Modification of the X-Ray Diagnostics of Electron Energy Distributions in Gyrotrons

Oleg Louksha, Alexander Arkhipov, Natalya Dvoretskaya, Gennadi Sominski
(St. Petersburg Polytechnical University, Russia)

Gerd Gantenbein, Andrey Samartsev
(Karlsruhe Institute of Technology, IHM, Germany)

IRMMW-THz
Tucson 2014

Abstract — Scattered x-rays were utilized for determination of the electron energy distributions at a gyrotron collector. Performed calculations and experiments demonstrated that scattering in the diagnostic window has only minor effect on the radiation spectra in the gyrotron-relevant conditions. The primary advantage of the proposed diagnostic scheme consists in reduction of the density of treated x-rays flux down to the optimal level for spectrometers of the energy-dispersive type. The experimental configuration for full-beam-averaged data acquisition has been practically tested. A modification of the set-up is discussed aimed to obtain information with an optimal spatial resolution.

1. Diagnostic technique:

allows to determine energy distribution of electrons striking the gyrotron collector via measurement of bremsstrahlung x-ray spectra.

See details in:

[1] A. Arkhipov, N. Dvoretskaya, G. Gantenbein, et al. // *IEEE Trans. Plasma Science*. v. 41, pp. 2786-2789, October 2013

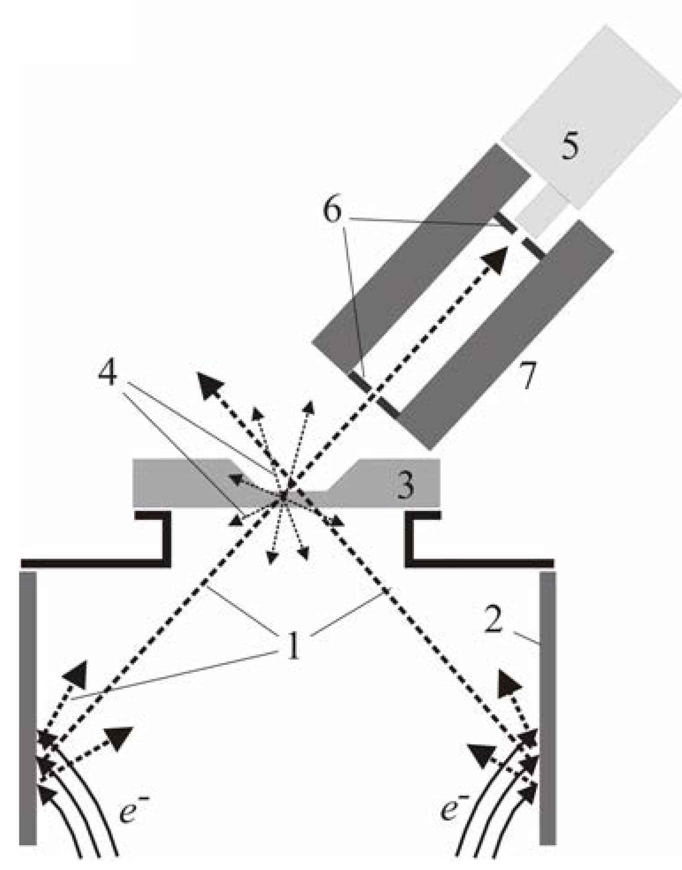
Knowledge of electron energy distributions can help:
- to check relevance of simulation codes;
- to control EOS adjustment quality (if we can measure electron spectra for different parts of the collector);
- to design energy recovery systems with collector depression.

Advantages of x-ray diagnostics:
- they are non-intrusive (using the x-rays that are generated at the collector in any case);
- in most cases, they don't require any changes in gyrotron design.

2. Experimental scheme "A"

Gyrotron: step-tunable (100–140 GHz, 1 MW).
Electron beam: 90 kV, 50 A

1 – direct x-rays produced by the beam (e^-);
2 – collector wall;
3 – diagnostic window (2 mm Al);
4 – scattered x-rays;
5 – spectrometer;
6 – x-ray collimators (W);
7 – spectrometer shielding from direct x-rays (Cu).



