Vibrating wire sensors with combined principle of operation for accelerator beam diagnostics

1. Abstract

The new generation of accelerators demands beam profiling instruments with very high accuracy and simultaneously a large dynamic range allow to measure very small and large amount of particles and possibility to measure the different sizes of beams with good spatial resolution. In this Proposal the measurements of accelerator beam profile are intended to do by means of vibrating wire monitors (VWM) both for thermal and resonant type of operation. In first type the low current beam profiling it is possible to perform with usage huge dependence of the vibrating wire oscillations frequency to the wire penetrating particles heat impact. A new type of vibrating wire monitors based on the usage of vibrating wire as a resonant target is proposed. The known frequency of vibrating wire allows to eliminate high level background of secondary/reflected particles and separate only necessary for profile recovery signal. Both methods will be developed, tested in the lab and implemented in AREAL accelerator (Candle SRI).

2. The problem statement and current state

The perfect knowledge of the accelerator beam parameters allows using that information to optimize these parameters and make them appropriate for experimentation and expand the beams scopes of application. One of the important characteristics of the accelerating beam is its transverse profile. In more cases, not only the transverse dimensions of the beam are important, but also the distribution of the particles in the beam cross-section. The new generation of accelerators demands beam profiling instruments with very high accuracy and simultaneously a large dynamic range allow to measure very small and large amount of particles (halo/core) in high current accelerators (for example in accelerator IFMIF - International Fusion Materials Irradiation Facility) - provided to produce high energy neutrons - Deuterons 40 MeV - at 250 mA beam current [1]), accelerators with very thin beams (for example in new generation of synchrotron radiation sources [2]) etc.

Wire scanners with known principle of operation are widely used for different types of beam profile measurements. This principle of operation consists in measurement of secondary particles/radiation arises at scattering of the beam particles with wire. The main disadvantages of this type wire scanners are the necessity of the additional system of particles/radiation measurement and great impact of background radiation in vacuum chamber.

By our group the new type of charged particles/radiation diagnostic methods based on vibrating wire was developed. The principle of operation is based on strong dependence of the resonant frequency to wire temperature (thermal principle). The tools made on this base in different tests and experiments show good accuracy, large dynamic range, great reliability and ability to work in the hard conditions. These tools have good spatial resolution and can be used for diagnostics the different origin of beams (electron, proton, ion and photon). Special (VWM) for neutron beam measurements.is developed. Specialized multiwire VWM with possibility of rotation along the beam axis can be used to recovery of complicated 2D profiles of large cross-section of electron. proton and even neutron beams.

In this Project a new type of VWM based on the usage of vibrating wire as a resonant target is proposed. The known frequency of vibrating wire allows to eliminate high level background of secondary/reflected particles and separate only necessary for profile recovery signal.

The first aim of developed VWM both with thermal principle of operation and in resonant target mode is to apply them for accelerator AREAL with 5 MeV energy and its upgraded stages with energy 20-50 MeV (ALPHA - Amplified Light Pulse for High-end Applications and BETA – Booster for Emerging Technology [3-8]).

The scientific purposes

In this Proposal the measurements of accelerator beam profile are intended to do by means of vibrating wire monitors both for thermal and resonant type of operation. The developed VWM will be applied for AREAL accelerator. It is necessary to mention that in today's diagnostics and control system of AREAL [4, 5] for beam transverse profile measurements the fully distractive for beam YAG:Ce scintillating crystals are used since the common type wire scanners would not generate sufficient signal-to-noise ratio. Usage of VWM in thermal mode of operation will overcome this restriction and take opportunity to use non-destructive instrument both in 5 MeV mode of operation and in ALFA and BETA 20-50 MeV facilities (under construction).

Taking into account unique parameters of AREAL accelerator (ultrashort ps bunch duration and corresponding pA range beam average current) the special VWM with fine resolution is planned to develop. Besides this a new type of where the vibrating wire serves as resonant target is intended to develop and tested. This new type resonant target VWM will drastically reduce the measurement time.

Research program

State of art and new method description

The operating principle of (VWM) is based on the measurement of the change in the frequency of a vibrating wire, which is stretched on a support, depending on the physical parameters of the wire and environment in which oscillations take place.

The tension change may occur due to temperature change of the wire, which results in frequency change of the wire oscillations. This change can be caused in particular by the passing of the charged particle beam/radiation through the material of the wire and may be the measure of the flow of particles scattered on a wire.

