Istituto per la Scienza e Tecnologia dei Plasmi
Consiglio Nazionale delle Ricerche

2026 CiP
1° Conferenza Italiana Plasmi

PLASMA START-UP IN TOKAMAKS: EXPERIMENTAL STUDIES AND MODELLING

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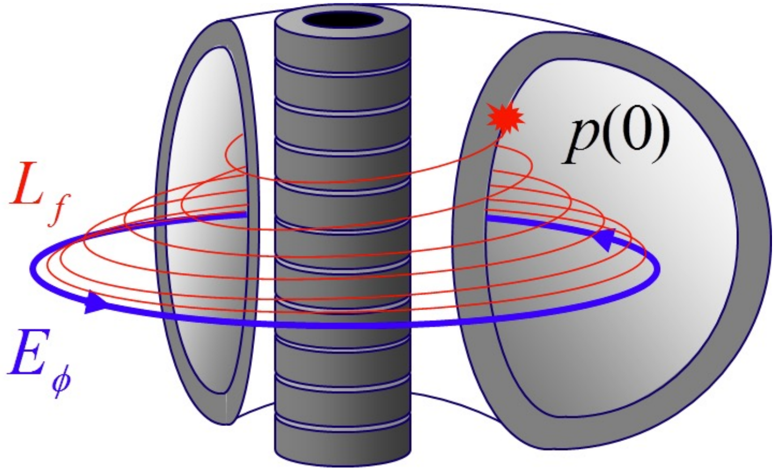
OUTLINE

- Introduction
- Experimental studies:
  - EC wave polarization
  - Effect of EC on impurity burn-through
  - Runaway formation
  - Role of poloidal magnetic configuration
- Modelling the EC start-up
  - Available tools
  - Results: ITER and JT-60SA
- Conclusions

Introduction – ohmic startup

The standard plasma start-up procedure relies on a time-varying magnetic field generated by a central solenoid, which induces a toroidal electric field (**ohmic start-up**).



Introduction – ohmic startup

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1th phase: Breakdown

- The electric field accelerates free electrons to ionize the neutral gas inside the vacuum chamber giving rise to other free electrons (**Townsend avalanche**).
- Number of free electron produced depends on the pressure and toroidal electric field.

2nd phase: Burn-through

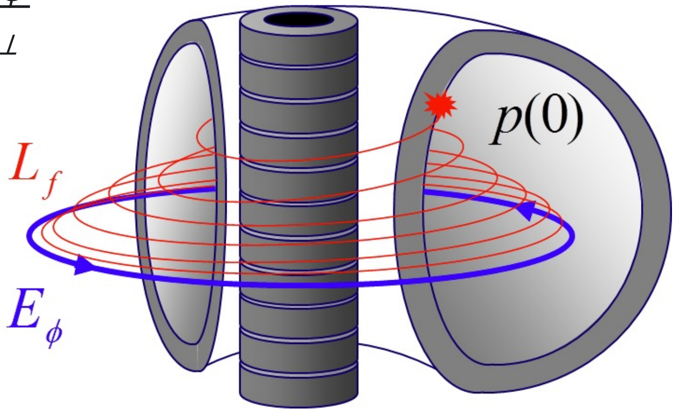
- Radiation losses (e.g., from low-Z impurities) limit electron temperature and plasma current
- Power lost during burn-through must be balanced increasing the electric field.

3nd phase: current ramp-up

Introduction – ohmic breakdown

- **Key parameters:**
  - neutral gas pre-fill (pressure) -> dominant electron-neutral collision
  - effective connection length L_f (analogous to electrode spacing in Townsend's theory)

$$L_f \approx a \frac{B_\phi}{B_\perp}$$



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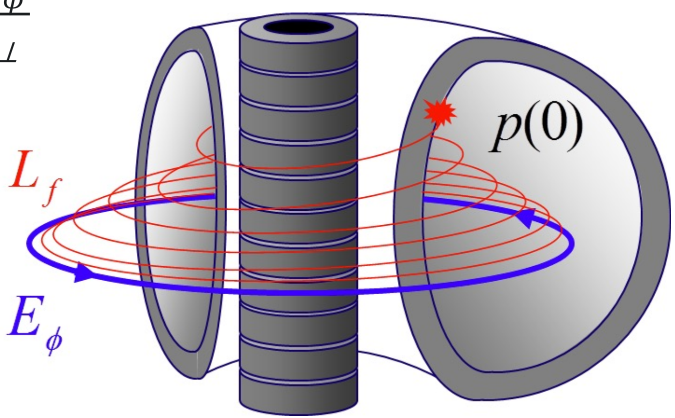

