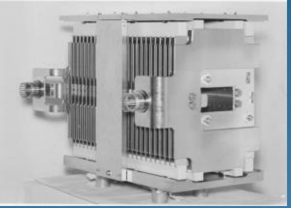
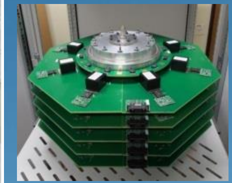
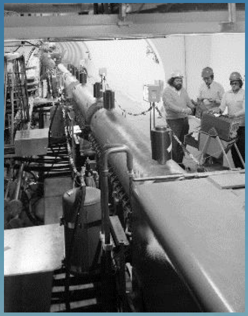
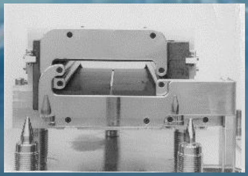






FCC-hh Injection and Extraction Kicker Topologies and Solid State Generators

T. Kramer, CERN TE/ABT

FCC-week 2016, Rome, Italy

Acknowledgements
D. Barna, M.J. Barnes, W. Bartmann, F. Burkart, L. Ducimetière, T. Fowler, B. Goddard, J. Holma, A. Lechner, J. Rodziewicz, V. Senaj, T. Stadlbauer, D. Woog

Outline of presentation

Injection

- Requirements
- Magnet
- Inductive Adder and Marx Generator

Extraction

- Redefined requirements
- Segmented kicker system

Dilution

- Considerations on dilution pattern
- Kickers and generators

CERN TE-ABT

FCC-hh Beam Transfer Systems

TE Special Technologies WP 3

Slides to be seen in context with the presentations of this morning (W. Bartmann, B. Goddard and F. Cerutti).

Injection Kicker System Requirements

	Unit	Injection
Kinetic Energy	TeV	3.3
Available system length	m	150
Deflection angle	**mrad**	**0.3**
Field rise/fall time (0.5 % - 99.5 %)	**ns**	**280**
Field flattop duration	**µs**	**2.25**
Field flattop ripple	**%**	**± 0.5**
System impedance	Ω	5 ?
Repetition rate	Hz	up to 115

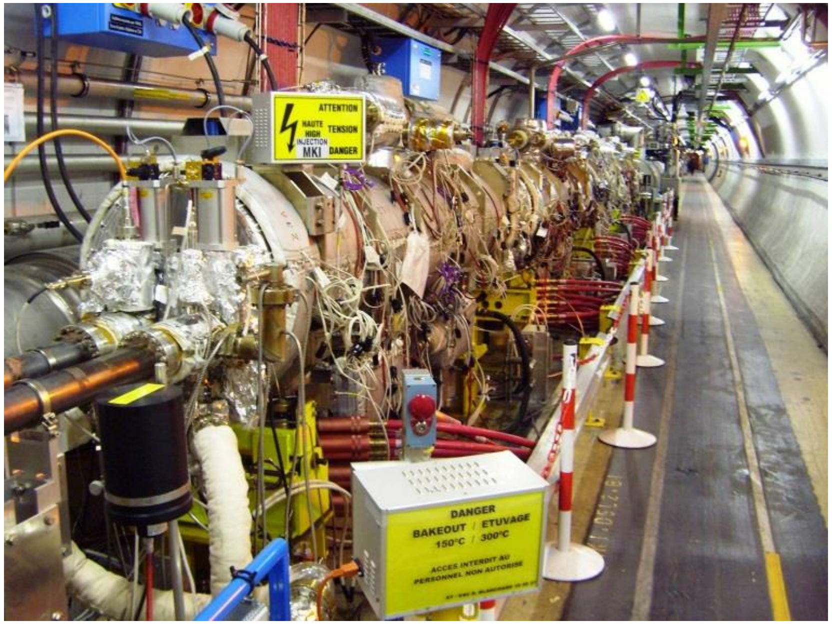
- Focused studies on **3.3 TeV** injection energy (lower energy variants are less demanding to design).
- 3.3 TeV **pulse duration** is limited to **2.25 µs** for machine protection reasons.
- Final system impedance depends on system optimization outcome.

Injection Kicker Magnet

- **Delay line type** magnet (will be initially based on the LHC injection kicker design).
- System will be **much shorter** than the available length of 150 m.
- Inside vacuum.
- Optimized beam screen.

