International Conference on Ion Source 2025

09/09/2025

Theoretical and numerical study of the ECRIPAC accelerator concept

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Outline and goals

ECRIPAC (Electron Cyclotron Resonance Ion Plasma Accelerator)

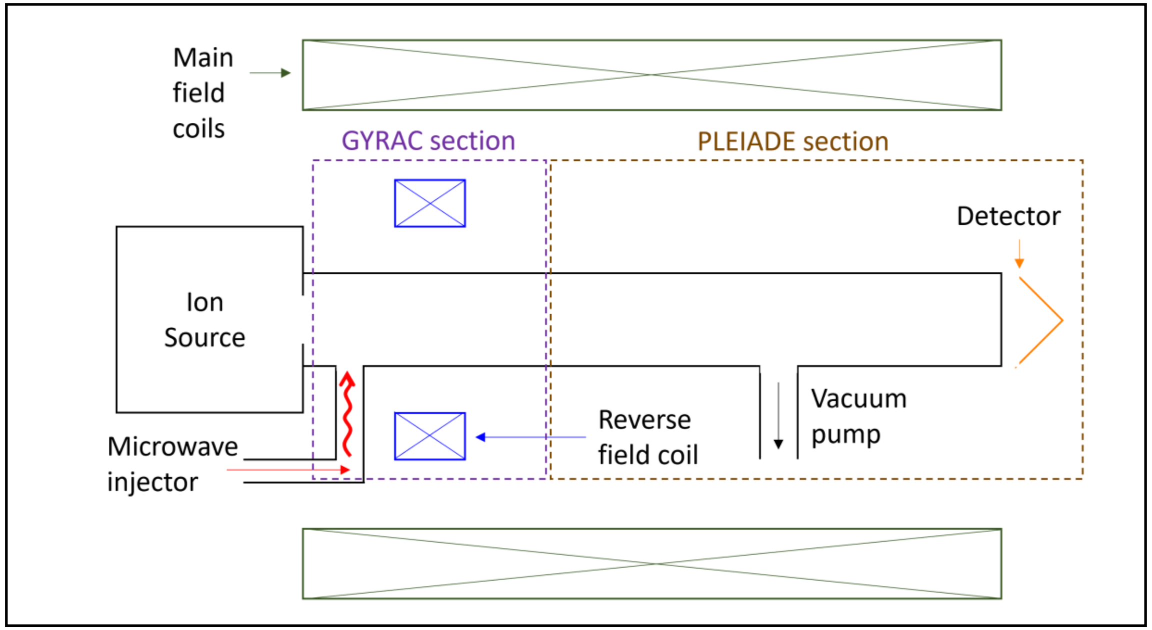
- Plasma accelerator conceptualized by **R. Geller** in the 1990.
- Physical principles **similar to ECR Ion Source**.
- **Scientific interest**: Reduced accelerator dimensions, established technologies and simple design.

Aim

- Numerically simulate ECRIPAC to assess device feasibility.

Methods

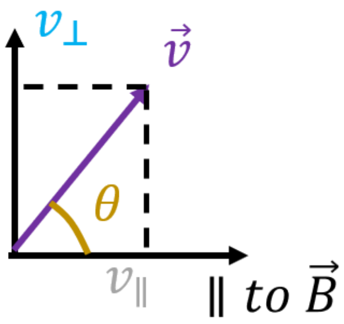
- Theoretical calculations.
- Monte Carlo electron simulation.
- PIC simulations (*work in progress*).



Electron heating in ECRIS

In ECRIS, electrons are confined inside a **magnetic mirror** and heated through **Electron Cyclotron Resonance.**

