MICROTRON CT SYSTEM ACHIEVING 250 μm SPACE RESOLUTION WHICH IS UNABLE BY LINAC

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Abstract

More than one MeV X-ray energy is necessary to visualize inside of iron object thicker than 8 cm. Particularly it is necessary when 3D metal printing technology is in fashion, hollow detailed big metal object must be tested to find inside defects.

We will show how X-ray CT image using Microtron (MIC) demonstrates space resolution as high as 250 μm. In addition very good contrast visualize density distribution at the density 0.1 g/cm^3. For instance Tantalum and Tantalum Oxide can be identified by MIC-CT. Measurement of density distribution is carried out by neutron, but when focal point is an order of 100 μm, it is possible by Compton scattering with X-ray energy higher than MeV, since Compton scattering cross section is proportional to the electron density, instead of atomic number, while the photo electron scattering is proportional to the atomic number Z^4.

INTRODUCTION

Photon Production Laboratory Ltd. (PPL) is a 20-year old venture company (see Fig. 1). One of the world's leading company holding particle accelerator technology. PPL is the only company who produce tabletop synchrotron light source MIRRORCLE [1] and compact Microtron MIC [2-8] accelerator. PPL provides fine resolution & high energy X-ray CT system which might be an only tool for testing 3D printing metal products. MIC-CT achieves 250 μm and MIRRORCLE-CT achieves 20 μm space resolution. Group company MIRRORCLE analysis center provides analysis service using these instruments mentioned.

Figure 1: New PPL laboratory is established in the spring of 2017. Analysis service is provided by MIRRORCLE Analysis Center Co. Ltd. using MIC-CT and MIRRORCLE synchrotron light source beam lines.

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In this paper we discuss how our MIC achieve 250 μm resolution [8] while LINAC achieve a few mm, and how high beam current 300 mA peak current is achievable, when LINAC can achieve around 100 mA.

MIC-CT SYSTEM AND OBTAINED 3D IMAGES

Fig. 2 shows X-ray CT manipulator and flat panel 2D Detector (FP) seen in the 1 m thick concrete shielding room. Maximum 70 kg object is acceptable on the manipulator. FP size is 40 x 40 cm^2 with 200 μm pixel size. Electron accelerator is the 6 MeV microtron MIC6 as shown in Fig. 3.

Figure 2: X-ray CT manipulator and flat panel 2D Detector (FP) are seen in the 1m thick concrete shielding room. Maximum 70 kg object is acceptable on the manipulator. FP size is 40 x 40 cm^2 with 200 μm pixel.

Figure 3: MIC6 is used for advanced X-ray CT nondestructive testing. Electron focal spot size 0.25 mm is achieved for X-ray imaging.

We limit beam current to around 50 mA peak, pulse width 1 μs, and repetition 500 Hz to avoid over exposure. We scan the manipulator at every half degree over 360 deg. Sample is usually set at SO = 1 m from the source point, and detector at SD = 2 m from the source to see the 0.25 mm resolving power. Some time that is SO: SD = 0.5 m: 2 m to achieve higher space resolution. Manipulator is scanned every half degree. Each exposure takes 1 to 2 sec.

So we can complete whole CT scan in 30 to 60 min. For large objects we apply helical scan as well as offset scan. Typical reconstructed results are shown in Fig. 4. Top picture is a whole body of motor engine. You will see the precise structure and differences in materials. Body is made of Al cylinder is made of stainless steel. Bottom is a 30 cm wide trans. You will see 1 mm wide coil in a 10 cm thick iron yoke. You will agree how coil image is sharp. The space resolution is 0.25 mm.

