CERN

FUTURE CIRCULAR COLLIDER

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

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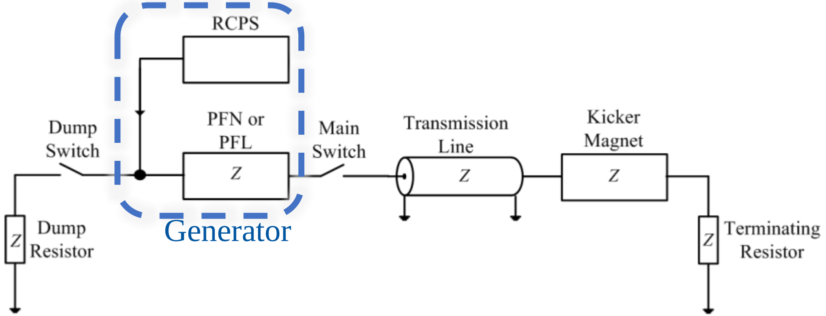
CERN, Geneva, Switzerland

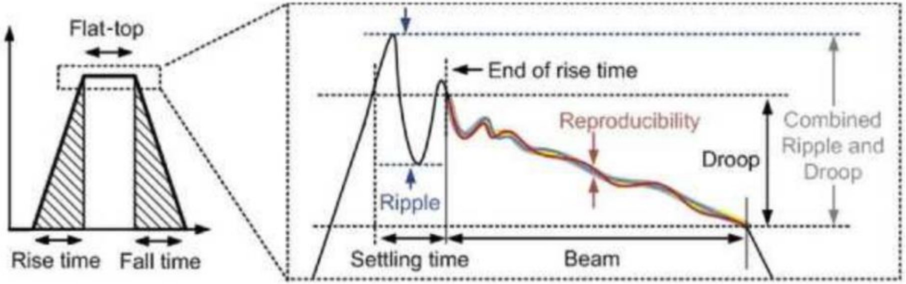
Outline

- Kicker system design principles
- FCC-ee kicker systems requirements
- Kicker systems design for DR, Booster and Collider
- Kicker systems integration
- Conclusion and next steps

Kicker system design

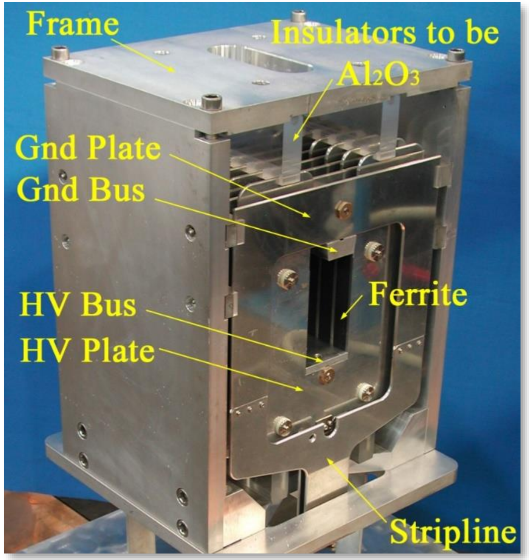
- A kicker magnet is designed to provide a required field magnitude, duration, rise and fall time and homogeneity
- The pulse generator provides a certain current and voltage output to match the requirements for the needed pulse
- Critical parameters are:
  - current and voltage values
  - system impedance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