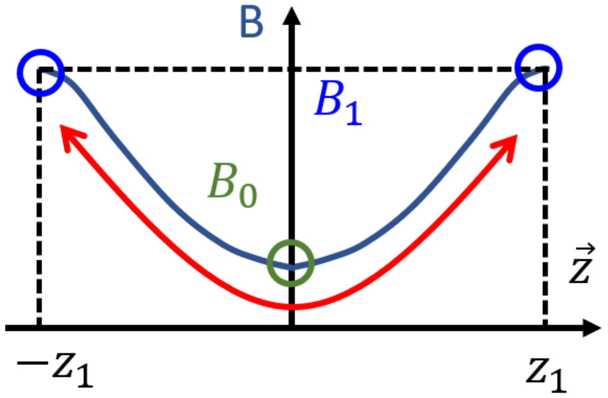
Magnetic mirror confinement



$$\frac{1}{2}m{v_\parallel}^2 + \frac{1}{2}m{v_\perp}^2 = const$$

$$\mu = \frac{m{v_\perp}^2}{2B} \sim const$$

Particle **reflected** and **confined** if $\sin\theta \geq \sqrt{\frac{B_0}{B_1}}$



Like a ball rolling up/down a hill!

$\nabla B > 0$: $v_\parallel$ converted to $v_\perp$

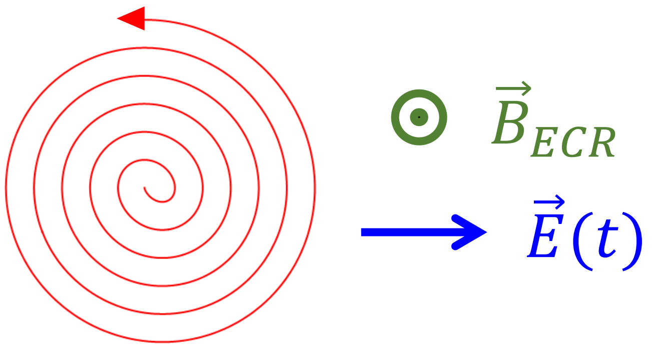
$\nabla B < 0$: $v_\perp$ converted to $v_\parallel$

Electron Cyclotron Resonance (ECR)

Electron e^- in magnetic field $\vec{B}$ and transverse time varying electric field $\vec{E}(t)$ rotating at ω_{HF}.

- e^- gain $\perp$ energy from $\vec{E}(t)$ if $\omega_{HF} = \Omega = \frac{eB_{ECR}}{m}$

e^- rotating at frequency Ω



From ECRIS to ECRIPAC

Relativistic **limitation for maximum** electron **energy** through ECR.

$$\Omega = \frac{eB_{ECR}}{\gamma m} = \frac{\Omega_0}{\gamma} \neq \omega_{HF} \quad if\, \gamma > 1$$

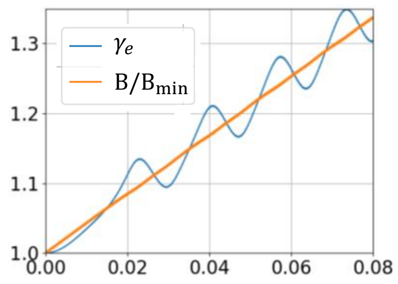
➢ Relativistic energy leads to resonance loss.

- **ECRIPAC solution**: magnetic mirror slowly increasing in time

Gyromagnetic autoresonance (GA): autoresonant acceleration of electrons in magnetic field ***B(t)*** smoothly growing in time.

➢ $\gamma_e(t) \approx \frac{B(t)}{B_{min}}$

✓ Experimentally verified!

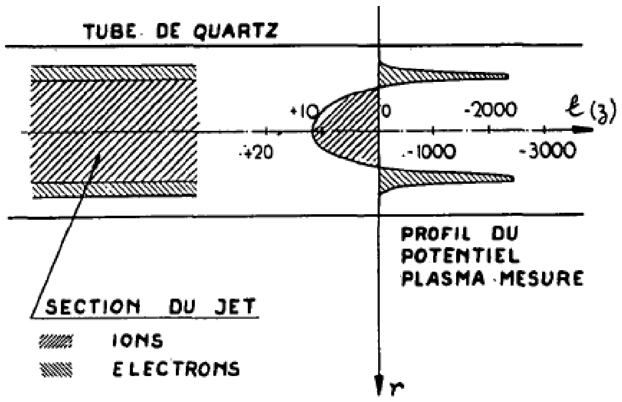


- What if I want to **accelerate ions**? Use the electron energy!

Ion entrainment: Local **difference in** *i*$^+$ and *e*$^-$ **density** arising from *e*$^-$ displacement generates a space-charge field which **accelerates** *i*$^+$.

