Semiconductor Switch Designs

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Acknowledgements
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FCC week, 23th-27th March 2015

Outline

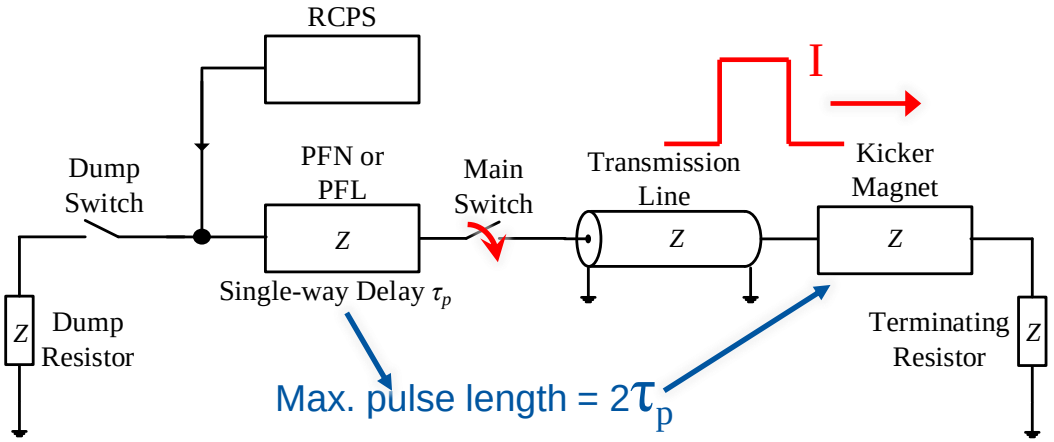
- Requirements for FCC injection kickers;
- An existing kicker system at CERN;
- The need for developments of semiconductor (solid-state) switches;
- Possible semiconductor switch topologies for injection;
- Requirements for FCC extraction (dump) kickers;
- Possible semiconductor switch topologies for extraction;
- Other R&D required;
- Timeline and tasks for R&D;
- Summary.

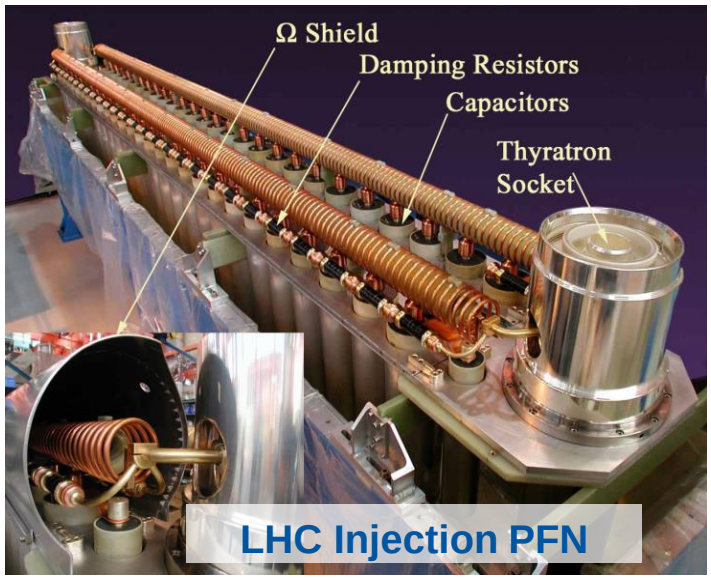
FCC injection kicker system requirements

		FCC Injection
Magnet technology		Delay line
Kinetic Energy	TeV	*3.3*
Kick	mrad	*0.29*
B.dl	T.m	3.2
Aperture height	mm	18 + 17 = 35
Aperture width	mm	18 + 17 = 35
Field rise/fall time	**µs**	**0.28**
Field flattop length	µs	2.25
Field flattop ripple	**%**	±0.5
System impedance	Ω	5
Assumed system magnetic length	m	*~30*
Magnet current	**kA**	**~0.31 to ~3.1**
Pulse voltage range	**kV**	**1.8 to 18**
Approximate number of injection kicker systems		**40**

An existing kicker system at CERN

Line Type Modulator:

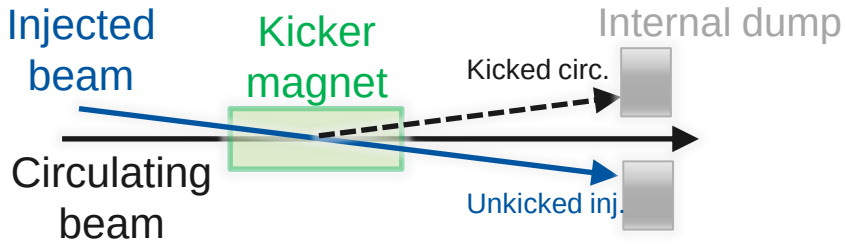




- In general, line type modulators are used with a main switch and a dump switch;
  - switch is typically a thyratron (**closing switch**);
- Impedance matched Pulse Forming Line/Network (PFL/PFN), to minimise reflections, but requires the PFL/PFN to be charged to **twice** the load **voltage**;
- **PFL** is probably most appropriate for FCC injection.

The need for new developments

Require a reliable kicker system, for FCC, to avoid mis-kicking beam:
BUT….



- Thyratrons:
  - **pre-fire** (self turn-on without a trigger signal) is a concern;
  - **long-term availability** is a real concern;
  - have limitations with regard to **dynamic range** and repetition rate;
  - is only a **closing** switch ⇨ need for PFN/PFL for energy storage.

Pulse Forming Line:

- **PFL** has **limitations**: it should be matched to the load **impedance**, but coaxial transmission lines are commercially available only with certain impedances;
- It is increasingly **difficult to source** coaxial transmission line for the highest voltage (~80 kV) kicker systems.

Suitable semiconductor switch topologies can help to solve the above problems.

Semiconductor Switches

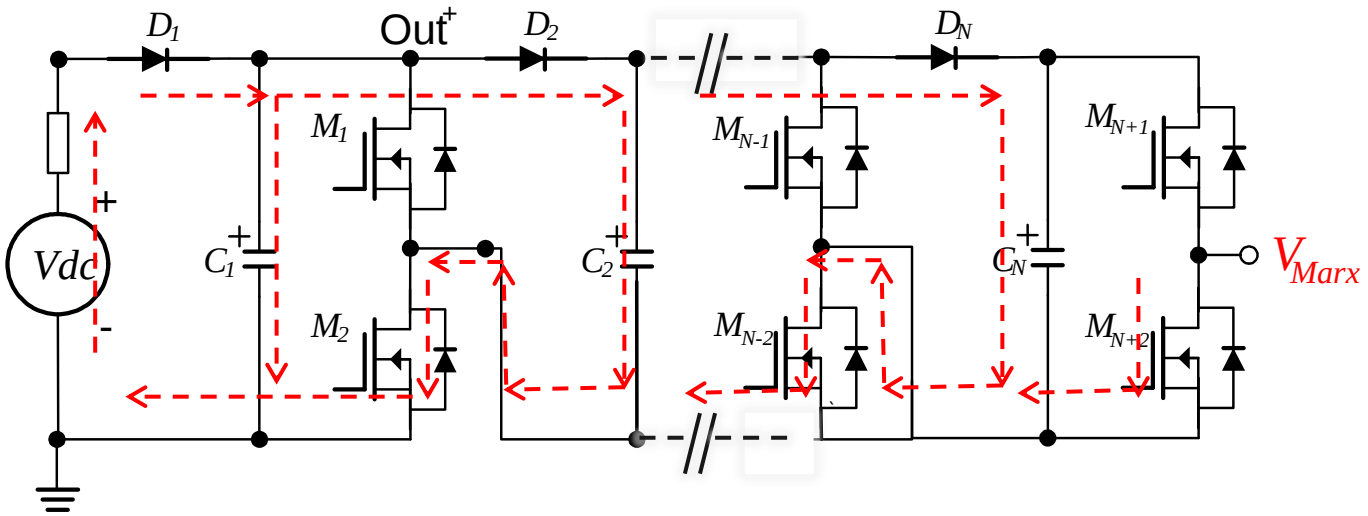
- Generally **reliable** and are **not prone to self-triggering**;
- Allow a wide **dynamic range** of operation;
- **Maintenance** is significantly reduced compared to gas switches;
- **Series** and **parallel** connection of **power semiconductor switches** can potentially achieve designs with very high pulse power.

