Plasma ignition and steady state simulations of CERN's Linac4 H^- ion source

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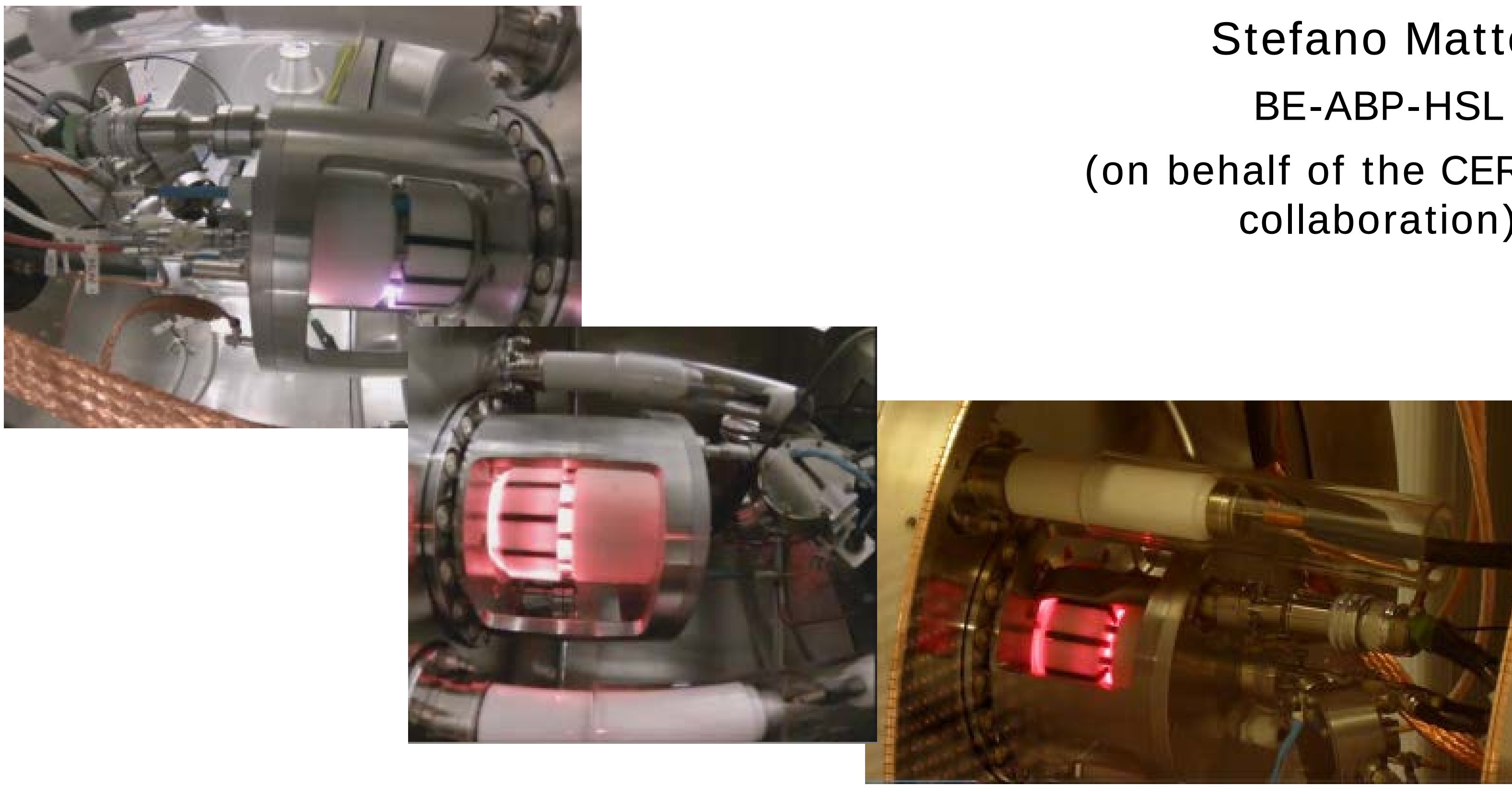
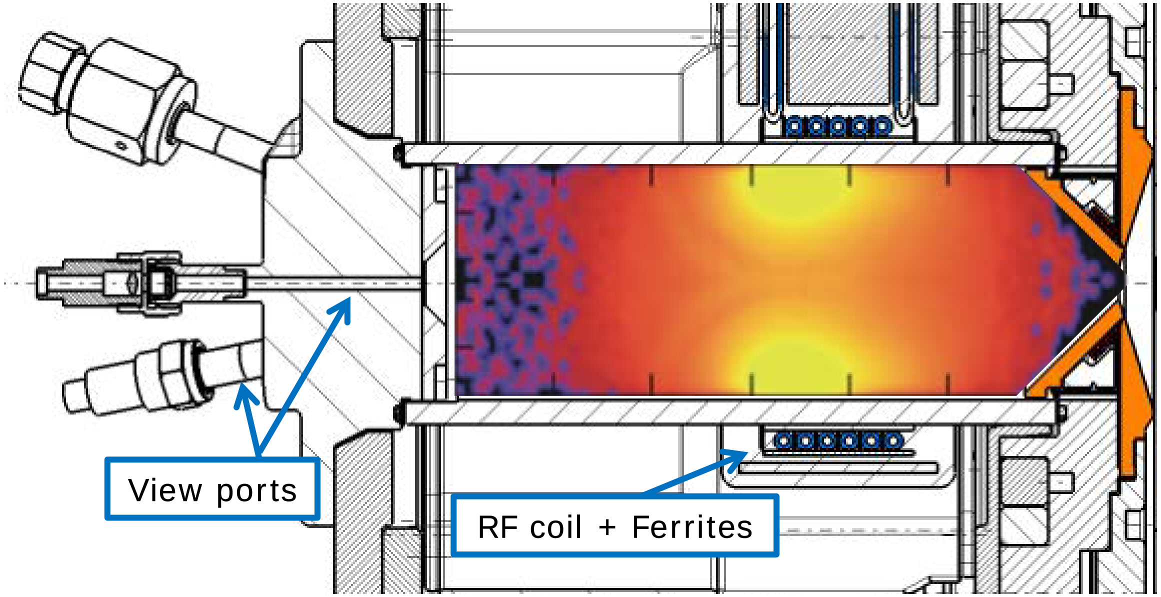
BE-ABP-HSL

