Electrodeless Diamond Beam Halo Monitor

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Beam halo measurement is important for novel x-ray free electron lasers which have remarkably high repetition rate and the average power. We propose diamond as a radiation hard material which can be used to measure the flux of passing particles based on a particle-induced conductivity effect. Our diamond electrodeless monitor is based on a microwave measurement of the change in the resonator coupling and eigen frequency. For measurements we put a sensitive diamond sample in a resonator that intercepts the halo. By measuring the change in RF properties of the resonator, one can infer the beam halo parameters scanning across the beam to map its transverse distribution. In recent experiments we used a Vertical Beam Test Stand (VBS), delivered DC electron beam of the 20-200 keV energy with the current up to 50 μA, to characterize several diamond samples. We have designed and fabricated a scanning diamond monitor, based on an X-band resonator, which was tested at Argonne Wakefield Accelerator (AWA) with a multi-MeV electron beam.

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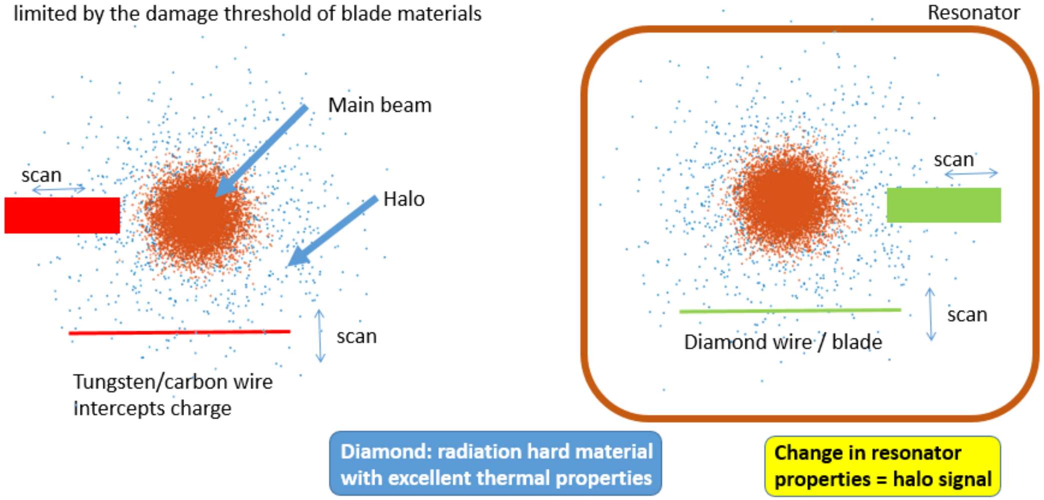
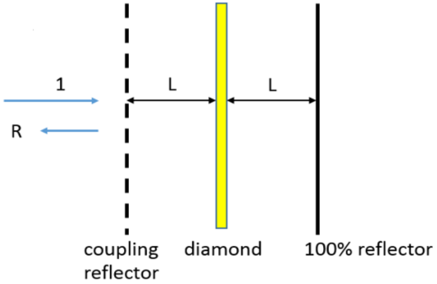
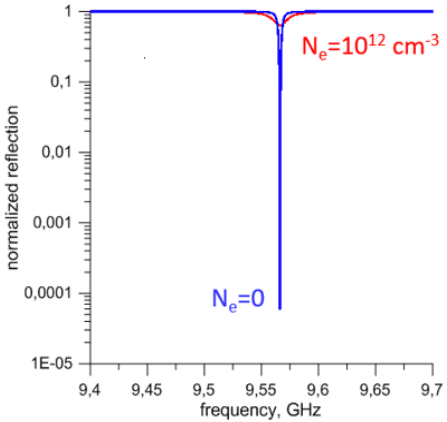
Concept of Electrodeless Beam Halo Monitor



Left: standard wire / blade beam halo scan.
Right: Proposed diamond blade beam halo scanning.



Model of resonator with inserted diamond sample.

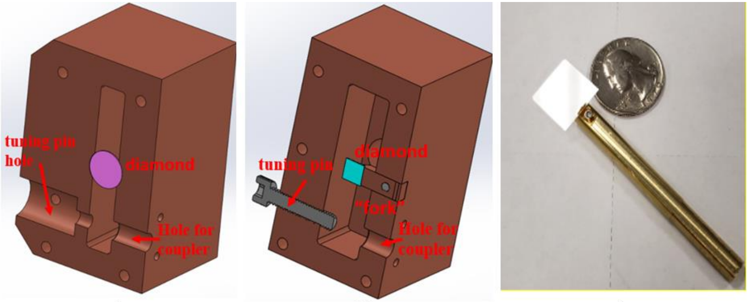


Simulation of S_{11} for beam and no beam for the resonator with critical coupling.

Tests of Diamond Samples at Vertical Beam Stand (VBS)

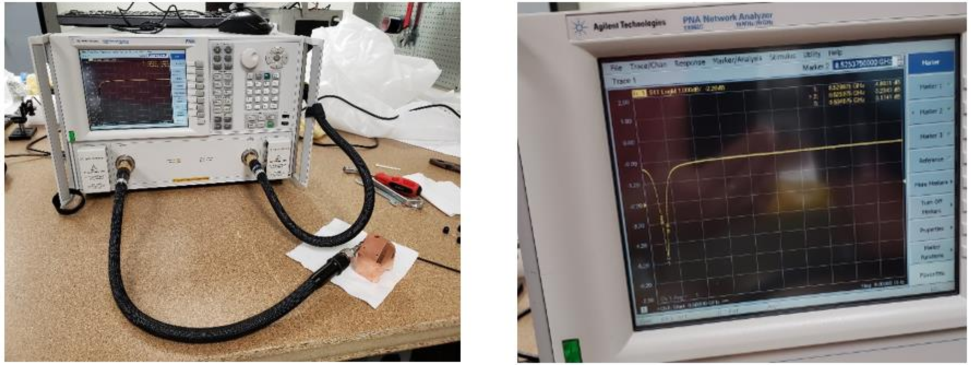
a) b) c)

Diamond samples: a – CVD electronic grade sample from Applied Diamonds Inc. (the biggest one), b – detector grade CVD diamond from II-VI, detector grade single crystal diamond from ElementSix.



a) b) c)

New resonators: a – copper resonator to accommodate circular diamond sample of II-VI, b – copper resonator to accommodate square diamond of Element6, c – "fork" support prototype for the Element6 diamond.

