First Intense Beam at JUNA 400 kV Underground Accelerator

L. Sun[1,2], B. Q. Cui[3], L. H. Chen[3], Q. Wu[1], J. Q. Li[1], Y. G. Liu[1], J. L. Liu[1], P. P. Wang[1], G. Lian[3], X. D. Tang[1,2], J. J. He[4], Z. H. Li[3], B. Guo[3], W. P. Liu[3], H. W. Zhao[1,2]

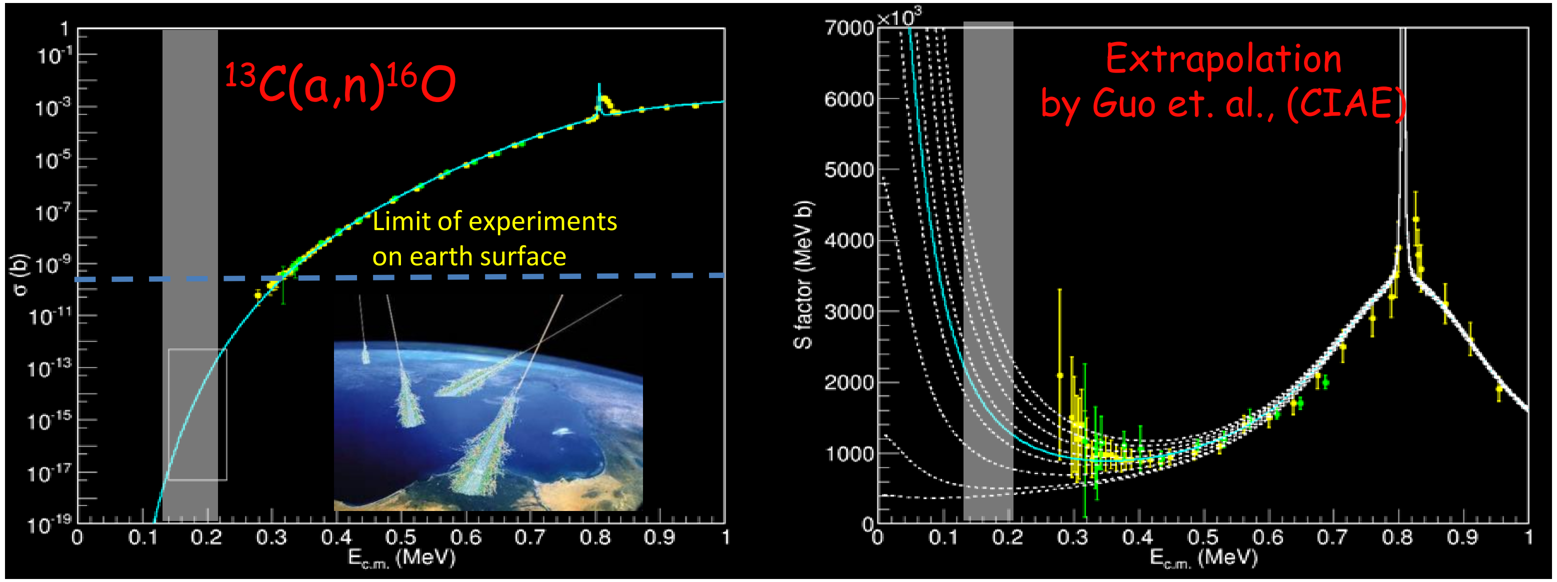
[1]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
[2]*School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China*
[3]*China Institute of Atomic Energy, Beijing 102413, China*
[4]*Beijing Normal University, 100875, China*

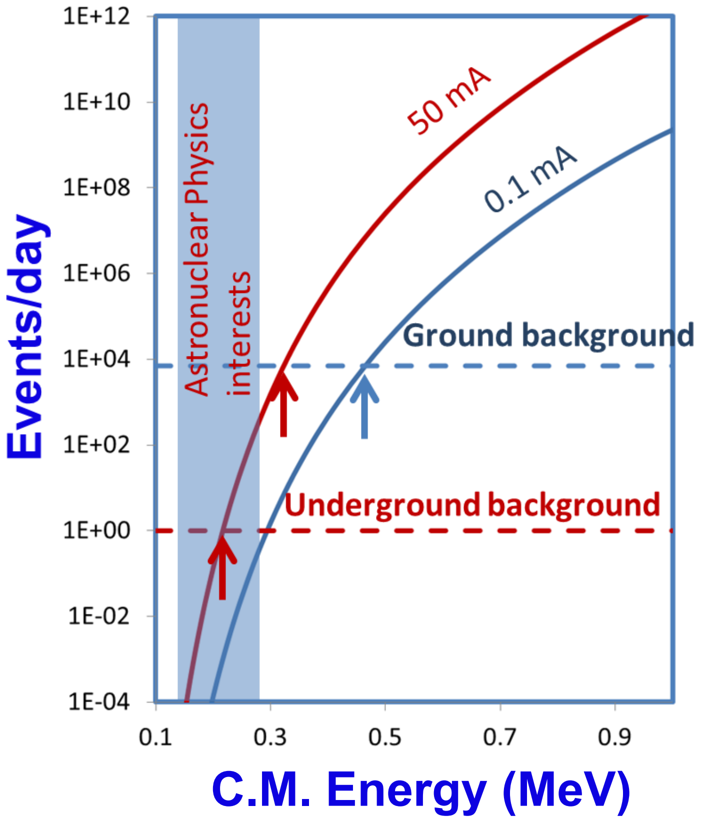
HIAT'22, June 27~July 01, 2022, Darmstadt, Germany

Outline

- Introduction of JUNA
- JUNA accelerator facility and its challenges
- Development of JUNA 400 kV accelerator facility
- JUNA first underground beams
- Scope of JUNA and JUNA-II

Introduction of JUNA

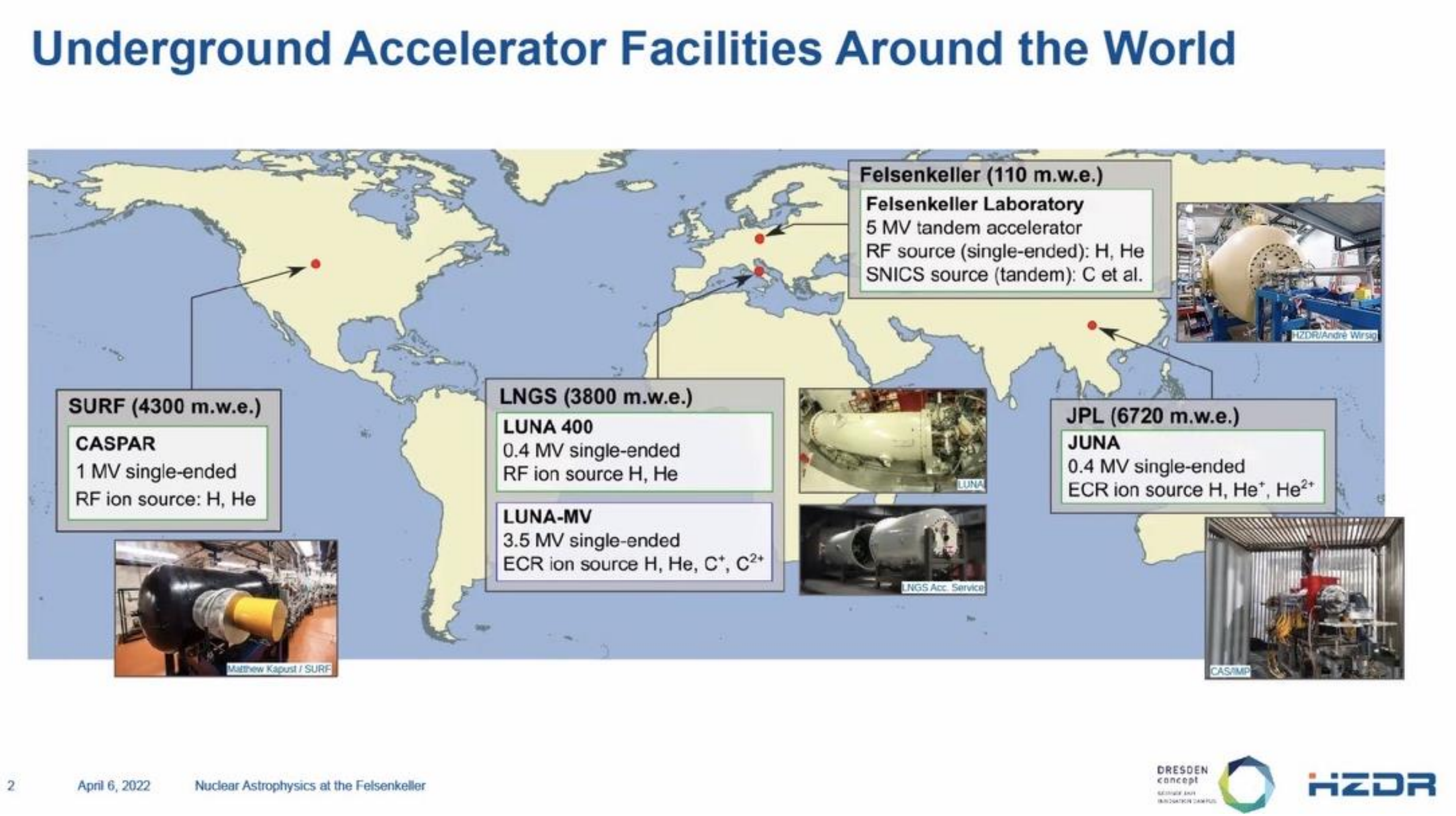




Low energy Astronuclear Physics:

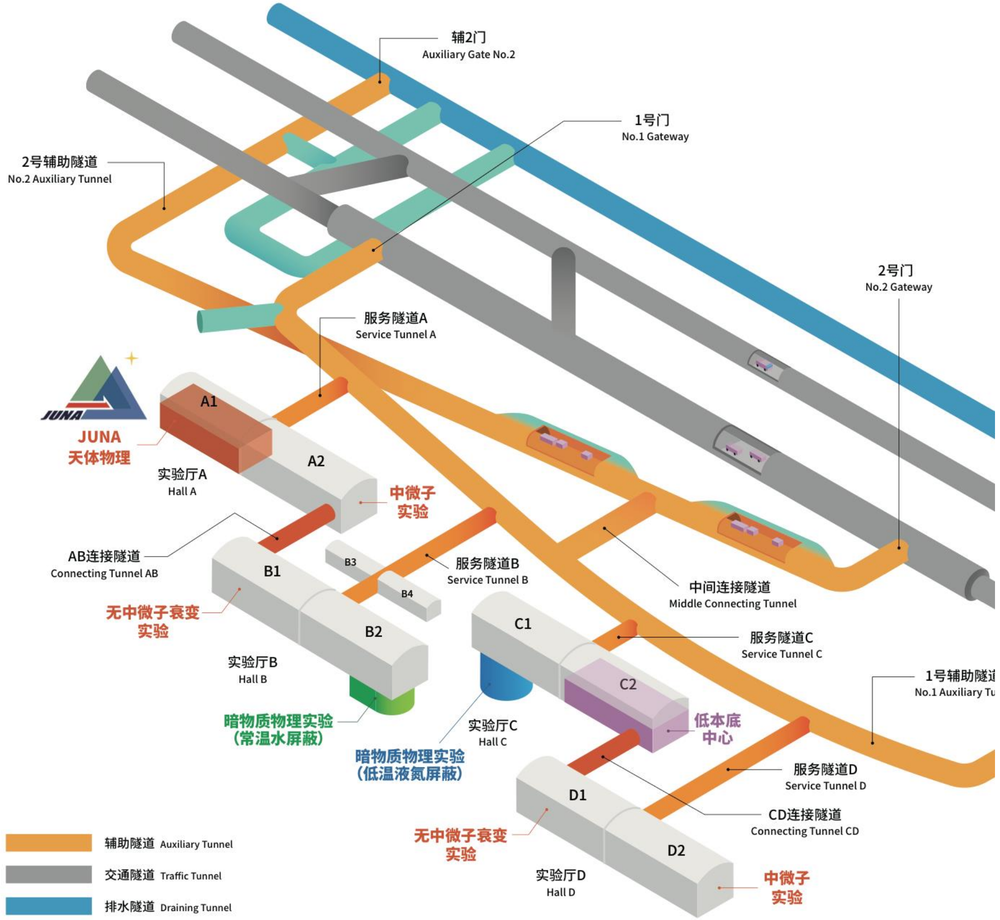
- **Very low background**
- **High beam intensity**

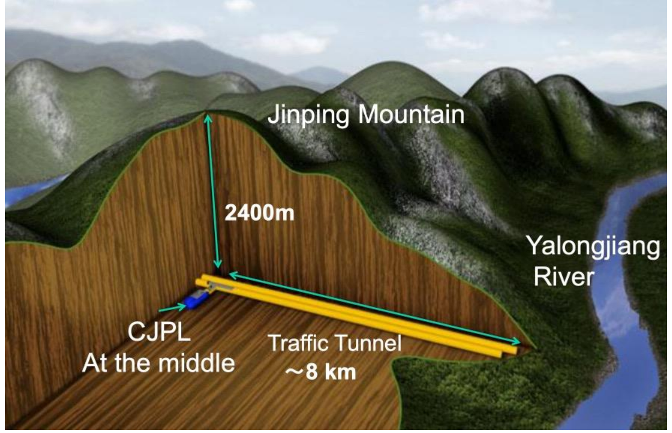
Introduction of JUNA

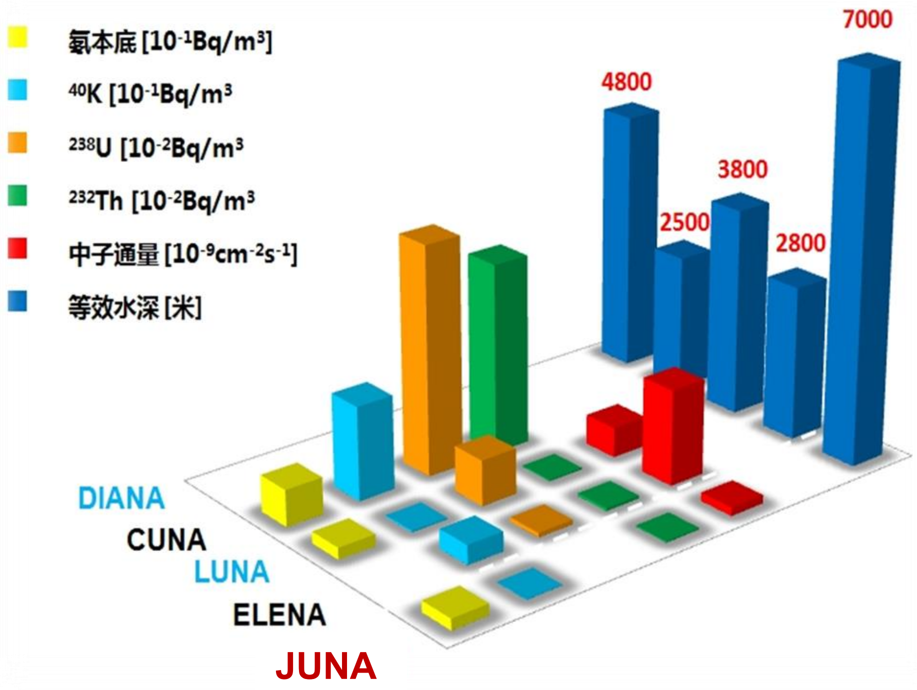


Introduction of JUNA

Jinping Underground Nuclear Astrophysics experiment







Introduction of JUNA

Key reactions of very low cross sections at stellar energy :

- $^{12}C(\alpha, \gamma)^{16}O$
- $^{13}C(\alpha, n)^{16}O$
- $^{25}Mg(p, \gamma)^{26}Al$
- $^{19}F(p, \alpha)^{16}O$

JUNA Accelerator and the Challenges

		JUNA	LUNA	DIANA	CASPAR project
Source type		**2.45 GHz ECR source**	RF source	2.45 GHz ECR source	RF source
I_q	H^+	**10 mA**	1 mA	100mA	0.1 mA
	He^+	**10 mA**	0.5 mA	50mA	0.1 mA
	He^{2+}	**2.0 mA**	/	/	/
Beam energy		**70~800 keV**	20~400 keV	50~400 keV	1 MeV

JUNA Accelerator and the Challenges

General Issues

- Low background control
- High reliability
- Low power consumption rate
- Footprint control

