HSMDIS

INFN

DIPARTIMENTO di MATEMATICA e INFORMATICA

Stationary-PIC simulation of High Stability Microwave Discharge Ion Sources

Team: Lorenzo Neri; Luigi Celona; Santo Gammino; Ornella Leonardi; Giuseppe Castro; Andrea Miraglia; Andrea Busacca; Francesco Grespan; Michele Comunian; Luca Bellan; Carlo Baltador; Giovanni Russo; Sebastiano Boscarino; Armando Coco.

GSI Accelerator Seminar 09/06/2022

Microwave Discharge Ion Source vs ECR Ion Source

Electron Cyclotron Resonance (ECR) is one of the most convenient method to excite the plasma in Ion Sources:

$$\omega_{RF} = \frac{q_e B}{m_e}$$

MDIS: ω_{RF}=2.45 GHz ➔ B≈875 Gauss ➔ normal conductive or permanent magnet magnetic system

MDIS: ω_{RF}=2.45 GHz ➔ λ_{RF}=12.2 cm ➔ cylindrical plasma chamber of 10x10 cm

ECRIS: ω_{RF}=18 GHz ➔ B≈6400 Gauss ➔ superconductive magnetic system

Gas
+
Magnetic field
+
Microwave power
=
Plasma
+
High voltage
=
Beam

Ion current (I) and **ion charge state (q)** depend on **density (N)** and **confinement time (T)**:

$$I \propto \frac{N}{T} \qquad \langle q \rangle \propto NT$$

MDIS: low T ➔ solenoidal magnetic field ➔ only transvers confinement ➔ high current (I≈100 mA) ➔ low charge state (+1)

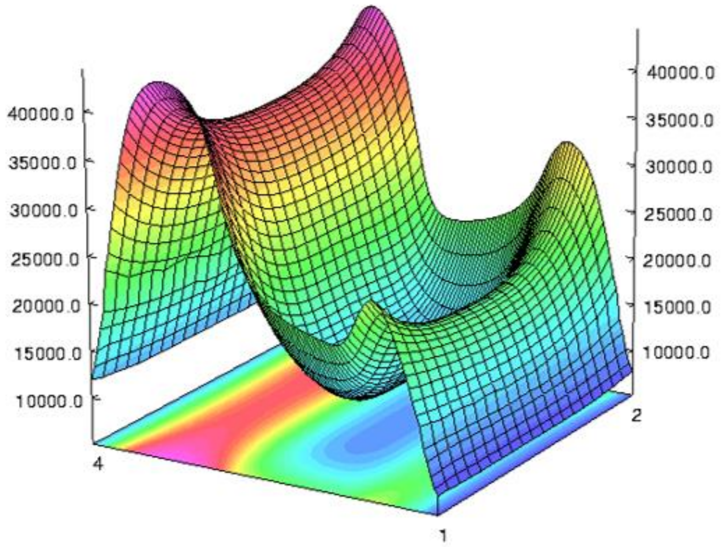
ECRIS: high T ➔ solenoidal magnetic field plus an hexapole magnetic field ➔ transvers and axial confinement ➔ low current (1mA maximum) ➔ high charge states (up to +50)

ECRIS: high T ➔ bigger cylindrical plasma chamber of 10x35 cm

Microwave Discharge Ion Source vs ECR Ion Source

ECRIS magnetic configuration

- **high T** ➔ B minimum configuration
- B_{ECR} is a closed surface at the center of the plasma chamber
- Magneto Hydro Dynamics stability ➔ $\frac{B_{est}}{B_{ECR}} > 2$
- Scaling lows: $I \propto \frac{{\omega_{RF}}^2}{M}$; $\langle q \rangle = \log {\omega_{RF}}^{3.5}$



MDIS magnetic configuration

Since 1991, following experimental evidences, B_{ECR} was placed at the injection and at the extraction ends of the plasma chamber

A high-current low-emittance dc ECR proton source

Terence Taylor and John S.C. Wills
Chalk River Laboratories, AECL Research, Chalk River, Ontario, KOJ 1JO, Canada

Received 18 June 1991

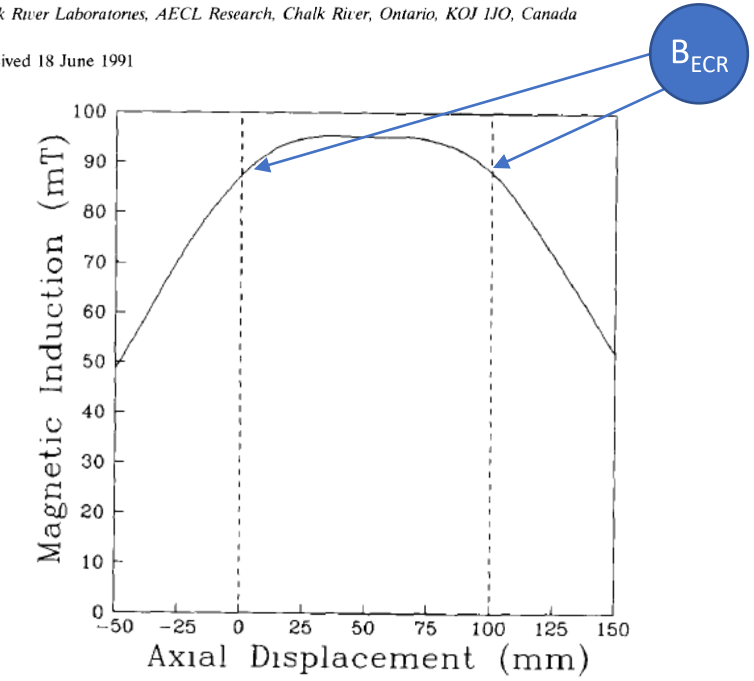
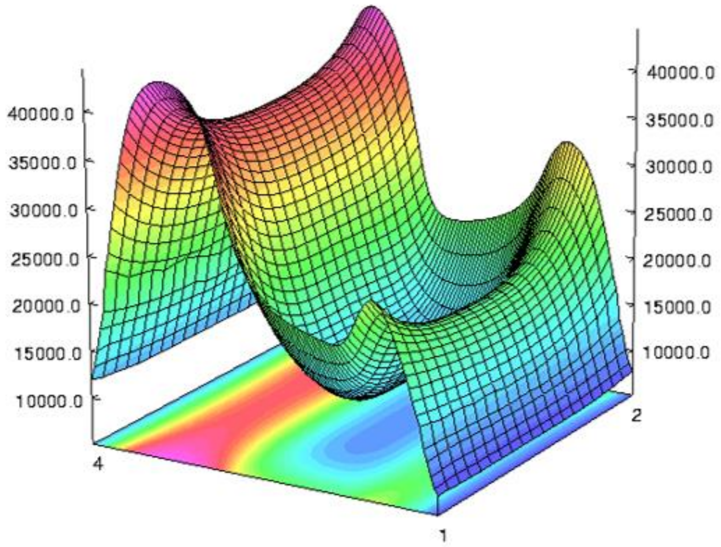


Fig. 3. Magnetic induction on the axis of the solenoids as a function of axial displacement from the microwave window. The dashed vertical lines define the axial extent of the plasma chamber.

Microwave Discharge Ion Source vs ECR Ion Source

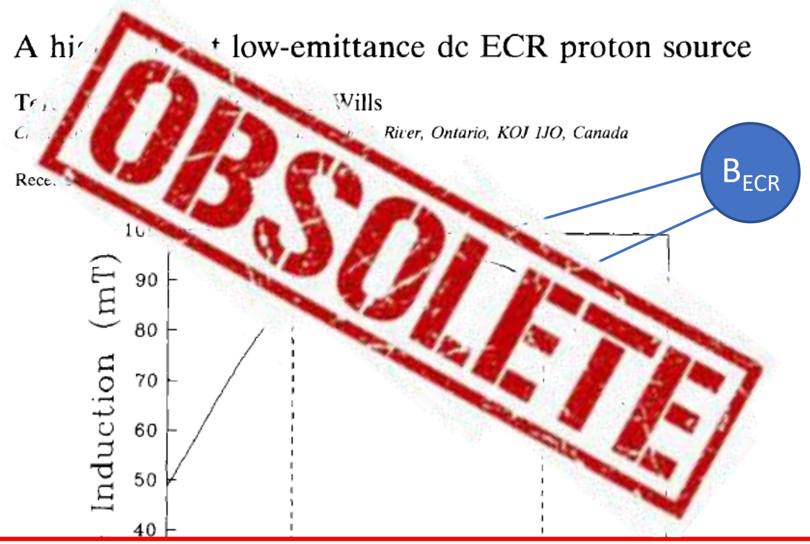
ECRIS magnetic configuration

- **high T** ➔ B minimum configuration
- B_{ECR} is a closed surface at the center of the plasma chamber
- Magneto Hydro Dynamics stability ➔ $\frac{B_{est}}{B_{ECR}} > 2$
- Scaling lows: $I \propto \frac{\omega_{RF}^2}{M}$; $\langle q \rangle = \log \omega_{RF}^{3.5}$



MDIS magnetic configuration

Since 1991, following experimental evidences, B_{ECR} was placed at the injection and at the extraction ends of the plasma chamber

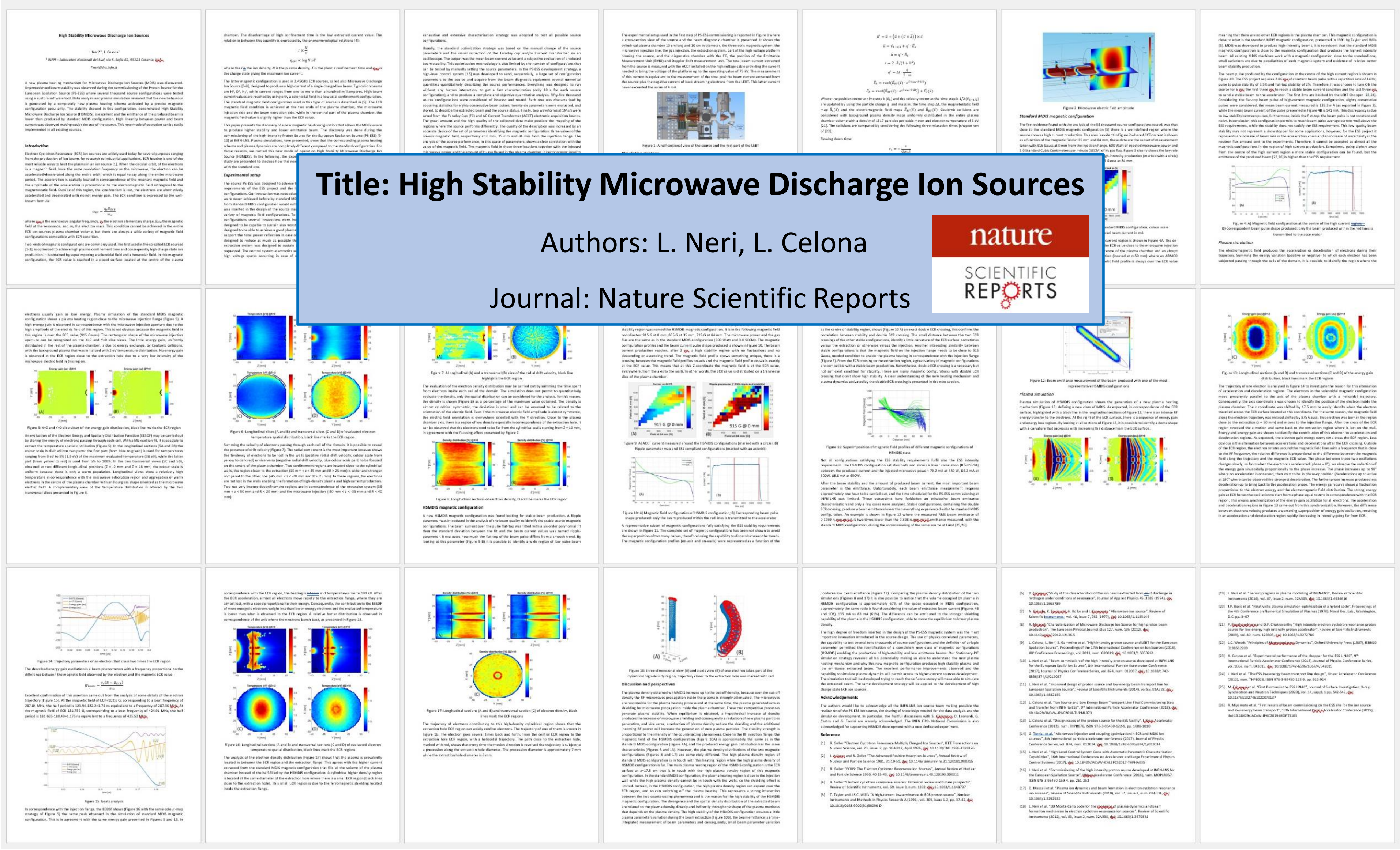


PS-ESS commissioning shows that this is not the best magnetic configuration

HSMDIS project will investigate on the physics behind this evolution and the possibility of further improvements

The dashed vertical lines define the axial extent of the plasma chamber.

First HSMDIS publication

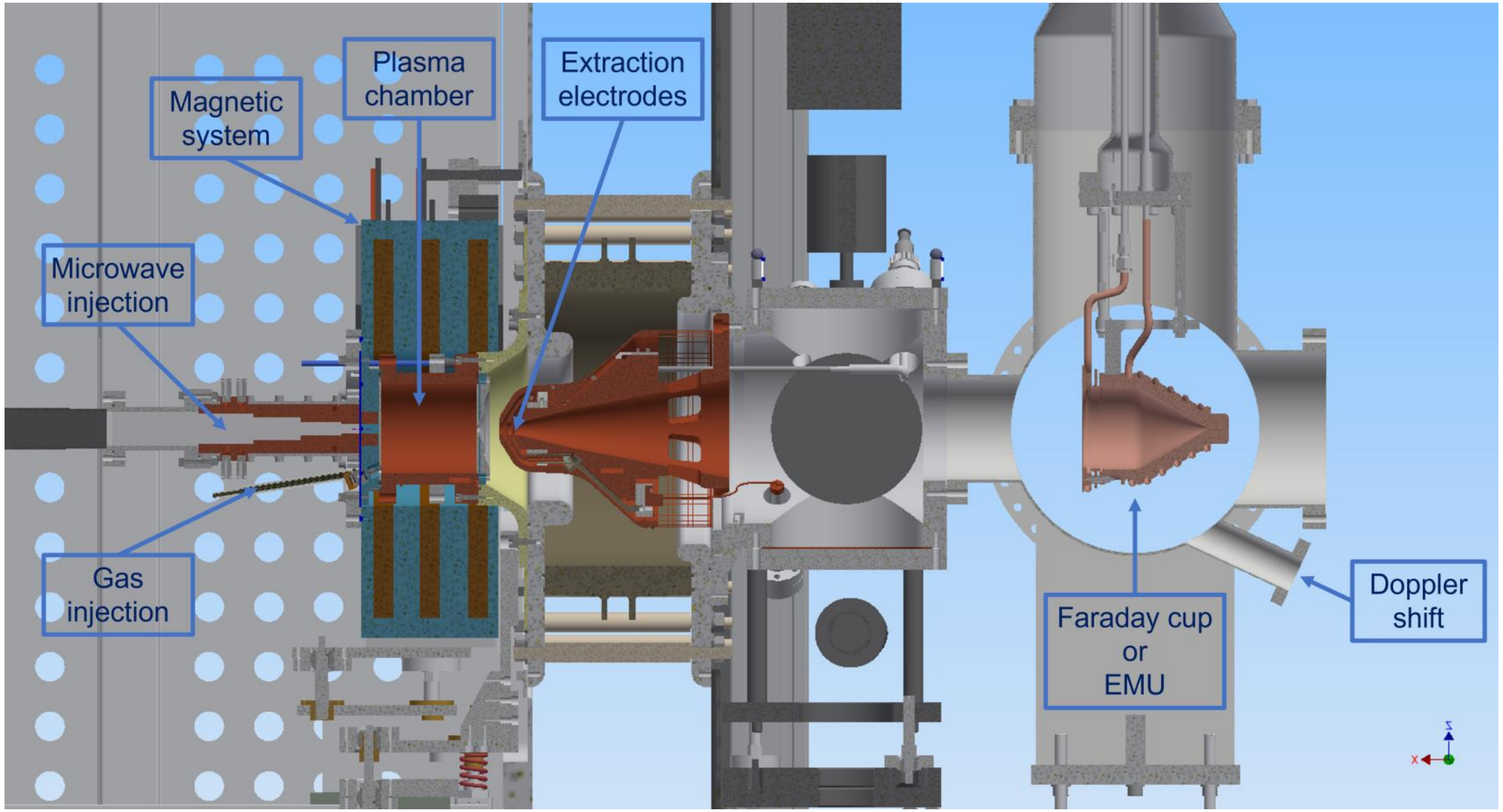


Title: High Stability Microwave Discharge Ion Sources

Authors: L. Neri, L. Celona

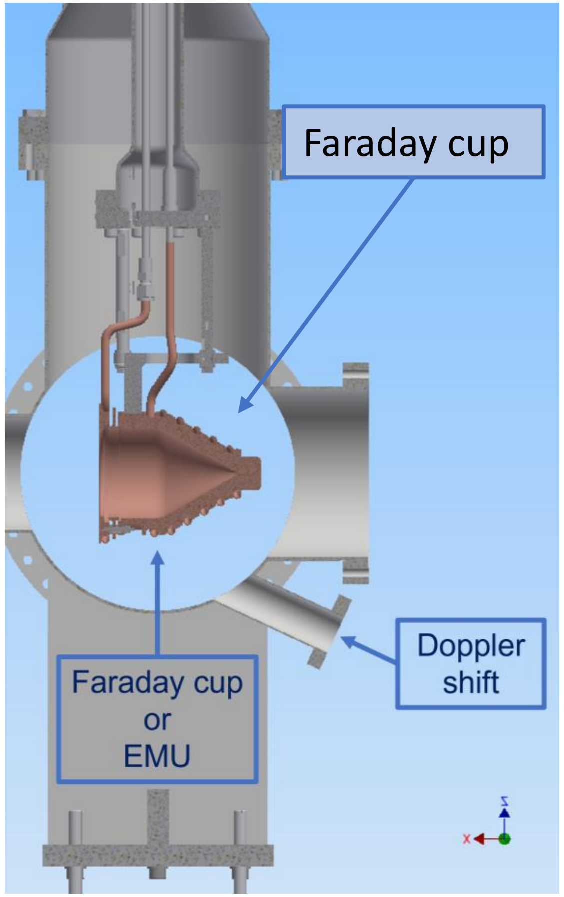
Journal: Nature Scientific Reports

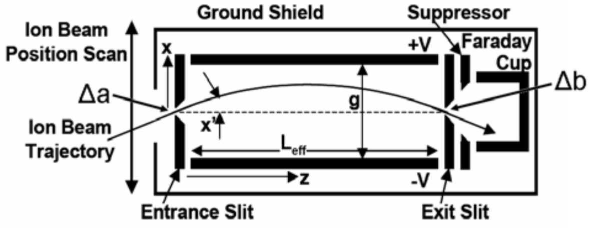
PS-ESS first experimental setup

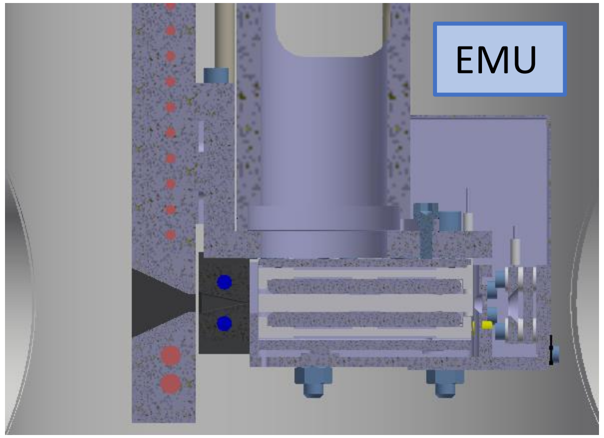


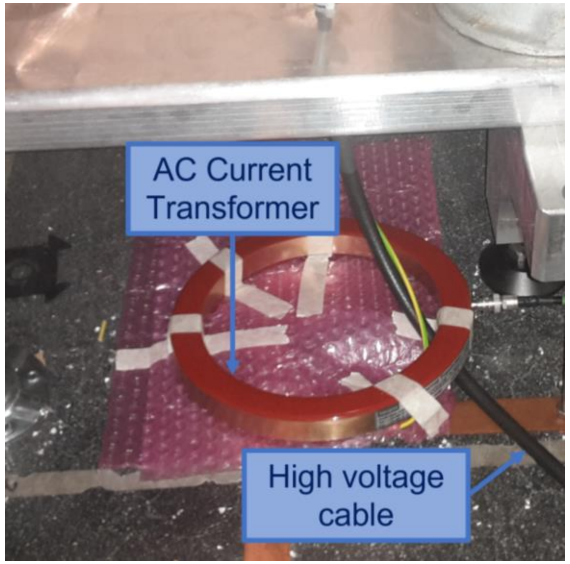
Proton Source for the European Spallation Source (**PS-ESS**)
Developed at INFN-LNS in Catania (Italy) 2012-2018
Installed in Lund (Sweden) in 2018-02-01

