Discussion on How to Get to 4 MW

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Outline

- Objectives for Project X upgrade
- Requirements to the Compressor ring
- Upgrade scenarios
- Conclusions

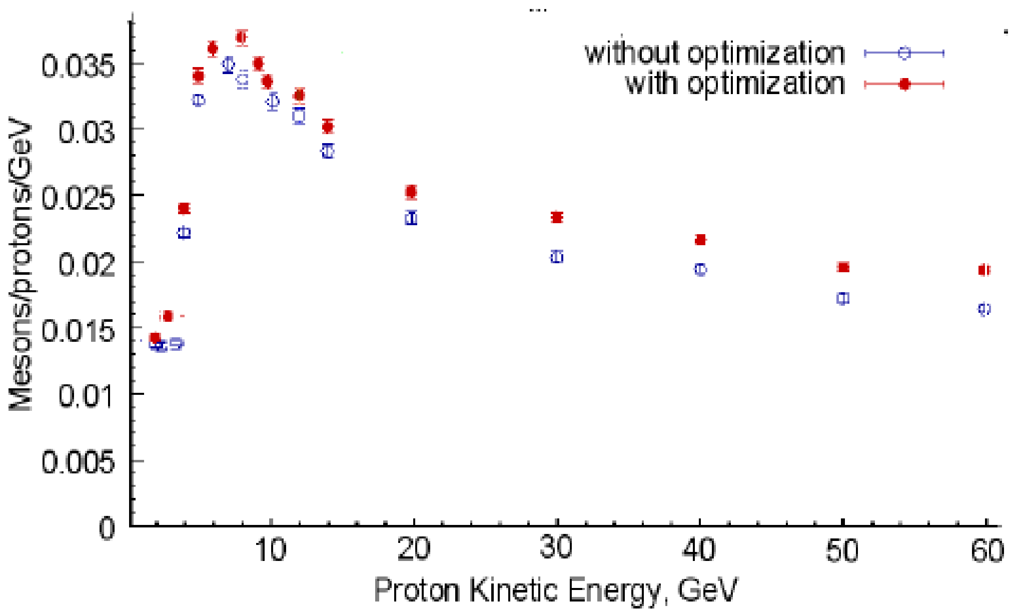
Objectives for Project X Upgrade

- Two future projects could profit from Project X upgrade
  - Muon collider (MC)
    - 4 MW, 15 Hz (single bunch, $2.1\cdot10^{14}$), 6 to 15 GeV
    - Bunch parameters on target: rms length - 2-3 ns , rms $\perp$ size ~2 mm
  - Neutrino factory
    - same requirements for power and bunch parameters but can operate at an order of magnitude higher bunch frequency, consequently, an order of magnitude smaller bunch intensity $\Rightarrow$ Easier to achieve
- MC requirements are used in further consideration
- We do not need just 4 MW we need 4 MW which can be used by MC

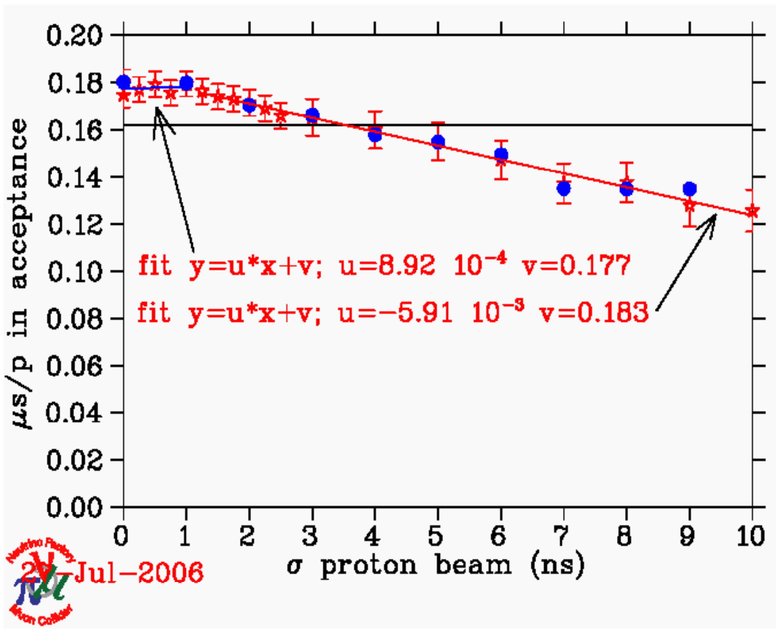
Objectives for Project X Upgrade

- Maximum muon yield per unit power is in vicinity of 8 GeV
- Efficiency of muon production decreases if bunch length is above ~2 ns

