BEAM QUALITY OF PULSED HIGH POWER CO2-LASERS

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Development Amplification Chain

EUV Litho 2018 Source Workshop, 06.11.2018

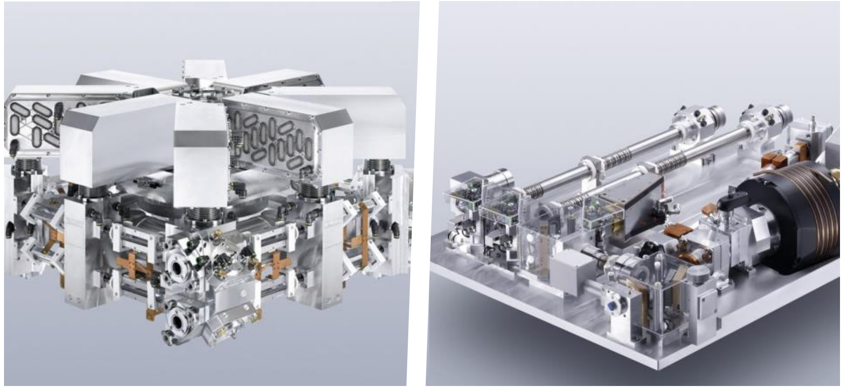
TRUMPF

World market leader in laser technology for material processing

Core competencies
- Laser technology
- Laser cutting and welding of sheet metal

13,420 employees

TRUMPF: Laser Technology business division



CO_2 and disk lasers

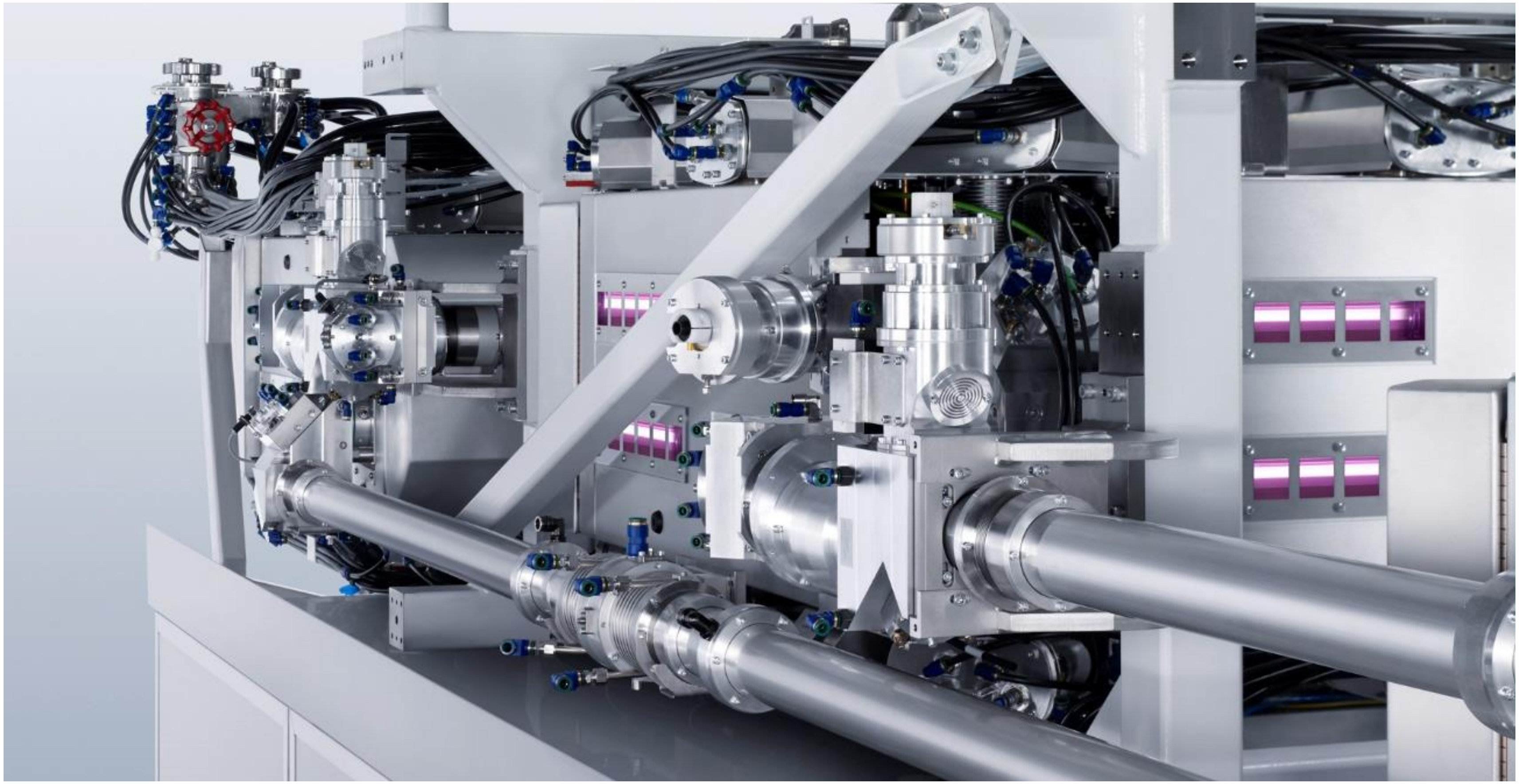
Laser systems

Laser marking systems

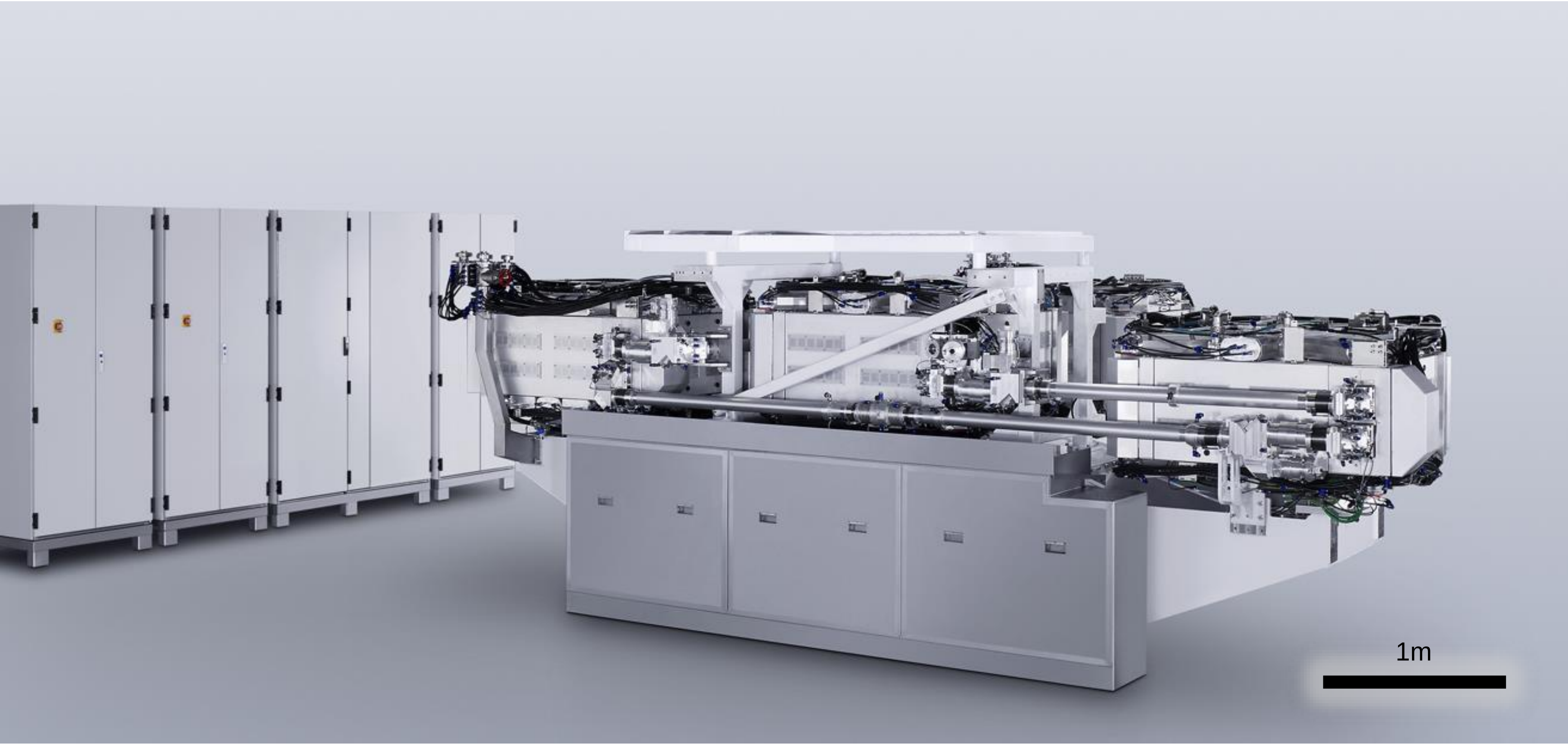
RF generators for industrial applications

TRUMPF Lasersystems for Semiconductor Manufacturing

Lasersystems for EUV lithography

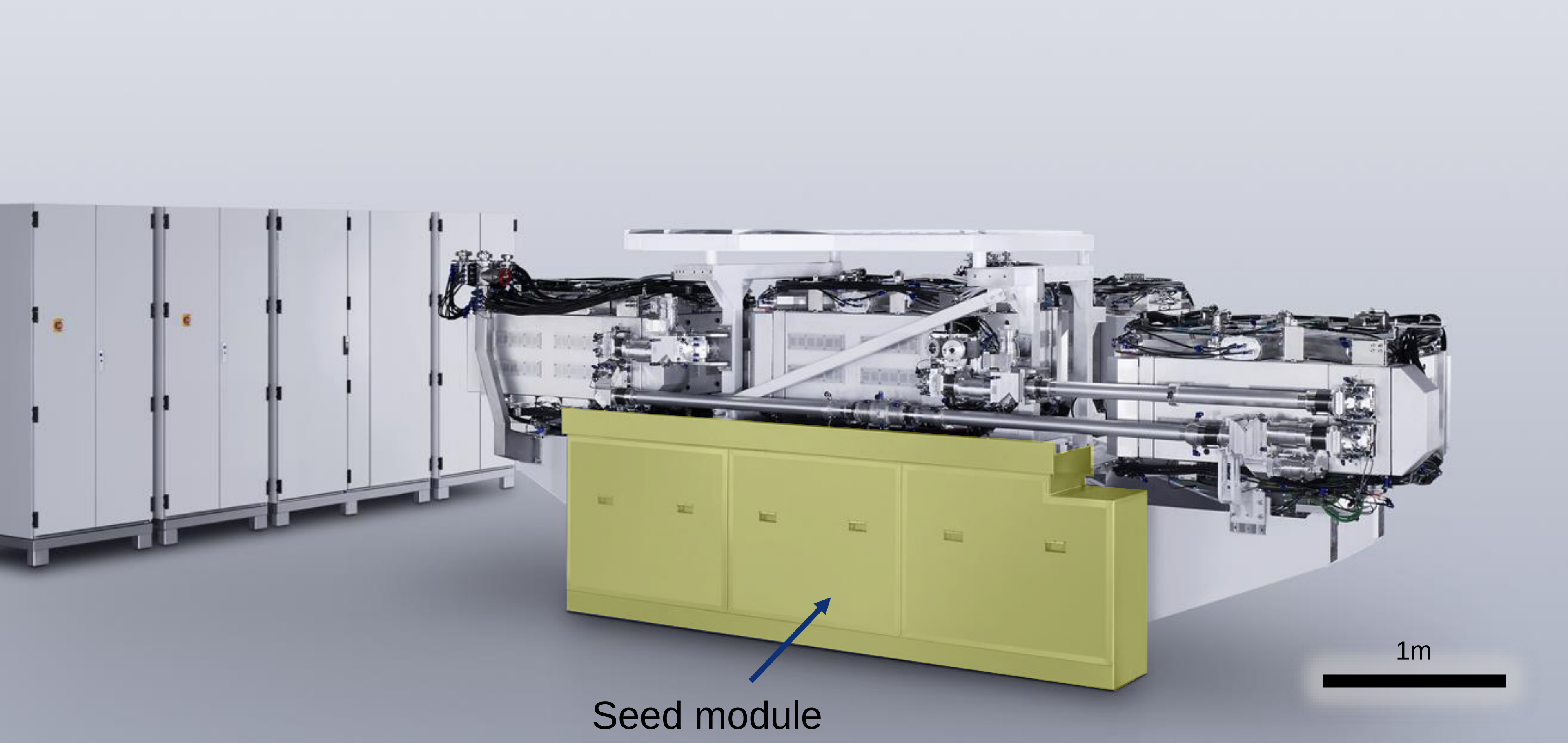


TRUMPF Laser Amplifier



TRUMPF Laser Amplifier

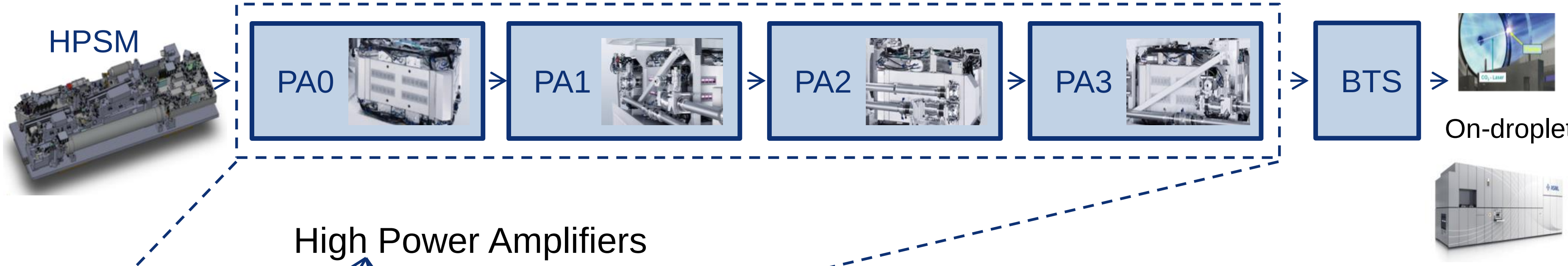
Seed module delivers high beam quality, low-power beam at 50 kHz

