ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

State-of-the-Art
Solid State Pulse Modulators

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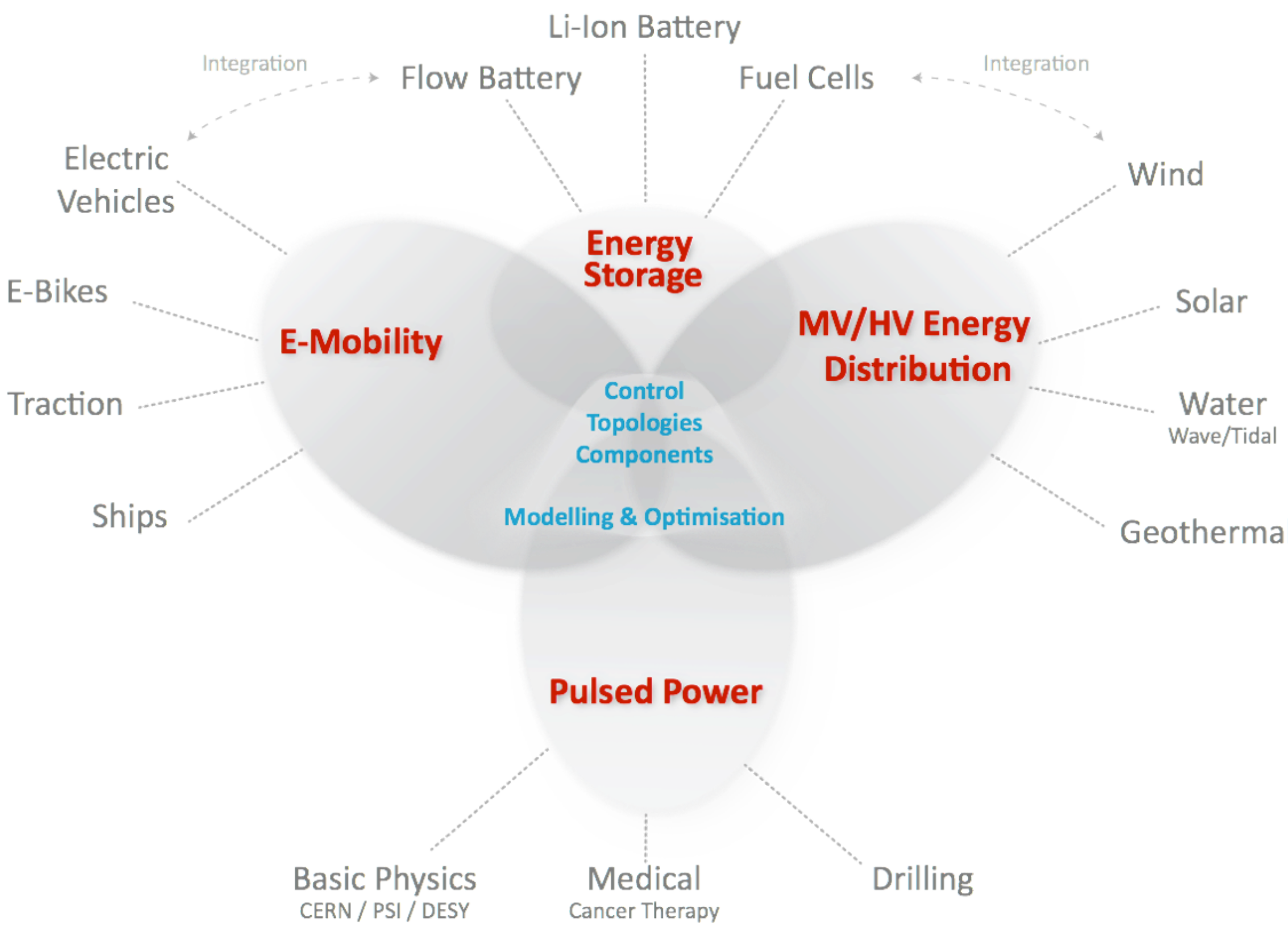
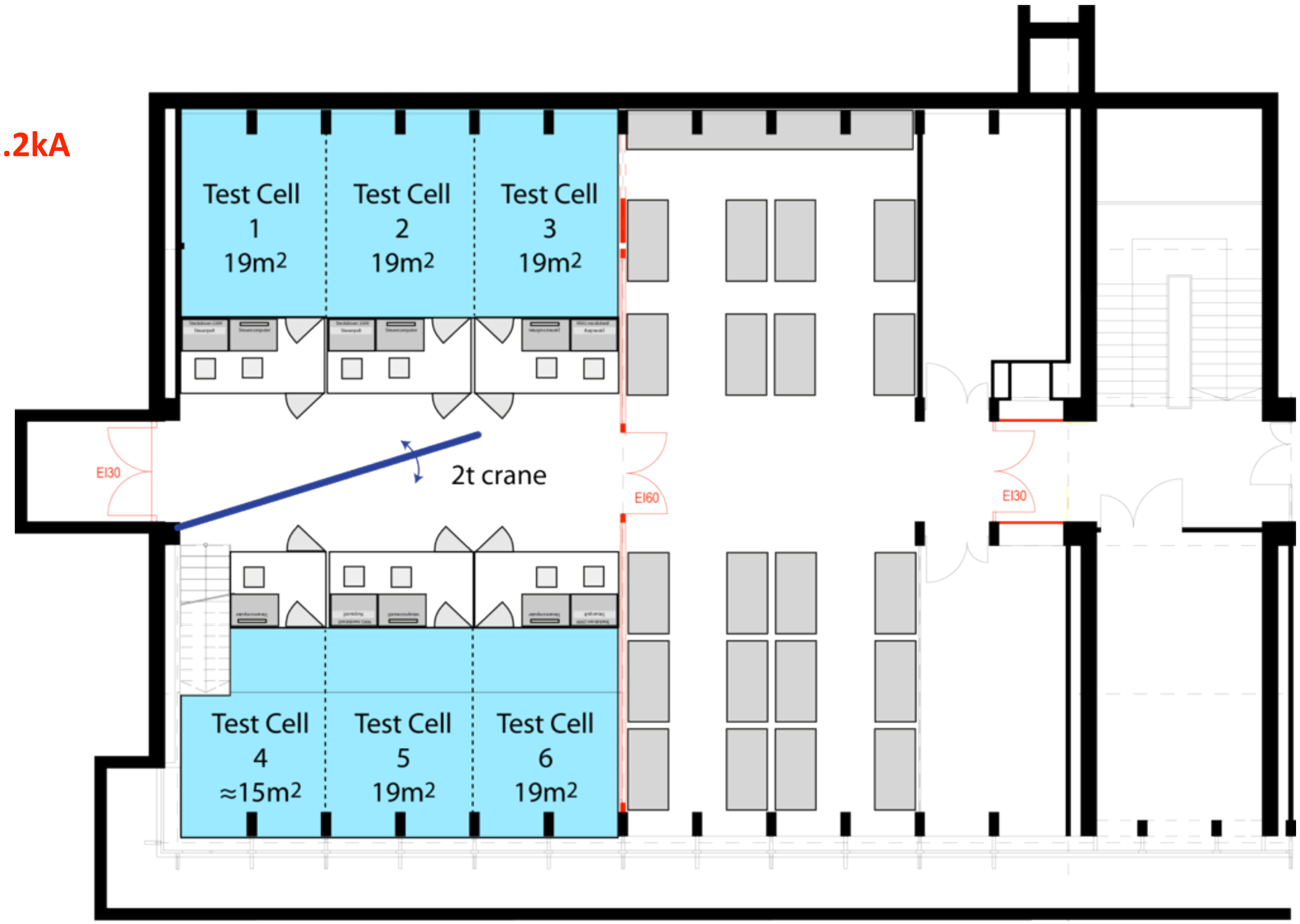
Focus Application Areas



High Power Laboratory - Facilities

- 3 Reconfigurable Faraday Test Cells
  3 Reconfigurable Fence-Test Cells
- Max. Cell Size: $57m^2$
- Sources:
  - 0..400V/800V 250kVA
  - 0..25kV_{AC} 250kVA
  - 0..35kV_{DC} 250kW
  - 0..2kV_{DC} 100kW /1.2kA (Bidirectional)
- 150kW Water Cooling
- 2 x 30kW Air Cooling
- 2t Crane



Pulse Modulator Basic Topologies

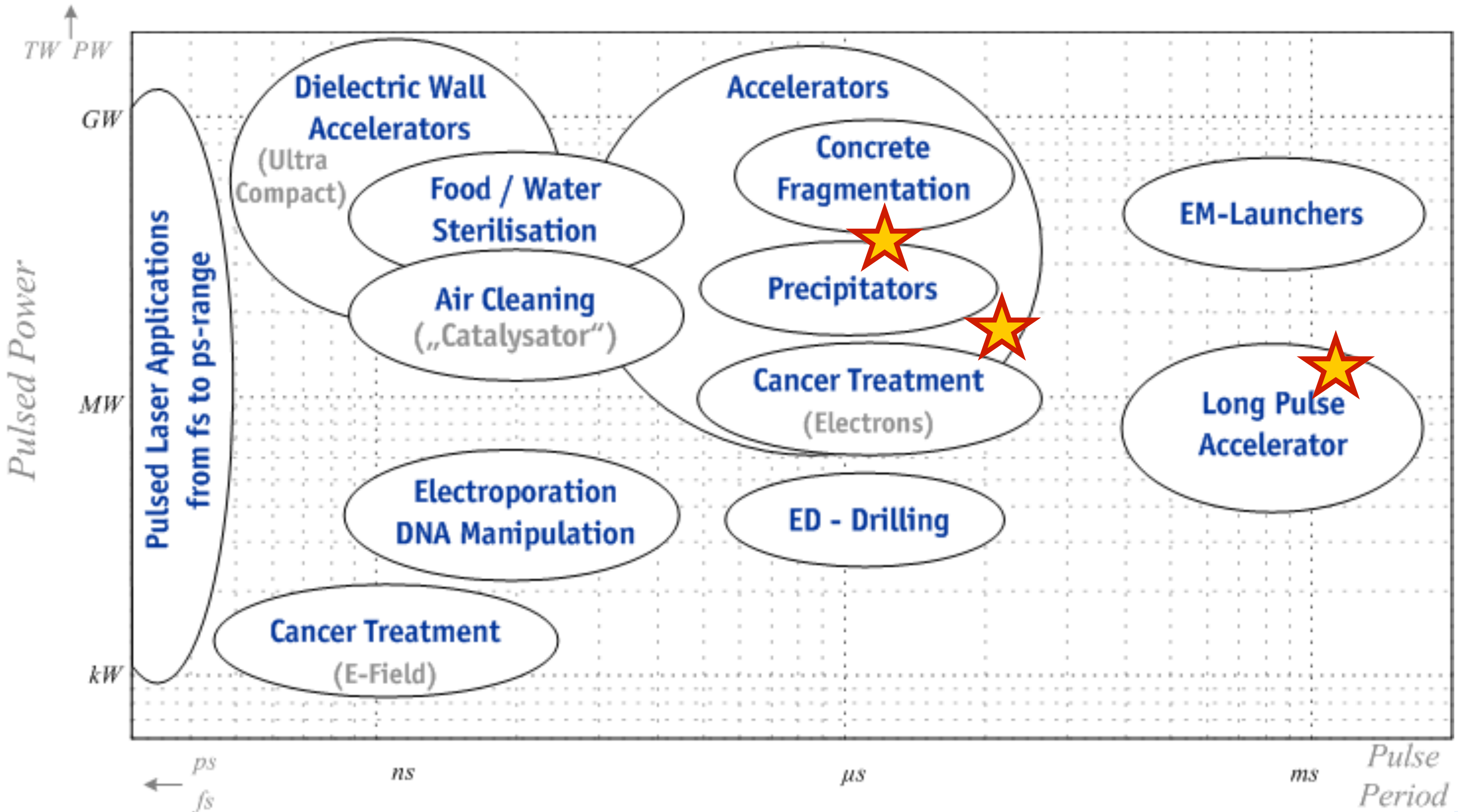
Pulsed Power / Pulse Length for typical Applications

1) Basic concepts
2) Short pulse modulator
- Matrix transformer
- Premagnetisation
- Bouncer / Gate unit
- Precise Charging

3) Mid range modulator
- Active bouncer

4) Long pulse modulator
- Basic concept
- Design of a module

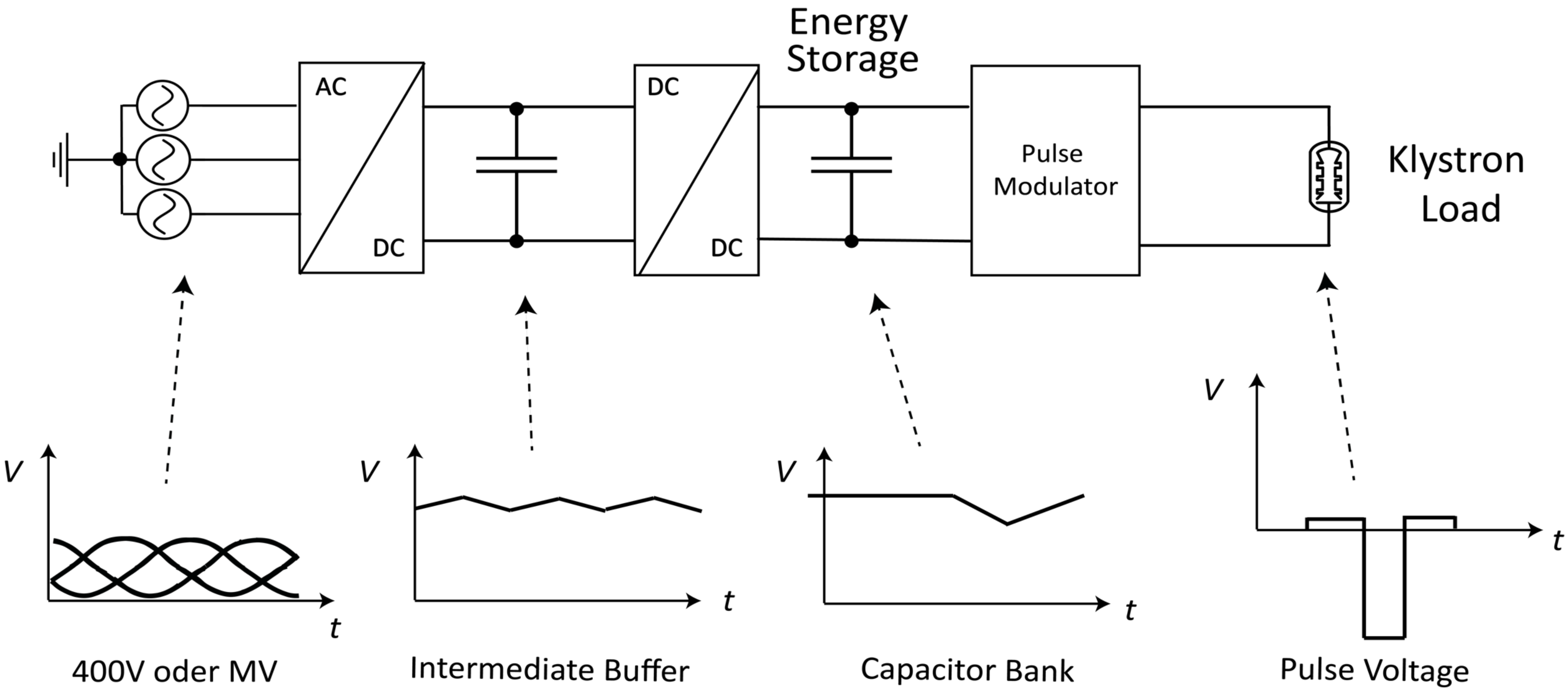
Collaboration:
- Ampegon, PPT, ABB, Lasslop
- PSI & CERN



Typical Topology of a Solid State Pulse Generator System

Typical topology of a solid state pulse modulator

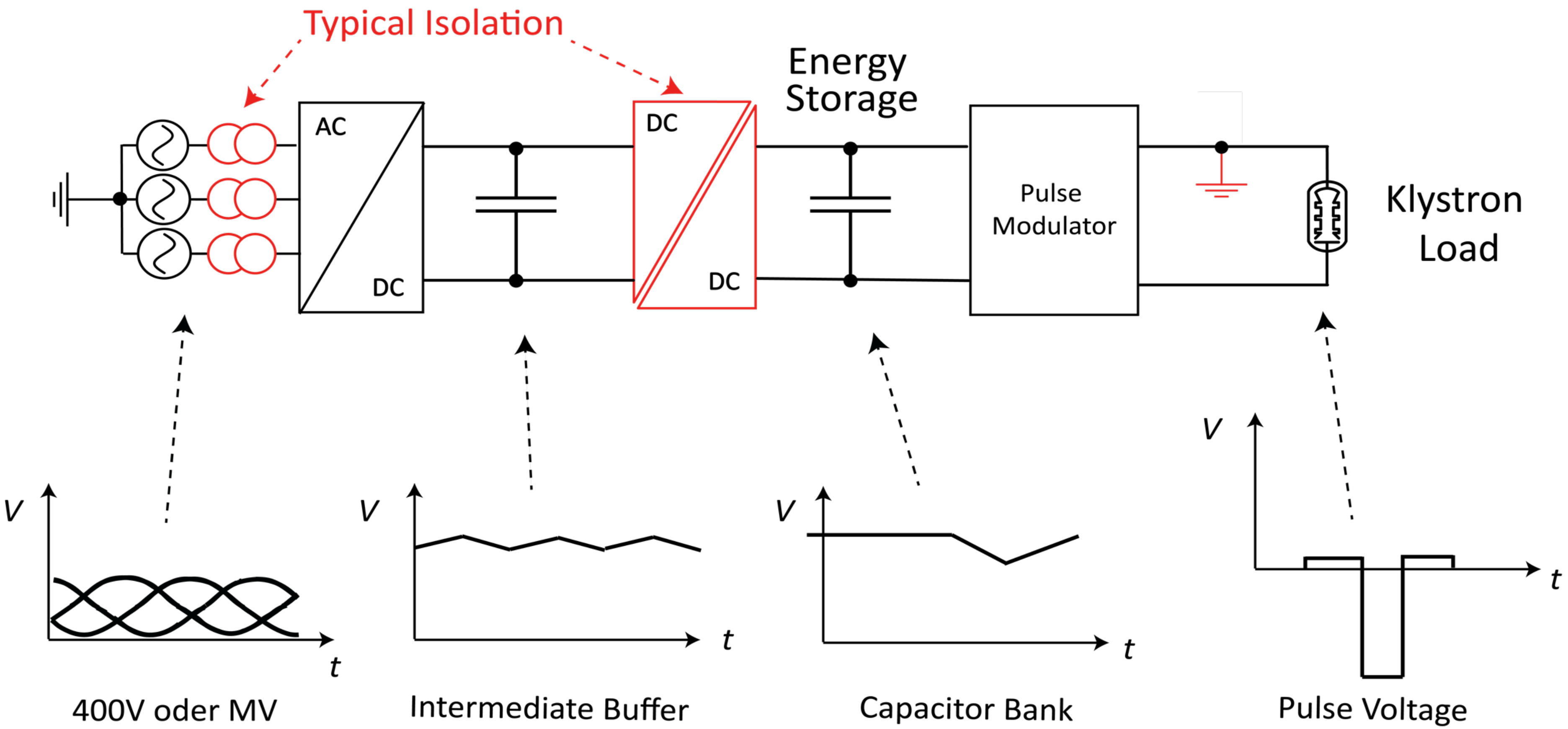
- AC/DC rectifier unit
- DC/DC converter for charging C-bank / voltage adaption
- Pulse generation unit
- Load e.g. klystron



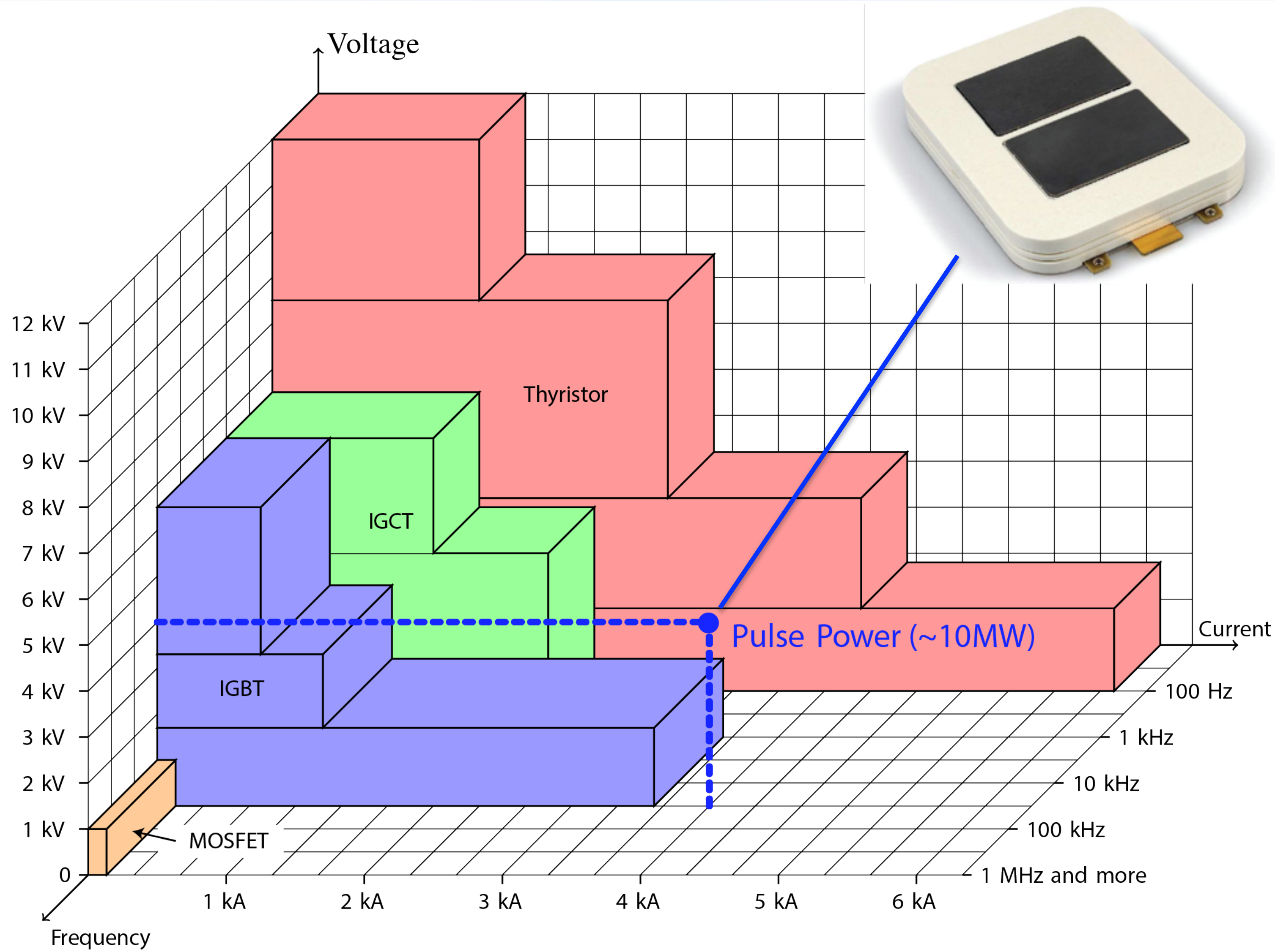
Typical Topology of a Solid State Pulse Generator System

Typical topology of a solid state pulse modulator

- **Isolation with 50Hz transformer or**
- **Isolated DC-DC converter**

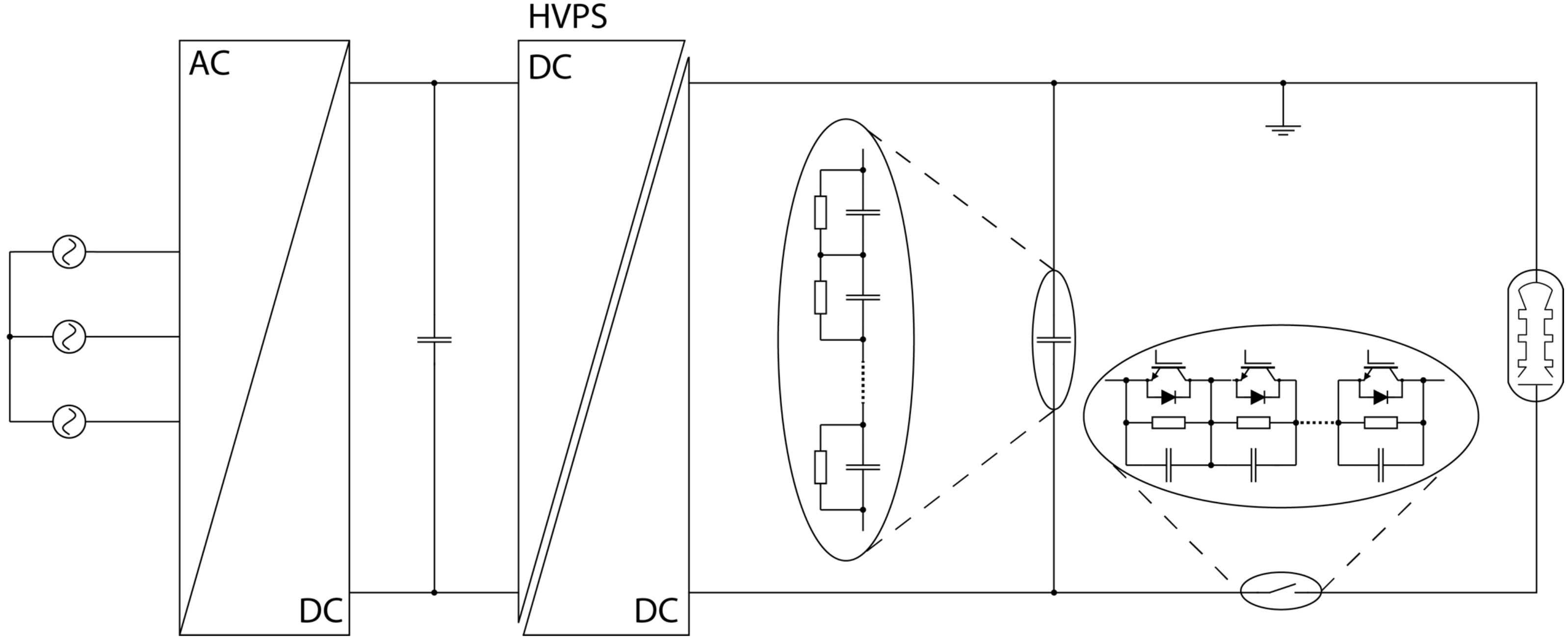


Solid State Switches



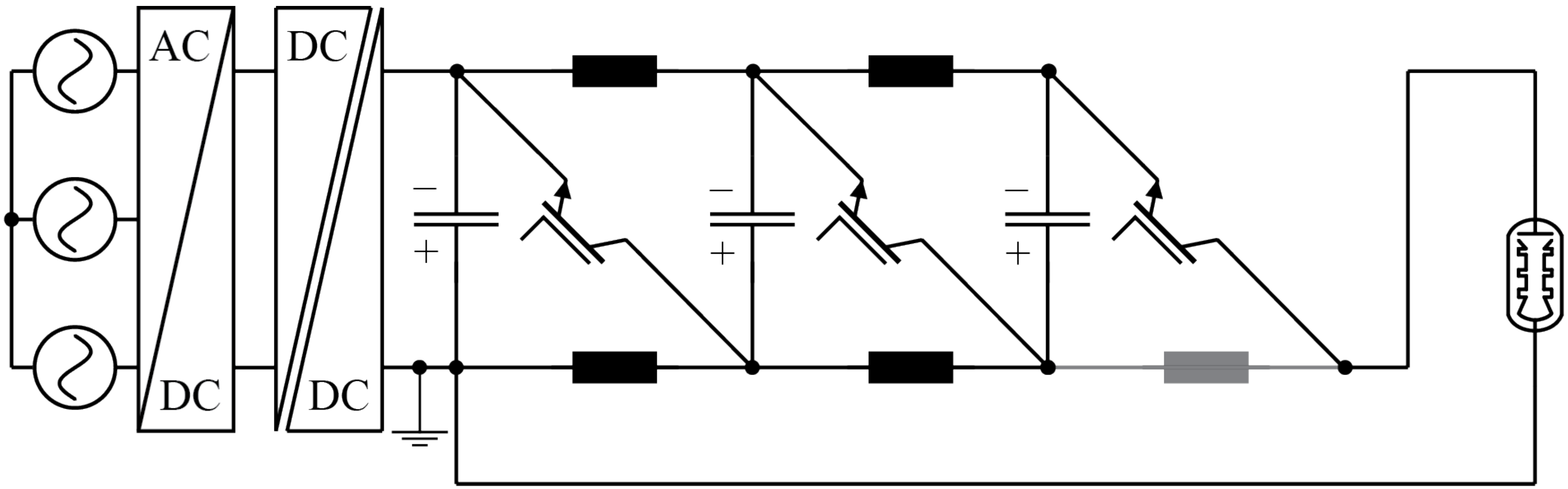
Modulator with High Voltage Switch

- **Simple concept, but high no of switches**
- **High voltage supply required**
- **Voltage balancing of switches required**
  - ➔ **Reduction of switch operating voltage**
  - ➔ **Additional losses (balancing circuit + high no of switches)**
  - ➔ **Parasitic oscillations possible**
- **Isolated gate-drives/supplies required**
- **Limitation of short circuit current is critical (*L* required)**
- **Switch needs to be synchronized**
- **Variable pulse length possible**



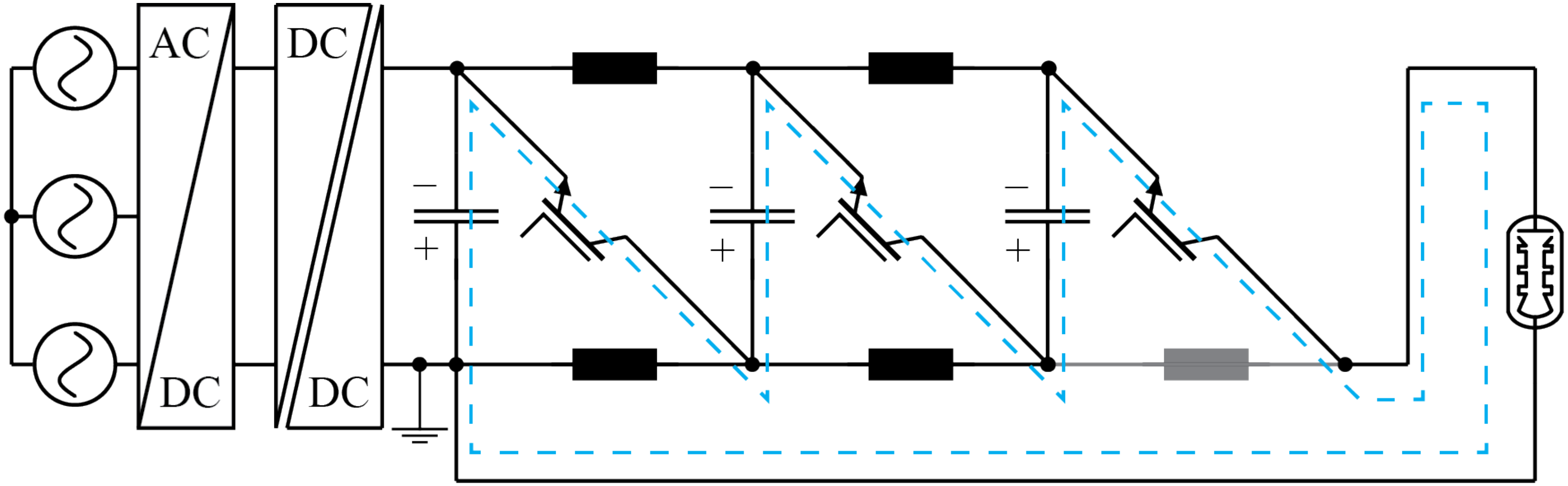
Modular: Marx-Type

- Voltage pulse by adding capacitor voltages
- Variable pulse voltage and arbitrary length possible
- Synchronous triggering of switches NOT required
  - ➔ Improved robustness
- Isolated gate-drives / gate-supplies



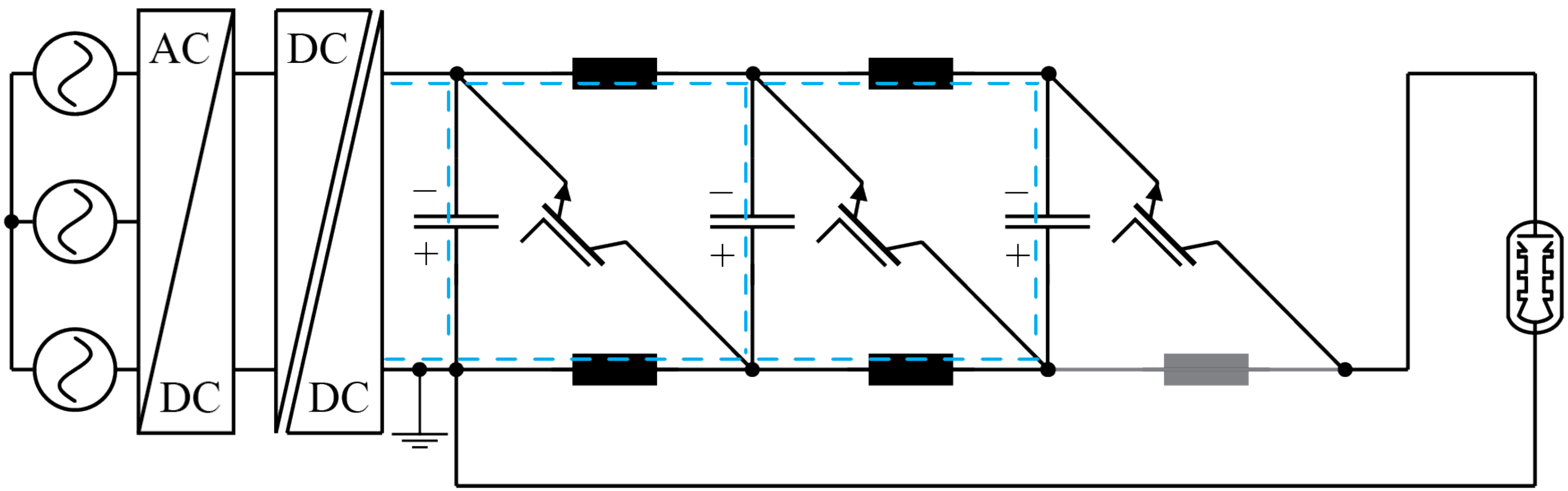
Modular: Marx-Type – Pulse Generation

- Voltage pulse by adding capacitor voltages
- Variable pulse voltage and arbitrary length possible
- Synchronous triggering of switches NOT required
  - ➔ Improved robustness
- Isolated gate-drives / gate-supplies
- Problem: Energy in case of short circuit (*L* required / bipolar Marx)



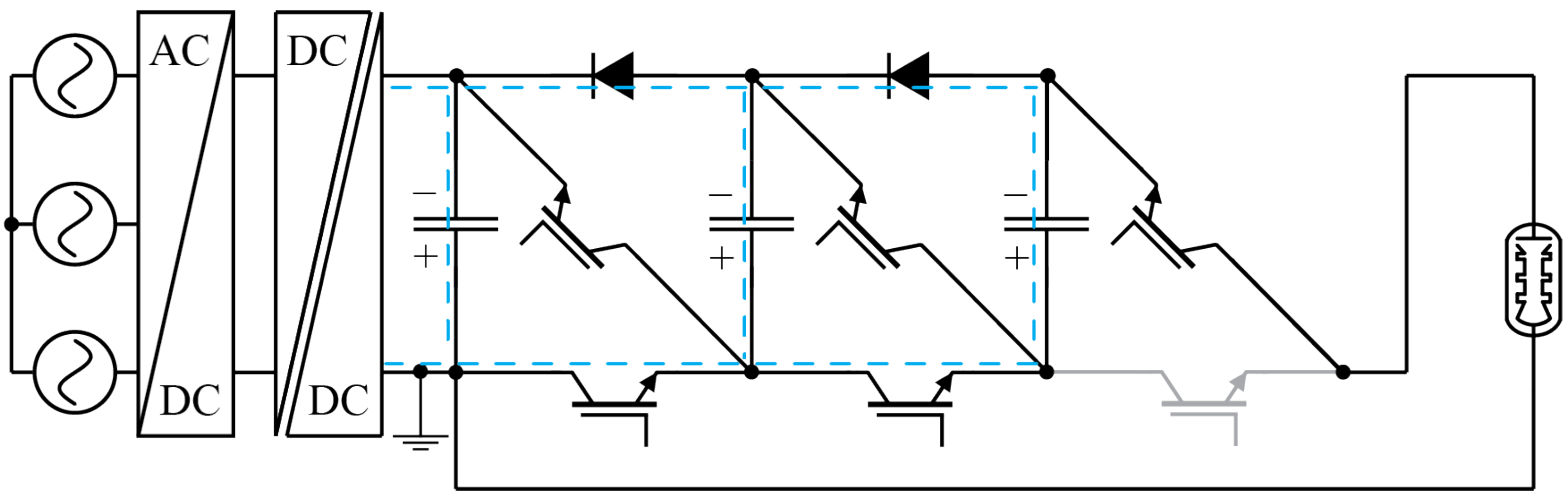
Modular: Marx-Type – Charging I

- **Voltage pulse by adding capacitor voltages**
- **Variable pulse voltage of arbitrary length possible**
- **Synchronous triggering of switches NOT required**
  - ➔ **Improved robustness**
- **Isolated gate-drives / gate-supplies**
- **Problem: Energy in case of short circuit (*L* required / bipolar Marx)**
- **Capacitor charging via resistor/inductor**
- **Parasitics ➔ Oscillations possible**



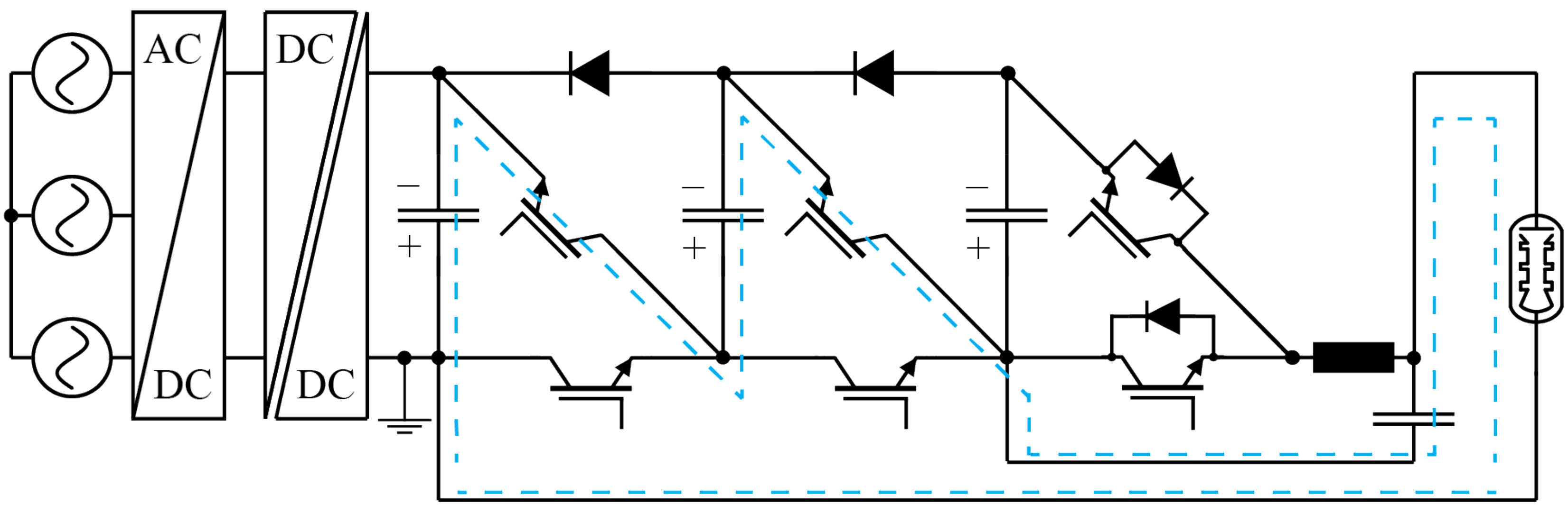
Modular: Marx-Type – Charging II

- Voltage pulse by adding capacitor voltages
- Variable pulse voltage of arbitrary length possible
- Synchronous triggering of switches NOT required
  ➔ Improved robustness
- Isolated gate-drives / gate-supplies
- Problem: Energy in case of short circuit (*L* required / bipolar Marx)
- Capacitor charging via resistor/inductor or switch/diode (➔ Long pulses)
- Parasitics ➔ Oscillations possible



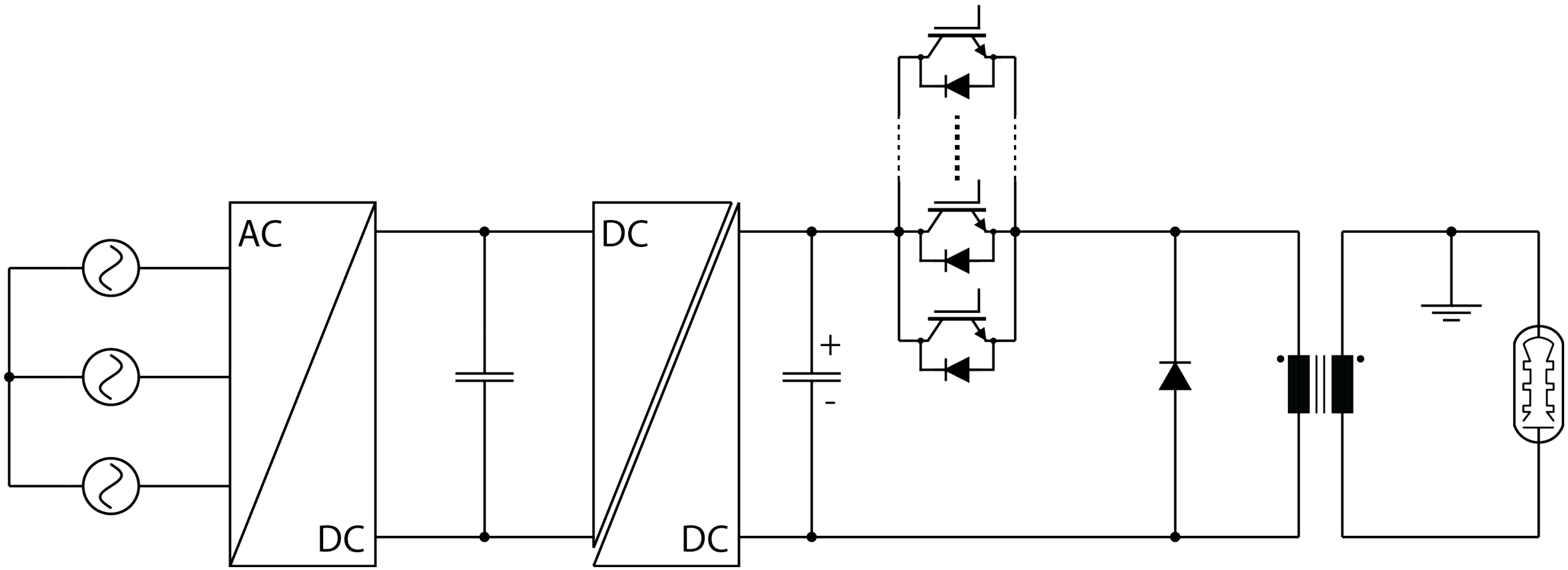
Modular: Marx-Type + PWM Cell

- Voltage pulse by adding capacitor voltages
- Variable pulse voltage of arbitrary length possible
- Synchronous triggering of switches NOT required
  - ➔ Improved robustness
  - ➔ Droop compensation / pulse shaping (PWM)
- Isolated gate-drives / gate-supplies
- Problem: Energy in case of short circuit (*L* required / bipolar Marx)
- Capacitor charging via resistor/inductor or switch/diode (➔ Long pulses)
- Parasitics ➔ Oscillations possible



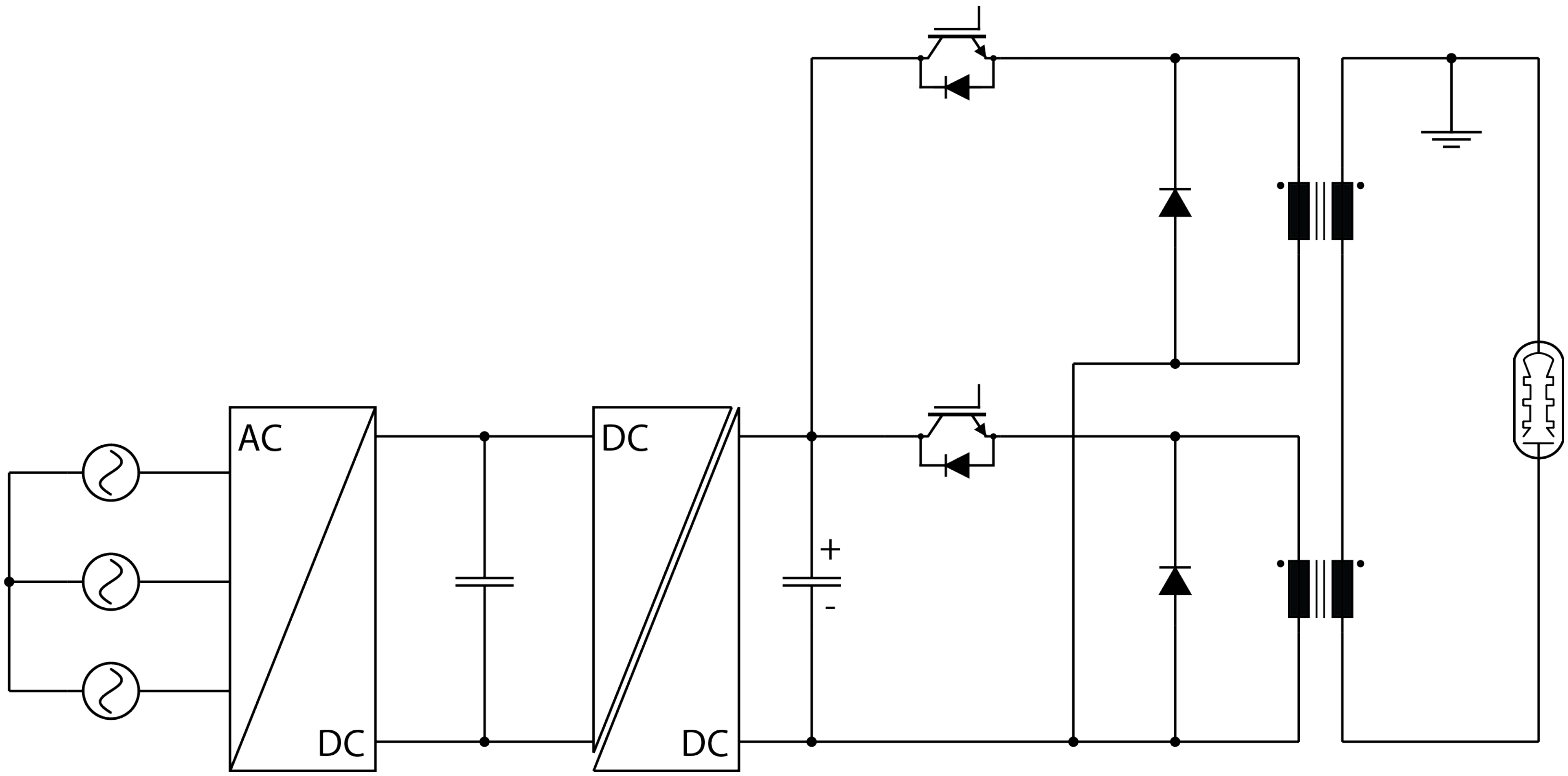
Pulse Transformer Based

- High pulse voltage is generated by transformer
- Adaption to switch operating voltage possible
- Series and/or parallel operation of switches
  - Series: Voltage balancing
  - Parallel: Current balancing
    - ➔ No of switches reduced
    - ➔ Separate gate drives
- Primary voltage does NOT influence pulse shape
- Pulse length is limited by transformer



