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RFQs and Neutron Radiography

Research Areas

- RFQ accelerator and other advanced RF linear accelerating structures such as IH-RFQ，IH-DTL，CH-DTL and so on
- Beam dynamics on high intensity beam transportation and non-linear accelerator physics
- ECR ion source (Proton, Deuteron and Heavy Ion Beam)
- Beam diagnostic, monitoring and controlling
- Technology and applications of neutron radiography and tomography

Main Achievements

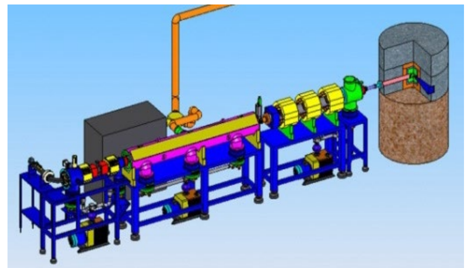

Fig.1a PKUNIFTY beam line setup

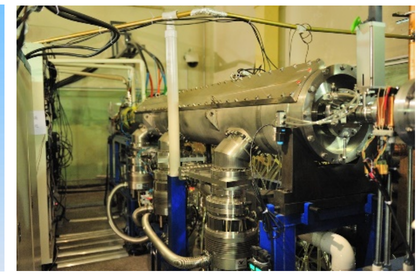

Fig.1b Deuteron RFQ

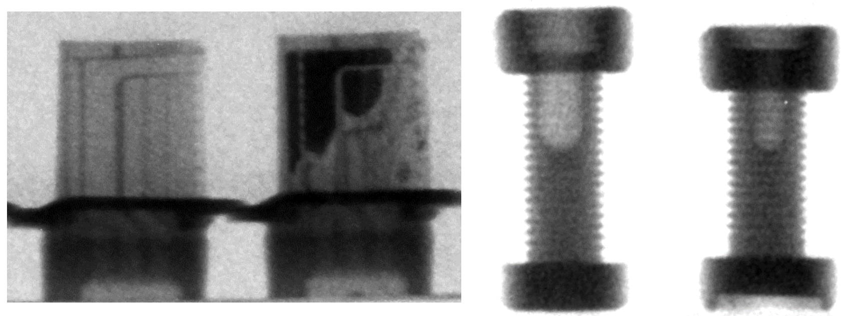

Fig.2 Neutron radiography examples taken by PKUNIFTY (up-left : first stage of turbine blades, Up-right : non destructive testing of ED)

- **PKUNIFTY (Peking University Neutron Imaging Facility)** has been completed at the end of 2012. In 2017-2018, It delivered 2MeV more than 20mA deuteron beam at 201.5MHz with duty cycle of 2% and repetition frequency of 100Hz. It consists of a high current deuteron ECR ion source, LEBT, deuteron RFQ, HEBT, Beryllium target and neutron imaging system(Fig.1a and Fig.1b). The 2.4 $\times$ 10^{11} neutron /cm^2s has been generated by deuteron-beryllium nuclear reaction. PKUNIFTY has been operating for the neutron image experiments several hundred hours. It shows the good application potential on neutron non destructive material detection.

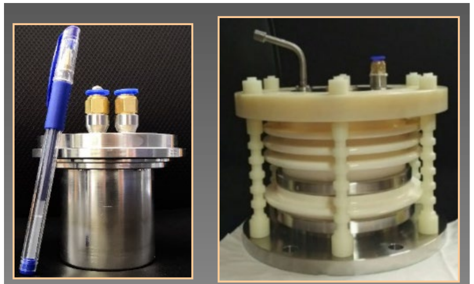

Fig.3 Miniaturized ECR ion source.

