Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Laboratory for High
Power Electronic Systems

Solid State Modulators
– Efficiency Considerations focussing on SiC Devices –

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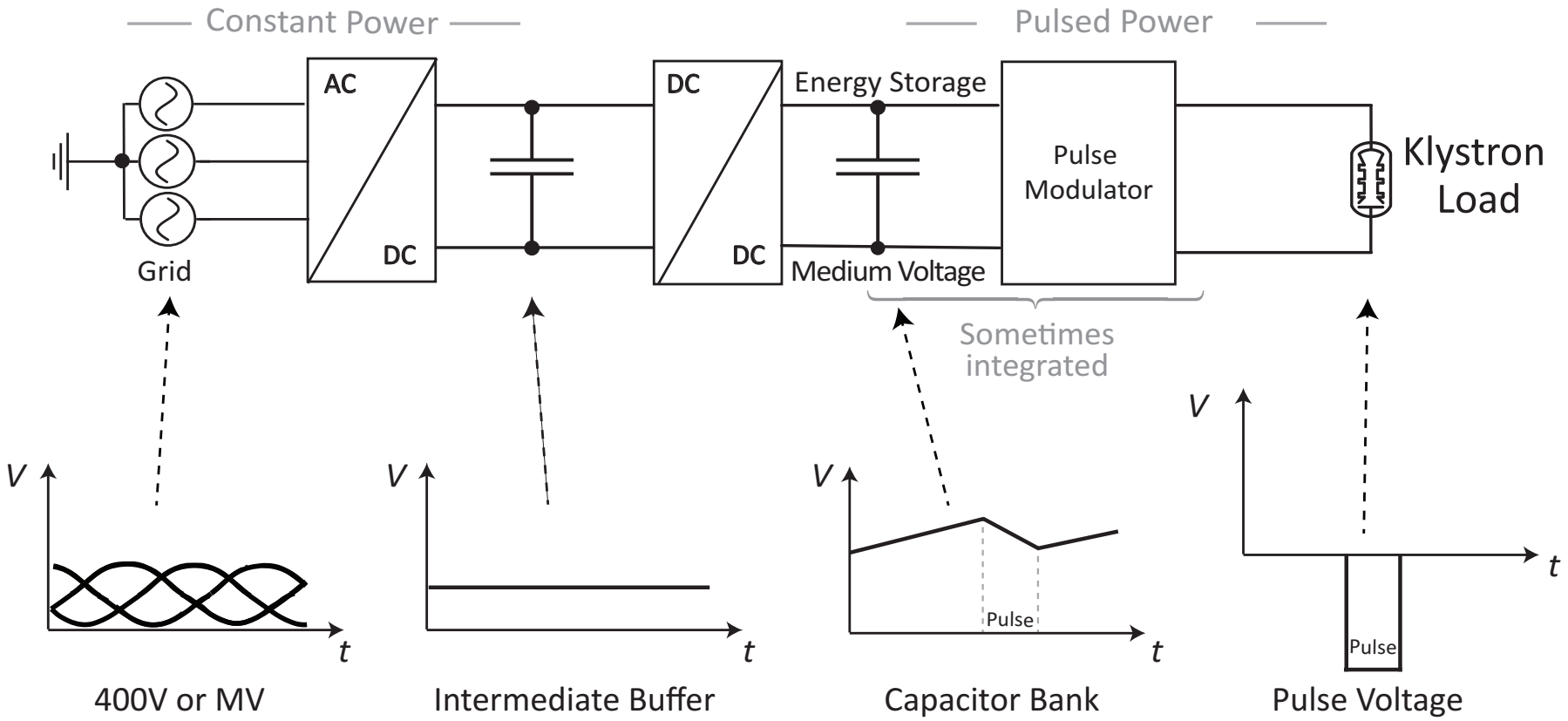
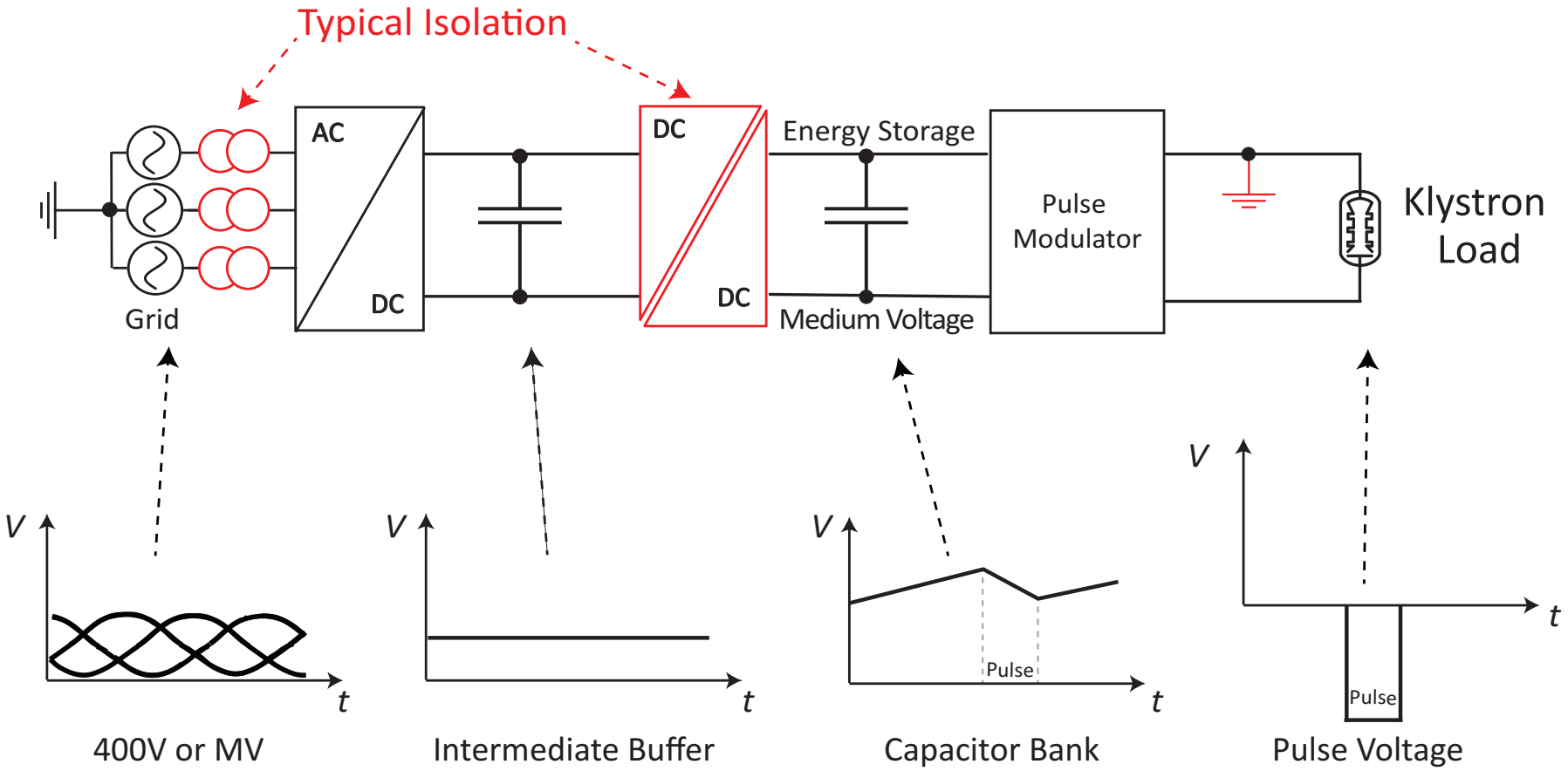
Typical Topology of Solid State Pulse Modulator Systems

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



Typical Topology of Solid State Pulse Modulator Systems

- **Grounded klystron load**
  - Isolation with 50Hz transformer or
  - Isolated DC-DC converter

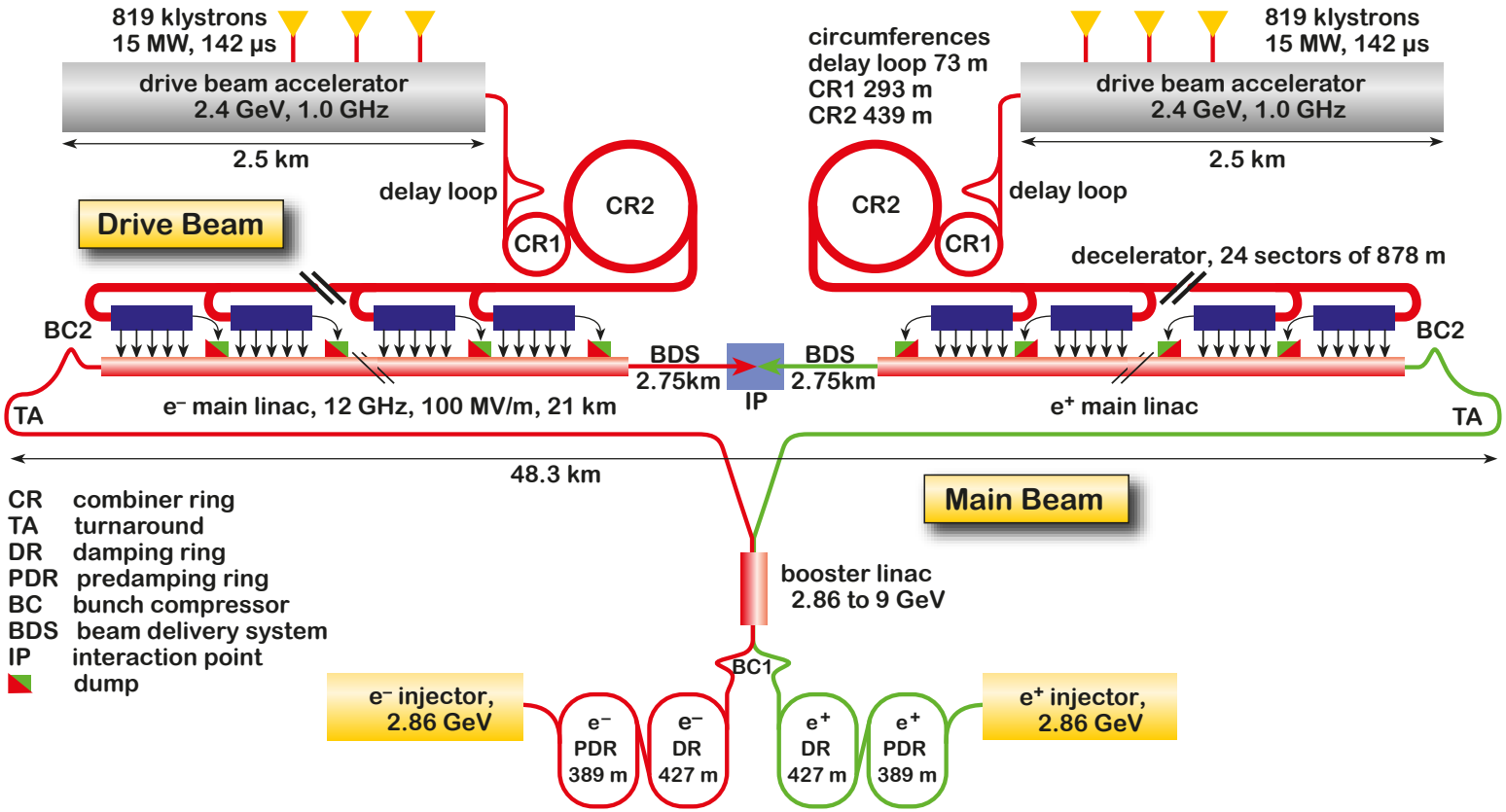


29 MW(35MW)/140 µs Modulator for CLIC

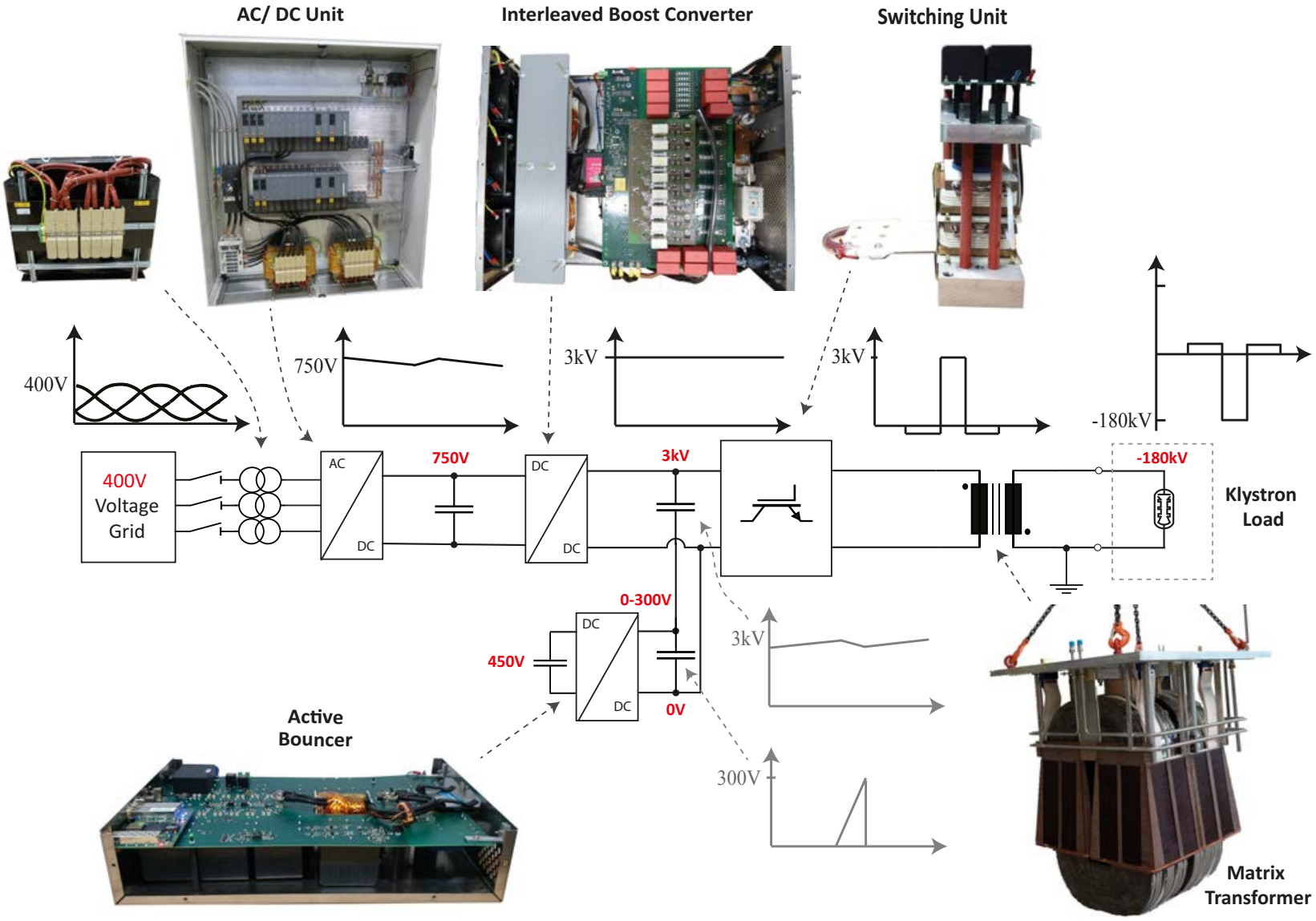
– System Efficiency –

CLIC System Specifications

- Output voltage 150...180 kV
- Output power (pulsed) 29 MW (- 35 MW)
- Flat-top length 140 µs
- Flat-top stability (FTS) <0.85 %
- Rise time <3 µs
- Settling time <8 µs
- Repetition rate 50 Hz
- Average output power 203 kW (- 245 kW)
- Pulse to pulse repeatab. <100 ppm

