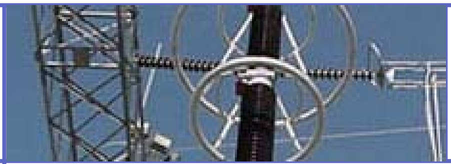
Power Converter Course, Warrington

12.05.2005

High Power Active Devices



Eric Carroll, ABB Switzerland

INTRODUCTION

Electronic Switches

- **Thyristor**

  Can be turned ***on*** by gate signal but can only be turned ***off*** by reversal of the anode current

- **Gate Turn-Off Thyristor (GTO)**

  Can be turned ***on*** and ***off*** by the gate signal but requires large capacitor (snubber) across device to limit dv/dt

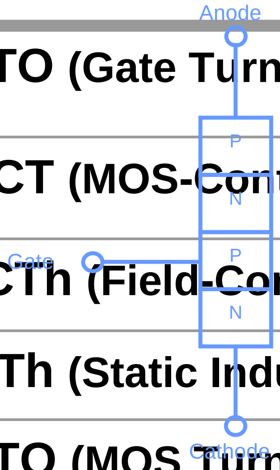
- **Transistor *(transitional resistor)***

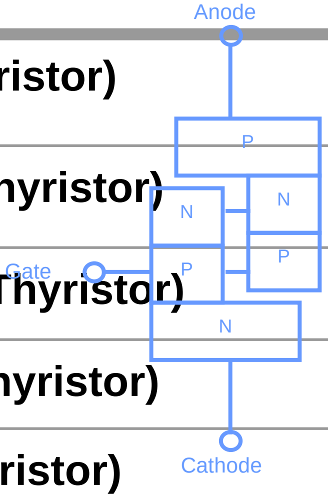
  Can be turned ***on*** and ***off*** by the gate (or base) signal but has high conduction losses (its an amplifier, not a switch)

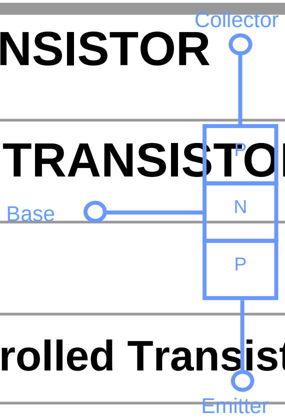
- **Integrated Gate Commutated Thyristor (IGCT)**

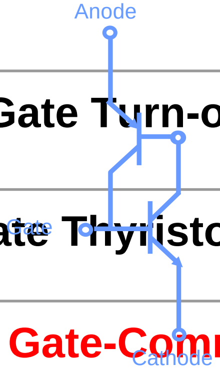
  Can be turned *on* and *off* by the gate signal, has low conduction loss and requires no dv/dt snubber

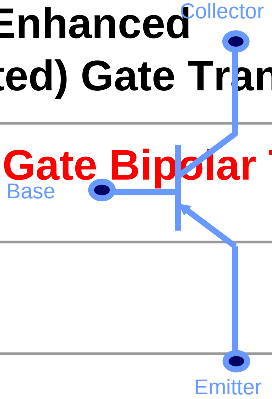
Available Self-Commutated Semiconductor Devices





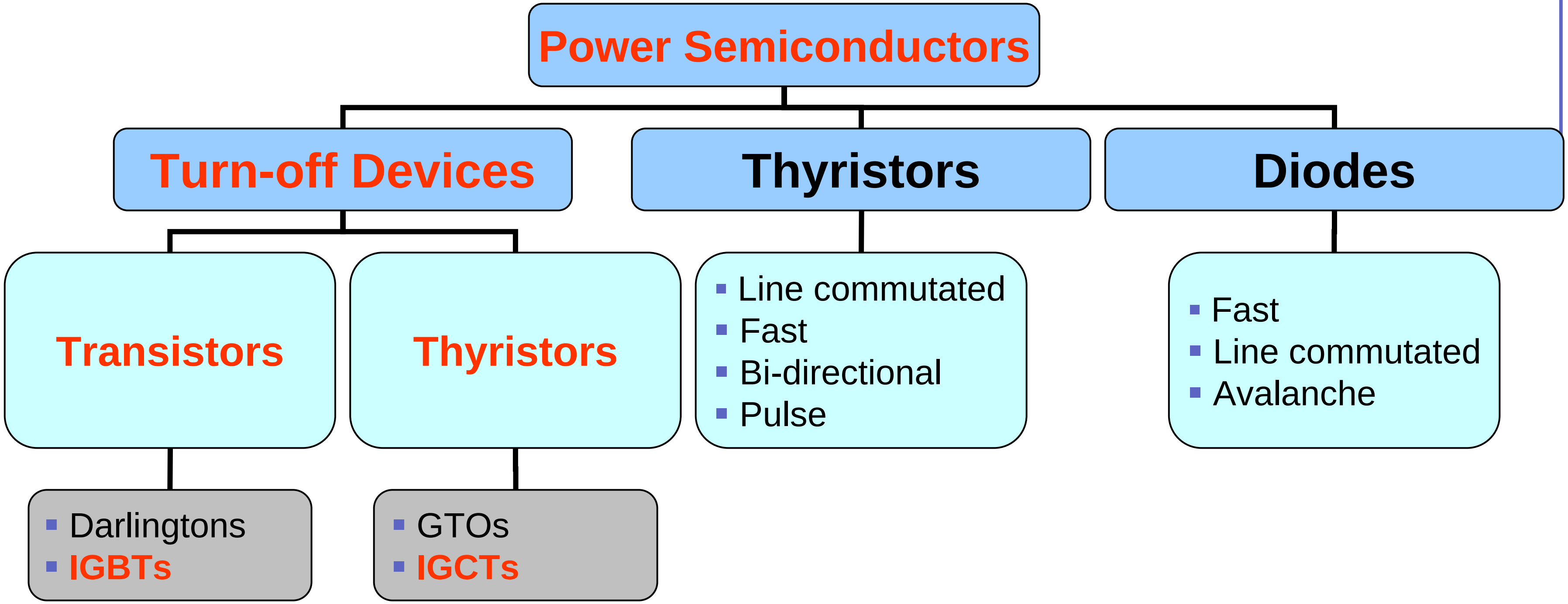






THYRISTORS	**TRANSISTORS**
GTO (Gate Turn-Off Thyristor)	**BIPOLAR TRANSISTOR**
MCT (MOS-Controlled Thyristor)	**DARLINGTON TRANSISTOR**
FCTh (Field-Controlled Thyristor)	**MOSFET**
SITh (Static Induction Thyristor)	**FCT (Field Controlled Transistor)**
MTO (MOS Turn-Off Thyristor)	**SIT (Static Induction Transistor)**
EST (Emitter-Switched Thyristor)	**IEGT (Injection Enhanced (insulated) Gate Transistor)**
IGTT (Insulated Gate Turn-off Thyristor)	**IGBT (Insulated Gate Bipolar Transistor)**
IGT (Insulated Gate Thyristor)	
IGCT (Integrated Gate-Commutated Thyristor)	

High Power Turn-off Devices



Power Semiconductors

Turn-off Devices

Thyristors

Diodes

Transistors

- Darlingtons
- **IGBTs**

Thyristors

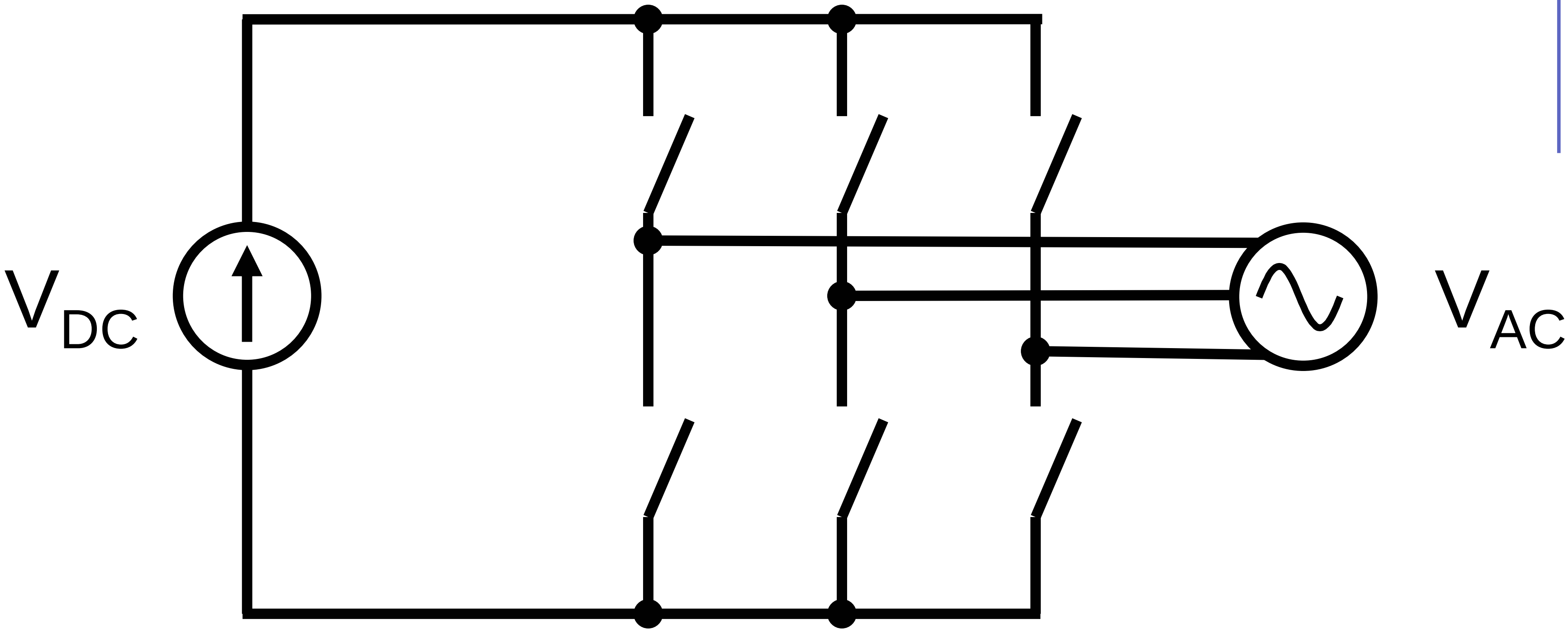
- GTOs
- **IGCTs**

- Line commutated
- Fast
- Bi-directional
- Pulse

- Fast
- Line commutated
- Avalanche

Power Semiconductors …

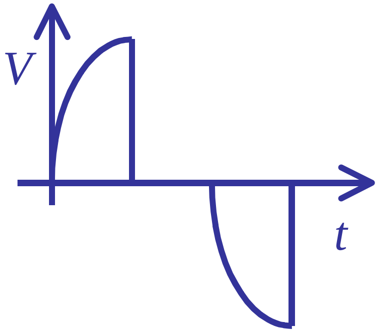
are switches….



….for converting electrical energy

Turn-on Switches (Thyristors)

Thyristors (PCTs)

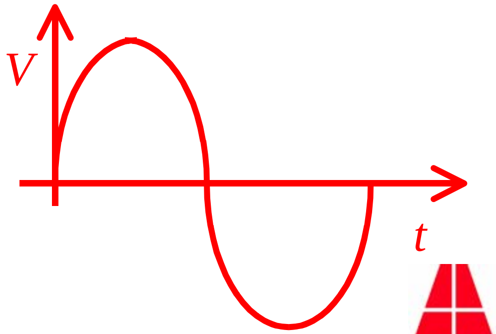


- **thyristors produce voltage distortion *in phase control mode***

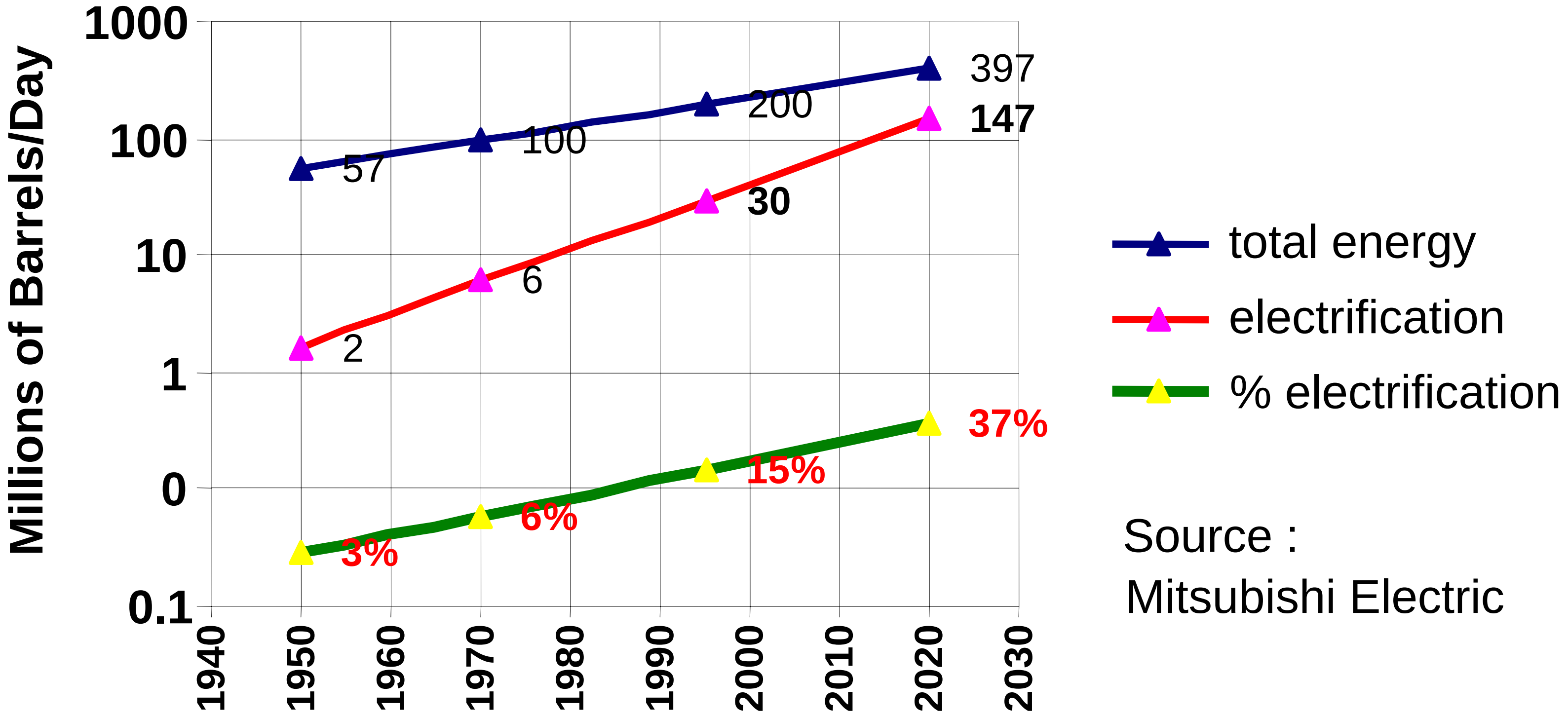
- **will *ultimately* be replaced by ToDs, *except...***

in AC configuration for:

- **transfer switches**
- **tap changers**
- **line interrupters**



World Energy Consumption …



Source :
Mitsubishi Electric

... drives the need for high power electronics

Energy trend

By 2020:

- **Energy consumption will double**
- **Electricity generation will double**
- **Electrification of end-consumption will quintuple**

Today, only 15% of electricity flows via electronics

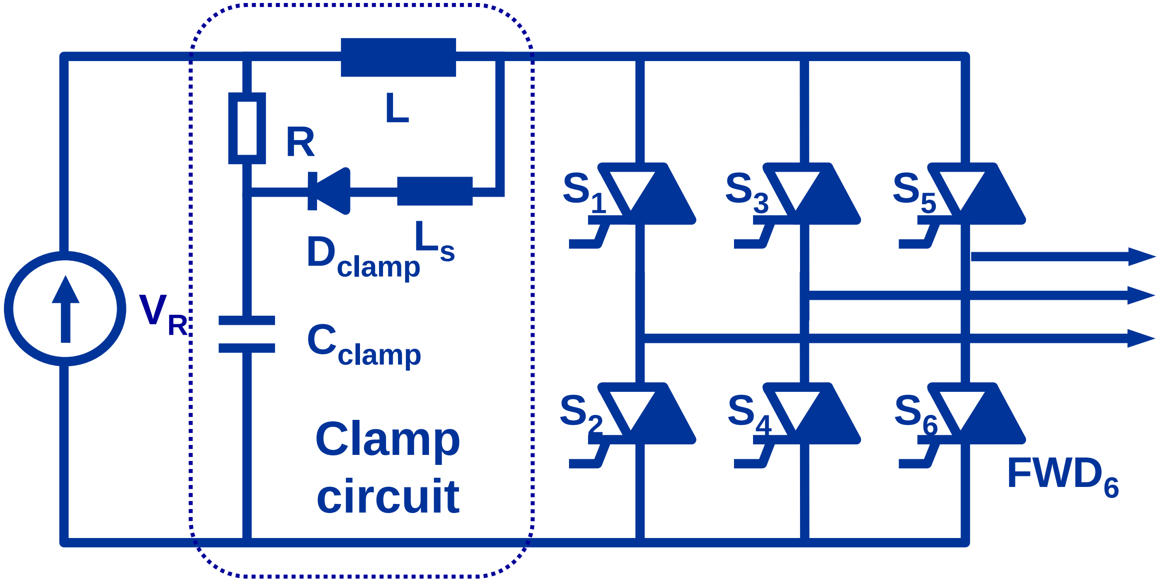
Medium Voltage conversion has only been economically possible in the last 10 years

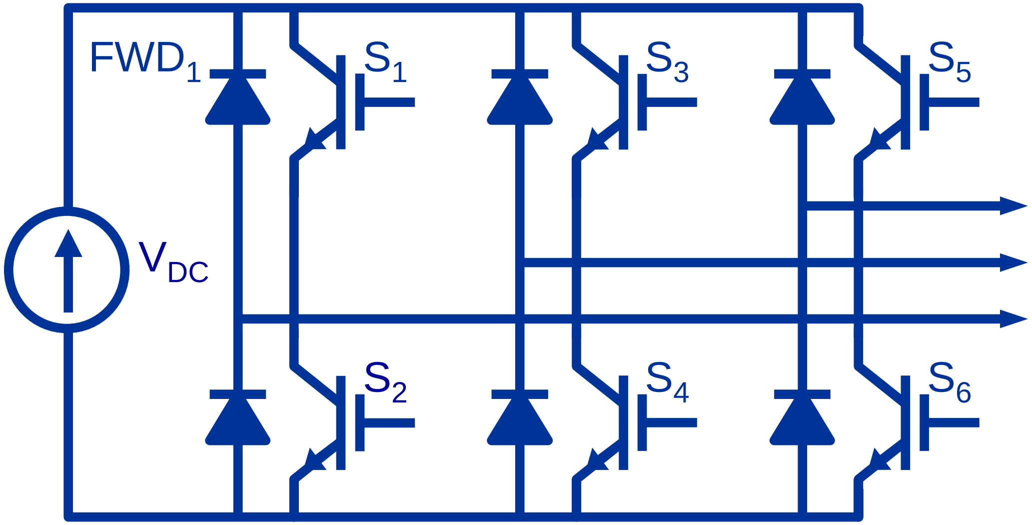
Power conversion at MV levels set to grow faster than LV (20% p.a.)

