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Single Stable Wire Monitor to measure beam profile in FFA rings

E. Yamakawa, C. Willcox, A. Partica

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- Summary

Simulation for profile measurements in Kyoto FFA with Single Stable Wire monitor

- To reproduce beam profile measurements done in Dec. 2019 at Kyoto FFA, the tracking simulation is applied with Φ142um wire.
- 4x4 transfer matrix (cell) is used to transfer particles, which is derived by Twiss parameters and tune as presented in the table.
- Synchrotron motion is included in this simulation.
- Instead of moving beam position turn by turn, the wire position is moved in this simulation. Wire positions for individual particles are adjusted by its dispersion at each turn:

$$X^i_{wire} = X^i_{t.s} - \frac{R^i_s}{k+1}\left(\frac{P^i - P^i_s}{P^i_s}\right)$$

- Adiabatic damping is not taken into account.
- When the particle hit the wire, the calculation is stopped. That represents beam loss due to large scattering angle at the wire.

Parameters at the wire location

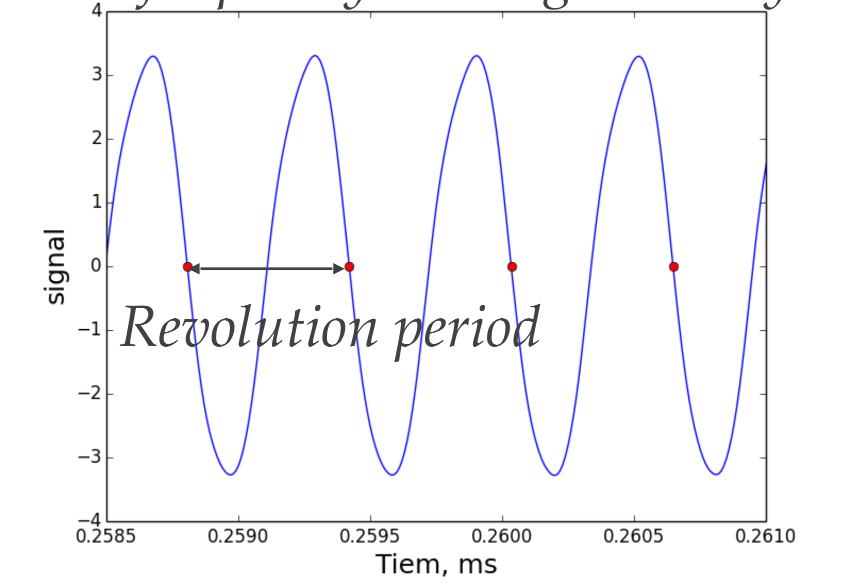
Beam energy	16.1 MeV
Reference orbit	4.694 m
Field index (k)	7.5
RF Voltage	4kV
Ring Tune	(3.85, 1.2)*
Beta function at the centre of straight section	(2.5m, 2.8m)
Periodicity	12

*K. Suga, et., al, "REMODELING OF 150 MeV FFAG MAIN RING AT KURNS TO PION PRODUCTION RING ", IoP conference, doi:10.1088/1742-6596/1350/1/012070

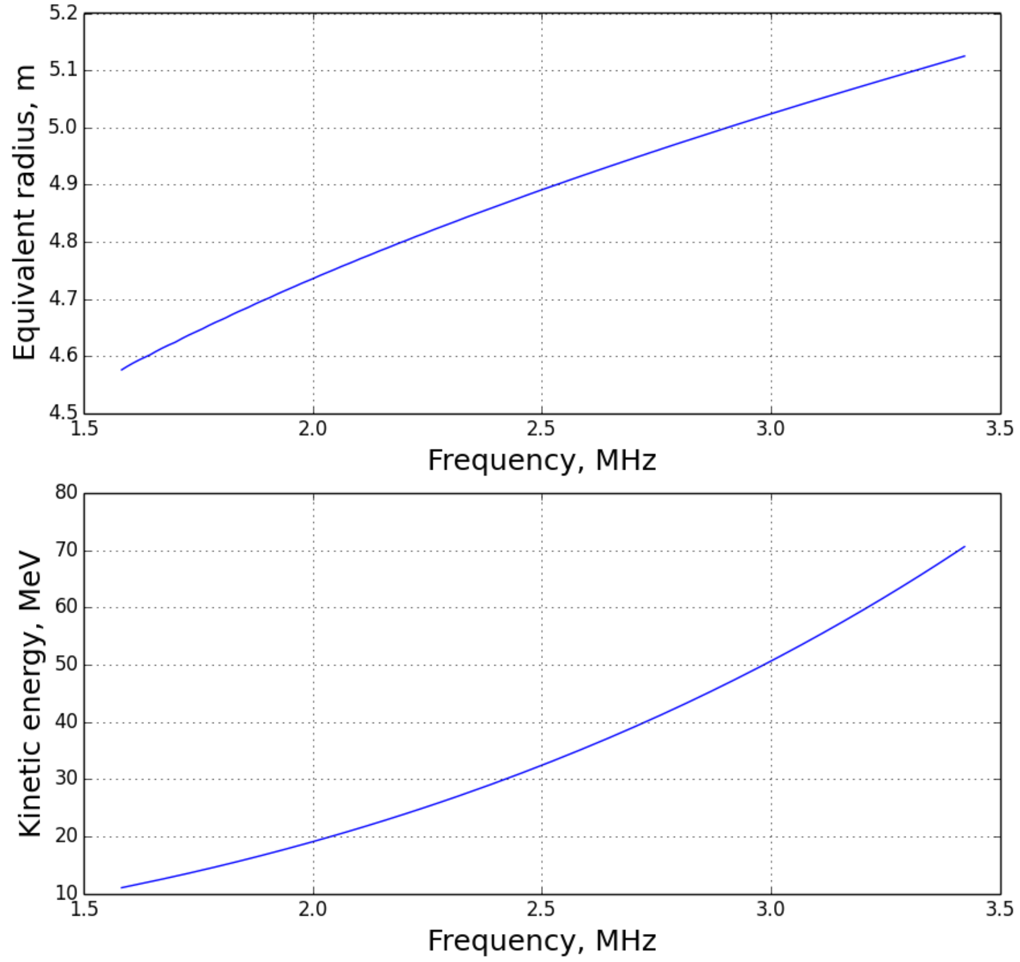
Estimation of turn separations of synchronous particle from RF signals

- Revolution frequency (F_{rev}) is computed from RF signal monitored by Oscilloscope.
- Using F_{rev}, equivalent radius and beam energy are estimated by interpolation using conversion graph.
- Turn separations around 16.1 MeV are calculated.

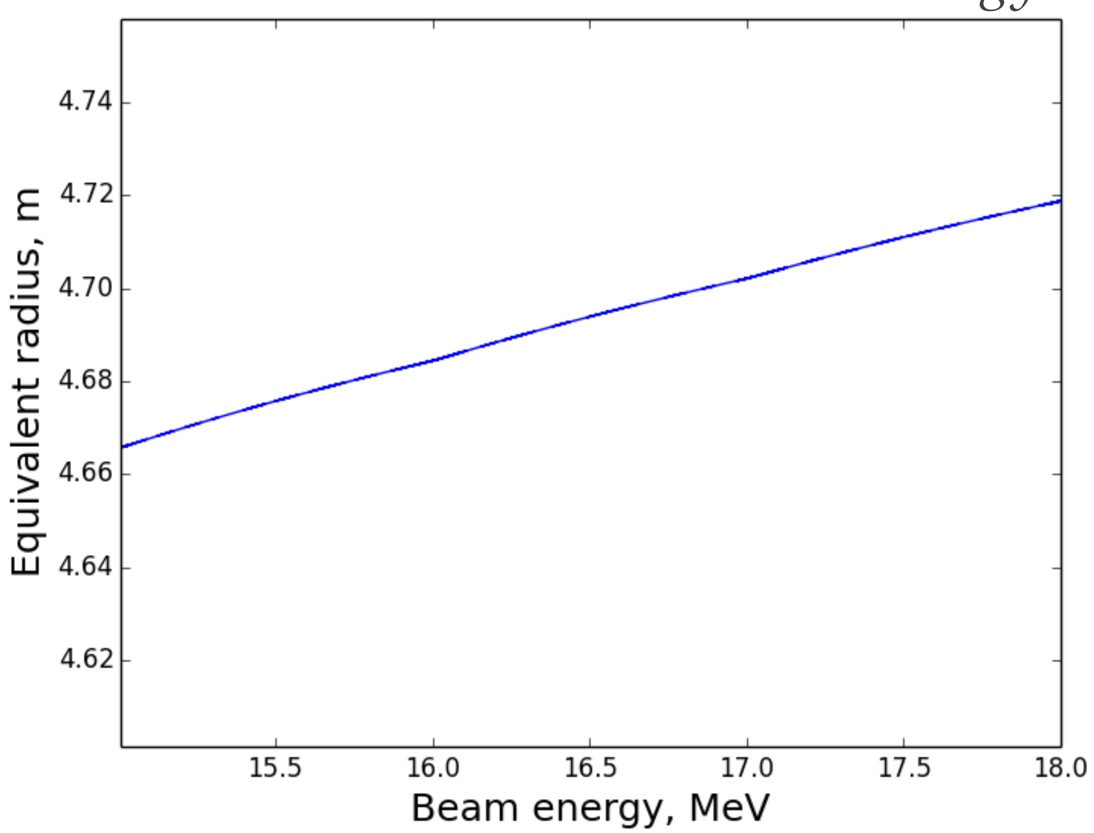
RF frequency sending to cavity



Conversion table

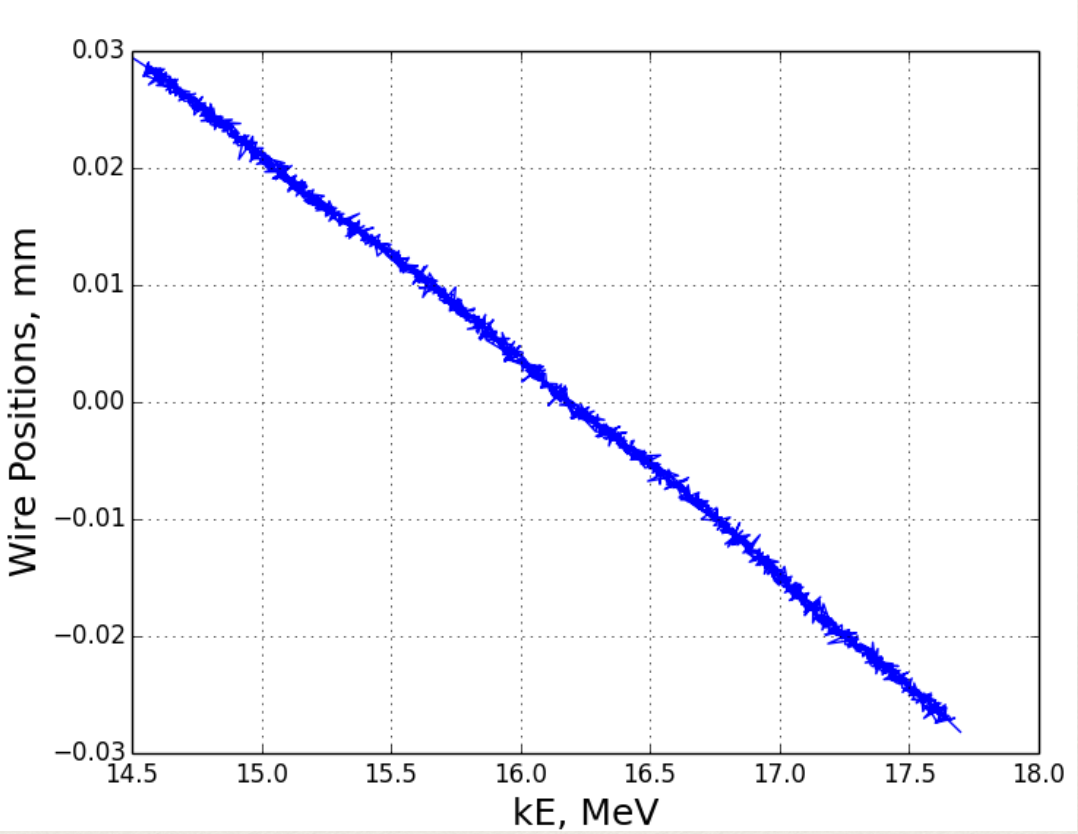


Estimated beam radius at each energy



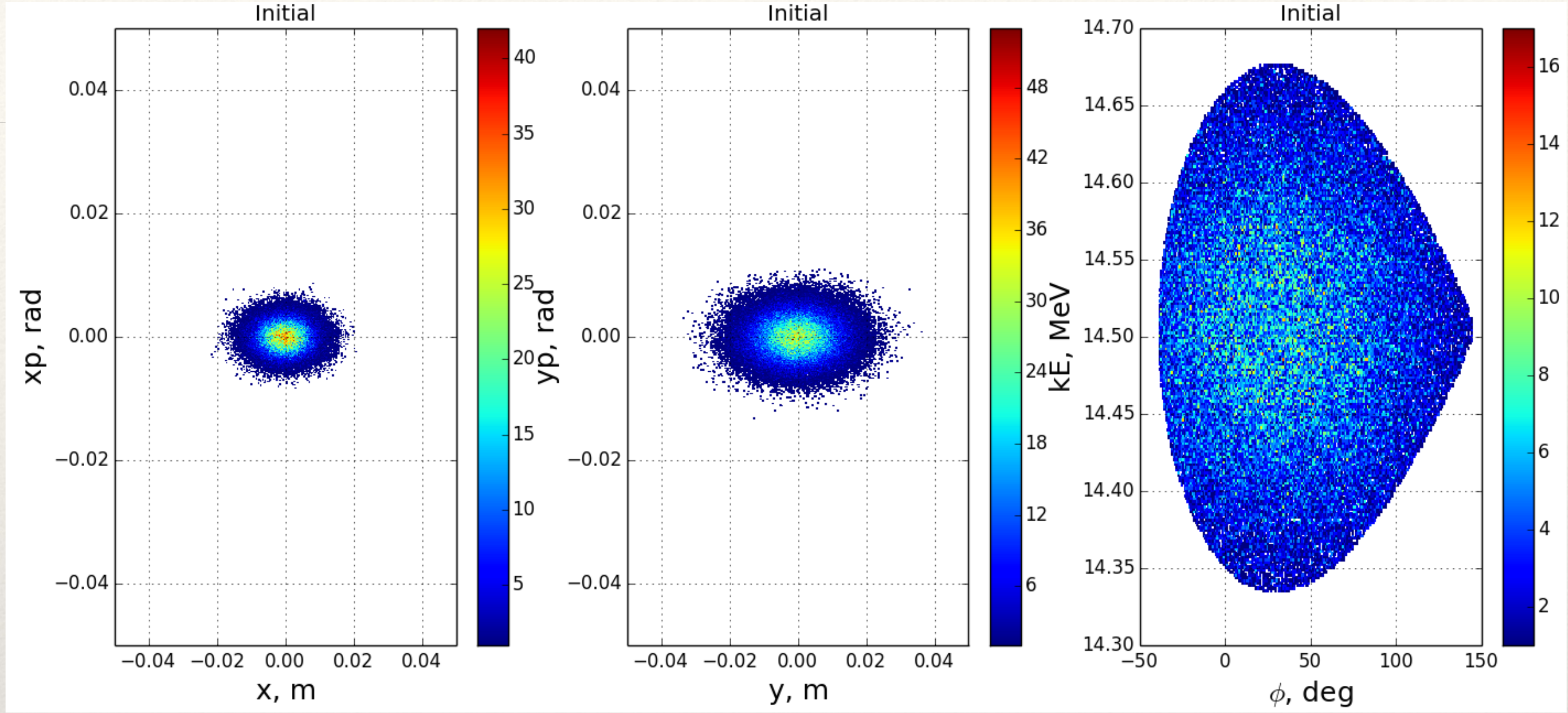
Estimation of turn separations of synchronous particle

