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Fast Electrically-Controlled Ferroelectric Tuners for RF Cavities.

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Abstract

Fast electrically-controlled tuners for RF cavities are proposed. Their usefulness for efficient RF manipulation and technical details are discussed.

General Description

One of the critical elements of RF cavities for accelerator application is the frequency tuning system. It is necessary to tune cavity into resonance and maintain resonance frequency during operation. Both "slow" and "fast" tuners are immanent elements of SRF cavities, where the resonance frequency may vary during the operation because of mechanical vibrations.

Recently, different designs of the fast tuners are developed and routinely used for RT and SRF cavities – ferrite, pin diode, and piezo. Piezo-ceramic actuators that recently widely used for "fast" tuning the length of the cavity to compensate shift in resonance frequency have many limitations including longevity of the piezo[1].

Utilization of the ultra-fast electrically-controlled ferroelectric elements for accelerator application has been suggested long time ago[2]. As results of the collaboration of the FNAL and Euclid Techlabs in 2006 a novel ferroelectric-based tuner has been invented[3], then "prove-of-principle" prototype built[4] and tested[4] with an SRF cavity.

The main feature of a ferroelectric tuner is that it is placed outside the cryo-module in the transmission line and does not contain mechanical elements.

Advantages of ferroelectric tuner (FE) versus existing tuning systems:

1. FE tuner will be able to tune SRF and RT (room temperature) cavities without mechanical elements, just using control with electrical (Voltage) pulse on the ceramic. Absence of the mechanical elements that must operate at cryogenics temperatures and insulated vacuum will significantly increase reliability and maintainability of the tuner and decrease accelerator downtime.
2. FE is fast (~100ns response time)[5]. FE tuner will be able to keep cavity in tune during short RF pulse. This will significantly decrease required maximum RF power.

3. FE could be used for fast changing coupling of the cavity. FE could be used for applications that required extremely fast beam re-bunching. (Appendix B. A.

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Burov -Proposal for re-bunching to make the MI bunches shorter that will make big impact on FNAL's Neutrino Program);

4. Fine tuning (resonance control) in the low beta cavities (like HW resonators) will be significantly benefit from FE tuner compare with widely used now pin-diode (VCX-systems)
5. FE tuners provides necessary fine tuning for PIP II in both CW and pulsed regime. FE tuner could be used for PIP II project (may be inserted later outside of the CM for operation in the pulsed mode to save power consumption 4 times)
6. Fast FE tuner will have significant advantage over piezo tuner for the cavities with very narrow bandwidth cavities for ERL machine. Based on estimations RF power consumption in ERL that will deploy FE tuner will go down in ~10 times.

Unique ferroelectric material is developed by Euclid in collaboration with FNAL scientists and is ready to use. Low – power prototypes have been built (with participation of FNAL scientists) and successfully tested at BNL and CERN with SRF cavities. There are set of technological tasks that need to be addressed to make ferroelectric materials fit for high-power tuners. The goal of the project is to build high-power prototype of the ferroelectric tuner and test it at high power first time in the world.

Significance

In superconducting linear accelerators for High Energy Physics and other applications there are several factors which significantly affect the required wall-plug power. With small beam loading, rf power requirements are determined in significant degree by change of the resonance frequency of acceleration cavities. With existing production technique SRF cavities required quite large range (100's of the kHz) of the tuning to bring cavities to operational frequency after resonators cool-down to T=2 K. Typically, SRF cavities built from thin Niobium sheets to deliver good heat transfer from inter surface of the cavity to bath of the liquid helium. As result SRF cavity structure became extremely sensitive to mechanical perturbations (microphonics) reaching cavity structure form the outside. Sources of the microphonics are external mechanical noise (pumps, traffic near accelerator, cryogen flow induced vibration, etc.) In case when SRF cavities operated at RF-pulse mode Lorentz forces could change cavity frequency up several kHz during just 1-10 ms pulse.

Compensation can be either by changing the cavity geometry to offset detuning, and/or to apply a corrective phase shift to the reflected rf wave that is reintroduced to the cavity so as to cancel phase instabilities.

The first strategy is accomplished by internal or external motors, or fast internal mechanical piezoelectric tuners necessary to tune cavity into resonance and maintain resonance frequency during operation. Electro-mechanical system that performed that function call Tuner. Tuner could be built from two sub-system: slow/coarse tuner and fast/fine tuner. Mechanical mechanism that change cavity's frequency by mechanically compressing or stretching cavity called "slow/coarse" tuner. Slow/coarse tuner could deliver forces up 10's of kN and change length of the cavity up to several millimeters. Typical speed of frequency change by slow/coarse tuner is below 1kHz/sec. Slow/coarse tuner could tune cavity close to operational frequency. But to keep cavity on the resonance (compensate microphonics and LFD) required fast/fine tuner. Recently, different designs of the fast tuners are developed and routinely used for RT and SRF cavities – ferrite, pin diode, and piezo. Piezo-ceramic actuators, that recently widely used for "fast" tuning the length of the cavity to compensate shift in resonance frequency, deployed in several large scale SRF LINACs (EuXFEL- 1600 actuators and LCLS II -700 actuators). Important to mentioned that piezo-ceramic actuators, despite broad application as active element in fast/fine tuners, have many limitations including longevity of the piezo. Fast tuner based on the piezo-actuator tuning cavity by changing electrical length of the cavity by means of changing mechanical size of the cavity. Piezo-electrical actuator is fast device with resonance frequency of the typical piezo-stack above 10's of kHz. But when piezo-actuator working as part of the SRF cavity tuner, maximum tuning rate speed of the cavity frequency changing with piezo tuner limited to the mechanical response of the dressed cavity/tuner system. Major mechanical resonance of the dressed cavity/tuner system is usually in the range of 250Hz (+/-100Hz). As a results piezo-actuator could not change cavity frequency faster that ~1MHz/sec that could limit application of the piezo-tuners for some specific applications.

The second approach utilizes fast phase shifters that are external to the cryomodules, whereas piezoelectric and other mechanical tuners require operation at cryogenic temperatures and thus permit only limited access in the event of a failure. The cavity tuning in this case could be based on the approach when electrical length could be changed if some materials with changeable electrical/magnetic properties installed in the cavity volume with electromagnetic fields. Mechanical size of the cavity will state the same. In case of active media is ferromagnetic with changeable magnetic permeability, we have a well-known ferromagnetic tuner base on ferrite phase shifter. Ferrite phase shifters are presently limited in their response time, which is not small enough for many typical SRF applications. The limitation comes mainly from the eddy currents in the ferrite material and from a bias circuit.