Problem:
x-ray intensity is too high to measure with an energy-dispersive spectrometer with a solid-state sensor. Photon count rate limit is ~10^5 sec^{-1}. To reduce the input photon flux to this value, we have to install two spaced collimators with 0.1 mm pin-holes. They restrict the spectrometer "field of view" to ~1 mm^2 of collector area.

But: 1) "Blind" adjustment of the view line at the desired collector spot through Al window; 2) the data from 1 mm^2 may be not representative for the whole beam.

3. Solution:

to use radiation **Compton-scattered** in the window.

For parameters and geometry of our experiment, it has much lower intensity and practically the same spectrum as the direct bremsstahlung x-rays.

Thompson's formula for scattering cross-section:

$$d\sigma / d\Omega = \frac{r_0^2}{2}\left(1+\cos^2\theta\right)$$

where r_0 is the classical electron radius, θ is scattering angle. No dependency from photon energy E.
Photon energy after scattering:

$$E' = \frac{E}{1+(E/mc^2)\cdot(1+\cos\theta)}$$

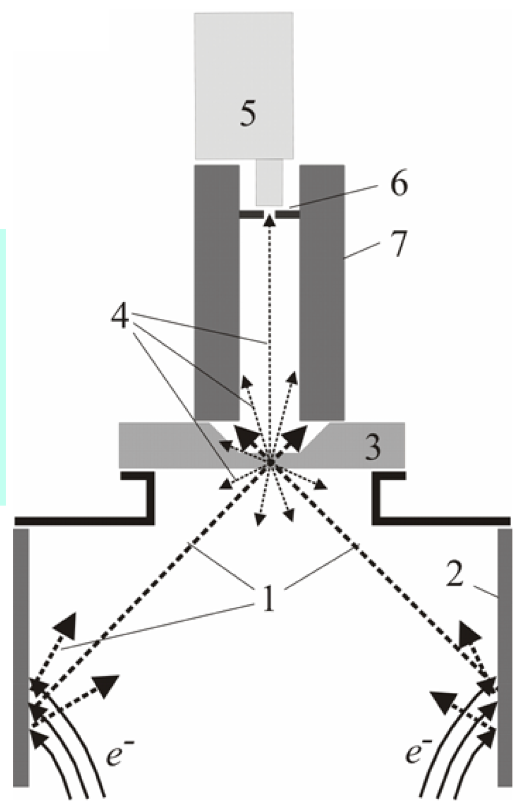
for typical θ = 25° and E = 50 (100) keV the energy loss is only 0.4 (1.5) %, and the corresponding errors can be further reduced by the data treatment procedures described in [1].

Conclusion: we can use scattered x-rays for determination of electron energy distributions.

4. Scheme "B"

In this scheme, the spectrometer is protected from direct x-rays and collects the radiation scattered in the window:

1 – direct x-rays produced by the beam (e^-); 2 – collector wall; 3 – diagnostic window; 4 – scattered x-rays;
5 – spectrometer; 6 – x-ray collimators (W);
7 – spectrometer shield.

