# Numerical calculations of wave generation from a bunched electron beam in space

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We present our numerical approach and preliminary results of the calculations of whistler and X mode wave generation by a bunched electron beam in space. The artificial generation of whistler and X mode plasma waves in space is among the candidate techniques to accomplish the radiation belt remediation (RBR), in an effort to precipitate energetic electrons towards the atmosphere to reduce their threat to low-Earth orbit satellites. Free-space propagation of an electron pulse in a constant background magnetic field was simulated with the CST particle-in-cell (PIC) solver, with the temporal evolution of the beam recorded. The SpectralPlasmaSolver (SPS) was then modified to use the recorded electron pulse propagation to calculate the real-time plasma waves generated by the beam. SPS simulation results of the wave generation for the upcoming Beam-PIE experiment as well as an ideal bunched electron beam are shown.

## Wave Generation by Pulsed Electron Beam

### CANDIDATE TECHNOLOGY FOR RADIATION BELT REMEDIATION (RBR)

Pulsed electron beam generates plasma waves initiated via Landau damping.
Whistler mode and X mode are of interest.
Plasma waves interact with MeV electrons and precipitate them towards the atmosphere.

### THE BEAM PLASMA INTERACTIONS EXPERIMENT (BEAM-PIE)

An upcoming experiment generating pulsed electron beams from a space-borne accelerator and detecting the plasma waves generated by the electron beams.

### AN IDEALIZED BUNCHED ELECTRON BEAM

An ideal electron beam with smaller initial length and negligible initial energy spread.

## Wave Generation Calculation Workflow

### STEP 1 – CST PARTICLE-IN-CELL (PIC) SIMULATION OF BEAM PROPAGATION

An input beam file to CST PIC solver is obtained from another program.
CST PIC solver calculates the propagation of the beam along the background magnetic field.
3D position monitor records the electron beam propagation.

### STEP 2 – CONVERSION OF CST PIC RESULTS TO SPS INPUT FILES

CST PIC 3D position monitor results are converted to the 3D distribution of the longitudinal current density.

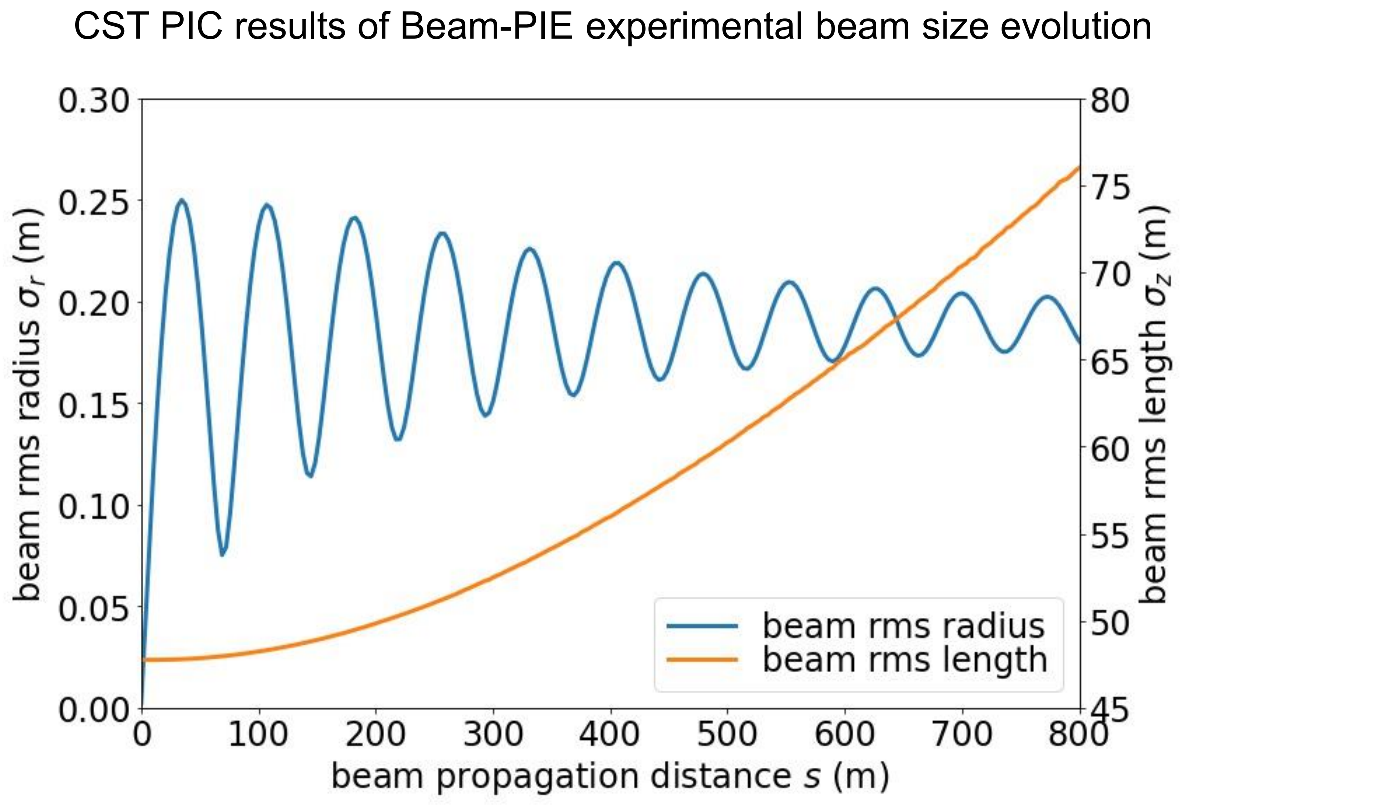
### STEP 3 – SPS CALCULATION OF WAVE GENERATION