Additional magnet requirements

Magnet filling time	ns	≤ 200
Magnet current	kA	2.6
Magnet voltage	kV	13

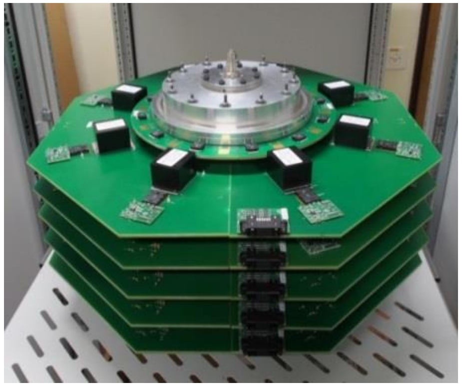


Injection Generator: Inductive Adder

- Design ongoing, impedance and dielectric evaluated (oil), magnetic cores specified.
- Characterization of components started.
- Assembly of prototype planned for 2017.
- Prototyping will profit from CLIC high precision developments.
- Successful development will have benefits for the CERN accelerator complex.

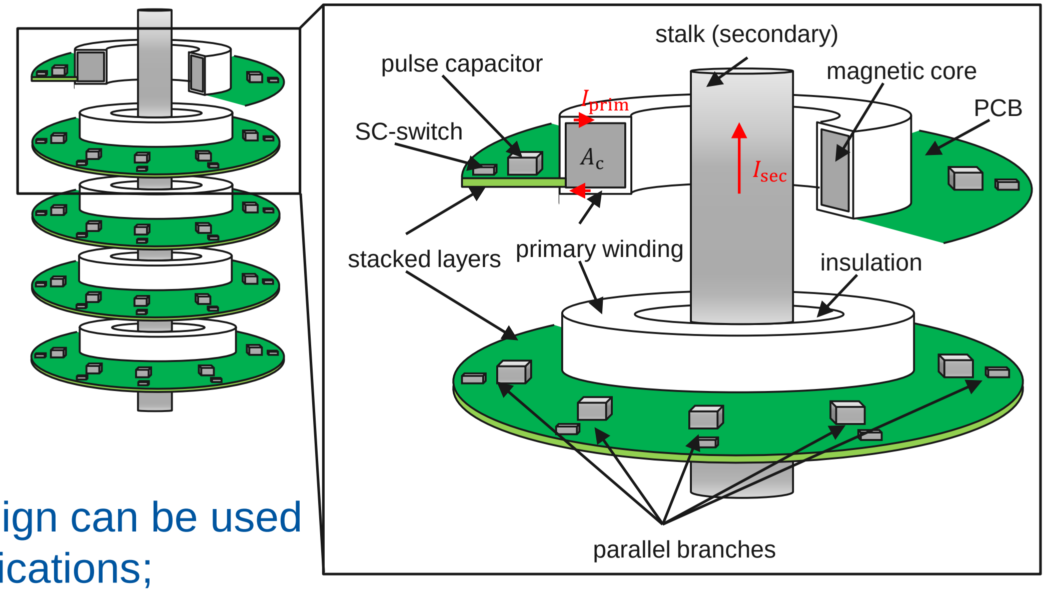
Additional generator requirements:

Generator current	kA	2.6
Output voltage range	kV	1.3 to 13
Output pulse rise time (0.5%-99.5%)	ns	80



Injection Generator: Inductive Adder

- Energy stored in **distributed capacitors.**
- Capacitors are partially **discharged via SiC MOSFET** switches **in parallel** branches.
- Several **layers add up** to the required output voltage.

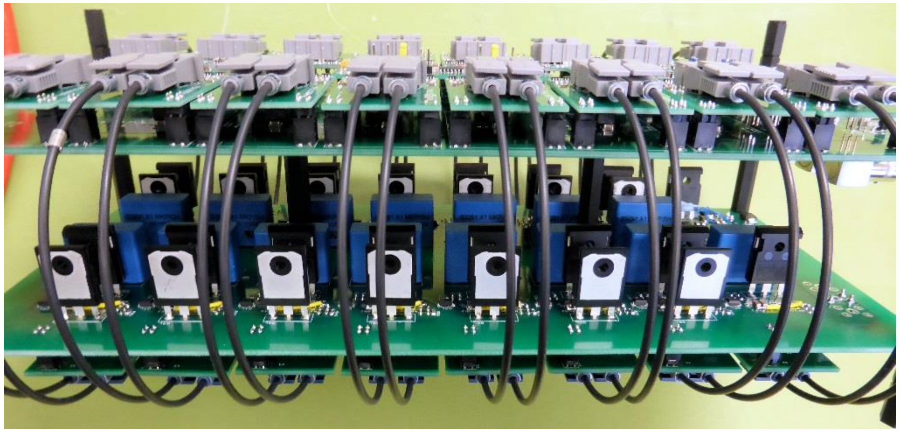


- **Advantages:**
  - **Modularity:** the same module design can be used for different voltage/current specifications;
  - **Short rise and fall times** can be achieved;
  - Output pulse **voltage can be modulated** -> very good flat top quality.
  - Switches and control electronics are referenced to ground.
- **Disadvantages:**
  - Output transformer limits maximum **pulse length** to typically ~3 μs;

Poster: “Inductive Adder Type Solid-State Pulse Modulator Development for Kicker Systems of the Future Circular Collider” by D. Woog et al.

