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Simulation study of the ECRIPAC accelerator concept

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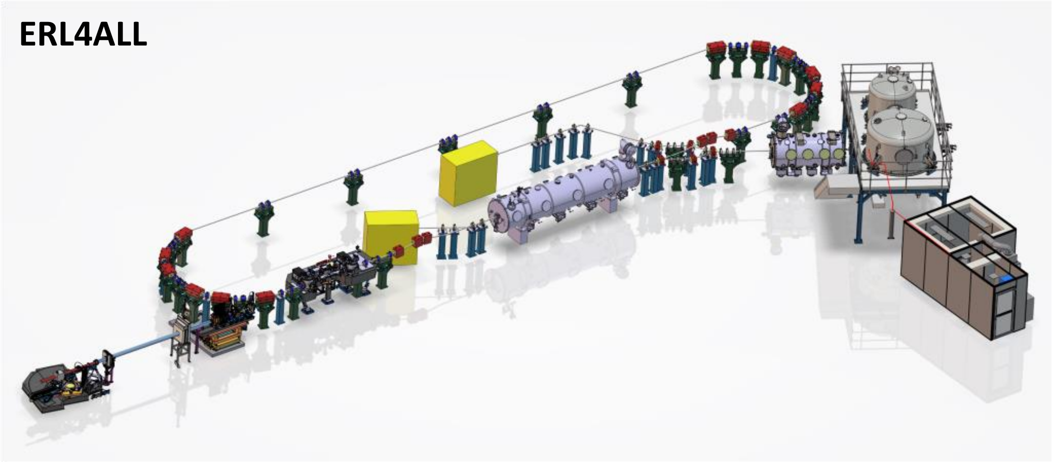
UGA Université Grenoble Alpes

Context

Pole Accélérateurs et Sources d'Ions



- Accelerate charged particles through electric and magnetic field.
- Several kinds of particle accelerator (linear, circular, plasma-based …)

Context

Pole Accélérateurs et Sources d'Ions

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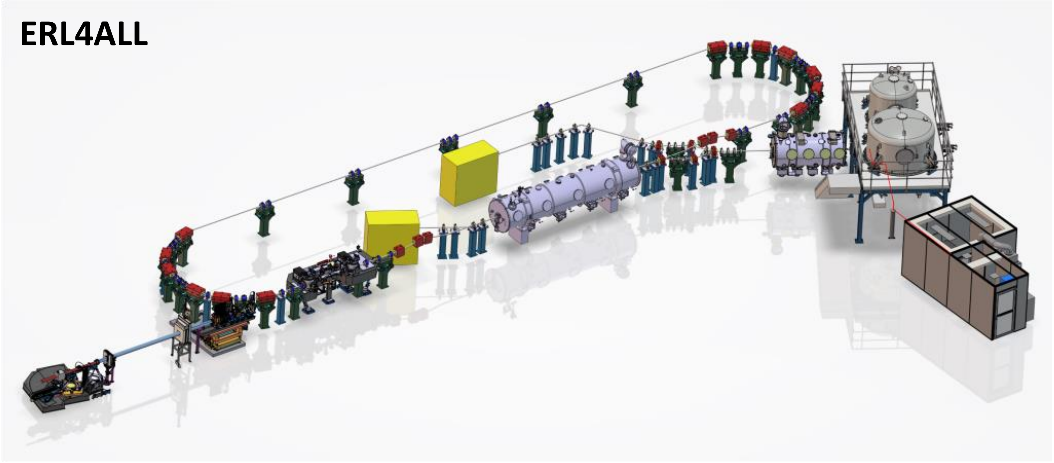

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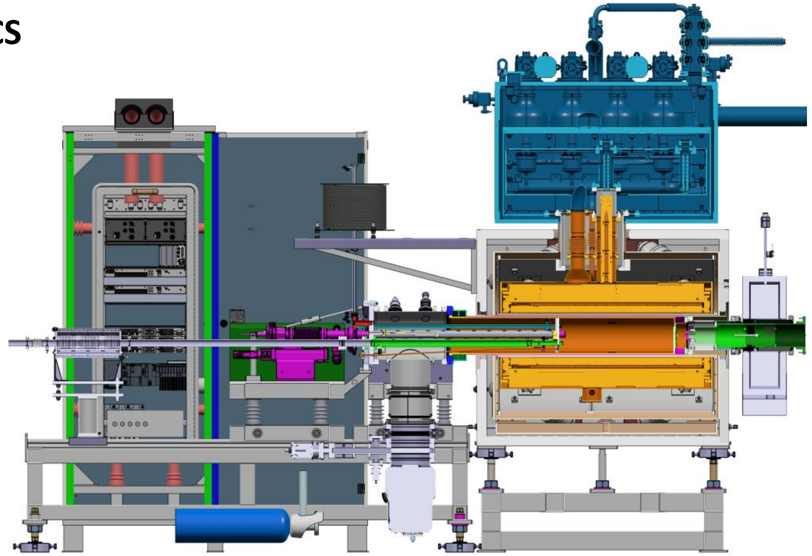
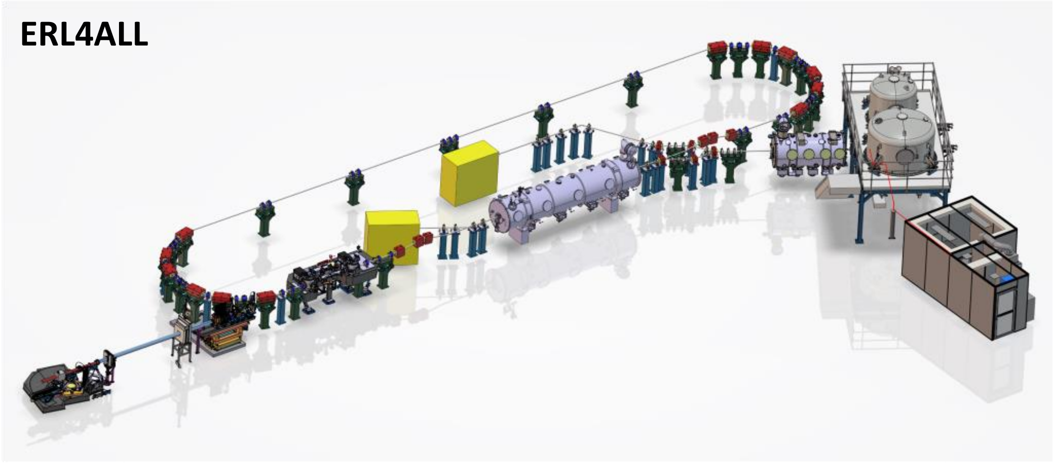


- Generate ions inside a plasma using Electron Cyclotron Resonance (ECR).

Context

Pole Accélérateurs et Sources d'Ions



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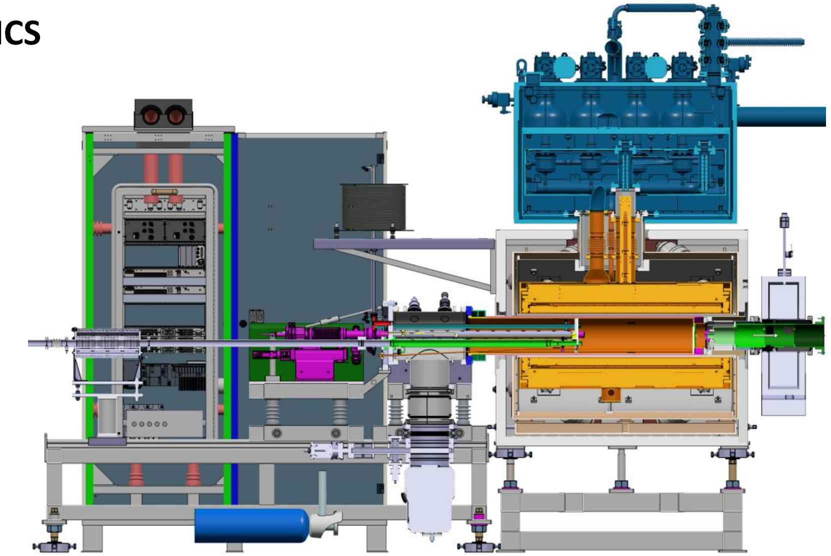
- Several kinds of particle accelerator (linear, circular, plasma-based …)



- Generate ions inside a plasma using Electron Cyclotron Resonance (ECR).

ECRIPAC

Thesis outline and goals

ECRIPAC (Electron Cyclotron Resonance Ion Plasma Accelerator, R. Geller, 1990)

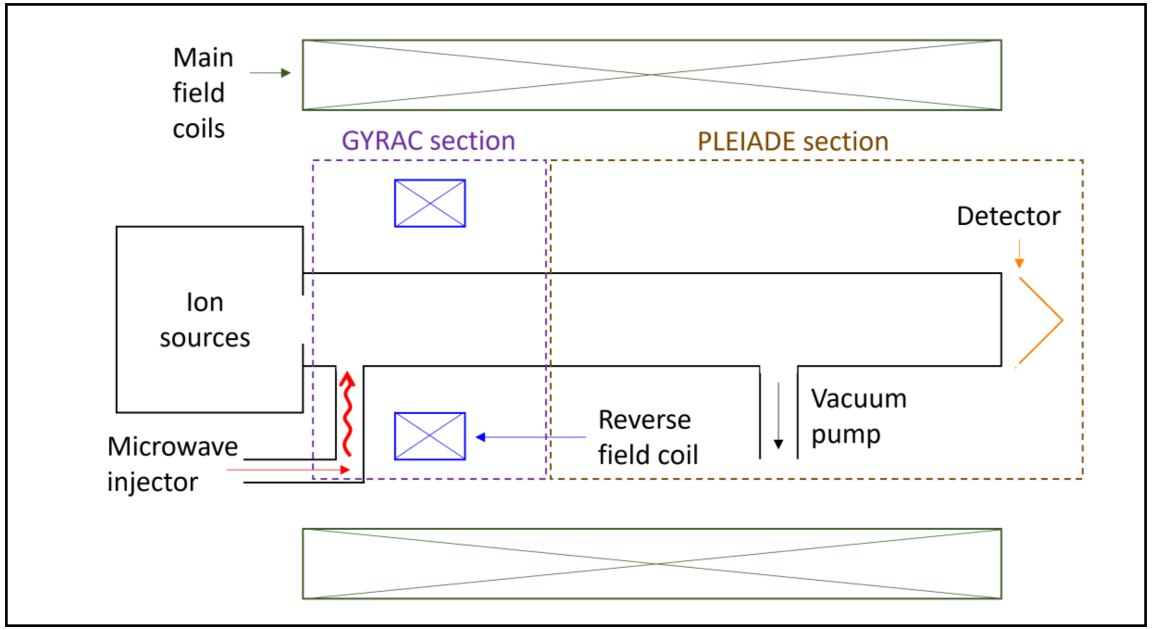
- ECR plasma accelerator with adjustable ion energy, up to 100s MeV/nucleons.
- **Scientific interest**: Reduced accelerator dimensions, established technologies and simple design.

Aim

- Numerically simulate ECRIPAC to asses device feasibility.

Methods

- Theoretical calculations.
- Monte Carlo electron simulation.
- Particle-In-Cell simulation.



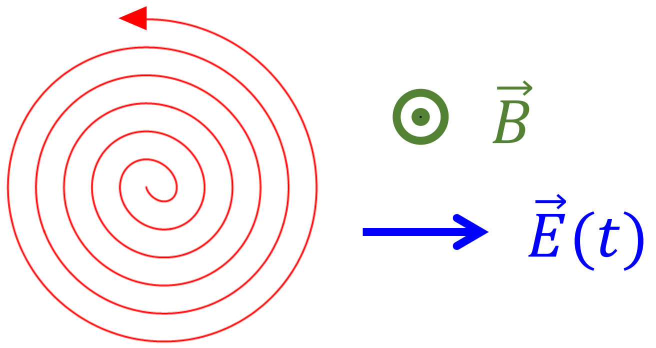
Some physical basis

Electron Cyclotron Resonance (ECR)

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

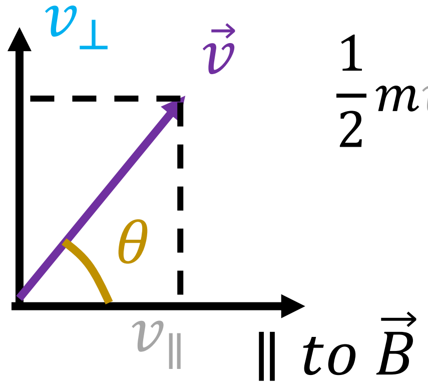
- e^- gain ⊥ energy from $\vec{E}(t)$ if $\omega_{HF} = \Omega = \frac{eB}{m}$

e^- rotating at frequency Ω



Magnetic mirror confinement

Charged particle propagating towards ⇧ **B.**



$$\left.\begin{aligned} \frac{1}{2} m v_\parallel{}^2 + \frac{1}{2} m v_\perp{}^2 &= const \\ \mu = \frac{m v_\perp{}^2}{2B} &\sim const \end{aligned}\right\}$$

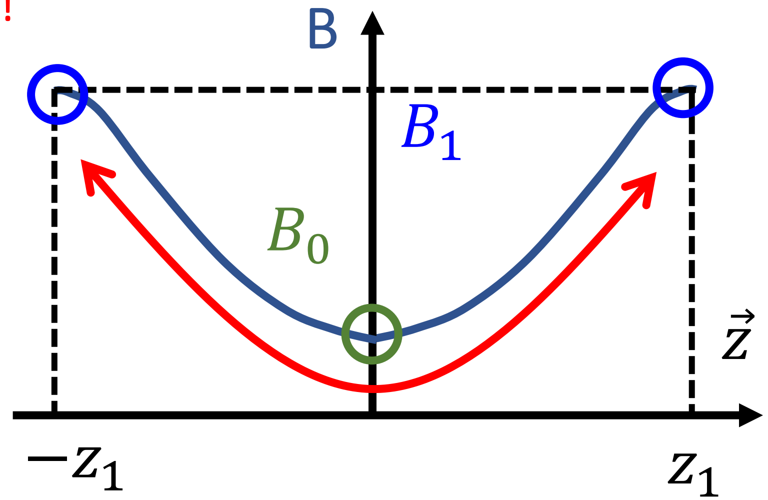
$$if\ \sin\theta \geq \sqrt{\frac{B_0}{B_1}}$$

Particle reflected and confined!

Like a ball rolling up/down a hill!

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

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



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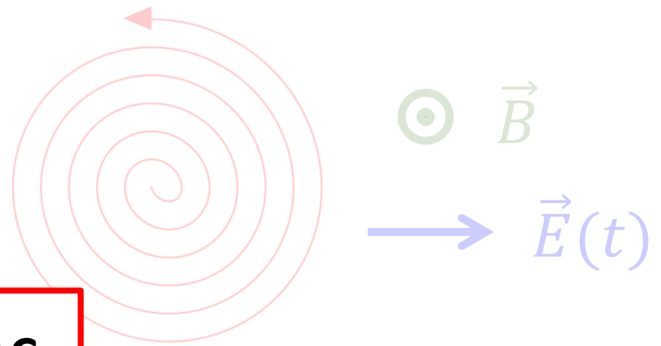


Two main physical phenomena inside ECRIPAC

- Gyromagnetic autoresonance.
- Ion entrainment.

Magnetic mirror conf…

Charged particle propagating …

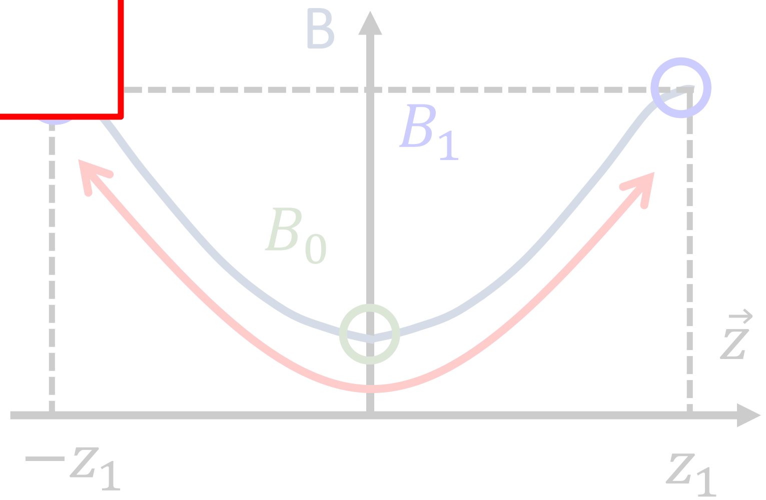
$$\frac{1}{2}mv_\parallel{}^2 + \frac{1}{2}mv_\perp{}^2 = const$$

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

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

$$if\ \sin\theta \geq \sqrt{\frac{B_0}{B_1}}$$

Particle reflected and confined!



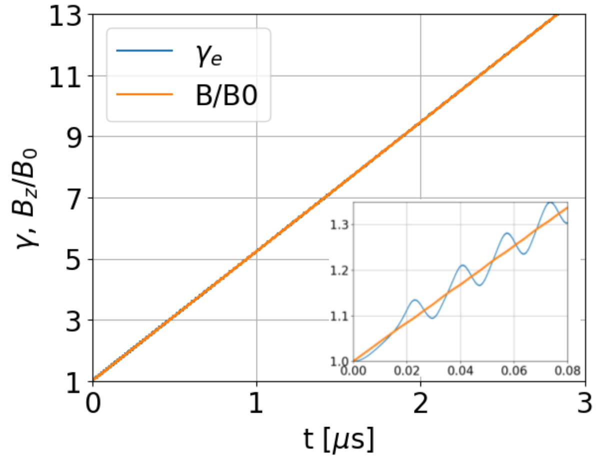
GYRAC principle: Gyromagnetic autoresonance (GA)

Autoresonant acceleration of electrons in magnetic field smoothly growing in time.

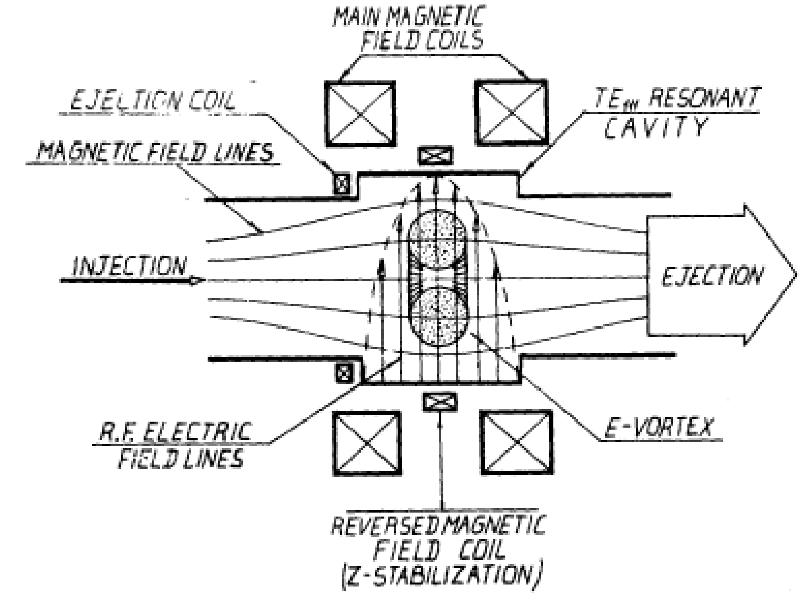
✓ **Experimentally verified!**

- γ_e increases quasi-synchronously with magnetic field growth through relativistic ECR.

$$\omega_{HF} = \Omega = \frac{qB(t)}{m_e \gamma_e} \qquad \gamma_e(t) \approx \frac{B(t)}{B_0}$$



GYRAC accelerator prototype



Golovanivsky (1982), IEEE Transactions on Plasma Science 10 (pp. 120-129).

PLEIADE principle: Ion entrainment

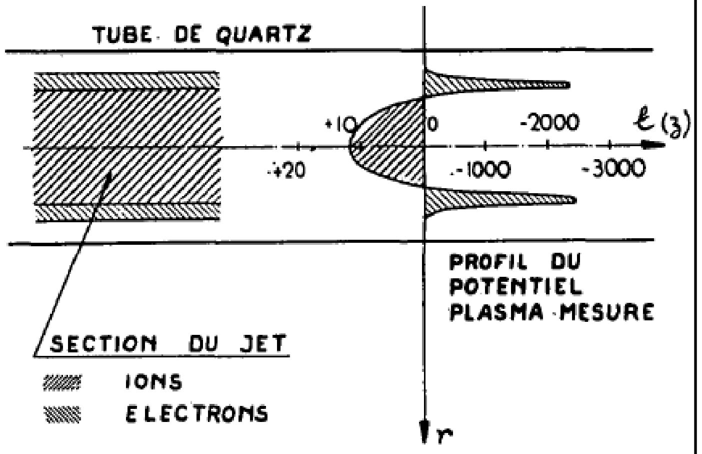
Local **difference in** ion and electron **density** arising from electron displacement in a magnetic field with $\nabla B < 0$ generates a space-charge field which **accelerates** the **ions**.

✓ **Experimentally verified!**

Cylindrical plasma shape

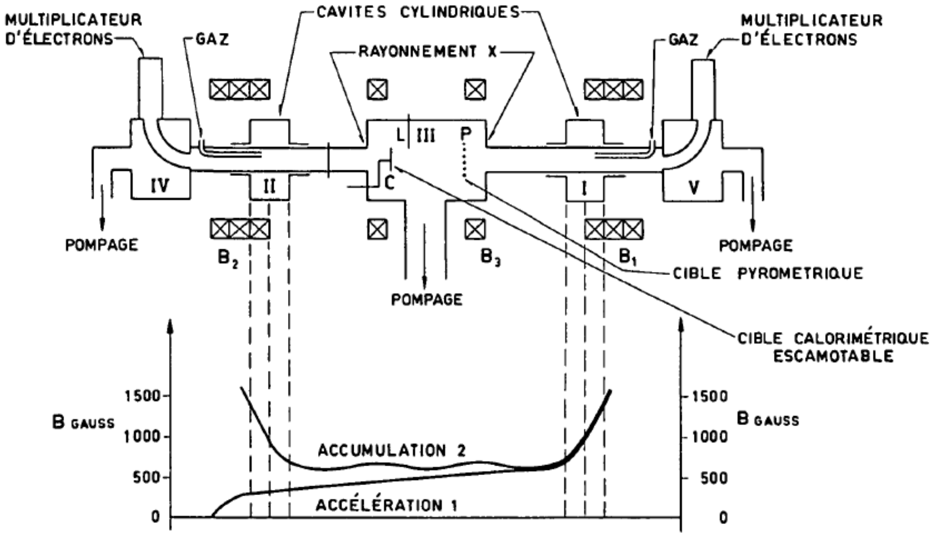
- Electron in outher region and ions in inner region.
- $v_{e\parallel} \approx v_{i\parallel}$.

$$W_{e\perp}^{res} - W_{e\perp}^{ext} \approx W_{i\parallel}^{ext}$$



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

PLEIADE accelerator prototype



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

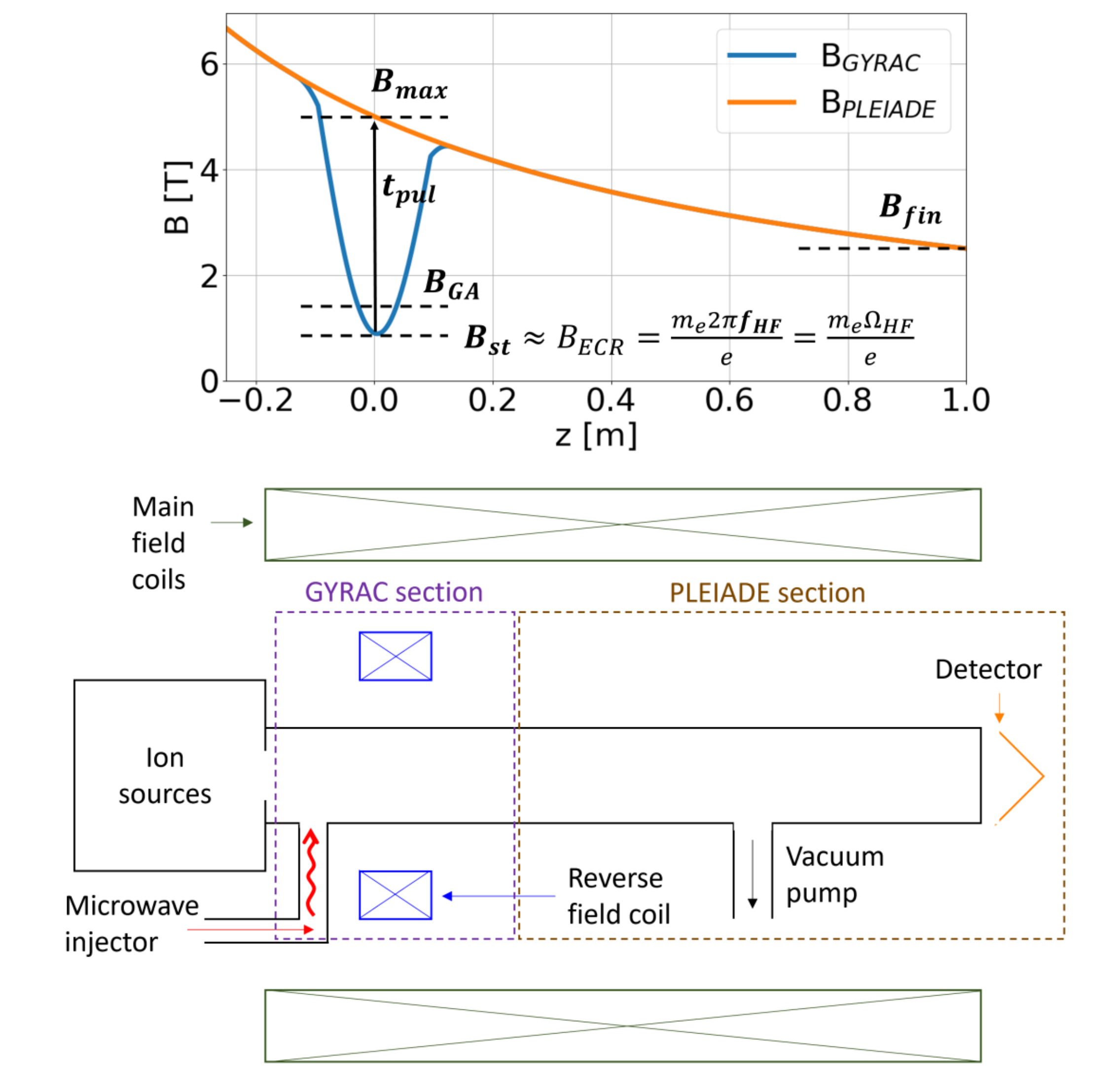
ECRIPAC structure

Structure

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

Working cycle phases:

- **Gyromagnetic autoresonance (GA).**
- **Plasma compression (com).**
- **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*

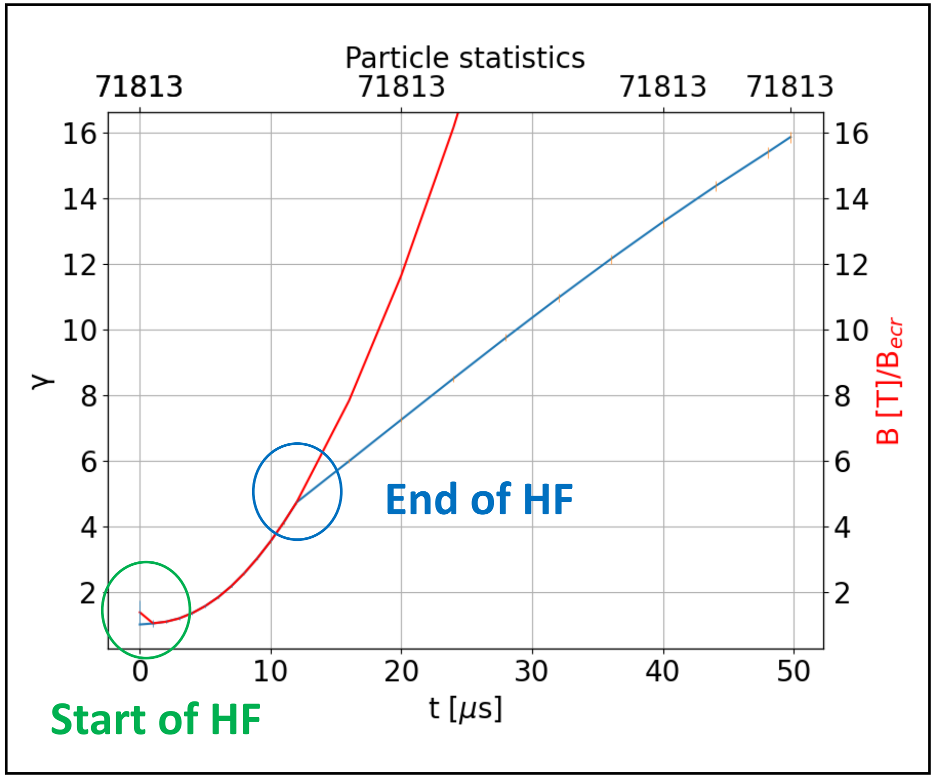
$B_{st} \leq B_{res}$ for stability reasons

$f_{HF} = 2.45\ GHz$

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

$$r_{orbit} = \frac{v}{\omega_{HF}} \leq \frac{c}{\omega_{HF}} \approx 1.95\ cm$$

- **Limitation:** Results obtained in single electron approximation.
  - ➢ PIC simulations required for behaviour inside a plasma.



Plasma compression (com) phase

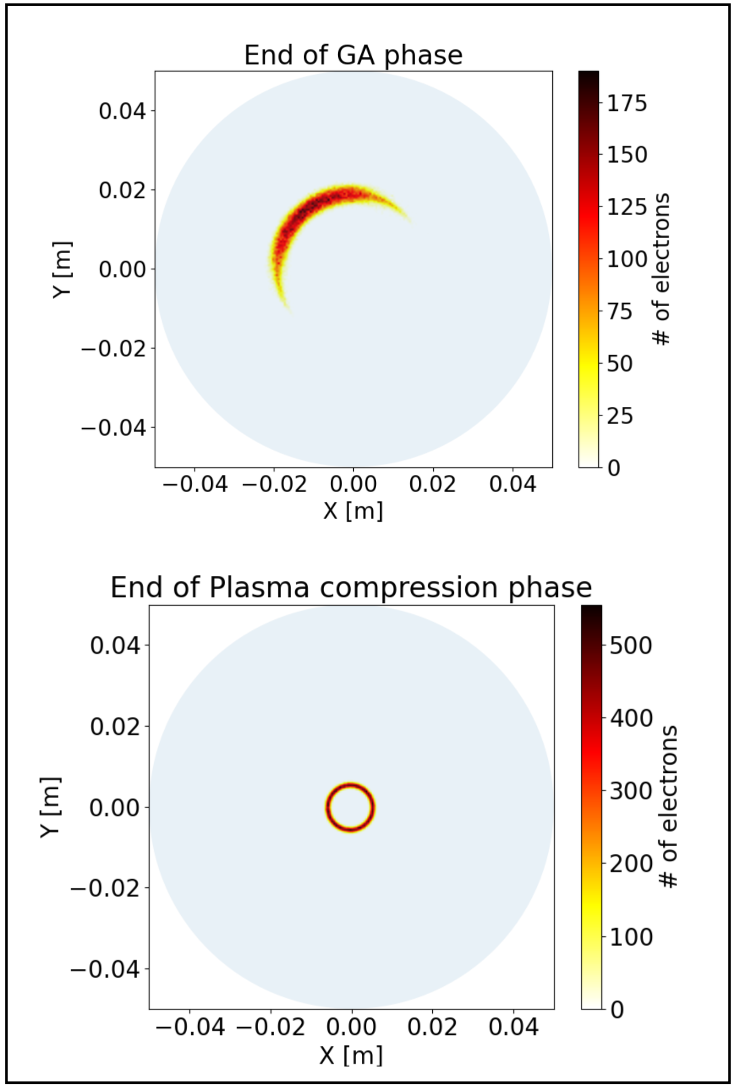
Role

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 improves ion entrainment.

- 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

- $\frac{dB_{PL}}{dz} < 0$: ∇B force converts $W_{e\perp}$ **in** $W_{e\parallel}$.
- $\frac{d^2B_{PL}}{dz^2} > 0$: Minimize macroscopic instabilities.
- $v_{e\parallel} \approx v_{i\parallel}$: Collective field converts W_e **into** W_i .

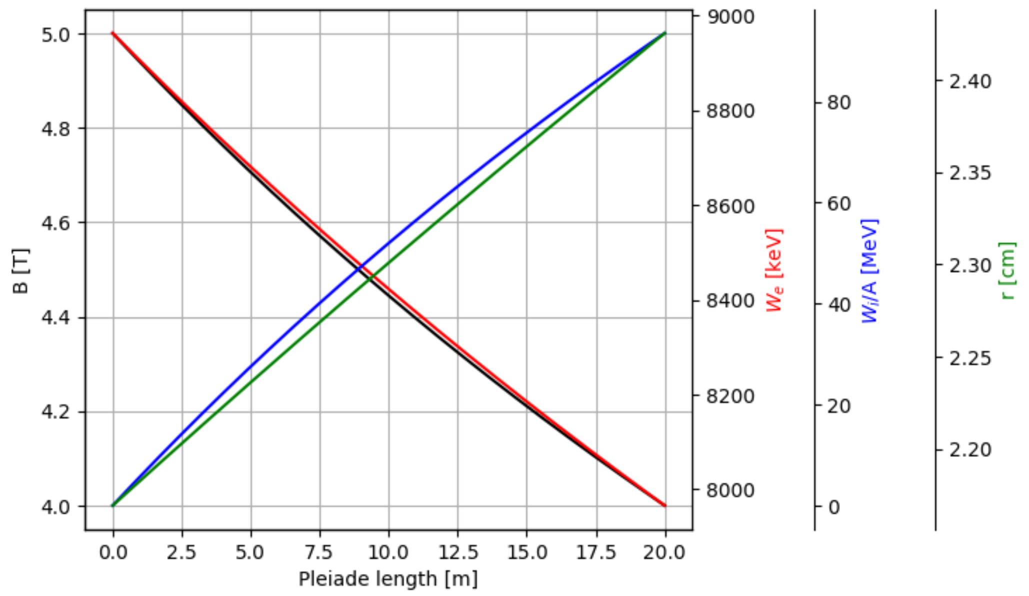
$$W_{e\perp,com} - W_{e\perp,PL} \approx W_{i\parallel,PL}$$

- $N_{ions} << N_{electrons}$

$$\frac{W_i}{A} \approx 469\ \frac{\gamma_{e,com}^2 - 1}{\gamma_{e,com}^2}\left(1 - \frac{B_{fin}}{B_{max}}\right)\frac{MeV}{nucleon}$$

Role

Ion acceleration due to ion entrainment by electrons.



PLEIADE phase: Stability

- **Non shake out condition**: Ion (charge Ze, $mass\ Am_a$) acceleration is larger than electron acceleration.

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

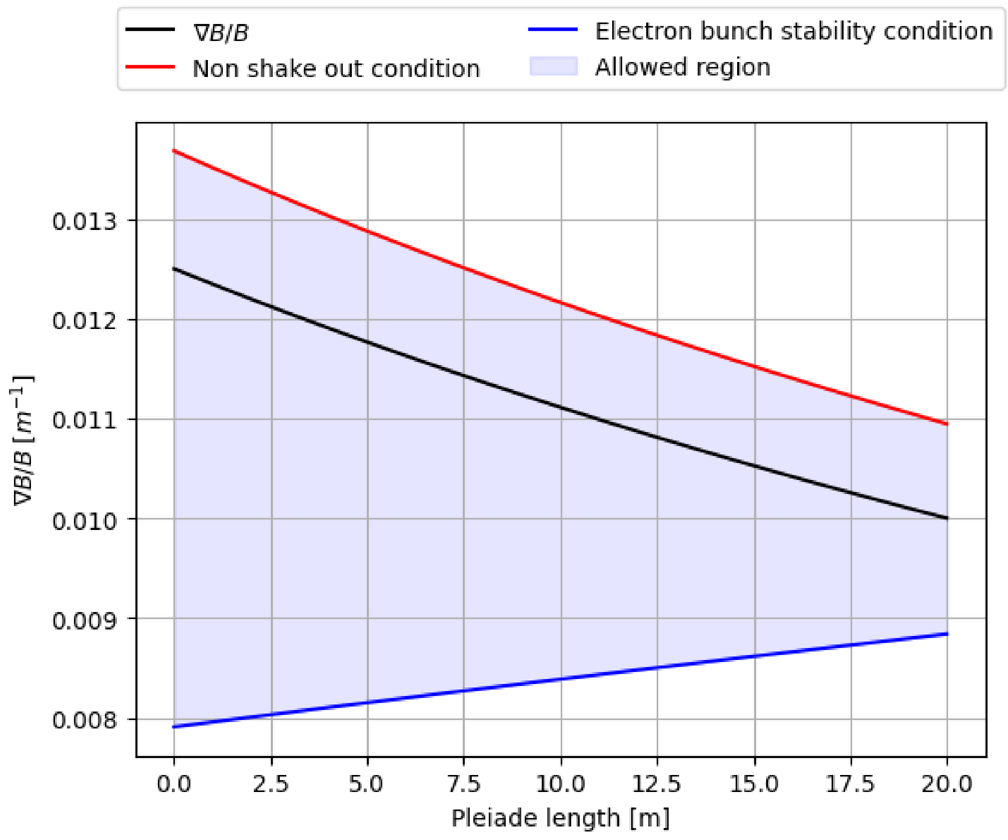
- **Electron bunch stability**: Coulomb repulsion is weaker than ∇B force.

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

- Minimum γ for stable acceleration. $\gamma_{e,com} > \gamma_{e,lim} = \left(\frac{m_a A}{m_e Z}\right)^{\frac{1}{3}}$

➢ Error in original paper: underestimation by a factor of 7.

- Limitations on magnetic field for accelerator stability.