The frequency of the monitor, depending on the original wire tension, material, and size of the sensor, is in the range of 1-10 kHz. Typical range of the output - the frequency shift - is more than 0.01 (lower limit) and less than 1000 Hz (upper limit), i.e. the dynamic range of up to several units at 1e+5 is achievable. Monitor resolution is several units of 0.001 Hz and measurement accuracy is better than 0.01 Hz. Depending on the material of the wire and its geometric dimensions, such accuracy often corresponds to the accuracy of measuring of the change of the wire temperature less than 1 mK [9, 10].

The heat transfer from beam to wire depends on particle type, energy, and composition of wire material, as well as wire thermal conductivity coefficient and monitor location and environment. Till now by VWM we have been able to measure in average 1-10 nA electron current. These values exceed the AREAL beams average current, which is in the pA range. Therefore, to provide AREAL accelerator low current beam measurements it is necessary to increase the VWM resolution and accuracy. In this proposal, it is planned to do it with the following methods:

- to use materials with low thermal conductivity,
- to develop monitors of a miniature design, where it will be possible to place thin wires with a diameter of several tens of micrometers,
- to install the monitor in a vacuum chamber, which will avoid convective thermal conductivity effects.

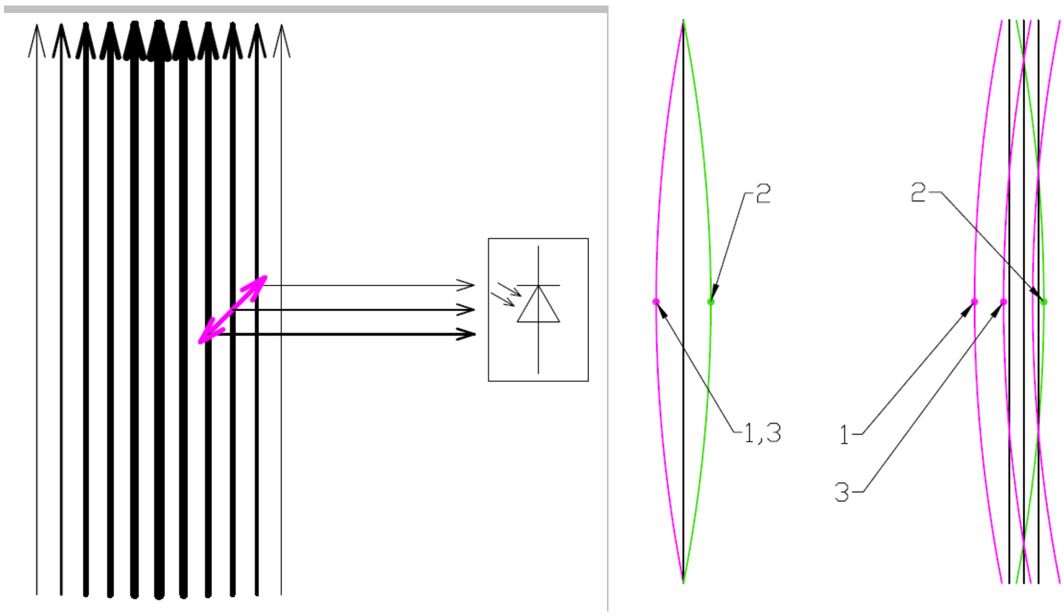
In addition, it is planned to carry out the first experiments based on a new method, where the vibrating wire will be used as a resonant target. As a way of measuring reflected/scattered particles/photons this method allows to use special high-speed hard radiation photodiodes and sensitive photo electronic amplifiers. The role of the wire usage is that the measurements will be carried out in synchronism with the vibrations of the wire. This method allows separating the signal generated by beam scattering on the wire from the surrounding background and considerable improve scanner parameters in comparison with tools with non-vibrating wire.

The scan of beam with VWM needs a set of frequency measurements in several positions. The electronic board of the VWM for each wire consists of the two main units: wire oscillation generator and the frequency measurement unit. The core of this unit is microcontroller PIC18F25xx series. The data transfer to computer is provided via RS232 or USB interface.

In below we present the new principle of using a vibrating wire as a resonant target.