PS-ESS first experimental setup

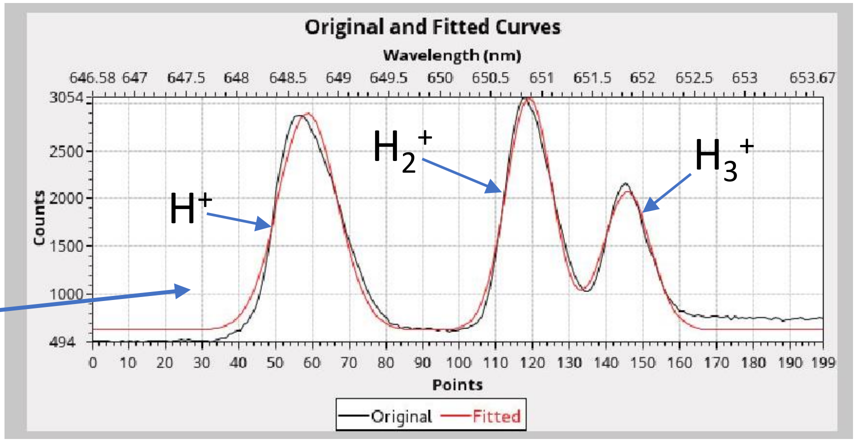








Doppler Shift of Hydrogen Balmer α ray at 656.3 nm



Diagnostics

Faraday cup for beam current measurement: 80 mm diameter, precision ±0.2 mA, 1 Ms/s

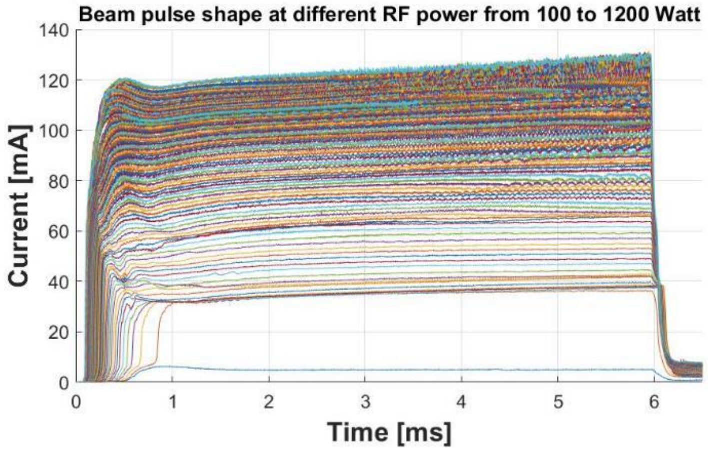
ACCT for the measurement of the total beam current extracted: bandwidth from 3Hz to 1MHz, droop compensation circuit, 1 Ms/s, accuracy 0.1%, precision ±0.2 mA

EMU (Alison scanner) for the emittance measurement: precision 0.1 mm, precision 0.2 mrad, 1 Ms/s, precision ±0.2 mA

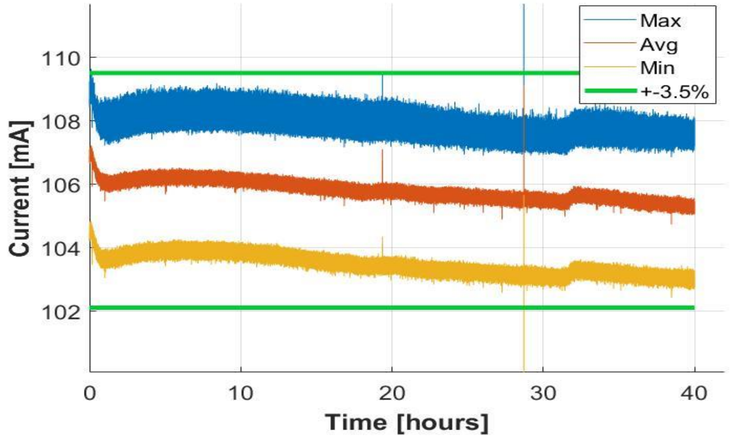
Doppler shift for the H^+, H_2^+ and H_3^+ fraction measurement: precision 1%

The capability to satisfy ESS requirement…

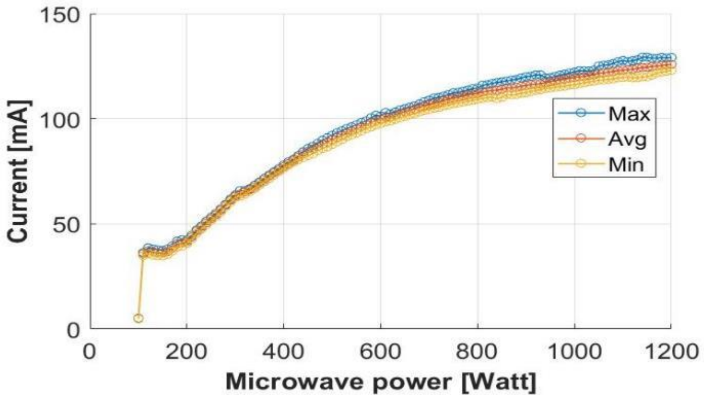
Intra-pulse stability < ±2%

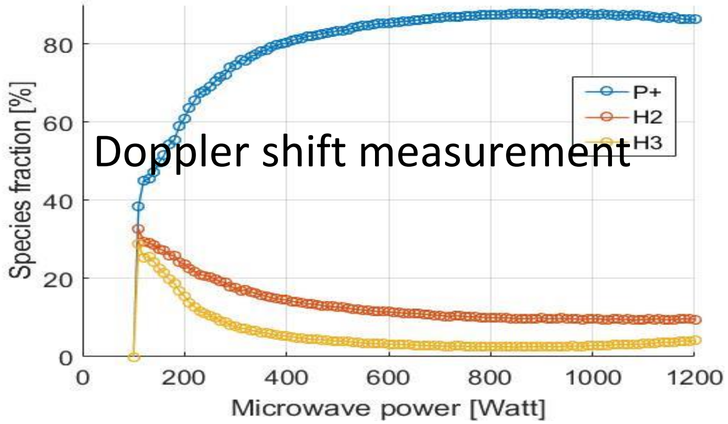


Pulse to pulse stability < ± 3.5%



Minimum proton current range 67-74 mA





Doppler shift measurement

Background of HSMDIS project

PS-ESS was fully commissioned at LNS and performance were validated by ESS personnel

Requirement	Value	**Measurement done for configurations that satisfy the ESS stability requirements**	**Comments**
Total beam current	>90 mA	40 - 140 mA	✓
Nominal proton beam current	74 mA	40 - 105 mA	✓
Proton beam current range	67-74 mA	40 - 105 mA	✓
Proton fraction	>75%	Up to 85%	✓
Pulse length	6 ms	6 ms	✓
Pulse flat top	3 ms	3 ms	✓
Flat top stability	±2 %	< ±2 % up to 1.5%	✓
Pulse to pulse stability	±3.5 %	< ±3.5 % up to 3%	✓
Repetition rate	14 Hz	14 Hz	✓
Beam energy	75±5 keV	75 keV	✓
Energy adjustment	±0.01 keV	±0.01 keV	✓
Transverse emittance (99%)	1.8 pi.mm.mrad	1.06 pi.mm.mrad @ 82 mA	✓
Beam divergence (99%)	<80 mrad	50 mrad @ 82 mA	✓
Start-up after source maintenance	32 hours	32 hours	✓

Second source with second part of the commissioning was not needed

2018-02-01 Source fully assembled in Lund by INFN-LNS team

PS-ESS Team: L. Neri, L. Celona, S. Gammino, A. Miraglia, O. Leonardi, G. Castro, G. Torrisi, D. Mascali, M. Mazzaglia, L. Allegra, A. Amato, G. Calabrese, A. Caruso, F. Chines, G. Gallo, A. Longhitano, G. Manno, S. Marletta, A. Maugeri, S. Passarello, G. Pastore, A. Seminara, A. Sparta, S. Vinciguerra.

Acknowledgment to LNS Accelerator Division, Technical Division, Administration and External Funds.

Background of HSMDIS project

15-11-2018 official delivery with
Italian President Mattarella and Sweden King

2018-02-01 Source fully assembled in Lund by INFN-LNS team

PS-ESS Team: L. Neri, L. Celona, S. Gammino, A. Miraglia, O. Leonardi, G. Castro, G. Torrisi, D. Mascali, M. Mazzaglia, L. Allegra, A. Amato, G. Calabrese, A. Caruso, F. Chines, G. Gallo, A. Longhitano, G. Manno, S. Marletta, A. Maugeri, S. Passarello, G. Pastore, A. Seminara, A. Sparta, S. Vinciguerra.

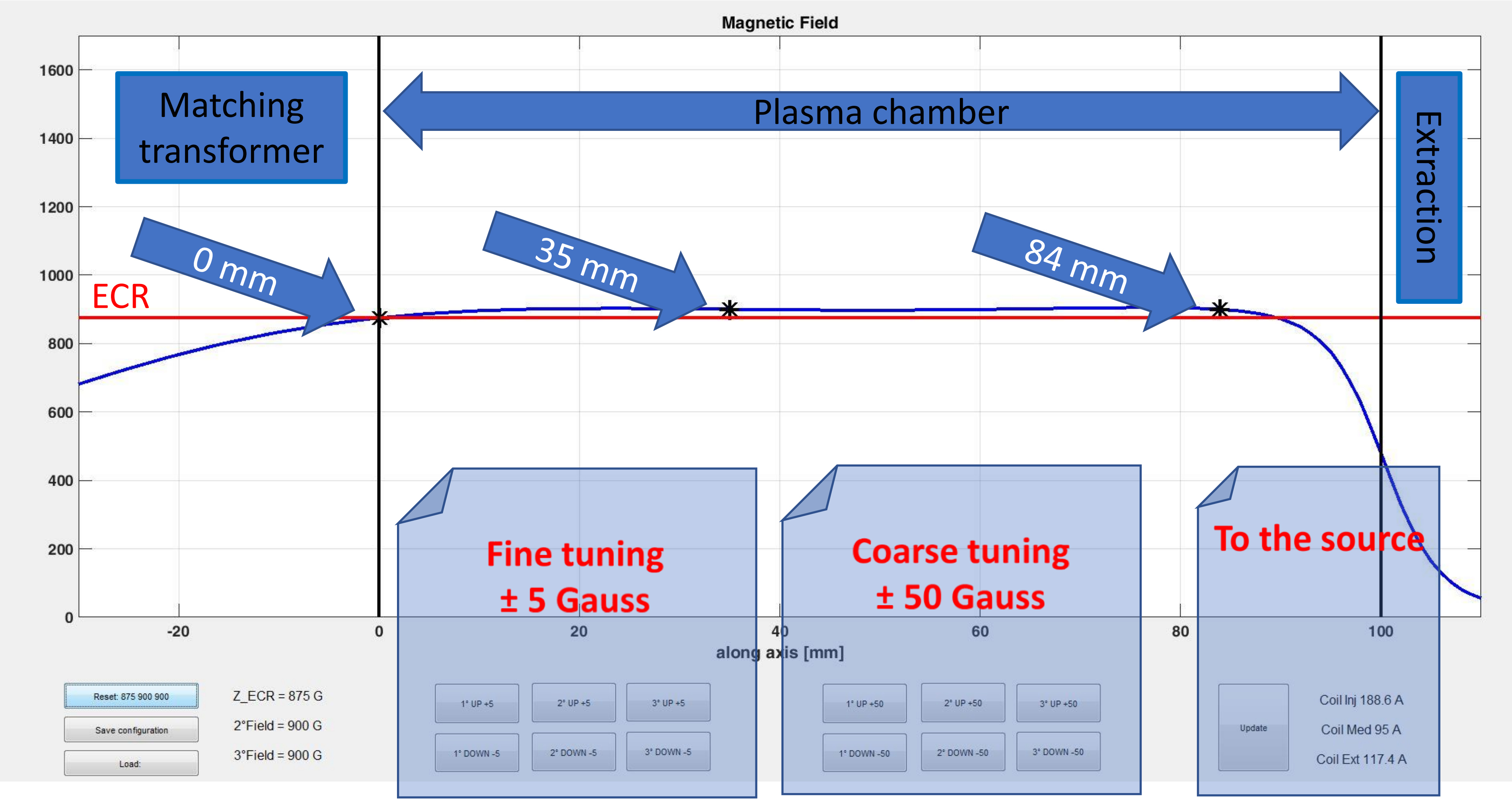
Acknowledgment to LNS Accelerator Division, Technical Division, Administration and External Funds.

Describe source configuration exposing physic correlation with the magnetic field

Source configuration:
OBSOLETE

- Coil 1
- Coil 2
- Coil 3
- Microwave power
- Gas flux

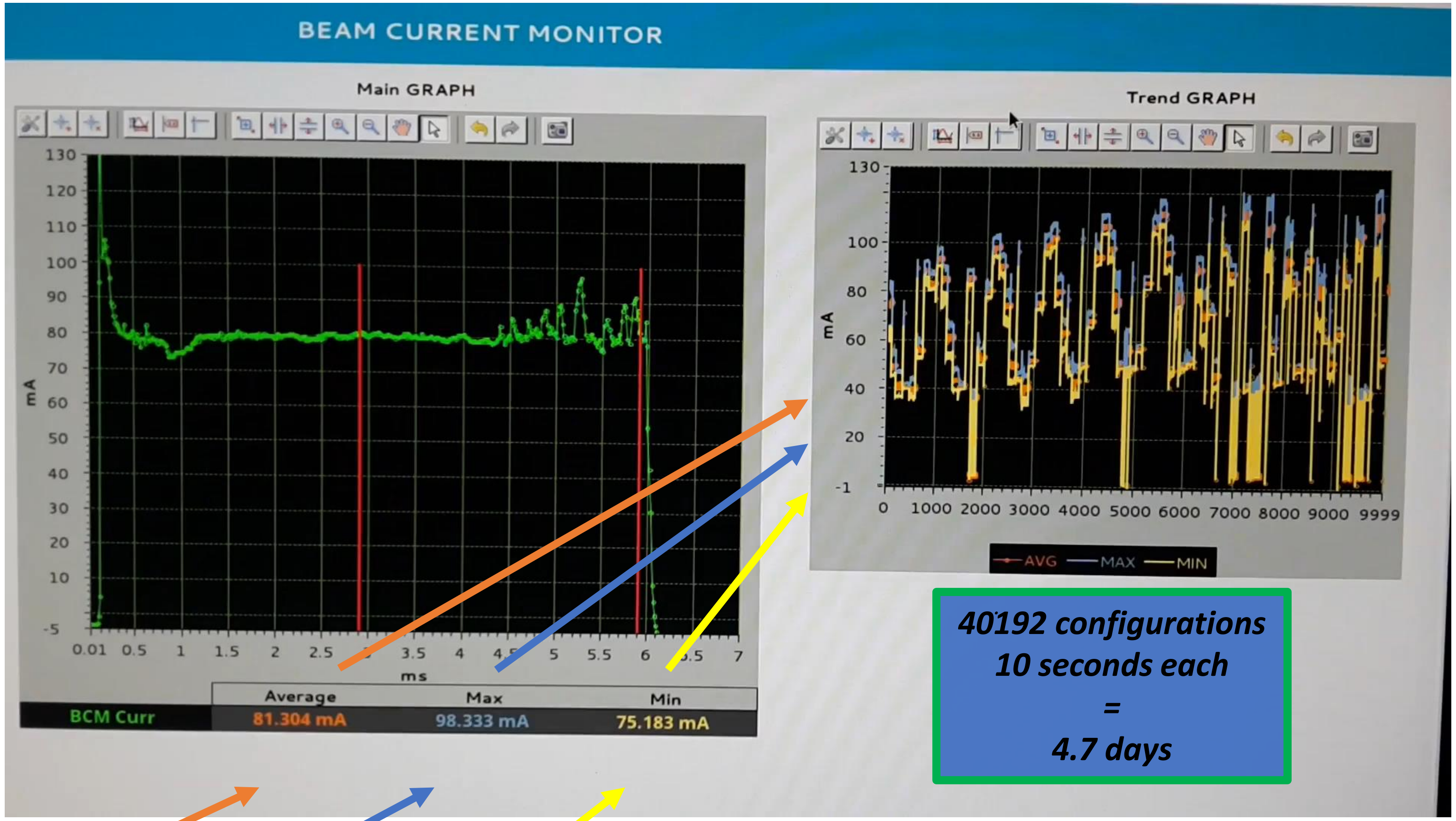
Physics says that **only Magnetic field is directly correlated to source behaviour** and not the coil currents



Source configuration:
- B Field @0mm
- B Field @35mm
- B Field @84mm
- Microwave power
- Gas flux

Comsol ← Matlab → EPICS

Semi-automatic beam characterization tool



40192 configurations
10 seconds each
=
4.7 days

In the graphical interface: average, maximum and minimum are evaluated, and the trend showed for the beam pulse between 2.9 ms and 5.9 ms .