SELF- COMMUTATED INVERTERS

Basic Topologies

IGCT Inverter

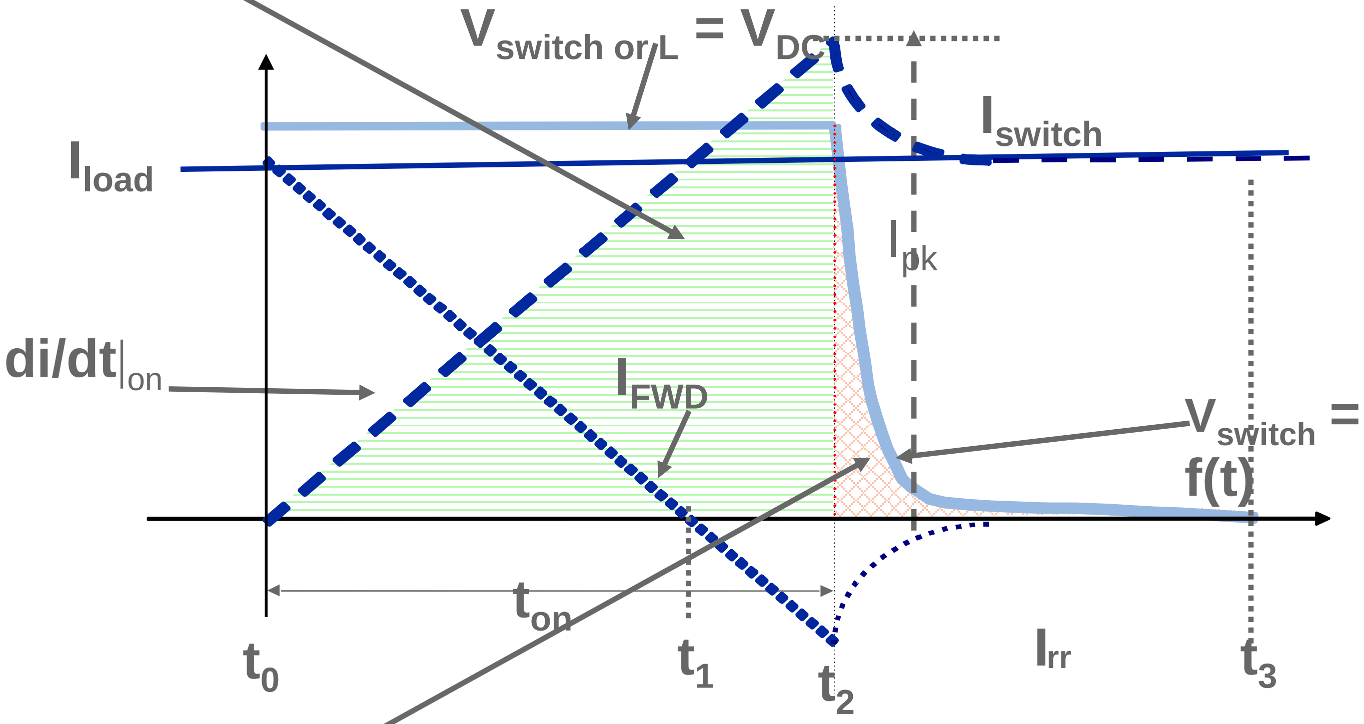




IGBT Inverter

Turn-on waveforms for IGCTs and IGBTs

$$E_{on-circuit} = (t_2 - t_0) \bullet V_{dc} \bullet (I_{load} + I_{rr})/2....(1)$$



$$E_{on-device} \approx I_{load} \bullet \int_{t_2}^{t_3} V_{switch}(t).dt............(2)$$

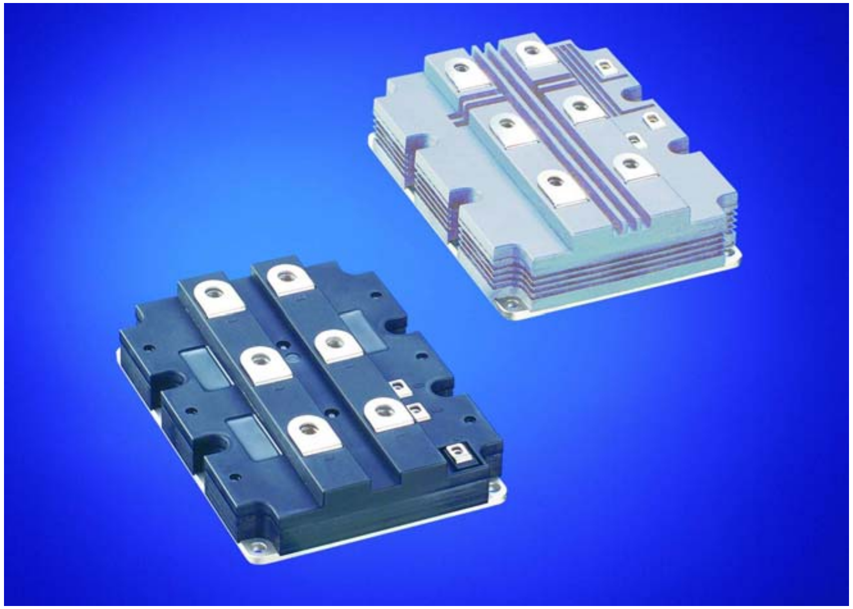
DEVICES

IGBTs

IGBTs – key features

- Transistors with insulated gate
- Allow dv/dt and di/dt control via gate signal
  (losses)
- High on-state voltage
  (transistor)
- High turn-on losses (no snubber)
- Low gate power requirements
  (voltage control)
- No passives required
  (independant dv/dt and di/dt control)

HiPak™ High Power IGBT Modules



Voltage	Current	Type	Part Number	V_{ce} 125°C	V_F 125°C	Eoff 125°C	Eon 125°C	Vdc
2500V	1200A	Single	5SNA 1200E250100	3.1V	1.8V	1.25J	1.15J	1250V
3300V	1200A	Single	5SNA 1200E330100	3.8V	2.35V	1.95J	1.89J	1800V
3300V	1200A	Single	5SNA 1200G330100*	3.8V	2.35V	1.95J	1.89J	1800V
6500V	600A	Single	5SNA 0600G650100*	4.7V	4.0V	3.5J	4.0J	3600V

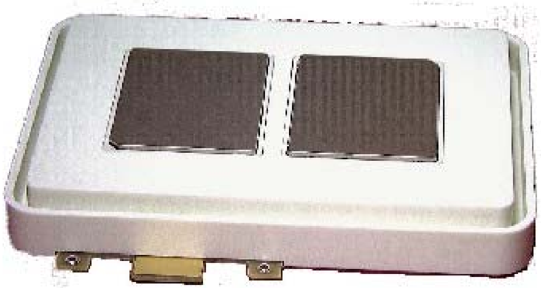
* High voltage version

AlSiC base-plate & AlN substrate

StakPak™ - stackable press-packs (collector side)

StakPak-H4: 2.5 kV/1300 to 3000 A

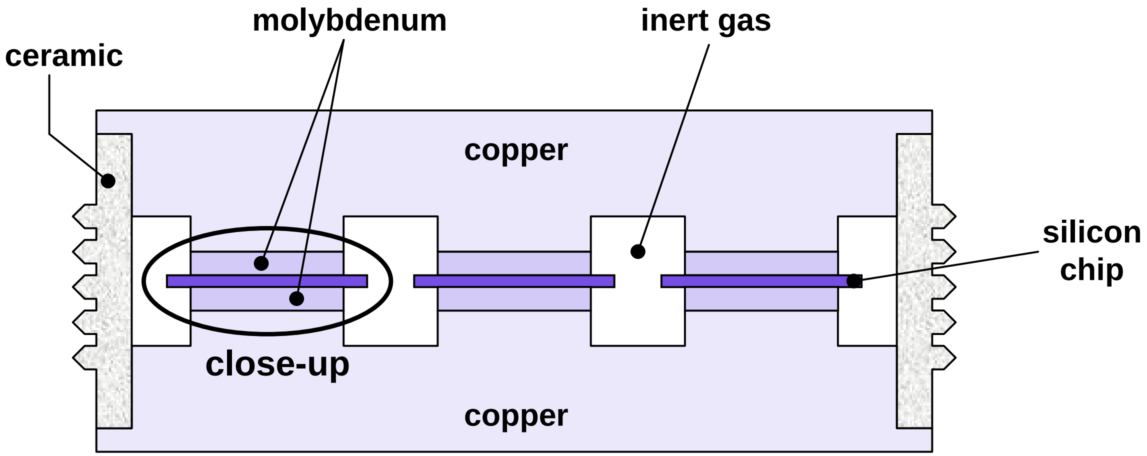
StakPak-L2: 4.5 kV/600 to 1000 A



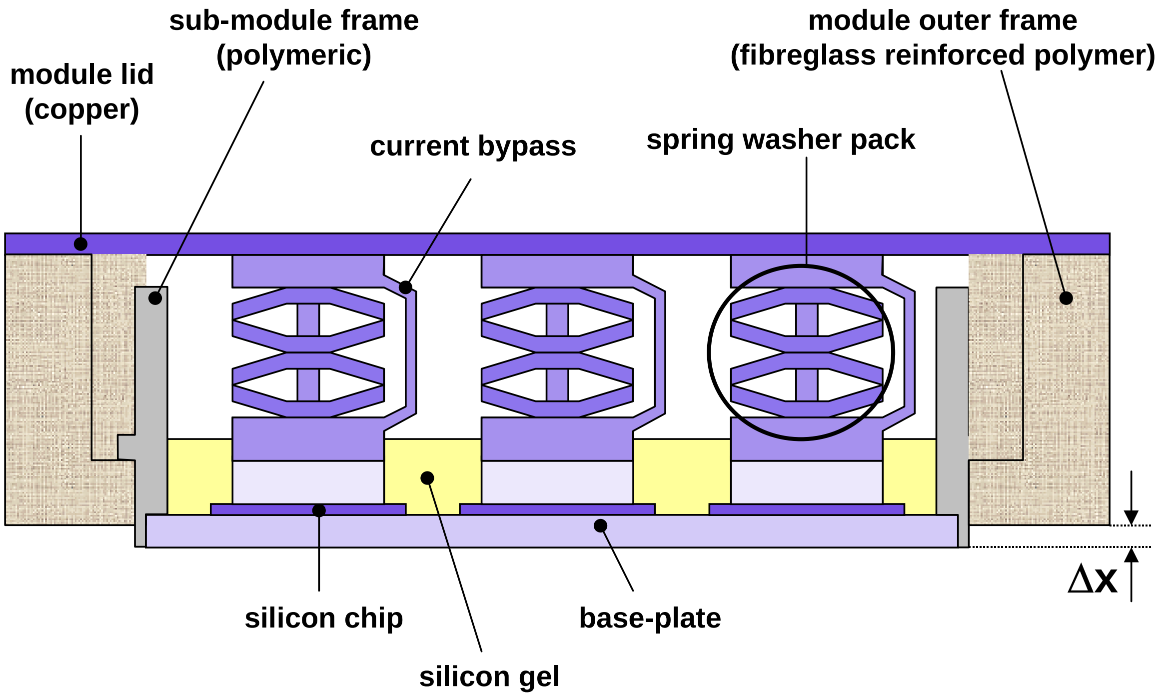
StakPak-H6: 2.5 kV/ 2000A to 3000 A

StakPak-J6: 4.5 kV/2000 to 3000 A

IGBT Press-packs



Conventional IGBT press-pack:
requires tight mechanical tolerances

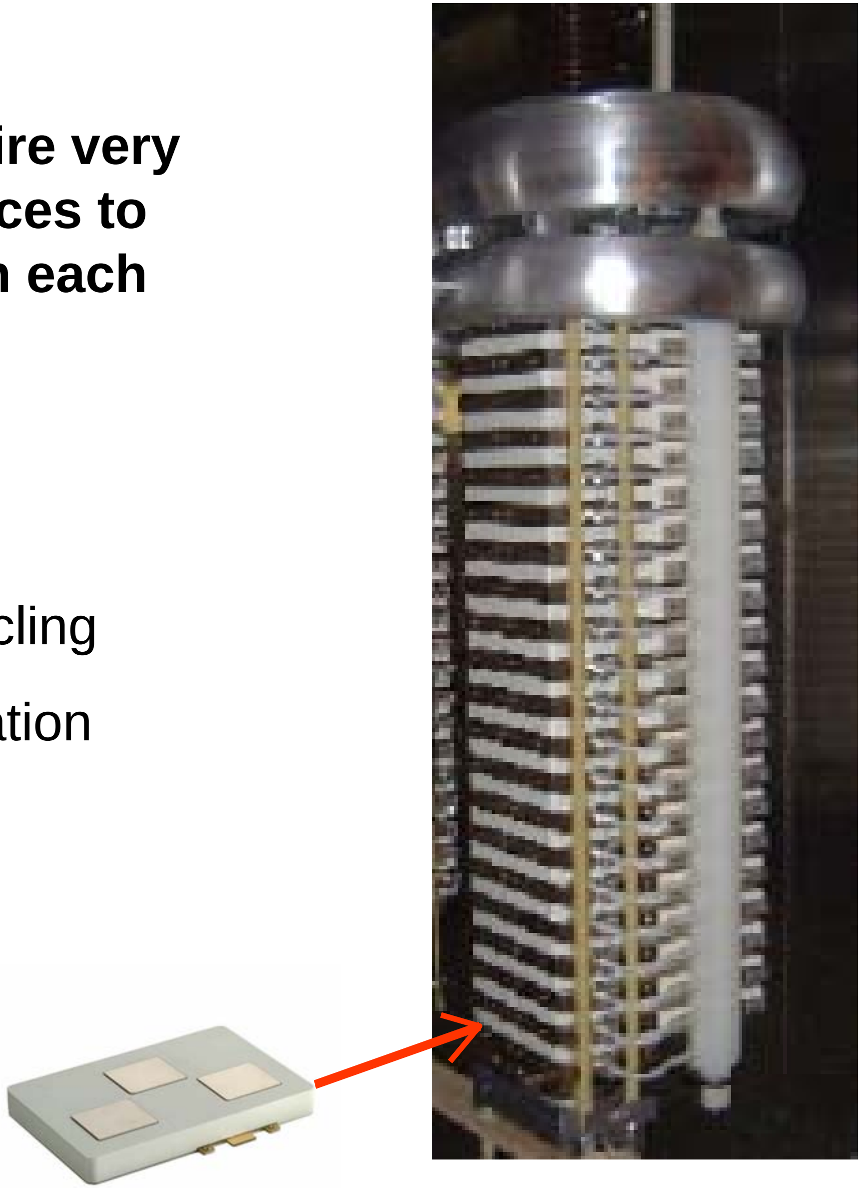


StakPak™ IGBT press-pack with individual springs:
suitable for long stacks with compounded tolerances

StakPak™ HVDC Valve

Long stacks would require very tight mechanical tolerances to ensure identical force on each chip in each housing:

- on assembly
- over time
- with temperature cycling
- with shock and vibration

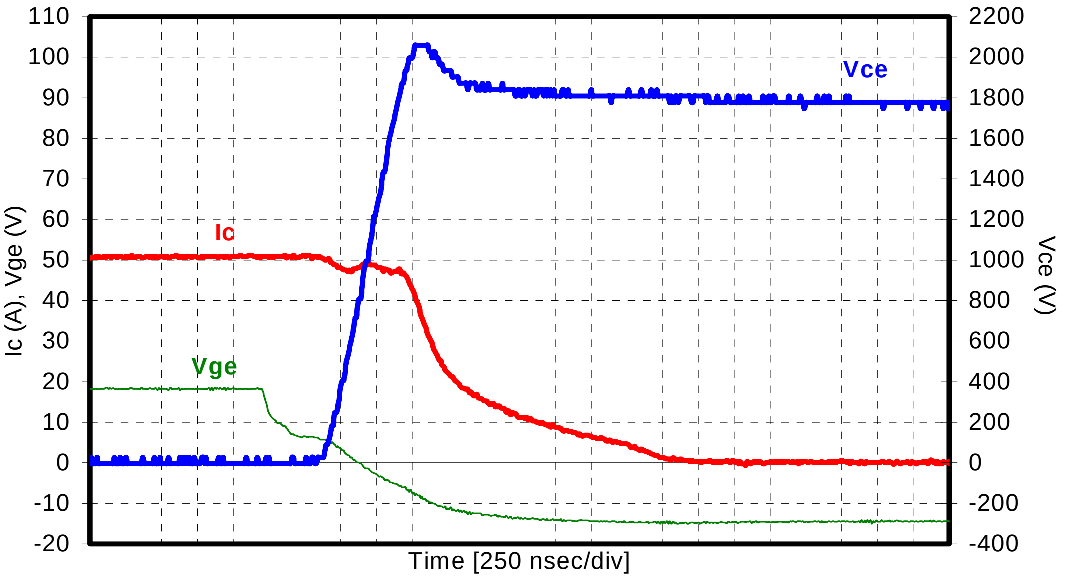


IGBT Trends

IGBT Trends

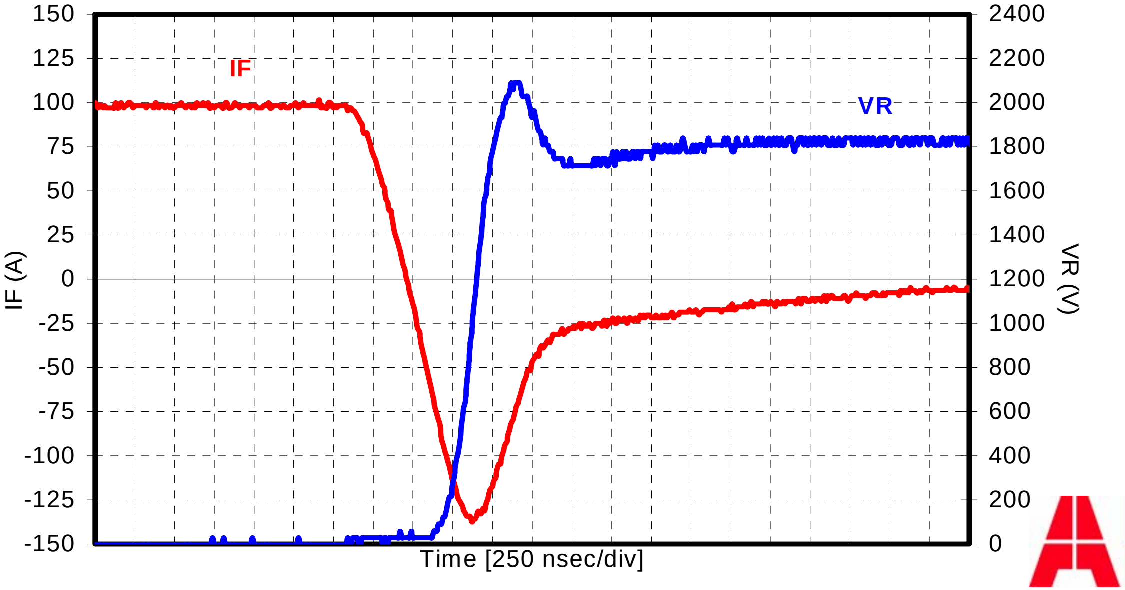
- Higher voltages
- Higher *Safe Operating Area* (SOA)
- Softer (controlled) switching

