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THE CONCEPTUAL DESIGN OF THE CHINA WHITE NEUTRON SOURCE*

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Abstract

In order to feed the nuclear data needs for design of the Chinese Accelerator Driven sub-critical System (CADS) and new generation nuclear energy systems, we plan to construct the China White Neutron Source (CWNS). The CWNS will be composed of a Proton Linac, an Accumulator Ring, a Target and Experimental Facilities. The linac is designed to deliver a proton beam having an average current of 1 mA at energy up to 300 MeV. The revolution frequency of the accumulator ring will be ~1.4 MHz. Two spallation targets are planned, with one for short pulsed modes and the other for micro-pulsed mode.

INTRODUCTON

Many high-current, high-energy proton accelerators have been built or are planned to be built worldwide for multidisciplinary applications, for example ISIS, SNS, JPARC, ESS, CSNS and CADS. The main purpose of all these projects is to provide an intense neutron source to support a variety of research applications. One of the important applications for spallation neutrons is nuclear data measurement. Nuclear data play a key role in the design of nuclear energy systems and especially for the new generation of nuclear energy systems such as ADS. The CWNS will be built to support nuclear data measurements in both the fast and resonant regions.

LAYOUT OF THE CWNS

The CWNS includes a 300 MeV proton linear accelerator, an accumulator ring, a target station and multiple experimental stations as shown in Figure 1. The proton linac is composed of two Radio Frequency Quadrupole accelerators (RFQ), a Drift-Tube Linac (DTL) and a Coupled-Cavity Linac (CCL).

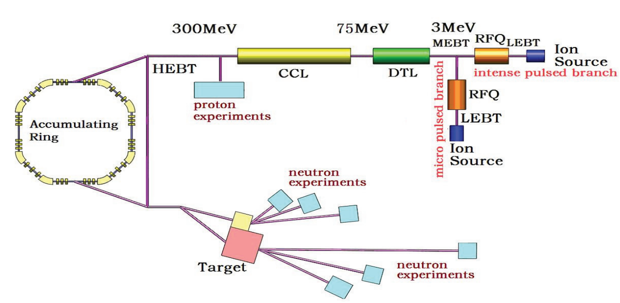

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Figure 1: Schematic of the CIAE complex.

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Design Philosophy

Measurements of nuclear data in the fast neutron region require very short neutron pulses while measurements in the resonance region require very intense neutron pulses. To meet the multidisciplinary requirements of this research facility, three modes of operation will be provided: a long-pulsed mode, a short-pulsed mode and a micro-pulsed mode. The long-pulsed mode will be operated for proton experiments. The short-pulsed mode will be operated for nuclear data measurements in the resonance neutron energy region while the micro-pulsed mode will support nuclear data measurements in the fast neutron region. In addition to the temporal structure, other beam parameters will be adjustable to meet the different experimental requirements as shown in Table 1. The time structure of the beam at the experimental stations for the three modes is shown in Figures 2, 3 and 4.

Table 1. Beam Parameters of Three Operating Modes

Mode	Long-pulse	Short-pulse	Micro-pulse
Macro-pulse frequency	50 Hz	25~100 Hz	50 Hz
Macro-pulse length	0.4 ms	0.2~0.8 ms	0.4 ms
Average beam current	1 mA	280 µA	1.8 µA
Average beam power	300 kW	84 kW	0.54 kW
Peak beam current	50 mA	11~45.7 A	50 mA
Beam pulse length	400 us	50~200 ns	<1 ns
Beam energy	100~300 MeV	300 MeV	300 MeV

CONCEPTUAL DESIGN OF THE FRONT-END

It is impractical for a single Low-Energy Beam Transport line (LEBT) and RFQ to provide beams in both the short- and the micro-pulsed modes. Our front-end is therefor designed to have two branches; one branch for intense beam pulses and the other for micro-pulses. The intense pulsed beam branch can work in both the long- and short-pulsed modes while the micro-pulsed branch will provide only micro-pulses.

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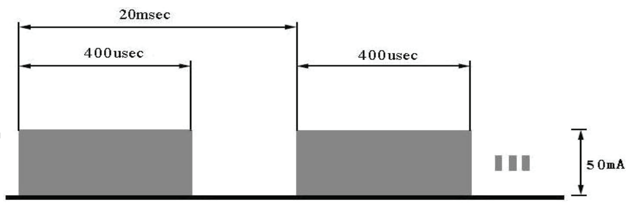

Figure 2: Time structure of the long-pulsed mode.

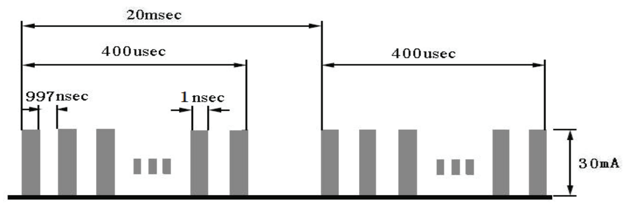

Figure 3: Time structure of micro-pulsed mode.