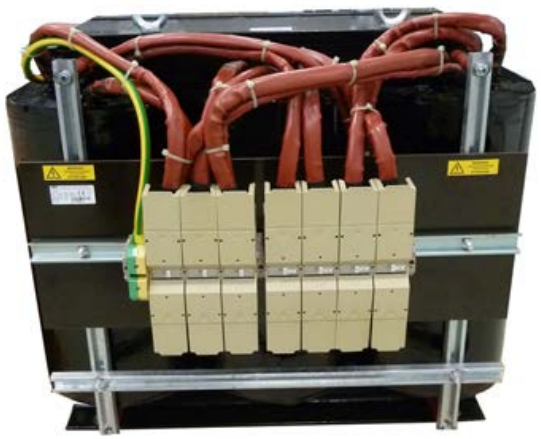


CLIC Solid State Modulator – System Overview

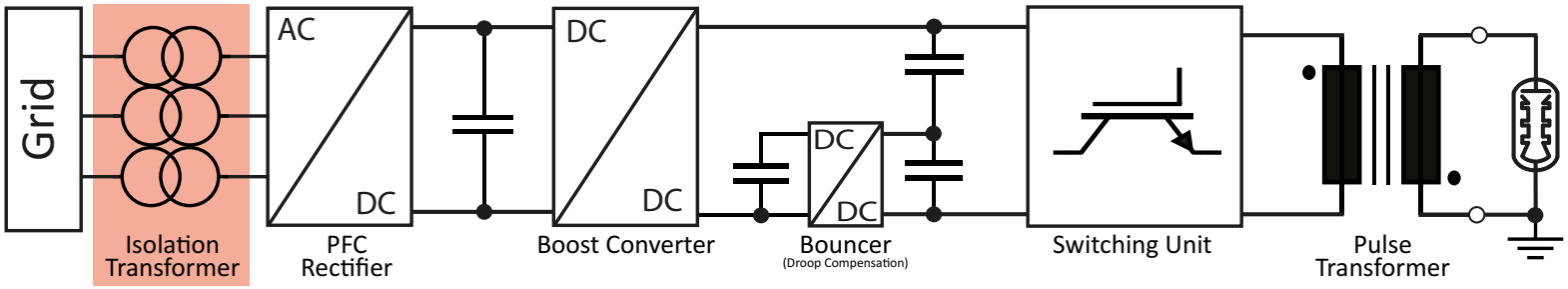


CLIC Modulator – Grid/Isolation Transformer

- Voltage — 3×400 V to 3×400 V @ 250 kVA
- Core material — Silicon steel
- Winding material — Aluminium
- Weight — 890 kg
- Efficiency — 98.8 %
  ($P_{Core} = 700\,\mathrm{W}$ & $P_{Wdg} = 2.3\,\mathrm{kW}$)



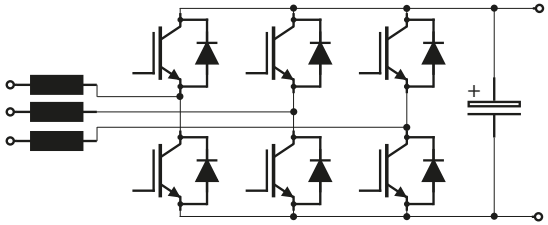
- Higher efficiency
  - Better core material — E.g. Amorphous ($P_{Core} - 60\,\%$)
  - Copper winding — Higher conductivity ($P_{Wdg} - 35\,\%$)
  - Efficiency — ➡ ≈99.2 % (Estimated)
    (Larger volume ➡ Higher efficiency)

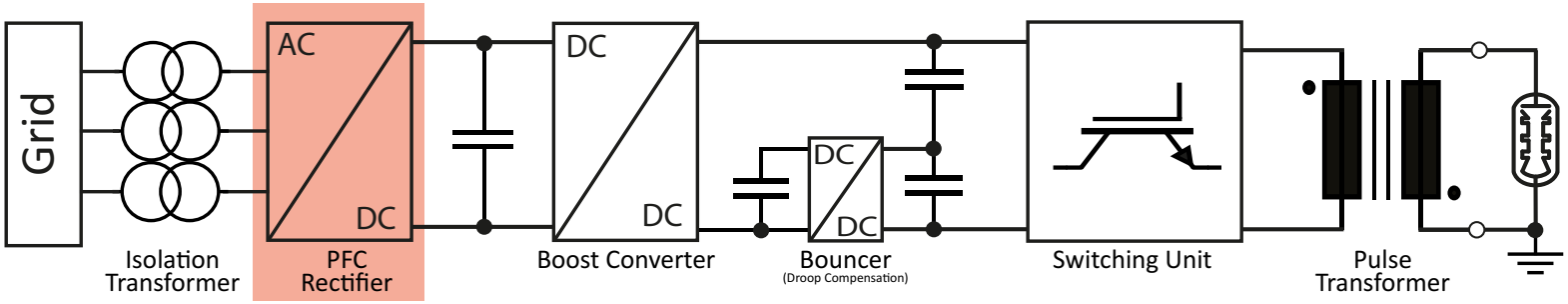


CLIC Modulator – AC/DC Converter Efficiency

- Type (B&R) — ACOPOSmulti 8BVP1650
- Topology — 2-level PFC-rectifier
- Switches — 1.2 kV Si IGBTs
- Voltage conversion — 400 $V_{AC} \rightarrow$ 750 V_{DC} (620 V – 800 V)
- Efficiency — 97.47 %

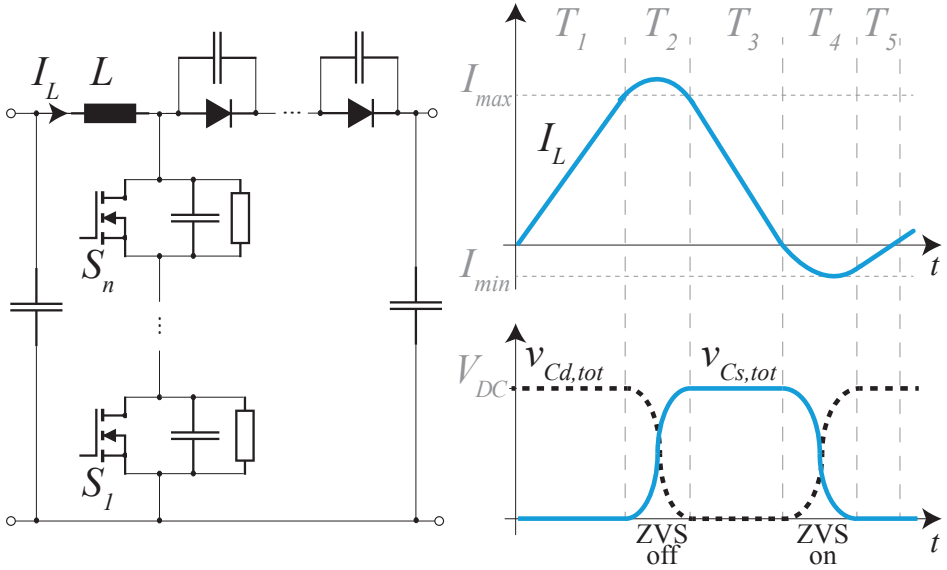
- Higher efficiency
  - 1.2 kV SiC MOSFETs — Lower P_{Cond} & P_{SW}
  - Optimised design — E.g. higher volume / lower f_{SW}
  - Efficiency — ➡ ≈99 %

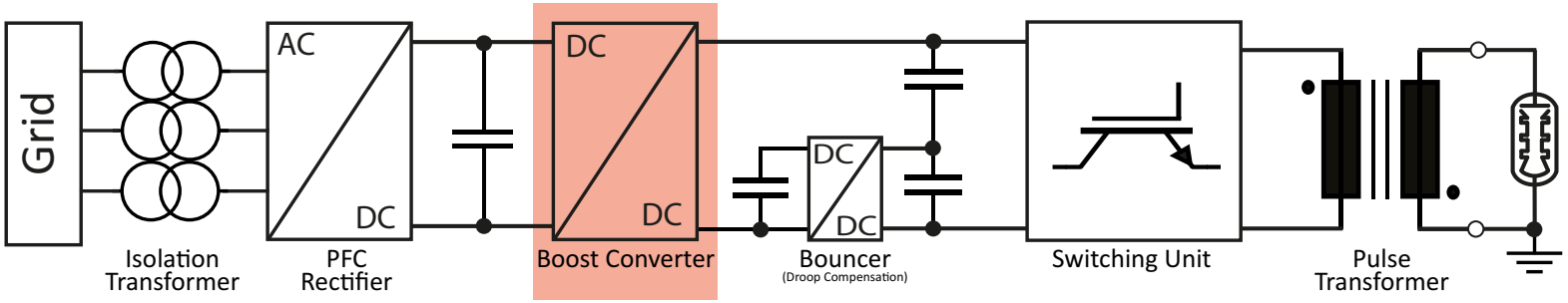




CLIC Modulator – Boost Converter Basic Operation

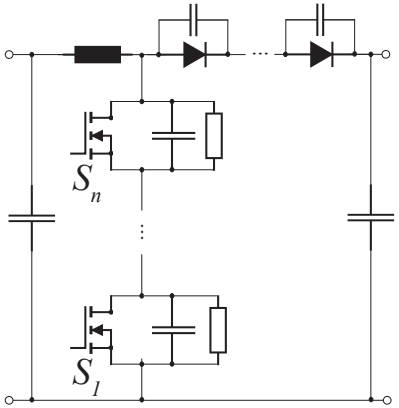
- Input voltage — 600 V – 800 V
- Output voltage — 3 kV
- Switching frequency — 70 kHz – 240 kHz
- Output power — 40 kW
- 650 V Si MOSFETs — 8 in series
  - ➡ C_s/R for balancing
- Boundary cond. mode
- 6-fold interleaving ➡ 6 × 40 kW