Injection: Marx Generator

Alternative solution for **longer flat top** requirement.

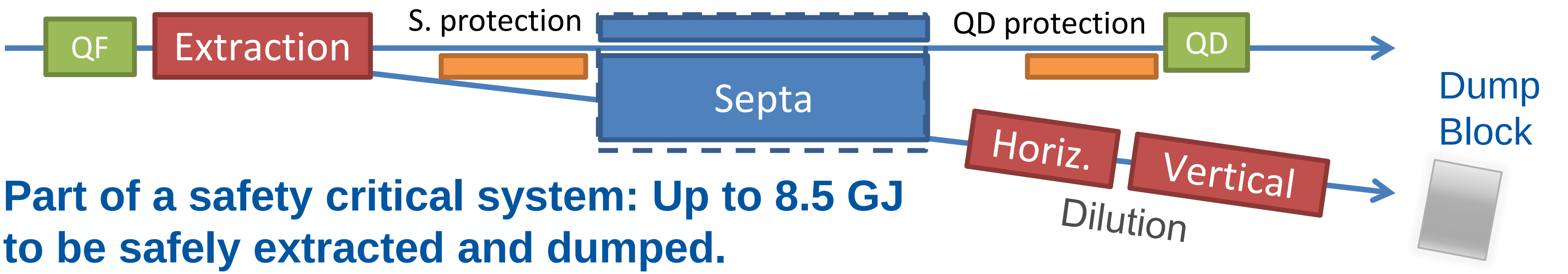


- Capacitors **charged in parallel**, and **discharged in series** ⇨ high voltage output.
- **No output transformer** ⇨ maximum pulse length limited by droop of capacitor voltage.
- **Modularity**: the same design can be used for different voltage specifications.

- Switches and control electronics are **not referenced to ground**.
- Fail safe circuits to be investigated.
- **No modulation layer**.
- **Proposal** to develop a high power Marx Generator, under Portugal 2020 programme, for replacing thyratrons and PFN/PFL has been submitted.

Poster: "Marx Generator Solid-State Pulse Modulator Application to Kicker Systems of the Future Circular Collider" by M.J. Barnes et al.

Extraction Kicker System



- **Part of a safety critical system: Up to 8.5 GJ to be safely extracted and dumped.**
- **Extraction** Kickers & Generators
- **Horizontal Dilution** Kickers & Generators
- **Vertical Dilution** Kickers & Generators

	Unit	Extraction	Dilution
Kinetic Energy	TeV	3.3 to 50	3.3 to 50
Available length	m	130	150
Deflection angle	mrad	0.13	0.21
Field rise time (0.5-90%)	µs	1	
Field flattop duration	µs	≥ 333	~350
Magnet current	kA	0.5 to 8	11
Output voltage range	kV	~10	~20

- Initially challenging requirements. BT-Optics team developed very beneficial layout!
- Started with ultra high current considerations (tr=10µs).
- Evolved to a fast but **segmented system** for machine protection and feasibility reasons.

Extraction Kicker Magnet

Preliminary Design Concept :

- Based on (robust) LHC extraction kicker design.
- Outside vacuum (ceramic chamber).
- Segmented system (300 units per beam):
  - Allows for low inductance and fast rise time
  - Impact of one unit on beam <1σ
  - 10 “Hot spares” included (increases system availability)
- With the help of the developed beam optics we succeeded to achieve **reasonable** design values!

Parameters (per module)	
Number of Modules	300
B.dl [T.m]	0.076
k [µrad]	0.517
B [T]	0.25
Length [mm]	300
Inductance [µH]	0.38
Current [kA]	7.3
Voltage [kV]	10 *
Aperture (h/v) [mm]	36/36

* assuming additional circuit inductance (1µH)

Extraction Kicker Generator

- One generator per Magnet (10 kV / 7.3kA / **1µs** system rise time)
- Challenge: Compensation stage to be designed for **330 µs**.
  - Long flat top needs some thought (compensation circuits).
- Possibly using **GTO switch** technology:
  - long "on" state duration (330µs) – segmented system (lower current helps a lot vs. very high current concept)
  - Promising developments within the "wide band gap" sector.
  - **Direct laser triggering** being investigated.