Ion Source

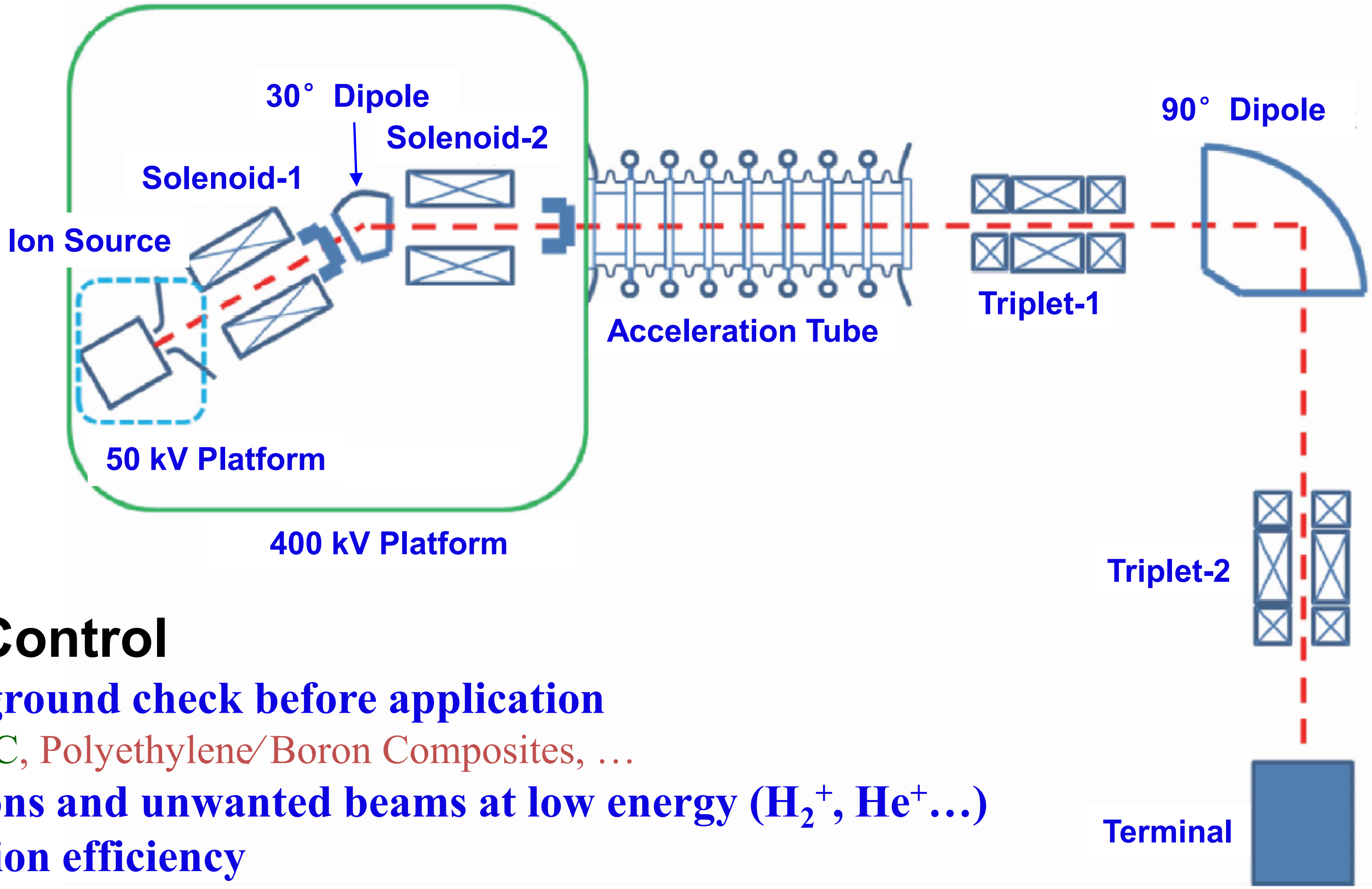
- Production of intense He^{2+}
- Contamination removal
- Beam quality control

Accelerator

- Wide beam energy range
- Low energy spread
- Beam quality control
- High mass resolution

JUNA Accelerator Challenges

JUNA Accelerator and the Challenges



Low Background Control

- **Main materials background check before application**
  Stainless Steel, OFC, Polyethylene/Boron Composites, …
- **Remove contaminations and unwanted beams at low energy (H_2^+, He^+…)**
- **High beam transmission efficiency**
- **High mass resolution dipole to remove contaminant (D^+ from $^4He^{2+}$)**

JUNA Accelerator and the Challenges

Intense He^{2+} production

Parameters	Values
Beam Energy (keV/q)	30~50
Frequency (GHz)	2.45
P_{rf} (kw)	0.3~2.0
Extraction system	4-electrode
n.rms emittance (π.mm.mrad)	<0.2
Beam Intensities (emA)	
H^+	> 10
He^+	> 10
He^{2+}	>2.0

2.45 GHz microwave source →H^+ & He^{2+} ??

- **Low electron energy (production)**
- **High gas pressure (recombination)**

He^+ generation:

$e + He \rightarrow He^+ + 2e$

E=24.6 eV

He^{2+} generation:

$e + He^+ \rightarrow He^{2+} + 2e$

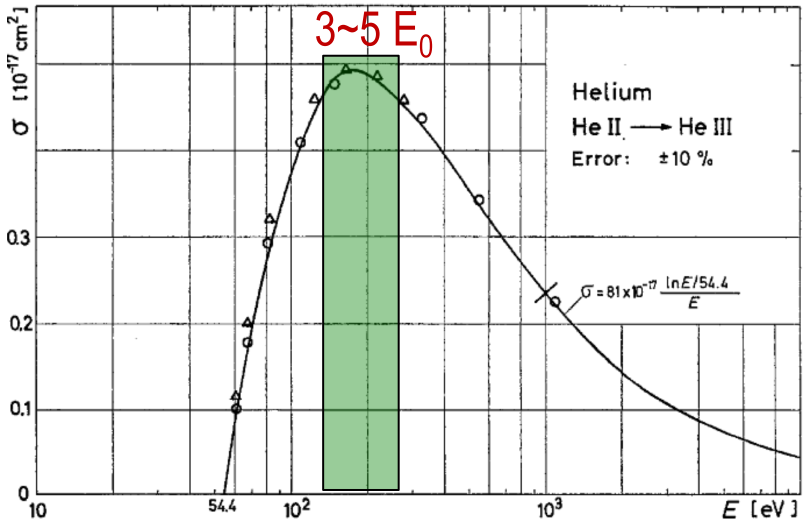
E=54.4 eV

H^+ generation:

$e + H_2 \rightarrow e + H + H$

$e + H \rightarrow 2e + H^+$

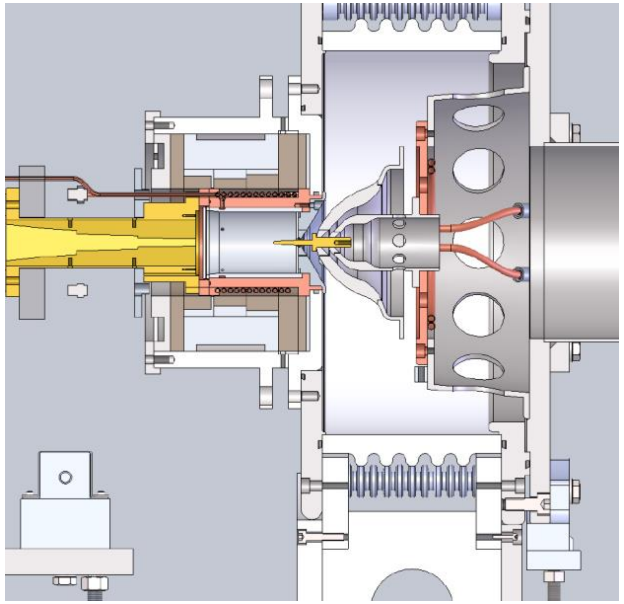
E=13.6 eV

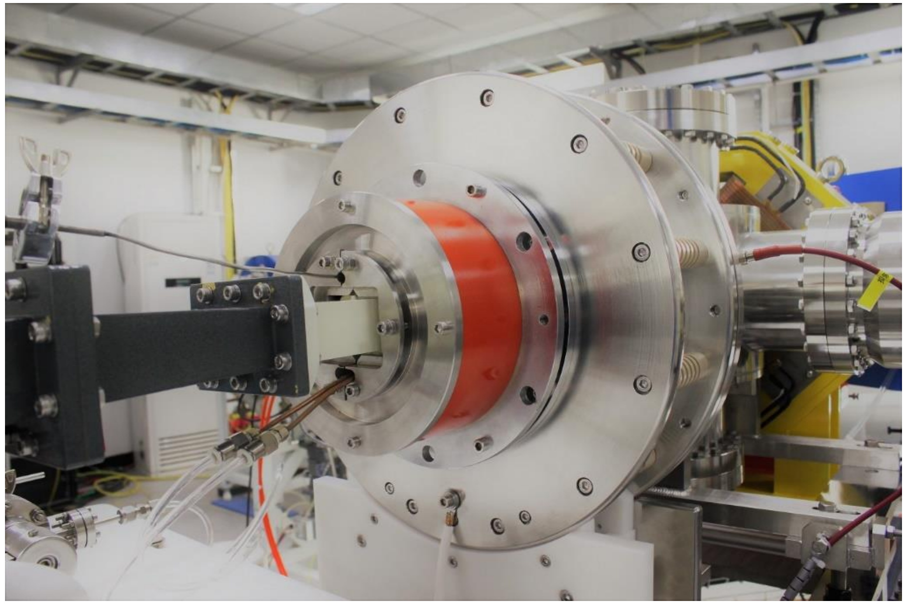


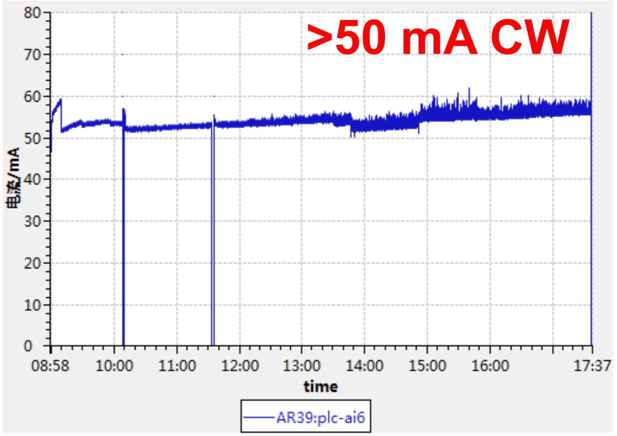
For He^{2+} production: $Te_{opt.}$ ~ 100-200 eV

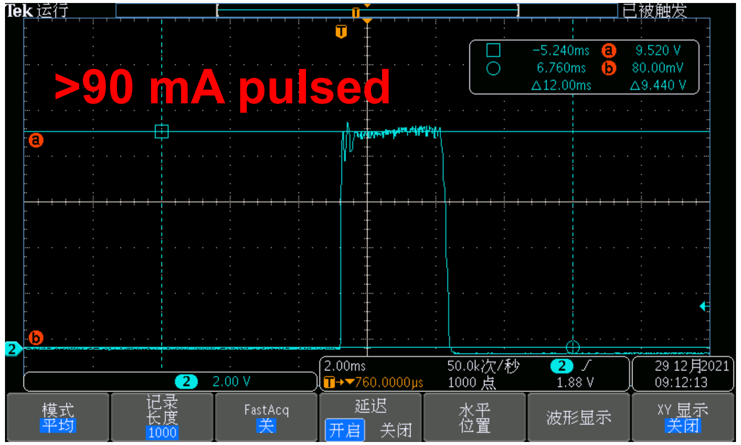
JUNA Accelerator and the Challenges

Intense He^{2+} production





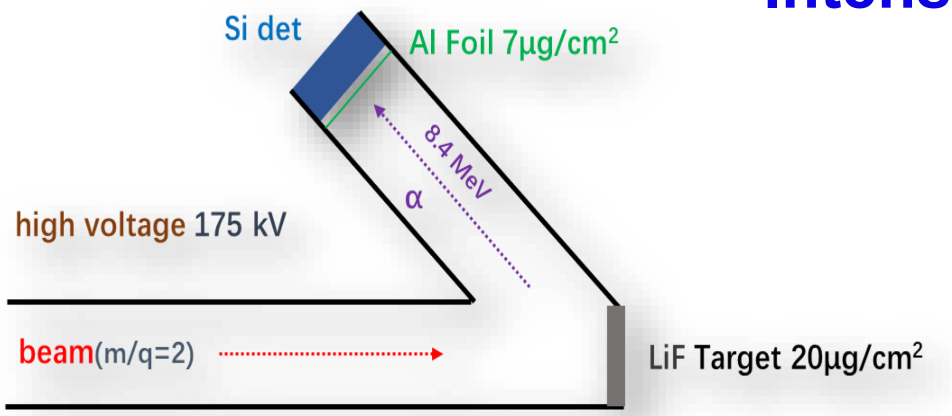


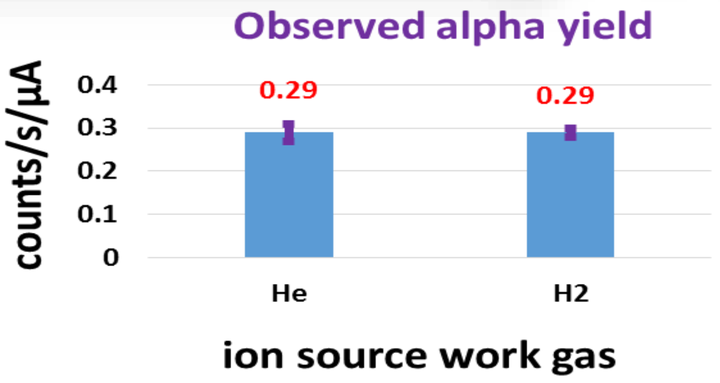


Parameters	Values
Extraction HV (kV)	30~50
Frequency (GHz)	2.45
P_{rf} (kW)	0.3~1.0
Extraction system	3-electrode
n.rms emittance (π.mm.mrad)	<0.2

JUNA Accelerator and the Challenges

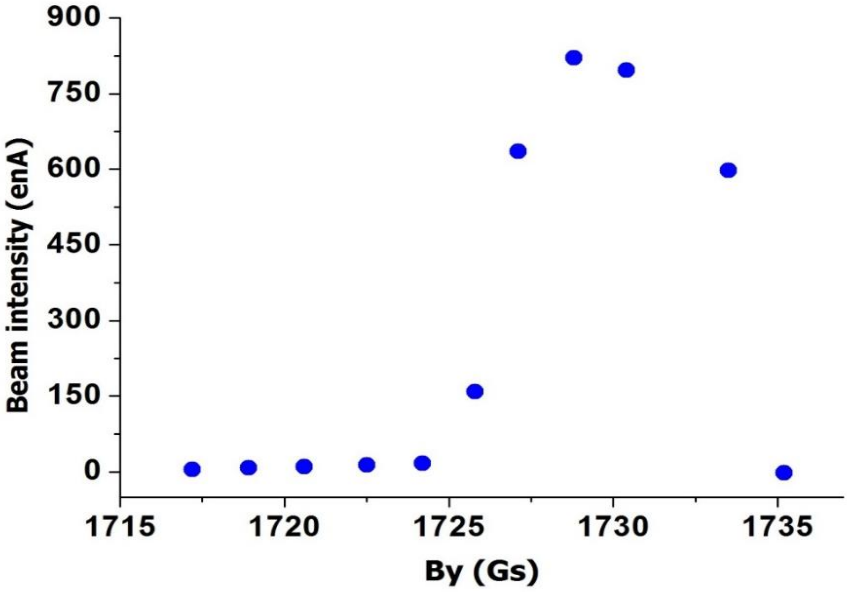
Intense He^{2+} production





Via nuclear reaction

- ^7Li (H,α)α reaction
- **No indication of intense He^{2+} beam**



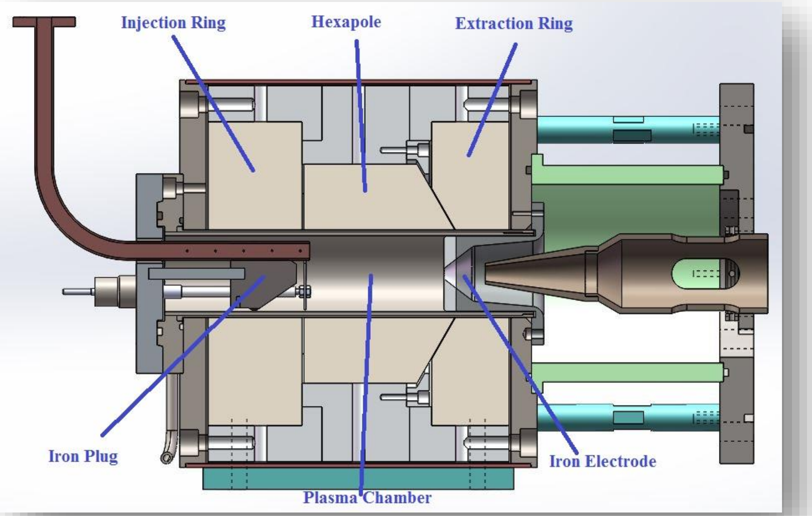
No indication of intense He^{2+} beam in the spectrum

