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

Diagram:
- Constant Power
- Pulsed Power
- Grid
- AC/DC rectifier unit
- DC/DC converter for charging C-bank / voltage adaption
- Pulse generation unit
- Load e.g. klystron
- 400V or MV
- Intermediate Buffer
- Capacitor Bank
- Pulse Voltage
- Klystron Load

Sometimes integrated
**Typical Topology of Solid State Pulse Modulator Systems**

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

![Diagram of typical topology](image)
29 MW$^{(35 \text{MW})}$ / 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 repeatability**: <100 ppm

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Drive Beam

- 819 klystrons
  - 15 MW, 142 µs
- Drive beam accelerator
  - 2.4 GeV, 1.0 GHz
- Circumferences
  - Delay loop 73 m
  - CR1 293 m
  - CR2 439 m
- Decelerator
  - 24 sectors of 878 m
- CR2
- CR1
- BDS
  - 2.75 km
- IP
  - 48.3 km

Main Beam

- 819 klystrons
  - 15 MW, 142 µs
- Drive beam accelerator
  - 2.4 GeV, 1.0 GHz
- Circumferences
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**Note:**
- **CR**: Combiner ring
- **TA**: Turnaround
- **DR**: Damping ring
- **PDR**: Predamping ring
- **BC**: Bunch compressor
- **BDS**: Beam delivery system
- **IP**: Interaction point
- **dump**
CLIC Solid State Modulator – System Overview

AC/DC Unit

Interleaved Boost Converter

Switching Unit

400V Voltage Grid

750V

3kV

3kV

-180kV

0V

300V

-180kV

400V

3kV

450V

0-300V

Klystron Load

Active Bouncer

Matrix Transformer
CLIC Modulator – Grid/Isolation Transformer

- **Voltage**
- **Core material**
- **Winding material**
- **Weight**
- **Efficiency**

**3 × 400 V to 3 × 400 V @ 250 kVA**

- **Silicon steel**
- **Aluminium**

- **Weight** 890 kg
- **98.8 %**

\( (P_{\text{Core}} = 700W \& P_{\text{Wdg}} = 2.3kW) \)

**Higher efficiency**
- Better core material
- Copper winding
- Efficiency

- **E.g. Amorphous** \( (P_{\text{Core}} \approx 60\%) \)
- **Higher conductivity** \( (P_{\text{Wdg}} \approx 35\%) \)

\( \Rightarrow \approx 99.2\% \) (Estimated)

(Larger volume \( \Rightarrow \) Higher efficiency)
CLIC Modulator – AC/DC Converter Efficiency

- Type (B&R)
- Topology
- Switches
- Voltage conversion
- Efficiency

Higher efficiency
  - 1.2 kV SiC MOSFETs
  - Optimised design
  - Efficiency

ACOPOSmulti 8BVP1650
- 2-level PFC-rectifier
- 1.2 kV Si IGBTs
- Voltage conversion
  - 400 V$_{AC}$ → 750 V$_{DC}$ (620 V – 800 V)
- Efficiency
  - 97.47 %

Lower $P_{\text{Cond}}$ & $P_{\text{SW}}$
- E.g. higher volume / lower $f_{\text{SW}}$
- $\Rightarrow$ $\approx$ 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
- Boundary cond. mode
- 6-fold interleaving: 6 × 40 kW

![Diagram of CLIC Modulator – Boost Converter Basic Operation](image)

- Grid
- Isolation Transformer
- AC
- PFC Rectifier
- DC
- Boost Converter
- Bouncer (Drop Compensation)
- Switching Unit
- Pulse Transformer

- DC
- V_{DC}
- I_{max}, I_{min}
- T_1, T_2, T_3, T_4, T_5
- V_{Cd,tot}, V_{Cs,tot}
- zvs off, zvs on

**Key Points**

- **Input voltage**: 600 V – 800 V
- **Output voltage**: 3 kV
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- **Output power**: 40 kW
- **650 V Si MOSFETs**: 8 in series
- **Boundary cond. mode**
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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%

![Diagram of CLIC Modulator](image_url)

**Fans**
**Inductor**
**Output capacitors**
**HV output**
**Power input**
**Input fuse**
**PCB with isolated gate drives**