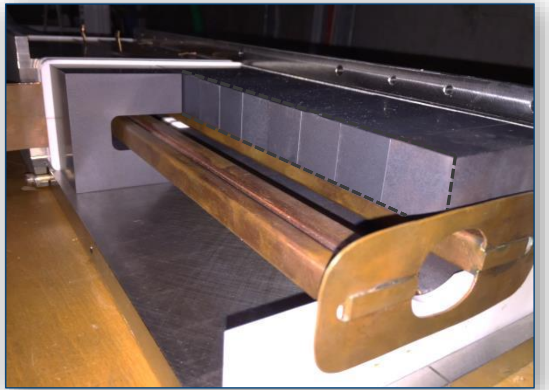


Magnet topologies

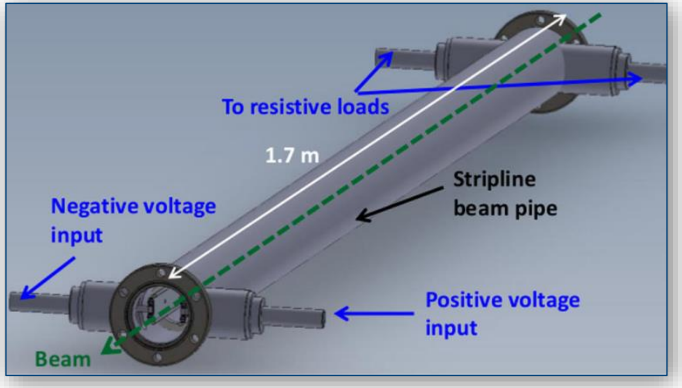
Transmission line



Lumped inductance



Stripline



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
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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		

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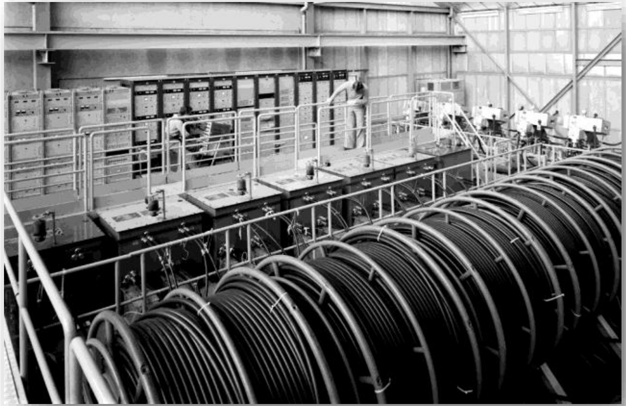
Transmission line	▪ Fast rise time << 1µs ▪ Strong deflecting field ▪ At CERN: 80 kV, 5 kA	▪ Complex to manufacture and costly ▪ Impedance matching important ▪ High beam coupling impedance
Lumped inductance	▪ Simple and robust magnet design ▪ Can be out of vacuum ▪ Strong deflecting field ▪ At CERN: 30 kV, 25 kA	▪ Suitable for rise time ≥ 1µs ▪ Needs minimizing interconnection inductance ▪ High beam coupling impedance

Generator topologies

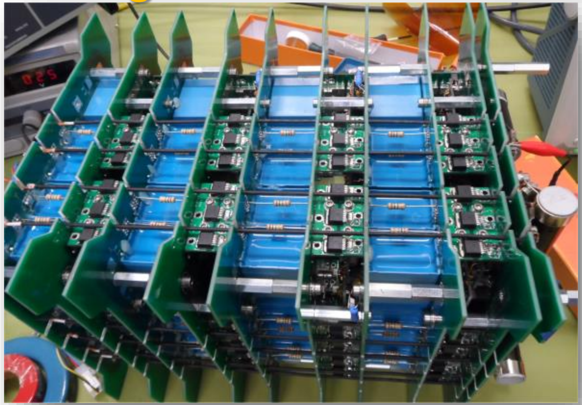
PFN

PFL



Inductive adder

Marx generator



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
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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