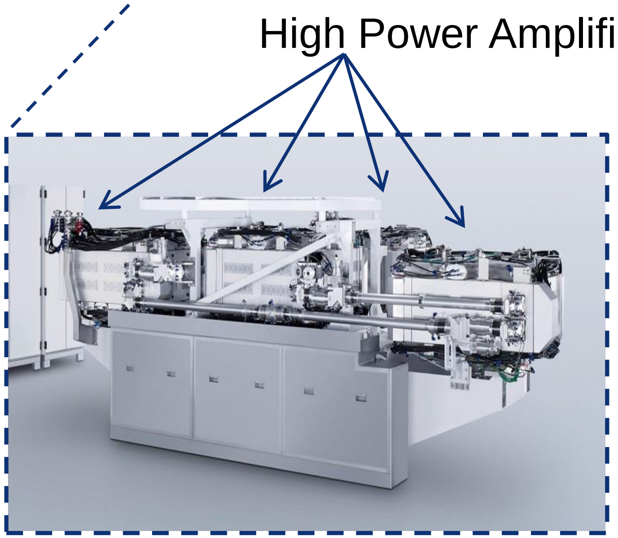


TRUMPF Laser Amplifier

TRUMPF Laser Amplifier

Combination of Several Amplifier Stages

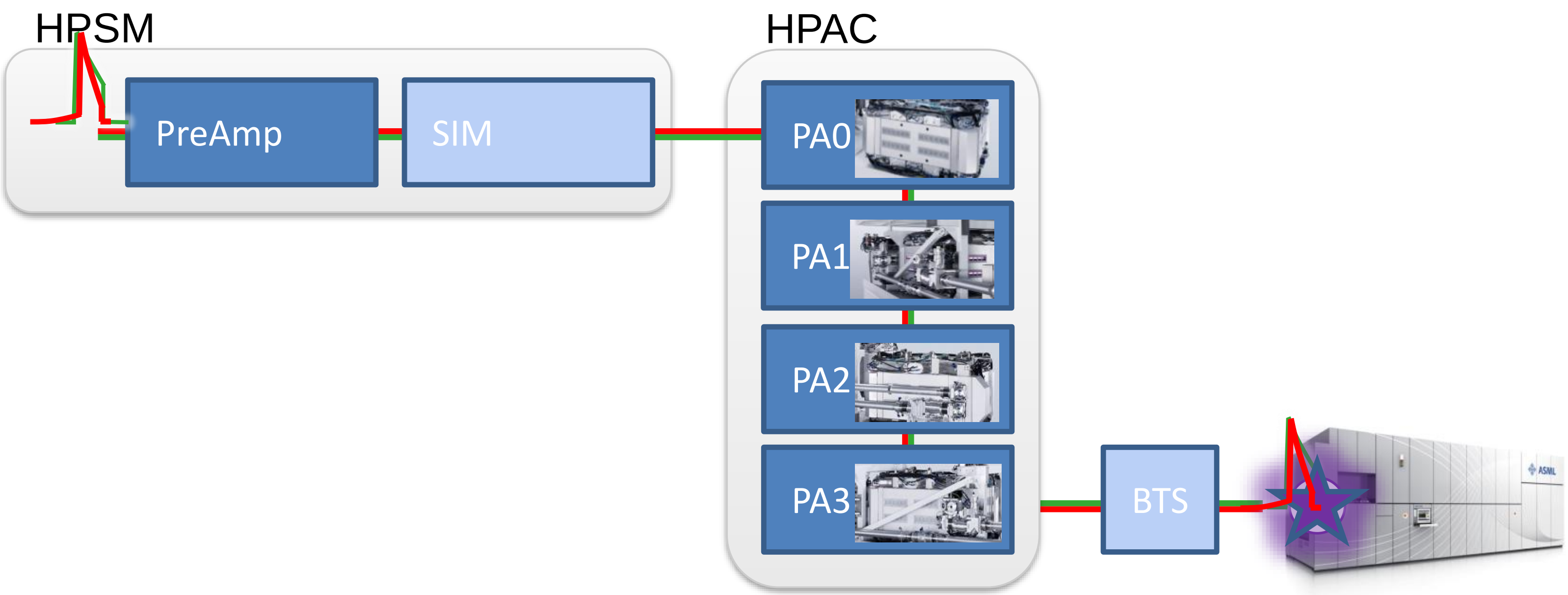




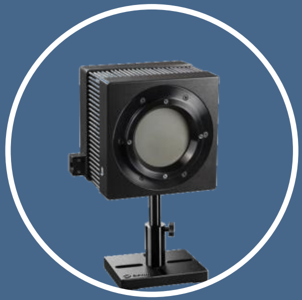
- 4 cascaded power amplifiers (PAs) in HPAC
- Individually optimized geometry and settings
- Connected by relay optics
- Extensive metrology between amplifiers & at DL exit

TRUMPF Laser Amplifier

A seed-isolation module protects the seed module from backreflections



Relevant parameters of pulsed lasers for EUV generation



Large average power

Relevant parameters of pulsed lasers for EUV generation

Challenge: How do we gain more power with current system?

Improved cooling?

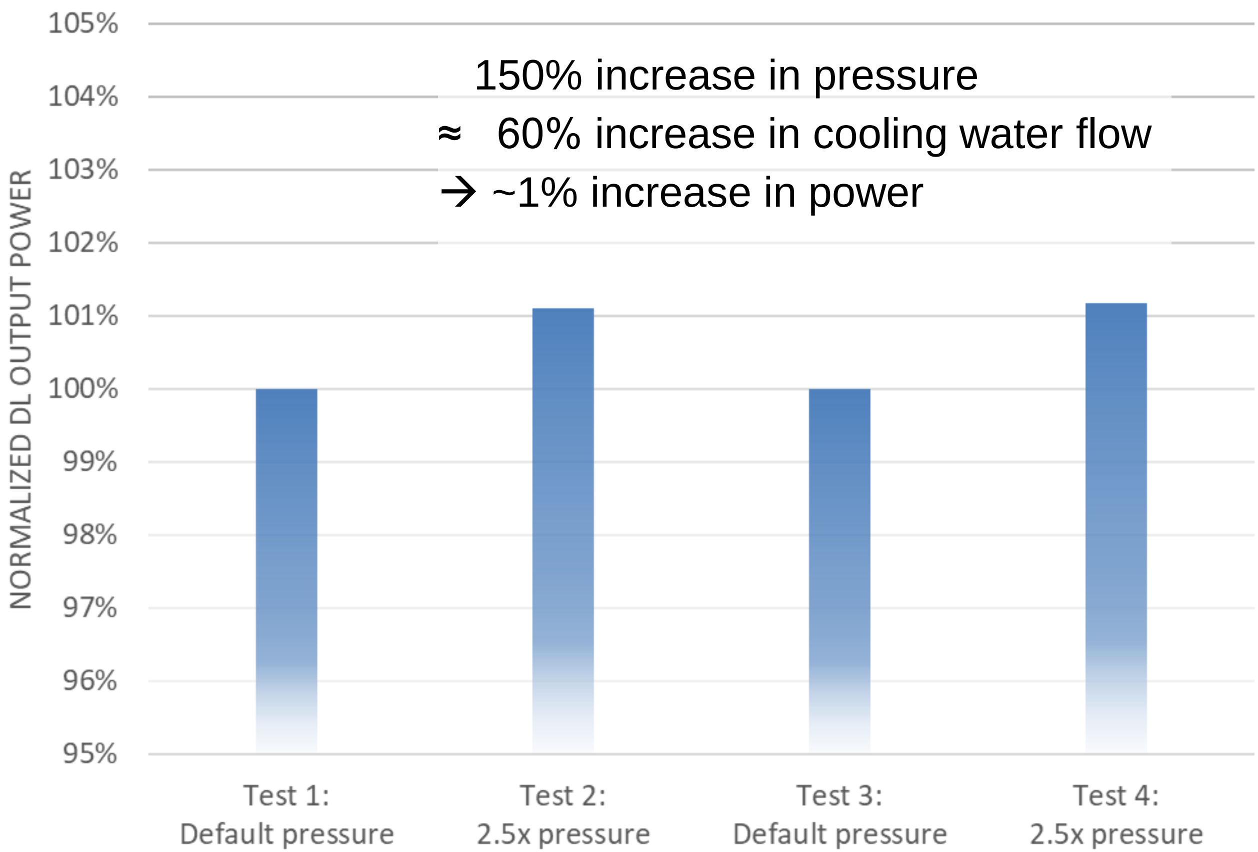
Optimized gas mixtures?

Better beam caustic matching?

Power amplifier optimization

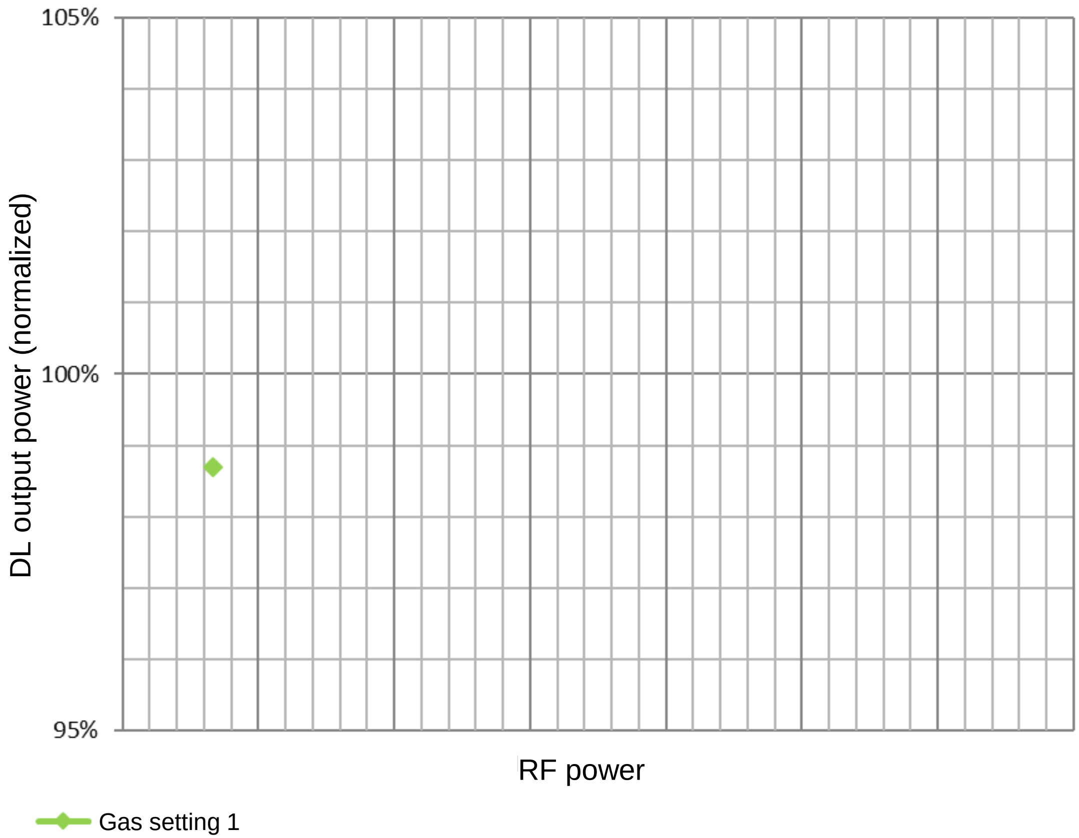
Lever on power via increased cooling water flow is low

Improved cooling?



