FLASHForward▸▸ Plasma Targets

A short overview

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Outline

1. **Gas-targets and requirements**
    - Stable, reproducible plasma density profiles
    - No emittance spoilers
2. **Hydrogen fragmentation dynamics**
    - How does atomic and molecular behavior differ?
    - Special case: Ultrashort ionisation beams
3. **Diagnostics**
    - Options for density and homogenity determination of upcoming plasma targets
4. **Plasma based beam optics**
    - compact high field strength focussing

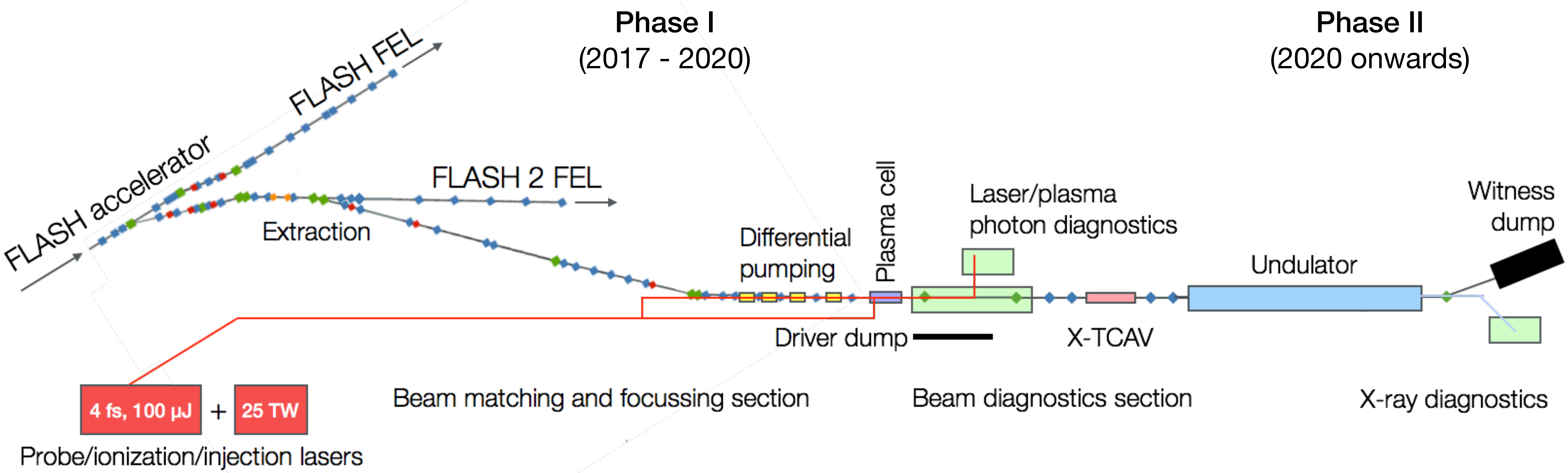
FLASHForward beamline

FLASHForward is

- an extension to the FLASH 1.2 GeV superconducting RF FEL facility
- a new experiment for beam-driven plasma wakefield accelerator research

Scientific Mission

- to demonstrate beam quality from a plasma-based wakefield accelerator suitable for first applications in photon science as a stepping stone towards high-energy physics applications



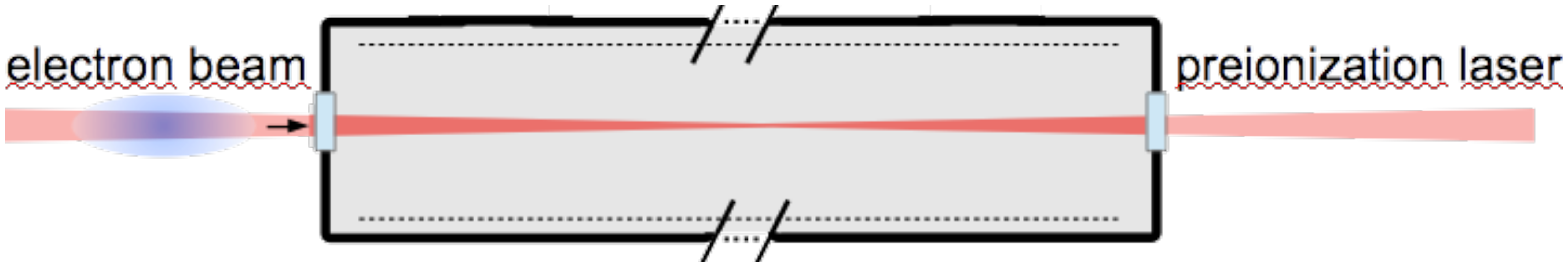
1: Requirements and resulting target concept

- compatible with accelerator vacuum standards at FLASH
- no emittance spoilers
- full transverse (optical) probing
- easily replaceable (8h)
- failsafe operation
- supporting multiple injection scenarios
- plasma density
  - acceleration: up to 5×10^{17} cm^{-3}
  - injection: up to 5×10^{18} cm^{-3}
  - recent modification:
    few 10^{19} cm^{-3} for targets of few cm length

1: General gas target concepts

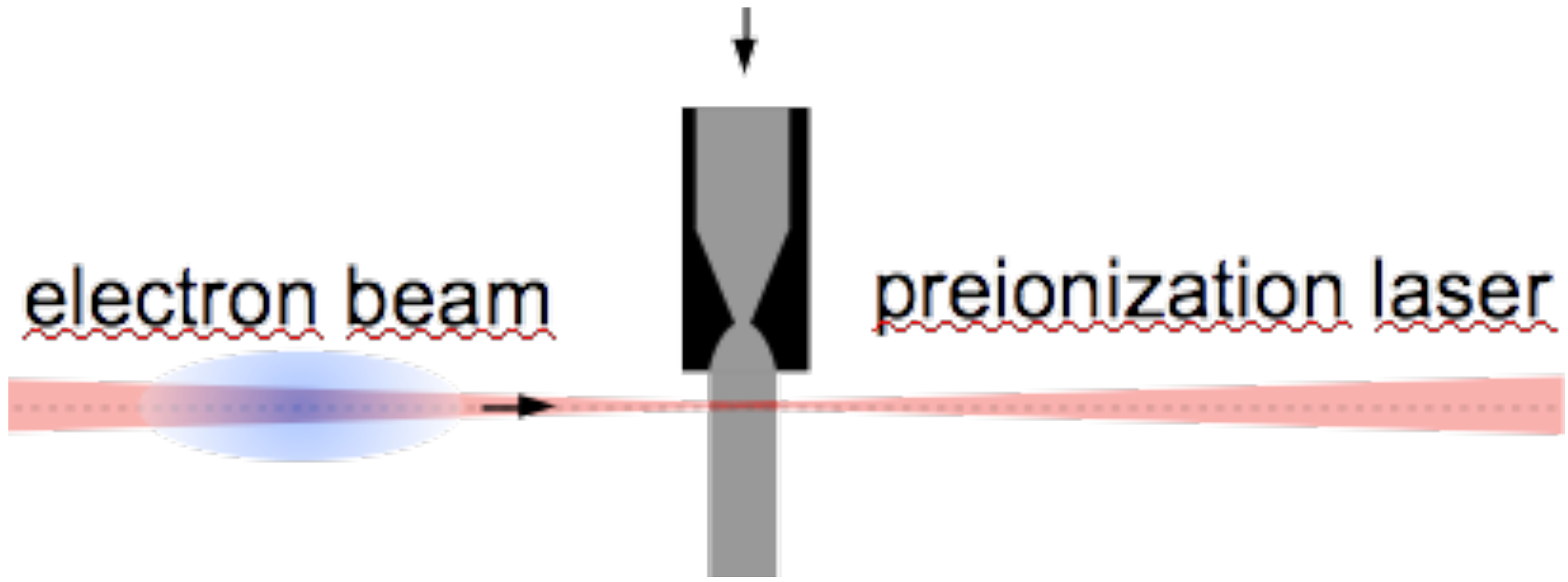
Gas Vapour Ovens:

- density controlled thermally (slow)
- proven homogeneity especially for long targets
- operation usually with windows



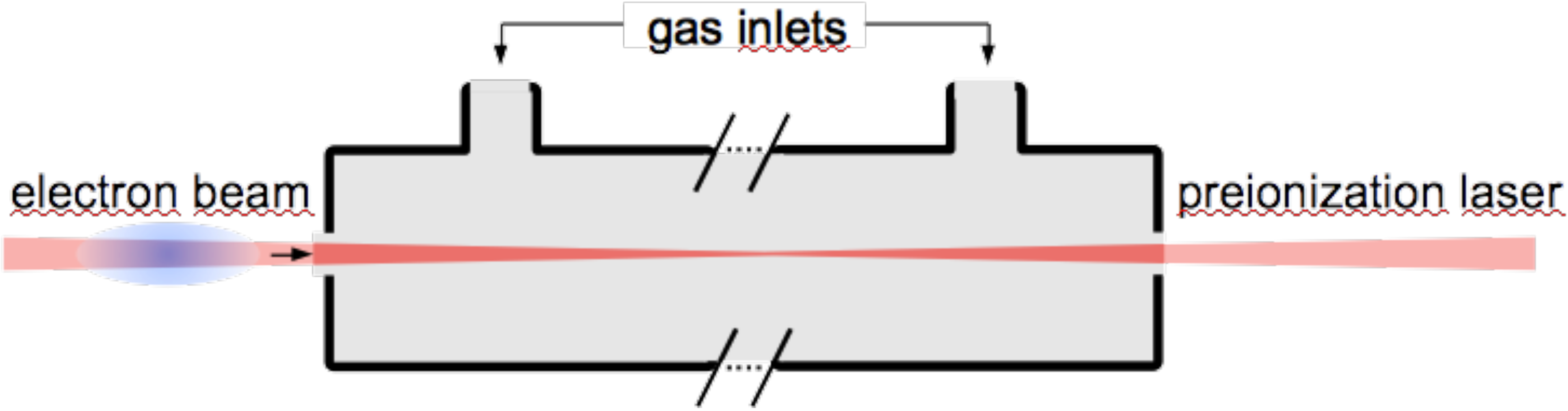
Gas Jets:

- pulsed operation
- poor scaling for long targets
- Valve components not suitable for accelerator vacuum



Gas Cells:

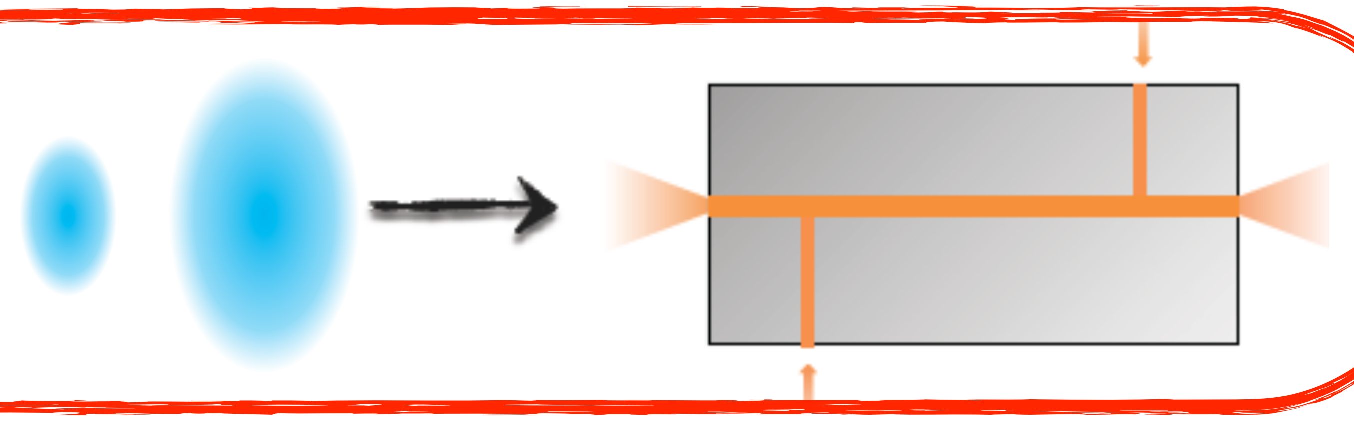
- large volume / long filling times
- homogenous gas density distribution
- windowless design with components suitable for FLASH vacuum
- Optional: Plasma generation via electrical HV discharge



