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Overview of and Challenges for the FCC-ee Fast Pulsed Beam Transfer Systems

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Outline

- Outcome from feasibility study and kicker design outline

- Challenges and need for R&D/prototyping

    - Stripline kicker + Inductive adder
    - Lumped inductance kicker + generator
    - Other considerations

- Conclusions

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Feasibility study

Injection/Extraction Systems Across the Complex, S.Yue

- Kicker systems are designed based on the following **key considerations**:
  - Optics design
  - Cost, power consumption & environmental impact
  - Integration
  - Ionizing dose levels
  - Machine protection impact
  - Operational needs
  - Collective effects

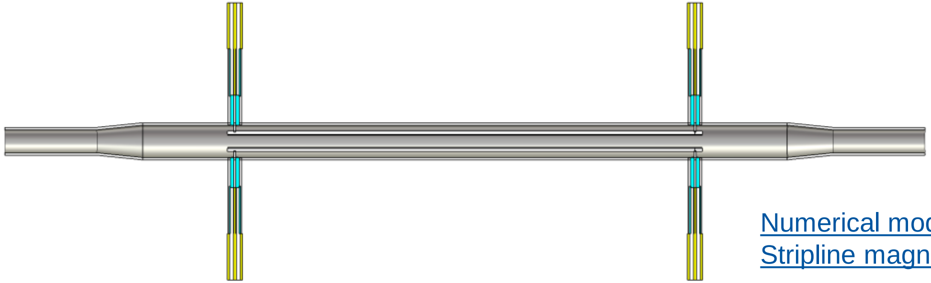
- **Multiple system specification changes** have required a reconsideration of the design choices or **design reiterations**

- **Some parameters remain undefined** or to be confirmed:
  - Beam stay clear region
  - Rise and fall time definition
  - Flat top quality

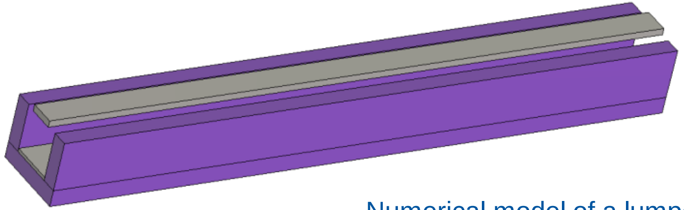
- **No major showstoppers**, but **several challenges** have been identified

Kicker systems outline

	Damping ring	Booster injection	Booster extraction	Booster Dump	Collider injection	Collider dump
Magnet topology	Stripline	Stripline	Lumped inductance	Lumped inductance	Lumped inductance	Lumped inductance
Generator topology	Inductive adder	Inductive adder	Marx generator	LBDS-like generator	Marx generator	LBDS-like generator
Element under vacuum	Yes	Yes	No	No	No	No
Elements / Systems	2/4	1/2	14/2	9/2	6/2	9/2
Novel technology	Yes	Yes	Yes	No	Yes	No
R&D required/ Prototyping required/ Conventional technology	R&D - prototype required	R&D - prototype required	R&D - prototype Required	Prototype required	R&D - prototype required	Prototype required



