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Yamagata University

Commissioning and first operation of East Japan Heavy Ion Center at Yamagata University

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3) Accelerator Engineering Corporation

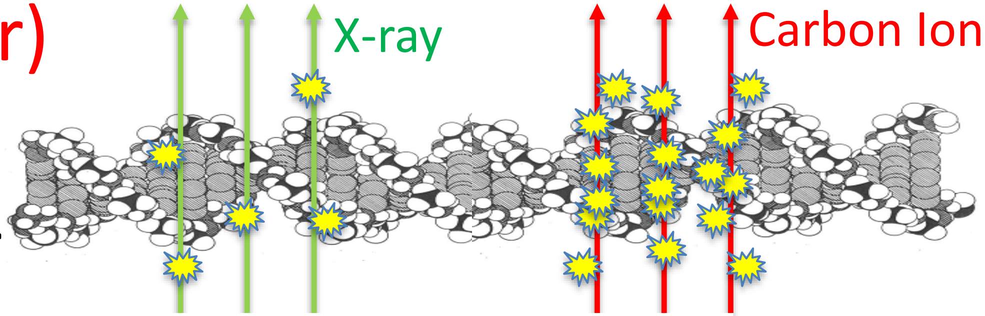
Outline

- Introduction of Carbon Ion Radiotherapy
- Facility and Treatment Machine
- Commissioning of East Japan Heavy Ion Center
  - Commissioning for clinical irradiation
  - Commissioning of rotating gantry
- First Operation Experience
  - Treatment statistics
  - Accelerator and Ion source operation
- Future Development

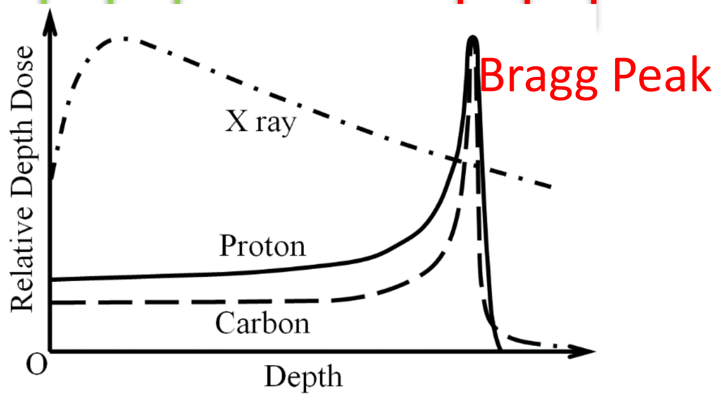
Introduction of Carbon Ion Radiotherapy

Carbon Ion radiotherapy

- Radiotherapy, Irradiate carbon ions of up to 430 MeV/u into human body for cancer therapy
- Strong points compared with conventional X-ray Therapy…
- High LET (Linear Energy Transfer)
  →Cause severe damage to DNA
  →Effective for radioresistant cancer



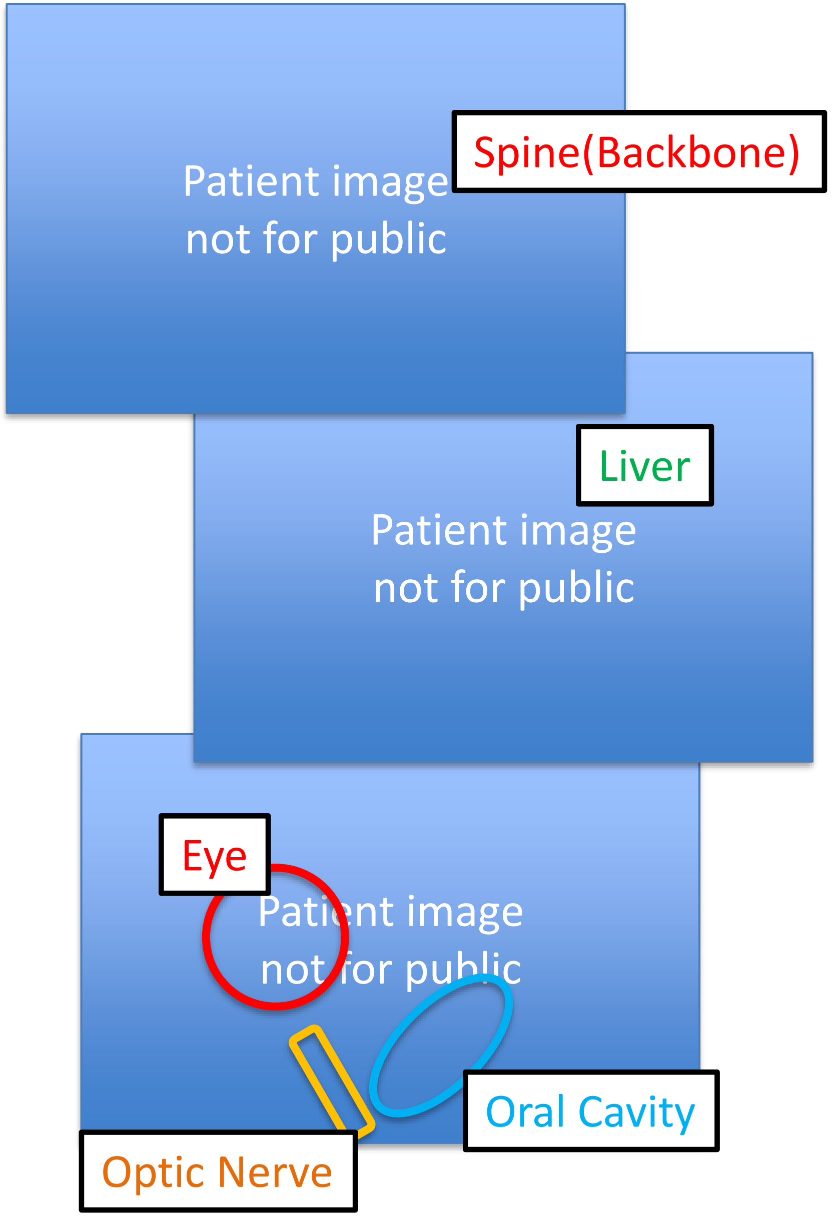
- Bragg Peak
  →Dose concentration to target
  →Protect normal tissues close to target
  →Higher dose than X-ray is available



Effective damage concentrated to target !

Target of Carbon Ion Radiotherapy

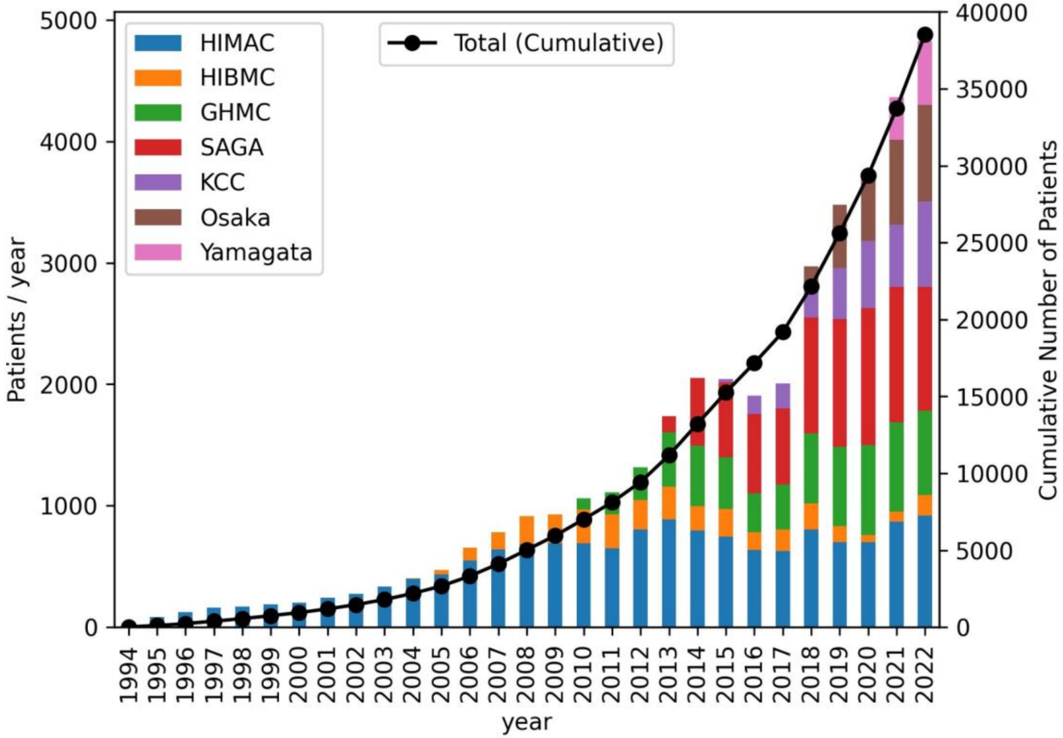
- Radioresistant Cancer
  - Sarcoma (Bone & Soft tissue cancer)
  - Adenocarcinoma (Prostate, Uterus, Etc..)
- Cancer with Huge Mass
  - Liver, etc.
  - Huge tumor→Hypoxia in the center→Radioresistant
- Close to important Organ
  - Head (Optic Nerve)
  - Pancreas(Duodenum)
  - Prostate(Rectum)

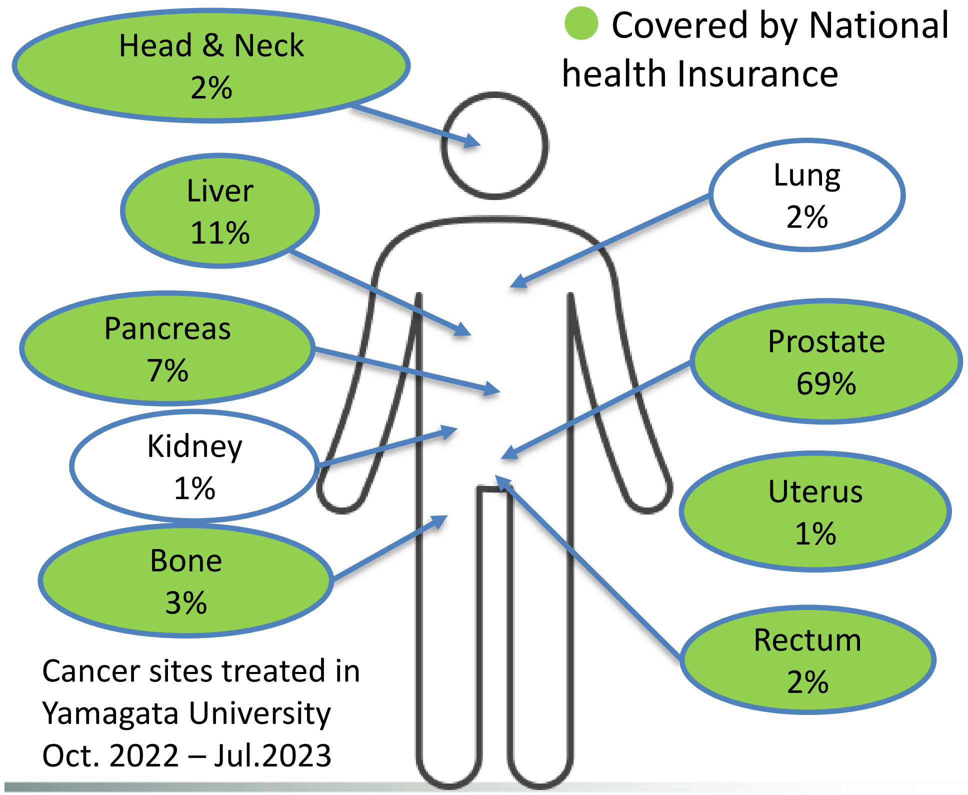


Carbon Ion Radiotherapy is the only way to treat some types of cancer

Progress of Heavy Ion Therapy

- 1975-1992 Ion therapy (He, Ne, etc.) at Bevatron, LBL ,USA
- 1994- Carbon Ion Therapy at HIMAC, Japan
- 2010- Compact Carbon Ion Treatment Facilities
- >35000 patient treated by 7 facilities in Japan



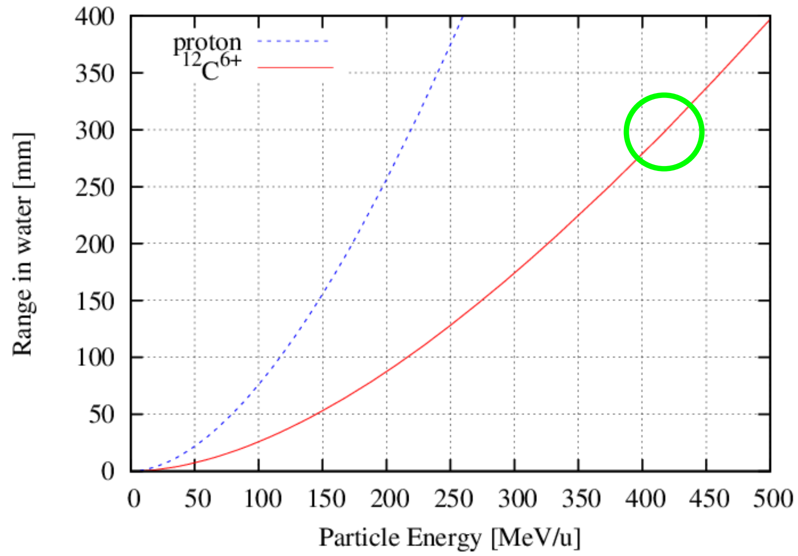


Cancer sites treated in Yamagata University Oct. 2022 – Jul.2023

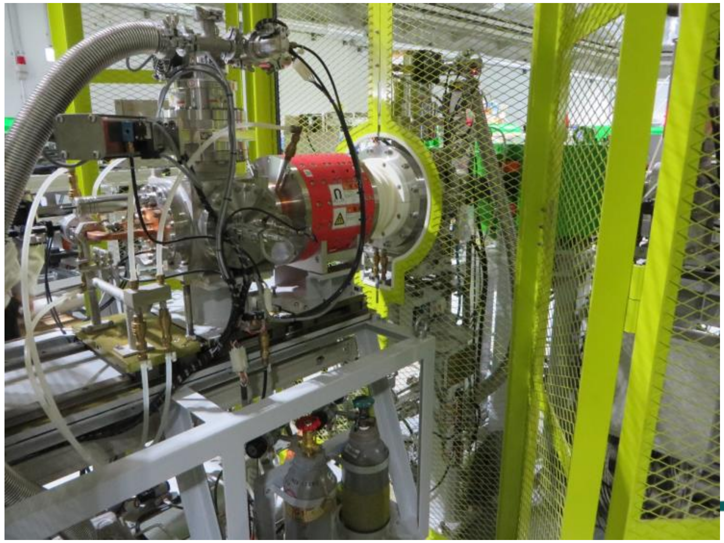
Carbon Ion Radiotherapy is a necessary technology in Today's Medicine

