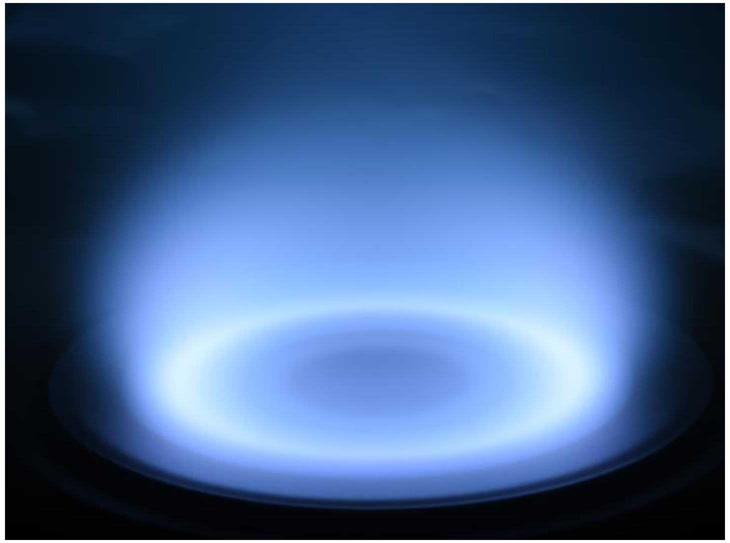

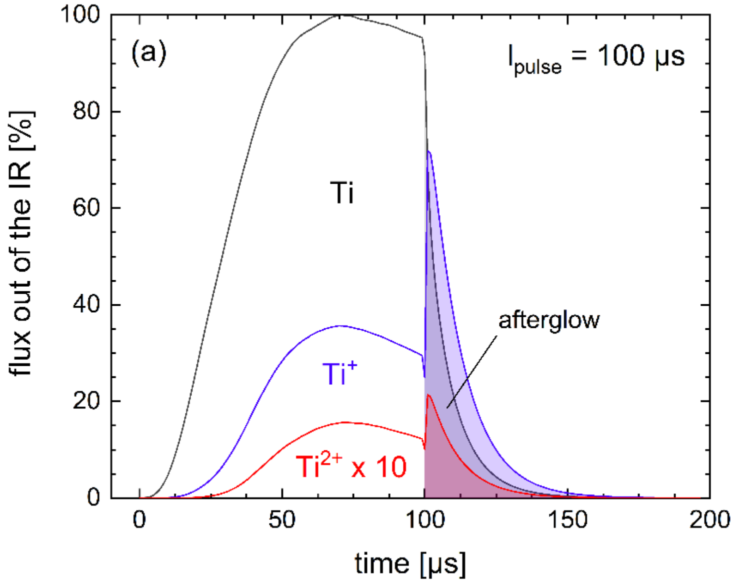

Optimizing the deposition rate and ionized flux fraction by tuning the pulse length in high power impulse magnetron sputtering

Martin Rudolph, Nils Brenning, Michael A. Raadu, Hamidreza Hajihoseini, Jón Tómas Guðmundsson, Tiberiu Minea, André Anders, Daniel Lundin

IOPS, April 22nd, 2021

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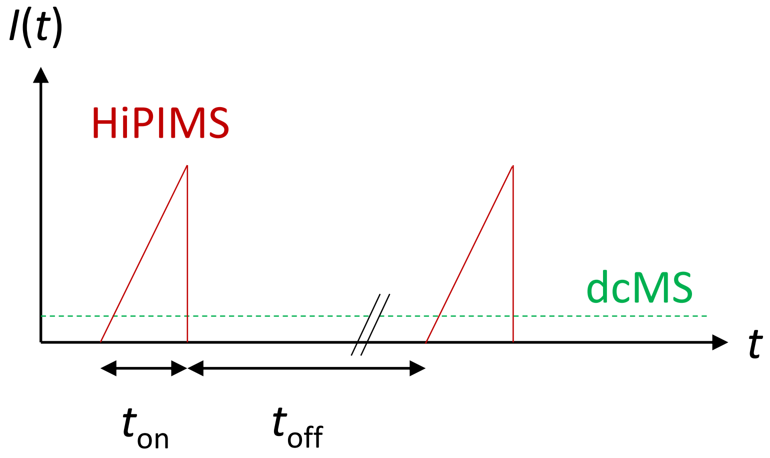
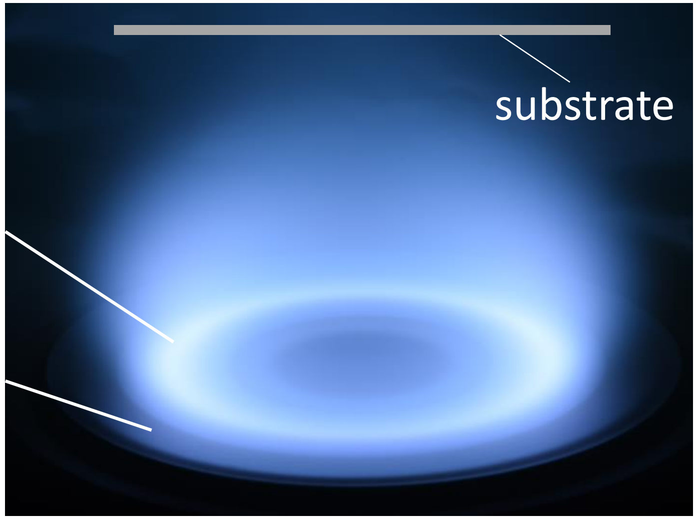
High power impulse magnetron sputtering



ionization region

Ti target (cathode)



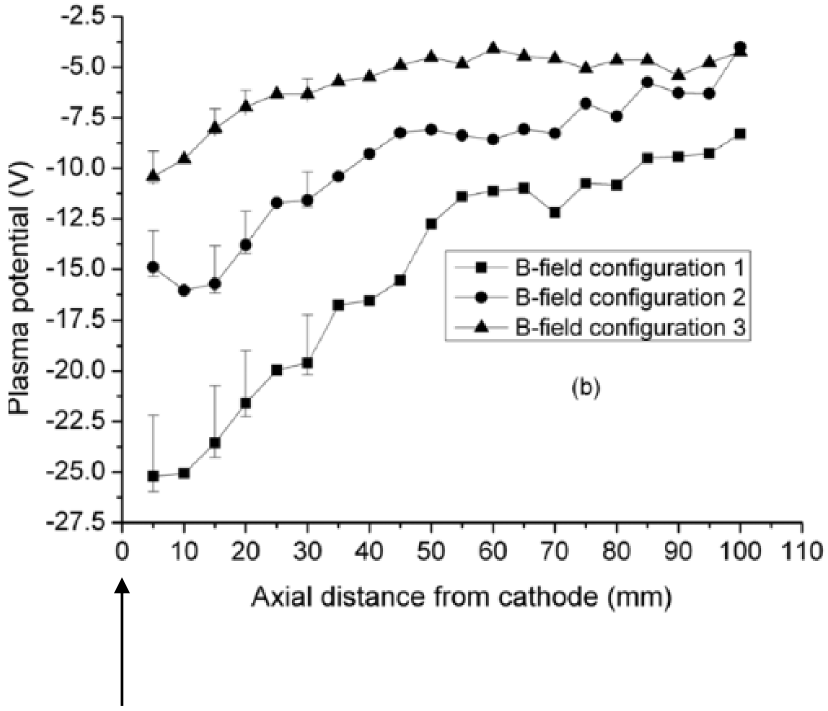
Ar/Ti HiPIMS discharge

- power supplied in pulses with high peak currents
  - high electron density
  - high fraction of target species ions in the flux to the substrate
- improves certain film properties
  - density
  - film-adhesion
  - …