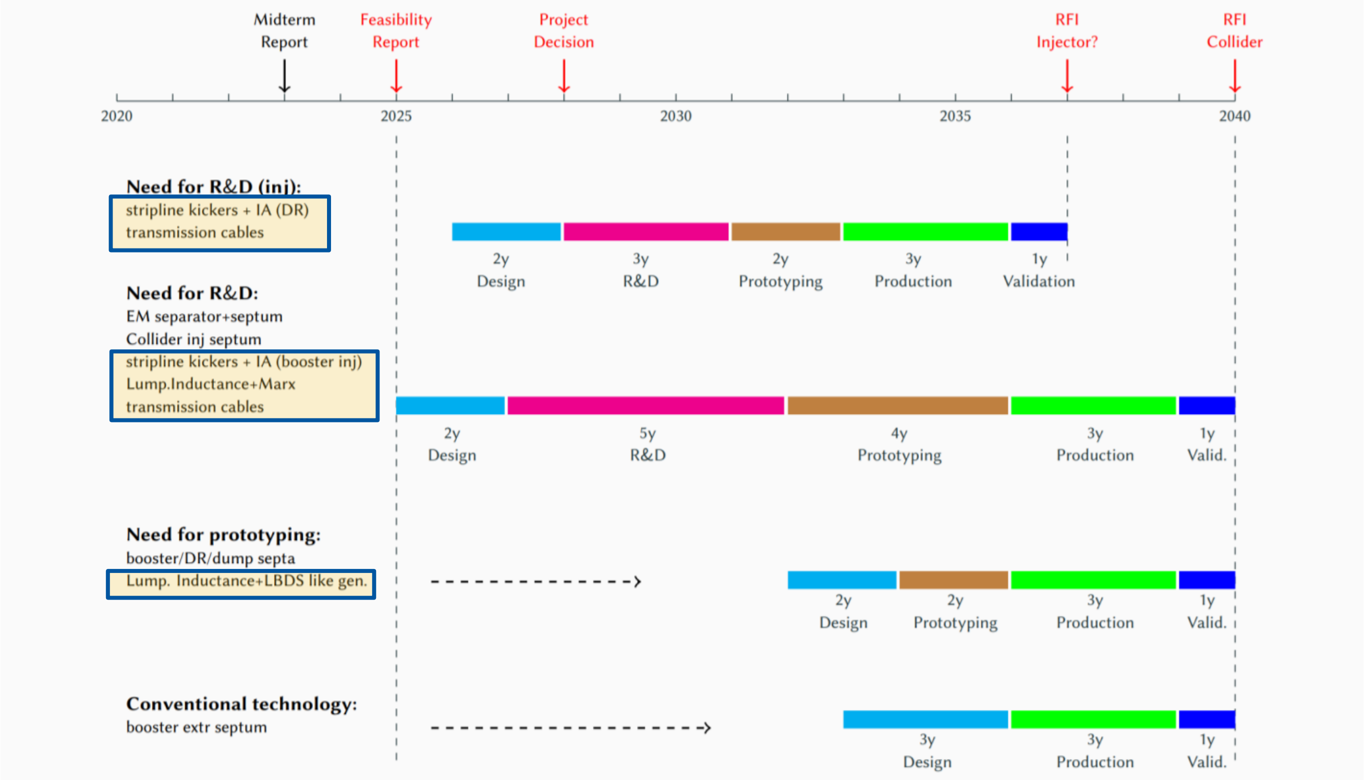
Numerical model of a Stripline magnet



Numerical model of a lumped inductance magnet

R&D and prototyping timeline

- R&D and prototyping activities have been planned and a timeline has been established to ensure a timely systems readiness



Kicker systems design choice criteria

- Magnets and generator topologies have been designed to be cost-efficient, simplify their maintenance and improve machine protection aspects. Priorities are:
  - Standardization of equipment
  - Limited generator voltage solutions
  - Avoidance of oil-filled generators or SF6 cables
  - Limited power dissipation and cooling requirements

- Looking back:
  - Profited of LEP experience and considered similar kicker solutions

- Looking ahead:
  - Considered benefits and long-term availability of novel technologies
  - i.e. solid state switches favoured over thyratrons; modular solutions preferred due to easier maintenance

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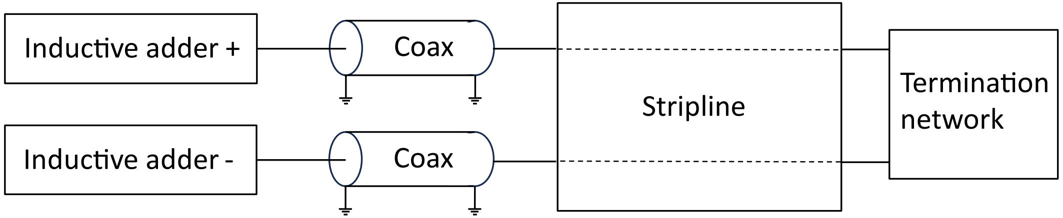
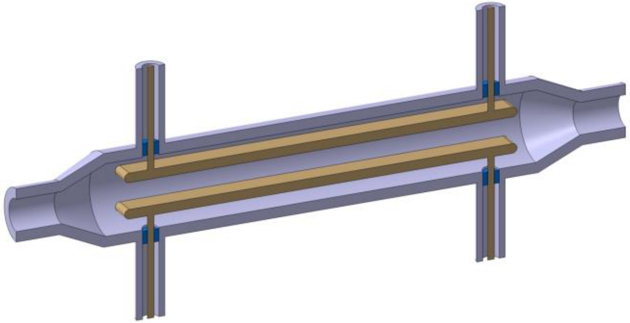
Stripline + Inductive Adder

