# Application Progress of CYCIAE-100 high current proton Cyclotron

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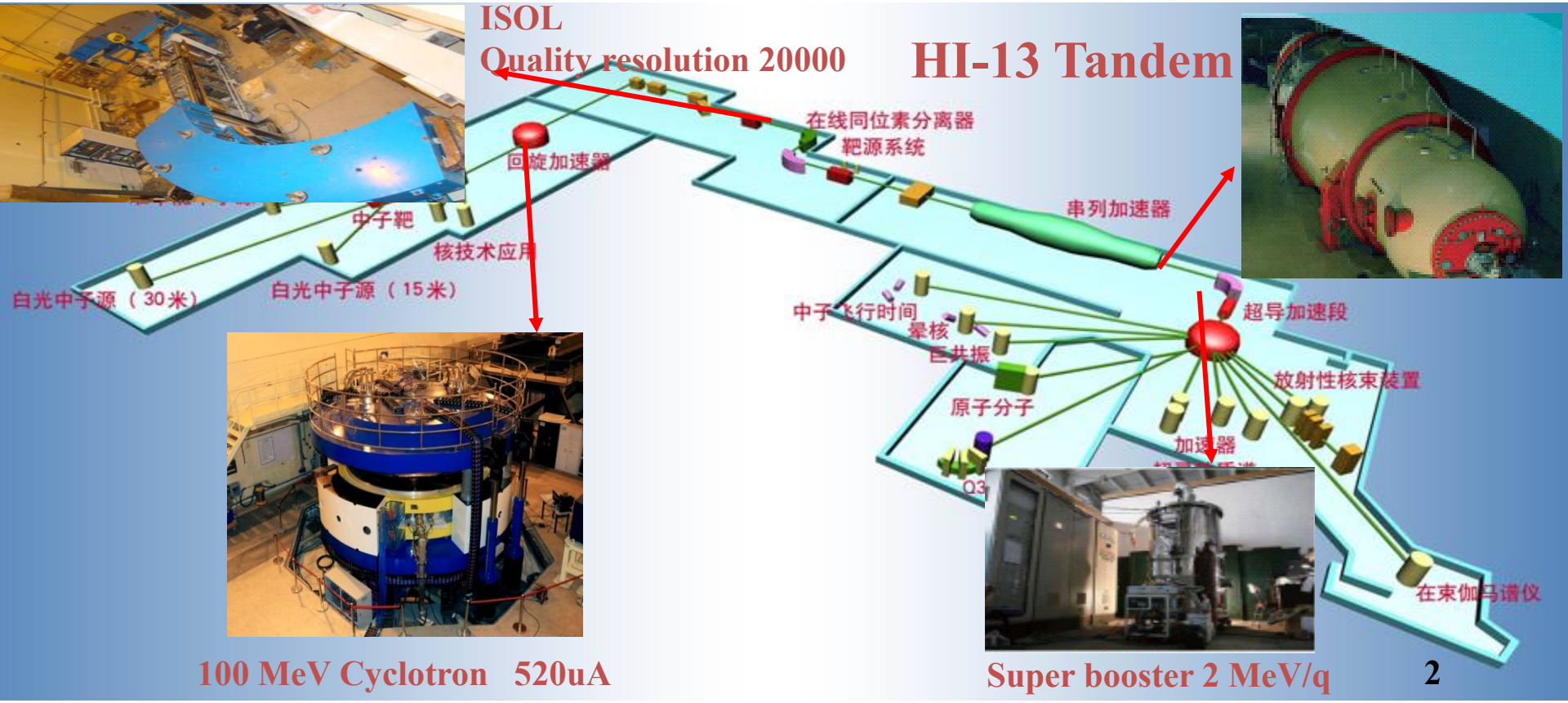
# Outline

- **Overview of BRIF and CYCIAE-100**
- **Application and research**
- **Conclusion**

# (Beijing Radioactive Ion-beam Facility)

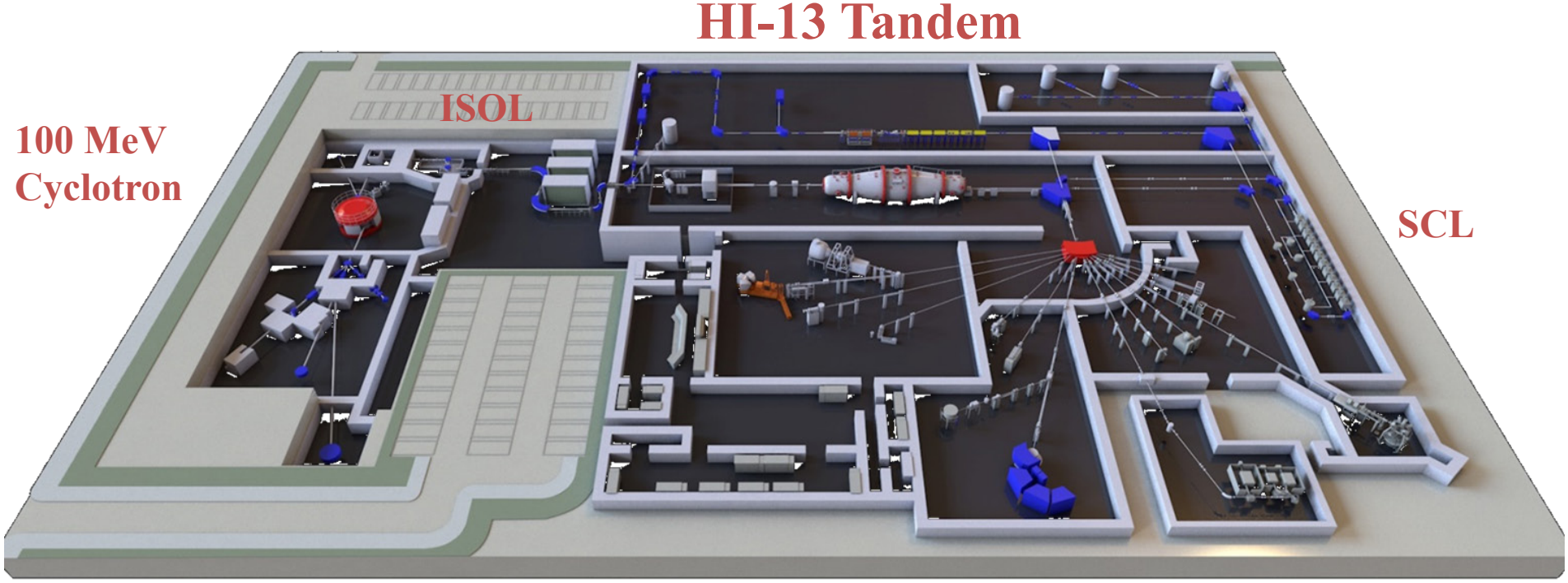
- building 3775 m2 , total investments 365 M RMB, construction started in April 2011, completed in 2014, opening for user experiments in 2016.
- The main performance indexes have reached the international leading level.



# BRIF Model

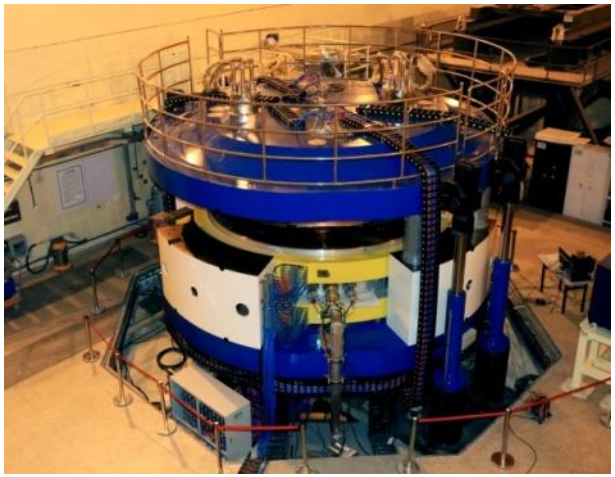
- 100MeV/520uA H- AVF cyclotron(**CYCIAE-100**);
- **I**sotope **S**eparator **O**n-**L**ine 20000 mass resolution（**ISOL**）；
- After the tandem, a 2MeV/q superconducting linac booster（**SCL**）；
- Multiple beam lines and experiment terminals.

multi-use of one device, combination of two devices, and combination of multiple devices



# CYCIAE-100 ( a 100 MeV proton cyclotron)

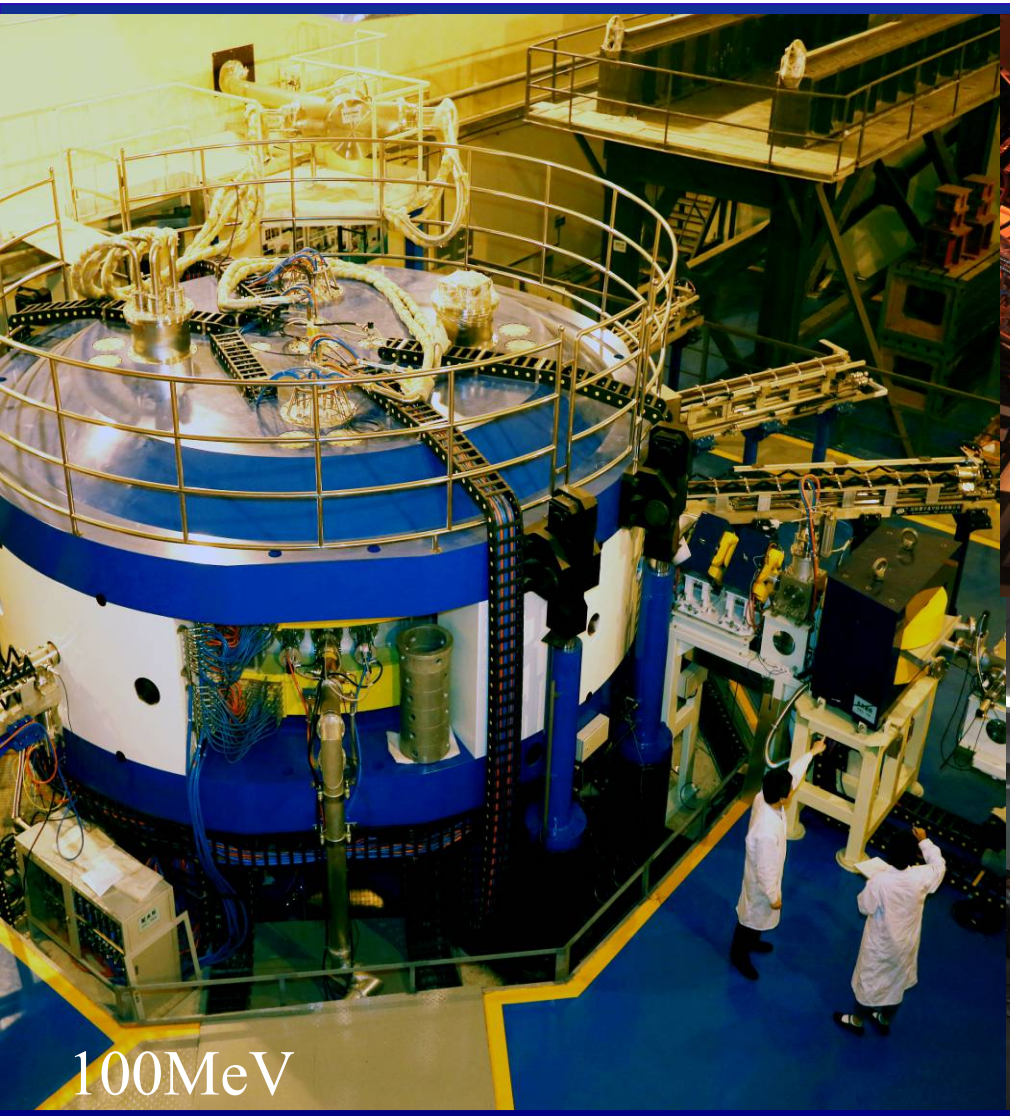
- On July 4th 2014, got first 100MeV/20μA proton beam from CYCIAE-100, awarded as Top10 scientific achievements of 2014 in China.
- Productions of intense proton and radioactive ion beam (RIB) ,carrying out research on nuclear data, radiation effect, material and life sciences and medical isotope production etc.

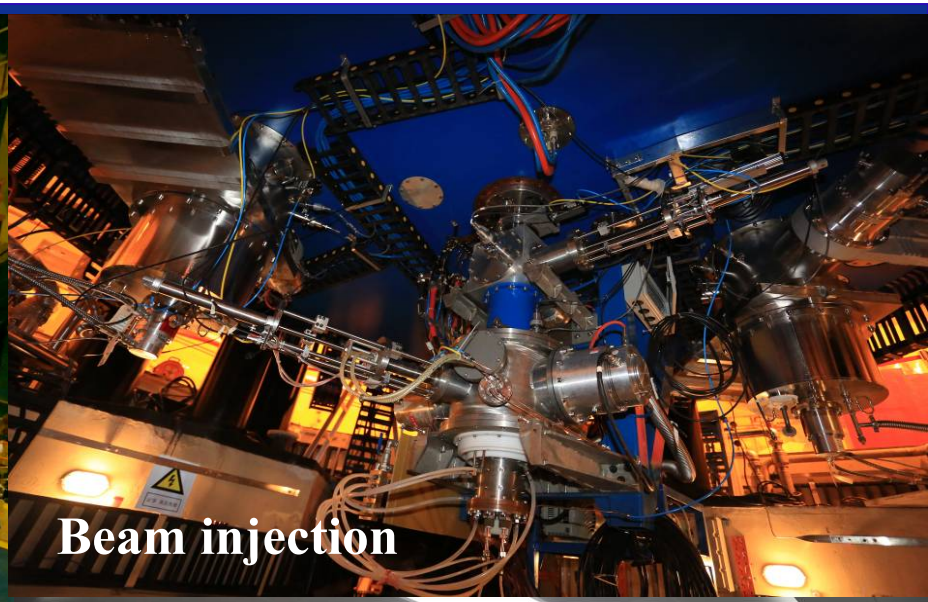


**Compact cyclotron**
**100 MeV /520 μA**


**Witness the cyclotron beam for the first time**

# Introduction to CYCIAE-100

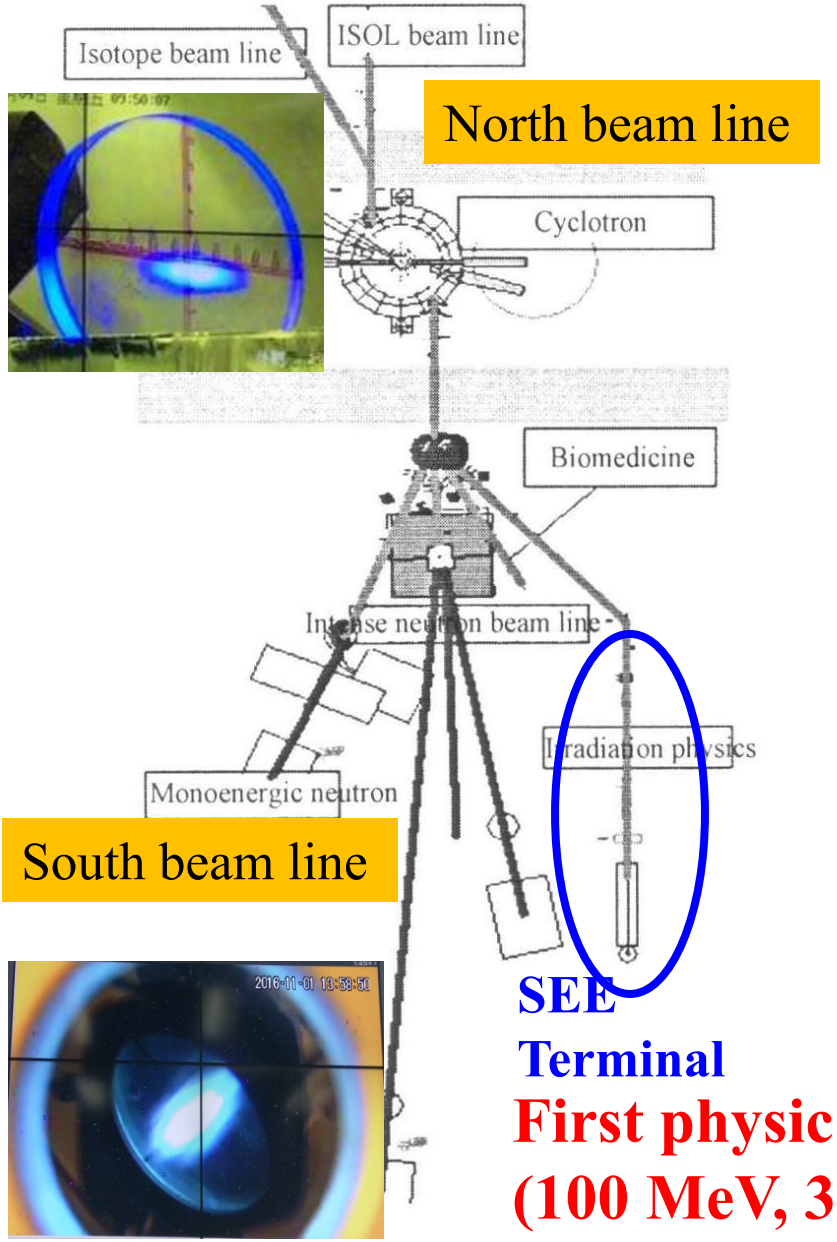


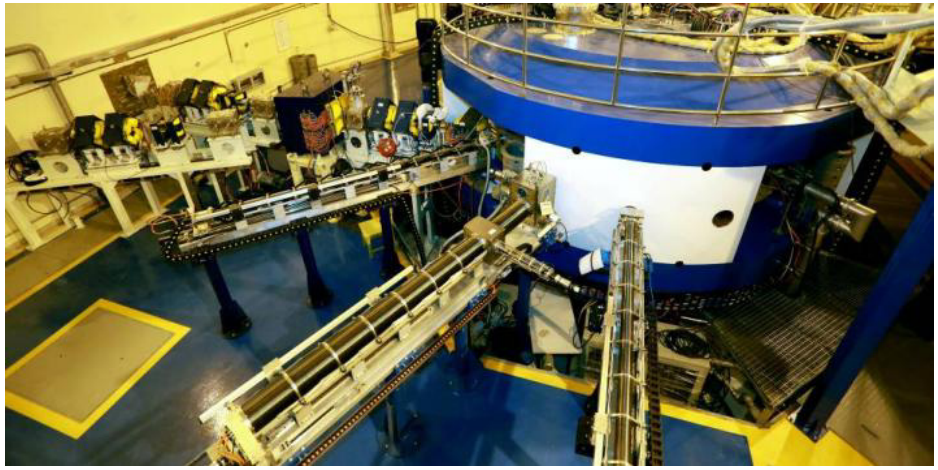





**The largest compact AVF cyclotron in the world**

# Introduction to CYCIAE-100

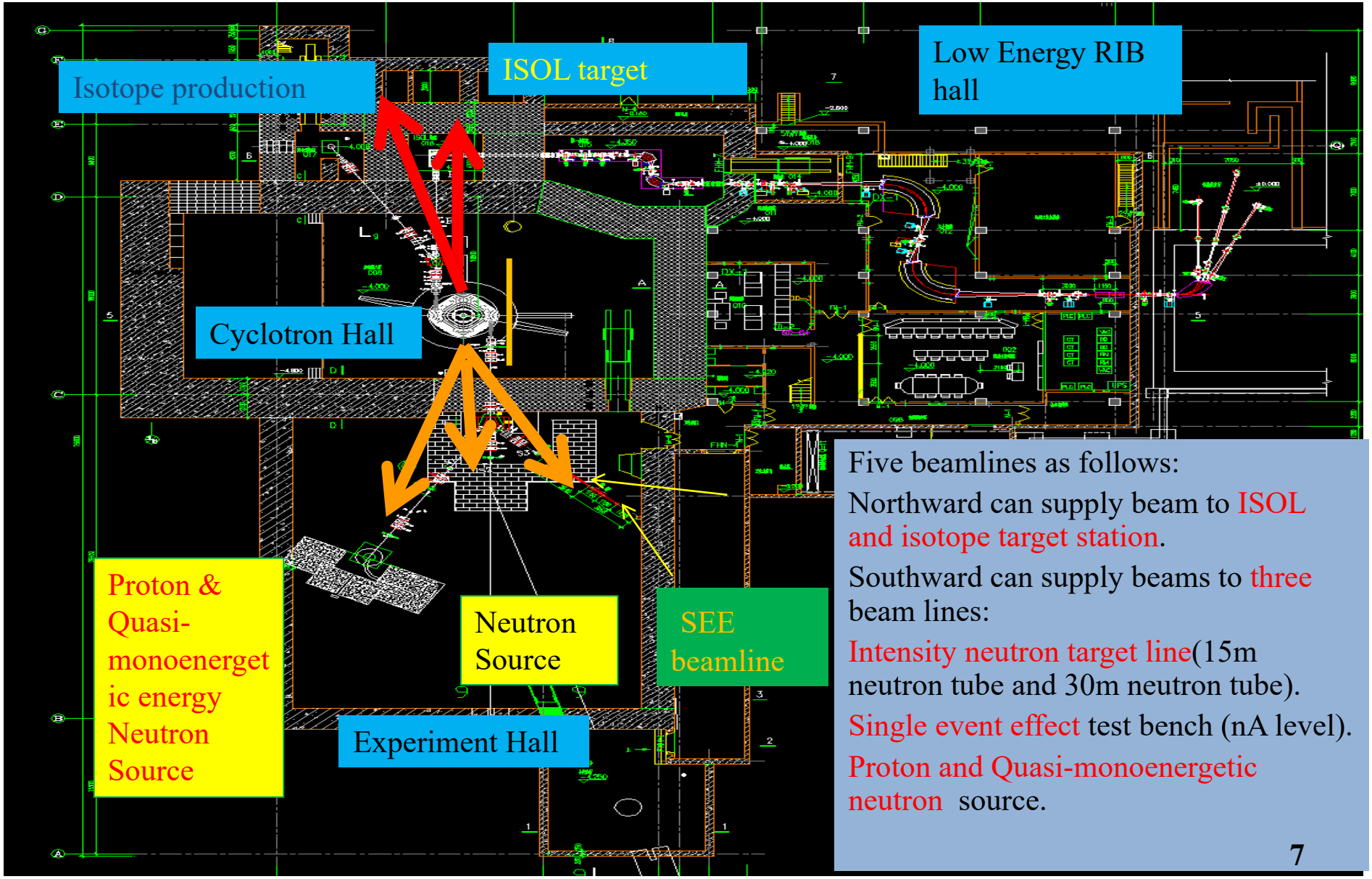


- High beam current -2pA-520uA max
- Beam energy range -70-100MeV
- High transport efficient- 99.9%
- Low operating cost
- Low magnification
- Simultaneously bio-extraction
- Multi-modes

**First physic experiment (SEE) in Nov. 2016 (100 MeV, 30nA)**

# 100 MeV Proton Cyclotron




Five beamlines as follows:

Northward can supply beam to ISOL and isotope target station.

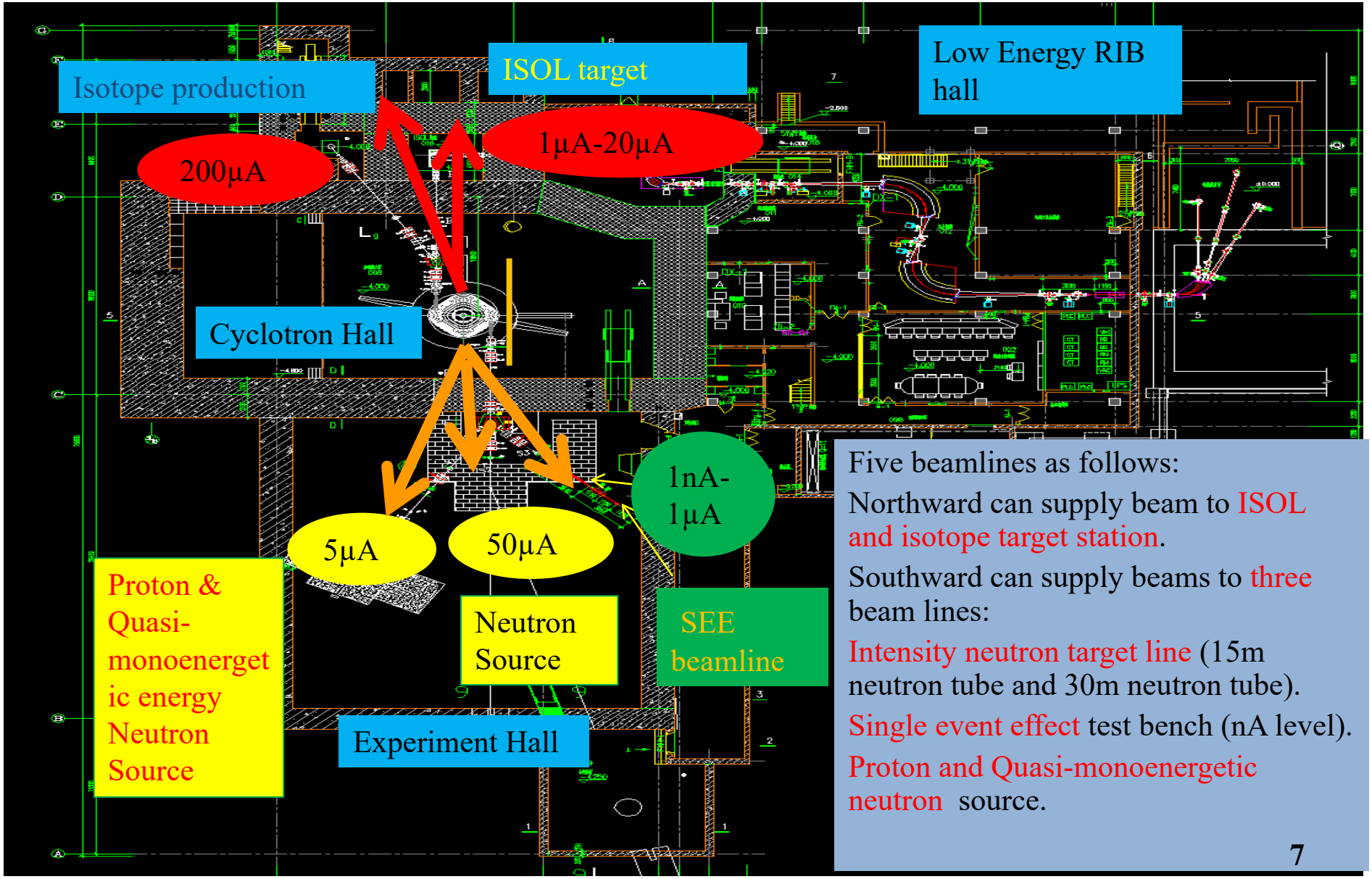
Southward can supply beams to three beam lines:

Intensity neutron target line(15m neutron tube and 30m neutron tube).

Single event effect test bench (nA level).

Proton and Quasi-monoenergetic neutron source.

# 100 MeV Proton Cyclotron

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# Application and research

**Up to Dec, 2022，100MeV cyclotron has produced over 5000 hours beam time for users**

**Users from different area**

- **Institutes for nuclear physics**
- **Medical schools**
- **Institutes for electronic and space technology**
- **Universities**

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CASC 中国航天
中国科学院新疆理化技术研究所 The Xinjiang Technical Institute of Physics & Chemistry CAS
中国空间技术研究院 China Academy of Space Technology
中国同辐股份有限公司 China Isotope & Radiation Corporation CNNC
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中国科学院近代物理研究所 Institute of Modern Physics, Chinese Academy of Sciences
国防科學技術大學 National University of Defense Technology

# Application and research

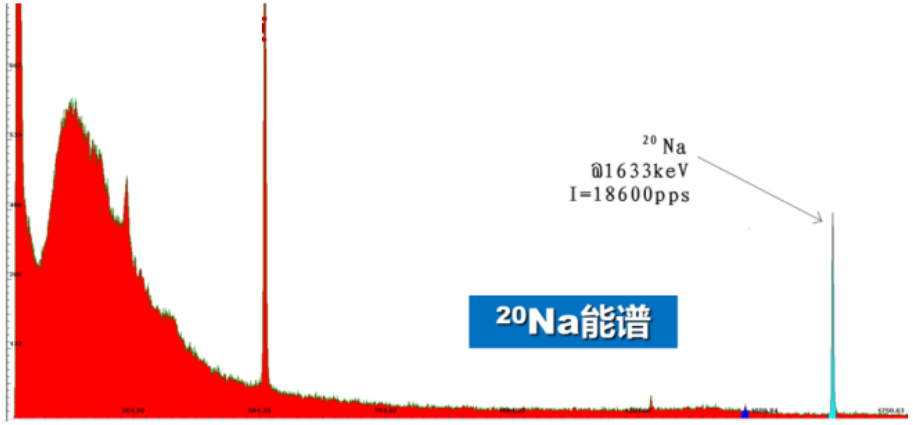
**The Usage of Cyclotron in our lab**

- nuclear physics research
  - Nuclear reaction, nuclear structure
- Radiation effect Research
  - Proton , neutron SEE, radiation resist
- Medical and other applications
  - Medical isotope production, proton therapy

# Application and research

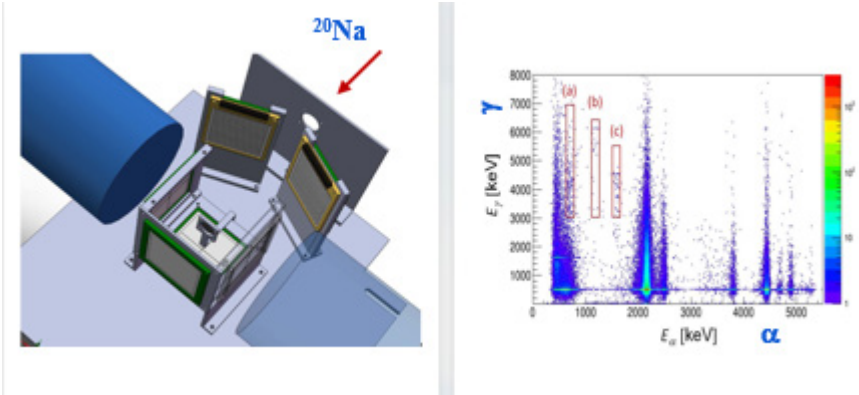
## Innovative achievements in radioactive nuclear beam physics

- The highest quality Na-20 radioactive beam is produced by using high resolution ISOL device in 2015, and the strange decay mode of β-γ-α of $^{20}$Na (Sodium)is discovered for the first time in the world.




$^{20}$Na energy spectrum diagram

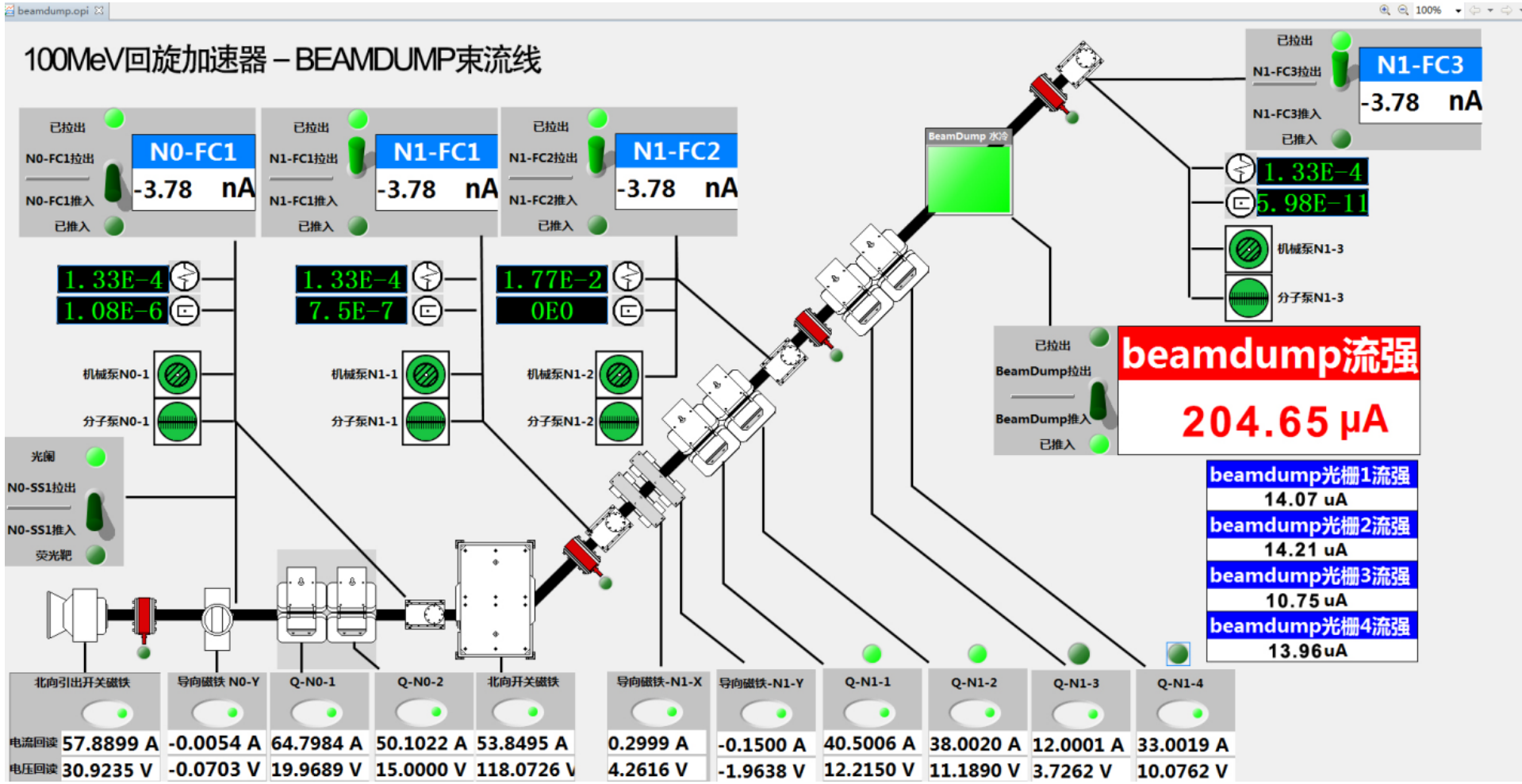
- brought China's nuclear astrophysics, radioactive nuclear beam physics and other scientific research into the international forefront.




$^{24}$Mg(p,xpn)$^{20}$Na

# Application and research

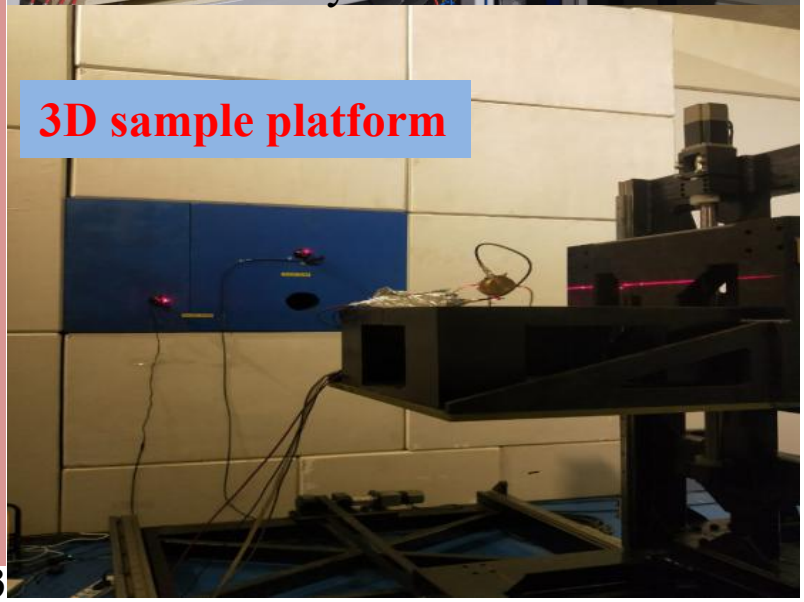
100MeV cyclotron achieved the design goal of 200 μA in 2018,
Then promote the beam current to 520 μA max at last.



# Application and research

## Quasi-monoenergetic neutron experiment

- calibration of high energy neutron,a bottleneck restricting space neutron detection .
- the quasi-monoenergetic neutron reference radiation field in the energy region above 20MeV is established, and the calibration technology of neutron spectrometer is studied.
- China is the second country in the world with neutron reference radiation field and calibration ability in the energy region above 20MeV.

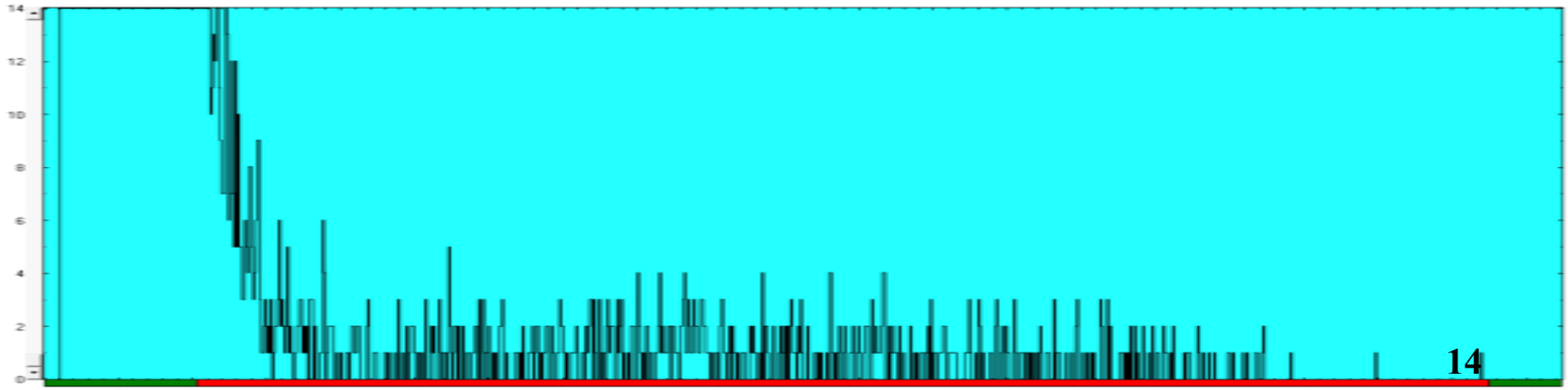



# Application and research

## Quasi-monoenergetic neutron platform

- The quasi-monoenergetic neutron target consists of three beryllium targets with thickness of 0.4mm, 0.5mm and 0.6mm and one fluorescent target.
- Beryllium and beryllium oxides have strong chemical toxicity, so the quasi-monoenergetic neutron target is completely sealed and maintains a certain negative pressure. “
- Prof. Li will give details in Session FRB-1.

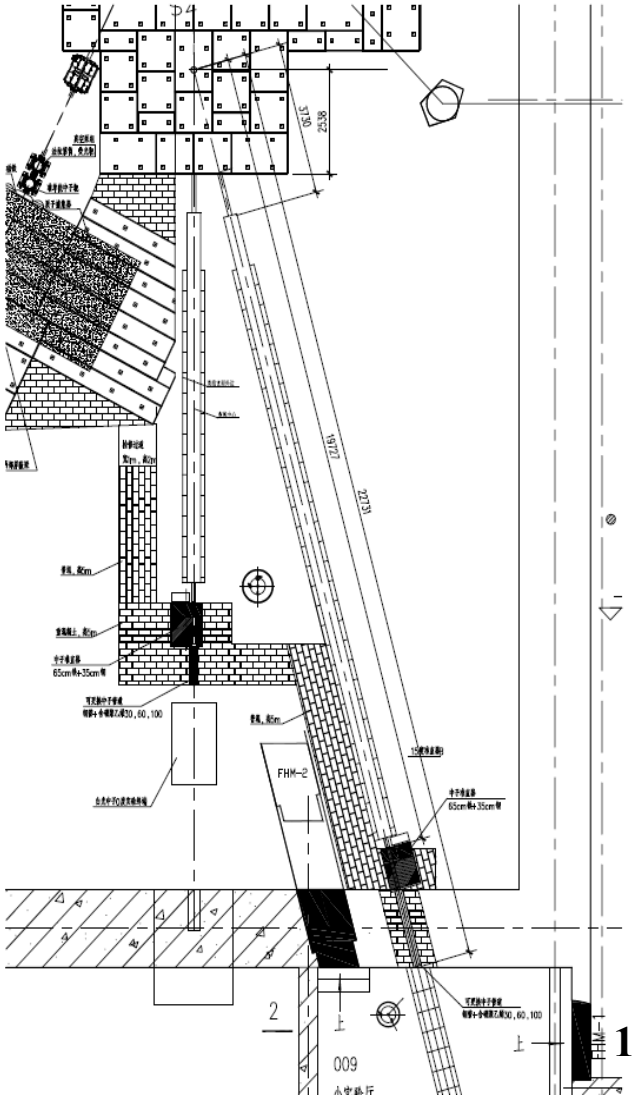
Fission ionization chamber measurement signal



# Application and research

## High energy neutron platform of Nuclear data

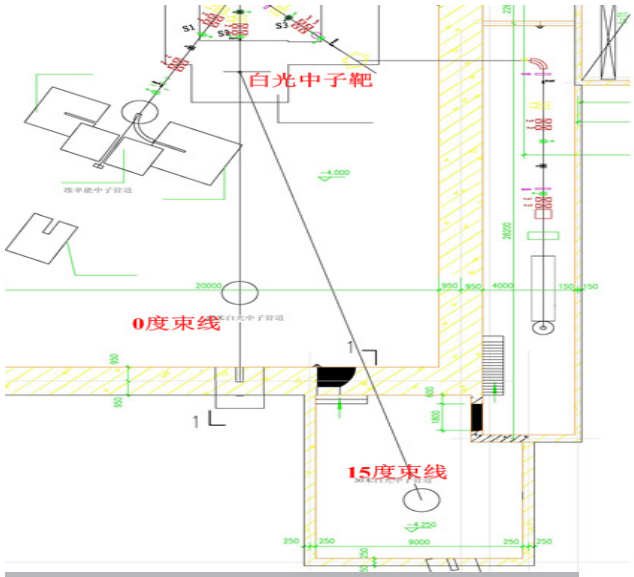
- Continuous spectrum neutron nuclear data Measurement platform.
- The construction of beam line and experimental terminal was completed in 2021.
- Proton bombardment of tungsten target to produce neutrons

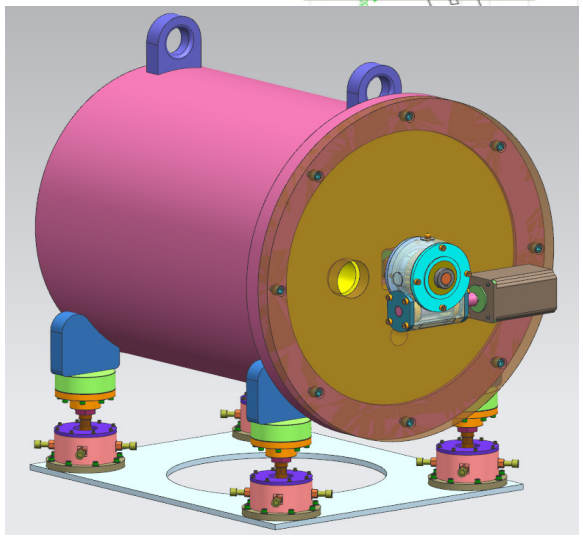


# Application and research

## High energy neutron platform of Nuclear data

- The co-axiality error between neutron collimation hole and neutron beam pipe is less than 0.10mm.
- The collimator is composed of 35cm copper at the front end and 65cm iron at the rear segment.
- four kinds of collimating aperture choices of 30mm, 60mm, 100mm and complete shielding.

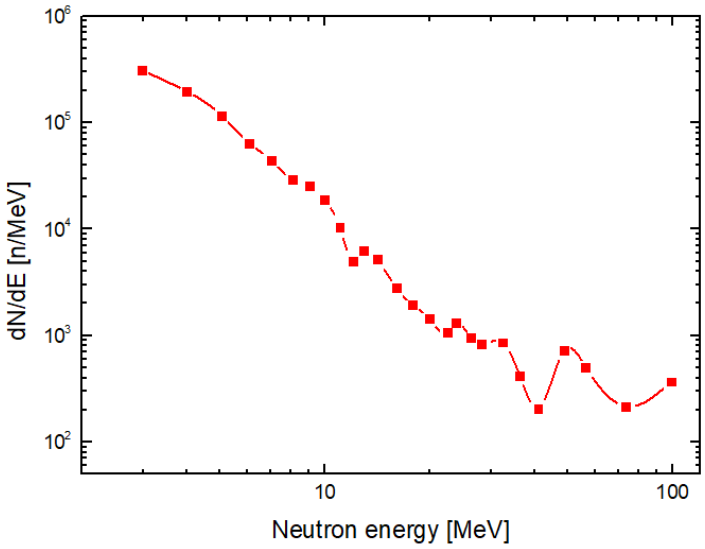


# Application and research

## High energy neutron platform of Nuclear data

- Measurement of spectrum by double liquid scintillation neutron time-of-flight method
- Neutron energy range is 3-100MeV
- When the proton current is 1 μA, the measured neutron Fluence in the energy region of 3 -100 MeV is about 3.28 × 10 E4 $cm^{-2}s^{-1}$.



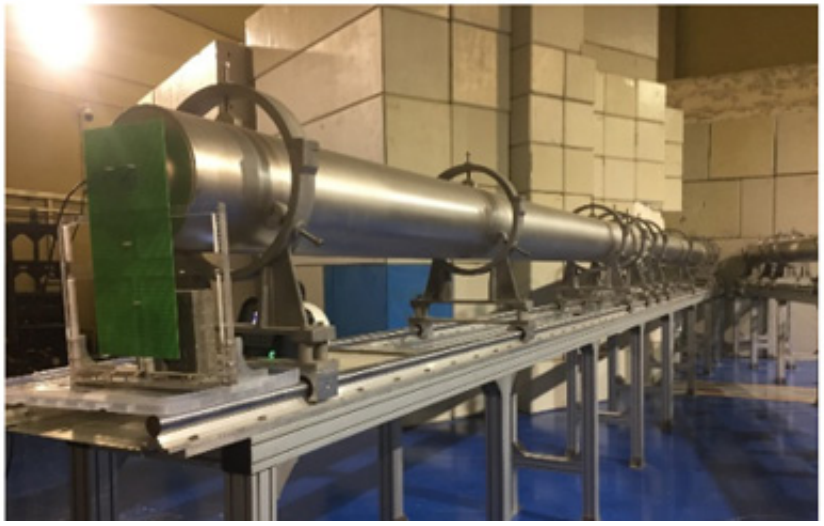

Comparison between theoretical and experimental values of neutron spectrum (1 μ A proton)

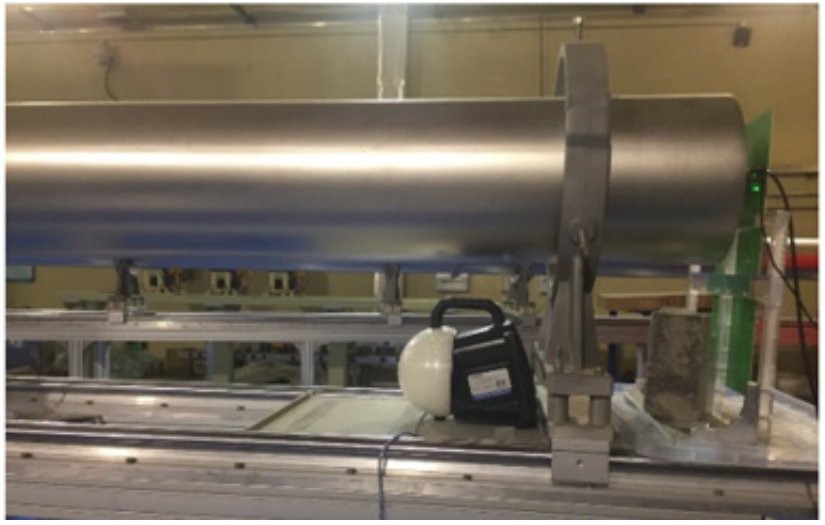
| | 0-1MeV | 1-3MeV | 3-10MeV | 10-100MeV | Total |
|---|---|---|---|---|---|
| Theoretical | 3.53E4 | 2.59E4 | 1.90E4 | 0.74E4 | 7.95E4 |
| | 44.4% | 32.6% | 23.9% | 9.3% | 100% |
| Experimental | / | / | 2.87E4 | 0.41E4 | 3.28E4 |
| | / | / | 87.6% | 12.4% | 100% |

# Application and research

## High energy neutron platform of Nuclear data

- The first neutron single event effect (SEE) experiment was carried out using neutron beam line.
- Three kinds of SRAM devices with different characteristic sizes were tested by single event reversal (SEU).
- the beam from ion source was pulsed as 5MHz， Experiments related to pulsed neutron beam can be carried out, which greatly improves the research conditions of continuous spectrum in China.

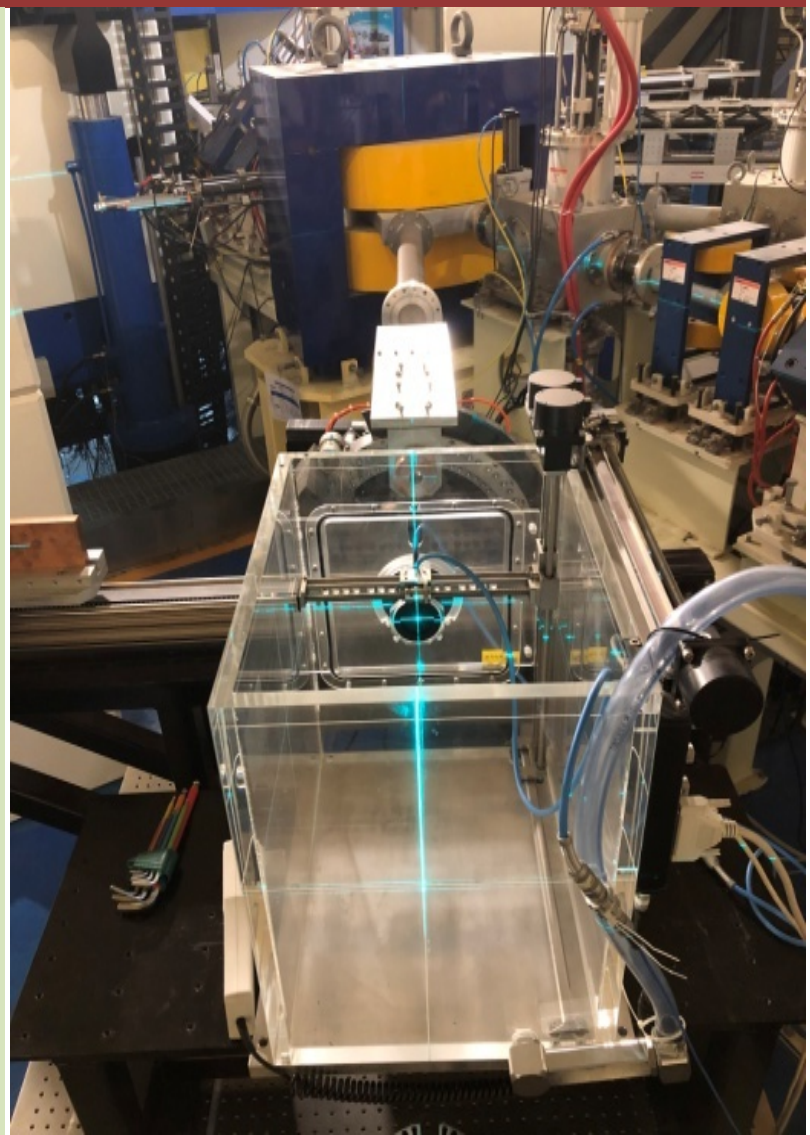




# Application and research

## Radiation dose measurement

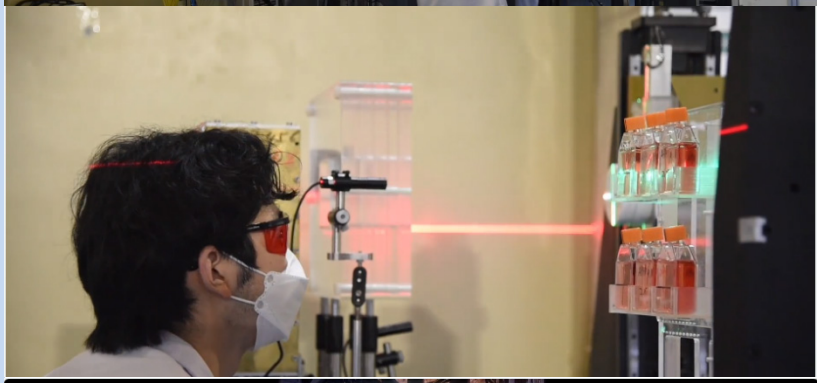
- **purpose:** proton beam water absorbed dose determination technology, measure the proton beam water absorbed dose absolutely and relatively in two ways
- establishing the proton beam water absorbed dose transfer system, and provide measurement technical support for astronaut proton dose monitoring.
- **results:** measurements of water absorbed dose of proton beam were completed (0.8Gy/min, 1nA).



# Application and research

## Biological and medical experiments irradiated by protons

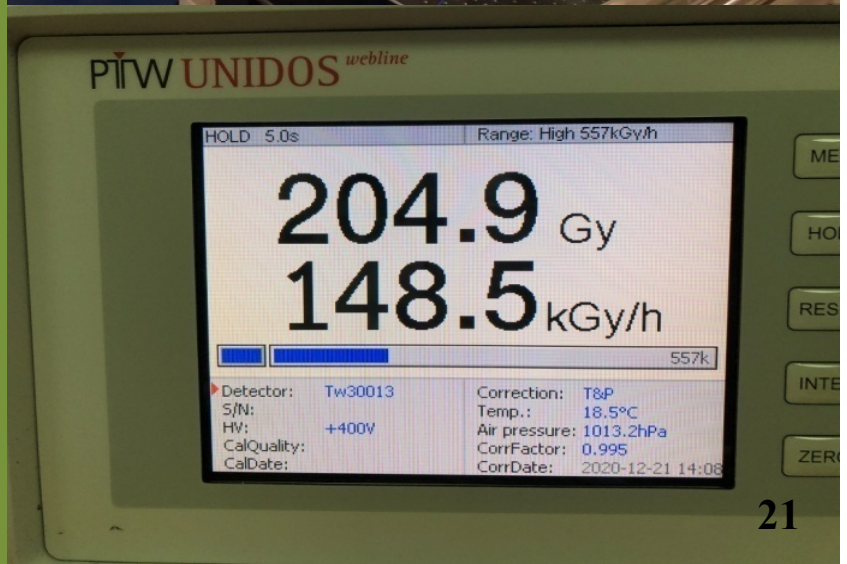
- In the face of complex space radiation environment, Proton radiation has an important effect on the life and health of astronauts of space mission.
- The batch of important data of intestinal microflora of mice irradiated by intermediate energy proton were successfully obtained and confirmed for the first time that proton irradiation had an effect on intestinal microflora in mice.
- enhance the health protection ability of astronauts, which will provide a solid scientific and theoretical support for the smooth promotion of China's deep space exploration.



# Application and research

## Biological and medical experiments irradiated by protons

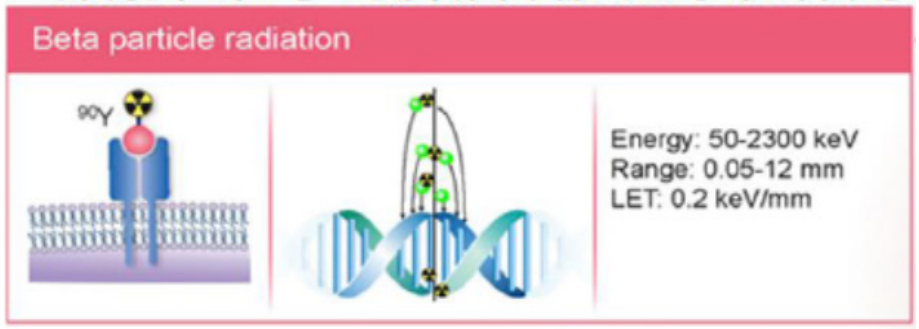
- Radiotherapy , a common method for the treatment of cancer. FLASH imaging is delivered at an ultra-high dose rate (> 40Gy/s), Reducing the normal tissue toxicity .
- on the N3 line of 100MeV cyclotron, three-dimensional water phantom PTW, Bragg peak ionization chamber , reference ionization chamber and finger ionization chamber were used for dose measurement.
- The ultra-high dose rate of 40.76Gy/s (204.9 for 5 second) is obtained in this test, which can be used in the study of proton FLASH.

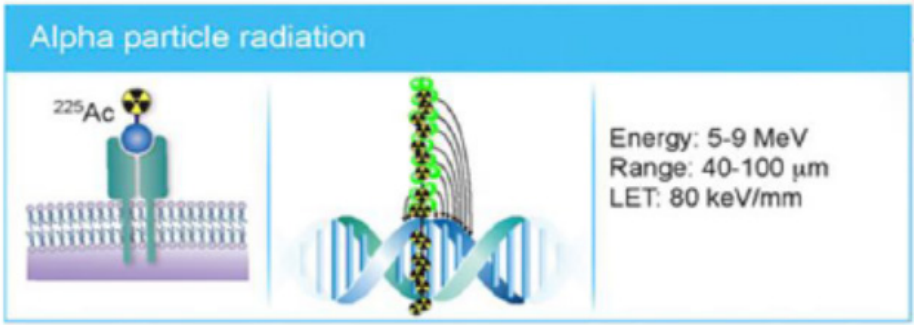


# Application and research

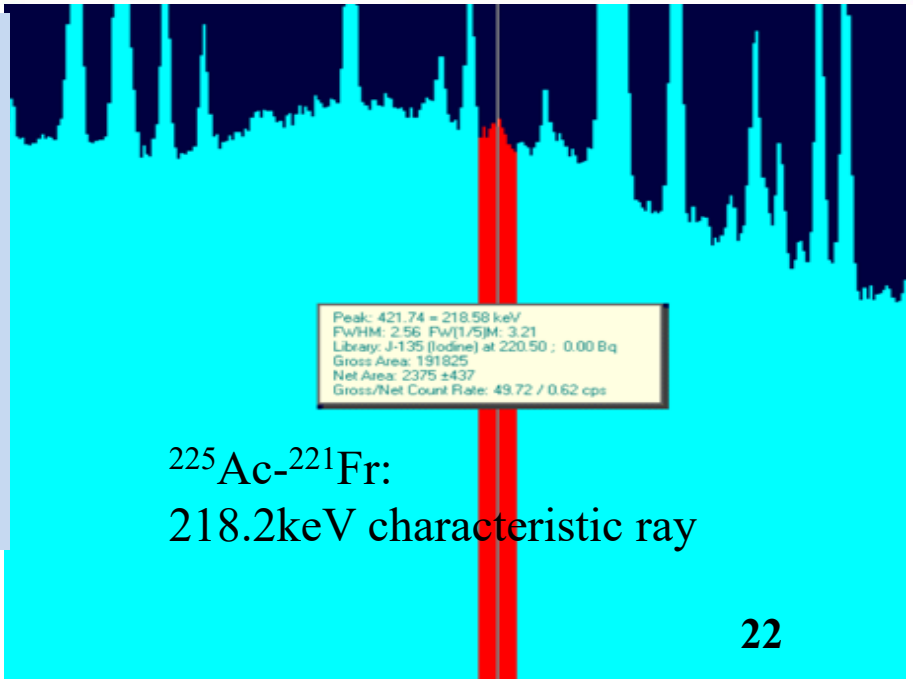
## **Isotope production** experiments irradiated by protons

**The first production of Ac-225 with 100MeV cyclotron in China**



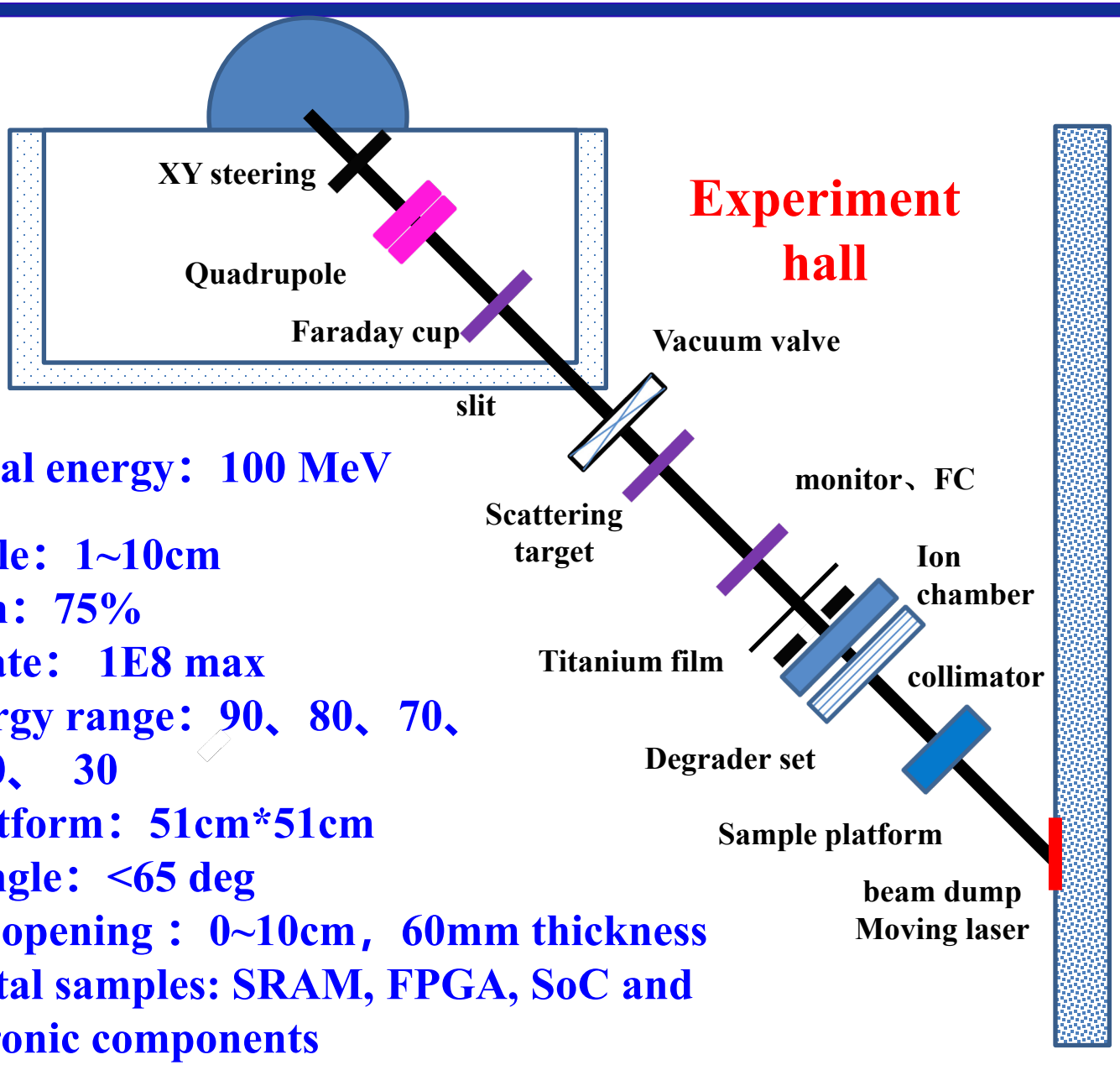




- Through the design and research of isotope solid target system, a high power solid target radionuclide experimental device has been successfully developed, and core technologies have been mastered.
- It has laid a solid foundation for the research of other nuclides related to the production of accelerators.




$^{225}$Ac-$^{221}$Fr:
218.2keV characteristic ray

# SEE Proton line Phase I

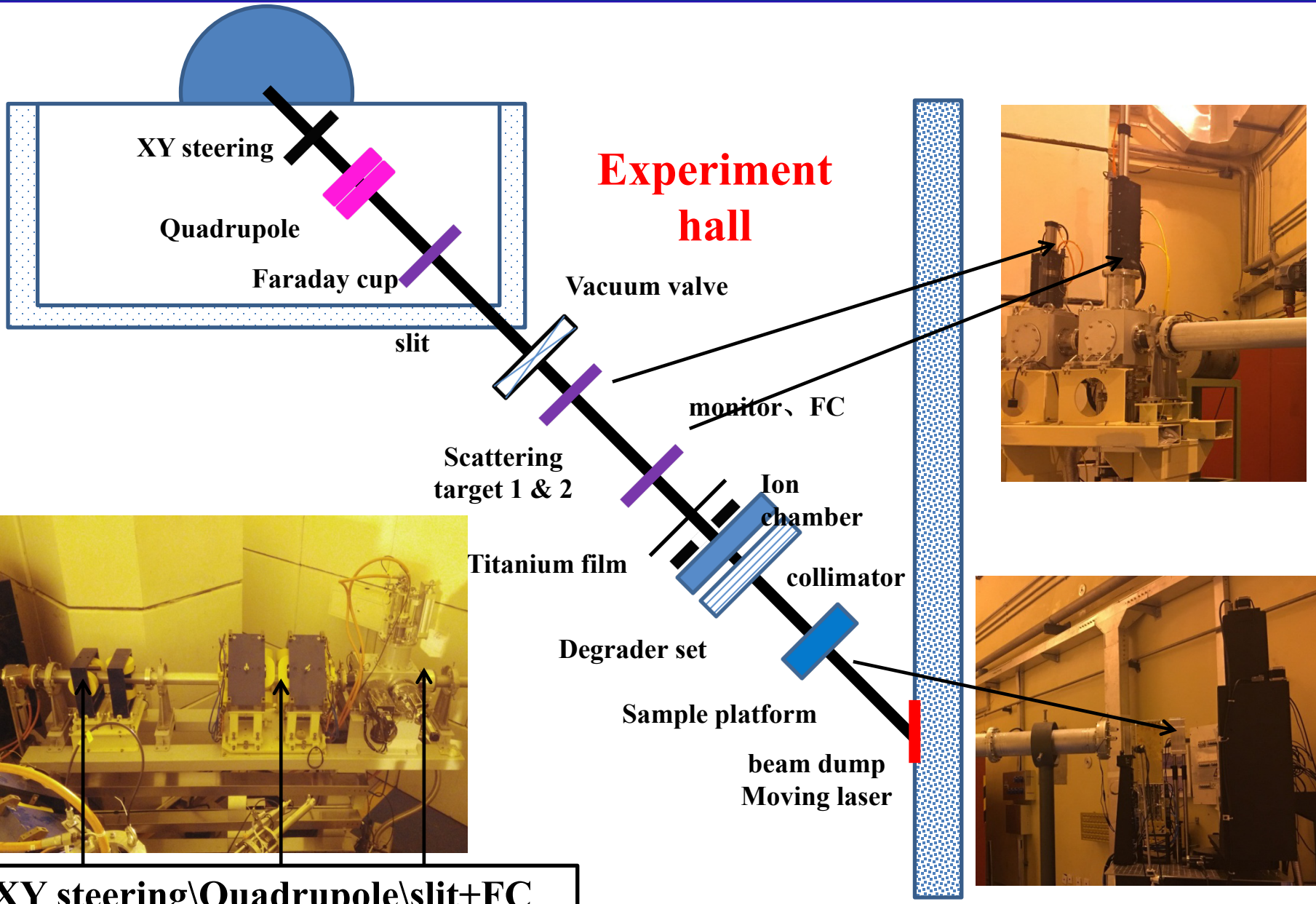



Proton initial energy：100 MeV

Beam profile：1~10cm
distribution：75%
Injection rate： 1E8 max
Proton energy range：90、80、70、60、50、40、 30
Sample platform：51cm*51cm
Rotation angle：<65 deg
Collimator opening ：0~10cm，60mm thickness
Experimental samples: SRAM, FPGA, SoC and other electronic components

Test system area

# SEE Proton line Main parts



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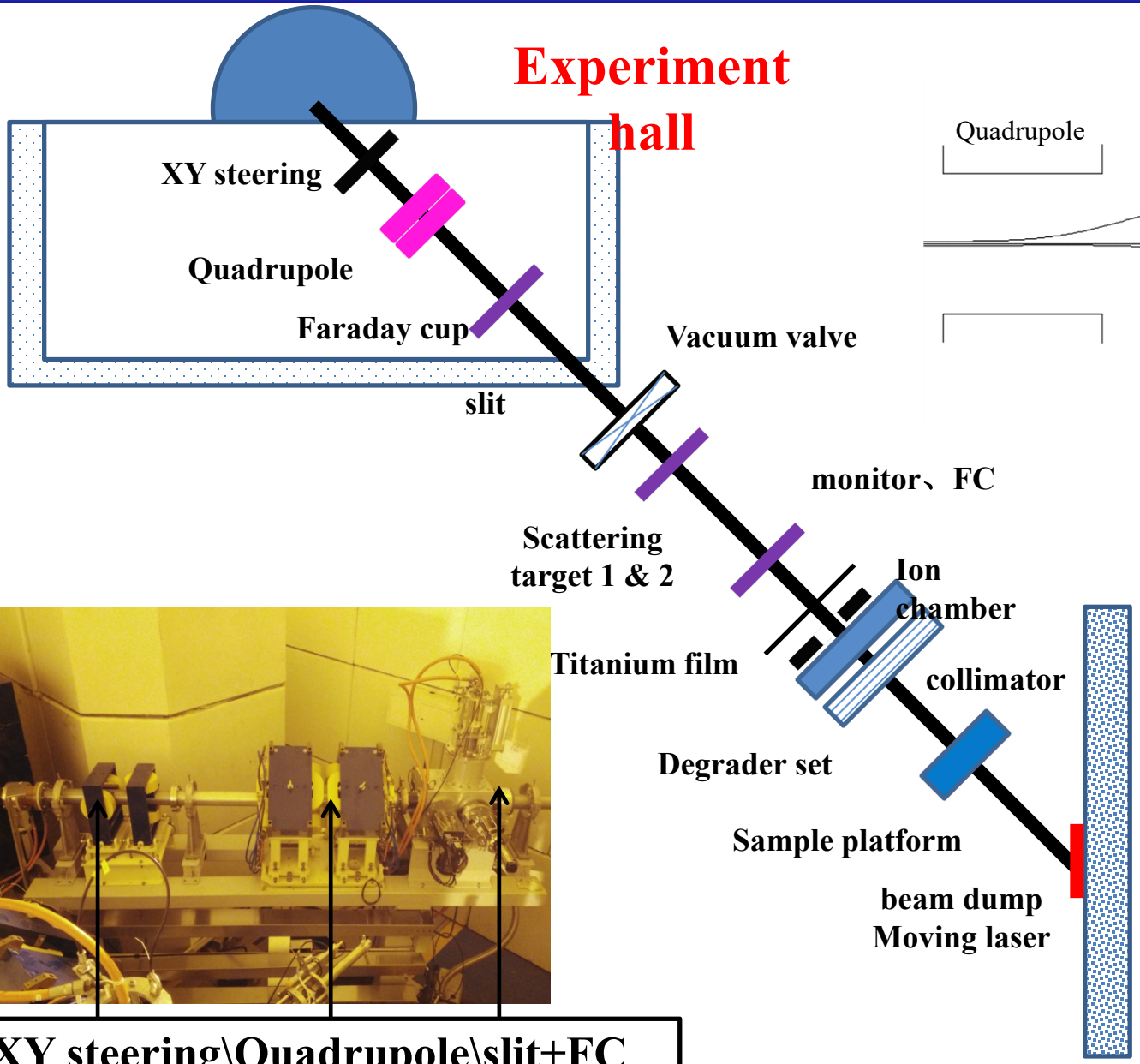
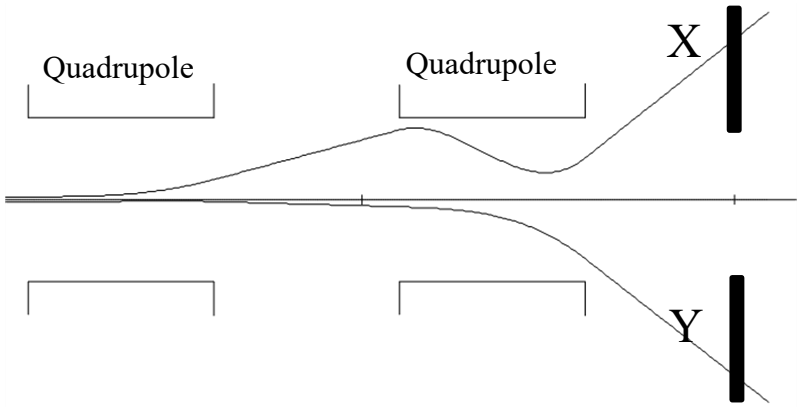


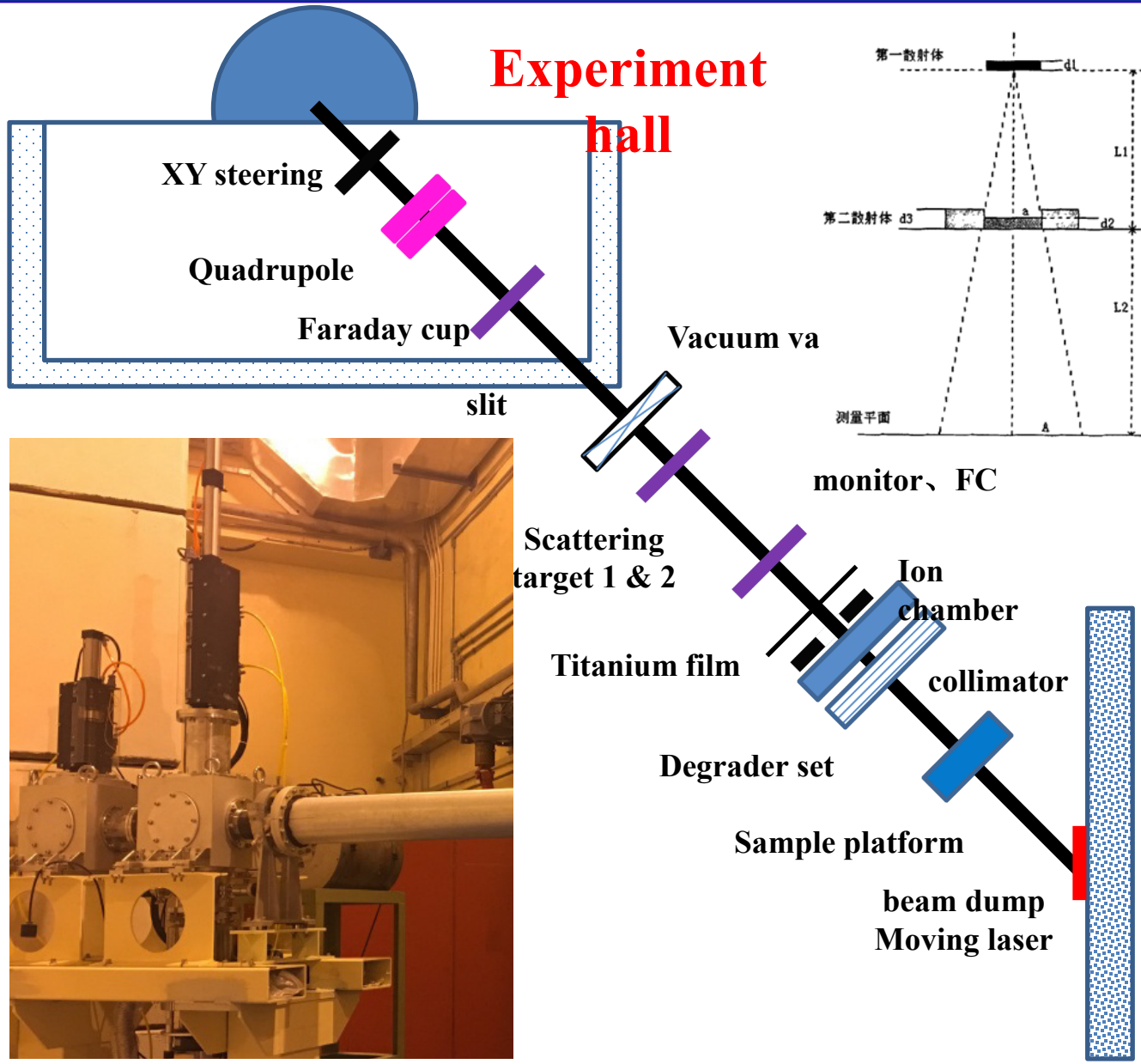



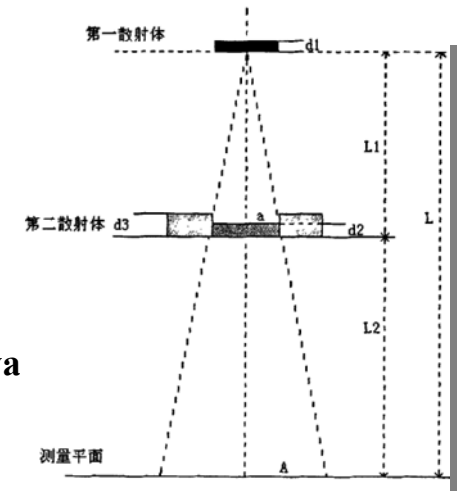


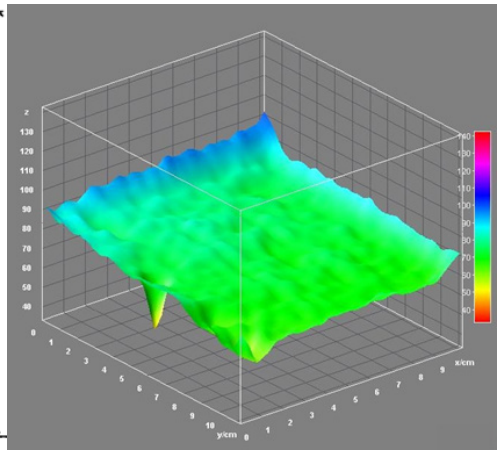

XY steering\Quadrupole\slit+FC

**Beam lowering system**

# SEE Proton line Main parts



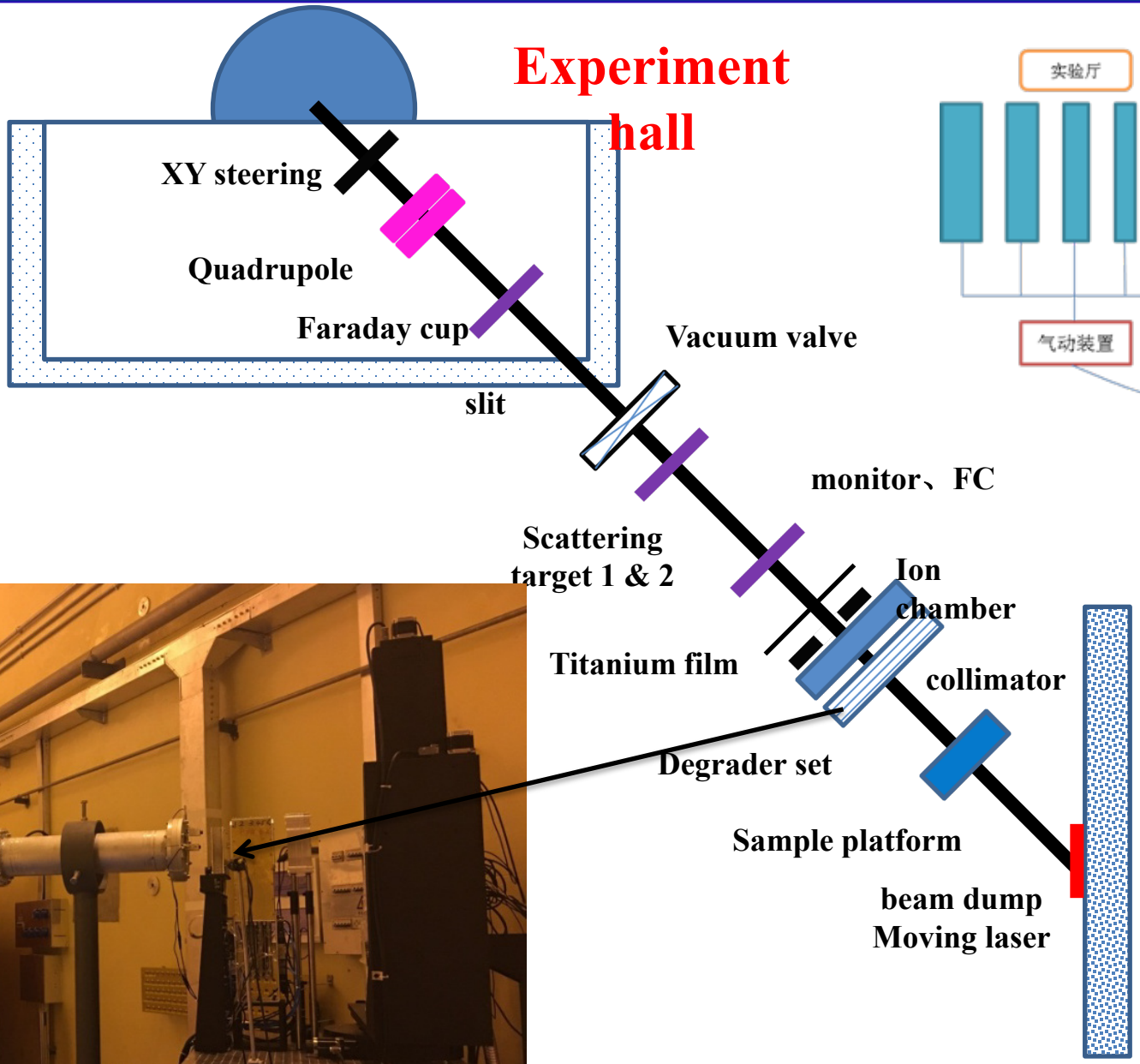



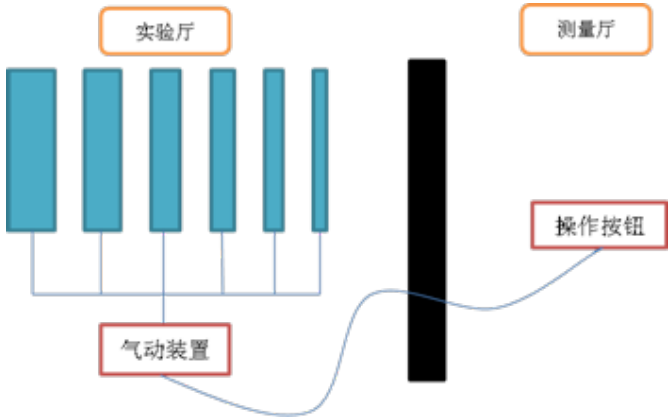



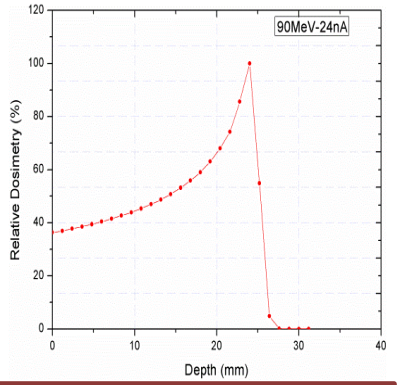


**Beam scattering system**

# SEE Proton line Main parts

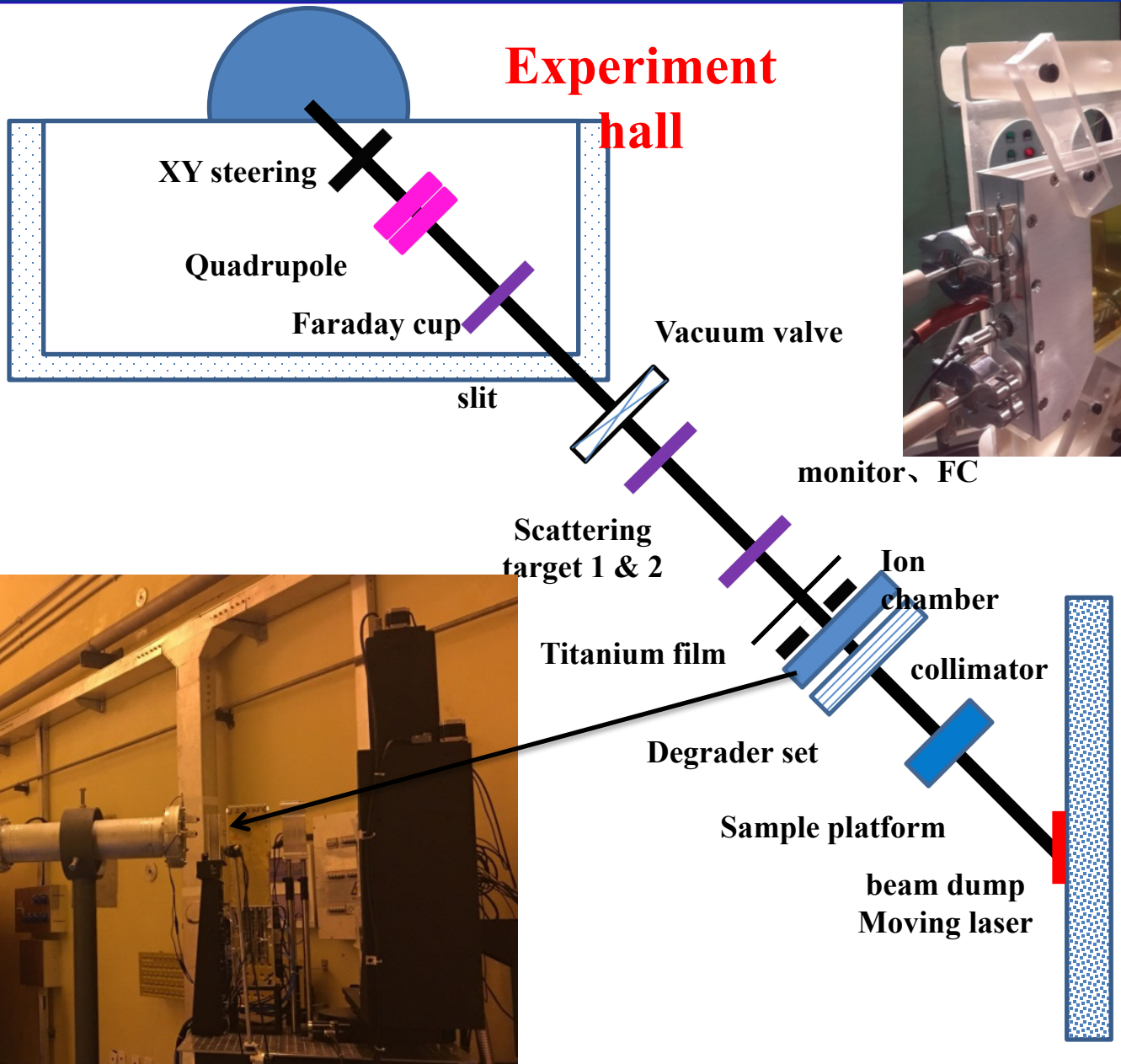


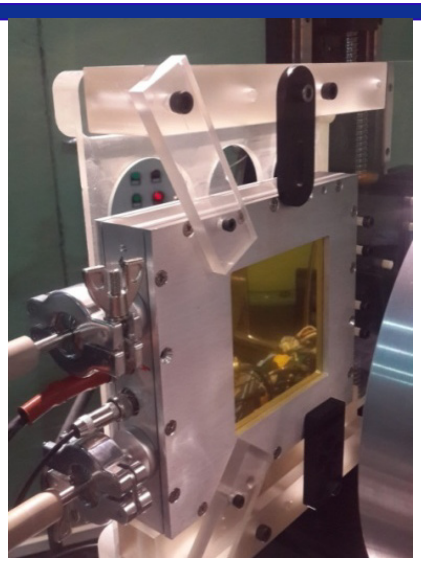



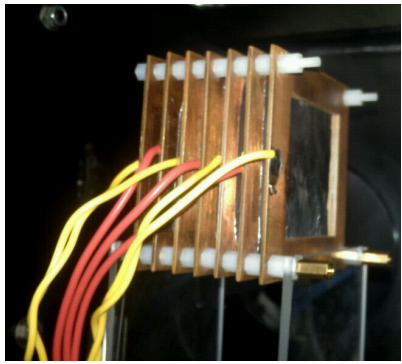



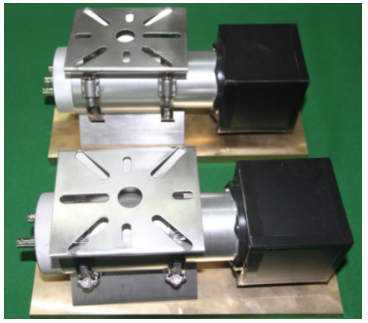

**Beam degrading system**

# SEE Proton line Main parts



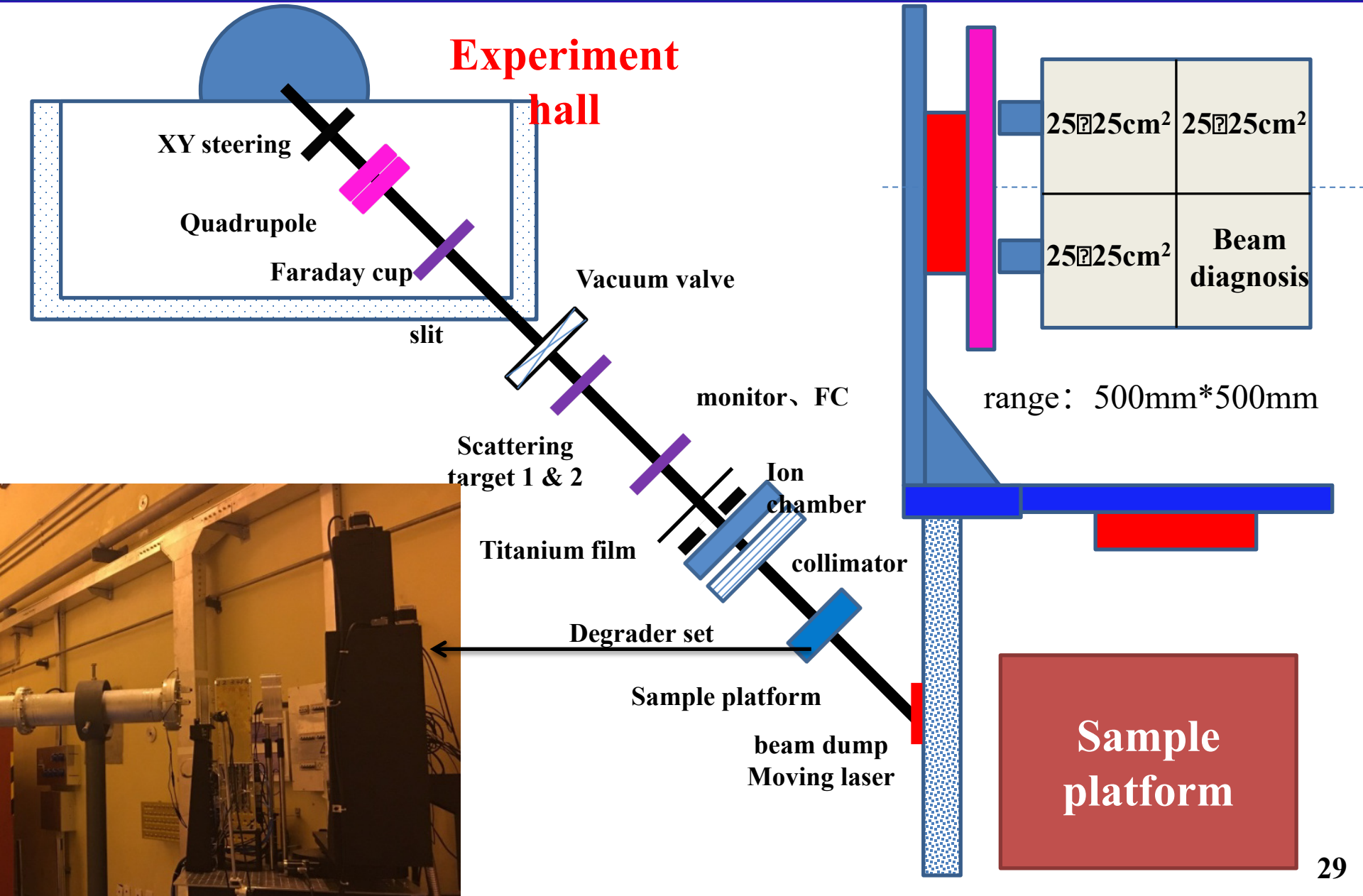






**Beam diagnosis system**

# SEE Proton line Main parts

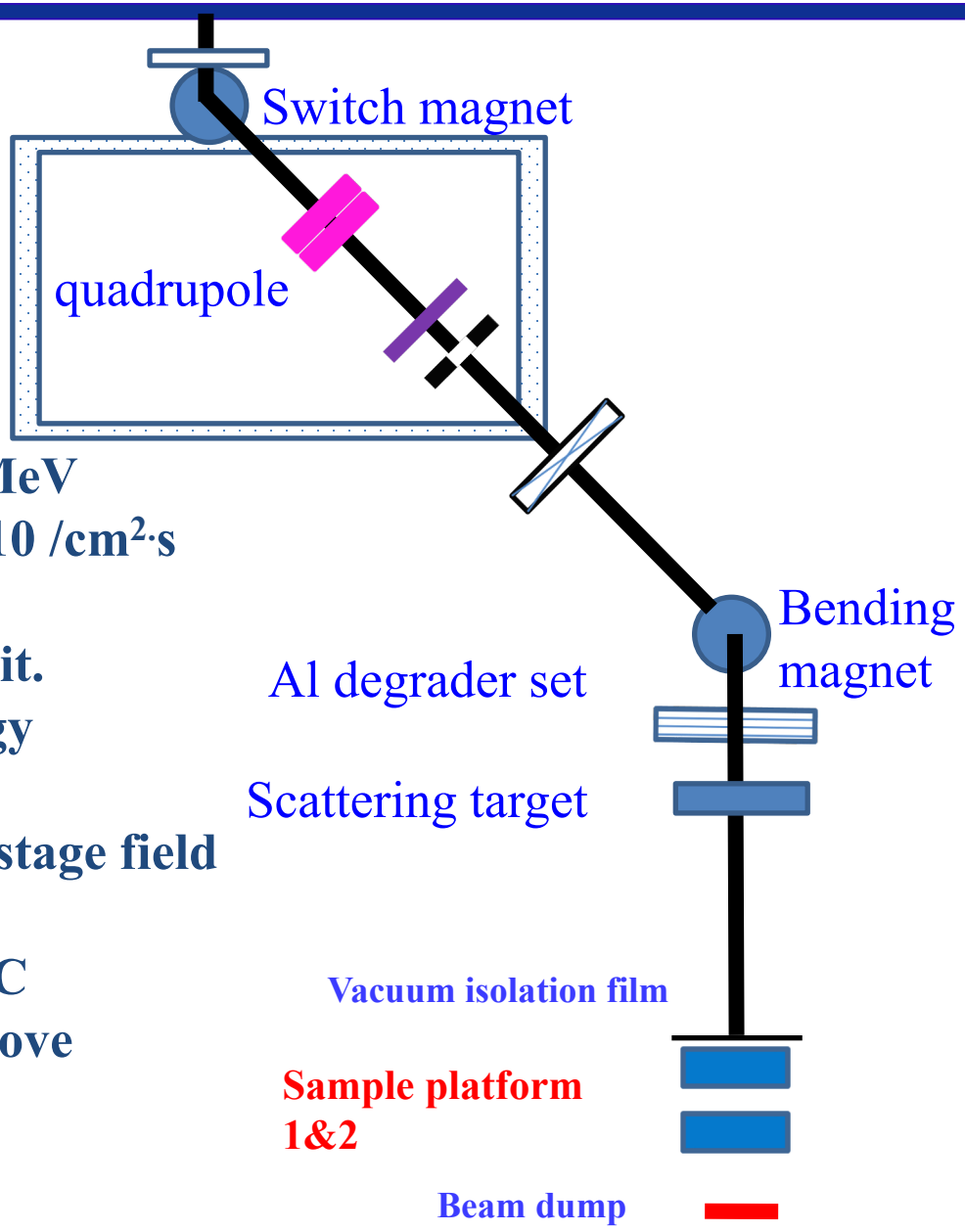


# SEE Proton line Phase II

- ✓ Beam energy：10-100 MeV
- ✓ Injection rate：1E6-1E10 /cm$^2$·s

- ✓ Beam drop: defocus + slit.
- ✓ Energy reduction: energy reduction tablet.
- ✓ Beam expansion: multi-stage field

- ✓ Beam diagnosis：SC+FC
- ✓ DUAL platform to improve efficiency

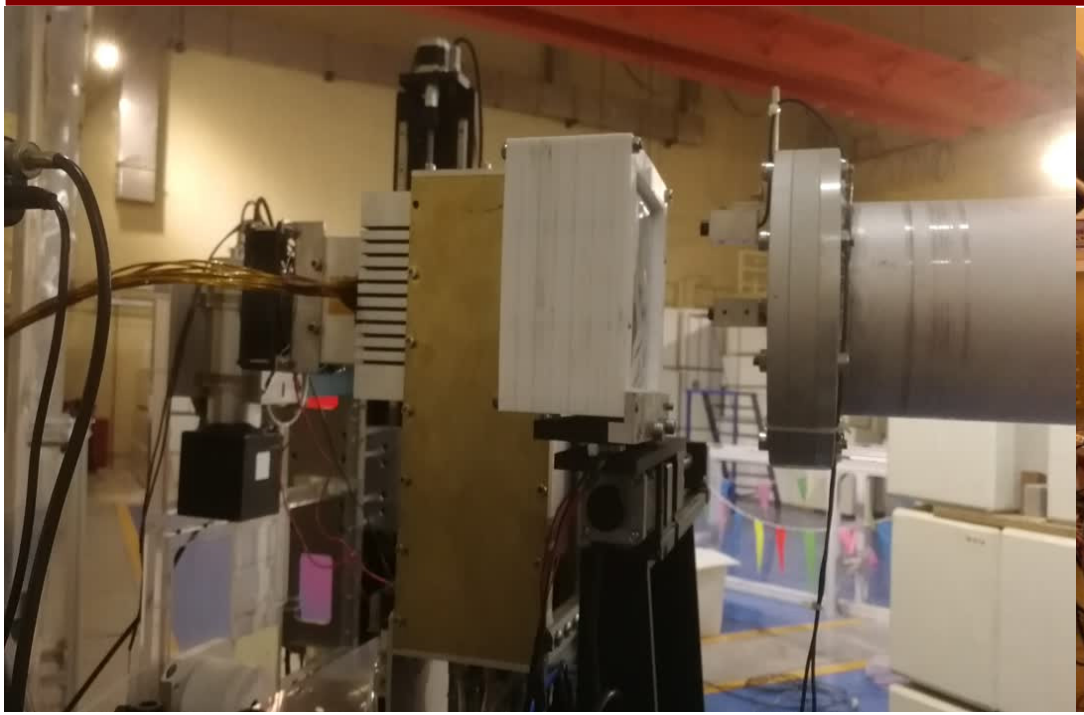


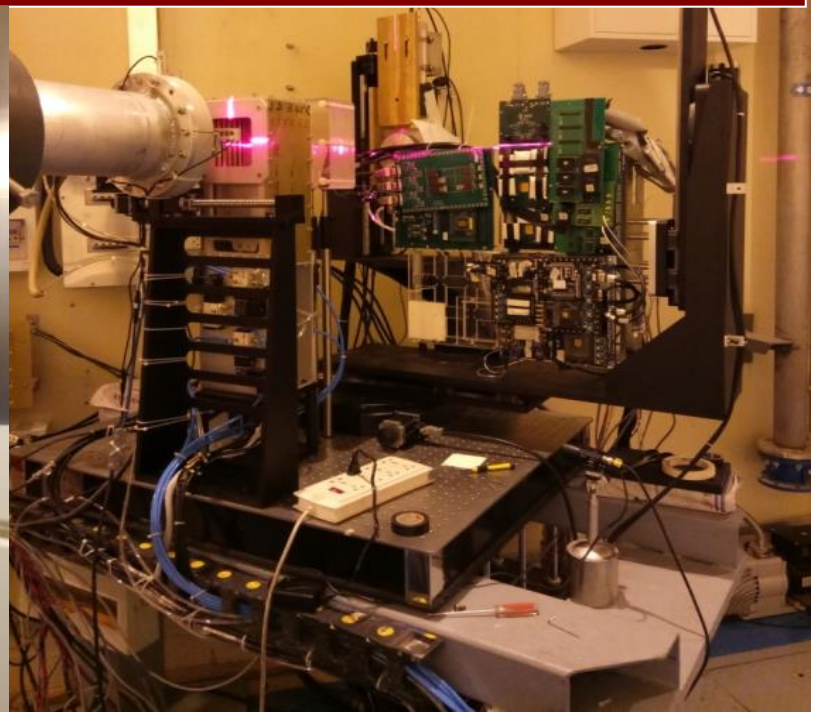
# Application and research

## CIAE first SEE experiment

Background: cell density of devices in the circuit continue to increase, the range of radiation of a single particle can cover multiple devices. Furthermore, the charge collection effect is caused by multiple nodes in the circuit, and the displacement effect is produced in the circuit.

**0.25μm 8×512k×8bits CMOS SRAM**



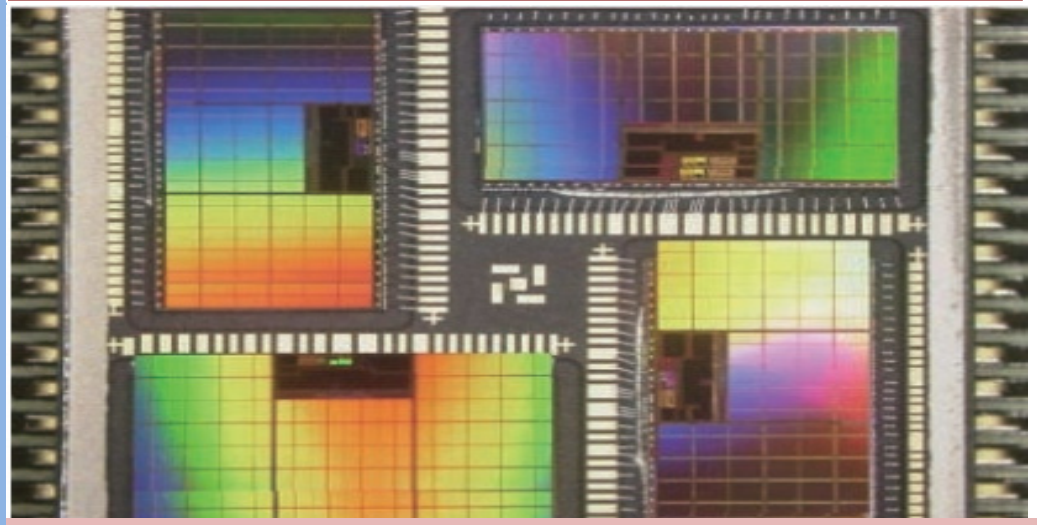


# Application and research

## Space environment radiation effect

- Result: the CMOS device has a shift effect when the proton irradiation flux is 2E11 , and the overall performance of the device decreases with the emergence of the displacement effect.
- the space proton has a displacement effect on aerospace CMOS devices, which should be considered and strengthened in the practical application environment.

**0.25μm 8×512k×8bits CMOS SRAM**

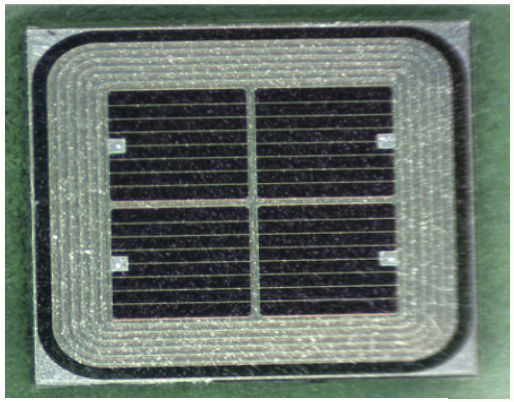


- CIAE jointly carried out the first experiment on the proton single event effect in Nov. 2016, Fill the gap in the anti-radiation experiment of intermediate energy protons in China.

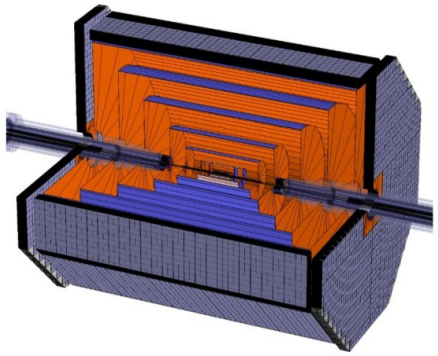
# Application and research

## Innovative achievements in radioactive effect

Time resolution of two low-gain avalanche amplified silicon sensors is lower than 30ps after irradiation with contrast to Spain and Japan about 50ps

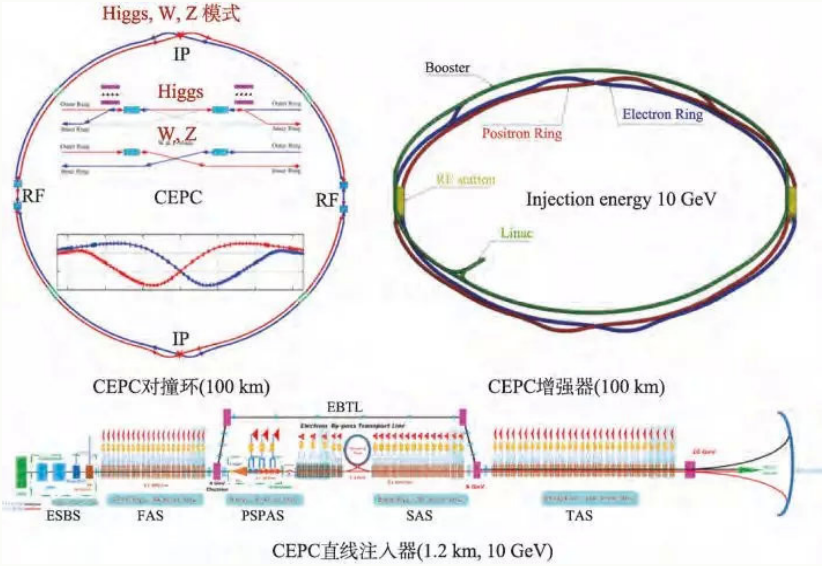


LGAD chip，
2.6mm*2.3mm



Detector profile

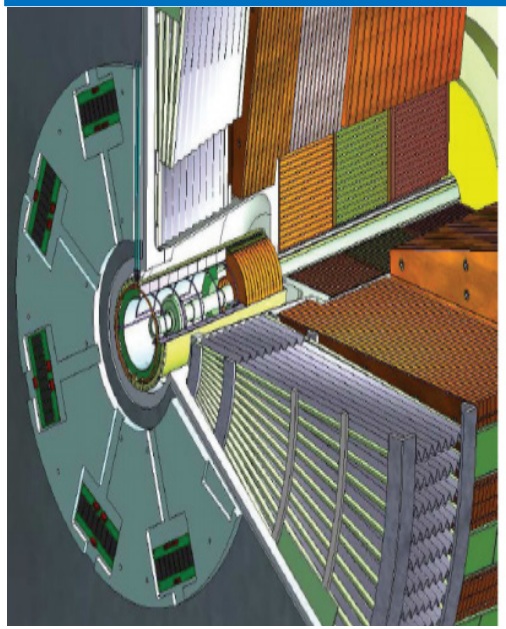
CEPC Model

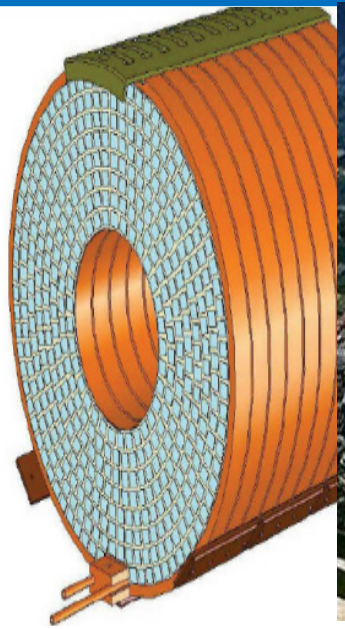


# Application and research

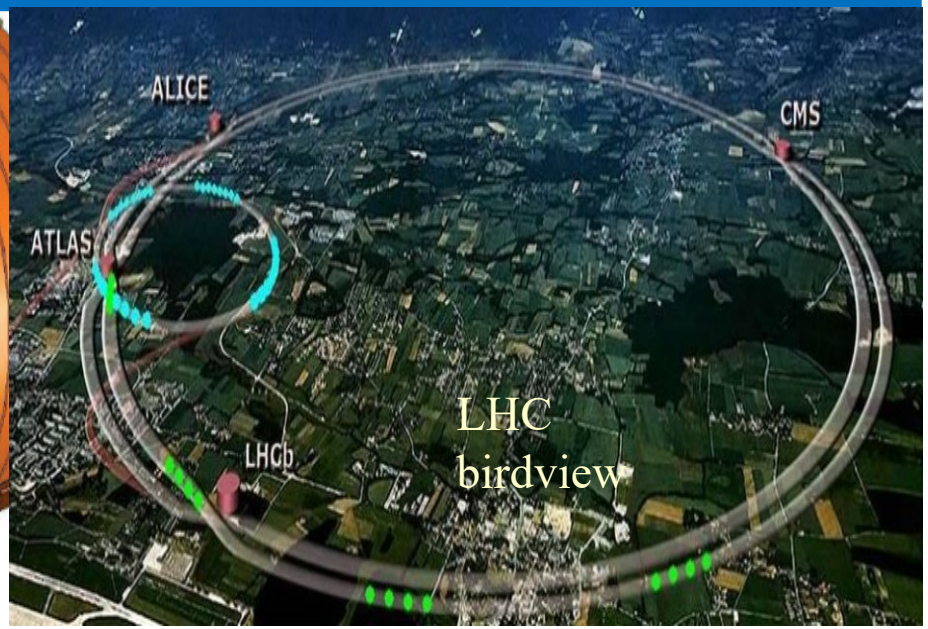
## Innovative achievements in radioactive effect

### Experimental verification of key technologies of LHC/ATLAS single crystal diamond detector





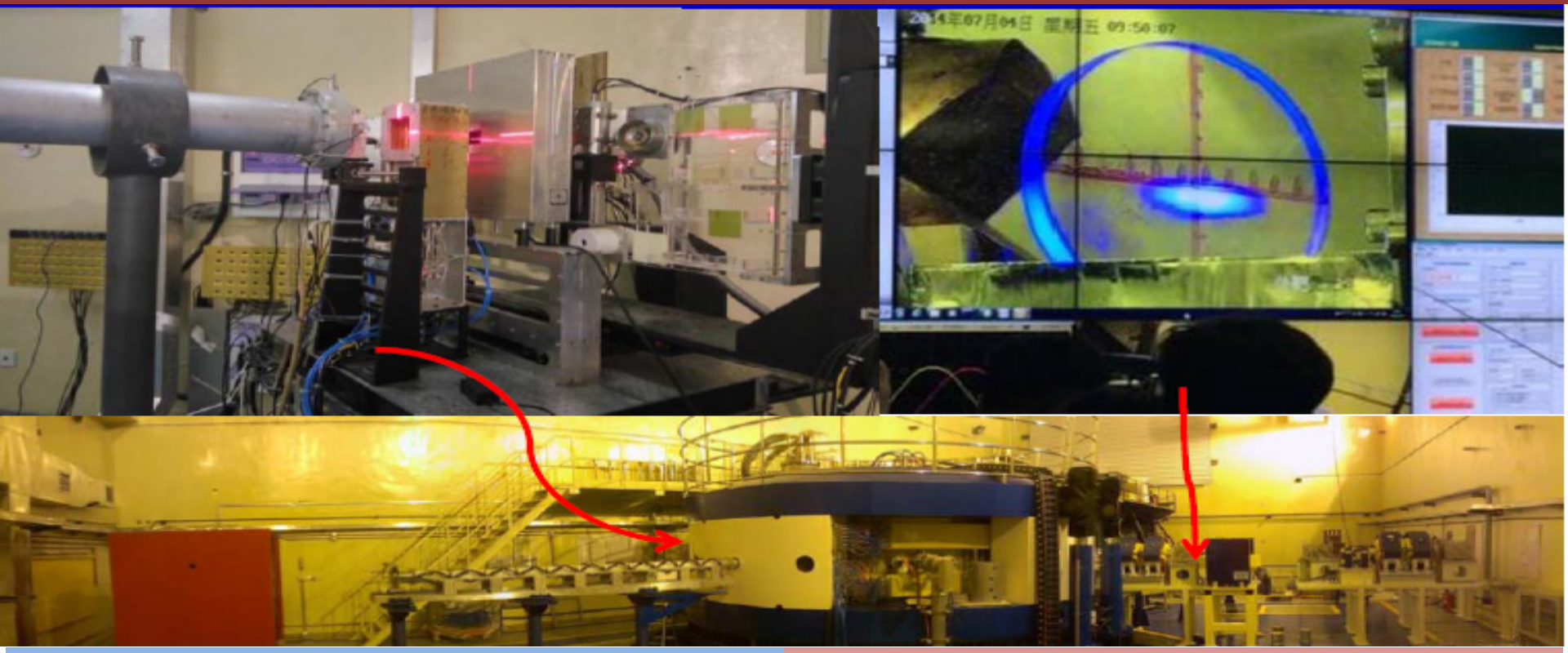
ATLAS Calorimeter




**Proton irradiation of single crystal diamond module; Radiation protection effect of typical materials for manned spacecraft**

# Application and research

## Biological and medical experiments irradiated by protons



Effects of proton irradiation on oxidative damage of mitochondria in tumor cells with 1 pA at S3

single crystal diamond experiment with 300 nA at N1

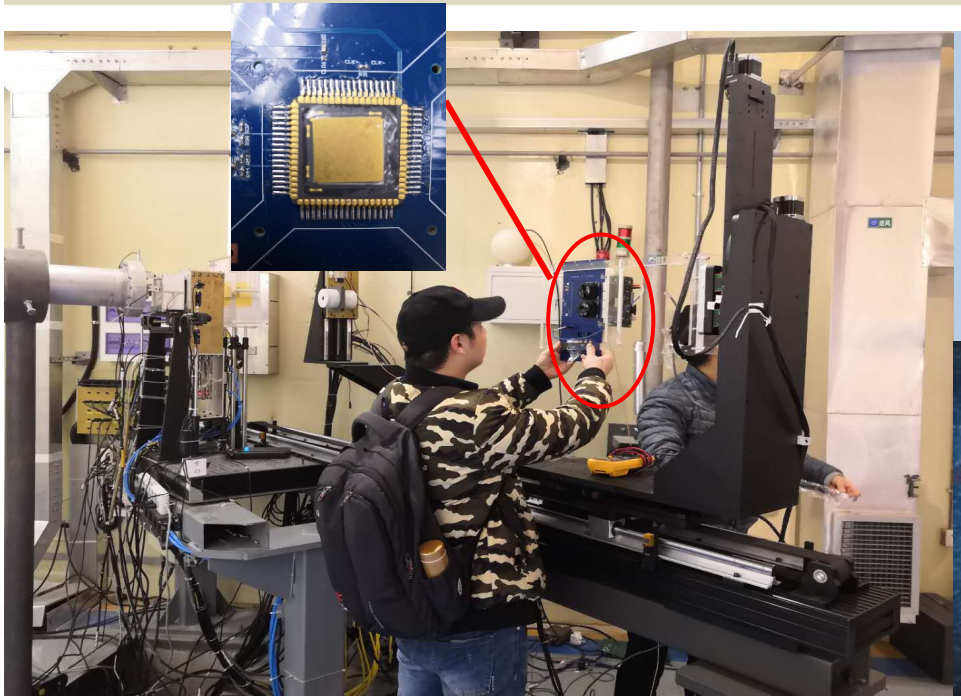
First dual extraction beam for users

# Application and research

## Innovative achievements in radioactive effect

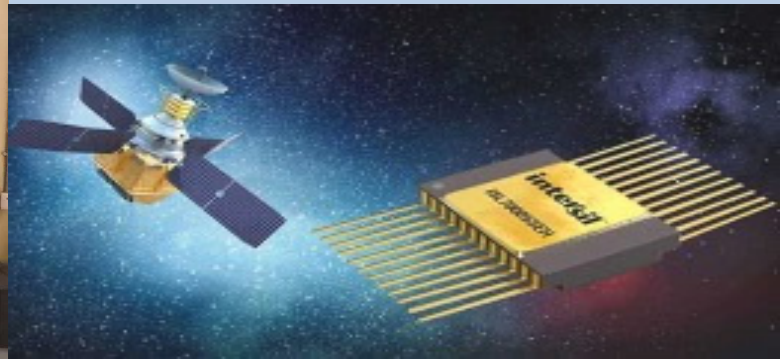
0.18 μm mixed signal integrated circuit

- Objective: to verify its resistance to proton irradiation, compare the experimental results of protons and heavy ions, and study the radiation damage mechanism of 0.18 μm CMOS devices.
- Results: the four devices reached the total dose of 5E10 in turn, and no obvious SEL and SEFL occurred.



Study on single event effect of 14nm and 65nm SRAM integrated circuits

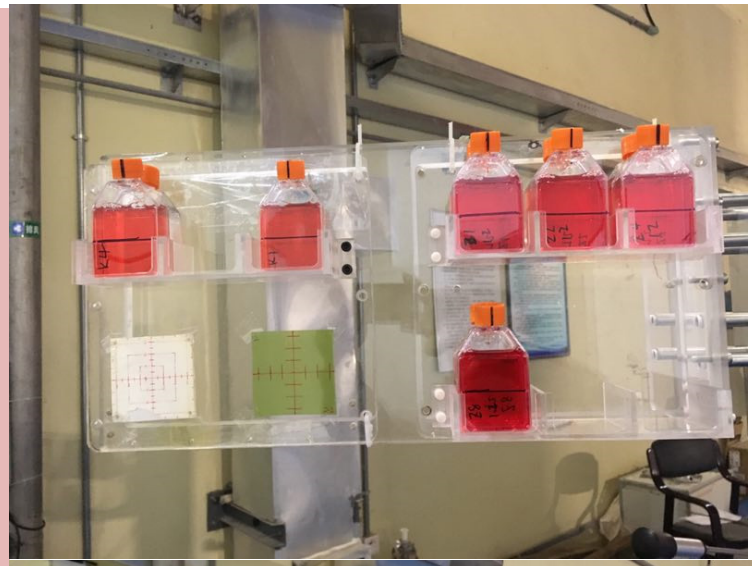
- Results: the function of the main control FPGA is abnormal.



# Application and research

## Biological and medical experiments irradiated by protons

- Sensitivity of nasopharyngeal carcinoma and glioma to proton irradiation.
- A375 cancer cells were irradiated by proton to study the changes of cell survival rate, cell cycle change, apoptosis and DNA damage with dose.



# Outline

- Overview of BRIF and CYCIAE-100
- Application and research
- Conclusion

# Conclusion

- CYCIAE-100 facility as the core of BRIF, is playing more and more important role in the nuclear data, radiation effect, agriculture, medical and isotope production area.
- We will continue to improve the **performance and efficiency** of the accelerator, complete the upgrading of aging devices, and maintain the stability of the beam.
- In the future, it is planned to continue to **expand the facility** capacity, give full play to the potential of large scientific devices in the application of accelerator neutron sources and Nuclear waste transmutation(ADS), and make vital contributions to the promotion of the country's scientific and technological strength.

# Thank you !