Compact Carbon Ion Accelerator

- Need 430 MeV/u $^{12}C^{6+}$ beam, for 300 mm range
- Synchrotron w/ slow extraction (precise dose control)



ECR Ion Source
C^{4+} 10 keV/u



RFQ + IH-DTL Injector
C^{6+} 4 MeV/u

Synchrotron (C ~ 63 m)
C^{6+} 55.6-430 MeV/u

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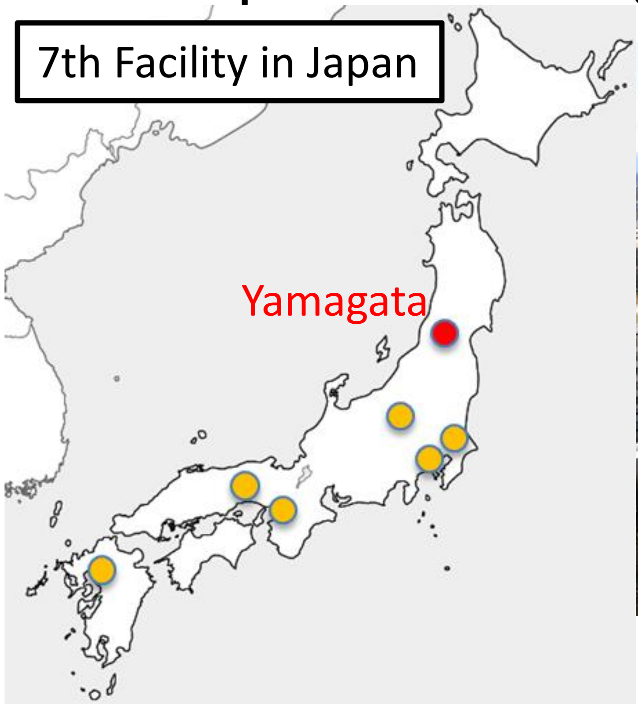
Facility and Treatment Machine

East Japan Heavy Ion Center

- East Japan Heavy Ion Center (EJHIC), Faculty of Medicine, Yamagata University
  - World Smallest Carbon Ion Facility (45 x 45 m)
  - Full energy Scanning Irradiation
  - Superconducting Rotating Gantry

Exported to Yonsei University and Seoul University in Korea

7th Facility in Japan



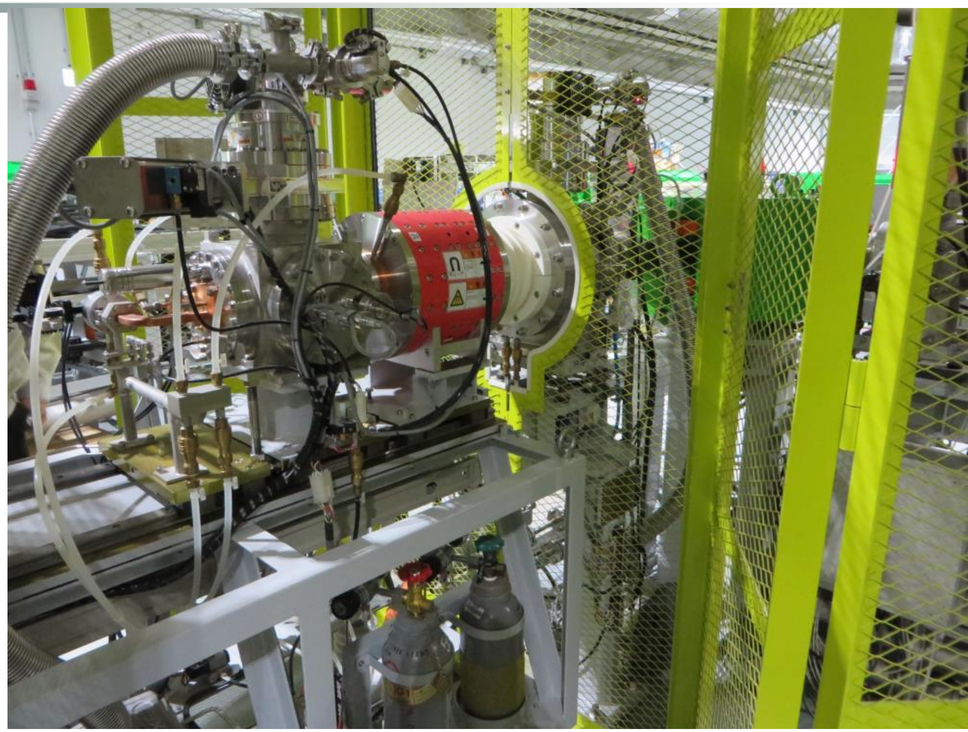
Manufacturer: Toshiba Energy Systems & Solutions Co.

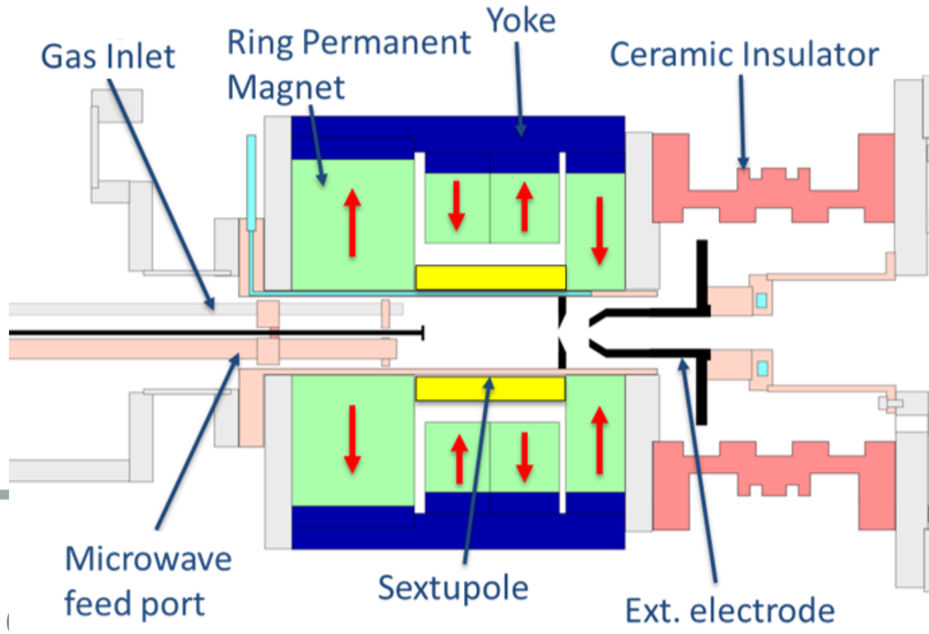
New Standard model of 2020s' Compact Carbon Ion Therapy Facility

Ion Source

- Kei2 series 10 GHz ECR Ion source
  - M. Muramatsu et. al., Rev. Sci. Instrum. 76, 113304 (2005).
- Permanent magnet of mirror and sextupole field, designed to maximize C^{4+} beam current.
- 150-300μA C^{4+} available

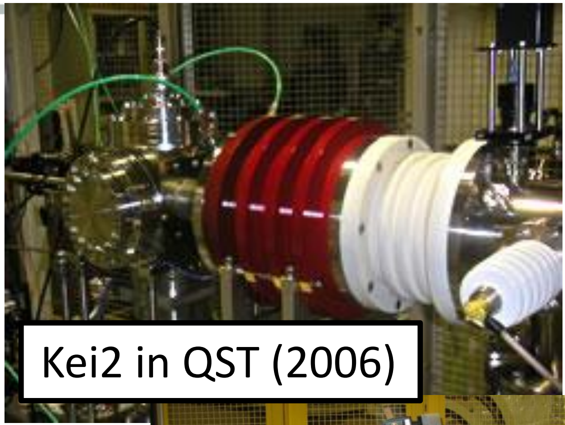
Magnetic Field	All Permanent Magnet Max. Mirror Field: 0.8 T
Extraction Electrode	25 mm Diameter
Anode Electrode	ϕ6 mm hole
RF Amplifier	Travelling Wave Tube (TWT) NEC LD79X75A1 (Max.750 W)
RF Frequency	10 GHz
RF Power	200 W (typ.)
Gas species	Methane (CH_4)
Ion Species	C^{4+}
Ext. Voltage	30 kV (10 keV/u)
Norm. Emittance	~1 π･mm･mrad



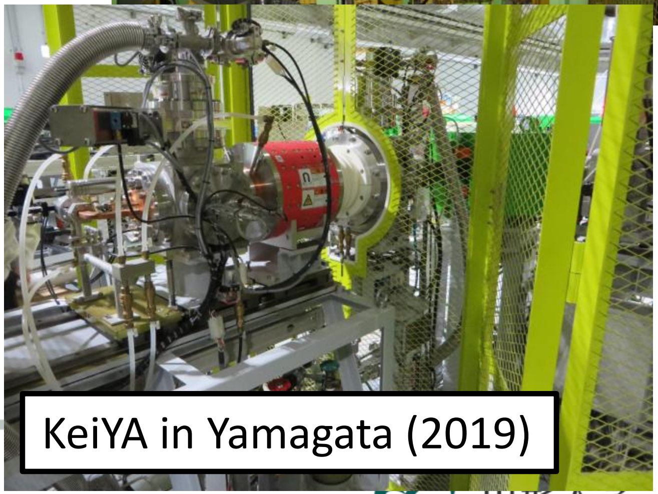


Improvement of ECR Ion Source

- Kei2 Series are gradually improved for stable operation
  - Problem: carbon deposit to ext. electrode → Increase of discharge
- Reduce gas conductance through holes of anode electrode
- Shrink diameter of extraction electrode: 29 mm→25 mm
- Helium Support gas to reduce CH_4 gas
- Low current operation (enabled by efficiency improvement in synchrotron)
- Improvement of maintenance interval
  - Gunma: 6 month(2013-), 1 year(2019-)
  - Yamagata: 2 year(2021-)

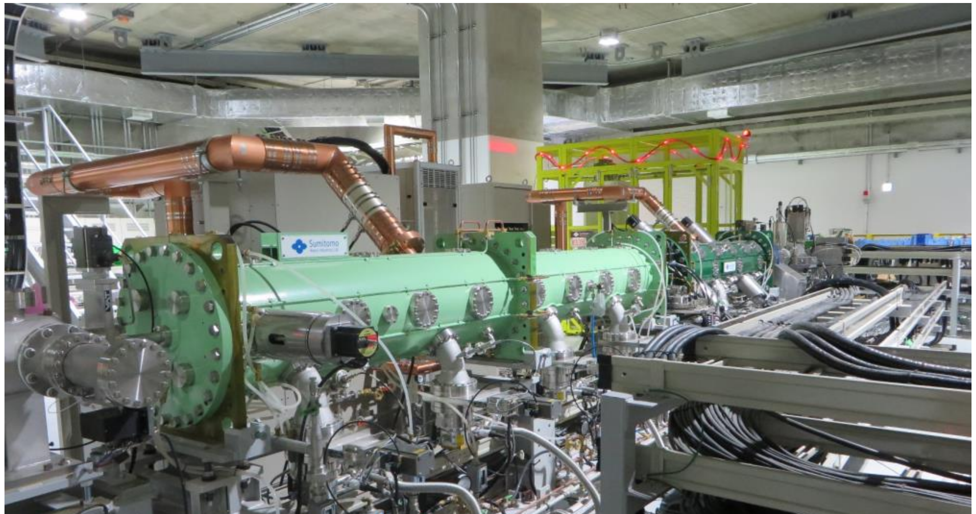

Kei2 in QST (2006)

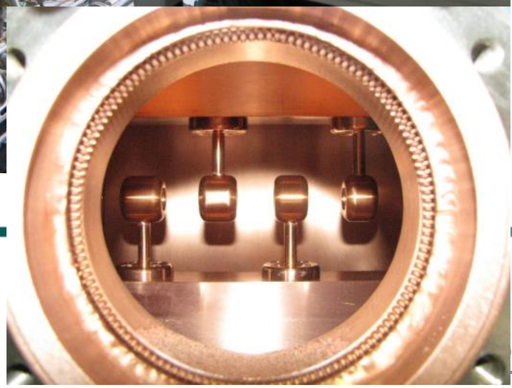

KeiGM in Gunma(2009)


KeiYA in Yamagata (2019)

Injector Linac

- Compact Injector placed inside the synchrotron
- APF(Alternate Phase Focusing) IH-DTL
- Electropolished surface (RFQ Discharge reduced) New!
- Charge stripper carbon foil after IH-DTL: $C^{4+} \rightarrow C^{6+}$





	RFQ	IH-DTL
RF Frequency	200 MHz	200 MHz
RF Power	150 kW All Solid State	500 kW Solid State + Tetrode
Inj. Energy	10 keV/u	600 keV/u
Ext. Energy	600 keV/u	4 MeV/u
Inner Diameter	~35 cm	～ 35 cm
Tank Length	2.5 m	3.5 m
Max. Surface field	23.6 MV/m (x1.6 Kilpatrick)	23.6 MV/m （x1.6 Kilpatrick）

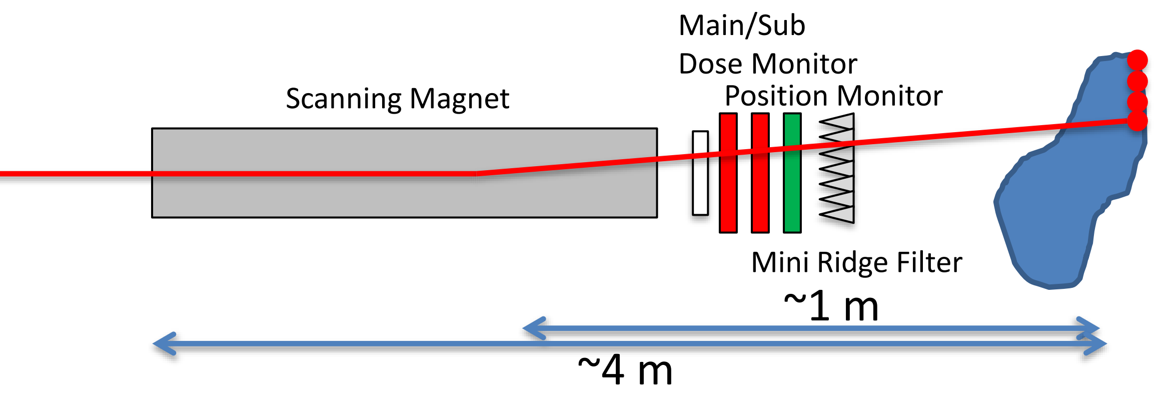
Synchrotron

- Synchrotron with slow extraction system
- 600 extraction energy New!
- Reduce bending magnet gap length → Energy saving operation New!