The idea of the method is that the photons scattered on the wire are measured synchronously with the vibrations of the wire. Due to the high frequency of the wire oscillations (few kHz), it needs less than 1 ms of the measurement time at each scan position, which results in only tens of ms of total scan time. The differential signal is produced through two serial measurements of the photons reflected from the opposite positions of the vibrating wire oscillations. This procedure eliminates a high level of background noise and also minimizes the noise in the electronic circuits. The proposed method is also applicable to scan beams of other types, e.g. neutrons (see [11]), protons, electrons and ions. The advantage over the VWM thermal mode operation is possibility to carry out two measurements during the period of wire oscillation. So, in 20-50 ms a few mm diameter beam scan can be performed. This type of scanners below will be called (RT-VWM) (Resonant Target - Vibrating Wire Monitor).

In Fig.1 the nonuniform measured beam flux is represented by vertical lines with different thicknesses in which placed the vibrating wire at the first harmonic. The direction of wire oscillation is perpendicular to the drawing plane, and the wire center is moving along an inclined segment The reflected from the vibrating wire the photons are moving along the horizontal lines the width of which is comparable with the beam density. In the case of photons, the measurements are made by the fast photodiode or by sensitive photomultiplier. The measurements are carried out in synchronism with the wire’s oscillation when the wire is in the maximal deviating position from the middle. The required stroboscopic signal is provided by converting the sine-signal of autogenerator circuit into a rectangle-signal through a comparator circuit.



a) b) c)

Fig.1. Schematic view (a) of the measured beam with nonuniform profile. The nonuniform beam flux is represented by vertical lines with different thicknesses. The thicker lines correspond to the larger values of beam intensity. The direction of wire oscillation is perpendicular to the drawing plane, and the inclined segment (magenta line) indicates the movement of the vibrating wire center. The different fluxes of reflected photons at these positions, which are illustrated by horizontal

arrows with different thicknesses, are measured by the fast photodiode. Schematic view (b) of the vibrating wire in the maximal deviating positions from the fixed stable position (black line): 1, 3 - "left" measurements, 2 - "right" measurements. Schematic view (c) of the vibrating wire moving to the right: during one period of the wire oscillation, the "left" measurements 1 and 3 shift proportional to scan speed. All schematics are not to scale.

The measurement algorithm proposed in this work is based on subtraction of series of half-period measurements, which enables to eliminate background. In Tab.1 the typical parameters of RT-VWM two modifications are presented.

Tab.1. Two RT-VWM modifications typical parameters

L, mm	F, Hz	a, mm	$2a/F$, mm/s	A, mm	V_{MAX}, mm/s	t_S, ms	N
40	2500	0.15	750	3	150	20	100
80	1250	0.30	750	3	75	40	100

Here, L - is the wire length, F – is the wire frequency, a - wire diameter, $2aF$ - wire oscillation mean speed. (the diameter of wire in both cases is 0.1 mm), A – the size of beam, V_{MAX} - is the maximum of scan speed, t_S -the minimal time of scan, N- the total number of measurements during the one scan. We note that the scan speed of the shorter wire can be increased twice.

Method was successfully tested on the laser beams [12, 13].

The way of implementation

The measurement system development and manufacturing.

The measurement system testing on laboratory test-bench with usage of the laser beam and equivalent DC current sources.

Vacuum tests in laboratory.

The system installation in AREAL accelerator.

The system testing on the AREAL accelerator including tests of interface.

The measurement system instrumentation on the beam of AREAL accelerator.

The measurement system calibration and documenting.

The experiments layout

For AREAL accelerator beam profiling by VWM with thermal principle of operation the following layout presented in Fig.2 is proposed.

