Experimental benchmarking of the EM-PIC-MCC code NINJA and its application for simulating the Linac4 H^- ion source plasma

S. Briefi[1,2], S. Mattei[3], D. Rauner[1,2], J. Lettry[3] and U. Fantz[1,2]

[1] AG Experimentelle Plasmaphysik, Universität Augsburg, 86135 Augsburg

[2] Max-Planck-Institut für Plasmaphysik, Boltzmannstraße 2, 85748 Garching

[3] Linac4 ion source team, CERN-ABP, 1211 Geneva 23

The authors would like to thank the Deutsche Forschungsgemeinschaft (DFG) for their support within the project BR 4904/1-1.

Introduction

- Upgrade in the first part of the LHC injector chain

Up to now: Ion source for H^+ → Linac2 (50 MeV) → PSB → … → LHC (7 TeV)

Ion source for H^- → Linac4 (160 MeV)

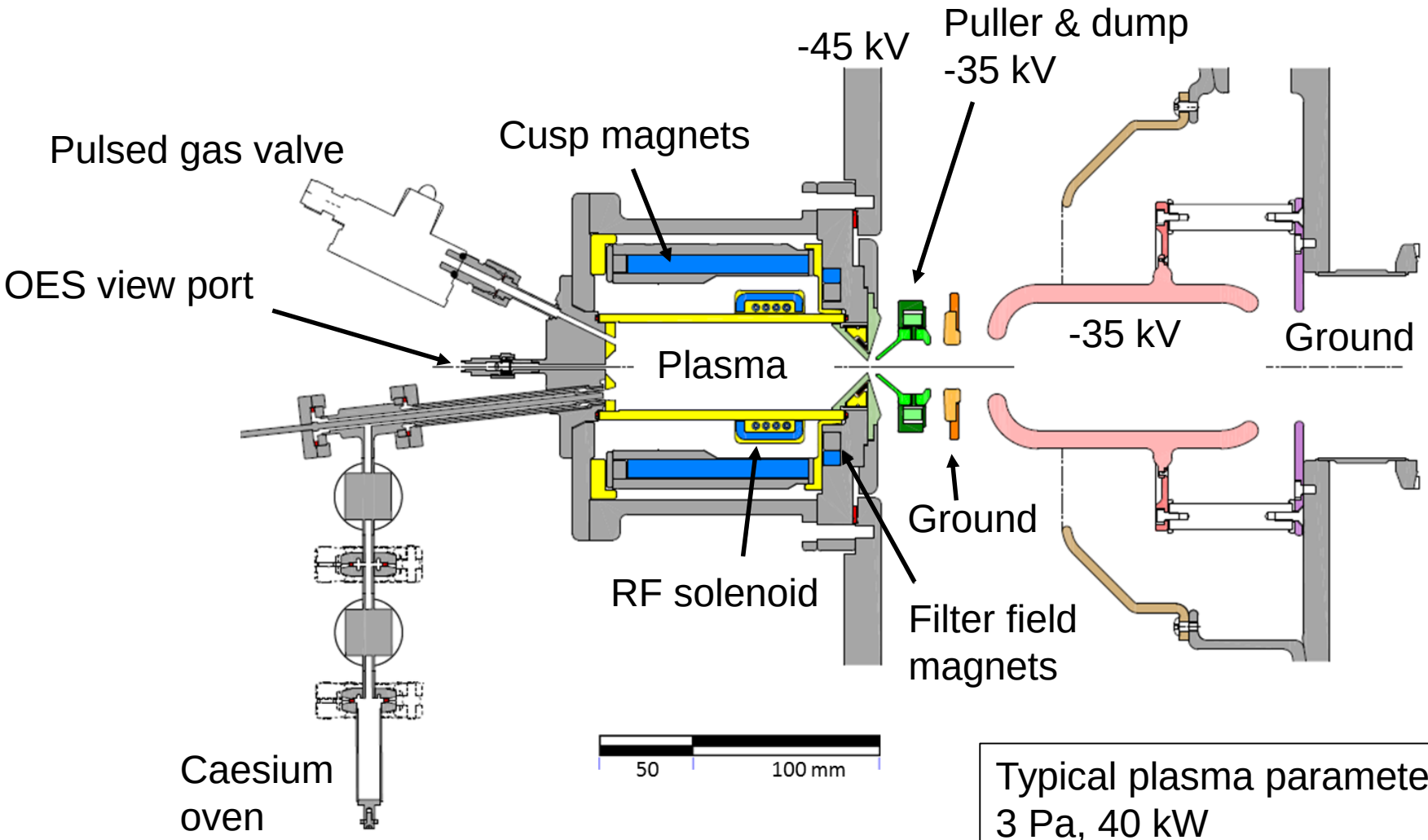
Charge-exchange injection

- **Aim** → Doubling of the beam brightness & intensity inside PSB
  → Improvement of the injection efficiency from 60 to 99%