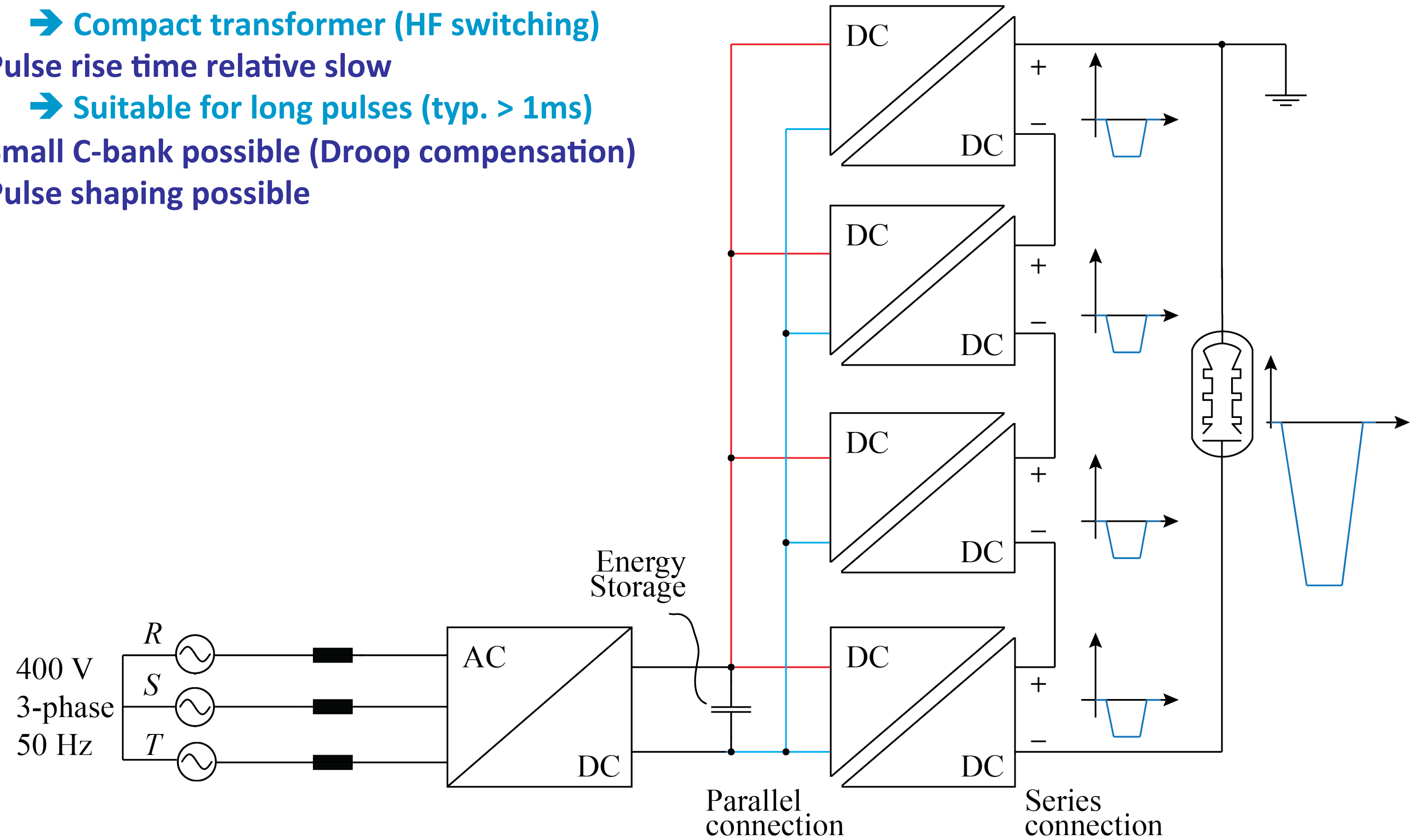
Pulse Transformer Based – Matrix Transformer

- **Separate windings/transformers per switch**
  - ➔ **Voltage/current balancing is achieved**
- **Name: *Split Core / Matrix Transformer / Inductive Adder*** **(same basic concept)**
  - ➔ **Further details: Later**



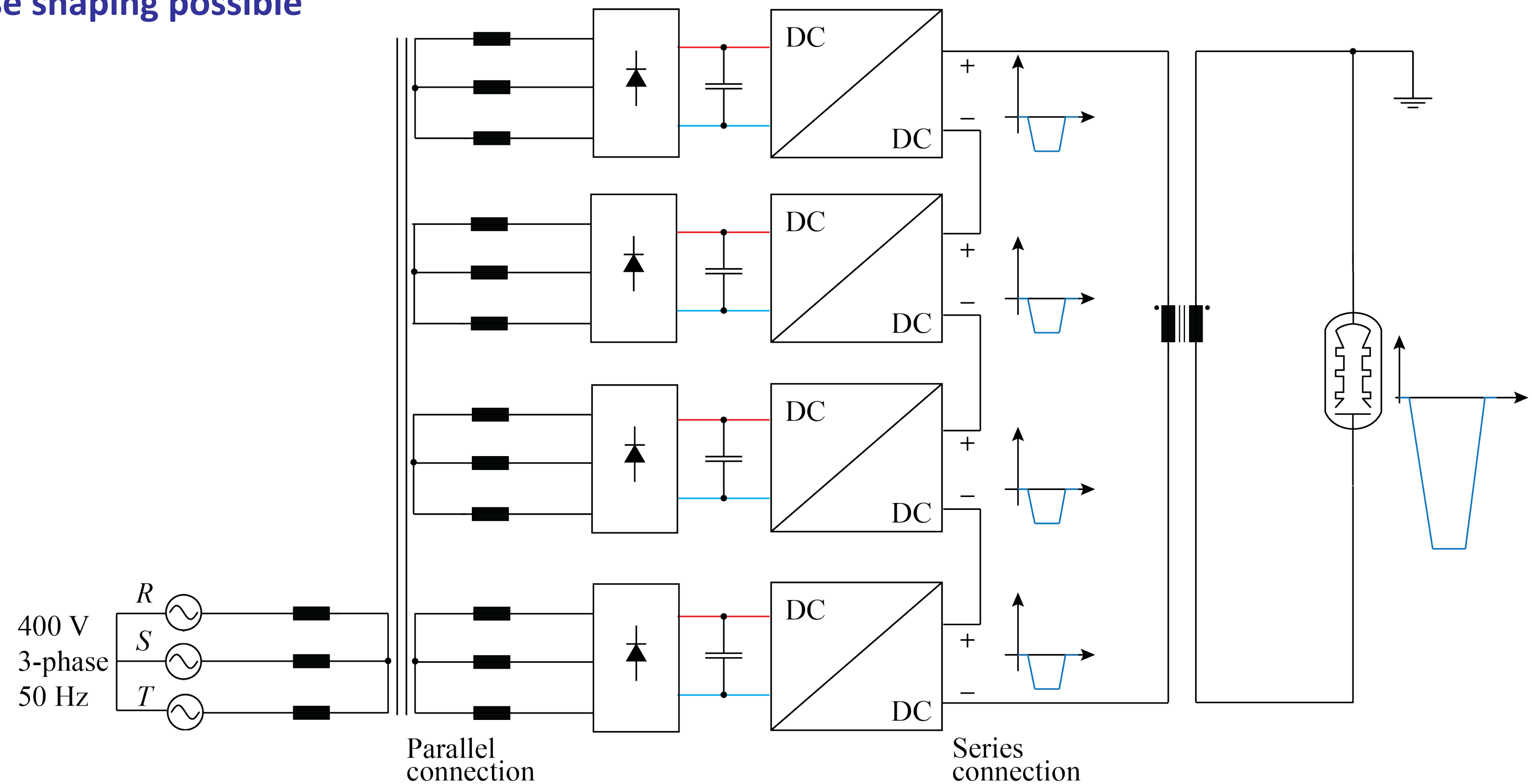
DC-DC Converter Based

- **Adding output voltage of isolated DC-DC converters**
  - **- Parallel in / seriel out**
  - **➔ Compact transformer (HF switching)**
- **Pulse rise time relative slow**
  - **➔ Suitable for long pulses (typ. > 1ms)**
- **Small C-bank possible (Droop compensation)**
- **Pulse shaping possible**



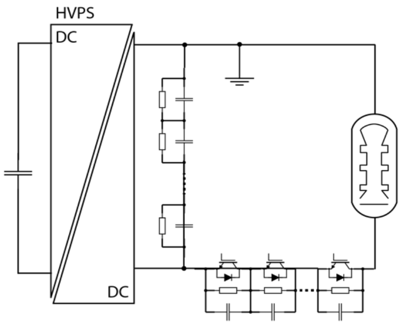
DC-DC Converter Based – PSM Modulator

- **Adding output voltage of non-isolated DC-DC converters**
  - ➔ **Generate primary voltage for transformer**
- **Pulse rise time relative slow**
  - ➔ **Suitable for long pulses (typ. > 1ms)**
- **Pulse length limited by pulse transformer**
- **Pulse shaping possible**

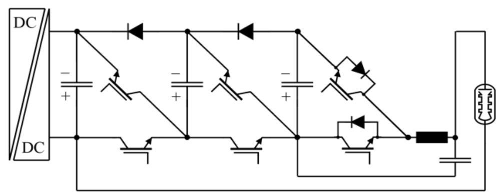


Topology Comparison

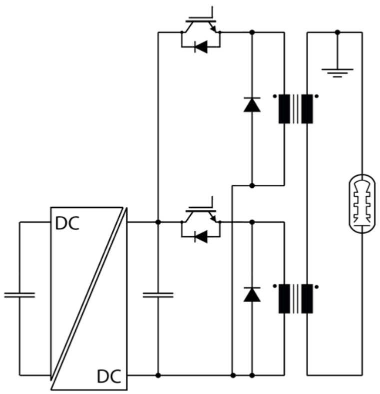
Direct Modulator



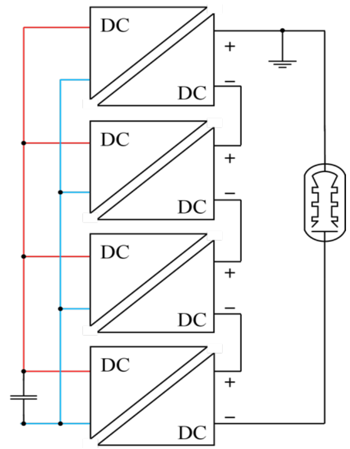
Marx Type



Matrix Pulse Trafo



DC-DC Converter



Transformer Based

Arbitrary Pulse Length

Arbitrary Length

Fast Rise Time

Inherent Short Circuit Current Limitation

Adaption to Switch Operation Voltage

Power Electronics on Low Voltage

No Sync of Semiconductors

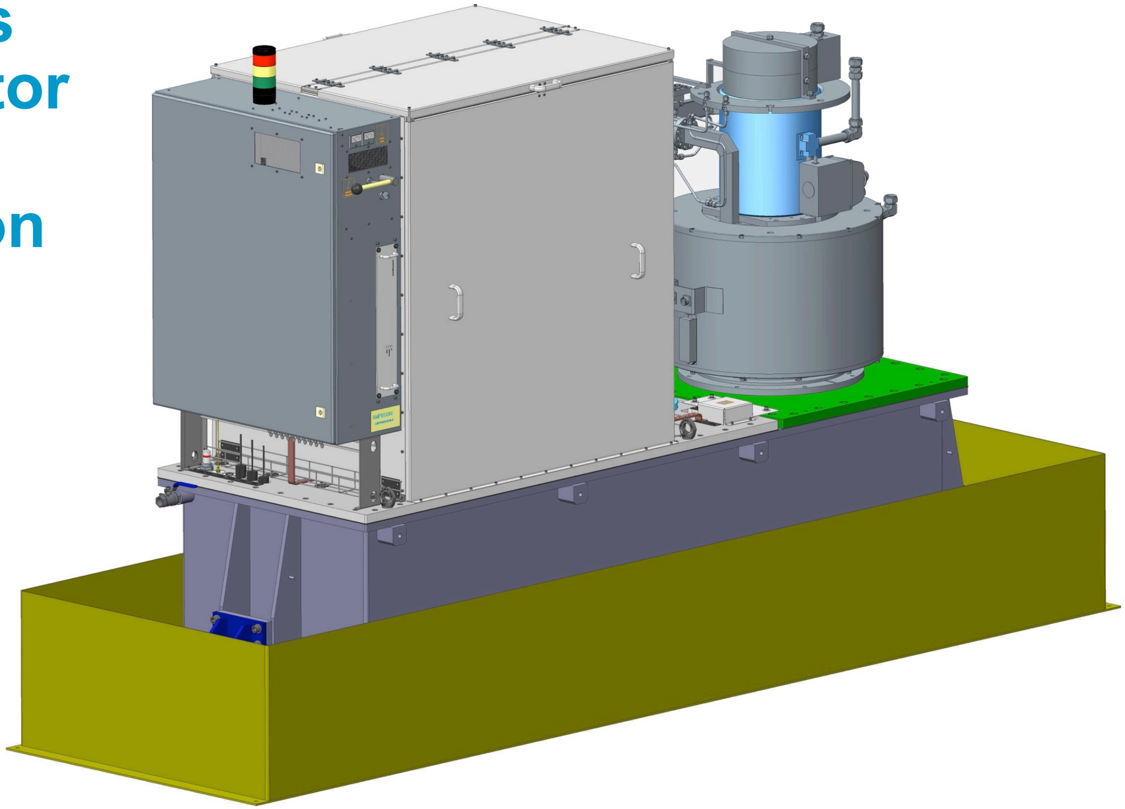
or Modules necessary

High number of Switches

High # of Switches

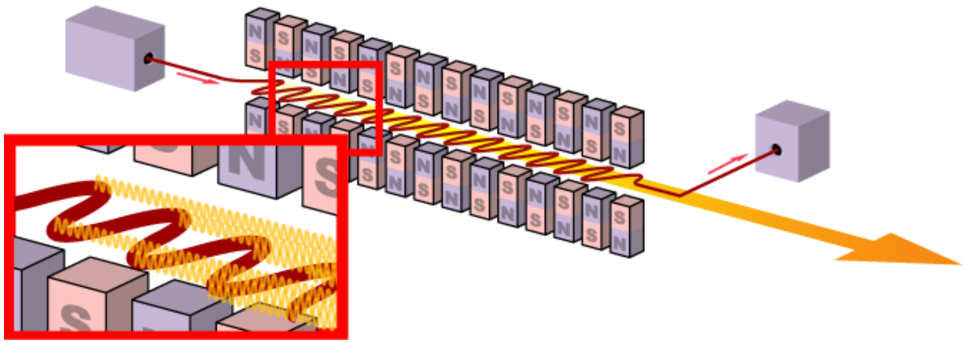
Short Pulse Modulator
(~ µs-range)

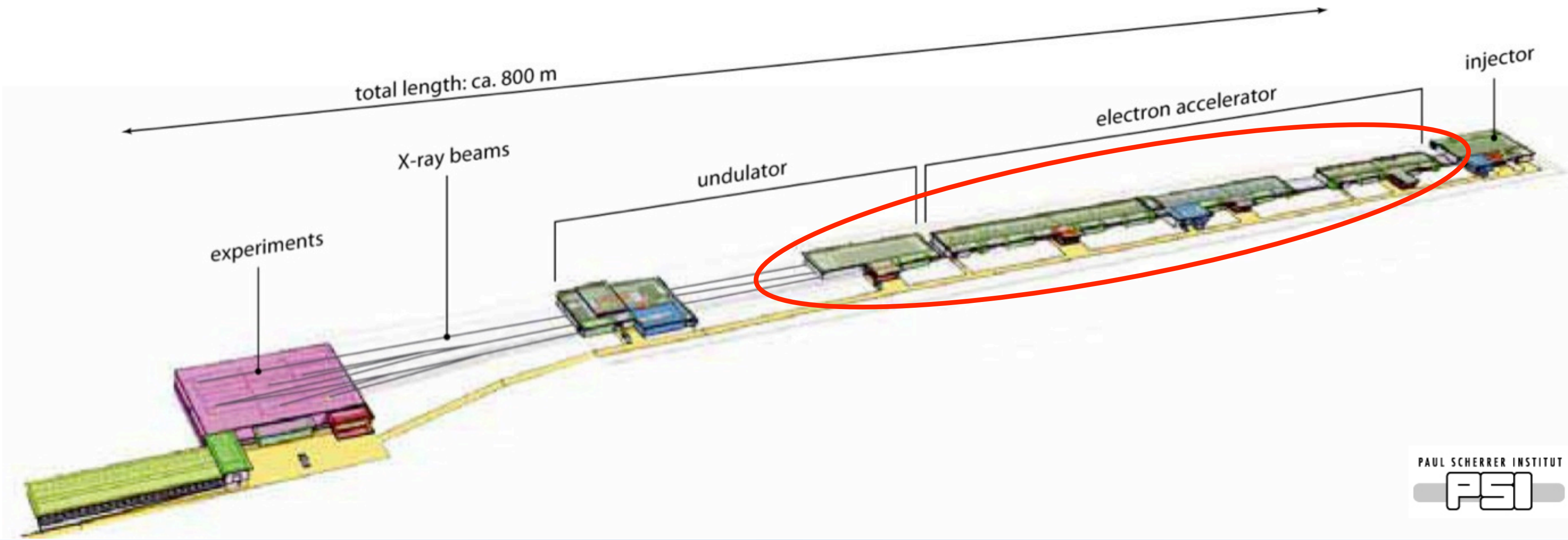
127MW/370kV/3µs
Solid State Modulator
with
Ultra High Precision



SwissFEL ➔ Seminar: Swiss FEL – this evening by Dr. Braun

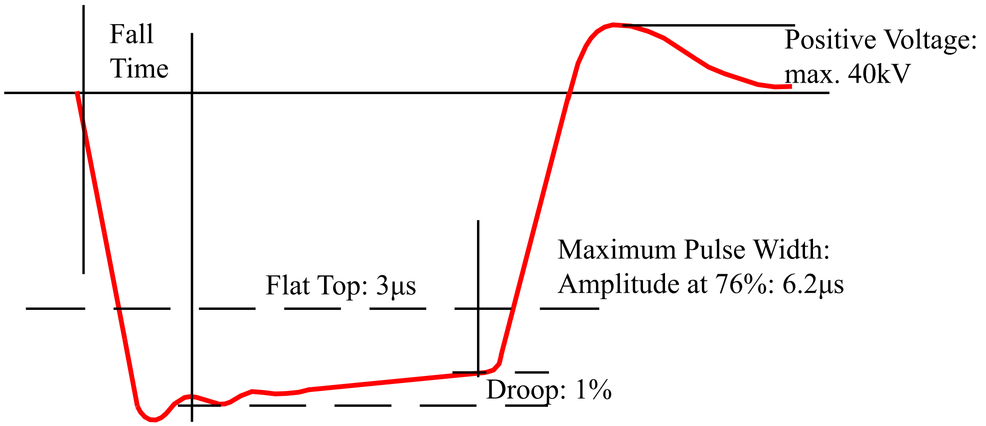
Free electron laser	➔ X-Rays
Electron beam energy	5.8GeV
Repetition rate	100Hz
Total electric power	5MW
Wavelength range	1Å to 70Å

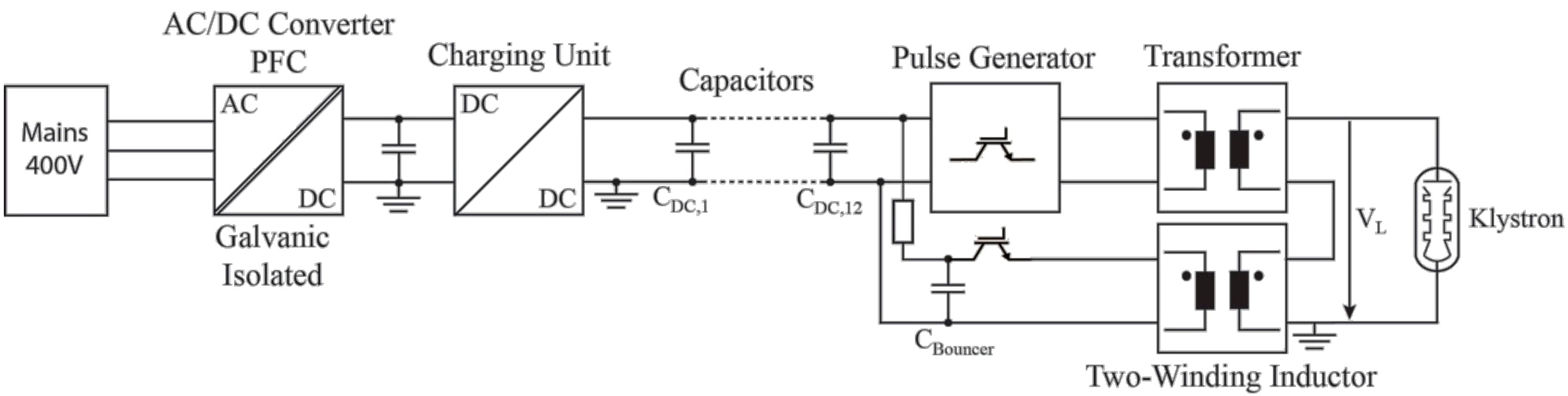




127 MW Solid-State Modulator

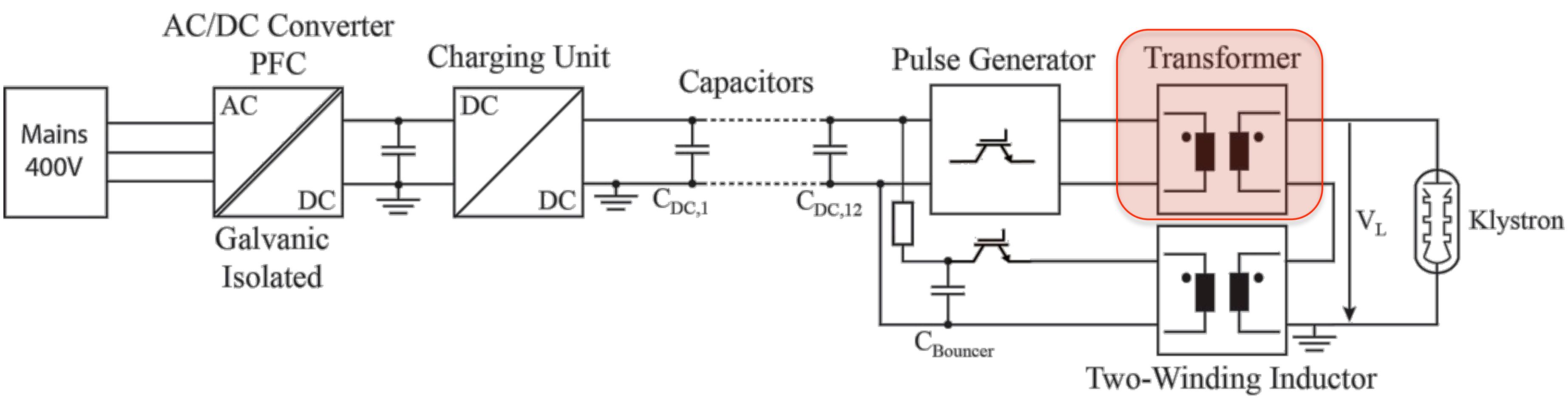
- DC supply voltage V_{DC} = 3kV ± 30mV
- Output voltage V_L = 370kV
- Output power P_{PEAK} = 127MW
- Average power P_{AVG} = 36kW
- Pulse length T_{PULSE} = 3µs
- Repetition rate f_{PULSE} = 100Hz-1kHz
- Fall time T_{FALL} < 1µs
- Voltage drop ΔV_{TP} < 1%
- Repetition accuracy < 10^{-5}





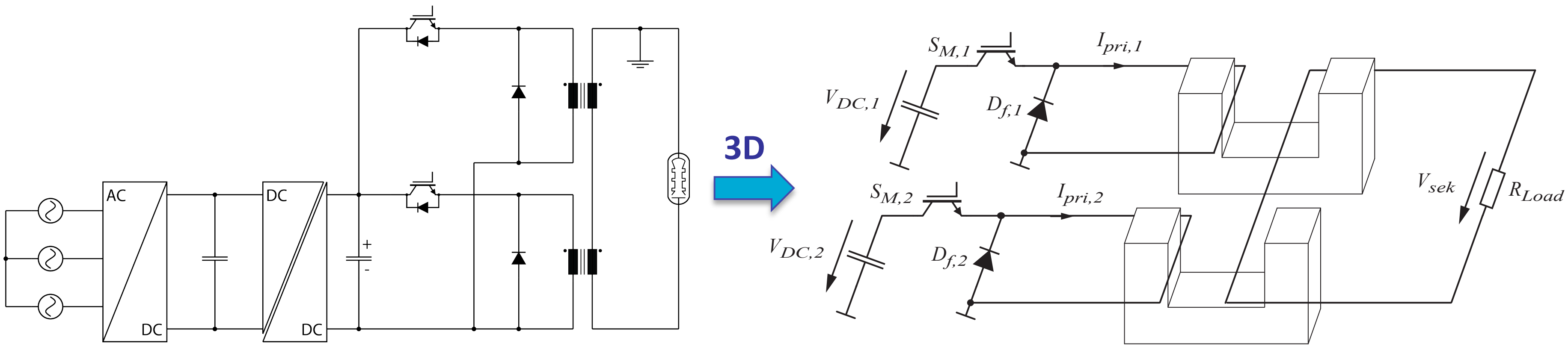
Short Pulse Solid State Power Modulator

Matrix Transformer Concept



Matrix Transformer – Basic Concept I

- **Separate primary windings:**
  - **- Inherent current balancing**



Matrix Transformer – Basic Concept I

- **Separate primary windings:**
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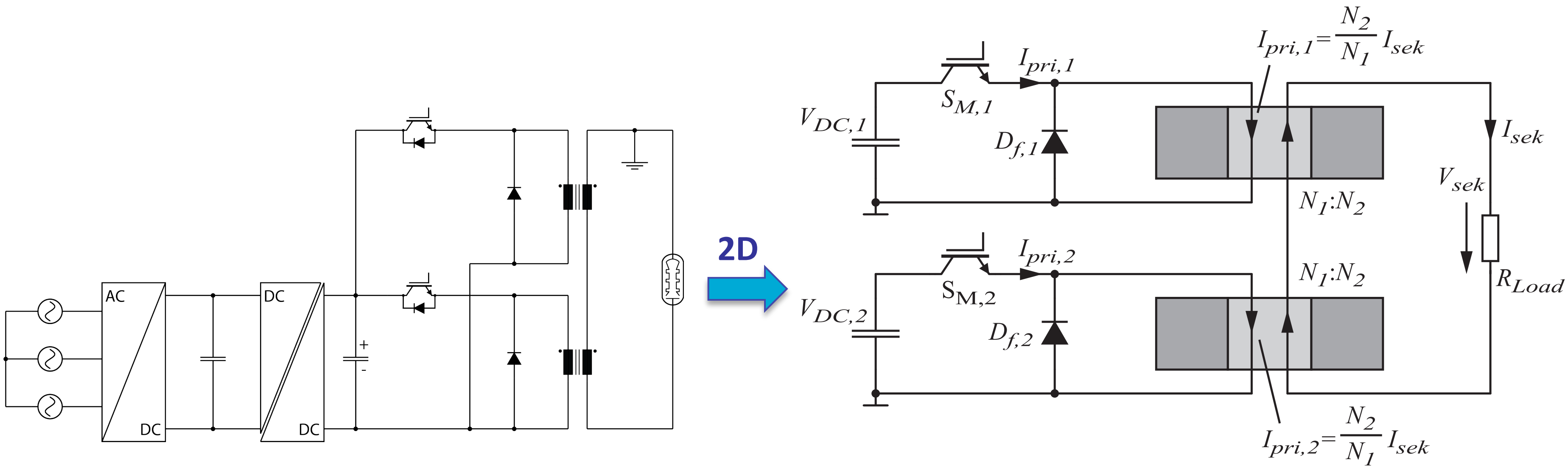
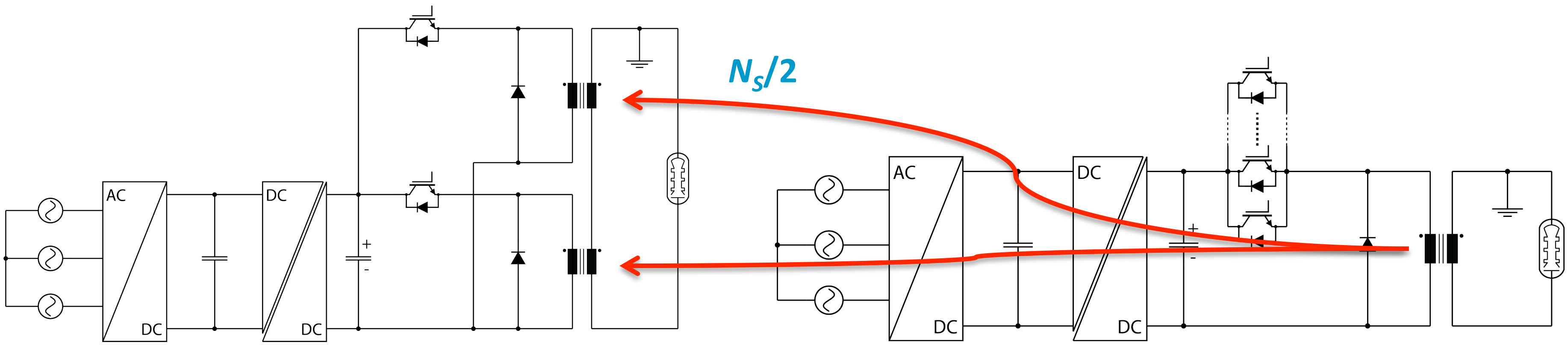


Matrix Transformer – Basic Concept II

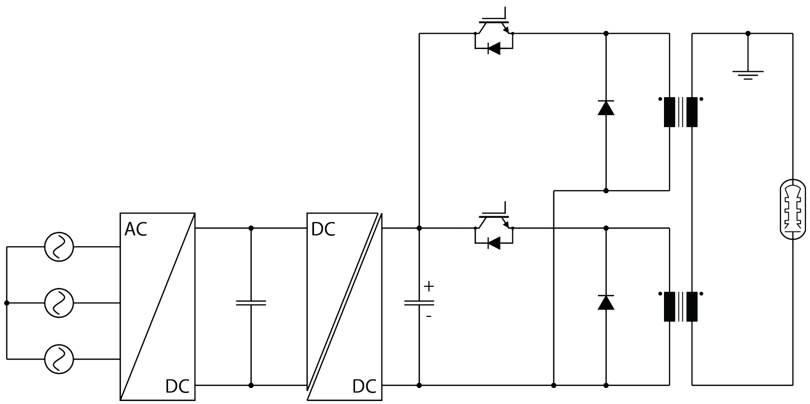
- **Separate primary windings:**
  - **- Inherent current balancing**
  - **- 2 windings + 2 cores**
    - **➔ Series connection on secondary side**
  - **- Secondary turns ➔ $N_S/2$**

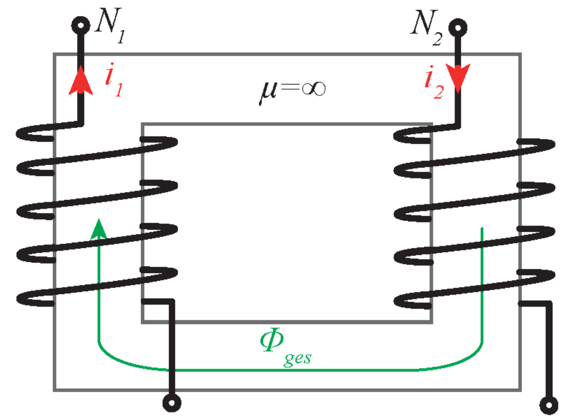


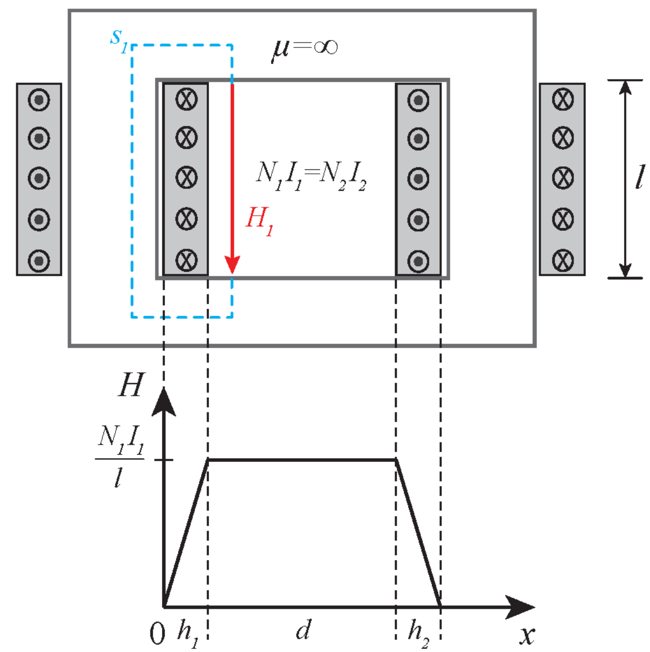
Matrix Transformer – Leakage Inductance

- **Leakage inductance L_σ:**
  - Slower rise time
  - Overshoot (Oscillation)
    - ➔ Lower efficiency
- **Calculation of L_σ:**
  - Magnetic field between windings
  - Energy stored in field = Energy in L_σ
- **L_σ depends on:**
  - Volume between windings
  - Number of turns

$$L_\sigma \sim \mu_0 N^2 \frac{l_W}{l}\left(\frac{h_1}{3} + d + \frac{h_2}{3}\right)$$



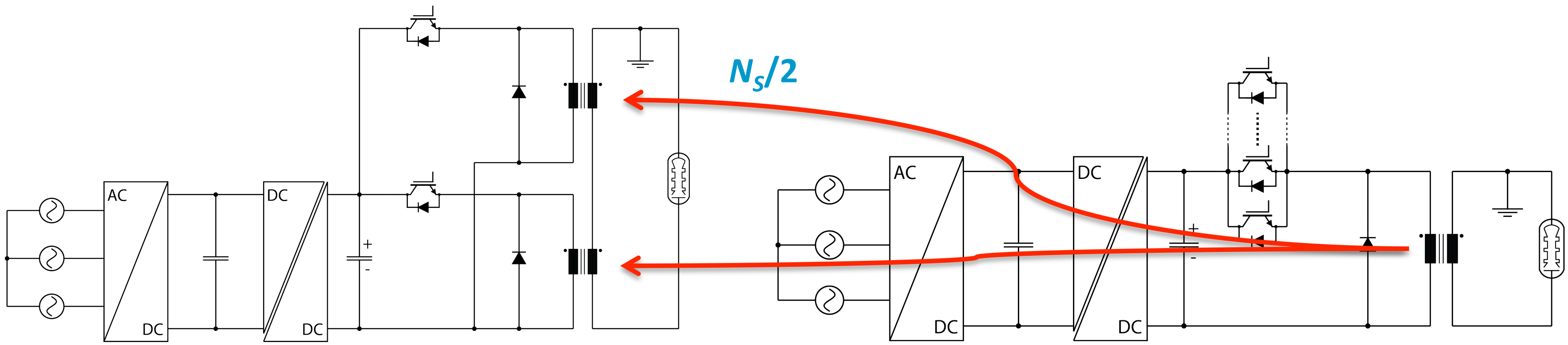




Matrix Transformer – Basic Concept II

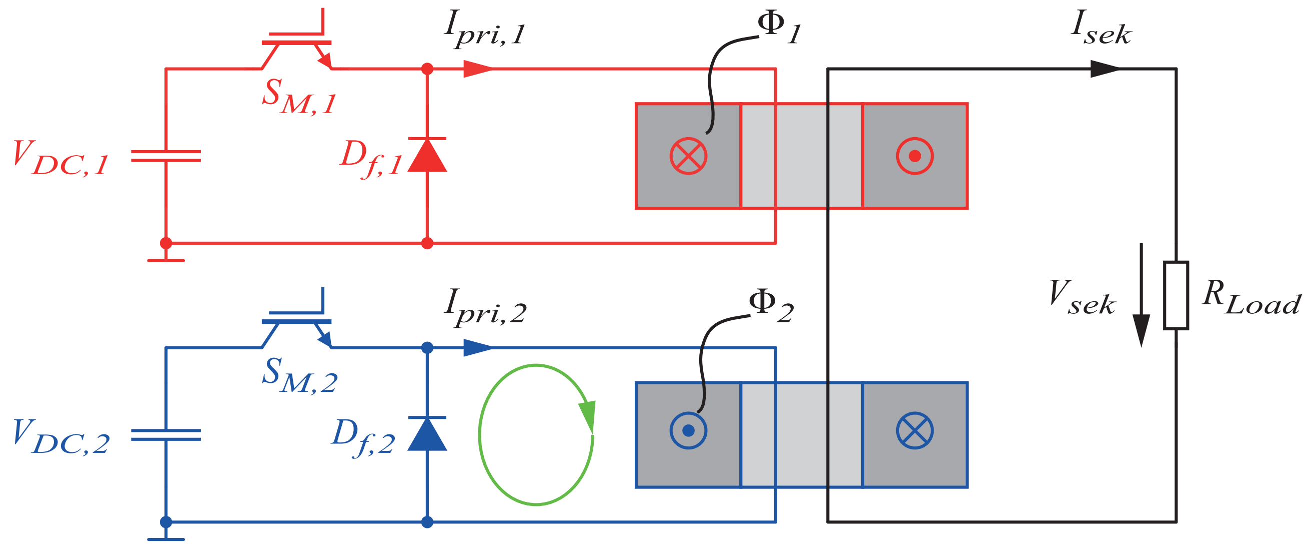
- **Separate primary windings:**
  - **- Inherent current balancing**
  - **- 2 windings + 2 cores**
    - **➔ "Virtual series connection"**
  - **- Secondary turns ➔ $N_S/2$**
- **Advantages:**
  - **- $N_S/2$ ➔ Leakage inductance ↓**
  - **- No series/parallel connected IGBTs**
- **Disadvantages:**
  - **- Doubling of core volume**

$$L_{\sigma,Matrix} \sim 2Vol\left(\frac{N}{2}\right)^2 \sim \frac{L_{\sigma,Old}}{2}$$



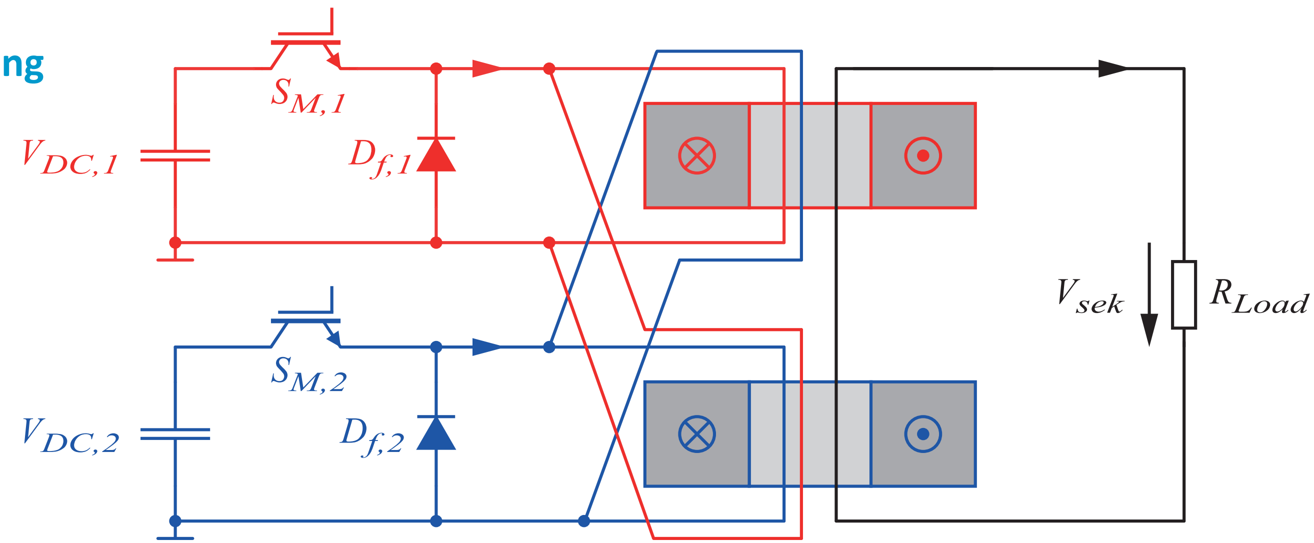
Matrix Transformer – "Cross Conduction"

- **Problem: Non synchronous switching (e.g. $S_{M,2}$ delayed)**
  - Turn on of $S_{M,1}$: Induces flux Φ_1
  - Φ_1 induces voltage in secondary ($V/2$)
  - Current I_{sek} flows in secondary
  - Current I_{sek} induces flux Φ_2
  - Φ_2 induces voltage in primary 2
  - Diode $D_{f,2}$ starts to conduct ($I_{pri,2}$)
  - Turn on of switch $S_{M,2}$
    - ➔ Hard commutation of diode $D_{f,2}$



Matrix Transformer – "Cross Conduction" – Additional Winding

- **Problem: Non synchronous switching (e.g. $S_{M,2}$ delayed)**
  - Turn on of $S_{M,1}$: Induces flux Φ_1
  - Φ_1 induces voltage in secondary ($V/2$)
  - Current I_{sek} flows in secondary
  - Current I_{sek} induces flux Φ_2
  - Φ_2 induces voltage in primary 2
  - Diode $D_{f,2}$ starts to conduct ($I_{pri,2}$)
  - Turn on of switch $S_{M,2}$
    - ➔ Hard commutation of diode $D_{f,2}$
- **Solutions:**
  - Cross windings
    - or better:
  - Synchronized switching
    (Small delay is o.k.)

