CERN

FUTURE
CIRCULAR
COLLIDER

Failure Modes During Injection and Extraction

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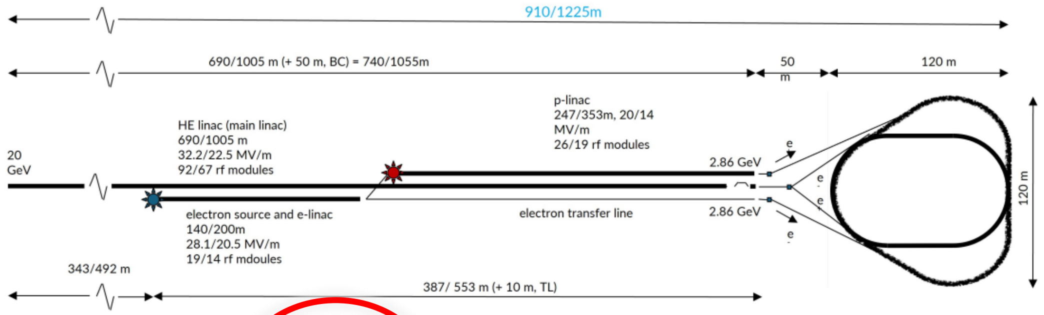
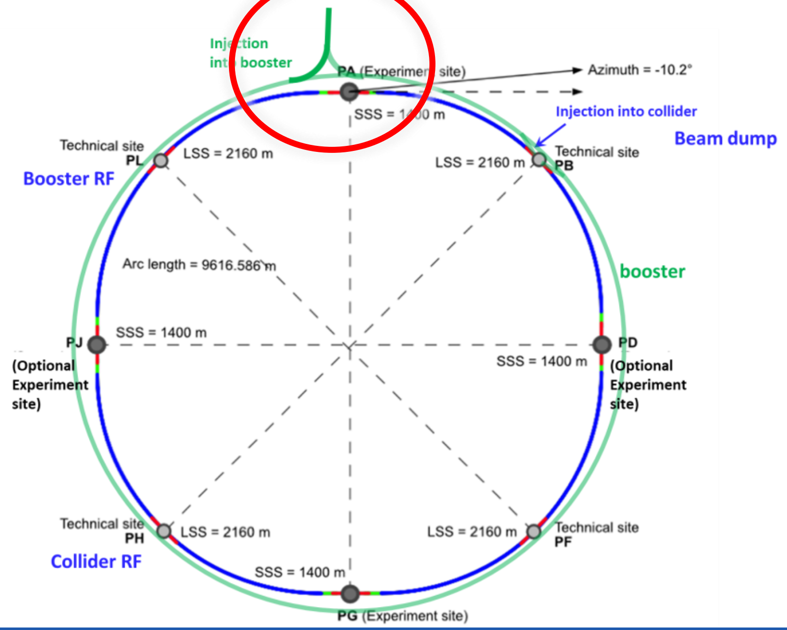
Outline

- Layout & Beam Parameters
- Booster injection/extraction/dump systems
- Collider injection/dump systems
- Possible failures and mitigations
- Electromagnetic separator

Layout and Beam Parameters





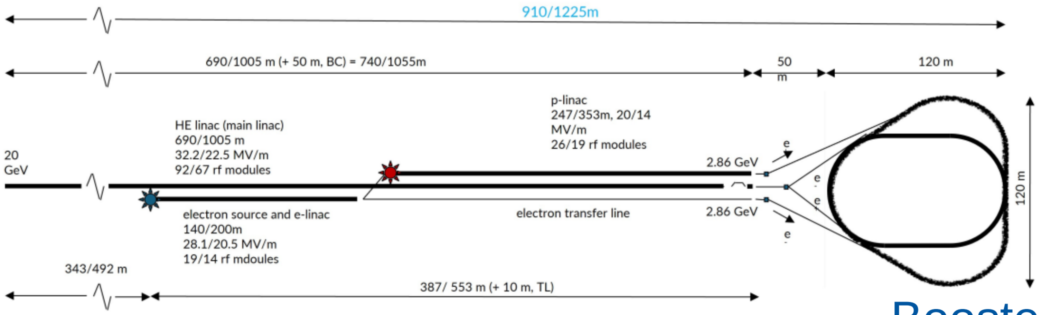
- Injectors provide the booster with 4 bunches per pulse, separated by 25 ns at 20 GeV with a 100 Hz repetition rate

