清華大學 Tsinghua University

Ultra-high dose rate X-ray radiator for studying flash radiotherapy

Hao Zha

Asian Forum for Accelerators and Detectors 2023

Outline

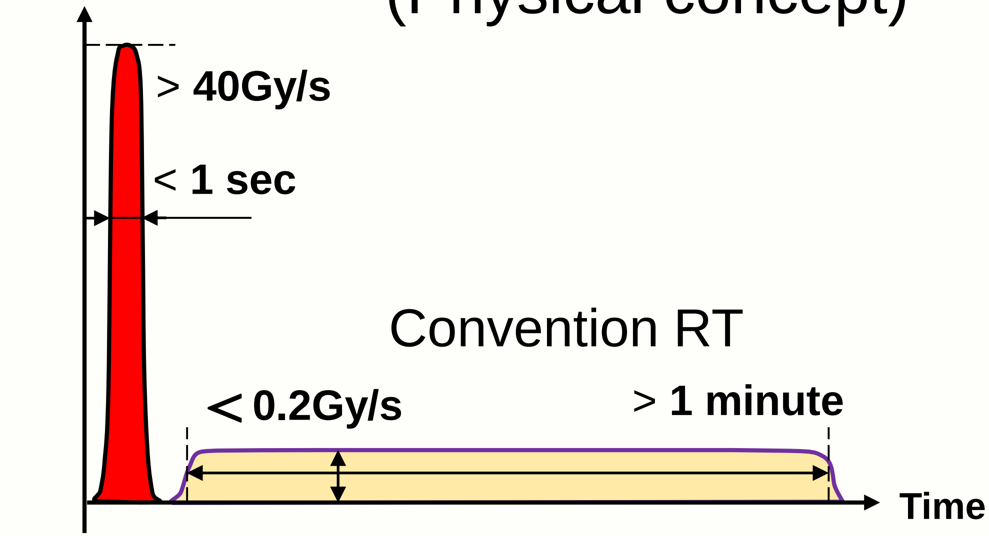
- **Introduction of Flash-RT**
- Why we choose X-ray?
- Our developments
- Future plan

Introduction of Flash-RT

- Flash effect is now a very hot topic of radiotherapy
- Research were mostly done in the cell/animal level
- Potential of clinical benefit is significant

Ultra high dose rate → FLASH effect

(Physical concept) (Biological concept)



- ✓ Spare normal tissue
- ✓ Maintain same tumour control vs convention-RT

Toward clinical translation

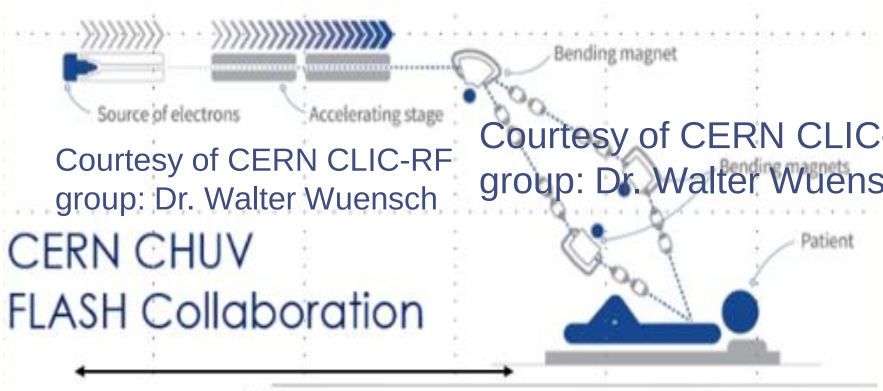
- Main challenge: lack of suitable accelerator/radiator

Particle/ Current radiator	Ultra high dose rate	Penetration depth	Quick energy modulation
Proton/ Cyclotron	**Available**	**Available**	**Not Available**
Carbon/ Synchrotron	**Not Available**	**Available**	**Not Available**
Electron/ LINAC	**Available**	**Not Available**	**No need**
X-ray/ LINAC	**Not Available**	**Available**	**No need**

Ongoing clinical trails

- Electron: superficial treatment only

Courtesy of CHUV research group



Courtesy of CERN CLIC-RF group: Dr. Walter Wuensch

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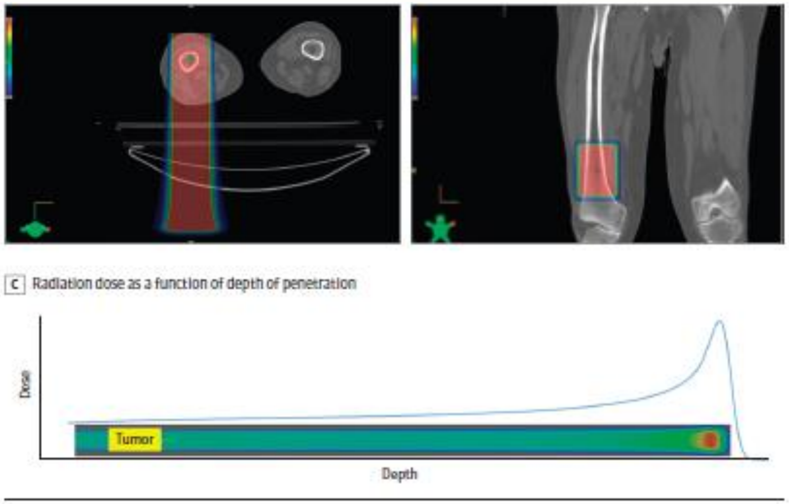
- Proton: shoot-through beam, losing the advantage of the Bragg peak

FAST01&02: Courtesy of University of Cincinnati Medical Center



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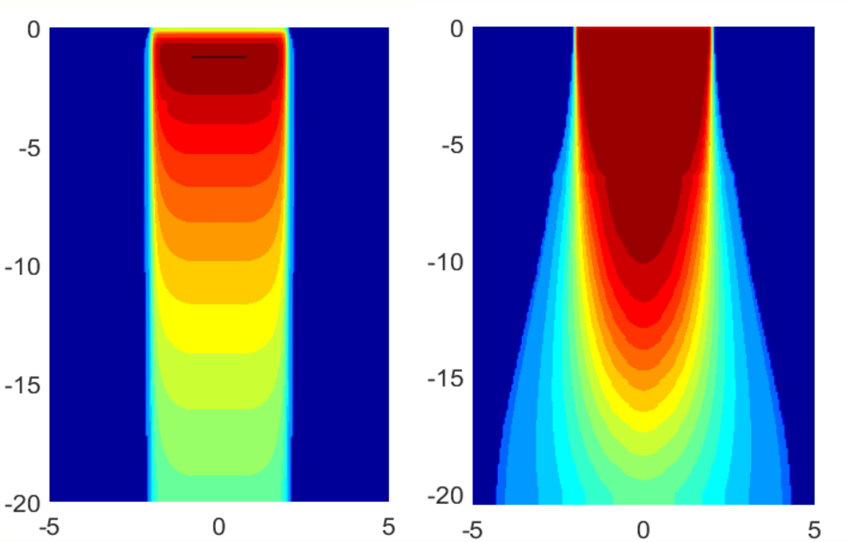
Advantages of X-ray

