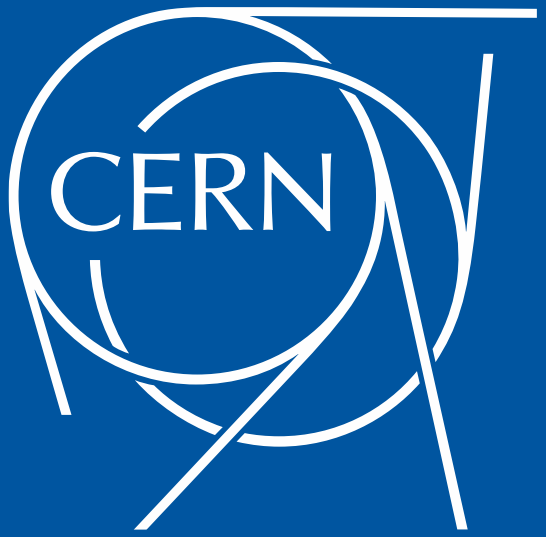
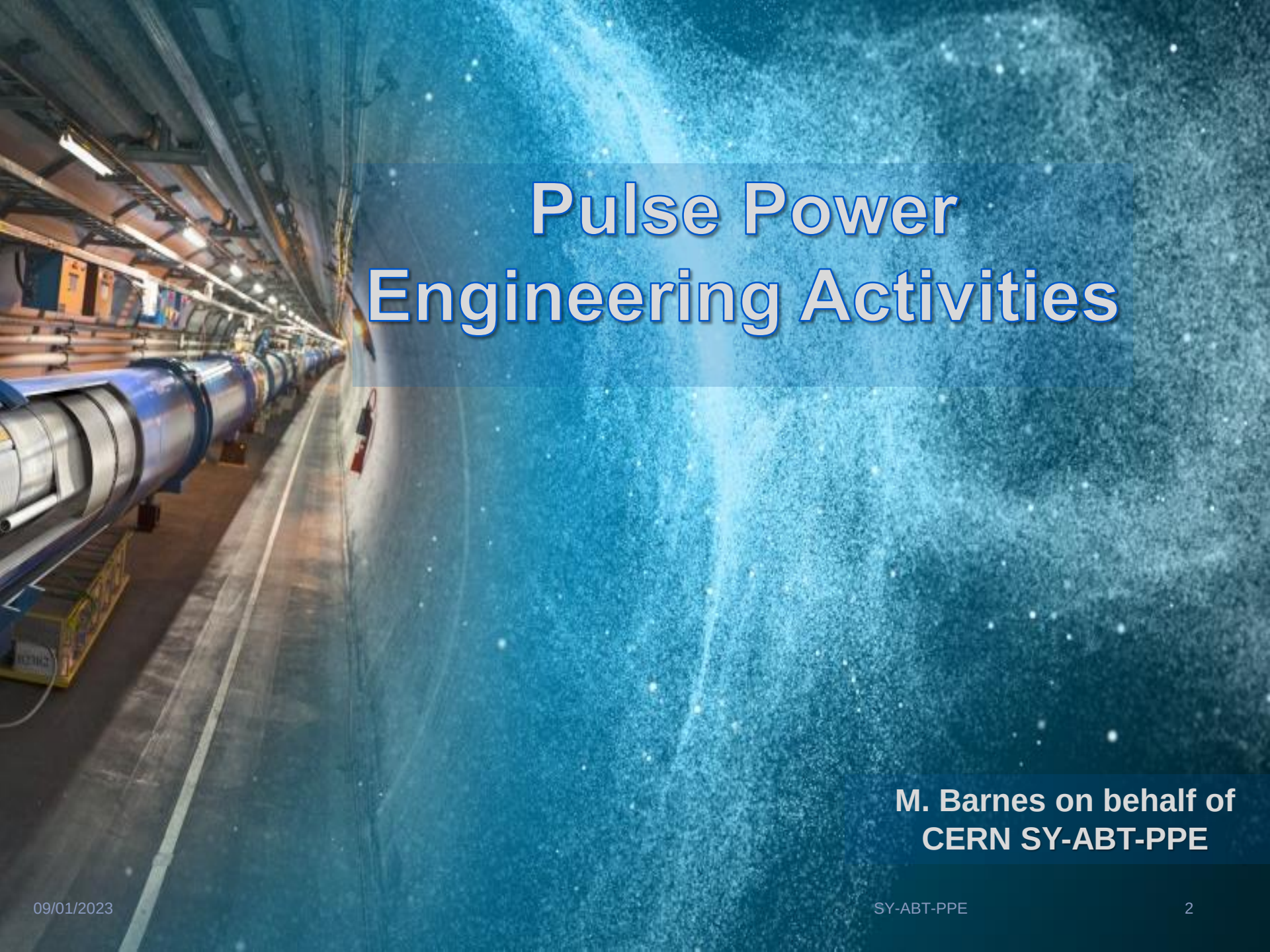