(on behalf of the CERN-KEIO collaboration)





External magnetic fields (cusp + filter) neglected

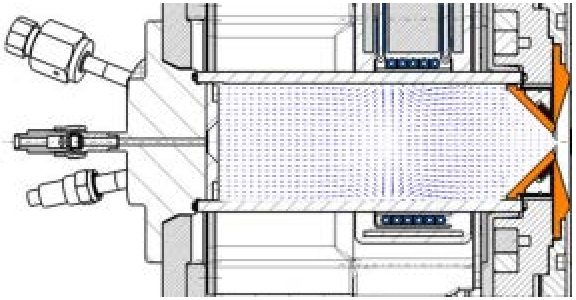
Plasma chamber
- L = 136 mm
- Φ = 48 mm

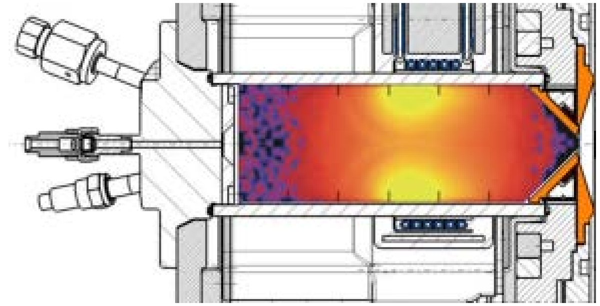
RF coil
- 3 to 6 turns
- 2 MHz
- 100 kW peak power available

Pulsed operation
- 2 Hz rep. rate
- 500 μs pulses
- Plasma newly ignited at each pulse

Simulate the RF-plasma coupling
- Plasma ignition
- Transition to steady state and stabilization during the pulse
- Long term goal: optimization of the source geometry and operational parameters (e.g. coil position, number of turns, RF power, H_2 pressure)

RF-plasma-light emission





Electromagnetic field simulations performed by Ansys HFSS

Courtesy of Alexej Grudiev

Field map →

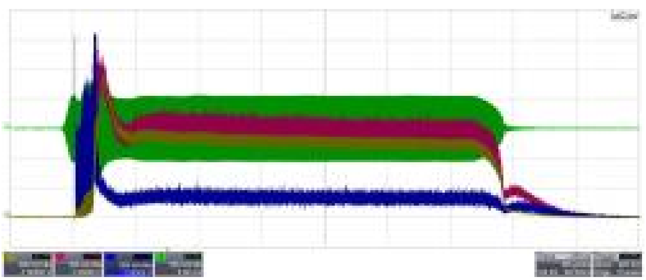
Plasma simulation
Electromagnetic
PIC-MCC