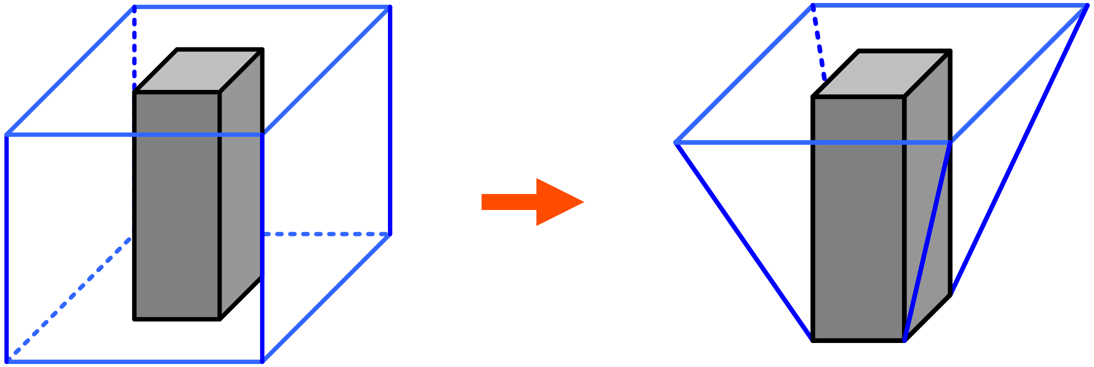


Matrix Transformer – Winding Shape

- **Winding shape:**
  - **- Parallel**
    - **➔ Large volume between Pri/Sec**
    - **➔ Large leakage inductance**
  - **- Cone shape**
    - **➔ Large distance @ high voltage**
    - **➔ Volume / 2 -> Leakage / 2**

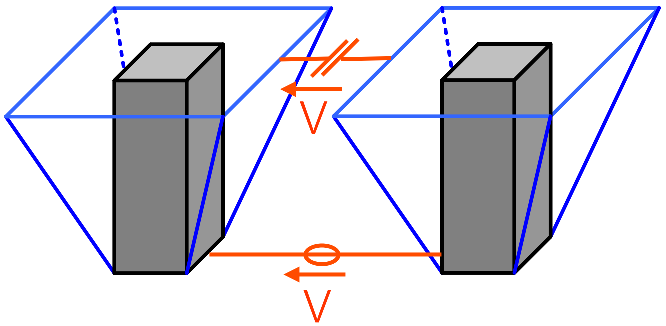
$$L_\sigma \sim \mu_0 N^2 \frac{l_W}{l}\left(\frac{h_1}{3} + d + \frac{h_2}{3}\right)$$

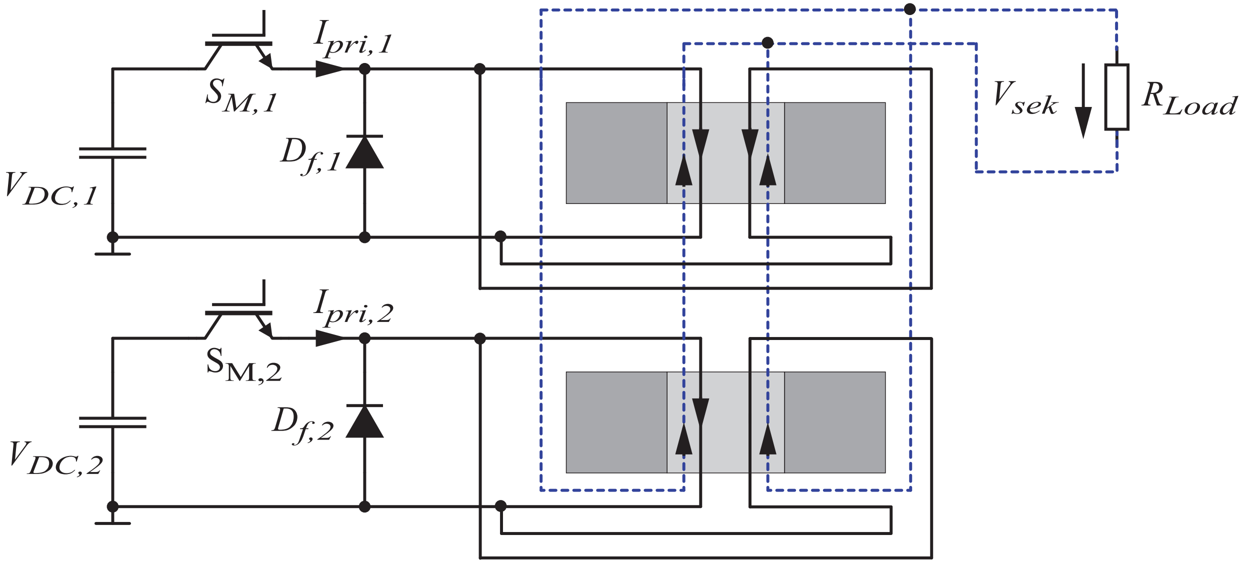
$$\sim Vol\, N^2$$



Matrix Transformer – Parallel Secondary Windings

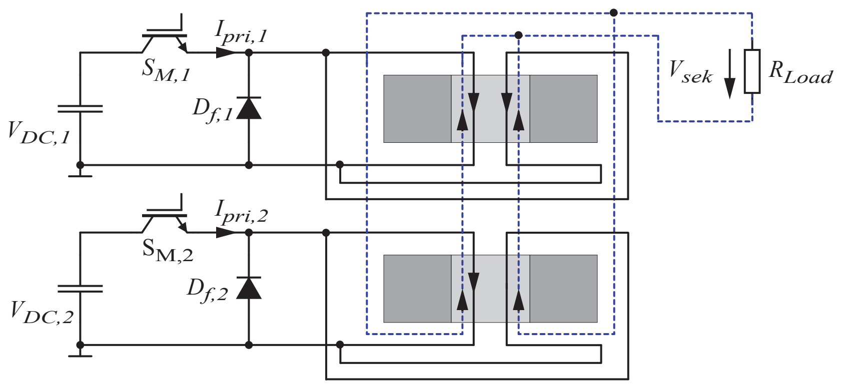
- **Parallel secondary winding:**
  - Parallel leakage inductance
    - ➔ Leakage / 2
  - Offset voltage possible
    - ➔ Cathode heating @ high potential

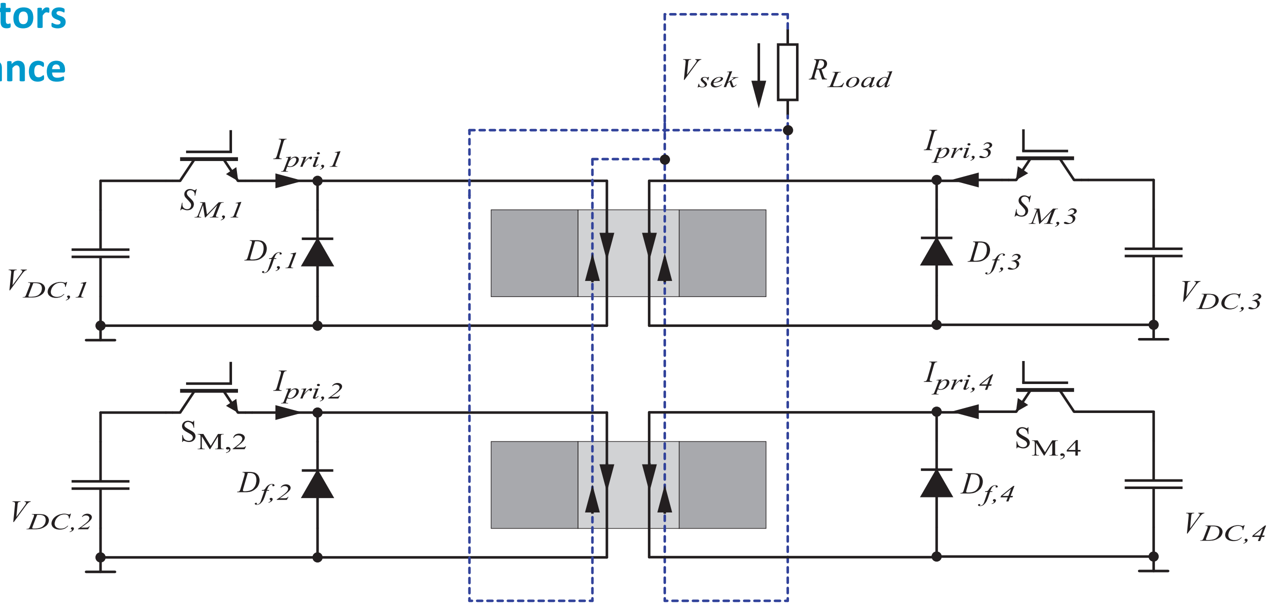




Matrix Transformer – 2 IGBTs on 1 Core

- **Pulsed power per switch: app. 10-11MW**
  - **Total power: 127MW**
    - ➔ **12 switches**
    - ➔ **12 cores**
    - ➔ **Large volume / weight**
- ➔ **2 separate switches per core**
  - **"Per core" 20-22MW**
    - ➔ **6 cores**
  - **Current sharing of 2 switches per core**
    - ➔ **Synchronization**
    - ➔ **Separate capacitors**
    - ➔ **Leakage inductance**

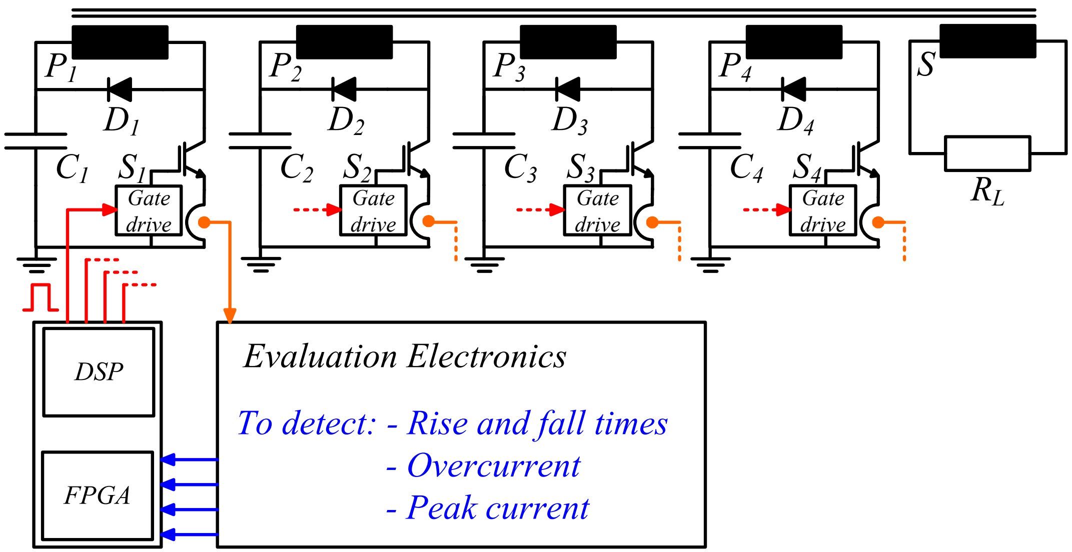




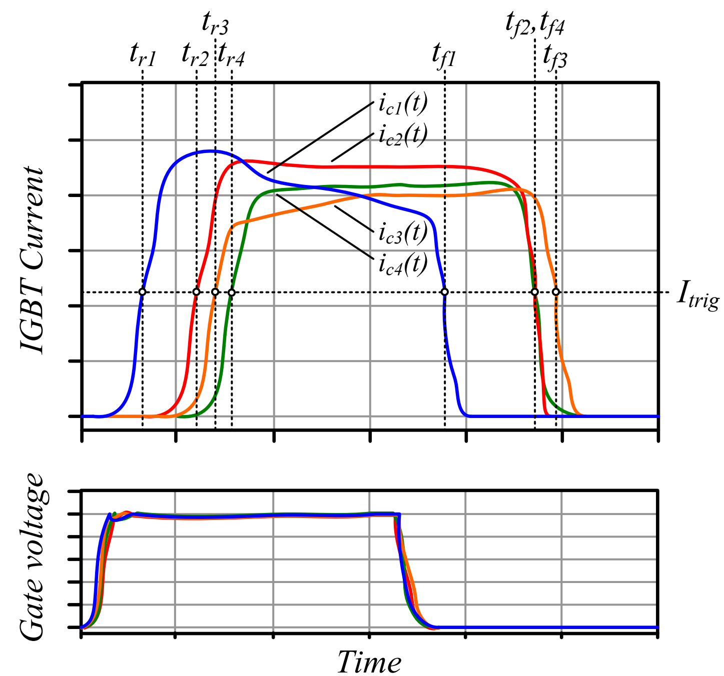
Only 2 out of total
6 cores are shown

Matrix Transformer – Switch Synchronisation

- **Problem: Non synchronous switching**
- **Solutions:**
  - **- Synchronized switching**
    - **➔ Detection of**
      - **Edges**
      - **Peak current**

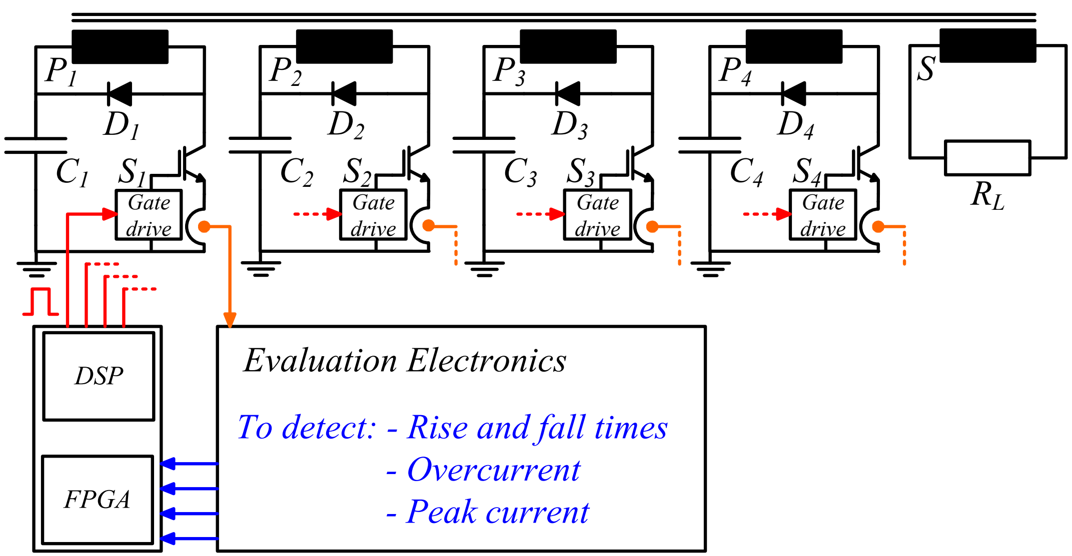


Simplified Current Waveforms

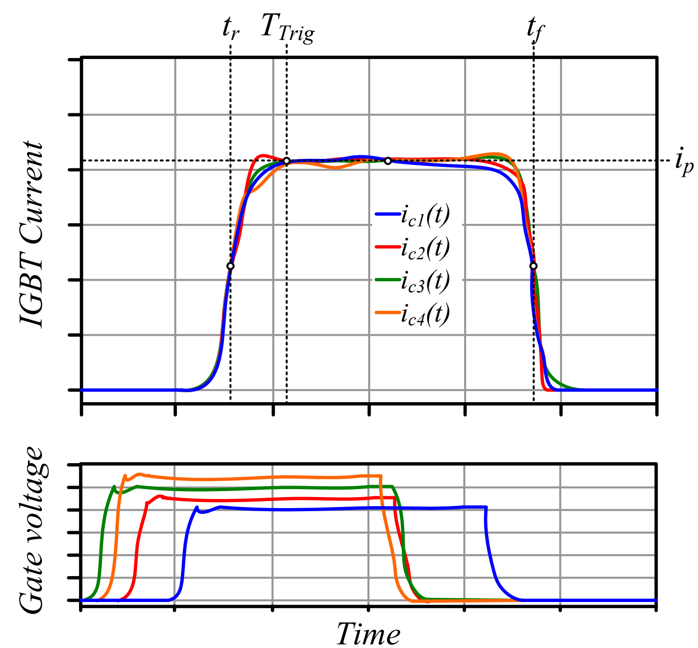


Matrix Transformer – Switch Synchronisation

- **Problem: Non synchronous switching**
- **Solutions:**
  - **- Synchronized switching**
    - **➔ Detection of**
      - **Edges**
      - **Peak current**
    - **➔ Synchronous turn on**
    - **➔ Positive temp. coefficient -> Static balancing**
    - **➔ "Separate" DC capacitors -> Static balancing**

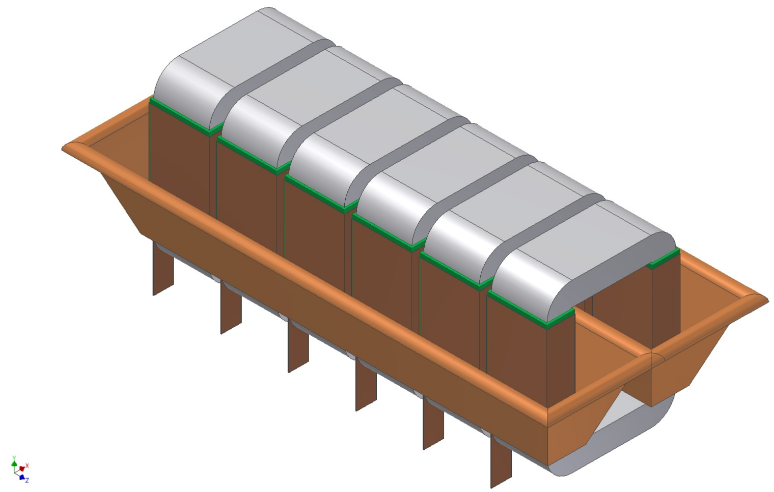


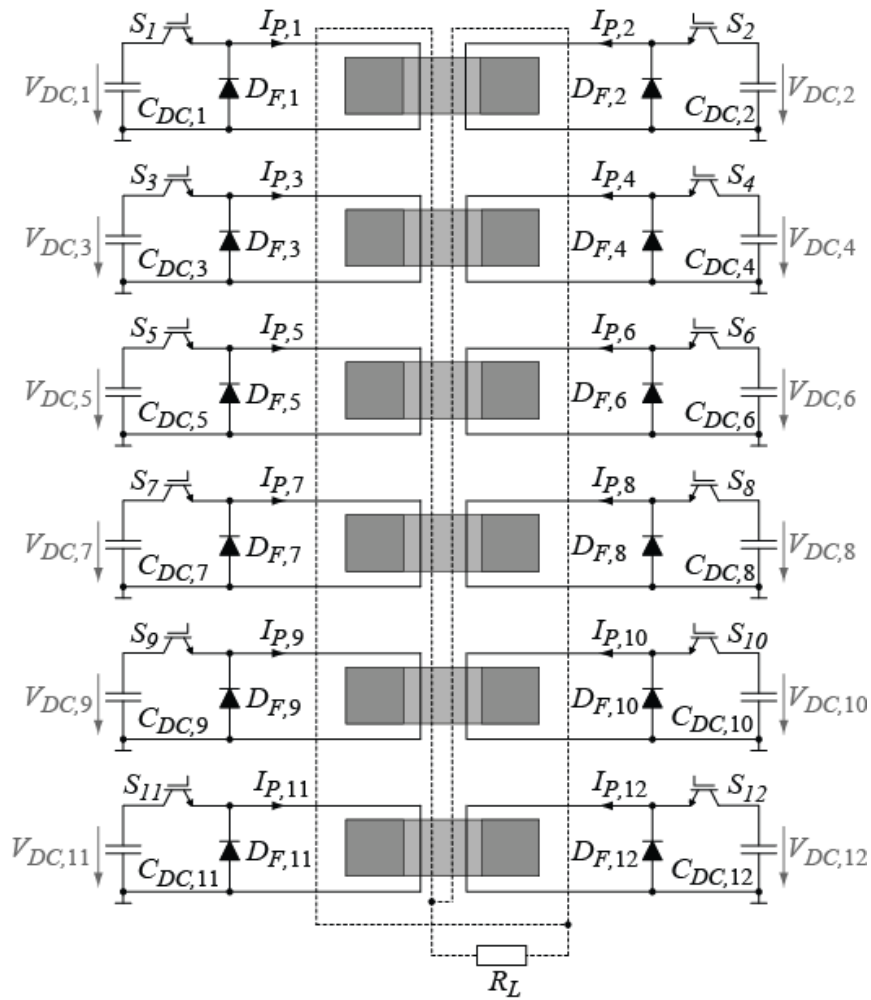
Simplified Current Waveforms



127MW Matrix Transformer Setup

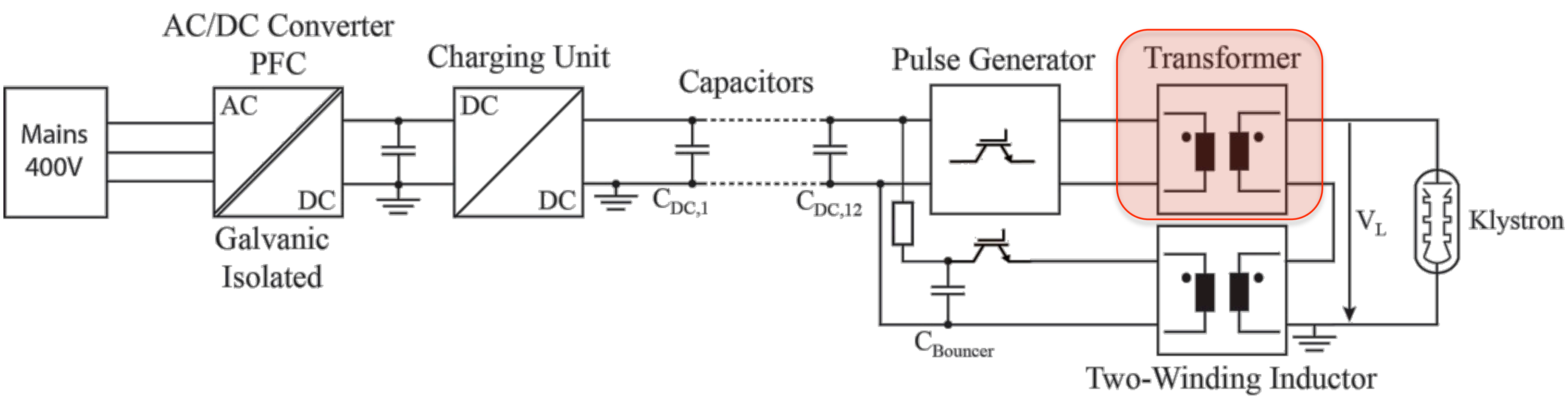
- **Matrix transformer**
- **12 IGBTs / 6 cores**
- **12 primary windings**
- **2 parallel secondary windings**
- **Current balanced between cores**





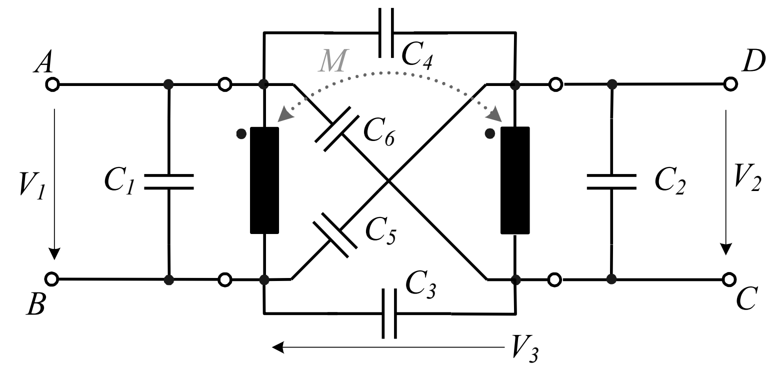
Short Pulse Solid State Power Modulator

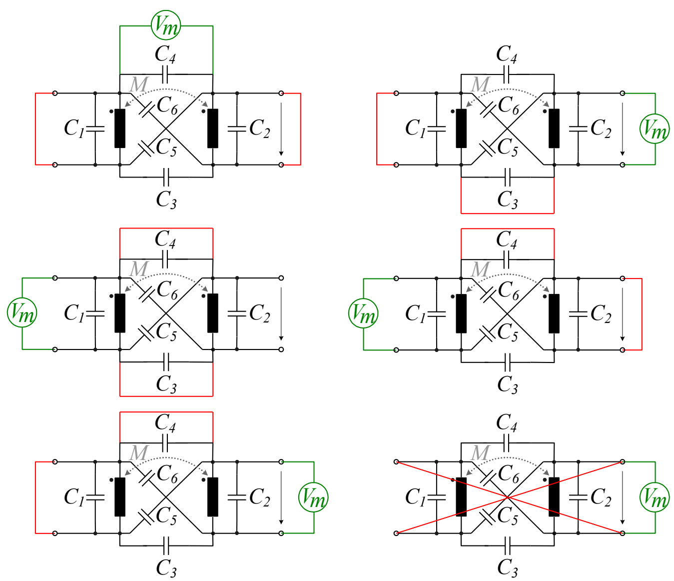
Pulse Transformer Design

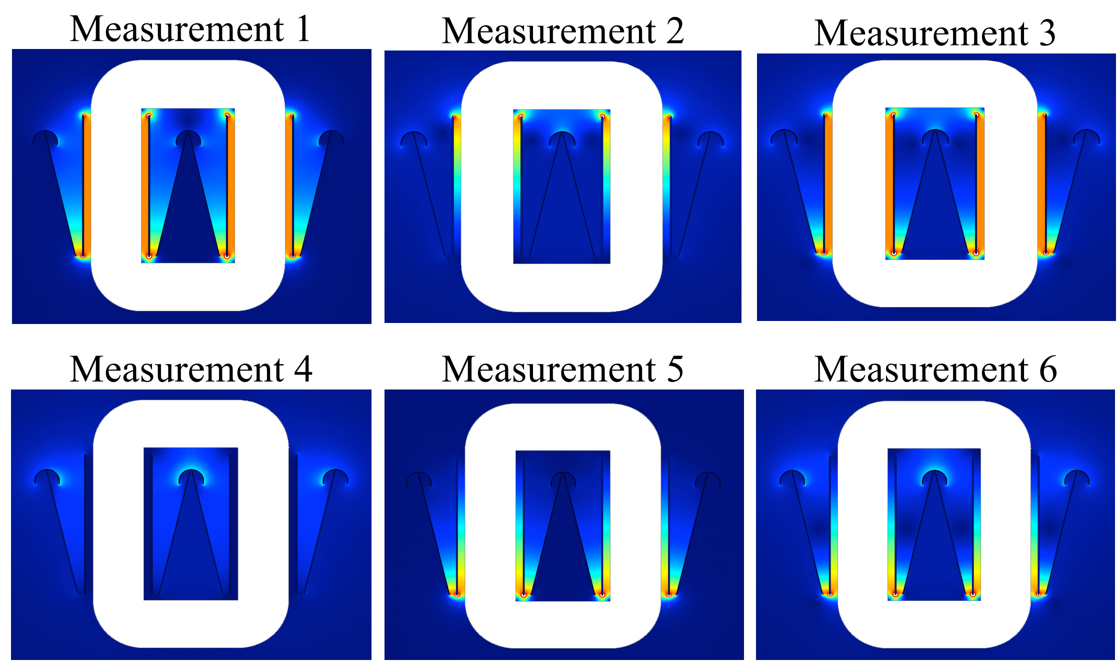


Pulse Transformer: Parasitic Capacitances

- **Electrical fields ➔ Parasitic capacitances**
- **General equivalent circuit: 6 capacitors**

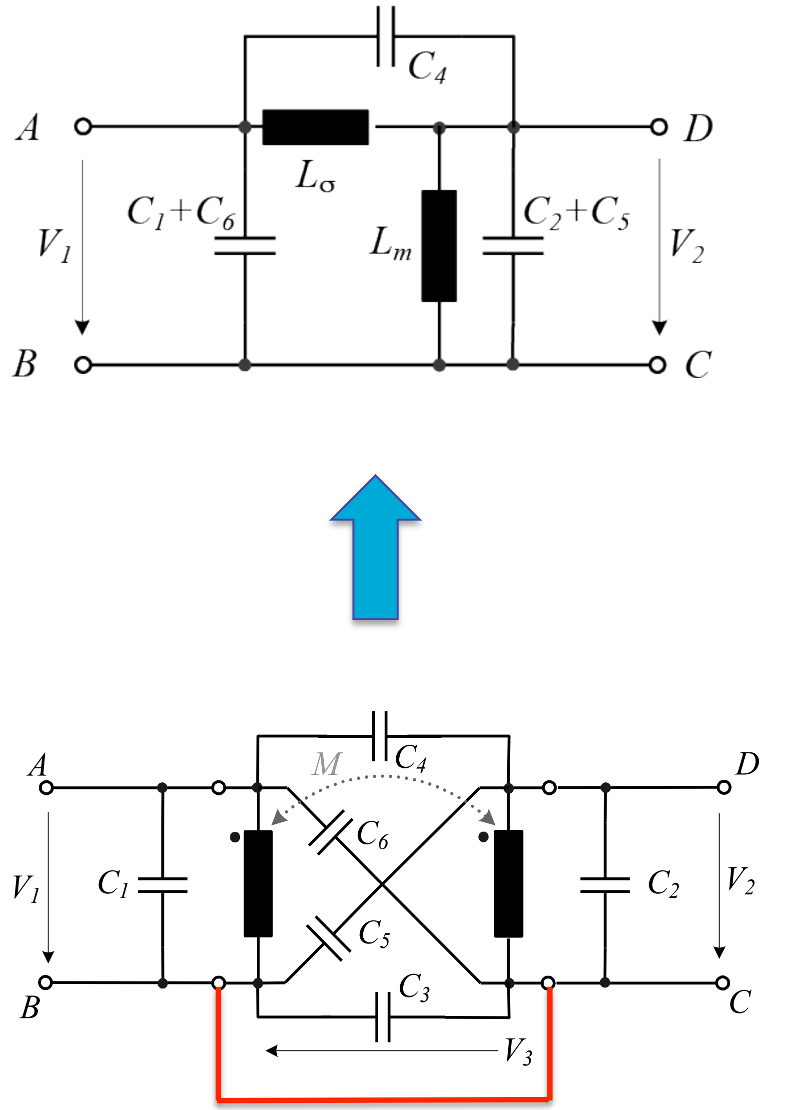






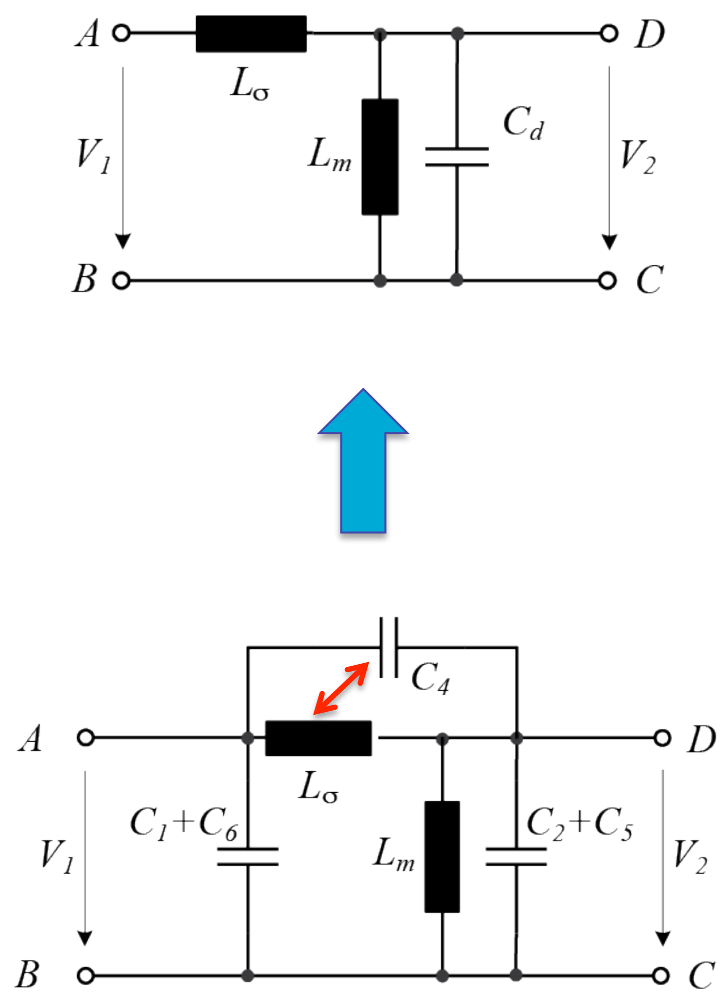
Pulse Transformer: Parasitic Capacitances – Simplification I

- **Electrical fields ➔ parasitic capacitances**
- **General equivalent circuit: 6 capacitors**
- **Common ground for primary/secondary**
  - **➔ Reduction to 3 capacitors**



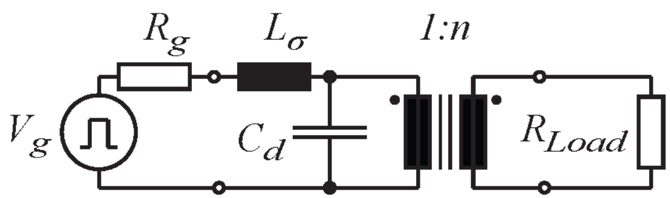
Pulse Transformer: Parasitic Capacitances – Simplification II

- **Electrical fields ➔ parasitic capacitances**
- **General equivalent circuit: 6 capacitors**
- **Common ground for primary/secondary**
  - **➔ Reduction to 3 capacitors**
- **Calculating energy equivalent capacitor @ output**
  + (Neglecting resonance L_σ/C_4)
  - **➔ Simple L_σ/C_d circuit**
  - **➔ $C_d \approx C_2 + C_4 + C_5$ (large N)**

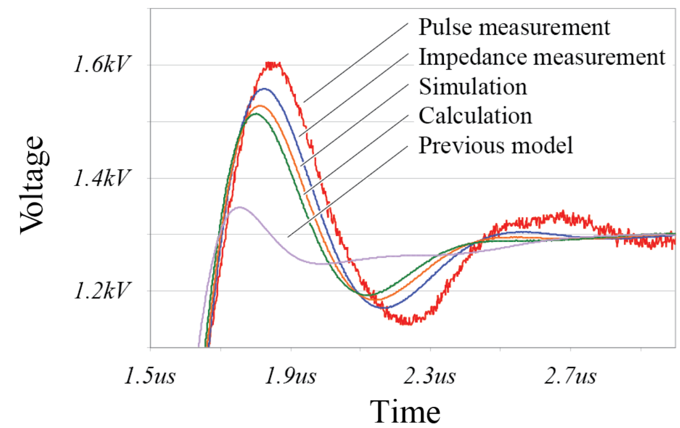


Pulse Transformer: Overshoot / Rise Time

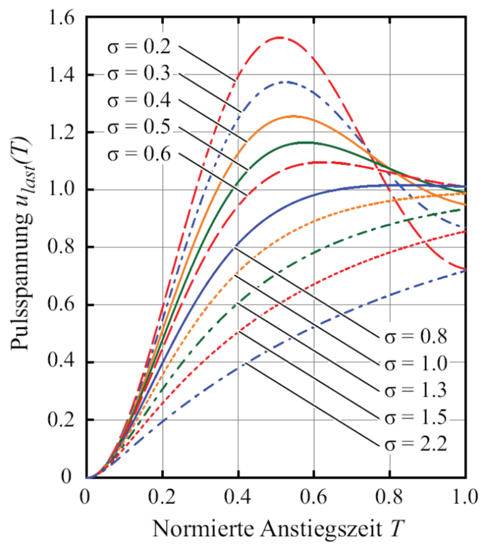
Simple equivalent circuit



Verification by measurement



Overshoot on the rising edge



Design conditions

$$T_r = 2\pi T_{10\%-90\%}\sqrt{L_\sigma C_d}$$

$$\sigma = \frac{1}{2R_{Load}}\sqrt{\frac{L_\sigma}{C_d}}$$

Capacitance Calculation with Mirror Charges

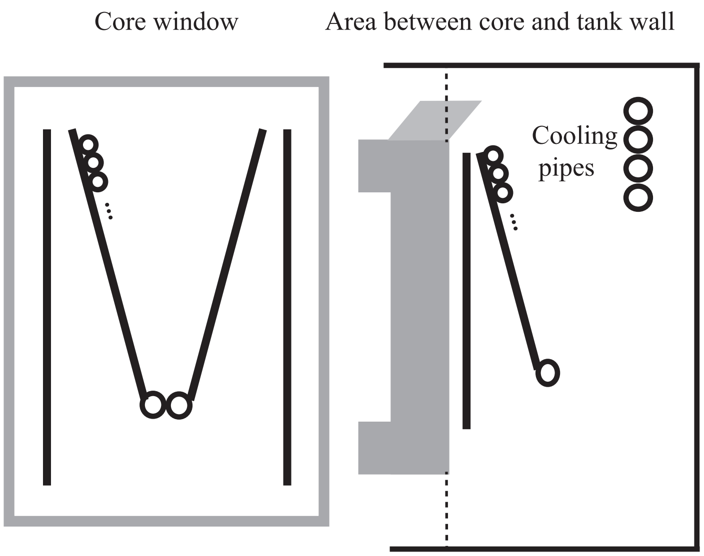
- **Geometry interpreted as multi-conductor system**
- **Mirror charges for**
  - **- Core window**
  - **- Core leg / tank wall**
- **Fast calculation > 100x faster than FEM**

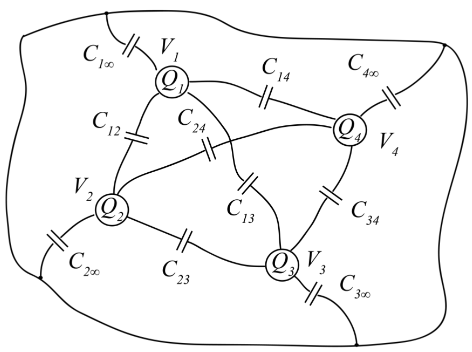
Without mirror charges

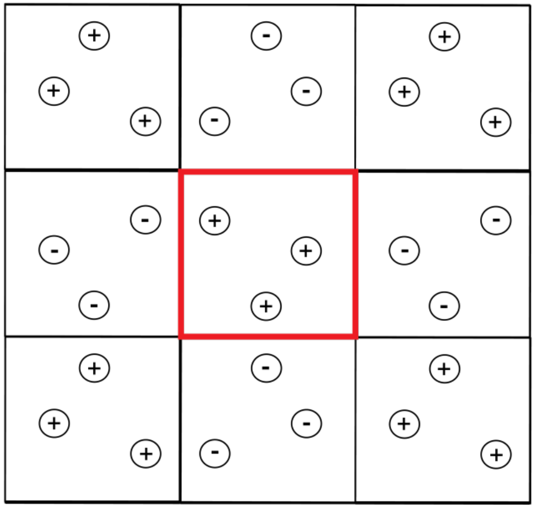
$$p_{ij} = \frac{1}{2\pi\varepsilon_0\varepsilon_r}\ln(d_{ij})$$

$$[Q] = [p]^{-1}[\Phi'] = [c][\Phi']$$

$$C'_{ij} = -c_{ij} \qquad C'_{i\infty} = \sum_{j=1}^{N} c_{ij}$$



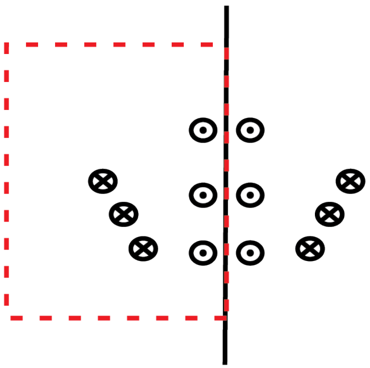




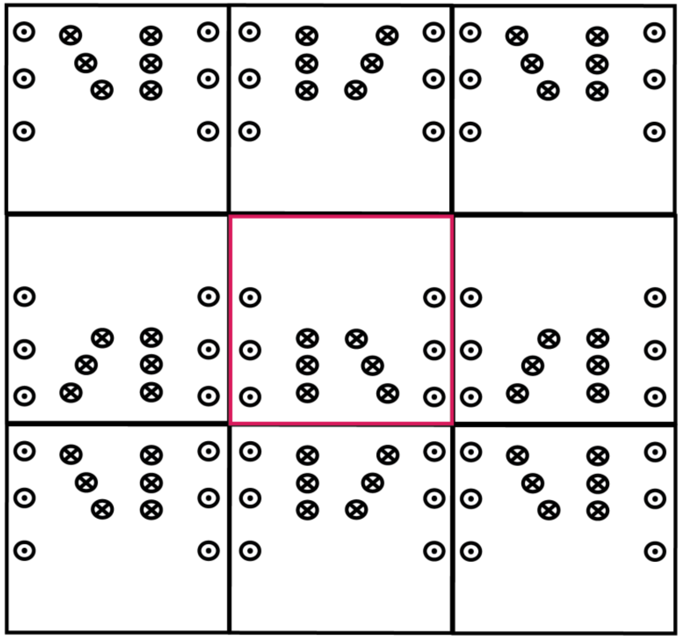
Inductance Calculation with Mirror Line Currents

- **Geometry interpreted as multi-conductor system (line current)**
- **Current mirror method for magnetic surface**
- **Mirroring:**
  - **- Core window ➔ box mirroring**
  - **- Outside core ➔ wall mirroring**
- **Fast calculation > 500x faster than FEM**

Wall Mirroring



Box Mirroring



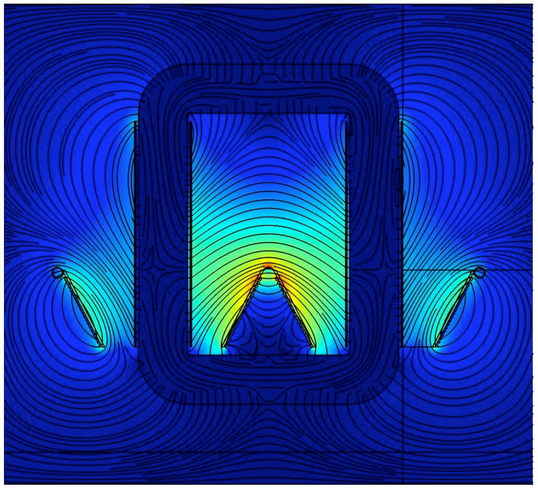
Considering self inductance

$$r'_i = r * e^{-\frac{\mu}{4}}$$

$$L'_{ii} = \frac{\mu_0}{2\pi} \ln\left(\frac{1}{r'_i}\right)$$

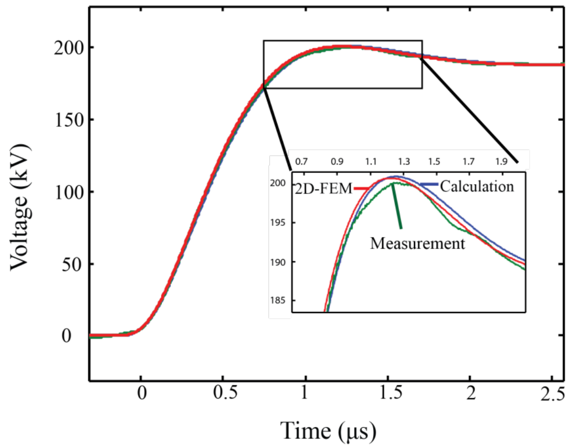
Mutual inductance

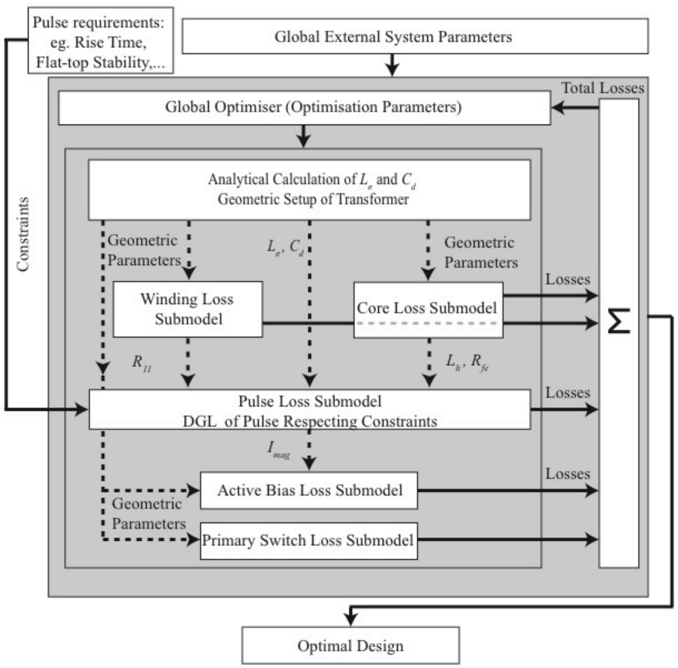
$$L'_{ij} = \frac{\mu_0}{2\pi} \ln\left(\frac{1}{d_{ij}}\right)$$

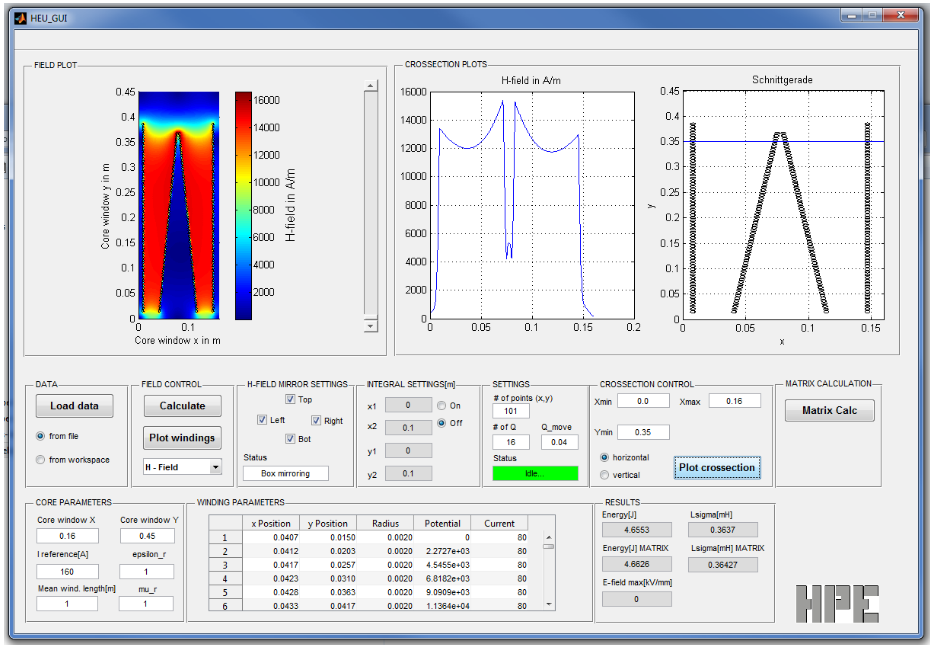


Transformer Parasitics Modelling

- **Analytic equations for transformer optimisation**
- **Visualisation tool (no toolbox required)**
- **Pulse shape prediction with non-linear ODE**
- **Good matching with FEM & measurement**





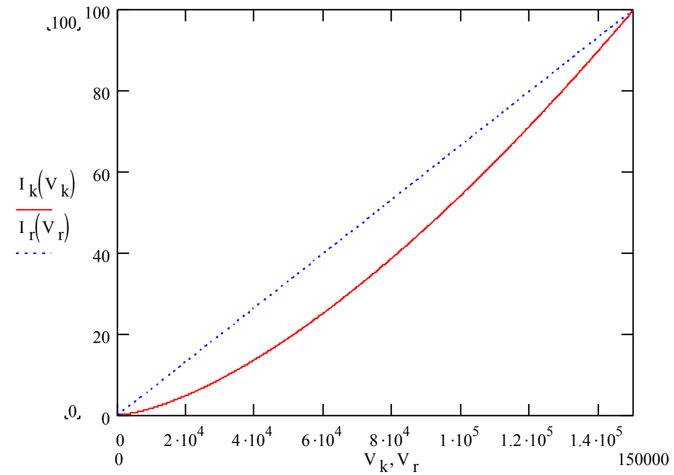


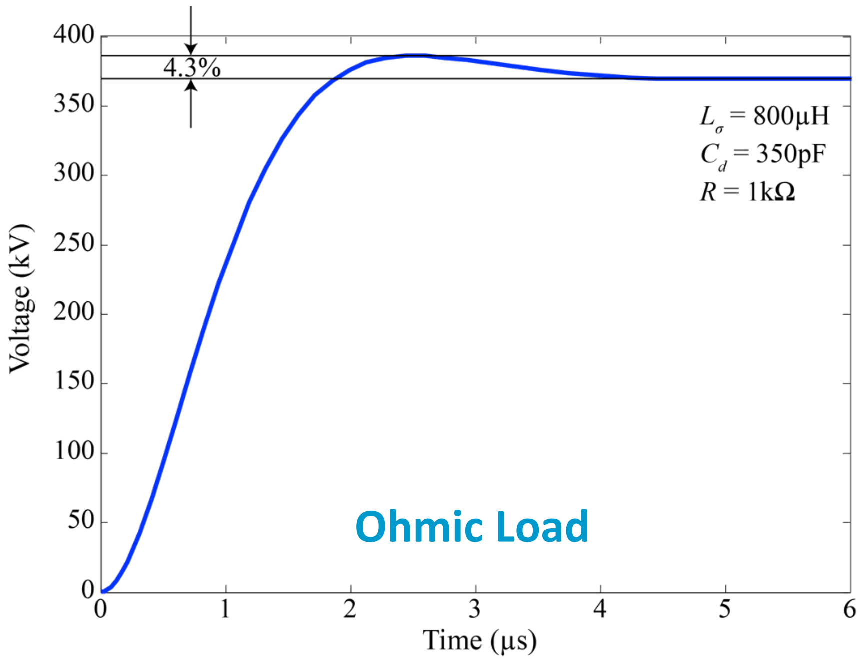
Pulse Transformer: Damping due to Klystron Load