Some applications require fast change of external coupling of cavities (see Appendix B). Changes must be fast, and mechanical or magnetic switches /phase shifters cannot be used.

We are suggesting using a ferroelectric with changeable permittivity as active material. Ferroelectric tuner promises to be much faster device with more convenient.

One of the possible applications is providing of the pulse operation regime of PIP II superconducting linac. Note that present linac operation scenario suggests pulsed beam operation for the beam and CW operation for RF, which leads to poor efficiency, ~2e-3. This scenario is considered because of high LFD for the linac cavities. Application of the ferroelctric phase shifters would allow reduction of the linac wall-plug power consumption up to 4 times compared to present PIP II linac operation scenario. As it is shown in Appendix A, the external ferroelectric phase shifters are capable to provide necessary cavity detune for LFD compensation for all the linac SRF cavities.

Another application is for optimization the proton beam structure in the Fermilab Main Injector (MI) for better resolution, see Appendix C, by A. Burov; the loaded Q-factor is needed to increase 400 times, from 500 to 2e5 in few hundred of μsec to make this scenario possible. Ultra-fast electrically-controlled switches based on ferroelectric phase shifters allow this, see Appendix B.

Both applications are in the frame of the Fermilab mission.

Note that the ultra-fast ferroelectric phase shifters would find wide application in different superconducting and room-temperature accelerators – ion accelerators for light sources, FELs, synchrotrons, etc.

The goal of the project is to design, built and test at high RF power - first time in the world – the prototype of ultra-fast high power RF tuner for accelerator applications based on the new unique material developed by Euclid Techlabs in the frame of DoE SBIR grants in collaboration with Fermilab scientists. The low-power tuner prototypes have been built (see Appendix A) by FNAL scientists in collaboration with Euclid Techlabs, and tested at low power at BNL and CERN. The final step should be done – high power tests. The tuner has a wide field of applications for different accelerator projects at Fermilab and worldwide (see Appendixes A and B).

Outlines of project steps/milestones:

1 Development of the specifications for ferroelectric tuner that will match major FNAL projects (modifications of the FNAL MI; PIP II, etc.).
2 Design of the prototype.
3 Construction of the ferroelectric tuner prototype (it will include several intermedium prototype systems to test sample of the ceramic form vendor)
4 Development of the specialized test stands (than will include development of high-power electronics to control tuner)
5 Test of the prototype at high power, it was never done yet with ferroelectric tuners. Test will be done with warm dummy cavity/warm termination. Test with cold SRF cavity will required $500k in addition to the requested budget).
6 Results analysis and publications.
7 Development of the path for implementation of the ferroelectric tuner technology for FNAL's major accelerator projects and/or other accelerator projects.

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Appendix A.

External Fast Electrically-Controlled Ferroelectric Tuner for RF Cavities

With existing production technique SRF cavities required quite large range (100's of the kHz) of the tuning to bring cavities to operational frequency after resonators cool-down to T=2K. Typically, SRF cavities built from thin Niobium sheets to deliver good heat transfer from inter surface of the cavity to bath of the liquid helium. As result SRF cavity structure became extremely sensitive to mechanical perturbations (microphonics) reaching cavity structure form the outside. Sources of the microphonics are external mechanical noise (pumps, traffic near accelerator, cryogen flow induced vibration, etc.) In case when SRF cavities operated at RF-pulse mode Lorentz forces could change cavity frequency up several kHz during just 1-10 ms pulse.

It is obvious that to operate SRF cavities necessary to tune cavity into resonance and maintain resonance frequency during operation. Electro-mechanical system that performed that function call Tuner. Tuner could be built from two sub-system: slow/coarse tuner and fast/fine tuner.

Mechanical mechanism that change cavity's frequency by mechanically compressing or stretching cavity called "slow/coarse" tuner. Slow/coarse tuner could deliver forces up 10's of kN and change length of the cavity up to several millimeters. Typical speed of frequency change by slow/coarse tuner is below 1kHz/sec. Slow/coarse tuner could tune cavity close to operational frequency. But to keep cavity on the resonance (compensate microphonics and LFD) required fast/fine tuner.

Recently, different designs of the fast tuners are developed and routinely used for RT and SRF cavities – ferrite, pin diode, and piezo. Piezo-ceramic actuators, that recently widely used for “fast” tuning the length of the cavity to compensate shift in resonance frequency, deployed in several large scale SRF LINACs (EuXFEL- 1600 actuators and LCLS II -700 actuators). Important to mentioned that piezo-ceramic actuators, despite broad application as active element in fast/fine tuners, have many limitations including longevity of the piezo[1].

Fast tuner based on the piezo-actuator tuning cavity by changing electrical length of the cavity by means of changing mechanical size of the cavity (figure 1). Piezo-electrical actuator is fast device with resonance frequency of the typical piezo-stack above 10’s of kHz. But when piezo-actuator working as part of the SRF cavity tuner, maximum tuning rate speed of the cavity frequency changing with piezo tuner limited to the mechanical response of the dressed cavity/tuner system. Major mechanical resonance of the dressed cavity/tuner system is usually in the range of 250Hz (+/-100Hz). As a results piezo-actuator could not change cavity frequency faster that ~1MHz/sec that could limit application of the piezo-tuners for some specific application (see Appendix B, by A. Burov; document/request for optimization the proton beam structure in the Fermilab Main Injector (MI) for better resolution of the related neutrinos” for the last $1-2$ms, the Q-factor is needed to increase 10 times, from 500 to 5000 to make this scenario possible.).

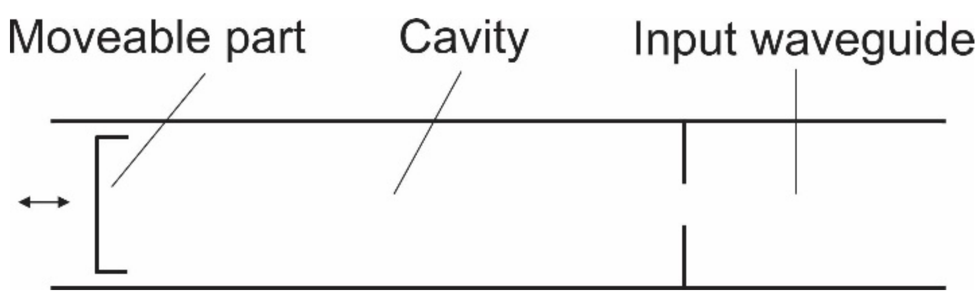

Figure 1: Scheme of the tuning cavity frequency by changing mechanical sizes of cavity.