- Examples of suitable switch technologies are:
  - Marx Generator;
  - Inductive Adder;

- Depending upon the switch technology, solid-state modulators can be **opened** when conducting full load current, hence;
  - only a portion of the **stored energy** is delivered to the load during the pulse (therefore a PFL or PFN is not required);
  - potentially limit **fault current** in the event of a magnet (load) electrical breakdown;
  - **source impedance** can be low, hence source voltage does not need to be doubled.

FCC Injection: Marx Generator

Operation: Capacitors charged in parallel (shown: even # switches on), and discharged in series (odd # switches on) ⇨ high voltage output.



- ✓ Low source **impedance**;
- ✓ **No output transformer** ⇨ maximum pulse length limited by capacitor values and load;
- ✓ **Modularity**: same design can be used for different voltage (and current) specifications;
- x Switches and control electronics are not referenced to ground;

An **international collaboration** has been proposed between CERN and ISEL, Portugal, to investigate Marx Generators as a potential replacement for thyratrons (in existing systems at CERN too).

FCC Injection: Inductive Adder

- Adder originally developed at SLAC/LLNL;
- Extremely **high precision** prototype built at CERN, for CLIC, based on MOSFETs (fast switching).

✓ **Modularity**: the same design can be used for different voltage and current specifications;

✓ **Short rise time** can be achieved (< 10 ns);

✓ Potentially interesting for **consolidation** of existing (short pulse) systems too;

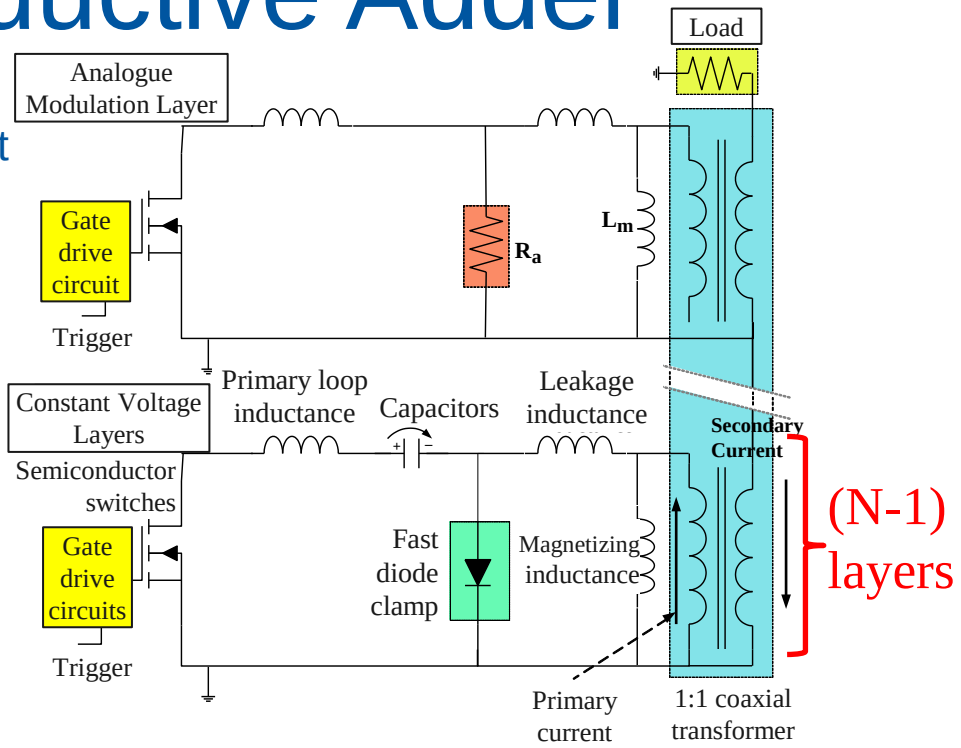
✓ Switches and control electronics are referenced to ground;

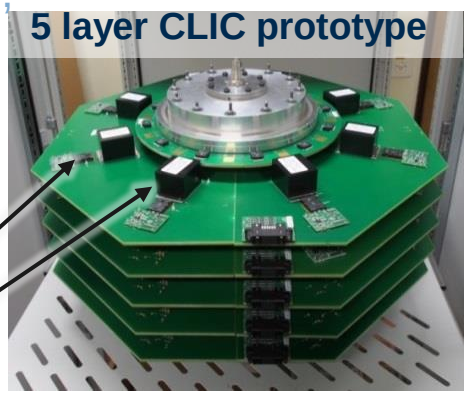
✓ Promising technology for **FCC injection**;

