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ABT: Hardware design for beam transfer equipment and related challenges

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Outline

- Baseline design for kickers and septa
- Challenges and main design criteria
- R&D and prototyping
- Conclusion

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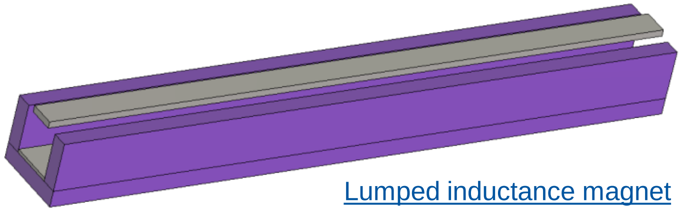
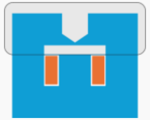
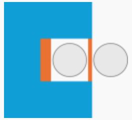
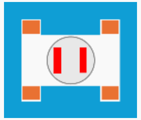
Kickers

	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	PFN/Marx generator	LBDS-like generator
Magnet under vacuum	Yes	Yes	No	No	No	No
Elements / Systems	2/4	1/2	10/2	6/2	4/2	6/2
Physical length [m]	3	1.5?	12	12	4	12
Novel technology	Yes	Yes	No	No	No	No
R&D required/ Prototyping required/ Conventional technology	R&D required	R&D required	R&D required	Prototype required	R&D required	Prototype required


Stripline magnet


Lumped inductance magnet

Septa

	Booster injection	Booster extraction	Booster Dump	Collider injection	Collider dump	Separator septum	E-M separator
Diagram							
Magnet topology	Under vacuum Lambertson	Outside vacuum Direct Drive	Low Power outside vacuum	Under vacuum Direct Drive	Low Power outside vacuum	Low Power outside vacuum	
Operation	DC	Pulsed	DC (ramped)	Pulsed	DC	DC	
Magnet under vacuum	partially	no	no	yes	no	no	partially
Elements / Systems	2/2	1/2	3/2	6/2	2/2	10/2	10/2
Physical length [m]	6	3	5.4	7.2	4	25	
Novel technology	Yes	No	Yes	No	Yes	No	yes
R&D required / Prototyping needed / conventional technology	Prototype required	Conventional technology	Prototype required	R&D required	Prototype required	Prototype required	R&D urgently required

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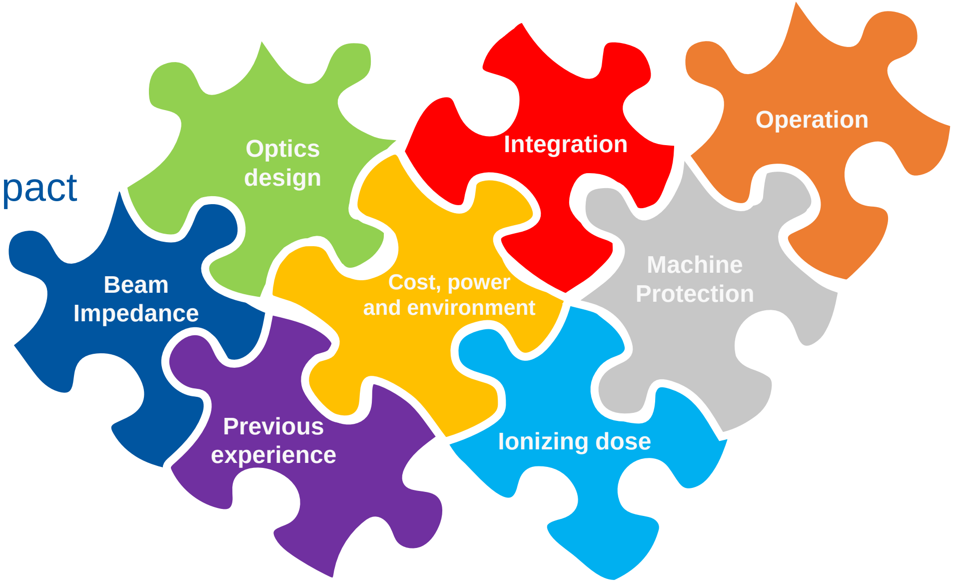
Feasibility study