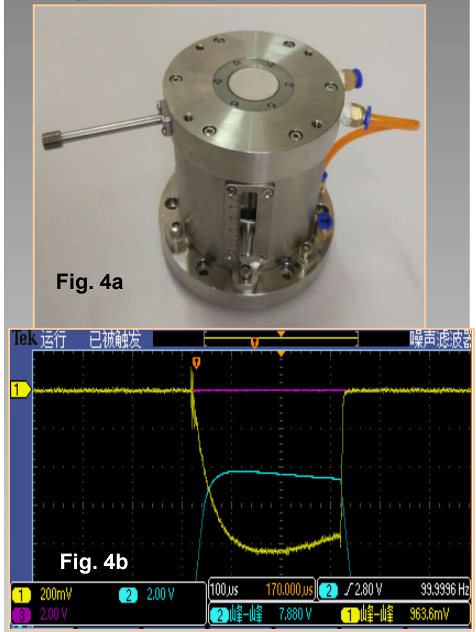

Fig. 4 H^- ECR ion source and test results.

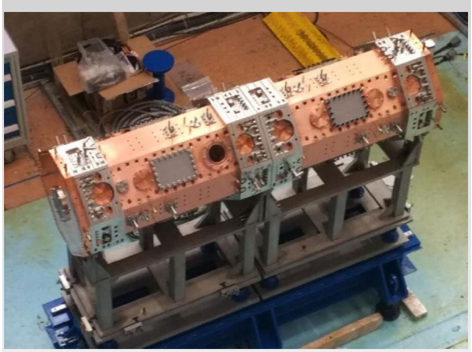

Fig. 5 973 Deuteron RFQ

- **Miniaturized ECR ion source development.** To meet the requirement of some small accelerator such as neutron tube, we developed a miniaturized ECR ion source. Its plasma chamber dimension is Φ30 mm×40 mm (Fig.3-left) and the whole size of the ion source that including RF matching section, plasma chamber(Fig.3-Right), and 45 kV tree - electrode extraction system is Φ180 mm×130 mm. A co-axial is used for RF transportation. A 52mA pulsed H+ beam with duty factor of 10%(1ms/100Hz) and a 21 mA CW H+ beam has been obtained from this source. Beside, a very stable 3 mA H+ CW beam at RF 30 W and a 2 mA He+ with 10 W RF can been easily generated with this compacted source (S. X. Peng Chin. Phys. B, 27(5) (2018): 055204). Recently, the beam currents have been updated up to 64mA (pulsed) and 27mA (CW).
- **2.45 GHz microwave driven volume H- source** A H- source (Fig.4) based on 2.45GHz microwave was developed at PKU. It can generate 8.5 mA H- beam at 50 keV. It has been used to deliver H- beam for Xi'Paf since the end of 2017.
- **973 RFQ.** (Supported by NSFC 2014CB845503 and cooperated with IMP) A 50mA CW deuteron RFQ has been designed and fabricated at Peking University. It accelerates 50mA deuteron from 50keV to 1MeV within 1.8m length. The equapartition and matching method, phase advance optimization method are used to optimize beam dynamics, the designed transmission efficiency is 98%. The new structure RFQ of four-vane with coupling window can separate the quadruple mode(working mode) from other modes by simple structure without Pi-mode rod or dipole-mode rods. We adopt it to avoid sparking caused by the complex internal structure. The window's parameters are adjusted and optimized to make the field along the cavity flat. The RFQ cavity's machine error is less than 20μm and the total installation error is less than 50μm. The low power test of cavity shows the unflatness of field is less than ±2%. The high power test of cavity was done in June 2018. The electrode voltage reached the design value and kept stable. A beam line is set up for RFQ beam commissioning. We use H_2^+ instead of D+ for beam experiment because of radiation safety. 1.78mA H_2^+ beam is obtained at the exit of RFQ cavity and the beam transmission efficiency is 91%.

