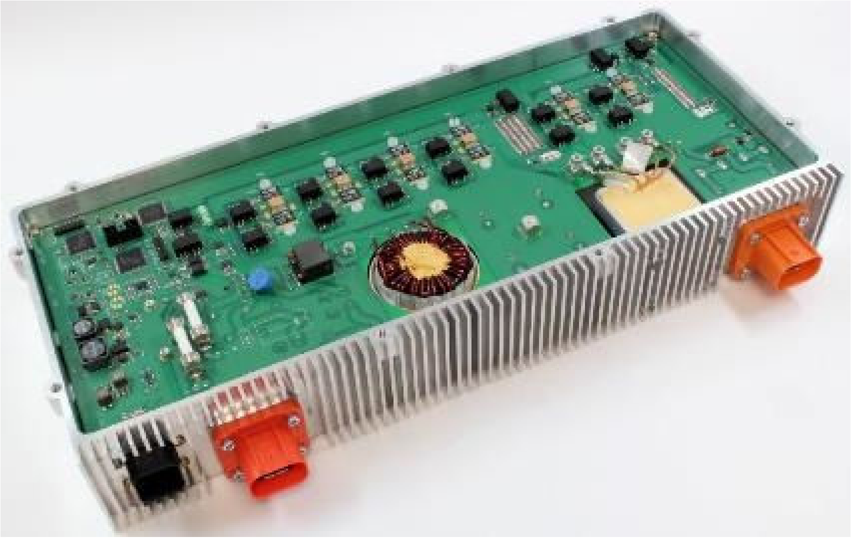
Continental
The Future in Motion



Gallium Nitride (GaN) enables High-Efficient and Bidirectional Auxiliaries – an On-Board Charger Case Study

May 20th, 2019

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GaN On-Board Charger

Agenda

Gallium Nitride (GaN)
Technology Promise

It will be cheap

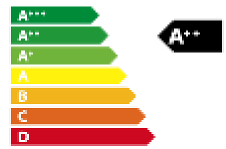
It will be small

It will be efficient

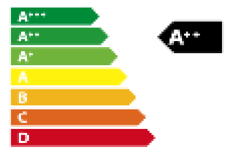
GaN Transistors
Material Properties

› GaN has unique material and electronic properties due to wide-bandgap

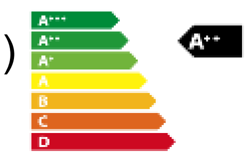
- Low $R_{DS(on)}$
  - ➔ Reduced conduction losses



- Low parasitic capacitance
  - ➔ Fast switching at low losses
  - ➔ High frequency for smaller passive components



- Reverse conduction at low losses (performance similar to SiC Schottky diode)
  - ➔ Intrinsic advantage for bidirectional operation



- High temperature operation capability
  - ➔ At the moment not in focus due to assembly technology and efficiency targets

GaN Transistors
Semiconductor Manufacturing

YOLE Développement **GaN power device industry: the supply chain is acting to support market growth**

Source: http://www.yole.fr/Power_GaN_SupplyChain_HEMTcomparison.aspx#.Ww8Fmu6FPDc

CISION PR Newswire The GAN market is Estimated to Hit $2.7 Billion by 2020

Source: https://www.prnewswire.com/news-releases/the-gan-market-is-estimated-to-hit-27-billion-by-2020-677614283.html

› GaN transistors can be grown on standard (and cheap) Si wafers

GaN structures
on standard Si wafer

› Highly interesting for industry / consumer market due to better efficiency than Si transistors (e.g. power supplies for server farms)

➡ Penetration of consumer market will smooth the way for automotive market?