FCC-ee Kickers requirements

	Damping Ring	Booster injection	Booster extraction	Booster dump	Collider injection	Collider dump
Energy [GeV]	1.54-2.86 (tbc)	20	45 – 182.5	45 – 182.5	45 – 182.5	45 – 182.5
Beam line length [m]	tbc	5.5	15	15	15	15
Total kick angle [mrad]	3	0.09	0.429	0.3	0.072	0.3
Aperture (beam stay clear) (⌀) [mm]	30	30	60	60	60	60
Rise / fall time [ns]	82	25	1100	1100	1100	1100
Flat top length [μs]	0.08	0.08	30 – 304 (tbc)	304	30 – 304 (tbc)	304
Flat top quality [%]	±0.5 (tbc)	±0.5 (tbc)	±0.5 (tbc)	5 (tbc)	±0.5 (tbc)	5 (tbc)
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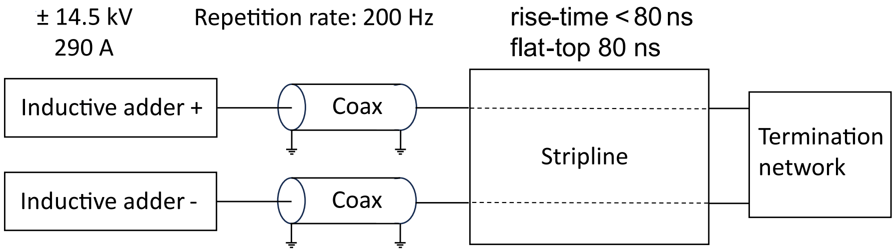
Damping ring (1.54 GeV)

- The same system is suitable for injection and extraction
- **Magnet:** Stripline to satisfy fast rise and fall time requirements
- **Generator:** Inductive adder can provide the short flat top and the required homogeneity



- Impedance matching optimization needed to limit both pulse reflections and beam coupling impedance
- Coaxial cable length **≤30m** to achieve rise time and field homogeneity

Damping ring (2.86 GeV)

- **Magnet:** Stripline to satisfy fast rise and fall time requirements
- **Generator:** Inductive adder can provide the short flat top and the required homogeneity

- Similar system developed for CLIC DR:
    - 12.5kV - 250A
    - feasibility confirmed through prototyping
    - slightly slower rise time wrt FCC DR requirements
    - Inductive Adder + cable delay = 13ns (~2.5m)

CLIC PDR & DR Kicker Specifications

Parameter	PDR	DR
Beam Energy (GeV)	2.86	2.86
Deflection Angle (mrad)	2	1.5
Aperture (mm)	40	20
Field rise and fall time (ns)	700	1000
Pulse flat top duration (ns)	~160	~160
Flat top reproducibility	$1x10^{-4}$	$1x10^{-4}$
Injection stability (per system)	$\sim2x10^{-2}$	$\sim2x10^{-3}$
Extraction stability (per system)	$\sim2x10^{-3}$	$\sim2x10^{-4}$
Injection field homogeneity (%)	±0.1	±0.1
Extraction field homogeneity (%)	±0.1	±0.01
Repetition rate (Hz)	50	50
Available length (m)	~3.4	~1.7
Stripline pulse current [50 Ω load] (A)	±340	±250

➢ Coaxial cable length **≤30m** to achieve rise time and field homogeneity

➢ Impedance matching optimization needed to limit both pulse reflections and beam coupling impedance

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- Coaxial cable length **≤30m** to achieve rise time and field homogeneity
- Impedance matching optimization needed to limit both pulse reflections and beam coupling impedance
- **Feasibility ok for both injection schemes, but need to freeze requirements to develop proper magnet design**

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Booster

Injection

- **Magnet**: Stripline
- **Generator**: Inductive adder

Extraction

- **Magnet**: Lumped inductance
- **Generator**: Marx generator

Dump

- **Magnet**: Lumped inductance
- **Generator**: Main capacitor discharge stage boosted by droop compensation stage(s)

	Booster injection	Booster extraction	Booster dump
Kicker / Systems	1/2	10/2	6/2
Impedance [Ω]	50	10	10
Current [kA]	0.36	1.4	1.7
Voltage [kV]	±13.4	14.5	5
Element aperture [mm]	30	70	70
Integrated field [mT.m] [MV]	3 0.9	26.5	30
Effective length [m]	1	1	1
Physical length [m]	1.4	1.4	1.4

