SCANNING SYNCHRONIZATION OF COLLIDING BUNCHES FOR MEIC PROJECT*

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Abstract

Synchronization of colliding beams is one of the major issues of an electron-ion collider (EIC) design because of sensitivity of ion revolution frequency to beam energy. A conventional solution for this trouble is insertion of movable bent chicanes in the arcs space. In our report we consider a method to provide space coincidence of encountering bunches of the crab-crossing orbits in the Interaction Region (IR) while repetition rates of two beams do not coincide. The method utilizes pair of fast kickers realizing a bypass for the electron bunches as the way to equalize positions of the colliding bunches at the Interaction Point (IP). A dipole-mode warm or SRF cavities fed by the magnetron transmitters are used as fast kickers, allowing a broad-band phase and amplitude control. The proposed *scanning synchronization* method implies stabilization of luminosity at a maximum via a feedback loop. This synchronization method is evaluated as perspective for the Medium Energy Electron-Ion collider (MEIC) project of JLab with its very high bunch repetition rate.

INTRODUCTION

In the MEIC's [1] medium ion energy range, maintaining a constant ion revolution frequency (given by the revolution frequency of electrons) with energy is troubled by a non-negligible change of the reference orbit in magnets. The earlier proposed baseline way of solving this problem is twofold. Firstly, at certain discrete energies corresponding to different harmonic numbers of the ion collider ring, synchronization of collisions is restored. The energy values are fairly closely spaced below at $\gamma \ll \sqrt{2q}$, where γ is ion Lorentz-factor, and q is number of bunches on the ion orbit. The correspondent maximum energy is about 36 GeV/u due to the very short bunch spacing of about 40 cm in MEIC, which may provide enough options for heavy ions with energies of only up to 40 GeV/u. However, there is a big energy gap from 36 to 100 GeV for protons. Covering the gaps between the harmonic energies is the second part of the synchronization problem. A number of different approaches to this issue have been proposed. Conceptually the simplest one is to adjust the ion ring circumference within the range of plus or minus a half of the 748.5 MHz RF wave length, i.e. by ±20 cm, using path-length movable chicanes as it is shown in Fig. 1, [2].
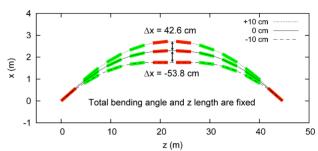
Figure 1: Schematic of an arc path-length chicane with movable magnets.

SCANNINNG SYNCHRONIZATION DYNAMIC CONCEPT

We consider a possibility of synchronization of the electron-ion colliding beams avoiding change of the orbit circumference. Instead, we consider a scheme of the cross-colliding beams with collision point moved periodically by a small scanning the beam directions in real time. For very most of the e-i bunch pairs, this scanning compensates for time delay of ion arrival at the nominal (central) Interaction Point (IP). The direction tilt of bunches is produced by RF deflecting resonators with varying amplitude and/or phase of the RF voltage, Fig. 2.
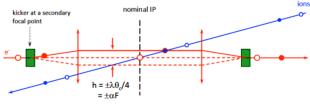

Figure 2: Schematics of the RF controlled bypass of e-beam for e-i synchronization by moving the collision point in real time.

The RF kicker is supposed to provide transverse variation of bunch trajectories in the Interaction Region (IR) in range of: $h = \pm \lambda\theta/4 = \pm\alpha F$.

Here: λ=40 cm is bunch spacing, θ =50 mr is crossing angle, α is kick angle produced by the maximum RF voltage amplitude, and F is focal distance of the IR focusing magnet block. At F =4 m we obtain h =5 mm, and required maximum kick α =1.25 mr. Maximum longitudinal deviation of the collision point will be 10 cm. Note that, in case that shift of the *collision point* (CP) is shared equally with the ion beam, the bypass parameters for each of two beams are reduced by a factor of 2, together with the similar reduction of the CP deviation.

The effective integrated transverse voltage for 100 GeV protons will be 62.5 MV, for 10 GeV electrons only 10% of this. Note that, these quantities are just equal the correspondent crabbing voltages for two beams multiplied by factor 1.57. All these voltage would be reduced by another factor 2 at bunch repetition rate 1.5 GHz.
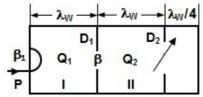
A cycle of the RF voltage control implies two tacts: the *collisions* tact (CT) and the *switching* tact (ST). In CT, RF amplitude (including sign) changes linearly with time (according to the diagram of Fig. 2). During ST, the kicking RF voltage is supposed to be quickly returned to its initial amplitude and phase to start the next cycle. The cycle duration will be equal to the two inverse differences in the revolution frequencies of two beams. Minimum duration of the total cycle is equal to 2 periods of beam revolution.

Finally, a complete dynamic concept of scanning synchronization requires correction of focal distance of both beams in tact with moving the collision point. This can be achieved in automatic regime by introduction of small constant sextupole magnets before the FFB of a proper strength.

Considerations of combined schemes of crabbing, scanning synchronization and focus correction together would be needed for working out optimum RF/beam optics configurations of the EIC colliders.

THE CONCEPT OF IMPLEMENTATION OF THE SCANNING SYNCHRONIZM

The concept is based on a fast energy transfer between coupled high-Q cavities operating at the same frequency $f=c/\lambda$ (here: λ is the wavelength in a free space). The energy transfer is realized by a fast transient process of beats, [3], when the energy stored in one of cavities is transferred into the second one at the energy recovery. The transient process can be interrupted or continued by a control. Schematic realization of the concept is shown in Fig. 3. Initially the RF energy is stored in a waveguide-type (utilized as a deflecting) cavity I with Q-factor Q_1. The cavity I is coupled with a generator by a coupling loop with the coupling coefficient of β_1. The first cavity is a storage cavity. It is coupled by a diaphragm D_1 at the coupling coefficient of β with the second waveguide-type cavity II having length of $5/4\lambda_W$ (here: λ_W is the wave length in waveguide). The second cavity consists of two parts separated by a diaphragm D_2. The first part of the cavity II (buffer cavity) has a resonant length of λ_W. In the diaphragm D_2 is implemented a very fast switch shortening the diaphragm.

Figure 3: Conceptual scheme of the coupled cavities for the energy transfer.

Initially the RF source at power P is ON and the RF energy is stored in the cavity I. The stored energy is described by the following equation, [3]:

$$W_1 = 2\lambda\beta_1 Q_1 P / \left(\pi \cdot c(1 + \beta_1)^2\right). \quad (1)$$

Since the total length of the cavity II (when the switch is not shortened) is far from resonance, the power in the buffer cavity is negligible. In beginning of the transfer process the RF source is turned OFF and switch shortest the diaphragm D_2. The buffer cavity becomes resonant; the transient process of the beats starts up and continued transferring the stored energy from cavity I to the buffer cavity and back. If after the odd number of half-periods of beats the switch stops shortening of diaphragm D_2, the stored energy (except losses caused by energy dissipation) is in the cavity I with opposite phase of oscillation. The characteristic time of the energy dissipation process at the beats, τ, is:

$$\tau = \left(2\lambda/\pi \cdot c\right) \cdot \left(1/Q_1 + 1/Q_2\right)^{-1}. \quad (2)$$

The energy W_2 transferred into the second cavity is described in time domain by the following equation, [3]:

$$W_2(t) = \left(\pi^2 c^2 \beta^2 W_1 / \lambda^2 \Omega^2\right)\exp(-2t/\tau)\sin^2(\Omega \cdot t), (3)$$

where: $\Omega = \left((\pi \cdot c/2\lambda)\sqrt{4\beta^2 - (1/Q_1 - 1/Q_2)^2}\right)$ is a

characteristic angular frequency of the transfer. Examples of the transferred energy W_2 in time domain at $\beta_1 = 1$ $\beta = 0.1$, various values of Q_1, and at $Q_2 = 5 \cdot 10^2$ (this value is determined generally by parameters of the implemented switch) are plotted in Fig. 4.
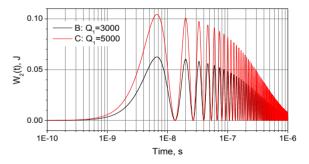

Figure 4: The energy transfer by the beats method in time domain.

The plots demonstrate very rapid transfer of the energy by the beats between the two cavities having the same resonance frequencies. To implement the features of the coupled cavities into the scanning synchronization method, the following sequence of operation has to be performed: the RF power has to be turned ON, the fast switch is OFF and the RF source has to change amplitude in the storage cavity used as a deflecting one to keep the amplitude increasing from minimum value to maximum value during 2 turns of electrons (1 cycle) in the ring ($\sim$ 13.4 µs). Until the fast switch is OFF, the buffer cavity is detuned in length and amplitude of oscillation is negligible there. The Low Level RF (LLRF) system within a feedback loop provides the required linearity of variation of the deflecting field. When the amplitude in

the storage (deflecting) cavity is reached the required value, the fast switch is turned ON, the RF source is turned OFF and the transfer of the energy between the storage and the buffer cavities starts up by the beats. After odd number of half–periods of beats the fast switch is turned OFF and the RF source (in opposite phase to restore the required amplitude in the storage cavity, lowered by some dissipation during the transfer) begins power the storage cavity and so one.

MAGNETRON RF SOURCE FOR THE SCANNING SYNCHRONIZATION

As it was shown above the RF sources intended to feed the coupled cavities at the energy recovery have to operate in CW mode allowing a wide-band phase and power control and relatively short time for turning ON-OFF. Transmitters based on 2-cascade injection-locked magnetrons with power combining by a 3 dB hybrid, [4], allow all such manipulations at precisely-stable carrier frequency, [5]. Conceptual scheme of the transmitter is shown in Fig. 5, [ibid]. The transmitter consists of two identical channels (A and B) of cascaded injection-locked magnetrons, combined in power by a 3-dB hybrid. The wide-band phase control is provided by simultaneous and identical phase variation in both channels, while the power control is provided by phase difference in channels. Short time ON-OFF operation one can provide as the power control.
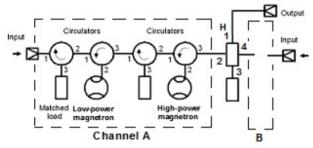

Figure 5: Block-diagram of the magnetron transmitter available for phase and power control. H is a 3-dB hybrid.

The 2-cascade injection-locked magnetron model utilizing 2.45 GHz, 1 kW magnetrons demonstrated reducing of the required locking power, to -25 dB, [5]. Measured bandwidth of the phase and power control of the transmitter model is up to a few MHz, [ibid.]. The 2-cascade magnetron model was tested for 180 deg. phase flip. The magnetron phase response for the 15 ns flip time rise is shown in Fig. 6.
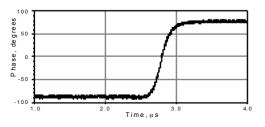

Figure 6: Measured response of the frequency-locked magnetron on a fast 180 degrees phase flip measured at

ratio of the output power to locking power of 26.5 dB. Inaccuracy of measurements by the phase detector is about of ±10 deg.

The transmitter parameters look feasible to realize the energy recovery at the scanning synchronization process.

CONTROL OF THE ENERGY TRANSFER IN THE COUPLED CAVITIES

Control of the energy transfer in the coupled cavities at low power was demonstrated using p-i-n diodes as fast microwave switches. At the pulse repetition rate of 40 kHz in the deflecting cavity was obtained max. magnetic field amplitude of 0.32 mT at the RF power of 20 W, [3]. A perspective approach for high power may be utilization of photoconductive semiconductor switches (PCSS). The switches use photoconductivity of a materials caused by absorption of a triggering laser light at an applied electric field of a few kV/cm. Experimental tests with a Ga-As bulk have shown rise time and delay effects which decrease dramatically with increasing electric field across the switch and/or optical energy used in activating lock—on. The recovery time of ~30 ns was demonstrated at the triggering energy ≤ 100 μJ and commutated current of hundreds Amps.

SUMMARY

A novel method of the *scanning synchronization* of colliding bunches for the MEIC project has been proposed. The method utilizes a controlled RF deflection of electron bunches, combined with the intrinsic magnetic optics of the Interaction Region, providing a periodically moving (in length) bypass controlled by the RF power. A novel method of *energy recovery* in the deflecting cavities, based on a fast transfer of stored energy by beats in coupled high Q-factor cavities has been proposed and considered for use at the scanning synchronization. The RF energy recovery method will allow a significant decrease of the RF power required for the deflecting cavities of the scanning synchronization method.

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