Anders, *J. Appl. Phys.* **121**, 171101, 2017
Gudmundsson et al., *J. Vac. Sci. Technol.* A **30**(3), 2012

Loss in deposition rate

Emissive probe measurements of the plasma potential



target surface

- extended presheat
  - electric field directed towards the target
  - in the ionization region
- principal cause for the loss in deposition rate
  - high probability of target species ionization α_t
  - electric field in the ionization region

Mishra *et al.*, *PSST* **19**, 045014, 2010

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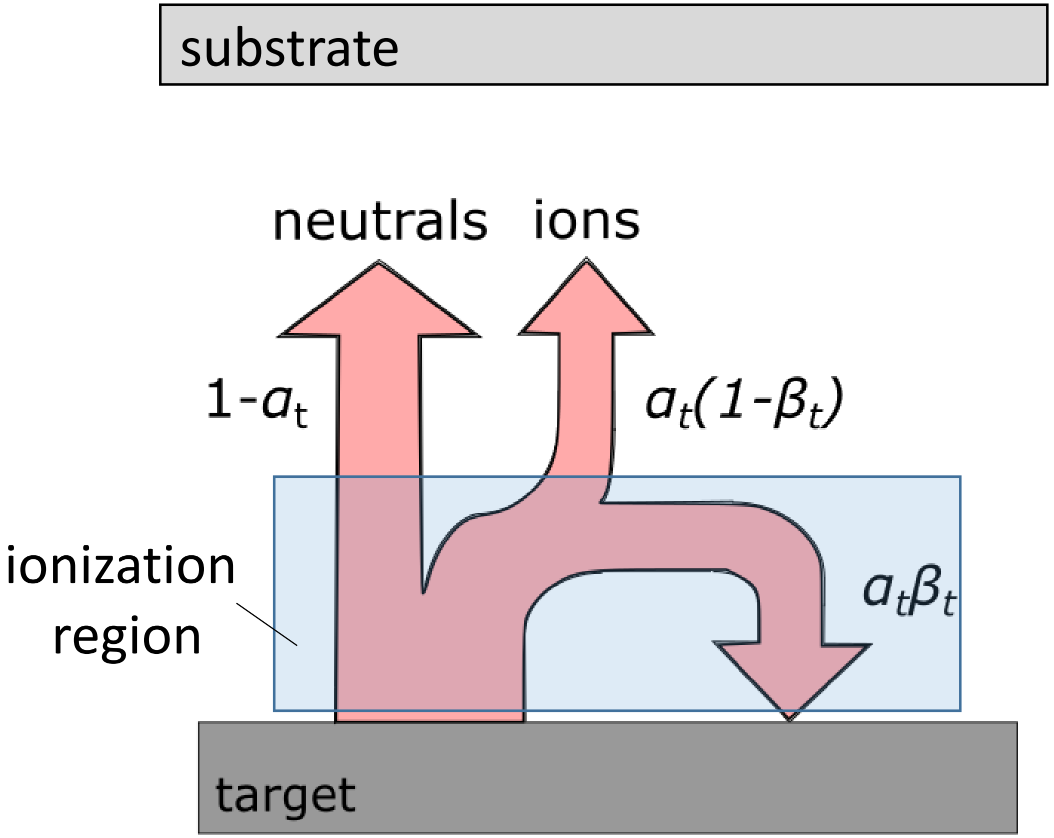
Deposition rate and ionized flux fraction

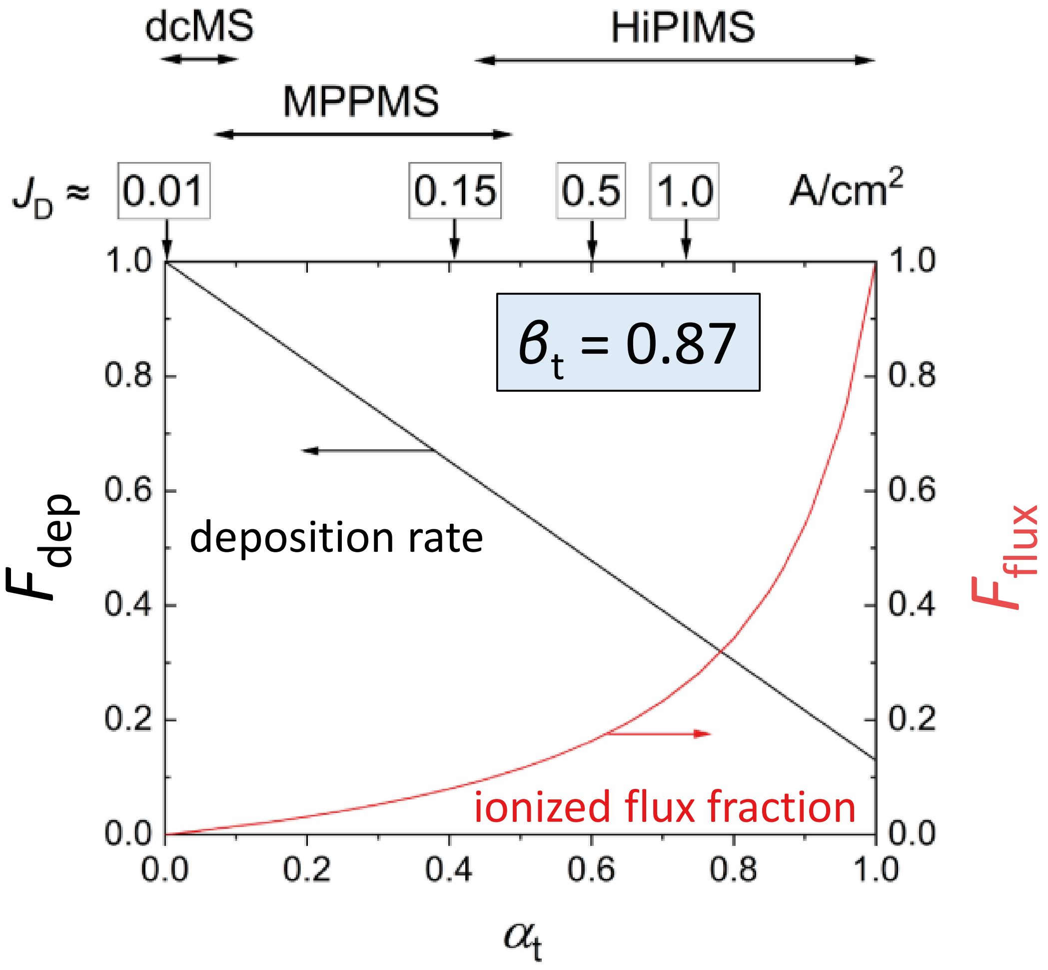


- material pathways model (Christie, 2005)
- ionization probability of target species α_t
- probability of target ion back-attraction β_t
- **deposition rate** (sputter-rate normalized) $F_{dep} = 1 - \alpha_t\beta_t$
- **ionized flux fraction**: $F_{flux} = \frac{\alpha_t(1-\beta_t)}{(1-\alpha_t\beta_t)}$

Goal: Increase deposition rate while not compromising the ionized flux fraction

Christie, *JVSTA* **23** (2), 330, 2005
Rudolph *et al.*, *JAP* **129**, 033303, 2021

Case study I: constant β_t, variable α_t



- α_t scales with the discharge current
- increased deposition rate is linked to a lower ionized flux fraction

For a constant β_t, it is impossible to Increase the deposition rate without compromising the ionized flux fraction.

