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(A SIMPLE) INVESTIGATION ON THE ORIGIN OF HIGH ENERGY X-RAYS OBSERVED IN 3RD GEN. ECRIS

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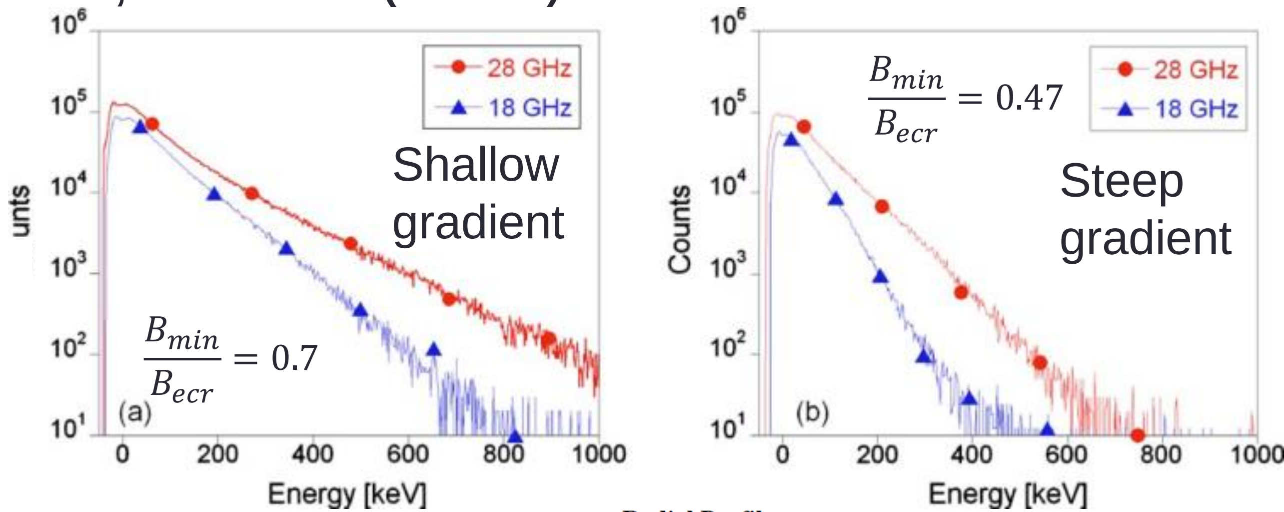
OUTLINE

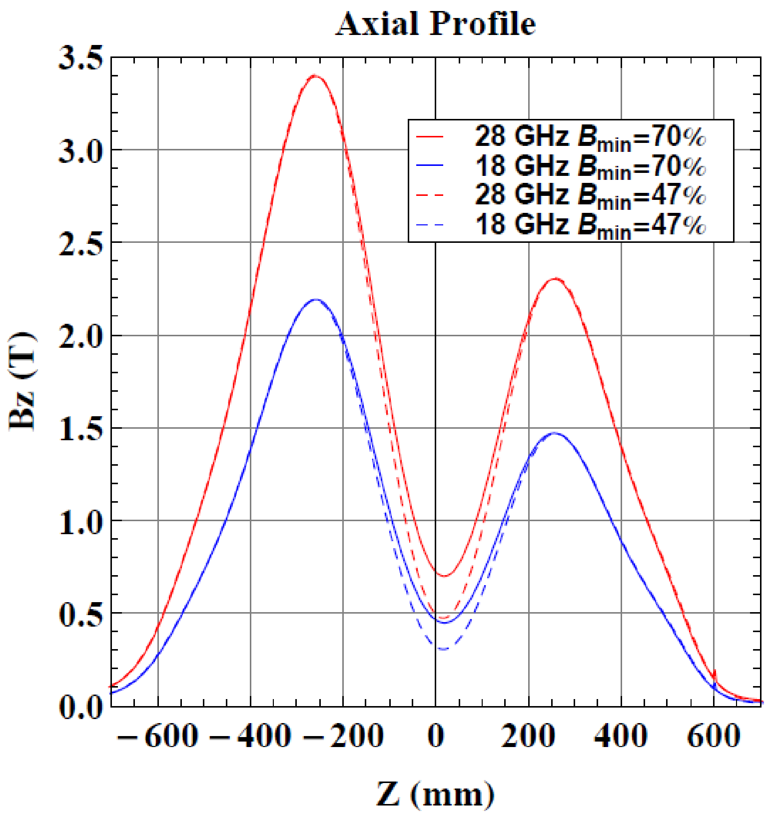
- VENUS Hot x-ray data revisitation
- Possible origin for hot x-rays in ECRIS
- A simple model to investigate hot electrons origin
- Model testing with VENUS data
- Conclusion

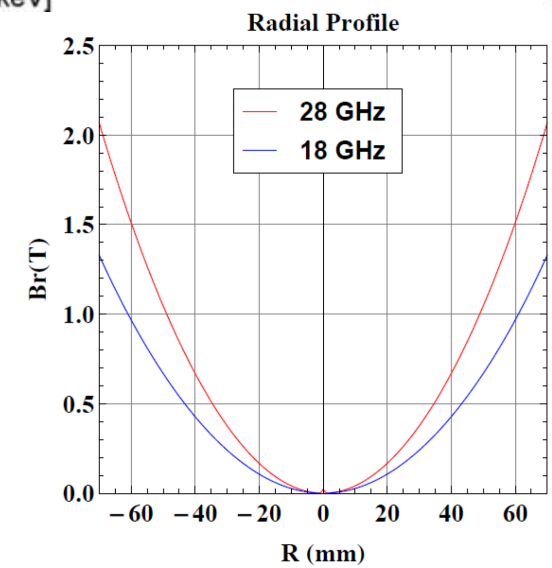
Experimental x-ray spectrum data from VENUS

- Rev. of Scient. Instrum. **79**, 033302 (2008)

FIG. 6. (Color online) Comparison of the bremsstrahlung spectra for 28 GHz heating to 18 GHz heating at scaled fields with a B_{min}/B_{ECR} of 0.70 (a) and 0.47 (b).