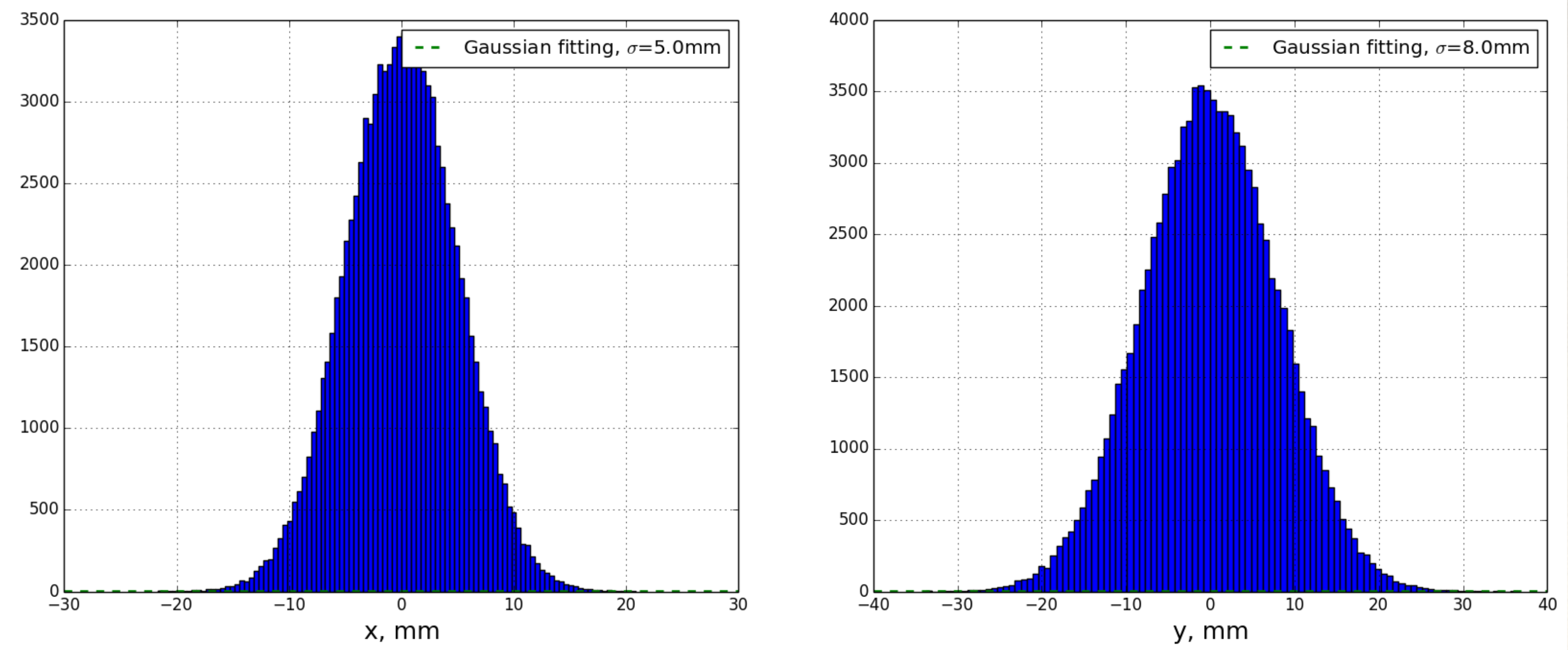
- Turn separation is computed by measured RF pattern.
- Wire position is moved over the beam full size and its range is ±28 mm w.r.t. C.O. of 16.1 MeV.
- Wire encounters the beam 1549 times over the range.



Initial bunch distribution in Kyoto FFA

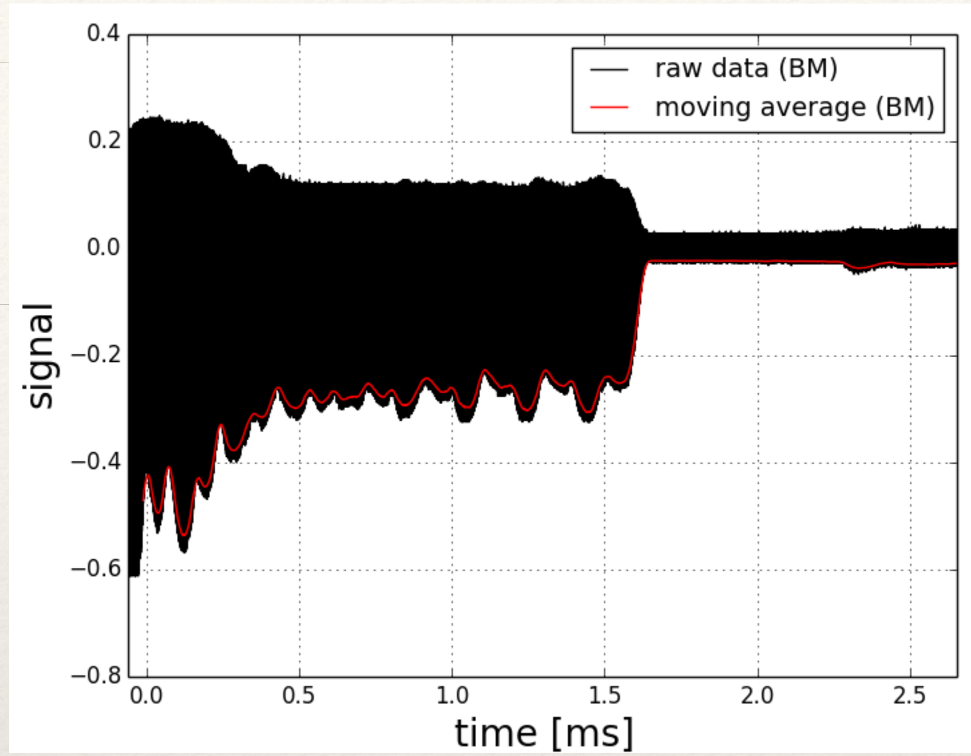
- 10^5 initial particles are generated with Gaussian distribution: (σ_x=5mm, $\sigma_{x'}$=2 mrad, σ_y=8mm, $\sigma_{y'}$=2.9 mrad) in transverse independently.
- In Longitudinal, Gaussian distribution in energy and phase with $\sigma_{\Delta E}$=100keV and σ_ϕ=70degs ($\mu=\phi_s$) is generated independently.

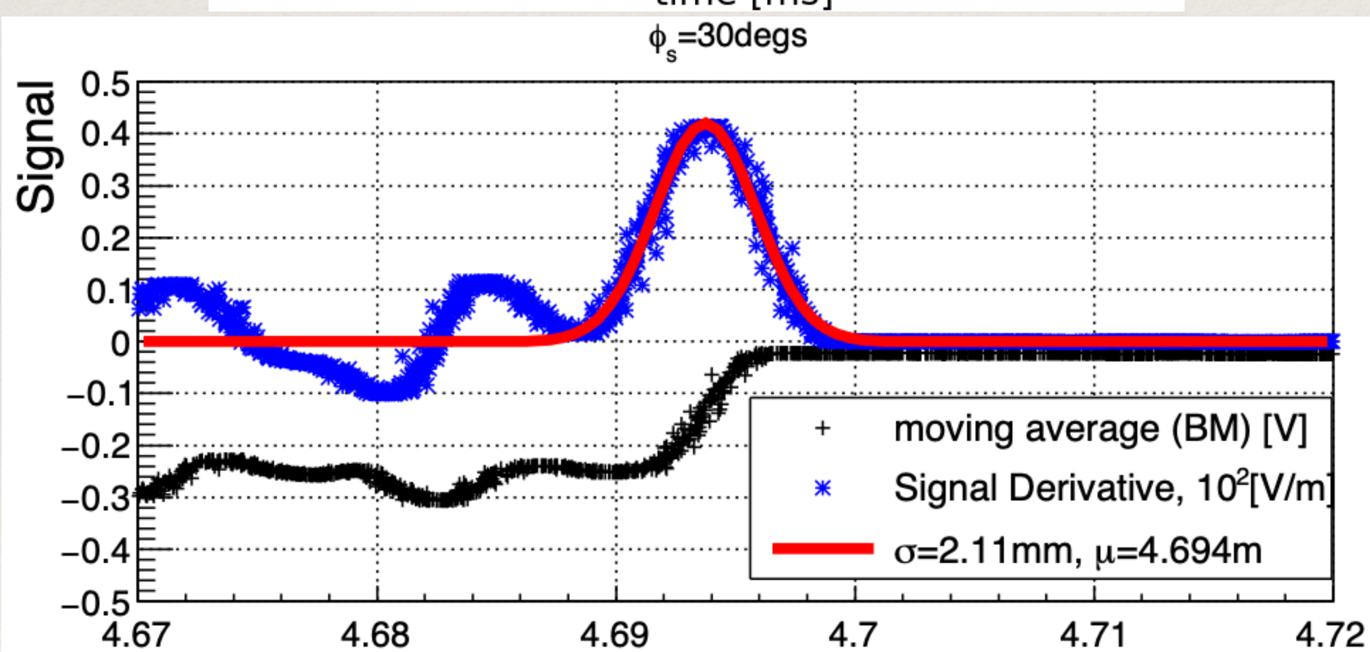


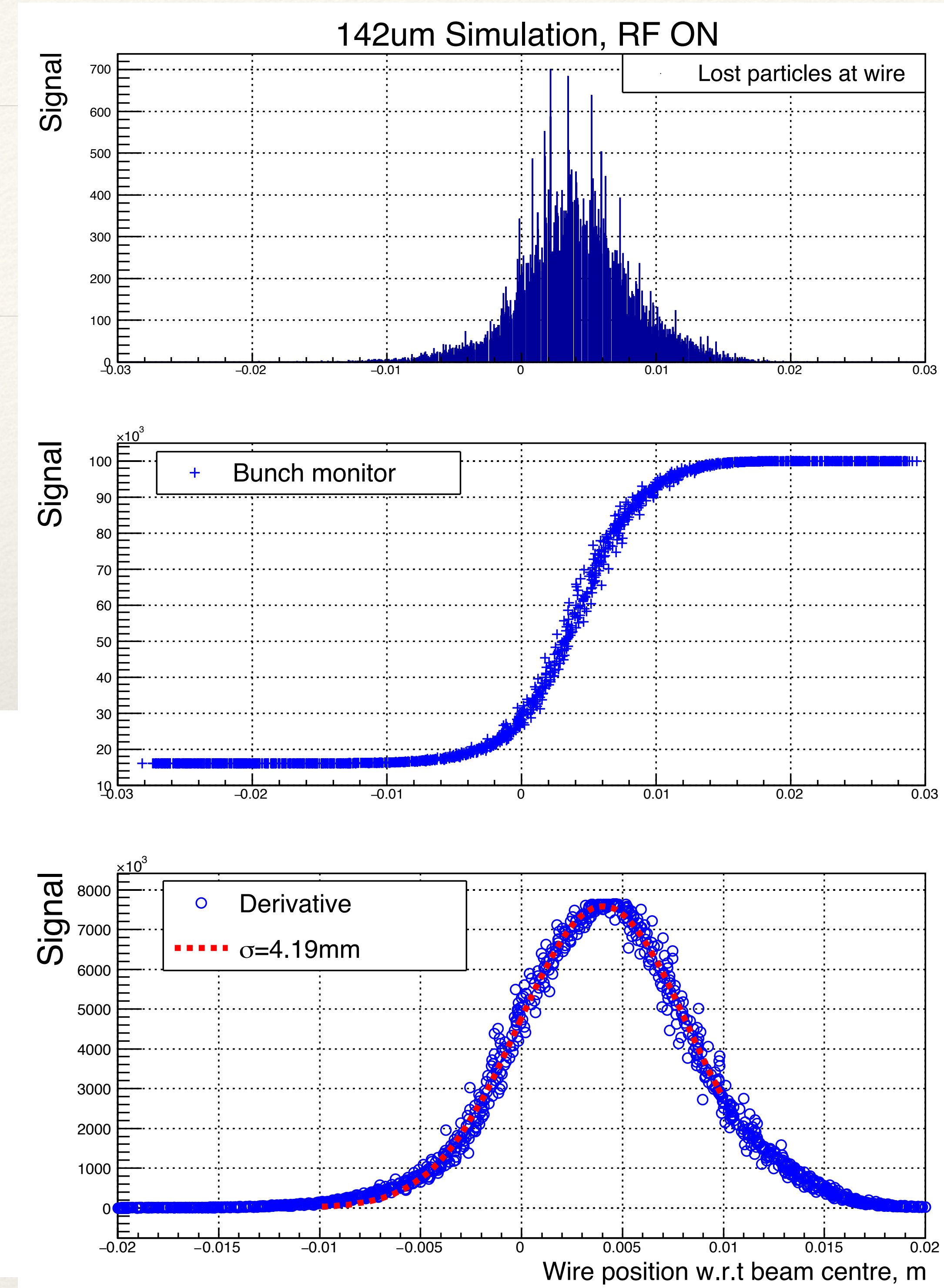


Experiments with Φ142 um wire in Kyoto FFA

Experiment taken by 13th Dec. 2019



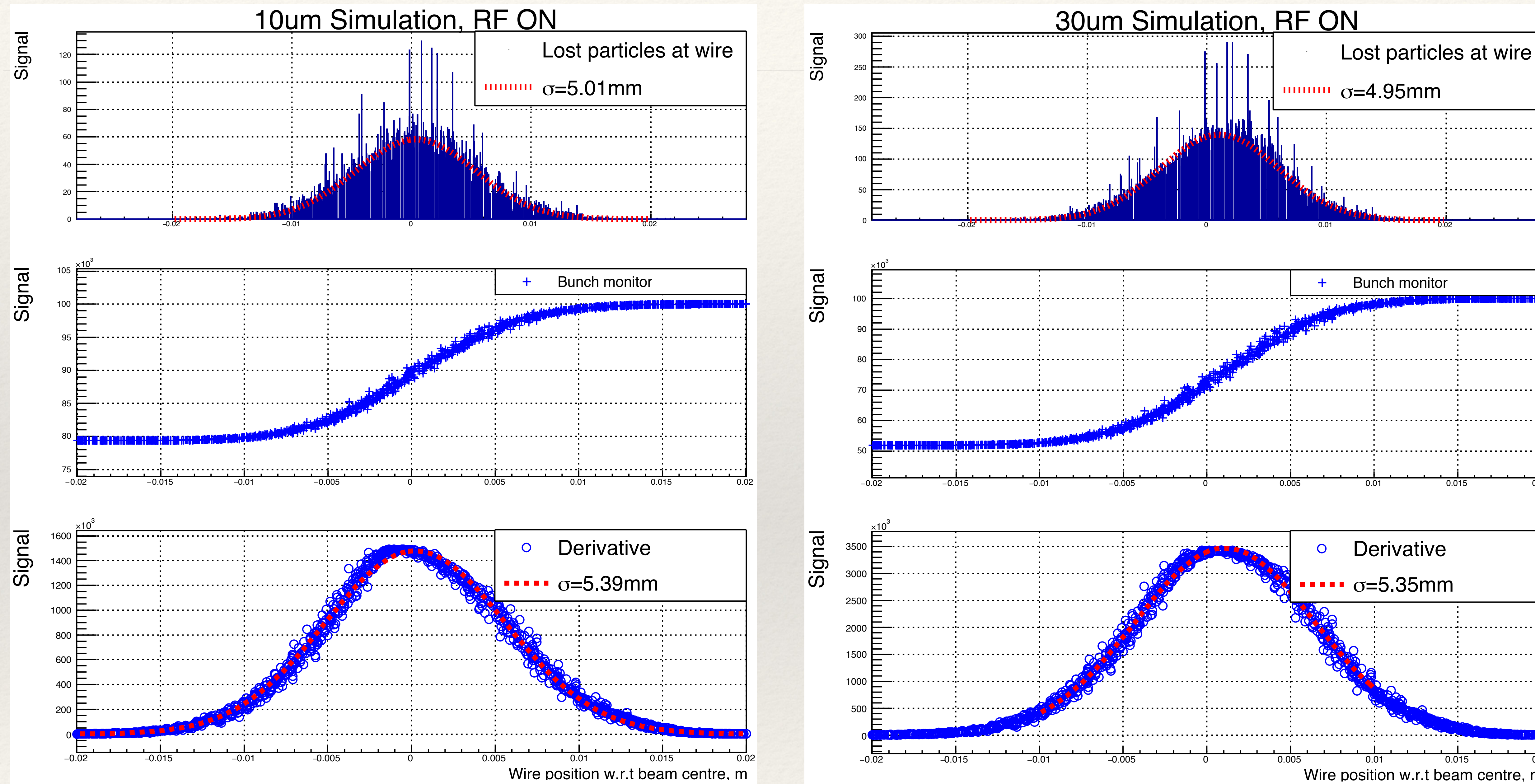




- <u>Half beam size estimated by simulation is twice bigger than the measured half beam size (bunch monitor signal).</u>

Profile estimation with ϕ10 & ϕ30 um wire at Kyoto FFA

- The same simulation is applied with Φ10 and 30um wires (phis=30degs).
- Initial beam size is 5mm.



