



FCC-hh kicker systems: Status and R&D plans

M.J. Barnes W. Bartmann, A. Chmielinska, B. Goddard, T. Kramer, D. Woog (CERN, TE-ABT)
L.M. Redondo (Instituto Superior de Engenharia de Lisboa, Portugal)
A. Kandrasyeu (Energy Pulse Systems, Portugal)



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Content

Status and R&D plans for

- Injection
 - Requirement's
 - Magnet & Beam Screen
 - Novel pulse generators under development (Marx, Inductive adder)
- Extraction & Dilution
 - Requirement's, magnet & pulse generators
- Summary/Outlook



Status & R&D plans

FCC-hh INJECTION KICKER

Requirements for FCC injection

Injection parameters (from LHC at 3.3 TeV):

Parameter	Unit	Value
Kinetic Energy	[TeV]	3.30
Angle	[mrad]	0.18
Pulse flat top length	[μ s]	2.00
Flat top tolerance	[%]	± 0.50
Voltage	[kV]	15.0
Current	[kA]	2.4
System impedance	[Ω]	6.25
Field rise time	[μ s]	0.43

Optimized for low system voltage

Injection system parameters:

Kicker Magnet	Unit	Value
System Length	m	40
Deflection	mrad/Tm	0.18/2
Number of Modules		18
Flux Field	T	0.063

Pulse Generator	Unit	Value
Characteristic impedance	Ω	6.25
Rise time	ns	75
Output voltage	kV	15.0
Output current	kA	2.4

355 ns magnet fill time + **75 ns** current rise time

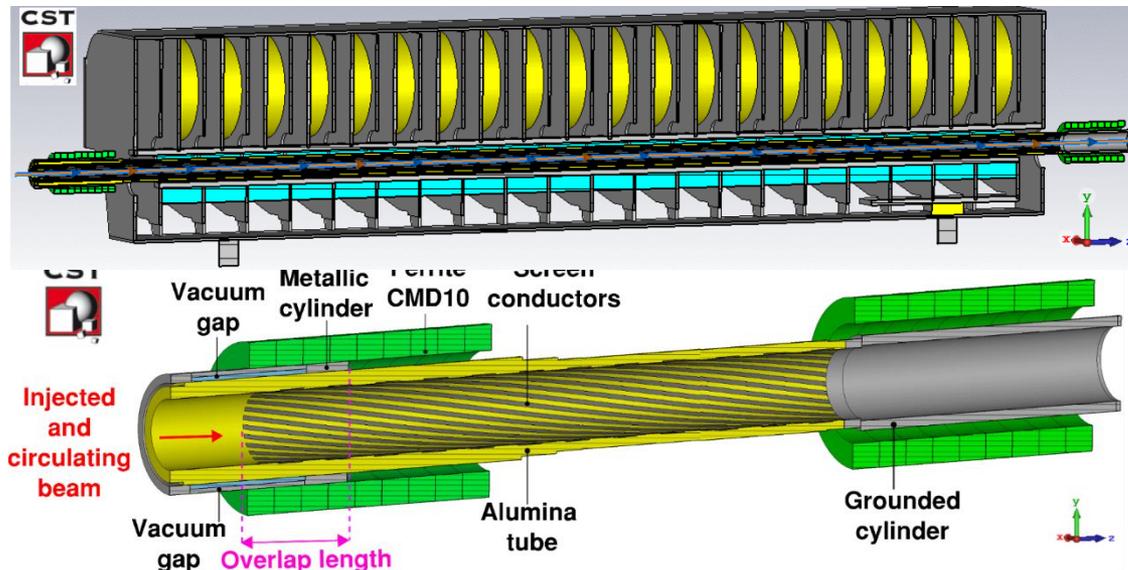
Injection Kicker Magnet & Beam screen

- Basic magnet concept available, detailed design to be worked on (beyond CDR).
- Total installation length reduced to 1/3 of initial estimates.
- Major R&D efforts on optimized beam screen design.

Future:

- Validation of beam screen in CLEAR?
- Prototype of one full injection system module desirable

Hardware parameter	Unit	Kicker
Deflection	mrad	0.18
Integrated field	T·m	2.0
Total magnet length	m	40
Good field region (h/v)	mm	32/32
Field rise time	μ s	0.43
Flattop length	μ s	2.0
Flattop stability	%	± 0.5



see talk of A. Chmielinska, this session, and PhD thesis, to be published in 2019