- **Input capacitors**
- **Snubber Capacitor 2%**
- **Boost Inductor 11%**
- **Diode Switching 3%**
- **Diode Conduction 20%**
- **MOSFET Conduction 58%**
- **MOSFET Switching 6%**
CLIC Modulator – "SiC" Boost Converter

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

- MOSFET Conduction: 46%
- MOSFET Switching: 3%
- Diode Conduction: 22%
- Boost Inductor: 25%
- Snubber Capacitor: 4%

- 2× C3M0016120K
- 2× IDW40G120C5B

Higher efficiency ▶ 4×1.2 kV SiC MOSFETs 
▶ 4×1.2 kV SiC Diodes 
▶ Efficiency: ≈ 98.6% (Old: 97.2%)
CLIC Modulator – Switching Unit

- ABB StakPak (5SNA1250B450300)
- Active reset switch
- 4 units in parallel
- Pulse current
- Efficiency

Higher efficiency
- Semiconductors
- Efficiency

4.5 kV / max. 3 kA (pulsed)

4 × 2.4 kA (\( P_P = 29 \text{ MW} \))

98.6% (Switching losses: 87% of \( P_{tot} \))

SiC MOSFETs
(assumption: 1.2 kV devices)
(4 in series / 3 parallel)

⇒ 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): >600 A (per module)
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 $L_b = 26 \mu$H: 4×Metglas AMCC32
With IGBTs

- Total AVG losses: 1.56 kW
- Module efficiency:
  - Efficiency:
    - Bouncer-Level: 91.0%
    - System-Level: 99.4%

![Active Bouncer Module diagram](image)

- Inductor losses: 18%
- HS IGBTs conduct: 7%
- HS IGBTs switching: 51%
- LS diodes: 14%
- LS IGBTs: 4%
- SC IGBTs: 3%
- HS diodes: 3%

Active Bouncer Module

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- HS diodes: 3%

Active Bouncer Module

16 | 33
CLIC Modulator – SiC Bouncer Efficiency

- With IGBTs
  - Total AVG losses
  - Module efficiency
  - Efficiency

- With SiC MOSFETs
  - Total AVG losses
  - Module efficiency
  - 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

SiC-based converter:
- Inductor losses: 35%
- HS diodes: 5%
- SC SW: 4%
- LS SW: 9%
- LS diodes: 27%
- HS SW conduction: 12%
- HS SW switching: 8%

Si-based converter:
- HS switch conduction: 12%
- HS switch switching: 8%
- LS diodes: 27%
- SC SW: 4%
- LS switch: 9%
- HS SW: 5%

Graph showing power distribution between Si-based and SiC-based converters.
CLIC Modulator – Pulse Transformer

- Matrix transformer
- Turns ratio
- Core material

2 cores / 4 primary windings
62 \( \Rightarrow \) 4:2\( \times \)124
SiFe / 50 µm

Matrix transformer 2 cores / 4 primary windings

Turns ratio 62 → 4:2(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)

[Diagram showing time to flat top, allowed droop, fall time, and reverse voltage]

- “Dissipated” pulse “energy”
- Flat top (Used pulse “energy”)
- Allowed droop

- Winding Losses: 4%
- Core Losses: 8%
- Pulse Shape: 88%
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

- Pulse Shape/Transformer 28%
- Grid Transformer 10%
- Bouncer 5%
- Switching Unit 12%
- Booster 24%
- PFC 21%

Improved System

- Grid Transformer 39%
- Pulse Shape/Transformer 10%
- Bouncer 5%
- Switching Unit 8%
- Booster 21%
- PFC 15%

24.8 kW
13.4 kW

Conventional SiC-based

<table>
<thead>
<tr>
<th>Original</th>
<th>Improved</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC</td>
<td>DC</td>
</tr>
<tr>
<td>AC</td>
<td>DC</td>
</tr>
<tr>
<td>Grid</td>
<td>Isolation Transformer</td>
</tr>
<tr>
<td>AC</td>
<td>DC</td>
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<td>DC</td>
<td>PFC Rectifier</td>
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<td>DC</td>
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<tr>
<td>DC</td>
<td>Boost Converter</td>
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<tr>
<td>DC</td>
<td>Bouncer (Droop Compensation)</td>
</tr>
<tr>
<td>DC</td>
<td>Switching Unit</td>
</tr>
<tr>
<td>DC</td>
<td>Pulse Transformer</td>
</tr>
</tbody>
</table>