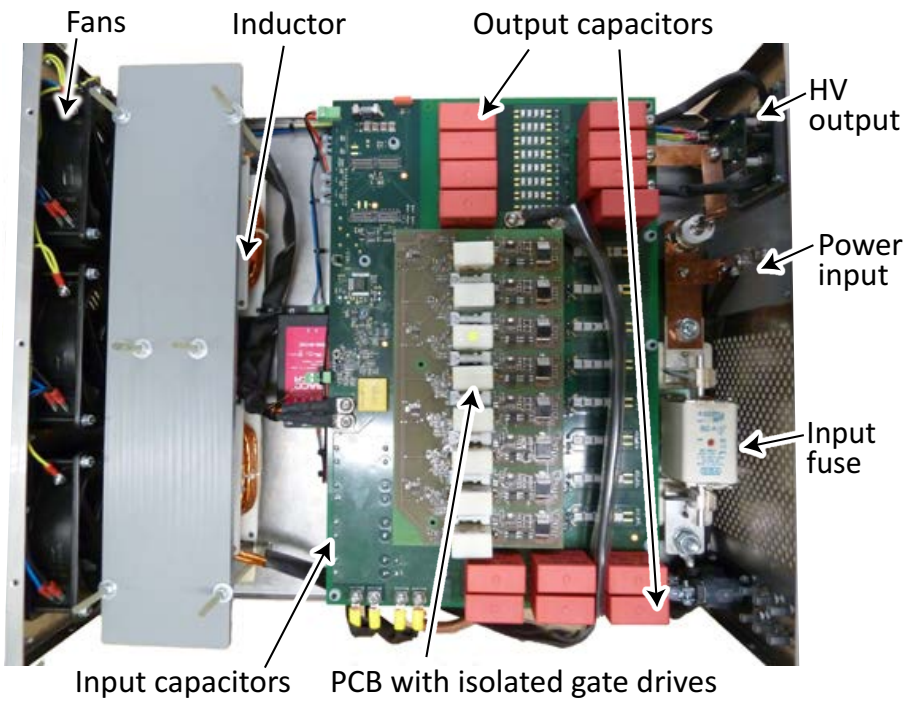


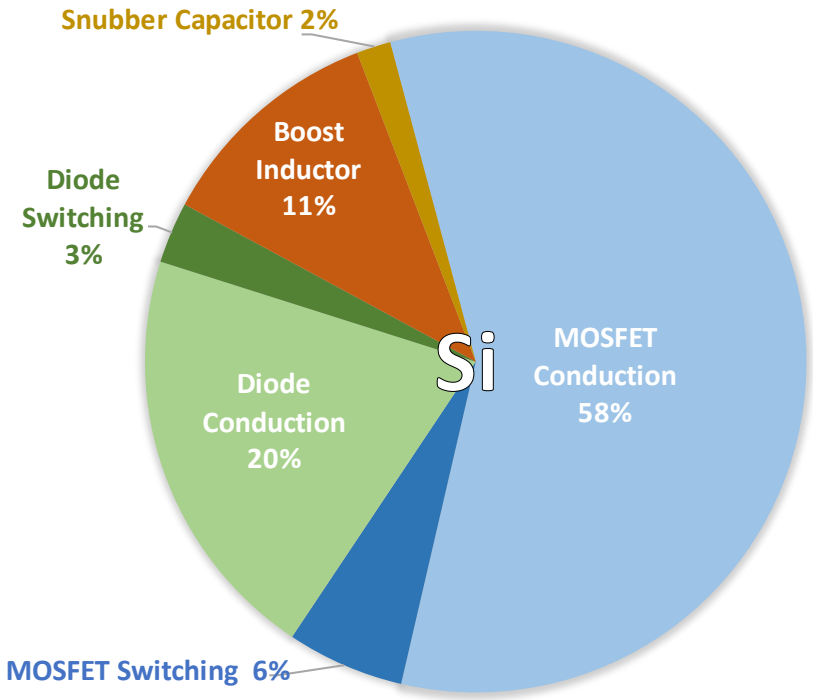


CLIC Modulator – Boost Converter Efficiency

- Nom. voltages — 750 V → 3 kV
- Output power — 40 kW
- Switching frequency — 70 kHz – 240 kHz
- 8×650 V Si MOSFETs — 2× Infineon IPZ65R019C7
- 4×1.2 kV diodes — Microsemi APT75DQ120B
- Efficiency — 97.2 %

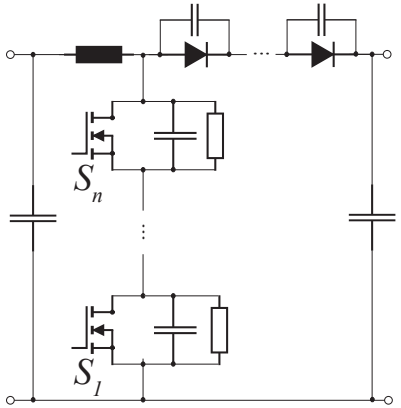


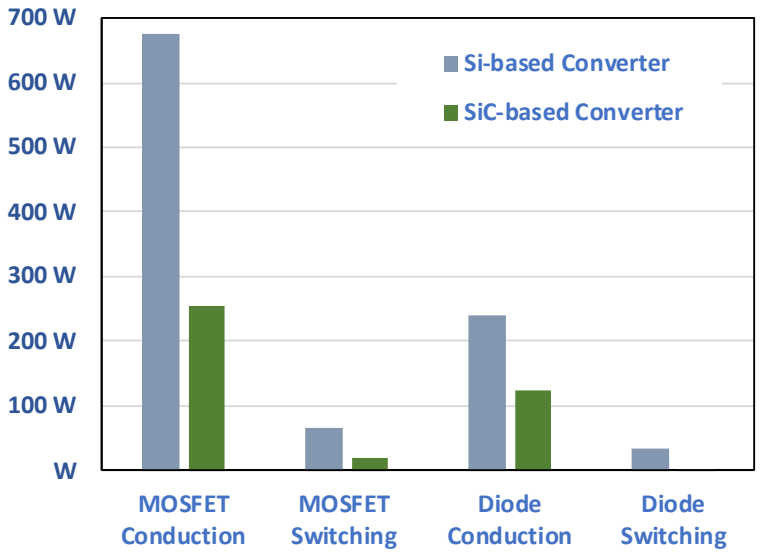


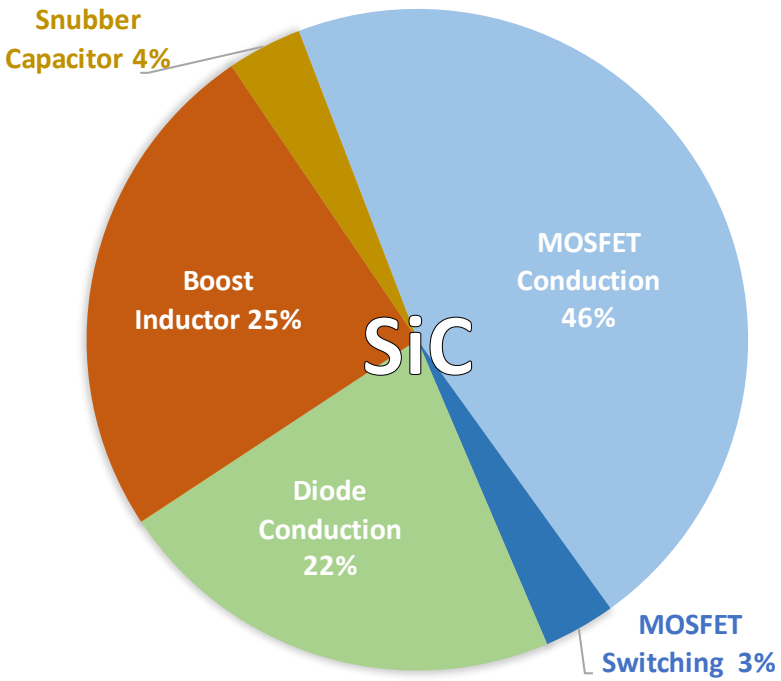


CLIC Modulator – "SiC" Boost Converter

- Voltages — 750 V → 3 kV
- Switching frequency — 70 kHz – 240 kHz
- Higher efficiency
  - 4×1.2 kV SiC MOSFETs — 2×C3M0016120K
  - 4×1.2 kV SiC Diodes — 2×IDW40G120C5B
  - Efficiency — ≈ 98.6 % (Old: 97.2 %)



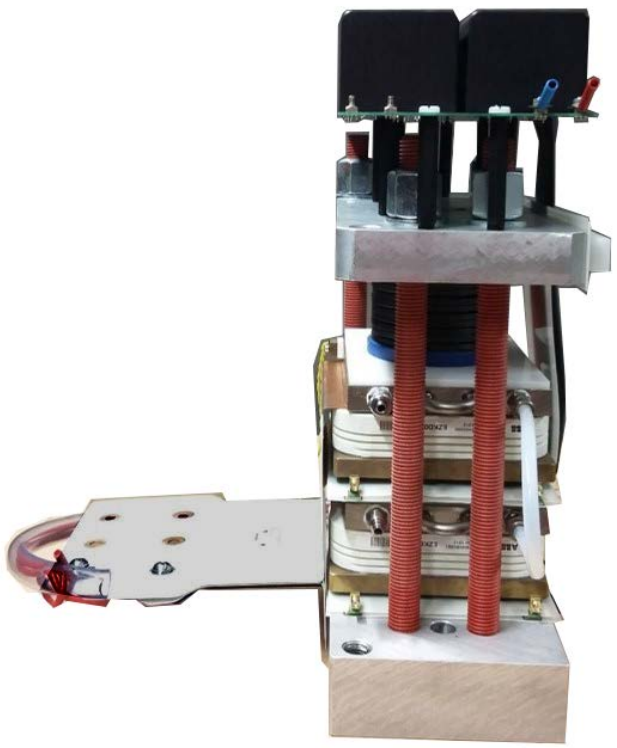


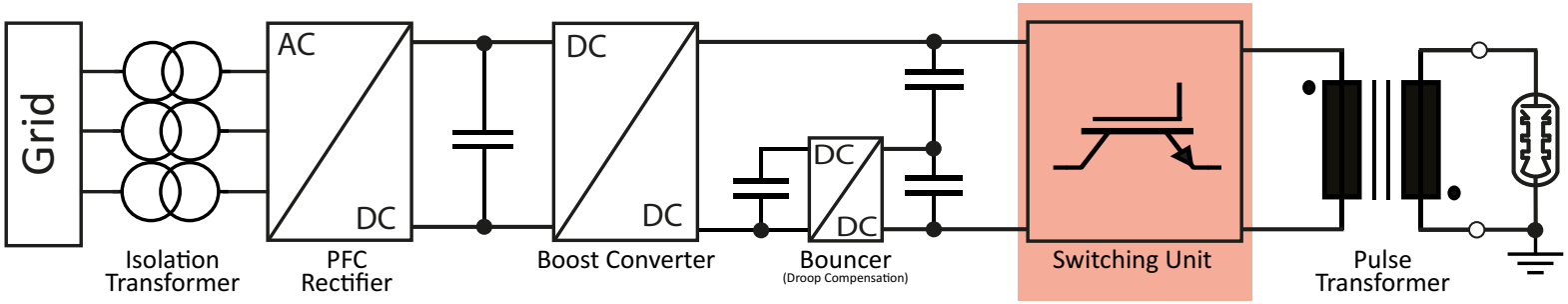


CLIC Modulator – Switching Unit

- ABB StakPak (5SNA1250B450300) — 4.5 kV / max. 3 kA (pulsed)
- Active reset switch
- 4 units in parallel
- Pulse current — 4×2.4 kA (@ $P_P = 29$ MW)
- Efficiency — 98.6 % (Switching losses: 87% of P_{tot})

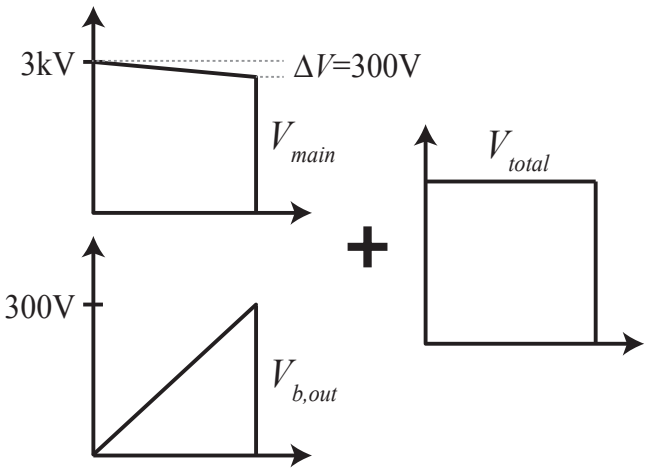
- Higher efficiency
  - Semiconductors — SiC MOSFETs (assumption: 1.2 kV devices) (4 in series / 3 parallel)
  - Efficiency — ➡ 99.5 %

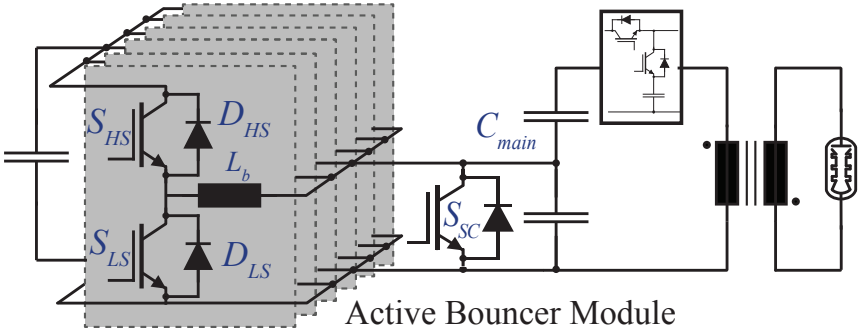


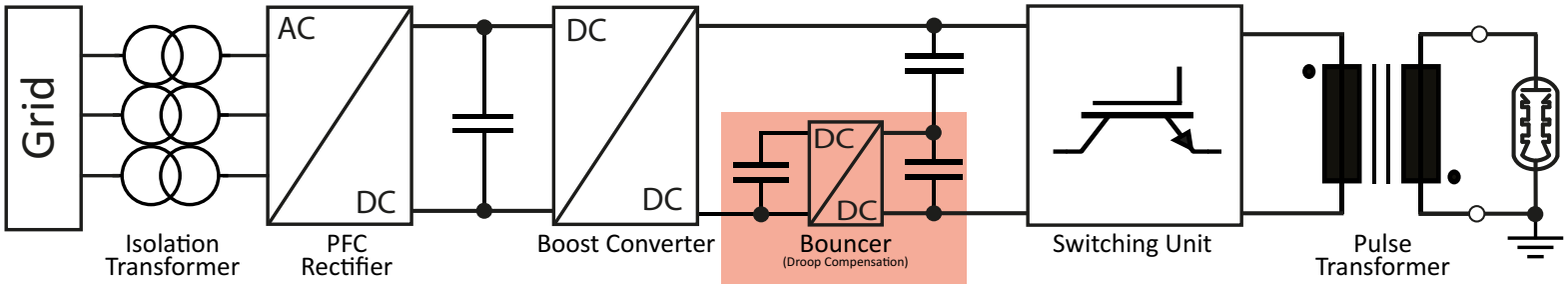


CLIC Modulator – Bouncer

- Output voltage 0…300 V (10 % droop)
- Input voltage 450 V
- 24-fold interleaving
- Ultra low ripple
- Semiconductors IGBTs