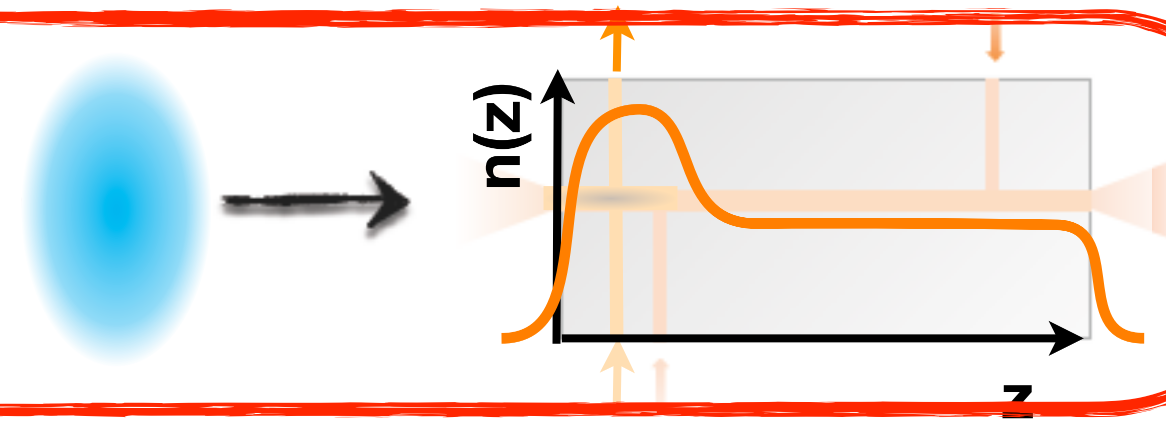
1: Injection scenarios

- Quality of accelerated beam strongly linked to control over initial population of wake-phase space at injection
- Required: Plasma target structures with sufficient flexibility

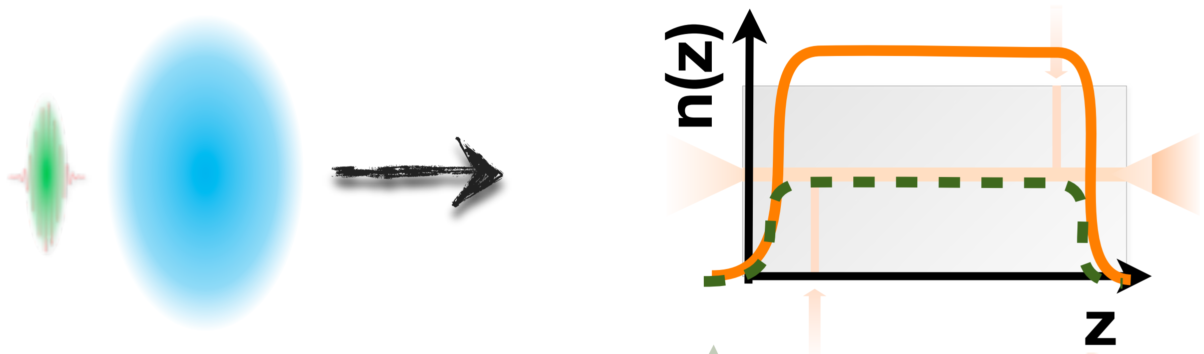
- *External:* witness generation at photo gun by second laser pulse and transport through accelerator to plasma cell
  - → first double bunch generation experiments performed
  - → Experimental aims: staging study, bunch emittance evolution



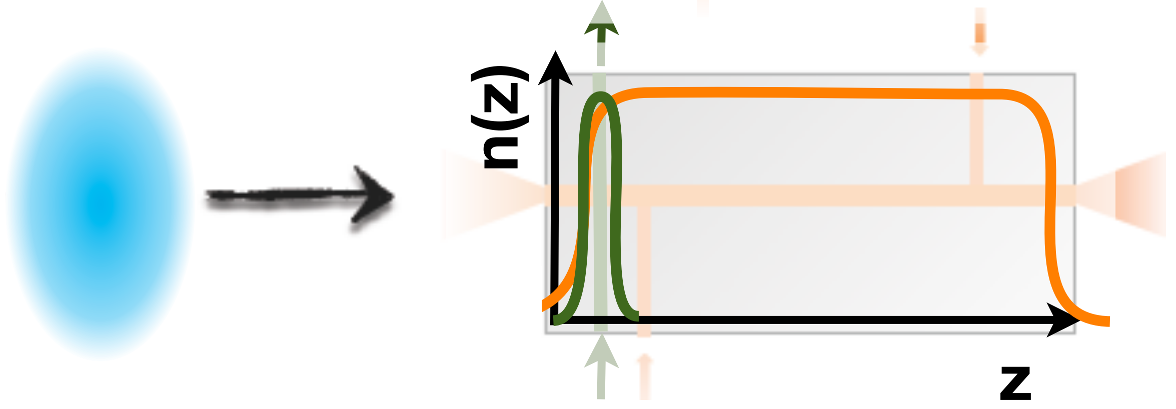
- *Internal:* density-downramp injection
  - → J. Grebenyuk *et al.*, NIM A **740**, 246 (2014)
  - → injection on negative density gradient
  - → demonstrated only in LWFA, new concept to PWFA



- *Internal:* laser-triggered ionization injection (“Trojan Horse”)
  - → B. Hidding *et al.*, Phys. Rev. Lett. **108**, 035001 (2012)
  - → interesting because of ultra small emittance (~ nm)
  - → few fs synchronization required → available at **FLASH**



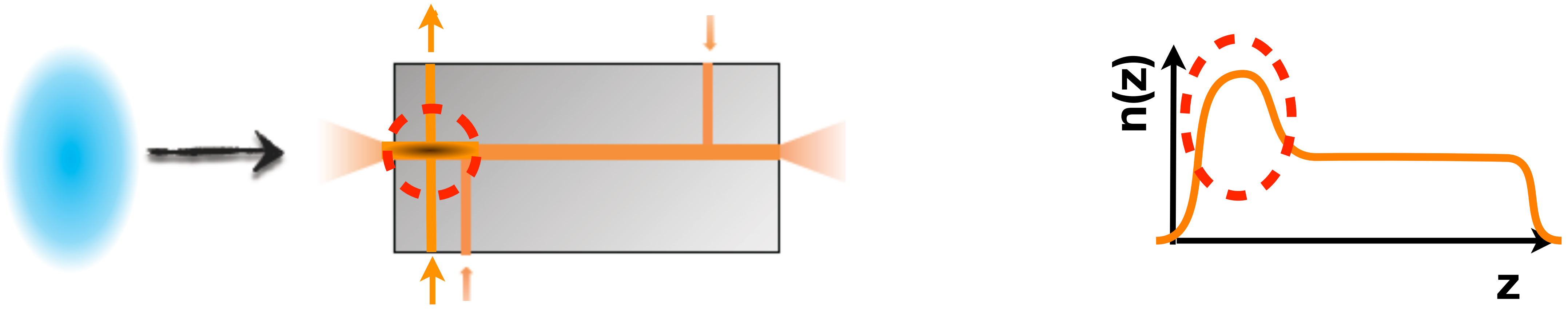
- *Internal:* beam and wakefield-triggered ionization injection
  - → A. Martinez de la Ossa *et al.*, NIM A **740**, 231 (2014)
  - → sub-fs bunches, kA current, sub µm emittance
  - → requires beam current higher than 7.5 kA



1: Density-downramp injection

Fluid dynamic downramp concepts:

- single gas species, all ionized via pre-ionisation laser
- gas velocity based, require higher pressure applied to a dedicated gas distribution port
- concept: expansion to increase from nozzle (jet like)



- downramp length determined by hydrodynamic properties
- here: DC operation required since no fast gas valves allowed (vacuum requirements)
- result: high gas flux required, demanding for vacuum pumps!
- Flow can be reduced by modifying density transition. e.g. razorblade, ...

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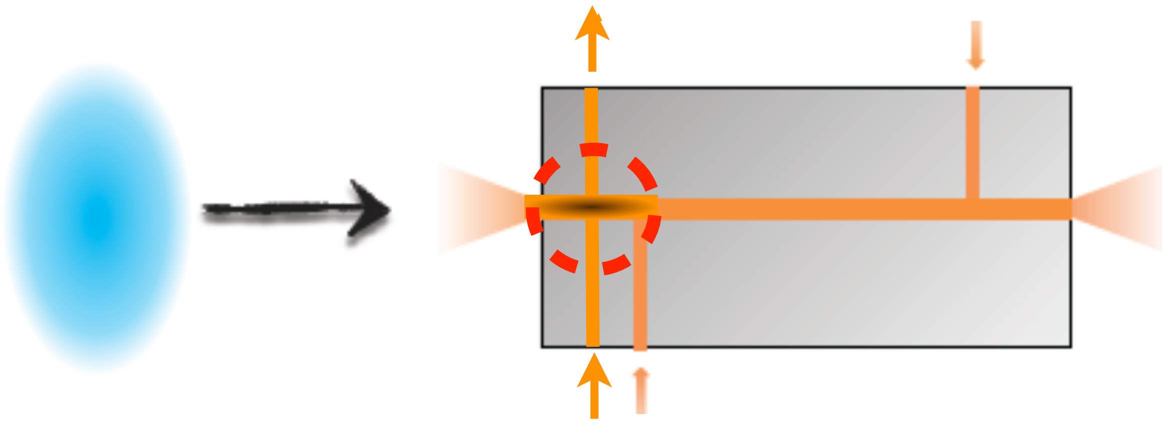
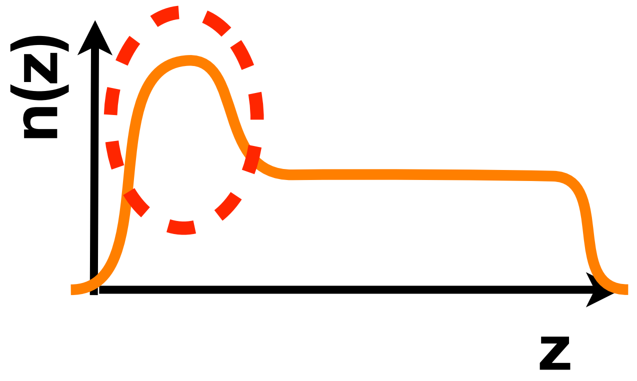
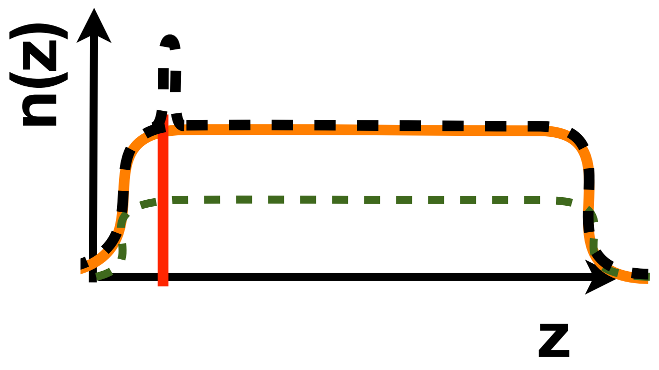
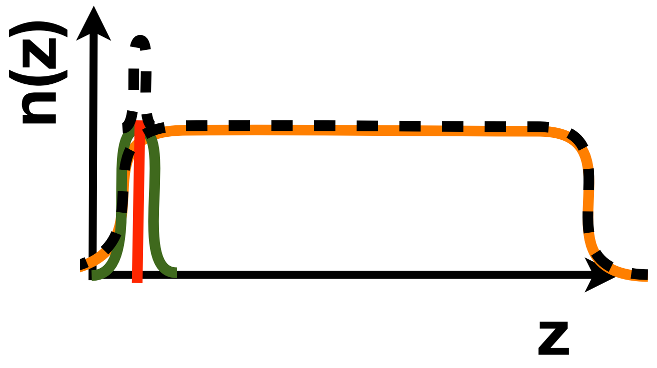




