Ponderomotive plugging in the Novatron magnetic fusion mirror device

Albert Mollén[1], T. Jonsson[1], K. Bendtz[2], R. Holmberg[2], J. Jäderberg[2], C. Möller[2], K. Lindvall[2], A. Moro[2], J. Scheffel[1,2], A. Tibbling[2], N. Veem[2]

[1]KTH Royal Institute of Technology, Stockholm, Sweden
[2]Novatron Fusion Group AB, Stockholm, Sweden

A ponderomotive force is a nonlinear force experienced by a charged particle moving in an inhomogeneous oscillating electromagnetic field. In a magnetic mirror, plasma confinement can be improved by applying a radiofrequency wave to induce a ponderomotive force. We discuss how this can be realized in the Novatron fusion device.

Acknowledgments

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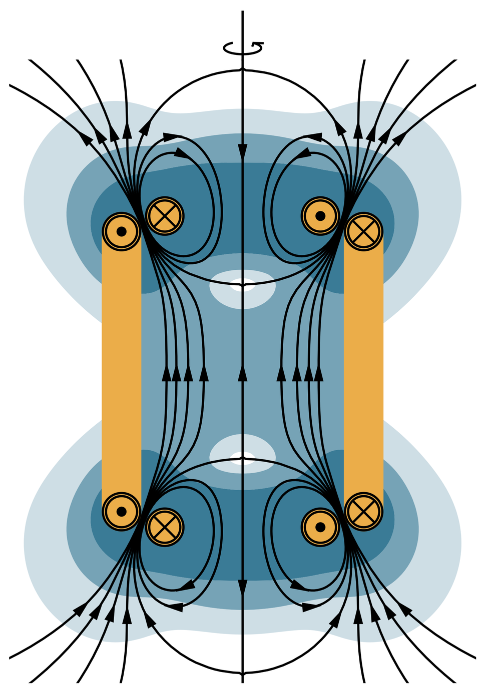
The Novatron is a magnetic confinement concept for fusion

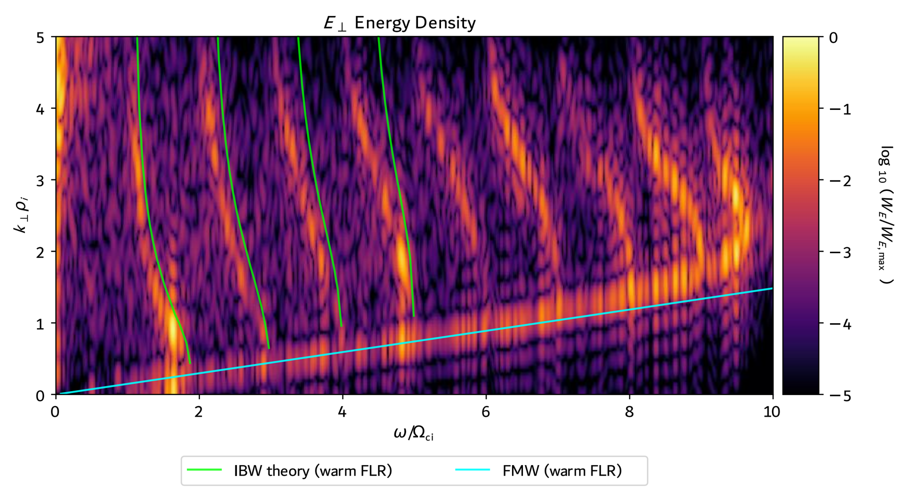
- Combined double-cusp - mirror geometry.
- Axisymmetric configuration.
- Favorable magnetic curvature.
- Stable against interchange instabilities.
- Low radial neoclassical transport losses.
- Requires end plugging to suppress axial losses.
- Cusped geometry useful for ponderomotive plugging.



The archetypal Novatron central cell.