CERN



Pulse Power Engineering Activities

M. Barnes on behalf of CERN SY-ABT-PPE

SY-ABT Group

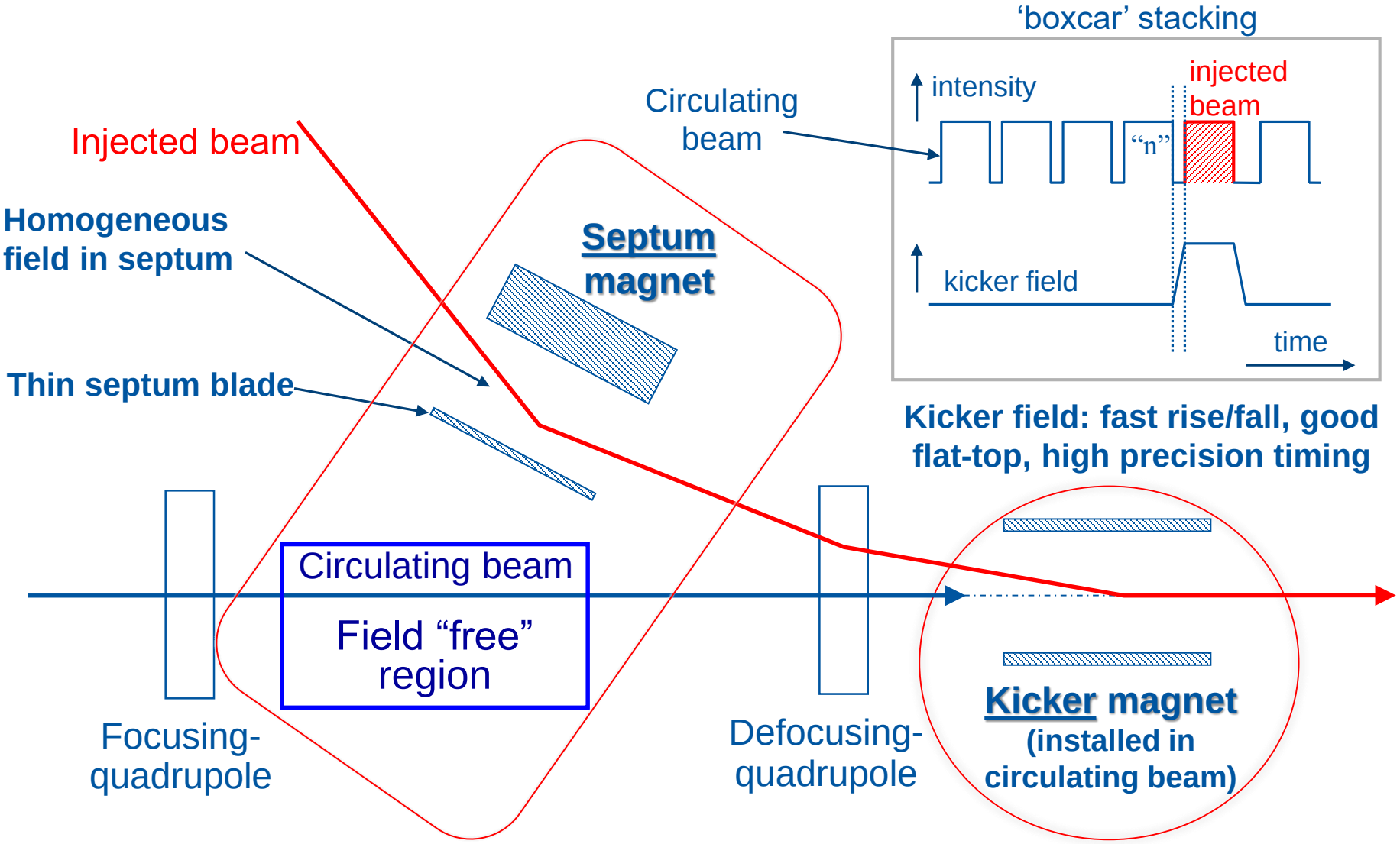
Accelerator Beam Transfer Group

Scope: Development, construction, operation and maintenance of kicker, septa and associated electronics.

6 Sections:

- Beam Transfer Physics (BTP)
- Beam Transfer Controls (BTC)
- Beam Transfer Electronics (BTE)
- Septa (SE)
- **Pulsed Power Engineering (PPE)**
- Kicker Design & Construction (KDC)

Beam Transfer Between Accelerators



SY-ABT Kicker Activities

- **Designed, produced and operates** over **80 kicker systems** in the accelerator complex, beam transfer lines between accelerators and up to targets.
- **Rise times** from 5ns (CLIC) to 2.8 µs (LHC).
- **Pulse durations** up to 90 µs (typically <1% ripple).
- **Pulsed currents** up to 400 kA.
- **Voltages** up to 80 kV.
- **Competencies** in pulsed power technology, high voltage engineering, mechanical design and production, handling of UHV, testing and maintenance.