Kickers and septa magnets 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



The main challenge lies in maintaining a well-balanced final design that accounts for all these factors and their interdependencies, like solving a complex puzzle

Optics design

- The specifications for kickers and septa are primarily determined by the lattice design

- Any changes to these parameters necessitate a re-evaluation of the feasibility study and a reconsideration of the design choices for the kickers and septa systems

- Foresee lattice design iterations where the kicker or septa design may fail to meet required parameters due to technical limitations

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

Cost, power consumption & environmental impact

❑ Cost considerations:

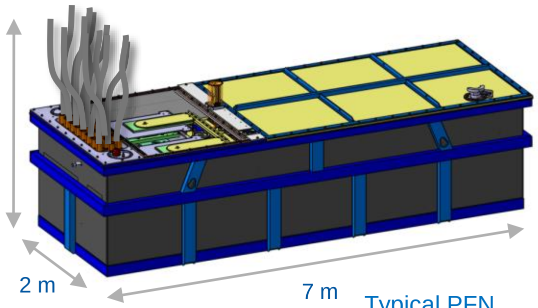
- **Standardization of equipments**: implementing standardized solutions across all systems reduces costs and simplifies maintenance
- **Limited generator voltage**: it improves reliability and enhances long-term performance while reducing maintenance costs
  - Avoiding oil-filled generators mitigates (environmental) risks and maintenance complexities
  - Out-of-vacuum magnets can lower costs and are less complex to maintain

❑ Power efficiency and environmental impact:

- **Avoidance of "difficult" materials**: like gas or liquid filled cables (e.g., SF6, FC-77)
- **Electrical consumption and heat load limitation**: to enhance energy efficiency, reduce cooling requirements and decrease the environmental footprint
- **Energy recovery**: Exploring energy recovery options for generators can significantly lower operational costs

Integration

- **Magnet length considerations:**
  - The length of the magnet must account for the space required for the tank or flanges, ensuring proper installation and functionality
- **Services galleries:**
  - **Radiation sensitivity**: all radiation-sensitive components, such as generators and controls, cannot be installed directly in the tunnel
  - **Cable length implications**: the location of the service galleries directly affects the length of cables required between the magnet and the generator
  - **Space requirements**: adequate space must be estimated for the generator, control systems, and any additional equipment facilitating maintenance, including spares



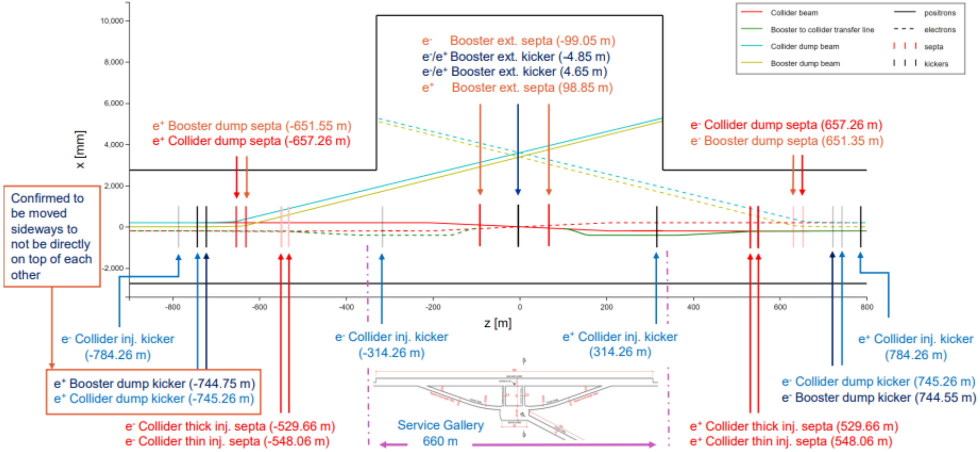
Typical PFN generator design

FCCee POINT B (mostly) KICKERS and SEPTA Footprints

KICKERS	Cable length (m)	Generator type	No. per beam	Total for FCC (e+/e-)	Hot spares generators	Generator Footprints (m)	Racks per generator	Total racks per beam + control racks	Inc. hot spares
Collider injection	250	PFN BI.DIS	2+2 (2 alcoves)	8	1 per alcove	2 x 3.5 x 2.5h	2	4+4 (+4 per alcove)	6+4 6+4
Collider dump	250	MKD generator	6	12	2	1 x 2 x 3h	2	12+3	16+3
Booster injection	30	Inductive adder	1	2	1	2 x 2	2	2+3	4+3
Booster extraction	100	Marx generator	10	20	4 per beam or 6 shared	7 x 2 x 3h	2	20+3	28+3
Booster dump	250	MKD generator	6	12	2	1 x 2 x 3h	2	12+3	16+3
		Unconfirmed / new iteration					standard size of rack is 600 x 1000 x 2400 mm		