Power amplifier optimization

Gas mix optimized for each amplifier stage individually



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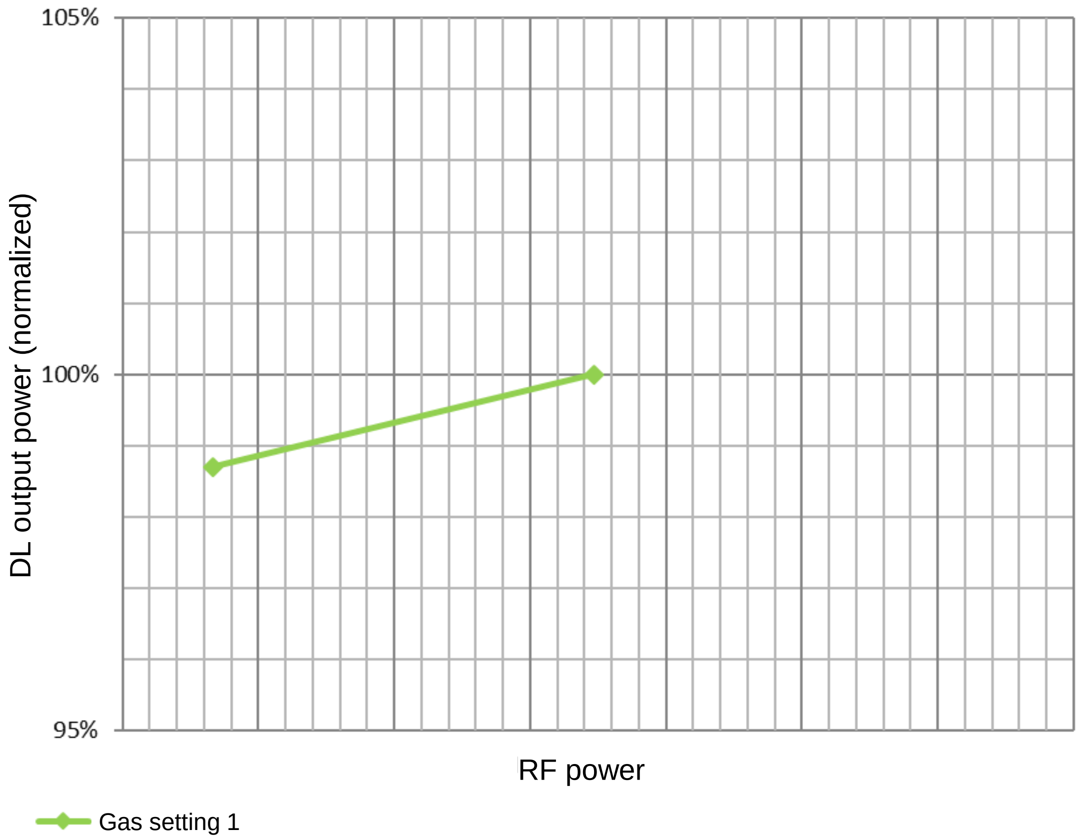

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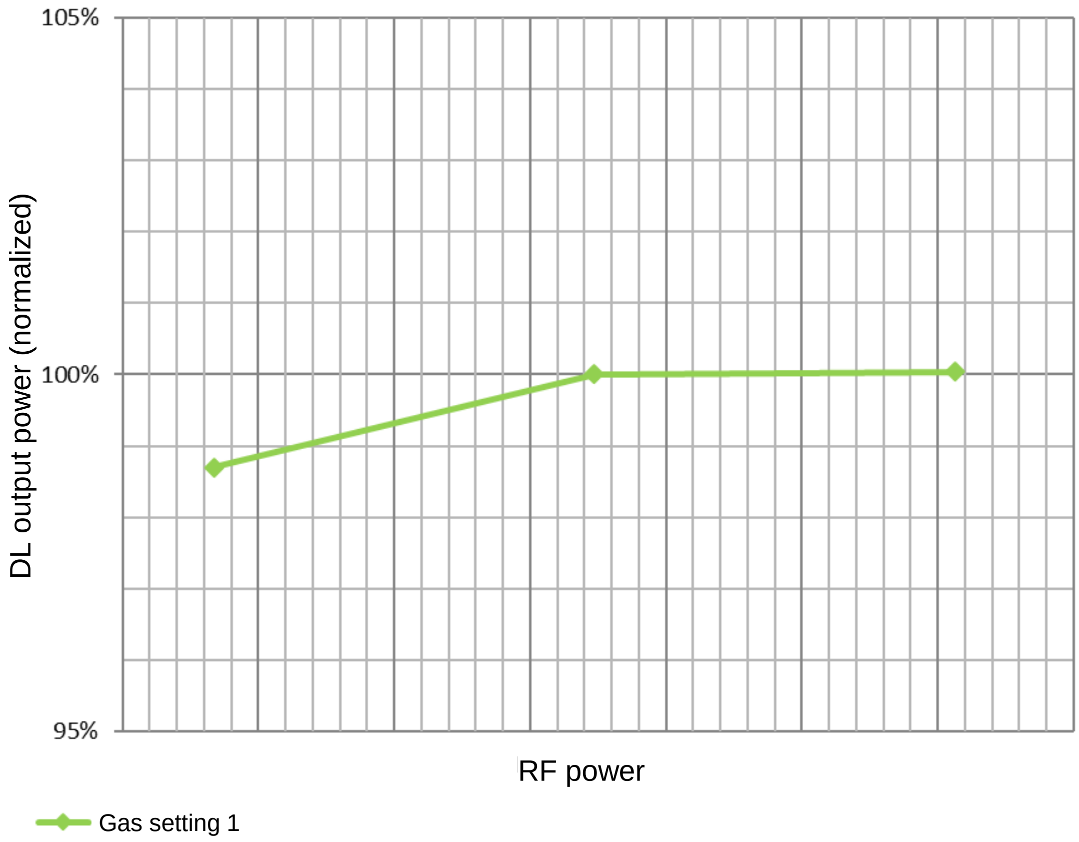

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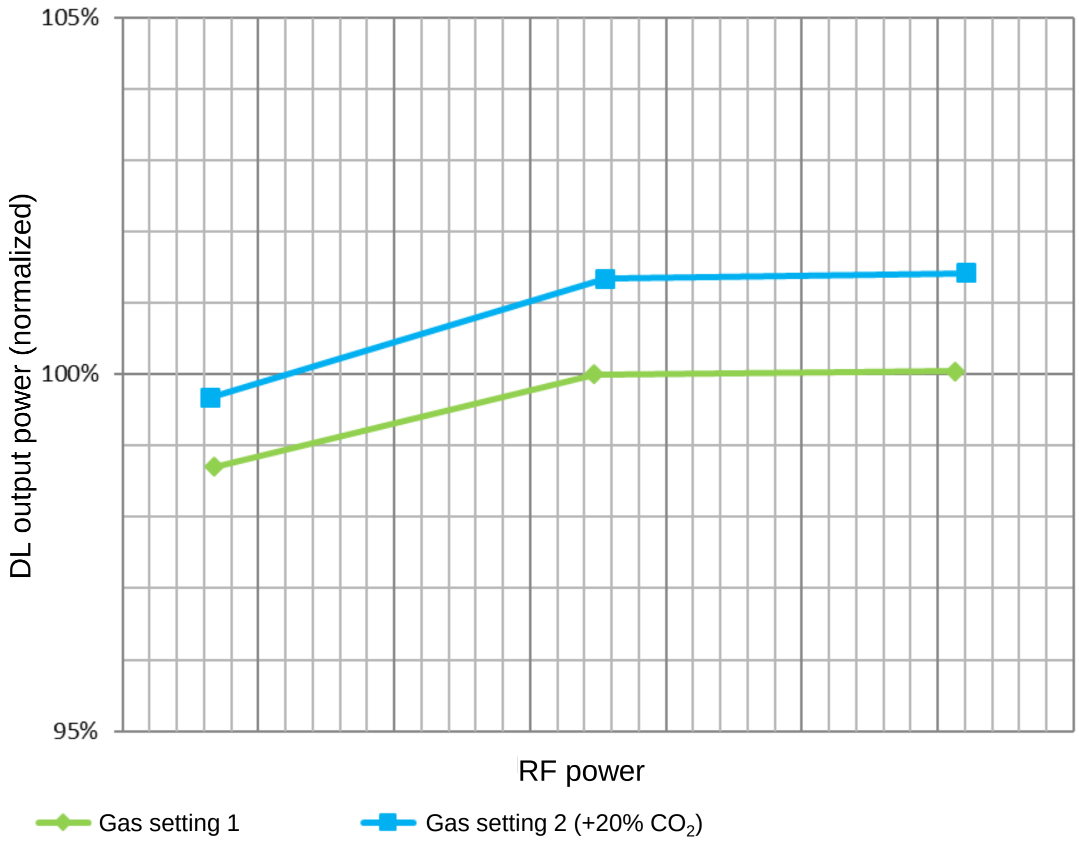

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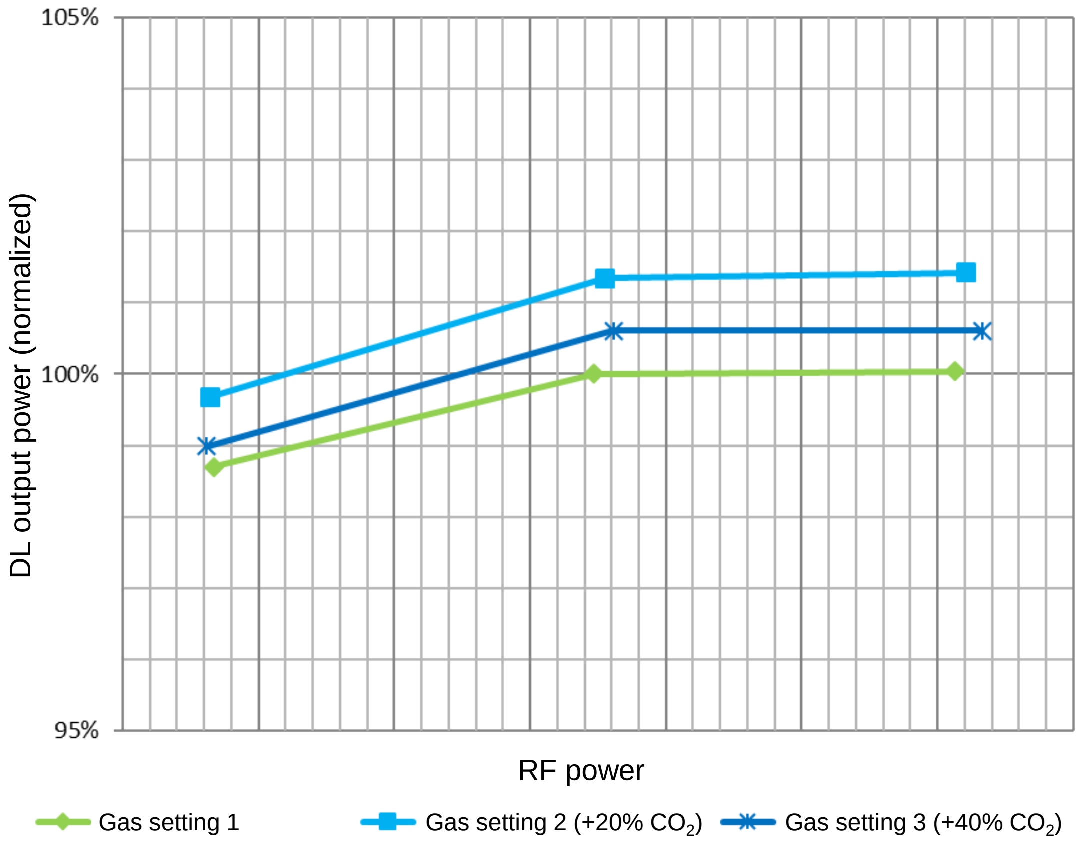

Power amplifier optimization

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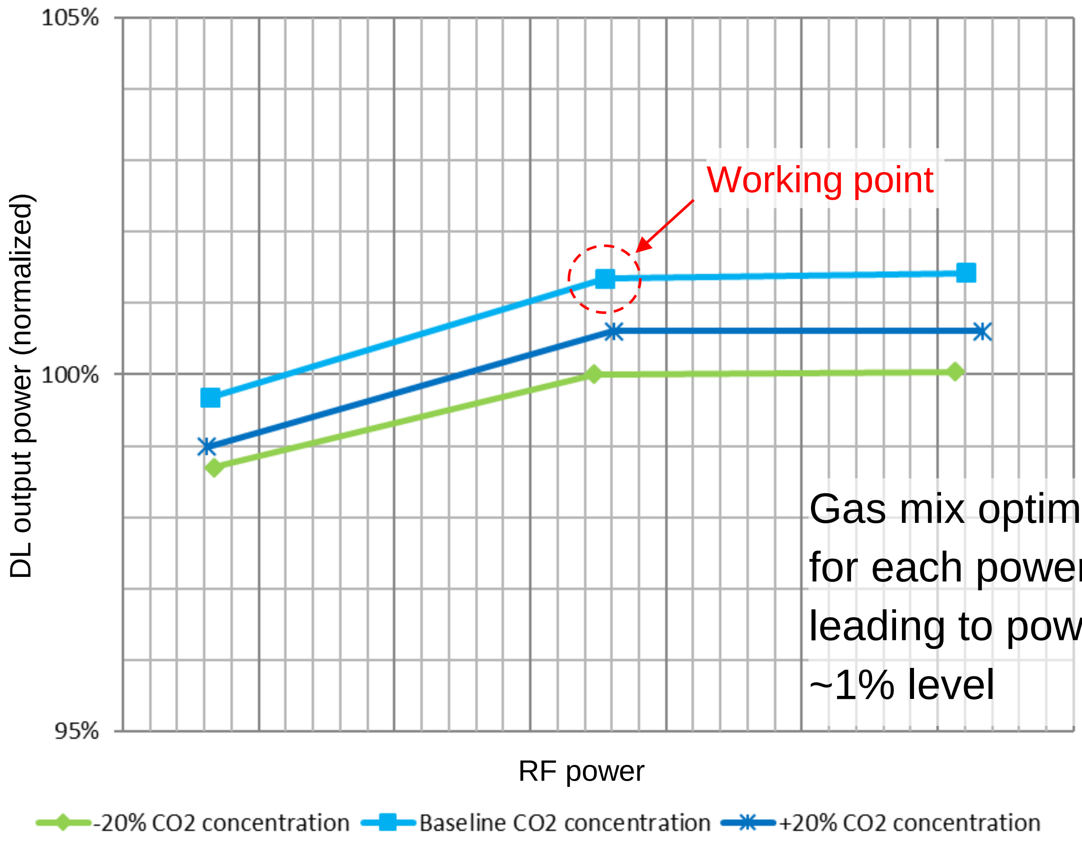


Gas mix optimizations are carried out for each power amplifier individually, leading to power improvements on ~1% level

Power amplifier optimization

Optimizing beam input parameters into HPAC

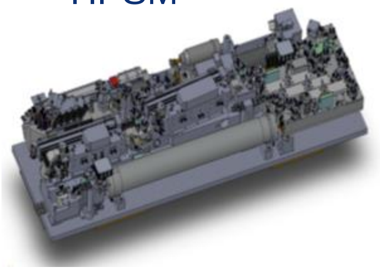
Better beam caustic matching?