SPS calculates the real-time plasma wave generation over the course of the recorded electron beam propagation as simulated in the CST PIC solver.

## CST PIC Simulations

The longitudinal beam size increases due to the space charge force.
The transverse beam size oscillates due to the drive from the space charge force and the confinement by the magnetic field.

CST PIC results of Beam-PIE experimental beam size evolution




## SPS Simulations

The SpectralPlasmaSolver (SPS) code is a high performance 3D fluid-kinetic numerical solver of Vlasov-Maxwell equations.

### MODIFICATION OF SPS CODE

The original version of SPS does account support numerical description of the current densities. The modified version of SPS imports and uses the numerical description of the temporal evolution of the longitudinal current density.

### SIMULATION PARAMETERS

| Beam-PIE experimental beam | |
|---|---|
| Beam voltage | 22.6 kV |
| Beam charge | 13.9 nC |
| Initial total beam length | 211 m |
| **Idealized bunched beam** | |
| Beam voltage | 15.0 kV |
| Beam charge | 10.0 nC |
| Initial total beam length | 7 m |

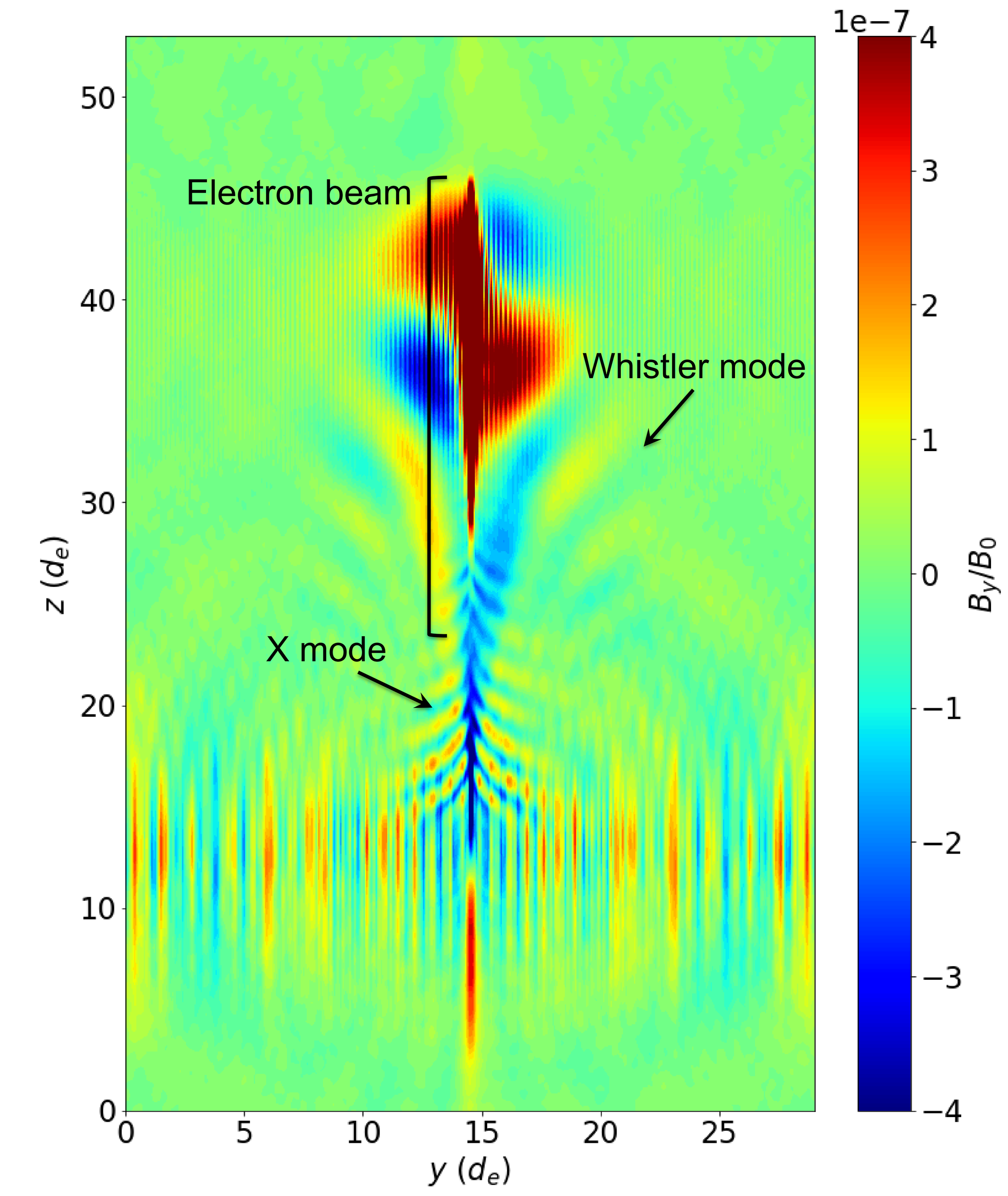
| Basic parameters | |
|---|---|
| Background magnetic field | $4.53\times10^{-5}$ T |
| Electron cyclotron frequency | 1.27 MHz |
| Electron plasma frequency | 2.54 MHz |
| Electron inertial length | 18.82 m |