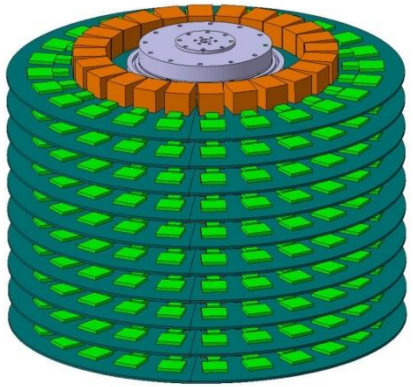
✓ Output pulse voltage can be **modulated**;

✓ **Redundancy** easy to build-in;

X **Output transformer** ⇨ maximum pulse length limited to typically ~3 µs;





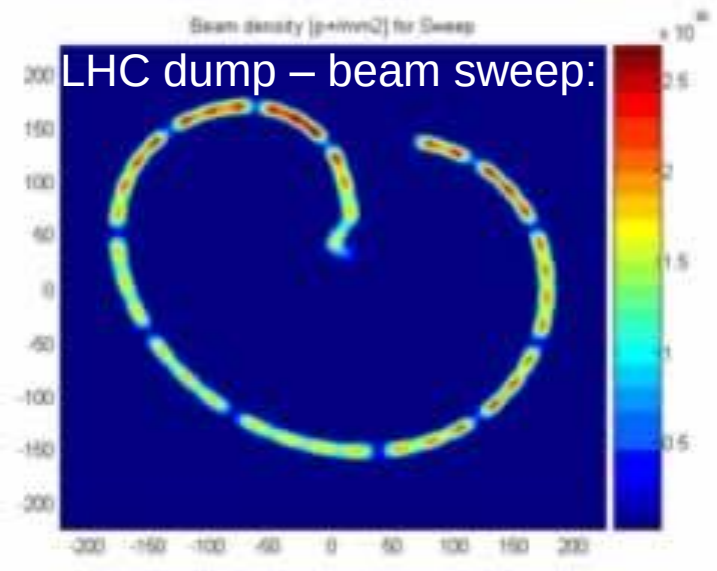


FCC extraction kicker system requirements

		FCC Extraction
Magnet technology		Lumped inductance
Kinetic Energy	**TeV**	***3.3 to 50***
Kick	mrad	*0.15*
B.dl	T.m	1.6 to 25
Aperture height	mm	36
Aperture width	mm	36
Field rise/fall time	**µs**	≤3
Field flattop length	**µs**	**350**
Field flattop ripple	**%**	10
System impedance	Ω	
Assumed system magnetic length	m	*~90*
Magnet current	**kA·Turns**	**~0.55 to ~8.3**
Output pulse voltage range	**kV**	
Approximate number of extraction kicker systems		**300**

Existing LHC Extraction System

- Generator voltage must **track the beam energy** and have a low pre-fire rate.
- Gate Turn-Off Thyristor's, modified to be **fast turn-on devices**, are connected in series ⇨ high di/dt;
- Allows a **wide dynamic range** of operation;
- Fourteen extraction kicker systems per beam:
  - for safety reasons, in case of pre-fire of one generator, all are triggered ⇨ asynchronous dump.
- Two parallel generators (**redundancy**).



- Voltage: 2.2kV – 30kV;
- Current: 1.3kA – 18.5kA;
- Current flat top: 95μs.

FCC Extraction System

System must be **ULTRA RELIABLE**

- Consider an **highly segmented** system:
  - hence pre-fire of one generator does unduly influence beam;
  - not necessary to trigger other generators ⇨ doesn't give an asynchronous dump;
  - redundancy..

Talk by W. Bartmann (Tuesday)

- Several switch topologies under investigation:
  - Scale **existing LHC extraction generator** for FCC (for segmented system ⇨ reduced current compared to LHC generator);
  - Brainstorming ⇨ idea based on an **opening semiconductor switch**:
    - switch is **normally closed** (conducting current) during inj. and ramp;
    - switch opened to switch off current and extract beam;
    - current proportional to kinetic energy of beam;
    - "fail safe" (no current ⇨ beam extracted);
    - **BUT high losses**, maybe superconductivity can be used???

Other R&D Required (Inj. & Ext.)