GaN for Power Electronics
Focus Applications

› 48V converter

› High voltage converter up to 650V

48V / 12V DCDC

400V / 12V DCDC

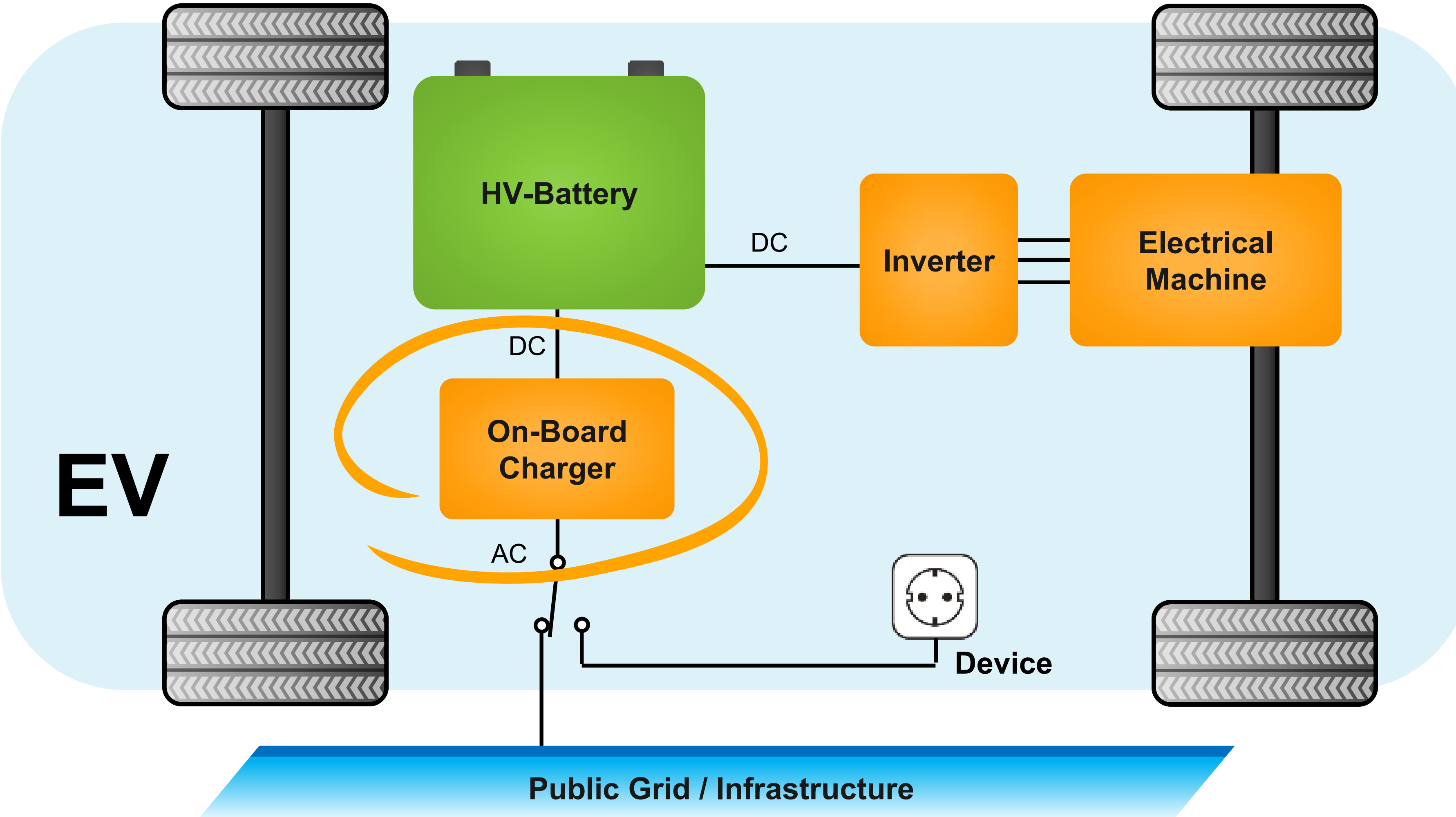
On-Board Charger

48V Inverter

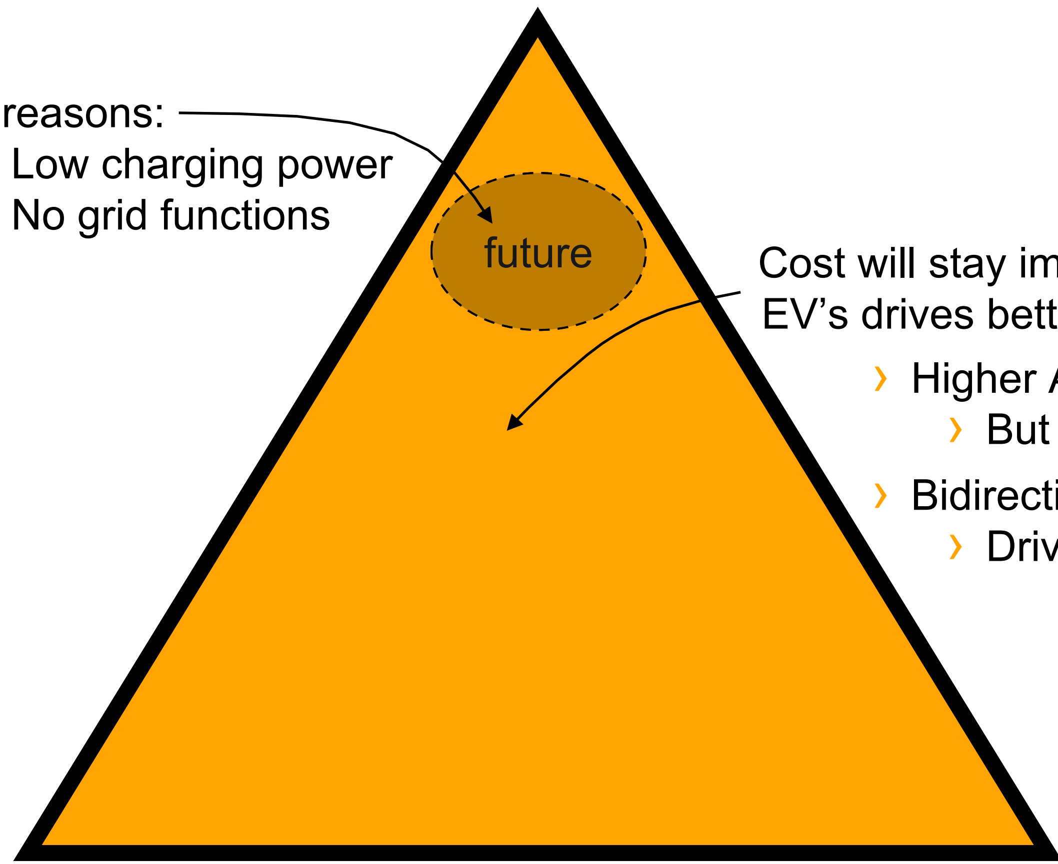
Wireless Charger

400V Inverter

Battery Electric Vehicles
Architecture



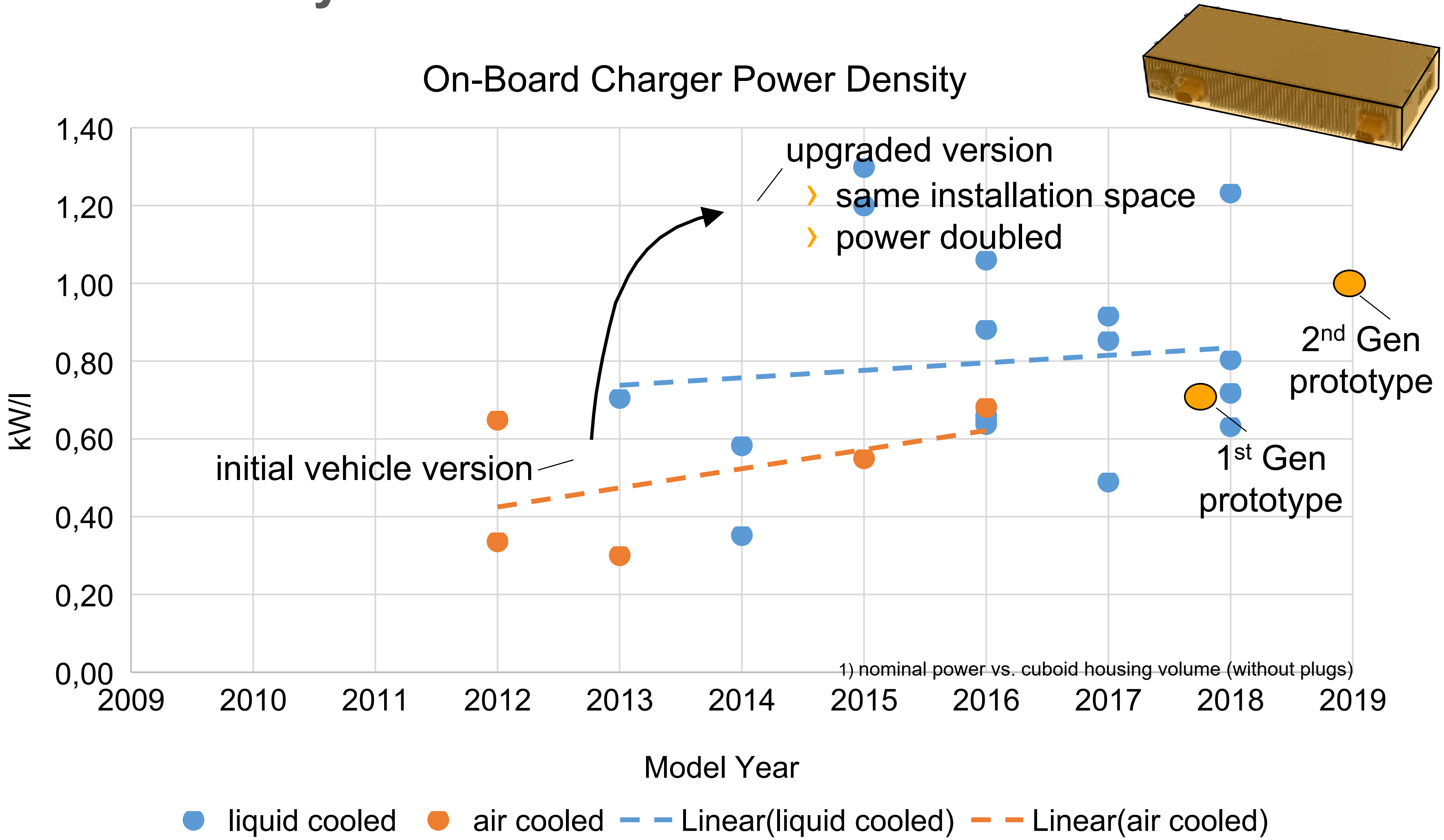
Auxiliaries: On-Board Charger and HV-LV DCDC
Design Corner Points



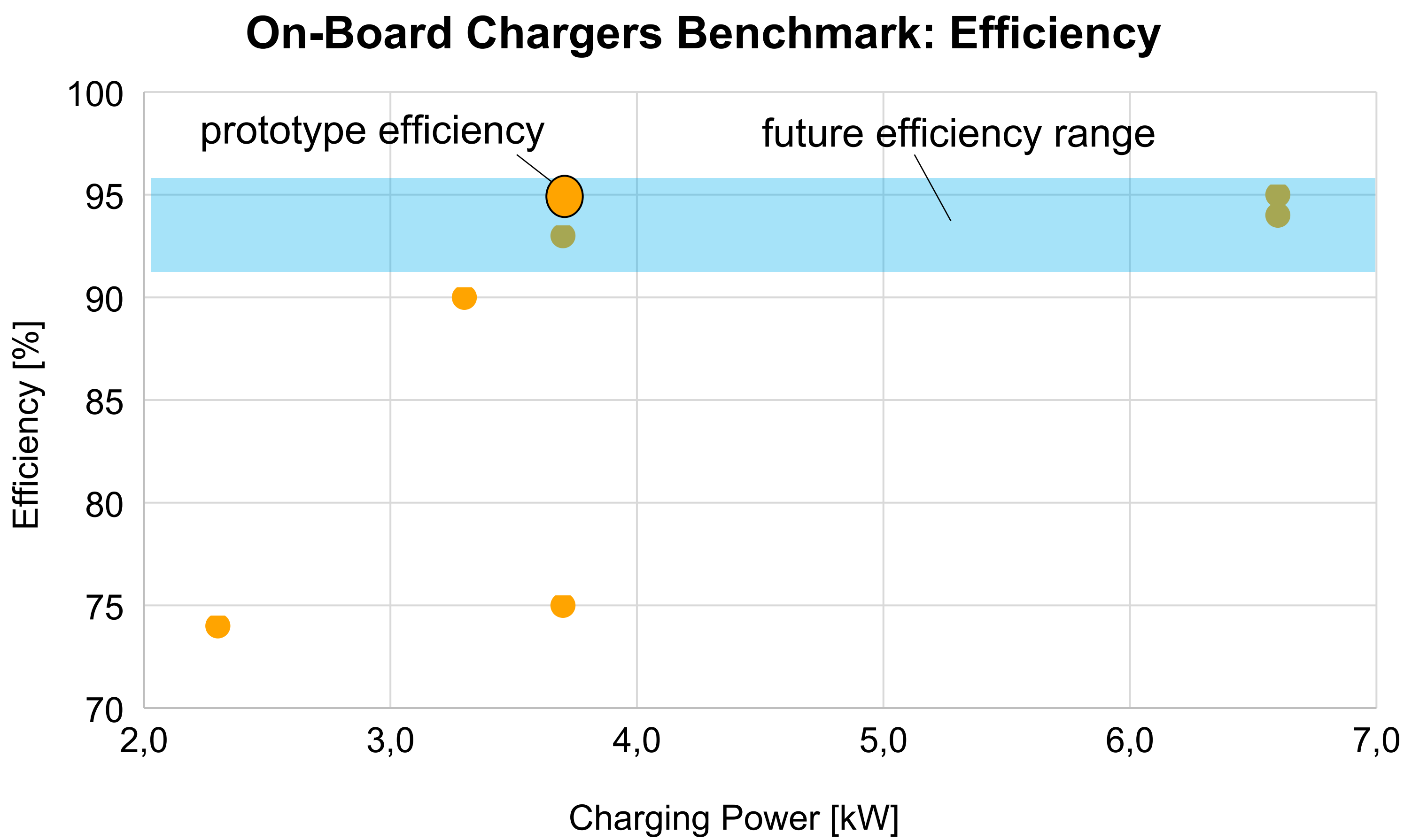
Main reasons:
- Low charging power
- No grid functions

Cost will stay important but usability for EV's drives better On-Board Chargers:
- Higher AC charging power
  - But limited installation space
- Bidirectional functions
  - Driver for efficiency