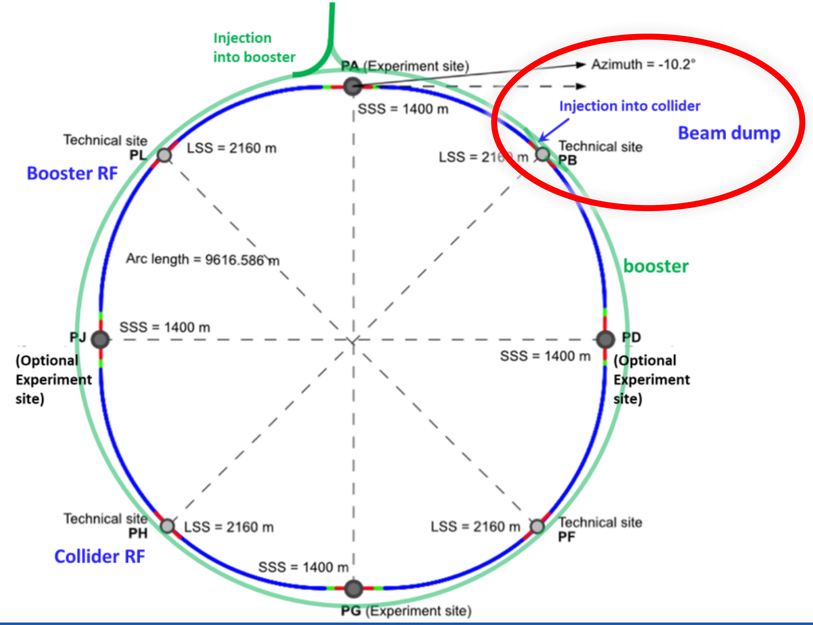
Booster injection

Modes	Z	W	ZH	ttbar
Energy [GeV]	20	20	20	20
#bunches	4	4	4	4
# ppb [1E10]	2.14	1.45	1.32	1.64
Stored Energy [J]	273.9	185.6	168.9	209.9
r.m.s. H emittance	~250 pm	~250 pm	~250 pm	~250 pm
r.m.s. V emittance	~250 pm	~250 pm	~250 pm	~250 pm
Energy Density* [MJ/mm^2]	~0.01	<0.001	<0.001	<0.001

* Assuming β = 100 m

Layout and Beam Parameters





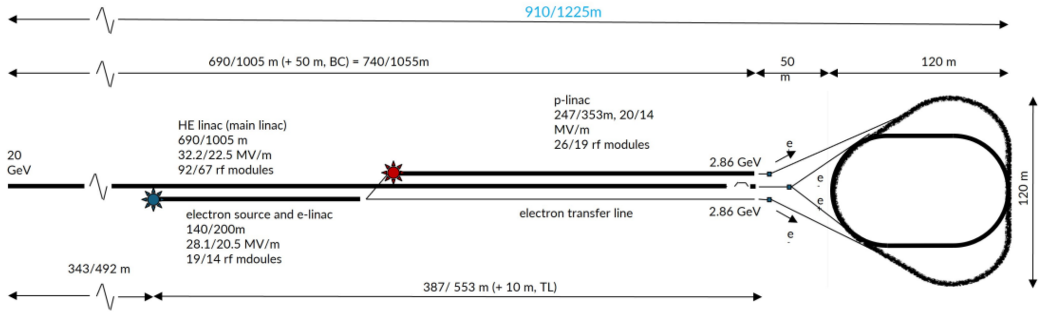
- Injectors provide the booster with 4 bunches per pulse, separated by 25 ns at 20 GeV with a 100 Hz repetition rate

Booster extraction/dump+Collider injection

Modes	Z	W	ZH	ttbar
Energy [GeV]	45.6	80	120	182.5
#bunches	1120	890	380	56
# ppb [1E10]	2.14	1.45	1.32	1.64
Stored Energy [J]	**0.18E06**	**0.17E06**	**0.10E06**	**0.03E06**
r.m.s. H emittance	~120 pm	~270 pm	~600 pm	~1.4 nm
r.m.s. V emittance	~40 pm	~0.5 pm	~1 pm	~3 pm
Energy Density * [MJ/mm^2]	~25	~135	~35	~4

* Assuming β = 100 m

Layout and Beam Parameters



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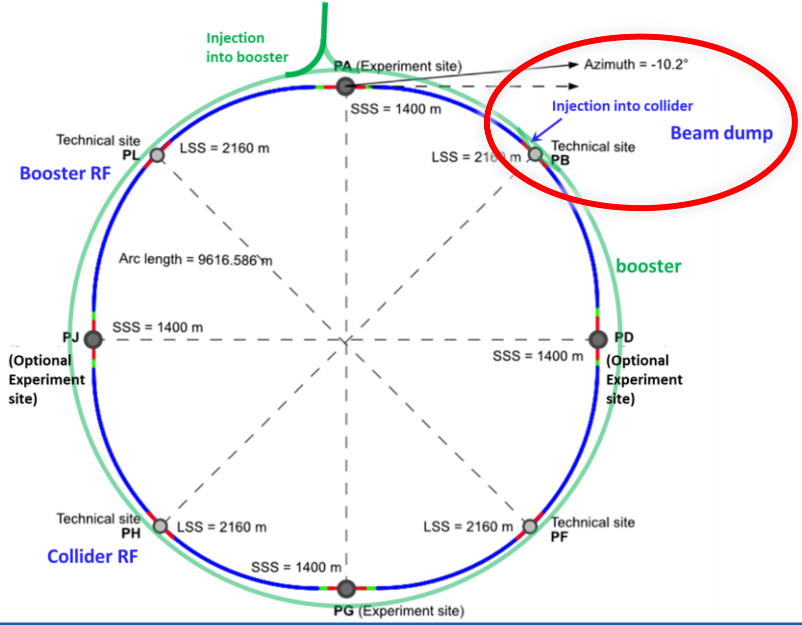