- Narrow penumbra (10%-90% : 6 mm)
- Large field and better conformal
- Easier dosimetry and shielding
- Possible of **a compact and economic solution**

6 MV X-ray 75 MeV electron

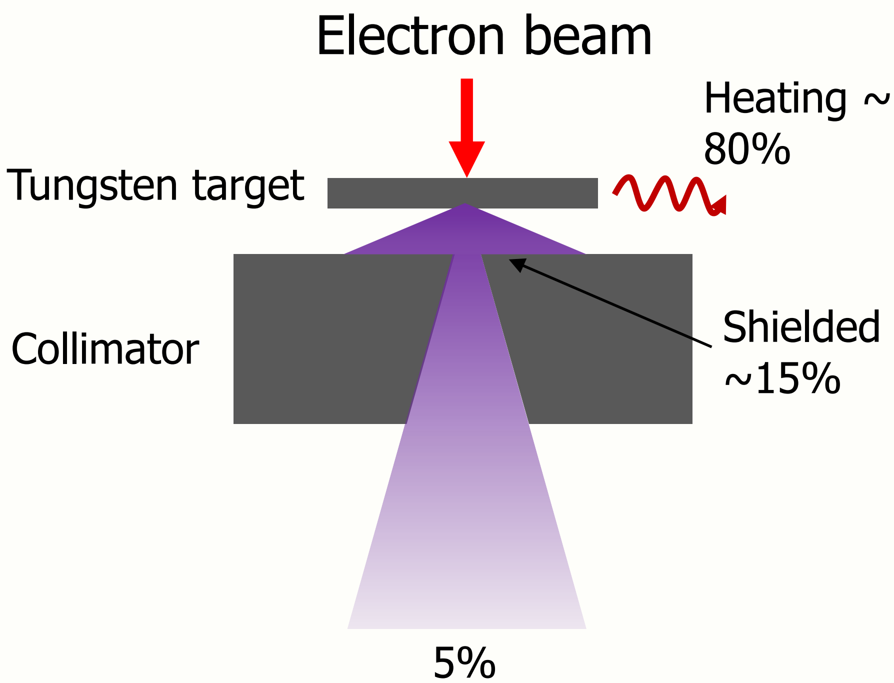


Particle	Energy need	Accelerator size
X-ray	6~10 MeV	< 1 m
Electron	> 100MeV	~ 10 m
Proton	230 MeV	> 3 m
Carbon	480 MeV/u	> 20 m

Dose rate issue

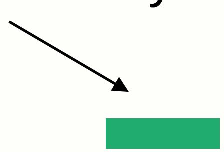
- Main challenges: very low dose rate

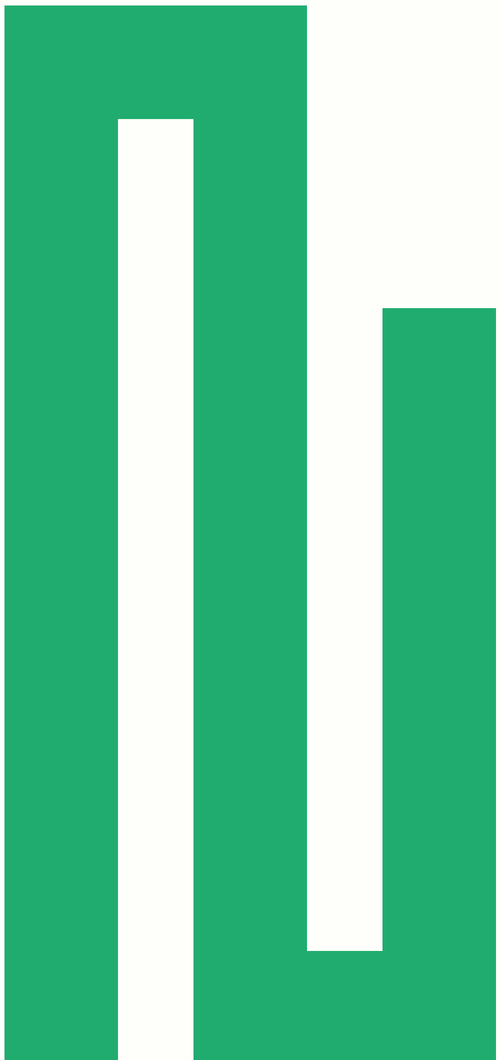
Criteria of triggering FLASH effect ≧ 40 Gy/s



Most of the current machines：

600～1200 cGy/min = 0.1～0.2 Gy/s



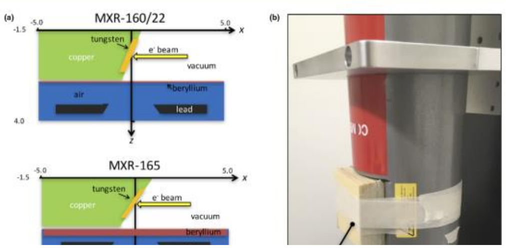


UHDR X-ray generation

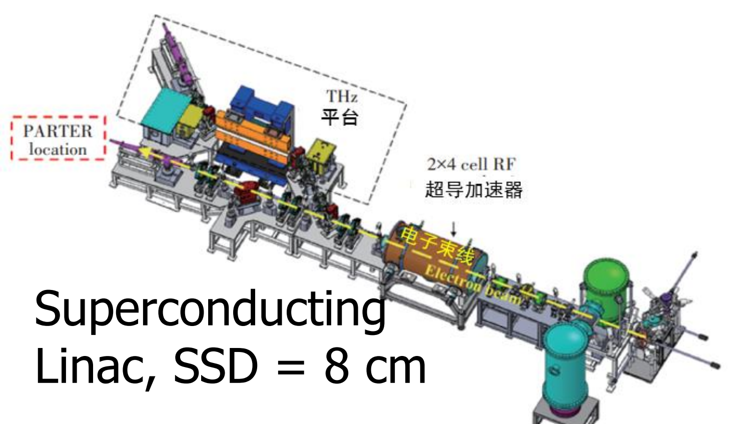
- UHDR X-ray for animal experiments is available
  - Very close to the source (dose rate ∝ SSD^{-2})
  - Single-angle radiation