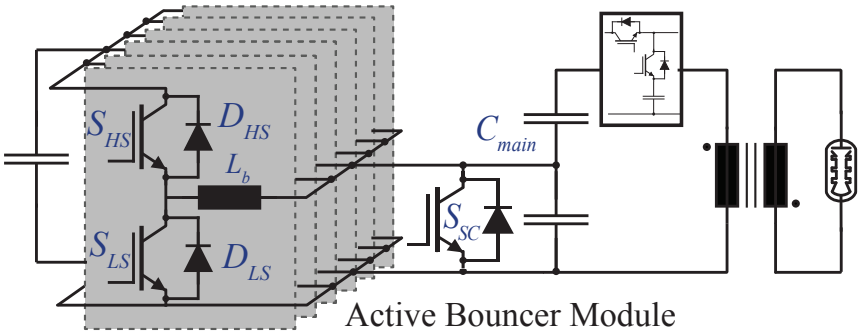


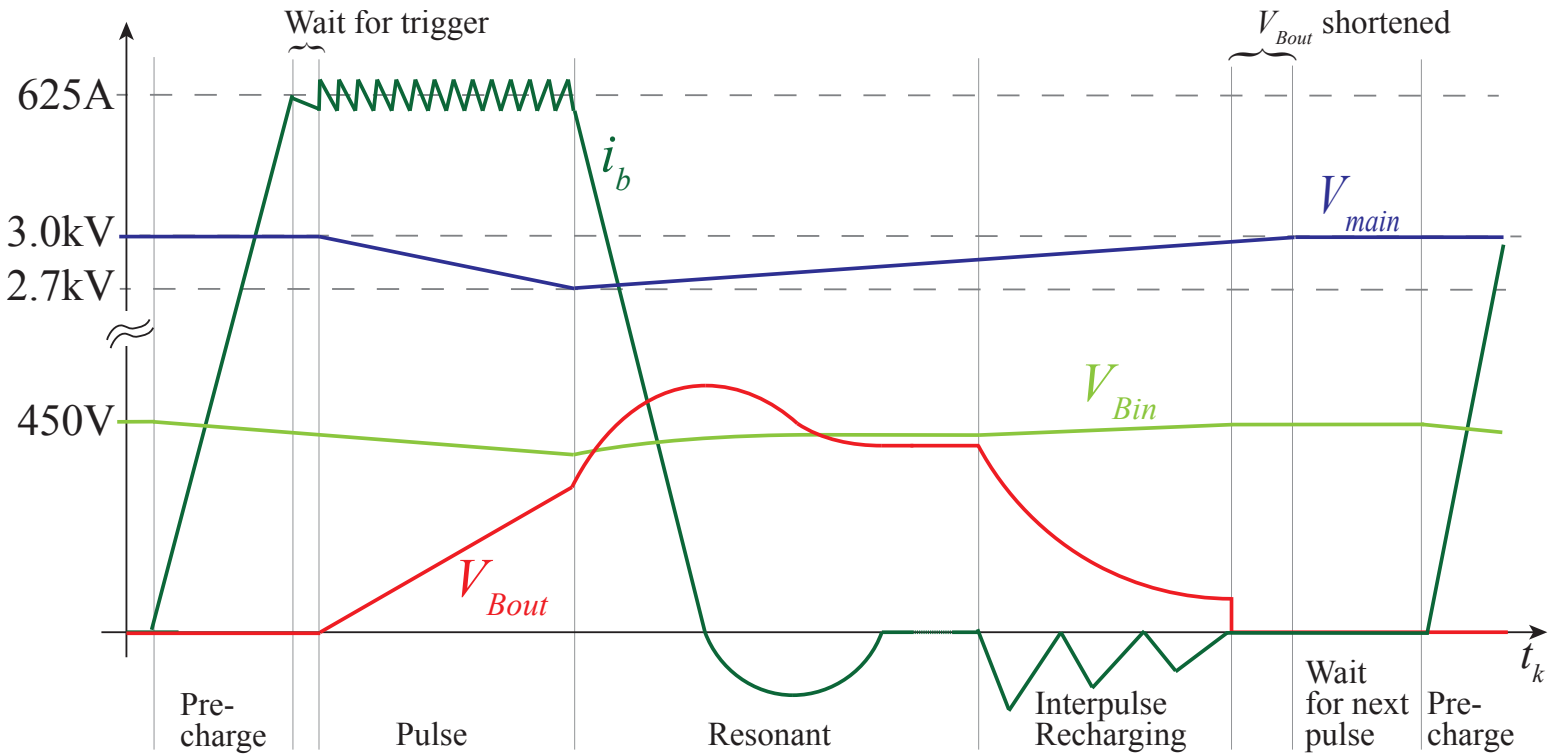




CLIC Modulator – Bouncer Operating Principle

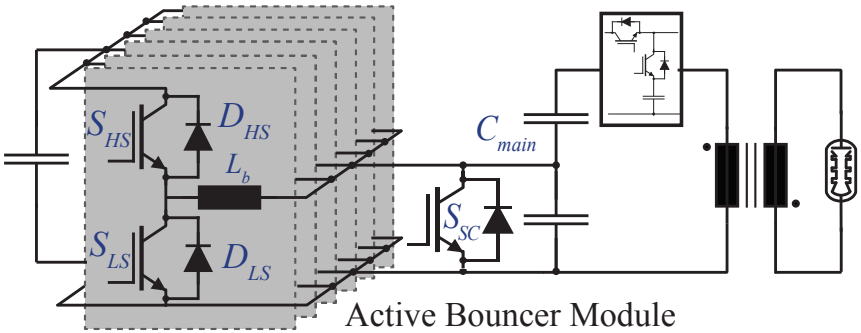
- Output voltage 0…300 V
- Input voltage 450 V
- Output current (pulse) (per module) >600 A

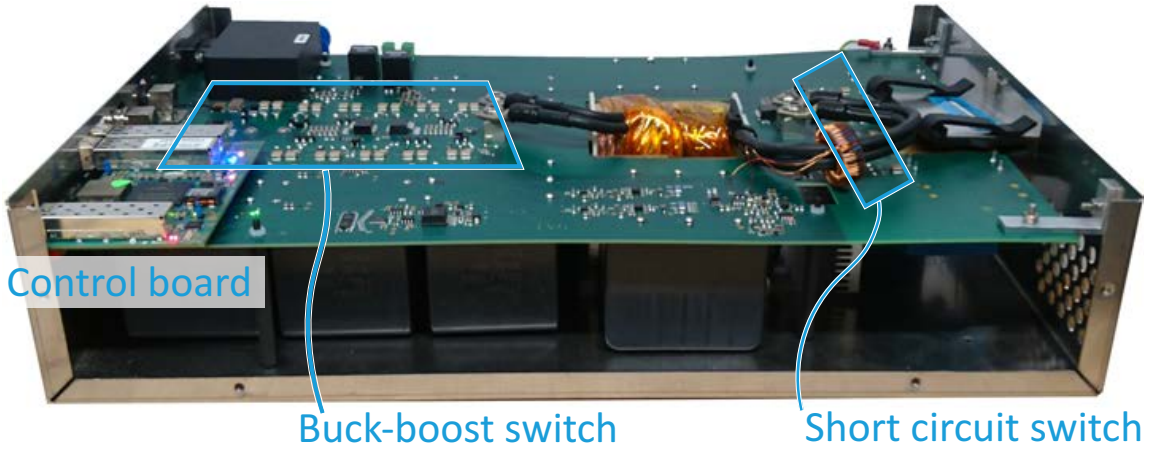




CLIC Modulator – Bouncer Components

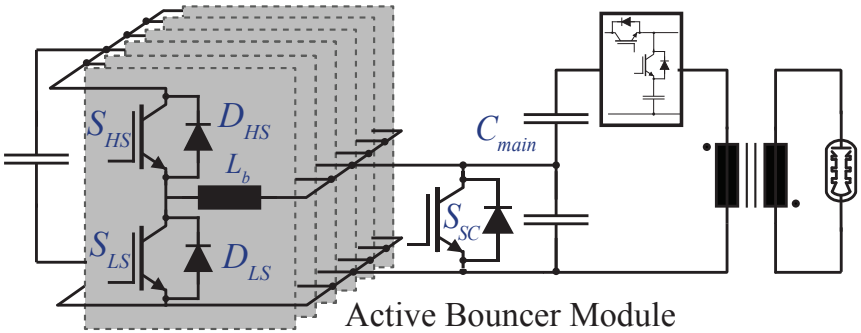
- Output voltage 0...300 V
- Input voltage 450 V
- 4×6-fold interleaving
- Switching frequency 100 kHz
- Per module:
  - S_{LS}-IGBTs 2×IGW50N65H5
  - D_{LS}-Diodes 4×IDW40E65D1
  - S_{HS}-IGBTs (w. diode) 6×IKW50N65F5
  - S_{SC}-IGBTs (w. diode) 6×IKW50N65F5
  - Inductor L_b = 26 µH 4×Metglas AMCC32

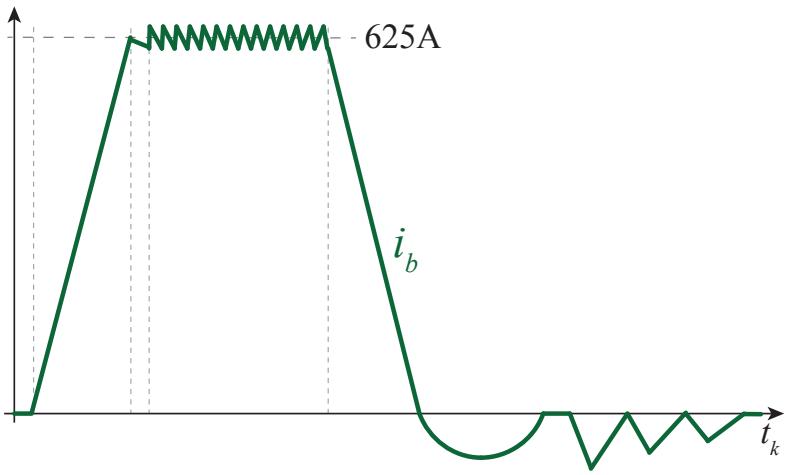


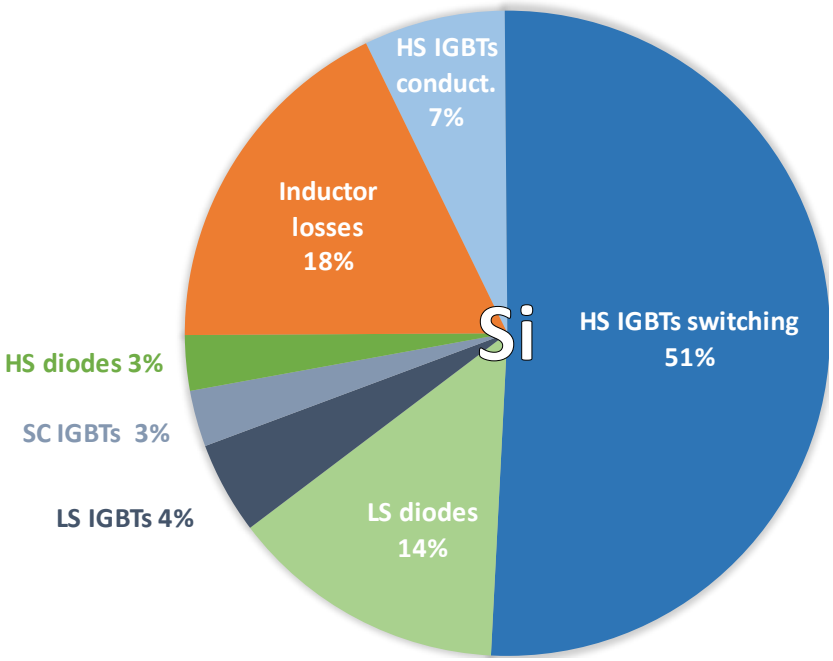


CLIC Modulator – Bouncer Efficiency

- **With IGBTs**
  - Total AVG losses 1.56 kW
  - Module efficiency 91.0 % Bouncer-Level
    - ➡ Efficiency 99.4 % System-Level

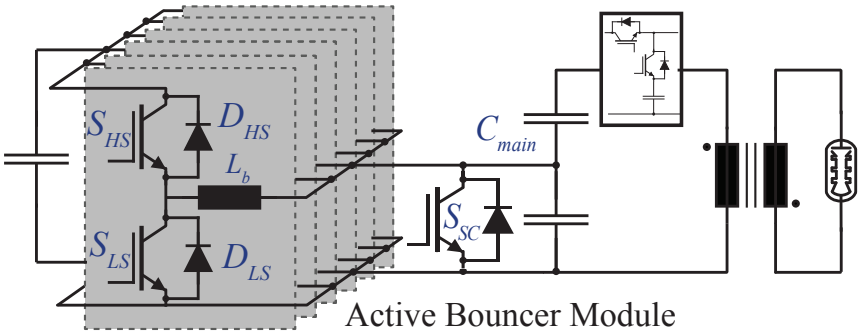


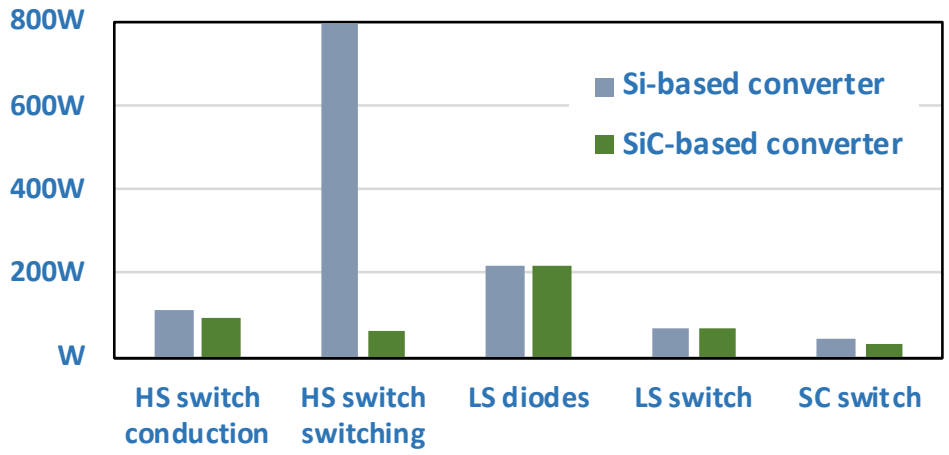


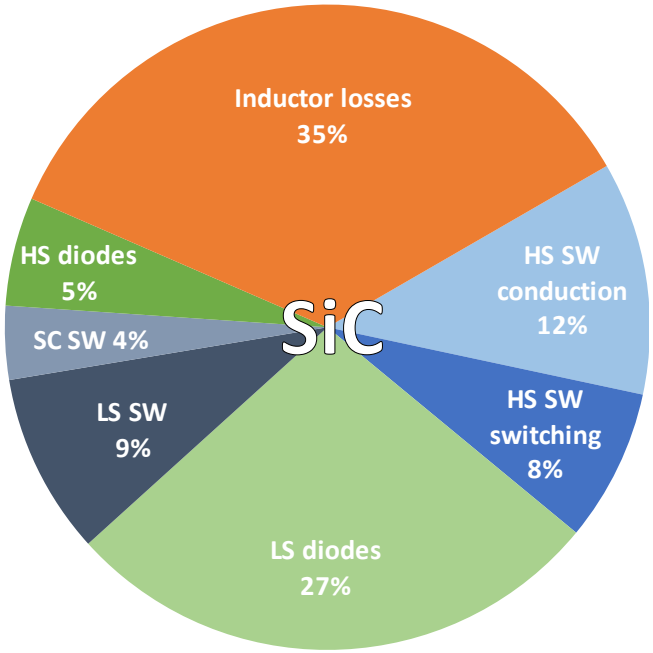


CLIC Modulator – SiC Bouncer Efficiency

- **With IGBTs**
  - Total AVG losses 1.56 kW
  - Module efficiency 91.0 % Bouncer-Level
  - ➡ Efficiency 99.4 % System-Level
- **With SiC MOSFETs**
  - Total AVG losses 0.79 kW
  - Module efficiency 95.2 % Bouncer-Level
  - ➡ Efficiency 99.7 % System-Level

