Sub-Terahertz Emission by Two-Stream Instability of REB in Magnetized Plasma and by Two-Channel Planar FEM with Combined Electrodynamic System

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Outline:

Introduction

1. Generation of Sub-THz EM Radiation in Turbulent Plasmas on the Basis of Plasmon-Plasmon Merging

2. Generation of Sub-THz EM Radiation on the Basis of a Two-Stage Scheme in a Planar FEM

3. Development of Novel Quasi-Optical Components & Systems for Diagnostics of Sub-THz Radiation

Conclusions
On April 9, 2010, the Russian Prime Minister Vladimir Putin signed Decree No. 220 “Measures to Attract Leading Scientists to Russian Educational Institutions” Contract # 11.G34.31.0033, November 24, 2010 (3.2 Mio €) Leading Scientist: Prof. Manfred K.A. Thumm (Head of Laboratory) Vice Head: Prof. Andrey V. Arzhannikov, Novosibirsk State University

Investigation of Novel Schemes to Generate mm- and Sub-mm Wave EM Radiation by High Power Relativistic Electron Beams (REBs) in Vacuum and Plasma Devices and Application of Strong Microwaves for Fusion Energy Research and Material Processing

New Laboratory:

“Laboratory of Advanced Research on Millimeter and Terahertz Radiation”
Five teams of the project were implemented:

1. **Generation of Sub-mm EM Radiation in Plasmas on the Basis of Plasmon-Plasmon Merging**

2. **Generation of Sub-mm EM Radiation on the Basis of a Two-Stage Scheme in a Planar FEM**

3. **Development of Novel Quasi-Optical Components & Systems for Diagnostics of Sub-mm-Wave Radiation**

4. **Application of Microwaves for ECRH of Plasmas in a Magnetic Mirror Device**
   (GDT at BINP, 2x0.45 MW Gyrotrons, 54.5 GHz, HE$_{11}$ Waveguides)

5. **Microwave Processing for Production of Novel Materials**
   (Anorganic and Organic Chemistry)
1. Generation of Sub-THz EM Radiation in Plasmas on the Basis of Plasmon-Plasmon Merging

GOL-3 Plasma Facility, *Budker Institute of Nuclear Physics (BINP) SB RAS*

**Electron beam**
- energy ~ 0.8 - 1 MeV
- current ~ 20 - 30 kA
- duration ~ 8 - 10 µs
- energy content ~ 120 kJ

**Magnetic field**
- multi-mirror field
  - $B_{\text{max}} / B_{\text{min}} = 4.8 / 3.2$ T
  - 52 cells
  - capacity storage 30 MJ

**Plasma**
- length $L \sim 12$ m
- density $n_0 = 10^{14} - 10^{15}$ cm$^{-3}$
- temperature $T_e \approx T_i \sim 1 \div 2$ keV
Turbulent Plasma Heating by Powerful E-beam

GOL-3:
- Langmuir turbulence pumping via Cherenkov wave-beam resonance:
  \( \omega_p \approx k \cdot v_{\text{beam}} \)
- Very large increase of effective collision frequency: \( \nu > 10^3 \nu_{\text{Coulomb}} \)
- Fast relaxation of REB in the plasma
- Suppression of longitudinal electron losses
- Fast (5-10\(\mu\)s) heating of plasma electrons and ions up to \( T \sim 1 - 2 \text{ keV} \)

\[ n_0 = 10^{14} \div 10^{15} \text{ cm}^{-3} \]

**EM-wave generation by Langmuir turbulence**

- Langmuir wave to photon conversion due to density fluctuations:

  \[ (\mathbf{k}_1^l, \omega_p) \rightarrow (\mathbf{k}_{ph}^l, \omega_p) \delta n \]

  \( \omega_p \)-process

  EM-wave rapidly attenuates in plasma

- Nonlinear conversion of two Langmuir waves into one photon (3-wave interaction)

  \[ (\mathbf{k}_1^l, \omega_p) \rightarrow (\mathbf{k}_{ph}^l, 2\omega_p) \]