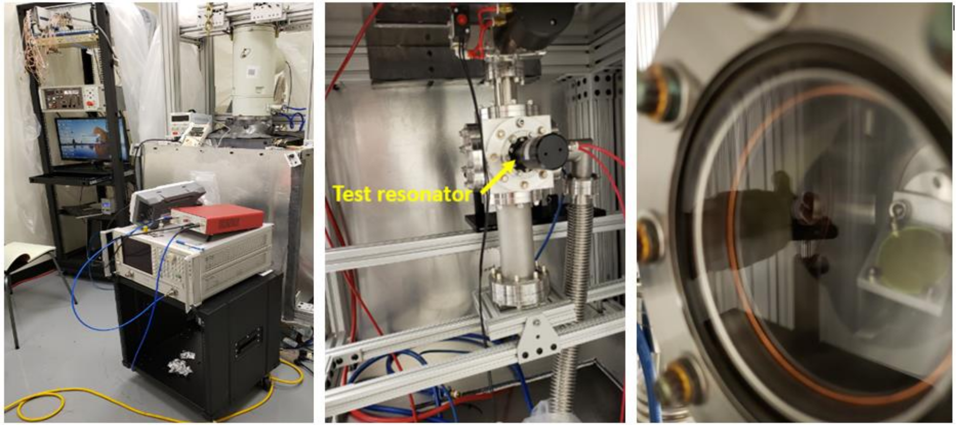


a) b)

Tuning of the copper resonator with built-in diamond sample (II-VI disk) before installation at VBS: a – network measurement setup, b – final curve for the tuned resonator.

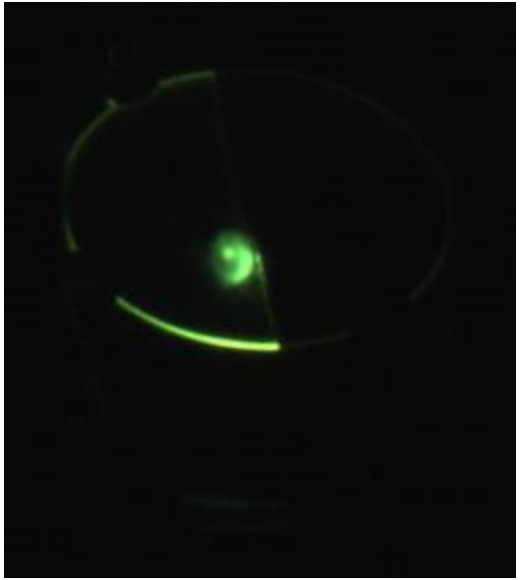
VBS Installation

VBS delivers a DC electron beam of the 20-200 keV energy with the current up to 50 μA.



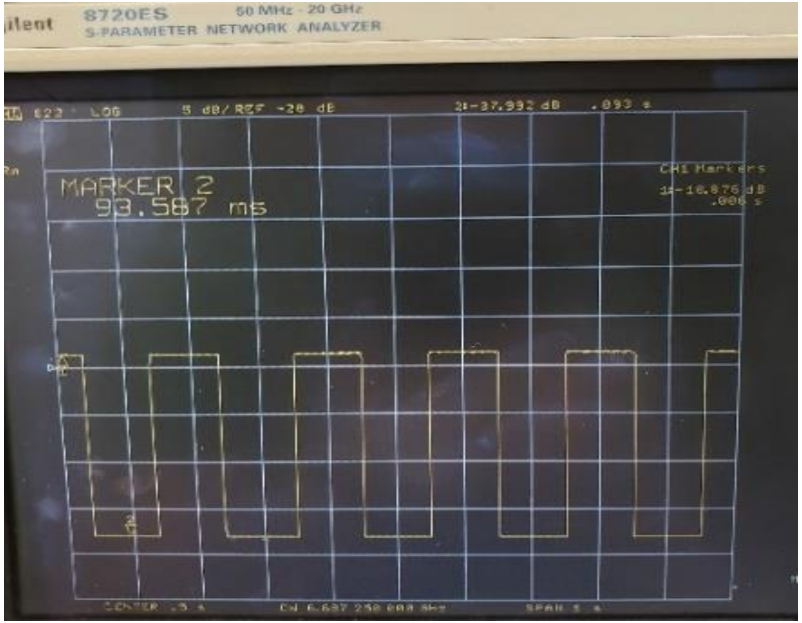
a) b) c)

VBS test stand with installed test resonator: a – overall view, b – test resonator in vacuum chamber installed in the bottom, c – view through quartz window to YAG-screen.

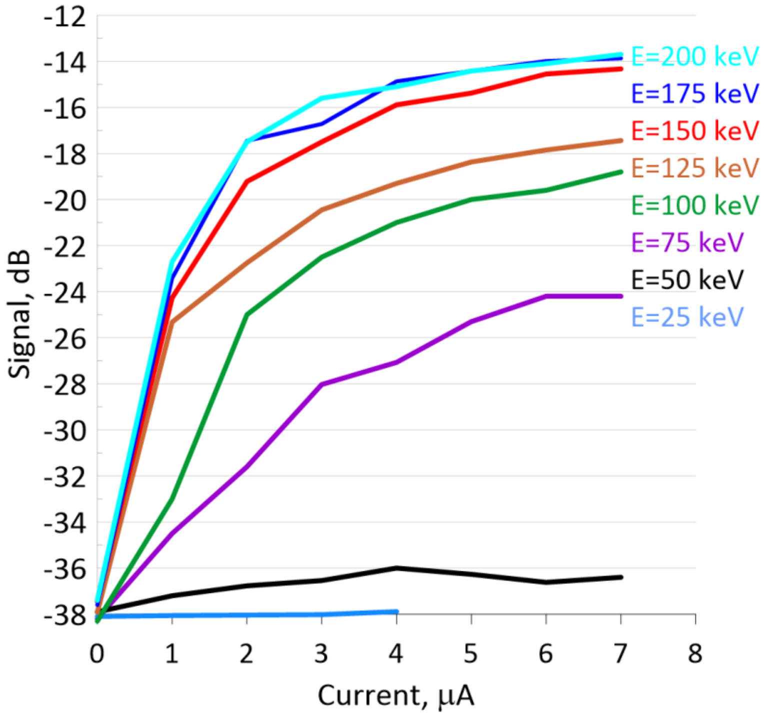


YAG-screen luminescence under beam exposure.