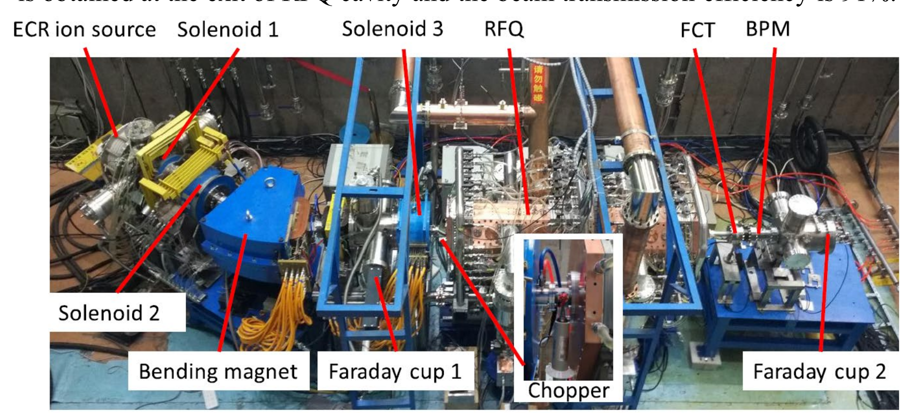

Fig. 6 973 D+ RFQ beam commissioning setup.

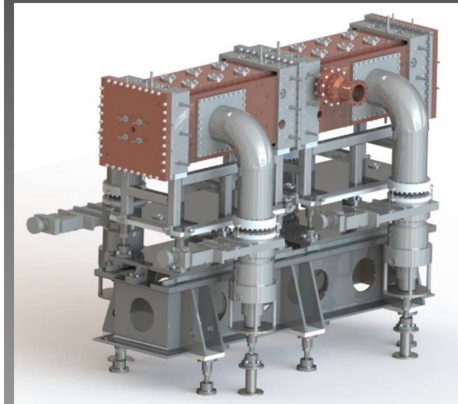

Fig.7 585 RFQ is under construction

Fig. 8 Patent for ECR H- source

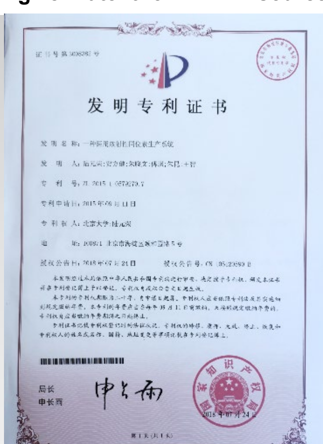

Fig. 9 Patent for Medical Isotope production

- A special deuteron RFQ has been designed for the Southwest physical institute. The **585 RFQ (see Fig.7)** will accelerate 10mA deuteron from 50keV to 1.5MeV within 2.2m long, working at 162.5MHz with maximum pulse repetition 200Hz and duty factor of 1%. The simulated transmission efficiency is 99%, the nominated RF power without beam is about 45kW, a 120kW solid state RF amplifier has been ordered from Kaiteng Company located in Sichuan. It makes RFQ possible to accelerate 3He+ to 2.25MeV. The RF structure and EM design has been carried out. The RFQ cavity is now under construction in IMP.
- **BISOL RFQs.** Peking University (PKU) and China Institute of Atomic Energy (CIAE) are jointly proposing to construct the Beijing Isotope-Separation-On-Line (BISOL) beam facility. This facility, aimed at both basic science and application goals, is based on both reactor and accelerator-driven systems, as shown in figure 1. The reactor-driven system is relying on the existing China Advanced Research Reactor (CARR) at CIAE. The accelerator-driven system, accelerating high intensity deuteron beams to 40MeV, will run as an intense accelerator-driven neutron source and radioactive ion beam (RIB) source. The RIBs coming from these two independent systems will be highly charged and then accelerated to 150 MeV/u by the post-accelerator.