From plasma modelling :

Field @ 0 mm ==> 835:20:975 G
Field @ 35 mm ==> 795:40:1395 G
Field @ 84 mm ==> 675:40:1995 G
H_2 flow ==> 2:1:5 SCCM
RF power ==> 600:200:1200 W

40192 configurations

From evidence of stable configurations:

Field @ 0 mm ==> 795:20:1015 G
Field @ 35 mm ==> 515:40:1075 G
Field @ 84 mm ==> 235:40:1075 G
H_2 flow ==> 3.35:0.25:3.85 SCCM
RF power ==> 550:50:650 W

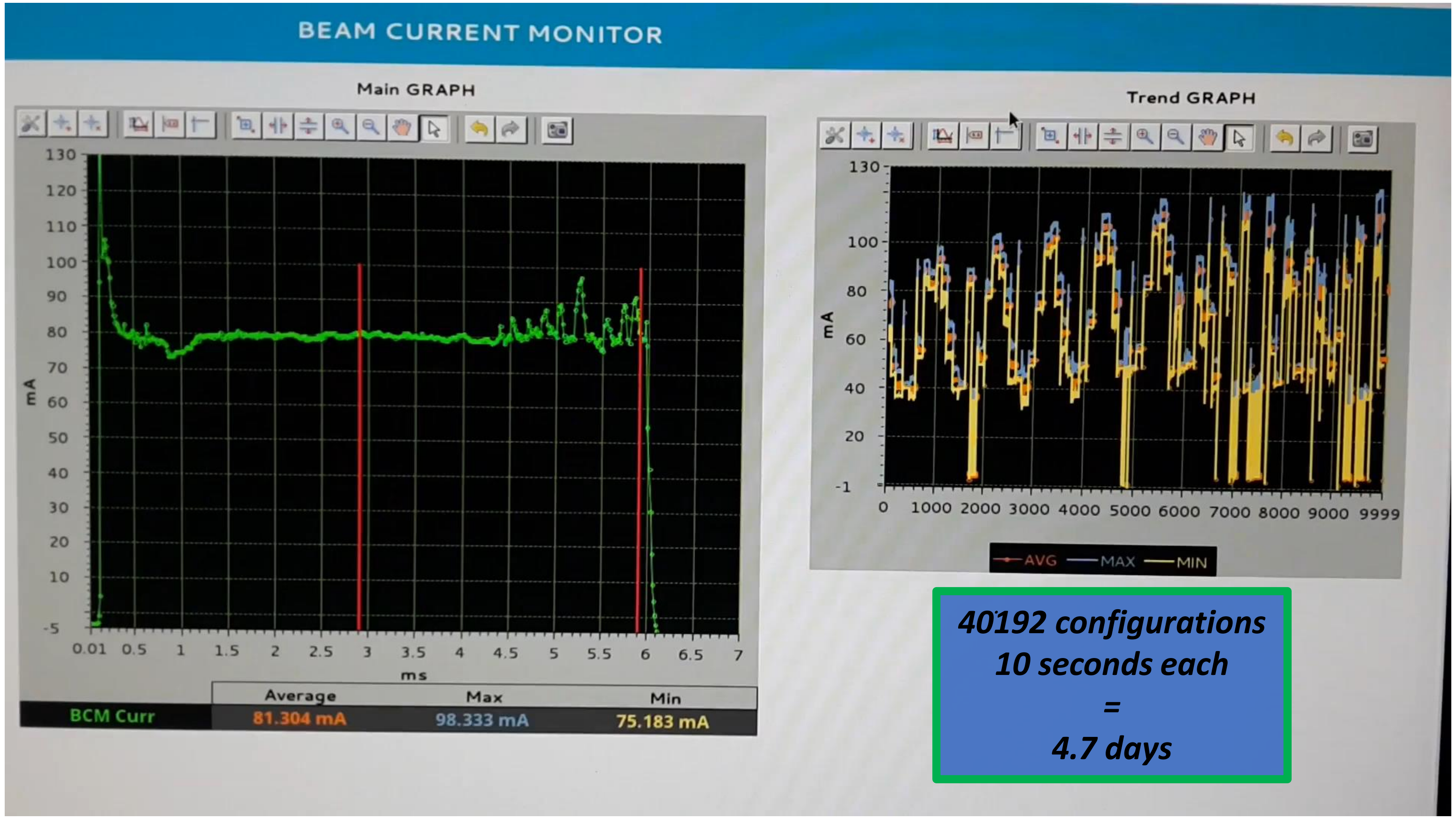
15480 configurations

With Doppler Shift Measurement:

H_2 flow ==> 3.5 SCCM
RF power ==> 175:75:325 W

5160 configurations

Semi-automatic beam characterization tool



40192 configurations
10 seconds each
=
4.7 days

From plasma modelling :

Field @ 0 mm ==> 835:20:975 G
Field @ 35 mm ==> 795:40:1395 G
Field @ 84 mm ==> 675:40:1995 G
H_2 flow ==> 2:1:5 SCCM
RF power ==> 600:200:1200 W

40192 configurations

From evidence of stable configurations:

Field @ 0 mm ==> 795:20:1015 G
Field @ 35 mm ==> 515:40:1075 G
Field @ 84 mm ==> 235:40:1075 G
H_2 flow ==> 3.35:0.25:3.85 SCCM
RF power ==> 550:50:650 W

15480 configurations

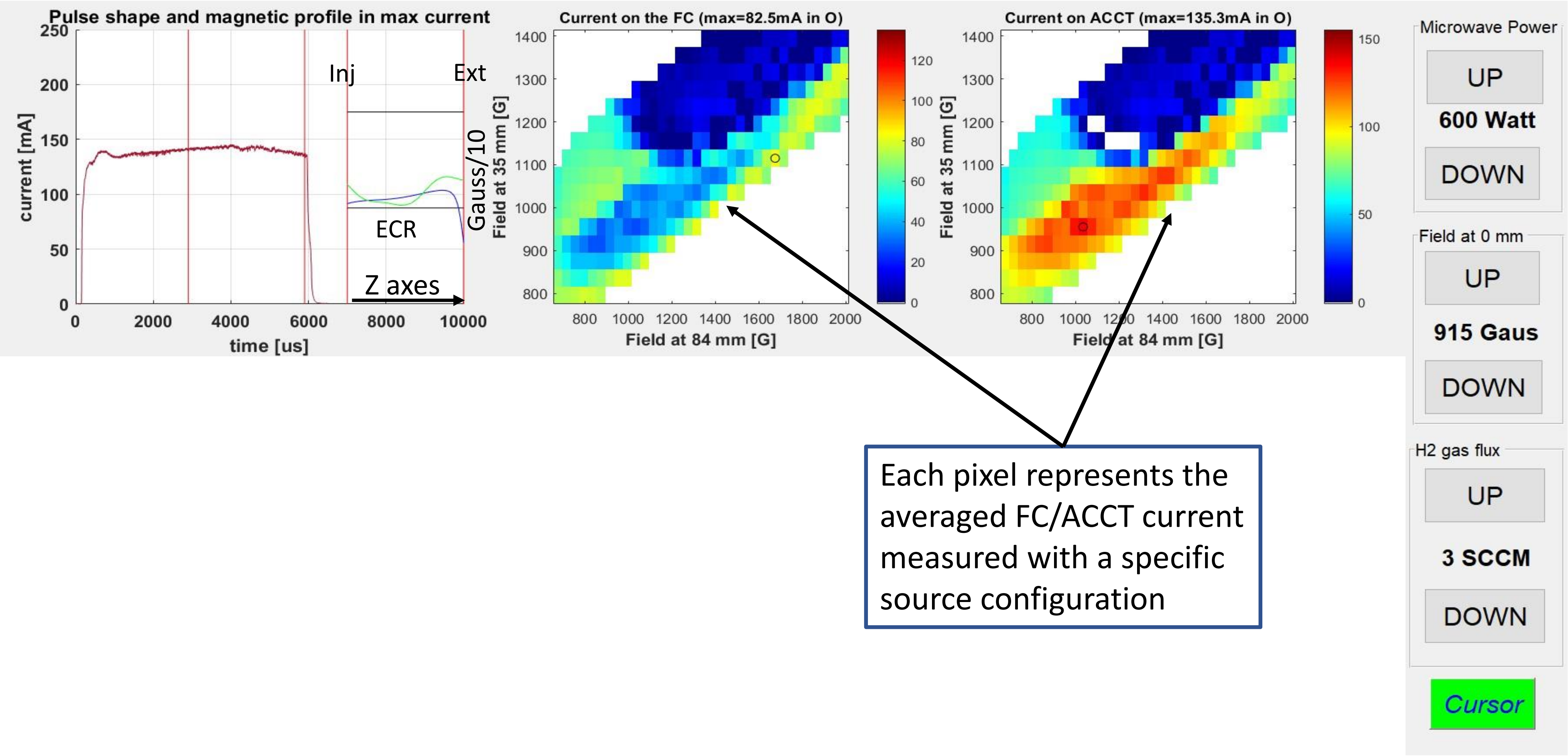
With Doppler Shift Measurement:

H_2 flow ==> 3.5 SCCM
RF power ==> 175:75:325 W

5160 configurations

With extremely high flexibility and with the capability to test thousands of configuration without survey ➔ <u>we don't need a predictive simulation tool</u>
➔ <u>we need a simulation tool able to disclose the reasons for different behaviors</u>

Visualization of collected data



Each pixel represents the averaged FC/ACCT current measured with a specific source configuration

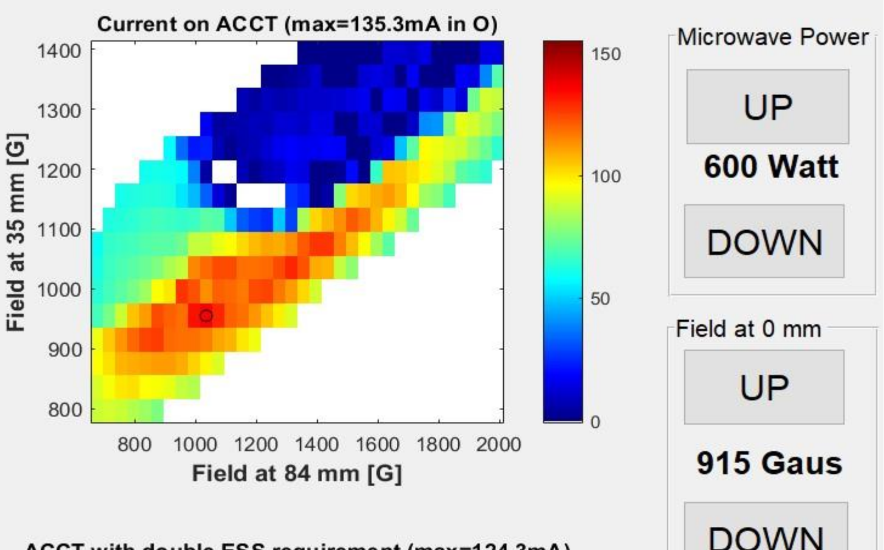
Visualization of collected data

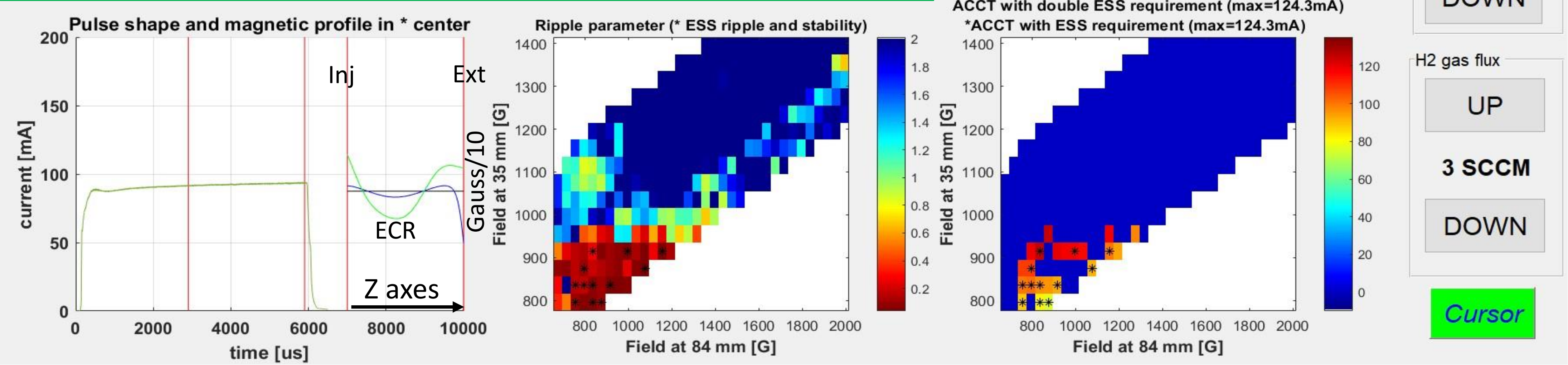
ESS requirements:

- The beam pulse current variation <2.0% of flat top mean current
- The flat top mean current variation <3.5% from pulse to pulse.

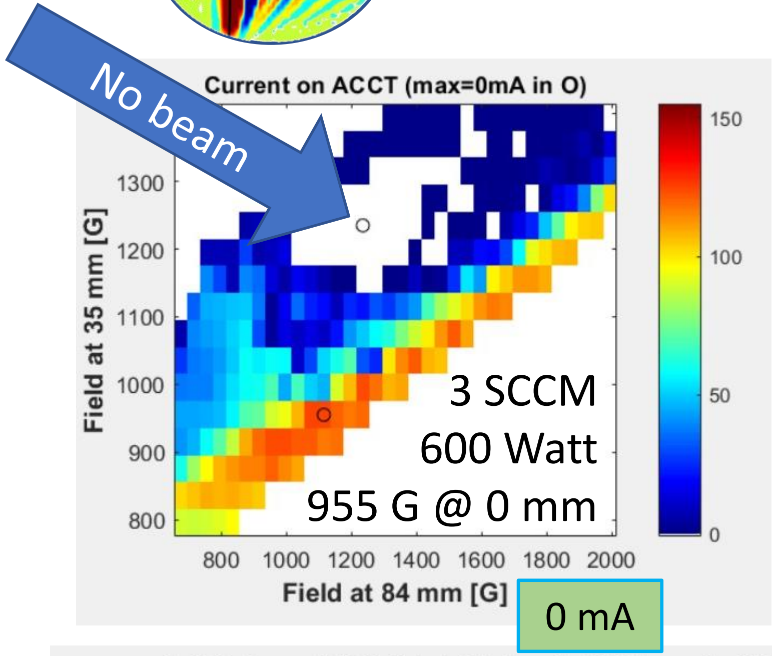
We introduced a **Ripple parameter** to quantify how much the beam is noisy:

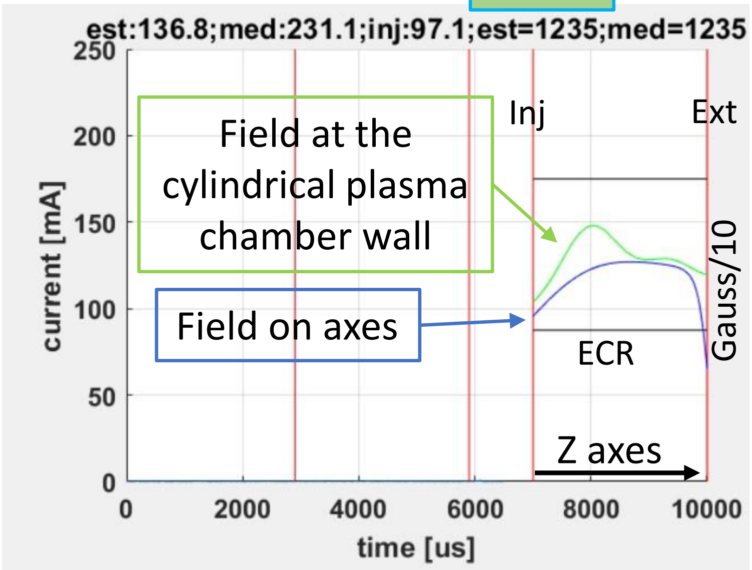
- Standard deviation between beam current and 6th order polynomial fit of the flat top part





The three most relevant source behaviors





The three most relevant source behaviors

A high-current low-emittance dc ECR proton source

Terence Taylor and John S.C. Wills
Chalk River Laboratories, AECL Research, Chalk River, Ontario, KOJ 1JO, Canada

Received 18 June 1991

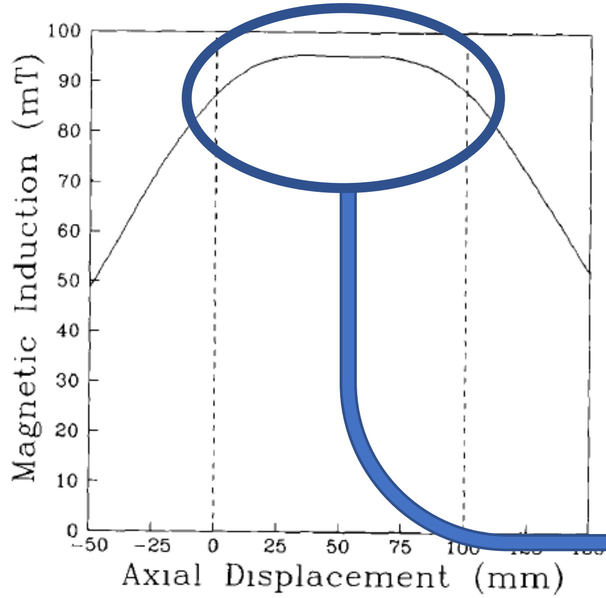
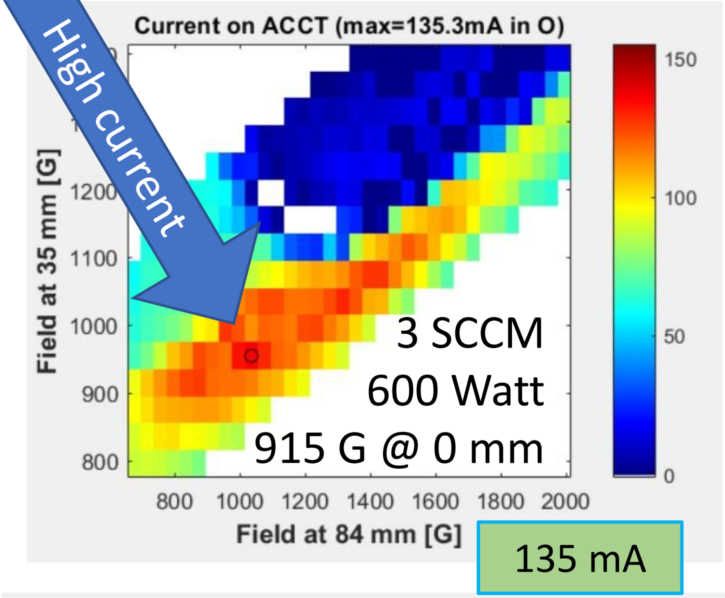
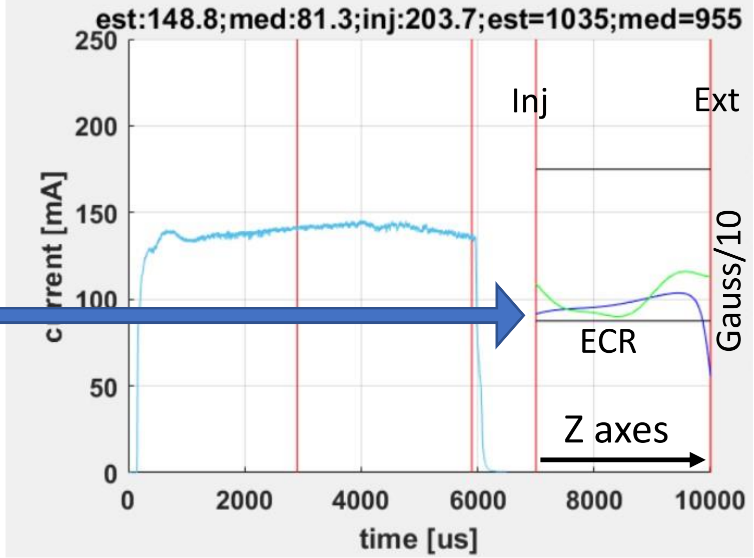


Fig. 3. Magnetic induction on the axis of the solenoids as a function of axial displacement from the microwave window. The dashed vertical lines define the axial extent of the plasma chamber.