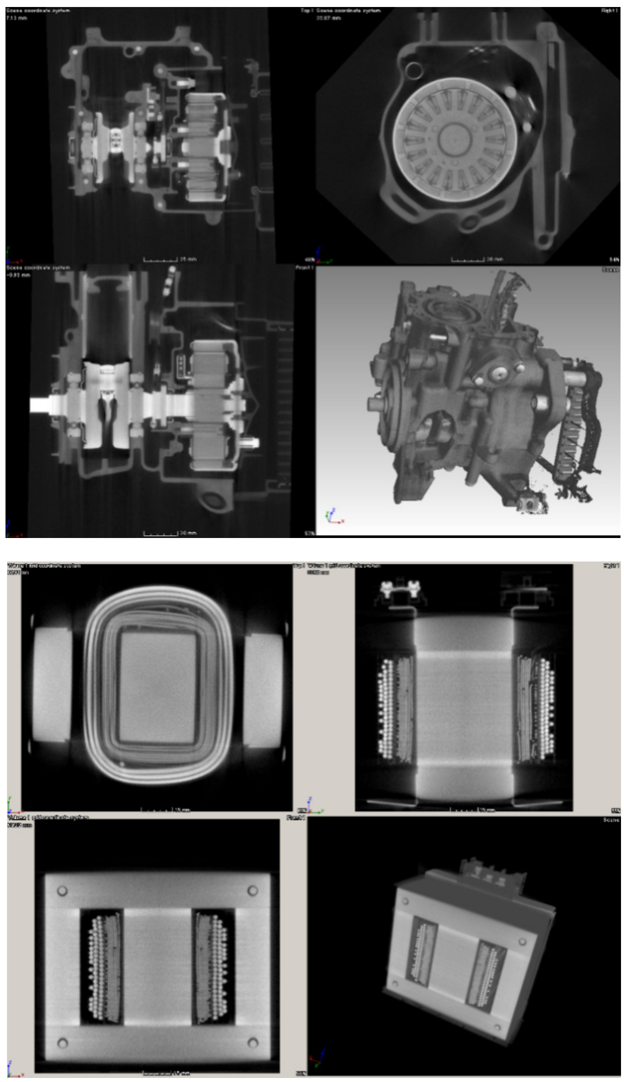


Figure 4: Top is cross sections of a motor engine. Bottom is a 30cm wide trans.

SPACE RESOLUTION POWER OF THESE FINE CT IMAGES

Focal spot size [8]

Beam spot size of MIC at focal point strictly defines the special resolution of X-ray image. MIC beam is focused on the X-ray converter through set of FD quadrupole magnets.

Beam size is measured by 1mm diameter pin hole made of lead or by the knife edge profile as seen Fig. 5 (top) for 6 MeV MIC as well as Fig. 5 (bottom) for 0.95 MeV MIC.

Since Fig. 5 (top) is the 3 times magnified the real spot size is 0.27 mm W and 0.36 H for MIC1, and Fig. 5 (bottom) the 2 times magnified one, the real spot size is 0.23 mm W and 0.26 mm H for MIC6.

The resulting fine image is inspected by MTF method by CT scanning of standard phantom indicated in Fig. 6. As a result 10 % MTF 2.39 LP/mm is obtained which is equivalent to 209 μm resolution.