On-Board Chargers
Power Density Benchmark



On-Board Chargers
Efficiency Benchmark



GaN On-Board Charger

Agenda

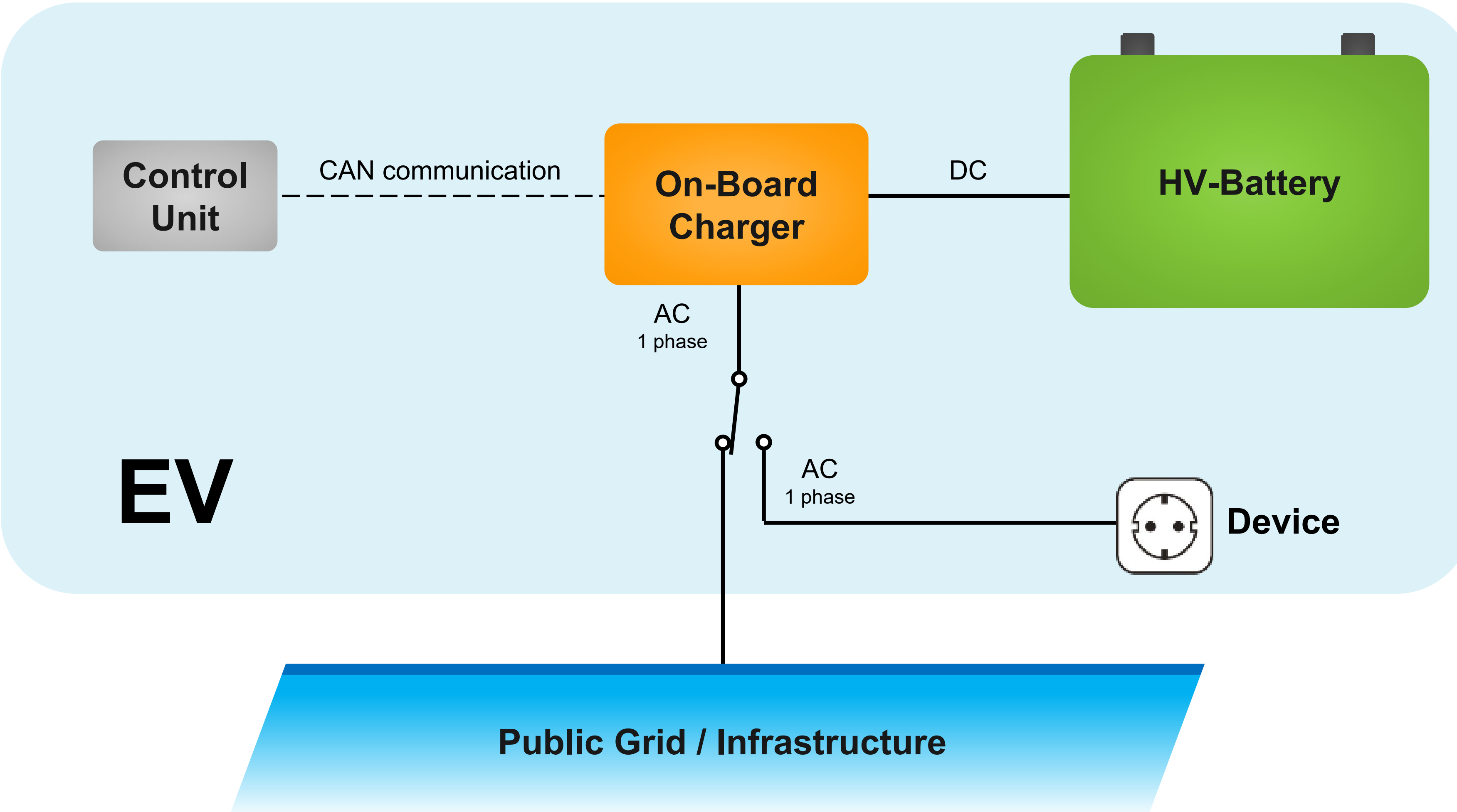
GaN On-Board Charger Laboratory Prototype
Key Requirements

1. **Bidirectional: vehicle to grid and vehicle to device**
2. **Wide-bandgap semiconductor switches: GaN (Gallium Nitride)**
3. **Air-cooled**

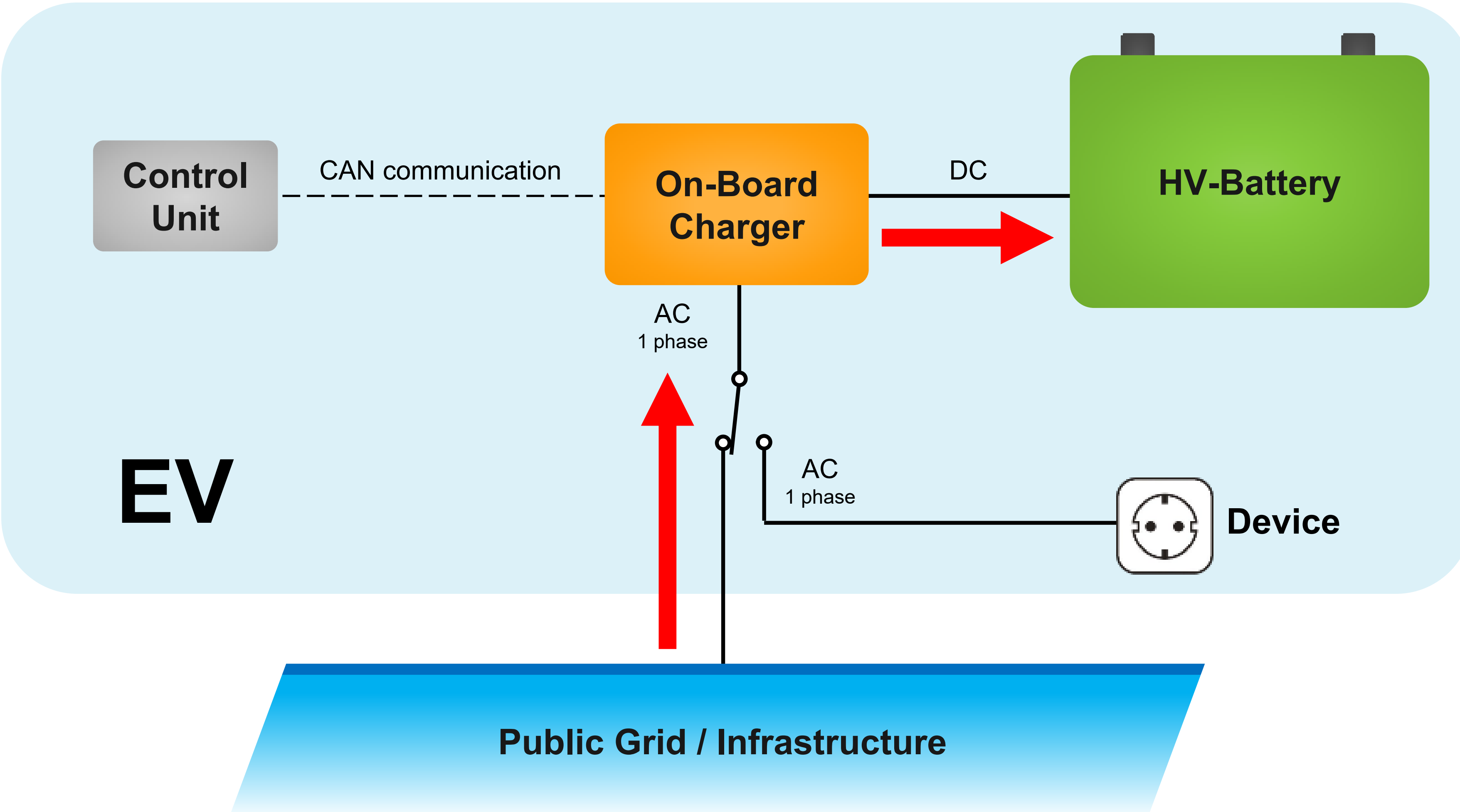
Further Technical Specification:

- Single-phase charger with efficiency up to 95%
- Galvanically separated
- Nominal power: 3.7kW ($I_{AC\ max}$ = 16A_{rms})
- AC Input voltage: 80V_{rms} – 265V_{rms} } Compatible with global public grid
- Supply frequency: 45Hz – 65Hz }
- Battery voltage: 270V – 470V
- Active power factor correction (>= 0.98)
- Consideration of EMC standards