Ion	C^{6+}
Inj. Energy	4 MeV/u
Ext. Energy	55.6 - 430 MeV/u (600 step)
Circumference	63.3 m
Ope. Cycle	< 6 s, Extended flattop > 30 s
Beam current	3×10^9 ppp
Ext. Intensity	$3 \times 10^7 \sim 1 \times 10^9$ pps

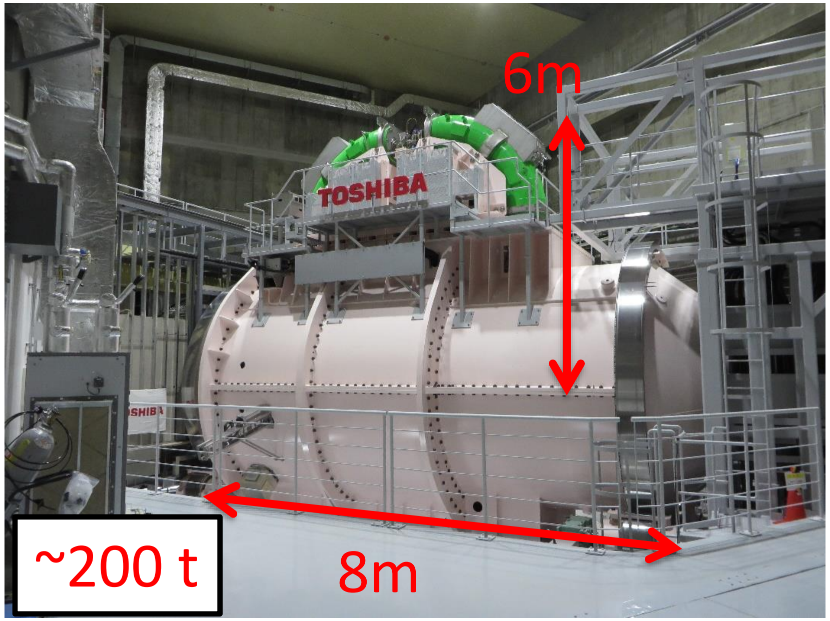
Irradiation System

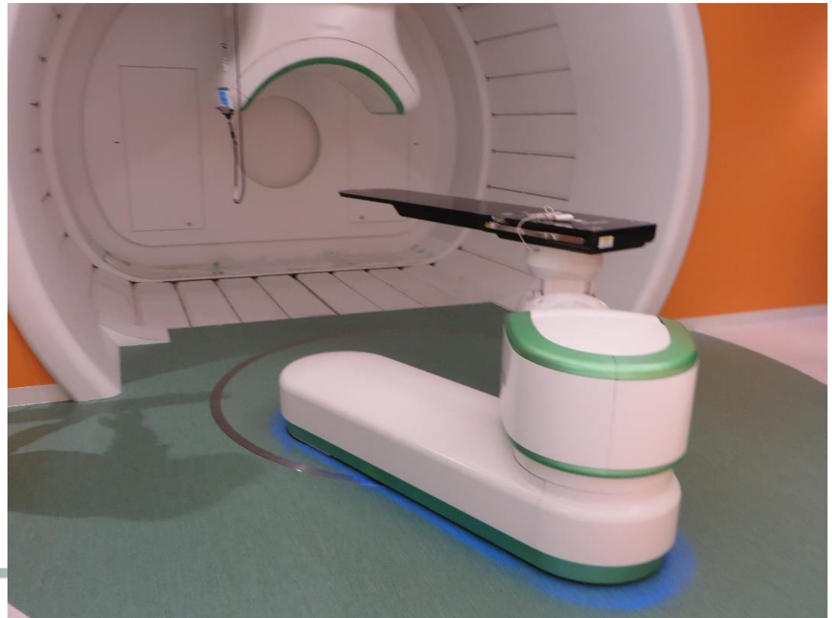
- Scanning Irradiation System
  - Scan pencil beam (2-3 mm in 1σ) to paint 200 x 200 mm
  - Range control by synchrotron energy (~300 mm, 0.5 mm step) without any range shifter (plastic block)
  - Irradiated dose measured by Dose Monitor (ionization chamber)
  - Monitor beam position and size in Position Monitor (MWPC)



Rotating Gantry

- World smallest carbon ion gantry using superconducting magnets
- 6 Combined function magnets
  (6 BMs + 12 QMs) ~3.5 T
- 3 GM cryocooler for 1 BM
- Flexible beam angle
  - With conventional fixed beam port, patient must be tilted to use multiple beam angle
  - With gantry, patient can lie down comfortably with no tilting





Commissioning of East Japan Heavy Ion Center

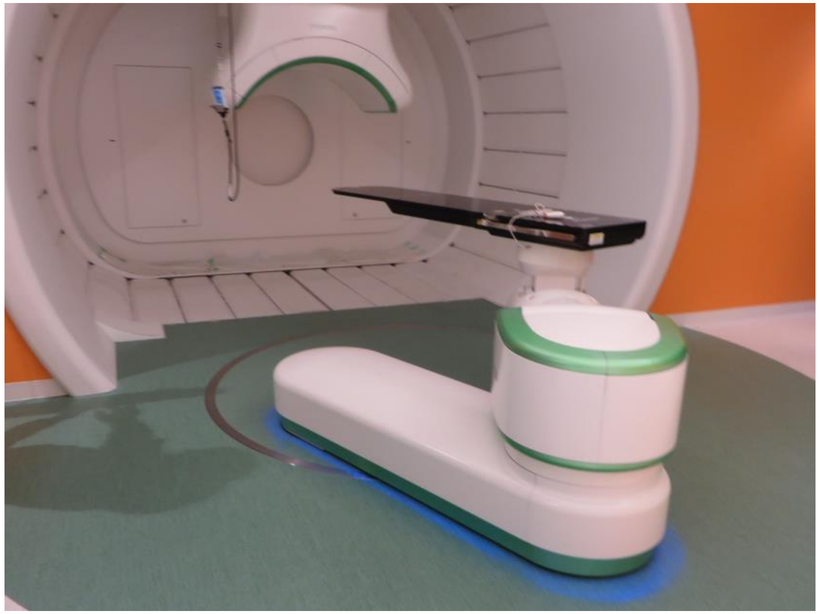
Commissioning Strategy

Fixed Horizontal Irradiation Room

Beam angle: 90 or 270 deg
Only for Prostate Cancer

Irradiation target is limited,
but easy to commission

Rotating Gantry Irradiation Room

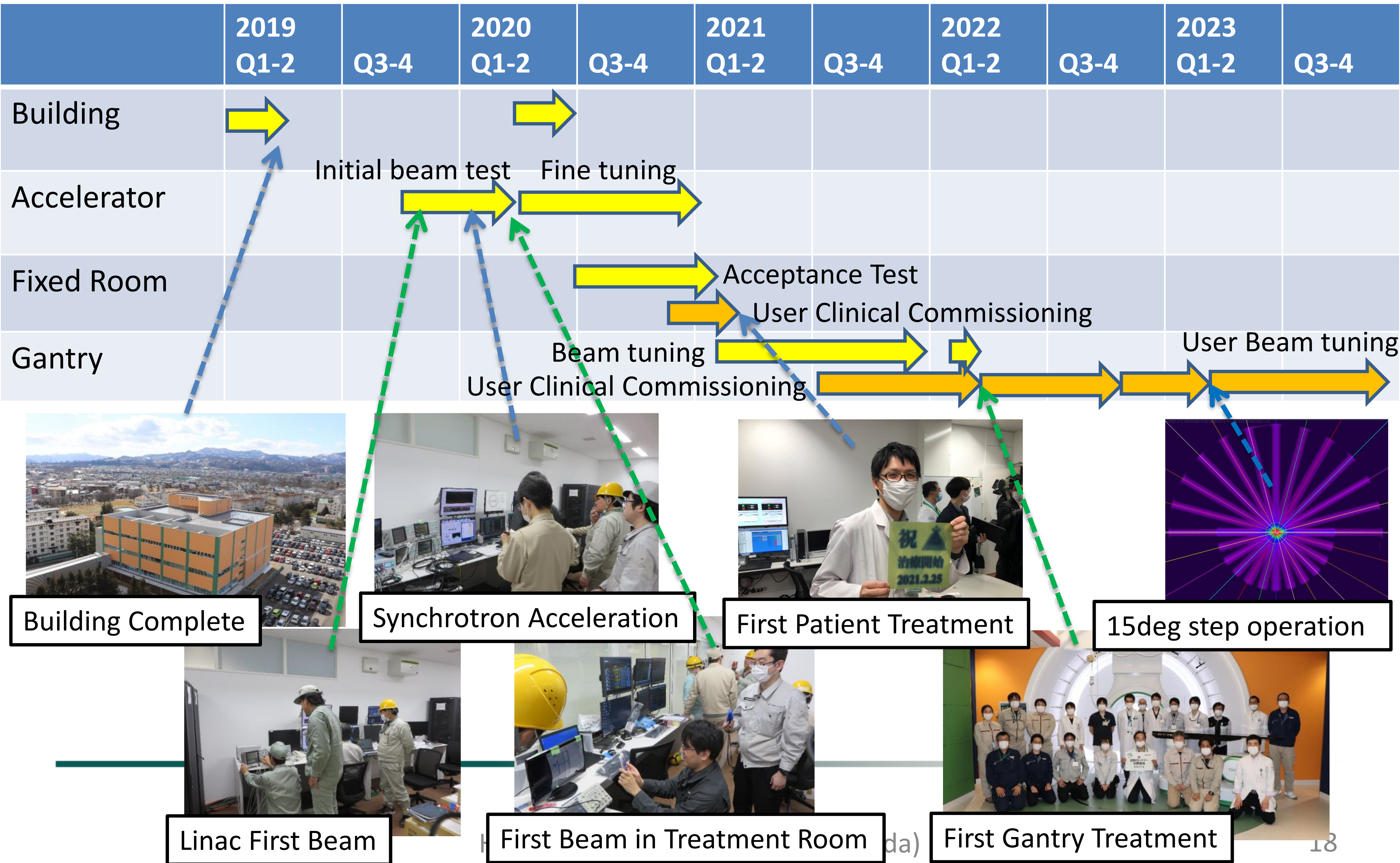


Beam angle: 0-359 deg (1deg step)
All sites (Head & Neck, Lung, Liver, Pancreas, Rectum, Bone & soft tissue)

No limitation of target,
but difficult to commission

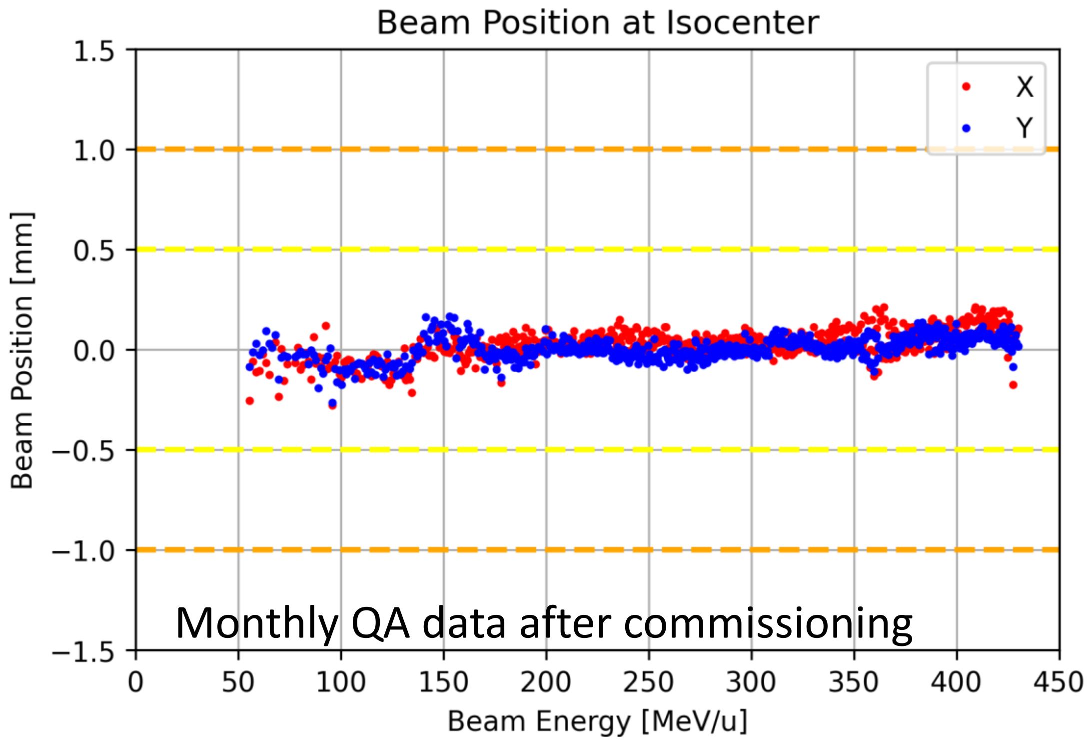
Commission fixed port first, gantry next