Via Accelerator Mass Separator

- Beam energy 260 keV/q
- M/ΔM ＞260，slit=0.36 mm
- He^{2+}vs.H_2^+: M/ΔM~140

JUNA Accelerator and the Challenges

Intense He^{2+} production



- Ultra compact
- Intense medium charge state ion beam production
- Low power consumption

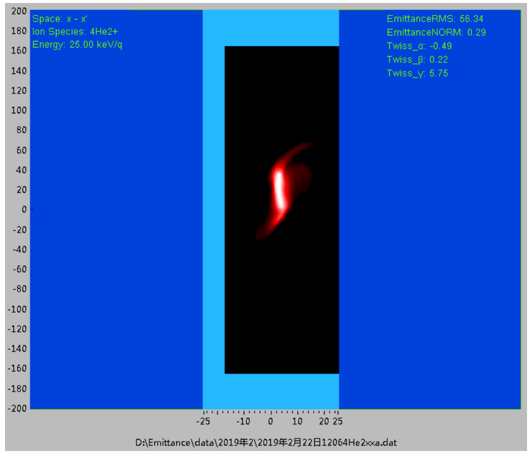
LAPECR1 ion source specs

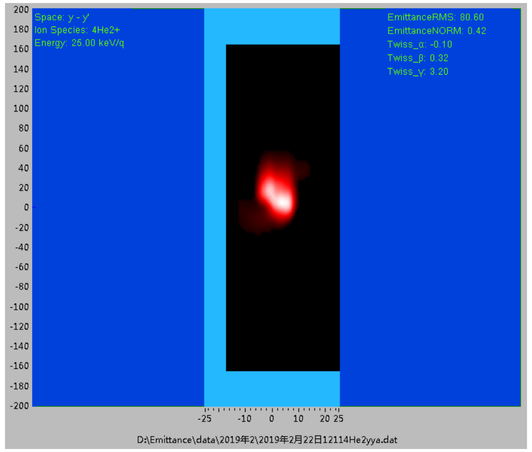
Parameters	Unit	Design
B_{in}(with iron insert)	T	0.62(1.40)
B_{ex}(with iron insert)	T	0.62(0.70)
B_{min}	T	0.38
B_r	T	1.0
Chamber ID	mm	Ø40
Mirror Length	mm	74
Lecr	mm	55
NdFeB	/	N50M/N52M
Frequency	GHz	14.5
Size	mm	Ø202*200

JUNA Accelerator and the Challenges

Typical He^{2+} results：

- ✓ microwave 425 W @14.5 GHz
- ✓ Extraction HV: 20 kV
- ✓ Output: >1.5 emA He^{2+}

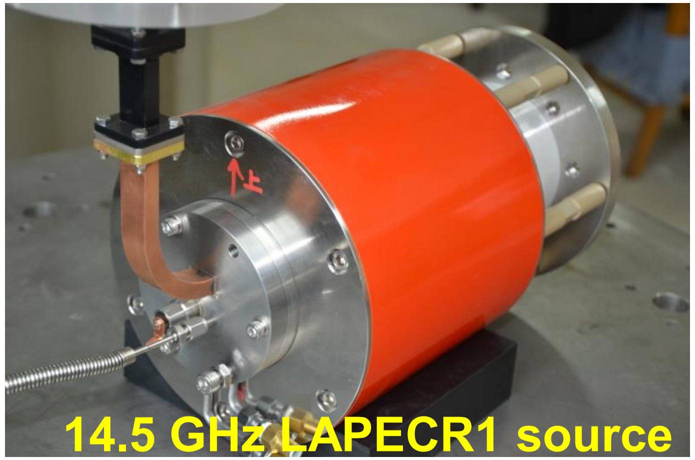


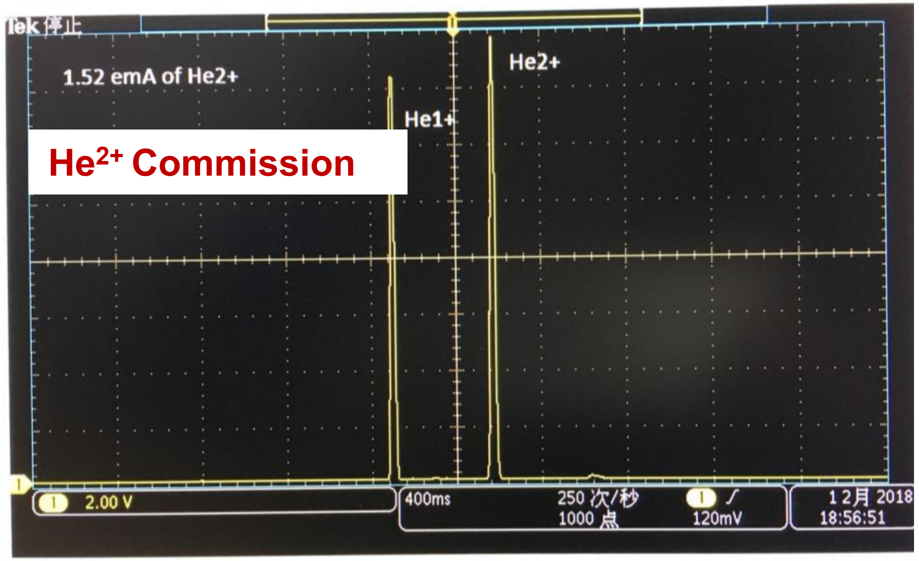


~1 emA He^{2+}Beam quality (no optimized)

- $\varepsilon_{n.rms\_x}$=0.29 πmm.mrad
- $\varepsilon_{n.rms\_y}$=0.42 πmm.mrad

Intense He^{2+} production

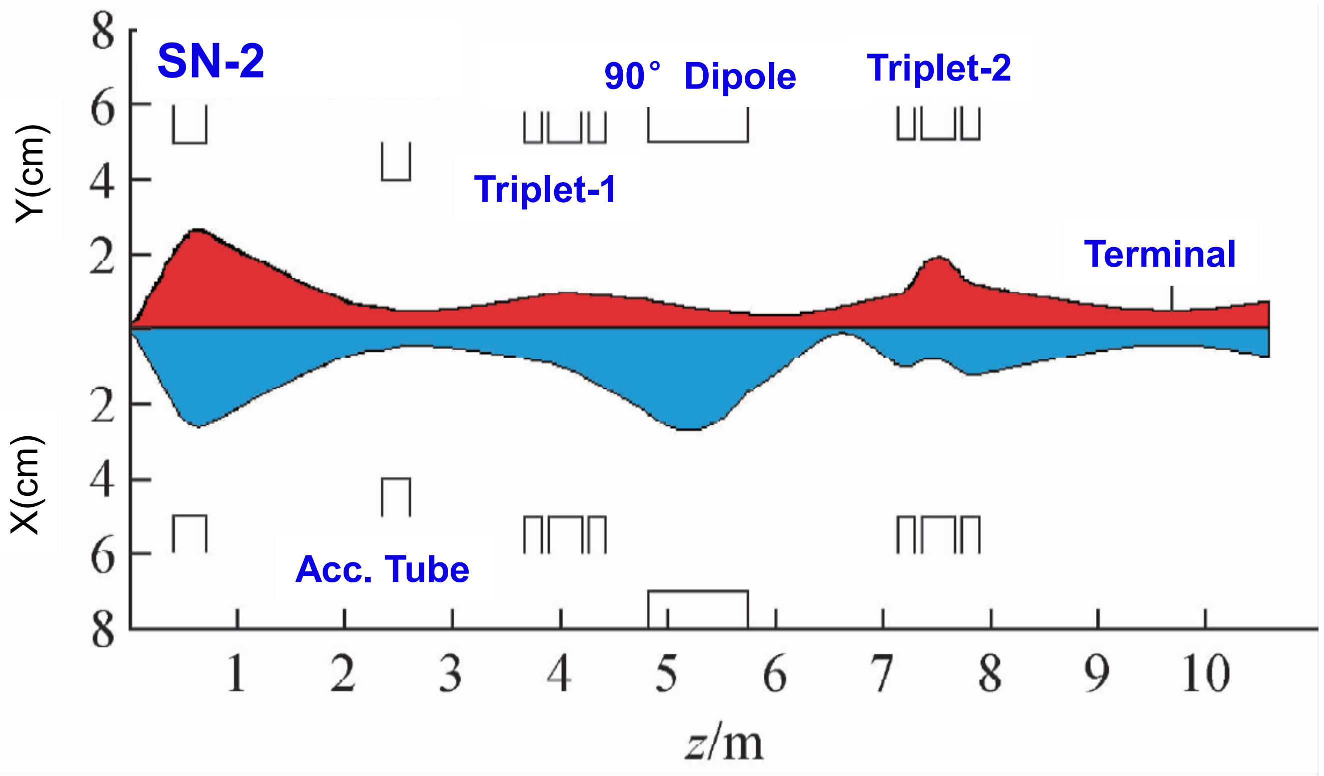




JUNA Accelerator and the Challenges

Beam transmission at high intensity

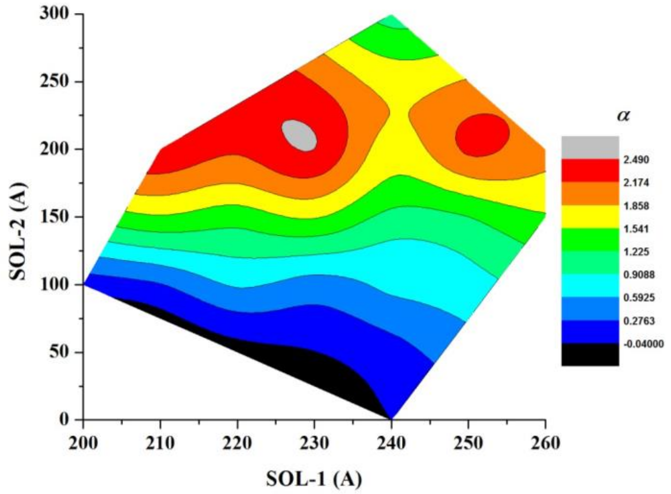
- Well controlled beam envelope to maximize beam transmission
- Well defined symmetric ion beam at target area

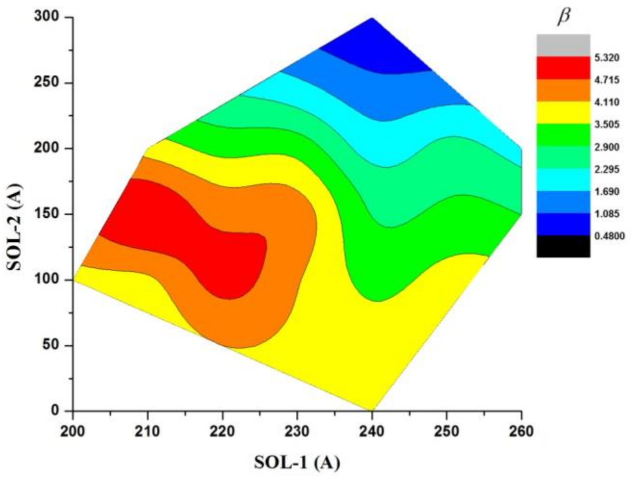


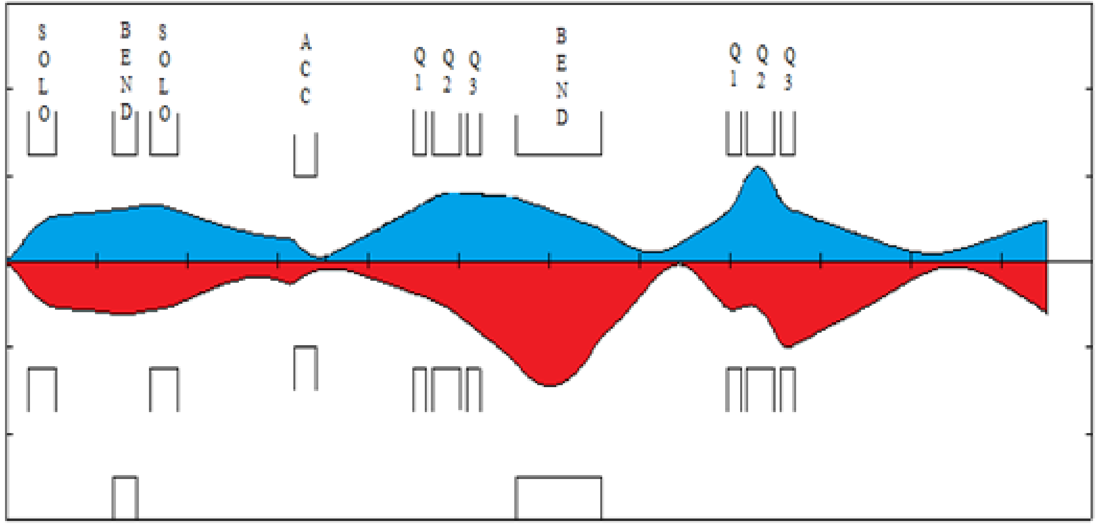
JUNA Accelerator and the Challenges

Beam flexibilities in wide energies and intensities

- **Flexible optimization of beam matching to target area**
- **Well controlled beam quality within wide beam energy (70~800 keV) and intensity (0.1~10 emA) ranges**







ions	Energy (keV)	current（emA)	α	β(cm/mrad)	γ (mrad/cm)
H+	70	10	1.60937	0.38107	9.421029724
H+	150	10	1.67518	0.21358	17.82108827
H+	250	10	1.49579	0.12974	24.95288827
H+	400	10	1.33821	0.09643	28.94126313
He+	200	10	1.5882	0.22399	15.72560936
He+	300	10	1.48113	0.15681	20.36697964
He+	400	10	0.96692	0.06246	30.978775
He2+	400	5	1.52517	0.12984	25.61724837
He2+	600	5	1.52517	0.12984	25.61724837
He2+	800	5	1.47484	0.1174	27.04559647