ϕ10um and ϕ30um CNT wires reconstruct beam profile in KURNS FFA. To be tested.

WSM in JPARC 3MeV Linac

- ϕ100um CNT wire is used. Density of CNT is 1.4 g/cm^3. Resistance is about 1.2-1.4 Ωcm. Thermal conductivity is about 20 - 25 W/m/K.
- The endurance test of radiation & heat damage on wire has not been applied since 2017.
- They have not measured wire temperature, nor estimated the temperature numerically. They suppose the maximum temperature on ϕ100 um CNT will be less than 1000°C.
- The wire is sandwiched by ceramic washers and its strength is not loose nor severely tight.
- There is no special connectors to release tensions on the wire. They don't irradiate H- beam on the wire for a long time (a few minute). The temperature of wire is low enough, so they think the length of CNT wire stays constant during the measurement.

Parameters at Linac 3 MeV line

H- Energy	3 MeV
Peak pulse current	56 mA
rep. rate	2.5 Hz
Pulse length	50 us
CNT wire diameter	100 um

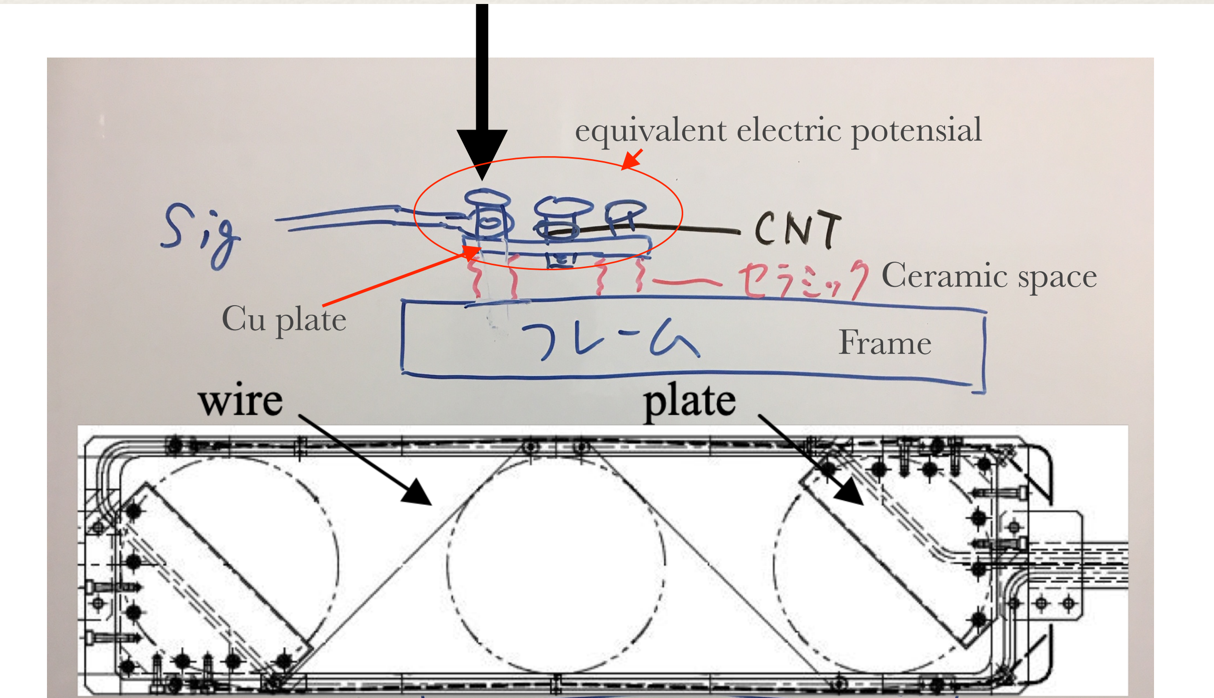
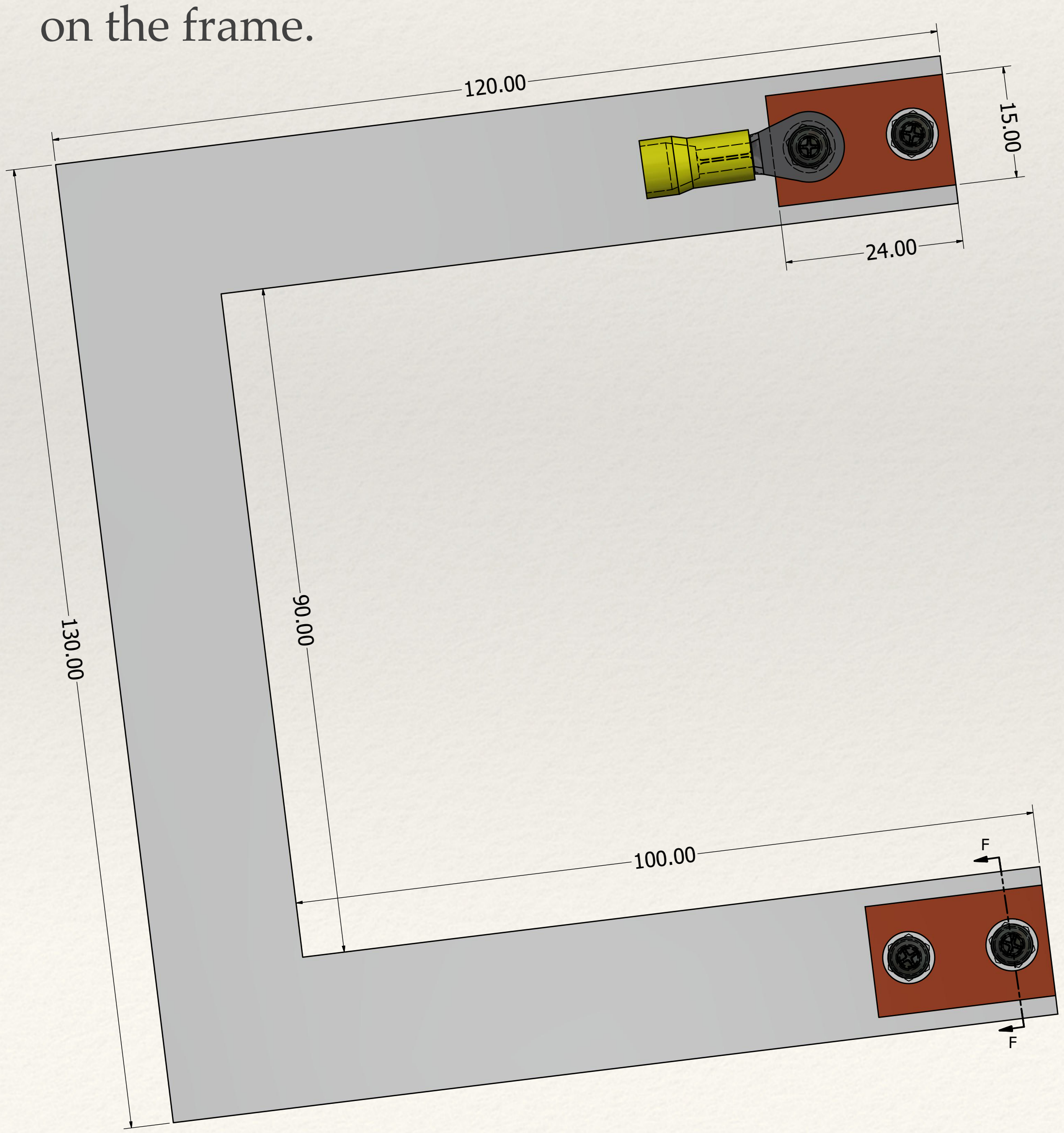


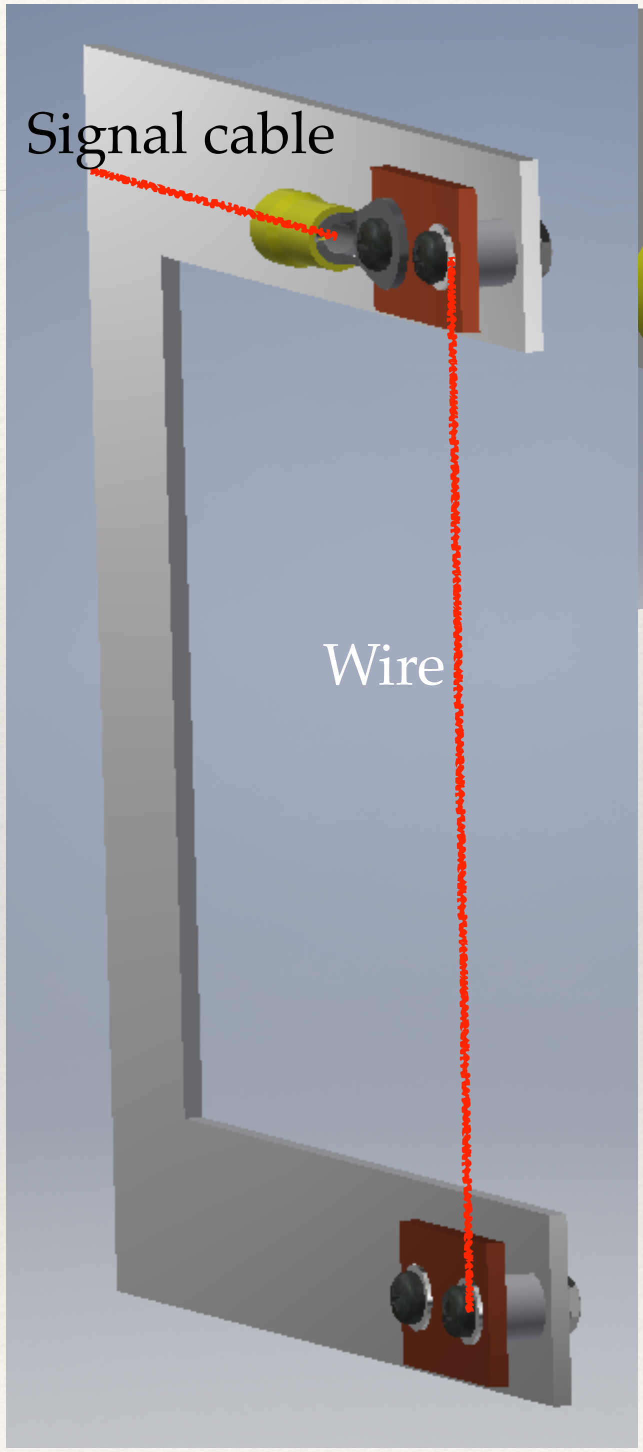
Figure 2: Frame of Wire Scanner Monitor. Flame, wire and plate are made of ceramics, tungsten and carbon respectively.

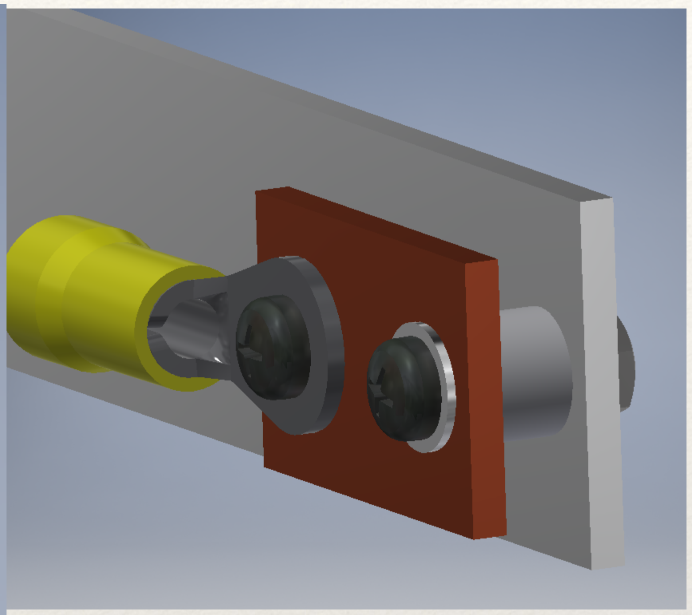
Proceedings of IPAC'10, Kyoto, Japan

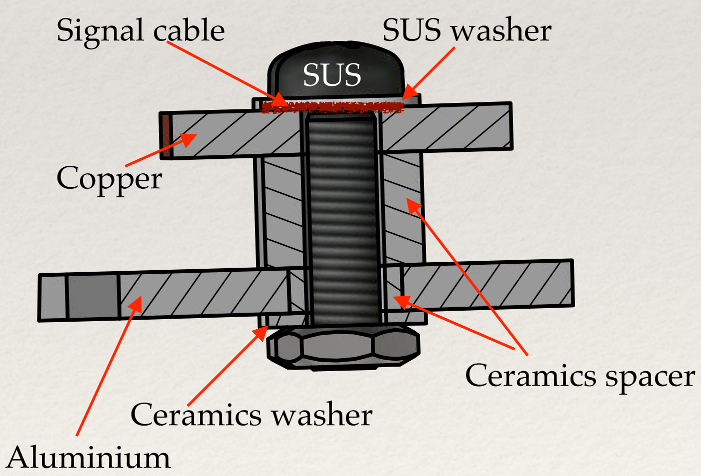
Frame design for FFA WSM

- Aluminium frame is grounded to the probe (and chamber). The wire is sandwiched by ceramic washers.
- Negative voltage is applied on the wire via signal cable and successive amplifier.
- Frame design must be optimised with beam experiments at Kyoto FFA for final design of FETS-FFA WSM, especially the way to fix the wire on the frame.