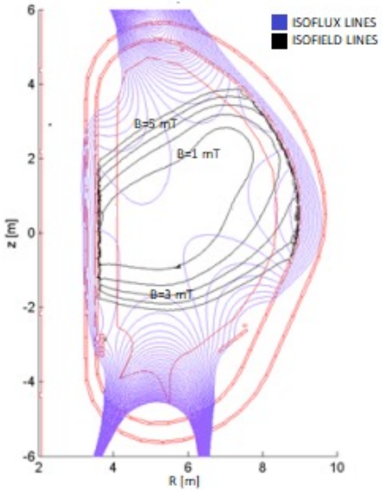

G.De Tommasi 2015

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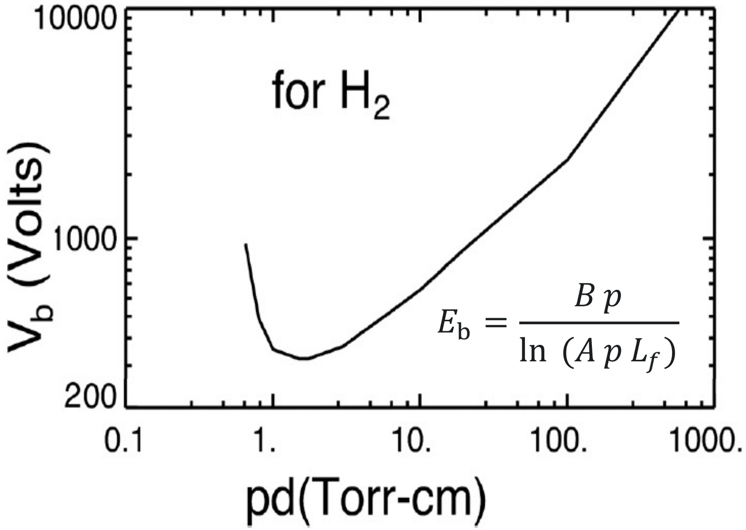
Muller Pop 2013



Motivation

In present day tokamaks, **toroidal electric field is limited (0.3 V/m in ITER)** due to the thick vacuum vessel and superconducting coils and may limits the operations boundaries.

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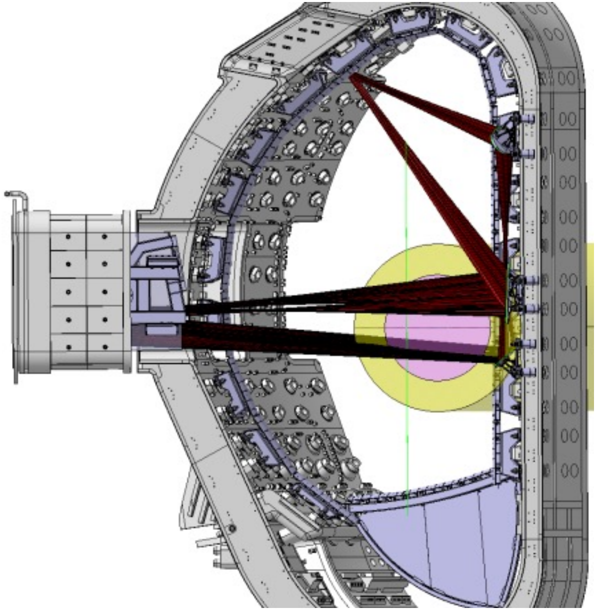
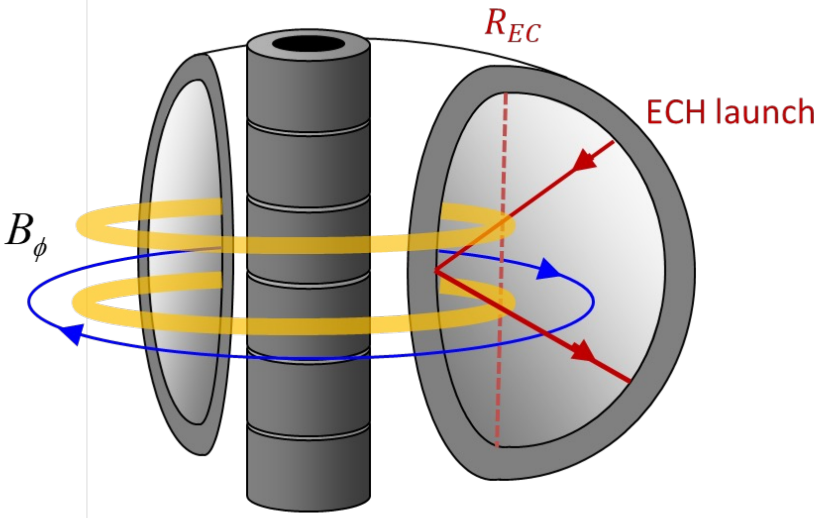


Possible solution

- Since the early 1990s(*) **Electron Cyclotron (EC) waves heating is considered a valid solution** to sustain the initial phase of the discharge at low toroidal electric field

EC pre-ionization process



- Free electron is accelerated perpendicular to the magnetic field since it absorbs X-mode.

- If the ECH beam has sufficient power density, it can increase the electron energy above the ionization energy[1] (**collisionless-heating**):

  $E_{max,n=2} \cong 2.1\, P^{1/2} / (f\, w_{av})$ where $w_{av} = (w_y w_z)^{1/2}$

  $E_{max,n=1} \cong 15.6\, P^{1/3} / (f\, w_{av})^{2/3}$ [KeV, MW, GHz, m]

- Free electrons with sufficient energy, travel along the toroidal field lines, ionizing further neutrals via **collisions**, creating a toroidal ring of plasma intersecting with the ECH beam at the (Rec) resonance[2].