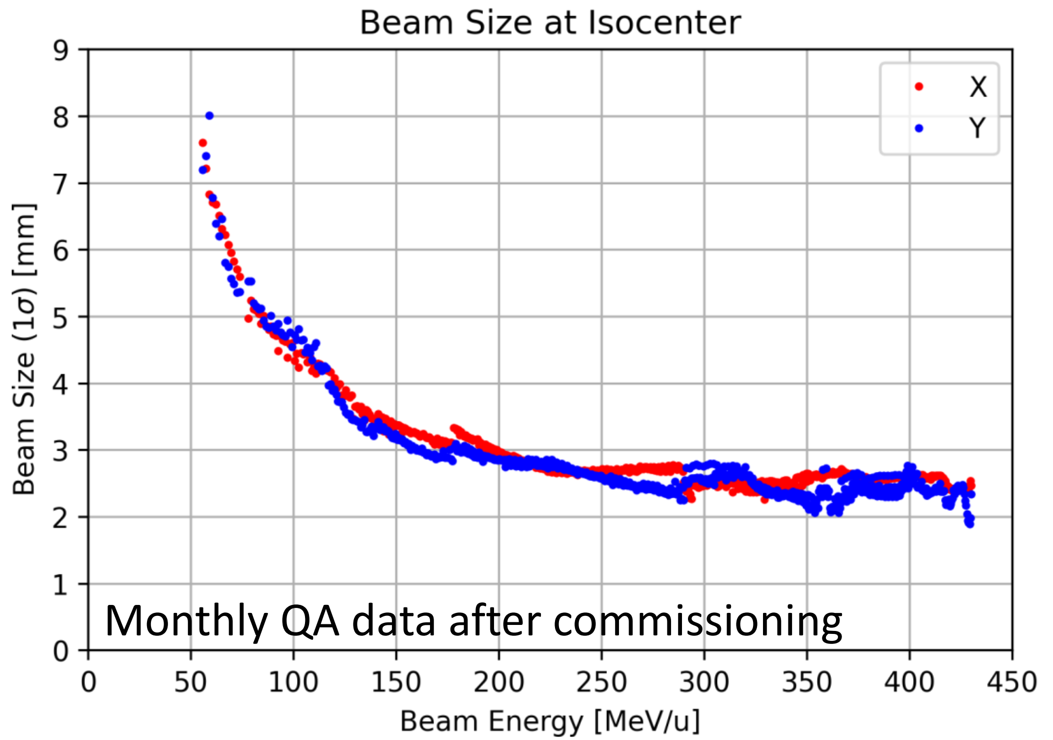
Commissioning History



Beam position and size

- Beam position and beam size were measured at the isocenter (3-dimensional irradiation center)
- Beam size was optimized within ±20% to calculation
- Beam position was corrected within ±0.5 mm





Check basic beam parameter for 600 energies

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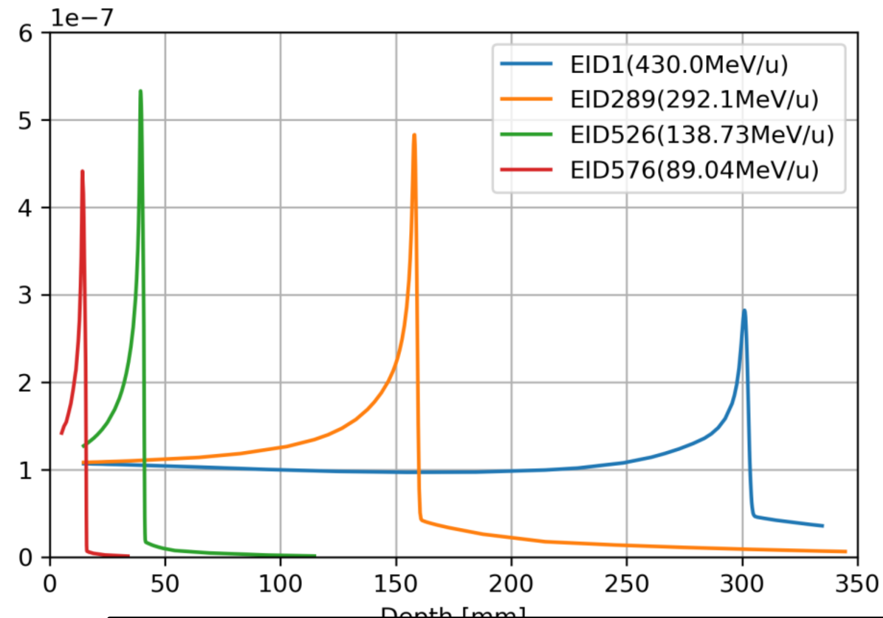
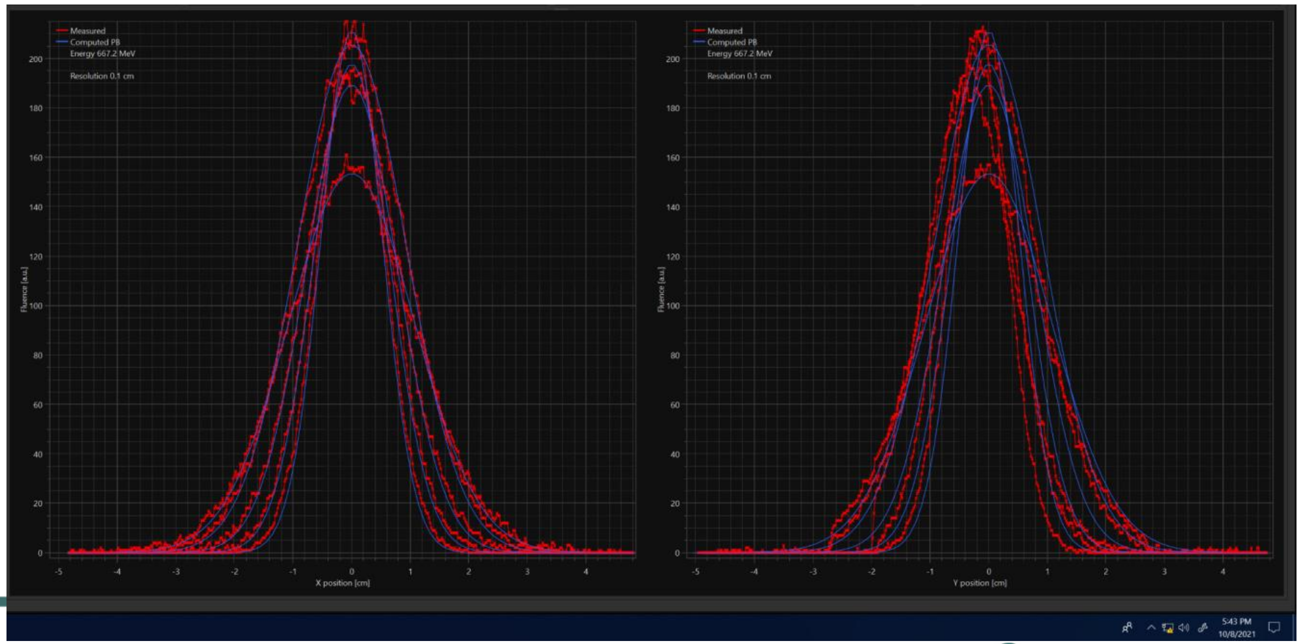
Beam data measurement

- Treatment planning system calculates and optimizes dose distribution based on pencil beam model
- To determine modeling parameter, longitudinal and lateral beam profiles of representing beam energy was precisely measured

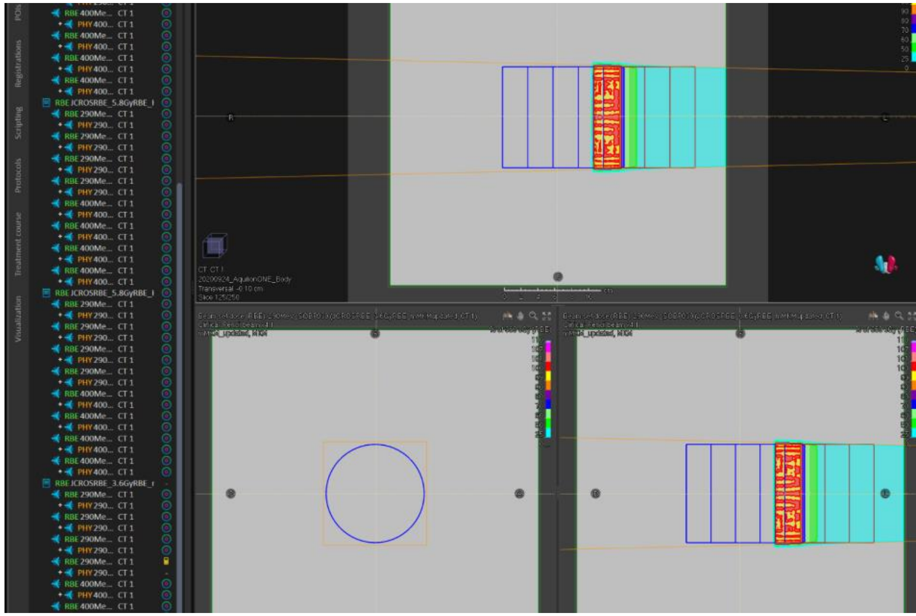


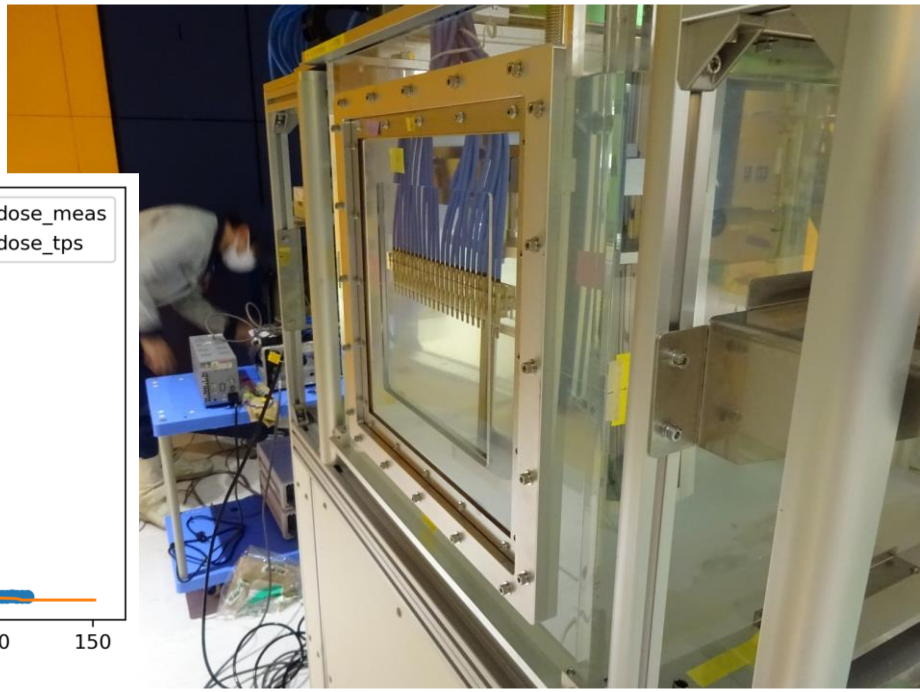


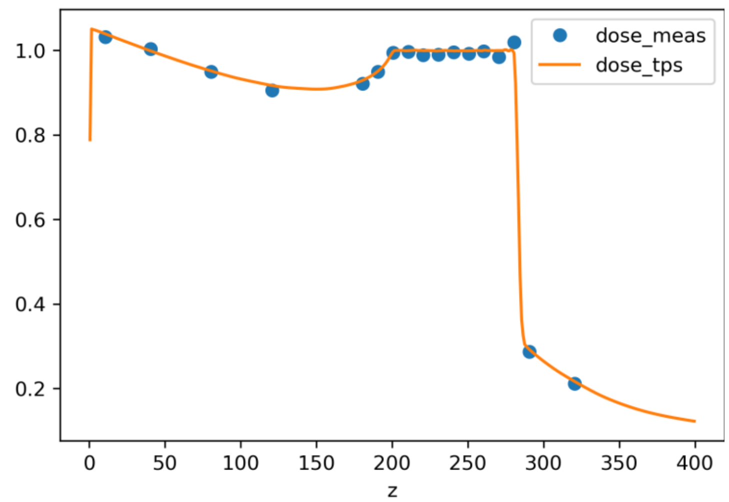
Precise beam data is required for dose calculation in human body

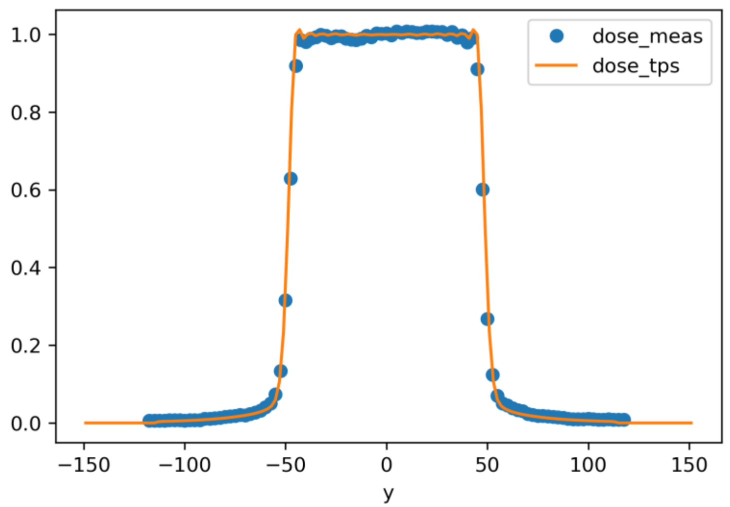
Validation of the beam modeling

- Dose distributions in water were measured in various depth and field size
- Compared with that calculated by the treatment planning system
- Results were acceptable
  - Dose Difference < 3%
  - Field size error < 2 mm