Brenning *et al.*, *JVSTA* **38**, 033008, 2020

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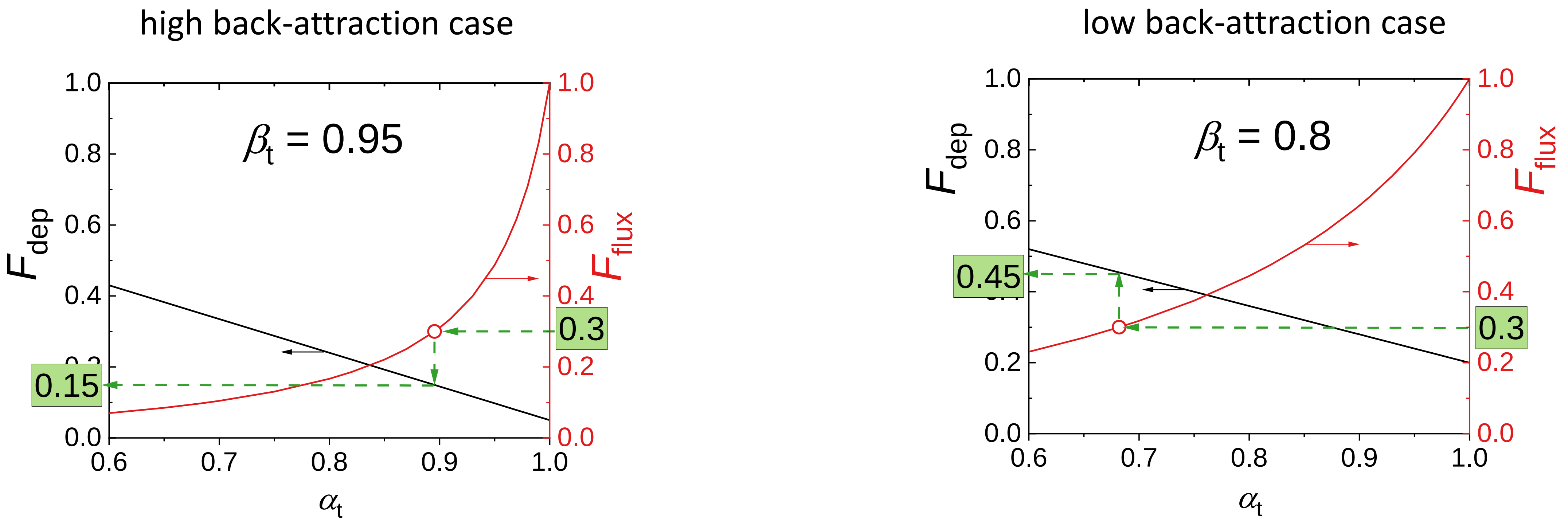
Case study II: β_t as a single figure of merit for HiPIMS discharges

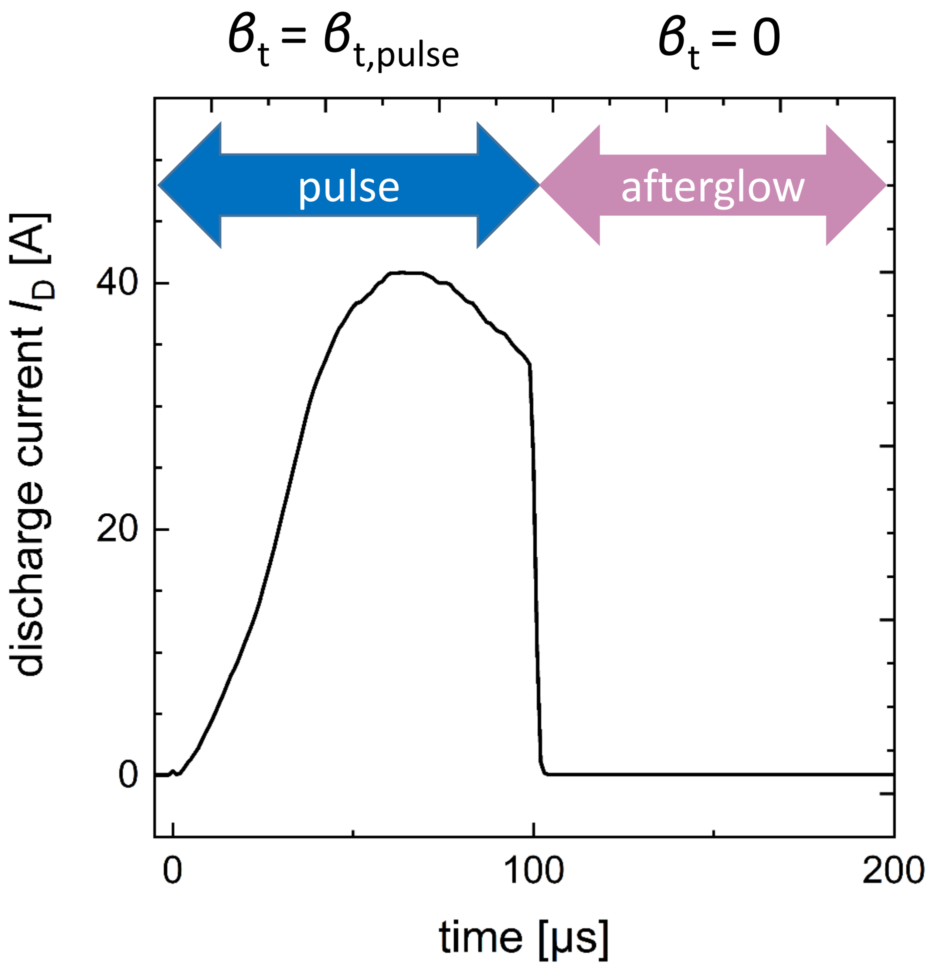


A low target ion back-attraction β_t gives a better combination of F_{dep} and F_{flux}.

β_t can be used as a *single figure of merit* for a HiPIMS discharge.

Brenning *et al.*, *JVSTA* **38**, 033008, 2020

Making use of the afterglow to lower the ion back-attraction



- β_t is an average value for one period

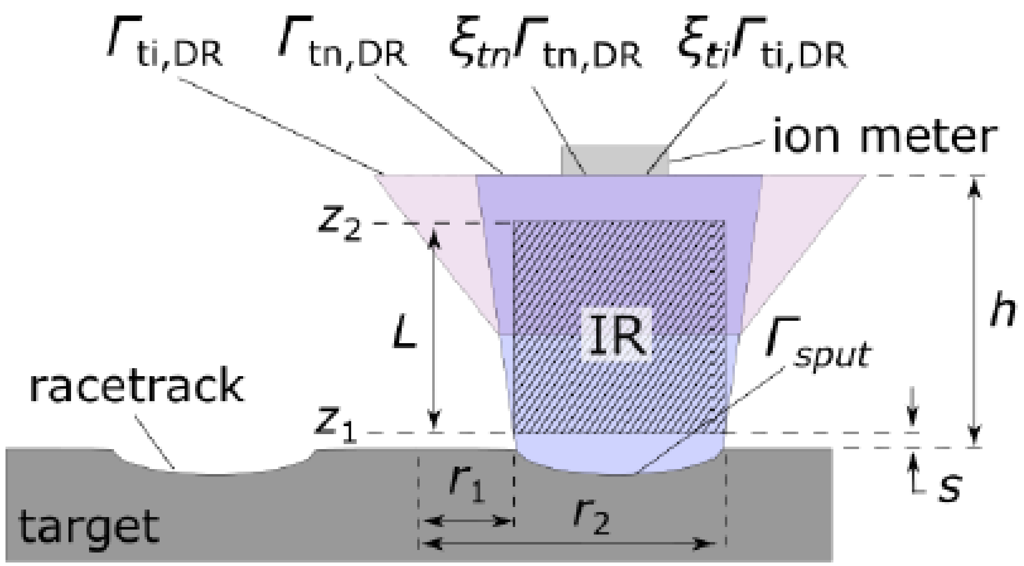
$$\beta_t(t) = \begin{cases} \beta_{t,pulse} & \text{during the pulse} \\ 0 & \text{in the afterglow} \end{cases}$$

- increase the relative contribution from the afterglow to the deposition rate

Idea: Shortening the pulse length while keeping the peak discharge current high.

