BEAM DYNAMICS SIMULATION IN HIGH POWER DRIVER LINAC USING BEAMDULAC-SCL CODE

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A number of superconducting linear accelerators-drivers of high-power proton beams are discussed at present. Such accelerators are necessary for accelerating driven systems (ADS) and spallation neutron sources (SNS). The successful development of the conventional nuclear power plants based on reactors utilizing fissile isotope as ^{235}U, ^{239}Pu completely satisfied available requirements both civil nuclear power engineering and nuclear weapon complex for a long time. But last time the safety requirements for traditional nuclear reactors based on the uranium (or uranium-plutonium) fuel are hardening, impossibility of receiving necessary amount of uranium of some countries and large amount of accumulated radioactive waste leads to R&D of fast reactors and subcritical nuclear systems. Waste processing can be also done using ADS with external source of neutrons – a proton accelerator with a beam power of 1…10 MW. The parameters of an accelerator-driver obtained by numerical simulation in the updated BEAMDULAC-SCL code are presented in this report.

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INTRODUCTION

Safety requirements for traditional nuclear reactors operating of the uranium (or uranium-plutonium) fuel, the inability to obtain the necessary amount of uranium by some countries, and a large amount of accumulated radioactive wastes led to an interest of fast neutron reactor and nuclear subcritical facilities development. Currently several fast neutron reactors are operating in Russia and foreign countries. The electronuclear facility including external neutron source – proton accelerator with a beam power of 1…10 MW is an alternative technology. Nuclear facility using high-power proton accelerator as an external source are called Accelerating Driven System (ADS).

Parameters of proton linacs for three tasks (uranium fuelded subcritical reactors, thorium fueled reactor, the transmutation of radioactive wastes) are close: the proton beam having output energy of about of 1 GeV and beam power of several MW. It should be noted that such beam power are achieve in modern accelerator technology but has received only at few research centers, industrial accelerator with such parameters does not under operation at present.

Several programs of subcritical nuclear facilities are under development now. The international project of the European Union – EUROTRANS [1], which includes: ADS-demonstrator MYRRHA, XT-ADS reactor, transmutation production reactor EFIT, linear accelerators TRASCO (Italy) and others is most significant. Designing of subcritical demonstration reactor MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) [2] beginning in Belgium. Similar project of OMEGA program developed in JAERI / Tokai [3] Japan, and projects SMART (Subcritical Minor Actinide Reduction Through Transmutation) and DOI-ADS in USA. The thorium reactor projects are considered in India and the UK (ThorEA) [4]. The ADS R&D is started in China (Chinese ADS). Considering a joint project of the European Union and Japan under create the facility for the transmutation of nuclear waste and simulation experiments to radiation resistance study of reactor materials IFMIF (International Fusion Materials Irradiation Facility), in which the accelerator must have a lower energy (40 MeV) but higher (up to 50 mA) current and its prototype EVEDA (France, Japan) [5], a similar facility ESS-B are being developed in Spain.

All high current accelerator projects for nuclear power engineering or neutron generators are expect developing the same schemes: a linear accelerator includes the short room temperature low-energy linac and main part consisting of independently superconducting accelerating and focusing elements with output energy of up to 1…2 GeV.

Normally conducting part of the accelerator-driver is proposed to develop based on CW RFQ linac and new generation of accelerating H-type cavities, such system are more compact than using conventional E-type structures (Alvarez-type accelerator) and require lower power supply.

Currently the high energy superconducting accelerators are developing by the general concept: they consist of an independently phased cavities sequence which are used to accelerate the beam, and normal or SC solenoids or quadrupoles for their focusing.

1. ACCELERATOR PERIOD LAYOUT

Let's we consider the linear accelerator, consisting of independently phased cavities and solenoids sequence (Fig. 1).