Problems in state of the art

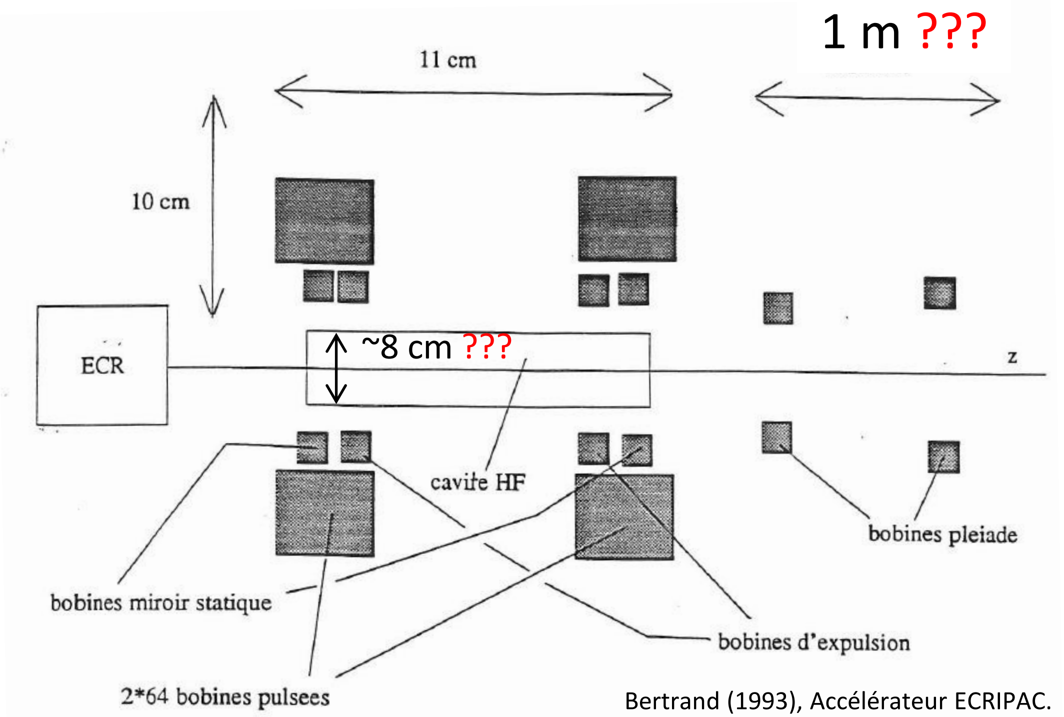
ECRIPAC numerical simulations

- Bertrand (1992, EPAC 92 - Third European Particle Accelerator Conference).
- Umnov et al. (2004), Kube et al. (2005), Kube thesis (2007).
- ➢ Only 2 studies, quite **old** and **not self-consistent.**

Need for a new and accurate self-consistent simulation of ECRIPAC!

Unknown parameters

➢ Timescales??? External fields intensity??? Plasma parameters???



Bertrand (1993), Accélérateur ECRIPAC. aspects théoriques et numériques

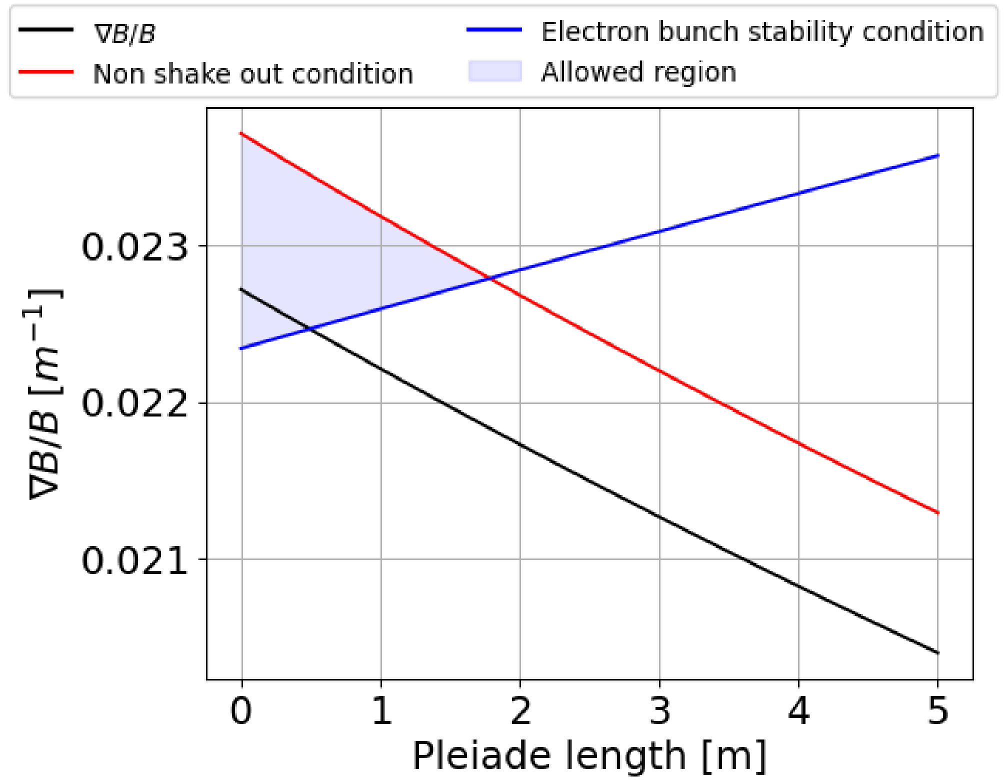
Need theoretical investigation to set the parameters of the accelerator!

Main limitations: Existence of stability for ion acceleration

Need $\gamma_{e,com} >> \gamma_{lim}$ to ensure existence of stability region.

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

$\gamma_{e,com}$ is too low.

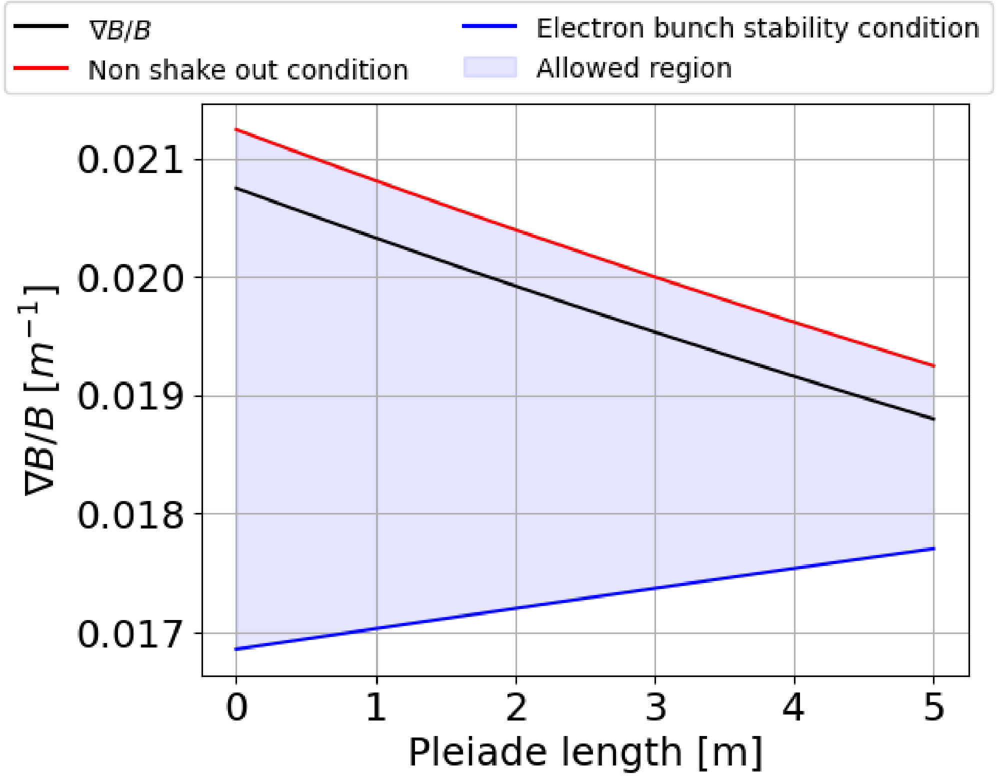


$\gamma_{e,com}$ ⇧

B_{max} ⇩

B_{fin} ⇧

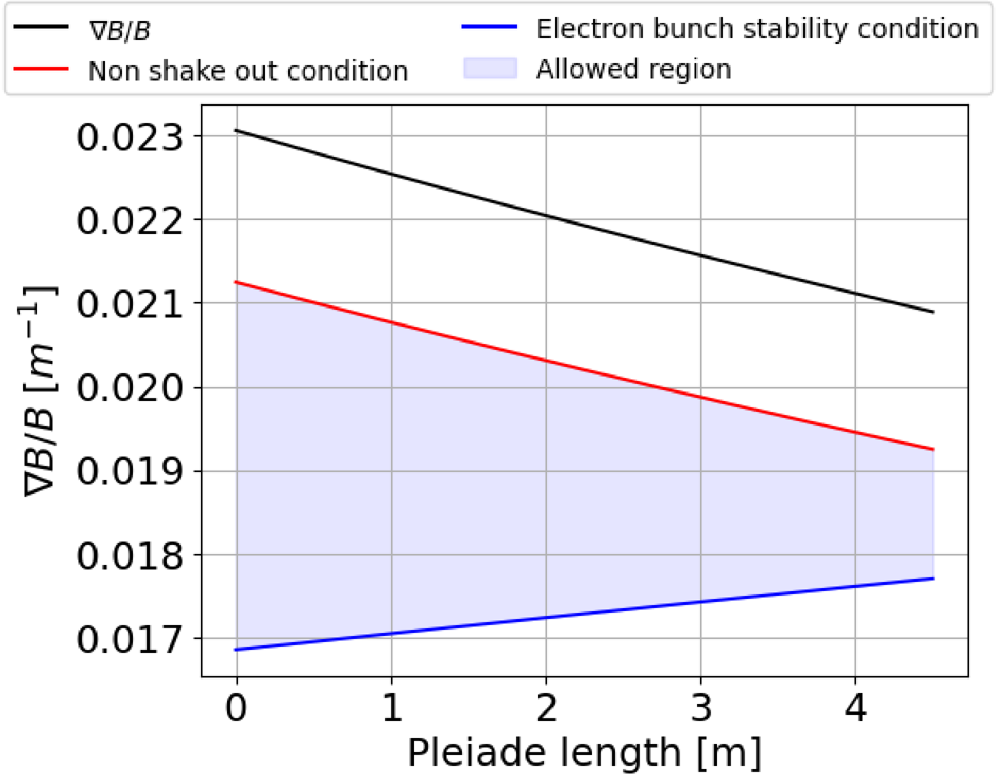
$\gamma_{e,com}$ allows stability.



Main limitations: PLEIADE section cavity length

PLEIADE section cavity length ($\boldsymbol{l_{PL}}$) must be tuned to **allow** accelerator **stability.**

l_{PL} is too short.



l_{PL} ⇧

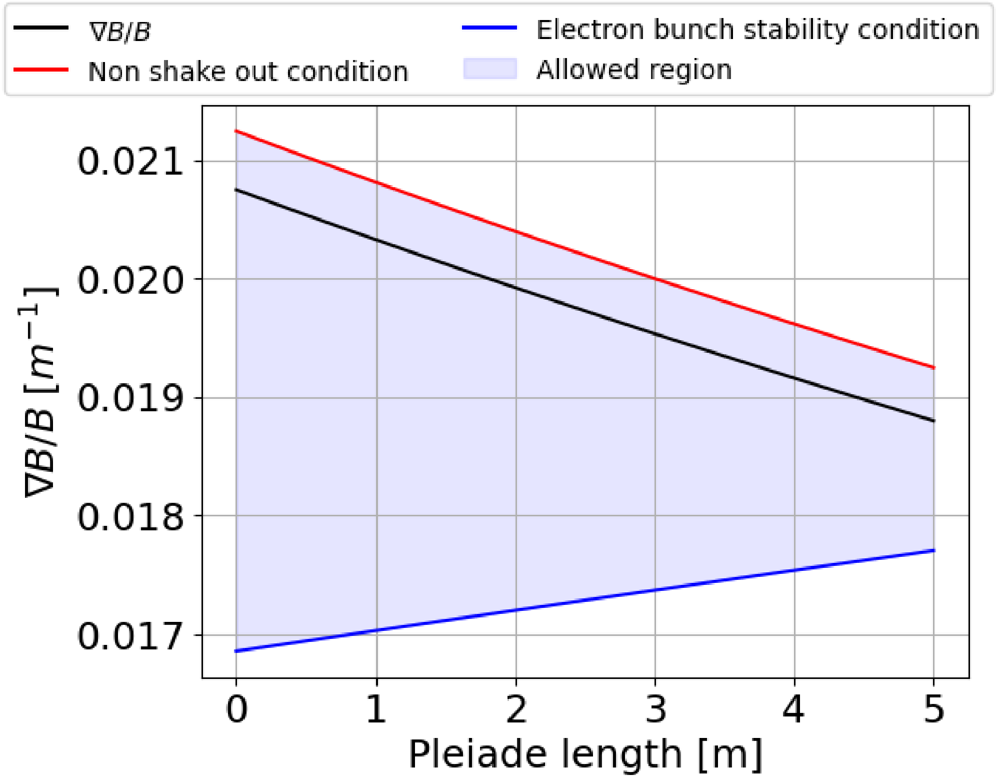
$\gamma_{e,com}$ ⇩

n_e ⇧

B_{fin} ⇧

f_{HF} ⇧

l_{PL} is correct.



ECRIPAC parameters analysis

Aim

Obtain ions of desired energy keeping a reasonable accelerator length.

➢ Study through **parameter space analysis $\gamma_{e,com}$ vs B_{fin}.**

* Nominal values

Plasma parameters

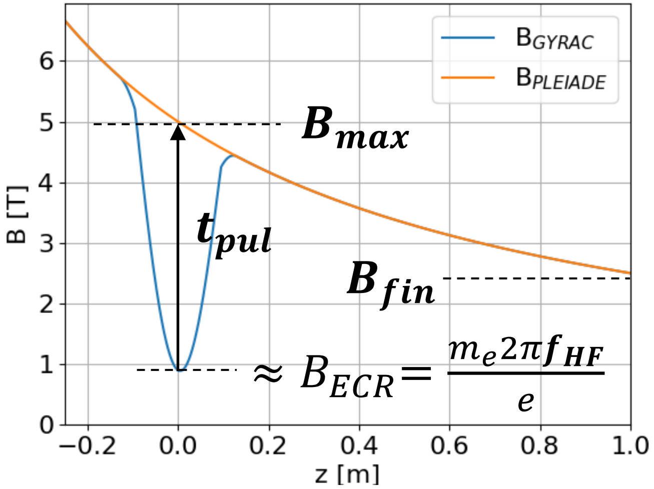
- **A/Z** ratio of accelerated ions (2).
- Electron plasma density n_e (10% n_c).
- Initial plasma disk radius $r_{disk,0}$ (2 cm).

Requirements

- $\gamma_{e,com}$: Lowest value ensuring stability existence.
- l_{PL}: Lowest value allowing stability.

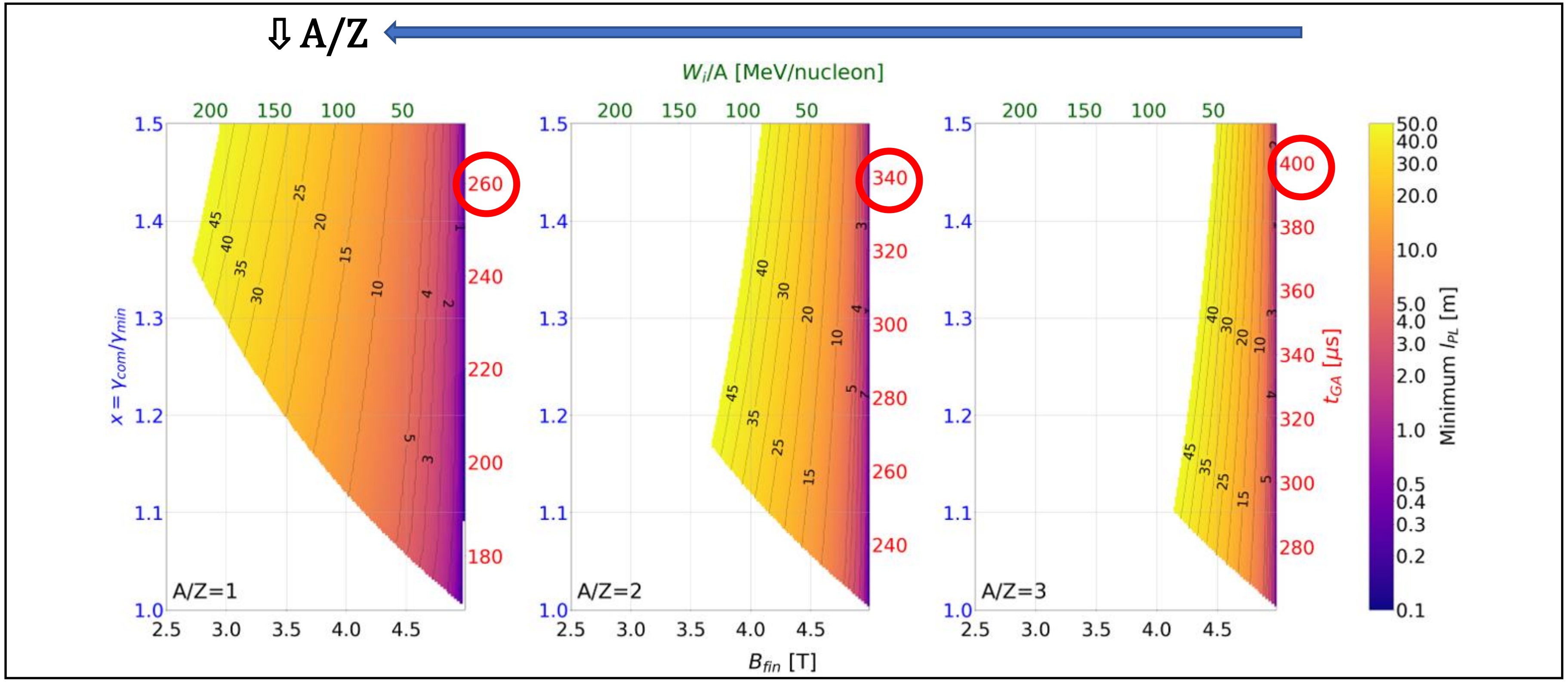
External field parameters

- t_{pul} (1 ms).
- B_{max} (5 T).
- f_{HF} (2.45 GHz).
- B_{fin}.



➢ Optimized B_{PL} profile: $B(z) = \frac{1}{B_{max}^{-1} - k \cdot z}$

Example of parameter space: A/Q



⇩ A/Z:

- ⇧ **Stability** region surface (stability at ⇩ B_{fin} and ⇧ W_i/A).
- ⇩ $\boldsymbol{l_{PL}}$ for stability.
- ⇩ $\boldsymbol{t_{GA}}$ (⇩ γ_{lim} required to accelerate ions).

ECRIPAC parameters influence

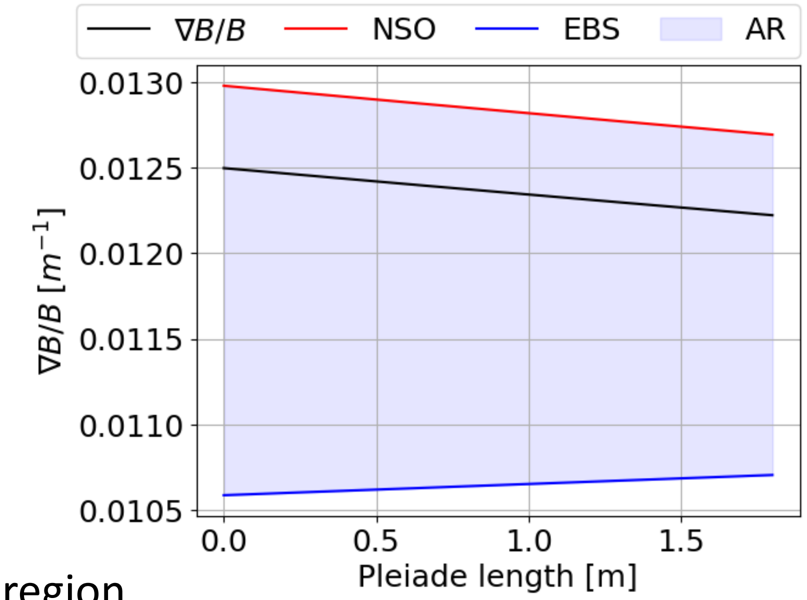
✓ Detailed investigation of ECRIPAC parameter successfully completed.
➢ More details in backup slide due to time constraints.

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

- $\boldsymbol{B_{max}}$ has beneficial effect but introduces technological complications.
- $\boldsymbol{f_{HF}}$ must be tuned according to applications.

Prototype design for a He^{2+} compact accelerator @ $\boldsymbol{f_{HF} = 2.45\ GHz}$:

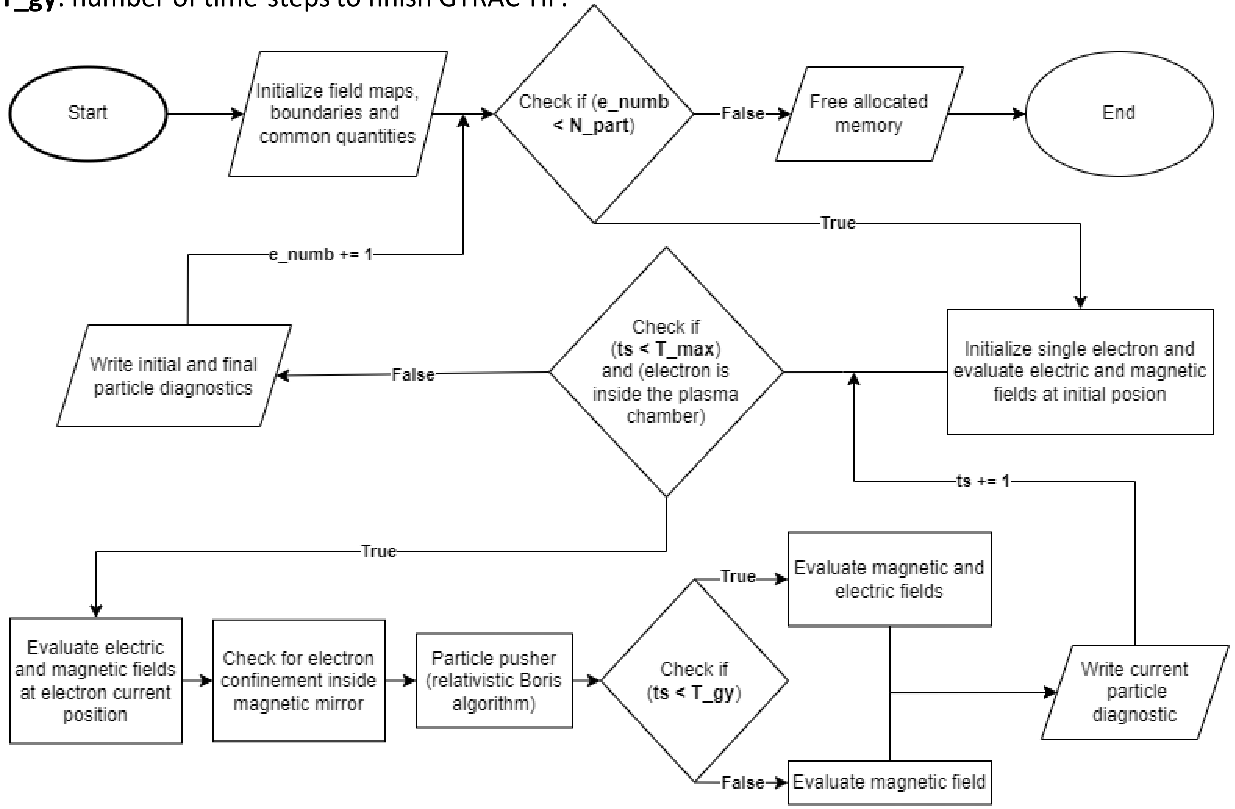
- $\mathbf{n_e}$ = 15% $\mathrm{n_c}$ = $1.12 \cdot 10^{10}\ \mathrm{cm^{-3}}$
- $\mathrm{B_{fin}}$ = 4.89 T
- t_{GA} = 240.8 μs
- $\mathbf{l_{PL}}$ = 1.8 m
- $\mathrm{W_{e,com}}$ = 7.9 MeV
- $\Delta \mathrm{r_{PL}}$ = 0.02 cm
- $\mathbf{W_i/A}$ = 9.53 MeV/nucl.



NSO: Non shake out condition. - EBS: Electron bunch stability. - AR: Allowed region.

3D Monte Carlo Particle-Tracking code

- **N_part**: total number of electrons simulated.
- **T_max**: maximum allowed number of time-steps.
- **T_gy**: number of time-steps to finish GYRAC-HF.
- **ts:** current time-step.
- **e_numb:** current number of electrons propagated.



Validated with literature on GYRAC accelerators (**simulations + experiments**) (backup slides).

- **Single-electron approximation** (no collisions)

- **Common variables**:

➢ **Number of e^-**: *100000*.

➢ **Chamber radius**: *5 cm*.

➢ **Static field**: $B_0 \approx 0.0875\ T,\ B_{max} = 5\ T,$ $\mathrm{B_{fin,PL}} = 4.89\ \mathrm{T}$

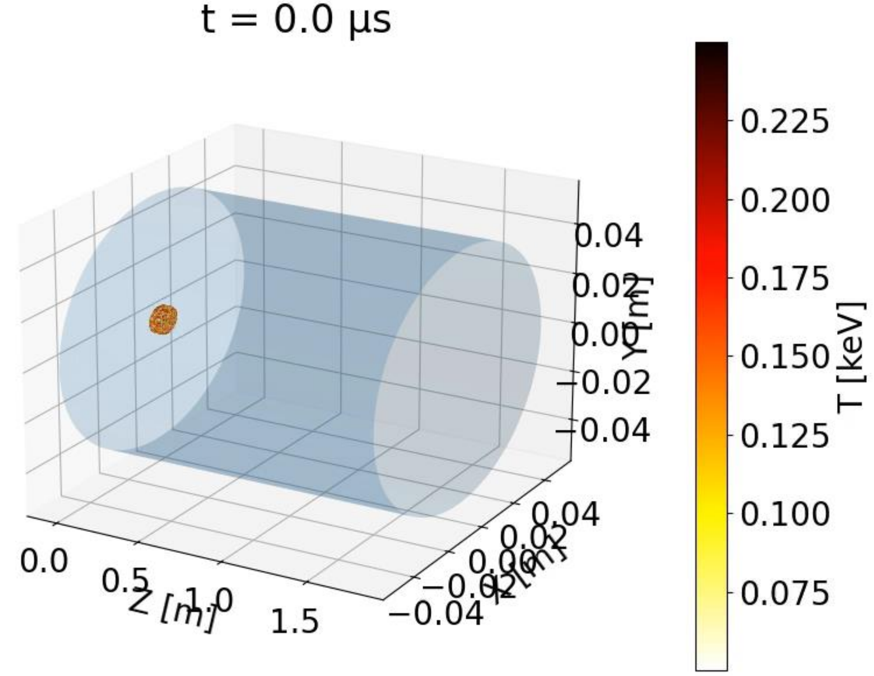
➢ **IC**: electrons inside a cylinder, random energy in given range, electrons must survive at least 10% of t_{SGA}.

- **External fields**:

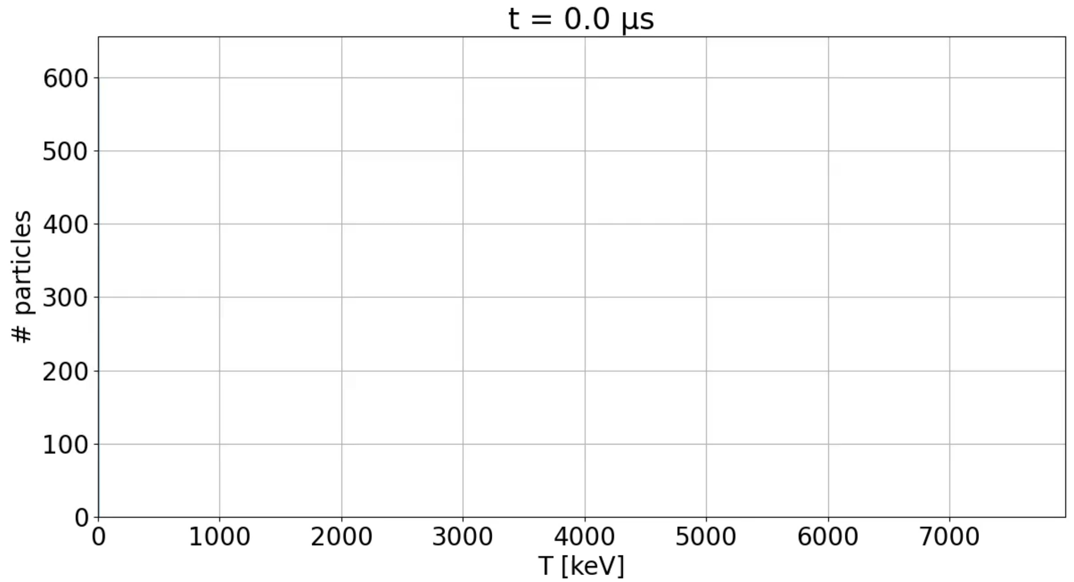
➢ **Static B, pulsed B, induced E:** 2D axisymmetric field map (Poisson Superfish, COMSOL).

➢ **Microwave:** analytical *TE111* mode @ *2.45 GHz*.

Monte Carlo simulations – Full electron population



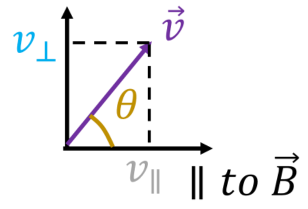
- **GA phase**: rotating electron bunch with increasing energy.
- **Compression phase**: electron ring that gradually compresses and increases its energy.
- **PLEIADE phase**: electron cloud descending magnetic field gradient converting ⊥ into ∥ energy.



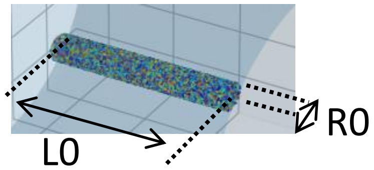
- **Electrons trapped in GA (≈70%):** bunch with approximately gaussian shape in energy continuously increasing its energy.
- **Electrons not trapped in GA (≈30%):** mostly located in the centre of the cavity, energy slowly increasing during compression phase.

Monte Carlo simulations – Parametric study

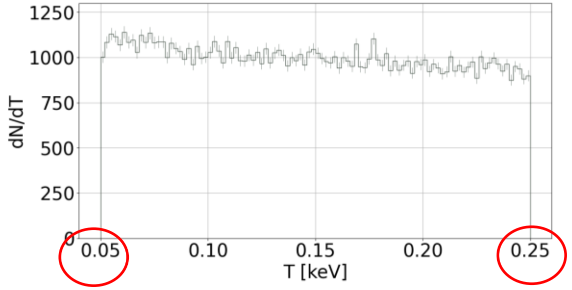
Initial conditions (IC)



- Initial velocity pitch angle

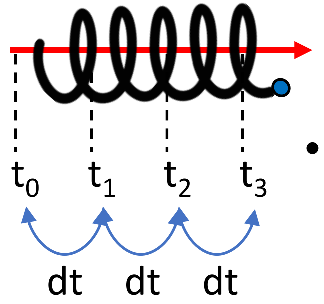


- Initial cylinder radius and length



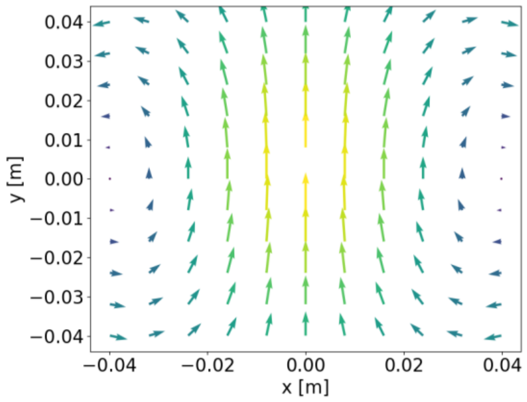
- IC energy range limits

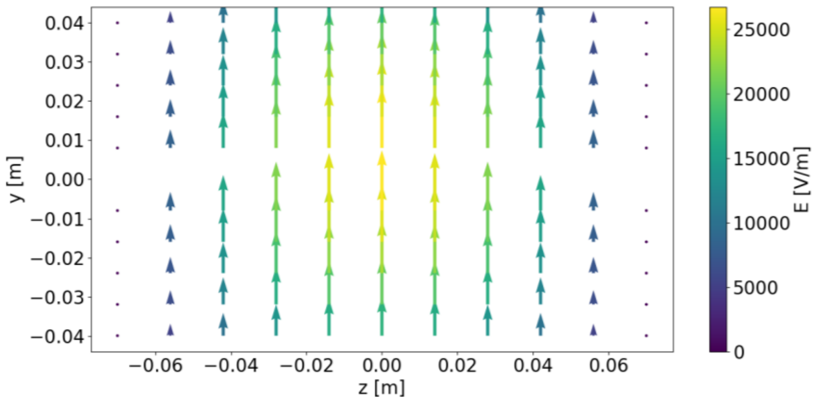
Simulation convergence



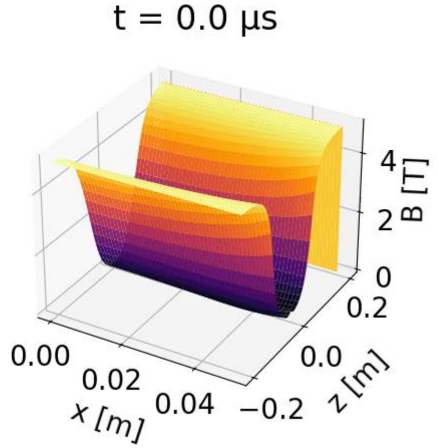
- Time-step

External fields

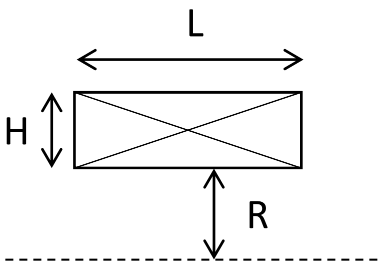




- Microwave intensity and cavity mode



- Magnetic field growth rate



- Pulsed coil length

Parametric study – Microwave intensity

Microwave intensity

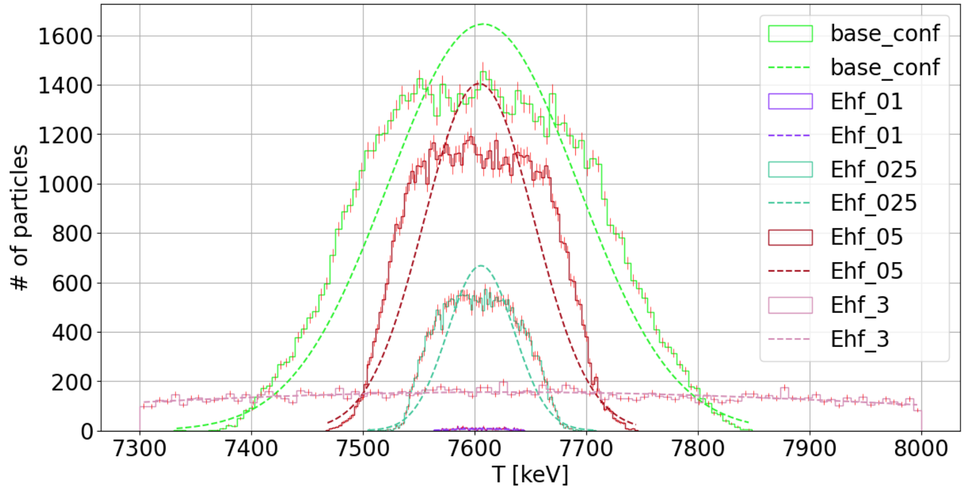
Ehf_01: $E_{hf} = 0.1\ kV/cm$

Ehf_025: $E_{hf} = 0.25\ kV/cm$

Ehf_05: $E_{hf} = 0.5\ kV/cm$

base: $E_{hf} = 1\ kV/cm$

Ehf_3: $E_{hf} = 3\ kV/cm$



Simul.	% conf.	% trap. SGA	T0 [keV]	σ [keV]
Ehf_01	83.55%	0.68%	7606	25
Ehf_025	79.13%	27.46%	7606	30
Ehf_05	84.00%	68.45%	7604	49
base	76.89%	71.81%	7608	85
Ehf_3	23.44%	19.81%	7625	416

⇧ $\boldsymbol{E_{HF}}$ leads to **lower confinement**, **better trapping** and **larger energy spread**.

- If E_{HF} is too high (Ehf_3), drastic reduction in confinement also lowers trapping.
- **Same findings** as Kube **PIC simulation**.

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**: highlighted accelerator limitations and influence of ECRIPAC parameters. Reversed pulsed field coil feasible with current technology.
  - ✓ **Monte Carlo simulation**: properly simulates electron behaviour inside ECRIPAC. Allowed to study effect of several parameters on electron behaviour.
    - ➢ Fixed geometry and external fields for particle-in-cell (PIC) simulation.

Paper ready to be submitted

Results will be presented at conferences this year

Perspectives

- **Choose/Write/Adapt PIC code** and its settings for full-scale simulation.
  - ➢ **Considerations for PIC code**: 3D is required, EM can be advantageous, allow use of external fields.
  - ➢ **Best candidate** at the moment is **SMILEI** (open source EM 3D PIC).

Thanks for your attention!

LPSC GRENOBLE | MODANE

UGA Université Grenoble Alpes

Questions?