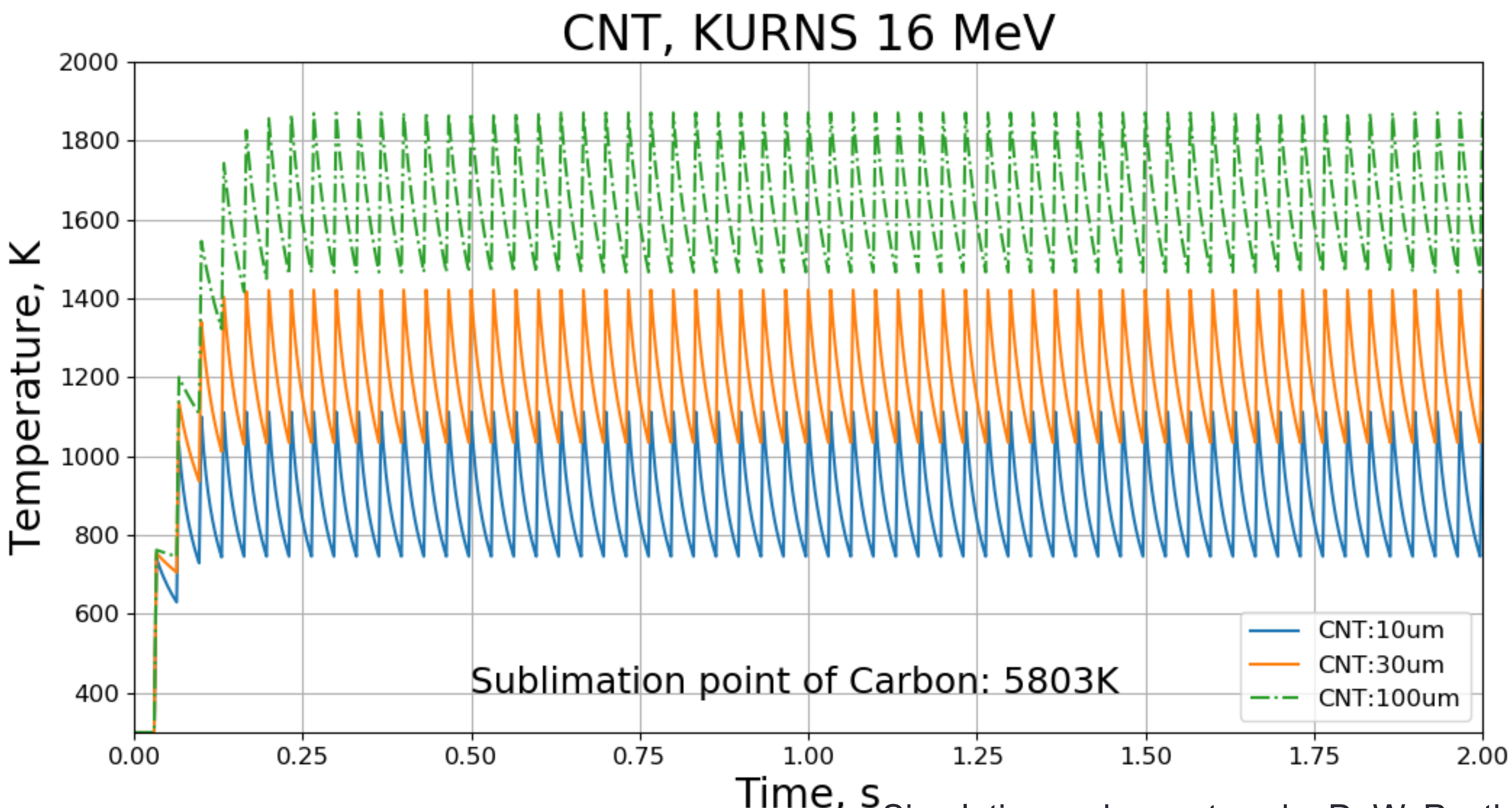




Heat estimation of CNT wire for Kyoto FFA

- Simulation assumptions:
  - Wire will hit the bunch core (σ)
  - Diameter of CNT wire : 10um, 30um and 100um
  - Wire density:1.4*1 (CNT)
  - Heat capacity: 750*2 J/g/K (CNT) at 300K
  - Beam energy : 16 MeV
  - Time duration beam hits the wire (dt) : 833us
  - Beam size (σ) : 5mm
  - Beam peak current (Ip) : 18 mA ($Np=3x10^{10}$)
  - Pulse rate : 30 Hz

*1: HiTaCa developed by Hitachi Zosen Corporation
*2 : 'The specific heat and effective thermal conductivity of composites containing single-wall and multi-wall carbon nanotubes', Nanotechnology **20** (2009) 245705, doi: 10.1088/0957-4484/20/24/245705



Simulation code courtesy by D. W. Posthuma de Boer.

Heat damage on the wire will not be harmful.

Estimated maximum current signal from wire

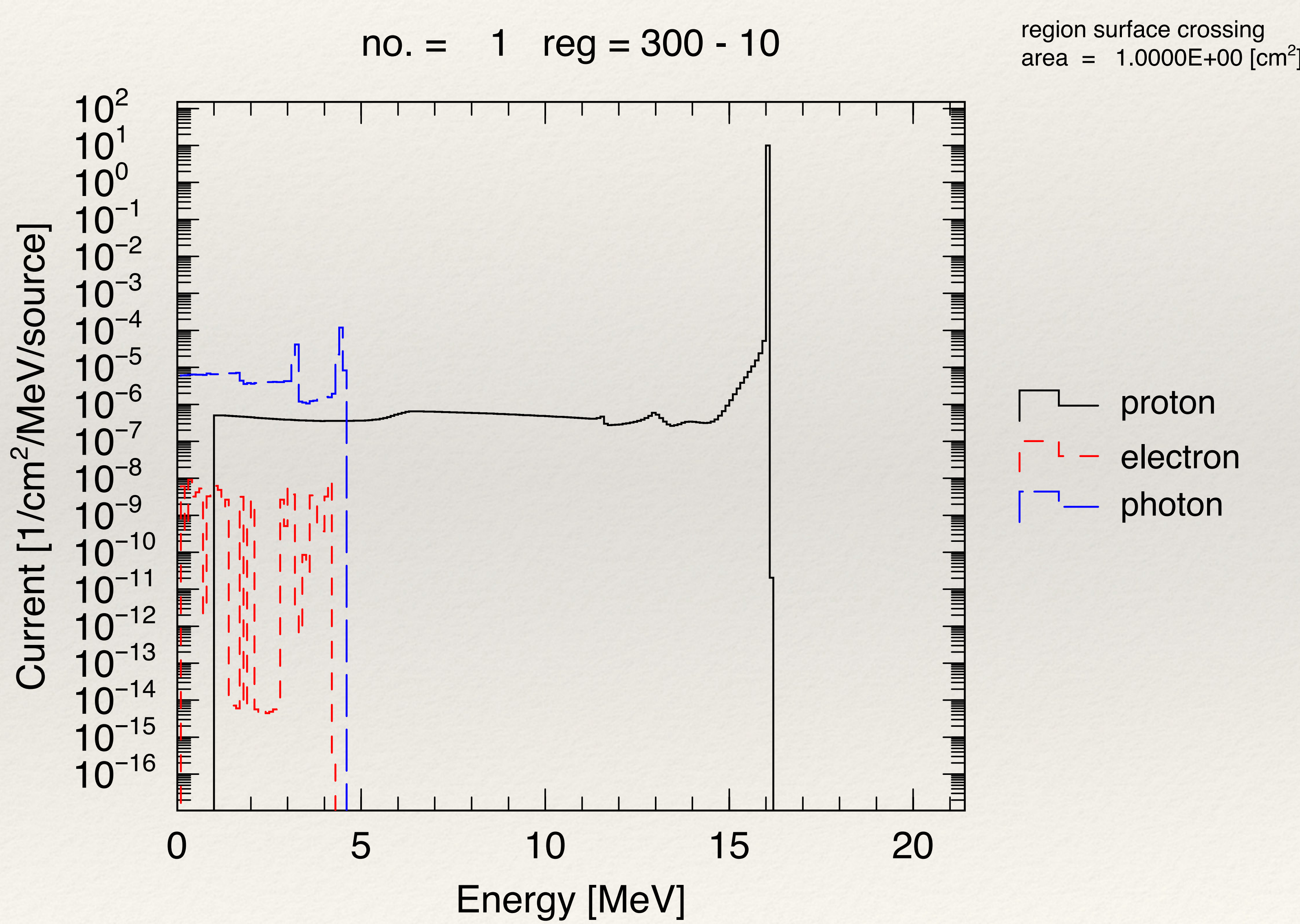
	Kyoto FFA at wire position	**FETS-FFA Injection**	**FETS-FFA Extraction**
Energy, MeV	16	3	12
Bunch intensity (Np)	3E+10	5E+10	5E+10
Bunch length (Tb), ns	268	288	115
RF frequency, MHz	1.86	1.91	3.8
Bunch current, mA	18	28	70
RF frequency bandwidth, MHz	1.6 - 5.2		
Harmonic number	1	2	2
dE/dx, MeV.cm²/mg	0.02807	0.1052	0.03543
SEY	0.126	0.474	0.160
Estimated max. signal current* from wire, mA	2.26	13.2	11.1

* Current signal = SEY * Np * 1.6E-19 / Tb

Current amplifier is required for the measurement.

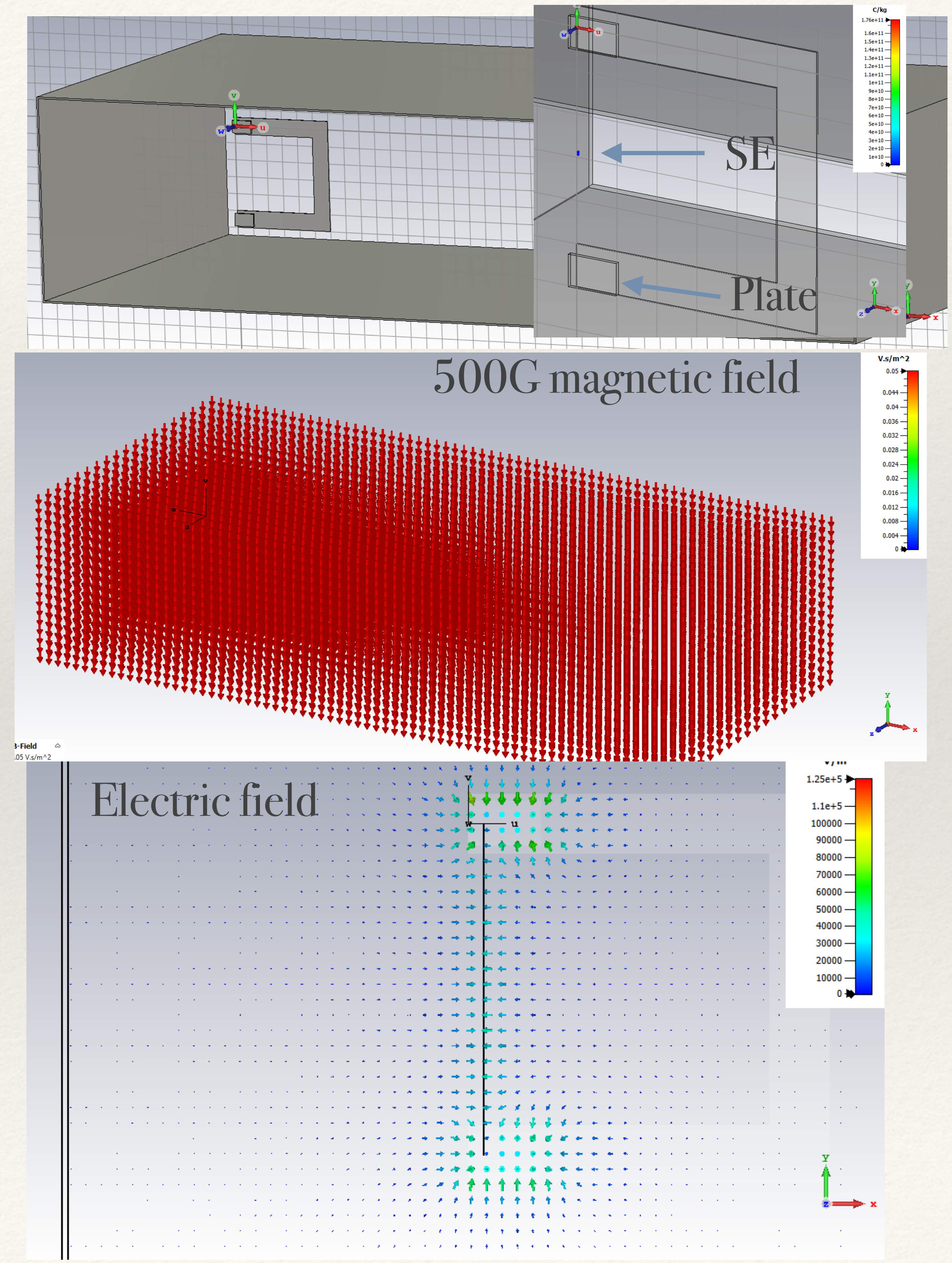
Energy distribution of SE from 10um CNT

- Energy distribution of SE from the wire is computed by PHITS code.
- In PHITS, 2x2 cm² with thickness of 10um CNT sheet is generated in this model.
- 16.1 MeV pencil beam (proton) is injected perpendicularly to the CNT sheet.
- The particles emitted from the wire is counted and plotted in the figure.
- <u>In this model, the energy range of SEs is from 100 keV to 4.3 MeV.</u>



SE trajectories under EM fields

- Trajectories of 100 keV, 1MeV and 4 MeV electrons are estimated by CST Particle Tracking Simulation with EM conditions:
  - ϕ10 and ϕ30 um wires are considered.
  - Negative electrical potential is applied on the surface of wire (PEC) and plates (PEC).
  - 500 Gauss stray field is applied in the vacuum chamber.
  - Vacuum chamber (PEC) and wire frame (PEC) are grounded.
  - The wire is not attached on the wire frame.
  - SEs are generated around the centre of wire.