Pulsed Power Systems

Typical Kicker System Topology

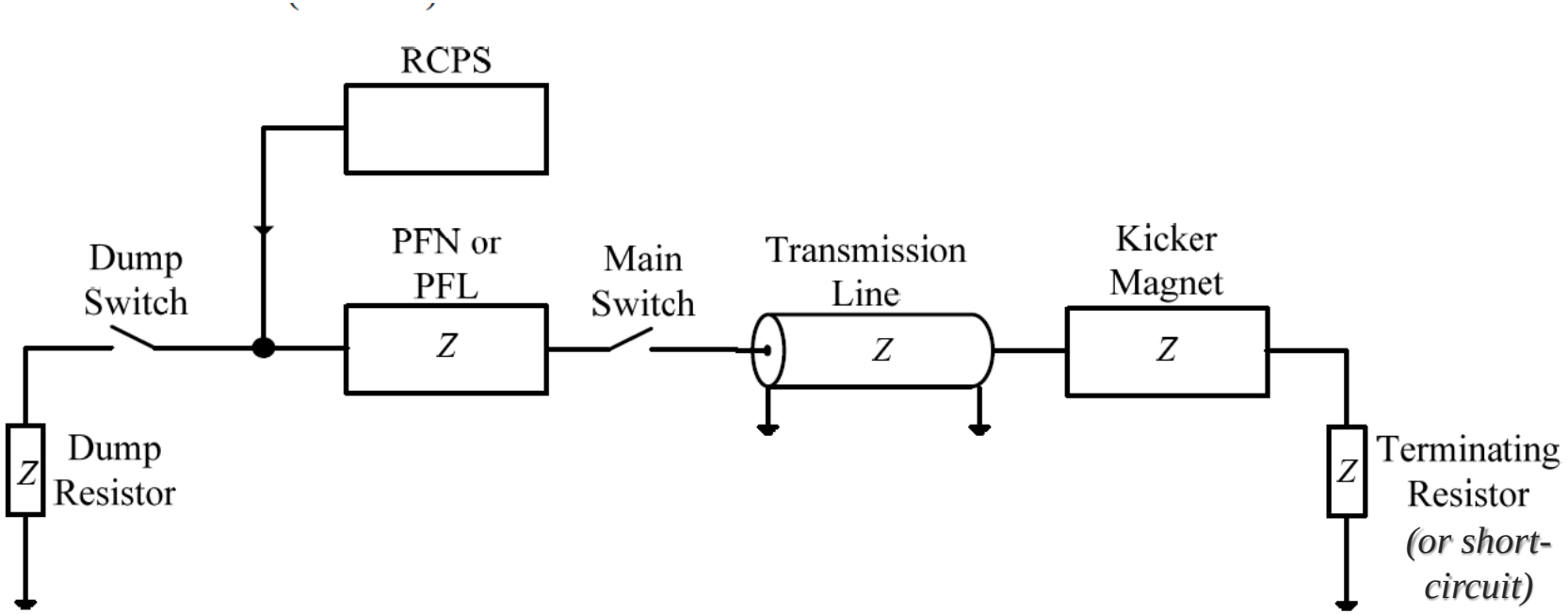
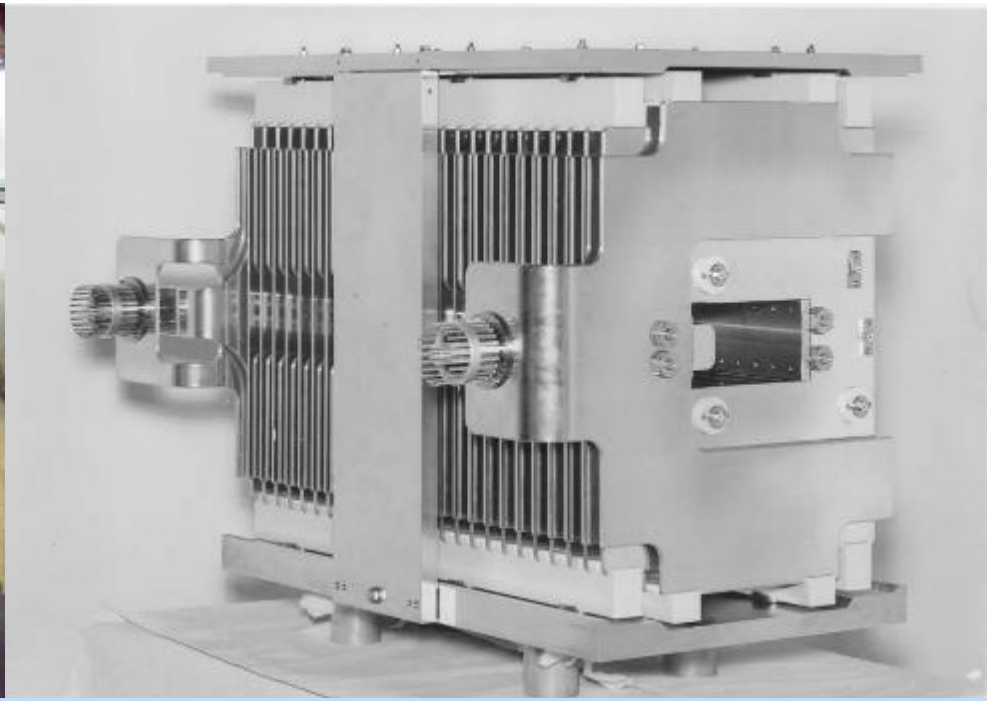