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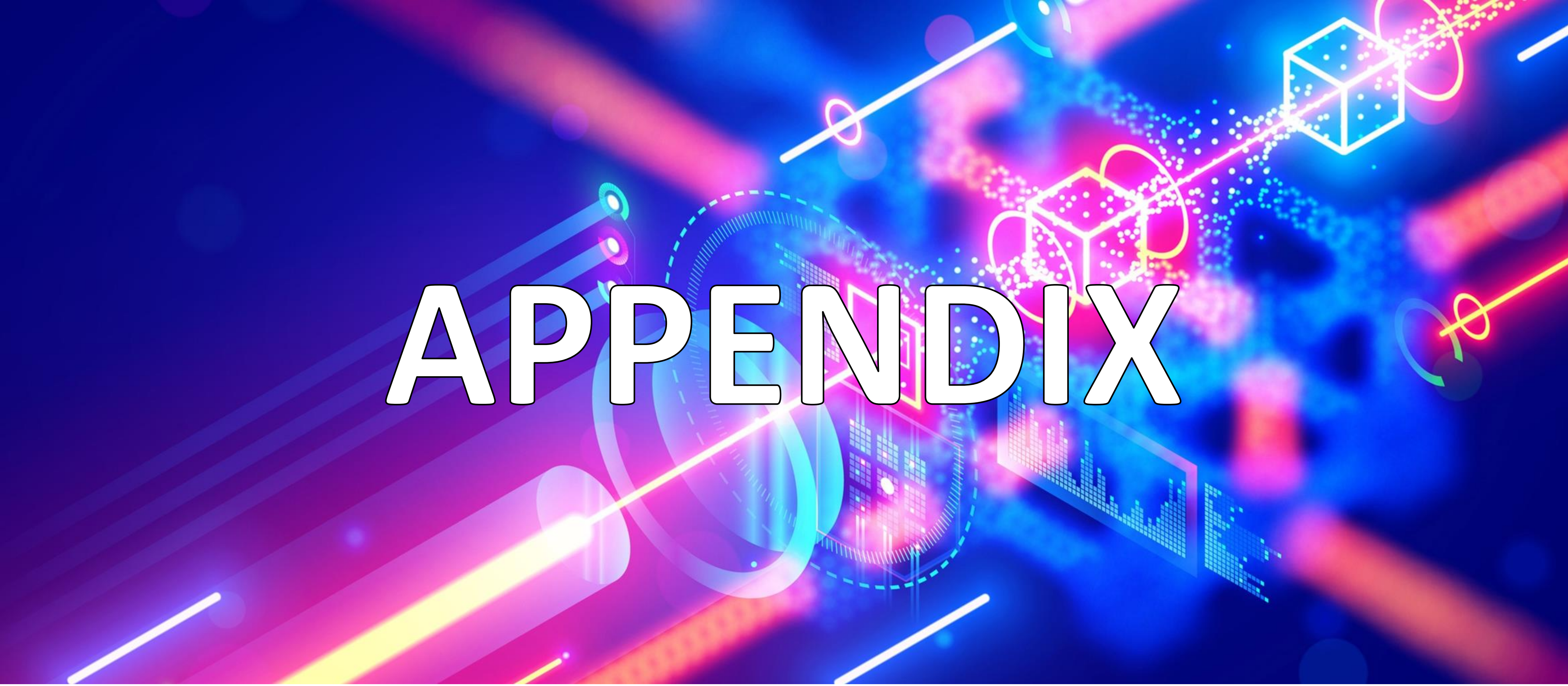
APPENDIX



GA phase: limitations

Previous results obtained for single electron approximation.

- **Pure electron population**: collective and external fields sufficiently low.
- **Plasma**: behaviour is **NOT** clear, need PIC simulation

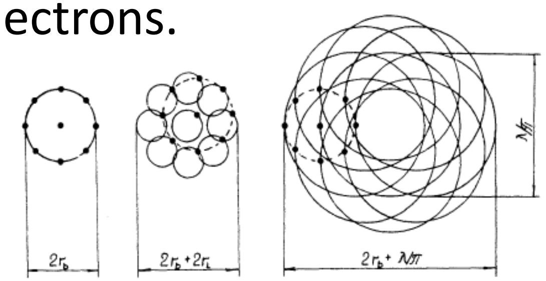
$$g_0 = \frac{eE}{m_e c \omega_{HF}} = \frac{E}{cB_{res}}$$

Main limitations

- Acceleration stability $\propto B(t)/B0$ and magnetic mirror trap.
- Synchrotron radiation limits γ_{max}.
- Collective effects could limit number of electron accelerated.

- **Collective fields**: limitations on numbers of electrons.

$$\begin{cases} N < N_{max} = 2.230 \cdot 10^{12} \cdot \lambda g_0 \quad when\ g_0 < 1 \\ N < N_{max} = 5.648 \cdot 10^{12} \cdot \lambda \quad when\ g_0 > 1 \end{cases}$$

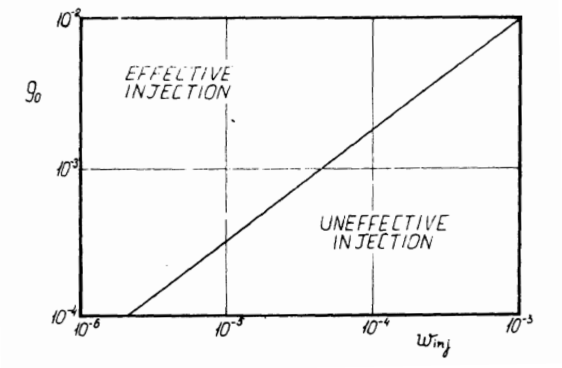


Golovanivsky (1982), IEEE Transactions on Plasma Science

- **Mirror field**: limitations on mirror ratio.

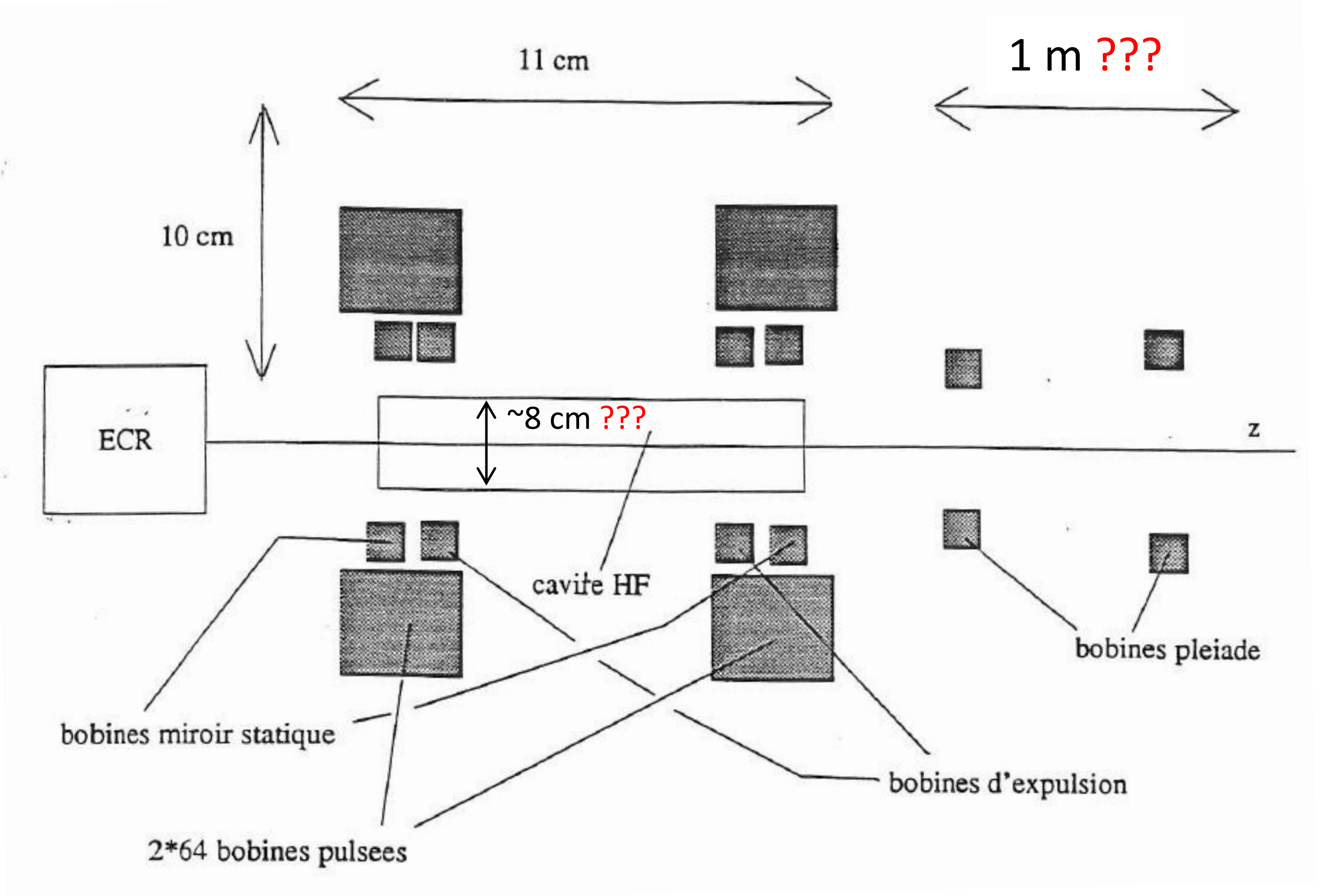
$$1 + 2.533 \cdot \frac{w_{inj,e}^2}{g_0^2} \leq R < 1 + 0.462 \cdot g_0^{\frac{2}{3}}$$

$$\Rightarrow g_{0,crit} = 1.895 \cdot w_{inj,e}^{\frac{3}{4}}$$



Golovanivsky (1982), IEEE Transactions on Plasma Science

ECRIPAC: Approximative working parameters



Bertrand (1993), Accélérateur ECRIPAC. aspects théoriques et numériques

Timescales

- GA phase (RF ON) ≈ 10-100 µs ???
- Compression phase (RF OFF) ≈ 1 ms
- PLEIADE phase (RF OFF) ≈ 1-10 ns

Magnetic fields

- NbTi magnets + pulsed Cu coil
- Peak field ≈ 5 T ???
- Final field ≈ 2.5 T ???

µwave injector

- Frequency = 2.45 GHz ???
- Power ≈ 30 kW
- Mode = TE011 ???

Plasma parameters

- Electron density ≈ 10^{10} cm^{-3} ???

Existing ECRIPAC numerical studies

Bertrand (1992, EPAC 92 - Third European Particle Accelerator Conference)

- Time dependent **Vlasov equations solver in 6D phase space** (with and without gyrokinetic approach).
- **Not self-consistent simulation**: Each phase simulated individually with IC obtained from theory.

Umnov et al. (2004), **Kube et al.** (2005), **Kube thesis** (2007)

- **1D electrostatic (ES) PIC** simulation and **3D electromagnetic (EM) PIC** simulation of a proton plasma.
- Most valuable source for information/validation, but still **incomplete**:
  - **Dubious PIC settings**: coarse spatial and temporal grid (CFL condition not respected).
  - GYRAC-HF and GYRAC-compression do **not use ECRIPAC settings**.
  - PLEIADE is **not self-consistent**: theoretical IC and analytical fields.

Need for a new and accurate self-consistent simulation of ECRIPAC!

- Study in successive steps: Theoretical study. → MC simulation of electrons. → Full PIC simulation.

Kube thesis - Overview

Context

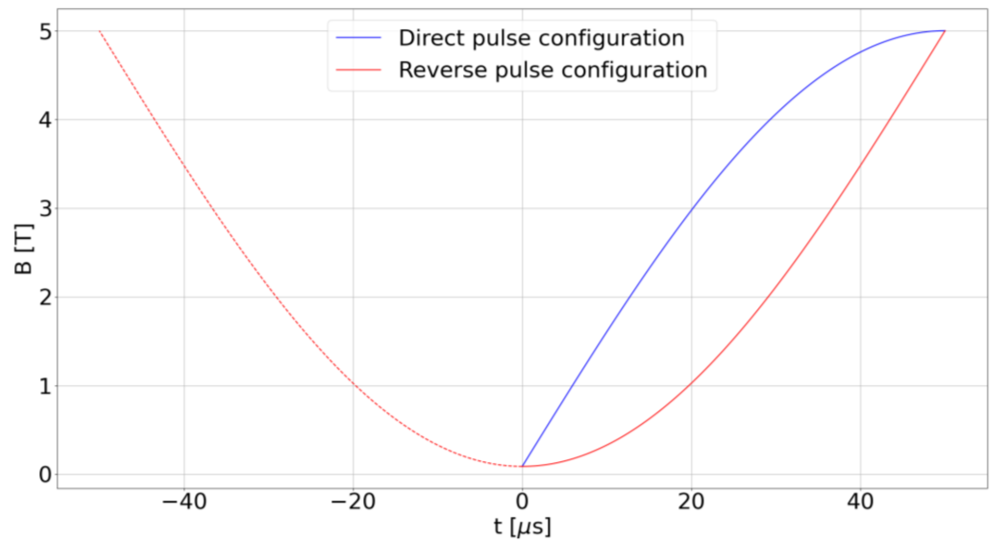
- Work developed between **2005** and **2007** in Russia.
- Results presented only in Russian conferences and Russian journals.
- Simulations on **personal computer**.
  - Best CPU (2005-2007): dual/quad core, 2.5/3 GHz.
- Unknown programming language.

Thesis structure

1. Synchrotron Gyromagnetic Autoresonance (**SGA**) **simulations**.
2. **Plasma compression.**
3. Collective **acceleration of protons (1D ES PIC).**
4. Collective **acceleration of protons (3D EM PIC).**

Interesting notions from literature (experimental result)

- ⇧ $\frac{dB}{dt}$ ⇨ better trapping in magnetic mirror.
- Direct pulse configuration leads to higher capture into SGA compared with reverse pulse configuration.



Kube thesis - SGA

3D electrostatic PIC code

- **Populations**: 10^5 macroparticles per species (*e*⁻ relativistic, *i*¹⁺ non-relativistic).
- **Spatial grid**: $dx = 3.12\ mm\ or\ 1.56\ mm$ ($\lambda_{D,max} \approx 0.1\ mm$).
- **Temporal grid**: $dt = \frac{T_{HF}}{250}$ *(1.63 ps @ 2.45 GHz).*
- **External fields**: magnetic fields with field maps (?), microwave with TE111 analytical formulation.
- **IC**: homogeneous plasma inside cylinder (dynamically injected or statically generated).

Results

- **Effect of IC**: No significant effect → Static one for lower computational cost.
- **Effect of cylinder radius**: ⇩ $\frac{r_0}{r_{Lar}}$ (< 1) → ⇧ Ion losses.
- **Effect of plasma**: pure electron beam has much higher losses than full plasma.
- **Effect of HF wave**: ⇧ E_{HF} → More e^- trapped in SGA, broader energy spectrum.
- **Effect of mirror ratio**: ⇧ R → ⇧ n_e (shorter e^- bounces), more e^- trapped in magnetic mirror (?).
- **Magnetic field increase rate (constant propagation time):** ⇧ $\frac{dB}{dt}$ → ⇧ W_e (⇧ B_{final}), more e^- trapped in magnetic mirror and in SGA, ⇧ W_i, after optimal value ⇧ ion losses.

(?): settings not specified, hence supposed as most probable approach.

Kube thesis – SGA simulations - Settings

3D electrostatic (ES) PIC

❖ **Populations:**

Electrons e^-

- Relativistic.
- $N_e = 10^5\ macroparticles.$

Ions i^+

- H or Ar plasma.
- Unmagnetized and non-relativistic.
- Singly-charged.
- $N_i = 10^5\ macroparticles.$

❖ **PIC settings:**

- Particles at wall are lost.

Spatial grid (10 x 10 x 10 cm)

- *32 x 32 x 32* $(\boldsymbol{dx = 3.12\ mm})$.
- *64 x 64 x 64* $(\boldsymbol{dx = 1.56\ mm})$.

Temporal grid

- Timestep : $dt = \frac{T_{HF}}{250}$ *(**1.63 ps** @ 2.45 GHz).*

❖ **External fields and other settings**

- **Magnetic fields**: field maps (?).
  - Pulsed coil increases linearly with time.
- **Microwave**: TE111 analytical formulation (Bessel @ 1st order).
- All **other parameters** as experimental design.

Initial conditions: homogeneous plasma inside cylinder $(\boldsymbol{r = r_0})$

1st condition: dynamic

- Cylinder axially injected at low speed.
- Injection time according to $\frac{B_{max}(0)}{B_0} = 1 + 1.89 g_0^{\frac{2}{3}}$.

2nd condition: static

- Cylinder @ $t = 0$.
- **Monoenergetic** electrons with **random velocity** direction.
- $W_{i^+} = 0$.

(?): settings not specified, hence supposed as most probable approach.

Input settings

- $W_e = 1 - 10\ eV$
- $n_e = 5 \cdot 10^9 - 5 \cdot 10^{10}\ cm^{-3}$
- $r_0 = 0.4 - 3\ cm$
- $E_{HF} = 0.5 - 3\ \frac{kV}{cm}$
- *Mirror ratio:* $R = 1.04\ and\ 1.1$

Kube thesis – SGA simulations - Results

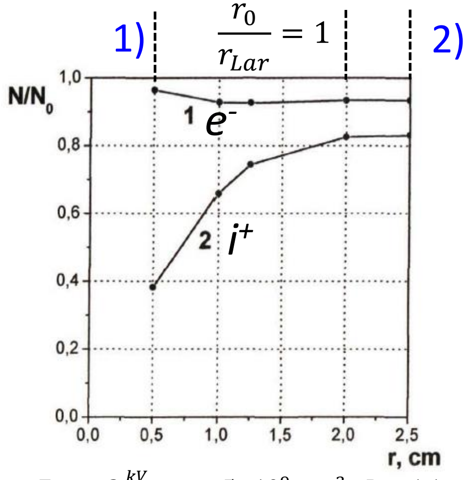
Effects of initial condition

- **Dynamic vs static IC → No difference**! Use static condition to reduce computational cost.

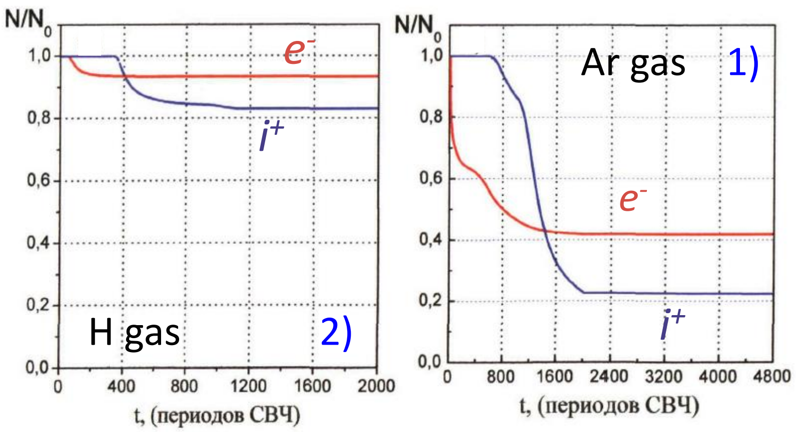
- **Effect of cylinder radius r_0** (1) $r_0 = 0.5\ cm$, 2) $r_0 = 2.5cm$)

➢ ⇩ $\frac{r_0}{r_{Lar}}$ (< 1) → Complete charge separation → ⇧ $\frac{E_{pl}}{E_{HF}}$ (> 1) → ⇧ **Ion losses.**

➢ ⇧ $\frac{r_0}{r_{Lar}}$ (> 1) → Weak charge separation →⇩ $\frac{E_{pl}}{E_{HF}}$ (< 1) →⇩ **Ion losses.**



$E_{HF} = 2\frac{kV}{cm}$, $n_e = 5 \cdot 10^9 cm^{-3}$, $R = 1.1$



$E_{HF} = 2\frac{kV}{cm}$, $n_e = 5 \cdot 10^9 cm^{-3}$, $R = 1.1$

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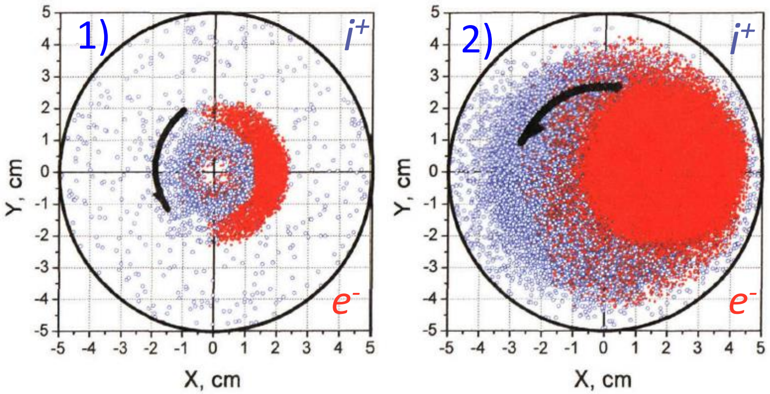
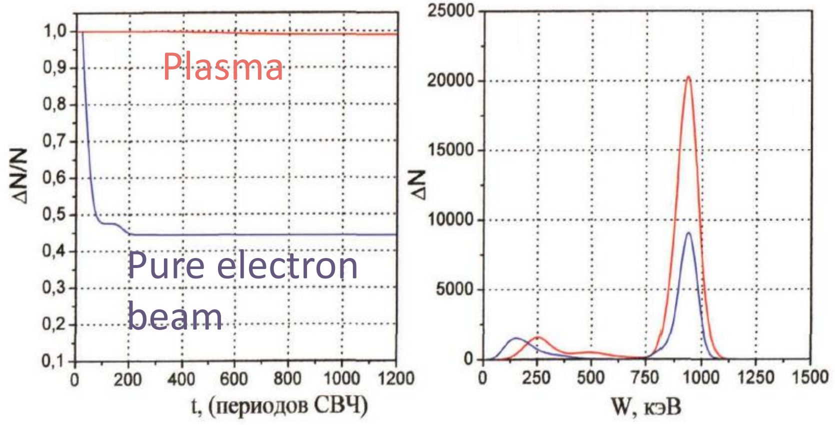




$E_{HF} = 3\frac{kV}{cm}$, $n_e = 5 \cdot 10^8 cm^{-3}$, $R = 1.1$, $r_0 = 1\ cm$

➢ **Ar** gas **losses stabilize much later** than H gas losses.

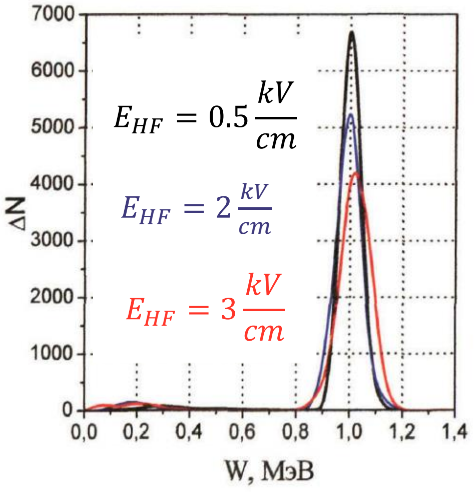
➢ **Pure electron beam** suffer much **more losses** than plasma.

Kube thesis – SGA simulations - Results

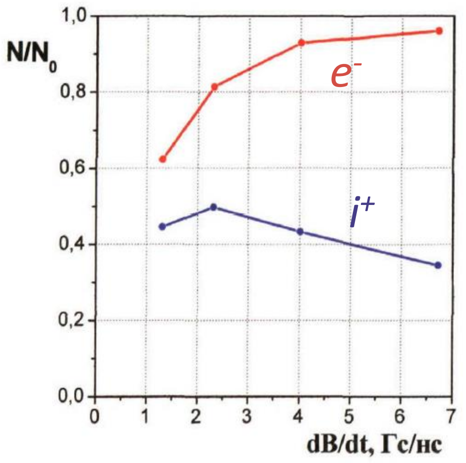
Effects of external fields

- **HF wave intensity**: ⇧ E_{HF} → **More** e^- **trapped** in SGA, **broader** energy spectrum.
- **Mirror ratio**: ⇧ R → ⇧ $\boldsymbol{n_e}$ (shorter e^- bounces), **more** e^- **trapped** in magnetic mirror (?).
- **Magnetic field rate of increase (constant propagation time):**
  - ⇧ $\frac{dB}{dt}$ → ⇧ $\boldsymbol{W_e}$ (⇧ B_{final}), **more** e^- **trapped** in magnetic mirror ($\propto$ *also on* n_0).
    - ❖ If $\frac{E_{pl}}{E_{HF}} \approx 1$: more e^- trapped in SGA.
  - ⇧ $\frac{dB}{dt}$ → ⇧ $\boldsymbol{W_i}$ (accelerated by E_{pl} due to ⇧ r_{Lar}), after optimal value ⇧ **ion losses**.

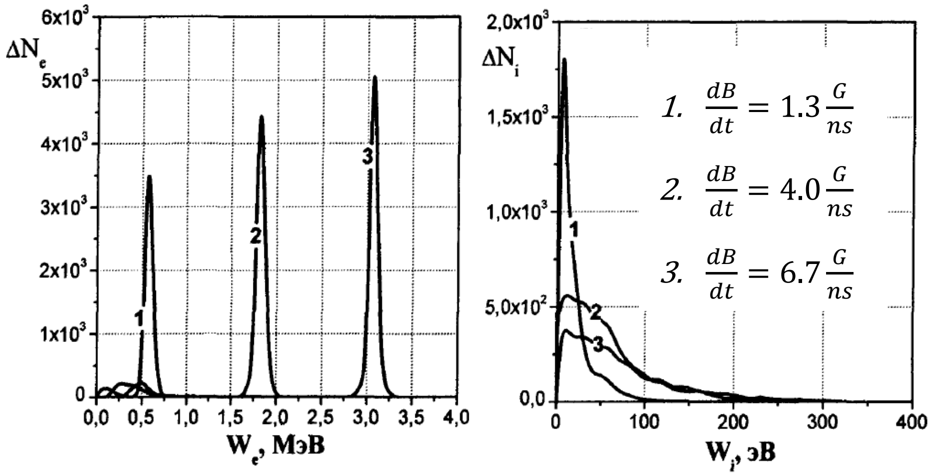
???



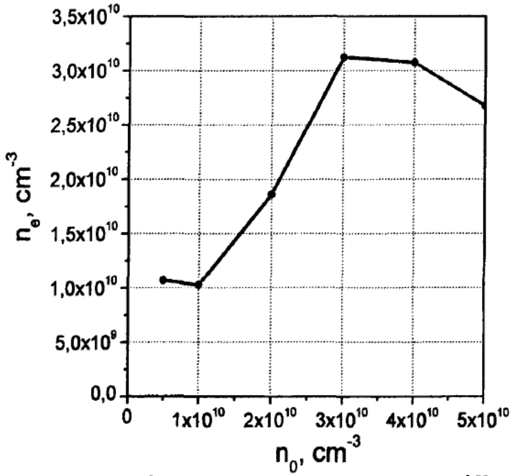
$n_e = 5 \cdot 10^9 cm^{-3}$, $r_0 = 0.5\ cm$, $R = 1.1$



$n_e = 1 \cdot 10^{10} cm^{-3}$, $r_0 = 0.5\ cm$, $E_{HF} = 2\frac{kV}{cm}$



$n_e = 1 \cdot 10^{10} cm^{-3}$, $r_0 = 0.5\ cm$, $E_{HF} = 2\frac{kV}{cm}$



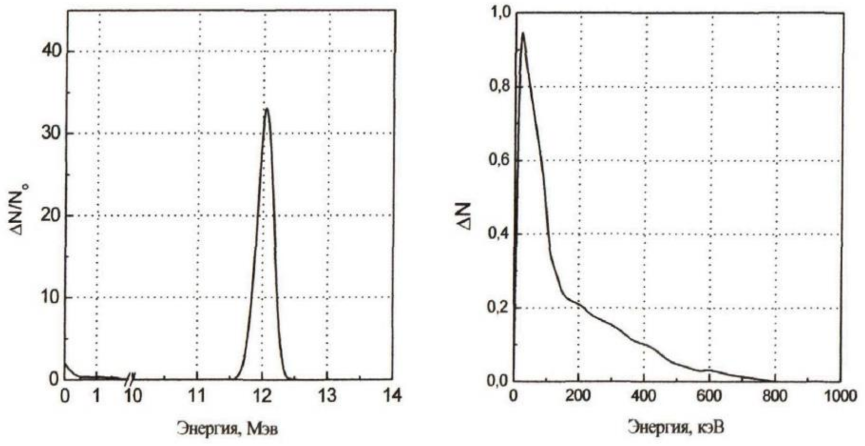
$\frac{dB}{dt} = 4\frac{G}{ns}$, $r_0 = 0.5\ cm$, $E_{HF} = 2\frac{kV}{cm}$

Kube thesis – SGA simulations - Results

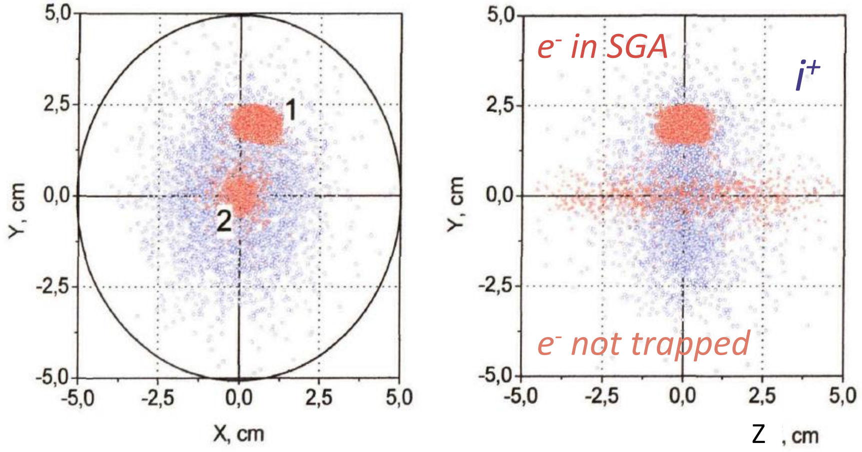
Further considerations

- Possible to **control** bunch **parameters** in wide ranges.
- **After bunch formation** ($W > 1\ MeV$), its **parameters change slowly** with ⇧ W_e.
  - n_e slowly increases due to axial compression ($V_{bunch} \approx 2\ cm^3$).
- Plasma **self electric field maximum** right **after charge separation**, reach asymptotic value of $\approx 2 \cdot E_{HF}$.

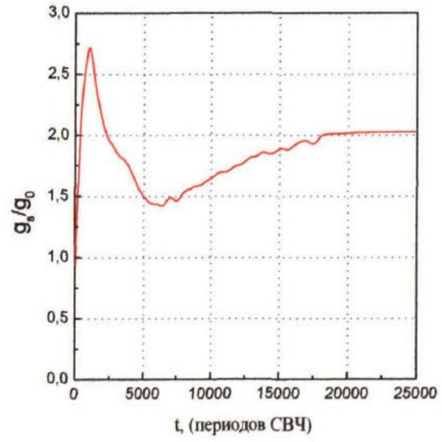
$n_e = 1 \cdot 10^{10} cm^{-3}, r_0 = 0.4\ cm, \mathrm{E_{HF}} = 3\,\frac{\mathrm{kV}}{\mathrm{cm}}$



$n_e = 1 \cdot 10^{10} cm^{-3}, r_0 = 0.4\ cm, \mathrm{E_{HF}} = 3\,\frac{\mathrm{kV}}{\mathrm{cm}}$



$n_e = 1 \cdot 10^{10} cm^{-3}, r_0 = 0.4\ cm, \mathrm{E_{HF}} = 3\,\frac{\mathrm{kV}}{\mathrm{cm}}$ (???)



Bunch extraction (Not really of interest for the project)

- **Radial extraction** (plasma decompression): ⇧ $\left|\frac{dB}{dt}\right|$ → ⇩ $t_{extraction}$, ⇧ $P_{deposited}$.
- **Axial extraction** (as PLEIADE): more effective than radial (⇩ $t_{interaction} \approx ns$, ⇧ $N_{particles}$), multiple (*n*) bunches at same time with TE_{11n} cavity mode.

Kube thesis – Plasma compression

3D electromagnetic PIC code

- **Populations**: 10^5 macroparticles per species (*e*$^-$ relativistic, *i*$^{1+}$ relativistic).
- **Spatial grid**: $dx = 1.56\ mm\ or\ 0.78\ mm$ ($\lambda_{D,max} \approx 0.1\ mm$).
- **Temporal grid**: $dt = \frac{T_{HF}}{250}$ *(1.63 ps @ 2.45 GHz)* (?).
- **External fields**: magnetic fields with field maps (?), microwave with TE111 analytical formulation (?).
- **IC**: new simulations or results from previous phase.

Results

- **Effect of SGA time (fixed pulsed rise time)**: ⇧ t_{SGA} (⇩ t_{comp}) → ⇧ W_e, ⇩ plasma compression.
- **No electron losses during compression**, for ⇩ r_0 no ions losses.
- **Magnetic field increase rate:** ∃ upper critical upper value for dB/dt (∝ IC, *20 G/ns* in thesis) over which plasma disintegrate and SGA/compression don't take place.

(?): settings not specified, hence supposed equal to previous step or most probable approach.

Kube thesis – Plasma compression - Settings

3D electromagnetic (EM) PIC

❖ **Populations:**

Electrons e^-

- Relativistic.
- $N_e = 10^5\ macroparticles$ (?).

Ions i^+

- H or Ar plasma (?).
- Magnetized and Relativistic.
- Singly-charged (?).
- $N_i = 10^5\ macroparticles$ (?).

❖ **PIC settings:**

- Particles at wall are lost.

Spatial grid (10 x 10 x 10 cm)

- *64 x 64 x 64* $(\boldsymbol{dx = 1.56\ mm})$
- *128 x 128 x 128* $(\boldsymbol{dx = 0.78\ mm})$.

Temporal grid

- Timestep : $dt = \frac{T_{HF}}{250}$ ***(1.63 ps** @ 2.45 GHz)* (?).

❖ **External fields and other settings**

- **Magnetic fields**: field maps (?).
  - Pulsed coil increases linearly with time (?).
- **Microwave**: TE111 analytical formulation (Bessel @ 1st order).
- All **other parameters** as experimental design (?).

(?): settings not specified, hence supposed equal to previous step or most probable approach.

Initial conditions: homogeneous plasma inside cylinder $(\boldsymbol{r = r_0})$.

- Simulate once again with previous IC.
- Use directly **previous results**.

Input settings

- $W_e = 10\ eV$
- $W_i \approx 1\ eV$
- $n_e = 5 \cdot 10^9 - 5 \cdot 10^{10}\ cm^{-3}$
- $r_0 = 0.4 - 2.5\ cm$
- $E_{HF} = 2\frac{kV}{cm}$
- $t_{SGA} = 1 - 4\ \mu s$

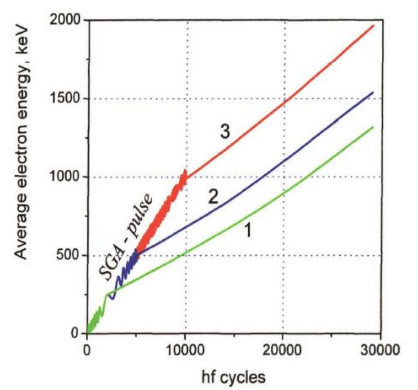
Kube thesis – Plasma compression - Results

❖ **Fixed pulsed field rise time t_{pul}.**

- ⇧ t_{SGA} (⇩ t_{comp}) → ⇧ W_e, ⇩ plasma **compression**.
- ⇩ t_{comp} (⇧ t_{SGA}) →⇩ W_e, ⇧ plasma **compression**.

Optimal SGA up to $W_e = 250 - 500\ keV$.

1. $t_{SGA} = 1\ \mu s$
2. $t_{SGA} = 2\ \mu s$
3. $t_{SGA} = 4\ \mu s$

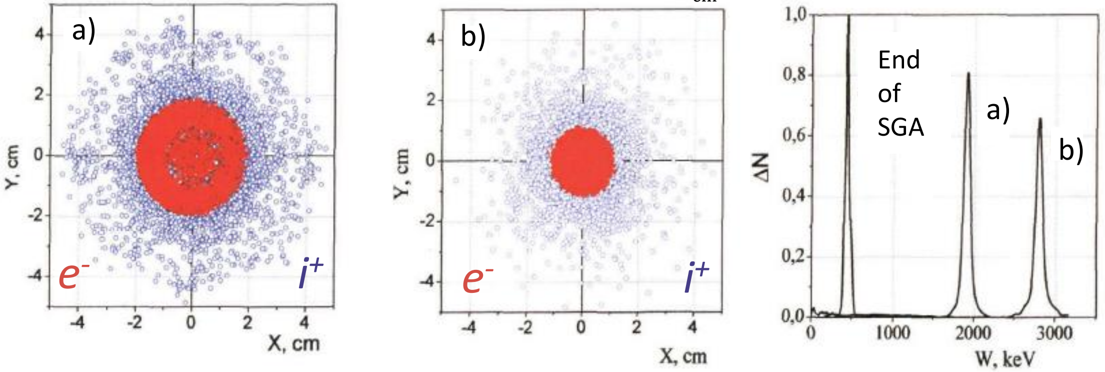


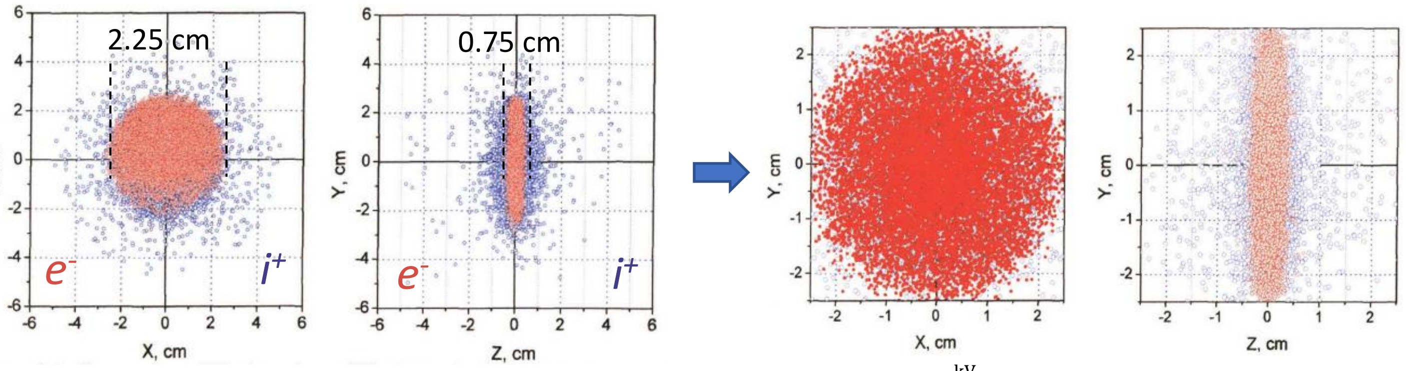
❖ **Effect of cylinder radius r_0 during compression.**

- ⇩ r_0 ($= 0.5\ cm \rightarrow n_{e,fin} = n_e \cdot 4,\ W_{e,fin} = W_e \cdot 6$)
  - Electron **bunch morphs** into a **half-ring** [*a)* $B = 8kG$] and later into a **disk** [*b)* $B = 12kG$].
  - **No** ions and electron **losses**.
  - During compression, e^- **energy spectrum broaden**.