Soft switching: 3.3kV SPT* IGBT/Diode chip-set



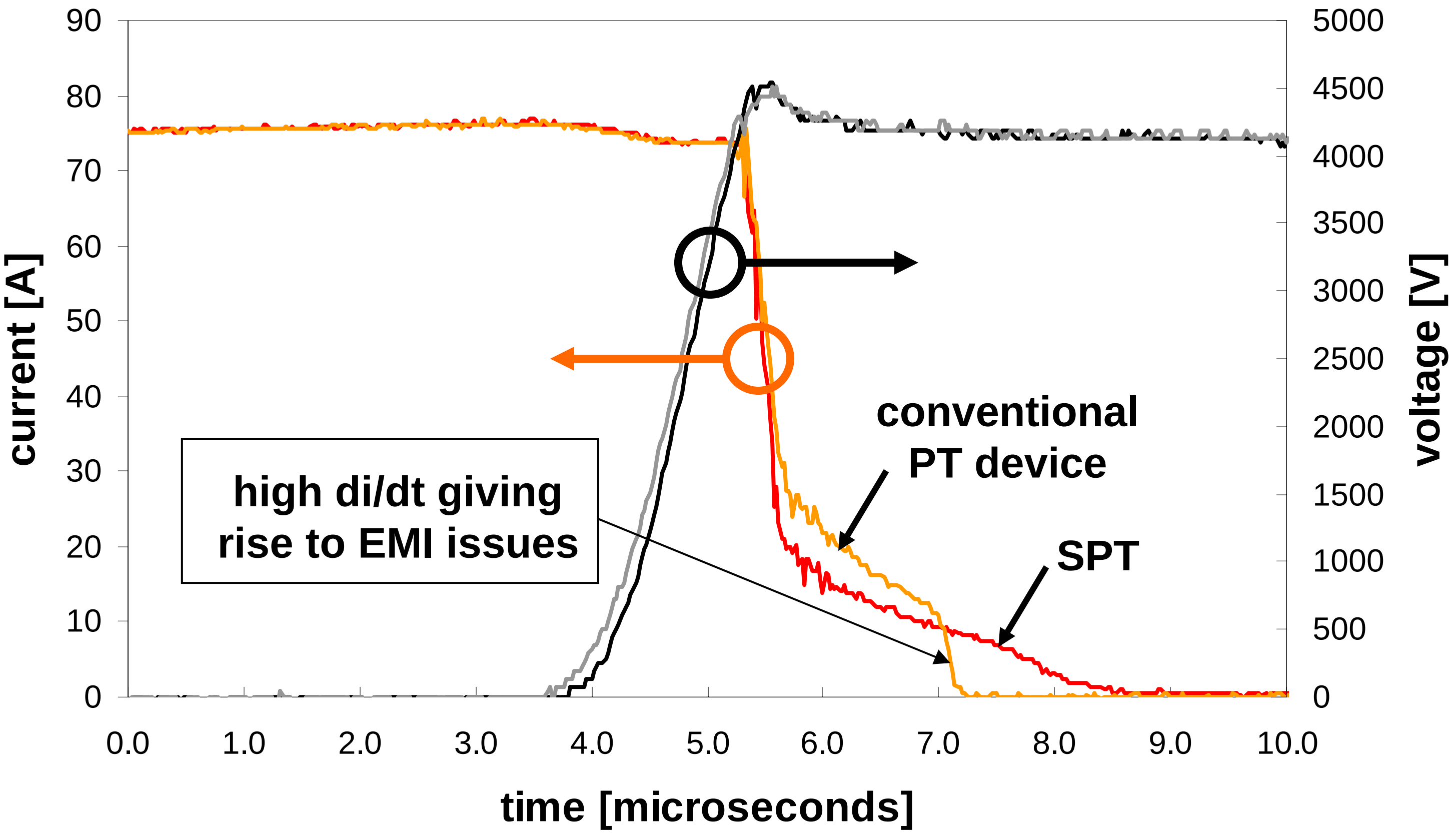
IGBT Turn-off
V_{cc}= 1800V
I_c= 50A
R_{Goff}= 33ohm
L_s= 2.4μH
T_j= 125°C