Muon yield on the beam energy for MC



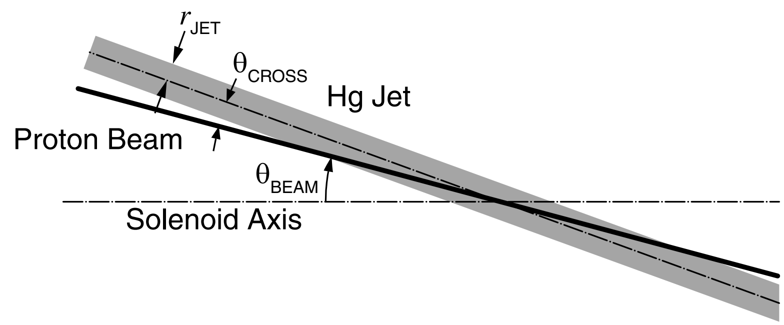
Muon yield on the bunch length for MC



Project X Beam Power Limitations for MC Compressor Ring

- Betatron tune shift due to beam space charge, $\delta\nu_{SC}$
  - An increase of beam emittance is limited by focusing on the target
    - $\sigma \approx 2$ mm, $\beta \approx 0.2$ m $\Rightarrow \varepsilon_{rms} \leq 20$ mm mrad
    - weak dependence on beam energy
  - Results in beam loss at the end of compression
- Longitudinal microwave instability
  - develops at the end of injection
  - is extremely fast
  - results in an increase of initial longitudinal emittance and, consequently, bunch lengthening

X. Ding, UCLA



r_{jet}=5mm, θ_{beam}=80 mrad, θ_{cross}=28 mrad

$L_{interact} = r_{jet} / \theta_{cross}$ = 178 mm

Betatron Tune Shift due to Beam Space Charge

- For practical parameters of the compressor ring factor $F = F(\beta_x, \beta_y, \varepsilon_x, \varepsilon_y, D)$ has comparatively weak dependence on optics
  - Increasing D in arcs can decrease F by ~2 times

$$\delta\nu_{SC} = \frac{r_p N_p}{4\pi\beta^2\gamma^3\varepsilon}\frac{C}{\sqrt{2\pi}\sigma_s}F$$

- Gaussian beam is implied

- Assuming that C $\propto$ E, it results in a cubic dependence of $\delta\nu_{SC}$ on the beam energy

$$\delta\nu_{SC} \propto P / \gamma^3$$

$$\delta\nu_{SC} = 0.065\left(\frac{P}{1\mathrm{MW}}\right)\left(\frac{9.52^3(9.52-1)}{\beta^2\gamma^3(\gamma-1)}\right)\left(\frac{\mathrm{C}}{263\mathrm{m}}\right)\left(\frac{60\,\mathrm{cm}}{\sigma_s}\right)\left(\frac{f_{rep}}{15\,\mathrm{Hz}}\right)\left(\frac{20\,\mathrm{mm\,mrad}}{\varepsilon_{rms}}\right)F$$

- For 4 MW at 8 GeV $\delta\nu_{SC}$ ~ 0.15 (F=0.5, $\varepsilon_{n95\%}$=1150 mm mrad (ε_{rms}=20 mm mrad))

Longitudinal Microwave Instability

- Stability boundary

$$A(y)=\left(i\int_{\delta\to+0}\frac{d\psi_0/dz}{y+z-i\delta\,\mathrm{sign}(n)}dz\right)^{-1},\quad y=\frac{\delta\omega}{n\omega_0\eta\sigma_p}$$

where

$$A\equiv\frac{eI_0}{2\pi\,cp_0\,\beta\eta\sigma_p{}^2}\left(\frac{Z_n}{n}\right)$$