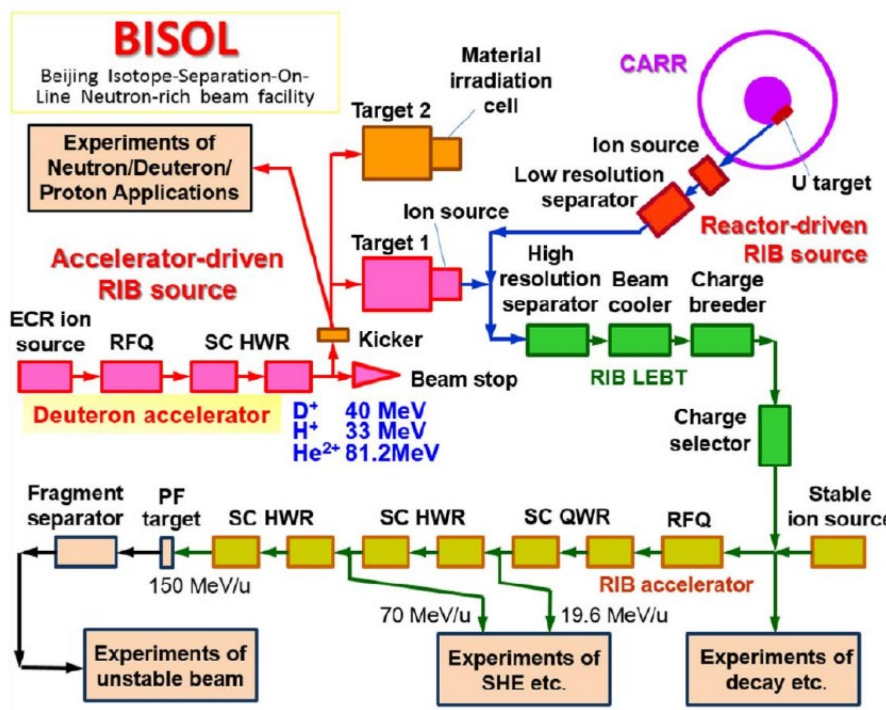

Fig. 10 BISOL Project

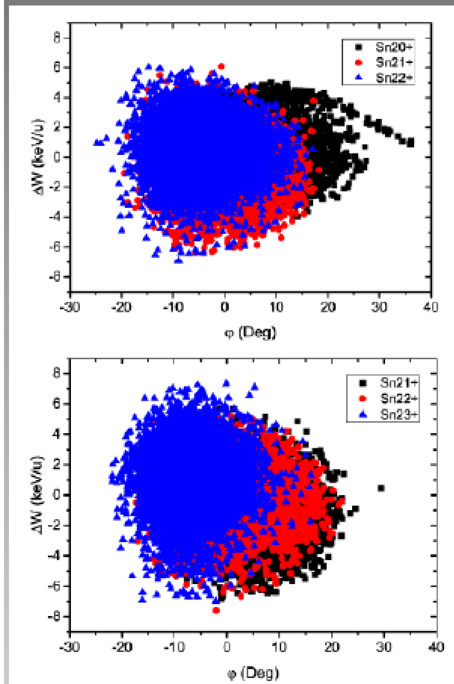

Fig. 12 Output phase space distribution

- **The BISOL deuteron driver linac** aims to accelerate the beam up to 40 MeV with a maximum beam current of 10 mA in phase I, rising to 20 mA for phase II. In addition, this deuteron driver linac can also be operated independently as the Multi-Aimed Intense Neutron Source (MAINS), which will be a significant facility for the preliminary test and evaluation of materials under intense irradiation, especially for the future 4th generation of fission reactor and foreseen fusion reactor. It consists of a low energy beam transport line (LEBT), a radio frequency quadrupole (RFQ), a medium energy beam transport line (MEBT), a superconducting rf (SRF) linac with four cryomodules, a high energy beam transport line (HEBT) and a liquid Lithium target system (LLT). It makes use of (d, n) reaction to produce fast neutrons with the flux of $(2\sim5)\times10^{14}$ n/cm^2/s in the energy range of 1-20 MeV. The deuteron beam is extracted directly from the ECR-IS with the energy of 50 keV, and then accelerated up to 3 MeV and 40 MeV by the RFQ and SRF linac, respectively. The SRF linac consists of two different types of half wave resonator (HWR) cavities with geometry beta βg of 0.09 and 0.16, which will be installed in four cryomodules.
- **A continuous-wave (CW) heavy-ion radio frequency quadrupole (RFQ)** has been designed to accelerate radioactive beams from the Beijing Isotope Separation On-Line (BISOL) facility. This RFQ will accelerate high-charge-state ions such as 132Sn21+ from 3 keV/u to 300 keV/u with a vane length of 3.77m at a frequency of 81.25 MHz. The transmission efficiency reached 98.1% in simulation. The output longitudinal normalized rms emittance is 0.31 keV/u□ns. Tolerance analysis shows that this RFQ can handle a wide range of non-ideal beams while retaining a relatively high transmission efficiency and low longitudinal emittance. In order to increase the intensity of the radioactive ion beams (RIB), this RFQ will accelerate multi-charge-state beams simultaneously. In the case of the tin beam (Sn), we have studied the transmission of adjacent charge state beams and multi-charge-state beams in this RFQ (Fig.12 up is for simultaneous acceleration of Sn^{20+}, Sn^{21+} and Sn^{22+}; Fig.9 down is for Sn^{21+}, Sn^{22+} and Sn^{23+}). The transmission efficiency and output transverse beam quality of the multi-charge-state beams are close to the results of the single-charge-state beam, but the output longitudinal emittance is larger. We have selected a 4-vane RFQ design with dipole stablizer rods, due to the considerations of power consumption, the flatness of electric field, cooling convenience and machining efficiency. The full 3D simulations with multi-physics analysis have been performed.