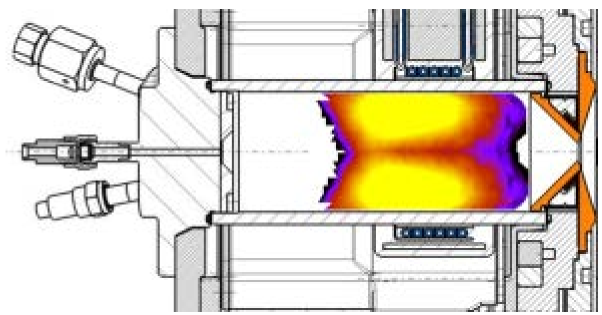
↓ EEDF

Collision-Radiative model

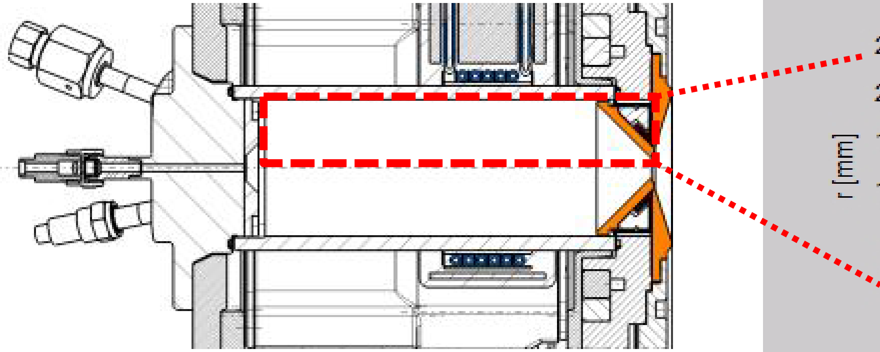
Courtesy of Takanori Shibata

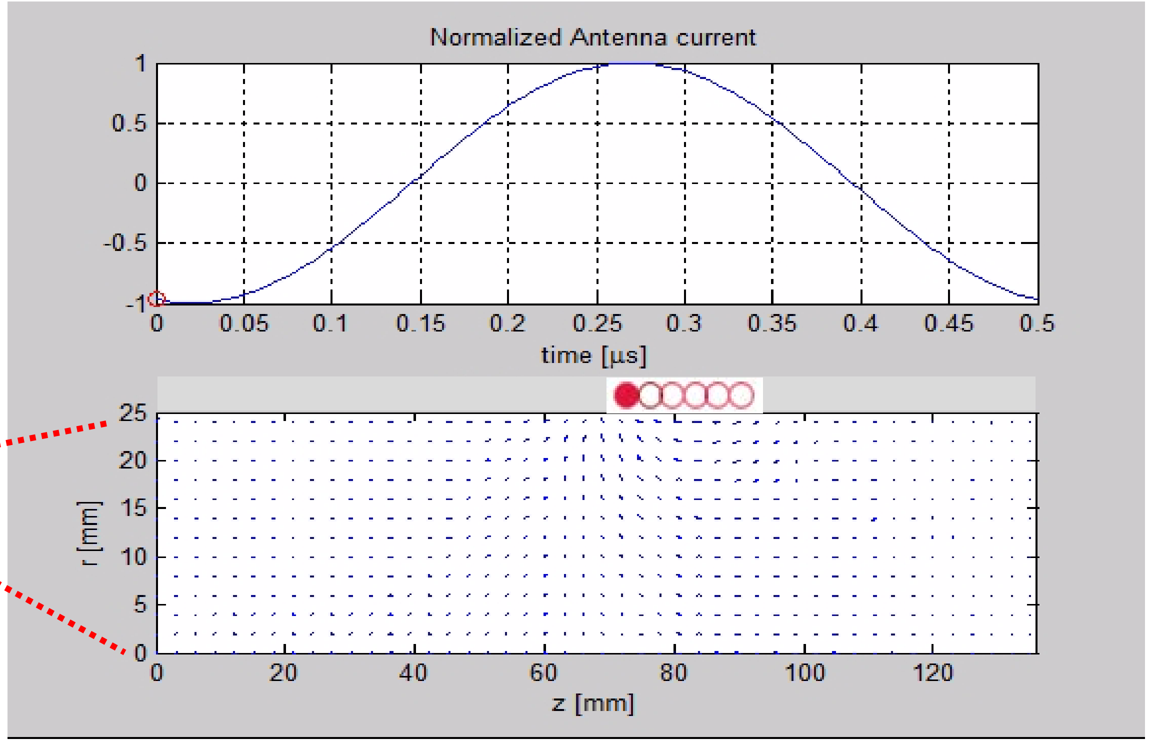
Experimental verification by Optical Emission Spectroscopy and photometry ↔ Collision-Radiative model





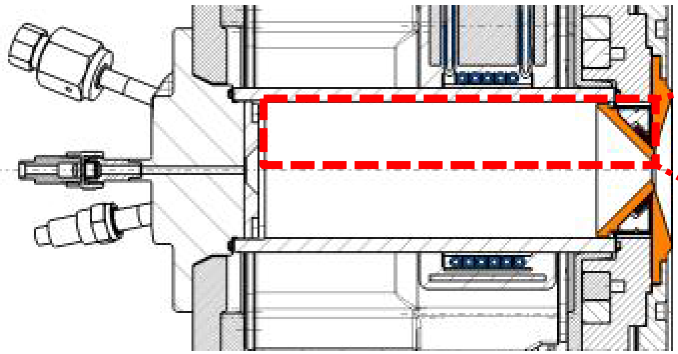
Vacuum electric field

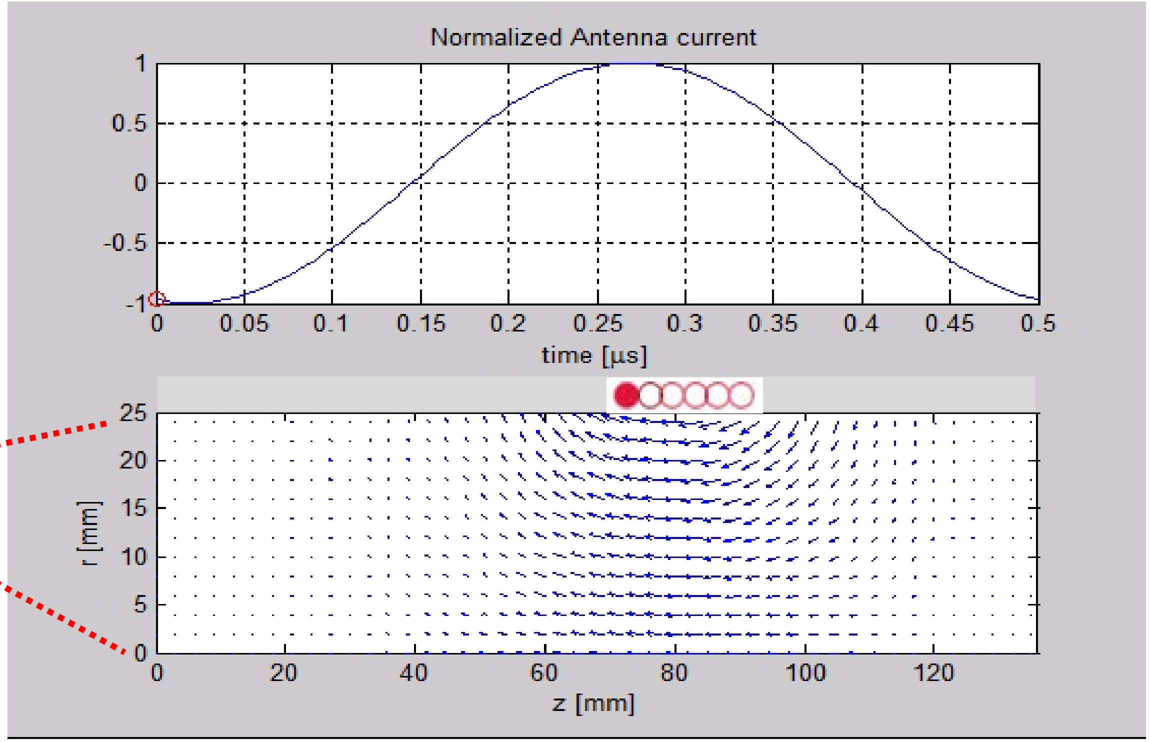




Courtesy of Alexej Grudiev

Vacuum magnetic field





Courtesy of Alexej Grudiev

2.5 D model in cylindrical coordinate system

- 3D3V particle dynamics
- EM fields calculated in 2D averaging in θ-direction
- $E = E_{RF} + E_{pl}$ $B = B_{RF} + B_{pl}$