Experimental Results Obtained at VBS

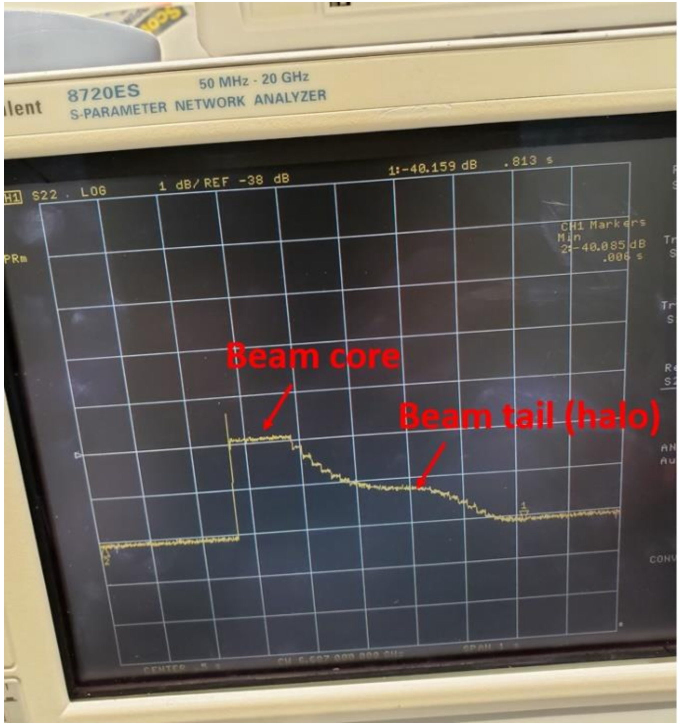


Monitor time response caused by 5 Hz on/off steered beam.

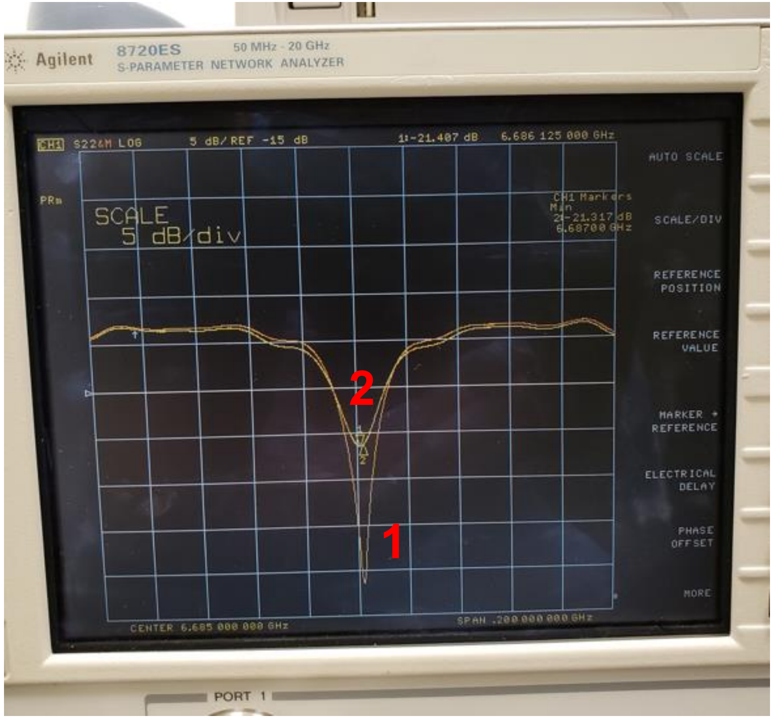


Experimental plot of beam monitor response amplitude vs beam current for several beam energies.

Experimental Results Obtained at VBS (continuation)

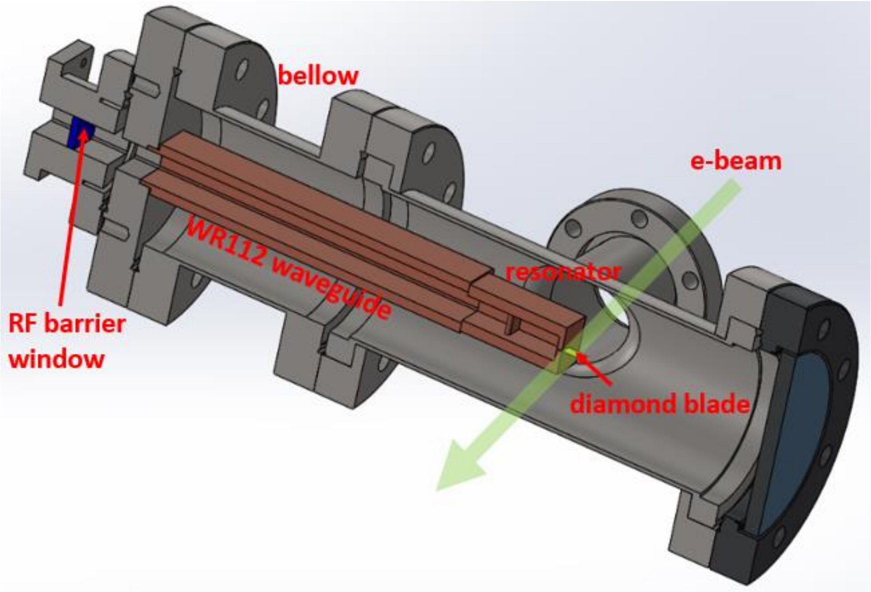


Measured profile of VBS electron beam.

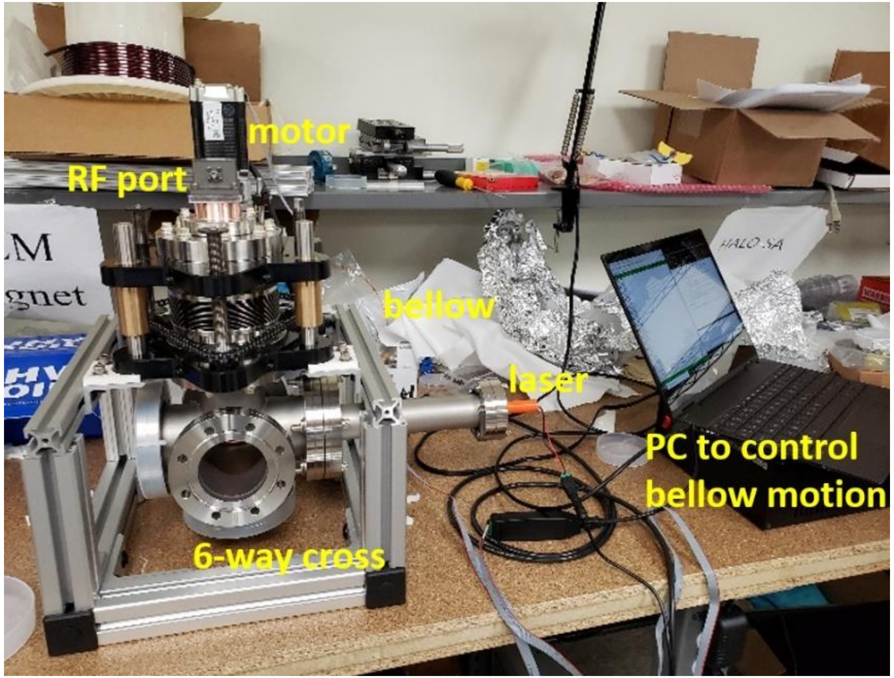


S_{11} parameter vs frequency for the resonator before beam exposure (curve 1) and under beam exposure (curve 2).