- Injection system: cable length **≤30m** to achieve rise time and homogeneity
- Extraction system: long flat top requires large charging capacitor (hence generator space, x10)
- Dump system: cable length **<100m** to achieve rise time and field homogeneity
- **Heat load, radiation impact, beam coupling impedance need to be accounted for in the design optimization**

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Collider

Injection

- **Magnet**: Stripline
- **Generator**: Marx generator

Dump

- **Magnet**: Lumped inductance
- **Generator**: Main capacitor discharge stage boosted by droop compensation stages

	Collider injection	Collider dump
Elements / Systems	2/2	6/2
Impedance [Ω]	50	10
Current [kA]	0.32	1.2
Voltage [kV]	±16	5
Element aperture [mm]	70	70
Integrated field [mT.m] [MV]	5.5 1.5	30
Effective length [m]	3	1
Physical length [m]	3.6	1.5

- Injection system: cable length **≤250m** to achieve rise time and homogeneity
- Dump system: cable length **<100m** to achieve rise time and field homogeneity
- **Heat load, radiation impact, beam coupling impedance need to be accounted for in the design optimization**

Kicker hardware systems integration

Integration of magnet in the tunnel:

- Magnet length accounts for tank and flanges space allocation
- Radiation sensitive components requires knowledge of radiation map in the tunnel and dedicated tests

Services galleries:

- All radiation sensitive elements can’t be installed in the tunnel (generator and controls)
- Galleries’ location determines the length of cables between magnet and generator, hence affecting the systems’ final performance

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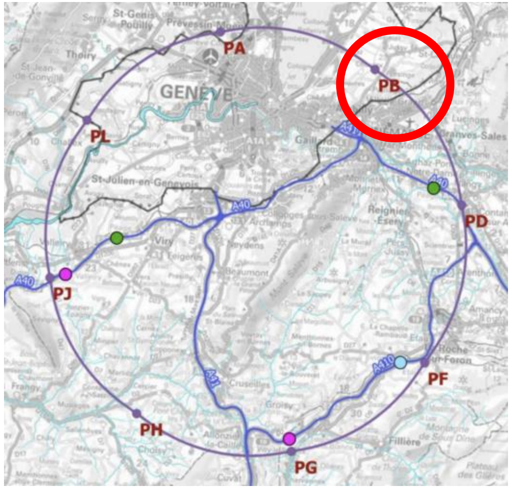
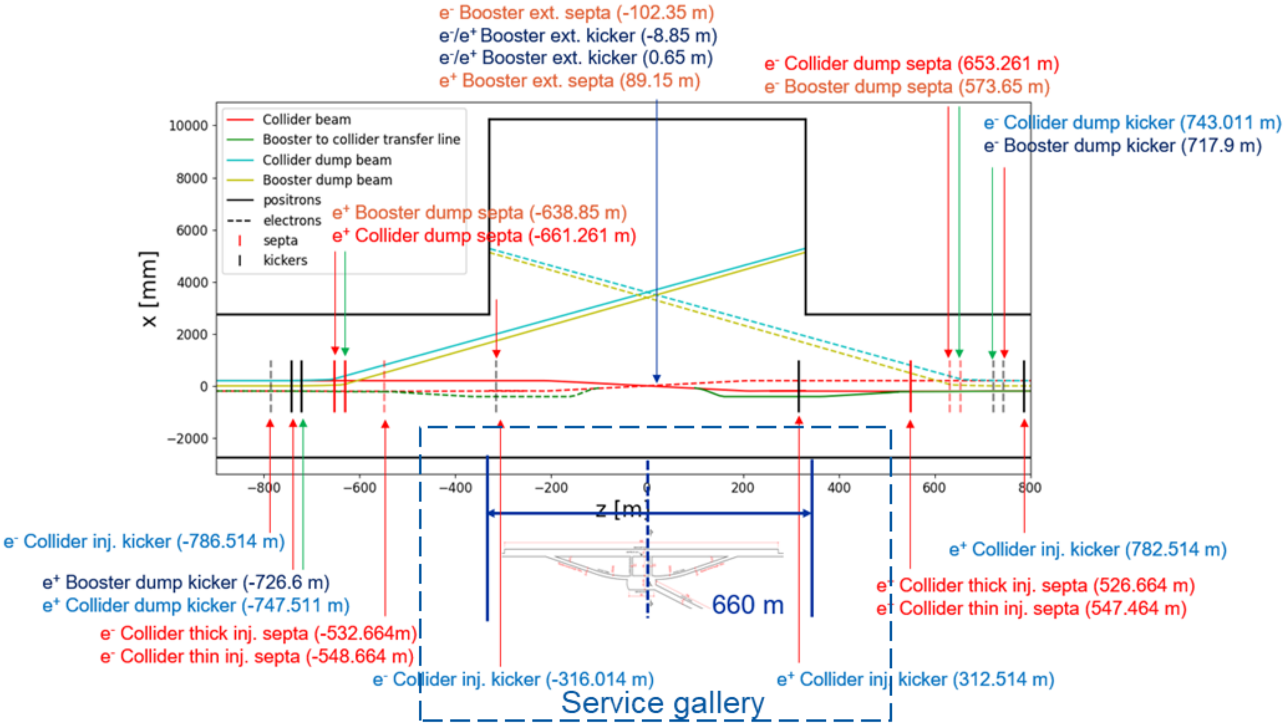
Experience from LEP