Power amplifier optimization

Optimizing beam input parameters into HPAC

Better beam caustic matching?

HPSM



PA0

→

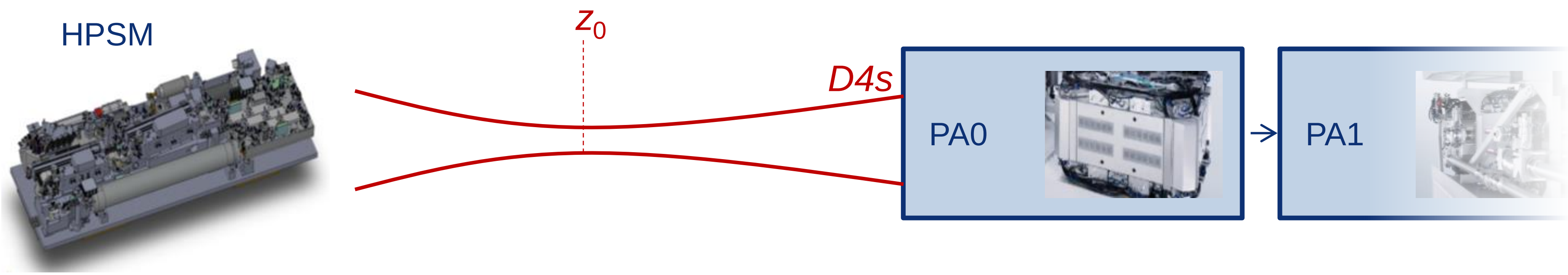
PA1

Better beam caustic matching?

TRUMPF

Power amplifier optimization

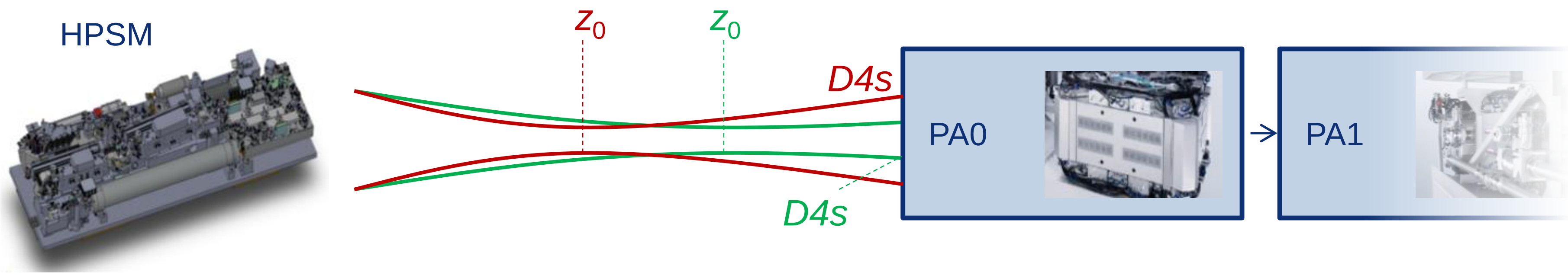
Optimizing beam input parameters into HPAC



Better beam
caustic matching?

Power amplifier optimization

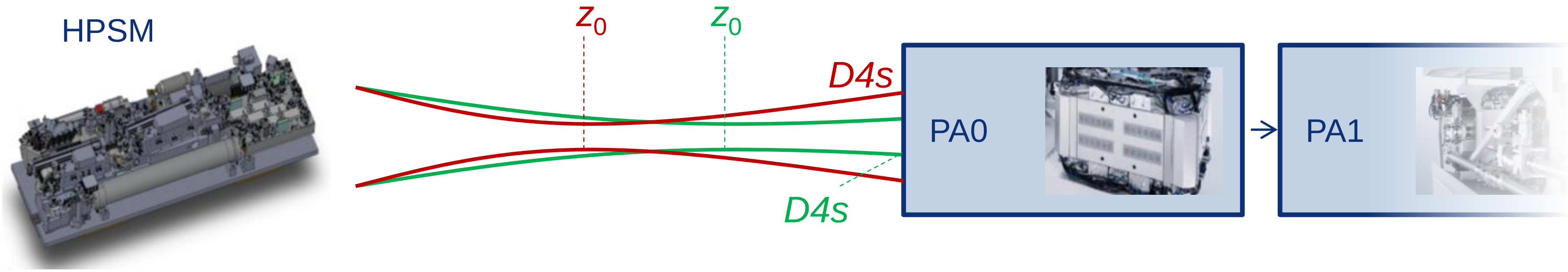
Optimizing beam input parameters into HPAC

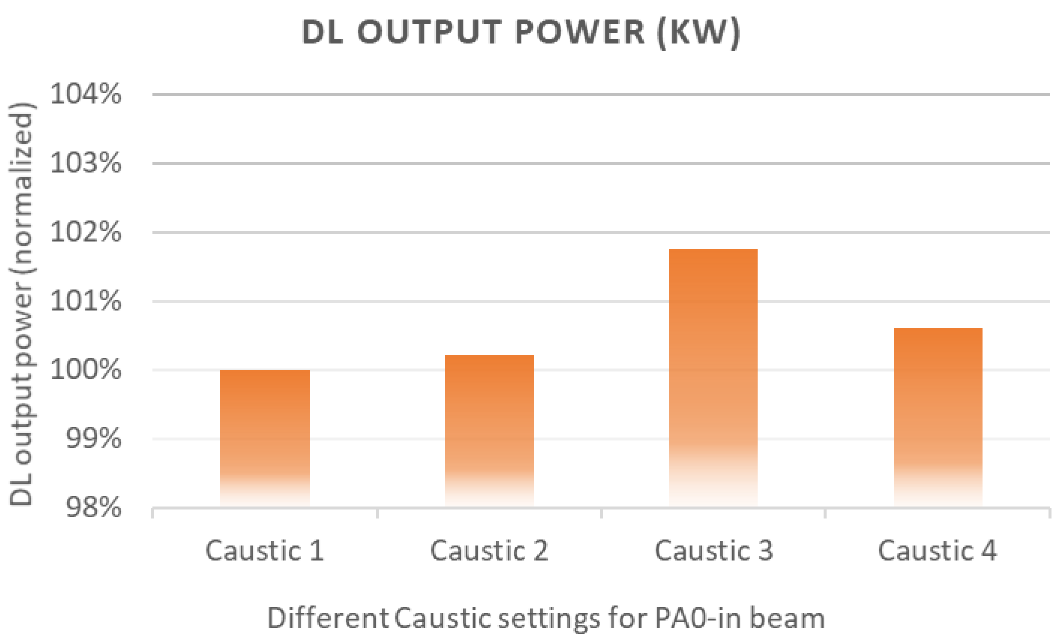


Better beam caustic matching?

Power amplifier optimization

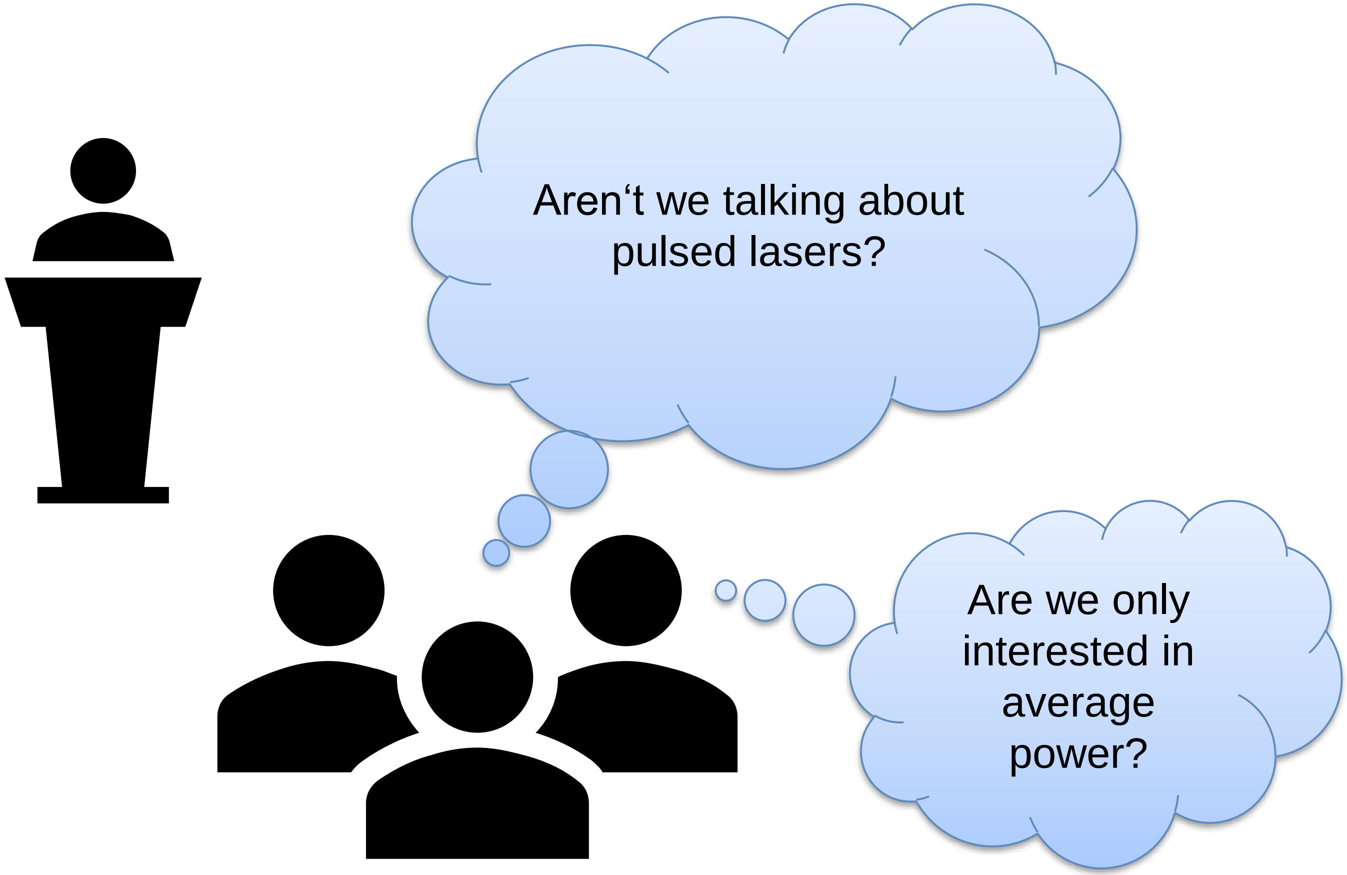
Optimizing beam input parameters into HPAC





Caustic optimizations are carried out for each power amplifier individually, leading to power improvements on ~2% level

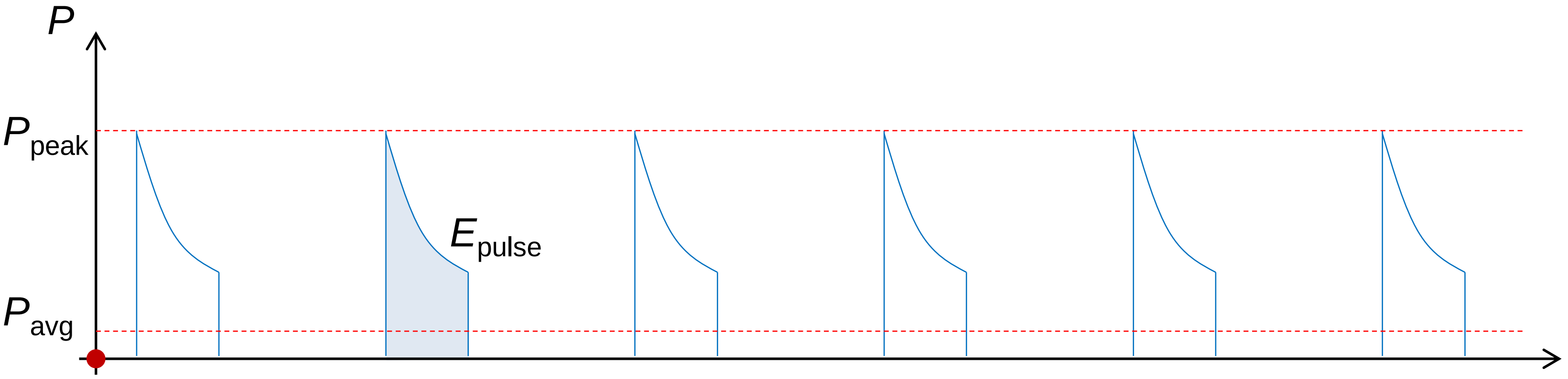
Relevant parameters of pulsed lasers for EUV generation