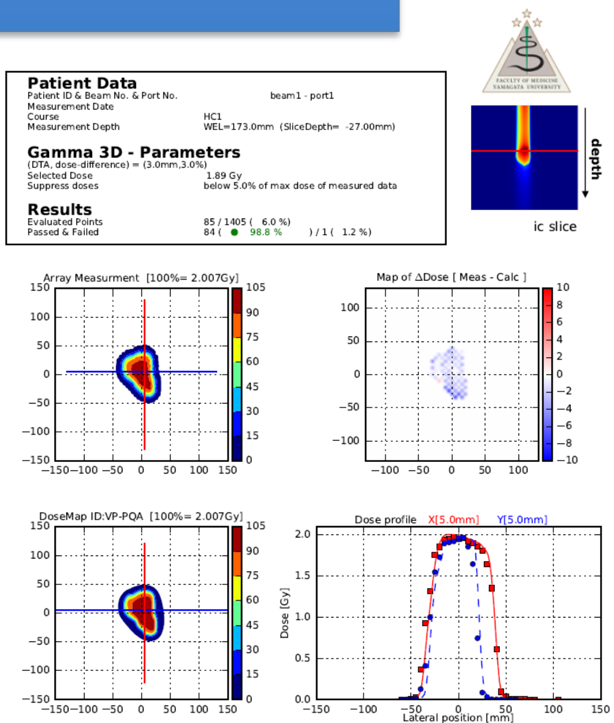


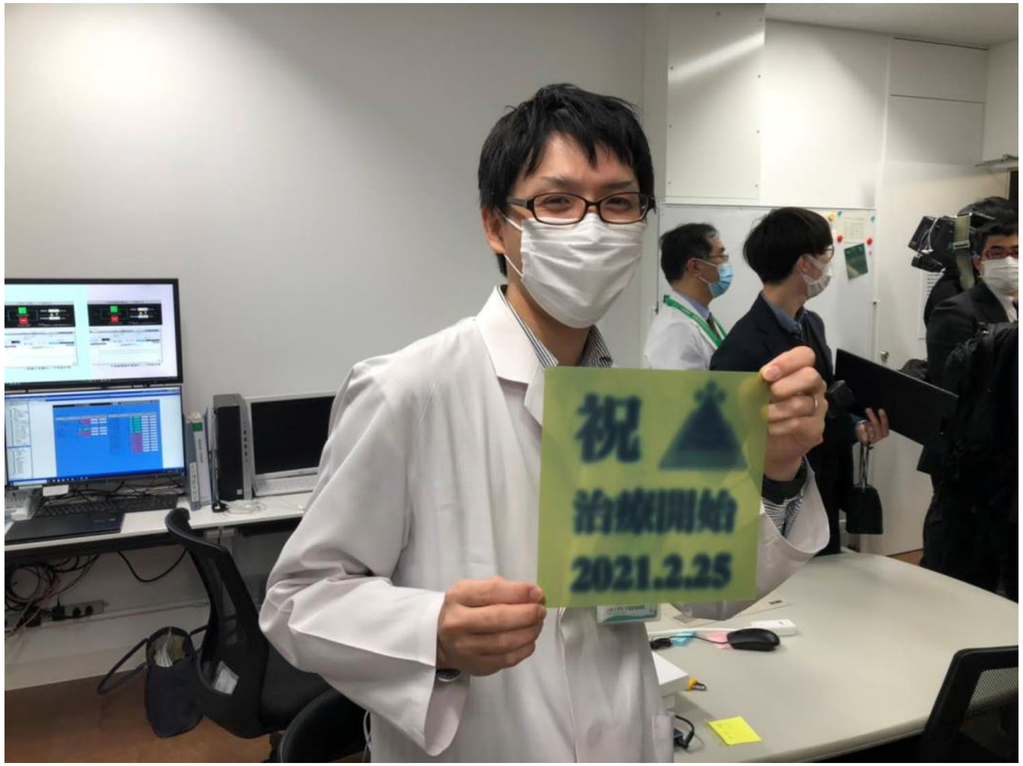


First Treatment

- Treatment planning → Patient QA measurement
- First Treatment for prostate cancer on 25 Feb 2021

Patient image
not for public



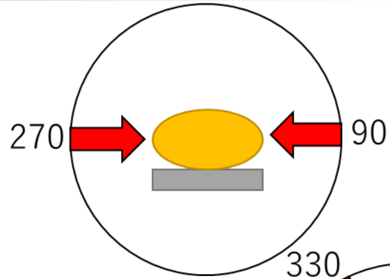


Long Way to Gantry...

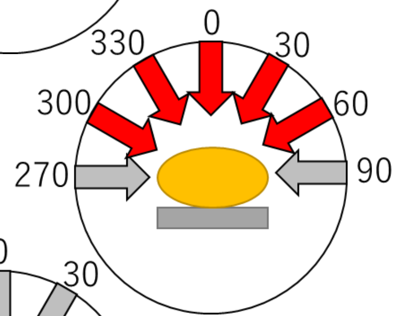
- Commissioning of Rotating Gantry took long time
  - Beam data must be compatible with fixed port
  - Many parameters for multiple beam angle
  - Difficult to control beam orbit in gantry
- Commissioning in parallel with treatment (9:00-17:00)
  - 10 month of beam tuning by manufacturer (21:00-7:00)
  - 9 month of user commissioning (17:00-21:00)
- Many improvements applied
  - User interface of accelerator control system for quick tuning
  - Implement ultrafast beam position feedback system
  - Interlock threshold optimization of beam size, beam intensity

Commissioning steps

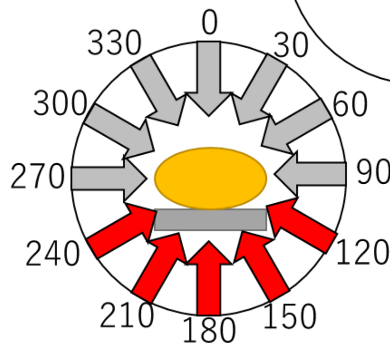
- 1st step: Prostate by 2 angles **Mar 2022**
  - Make initial experience



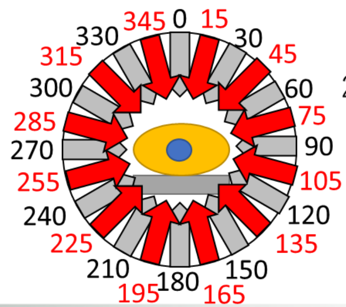
- 2nd step: Head and Neck by 7 angles **May 2022**
  - With tilting patients slightly

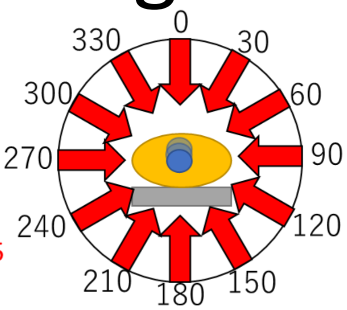


- 3rd step: Pelvis by 12 angles (30° step)
  - Beam passing through the couch **Jul 2022**



- 4th step: Lung, Liver, Pancreas by Respiratory Gating
  - All treatment site accepted **Sep 2022**
- 5th step: 24 angles (15° step) **Mar 2023**

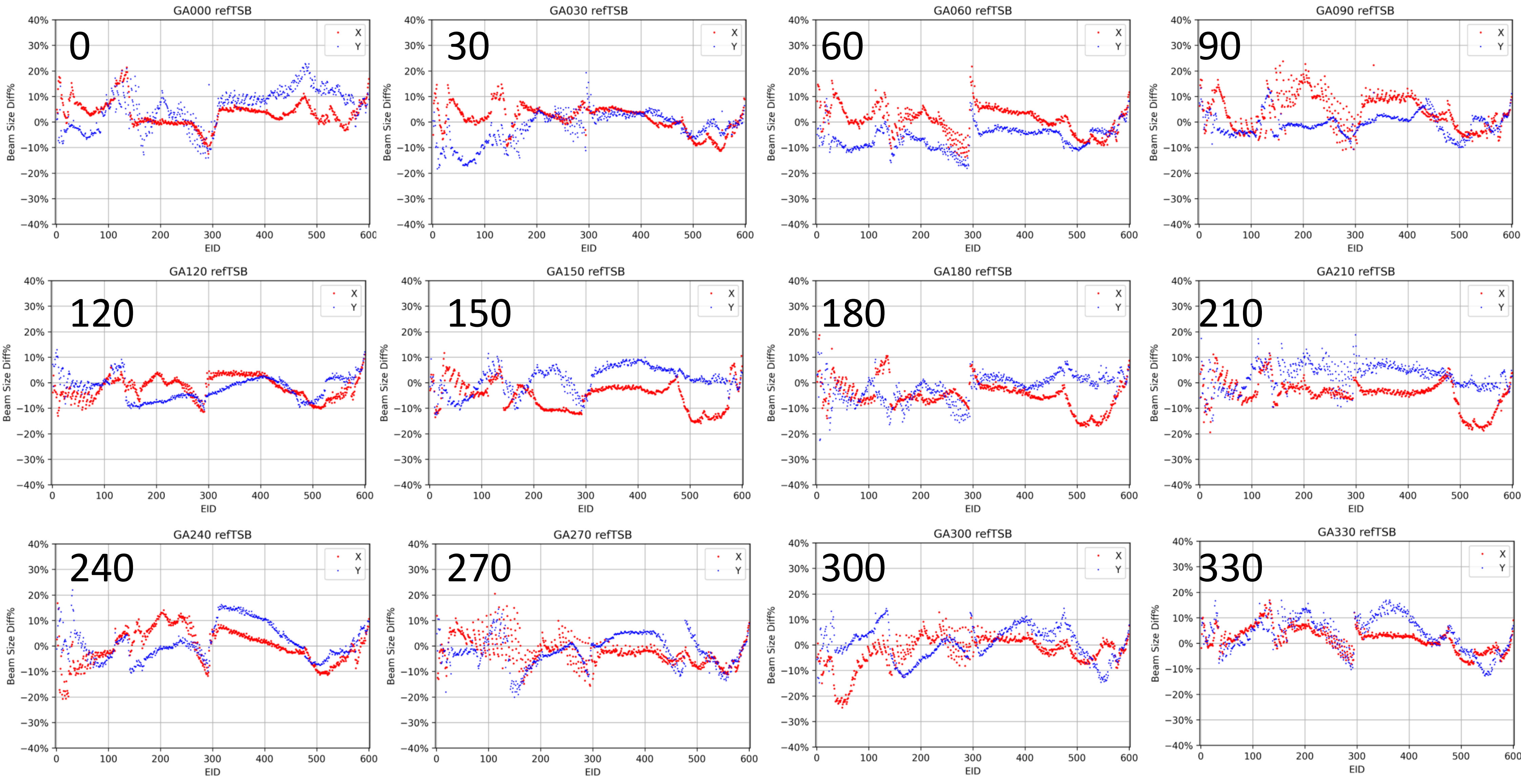




Start new treatment quickly, but safely

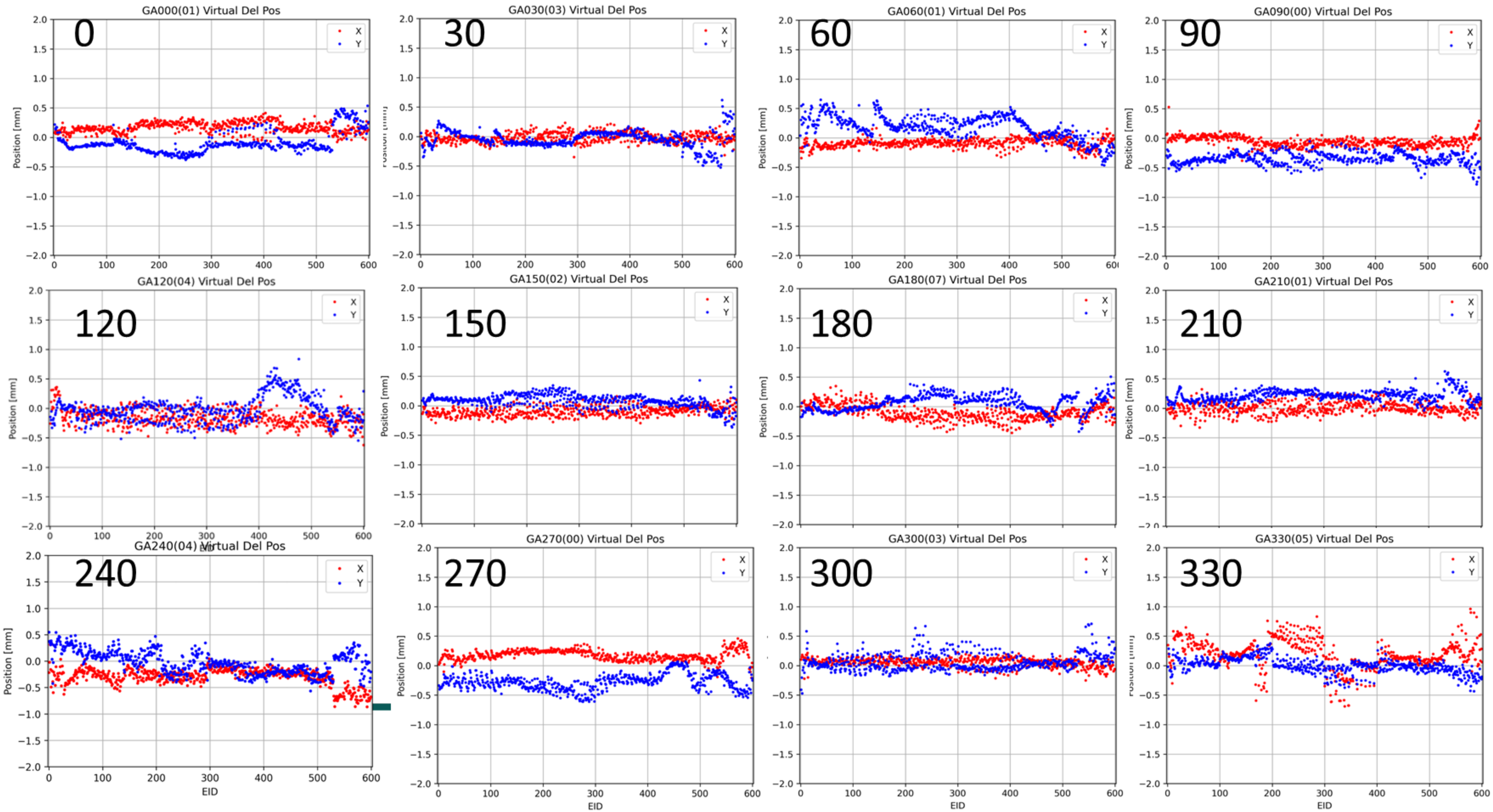
Beam Size

- Fine tuning of several superconducting quadrupoles by Toshiba
- Beam size deviation from the reference (fixed port) within ±20%