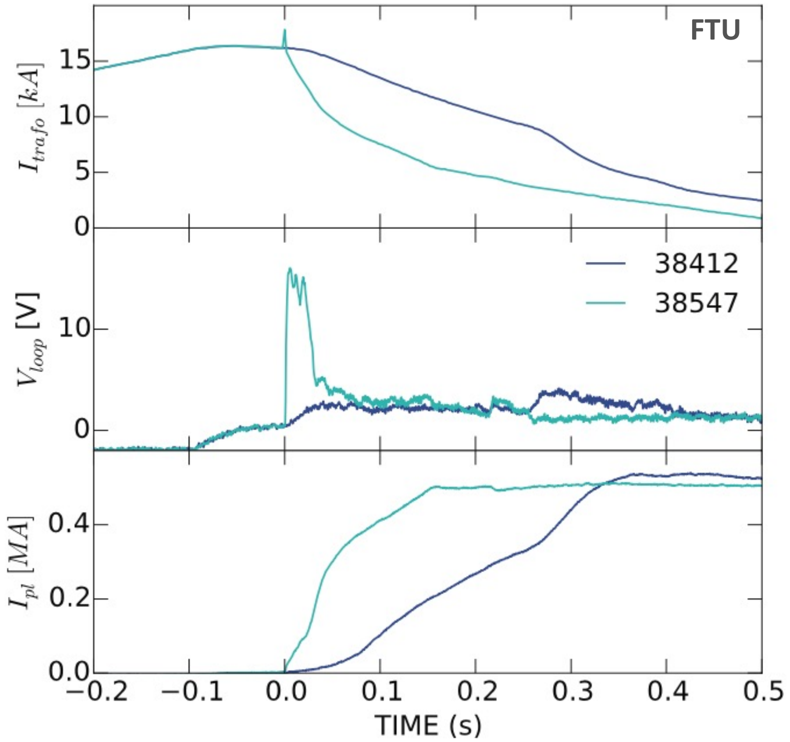
- The plasma may expand from these rings further into the vessel.

[1] D. Farina, Nucl. Fusion 58 (2018) 066012.
[2] J. Stober, et al., Nuclear Fusion 2011 51 083031

EC assisted start-up

Electron Cyclotron waves can assist plasma initiation by providing additional heating in 2 specific ways:

- Ionize neutrals (**pre-ionization**) -> relaxing Paschen criterion
- during the **burn-through** phase

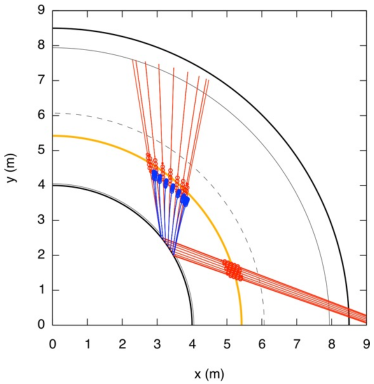


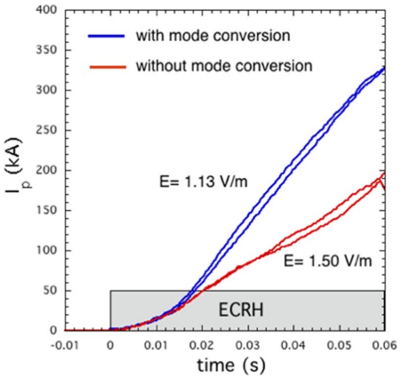
Granucci NF2015

EXPERIMENTAL RESULTS

Experiment: Effect of oblique EC injection

- O1- (to avoid low density cut-off) and X2-schemes
- **before Breakdown** O1 is much faster than X2 (lower **time delay** between the start of the ECRH and a measurable plasma ionization, as Hα emission)
- **after Breakdown** and at low density, absorption is dominated by X component generated after reflection at the inner wall. In FTU, oblique EC injection have demonstrated the importance of **polarization conversion** (O1/X1) to maximize the fraction of power coupled to X mode



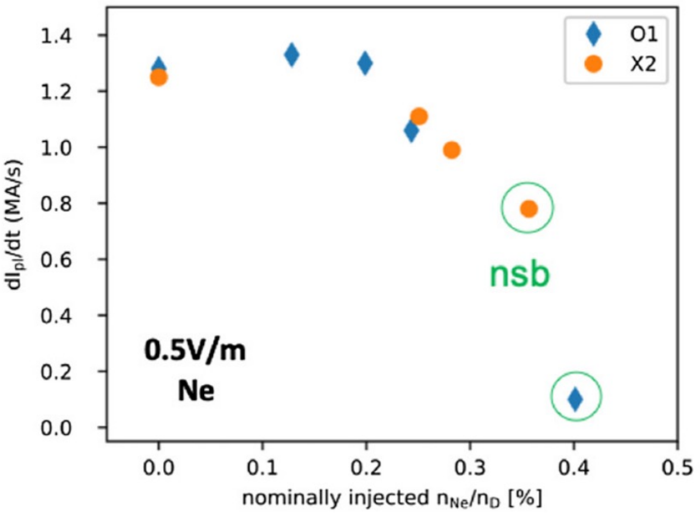


Pucella NF 2015

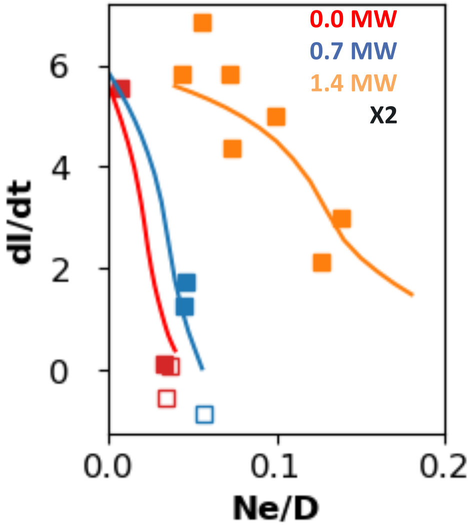
Experiment: Effect of EC on impurity burn-through