Ionisation based downramp concepts:

- multi-species gas density distribution, either with pre-mix or localized addition
- pre-ionization laser only ionizes single species, second species ionized by transverse laser pulse
- strongly localized ionisation, ionisation volume and density gradient determined by laser-properties



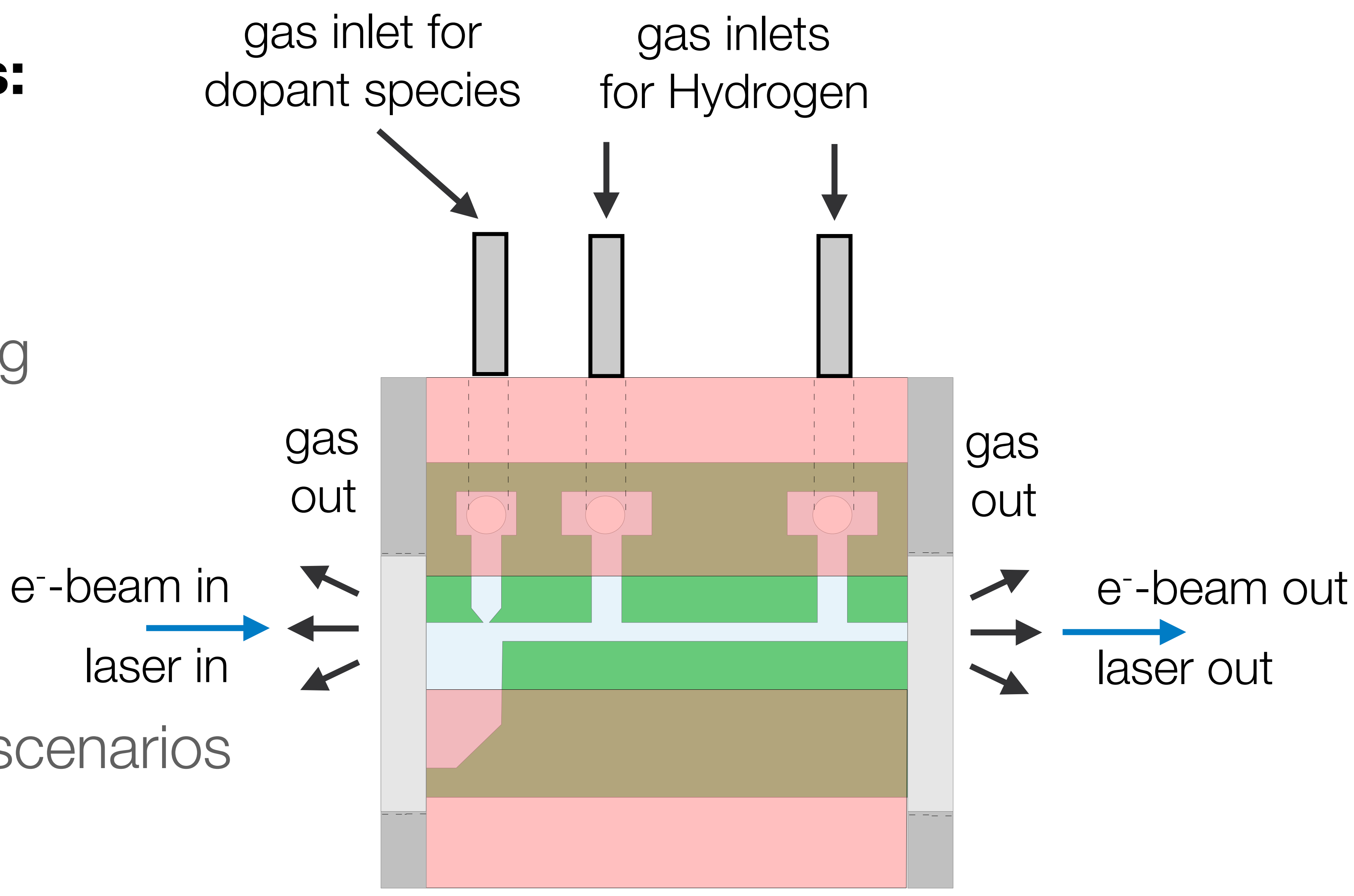


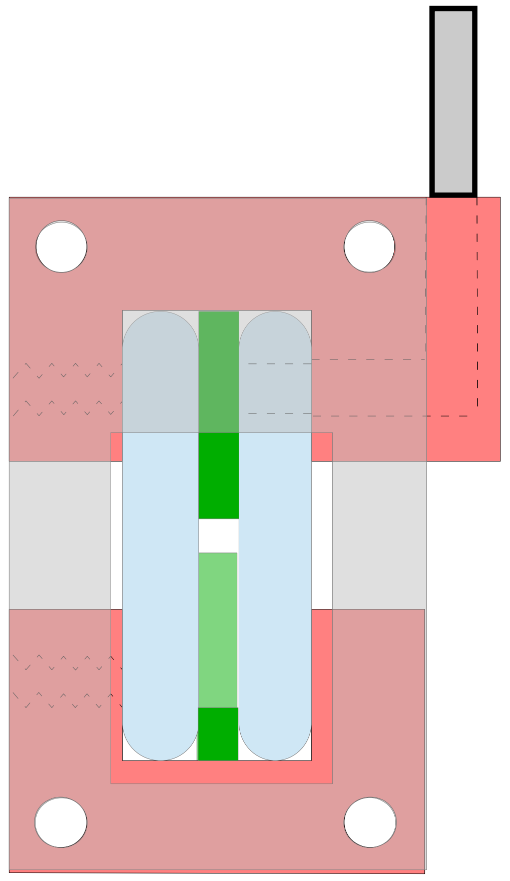
demonstrated at E210

1: Requirements and resulting target concept

Desired design requirements:

- no emittance spoilers
- full transverse (optical) probing
- easily replaceable (8h)
- failsafe operation
- supporting multiple injection scenarios
- plasma density
  - acceleration: up to 5 x 10^{17} cm^{-3}
  - injection: up to 5 x 10^{18} cm^{-3}
  - recent modification: few 10^{19} cm^{-3} for short distances



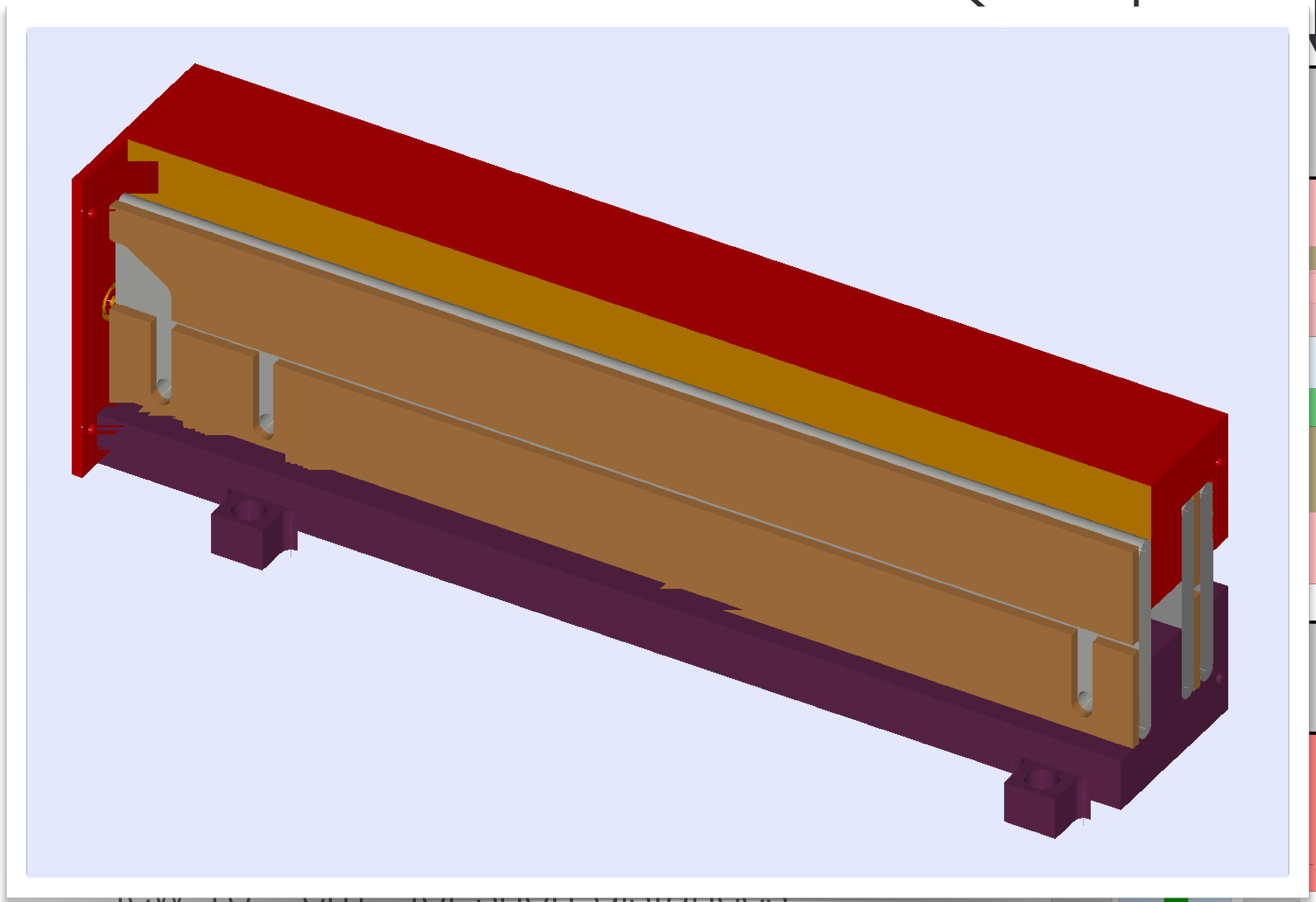


Target concept:

- Gas inlets
  - separate pressure control
  - multiple species operation
- Continuous gas flow design
  - no windows required
  - no soft valve seats
- “Nozzle” inlet included
  - Spatially confined species
  - localized density peak
- Transverse optical access
  - full profile diagnostics

1: Requirements and resulting target concept

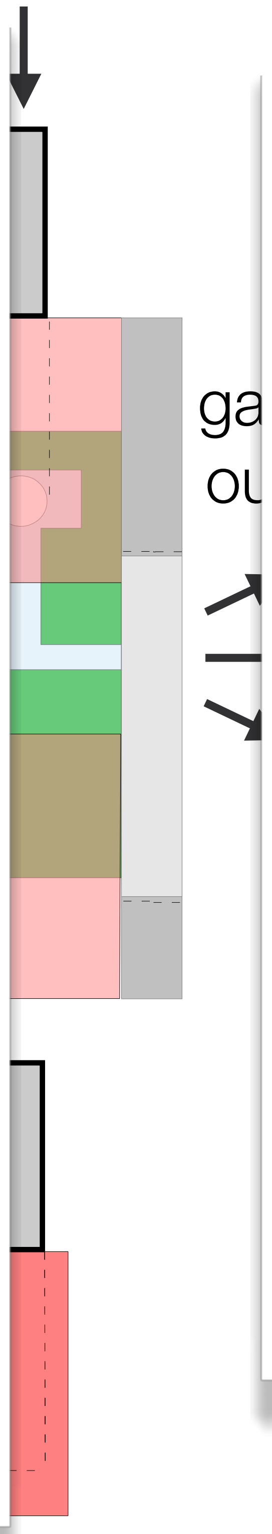
Desired design requirements:



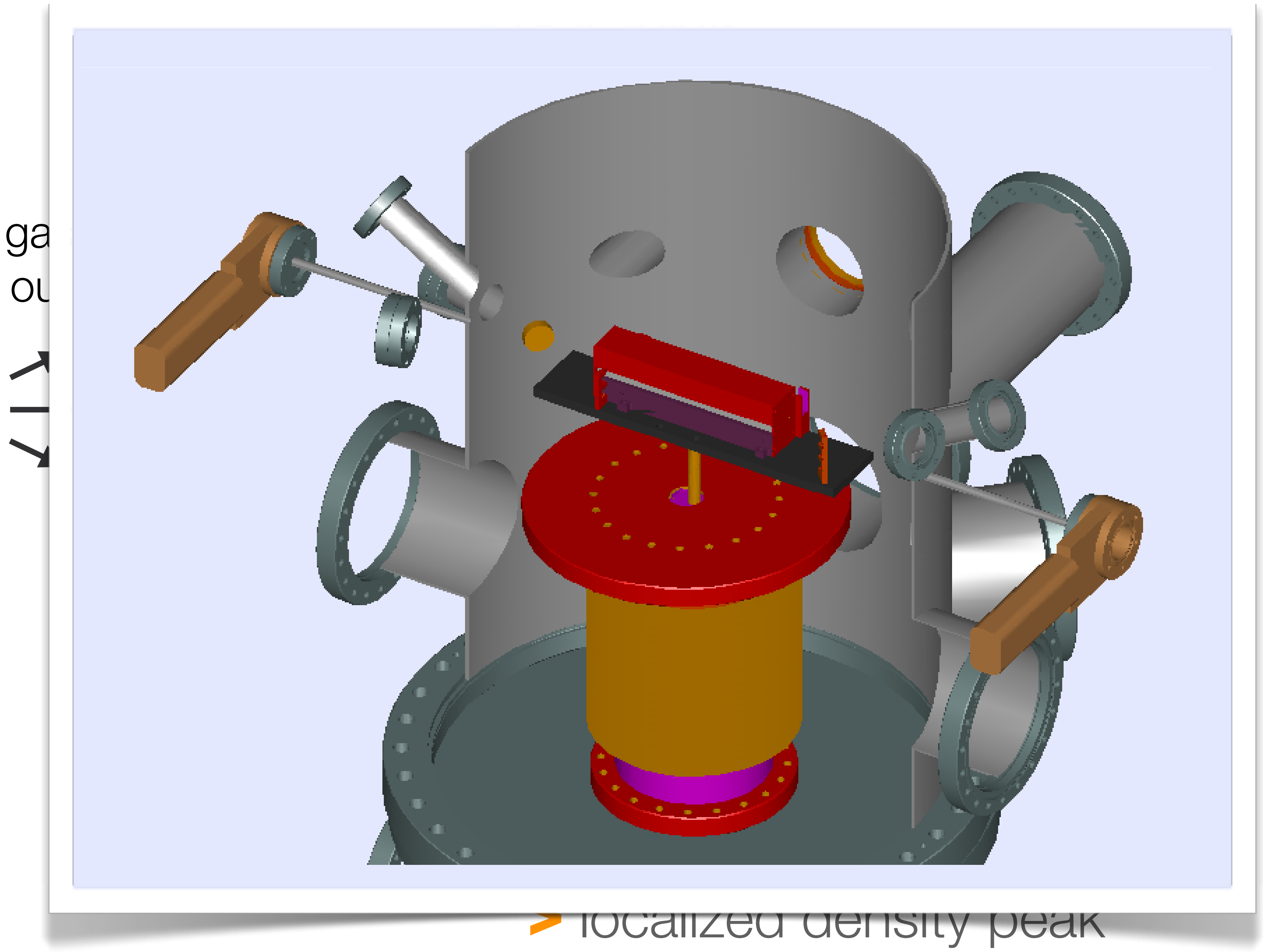
few 10 cm for short distances

gas inlet for
dopant species

gas inlets
for Hydrogen



Target concept:

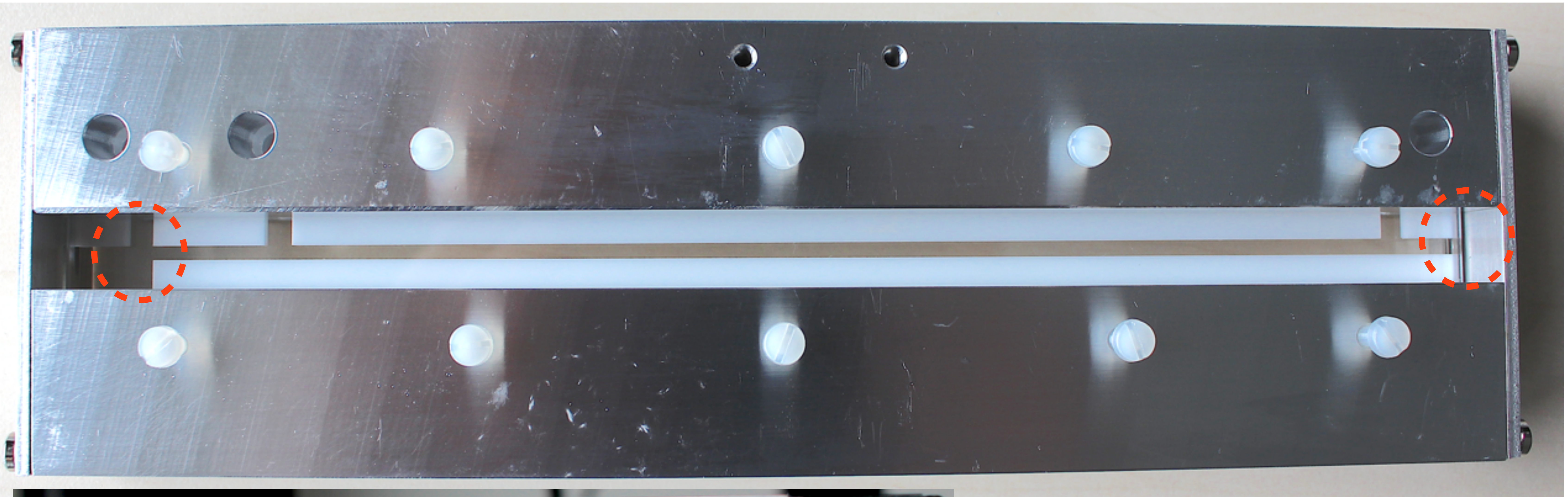


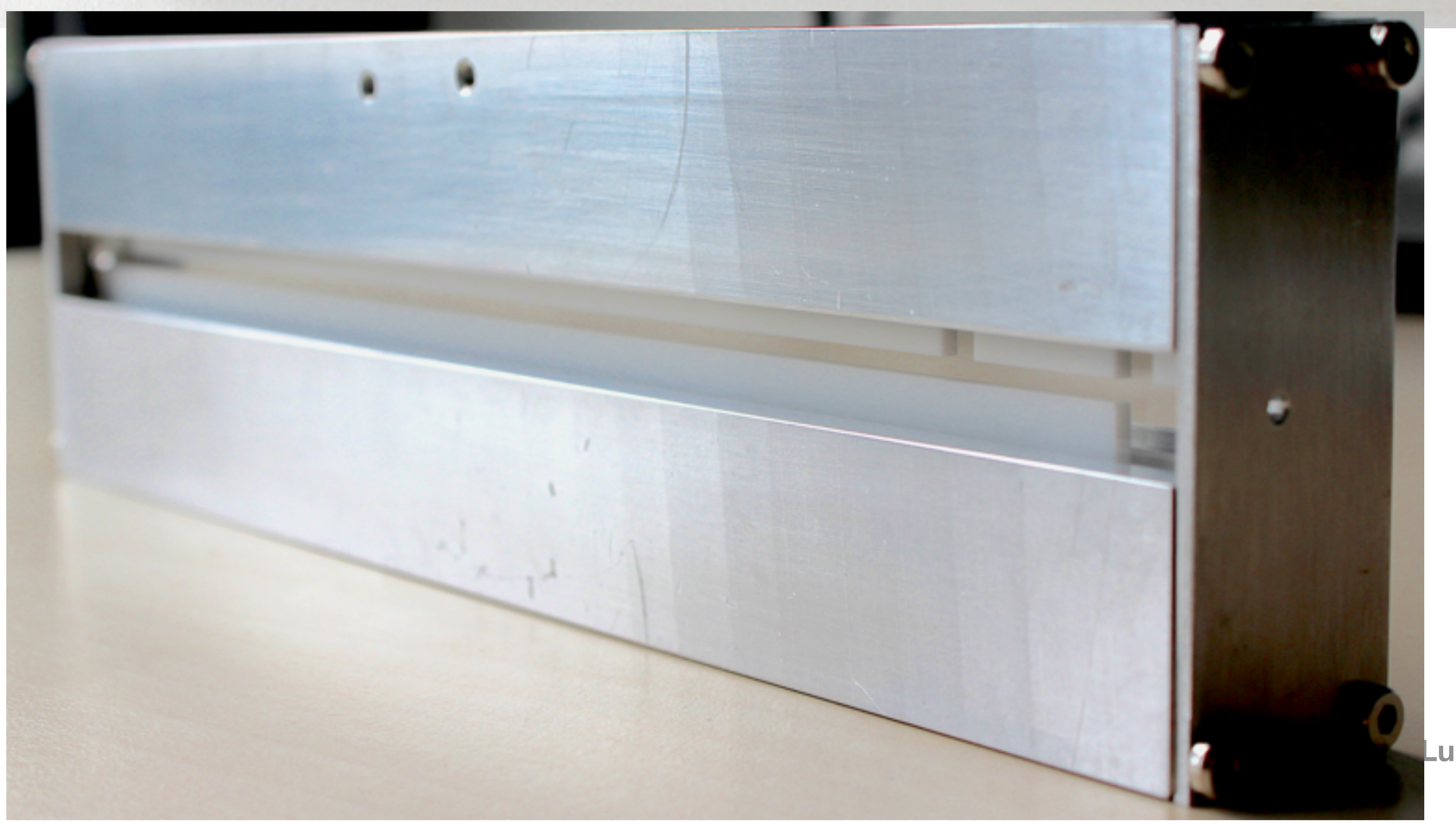
> localized density peak

> Transverse optical access

> full profile diagnostics

1: Target prototype



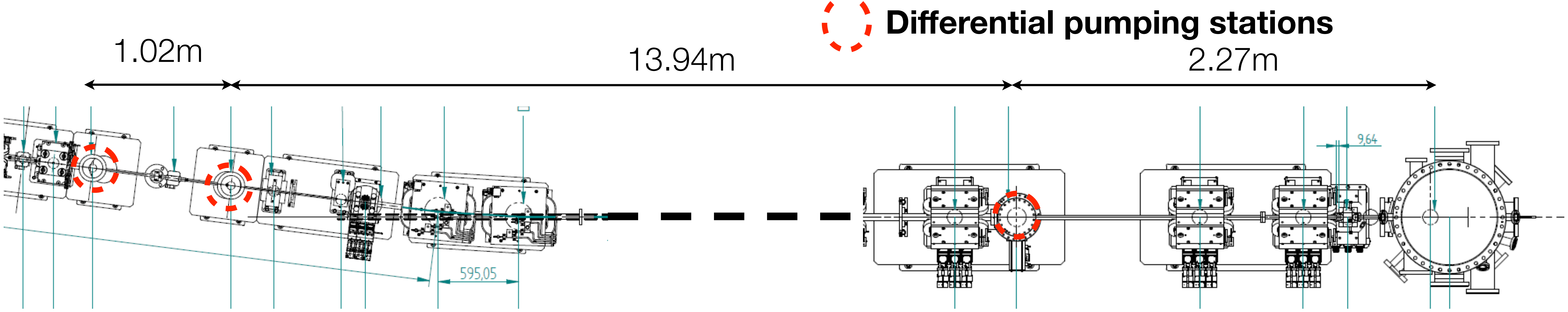


- First experiments with prototype target are expected in Q4 2016
- Crucial points: vacuum compatibility, leak rate, density distribution, lifetime