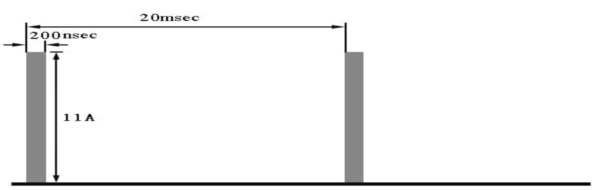

Figure 4: Time structure of short-pulsed mode.

Because the intense pulsed branch of the front-end is of conventional design we have not described it in detail here. We have however prepared a preliminary design for the micro-pulsed branch [1] which we introduce below.

LEBT of the Micro-pulse Branch

The LEBT for the micro-pulse branch of the front-end includes a 1 MHz chopper and two magnetic solenoid lenses followed by a 5 MHz buncher. First the chopper cuts the macro-pulses to a length of 50 ns. This short beam pulse is then transported to the buncher that compresses it to a length of 3 ns at the entrance of the RFQ. The layout of this LEBT is shown in Figure 5.

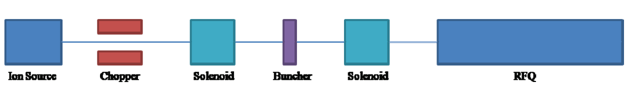

Figure 5: Layout of the micro-pulse branch.

If the peak current extracted from H^+ ion source is 3 mA at 30 keV, the peak current of the bunched beam at the end of LEBT will be ~50 mA. The temporal length of the core of the beam will be ~2 ns. Figure 6 shows the transverse and longitudinal phase-space projections of the beam distribution at the entrance to the micro-pulse RFQ.

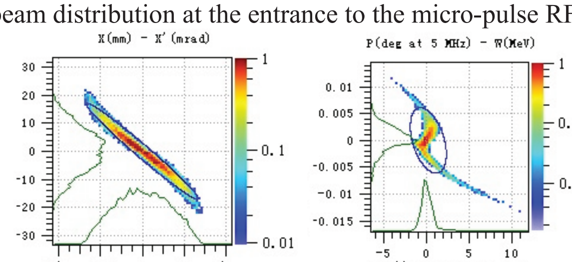

Figure 6: Particle distribution in transverse (left) and longitudinal (right) planes at the end of the LEBT.

RFQ

After bunching, the energy spread in the micro-pulse beam will be very large, ≥15%, making the design of the RFQ very challenging. The designed RFQ can accept a 10% energy spread.

MEBT

In some accelerators, such as CPHS [2] and PEFP [3], the RFQ and DTL are designed to be "close-coupled" without requiring a Medium Energy Beam Transport line (MEBT) to provide matching. Because our front-end has two branches injecting one main accelerator, we will require a MEBT to match both the short- and micro-pulsed beams into the DTL.

PRELIMINARY DESIGN OF DTL & CCL

The main accelerator is composed of a DTL and a CCL. We would traditionally choose the transition energy between the two structures to occur at energy where their respective shunt impedances (ZT^2) are equal. Figure 7 shows that the optimum transition energy would be at 75 MeV. Taking other practical constraints into account, such as rf power partitioning, we may move the transition energy to a value slightly greater than 75 MeV.

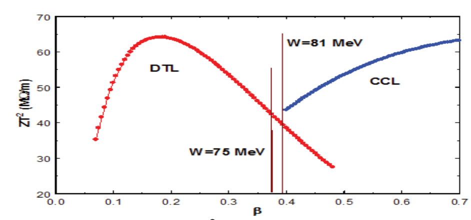

Figure 7: ZT^2 as a function of β.

The main accelerator will be capable of accelerating both Protons and H^- ions either singly or simultaneously. To provide this feature we have selected the frequency of the CCL to be the 3rd harmonic of DTL frequency.

DTL

The DTL, operating at a frequency of 325 MHz, will accelerate beam from 3 to 75 MeV in just under 25 m. It will consist of four tanks each powered by a 3 MW klystron. The main design parameters for the DTL architecture are summarized in Table 2.

Table 2. DTL Design Parameters

Tank	No of Cells	Length m	W_{final} MeV	Power MW
1	57	7.24	22.29	2.309
2	24	5.53	40.36	2.305
3	20	5.73	57.99	2.361
4	18	5.93	75.00	2.384
Total	126	24.44		9.36

The Hofmann stability diagram in Figure 8 shows schematically the instability stop bands that can lead to resonant emittance transfer in high current beams for emittance ratios $\varepsilon_z/\varepsilon_x \approx 1.2$. We can see that our design lies safely between the first and second resonances.