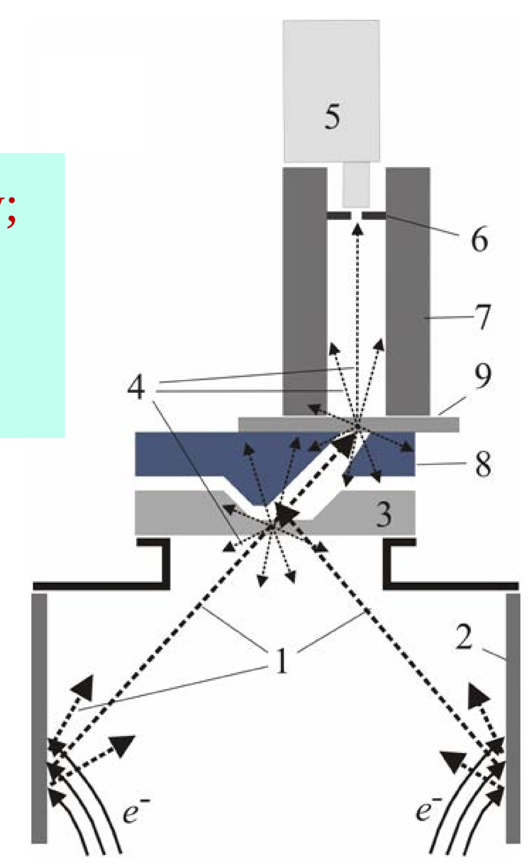


The acquired data are averaged over the whole electron beam. The optimal input photon rate ~10^5 sec^{-1} is obtained with 0.1 mm collimator pin-hole.
The possibility to use Compton-scattered x-rays for determination of electron energy distributions opens new prospects for the proposed diagnostic techniques that can be applied to serial gyrotrons and devices of other types not equipped with diagnostic windows.

5. Scheme "C"

Two additional elements of x-ray optics are introduced:

1 – direct x-rays; 2 – collector wall; 3 – diagnostic window;
4 – scattered x-rays; 5 – spectrometer;
6 – x-ray collimators (W); 7 – spectrometer shielding;
8 – x-ray mask (Cu); 9 – scattering plate (Al).



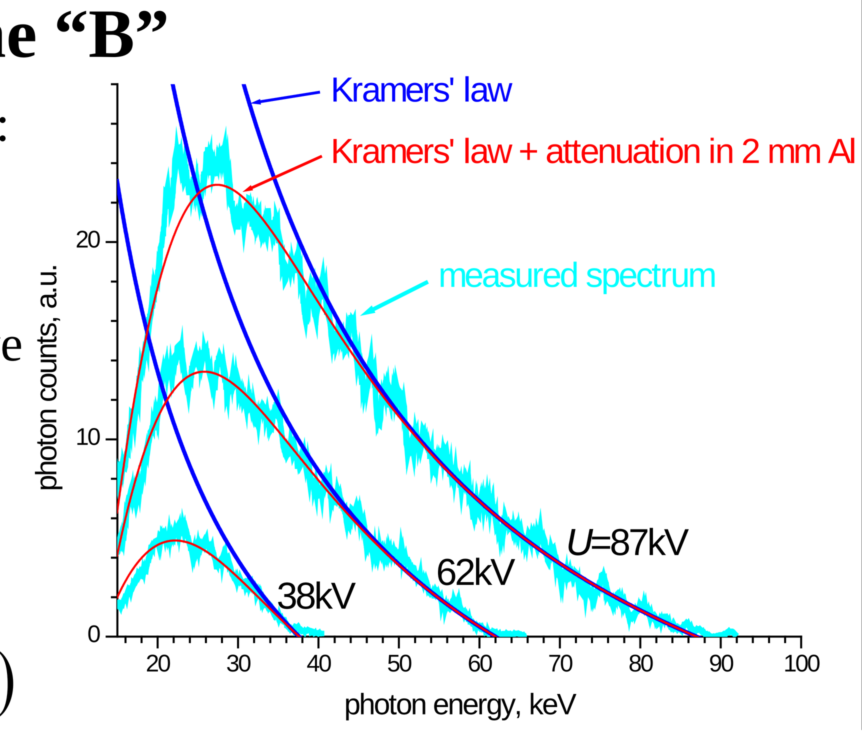
The scheme serves to acquire spatially resolved data, for instance, to determine values of electron efficiency (i.e. how much energy has been transferred from electrons to rf field) for different parts of the beam. If these values are substantially different, the beam needs better adjustment -- for some azimuths, electrons pass through the cavity wrong radii, where their interaction with the rf field is weaker.
Difference from layout "A": the data refer to approximately 1/10 of collector area, not 1 mm^2.