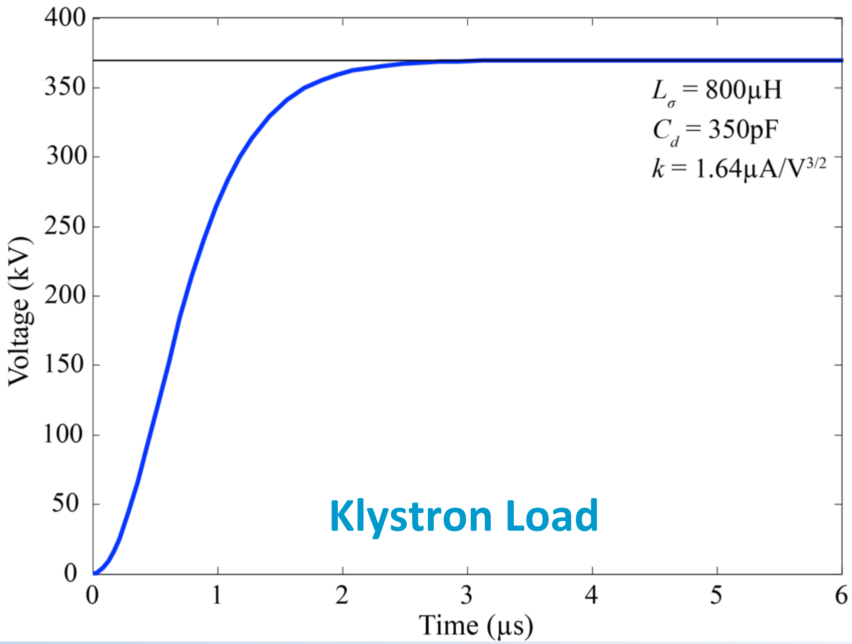
- **Klystron-Model:**

$$I = k \cdot V^{1.5}$$

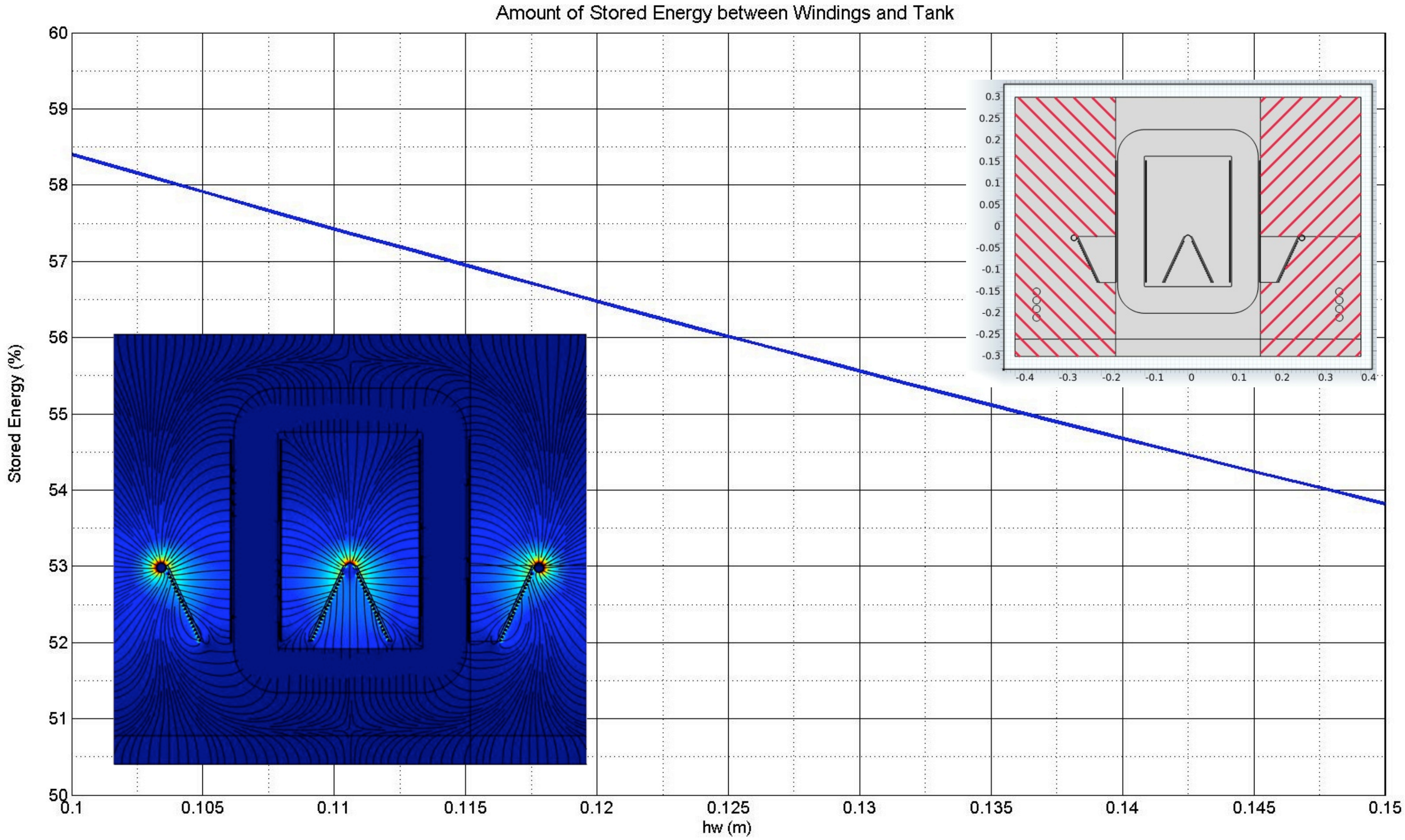
with k = Perveance





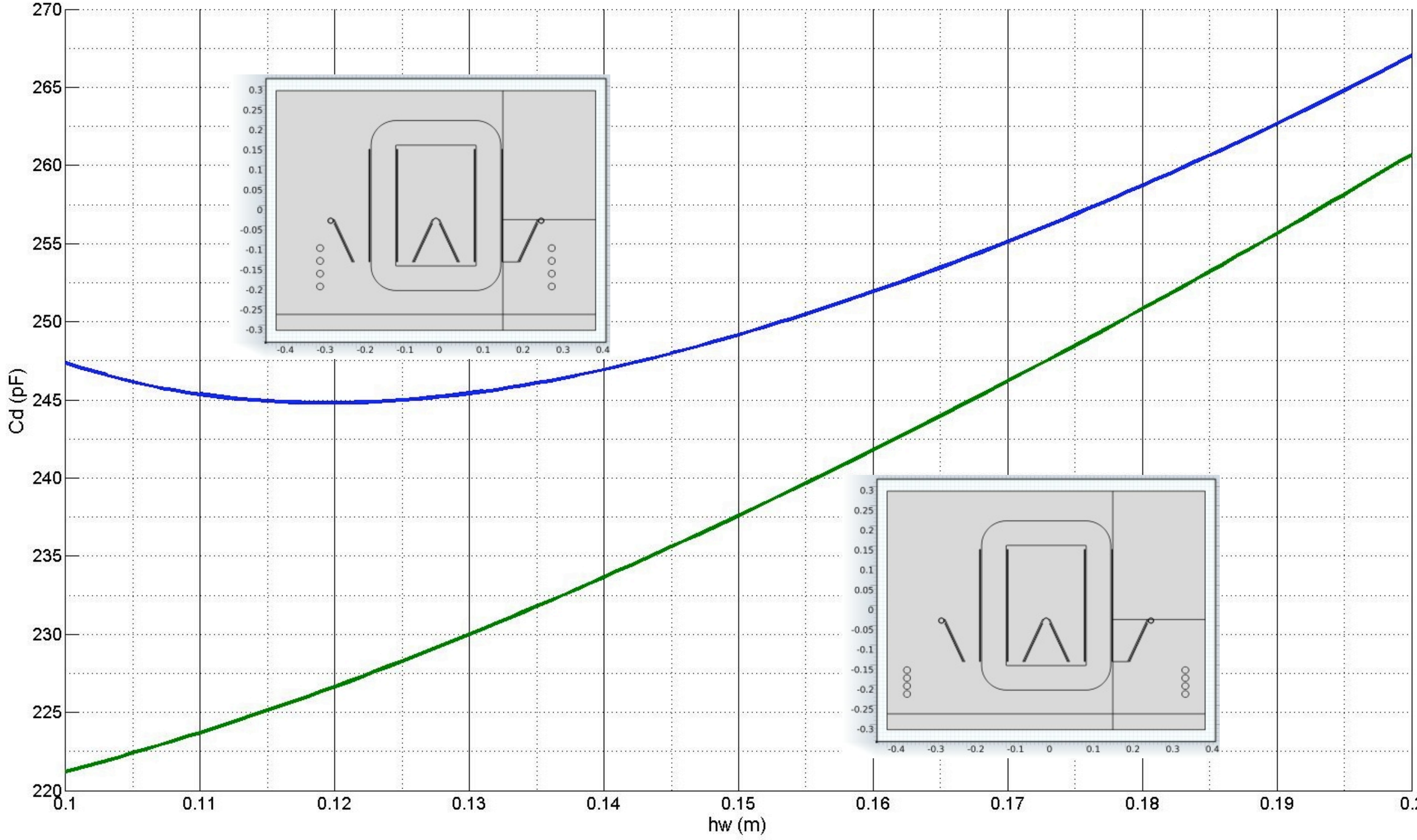


Capacitance: Stored Energy between Windings and Tank



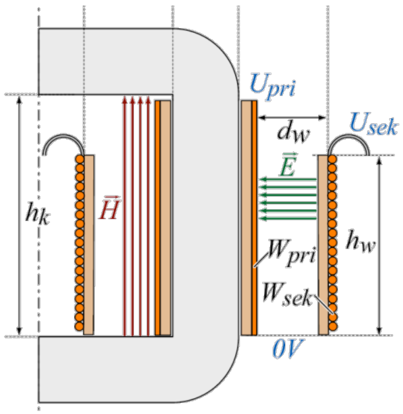
Capacitance: Influence of Cooling Pipes

- **Cooling pipes close to winding ➔ Capacitance ↑**



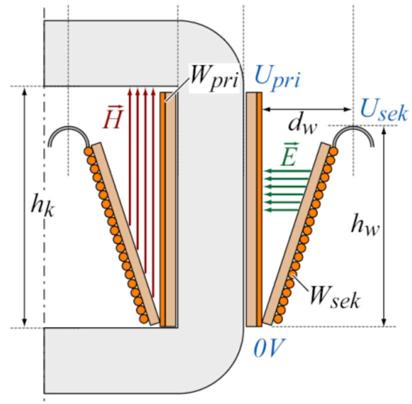
Pulse Transformer: Winding Arrangement

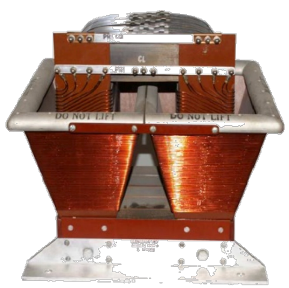
Parallel Winding



$$\frac{1}{3}\cdot\varepsilon\mu\frac{N_{sek}^2\cdot l_w^2\cdot h_w}{h_k}$$

Non-Parallel Winding



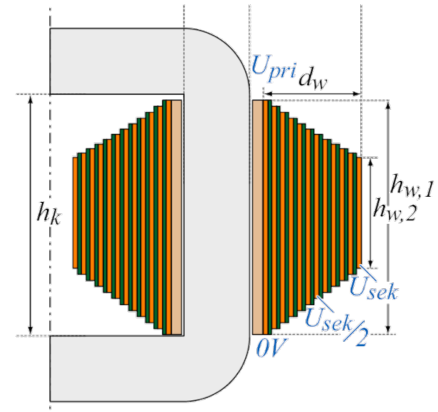


$$\frac{1}{4}\cdot\varepsilon\mu\frac{N_{sek}^2\cdot l_w^2\cdot h_w}{h_k}$$

Smallest LC-Product

$$T_r = 2\pi T_{10\%-90\%}\sqrt{L_\sigma C_d}$$

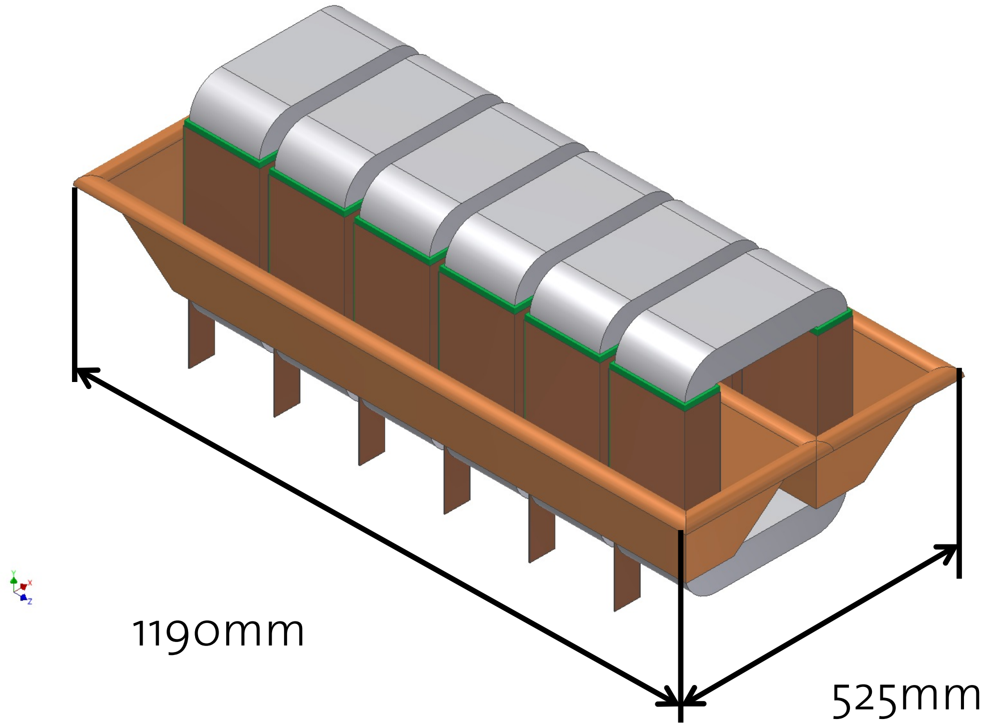
Foil Winding



$$\frac{k+1}{3}\cdot\varepsilon\mu\frac{N_{sek}^2\cdot l_w^2\cdot h_w}{h_k}$$

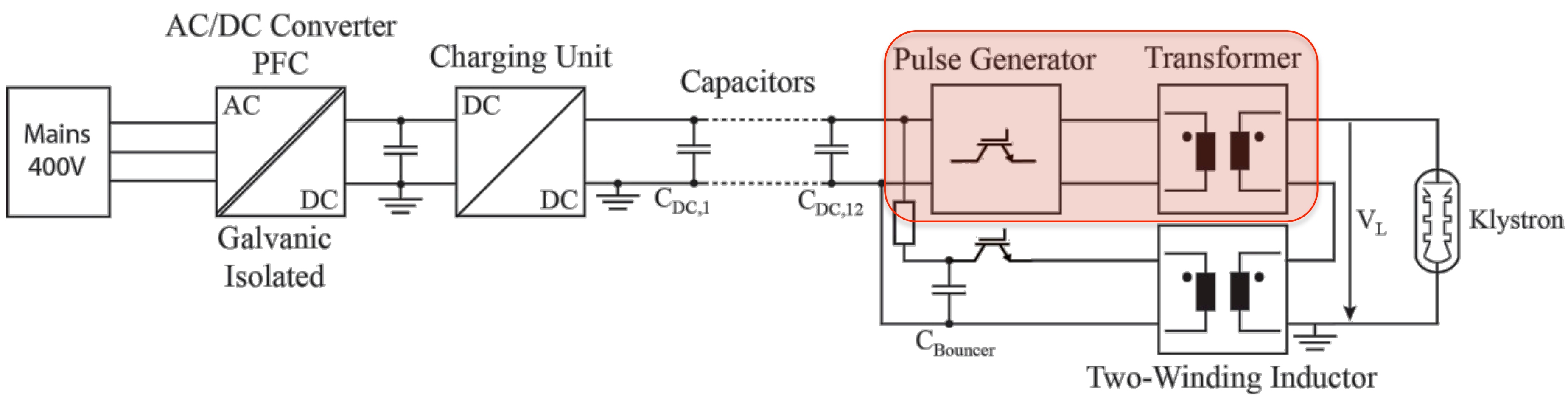
Pulse Transformer: Final Design

- **Core material:**
  - **2605SA1**
- **Primary windings:**
  - **3 kV input voltage**
  - **Copper foil, *d* = 1mm**
- **Secondary windings:**
  - **370 kV output voltage**
  - **21 Turns → 17.6 kV per turn**
  - **Round conductor, *d* = 3mm**



Short Pulse Solid State Power Modulator

Premagnetisation



Premagnetisation – Basic Concepts

- **Bipolar flux swing**

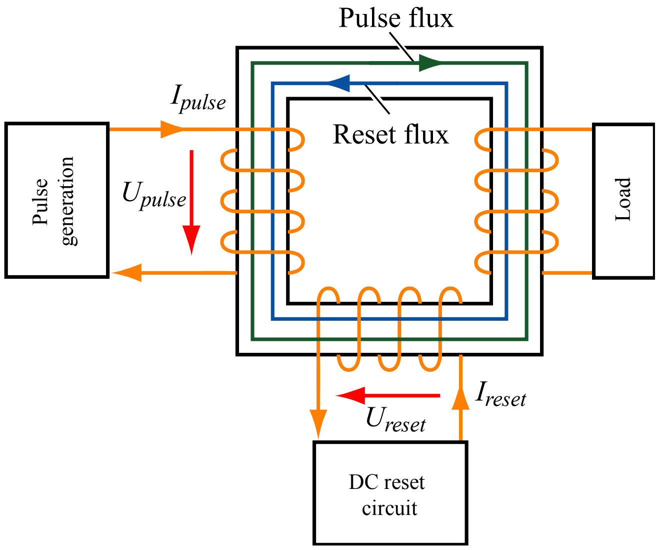
$$A_{Core} = \frac{V_{Sec}}{N_{Sec} \, \Delta B / T_P}$$

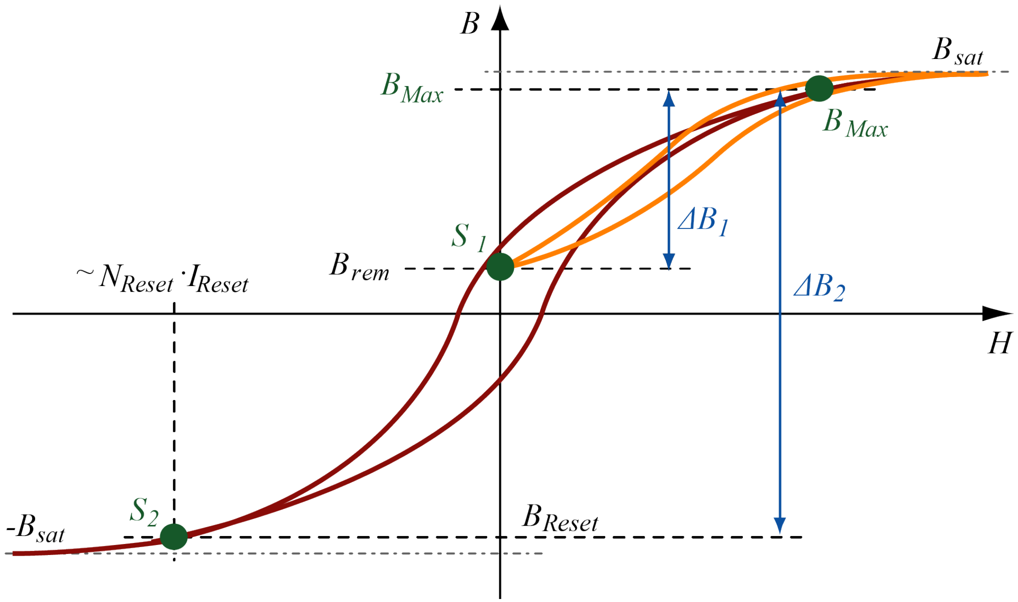
➔ **Core area / 2**

➔ **Reduction of LC-product**

➔ **Lower turn length**

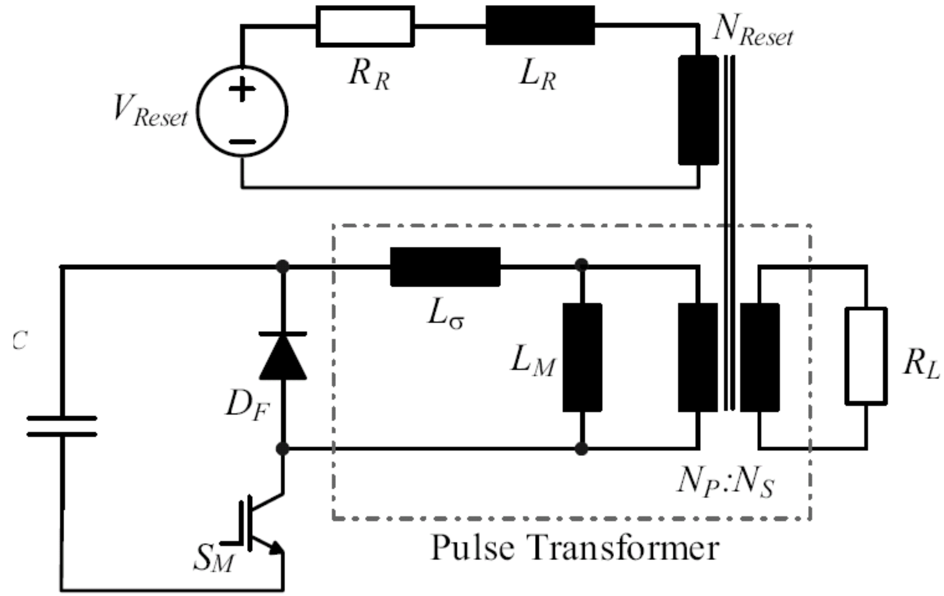
- **Additional components required**
- **Energy recovery possible (active circuit)**

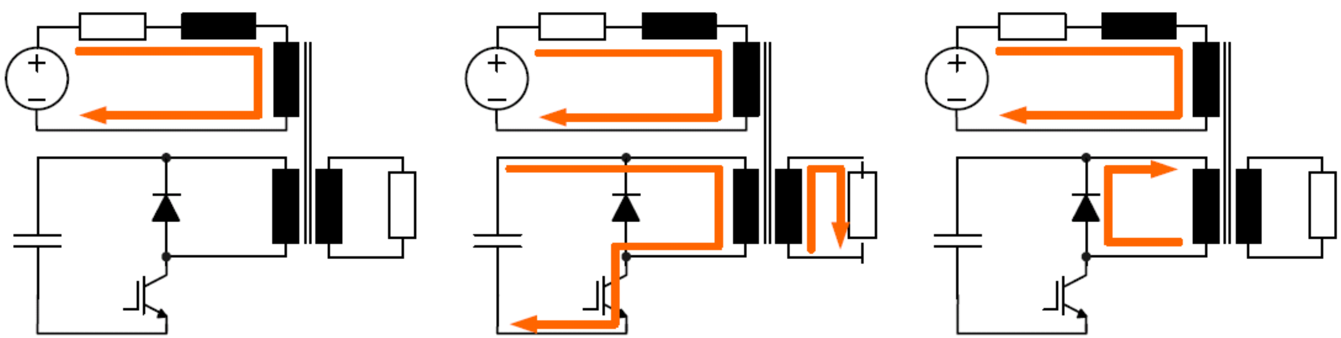




DC Premagnetisation

- **3rd winding on core**
- **DC choke + voltage source**
  - ➔ **Current source for bias current**
- **Additional copper losses**





(a) *Premagnetisation* (b) *Pulse* (c) *Demagnetisation*

DC Premagnetisation

- 3^{rd} winding on core
- DC choke + voltage source
  - ➔ Current source for bias current
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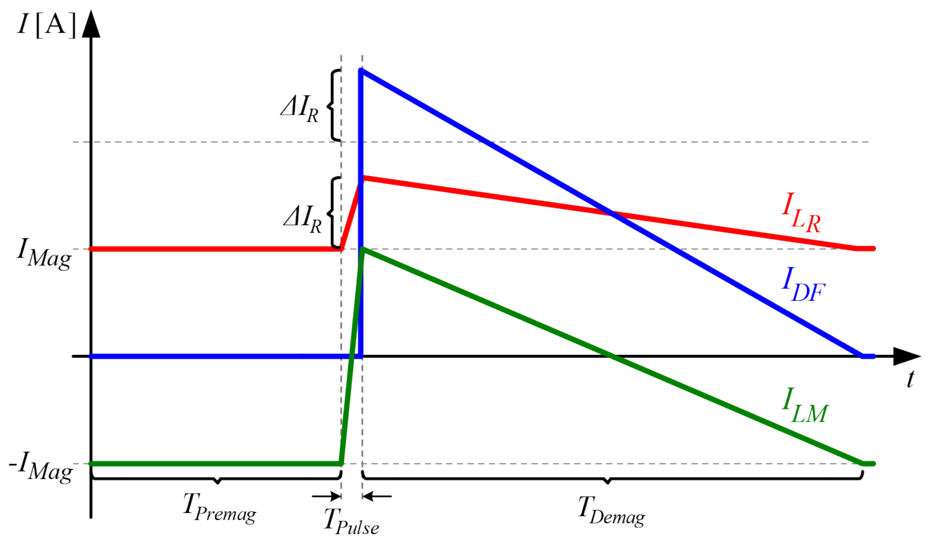
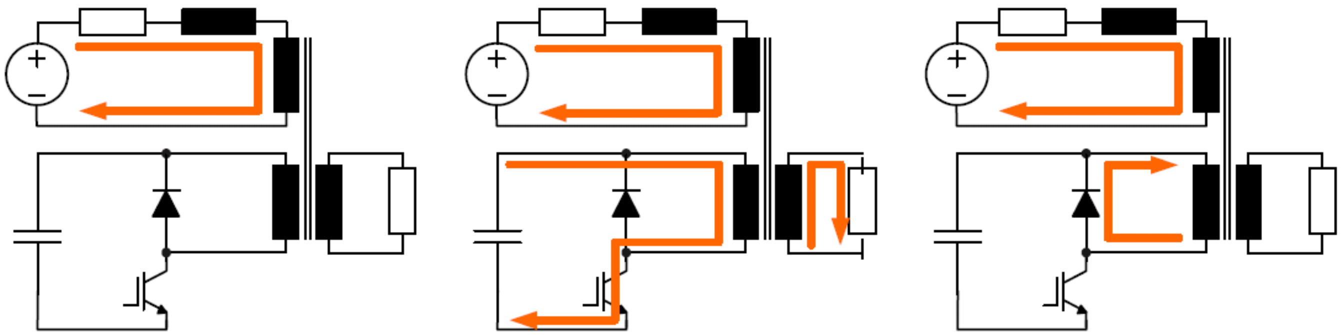
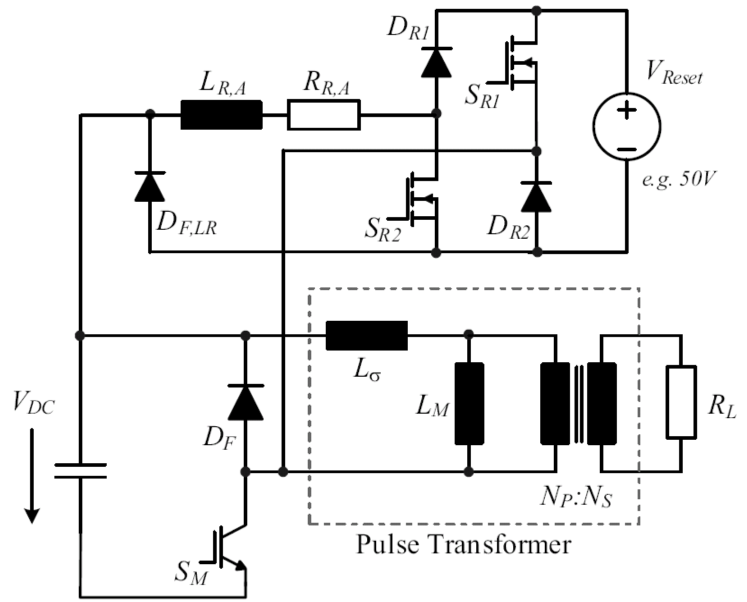


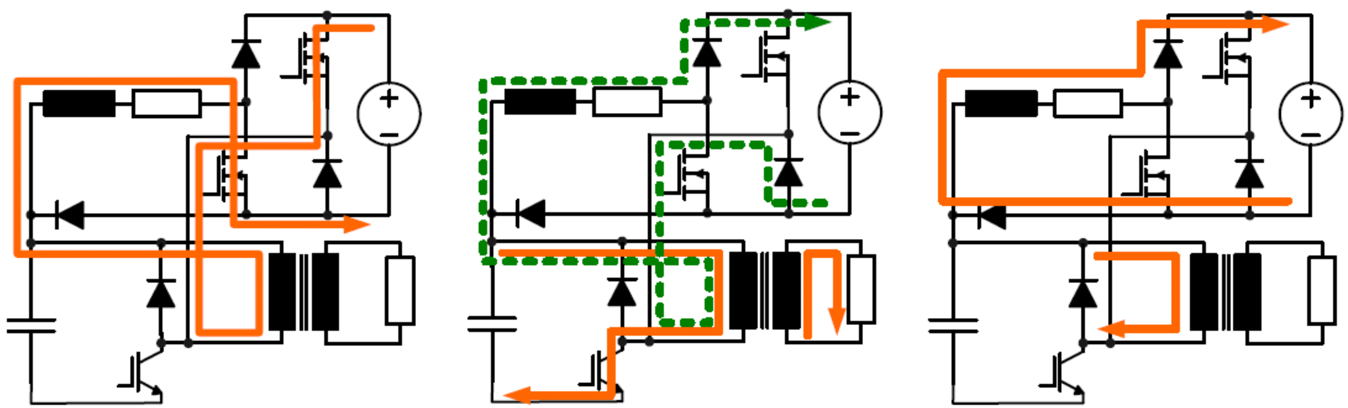


(a) *Premagnetisation* (b) *Pulse* (c) *Demagnetisation*

Improved DC Premagnetisation

- **Energy recovery possible (magnetization *L*)**
- **Pulse-by-pulse premagnetisation**
  - **- Low voltage MOSFETs/Diodes**
  - **- Choke for current source behaviour**
  - **- Low voltage source**
  - **- Negative output voltage during premagnetisation**





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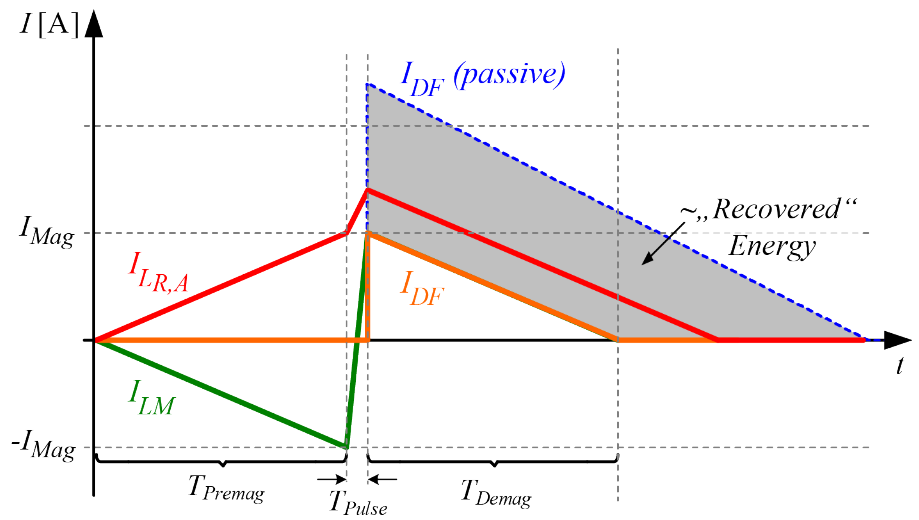
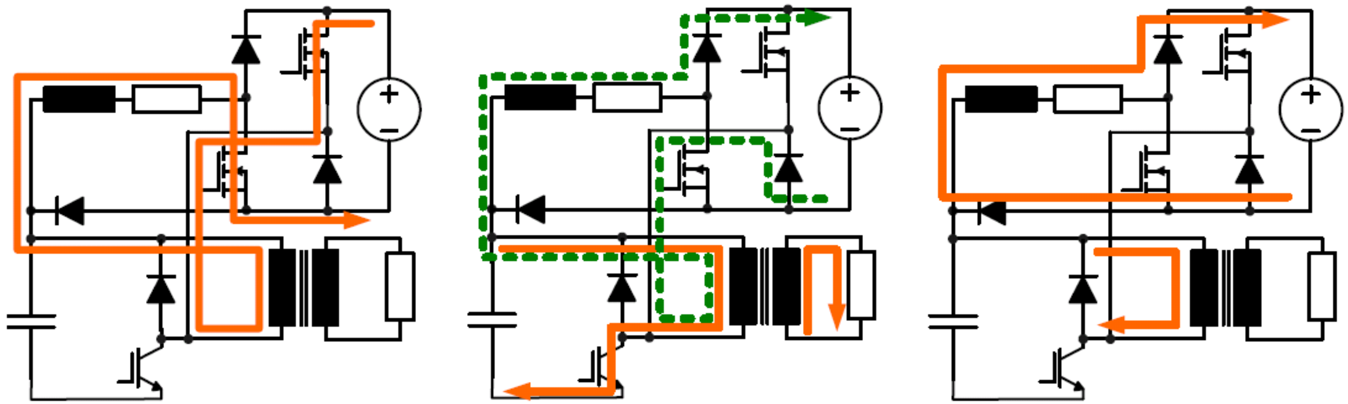
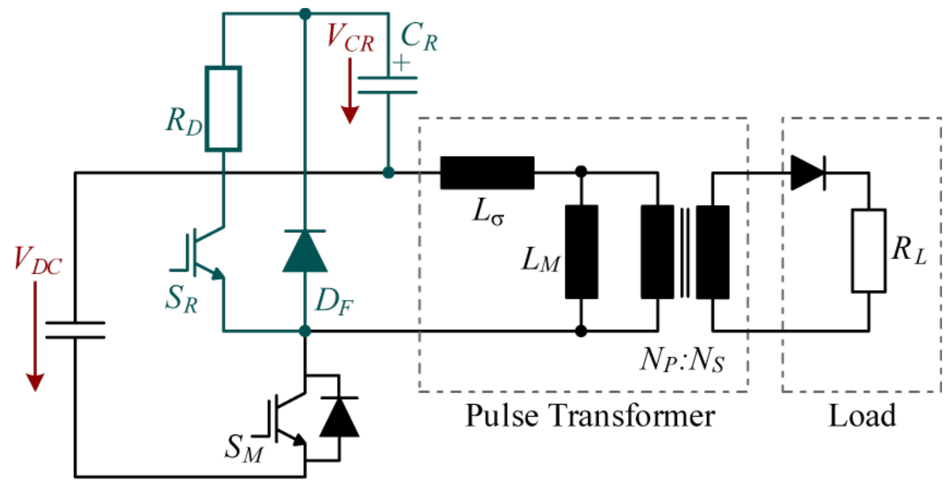


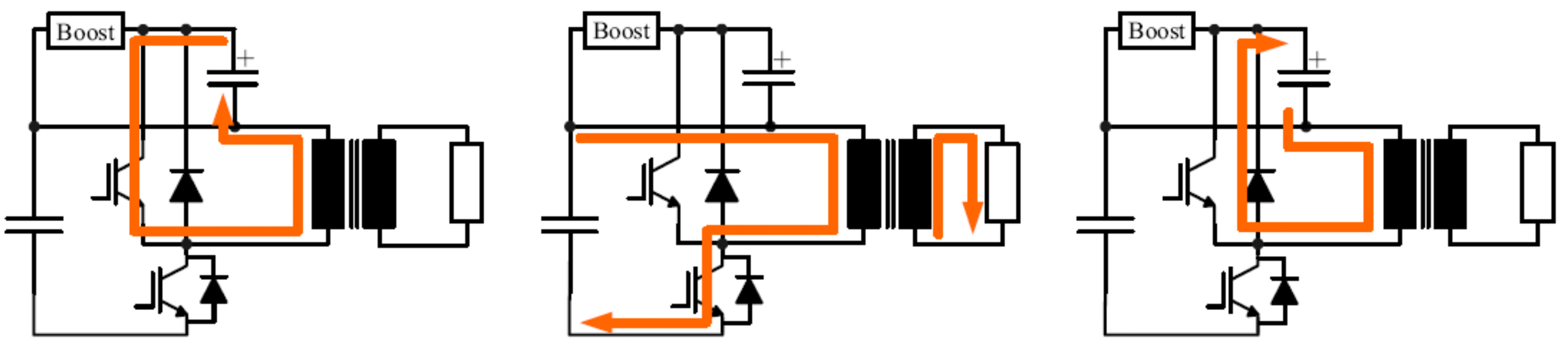


(a) *Premagnetisation* (b) *Pulse* (c) *Demagnetisation*

Active Premagnetisation

- **No premagnetisation-choke required**
- **Energy recovery possible (via D_F)**
- **Pulse-by-pulse premagnetisation**
- **Negative V_{Out} during premagnetisation**
- **Self regulating (no supply required)**





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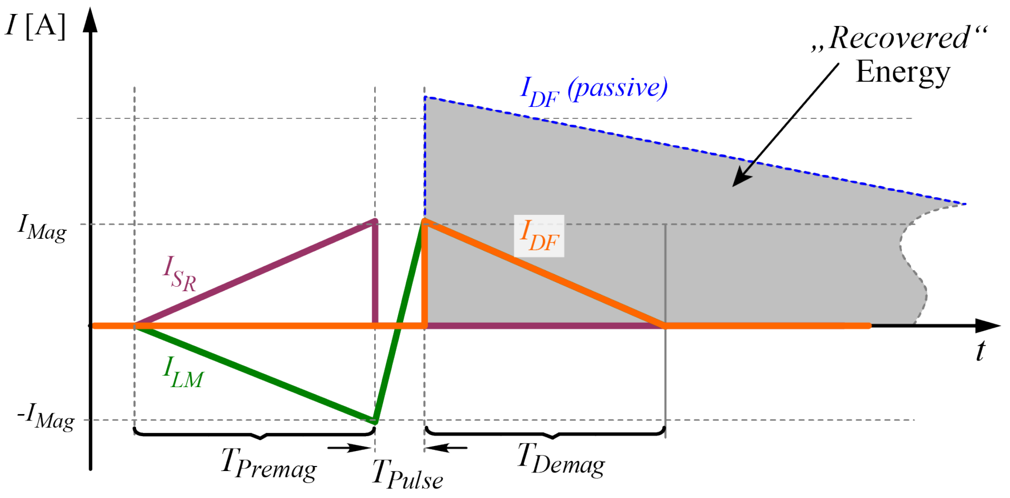

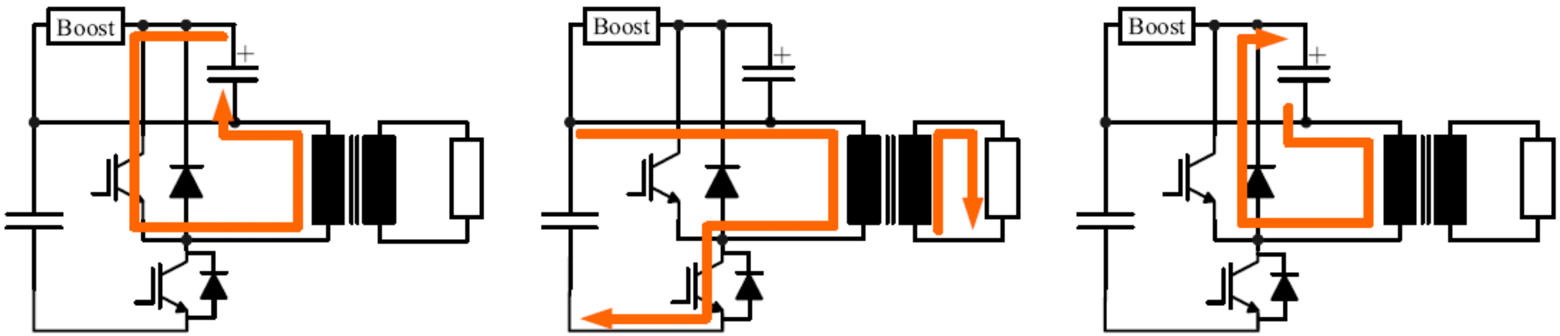

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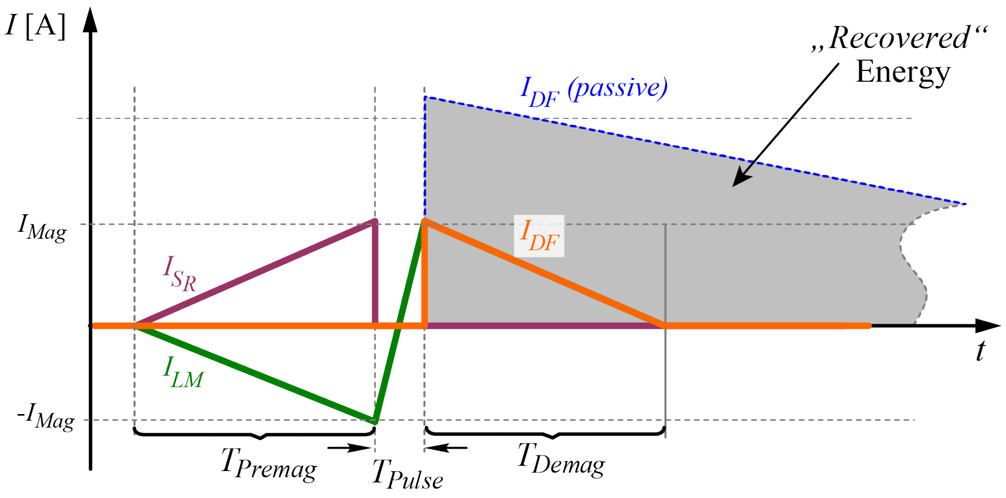
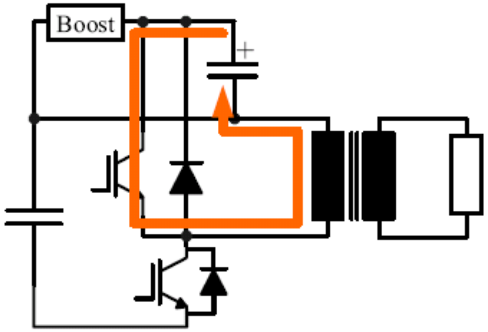
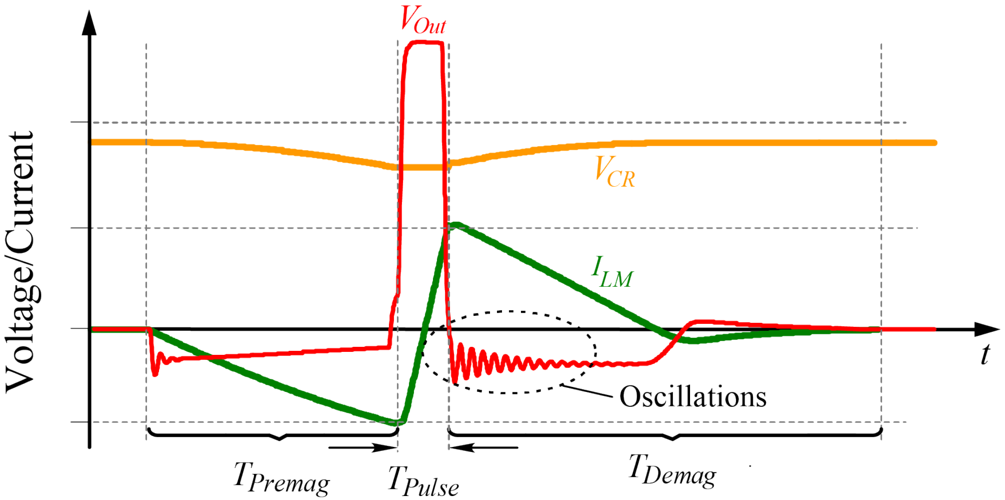


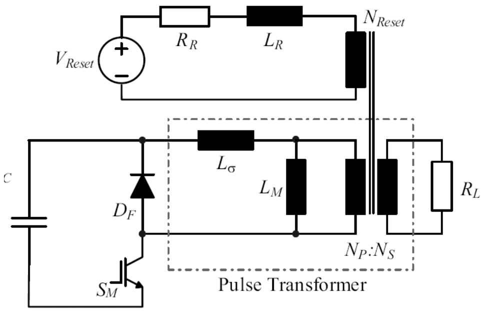


(a) *Premagnetisation*

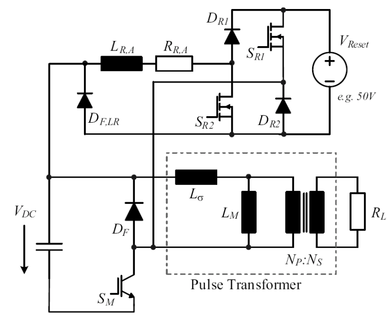


Premagnetisation - Comparison

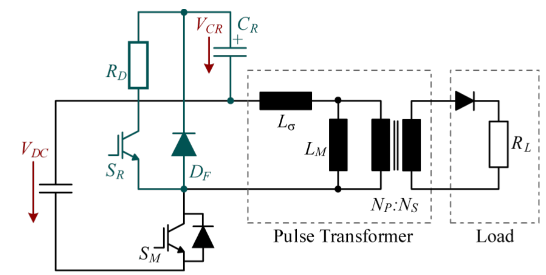
Passive



Advanced



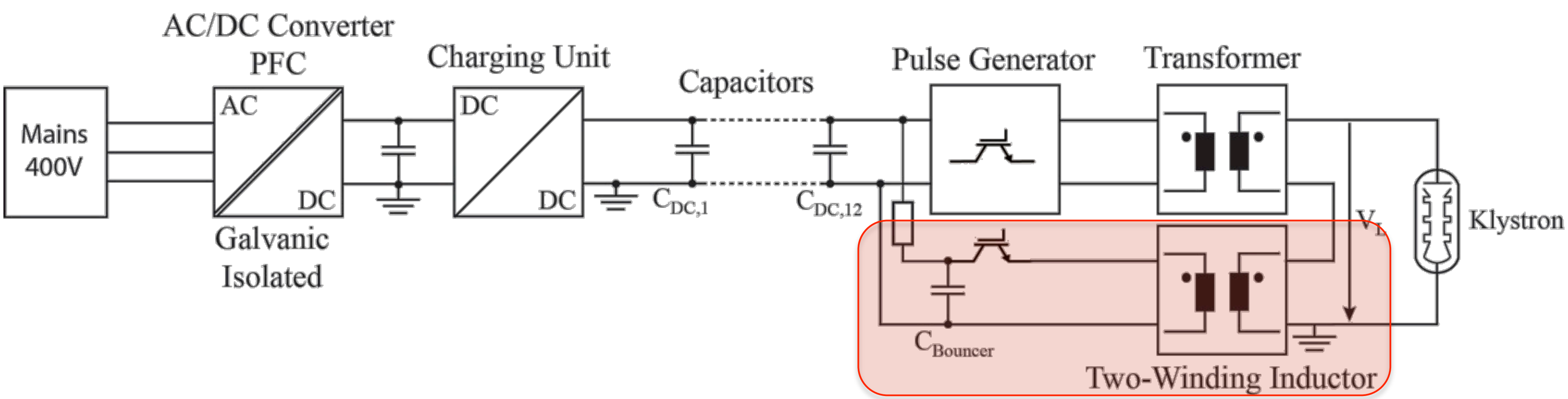
Active



	Passive	Advanced	Active
Complexity	Simple/Robust	high	medium
Components	Voltage Source low I / low V	MOSFET/Diode high I / low V	IGBT high I / high V
	Inductor low I / high V	Diode $D_{F,LV}$ high I / high V	Capacitor high I / med. V
3rd Winding	yes	no	no
Forward V_{DF}	high (~ 10V)	high (~ 10V)	low (2V)
Volume	high	high	medium
Losses	7.25 J	2.38 J	0.85 J
Numbers for 20MW modulator	1.45 kW	476.4 W	169.4 W