1. Gas removal

- Maximum continuous gas flow of **20 mbar l/s** hydrogen into main chamber
- at beamline intersection to FLASH2 pressure has to be < **10^{-8} mbar**
- additionally to main chamber 3 differential pumping sections in beam-line
- efficient for pumping: small diameter pipes
  bending magnet

- Pumping speeds required:
  - Experimental chamber:
    - 2500 l/s turbo pump, 450 m^3/h backing pump
  - First stage:
    - 600 l/s turbo pump, 35m^3/h backing pump
  - Second stage:
    - 600 l/s turbo pump, 35m^3/h backing pump
  - Third stage:
    - 450 l/s turbo backed by 300l/s turbo, 35m^3/h backing pump



1. Ionisationlaser in-coupling

- FLASH beam does not ionize by itself
- Laser inserted at final bending magnet
- Laser vacuum separated from beam line vacuum
- All reflective focussing optics and thin window to allow for small B-inetgral
- focal length of about 18m

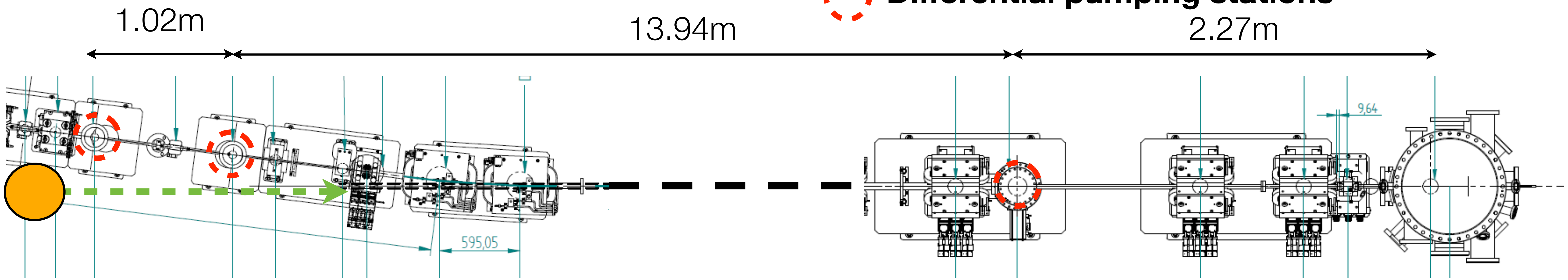
Currently:

- Starting first experiments with comparable focussing geometry
- Verify that plasma parameters are compatible with planned experiments

● **Focussing optics chamber**

➔ **Beampath of ionisation laser**

◌ **Differential pumping stations**



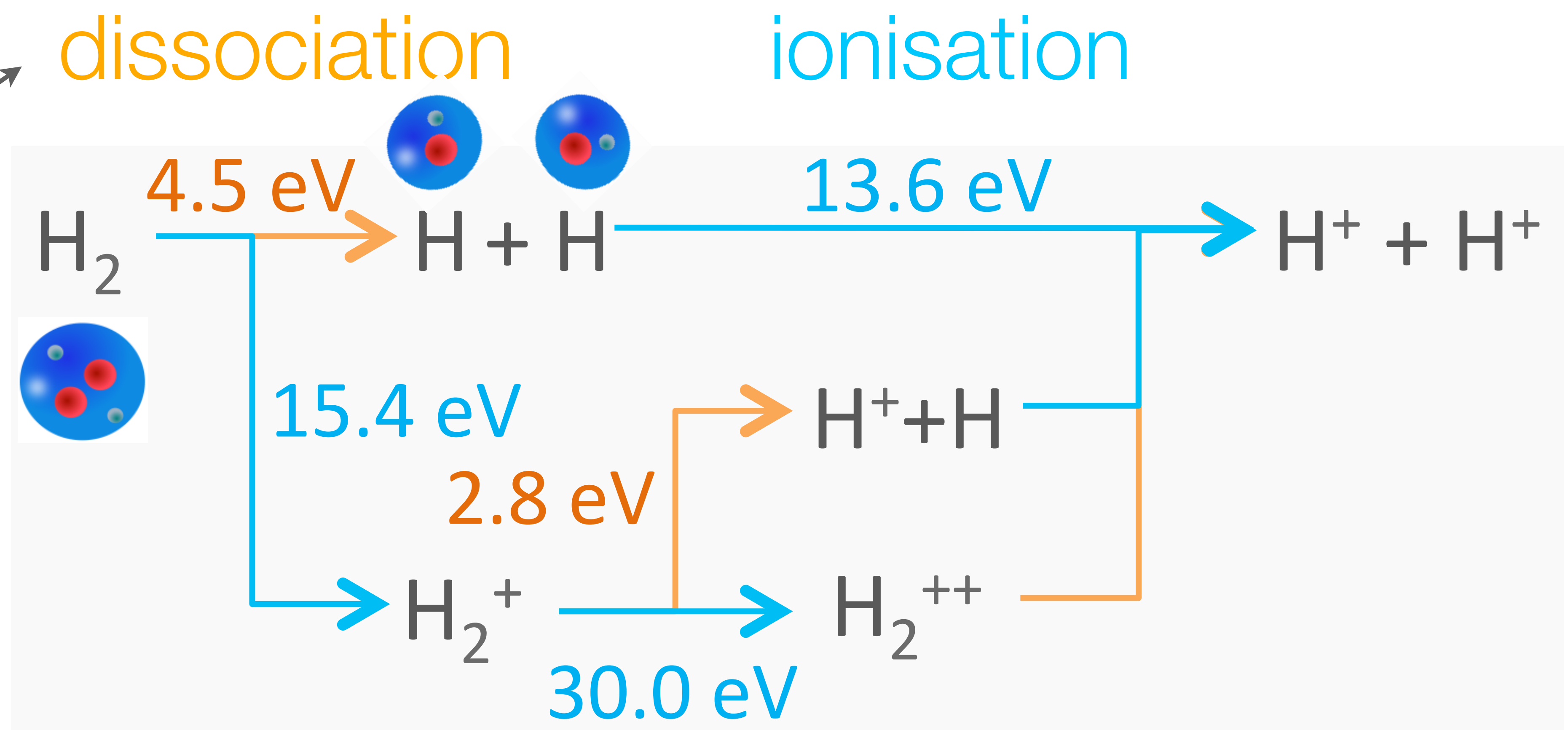
2: Ionisation: Atomic vs. molecular treatment

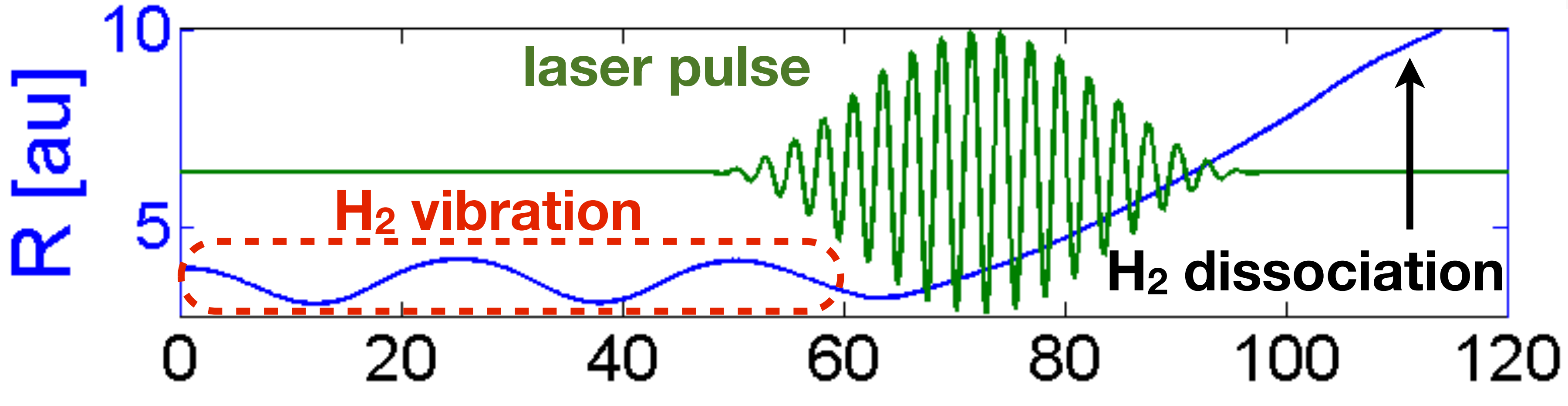
- So far atomic ionization potential used

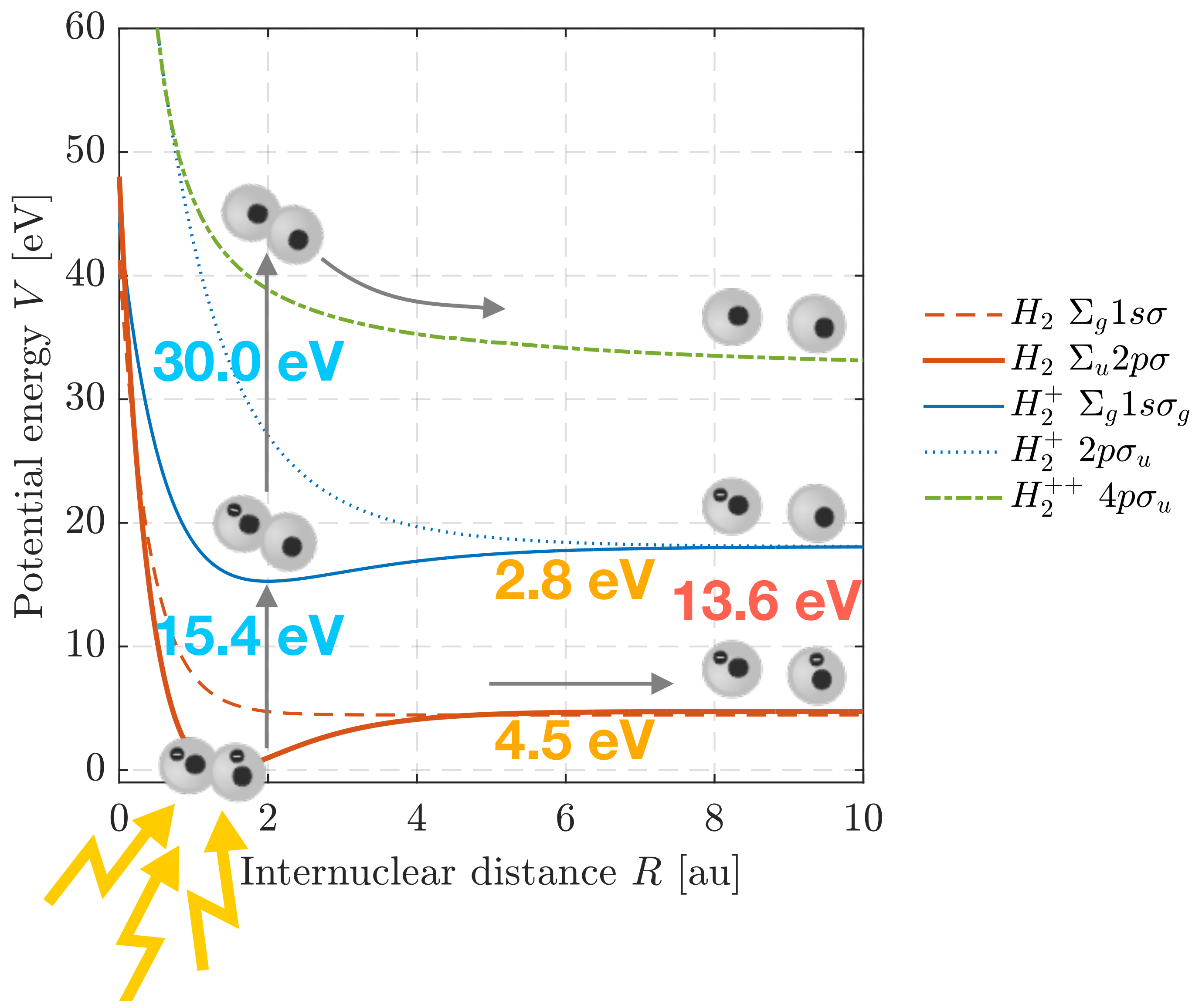
$$H \xrightarrow{13.6\ \mathrm{eV}} H^+ + e^-$$

- molecular fragmentation dynamics are more complex

takes time
H_2 ~ 20-40fs!