Monte Carlo Collision method

- 540 reactions: e^--neutral and e^--ion collisions simulated by the Null-Collision method, e.g.
  - Elastic collision: $e^- + H \longrightarrow e^- + H$
  - Ionization: $e^- + H \longrightarrow e^- + H^+ + e^-$
  - Dissociation: $e^- + H_2(X^1\sum_g^+) \longrightarrow e^- + H(1s) + H(1s)$
- NO ion-ion collision nor ion-neutral collisions at present
- Gas taken as a background gas of constant density at 3 Pa

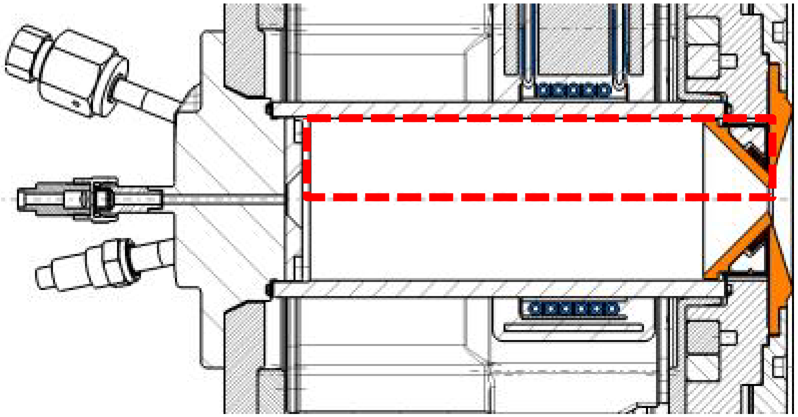
Code parallelized via Message Passing Interface (MPI)

Simulation parameters

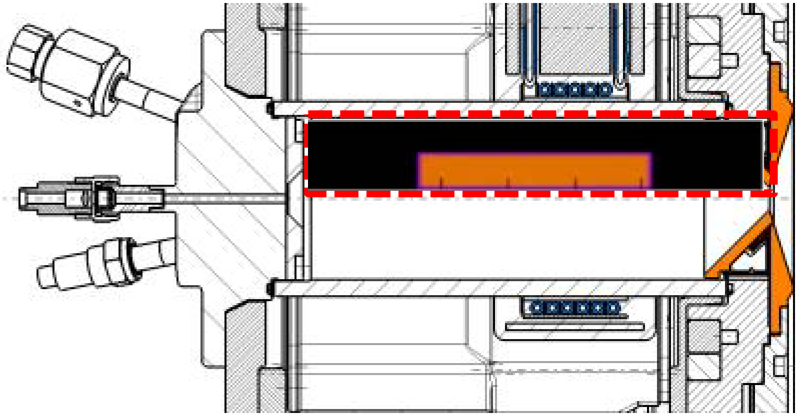
Parameter	Ignition	Steady state
Initial particle number	4800	24000
Specific weight	5×10^4	1×10^7
Initial e^- density	1×10^{12} m^{-3}	1×10^{15} m^{-3}
Initial p^+ density	1×10^{11} m^{-3}	1×10^{14} m^{-3}
Initial H_2^+ density	9×10^{11} m^{-3}	9×10^{14} m^{-3}
RF power	7 kW	7 kW
Cell size	1x1 mm	1x1 mm
H_2 gas pressure	3 Pa	3 Pa
H_2 temperature	300 K	300 K
Initial e^- temperature	15 eV	1.5 eV
Time step	10^{-12} s	10^{-12} s
Collision time step	10^{-10} s	10^{-10} s

Resources – EPFL cluster
2 nodes of 48 cores each – 96 cores
AMD Opteron 6176 (Magny-Cours) à 2.3 GHz
196 GB RAM per node – 392 GB
Simulation time – 400 cores day per μs