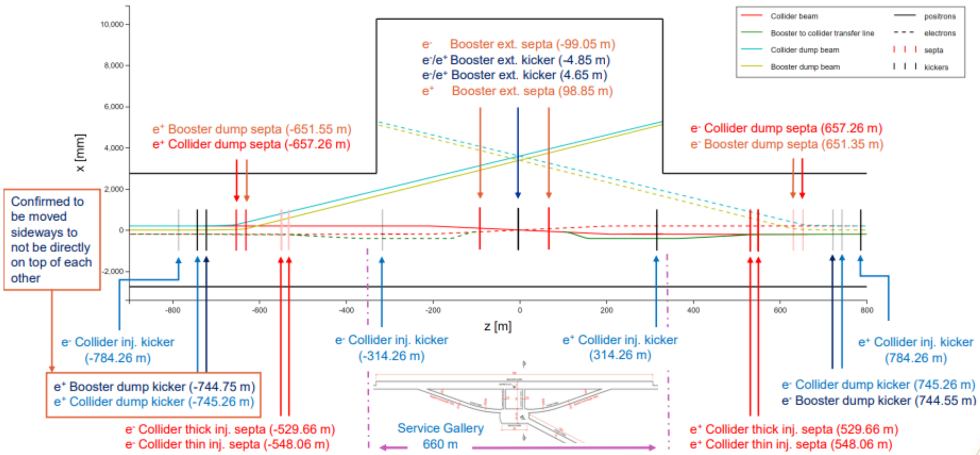
SEPTA	Cable length (m)	Generator type (power converter)	No. per beam	Total for FCC (e+/e-)	Hot spares generators	Power converter racks footprint	Additional equipment near magnet
Collider injection	120 aim 150 max	Combined racks per magnet	6 (1 thin, 5 thick	12	N/A	4w x 0.9d x 2.2h	Transformer (1m³) Water-cooling (0.25w x 1.5l x 1.2h)
Collider dump	500	Combined racks	1	2	N/A	2.5w x 0.9d x 2.2h	Water-cooling (0.25w x 1.5l x 1.2h)
Booster injection	150 (reasonable	-	-	-	N/A	-	-
Booster extraction	120 aim 150 max	Combined racks	1	2	N/A	4w × 0.9d × 2.2h	Transformer (1m³) No Water-cooling?
Booster dump	150 (reasonable)	Combined racks Beam energy tracking system	1	2	N/A	4w × 0.9d × 2.2h 0.8w x 0.9d x 2.2h	Water-cooling (0.25w x 1.5l x 1.2h)
EM Separator	Many 100's	Combined high voltage racks HV switches Combined high current racks	2 (+ & -)	4	N/A	4w x 0.9d x 2.2h 3.2w x 0.9d x 2.2h	Decoupling resistors and ground switches 2x 0.35w x 0.8d x 1.5h per tank