- **Study performance** of various semiconductors, e.g. SiC, MOSFETS, IGBTs, …. (now & 10-20 years time???);
- **Magnetic materials**;
- **Ultra reliable** triggering/controls;
- Other ideas for **switch topologies**;
- **Failure** mode analysis;
- **Redundancy;**
- **Fault tolerance**;
- **Reliability**;
- Possibility of locating generator in tunnel, under magnet;
  - Shielding of electronics;
  - **Radiation tolerant** components;
- Low source impedance may result in high fault current;
  - **Controls** must detect fault current and limit magnitude;
- **Triggering method(s)**, e.g. fibre optics;
- …….

Timeline and tasks

2015:

- **Task 1:** Complete proposal (objectives, timeline, identify lab space, secure resources, secure budget, and establish formal collaborations).
- **Task 2:** Study overall concepts and kicker system options, and define key parameters for FCC injection and/or extraction kicker generators.

2016 - 2017:

- **Task 3:** Test and select individual components (switches and magnetic materials for cores), design of the prototype for FCC injection. [collaborations sought]

2018:

- **Task 4:** Document results and **CDR write-up**.
- **Task 5:** Construct the prototype system (generator, transmission lines, load).

2019:

- **Task 6**: **Test the prototype**.

Note: timeline is dependent upon resources and budget availability…..

Collaborations very welcome!

Summary

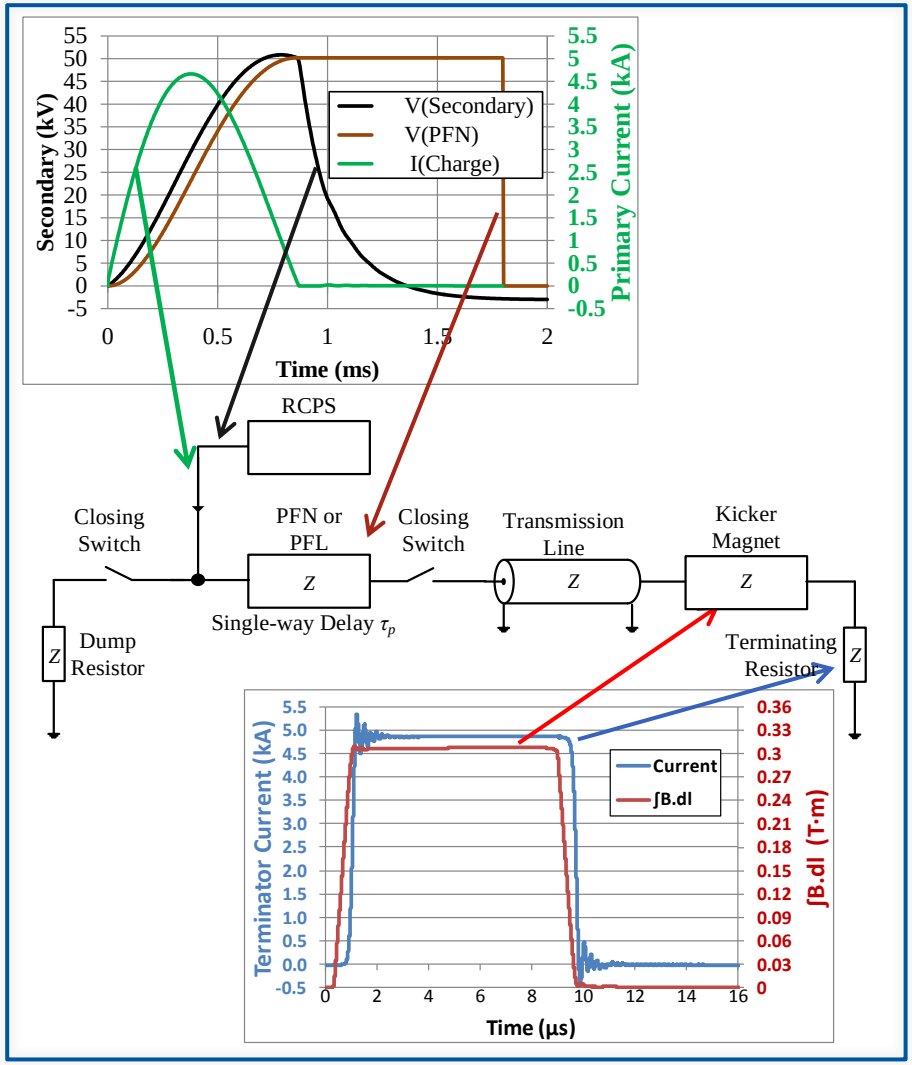
- Very **challenging** requirements;
- **High reliability** kicker systems are required for FCC;
- Parallel and series arrays of semiconductor switches are promising for both FCC and consolidation of existing kicker systems;
  - **eliminate pre-fire** associated with thyratrons;
  - eliminate need for very high voltage rating **coaxial cable**;
  - built in **redundancy**;
  - **modularity**.
- Closing and opening capability eliminates the need for a **PFL/PFN**;
  - Source impedance can be low, allowing a relatively small number of series connected power semiconductors. BUT requires a careful consideration of fault conditions;
- **Redundancy, fault tolerance, radiation tolerance**,…