Relevant parameters of pulsed lasers for EUV generation

Relevant parameters of pulsed lasers for EUV generation

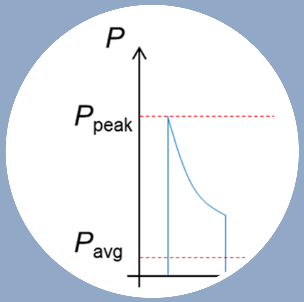
Average and peak power



Relevant parameters of pulsed lasers for EUV generation

Both, average and peak power, are important parameters

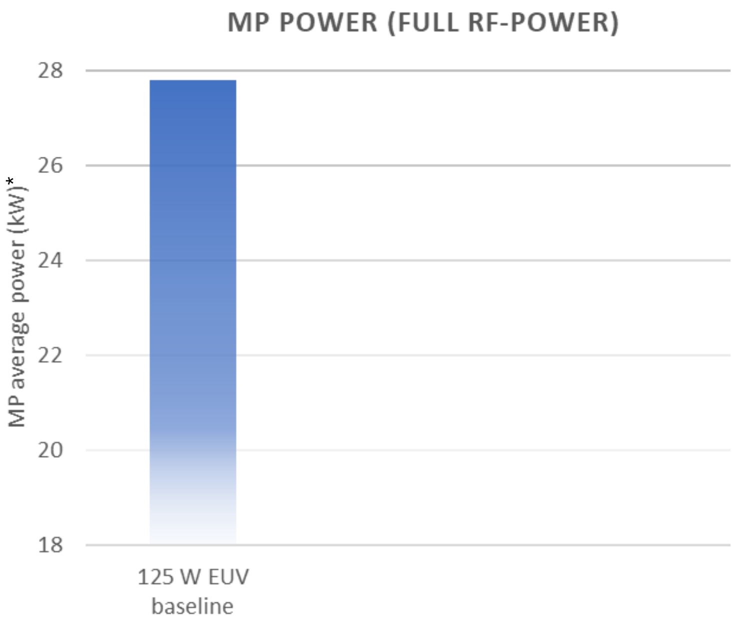
Large average power



High peak power

Power scaling at 50kHz over the past few years

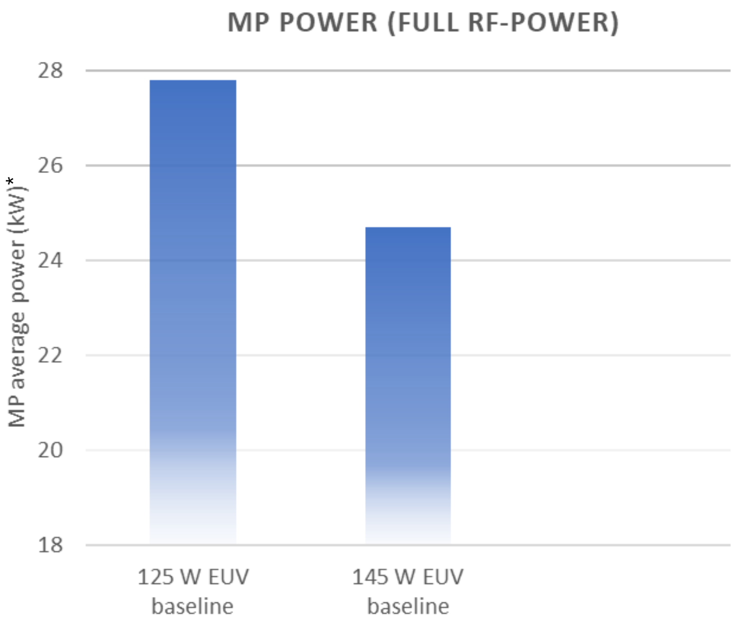
How has average power developed over different system generations?



* Power values are taken from population data

Power scaling at 50kHz over the past few years

145 W (EUV) baseline based on 11% less average CO_2 laser power



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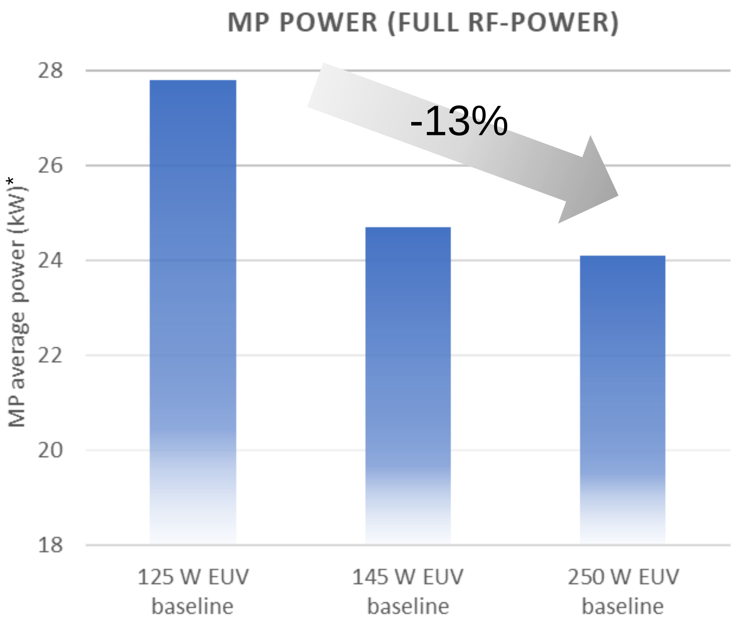
Power scaling at 50kHz over the past few years

Even further decrease of average CO_2 laser power for 250 W (EUV) baseline



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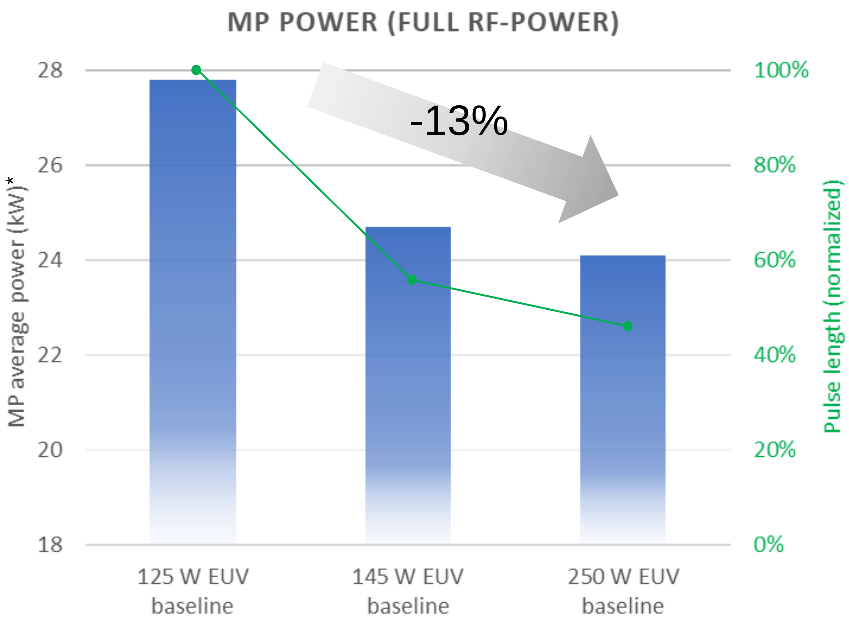
Power scaling at 50kHz over the past few years

Reason: Decreasing pulse lengths over system generations



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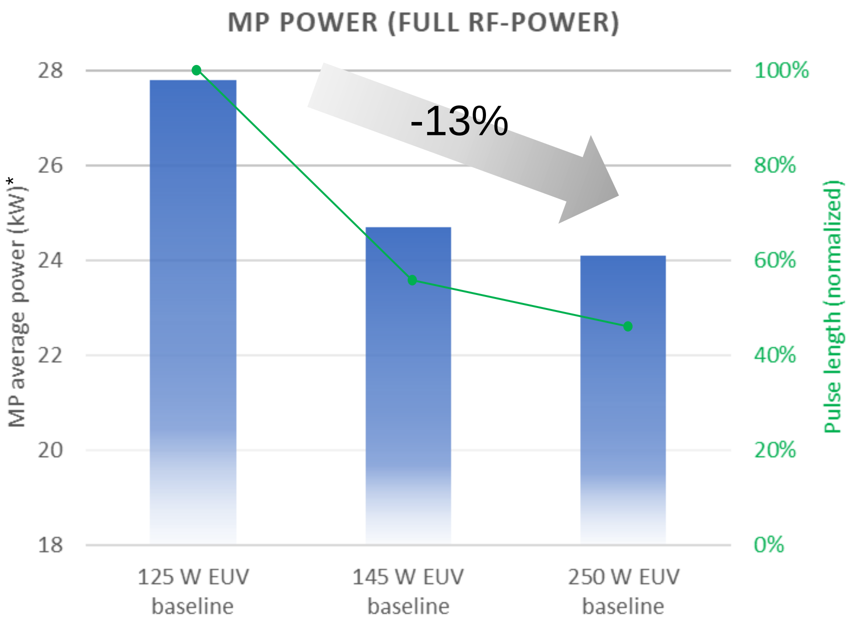
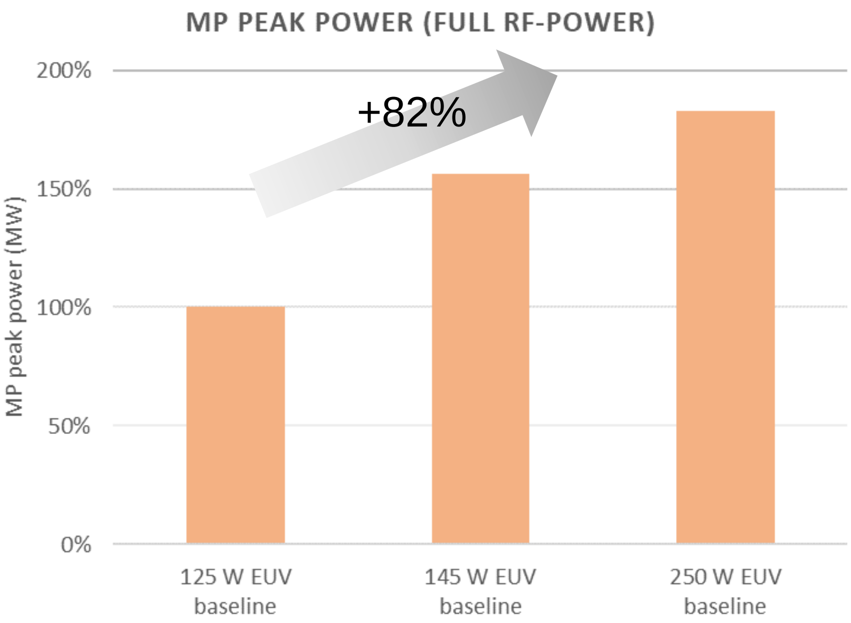
Power scaling at 50kHz over the past few years

Small decrease in average power, but significant increase in peak power





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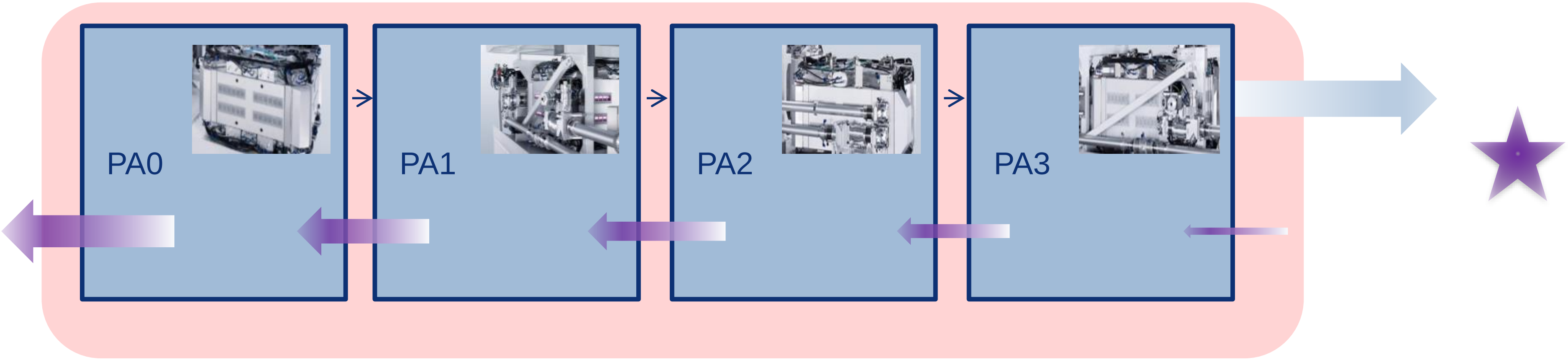
Power scaling at 50kHz over the past few years

Can we always use maximum power?