- **Kicker:** Stripline to satisfy fast rise and fall time requirements
- **Generator:** Inductive adder can provide the short flat top and the required homogeneity
- The coaxial cable length is based on integration constraints, but ≤30m needed to achieve rise time and field homogeneity

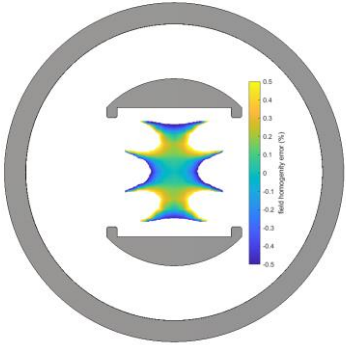


	Damping ring	Booster injection
Requirements		
Energy [GeV]	2.86	20
Kick angle per unit [mrad]	1.5	0.09
Rise / fall time [ns]	82	25
Flat top length [ns]	80	80
Flat top quality [%]	±0.5	±0.7
Repetition rate [Hz]	100	100
Available length [m]	1.5	5.5
Design parameters		
N. Of Magnets/ System(s)	2 / 4	1 / 2
Impedance [Ω]	50	50
Current [A]	640	260
Voltage [kV]	±32	±13.4
Plate separation [mm]	30	30
Integrated E-field [MV]	3	0.9
Integrated B-field [mT.m]	7.1	3
Effective length [m]	1	1
Physical length [m]	1.5	1.5

Stripline kicker



- Relatively simple and compact kicker design
- A preliminary design has been developed, with main challenges being identified:
  - Field homogeneity
    → Optimized electrodes shape design
  - HV issues
    → HV limited to < 50kV
    → SR impact?
  - Operational experience
    → Magnet topology already prototyped for CLIC, but not currently operated
    → Learn from other electrons laboratory' experience
  - Impedance matching



Stripline kicker – Impedance matching

- Stripline kickers work in two operating modes, with two different characteristic impedances
  - **Odd mode**
    - → Seen by the bipolar pulse from the generators when kicker is on
    - → Reflections affect the pulse quality
  - **Even mode**
    - → Seen by the beam when kicker is off
    - → Reflections affect the beam coupling impedance

- An optimization process is required to achieve the field tolerances and limit the beam impedance
  - One impedance is matched by the terminations at the expense of the other
  - Beam impedance limits not yet specified

- A more complex matching network might be needed if a good compromise can't be found:
  - Need to design a termination element between the electrodes
    - → in-vacuum: complex design due to concerns about power losses and vacuum compatibility
    - → outside-vacuum: would be prone to mismatches at the feedthroughs
  - **R&D and prototyping is needed!**

Inductive adder

- Compact and modular design and only solid-state switches used
- No operational experience
  - Generator topology already prototyped but not yet implemented at CERN
- A lot of know-how has been acquired from previous prototyping
- The unprecedented specifications (<25ns rise time and 30m connecting cable length) **require dedicated R&D and prototyping**

Requirements

`	Booster injection	Damping ring	CLIC PDR-DR
Energy [GeV]	20	2.86	2.86
Kick angle per unit [mrad]	0.09	1.5	2-1.5
Rise / fall time [ns]	25	82	700-1000
Flat top length [ns]	80	80	160
Flat top quality [%]	±0.5	±0.5	±0.01
Repetition rate [Hz]	200	100	50

Lumped inductance kicker – Generator

- **Kicker:** a ferrite-loaded lumped-inductance magnet can still comply with the most recent and more stringent fast rise and fall time requirements

- **Generator:**
  - Marx generator for booster extraction and collider injection
  - LBDS-type generator for dump systems, due to more relaxed flat-top homogeneity requirements

- The length of the cable connecting the generator to the beamline elements is presently hundreds of meters:
  - Resulting from the current integration scheme
  - Impact on kicker pulse quality

Requirements

	Booster extraction	Collider injection	Booster dump	Collider dump
Energy [GeV]	45 – 182.5	45 – 182.5	45 – 182.5	45 – 182.5
Kick angle per unit [mrad]	0.014	0.013	0.033	0.033
Rise / fall time [ns]	600	600	600	600
Flat top length [us]	304	304	304	304
Flat top quality [%]	±0.6	±1.5	±20	±20
Repetition rate [Hz]	0.3	0.3	1	0.1
Beam aperture [mm]	60	60	60	60
Available length [m]	TBD	TBD	TBD	TBD