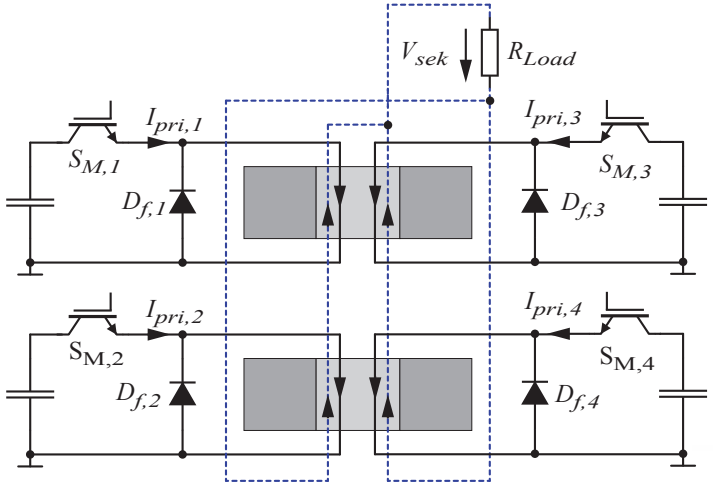


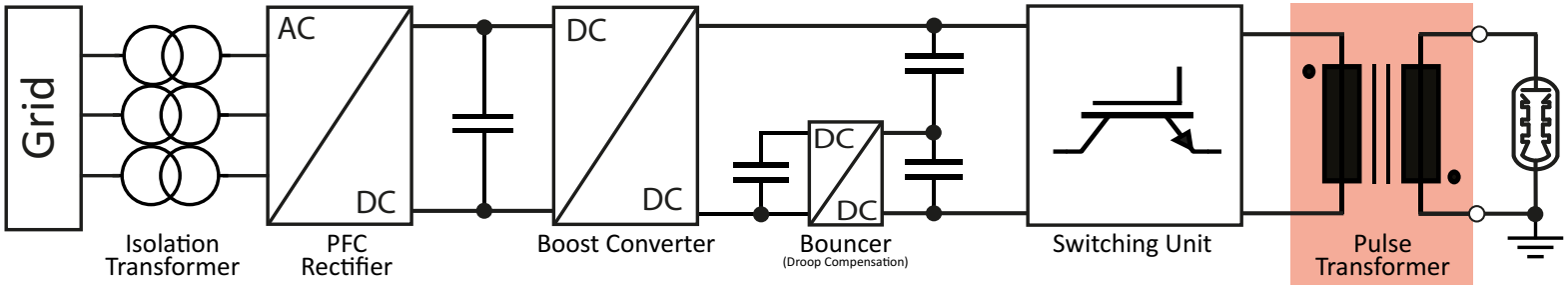




CLIC Modulator – Pulse Transformer

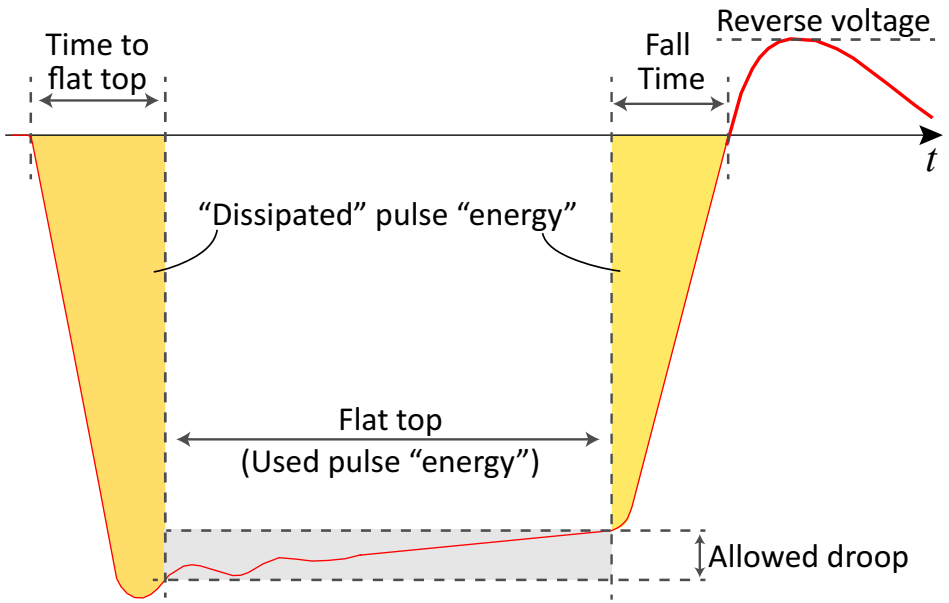
- Matrix transformer — 2 cores / 4 primary windings
- Turns ratio — 62 ➡ 4:(2×124)
- Core material — SiFe / 50 µm

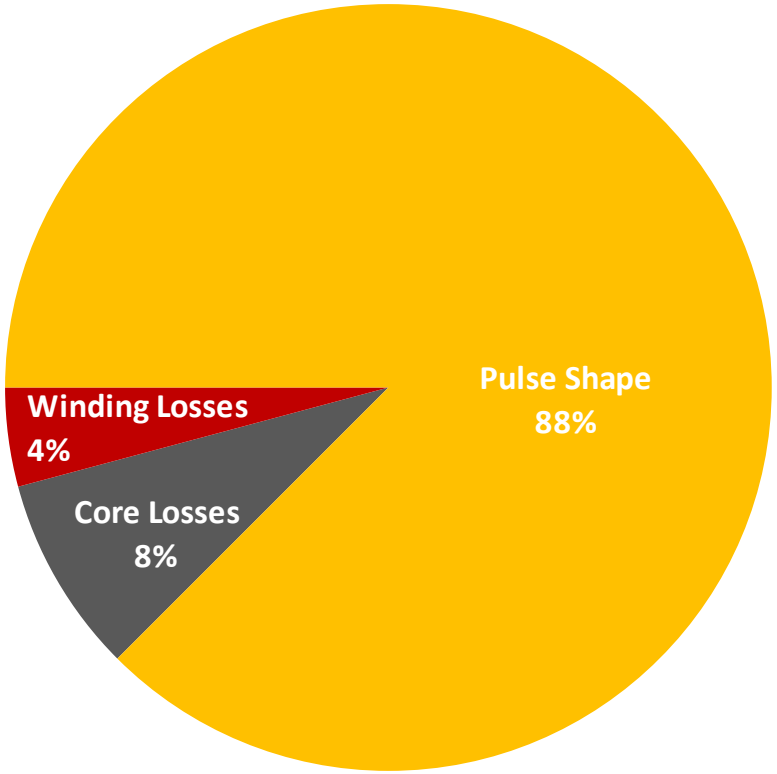




CLIC Modulator – Pulse Shape/Transformer Efficiency

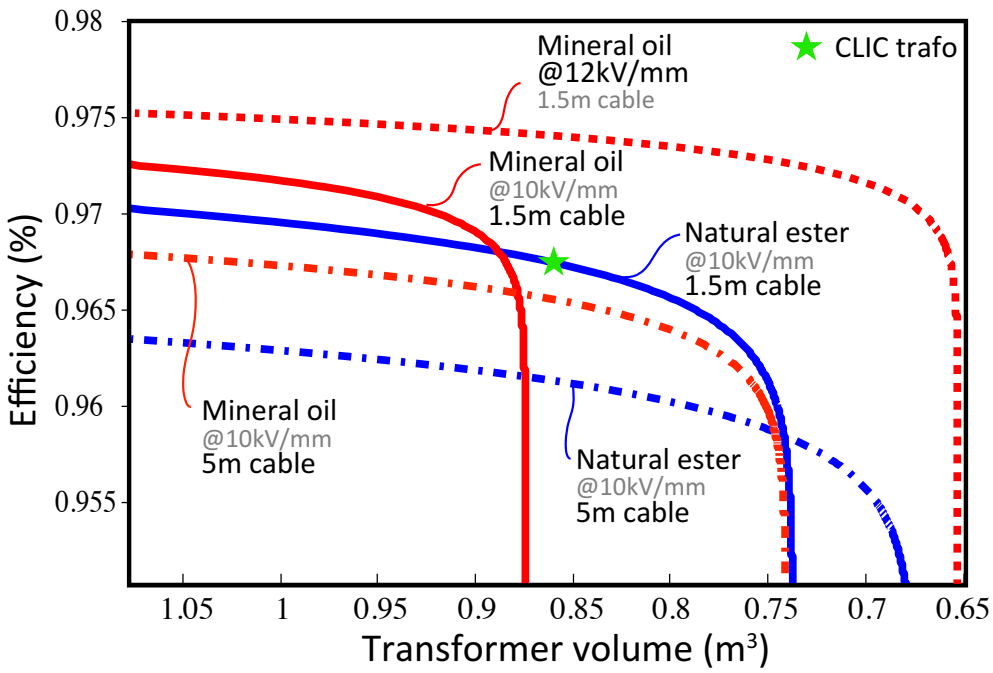
- Rise + settling time 4.6 µs
- Fall time <3 µs
- Flat top 140 µs
- Efficiency 96.7 % (Trafo + Pulse shape)





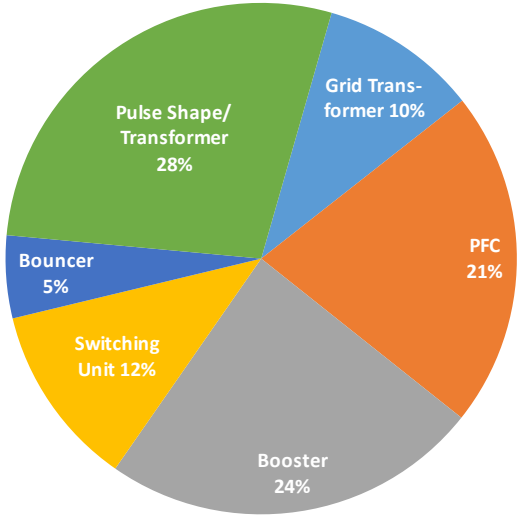
CLIC Modulator – Higher Transformer Efficiency

- **Core material** — **SiFe 25 µm lamination**
  Amorphous material
- **Insulating oil** — **Ester 7131** $\varepsilon_r = 3.2$ ➡ **Mineral oil** $\varepsilon_r = 2.2$
- **Shorter load cable**
- **Transformer design** — **Critical damping** (slightly underdamped)
  Larger volume / Core splitting
- **Estimated efficiency** — $\approx \geq$**97.5 %**