- Injection and dump systems:
  - A fast Resonant Charging Power Supply (RCPS) in surface building + small final generator near each magnet (~0.3-0.5 m^3)
  - 100m long cable in between
- That was possible because thyratron switches are not sensitive to radiation
- Significant concern on the availability of high voltage thyratron switches → use semiconductor switches only (in service areas or dedicated low-radiation space)

Kickers and septa in Point B





P.Trubacova, Reunion Integration FCC 15.05.2024

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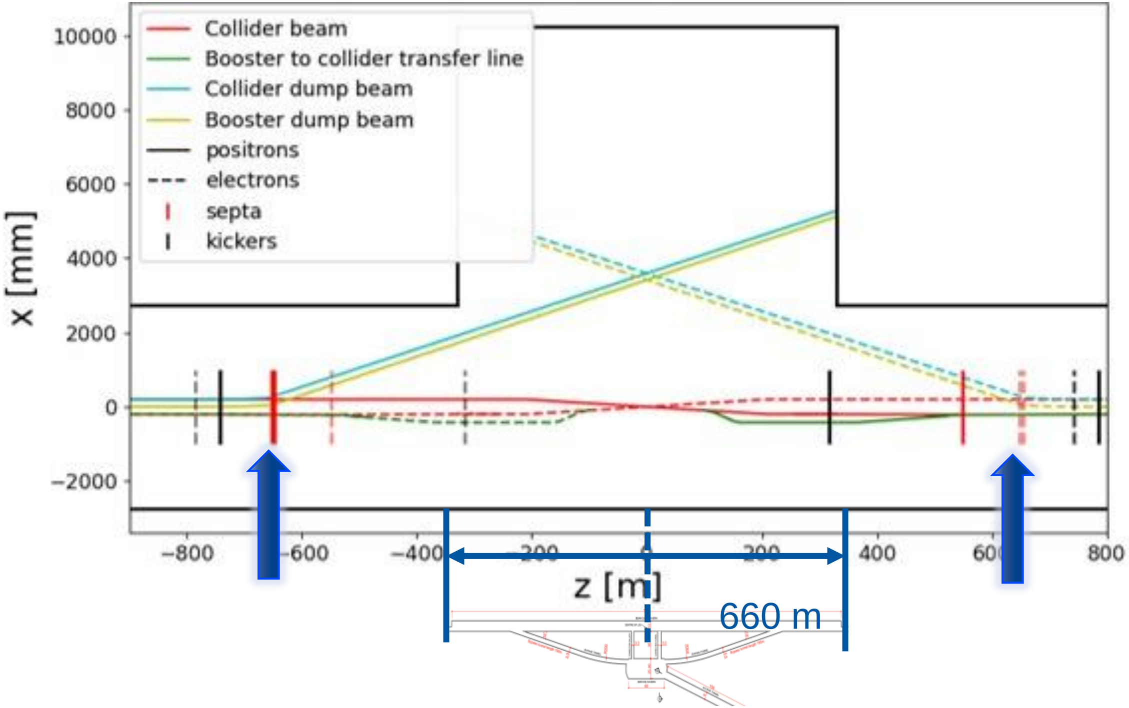