1D Scanning Halo Monitor

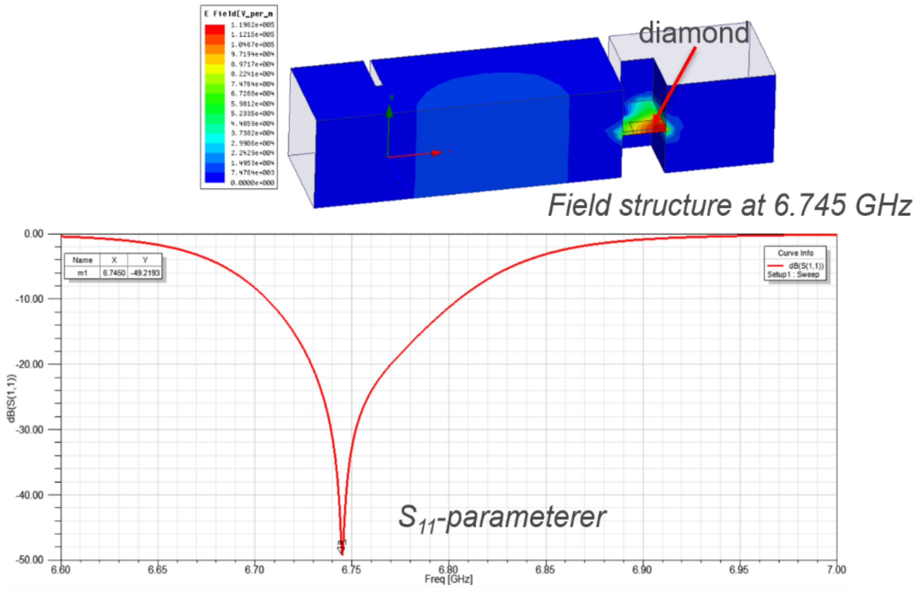


Sketch of scanning halo monitor with diamond blade and motorized bellow.

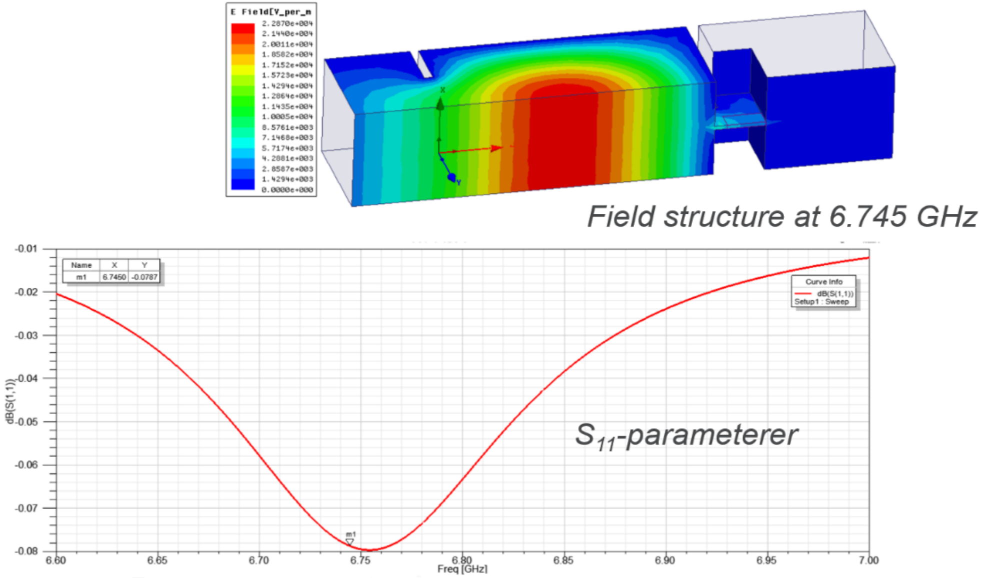


1D scanning monitor under mechanical test.

RF Design for Resonator of Halo Monitor



S_{11} parameter of the resonator with diamond not exposed by beam (N_e=0 cm^{-3}, tanδ=10^{-3}).



S_{11} parameter of the resonator with diamond exposed by beam (N_e=10^{14} cm^{-3}, tanδ=0.3).

Simulation of Nonlinear Resonator Properties

Parameters for simulation:

Q_0=5000 (without diamond)