- 98.8% 97.5%
- 99.2% 99.0%
- 97.2% 98.6%
- 99.4% 99.7%
- 98.6% 99.5%
- 96.7% 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: $1:21 \times 6 \Rightarrow 1:126$
- Core material: SiFe / 50 µm
- Rise time: $\approx 1 \mu s$
- Fall time: $\approx 0.9 \mu s$
- Pulse shape: $\approx <82 \%$
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: ≤ 150 µs
- Repetition rate: 14 Hz

**Diagram:**
- **Electrical Network**
  - Klystron modulator (Power Supply)
  - Similar to RF powering cell #1
  - SC cavity #A
  - Klystron A
  - RF power
  - SC cavity #B
  - Klystron B
  - RF power
  - Beam

**Similar to RF powering cell #1**
ESS Modulator – Basic Configuration

- Pulse power: 2.88 MW
- Pulse voltage: 115 kV
- Pulse width: 3.5 ms
- Rise/fall time: ≤ 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: ≤ 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**
- **Module loss distribution:**
  - H-bridge: 6 x 650V MOSFETs (STY139N65M5)
  - 650 V MOSFETs (STY139N65M5)
  - H-bridge: 6 x 650V MOSFETs in parallel
  - Diodes: 6 x 650V MOSFETs in parallel
  - Series-inductor: 6 x 650V MOSFETs in parallel
  - Series-capacitor: 6 x 650V MOSFETs in parallel
  - Parallel-capacitor: 6 x 650V MOSFETs in parallel
  - **H-bridge**: 1,150 W (179 W \( P_{Cond} \))
  - **Rectifier diode**: 173 W (APT60DQ120SG)
  - **Series inductor**: 1,152 W (Air core with litz)
  - **Series capacitor**: 56 W (NP0 / 896 pieces)
  - **Parallel capacitor**: 18 W (NP0 / 864 pieces)
  - **\( \Sigma \)** 505 W (per module)
  - **\( \Sigma \)** 505 W (per module)
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\[ \text{H-bridge: 6 x 650V MOSFETs in parallel} \]

\[ \text{Diodes} \]

\[ \text{C}_S \]

\[ \text{C}_P \]
ESS Modulator – Step-up Transformer/Pulse Shape

- Transformer
- Losses (per module)
  - Core
  - Primary winding
  - Secondary winding
- Rise time
- Fall time
- Pulse shape (total)

2:40 / Midel 7131

- 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%

![Diagram of transformer with labeled components and measurements](Image)
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
  - 1.7 kV SiC Diode
  - $L_s \Rightarrow 2 \times L_s @ \frac{1}{2} I$
  - New core material
  - New efficiency $\approx 94.4\%$ (+1.5% / Old: 92.9%)

- **Further improvements**
  - More parallel devices
  - Higher $f_{SW}$ $\Rightarrow$ Shorter $t_r/t_f$
  - Higher overrating $\Rightarrow$ Shorter $t_r/t_f$
  - New system optimisation
ESS Modulator – System Efficiency & Loss Distribution

- Resonant converter
  - Si-based: 92.9%
  - SiC-based: 94.4%

- PFC charging
  - Si-based: 97.5%
  - SiC-based: 99.0%

- Electrical system
  - Si-based: 90.5%
  - SiC-based: 93.5%

- Pulse shape
  - Si-based: 97.8%
  - SiC-based: 97.8%

- Total efficiency
  - Si-based: 88.5%
  - SiC-based: 91.4%

Si-based:
- Pulse Shape: 17.8%
- PFC Charging: 20.3%
- Rectifier: 9.9%
- Transformer: 10.0%
- Resonant Tank: 19.3%

SiC-based:
- Pulse Shape: 25.4%
- PFC Charging: 11.4%
- Rectifier: 14.0%
- Transformer: 12.1%
- Resonant Tank: 17.8%
- H-bridge: 19.2%
Conclusion

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

- **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 \( \varepsilon_r = 3.2 \quad \Rightarrow \quad \) Mineral oil \( \varepsilon_r = 2.2 \)
  - Transformer design
    - Critical damping (slightly underdamped)
    - Larger volume / Core splitting
  - Short load cable
  - Fix operating point

![Efficiency vs Power Density Graph](image)

- **Efficiency Limit**
- **Power Density Limit**

\[ \eta - \rho - \text{Pareto-Front} \]