RF Sources for Scanning Synchronization of Colliding Bunches for MEIC Project

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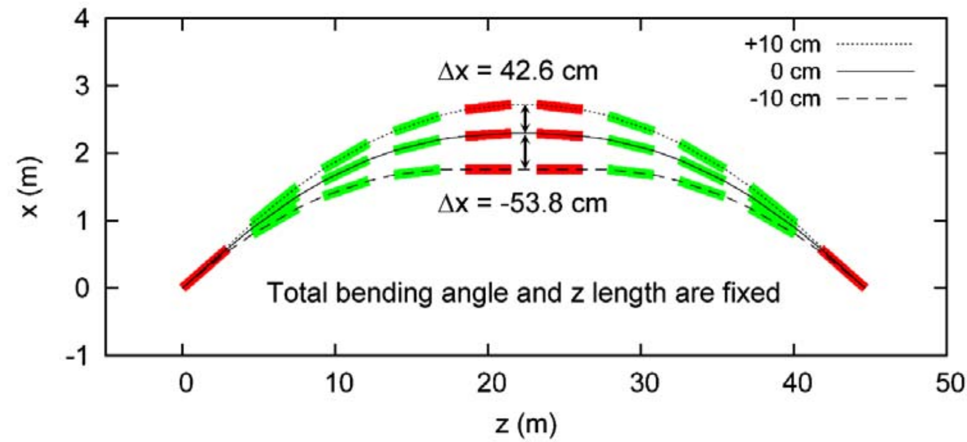
SYNCHRONIZATION OF E-I BUNCHES IN MEIC

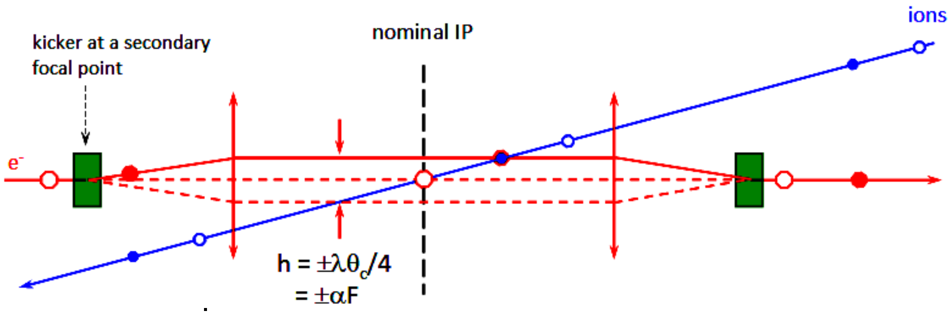
Synchronization of colliding beams is one of the major issues of an electron-ion collider (EIC) design because of sensitivity of ion revolution frequency to beam energy. A conventional solution for this trouble is insertion of movable bent chicanes in the arcs space, [1].



To avoid reconstruction of the existing beamline which has to be repeated for each new energy of the ion ring a ***scanning synchronization*** of the electron bunches has been proposed, [2].
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 cavities fed by the RF sources allowing a wide-band phase and amplitude control are used as the fast kickers. The proposed ***scanning synchronization*** method implies stabilization of luminosity at a maximum via a feedback loop.

THE SCANNING SYNCHRONIZATION CONCEPT

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 varied amplitude and (or) phase of the RF voltage.



The RF kicker is supposed to provide transverse variation of bunch traces in the Interaction Region (IR) in range of:

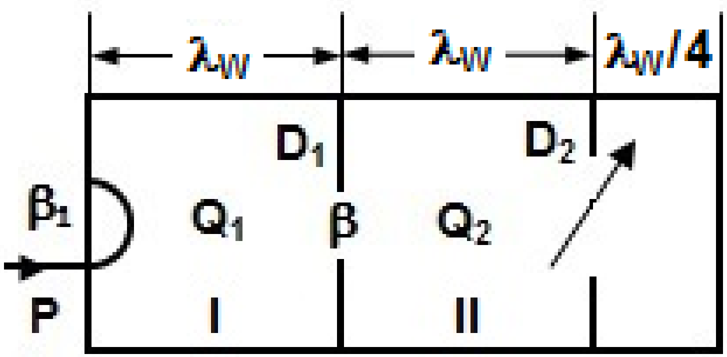
$$h = \pm\lambda\theta/4 = \pm\alpha F$$

Here: λ=40 cm is bunch spacing, θ =50 mr is crossing angle, α is a kick angle produced by the maximum RF voltage amplitude, and F is focal distance of the IR focusing magnet block. At F =4 m, h =5 mm, and required maximum kick α =1.25 mrad. Maximum longitudinal deviation of the collision point will be 10 cm.

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). During ST, the kicking RF voltage is supposed to be quickly returned to its initial amplitude and phase to start the next cycle. Minimum duration of the total cycle is equal to 2 periods of beam revolution.

THE ENERGY TRANSFER CONCEPT AT THE SCANNING SYNCHRONIZATION

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.



Conceptual scheme of the coupled cavities for the energy transfer.

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 wavelength 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.

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]:

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

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:

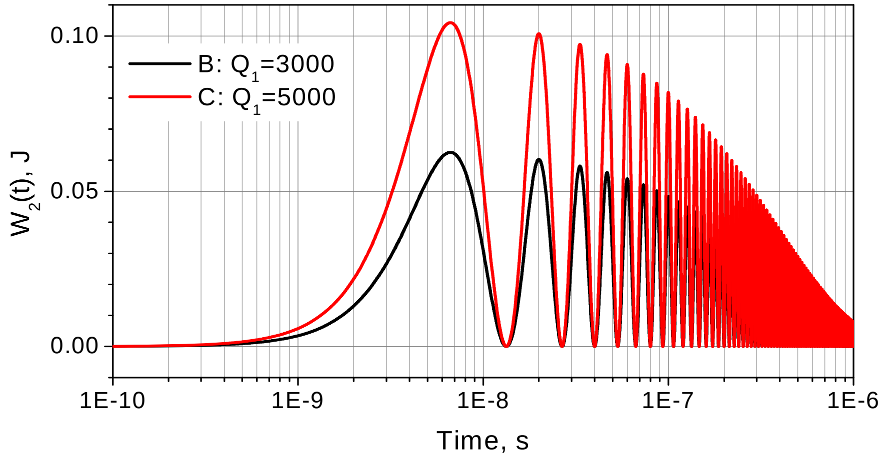
$$\tau = (2\lambda/\pi \cdot c)\cdot(1/Q_1 + 1/Q_2)^{-1}.$$

The energy W_2 transferred into the second cavity is described in time domain by the following equation, [2]:

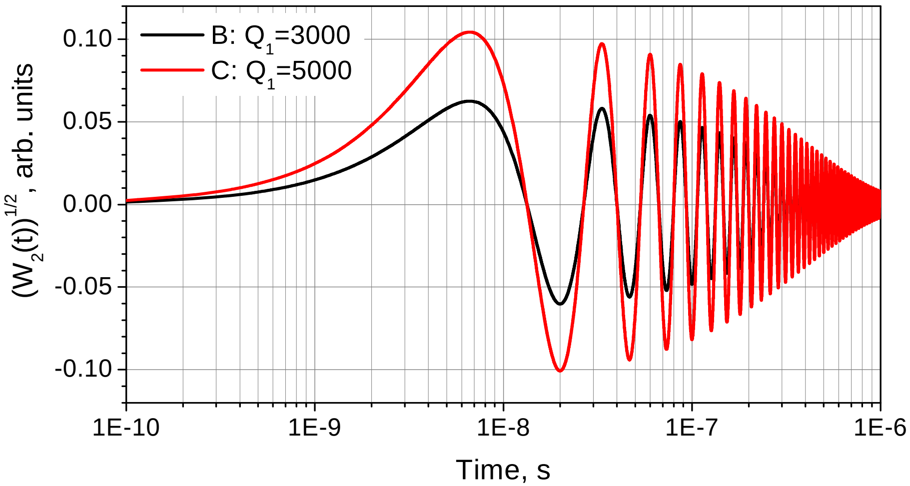
$$W_2(t) = \left(\pi^2 c^2 \beta^2 W_1 / \lambda^2 \Omega^2\right)\exp(-2t/\tau)\sin^2(\Omega \cdot t),$$

where: $\Omega = \left((\pi \cdot c \big/ 2\lambda)\sqrt{4\beta^2 - (1/Q_1 - 1/Q_2)^2}\right)$ is a characteristic angular frequency of the transfer.

THE ENERGY TRANSFER MODELLING



Examples of the transferred energy W_2 in time domain at β_1 =1, β =0.1, various values of Q_1, and at Q_2 =$5\cdot10^2$ (this value is determined generally by parameters of the implemented switch).



Polarity of the voltage (plotted in arb. units) in the buffer cavity during the beats.

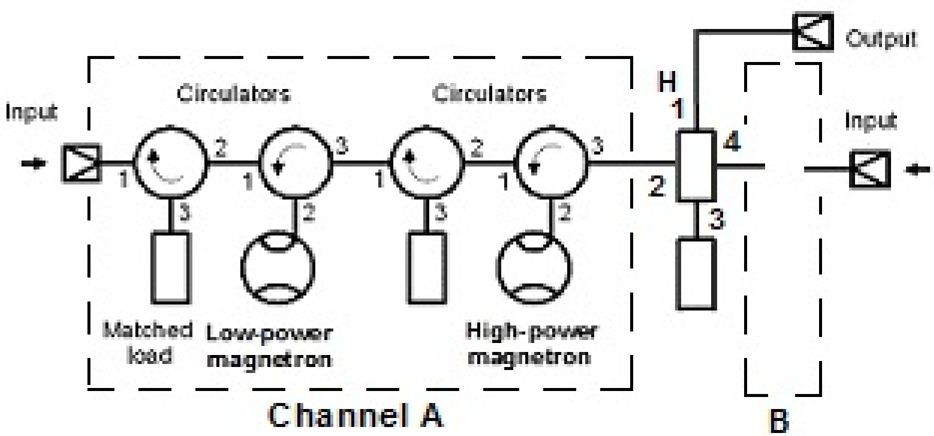
The transfer characteristic frequency, $f=\Omega/2\pi$ is 37.5 MHz.
The characteristic time of the energy dissipation, τ, is 0.36 and 0.39 μs for $Q_1=3\cdot10^3$ and $5\cdot10^3$, at the given coupling coefficients, respectively.

SEQUENCE OF OPERATIONS AT THE ENERGY TRANSFER

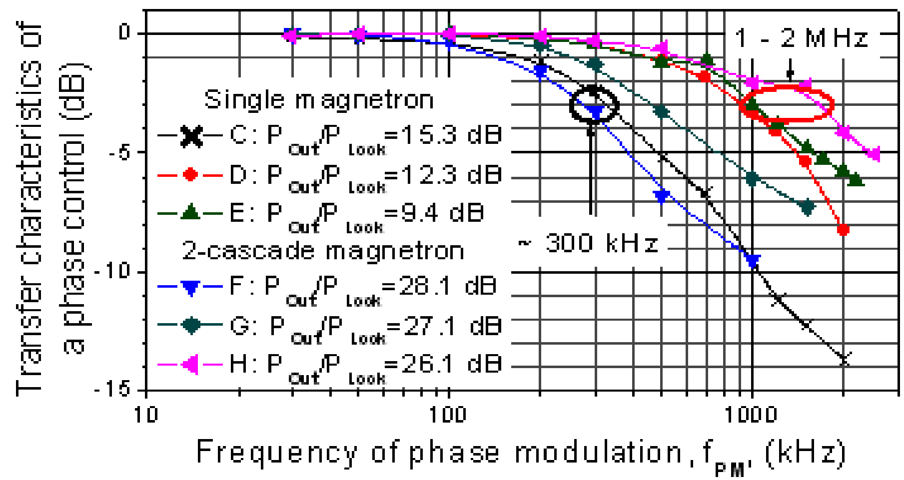
When the RF power is turned ON, the fast switch is OFF and the RF source has to change amplitude in the storage cavity used as a deflecting one to keep the amplitude increasing from minimum value to maximum value during 2 turns of electrons (1 cycle) in the ring (~ 13.4 ms). Until the fast switch is OFF, the buffer cavity is detuned in length and amplitude of oscillation is negligibly low. 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 some 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 powering the storage cavity and so one.

MAGNETRON RF SOURCE FOR THE SCANNING SYNCHRONIZATION

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 a short time for turning ON-OFF. Transmitters based on 2-cascade injection-locked magnetrons with power combining by a 3 dB hybrid, [4], are suitable and efficient RF sources for such manipulations at precisely-stable carrier frequency, [5].

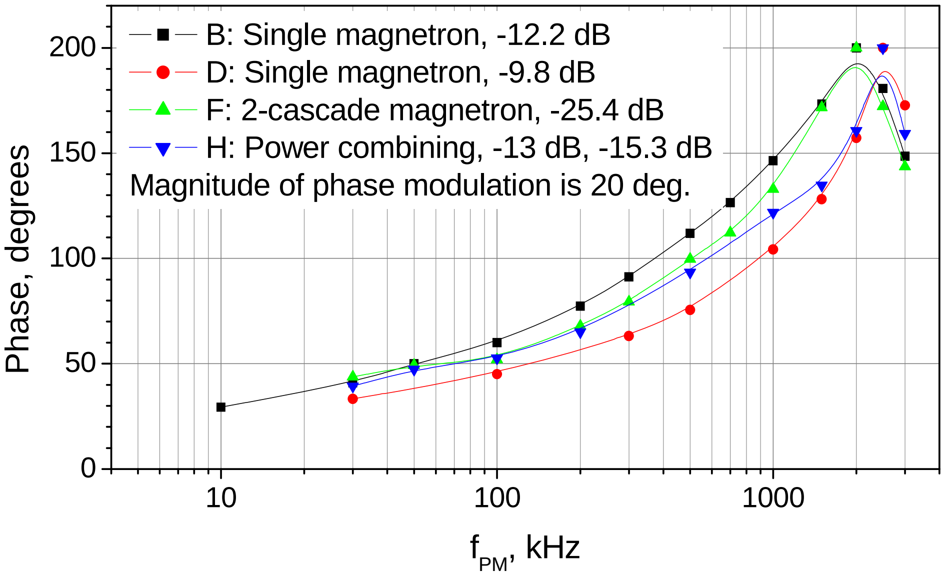


The wide-band phase and power control is provided by a phase-modulated injection-locking signal at power about of -25 dB in accordance with measured magnitude and phase characteristics of injection-locked magnetrons.

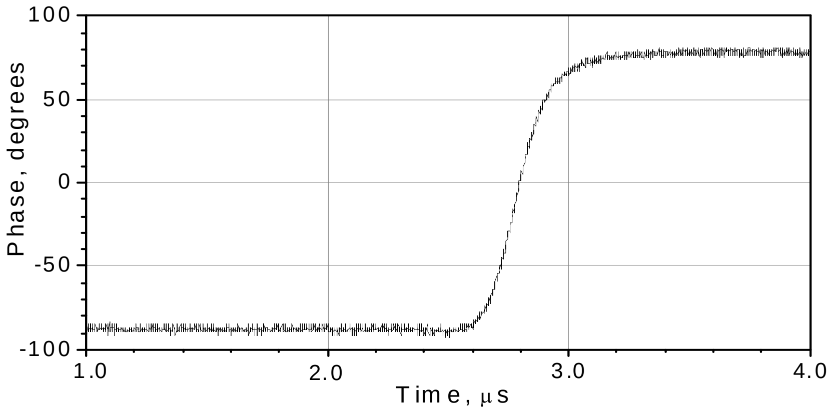


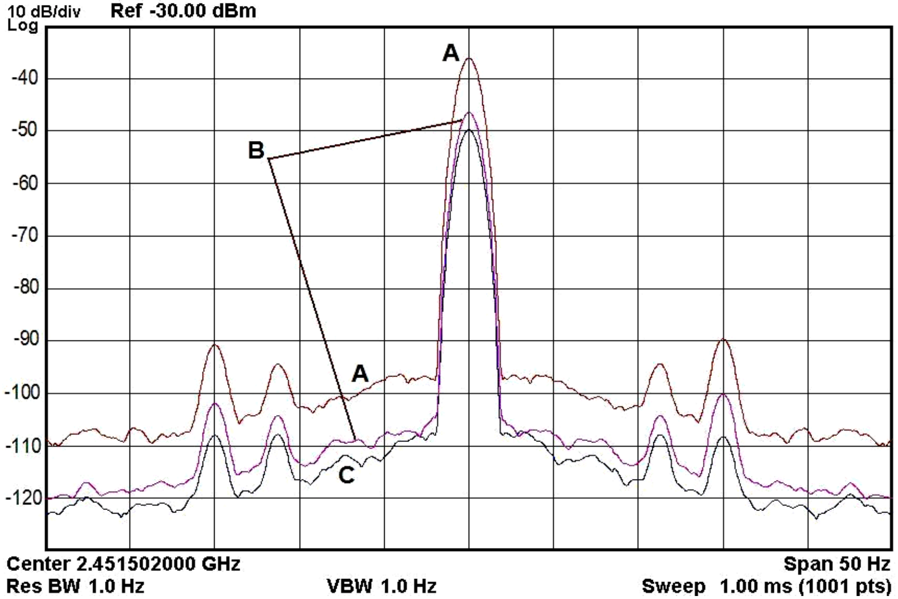
Transfer function magnitude characteristics (rms values) at the phase modulation measured in phase modulation domain with single and 2-cascade injection-locked magnetrons at various values of the locking signals. Black and red ovals show the f_{PM} cutoff at -3 dB level.

Phase response of magnetron vs. f_{PM}.



Phase response of a 2-cascade magnetron on a 180 degrees step function.





Carrier frequency spectra of a CW magnetron injection-locked by phase-modulated signal, [5].

A- the phase modulation is OFF.
B- f_{PM}= 2 MHz, magnitude of the modulation is 3 rad,
C- the phase modulated injection-locking signal.

Injection-locked magnetron transmitter allows wide-band phase/power control at precisely-stable carrier frequency.

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 by beats of the stored energy in coupled high Q-factor cavities has been proposed and considered for use at the scanning synchronization.

The proposed RF energy recovery method using efficient transmitters based on magnetrons frequency-locked by phase-modulated wide-band signal will be cost-effective and will allow a significant decrease of the RF power required for the deflecting cavities at the scanning synchronization.

REFERENCES

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[4] G. Kazakevich and V. Yakovlev, Project X document 896, http://projectx-docdb.fnal.gov
[5] G.M. Kazakevich et al., NIM A 760 (2014) 19-27