  \( 2\omega_p \)-process

  EM-emission at \( 2\omega_p \) and \( \omega_p \) carries direct information on the energy density of the Langmuir oscillations \( W^l \)
The Thomson scattering diagnostics gives the radial distribution of the plasma density at two times during microwave generation. Simultaneous analysis of the spectral density of the microwaves is carried out near $2\omega_p$ by a 4 channel polychromator and single detectors.
TK (Thomas Keating Ltd) absolute power/energy meter, operation range of $10^{-6} \text{ J} \div 10^{-1} \text{ J}$, time resolution – 10 ms.

Efficiency 50% in wide waveband $0.05 \div 3$ THz.
Measurements on $2\omega_p$-Emission

Rad. Power on Detector (200 – 350 GHz):

$P_{\text{det}} \approx 1 \text{ mW}$

Specific Radiated Power:

$P_{\text{spec}} \approx 1 \text{ kW/cm}^3$
Spectral Tuning by Plasma Density Variation

- Experiments with increase of initial gas density («thin» electron beam (Ø11mm)) (with diaphragm)

\[ n_0 \approx 2 \cdot 10^{14} \text{ cm}^{-3} \]
\[ 2\omega_p / 2\pi \approx 260 \text{ GHz} \]

\[ n_0 \approx 4 \cdot 10^{14} \text{ cm}^{-3} \]
\[ 2\omega_p / 2\pi \approx 360 \text{ GHz} \]

Spectrum tuning is in agreement with theory!
Bolometer Measurement of Terahertz Wave Emission vs Distance from Beam Entrance into the Plasma Column

\[ B = 4 \text{ T}, \quad n_e \approx 2 \cdot 10^{14} \text{ cm}^{-3}, \]

\( 70 \text{ mJ} \cdot \text{Sr}^{-1} \cdot \text{cm}^{-3} \)
\( P_{\text{exp}} \approx 4 \text{ kW/(Sr} \cdot \text{cm}^3) \)

Shot-by-shot statistics with re-location of the bolometer (integrated emission spectrum)

If \( n = 2 \cdot 10^{14} \text{ cm}^{-3} \)
\( T_e = 2 \text{ keV} \)

Suppose \( W/k_B T \approx 0.1 \)
then \( P_{\text{TEM}} \approx 7 \text{ kW/cm}^3 \)
\( P_{\text{exp}} \approx 5 \text{ kW/cm}^3 \)

\( Q_{\text{plasma}} \approx 1.5 \text{ kJ} \)
Generation of mm-Wave Radiation in a One-Channel Sheet-Beam FEM (Previous Experiment)

Electrodynamic system of planar FEM

Eigenmodes of the hybrid resonator

Regimes with a high level of mm-wave radiation spectral power density near the frequency close to one of the eigenmodes of the hybrid Bragg resonator during all the 0.5 µs pulse have been observed in the experiments.

*JETP Letters, 2008, Vol. 87, No. 11, pp. 618 – 622*
Future Experiment at the end of 2012 on Generation of Sub-THz EM - Radiation on the Basis of a Two-Stage Scheme in a Planar FEM

**Active Undulator**
- Period = 4 cm
- Amplitude of $B_{\perp}$ = 0.17 T
- $B_{\parallel}$ = 1.5 T
- Inhomogeneity < 7%
- Amplitudes of high harmonics of the field < 1%

**Two Electron Beams**
- Energy ~ 0.8 MeV
- Current ~ 3 kA
- Duration ~ 3-5 μs
- $S_b$ = 0.4 cm x 7 cm

**Bragg Resonator**
- Upstream reflector: 2D “chessboard” profile, L = 20 cm, period = 4 mm, depth = 0.17 mm,
- Regular part: L = 70 cm,
- Downstream reflector: 1D “rectangular” profile, L = 20 cm, period = 2 mm, depth = 0.07 mm,
- $Q$ = about 1000