- ⇧ r_0 ($= 1.25\ cm \rightarrow n_{e,fin} = n_e \cdot 5$)
  - **No** electron **losses**.
  - **Axial** compression **more significant** than **radial** one.
  - **Inhomogeneous** n_e and n_i → Max in the center.

$n_e = 1 \cdot 10^{10} cm^{-3}, r_0 = 0.5\ cm, E_{HF} = 2\frac{kV}{cm}$



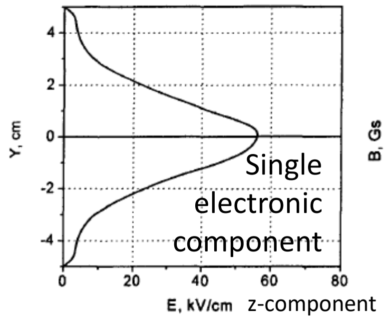


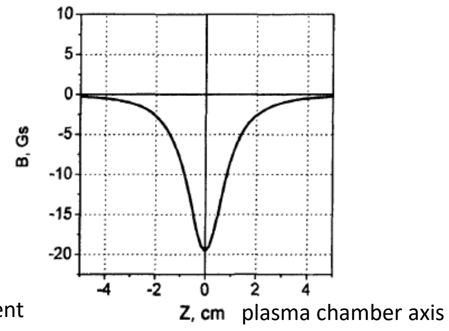
$n_e = 1 \cdot 10^{10} cm^{-3}, r_0 = 1.25\ cm, E_{HF} = 2\frac{kV}{cm}$

Kube thesis – Plasma compression - Results

- **Induced fields**

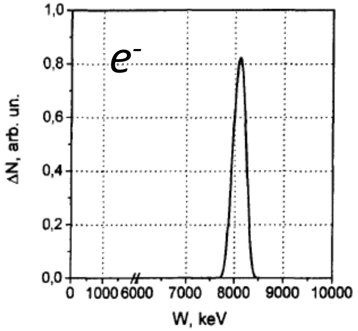
➢ Electric field E_{ind} → MAX at $r = 0$ (plasma chamber axis).
➢ Magnetic field B_{ind} → Opposite to main field generated by coils.

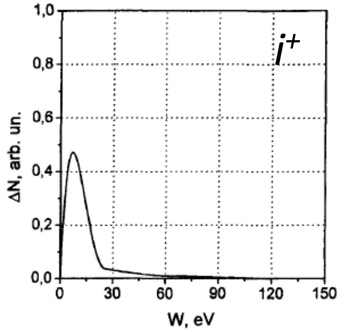




- $\frac{r_0}{r_L} > 1$ **simulation**

➢ Energy: $W_e = 5 - 8\ MeV$ (almost fully transversal), $W_i < 100\ eV$.
➢ Density: $n_e = 5 \cdot 10^{10} - 5 \cdot 10^{11}\ cm^{-3}$.
➢ Charge: e^- losses < i^+ losses → Plasma negatively charged (< *10%*).

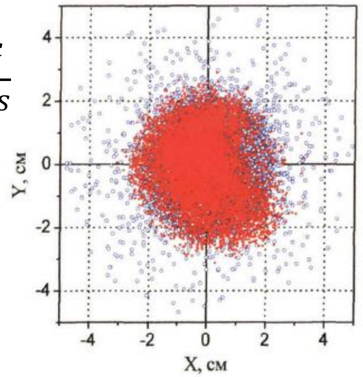


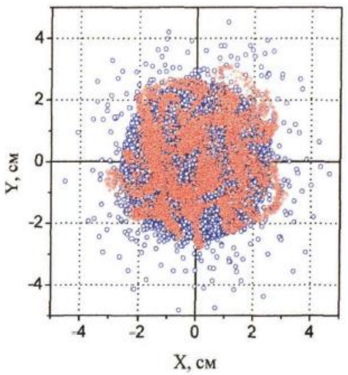


- **∃ critical upper value for dB/dt** ($\propto$ IC)

➢ E_{ind} too strong: electron disintegrate into separate bunch, loss of axisimmetry and compression phenomena.

$\frac{dB}{dt} > 20 \frac{G}{ns}$





Kube thesis – Proton acceleration (1D ES PIC)

1D electrostatic PIC code

- **Populations**: 25000 macroparticles per species (e^- *relativistic*, p^+ *non-relativistic*), 400 macroparticles per cell.
- **Spatial grid**: $dx = 0.5\ mm$ ($\lambda_{D,max} \approx 0.1\ mm$).
- **Temporal grid**: $dt = \frac{T_{HF}}{250}$ *(1.63 ps @ 2.45 GHz)* (?).
- $\Downarrow \boldsymbol{n_e}$ due to $\Uparrow r_{Lar}$ when moving **towards** $\Downarrow \boldsymbol{B}$ taken into account in charge density calculations.
- **External fields**: Linear or exponential field profile with analytical formulation (?).
- **IC**: **Gaussian** spatial distribution of e^- and p^+ for disk-shaped plasma (?).

Results

- $\Downarrow \frac{dB}{dz} \rightarrow$ no charge separation ($\boldsymbol{n_e} \approx \boldsymbol{n_i}$ **everywhere**), $\Uparrow \boldsymbol{N_p}$ accelerated, $\Downarrow \boldsymbol{W_i}$.
- $\sim \frac{dB}{dz} \rightarrow$ charge separation with $\boldsymbol{n_e} \approx \boldsymbol{n_i}$ **central region** (*10-12 cm*), $\Downarrow \boldsymbol{N_p}$ accelerated, $\Uparrow \boldsymbol{W_i}$.
- $\Uparrow \frac{dB}{dz} \rightarrow$ plasma disintegration ($\Downarrow\Downarrow \boldsymbol{N_p} < 1\%$), $\Uparrow\Uparrow \boldsymbol{W_i}$.
- **More compact acceleration with exponential profile** and same parameters compared to linear profile.

(?): settings not specified, hence supposed equal to previous step or most probable approach.

Kube thesis – Proton acceleration (1D ES PIC) - Settings

Populations:

- Particles per cell = 400.

Electrons e^-

- Relativistic.
- $N_e = 25000\ macroparticles.$

Protons p^+

- Unmagnetized and non-relativistic.
- $N_p \leq 25000\ macroparticles.$
  - $\chi = \frac{N_e - N_p}{N_e} \cdot 100 \leq 100\%$

1D electrostatic (ES) PIC
(due to axial size << radial size)

PIC settings:

- Particles at wall are lost.

Spatial grid (300 cm)

- *6000* $(\boldsymbol{dx = 0.5\ mm})$.

Temporal grid

- Timestep : $dt = \frac{T_{HF}}{250}$ *(**1.63 ps** @ 2.45 GHz)* (?).

External fields and other settings

- **Magnetic fields**: analytical formulation (?).
  - **Linear** or **exponential** profile.
  - $B_0 = 21870\ G,\ \frac{dB}{dz} = 5 - 60\ \frac{G}{cm}$
- ⇩ $\boldsymbol{n_e}$ due to ⇧ r_{Lar} when moving **towards** ⇩ $\boldsymbol{B}$ taken into account in charge density calculations.

(?): settings not specified, hence supposed equal to previous step or most probable approach.

Values used for specific simulation.

Initial conditions: hypothesis from previous calculations

- **Gaussian** spatial distribution of e^- and p^+.
- Disk-shaped plasma (?).

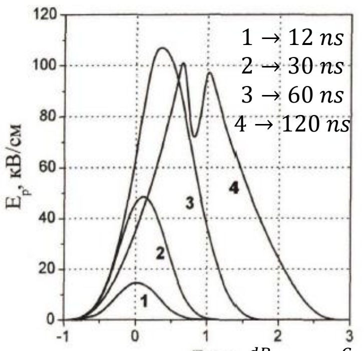
Input settings

- $W_e = W_{e,\perp}\ (= 12\ MeV)$
- $W_i = 0$
- $n_e = 5 \cdot 10^{10} - 5 \cdot 10^{11}\ cm^{-3}$ (?) $(= 1 \cdot 10^{11}\ cm^{-3})$
- $\chi = 5 - 80\%$

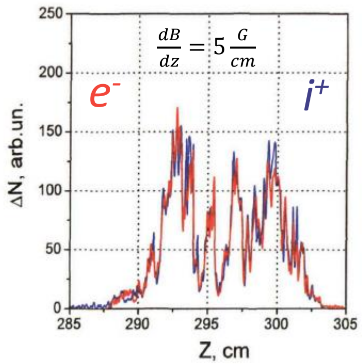
Kube thesis – Proton acceleration (1D ES PIC) - Results

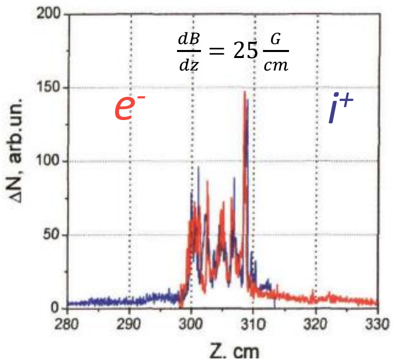
❖ Linear profile

- **Induced field:** $E_{ind,\,MAX} = 108\ kV/cm$
- **Magnetic field gradient:**
  - ➢ ⇩ $\frac{\boldsymbol{dB}}{\boldsymbol{dz}}$ → no charge separation ($\boldsymbol{n_e} \approx \boldsymbol{n_i}$ **everywhere**), ⇧ $\boldsymbol{N_p}$ accelerated, ⇩ $\boldsymbol{W_i}$ (⇩ E_{ind}).
  - ➢ $\sim \frac{\boldsymbol{dB}}{\boldsymbol{dz}}$ → charge separation with $\boldsymbol{n_e} \approx \boldsymbol{n_i}$ **central region** (*10-12 cm*), ⇩ $\boldsymbol{N_p}$ accelerated (*20%*), ⇧ $\boldsymbol{W_i}$ (*16 MeV with L = 3 m*).
  - ➢ ⇧ $\frac{\boldsymbol{dB}}{\boldsymbol{dz}}$ → plasma disintegration (⇩⇩ $\boldsymbol{N_p} < 1\%$), ⇧⇧ $\boldsymbol{W_i}$.
- **More results on paper**:
  - ➢ $n = 3 \cdot 10^{12} cm^{-3},\ W_e = 10\ MeV,\ B_0 = 1.75\ T,$ $\nabla B = 100\ G/cm, \chi = 80\%,\ L = 100\ cm\ \rightarrow \boldsymbol{W_i = 200\ MeV}$

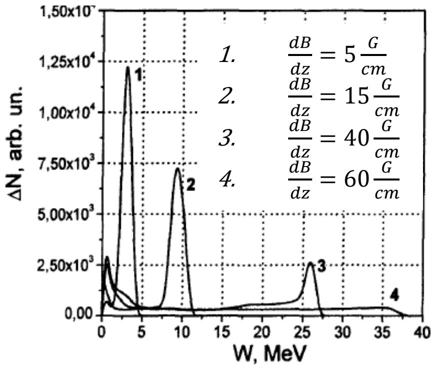


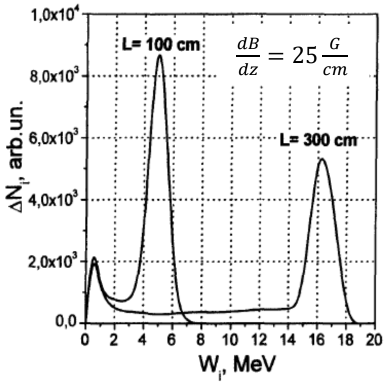
$\frac{dB}{dz} = 25\frac{G}{cm}$





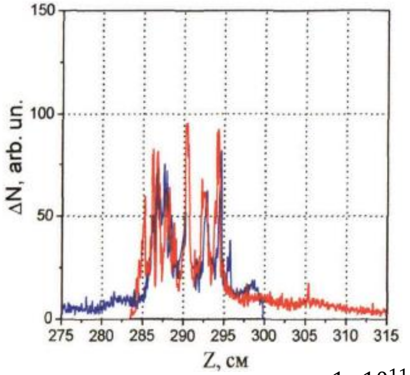
For all pictures:
$n_e = 1 \cdot 10^{11}\ cm^{-3}$,
$W_e = 12\ MeV$

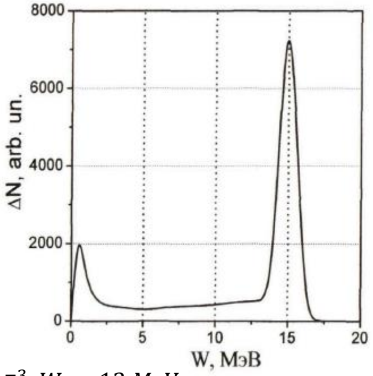




❖ Exponential profile

- **More compact acceleration** with same parameters compared to linear profile.
  - ➢ *L = 300 cm,* 18% N_p accelerated, $W_i = 15\ MeV$, narrower energy spectra.





$n_e = 1 \cdot 10^{11}\ cm^{-3}, W_e = 12\ MeV$

Kube thesis – Proton acceleration (3D EM PIC)

3D electromagnetic PIC code

- **Populations**: 100000 macroparticles per species (*e*⁻ relativistic, *p*⁺ non-relativistic).
- **Spatial grid**: $dx = 2.84 \; or \; 1.42 \; mm$ ($\lambda_{D,max} \approx 0.1 \; mm$).
- **Temporal grid**: $dt = \frac{T_{HF}}{250}$ *(1.63 ps @ 2.45 GHz)* (?).
- **External fields**: analytical formulation (?) with $\frac{d^2B}{dz^2} > 0$.
- **IC**: **Gaussian** spatial distribution (?) of *e*⁻ and *p*⁺ for disk-shaped plasma (?).

Results

- **∃ optimal** $\left(\frac{dB}{dz}\right)_{opt}$ for given IC.
  - $\frac{dB}{dz} > \left(\frac{dB}{dz}\right)_{opt}$: ⇩⇩ N_p (*shaking-off:* charge separation is too fast), $W_i < W_{i,opt}$.
  - $\frac{dB}{dz} < \left(\frac{dB}{dz}\right)_{opt}$: ⇧ N_p, ⇩ W_i (plasma remains too compact).
- Energy **lower than theoretical** calculations.
- **More stable** than relativistic ***e*⁻ rings**.

(?): settings not specified, hence supposed equal to previous step or most probable approach.

Kube thesis – Proton acceleration (3D EM PIC) - Settings

3D electromagnetic (EM) PIC

❖ **Populations:Electrons e^-**
- Relativistic.
- $N_e = 100000\ macroparticles.$

Protons p^+
- Magnetized and non-relativistic.
- $N_p \leq 100000\ macroparticles.$
  - $\chi = \frac{N_e - N_p}{N_e} \cdot 100 \leq 100\%$

❖ **PIC settings:**
- Particles at wall are lost.

Spatial grid (5 x 5 x 100 cm)
- *32 x 32 x 352* $(\boldsymbol{dx = 2.84\ mm})$.
- *64 x 64 x 704* $(\boldsymbol{dx = 1.42\ mm})$.
- Timestep : $dt = \frac{T_{HF}}{250}$ *(**1.63 ps** @ 2.45 GHz)* (?).

❖ **External fields and other settings**
- **Magnetic fields**: analytical formulation (?).
  - $\frac{d^2B}{dz^2} > 0,\ \frac{dB}{dz} = 5 - 40\frac{G}{cm}.$

(?): settings not specified, hence supposed equal to previous step or most probable approach.

Values used for specific simulation.

Initial conditions: hypothesis from previous calculations (?)
- **Gaussian** spatial distribution of e^- and p^+ (?).
- Disk-shaped (*r, dz*) plasma (?).

Input settings
- $< W_e \geq 8\ MeV\ (= W_{e,\perp}?)$
- $W_i = 0$ (?)
- $n_e = 5 \cdot 10^{10} - 5 \cdot 10^{11}\ cm^{-3}$ (?)
- $dz = 0.75\ cm$
- $r = 2.5\ cm$
- $\chi = 10\%$

Kube thesis – Proton acceleration (3D EM PIC) - Results

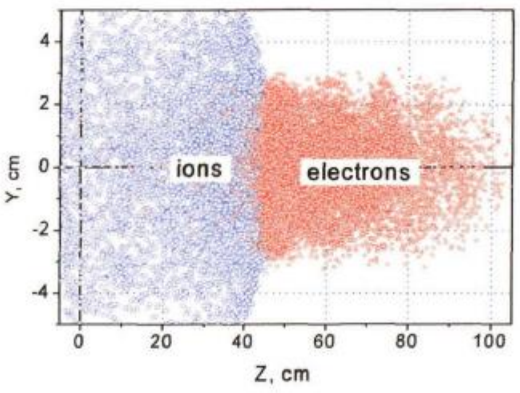
General considerations

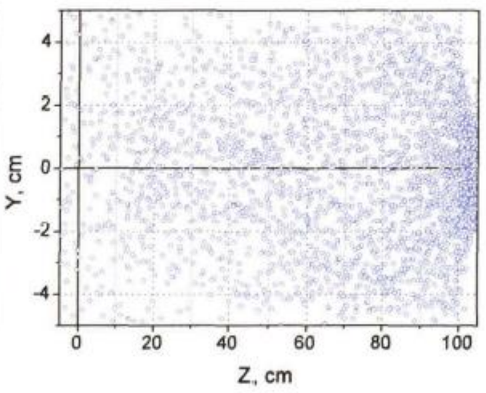
- Axial separation of charges (partial/almost total) leads to p^+ acceleration by induced field E_{ind}.
  - ➢ **Not captured** p^+ (*≈85-90%*) are **scattered** at wall.
- Energy **lower than theoretical** calculations (*5 MeV with L = 1 m @ given IC*).
- **More stable** than relativistic $\boldsymbol{e^-}$ **rings**.

Effect of magnetic field gradient

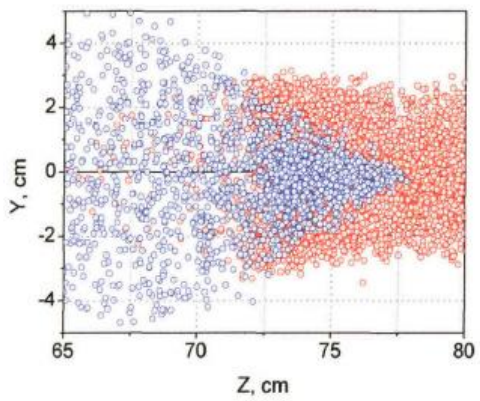
- **∃ optimal** $\left(\frac{dB}{dz}\right)_{opt}$ for given IC.
- $\frac{dB}{dz} > \left(\frac{dB}{dz}\right)_{opt}$: ⇩⇩ N_p (*shaking-off:* charge separation is too fast), $W_i < W_{i,opt}$.
- $\frac{dB}{dz} < \left(\frac{dB}{dz}\right)_{opt}$: ⇧ N_p, ⇩ W_i (plasma remains too compact).

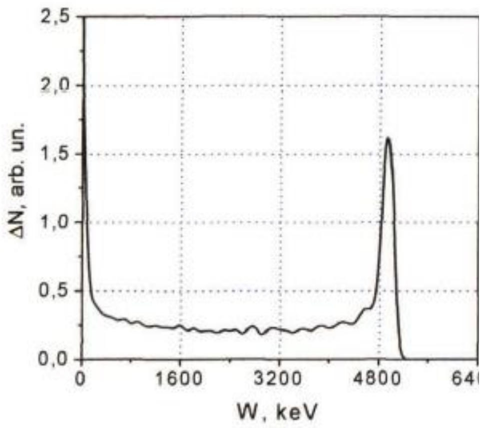
$n_e = 5 \cdot 10^{10}\ cm^{-3}$



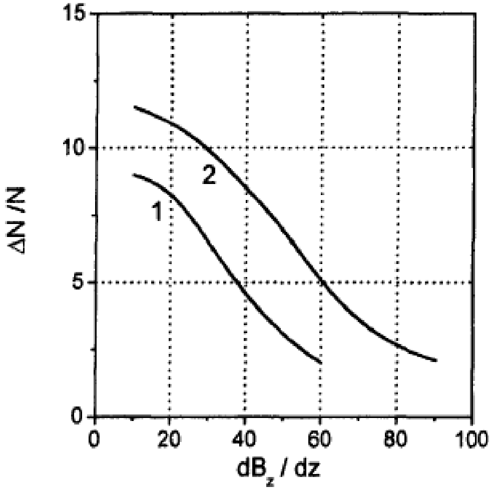


$n_e = 5 \cdot 10^{10}\ cm^{-3}$

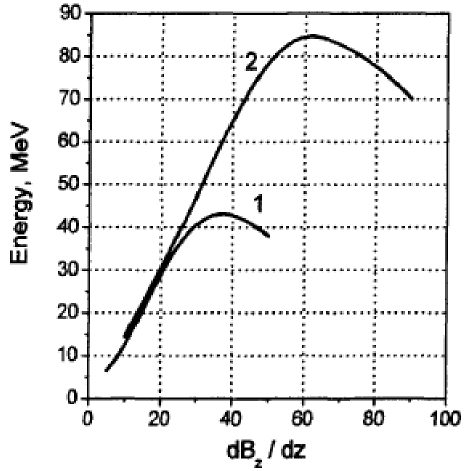




$n_e = 5 \cdot 10^{10}\ cm^{-3}$



1. $n_e = 1 \cdot 10^{12}\ cm^{-3},\ dz = 0.5\ cm,$ $r = 1.5\ cm, W_e = 12\ MeV$
2. $n_e = 1 \cdot 10^{12}\ cm^{-3},\ dz = 0.5\ cm,$ $r = 1.0\ cm, W_e(?) = 12\ MeV$



1. $n_e = 1 \cdot 10^{11}\ cm^{-3},\ dz = 0.75\ cm,$ $r = 2.5\ cm, W_e = 16\ MeV$
2. $n_e = 1 \cdot 10^{12}\ cm^{-3},\ dz = 0.5\ cm,$ $r = 1.5\ cm, W_e(?) = 16\ MeV$

Kube thesis – Outcome and problems

Interesting outcome

- ECRIPAC seems to work!

1st Phase: SGA

- **Plasma** leads to **much better** trapping than pure electron beam.
- Settings for **improving SGA**: ⇧ $\boldsymbol{r_0}$, ⇩ $\boldsymbol{A}$ (probably ⇩ A/Q *ratio*). → Same as my theoretical study!
- Parameters **to tune**: $\boldsymbol{E_{HF}}$, $\boldsymbol{dB/dt}$.

2nd Phase: Plasma compression

- **Minimize $\boldsymbol{t_{SGA}}$** to obtain correct W_e to **improve compression**.
- Attention to critical value of $\boldsymbol{dB/dt}$.

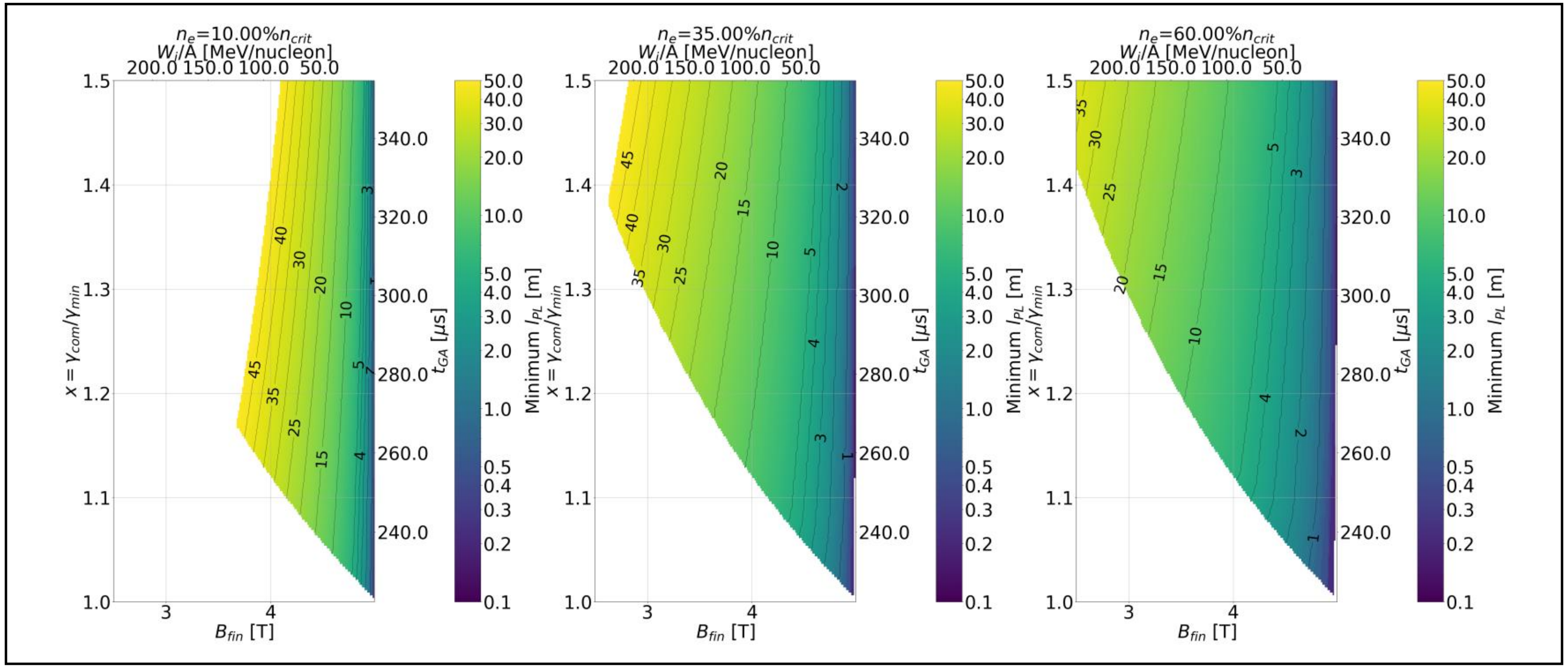
3rd Phase: PLEIADE

- Tune $\boldsymbol{dB/dz}$ to optimal value.
- Choose correct field profile.

Problems

- **Results are not reproducible:** missing information, especially for IC and field configuration.
- **Doubt on grid precision:** $dx_{grid} > \lambda_D$
  - ***SGA/compression***: $dx_{grid,min} = 0.78$ mm, $\lambda_{D,max} \approx 0.1\ mm$.
  - ***PLEIADE***: $dx_{grid,min} = 0.5$ mm, $\lambda_{D,max} \approx 0.1\ mm$.
- **Doubt on timestep precision:** $dt \approx 1.6\ ps$, CFL condition (3D, $dx = \lambda_{D,max}$) $\approx 0.2\ ps$
- **Necessity for 3D PIC:** not axisymmetric rotating bunch in SGA.
- **Not self-consistent:** PLEIADE phase starts from hypothesis and not previous simulations' data.
- **Unphysical assumptions**: how can you generate 12 MeV electrons with 2.1 T maximum fields?

Parameter space: n_e

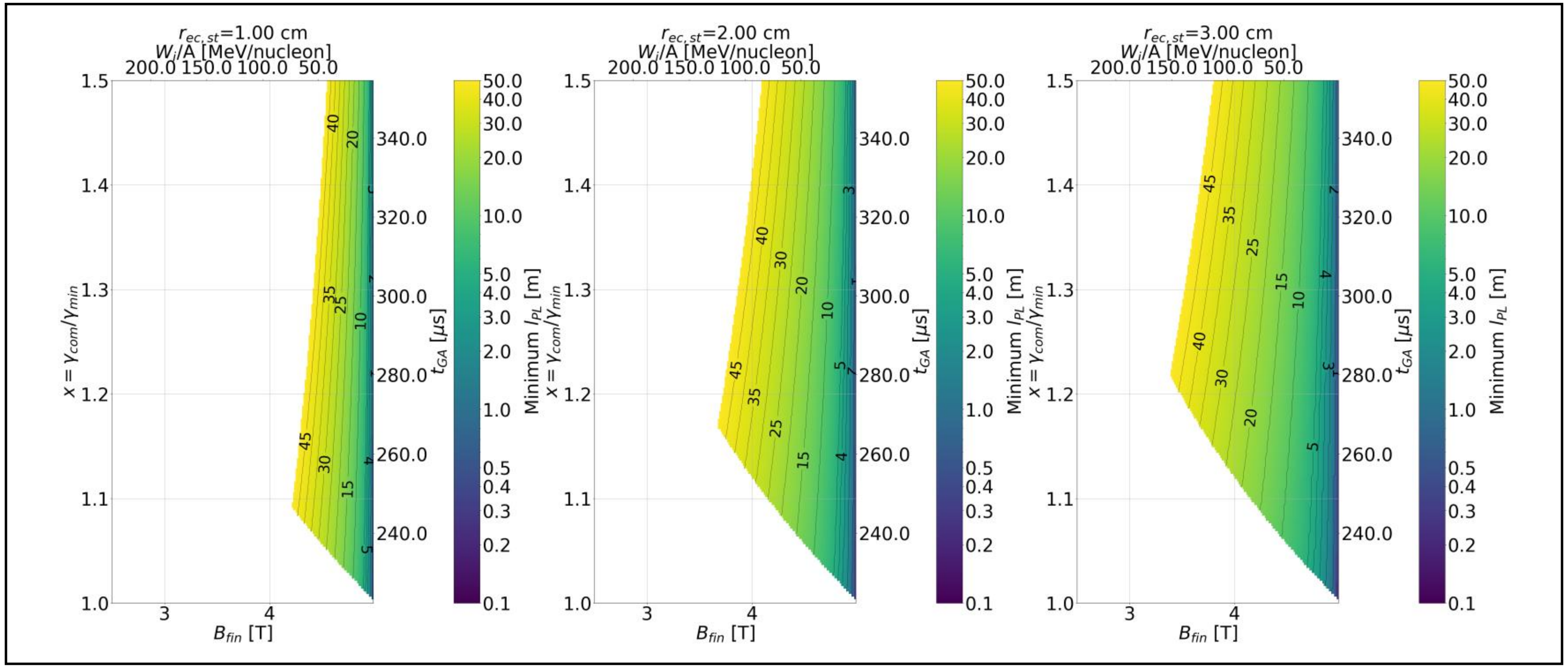


⇧ $\boldsymbol{n_e}$:

➕ ⇧ **Stability** region surface (stability at ⇩ B_{fin} and ⇧ W_i/A).

✖ Possible problem near critical density $\boldsymbol{n_{cr}}$?

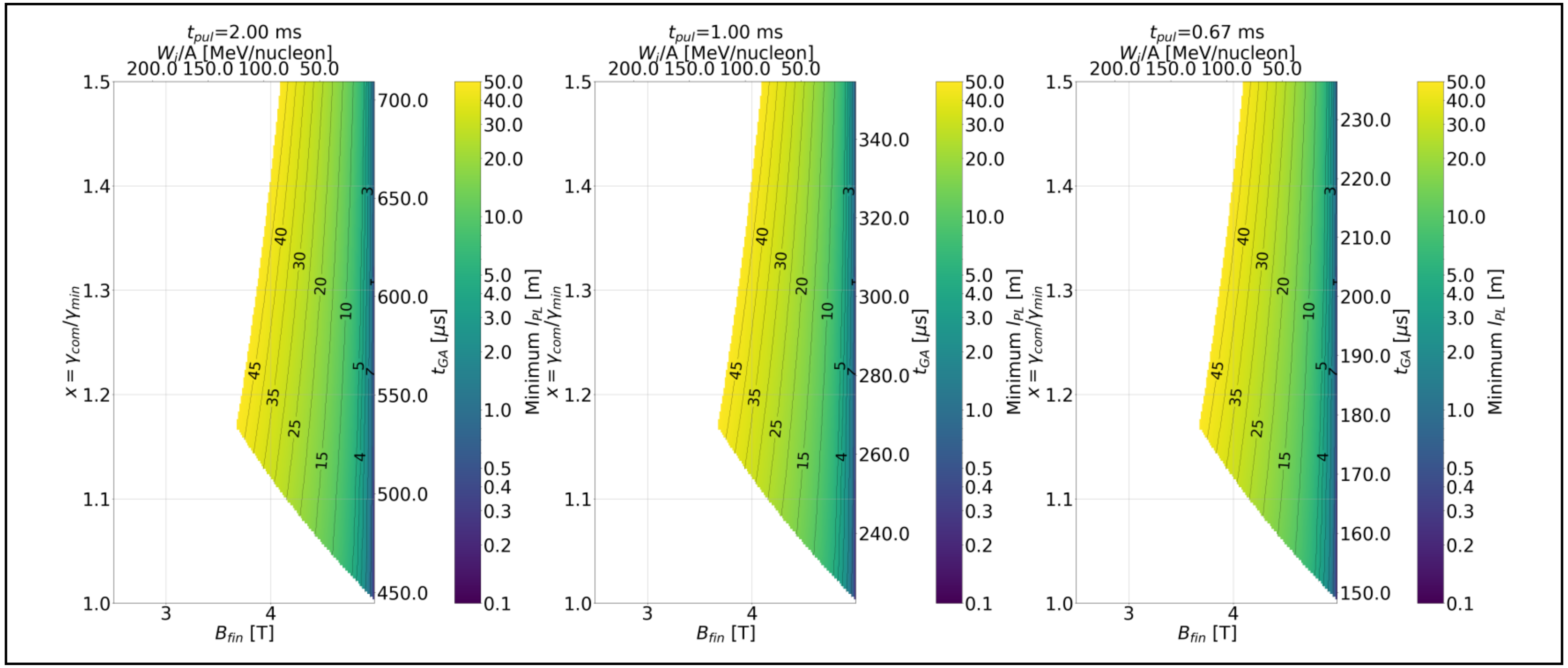
Parameter space: $r_{disk,0}$



⇧ $r_{disk,0}$:

- ⇧ **Stability** region surface (stability at ⇩ B_{fin} and ⇧ W_i/A due to ⇧ N_e).
- ⇧ **Cavity** dimensions → Technological complications.
- N.B.: $r_{cavity} > r_{disk,0} + r_{Lar,GA}$.

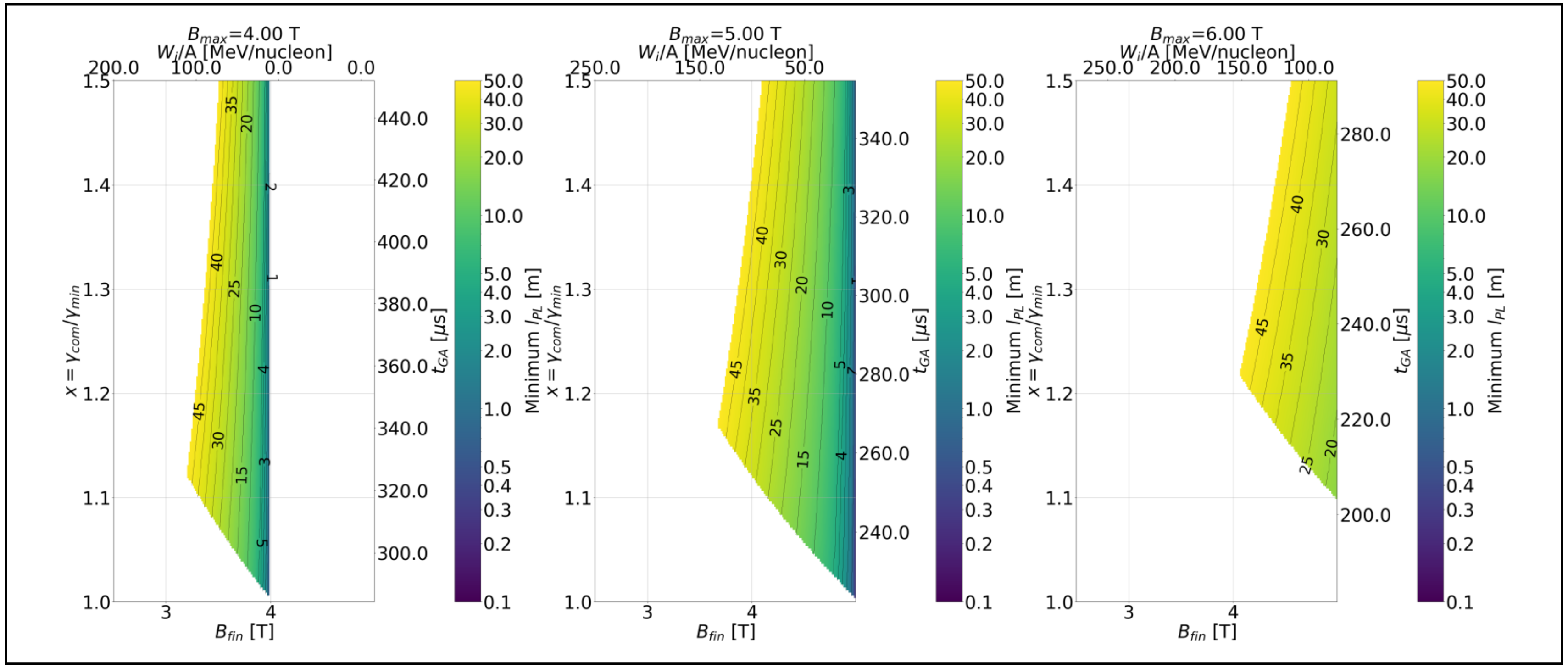
Parameter space: t_{pul}



$\Downarrow \boldsymbol{t_{pul}}$:

- ➕ $\Downarrow \boldsymbol{t_{GA}}$ (same γ_{lim} required to accelerate ions).
- ✖ Risk to **not respect adiabatic** hypothesis.
- N.B.: no significant effect, affects only t_{GA}.

