ISBN: 978-3-95450-202-8 doi:10.18429/JACoW-HB2018-TUA2WC02

STATUS OF R&D ON NEW SUPERCONDUCTING INJECTOR LINAC FOR NUCLOTRON-NICA

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Abstract

The progress in R&D of QWR and HWR superconducting cavities will be discussed. These cavities are designed for the new injection linac of Nuclotron-NICA facility at JINR. The goal of new linac is to accelerate protons up to 25 MeV (and up to 50 MeV at the second stage) and light ions to ~7.5 MeV/u for Nuclotron-NICA injection. Current results of beam dynamics simulations, SC cavities design and SRF technology development will be presented in this paper.

INTRODUCTION

Nuclotron-based Ion Collider fAcility (NICA) is new accelerator complex under construction at JINR [1-5]. It was proposed for ion collision and high-density matter study. NICA facility will include the operating ion synchrotron Nuclotron and new booster and two collider rings being under construction. The injection system of Nuclotron-NICA was upgraded in 2011-2016. The pulse DC forinjector of Alvarez-type DTL linac LU-20 was replaced by the new RFQ developed and commissioned by joint team of JINR, ITEP and MEPhI [6] and is under operation since December, 2015. New RFQ linac can accelerate ions with charge-to mass ratio Z/A>0.3. The first technical session of Nuclotron with new injector was ended on May-June, 2016, [7] and regular experimental sessions were done in 2016-2018. The LU-20 with new RFQ for-injector was used for p, p↑, d, d↑, He, C and Li ions acceleration till now. The other heavy ion linac for particles with Z/A=1/8-1/6 was developed by joint team of JINR, Frankfurt University and BEVATECH and commissioned in 2016.

It must be noted that LU-20 operation causes many technical issues because of its age: it was commissioned in 1972. The possibility of LU-20 replacement by the new linac of 30 MeV energy for protons [8-12] and ≥7.5 MeV/nucleon for deuterium beam is discussed now. Project should also include an option of the linac upgrade for the proton beam energy upgrade up to 50 MeV by means of a number of cavities in additional section. It is proposed that new linac will include a number of superconducting (SC) cavities.

The key problem of SC cavities and SC linac construction for Nuclotron-NICA is the absence of SRF technology in Russia today. The development of the SRF technologies is the key task of new Russian - Belarusian collaboration started on March 2015. Now the JINR, NRNU MEPhI, ITEP of NRC "Kurchatov Institute", INP BSU, PTI NASB, BSUIR and SPMRC NASB are participating in new collaboration.

Two possible schemes for new linac were discussed. First it was proposed to use a number of superconducting cavities for medium and high energy ranges of the linac starting 2.5 or 5 MeV/u. The second way is to start SRF part of the linac from 10-15 MeV.

LINAC GENERA LAYOUT AND BEAM DYNAMICS

In the first case linac will consist of several superconducting independently phased cavities and focusing solenoids. Starting 2014 three SC linac designs were proposed, simulated and discussed [8-12]. The normal conducting 2.5 MeV RFQ and five [8] or four [9] SC cavities groups respectively were in the first and the second linac designs. Main results of the beam dynamics

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simulations were presented in [8-12] in detail. The basic parameters of the linac are the following: the injection energy for SC part of linac is increased to 5 MeV (as LU-20 gives at present, but normal conducting cavities for 5-13 MeV energy band are also discussed). The normal conducting part will consist of 2.5 MeV/nucleon RFQ linac followed by QWR cavities for the acceleration of beams with charge-to-mass ratio Z/A>1/2. Main parameters of the linac are presented in Figure 1.

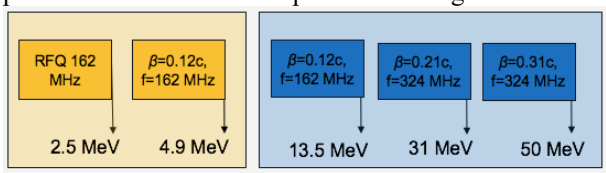

Figure 1: General layout of new injector linac. The section from 5 to 13 MeV can be chosen normal conducting or superconducting.

The second way was proposed later to decrease the time of linac R&D and construction. It was proposed to use RFQ section and a number of IH-DTL normal conducting sections for energies up to 5 MeV/u. These sections will be developed and constructed by BEVATEC Ltd. The section for energies from 5 to 13 MeV will consist of a number of identical normal conducting cavities being under development by ITEP now. SC cavities will be used starting only at 13 MeV and early developed QWRs are not necessary in this layout. Only HWRs are used and today all Russian-Belorussian SRF activities are directed to their development and manufacturing.

The beam dynamics simulation for superconducting part of the first linac layout was done using BEAMDULAC-SCL code designed at MEPhI [13-15]. For the chosen types of accelerating cavities (QWR for low energies and HWR for higher energies) the third version of SC linac design was developed and now the accelerator is divided into three groups of cavities with geometric velocities β_G = 0.12, 0.21 and 0.314. It was also proposed that linac normal conducting part for the energy band of 2.5-5 MeV will consist of QWRs with the parameters equal to SC QWRs of 1st group (so-called 0th group).

The accelerating RF field was limited by 6.0 MV/m for superconducting QWR and HWR cavities. It is caused by the electrical field overvoltage limited by the factor ~6 due to the simplest QWR design chosen to gain the first manufacturing experience. Contrary to it the peak solenoid field was increased to 2.0-2.5 T and a beam envelope limitation was also increased from 3 to 5-6 mm [9]. The number of cavities in the 1st and the 2nd groups should be increased due to lower accelerating gradient E_{acc} (≤6 MV/m instead of 7.5 MV/m for the 2nd linac version). The beam dynamics of deuterium ions was studied also [9].

Parameters of the 0th, the 1st and the 2nd groups of cavities are shown in Table 1. The slipping factor will be not higher than 24% for proton and deuterium beams here (see Figure 2). The number of QWR cavities in the 1st group should be increased from five to eight both to decrease the accelerating field and to have deuterium ion beam of 7.5-8.0 MeV/nucleon after the 1st group (see below). The total length of the linac increases by 1.9 m.

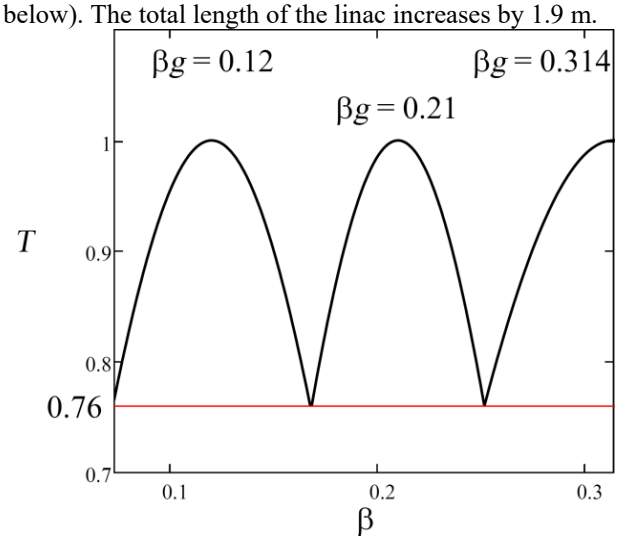

Figure 2: The slipping factor T for proton and deuterium beams, identical QWR's with β_g=0.12 are used for the 0th and the 1st groups.

Table 1: Current Parameters of the SC Linac for Proton and Deuterium Beams Acceleration.

Cavity group	**0 ***	**1**	**2**	**0 ***	**1**	**2**
	Proton beam			**Deuterium beam**		
β_g	0.12		0.21	0.12		0.21
F, MHz	162		324	162		324
T, %	24.0		24.0	24.0		24.0
N_{gap}	2		2x2**	2		2x2**
L_{res}, m	0.222		0.39	0.222		0.39
L_{sol}, m	0.2		0.2	0.2		0.2
L_{gap}, m	0.1		0.1	0.1		0.1
L_{per}, m	0.622		0.79	0.622		0.79
N_{per}	3	8	8	3	8	8
L, m	1.87	4.98	6.32	1.87	4.98	6.32
E_{acc}, MV/m	4.50	5.86	6.4	4.50	5.86	6.4
U_{res}, MV	1.0	1.3	1.25	1.0	1.3	1.25
Φ, deg	–20	–20	–20	–20	–20	-90
B_{sol}, T	1.35	1.3	1.9	1.8	2.0	1.0
W_{in}, MeV	2.5	4.9	13.47	2.5	3.65	8.3
β_{in}	0.073	0.102	0.168	0.073	0.088	0.133
W_{out}, MeV	4.9	13.47	31.0	3.65	8.3	8.3
β_{out}	0.102	0.168	0.251	0.088	0.133	0.133
K_T, %	100	100	100	100	100	100

* cavities in 0th group are normal conducting.
** two 2-gap HWR per one period

The deuterium beam dynamics was simulated later for this version of linac layout. The amplitude of RF field of 5.86 MV/m is quite enough to accelerate deuterons up to

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energy 8.3 MeV (see Table 1), it corresponds to the project aim and the 2nd and the 3rd groups of cavities can be used in transit regime for the deuterium beam. Note that the solenoid field in the 1st group of cavities should be increased up to 2 T for the deuterium beam.

SC QWR DESIGN

The operating frequency of the linac was chosen first equal to 162 MHz for QWRs with further increase to 324 MHz for HWR cavities. Results of the 162 MHz SC QWR cavities design were early presented on IPAC'2017 [16]. The simplest design (Figure 3) of QWR with cylindrical central conductor was chosen to work out fabrication and testing routines.

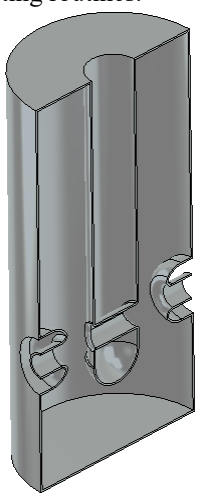


Figure 3: General view of 162 MHz QWR for $\beta_g = 0.12$.

Simplest design of this prototype satisfies the initial data. In addition, it helps to decrease the fabrication time and necessary funding for SRF technology development. But the ratio of peak to accelerating field for this design is high E_p/E_{acc} ~6 and we should limit the RF field to only E_{acc}=6 MV/m (the limit surface field should not exceed 35 MV/m).

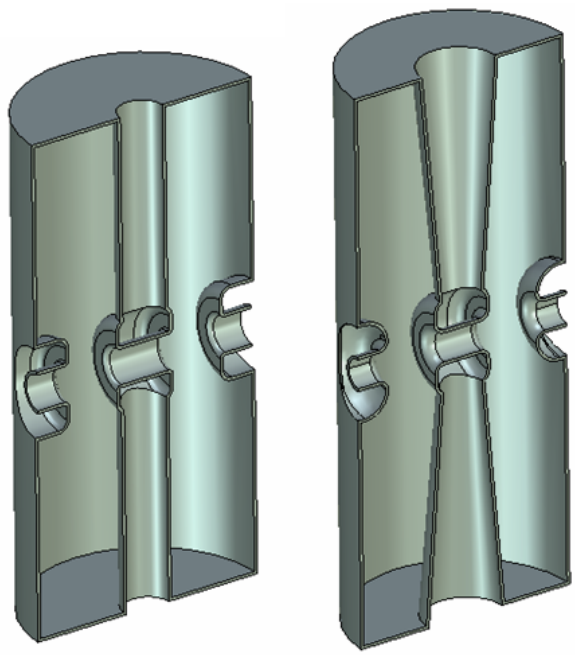
Then the helium vessel was designed at PTI NASB. The vessel design (shown on Figure 4) includes QWR inside, frequency tuning plunger mounted on the cavity bottom, two beam ports with flanges, the RF power coupler, field measurement pickup, helium and vacuum ports, etc.

It was proposed to shift the operating frequency of QWR cavities to 162.5 MHz as it is mostly used in many international laboratories. It can be easily done by means of the sorter central conductor and the cavity shell.

SC HWR DESIGN

The operating frequency was initially chosen to 324 MHz for HWRs [9, 17] but today it is proposed to shift it to 325 MHz as it is mostly used. Two types or HWR were simulated and studied (see Figure 5): simplest design with the cylindrical central conductor and improved design with the conical one. The second design is more difficult for manufacturing but give much lower values of the magnetic and the electric overvoltage [18]. Components of the central conductor are planning to manufacture at PTI NANB by means of the polymer hydroforming technology and it give us some optimism for its quality.

Figure 4: General view of 162 MHz QWR design model for $\beta_g = 0.12$, the RF frequency tuner is placed bottom of the cavity, the RF load loop and the measurement loop are not visible.



a b

Figure 5: Two types of HWR's with β_g=0.21: with the cylindrical central conductor (a) and with the conical one (b).

Geometric and electrodynamics parameters for both types of the cavities are presented in Table 2. It can be

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seen that the simplest cavity design having the cylindrical central conductor breaks the surface field limitation. For accelerating field of 7.7 MV/m the magnetic field on the surface exceeds 50 mT mentioned above as MFQS origin and reaches 80 mT. For a conical central conductor design, due to drift tube rounding and increasing the central conductor radii in the cavity cover, it is possible to reduce the peak electric field to E_p/E_a = 3.3. Peak magnetic field to accelerating gradient ratio B_p/E_a in this case is 5.6 mT/(MV/m). Data presented in Table 2 show that both QWR designs satisfy the requirement for the accelerating gradient. By the second design with the conical central conductor cavity has much better parameters to prevent the multipactor discharge. This discharge is observed for coaxial cavities for low RF field levels and leads to the tuning and commissioning time increase.

Table 2: RF Parameters of 325 MHz HWR for βg = 0.21

Parameter	**Value**	
HWR type	**(a)**	**(b)**
Operating frequency, f, MHz	324	
Geometrical velocity, β_g	0.21	
Cavity height, mm	431	448
Cavity radius, mm	97	97
Ratio of the peak electric surface field to the accelerating field, E_p/E_{acc}	3.9	3.3
Ratio of the peak surface magnetic field to the accelerating field, B_p/E_{acc}, mT/(MV/m)	7.3	5.6
Effective shunt impedance, r/Q_0, Ohm	252	303
Geometric factor, $G=R_s/Q$, Ohm	57	58

TEST CRYOSTAT DESIGN

It is proposed to use one cryostat to test either QWR's and HWR's. The liquid nitrogen free cryostat type was chosen. This cryostat has two liquid helium jackets. One detachable titanium jacket will be used for preliminary cryogenic tests only and the second jacket will be welded to the cavity for final tests. Beam ports should be closed by vacuum covers for these tests. Two different carrying insert covers used individually with two jackets. The general view and main dimensions of the designed cryostat is shown in Figure 6. Now the cryostat is ready for development and drawings preparation for the future manufacturing.

RF COUPLER FOR QWR/HWR

Each SC cavity will be equipped by the RF coupler and the RF measurement pickup. Coaxial power coupler type was chosen both for QWRs and HWRs [19] (see Figure 7). Coupler coaxial line has two identical ceramic vacuum windows. Two different feeding line shapes were considered: straight one (as shown on Fig.7) with feeding port located on the cryostat side and the second one with 90 degree elbow. The latter allows simpler cryostat design with RF power feedthrough via top cover.

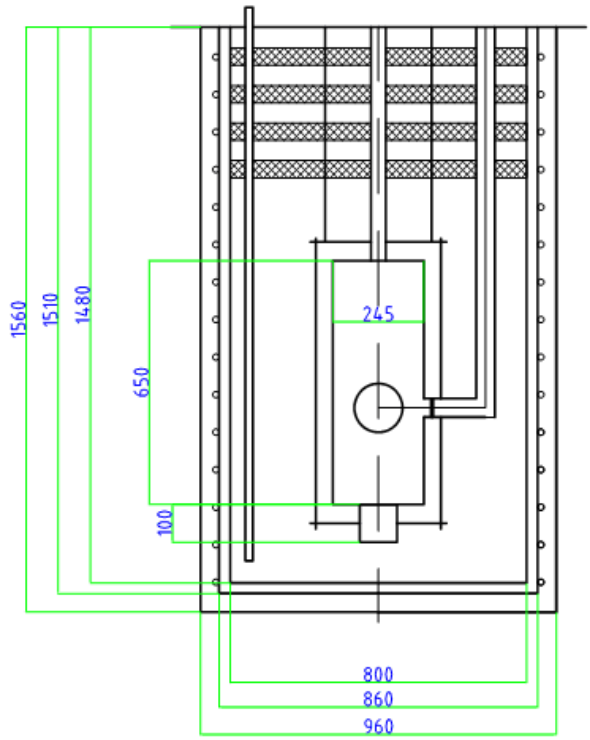

Figure 6: The general view and main dimensions of the cryostat for cryotests of QWR's and HWR's.

Outer and inner conductors of the coupler will be made of stainless steel. Optional thin layer of plated copper is considered for better electrical and thermal conductivity. This design was chosen because of low overall cost and cavity production capabilities despite the phase slipping occurred. It was decided to develop one power coupler suitable for all cavities. It requires cavity external Q-factor value to be varied for different cavities in the sections. Power coupler antenna is cylindrical and it couples to electric field in the cavity. The required external Q-factor tuning range calculated to be covered by the antenna with total tip penetration is varied within ±10 mm.

Half-wave cavity power coupler located on the beamports plane has the same design as coupler for QWR described above (Figure 8). Coaxial line inner and outer conductors diameters are 20.44 mm and 47.5 mm. Necessary external Q-factor adjustment for coupling factor Q_0/Q_{ext} fall in desired range $\chi=(1.5 \ldots 3)\cdot 10^3$. That requires antenna tip is retracted to 21...25 mm off the cavity wall (see Figure 9). Relatively small travelling is provided by bellows on feeding line outer conductor. The actuating mechanics able to operate in cryostat is under development.

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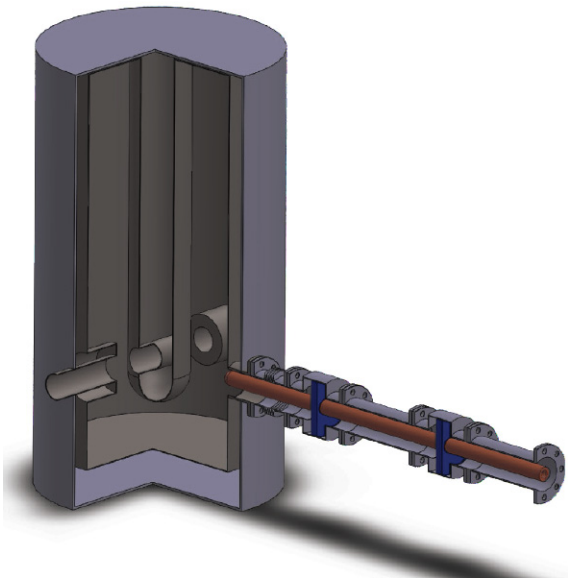

Figure 7: Assembly of the QWR with the coupler.

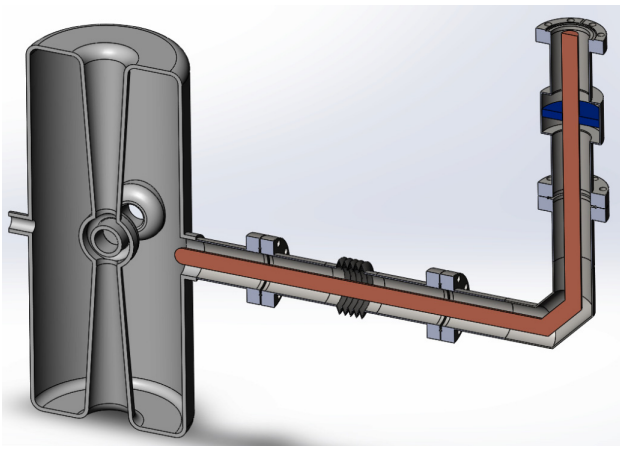

Figure 8: HWR with the coupler and field measurement pickup.

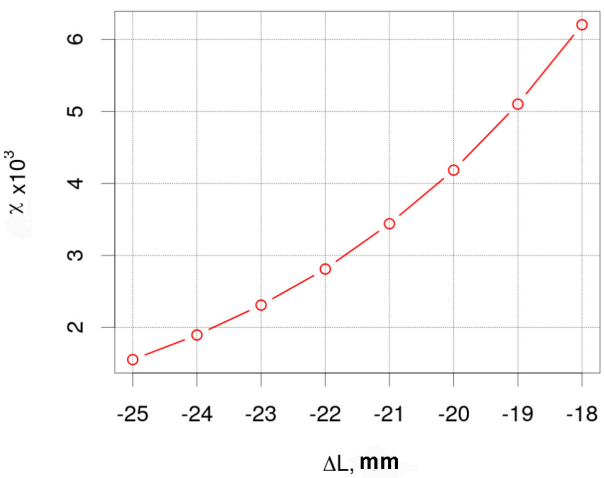

Figure 9: Coupling factor vs. antenna tip retraction length.

CONCLUSION

Current results of new SC proton linac development for JINR NICA project were discussed. Beam dynamics simulation and cavities results were briefly presented. The design of QWR and HWR for new linac was discussed. Current activities in the test cryostat design and the RF couplers are also described.

ACKNOWLEDGEMENTS

Authors would like to thank Dr. W. Barth, Dr. S. Yaramyshev (GSI/HIM/MEPhI), Dr. M. Miski-Oglu and Dr. V. German (GSI/HIM) for fruitful discussions and support.

REFERENCES

[1] G. Trubnikov, N. Agapov, V. Alexandrov *et al.*, in *Proc. IPAC'10*, p. 693, 2010.

[2] O. Kozlov, H. Khodzhibagiyan, S. Kostromin *et al.*, in *Proc. IPAC'*11, p. 1108, 2011.

[3] A.V. Butenko, E.E. Donets, E.D. Donets *et al.*, in *Proc. IPAC'13*, p. 3915, 2013.

[4] A.V. Butenko, E.E. Donets, E.D. Donets *et al.*, in *Proc. IPAC'14*, p. 2103, 2014.

[5] A.V. Butenko, A.M. Bazanov, D.E. Donets *et al.*, in *Proc. IPAC'17*, pp. 2366-2368, 2017.

[6] V.A. Andreev, A.I. Balabin, A.V. Butenko *et al.*, *Problems of Atomic Science and Technology. Series: Nuclear Physics Investigations*, vol. 6, no. 88, pp. 8-12, 2013.

[7] A.V. Butenko *et al.*, in *Proc. RuPAC'16*, pp. 153-155, 2016.

[8] G.V. Trubnikov, T.V. Kulevoy, S.M. Polozov *et al.*, *PEPAN Letters*, vol. 13, no. 7, pp. 943-946, 2016.

[9] G.V. Trubnikov, T.V. Kulevoy, S.M. Polozov *et al.*, in *Proc. IPAC'16*, pp. 941-943, 2016.

[10] M. Gusarova, T. Kulevoy, M.V. Lalayan *et al.*, in *Proc. RuPAC'16*, pp. 273-275, 2016.

[11] G.V. Trubnikov, A.V. Butenko, N. Emelianov, *et al.*, in *Proc. IPAC'17*, pp. 3282-3285, 2017.

[12] G.V. Trubnikov, T.V. Kulevoy, S.M. Polozov *et al.*, in *Proc. RuPAC'16*, pp. 626-628, 2016.

[13] A.V. Samoshin, *Problems of atomic science and technology*, vol. 4, no. 80, pp. 78–82, 2012.

[14] E. S. Masunov, A. V. Samoshin, *Technical Physics*, vol. 55, Issue 7, pp. 1028-1035, 2010.

[15] E. S. Masunov, A. V. Samoshin, *Atomic Energy*, vol. 108, Issue 2, pp. 141-153, 2010.

[16] D.V. Surkov, M.A. Gusarova, M.V. Lalayan *et al.*, in *Proc. IPAC'17*, pp. 1058-1060, 2017.

[17] M.A. Gusarova, M.V. Lalayan, N.P. Sobenin *et al.*, in *Proc. IPAC'17*, pp. 1061-1063, 2017.

[18] M. Gusarova, A.A. Gorchakov, M.V. Lalayan *et al.*, in *Proc. SRF'17*, pp. 125-127, 2017.

[19] M.V. Lalayan, T.A. Bakhareva, M. Gusarova, S. V. Matsievskiy, in *Proc. SRF'17*, pp. 61-63, 2017.

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