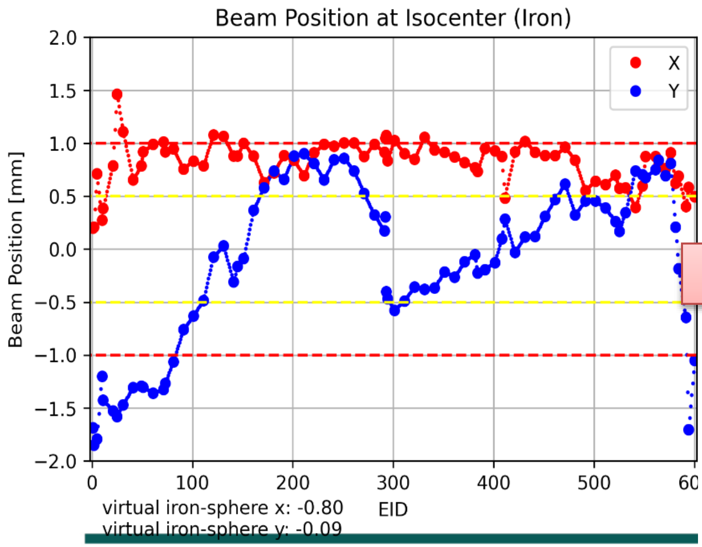
Beam Position

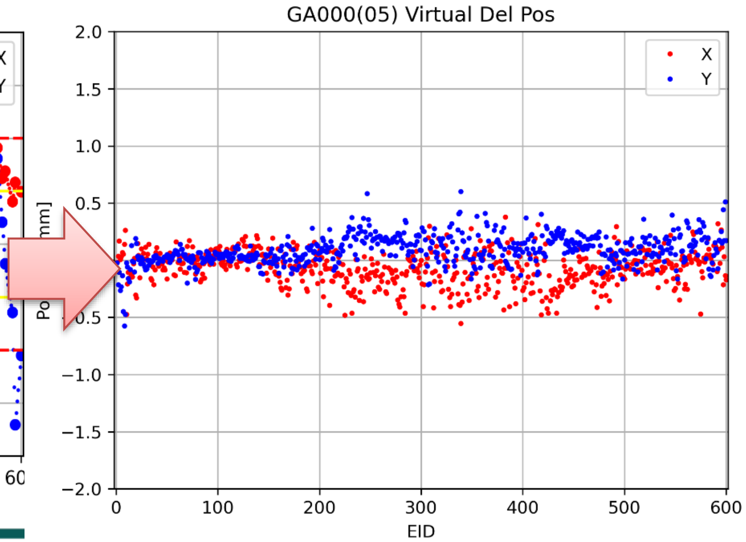
- Correct and keep the beam position for many angles by user
- Kept within ±1 mm by monthly QA measurement



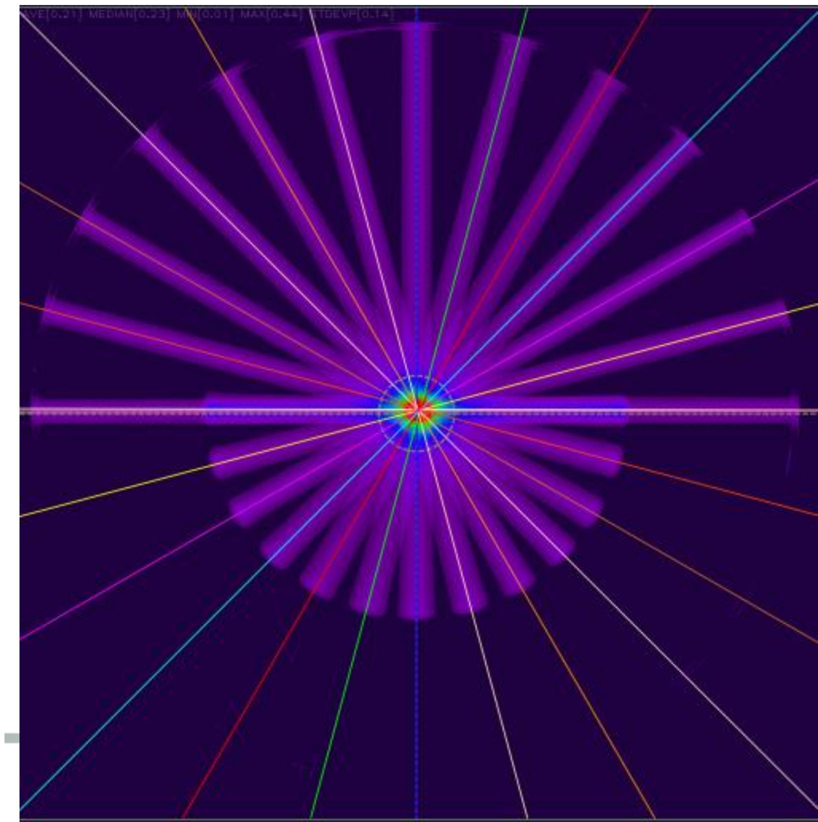
15-degree step commissioning

- With 15deg step, most patients does not need slight tilting
- Interpolation technique is necessary
- Automated energy-interpolated orbit correction tool (143 measurement → 600 energy) developed by user
- 1 angle optimized in 2-3 hour





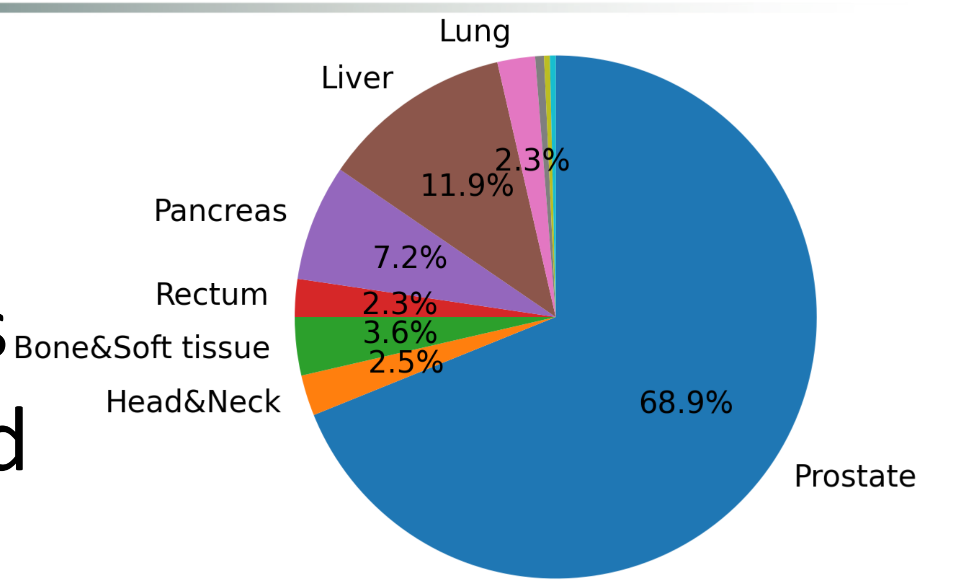
Starshot using cylindrical scintillator



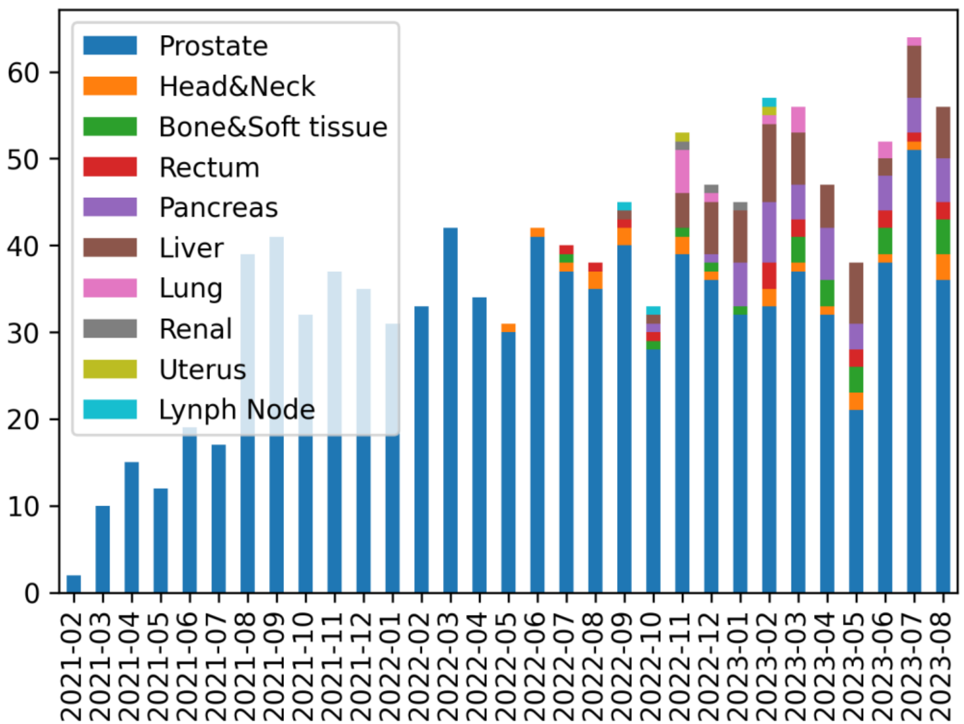
First Operation Experience

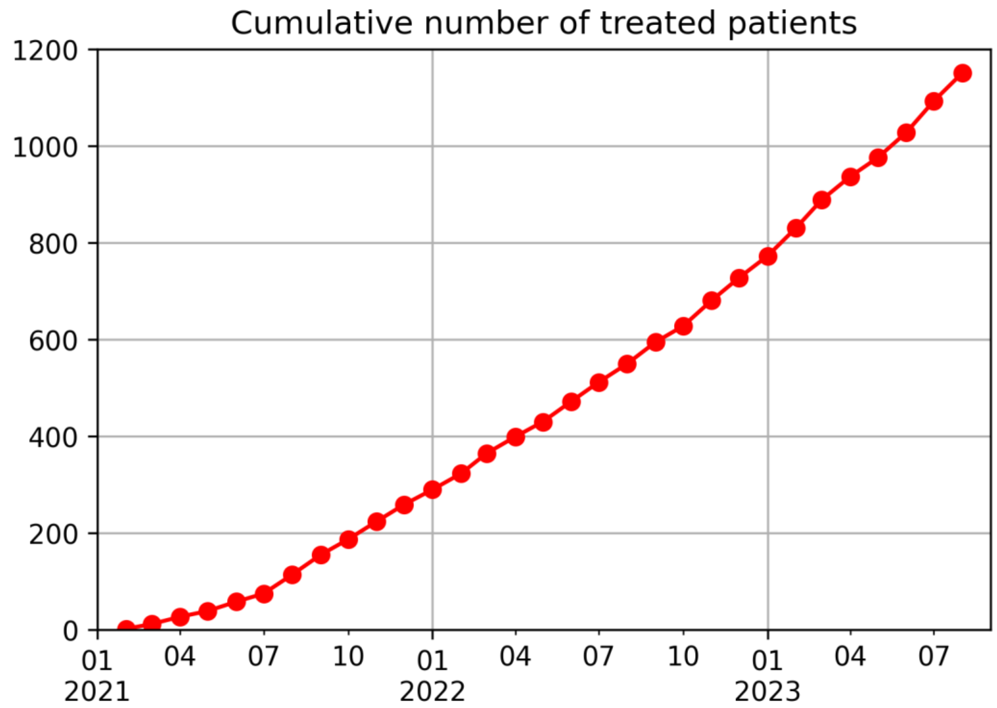
Treatment Statistics

- 1151 Patient were treated in EJHIC by Aug. 2023
- Many Prostate, Liver, Pancreas patients were treated (covered by national health insurance)



Percentage of treated site from Oct.2022 to Aug.2023





Operation Schedule

No Annual maintenance
(all weekend maintenance)

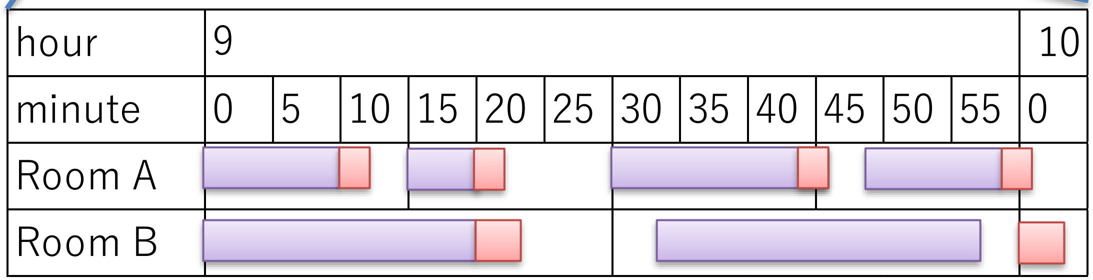
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

3 Medical Physicists (Yamagata U)
6 Operators (AEC)
3 Support Engineer (Toshiba)

On-duty Medical Physicist (1)
Operator Shift A (2)
Operator Shift B (2)