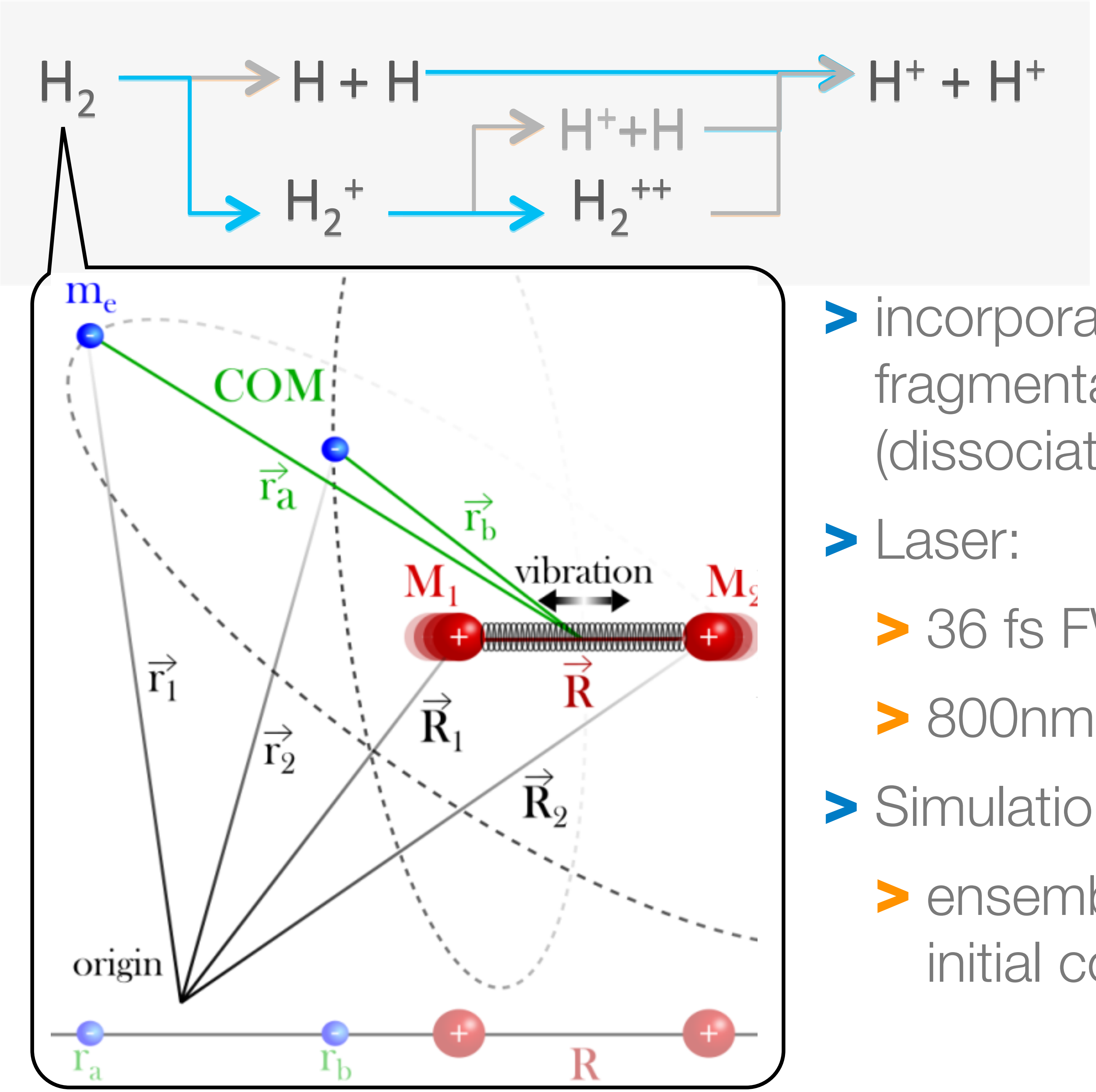






G. Tauscher et al., to be published

2: Fragmentation - Classical 1D model



- incorporating full fragmentation dynamics (dissociation & ionisation)
- Laser:
  - 36 fs FWHM gaussian
  - 800nm
- Simulation:
  - ensemble with varying initial conditions (1000)

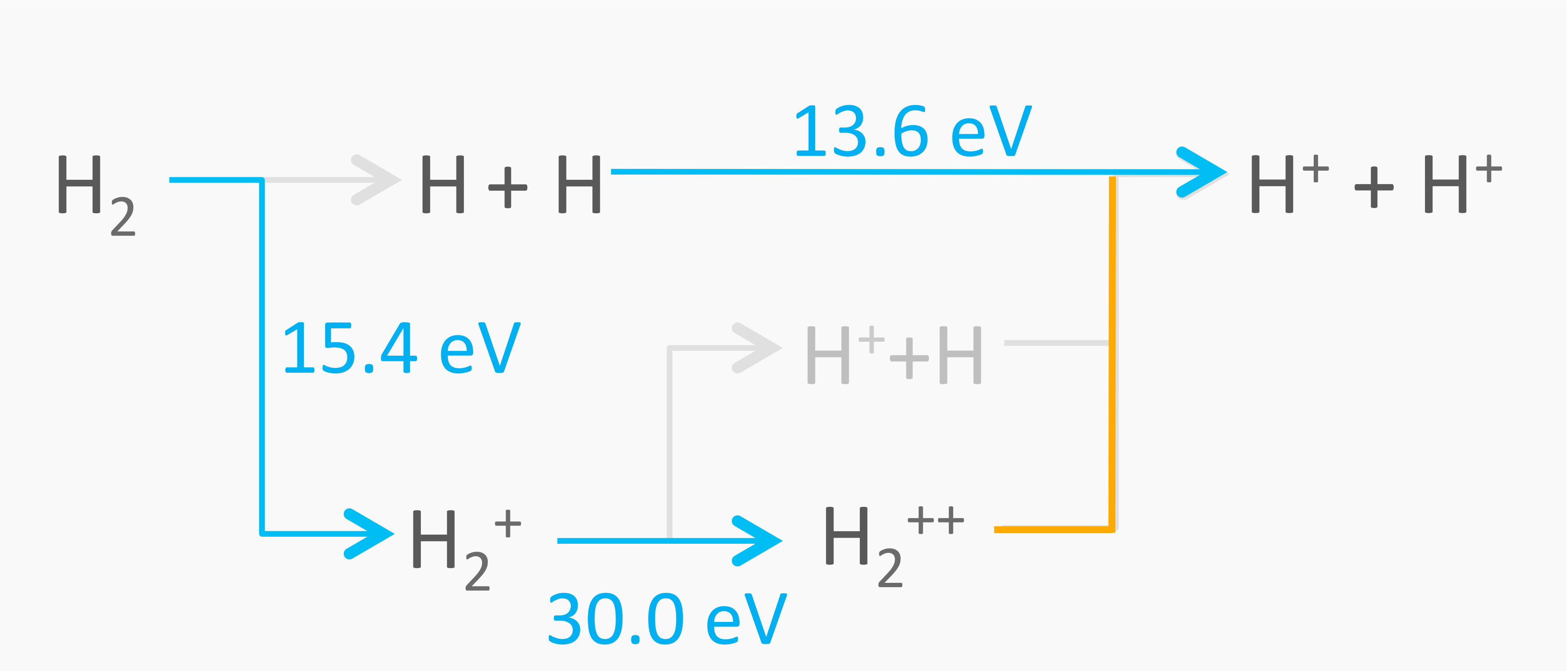
[1] Qu et al., Phys. Rev. A vol. 57 no. 6 (1998)

- Dissociated hydrogen barely ionises at end of pulse!
- Short pulses:
  Dissociative path does not contribute for full ionisation cases.

to be published...

G. Tauscher et al., to be published

2: Pure ionisation channels - atomic vs molecular



H_2

$H + H$

13.6 eV

$H^+ + H^+$

15.4 eV

$H^+ + H$

H_2^+

H_2^{++}

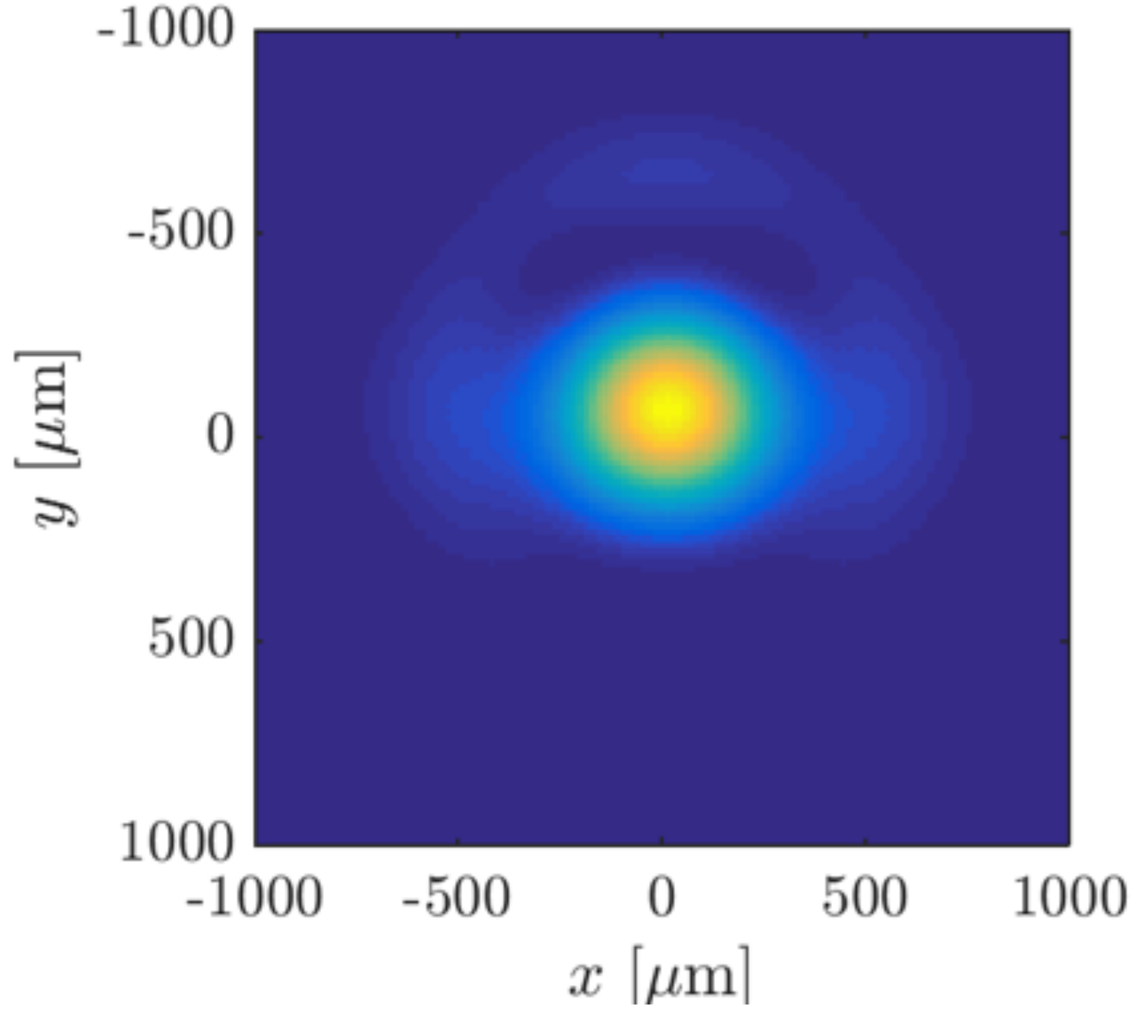
30.0 eV

- Ionisation treatment
  - Rate equations describing population
  - Γ_{TBSI} : ionisation rates via extended ADK theory
- Laser:
  - 18 fs FWHM gaussian
  - 800nm