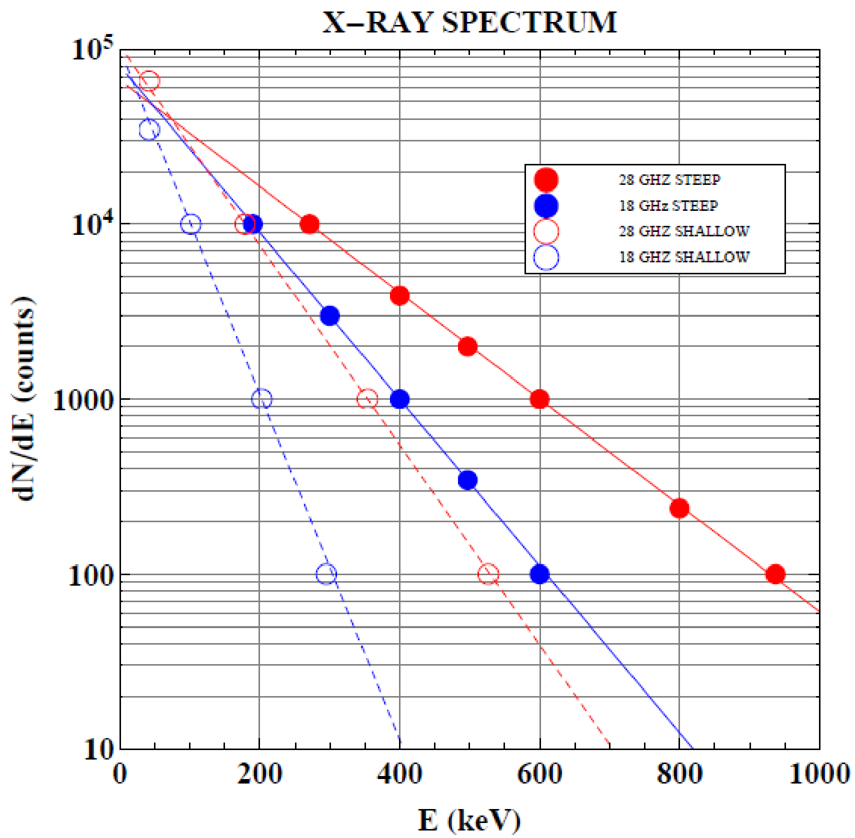






X-RAY hot tail spectrum fit

- Boltzmann energy distribution with a temperature kT :
  (Fit estimated from the paper plot)
  - Hot electron tail: $\frac{dN}{dE} = N_0 e^{-\frac{E}{kT}}$
  - 18 GHz: Shallow $kT \sim 91.2 \pm 2\ keV$
    Steep $kT \sim 47.7 \pm 2\ keV$
  - 28 GHz: Shallow $kT \sim 139.5 \pm 2\ keV$
    Steep $kT \sim 72.7 \pm 2\ keV$



- Axial Magnetic Mirror ratio:
  - Steep : R_{inj}=7.44 R_{ext}=4.9 R_{rad}=4.47
  - Shallow: R_{inj}=4.85 R_{ext}=3.28 R_{rad}=3

The hot x-ray tail temperature scales with… f_{ECR}

- Comparison of the x-ray tail plots
  - Plots normalized → same max. intensity
    - Consider that each hot electron undergoes an energy boost when $f_{ECR}: 18 \rightarrow 28\ GHz$
  - For a given x-ray flux intensity:

$$e^{-\frac{E_2}{kT_2}} = e^{-\frac{E_1}{kT_1}} \Rightarrow E_2 = E_1 \frac{kT_2}{kT_1}$$

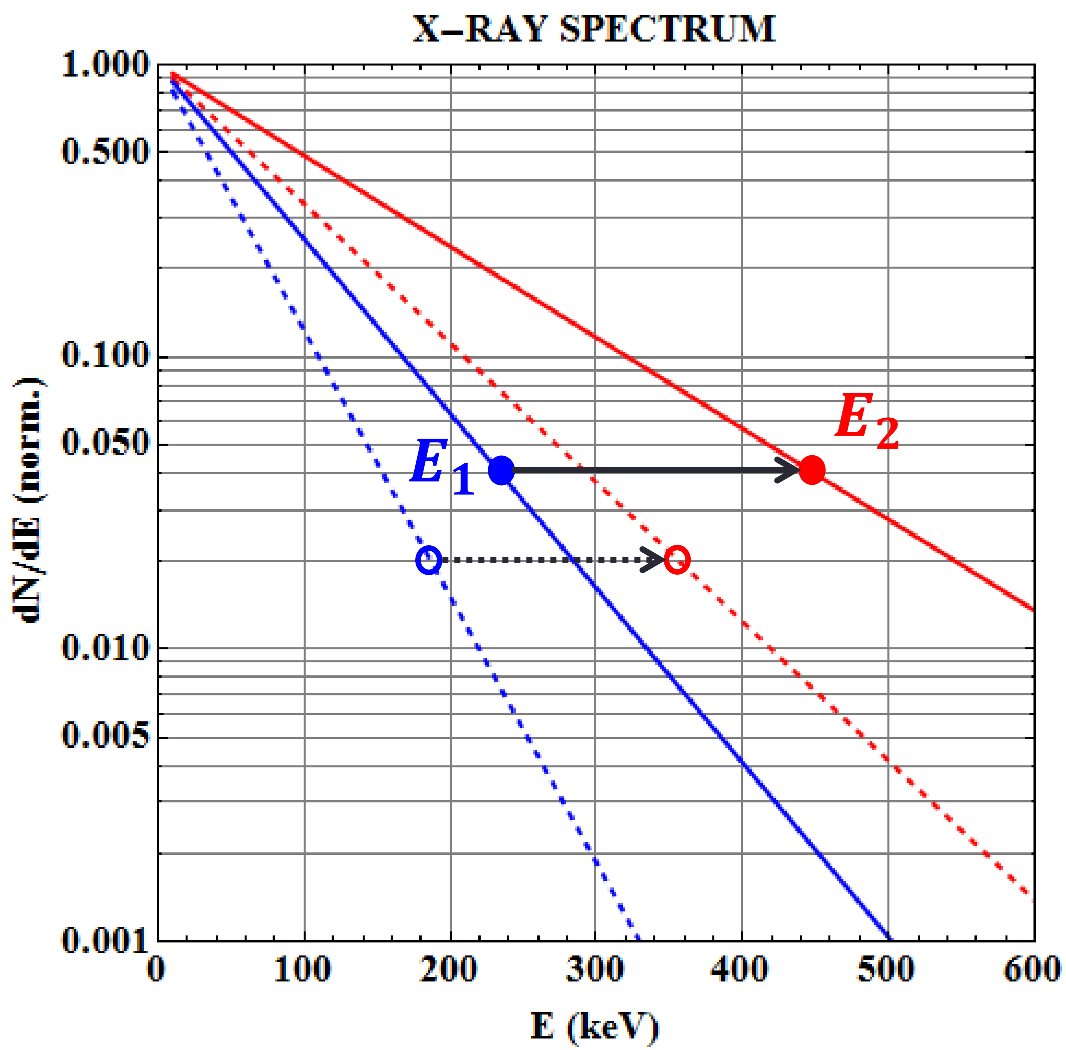
- Shallow gradient 18→28:

$$\frac{kT_2}{kT_1} = \frac{72.7}{47.7} = 1.52 \pm 0.11$$

- Steep Gradient 18 → 28:

$$\frac{kT_2}{kT_1} = \frac{139.5}{91.2} = 1.53 \pm 0.06$$

- Amazingly: $\frac{\mathbf{28}}{\mathbf{18}} = \mathbf{1.55}$ ...
- The x-ray spectrum temperature scales with the ECR frequency…