Fig. 4: Simplified schematic of a kicker system

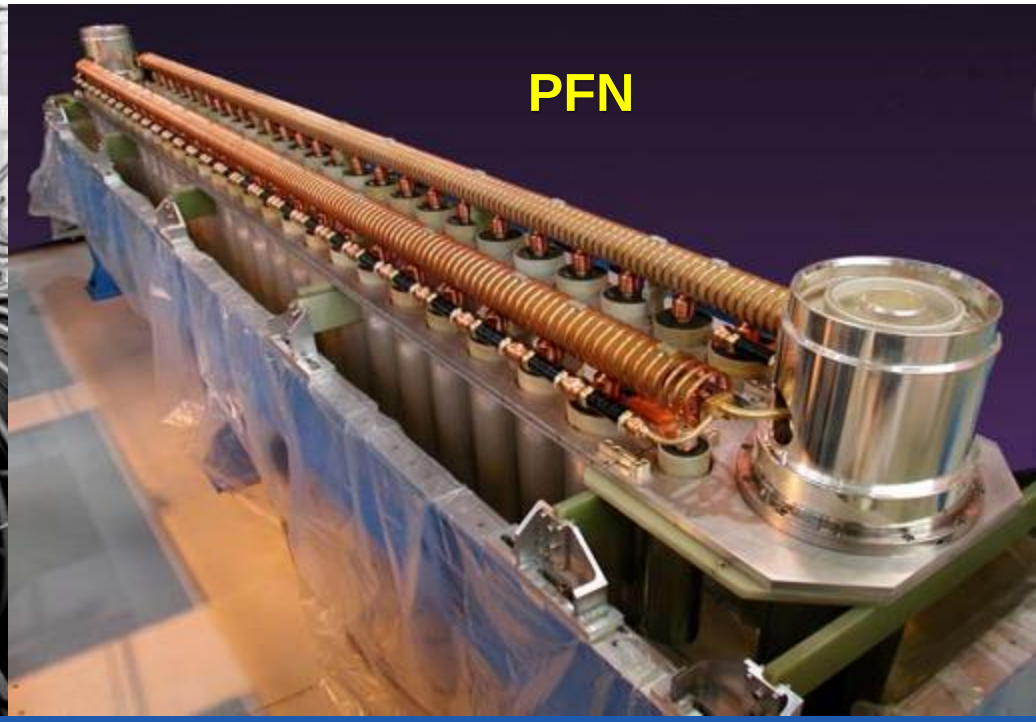
Transmission Line Kickers



- Used for “faster” systems (30 ns – 800 ns range)
- Currents up to 5 kA
- Voltages up to 80 kV

Pulse Generators

- PFL and PFN based Generators
- Very fast systems (30 ns current rise time) mostly use PFL's and thyratron switches (di/dt)
- "Slower" systems (0.2 - 3 µs rise-time) are generally based on PFN and GTO, IGBT or MOSFET technology (stacked).



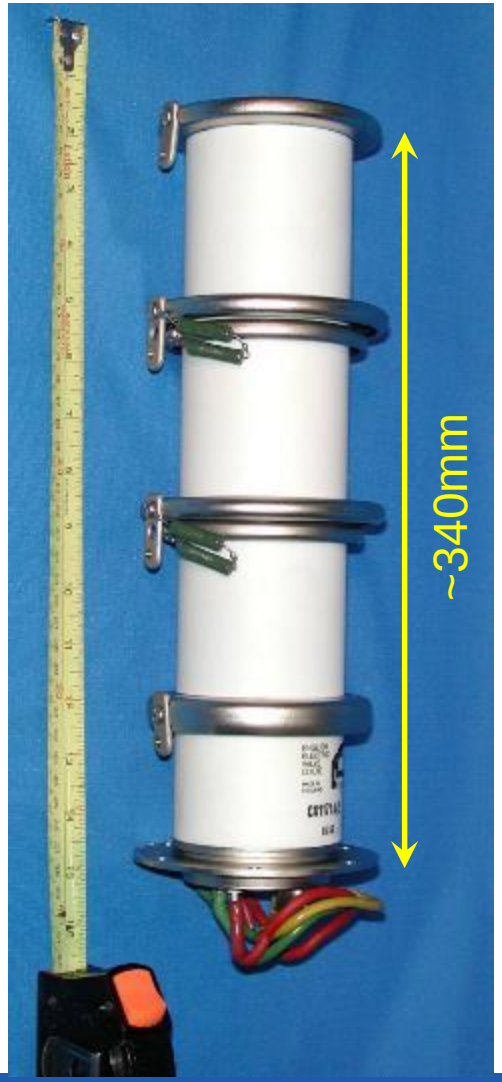
Thyratron Switches

Deuterium filled thyratrons are still used as the power switch for most kicker systems.