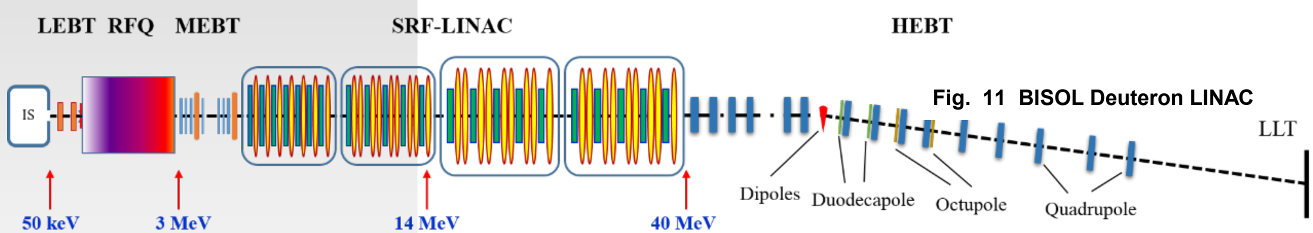

Fig. 11 BISOL Deuteron LINAC

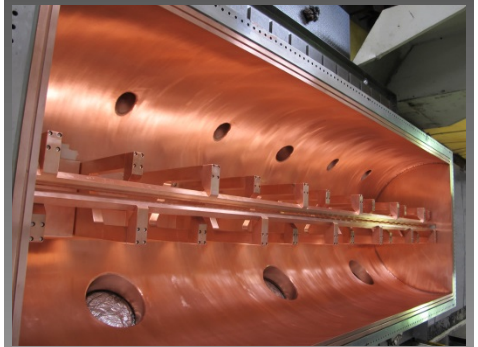

Fig. 13 Inner structure of SSC-RFQ

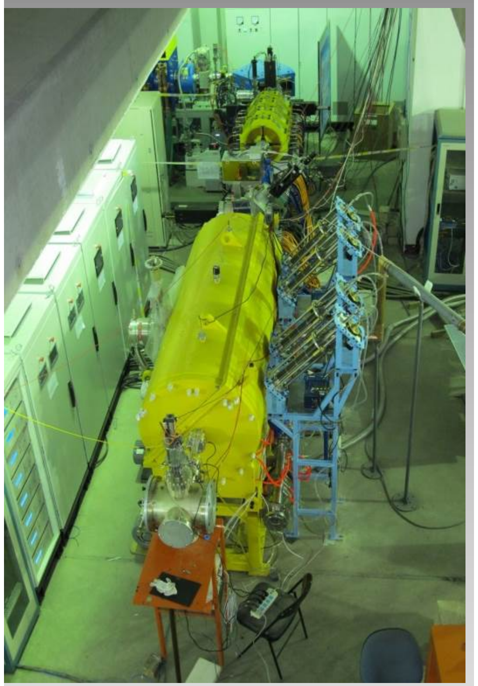

Fig. 14 Outline of SSC-RFQ

➢A 53.667MHz **high charge state heavy ion RFQ accelerator** has been designed and constructed a part of SSC-LINAC injector for HIRFL-CSR. The injection and exit energy of this RFQ is 3.728keV/u and 143keV/u. Beam dynamics design is optimized for 0.5pmA $^{238}U^{34+}$ or maximum 17emA (the measured beam current) with the minimum charge mass ratio is 1/7. Finally, it uses a 2.5 m RFQ to realize the transmission efficiency of 94% for $^{238}U^{34+}$. RFQ Cavity was manufactured by kelin in Shanghai, the inner structure was shown in Fig.13. The outline of SSC-RFQ was shown in Fig.14. The S11 of the power coupler is adjusted to -50 dB, and the Q_0 of the cavity is 6440, which