Butler et al., *PSST* **27**, 105005, 2018

The ionization region model (IRM)



- time-dependent global discharge model of the ionization region of a HiPIMS discharge
- well-knowns: pressure, gas, target, geometry, collision rate coefficients, diffusion rates
- unknowns:
  - target ion back-attraction during pulse $\beta_{t,pulse}$
  - electric potential drop over the IR: V_{IR}
- requires experimental input
  - $U(t)$ and $I(t)$
  - ionized flux fraction F_{flux}

IRM provides α_t and β_t of an experimental discharge

Raadu *et al.*, *PSST* **20**, 065007, 2011
Rudolph *et al.*, *JAP* **129**, 033303, 2021
Huo *et al.*, *J. Phys. D* **50**, 354003, 2017
Lundin *et al.*, *PSST* **24**, *035018,* 2015

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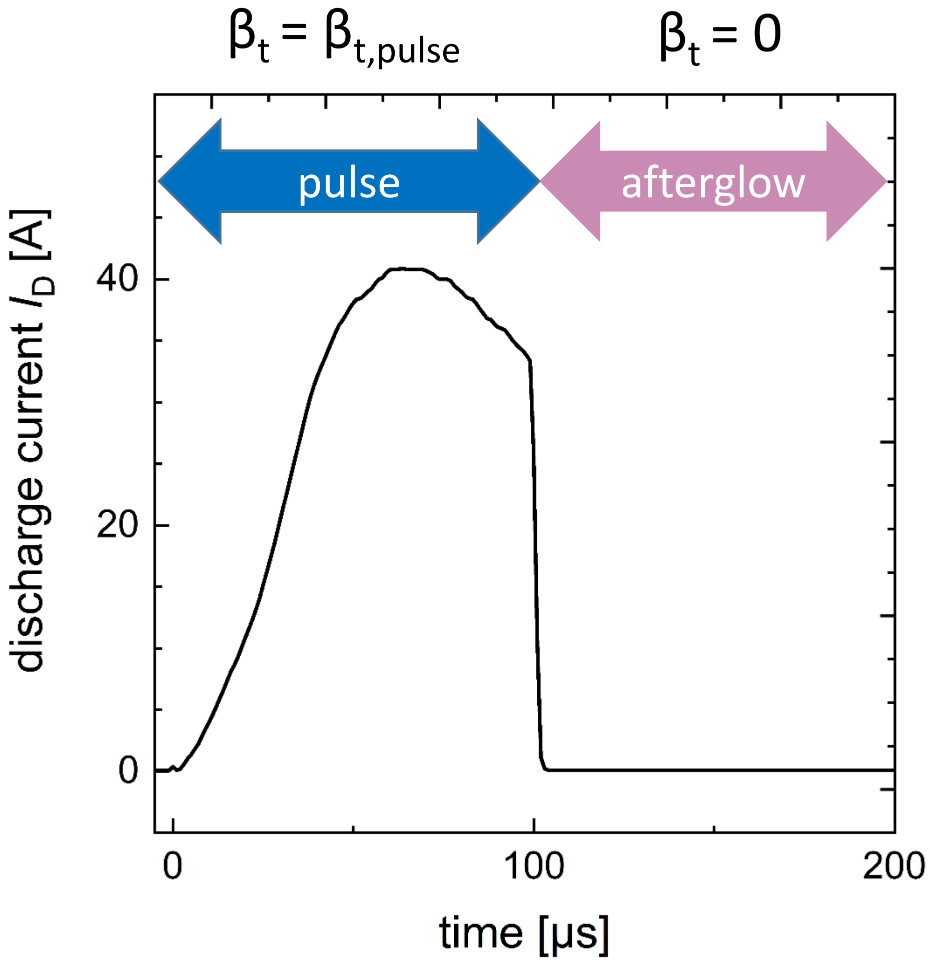
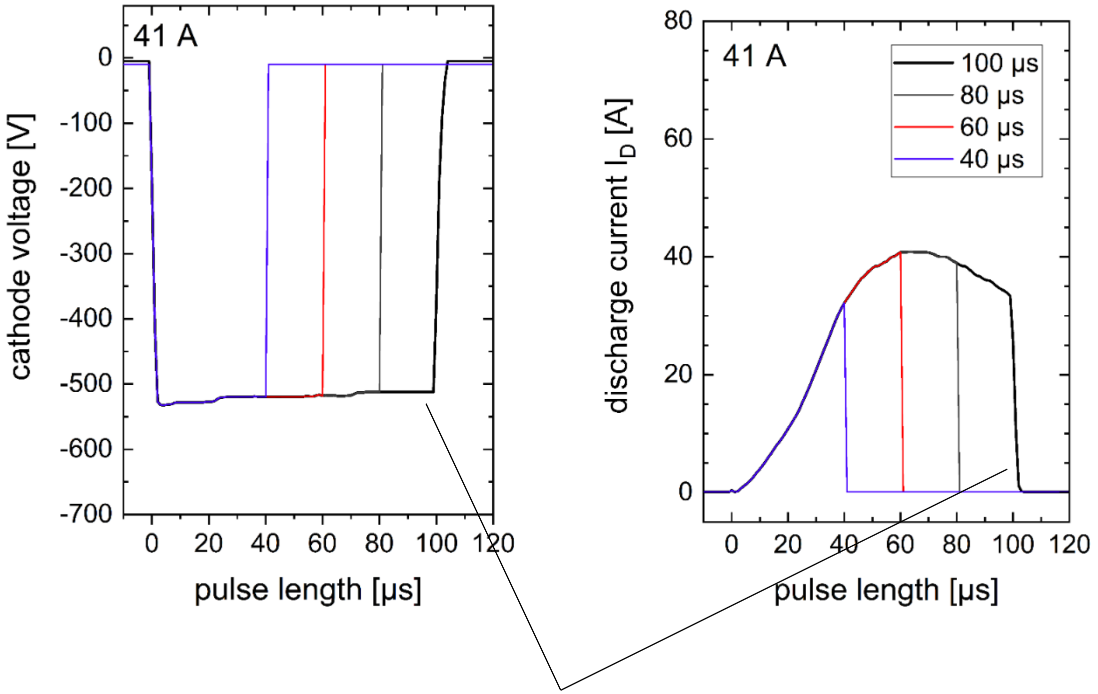
Modelling the afterglow



- modifications to existing IRM :

$$\beta_t(t) = \begin{cases} \beta_{t,pulse} & \text{during pulse} \\ 0 & \text{in the afterglow} \end{cases}$$