Integration – Point B

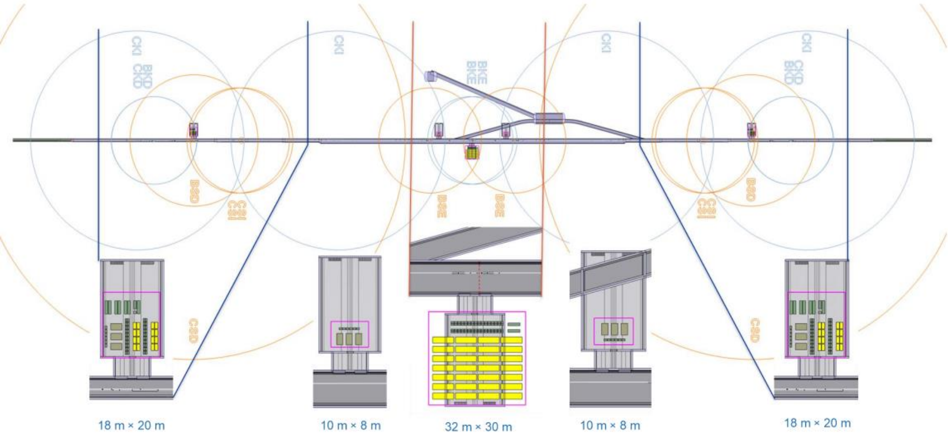


- Space requirements for kickers and septa estimated in **point B**
- Integration considerations should be initiated in **Point A** for the Booster

Integration – Point B



- Space requirements for kickers and septa estimated in **point B**
- Integration considerations should be initiated in **Point A** for the Booster
- As result of detailed study and more iterations, we **relaxed cable length specifications** where feasible to ease integration.
- Proposed alcoves layout as an **alternative to the baseline**



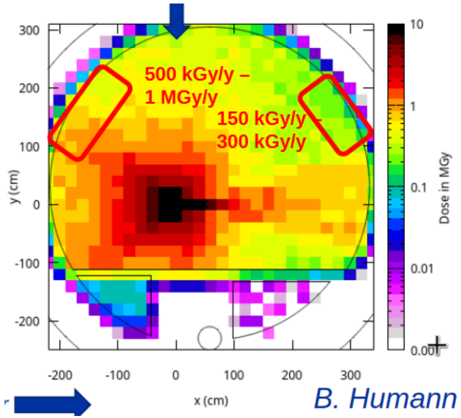
FCC-ee Underground Structure at point B

Ionizing dose levels

- Use of solid-state generators and semiconductor switches:
  - Significant concern on the availability of high voltage thyratron switches
  - Need service areas or dedicated low-radiation space

- Synchrotron light effects:
  - To be accounted for during design phases, i.e for EM separator and stripline magnet electrodes
  - Dedicated mask required for EM Separator
  - Electrostatic septa now avoided as too sensitive to X-ray impact, which leads to break downs

- Need for reliable radiation mapping:
  - Straight section doses to be estimated
  - Choice of components, i.e. cables, isolators
  - Radiation tests prior to installation to ensure component suitability



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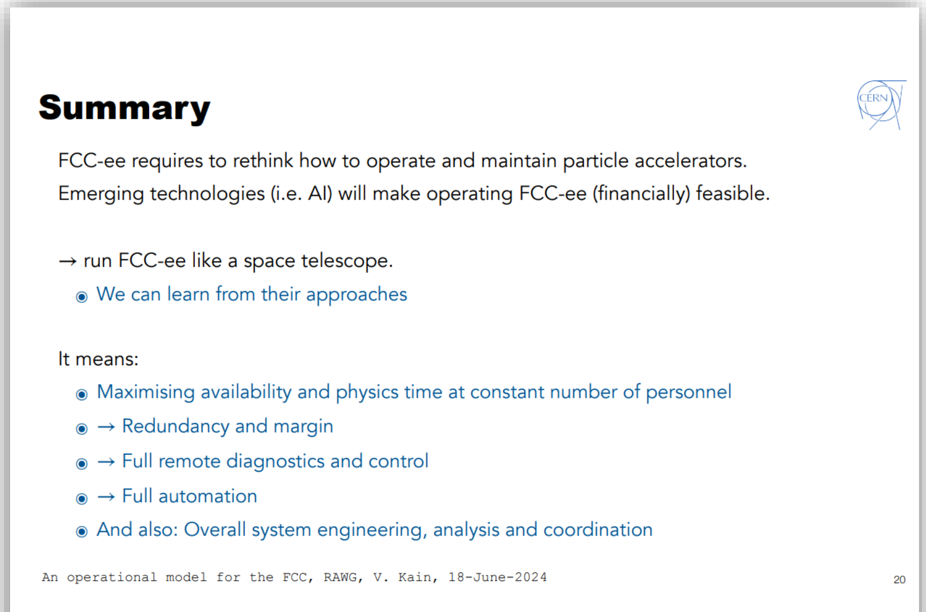
Machine Protection

