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MANIPULATING H^- BEAMS WITH LASERS*

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Abstract

In recent years lasers have been playing a vital role in many H^- beam measurements and experiments. This talk will review current state of development of various applications using lasers for manipulating H^- ion beams in accelerators. A wide range of applications will be reviewed such as beam diagnostics, laser-assisted charge-exchange injection, generation of arbitrary H^0 pulse patterns and others. An overview of ongoing developments and prospects for other laser H^- beam interactions will also be given.

INTRODUCTION

Laser systems have been routinely in use at many H^- beam facilities around the world since the last four decades. At the early stage of their application with H^- beams, lasers were mainly used for non-invasive diagnostics of low-energy H^- beams [1, 2]. Over the last two decades, significant advancement of laser technology accompanied with increasing demands of H^- beam manipulation with lasers have enabled a wider use of lasers at such facilities. Nowadays, laser manipulations of the H^- beams are an important subject for the state-of-the-art high-intensity proton accelerators with many purposes such as, laser assisted charge exchange injection [3-5], laser notcher (H^- beam chopper) [6] and extraction [7, 8], phase space sculpting [9], etc.

The basic principles of H^- beam manipulation with lasers is based on photodetachment processes [1] by either removing a loosely bound outer electron or exciting the ground state second electron to a higher energy state to completely remove it from the H^- ions. The former is producing neutral H^- (H^0) and therefore called H^- neutralization and the latter is called laser charge exchange injection or laser stripping. For the neutralization process, the energy required for photodetaching an electron is about 0.75 eV, and the interaction cross section is about $4\mathrm{x}10^{-17}$ cm^2 for photons of about 1.17 eV (1064 nm). Therefore, a significant fraction of the ion beam can be neutralized by focusing a1064 nm laser beam, for example, with pulse energy on the order of 100 mJ. However, depending on the ion beam energy, photodetaching the second inner bound electron would require much higher laser energy and power and difficult to achieve.

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In this paper, we review current state of development of various topics such as non-invasive beam diagnostics, beam chopping and extraction, and laser assisted charge exchange using lasers for manipulating H^- ion beams in accelerators. An overview of ongoing new developments at various H^- facilities and prospects for H^- manipulation will be discussed.

NON-INVASIVE BEAM DIAGNOSTICS

Laser-based diagnostics for H^- beams work by using a laser beam to neutralize some of the ions in the ion beam. The secondary particles produced (electrons and H^0) are separated from the remaining H^- ions using a simple dipole magnet and are then used to diagnose the ion beam. To use the electrons for beam diagnosis, a Faraday Cup (FC) is used to measure the amount of charge that has been detached; to use H^0, typically a scintillator and a Photo Multiplier Tube (PMT) are used to detect the scintillating photons [10]. The scheme used at the Spallation Neutron Source (SNS) is shown in Fig. 1.

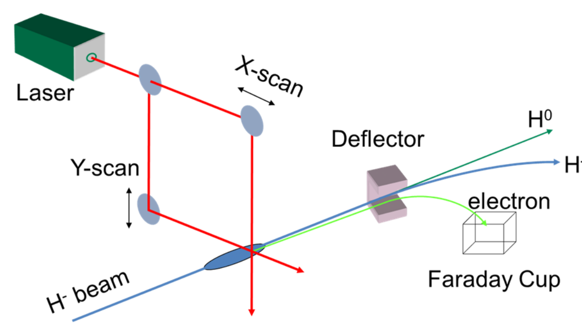

Figure 1: A layout of the laser wire beam profile monitor in SNS HEBT.

In the photodetachment process, the neutralized beam (H^0) maintains nearly the original phase-space parameters of the H^- beam from which it was extracted. The transverse spatial profile, transverse divergence, emittance, energy, energy spread, and phase spread characteristics of the H^0 and H^- beams are nearly identical and can be deduced. During the process, neither the laser photon nor the photodetached electron transfer significant momentum to the H^0 atom. Therefore, the whole process is non-invasive. Three types of laser-based diagnostics (Transverse beam profile, emittance and longitudinal bunch shape monitors) have been developed and operational at SNS for measuring H^- beam.

The system called HEBT (High Energy Beam Transport) laser wire beam profile monitor consists of 9 measurement stations that covers 23 cryomodules in the Super Conducting Linac (SCL) section of the SNS. A 250 meter free space transport line sends a single Q-switched Nd:YAG laser

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(1064 nm, 30 Hz, 7 ns, 1 J) beam to remote stations to interact with H^- beams at energies ranging from 186 MeV to 1 GeV. The laser pulse energy is continuously tunable from the mJ level to over 1 J by using two sets of half-wave plates and polarization beam splitters installed right after the laser. The laser beam diameter at the interaction point is about 100 µm. The scanning translation stages have a travel range of 46 mm with a µm order resolution. Normally a scan step of 250 µm results in a sufficient resolution of profiles. Figure 2 shows H^- beam profiles measured in transverse xy-plane by the laser wire system in SNS HEBT.

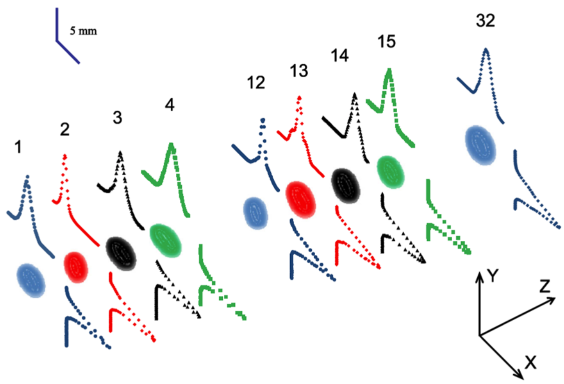

Figure 2: H^- beam profiles measured in transverse xy-plane by the laser wire system at SNS HEBT. Numbers represent cryomodule in the SCL. The H^- beam is propagating along the Z direction. Scale bars represent 5 mm. Each elliptic shape represents the distribution of the H^- beam with the measured beam size [10].

The emittance measurement is in principle a slit-detector style emittance scanner except the conventional mechanical slit is replaced by a laserwire. After the partial neutralization, the measurement of the H^0 beam angular distribution is conducted through the measurement of its transverse profile after its propagation over a certain distance. The HEBT emittance monitor at SNS [11] uses the same laser beam used in the laser wire system. A wire scanner made of titanium detaches the remaining electron in H^0 that is produced by laser wire upstream. The FC located after a separate dipole magnet is used to measure the profiles of the detached electron density. Finally, the emittance of the H^- beam along the corresponding axis can be obtained by scanning the incident laser beam. Figure 3 shows a typical emittance measurement in SNS HEBT.

The longitudinal bunch shape monitor is located in Medium Energy Beam Transport (MEBT) section of SNS. A fiber coupled mode-locked Ti:Sapphire laser (800 nm, 80.5 MHz, 10 ps) is phase-locked to the fifth subharmonic of the SNS ion beam frequency (402.5 MHz). When the phase between the laser pulse and the ion beam micro-bunch is properly aligned, the laser pulses interact with every fifth micro-bunch of the 2.5 MeV H^- beam. The photon–ion interaction detaches a small portion of the electrons from the ion beam, and the liberated electrons are guided into an electron detector by a bending magnet. The amount of the detected charge is proportional to the ion beam density within the photon–ion interaction region [12]. Figure 4 shows H^- beam longitudinal bunch profile measured in SNS MEBT.

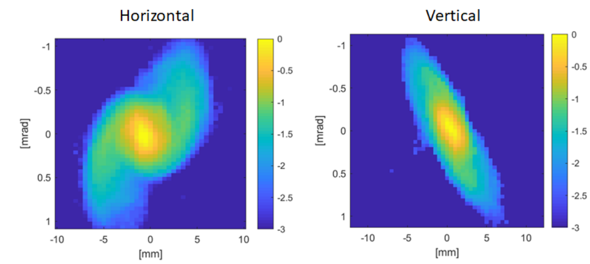

Figure 3: The contour map of H^- beam emittance measured in SNS HEBT [11].

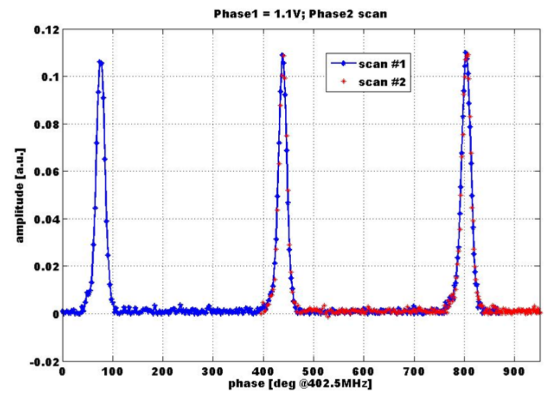

Figure 4: H^- beam longitudinal bunch profile measurement in SNS MEBT [12].

BEAM CHOPPING

Beam extraction process in Fermilab Booster relies on fast kickers to deflect the H^- beam. This process, while effective at creating the extraction notch, was responsible for about 30% of the total beam power loss in the Booster tunnel and creates significant residual activation. In order to decrease the beam loss in the Booster, Fermilab has built a laser notcher system to create the required series of notches within a Linac beam pulse at 750 keV [6]. The technique employed to produce the notches in the Linac pulse is to completely remove the outer electron of selected H^- ions using photodetachment.

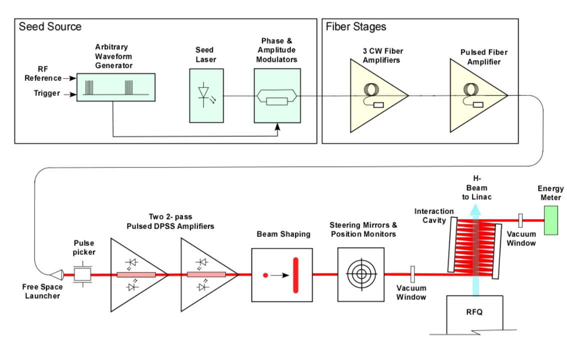

Figure 5: Block diagram of the laser system and non-resonant interaction cavity for Fermilab MEBT laser notcher system [6].

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The laser pulses contain 2.5 ns pulses with a repetition rate of 201.25 MHz bunched in 80 ns bucket which repeats at 450 kHz rate that is further bunched in 35 µs with a repetition rate of 15 Hz. The goal was to create 80 ns long notches to allow sufficient rise time for the Booster extraction kicker.

The laser system composed of flexible CW fiber and burst-mode solid-state laser amplifier system with a master-oscillator power-amplifier (MOPA) architecture. Figure 5 shows a block diagram of the laser system. After the final amplifier the transverse spatial profile is modified to create a roof-top profile and a cylindrical telescope is used to create a narrow horizontal profile at the entrance of the non-resonating cavity. The top pane in Fig. 6 shows the beam current monitor and laser temporal waveform measured by photodiode for an entire Linac cycle. The bottom pane shows an expanded view of the first notch along with the laser pulses that neutralize each H^- bunch within the 80 ns notch. Combining the laser and non-resonant cavity which allows laser pulses to be bounced 27 times, the H^- bunches were neutralized at the level up to 96%.

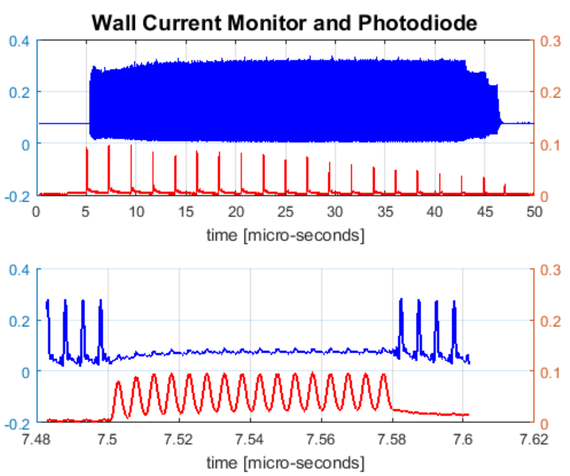

Figure 6: Fermilab current monitor and laser temporal waveform measured by photodiode showing the burst spacing (top pane) and the detail of the first notch (bottom pane) [6].

BEAM EXTRACTION

Using a flexible laser pulse structure and high output power, one can neutralize certain portion of H^- beam pulse in time domain and create a desired H^0 beam from the parent H^-. Proper conversion of H^0 to protons will result in an extraction of a small amount of secondary beams that is required by the scientific application. An extraction of 8 W proton beam from 3.0 MeV Linac using 9 ns laser with 25 Hz repetition rate at J-PARC has been reported [7].

Recently, a non-intrusive proton beam extraction method based on the laser neutralization of 1 GeV H^- beam in SNS HEBT has been demonstrated experimentally [8]. The extracted protons could be used for the generation of muons with a temporal structure optimized for Muon Spin Relaxation/Rotation/Resonance (µSR) applications [13]. Since the maximum flux of the extracted proton beam only accounts for 0.2% of the total proton beam used for neutron production and will result in negligible impact on the SNS operation. The schematic of laser-based proton pulse extraction from the SNS HEBT for muon generation is shown in Fig. 7. The goal of the experiment is to develop a laser system with 30 ns 50 kHz pulse structure, achieve neutralization of H^- beam and separation of H^0 beam from the existing SNS accelerator beam line, conversion of H^0 to protons at the SNS Linac dump.

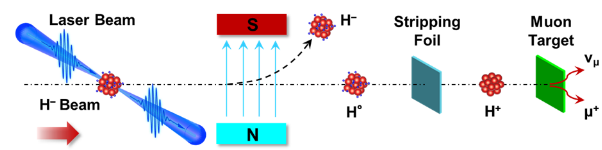

Figure 7: Schematic of laser-based proton pulse extraction from the SNS accelerator beam line for muon generation.

The block diagram of laser amplifier system is shown in Fig. 8. As the 30 ns 50 kHz pulse structure is beyond the normal parameter regime of Q-switched or mode-locked lasers, a master oscillator power amplifier (MOPA) scheme is considered for the generation of such pulses. The master oscillator consists of a narrow line width continuous-wave (CW) fiber laser and an intensity electro-optic modulator (EOM) for laser pulse generation. Since the subsequent fiber amplifiers require laser pulses that have a certain duty factor (typically larger than 1.5%), the initial laser pulses are generated at 700 kHz. The power amplifiers consist of a pre-amplification stage with fiber amplifiers, a 50 kHz pulse picker using an acousto-optic modulator (AOM), and diode-pumped solid-state (DPSS) amplifiers.

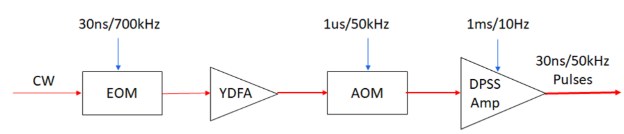

Figure 8: Block diagram of laser system for generation of 30 ns 50 kHz laser pulses [8].

The initial goal of the project is to achieve 30 ns 50 kHz laser pulses with the peak power exceeding 100 kW to ensure a measurable fraction of electrons can be detached from the neutralized H^- beam. After bunching the pulses with 1 ms 10 Hz structure, the laser beam is sent to the accelerator beam line using an existing free-space 40-meter laser transport line. Figure 9 shows the signal amplitude at various laser levels from photodetached electrons (detected by FC) and H^0 atoms (detected by scintillator and PMT) at the HEBT emittance measurement station. At an estimated maximum laser peak power of 125 kW at the laser-ion interaction point, we measured the neutralization efficiency to be ~0.14% which is only about 40% of the theoretical prediction. To achieve a neutralization efficiency around 90% and therefore enable high-flux muon generation based on the extracted proton pulses, several approaches need to be make. (1) introduce micro-bunches at 402.5 MHz structure (2) optimize laser-ion beam parameters (3) adding more amplifiers and combining them with

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non-resonating cavity to increase the neutralization efficiency.

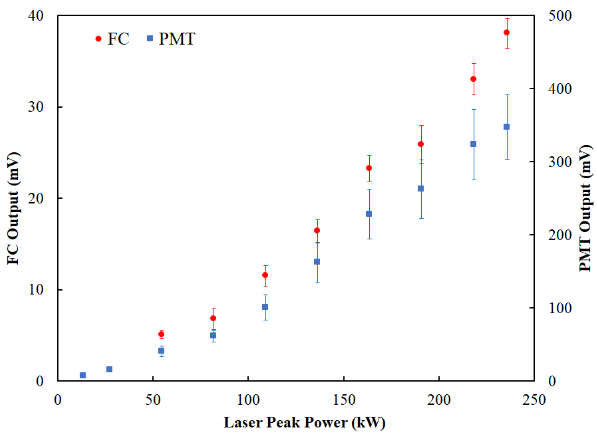

Figure 9: Detected electron pulse magnitude from Faraday Cup and PMT versus laser peak power. The error bars are the standard deviation of 10 pulses [8].

LASER ASSISTED CHARGE EXCHANGE

Laser-assisted charge exchange injection uses lasers to completely photodetach the second electron from the H^- beam. It offers an attractive alternative to the foil-based charge exchange injection which has serious limitations on survivability at high beam powers and producing of beam loss from particle scattering. In SNS version of laser-assisted charge exchange model, the first, loosely bound outer electron is Lorentz stripped by a high field dipole magnet, converting H^- to H^0. And then a laser is used to produce resonant excitation of the remaining electron to a higher quantum state (H^{0*}) with lower binding energy [3], and then it is Lorentz stripped by a second dipole magnet to produce a proton (H^{0*} to H^+). SNS has conducted two experiments [4, 5] to pioneer the experimental demonstration of laser stripping in the last decade. In both experiments, more than 95% stripping efficiencies have been demonstrated for SNS beam energy of 1.0 GeV. Figure 10 shows the results of 2016 experiment which uses a UV (355 nm) laser to excite 10 µs 10 Hz H^- beam at 1.0 GeV energy. Since then there has also been an alternative concept developed by J-PARC on single mini pulse stripping by only lasers for H^- beam at 400 MeV [14]. However, in all these concepts laser power was the limiting factor to achieve higher stripping efficiency for a longer ion beam at the order 100 µs or longer, especially for a beam energy below 2.0 GeV. Recently, SNS has developed a new scheme called sequential excitation to overcome these limitations.

In this concept we proposed to use sequential excitation to excite the H^0 atom from the ground 1s state to the *2p* state (1s→2p), followed by excitation from the *2p* to the *3d* state (2p→3d) using the same recycled laser (see Fig. 11). Each step of the sequential excitation 1s→2p and 2p→3d requires less laser power due to stronger quantum electric dipole transition of the H atom compared with the single step 1s→3p excitation [15]. This allows us to use green laser (515 nm or 532 nm) with 6 times less power as compared to single step excitation scheme that requires UV (355 nm) laser. It is also worth to point out that, in sequential excitation scheme, the two laser beams will have independent controls for the angle and position for precise alignment with the ion beam.

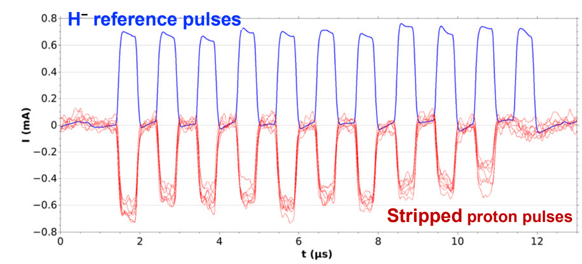

Figure 10: The average beam current for an 11 µs H^- beam measured by the beam current monitor at the interaction point before stripping (blue), and stripped proton beam pulses on the same beam current monitor during stripping (red) [5].

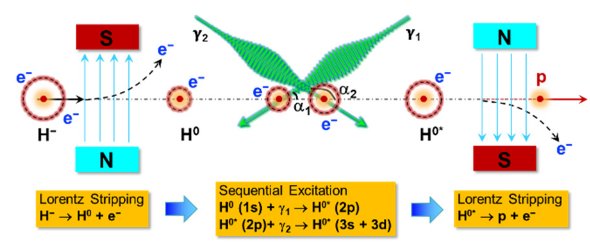

Figure 11: Schematic of sequential laser stripping concept [15].

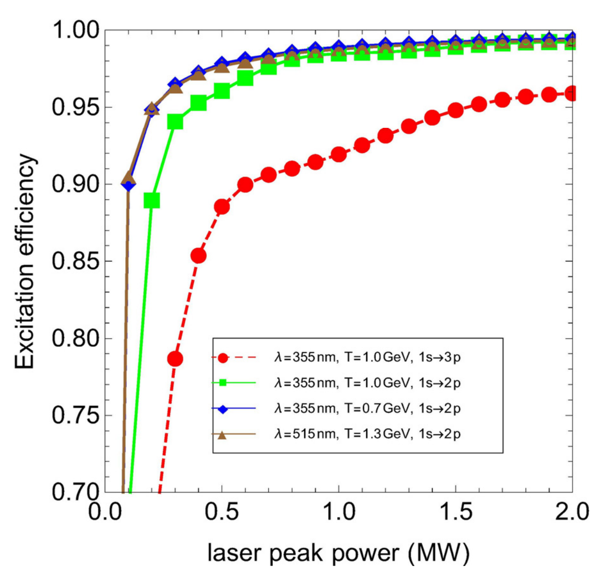

Figure 12: The estimated stripping efficiency as a function of laser power for different ion beam energies in sequential laser stripping concept. The red dashed line shows the case for conventional three step (single excitation) stripping process [15].

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As shown in Fig. 12, in sequential excitation process, the estimated stripping efficiency as a function of laser power for different ion beam energy is very different in the sequential excitation and single-step excitation processes. It shows clearly that sequential excitation process will reduce the required laser power by about a factor of 6. In the Proton Power Upgrade (PPU) project at SNS, the H^- beam energy will be increased to 1.3 GeV as a part of the SNS power upgrade to double the proton beam power from the current 1.4 MW to 2.8 MW. Also as shown in Fig. 12, laser stripping of a 1.3 GeV hydrogen beam provides an ideal case for application of the sequential excitation scheme. Lastly, the practical implementation of laser stripping at full beam current at SNS had limitation due to minimum squeezable longitudinal ion beam size restricted by space charge effects. Now by introducing dispersion that allows crab-crossing collision at the interaction point, it seems possible to try the stripping experiment at full beam current [16]. Theoretical calculation has confirmed this approach and proof-of-principle experiment has been planned for later this year.

PERSPECTIVES

H^- beam manipulation with lasers has been rapidly progressing especially topics related to using neutralization to achieve beam chopping, beam halo reduction [17], beam extraction and arbitrary beam pattern generation. Laser-assisted charge exchange has great potential to play an important role in realizing high intensity high brightness proton beams in the accelerator. Concepts such as utilizing lasers to control the longitudinal emittance and reduce the beam halo for Fermilab momentum collimation has important contribution to topics for studying high power proton beam machines for the future. The concept of phase space sculpting [9] uses a laser to extract a narrow beam of neutralized hydrogen from the parent H^- ion beam before it gets stripped by a foil. In this concept, subsequent foil stripping and capture of protons into a storage ring generates cool proton bunches with significantly reduced emittance compared to the parent H^- ion beam. Beam extraction by arbitrary pulse patterning technique allows parasitic generation of secondary beams with many purposes such as SNS μSR project [13] and SEE project [18]. Our laser stripping studies indicated that laser-assisted charge exchange injection has the great potential to replace the foil-based injection mechanism to realize multi MW proton beams with minimized losses. By using power enhancement cavity for burst-mode lasers [19] and utilizing fiber laser and diode-pumped solid-state laser amplifier technology, we can reduce power required for full cycle laser stripping. Sequential excitation and crab-crossing ideas have indicated that we are moving one step closer to the practical implementation of laser stripping at SNS. Through the fast development of laser technology, we only expect more opportunities and possibilities with H^- beam manipulation with lasers. However, challenges arising from the laser pointing stability at the laser-ion interaction point has become an important problem to solve. Especially when high energy lasers need to be placed remote location and transported to long distance in order avoid radiation damage. There have been significant studies taken place in order to improve laser stability such as active beam position feedback system [20]. A dedicated laser beam transport line, better collimation of laser beam and using anti-resonant hollow core fiber technologies for high energy beam delivery [21] would certainly help and important to investigate.

ACKNOWLEDGEMENTS

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