Trajectories of 100 KeV SE under EM fields

- Larmor radius (cyclotron radius) of 100 keV electron is about 21mm under magnetic field of 500 Gauss.
- Applying -500V on the wire surface, the electrons drift away from the ϕ10um wire but spirals around ϕ30um wire (Figs.1 and 2)

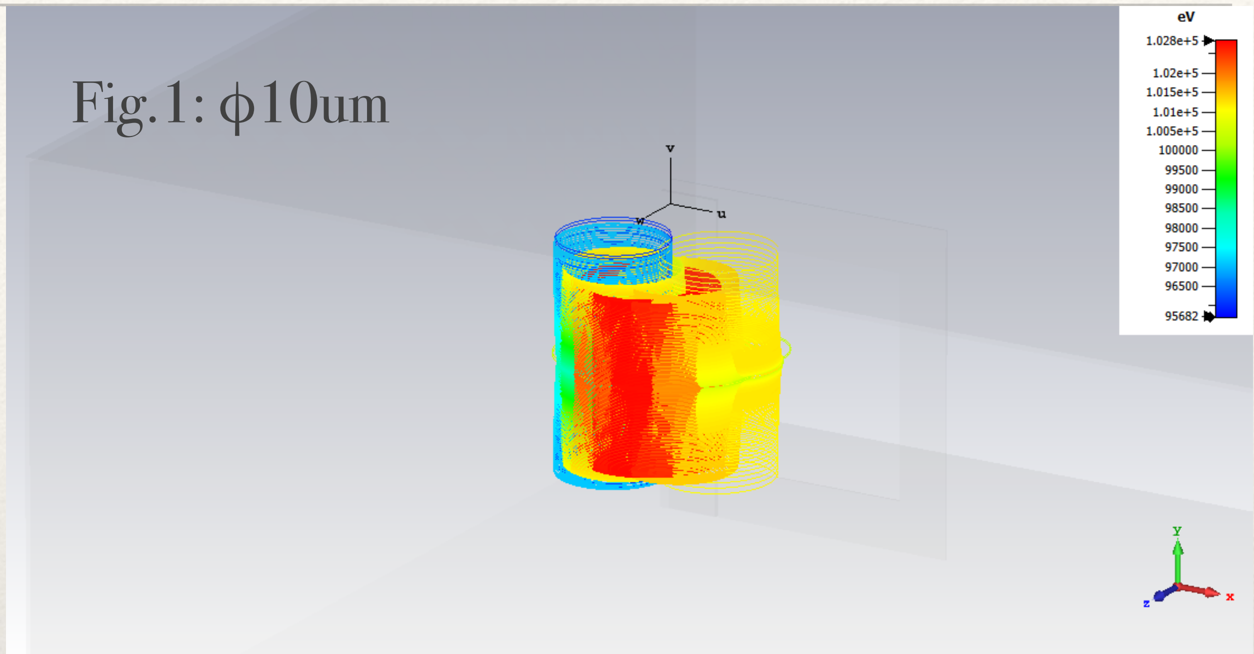


Fig.1: ϕ10um

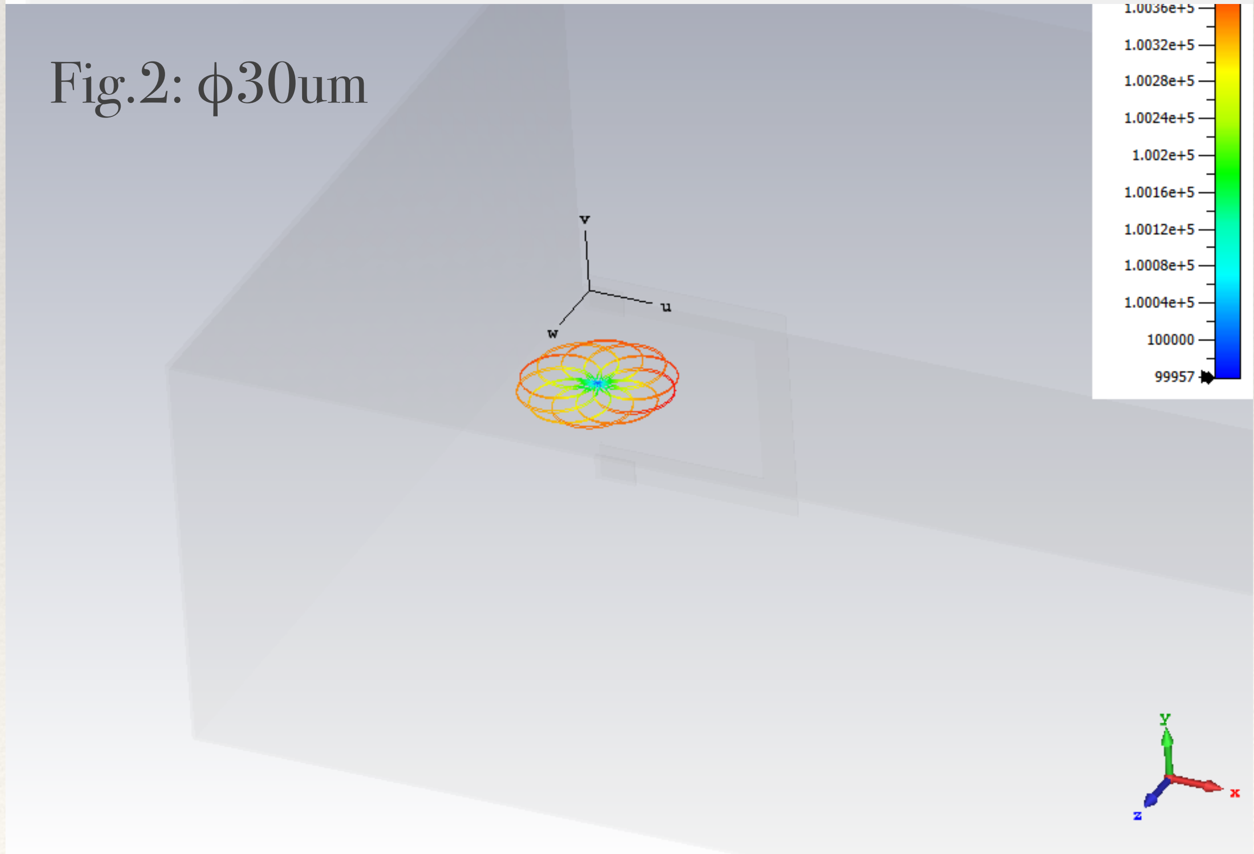


Fig.2: ϕ30um

Trajectories of 1 MeV SE under EM fields

- Larmor radius (cyclotron radius) of 1 MeV electrons is about 67mm under magnetic field of 500 Gauss.
- Applying -1200V on the wire, the electrons drift away from the ϕ10um wire, but spiral around ϕ30um (Figs. 1 and 2).

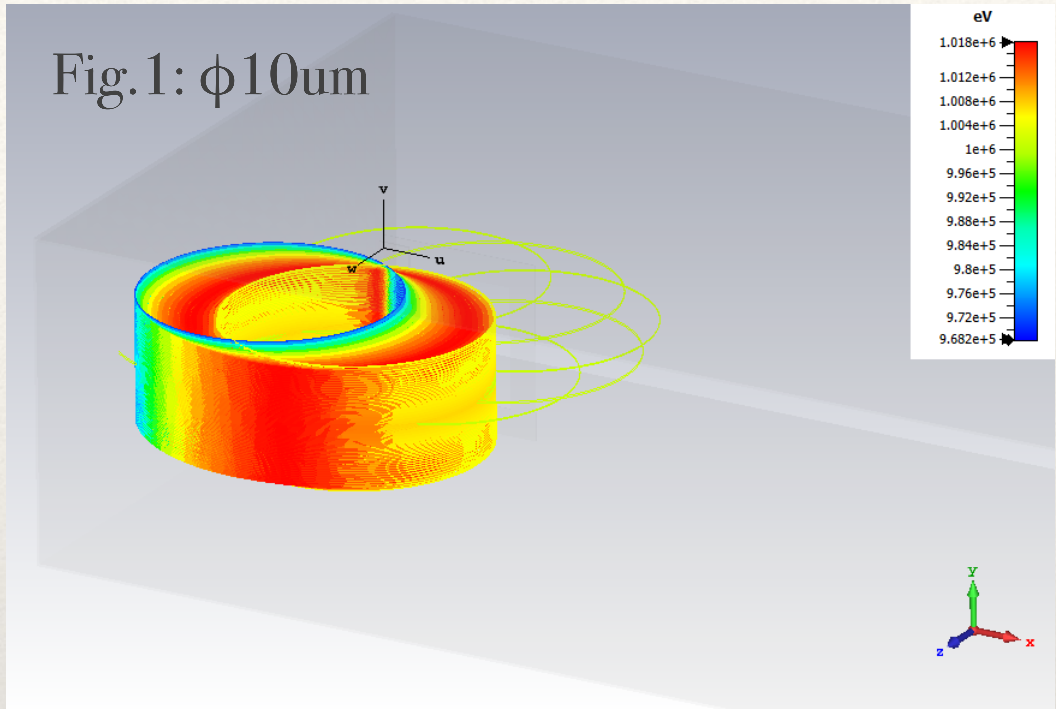


Fig.1: ϕ10um

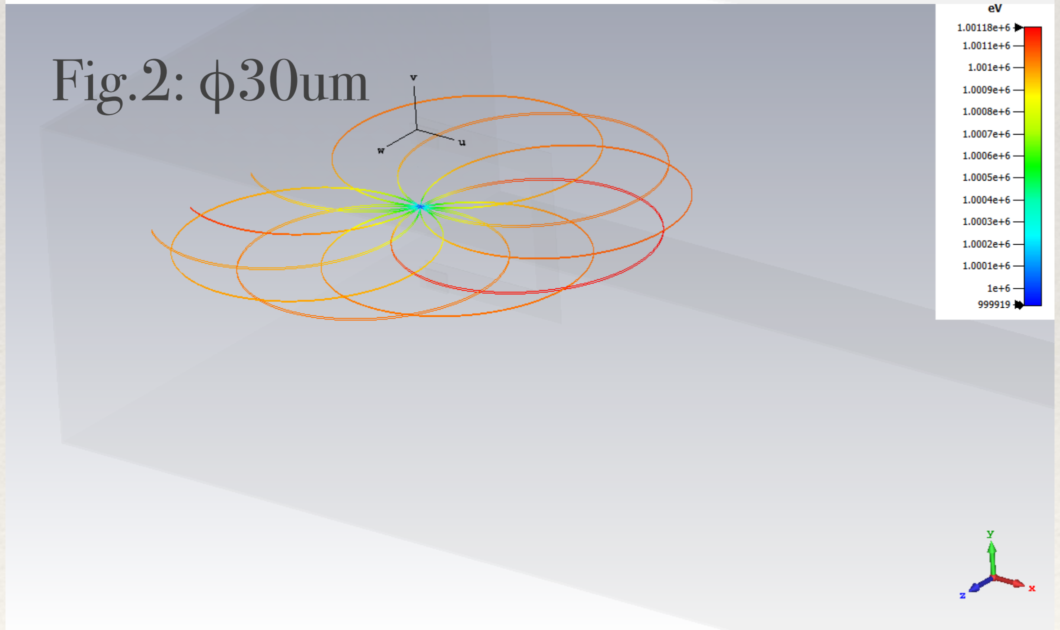
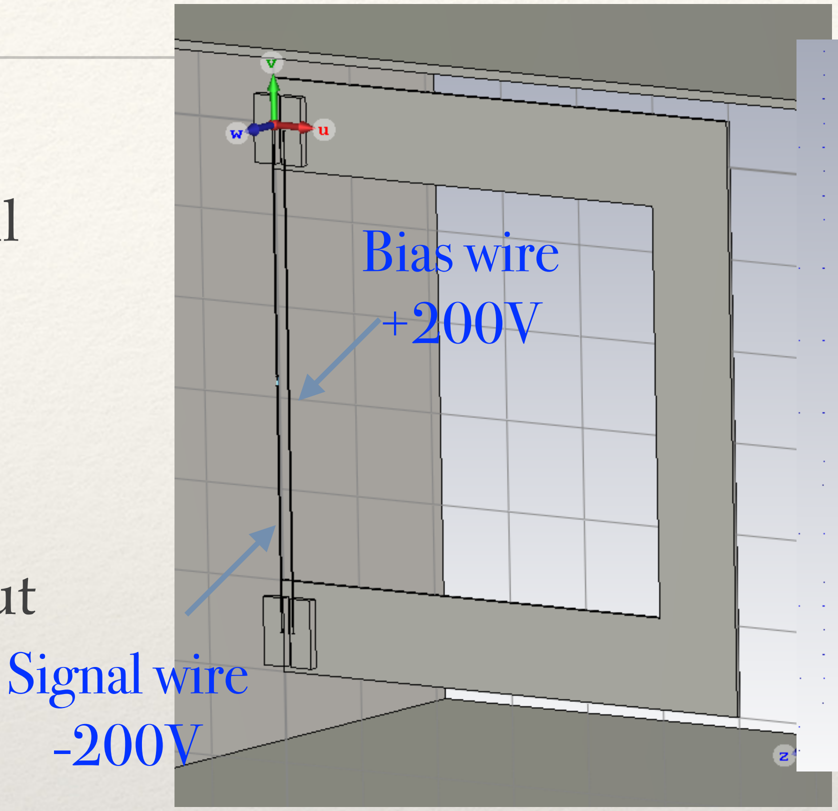
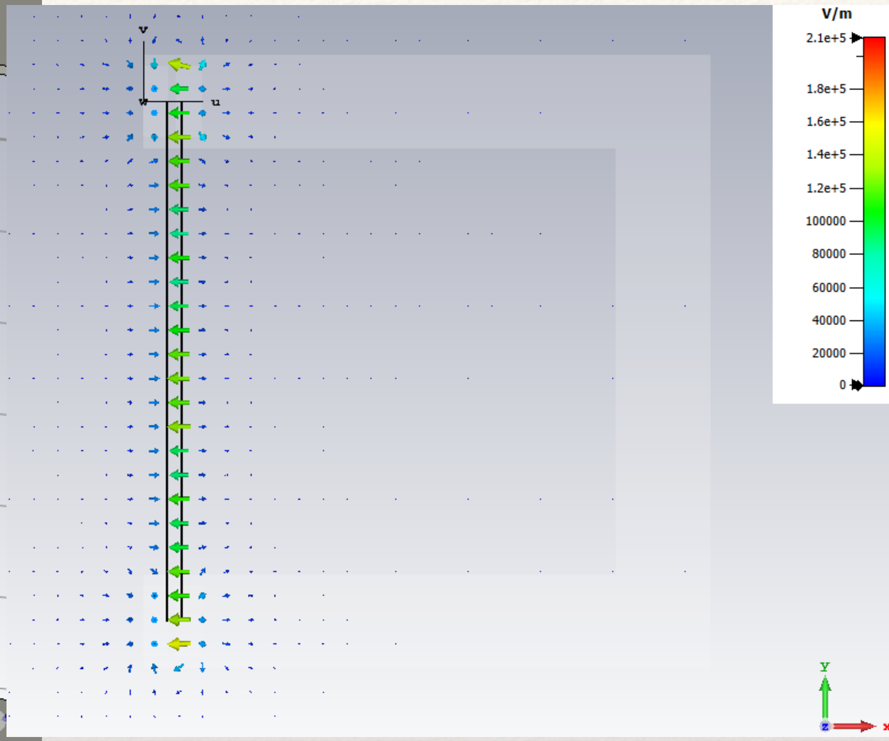


Fig.2: ϕ30um

Trajectories of SE under EM fields with additional bias wire

- The additional bias (CNT) wire is installed at 3mm apart from the signal (CNT) wire.
- -200V is applied on the signal wire. +200V is applied on the bias wire.
- The bias wire will work for ϕ10um but not for ϕ30um.