Ion-Bernstein waves

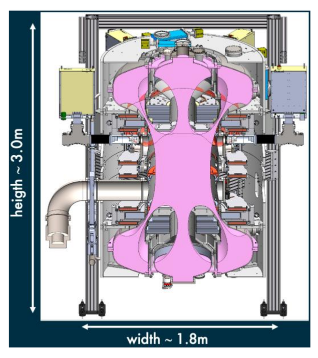
- Energy dissipation by collisions indicates that plugging ions is more efficient than electrons.
- Want high fraction of electric wave energy + low group velocity → electrostatic waves.
- Ion-Bernstein wave good candidate for plugging.
- Propagates between resonance and cut-off at two harmonic ion-cyclotron frequencies $n\Omega_{ci}$.
- Characterized by $k_\perp \rho \sim 1$.
- For finite $k_\perp \rho$ the spatial variation of the wave electric field along a gyro orbit is important → extend classical picture of ponderomotive force.



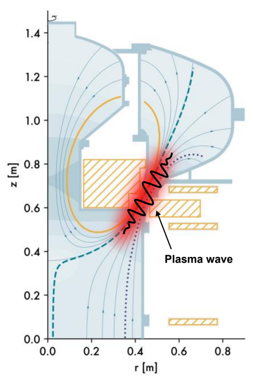
Spectrum of the perpendicular energy density in $\mathbf{E}$ *from a particle-in-cell simulation with WarpX. The simulation is set up with electrodes generating a radiofrequency wave at* $\omega = 1.6\,\Omega_{ci}$.

1st Novatron device

N1 target parameters	
$B_{\max}$	0.4 T
B_{midplane}	0.07 T
n	$\sim 10^{18}\ \text{m}^{-3}$
T_e	30 eV
T_i	~100 eV
ECRH	36 kW, 2.45 GHz
ICRH	5 kW, 0.7 – 1.2 MHz

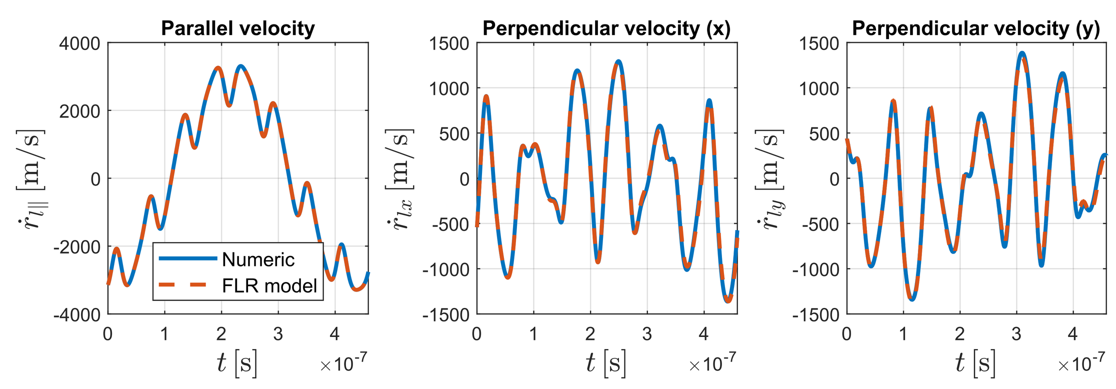


- Operational since early 2025.
- ICRH under commissioning.
- Diagnostics under development to quantify ponderomotive effects, e.g., Electro-optic probes.
- Electrodes designed for RF plugging at the mirror throats.