- Injection of impurity during pre-fill phase to mimic unfavourable condition such as those expected in case of impurity influx from the wall
- EC successfully sustains the burn-through, independently of the injection schemes.

FTU



AUG

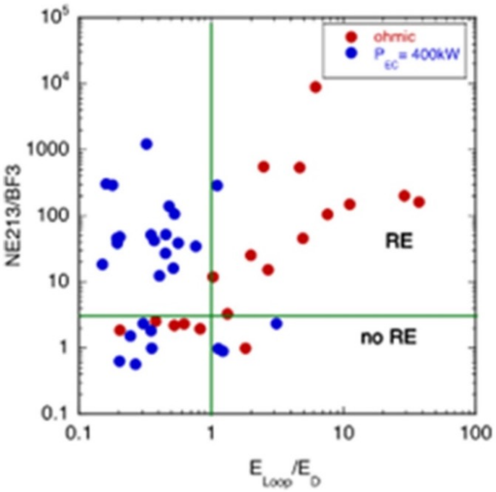


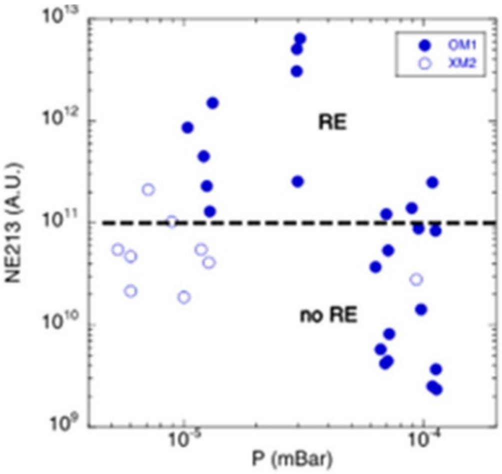
Experiment: Runaway Electrons formation

- **EC wave acts as seeding for fast electrons**: in FTU, EC enables RE below Dreiser field threshold.

- Low pre-fill gas pressure leads to higher RE levels -> **gas pressure** as a **key control parameter**
- **X2 less effective**, in agreement with [D. Farina NF 2018]

- **Issue for ITER->** Need to develop an early monitoring system integrated with control tools



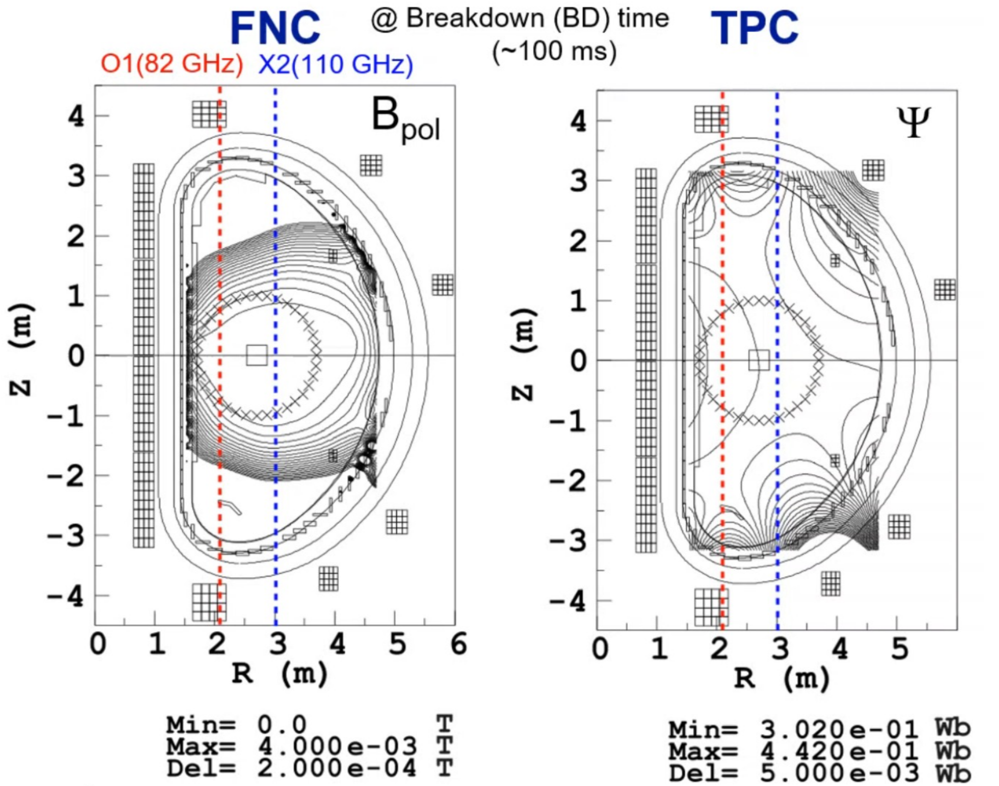


Pucella 2017

Experiment: Role of poloidal magnetic configuration in JT-60SA

- Etor = 0.15 V/m
- 2 configurations tested with
  - 1st (82 GHz) and 2nd (110 GHz) harmonics used
  - Both He and H
- **Field Null Configuration**: to confine inductively accellerated electrons ith long connection lenghth
- **Trapped Particle Congiguration**: to confine EC accellerated electrons by mirror trap effect