is about 97% of the simulation value. The electric field distribution along the axis is evaluated by the perturbation method. The unflatness of electric field distribution is ±2.5%. The vacuum has reached 3.2×10^{-6}pa, the rf commissioning has been accomplished. The beam commissioning for O^{5+} and Ar^{8+} has been accomplished. The beam transmission for Ar8+ is 94.2% at CW RF power 18kW, output beam energy is 142.8keV/u (Fig.15). The uranium beam acceleration was commissioned in the middle of 2018 successfully. On 17th Dec, 2019, SSC linac delivered 9eμA $^{40}Ar^{7+}$ beam to SSC, finally, SSC outputs $^{40}Ar^{7+}$ 300enA with the energy of 5.98MeV/u , the operation is very stable. Especially, SSC can deliver the $^{209}Bi^{32+}$ with transmission greater than 80% (Courtesy IMP Prof. Yin Xuejun).

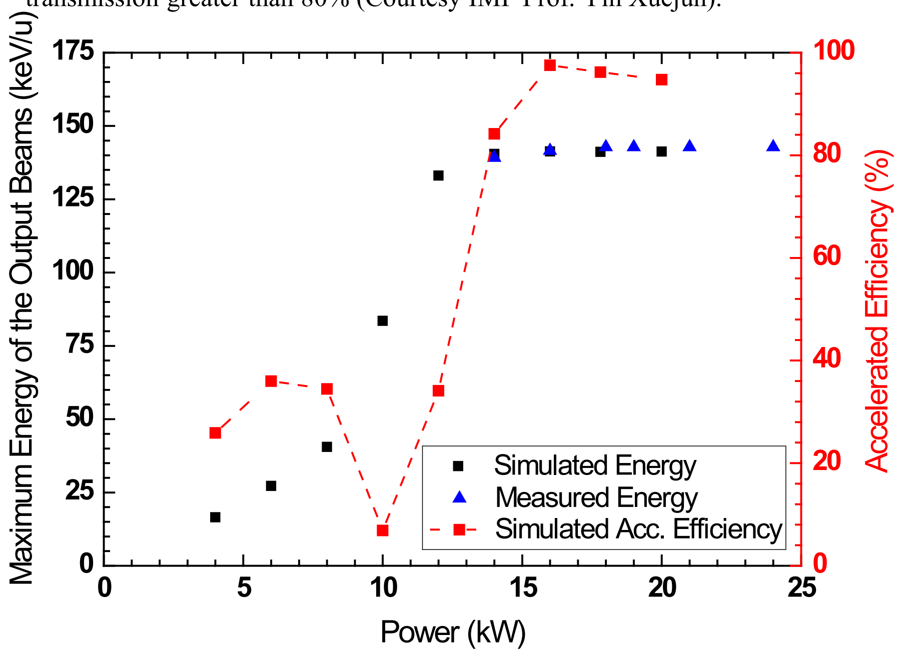

Fig. 15 SSC-RFQ beam commissioning results