Design Paramets

	Booster extraction	Collider injection	Booster dump	Collider dump
N. Of Magnets/ System(s)	14 / 2	8 / 4	9 / 2	9 / 2
Impedance [Ω]	10	10	10	10
Current [kA]	0.7	0.7	1.7	1.7
Voltage [kV]	7	7	17	17
Integrated B-field [mT.m]	3	8.12	21	21
Element aperture [mm]	70	70	70	70
Effective length [m]	0.7	0.7	0.7	0.7

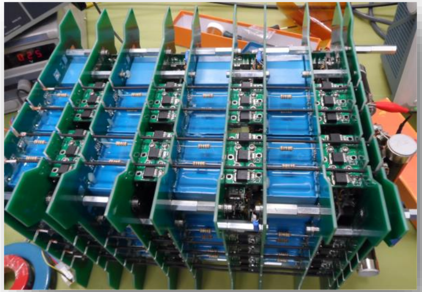
Lumped inductance kicker

- **Simple and robust magnet**, which can be operated **out-of-vacuum**
  - Easier maintenance
  - Reduced machine protection issues

- **Design re-iterations** were needed as well as an **increased number of magnets** to adapt to the new 600ns abort gap requirement
  - Impact on cost and integration

- **Beam impedance** or **Electron Cloud** instabilities can be addressed employing surface **coating**:
  - Dedicated simulations needed to assess coating impact, considering the faster rise time requirements
  - Need to clarify beam impedance requirements

Generator for LI kicker



- Marx generator (Booster extraction, Collider injection)
  - Compact and modular design using only solid-state switches
  - No operational experience but know-how acquired from previous prototyping
  - Unprecedented very challenging long flat top, combined with long cable length
    → Requires tests on real equipment, to eventually develop compensation solutions
  - **Need of R&D and prototyping of a LI magnet driven by a Marx generator**!
- LBDS like generator (Booster and Collider dump)
  - Driven by a main capacitor discharge stage sustained by a droop compensation stage
  - Prototyping is necessary given the unprecedented requirements

Other considerations

- Other studies, supported by R&D are foreseen on:

  - **F-Gas free** insulation solutions
  - **Radiation impact** on components
  - Control development for **highly reliable systems**
  - **Automatized** maintenance and repair
  - Interlock systems and/or absorbers for **machine protection**

- Detailed integration studies needed

FCC-ee Integration Requirements for Injection-Extraction Equipment, D. Standen

  - **Review space requirements**: accounting for magnets, generators, control systems, and any additional equipment facilitating maintenance, including spares
    → Cold spares vs Warm spares?
  - **Establish final length for cables** connecting beamline elements to generators

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Conclusions

- Kicker systems have been designed accounting for **cost, availability, reliability,** and address **integration, operational and radiation constraints**

- **Design choices** have been detailed **in the FSR**

- The **main design challenges** have been identified and **mitigating solutions** already considered

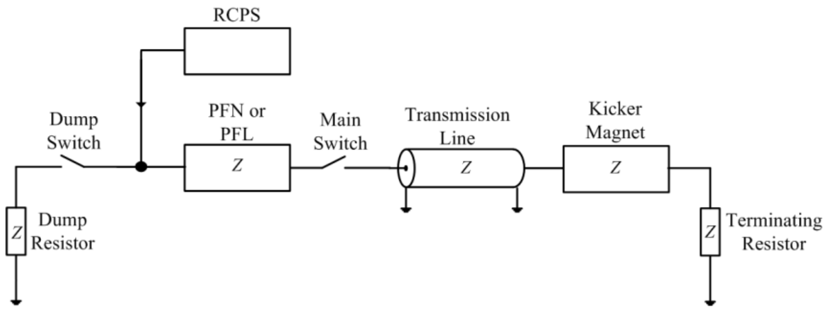
- **Given the unprecedented specifications, R&D and prototyping are planned** to develop new technologies and optimize existing ones to achieve target parameters

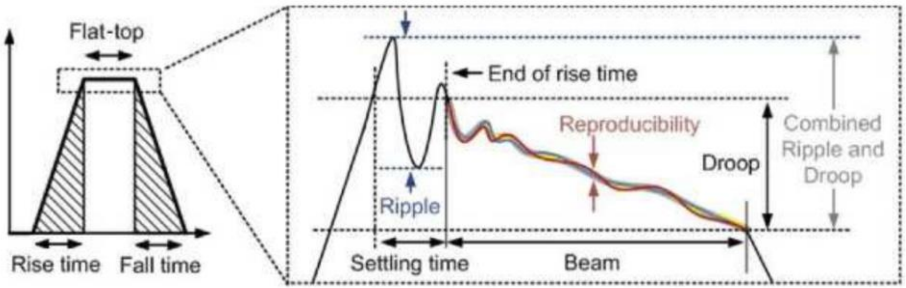
Thank you for your attention!

Spare slides

Kicker system design

- A kicker magnet is designed to provide a required field magnitude, duration, rise and fall time and homogeneity
- The pulse generator provides a certain current and voltage output to match the requirements for the needed pulse
- Critical parameters are:
  - current and voltage values
  - system impedance
  - pulse rise time and fall time, droop, flat-top stability, pulse-to-pulse stability
  - repetition rate



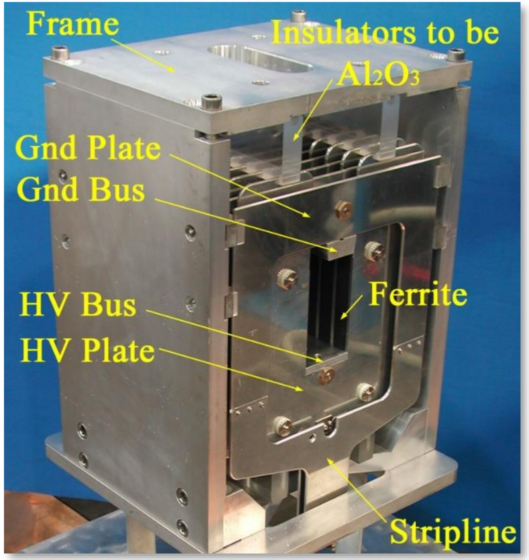


Magnet topologies

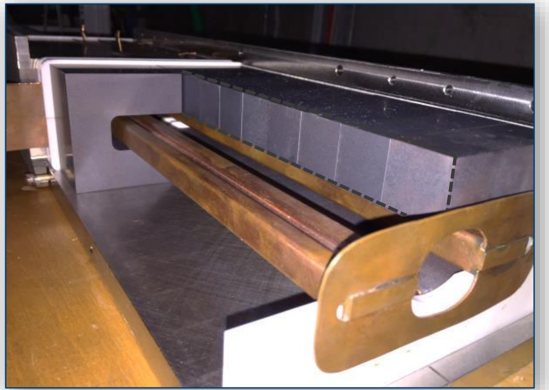
	PRO	CONS
Stripline	▪ Compact design ▪ Very fast rise time (few ns) ▪ Low beam coupling impedance	▪ Weaker deflection ▪ Impedance matching important ▪ Challenging flat-top stability ▪ More power consumption
Transmission line	▪ Fast rise time << 1μs ▪ Strong deflecting field	▪ Voltages up to 80 kV ▪ Complex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

Magnet topologies

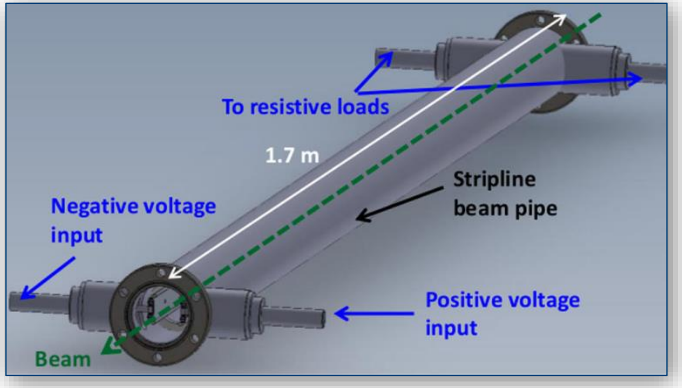
Transmission line



Lumped inductance



Stripline



Generator topologies

	PRO	CONS
PFN	▪ Compact design ▪ Low droop and long pulses > 3μs ▪ Voltage up to 80 kV	▪ Complex 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 < 3μs ▪ Ripple-free (flat) pulses	▪ Significant droop in pulses > 3μs ▪ Above 40 kV SF6 used at CERN ▪ Bulky: 3μs pulse 300 m of cable
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 (<3μs) ▪ Sensitive to radiation

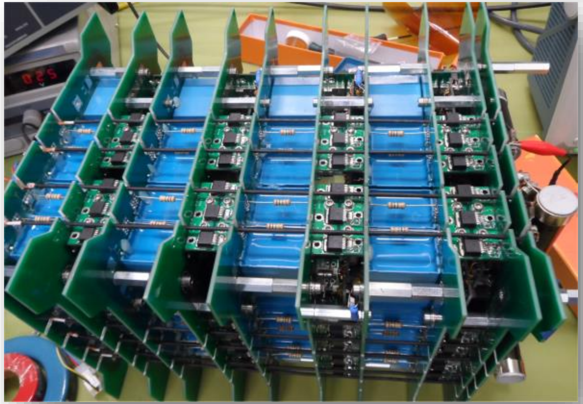
Generator topologies

PFN

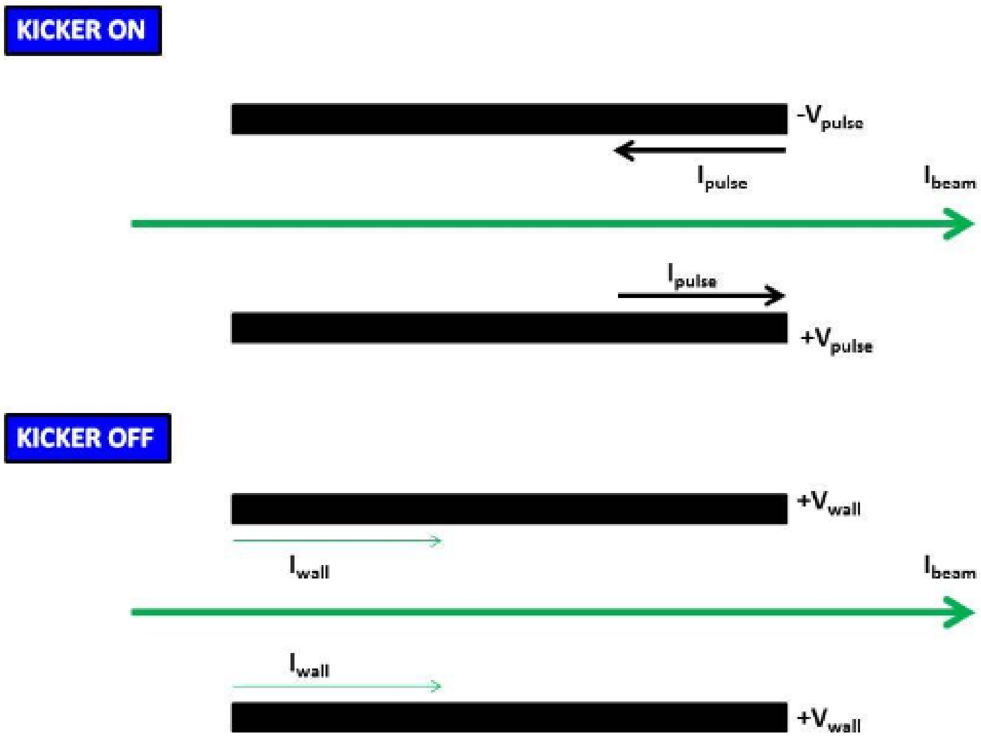
PFL

INDUCTIVE ADDER

FCC GENERATOR



Cross Section Design



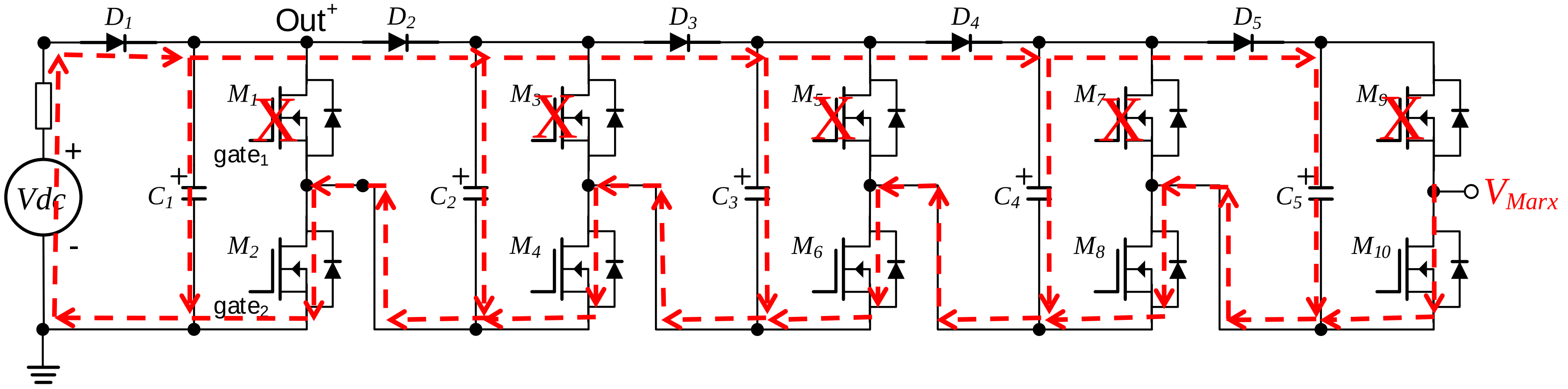
KICKER ON = ODD MODE
KICKER OFF = EVEN MODE

- When the electrodes are excited with opposite polarity voltages, the current flow is in opposite directions in each stripline electrode: this is the **odd mode**.
  - ➢ an electromagnetic field is created between the electrodes, giving a transverse kick to the beam

- When unkicked circulating beam passes through the aperture of the striplines, it induces image currents in the