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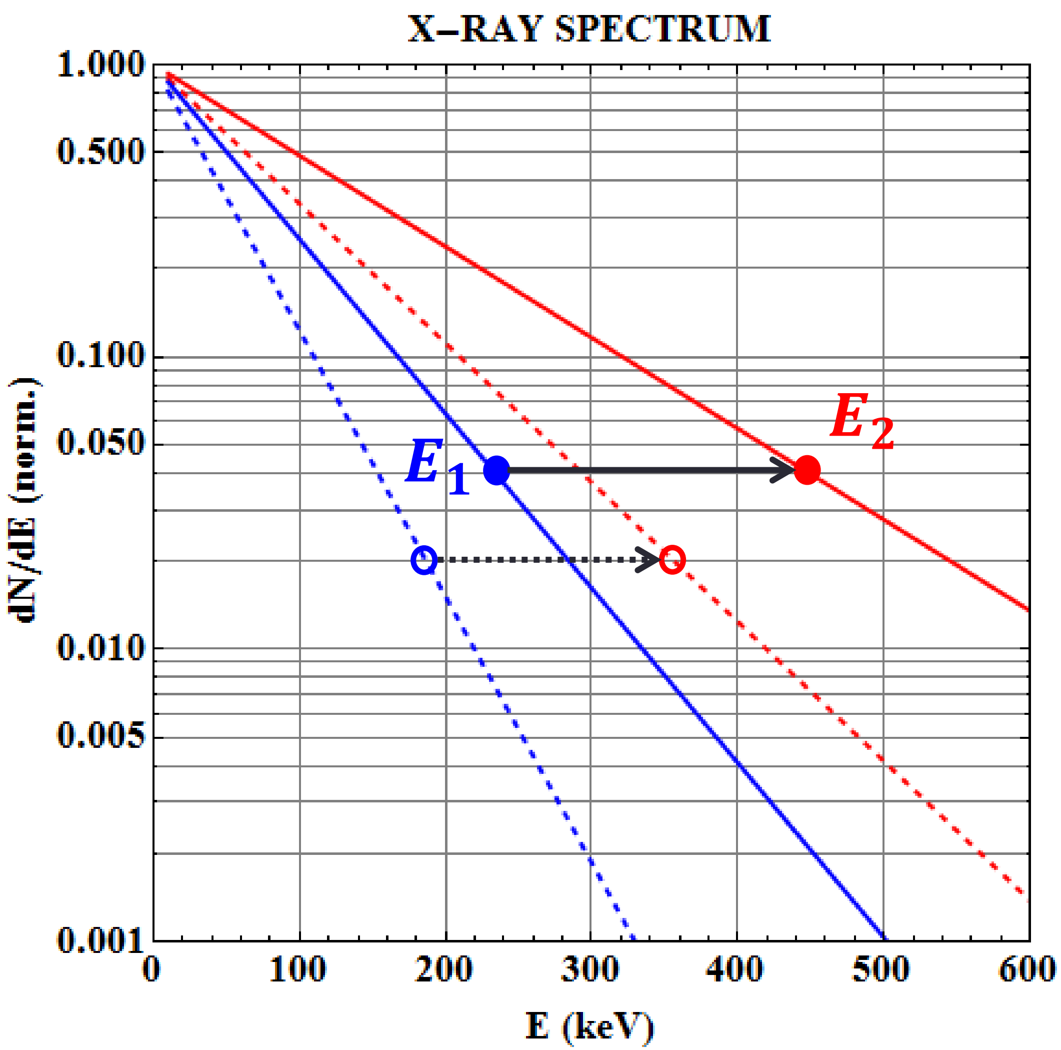


Magnetic field influence on the x-ray temperature

- Temperature ratio for shallow/steep gradient at $f_{ECR} = Const.$
  - 18 GHz: $\frac{kT_{shallow}}{kT_{steep}} = \frac{91.2}{47.7} = 1.91 \pm 0.0x$
  - 28 GHz: $\frac{kT_{shallow}}{kT_{steep}} = \frac{139.5}{72.7} = 1.92 \pm 0.0x$

Not a coïncidence…
→Magnetic origine

- The axial magnetic gradient effect on kT (1.91) is larger than the frequency effect presented earlier (1.51) ...

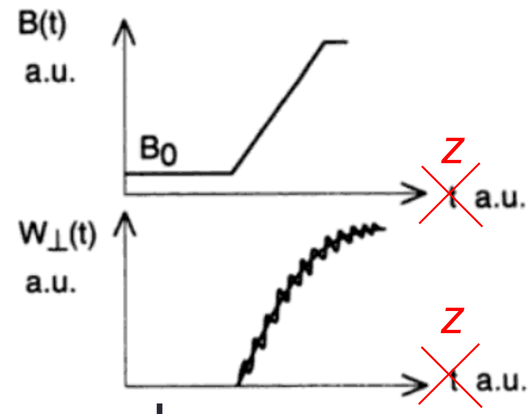
- Can we explain all of this?
  - Let's dig this further…

A serious candidate for the hotter 28 GHz x-ray tail: RF electron scattering

- Since the 60's RF scattering is considered to be the dominant term to deconfine hot electrons:
  - $\frac{d\gamma m v}{dt} = -e\vec{v} \times \vec{B} - e\overrightarrow{E_{RF}} - e\vec{v} \times \overrightarrow{B_{RF}}$
  - $B_{RF} \sim \frac{E_{RF}}{v_\varphi}$
- Models using whistler wave absorption predict that:
  - v_φ increases with f_{ECR}
  - Low RF frequency → large RF scattering for hot electrons → limited hot x-ray tail temperature
  - High RF frequency → low RF scattering → high hot x-ray tail temperature
- Experimentalist frustration: v_φ is not a physical observable…

A Possible Origin of the high energy x-ray tail

- Spatial Gyrac Effect (Golovanivsky's auto-resonance in a magnetic gradient)
  (see The Bible: Geller Book)
  - $\vec{B}(z) = (B_0 + \frac{\partial B}{\partial z} z)\vec{z}$
  - $\omega_0 = \frac{eB_0}{m} = \omega_{RF}$
  - $\frac{d\vec{p}}{dt} = -\frac{\omega_0}{\gamma}\vec{p} \times \vec{z} - e\overrightarrow{E_{RF}}$



- Provided an appropriate initial $v_{\parallel}$, the electron can become relativistic in a single pass through the B gradient

$$\omega_{RF} = \frac{\omega_0}{\gamma}$$

$$\omega_{RF} = \frac{eB\nearrow}{\nearrow mc} = \text{constant.}$$

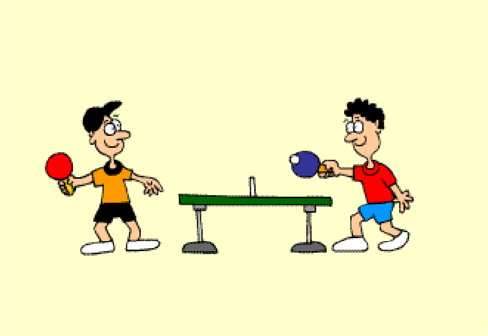
$$W_{e\perp} = m_0c^2\left[\frac{B(t)}{B_0} - 1\right] = 0.51\left[\frac{B(t)}{B_0} - 1\right] \text{MeV.}$$

Take: $B_0 = 1T, B_{max} = 3.5\,T \Rightarrow W_{\perp} \sim 1.2\,MeV$

A high electric field favors this scenario

A simple model for hot electron energy

$$W_{\perp} = \sum_{i=1}^{N} \epsilon_i \sim N\epsilon$$



- ϵ = Mean ECR boost when the e^- crosses the ECR zone
- N Number of e^- passage through the ECR

- The electron energy can increase by two means:
  - A higher electronic confinement :

    $$\epsilon = Const.\,, W_{\perp} \uparrow because\ N \uparrow with\ f_{ECR}$$

  - A higher ECR gain per passage :

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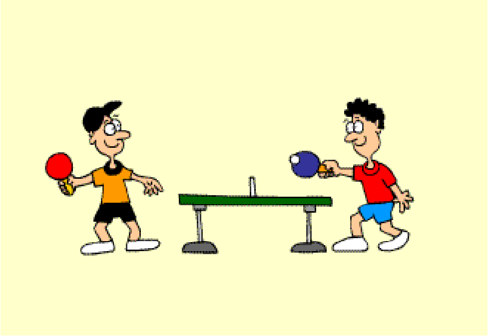

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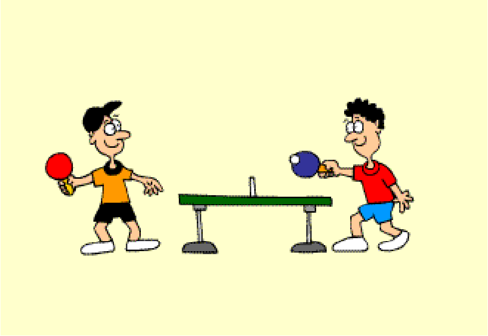