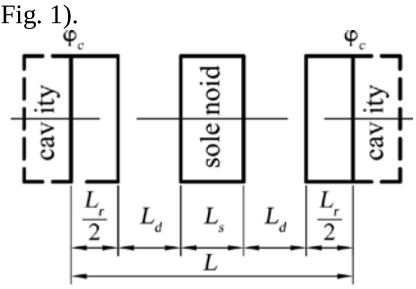

Fig. 1. Layout of structure period

For low- and medium-velocity proton beams the quarter- and half-wave resonators with few gaps are commonly used as accelerating structures. If SC cavities are used they should be the same, otherwise the facility cost sufficiently increase. This means that the phase velocity of the wave should be constant in each cavity. With a large number of resonators is economically advantageous to divide them into several groups, consists of an identical resonators. Obviously, in such acceleration system will always to violate the principle of synchronicity, when the synchronous particle velocity equal to the phase velocity of the accelerating wave at any time. I.e. in this case it appears a slipping of the particles relative to the accelerating wave. The slipping value must not exceed acceptable value the acceleration rate is rapidly reduced, beam longitudinal and transverse stability violates and the transmission coefficient decreases if not. Therefore the number of identical resonators should be limited and the number of cavities groups having different geometry should be minimal.

Particles are accelerated and slipping relative to the RF field in dependence of the ratio between the particle velocity β and the phase velocity of the wave in cavity β_g. The beam motion can be both longitudinally stable and accelerated in the whole system by control the driven phase of the accelerating structure and the distance between the cavities [6]. The beam focusing can be provided by solenoids or permanent magnet lenses (PML) which follow of the cavity [7].

The conditions of longitudinal and transverse beam stability for the structure consisting from the periodic sequence of cavities and solenoids were studied early using transfer matrix calculations [8]. It is very important to know the bucket size since it relates to the longitudinal RF focusing in SC linac design. The smooth approximation can be used in order to investigate the nonlinear proton beam dynamics in such accelerating structures and to calculate the longitudinal and transverse acceptances.

The results of self-consistent beam dynamics investigation in accelerating structures by means of BEAMDULAC-SCL code are discussed in this paper. The BEAMDULAC code is developing in MEPhI since 1999 for high current beam dynamics simulation in linear accelerators and transport channels.

2. THE ACCELERATER STRUCTURE PARAMETERS

In the case when we require that the slipping factor value does not exceed 20%, the SC part of 1 GeV accelerator should be divided into five parts with β_g = 0.31, 0.36, 0.48, 0.65 and 0.875 respectively (Fig. 2). In first section with β_g = 0.31 (see Fig. 2, red color) the 2 gaps 324 MHz cavities and 5-gaps 972 MHz cavities are used in other sections.

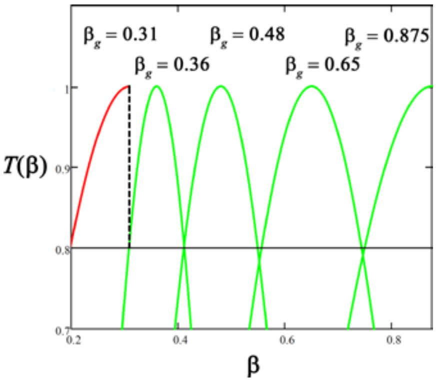

Fig. 2. Slipping factor value versus beam velocity

The parameters of each section are given in Table. To reduce the paper size we present beam dynamics analysis results only for the last part having the beam energy range from 456 to 1000 MeV. The analysis of beam dynamics in the other sections is similar. The field amplitude for each cavity is equal 10.3 MV/m, the cavity length 0.68 m, the particle phase into RF field -20º, frequency f = 972 MHz. Fig. 3 shows that with the chosen accelerator parameters the phase advance of the longitudinal and transverse oscillations are not close to each other, which will prevent a coupling resonance, so beam motion will be stable. Note that the chosen value of the magnetic field makes it possible to keep the beam envelope lower than 7 mm.