The three most relevant source behaviors

A high-current low-emittance dc ECR proton source

Terence Taylor and John S.C. Wills
Chalk River Laboratories, AECL Research, Chalk River, Ontario, KOJ 1JO, Canada

Received 18 June 1991

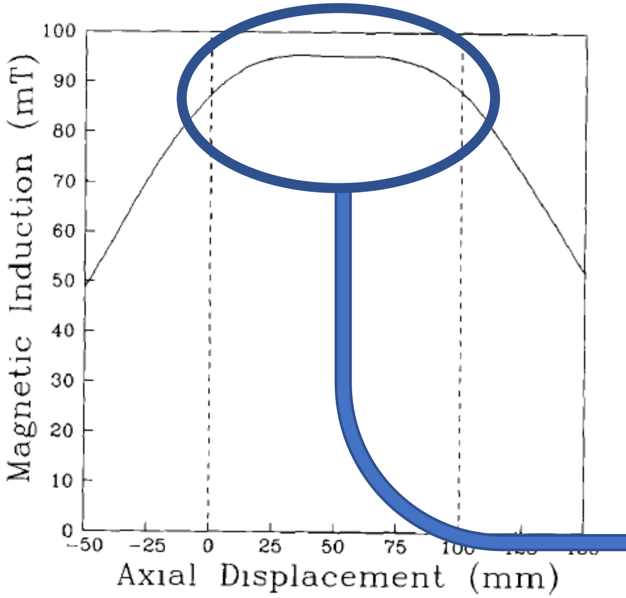
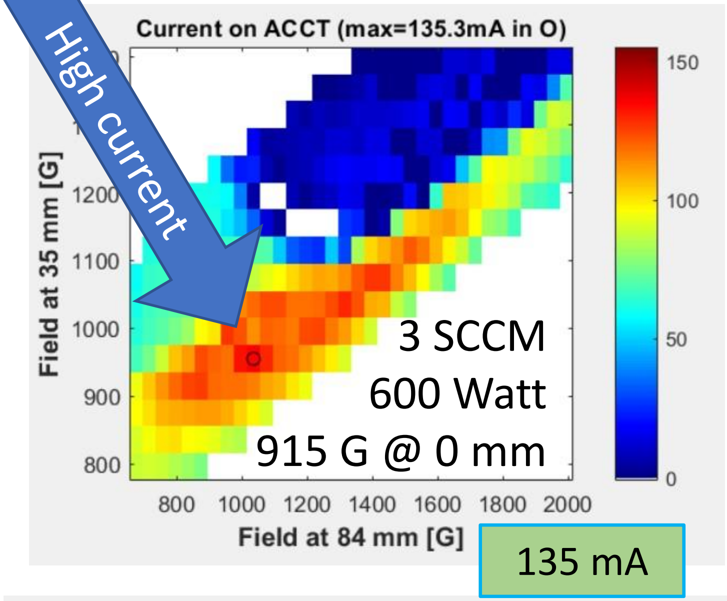
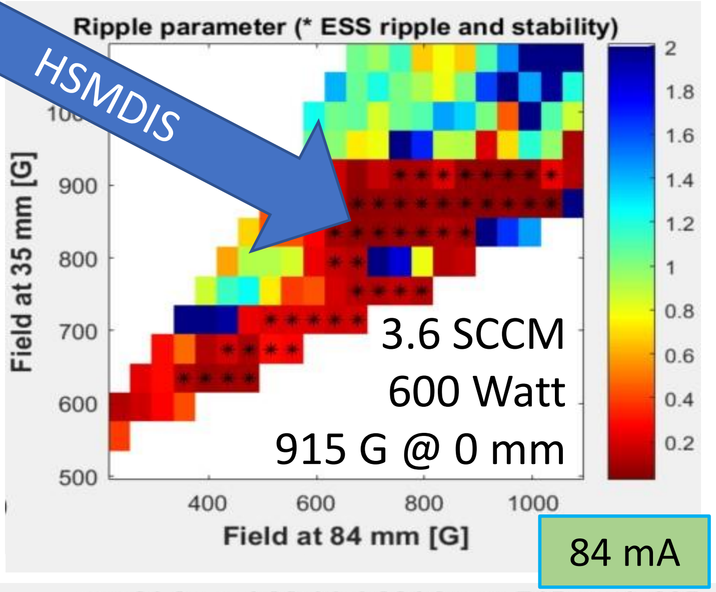
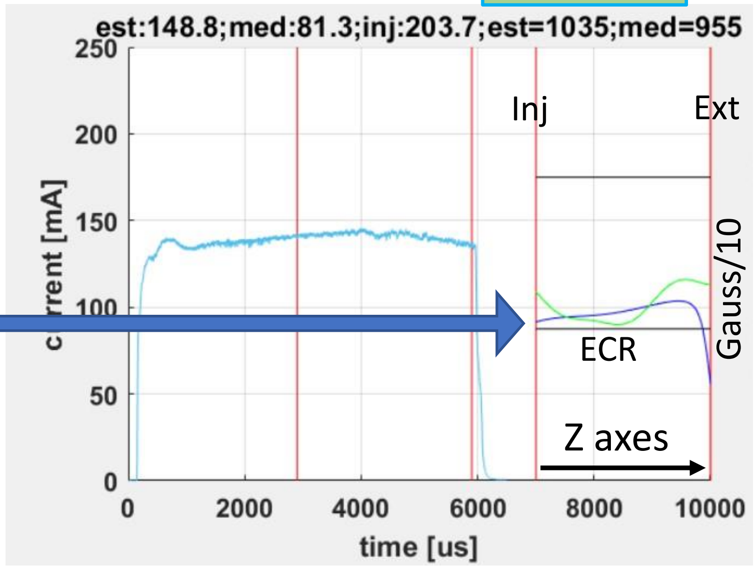
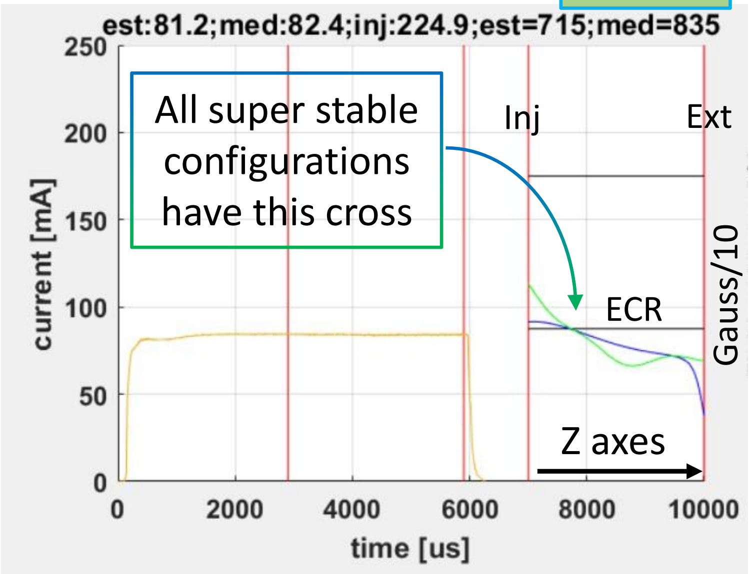


Fig. 3. Magnetic induction on the axis of the solenoids as a function of axial displacement from the microwave window. The dashed vertical lines define the axial extent of the plasma chamber.





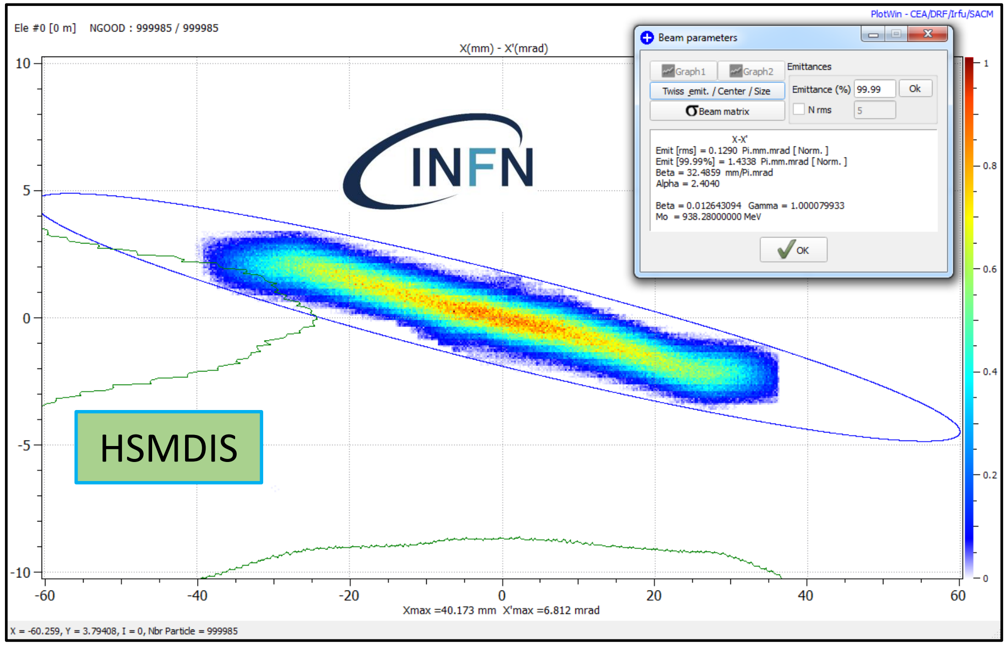




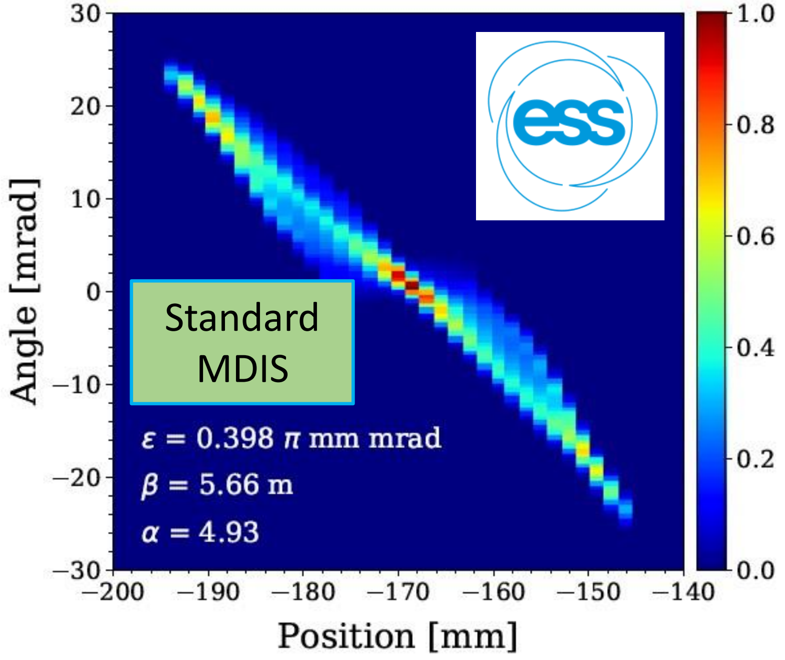
Different magnetic configurations produce different emittances

Inside HSMDIS project we will work to understand the reasons for lower emittance beam produced with HSMDIS magnetic configuration

$\varepsilon_{[rms]}$=0.129 pi.mm.mrad @LNS

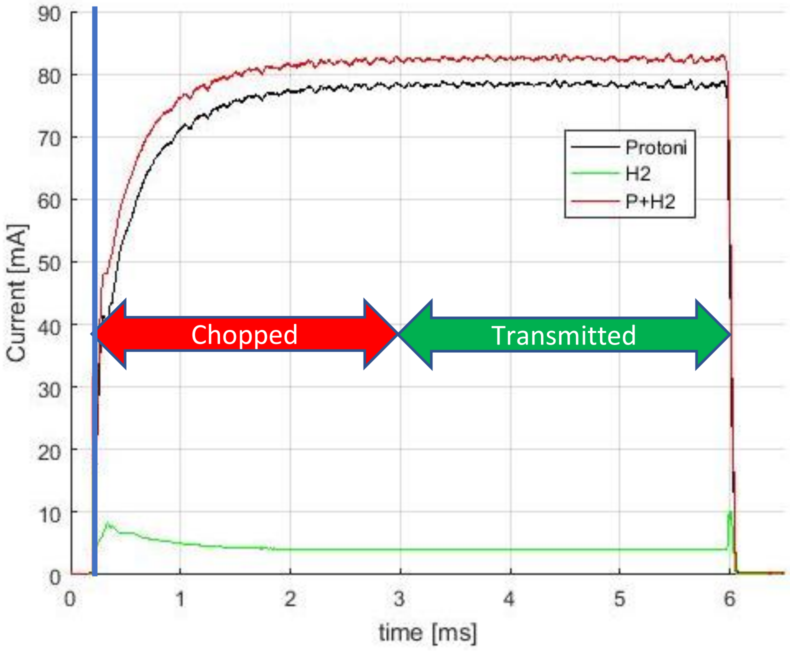


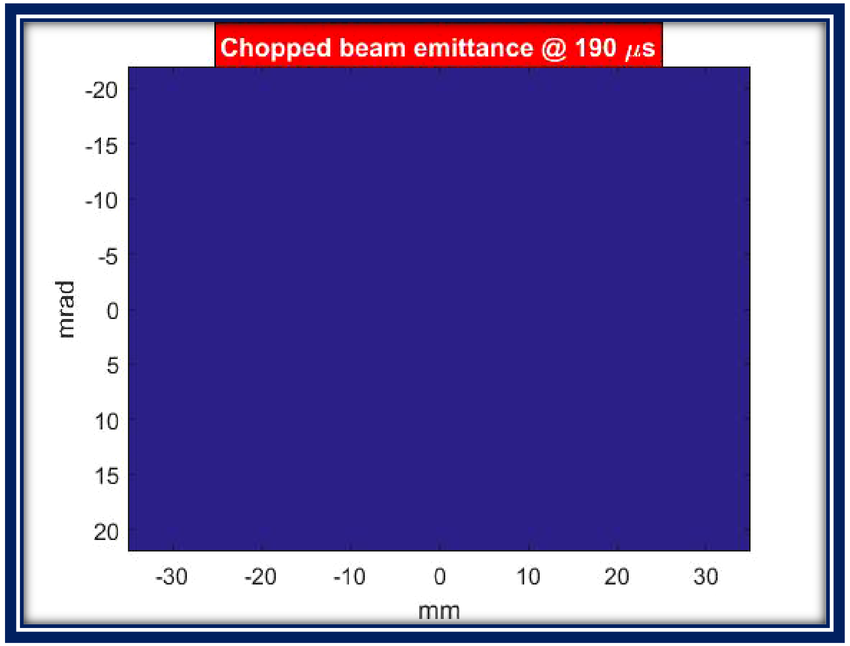
$\varepsilon_{[rms]}$=0.398 pi.mm.mrad @ESS



Different magnetic configurations produce different emittances

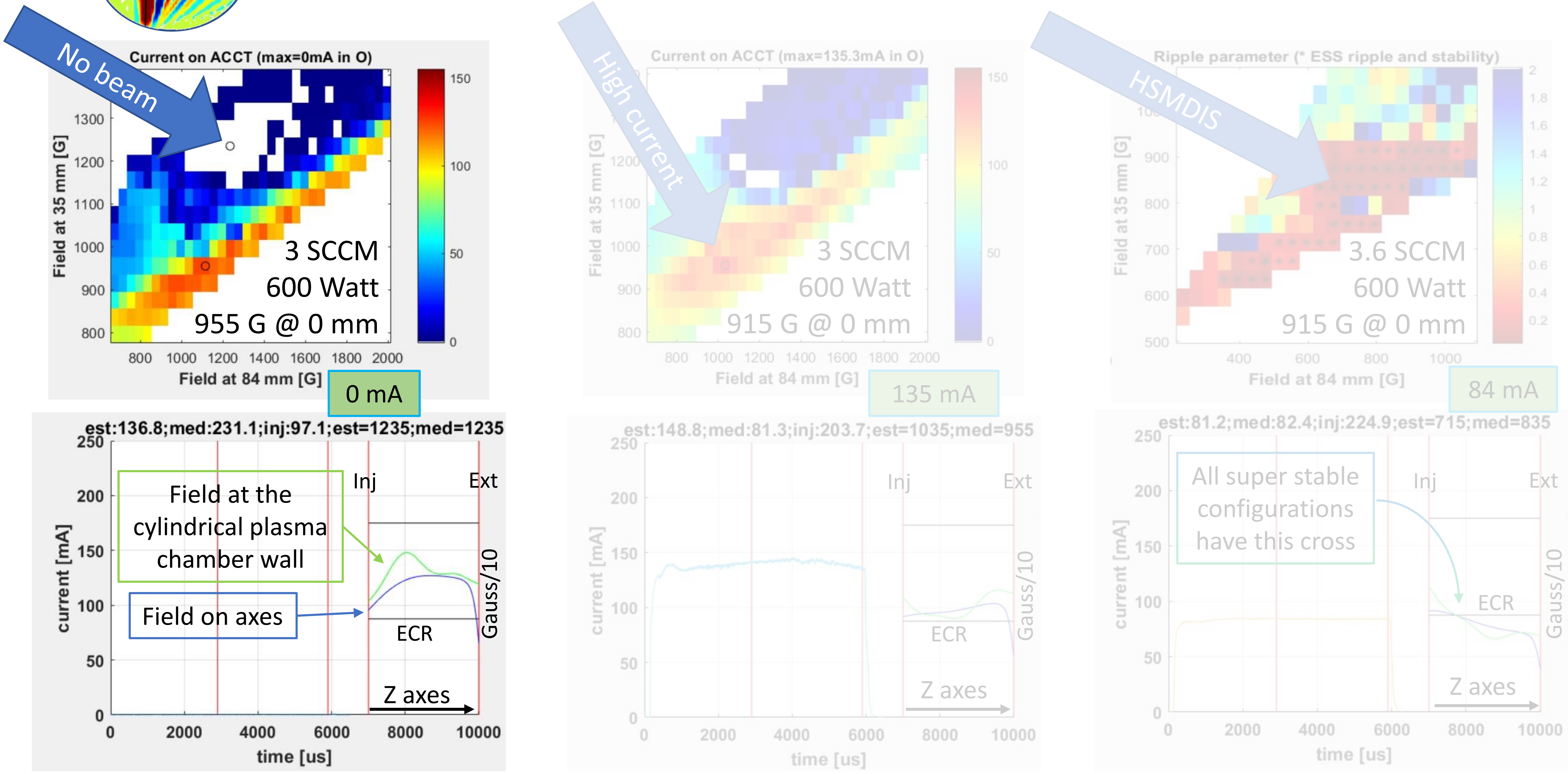
Inside HSMDIS project we will work to understand the reasons for lower emittance beam produced with HSMDIS magnetic configuration





Matlab 🡐 🡒 EPICS

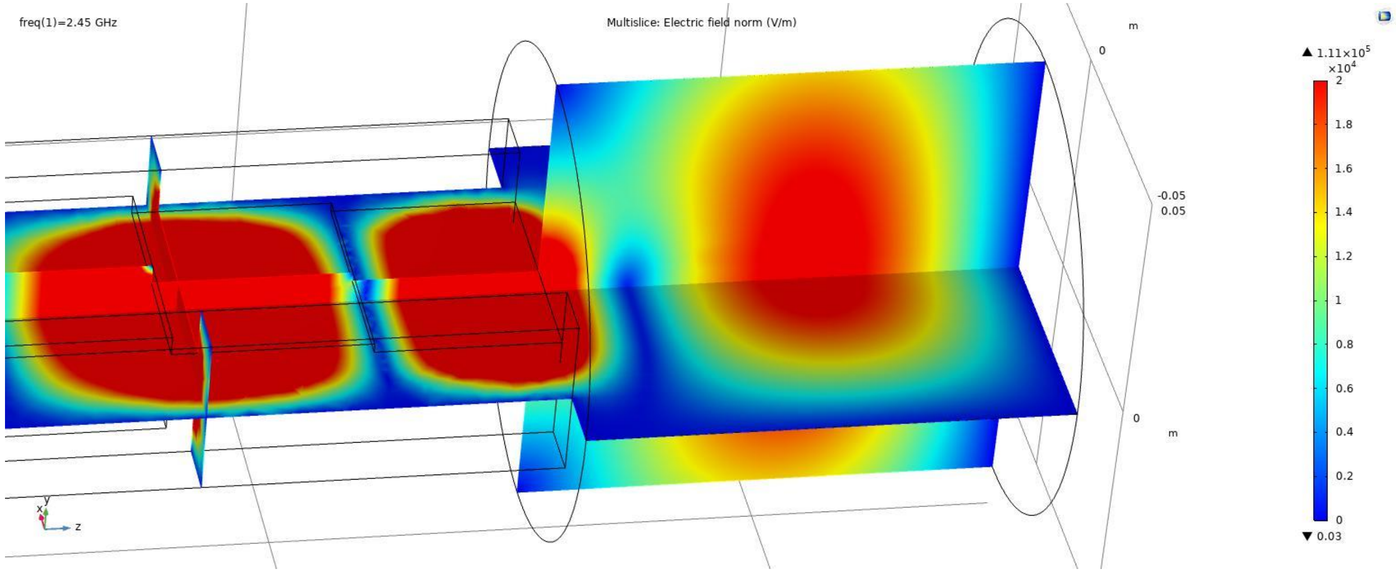
The three most relevant source behaviors

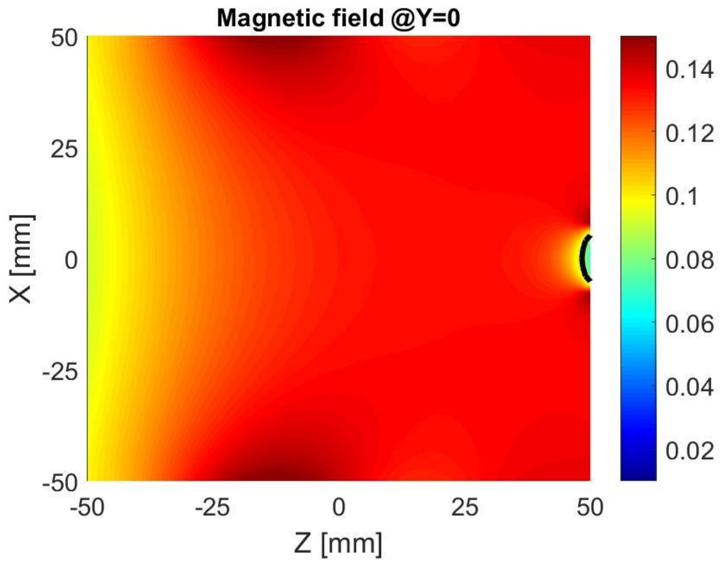


Simulation of “0 mA” configuration

At the startup of the plasma the plasma density is zero ➔ No Coulomb collision
➔ No space charge
➔ No tensorial permittivity

Simplest possible simulation: Electrons motion in a 3D magnetic field map + 3D electromagnetic field map computed in an empty plasma chamber.