Experimental input to the IRM



Black: Original discharge with 100 μs-long pulse

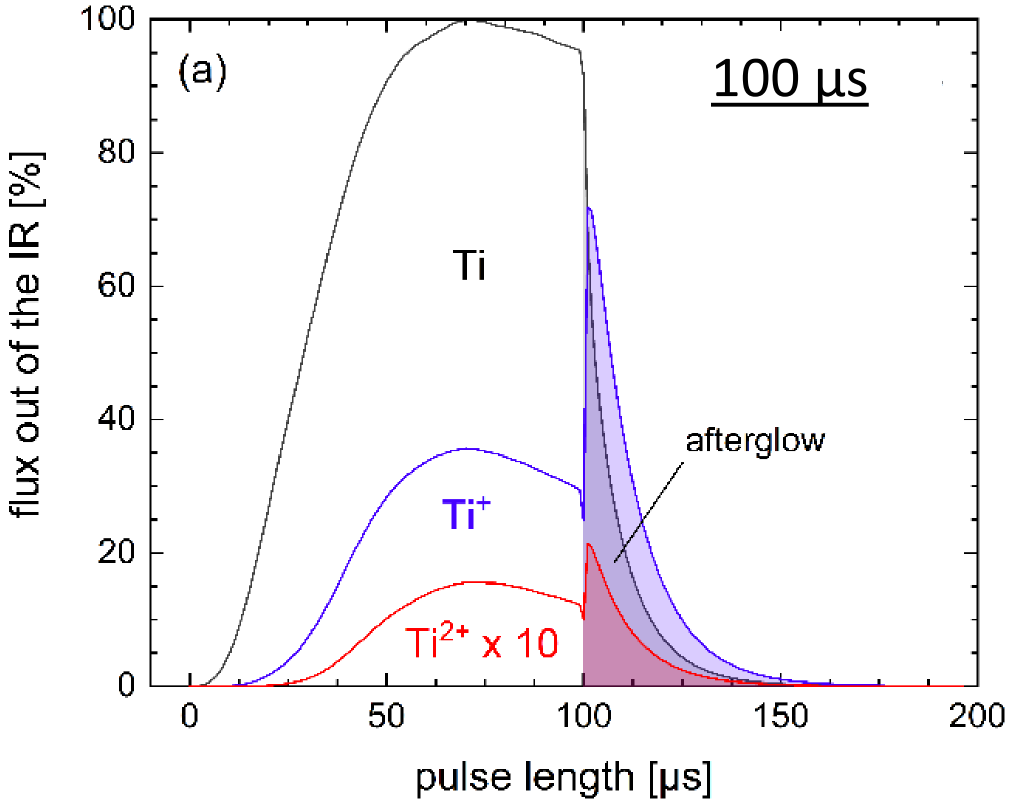
- Original discharge: 100 μs-long pulse (Haji. 2019*)*
  - 4'' Ti target
  - 300 W average power
  - 41 A (and 76 A) peak discharge current
- Virtually cutting the pulses short

  t_{pulse} = **100μs, 80 μs, 60 μs, 40 μs**
- Discharge evolution follows the experimental one until the pulse is virtually switched off
- Discharge current at end of pulse remains (close to) constant

Hajihoseini *et al., Plasma* ***15*** *(2),* 2019

Result for a 100 µs-long pulse

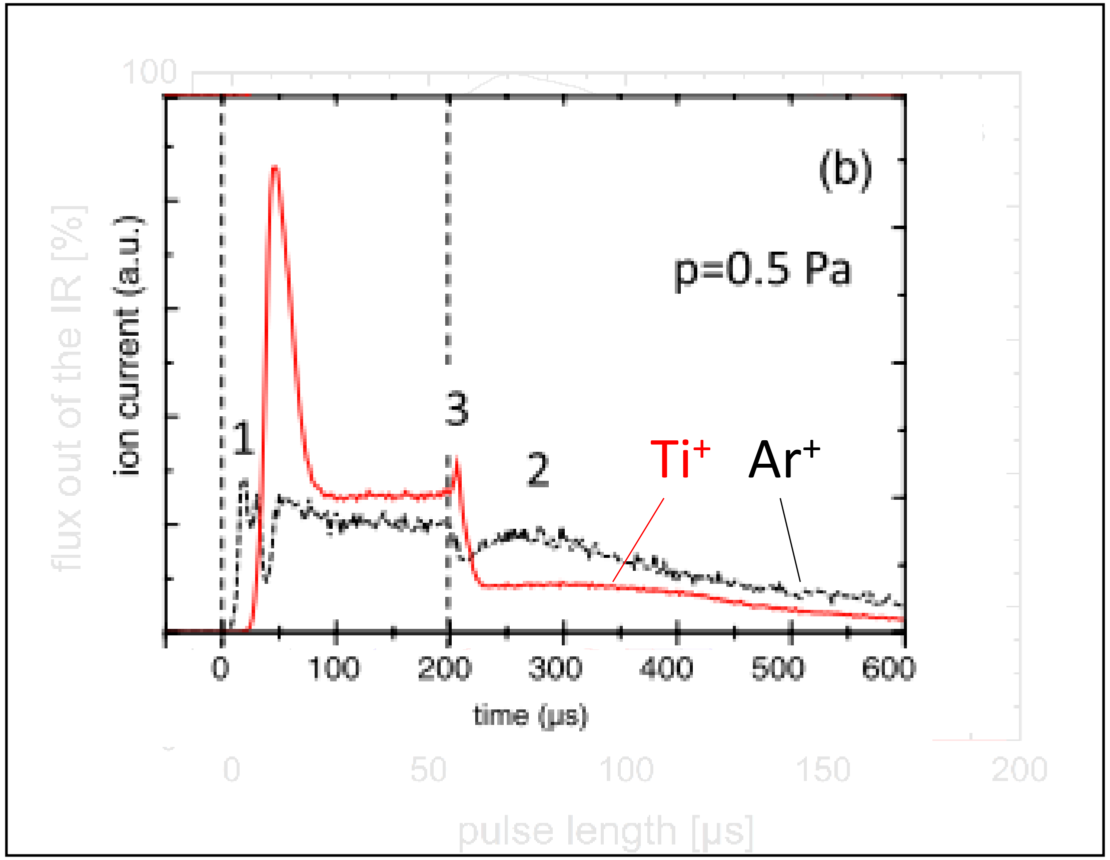
flux of film-forming material (Ti, Ti^{+}, Ti^{2+}) out of the IR during one HiPIMS pulse



- jump in ion flux when pulse is switched off
  - loss of ion back-attraction
  - ion production ceases slowly only

Rudolph *et al.*, *PSST* **29**, 05LT01, 2020

Result for a 100 µs-long pulse



- jump in ion flux when pulse is switched off
  - loss of ion back-attraction
  - ion production ceases slowly only

- **Experimental support by Breilmann *et al.***
  - time-resolved mass spectrometry
  - peak in ion current after end of pulse
  - explained by acceleration mechanism from jump in plasma potential

Breilmann *et al.*, *J. Phys. D* **46**, 485204, 2013

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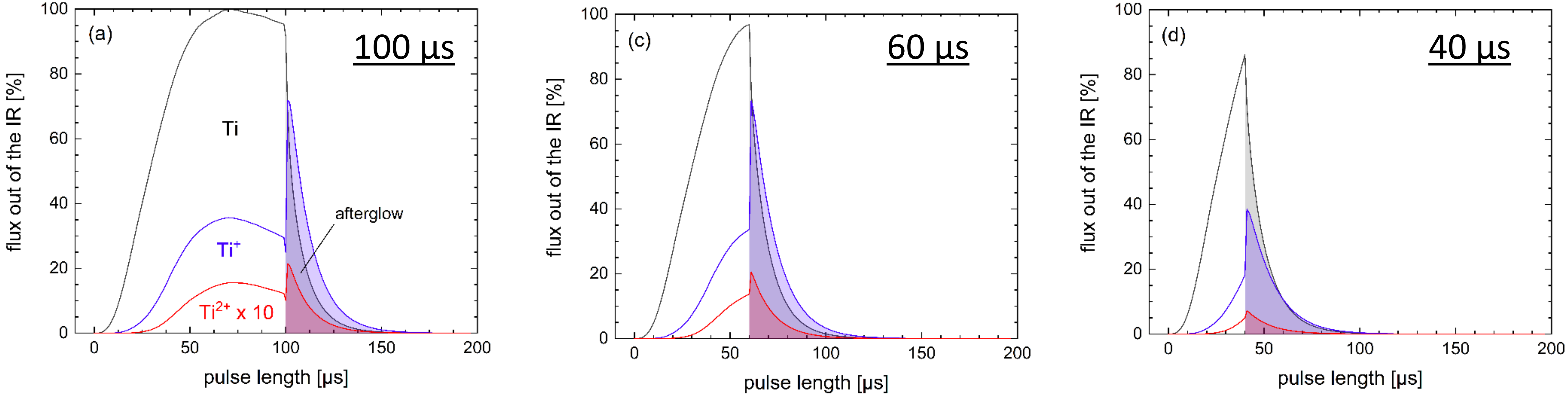
Shortening the pulses