Diode Turn-off
V_R= 1800V
I_F= 100A
R_{Gon}= 33ohm
L_s= 2.4μH
T_j= 125°C

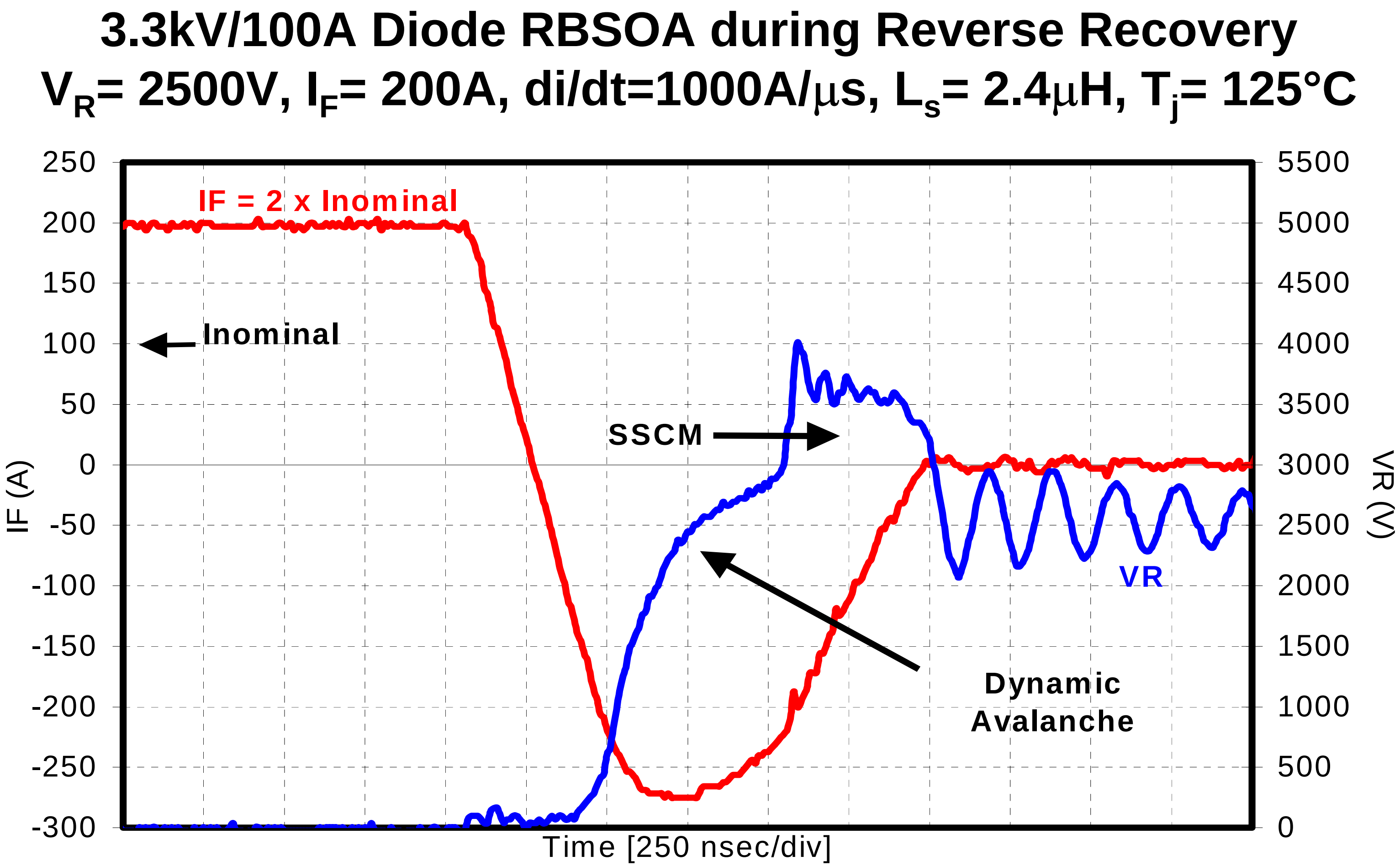


* Soft Punch Through

Soft switching: 8 kV IGBT PT vs SPT



3.3kV Diode RBSOA Performance

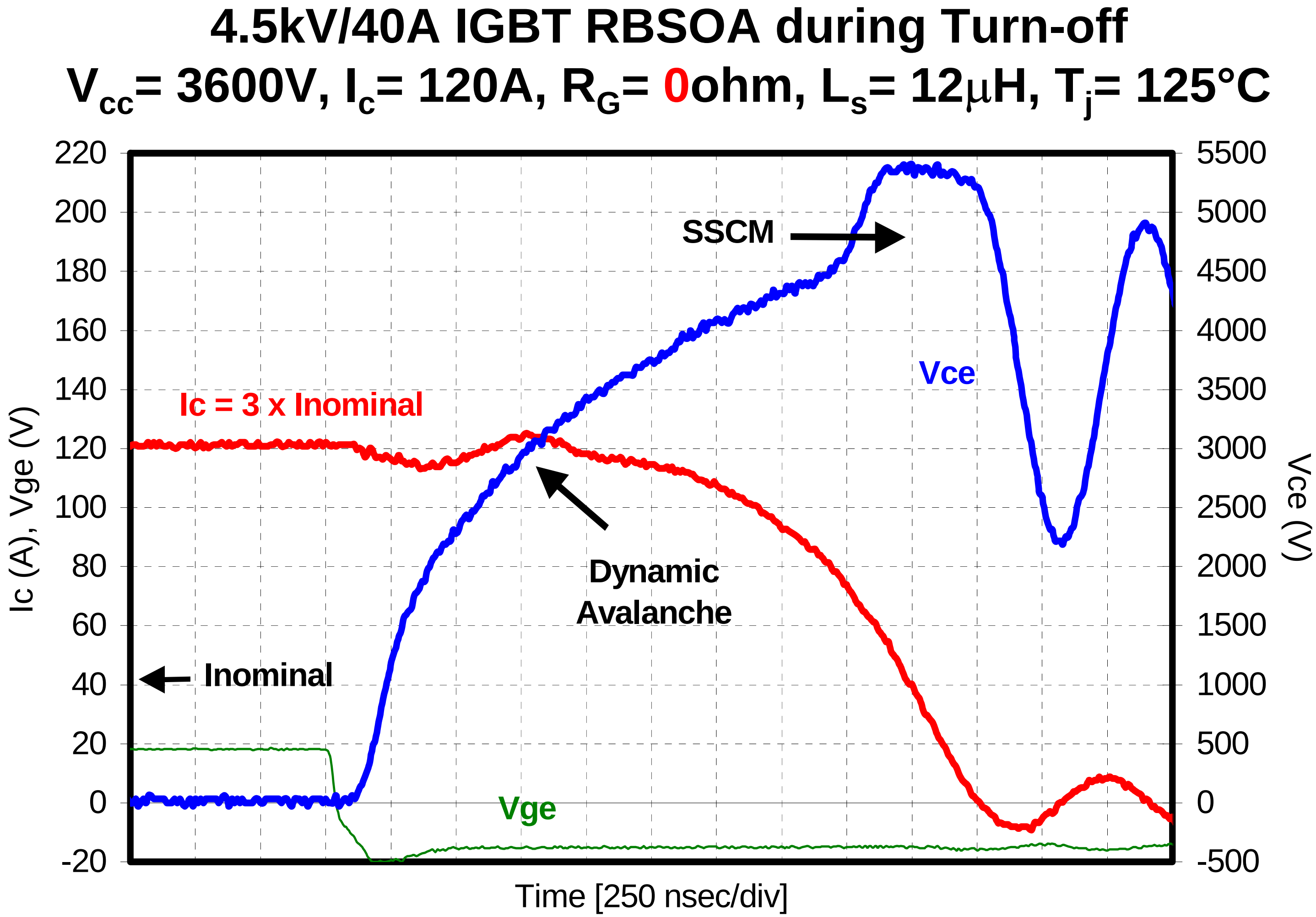

3.3kV/100A Diode RBSOA during Reverse Recovery

V_R= 2500V, I_F= 200A, di/dt=1000A/μs, L_s= 2.4μH, T_j= 125°C

Peak Power = 0.8 MW/cm²

No clamp, no snubber

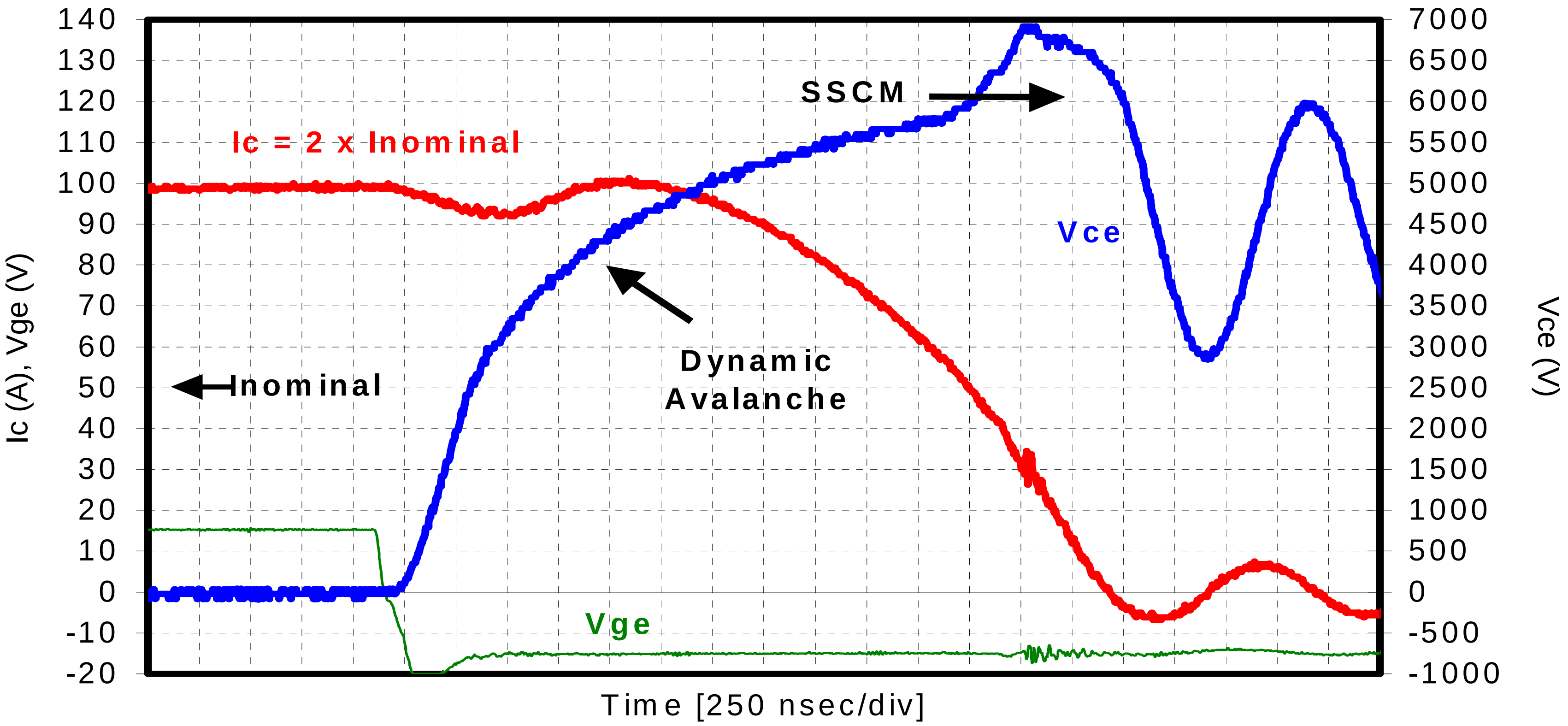
4.5kV IGBT RBSOA Performance



Peak Power = 0.5 MW/cm²

No Clamp, No Snubbers

6.5kV IGBT RBSOA Performance



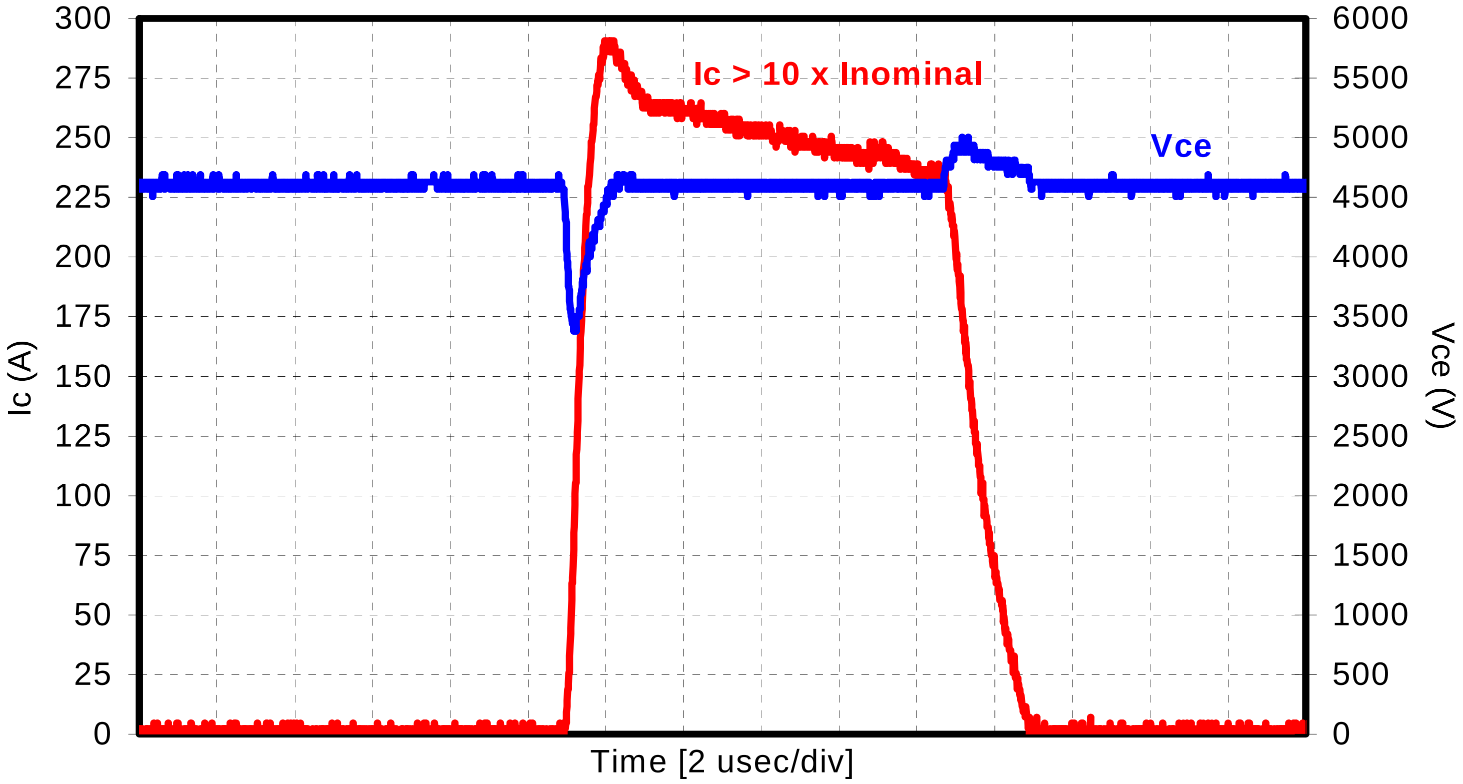
Peak Power = 0.25 MW/cm²

No Clamp, No Snubbers

6.5kV IGBT Short Circuit Performance

6.5kV/25A IGBT SCSOA during Short Circuit

V_{cc}= 4500V, I_{cpeak}= 290A, V_{GE}= 18V, L_s= 2.4µH, T_j= 25°C

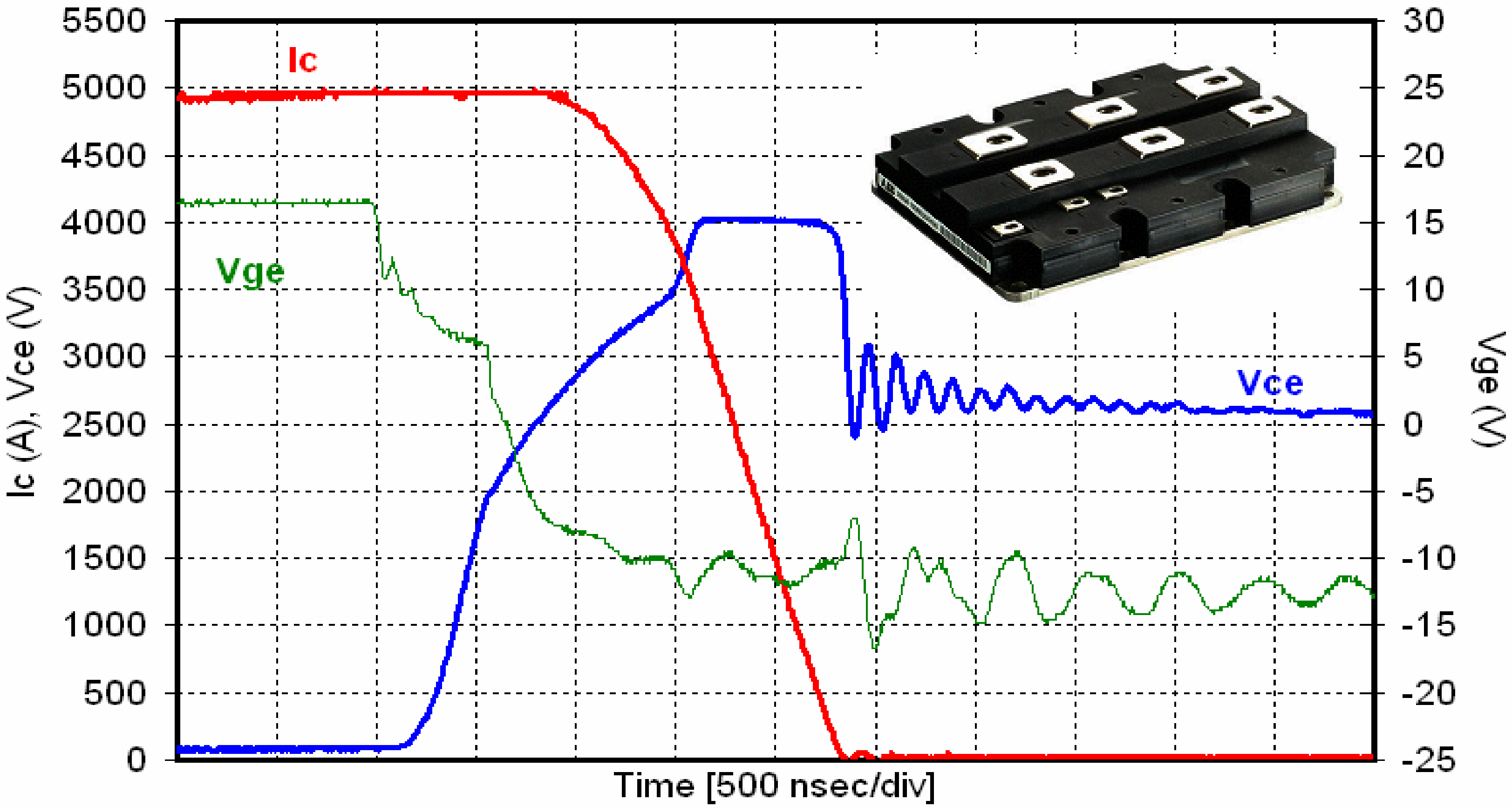


Peak Power = 1.35 MW/cm²

No Clamp, No Snubbers

3.3kV IGBT Module RBSOA Performance

3.3kV/1200A IGBT module during Turn-off (24 IGBTs)
V_{cc}= 2600V, I_c= 5000A, R_G= 1.5ohm, L_s= 280nH, T_j= 125°C



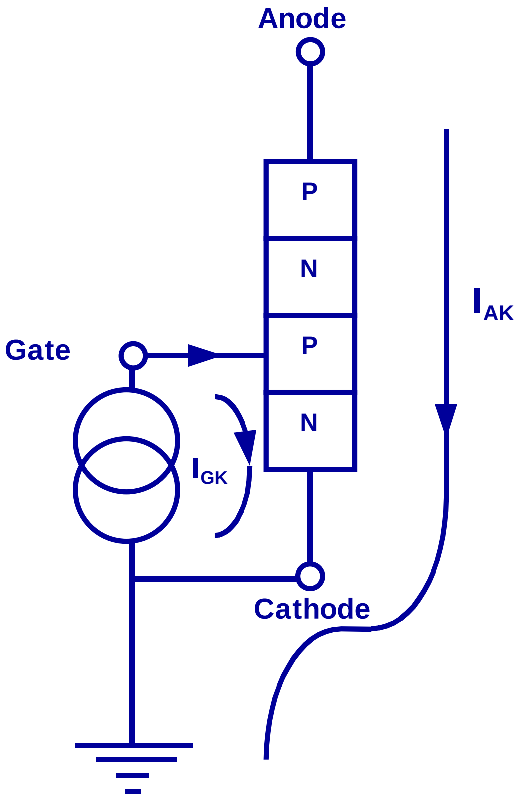
No clamp, no snubbers

IGCTs

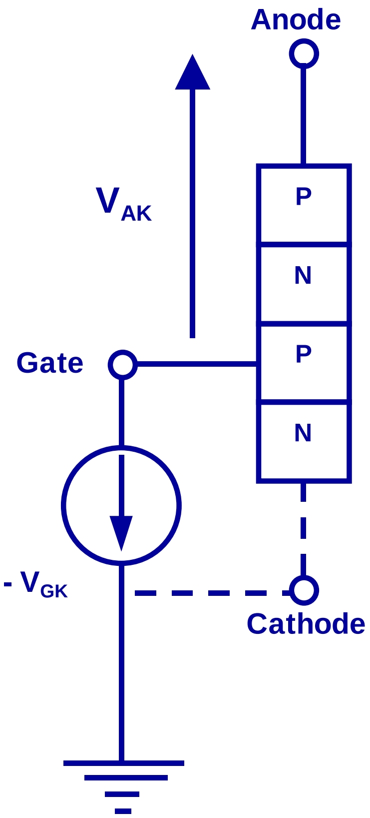
IGCTs – key features

- Thyristor with integrated gate unit
- Low on-state voltage
  (thyristor)
- Negligible turn-on losses
  (turn-on snubber)
- No explosive failures
  (fault current limitation by circuit)