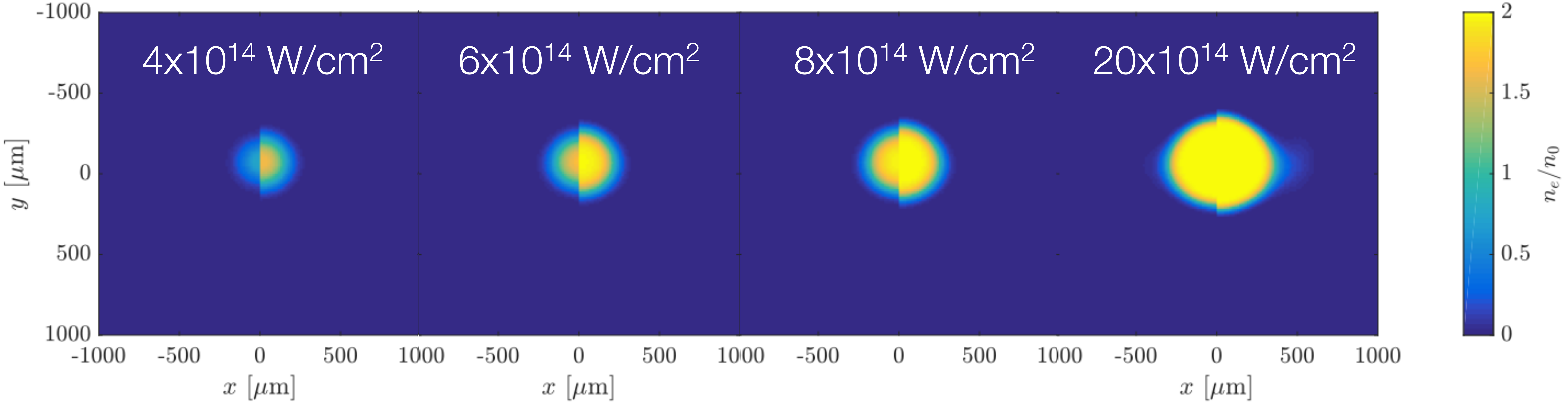
to be published...

G. Tauscher et al., to be published

2: Resulting electron densities at focus



- Focus of ideal gaussian laser beam using 2 spherical mirrors ~3° off axis through 2mm quartz-glass window
- Initial beam diameter 45mm 1/e^2, f_{res} ~18m
- Laser pulse duration 25fs FHWM

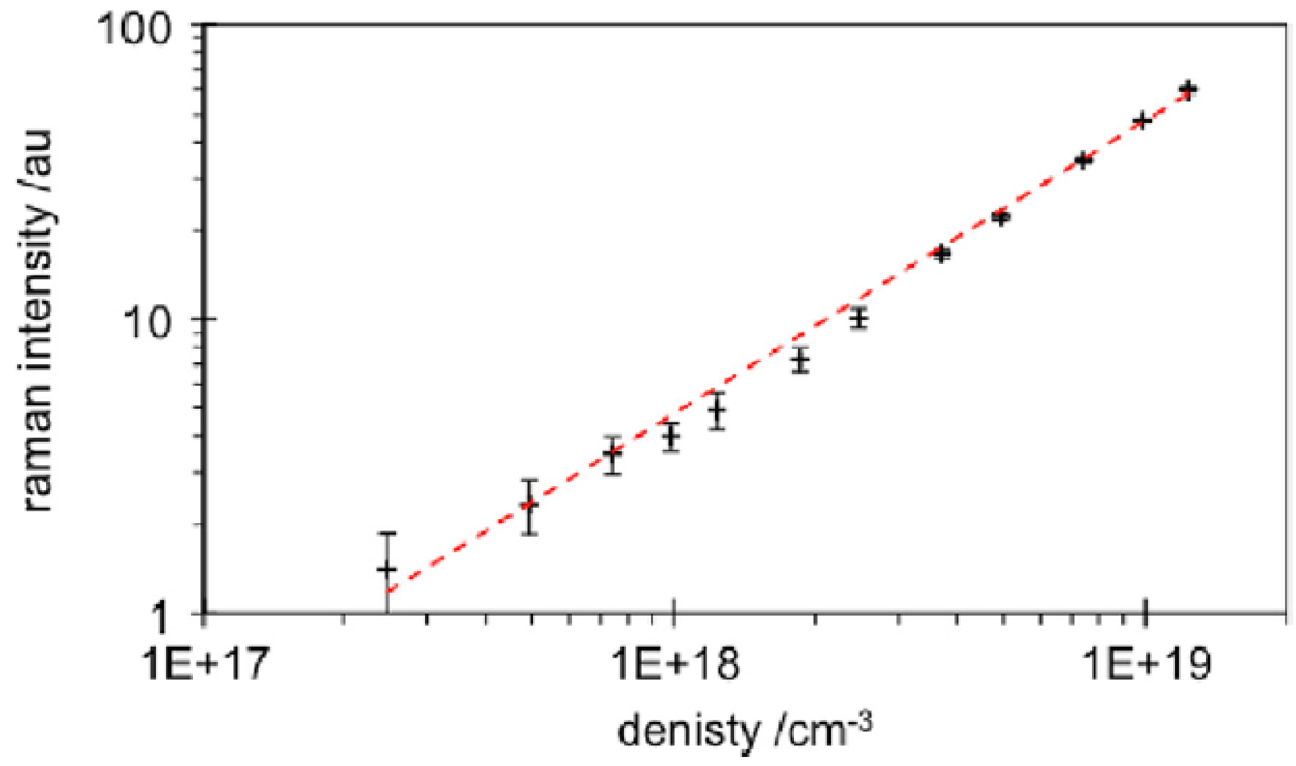


3: Diagnostics: Considerations

- Low density requires novel diagnostic techniques
  - Interferometry reliable down to ~ 10^{18} cm^{-3}
- Gas profilometry as a first characterization
  - Initial species-specific gas distribution
  - Photon scattering on gas molecules
  - Benchmark for CFD simulations
- Use emitted light for diagnostics: Plasma spectroscopy
  - Online measurement
  - Non invasive
  - spatial and temporal resolution

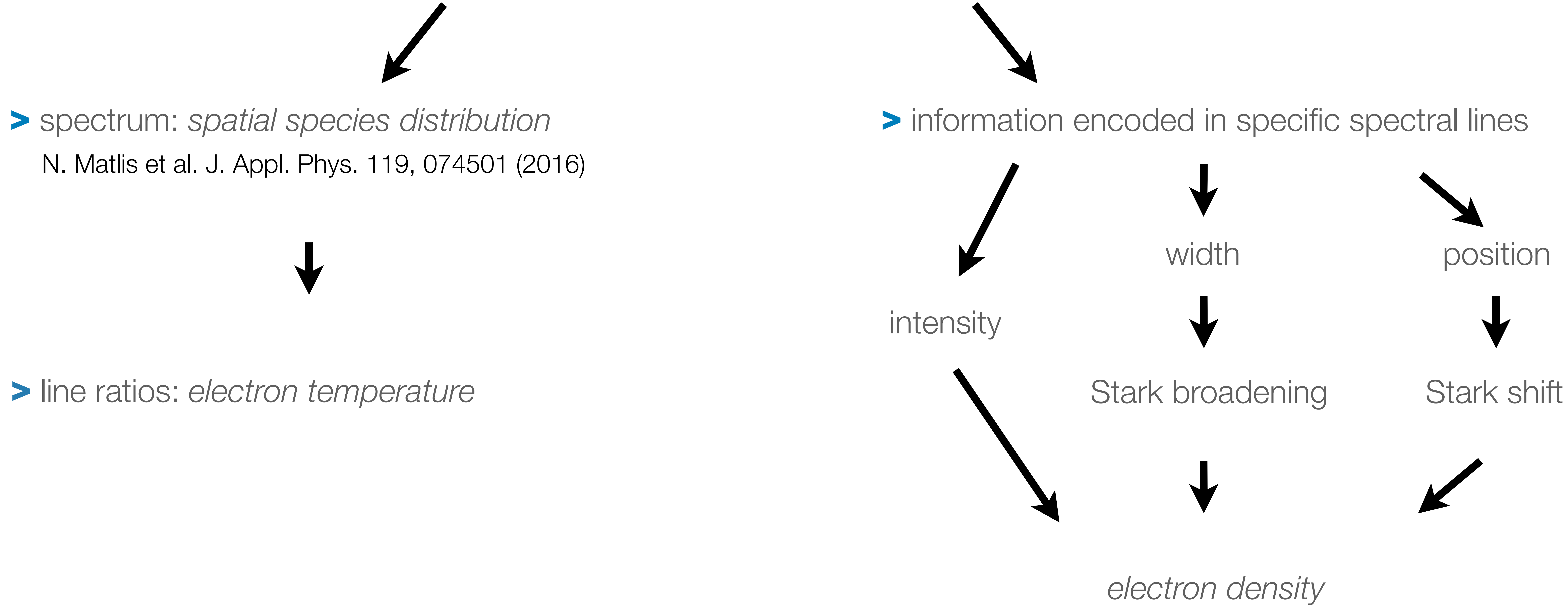
Longitudinal interferometry: No local information