flux of film-forming material out of the IR for different pulse lengths

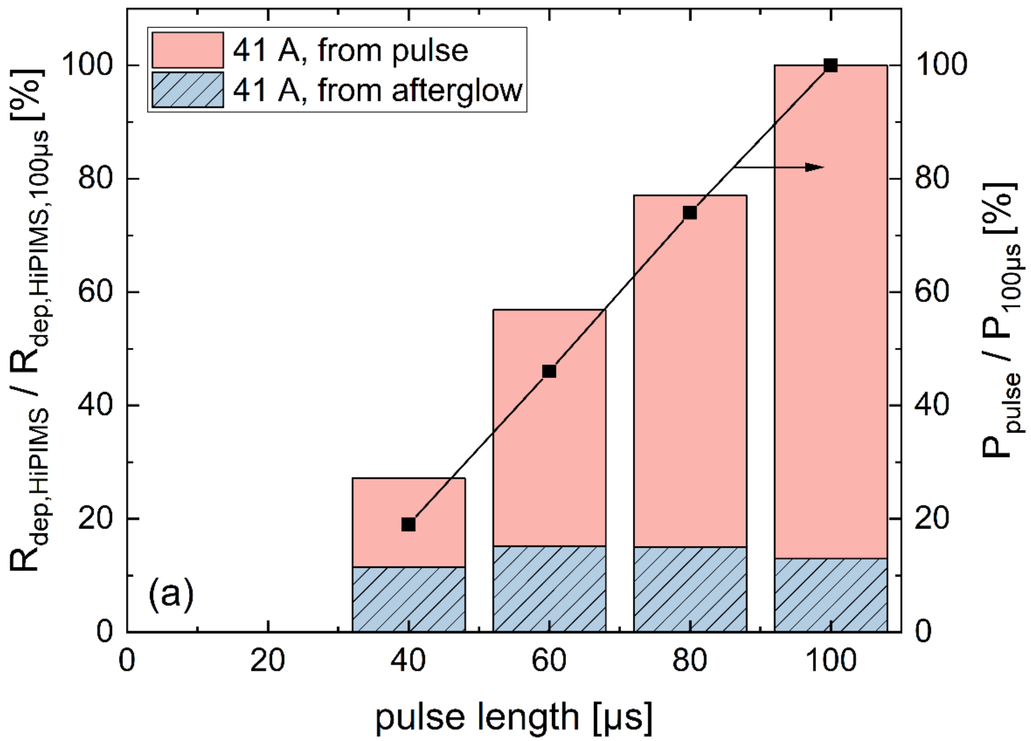
- lower flux during the pulse
- constant flux during the afterglow

Growing contribution to the flux out of the IR from the afterglow with shorter pulses.

Rudolph *et al.*, *PSST* **29**, 05LT01, 2020

Contributions to the deposition rate

Contribution from pulse and afterglow to the deposition rate



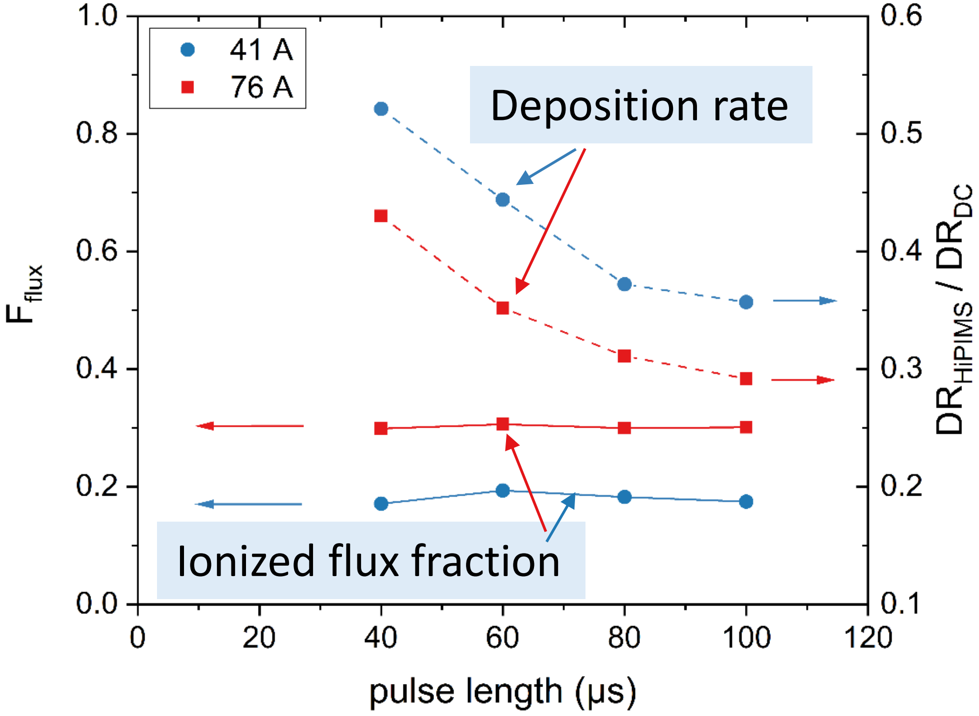
Shorter pulses give…

- growing contribution from afterglow
- faster decrease in power/pulse compared to deposition rate

Gain in deposition rate is possible for constant average power (frequency to be increased)

Rudolph *et al.*, *PSST* **29**, 05LT01, 2020

Shorter pulses at constant average power



- Increasing the frequency to constant average power

Increase in deposition rate by 40 to 50 %
Constant ionized flux fraction

- Side note: limit to decreasing the pulse length given by the time to build-up a high n_e and the typical time for ionization