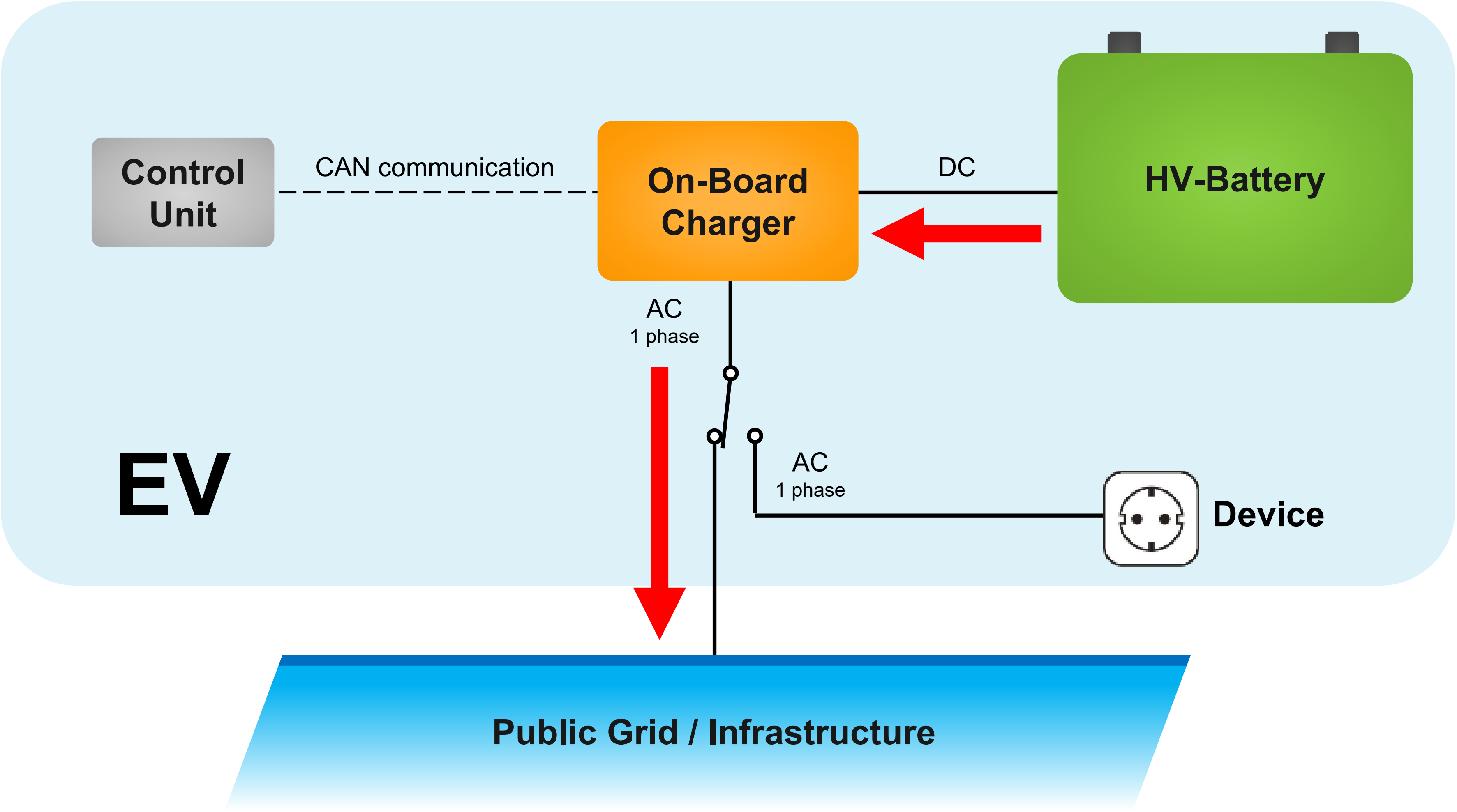
GaN On-Board Charger
System Overview



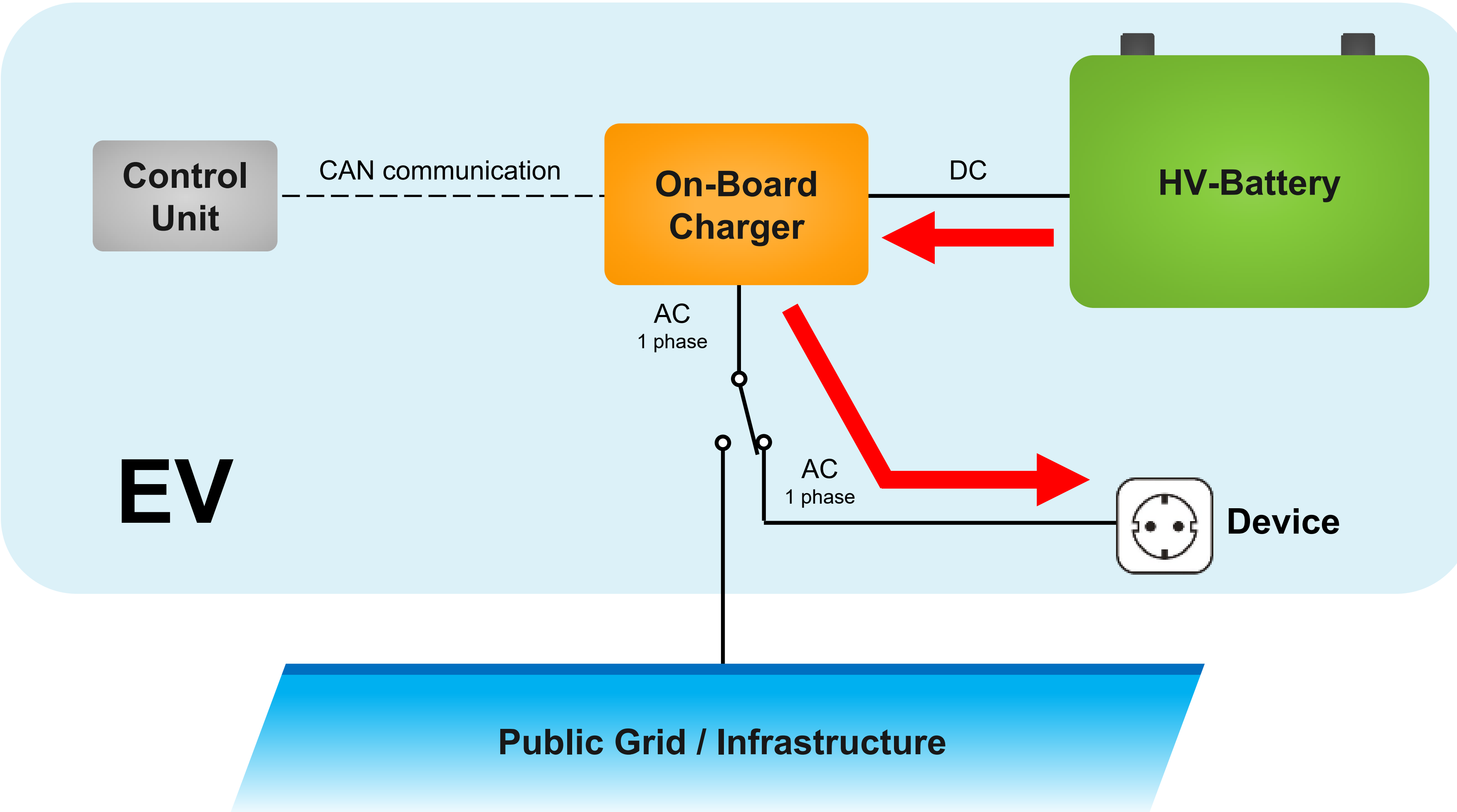
GaN On-Board Charger
AC Charging



GaN On-Board Charger
Vehicle to Grid (V2G)

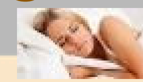


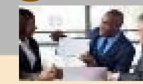
GaN On-Board Charger
Vehicle to Device (V2D)

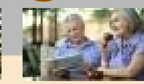


Future Use Cases
Vehicle integrated in Grid

Bi-Directional





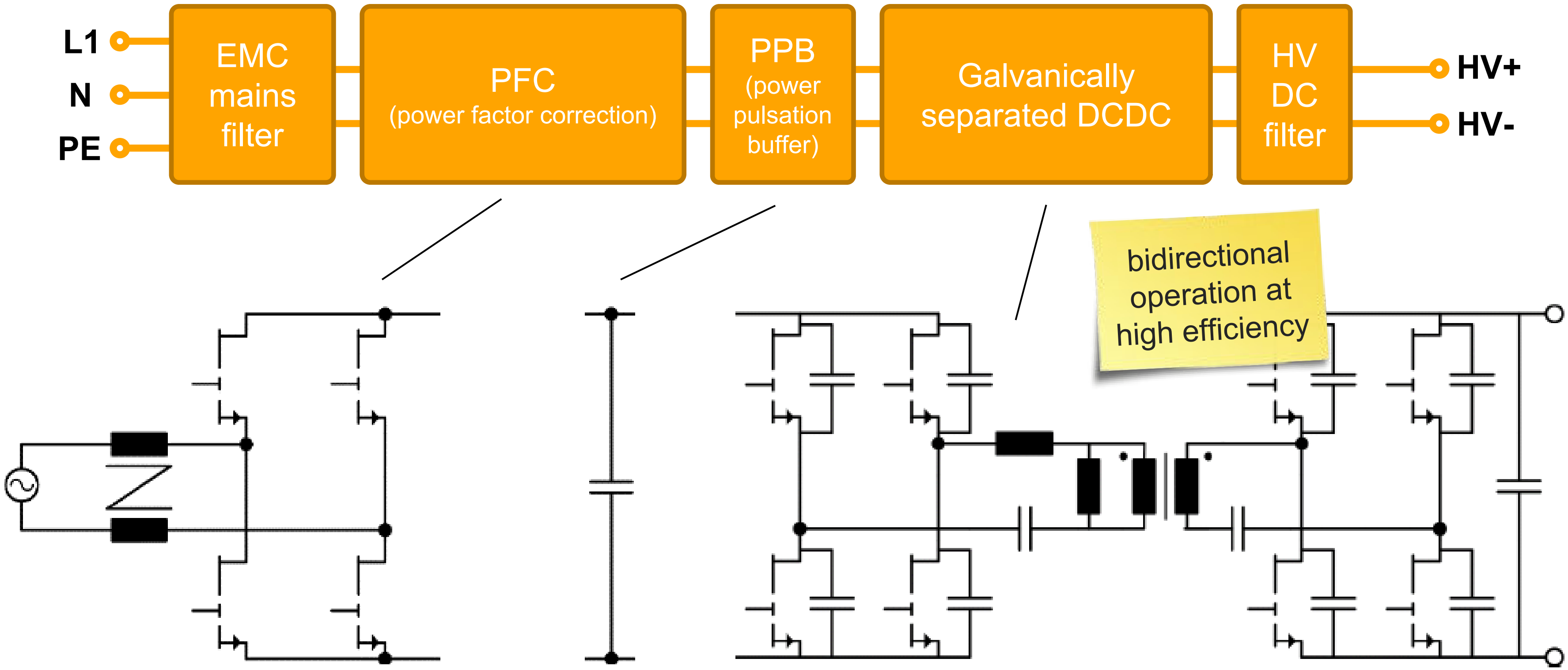


Bi-Directional	Not plugged	Charge @ Home	Charge @ Work	Charge @ Shop	Charge @ Rest
Vehicle-2-Device Selection lever on P, 1-ph socket *"My car is my office"*, workshop, camping	✓	✓	✓	✓	✓
Vehicle-2-Home Optimize my energy consumption Black-out back-up		✓			
Vehicle-2-Site Peak load damping Power cost optimization, vehicle swarm			✓		
Vehicle-2-Grid Mains stabilization Mega vehicle swarm, protocol, payment		✓	✓	✓	✓