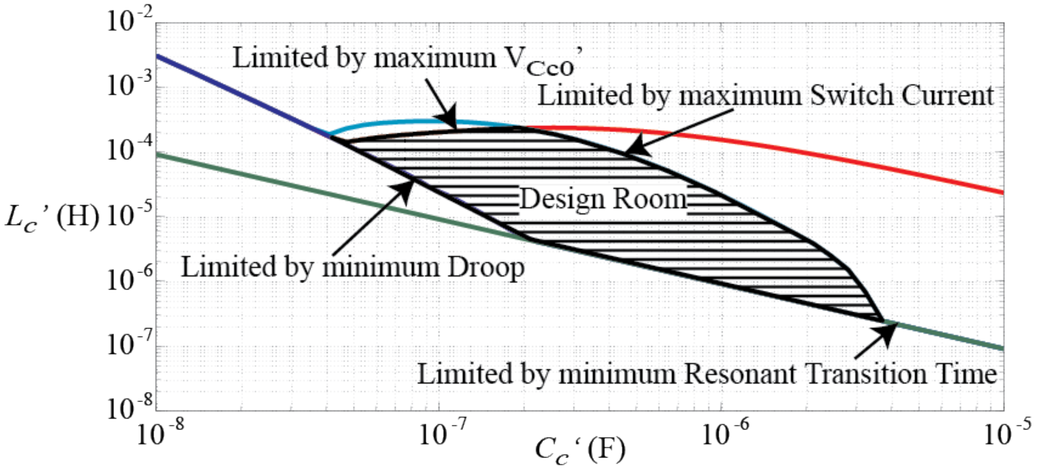
Short Pulse Solid State Power Modulator

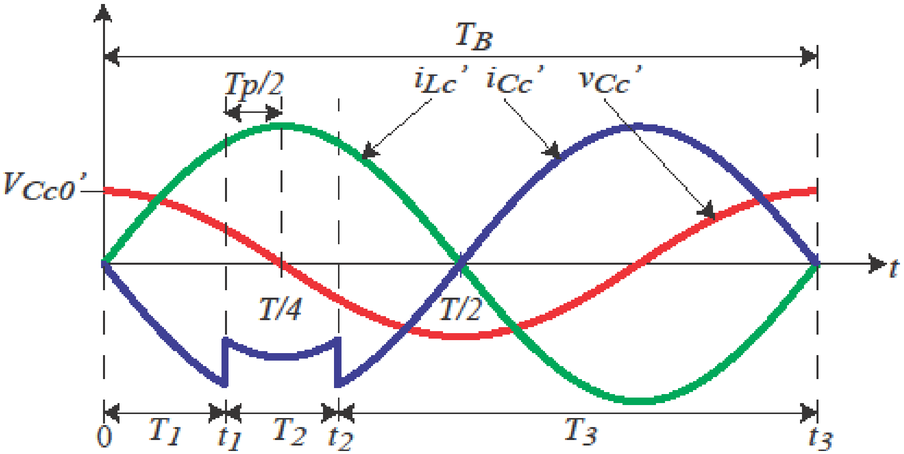
Bouncer

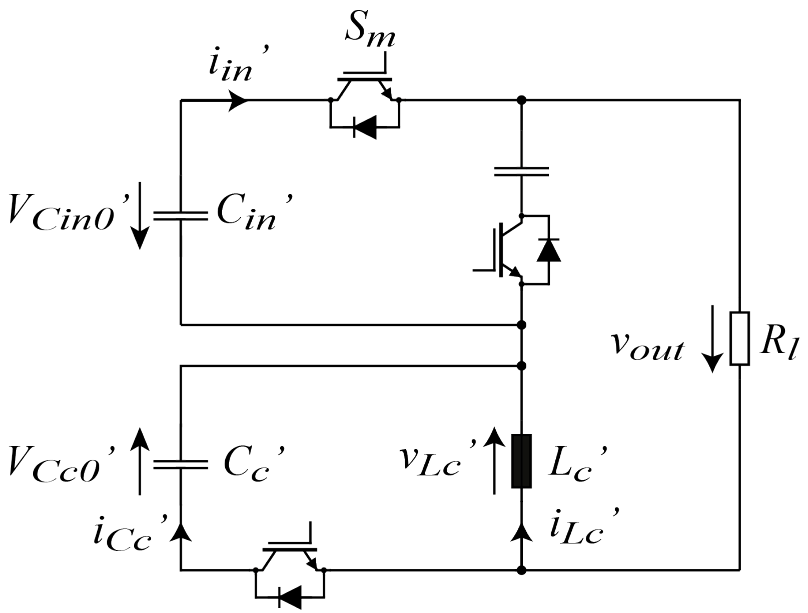


LC-Bouncer – Principle of Operation

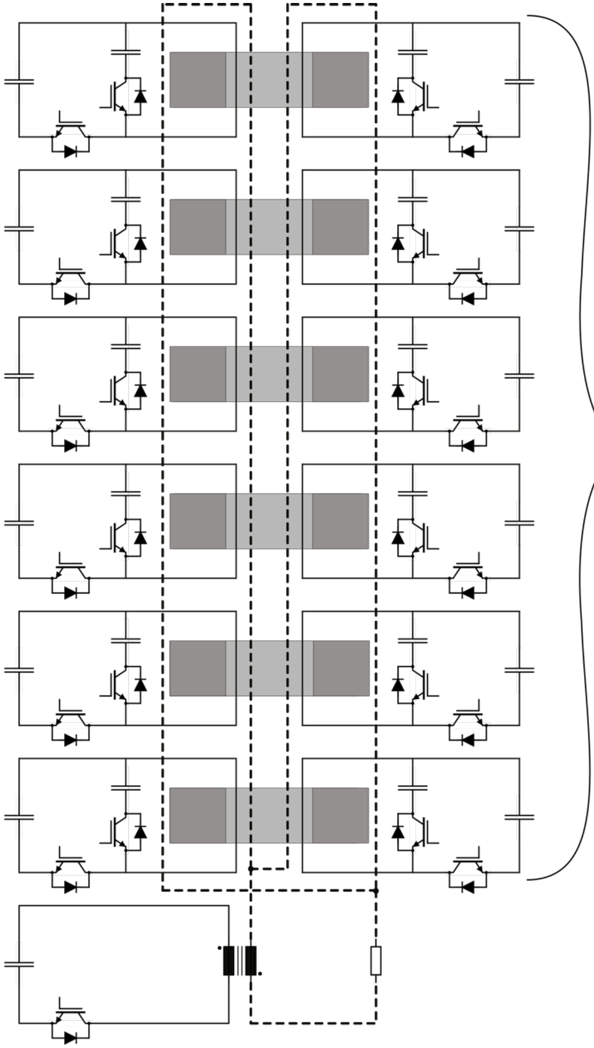
- ***LC*-oscillation: C_c & L_c**
  - Inductor voltage is added to pulse
  - Synchronisation: Mid of pulse = *T*/4
- **Two winding inductor**
  - ➔ Adaption to switch voltage
- **Design room is constraint by**
  - Max. switch current
  - Max. switch voltage
  - *LC*-oscillation frequency
  - Allowed droop



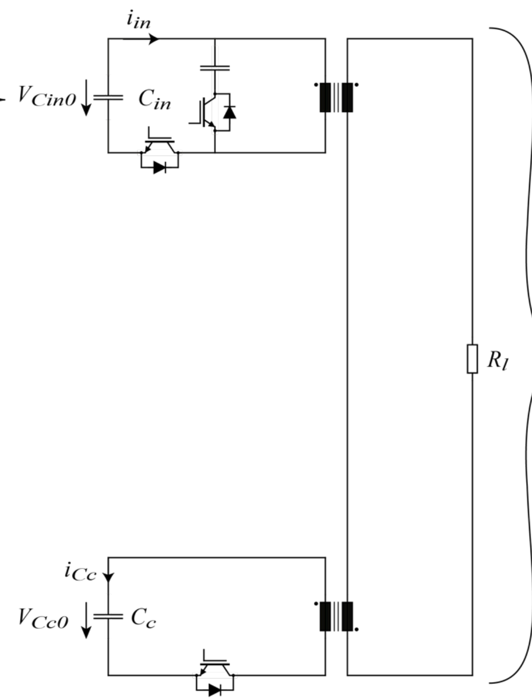




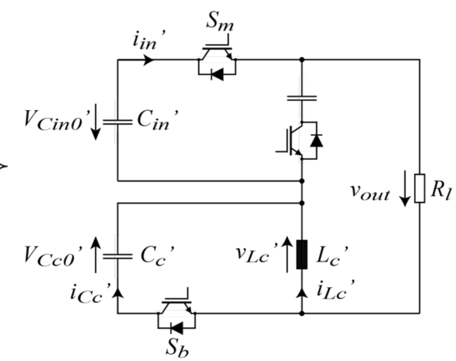
LC-Bouncer based on 2-Winding Inductor



Modulator with Matrix Transformer and
Two-Winding Inductor Bouncer



Circuit with simplified Matrix Transformer

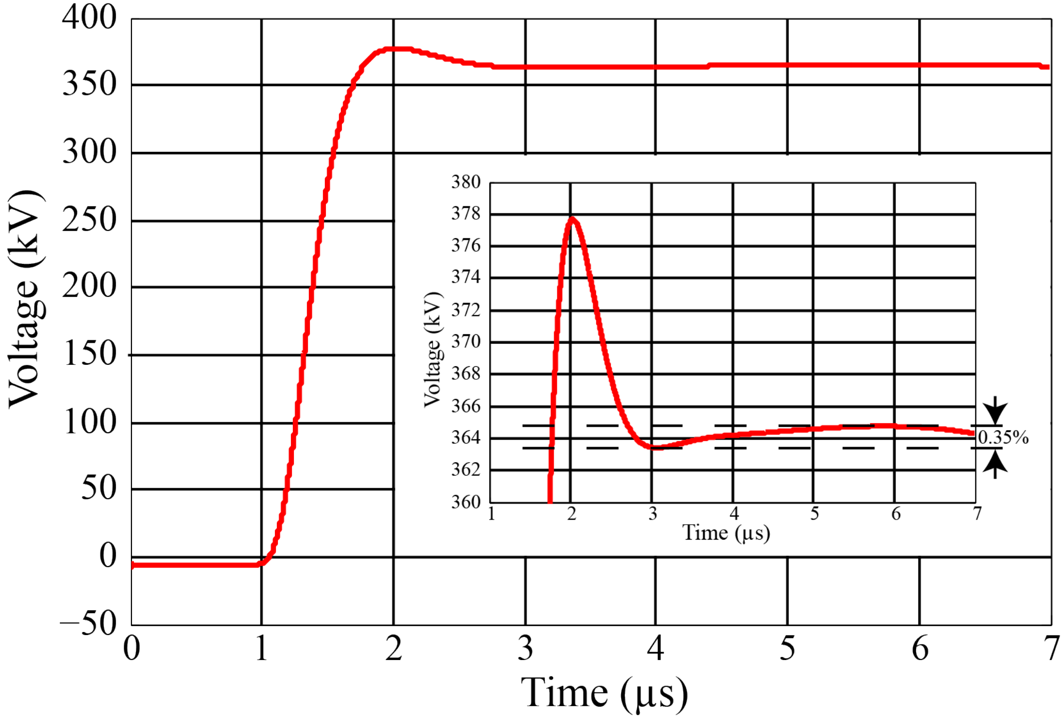


Simplified Circuit without Galvanic Insulation,
Values refered to Secondary Side

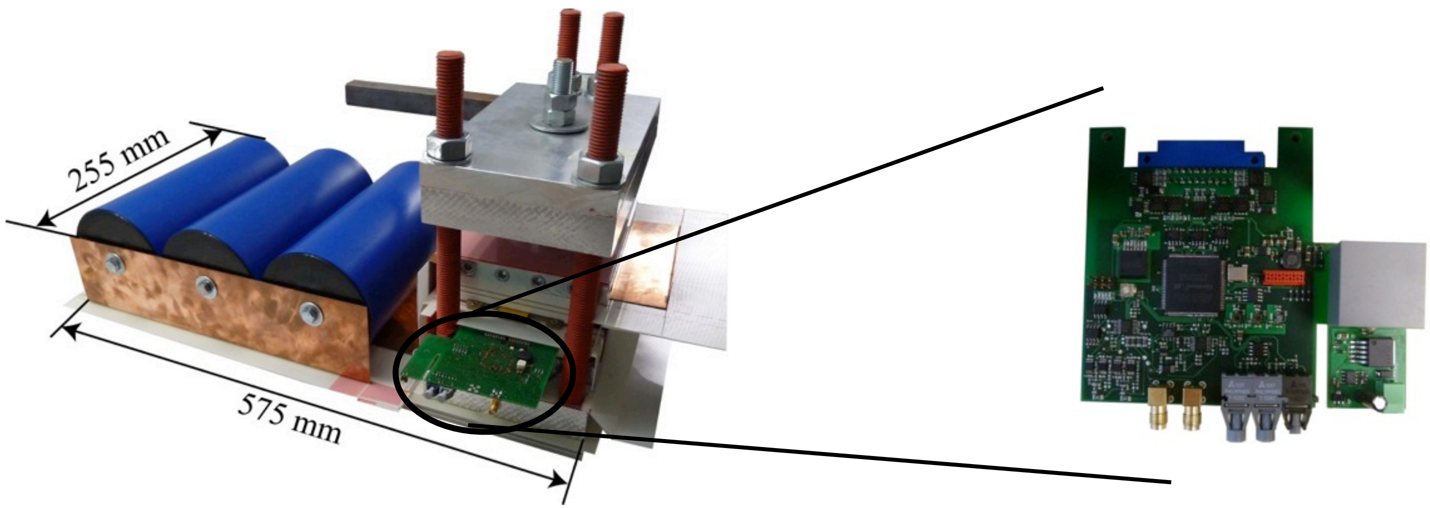
LC-Bouncer – Design Results

- **Capacitor:**
  - Capacitance 1.5µF
  - Initial voltage 3kV
- **Inductor:**
  - Inductance 3.3 µH
  - Inductor core AMCC-800A
  - Dimensions 90x130x70 mm
  - No of primary turns 3
  - No of secondary turns 6
  - Peak current 1.7kA

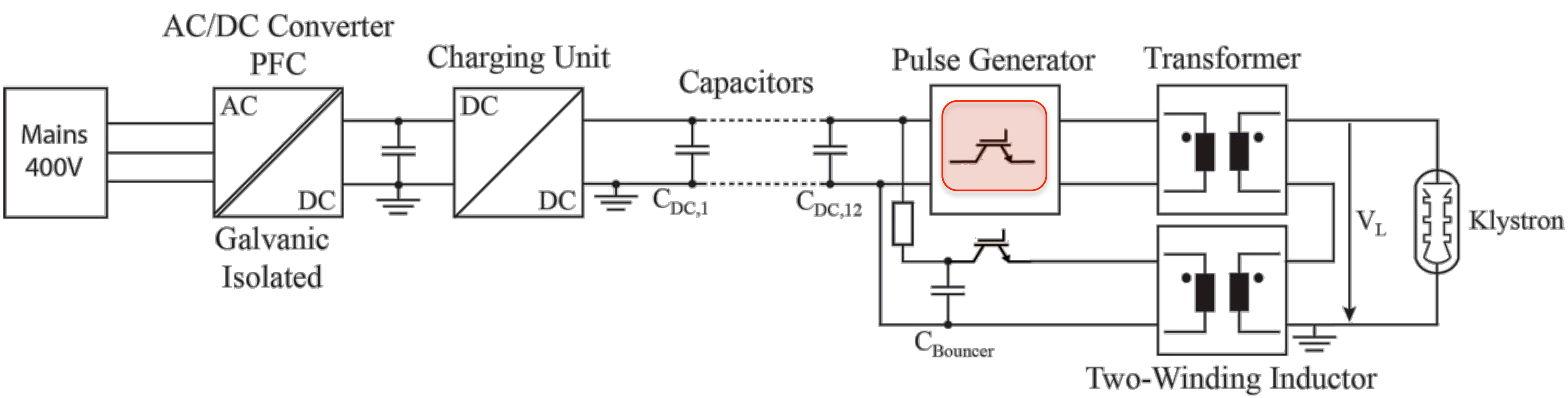
- **Jitter of bouncer**
  ➔ **Major impact on repeatability**



Short Pulse Solid State Power Modulator

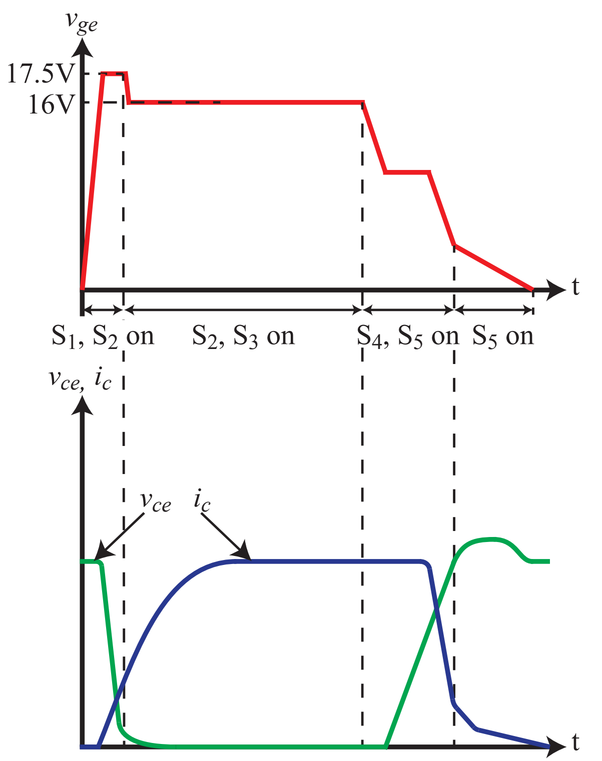


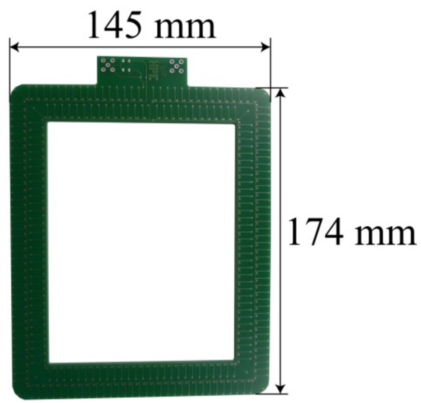
Switching Unit / Gate Drive

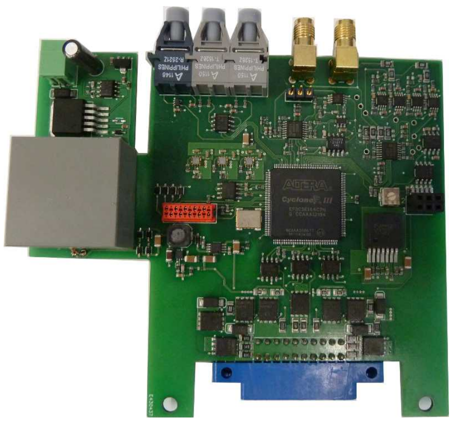


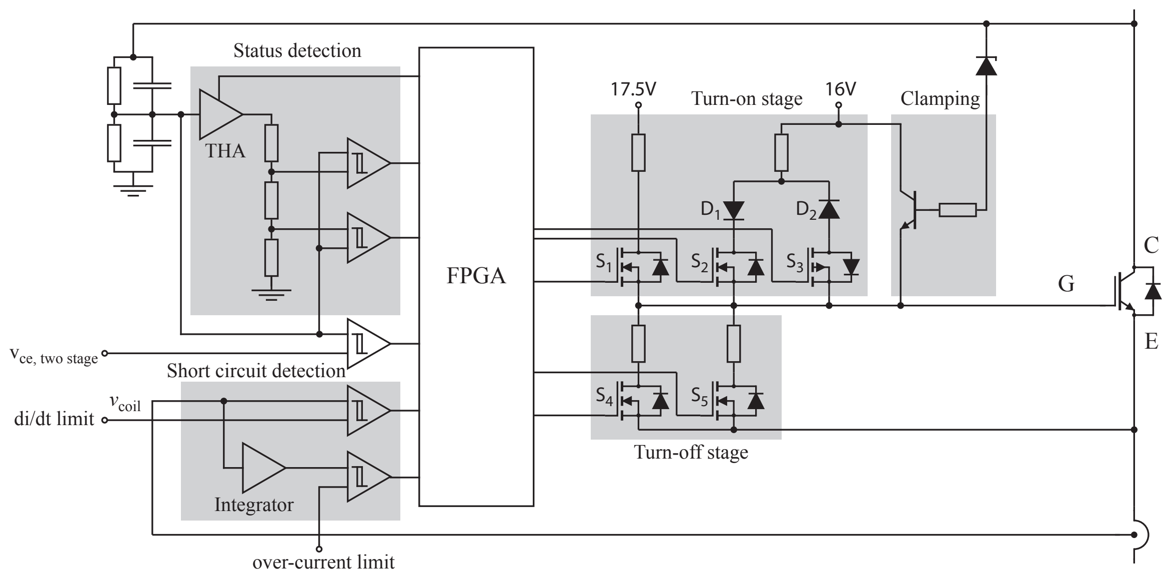
Gate Drive

- **Fast turn on of IGBT**
  - ➔ **Multi-stage turn on**
- **Fast turn off of IGBT**
  - ➔ **Multi-stage turn off**
  - ➔ **Voltage clamping**
- **Fast over-current / over-d*i*/d*t* detection**
  - ➔ **Rogowski coil**



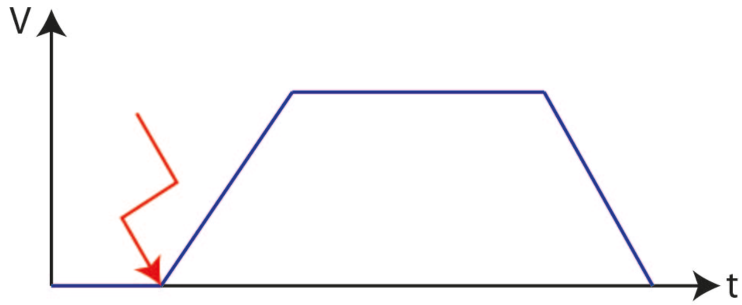


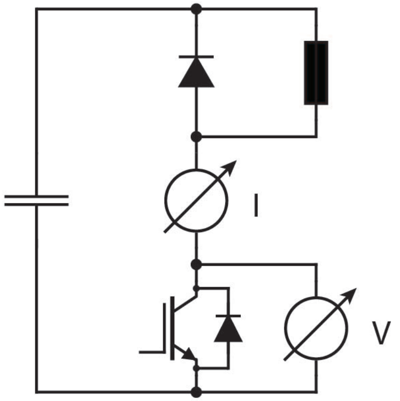




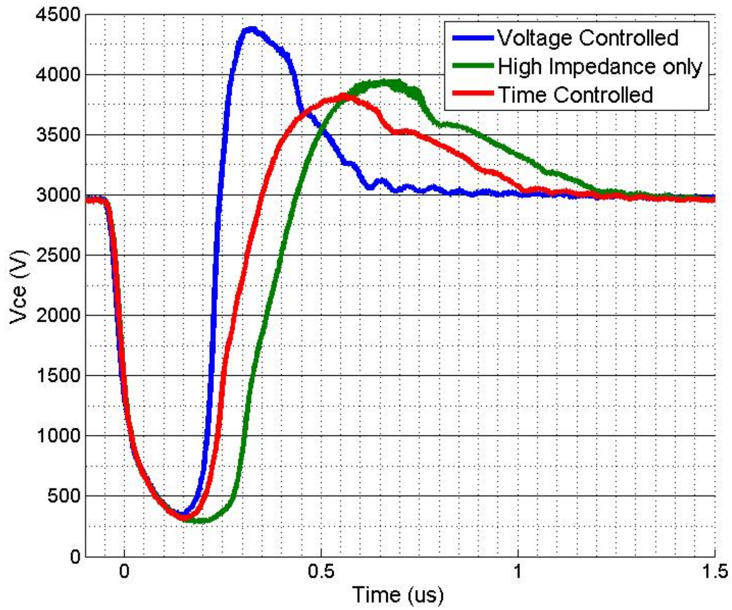
Turn on with existing Short Circuit

- **Short circuit inductance: 50nH**

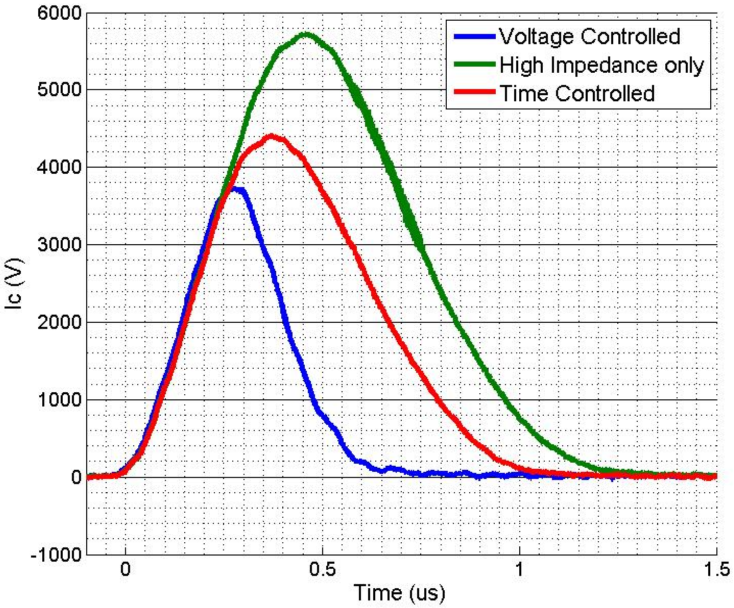




Collector-Emitter Voltage

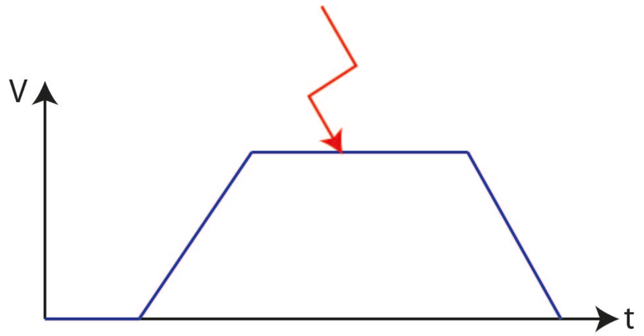


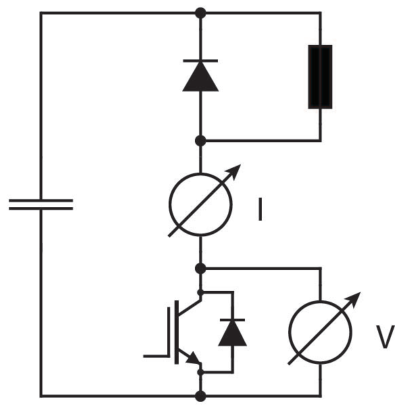
Collector Current



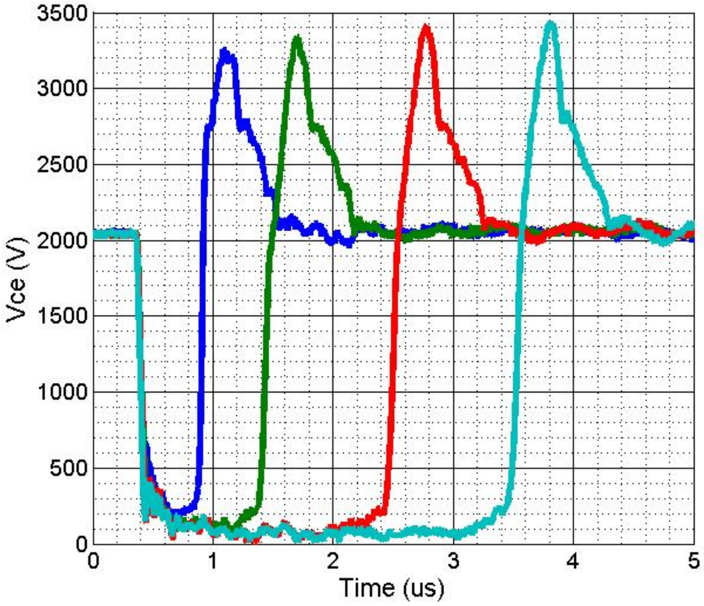
Short Circuit during Pulse

- **Short circuit @ 50nH / 2kV / 500ns...3µs**

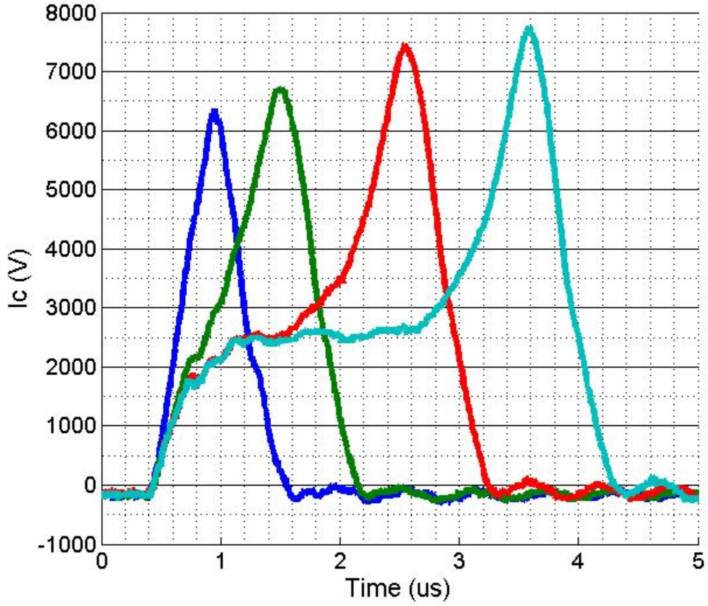




Collector-Emitter Voltage

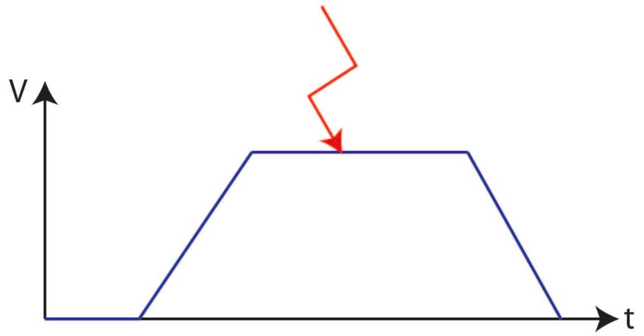


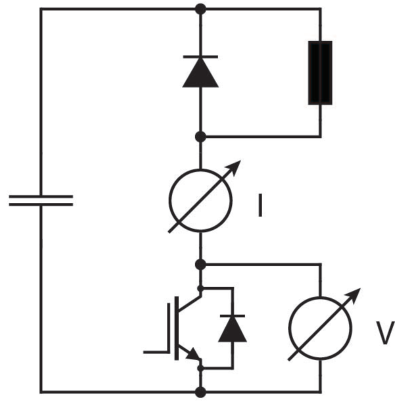
Collector Current



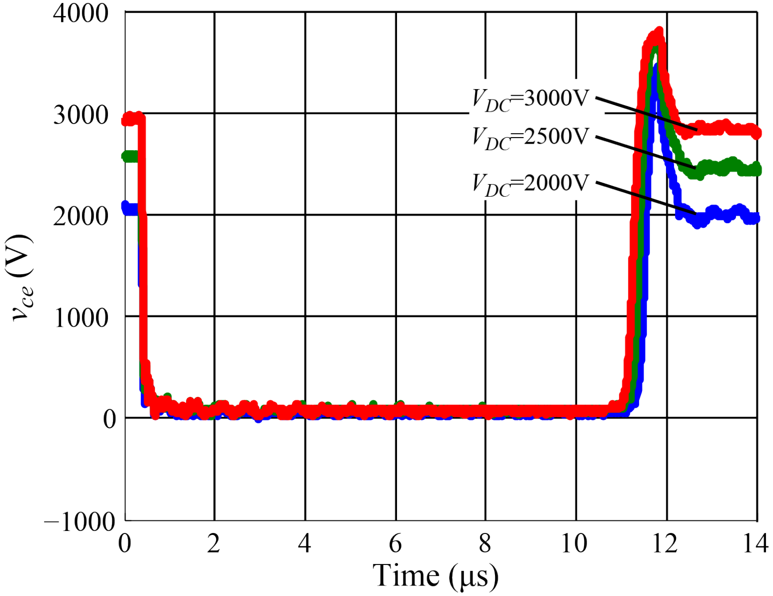
Short Circuit during Pulse – Long Pulse

- **Short circuit @ 50nH / 3kV / 10µs**

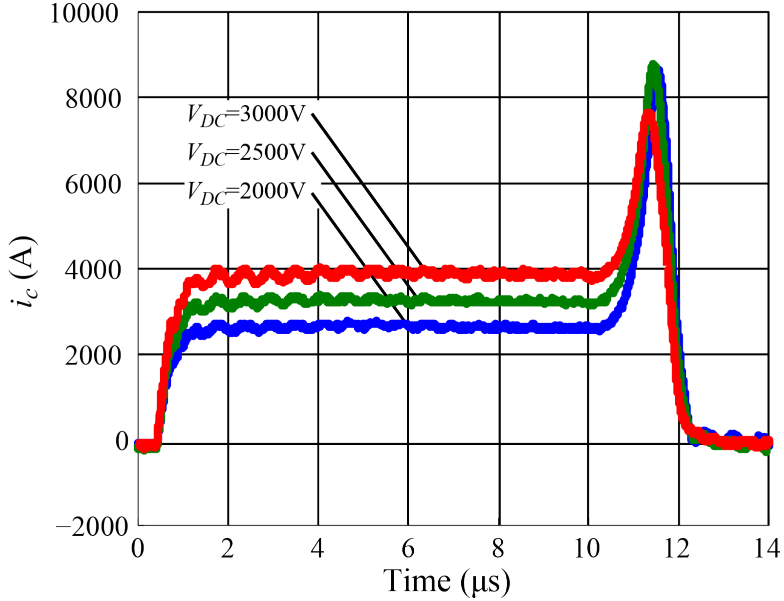




Collector-Emitter Voltage

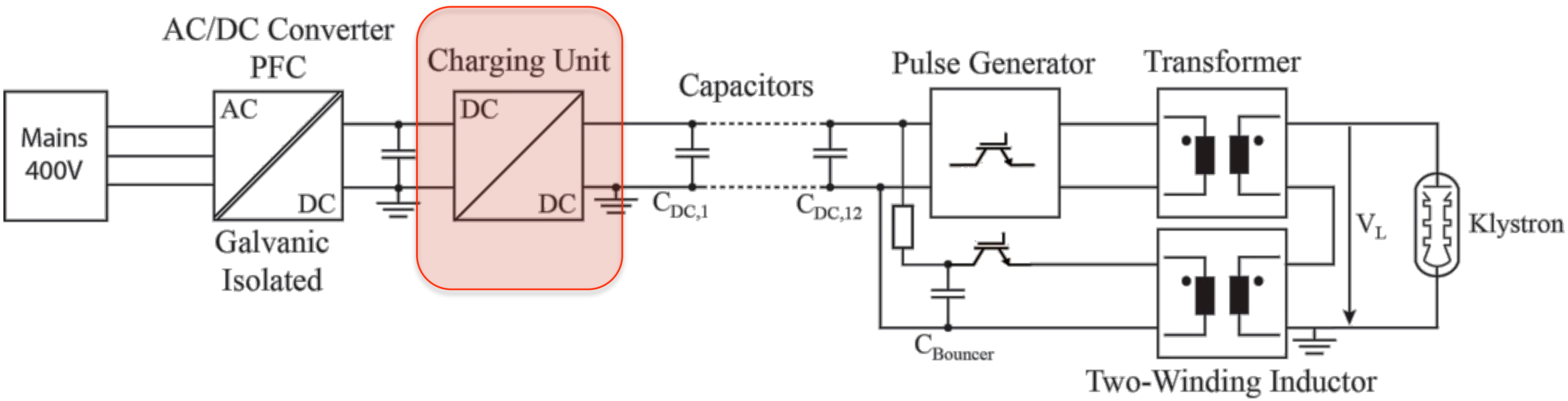


Collector Current



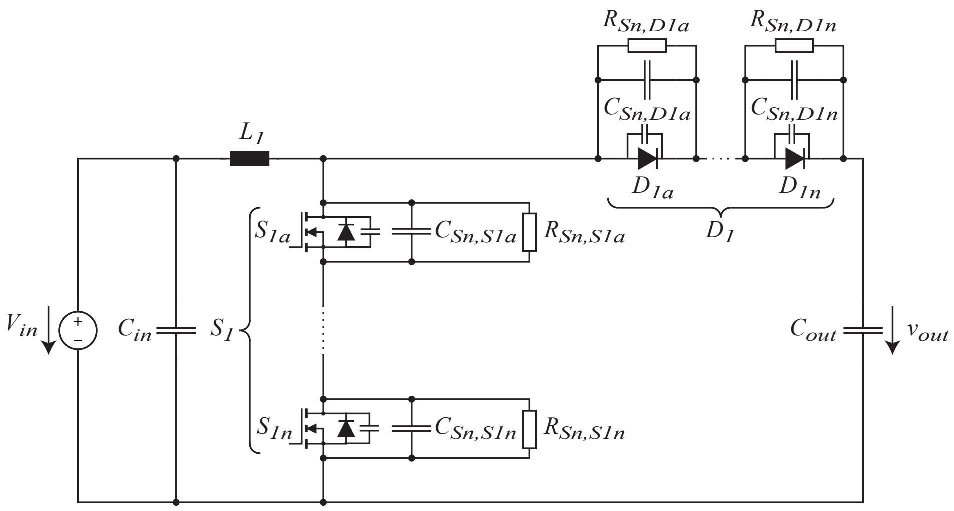
Short Pulse Solid State Power Modulator

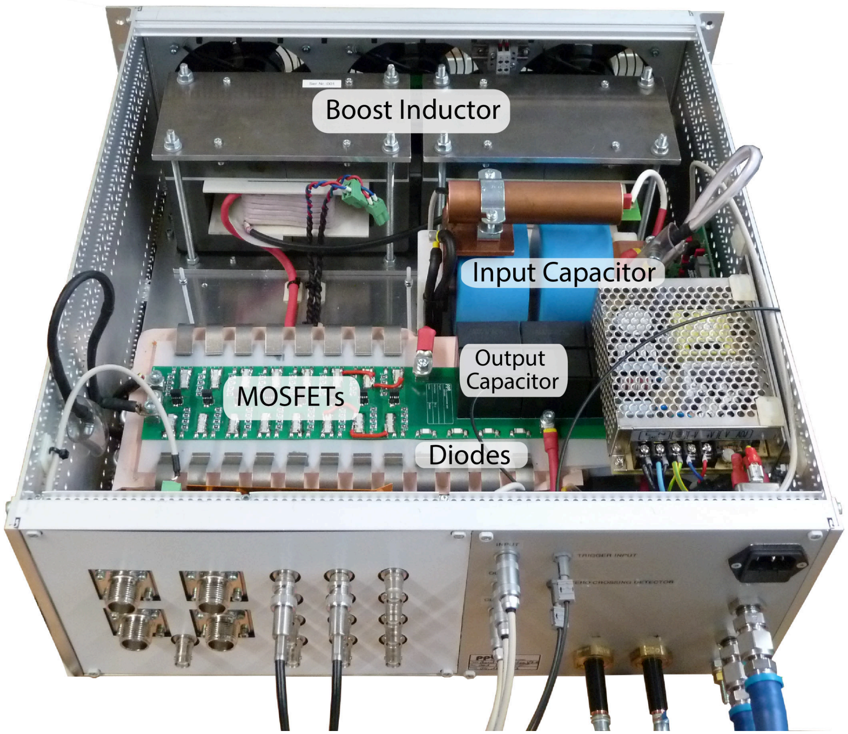
Ultra Precise Charging



Ultra-Precise Charging Converter

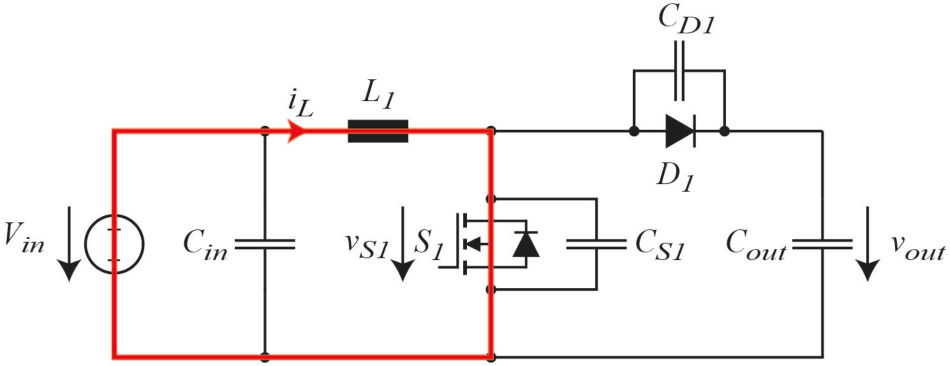
- **Triangular current mode (TCM)**
- **Two interleaved converters**
- **Input voltage** V_{IN} = 1.3kV
- **Output voltage** V_{Out} = 3kV ± 30mV
- **Output power** P_{Out} = 2 x 40kW
- **Switching freq.** f_S = 70 – 250kHZ
- **Repeatability** 10ppm

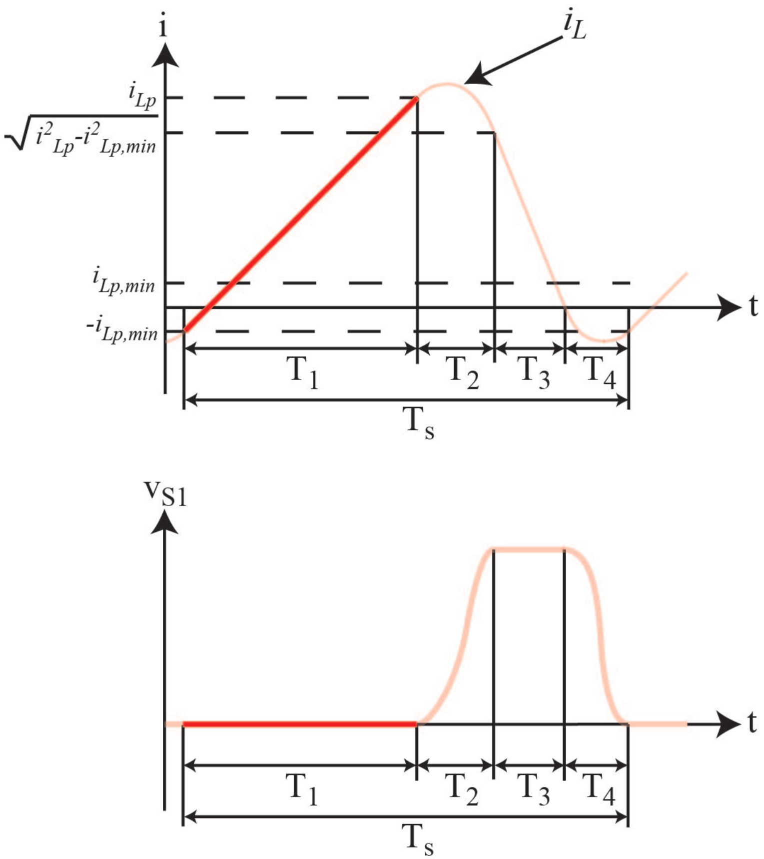




Operating Principle – Charging of Inductor

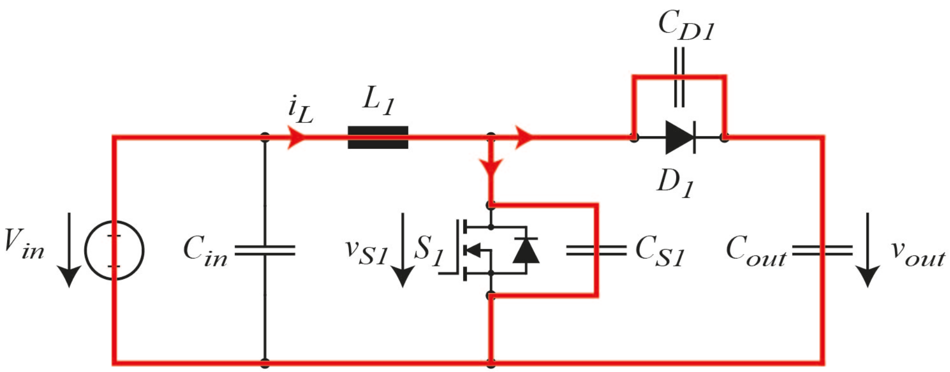
- **Interval T_1**
  - **- Inductor current increases**

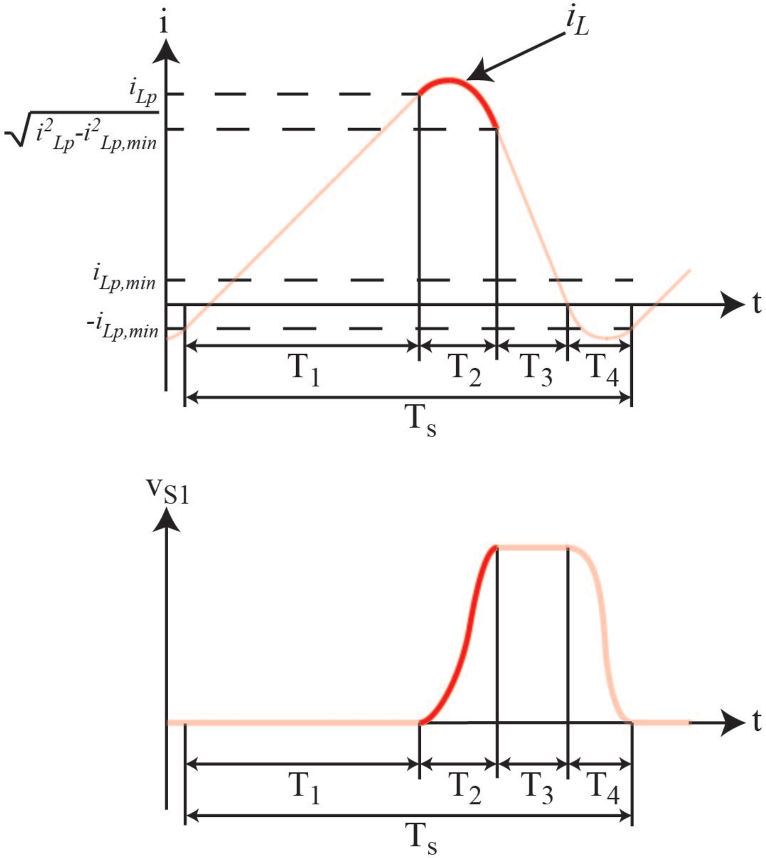




Operating Principle – Resonant Transition

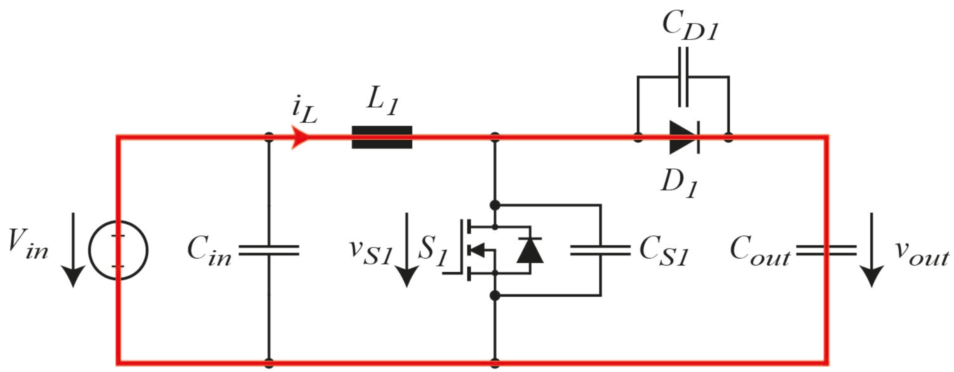
- **Interval T_2**
  - **- ZVS turn off of S_1**
  - **- Resonant transition**
  - **- C_{S1} is charged to v_{out}**
  - **- C_{D1} is discharged to 0**