➢ $\boldsymbol{v}_{e\parallel} \approx \boldsymbol{v}_{i\parallel} \rightarrow W_{e\perp,c} - W_{e\perp,PL} \approx W_{i\parallel,PL}$

✓ Experimentally verified!



Bardet et al. (1965), Nuclear Fusion 5 (pp. 7-16).

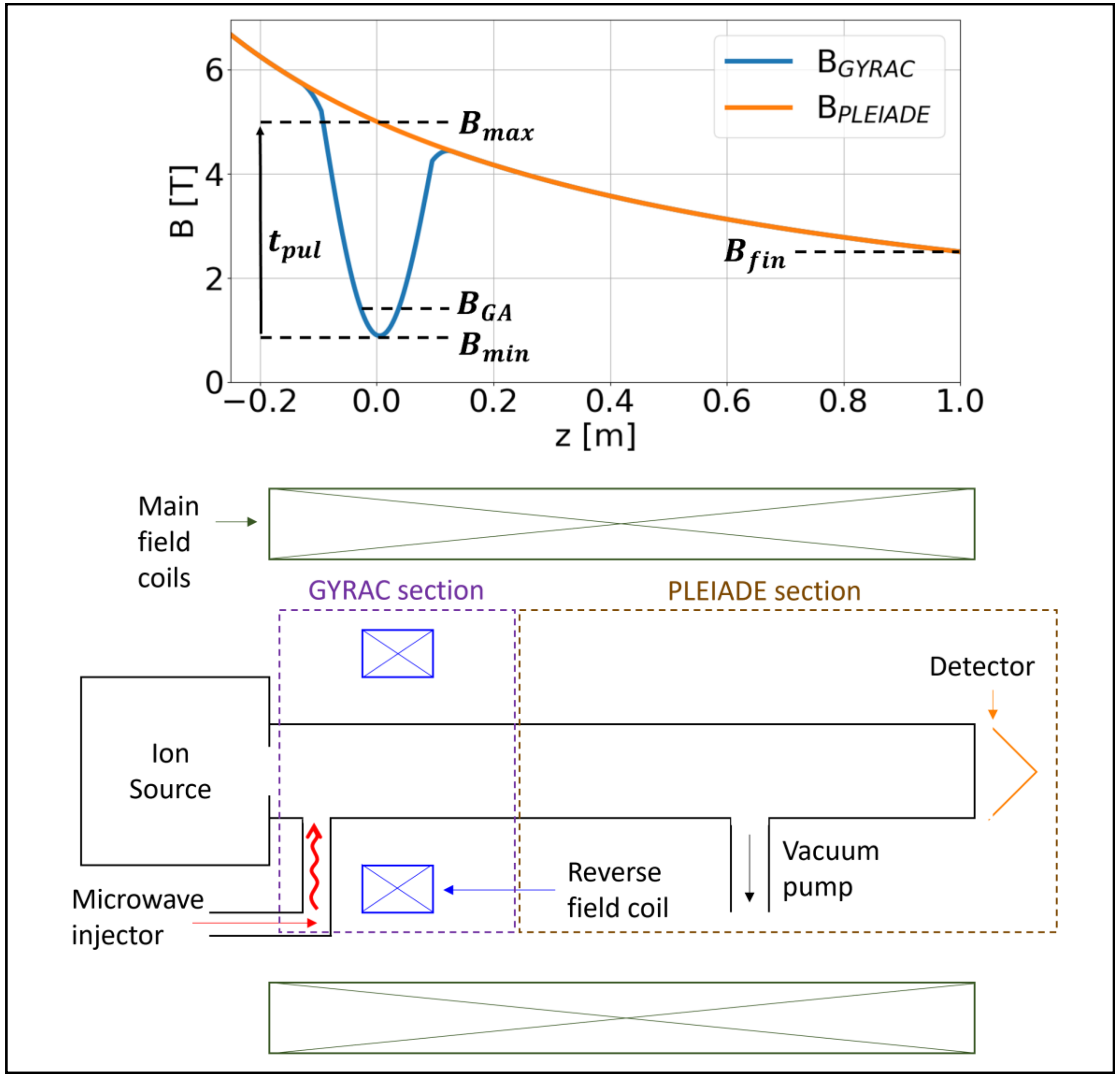
ECRIPAC structure

Structure

- **Injector**: ion source (ECRIS).
- **GYRAC section:** resonant cavity, microwave injector, main coils and reverse field coil (magnetic mirror).
- **PLEIADE section:** beam transport tube, main coils.