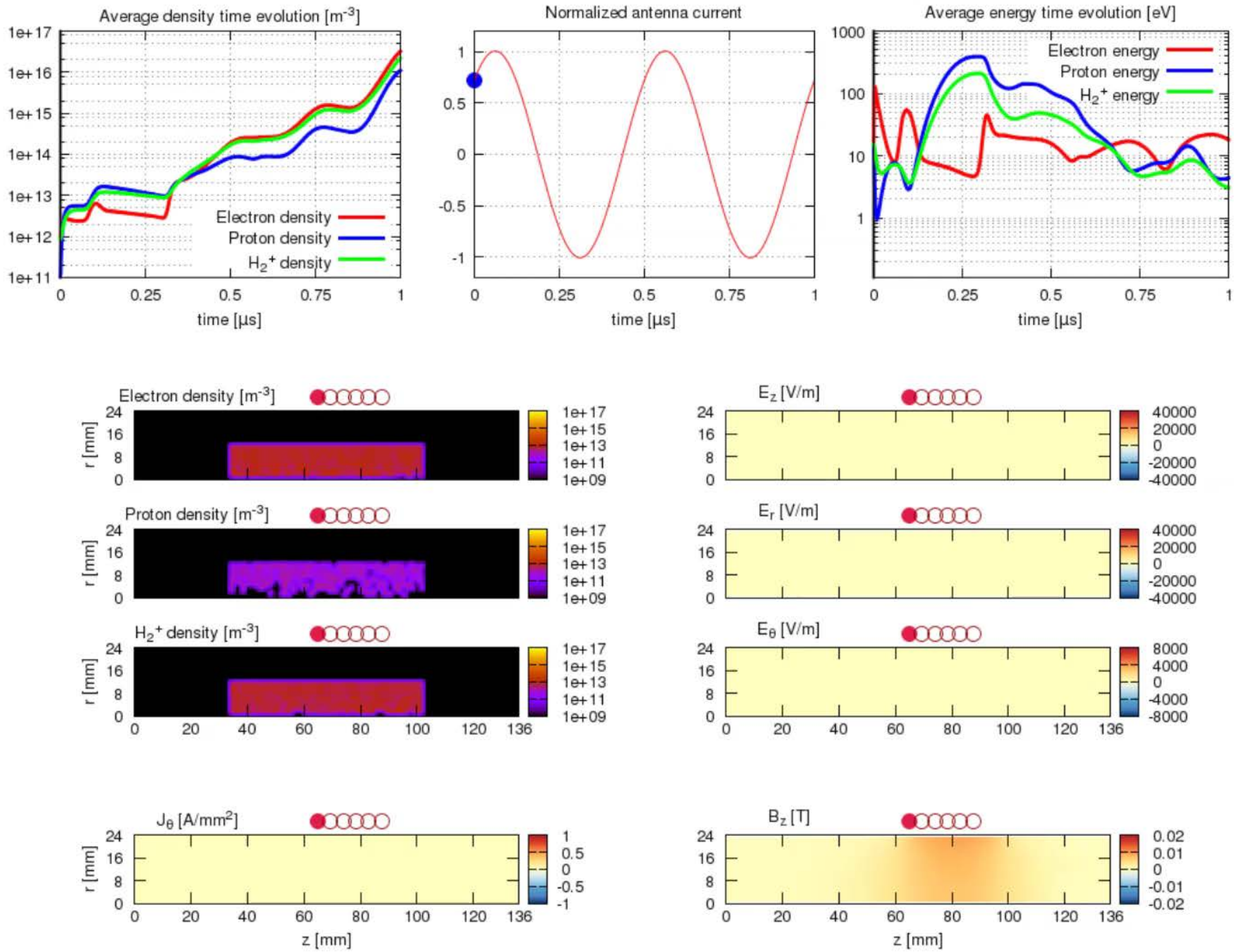
Simulation domain



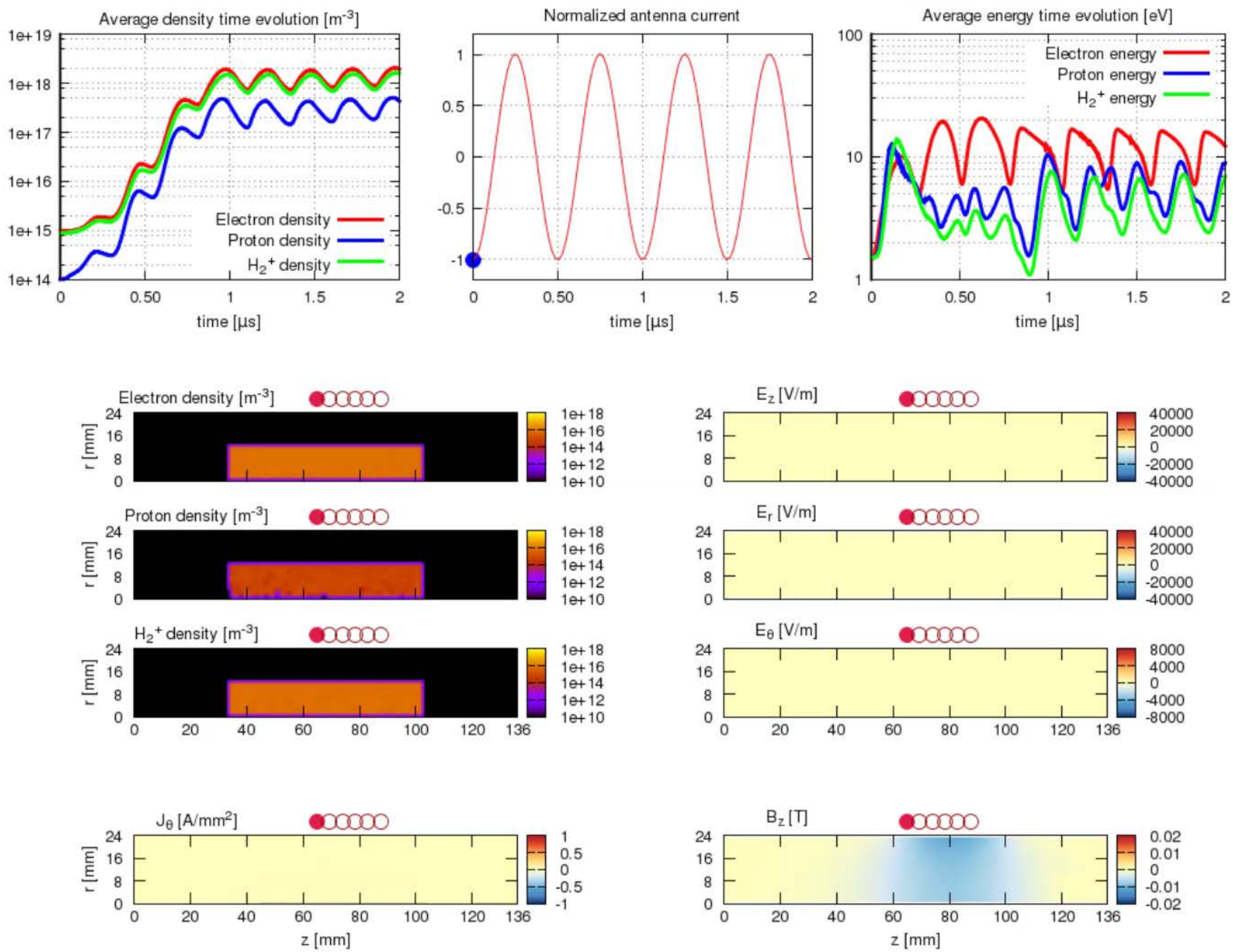
Initial condition



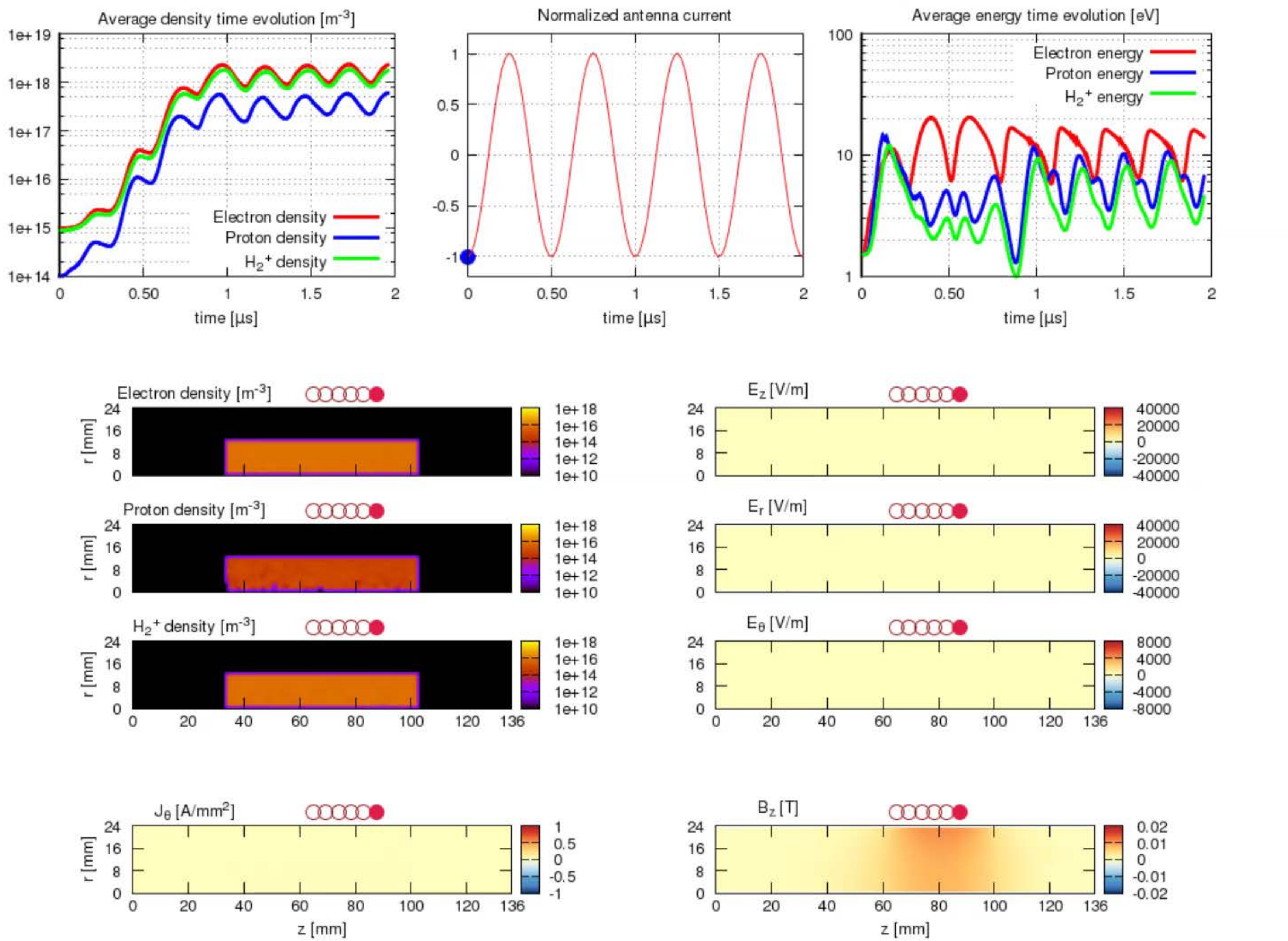
Capacitive plasma ignition



Inductive heating to steady state



Inductive heating to steady state – Inverted polarity



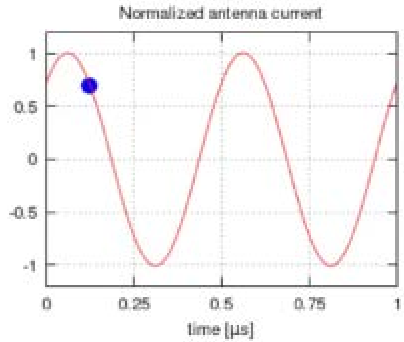
Remarks

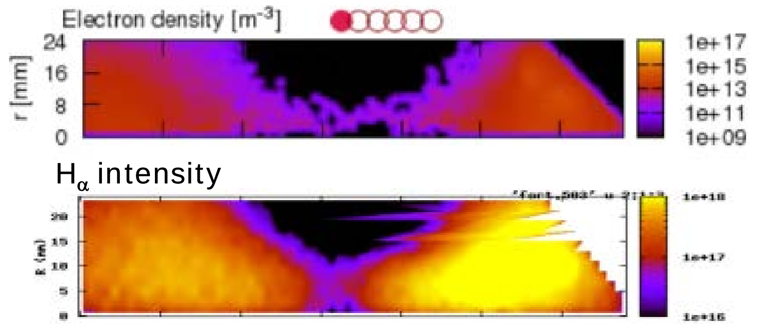
- **Plasma ignition**
  - Dominated by the capacitive coupling