$\Rightarrow$ stability condition can be approximated as

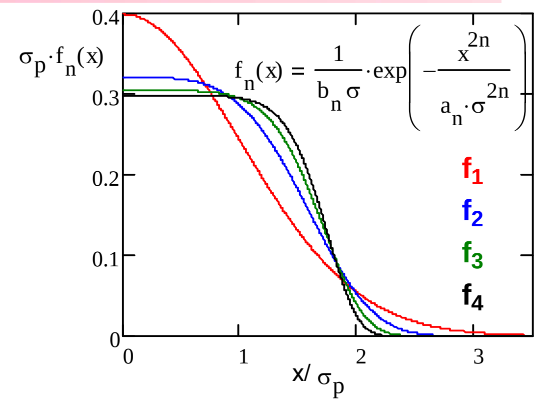
$$\frac{eI_0}{2\pi cp_0\beta\eta\sigma_p{}^2}\left|\frac{Z_n}{n}\right|\le 2$$

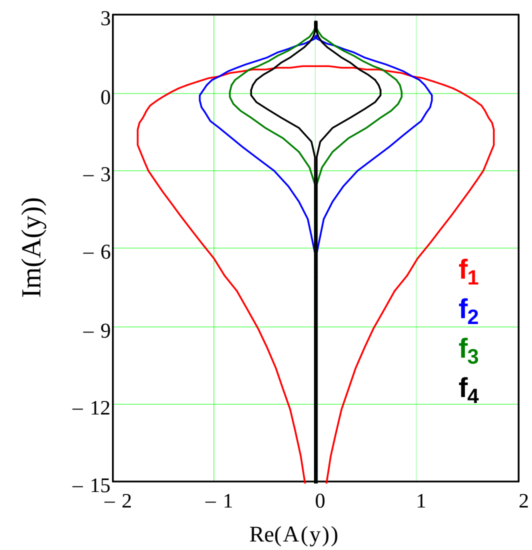
- For E≤16 GeV longitudinal impedance is dominated by the space charge impedance

Re(Z_n/n) << Im(Z_n/n) = $Z_0\ln(a/1.06\sigma)/\beta\gamma^2$

assuming phase space conservation during bunch rotation

$$\Rightarrow P_{\max}\approx 0.72\,\mathrm{MW}\left(\frac{\gamma^3(\gamma-1)}{9.52^3(9.53-1)}\right)\left(\frac{f_{rep}}{15\,\mathrm{Hz}}\right)\left(\frac{(L_b\sigma_p)_{final}}{60\,\mathrm{cm}\times1\%}\right)^2\left(\frac{10\,\mathrm{m}}{L_{init}}\right)\left(\frac{\eta}{0.0259}\right)$$





Project X

Longitudinal Microwave Instability Mitigation

- Increase slip factor
  - It implies operation well above transition
  - Slip factor increase is limited by the beam dispersive size
    - $\sigma_p \approx a_{max} / D$, $\alpha \approx \eta \approx D / R_0$,
      $\Rightarrow \sigma_p \eta \sim a_{max}/R_0$
  - In practical terms $P_{max} \propto \gamma^4 a_{max} / (R_0 L_{init})$

