Project X
Main Injector

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Main Parameters and Their Choice

- MI upgrade has 7.5 times larger power: 0.3 MW → 2.3 MW
  - Faster ramps: 2.2 s → 1.4 s
  - 5 times larger number of particles: $(0.34 \rightarrow 1.7)\cdot 10^{14}$
- No major modifications to MI magnetic and vacuum systems
- Upgrades
  - Increased beam power will require more powerful RF system
  - Increased intensity will require more powerful instability dampers
  - Single turn full length injection will require modification of injection kicker

Design Objectives

- To keep Coulomb tune shift being sufficiently small
  - Increased beam emittance: 15 $\rightarrow$ 25 mm mrad
  - KV-distribution
    - For the same 95% emittance it reduces tune shifts by 3 times comparing to Gaussian beam
  - Minimize longitudinal density
    - Keep bunch long during initial stages of acceleration
    - Second harmonic RF
- To prevent coherent instabilities
  - Bunch-by-bunch transverse damper with 10 turns damping time
  - Increased longitudinal emittance
  - Large synchrotron tune spread due to Second harmonic RF
  - Large chromaticity
  - Feed-forward in RF system to minimize effects of beam loading
  - Bunch-by-bunch longitudinal damper
  - Large γ_t-jump at transition crossing

Main Parameters of Main Injector

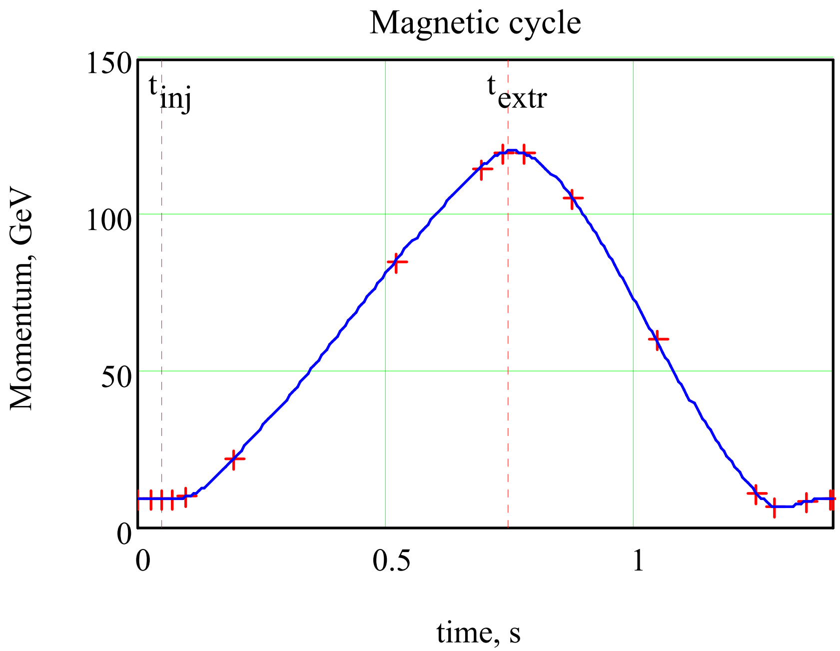
	Present	New
Injection kinetic energy, GeV	8	
Extraction kinetic energy, GeV	120	
Circumference, m	3319.42	
Revolution frequency at injection, kHz	89.815	
γ transition, γ_t	21.62	21.62
γ-transition jump, $\Delta\gamma$	-	2
Cycle duration, s	2.2	1.4
Total number of particles	$3.4\cdot10^{13}$	$1.7\cdot10^{14}$
Beam current at injection, A	0.49	2.45
Betatron tunes, Qx/Qy	26.42/25.41	26.45/25.46
Normalized 95% emittance, mm mrad	15/15	25/25 †
Norm. acceptance at injection, mm mrad	40/40	40/40
90% longitudinal emittance, eV s	0.4	0.5
Maximum Coulomb tune shifts, $\Delta Qx/\Delta Qy$	0.033/0.038	0.043/0.046
Number of bunches	480	548
Number of particles per bunch	$7\cdot10^{10}$ ($9\cdot10^{10}$ ‡)	$3.1\cdot10^{11}$
Betatron tune chromaticity	-10 - +10	-20 - +20
Abort gap, μs	1.6	0.7
Maximum power intercepted by collimation system, kW	<1.6	<1.6
Average beam power on the target, MW	0.3	2.3