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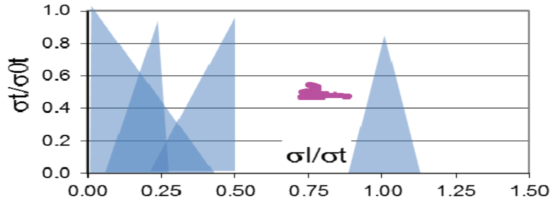

Figure 8: Hofmann coherent resonance diagram for the DTL.

CCL

The CCL, operating at a frequency of 975 MHz, will accelerate beam from 75 to 300 MeV. It consists of 8 multi-tank modules, each powered by a single 5 MW klystron. Table 3 summarizes the design architecture of the CCL. Figure 9 shows the Hofmann stability diagram for the CCL where we see that this design just crosses the tip of the first resonance.

Table 3. CCL Design Parameters

Module number	Tanks per module	Cells per tank	Length m	W_{final} MeV	Power MW
1	16	9	11.45	86.7	1.23
2	12	11	10.90	108.9	3.02
3	12	11	12.06	137.2	3.94
4	12	11	13.15	167.2	3.94
5	12	11	14.13	198.7	3.95
6	12	11	15.01	231.3	3.95
7	12	11	15.80	264.8	3.95
8	12	11	16.52	300.1	4.14
Total	100	1068	109.01	300.1	28.13

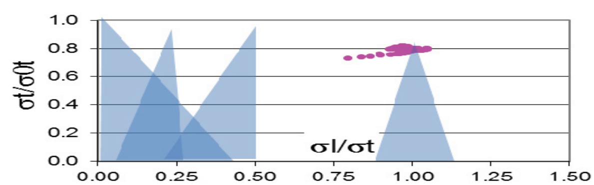

Figure 9 Hofmann coherent resonance diagram for the CCL.

Beam Dynamics Simulations

Figure 10 shows an end-to-end simulation of the DTL and CCL from 3 to 300 MeV at 50 mA. In this simulation, without any matching between the DTL and CCL, we see that a longitudinal mismatch occurs at the entrance to the CCL where the rf frequency increases by a factor of 3. This mismatch drives a small transverse oscillation but does not result in any beam loss at an emittance of 5 rms.

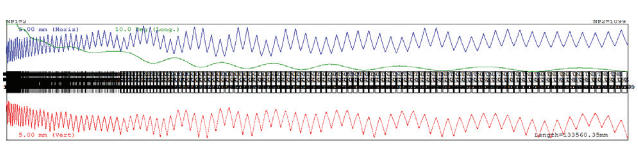
Figure 10: End-to-end simulation of the linac to 300 MeV at 50 mA.

By turning off modules 6, 7 and 8 we can accelerate the beam to ~200 MeV and transport it to the end of the CCL without loss and without changing any of the EMQ gradients as shown in Figure 11.

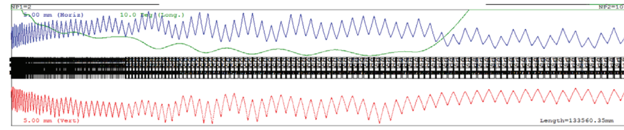
Figure 11: End-to-end simulation of the linac to 200 MeV at 50 mA.

By turning off modules 3 through 8 we can accelerate the beam to ~109 MeV and transport it to the end of the CCL without loss and without changing any EMQ gradients as shown in Figure 12.

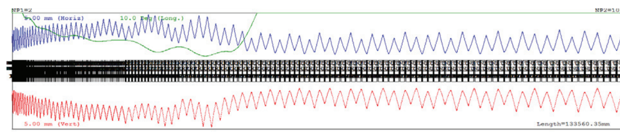
Figure 12: End-to-end simulation of the linac to 109 MeV at 50 mA.

We can conclude from these simulations that by powering only selected modules, this linac can deliver 50 mA beams at a minimum of 7 discrete energies. We can further conclude that by powering different modules on alternate macro-pulses, this linac can deliver beams having multiple energies, different pulse lengths and beam currents essentially concurrently. The beams can be either the same or different ions and could be magnetically separated at the linac exit.

THE PRELIMINARY DESIGN OF AR

The Accumulator Ring (AR) is the key instrument for providing the short, intense beam pulses to support neutron experiments in the resonance region. The lattice, consisting of triplets, has the smaller betatron function in the long central drift section. The input beam is 300MeV/20mA, and the duty factor is about 2.5%. The circumference of the ring is about 133.6m. The average current is about 275uA.

TARGET AND EXPERIMENTAL STATIONS

As shown in figure 1, two spallation targets are planned, with one for short pulsed modes and the other for micro-pulsed mode. For each target, three neutron tunnels are designed. For the nuclear data measurement in the resonance energy region, three tunnels with 200 m, 100 m and 50 m flight path are planned for different experiments. While for fast neutron experiments, three tunnels with 40, 20 and 10 meters are designed.

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