Working cycle phases:

- **Gyromagnetic autoresonance (GA).**
- **Plasma compression (C).**
- **PLEIADE (PL).**



Gyromagnetic autoresonance (GA) phase

Role

Increase electron energy through gyromagnetic autoresonance.

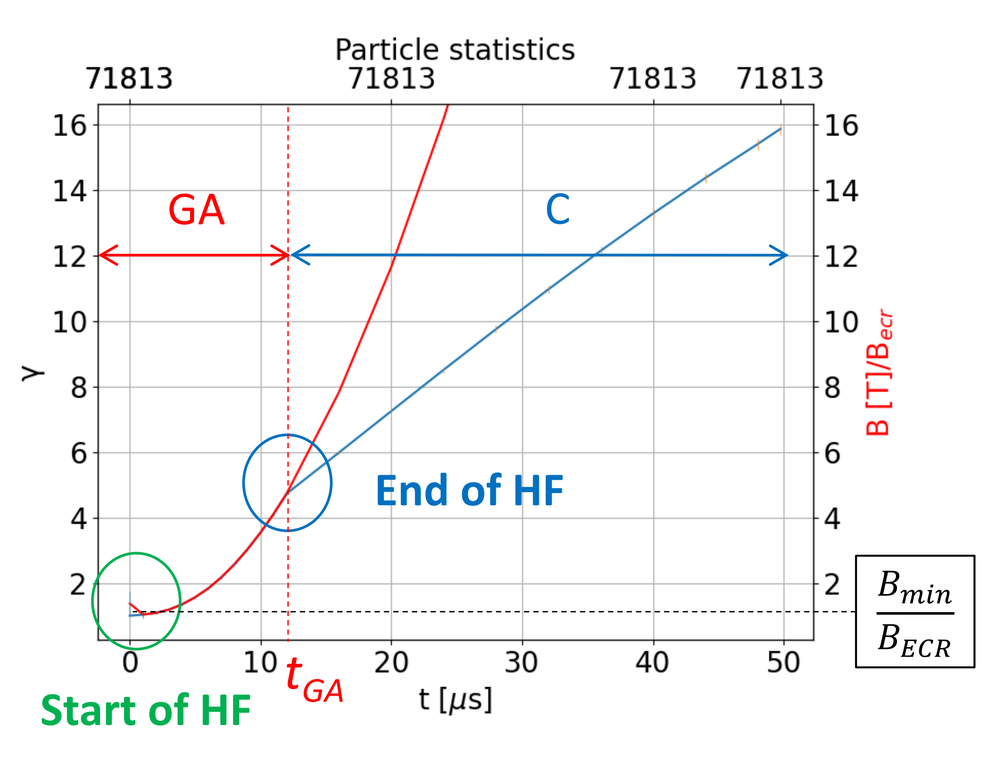
- **Plasma and HF wave injection** at reverse field peak value.

$B(t)$ *sinusoidal increase in time*

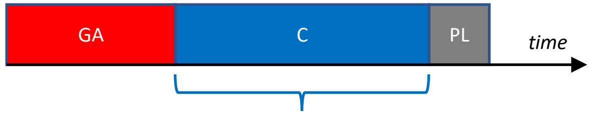
$B_{min} \leq B_{ECR}$ for stability reasons

$f_{HF} = 2.45\ GHz$

$$\gamma_{GA} \approx \frac{B(t_{GA})}{B_{min}} \qquad r_{orbit} = \frac{v}{\omega_{HF}} \leq \frac{c}{\omega_{HF}} \approx 1.95\ cm$$