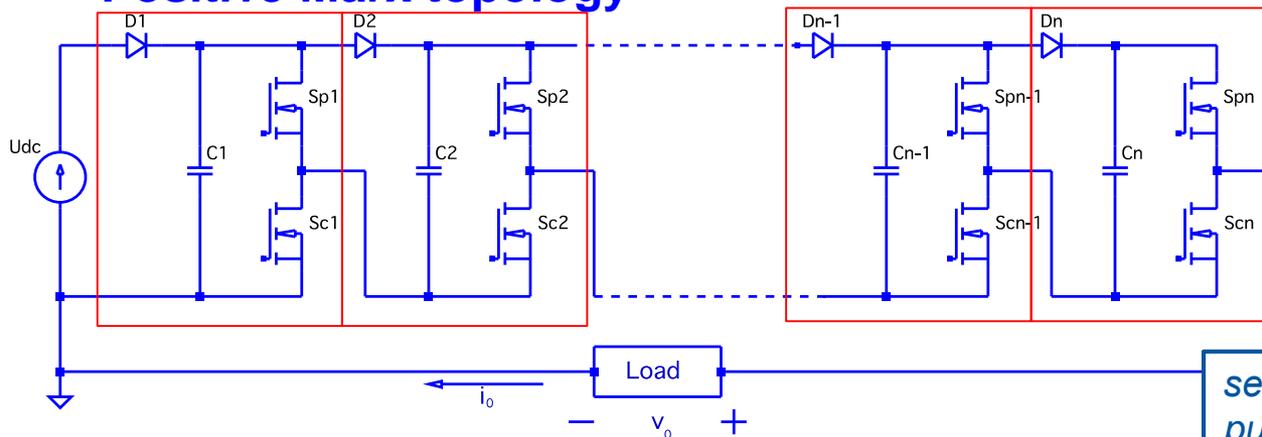
Solid-state Marx generator

Ongoing collaboration with ISEL and EPS

Specifications

- Output voltage: **16 kV**; Output current pulse: **2.56 kA**; Termination: **6.25 Ohm** resistor;
- Pulse flat top duration: 2 μ s; Pulse flat top tolerance: $\pm 0.5\%$ (80V);
- Current rise/fall time: **75 ns** (0.5% to 99.5%);
- Burst rate of 10 Hz for 10 s, the time period between bursts is 10 minutes;

Positive Marx topology



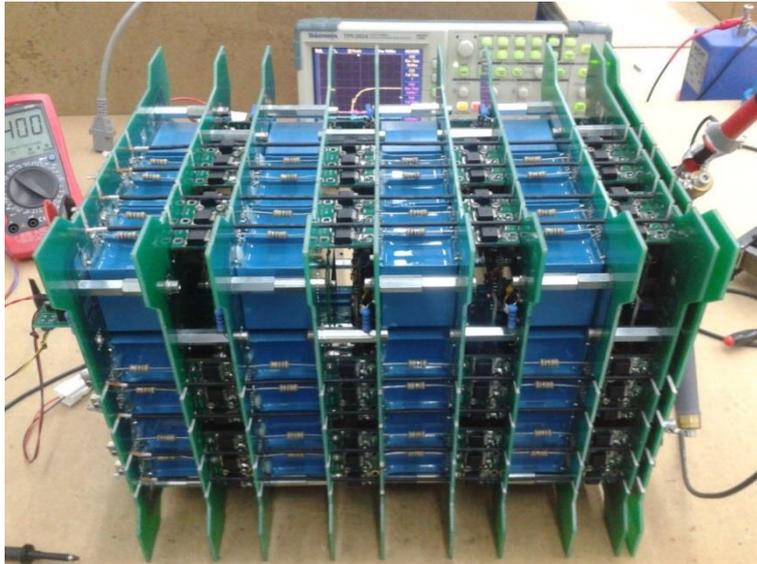
- Spi for pulsing
- Sci for charging n stages & pull down
- Each holds U_{dc}
- Output $\approx n \cdot U_{dc}$

24 // switches + 8 // capacitors, per stage

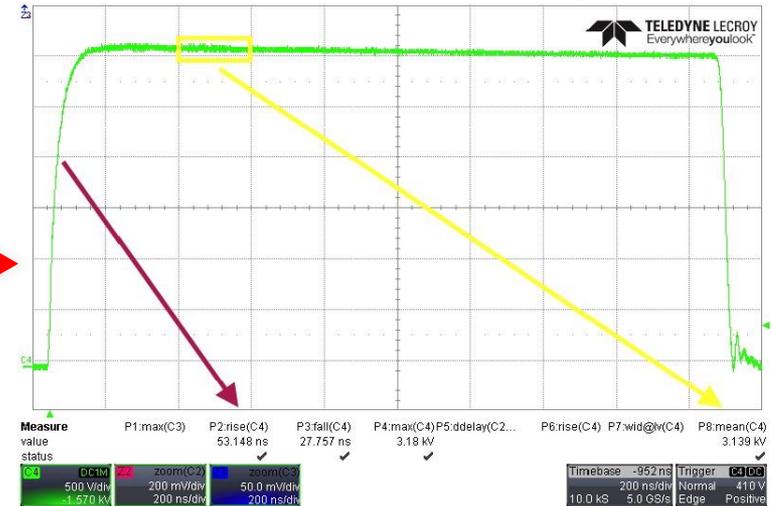
see talk of M. Barnes, "Marx prototype pulse generator design and initial results", FCC week 2018

Marx Prototype (4 stages)

Coaxial Marx layout



2.7 kA for a 3.2 kV pulse



Operating conditions:

$U_{dc}=800V$, $R=4\Omega$ // 4

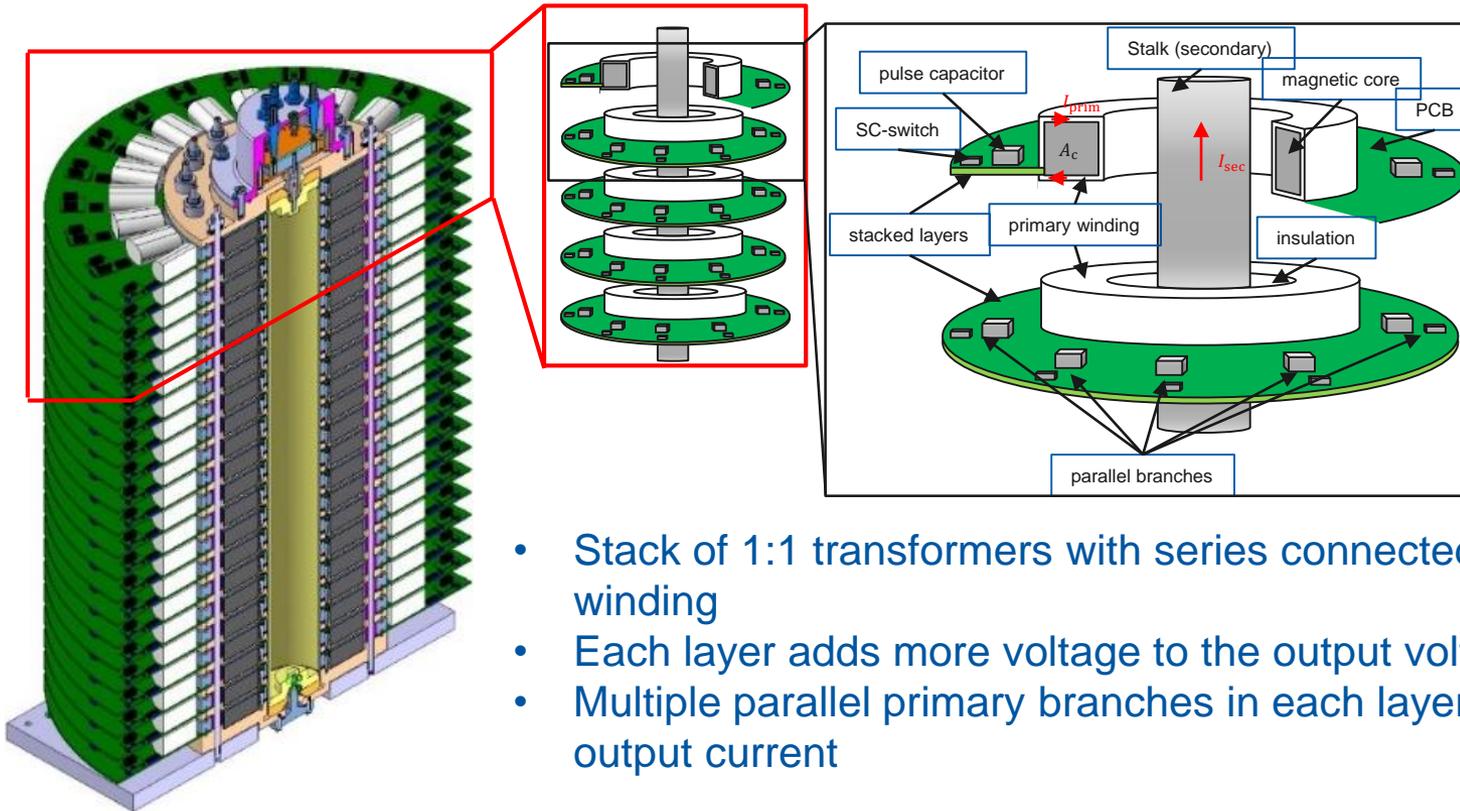
- **tr/tf** are **53ns** and **28ns** (10%-90%)
- Low droop (<0.5%)
- Circuit time constant of 24 ns
- Circuit inductance of about 28 nH (4 stages)

500 V/div, 200 ns/div

Next steps:

- Full scale prototype
- Performance validation
- Evaluation of behavior under fault conditions
- Novel droop compensation

Inductive adder



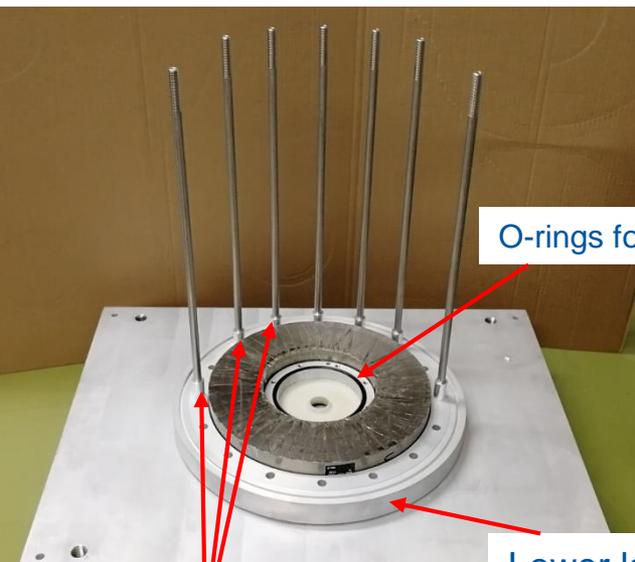
- Stack of 1:1 transformers with series connected secondary winding
- Each layer adds more voltage to the output voltage
- Multiple parallel primary branches in each layer provide the output current

