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Plasma Fluctuation Spectra as a Diagnostic Tool for Submicron Dust

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OUTLINE

- Motivation
- Effect of dust on plasma fluctuation spectra; Predictions of kinetic model of dusty plasmas
- Experimental set-up
- Results of spectral measurements
- Results of ex-situ dust analysis
- Comparison with the model- dust plasma parameters
- Conclusions, outlook

MOTIVATION

Current techniques for detection of *in situ* produced dust are usually restricted to a specific dust size range;

- micron and larger particles can be monitored by fast cameras
- for the submicron dust different radiation scattering methods can be applied (Thomson scattering, extinction spectrometry)
- postmortem analysis techniques are most developed
- use of mass spectrometry to detect the presence of macromolecule precursors of dust formation

There is gap of efficient and affordable on-line detection methods for detection of submicron particles.

- We propose and show that the measurements of electrostatic fluctuation spectra in dusty plasmas can constitute a basis for *in situ* diagnostic of invisible submicron dust.

BASIC IDEA OF THE METHOD

- **The presence of charged dust particles can change the plasma properties and, in particular, the amplitude and spectrum of the plasma density fluctuations.**

  V. N. Tsytovich and U. de Angelis, Phys. Plasmas **6**, 1093 (1999)

  U. de Angelis et al, Plasma Phys. Controlled Fusion **48**, B91 (2006)

- **These are due to particle discreteness and are always present in any system of particles, even at equilibrium, in contrast to driven perturbations, waves, and instabilities.**

- **CAN THEY BE MEASURED???**

- **Brush cathode -stable operation in the abnormal glow regime where the only fluctuations present are those associated with the thermal motion -**Karl-Birger Persson, J. Appl. Phys **36**, 3086 (1965)
- **Measurements of the cross spectrum of plasma density fluctuations**

  K. Geissler, R. Greenwald, and W. Calvert, Phys. Fluids **15**, 96 (1972)

- **Current devices: the plasma density fluctuations are enhanced by dust effects to a level measurable above the background noise**

  S. Ratynskaia et al, Phys. Plasmas **17**, 043703 (2010)
- **The spectral modifications and enhancement depend on dust size, density, and charge – a base for dust diagnostic**

DUSTY PLASMA KINETIC MODEL; ASSUMPTIONS

V. N. Tsytovich and U. de Angelis, Phys. Plasmas 6, 1093 (1999)

- ✓ All plasma components are in gaseous state
- ✓ Electron/ion binary collisions neglected compared to dust/plasma collisions
- ✓ Only the discreetness of the dust component is taken into account, ions/electrons are treated as continuous fluids in phase space
- ✓ Spherical grains with radius much smaller than Debye radius
- ✓ The charge on the grain is sufficiently large and dust charge fluctuations are small
- ✓ The dust grains are characterized by positions, momenta and charges, the charge is an independent variable and not a function of the position
- ✓ No external magnetic and electric fields.

GENERALIZATION OF THE KLIMONTOVICH EQUATION

Klimontovich equation for dust particles:

added term from the Liouville equation, due to the charge expansion of the phase-space and the charging equation

$$\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\frac{\partial}{\partial \mathbf{r}} + q\mathbf{E}\cdot\frac{\partial}{\partial \mathbf{p}}\right) f_p^d(\mathbf{r},q,t) + \frac{\partial}{\partial q}\left(I_{ext} + \sum_\alpha I_\alpha\right) f_p^d(\mathbf{r},q,t) = 0$$

currents from the dust grain, without fluctuating parts

particle fluxes to the grain

$$I_\alpha = \int \sigma_\alpha(q,u) e_a u f_p^\alpha(r,t) \frac{d^3 p}{(2\pi)^3}$$

Klimontovich equation for the plasma species:

$$\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\frac{\partial}{\partial \mathbf{r}} + e_\alpha\mathbf{E}\cdot\frac{\partial}{\partial \mathbf{p}}\right) f_p^\alpha(\mathbf{r},t) = S_\alpha - \left(\int \sigma_\alpha(q,u) u f_{p'}^d(q) dq \frac{d^3\mathbf{p}'}{(2\pi)^3}\right) f_p^\alpha$$

external non-fluctuating source of plasma particles

dust acting as a sink of plasma particles

MAIN MODEL PREDICTIONS (to the right, left - multicomponent results)