Poster: "Prospects for laser triggering of large arrays of semiconductor switches" by Janusz Rodziewicz

- Again **reasonable** basic design values achieved but:
  - **Reliability** will be extremely important!
  - **Radiation effects** will be a serious issue which needs to be addressed.
  - **Controls and trigger (re-trigger**) interface will be challenging.

Talk: "Controls architecture challenges for beam dump kickers" by P. Van Trappen, Thursday

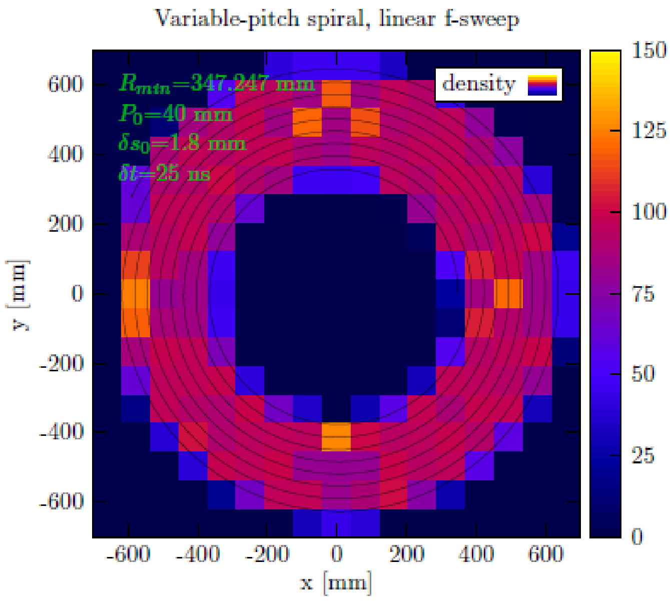
Dilution Kicker System

- Dump **pattern crucial** for survival of dump block!
- **No crossing**, 1.8 mm minimum bunch separation.
- **Spiral** seems to be the only good solution.
- **Painting inwards** to ease hardware design.
- Resulting dump radius of **~600 mm**!

Talk: “Absorber for beam dumping ” by A. Lechner et al.

Poster: “FCC Dump Pattern Studies” by D. Barna (Wigner Institut)

- Same **radiation concerns** as for extraction!
- Horiz. and vertical system could use the **same generator design**.
  - Vertical generators would be triggered at 90 degree of horizontal sine wave (= 5µs @50kHz).
  - Ok for scheduled dump but for asynchronous events only the horiz. dilution is available immediately. (First 5 µs of beam would be painted on a horizontal line before the spiral starts.) Impact to be checked.



Dilution Kicker Magnets

- Unexpectedly the most challenging system!
- **Highest B.dl to deliver** and **aperture** of the vertical system **increases** with length.
- Introduced **2 vert. magnet types**.
- **Quad** after horiz. kickers for “over focusing” **under study**.
- **Short magnets** to allow for 3-turn coil and higher dilution frequency.
- **High number** of magnets: Impact of missing (or misbehaving) unit lower (to be optimized).

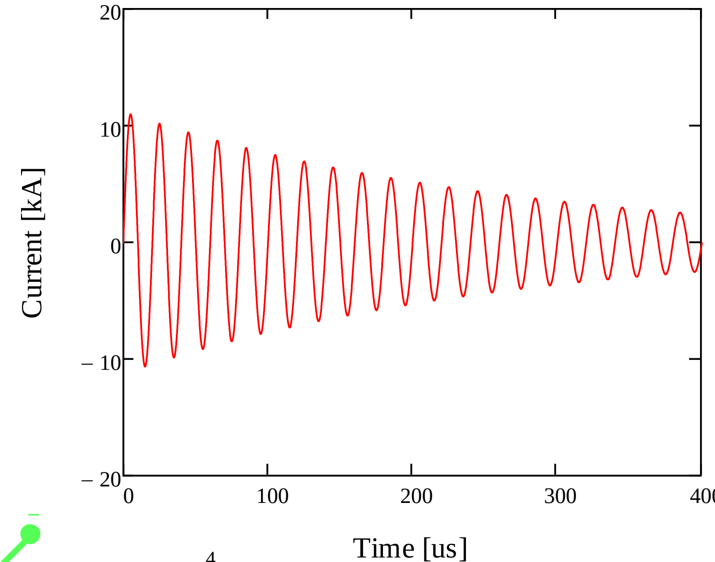
	Unit	Value
B.dl	Tm	35
Lever arm	m	2800
Angle	mrad	0.21
Max. deflection	m	0.588
Design frequency	kHz	50