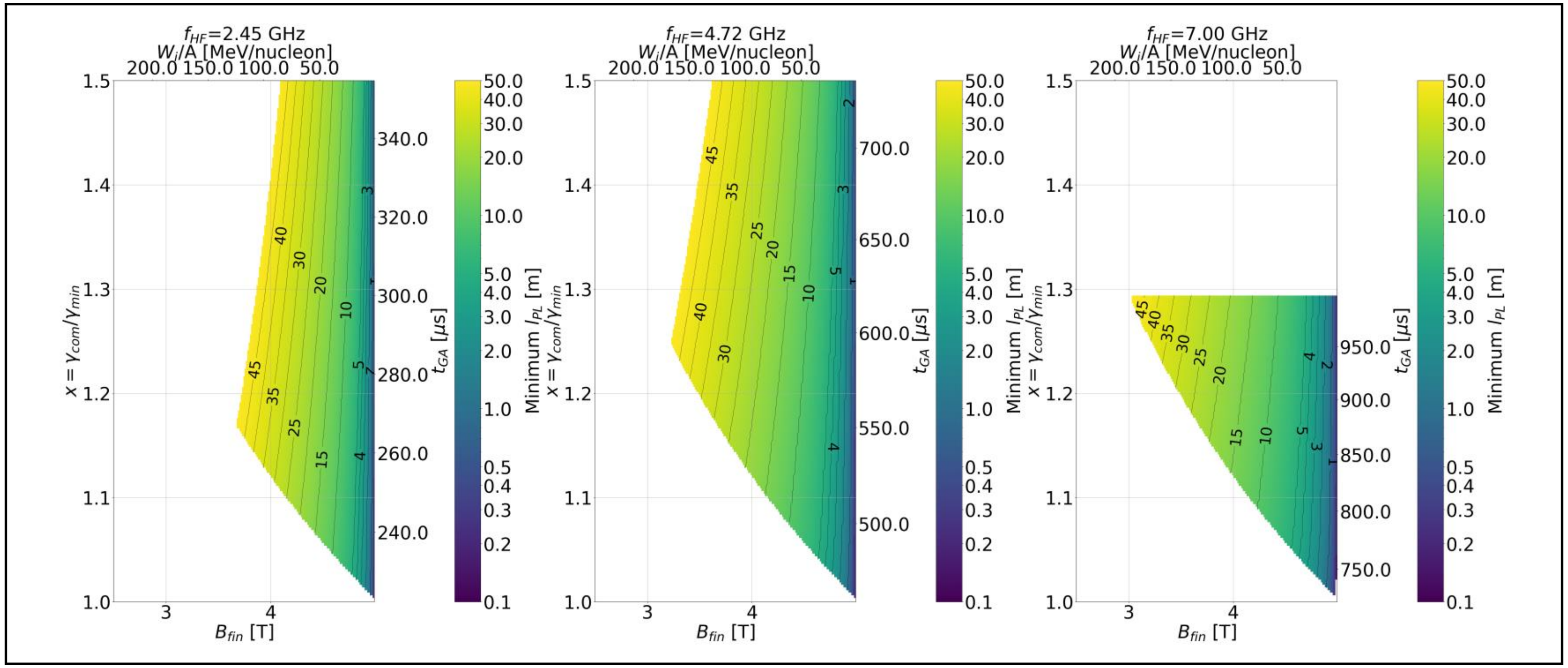
Parameter space: B_{max}



$\Uparrow \boldsymbol{B_{max}}$:

- $\Uparrow \boldsymbol{W_i/A}$ and $\Downarrow \boldsymbol{t_{GA}}$.
- $\Uparrow$ **Stability** region surface.
- **Shift stability region** to $\Uparrow B_{fin}$ → Technological complications.

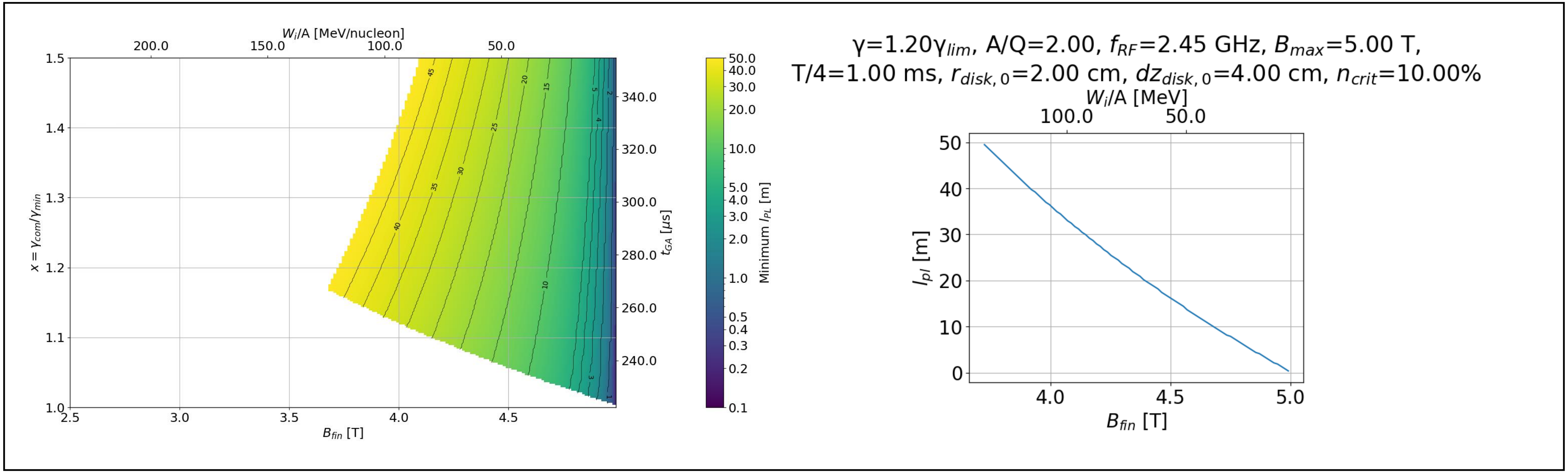
Parameter space: f_{HF}



⇧ f_{HF}:

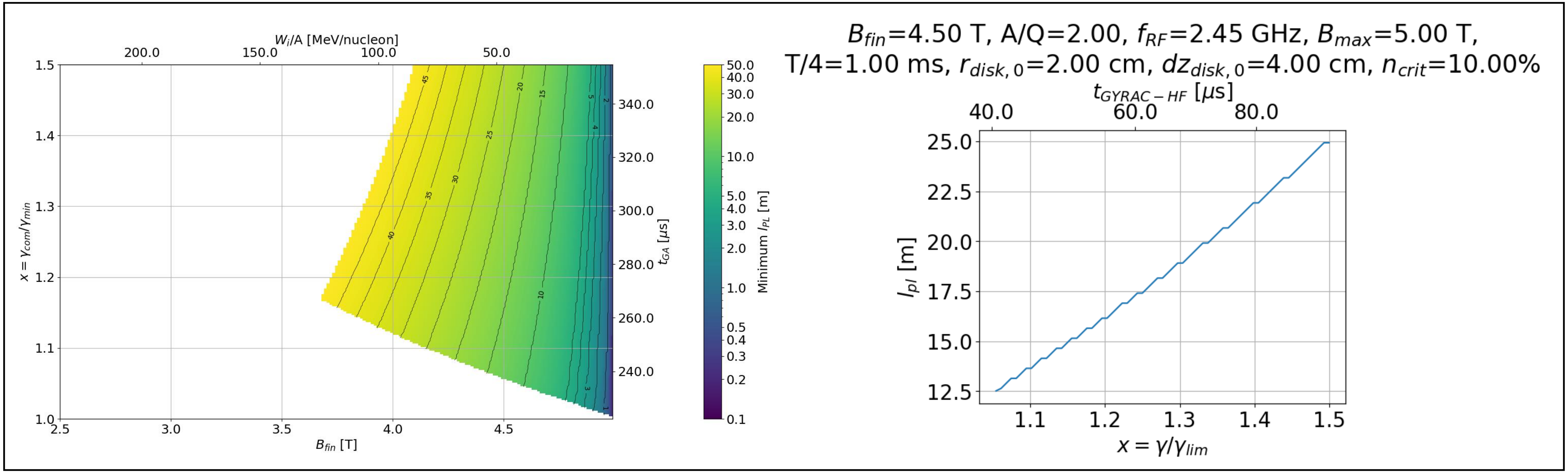
- ⇧ **Stability** region surface (stability at ⇩ B_{fin} and ⇧ W_i/A) .
- ⇧ t_{GA} (because ⇧ B_{ECR}).
- If $\gamma_{e,GA} > \gamma_{e,com}$ it can ⇩ **Stability** region surface.

Magnetic field at end of PLEIADE



⇩ B_{fin}:
- ⇧ W_i/A
- ⇧ l_{PL}

Electron energy at end of GYRAC - Compression



⇧ γ_e:

- ✖ ⇧ t_{GA}
- ✖ ⇧ l_{PL}
- N.B.: more a requirement than a parameter. **Best is lowest value** which allows stability

ECRIPAC parameters effects

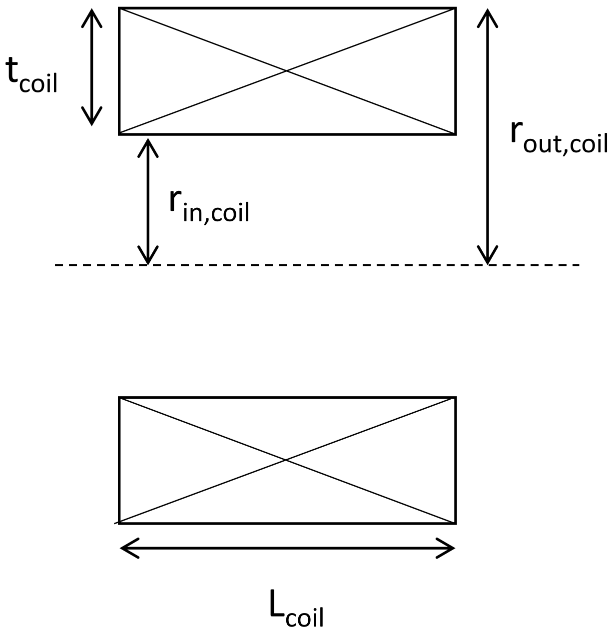
**WP: Wave-plasma interaction*

Parameter	Parameter behaviour	Advantages	Disadvantages
$\boldsymbol{B_{max}}$	⇧	• ⇧ W_i/A • ⇩ t_{GA} • ⇩ l_{PL}	• ⇧ B_{fin} required
$\boldsymbol{t_{pul}}$	⇩	• ⇩ t_{GA}	• Weaker adiabatic hypothesis
$\boldsymbol{f_{HF}}$	⇧	• ⇩ l_{PL}	• ⇧ t_{GA} • Can ⇩ stability region
$\boldsymbol{B_{fin}}$	⇩	• ⇧ W_i/A	• ⇧ l_{PL}
A/Z	⇩	• ⇩ l_{PL} • ⇩ t_{G-HF}	-
$\boldsymbol{n_e}$	⇧	• ⇩ l_{PL}	• *WP** problems near n_{cr}
$\boldsymbol{r_{disk,0}}$	⇧	• ⇩ l_{PL}	• ⇧ r_{cavity}

ECRIPAC suited to accelerate highly-charged ions using a dense plasma.
➢ External fields must be tuned according to accelerator applications.

Pulsed coil design

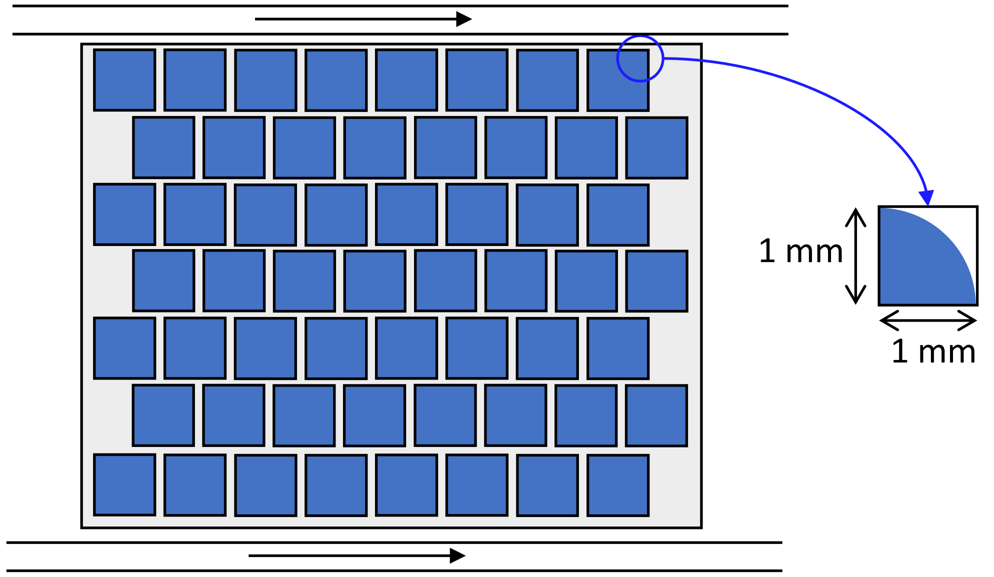
Basic geometry



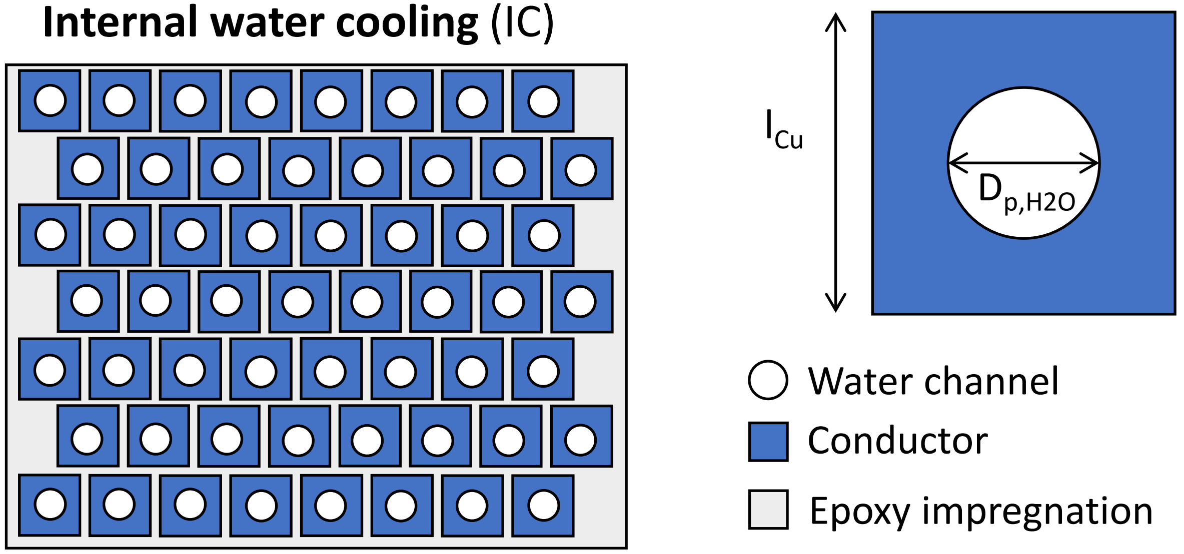
Furter details:

- Uniform epoxy thickness
- Conductor volume correction

- **External water cooling** (EC)



- **Internal water cooling** (IC)



Preliminary pulsed coil design

Design coil Hp:

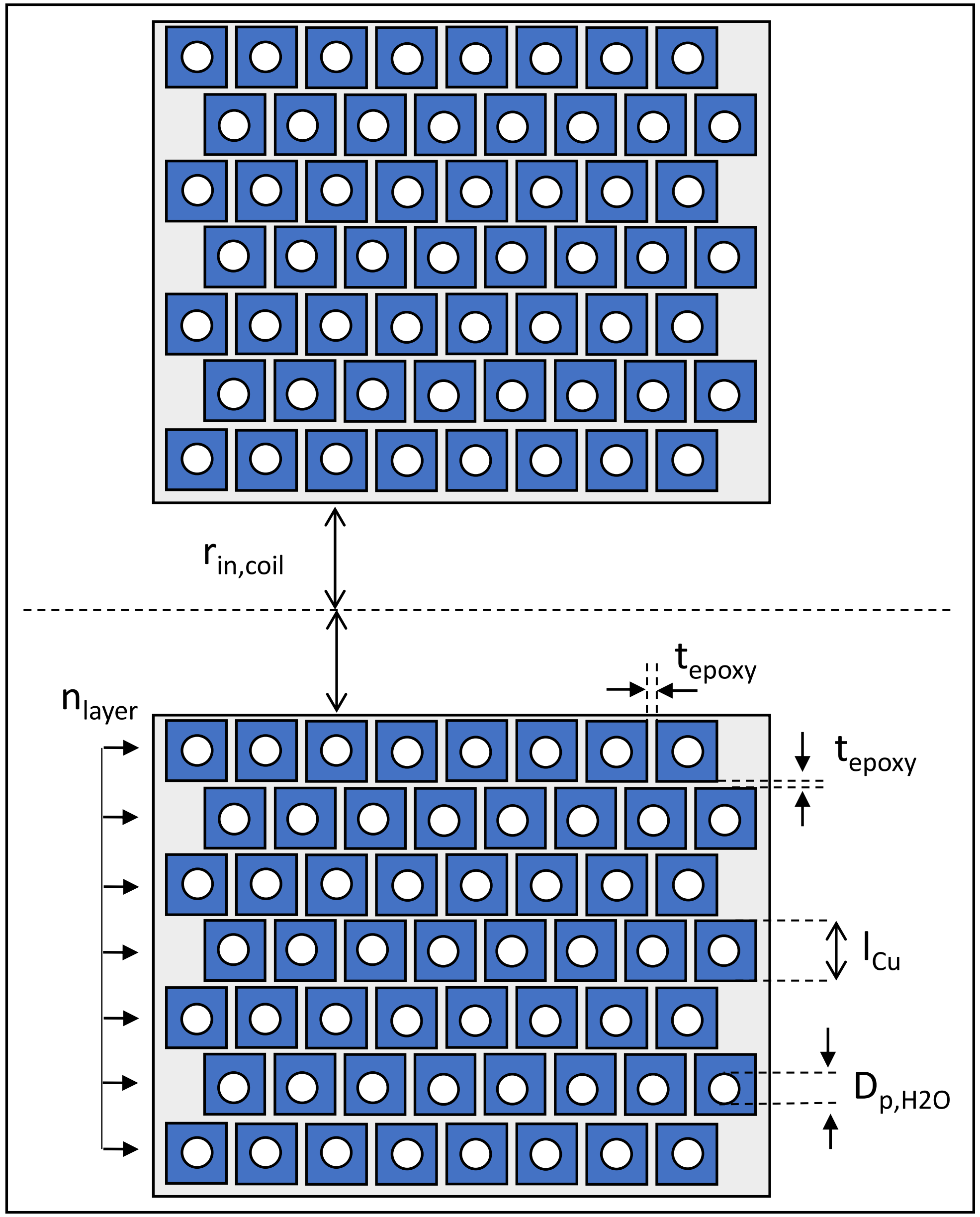
- Internal water cooling, copper windings.
- Uniform epoxy thickness.

Inputs:

- $r_{in,coil}$
- n_{layer}
- $N_{winding}$
- l_{Cu}
- t_{epoxy}
- $D_{p,H2O}$
- B_{max}
- High Voltage (HV)
- Q_{H2O}

Requirements:

- $t_{coil} \approx 2$ ms $(2 \cdot t_{pul})$
- ⇩ $C < 1$ mF
- $\Delta P_{H20} < 15$ bar
- ⇩ $\Delta T_{H20} < 30$ °C
- ⇩ W_{heat}
- ⇩ $\sigma_{hoop} < \sigma_{y,Cu} = 33.3$ MPa



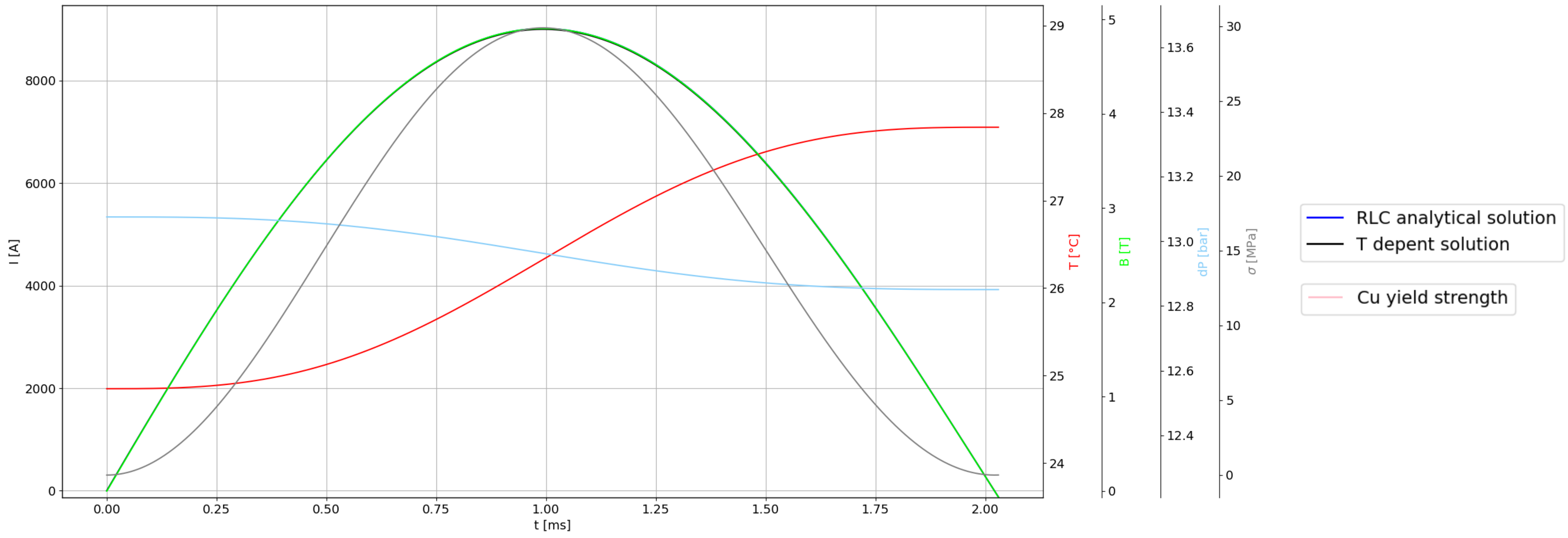
Possible pulsed coil prototype

Inputs:

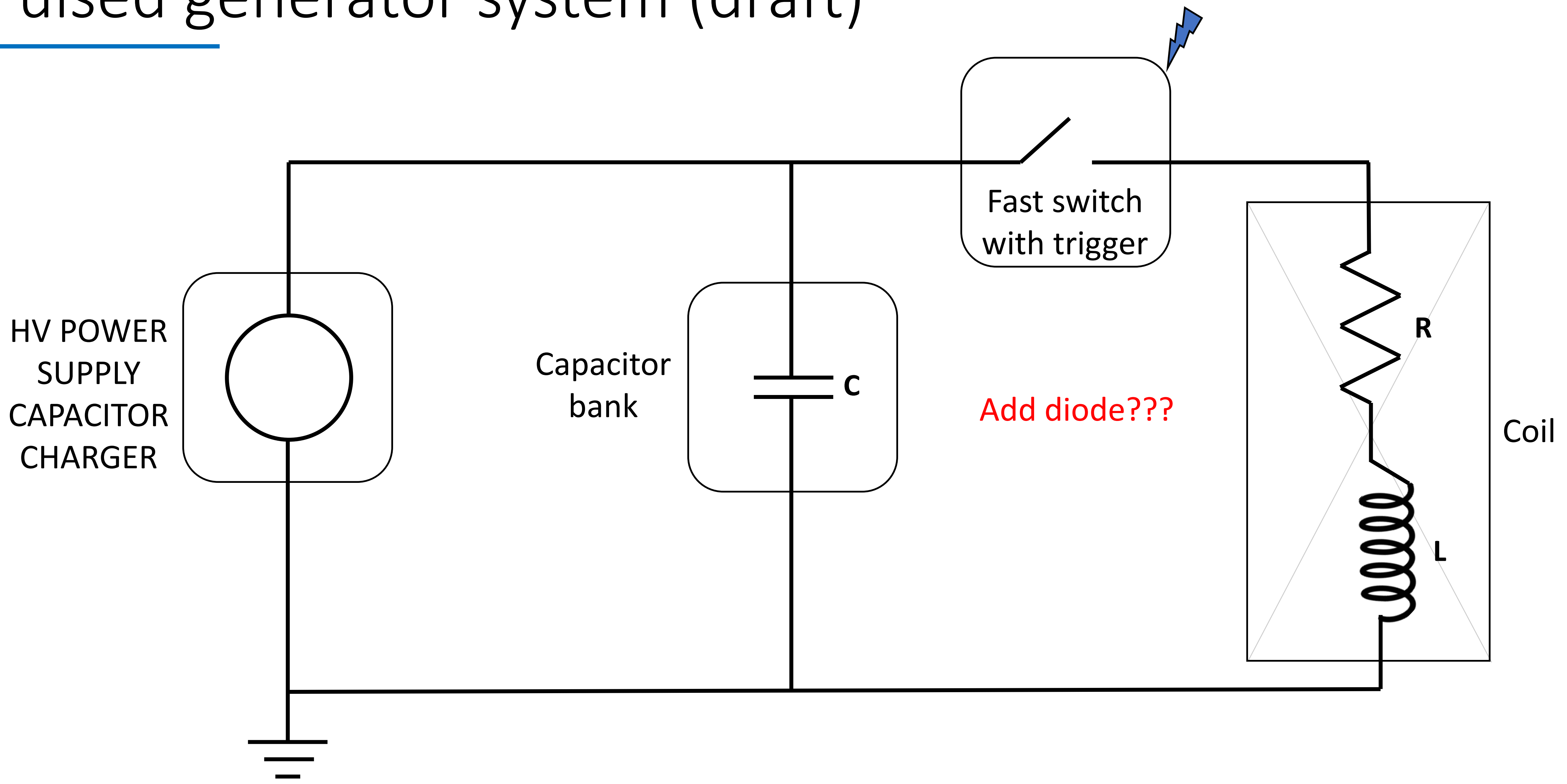
- $r_{in,coil}$ = 5 cm
- n_{layer} = 7
- $N_{winding}$ = 59
- l_{Cu} = 4 mm
- t_{epoxy} = 0.5 mm
- $D_{p,H2O}$ = 2 mm
- B_{max} = 4.91 T
- HV = 10 kV
- Q_{H2O} = 0.4 l/min

Requirements:

- T_{pulse} = 4.04 ms
- $C = 0.92$ mF
- $\Delta P_{H20} = 13.08$ bar
- $\Delta T_{H20} = 2.99$ °C
- $W_{heat} = 3.03$ kJ
- ⇩ $\sigma_{hoop} = 29.9$ MPa $< \sigma_{y,Cu}$



Pulsed generator system (draft)



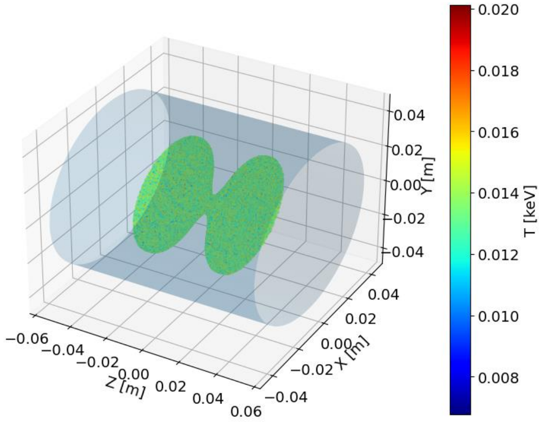
3D Monte Carlo PT code – IC (for [3-5])

Position

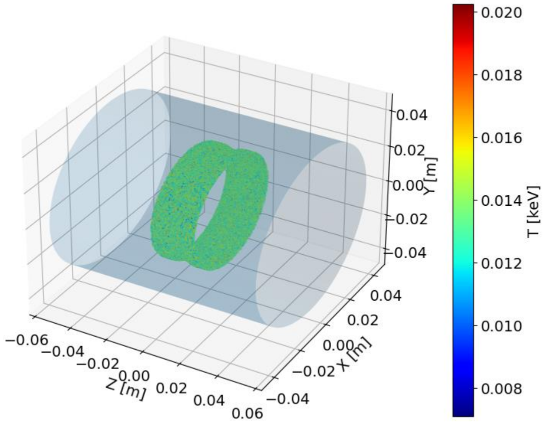
- Satisfying $0.98 \cdot B_{ECR} \leq B \leq 1.02 \cdot B_{ECR}$ inside centered sphere of radius 2.8 cm.

➢ **Alternative approach:** consider only particles which remain confined for 10 µs in the starting mirror trap

➢ B (0, 0) < B_{ECR}

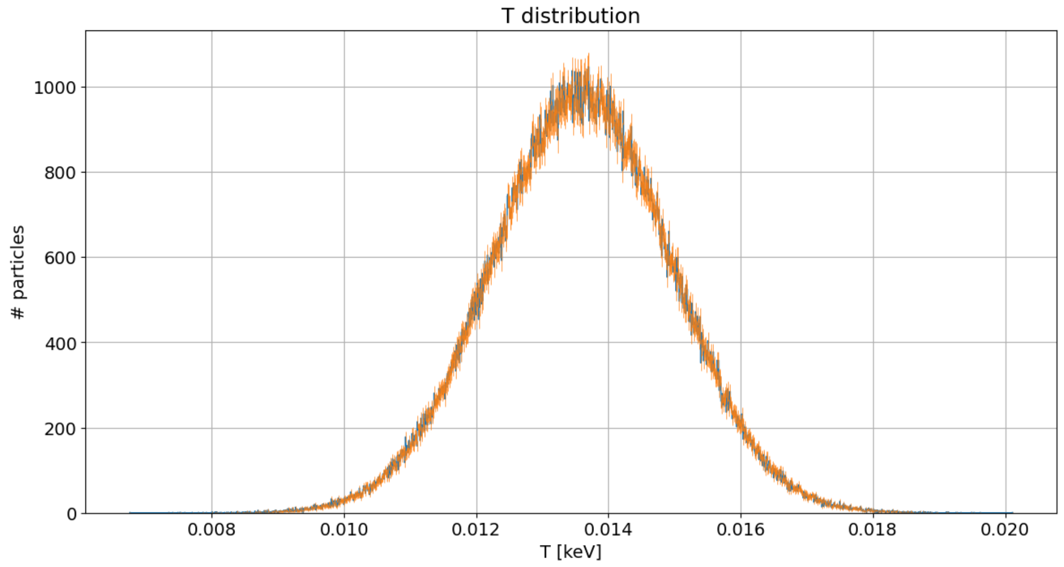


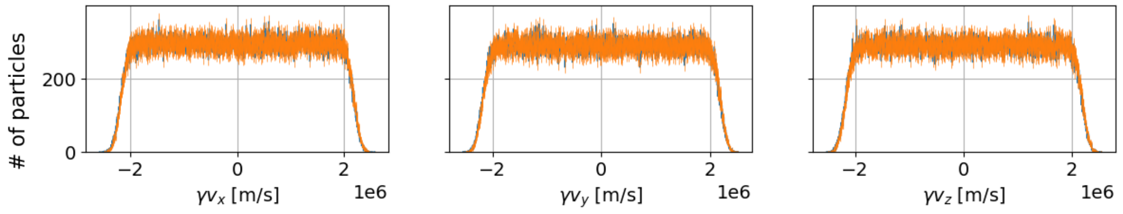
➢ B (0, 0) > B_{ECR}



Energy

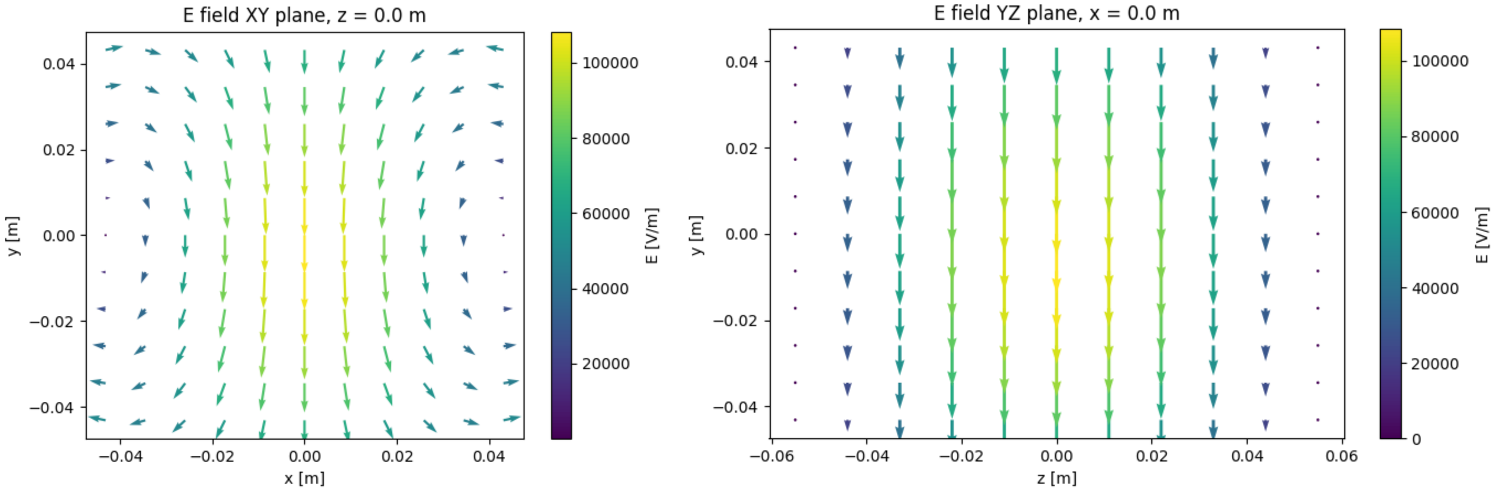
- Gaussian distribution around hydrogen ionization potential ($\sigma = 0.1 \cdot I_{p,H}$).



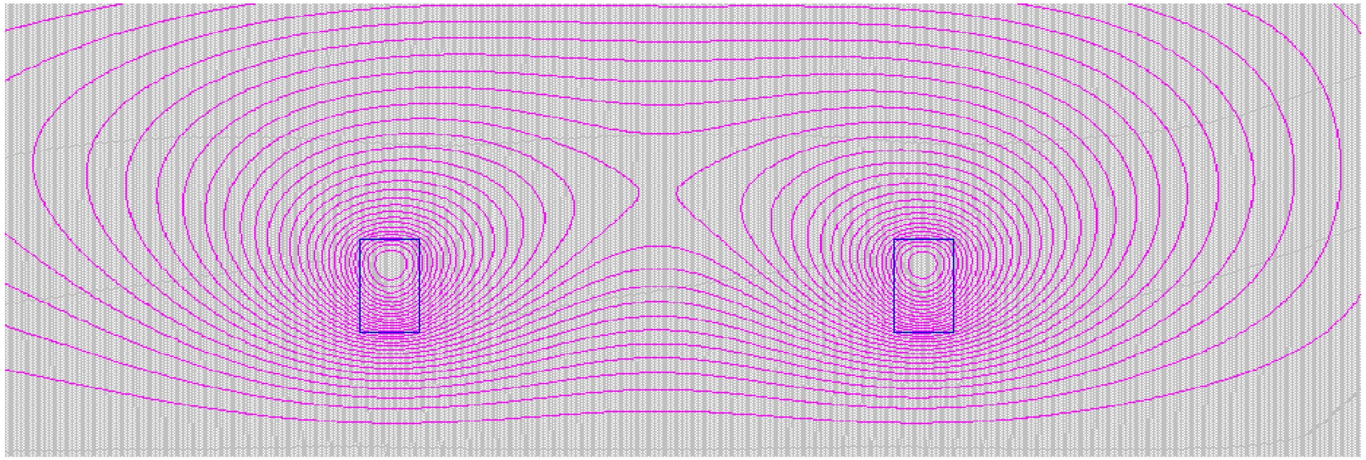


3D Monte Carlo PT code – E and B field modeling (for [3-5])

- **TE111 mode**: analytical formulation (both E and B fields).
  - ➢ f_{HF} = 2.45 GHz, R_{cavity} = 4.315 cm, L_{cavity} = 11 cm, $E_{HF} \approx$ 1 kV/cm



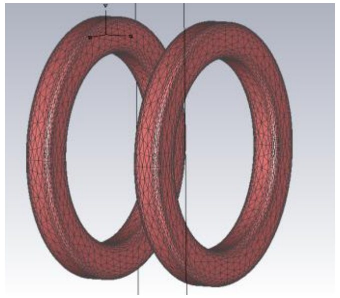
- **Static field coils**: field maps through Poisson Superfish.
  - ➢ R from 4.82 cm to 8.32 cm, z from ± 6 cm to ± 7.5 cm

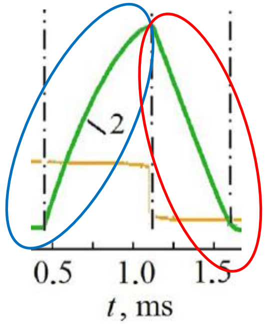


3D Monte Carlo PT code – E and B field modeling (for [3-5])

Pulsed field coils (B + induced E)

- Field maps in frequency domain from CST studio or COMSOL.
- R from 6.18 cm to 7.23 cm, z from ± 3.28 cm to ± 4.12 cm.
- Sinusoidal increase.
- Linear decrease.