GaN On-Board Charger
Agenda

1 Motivation
2 Requirements
3 **Prototype**
4 Commissioning

GaN On-Board Charger
Bidirectional Charger Topology



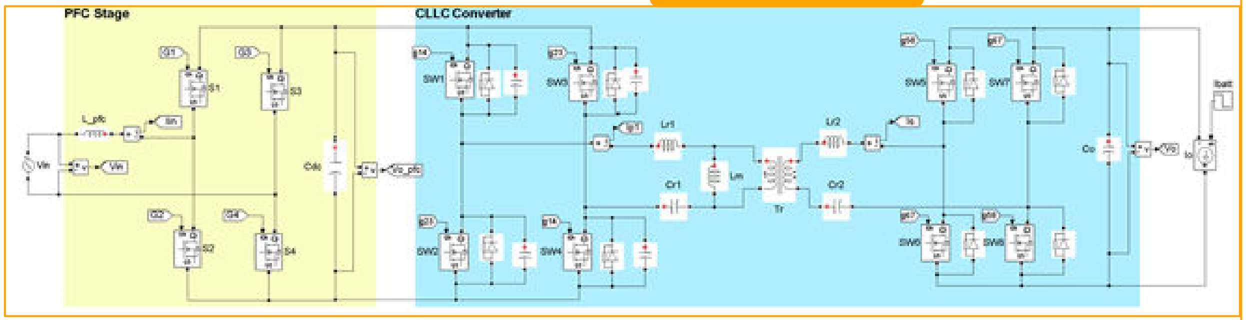
90kHz full active bridge with coupled inductor

DC link capacitor

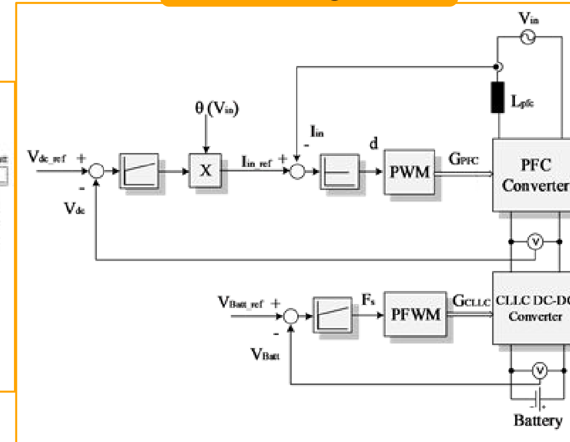
200 kHz Resonant CLLC full bridge

GaN On-Board Charger
Simulation

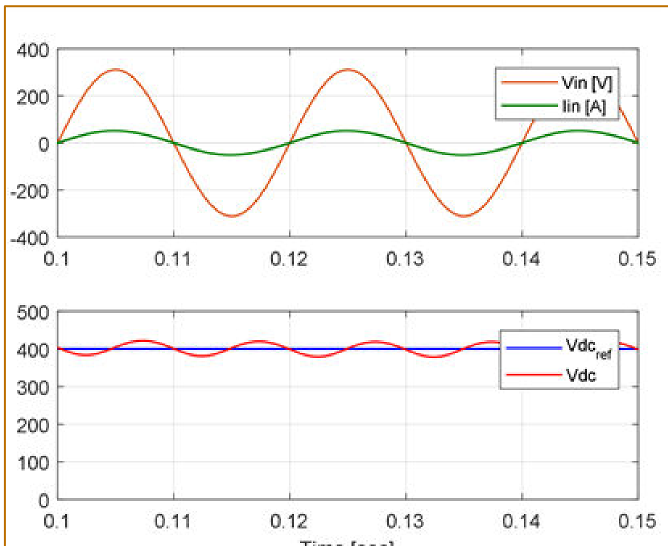
MATLAB Model

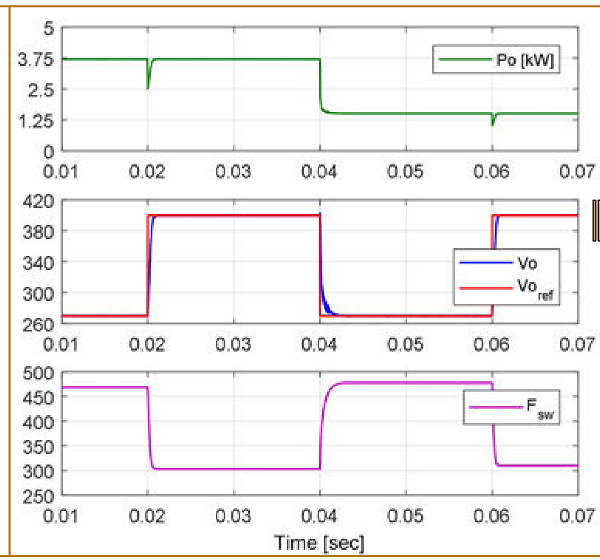


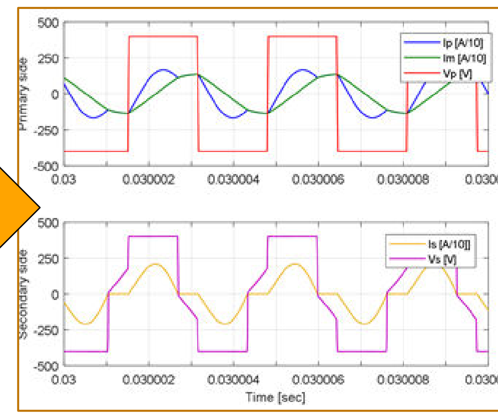
Control Algorithm



OBC Control in Charging and Grid-connection Mode

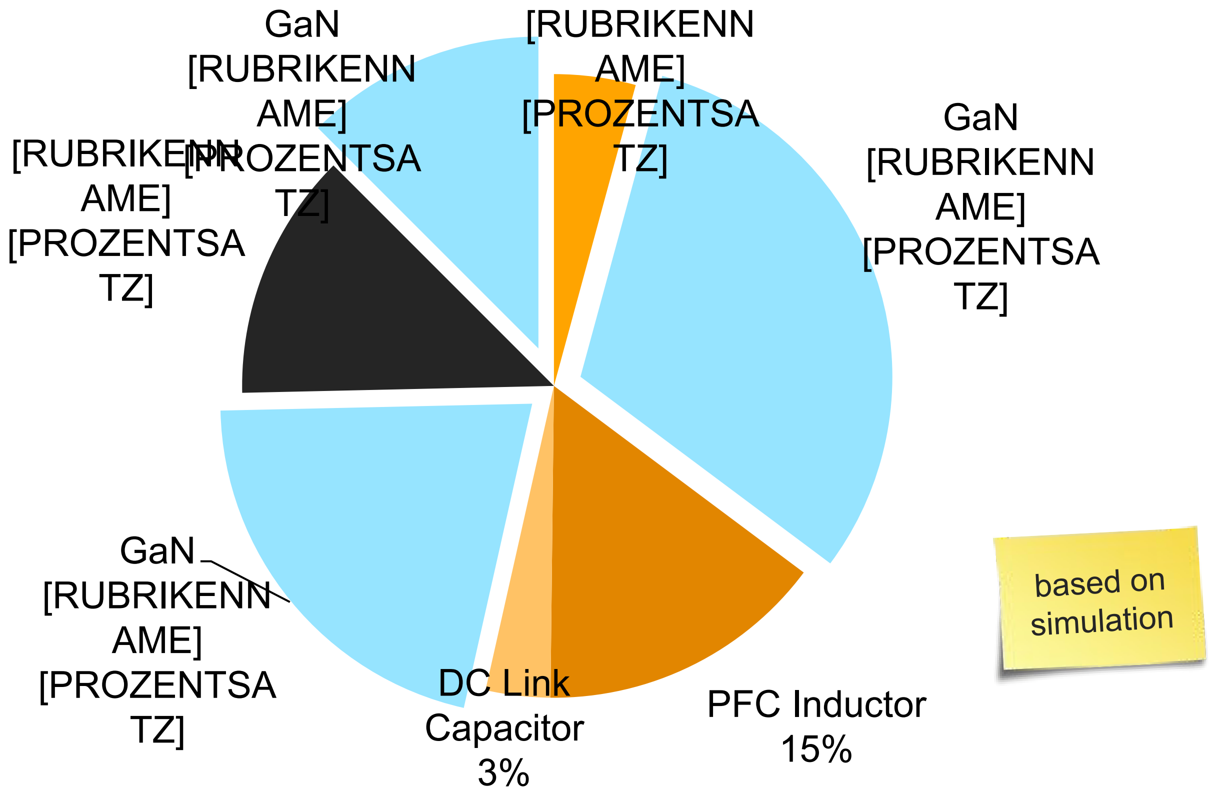






GaN On-Board Charger
66% Power Dissipated by Semiconductors

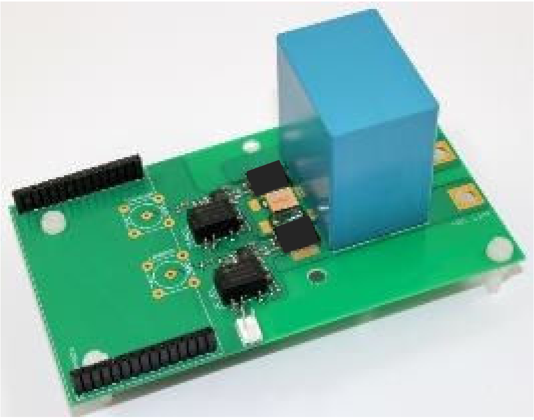
› Improved transistors (e.g. GaN HEMTs) are good lever for increasing efficiency