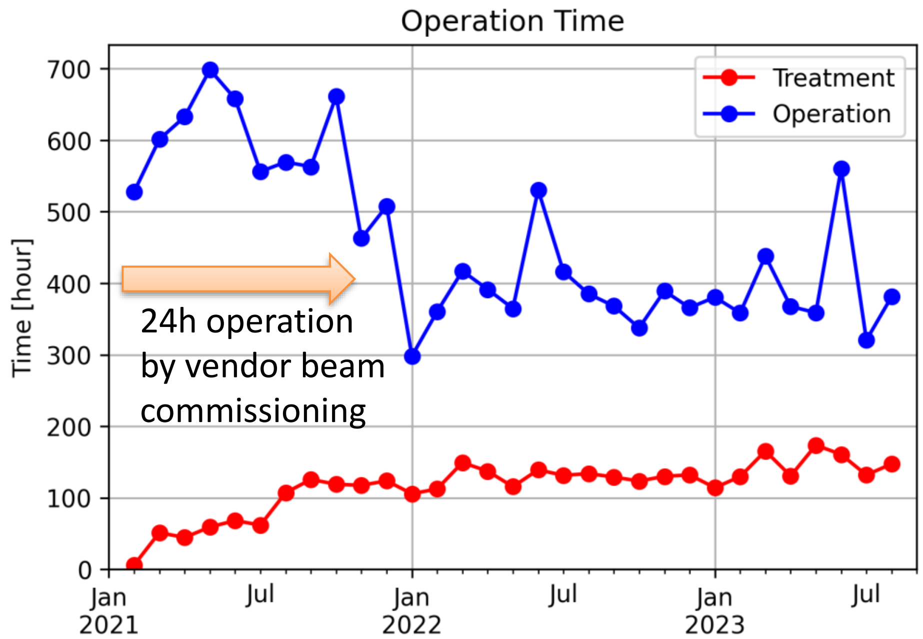
	0	7:00	7:30	9:00 – 12 13 – 15 – 18	18 – 22	22
Monday				Weekly QA	Beam Tuning	Shutdown
Tuesday		Startup	Machine QA	Treatment	Patient QA	Shutdown
Wednesday		Startup	Machine QA	Treatment	Machine QA	Shutdown
Thursday		Startup	Machine QA	Treatment	Machine QA	Shutdown
Friday		Startup	Machine QA	Treatment	Patient QA	Shutdown
Saturday				Maintenance		
Sunday				Maintenance		

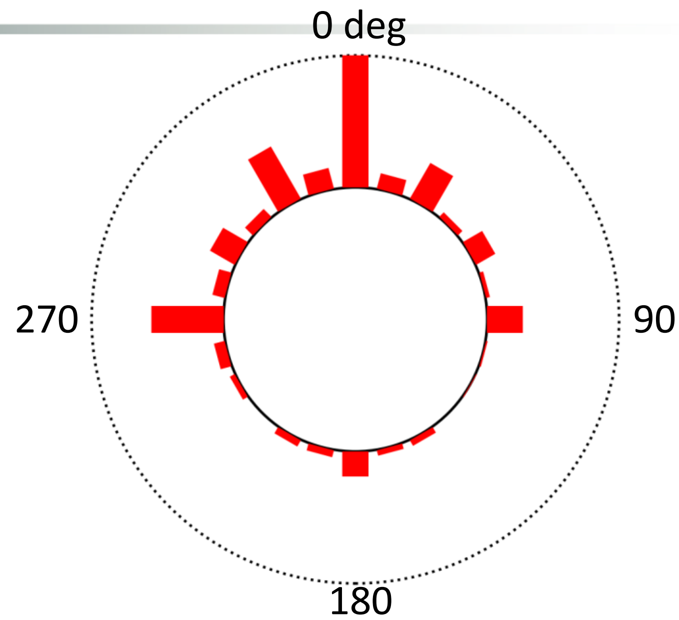
15 ~ 30 min /patient
40-50 irradiations/day
4-12 irradiations/patient



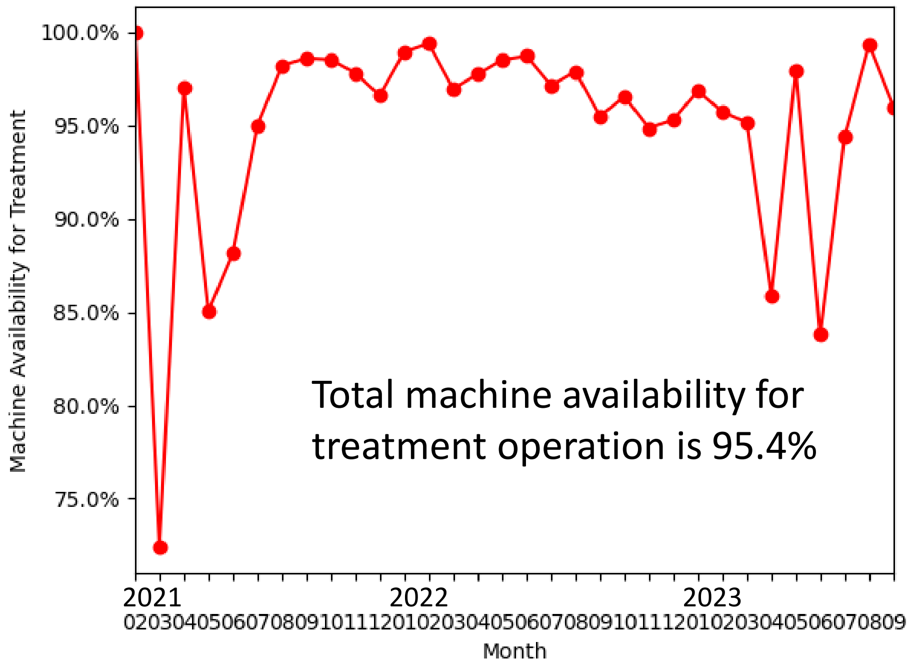
Treatment-dedecated operation style

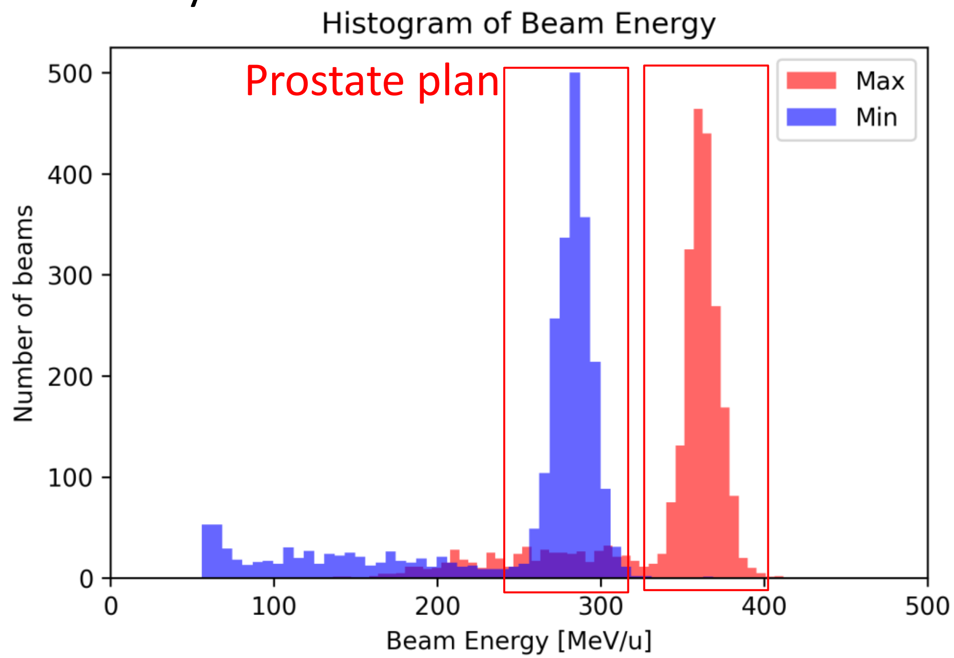
Operation statistics





Gantry angle statistics of treatment beams (except prostate)
May 2022 – Jul 2023

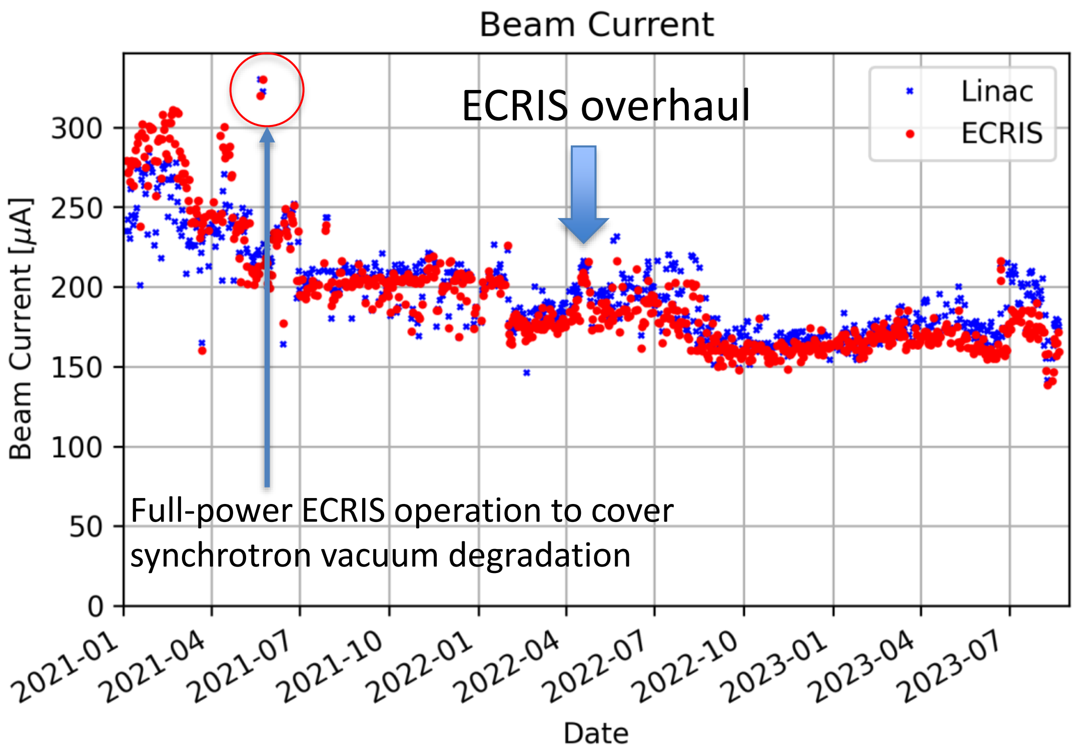


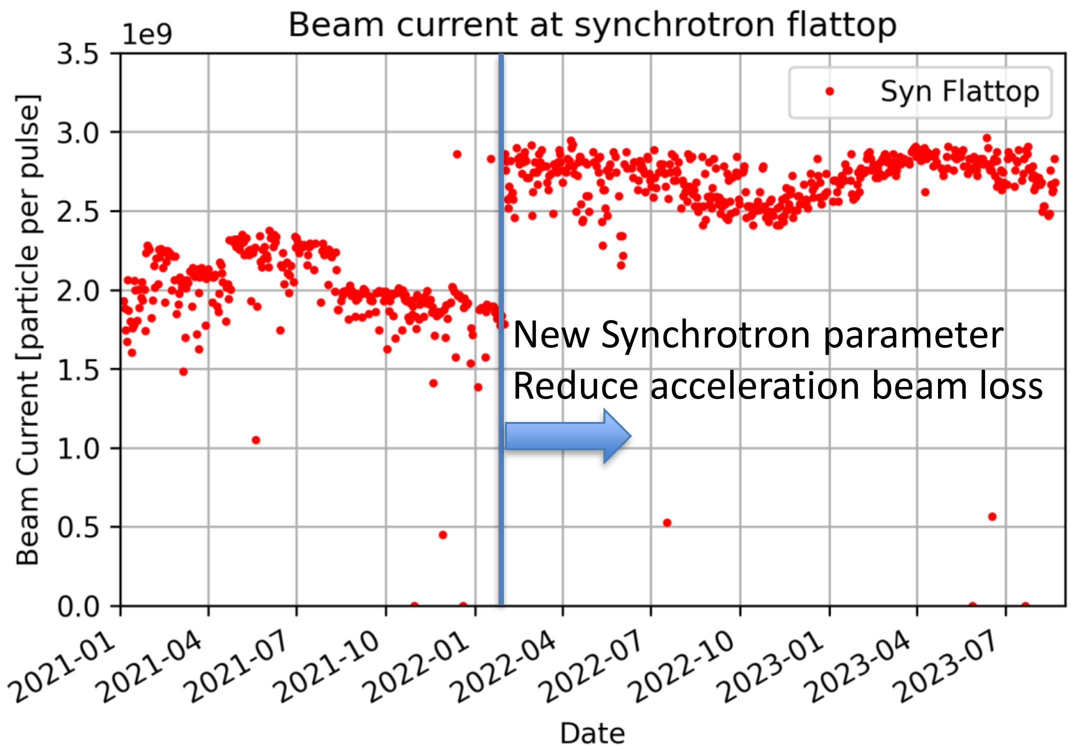


Victor

Beam Current

- Beam current of Ion source has been kept stably
- Fine tuning of RF power and gas flow at daily startup on demand
- After efficiency improvement of synchrotron, ECRIS output of 170 µA is a optimal to keep the operation beam current in synchrotron