- 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:
  - They are typical for high voltage fast pulsed systems (breakdown, erratic, missing, mis-kick)
  - Additional challenges are introduced by synchrotron radiation, high stored energy and energy density
  - Iteration needed at design phase to find best trade-off between magnets performance, reliability, availability and machine protection aspects

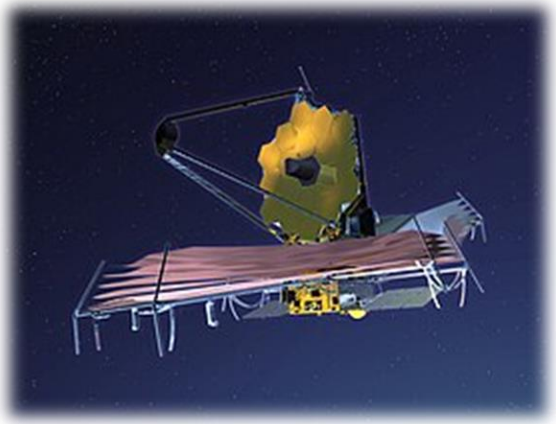
- Mitigations consist of:
  - Redundancy, monitoring and fast reaction to failures, passive protection, retriggering mechanism etc.
  - Rad-hard electronics where needed
  - Segmentation and voltage reduction to reduce risk and consequence of failures
  - Out of vacuum magnets, minimum beam coupling 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)

FCC-ee operational model

The design of kickers and septa systems is based on the new FCC operational model, which aims to maximize availability and reliability, while reducing maintenance and intervention needs, enhancing automation and AI integration.



Courtesy of V. Kain

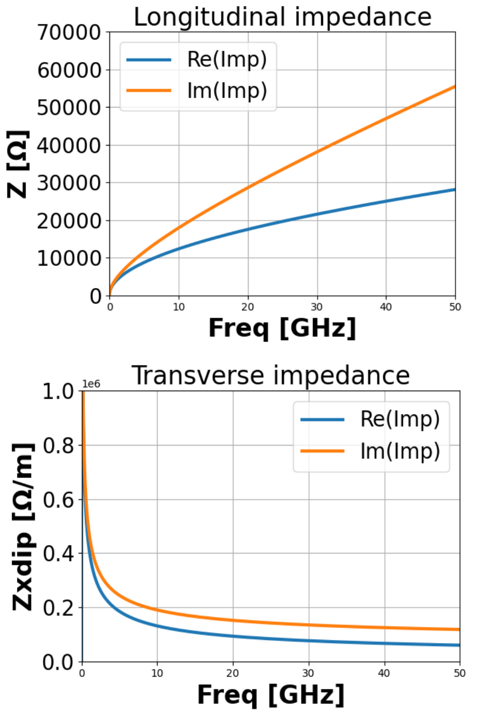


Collective effects

- Magnet design requires optimization to limit beam coupling impedance and e-cloud:
  - Coating foreseen in lumped inductance magnets
  - Stripline needs proper design to minimize impedance or integration of a resistive network
  - EM separator requires proper electrode design
  - Beam stay clear region needs to be defined, as it largely affects impedance
  - Vacuum requirements and equipment integration need to be clarified for septa to assess impedance impact

- Resistive wall impedance presently used as target (<<10x):
  - Beam induced heating needs dedicated study to design proper beam screens
  - Complete magnet design needed for accurate prediction at high frequencies

Resistive wall impedance



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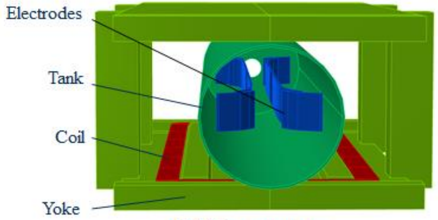
Future work: R&D and prototyping

- Kickers
  - **Stripline magnet driven by an inductive adder:** to optimize the design, balancing the trade-off between impedance matching and beam coupling
  - **Lumped inductance magnet driven by a PFN or Marx generator:** it requires the development of proper compensations for such long cable connection to achieve rise time and flat-top specifications for long pulse durations