$$n = -(R/B_z)(\partial B_z/\partial R).$$



SIMULATION

Modelling: Tools for start-up

- **BKD0 code:** 0D simulation of time evolution of main plasma parameter after breakdown [Granucci, NF 2015]

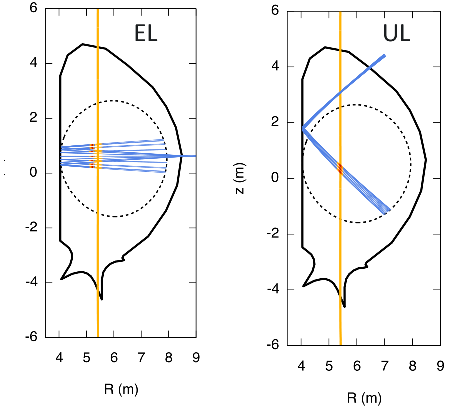
- **GRAY code:** quasi-optical beam-tracing for self-consistent calculation of the EC power absorption [Farina, FST 2007]

- **CREATE-BD code:** 2D linearized magnetic model derived from CREATE-NL, models the entire start-up sequence

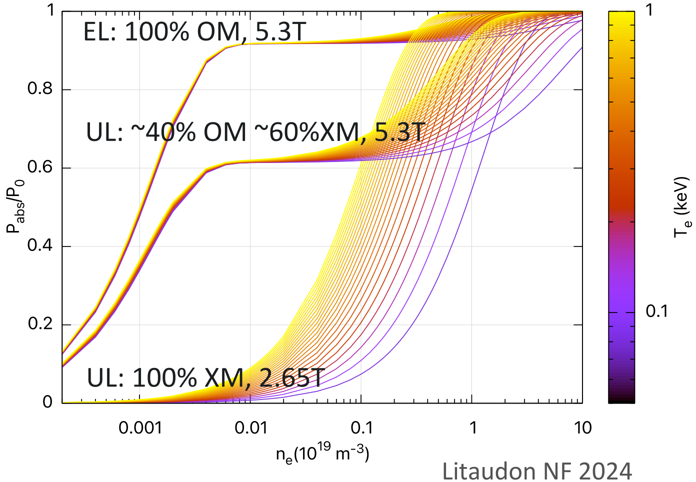
  [Albanese, FED 2015] [Di Grazia, Fus Eng 2022]

Results: GRAY for ITER

- The dependence of EC absorption on electron density and temperature has been assessed for the ITER first plasma start-up.
- As expected, at low density, absorption is dominated by XM component generated after reflection at the inner wall. This fact stresses the importance of maximizing the fraction of power coupled to XM in the assumed first plasma scenario.
- With XM a successful start-up scenario is obtained with 1 MW of ECRH and a neutral pressure of 200 mPa.