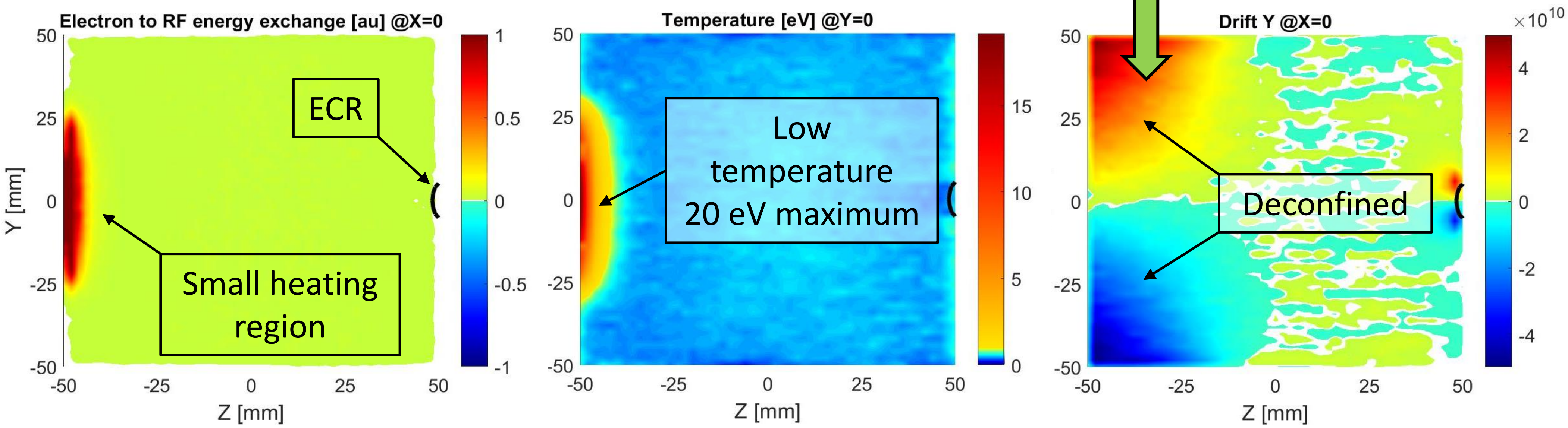


Simulation of “0 mA” configuration

At the startup of the plasma the plasma density is zero ➔ No Coulomb collision
➔ No space charge
➔ No tensorial permittivity

Simplest possible simulation: Electrons motion in a 3D magnetic field map + 3D electromagnetic field map computed in an empty plasma chamber.

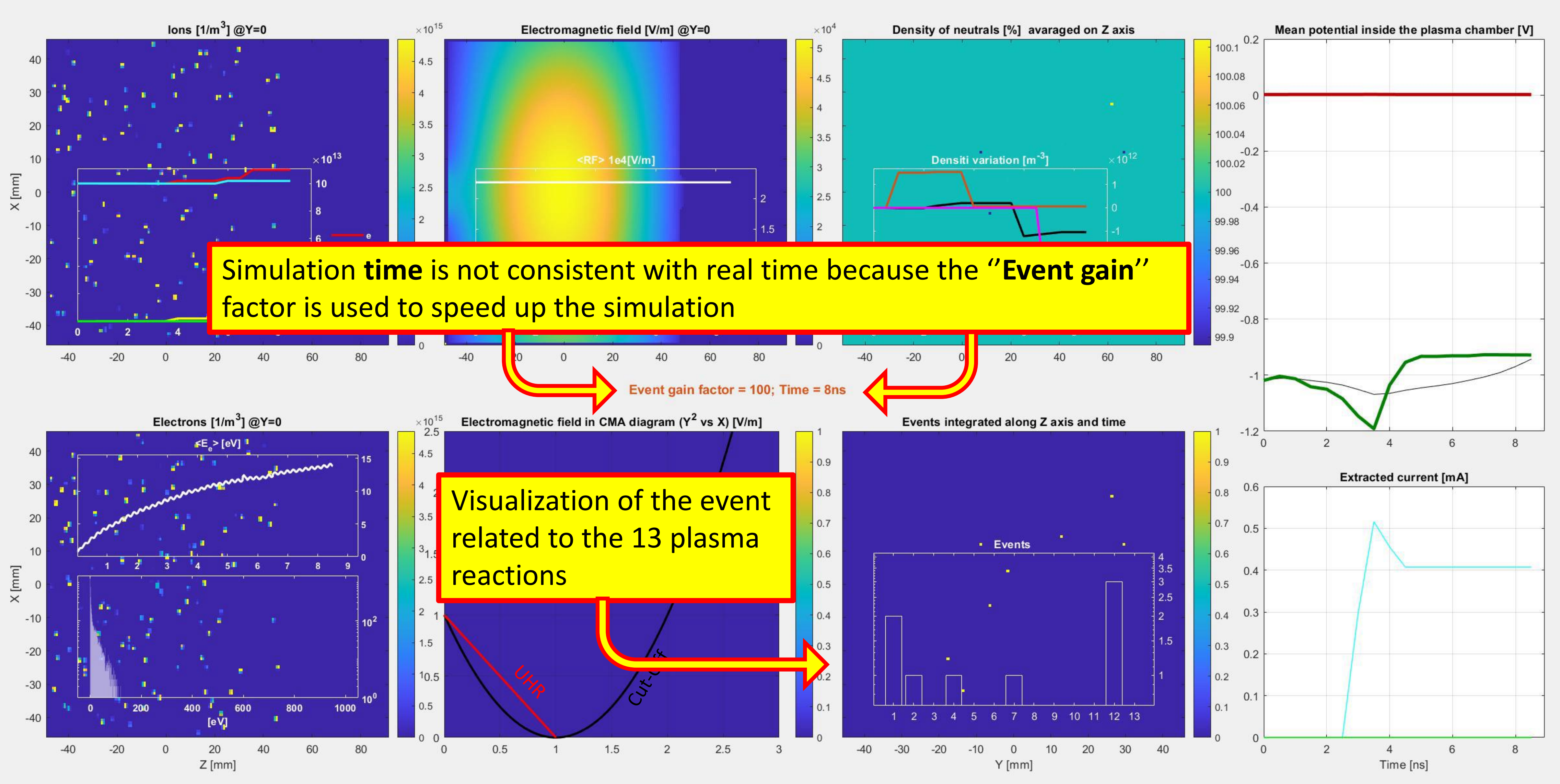
From the very first electrons are accelerated by the electromagnetic field, we can observe a strong deconfinement that do not allow the plasma ignition.



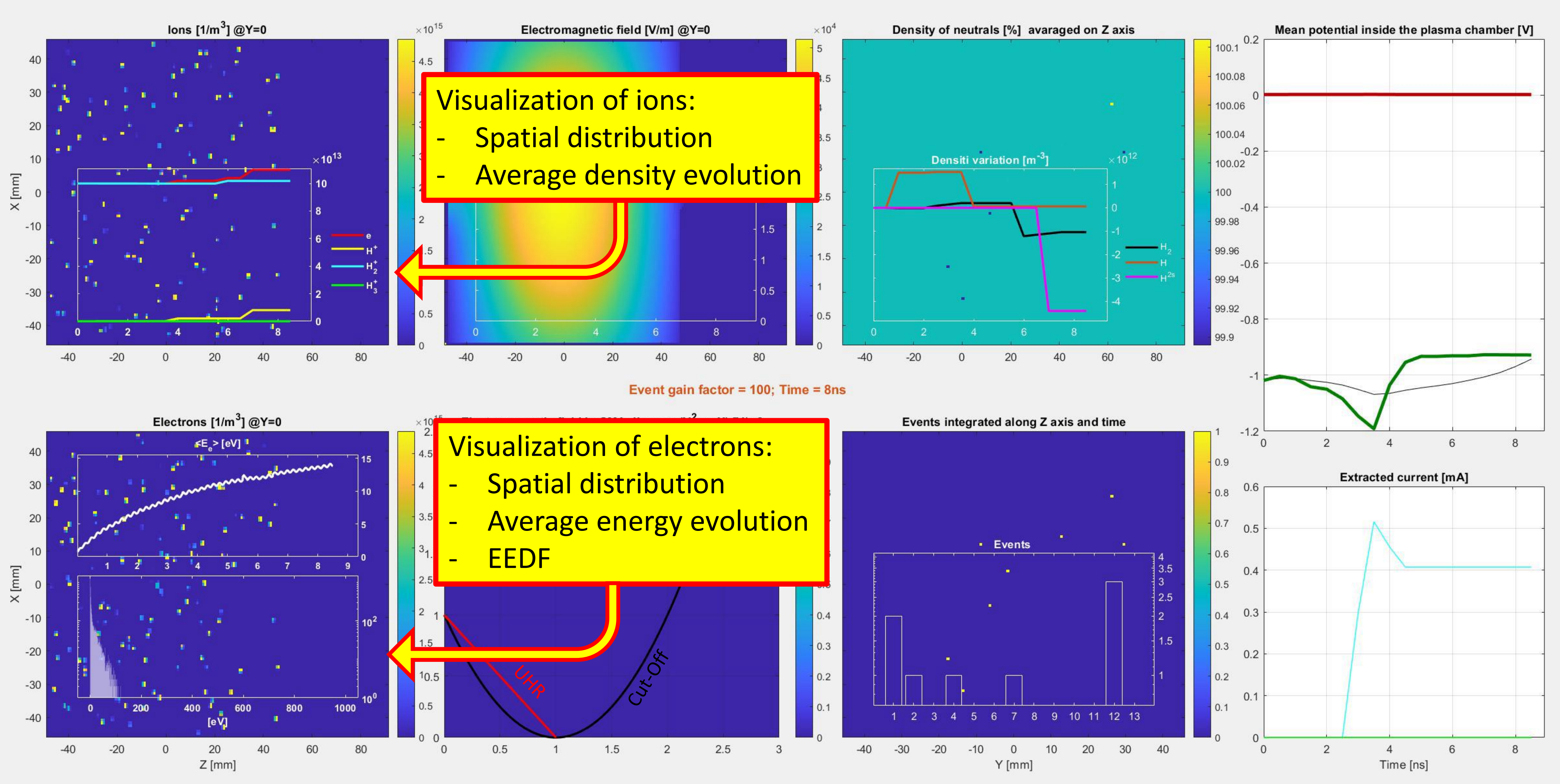
Stationary - Particle In Cell

- Motion of electrons with a time step of 5E-12 s (Boris mover)
- Motion of ions with a time step of 5E-10 s (Boris mover)
- Grid-based Langevin equations to model Coulomb collisions via drag and diffusion coefficients
- Reactions inside plasma + reactions in the walls
- Maps of neutrals and neutrals dynamics
- Three-dimensional RF (2.45GHz) electromagnetic simulation with tensorial permittivity
- Electrostatic simulation (step1)
- Electrostatic simulation (step2)

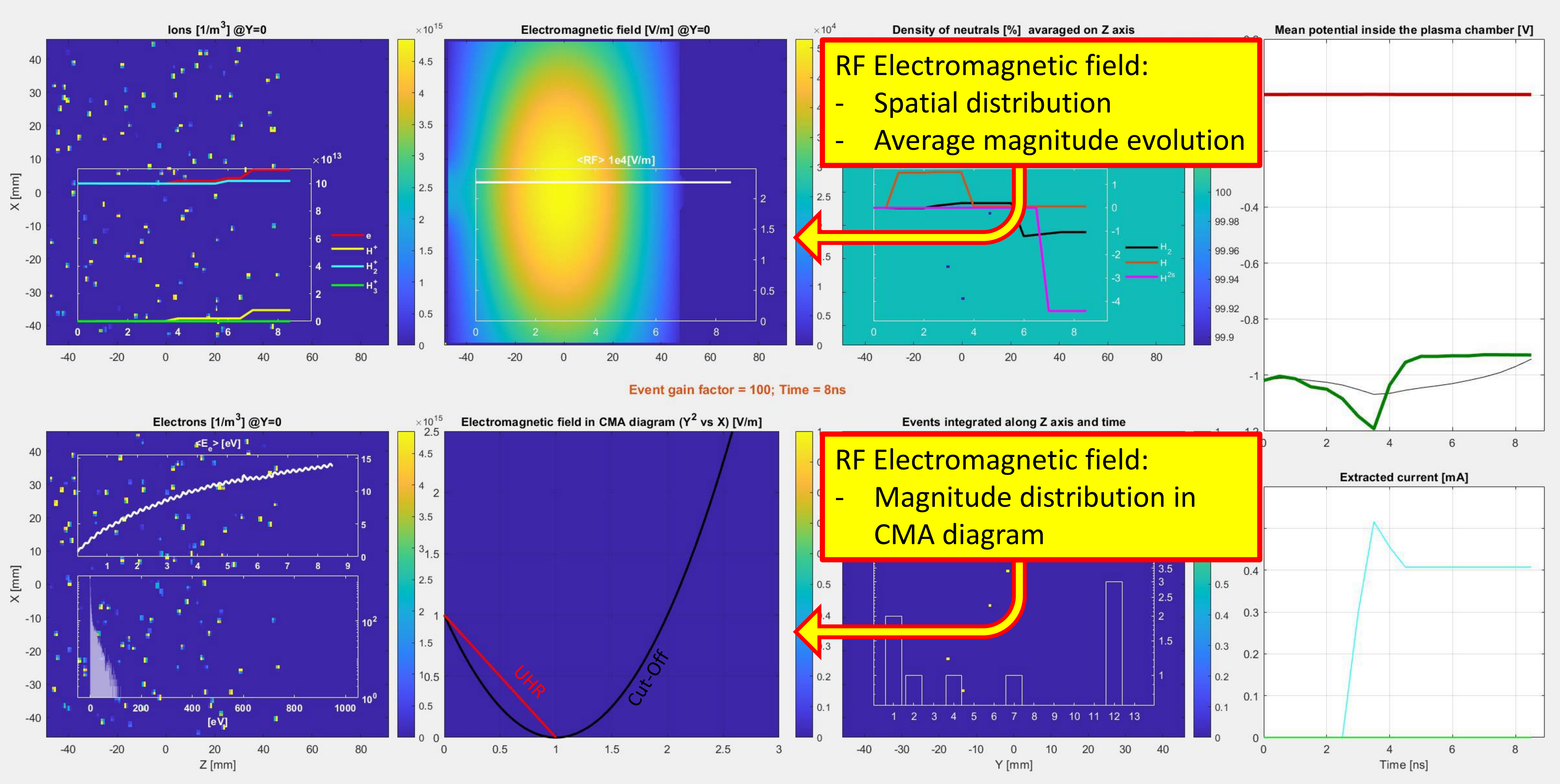
Stationary - Particle In Cell: MDIS magnetic configuration (*step 1*)



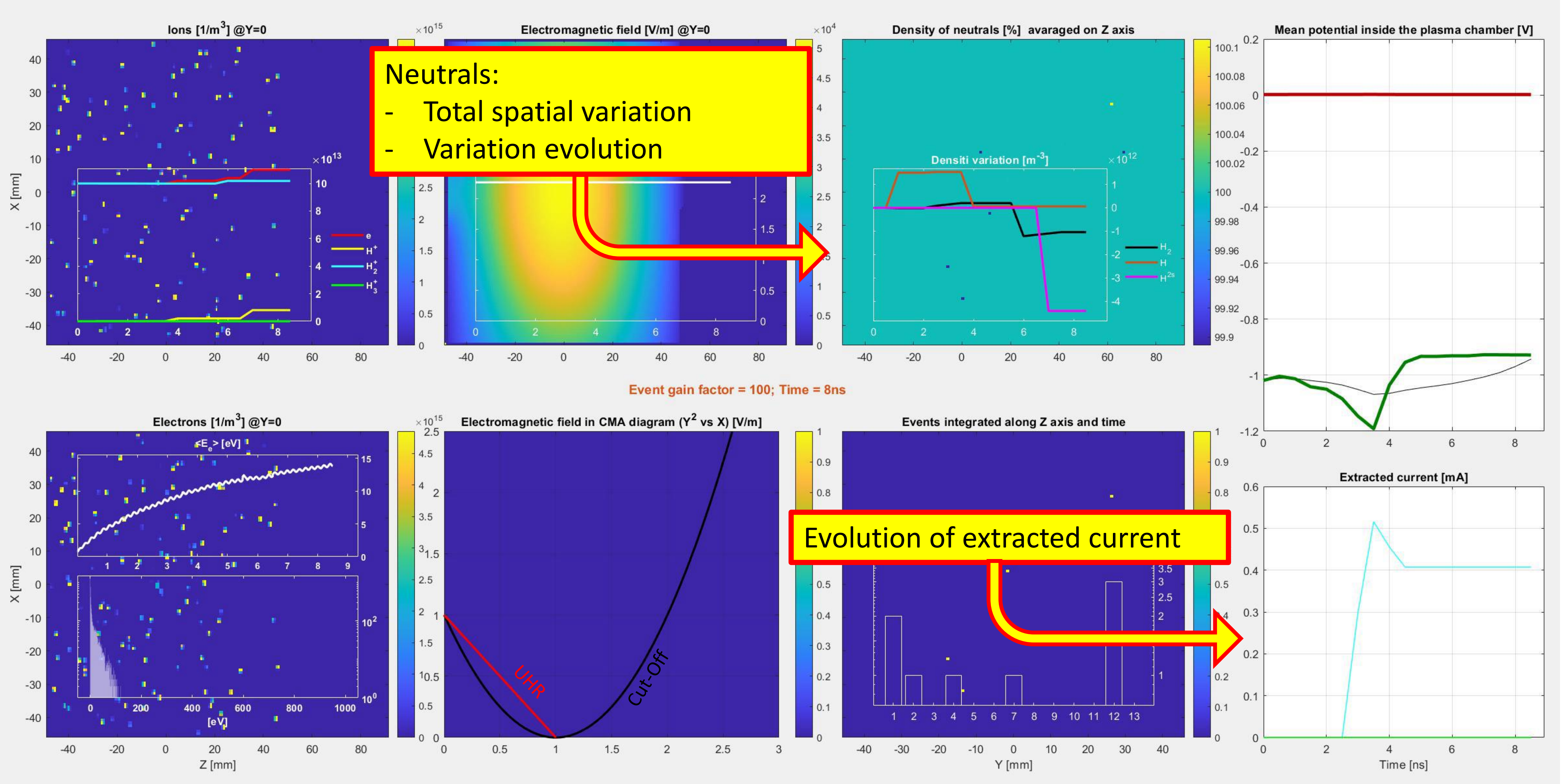
Stationary - Particle In Cell:
MDIS magnetic configuration (*step 1*)