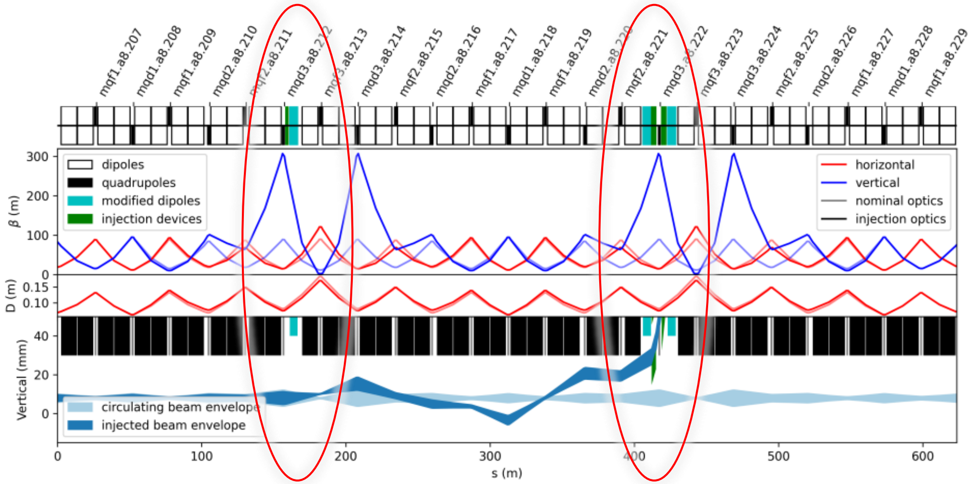
Collider extraction/dump

Modes	Z	W	ZH	ttbar
Energy [GeV]	45.6	80	120	182.5
#bunches	11120	1790	380	56
# ppb [1E11]	2.14	1.45	1.32	1.64
Stored Energy [J]	**17.5E06**	**3.4E06**	**1.0E06**	**0.3E06**
r.m.s. H emittance	~700 pm	~2 nm	~700 pm	~1.5 nm
r.m.s. V emittance	~2 pm	~2 pm	~1.5 pm	~1.5 pm
Energy Density * [MJ/mm^2]	~4.8E03	~4.8E02	~3E02	~5E01

* Assuming β = 100 m

Booster Injection

- Vertical bunch to bucket injection in the arcs
- 2 systems: one for e+ and one for e-
- Each system made of:
  - 2 eddy current septa (10 and 18 mm thick blades)
  - 1 stripline kicker + inductive adder
- Number of mis-kicked bunches in case of spurious/no firing: 5
- Injection not critical but need to envisage protection of septa from circulating beam



Kickers /Systems	1/2
Impedance [Ω]	50
Current [kA]	0.3
Voltage [kV]	±16
Element aperture [mm]	30
Integrated field [mT.m]	4
Effective length [m]	1
Physical length [m]	1.4
Total kick angle [mrad]	0.09
Aperture (beam stay clear) (⌀) [mm]	30
Rise / fall time [ns]	25
Flat top length [μs]	0.08
Flat top quality [%]	±0.5 (tbc)
Repetition rate [Hz]	100

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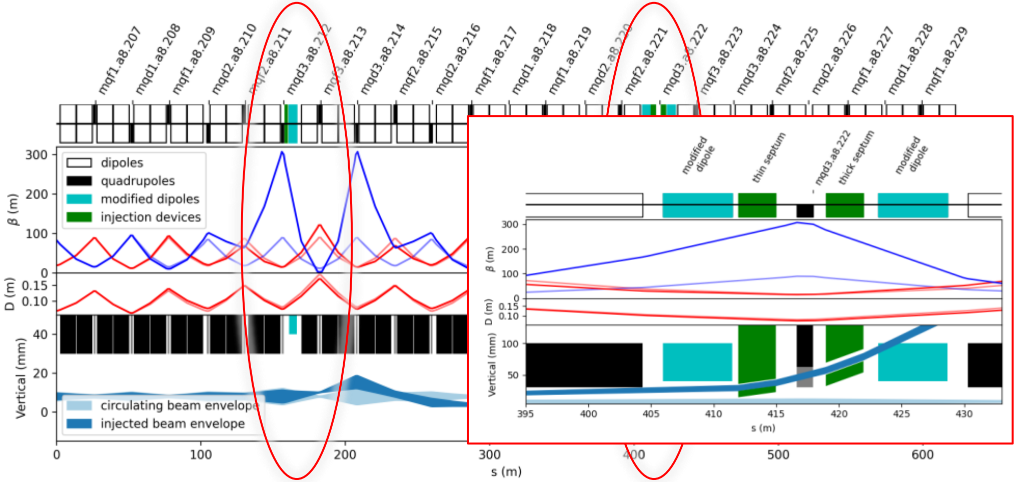