Rudolph *et al.*, *PSST* **29**, 05LT01, 2020

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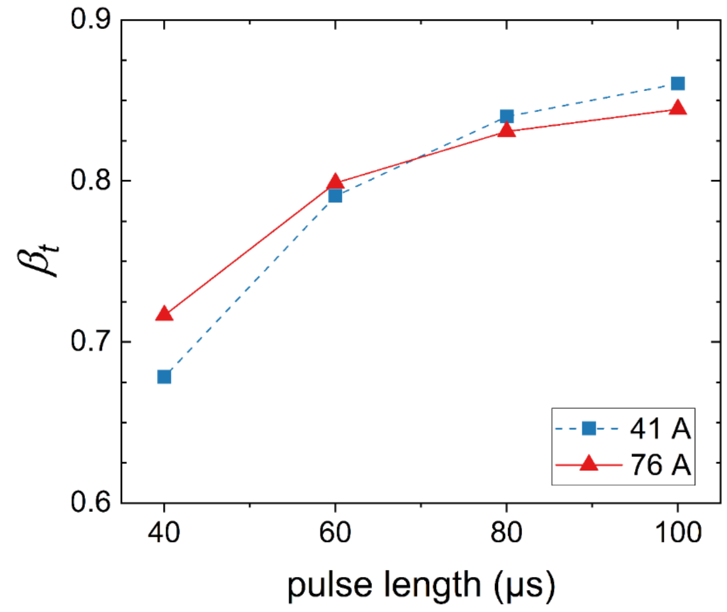
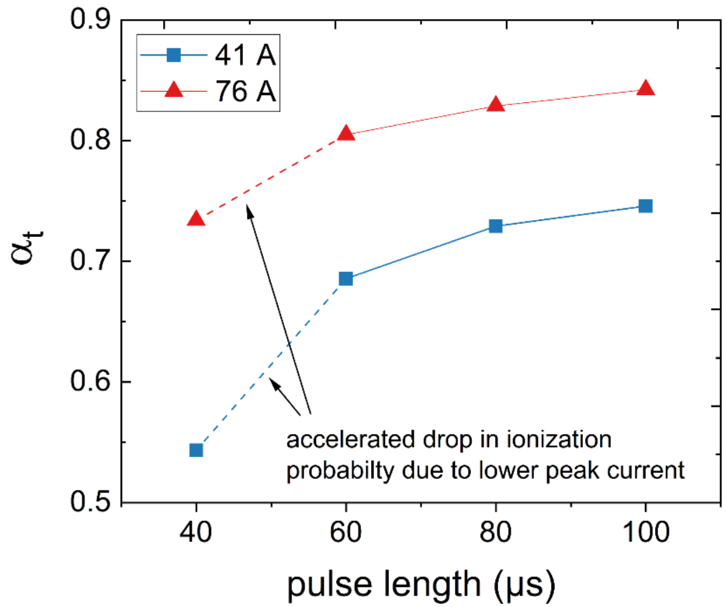
Internal discharge parameters α_t and β_t





Shorter pulses

- decrease target ion back-attraction β_t from larger contribution of afterglow to the flux out of the IR
- decrease ionization probability α_t
  - effect of shorter time for ionization
  - indicates limit for pulse length

Increasing $F_{\mathrm{dep}} = 1 - \alpha_t\beta_t$.

Overall constant $F_{\mathrm{flux}} = \frac{\alpha_t(1-\beta_t)}{(1-\alpha_t\beta_t)}$ for the discharge *and* the pulse lengths investigated

Brenning *et al.*, *JVSTA* **38**, 033008, 2020

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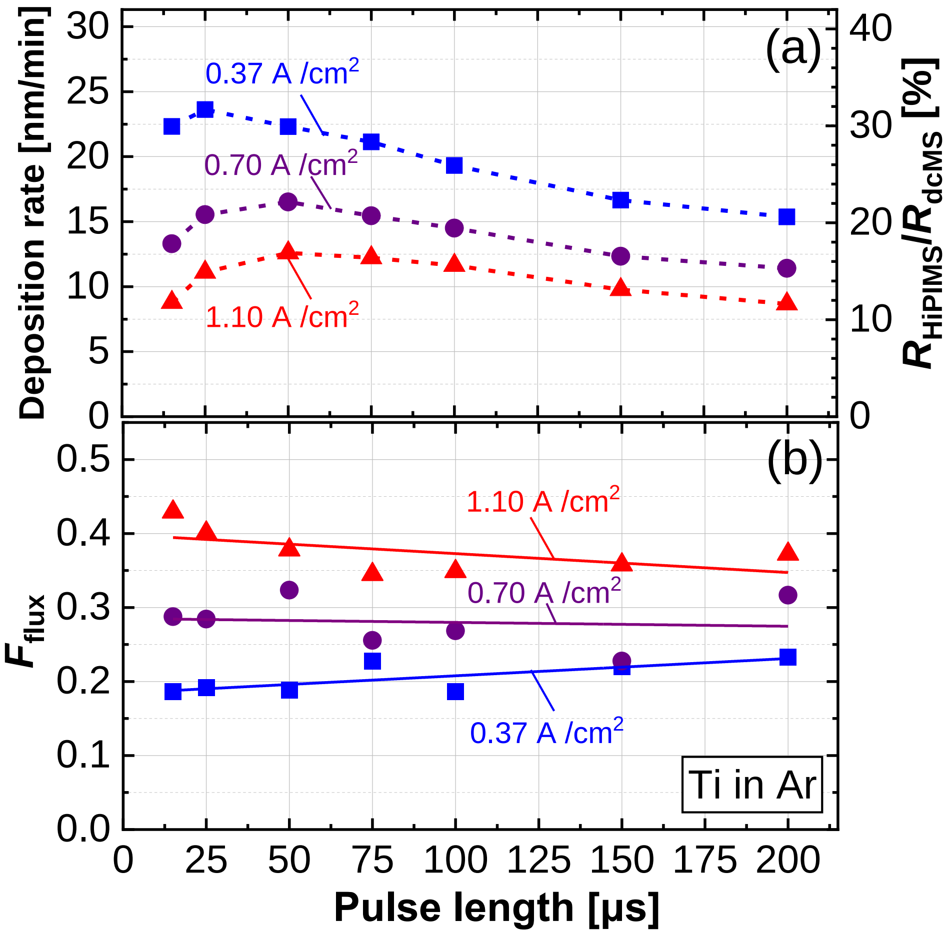
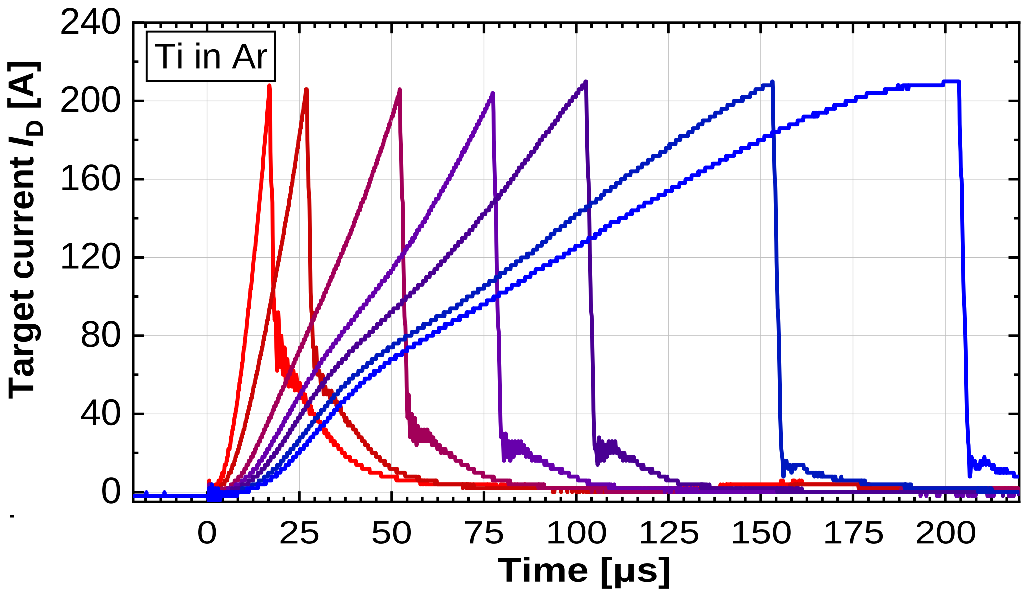
Experimental verification





6“ circular magnetron with Ti target
pulse length between 15 and 200 µs
peak discharge currents between 0.37 and 1.1 A/cm^2

Experiments verify the IRM findings.