- H^- ion source parameters

RF frequency	2 MHz, up to 100 kW
Duration of plasma pulse	500 µs
Duration of beam extraction	400 µs
Repetition rate	2 Hz
Beam energy	45 keV
Extraction aperture	6.5 mm
H^- current	45 mA
Nominal Emittance	0.25 π mm mrad

Setup of the Ion Source



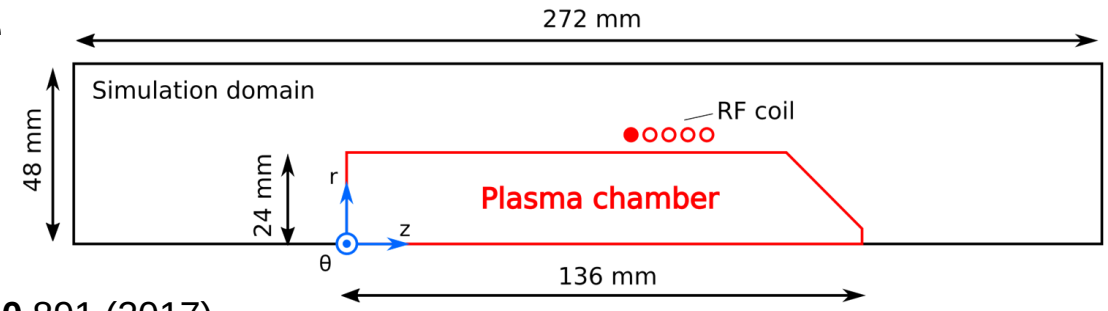
Typical plasma parameters
3 Pa, 40 kW
$n_e \sim 10^{19}$ m^{-3}, $T_e \sim 4$ eV

Motivation

- For dedicated optimization of H^- yield detailed knowledge of plasma parameters (n_e, T_e, T_{vib}, n_H) mandatory
- Ion source design very compact → bad accessibility for diagnostics
  - Optimization mainly based on variation of external parameters
  - Optical emission spectroscopy yields line-of-sight integrated results
- Development of electromagnetic PIC Monte Carlo collision code NINJA
  MATTEI ET AL., J. COMPUT. PHYS. **350** 891 (2017)
  - Self-consistent calculation of plasma parameters as result of the RF field
  - Spatially resolved investigations & dedicated process evaluations possible
- Benchmark measurements of NINJA
  - At diagnostically well-accessible lab experiment CHARLIE
  - At Linac4 ion source

The EM-PIC-MCC code NINJA

- 2.5 D Particle-In-Cell module
  - 2D EM field due to azimuthal symmetry, 3D3V particle dynamics
  - H^+, H_2^+, H_3^+, H^- and electrons considered
  - Implicit time integration scheme
    - → Relaxes numerical requirements on Δt and Δx considerably
    - → Enables simulation of high-density ion source plasma
- Monte Carlo Collision module
  - More than 200 reactions
  - Electron/ion – neutral, electron – ion, Coulomb collisions
- Neutral transport module
  - Kinetic tracking of H and $H_2(v)$