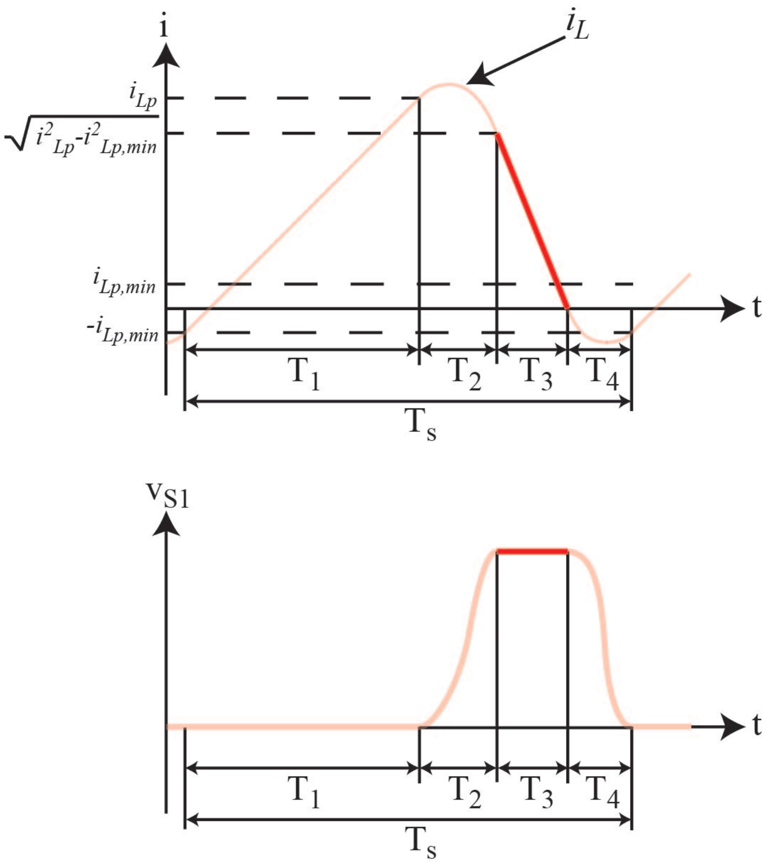




Operating Principle – Charging of Output Capacitor

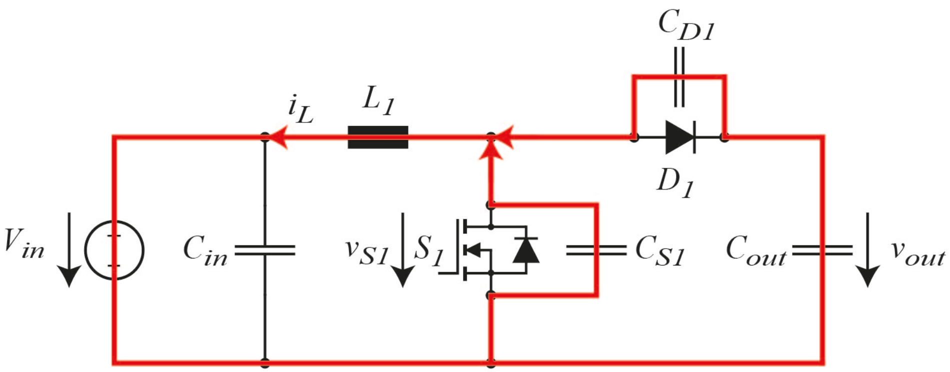
- **Interval T_3**
  - **- Inductor current decreases**
  - **- C_{out} is charged through D_1**

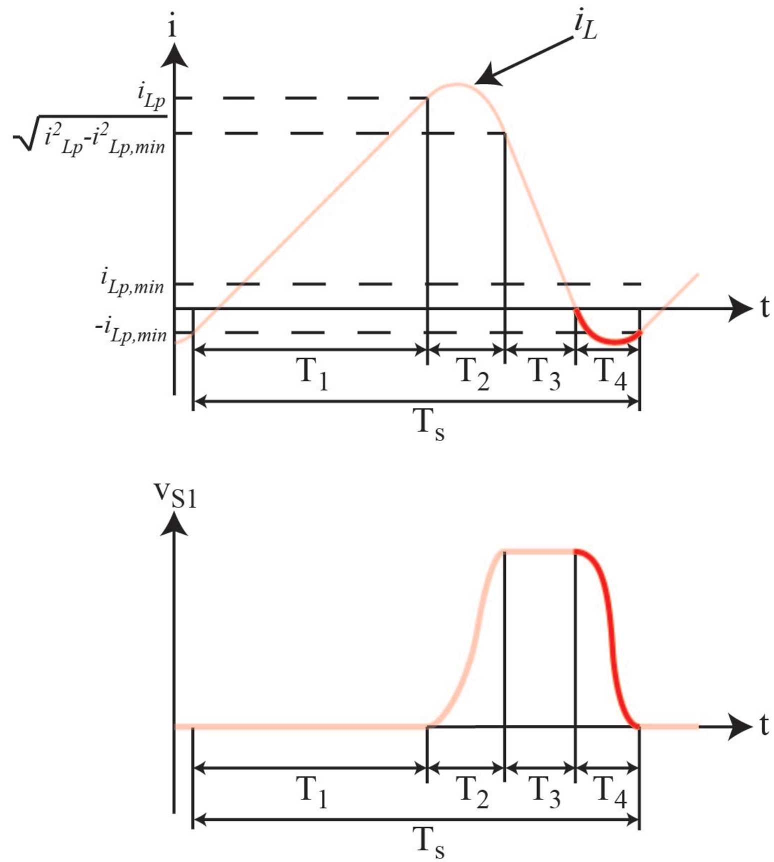




Operating Principle – Resonant Transition II ➔ ZVS Turn on off S_1

- **Interval T_4**
  - **- Resonant transition**
  - **- C_{D1} is charged to v_{out}**
  - **- C_{S1} is discharged to 0**
  - **- $C_S = C_{D1} + C_{S1}$**
  - **➔ Negative i_L**
- **Range of ZVS operation is limited**



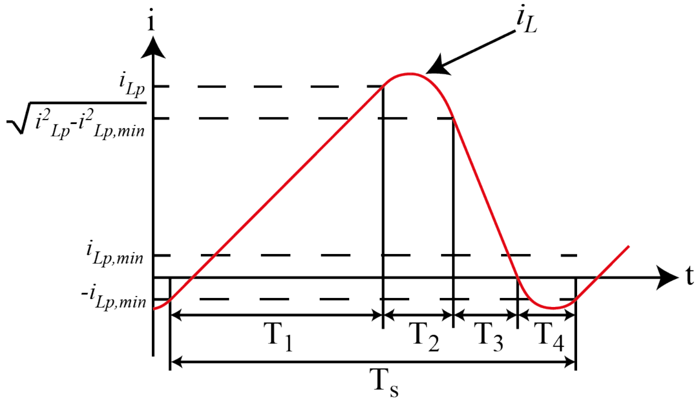


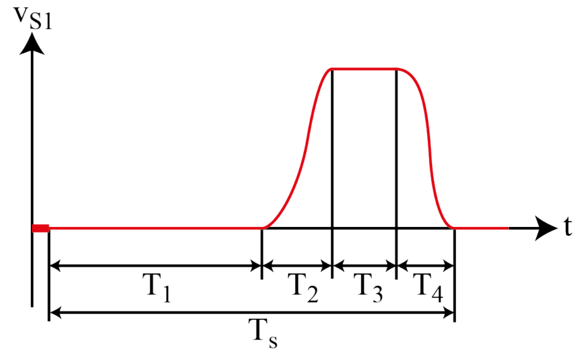
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

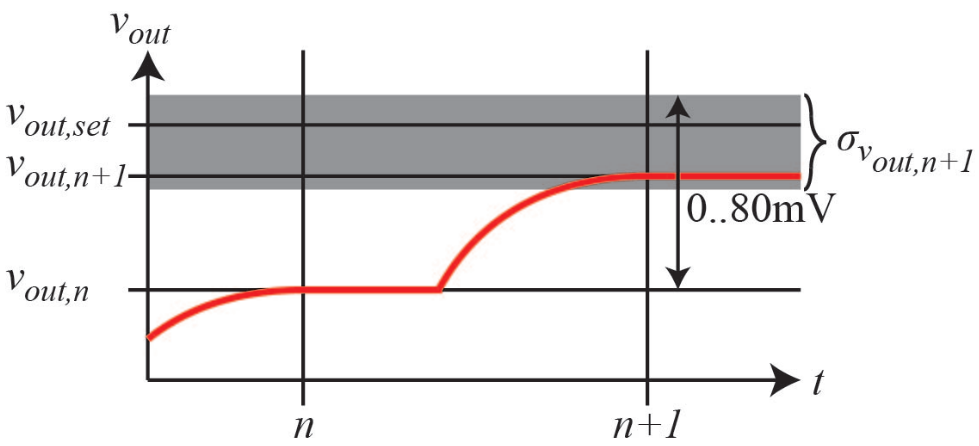
HPE
Laboratory for High
Power Electronic Systems

Control – Ultra precise charging

- Switching cycles are independent
- Cycle-to-cycle feedback control
- Required peak current / on-time is calculated for the next cycle
- i_{Lp}=0..80A ➔ Δv_{out}=0..80mV

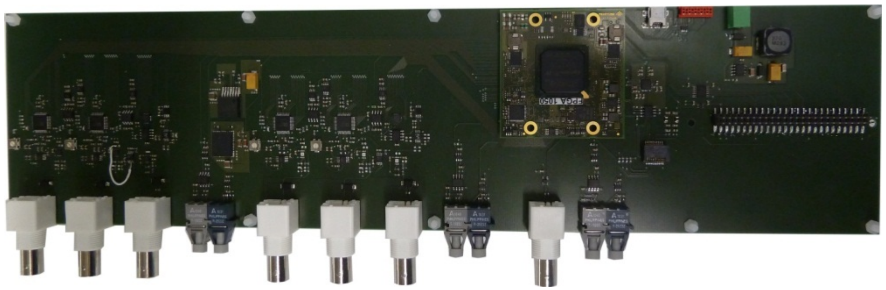


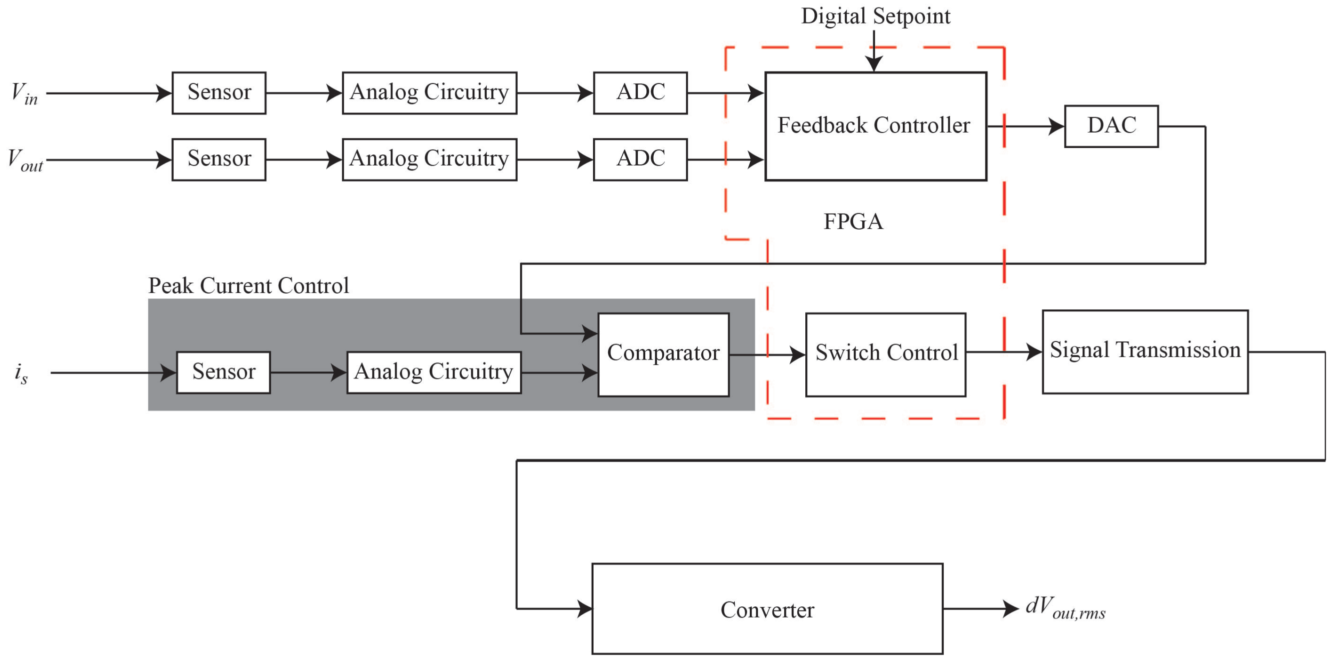




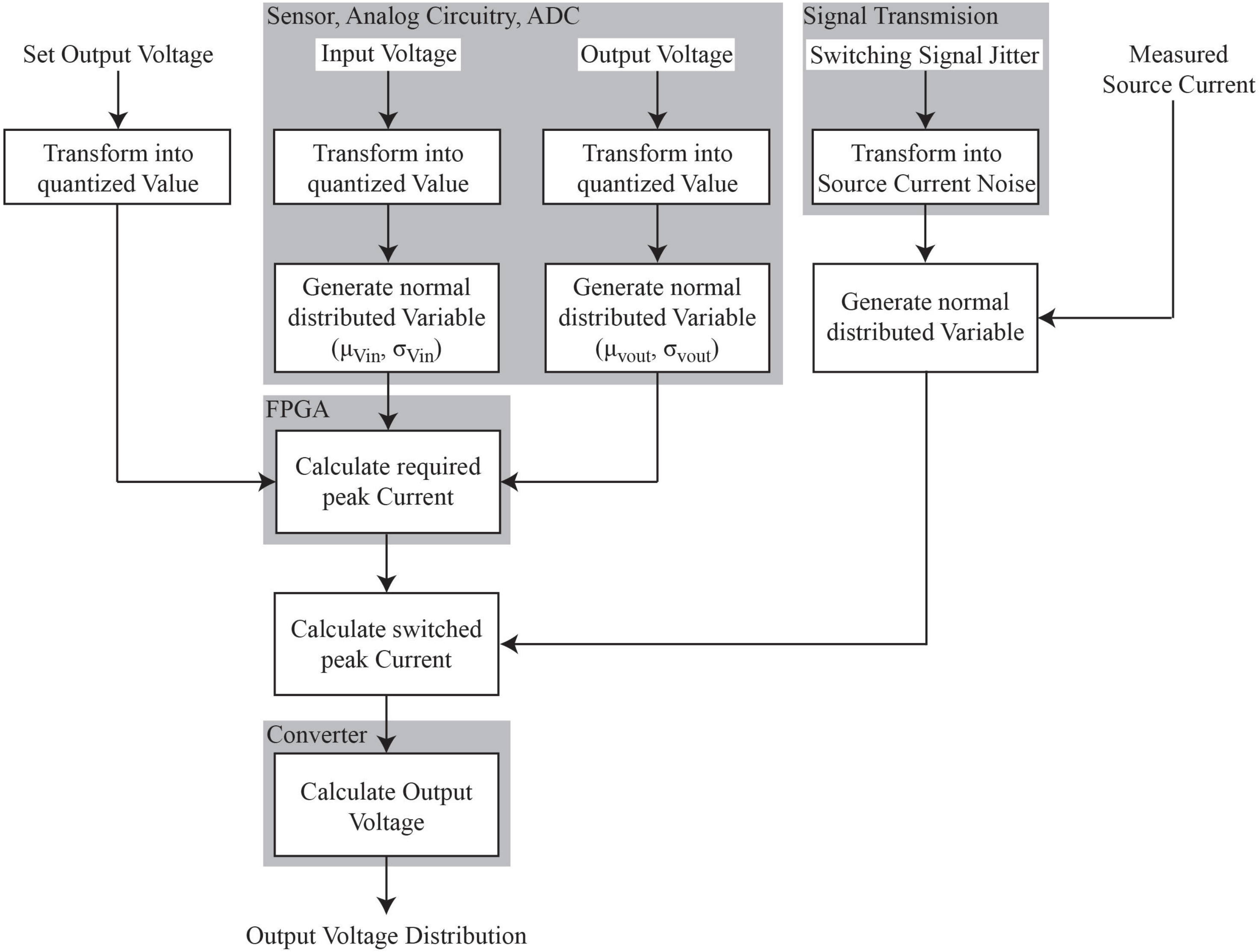
Control Hardware – Factors influencing Repeatability

- Input voltage measurement SNR
- Output voltage measurement SNR
- Switch current measurement SNR
- ADC resolution
- Quantization related errors
- DAC resolution
- Converter limitations
- Finite resolution in digital domain
- Switching signal jitter



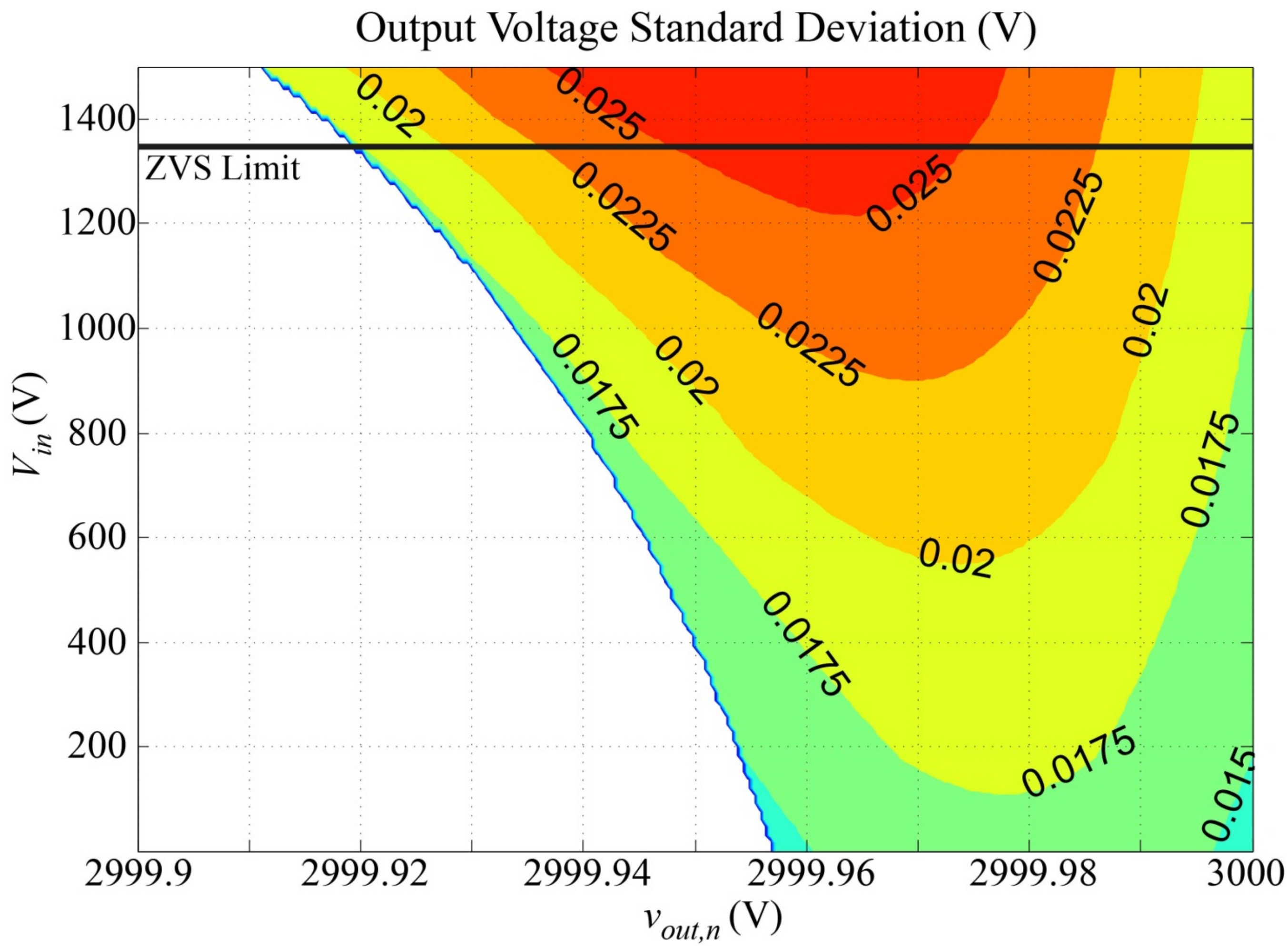


Precision Analysis: Algorithm

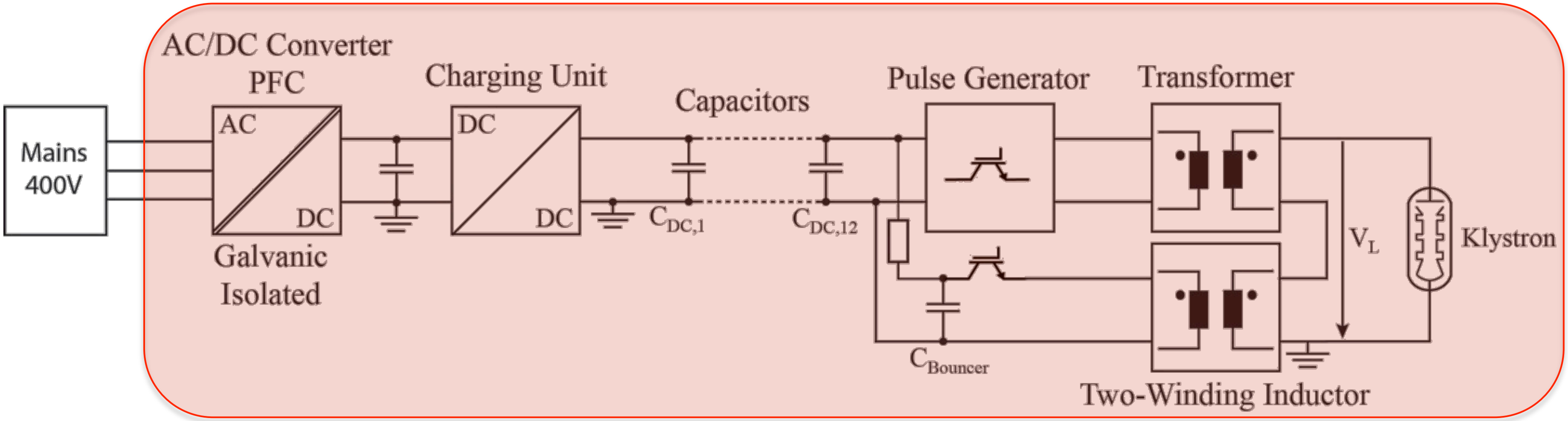


Charging Precision Analysis – Aim: ± 0.03V

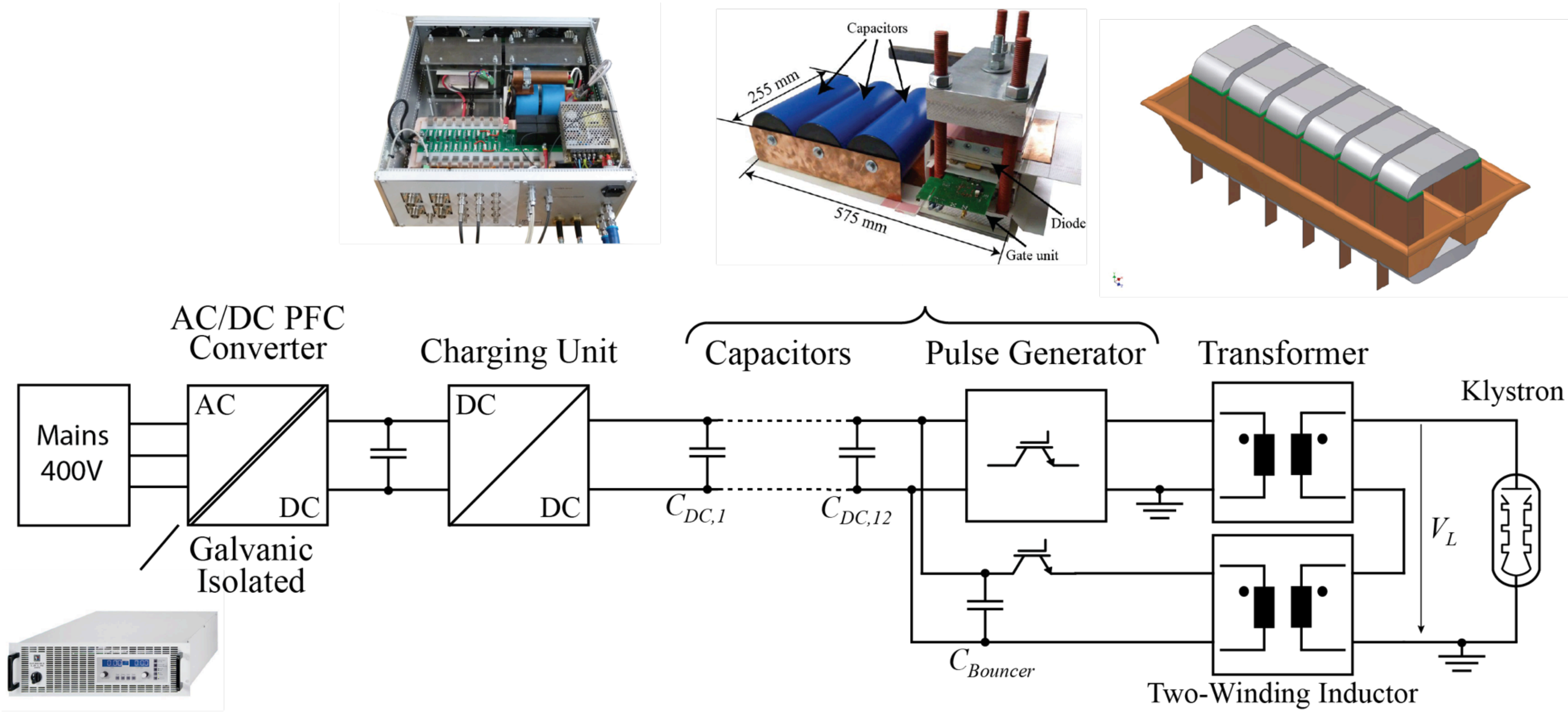
- **ADC** **18Bit**
- **DAC** **12Bit**
- **Jitter** **5ns**
- **SNR_{Vmeas}** **92.5dB**
- **SNR_{Vmeas}** **60dB**
- **Signal Delay** **260ns**



Short Pulse Solid State Power Modulator



Solid-State Modulator with Pulse Transformer & PFC Supply

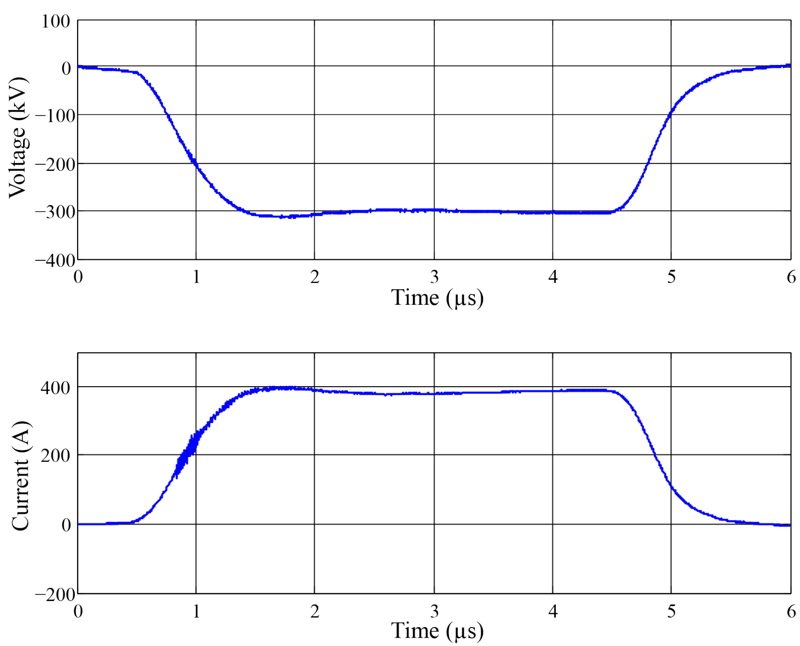


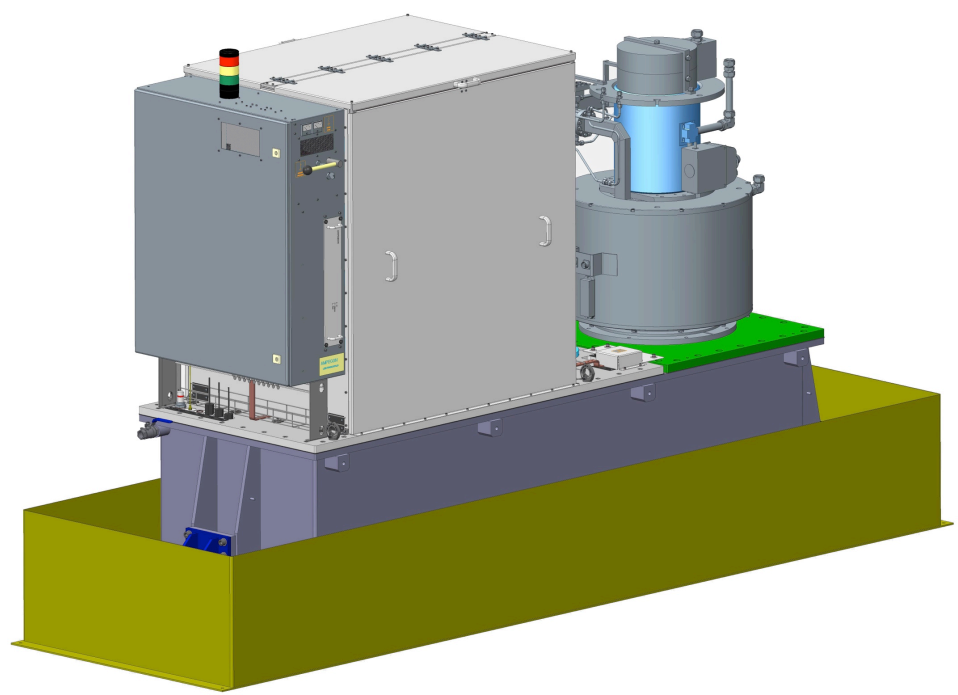
PFC / Charging Unit **Pulse Generator** **Pulse Transformer**

System Setup – 127MW / 370kV / 3μs

- **12 Sub-units**
- **24 Press-pack IGBTs**
  - **12 Main switches**
  - **12 Pre-magnetisation switches**
  - **(1 bouncer switch)**
- **6 Transformer cores**

➔ **Final testing mid 2014**



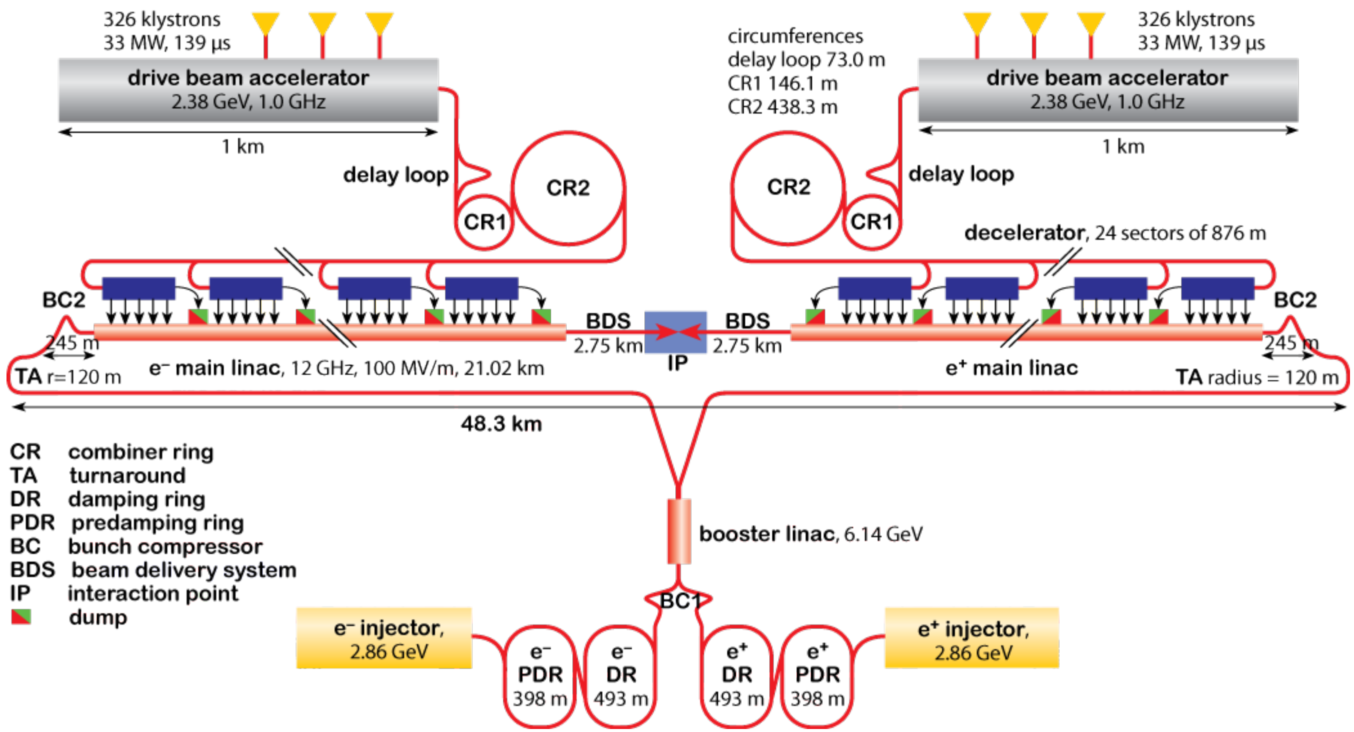


Medium Long Pulse Modulator
(~ 100μs)

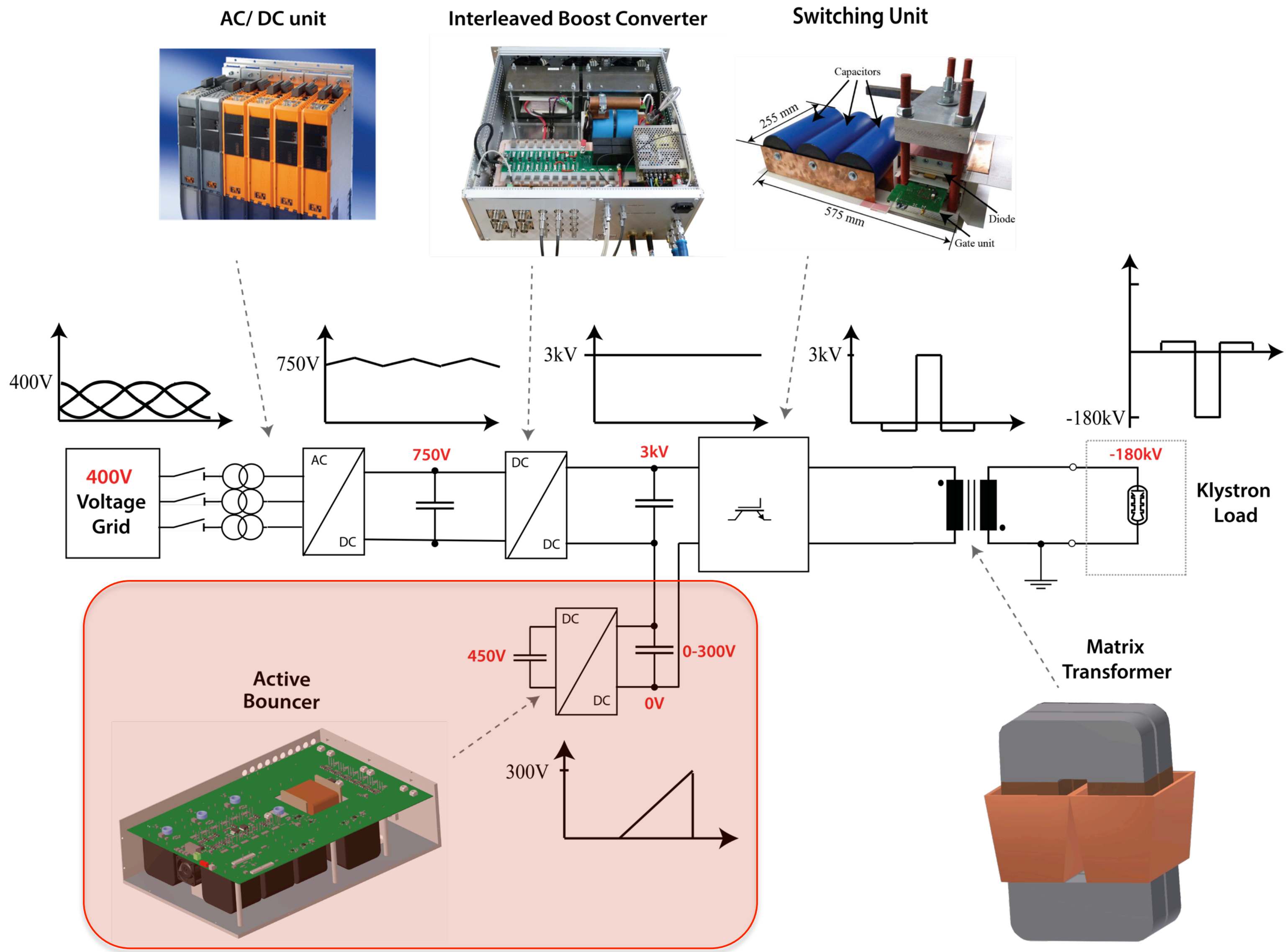
Ultra High Precision Klystron Modulators for Compact Linear Colliders (CLIC)

CLIC System Specifications

- **Pulse voltage** — **180kV**
- **Pulse power** — **35MW**
- **Pulse duration** — **140µs**
- **Repetition rate** — **50Hz**
- **Rise/fall time** — **3µs + 5µs settling**
- **Max. pulse droop** — **0.85%**
- **Reproducibility** — **10ppm**
- **System efficiency** — **> 90%**

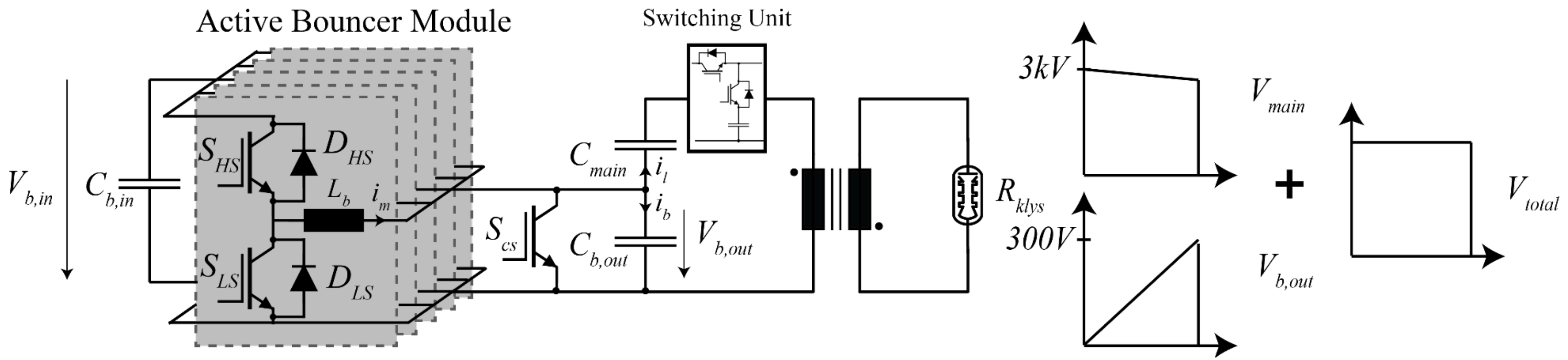


Modulator System - Overview



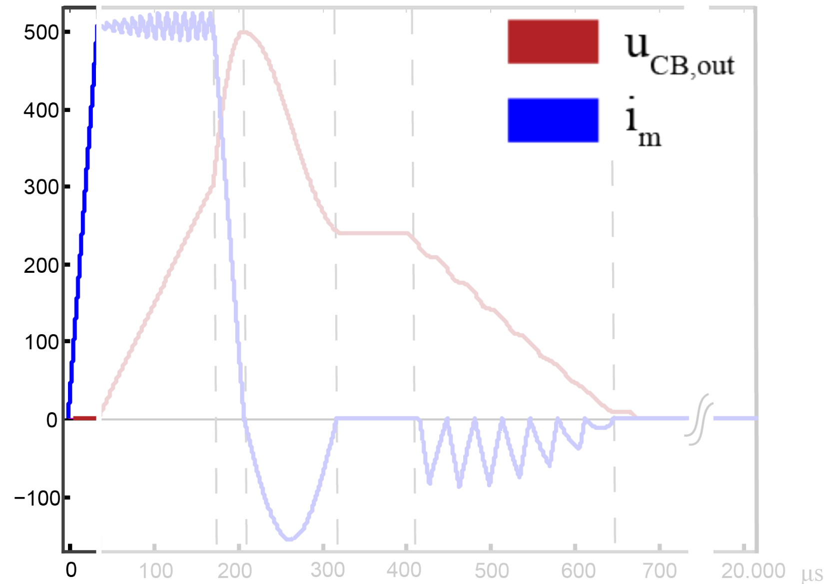
Active Bouncer Topology

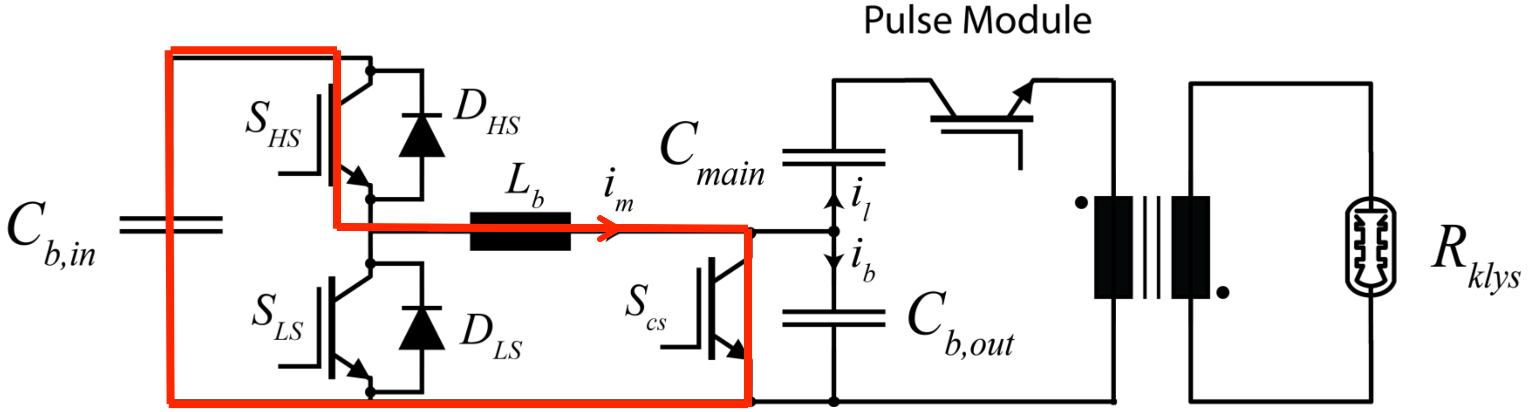
- **Interleaved buck-boost converter with short circuit switch**
- **Voltage levels:**
  - **V_{main} = 3kV**
  - **$V_{B,In}$ = 450V**
  - **$V_{B,Out}$ = 0 – 300V**
    - ➔ **10% drop in main capacitor**
- **Aim: 10ppm repeatability**
  - ➔ **< 5 ppm ripple induced by bouncer**
  - ➔ **24-fold interleaving (4 x 6)**
    - ➔ **Effective ripple frequency up to 2.4 MHz**
    - ➔ **Parallel redundancy**



Operation Principle – Before Main Pulse

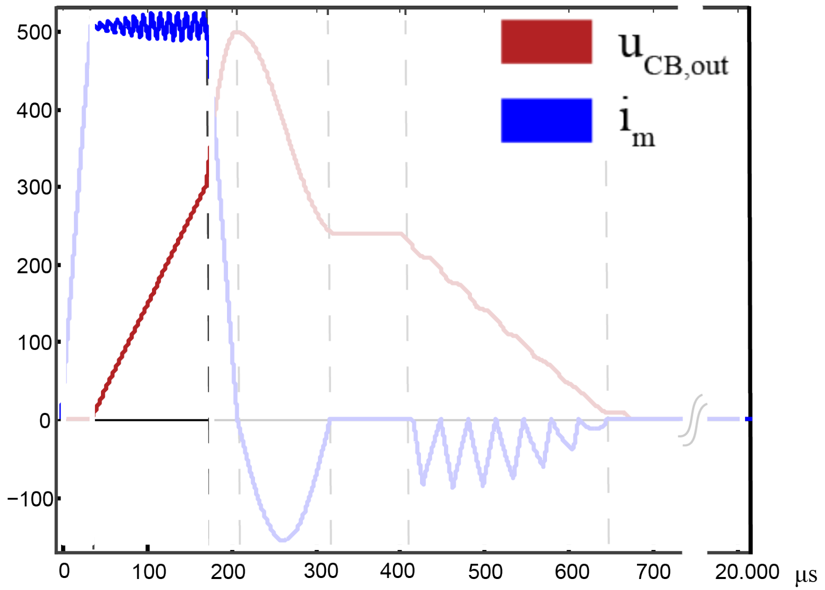
- **Ramp up before main switch is closed:**
  - **- $C_{b,out}$ is shortened**
  - **- Current in L_b increases**



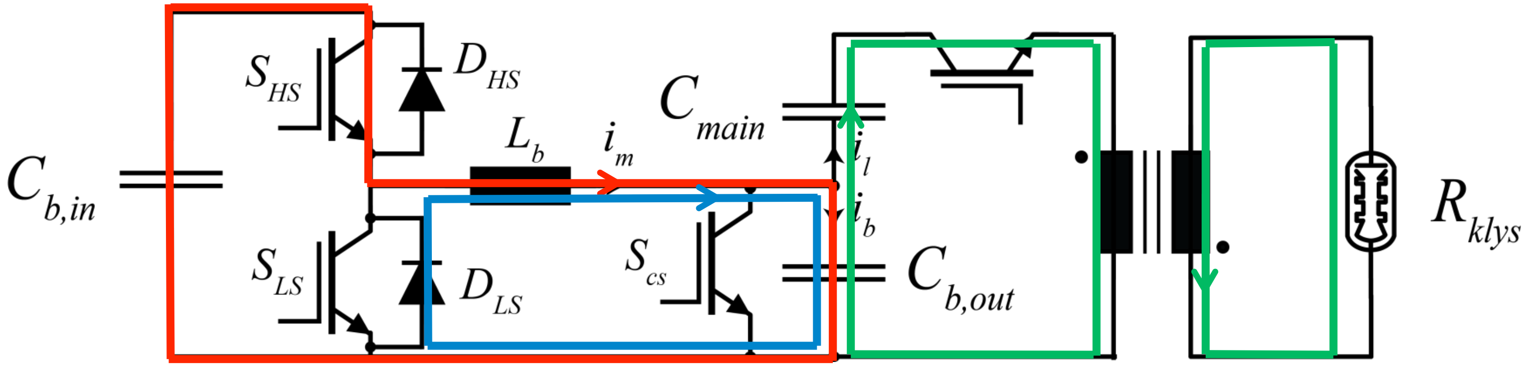


Operation Principle – Output Pulse

- **Interleaved buck operation during pulse:**
  - f_{switch} = 100kHz
  - $i_m = i_b + i_m$

