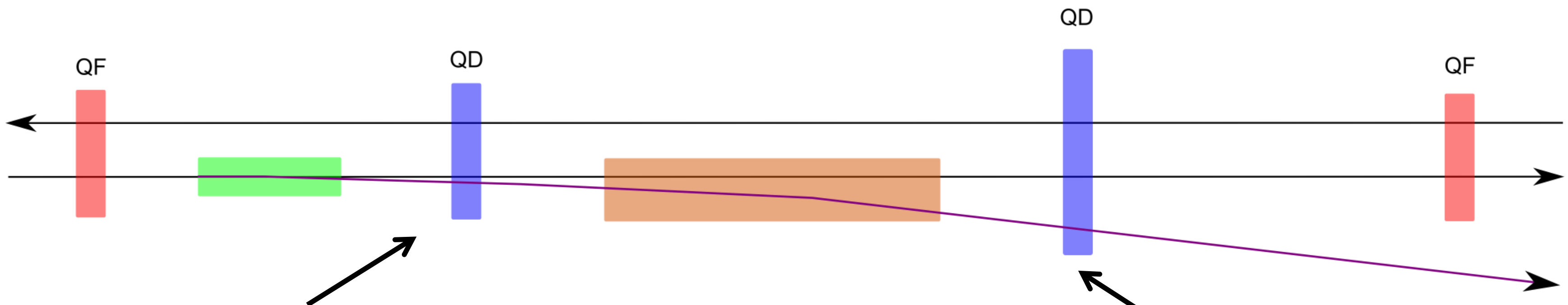
Need strong, good field quality septum



- Asymmetric insertion optics
  - Avoid asynchronous dumps by accepting single kicker erratic
  - High segmentation of kicker system (200-300 modules)
  - Asymmetric optics
    - to reduce oscillation from single kicker failure (small hor beta)
    - to reduce kicker strength and dilute beam at absorbers (high betas at septum)



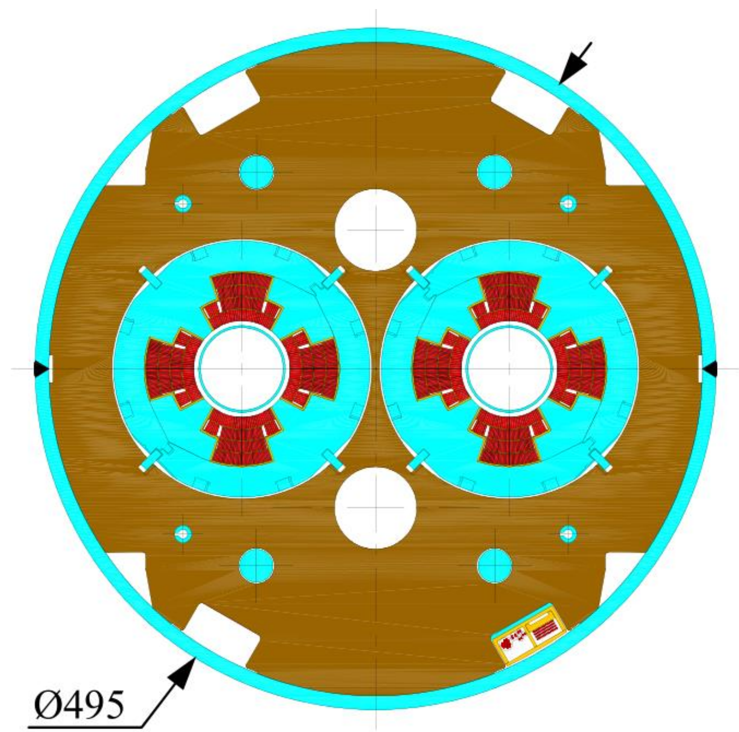
Requirements for special quadrupoles



Enlarged quadrupole

Triple chamber quadrupole?