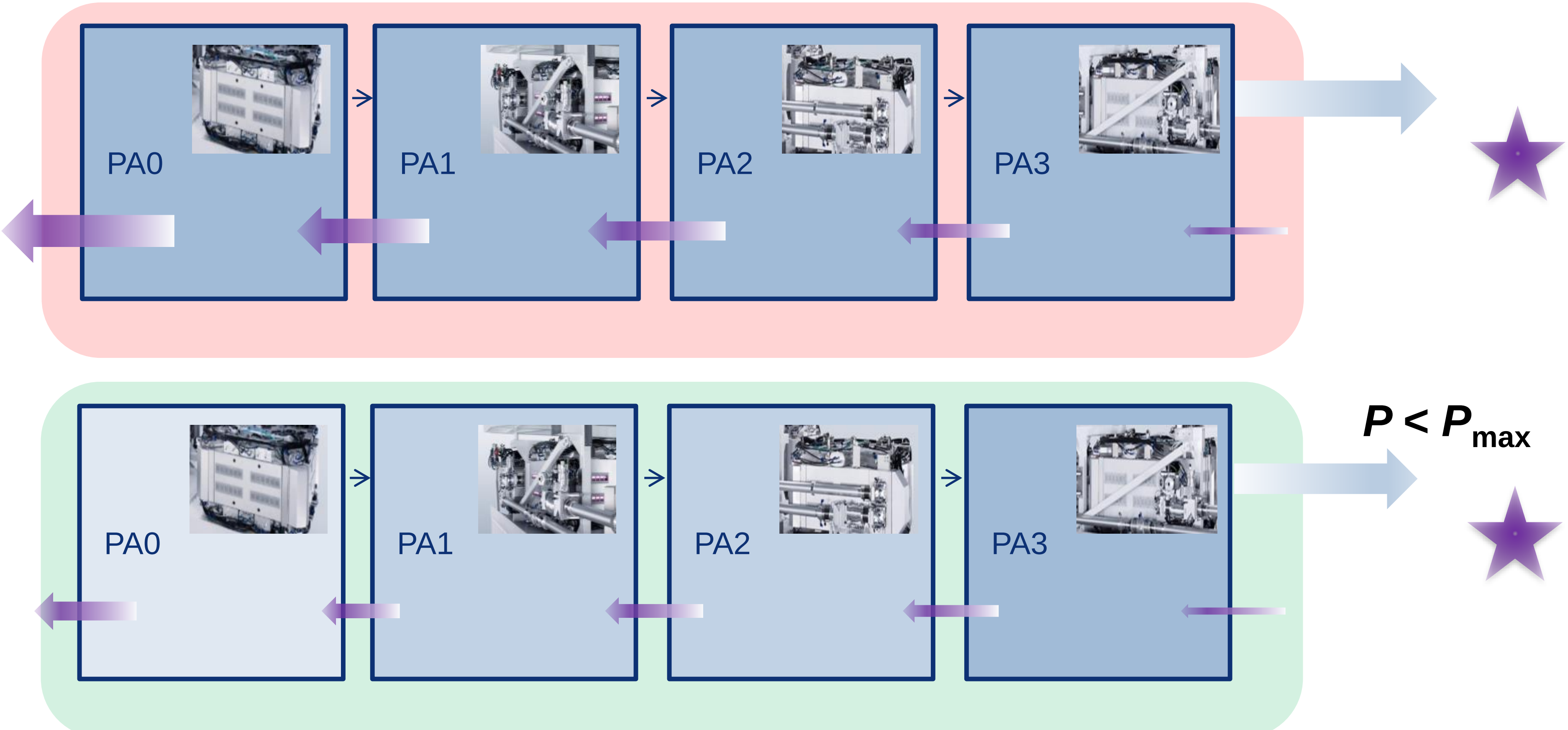
Power scaling at 50kHz over the past few years

Maximum output power also leads to significant back reflections and cannot be used on-droplet



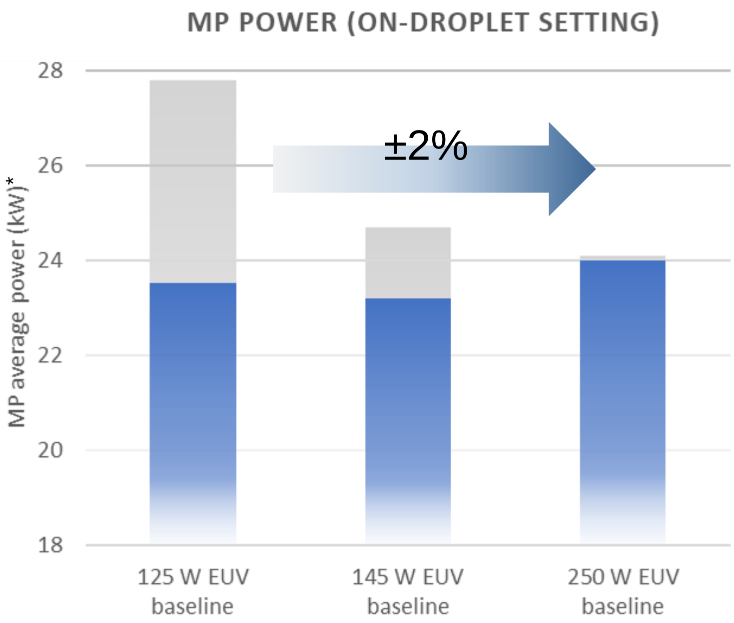
Power scaling at 50kHz over the past few years

Via gain balancing in the PA's a small decrease in output power and significant decrease in back-reflected power can be obtained



Power scaling at 50kHz over the past few years

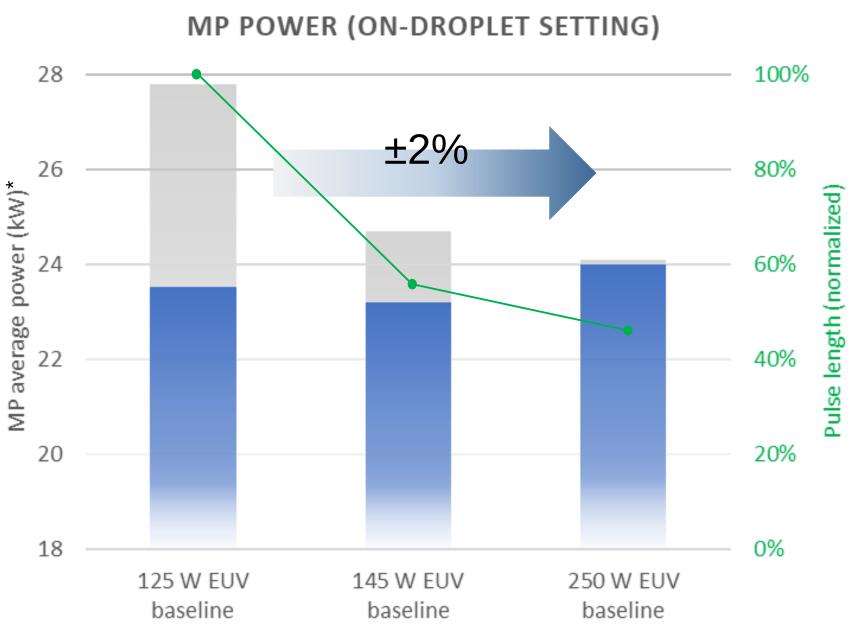
On-droplet power has not changed much for different system generations

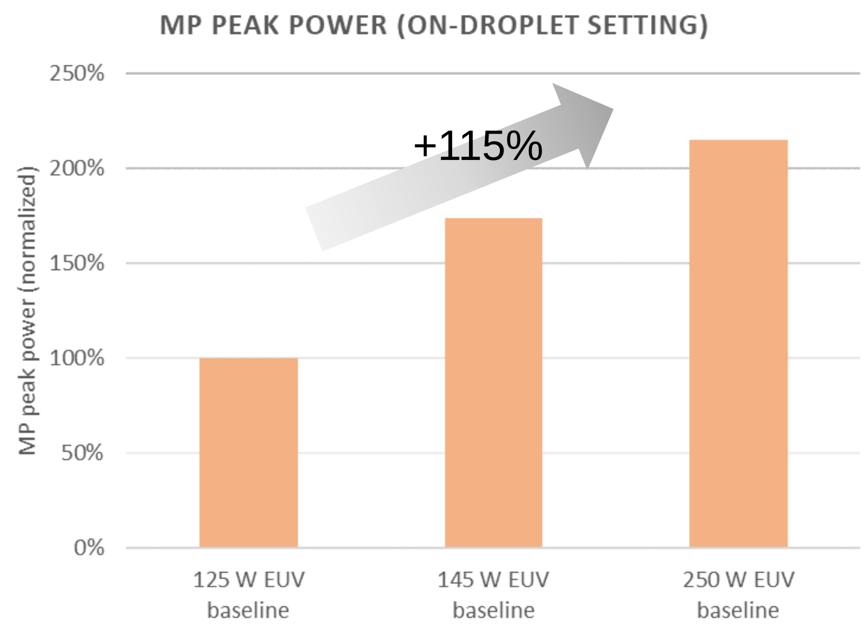


* Power values shown are nominal available powers, excluding effects like gain stripping

Power scaling at 50kHz over the past few years

Effect for peak power increase even more pronounced on-droplet





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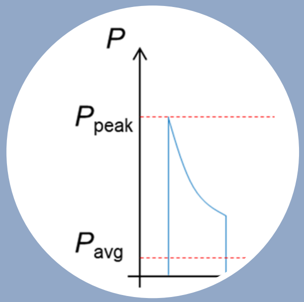
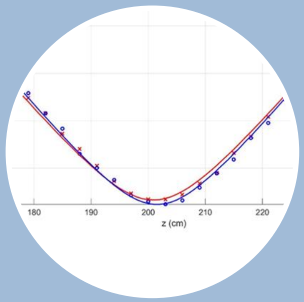
Relevant parameters of pulsed lasers for EUV generation

Large average power



High peak power



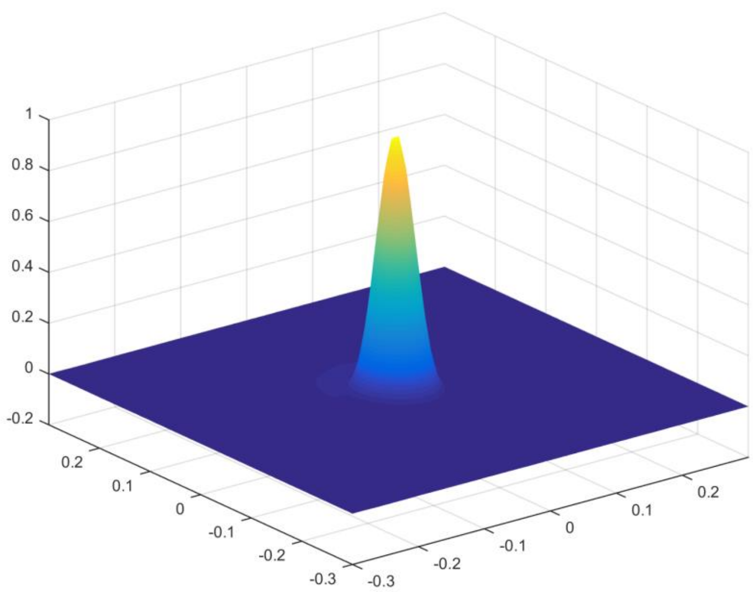
Good beam quality

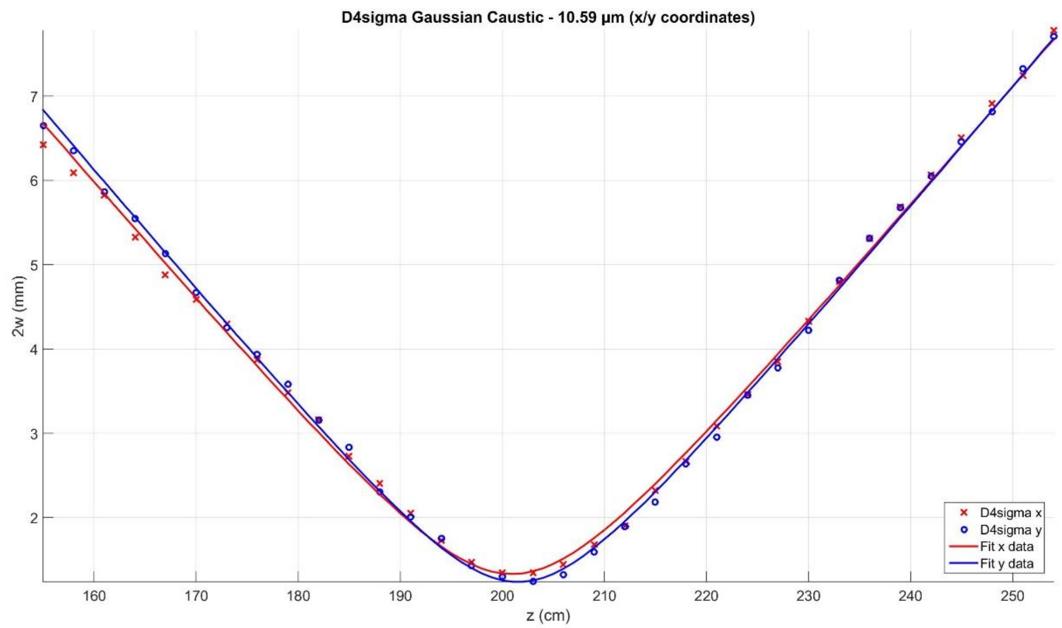
Beam quality

Each system is qualified w.r.t. beam quality, curvature, astigmatism, etc.