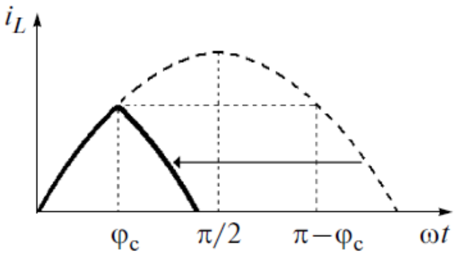




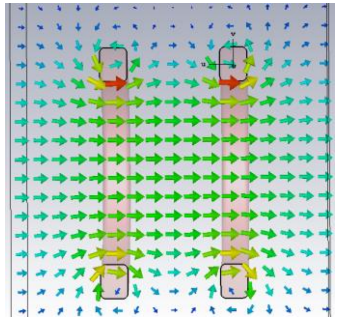
Sinusoidal increase

- $B_{pulsed,max}$ at commutation angle $\phi_c = \pi/3$
- Rise time t_{pulsed} = 4 µs: f_{pulsed} = 41.67 kHz,

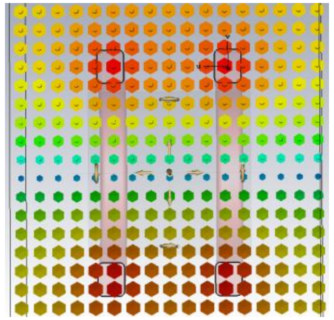
$B_{\pi/2} = 2 \cdot B_{pulsed,max}/\sqrt{3}$



B



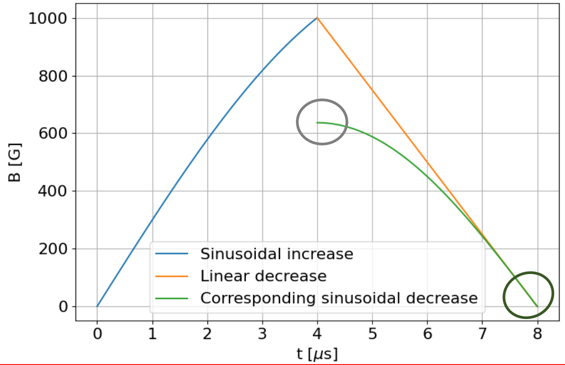
E



Linear increase

- **B:** linear interpolation between $B_{pulsed,max}$ map and null field.
- **E:** Field maps in frequency domain of corresponding sinusoidal decrease for small time values (sin(x) ≈ x, cos(x) ≈ 1) - f_{pulsed} = 62.5 kHz,

$B_{\pi/2} = 2 \cdot B_{pulsed,max}/\pi$

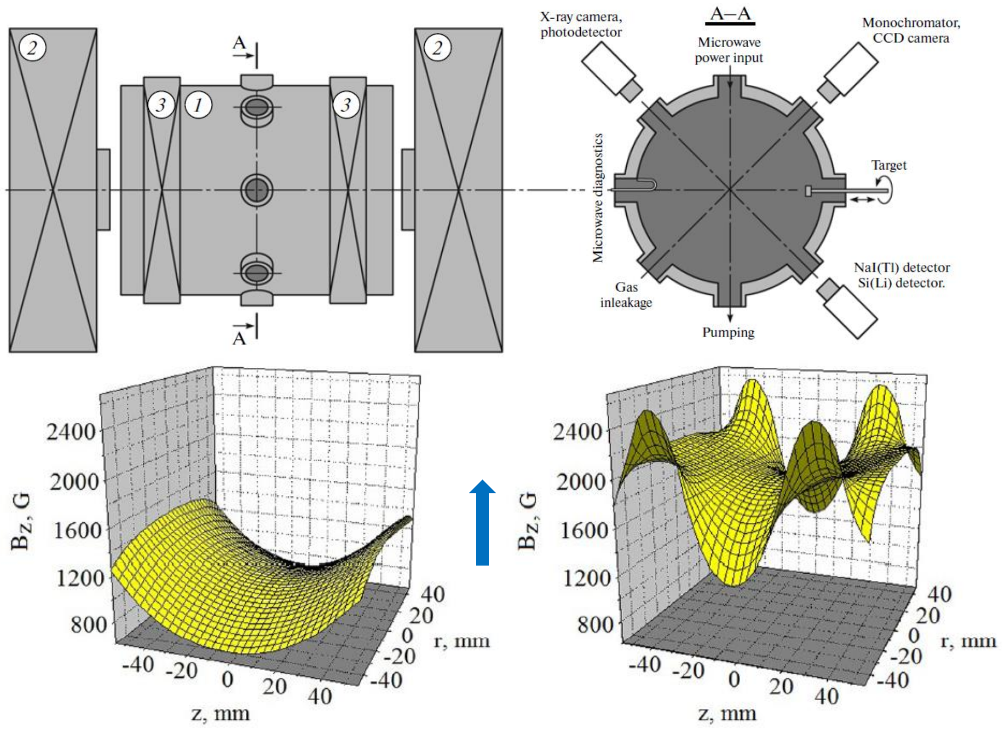


Available literature: GYRAC numerical simulations

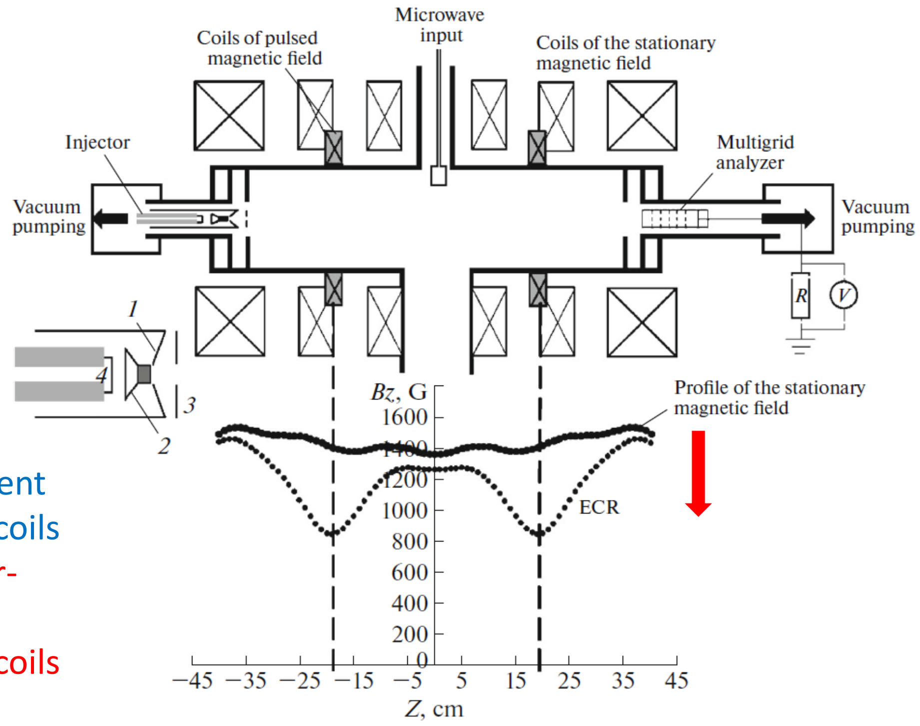
- **Orozco team** (Colombia) – **MC PT code in SEA**, both spatially homogeneous magnetic field and magnetic mirror trap [1,2]. → **Used for preliminary validation.**

- **Andreev team** (Russia) – **ES PIC code**, magnetic mirror trap (**GA + Decompression**), comparison with **experimental results**. → **Most complete results for main comparison.**

➢ **Basic GYRAC (BG)** setup [3-5]



➢ **Long mirror (LM)** setup [6-12]



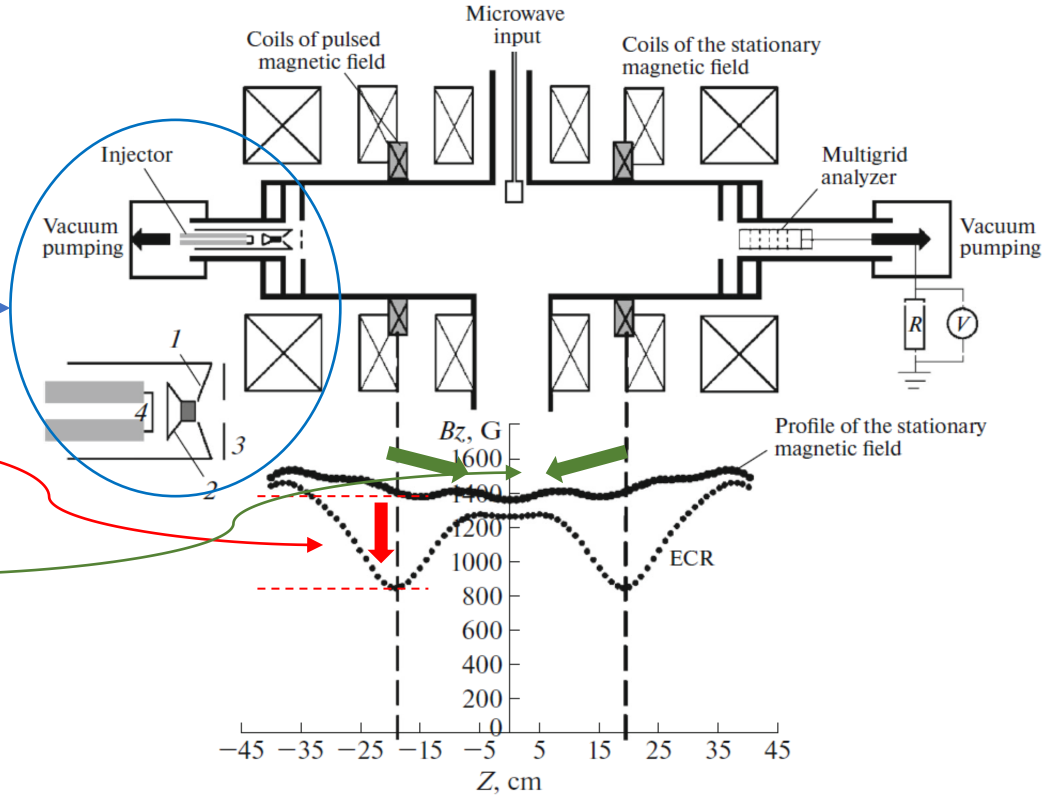
- Co-current pulsed coils
- Counter-current pulsed coils

Andreev team (LM) – Paper [6-12]

Numerical and experimental results for processes in common with ECRIPAC **not** present in previous paper

➢ **Physical insights and possible material for code validation**

- Injection of external electron beam inside resonant cavity
- Current in pulsed coils in opposite direction with respect to main coils
- Experimental observations of ion energy increase due to PLEIADE effect
- Further phenomena: electron bunches merging, TE118 cavity mode …



MC code validation summary

✓ Good agreement
X Small discrepancies

Otero team – Paper [1,2]

❖ **Limitations and problems**

- **[1]**: Wrong reported implementation for TE011.
- **[2]**: Unreliable data → Impossible to reproduce results.

❖ **Validation**

- **[1] Single particle**: Comparison of γ_e and r_{Lar} for ≠ α.
- **[1] Electron cloud**: Final γ_e distribution, Trapping efficiency and deconfinement.
- **[2] Comparison with Golovanivski analytical (same approach)**: Good agreement with plane wave HF, Premature de-trapping with TE_{111} HF.

Andreev team – Paper [3-5]

❖ **Limitations and problems**

- No data for magnetic field distribution.
- Unclear initial condition.
- Electrostatic interactions (PIC).

❖ **Validation**

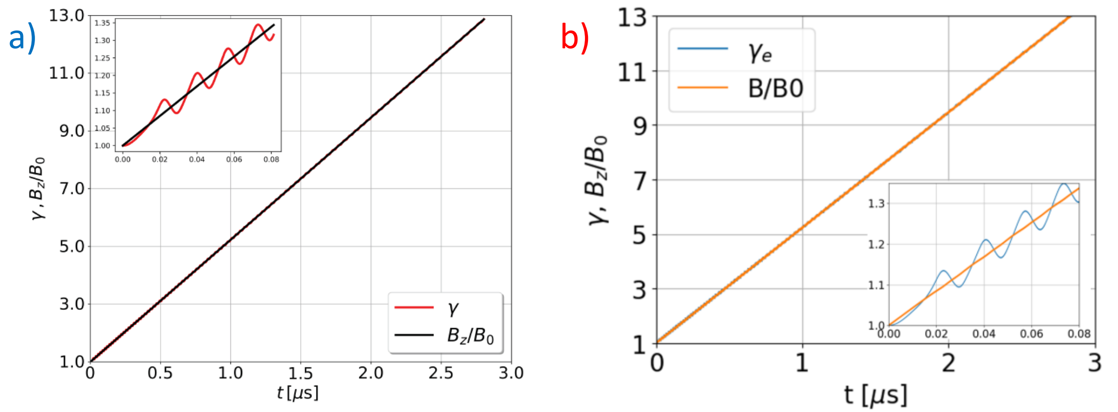
- **Electron behaviour**: γ_e and r_{Lar} evolution, $W_{e\perp}$ accumulation, Electron de-trapping, Electron cloud distribution.
- **Deconfinement spectrum**: GA and decompression deconfinement peaks, $\langle W_e \rangle$ loss spectrum.
- **Energy spectrum**: ⇩ W_e region (ECR electrons), ⇧ W_e region (De-trapped electrons), ⇧⇧ W_e region (Trapped electrons → Depends only on B_{pu}).
- **Trapping efficiency:** Depends on B_{in} and is maximum at optimal B_{in}.

More details in backup slide due to time constraints.

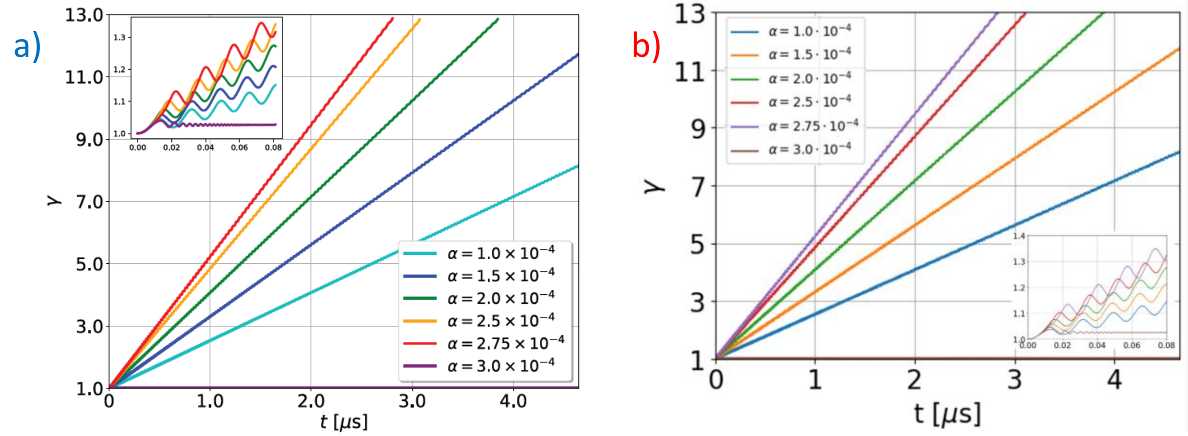
MC code preliminary validation: Paper [1]

a) Paper results
b) My results

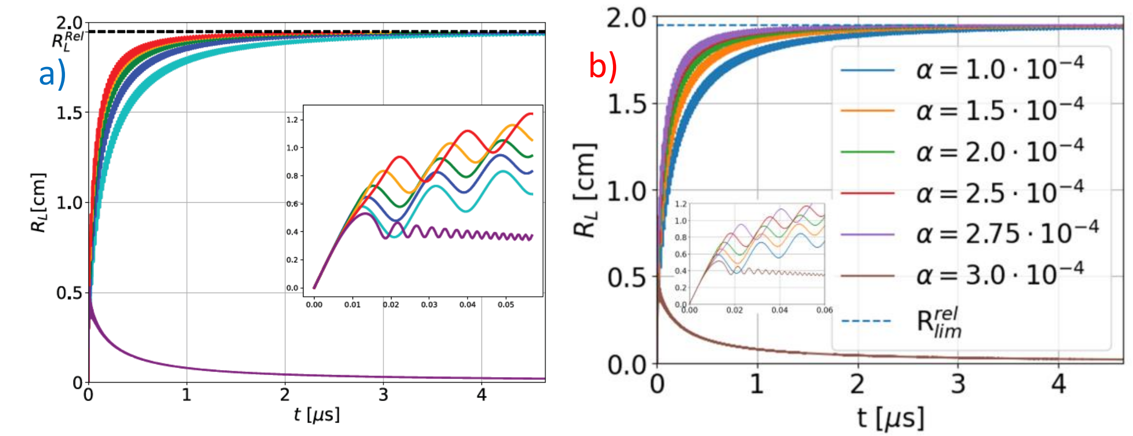
- Evolution of normalized energy vs normalized B field.



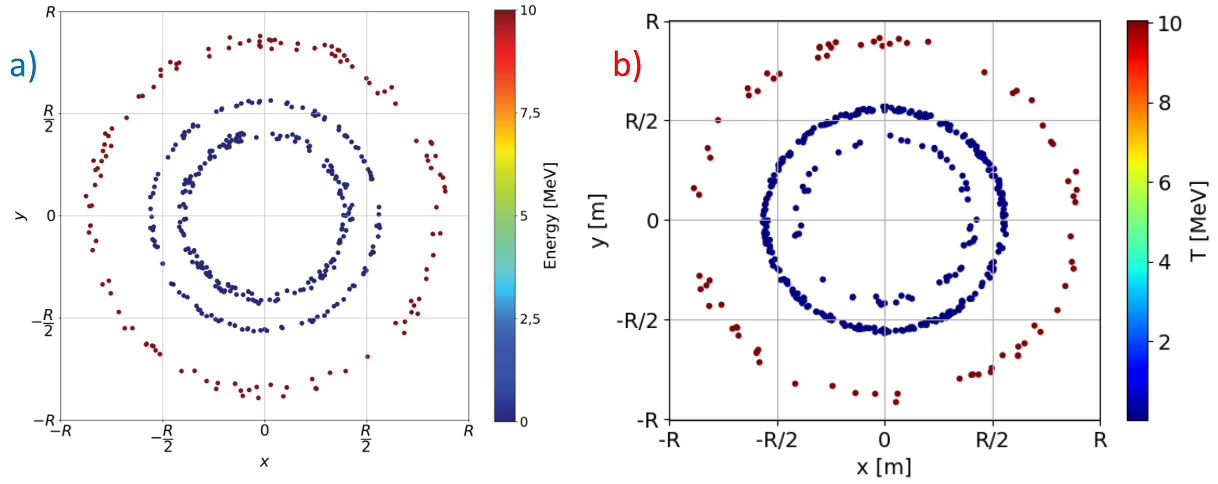
- Normalized energy increase at different α.



- Larmor radius increase at different α.



- Position and energy distribution for $\alpha = 2.75 \cdot 10^{-3}$.



Orozco team – Paper [1]

- **Simulation**: PT code in single-electron approximation, TE011 mode at 2.45 GHz and homogeneous magnetic field $B(t) = B_0(1 + \alpha\tau)$.

- **Results:**

1. Physical quantities evolution for electron at rest in (0, R/2, 0) for $10^{-4} < \alpha < 3 \cdot 10^{-4}$
2. Evolution of ring-like cloud of electrons at rest in (3R/8 < r < 9R/16) for $10^{-4} < \alpha < 2.75 \cdot 10^{-4}$

α	Data	% CP	% UCP	% EP	T_{max} [MeV]
$1.0 \cdot 10^{-4}$	Mine	96.1	0	3.9	3.67
	Otero	95.9	0	4.1	3.64
$1.5 \cdot 10^{-4}$	Mine	57.6	0	42.4	5.49
	Otero	68.4	0	31.6	5.45
$2.0 \cdot 10^{-4}$	Mine	33.1	0	66.9	7.32
	Otero	48.8	0	51.2	7.27
$2.5 \cdot 10^{-4}$	Mine	19.3	0	80.7	9.15
	Otero	35.3	0	64.7	9.08
$2.75 \cdot 10^{-4}$	Mine	7.8	33.3	58.9	10.07
	Otero	12.3	29.2	58.5	10

CP: captured particles, UCP: not captured particles, EP: escaped particles

Problems:

- Discrepancies in electron distribution.
- Wrong analytical formulation of TE011 mode in the paper.

Orozco team – Paper [2]

- **Simulation**: PT code in single-electron approximation, TE111 mode at 2.45 GHz.

- **Results:**

1. Comparison of numerical solution with Golovanivski analytical solution (PDE system solved with RK-4) for given initial condition and homogeneous magnetic field $B(t) = B_0(1 + \alpha\tau^2)$.
2. Evolution of spherical electron cloud (R = 2.28 cm, Maxwellian energy distribution around case 1 = 2 eV and case 2 = 5 keV) inside mirror trap increasing as $B(t) = B_0(1 + \alpha\tau)$ and $\alpha = 7 \cdot 10^{-4}$.

- **Problems**: Completely unreliable data – Impossible to reproduce results.
  - Initial condition of 1) are wrong.
  - Coil data provided in the paper do not produce $\alpha = 7 \cdot 10^{-4}$.

MC code preliminary validation: Paper [2]

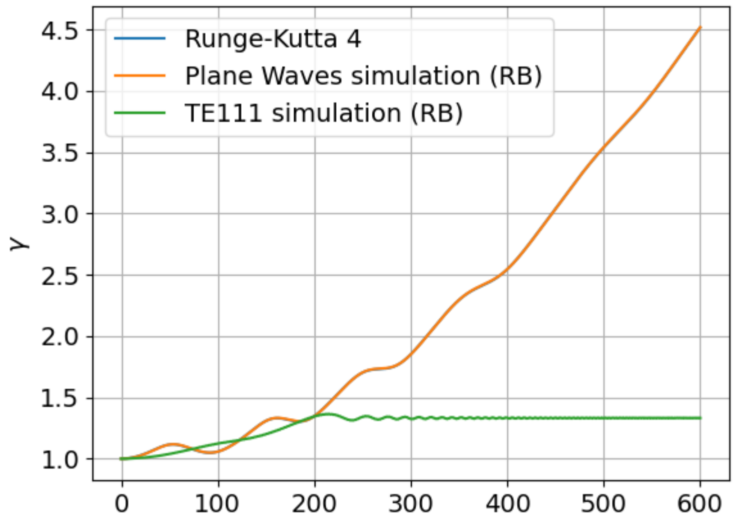
Unreliable data, impossible to reproduce results.

- Same validation approach: Comparison of numerical solution with Golovanivski analytical solution (PDE system solved with RK-4) for given initial condition and homogeneous magnetic field $B(t) = B_0(1 + \alpha\tau^2)$

- Hp: plane wave approximation

$$\begin{cases} \dfrac{d\gamma}{d\tau} = -g_0\left(1 - \dfrac{1}{\gamma^2}\right)^{\frac{1}{2}} \cos\phi \\ \dfrac{d\phi}{d\tau} = \dfrac{b - \gamma + 1}{\gamma} + g_0(\gamma^2 - 1)^{-\frac{1}{2}} \sin\phi \end{cases}$$

- NR: Not relativistic
- RB: Relativistic Boris algorithm



- ✓ Good agreement with plane waves simulation.
- ✓ Early de-trapping with TE111 simulation.

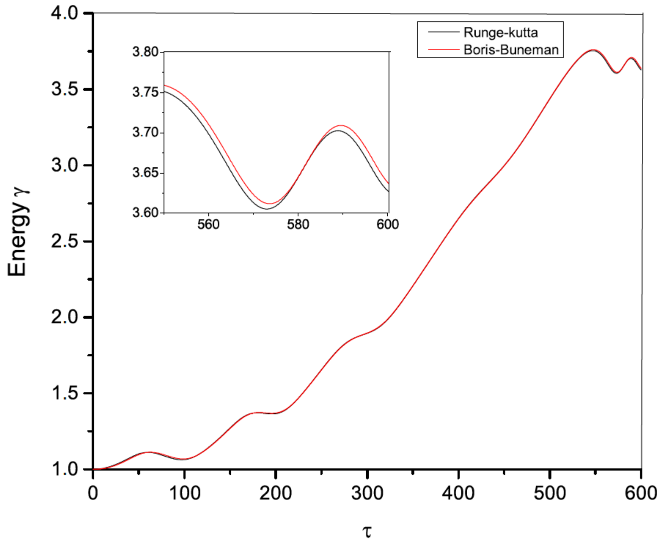
Orozco team – Paper [2] validation

For given initial condition, **GYRAC should not be theoretically possible**:

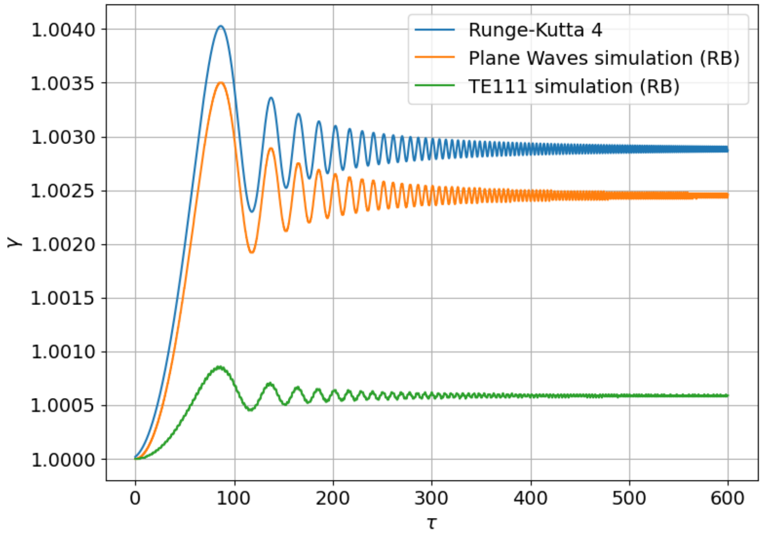
$$\mu_{0,NR} = \frac{2b}{g_0^2 \tau^2} = 1.53\text{, stability for } \mu_{0,NR} < 1$$

NR: Not relativistic
RB: Relativistic Boris algorithm

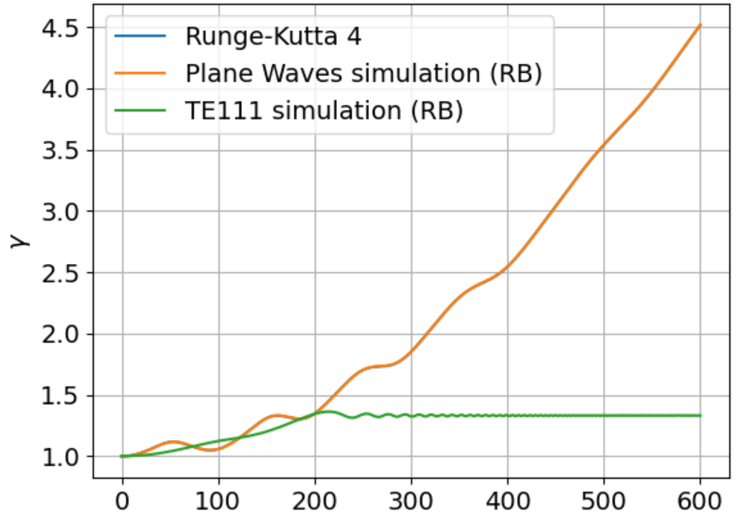
- Paper solution
(stable, E = 0.3 kV/cm)



- Simulation solution
(NOT stable , E = 0.3 kV/cm)



- Test at stable solution
(stable , E = 3 kV/cm)

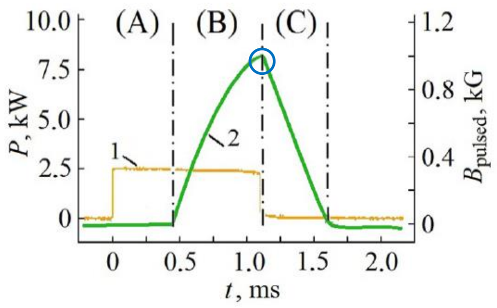


Good agreement of analytical solution (plane waves approximation) and TE111 mode numerical solution **not** observed in simulations.

Andreev team (BG) – Paper [3-5]

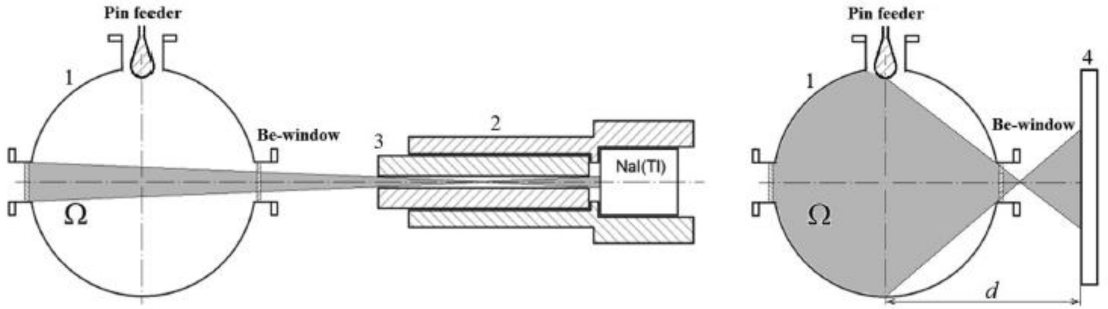
- **Simulation**: ES PIC, TE111 mode at 2.45 GHz and magnetic mirror trap, plasma generated inside cavity through ECR.
  - ➢ Same parameters as experimental setup except pulsed field rise time (from ≈ 500 μs to 5 μs).

➢ HF wave
➢ Pulsed field
➢ Commutating angle ≈ π/3



Experimental diagnostics:

- Bremsstrahlung measurement.
- X-ray imaging.



GYRAC parameters study

- **Variation of B_{in} (0,0):** 860 G, 875 G, 900 G, 925 G, 960 G (**Nom.)**
- **Variation of B_{pu}:** 800 G, 1000 G c1200 G
- **Variation of E_{HF}:** 0.8 kV/cm, 1.0 kV/cm (**Nom.)**, 1.2 kV/cm

Problems and differences

- No data for magnetic field distribution.
- Unclear initial condition.
- Electrostatic interactions (PIC).

3D MC PT code – Simulation details (for [3-5])

Pulsed field time-behaviour

- Frequency = 41.67 KHz
- Commutation angle = π/3
- Linear field decrease.

Simulated time constants

- T_{max} = 8 µs
- T_{gyrac} = 4 µs
- T_{ECR} = None (IC-AP) – 10 µs (IC-C)
- Time-step saving (MTS only) = 0.2 µs

Statistics

- IFTS = 5e5 particles
- MTS = 1e5 particles

Particle initial position

- $0.98 \cdot B_{ECR} \leq B_{e0} \leq 1.02 \cdot B_{ECR}$
- ➢ All particles (IC-AP) or confined for 10 µs (IC-C) : No significant difference

Configuration	$B_{initial}$ (0,0) [G]	B_{pulsed} [G]	E_{HF} [kV/cm]
Nominal	960	1000	1
Bin860	860	1000	1
Bin875	875	1000	1
Bin900	900	1000	1
Bin925	925	1000	1
Bpu800	960	800	1
Bpu1200	960	1200	1
Bpu1500	960	1500	1
Ehf0.8	960	1000	0.8
Ehf1.2	960	1000	1.2

IFTS: initial and final time-steps. - **MTS**: multi time-steps.

MC code main validation: Paper [3-5]

- Bin875 configuration used for higher statistics on trapped electrons.

<u>**Trapped electron cloud**</u>

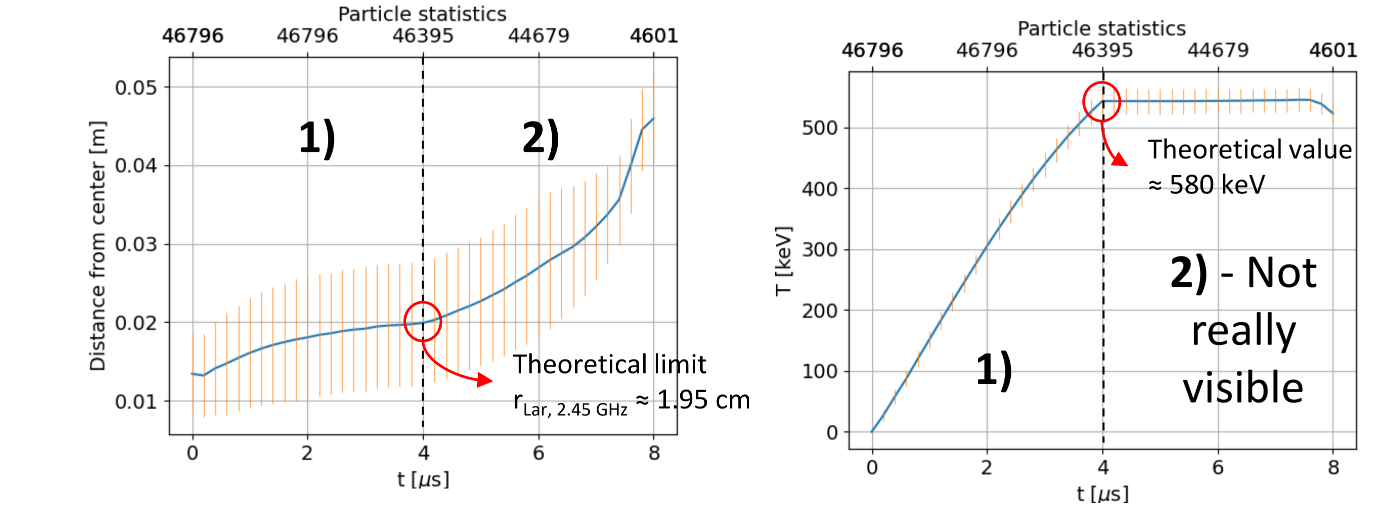
- **Theoretical behaviour**

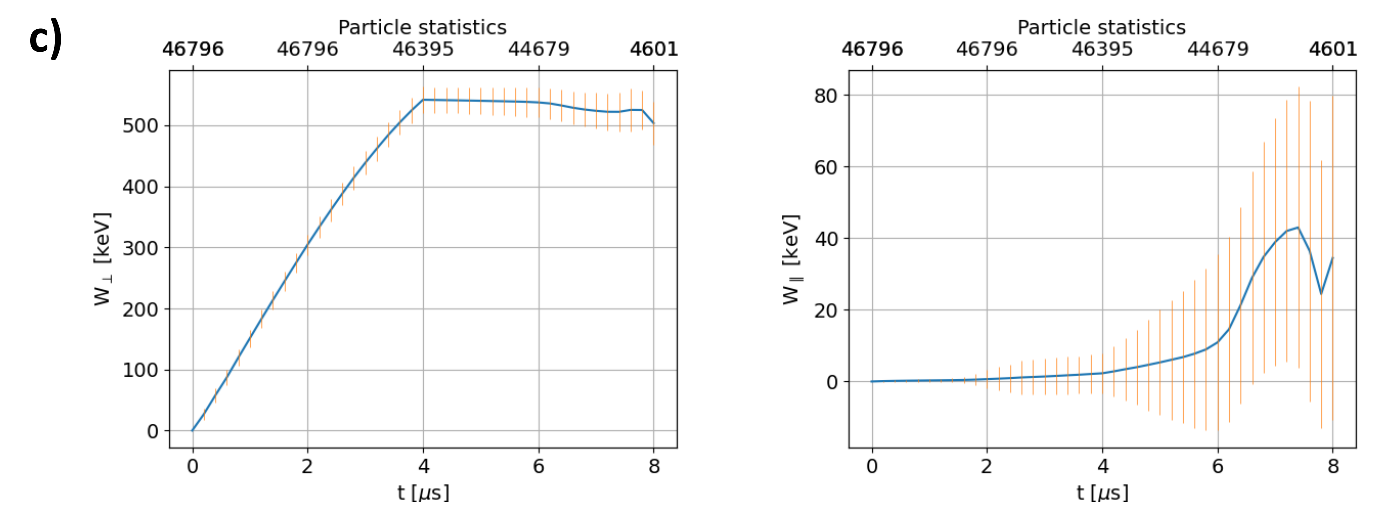
1) GA: ⇧ bunch dimension, ⇧ $T_{e^-,av}$.
2) Decompression: ⇧ bunch dimension, ⇩ $T_{e^-,av}$.

- **Observed behaviour**

a) Counter clockwise rotation of electron cloud (*N*) → **Verified.**
b) Only a fraction of electron trapped in GA (*N*+*E*) → **Next slides.**
c) Accumulation of ⊥ electron energy during GA (*N*+*E*).

N: Numerical results. - *E*: Experimental results.





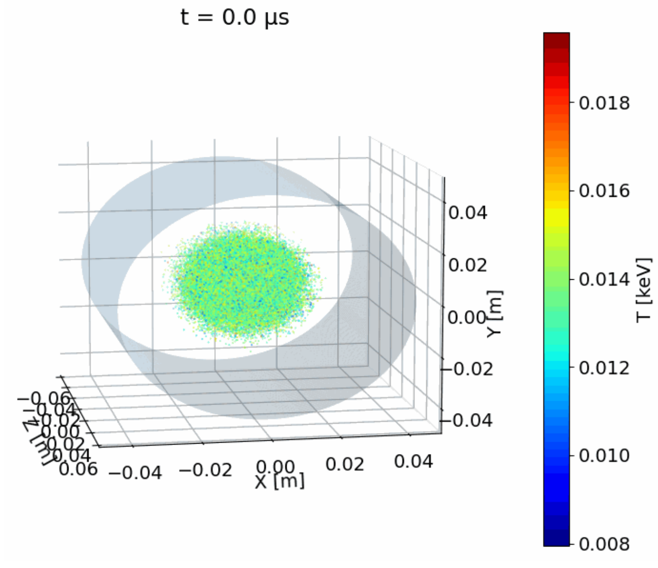
MC code main validation: Paper [3-5]

Electron cloud distribution

1) **Trapped electrons**: ring-like structure during decompression.
2) **Non-trapped electrons**: mostly located in the center.

Electron behaviour

a) **GA**: ⇧ r_{bunch}, ⇧ $T_{e^-,av}$.
b) **Decompression**: ⇧ r_{bunch}, ⇩ $T_{e^-,av}$.
c) De-trapping during GA.

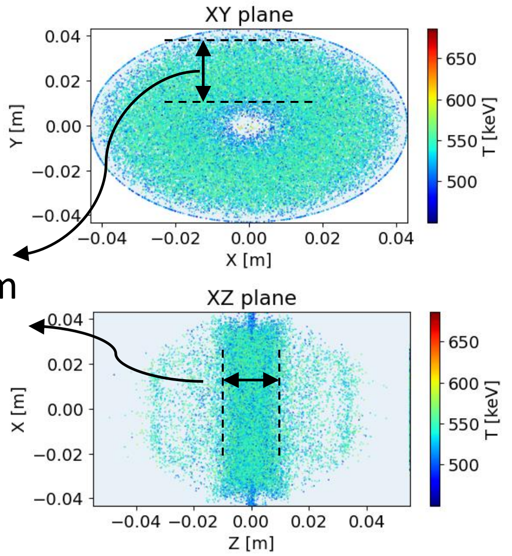


1)

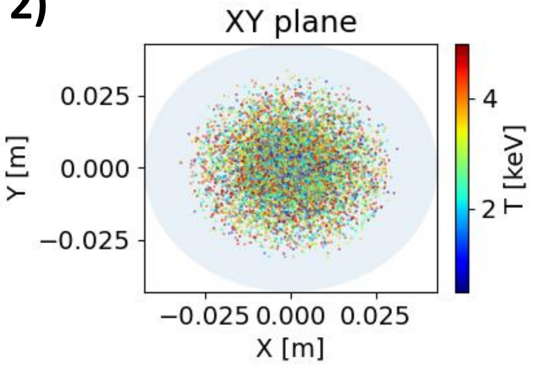
t = 6 μs

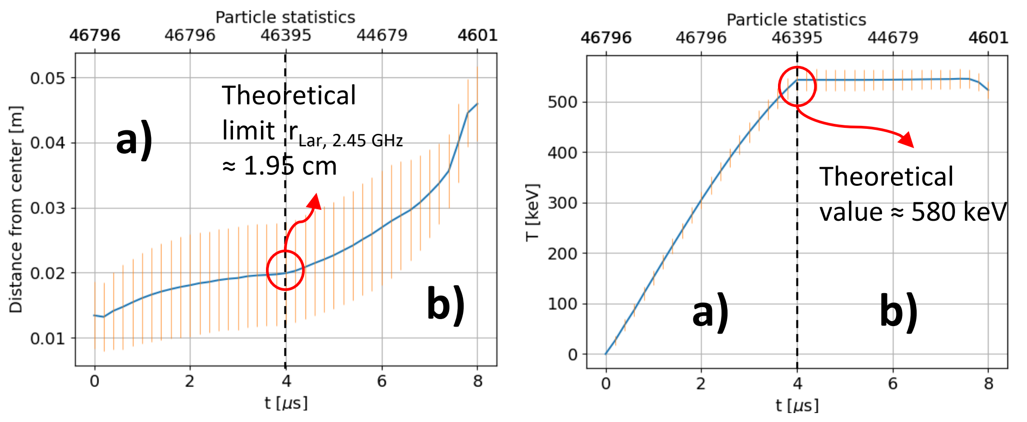
- $t_{radial} \approx 3$ cm
- $t_{axial} \approx 1.5$ cm

➢ Same values as PIC simulations!