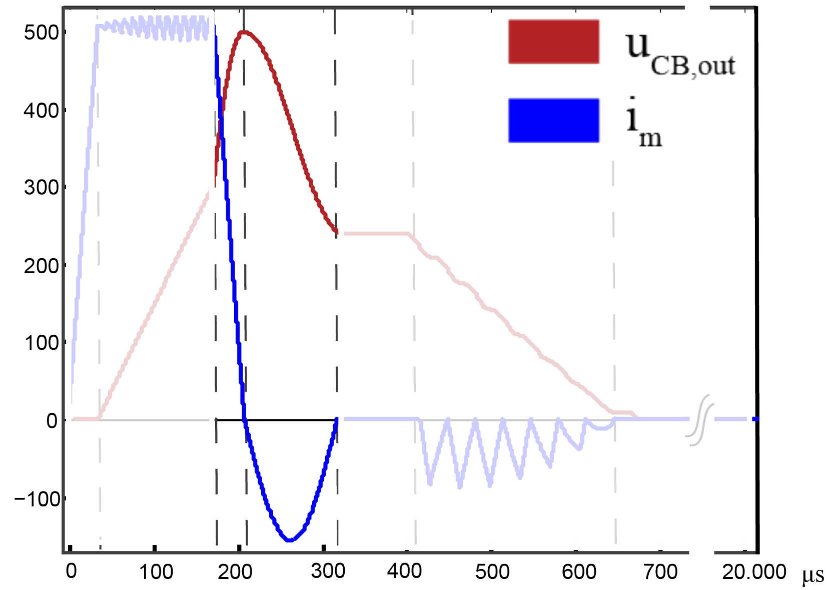


Pulse Module

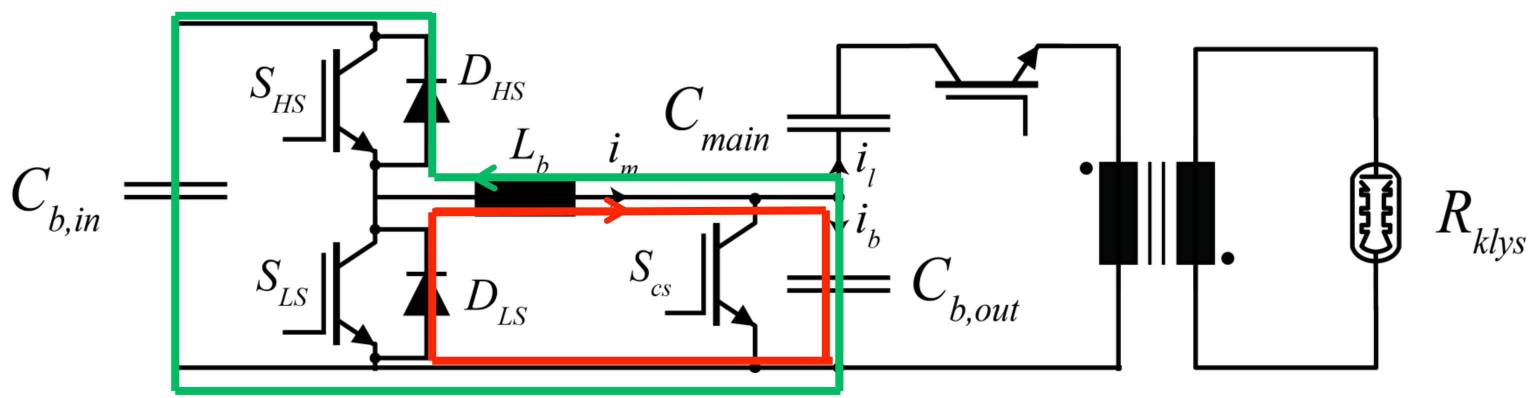


Operation Principle – After Main Pulse

- **Resonant transition $C_{b,out}$ & L_b**

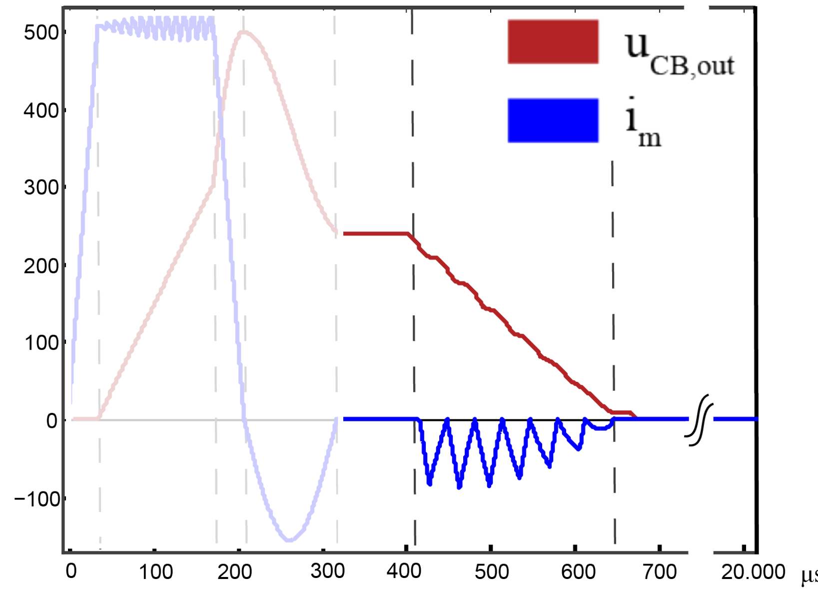


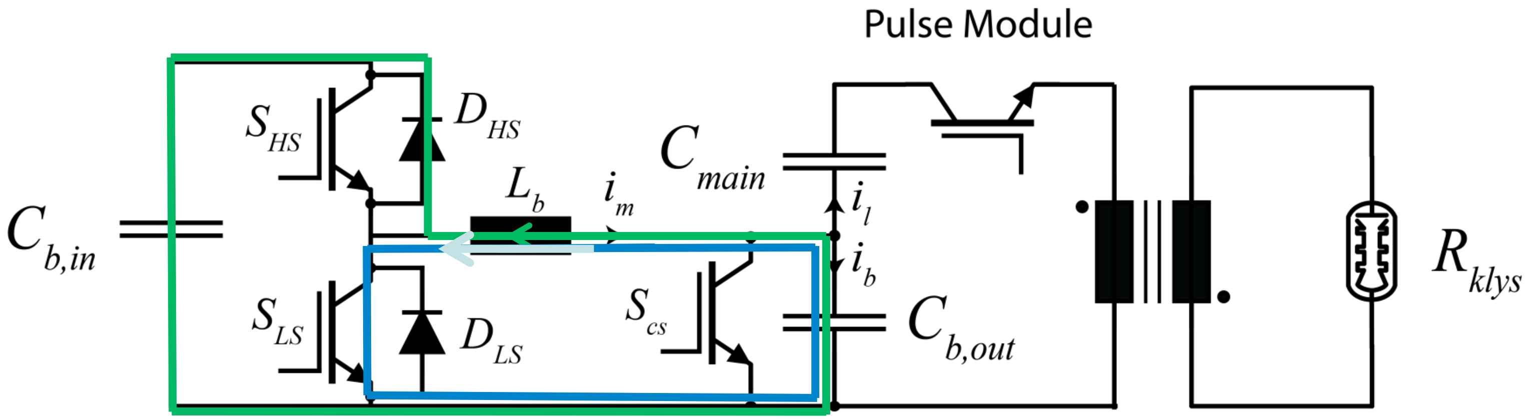
Pulse Module



Operation Principle – After Main Pulse

- **Interleaved boost operation:**
  - f_{switch} = 20kHz
- **Final discharge of $C_{b,out}$**
- **Pulse pause**





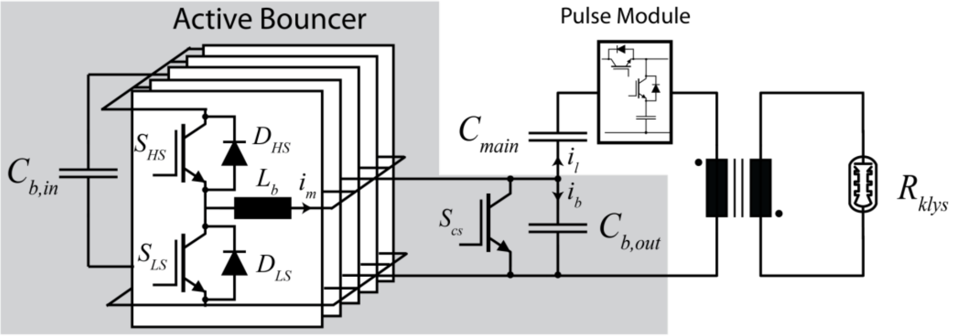
Ideal Interleaving

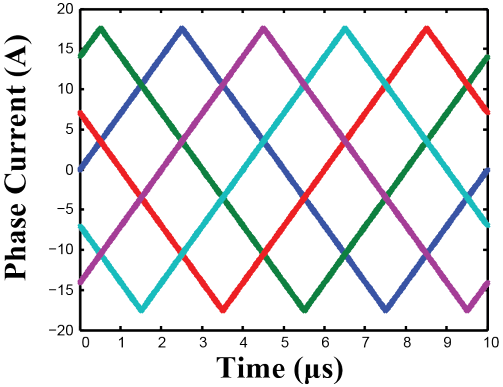
- **Stored energy in inductances is kept constant**
  - ➔ **L_{equal} = const.**
  - ➔ **L_{Ph} ⇧ with # of interleaved stages *N***

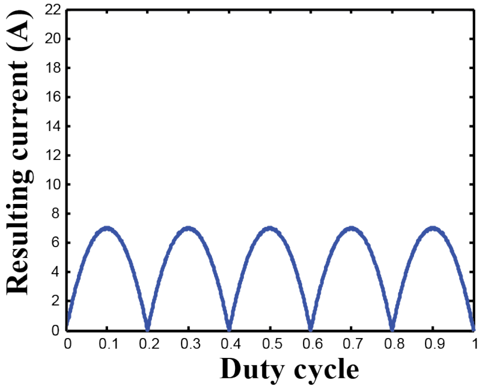
$$L_{Ph} \sim NL_s$$

- **Per phase equal *L* values** $L_{Ph1} = L_{Ph2}$
- **Current ripple:** $I_{Rip} \sim \frac{1}{N^2}$
- **Ripple frequency:** $f_{Rip} \sim N$

➔ **Output voltage ripple:** $V_{Rip} \sim \frac{1}{N^3}$







Interleaving with Tolerances

- **Analysis in time-domain for each switching period**
- **Component tolerances are considered**
- **Jitter of switches are considered**

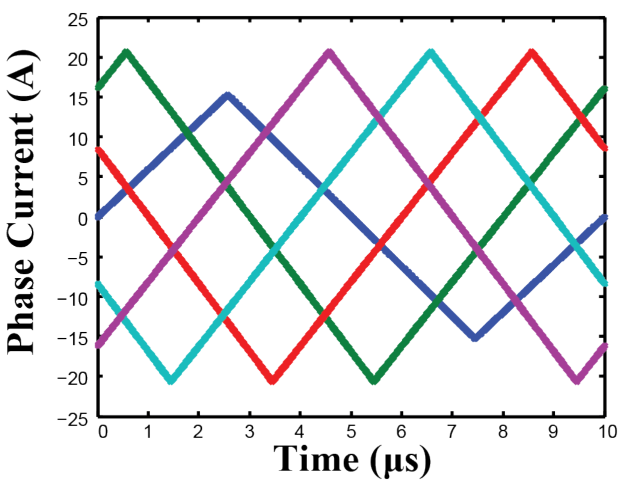
$$i_k(t) = \begin{cases} \frac{V_{b,in}\,(1-D)}{L_k} \cdot t - \frac{V_{b,in}\,D\,(1-D)}{2\,L_k\,f_s} & \text{if } 0 < t < \frac{D}{f_s} + t_{jit} \\ \frac{V_{b,in}\,D\,(1-D)}{2\,L_k\,f_s} - \frac{V_{b,in}\,D}{L_k} \cdot t & \text{if } \frac{D}{f_s} + t_{jit} < t < \frac{1}{f_s} \end{cases}$$

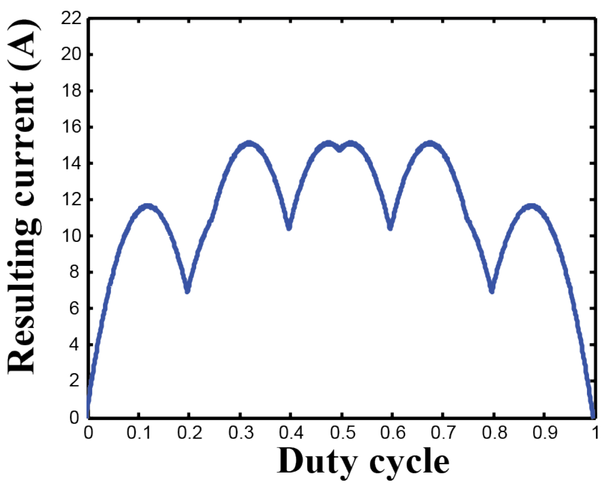
- **Assumption: Inductance values measured at start-up**
- **Worst case:**

$$L_1 = (1 + x\%)\,L$$

- **All others:**

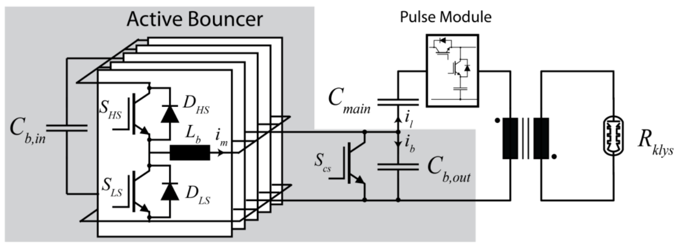
$$L_1 = (1 - x\%)\,L$$

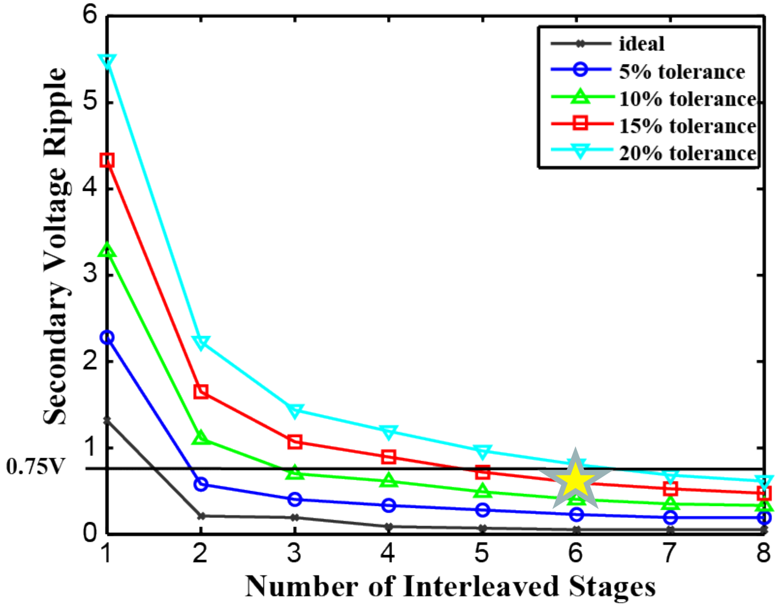


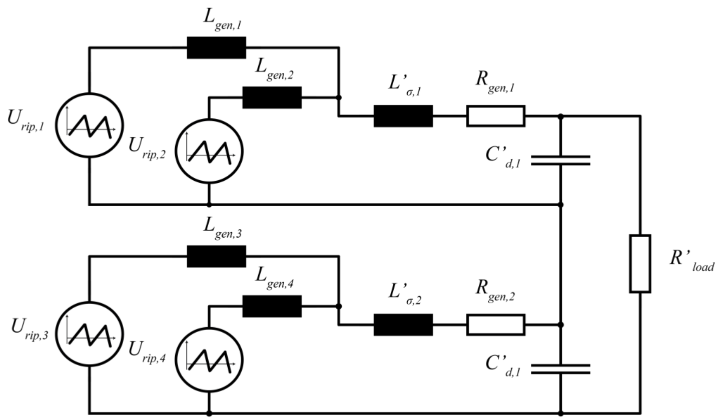


Interleaving with Tolerances – System Transfer Function

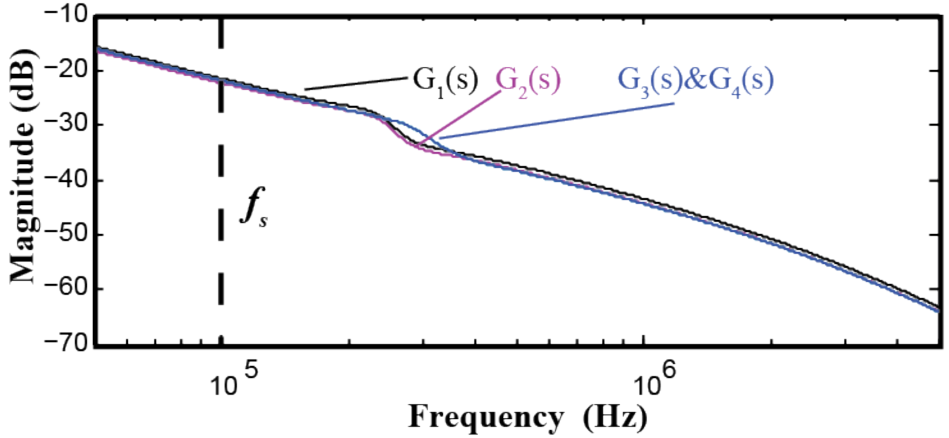
- **Identification of system transfer function**
  - **- Incl. freq. dependency of $R_{winding}$**
  - **- Incl. tolerances in parasitics**
- **Tolerance: worst case**
- **Switching jitter: 5ns**
- **Most unfavourabel configuration chosen**
- **Component tolerances of 15%**
  - **➔ 6 interleaved modules**





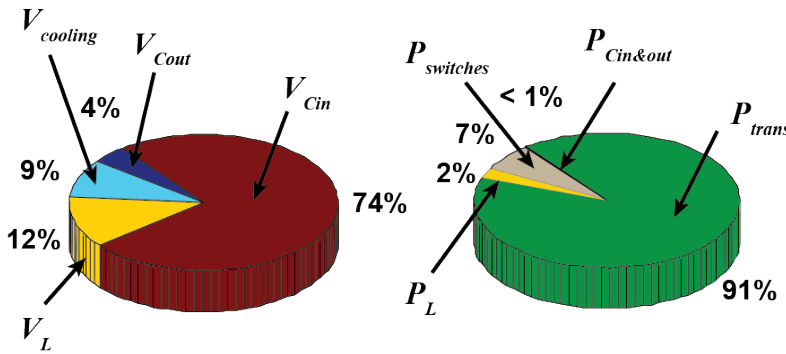


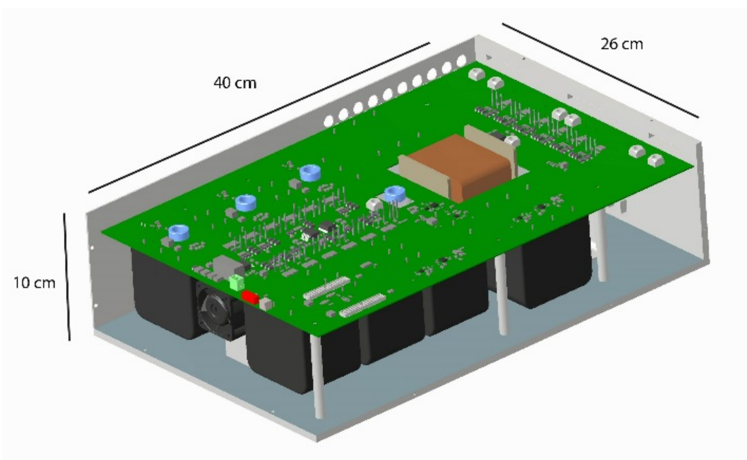
Current ripple to output voltage

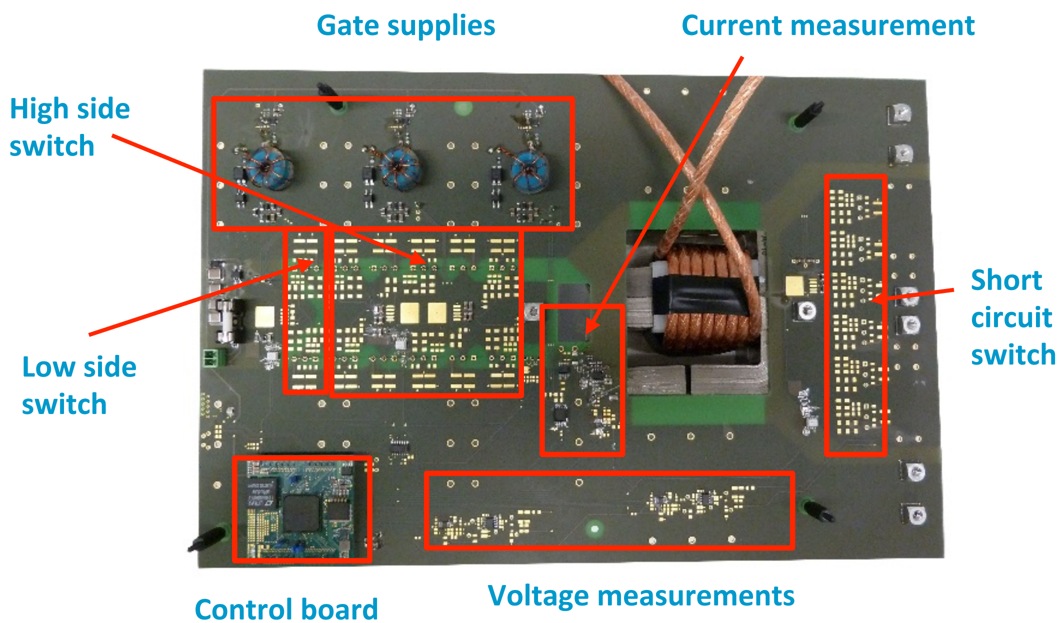


Active Bouncer Prototype

- **Switching frequency** — **100kHz**
- **Pulse current per module** — **700A**
- **Bouncer efficiency** — **91%**
  - ➔ **System efficiency** ↓ — **-0.45 %**
- **Bouncer volume** — **10.4 dm^3**
- **Total losses** — **2307W**



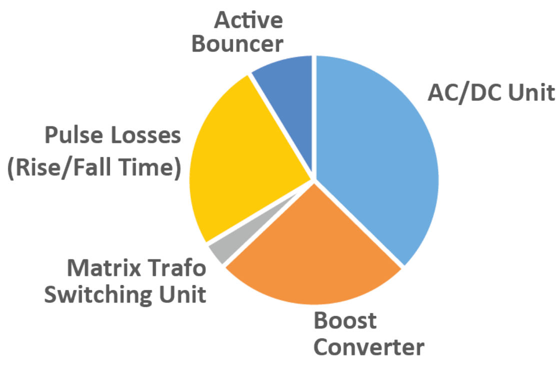


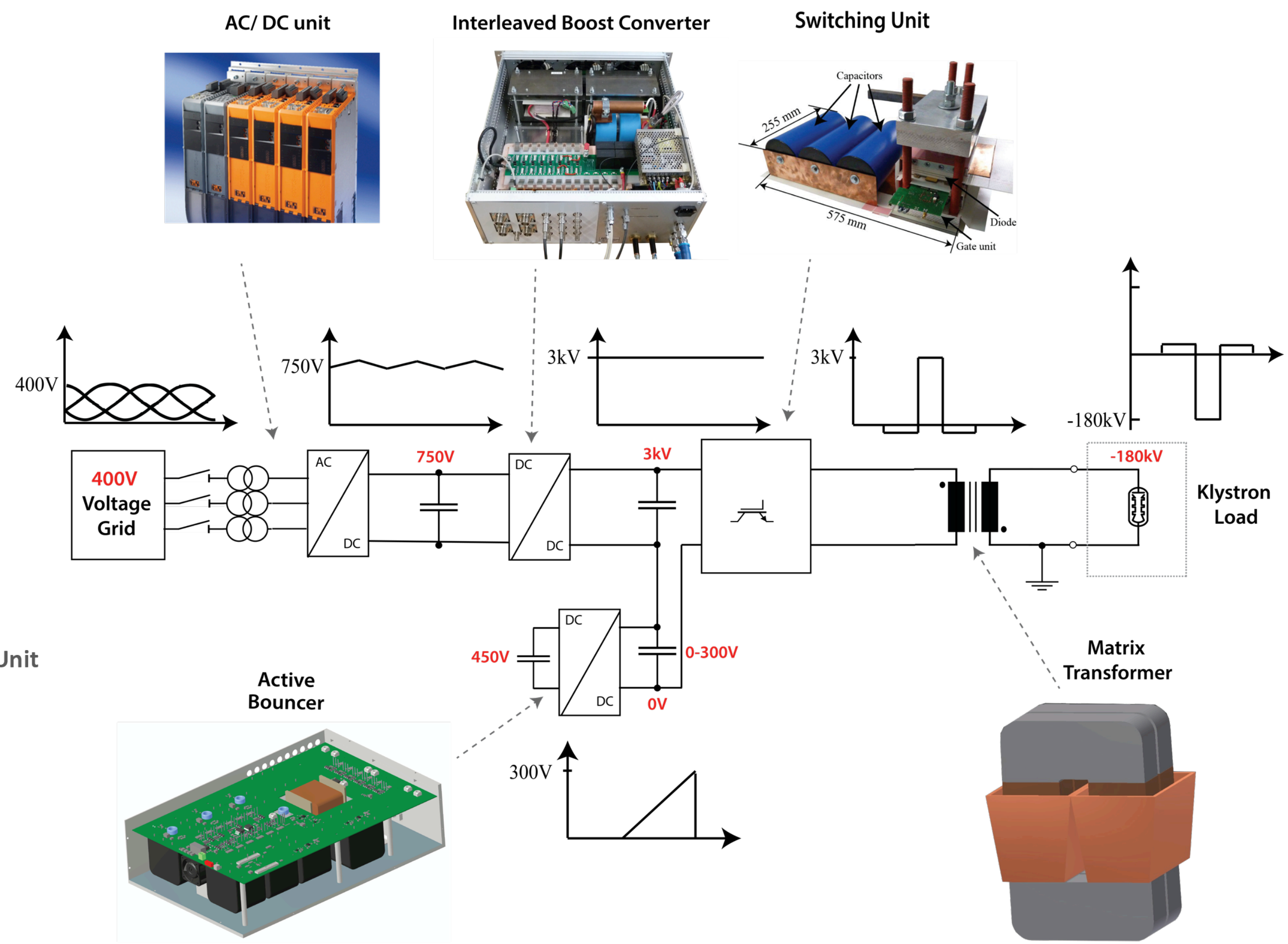


Modulator System - Efficiency

- **Energy in klystron in case of arc**
  < 10J (without cable)
- **Efficiency ≈ 91%**
- **Final testing: 2015/2016**

Loss Distribution





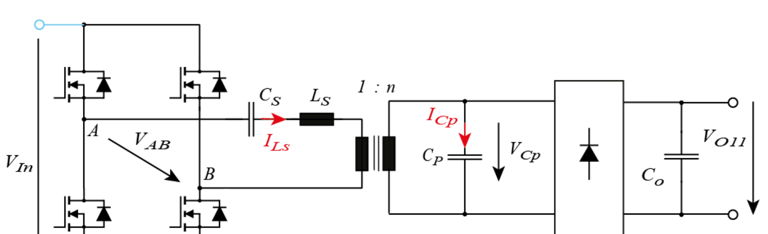
Long Pulse Modulator
(> 1ms)

Resonant DC-DC Converters
for
Long Pulse Klystron Modulators

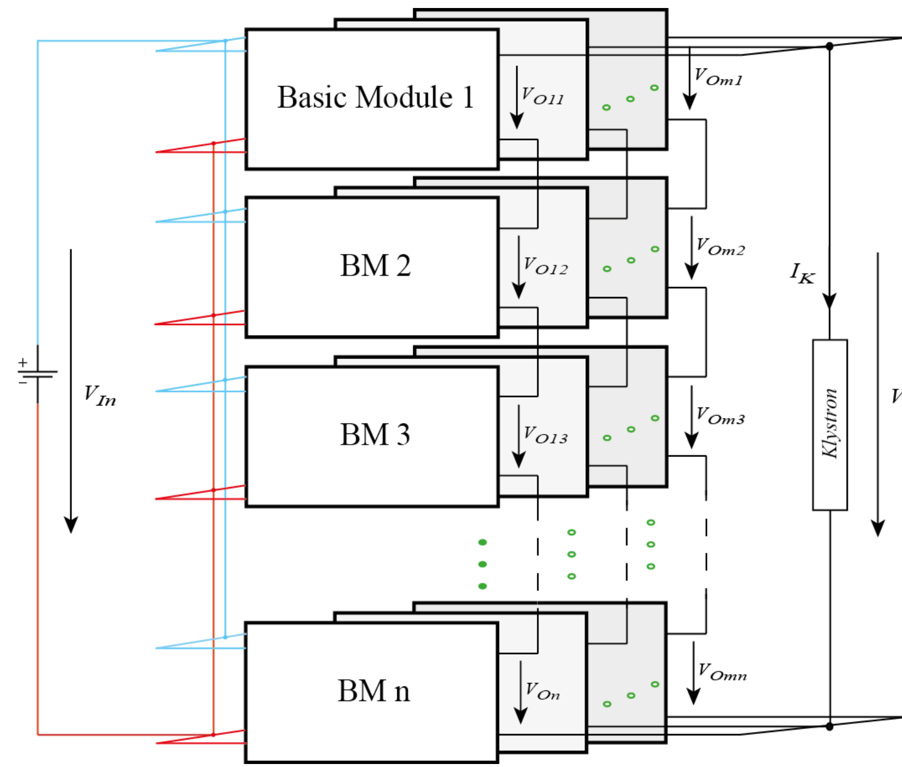
European Spallation Source (ESS)
(Lund)

Solid State Long Pulse Modulator

- **Pulse power** — **2.88MW**
- **Average power** — **133kW**
- **Efficiency** — $\eta \geq 90\%$
- **Pulse width** — $T_{PW} = 3.5\text{ms}$
- **Pulse voltage** — $V_{out} = 115\text{kV}$
- **Pulse repetition rate** — $P_{RR} = 14\text{Hz}$
- **Rise/fall time** — $T_R / T_F \leq 150\mu\text{s}$
- **Short circuit energy** — $E_{Arc} \leq 10\text{J}$



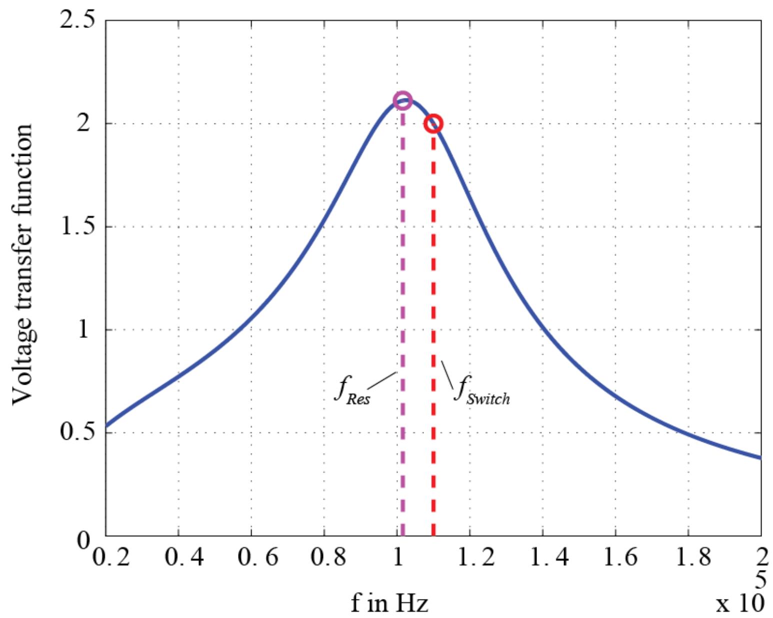
Basic Module 1

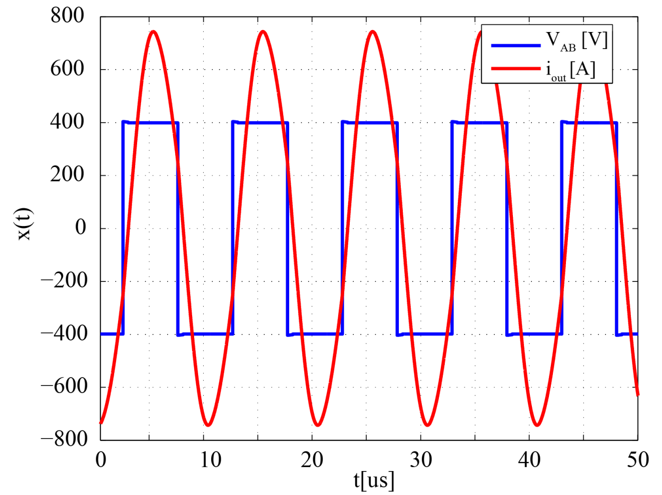


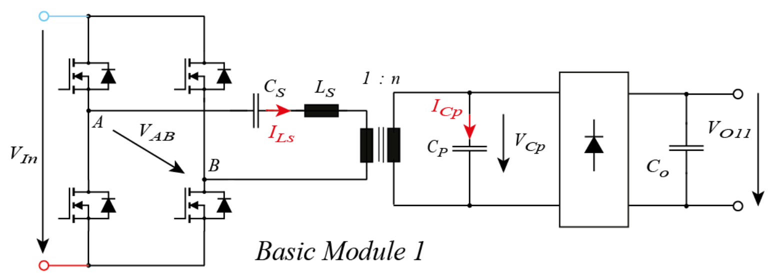
Solid State Long Pulse Modulator – Resonant Converter

- **Switching frequency > resonance frequency**
  - ➔ **Soft switching for all MOSFETs (ZVS)**
  - ➔ **High efficiency**
- **Inherent limitation of short circuit current**

- **Switching frequency** **~100kHz**
- **Module input voltage** **400V**
- **Module output voltage** **14.4kV**
- **Module pulse power** **180kW**

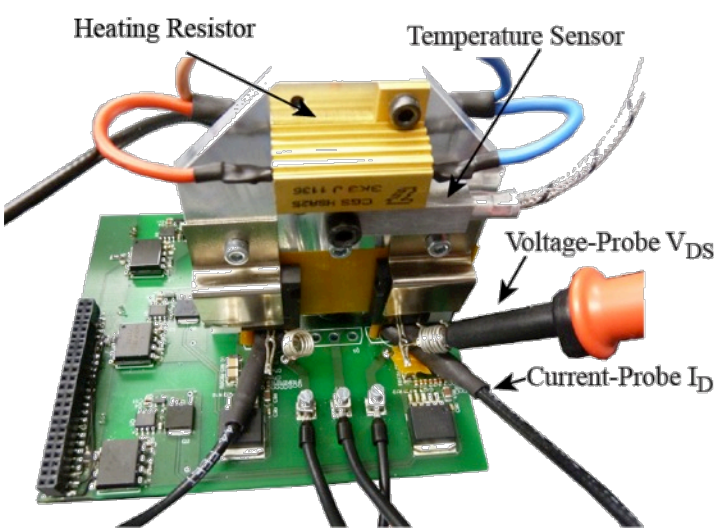


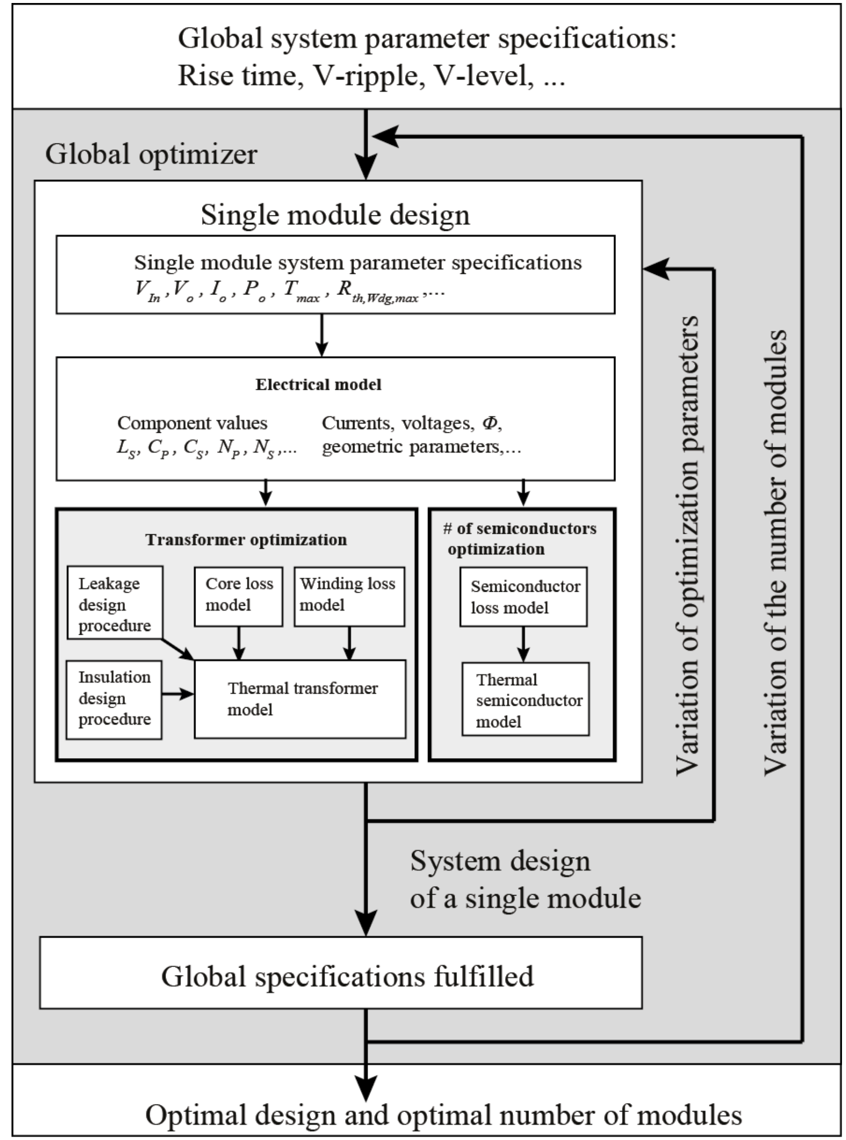




Global Optimisation

▪ **Pulse power**	**2.88MW**
▪ **Average power**	**133kW**
▪ **Efficiency**	$\eta \geq 90\%$
▪ **Pulse width**	$T_{PW} = 3.5ms$
▪ **Pulse voltage**	$V_{out} = 115kV$
▪ **Pulse repetition rate**	$P_{RR} = 14Hz$
▪ **Rise/fall time**	$T_R / T_F \leq 150\mu s$
▪ **Short circuit energy**	$E_{Arc} \leq 10J$

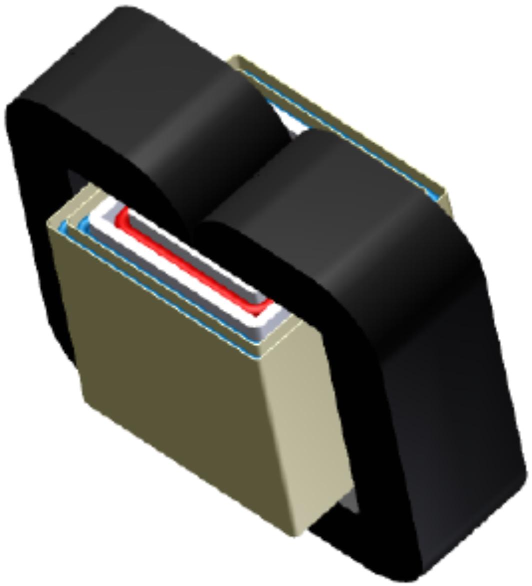


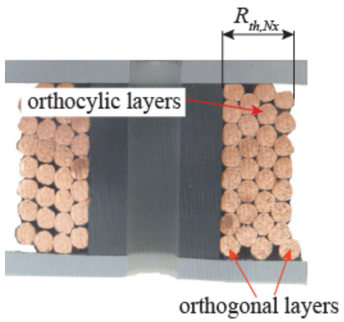


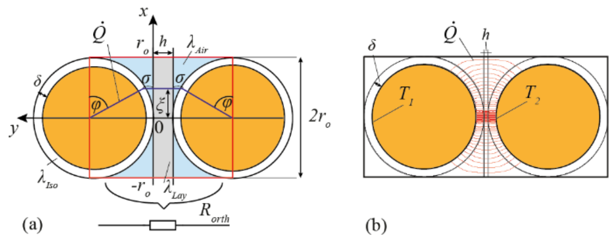
Thermal Transformer Model

- **Thermal equivalent network**
- **Core/winding: Heat conduction**
- **Novel models for solid & litz wire**

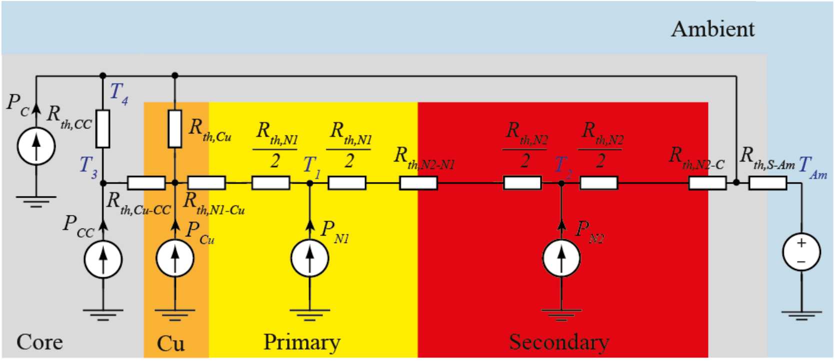
	Measured results					Calculated results	
	T_1[°C]	T_2[°C]	ΔT[°C]	$\dot{Q}$[W]	$R_{th,Nx}$[°C/W]	$R_{th,Nx}$[°C/W]	Error [%]
Round wire	115.1	69.5	45.6	22.1788	2.06	1.539	−25.3
Litz wire	105.7	53.1	52.6	20.98	2.51	2.04	−18.72





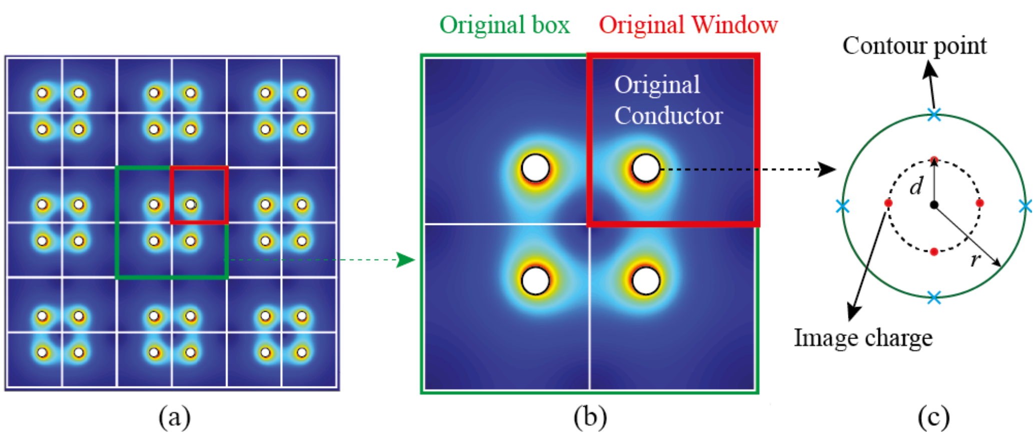


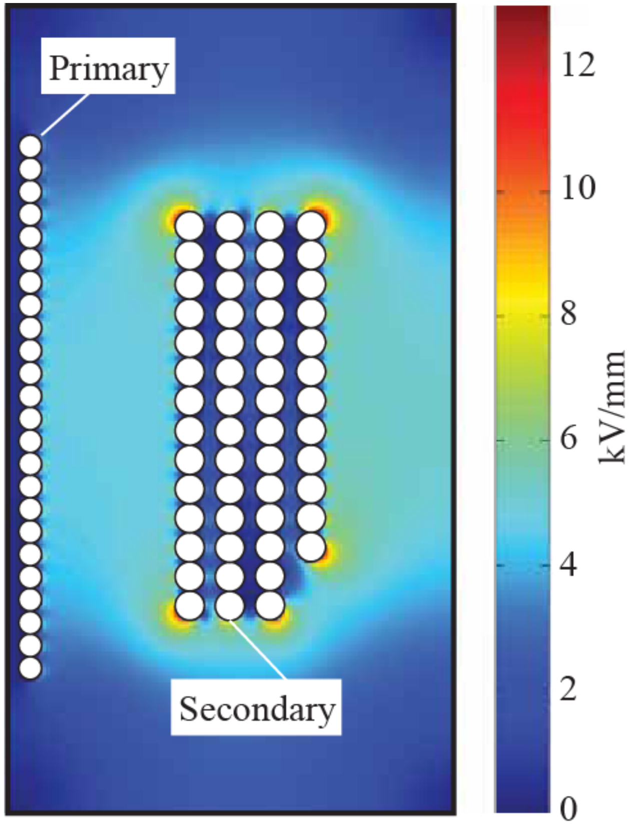
R_{th} between Turns



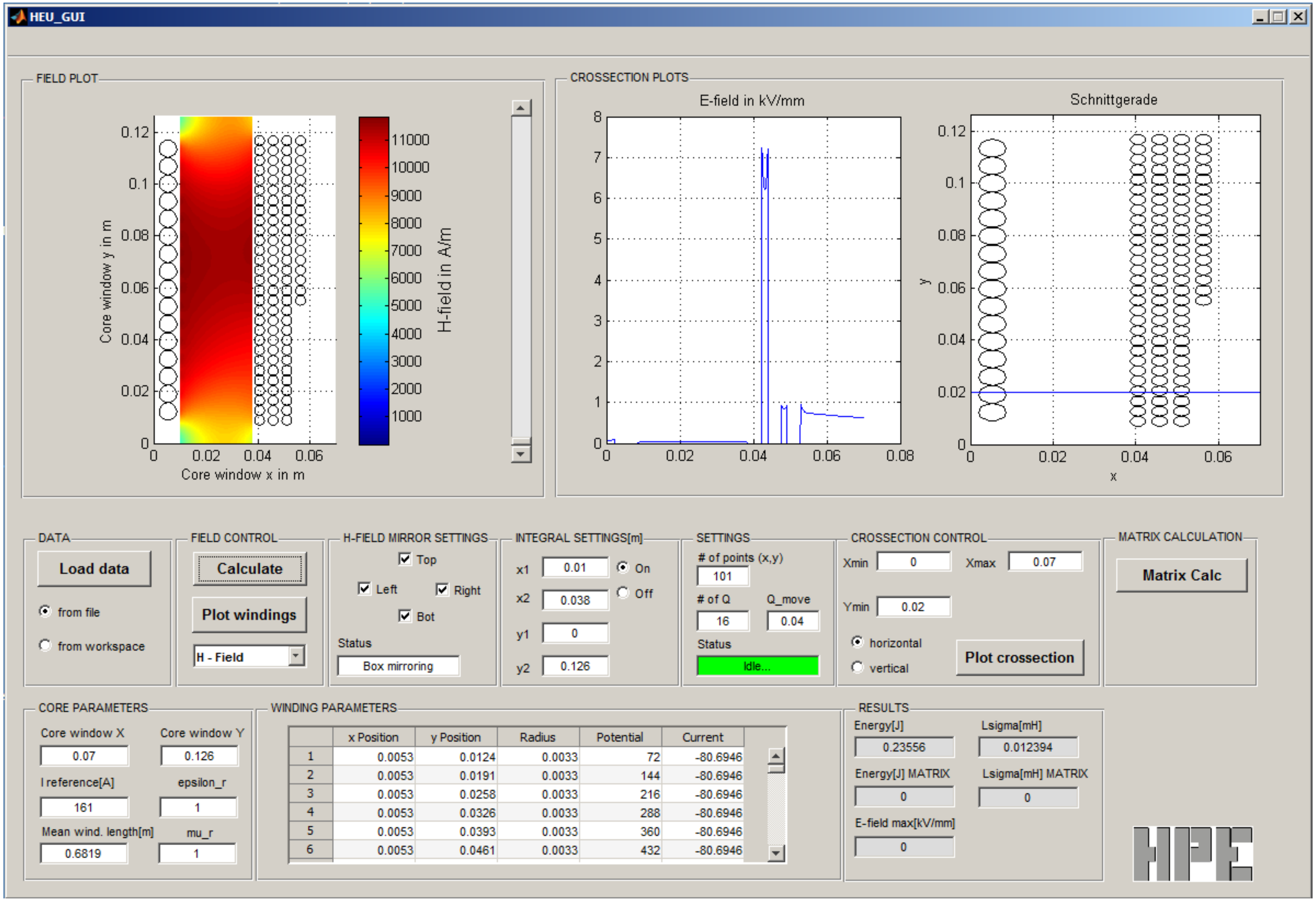
Insulation Design Procedure

- **E-field ➔ Charge simulation method**
- **Turns ➔ Line charge**
- **Modeling of arbitrary configurations**
- **Maximum E-field estimation**