Beam offset:
Injection up to 18 mm
Extraction up to 9 mm

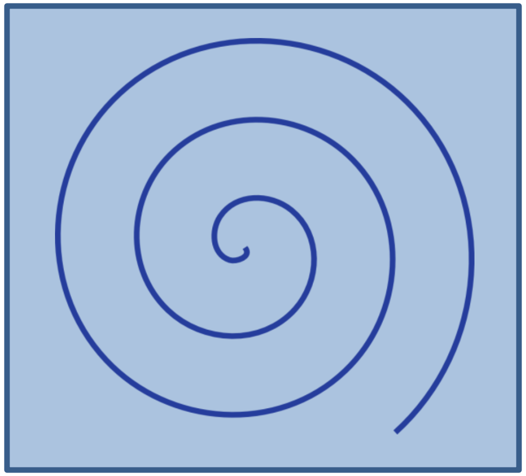


Dump block limitations

See talk by A. Lechner: Energy deposition challenges

- Assume 1.5 km dump line without active dilution
  - 400 µm rms beam size at dump
- Assuming graphite (1.2-1.77 g/cm^3)
  - Limit in energy density such that peak temperature of ~1500°C not exceeded
  - Minimum of ~1.8 mm separation between bunches → requires min of 20 m linear sweep length!
- Actively dilute beam in dump line (beta function of 100 km)
  - 2.0 mm rms beam size
  - Still need ~1.5 mm separation between bunches - **not much gain from active dilution**

	Unit	25 ns	5 ns
Bunch population		1e11	0.2e11
# bunches		10600	53000
Transv. emittance normalised	um	2.2	0.44
Spotsize at dump (rms) for 1.5 km dump line	mm	0.4 - 1.6	0.2 – 0.7
Total beam energy	GJ	8.5	8.5
Average power (5 h fills)	kW	500	500



Summary

- Challenges
- Study direction and R&D programs
- Timeline

Challenges

- Beam energy at HEB-FCC transfer and FCC injection
- Fast injection kicker field rise and recharging
- Injection protection: passive, maybe also active
- Asynchronous dump mitigation
  - Kicker system segmentation
  - Kicker generators: ultra-reliable triggering
- Asynchronous dump protection devices
- Dump absorber
- Beam dilution
- Special insertion magnets
- Limited access possibilities: hot spares, remote handling
- Controls and electronics: remote, compact, reliable, radiation hardness
- Power consumption/recycling
- Constraints on filling schemes from injection and dump

Study directions and R&D programs

- Conceptual
  - Separate extraction systems and link to other systems
  - Failure mitigation (retriggering or segmented kicker system, #abort gaps)
  - Beam dilution
  - Minimize impact of injection and extraction on FCC filling scheme
- Kicker system
  - Generator: fast field rise time, short pulses and fast generator recharging; semiconductor switches
  - Magnet: Beam screen and ferrite cooling
  - Segmentation and built-in redundancy
- Septa:
  - High field Lambertson with high saturation material shims and NC or SC coils
  - Massless septum to deflect mis-kicked beam into dedicated injection dump channel
  - Superconducting septum
- Electronics
  - Radiation to electronics mitigation
  - Ultra-high reliability triggering and synchronisation concepts for highly segmented systems
- Dump absorber and passive protection devices:
  - Study new materials and concept of sacrificial absorbers
  - Beam dilution requirements

Timeline

- 2015:
  - Detailed R&D program proposal for kicker generator, kicker and septum magnet, electronics
  - Finalize conceptual studies for injection, extraction and failure mitigation
  - Specify kicker systems, septa and special insertion magnets
- 2016:
  - Finalize linear optics of injection and dump lines; dilution pattern
  - Specify passive protection devices and massless septum for injection protection
- 2017:
  - Finish error studies, specify power converter stability and field homogeneities
  - Measurement report of individual components for kicker generators; design report prototype
  - Finished design of kicker beam screen and ferrite cooling; radiation hard sensor board developed
- 2018:
  - Finish prototype construction of kicker generator, kicker beam screen and septum
  - **CDR write-up**
- 2019:
  - Document prototype testing results of kicker generator, magnet, electronics and septa magnets