Plasma compression (C) phase



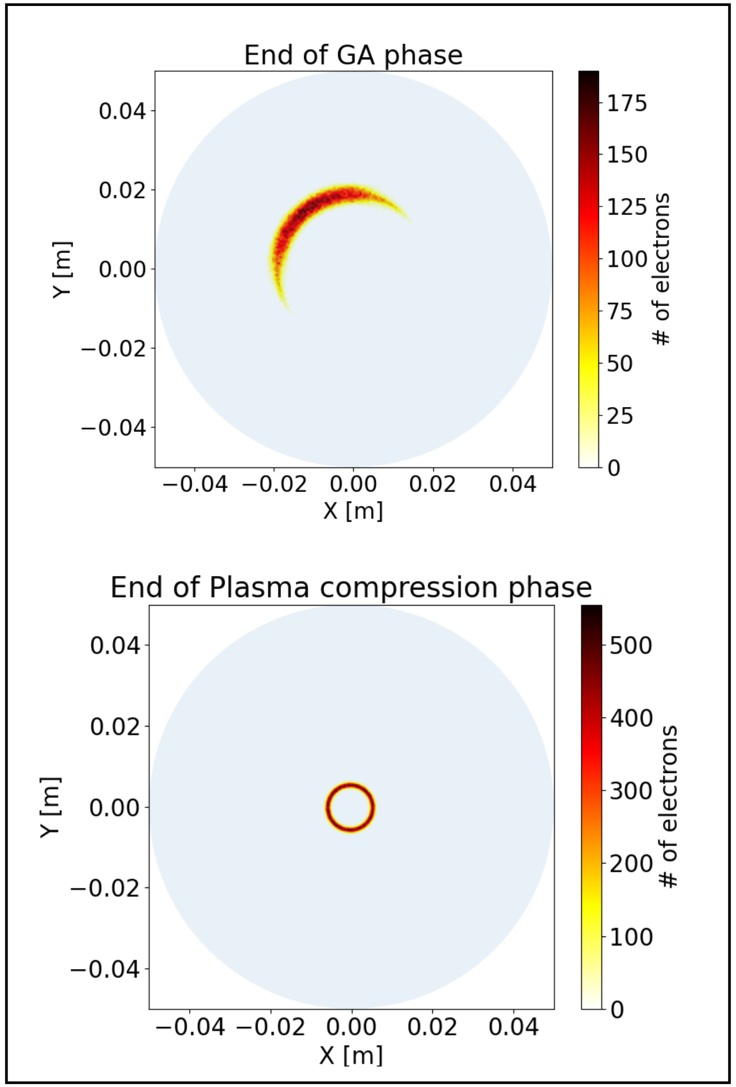
Role
Compress electron cloud and further increase electron energy.

- **HF wave injection stops**, magnetic field continues to increase up to the main field restoration.
- **Plasma compressed** into a thin disk by electric field induced by time-varying magnetic field.
    - ⇧ n_e beneficial for ion acceleration.

- Constant of motion in adiabatic approximation.

$$\begin{cases} p^2/B = const \\ r^2 B = const \end{cases}$$

$$\gamma(t) = \left(1 + (\gamma_{GA}^2 - 1)\frac{B(t)}{B(t_{GA})}\right)^{\frac{1}{2}}$$



PLEIADE (PL) phase

Role

Ion *(i^+)* acceleration due to ion entrainment by electrons *(e^-)* .

Stability conditions for *i^+* acceleration (charge Ze, mass Am_a)

- **Magnetic field profile:** $\frac{dB_{PL}}{dz} < 0$ and $\frac{d^2B_{PL}}{dz^2} > 0$.
- **Non shake out condition (NSO):** i^+ acceleration > e^- acceleration