- The spectral density of ion density fluctuations

$$S^{i}_{\mathbf{k},\omega} = \langle \delta n^{i}_{\mathbf{k},\omega} \delta n^{i*}_{\mathbf{k},\omega} \rangle$$
$$= S^{i(0)}_{\mathbf{k},\omega} \left(1 - 2\,\mathrm{Re}\left\{ \frac{\chi^{i*}_{\mathbf{k},\omega}}{\varepsilon^{*}_{\mathbf{k},\omega}} \right\} \right)$$
$$+ \frac{|\chi^{i}_{\mathbf{k},\omega}|^2}{|\varepsilon_{\mathbf{k},\omega}|^2} \left(S^{i(0)}_{\mathbf{k},\omega} + S^{e(0)}_{\mathbf{k},\omega} + Z_d^2 S^{d(0)}_{\mathbf{k},\omega} \right)$$

- The correlators of the natural density fluctuations of the three species are defined as

$$S^{\alpha(0)}_{\mathbf{k},\omega} = \langle \delta n^{\alpha(0)}_{\mathbf{k},\omega} \delta n^{\alpha(0)*}_{\mathbf{k},\omega} \rangle = \frac{1}{(2\pi)^3} \int \Phi^{\alpha}(\mathbf{v}) \delta(\omega - \mathbf{k}\cdot\mathbf{v}) d\mathbf{v}$$

- The spectral density of ion density fluctuations

$$S^{i}_{\mathbf{k},\omega} = |N^{i}_{\mathbf{k},\omega}|^2 S^{d(0)}_{\mathbf{k},\omega}$$

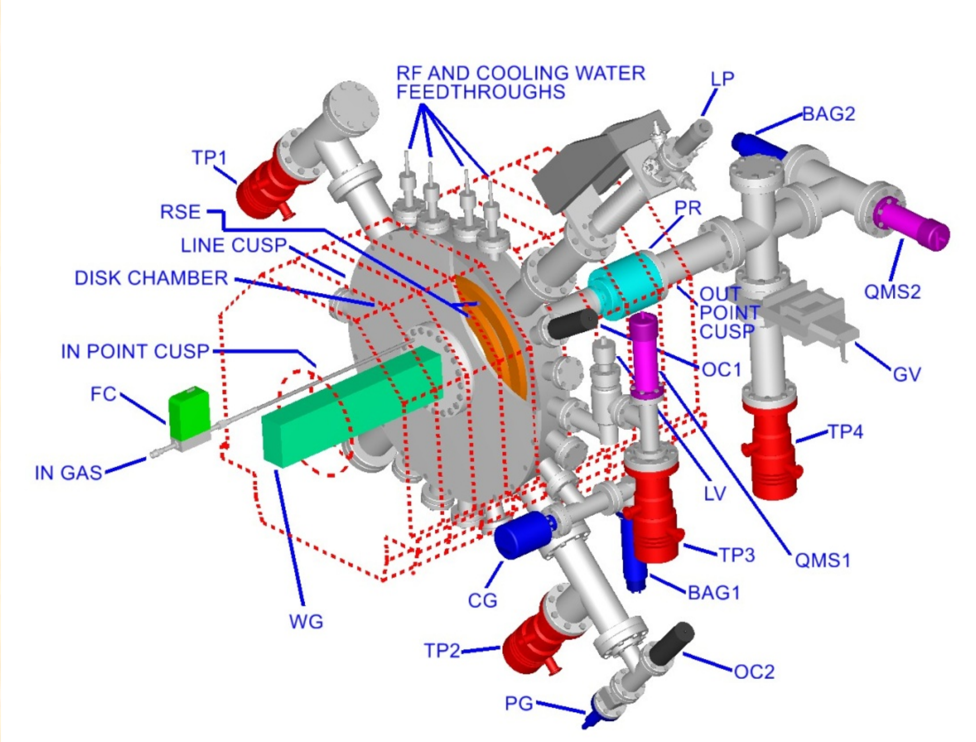
- The response $N^{i}_{\mathbf{k},\omega}$ contains
- the dust responses susceptibility,
- the effects of the dust charge and field induced density fluctuations
- the effects of the collisions of plasma particles with dust