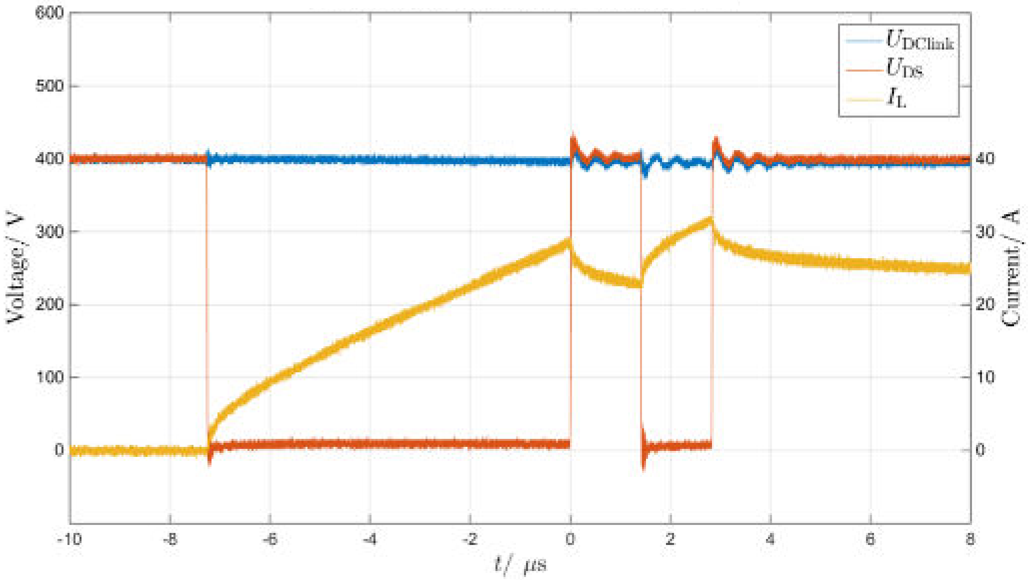
GaN Transistors

Double Pulse Test: GaN 7 times faster than Silicon

- Transistor: 650V; 25mΩ
- Half-bridge with low-inductive PCB layout
- Fast slew rates at small voltage overshoot



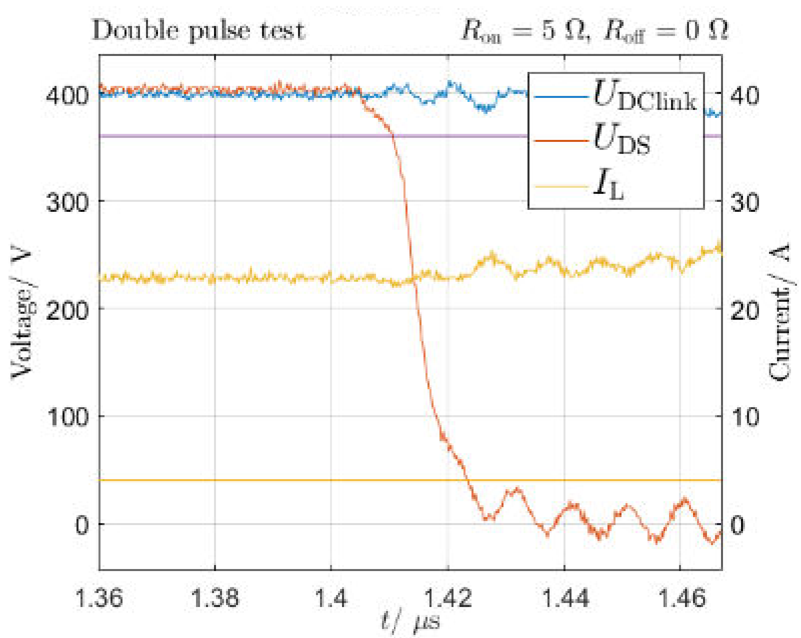
double pulse test board

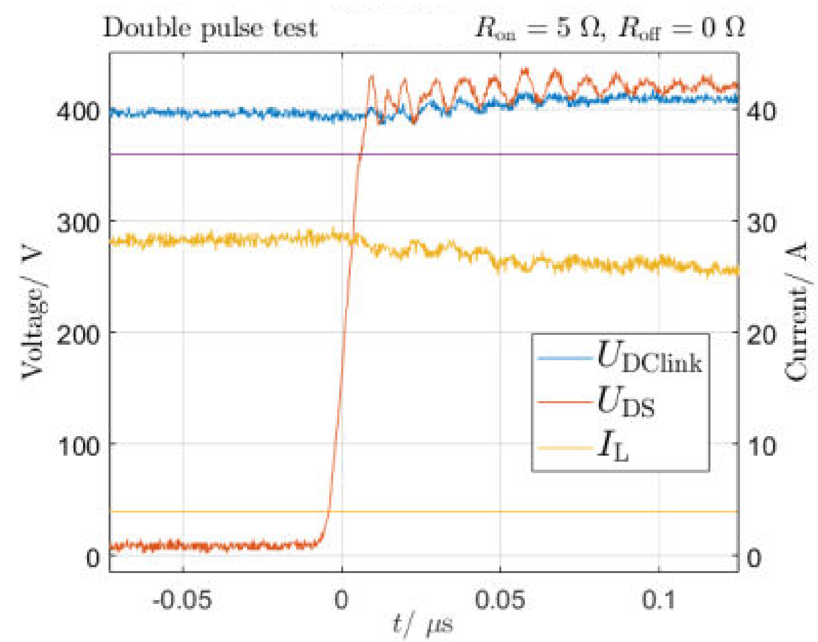


Turn on resistance	Turn on [kV/µs]	Turn off [kV/µs]
0 Ω	39	37
2 Ω	38	36
5 Ω	25	37
10 Ω	21	37

V_{DC} = 400V; Turn off resistance = 0 Ω

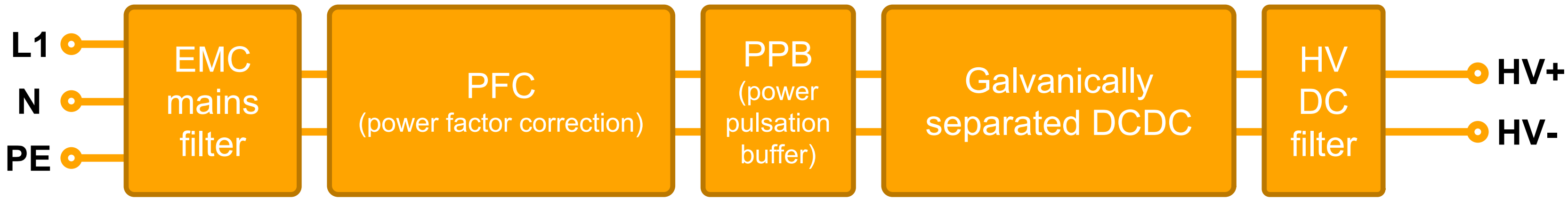
GaN Transistors
Double Pulse Test: Small Overvoltage, Small Ringing

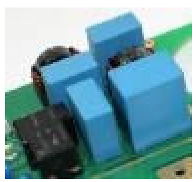




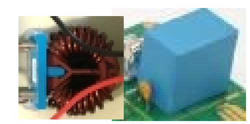
- Turn-on @ V_{DC} = 400V
- Turn-off @ V_{DC} = 400V