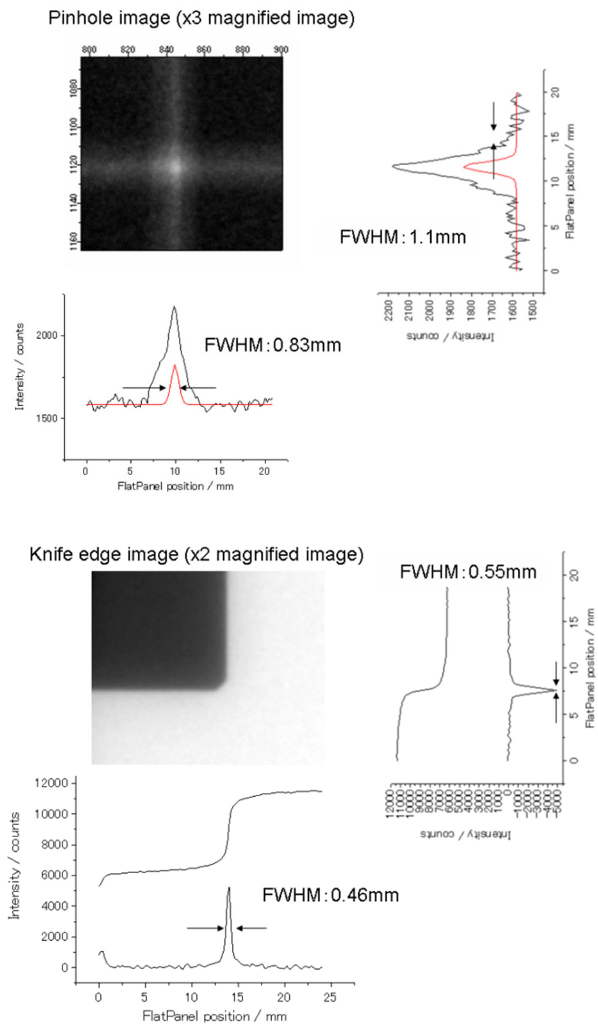
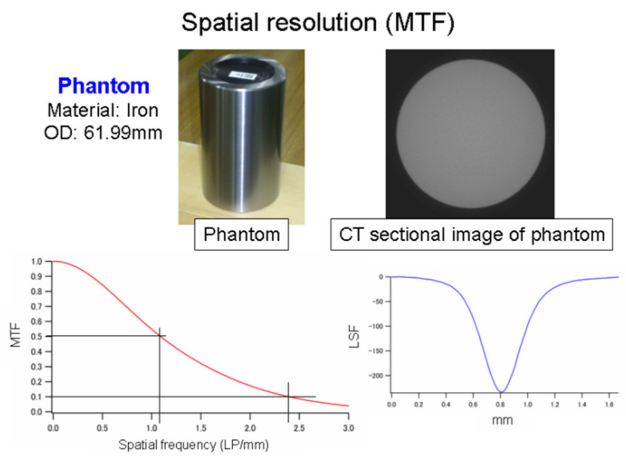


Figure 5: MIC beam spot size is measured by pinhole (top) for MIC1 and by knife edge (bottom) for MIC6.

Density resolving power [5]

When high energy X-ray is used we are able to measure the density distribution, because the scattering mechanism is Compton scattering and the scattering cross section is linearly proportional to the electron density. When however the X-ray energy is lower than 100 keV, the scattering mechanism is photo-electron effects and cross section is proportional to the atomic number Z in factor 4.

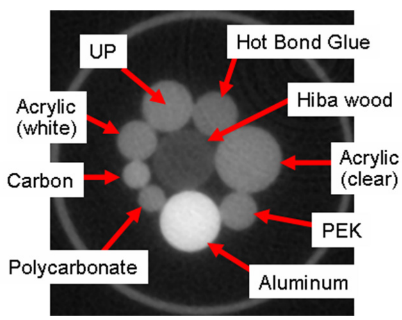
The density resolving power of the X-ray energy higher than 1MeV was unclear before, but it is now clear because the space resolution is extremely improved with MIC. When the space resolution is low, the density contrast is smeared off.



	50%MTF	10%MTF
N=1	1.09	2.39

1.09 LP/mm corresponds to spatial resolution of 459 um
2.39 LP/mm corresponds to spatial resolution of 209 um

Figure 6: MTF inspection of CT resolution taken by standard phantom 61.99 mm wide iron rod.



Material	Density (g/cm³)	Gray value
Hiba wood	0.45	2.9933
Hot bond glue	0.96	5.0242
Acrylic (white)	1.12	5.7560
Polycarbonate	1.17	5.7024
PEK	1.19	5.8085
UP	1.19	5.7607
Acrylic (clear)	1.19	5.9556
Carbon	1.67	6.5941
Aluminum	2.64	11.2040
Air	0.00	0.4061