- These effects scale with

$$\epsilon \sim n_d (\lambda_D)^3 (a_g / \lambda_D)^2$$

- For small ε the response

$$|N^{i}_{\mathbf{k},\omega}|^2 = Z_d^2 \frac{|\chi^{i}_{\mathbf{k},\omega}|^2}{|\varepsilon_{\mathbf{k},\omega}|^2}$$



Discharge parameters:

Microwave frequency: f = 2.45 GHz
Launcher: Truncated waveguide $TE_{1,0}$
Microwave power: P_{sour} = 350 W
Neutral pressure: $P_n = 2\times10^{-3}$ mbar
Gas flux: F_g = 0.45 sccm

Cusp ratio B_{point}/B_{line} : 0.3T / 0.19T
Point to point distance: 78 cm
Line cusp radius: 19 cm

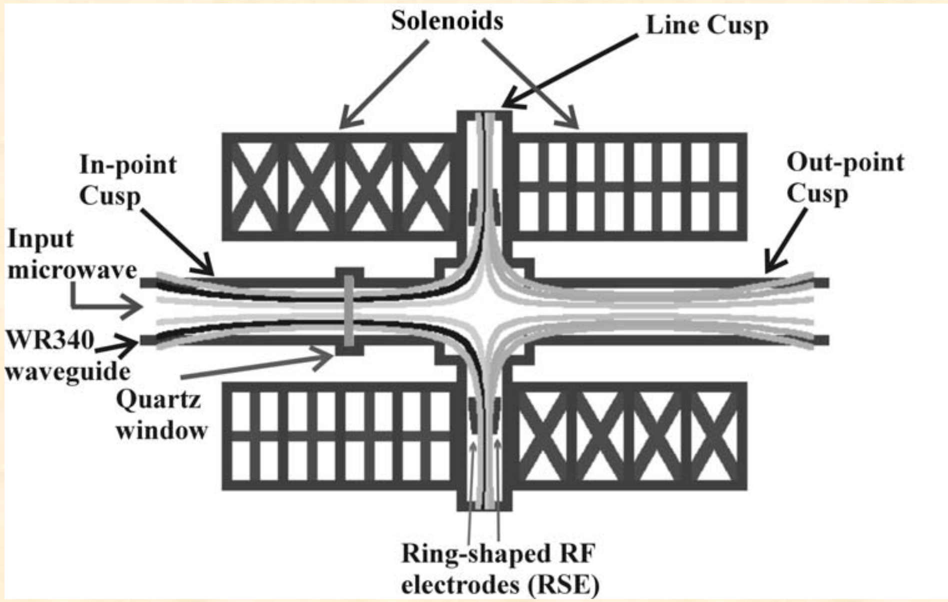
Typical plasma parameters

Plasma density: $n_e \sim 10^{11}$ cm^{-3}
Electron temperature: T_e ~2-3 eV
Ion temperature; Ti ~0.03 eV

Gas mixtures

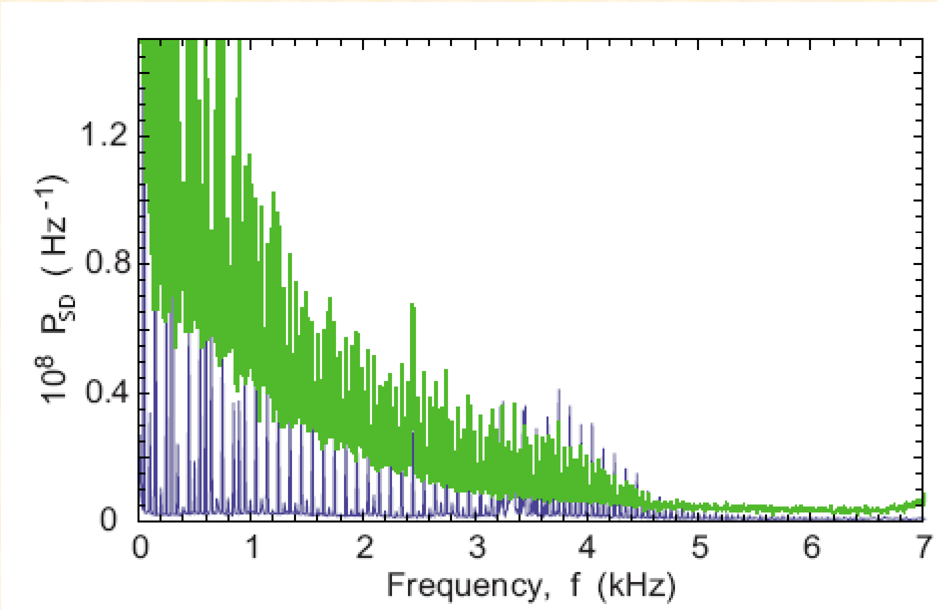
Ar (dust free)
Ar-NH3 (dust free but similar ions with CH4)
Ar-CH4 (carbon dust particles formed)