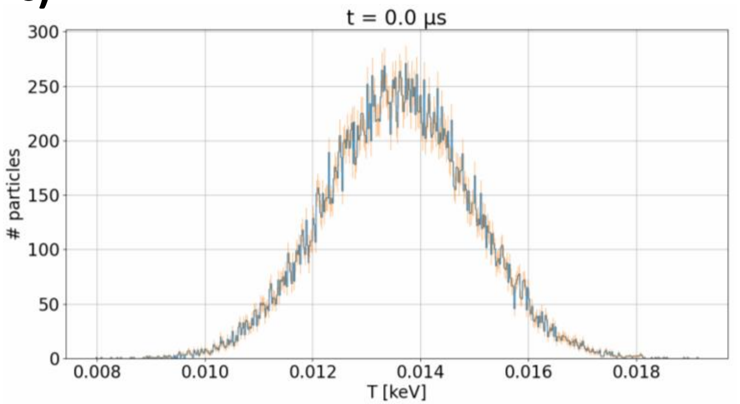


2)





c)

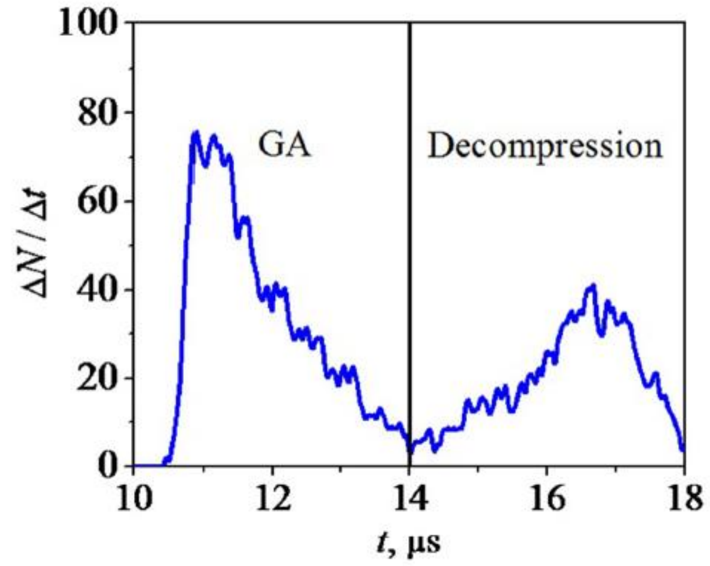


MC code main validation: Paper [3-5]

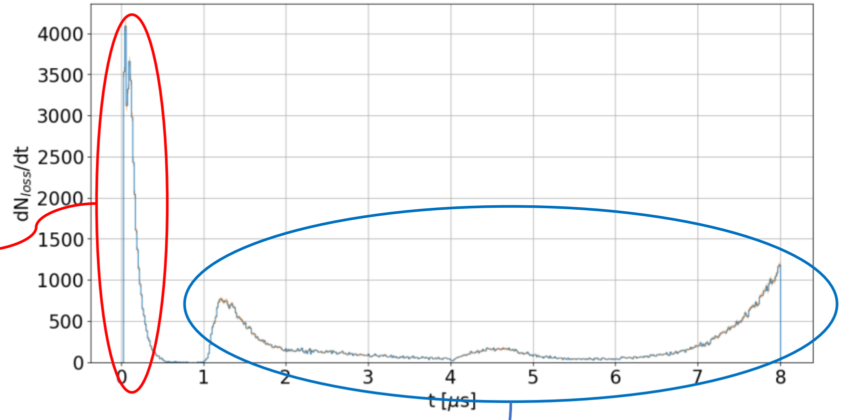
Electron losses both in Gyromagnetic Autoresonance (GA) and decompression.

➢ Possible discrepancies: PIC, low statistics.

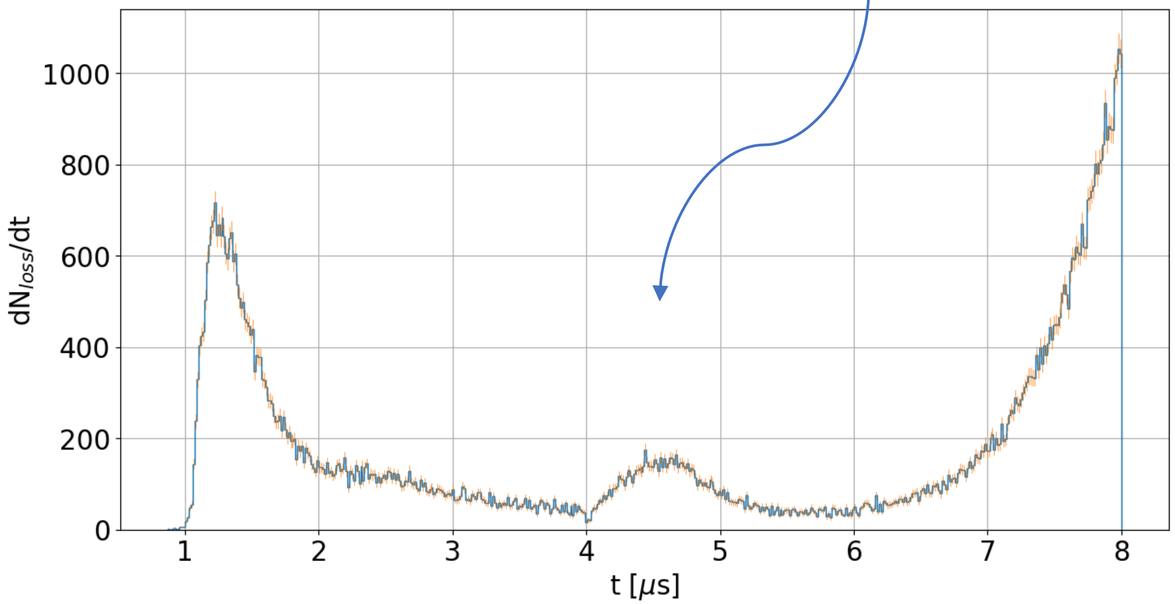
Andreev numerical results (nominal).



My results (nominal).



Electron losses due to I.C. and ECR

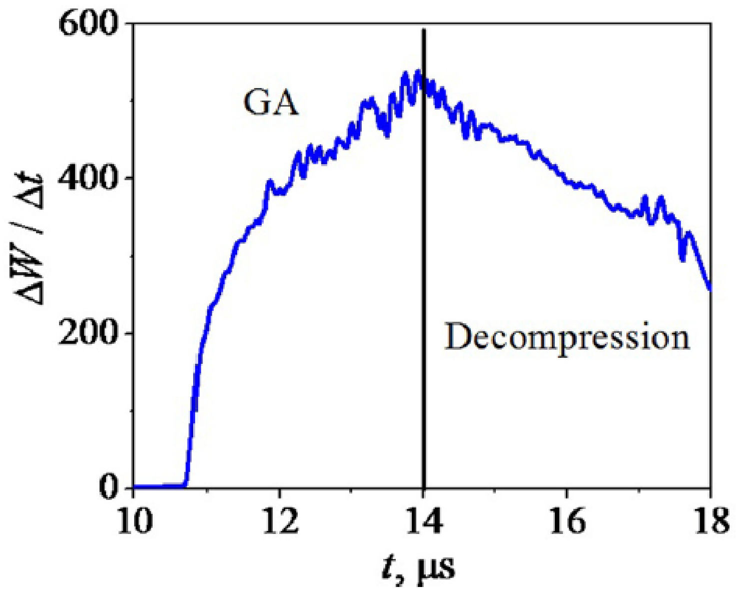


MC code main validation: Paper [3-5]

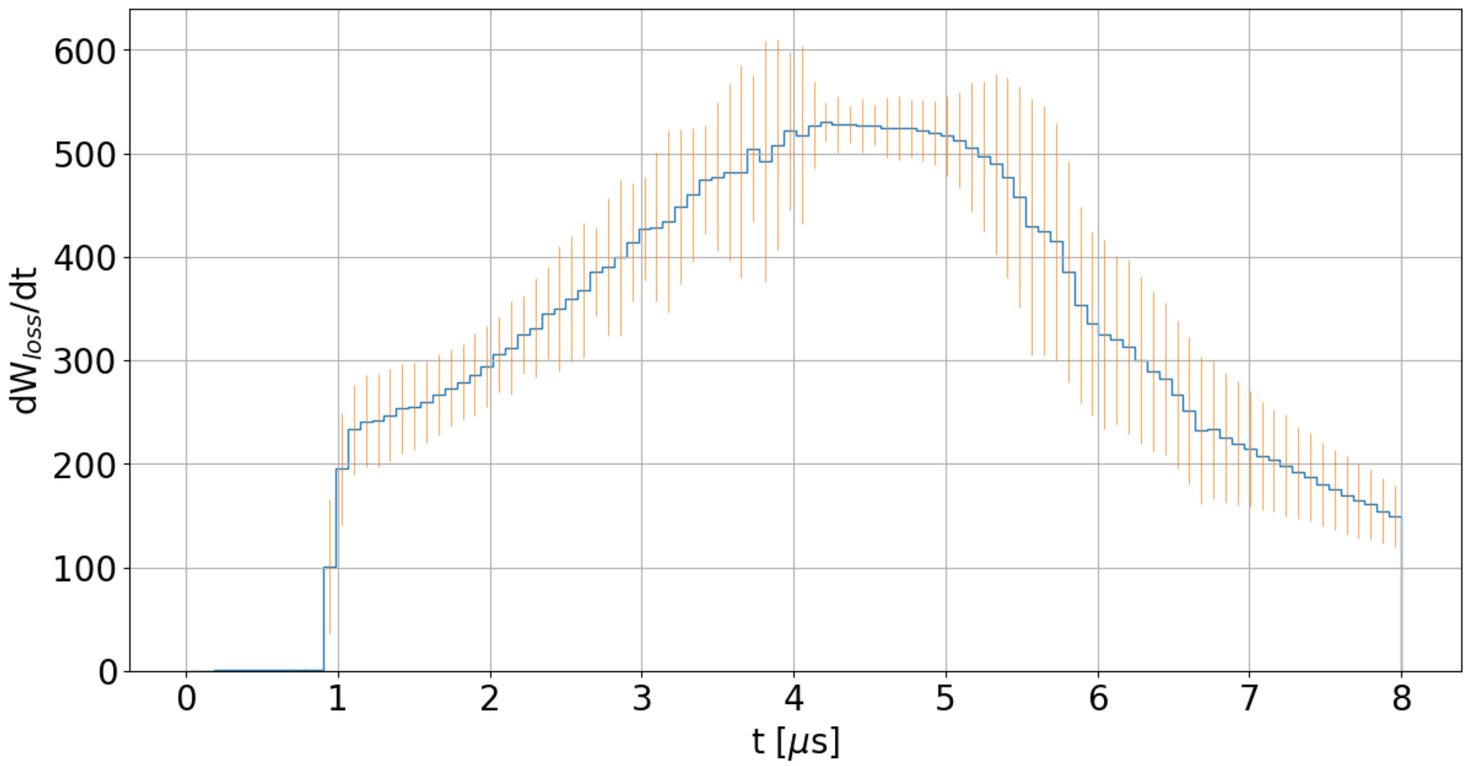
Maximum energy loss at the end of GA, decrease during decompression.

➢ Good agreement for **peak (≈ 500 keV)**, final value differs by ≈ 100 keV.

Andreev numerical results (nominal).



My results (nominal).



MC code main validation: Paper [3-5]

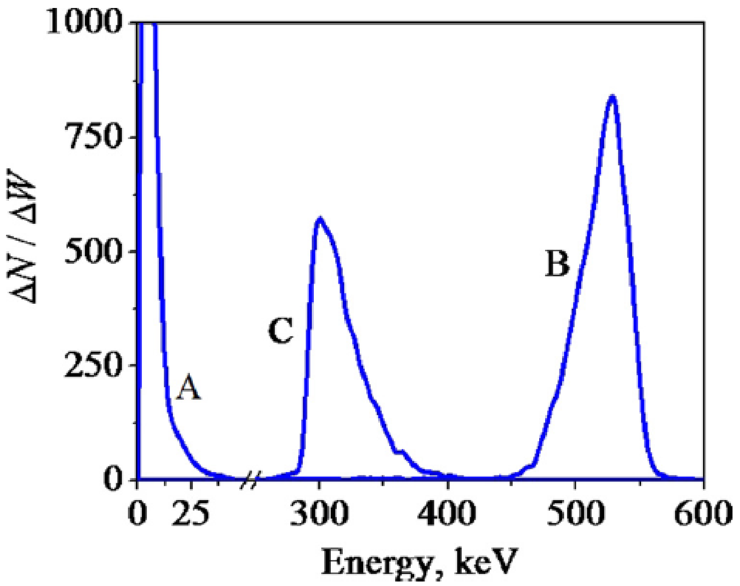
Spectrum peak of trapped electrons at ≈ **520 keV.**

- Very good agreement between simulations.

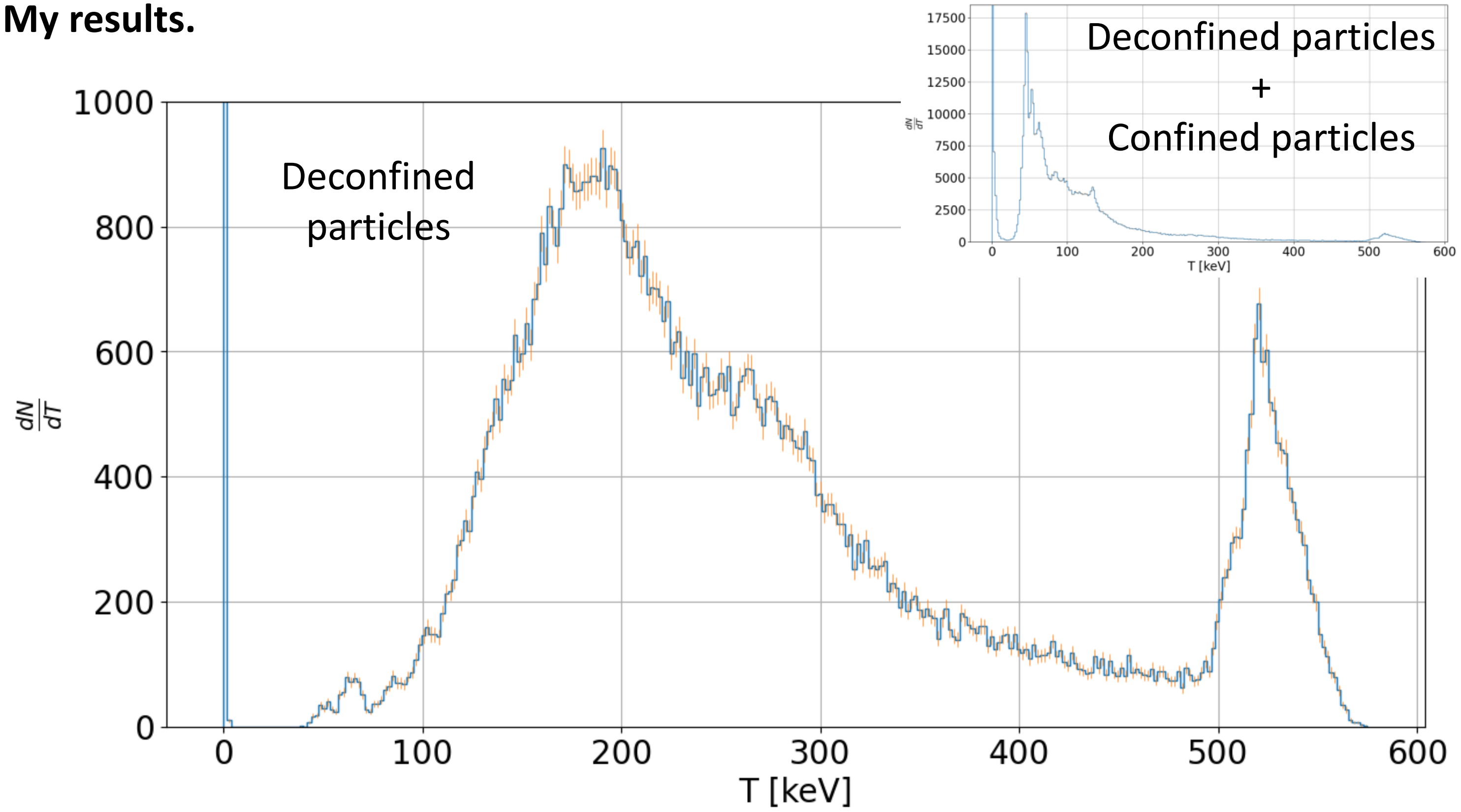
- A: Initial plasma electrons (due to ECR).
- B: Trapped electrons at end of GA.
- C: De-trapped electrons.

Andreev numerical results.

- A, B and C are spectrums at different stages.



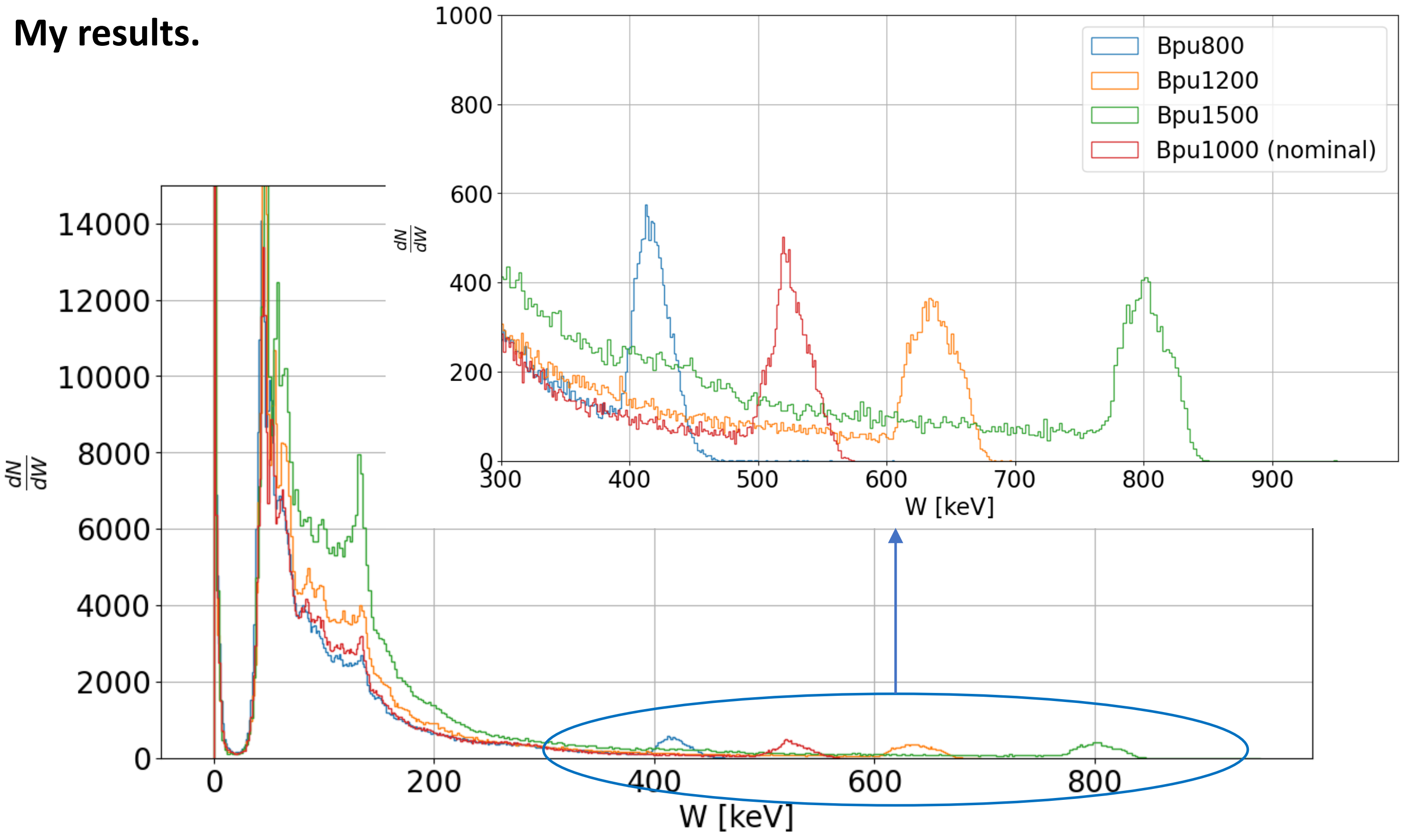
My results.



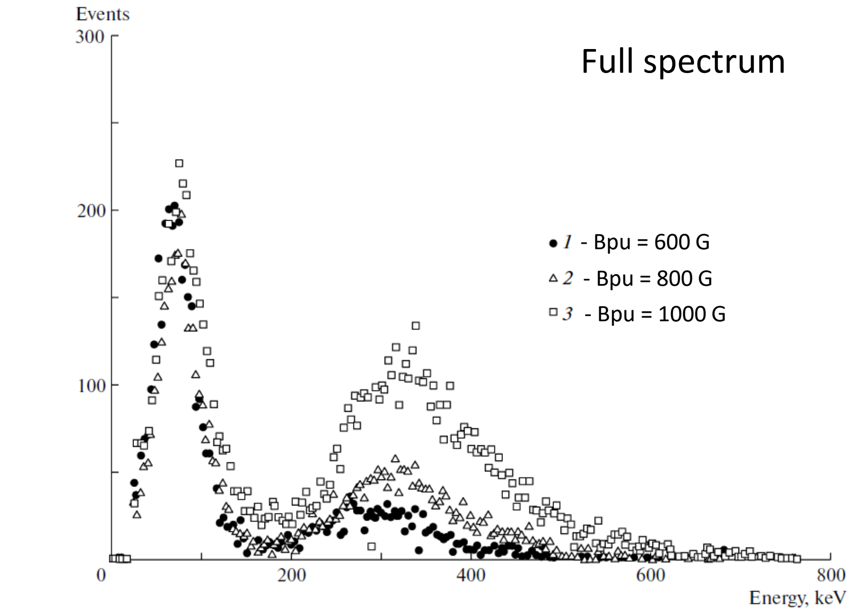
MC code main validation: Paper [3-5]

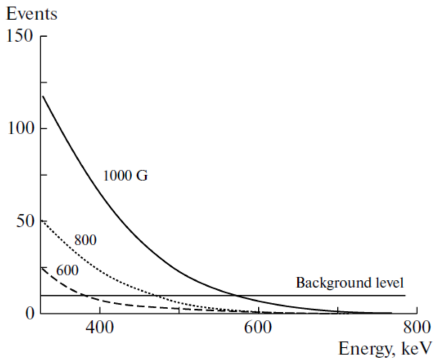
Electron energy **only** depends on amplitude of B_{pulsed}.

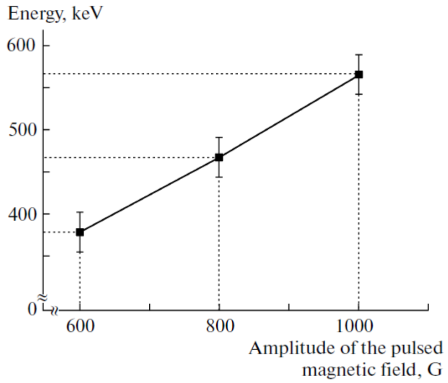
My results.



Andreev experimental bremsstrahlung results.



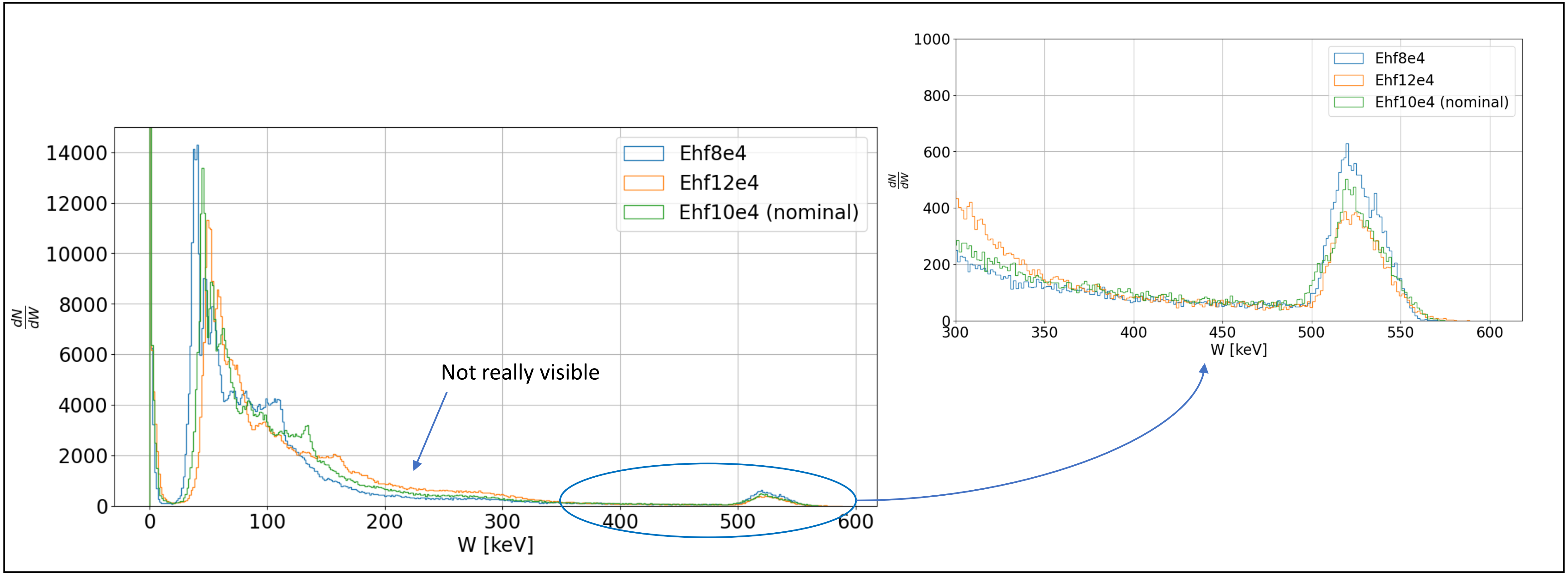




High-energy tail

MC code main validation: Paper [3-5]

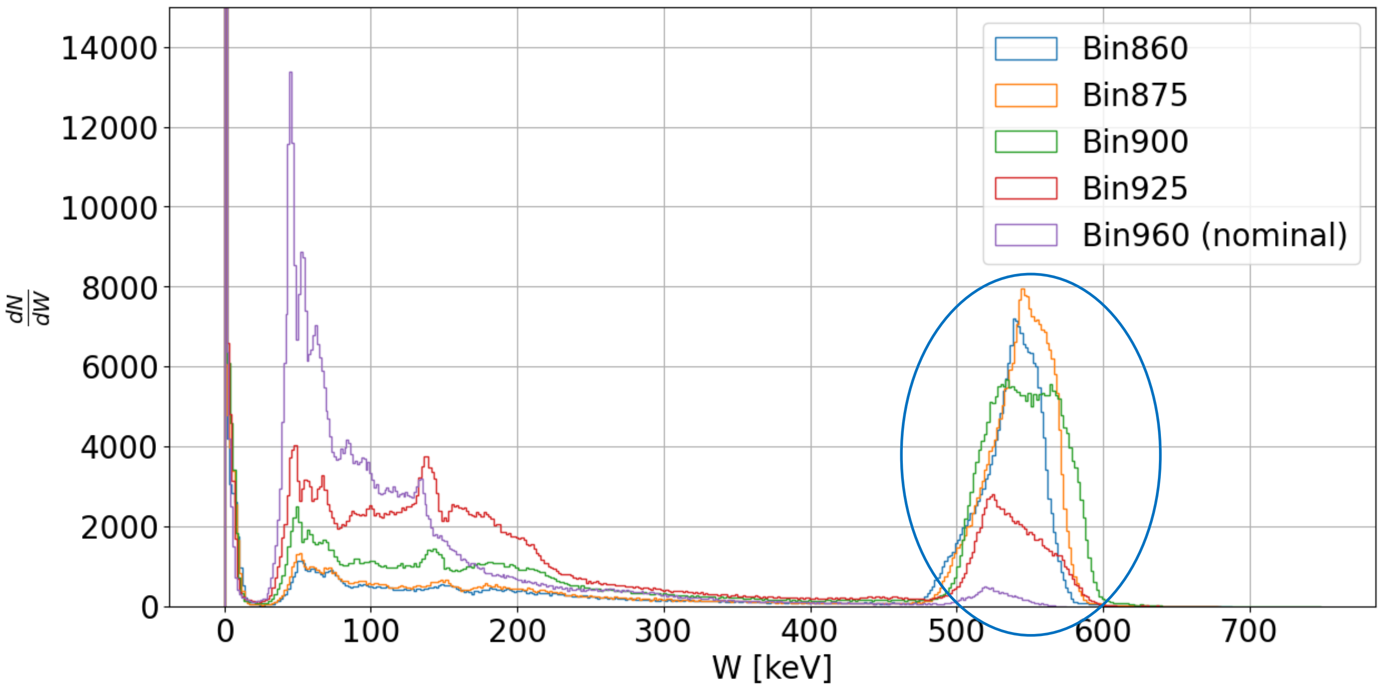
⇧ E_{HF} does **not** increase electron energy but leads to energy spreading.



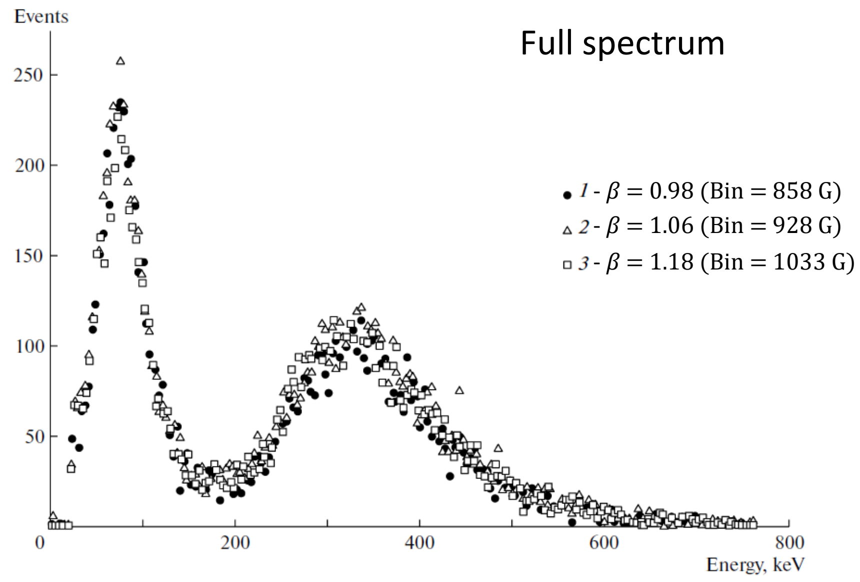
MC code main validation: Paper [3-5]

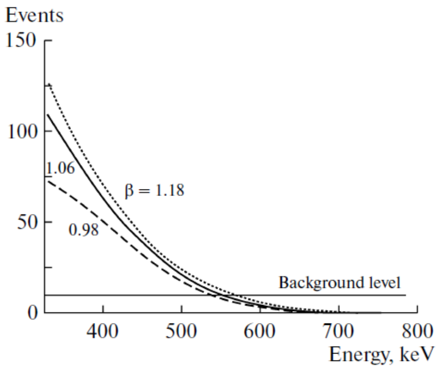
Electron energy does **not** depends on B_{in}.
➢ Trapping efficiency in GA influenced by $B_{initial}$.

My results.

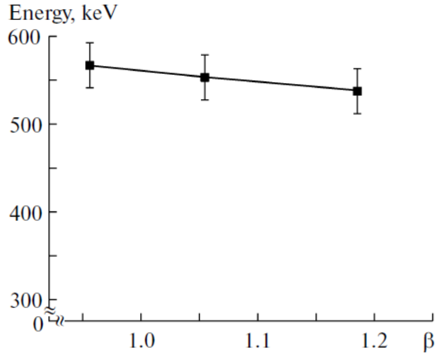


Andreev experimental bremsstrahlung results.





High-energy tail



Bremsstrahlung ultimate energy

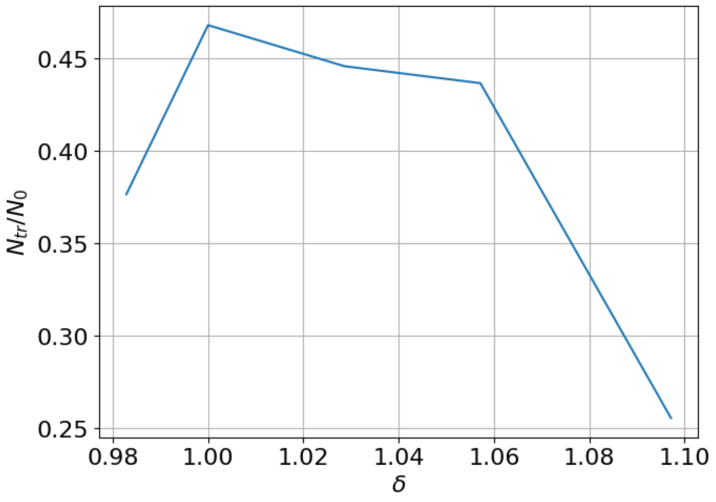
MC code main validation: Paper [3-5]

Trapping efficiency in GA depends on B_{in}.

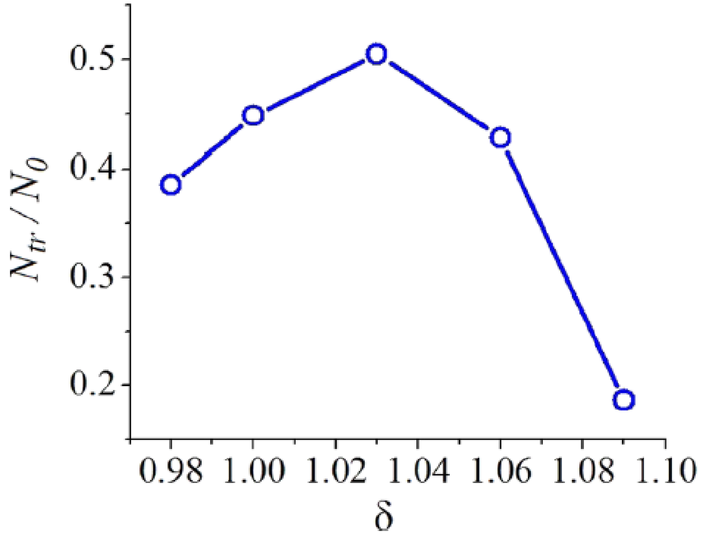
- Difficult to establish number of trapped particles due to de-trapping. → My criteria: T > 400 keV.
- B_{pu} = 1000 G and t_{pul} = 4 μs → $\alpha_{linear} = 1.85 \cdot 10^{-5}$, $\alpha_{sin} = 2.92 \cdot 10^{-5}$

$$\delta = B_{initial}(0,0)/B_{ECR}$$

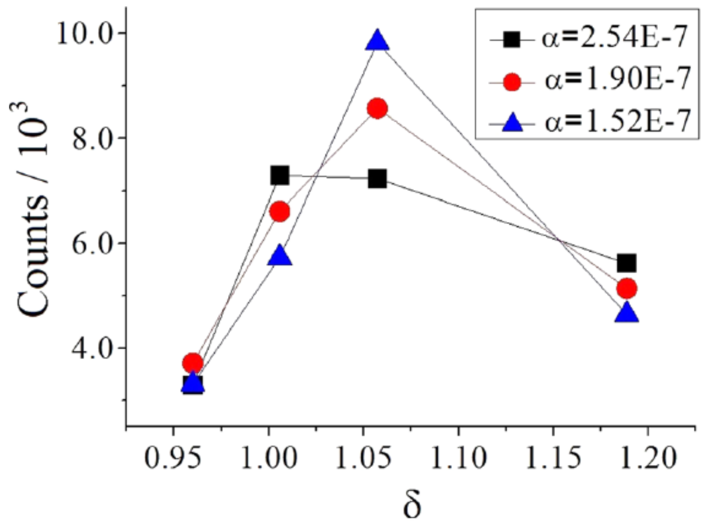
My results.



Andreev numerical results.



Andreev experimental results.