Three-gap thyratrons can hold-off 80 kV and switch 6 kA with a 30 ns rise-time (10% to 90%) [~150 kA/μs].

BUT: care must be taken, e.g.:

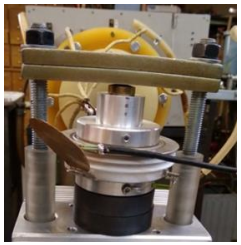
- Coaxial housings for low inductance;
- Adequate insulation to the housing;
- Erratic turn-on (turn-on without a trigger being applied): reduced significantly by “fast” (~ms) charging of the PFN/PFL (RCPS);
- Appropriate thyratron for anticipated short-circuit and fault conditions;
- **Long-term availability ???**

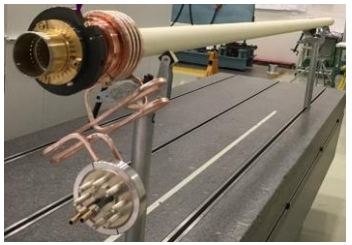
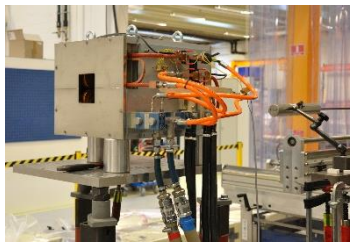


Main R&D Areas

- **Inductive Adders**
- Fast solid-state Marx generators
- Ionization wave triggering of thyristors
- SF6-free, low attenuation, coaxial high voltage cables
- Beam screens for kicker magnets in high energy / intensity machines
- Bumpers & kickers for medical machines



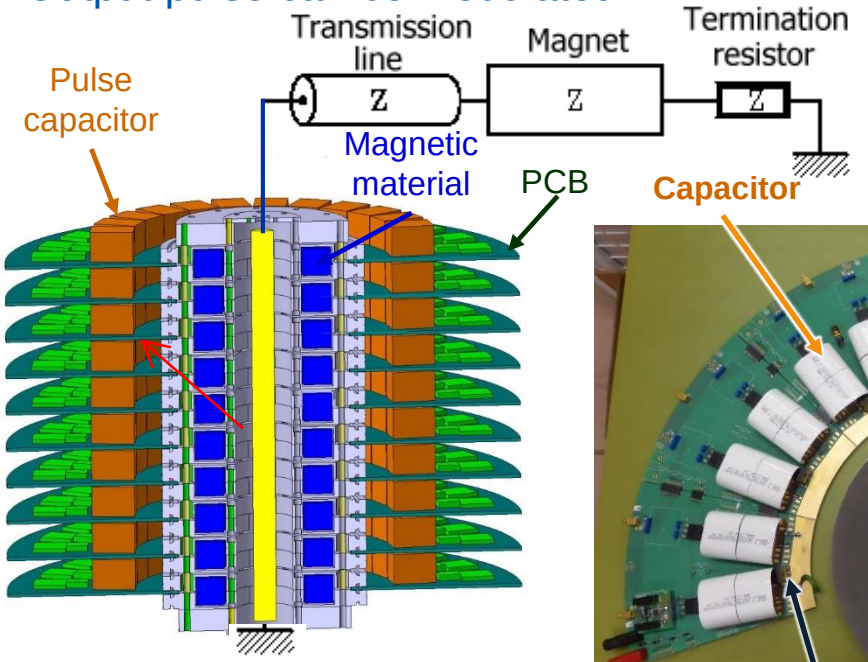


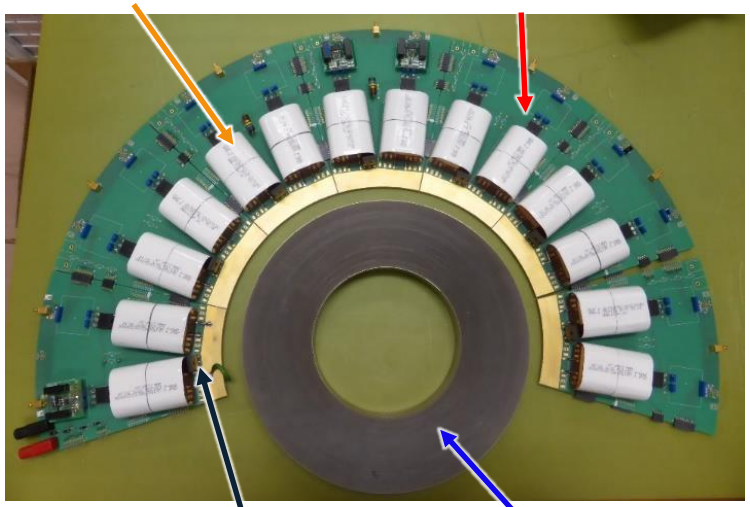
Overview of Inductive Adder Activities

New Pulse Generator Architecture: Inductive Adder (IA)

- Turn-on AND Turn-off Capability (MOSFETs or IGBTs) – hence PFN/PFL is NOT required;
- Excellent scalability for current and voltage;
- Polarity of output pulse easily changed;
- Output pulse can be modulated.