Other approach for cavity tuning could be based on the approach when electrical length could be changed if some materials with changeable electrical properties installed in the cavity volume with electromagnetic fields. Mechanical size of the cavity will state the same (figure 2).

In case of active media is ferromagnetic with changeable magnetic permeability, we have a well-known ferromagnetic tuner. We are suggesting to use a ferroelectric with changeable permittivity as active material. Ferroelectric tuner promises to be much faster device with more convenient control and without magnetic field. Absence of magnetic field makes it practical for superconductive cavities.

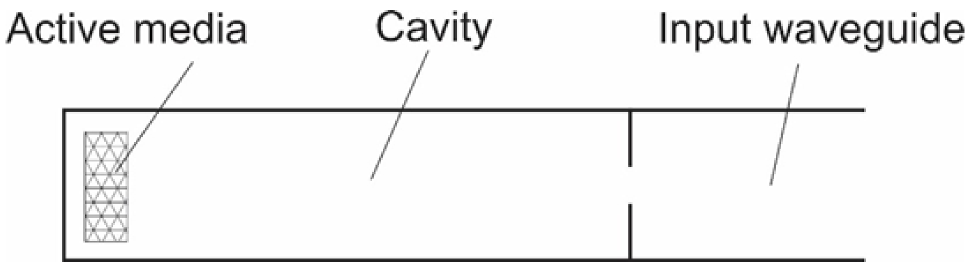

Figure 2: Scheme of the tuning cavity frequency with active media placed in the cavity volume.

In the scheme presented on Figure 2 active material placed inside of cavity. But it is more practical to have tuner outside of cavity and, probably, outside of cryomodule for several reasons: material cannot be compatible with high vacuum of cavity (especially for superconductive cavities); difficulty to apply a control system into cavity volume to change properties of active materials; high electromagnetic fields inside of cavity volume. More practical scheme is presented in Figure 3: tuner is separate device connected with cavity through additional port and RF window.

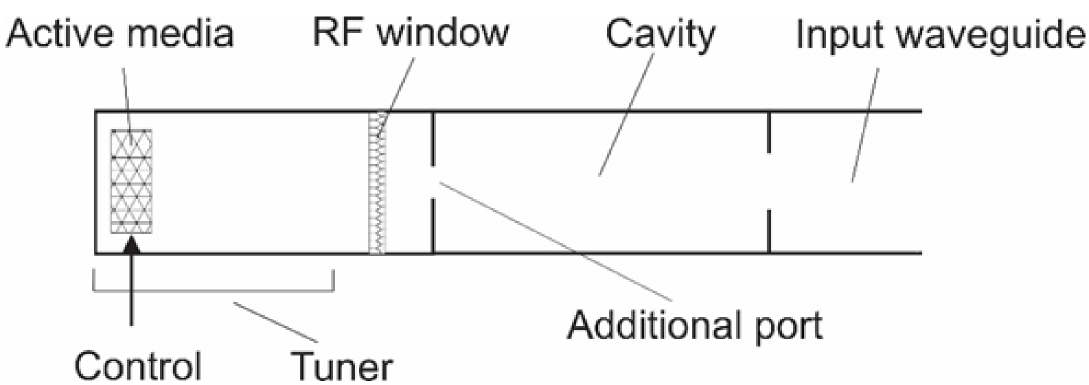

Figure 3: Scheme of the tuner, when active media (ferroelectric) placed into separate from SRF cavity volume. Cavity has additional (to input waveguide) port. Cavity and tuner coupled through RF window.

Property of ferroelectric material.

Ferroelectric material changes its permittivity under applied external electric field. Impotent parameter of ferroelectric is tunability: how much permittivity change per electric field unit. For example, if ferroelectric element works in air, a controlling electric field cannot exceed air breakdown limit. Necessary changing of permittivity should be reached within this limit.

Other limiting parameters is a changing ferroelectric permittivity with temperature changing. Variation of permittivity with temperature variation should be much smaller then

operating variation. Temperature is defined by losses in ferroelectric, thermal conductivity, heat capacity (in case of pulse operations). Combination of these parameters along with cooling and design determines the level of average and pulse operating RF powers.
One of the best ferroelectric material is produced by Euclid TechLab. It has the good combination of tunability and losses. Parameters of this material are presented in Table 1.

Table 1.

Parameters	Value
Dielectric constant, ε	~ 150
Tunability, Δε	~ 6% at 15 kV/cm
Loss tangent, tan δ	~ 5E-4
Thermal conductivity, K	~ 7 W/m-K
Temperature tolerance, $d\varepsilon/_{dT}$	(1-3) /K
Response time	< 10 ns
Specific heat, C	0.605 kJ/kg-K
Density, ρ	4.86 g/cm3
Coefficient of thermal expansion	10.1x1E-6/K
Breakdown limit	200 kV/cm

Possible configuration of ferroelectric tuner.

Most obvious (simple) configuration of ferroelectric phase shifter (tuner) is ferroelectric ring installed into coaxial line. High voltage bias is applied between inner and outer conductor of coaxial. It changes dielectric constant of ferroelectric and change electric length of ferroelectric and change the phase of reflected wave. Possible configuration is present on Figure 4. One end of coaxial line is RF port, other end is RF short (full reflection) and it is “open” for DC voltage.

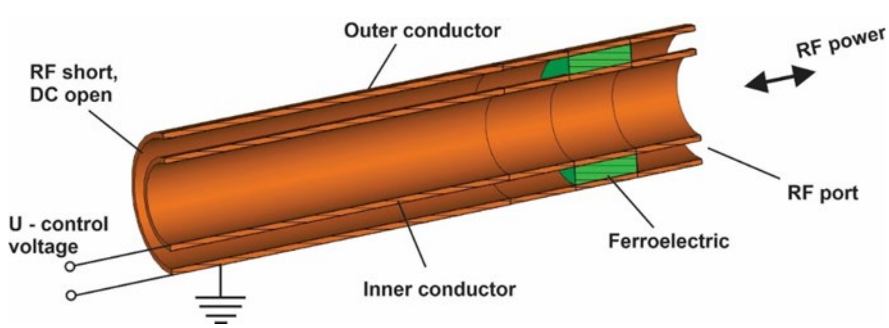

Figure 4. Electrical configuration of ferroelectric tuner.