Principle of IGCT Operation

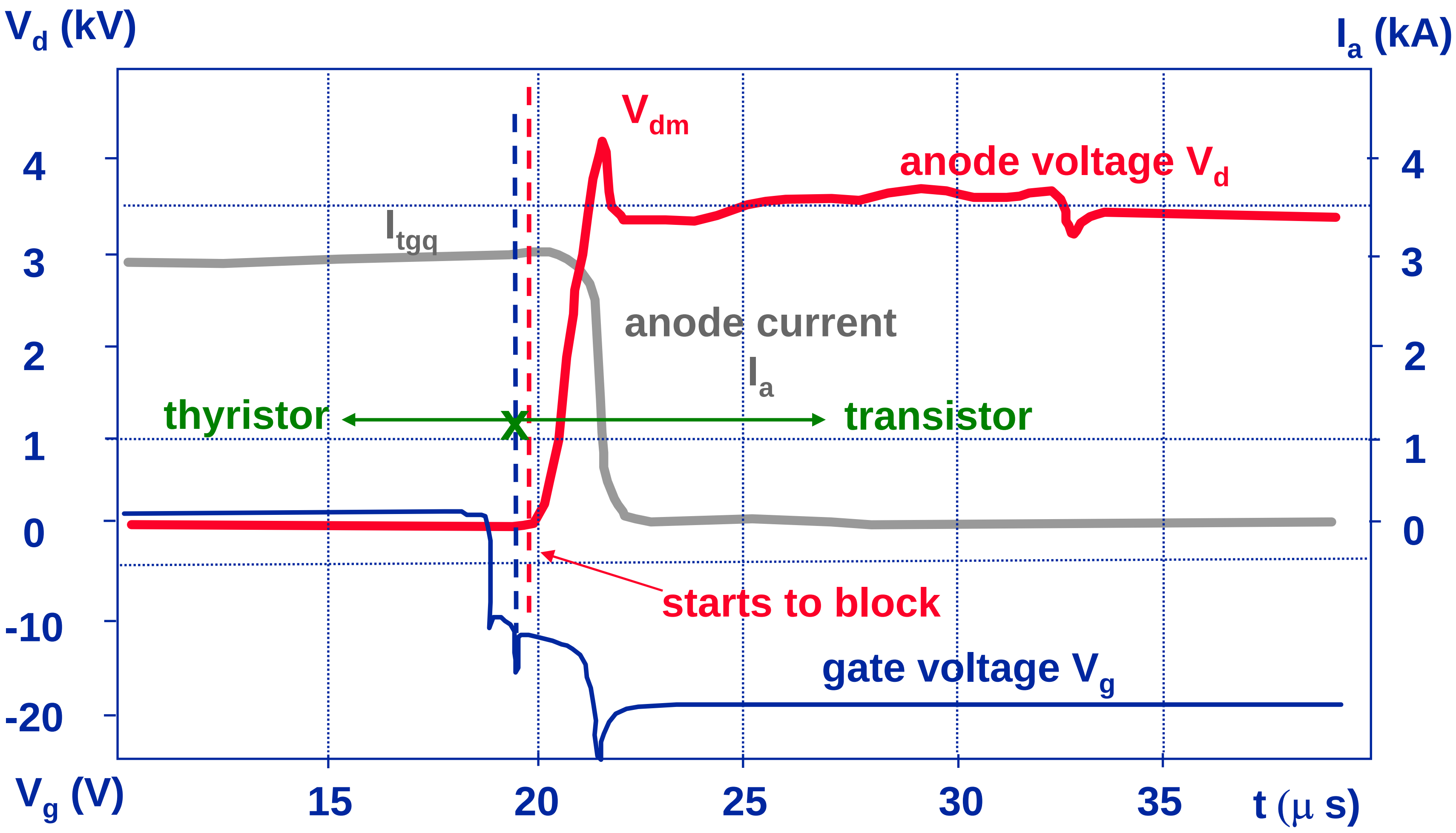


Conducting Thyristor

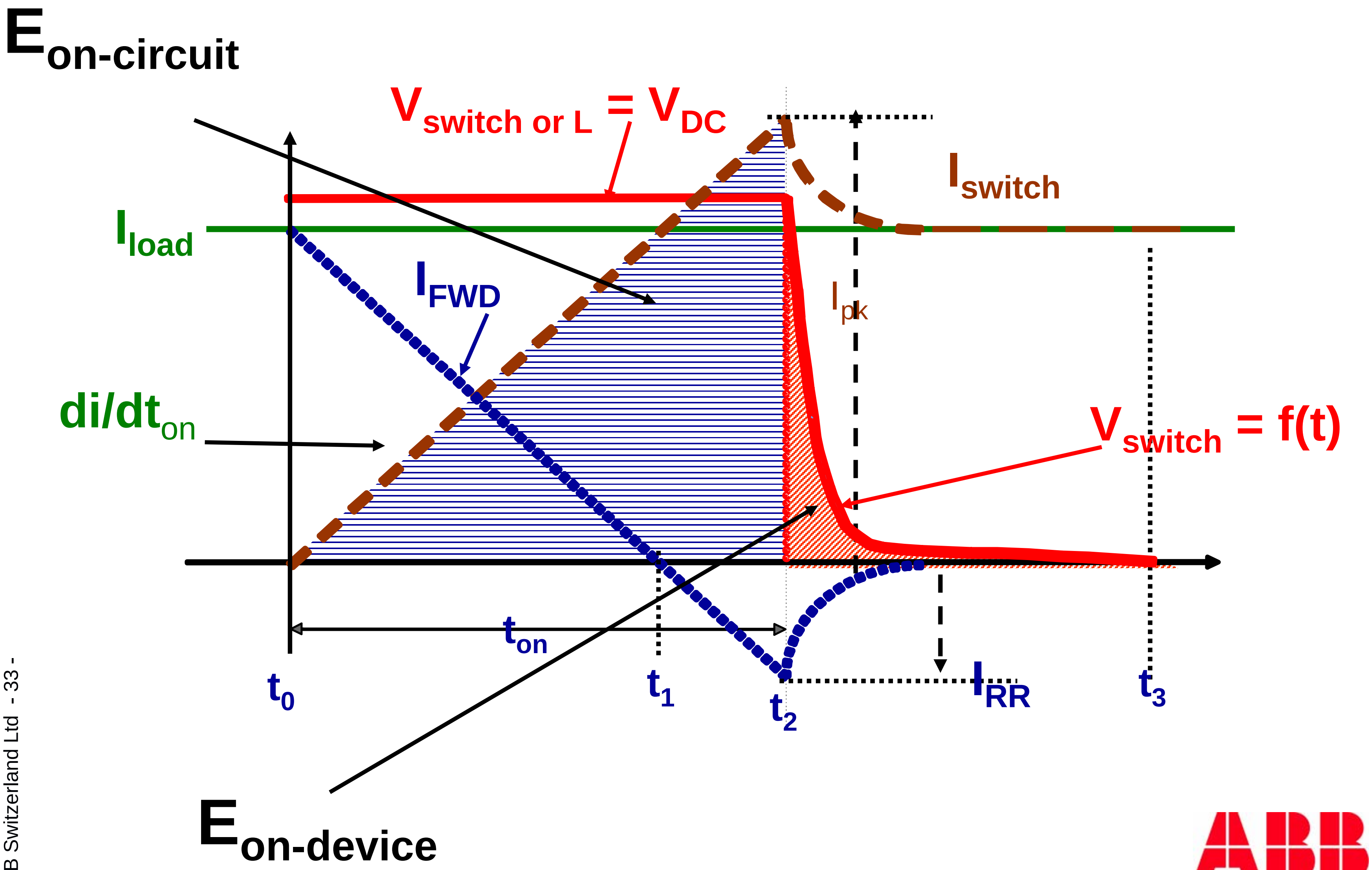


Blocking Transistor

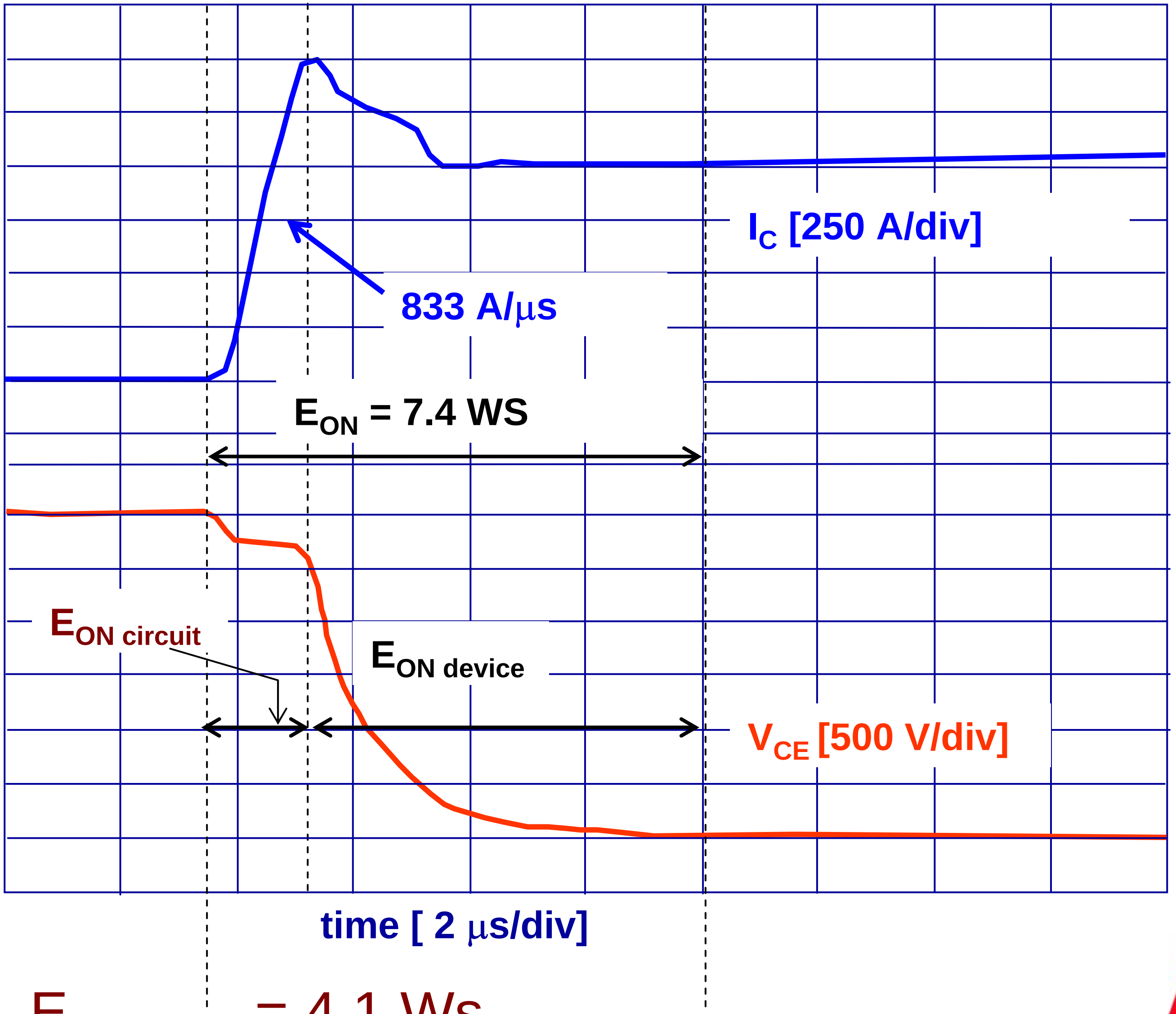
IGCT turn-off



General turn-on waveforms for IGCTs and IGBTs

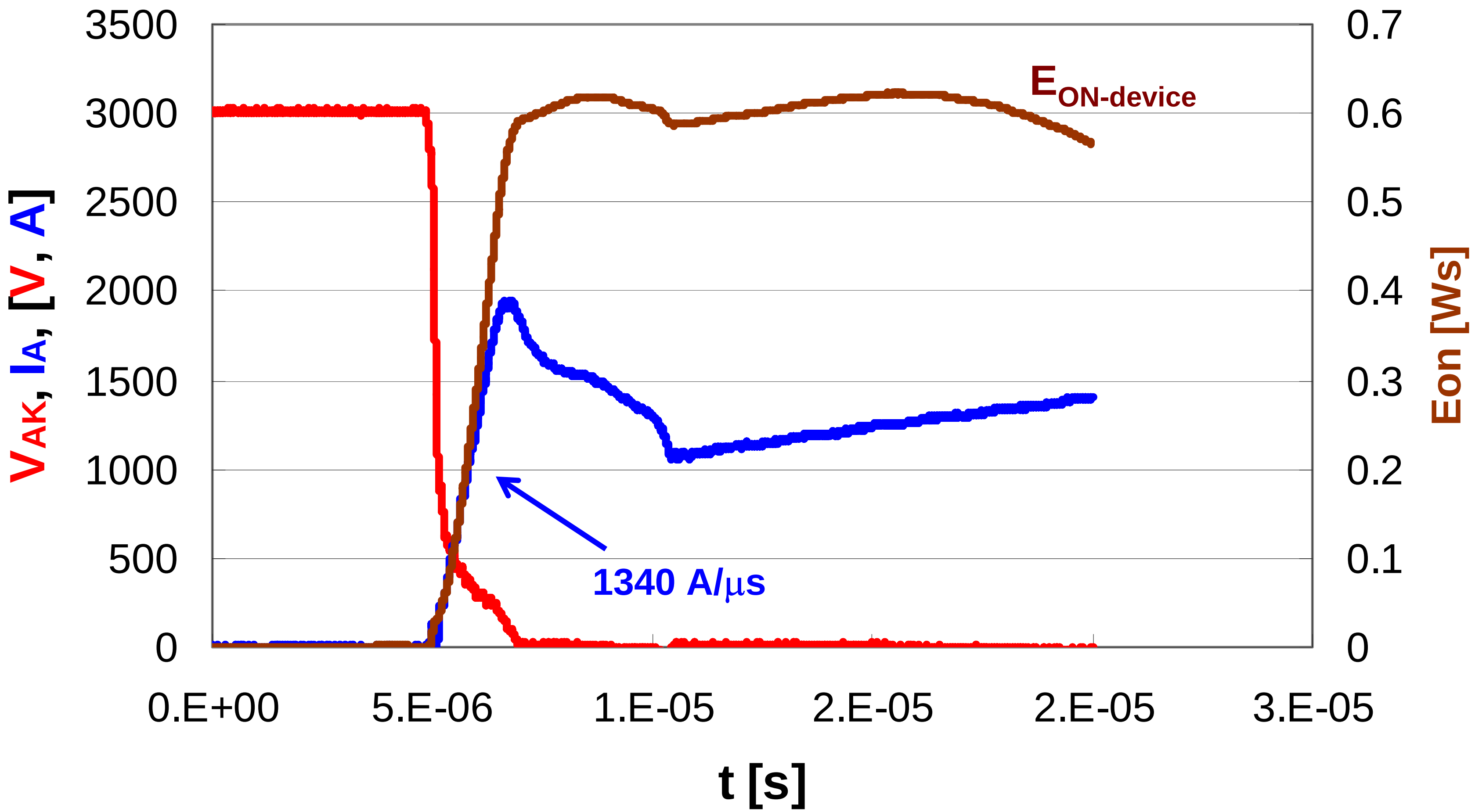


1500 A IGBT turning on 1000 A from 3000 V



$E_{ON\text{-}circuit}$ = 4.1 Ws

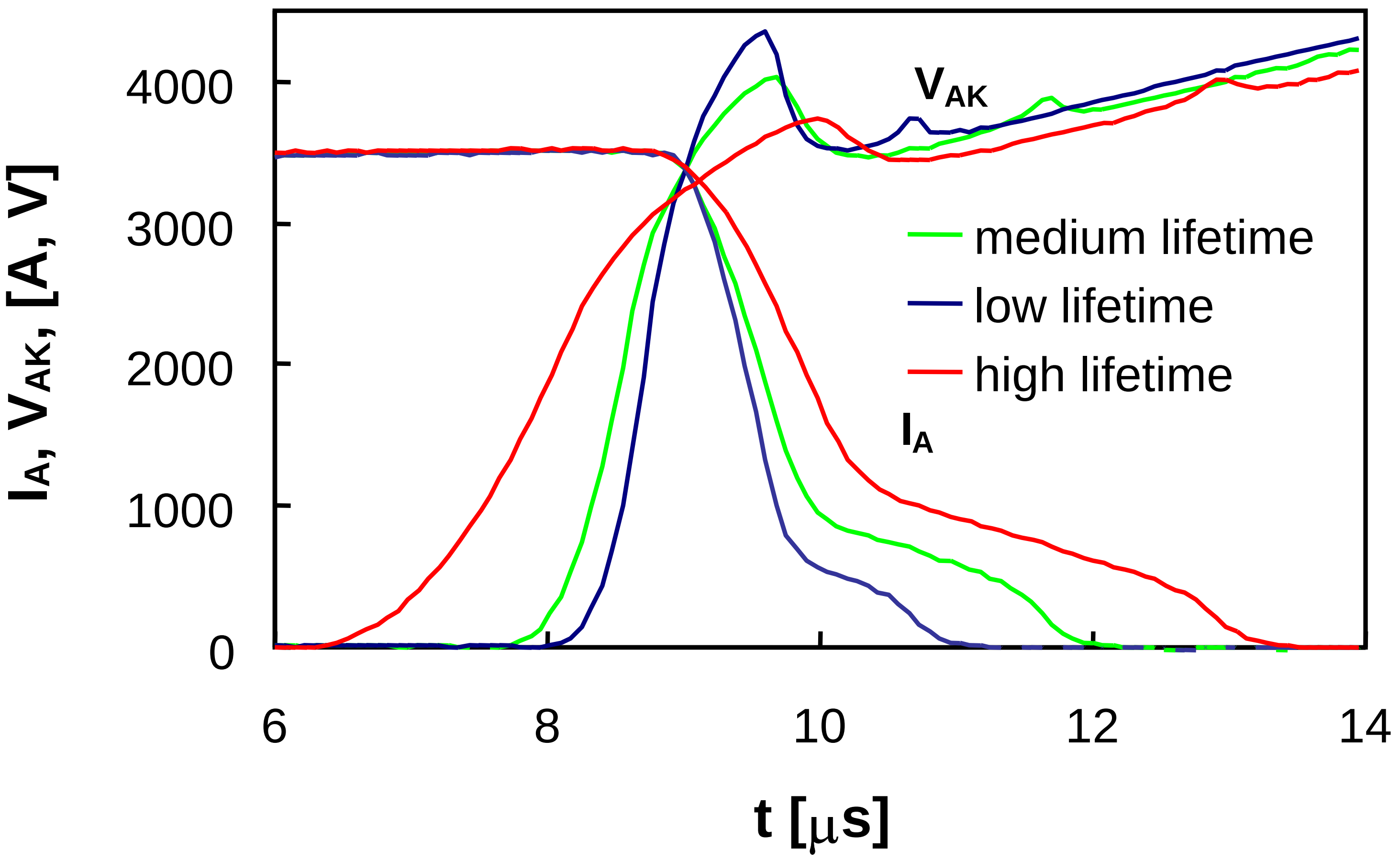
4000 A IGCT turning on 1000 A from 3000 V



$$E_{on-circuit} = (t_2 - t_0) \bullet V_{dc} \bullet (I_{load} + I_{rr})/2 \ldots (1)$$

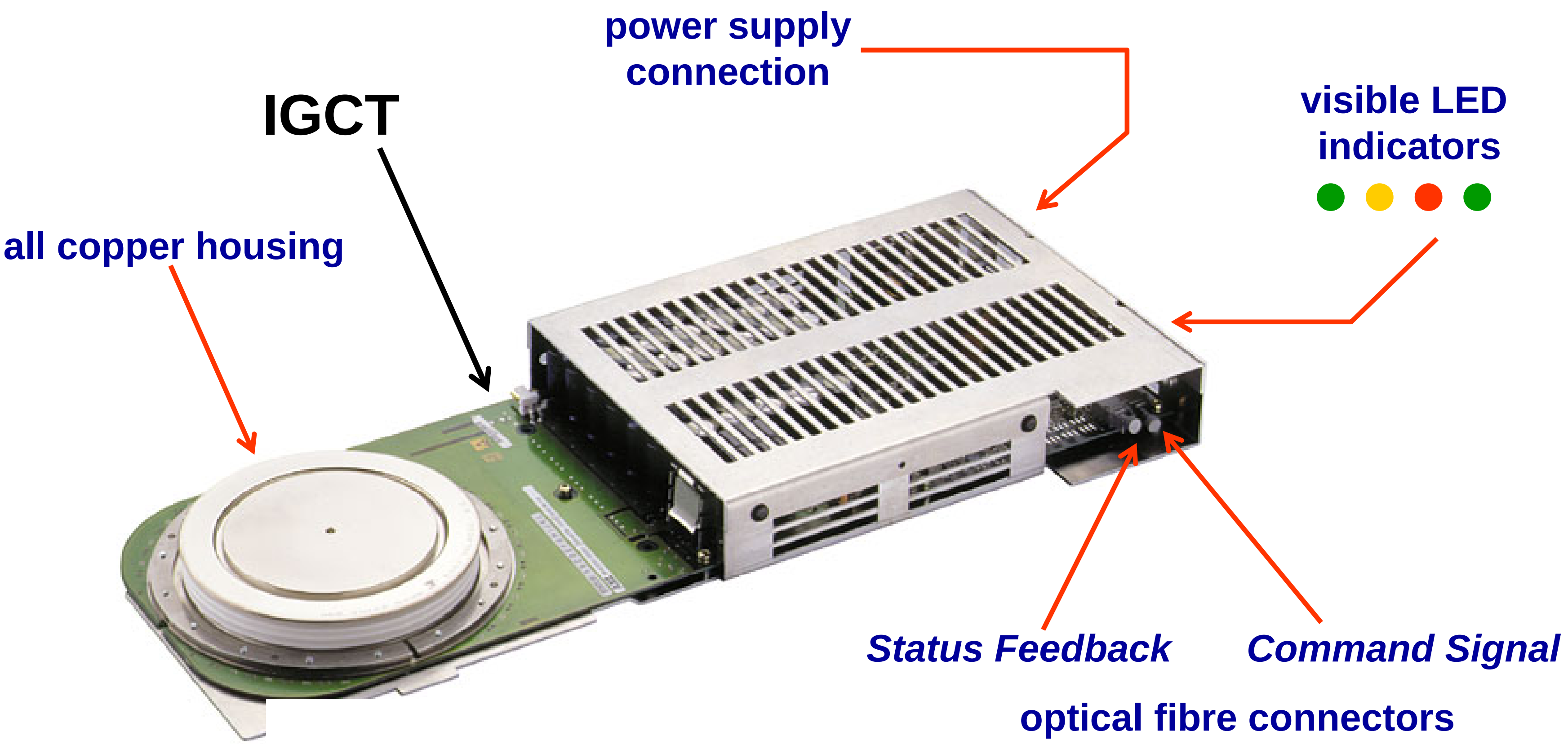
=1.5 µs • 3000V • 1900 A /2 = 4.3 Ws

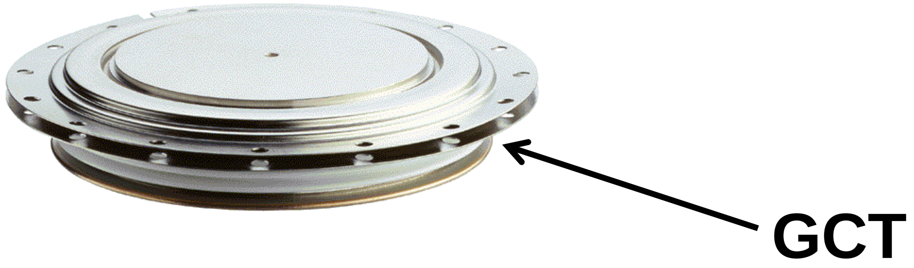
Adjustment of dv/dt by lifetime control



Low inductance housing

4 kA/4.5 kV IGCTs

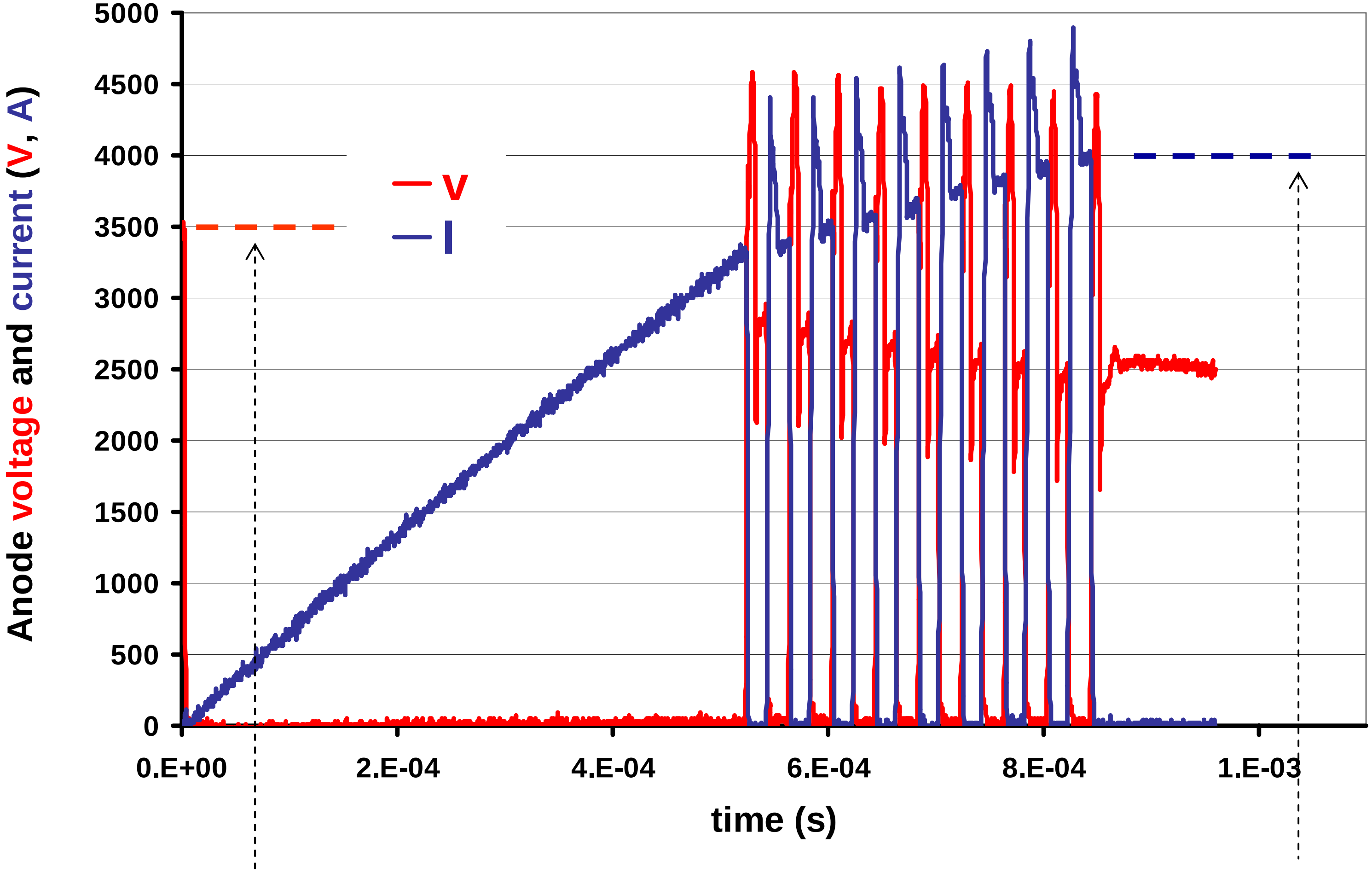




30 MW IGCT Power Management

15 + 15 MW 3-Level Back-to-Back Converter
for three-phase to single-phase conversion ***Converter efficiency = 99.2%***