  - Low plasma density allows the RF fields to penetrate in the middle of the plasma chamber to induce a push-pull effect
  - Protons and H_2^+ less influenced by the external fields due to larger inertia

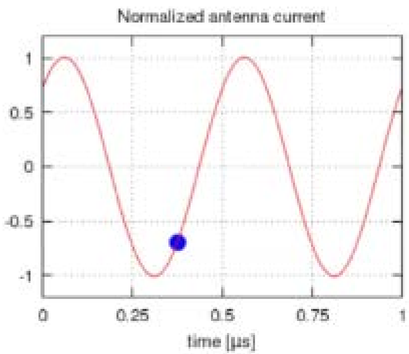
- **Steady state regime**
  - At higher density the plasma heating is dominated by the inductive coupling
  - 4 MHz ripple observed in the plasma e^-/ion density and energy
  - Hints into plasma waves in the azimuthal direction (investigation ongoing)
  - RF high voltage polarity has a strong influence on the plasma parameters spatial distribution
  - Equilibrium is the result of the balance of production vs. losses

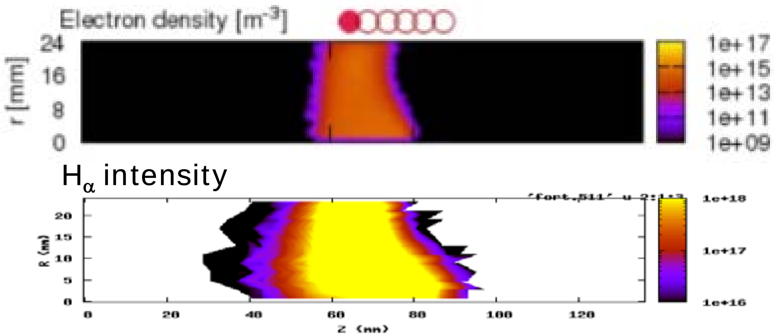
Collision Radiative model prediction

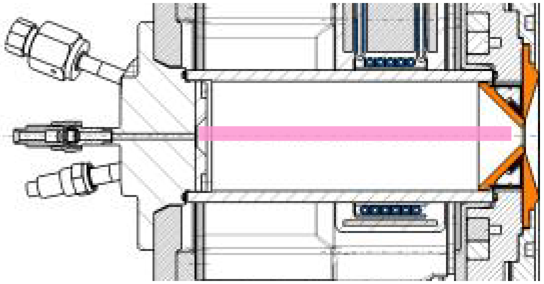
Preliminary results on 1 cycle during plasma ignition