SSD: source to surface distance
SAD: source to axis distance

- Clinical use needs large SAD and multiple-angle

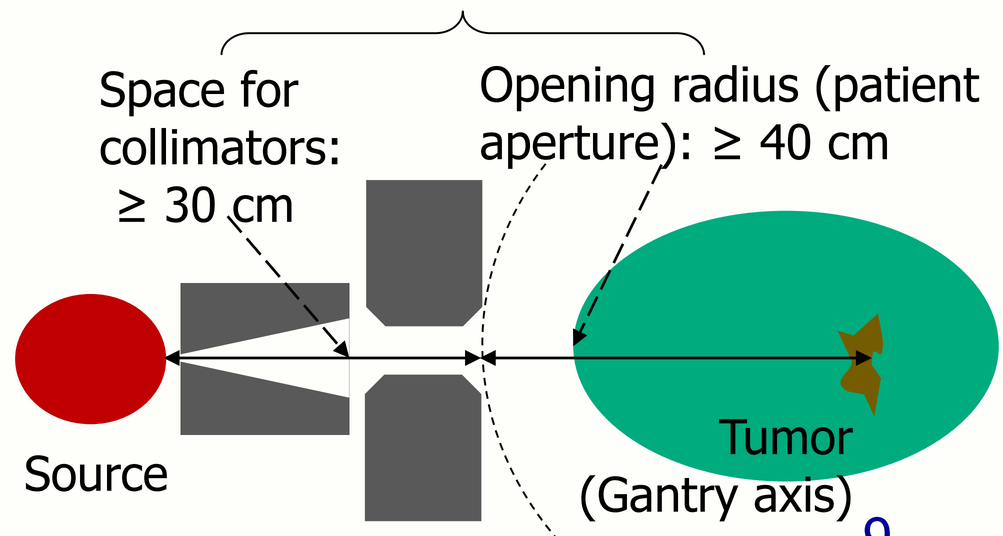


X-ray tube
SSD = 5 cm



Superconducting
Linac, SSD = 8 cm

Clinical usable SAD ≥ 70 cm



Clinical solution for X-ray flash-RT

- Increase dose rate 0.1 → 40Gy/s

Current accelerator technology is available, but with huge size :

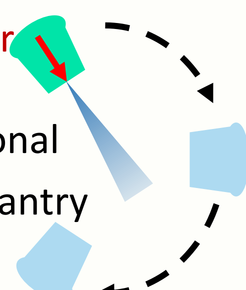
Conventional tube

- Ultra fast multiple-angle radiation

Almost impossible for a gantry rotating at this fast speed (~ 0.1 s) while maintaining high accuracy:

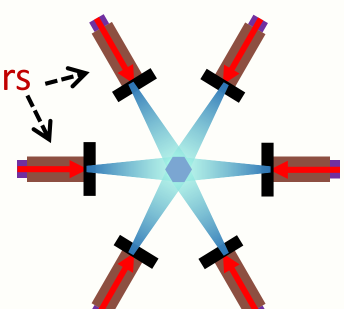
Multiple radiators statically installed!

Radiator



Conventional rotating gantry

6 Radiators



Very Huge machine size, losing **key advantage** of X-ray in FLASH-RT

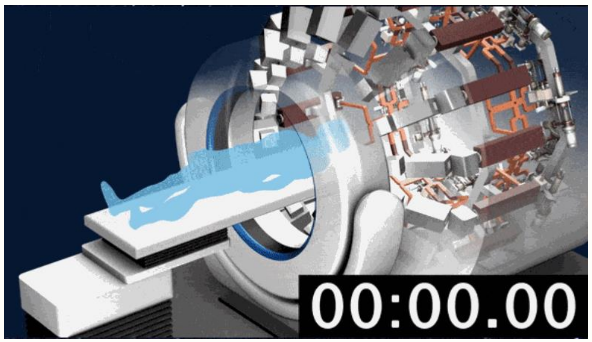
↓

We need a **compact** UHDR X-ray radiator

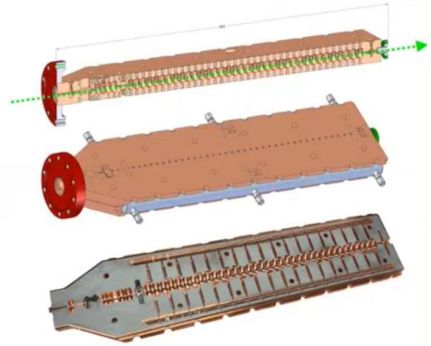
Proposed solutions

Stanford university: PHASER project

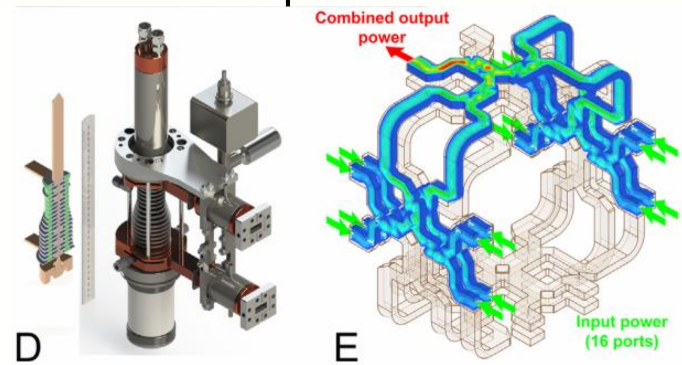
An animation of treatment using PHASER:



X-band strong current linac

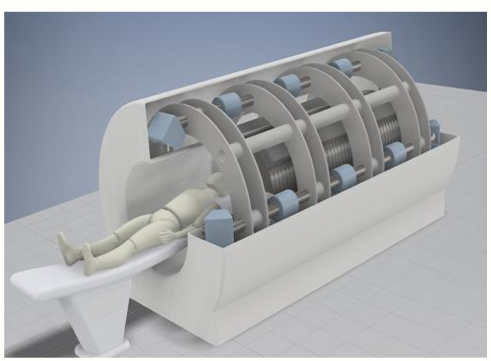


16 ports MIMO power switcher

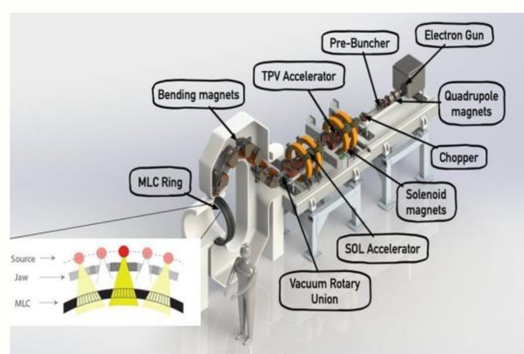


However, the measured data shows 15 Gy/s at SAD = 50 cm only, still not enough for criteria of flash-RT