$\tan\delta=10^{-5}$

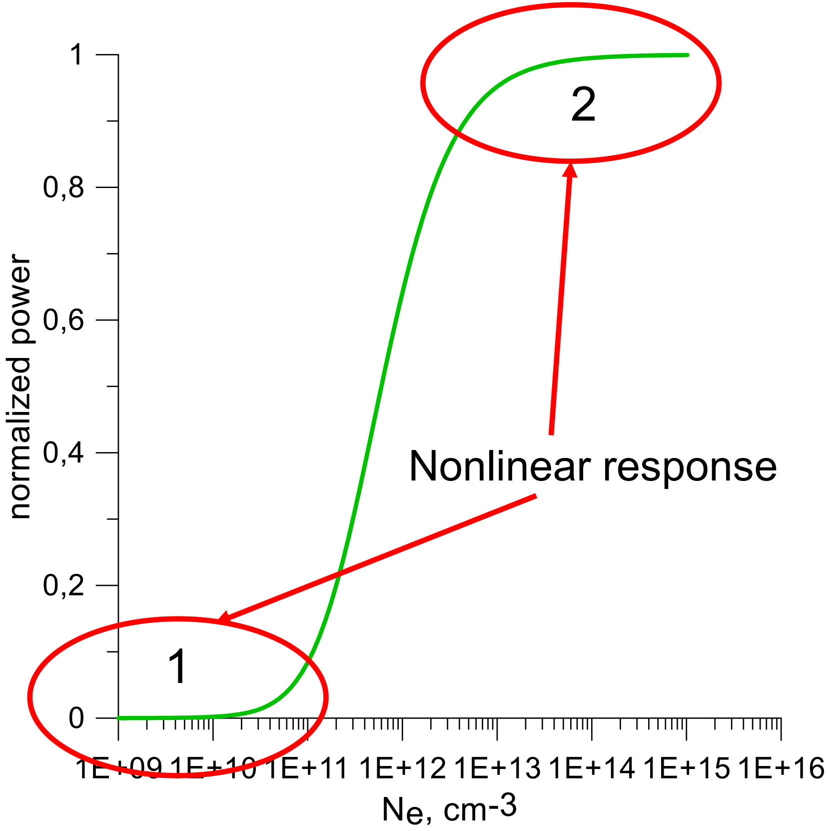
$\varepsilon_0=5.7$

Diamond width=100 μm

$\mu_e=1714\ cm^2/Vs$, $\mu_h=2064\ cm^2/Vs$

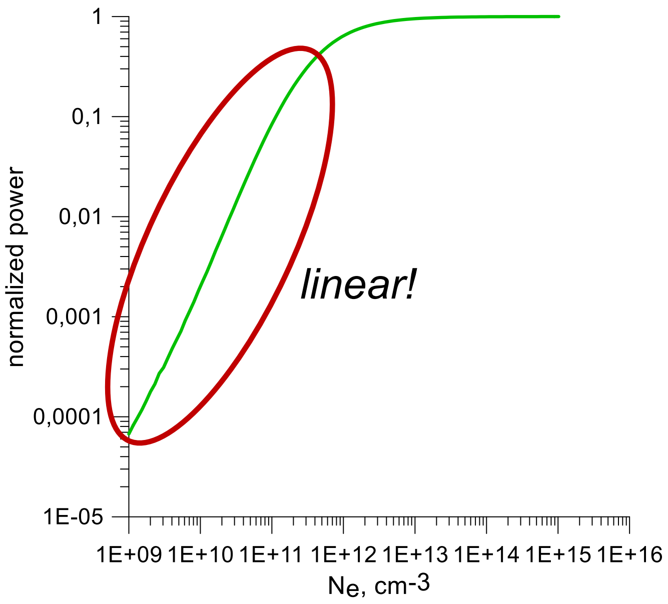
$\varepsilon=\varepsilon_0+ i\varepsilon_0 \tan\delta+i4\pi\sigma/\omega$

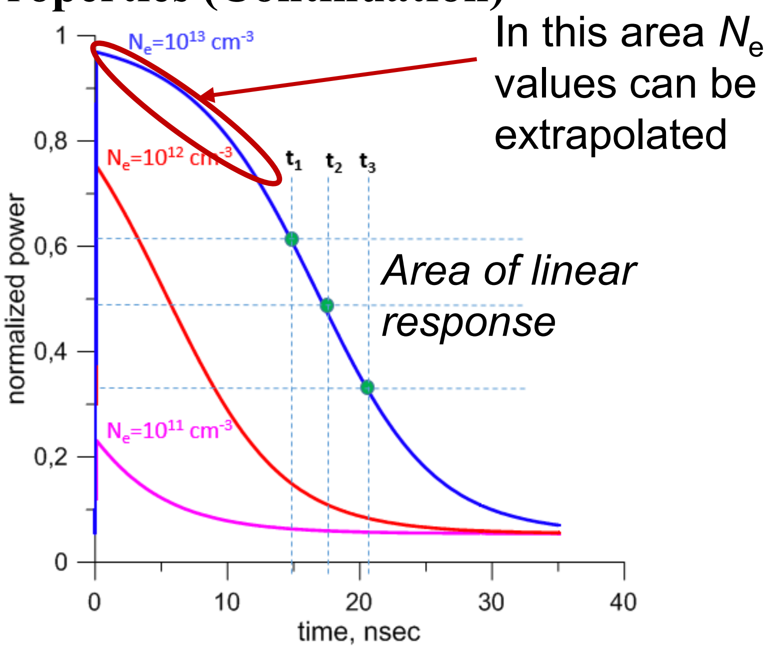
where $\sigma=eN_e\times(\mu_e+ \mu_h)$



Reflection vs concentration of free carriers

Simulation of Nonlinear Resonator Properties (Continuation)

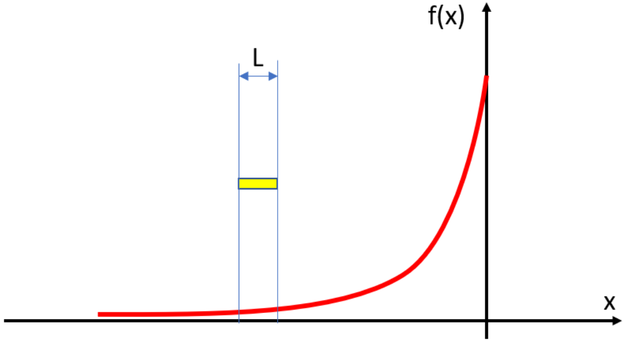




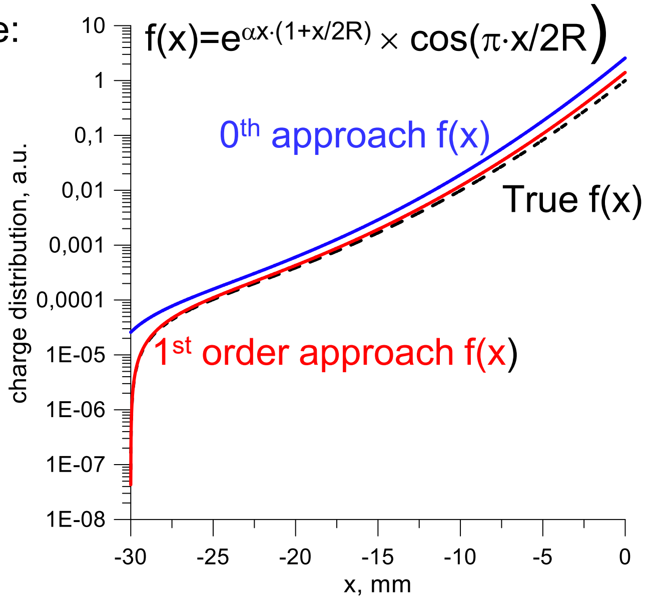
The first nonlinear part (for small N_e) could be considered in coordinates log(R) as a function of log(N_e).
In these coordinates the dependence is linear for small N_e.

The second non-linear part (for large N_e) could be measured using the recorded oscillograms of signals. Because for high N_e case the concentration N_e evolves as $N_e=N_0*\exp(-t/\tau)$, it inevitably covers all N_e values when the measured response remains linear one. One can take several points of R, where the response is linear, for several consequent times t_1,t_2, … t_3 and to retrieve all other N_e values.