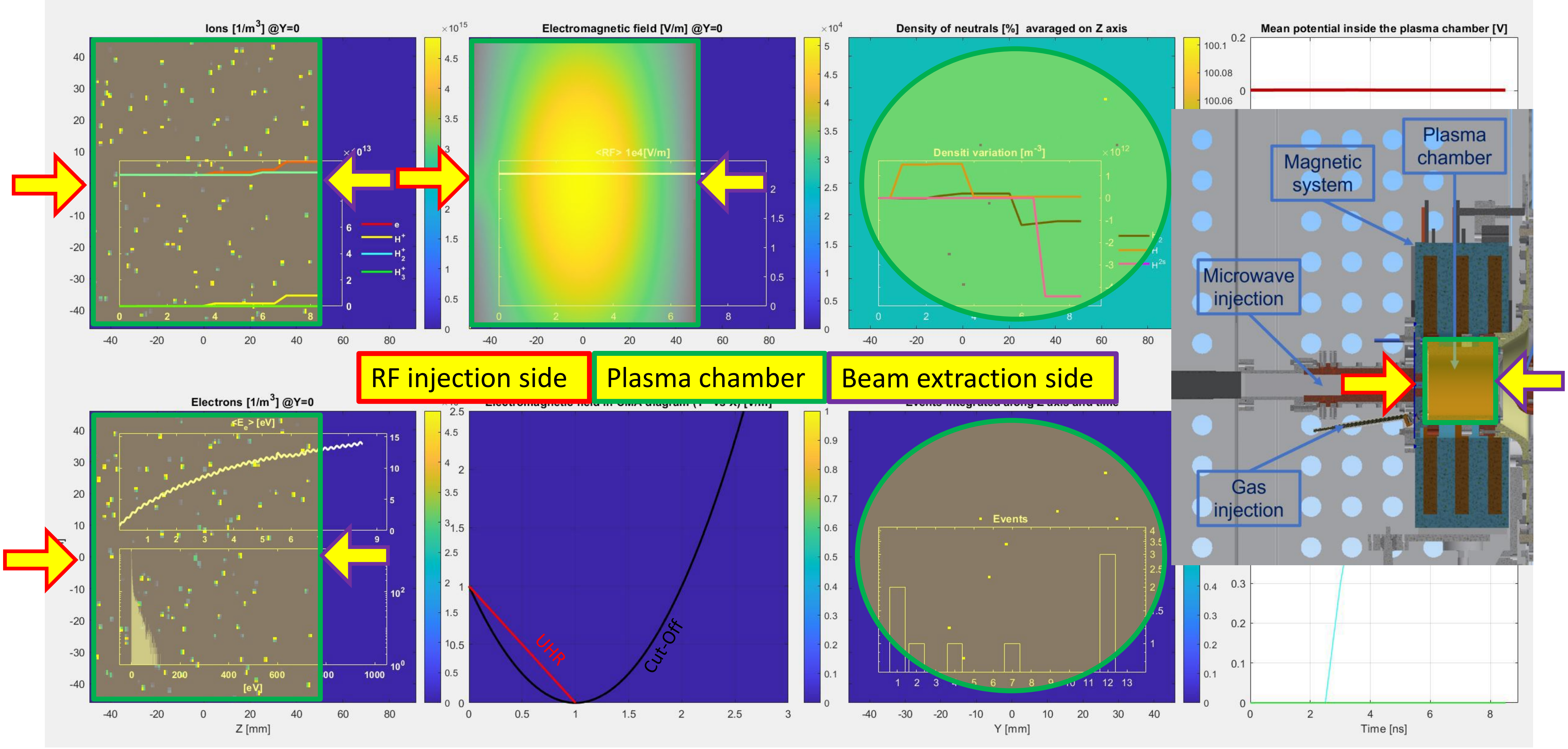
Stationary - Particle In Cell:
MDIS magnetic configuration (*step 1*)



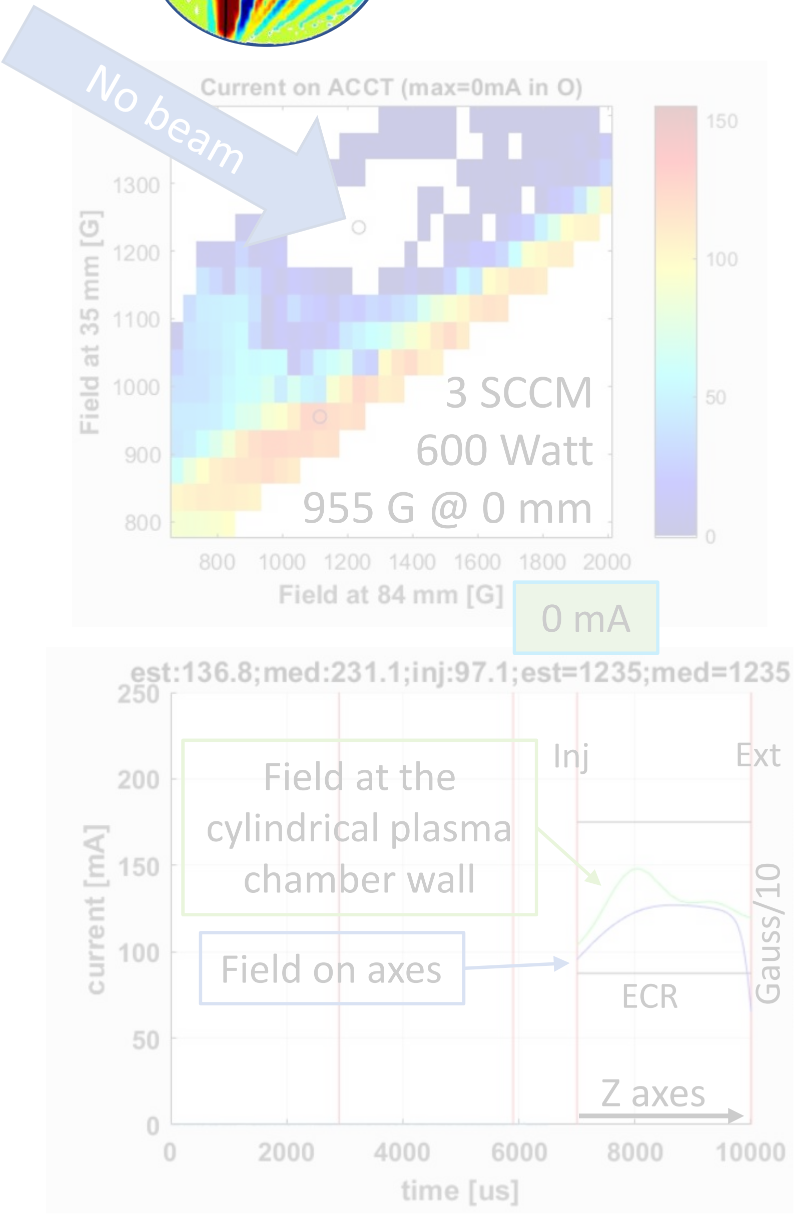
Stationary - Particle In Cell:
MDIS magnetic configuration (*step 1*)