- ✓ **Good beam quality** $M^2 \leq 1.4$
- ✓ **Low astigmatism**
- ✓ **Highly collimated beam**
- ✓ **Beam homogeneity and symmetry**

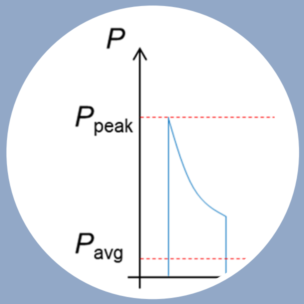
Through-focus measurement is used for each system to ensure good beam quality:



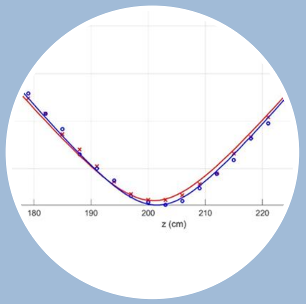


Relevant parameters of pulsed lasers for EUV generation

Large average power

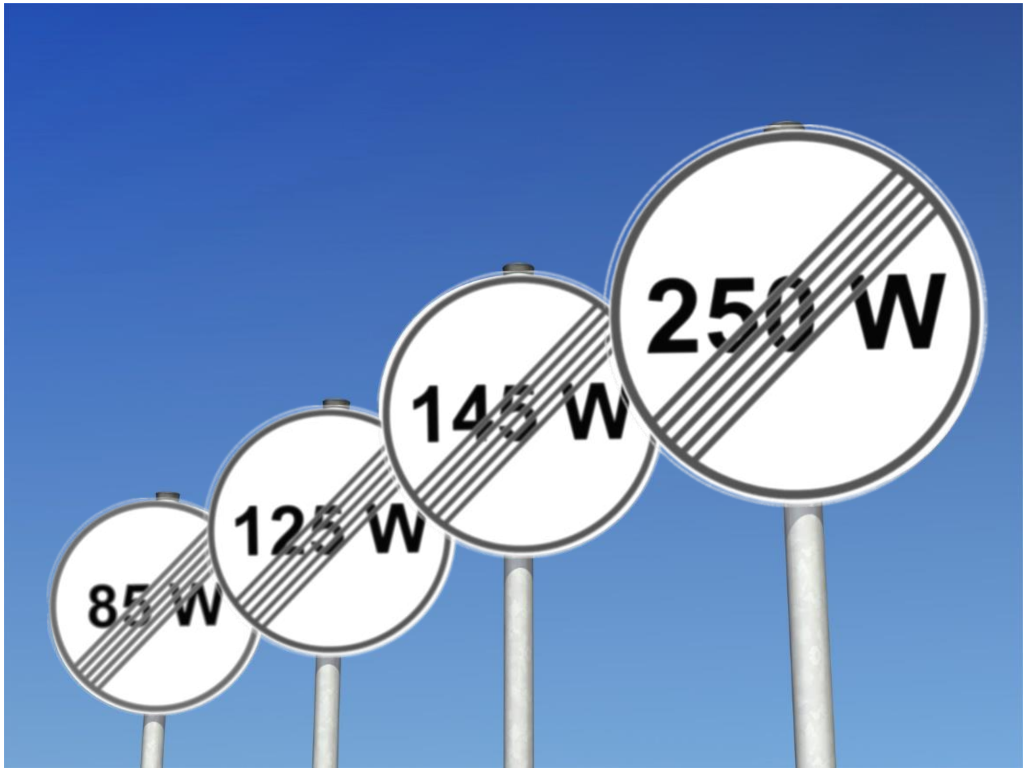


High peak power



Good beam quality

TRUMPF

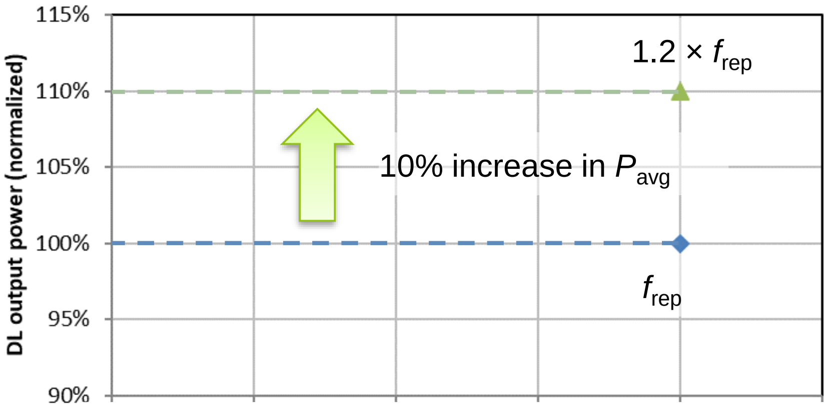


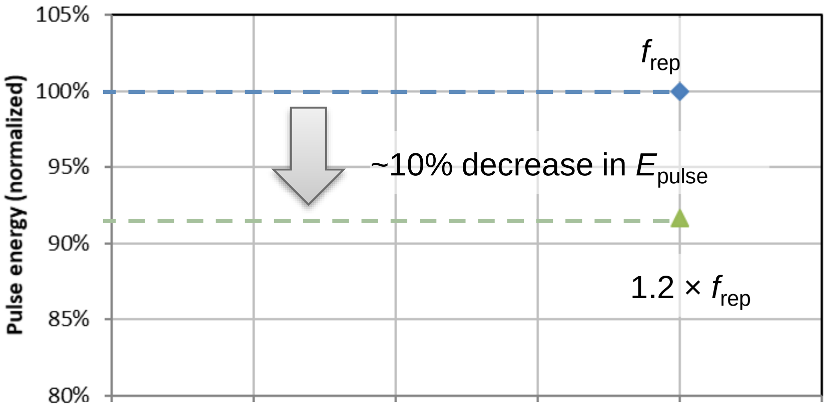
Roadmap for future EUV scaling

Roadmap for future EUV scaling

How much power can we gain by scaling the repetition rate?

Experiments with 20% repetition rate increase:



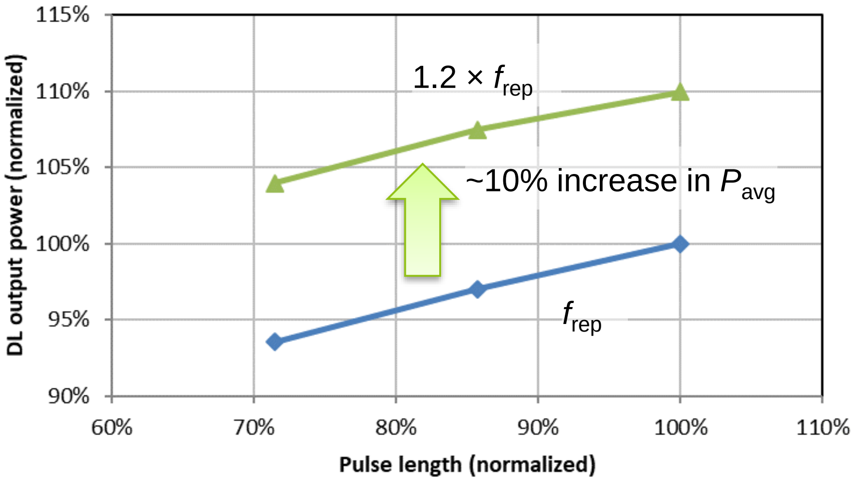


→ Reason: Gain does not recover fully after $1/f_{rep}$

Roadmap for future EUV scaling

How much power can we gain by scaling the repetition rate?

Experiments with 20% repetition rate increase and different pulse lengths



→ For average power repetition rate scaling effects are independent of pulse length.

Roadmap for future EUV scaling

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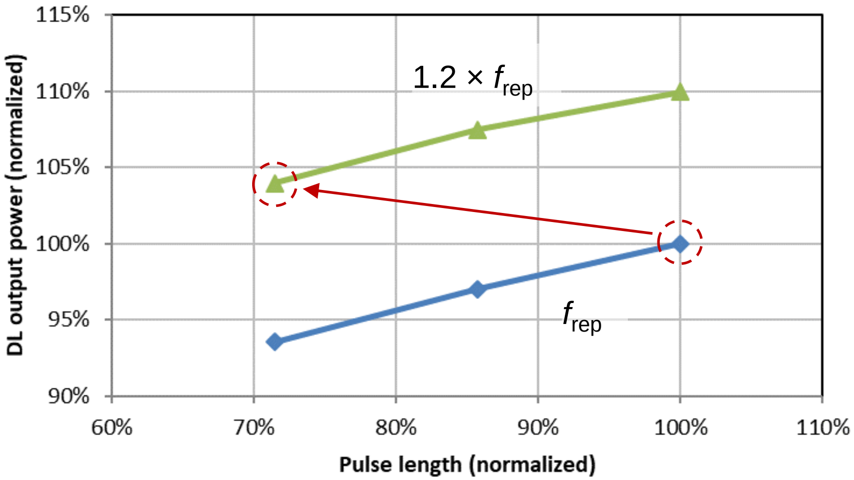
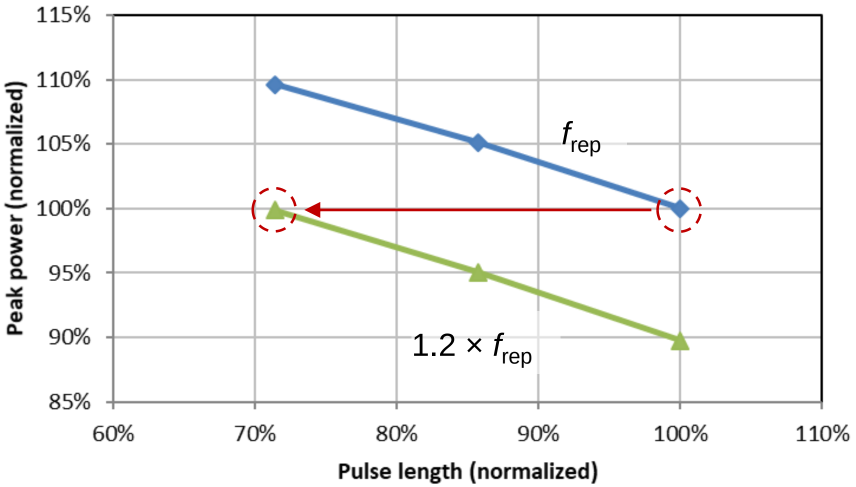


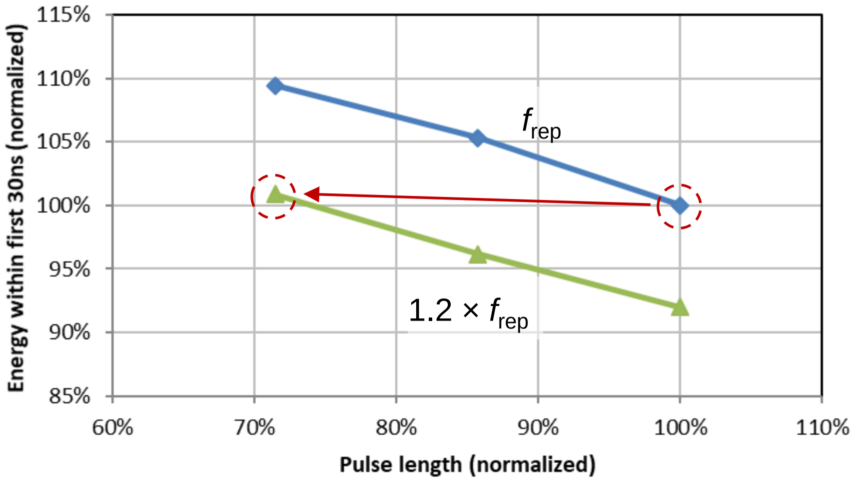
→ For average power repetition rate scaling effects are independent of pulse length.

Roadmap for future EUV scaling

How much power can we gain by scaling the repetition rate?

As seen on previous slides:
Peak power and the energy situated in the first part of the pulse is relevant:





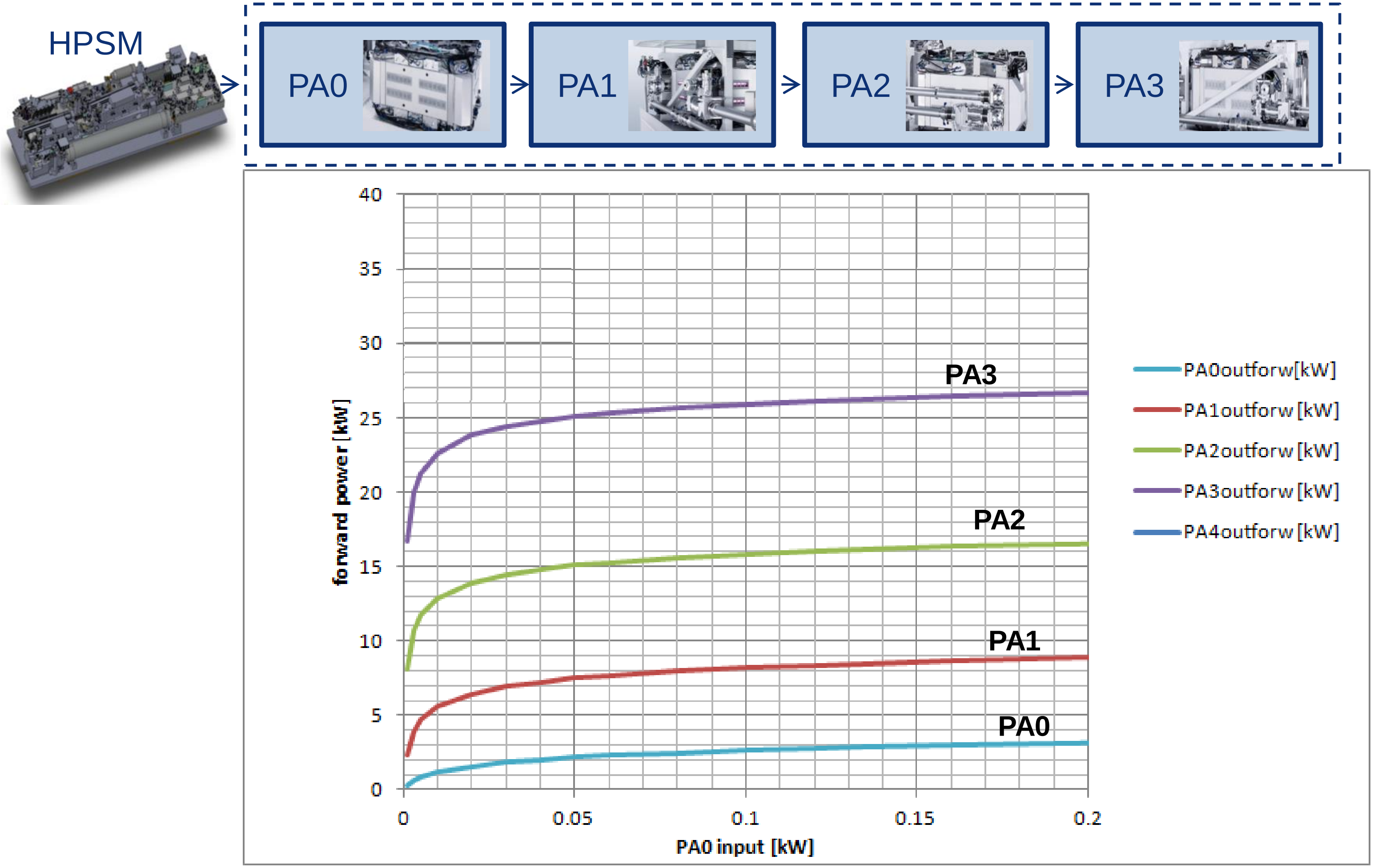
By scaling the repetition rate and simultaneously going to shorter pulses, the pulse energy in the first part each pulse can be kept constant.