## SPS Wave Generation Results

Electron inertial length $d_e = c/\omega_{pe}$ = 18.82 m.
Plasma wave field structure shown as the distribution of $B_y$ / $B_0$.

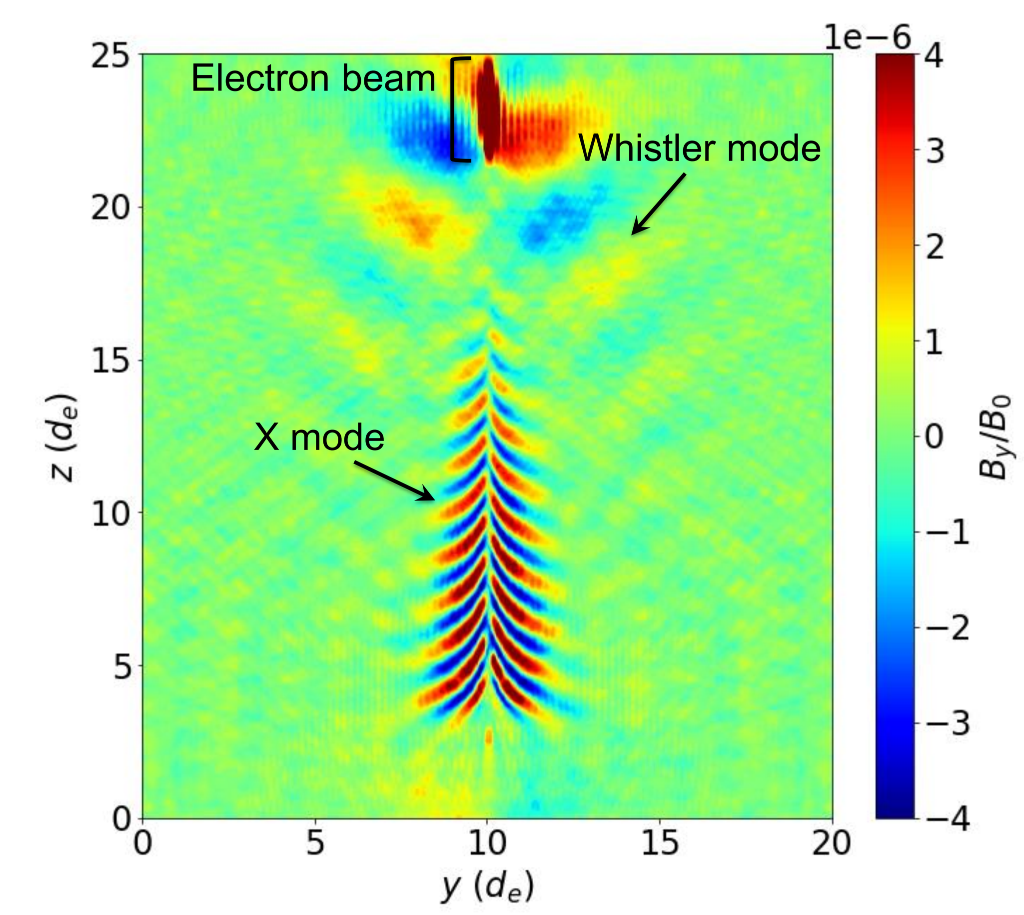
### BEAM-PIE EXPERIMENTAL BEAM

Beam propagation 504.5 m from 12.0 $d_e$ to 38.8 $d_e$.
Average radiation power 1.8 mW.
Total radiation energy 11 nJ.



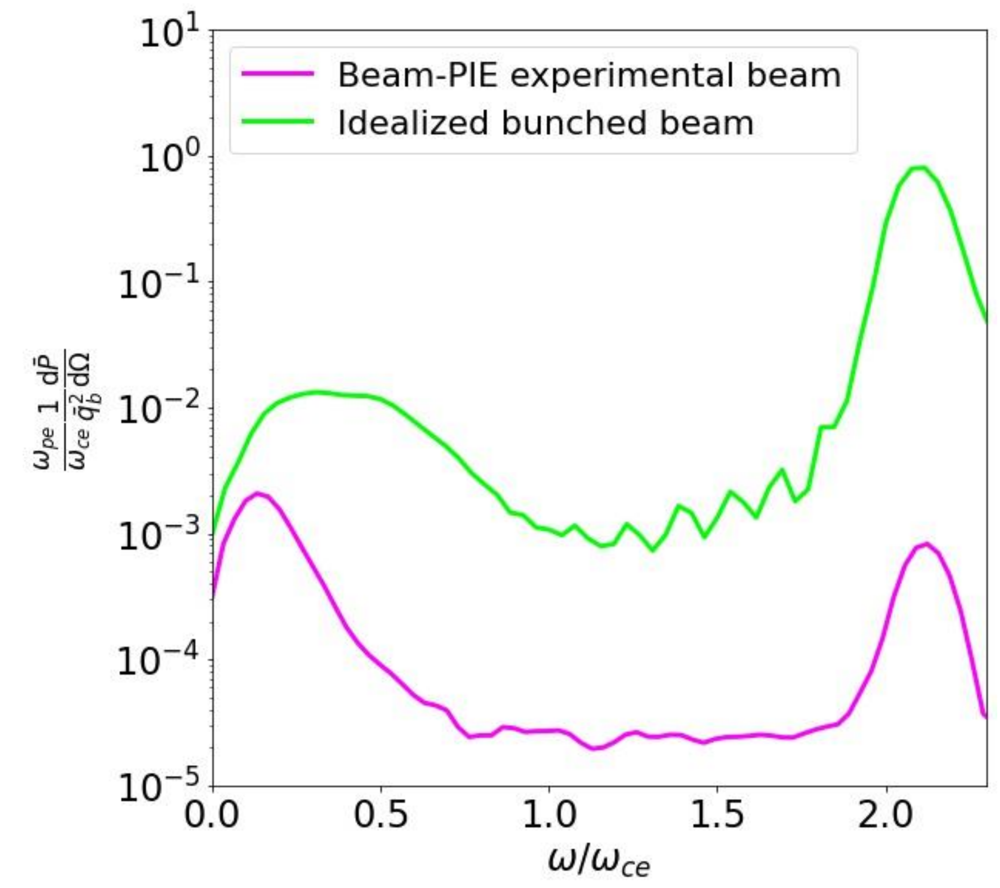

### IDEALIZED BUNCHED BEAM

Beam propagation 362.1 m from 4.0 $d_e$ to 23.2 $d_e$.
Average radiation power 0.20 W.
Total radiation energy 1.0 μJ.




## Plasma Wave Spectra

Plasma wave radiation power calculated from SPS simulation results, by the surface integral of the Poynting vector flux through an envelop surrounding the electron beam.
Shorter electron beam radiates more efficiently due to improved coherence, with more pronounced enhancement of X-mode radiation.

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