6. Experimental testing: scheme "B"

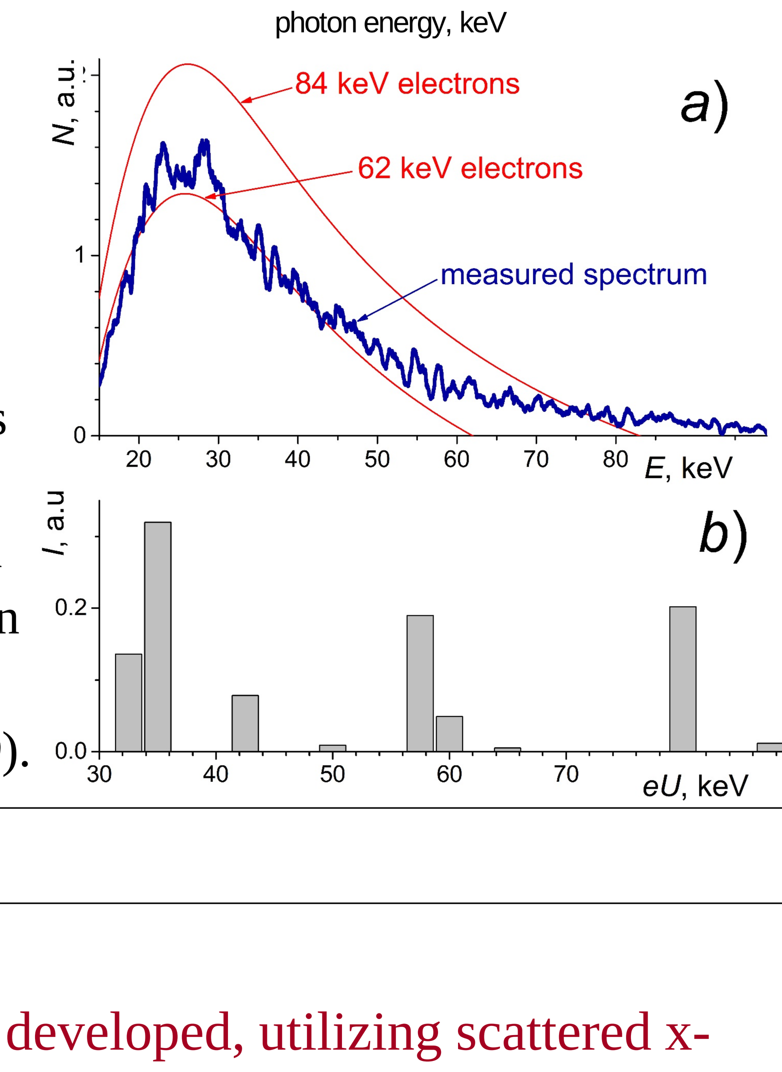
Tests of the technique using scattered x-rays:

Experiment 1:
low-current gyrotron regimes -- below the threshold of rf oscillations. All electrons have the energy corresponding to gun voltage U. The voltage was varied. The measured x-ray spectra showed good agreement with theory (Kramers' law):

$$N(E) = \text{Const}\cdot\left((eU/E)-1\right)$$



Experiment 2:
The technique was used for a regime with greater beam current (84 kV, 29 A), when the gyrotron generated high-power microwaves of 510 kW, approximately 50 % of its nominal power. In the top plot, the measured spectrum is compared with the spectra for the low-current regimes to demonstrate qualitative difference in their shapes. Processing of these data (plot *a)*) in accordance with the method [1] gave us the re-constructed electron energy distribution (plot *b)*).



Summary:

1. An original diagnostic technique has been developed, utilizing scattered x-rays for measurement of electron energy in spent electron beams of gyrotrons;
2. The technique has been tested in experiments at high-power gyrotrons and gave plausible results (electron distributions);
3. The performed tests demonstrated prospects of the technique and allowed to accumulate a certain experience of its practical use, that can help to apply it with various high-power devices.