- Modular & versatile concept
- Off the shelf switches and capacitors
- Potential replacement for thyratrons and SF6 filled PFL cables

For basic concepts see PRAB journal article "Future circular collider injection and extraction kicker topologies and solid state generators", accepted for publication, or talks of D. Woog, FCC week 2017 & 2018

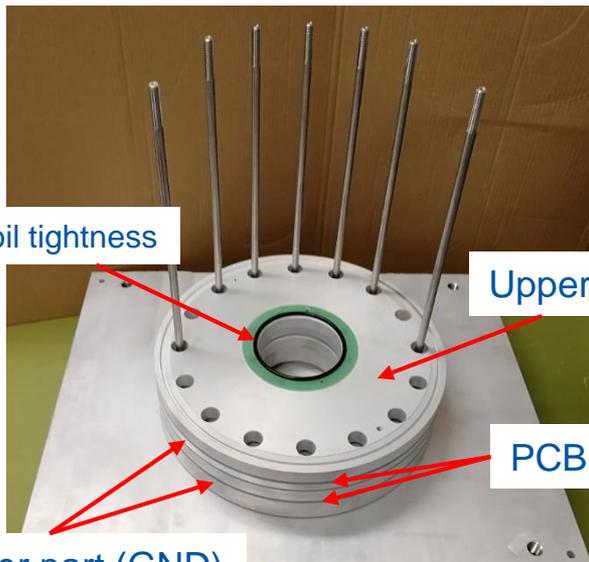
Prototype Hardware

Magnetic core of first layer

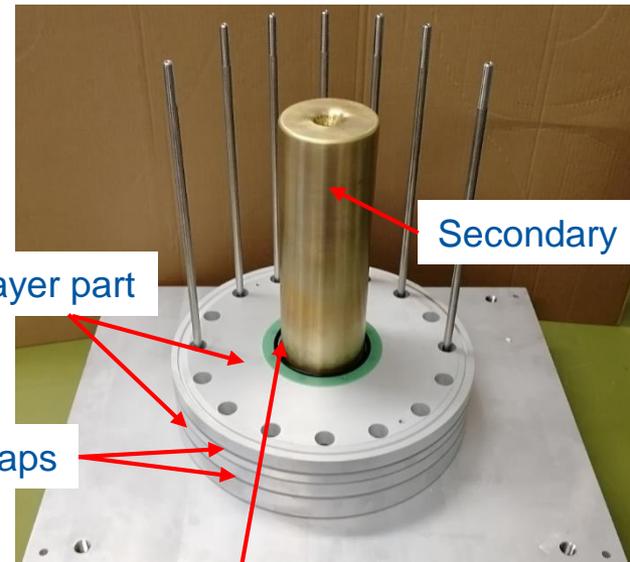


Conducting spacers
between layers

Two layers of the IA

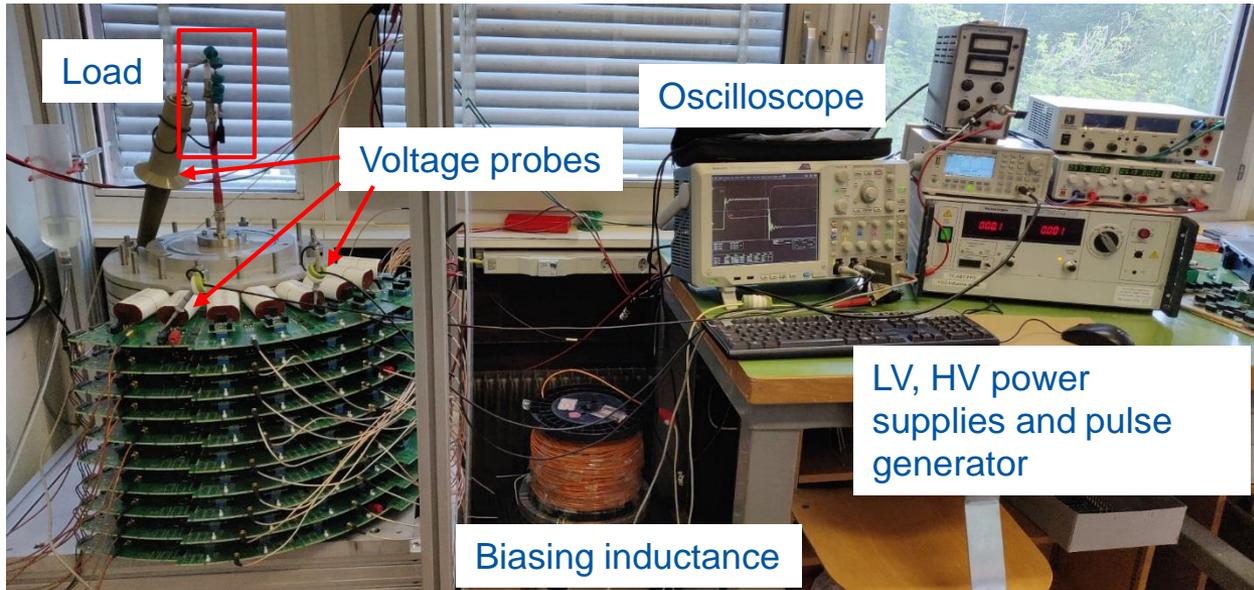


Two layers with secondary



Small Scale Prototype

Test bench of a 10 layer prototype with 8 parallel branches



Used for:

- Magnet core selection
- Validation of principle
- Biasing circuit development
- Cost & time saving electronics development

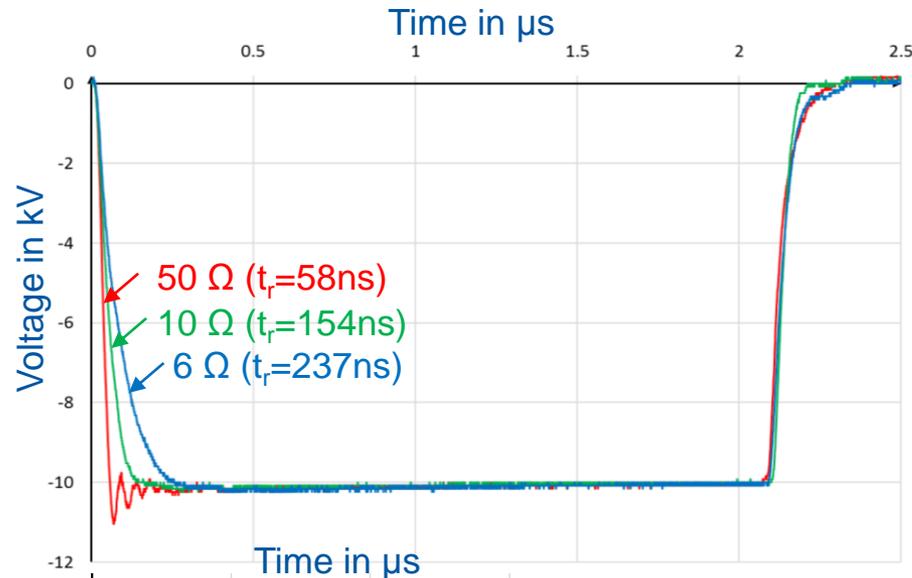
Most parts can be used for full scale prototype.

R2E aspects:

Assuming deployment in shielded gallery. R2E tests on SiC switches ongoing.

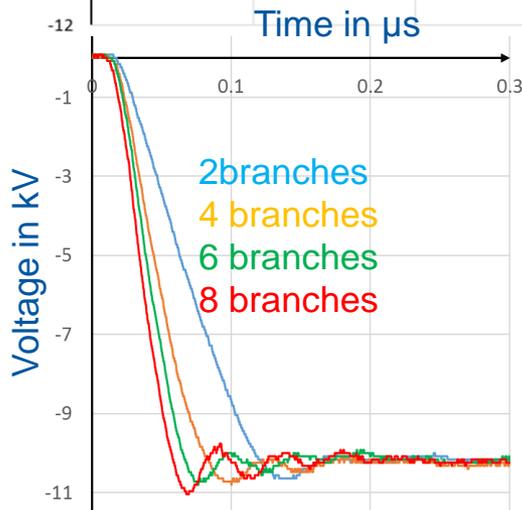
Small Scale Prototype

10 layer prototype waveform



Challenge: Rise time for low impedance

t_r for low Z will be reduced by increasing the number of parallel branches (from 8 to 24)



Rise time variation with different branches: Reduction of **primary inductance** reduces pulse rise time

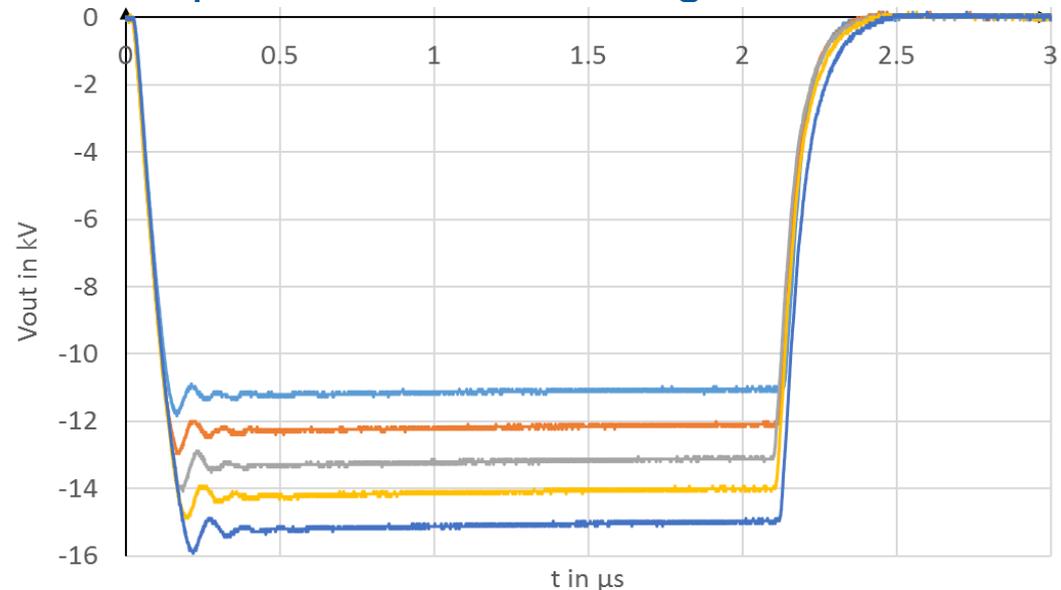
Full scale IA prototype



- 22 layers, assembly finished (just in time for FCC week)
- 1st HV output pulses generated @ low current
- **Meets voltage specifications**
 - But low impedance is challenging again (small insulation gap)