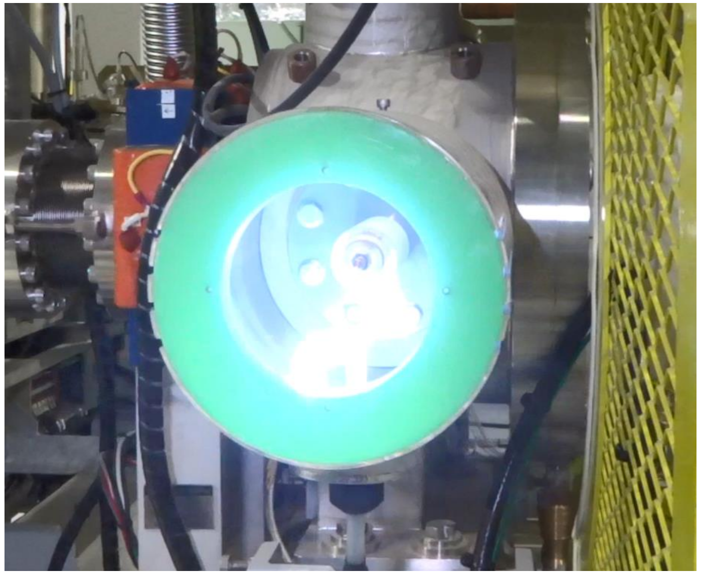


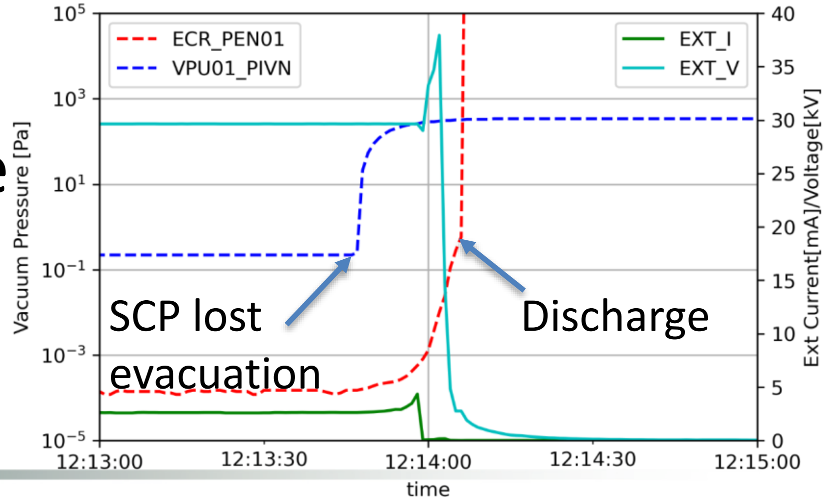


Tuning of accelerator is also important for stable operation of ECRIS

Troubles of ion source (1)

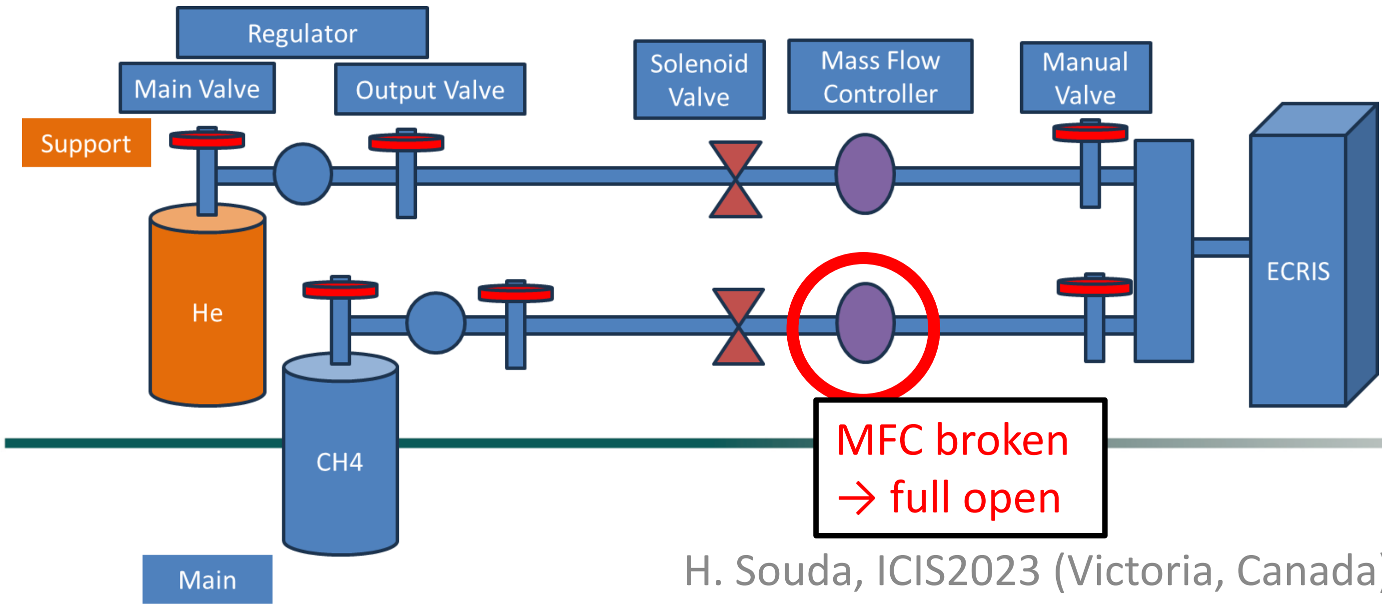
- 11 Jun 2021: Einzel Lens power supply overvoltage (7.5 h downtime)
  - Lost PWM feedback signal and increase output voltage infinitely
  - caused discharge in the air
- 19 Oct 2022: Vacuum loss by scroll pump breakdown caused by aged chip-seal (40 min downtime)
  - At first assumed a accidental discharge
  - Maintenance period of scroll pump (~3y) was modified





Troubles of ion source (2)

- 20 Jun 2023: Mass flow controller failure of CH_4 gas pipe caused continuous discharge (2 days treatment stop)
  - In the recovery work to change gas line of main gas (CH4) and support gas (He), I made serious mistake
  - When evacuating gas pipes after changing gas bottle, forgot to close CH_4 main valve, resulted in total loss of CH_4 gas
  - Time loss of 6 hour to find available CH_4 gas
  - For treatment machine, back-to-basics stance and well-checked manual are important even for skilled physicist or operator to prevent critical failure…



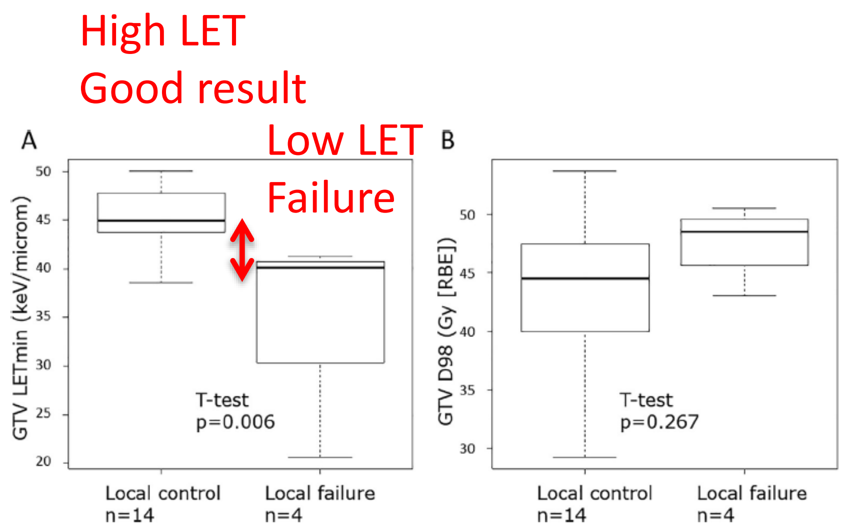
Future development

Future Development in Yamagata

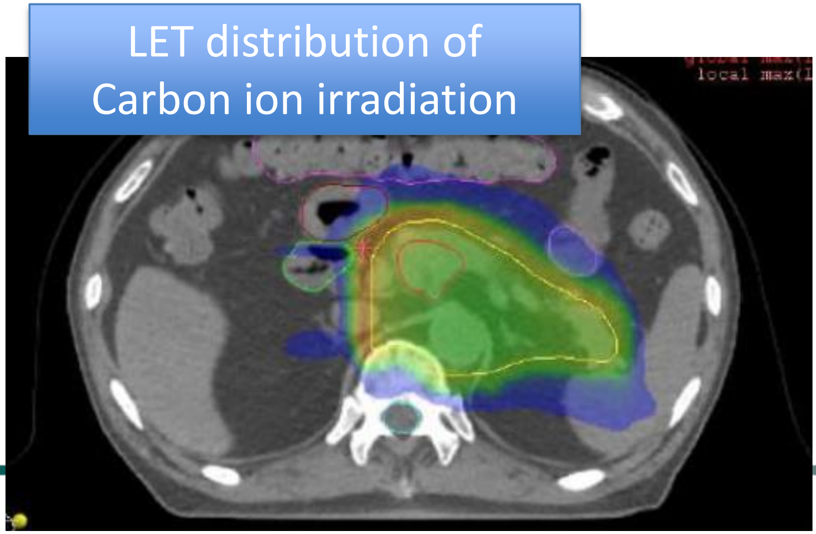
- 5 degree-step operation of gantry
  - It is easy to once optimize parameter, but is difficult to keep beam position for 72 angles within ±1 mm…
  - Reduce parameter difference between gantry angles
  - Orbit correction with angle interpolation test was successful
- Adaptive therapy using in-room CT
  - Carbon Ion Irradiation has sharp dose distribution, is vulnerable to positioning error or internal organ movement
  - Before irradiation, use in-room CT to see target tumor position and change the treatment plan immediately
- Improve machine to increase irradiation precision, patient comfort … to provide higher-quality medical care

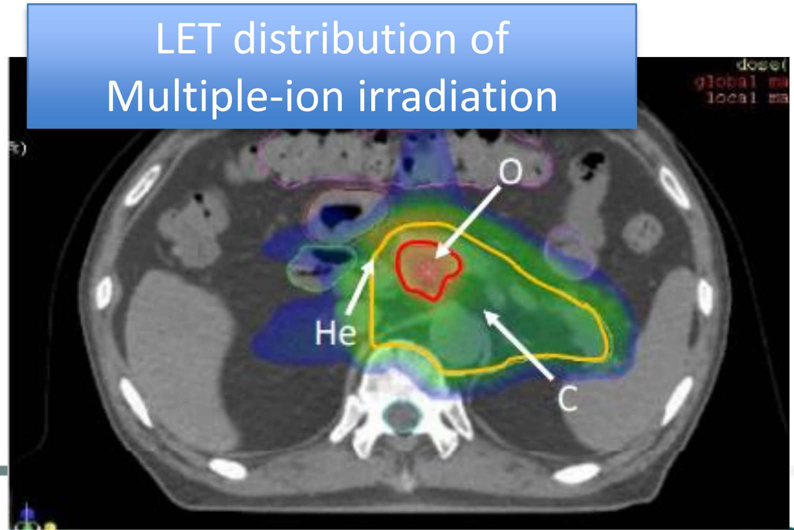
Development of LET control

- Good clinical outcome of carbon ion therapy result from high LET
- But in usual way, highest LET is not concentrated to cancer …
- Using multiple ions, uniform dose and high LET on target is achieved
- Multiple-ion irradiation has been started in HIMAC, QST



Y. Hagiwara *et al.*, Clin Transl Radiat Oncol. **21**: 19–24 (2020).





https://www.qst.go.jp/site/press/20220524.html

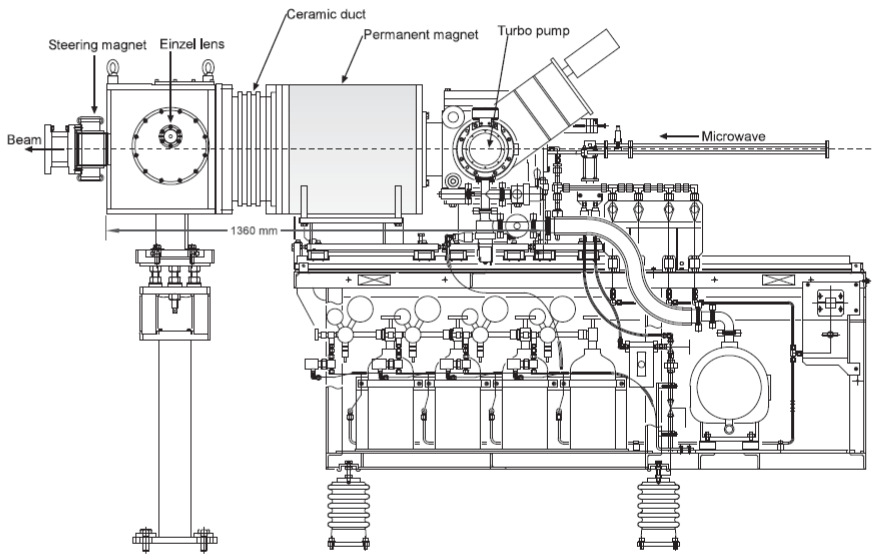
Development of ECRIS for Multi-ion

- To realize multi-ion irradiation in compact facilities, multiple ions by single ion source is required
- 14 GHz ECRIS w/ permanent magnet (field optimized by measurement using NIRS-HEC) was developed in QST

M. Muramatsu et al, J. Phys.: Conf. Ser. 2244 012094 (2022)

- Gas pulse operation to switch ion species of $^{4}He^{2+}$, $^{12}C^{4+}$, $^{16}O^{6+}$, $^{20}Ne^{7+}$
- Will be installed to next-generation treatment accelerator of superconducting synchrotron in QST

Y. Iwata et al., Nucl. Inst. Meth., A1053, 168312 (2023)



Summary

- East Japan Heavy Ion Center, Faculty of Medicine, Yamagata University is a new standard model of carbon ion therapy facility with full-energy scanning system and superconducting rotating gantry.
- Many improvement was applied for 10 GHz ECR ion source for stable operation. Maintenance interval of 2 year was achieved.
- Commissioning for clinical irradiation needs many measurement of beam parameters and dose distribution. For gantry, available beam angle gradually increased to start new treatment safely.
- 1151 patients were treated in 2.5 years.
- Adaptive therapy and LET control by multi-ion irradiation will be next key technologies of heavy ion therapy to further improve clinical results.

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- Toshiba Energy Systems & Solutions Co.
- Accelerator Engineering Company
- B-dot Medical Inc.

Thank you for listening!

08 March 2022: 1st Treatment at Gantry room