For meaningful comparison:
Discharges are similar macroscopically with lowest fluctuation levels achieved in every gas mixture

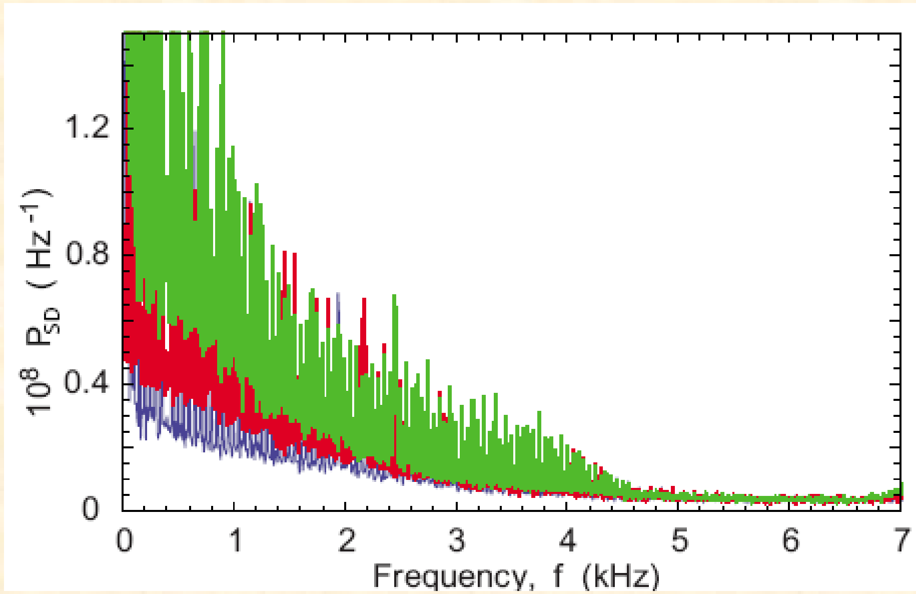


RESULTS OF SPECTRAL MEASUREMENTS

"Reference" spectrum measured in dust free Ar and Ar–NH3 plasmas (blue) and typical spectrum in dusty Ar–CH4 plasma (green)



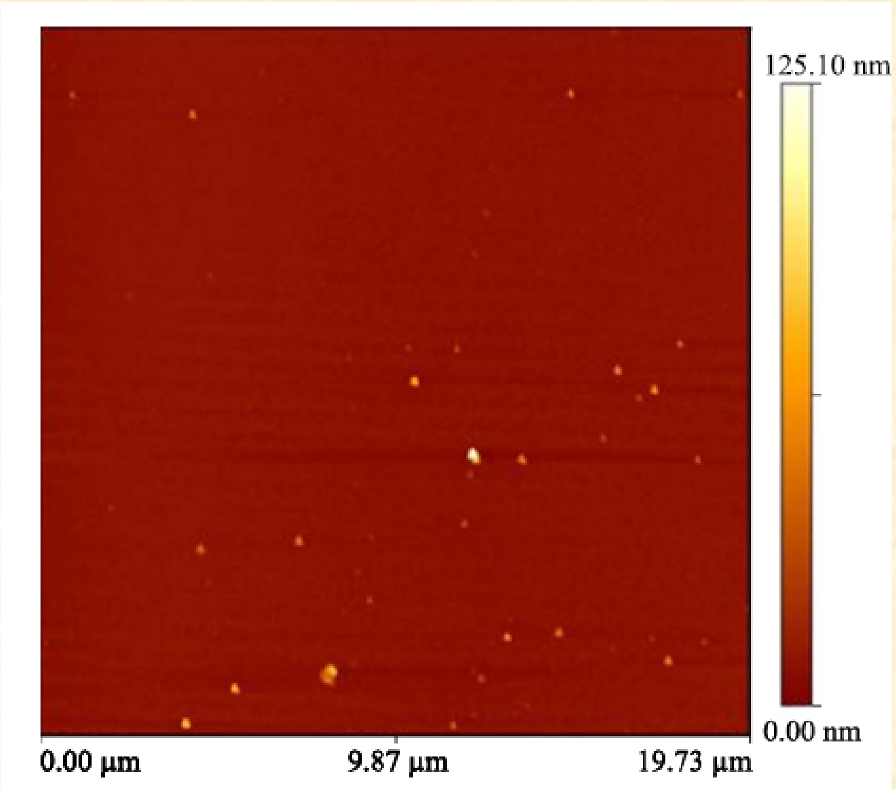
Typical power spectra measured in Ar–CH4 plasmas at 10 (blue), 20 (red), and 40 (green) minutes after the start of the discharge. After 40 min, the spectrum stops growing.