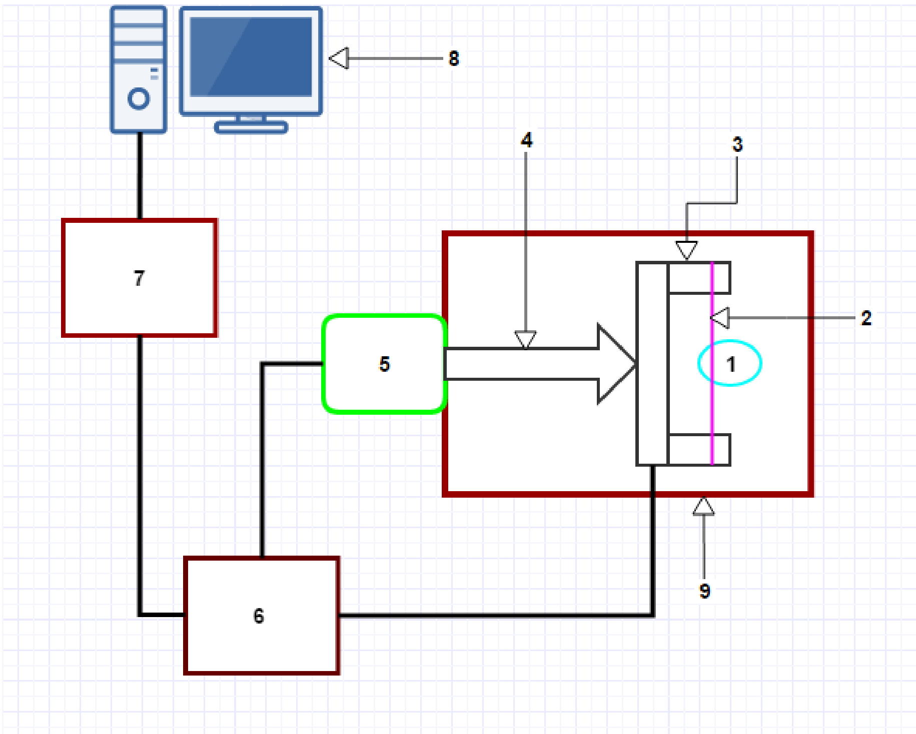


Fig.2. The measurement layout of the AREAL accelerator by means of precise VWM. 1 - the cross-section of the AREAL beam, 2 - vibrating wire, 3 - VWM, 4 - VWM feed system, 5 - stepper motor of the feed system, 6 - the wire oscillation autogenerator and stepper motor unit, 7 - VWM wire frequency measurement system equipped with RS232/USB interface, 8 - PC, 9 - special vacuum chamber.

For AREAL accelerator beam profiling by RT-VWM with resonant principle of operation the following layout presented in Fig.3 is proposed.

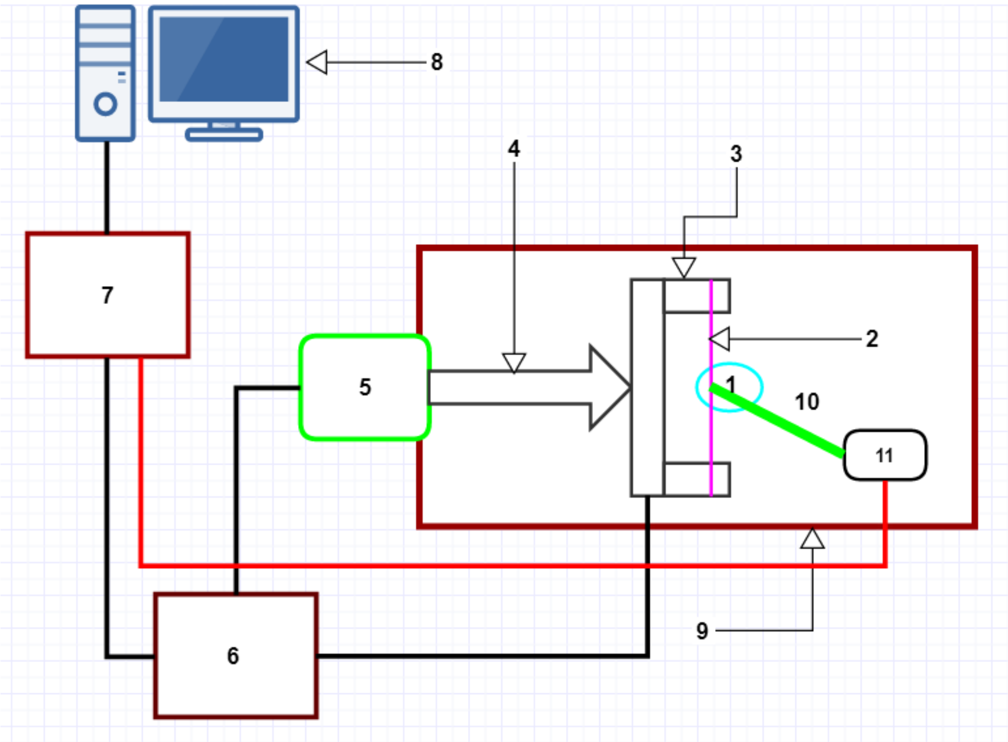


Fig.3. The measurement layout of the AREAL accelerator beam transversal profile measurement, where the vibrating wire serves as resonant target (RT-VWM). 1 - the cross-section of the AREAL beam, 2 - vibrating wire, 3 - RT-VWM, 4 - RT-VWM feed system, 5 - stepper motor of the feed system, 6 - the wire oscillation autogenerator and stepper motor unit, 7 - RT-VWM wire frequency and scattered from the vibrating wire particles/radiation measurement system, equipped with RS232/USB interface, 8 - PC, 9 - special vacuum chamber, 10 - the beam of scattered particles/radiation, 11- the system of scattered particles/radiation measurement synced with wire oscillation (special high speed hard radiation photodiodes or sensitive photomultipliers).