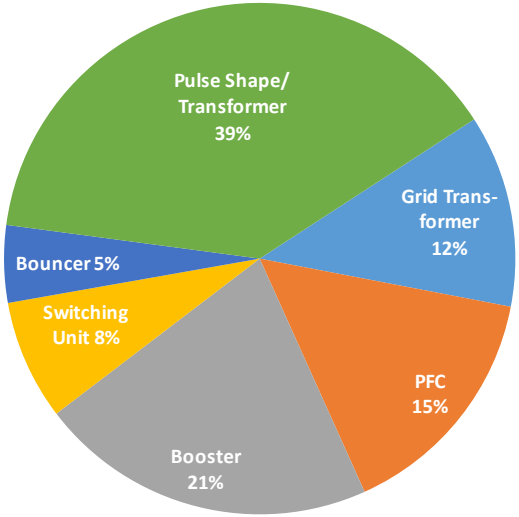


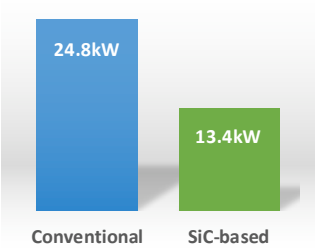
CLIC Modulator – System Efficiency

Original System

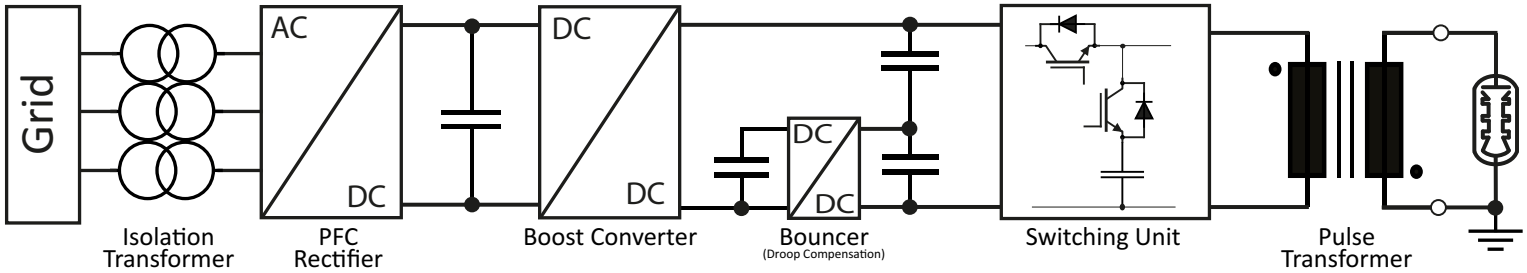


Improved System



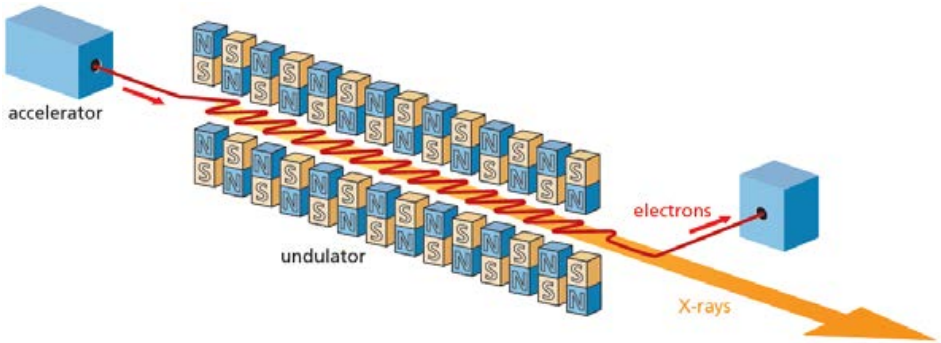


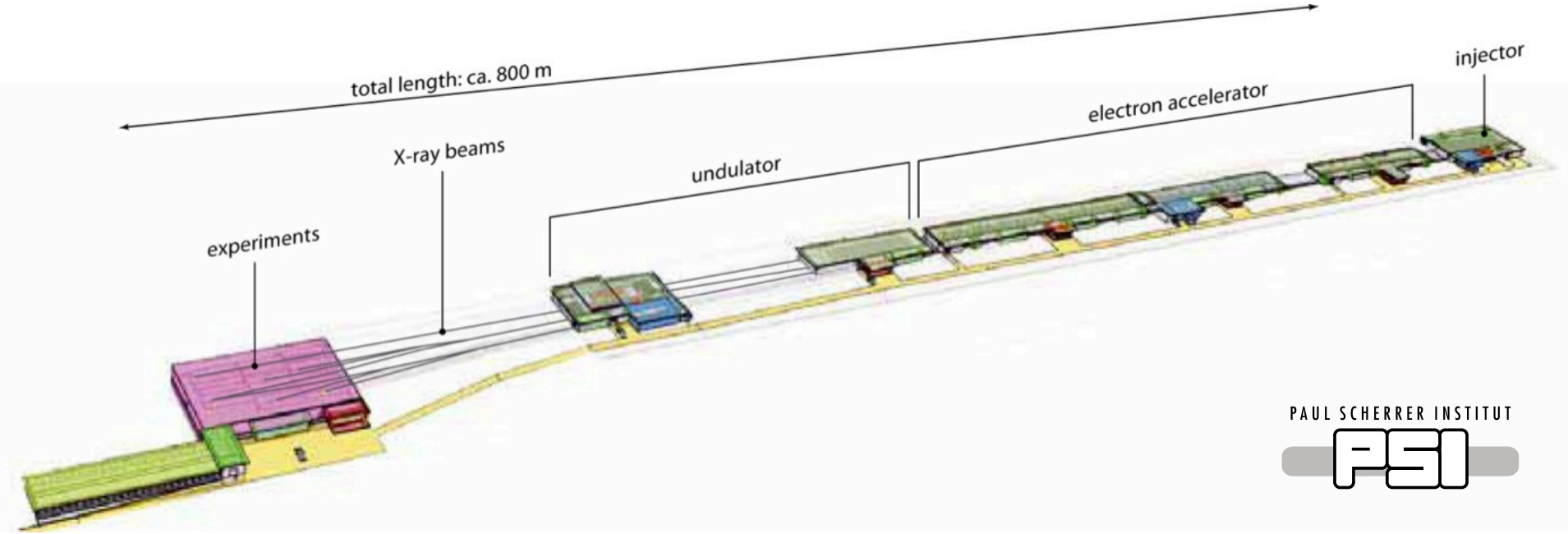
Original	**98.8%**	**97.5%**	**97.2%**	**99.4%**	**98.6%**	**96.7%**	**88.7%**
Improved	**99.2%**	**99.0%**	**98.6%**	**99.7%**	**99.5%**	**97.5%**	**93.6%**



SwissFEL Modulator – Pulse Efficiency @ Short Pulses

- Free electron laser ➡ X-Rays
- Electron beam energy 5.8 GeV
- Wavelength range 1 Å – 70 Å
- Output voltage 370 kV
- Output power (pulsed) 127 MW
- Flat-top length 3 µs
- Rise time $<$1 µs
- Repetition rate 100 Hz

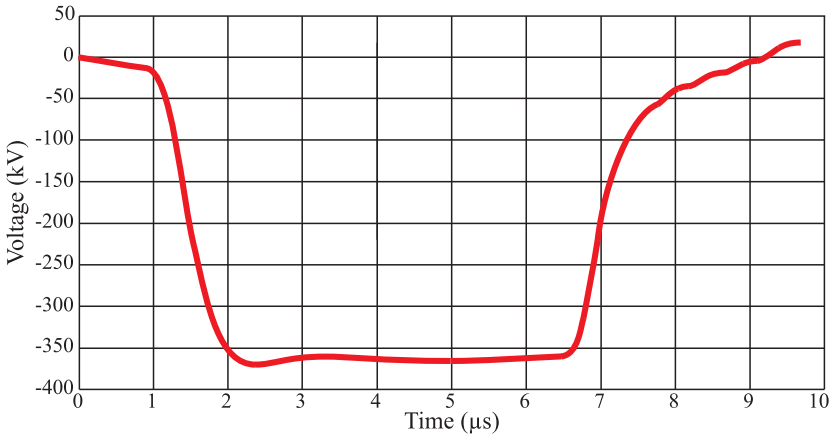


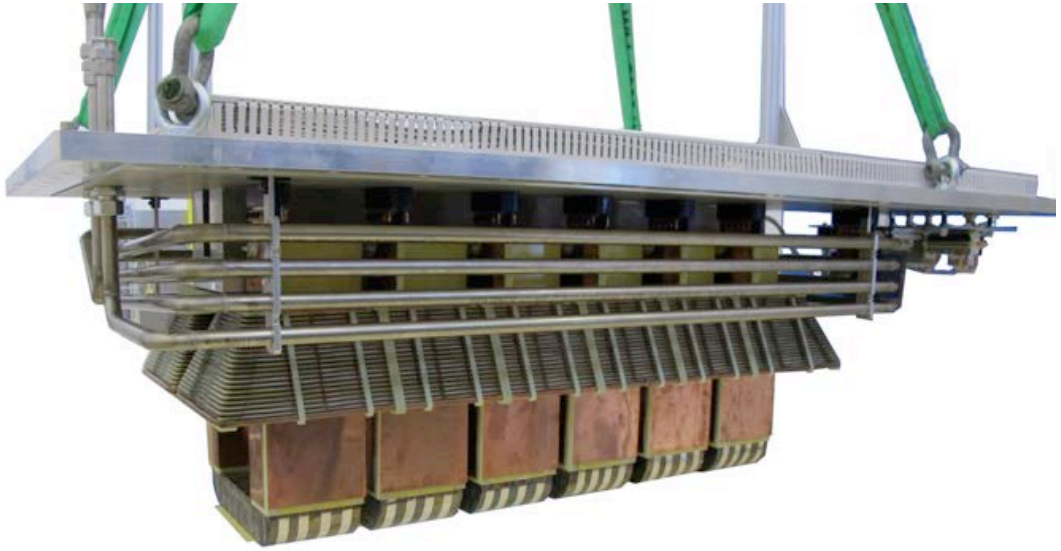


SwissFEL – Pulse Transformer

- Matrix transformer — 6 cores / 12 primary
- Turns ratio — 1:21 × 6 ➡ 1:126
- Core material — SiFe / 50 µm
- Rise time — ≈ 1 µs
- Fall time — ≈ 0.9 µs

➡Pulse shape — ≈ <82 %





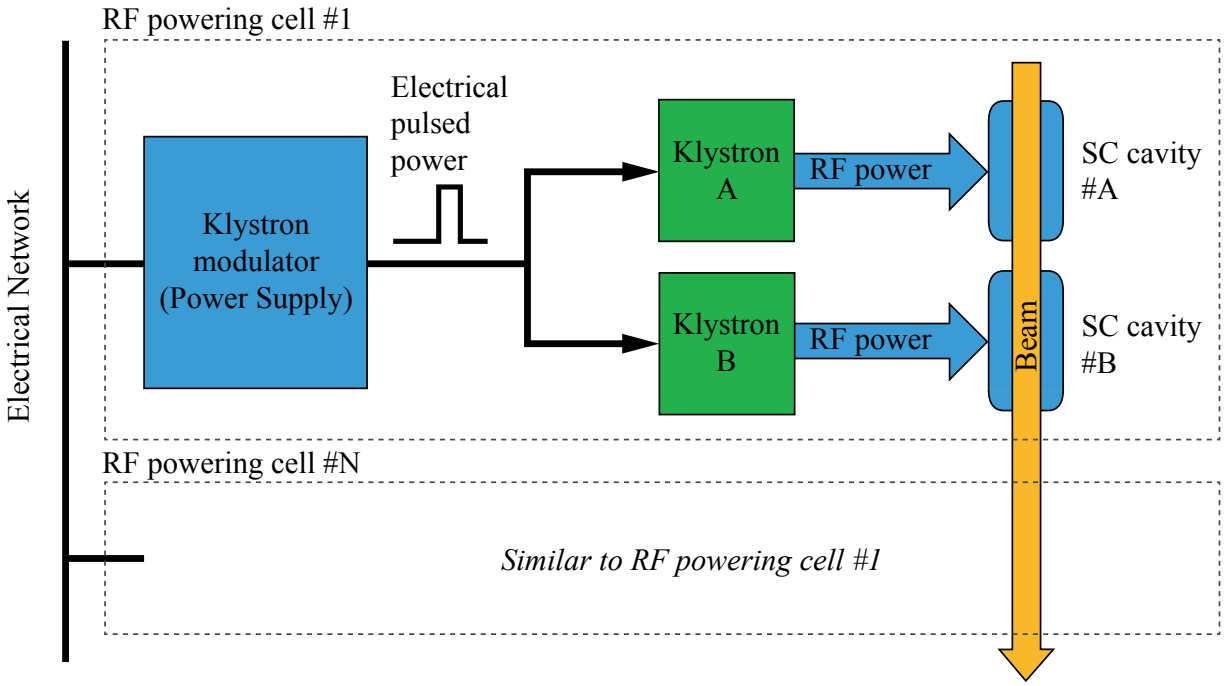
Solid State Modulators

2.88 MW / 3.5 ms Modulator for European Spallation Source (ESS)

ESS Modulator Specifications

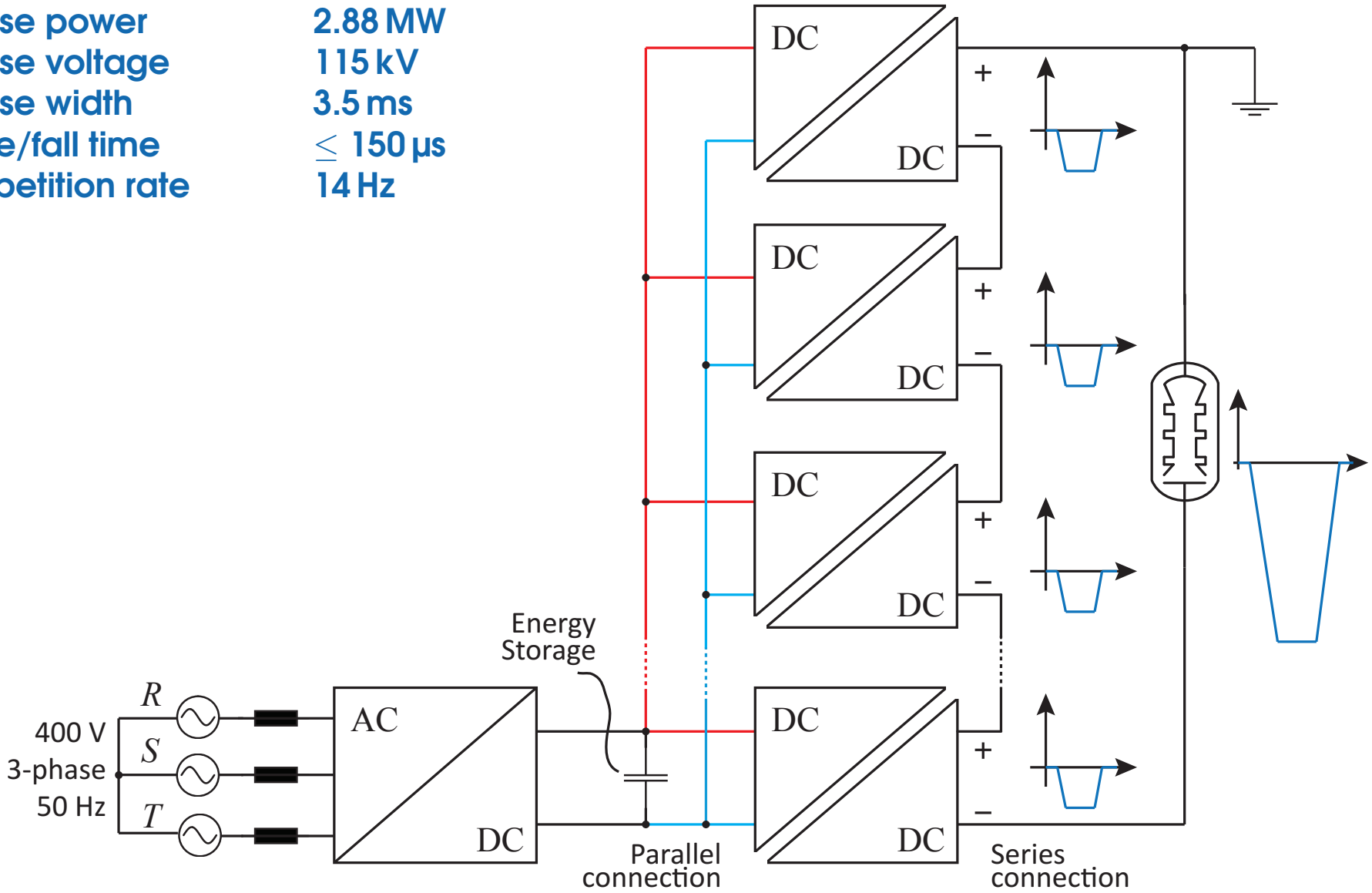
- Pulse power 2.88 MW
- Pulse voltage 115 kV
- Pulse width 3.5 ms
- Rise/fall time $\leq$ 150 µs
- Repetition rate 14 Hz