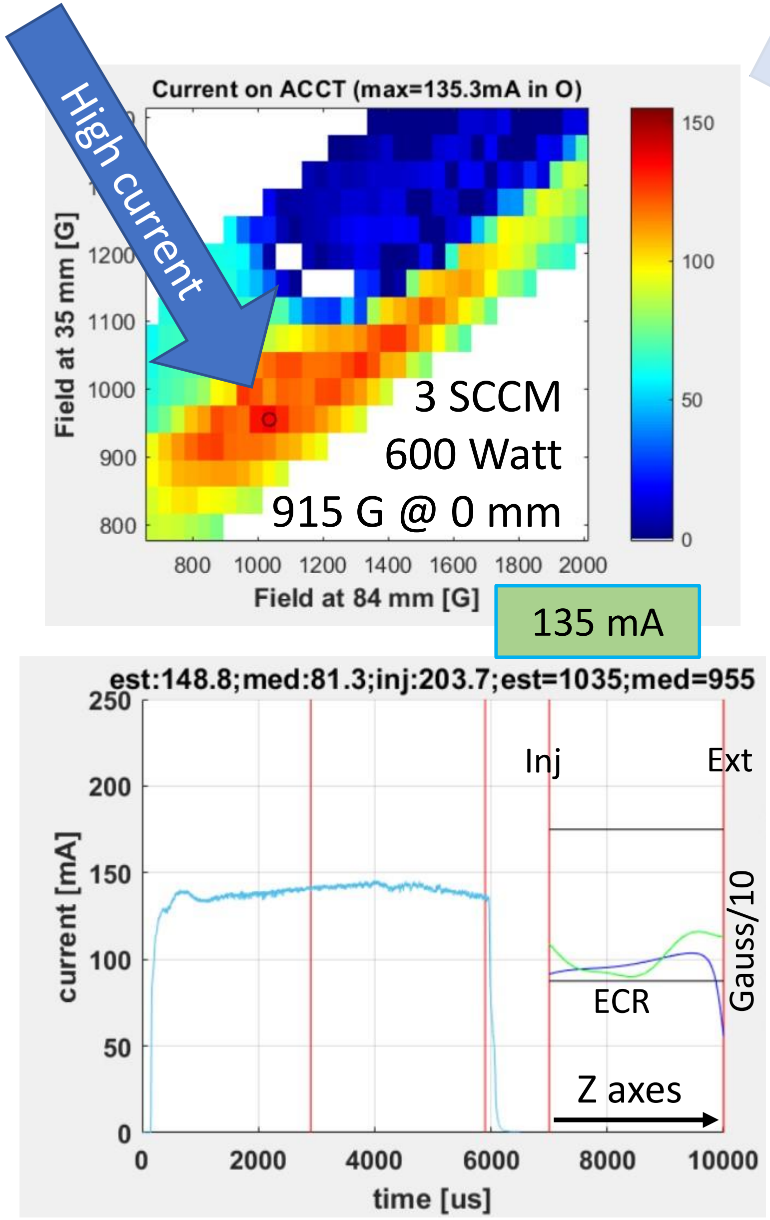


Stationary - Particle In Cell: MDIS magnetic configuration (*step 1)*

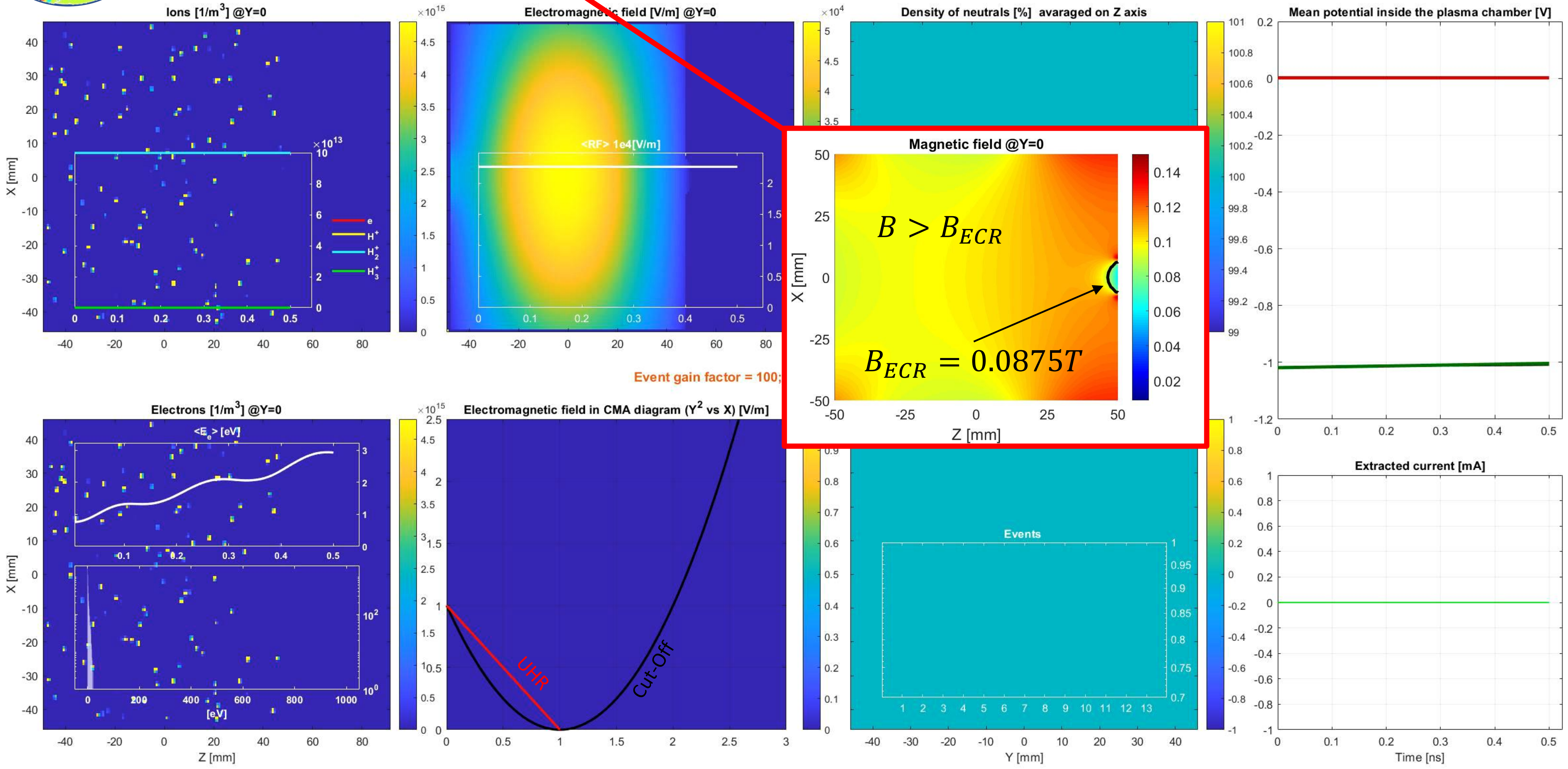


The three most relevant source behaviors

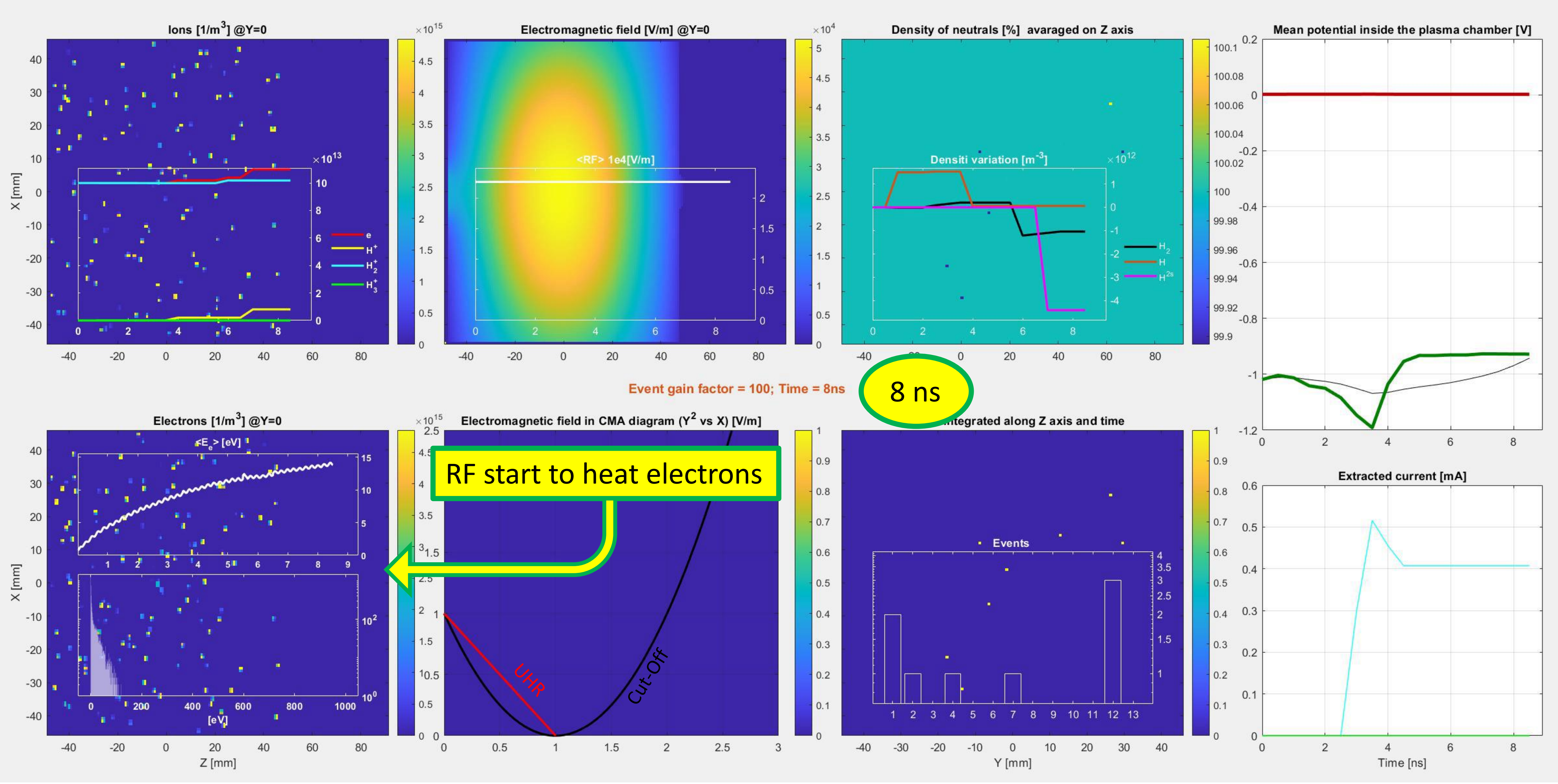




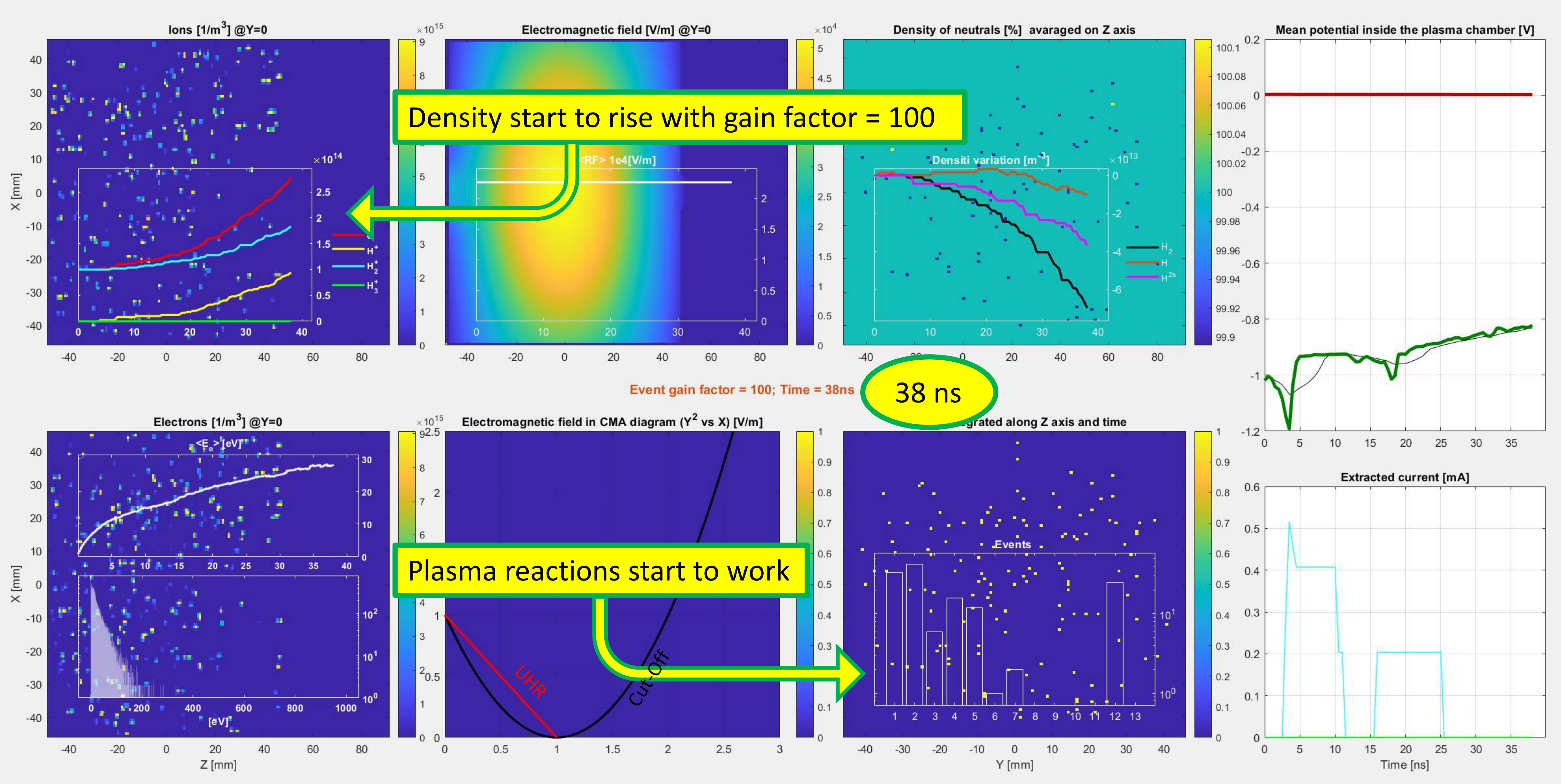
Stationary - Particle In Cell: MDIS magnetic configuration (*step 1*)



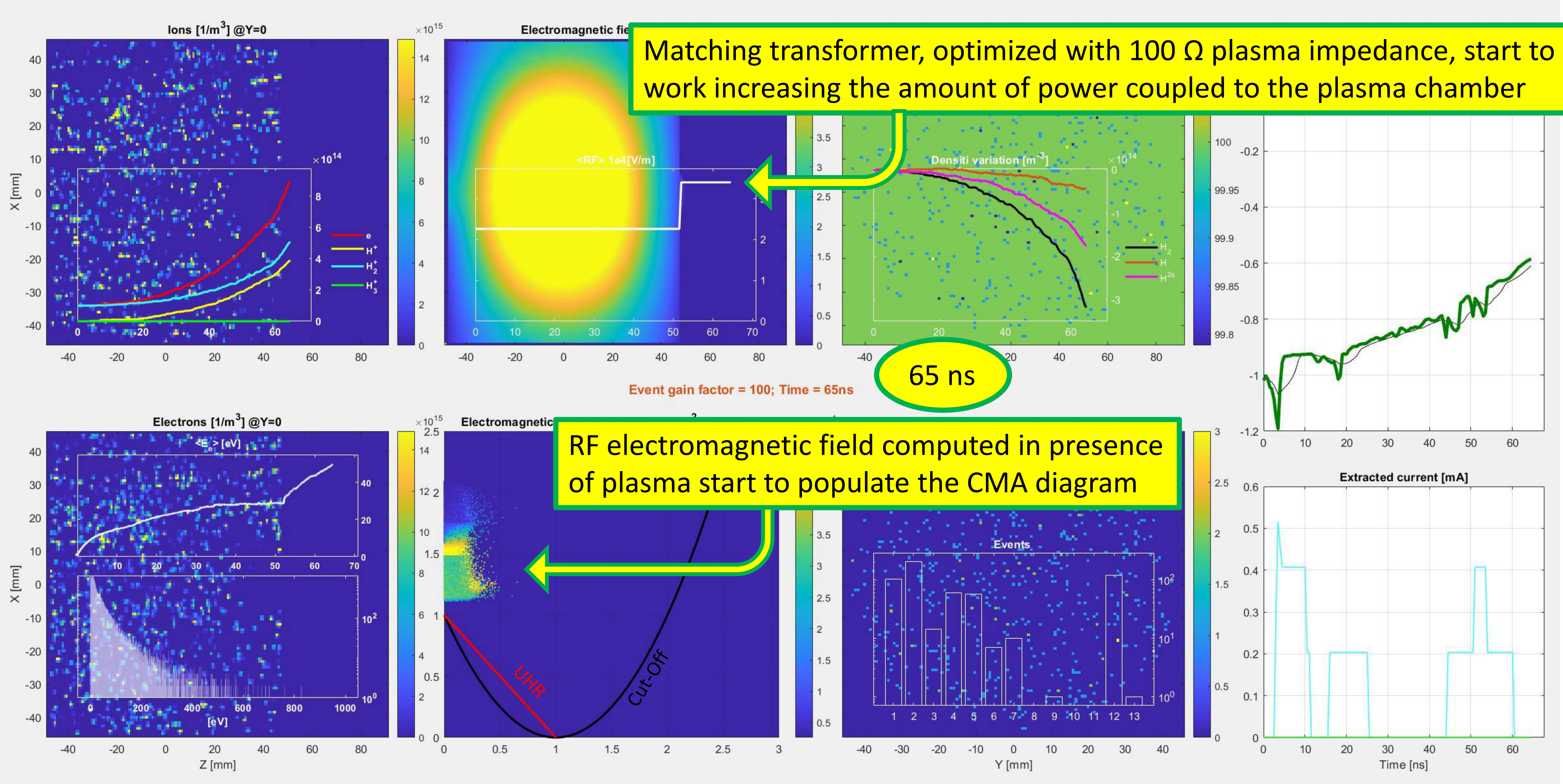
Stationary - Particle In Cell:
MDIS magnetic configuration (*step 1*)



Stationary - Particle In Cell:
MDIS magnetic configuration (*step 1*)



Stationary - Particle In Cell:
MDIS magnetic configuration (*step 1*)

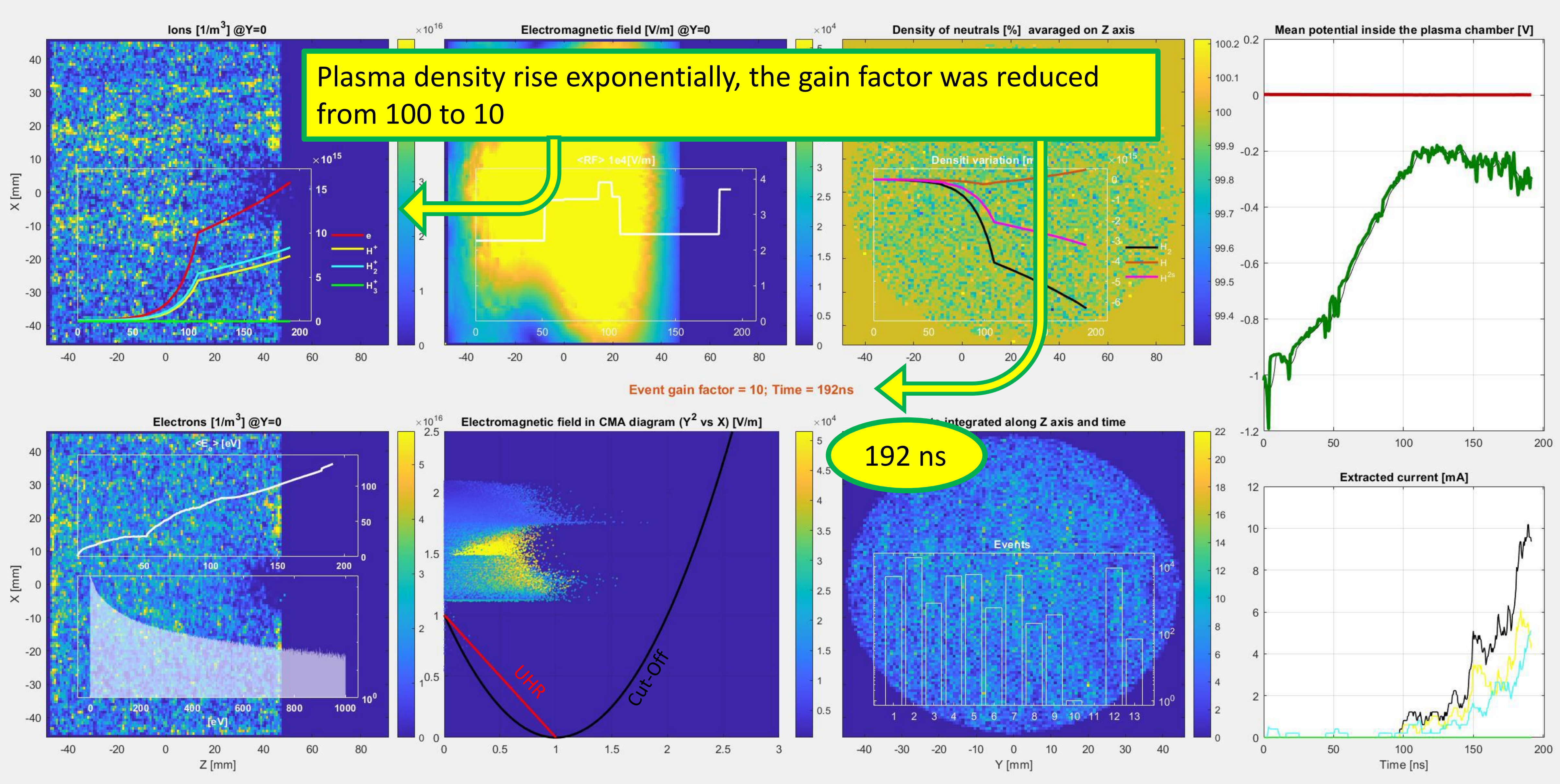


Matching transformer, optimized with 100 Ω plasma impedance, start to work increasing the amount of power coupled to the plasma chamber

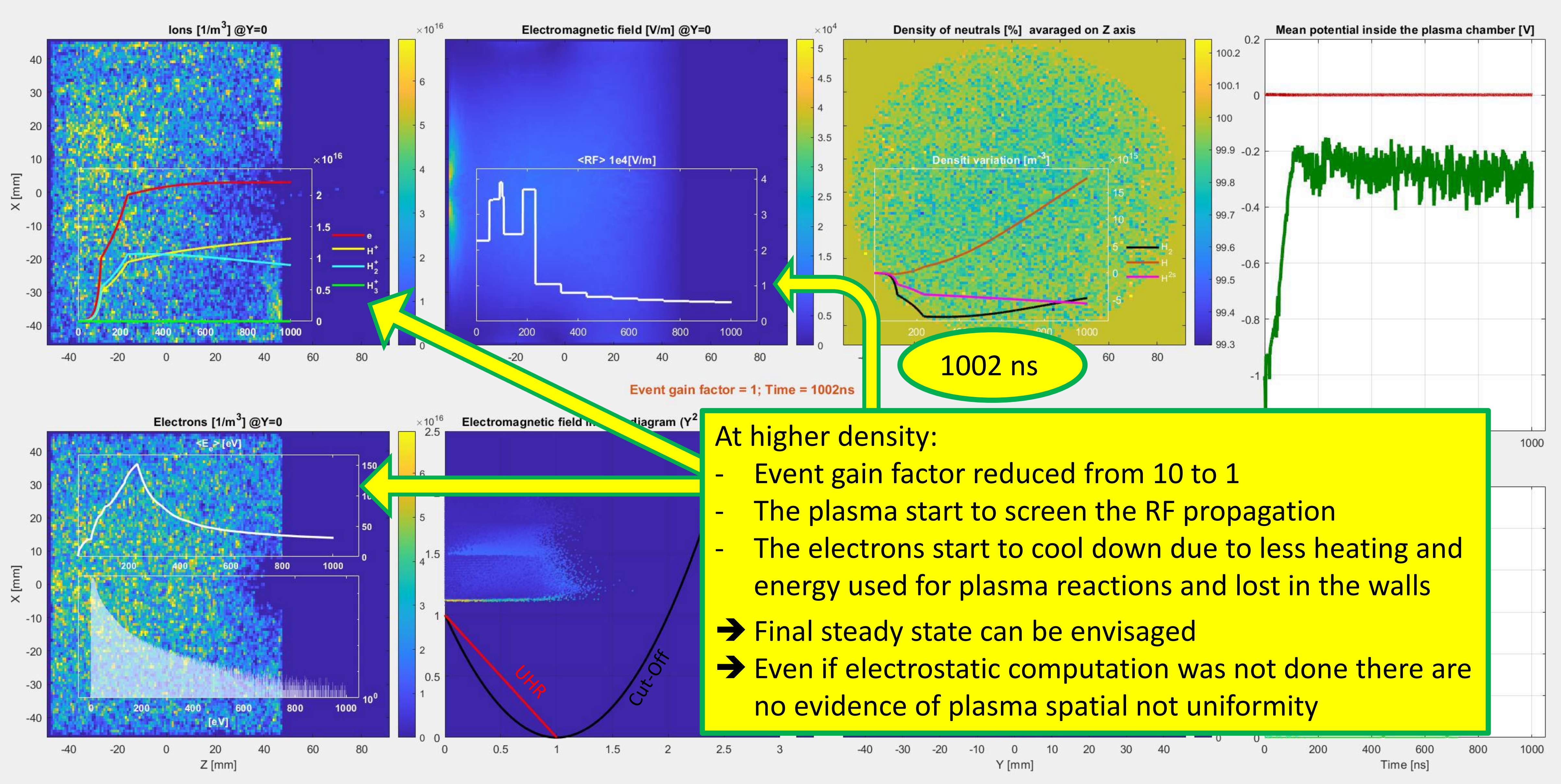
65 ns

RF electromagnetic field computed in presence of plasma start to populate the CMA diagram

Stationary - Particle In Cell:
MDIS magnetic configuration (*step 1*)



Stationary - Particle In Cell: MDIS magnetic configuration (*step 1*)



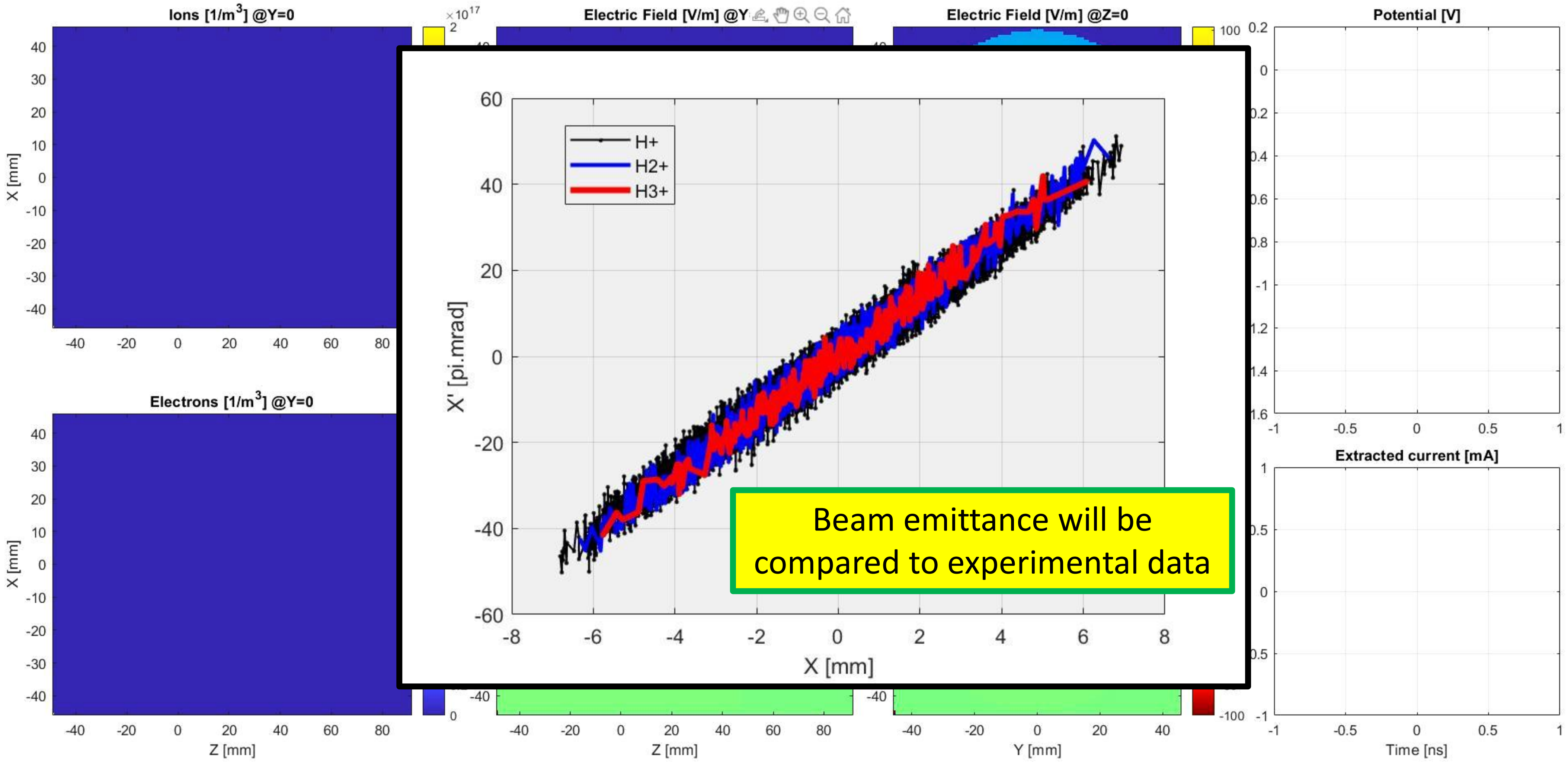
At higher density:

- Event gain factor reduced from 10 to 1
- The plasma start to screen the RF propagation
- The electrons start to cool down due to less heating and energy used for plasma reactions and lost in the walls