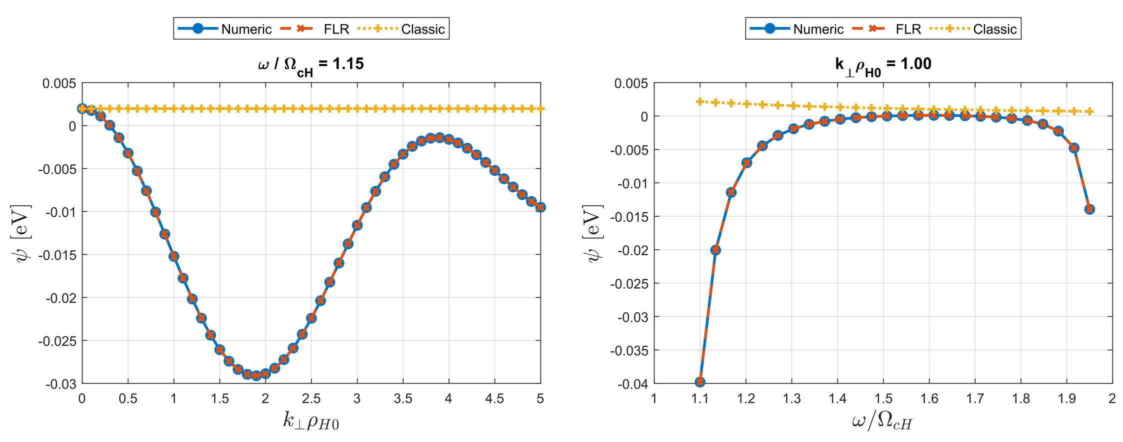


Comparison model vs simulation

Implemented a numerical particle pusher to verify our analytical model for ψ with $k_\perp \rho > 0$. Analyzing the correctness of the perpendicular terms.



Velocity $(\dot r_{lx}, \dot r_{ly}, \dot r_{l\parallel})$ *vs time comparing numerical and FLR-model.*



ψ *vs* $k_\perp \rho$ *and* ω *for an* H^+ *ion with* $B_0 = 1$ T, $(E_{0+}, E_{0-}, E_{0\parallel}) = (0,0,1)$ kV *and* $k_\parallel = 0$. *Numerical (blue), FLR (red) and classical model (yellow).*

Particle motion in presence of wave

Equation of motion for a charged particle

$$m\ddot{\mathbf{r}} = q(\mathbf{E} + \dot{\mathbf{r}} \times \mathbf{B})$$

$$\mathbf{B} = B_0 \hat{\mathbf{z}}, \qquad \mathbf{E} = \mathrm{Re}\{\mathbf{E}_0(\mathbf{r}) \exp(i\mathbf{k}\cdot\mathbf{r} - i\omega t)\}.$$

Single-particle Lagrangian

$$\mathcal{L}(\mathbf{r}, \dot{\mathbf{r}}, t) = m|\dot{\mathbf{r}}|^2/2 + q[\mathbf{A}_0(\mathbf{r}) + \mathbf{A}_1(\mathbf{r}, t)] \cdot \dot{\mathbf{r}}$$

$$\mathbf{A}_0(\mathbf{r}) = B_0(-r_y \hat{\mathbf{x}} + r_x \hat{\mathbf{y}})/2$$

$$\mathbf{A}_1(\mathbf{r}, t) = \mathrm{Im}\{\mathbf{E}_0(\mathbf{r}) \exp(i\mathbf{k}\cdot\mathbf{r} - i\omega t)/\omega\}.$$

Order particle motion

$$\mathbf{r}(t) = \mathbf{r}_g(t) + \mathbf{r}_l(t) + \mathbf{R}(t)$$

$\mathbf{r}_g(t) = \rho\cos\Omega_c t\,\hat{\mathbf{x}} - \rho\sin\Omega_c t\,\hat{\mathbf{y}} + \dot r_{g\parallel} t\,\hat{\mathbf{z}}$ - gyromotion

$\mathbf{r}_l(t)$ - wave-induced motion linear in $|\mathbf{E}|$

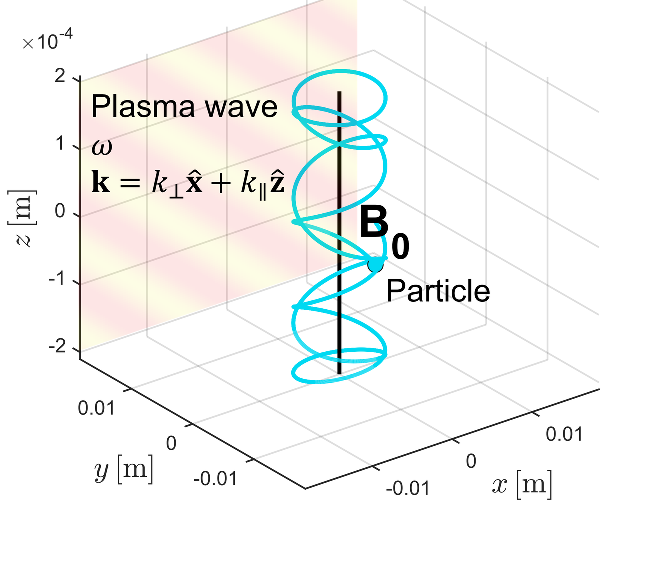
$\mathbf{R}(t)$ - second-order ponderomotive corrections

$$|\mathbf{r}_l(t)|/|\mathbf{r}_g(t)| \sim |\mathbf{R}(t)|/|\mathbf{r}_l(t)| \sim \varepsilon = |q\mathbf{E}_0|/(m\Omega_c^2 \rho) \ll 1.$$

$\Rightarrow$ Force from $\mathbf{E}$ of wave $\ll$ Lorentz force.