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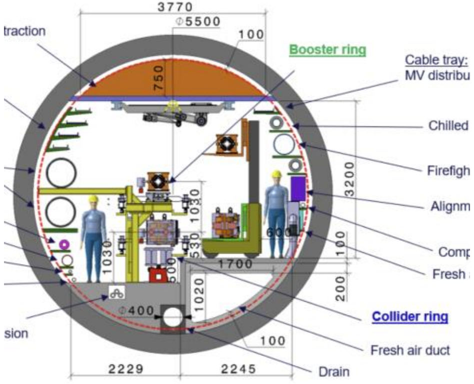
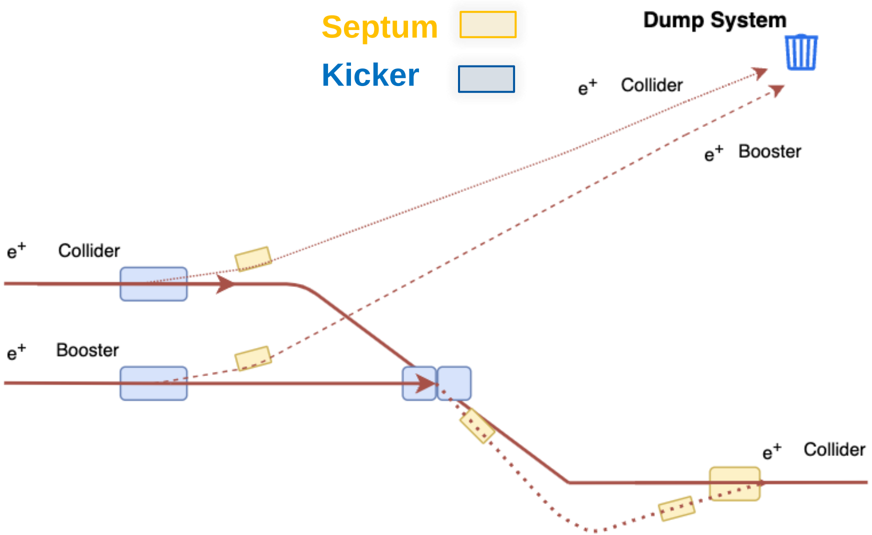
Booster Extraction

- Extraction to the collider:
  - Fast extraction (kickers + septa)
  - It occurs in the horizontal plane and the beam is vertically transferred to the collider
  - It happens always at fixed energy (for a defined physics mode) and all the bunches are extracted and transferred at once to the collider (1120 bunches at 45.6 GeV, 180 kJ, for Z mode) ➔ failure affecting all bunches
  - Same extraction kickers can be used for e- and e+
- Extraction to the dump:
  - Fast extraction (kickers + septa)
  - It occurs in the horizontal plane
  - It can happen at any energy between 20 GeV and top energy
  - All circulating bunches extracted at once ➔ failure affecting all bunches
  - Fully separated systems for e- and e+



Top view



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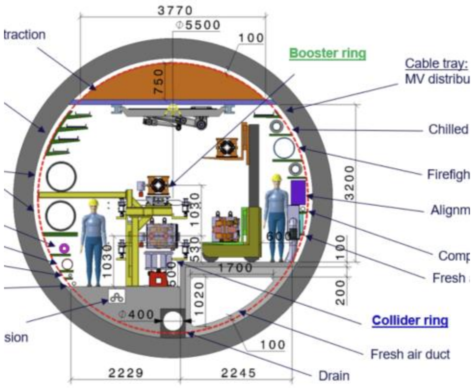

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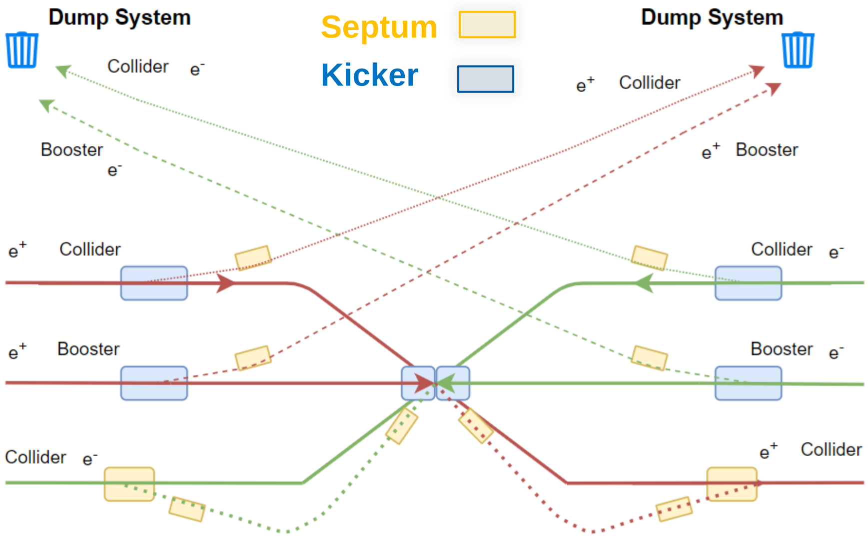