EUROPEAN SPALLATION SOURCE



ESS Modulator – Basic Configuration

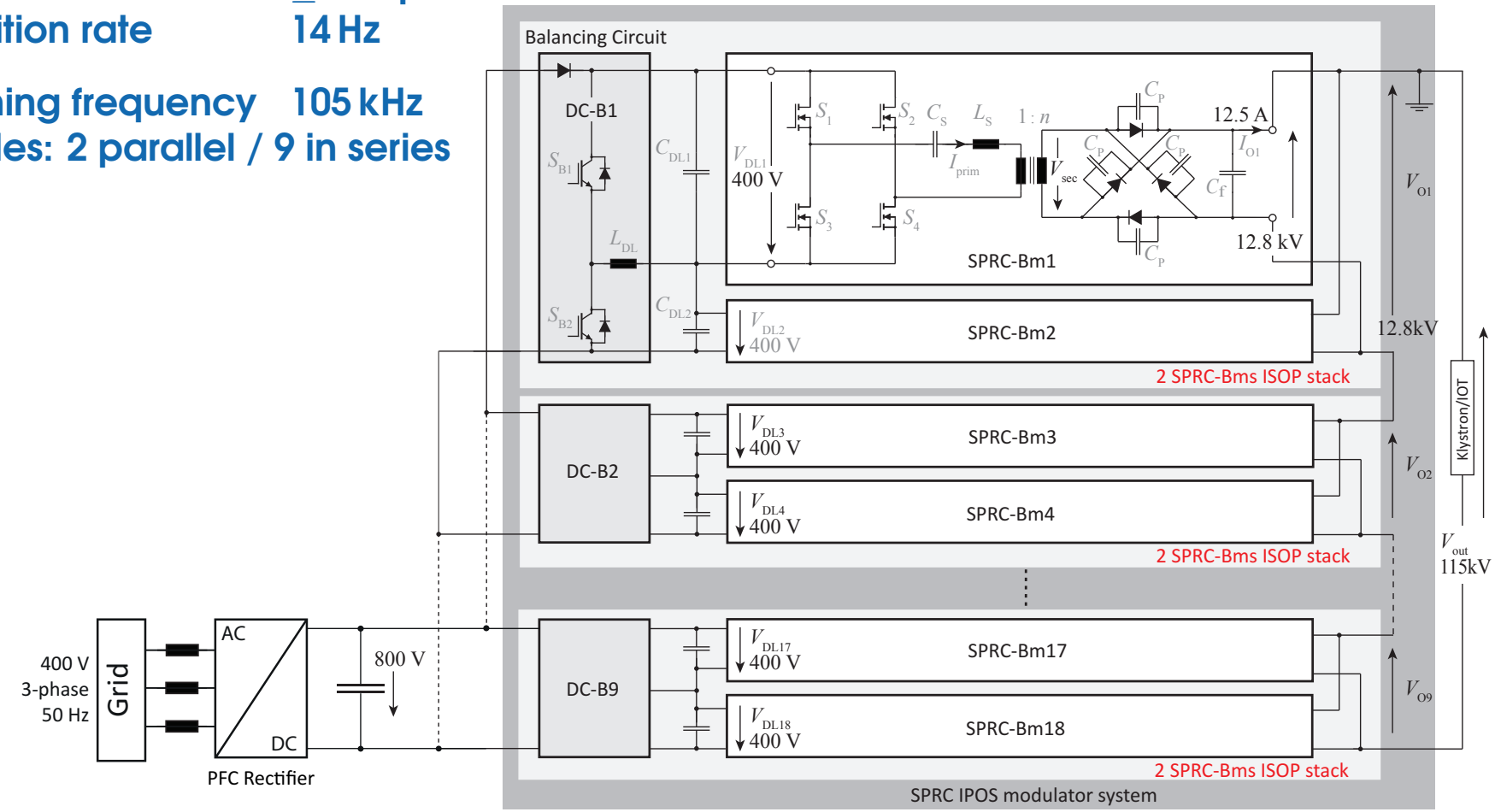
- Pulse power 2.88 MW
- Pulse voltage 115 kV
- Pulse width 3.5 ms
- Rise/fall time $\leq$ 150 µs
- Repetition rate 14 Hz



ESS Modulator – Basic Configuration

- Pulse power 2.88 MW
- Pulse voltage 115 kV
- Pulse width 3.5 ms
- Rise/fall time $\leq$ 150 µs
- Repetition rate 14 Hz

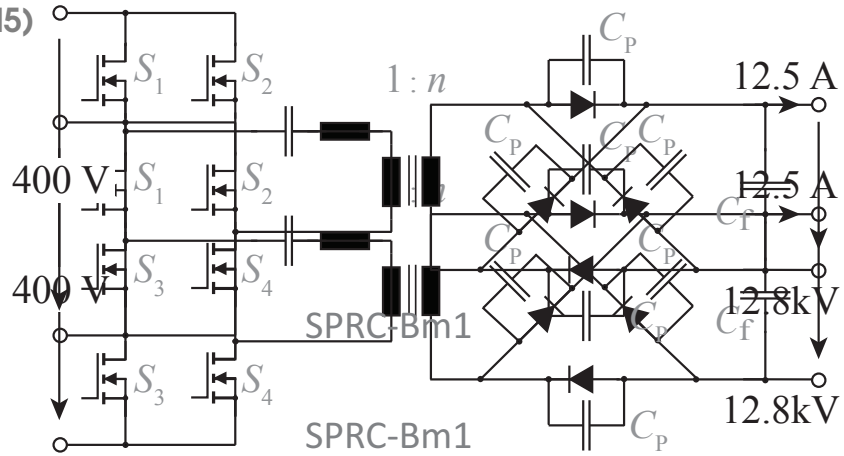
- Switching frequency 105 kHz
- Modules: 2 parallel / 9 in series



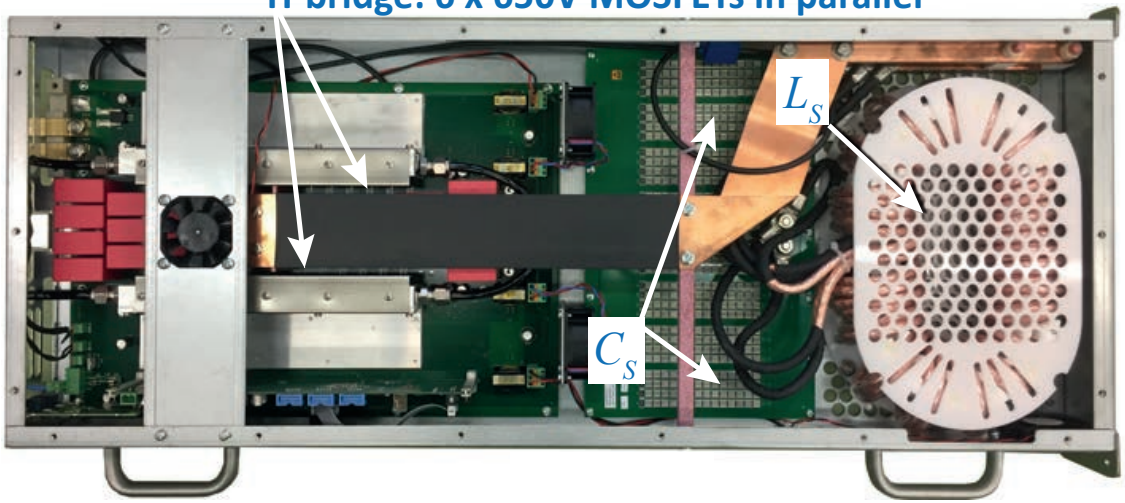
ESS Modulator – Series-Parallel Resonant Converter Module

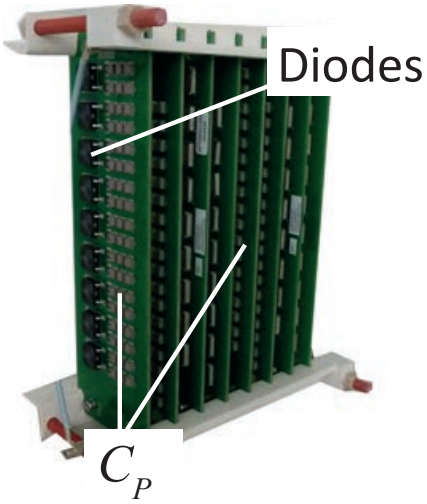
- **H-bridge** **650 V MOSFETs** (STY139N65M5)
- **Module loss distribution:**
  - H-bridge 221 W (179 W P_{Cond})
  - Rectifier diode 78 W (APT60DQ120SG)
  - Series inductor 132 W (Air core with litz)
  - Series capacitor 56 W (NP0 / 896 pieces)
  - Parallel capacitor 18 W (NP0 / 864 pieces)

  Σ **505 W** (per module)



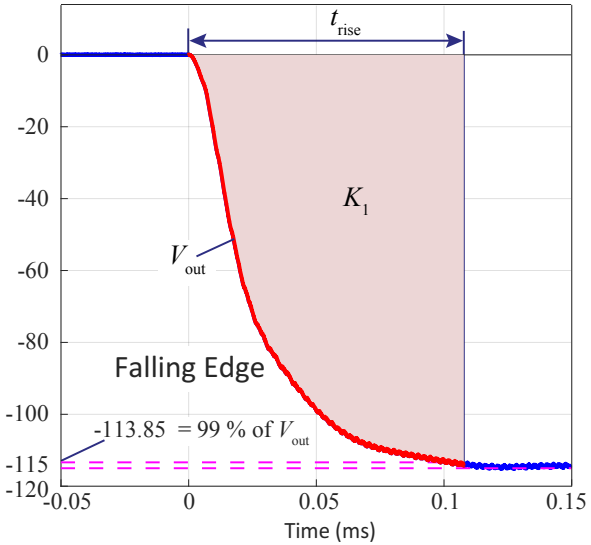
H-bridge: 6 x 650V MOSFETs in parallel

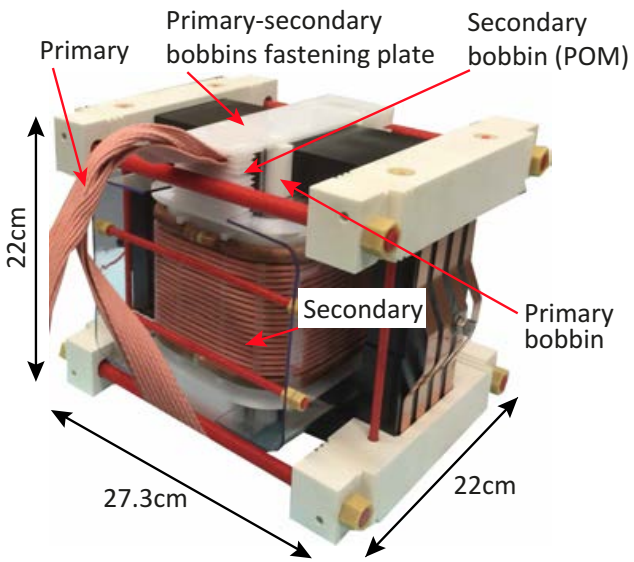


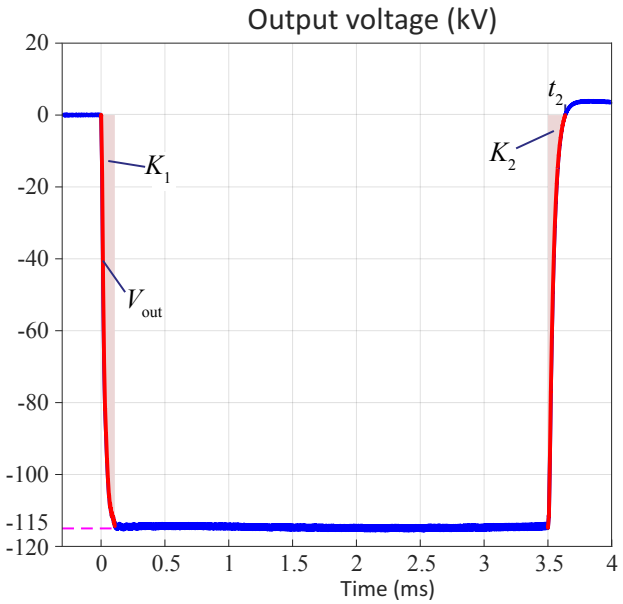


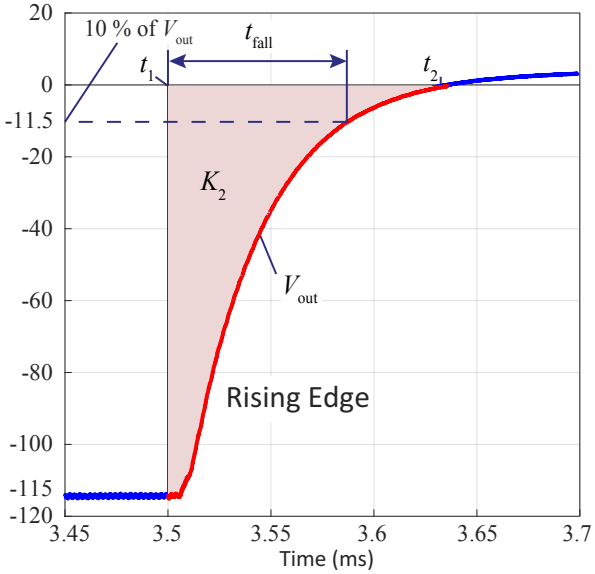
ESS Modulator – Step-up Transformer/Pulse Shape