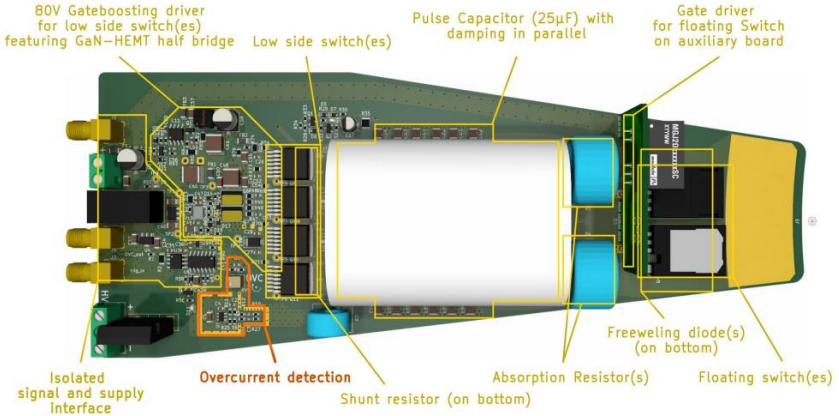


- *'n'* low voltage, primary, layers
- *'x'* parallel branches per layer
- Magnetic coupling



Inductive adder tested with beam at ALBA (Spain)

Development Overview



2011–2019

Gen1 (2011-2019): CLIC High precision (±0.02%), 50 Hz, resistive termination

2020-ongoing

Gen2.5 (2020-ongoing): Short circuit load (FCC)

Gen2 (2016-2020): FCC-hh Fast & high power. resistor termination

2016–2020

Gen3 (2021-ongoing): PS (fast & higher voltage) (ABT R&D)

2021-ongoing

Newest Generation IAs: Implementation in existing system

Two developments directions ongoing:

- **IA for short circuit loads**
- **IA for PS extraction kicker application:**
  - U = 40kV
  - Z = 15 Ohm
  - I = 2.6 KA
  - tr = 100 ns, tp = 2.6 µs
  - ~1 Hz rep. rate

- Proof of feasibility until 2024
- Possible installation during LS3 (2026)

Questions ?

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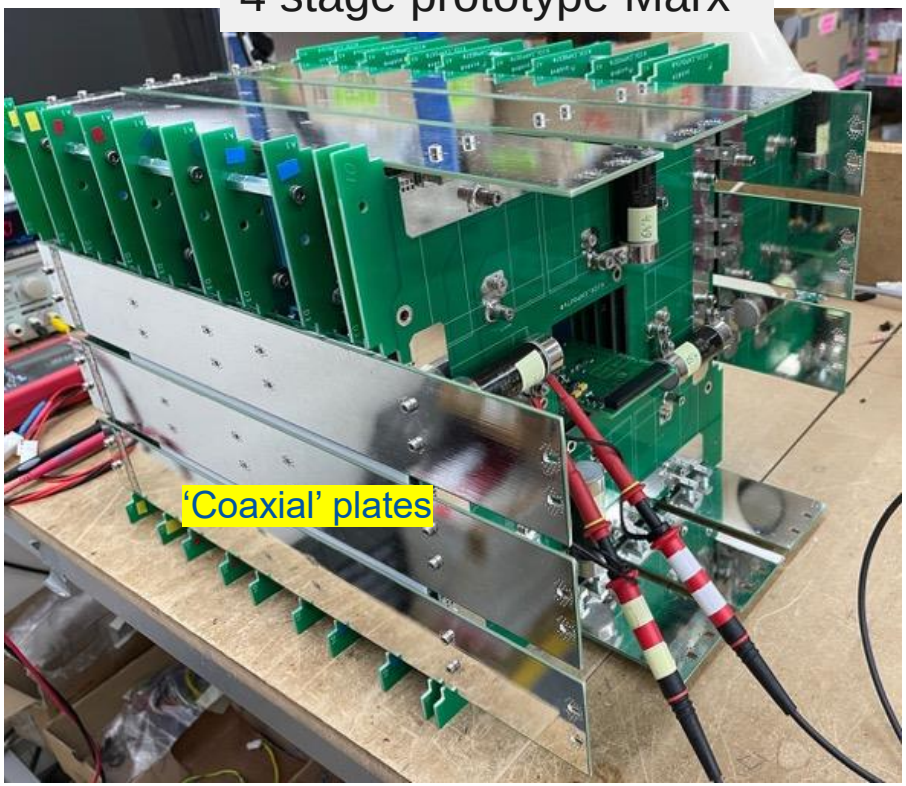
www.cern.ch