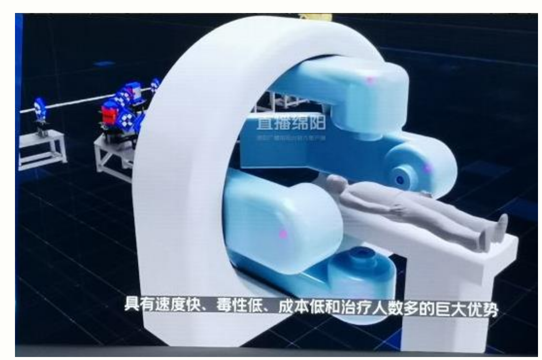
LLNL: induction accelerator with 4 parallel beam



UCLA & Radia beam: Fast rotating VMAT-flash



China Academy of Engineering Physics: Superconducting accelerator



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Principle of achieving UHDR X-ray

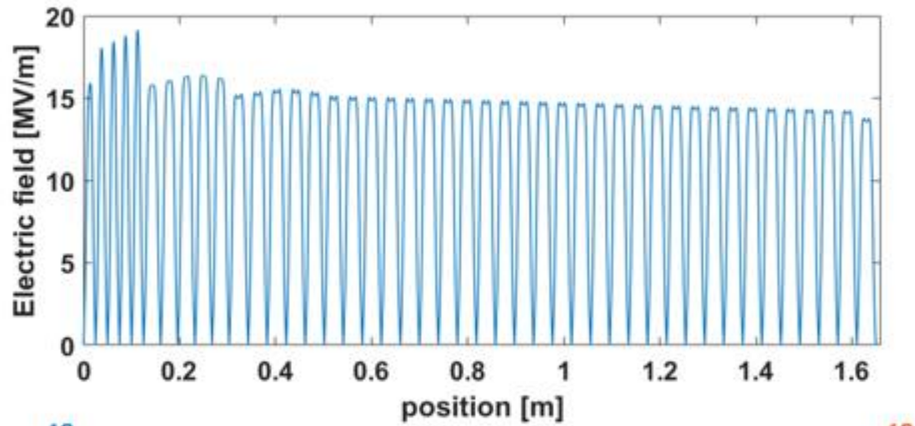
- Dose rate of electron hit tungsten (at 70 cm distance):

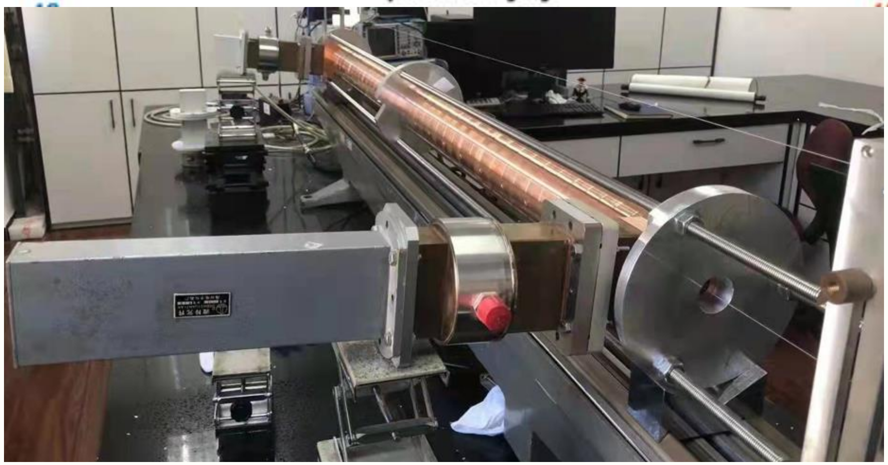
$$16 \times \left(\frac{Beam\ Energy}{[\mathrm{MeV}]}\right)^3 \times \frac{Average\ Current}{[\mathrm{A}]}\ [\mathrm{Gy/s}]$$

- 30 MeV × 100 μA → 43 Gy/s;
- Shielding for high energy beam is critical: higher penetration depth and neutron yield / induced radioactivity
- Widely accepted energy in clinical use: 6~10 MeV
- For 10 MeV: 1 kW beam power → 1.6 Gy/s, we need 25 kW beam power, which is still possible for the linear accelerator

Compact linac with large beam power

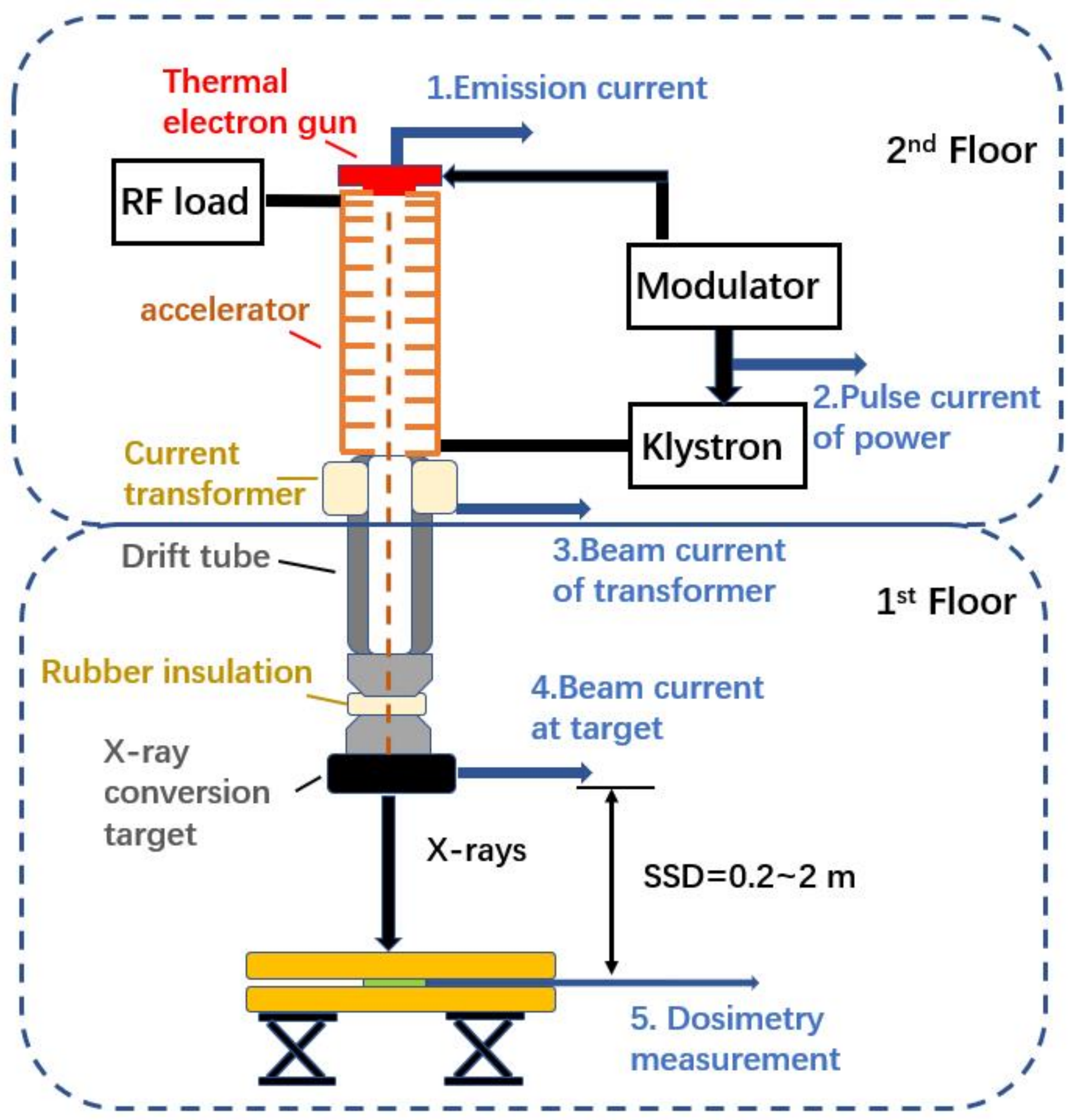
- We build a BTW structure for UHDR generation
- Frequency: S-band, Length: 1.6 m