Combined with the 20% repetition rate increase → **Overall gain of 20%**

Further power increase by even higher repetition rate possible and under investigation.

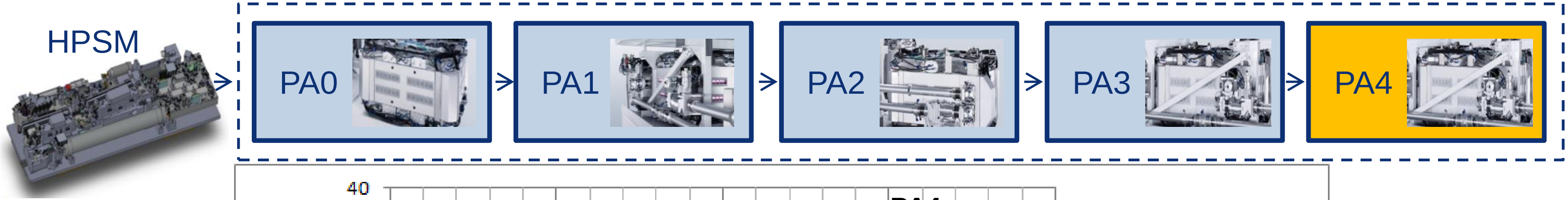
Roadmap for future EUV scaling

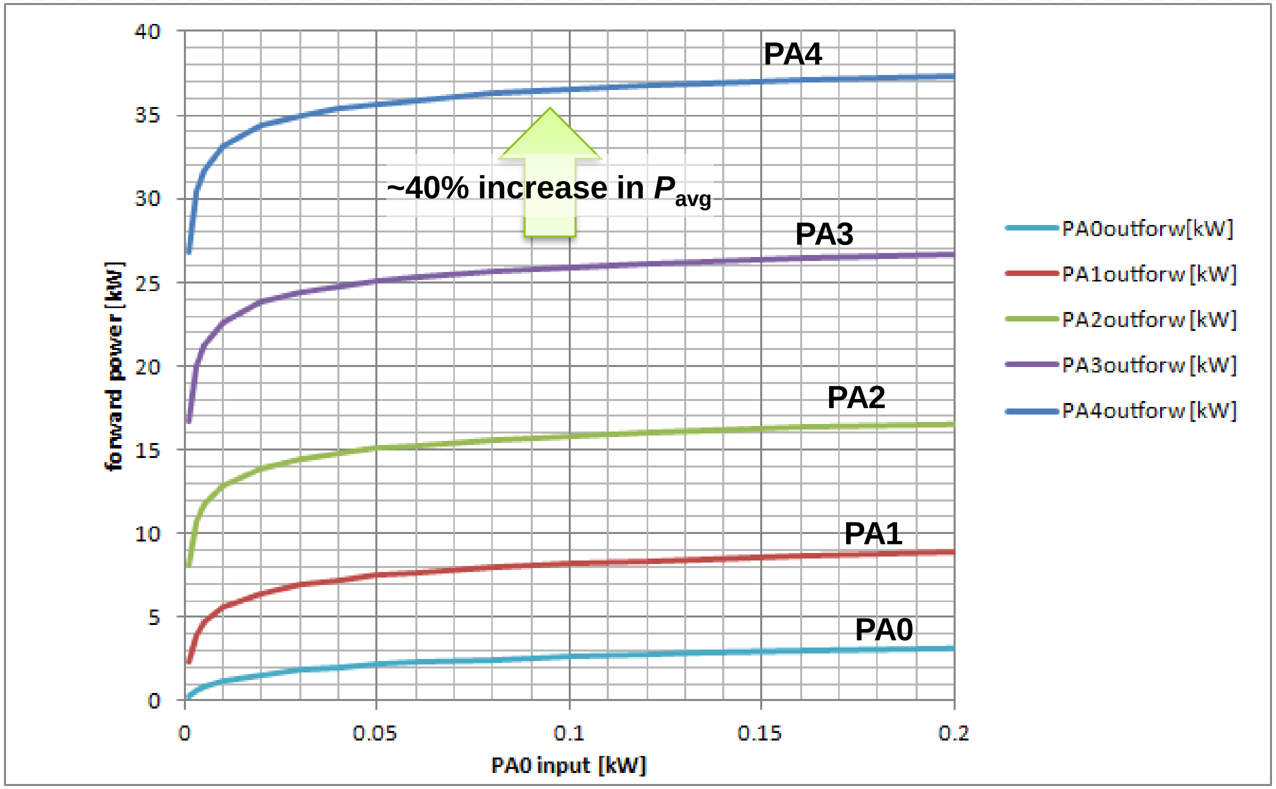
Power scaling via an additional power amplifier, Frantz-Nodvik simulations



Roadmap for future EUV scaling

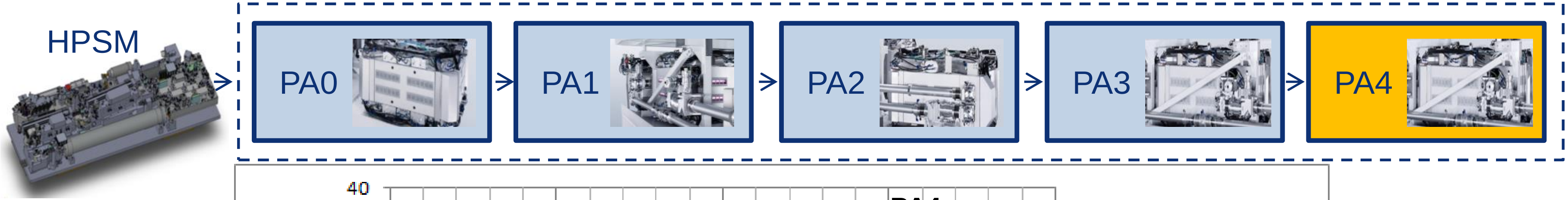
Power scaling via an additional power amplifier, Frantz-Nodvik simulations

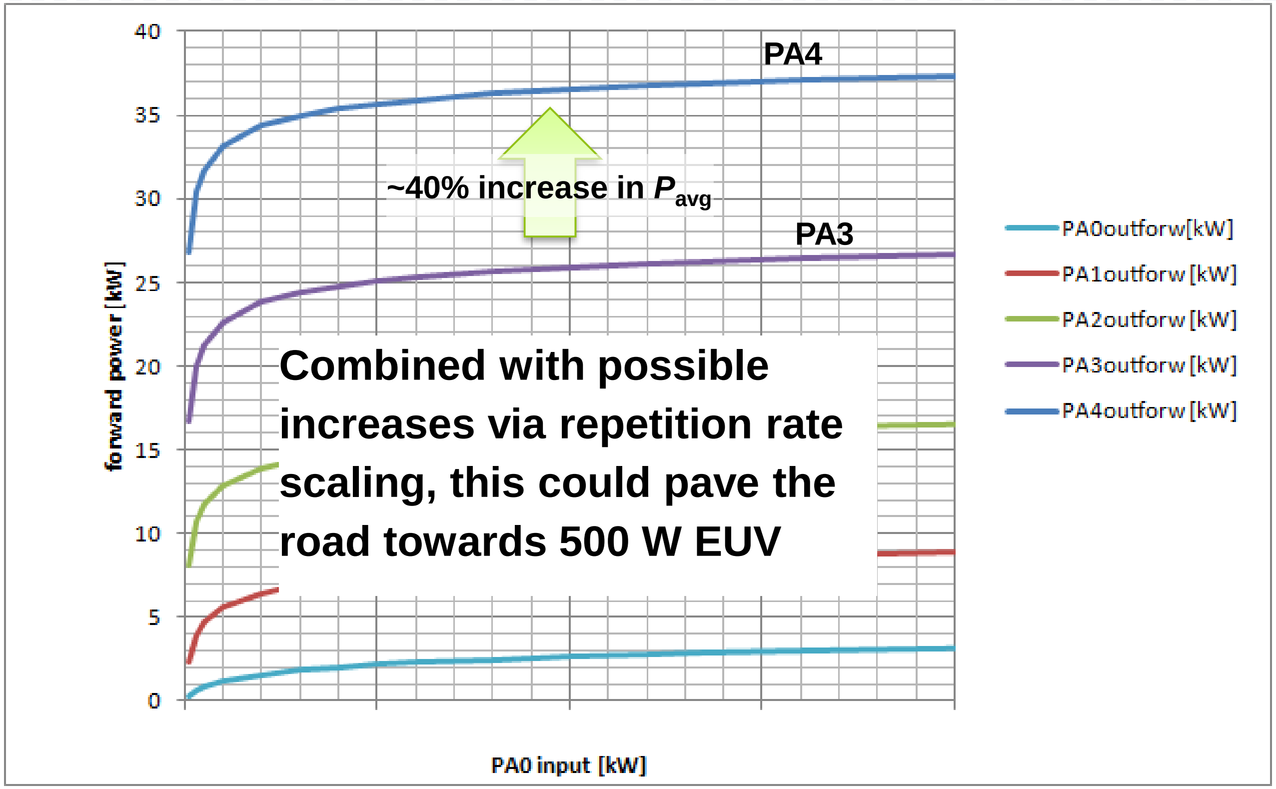




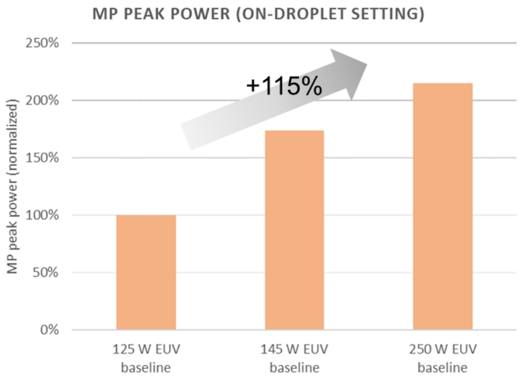
Roadmap for future EUV scaling

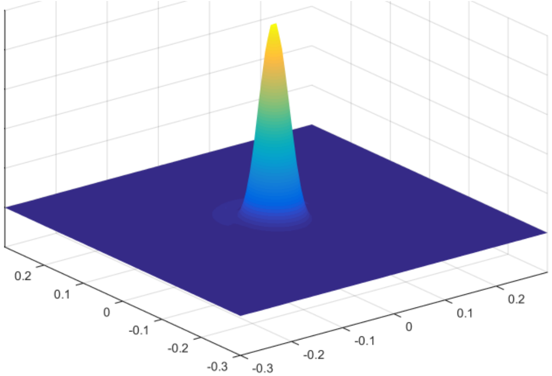
Power scaling via an additional power amplifier, Frantz-Nodvik simulations

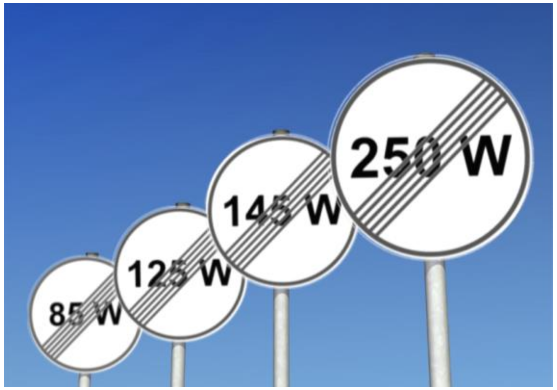




Summary







- ✓ Industrialized TRUMPF Amplifier including multi-stage amplification and seed isolation.
- ✓ Evolution of power and peak power has been enabler for 250 W EUV
- ✓ Good beam quality shown systematically for all field systems
- ✓ Roadmap towards higher EUV-power scaling

Thank you for your attention!