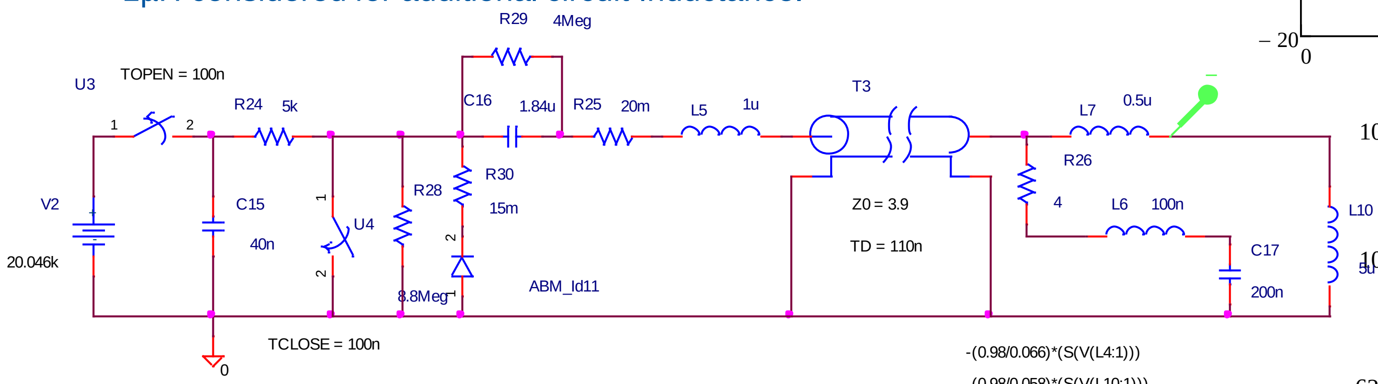
	Unit	Horiz.	Vert.1	Vert. 2
max. B-field	T	0.85	0.5	0.4
Magnetic length	m	0.85	0.9	0.9
Horiz. aperture	mm	62	81	104
Vertical aperture	mm	40	58	81

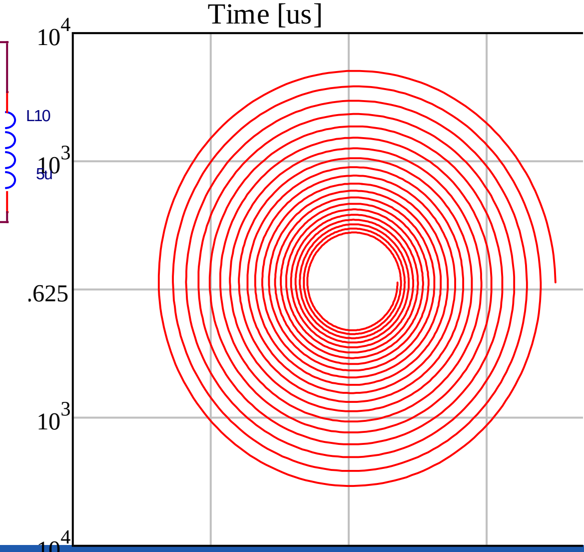
Dilution Kicker Generators

	Magnet Inductance [μH]*	I [kA]*	U [kV] **
Horizontal	5	9	22
Vertical 1	4.8	10.8	20.5
Vertical 2	4.4	11	19

* For magnet with three turn coil.
** 1μH considered for additional circuit Inductance.







- Reasonable main capacitance: 1.8 μF
- **Amplitude decay** needs **to be improved** to avoid getting higher density towards the centre.

Summary/Outlook

- **Three challenging kickers systems** in FCC-hh (Injection, extraction, dilution).
- Development of **semiconductor generators** will also have a benefit for the CERN accelerator complex.
- A **segmented extraction system** topology has been developed.
- Since the basic ideas have settled, interfaces to **reliability engineering, risk assessment and machine protection** need to be addressed next.
- **Radiation hard design** needs to be studied.
- Several **international collaborations** on kicker technologies established/proposed.
- Initially **challenging basic design requirements** have been translated together with all collaborators and the TE-ABT team into a **feasible design draft**

  no technology show stopper identified yet!
- Nevertheless: the big challenge will be the **system safety and reliability**!!

Discussions on the presented topics are very welcome!

Grazie per l'attenzione!
Thank you for your attention!