Shimizu *et al.*, *PSST* **30**, 045006, 2021

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Conclusion and outlook

- Shortening the pulse lengths while keeping the peak discharge current high …

  - can partially recover the loss in deposition rate between dcMS and HiPIMS
  - gives a constant ionized flux fraction for the discharges and the pulse lengths investigated

    (see Rudolph *et al*, *PSST* **29**, 05LT01, 2020)

- Modelling results are supported by experiments
  (see Shimizu *et al*, *PSST* **30**, 045006, 2021)

Acknowledgmenets

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Free State of Saxony and the European Regional Development Fund,
University of Iceland Research Fund,
Swedish Research Council and the
Swedish Government Strategic Research Area in Material Science.

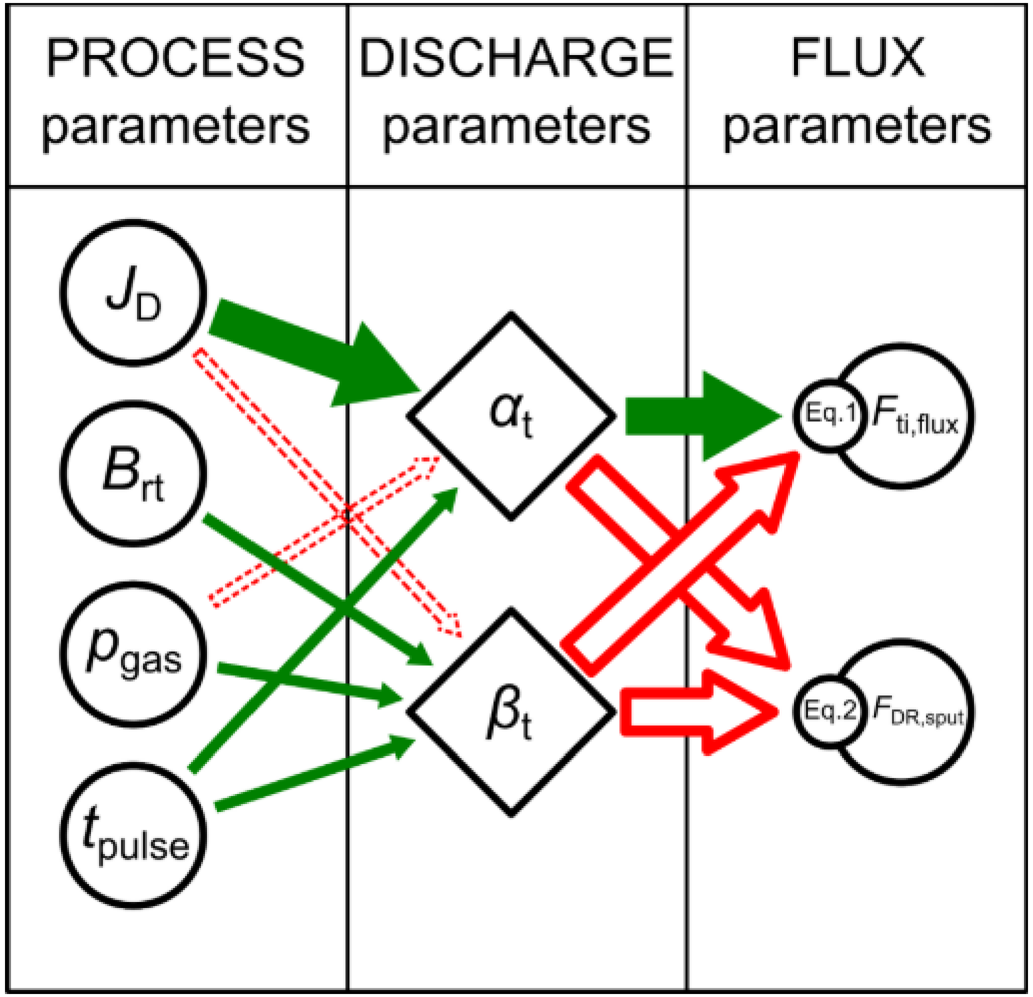
Appendix: HiPIMS optimization scheme

discharge current

magnetic field strength

working gas pressure

pulse length

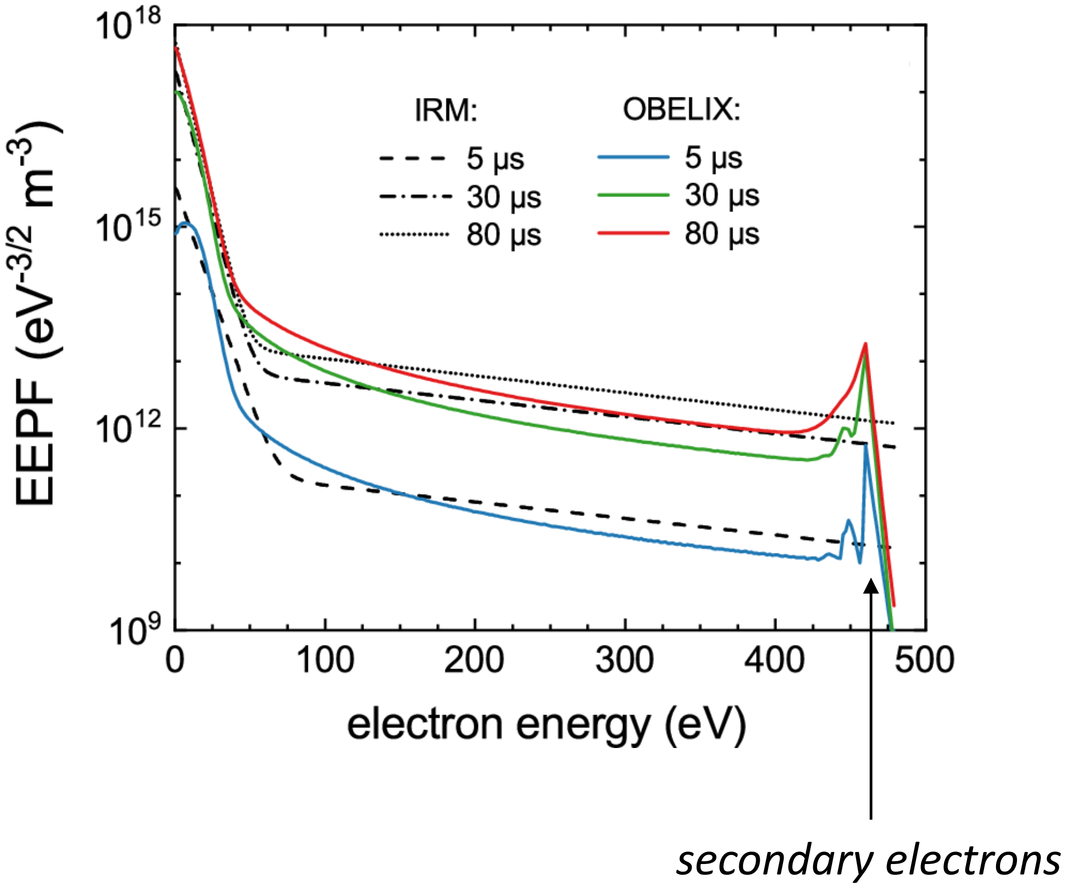


ionized flux fraction

deposition rate

Brenning *et al.*, *JVSTA* **38**, 033008, 2020

Appendix: EEPF in HiPIMS discharges



- IRM comparison to OBELIX*
  - IRM assumes bi-Maxwellian EEDF
  - Obelix solves the Boltzmann eq.
- Comparison shows a good match of the electron energy probability function (EEPF)

* **O**rsay **B**oltzmann equation for **EL**ectrons coupled with **I**onization and e**X**cited states kinetics (OBELIX)

Rudolph *et al.*, *PSST* **30**, 045011, 2021

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