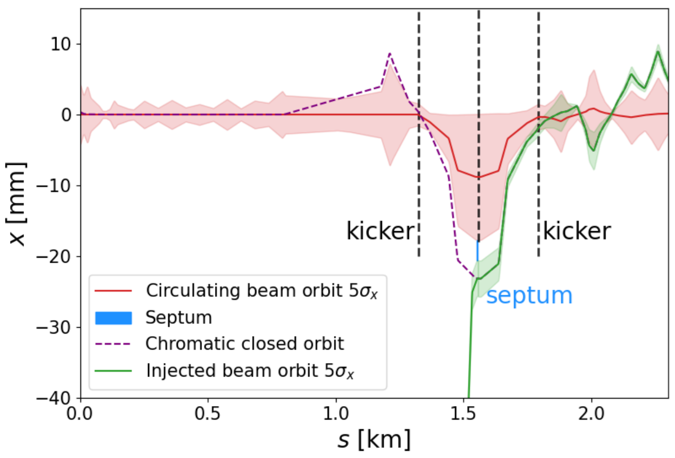
Booster Extraction

- Extraction to the collider:
  - Lumped inductance kickers (out of vacuum) + Marx generators
  - 1 pulsed outside vacuum septum with thin-walled vacuum chambers (5 ms half sine to allow > 304 μs flattop). Need edge cooling for blades.
  - Alternatively permanent magnet septum (need to evaluate if septum thickness requirements can be met, increase number of installed modules when increasing energy for different physics modes)
- Extraction to the dump:
  - Lumped inductance kickers (out of vacuum) + Main capacitors discharge stage boosted by droop compensation (like LHC)
  - 5 slowly ramped DC septa, outside vacuum magnet
  - Alternatively low power DC septum (more robust but need to verify if it can be ramped sufficiently fast)

	To collider	To dump
Kickers / Systems	10/1	6/2
Impedance [Ω]	10	10
Current [kA]	2	1.2
Voltage [kV]	14.5	5
Element aperture [mm]	70	70
Integrated field [mT.m]	26.5	30
Effective length [m]	1	1
Physical length [m]	1.4	1.4
Total kick angle [mrad]	0.429	0.3
Aperture (beam stay clear) (⌀) [mm]	60	60
Rise / fall time [μs]	1.1	1.1
Flat top length [μs]	30-304	304
Flat top quality [%]	±0.5	±5
Repetition rate [Hz]	10	1

Collider Injection

- Top-up injection:
  - Two kickers are placed with 180° phase advance between them (π-orbit-bump) to create a closed bump to bring the stored beam trajectory close to the injection septum
  - The bump is constant for up to a single turn (304 µs) while off before and after (rise and fall in 1.1 µs abort gap) ➔ possible affecting all circulating bunches (up to 11200, 17.5 MJ) in case of kicker failures and up to 88 bunches (Z-mode) in case of loss of synchronization ➔ oscillations and losses
  - On-axis injection: separation in momentum in a dispersive region ➔ longitudinal oscillations and damping
  - Stripline kickers* + Marx Generators
  - 5 pulsed direct drive magnetic septa under vacuum (possibly with remote positioning system of the 2.8 mm thick blade)

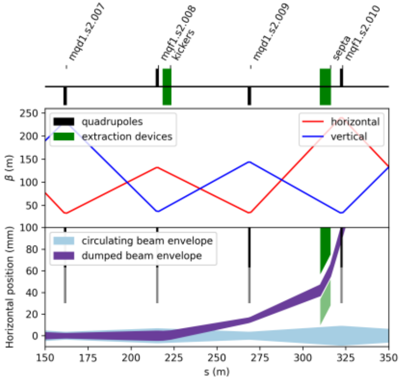


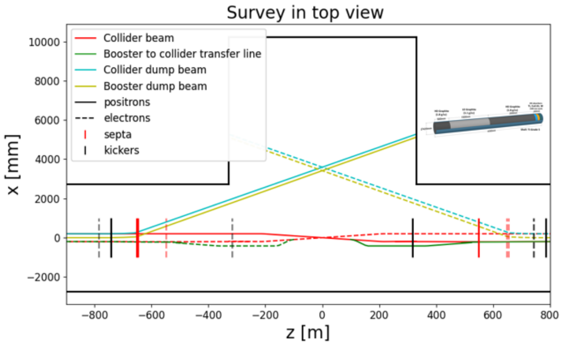
Kickers / Systems	2/2
Impedance [Ω]	50
Current [kA]	0.2
Voltage [kV]	±15
Element aperture [mm]	30
Integrated field [mT.m]	10.8
Effective length [m]	3
Physical length [m]	3.6
Total kick angle [mrad]	0.072
Aperture (beam stay clear) (⌀) [mm]	60
Rise / fall time [ns]	1100
Flat top length [µs]	30 – 304
Flat top quality [%]	±0.5
Repetition rate [Hz]	10