Next steps:

- Testing (to full performance) ongoing
- **Test Droop compensation**, modulation layers
- Short circuit protection to be designed



PhD thesis of D. Woog, to be published soon

Status & R&D plans

FCC-hh EXTRACTION & DILUTION KICKER

Extraction & Dilution Kicker

- **Highly segmented** extraction (150) and dilution kicker (30h/55v) system proposed
- **Extraction kicker:** Lumped inductance magnets with Ti coated chamber for impedance shielding, pre-charged capacitor (<6kV) to meet **tr of 1 μ s** (10% overshoot)
- **Dilution System:** 1.5m long lumped inductance magnet, inside vacuum. **Vertical** system more **challenging** due to larger aperture (12kV/16kA)

Extraction Kicker Requirements (CDR)

Extraction Kicker	Unit	Parameter
System Length	m	120
Number of Modules		150
max. BdL	Tm	7.5
Deflection	mrاد	0.045
Aperture height (h/v)	mm	50 /40
Module length	m	0.6
Inductance	nH	700
Current	kA	3.3
tr (0-100%; 10% OS)	μs	1
Voltage	kV	<6

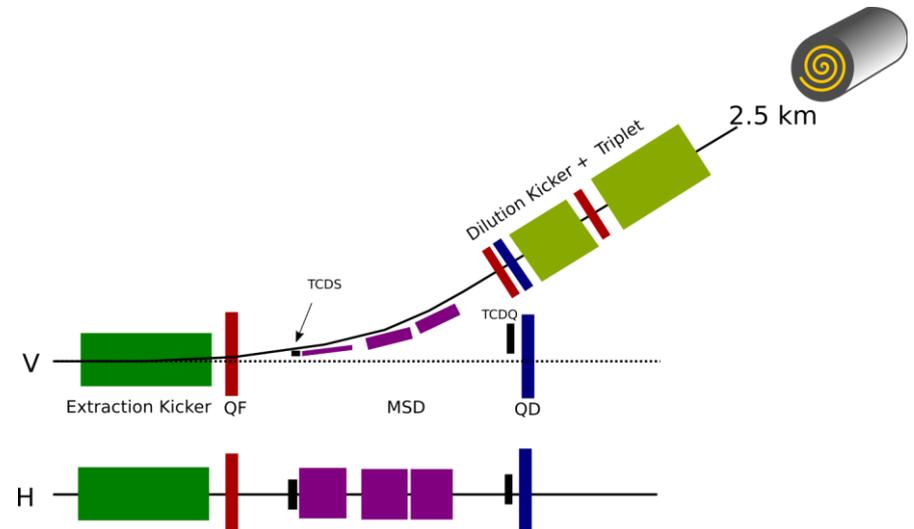
- **short magnets** (faster tr)
 - **smaller aperture** (higher field)
 - yields **high segmentation**
 - reduces prob. for asynch. dump due to relaxed requirements for pulse generators
- } compared with LHC

No dedicated R&D for hardware ongoing.

The hardware design however still needs to be studied in detail (beyond CDR).

Beam screen to be studied.

Prototype module to be foreseen for TDR.



see talk of A. Chmielinska, "Injection and Extraction Insertion", Tuesday

Dilution Kicker Requirements (CDR)

- 30 horizontal, 55 vertical kicker
- **50 kHz; constant frequency to meet dilution requirements**
- **Challenge: tolerances** – to keep dilution pattern
- **vertical system more challenging** due to large aperture (despite **focusing triplet structure**)

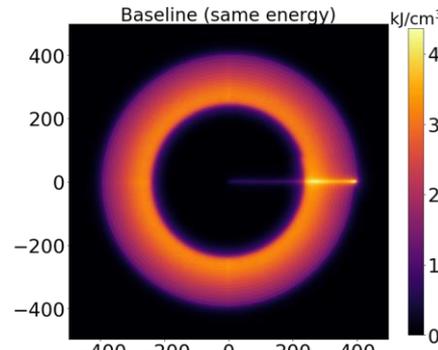
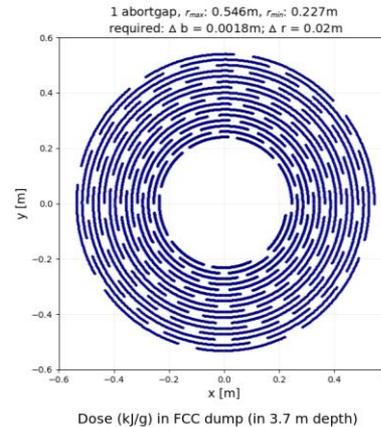