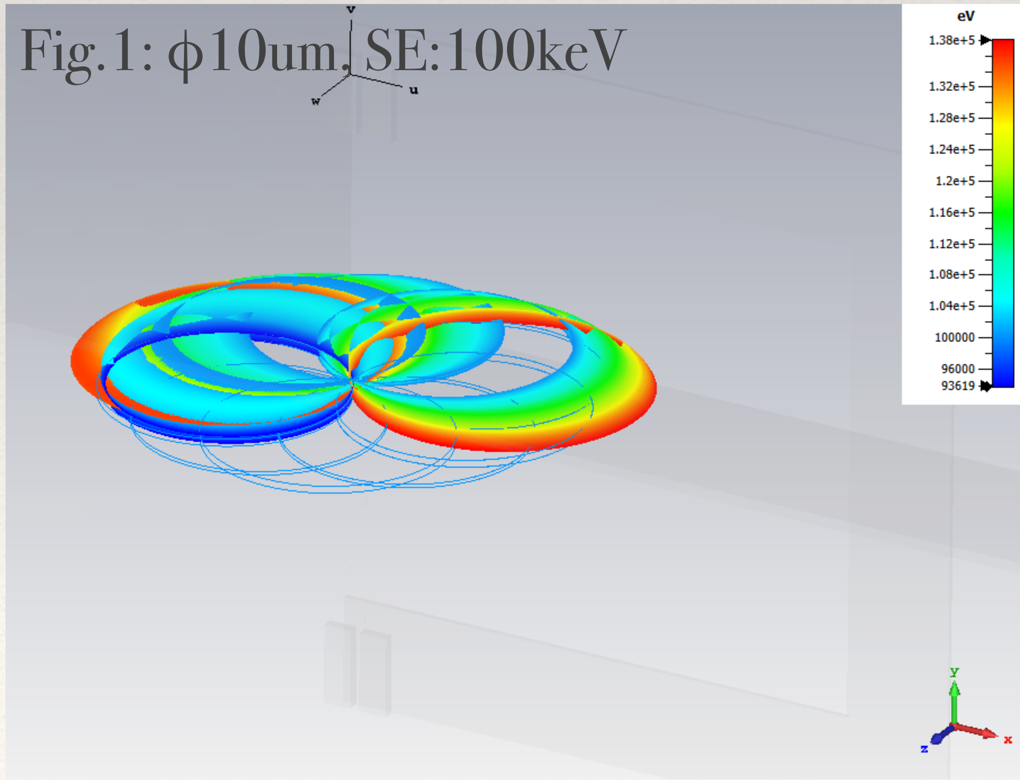


Fig.1: ϕ10um, SE:100keV

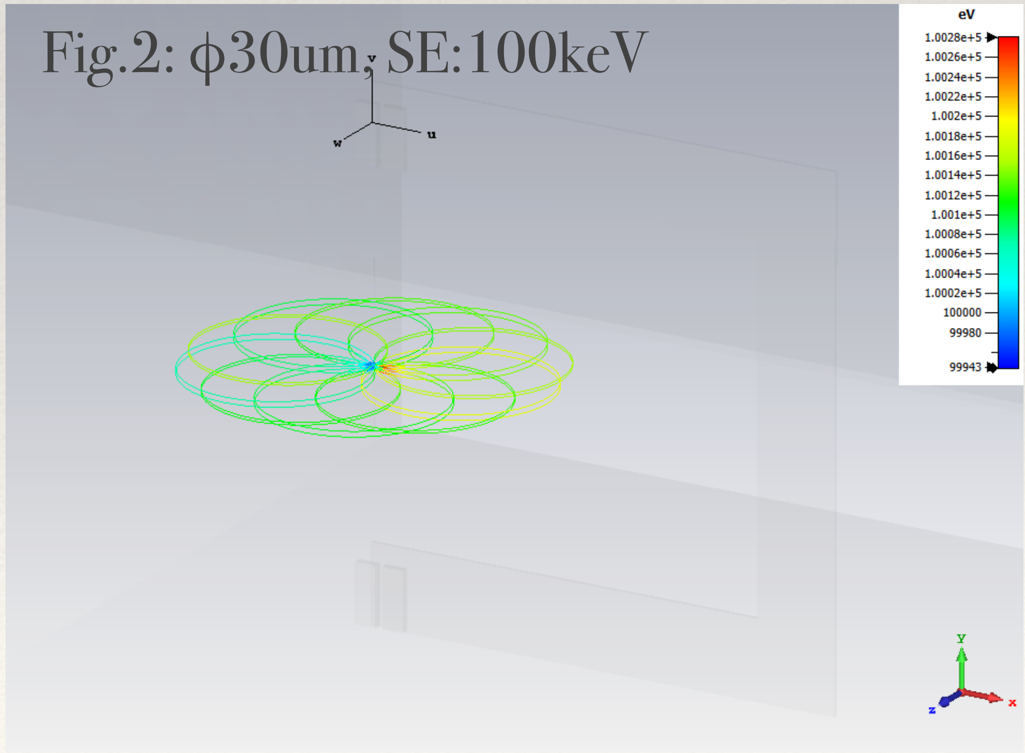
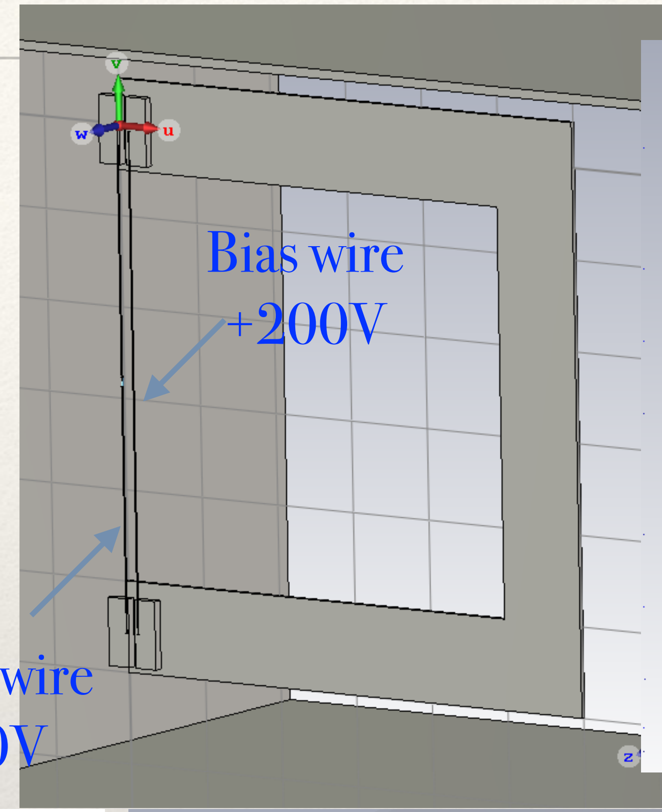
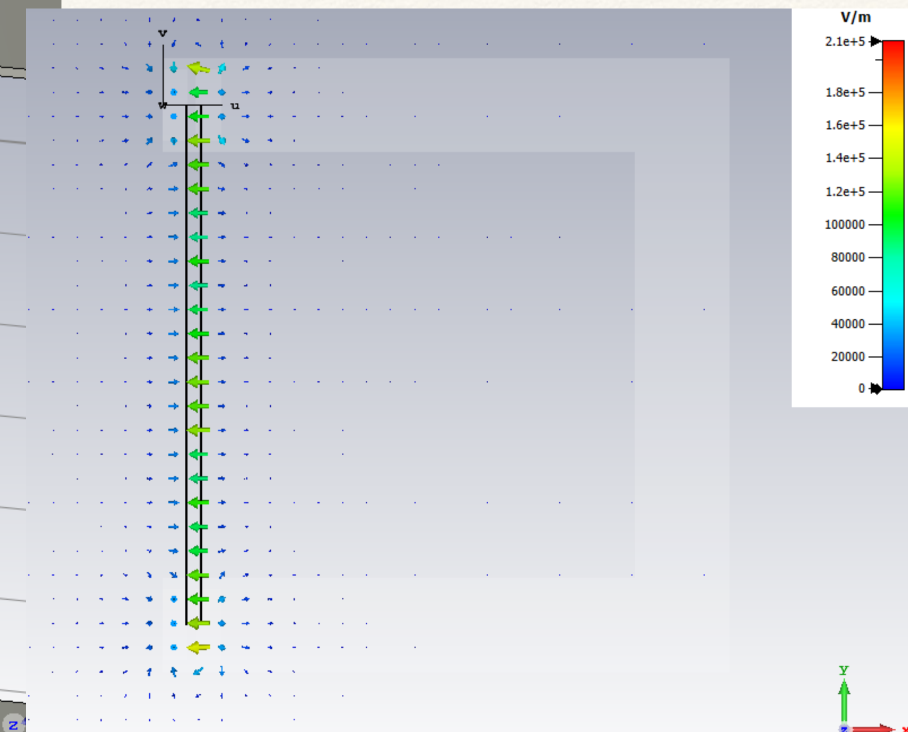


Fig.2: ϕ30um, SE:100keV

Trajectories of SE under EM fields with additional bias wire

- The additional bias (CNT) wire is installed at 3mm apart from the signal (CNT) wire.
- -200V is applied on the signal wire. +200V is applied on the bias wire.
- <u>The bias wire will not be very helpful to keep SEs away from the signal wire.</u>





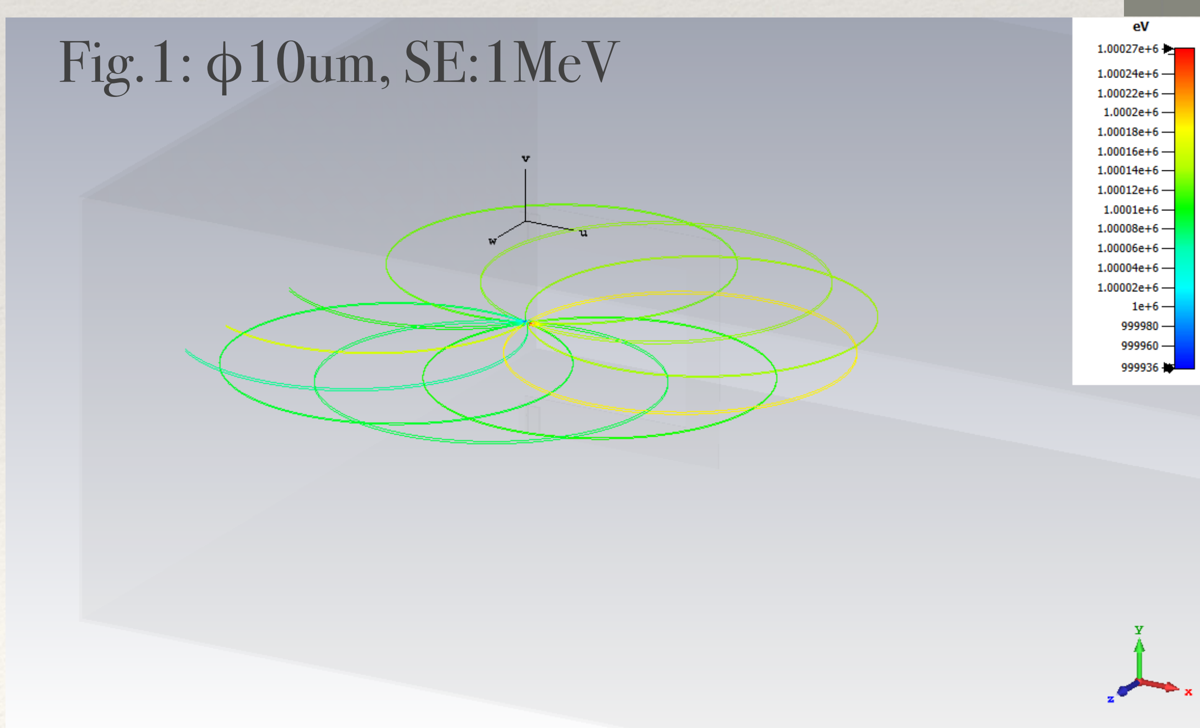


Fig.1: ϕ10um, SE:1MeV

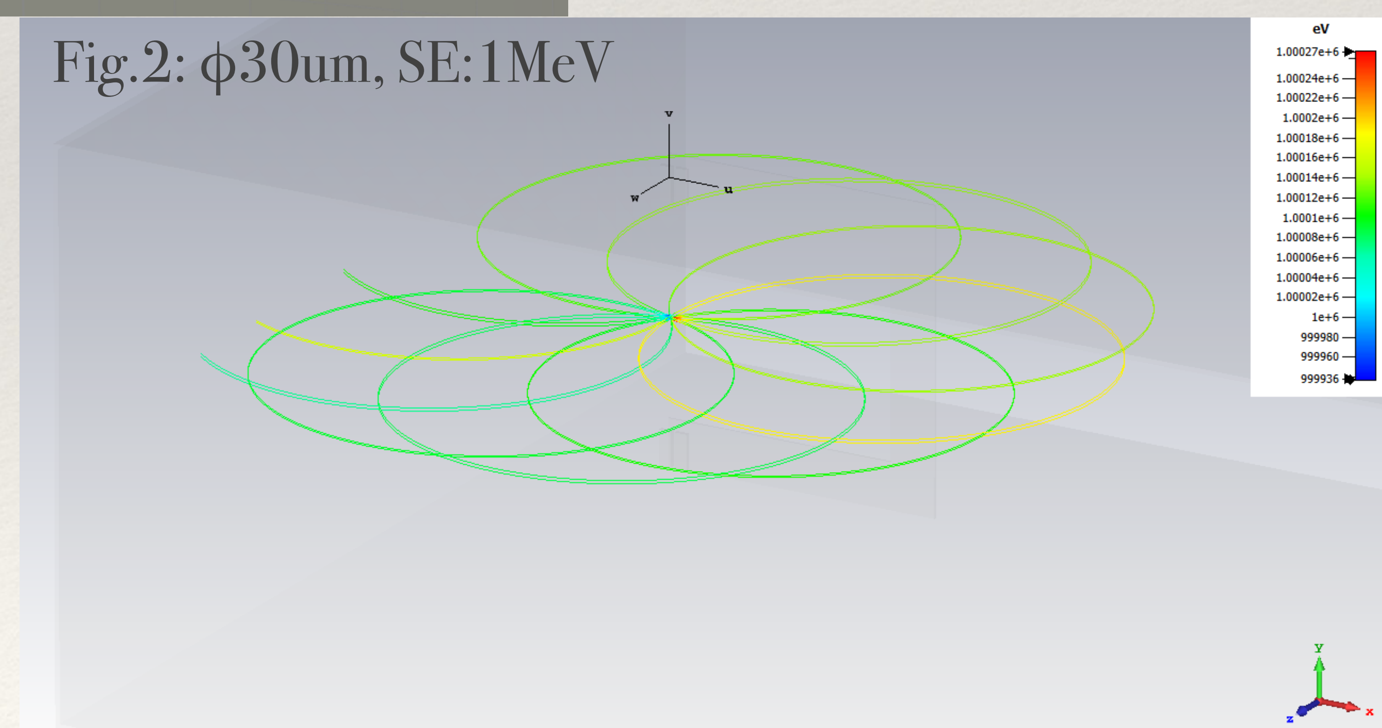
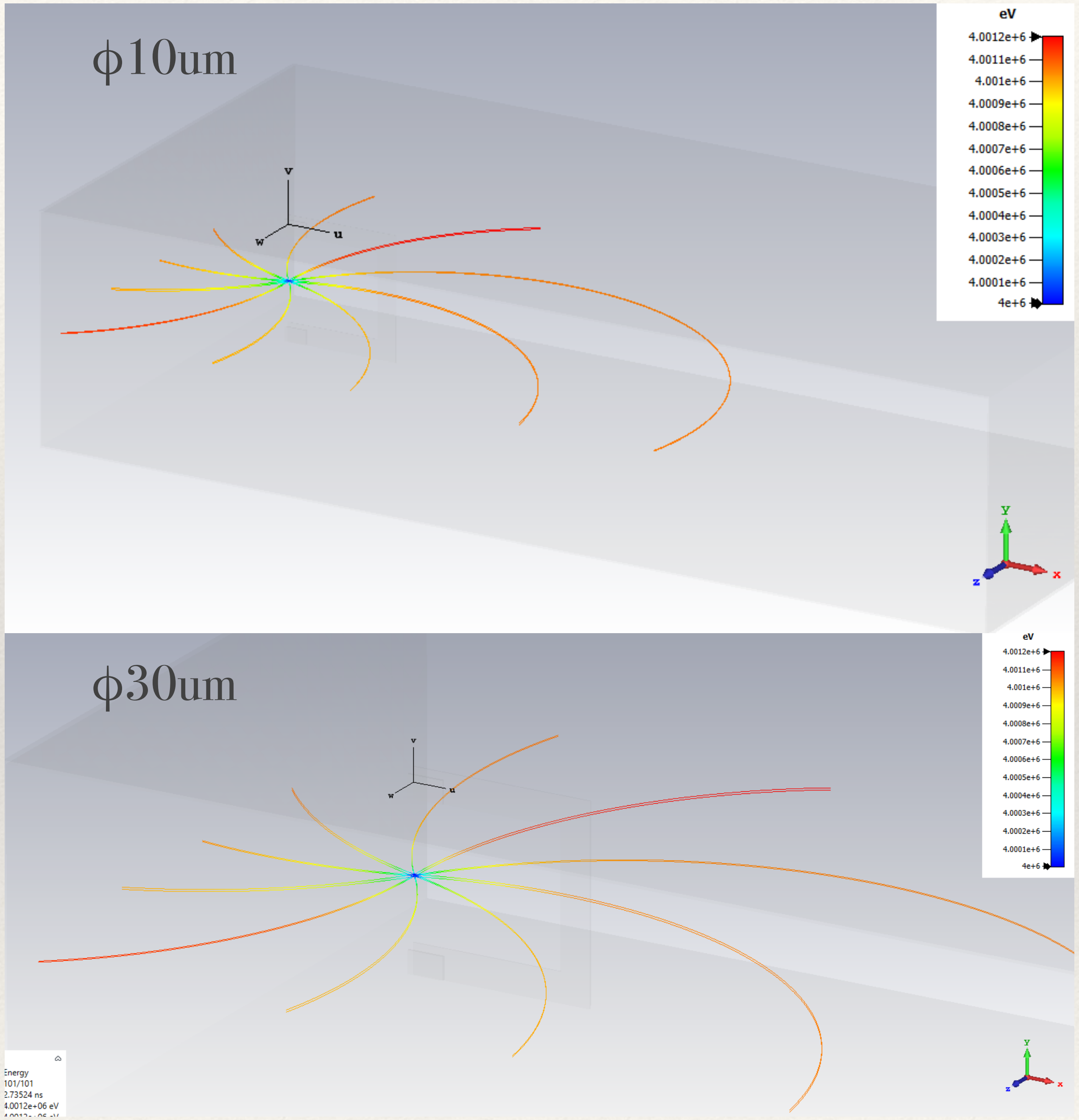