Power Density
Component Impact by High Switching Frequency









Filtering of higher frequencies beneficial, but effort due to higher dV / dt

no significant volume reduction

PFC Choke

~50% less volume

PFC DC link capacitor: buffers grid ripple

no volume reduction

Transformer

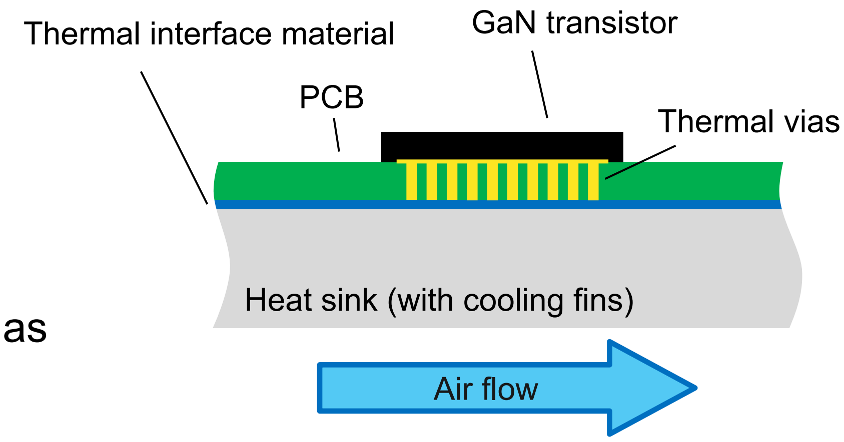
~50% less volume

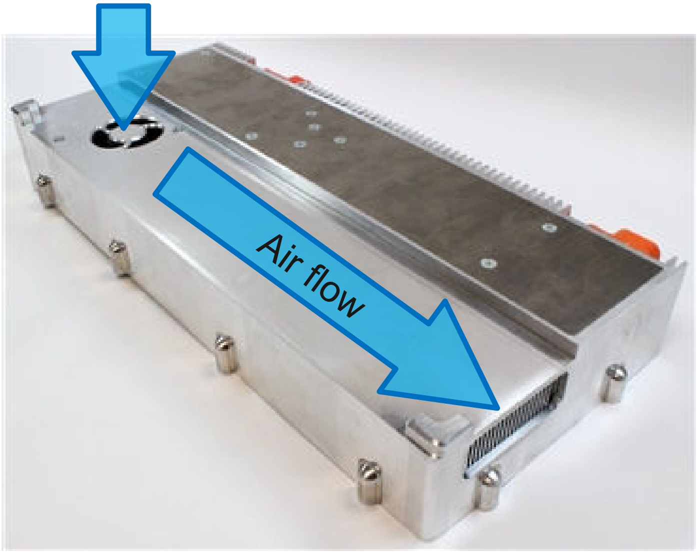
Filtering of higher frequencies beneficial, but effort due to higher dV / dt

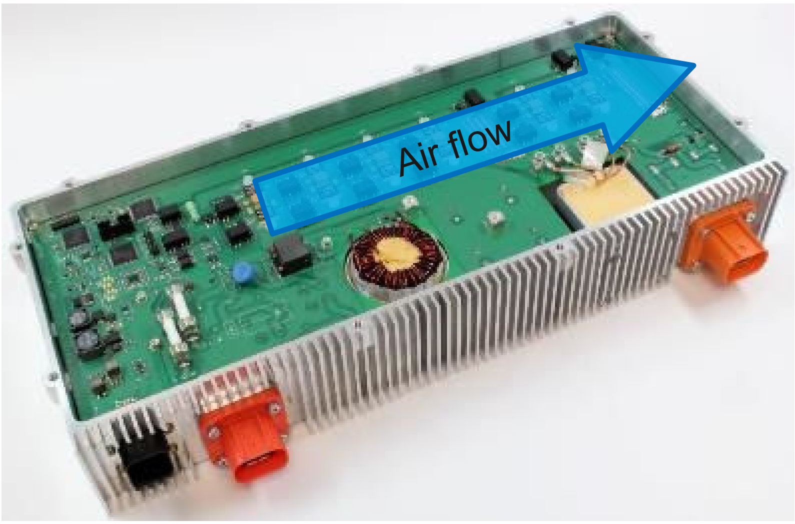
no significant volume reduction

GaN On-Board Charger
Cooling Concept: Simple and Integration friendly

- Air-cooled
- Bottom-side cooling
- Standard PCB: 1.6mm, 8 layers, FR4
- Heat transfer to heat sink through thermal vias
- Fan power consumption max. 4W







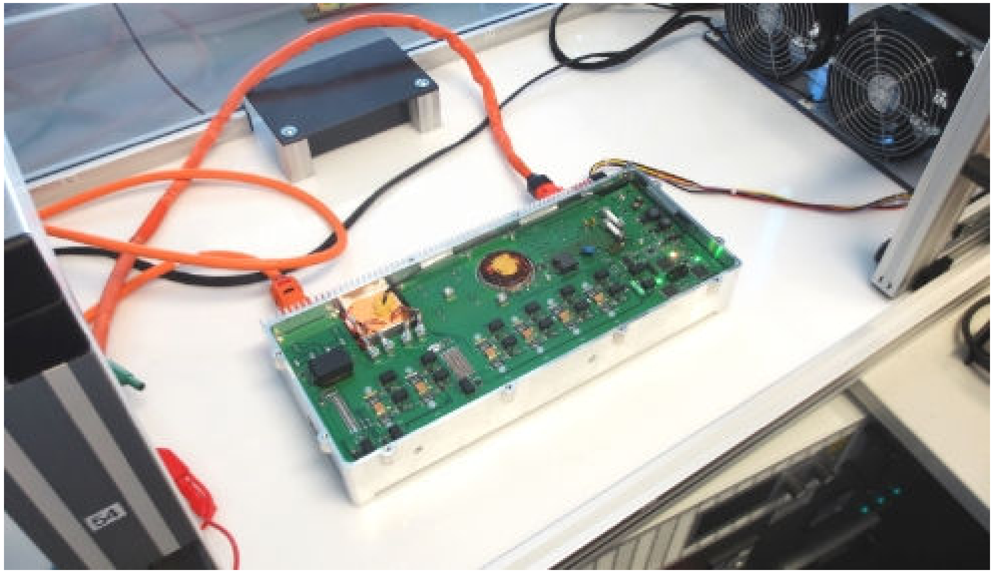
GaN On-Board Charger

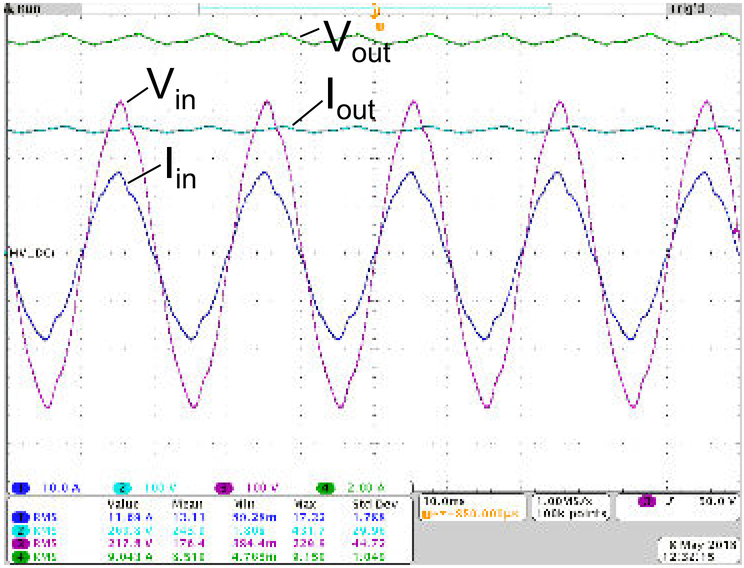
Agenda

GaN On-Board Charger
Commissioning

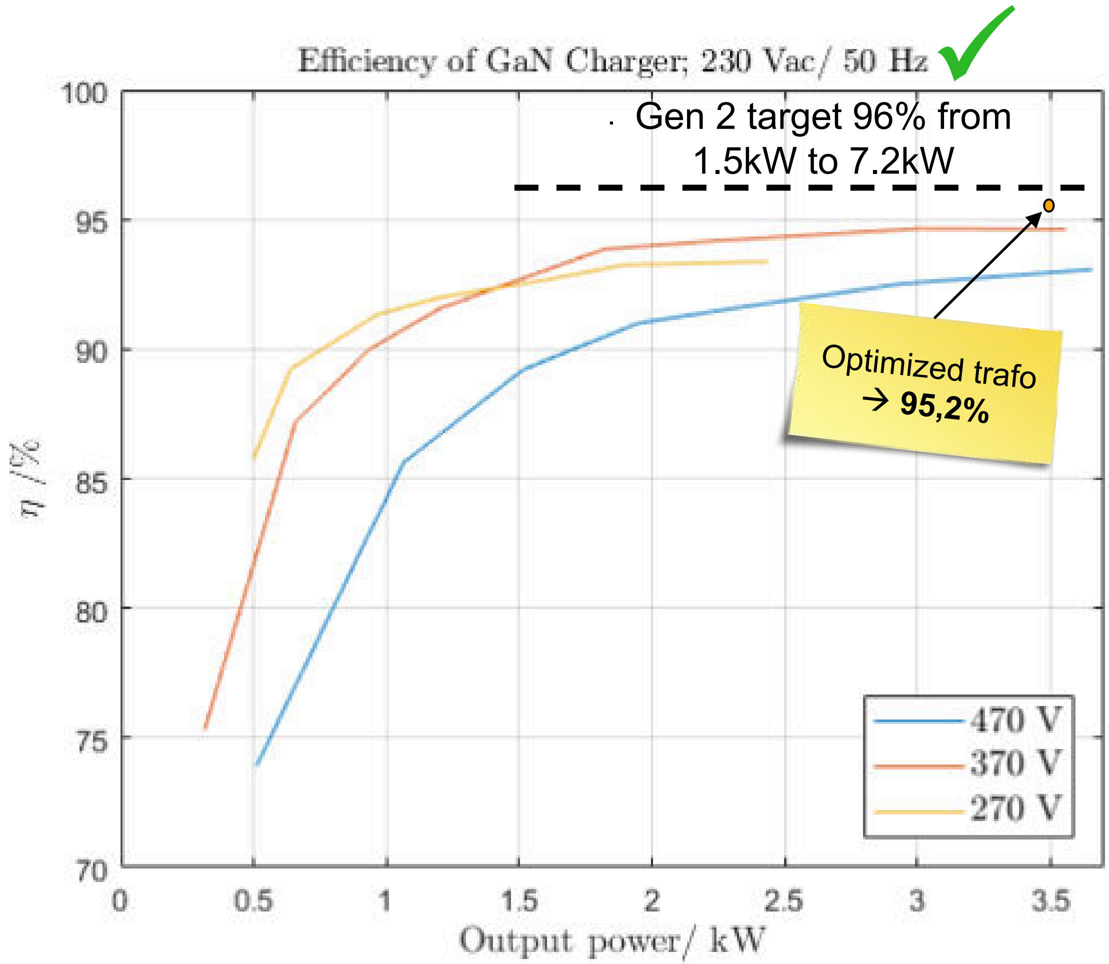
› Charging mode at ~220V_{rms} AC input voltage