Figure courtesy: D. Barna



Dose (kJ/g) in FCC dump (in 3.7 m depth)

MKBV dilution system:

- Aperture w/h = 40/46 mm
- 110 m, 55 modules
- 12 kV, 16 kA

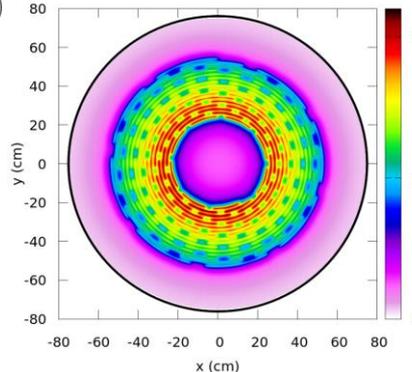
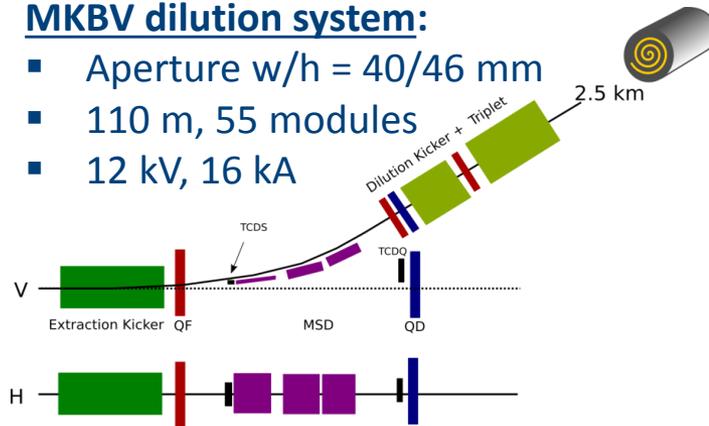


Figure courtesy: A. Lechner

	MKBH	MKBV
frequency [kHz]	50	50
tr [μs]	5	5
Installed L [m]	60	110
Gap field [T]	0.5	0.5
Modules	30	55
BdL [Tm]	22	42
gap height [m]	0.03	0.046
gap width [m]	0.03	0.04
Current [kA]	12	16
Voltage [kV]	8	12

No dedicated R&D for magnet.

The design of the generators however is challenging and will need to be addressed in more detail.

Studies on optimized dilution ongoing.

see poster of B. Facsko, D. Barna "Realization of the optimal beam dilution pattern of the FCC-hh ring using beating frequencies"

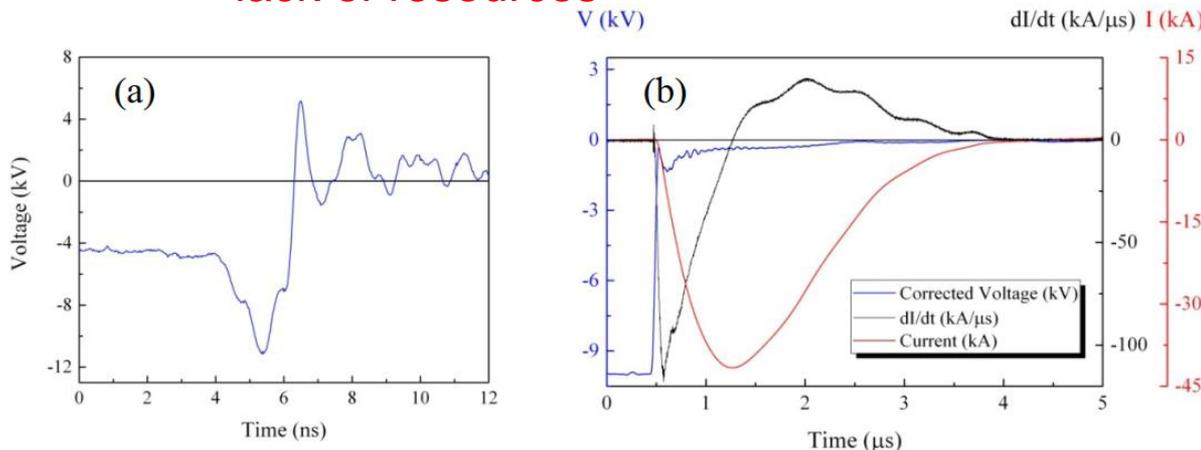
see talk of A. Lechner "FCC-hh dump", FCC week 2018

see talk of A. Chmielinska, "FCC-hh inj./extr.", FCC week 2019

Fast Switches

Impact ionization wave triggering

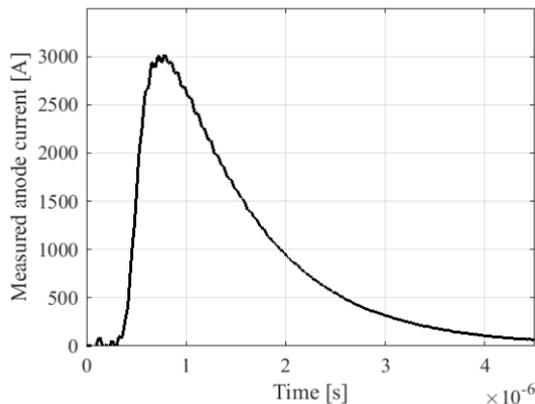
- Promising ultra fast triggering concept for thyristors
- Fast HV wave pushes thyristor into conduction
- Not in R&D plan but had the chance to performed feasibility test with 2 old LBDS GTOs at UB RAS, Ektarinburg
- Found fast di/dt , indeed non destructive, however circuit inductance limited rise time.
- Interesting topic & potential collaborator available
- But R&D currently not further followed due to
 - limited benefit for the systems as outlined in the CDR
 - lack of resources