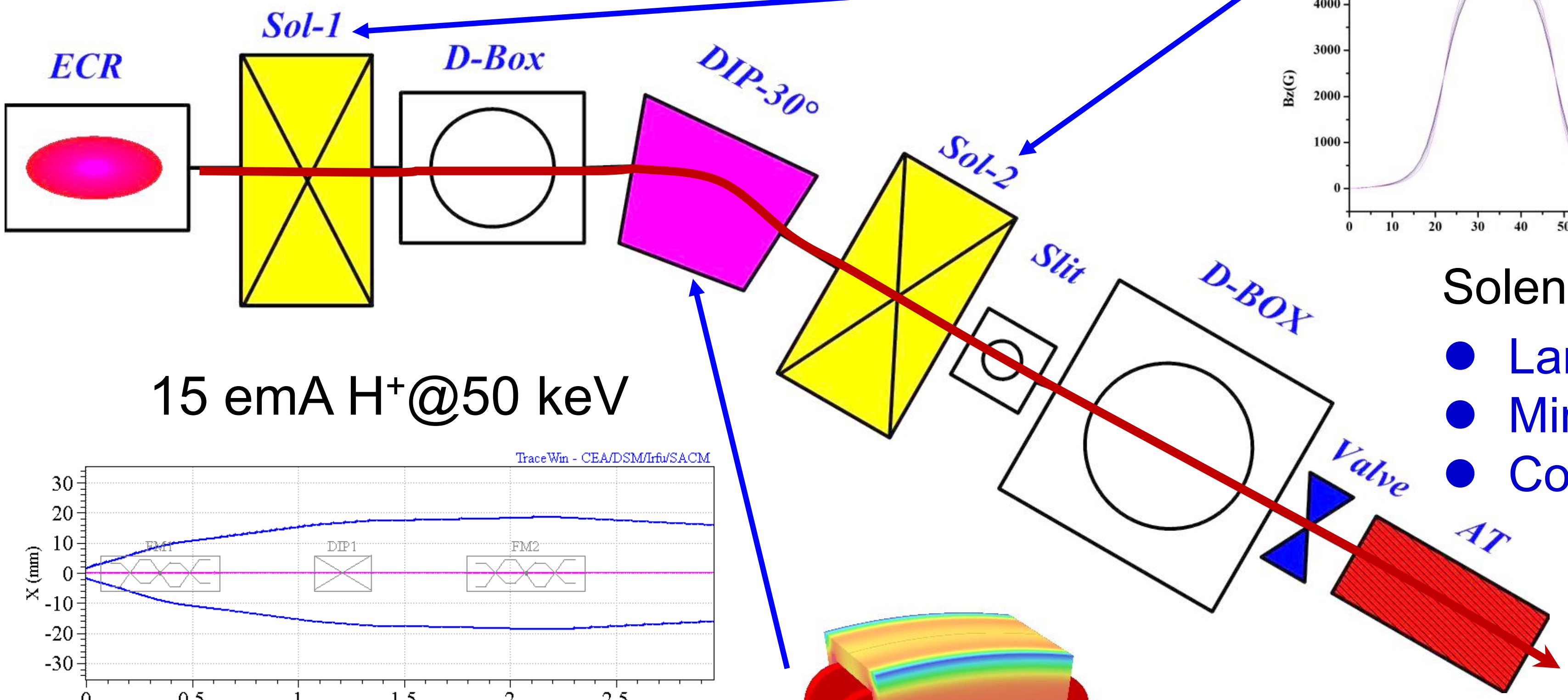
JUNA Accelerator and the Challenges

LEBT Concerns

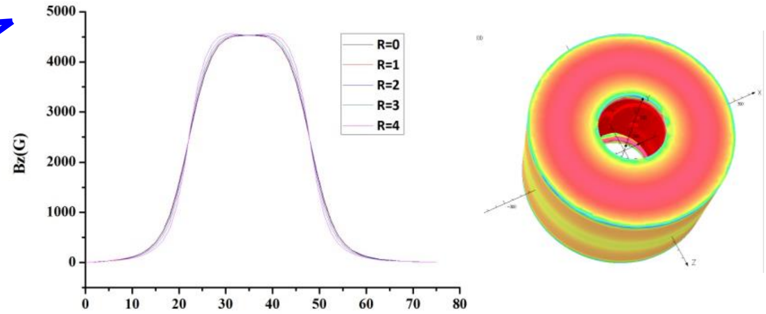
- Beam optics matching for Downstream Accelerator-Acc. Tube
  - High transmission efficiency
  - Beam optics
    - 2 sets of correctors for beam errors
    - 2-solenoid→Twiss parameters control
    - 30~50 kV extraction HV for different Acc. Tube HV
- Minimize contamination
  - 30° dipole magnet
    - Dump unwanted beam at low energy and far away from target area
    - Minimize beam loss of unwanted beam in Acc. Tube
  - Water cooling beam dump
- Lower the platform current load
  - Separate He^{2+} from He^{+}
- Beam diagnostics and control for experiments
  - Beam quality
  - Beam intensity

JUNA Accelerator and the Challenges

Ion source beam line

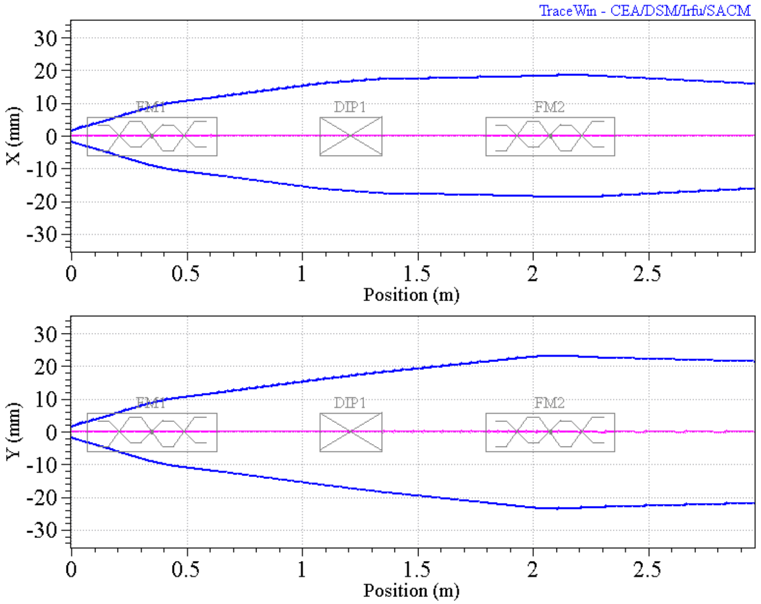


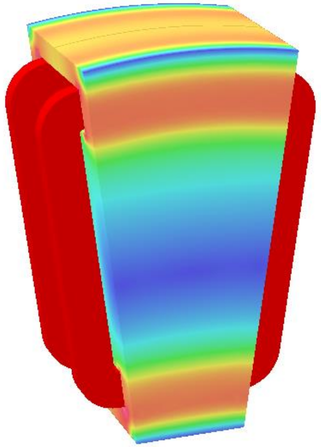
15 emA H^+@50 keV



Solenoid Design:

- Large bore design
- Minimize spherical aberration
- Corrector coils integrated





Dipole Magnet

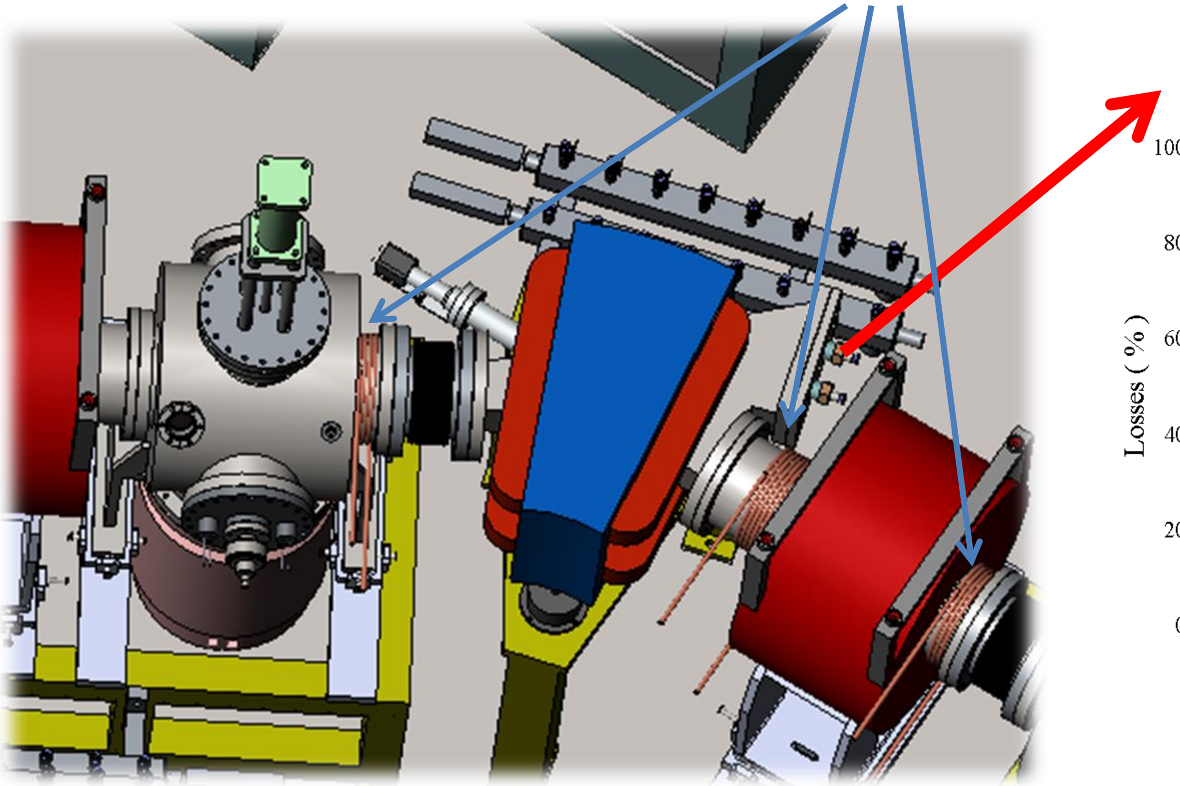
- Compact
- Less influence to beam quality
- Accommodate to platform footprint

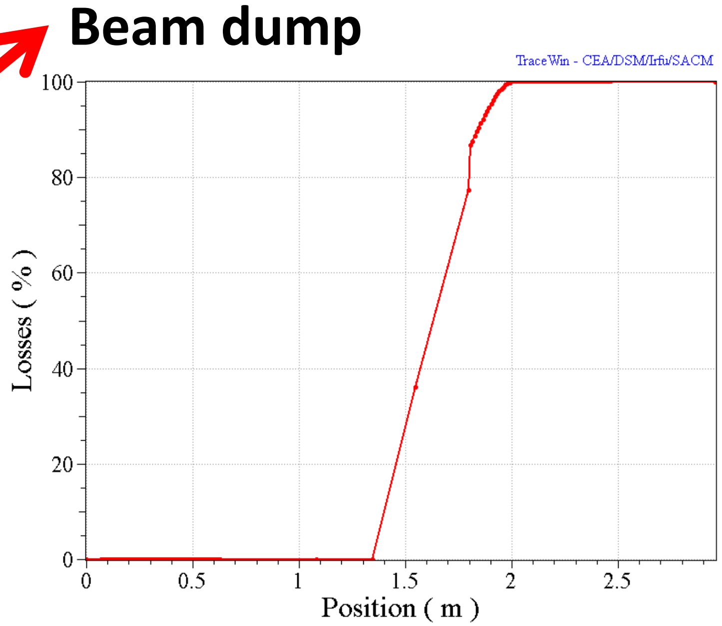
JUNA Accelerator and the Challenges

Ion source beam line

Filtering beam contaminants:

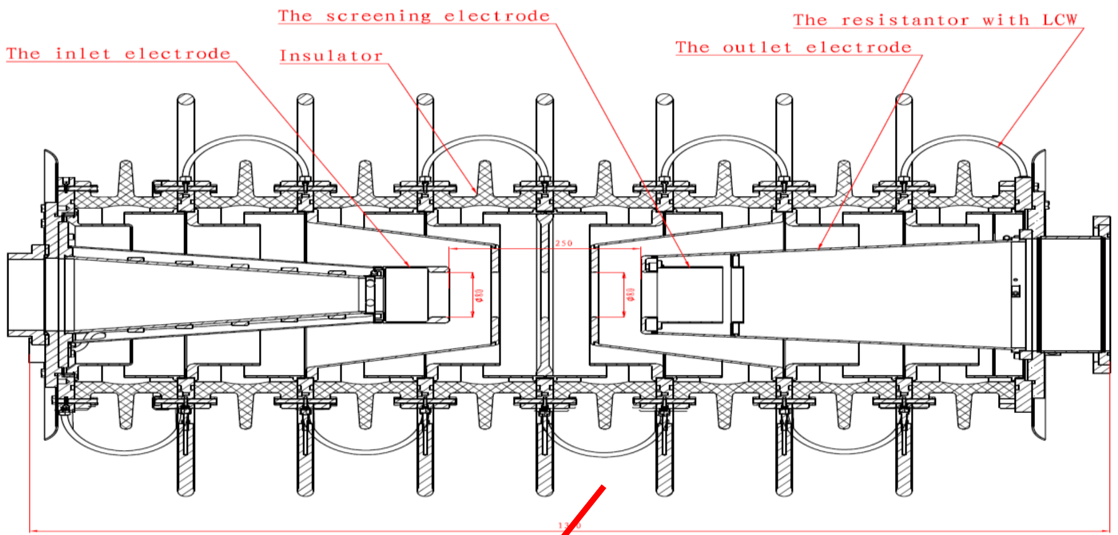
- D^+ out of H^+ beam
- He^{2+} out of He^+ beam





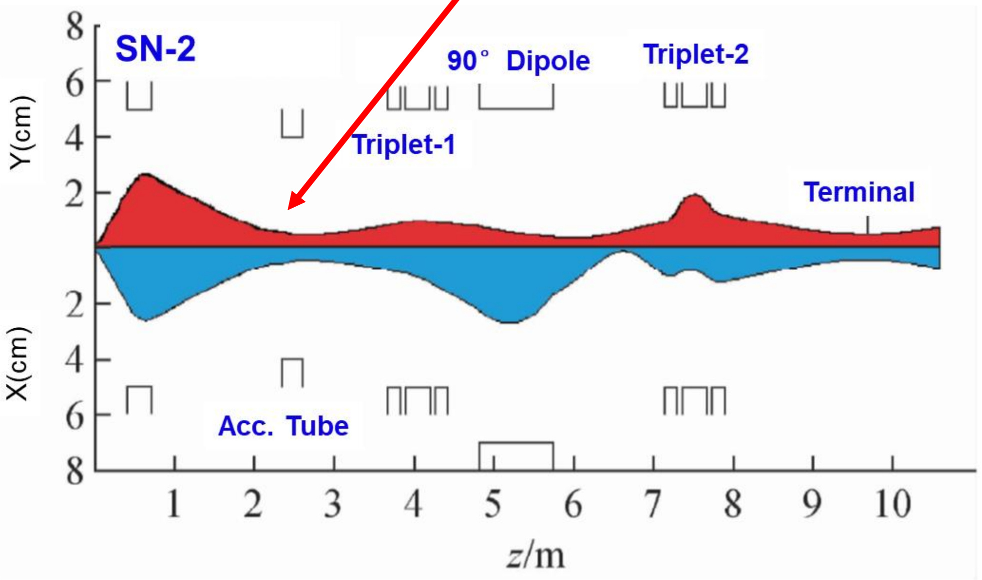
Unwanted beam loss simulation

Acceleration Tube



- Mitigate SPC influence
  - **High accelerating gradient** field, 4 gaps in 250 mm
  - ID Φ80 mm beam pipe
  - Screening electrode at the exit

- Structure Concerns
  - 99% Al_2O_3 ceramics for electric insulter
  - Electrodes and resistors cooled by LCW water
  - LCW water tube served as the resistor dividers



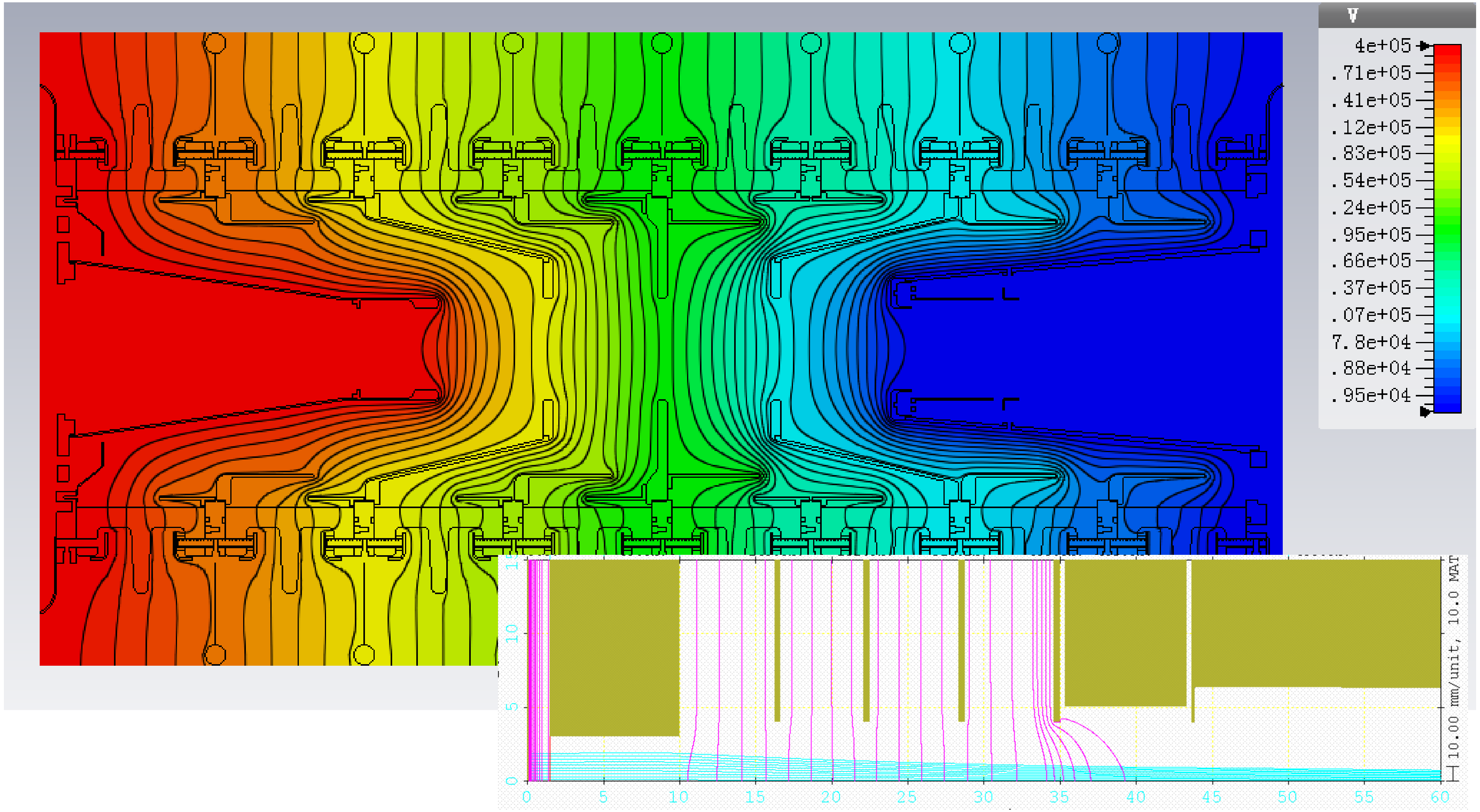
JUNA Accelerator and the Challenges

Acceleration Tube

E field Gradient:

- $E_{max\ in\ vacuum}$ <75kV/cm
- $E_{max\ in\ air}$<12kV/cm

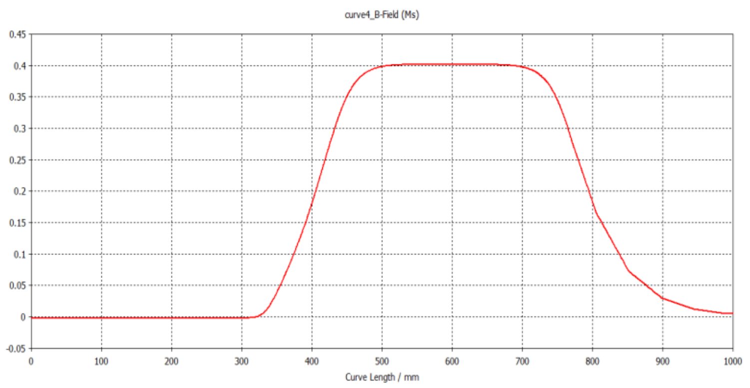
Acceleration tube scaled to 400 kV potential

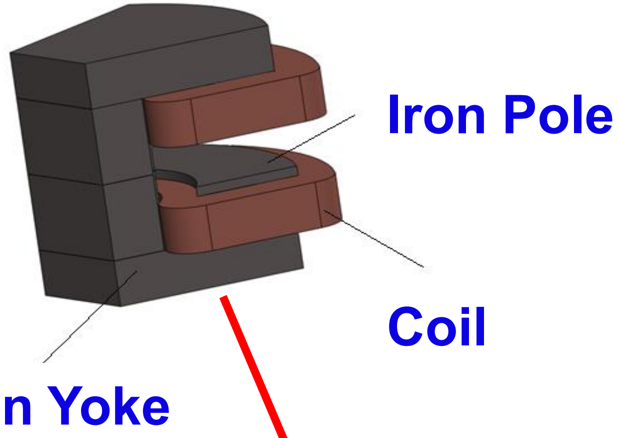


JUNA Accelerator and the Challenges

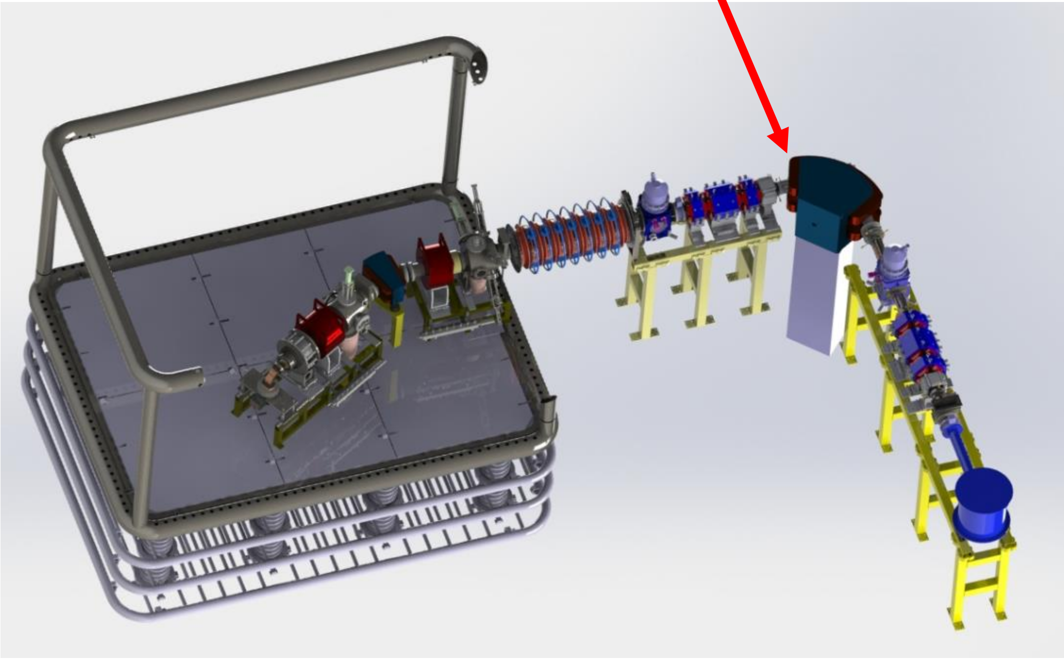
Main Dipole

- 90° C-Type Dipole
- 110 mm gap, r=600mm
- ±50mm Good field region with < 0.1% homogeneity
- Operational field: 500~3600 Gs



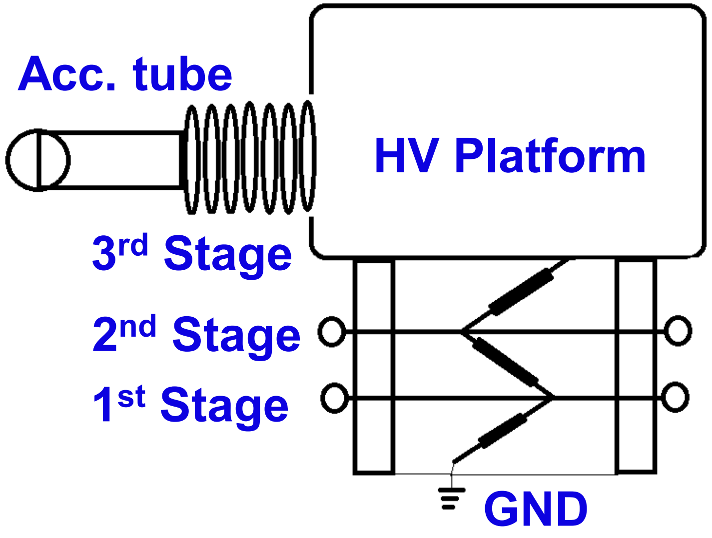


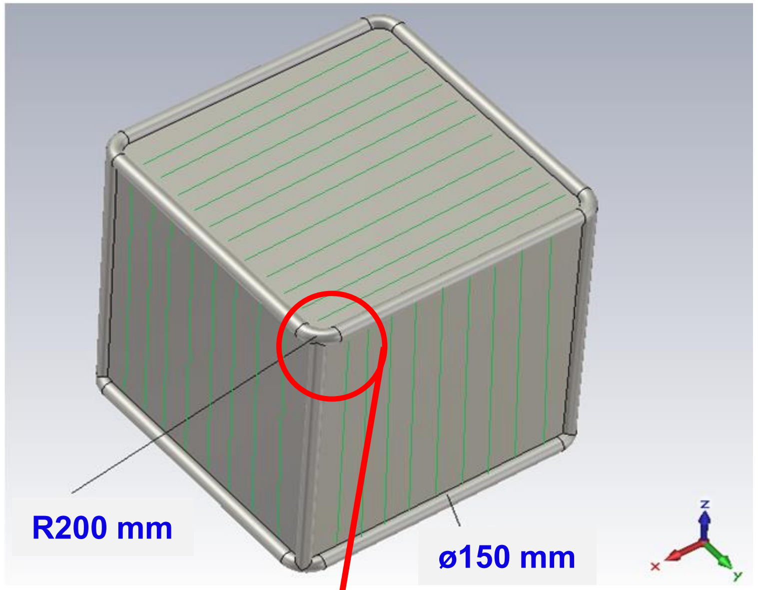
- **Distribute the beam to the terminal**
- **Remove D^+ from He^{2+} beam**
- **High transmission efficiency**
- **Minimize spherical aberration**



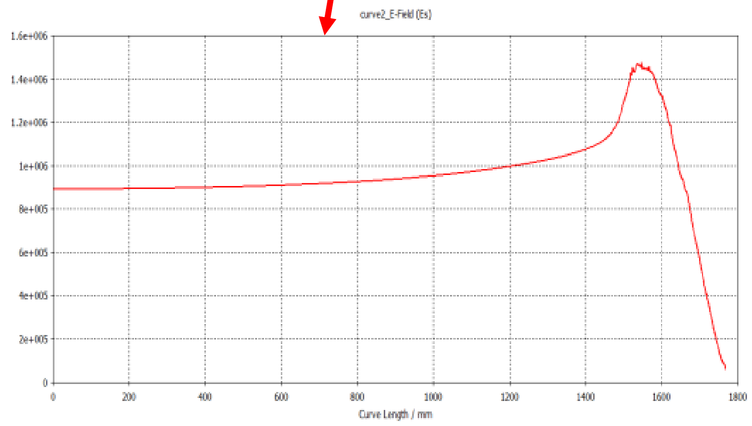
JUNA Accelerator and the Challenges

High voltage platform





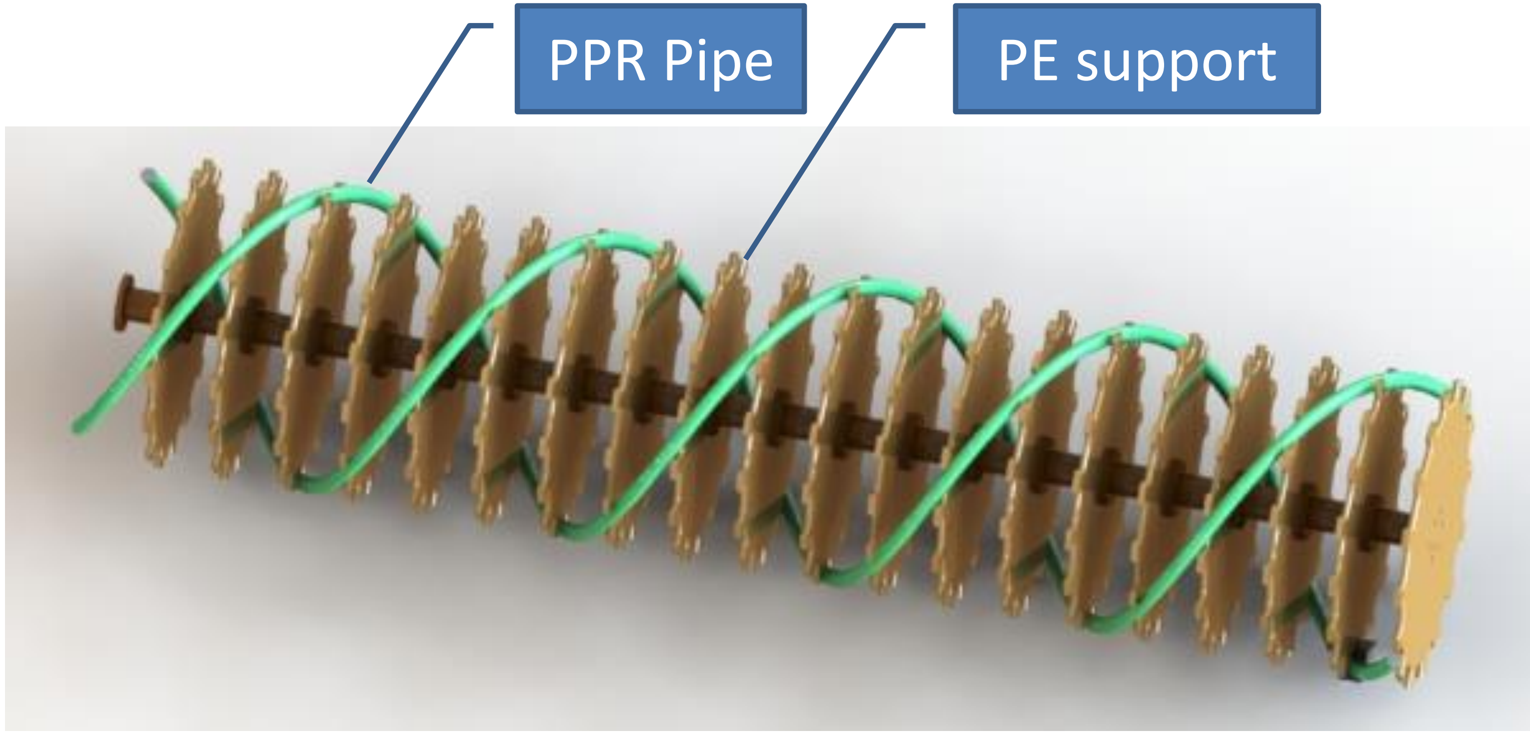
- Max. operation voltage: 350 kV
- Insulation post: 1550 mm
- Platform footprint: 4.8×3.6 m^2
- HV power supply stability: <1‰



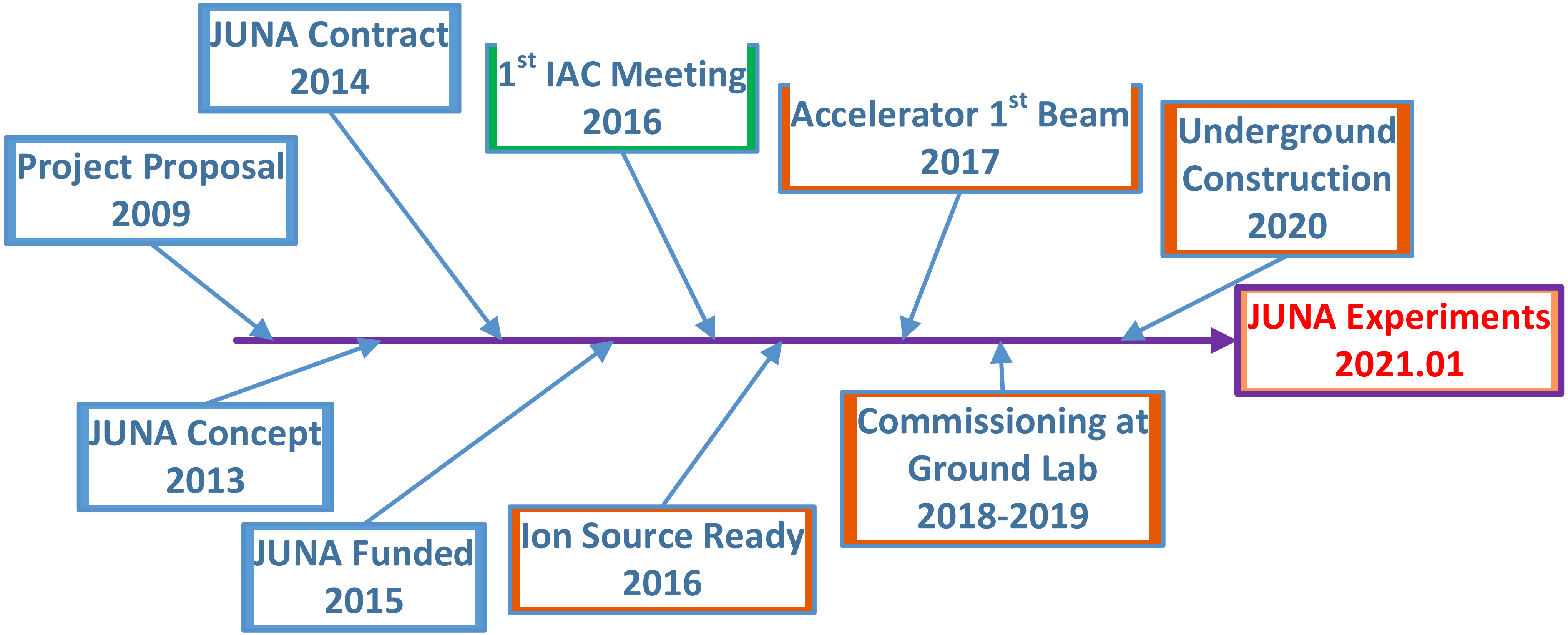
Max electric field <15 kV/cm

LCW manifold

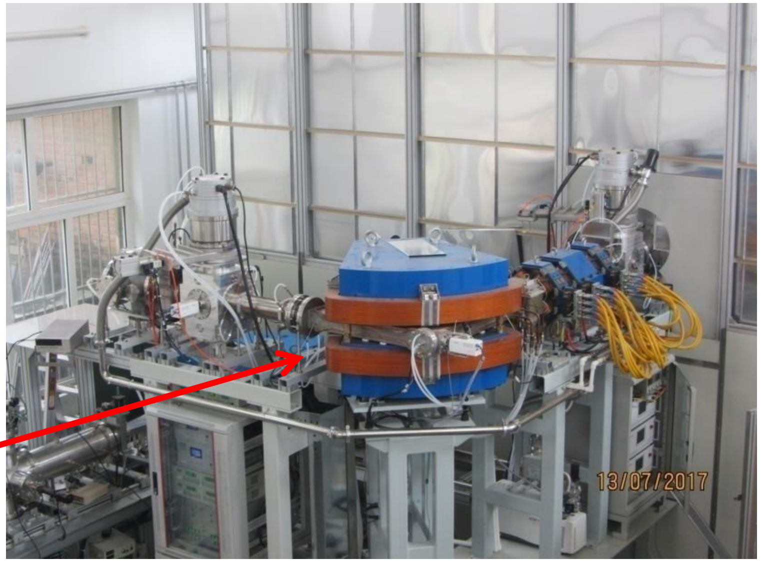
- Cooling capacity: 80 kW
- Water flow: 100 L/min
- Water resistance
  - 2 spiral insulator pipes
  - polypropylene (PPR,Φ32) pipe
  - supported by PE
- Pressure drop < 0.1 MPa @100 L/min
- Drain current@350 kV: ≤1 mA