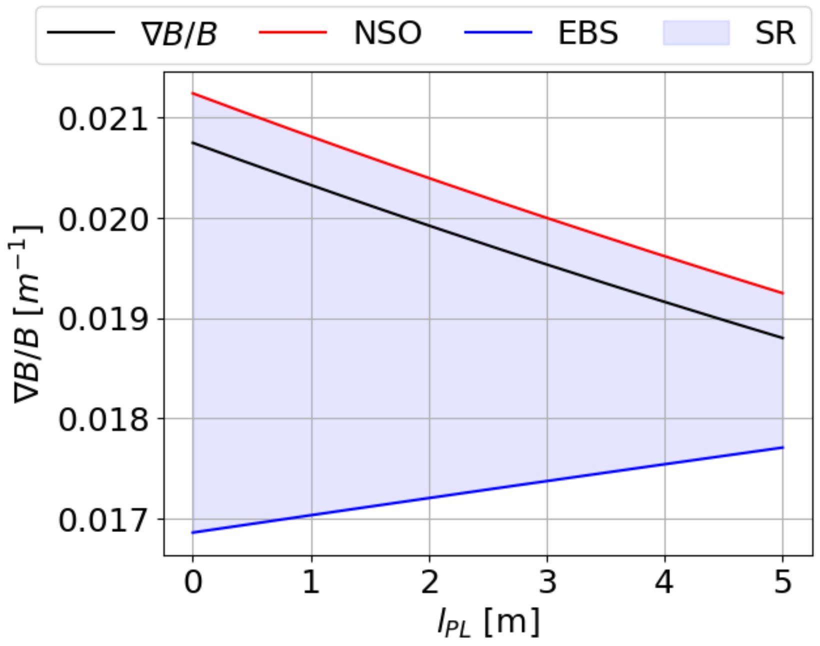
$$\left|\frac{\nabla B_z}{B_z}\right| \leq \frac{2Ze}{m_a c^2 A} E_{sc}$$

- **Electron bunch stability (EBS):** Coulomb repulsion < ∇B force.

$$\left|\frac{\nabla B_z}{B_z}\right| \geq \frac{2e}{m_e c^2 (\gamma_{e,C}^3 - \gamma_{e,C})} E_{sc}$$

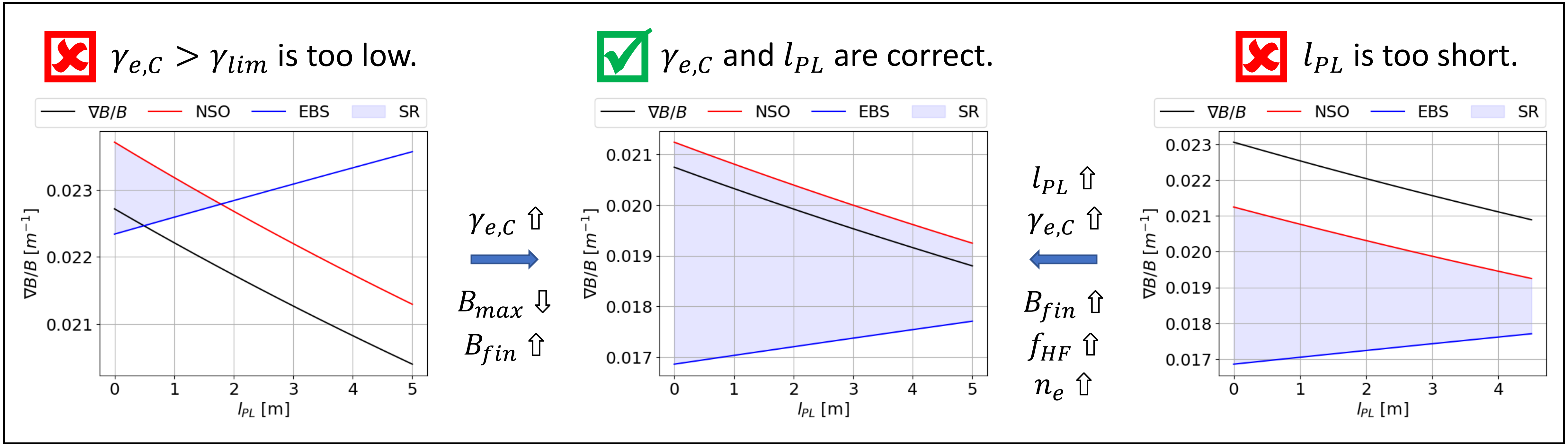
➢ γ_{lim} : Minimum γ for stable acceleration.

$$\gamma_{e,C} > \gamma_{lim} = \left(\frac{m_a A}{m_e Z}\right)^{\frac{1}{3}}$$



Stability condition of the accelerator

More stringent limitations than expected: $\gamma_{e,C} >> \gamma_{lim}$ and **appropriate** l_{PL}.



Parameter space analysis

Aim: Obtain ions of desired energy with lowest $\boldsymbol{\gamma_{e,C}}$ and $\boldsymbol{l_{PL}}$ ensuring stability.