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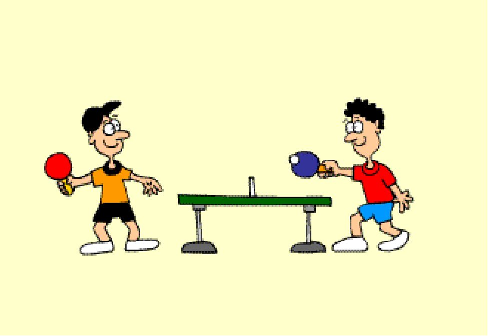

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Present Work hypothesis

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Simple model for Energy gain ϵ through the ECR zone (part 1)

- estimate of the Electron energy kick through the ECR zone:

$$\epsilon \sim \frac{q^2 {E_{RF}}^2 t^2}{2m}$$

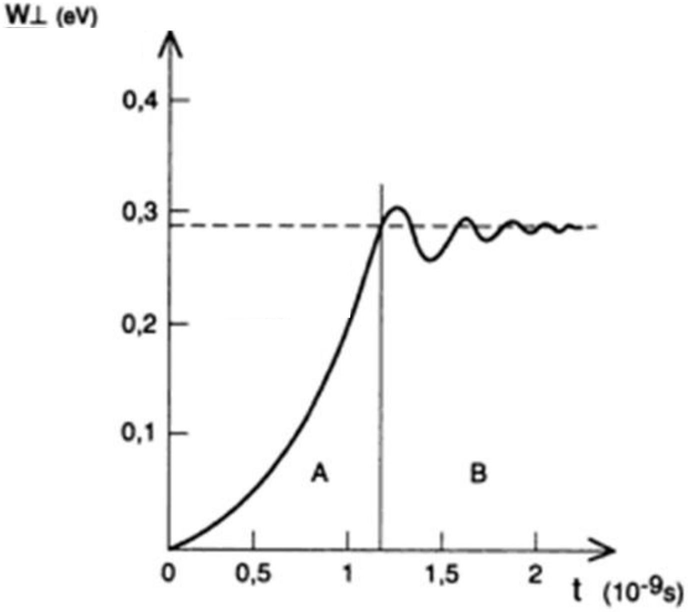
- Time through ECR zone : $t = \frac{\Delta l}{v_{||}}$
- Local Magnetic gradient along field line :

$$G = \frac{\partial B}{\partial l} = \frac{\Delta B}{\Delta l}$$

- ECR zone thickness: $\Delta l = \frac{\Delta B}{G}$

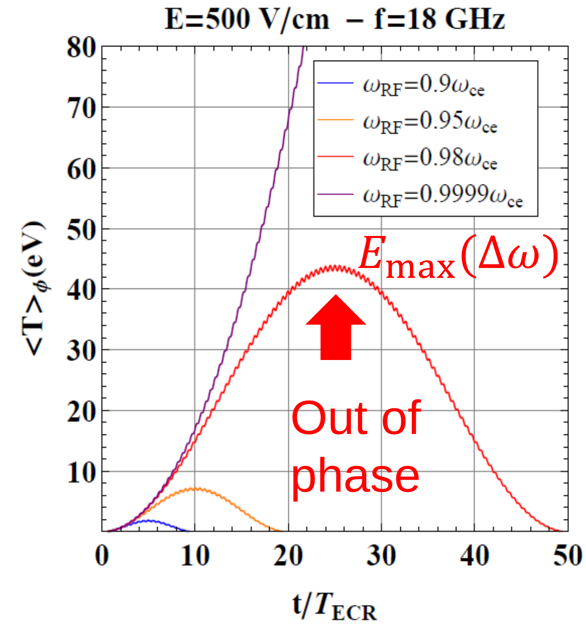
$$\Rightarrow \quad \epsilon \sim \frac{q^2 {E_{RF}}^2}{2m {v_{||}}^2} \frac{\Delta B^2}{G^2}$$

- What is ΔB?



ECR zone Magnetic Thickness ΔB

- estimated by studying : $\Delta\omega = \omega_{ec} - \omega_{RF}$
  - $\frac{\Delta B}{B} = \frac{\Delta\omega}{\omega}$
- Solve : $\frac{d\vec{v}}{dt} = \frac{q\vec{E}_{RF}}{m} \cos \omega_{RF} t + \vec{\omega}_{ec} \times \vec{v},\ \forall \omega_{RF}$
- Sweep: $\Delta\omega$
- get $E_{\max} = f(\frac{\Delta\omega}{\omega})$
- Plot $T_{\max} = f(\Delta\omega)$
- Get a resonance width $\frac{\Delta\omega}{\omega}$



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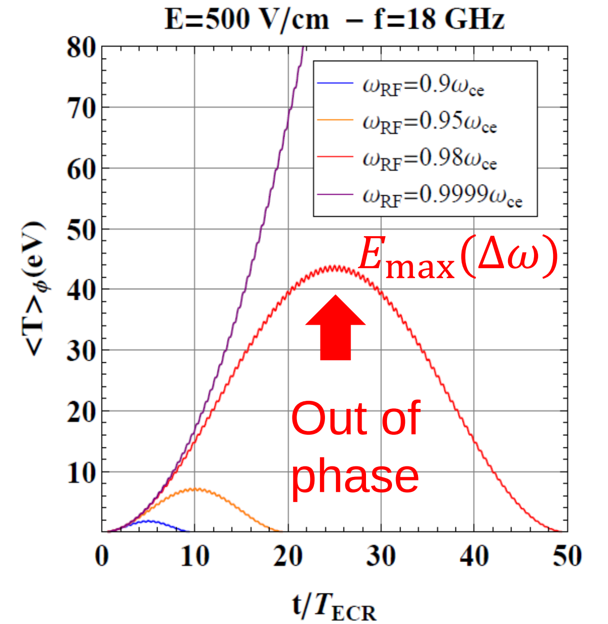
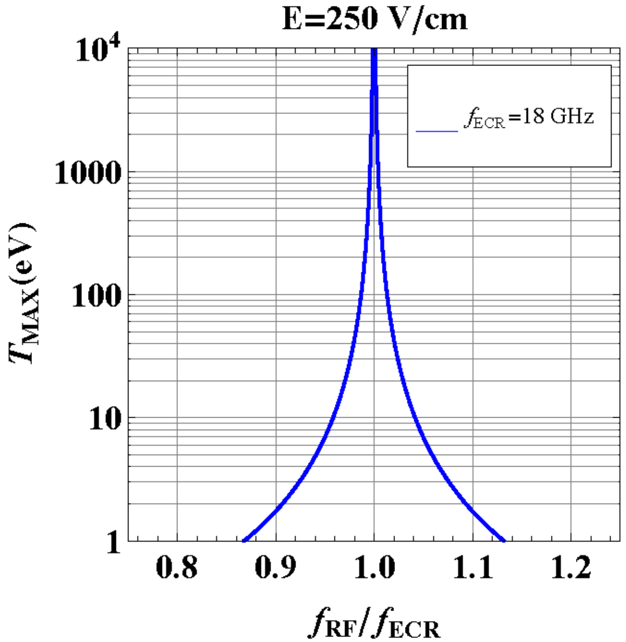