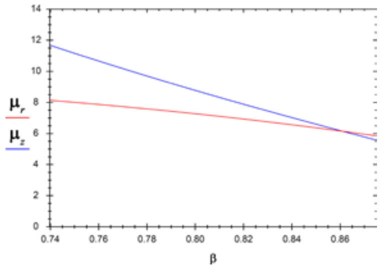

Fig. 3. Longitudinal and transverse Floke parameters

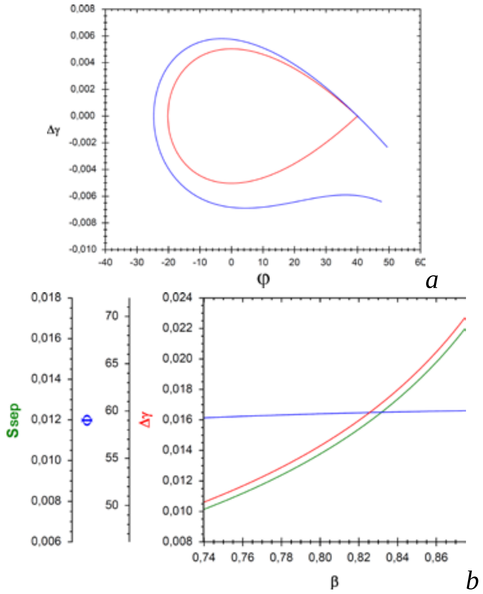

Fig. 4. Separatrix dimension during acceleration

Fig. 4 shows the longitudinal channel acceptance without dissipative effects (red curve) and the blue line defines it taking into account decaying in the injection time in 5-th section (a) and the separatrix size (maximum energy spread, red curve), the phase size (blue curve) and the separatrix area (green curve) during acceleration. We can see that the acceptance increases with β increase with the chosen parameters of the accelerator.

3. BEAM DYNAMICS NUMERICAL SIMULATION RESULTS

Beam dynamics in the polyharmonic field were carried out basing on the chosen parameters. Input beam parameters are shown on Fig. 5.

The simulation results are shown in the Fig. 6. The transmission efficiency is present in Table. Using of BEAMDULAC-SCL code, the number of periods of the accelerating structure can be defined, and therefore the total length of the accelerator. The total length of the accelerator which consists of five superperiods will be equal 199.8 m (see Table).

The accelerator parameters with solenoid focusing

№	β_g	W_{in}, MeV (β_{in})	W_{out}, MeV (β_{out})	Tr. ef. %	*f*, MHz	N_{zaz}	*E*, MV/m	*B*, T	L_{per}, m	N_{per}	*L*, m
1	0,31	20 (0.203)	49 (0.311)	100	324	2	5.3	1.65	0.688	20	13,76
2	0,36	49 (0.311)	91 (0.411)	93.5	972	5	5.3	2.2	0.679	30	20.37
3	0,48	91 (0.411)	184 (0,549)	95	972	5	8.5	3	0.772	32	24.7
4	0,65	184 (0.549)	456 (0.740)	99.9	972	5	10.3	3	0.9	56	50.4
5	0,875	456 (0.740)	1000 (0.875)	100	972	5	10.3	3	1.078	84	90.6