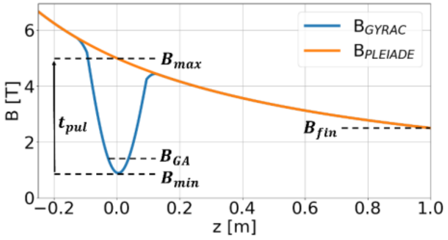
Parameter space ($\gamma_{e,C}$ *vs* B_{fin} *vs* l_{PL}) **analysis**

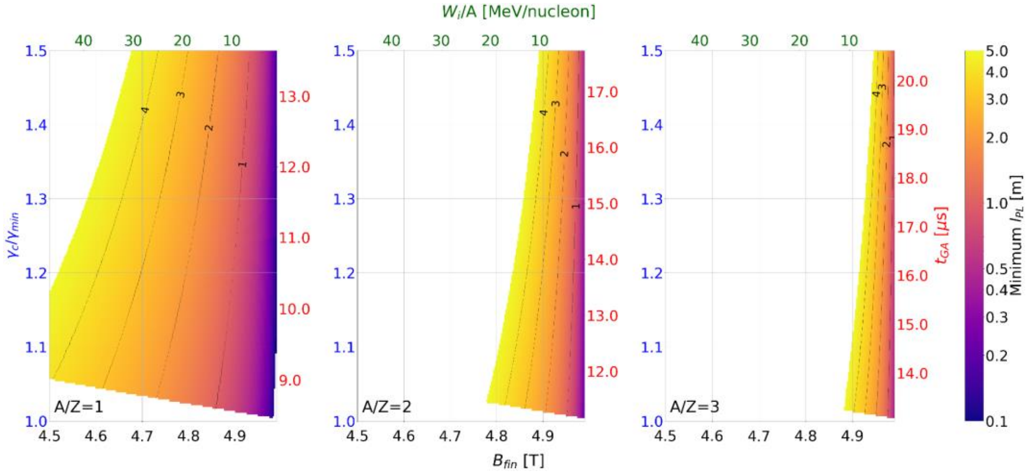
Plasma

- Ions **A/Z** ratio.
- e⁻ density $\boldsymbol{n_e}$.
- Initial plasma size $\boldsymbol{r_{disk,0}}$.

External field

- $\boldsymbol{t_{pul}}$.
- $\boldsymbol{B_{max}}$.
- $\boldsymbol{f_{HF}}$.





ECRIPAC suited to accelerate **highly-charged** ions with **small mass over charge** using a **large** and **dense plasma**.

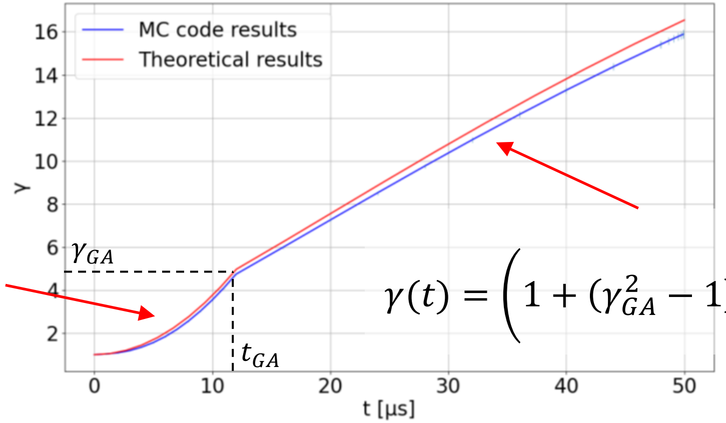
Prototype design for a **He²⁺ compact accelerator** @ $f_{HF} = 2.45\ GHz$

- $\mathbf{W_i/A}$ = 9.53 MeV/nucl.
- $\mathbf{l_{PL}}$ = 1.8 m
- $\boldsymbol{B_{max}} = 5\ \mathrm{T}$; $\boldsymbol{B_{fin}} = 4.89\ \mathrm{T}$; $\boldsymbol{B_{min}} = 0.086\ \mathrm{T}$