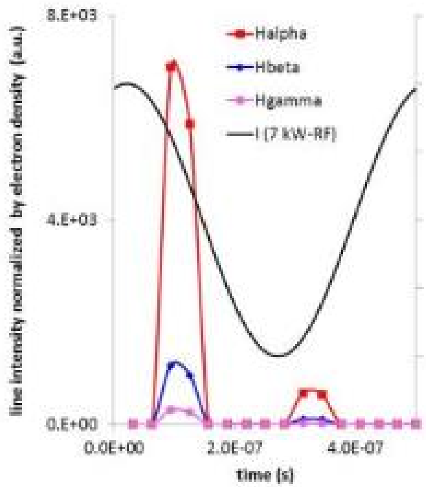








Integrated light central view port

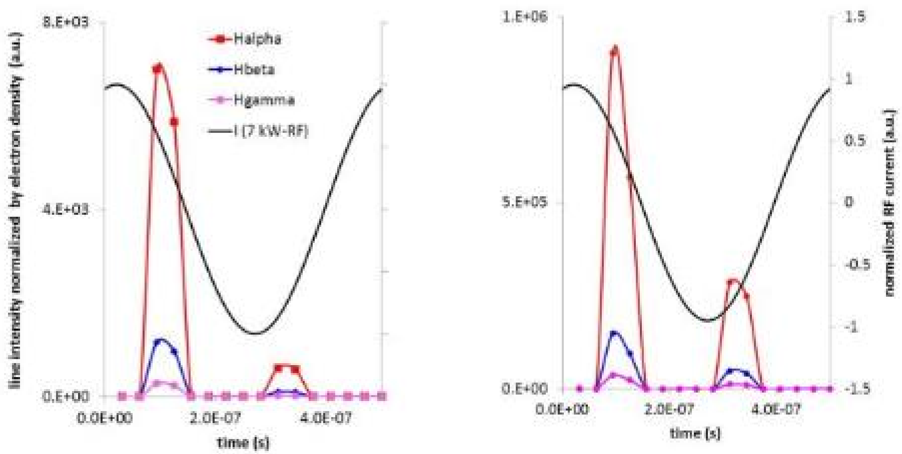


Courtesy of Takanori Shibata

CR model vs. Photometry

CR model prediction

on-axis view port | 30 deg. view port



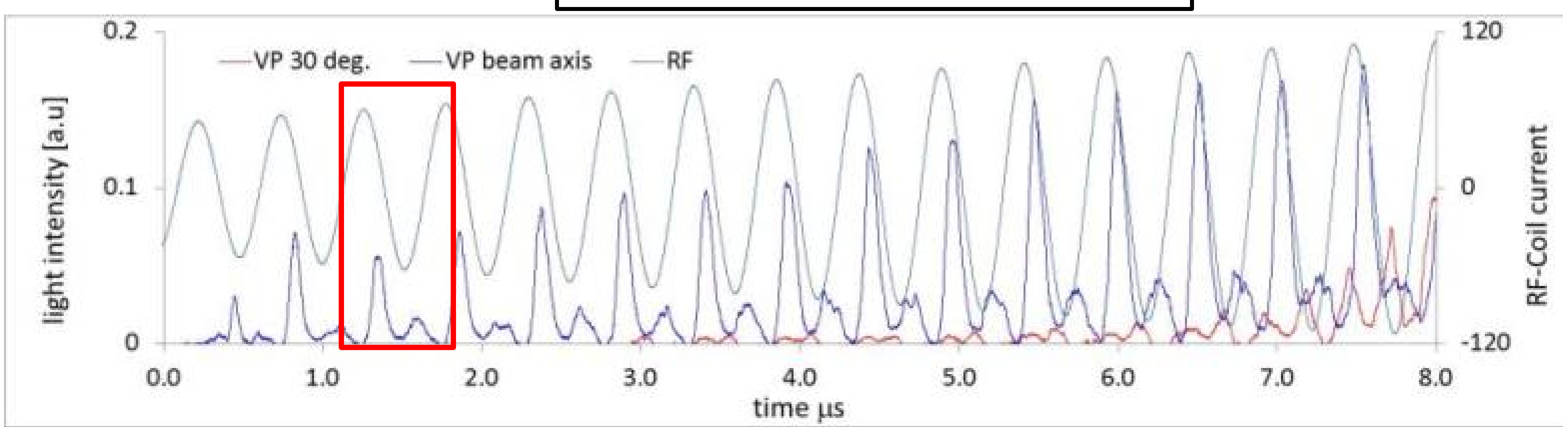
Preliminary results

Correlation between measurements and simulations in 1 cycle during the plasma ignition transient

Hard work ahead…
Experiment and simulation shall now focus on steady state plasma (suitable for H^- beam production)

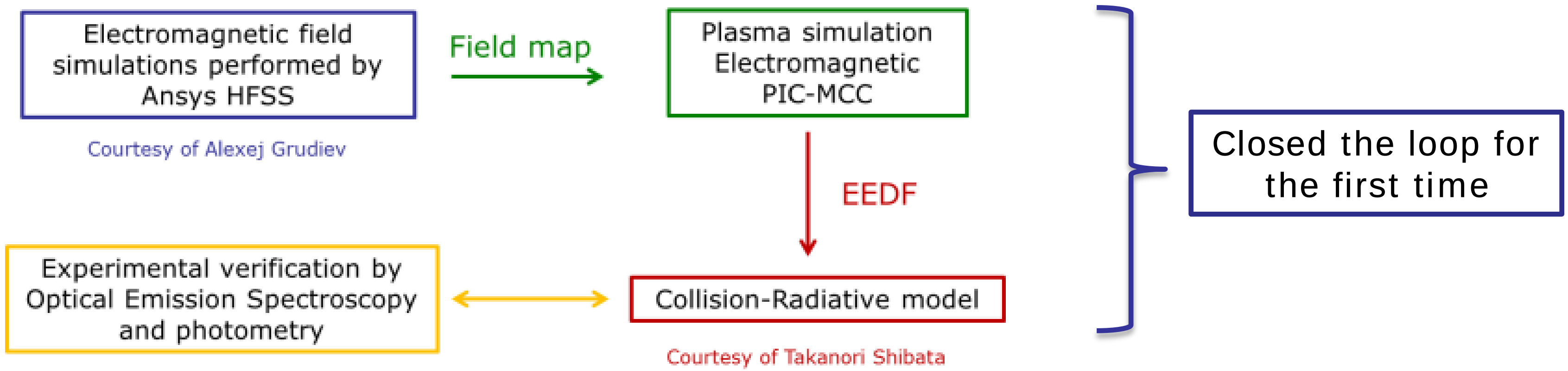
Courtesy of Takanori Shibata

Photometry measurements



We have simulated the plasma ignition and the steady state regime in the Linac4 H^- ion source

- Obtained first insights into the capacitive ignition and the transition to inductive heating mechanisms
- Steady state reached at a plasma density of 10^{18} m^{-3}
- Compared results between CR model prediction and photometry measurements
- Could lead to the simulation to the only observable during operation



Outlook

Inclusion of new physics

1. H^- production mechanisms – surface + volume (1 year)
   – Neutral transport
2. Ion collisions (3 months)
3. Coulomb collisions: e^--e^- (1 year)
   – Electron thermalization
   – Diffusion across the filter field
4. Wishful upgrade to fully 3D code to take into account the real magnetic field configuration

Informatics

Inclusion of new physics will result in a further computational cost

- Code optimization – speedup
- Hybrid parallelization

} End 2013

Sensitivity studies

- Runs with variation of the source parameters (e.g. RF power, H_2 pressure)
- Inclusion of average magnetic cusp field to get first insights

Experimental campaign

Thanks to all of our collaborators

- **KEIO University (Japan)**
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  - T. Pieloni (BE Dept.)
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THANK YOU FOR YOUR ATTENTION