Ferroelectric has a rather high value of dielectric constant (~ 150). It causes a high level of reflection of electromagnetic wave from boundary air – ferroelectric. There two way to make ferroelectric transparent to electromagnetic wave: to choose a ferroelectric length equal to whole number of half-wave length or to match ferroelectric at both sides, Figure 5. In the first case we have strong standing wave inside dielectric with maximum amplitude equal to amplitude in air. In the second case it will be pure travelling wave in dielectric with amplitude $\sqrt[4]{\varepsilon}$ times less then filed in air. Length of dielectric can be arbitrary length. Patterns of fields are presented on Figure 6. Intermediate configurations between these two configurations are possible as well. First configuration is most compact to get necessary phase shift, but it has highest specific RF losses. Second configuration provide the minimum phase shift per length of ferroelectric but has minimal specific RF losses. RF losses causes the pulse and average heating of ferroelectric, which change the dielectric constant of ferroelectric. It limits maximum pulse and average RF power. To estimate possible maximum pulse and average powers per ferroelectric unit, we will consider configuration with matched ferroelectric at both sides, Figure 5. Alumina ceramics can be used as good matching elements for ferroelectric with dielectric constant ~ 150.

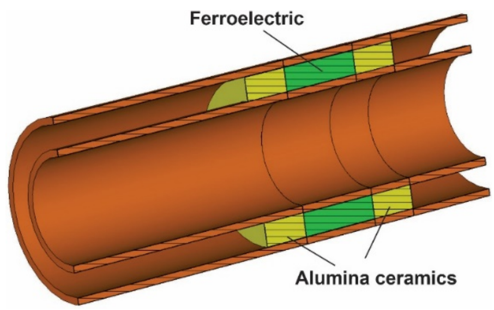

Figure 5. Example of ferroelectric with matching elements.

We made preliminary simulation for 325 MHz, 650 MHz for coaxial line close to standard 3-inch diameter. We used parameters of ferroelectric from Table 1. The goals were to find configurations which provide phase shift ~ 120 Degrees with 6% of change of dielectric constant (141-150 range) and estimate possible maximum average and pulse RF powers.

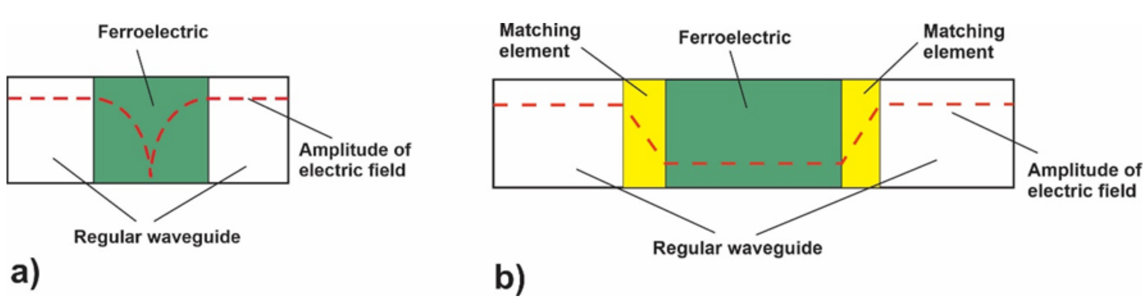

Figure 6. Two way to get transparent ferroelectric: a) length of ferroelectric is whole number of half-waves, b) ferroelectric completely matched at both sides.

325 MHz

Geometry of 325 MHz ferroelectric elements is presented at Picture 7. Two-way total RF losses of this element is 5.5% and losses in ferroelectric is 3%. Total (maximum) phase shift is 116 Degrees for 6% changing of dielectric constant.

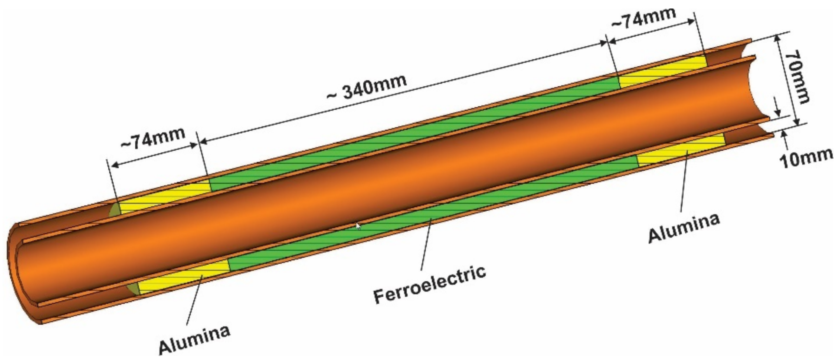

Figure 7: 325 MHz ferroelectric element.

To calculate the operating temperature, we applied a cooling liquid media with convection coefficient 1000 W/m2/K to inner and outer conductors. Dielectric constant is sensitive to temperature and temperature must be stabilized. For example, the element has to be warmed up by cooling media before operation and it has to be cooled during operation. We choose for estimation the operating temperature 45C.

Figure 8 presents results of thermal simulations. 45C temperature corresponds **43kW**, CW RF power.

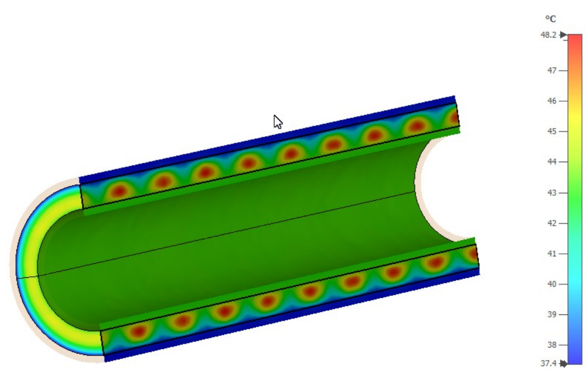

Figure 8: Temperature of 325 MHz ferroelectric element at 43kW CW RF power.