- The current alcove layout imposes long cables for some kickers and septa systems
- Two additional service areas would keep cable length "short" enough and serve efficiently more systems
- Booster injection integration need to be verified as well

Conclusion

- Simulation models for striplines and ferrite loaded magnets, including their generators, have been established to validate FCC-ee kickers feasibility
- No showstoppers were found but several challenges identified (matching and droop compensation, cable length..)
- Further work is needed to adapt to changing requirements and to harmonize the kicker sub-systems across the FCC machines

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…next steps:

- Evaluate systems beam coupling impedance and consequent heat deposition
    - Need to define beam impedance budget and eventually implement beam shielding solutions
- Implement solutions for limiting heat load due to power dissipation
- Define HW integration in the tunnel and in the galleries and consequent cable length
- R&D laboratory activities and early prototyping is envisaged to develop and implement effective pulse optimization solutions (DR stripline and LI magnet + long pulse generator)

Thanks for you attention

Spare slides

Simplified magnet design

"Given" Design Parameters

Deflection Angle → $\theta_{B,x} \approx \left[\frac{0.3 \cdot l_m}{p}\right] \cdot |B_y|$

Beam momentum

Apertures

Available Beam Line Length

B-field: $B = \frac{\mu_0}{V_{ap}} I$

Current: $I = \frac{U}{Z}$

Magnet / Module design:

Inductance/m length (N=1): $L' = \mu_0 \frac{H_{ap}}{V_{ap}}$

Total Inductance: $L_t = \mu_0 \frac{H_{ap}}{V_{ap}} l_m$

Split "Magnet" into *n* modules? $\tau_{fill} = \left(\frac{L_t}{Z}\right) / n$

Technology Limits:

- Max. voltage hold off
- Max. current
- Switch limits
- Cables
- etc.

Cell design:

Cell Inductance: $L_c = \frac{L_m}{n_c}$ ← no. of cells

Cell Capacitance: $C_c = \frac{L_c}{{Z_0}^2}$

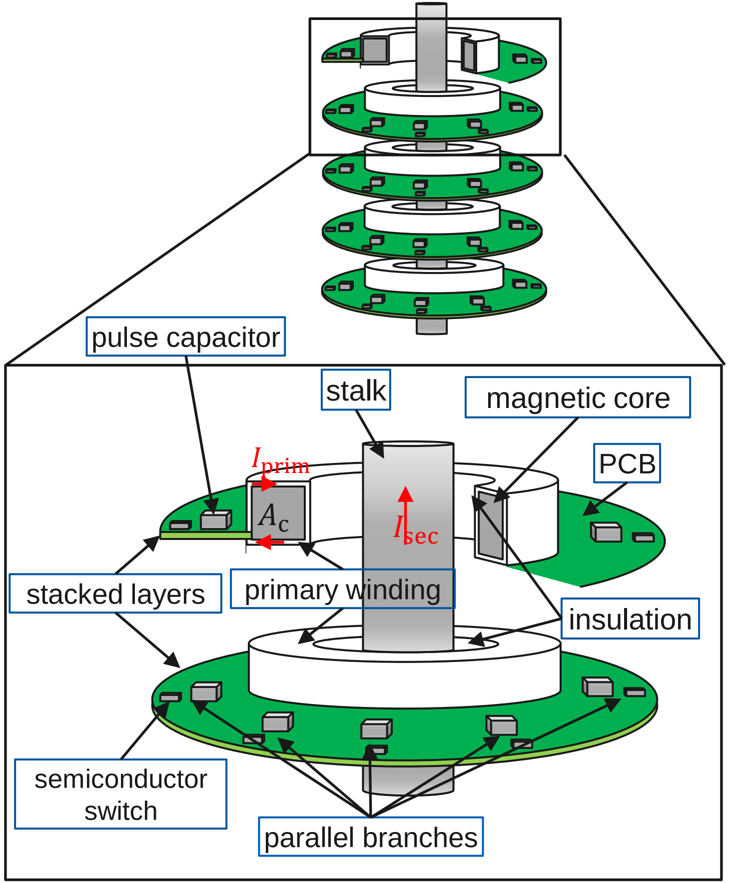
Feasibility aspect:

- Capacitance
- Mech. Apertures
- Voltage hold off

Cell Cut Off Freq.: $\omega_{0c} \approx \frac{2}{\sqrt{L_c C_c}}$ ← Needs to be high enough to not attenuate the rising or falling edges too much.

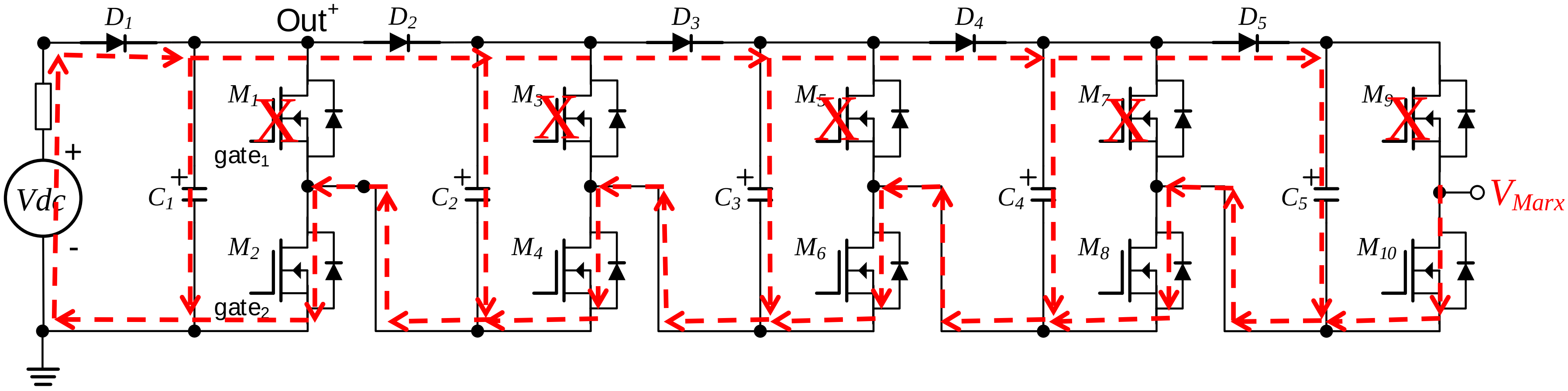
Inductive adder

- 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



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



Thyatrons vs semiconductor switches

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

Thyratrons

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

Versus:

Solid-state

- \+ Cost-effective
- \+ Easy to use
- \+ Off-the-shelf
- \+ Flexible
- \+ Modular
- \+ Maintainability
- \+ **Can be turned on and off (thus PFL/PFN is not required)**
- – 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.