Ratynskaia *et al*, PoP **17**, 043703 (2010)

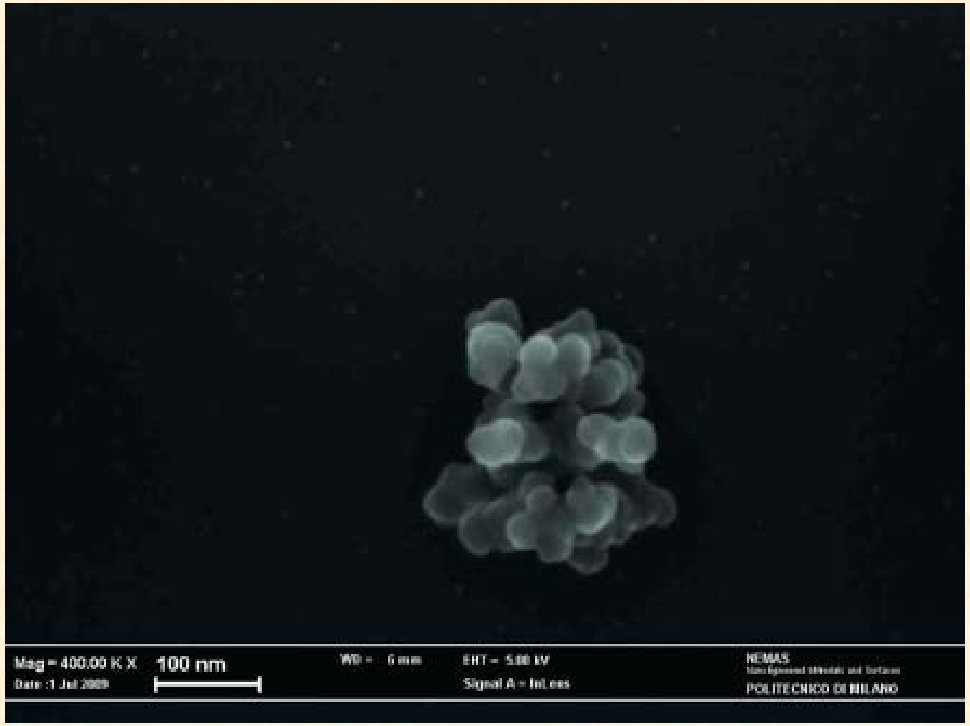
RESULTS OF AFM (left) AND SEM (right) ANALYSES

- Presense of grains 20-700 nm
- With increased exposure time greater number of large grains