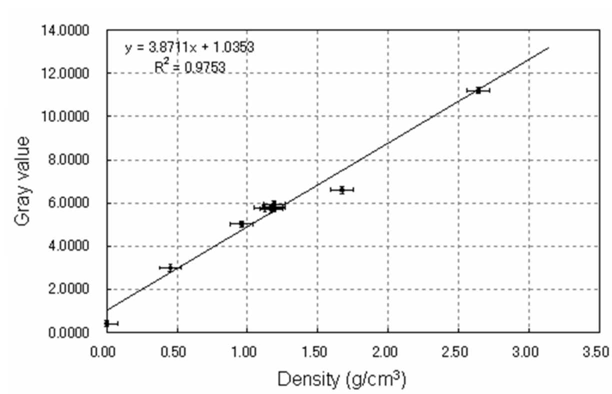
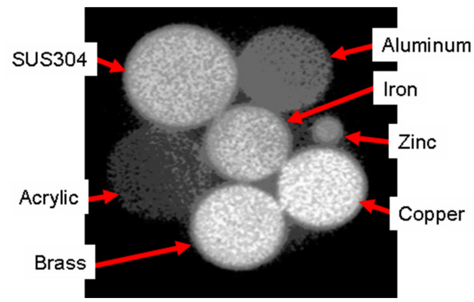


Figure 7: (top) X-ray CT image is taken for various materials. (middle) It is seen that the obtained gray values and densities are well correlated. (bottom) It is well shown that the density and gray values are linearly correlated.

Density at the ROI in 3D volume is proportional to the gray value at the ROI in the reconstructed image. Normalization factor is obtained by carrying out with the density known materials. Example is shown in Fig. 7.

The density resolution obtained in such method was 0.1 g/cm^3. This method is applicable to the light materials shown in Fig. 7 as well as heavy materials shown in Fig. 8.



Material	Density (g/cm³)	Density ratio	Gray value ratio
Acrylic	1.2	0.13	0.22
Aluminum	2.67	0.3	0.35
Zinc	7.14	0.8	0.76
Iron	7.8	0.88	0.9
SUS304	7.9	0.89	0.9
Brass	8.5	0.96	0.98
Copper	8.9	1	1

Figure 8: Our density measurement method is applied to heavy metals. Top is X-ray CT image taken for various metals. Bottom shows that the density ratio and obtained gray value ratio are well correlated.

Principle of MIC accelerator

MIC is a microtron accelerator that accelerates electrons under a magnetic field, and electrons are extracted from LaB_6 emitter directory by the 40 MV/m RF field set in a wall of RF cavity. Because of internal emitter MIC is very compact and gives high performance compared with LINAC.

Microtron was proposed by Vladimir Veksler in 1944 during the former Soviet era and developed mainly in the east side [2]. Because it accelerates electrons in the magnetic field, it has energy sorting function, it is small but low dispersion high energy electron accelerator. Since the energy dispersion is low, the focal size of the sub-millimetre can be easily achieved. Linear accelerator LINAC is invented in the United States has been used in the industry, but energy dispersion is large because low energy electrons which are not sufficiently accelerated are taken out together. Therefore, the focal size is several mm, and high-precision X-ray inspection can not be performed. The focal size of the MIC to the other is 0.25 mm.

Furthermore, we invented and demonstrated the principle of generating a peak beam current of 300 mA by making the magnetic field of MIC uniform [3, 4]. As a result, by attaching the X-ray target directly to the MIC, it realized a very small focal size of 0.25 mm with high brightness, making high-precision X-ray CT inspection possible.

CHARACTERISTICS OF MIC IS COMPARED WITH LINAC

Differences between MIC and LINAC are described below.

Differences in acceleration mechanism

Figure 9 shows that differences in acceleration mechanism between MIC and LINAC from our experience with the same energy and frequency. MIC accelerating under magnetic field has no back bombardment to the electron gun, so stable beam extraction is possible.

Difference in hard wear

Differences in hard ware between MIC and LINAC are shown in Fig. 10. In our MIC, an RF gun is built in the single acceleration cavity, so we do not need a high voltage floating power supply such as a grid pulsar.