† KV distribution is implied

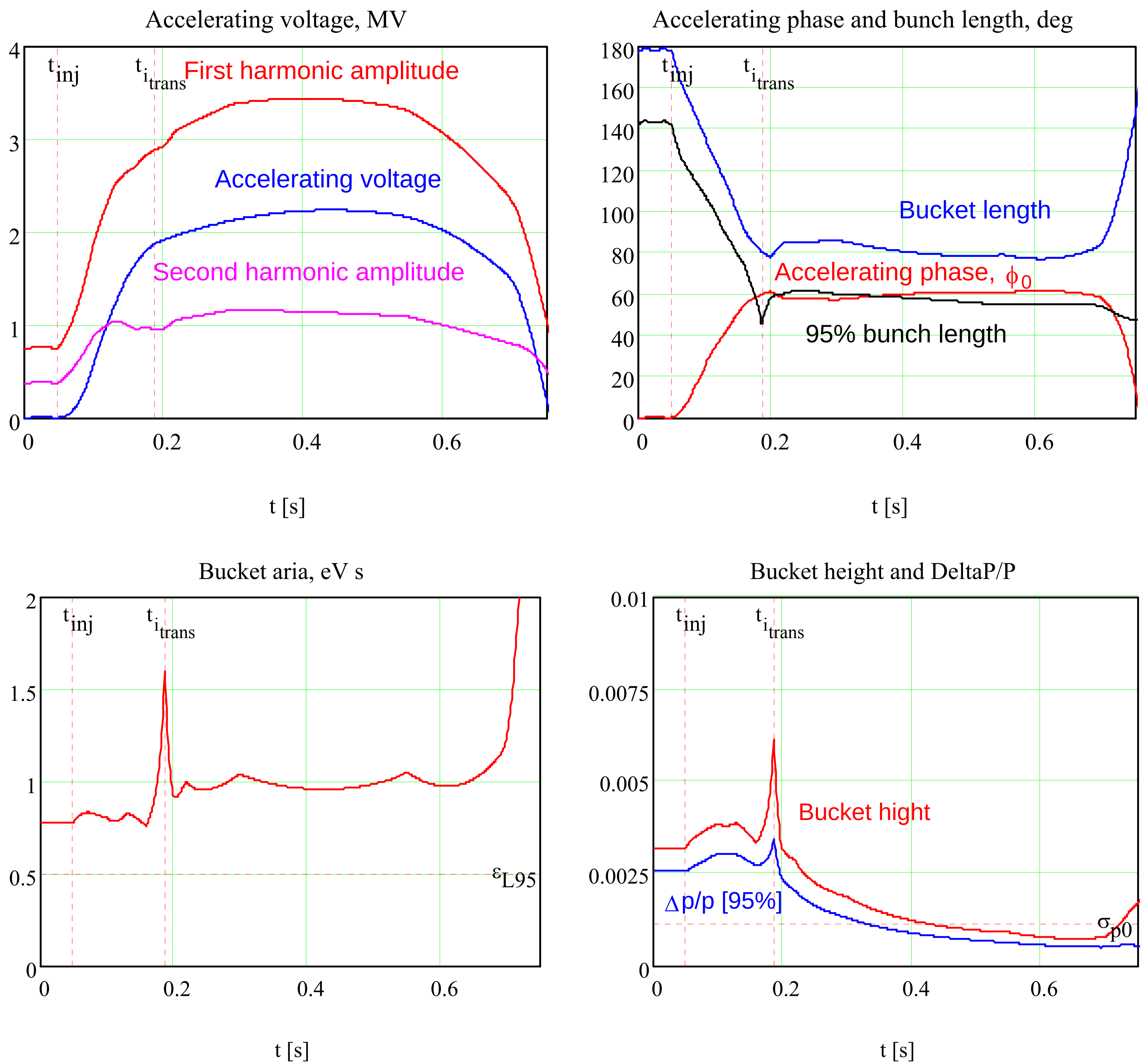
‡ Population of slip-stacked bunches for antiproton production

Beam and Machine Parameters during MI cycle

- Magnetic cycle is similar to the present MI injector cycle
- Presently, MI acceptance is limited by extraction Lambertson magnets to about 80 mm mrad.
  - Acceptance of 40 mm mrad is assumed for the upgrade leaving ~6 mm for steering errors.
- The same RF frequency
  - Frequency sweep 52.8 - 53.1 MHz
- RF phase and amplitude of the second harmonic are chosen so that to maximize the bucket size
  - $dV/d\phi = d^2V/d\phi^2 = 0$ in the bunch center
    - At injection it yields: $V_2 = V_0/2$



Dependence of beam momentum on time during MI magnetic cycle



RF and bunch parameters on time;

top left: red - 1-st harmonic voltage, blue accelerating voltage, magenta – 2-nd harmonic voltage;

top right: red – acc. phase, blue – bucket length, black – 95% bunch length;

bottom left: bucket area;

bottom right: red – bucket height, blue – 95% Δp/p

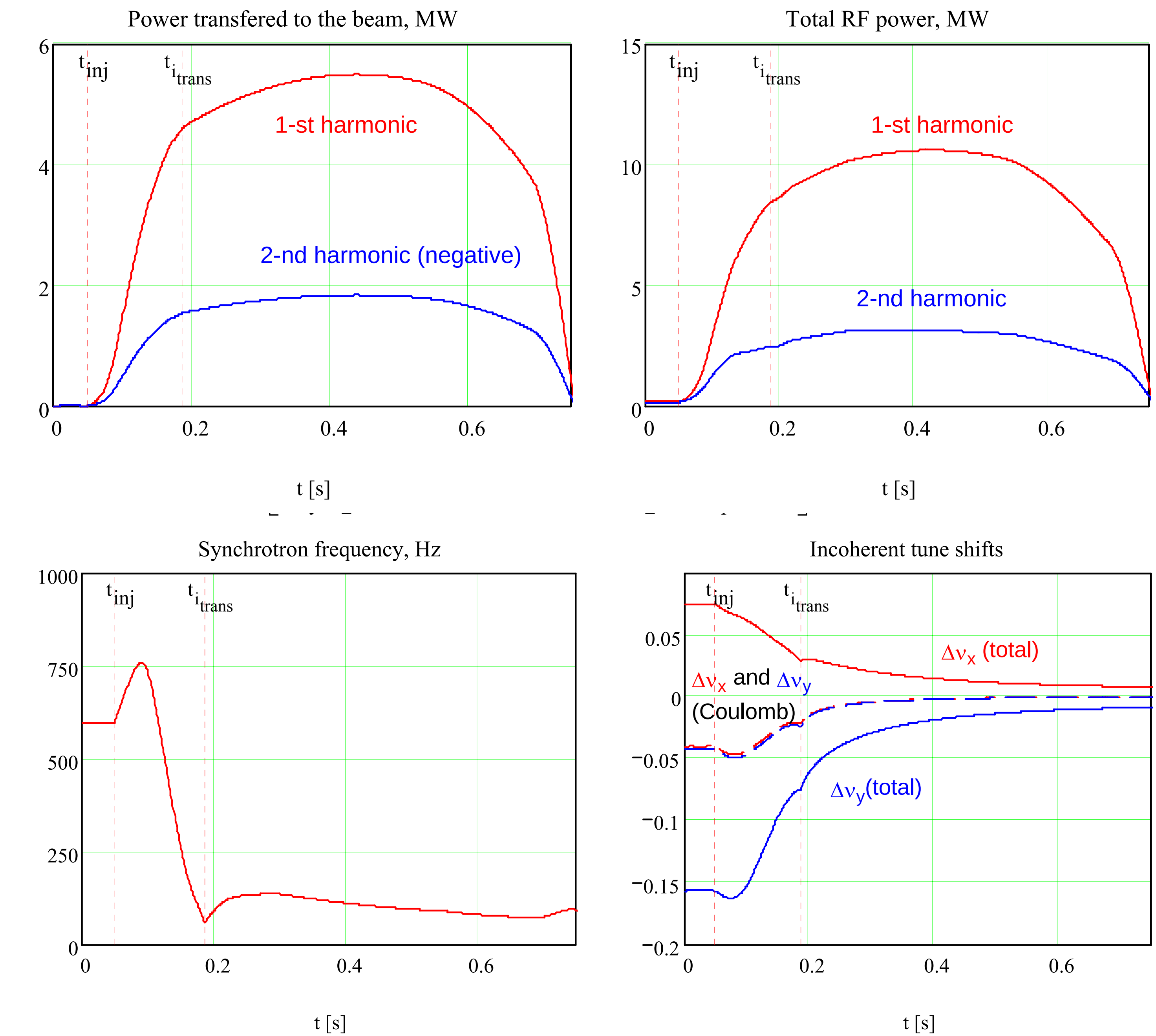


Figure 3. Dependence of RF power, maximum synchrotron frequency and incoherent tune shifts on the accelerating time.

- 2-nd harmonic voltage is phased to decelerate the beam

$$\begin{cases} V_{1acc} = V_0 \sin(\phi_0) \\ V_{2dec} = -\dfrac{1}{4} V_0 \sin(\phi_0) \end{cases}$$

  - That requires more power for beam acceleration comparing to single harmonic case
  - If we will find appropriate we can zero 2-nd harmonic in the second half of the cycle
- Coh. tune shifts are corrected by tune adjustments

RF Systems

Parameters of cavities operating at the first harmonic§

	Present	New
Harmonic number	588	
Frequency swing from injection to extraction, MHz	52.811 - 53.103	
Number of cavities	18	18
Shunt impedance per cavity, (R/Q)*Q, kΩ	500	100
Loaded Q	4000	4000
Maximum operating parameters		
RF voltage, MV	4.2	4.2
Peak RF power, MW	3.2	13
Average RF power, MW	0.8	5
Operating parameters required by presented accelerating scenario		
RF voltage, MV		3.43
Maximum RF power, MW		10.59
Maximum power transferred to the beam, MW		7.32
Maximum power lost in the cavity walls, MW		3.27
Average RF power, MW		4.1

- We keep the same number of cavities
  - available space, impedance and beam loading

§ The second harmonic RF system is used to decrease the bunching factor for MI upgrade. That reduces Coulomb tune shift and improves the beam stability.

Parameters of cavities operating at the second harmonic**

Frequency swing from injection to extraction, MHz	105.622 - 106.206
Number of cavities	5
Shunt impedance per cavity, (R/Q)*Q, kΩ	100
Loaded Q	4000
Maximum operating parameters	
RF voltage, MV	1.2
Peak RF power, MW	1.5
Average RF power, MW	0.9
Operating parameters required by presented accelerating scenario	
RF voltage, MV	1.16
Maximum RF power, MW	1.34
Maximum power transferred to the beam††, MW	-1.83
Maximum power lost in the cavity walls, MW	1.34

- High power tetrodes (EIMAC 8973 and Thales 526) with output powers and plate dissipations in excess of 1 MW are commercially available.
  - Thales TH628 diacrode is an alternative solution
- The final amplifier stage would be located in the tunnel as close as possible to a new low R/Q (25 ohm) RF cavity.

** Phase and amplitude of the 2-nd harmonic voltage are chosen to achieve flat density distribution in the bunch center and maximize the bucket size:

$$V(\phi,\phi_0) = V_0\left(\sin(\phi) - \frac{\cos(\phi_0)}{2}\sin\left(2(\phi-\phi_0)\right) - \frac{\sin(\phi_0)}{4}\cos\left(2(\phi-\phi_0)\right) - \frac{3}{4}\sin(\phi_0)\right) \quad (1)$$

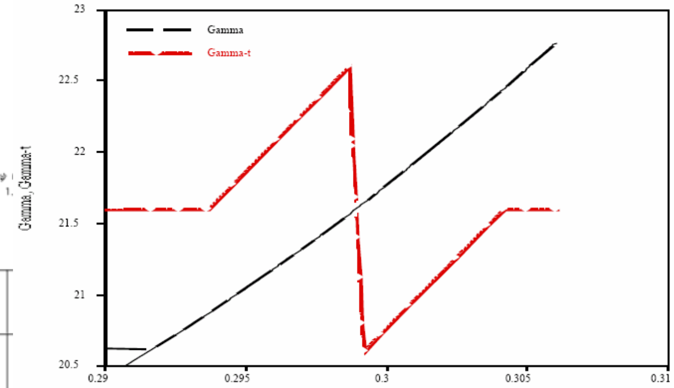
††One can see from Eq. (1) that the 2-nd harmonic is phased so that it decelerates the beam $\sim V_0 \sin(\phi/4)$; ⇒ the power transferred to the beam is negative.

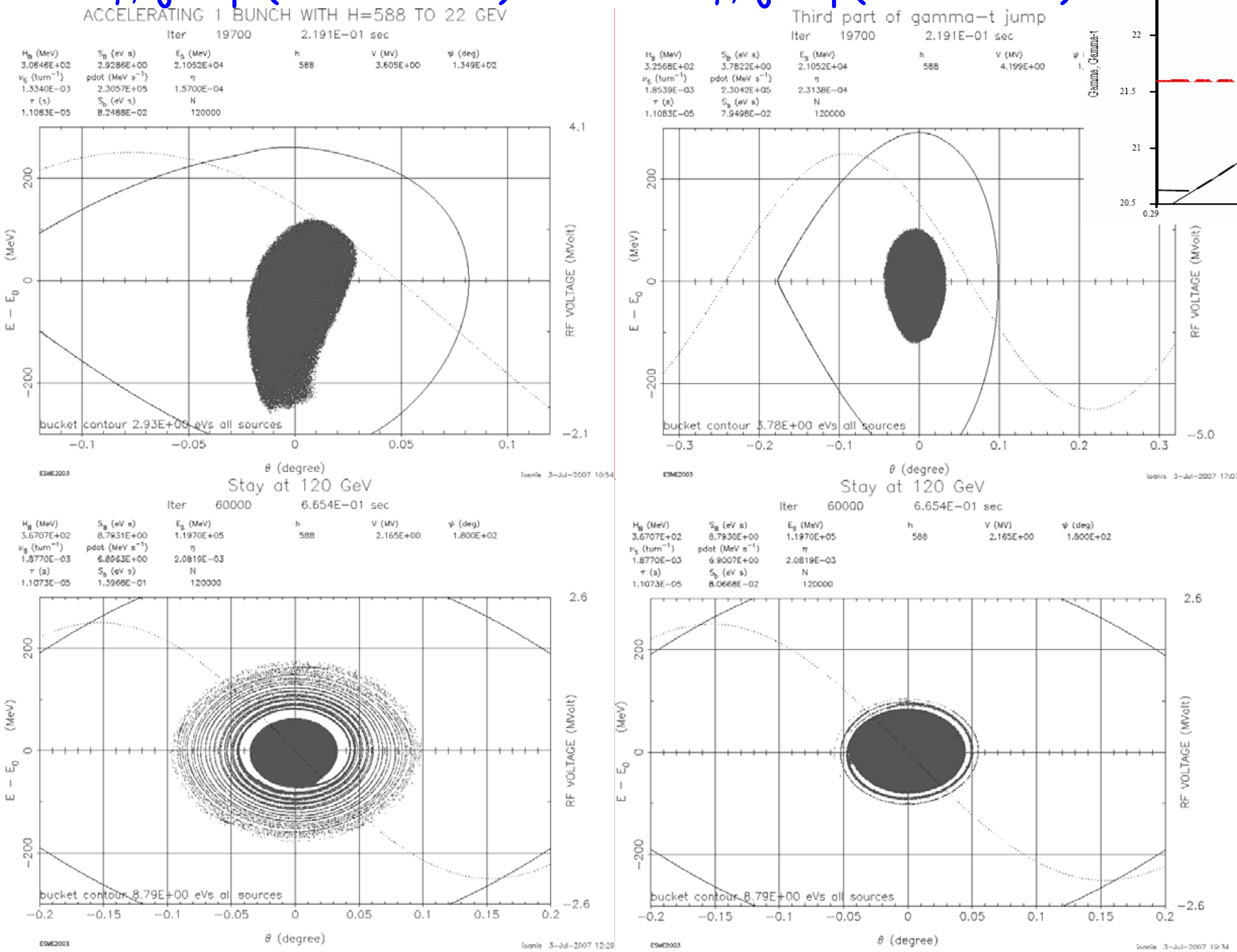
Transition Crossing

- Aggressive transition crossing
  - 8 sets of pulsed quadrupole triplets[‡‡]
    - Localized lattice perturbation in and in vicinity of dispersion free straights
  - $\Delta\gamma$ = 2 within 0.5 ms (20 times faster than at the ramp)
  - f_s=57 Hz $\Rightarrow$ 10 deg. synchrotron phase advance during transition
- Bunch is sufficiently long at transition, $\Delta\phi_{95\%} = \pm 45$deg
  - Longitudinal space charge field is almost 2 orders of magnitude smaller than focusing RF field
    $\Rightarrow$ small distortion of the potential well

[‡‡] W. Chou, et. al., "Design of a gamma-t-Jump System for Fermilab Main Injector", PAC-1997, Vancouver, Canada

No γ_t-jump ($\Delta\varepsilon/\varepsilon$ = 80%)   With γ_t-jump($\Delta\varepsilon/\varepsilon$ = 8%)





after transition,

120 GeV

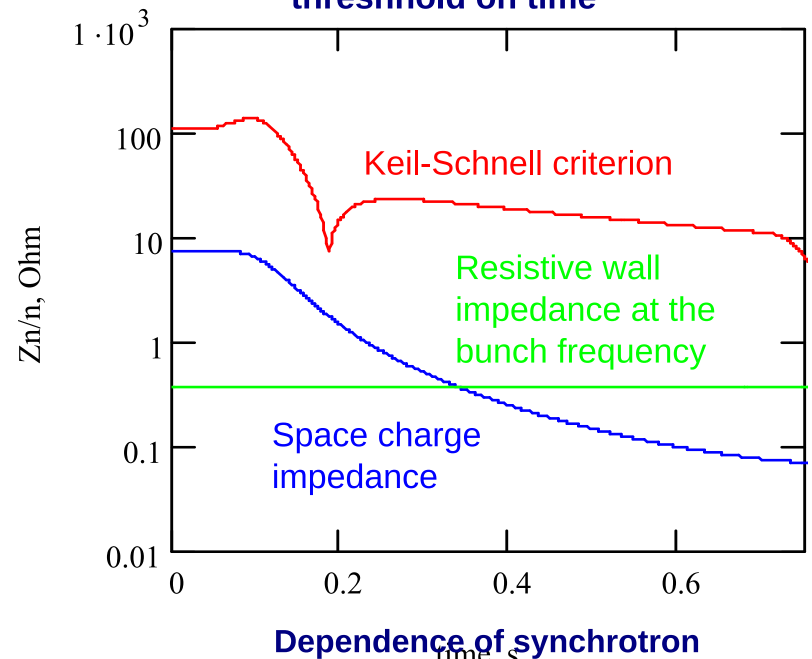
Results of ESME simulations of γ_t-jump (the second harmonic voltage is zero); top right – dependence of γ on time, center - phase space right after transition with (right) and without (left) a γ_t-jump, bottom - phase space at 120 GeV with (right) and without (left) a γ_t-jump.

Instabilities

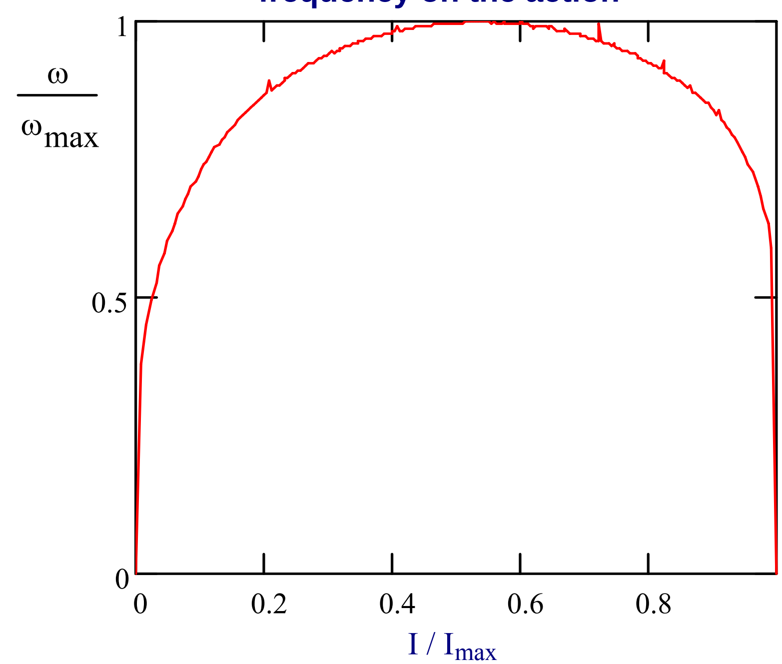
Longitudinal instabilities

- Longitudinal stability is achieved by use of
  - large longitudinal emittance
  - γ_t-jump
  - large spread of synchrotron tunes
- Micro-wave instability
  - Above γ_t it is driven by the beam space charge. There is sufficiently large stability margin even at the transition (factor of ~5)
    - Note that contributions to Z_n/n from vacuum chamber interruptions (BPMs, bellows etc.) are small ($\le 1\ \Omega$) and can be neglected
- Multibunch instabilities have to be stabilized by longitudinal damper

Dependence of stability threshhold on time

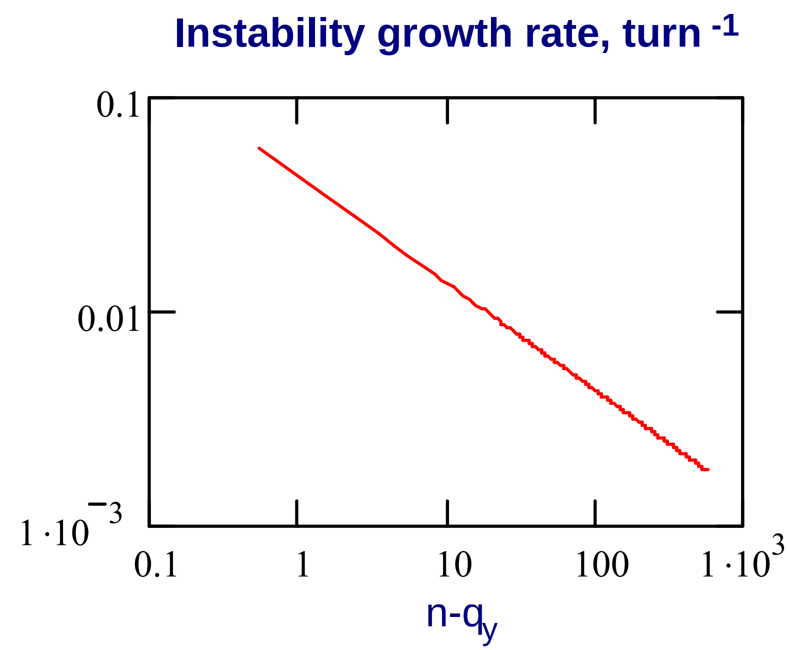


Dependence of synchrotron frequency on the action



Transverse instabilities

- At low frequencies f≤~0.5 GHz $Z_\perp$ will be dominated by wall resistivity
  - Presently, there is large contribution coming from laminated Lambertson septum magnets. In the future they have to be shielded similar to the Tevatron injection Lambertson magnet.
- Growth time of multibunch instability is about 12 turns
  - It will be stabilized by the bunch-by-bunch transverse damper. Similar to the present one but with more powerful amplifier
  - Power is set by initial injection errors, ~0.5 mm
- Single bunch instabilities will be stabilized by large chromaticity ($|\xi_{x,y}|$~20) similar to Tevatron and Recycler



Instability growth rate for vertical multibunch instability at zero chromaticity

Multipactoring and *ep*-instabilities

- Simulations show that with high probability it will be a problem
  - But there is large uncertainty in secondary emission yield
- If a full intensity electron cloud is generated the beam will be unstable and large beam loss will occur
- Nevertheless, experience with SLAC and KEK B-factories proves that the vacuum chamber conditioning by the beam is very helpful and allows one to avoid severe problems
  - Both B-factories are working with quite similar beam current, beam energy and bunch spacing
  - MI injector does not have SR. That should be helpful
- In early 2006, Fermilab began making electron cloud measurements in response to the 2005 simulations.
  - An electron cloud has been directly observed in the MI, but the correspondence to simulation is not exact.
  - There is an ongoing program of iterated simulation and experiments to explore the electron cloud

- Mitigation
  - Conditioning
    - Studies at SLAC and KEK have indicated that the secondary emission yield of all materials (including stainless steel) can be substantially reduced by bombardment of the electron cloud itself. If this is so, the machine will only require a "burn-in" period of the relevant exposed surfaces.
  - The vacuum system may be modified to ensure high vacuum and to increase the number of isolated sectors.
  - Bunch spacing (Micro-batches of 5-10 bunches)
    - It can be created by chopping linac beam at small energy.
- Worst case mitigation
  - TiN coating
  - RF system at other harmonic number
  - Installation of clearing electrodes

Beam loss

- Small emittance of linac beam allows one to form the well formed beam. That results in very small losses
  - at injection and extraction
  - during acceleration
- Particle loss due to non-linear dynamics is expected to be very small because of small Coulomb tune shift
- Instabilities
  - ep-instability is the major concern and needs to be stabilized
  - Other instabilities are not expected to be a problem
- Low MI vacuum (~10^{-7} Torr) results in significant beam loss
  - Particle loss ~$3\cdot10^{-4}$ per cycle
  - Power loss ~150 W
- IBS and Touschek loss is estimated to be below 10^{-5} and can be neglected
- Beam collimation system installed during this shutdown is capable to intercept 1.5 kW of beam loss
  - If it will be necessary 10-20 kW system still looks as a reliable choice

Conclusions

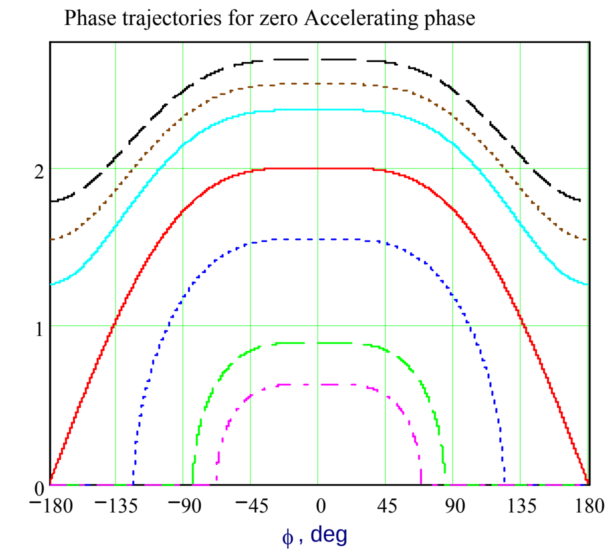
- There are no principle physics or technical limitations on future machine operation
  - Multipactoring of electrons and related to it *ep*-instability are the major points of concern
- Keeping machine operating reliably at full power of 2.3 MW will be a challenging problem
  - Machine protection and minimization of beam loss have to be major points to be addressed at next stages of design work

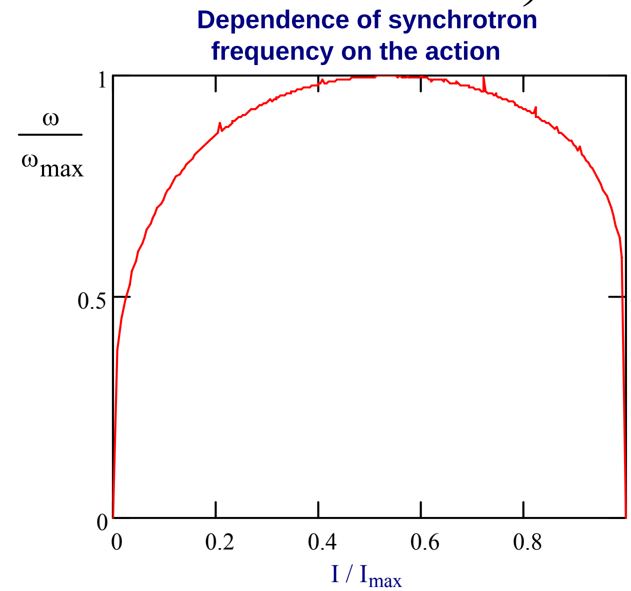
Backup slides

Two Harmonic Acceleration with flat bottom of RF bucket

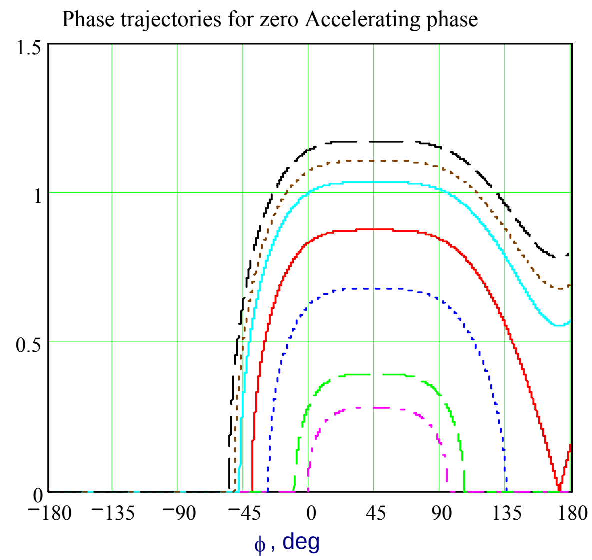
$$V(\phi,\phi_0) = V_0\left(\sin(\phi) - \frac{\cos(\phi_0)}{2}\sin\left(2(\phi-\phi_0)\right) - \frac{\sin(\phi_0)}{4}\cos\left(2(\phi-\phi_0)\right) - \frac{3}{4}\sin(\phi_0)\right)$$

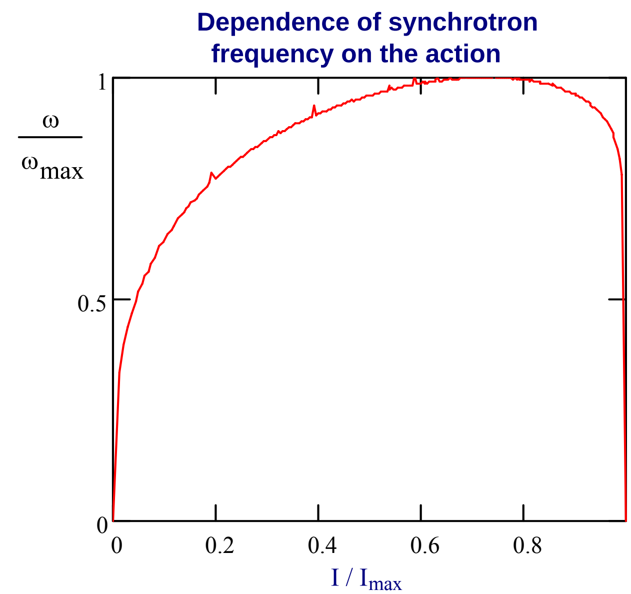
$\phi_0 = 0$





$\phi_0 = 45$ deg

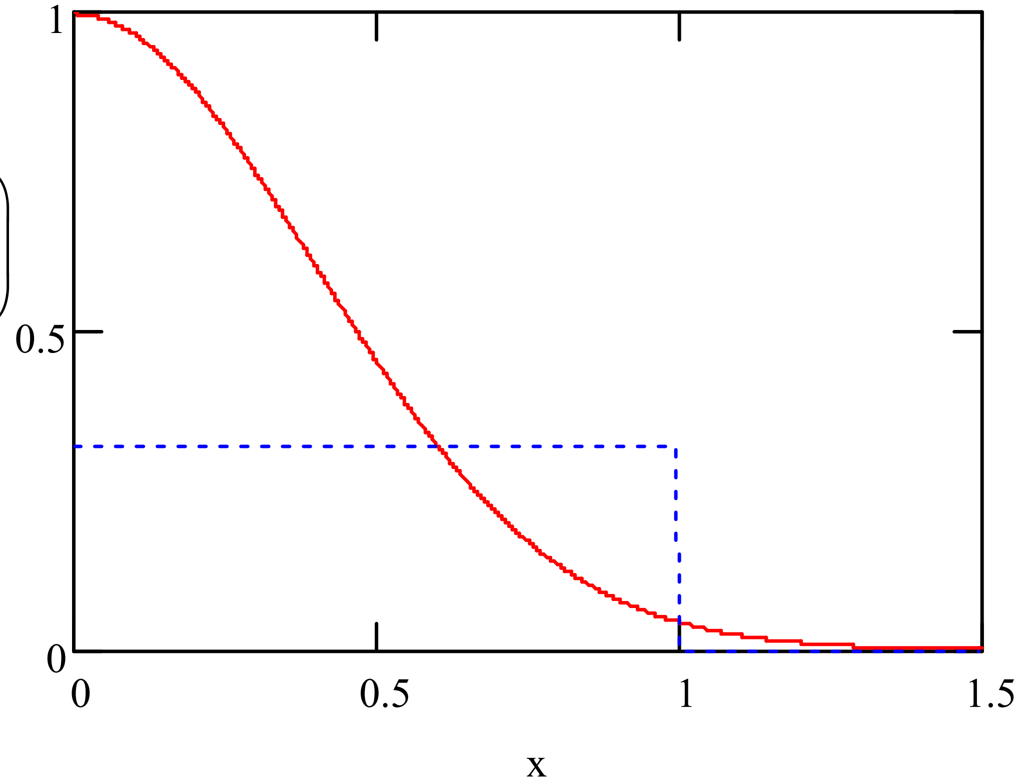




Tune shifts

$$\left(\frac{1}{\sqrt{2\cdot\pi}\cdot 2.5^{-1}}\right)^2\cdot\exp\left(-\frac{1}{2}\cdot\frac{x^2}{2.5^{-2}}\right)$$

$$\frac{1}{\pi}\cdot(x<1)$$



- For KV- distribution

$$\Delta\nu_x = \frac{r_p{}^2 N_p}{\pi\beta^2\gamma^3} B \left\langle \frac{\beta_x}{a_x\left(a_x + a_y\right)} \right\rangle_s \quad , \quad x \leftrightarrow y$$

B=2.2 – bunching factor

- For Gaussian distribution with $2.5\sigma_{x,y} = a_{x,y}$ we have tune shift increased by $2.5^2/2 \approx 3.125$ times larger