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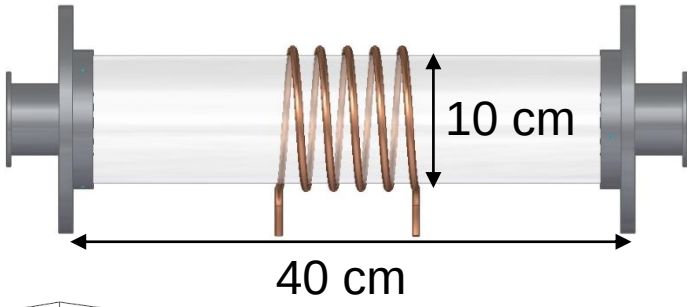
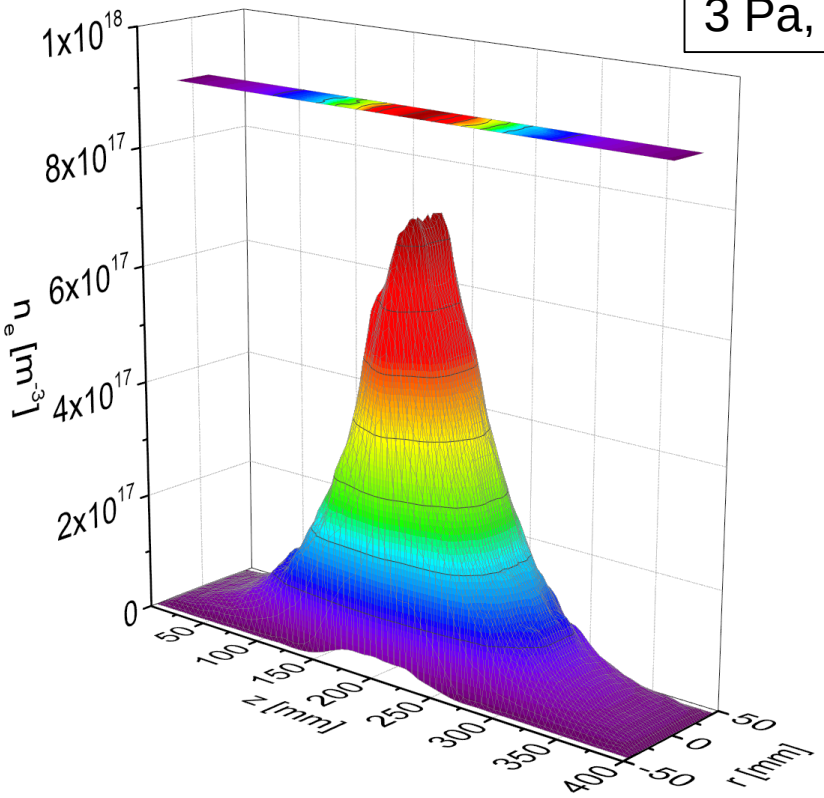
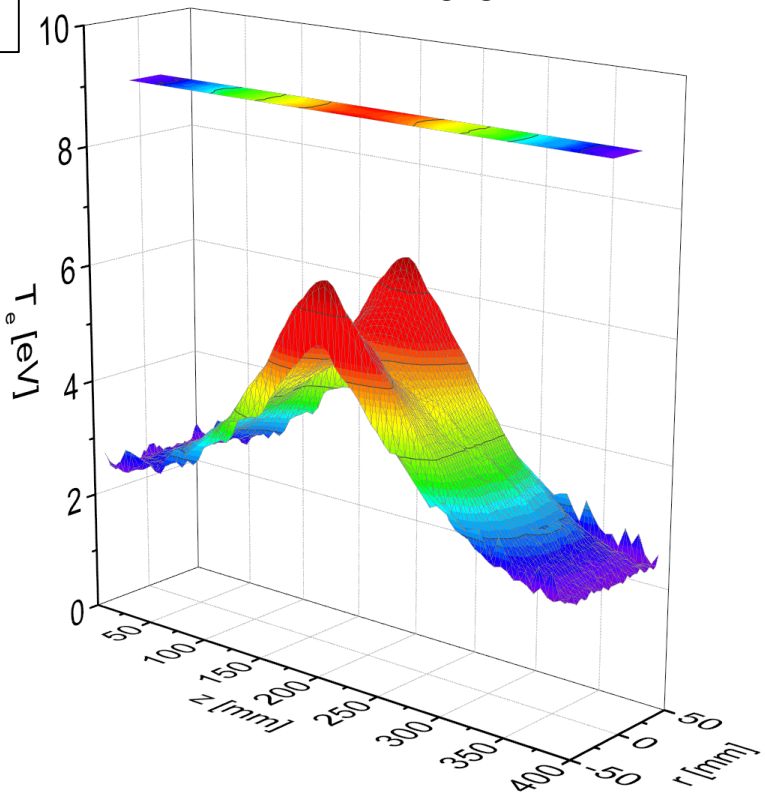
Benchmarking at CHARLIE