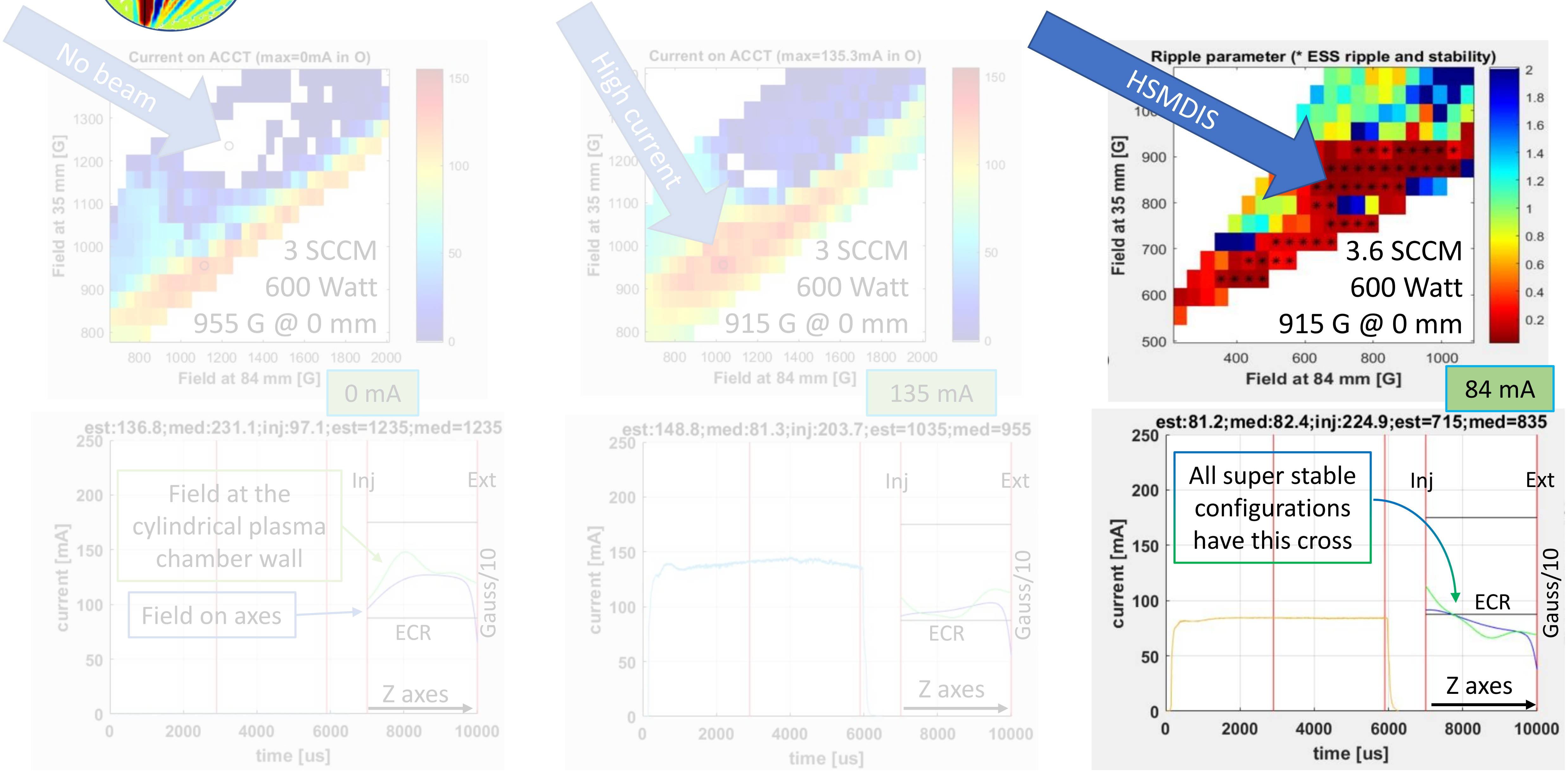
➔ Final steady state can be envisaged

➔ Even if electrostatic computation was not done there are no evidence of plasma spatial not uniformity

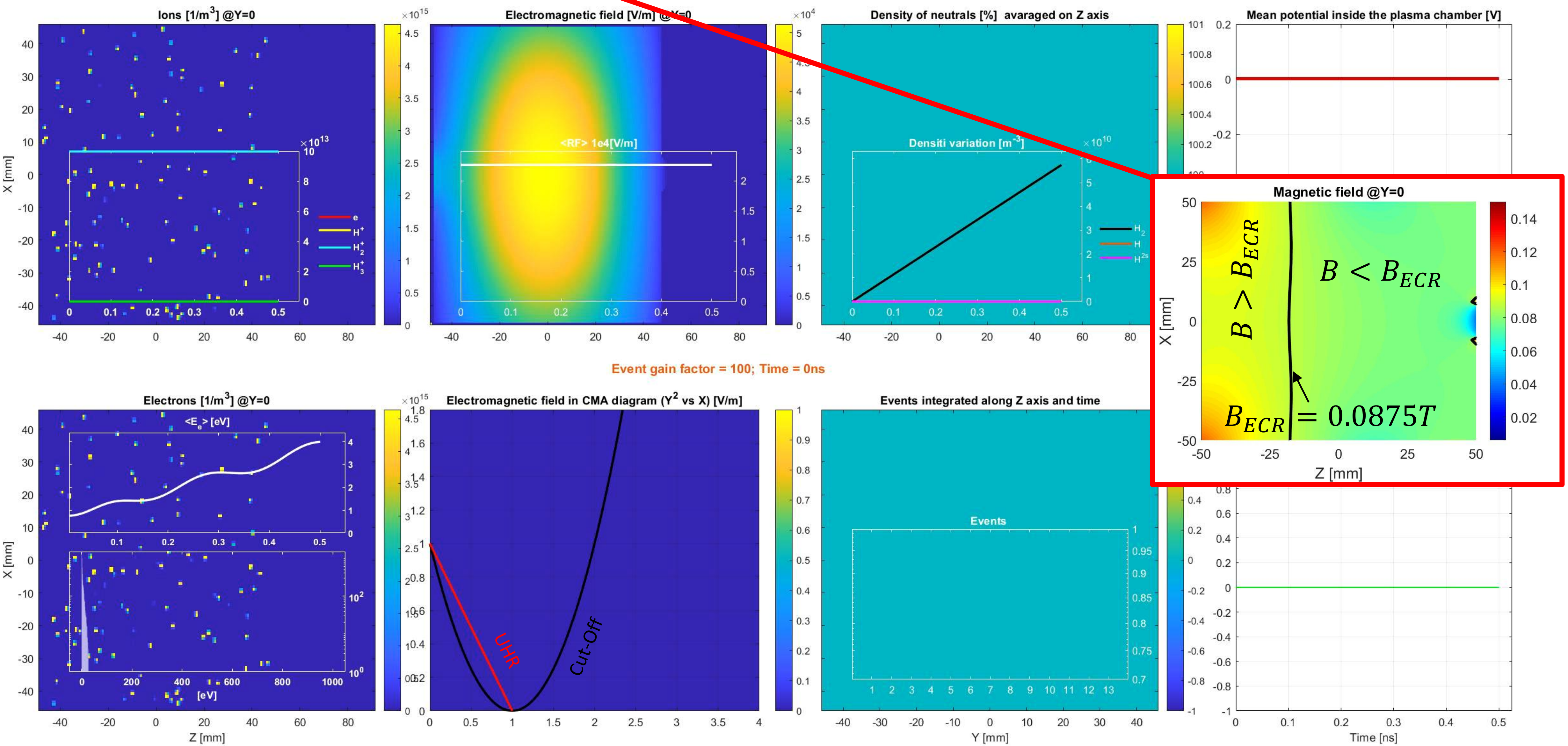
Stationary - Particle In Cell: MDIS magnetic configuration (*step 2)*



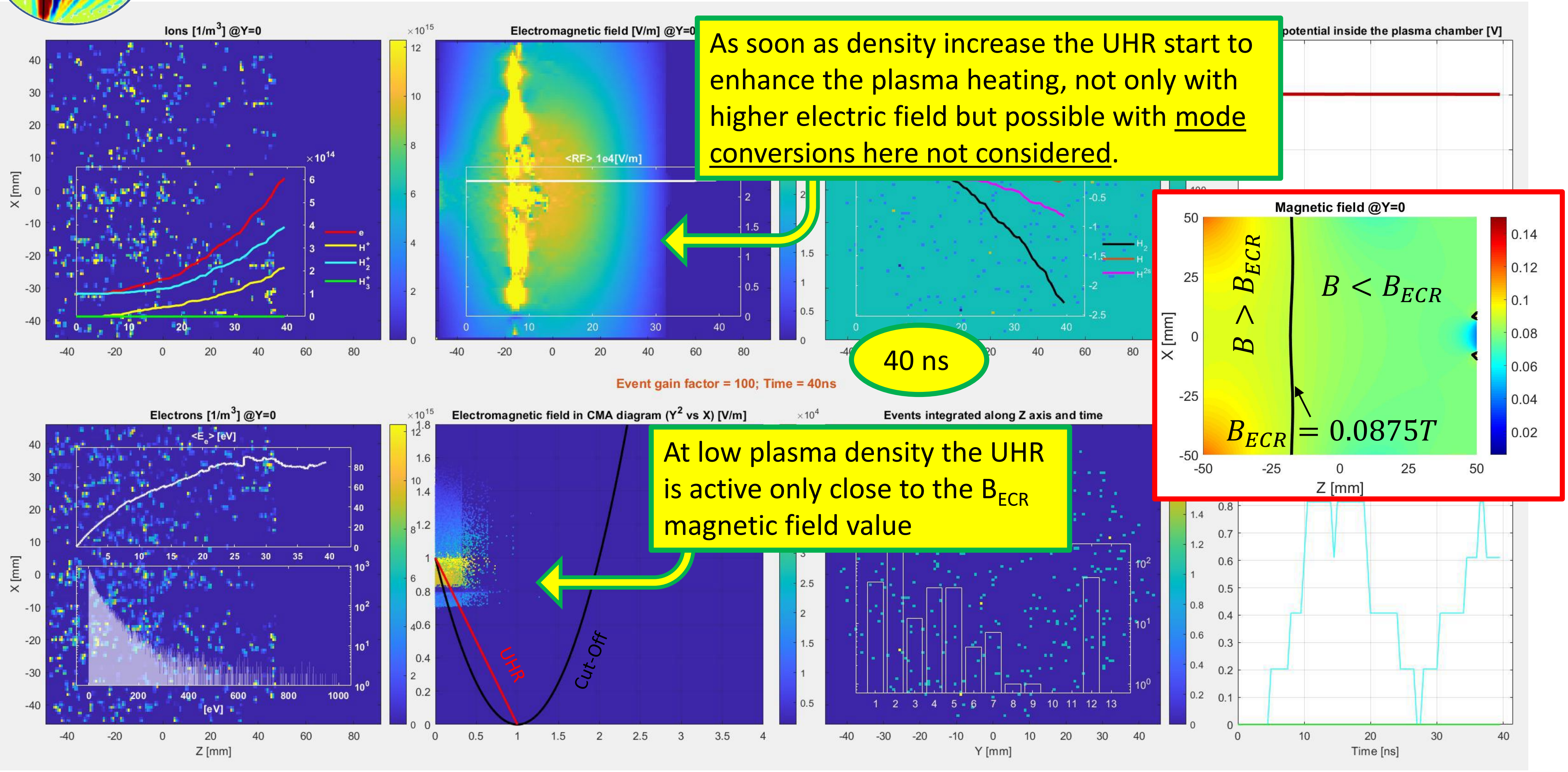
The three most relevant source behaviors



Stationary - Particle In Cell:
HSMDIS magnetic configuration (*step 1)*



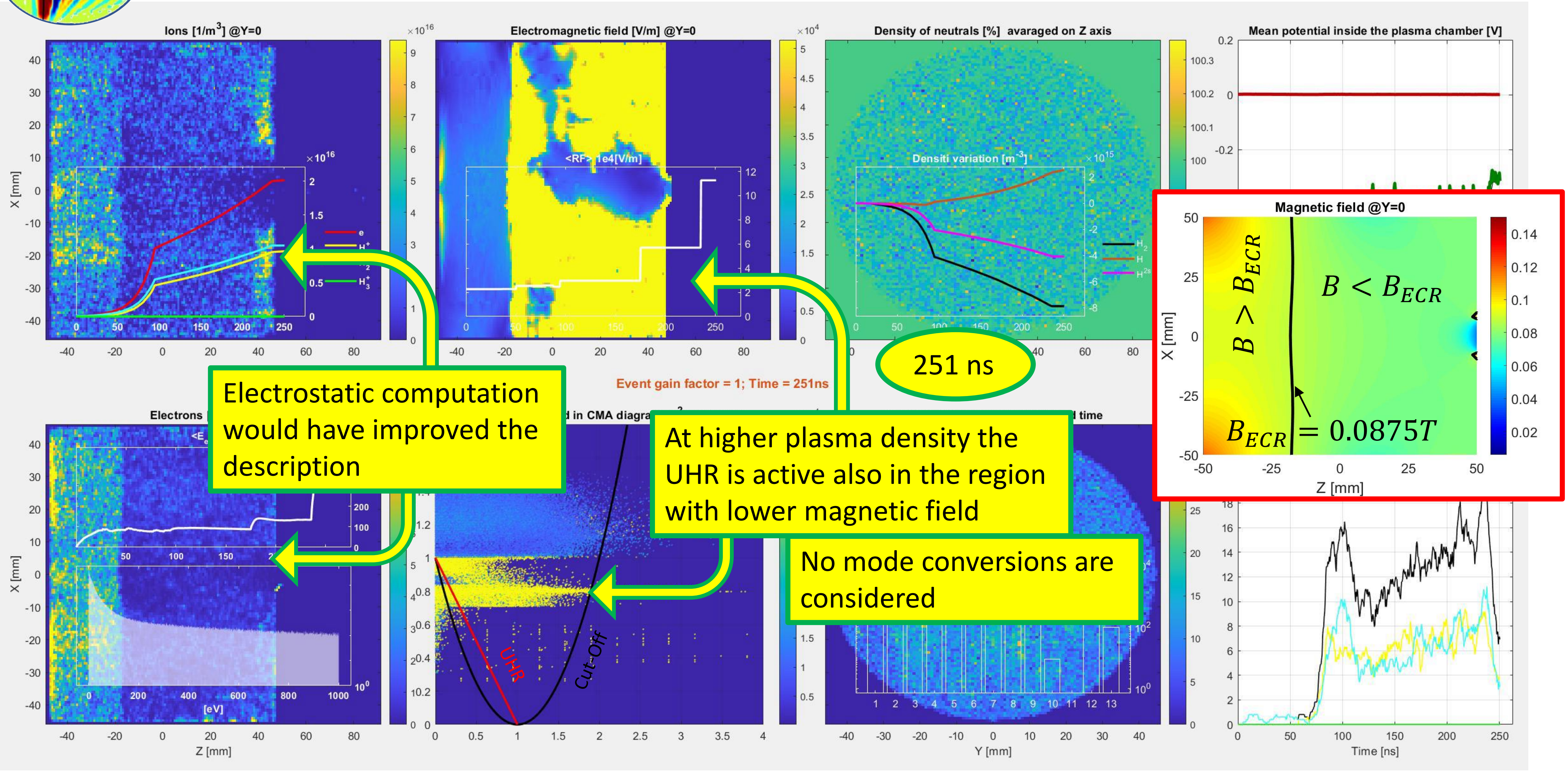
Stationary - Particle In Cell: HSMDIS magnetic configuration (*step 1*)



As soon as density increase the UHR start to enhance the plasma heating, not only with higher electric field but possible with <u>mode conversions here not considered</u>.

At low plasma density the UHR is active only close to the B_{ECR} magnetic field value

Stationary - Particle In Cell: HSMDIS magnetic configuration (*step 1*)



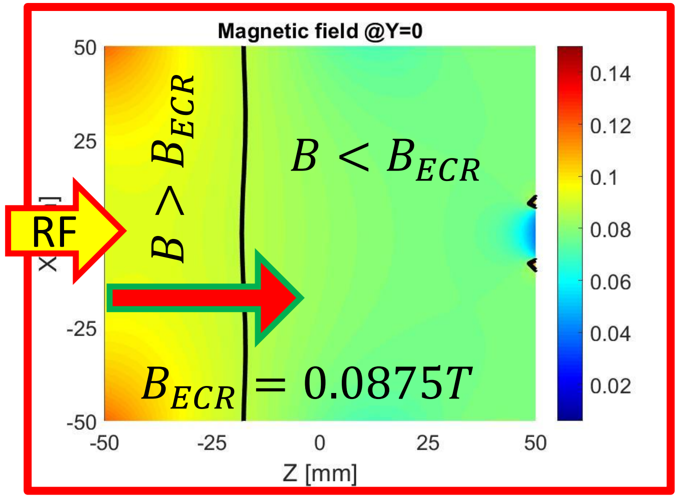
Stationary - Particle In Cell: HSMDIS magnetic configuration (*step 1)*

There are three main mechanisms of Electromagnetic to Electrostatic Bernstein Waves coupling.
The first is "High Field Side Launch" at UHR.

"Overdense plasma generation in a compact ion source"
G. Castro et al 2017 Plasma Sources Sci. Technol. 26 055019
DOI: 10.1088/1361-6595/aa61c4

Hypothesis:

Strong UHR heating
+
Sudden UHR switching off
=
Extremely stable plasma density



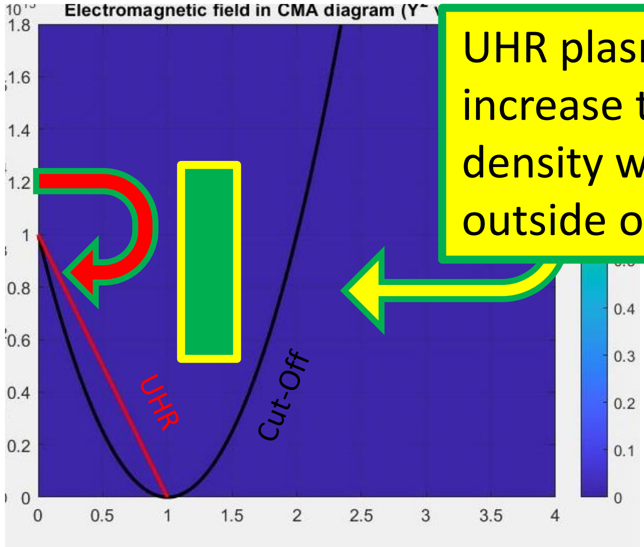
Source configuration

Observed behaviour

MDIS simulation

HSMDIS simulation | Hypothesis

Simulation suggest that UHR heating play an important role in HSMDIS



UHR plasma heating will increase the density until the density will push the system outside of the UHR region

Scopes

With extremely high flexibility and with the capability to test thousands of configuration without survey ➔ we don't need a predictive simulation tool ➔ we need a simulation tool able to disclose the reasons for different behaviors

Understanding of 2.45 GHz
High Stability Microwave Discharge
Ion Sources
HSMDIS

Conclusion

- We have identified the simulation strategies able to disclose the different mechanisms acting inside the 2.45 GHz ion sources with different magnetic configurations
- UHR heating play an important role in High Stability Microwave Discharge Ion Sources
- Hypothesis: High stability of HSMDIS is due to an extremely strong heating that suddenly disappear when the plasma is over the density compatible with the UHR

Work in progress

Particle In Cell

- Motion of electrons with a time step of 5E-12 s (Boris mover)
- Motion of ions with a time step of 5E-10 s (Boris mover)
- Grid-based Langevin equations to model Coulomb collisions via drag and diffusion coefficients
- Reactions inside plasma + reactions in the walls
- Maps of neutrals and neutrals dynamics
- Three-dimensional RF (2.45GHz) electromagnetic simulation with tensorial permittivity
- ~~Electrostatic simulation (step1)~~
- ~~Electrostatic simulation (step2)~~

- **2D axial symmetric electrostatic simulation**

The observed axial symmetry of the plasma density enable the simplification of the electrostatic simulation by using a 2D axial symmetric electrostatic model with electric field applied to ions and electrons

$$\nabla \cdot E = \frac{\rho}{\varepsilon}$$

We are working to achieve $\Delta x < 3.4\lambda_D$ and $\Delta t < 0.1\omega_p^{-1}$ ➔ to avoid instabilities in the simulation

Thank you for the attention