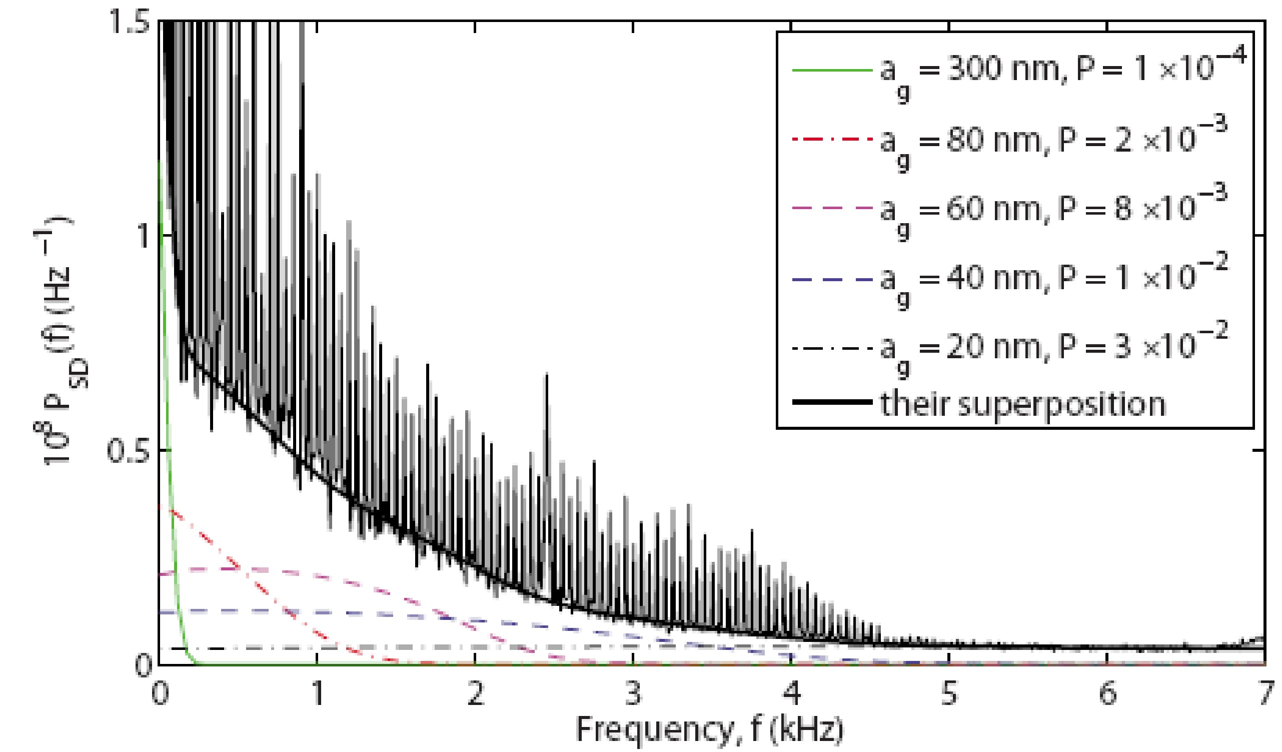
Ratynskaia *et al*, PoP **17**, 043703 (2010)

- Each grain is an agglomerate of nanospheres of few tens of nanometer produced in the plasma phase.
- The energy dispersion x-ray spectroscopy demonstrated the carbon composition of the particles.



EXTRACTING DUST PARAMETERS

The different density parameter P and grain size ag correspond to the following dust densities cm^{-3} : 7×10^3, 5×10^5, 3×10^6, 5×10^6 , and 2×10^7 from the largest to the smallest grain, respectively.



Experiment

$$P_{\rm SD}(f) = \frac{1}{T}\widetilde{\delta N}(f)\widetilde{\delta N}^*(f)$$

$$\delta N(t) \equiv \frac{I(t) - \bar{I}}{\bar{I}} = \frac{\delta n_i(t)}{n_i}$$

Theory

$$P_{\rm SD}(f) = \frac{4\pi^2}{n_i^2}\int_0^{k_{\max\parallel}} dk_\parallel \int_0^{k_{\max\perp}} dk_\perp k_\perp S^i_{\mathbf{k},\omega}$$

CONSLUSIONS

- Combination of ex situ identification of submicron dust characteristics and *in situ* monitoring of its formation within the plasma, and its influence on the ion fluctuation spectrum support the application of the theory of electrostatic fluctuations in dusty plasmas as a basis for a diagnostic technique.

- The enhancement of the power spectral density in the frequency range below the dust-ion acoustic mode has been demonstrated to be above the effective experimental noise level, and to provide, therefore, meaningful measurements that can be related to dust properties.

- Tests in other machines (e.g. afterglow plasmas) and development of ”user-friendly” diagnostic (software) are subjects of current research