Raman scattering: shown effective down to ~ 10^{17} cm^{-3}



3: Plasma Spectroscopy

> Light emitted by the plasma is a fingerprint of the plasma properties



> spectrum: *spatial species distribution*

N. Matlis et al. J. Appl. Phys. 119, 074501 (2016)

> line ratios: *electron temperature*

> information encoded in specific spectral lines

intensity

width

position

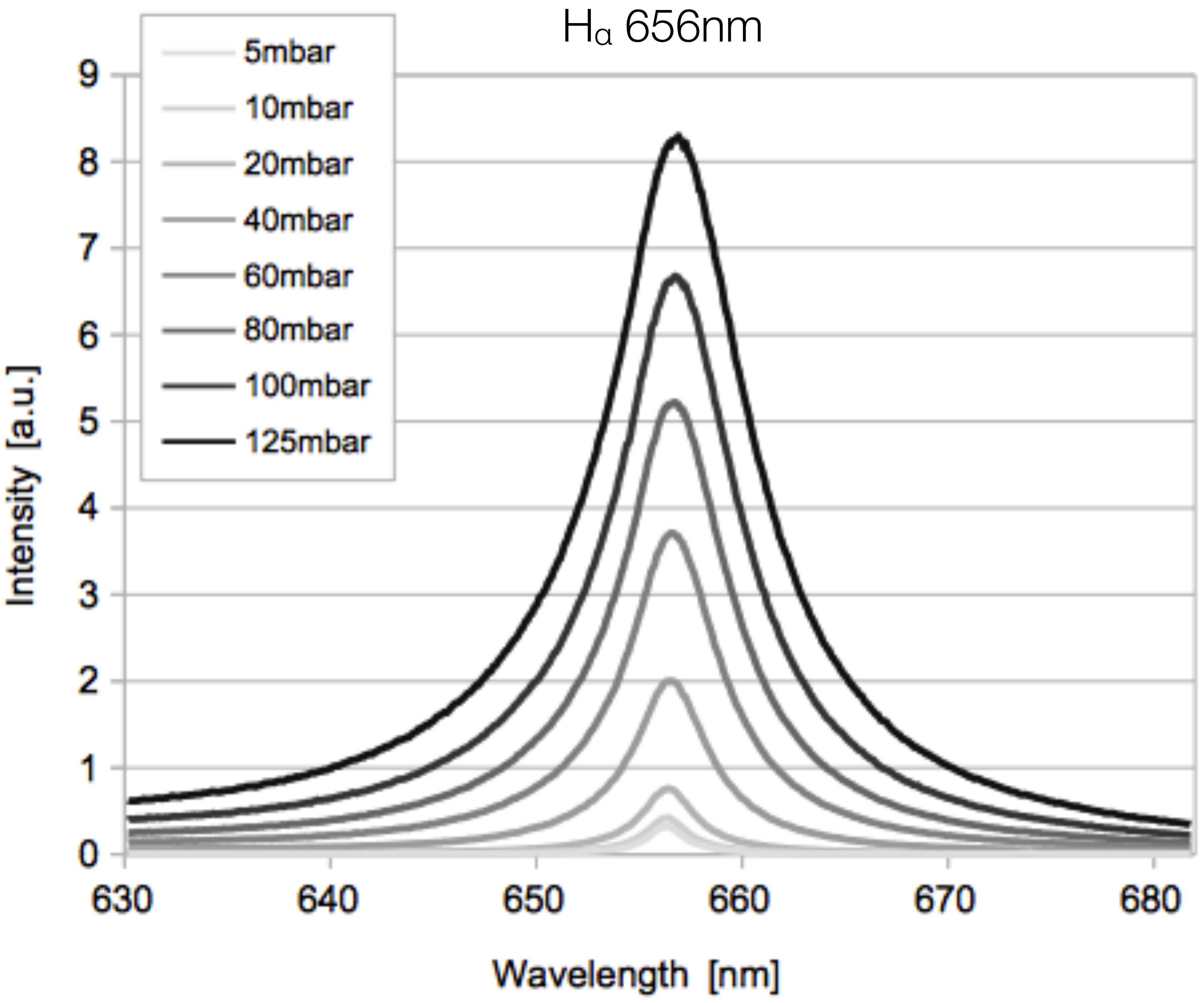
Stark broadening

Stark shift

electron density

> however: decoding information from spectroscopic information can be tricky

3: Density dependent line width and wavelength

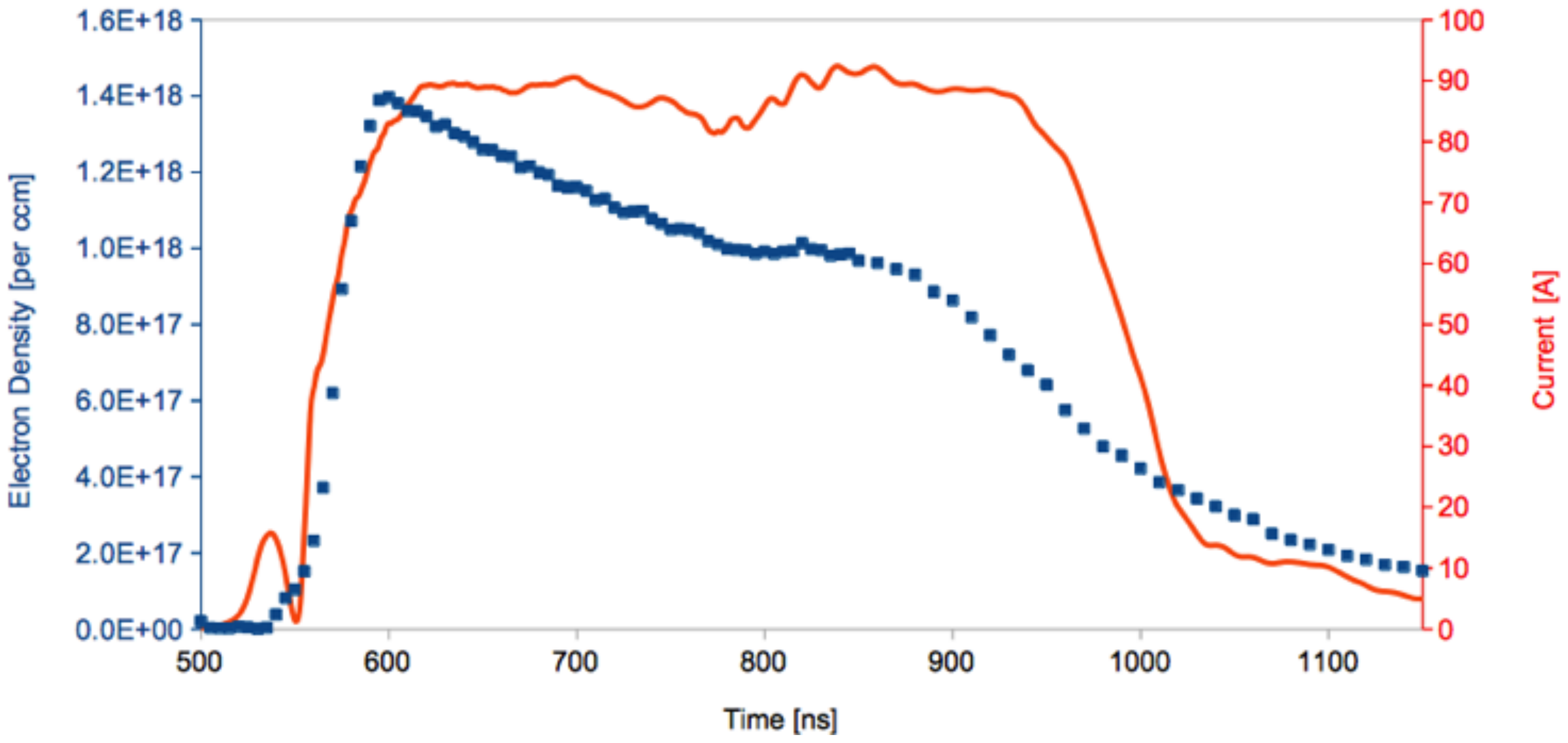


to be published...

L. Goldberg et al., to be published

3: Density determination via Stark Broadening

- FWHM[1,2] and shift linked to electron density
  - $n_e = C\,\Delta\lambda_{FWHM}^{3/2}$
- Instrument resolution (currently) 2.5×10^{15} cm^{-3}
- 2fs temporal, down to few µm spatial resolution
- currently: Obtaining calibration constant via cross calibration



to be published...

L. Goldberg et al., to be published

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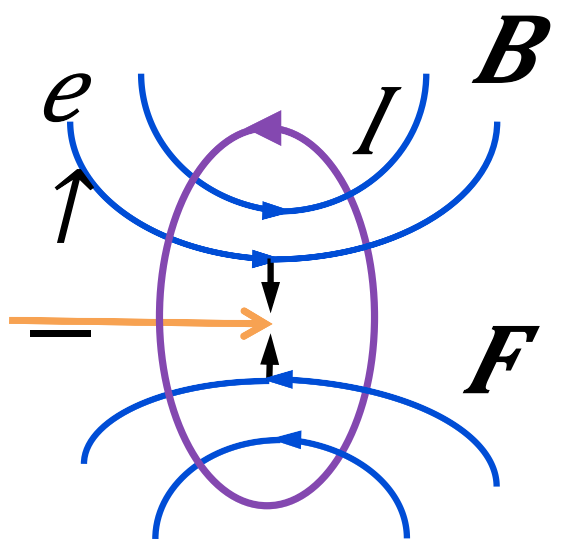
[1] H. Griem et al., Phys. Rev. 116, 4-16 (1959)

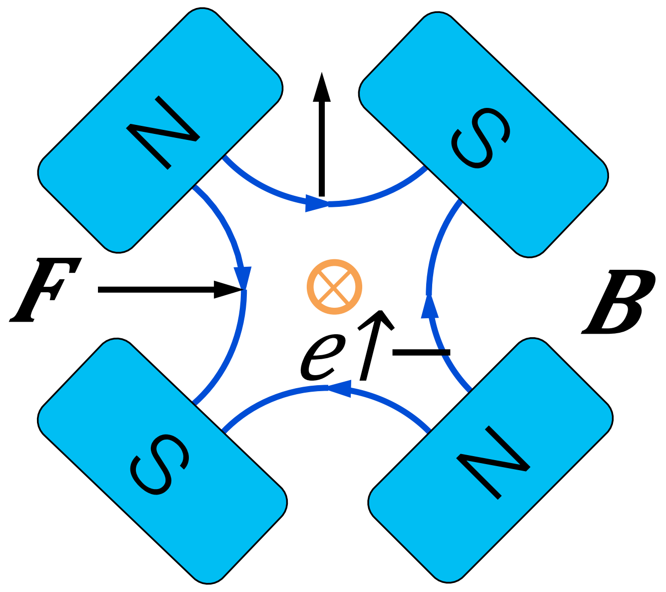
[2] J. Ashkenazy et al., Phys. Rev. A 43, 5568-5574 (1990)

4: Focussing beam optics



Solenoid:

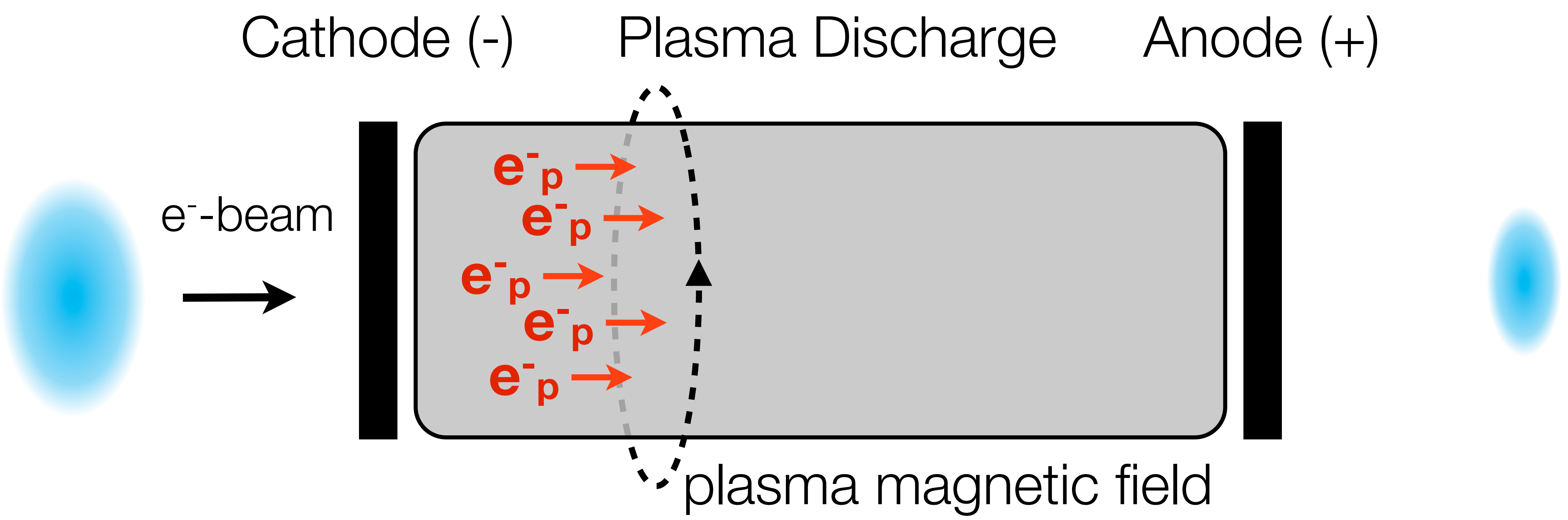
- focussing in all dimensions
- high cromaticity
- weak focussing for high energy



Quadrupole:

- focussing in one dimensions
- low cromaticity
- common g~100 T/m

Plasma lens:



- plasma electron current generates magnetic field
- result: F= I x B , focussing force for e-beam
  - focussing is symmetric in all directions!
- high gradients above g~1000 T/m easily achievable and have been demonstrated[1]
- compact
- leaks gas into vacuum

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1) van Tilborg et al. – 2015 - Active Plasma Lensing for Relativistic Laser-Plasma-Accelerated Electron Beams

Summary

- Plasma-target
  - First gas-target prototype has been fabricated
  - Will be tested (and optimized for DDR and tailored capture / release)
- Hydrogen fragmentation dynamics
  - Importance of timescales of ionising beams
  - Also: Even more attention needed when dealing with multi-species challenges (e.g. for ionisation injection)
- Diagnostics
  - Plasma spectroscopy offers insight into plasma parameters
  - Stark broadening offers an alternative approach to diagnose in regimes upcoming at high energy accelerators
- Plasma lensing
  - First results show focussing and beam steering at gradients of about 760 T/m
  - Upcoming campaign in early November

Thank you...