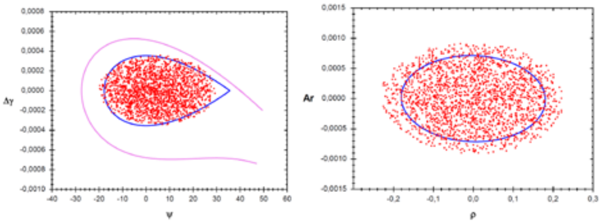

Fig. 5. The input beam longitudinal and transverse phase spaces

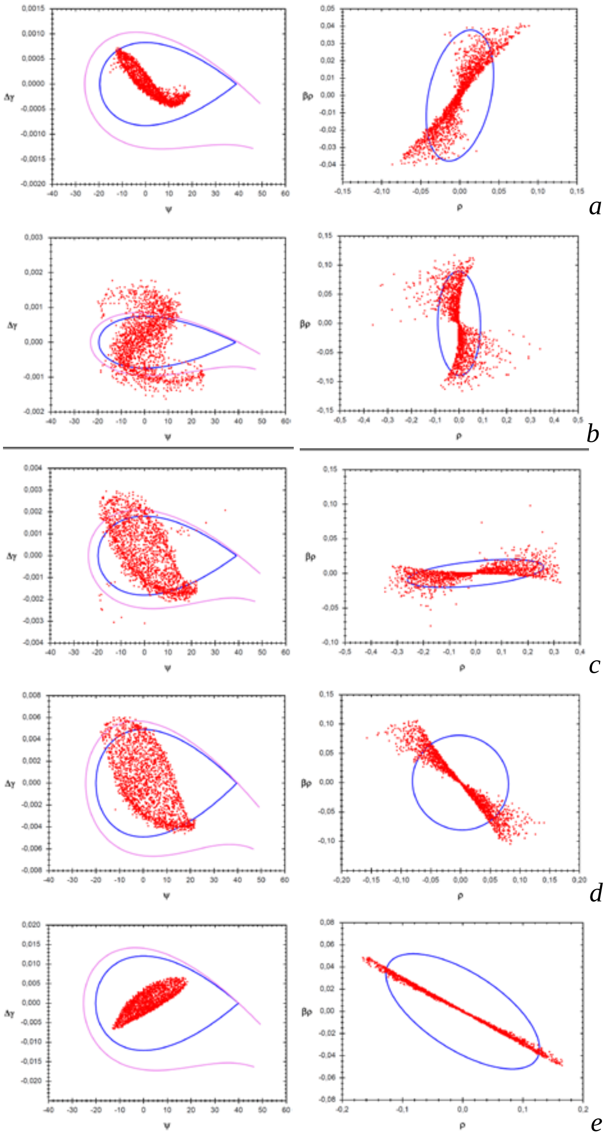

Fig. 6. The output beam longitudinal and transverse phase spaces after each sections

CONCLUSIONS

A complex analysis of the proton beam dynamics was done using the especially designed BEAMDULAC-SCL code. The analysis shows that it is possible to develop an ADS linear accelerator-driver with length about 200 m and magnetic field necessary for transverse focusing is not exceed of 3 T. Beam envelope control is possible in this case (see Fig. 3). Optimized linac parameters are shown in Table.

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МОДЕЛИРОВАНИЕ ДИНАМИКИ МОЩНОГО ПРОТОННОГО ПУЧКА В УСКОРИТЕЛЕ-ДРАЙВЕРЕ С ПОМОЩЬЮ ПРОГРАММЫ BEAMDULAC-SCL

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В последнее время в мире обсуждается несколько проектов сверхпроводящих линейных укорителей-драйверов мощных протонных пучков. Такие ускорители необходимы для подкритических ядерных систем и мощных нейтронных генераторов. Успешное развитие традиционной ядерной энергетики на основе реакторов, использующих делящиеся изотопы ^{235}U, ^{239}Pu, долгое время полностью удовлетворяло имеющиеся потребности как гражданской ядерной энергетики, так и ядерно-оружейного комплекса. Однако в последнее время ситуация стала меняться. Ужесточение требований безопасности традиционных ядерных реакторов на урановом (или уран-плутониевом) топливе, невозможность получения необходимого количества урана некоторыми странами, а также большое количество накопленных радиоактивных отходов привело к активизации работ по развитию реакторов на быстрых нейтронах и подкритических ядерных установок. Подкритическая ядерная установка, использующая внешний источник нейтронов – ускоритель протонов с мощностью пучка 1…10 МВт, может служить и для переработки радиоактивных отходов. Приводятся параметры ускорителя-драйвера, полученные с помощью моделирования в усовершенствованной программе BEAMDULAC-SCL.

МОДЕЛЮВАННЯ ДИНАМІКИ ПОТУЖНОГО ПРОТОННОГО ПУЧКА В ПРИСКОРЮВАЧІ-ДРАЙВЕРІ ЗА ДОПОМОГОЮ ПРОГРАМИ BEAMDULAC-SCL

С.М. Полозов, А.В. Самошин

Останнім часом у світі обговорюється декілька проектів надпровідних лінійних прискорювачів-драйверов потужних протонних пучків. Такі прискорювачі потрібні для підкритичних ядерних систем і потужних нейтронних генераторів. Успішний розвиток традиційної ядерної енергетики на основі реакторів, що використовують ізотопи, що діляться – ^{235}U, ^{239}Pu, довгий час повністю задовольняло наявні потреби як цивільної ядерної енергетики, так і ядерно-збройового комплексу. Проте останнім часом ситуація стала мінятися. Посилення вимог безпеки традиційних ядерних реакторів на урановому (чи уран-плутонієвим) паливі, неможливість отримання необхідної кількості урану деякими країнами, а також велика кількість накопичених радіоактивних відходів привело до активізації робіт по розвитку реакторів на швидких нейтронах і підкритичних ядерних установок. Підкритична ядерна установка, що використовує зовнішнє джерело нейтронів – прискорювач протонів з потужністю пучка 1…10 МВт, може служити і для переробки радіоактивних відходів. Наводяться параметри прискорювача-драйвера, отримані за допомогою моделювання у вдосконаленій програмі BEAMDULAC-SCL.