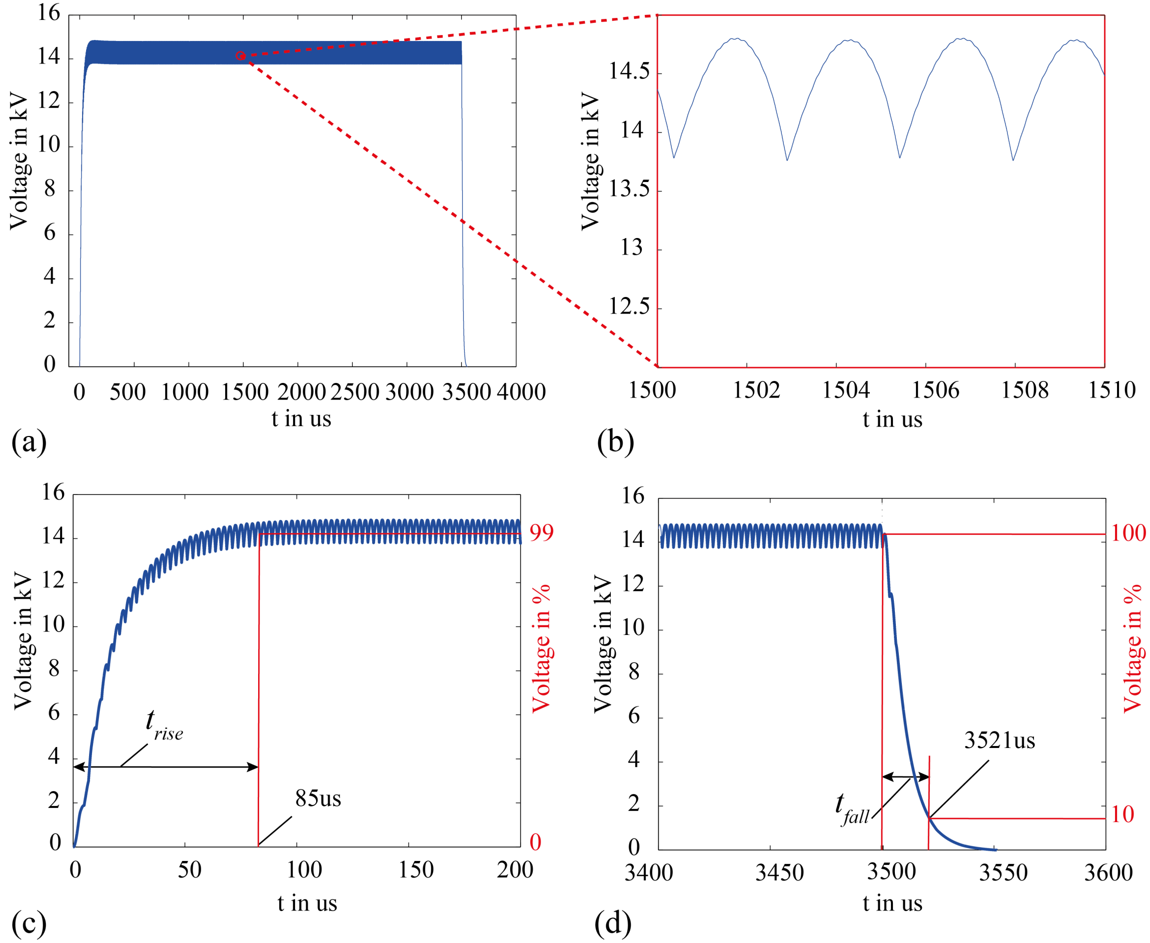




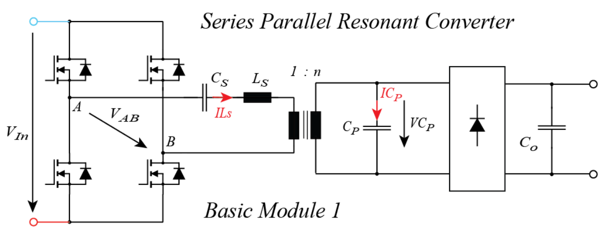
Transformer/Inductor Design Tool (E-/H-Field)



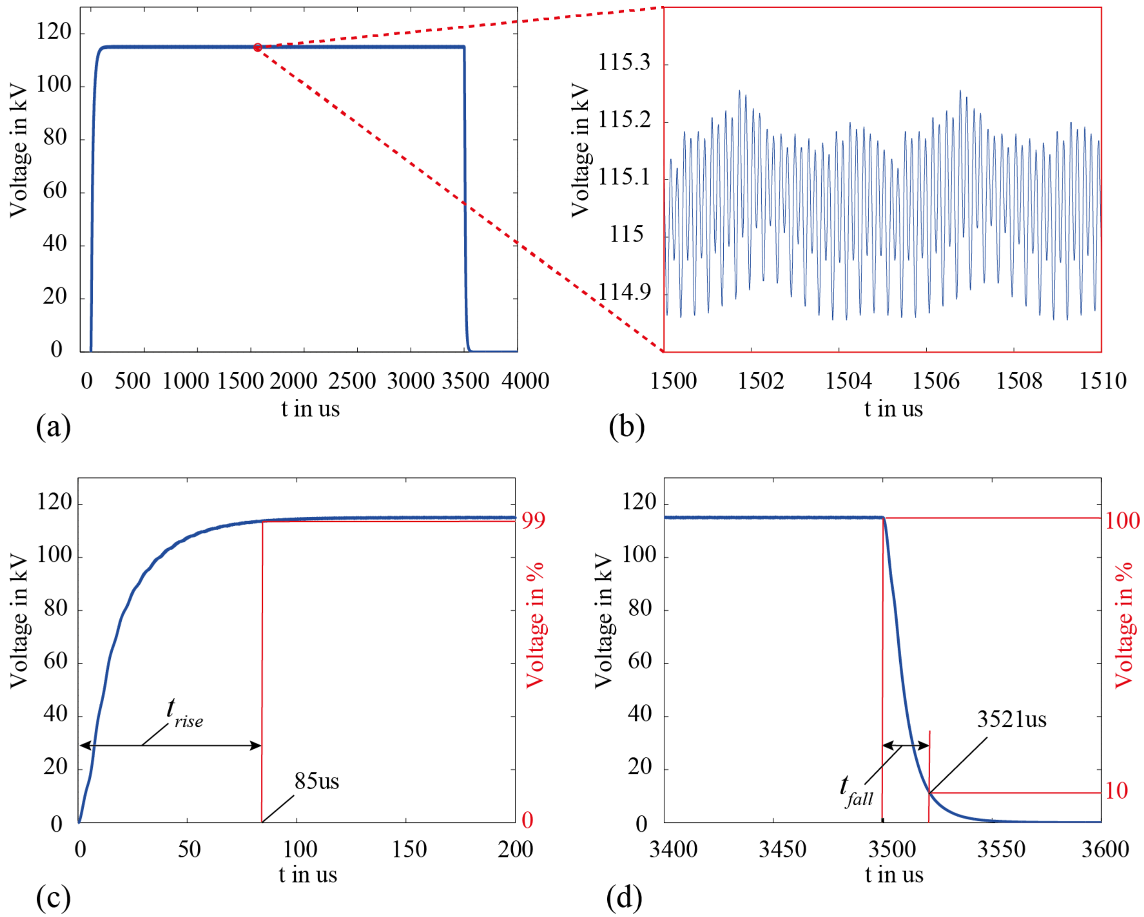
Simulation Results: Single Module



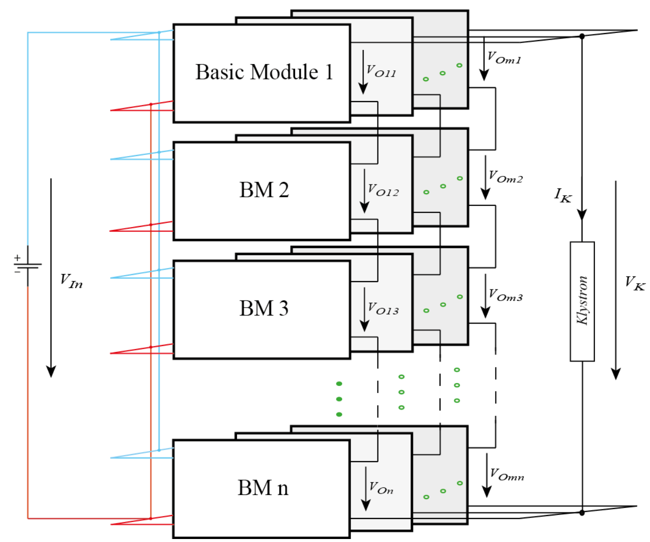
Resonant circuit parameters	
V_{out} = 14.4kV	L_s = 5.1µH
I_{out} = 12.5A	C_s = 0.837µF
P_{out} = 180W	C_p = 2.58nF
f = 100kHz	n = 18



Simulation Results: Complete System

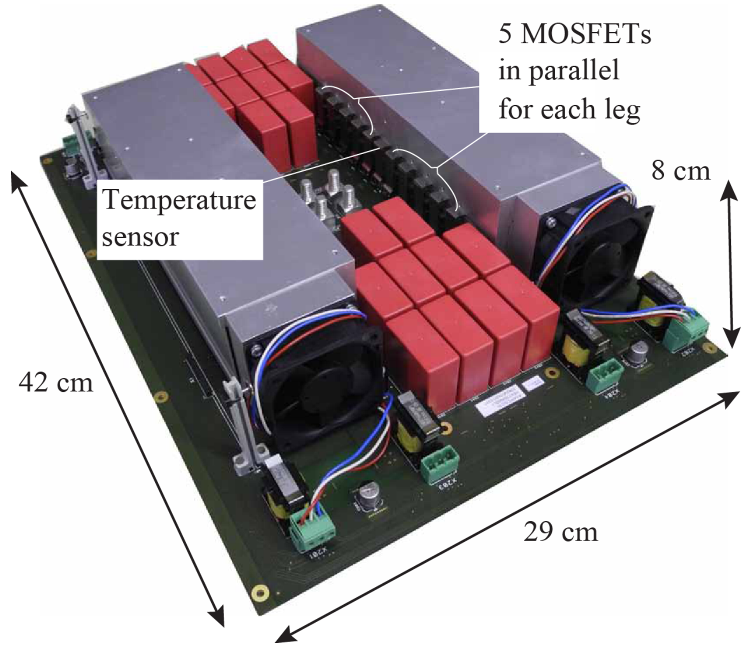


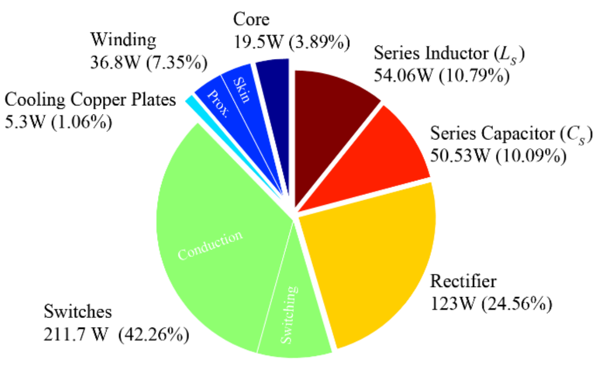
Resonant circuit parameters	
V_{out} = 115kV	P_{out} = 2.88MW
I_{out} = 25A	f = 100kHz



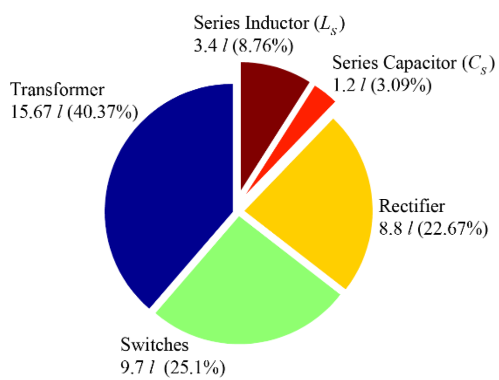
Prototype System

- **Specifications**
  - V_{Out} = 14.4 kV
  - I_{Out} = 12.5A
  - P_{Out} = 180kW
- **Constraints**
  - Flux density ≤ 150mT
  - Core/Wdg. temperature < 120°C
  - Max. electrical field < 15kV/mm
  - Leakage inductance = 5.1µH



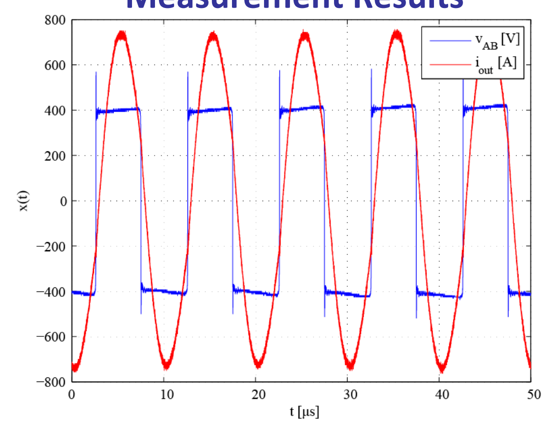


(a) Losses in W



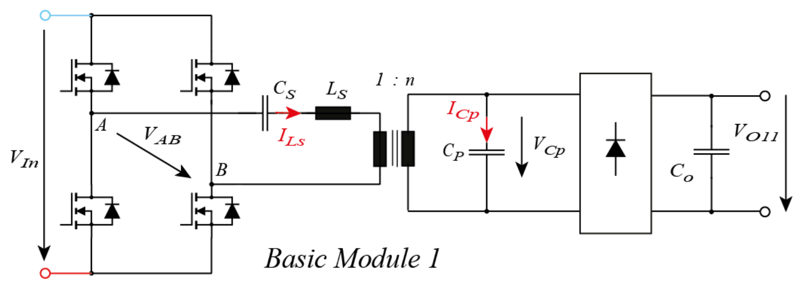
(b) Volume in l

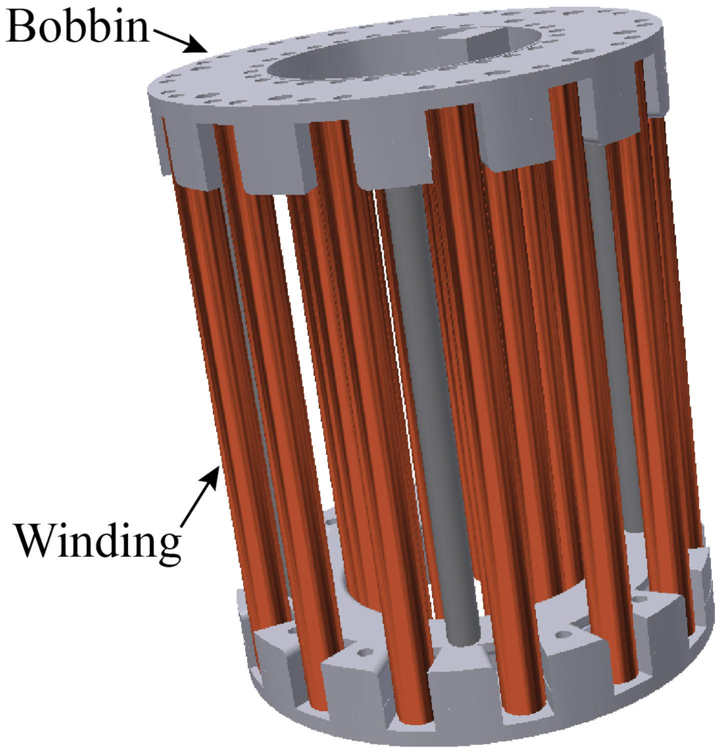
Measurement Results



Toroidal Air Inductor

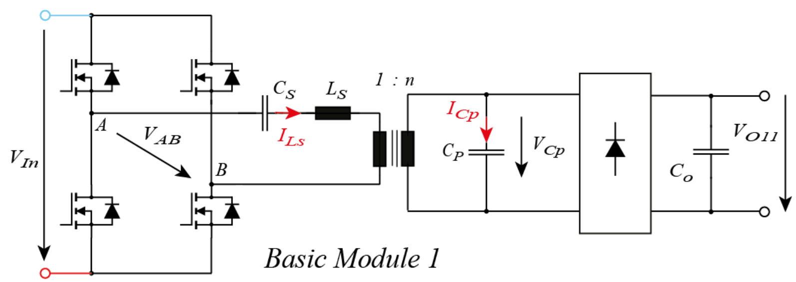
▪ Winding	N = 12
▪ Litz wire	8 x 2000 x 0.05
▪ Losses	54.06 W
▪ Dimensions	d_a = 152 mm
	h = 180 mm
▪ Volume	3.3 liter

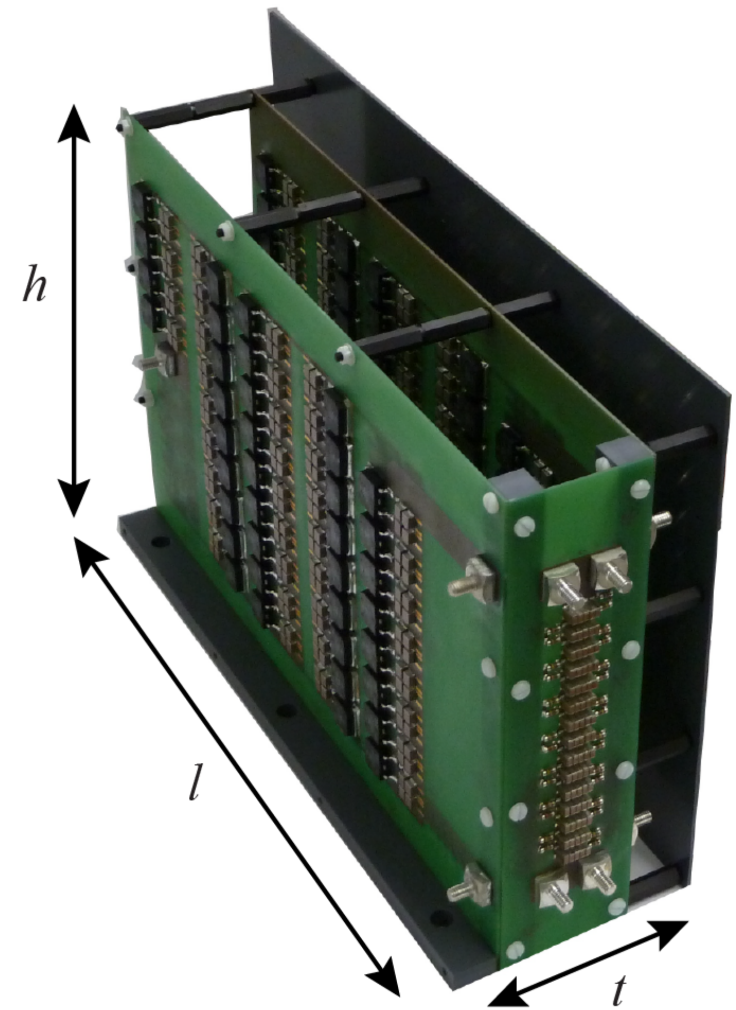




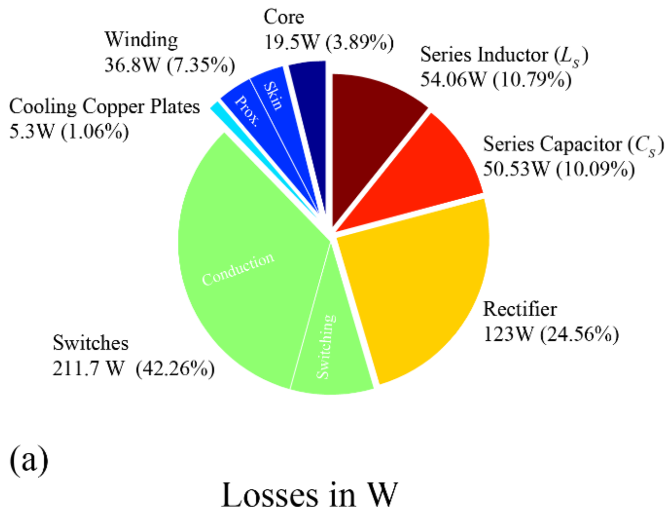
Results: Rectifier and Parallel Capacitor

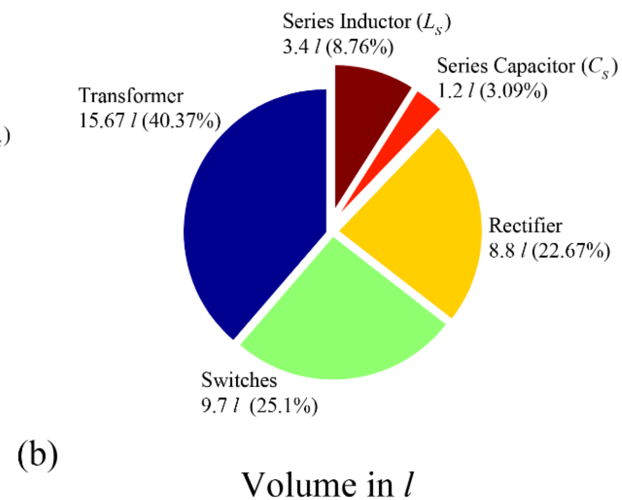
- **# of diodes** 156
- **Diode type** APT40DQ120SG (D3PAK)
- **# of capacitors** 624
- **Capacitor type** 100nF NPO SMD 2220
- **Total losses** 123 W
- **Dimensions** l = 375 mm
  t = 100 mm
  h = 235 mm
- **Volume** 8.8 liter
- **PCB test** $20kV_{DC}$

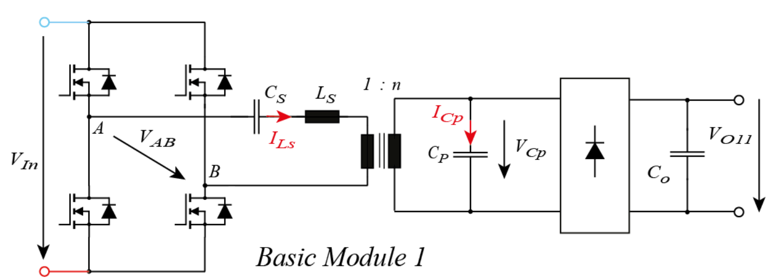




Performance DC-DC Converter







Performance of a single module

Volume	Pulsed power density	Efficiency
38.77 l	4.84 kW/l	94.9 %
t_{rise}	t_{fall}	
85 μs	21 μs	

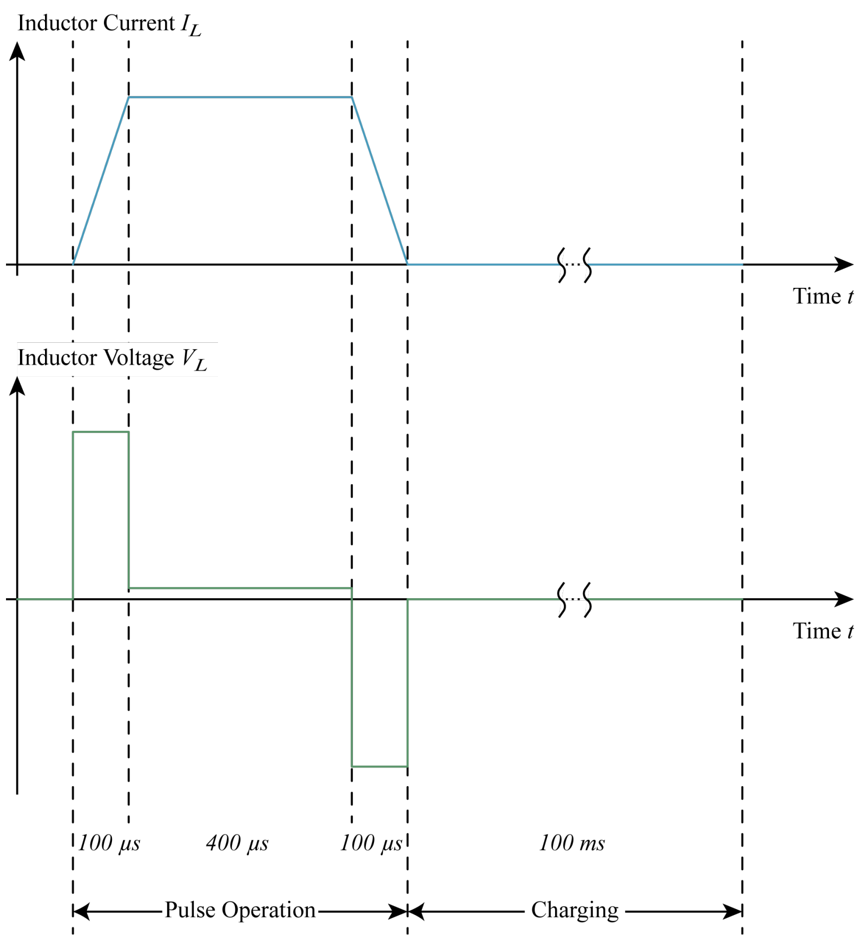
Overall system

t_{rise}	t_{fall}	Short circuit energy
85 μs	21 μs	3.7 J
# of SPRC-modules in parallel and series		2 x 8

Solid State Bipolar Pulsed Voltage Source for Kicker Magnets

Specifications

- **Low ripple**
- **High reproducibility**



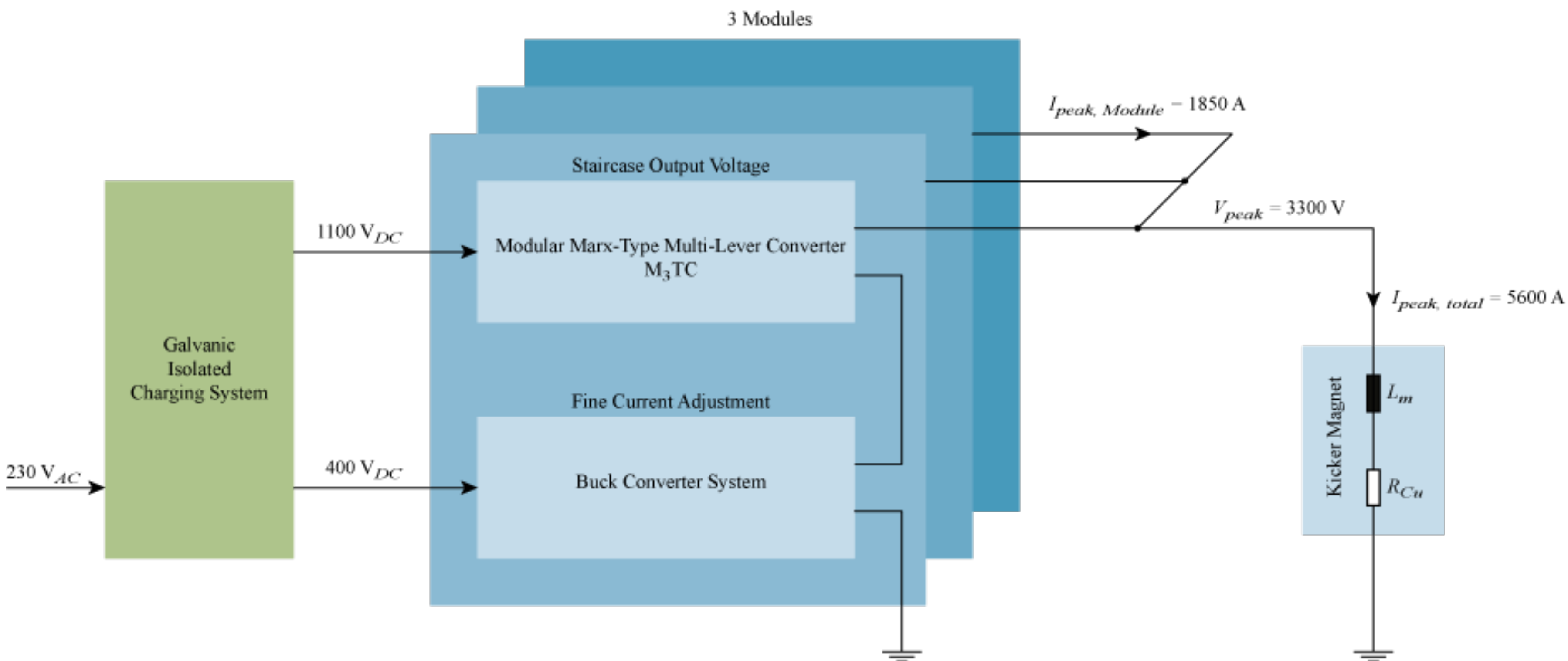
Max. Current	5600	A
Inductance	38	µH
Pulse Duration	600	µs
Rise / Fall Time	100	µs
Charge Duration	100	ms

Max. Current Gradient	56	A / µs
Min. Voltage V_L	2128	V

Inductor Pulse Energy E_L	595	J
Resistor Pulse Losses E_R	15.5	J

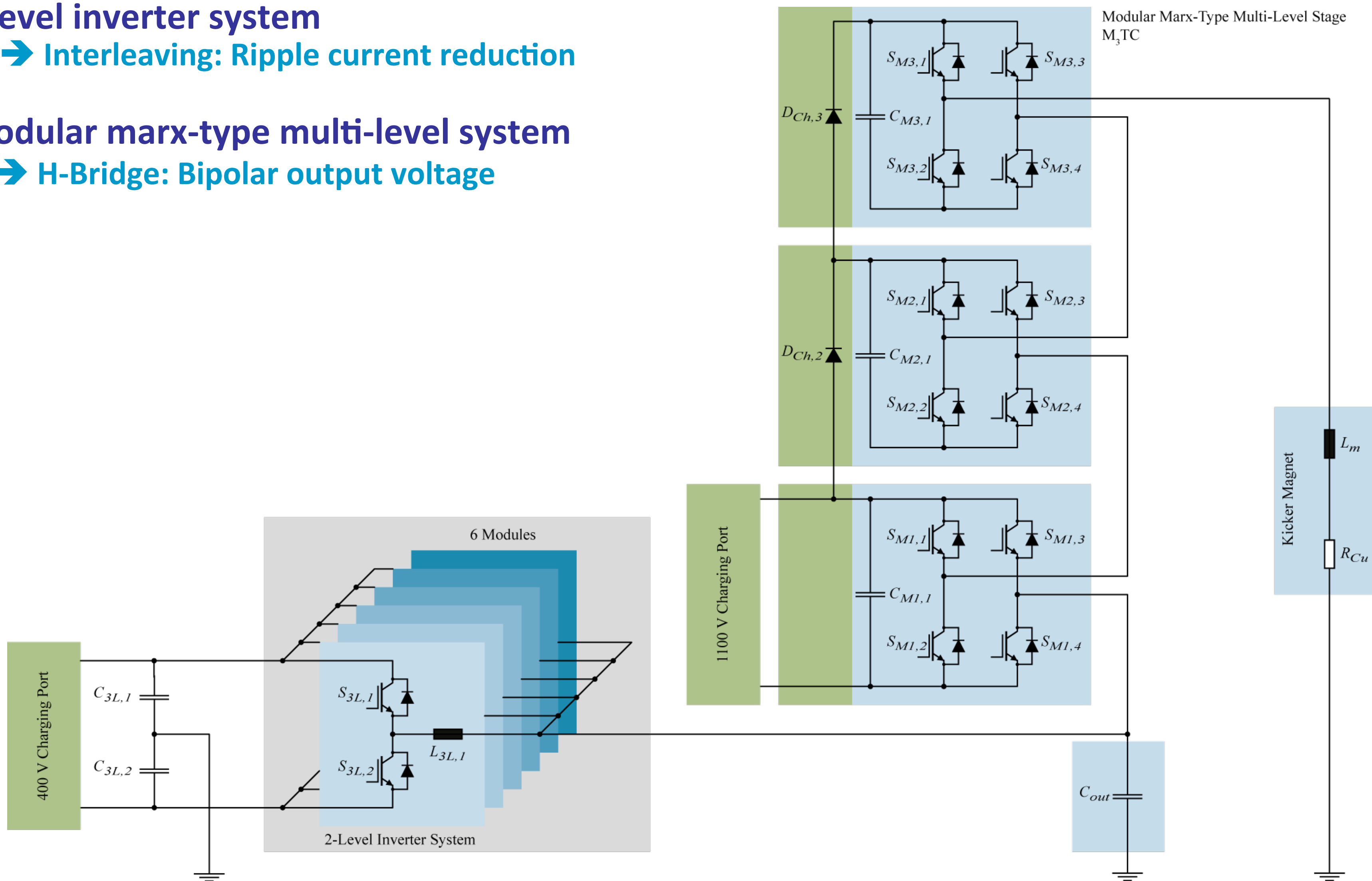
Bipolar Pulsed Voltage Source (BiPuVoSo)

- **2 level inverter system**
  - ➔ **Fine current adjustment**
  - ➔ **Loss compensation**
- **Modular marx-type multi-level system**
  - ➔ **Coarse current adjustment**



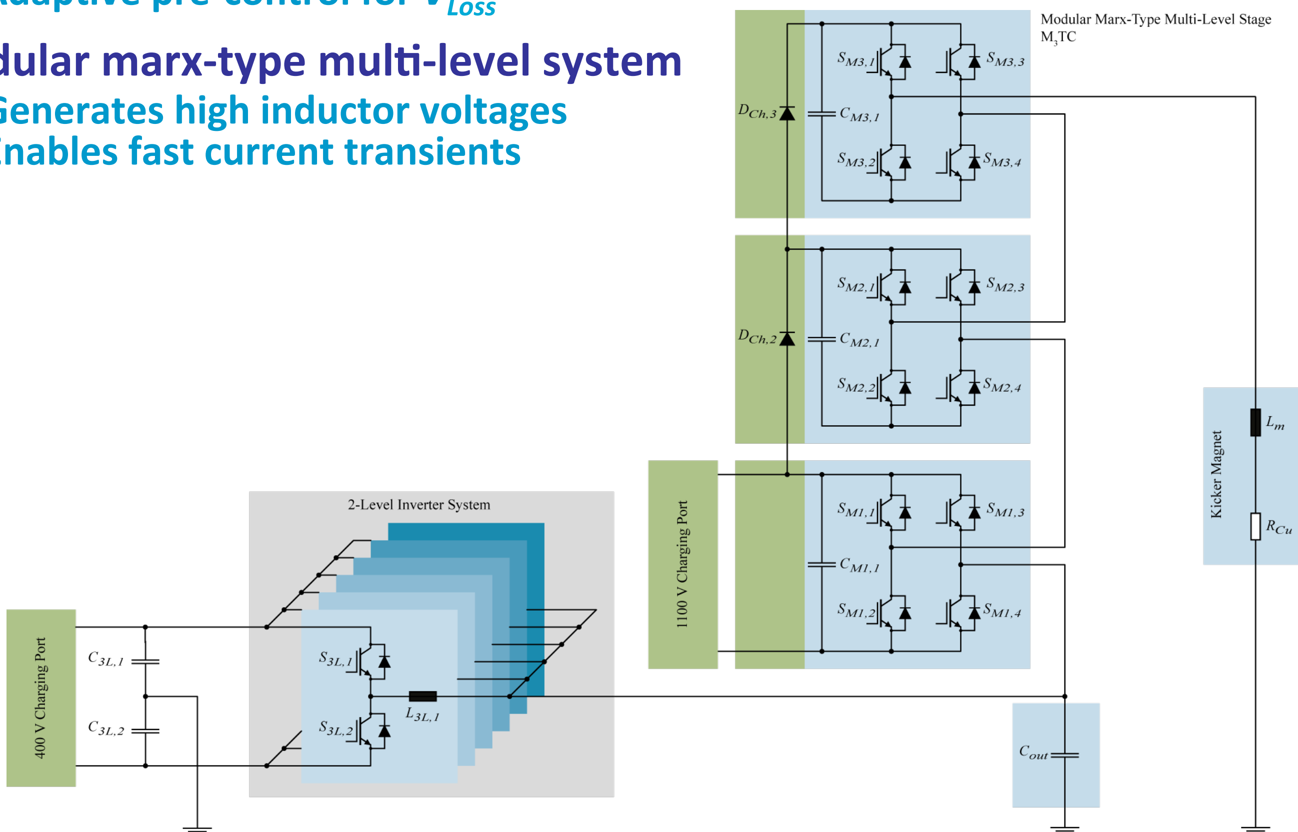
A BiPuVoSo Module in Detail

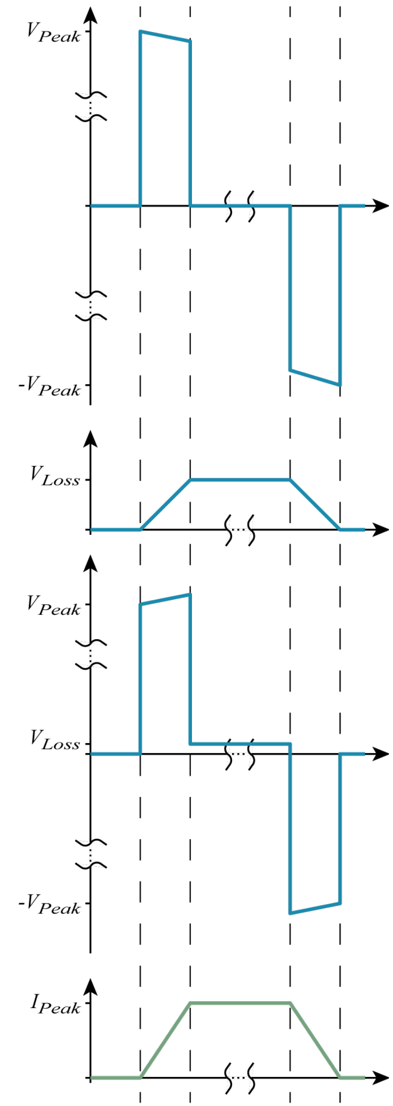
- **2 level inverter system**
  - ➔ **Interleaving: Ripple current reduction**
- **Modular marx-type multi-level system**
  - ➔ **H-Bridge: Bipolar output voltage**



Principle of Operation

- **2 level inverter system**
  - Small output current ripple
- **Ripple reduced by**
  - Interleaving of 6 inverters
  - Output capacitor C_{out}
  - Adaptive pre-control for V_{Loss}
- **Modular marx-type multi-level system**
  - Generates high inductor voltages
  - Enables fast current transients

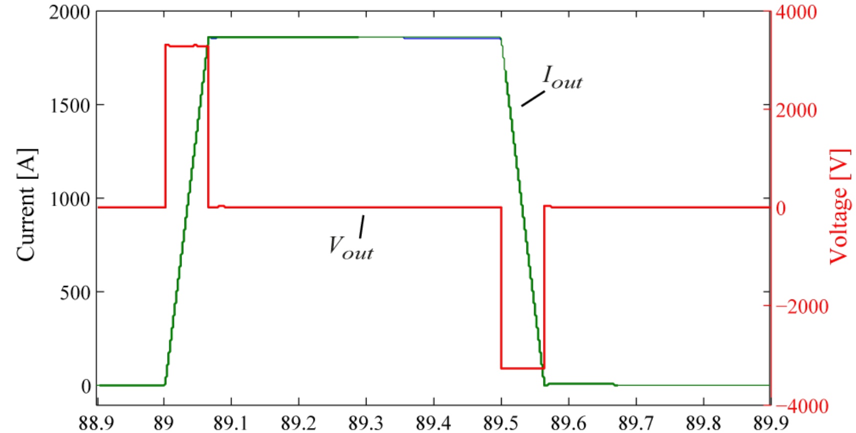


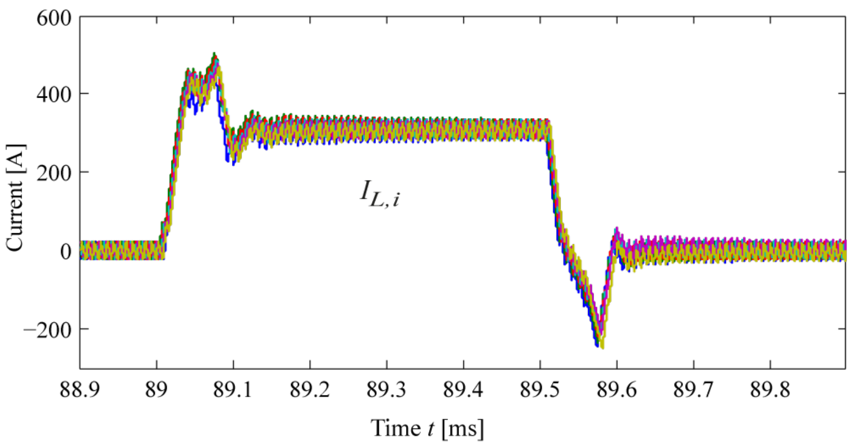


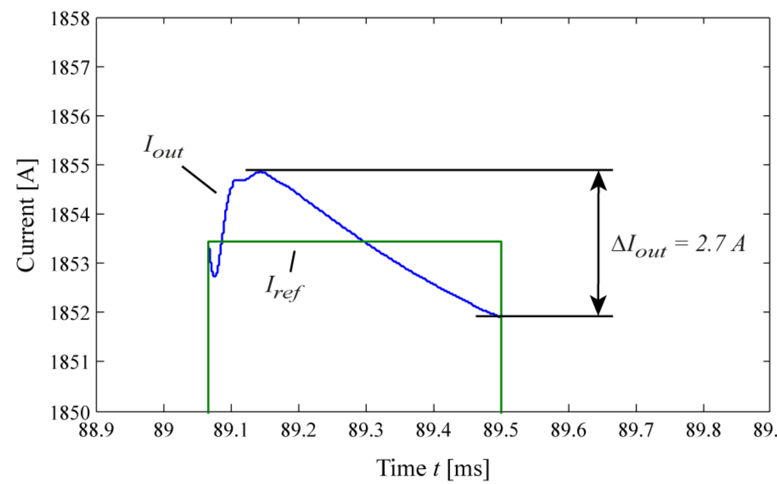
Simulation Results

- **Simulation of current pulse**
  - **- Flat top current deviation of 2.7A (0.15%)**
  - **- Repetition accuracy of 0.19 A ($1.025 \cdot 10^{-4}$)**
    - Only controller deviations
    - No jitter effects respected
    - No measurement errors considered

- **Interleaved buck converter**
  ➔ Balanced currents

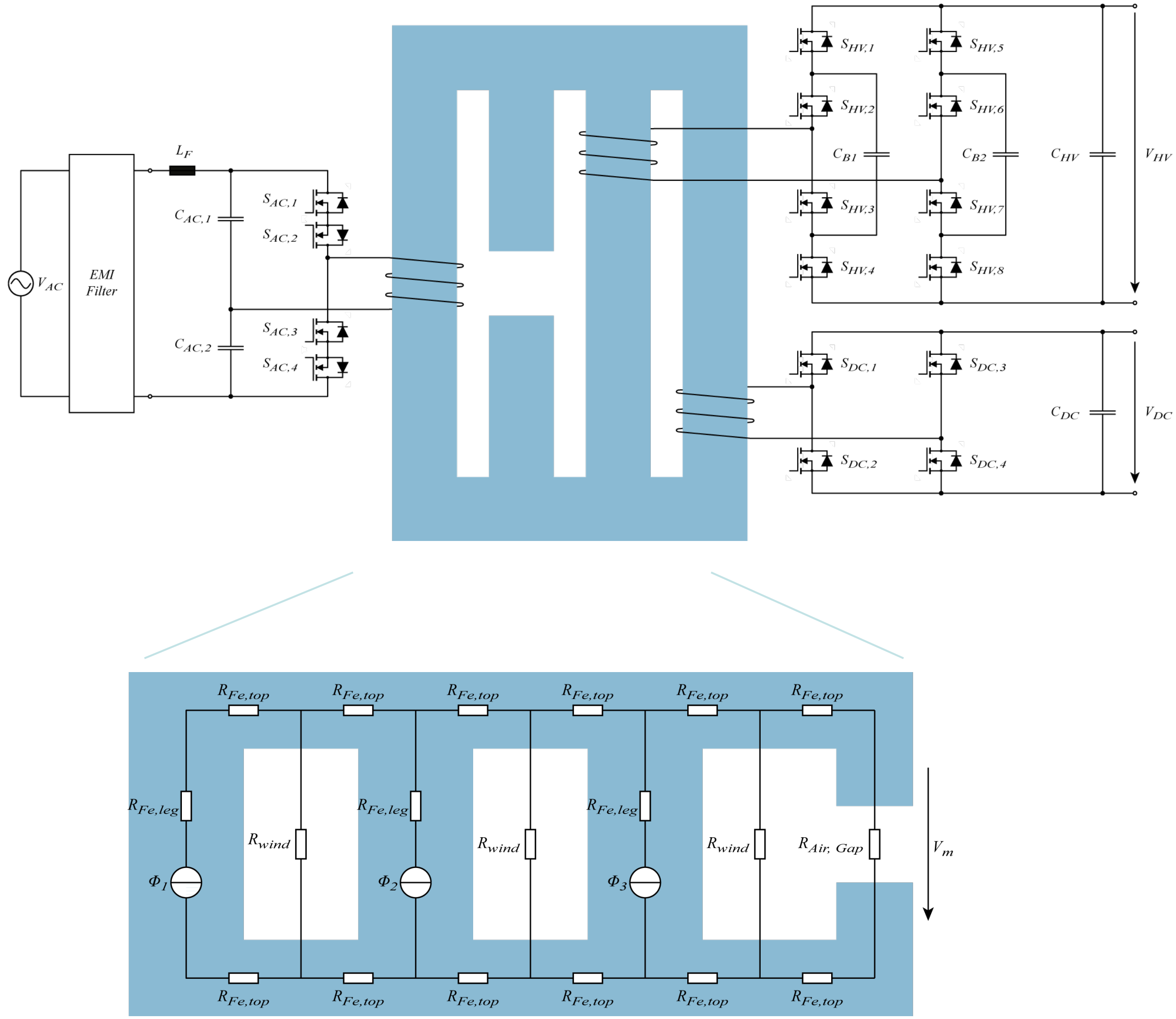






Charging Converter

- **Novell converter concept**
- **Galvanic isolation**
- **AC input**
- **Multi DC output**
- **Benefits**
  - Compact
  - High efficiency



Charging Converter

- **Novell converter concept**
- **Galvanic isolation**
- **AC input**
- **Multi DC output**
- **Benefits**
  - Compact
  - High efficiency

Current Source for Kicker Magnet

- **3.8kA pulse current**
- **400µs pulse**
- **38µH inductance**