In case of pulse operation, rf pulse heats up ferroelectric and this heating cannot be easily compensated. If we require the stability of dielectric constant ~ 10% from change range (from 9 units of dielectric constant, ~1 dielectric unit stability in absolute value). Real accuracy of phase shift could be much higher when feedforward and feedback controls will be applied. It means, the pulse temperature rise should be less than 0.5K. It corresponds to **940 J** of dissipated energy in ferroelectric. Losses in dielectric is 3% and it determines max energy in RF pulse as **~ 31 kJ**. For example, for pulse length ~ 5ms (possible length of pulse mode of PIP-II project) it corresponds **620 kW** pulse power.

Maximum dissipated energy for 650 MHz element is ~ **560 J** (10% stability). It corresponds **17.5kJ** in RF pulse (3.2% losses in dielectric). It will be **350 kW** in case of 5ms pulse length.

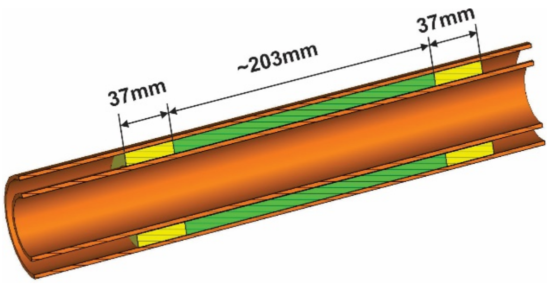

Figure 9. 650 MHz ferroelectric element.

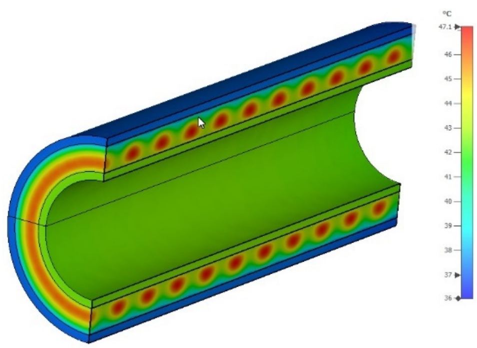

Figure 10: Temperature of 650 MHz ferroelectric element at 25kW CW RF power.

Estimations of tuning range of PIP-II cavities.

To understand practical applicability of ferroelectric tuner we chose PIP-II superconducting cavities as examples and calculate possible frequency shifts. Parameters of cavities are presented at Table 2. Limiting factor of ferroelectric tuner is power loss in ferroelectric and metal walls,

Table 2. Parameters of PIP-II superconducting cavities.

Cavity	Frequency, MHz	R/Q, Ohm	Acc. gain, MV	Storing energy, J
HWR	162.5	272	2.01	14.5
SSR1	325	242	2.05	8.5
SSR2	325	297	4.99	41.1
LB650	650	341	11.88	101.4
HB650	650	610	20.0	159.7

heating of ferroelectric. Simulations shows that optimal phase shift, which provide a ferroelectric tuner, is about 90 Degrees. Beyond this range the 'efficiency' of tuner drops – losses rise quickly. To satisfy 90 Degrees shift we will consider ferroelectrics elements which provide phase shift ~120 Degrees by 6% changes of dielectric "constant" (~15kV/cm bias).

Calculation shows the following power has to transmitted through phase shifter (tuner) back and forth to provide cavity frequency shift ΔF:

P = 48*ΔF – for PIP-II HWR cavity
P = 28*ΔF - for PIP-II SSR1 cavity
P = 140*ΔF - for PIP-II SSR2 cavity
P = 340*ΔF – for PIP-II LB650 cavity
P = 530*ΔF – for PIP-II LB650 cavity
P, W – power of through tuner, back and forth.
±ΔF, Hz – range of cavity tuning.

CW operation.

Temperature simulations shoes that maximum CW RF power for 325 MHz and 650 MHz ferroelectric elements can be ~ 43kW and ~25 kW consequently. We did not do simulation for 162.5 MHz, but let's suppose it can be ~ 70 kW. Tuning ranges corresponded to these power levels are presented in Table 3.

Table 3. Ranges of cavities tunings limited by ferroelectric temperature, CW mode operation.

Cavity	HWR	SSR1	SSR2	LB	HB
Tuning	± 1500 Hz	± 1500 Hz	± 300 Hz	± 75 Hz	± 50 Hz

Pulse operation.
Power pulse operation is limited by pulse heating of ferroelectric and change of permittivity. For 10% phase deviation we have following ranges of tuning for 5 ms pulse, Table 4.

Table 4. Ranges of cavities tunings limited by ferroelectric temperature, pulse mode operation, 5ms.

Cavity	HWR	SSR1	SSR2	LB	HB	
Tuning	± 21kHz	± 22kHz	± 4.5kHz	± 1kHz	± 0.65kHz	

Changing external coupling of cavity.

Some applications require fast change of external coupling of cavities. Changes has to be fast and mechanical of magnetic switches /phase shifters cannot be used. Ferroelectric phase shifter can be very fast device and can be used to change external coupling. Scheme of phase changes are presented in Figure 11. Changing phase (electrical length) between iris 1 and iris 2we can increase or decrease a cavity coupling to waveguide. Generally, a

cavity frequency will be change as well, but in points where coupling reaches maximum or minimum, there will be no frequency shift.
Suppose we need to change cavity external Q from Q1 to Q2. Analyses of tolerances shows that optimal Q0 which provided by only Iris 1 without Iris 2 should be $Q0 = \sqrt{Q1 * Q2}$. In this case phase shift of phase shifter between Q1 and Q2 is exactly 90 Degrees.

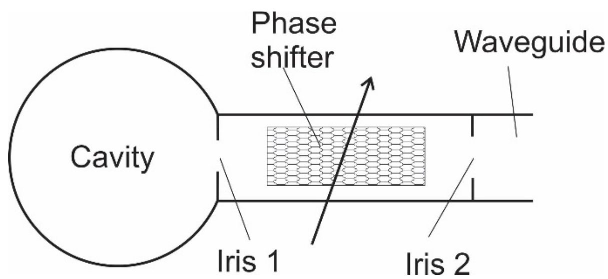

Figure 11: Scheme of changing external coupling of cavity.
Mechanically a phase shifter can made on a base of magic-T (Figure12). In this case the phase shifter can be phase shifter and iris 2 in the same time. Changing phases of in the arms in the same detraction change the electrical length (phase) of device. Changing phases in the opposite detraction change the of amplitude of reflection. Several coaxial phase shifters can be installed to each arm to increase operating power level. Diagram of possible configuration of cavity with changeable external coupling is presented on Figure 13.

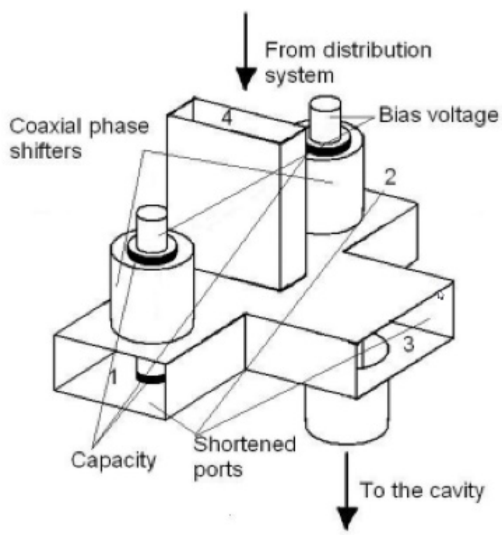

Figure 12: Ferroelectric phase shifter based on magic-T.

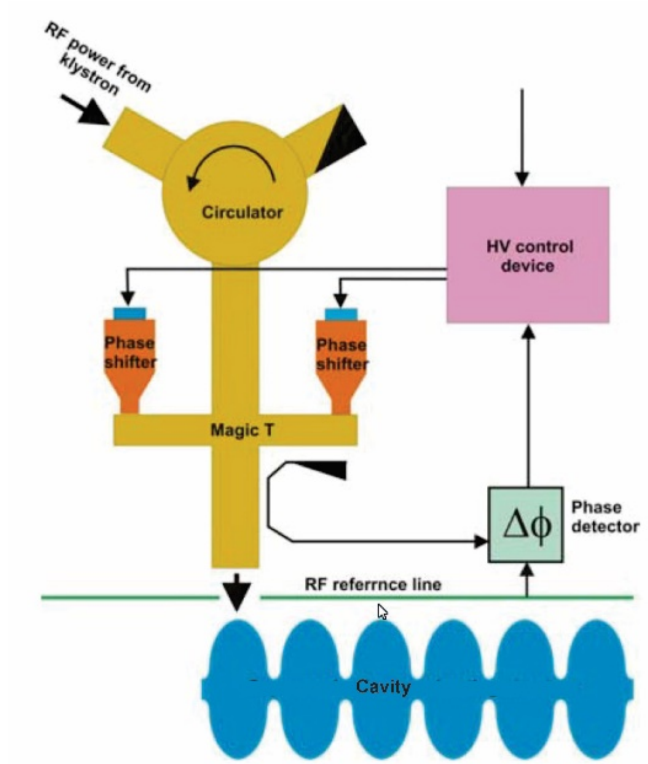

Figure 13: Possible configuration if cavity with changeable external coupling.

Appendix B.

Development ferroelectric ceramics for tuners.

In 2003 utilization of ferroelectric ceramics for ultra-fast high-power RF switched for accelerator application was suggested [1,2]. In the frame of collaboration, Euclid Techlabs, LLC developed new unique type of ferroelectric ceramics having very RF low losses at acceptable tunability [3,4,5,6]. In 2005 the ferroelectric tuner has been suggested for L – band superconducting cavities [7-10]. For this purpose, Euclid developed the improved ferroelectric material having lover dielectric constant, 450 versus initial 1600, low loss tangent and improved thermal conductivity. The L -band tuner prototype has been built by Yale Beam Lab and Omega-P, and tested at Fermilab at low RF power demonstrating speed of phase altering of ~0.5°/nsec [30]. Later the tuner has been successfully tested with SRF cavity at BNL [29].

Later, the FE material has been improved by Euclid [25-28] in the frame of the II SBIR project, entitled "Ferroelectric Based High Power Components for L-band Accelerator Applications" under Grant # DE-SC0007630. Euclid Techlabs in collaboration with Fermi National Accelerator Laboratory and Brookhaven National Laboratory has developed a fast (< 1us range) tuner based on this BST(M) ferroelectric elements with low dielectric constant (ε~150), which was designed to be used as the basis of an accelerator component intended for ERLs, eRHIC/JEIC, ILC, and other applications [8-24]. Specific features of this system are high tuning speed and amplitude and phase stability of its operation. The ferroelectric tuners have shown extremely high tuning speed, and thus should be extremely effective in this application. The main requirement for the electrical properties of ceramic materials to be used in such devices is a combination of the optimal value of the dielectric constant =100-150, a high level of electric field tunability K=6-8% at 15 kV/cm bias field in air and relatively low dielectric losses in the 400 MHz-1.3 GHz range. The design parameters for the 400 MHz tuner for the power test are an outer diameter of 27 mm, inner diameter of 17 mm, and length of 30.8 mm. RF power losses and temperature control for the design were studied. Variation of the dielectric constant of the BST(M) ferroelectric with the temperature increase has been measured. Operating temperature in the range of 40°C has been chosen to optimize the tuning range and power losses. The tuner was design by S. Kazakov, *et all* of Fermilab, and fabricated by Euclid Techlabs.

In May 2019 CERN has tested the prototype of the fast ferroelectric tuner with a superconducting cavity at low RF power, and frequency tuning has been successfully demonstrated [31,32]. The timescale in which the tuner can shift the cavity frequency across the entire tuning range was measured to be $< 50\ \mu$s, this is significantly faster than any other cavity tuning device. A maximum frequency tuning of ≈ 12 Hz was observed with an applied voltage of 3 kV, this could easily be increased by coupling more power to the tuner. A case study of a tuner applied to PERLE accelerator (Orsay, France) show RF power could be reduced by a factor of ≈ 15.

The ferroelectric tuner has never been tested yet at high RF power, it is one of the goals of the present proposal.

Appendix C.

Reduction of instantaneous energy loss

by fast variation of the cavity Q-factor

Some problems of Beam Physics can be better resolved with fast variations of Q-factors of focusing resonators. Here we describe just one example of such a benefit.

It has been recently suggested to optimize the proton beam structure in the Fermilab Main Injector (MI) for better resolution of the related neutrinos [34]. Specifically, it was suggested to increase number of bunches about 10 times, by turning off, after acceleration to 120GeV, the existing 53 MHz RF, and, after debunching, to rebunch the beam at ~10 times faster RF, i.e. at 500-600 MHz [35]. Possibilities of such manipulations may be limited by a longitudinal Sessler instability on the shunt impedance of the fast RF cavities [36]. To avoid or suppress this instability, either a proper feedback or a sufficiently low Q-factor are needed. The first option requires a special wide-band cavity fed by a high-power

RF source to compensate the impedance of the high frequency rebunching cavities. Within the second option, there is another fork of solutions: the Q-factor may be kept either constant or variable during the process. An advantage of the former way is its relative simplicity, but its disadvantage is requirement of high peak power of the feeding klystron at the end of the rebunching. To avoid these high peak energy losses, the Q-factor of the high-frequency cavities could be significantly increased at the end of rebunching, resulting in a dramatic reduction of the peak power. The computations below are intended to demonstrate that.

To avoid growth of the longitudinal emittance, the debunching and rebunching processes have to be adiabatic, i.e. the synchrotron frequency Ω_s has to change slow enough:

$$|\dot{\Omega}_s|/\Omega_s^2 \ll 1\,. \tag{1}$$

The optimal way to provide this is to keep the adiabatic parameter $|\dot{\Omega}_s|/\Omega_s^2$ constant and sufficiently small during the entire process. To provide this requirement, RF voltage has to fall and rise with time t as $V(t) = V_{\text{off}}\left(1 + t/\tau_{\text{off}}\right)^{-2}$ for the former case, at $t \geq 0$, and $V(t) = V_{\text{on}}\left(1 + (t_{\text{on}} - t)/\tau_{\text{on}}\right)^{-2}$ for the latter case, with $t \leq t_{\text{on}}$. To be adiabatic, the characteristic times of turning off and on, τ_{off} and τ_{on} respectfully, have to be large enough,

$$\tau_{\text{off}}\Omega_s(0) \gg 1;\;\; \tau_{\text{on}}\Omega_s(t_{\text{on}}) \gg 1.$$

For the discussed parameters of the MI beams, with $V_{\text{off}} = 4.5\text{MV}$ and $V_{\text{on}} = 4\text{MV}$, as in Ref. [37,38], it requires $\tau_{\text{off}} \geq 2\text{ms}$, $\tau_{\text{on}} \geq 1\text{ms}$. With shunt impedance R, in absence of the beam loading, the instantaneous energy loss P goes as (see, e.g. Ref. [30]):

$$P(t) = \frac{V^2(t)}{4R} \tag{2}$$

For a constant shunt impedance, this function is very fast, being effectively localized near $t = 0$ for the debunching stage and $t = t_{\text{on}}$ for the rebunching one, within the widths $\simeq \tau$.

To keep effects of the Sessler instability sufficiently small, the full shunt impedance at the high frequency RF must be small enough, $R_{\text{on}} \leq 0.1\text{MOhm}$; for two cavities it means two times smaller limit per cavity. With $R_{\text{on}}/Q = 200\text{Ohm}$, it limits the Q-factor $Q \leq 500$, resulting in the peak power, Eq. (2), $P = 40\text{MW}$, or 20MW per cavity.

On the other hand, clearly the Q-factor could be significantly increased at the last 1-2ms of rebunching, reducing the peak power, but still being acceptable with respect to the instability. Following this idea, we can assume the shunt impedance at the high RF frequency R_{on} being a function of time as

$$R_{\text{on}} = \text{Max}[0.1\text{MOhm},\ V_{\text{on}}^2/(4P_{max})]\,,$$

with the maximal peak power P_{max} being as low as the instability allows. The macroparticle analysis, similar to Refs. [37,38] and presented in Figs. 1-4 below, shows that $P_{max} = 2$MW is still tolerable. This means, that during the last $1 - 2$ms, the Q-factor has to jump 10 times, from 500 to 5000 to make this scenario possible.

Figure 1 shows the initial phase space distribution of the MI bunch matched to 4.5MV voltage at 53.9MHz RF at the top energy 120 GeV [37]. The doughnut shape reflects the slip-stacking coalescing of two bunches in one in the Recycler Ring (RR) right before injection in the MI. Figure 2 demonstrates the resulting particle distribution in 11 times faster RF, 593MHz, with 2 cavities, *R/Q*=90Ohm per cavity, *Q*=500, after $t_{\text{on}} = 60$ms of the total debunching-rebunching process with $\tau_{\text{off}} = 2.4$ms and $\tau_{\text{on}} = 1$ms; both 'off' and 'on' times were optimized to reduce the emittance growth. Particle losses to DC beam are computed as 0.1%, which is marginally acceptable.
Figure 3 shows the Q-jump required to keep the instantaneous energy loss, Eq. (2), within the limit of 2MW. Figure 4 demonstrates about the same bunches are formed as with the constant Q; the DC loss is also about the same.

Thus, we may conclude, that the possibility to vary the Q factor at the high frequency cavities, as fast as within a fraction of millisecond, can provide the requested rebunching in the MI with 10 times lower peak energy losses than for the constant Q-factor, with the same resulting beam quality.

In this scenario, the fast, high power RF switch should be developed. Ferroelectric switch described above, is an ideal candidate for this purpose.

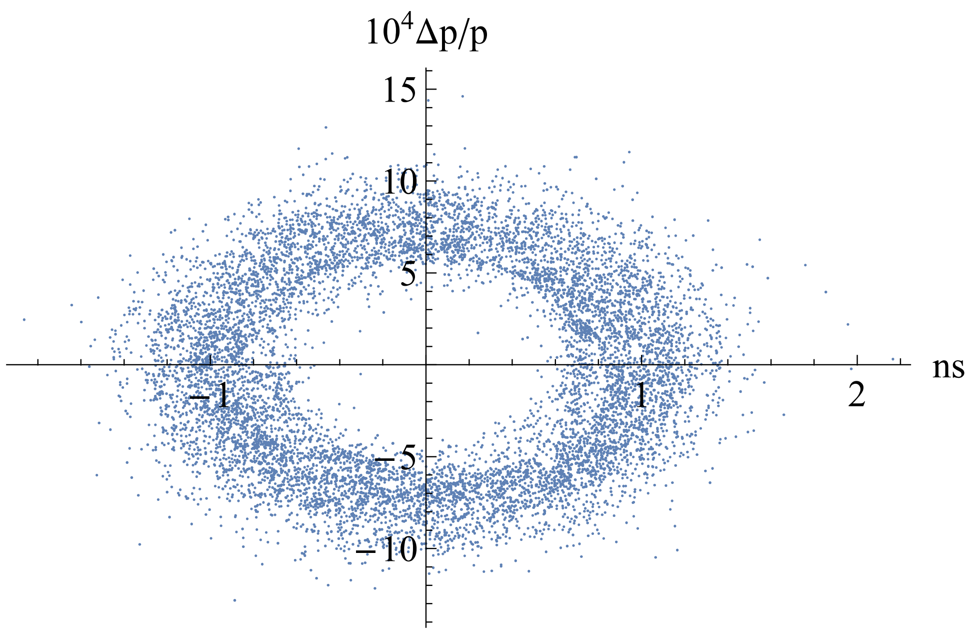

Fig. 1: Initial state of the MI bunch in the longitudinal phase space at 120GeV; the doughnut shape is due to the slip-stacking in the RR.

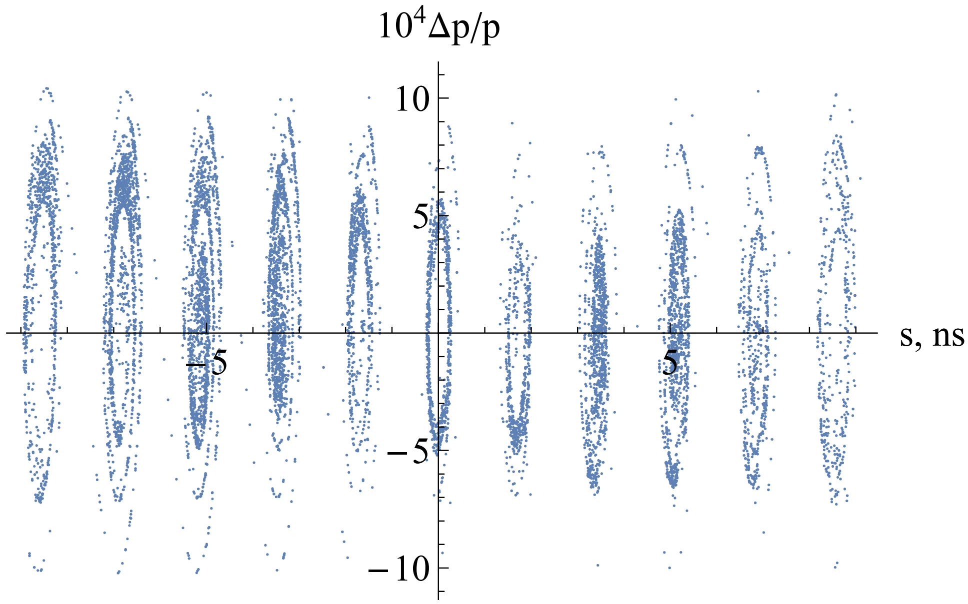

Fig. 2: Final bunches, Q=500 for the entire process, DC beam=0.1%.

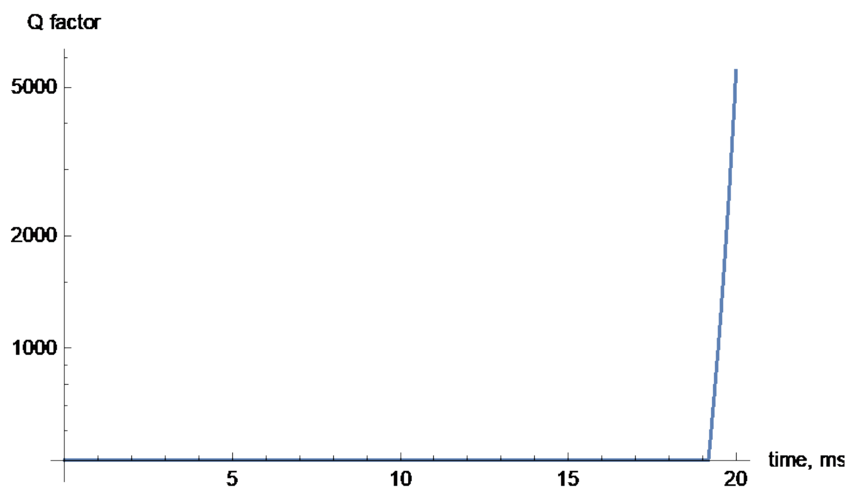

Fig. 3: Q-factor for high frequency RF at the last 20ms of the process, Q-jump with $P_{max} = 2$MW.

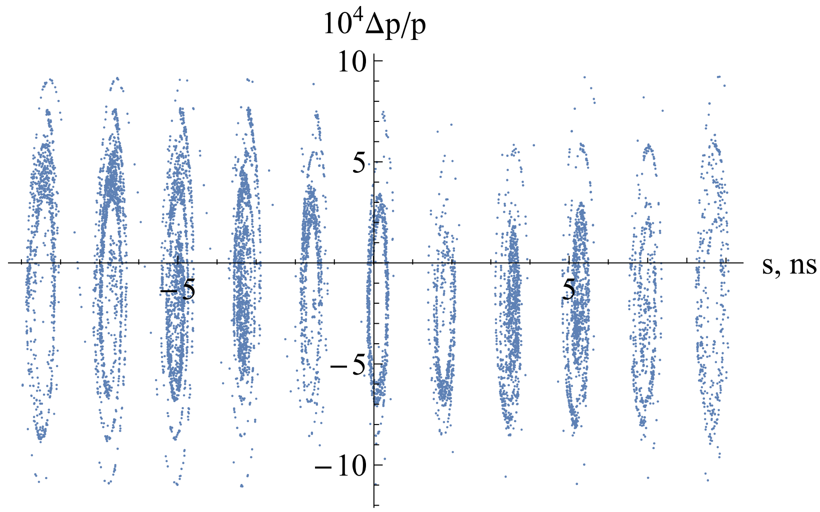

Fig. 4: Final bunches at the high-frequency RF; Q-jump with $P_{max} = 2\text{MW}$, DC beam = 0.1%.