- Cylindrical ICP, 1 MHz (up to 1 kW)
- Diagnostics
  - Floating double probe
  - OES (axial &lateral LOS)

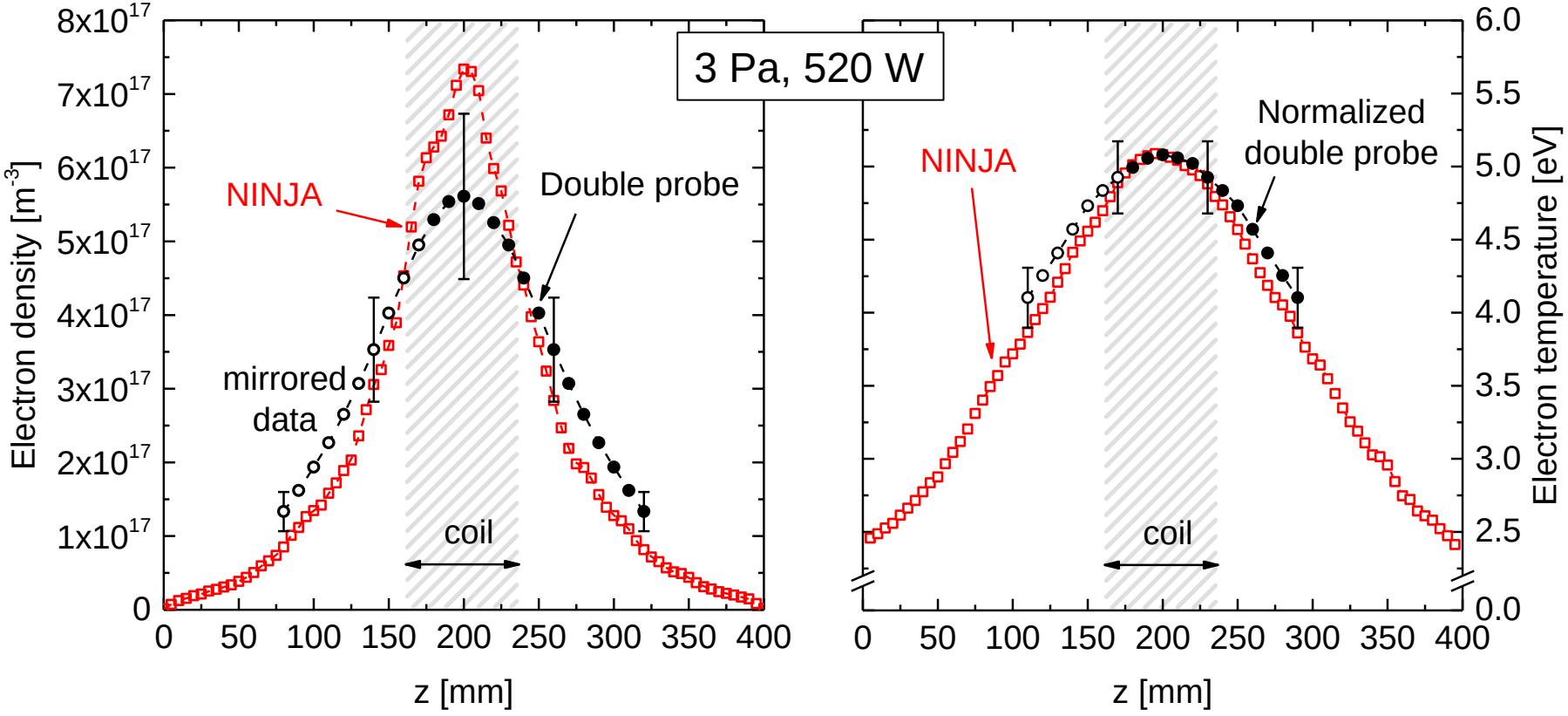


3 Pa, 520 W





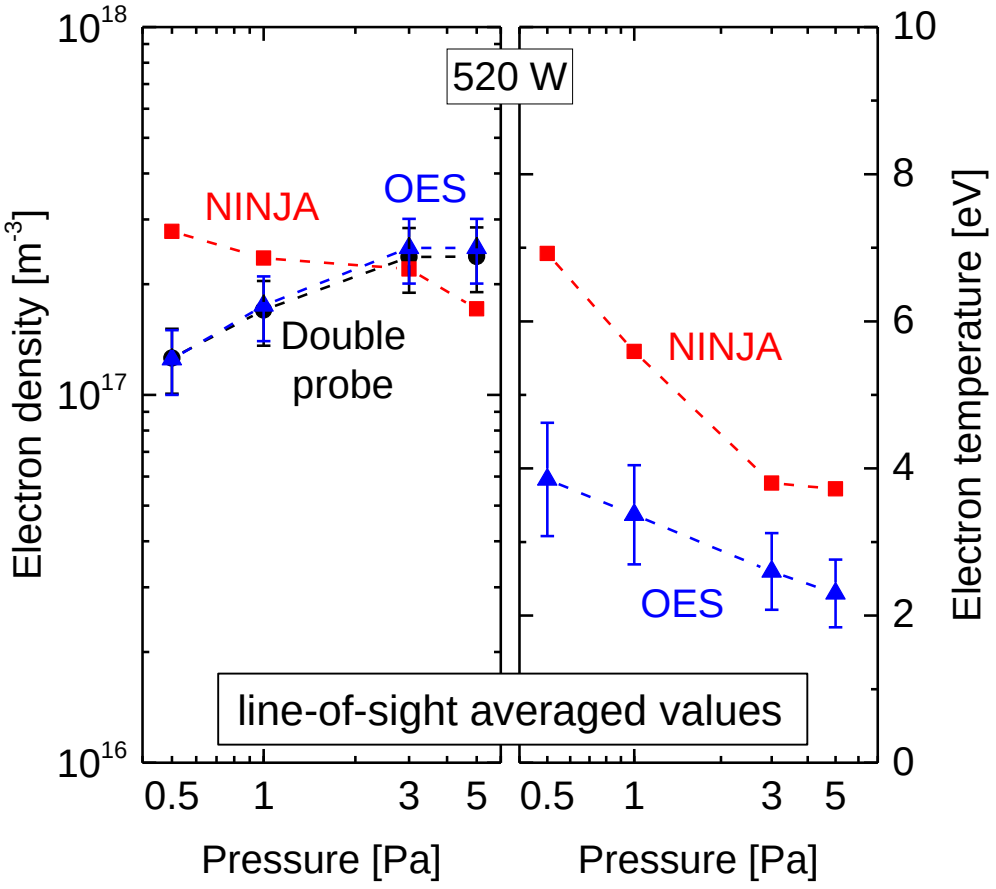
Benchmarking at CHARLIE – Profiles



- Good agreement of axial n_e and T_e profiles
- Measured radial emission profiles also coincide with NINJA results (not shown)

Benchmark of profiles successful

Benchmarking at CHARLIE – T_e and n_e



- Absolute values of n_e agree but different trends obtained
- Trends agree for T_e but different absolute values
- Assumption of strong inductive coupling in NINJA