4 kA/4.5 kV IGCT at 25 kHz in burst mode



$V_{DC\ start}$ = 3.5 kV

$T_{J\ start}$ = 25 °C

$V_{DM\ peak}$ = 4.5 kV

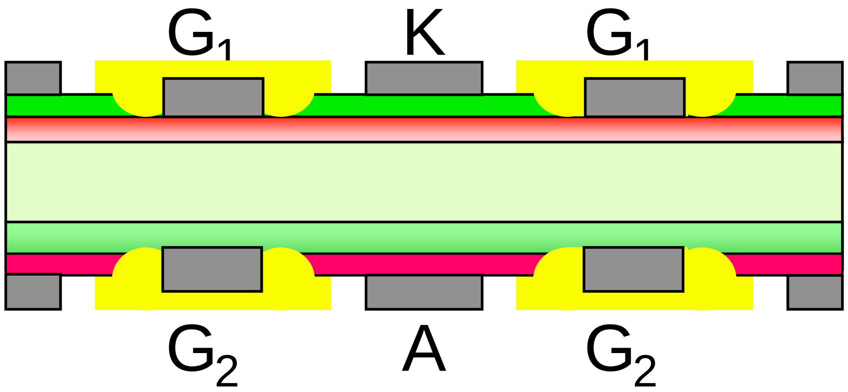
α = 0.5

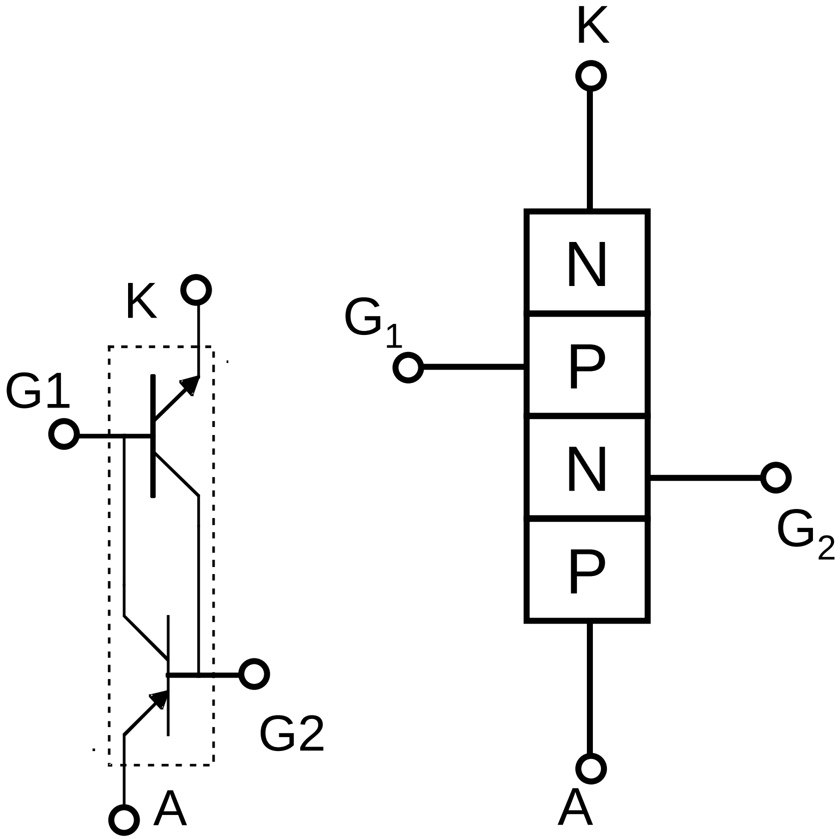
$I_{TGQ\ peak}$ = 4 kA

IGCT Outlook

IGDT

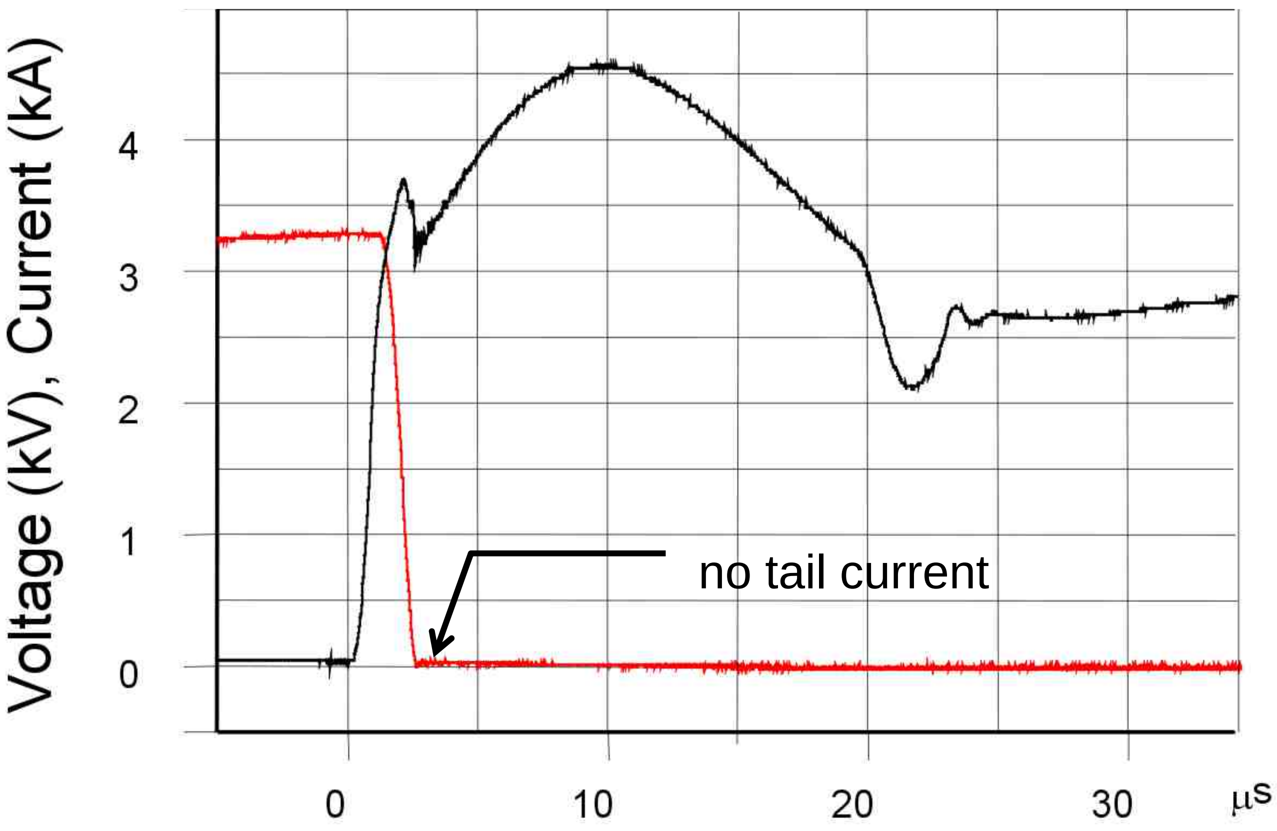
Structure of IGDT – Integrated Gate Dual Transistor





Dual Gate Turn-off Thyristor

91 mm 4.5 kV IGDT turn-off



Dual-gate IGCT @ 85°C - gates triggered simultaneously

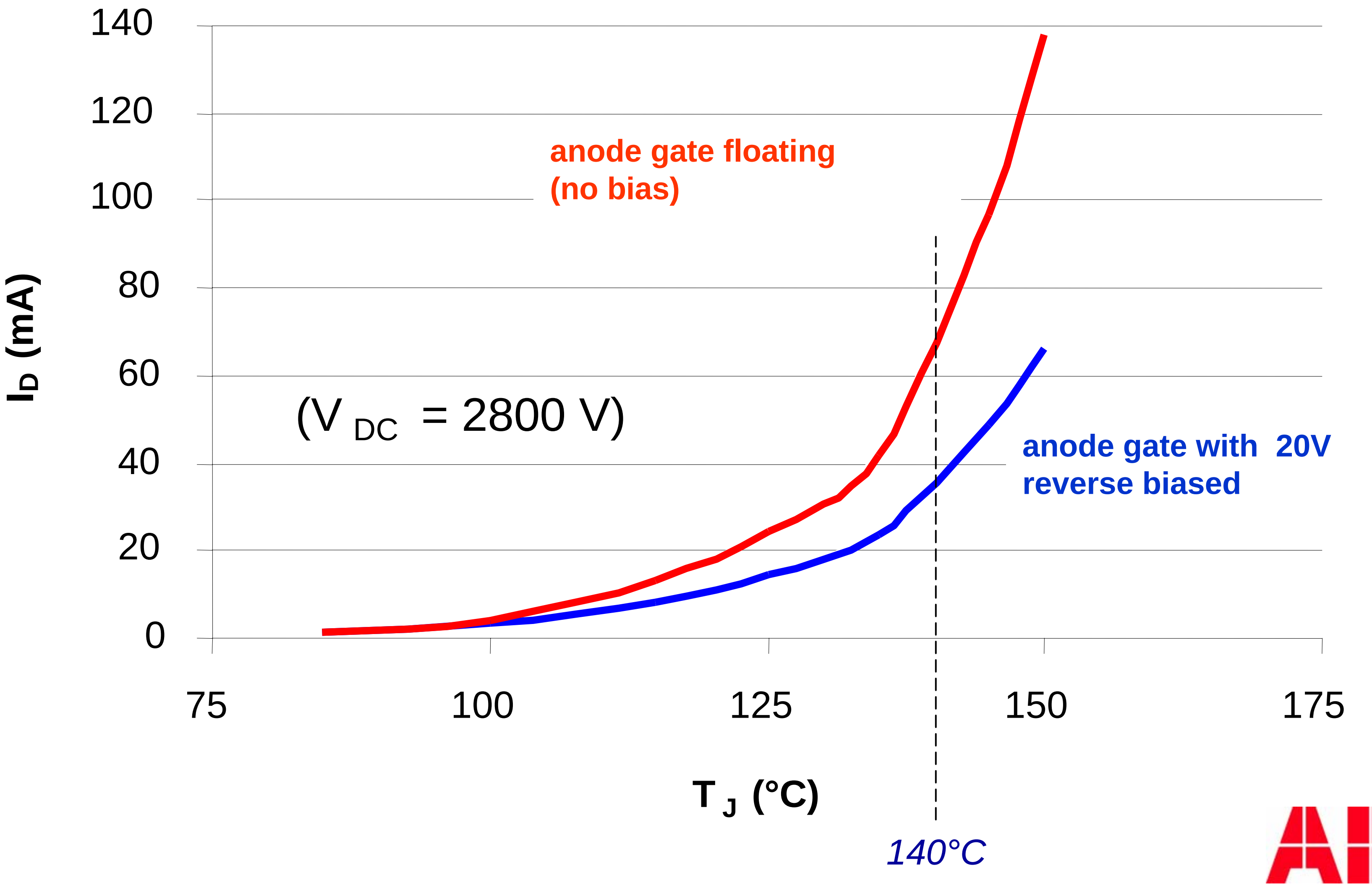
V_{DC} = 2.8 kV

I_{TGQ} = 3.3 kA

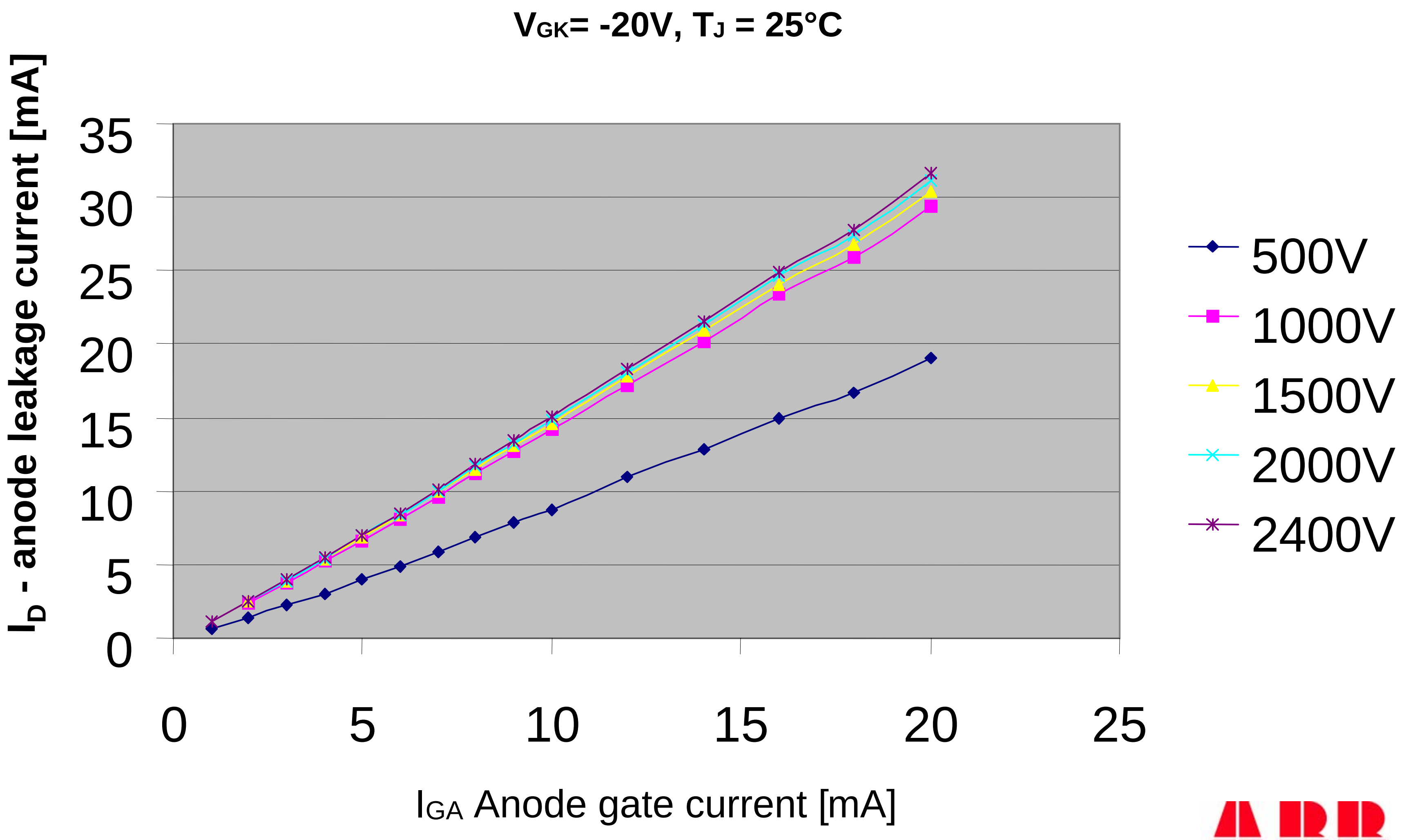
V_{DRM} = 4.5 kV

V_{TM} = 2.1 V @ 4 kA/125°C

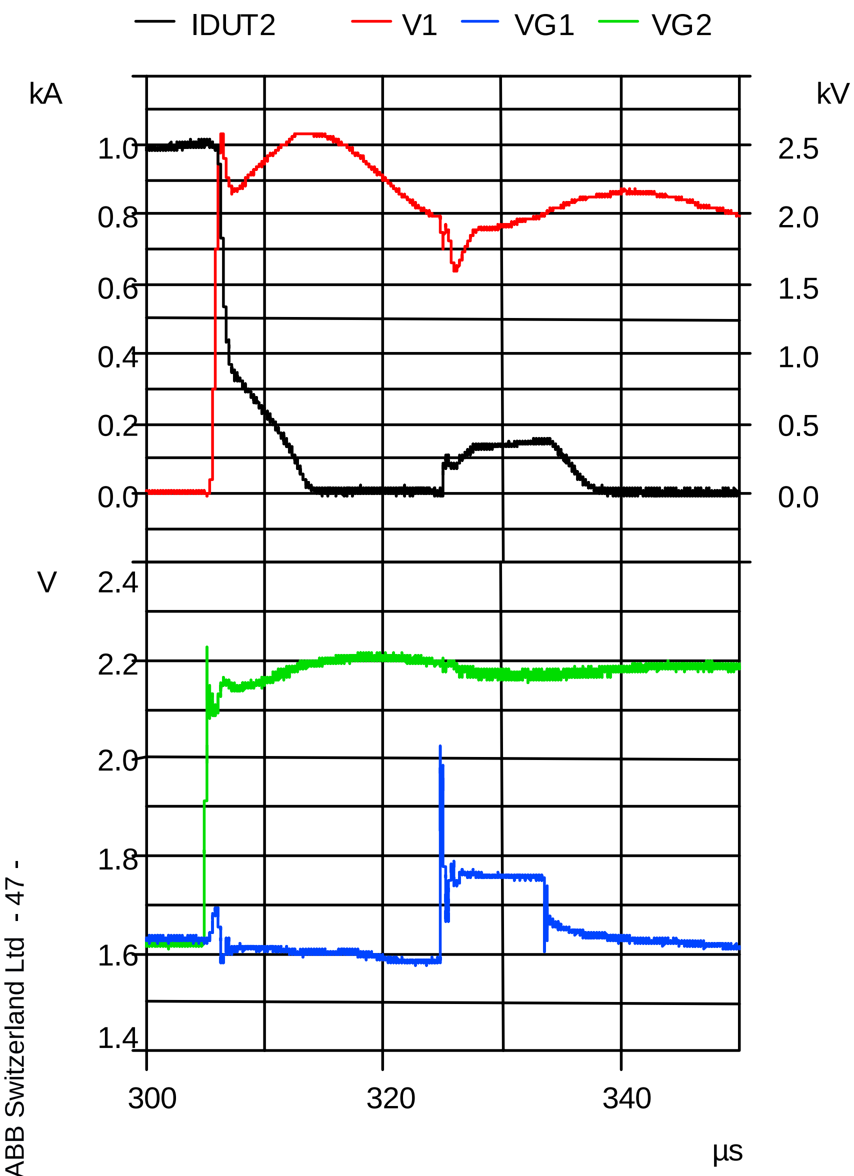
IGDT Series connection: leakage current reduction