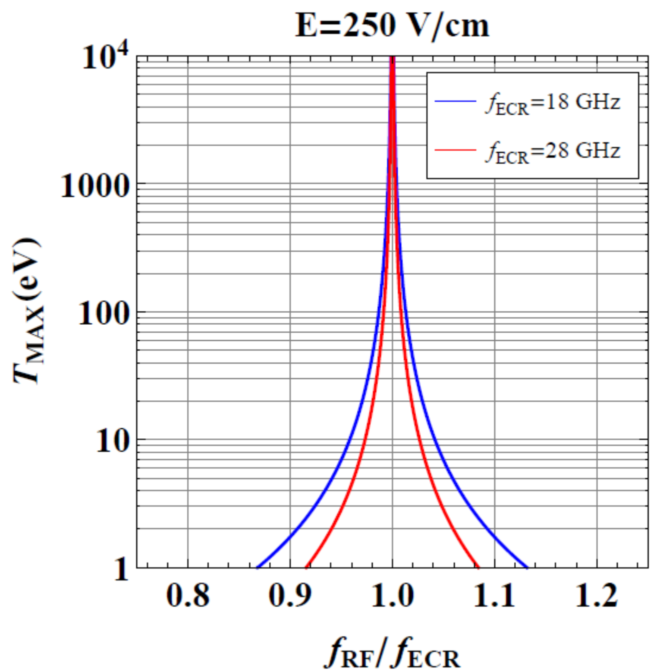


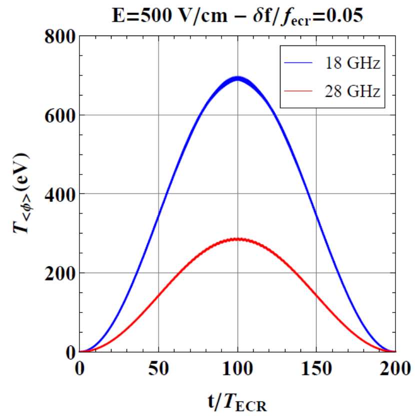
ECR peak width dependance with RF frequency

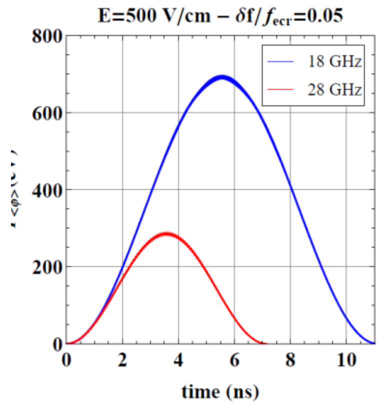
- The relative ECR peak width $\frac{\Delta\omega}{\omega}$ …decreases with f_{ecr}
  - The energy ocillation period with $\Delta\omega$ is $\Delta T = \frac{1}{\Delta f}$
  - Time of E_{max} reached at: $t_{max} = \frac{\Delta T}{2} = \frac{1}{2\Delta f}$
  - $\frac{\Delta f}{f_{ecr}} = \text{Const.} \Rightarrow t_{max} = \frac{\text{Const.}}{f_{ecr}}$

$$\Rightarrow t_{max}(28\ GHz) = \frac{18}{28} t_{max}(18\ GHz)$$

$$\Rightarrow E(t_{max}(28)) = \left(\frac{18}{28}\right)^2 E(t_{max}(18))$$







ECR peak width parameters

- The ECR peak width is proportional to the electric field intensity

$$\frac{\Delta\omega}{\omega} \sim 0.19 \times \frac{E_{RF}[\frac{V}{cm}]}{f_{ECR}[GHz]\sqrt{E_{max}}[eV]}$$

  - $\omega = \frac{eB}{m_e}$; $B = \frac{m_e \omega}{e} = \frac{2\pi m_e f_{ecr}}{e}$

- $\frac{\Delta B}{B} \sim 0.19 \times \frac{E_{RF}[\frac{V}{cm}]}{f_{ECR}[GHz]\sqrt{E_{max}}[eV]}$
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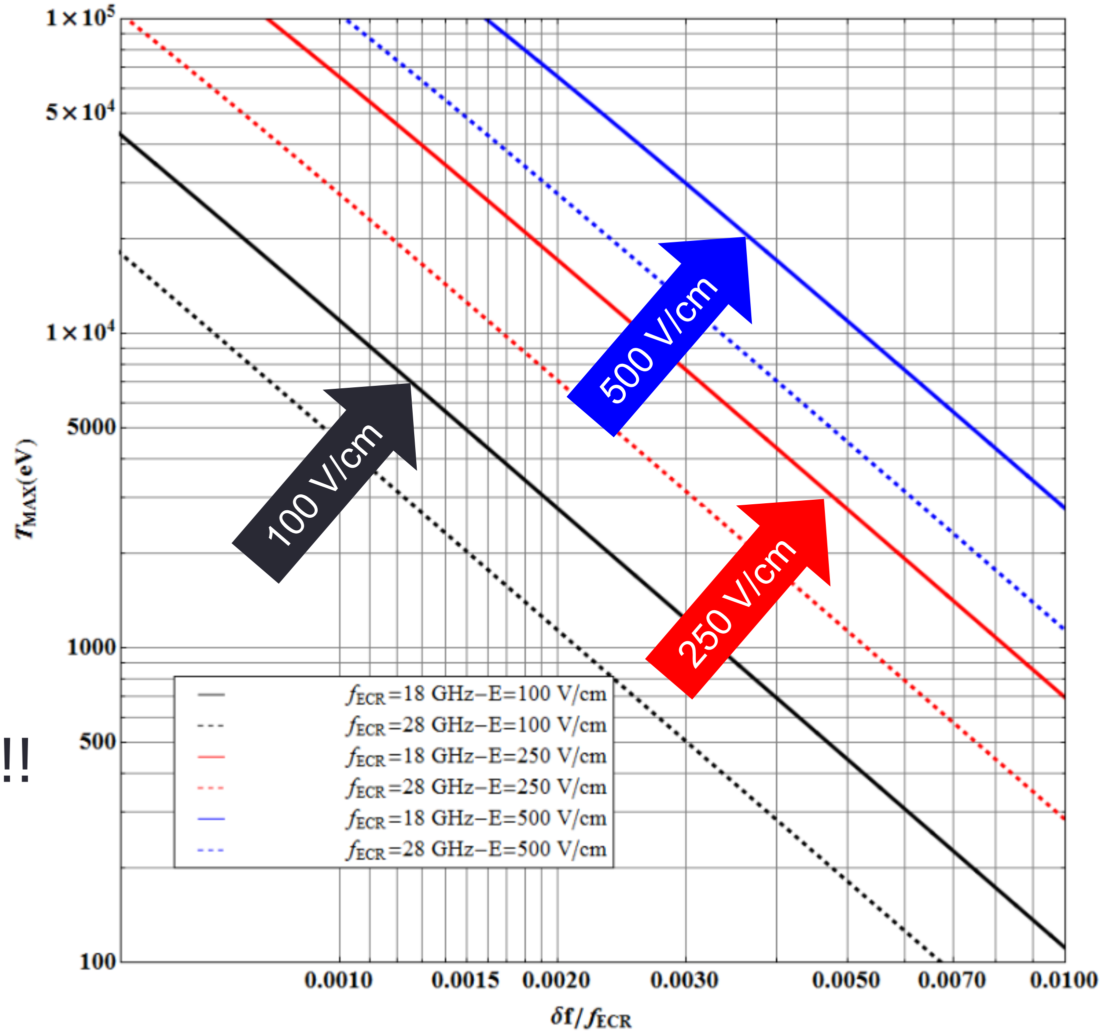
- ΔB Does not depend on f_{ecr}!!!