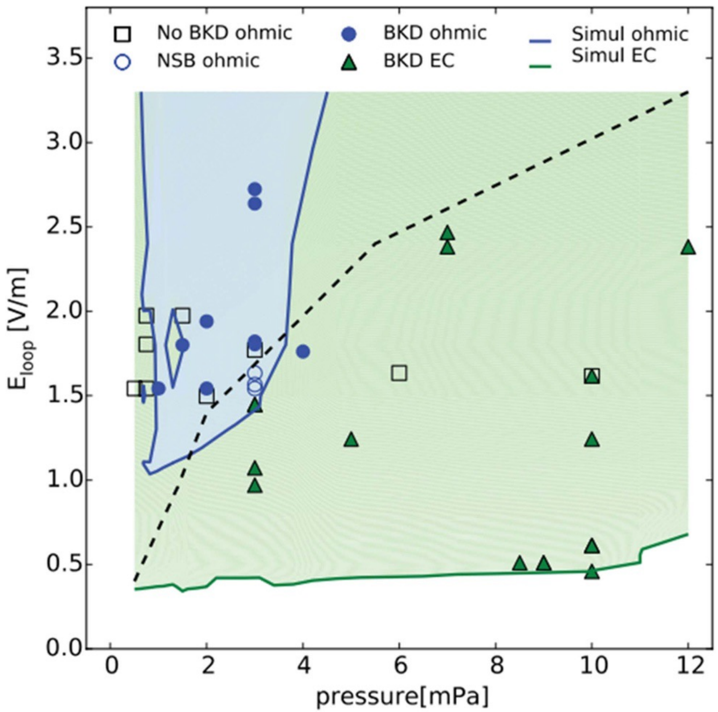
GRAY results - absorption



Litaudon NF 2024

Results: FTU operational parameters

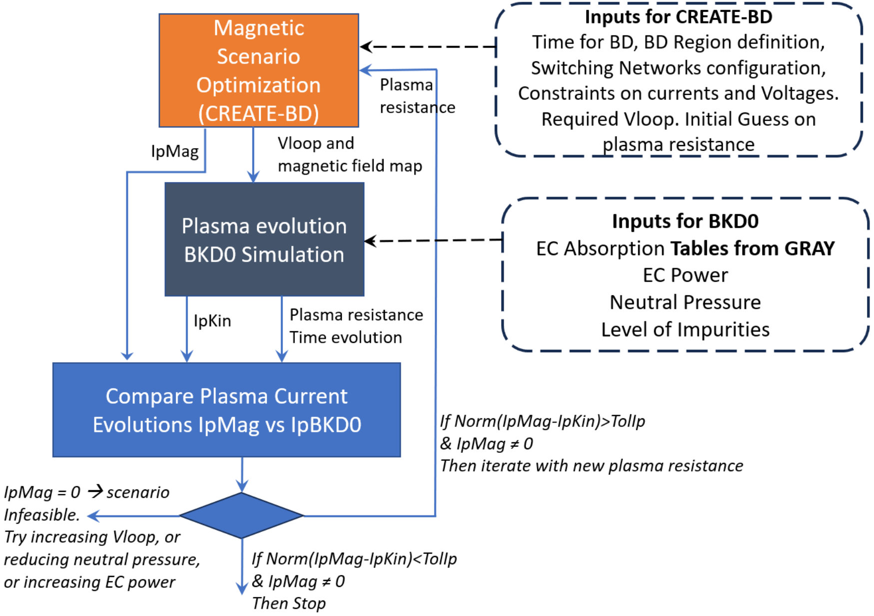
Granucci NF2015



- **Operational region in terms of Et(V/m) and p0 (mPa) on FTU**.
- The dashed line indicates the upper limitation to avoid to generate fast electron based on the Dreicer field.
- The dark blue and green areas bounded by solid line denotes the operation window based on BKD0 simulation for only ohmic and ECH assist, respectively.

Modelling: BKD0-GRAY-CREATE-BD

- The capability of predicting plasma behavior in the presence of uncertainties (impurities, pressure conditions, and EC assistance) is a fundamental aspect to make a reliable scenario simulation and design and reduce the number of experiments
- It has been applied on JT-60SA to evaluate its behavior with active constraints
- The code runs in short time (less than 1 minute) and can be used as a basis for intra-shot optimizations aimed at compensating uncertainties in the model prediction



JT-60SA: operational space before the experimental phase

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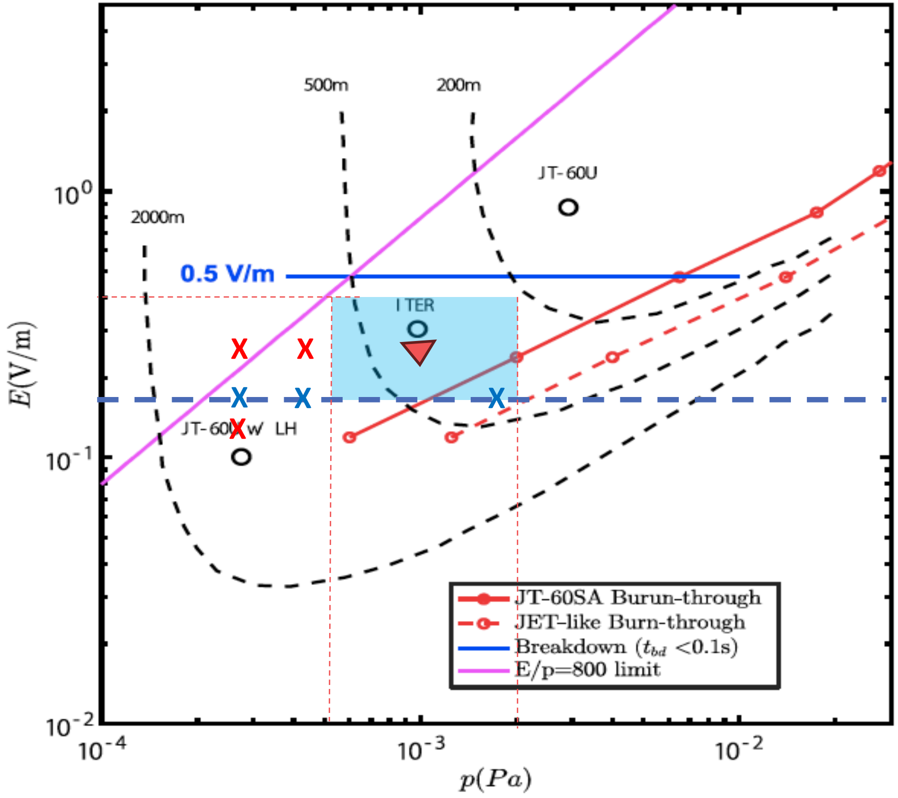