- **Transformer** 2:40 / Midel 7131
- **Losses (per module)**
  - Core 73.4 W (2×4× UU126/20 / N87 ferrite)
  - Primary winding 12.9 W (405 × 0.071mm / 18 parallel)
  - Secondary winding 11.1 W (1125 × 0.071mm)
- **Rise time** 107.8 µs (0→99%)
- **Fall time** 83.5 µs (100→10%)
- **Pulse shape (total)** 97.8 %



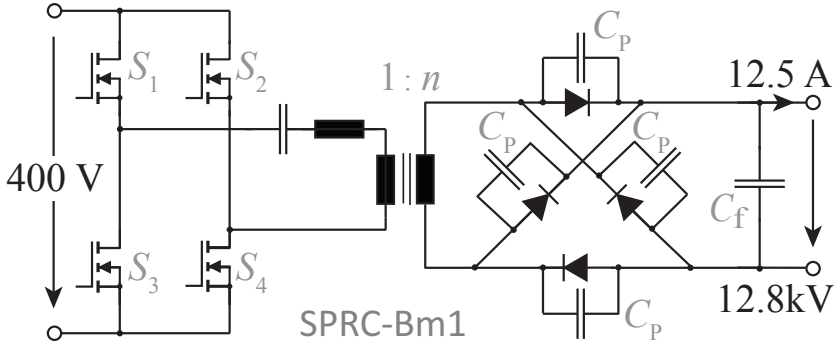


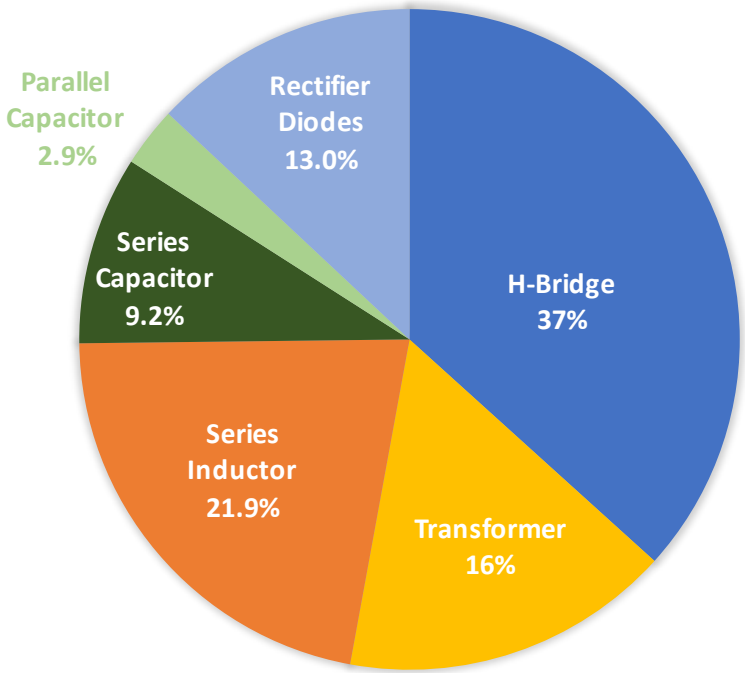




ESS Modulator – Module Loss Distribution

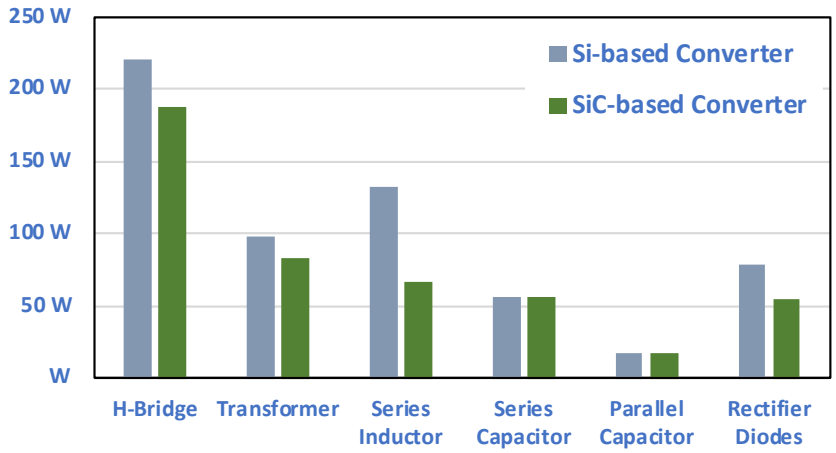
- **Resonant converter 92.9 %**
  (incl. transformer)
  (without pulse shape)

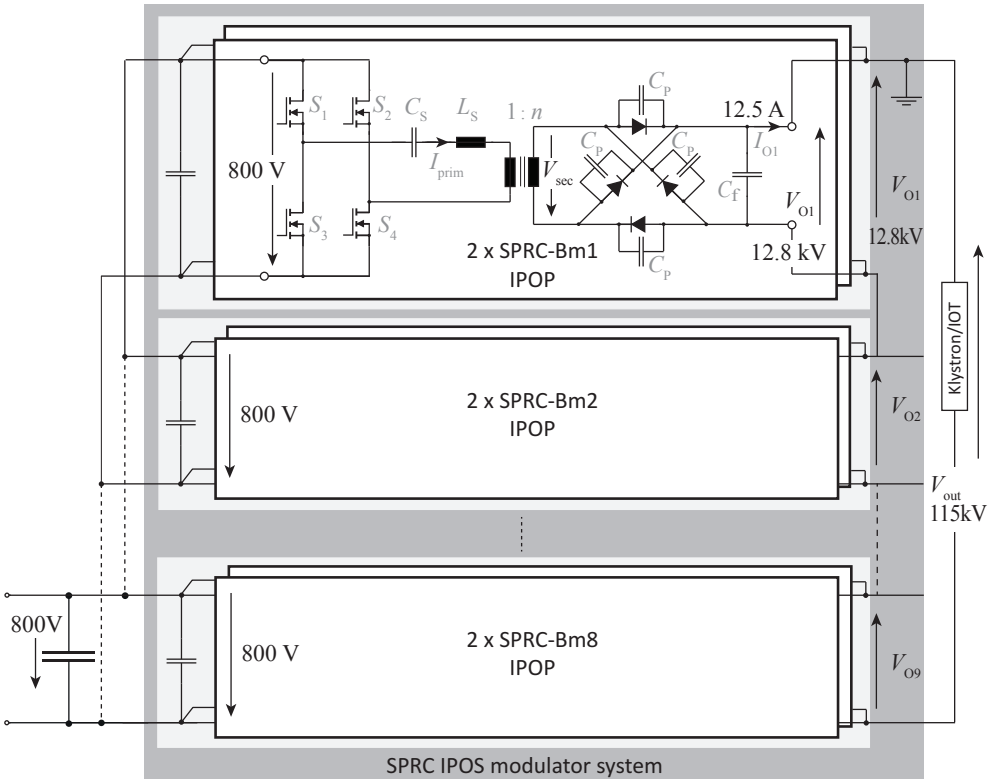




ESS Modulator – Converter with SiC

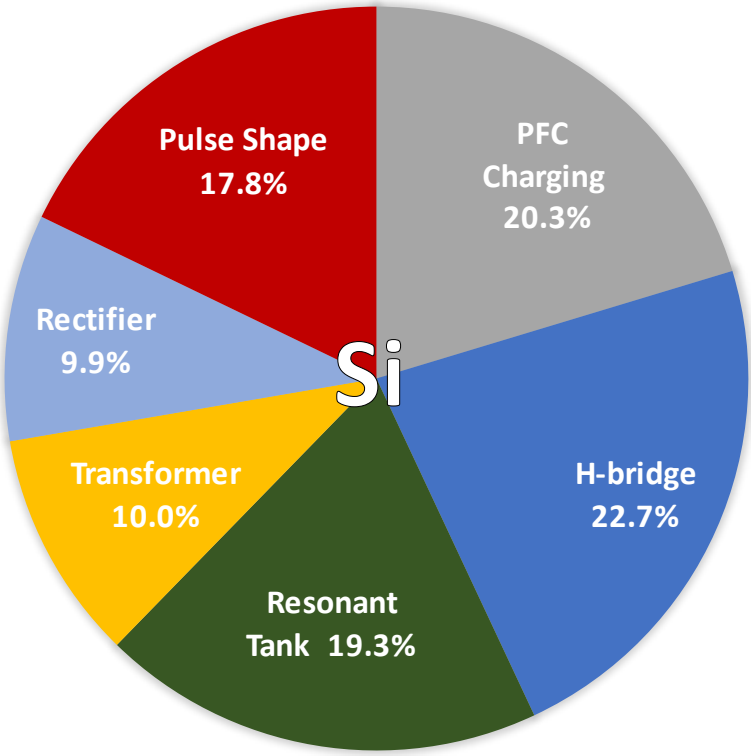
- **Improved efficiency**
  - 1.2 kV SiC MOSFETs — No balancing / Lower conduction losses
  - 1.7 kV SiC Diode — Lower losses in rectifier
  - $L_s \Rightarrow 2 \times L_s @ \frac{1}{2} I$ — 2 × volume / $\frac{1}{2}$ losses
  - New core material — N97 instead of N87
  - ➡ **New efficiency** — ≈ **94.4 %** (+1.5% / Old: 92.9 %)
- **Further improvements**
  - More parallel devices
  - Higher f_{SW} ➡ Shorter t_r/t_f
  - Higher overrating ➡ Shorter t_r/t_f
  - ➡ New system optimisation

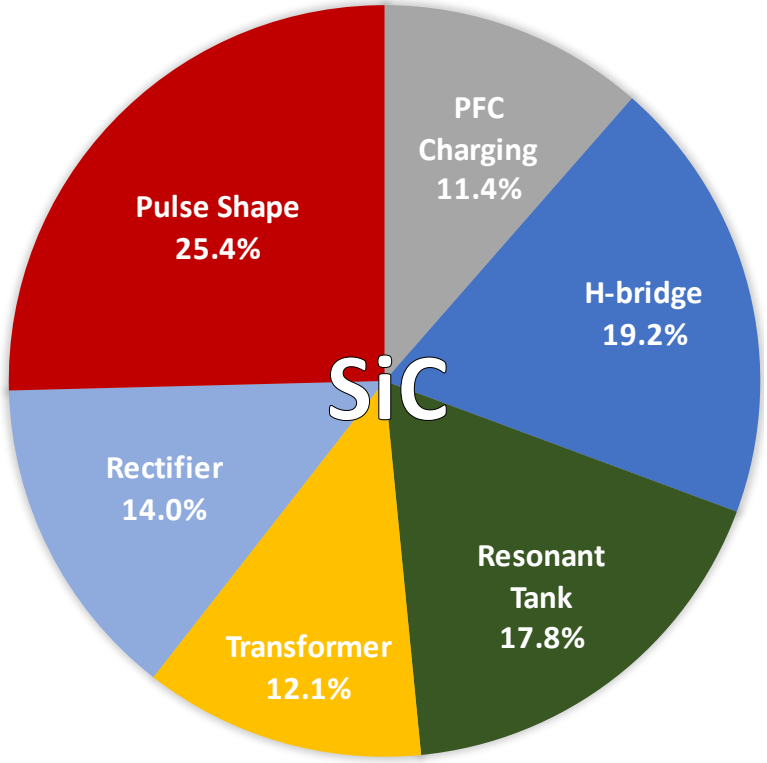




ESS Modulator – System Efficiency & Loss Distribution

	Si-based	SiC-based
▸ Resonant converter	92.9 %	94.4 %
▸ PFC charging	97.5 %	99.0 %
⇒ Electrical system	90.5 %	93.5 %
▸ Pulse shape	97.8 %	97.8 %
⇒ Total efficiency	88.5 %	91.4 %





Conclusion

- **Efficiency gain** (Assuming "drop-in" replacement)
  - CLIC Modulator $\Delta\eta = +\approx 4.9\,\%$ ➡ $\eta_{SiC} = 93.6\,\%$
  - ESS Modulator $\Delta\eta = +\approx 2.9\,\%$ ➡ $\eta_{SiC} = 91.4\,\%$

- **Higher Efficiency**
  - Switches/diode — Wide band gap devices (parallel SIC MOSFETs...)
  - Core material — SiFE 25 µm lamination or Amorphous
    Use of uncut cores
  - Insulating oil — Ester 7131 $\varepsilon_r = 3.2$ ➡ Mineral oil $\varepsilon_r = 2.2$
  - Transformer design — Critical damping (slightly underdamped)
    Larger volume / Core splitting
  - Short load cable
  - Fix operating point