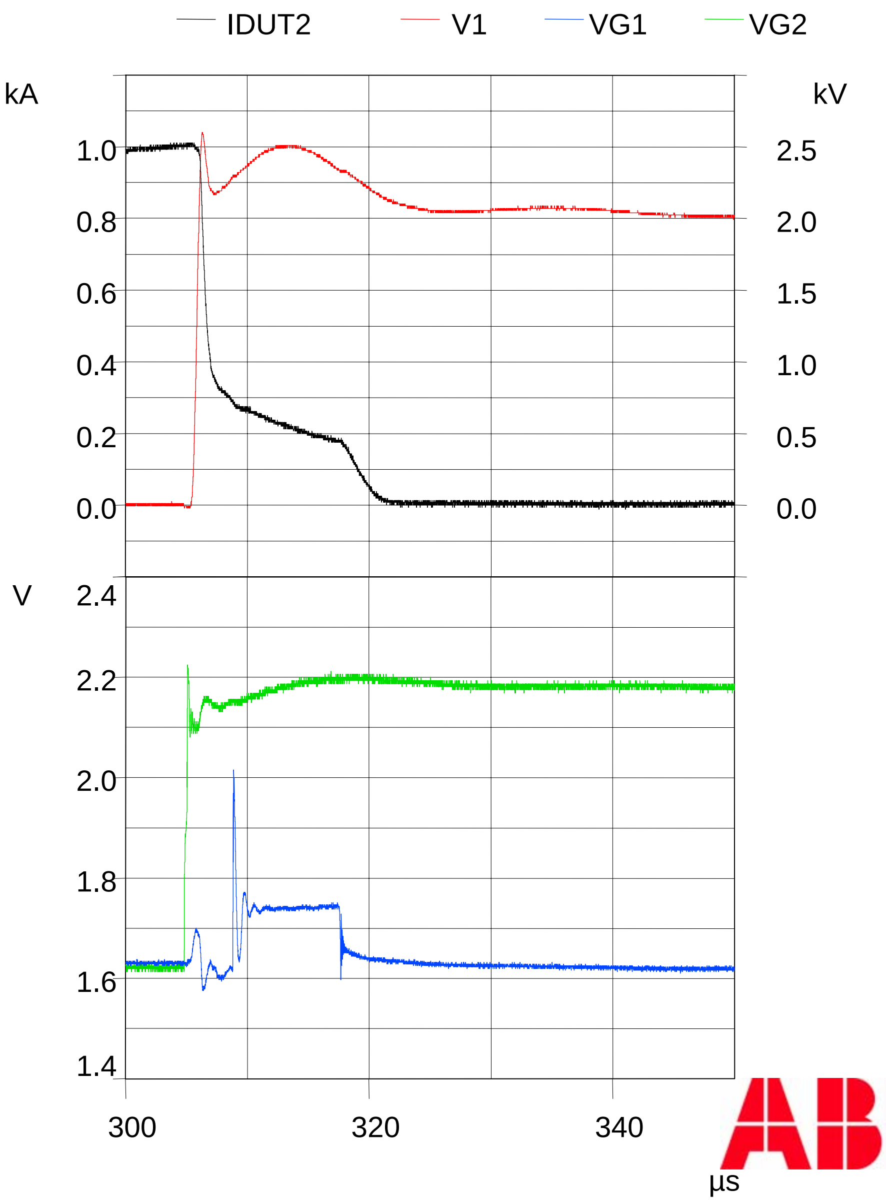


91 mm 4.5 kV IGDT - *Leakage current control*



IGDT anode gate control of tail current





Increased SOA

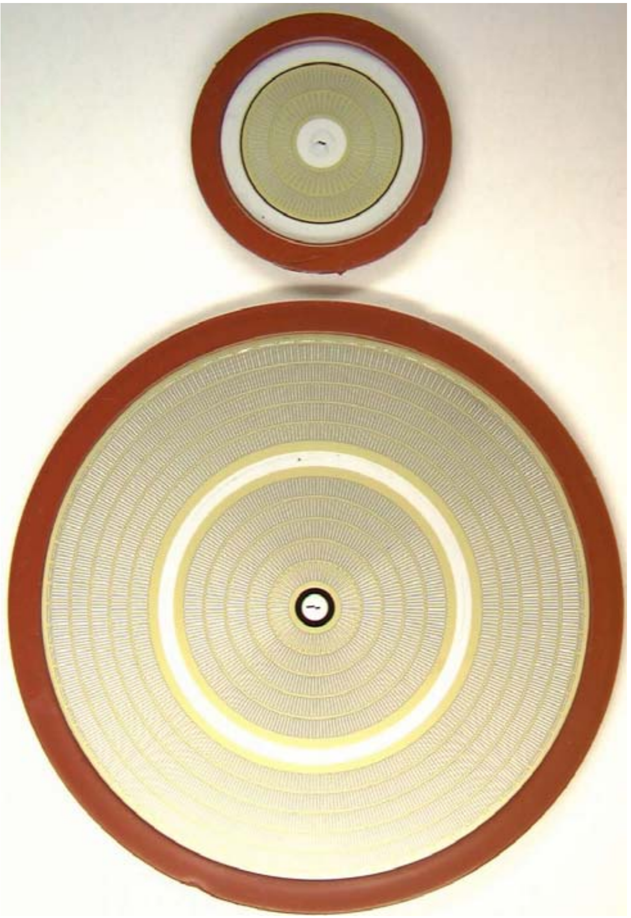
IGCT SOA improvement at 4.5 kV

TODAY

250 kW/cm^2

250 kW/cm^2

38 mm reverse conducting



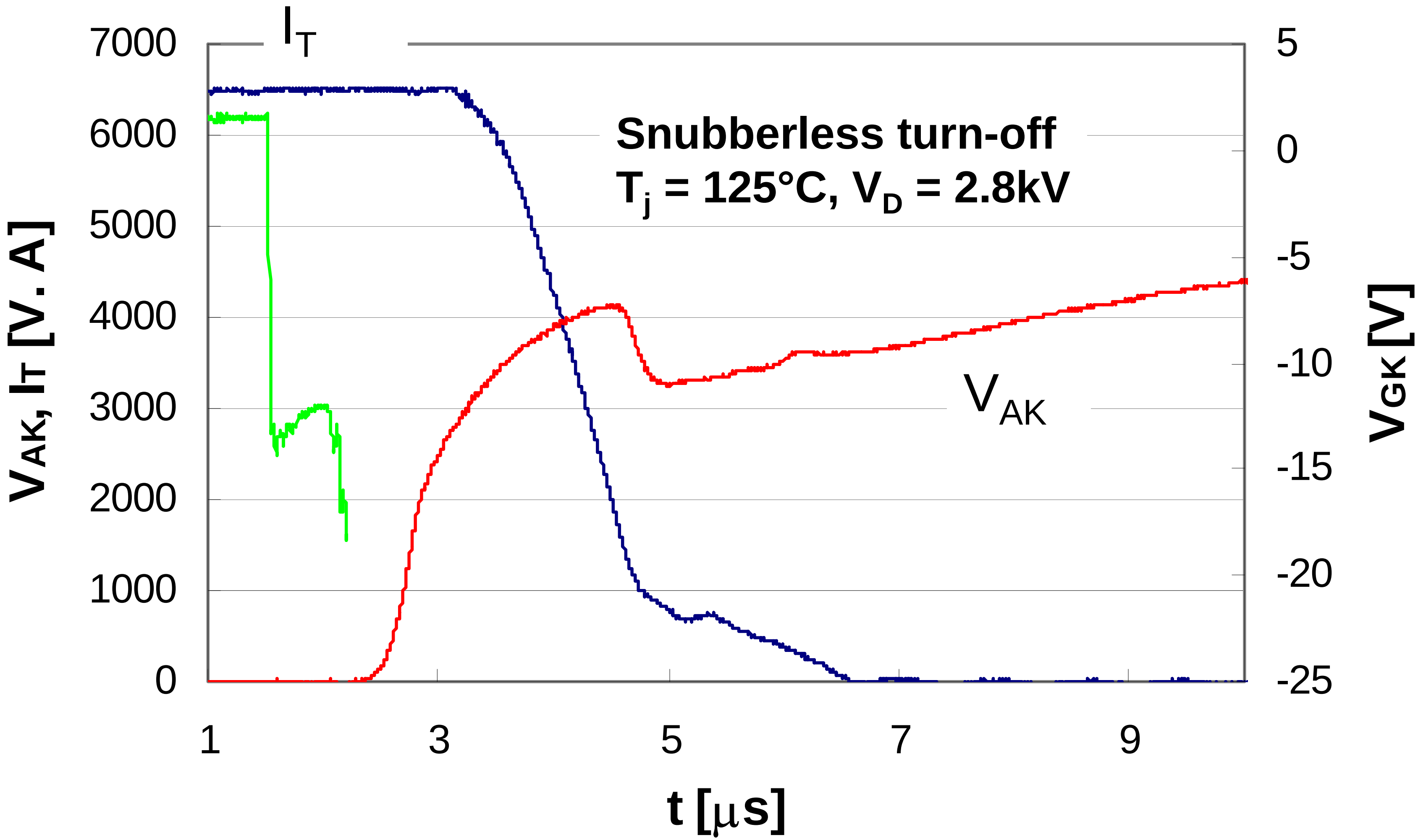
91 mm asymmetric

TOMORROW

1000 kW/cm^2

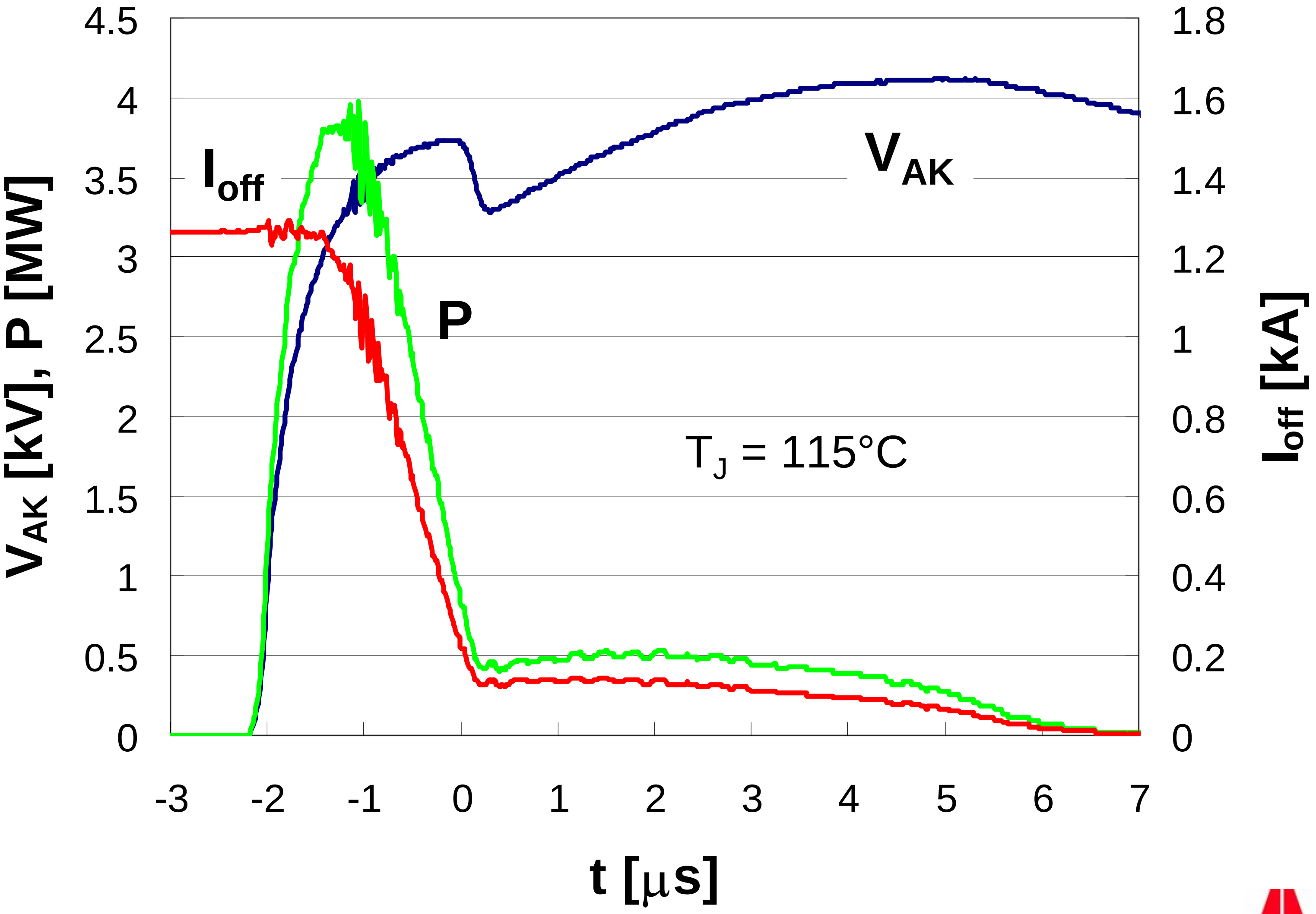
400 kW/cm^2

6.5 kA @ 2.8 kV_{DC} on 91 mm wafer



Developmental **4” 4.5 kV IGCT with improved GU and silicon design allowing 50% SOA improvement**

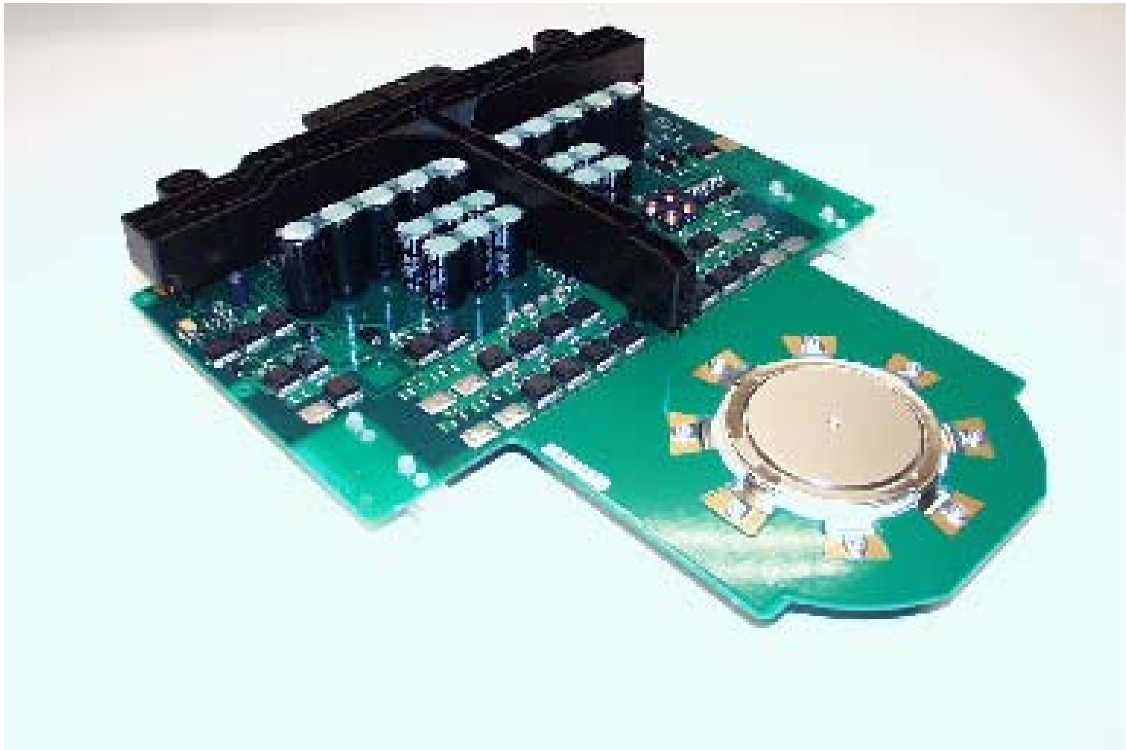
1.3 kA @ 2.8 kV$_{DC}$ on 38 mm RC wafer



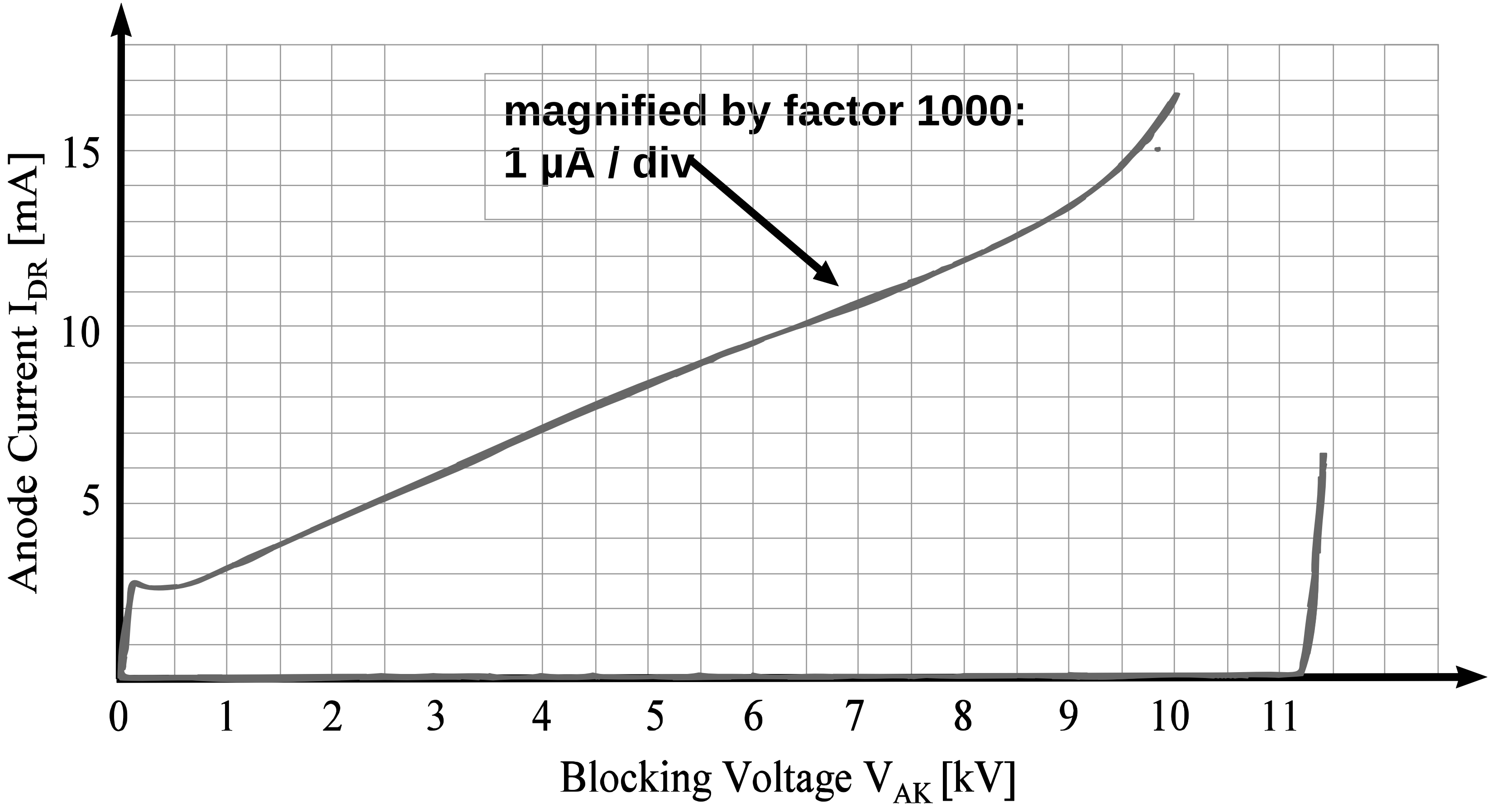
Developmental **2” 4.5 kV RC_IGCT with improved GU and silicon design allowing 300% SOA improvement**