See paper of Anton Gusev, Viliam Senaj "GTO Like Thyristors Triggered in Impact-Ionization Wave Mode", PPS conference 2019

Fast Switches- Laser triggering

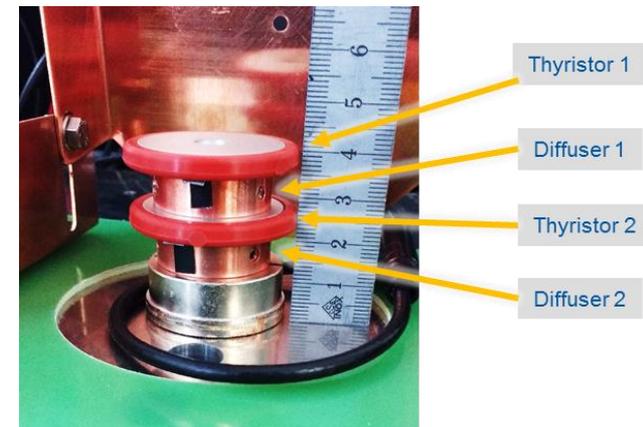
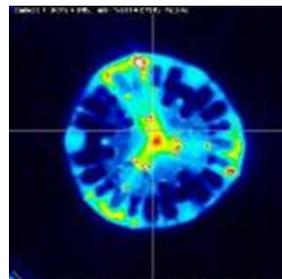
- Promising triggering technology (less turn on delay, higher di/dt , galvanic isolation)
- R&D ongoing, **established direct laser triggering test bench** at CERN
- Investigations of **local hot spots** occurring across the silicon wafer yielded significant **improvement of switching performance**
- With respect to the datasheet, the **di/dt** has been increased by a **factor of 40**, and the turn-on **delay reduced by a factor of 6**;
- **Proof of principle** done, but **more studies needed** to understand and define “feasible” specifications for industry.



Discharge current waveform obtained at the test bench. Test performed for Cdischarge initially charged to 4.8 kV and triggered with three laser sources



DYNEX DCR690G52



See talk of J. Rodziewicz, N. Magnin, “Laser Triggering of Thyristor Switches” FCC Week 2018 and EPE19 paper “Laser triggering of solid-state thyristors”, *tbp*

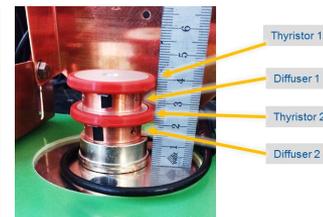
Summary

Substantial progress has been made in all work units with the delivery of the **CDR** content.

Despite LS2 the ST **R&D topics progressed very well**. Prototypes available, 2 PhD thesis + PRAB publication imminent.

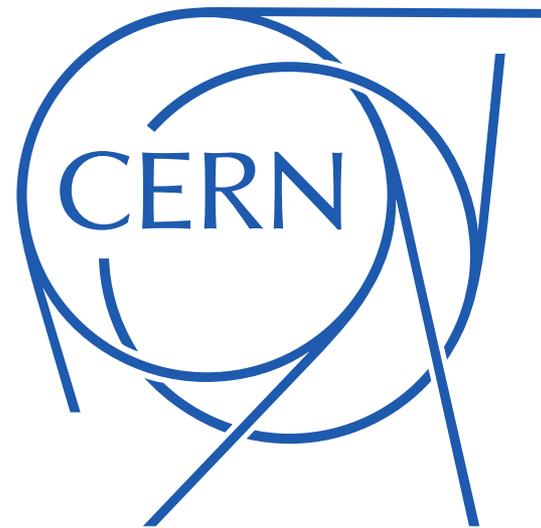
	Injection	Extraction	Dilution
Conceptual system design	CDR	CDR	CDR
Beam line hardware	R&D ongoing: <ul style="list-style-type: none"> Spiral beam screen 	CDR	CDR
Pulse generator hardware	R&D ongoing: <ul style="list-style-type: none"> Inductive Adder, Solid state MARX 	CDR	CDR

R&D ongoing: Laser triggering



Outlook

- Need to recover some momentum lost due to LS2.
- Continue ongoing R&D projects (need replacement of expiring contracts)
 - 1 PhD IA development
 - 1 FELL for detailed magnet, beam screen & pulse generator design
 - Possible collaboration for IA and dilution generators under consideration
- Long term plans:
Towards TDR design for injection & extraction kicker hardware
 - Prototype of 1 injection system module (beam screen + magnet + pulse generator for TDR design validation)
 - Prototype of extraction & dilution kicker pulse generator for validation of critical design



Thanks for your attention!