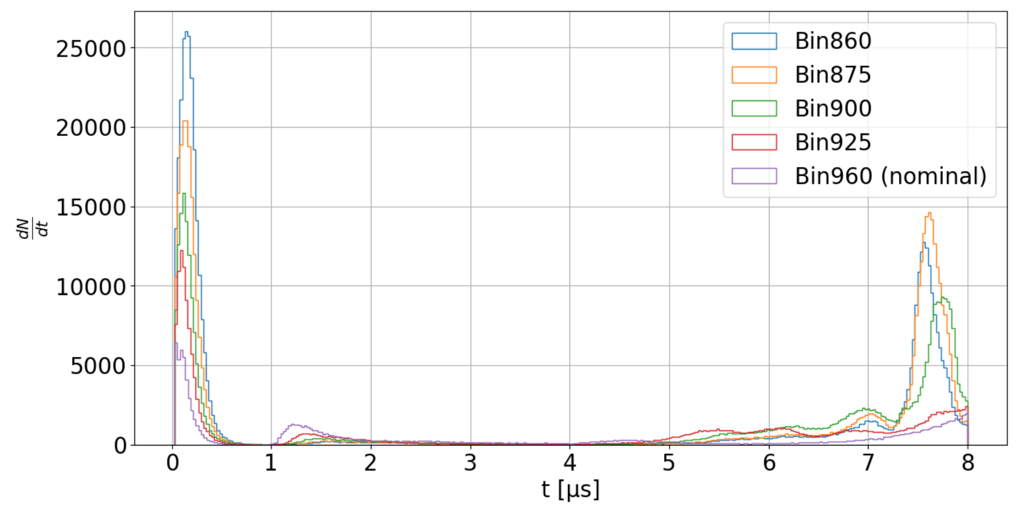
MC code Paper [3-5]: Loss spectrum

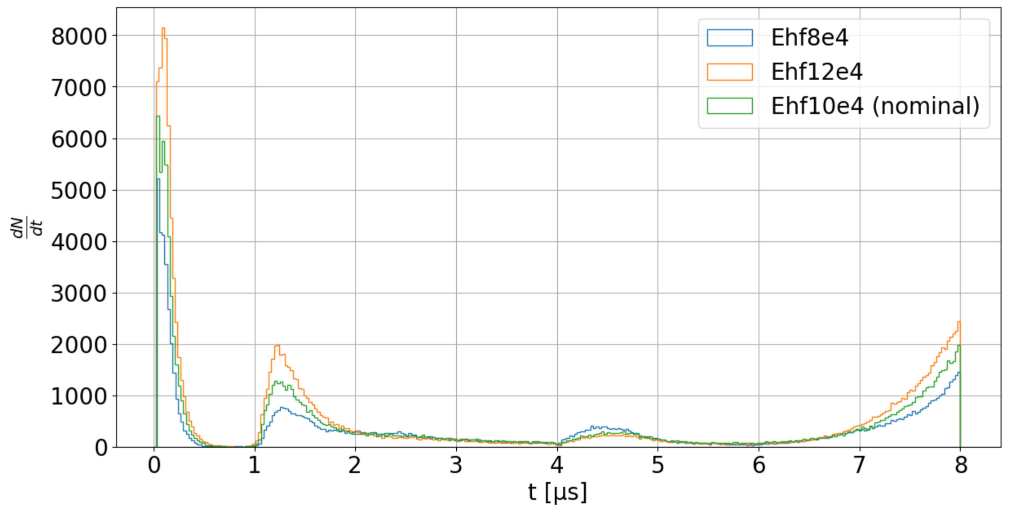
Parameters effect

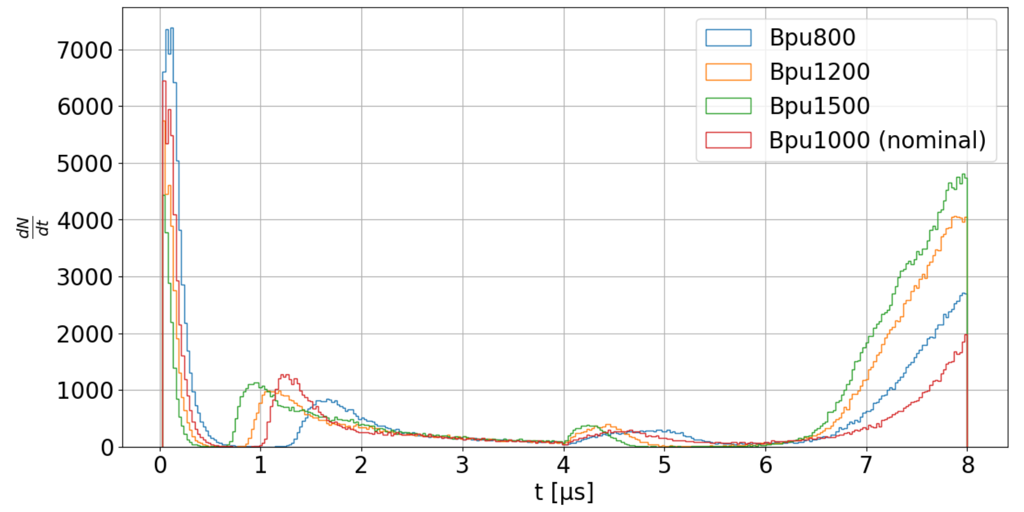
	ECR losses	GA losses	Dec. losses
⇧ Bin	⇩	⇧	⇩
⇧ Bpu	⇩	Shift ⇦	⇧
⇧ Ehf	⇧	⇧	⇧

ECR: Electron Cyclotron Resonance, GA: Gyromagnetic Autoresonance, Dec.: Decompression.

- ➢ Trends are not regular, in-depth study needed.







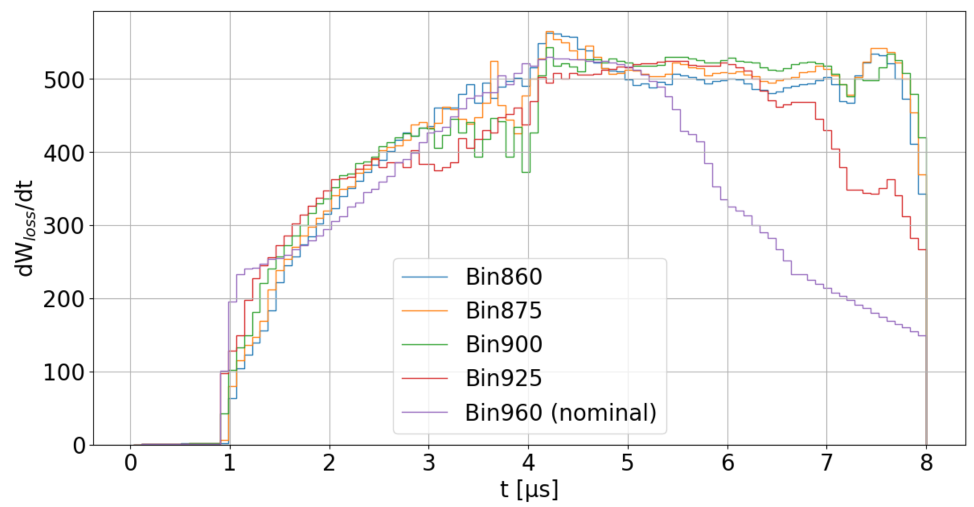
MC code Paper [3-5]: Average energy loss spectrum

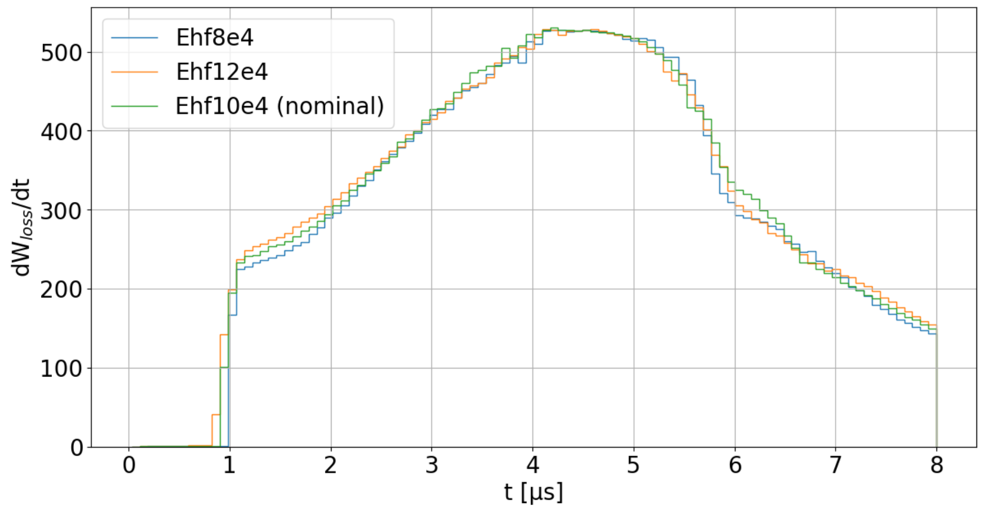
Parameters effect

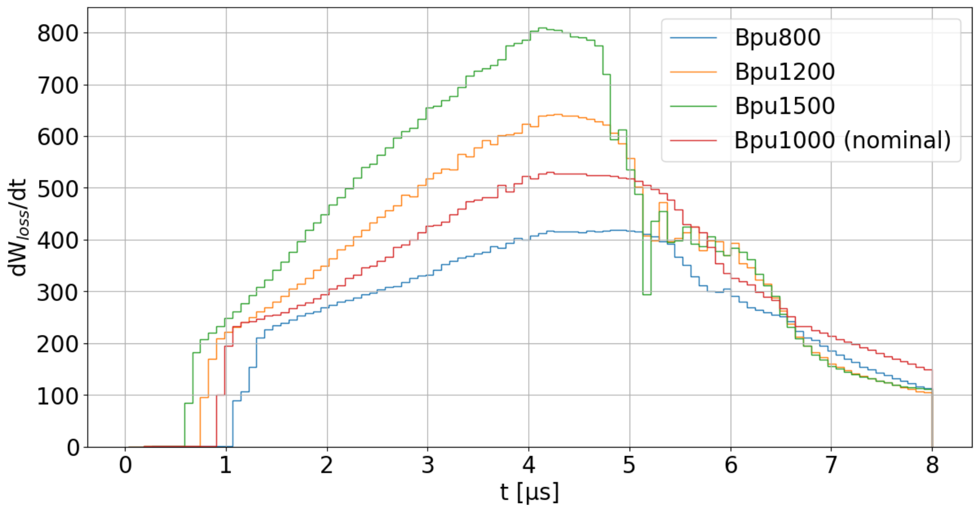
	GA av. E.L.	Dec. av. E. L.
⇧ Bin	No effect	⇩
⇧ Bpu	⇧, shift ⇦	Steeper decrease
⇧ Ehf	No effect	No effect

GA av. E.L.: Gyromagnetic Autoresonance average electron losses,
Dec. av. E.L.: Decompression average electron losses.

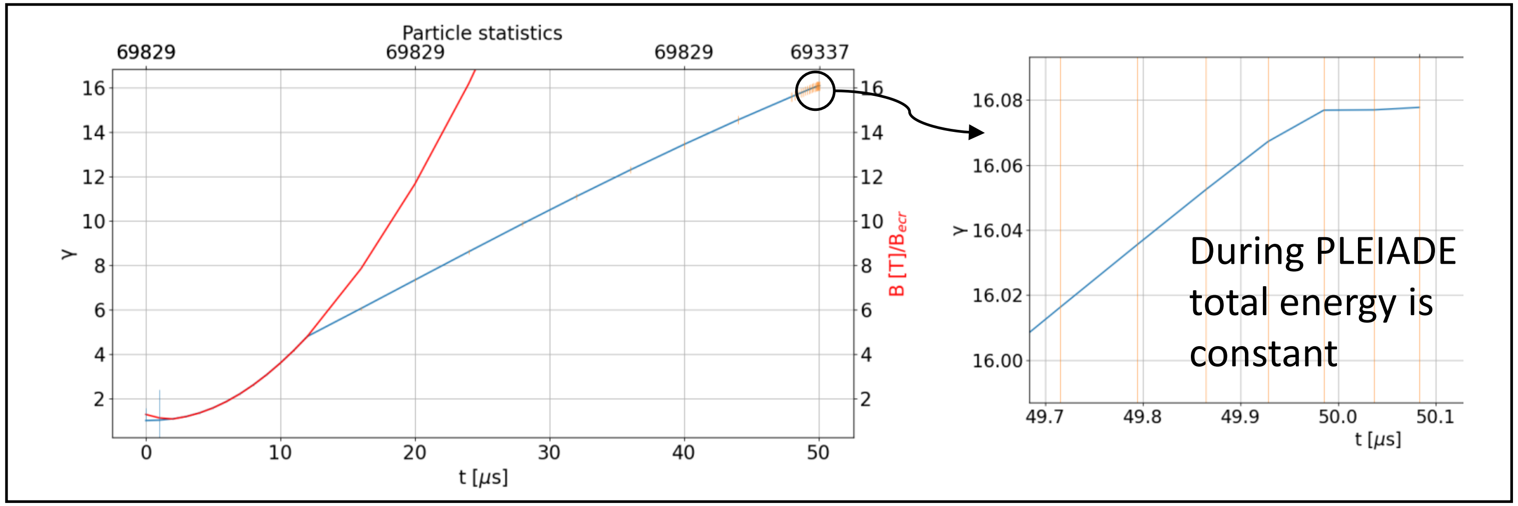
- Trends are not regular, in-depth study needed.

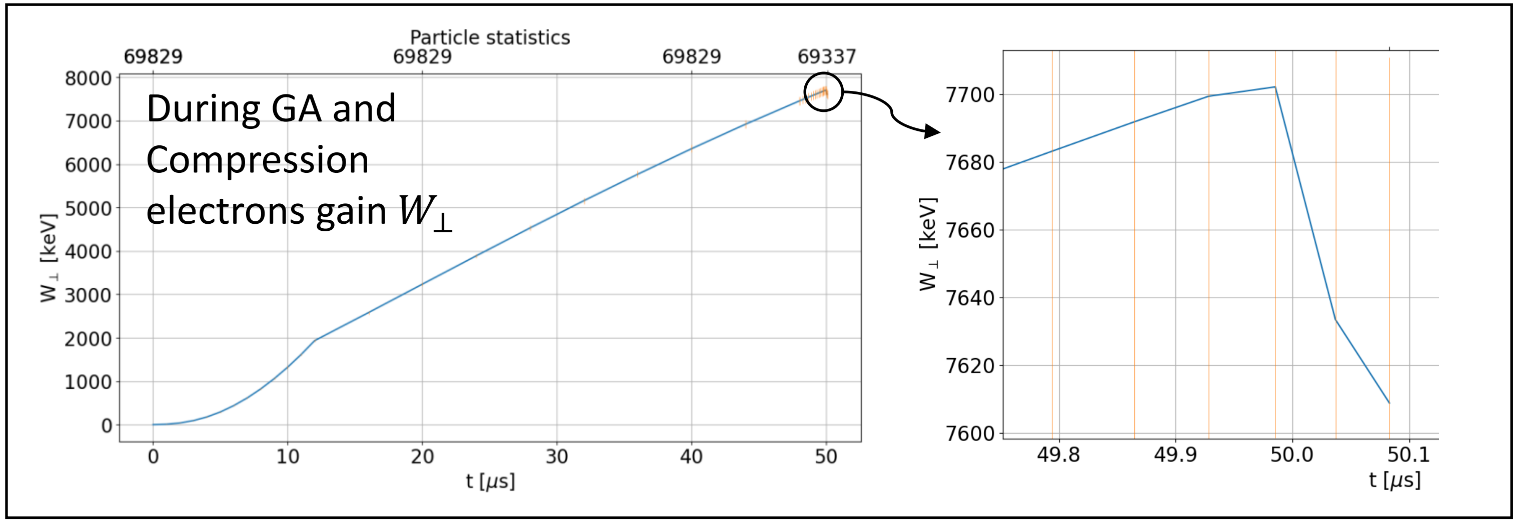


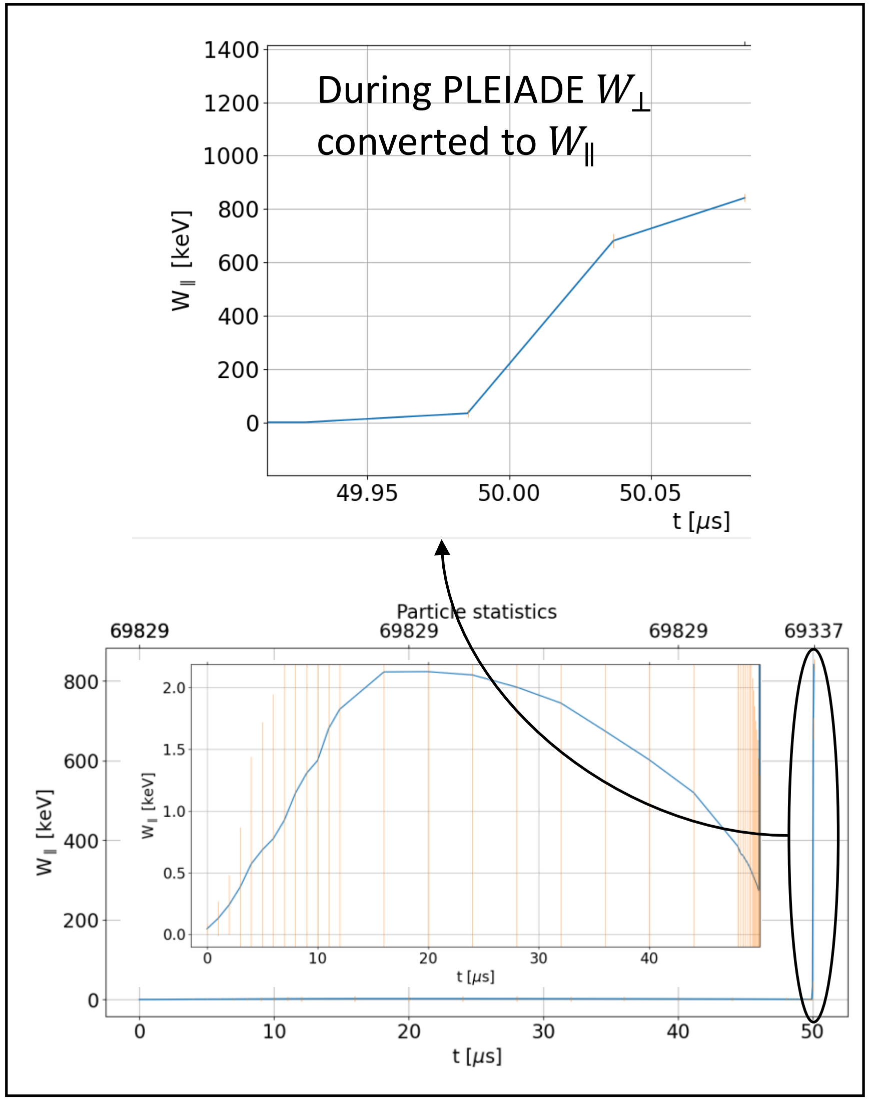




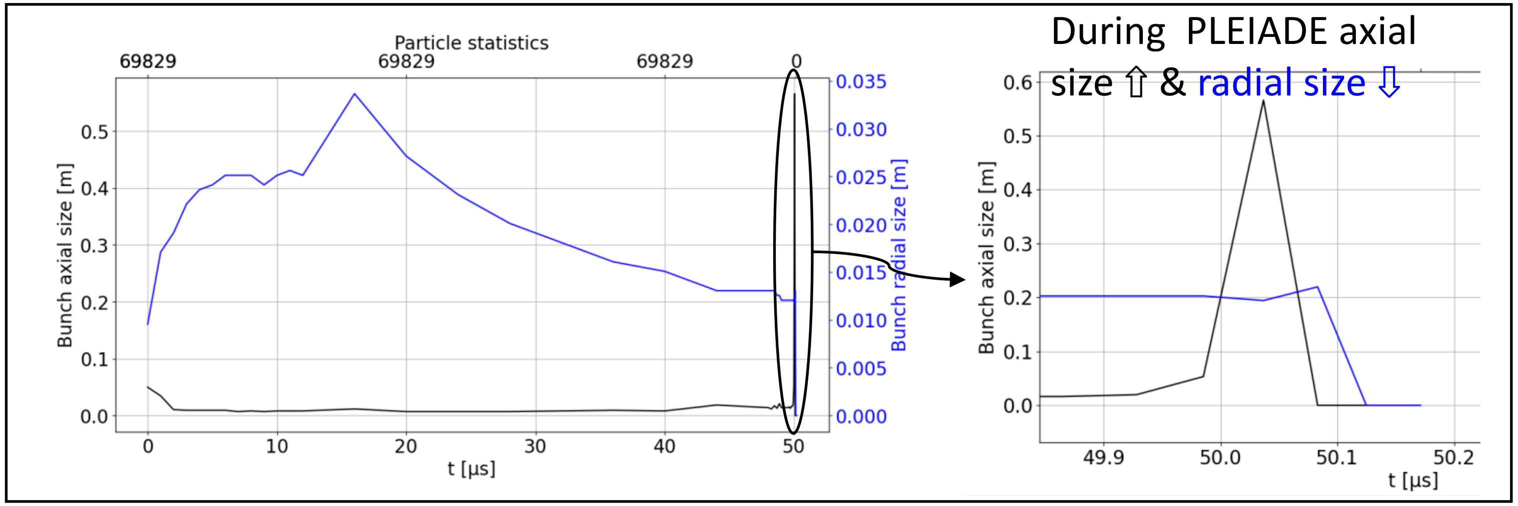
Monte Carlo simulations - Trapped electrons energy

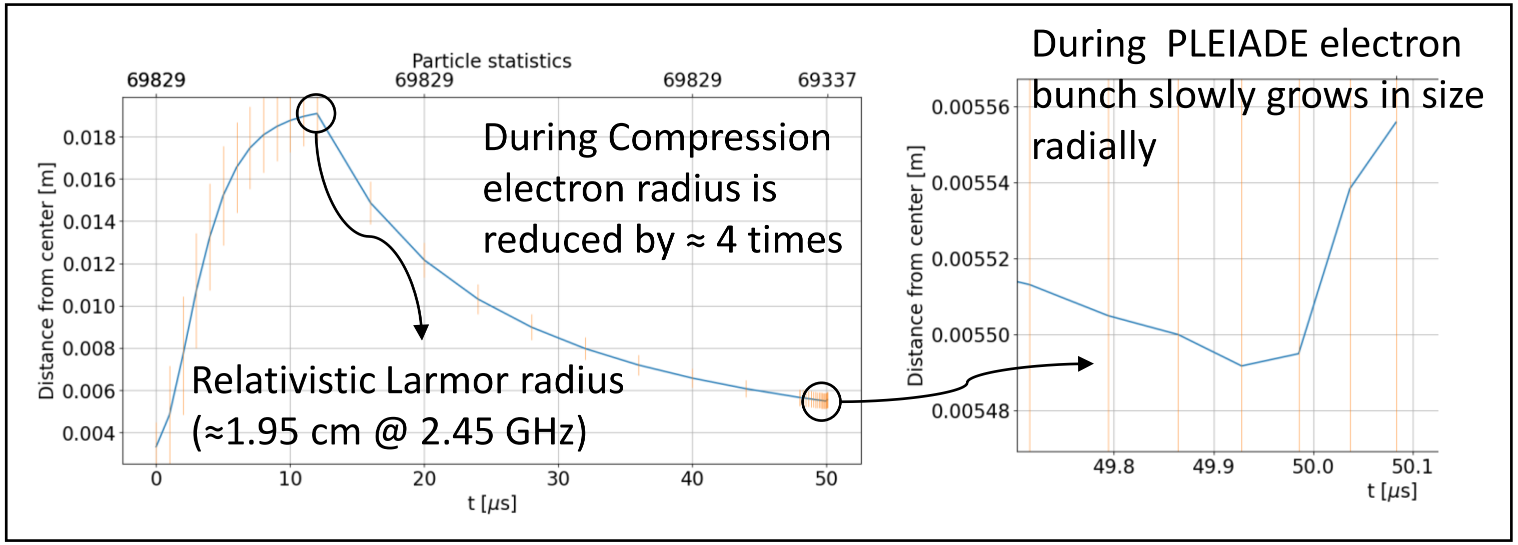


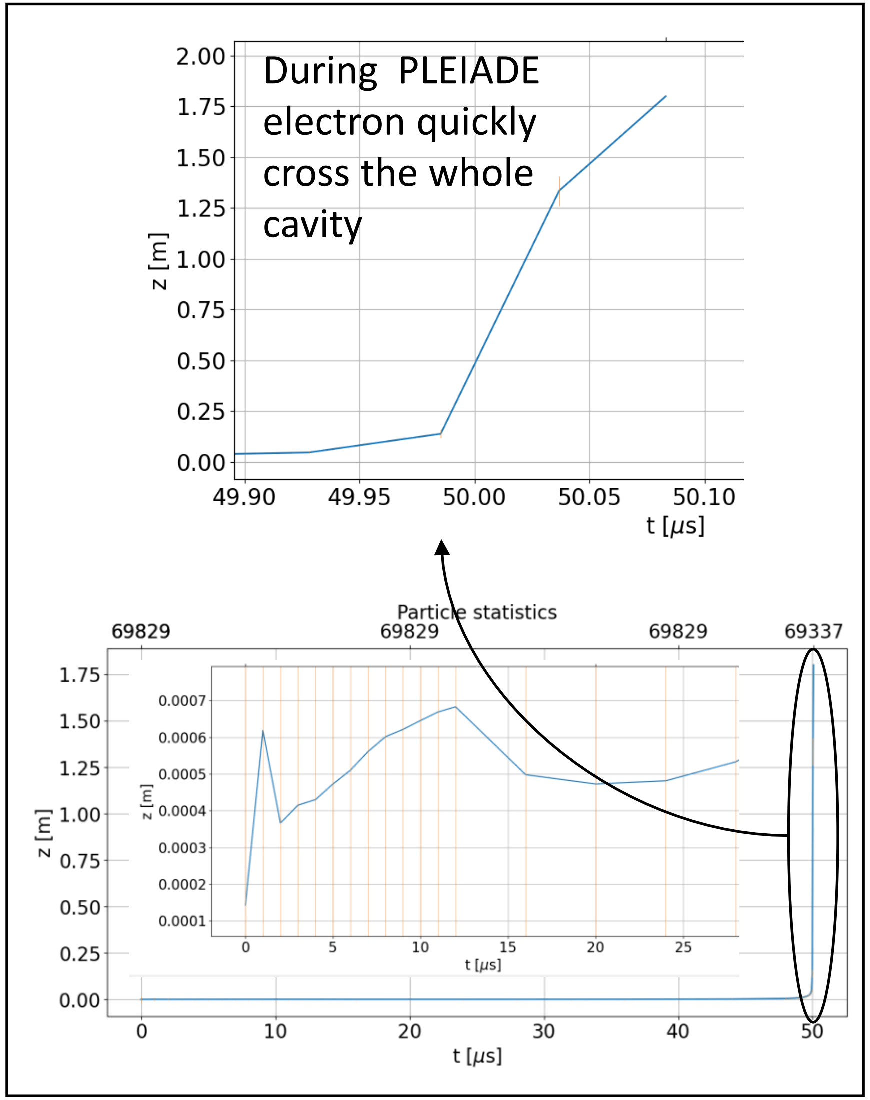




Monte Carlo simulations - Trapped electrons bunch size

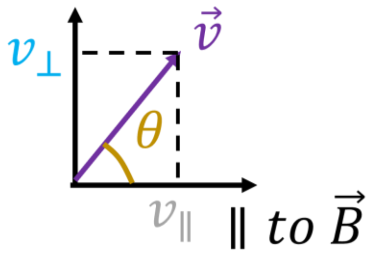






Parametric study – Initial pitch angle, length and radius of bunch

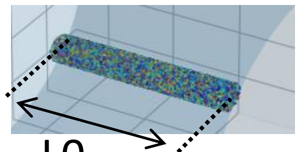
Initial velocity pitch angle



base: random point on sphere
Th_0: $\theta > 0$
Th_45: $\theta > 45°$
Th_85: $\theta > 85°$

- **No major influence** on the simulation.

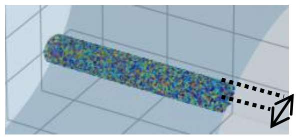
Initial cylinder length



L0_2: $L_0 = 2\ cm$
base: $L_0 = 5\ cm$
L0_Lcav: $L_0 = L_{cav}\ (8.64\ cm)$

- **No major influence** on the simulation.
- ➢ Lower trapping (-3%) in L0_Lcav due to e^- generated nearby walls.

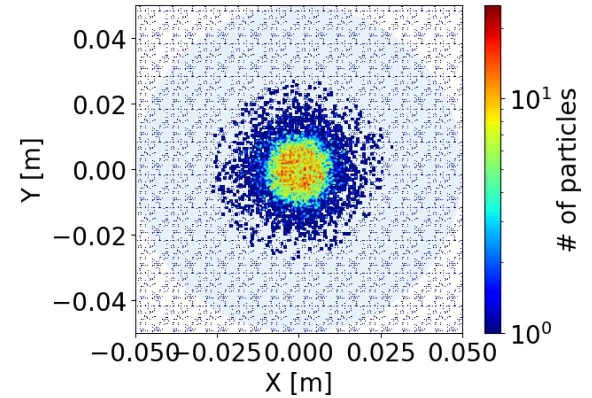
Initial cylinder radius



base: $R_0 = 5\ mm$
R0_15: $R_0 = 15\ mm$
R0_30: $R_0 = 30\ mm$

Simul.	% conf.	% trap. SGA
base	76.89%	71.81%
R0_15	38.38%	30.60%
R0_30	17.29%	12.19%

R0_30 – Trapped electrons only



- ⇧ $\boldsymbol{R_0}$ leads to **lower trapping and confinement**.
- ➢ **Missing effect**: in Kube PIC simulation ⇩ $\boldsymbol{R_0}$ leads to **larger ion losses**.

Parametric study – TE_{mnp} mode, Time-step

TE_{mnp} mode

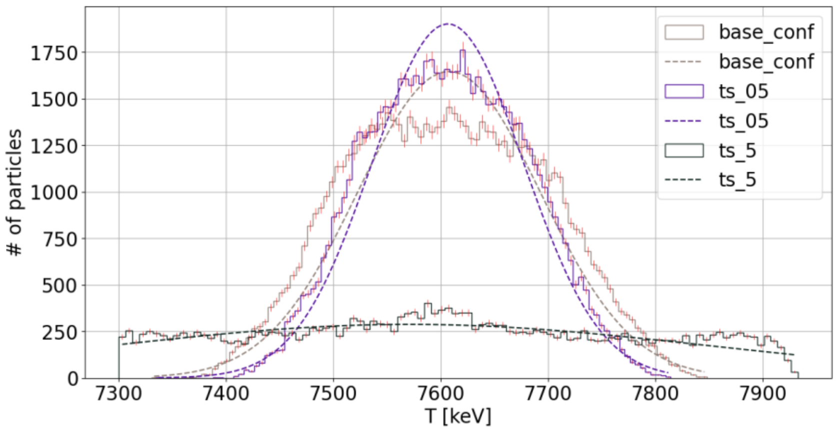
base: $TE(1)(1)(1)\ mode$
TE_1110: $TE(1)(1)(10)\ mode$

- **No major influence** on the simulation.
- ➢ Slightly lower trapping (-5%) for TE_1110.
- ➢ Higher p modes are needed for longer cavities.

Time-step

ts_05: $ts = 0.5\ ps$
base: $ts = 1\ ps$
ts_5: $ts = 5\ ps$

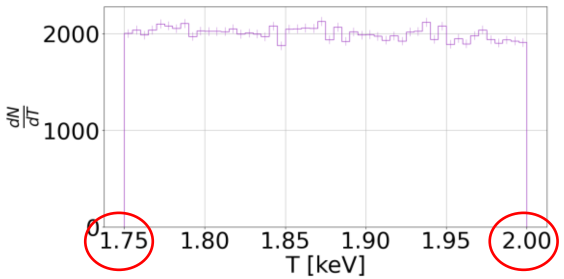
Simul.	% conf.	% trap. SGA	T0 [keV]	σ [keV]
ts_05	77.16%	72.49%	7606	71
base	76.89%	71.81%	7608	85
ts_5	72.51%	32.18%	7570	277



- **ts_5 breaks down simulation.**
- ➢ ts_05 improves energy dispersion, but **base** is a **better** trade-off due to **computational cost**.

Parametric study – Initial electron energy

IC energy range limits



base: $50\ eV < E_0 < 250\ eV$
E0_750_1000: $750\ eV < E_0 < 1000\ eV$
E0_1750_2000: $1750\ eV < E_0 < 2000\ eV$
E0_2750_3000: $2750\ eV < E_0 < 3000\ eV$
E0_3750_4000: $3750\ eV < E_0 < 4000\ eV$
E0_4750_5000: $4750\ eV < E_0 < 5000\ eV$

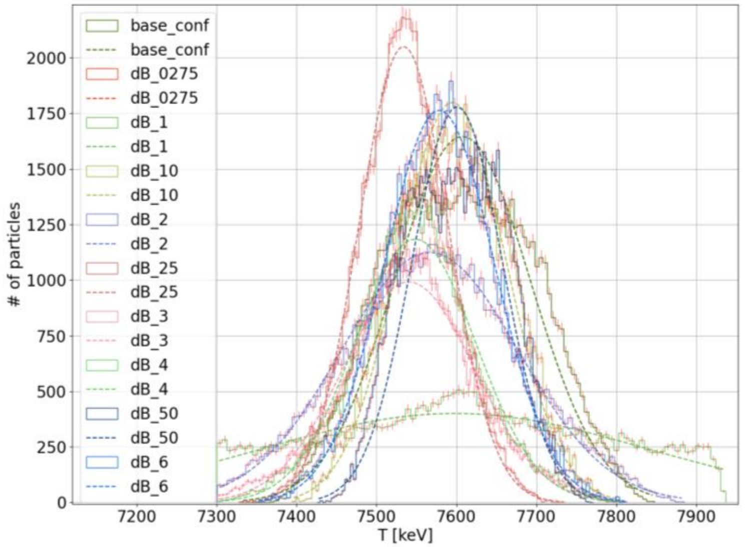
Simul.	% conf.	% trap. SGA
base	76.89%	71.81%
E0_750_1000	82.10%	61.15%
E0_1750_2000	81.84%	50.77%
E0_2750_3000	80.17%	47.19%
E0_3750_4000	78.45%	46.46%
E0_4750_5000	77.09%	46.01%

- ⇧ $\boldsymbol{E_0}$ leads to **worse trapping** in SGA.
  - ➢ **Closer to theory hyp.** considering electrons at rest.
  - ➢ Also lower confinement with exception of base.

Parametric study – Magnetic field growth rate

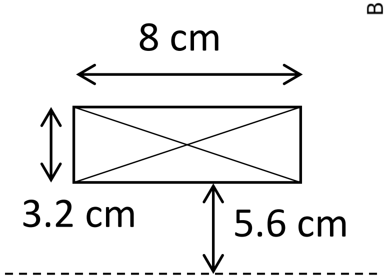
Simul.	f_{pul} [kHz]	dB/dt [G/ns]	% conf.	% trap. SGA	T0 [keV]	σ [keV]
dB_0275	0.275	0.05	93.75%	0%	-	-
dB_1	1	0.20	71.60%	39.15%	7598	240
dB_2	2	0.39	57.77%	53.69%	7567	111
dB_3	3	0.59	44.40%	40.68%	7540	82
dB_4	4	0.79	48.85%	44.86%	7549	76
base	5	0.98	76.89%	71.81%	7608	85
dB_6	6	1.18	70.81%	66.78%	7579	69
dB_10	10	1.97	80.85%	75.06%	7595	67
dB_25	25	4.91	77.24%	71.21%	7534	56
dB_50	50	9.82	91.76%	78.82%	7601	57

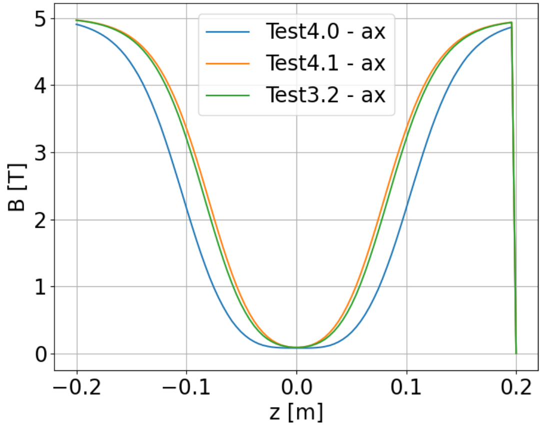
- $f_{pul} < 5$ **kHz** leads to **worse trapping and confinement** of the electrons in general.
- **Similar findings** to Kube **PIC simulation**.
- ➢ dB_50 having the best results is good news for the PIC simulation (lower computational cost).

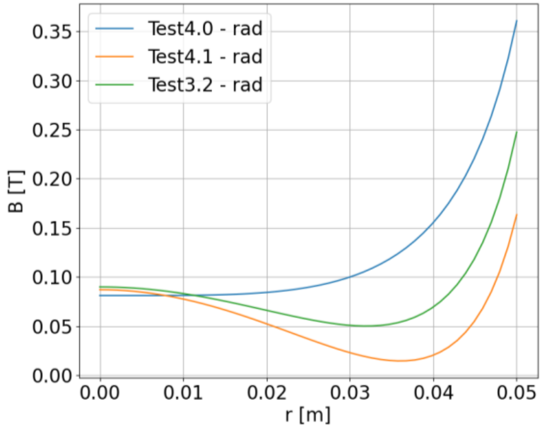


Parametric study – Pulsed coil length

- **Test4.0 – Longer pulsed coils**: longer magnetic mirror, but more regular radial field profile.
- **Test4.1 – Shorter pulsed coils**: shorter magnetic mirror, but less regular radial field profile.
- **Test3.2 – base_configuration**: compromise between the two.

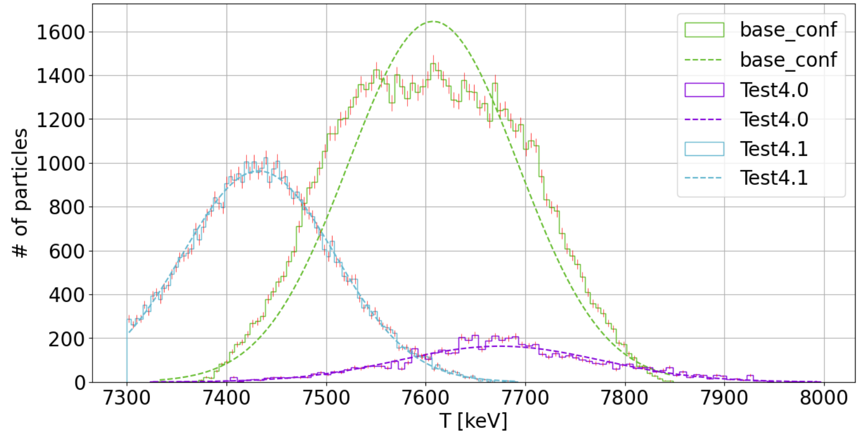






- **GA** very **sensitive** to **magnetic field profile**.
  - ➢ Longer magnetic mirror is simply not able to confine particles.

Simul.	% conf.	% trap. SGA	T0 [keV]	σ [keV]	dr [cm]	dz [cm]
base	76.89%	71.81%	7608	85	1.3	1.6
Test4.0	13.53%	6.69%	7674	102	1.3	2.8
Test4.1	65.25%	47.51%	7432	76	1.3	1.6



PLEIADE phase