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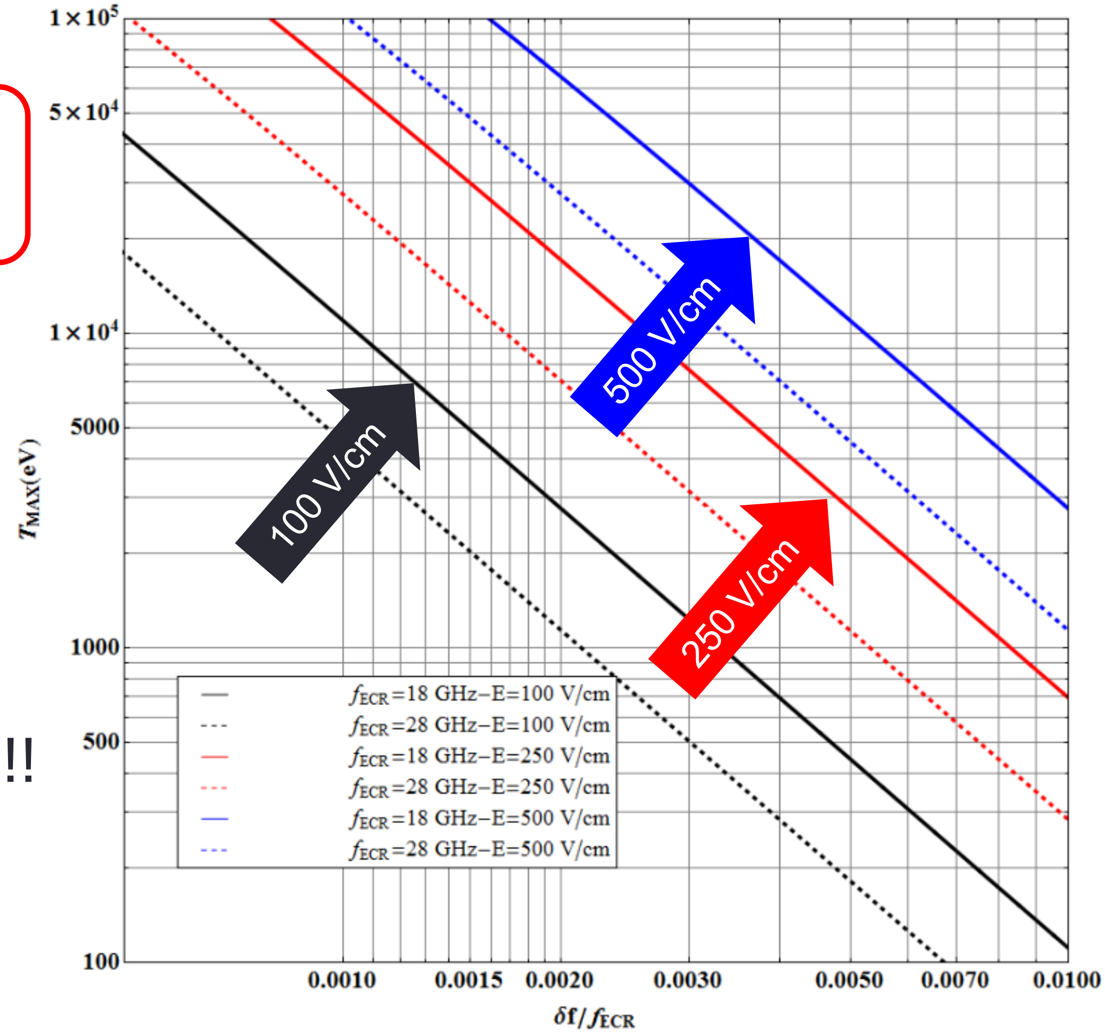

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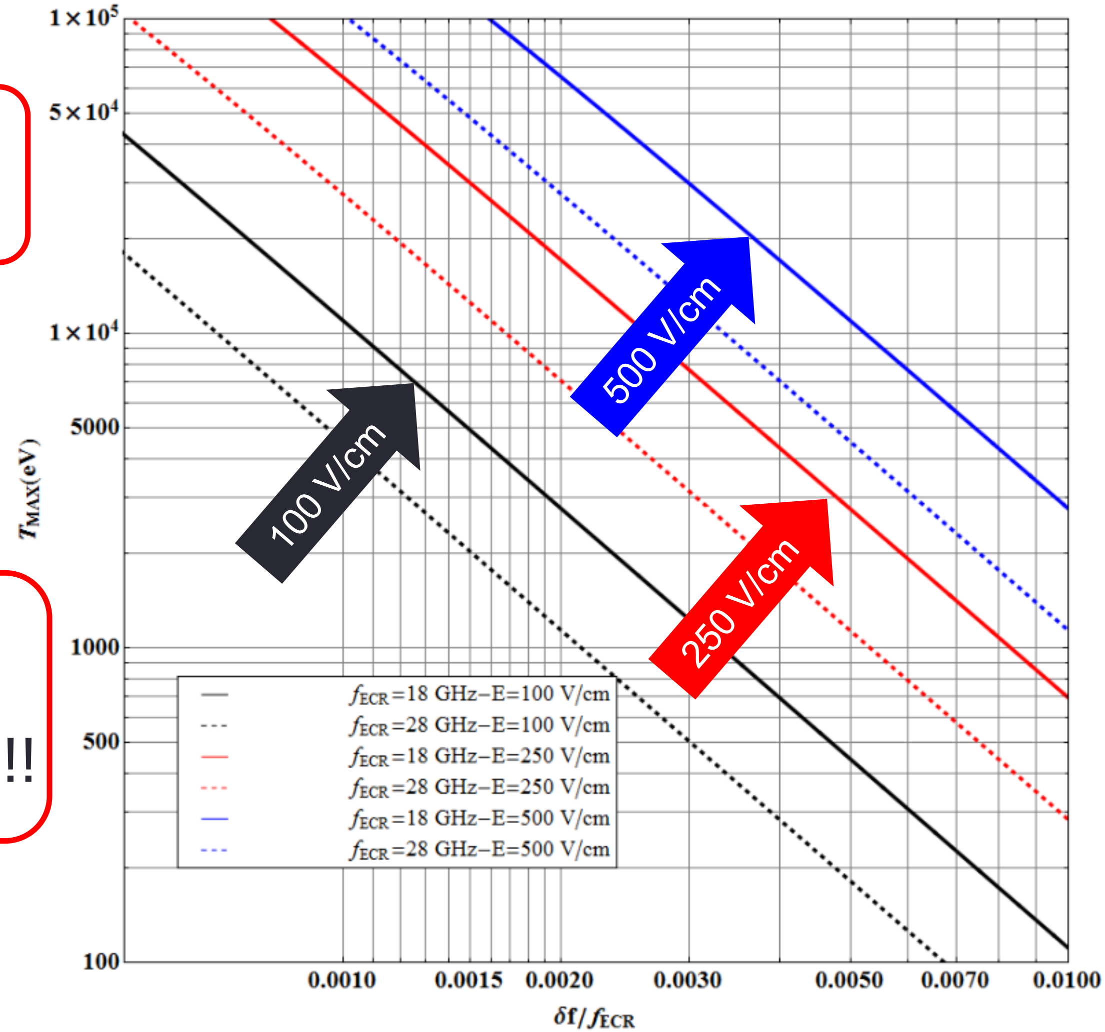


Simple model energy kick ϵ through the ECR zone (part 2/2)

- The energy boost estimate for an electron passing through the ECR zone is now:

$$\epsilon \sim \frac{q^2 {E_{RF}}^2}{2m{v_{||}}^2}\frac{\Delta B^2}{G^2} \propto \frac{q^2 {E_{RF}}^4}{2m{v_{||}}^2 G^2}$$

Simple model for RF power absorption in the ECR zone

- RF power absorbed in the ECR zone:

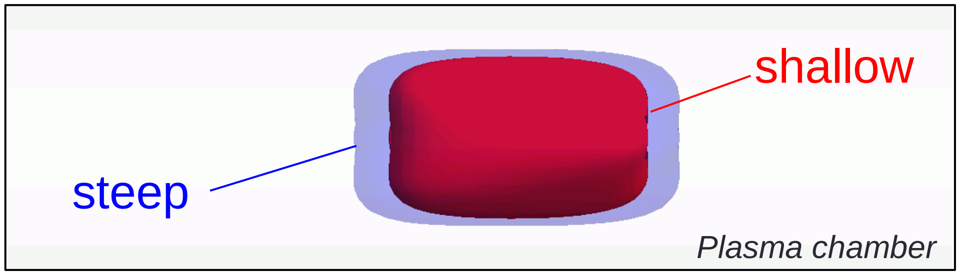
$$P_{RF\rightarrow ECR} \sim V_{ECR} \times {E_{RF}}^2 = S_{ECR} \times \Delta l \times {E_{RF}}^2$$

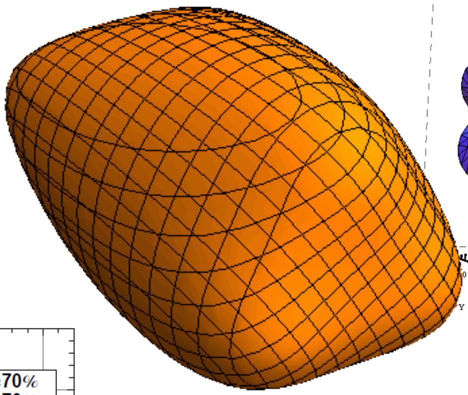
  - S_{ECR} ECR zone surface
  - Δl ECR zone thickness

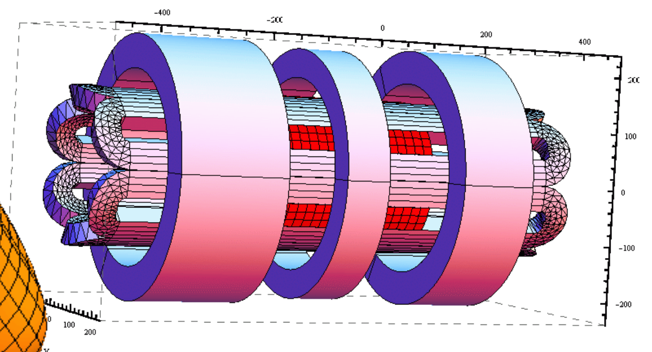
- Consequence: if V_{ECR} changes, then the number of passage of the RF wave in the cavity changes ⇒ RF cavity Q factor should change
  - $V_{ECR} \downarrow \Rightarrow E_{RF} \uparrow$
  - $V_{ECR} \uparrow \Rightarrow E_{RF} \downarrow$
- If we neglect wall dissipation and reflected power :
  - if $P_{RF\rightarrow ECR} \rightarrow \frac{P_{RF\rightarrow ECR}}{a} \Rightarrow then\ {E_{RF}}^2 \rightarrow a{E_{RF}}^2$
- Higher loss to the wall are expected and higher RF power needed to sustain the RF power absorbed in the ECR

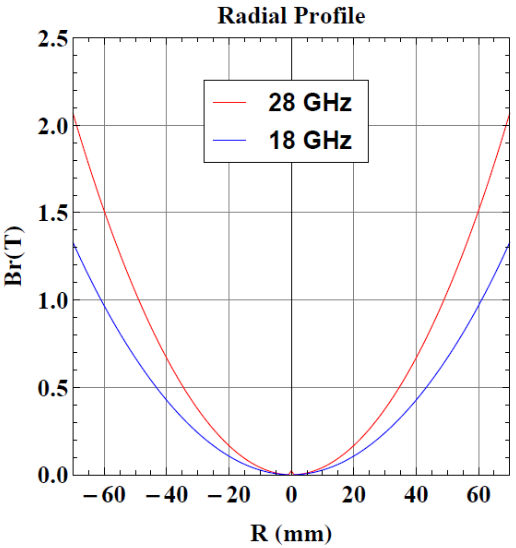
3D magnetic simulation of VENUS with Radia (ESRF)

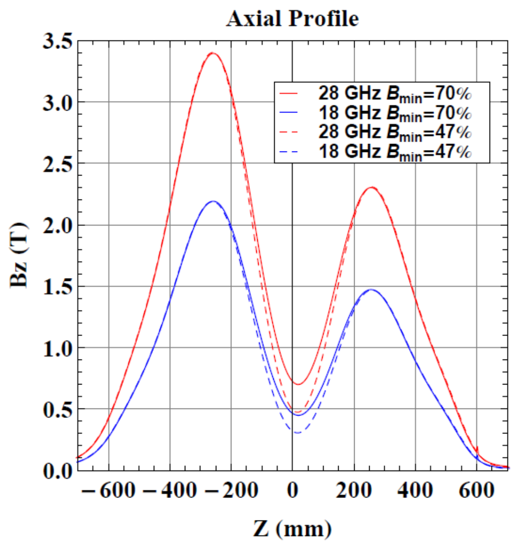
- Experimental magnetic configurations simulated for 18/28 GHz and steep/shallow axial magnetic profile
  - ECR zone geometry calculated along with the local magnetic gradients











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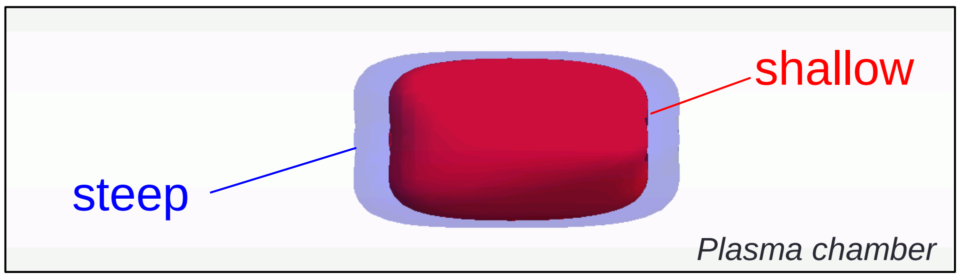
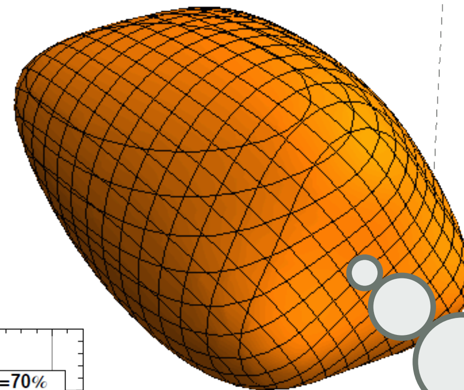
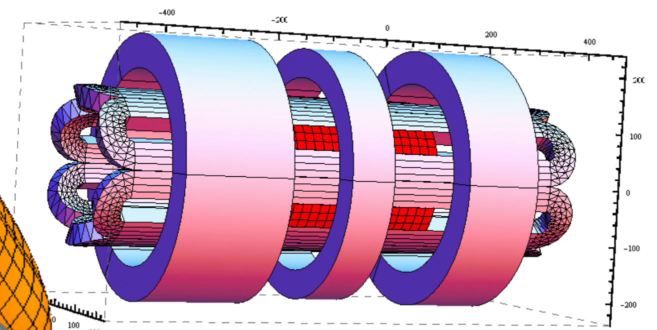
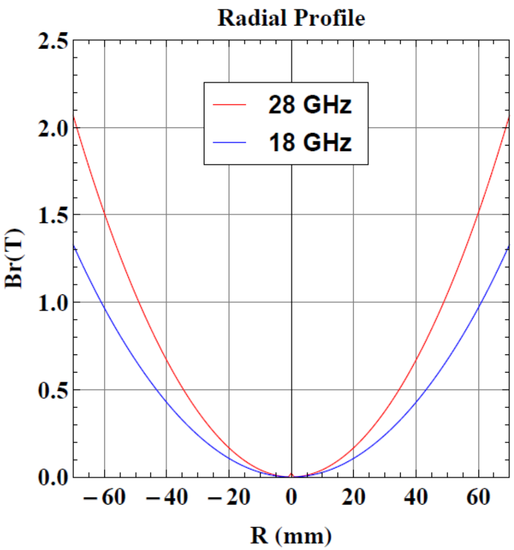
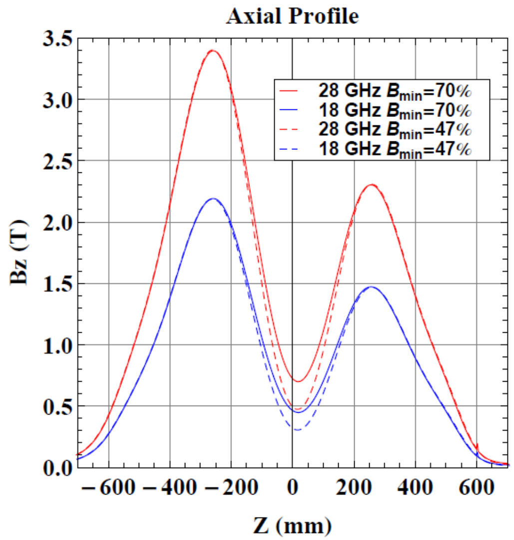