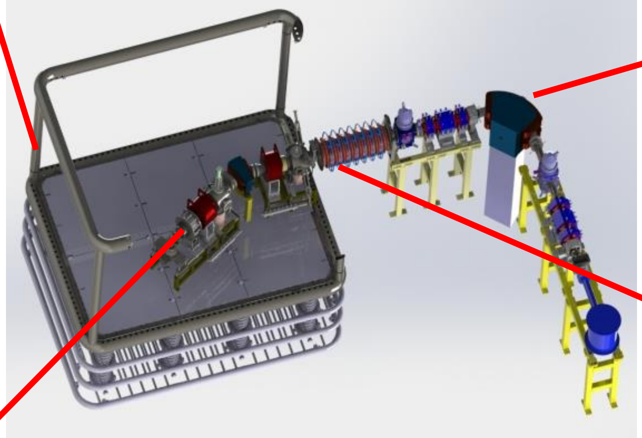


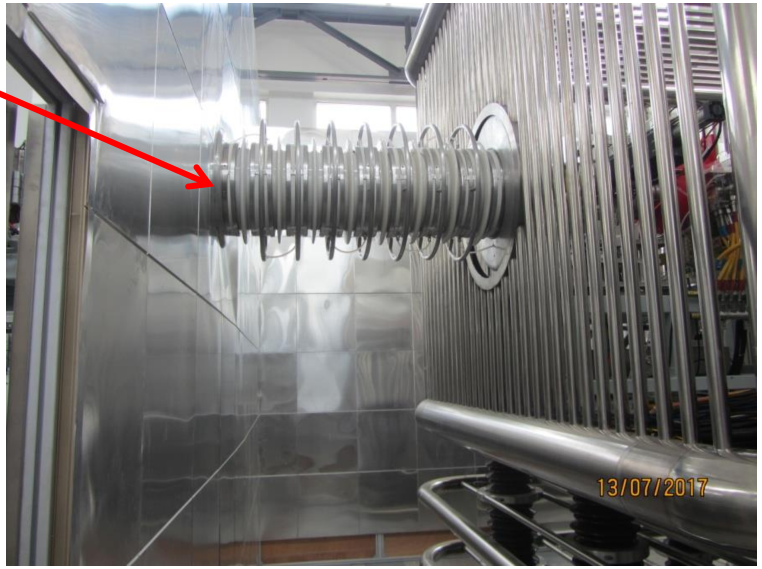
Development of JUNA: Milestones



Development of JUNA: JUNA at ground lab

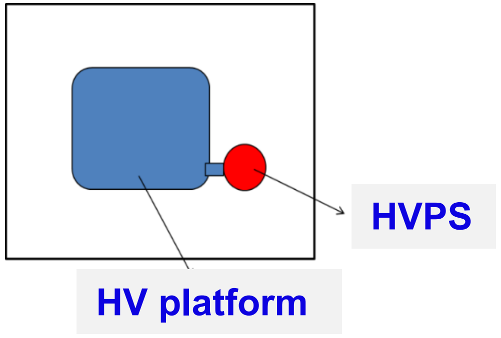


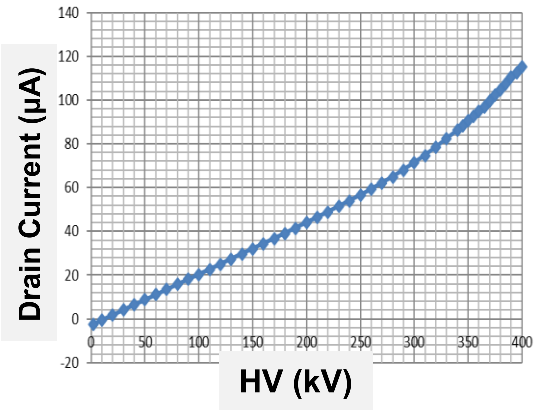


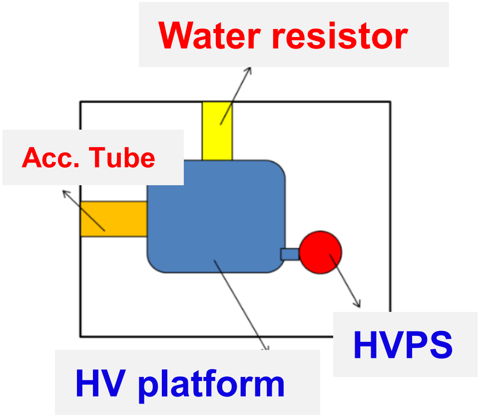


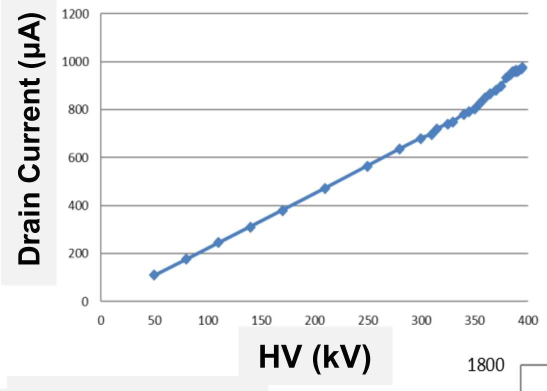
- Whole system assembly
- Beam commissioning
- Beam on target check

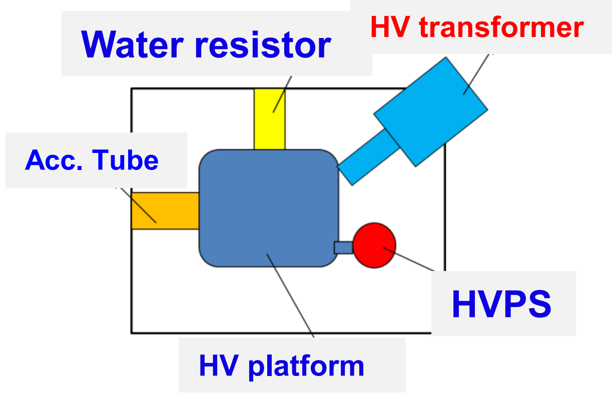
Development of JUNA: JUNA at ground lab

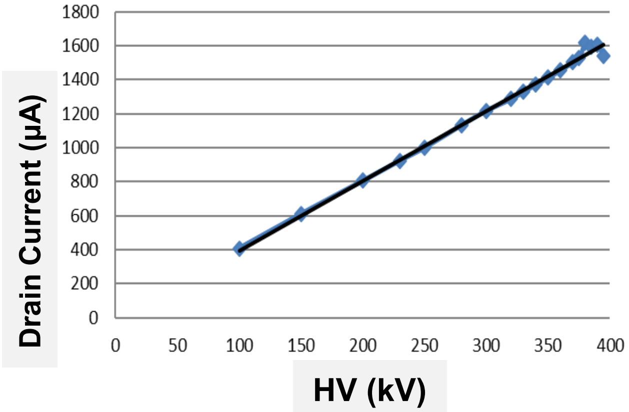






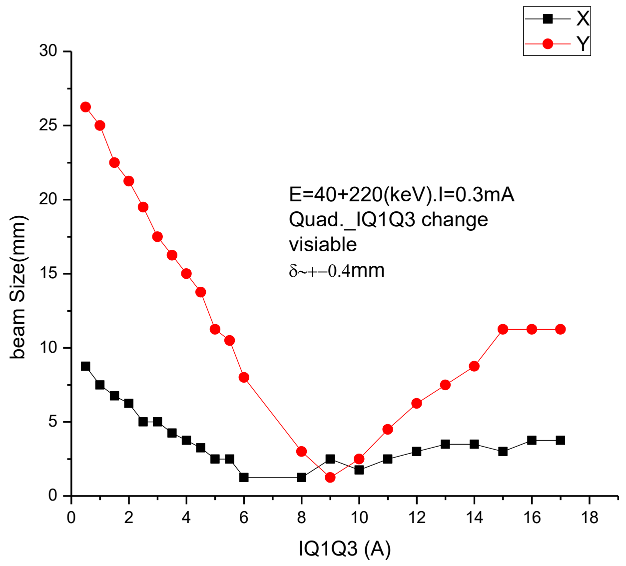


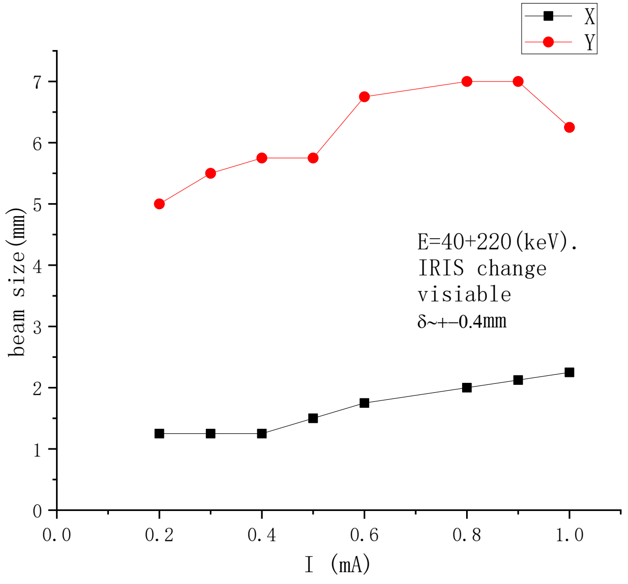


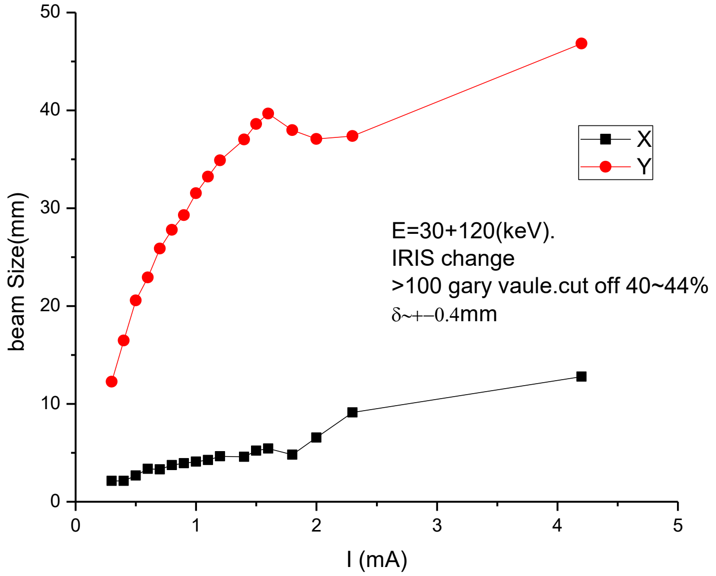


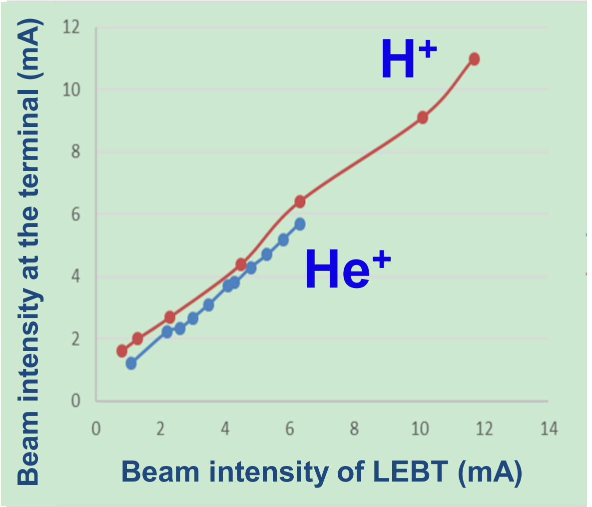
- Test the whole HV system in 3 steps
- Rated to 400 kV (350 kV operational goal)