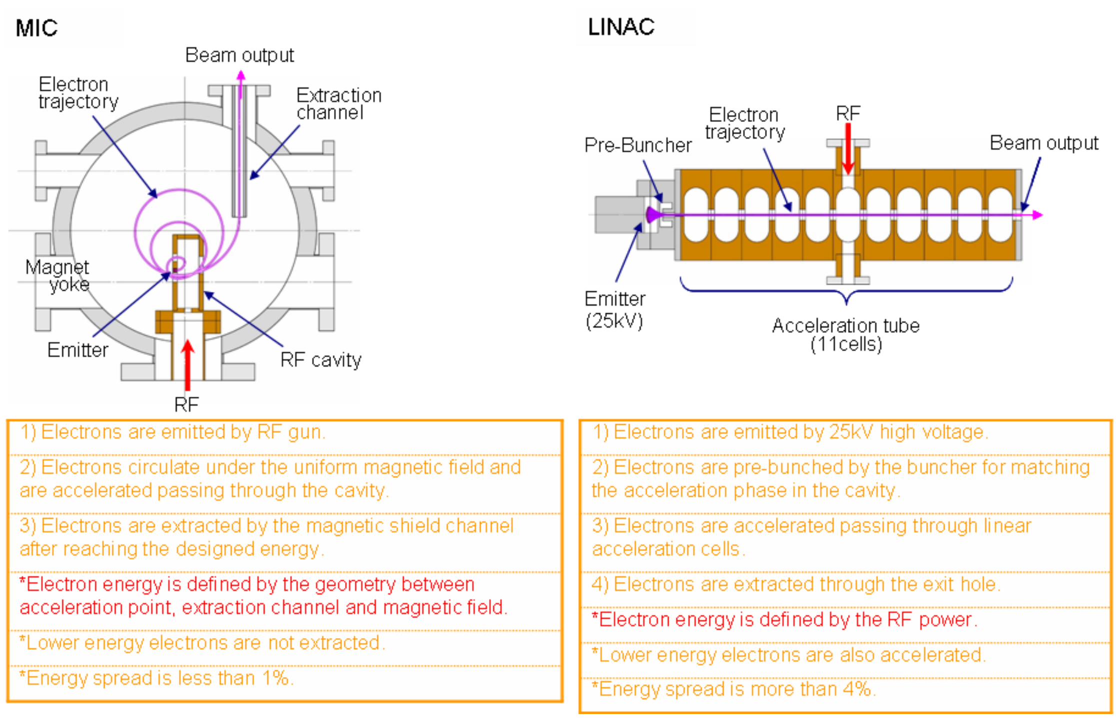


Figure 9: Differences in acceleration mechanism are shown between MIC (left) and LINAC (right).