* Compact magnets that allow longer cables than lumped inductance but in vacuum

Collider Extraction

- Extraction to the dump:
  - Fast extraction at fixed energy (for each physics mode). We assume that all bunches, up to 11200, are extracted at once towards a ~1200 m TL to external dump (same dump for booster and collider). Filling schemes done with several abort gaps each of 1.1 µs. Failures can impact all circulating bunches
  - Lumped inductance kickers (out of vacuum) + Main capacitors discharge stage boosted by droop compensation (like LHC)
  - 4 low power DC septa outside vacuum. Need to define leak field and field homogeneity in good field region.
  - Alternatively permanent magnet septa
  - Passive dilution (spoiler) looks sufficient to reduce the energy density at the dump





Kickers / Systems	**6/2**
Impedance [Ω]	**10**
Current [kA]	**1.2**
Voltage [kV]	**5**
Element aperture [mm]	**70**
Integrated field [mT.m]	**30**
Effective length [m]	**1**
Physical length [m]	**1.5**
Total kick angle [mrad]	**0.3**
Aperture (beam stay clear) (⌀) [mm]	**60**
Rise / fall time [µs]	**1.100**
Flat top length [µs]	**304**
Flat top quality [%]	**±5**
Repetition rate [Hz]	**0.1**

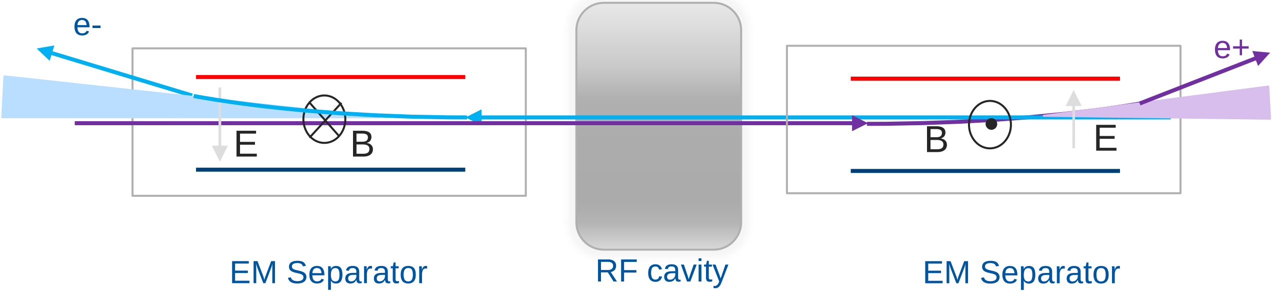
Failures

- Typical failures of fast systems:
  - Loss of synchronization with RF
  - Spurious firing of kickers (also induced by SEU)
  - Missing kickers (mainly for collider injection inducing large oscillations in the machine and losses)
  - Kickers pulsing at wrong energy/voltage
  - Flashover for in vacuum magnets (stripline)
  - Large ripples at flattop (in particular for extraction/injection to collider)
  - Non-pulsing septa
  - Wrong current in DC septa
  - Large orbit drifts at extraction
  - Beam coupling impedance affecting the beam

- Protection measures:
  - Passive (sacrificial) absorbers at dedicated locations in the ring and in the transfer lines to the collider and the dump (need to design optics to maximize spot-size to reduce energy density at absorbers)
  - Masks in front of septa (for mis-kicked beam and halo protection)
  - Energy tracking system for kickers and septa
  - Retriggering system for kickers
  - Redundancy
  - Use out of vacuum magnets (lumped inductance)
  - Use permanent magnets when/if possible for septa
  - Interlocked Beam Position Monitors
  - Further segmentation (more kickers and septa to reduce risk and sensitivity to failures)
  - Chunk extraction to reduce total waveform length and number of impacted bunches in case of failure (profit of multiple abort gaps)
  - Use low power septa (easier to monitor/interlock current in particular for booster dump)
  - Constant check of waveforms to detect ripples out of specs and drifts
  - Rad-hard components and sensitive electronics in shielded alcoves (compatibly with cable length limitations)
  - Optimized designs to minimize beam coupling impedance
  - Fast detection and reaction time (1 turn)

Collider Electro-Magnetic (EM) separator (point H)

- Installed upstream and downstream of RF section in ttbar mode.
- Used to assure both beams pass through centre of RF cavities, while avoiding synchrotron light hits the cavities.
- Magnetic field is cancelled by the electric field before entering the cavity, while adding up for particles exiting the cavities.
- 2 families of 10 EM separators powered in series (magnet) and parallel (separator), limiting the power converter footprint.