Measurement of Halo Charge Distribution Using Large Diamond Samples



Example:
L=3 mm
R=3 cm



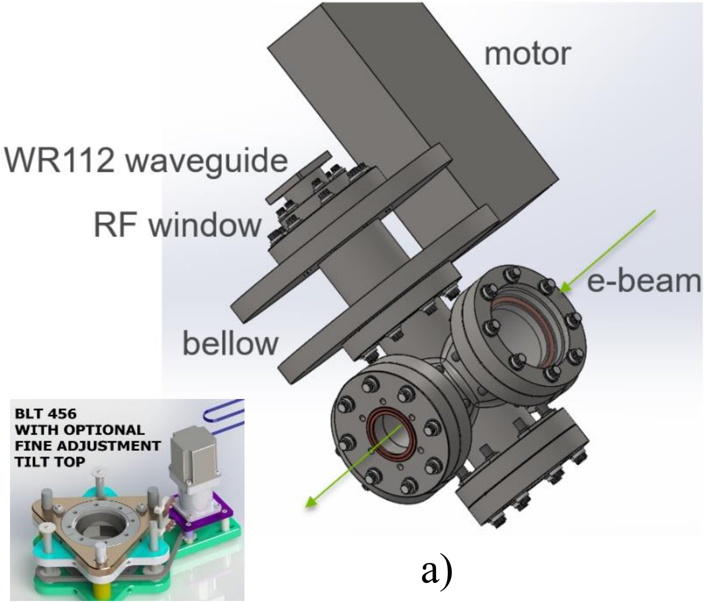
Let us assume that we can measure a signal which is proportional to a number of electrons captured by diamond blade. Halo monitor has diamond length *L* so that signal would be proportional to the integral:

$$Q(x) = \int_{x}^{x+L} f(s)ds$$

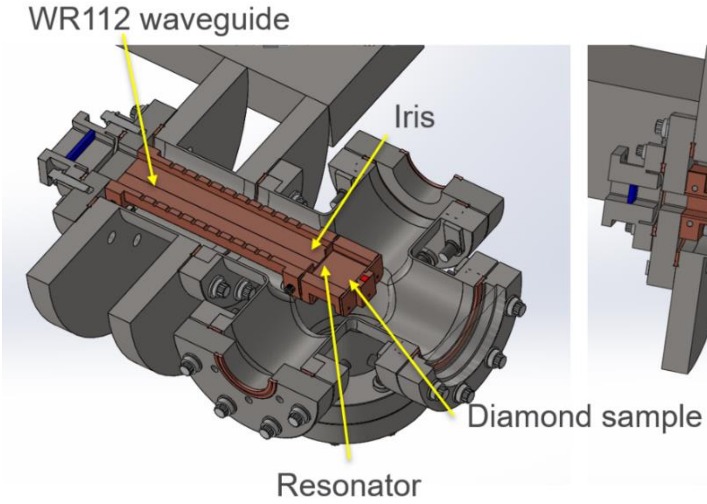
In the 0th approach one can write: $$Q(x) = \int_{x}^{x+L} f(s)ds = F(x+L) - F(x) \approx L \cdot f(x)$$

Next approach gives the first order differential equation to restore necessary particle distribution f(x): $$Q(x) = f(x) \cdot L + \frac{1}{2}\frac{df(x)}{dx} \cdot L^2$$

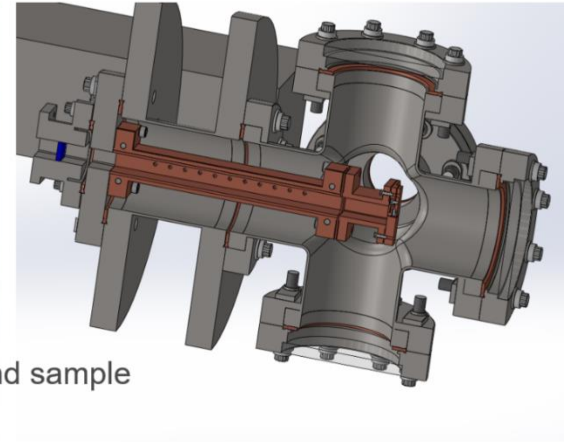
Engineering design of the 1D scanning beam halo monitor



a)



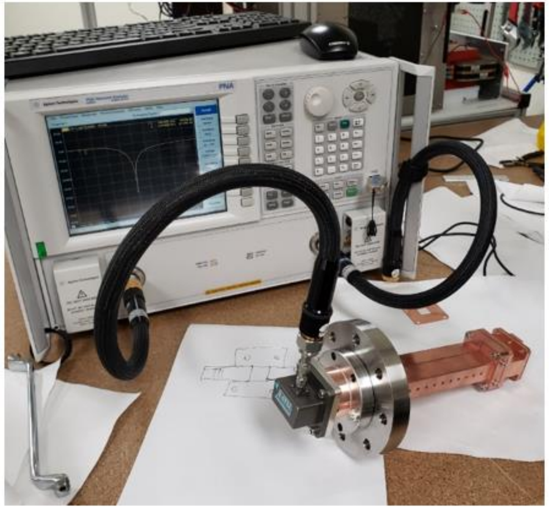
b)



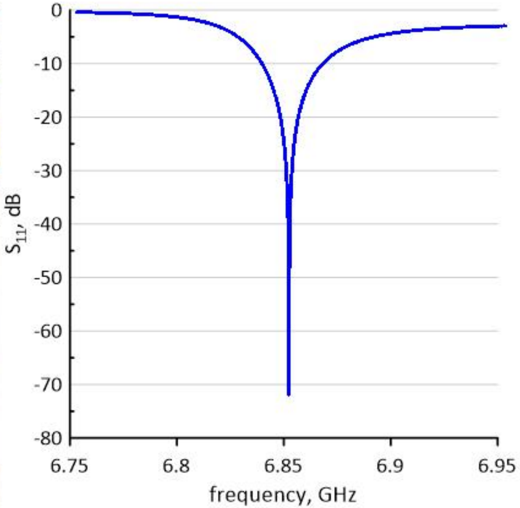
c)

a – appearance, b - general cut view, c – side cut view.

Experiments at AWA with Multi-MeV Electron Beam



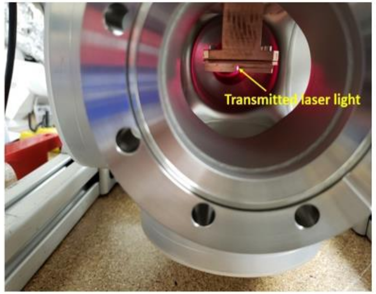
a)



b)

Measurements of S_{11} parameter for the resonator of the 1D scanning monitor (a) and S_{11} parameter of the resonator vs frequency (b).