Development of JUNA: JUNA at ground lab



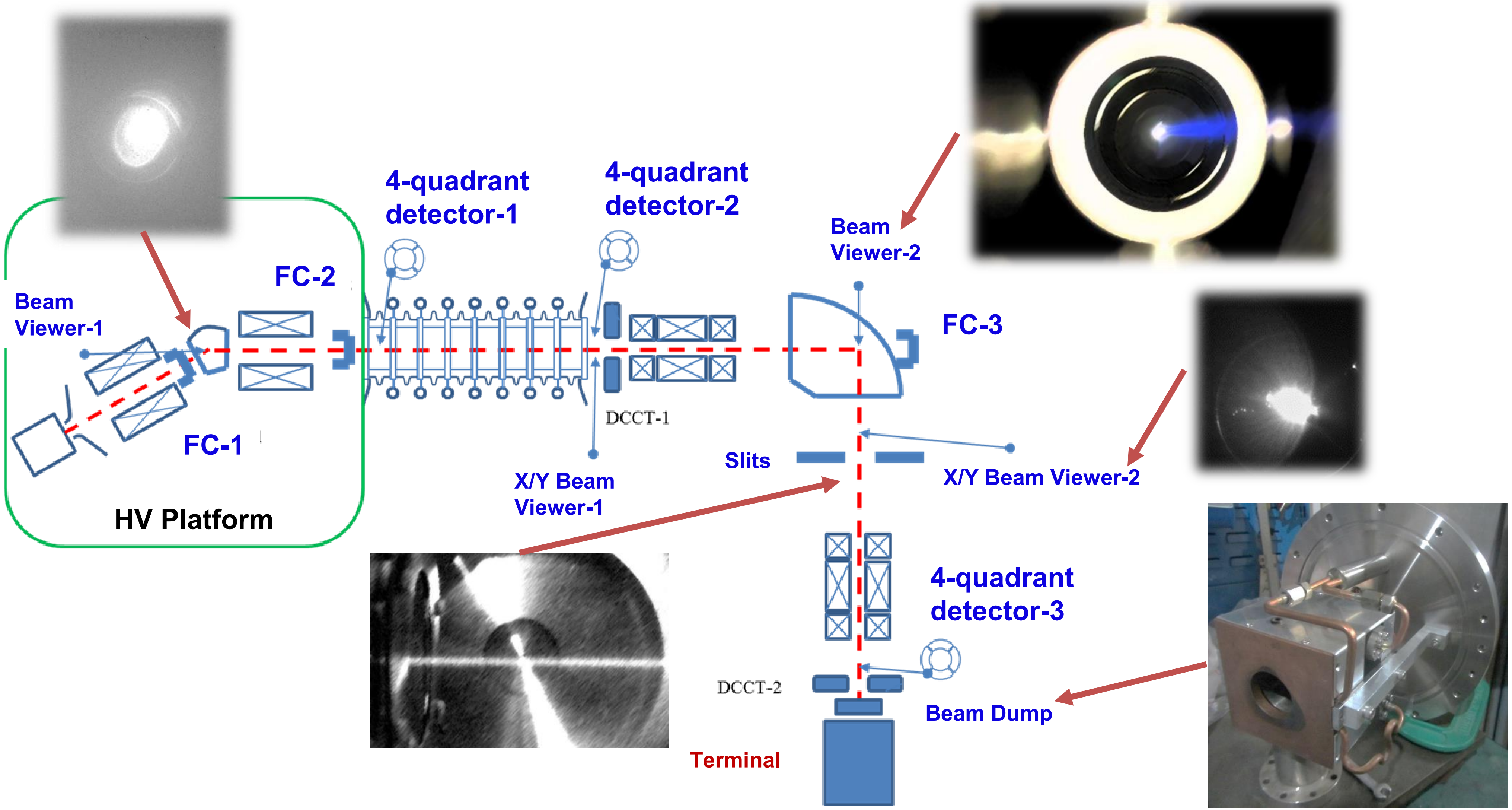




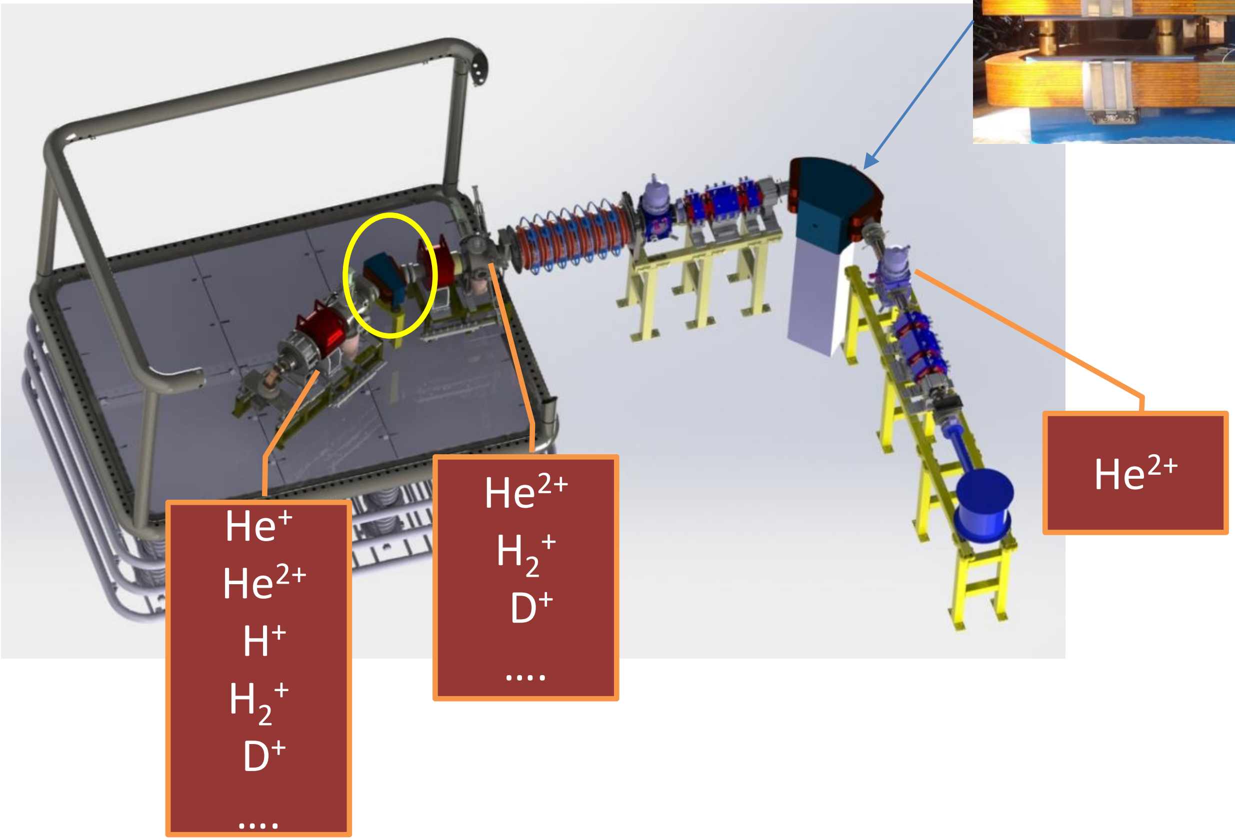


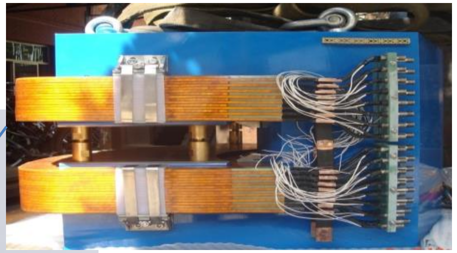
- **High beam transmission efficiency in the accelerator**
- **Accelerated currents: 12 mA or higher**
- **Performance and reliability demonstrated**

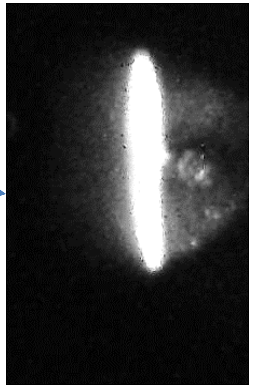
Development of JUNA: JUNA at ground lab

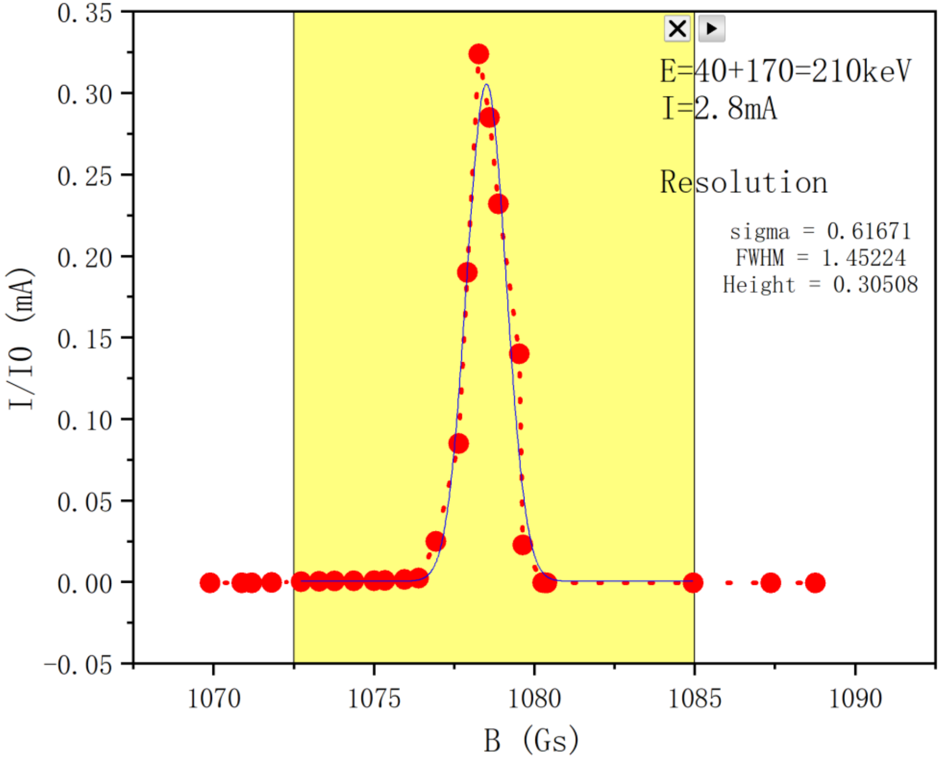


Development of JUNA: JUNA at ground lab









- This separation system: M/ΔM> 279
- He^{2+}&D^{+} separation: M/ ΔM>~160

Development of JUNA: JUNA at ground lab

Ion sources installed at ground lab test

Development of JUNA: JUNA at ground lab

Commissioning at Ground Lab:

- More than 1,000 hours beam time
- Tested all needed ion beams
- Accelerator performance, stability and reliability
- Some experimental tests

JUNA 1st Underground Beams: Construction

- $^{12}C(\alpha, \gamma)^{16}O$
- $^{13}C(\alpha, n)^{16}O$
- $^{25}Mg(p, \gamma)^{26}Al$
- $^{19}F(p, \alpha)^{16}O$

2020.9

Kickoff Meeting

2020.10

- **Accelerator components packing**
- **Shipment**
- **Arrival at JUNA site**

2020.11

- **Accelerator assembly on site**
- **Utilities readiness**
- **JUNA laboratory construction**
- **Ion source beam extraction**

2020.12

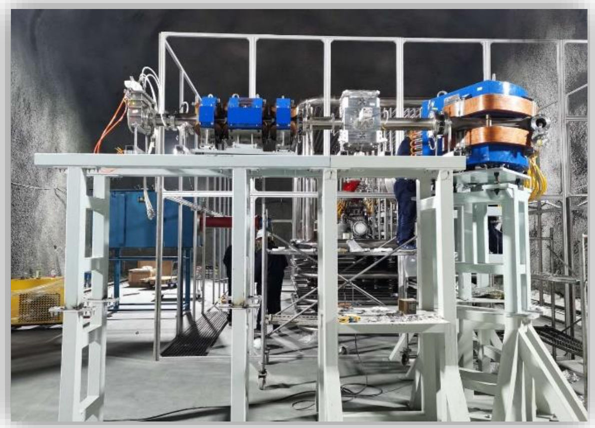
- **First accelerated beam**
- **Experiment preparation**

2021.1

Announcement of JUNA underground experiments started

JUNA 1st Underground Beams: Construction

Arrival



Construction

Completed

JUNA 1st Underground Beams: Operation

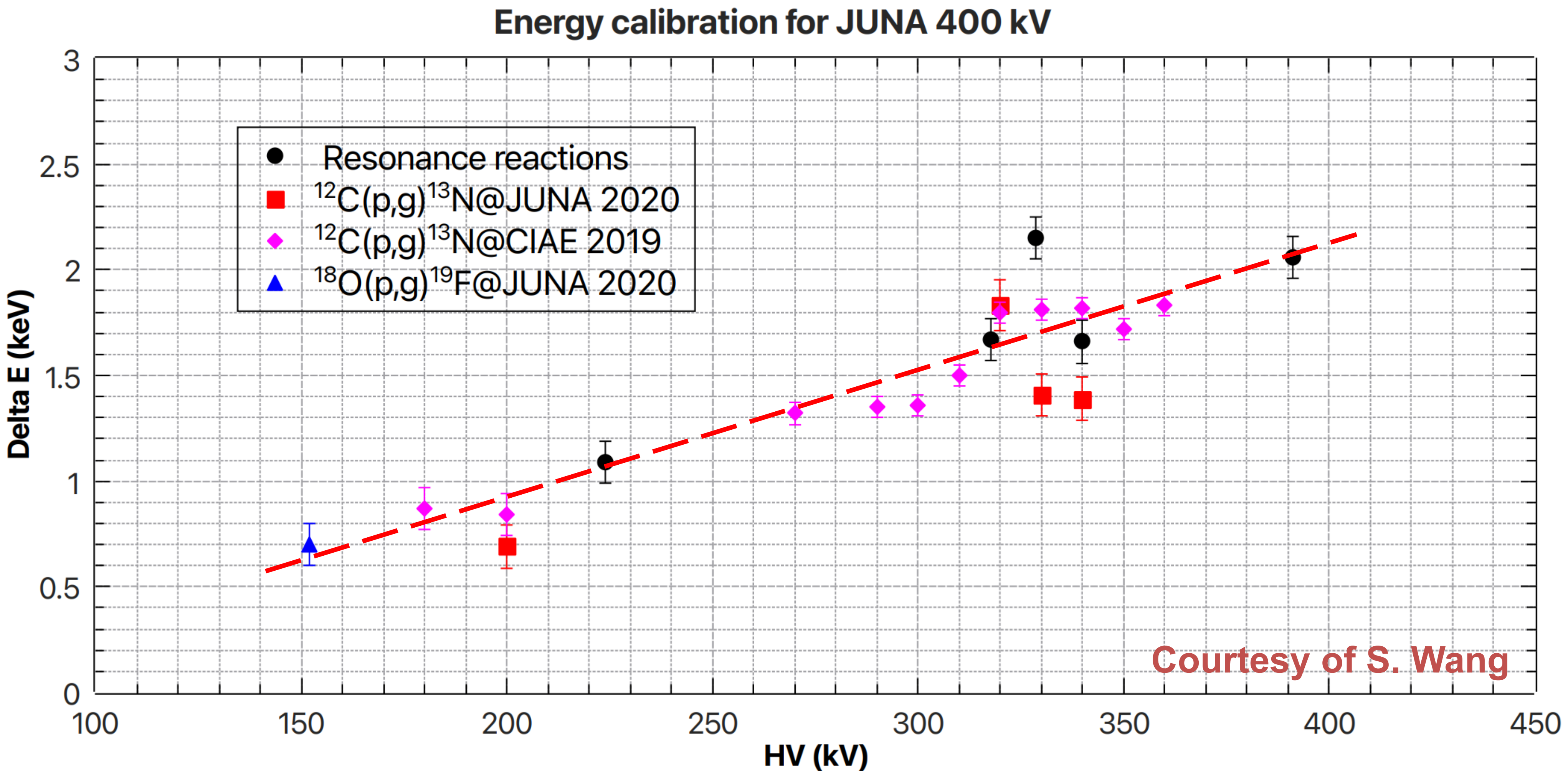
JUNA Beams: Jan. ~ April, 2021

Experiments	Ion Beam	E (keV)	I (emA)	Beam Exposure (C)
$^{12}C(p, \gamma)\ ^{13}N$	H^+	200 - 340	2.1	117
$^{25}Mg(p, \gamma)\ ^{26}Al$	H^+	110	2	1400
$^{19}F\ (p, \alpha\gamma)\ ^{16}O$	H^+	88 - 375	1-2	475
$^{13}C\ (\alpha, n)\ ^{16}O$	He^{2+}	400 - 785	0.4	12.4
	He^+	250 - 400	0.5-2.5	363
$^{12}C(\alpha, \gamma)\ ^{16}O$	He^{2+}	780	1	400

Best beam performance:

- H^+: 4.7 emA@70 keV
- He^+: 6 emA@390 keV
- He^{2+}: 2 emA@760 keV

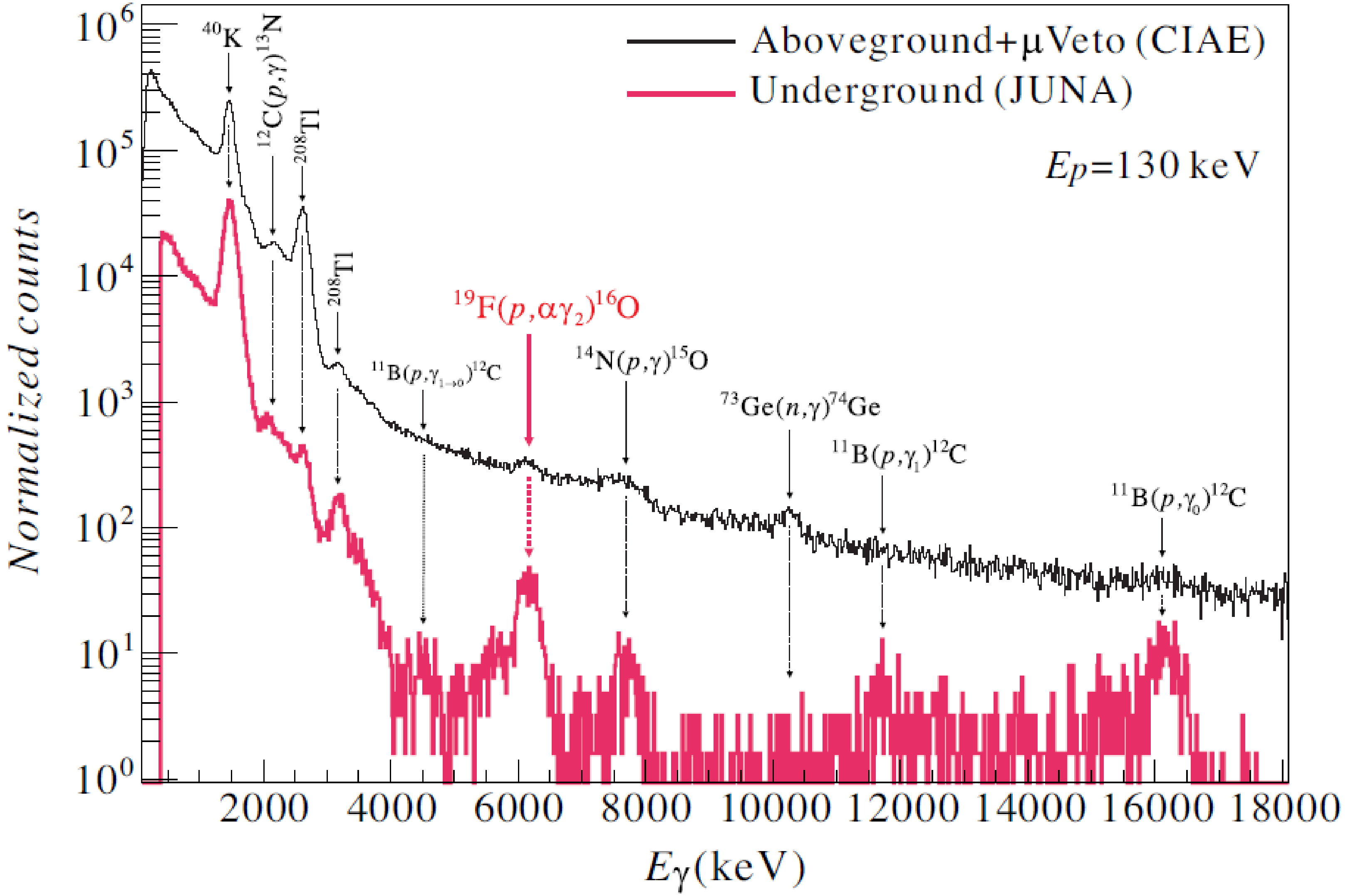
JUNA 1st Underground Beams: Operation



Linear dependence of the observed energy deviation vs. applied voltage

JUNA 1st Underground Beams: Operation

JUNA： $^{19}F(p, \alpha\gamma)^{16}O$ reaction spectrum



JUNA 1st Underground Beams: 1st Results


PHYSICAL REVIEW LETTERS **127,** 152702 (2021)