electrodes: the direction of current flow is the same in both electrodes – this is the **even mode**.
  - ➢ this generates an electromagnetic field, which gives a longitudinal kick to the beam and can produce beam instabilities.

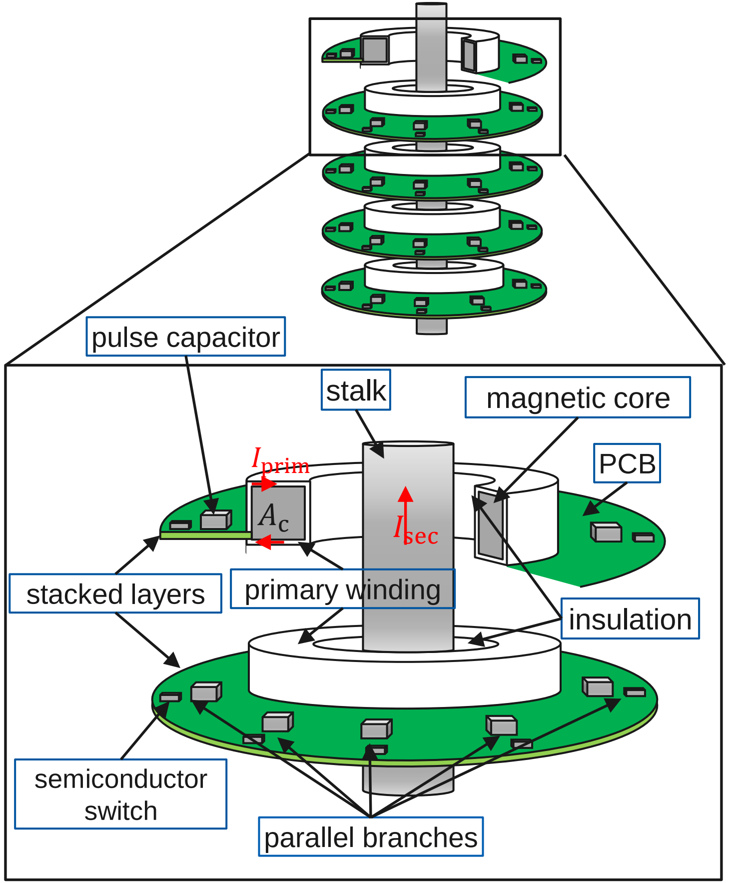
Marx generator

- In a Marx generator n capacitors are charged in parallel from a relatively low-voltage DC power supply, and discharged in series into the load
- The output voltage pulse has an amplitude approximately equal to the number of stages (n) times the input voltage (Vdc), Vmarx=n·Vdc
- 16 kV, 2.6 kA, 75 ns rise and fall prototype developed for FCC-hh