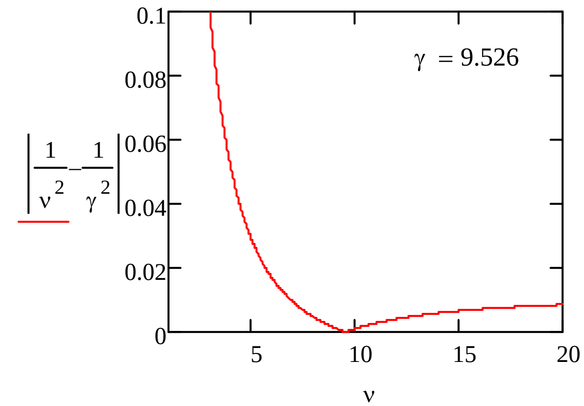
$\Rightarrow$ Reduce

Initial bunch length & Machine circumference

Increase

Energy & Horizontal aperture in dipoles

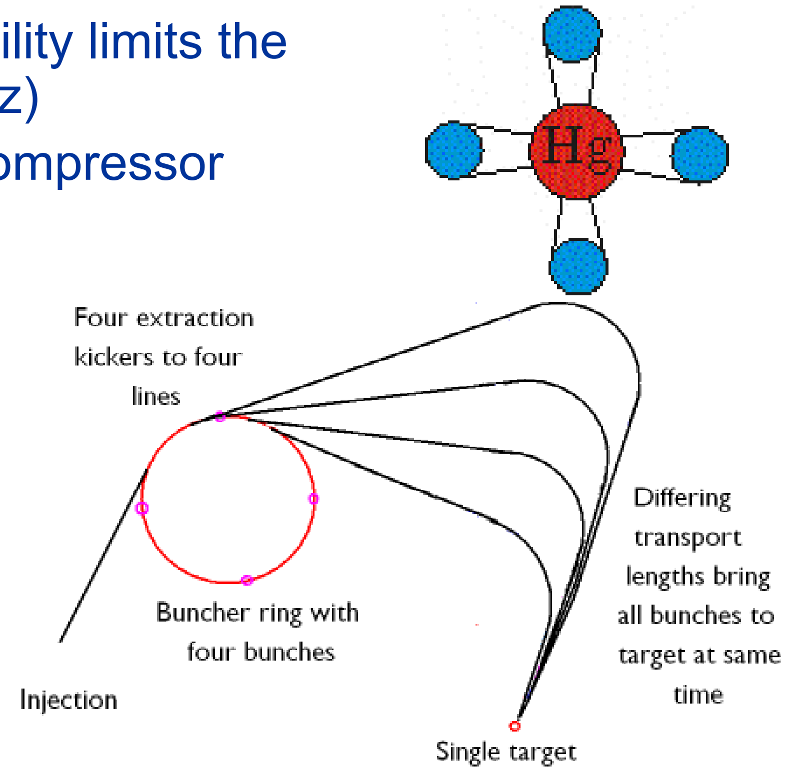
- Large slip-factor requires large RF voltage
  - Improves ratio of SC longitudinal field to the RF field
  - Small number of turns for bunch rotation
- There is no acceleration in the Compressor ring
  $\Rightarrow$ High conductivity vacuum chamber with good electrodynamics
  $\Rightarrow$ SC makes major contribution to the longitudinal impedance



Dependence of slip-factor on tune in the smooth focusing approximation for 8 GeV beam

Options for Compressor Ring

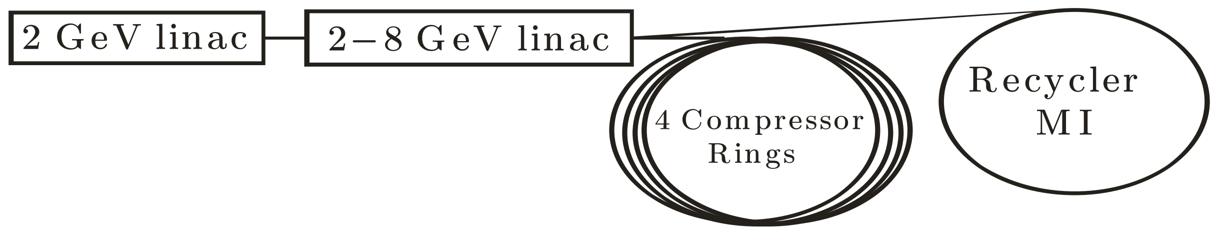
- At 8 GeV the longitudinal microwave instability limits the beam power to ~1 MW (single bunch, 15 Hz)
- There are two possible options for 4 MW compressor ring for muon collider
  - Increase energy to ≥12 GeV and use a single bunch
  - Stay at 8 GeV and use a multi-bunch solution (Ankenbrandt, Palmer)
    - Four bunches should be sufficient
    - Four compressor rings may present a better choice
      - $5.2 \cdot 10^{13}$ p per ring