**Principle of operation**: EM - wave generated by the lower sheet beam in a joined planar Bragg resonator of a FEM, is scattered (90°) on the upper beam with Doppler conversion from 4 mm (75 GHz) to approx. 0.5 mm (0.6 THz)

Status of Activities

Status of activity (1st stage of experiment):

• Experiments on simultaneous generation of 4-mm radiation in two independent channels of the FEM have been carried out

• Measurements of the radiation power, pulse energy and frequency spectrum of the generated 4-mm wave radiation at the exit of the 2-channel FEM

• Preparation and tests on the new equipment for the two-stage scheme of sub-mm generation: new active undulator for the lower beam, planar Bragg resonator for sub-mm waves (600 GHz) on the base of advanced Bragg structures

Purchased and elaborated equipment for diagnostics of MW- radiation:

4-channel spectral diagnostics on the base of band pass resonance filters

\( \mu W \)- calorimeter Thomas Keating absolute power (\( Q \approx 1 \mu J - 0.1 J \)) meter

1-channel and 2-channel heterodyne diagnostics
Schematic of Heterodyne Diagnostics for 2-Channel FEM
Two-Channel mm-Wave FEM (Present Experiment)

Parameters of the two-channel FEM:

Two sheet electron beams: $E_e \sim 0.8$ MeV, $I_b \sim 1 - 2$ kA, $S_b \sim 0.4 \text{ cm} \times 7 \text{ cm}$, $t \sim 3 - 4 \text{ µs}$.

Identical hybrid resonators for both channels:

Upstream reflector: 2D “chessboard” profile, $L = 20 \text{ cm}$, period = 4 mm, depth = 0.17 mm,
Regular part: $L = 32 \text{ cm},$
Downstream reflector: 1D “rectangular” profile, $L = 20 \text{ cm}$, period = 2 mm, depth = 0.07 mm, $Q = \text{about 1000}.$

Undulator: period: 4 cm, length of field increase: 24 cm, amplitude of transverse field $< 0.17 \text{ T}$, longitudinal field $< 1.5 \text{ T}.$
Experimental Results in 2011

Signals from 4-channel spectral diagnostics

μW- power in the 74.5÷75.5 GHz band vs undulator magnetic field

Energy of μW-pulse vs undulator magnetic field (measured by calorimeter)

Directional pattern of mm-wave radiation measured by an array of 100 Neon bulbs (20 cm x 20 cm)
Shot #7671 in 2012: Single-Mode and-Frequency Generation Synchronization (LO=72.5 GHz)
Summary of Two-Sheet-Beam FEM Experiments

- The feasibility to form two parallel sheet electron beams with acceptable parameters for generation of high power 4-mm waves (75 GHz) in a two-channel FEM has been demonstrated.

- Operation of the two channel FEM at different guiding and undulator magnetic fields was investigated. The behavior of power and energy of the microwave pulse agrees with theoretical predictions.

- Spectrum measurements show, that the most part (~ 70%) of the mm-wave power is generated in the frequency range of the longitudinal modes of the hybrid resonator (74.5 - 75.5 GHz).

- Demonstration of synchronization of mm-wave radiation in the two FEM channels (Experiments with connected 2D-Bragg reflector are currently being performed).

- The total energy of the mm-wave pulse detected by a calorimeter, is 4 - 6 J in each channel and its maximal power is about 20 - 40 MW in each channel.