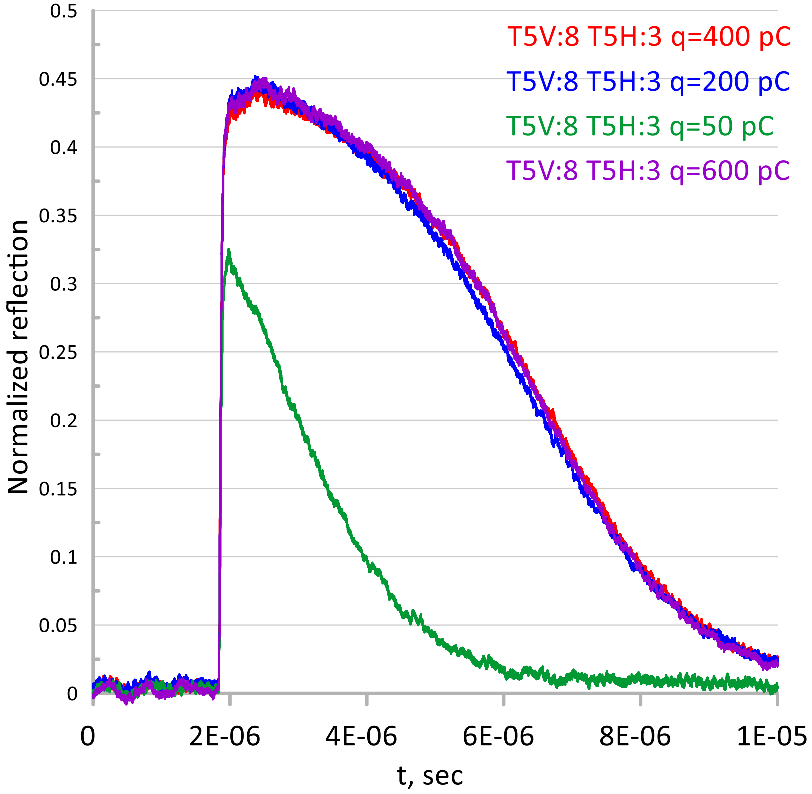
a)



b)

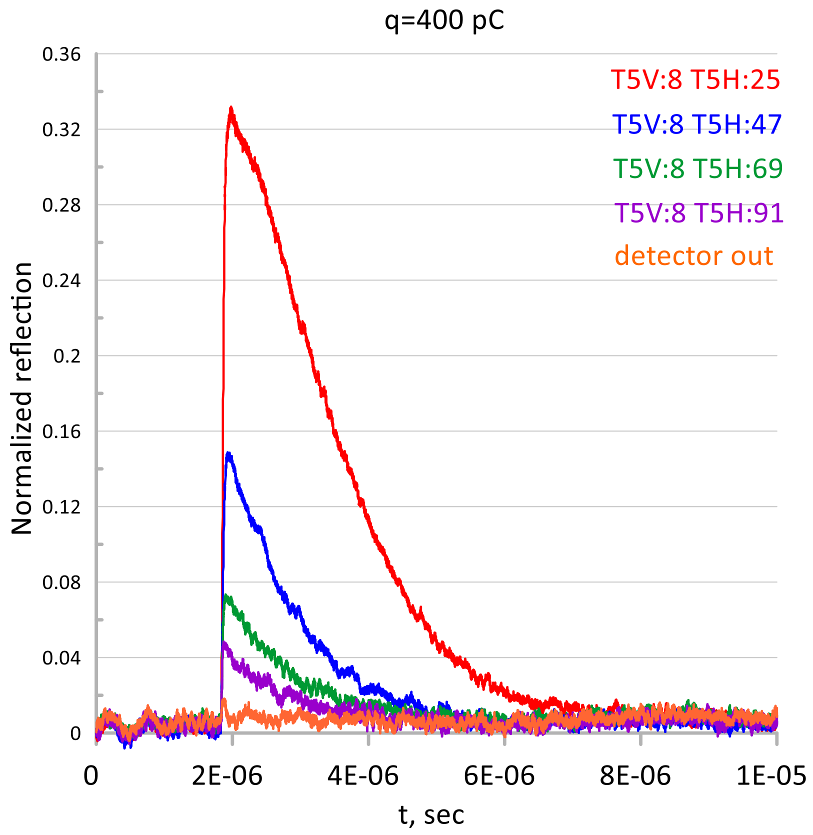
Alignment test: a - side view of the monitor when diamond sample is located at beam axis, b - front view of the monitor showing the laser beam transmitted through the diamond sample.

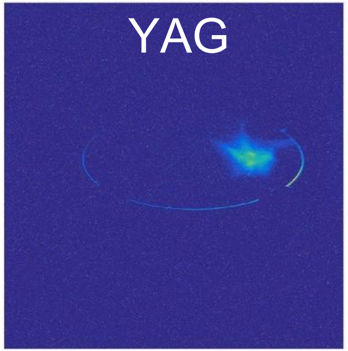
First Beam Test with a Diode

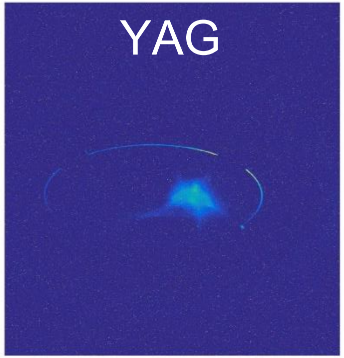


Diamond was located at the center of the beam pipe. We could change bunch charge.