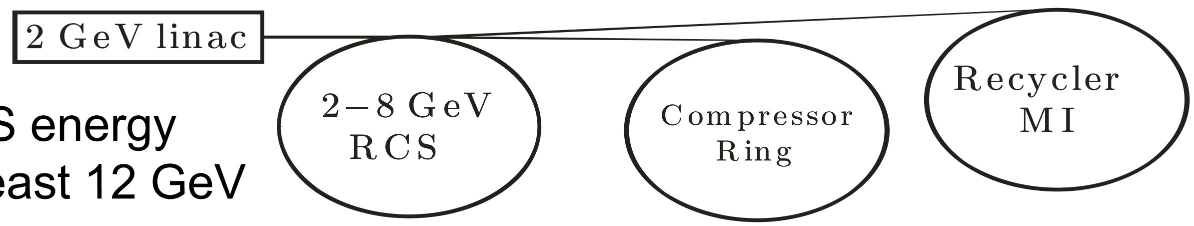
- Additional ring/rings may be required to mitigate RF beam loading
  - Accumulator + Buncher (as in CERN's neutrino factory proposal)

Options for Muon Collider Proton Driver

- Option 1 (4 MW)



- Option 2 (1 MW)
- Option 3 (4 MW)
  - Same as 2 but RCS energy is increased to at least 12 GeV

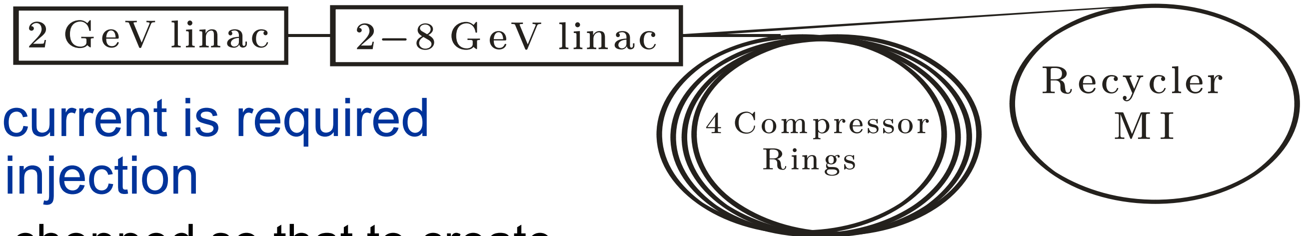


- All options require the 2 GeV linac to support ≥20 mA beam current

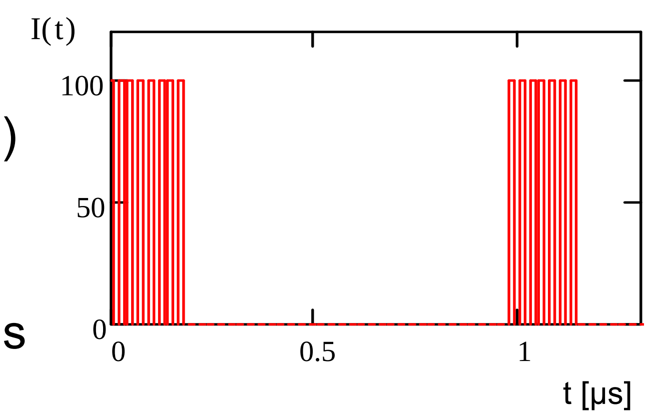
$\Rightarrow$ CW linac $\rightarrow$ Pulsed linac