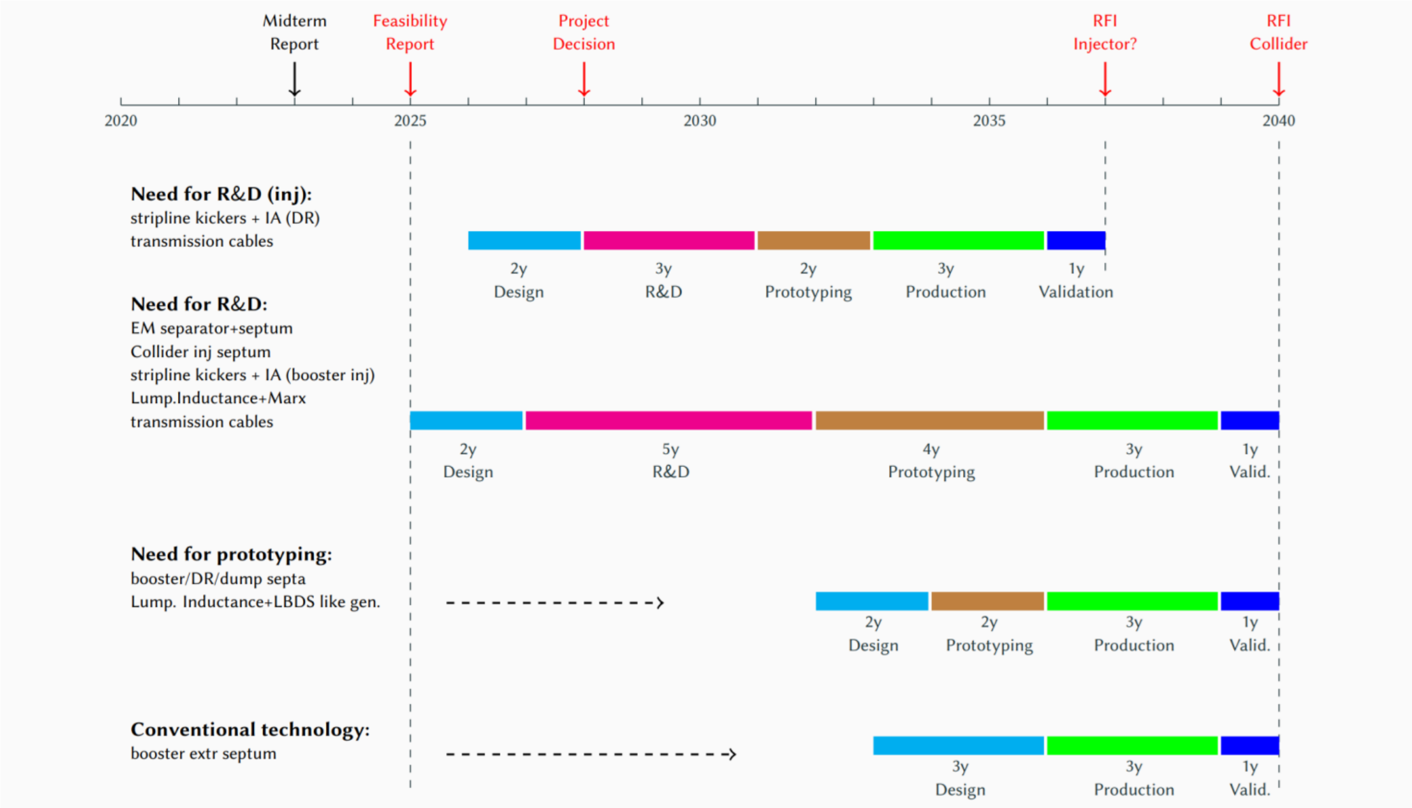
- Septa
  - **Lambertson septa** close to the design limit of the septum thickness. Bake-out requirements to be clarified from early on in the project.
  - Robustness of **direct drive septa** for Collider injection to be confirmed. May require novel cooling concepts

- EM-separator
  - If break down rate limit (tbd) cannot be reached, single RF concept in the collider will need review. **Urgent R&D required**
  - Requires local cancellation of the E and B field in one beam direction, while providing a homogeneous field in the opposite direction
  - The desired installation moment to be clarified early in the project



EM Separator

Future work: R&D and prototyping



Given the extensive R&D and prototyping needed, it may be beneficial to consider initiating R&D studies in the near future