Quarterly chart

1-2 The development of the VWM with high resolution development and manufacturing (choice of wire material, estimations of electron energy losses in wire material, choice of VWM design, development, manufacturing and tuning of the electronic units)

2-4 vacuum chamber design and manufacturing, high vacuum tests

3-4 VWM feed system development and manufacturing, coupling with vacuum chamber

5 the whole system tests on laser beam, system calibration with equivalent DC current sources

5-6- the whole system installation on the AREAL accelerator, vacuum tested

6 the system conjugation with AREAL accelerator control room, tests of interface

6-7 the system tests on the electron beam of accelerator, results processing, discussing and publishing

5 VWM as a resonant target layout development (RT-VWM)

5-6 the photodiode tests for photon measurements arose in process of electron scattering on the wire

7 the sensitive photomultipliers system development, manufacturing and tests for particles/radiation measurements arose in process of electron scattering on the wire

7-8 the first experiments on usage RT-VWM, results processing, discussing and publishing

Nessecary equipment and materials

- Electronic components, chips, microcontrollers
- Equipment and materials for vacuum chamber manufacturing
- Equipment and materials for mechanical layout manufacturing

3. The group experience and expected results

1. Diagnosis of electron beams

Scanning beams of charged particles was carried out on electron beam injector of Yerevan synchrotron injector with energy of 50 MeV and an average current of about 10 nA after collimation [14].

2. Proton beams

A series of experiments on the use of a vibrating wire monitors was carried out on the PETRA accelerator at DESY. The unique characteristics of VWM make it possible to measure the area of the halo of proton beam with an average current of about 15 mA and an energy of 15 GeV [15].

To date, the VWM was tested on the facility of Fermilab High Intensity Neutrino Source (HINS) with 50 keV proton beam [16]. In cooperation with UNIST (Ulsan National Institute of Science and Technology) Laboratory of Intense Beam and Accelerator vibrating wire monitor in 2016 was applied for large aperture proton beam measurements of Korea multi-purpose accelerator complex (KOMAC) [17].

3. Ion beams

VWM was tested on a beam of iron ions with energy of 20 keV and a current of 16 pA of energomass-analyzer EMAL- 2. Frequency shift was registered at the level of 0.15 Hz (the accuracy of measurement was about 0.01 Hz) [9].

4. Hard X-rays monitoring in vacuum

The measurements of the hard X-Ray beam were done on the APS Argonne National Lab (USA) photon source. This radiation left in the wire is only a small part of its energy, yet because of the high sensitivity of the VWM this energy is enough to warm the wire up to the offset frequency resolution. Experiments to measure the profile of the A undulator radiation from APS ANL with an energy in 6.5-19.5 keV range were successfully carried out [18, 19].

5. Hard X-rays monitoring in air

Five wires VWM was developed and tested in APS Argonne National Lab (USA) photon source [20]:

Experimental measurements of the electron beam parameters by synchrotron radiation were conducted at the synchrotron APS ANL.

The measurements were conducted out of the vacuum chamber behind of the flange-cap copper on one of the unused channels of synchrotron. Synchrotron radiation power of about 99.1 watts with a peak near 10 keV was mainly absorbed in the copper flange with thickness of 6 mm and only photons with an energy higher than 100 keV were came out of the flange (the tail of the spectrum of synchrotron radiation) with a power of 420 mW. Only 1.1 mW of power was absorbed on the wire and transformed into heat. Installed behind flange fixed five-wire VWM monitor provided five profiles of synchrotron radiation, which reflect the profile of the electron beam.