That discontinues 2 GeV physics program

Option 1 (4 MW) Pulsed Linac



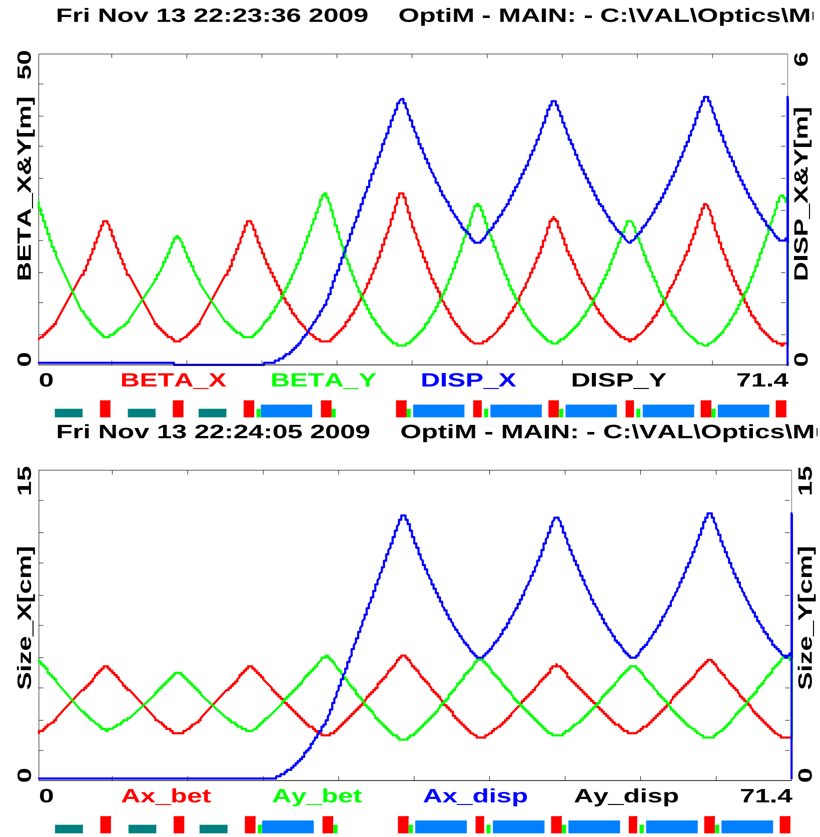
- Large linac beam current is required to ease the beam injection
  - Linac current is chopped so that to create a series of short bunches for injection
    - It increases the peak current but
    - Prevents momentum blowup by microwave instability during and immediately after injection
      - Peak current – 100 mA
      - Average current – 20 mA
      - Pulse duration – 1.67 ms (1740 turns)
      - Repetition rate – 15 Hz
- Linac current is RF split into 4 beams
  - Simultaneous injection into 4 compressor rings



Option 1 (4 MW) Compressor ring

- Objectives for optics choice
  - Large momentum compaction
    - Small transition energy
  - Small circumference

Ring parameter	
Circumference. m	285 m
Transition energy, GeV	2.44
$\nu_x \approx \nu_y$	5.6
Dipoles	2 T $\times$ 4.66 m
Quads	8 T/m $\times$ 0.8 m
accept./ε_{rms} [mm mrad]	130/8.8
$\delta\nu_{SC}$@extract. ($\delta\nu_x/\delta\nu_y$)	0.07/0.1