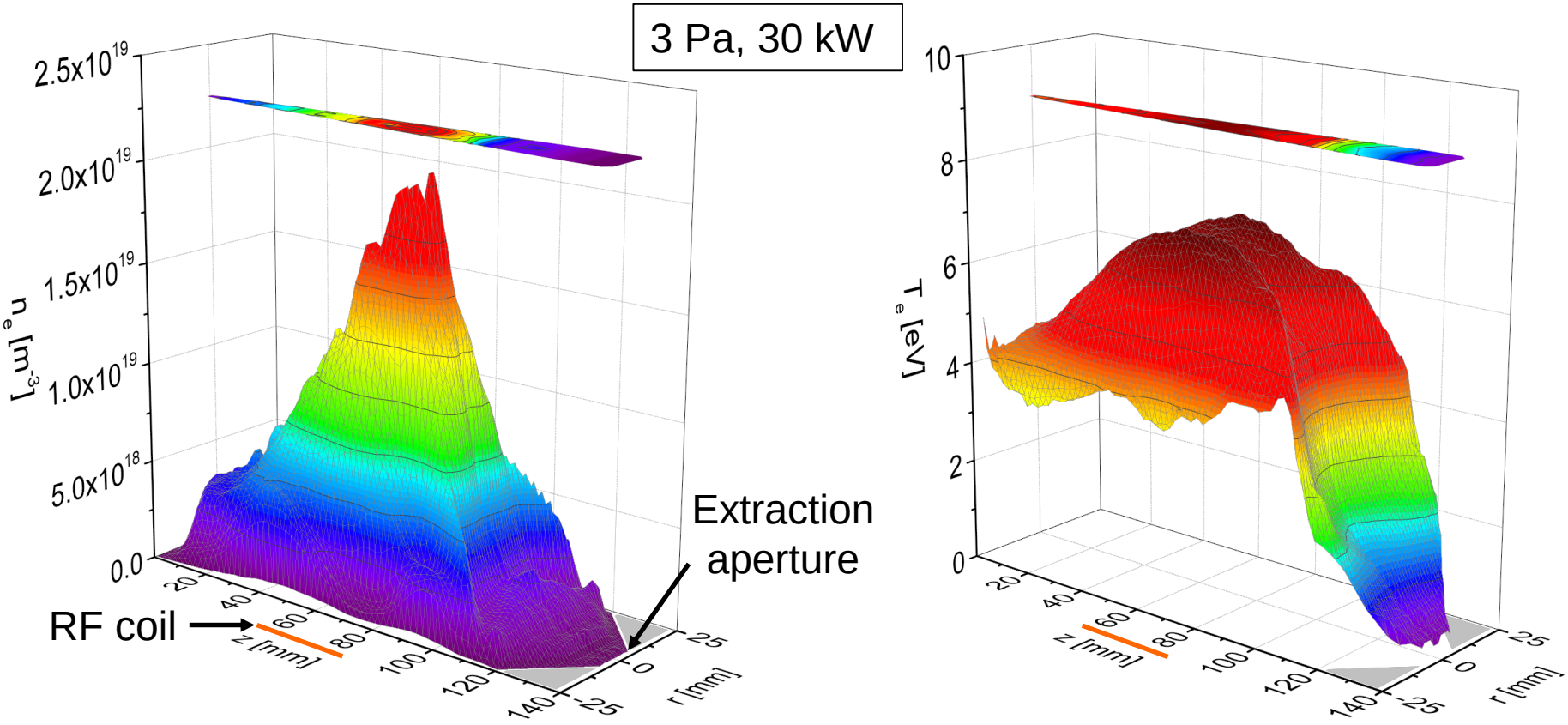
  $n_e \propto I_{RF,\,ant}$

- CHARLIE is in loosely coupled regime

  $n_e \not\propto I_{RF,\,ant}$