H. Urano Reviews of Modern Plasma Physics (2022)

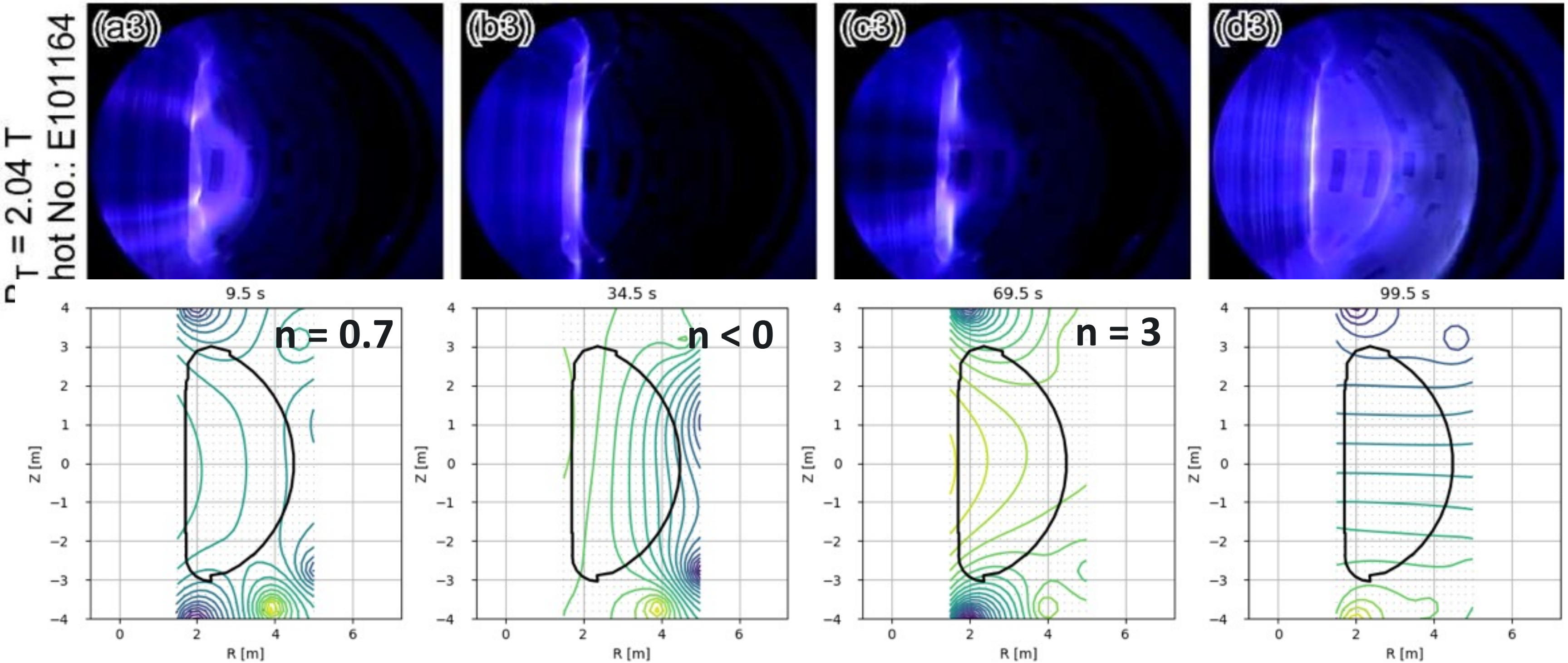
X ohmic failed breakdown

▼ ohmic failed burn-through

X FNC failed

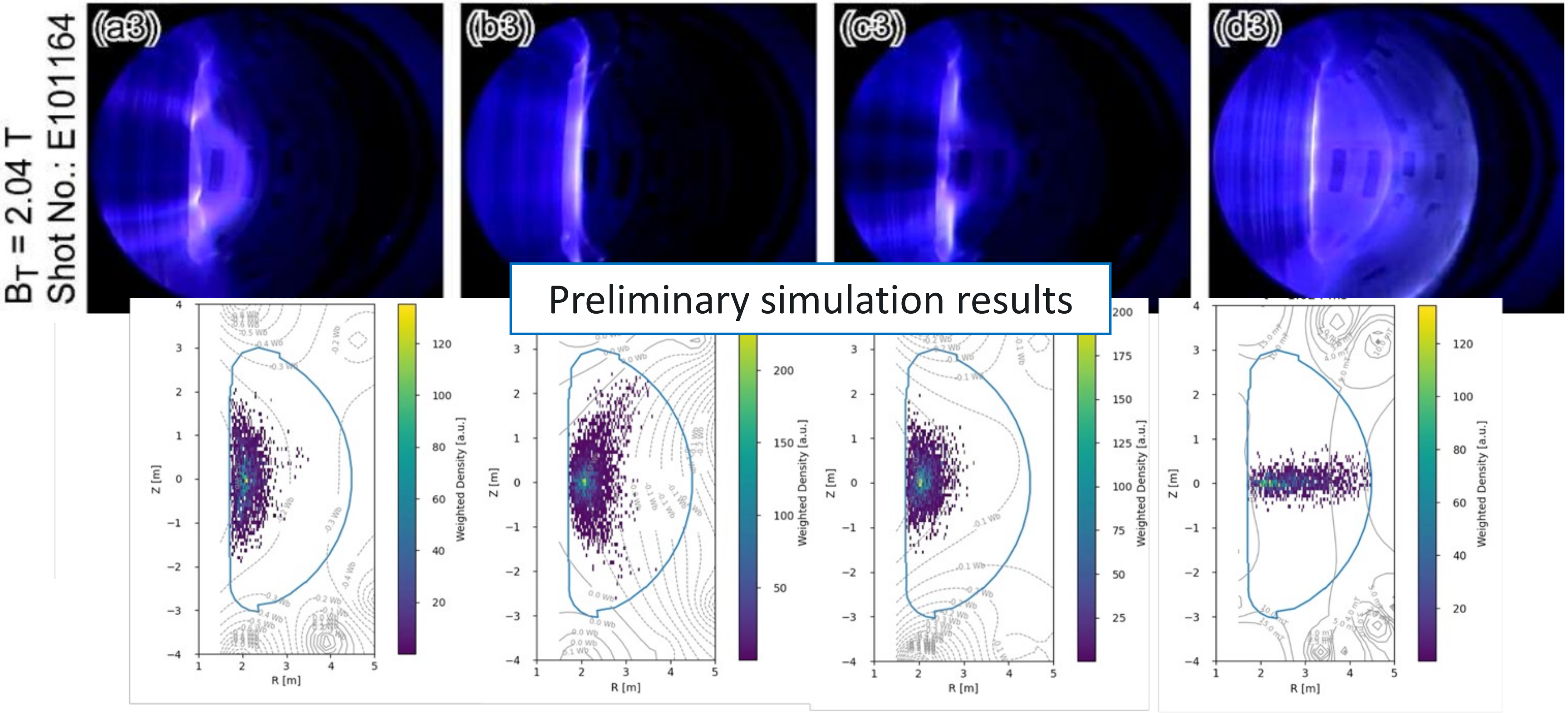
JT-60SA Operational space at bd with limited voltages by CREATE-BD/BKD0/GRAY