Fig.2: ϕ30um, SE:1MeV

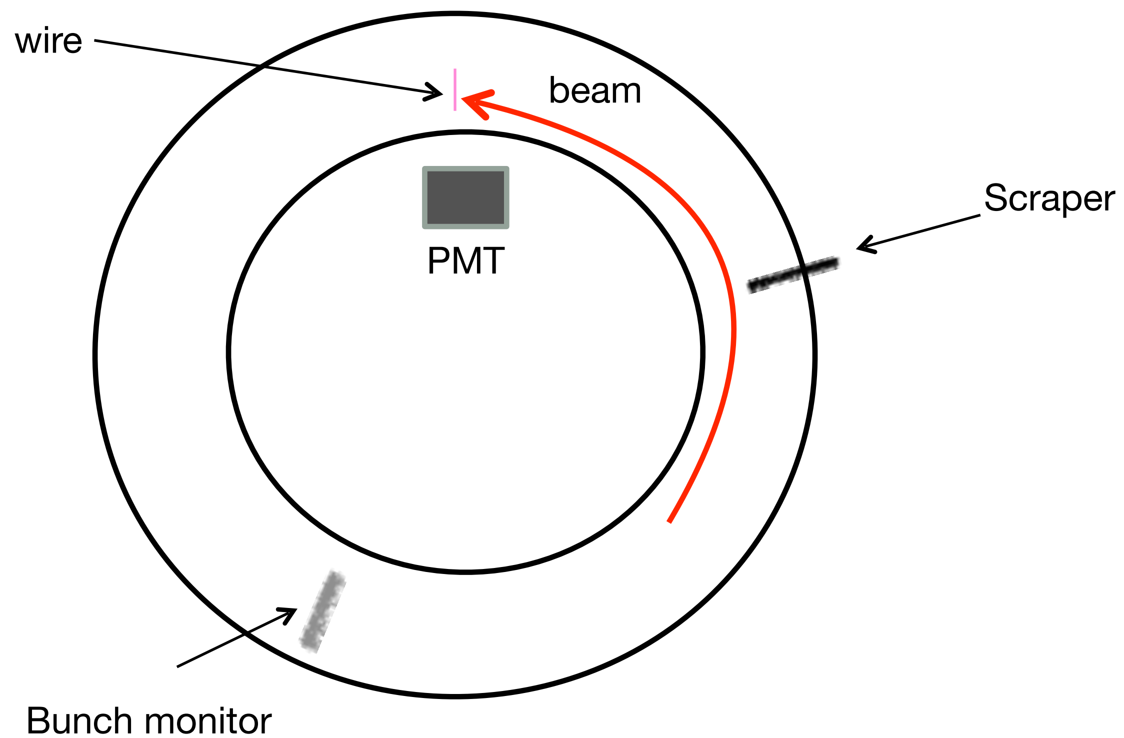
Trajectories of 4 MeV SE under EM fields

- Only signal wire is installed in this model.
- Larmor radius (cyclotron radius) of 4 MeV electrons is about 135 mm under magnetic field of 500 Gauss.
- -1200V bias voltage is applied on the signal wire. The electrons spiral around the wire and crashed at the vacuum chamber regardless wire thickness. (Fig.1 and 2)
- <u> As for 4 MeV, it might be not necessary to apply bias voltage on the wire, that is to be tested at Kyoto FFA for ϕ10 and ϕ30 um CNT wires.</u>



Request for wire monitor test in KURNS

- The aim of the test is to confirm if thin CNT wires (ϕ10 & ϕ30um) can estimate a transverse beam profile of circulating beam in FFA ring.
- Measurement:
  - Fix the wire position at 16 MeV orbit.
  - Current signal from the wire is monitored with bias voltages applied on the signal wire.
  - PMT + scintillation counter is also set to measure secondary photons from the wire.
  - To benchmark the WSM measurement, beam size is also measured by scraper.

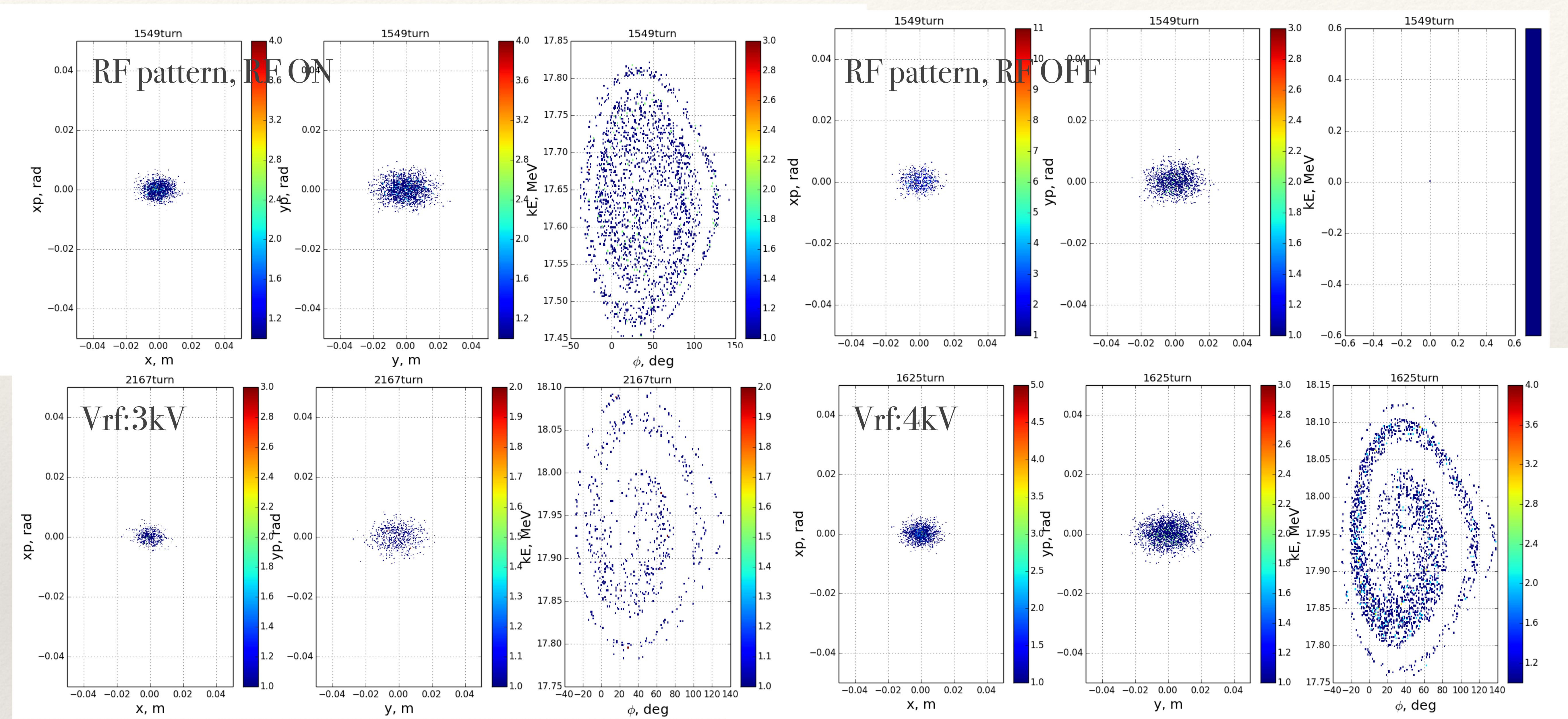


- Required spec of current amplifier:
  - <u>Bandwidth covers 1 - 10 MHz</u>
  - <u>Gain will be more than 10 kV/A</u>
  - <u>The bias voltage (< -1kV) can be applied on the amplifier</u>

Summary

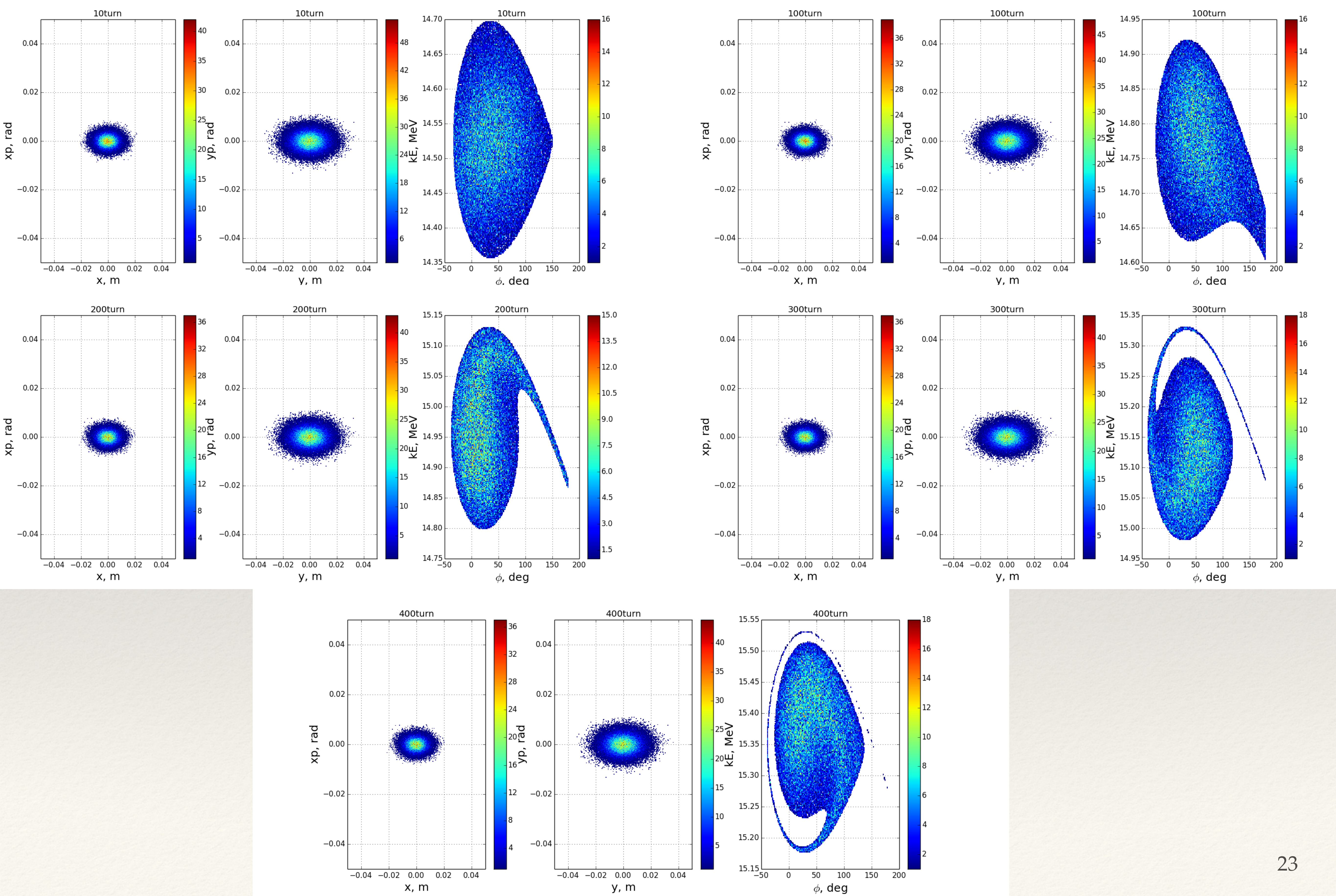
- WSM simulation studies have been done with ϕ142um to benchmark the simulation model.
  - Estimated beam size is twice bigger than the measured one even when synchrotron motion was included in the model.
  - One of the reason to explain this is that estimation of turn separation could be very different due to C.O. distortion etc?
  - However, if we use ϕ10 and ϕ30um CNT wires in KURNS, the beam profile could be measurable.
- The wire frame has been designed based on the one used at 3MeV LINAC in JPARC.
  - Expected maximum temperature on CNT wires would be less than 1400°C for ϕ30um.
  - According to CST and PHITS simulations, applying bias voltages might not be efficient to keep SEs away from the wire. This must be tested during experiments.
- CNT ϕ10um and ϕ30um cost 150,000JPY for each. The minimum length we can purchase is 10m long. The samples of both CNT wires will be delivered to KURNS (Ishi-san) end of this month, so worth for checking the frame design before beam test if it suits for such a thin wires.
- Shall we decide if we purchase a set of ϕ10 and ϕ30um CNT wires after the experiment with CNT samples?