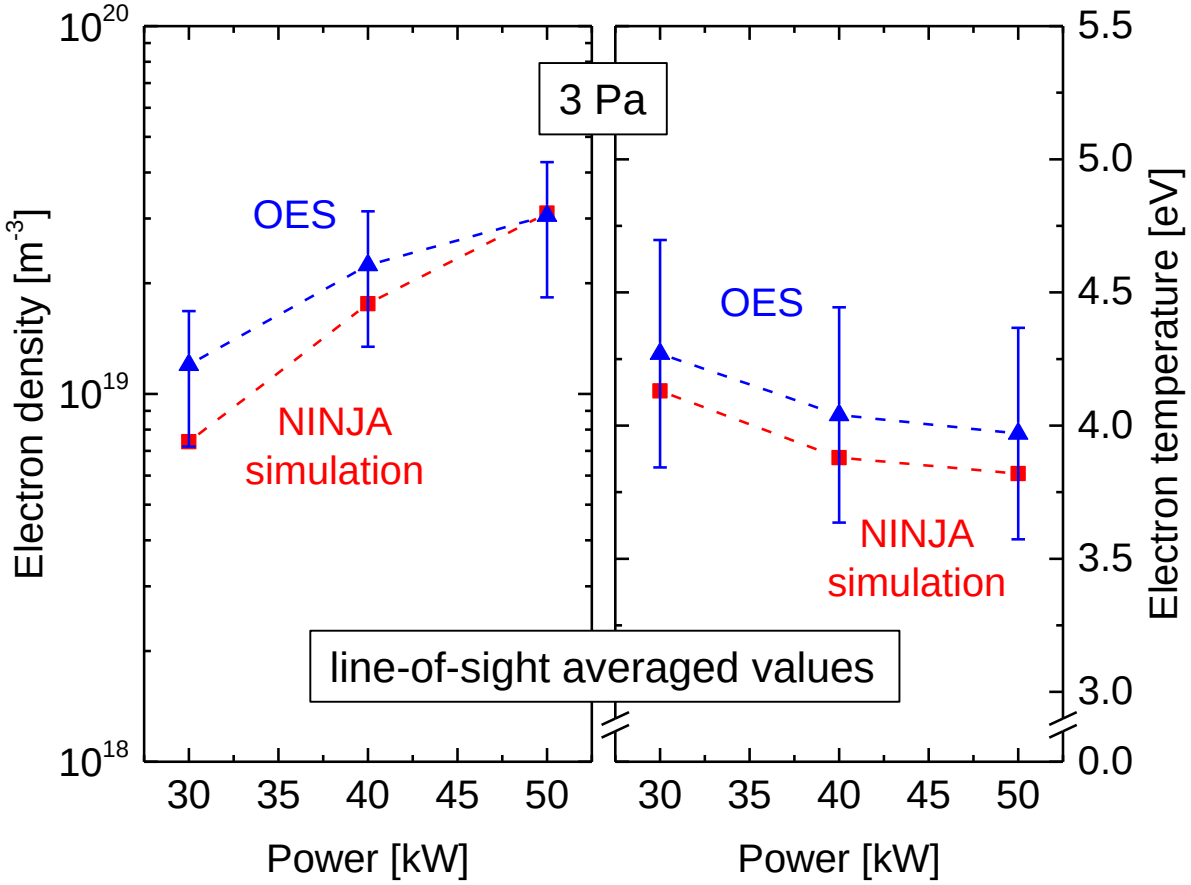
→ For CHARLIE: feedback loop plasma ↔ RF circuit required
→ Linac4 strongly coupled