ECWC in JT-60SA: study of pre-ionization phase



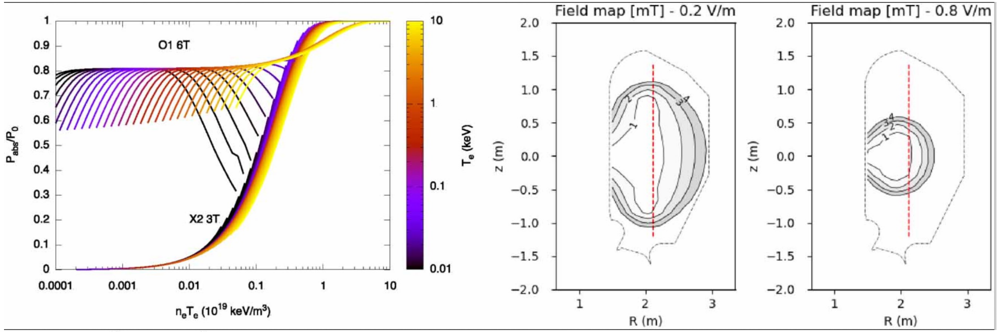
Simulation of magnetic configuration performed by CREATE.

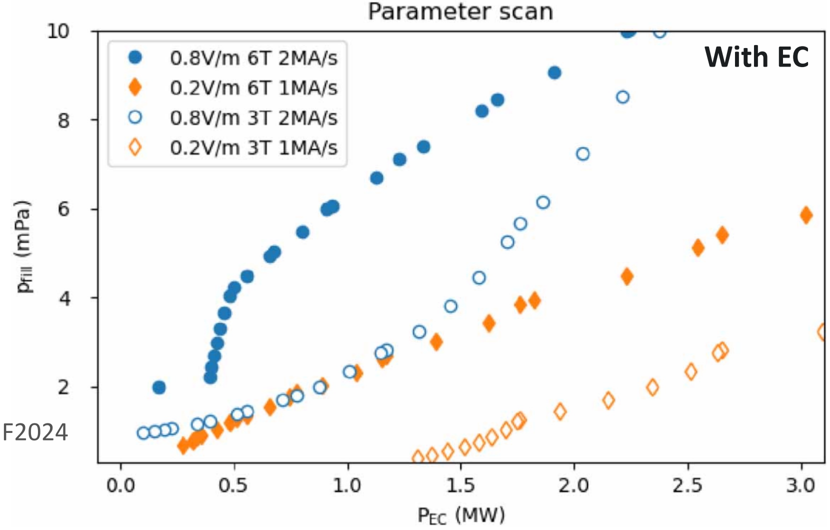
ECWC in JT-60SA: study of pre-ionization phase



Preliminary simulation results

Results: DTT operational parameters





Parameter scan calculated with BKD0, CREATE-BD and GRAY coupled simulations:

- At 0.8 V m^{-1} the operational window expands of a factor 4 for both the OM and XM modes.
- At 0.2 V m^{-1}, the rise is moderate for each MW injected, with a rate of 2 mPa/MW, exhibiting a different minimum threshold (0.25 MW for OM and 1.25 for XM).

Granucci NF2024

Conclusions

- To assist tokamak start-up and widen the operational space, electron cyclotron resonance heating represents a valid solution.

- Among recent experimental results, it is worth noting that the use of TPC seems a quite robust approach for assisted pre-ionization

- Several tools have been developed
  - to enable a reliable scenario simulation, reducing the number of required experiments for developing of the initial plasma scenario
  - data analysis.

- Preliminary simulation for the description of pre-ionization (plasma volume and density and temperature profiles)