Measurements with Steerable Electron Beam



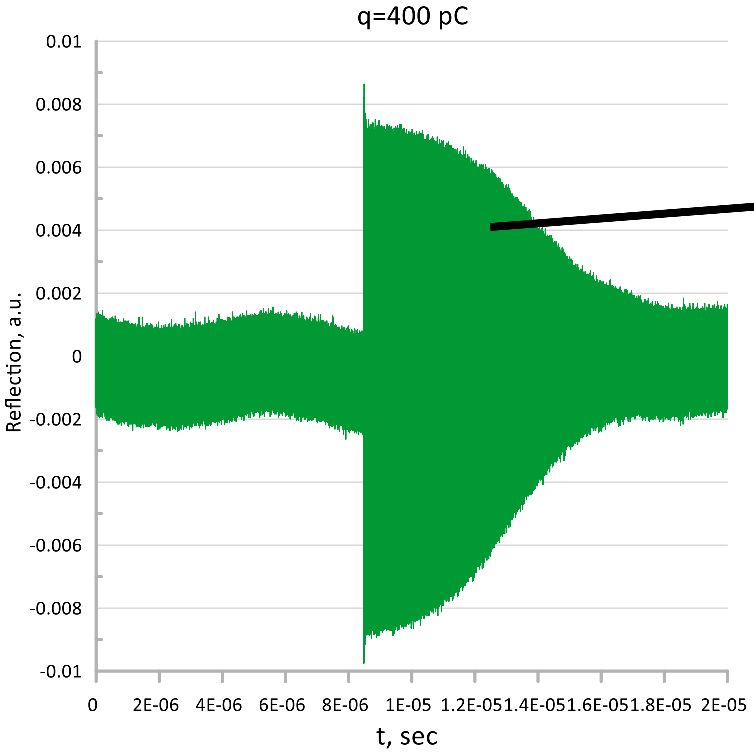


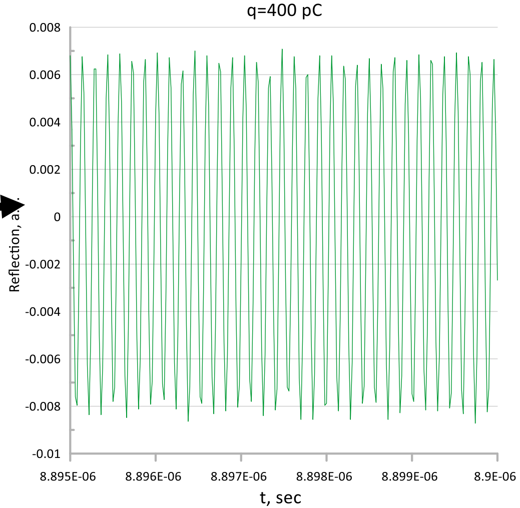


Detector out,
T5V: 8 – vertical beam shift
T5H: 25 – horizontal beam shift

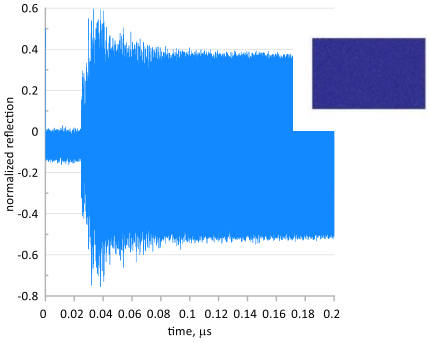
Detector out,
T5V: 8,
T5H: 3

Measurements with Broad Band Oscilloscope

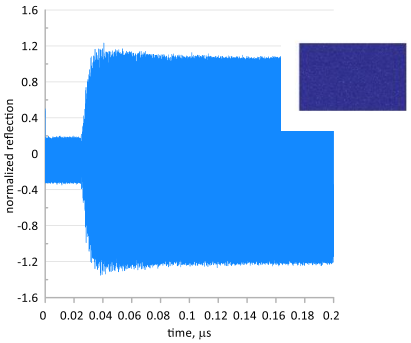




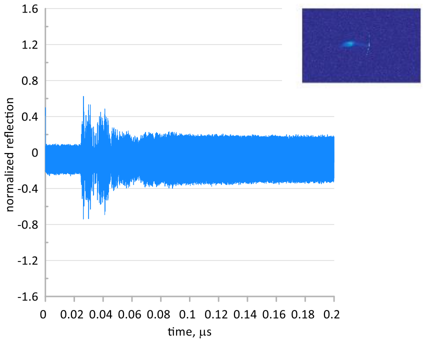
Measurement with Beam in Center and Resonator Moved Across Pipe



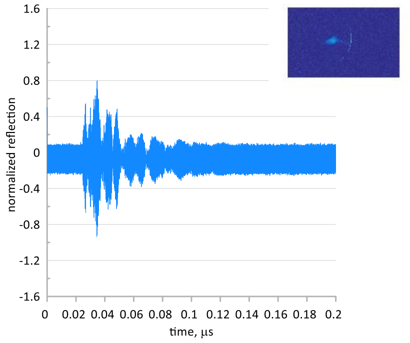
Charge 47 pC, position x=0 mm



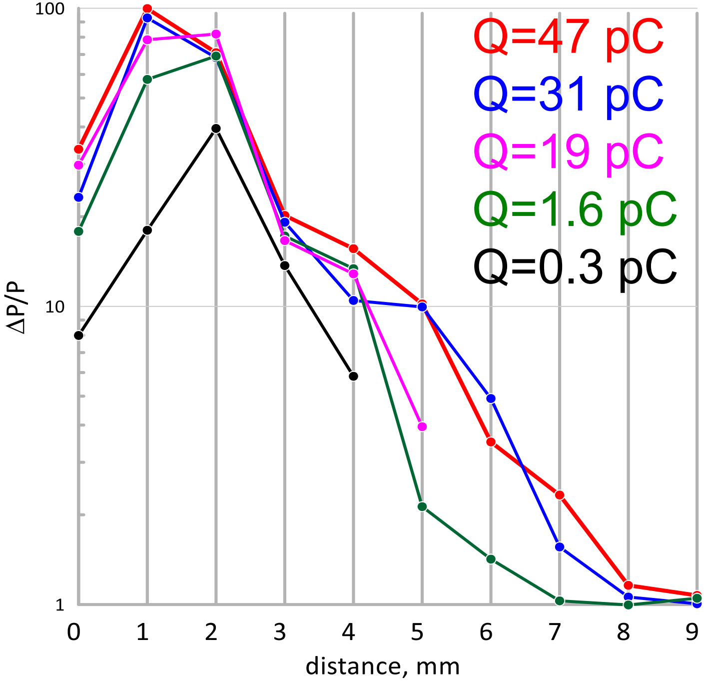
Charge 47 pC, position x=3 mm



Charge 47 pC, position x=6 mm



Charge 47 pC, position x=9 mm



Conclusion

1. We proposed diamond as a radiation hard material which can be used to measure the concentration of passing particles based on a particle-induced conductivity effect.
2. In first experiments we used a Vertical Beam Test Stand, delivered DC electron beam of the 20-200 keV energy with the current up to 50 μA, to characterize several diamond samples. Experiment has shown that detector grade single crystal diamond only can provide high detector sensitivity.
3. We have also designed and fabricated a scanning diamond X-band resonator, which was tested at Argonne Wakefield Accelerator (AWA). In the experiment at AWA we studied sensitivity and resolution of our monitor based on a single crystal diamond using multi-MeV, picosecond electron bunches.
4. The obtained results show that the monitor can reliably detect particles flying ~1 cm far from a 1 pC – 600 pC bunch core in transverse direction.