清華大學
Tsinghua University

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

Hao Zha

Senior research scientist, Tsinghua University

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Outline

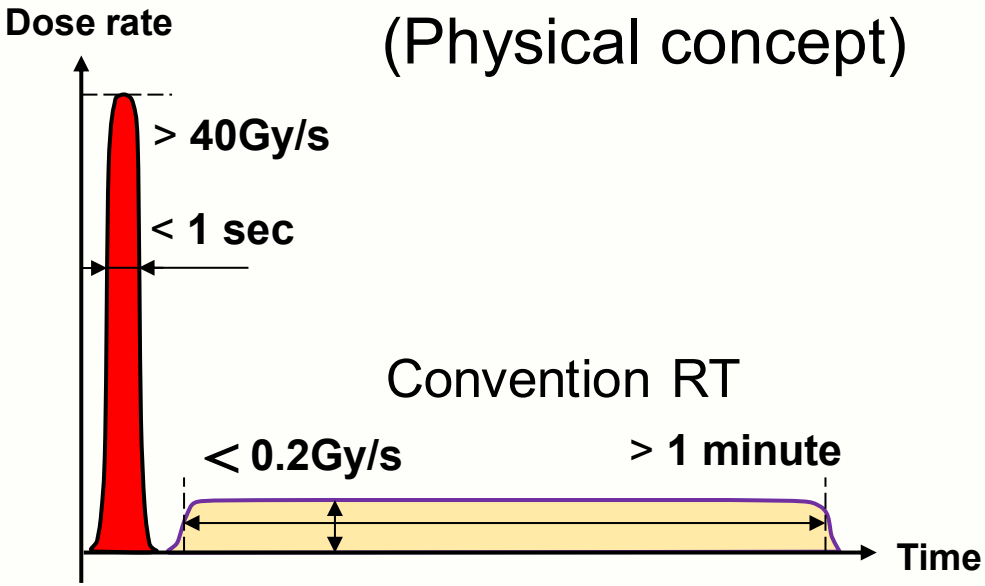
- **Introduction of Flash-RT**
- Why we choose X-ray?
- Our developments

Introduction of Flash-RT

- Flash effect is now a very hot topic of radiotherapy
- Researches were mostly done in the cell/animal level
- Potential of clinical benefit is significant but still progress slowly in worldwide

Ultra high dose rate

(Physical concept)



FLASH effect

(Biological concept)

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

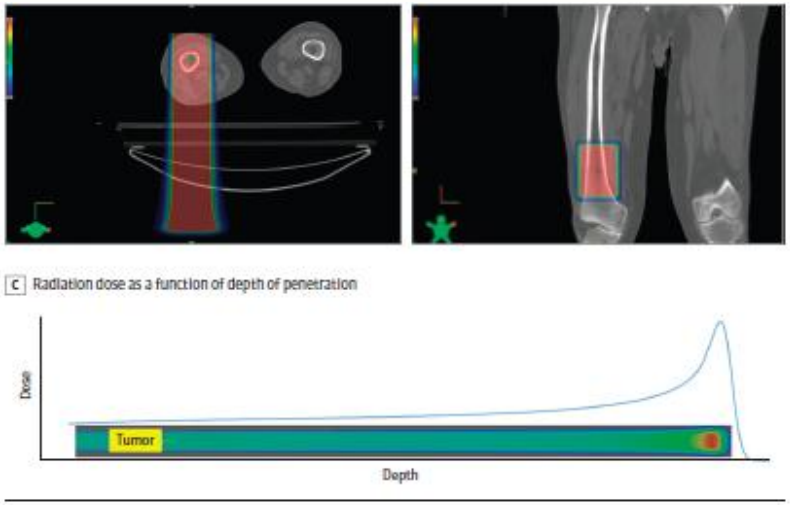
Ongoing clinical trails

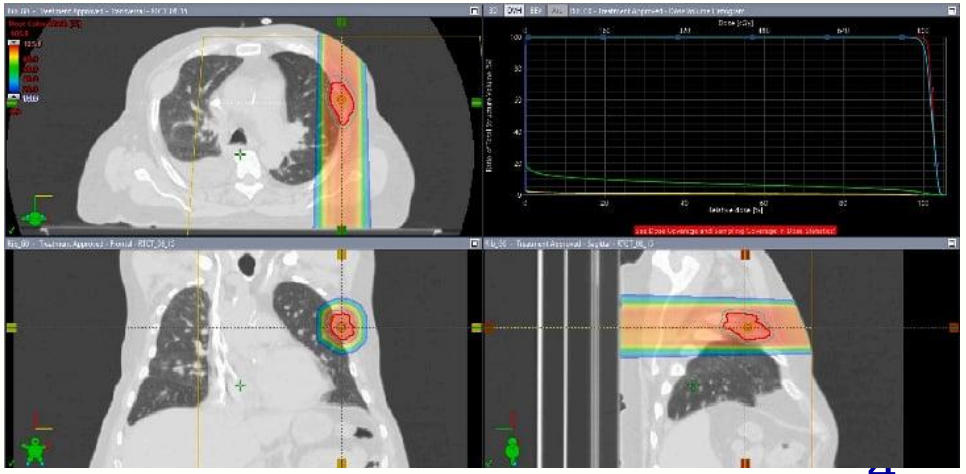
- Electron: superficial treatment only



Clinical trails up to 2026
FAST-Ⅰ/FAST-Ⅱ: Proton FLASH-RT /U.S.
LANCE-Ⅱ: Low energy Electron FLASH-RT/Switzerland
INPULSE-Ⅰ: Low energy Electron FLASH-RT/Switzerland
ChiCRT-2400080935: skin cancer/Europe
TheryQ: for skin cancer, multicenter trail in Europe

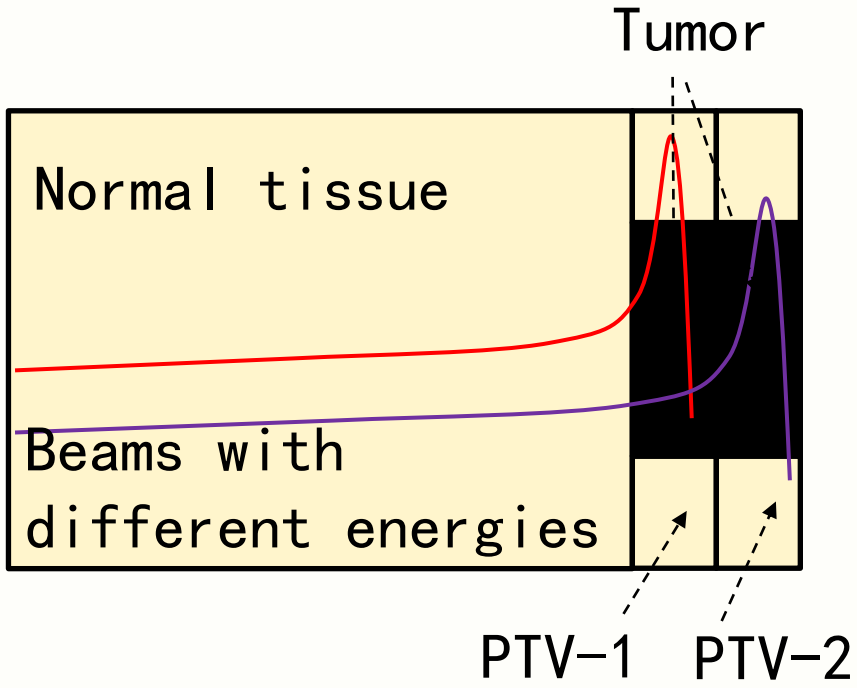
- Proton: shoot-through beam, losing the advantage of the Bragg peak

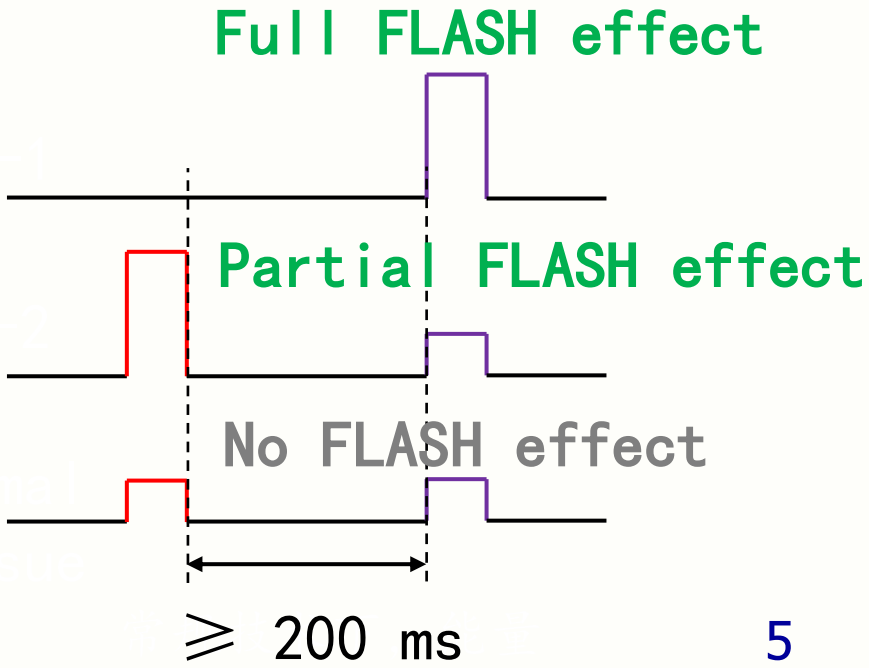




Main challenge of FLASH-RT using proton/heavy ion

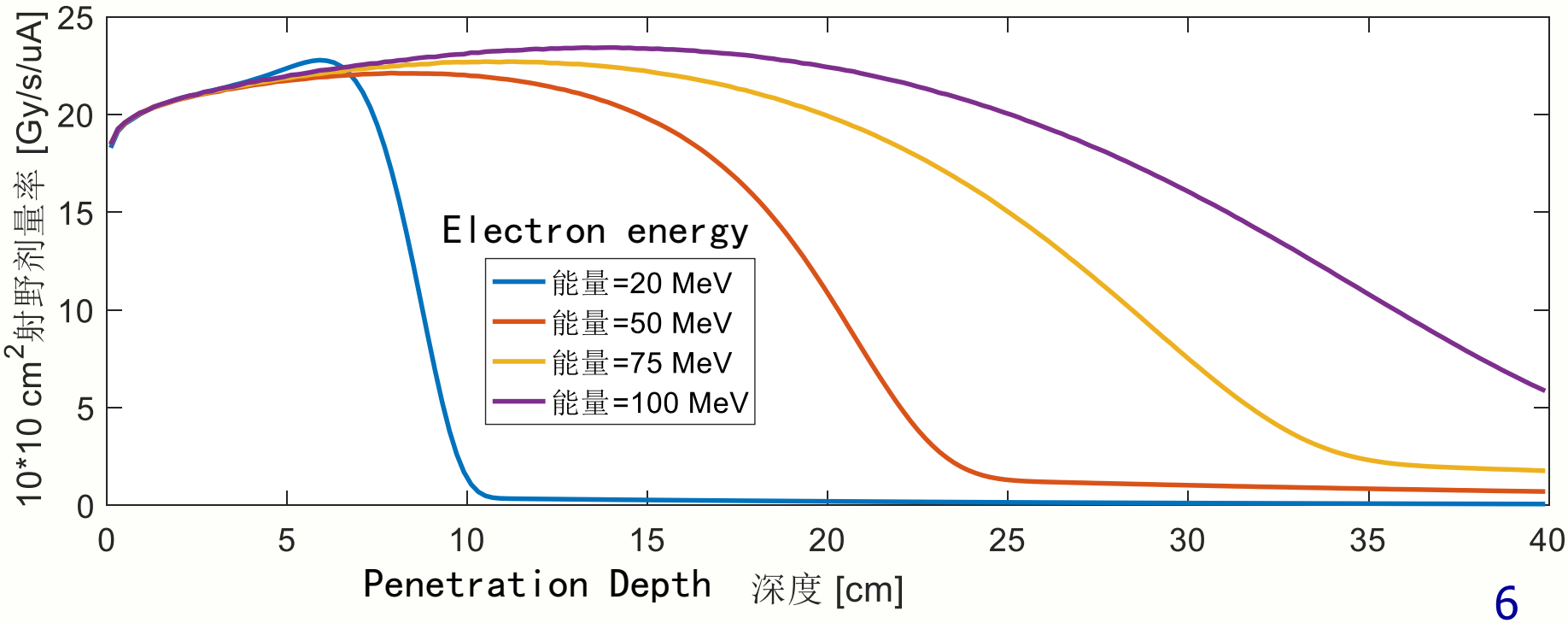
- Cyclotrons requires a significant time on magnet tuning/ switching, reduces the average dose rate in some tissues.
- Currently, a switching time of 50–100 ms has been achieved, but still not sufficient for FLASH-RT.





Main challenge of FLASH-RT using electrons (1)

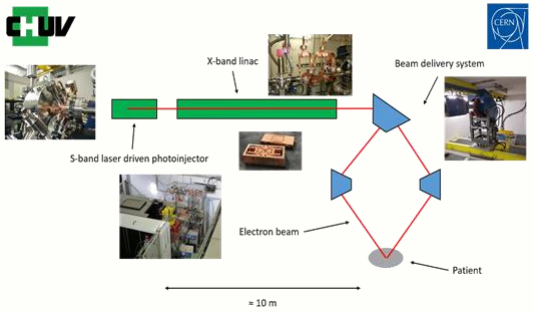
- Electrons yield very high dose rate: up to kGy/s ~ MGy/s
- The energy of convectional LINACs: 5~20 MeV
- Generating electrons of 100 MeV or higher energy , required **V**ery **H**igh **E**nergy **E**lectron accelerators (VHEE)



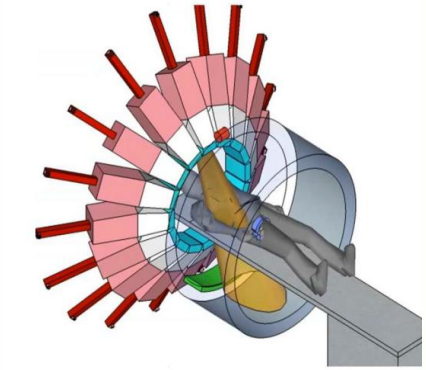
Main challenge of FLASH-RT using electrons (2)

- These facilities are large and expensive
- Compact design will be coming soon

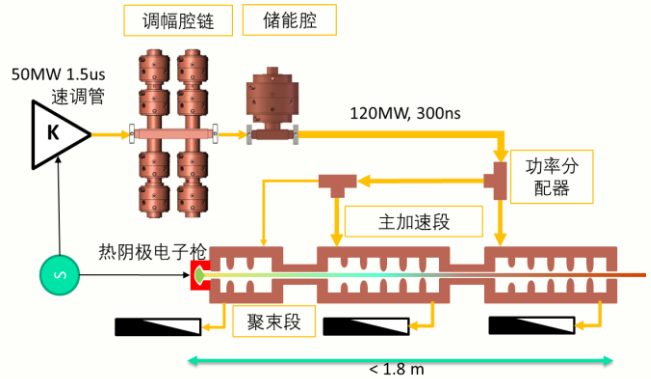
CERN-PMB：DEFT 130 MeV
10 m long X-band accelerator



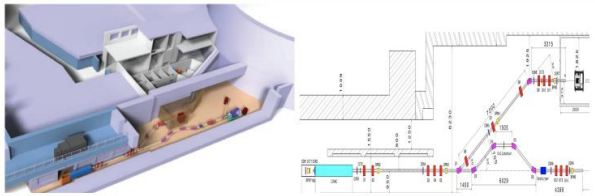
Stanford Univ.：PHASER 100 MeV
Nitrogen cooled X-band accelerator



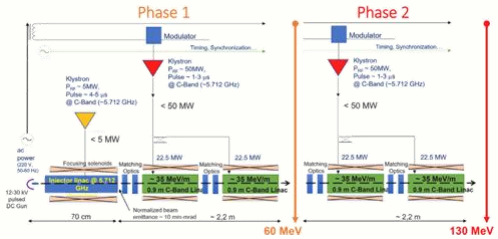
Tsinghua Univ.：100 MeV
Compact 2 m X-band accelerator



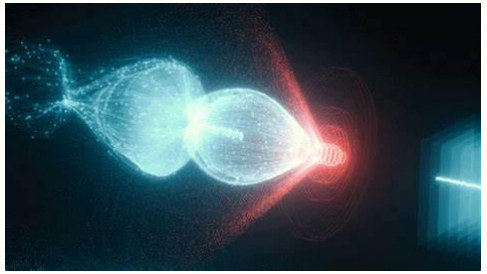
LAL France：PRAE 100 MeV
5 m long S-band accelerator



INFN Italy 130 MeV
7 m long C-band accelerator



Laser Plasma Wakefield accelerator:
Very compact but low dose-rate



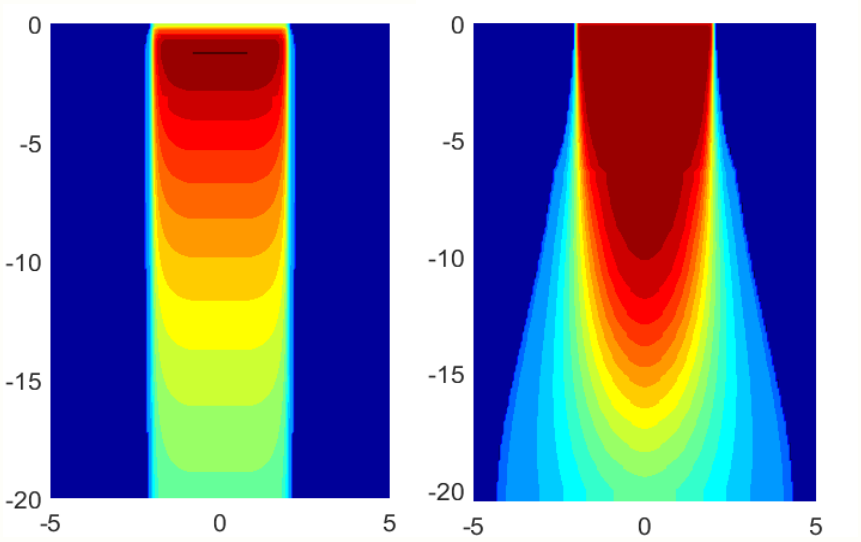
Outline

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

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**

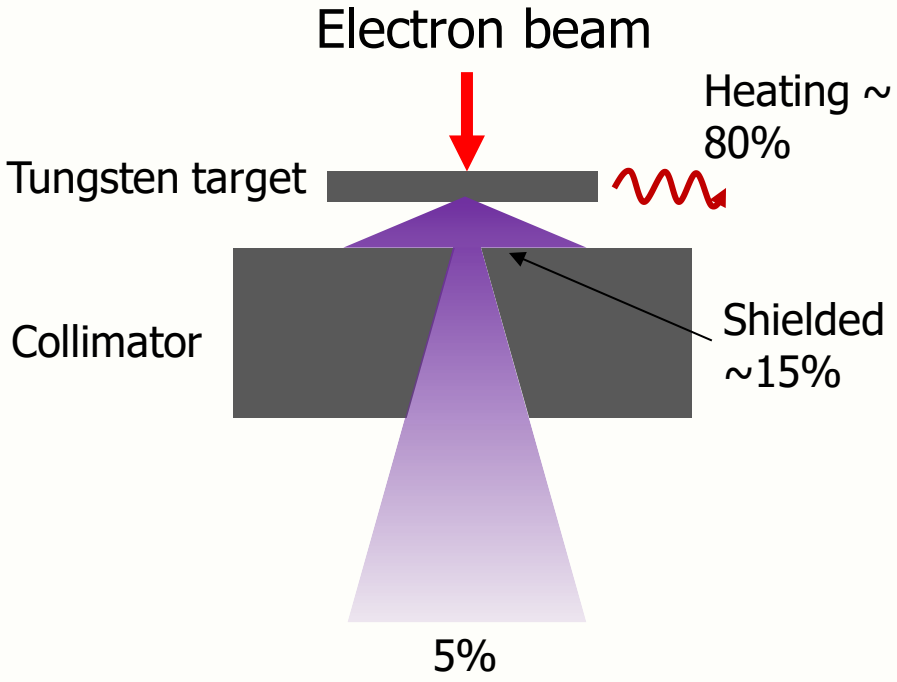
6 MV X-ray　　75 MeV electron



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

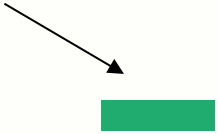
Challenge 1: Dose rate issue

- Main challenges: very low dose rate



Most of the current machines：

600～1200 cGy/min = 0.1～0.2 Gy/s



Criteria of triggering FLASH effect ≧ 40 Gy/s

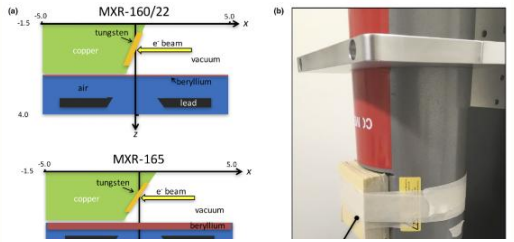


UHDR X-ray generation

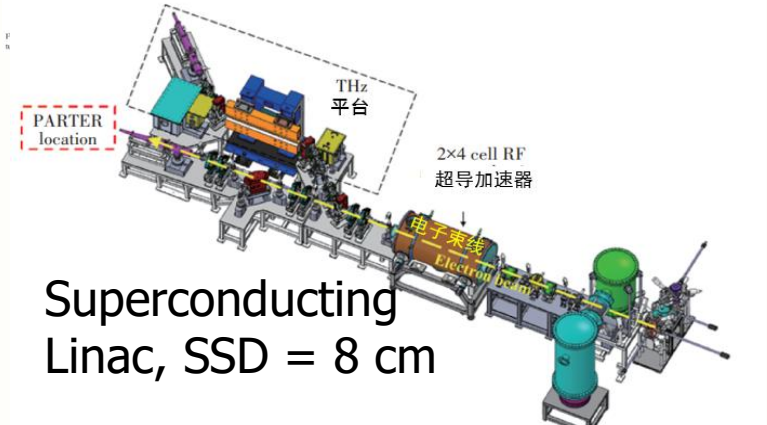
- UHDR X-ray for animal experiments is available
  - Very close to the source (dose rate ∝ SSD^{-2})
  - Single-angle radiation

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

- Clinical use needs large SAD and multiple-angle

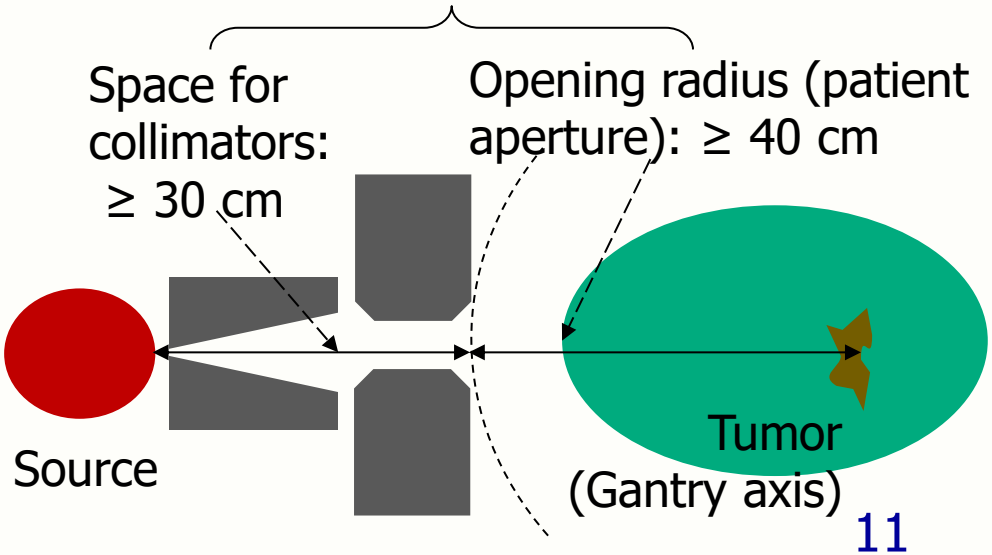


X-ray tube
SSD = 5 cm



Superconducting
Linac, SSD = 8 cm

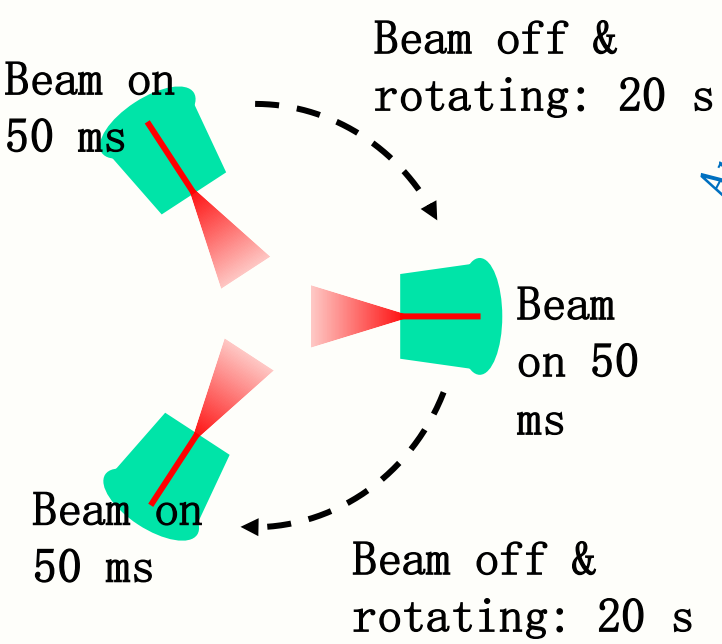
Clinical usable SAD ≥ 70 cm

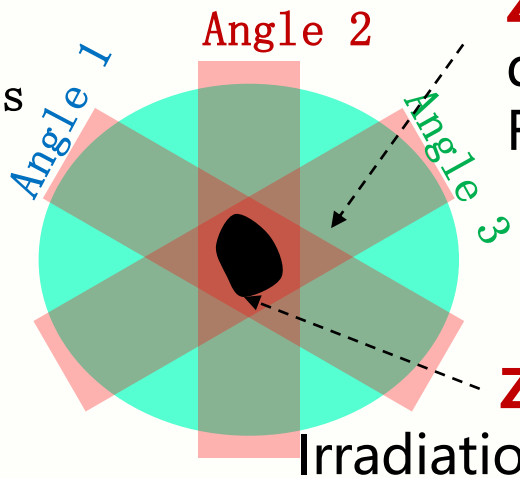


Challenge 2: Multiple-angle irradiation

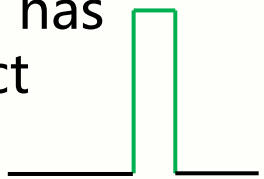
- FLASH-RT still requires dose conformality
- Multi-angle irradiation is essential
- Rotating gantry might be not applicable

Split irradiation mode

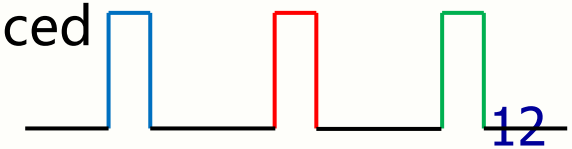




Zone 1: single ultra-high dose rate pulse, has Full FLASH effect



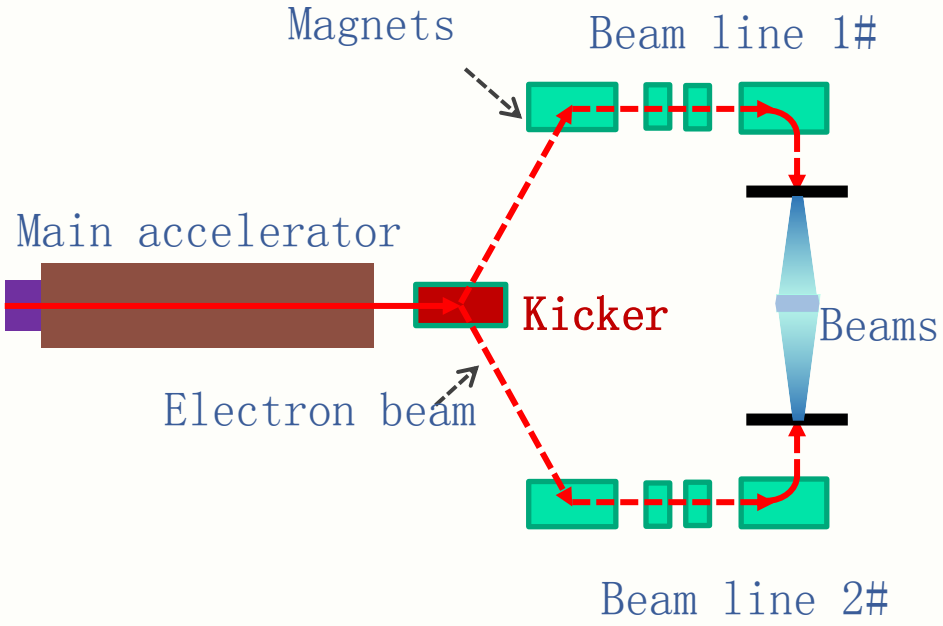
Zone 2: Cross-angle area Irradiation is split into multiple pulses, and the average dose rate is reduced



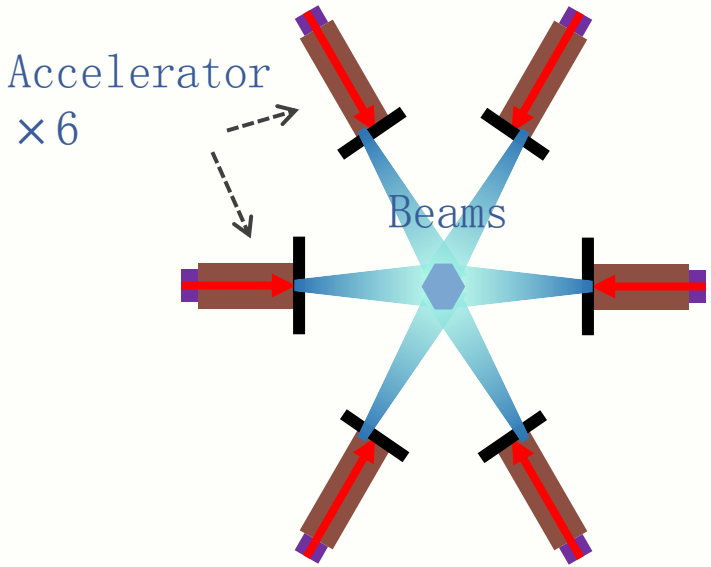
Static multiple-angle irradiator

- It is almost not possible for gantry rotating at the speed within the FLASH time
- Statically deploy multiple irradiators will be the only solution

①: One accelerator with multiple beam lines, like heavy ion facility



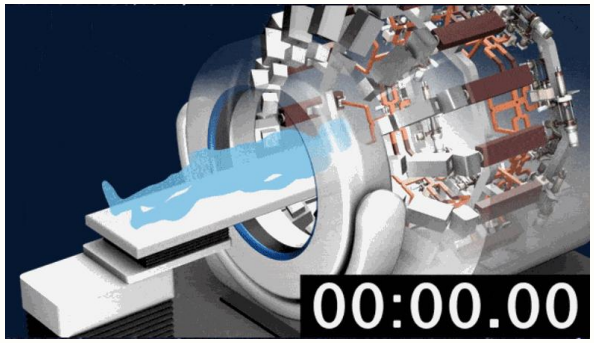
②: Multiple compact accelerators, easier control and stability



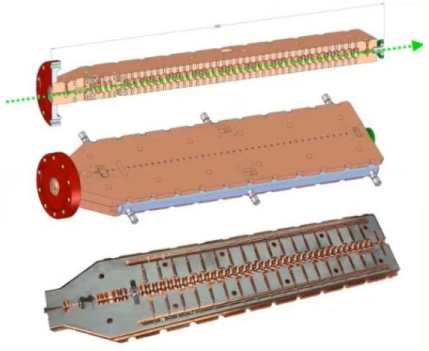
Proposed solutions

Stanford university: PHASER project

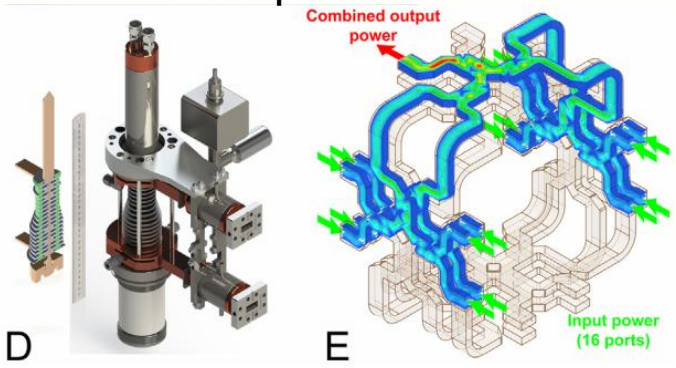
An animation of treatment using PHASER:



X-band strong current linac

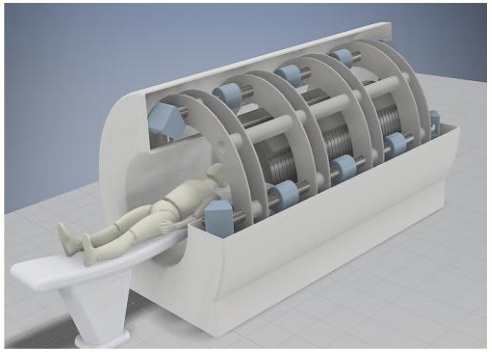


16 ports MIMO power switcher

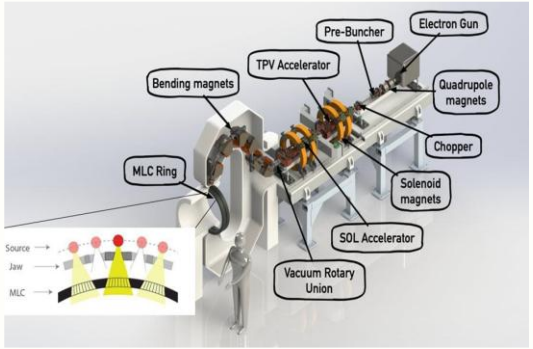


However, the measured data shows 15 Gy/s at SAD = 50 cm only, still not enough for criteria of flash-RT

LLNL: induction accelerator with 4 parallel beam



UCLA & Radia beam: Fast rotating VMAT-flash



Zhongjiu Flash Co. Ltd. in China: First MV-X Ray prototype in the world, but for single angle RT



Summary of challenges

Increase dose rate 0.1 → ≥ 40Gy/s

Current accelerator technology is available, but with huge size :

Conventional tube 

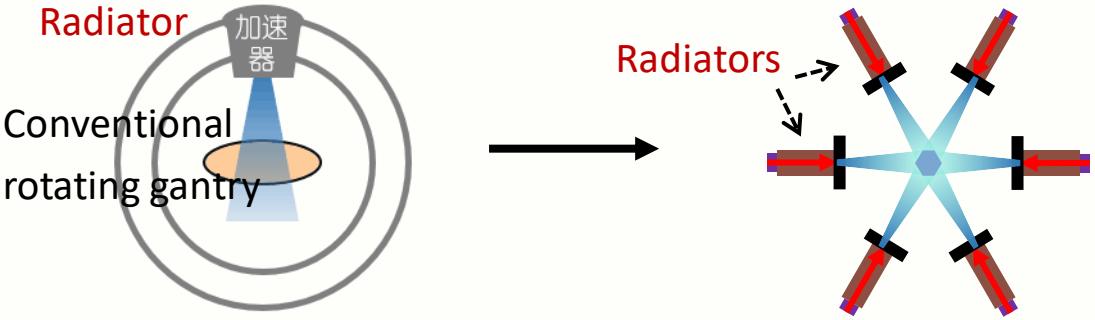


Ultra fast multiple-angle radiation

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

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

Multiple radiators statically installed!



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

Outline

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

Principle of achieving UHDR X-ray

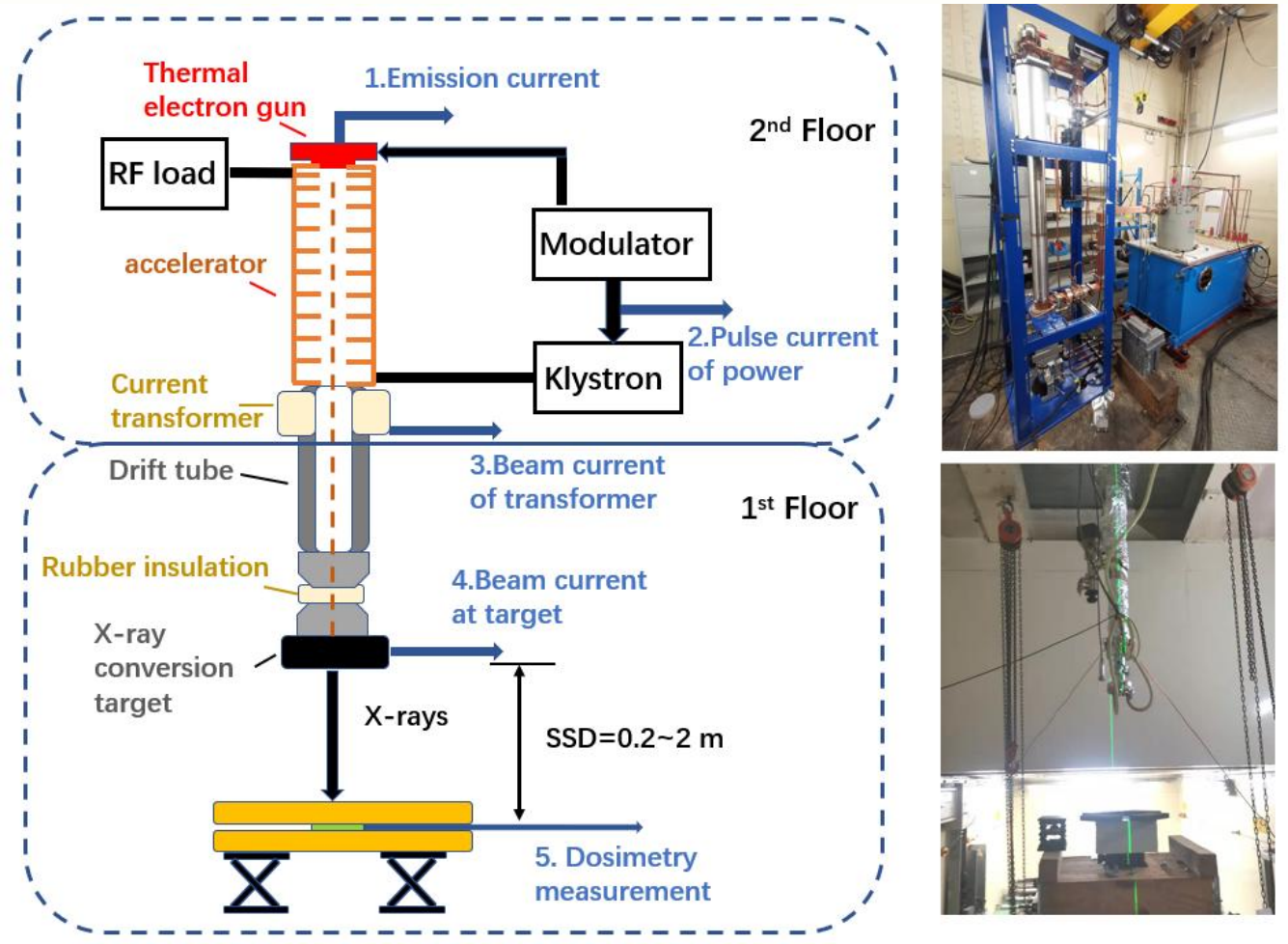
- Dose rate of electron hit tungsten (at SAD = 70 cm):

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

- 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

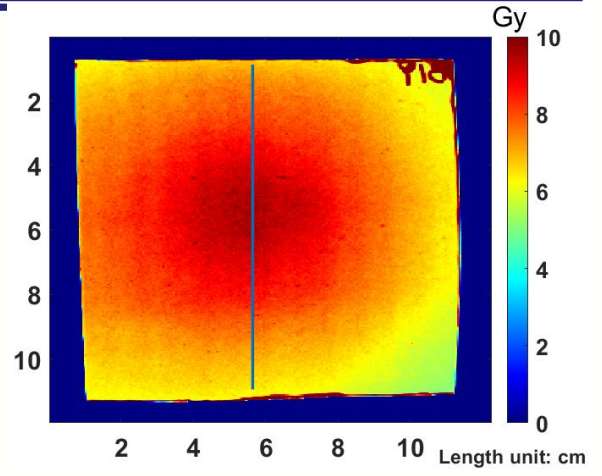
Compact linac with large beam power

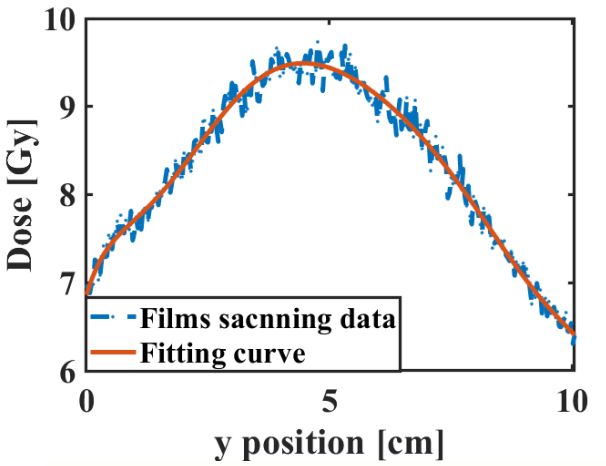
- We build a BTW structure for UHDR generation
- Frequency: S-band, Length: 1.6 m



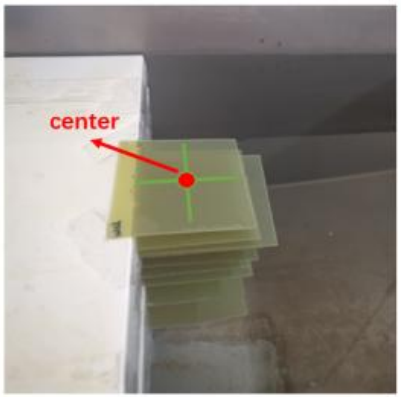
Experiment results

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

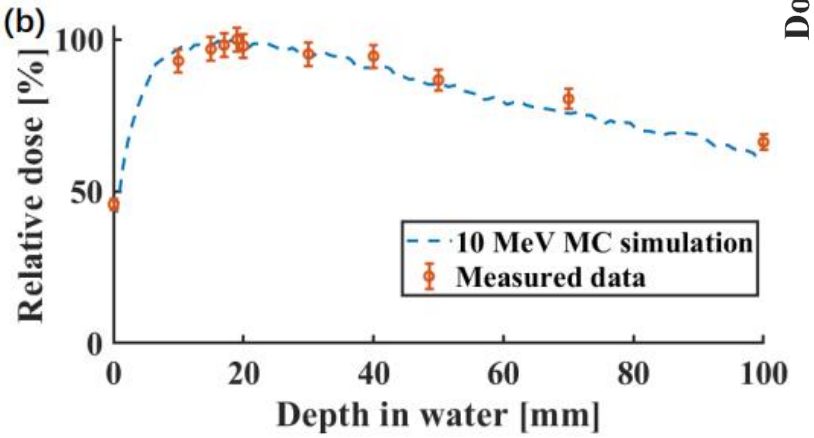




(a)



(b)



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

More compact linac

- We built a compact S-band standing wave linac, with higher current
- The power source is also upgraded, more compact & powerful accelerator
- Rotating target is developed

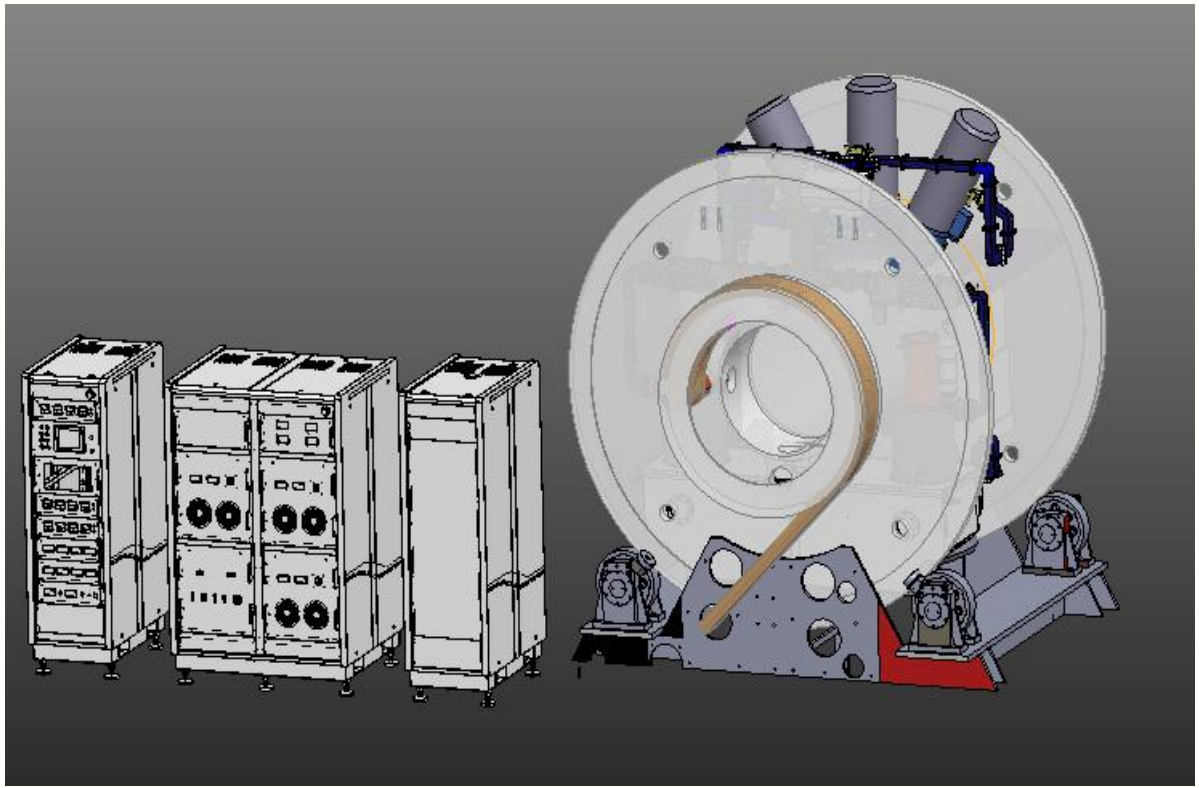
Parameter	Value
Peak power input	7.5 MW
Pulse current	Measured: 431 mA
Energy	10 MeV
Duty cycle	1%
Dose rate	72 Gy/s @ SAD = 70 cm

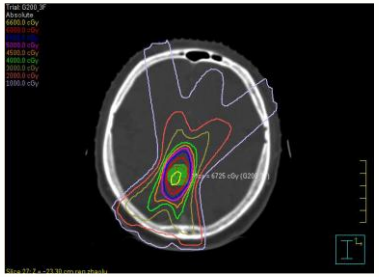


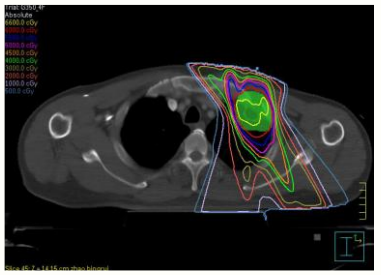


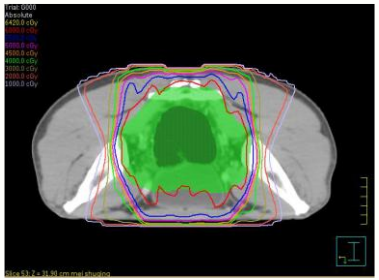
Proposal of clinical machine

- An array of 5 linacs, the angle distribution is carefully chosen, suitable for most of the treatment plan for lung/brain cancer
- 5-angle design is suitable for IMRT (5 fields);









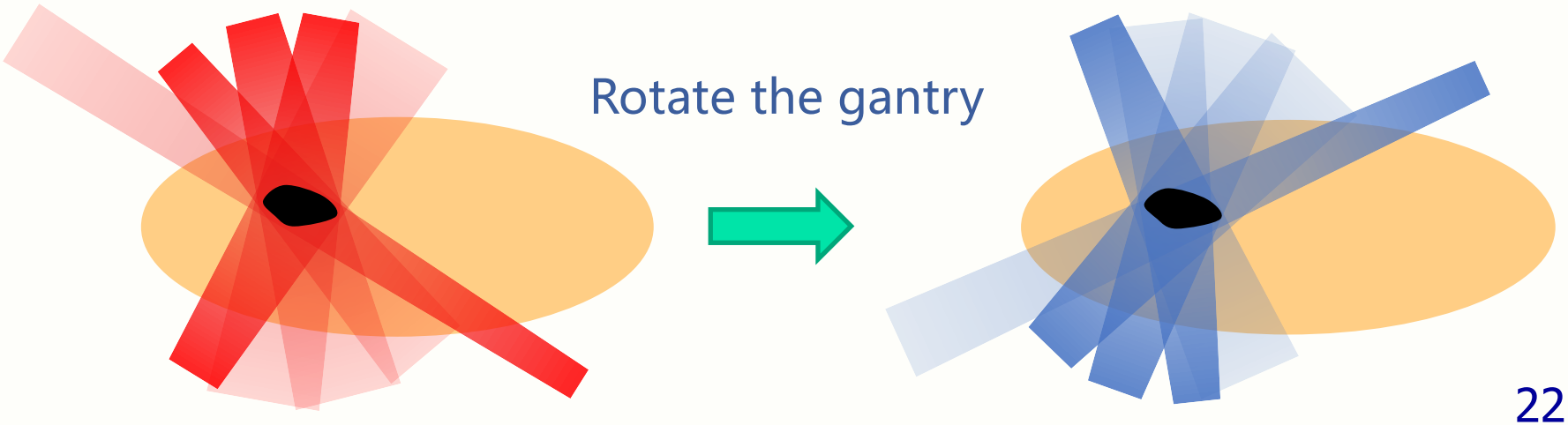
Is five angles sufficient for treatment?

- A typical IMRT requires 5/7/9 fields
- Flash-RT is not likely to be implemented in a single fraction (As a ref: SBRT needs 3~5 fractions)
- Radiation angles could be multiplied

location	Fields/ Angle	Minimum Fractionated ?
Head/Neck	5~7	1 or 2
Lung/Brest	5	1 is OK
Abdomen	5~9	Maybe 2

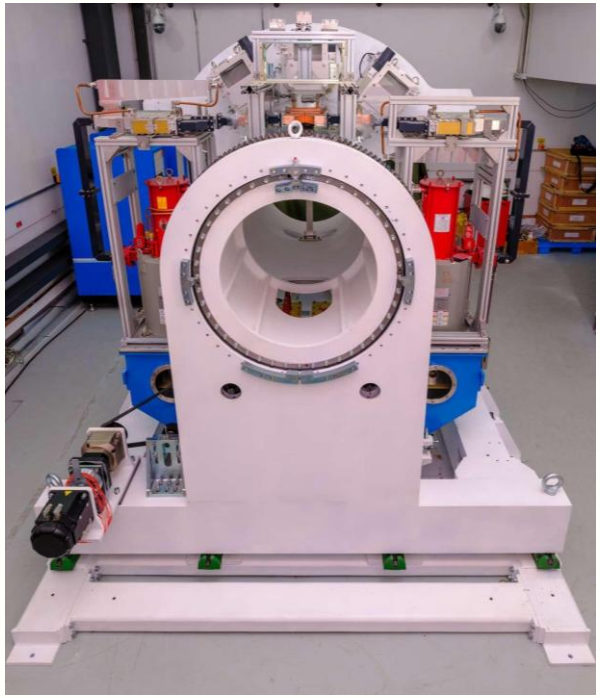
First fraction

Second fraction (Normally after one or several days)



First prototype of the multiple-angle irradiator

- We had built the compact prototype in 2025
- Diameter = 3 m, Length = 2.5 m, fit for convectional bunkers
- All five accelerators can achieved the goal 40 Gy/s (SAD = 80 cm), average dose rate = 42 Gy/s





Summary

- There are still many challenge in accelerator developments for FLASH-RT (of all particles: X-ray/Electron/Proton or ions)
- Compactness (also the cost-effectiveness) is the key advantage of using X-ray in a FLASH-RT facility
- We developed:
  - A compact S-band BTW linac which generated the UHDR X-ray at a clinically usable SAD (70 cm)
  - A 5-angle prototype for clinical X-ray FLASH-RT, and a dose rate of 42 Gy/s is achieved