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Conclusion

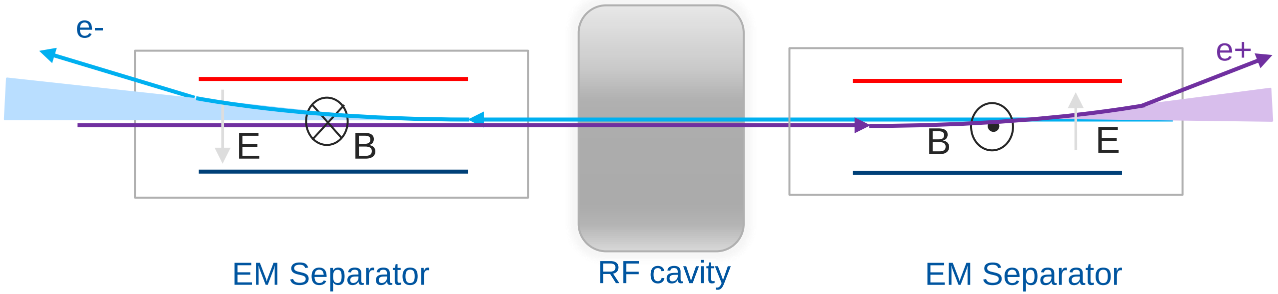
- The baseline design for kickers and septa has been established
- These designs are developed to optimize cost, availability, reliability, energy efficiency, and address integration, operational and radiation constraints
- New iterations are expected due to changing requirements; however, it is essential to adapt to the current hardware design in order to move forward with the next steps
- Given the unprecedented specifications, R&D and prototyping are envisaged to develop new technologies and optimize existing ones to achieve target parameters

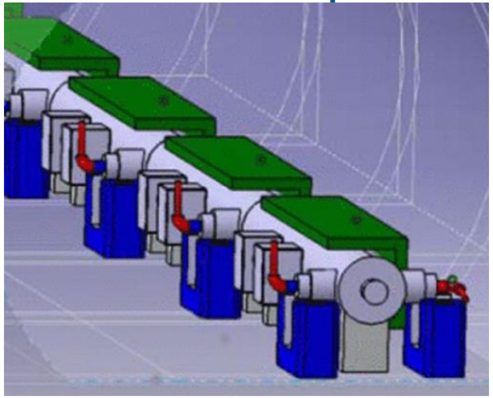
Optics design – Parameters table

	Damping Ring	Booster injection	Booster extraction	Booster dump	Collider injection	Collider dump
Energy [GeV]	2.86	20	45 – 182.5	45 – 182.5	45 – 182.5	45 – 182.5
Beam line length [m]	tbc	5.5 (tbc)	15 (tbc)	15 (tbc)	15 (tbc)	15 (tbc)
Total kick angle [mrad]	3	0.09	0.2	0.3	0.08	0.3
Aperture (beam stay clear) (⌀) [mm]	30	30	60	60	60	60
Rise / fall time [ns]	82.5	25	1100	1100	1100	1100
Flat top length [µs]	0.08	0.08	30 – 304	304	30 – 304	304
Rise and fall time definition	0.5% - 99.5% (tbc)	0.7% - 99.3% (tbc)	0.6% - 99.4% (tbc)	(tbc)	(tbc)	(tbc)
Flat top quality [%]	±0.5 (tbc)	±0.7 (tbc)	±0.6 (tbc)	±1.5 (tbc)	±20 (tbc)	±20 (tbc)
Repetition rate [Hz]	100	100	0.3	1	0.3	0.1

Collider: Electric-Magnetic (EM) separator

- Installed upstream and downstream of RF section in ttbar mode in point H.
- 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 the cavities.
- The 2 families of 10 EM separators [6] will be powered in series (magnet) and parallel (separator), limiting the power converter footprint.