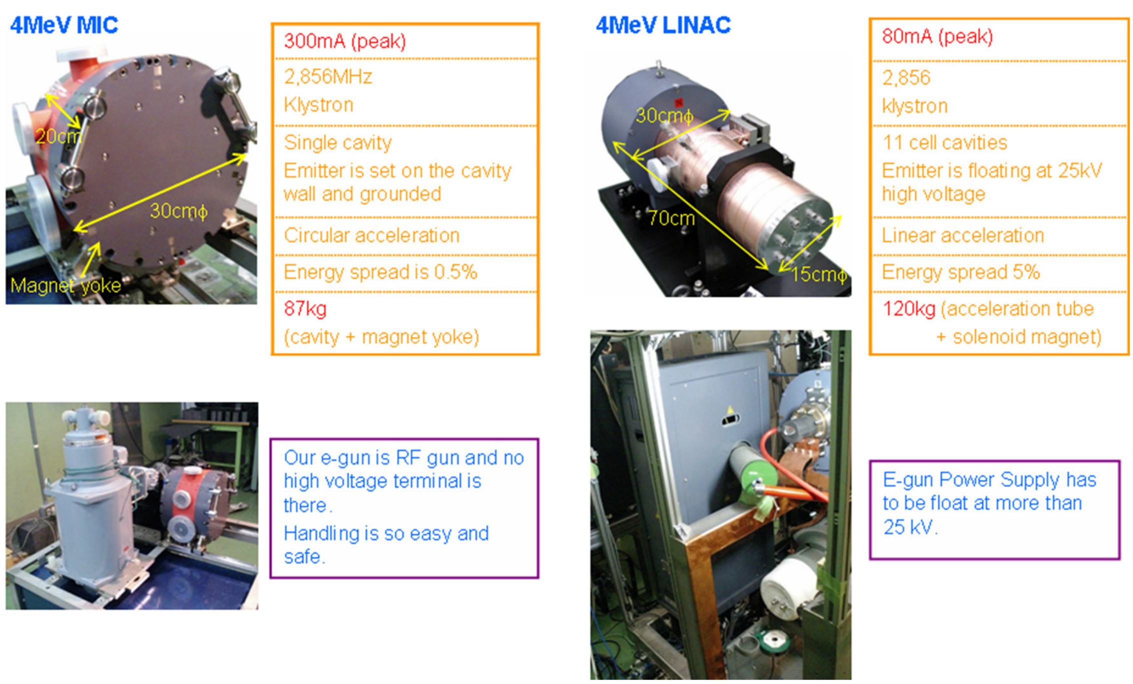


Figure 10: Differences in hard ware are shown between MIC (left) and LINAC (right).

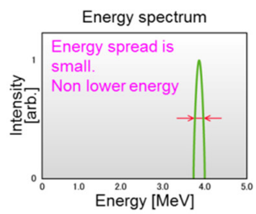
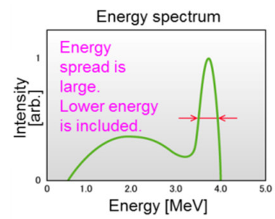
Difference in beam nature

As mentioned above, since MIC circulates and accelerates electrons under magnetic field, the energy spread of the electron beam extracted is less than 1%. While, with the linear accelerator LINAC accelerates all electrons, thus the energy dispersion is larger. Therefore, as shown in Table 1, the X-ray focal point of MIC achieves 0.25 mm due to the small energy dispersion.

Difference in imaging

X-ray images of a gas valve is taken with both MIC and LINAC are shown in Fig. 11. Smaller X-ray focal spot size demonstrate more details.

Table 1: Compare Differences in Beam Nature between MIC and LINAC

	MIC	LINAC
Difference in principle	Only particular energy electrons are selected	Every electrons are accelerated
Energy spectrum		
Focal point size	0.25mm	>1mm
Visibility	60cm thick concrete inside is visible by 1 MeV machine	30cm concrete inside is visible by 1 MeV machine

Sample MIC LINAC

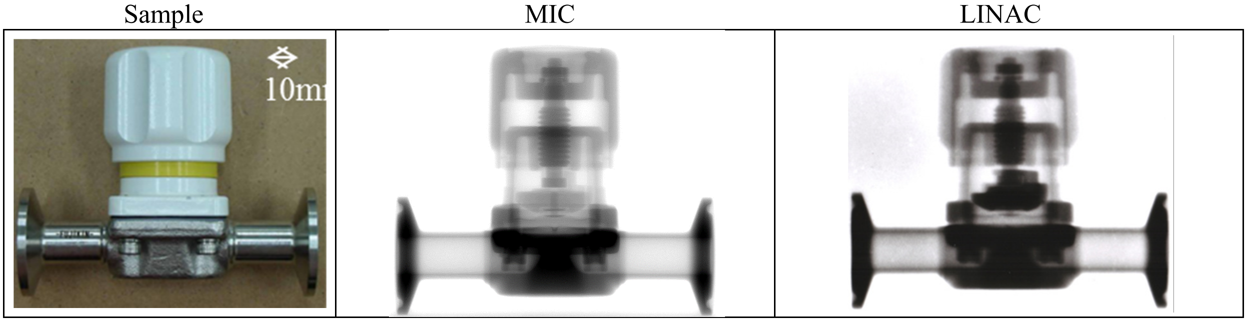


Figure 11: Difference in imaging between MIC and LINAC are shown. Because the focal spot size is smaller with MIC, the image of MIC has less blur than with LINAC, and image is clearer.

CONCLUDING REMARKS

We have presented how MIC microtron is advanced compared with LINAC. The beam focal point size is as small as 0.25 mm while LINAC is a few mm. Beam energy spread is 2 % while LINAC is more than 5 %. The beam peak current is 300 mA at maximum while LINAC is 100 mA. Size is only 30 cm wide for 4-MeV machine, while LINAC is 50 cm long. Cathode is grounded with MIC while LINAC is floating. It is obvious that MIC is more powerful as an electron gun, high power electron source used for sterilization, and as an injector of storage ring.

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