› Preparation for EMC measurements





GaN On-Board Charger
Efficiency measurements meet Expectations

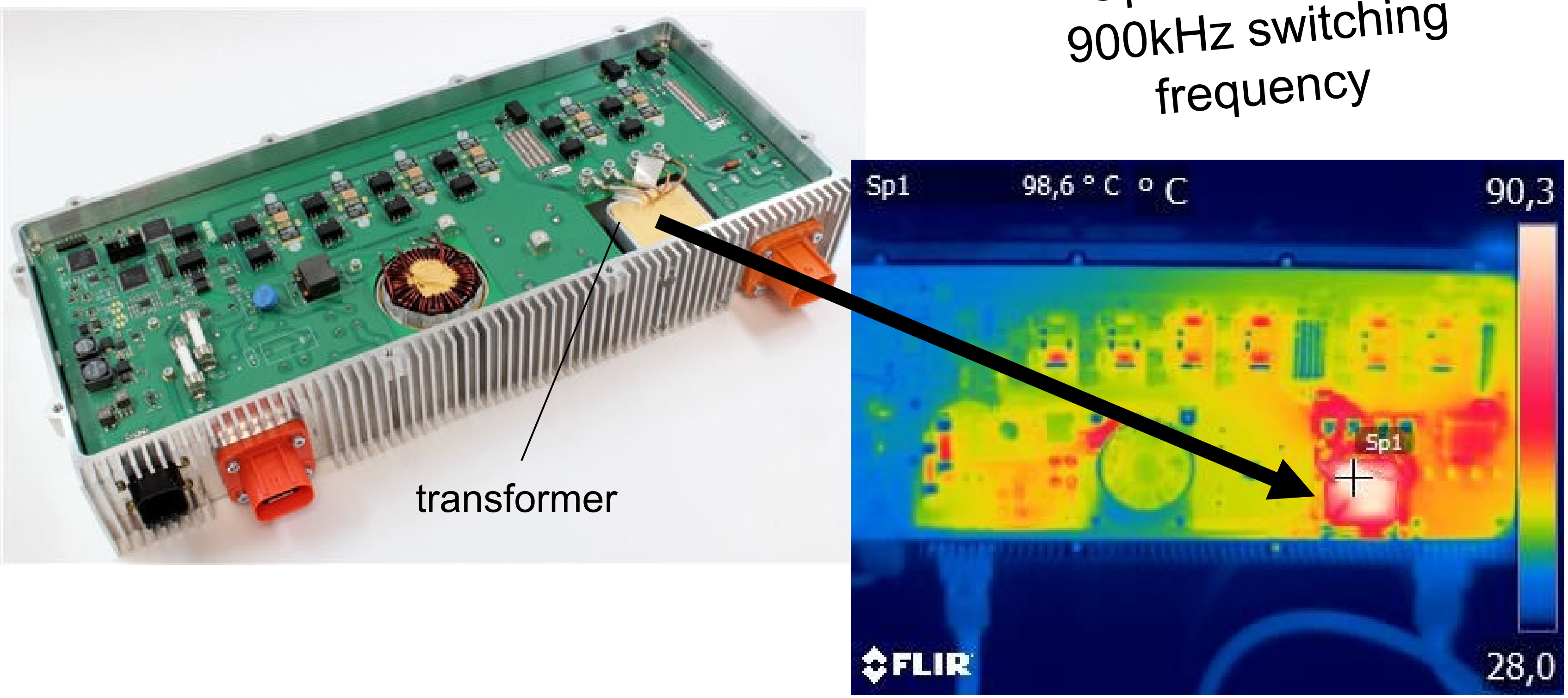


Generation 1 Prototype Measurement

GaN On-Board Charger
Commissioning: High Frequency Challenge for Passives

- GaN semiconductors thermally stable – passive components more challenging
- E.g. transformer operating at its limit due to fast switching

Operation up to 900kHz switching frequency



GaN On-Board Charger
Power Density

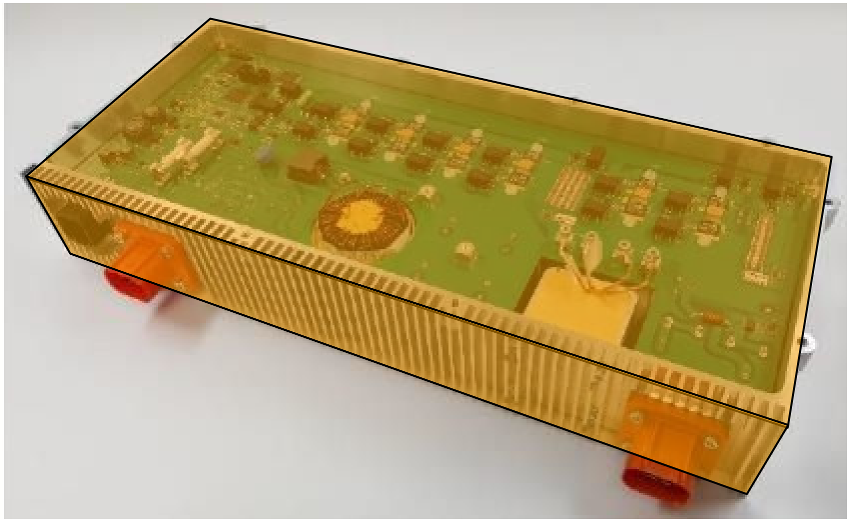
- 3.7kW (V_{out} 270V to 470V)
- Cooling: air

First <u>bidirectional</u> prototype with ~15% improved volume to state of the art air-cooled

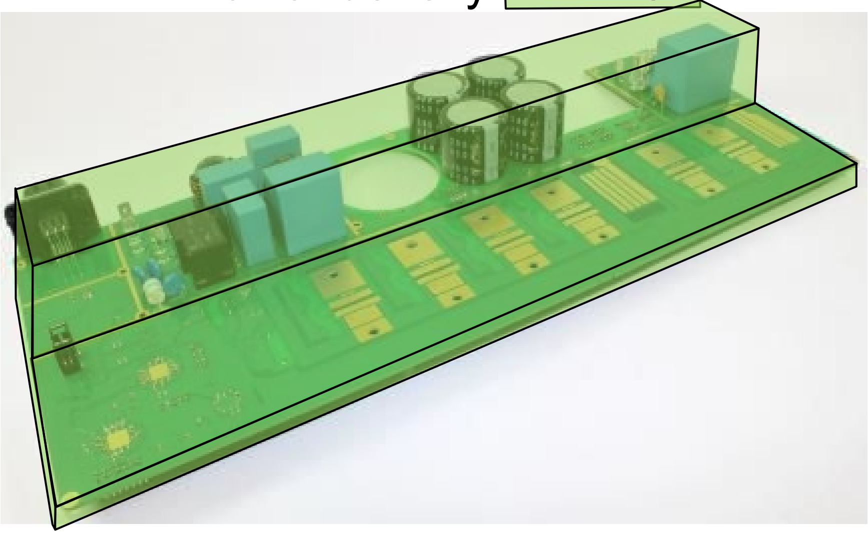
→

Outlook: power density <u>and</u> efficiency to match water-cooled state of the art 1kW/l

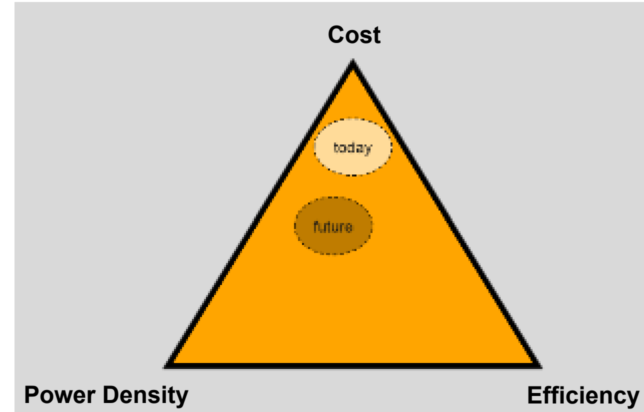
Power density: 0.7kW/l



Power density: 1.7kW/l



Conclusion GaN



- **Focus on Auxiliaries:** first use case **GaN On-Board Charger** prototype
- **Bidirectional** and **air-cooled in same package as liquid cooled and unidirectional**

- **GaN transistors** good lever for increasing **power density** and **efficiency**
- Due to high switching frequency: **passive components** additional **challenge** to GaN

- Future On-Board Charger with **enhanced functionality**: high charging power, bidirectionality
- **Design trade-off** between **volume, cost and efficiency enabled by GaN**

Yes, we GaN!