Simulations with Φ142 um wire in Kyoto FFA



	σ, mm
Experiment	2.11
RF pattern w/o Synchrotron motion	4.07
RF pattern w/Synchrotron motion	4.19
Ideal pattern of Frf withVrf =3 kV	3.01
Ideal pattern of Frf with Vrf = 4kV	4.04

Simulations with Φ10 um wire in Kyoto FFA



Hitzの垂直配向性CNT（カーボンナノチューブ）「HiTaCa®（ヒタカ）」が、産業に革命を起こす。

HiTaCa, Hitz vertically aligned CNTs, will achieve a revolution in industry.

Roll to Roll HiTaCaシート

Roll to Roll HiTaCa sheet

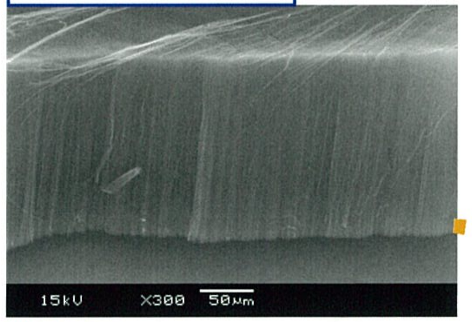
1m長さのシートの製造が可能になりました。
1 meter wide HiTaCa sheets can be produced.

CNT特長 Advantages of CNTs

- ・高分子材料並みの軽さ Lightweight comparable to polymer material
- ・機械的強度が高い High mechanical strength
- ・高弾性 High elasticity
- ・高い電気伝導性 High electrical conductivity
- ・高い熱伝導率 High heat conductivity
- ・化学的に安定 Chemical stability

HiTaCaシート拡大写真

SEM image



作製可能範囲 Specification

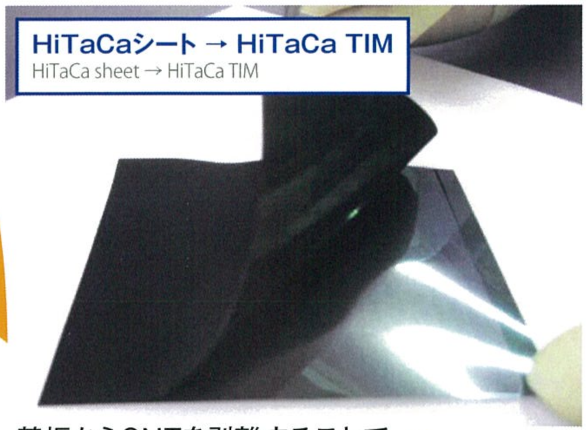
CNT種類 Number of layers	多層 Multilayered
CNT外径 CNT outer diameter	φ10~30nm
CNT長さ CNT length	50~500μm
本数密度 Tube density	10^{9}~ 10^{11}本/cm² 10^{9}~10^{11}tubes/cm²
嵩密度 Bulk density	10~100mg/cm³
純度 Purity	>99%
G/D比 G/D ratio	1~15
電気抵抗率 Electrical resistivity	厚み方向:0.001~0.1Ωcm 面方向:1Ωcm Thickness direction:0.001~0.1Ωcm Across surface:1Ωcm

CNTは炭素でできた直径がナノオーダーのチューブ状繊維です。
CNTs are tubular carbon fibers and their diameters are nanometer order.

Hitzは、均質性に優れた垂直配向性CNT「HiTaCa」を、大面積で製造しています。
We are manufacturing uniform large-area HiTaCa sheets.

HiTaCa TIM

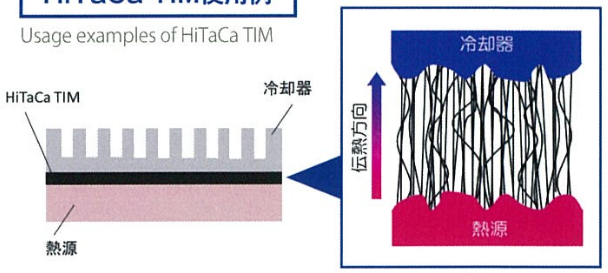
HiTaCa TIM



基板からCNTを剥離することで、放熱部材として使えます。
CNTs separated from substrates can be used as thermal interface materials.

HiTaCa TIM使用例

Usage examples of HiTaCa TIM



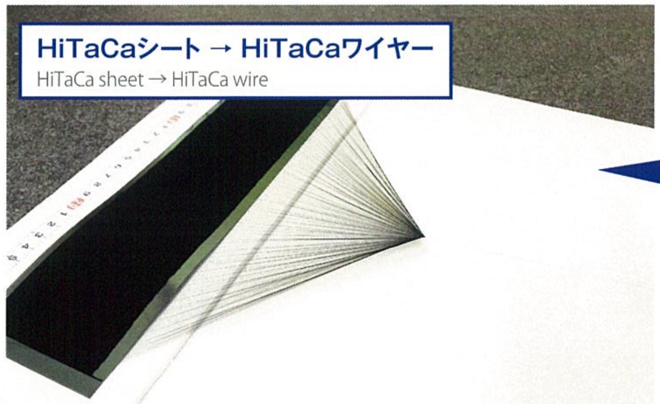
CNTの先端が接触界面の凹凸にタッチすることで界面熱抵抗を抑え、効率よく熱を逃がすことができます。
HiTaCa TIMs show small contact thermal resistance and efficiently dissipate heat because the tips of brushlike CNTs finely contact uneven surface.

HiTaCa TIM特長 Advantages of HiTaCa TIMs

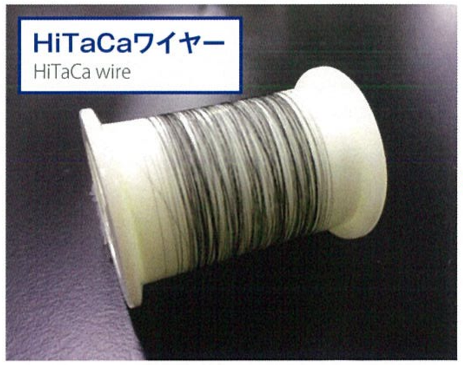
- ・界面熱抵抗が抑えられる Small contact resistance
- ・耐熱性が高い High heat durability
- ・繰り返し性能が高い Reusablility

HiTaCaワイヤー

HiTaCa wire



基板からCNTウェブを引き出し、紡ぐことでワイヤーを作製しています。
CNT wires can be made by spinning webs from CNT sheets.



HiTaCaワイヤー特長 Advantages of HiTaCa wires

- ・軽量 Lightweight
- ・引張強度が高い High tensile strength
- ・熱伸びしにくい Little thermal expansion
- ・しなやか Flexibility

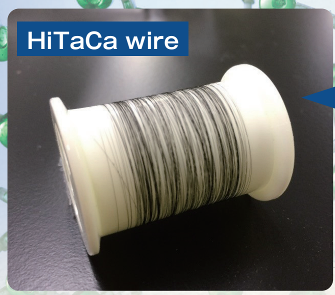
HiTaCa応用例

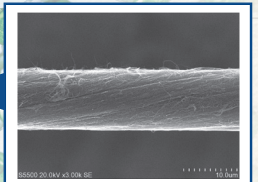
Applications of HiTaCa

注）本掲載データは代表値であり、保証値ではありません。 Note) The figures in this table are representative values and not guaranteed.

HiTaCa™ wire

lightweight/little thermal expansion/high tensile strength/flexible

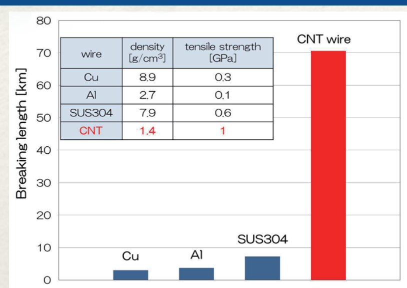




Diameter: ϕ10 μm
Breaking strength: 0.08 N (8gf)
Tensile strength: 1 GPa
Electrical resistivity: 1.0×10^{-3} Ωcm

Hitz HiTaCa wires are CNT yarns made of vertically aligned CNTs.
HiTaCa wires are stronger, lighter and more flexible than conventional metal wires and can be knitted and weaved.
Since there is little thermal expansion, HiTaCa wires can be used over a wide temperature range.

Comparison with conventional metal wires



wire	density [g/cm³]	tensile strength [GPa]
Cu	8.9	0.3
Al	2.7	0.1
SUS304	7.9	0.6
CNT	1.4	1

Breaking length = Breaking strength/Density

Applications

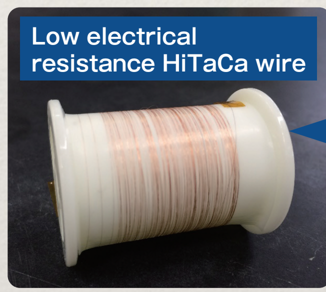
- ·Light wires for wire harnesses and signal lines
- ·Sensors
- ·Electromagnetic shield
- ·Heaters
- ·Space debris nets

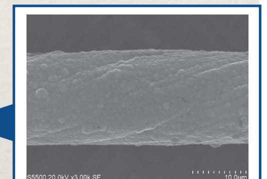
※Debris nets are used to catch wastes floating in the space.

Processing examples of HiTaCa wires

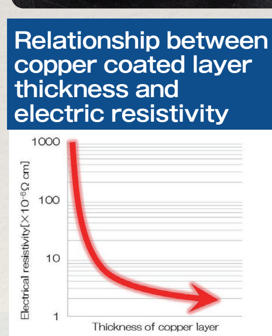
Even stronger and lighter wires can be made by twisting multiple CNT wires.

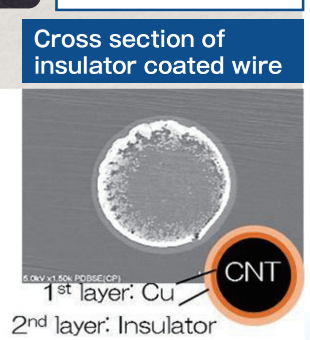
Low electrical resistance HiTaCa wire





Diameter: ϕ13.6 μm
Breaking strength: 0.12 N (12gf)
Tensile strength: 800 MPa
Electrical resistivity: 4.0×10^{-6} Ωcm





HiTaCa wires coated with metal decrease its electric resistivity.
We also provide insulator coated wires.

HiTaCa wire

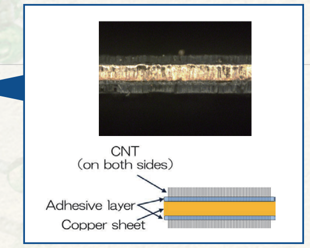
Type number	Diameter [μm]	Electric resistivity [$\times10^{-3}$ Ωcm]	Tensile strength [GPa]
HTC-W-10	10	1~3	1
HTC-W-20	20		

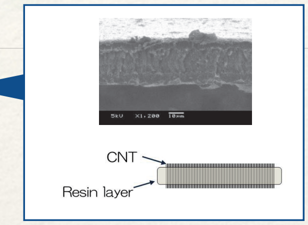
Type number	Diameter [μm]	Electric resistivity [$\times10^{-3}$ Ωcm]	Tensile strength [GPa]
HTC-W-30	30	1~3	1
HTC-W-50	50		

Note) The figures in this table are representative values and not guaranteed.

HiTaCa™ TIM

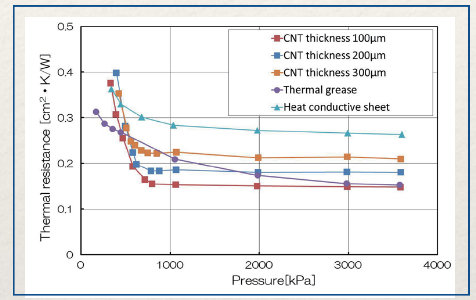
high heat durability/small contact resistance not depending on contact surfaces/reusability





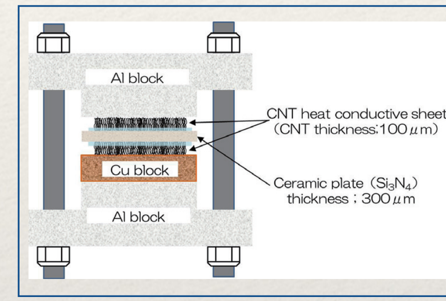
Hitz HiTaCa TIMs are thermal interface materials made from vertically aligned CNTs.
Since highly heat durable, HiTaCa TIMs can be used under various environments.
HiTaCa TIMs show small contact thermal resistance because the tips of brushlike CNTs finely contact uneven surface.

Relationship between pressure and thermal resistance



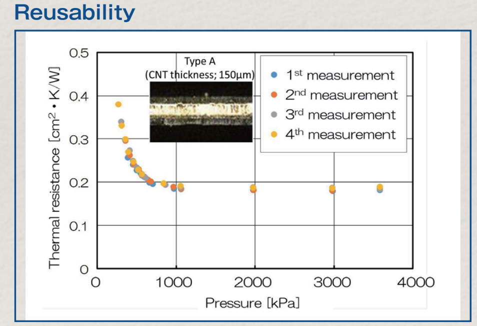
HiTaCa TIMs show smaller thermal resistance compared with TIMs on the market.

Schematics of thermal cycle test



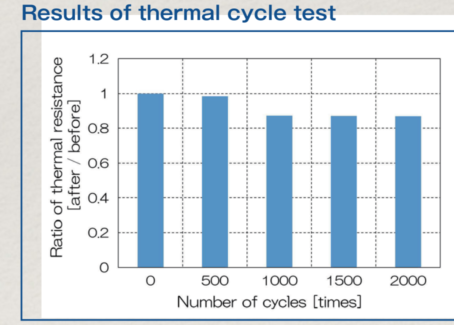
Cycle test conditions	Pressure:2MPa Temperature range:-40~90℃ Number of cycles:~2000times

Reusability



HiTaCa TIMs can be reused by applying a load.

Results of thermal cycle test



HiTaCa TIMs keep its performance even after thermal cycle for 2000 times.

HiTaCa TIM

Type number	CNT thickness[μm]	Thermal conductivity[W/mK]
HTC-T-100	100	20~25

Type number	CNT thickness[μm]	Thermal conductivity[W/mK]
HTC-T-300	300	20~25

Type	Type number	CNT thickness[μm]	Thermal conductivity[W/mK]
A	HTC-TA-100	100	20~25
	HTC-TA-300	300	

Type	Type number	CNT thickness[μm]	Thermal conductivity[W/mK]
B	HTC-TB-100	100	20~25
	HTC-TB-300	300	

Note) The figures in this table are representative values and not guaranteed.

Hitz
Hitachi Zosen
Business Planning & Technology Development Headquarters
Functional Materials Business Promotion Office
2-11, Funamachi 2-chome, Taisho-ku, Osaka 551-0022, Japan
Tel: +81-6-6551-9684 Fax: +81-6-6551-9210 E-mail:(t_inoue@hitachizosen.co.jp)
15th floor, Omori Bellport D-wing, 26-3, Minamioi 6-chome, Shinagawa-ku, Tokyo 140-0013, Japan
Tel: +81-3-6404-0845 Fax: +81-3-6404-0809 E-mail:(shiomi_a@hitachizosen.co.jp)

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Nominal parameters of FETS-FFA ring

- FETS-FFA ring: the vertical position of the beam varies with beam energy.

Parameters	
Beam energy, MeV	3 – 12(17)
Bunch intensity, ppb	10^{10}
Repetition rate, Hz	50 – 100 Hz
RF frequency bandwidth, MHz	1.91 – 3.8 (4.5)
Harmonic number	2
Straight section, m	1
Orbit excursion, m	0.69
Gap width of chamber, mm	> 60
Full beam size, mm	30

MCS at CNT 10um thick with 16 MeV protons