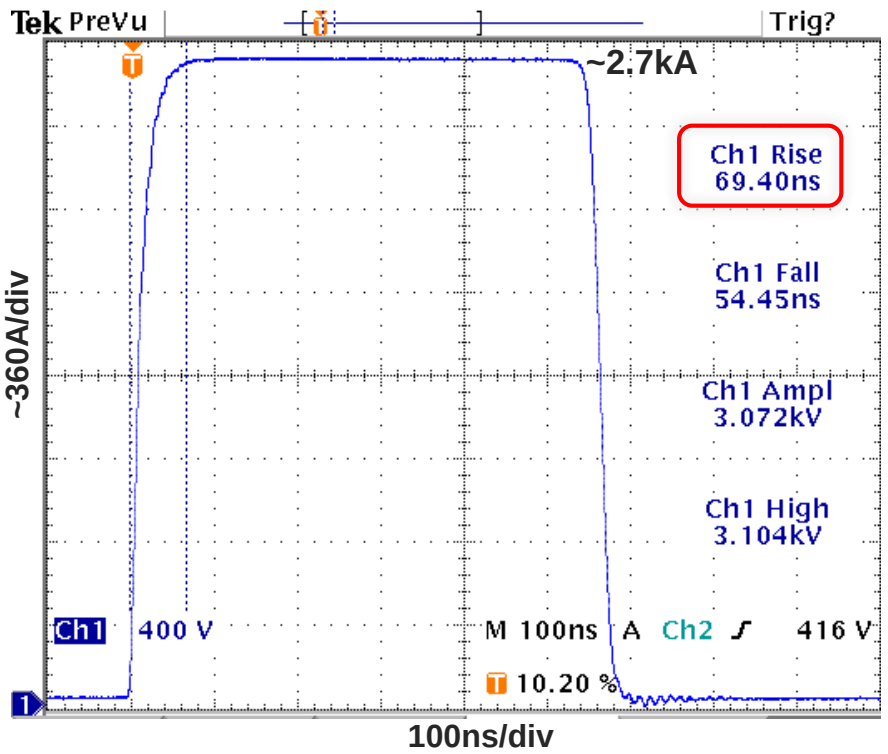
Semiconductor Based Marx Generator

Collaboration with Instituto Superior de Engenharia de Lisboa (ISEL) and EPS, Portugal:

- No magnetic material on output ⇨ long duration pulse capability;
- Prototype with up to 36 parallel SiC MOSFETs per stage;
- Return ‘coaxial’ plates to reduce inductance;
- Initially targeting: 16kV, 2.6kA, 75ns rise and fall (0.5% to 99.5%).

4 stage prototype Marx

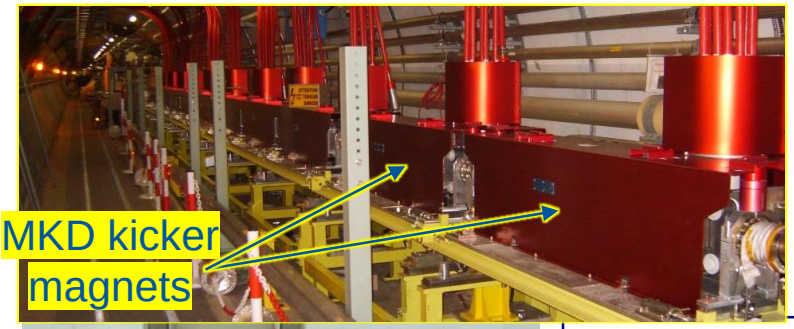


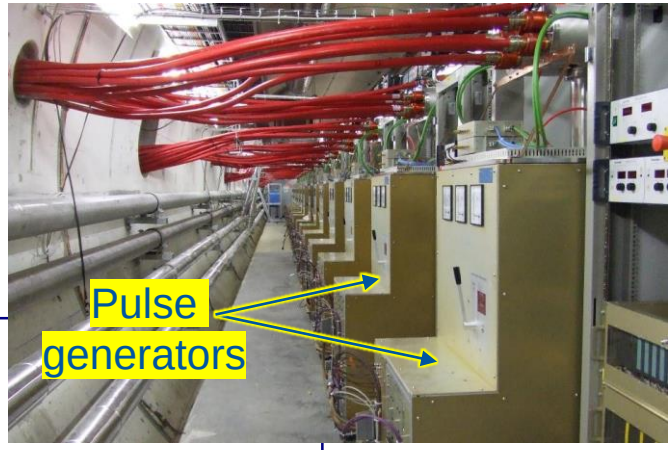


Extraction Kickers (MKD)

Function: safely extract beam from LHC towards 'dump block'.
Stored energy per LHC beam is up to 360 MJ = twice the kinetic energy of a Boeing 737 MAX8 at landing [~70 t at 250 km/h].!