Comments and suggestions are VERY welcome.

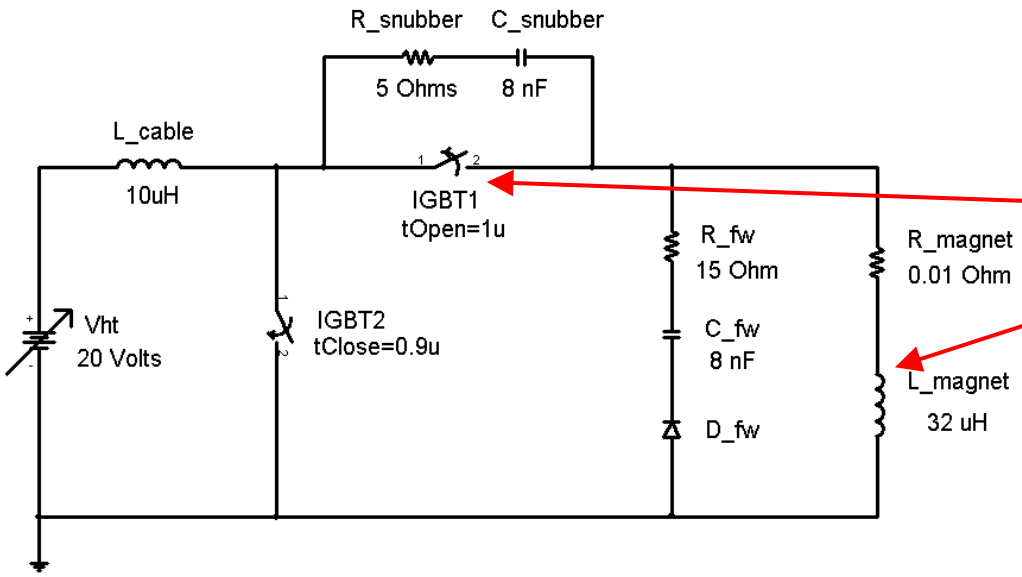
Thank you for your attention!

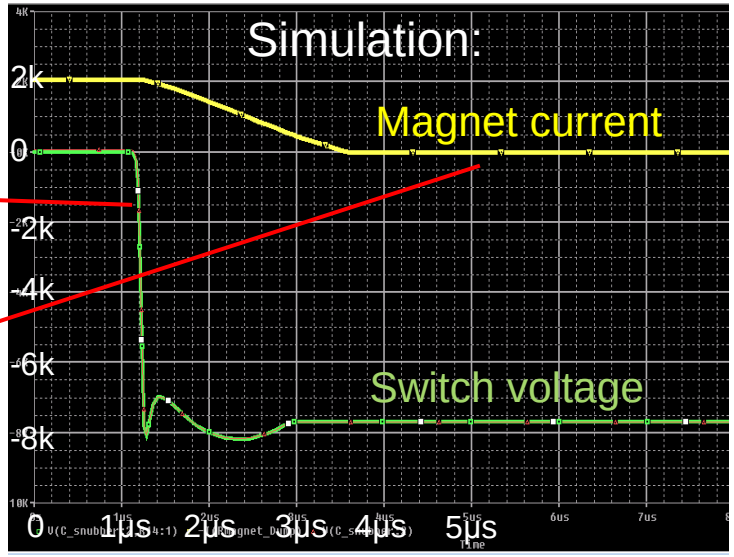
Spare Slides

Line type modulator example waveforms



FCC Extraction System: opening switch possibility





Example of normal and fault currents