6. Diagnosis of neutron beams

The proposal on the use of sensors based on the vibrating wires for measuring the intensity and profile of neutron beams has been prepared [11]. Neutron beams profile measurements are hardly feasible because of the weak interaction of neutrons with matter. Profile measurements of neutron beams can be useful in imaging, including medical, geology for the search of minerals and seismographic forecasting, in military technology, etc. The penetrating ability of neutrons could provide better results in the study of living tissues. Diagnosis is based on measurement of the change of the frequency of vibrations of a wire due to the heat dissipation arising in the exposure of the wire under the beam of thermal neutrons. To increase the heat output we suggested cover the basic wire with a layer of gadolinium having a record capture cross section of thermal neutrons (about 255000 barn). The thickness of the gadolinium layer should be about 1-2 microns. Characteristics of such sensor are as follows: measuring range 8×10^7 - 8×10^{12} n / cm^2 / s (response time 70 ms) in a vacuum, and 3×10^8 - 3×10^{13} n / cm2 / s (response time of about 15 ms) in the air. For the measuring of less intensities of neutron beams can be used the RT-VWM monitors with a composite wire containing gadolinium.

Expected results on Proposal fulfillment

As a result of Proposal fulfillment ultra-low-resolution vibrating wire monitor for picoamper electron beam profile measurements is expected to develop. It is planned to test and calibrate it on the laser beam, and then install into AREAL accelerator specially designed and manufactured vacuum chamber. In the vacuum chamber will be installed also monitor feed system. The chamber will be equipped by two flanges of accelerator tract standard. In addition, the vacuum chamber will be equipped with special insert that will provide testing a new modification of vibrating wire monitor in which the vibrating wire will be used as a resonant target. The new method allows to reduce measurement time to ms duration.

The measurement system development and manufacturing where vibrating wire is used as a resonant target

The photodiode and photomultiplier system tools testing on particles/radiation arose at beam scattering on the vibrating wire

The first experiments on method where vibrating wire will be used as a resonant target, experiment results processing, discussing and publishing.

The both proposed methods (thermal operating VWM and RT-VWM) were discussed in Candle synchrotron research institute. As a result, Candle SRI expressed its support in proposed diagnostics implementation in AREAL accelerator including ALPHA and BETA upgrades (see supporting letter from CANDLE in attachment 1).

4. List of used references

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Attachment 1. Supporting letter from CANDLE

«ՔԵՆԴԼ»
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«ՔԵՆԴԼ» սինքրոտրոնային հետազոտությունների ինստիտուտի՝ 5 ՄէՎ փնջի էներգիայով ԱՐԵԱԼ գծային արագացուցիչը հաջողությամբ աշխատում է արդեն մի քանի տարի: Այժմ նախատեսվում է արագացուցիչի մոդերնիզացիան, որի նպատակն է բարձրացնել փնջի էներգիան մինչև 50 ՄէՎ, և արագացուցիչը համալրել նոր գիտահետազոտական կայաններով (Amplified Light Pulse for High-end Applications - ALPHA and Booster for Emerging Technology Accelerators – BETA): Նշված նախագծերում, որպես փնջի լայնակի պրոֆիլի չափման միջոց, պլանավորված է օգտագործել YAG:Ce սցինտիլյացիոն էկրանների համակարգեր:

Ս. Գ. Հարությունյանի խումբը (Երևանի ֆիզիկայի ինստիտուտ) արդեն մի քանի տարի շարունակ մշակում է տատանվող լարով սքաներներ, որոնք ունեն շատ մեծ զգայունություն և կարող են չափել պիկոամպերային փնջերի լայնակի կտրվածքներ: Մեթոդի առավելություններից է նաև, որ այն չի քայքայում չափվող փունջը, և չափումները կարող են կատարվել առցանց ռեժիմով: Վերջին տարիներին խմբի կողմից մշակվել է մեթոդի նոր տարբերակ, որտեղ տատանվող լարը օգտագործվում է որպես թիրախ: Այդ ռեզոնանսային տարբերակը զգալիորեն կրճատում է չափման ժամանակը, սակայն մինչև հիմա փորձարկվել է միայն լազերային փնջերի վրա:

Սույն նամակով հաստատում ենք մեր մեծ հետաքրքրությունը ԱՐԵԱԼ գծային արագացուցիչում տատանվող լարով սքաներների փորձարկման և տեղադրման մեջ.

1. Մեծ զգայնությամբ ջերմային սկզբունքով գործող տատանվող լարով մոնիտոր,
2. Նոր ռեզոնանսային սկզբունքով աշխատող կարճատև չափումներ իրականացնող սքաներ:

Այս երկու տարբերակն էլ կարող են համադրվել գործող և նախագծվող YAG:Ce սցինտիլյացիոն համակարգերի հետ:

Հարգանքներով,
«ՔԵՆԴԼ» ՍՀԻ տնօրեն՝ պրոֆ. Վ. Ցականով