Benchmarking at Linac4 – T_e and n_e



- Electron energy decreases strongly towards extraction aperture
  - → Magnetic filter field works in the expected way
- EEDF very close to Maxwellian

Benchmarking at Linac4 – T_e and n_e



- Excellent agreement both in trends and absolute values

Benchmark of absolute plasma parameter values successful

Assessment of processes w.r.t. H^- yield

- H^- yield determined by processes in front of extraction aperture
  - NINJA results averaged in this region
  - Process assessment via 0D model balancing H^- production (only volume) and destruction rates
    RAUNER ET AL., AIP CONF. PROC. **1655** 020017 (2015)

- Experimentally no change in plasma parameters with Caesium

  → H^- destruction processes similar for volume and surface mode

Electron stripping	$H^- + e^- \rightarrow H + 2e^-$	~ 10%, due to filter field
Mutual neutralization	$H^- + H^+$ (or H_2^+, H_3^+) $\rightarrow H + H$ (or H_2, $H + H_2$)	~ 25%
Associative Detachment	$H^- + H \rightarrow H_2 + e^-$	~ 65%
Collisional Detachment	$H^- + H \rightarrow H + H + e^-$	
	$H^- + H_2 \rightarrow H + H_2 + e^-$	< 1%

Assessment of processes w.r.t. H^- yield

- Linac4 operation in volume mode
  - Extracted H^- current peaks at varying RF power at 40 kW
  - Detailed evaluation of 0D model for increasing power
    - Increasing T_{vib} → Higher H^- production rate
    - Increased dissociation → Reduced H^- production rate
      → Higher H^- destruction rates due to collisions with H atoms
- Linac4 operation in surface mode
  - H^- production on caesiated surface cannot be modelled by NINJA
    → Mesh too coarse
  - Detailed investigation only possible with beam formation codes
    → Plasma parameters in front of extraction aperture required as input

These parameters can be provided by NINJA

Summary

- EM-PIC-MCC code NINJA has been developed for detailed investigation and optimization of the Linac4 ion source plasma
- Benchmarking of the code performed at
  - CHARLIE experiment
    - → Successful benchmark of axial and radial profiles
    - → Absolute values and trends deviate due improper coupling regime
  - Linac4 ion source: successful benchmark of absolute values and trends
- Assessment of processes with respect to H^- yield
  - Volume mode: peaking behavior of extracted H^- current could be explained
  - Surface mode:
    - → Detailed investigation only possible with beam formation codes
    - → NINJA can provide required input plasma parameters