Editors' Suggestion Featured in Physics

Direct Measurement of the Astrophysical $^{19}F(p,\alpha\gamma)^{16}O$ Reaction in the Deepest Operational Underground Laboratory

L. Y. Zhang,[1] J. Su,[1] J. J. He,[1,*] M. Wiescher,[2,†] R. J. deBoer,[2] D. Kahl,[3] Y. J. Chen,[1] X. Y. Li,[1] J. G. Wang,[4] L. Zhang,[5] F. Q. Cao,[5] H. Zhang,[5] Z. C. Zhang,[6] T. Y. Jiao,[4] Y. D. Sheng,[1] L. H. Wang,[1] L. Y. Song,[1] X. Z. Jiang,[1] Z. M. Li,[1] E. T. Li,[6] S. Wang,[7] G. Lian,[5] Z. H. Li,[5] X. D. Tang,[4] H. W. Zhao,[4] L. T. Sun,[4] Q. Wu,[4] J. Q. Li,[4] B. Q. Cui,[5] L. H. Chen,[5] R. G. Ma,[5] B. Guo,[5] S. W. Xu,[4] J. Y. Li,[4] N. C. Qi,[8] W. L. Sun,[8] X. Y. Guo,[8] P. Zhang,[8] Y. H. Chen,[8] Y. Zhou,[8] J. F. Zhou,[8] J. R. He,[8] C. S. Shang,[8] M. C. Li,[8] X. H. Zhou,[4] Y. H. Zhang,[4] F. S. Zhang,[1] Z. G. Hu,[4] H. S. Xu,[4] J. P. Chen,[1] and W. P. Liu[5,‡]

[1]*Key Laboratory of Beam Technology and Material Modification of Ministry of Education, College of Nuclear Science and Technology, Beijing Normal University, Beijing 100875, China*
[2]*Department of Physics and The Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[3]*Extreme Light Infrastructure—Nuclear Physics, Horia Hulubei National Institute for Research and Development in Physics and Nuclear Engineering (IFIN-HH), Bucharest-Măgurele 077125, Romania*
[4]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
[5]*China Institute of Atomic Energy, Beijing 102413, China*
[6]*College of Physics and Optoelectronic Engineering, Shenzhen University, Shenzhen 518060, China*
[7]*Shandong Provincial Key Laboratory of Optical Astronomy and Solar-Terrestrial Environment, Institute of Space Sciences, Shandong University, Weihai 264209, China*
[8]*Yalong River Hydropower Development Company, Chengdu 610051, China*

(Received 23 June 2021; revised 1 August 2021; accepted 24 August 2021; published 7 October 2021)

Fluorine is one of the most interesting elements in nuclear astrophysics, where the $^{19}F(p,\alpha)^{16}O$ reaction is of crucial importance for Galactic ^{19}F abundances and CNO cycle loss in first generation Population III stars. As a day-one campaign at the Jinping Underground Nuclear Astrophysics experimental facility, we report direct measurements of the essential $^{19}F(p,\alpha\gamma)^{16}O$ reaction channel. The γ-ray yields were measured over $E_{c.m.} = 72.4$–344 keV, covering the Gamow window; our energy of 72.4 keV is unprecedentedly low, reported here for the first time. The experiment was performed under the extremely low cosmic-ray-induced background environment of the China JinPing Underground Laboratory, one of the deepest underground laboratories in the world. The present low-energy S factors deviate significantly from previous theoretical predictions, and the uncertainties are significantly reduced. The thermonuclear $^{19}F(p,\alpha\gamma)^{16}O$ reaction rate has been determined directly at the relevant astrophysical energies.

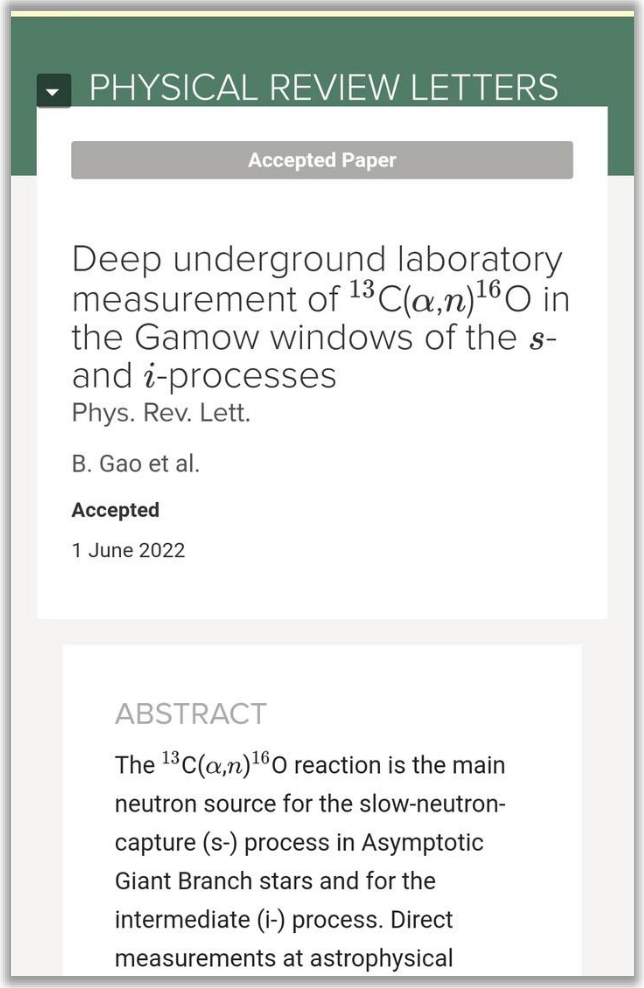
DOI: 10.1103/PhysRevLett.127.152702

The astrophysical origin of fluorine is puzzling. Fluorine is a monoisotopic element, and the stable nuclide ^{19}F is rather fragile—a curious and critically important point in nuclear astrophysics. It does not contribute to, nor is it synthesized in, the main nuclear reactions taking place in stars. ^{19}F has a limited number of atomic and molecular absorption lines in stellar spectra from which reliable abundances are derived, making the nucleosynthetic origin of ^{19}F the least understood of all the light elements [1]. In stellar interiors, ^{19}F is readily annihilated by the most abundant elements, hydrogen and helium, via the $^{19}F(p,\alpha)^{16}O$ and $^{19}F(\alpha,p)^{22}Ne$ reactions, respectively. In order to explain the presence of fluorine, a mechanism is required that enables it to escape from the hot stellar interior after it forms.

Theoretical calculations and observational data suggest several possible ^{19}F production sites [2,3]. Woosley and Haxton [4] calculated ^{19}F production in type II core-collapse supernovae by neutrino spallation on ^{20}Ne; Jorissen *et al.* [5] observed the ^{19}F overabundances (with respect to solar) in red giant stars and provided evidence for ^{19}F production during shell He burning in asymptotic giant branch (AGB) stars [6,7]; Meynet and Arnould [8] identified He burning in Wolf-Rayet stars. Kobayashi *et al.* [9] considered the neutrino-process nucleosynthesis as the major origin of ^{19}F in metal-deficient stars (type II and Ia supernovae and hypernovae), as well as AGB stars, and such supernova provides a celestial site to study the neutrino-nucleus interactions and flavor oscillations in high-density matter [10]. In addition, a signature of fluorine was indeed observed in the spectra of Nova Mon 2012 [11]; however, classical novae seem to account for $\leq 1\%$ of its solar abundance [12]. Therefore, it remains an open question, to what extent each candidate site may contribute to the Solar System and Galactic fluorine, and a precise rate of the $^{19}F(p,\alpha)^{16}O$ reaction plays an essential role.

$^{19}F(p, \alpha g)^{16}O$ reaction

$^{25}Mg(p, \gamma)^{26}Al$ reaction


PHYSICAL REVIEW LETTERS

Accepted Paper

Deep underground laboratory measurement of $^{13}C(\alpha,n)^{16}O$ in the Gamow windows of the s- and i-processes

Phys. Rev. Lett.

B. Gao et al.

Accepted

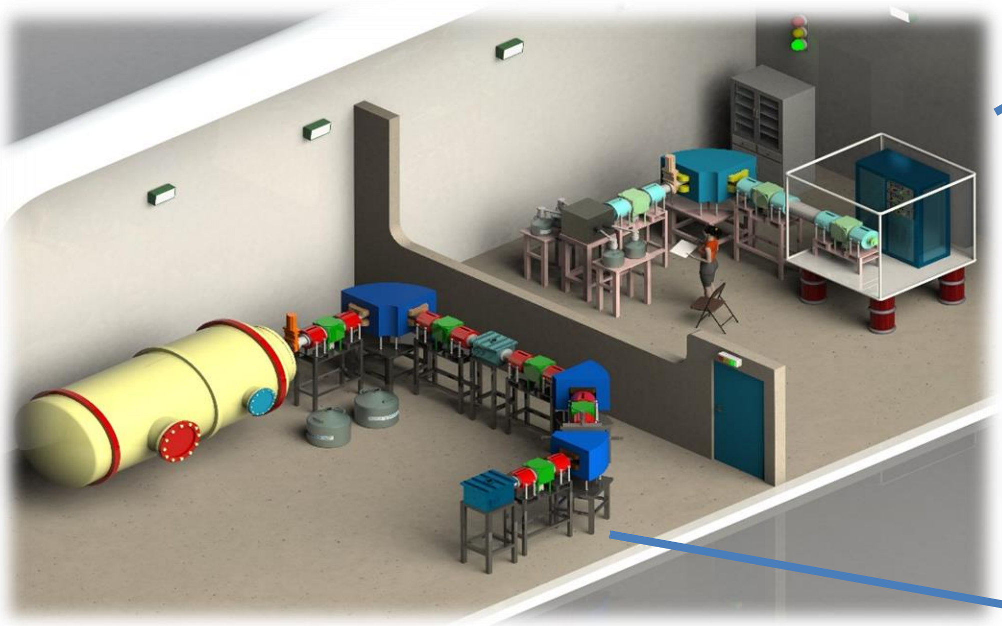
1 June 2022

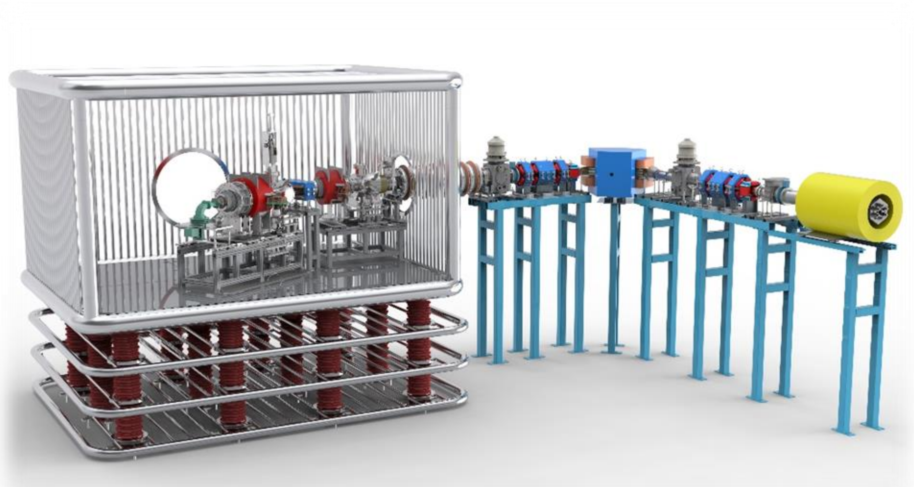
ABSTRACT

The $^{13}C(\alpha,n)^{16}O$ reaction is the main neutron source for the slow-neutron-capture (s-) process in Asymptotic Giant Branch stars and for the intermediate (i-) process. Direct measurements at astrophysical

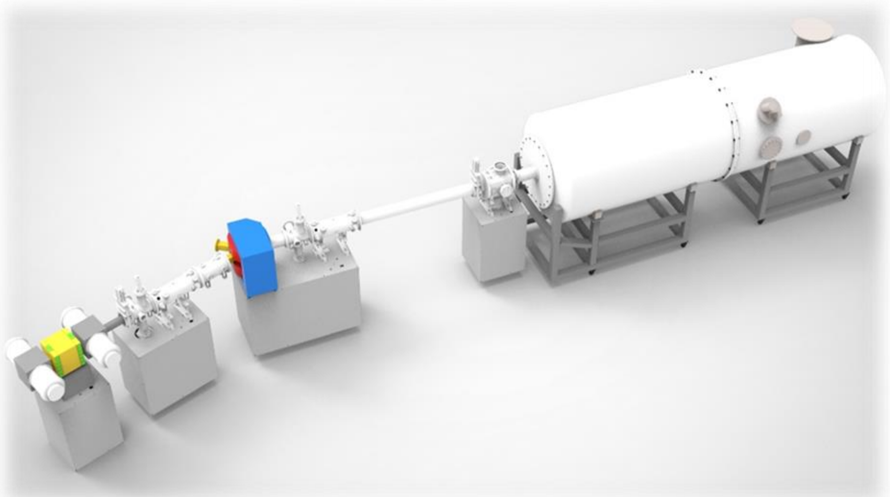
$^{13}C(\alpha, n)^{16}O$ reaction

Scope of JUNA





Phase-I: back to operation in 2023



Phase-II: 4 MV (^{12}C, ^{16}O, …) to be started in 2023

Acknowledgement

Collaboration Team

TSINGHUA UNIVERSITY 1911

SHANGHAI JIAO TONG UNIVERSITY 1896

SICHUAN UNIVERSITY 1896

SHANDONG UNIVERSITY 1901

SHENZHEN UNIVERSITY 1983

SUN YAT-SEN UNIVERSITY

中国原子能科学研究院
中核集团 CHINA INSTITUTE OF ATOMIC ENERGY

IMP 中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

CJPL 中国锦屏地下实验室
China Jinping Underground Laboratory

SDIC 国投集团 SDIC GROUP

雅砻江流域水电开发有限公司
YALONG RIVER HYDROPOWER DEVELOPMENT COMPANY, LTD.

IAC Members

M. Wiescher

T. Motobayashi

Z. J. Wang

C. Brune

M. Junker

D. Robertson

F. Strieder

D. Leitner

Q. Yue

Summary

- JUNA underground lab successfully constructed and used for the 4 critical reactions
- JUNA accelerator delivered mA H^+ and He^{2+} beams for the experiments
  - Large flexibility in beam energy choice (70~400 keV/q)
  - Intense beam production
  - Suitable for underground lab
  - Reliable and stable
- First beam on target leads to promising results
- JUNA will be recovered in 2023 and JUNA-II is foreseen

Thanks for your Attention!