10 kV IGCT

Engineering Sample of 68 mm 10 kV IGCT

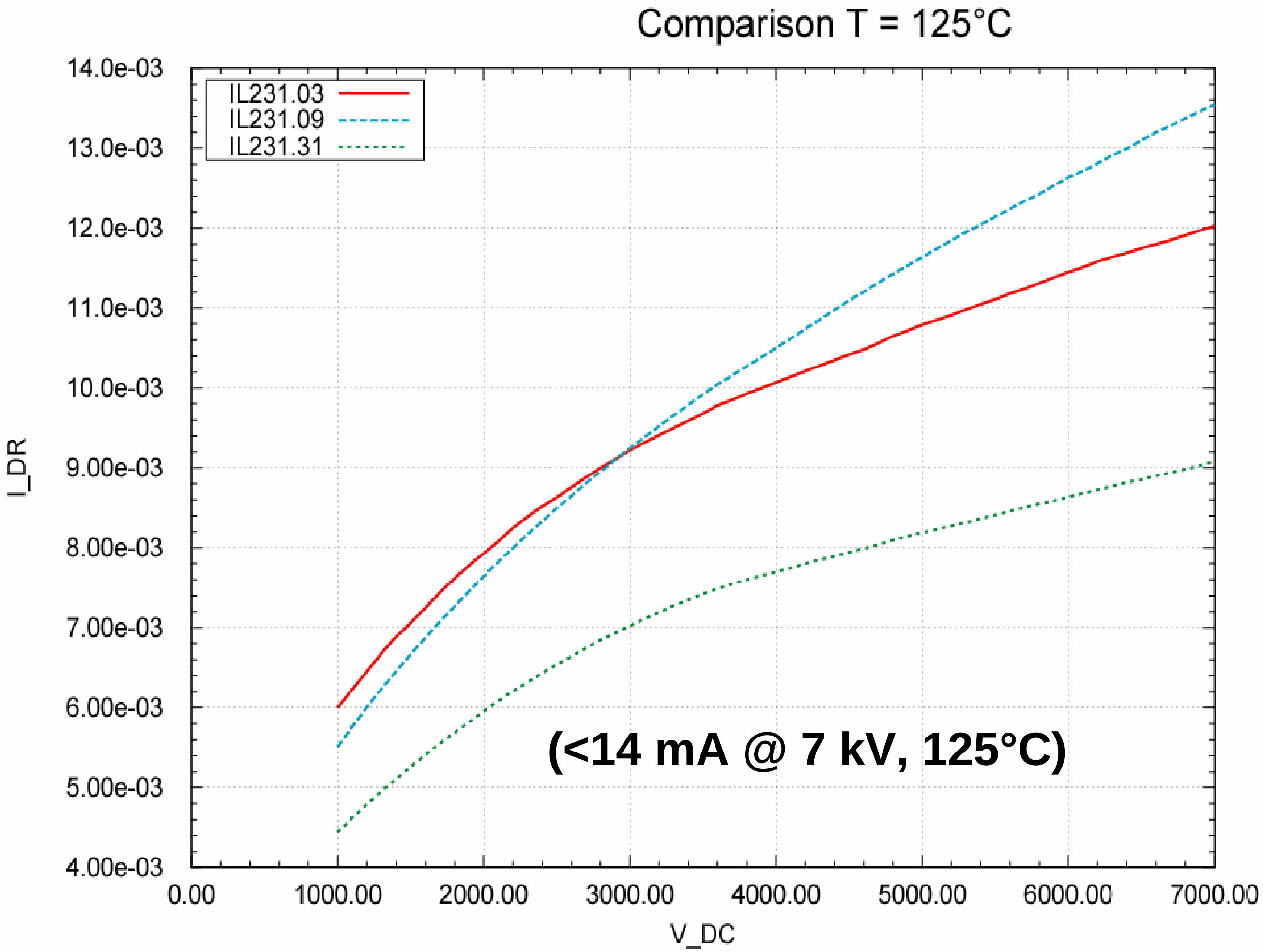


Forward Blocking Characteristics at 25°C



(<17 µA @ 10 kV, 25°C)

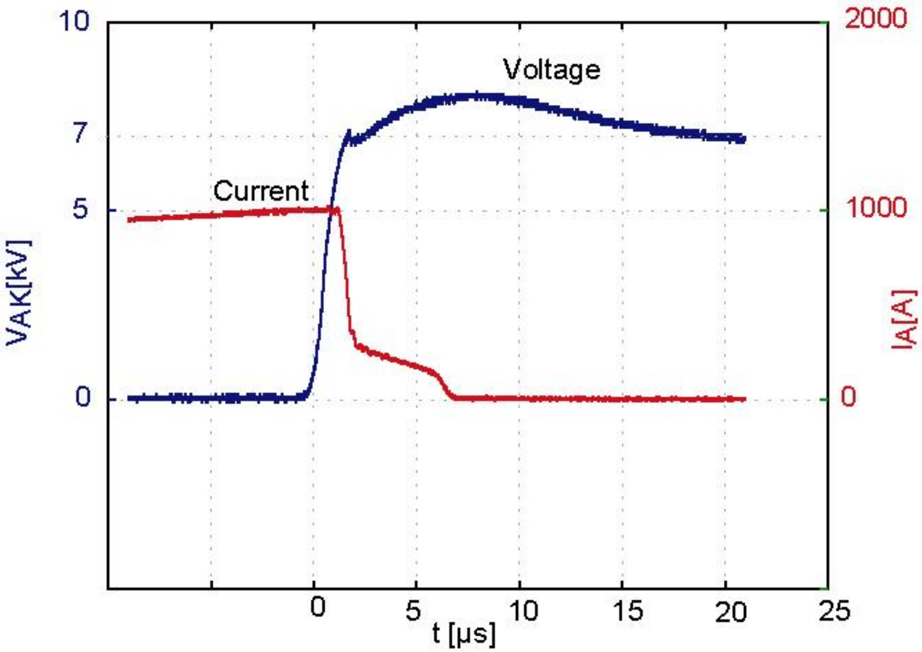
Forward Blocking Characteristics at 125°C

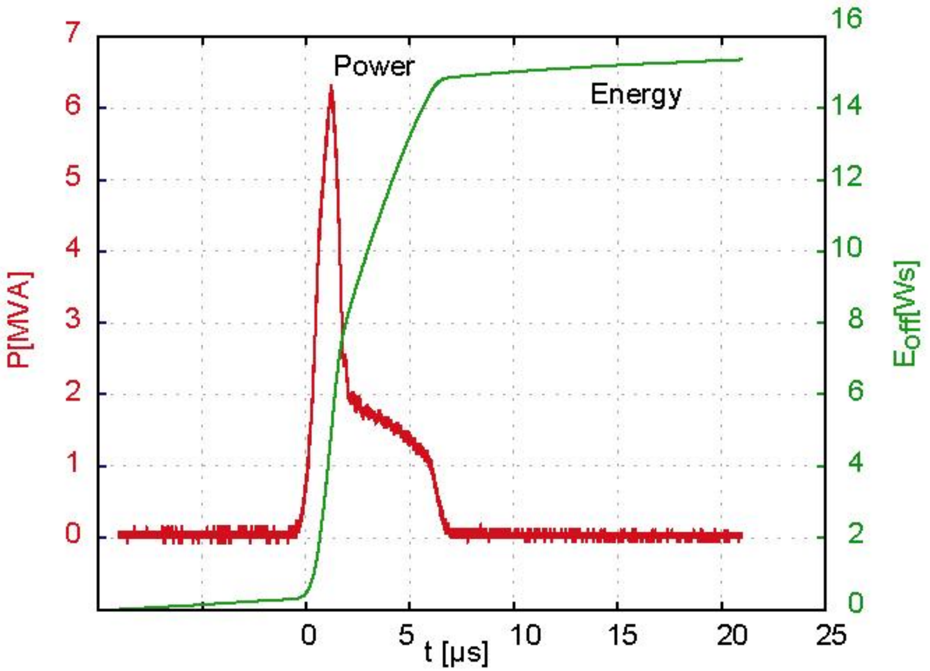


(<14 mA @ 7 kV, 125°C)

(8-13 mA @ 6 kV, 125°C, P_L=50W-80W (5%-10% of P_{RP})

Turn-off Waveforms (SOA)





Operating conditions:

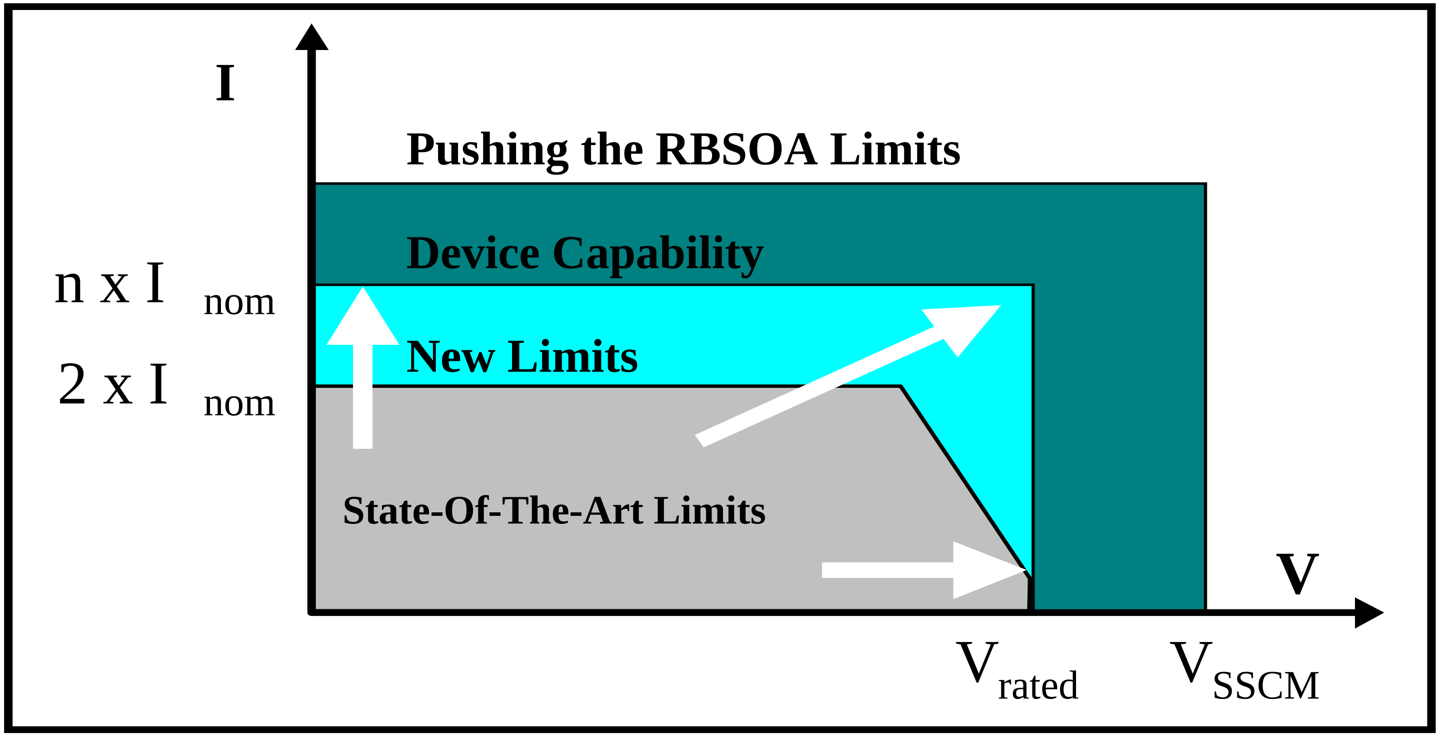
V_{DC}= 7kV, I_A = 1000A, T_j = 85°C

Switching characteristics:

E_{off} = 14.8 J, $V_{AK,max}$ = 8 kV, t_{off} = 8µs, t_f = 1µs, t_{tail} = 5µs, 250 kW/cm²

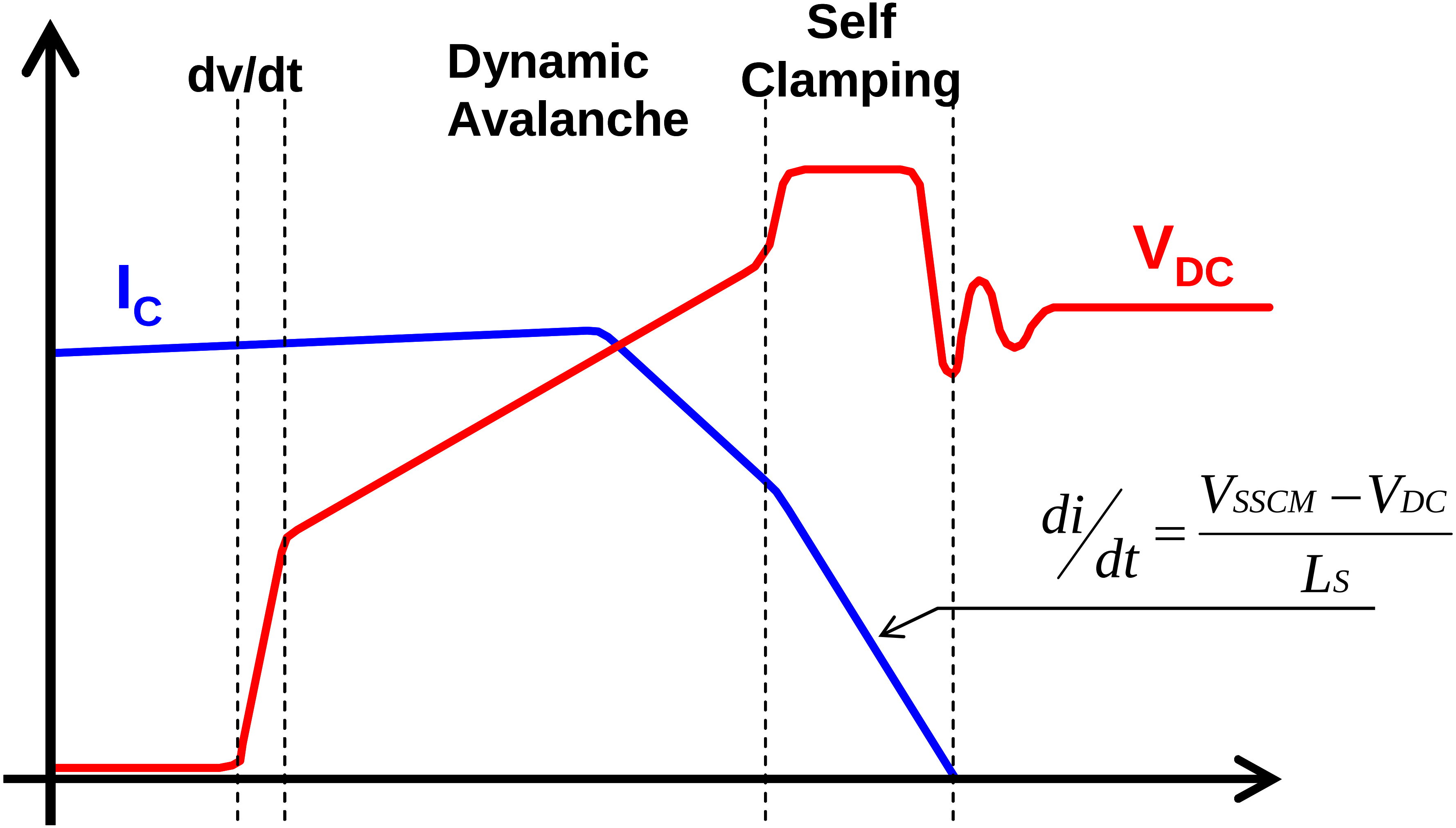
Conclusions

SOA Limits of HV Devices are increasing



- Under RBSOA operational conditions
  - Devices withstands dynamic avalanche mode
  - IGBTs withstands “SSCM” mode
  - Devices achieve the ultimate square SOA behaviour

Switching-Self-Clamping-Mode “SSCM”



$$\frac{di}{dt} = \frac{V_{SSCM} - V_{DC}}{L_S}$$

- IGBT SOA turn-off waveforms including SSCM
  - devices start to limit voltage during turn-off
  - over-voltage safely reaches the static breakdown after turn-off

- For high power conversion, only two devices possible today:
  - **IGBT**
  - **IGCT**

- Safe Operating Area is increasing from 250 kW/cm^2 to 1 MW/cm^2

- IGDT offers possibility of high voltage devices with low losses (future?)

Challenges

Challenges for HV Power ToDs

- **High voltage devices present following challenges:**
  - **Dynamic Avalanche ruggedness (for reliable operation)**
  - **Short Circuit Failure Modes (IGBT) and fault interruption (IGCT)**
  - **Design Trade-off between Losses and SOA**
  - **Critical Punch-Through voltages (for controllable voltage, low EMI)**
  - **High DC link voltage (leakage stability, cosmic ray withstand)**
  - **Large inductance and overshoot voltages in HV power systems**
  - **High frequency (limited by losses, T_J)**

Challenges for this decade

- **10 kV switches with 1 kHz snubberless operation**

  (for the 6.9 kV_{RMS} MV line for drives and power conditioners)

- **Snubberless series operation**

  (static and dynamic for MV lines > 6.9 kV_{RMS})

- **Power supply free operation**

  (autogenous power supply for series connection)

- **System cost-reduction**

  (e.g. pay-back times $\approx$ 1 year for MV Drives)

- **Reduced thermal resistance and increased T_J**

- **Reduced losses?**