- Rise time of 3.0 μs
- Fixed deflection angle of 0.28 mrad (for 450 GeV to 7 TeV): hence **voltage α beam energy**



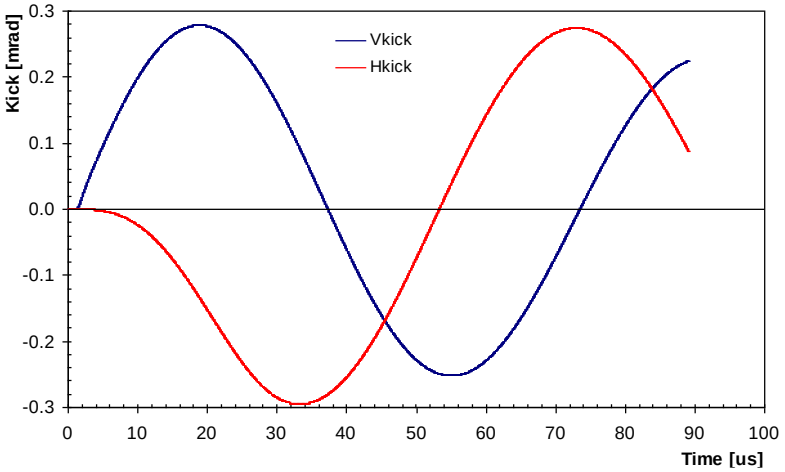


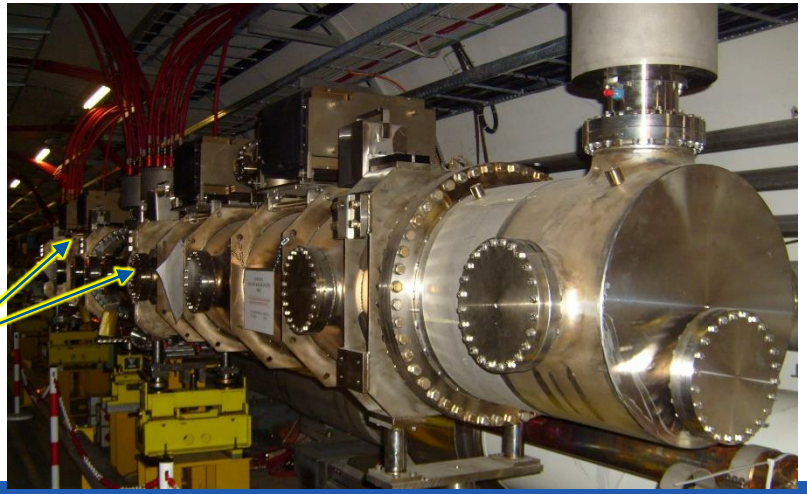
MKD generator parameters:

- Voltage: 1.7 kV – 27 kV;
- Current: 1.3 kA – 18.5 kA;
- Magnet current flat top: 91 μs;
- Maximum di/dt: 32 kA/μs (~1/5th of a thyratron).

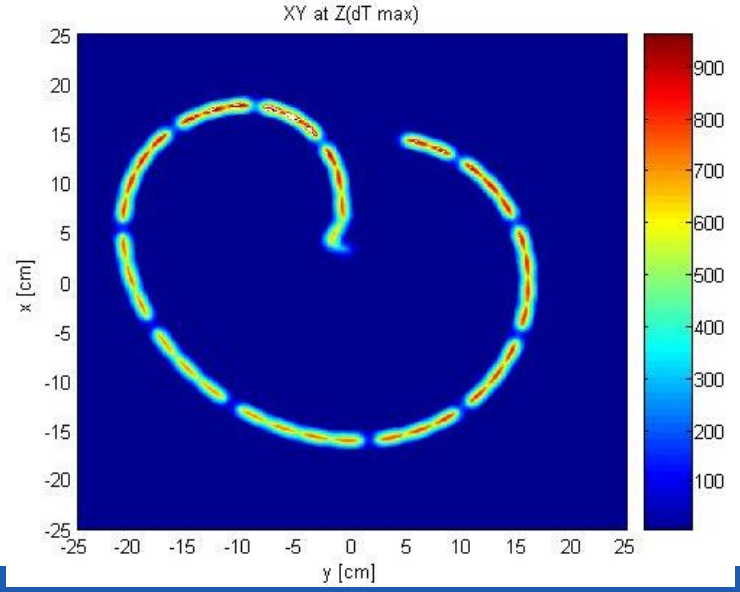
Dilution Kickers (MKB)

- Function: sweep beam to control energy density in a 7 m long dump block
  - Separate horizontal and vertical kicker systems
  - Sine and cosine-like current shapes over ≥90 μs
  - Peak deflection angle of 0.28 mrad (for 450 GeV to 7 TeV)
- Main components
  - Kicker magnets (4 Horiz. and 6 Vert. per beam)
  - Generators (1 per magnet)
  - Up to 27kV and 24kA (7 TeV)
  - Oscillation frequency ~13 kHz





MKB kicker magnets



Super-Boosted SiC MOSFET

- Impact ionization of high-power thyristor is under consideration for thyratron replacement;
- Switching in the impact-ionization wave mode occurs due to applying a steeply rising overvoltage pulse across anode and cathode;
- A dV/dt, of the triggering overvoltage pulse of more than **1 kV/ns** is required;
- Trigger generator must be able to increase the voltage across the thyristor to approximately twice the static breakdown voltage

SiC MOSFET circuit output: