Recovery Process Stability Study in Energy Recovery Accelerator

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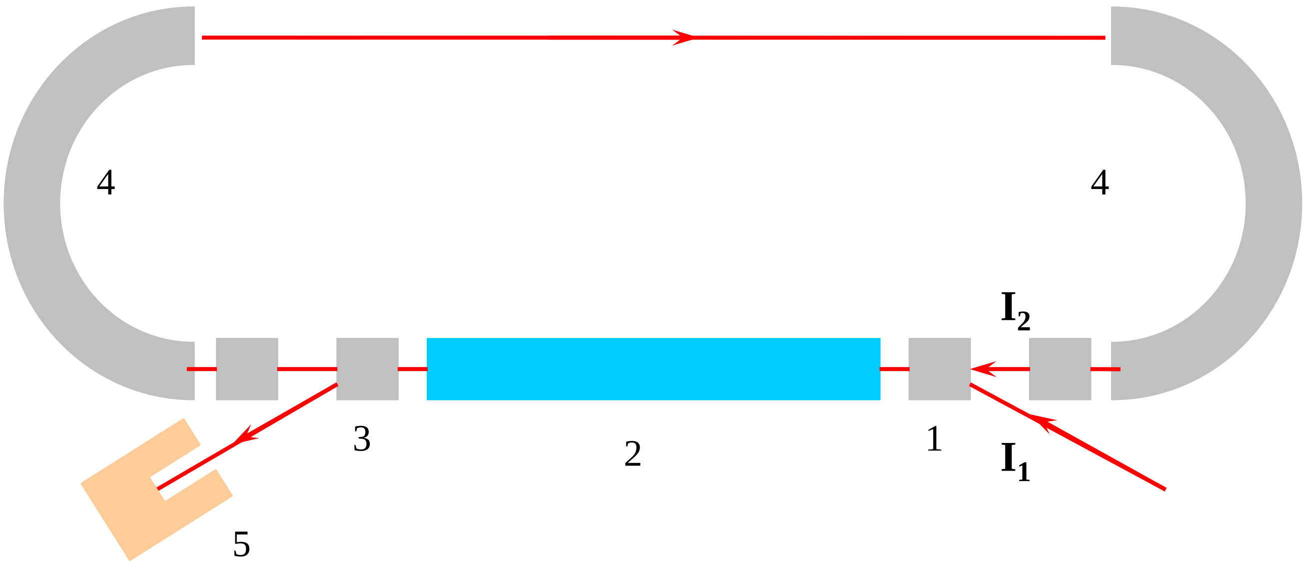

Fig.1. General layout of energy recovery linac. 1– magnet inflector, 2– main linac, 3 – magnet deflector, 4 – bending magnets, 5 – beam absorber.

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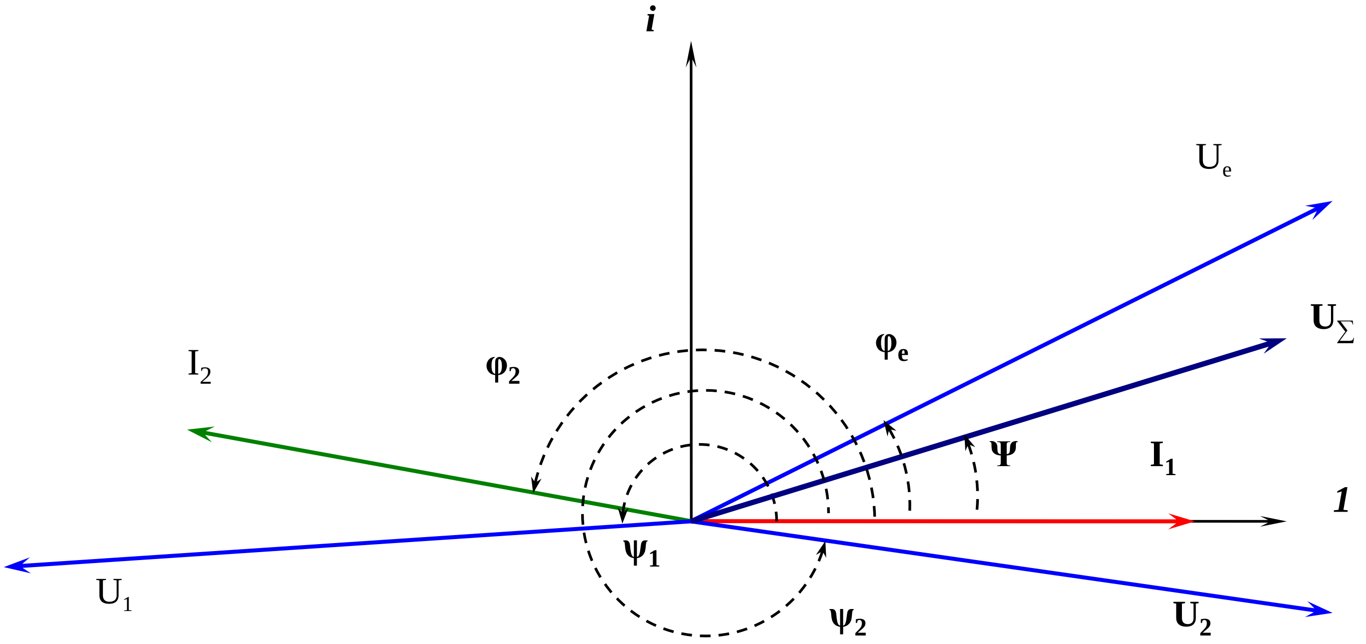

Fig.2. Voltages and currents on complex plane. I_1-accelerated beam, I_2-decelerated beam, U_0-the voltage induced in cavity by external rf generator, U_1-the voltage induced by accelerated beam, U_2-the voltage induced by decelerated beam, U_Σ-total voltage at the cavity gap.

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$$\hat{U}_{\Sigma}(t) = \hat{U}_{e}(t) + \hat{U}_{1}(t) + \hat{U}_{2}(t)$$

$$E = eU_{\Sigma}\cos(\psi) = \mathrm{Re}(e\hat{U}_{\Sigma})$$

all voltages are understand as energies acquired by unit charge after cavity passage.

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$$\frac{d^2u}{dt^2}+\frac{\omega_0}{Q}\frac{du}{dt}+\omega_0^2u=-\frac{\omega_0 R}{Q}\frac{dJ}{dt} \qquad Q=\frac{Q_0}{1+\beta},\ R=\frac{R_0}{1+\beta}$$

$$J(t)=I(t)\exp(i\omega t),\ u=U(t)\exp(i\omega t)$$

$I(t), U(t)$ ← Slow functions of time

$$\frac{dU}{dt}+\left(\frac{\omega_0}{2Q}+i\Delta\omega\right)U=-\frac{\omega_0 R}{2Q}I$$

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$$\frac{d\Delta\hat{U}}{dt} + \left(\frac{\omega_0}{2Q} + i\Delta\omega\right)\Delta\hat{U} = -\frac{\omega_0 R}{2Q}\Delta\hat{I}$$

$$\Delta\hat{I}_2 = \Delta(I_2 \exp(i\varphi_2)) = iI_2 \exp(i\varphi_2)\Delta\varphi_2$$

$$\Delta\varphi_2(t) = \frac{2\pi\alpha L}{\Lambda}\frac{\Delta E(t-T)}{E}$$

$$\Delta E = e\,\mathrm{Re}\,\Delta(\hat{U}_e + \hat{U}_1 + \hat{U}_2) = e\,\mathrm{Re}(\Delta\hat{U}_2)$$

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$$\frac{d\Delta u_{2x}}{dt} + \frac{\omega_0}{2Q}\Delta u_{2x} - \Delta\omega\Delta u_{2y} = A\sin\varphi_2 \Delta u_{2x}(t-T)$$

$$\frac{d\Delta u_{2y}}{dt} + \frac{\omega_0}{2Q}\Delta u_{2y} + \Delta\omega\Delta u_{2x} = -A\cos\varphi_2 \Delta u_{2x}(t-T)$$

$$A = \frac{\omega_0 R}{QU_\Sigma} I_2 \frac{\pi\alpha L}{\varepsilon\Lambda}$$

$$\Delta u_{2x} = \exp(kt) \qquad \Delta u_{2y} = a\exp(kt)$$

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$$k + \frac{\omega_0}{2Q} - a\Delta\omega = A\exp(-kT)\sin\varphi_2$$

$$ak + a\frac{\omega_0}{2Q} + \Delta\omega = -A\exp(-kT)\cos\varphi_2$$

$$k = 0$$

Static instability

$$\frac{2\pi L}{\varepsilon\Lambda}\frac{I_2 R}{U_\Sigma}\alpha(\sin\varphi_2 - \frac{2Q\Delta\omega}{\omega_0}\cos\varphi_2) = 1 + (\frac{2Q\Delta\omega}{\omega})^2$$

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$$\varphi_2 = \pi + \eta$$

$$\tan\eta > 2Q\Delta\omega/\omega_0 \qquad \alpha > 0$$

Negative feed back

But it is well known from feed back systems theory that negative in static sense feed back may become positive at definite frequency range resulting in unstable state.

$$k = \operatorname{Re} k + i \operatorname{Im} k = 0 + i\Omega$$

$$\frac{\omega_0}{2Q} = A\sin\varphi_2\cos\Omega T, \; \Omega = -A\sin\varphi_2\sin\Omega T$$

$$\Omega T \approx \frac{\pi}{2}, -A\sin\varphi_2 \approx \frac{\pi}{2T} \qquad \frac{2\pi L}{\varepsilon\Lambda}\frac{I_2 R}{U_\Sigma}\alpha\sin\varphi_2 \approx \frac{\pi}{2}\frac{\tau}{T}$$

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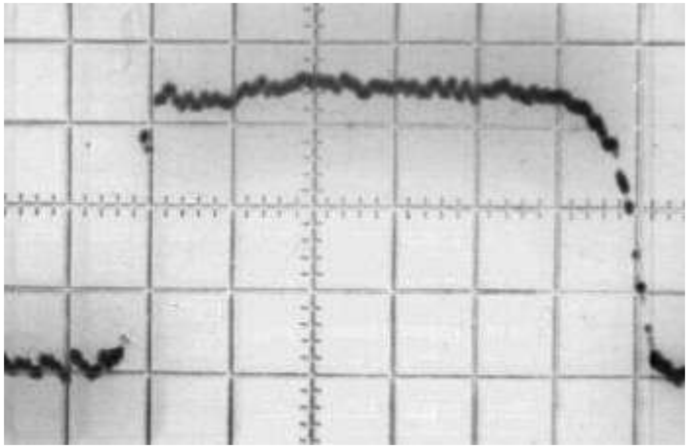
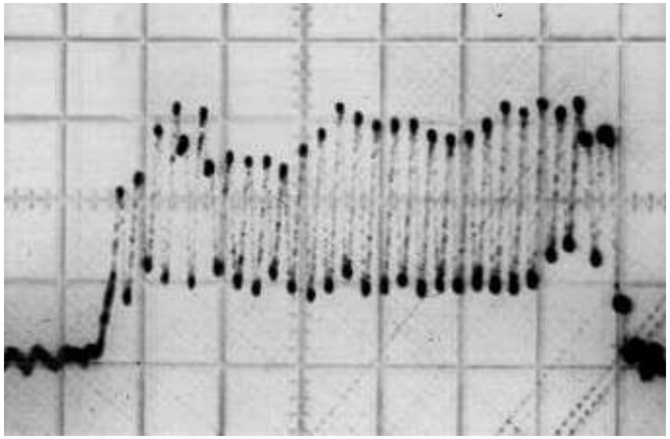


1



2

Beam current oscillograms of stable (1) and unstable (2) operation modes of racetrack microtron.

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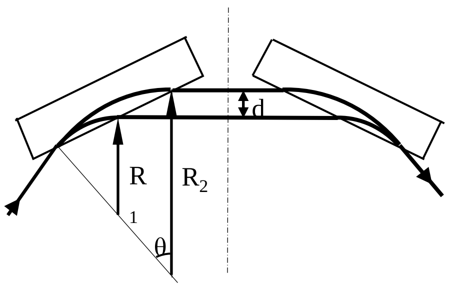
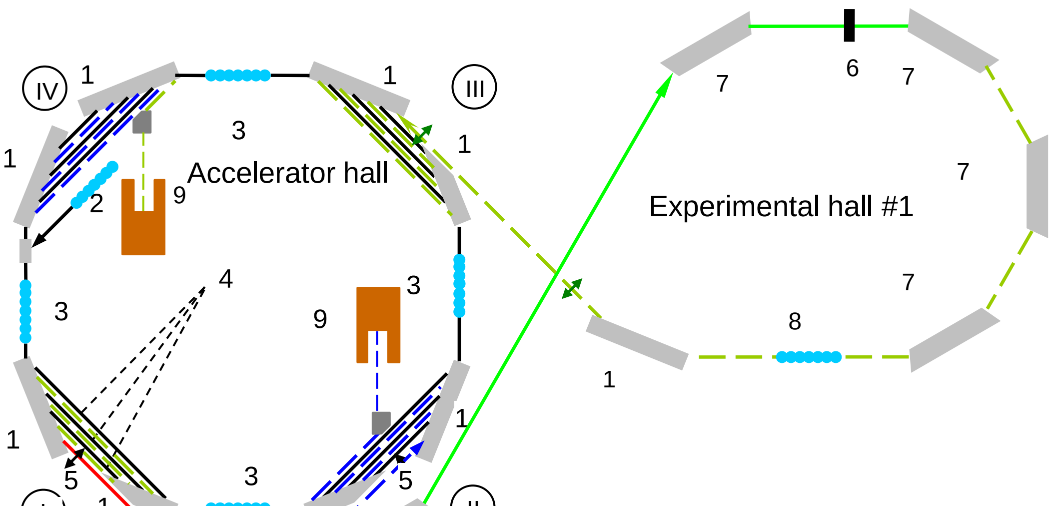


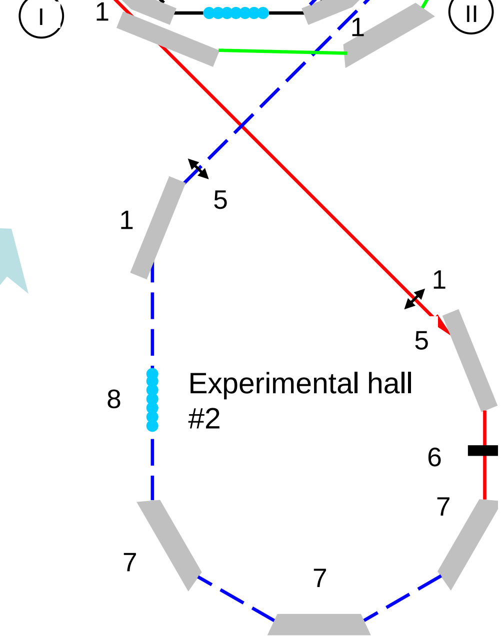
Electron trajectories in polytron

$$\Delta E(MeV) = 1.5 B(T) g\lambda \frac{1}{\vartheta - \sin\vartheta}$$

$$d = \frac{g\lambda}{2} \frac{1-\cos\vartheta}{\vartheta - \sin\vartheta}$$

New accelerator in existing environment





RF superconducting accelerator with beam energy recovery system at LPI (Troitsk of Moscow Region)

1 – dipole magnet, 2 – injector, 3 – superconducting linac, 4 – accelerator orbits, 5 – magnetic lens, 6 – target, 7 – magnets of the achromatic system, 8 – energy and spectrum correction accelerator, 9 – recovery beam absorber. I,II,III,IV stand for quadrant number

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Total energy	*2050 MeV*
Energy gain per turn	*600 MeV*
Energy gain in one linac	*150 Mev*
Injection energy	*100 MeV*
Number of turns	*3*
Magnetic field in dipoles	*1.36 T*
Dipole pole dimensions	*0.4 m*3.6 m*
Minimum/maximum radius of electron trajectory	*0.6 m / 4.7 m*
Linac frequency	*1.3 GHz*
*Cavity Quality factor and shunt impedance R/Q= V_{ac}^2/P_{dis}*Q at 2K*	*$5*10^9$* *1 kOm*
Accelerating gradient (MV/m)	*25*

TESLA type RF cavity
Cryogenic module

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The instability takes place for any sign of recovery angle and longitudinal dispersion.

If cavity detuning is zero:

$D \cdot \sin(\varphi) > 0$ – static instability

$D \cdot \sin(\varphi) < 0$ – dynamical instability

$D \cdot \sin(\varphi) = 0$ – the instability does not take place

THANK YOU!