- Failures:
  - B and E field longitudinal mismatch
  - Synchrotron light on HV electrodes inducing sparks that could give large kicks to the beam (ultra-fast failure)
- Mitigations:
  - Fast detection of oscillations (interlock BPMS) and beam extraction (if oscillations reasonably small)
  - Dedicated masks for synchrotron light

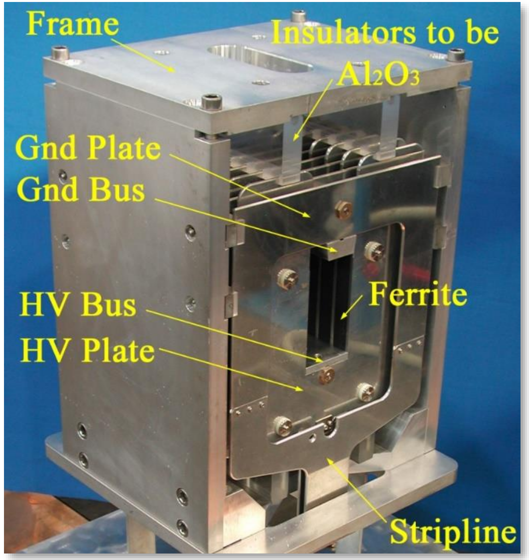
Conclusion

- Machine protection concerns start at booster extraction and Z-mode is the most critical
- Possible failures are typical of high voltage fast pulsed systems
- Additional challenges are introduced by synchrotron radiation and high stored energy and energy density
- Mitigations consist in:
  - Measures already applied in LHC (redundancy, passive protection, retriggering etc.)
  - Segmentation to reduce risk and consequence of failures
  - System design has to take into account minimization of failures (out of vacuum magnets, permanent magnets, minimum beam coupling impedance)
  - New concepts like sacrificial absorbers (for ultra-fast failures), chunk extraction etc. have to be considered
- Fast (how fast?) reaction to failures is considered as crucial and feasibility has to be assessed