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)

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>

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

Versus:

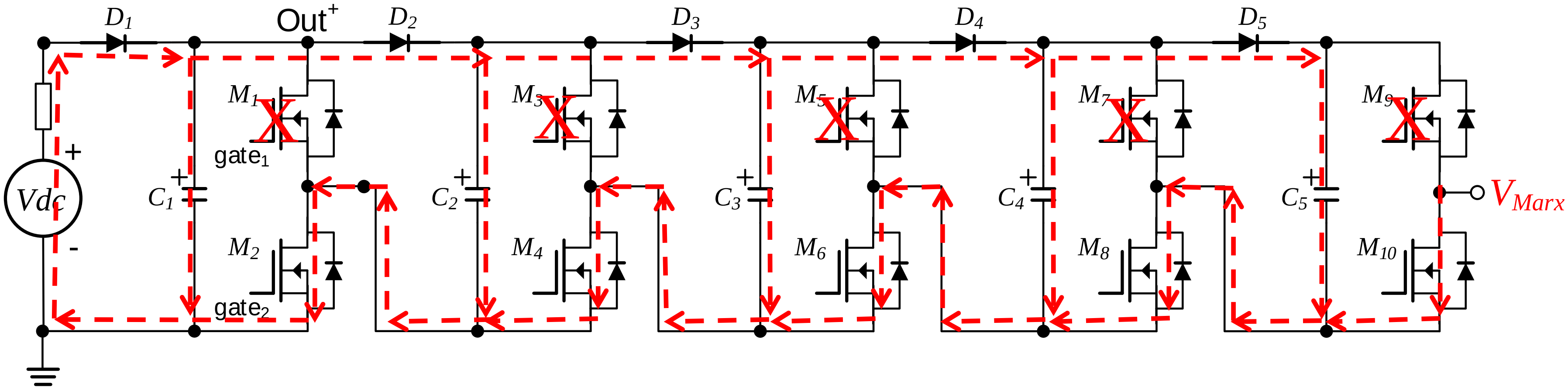
<u>Solid-state</u>

- \+ Cost-effective
- \+ Easy to use
- \+ Off-the-shelf
- \+ Flexible
- \+ Modular
- \+ Maintainability
- \+ **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.

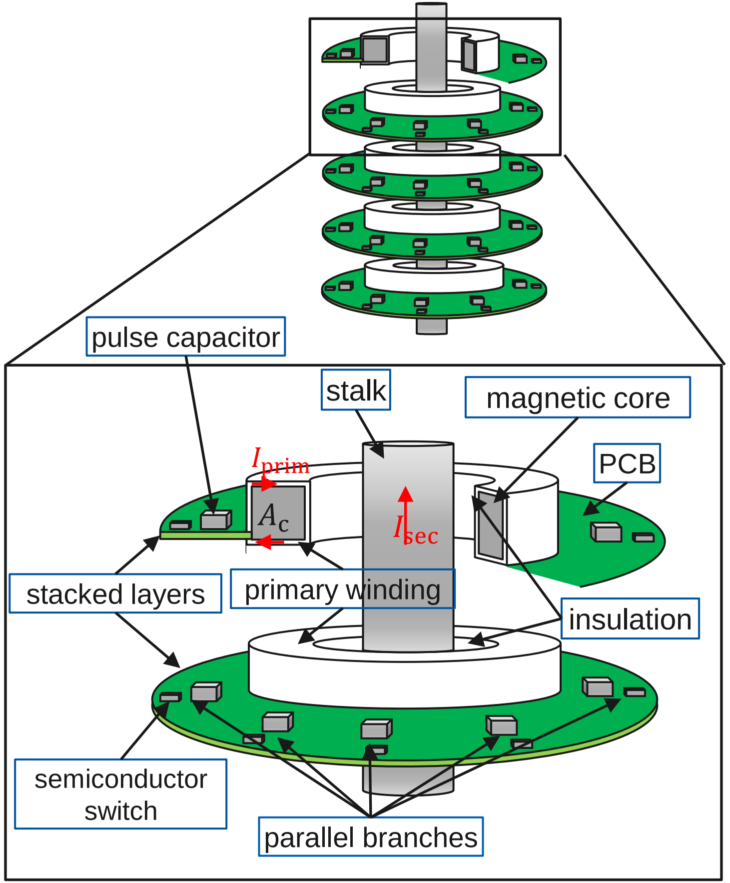
Marx generator

- 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



Previous experience

- **LEP:**
  - Experience from LEP serves as a valuable reference for the new design
  - However, higher synchrotron radiation power is expected due to the use of top-up injection

- **CLIC:**
  - A stripline kicker magnet driven by an inductive adder was studied and prototyped for the CLIC Damping Ring
  - While the specifications are similar to those for the FCC damping ring, further optimization is required to meet new requirements