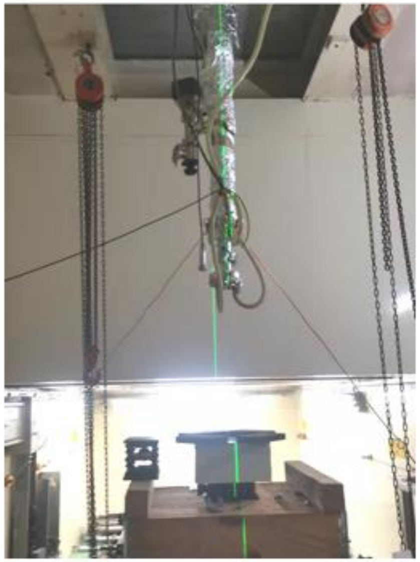




Parameter	Value
Peak power input	4.5 MW
Pulse current	320 mA
Energy	10 MeV
Repetition	650 Hz
RF pulse width	13.4 us
Current pulse width	12 us
RF-beam efficiency	57%
Duty cycle	0.78%
Average current	2.5 mA
Average beam power	25 kW

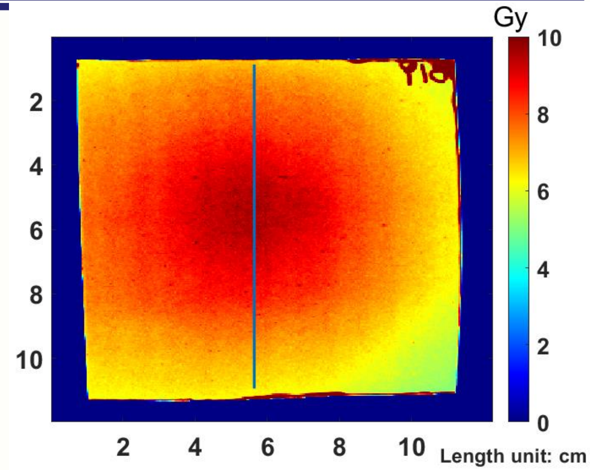
Compact linac with large beam power

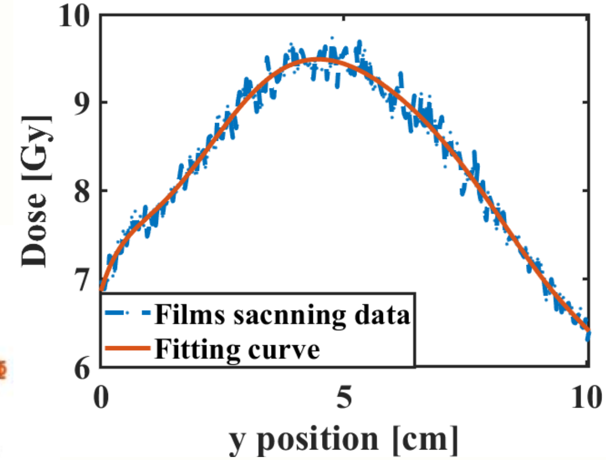


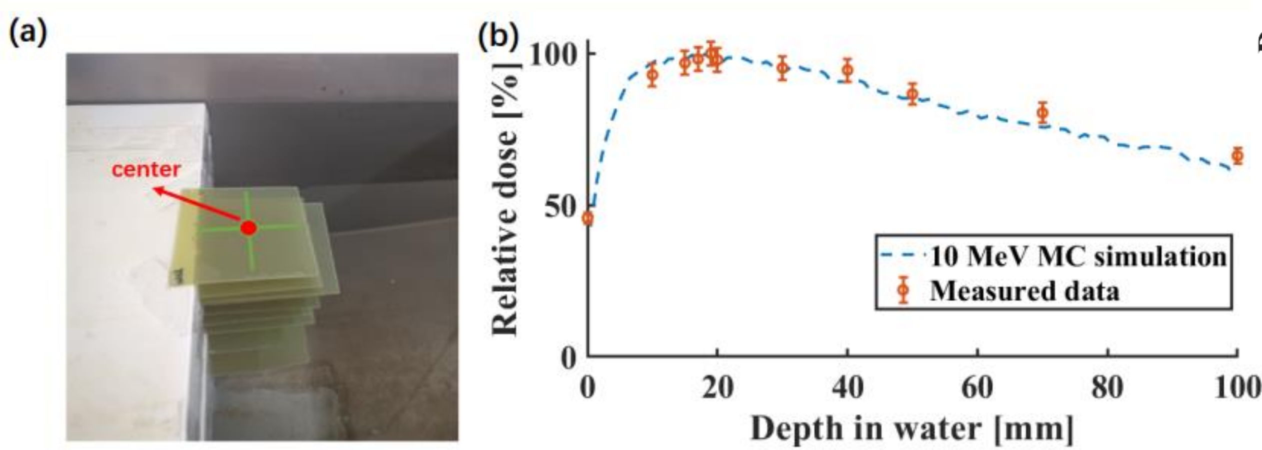


Experiment results

SSD	50 cm		67.9 cm			
Pulse number	74		112		144	
Irradiation time	106 ms		160 ms		206 ms	
Films	EBT3	EBT-DX	EBT3	EBT-DX	EBT3	EBT-DX
Max dose [Gy]	8.32 ±0.16	8.70 ±0.05	7.52 ±0.12	7.81 ±0.06	9.53 ±0.19	9.26 ±0.07
Max mean dose rate [Gy/s]	79.8 ±1.5	83.4 ±0.5	47.4 ±0.8	49.2 ±0.4	46.6 ±0.9	45.3 ±0.3
Max pulse dose rate [kGy/s]	9.11 ±0.17	9.54 ±0.05	5.42 ±0.09	5.63 ±0.04	5.33 ±0.11	5.18 ±0.04
Max bunch dose rate [kGy/s]	95.8 ±1.8	100 ±0.6	56.9 ±0.9	59.1 ±0.5	56.0 ±1.1	54.5 ±0.4



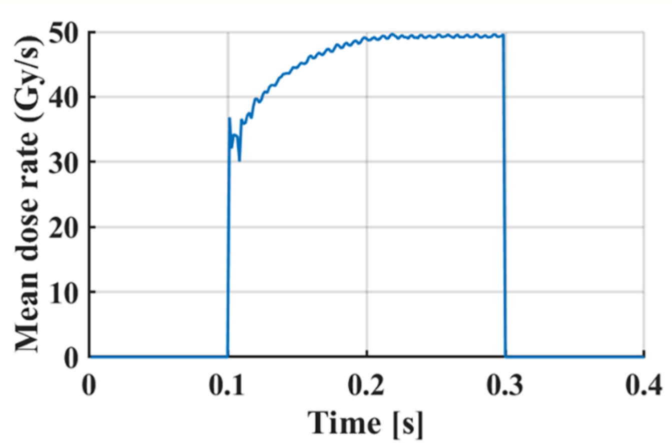


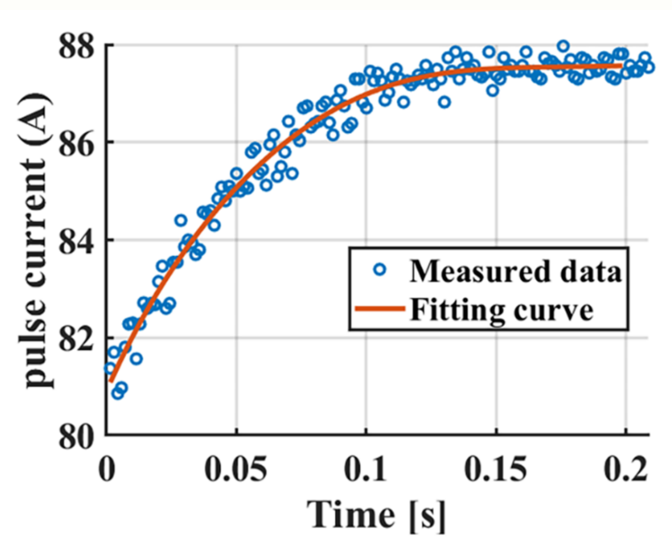


45 Gy/s @ SSD = 68 cm
Equivalent to
43 Gy/s @ SSD = 70 cm

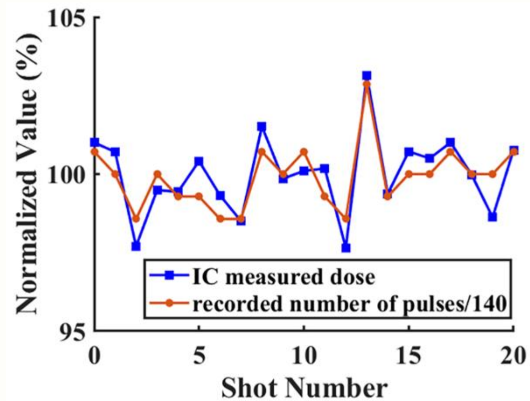
Stability

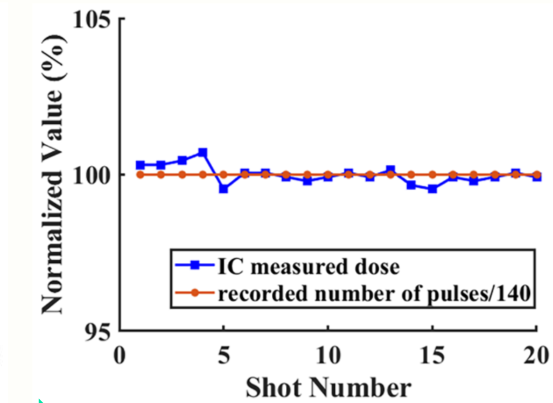
(a) During 0.2 s radiation





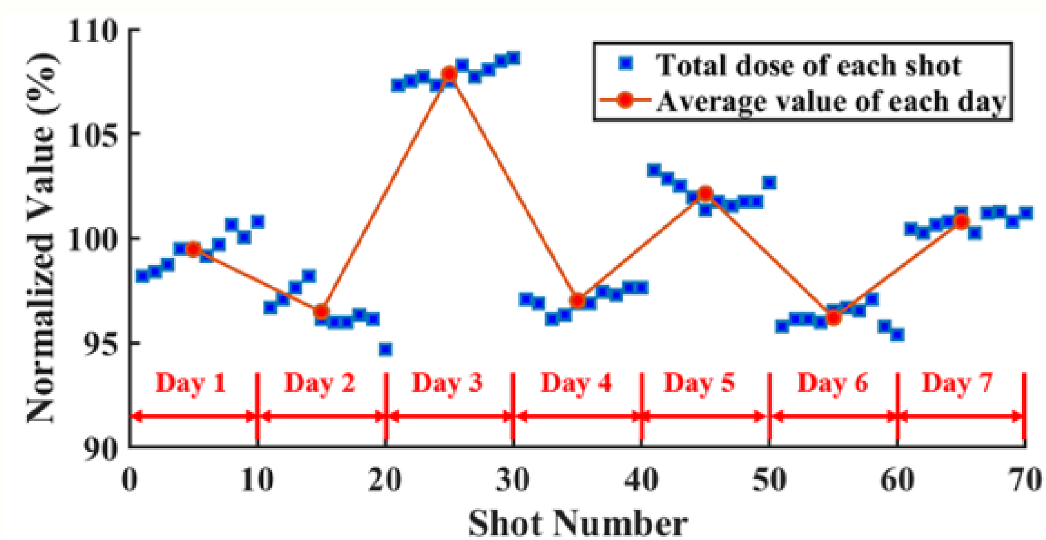
(b) Between each radiation





Counting time: std 1.3% → Counting pulse: std 0.3%

(c) Between days



Other experiments on UHDR X-rays

- We are already in FLASH-RT regime now: 43 Gy/s @ SAD=70cm

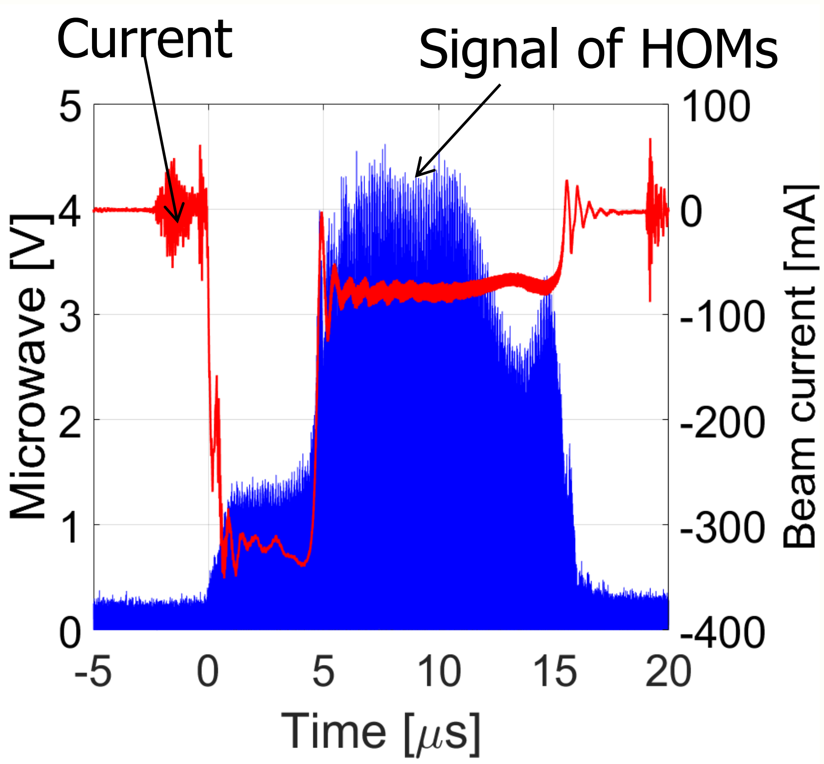
Accelerator	Beam Energy	Beam power	Measured dose rate	Equivalent dose rate @SAD=70cm
Australian Synchrotron facility	124 keV	Unknown	37~41 Gy/s	
ESRF@France	90~100 keV	178 mA e- in ring	37 Gy/s	
Dual x-ray tube, US	150 kV	3 kW	160Gy/s@4 cm	0.26 Gy/s
Superconducting linac@CAEP, China	8 MV	40~45 kW	1500 Gy/s@8 cm	20 Gy/s
BTW Linac @Tsinghua, China	10 MV	25~28 kW	80 Gy/s@50 cm 45 Gy/s@68 cm	43 Gy/s

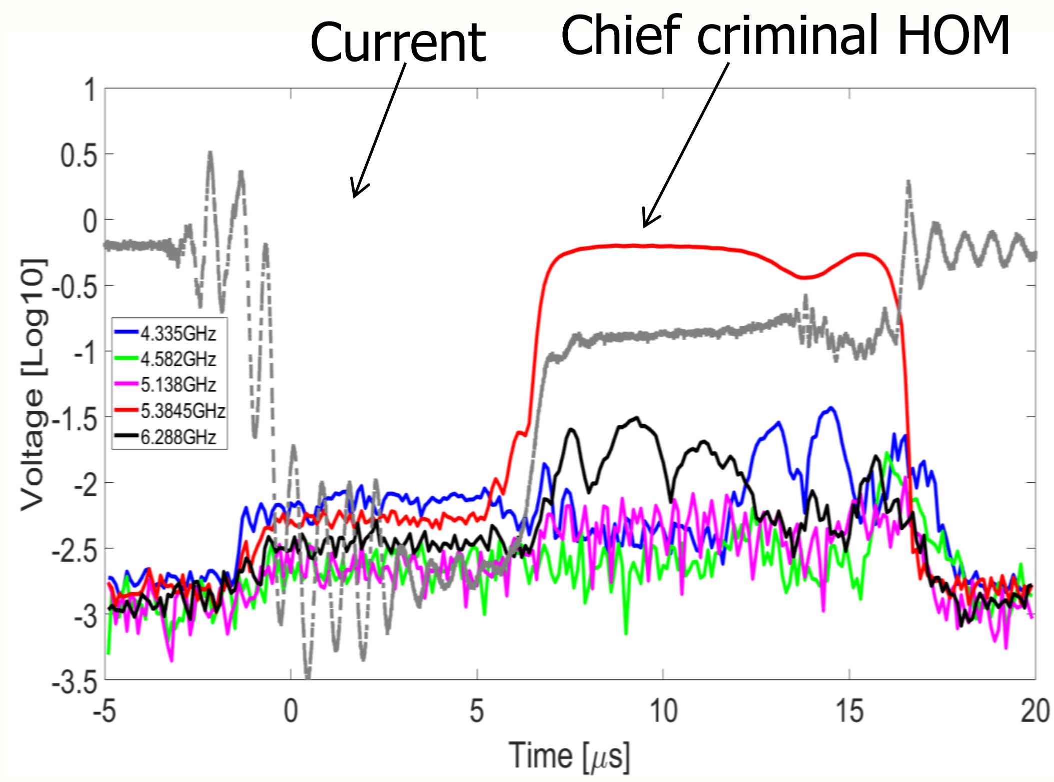
Noted: Induction accelerators also demonstrated very high dose-rate X-ray. However these facilities were big and not for UHDR-RT purpose

Towards more compact design

- We need a more compact linac and a larger current in future (500 mA)
- **First challenge: Bream break up effect**

Beam break up in an S-band structure (courtesy of Dr. Jiaru Shi)

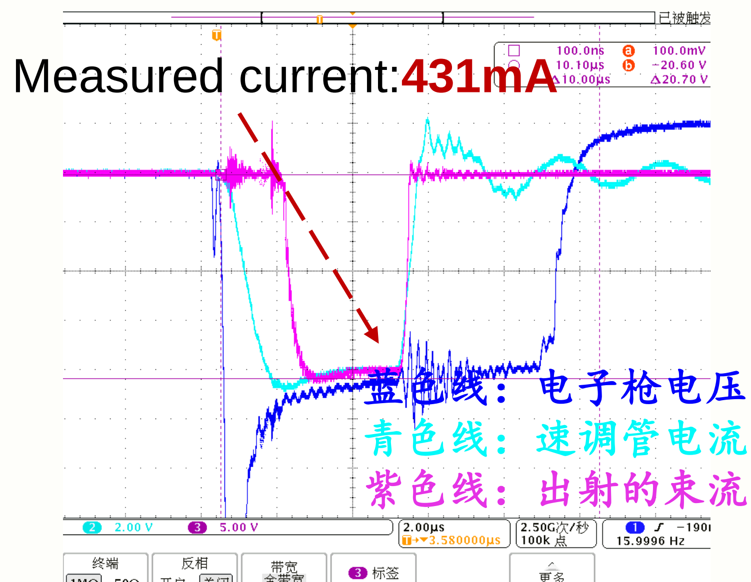




More compact linac

- We built a S-band standing wave linac, with higher current
- The power source is currently not available, still under developing

Parameter	Value
Peak power input	7.5 MW
Pulse current	Designed: 450 mA Measured: 431 mA
Energy	10 MeV
Duty cycle	1%
Dose rate	72 Gy/s @ SAD = 70 cm



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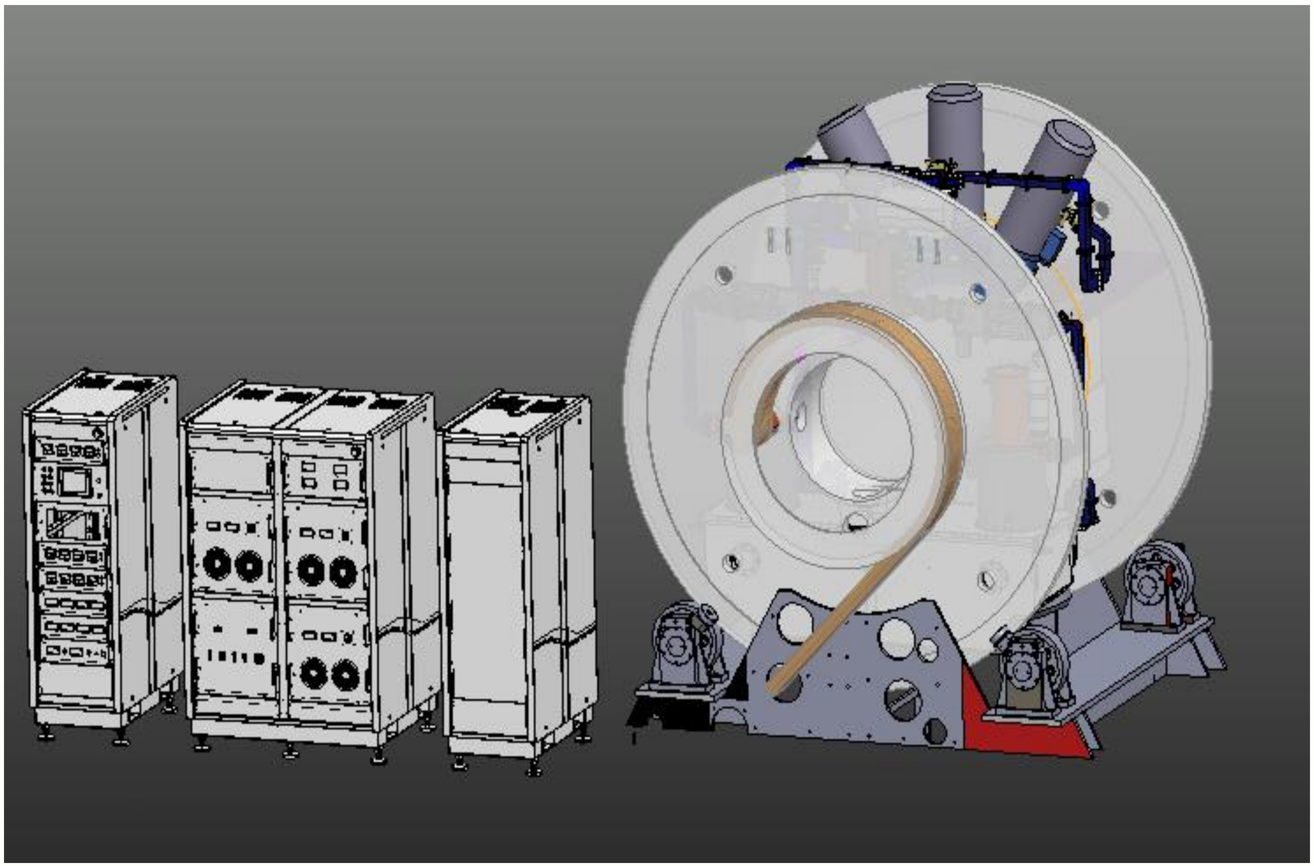
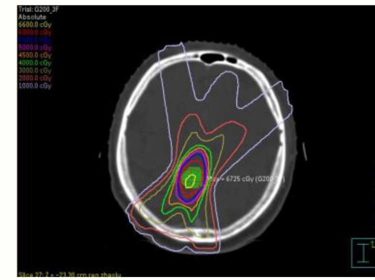
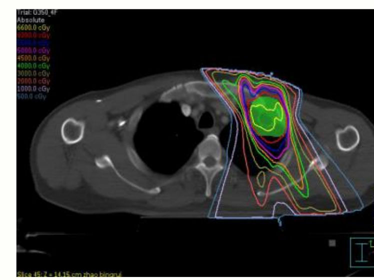
Proposal of clinical machine

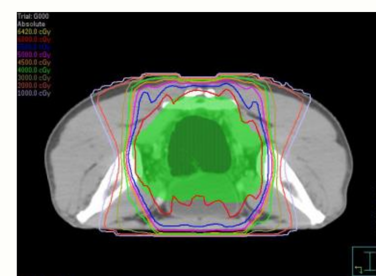
Proposal of clinical machine

- An array of 5 linacs, the angle distribution is carefully chosen, suitable for most of the treatment plan









Summary

- Compactness is the key advantage of using X-ray in a Flash radiotherapy machine
- We developed:
  - A compact S-band BTW linac which generated the UHDR X-ray (43 Gy/s) at a clinically usable SAD (70 cm)
  - A more compact S-band standing-wave linac. Preliminary tests shown the strong current (430 mA peaked) was achieved.
- Future plan: array of linacs for multiple-angle radiation