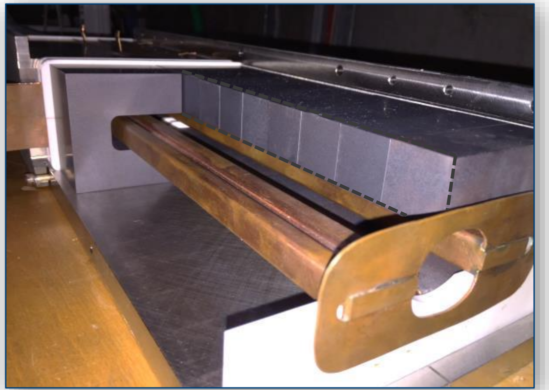
Backup slides

Kicker topologies

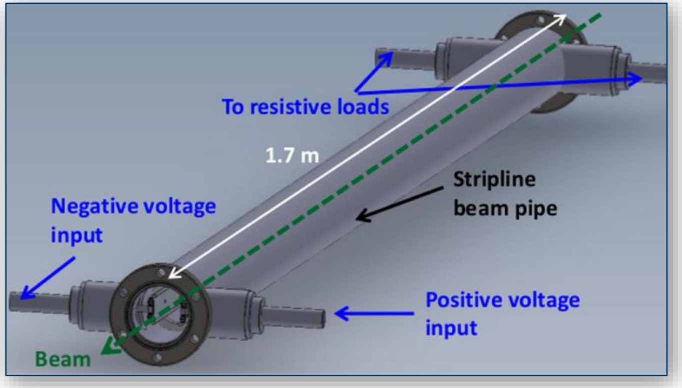
Transmission line



Lumped inductance



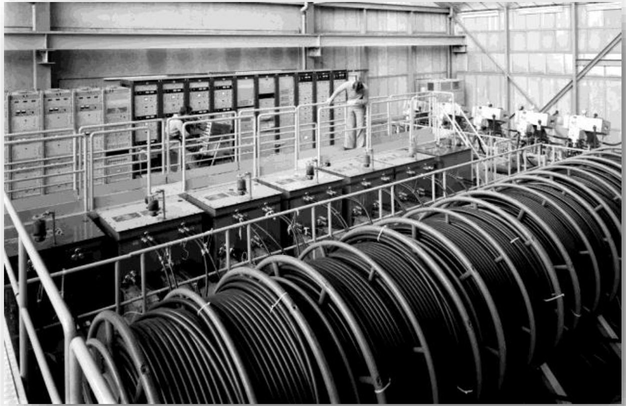
Stripline



Generator topologies

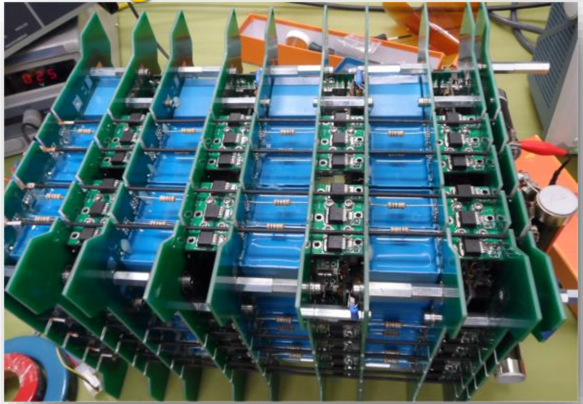
PFN

PFL



Inductive adder

Marx generator



Magnet topologies

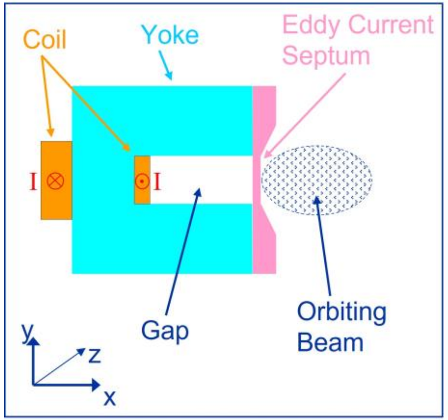
TYPE	PRO	CONS
Stripline	▪ Compact design ▪ Very fast rise time (few ns) ▪ Low beam coupling impedance	▪ Uses both E and B (voltage up to 50 kV and weaker deflection) ▪ Impedance matching important ▪ Challenging flat-top stability ▪ More power consumption
Transmission line	▪ Fast rise time << 1μs ▪ Strong deflecting field ▪ At CERN: 80 kV, 5 kA	▪ Complex to manufacture and costly ▪ Impedance matching important ▪ High beam coupling impedance
Lumped inductance	▪ Simple and robust magnet design ▪ Can be out of vacuum ▪ Strong deflecting field ▪ At CERN: 80 kV, 5 kA	▪ Suitable for rise time ≥ 1μs ▪ Needs minimizing interconnection inductance ▪ High beam coupling impedance

Generator topologies

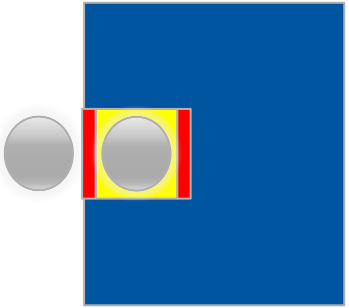
TYPE	PRO	CONS
PFN	▪ Compact design ▪ Low droop and long pulses > 3 μs	▪ Complex and costly constructions ▪ Risetime limited by cells cut-off frequency ▪ Pulses are prone to ripples - may require cells adjustment ▪ Require high voltage capacitors
PFL	▪ Simple design ▪ Short pulses < 3 μs ▪ Ripple-free (flat) pulses	▪ Significant droop in pulses > 3 μs ▪ Bulky: 3 μs pulse 300 m of cable ▪ Above 40 kV SF6 used at CERN
Marx Generator	▪ Long duration pulse capability ▪ High repetition-rate ▪ Low-voltage components ▪ Modular	▪ Sensitive to radiation ▪ Complex triggering system
Inductive adder	▪ Short and precise pulses ▪ Modular, redundant, scalable ▪ Easier triggering circuits	▪ Available pulse duration is affected by magnetic material (<3 μs) ▪ Sensitive to radiation

Septa Topologies

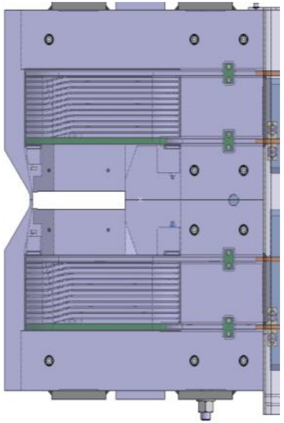
Eddy current



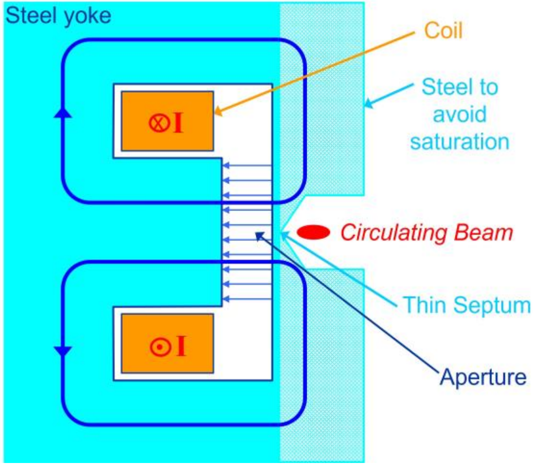
Pulsed outside vacuum



Low Power DC septum



Lambertson



Permanent magnet