Monte Carlo simulations

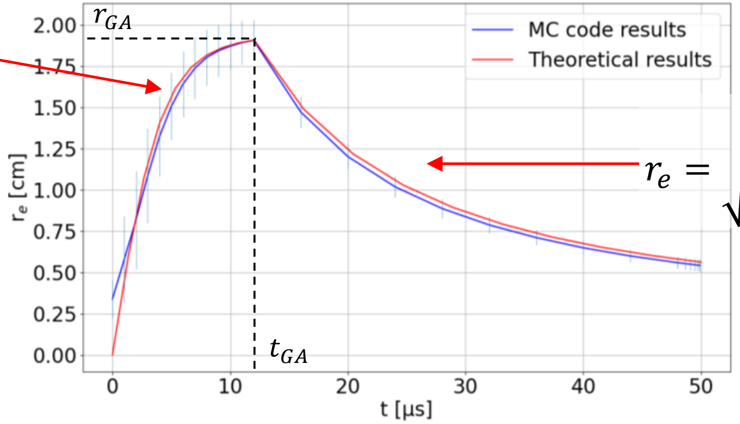
Very **good agreement** with **theoretical** treatment

$$\gamma_{GA} \approx \frac{B(t_{GA})}{B_{min}}$$



$$\gamma(t) = \left(1 + (\gamma_{GA}^2 - 1)\frac{B(t)}{B(t_{GA})}\right)^{\frac{1}{2}}$$

$$r_e = \frac{v_e}{\Omega_e}$$

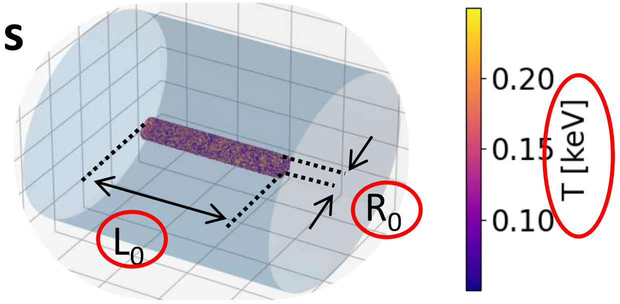


$$r_e = \sqrt{\frac{r_{GA}^2 B(t_{GA})}{B(t)}}$$

Investigation of physical parameters effects

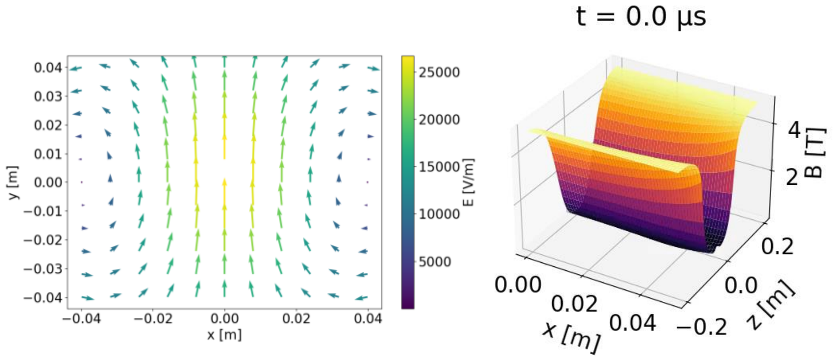
Particle initial conditions

- ⇧ **L0 → *No effect***: possible to reduce spatial grid size.



External field

- ⇧ $\frac{dB(t)}{dt}$ → ***No effect:*** possible to reduce simulation duration.



Conclusions and perspectives

Conclusions

- ECRIPAC great promises and lack of literature motivates further studies.
- Complexity of the system requires a study in successive steps
  - ✓ **Theoretical study**: more stringent limitations on stability condition than expected and highlighted influence of ECRIPAC parameters. Proposal of a prototype design for a He^{2+} compact accelerator.
  - ✓ **Monte Carlo simulation**: validates theoretical treatment of electron behaviour inside ECRIPAC. Allowed to study effect of several parameters on electron behaviour.

Perspectives

- Simulation of the entire plasma during the whole ECRIPAC operation.
  - ➢ Currently developing Particle-In-Cell (PIC) simulation using Smilei

Thanks for your attention!

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Questions?

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