- First Doppler up-shift experiments in 2012 will be in the SASE – regime (self-amplification of spontaneous emission).
Main features of ABS:

- The gap $b$ between the plates is a multiple of the half period of surface corrugation $d$ (n-integer): $b = nd/2$
- Principle of ABS is based on feedback between propagating (TEM) and quasi-cutoff (TM) waves, which is even possible at an oversize factor of $b/\lambda \sim 10 - 20$ where traditional Bragg structures show reduced selectivity
- On the basis of such feedback it is possible to combine the mechanisms of mode selection (utilized in gyrotrons and orotrons) with Doppler frequency conversion
- Tunability of the reflection by varying the distance $b$ between the plates

3. Development of Novel Quasi-Optical Components & Systems for Diagnostics of Sub-THz Radiation

**Basis:** Microstructured quasi-optical frequency selective elements

**Objectives:**
- Development of innovative technical solutions for different THz applications:
  - sub-mm wave radiometry of GOL-3 plasma;
  - new detectors & imaging at sub-mm waves;
  - planar focusing devices etc.
- Elaboration of a technological line for small-lot innovative manufacturing
- Formation of a small company specialized on developing THz instrumentation

Amplitude, phase and polarization responses are controlled via FSS topology
**Development Stages for Microstructured Sub-THz Quasi-Optics**

I. **Electromagnetic modelling and optimization**

   Ansoft HFSS™ v.13: NSU cluster
   - 160 Work Stations
   - (2 CPU x 4 core: 2.6GHz)
   - 2560 GB RAM

II. **Design and fabrication of quasi-optical devices**

   “Hardware”: BINP SB RAS, NSU
   - Photolithography &
   - Electroforming: ISP SB RAS

III. **Device testing and calibration (0.1-1.5 THz)**

   BWO-spectroscopy technique:
   - NSU

Available frequency bands:
- 620–1120 GHz (x3)
- 170–378 GHz
- 420–782 GHz (x3)
- 115–260 GHz
- 1000–1540 GHz (x9)
- 300–530 GHz (x3)
- 100–177 GHz
Multi-Channel Radiometric Systems for GOL-3 & ELMI-FEM Experiments

Parameters of novel filters:

**Triple FSS multiplex**
- **Topology:** Inductive tri-poles
- **Material:** Copper, 9 um thick
- **Fabrication technique:** Electroforming

- **FWHM ~ 12%**
- **Peak transmission > 90%**
- **Out-of-band transmission at higher frequency edge < 10^{-4}**
- **Clear aperture diameter - 70 mm**

![Transmission Graph](attachment:image.png)

Submm

Layout of 8-channel system (to be launched in 2012)

Filters

Beam splitters

Lenses

Schottky detectors
**Multi-Channel Radiometric Systems for GOL-3 & ELMI experiments**

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![Graphs showing transmission for 0.6 THz and 1 THz filters.](image)
Multi-Channel Radiometric Systems with Novel Frequency Selective Surface Filters

- FWHM ~ **12%**
- Peak transmission > **90%**
- Out-of-band transmission at higher frequency edge < **10^{-4}**
- Clear aperture diameter - **70 mm**
Real-Time THz Imaging using Metamaterial Absorbers

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**Image of unfocused BWO-beam**

**Images of focused BWO-beam upon real-time motion**

<table>
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<th>THz</th>
<th>A</th>
<th>B</th>
<th>C</th>
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<tr>
<td>0.30</td>
<td>110</td>
<td>12</td>
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<td>0.36</td>
<td>100.5</td>
<td>14.3</td>
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</table>

 Absorptivity: \( \lambda/d \sim 50 \) (180 for Patches)

Sim.: \( \Delta v/v_{res} \sim 4.5\% \)

Meas.: \( \Delta v/v_{res} \sim 6\% \)

Thermal insulation approx. 3 \( \mu \)W/K
Conclusions:

In addition to the Novosibirsk Terahertz NovoFEL, NSU and BINP are performing high power THz activities in the fields:

1. Generation of high-power sub-THz EM radiation in plasmas with two-stream instabilility generated by a relativistic electron beam

2. Generation of high-power sub-THz EM radiation by Doppler up-shift scattering (inverse Compton scattering) in a two-channel planar FEM

3. Development of novel quasi-optical components & systems for diagnostics of sub-THz radiation using frequency selective structures

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