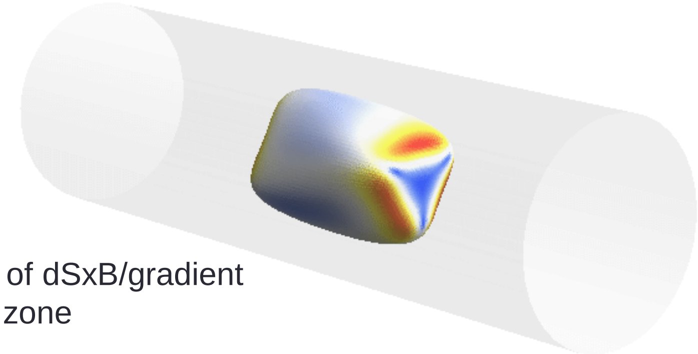








ECR zone characteristics for 18/28 - Shallow/Steep magnetic gradient



Distribution of dSxB/gradient on the ECR zone

	ECR surface *(cm²)*	Length *(mm)*	Max Radius (mm)	Max Grad. (T/m)	Min Grad. *(T/m)*	Mean Grad. *(T/m)*
18 GHz *steep*	530.3	170.6	49.3	22.72	6.67	17.16
18 GHz *shallow*	389.8	134.4	44.23	17.0	5.1	12.5
28 GHz *Steep*	519.2	167.1	49.50	35.4	10.4	26.7
28 GHz *shallow*	382.8	132.8	44.34	26.5	8.0	19.5

Steep/Shallow gradient analysis

	ECR surface (cm²)	Mean Grad. (T/m)	V_{ECR} (A.U.)	$\epsilon \sim \frac{1}{G^2}$
18 GHz *steep*	530.3	17.16	30.88	3.23×10^{-3}
18 GHz *shallow*	389.8	12.5	31.18	$6{,}4 \times 10^{-3}$
28 GHz *Steep*	519.2	26.7	19.44	1.40×10^{-3}
28 GHz *shallow*	382.8	19.5	19.63	$2{,}63 \times 10^{-3}$

$$W_\perp = \sum_{i=1}^{N} \epsilon_i \sim N\epsilon$$

18 GHz: $\frac{\epsilon_{shallow}}{\epsilon_{steep}} \sim 1.98$ $\qquad \frac{kT_{shallow}}{kT_{steep}} = 1.91$

28 GHz: $\frac{\epsilon_{shallow}}{\epsilon_{steep}} \sim 1.88$ $\qquad \frac{kT_{shallow}}{kT_{steep}} = 1.92$

- Good agreement to explain the shallow/steep temperature ratio
  - Same ECR Volume⇒ same E_{RF} ⇒ possible comparison of data
- The hot electron temperature is directly explained by the difference of magnetic gradient on the ECR zone
- The effect of e^-confinement time modification between steep/shallow gradient is negligible: $N \sim Const$.

Frequency effect

- The ECR volumes at $f_{ecr} = 18$ and 28 GHz do not match => Data More difficult to compare!
- $\frac{V_{ECR}(18)}{V_{ECR}(28)} \sim \frac{28}{18}$ $\Rightarrow$ The E_{RF} in the cavity is different (higher Q for 28 GHz)
- We assume: ${E_{RF}}^{\mathbf{2}}(28) \sim \frac{28}{18} {E_{RF}}^{\mathbf{2}}(28)$ to compensate the lower ECR absorption at 28 GHz per passage

	S_{ECR} (cm²)	Mean Grad. (T/m)	V_{ECR} (A.U.)	${E_{RF}}^2$	$\epsilon \sim \frac{{E_{RF}}^4}{G^2}$
18 GHz *steep*	530.3	17.16	30.88	1	3.23×10^{-3}
28 GHz *Steep*	519.2	26.7	19.44	1,55	$3{,}38 \times 10^{-3}$
18 GHz *shallow*	389.8	12.5	31.18	1	$6{,}4 \times 10^{-3}$
28 GHz *shallow*	382.8	19.5	19.63	1,55	$6{,}63 \times 10^{-3}$

$$\boldsymbol{W_\perp = \sum_{i=1}^{N} \epsilon_i \sim N\epsilon}$$

$$\frac{\epsilon_{steep\ 28}}{\epsilon_{steep\ 18}} \sim 1.05 \qquad \frac{kT_{steep,28}}{kT_{steep\ 18}} = 1.52$$

MODEL DOES NOT MATCH…

$$\frac{\epsilon_{shallow}28}{\epsilon_{steep18}} \sim 1.03 \qquad \frac{kT_{shallow\ 28}}{kT_{shallow\ 18}} = 1.53$$

Summary and Conclusion (1/2)

- VENUS measurements revisitation shows:
  - The hot x-ray temperature kT scales with f_{ecr}
    - Be Prepared to add extra cryocoolers for 4th Generation ECRIS cryostat!!!
  - The x-ray temperature ratio between shallow/steep gradient is well reproduced by the simple model proposed

    ⇒ Reduction of x-ray hot tail according to $|G|^2$

Summary and Conclusion (2/2)

- Investigation done shows that the ECR zone magnetic thickness is a constant independant of f_{ecr}

⇒ assuming scaling law magnetic field: for a given S_{ecr} ,The higher f_{ecr} , the lower the RF absorption in the ECR zone for a given E_{RF}

- The model developped cannot reproduce the fact that hot x-ray temperature tail experimentally scales with f_{ecr}
  - Model too simple
  - Electron RF scattering scenario reinforced

- But the model shows that the microwave absorption per passage decreases when f_{ecr} increases. Consequently, the electric field intensity increases in the plasma chamber (higher passage number, higher Q) which counter balance the effect.

- A consequence is that the loss to the wall should be higher at 24/28 GHz
  ⇒ more RF power is needed to get the same performance.


I don’t understand: there’s… nothing where you’re searching?


Yes, but here, at least, There is light!