Unitary complex transformation

$$E_\pm = (E_x \pm iE_y)/\sqrt{2}, \qquad r_\pm = (r_x \pm ir_y)/\sqrt{2}.$$



Ponderomotive potential with Finite Larmor radius corrections $k_\perp \rho > 0$

Ponderomotive potential obtained from time-average

$$\psi = \left\langle \mathcal{L}(\mathbf{r}, \dot{\mathbf{r}}, t)\Big|_{\mathbf{E}=0} - \mathcal{L}(\mathbf{r}, \dot{\mathbf{r}}, t) \right\rangle_t.$$

Classical cold plasma potential at $\rho \to 0$

$$\psi_{\text{classic}} = \frac{q^2}{4m\omega}\left(\frac{|E_{0+}|^2}{\omega - \Omega_c} + \frac{|E_{0-}|^2}{\omega + \Omega_c} + \frac{|E_{0\parallel}|^2}{\omega}\right).$$

FLR effects through Bessel functions $J_n \equiv J_n(k_\perp \rho)$

Wave-induced velocity

$$\dot r_{l\pm} = \frac{q}{2m}\sum_{n=-\infty}^{\infty} J_n \left[\frac{i^{n-1}E_{0\pm}\exp[i(n\Omega_c - \omega)t]}{n\Omega_c \pm \Omega_c - \omega} + \left(\frac{i^{n-1}E_{0\mp}\exp[i(n\Omega_c - \omega)t]}{n\Omega_c \mp \Omega_c - \omega}\right)^*\right],$$

$$\dot r_{l\parallel} = \frac{q}{m}\sum_{n=-\infty}^{\infty} J_n\,\mathrm{Re}\left\{\frac{i^{n-1}E_{0\parallel}\exp[i(n\Omega_c - \omega)t]}{n\Omega_c - \omega}\right\}.$$

Potential at $\rho > 0$

$$\psi_{\text{FLR}} = \frac{q^2}{4m}\sum_{n=-\infty}^{\infty}\Bigg\{J_n^2 \frac{\omega - 2n\Omega_c}{\omega(\omega - n\Omega_c)}\left[\frac{|E_{0+}|^2}{\omega - n\Omega_c - \Omega_c} + \frac{|E_{0-}|^2}{\omega - n\Omega_c + \Omega_c} + \frac{|E_{0\parallel}|^2}{\omega - n\Omega_c}\right] + J_n J_{n+1}\frac{\Omega_c}{\omega}\Bigg[\frac{|E_{0+}|^2 k_\perp \rho}{(\omega - n\Omega_c - \Omega_c)(\omega - n\Omega_c - 2\Omega_c)}$$
$$+ \frac{|E_{0-}|^2 k_\perp \rho}{(\omega - n\Omega_c + \Omega_c)(\omega - n\Omega_c)} + \mathrm{Re}\Bigg\{\frac{2E_{0+}E_{0-}^* k_\perp \rho}{(\omega - n\Omega_c - \Omega_c)(\omega - n\Omega_c)} + \frac{2^{1/2}E_{0+}E_{0\parallel}^* k_\parallel \rho}{(\omega - n\Omega_c - \Omega_c)^2} + \frac{2^{1/2}E_{0-}E_{0\parallel}^* k_\parallel \rho}{(\omega - n\Omega_c)^2}\Bigg\}\Bigg]\Bigg\}.$$

Summary

- Extended theory for the ponderomotive potential experienced by a charged particle moving in a static magnetic field and under the action of a radiofrequency wave to include finite gyro radius.
- For a wave with $k_\perp \rho \gtrsim 1$ neglecting Finite Larmor radius corrections can give incorrect sign of the ponderomotive potential.
- Plan to test predictions of ponderomotive plugging in upgrade of 1st Novatron device.

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Contact: amollen@kth.se