Inductive adder

- The IA is a solid-state modulator, which can provide relatively short and precise pulses
- An inductive adder consists of multiple parallel layers (also known as stages), each of which has a 1:1 transformer
- The single turn primary totally encloses a magnetic core; hence, the leakage inductance of this geometry is negligible
- The secondary winding of each of these transformers is connected in series: hence a step-up voltage ratio of 1:N is achieved by using N-layers, with adequate voltage isolation



Thyratrons vs semiconductor switchesr

Semiconductor switches can be used in fast high current pulsed power accelerator applications to replace thyratrons and PFLs.

<u>Thyratrons</u>

+ Radiation resistant
+ Generally reliable
+ Robust (fault tolerant)
+ Relatively high voltage
+ Relatively high current
– Long term availability
– Spontaneous turn on
– Can only be turned on

Versus:

<u>Solid-state</u>

+ Cost-effective
+ Easy to use
+ Off-the-shelf
+ Flexible
+ Modular
+ Maintainability
– Relatively low voltage
– Relatively low current

But…. Semiconductors have limited voltage and current rating. Hence, requires **series and parallel connection of power semiconductors** to achieve high pulsed power.

Machine Protection

- Machine protection concerns start at booster extraction and Z-mode is the most critical
- Failure types and probability depend on magnet kind and operational conditions:
  - Iteration needed at design phase to find best tradeoff between magnets performance, reliability, availability and machine protection aspects
- Potential failures have been estimated:
  - They are typical of high voltage fast pulsed systems (see next slides)
  - Additional challenges are introduced by synchrotron radiation, high stored energy and energy density
- Mitigations consist in:
  - Redundancy, monitoring and fast reaction to failures, passive protection, retriggering mechanism etc.
  - Rad-hard electronics
  - Segmentation and voltage reduction to reduce risk and consequence of failures
  - Out of vacuum magnets, minimum beam coupling impedance design, etc.
  - New concepts like sacrificial absorbers (for ultra-fast failures), chunk extraction etc. have to be considered (in booster extraction/dump, booster-to collider TL, collider injection and extraction)

Machine Protection – Booster Failures

Failure	Consequence	# affected bunches
Asynchronous extraction	xx bunches swept in the machine aperture	It depends on **reaction, re-triggering** and **rise time** (e.g. 44 for 1.1 us and 60 for 1.5 us)
Large ripples of extraction kickers	bunches extracted with oscillations, losses at the septum, septum mask and/or the transfer lines, poor transmission to the collider, large injection oscillations and losses in the collider	It depends on **the waveform shape** but in principle up to all (1120 for Z mode)
Up to 1ooXX extraction kickers missing .or. 1ooYY extraction septa not pulsing at nominal strength (0-100%)	mis-kicked bunches➔ oscillations in TL, losses (also possible at one single location), poor or no transmission, injection oscillations and losses in the collider	All (1120 for Z mode)

Machine Protection – Colliders Failures

Failure	Consequence	# affected bunches
Asynchronous extraction	xx bunches swept in the machine aperture	It depends on **reaction, re-triggering** and **rise time** (e.g. 44 for 1.1 us and 60 for 1.5 us)
Large ripples of extraction kickers	bunches extracted with oscillations, losses at the septum, septum mask and/or the transfer lines	It depends on the **waveform shape** but in principle up to all (11200 for Z mode)
Up to 1ooXXextraction kickers .or. 1ooYY extraction septa not pulsing at nominal strength (0-100%)	mis-kicked bunches➔ oscillations in TL, losses (also possible at one single location)	All (11200 for Z mode)
1ooXX missing injection bumpers .or. pulsing with higher current than nominal	miss-kicked circulating bunches ➔ oscillations (bump amplitude/xx) and losses at collimators, septum and septum mask.	All (11200 for Z mode)
1ooYY septum not pulsing at nominal strength (0-100%)	injected bunches mis-kicked ➔ injection oscillations and losses in the collider	All (1120 for Z mode)
Sparks in electromagnetic separator	large kicks to the full circulating beam and ultra-fast losses	All (56 for ttbar and 380 for ZH modes)

FCC Point B Magnet location (midpoint)