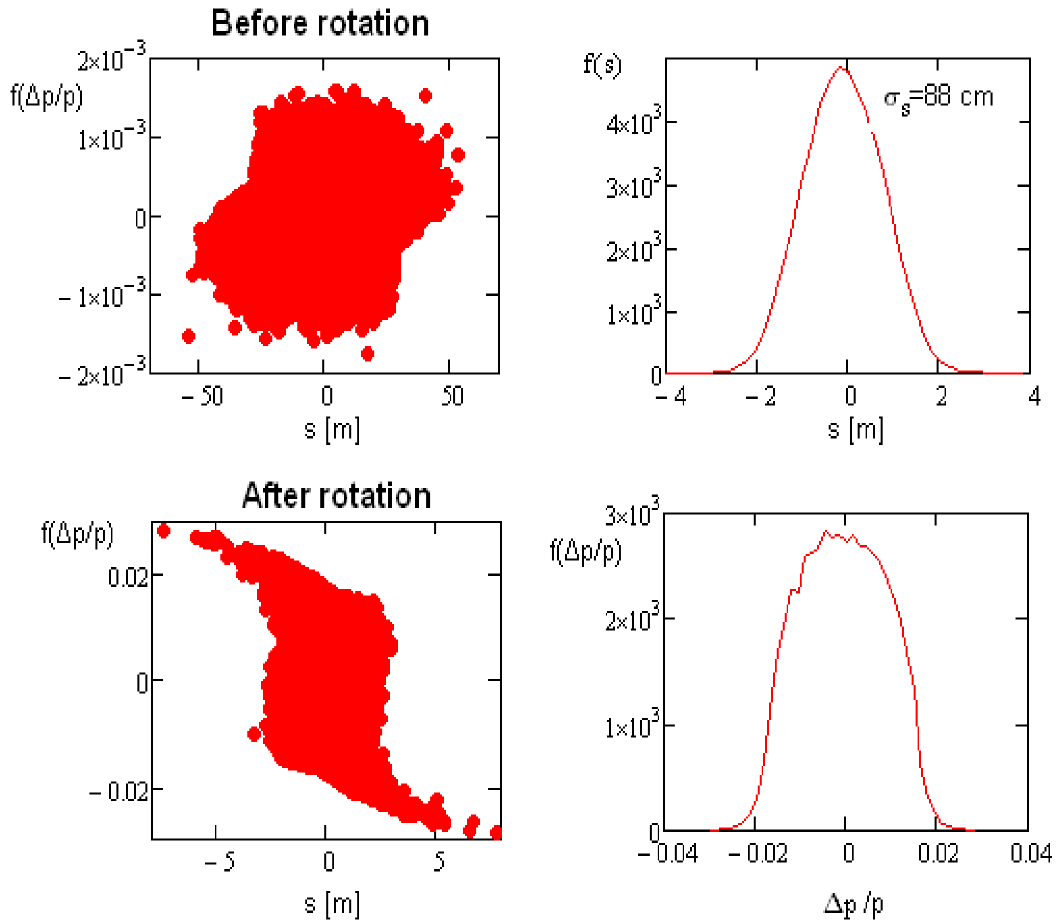


Twiss param.&Beam envelopes for quarter of the ring; ε=130 mm mrad, $\Delta p/p = \pm 0.025$

Option 1 (4 MW) Bunch Compression for the Case of 4 Compressor Rings

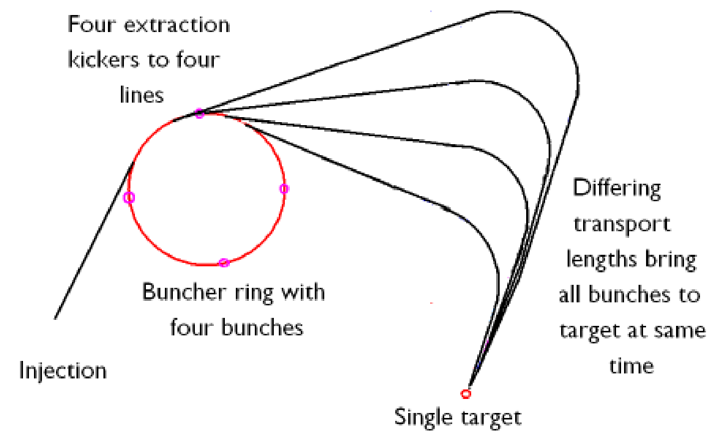
- σ_p at injection is chosen so that the beam current is ~1/3 of the instability threshold
  - Optimistically we can expect √3 times smaller bunch length after bunch rotation
    - It does not change other parameters

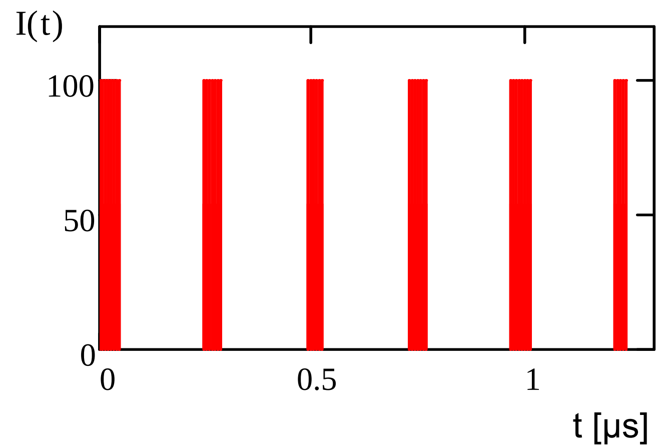
Ring parameter	
f_{RF} (h=1), MHz	1.04
V_{RF} @ injection, kV	6.6
V_{RF} @ rotation, MV	2.5
σ_p at injection (linac beam)	$4.2 \cdot 10^{-4}$
Duration of rotation., turn	146
Z_n/n (SC/stab.boundary), Ω	10/30



Option 1 (4 MW) Bunch compression for the Case of One Compressor Ring

- It is the same ring as for the option 1
  - But 4 bunches are simultaneously injected
  - Same injection time
  - Same linac duty factor
- Each bunch has the same intensity but is 4 times shorter
- Total injection loss is approximately the same as for the four rings
- 4 times larger total (43 A) and peak beam currents (174 A)
  - 4 times larger beam induced voltage on RF system

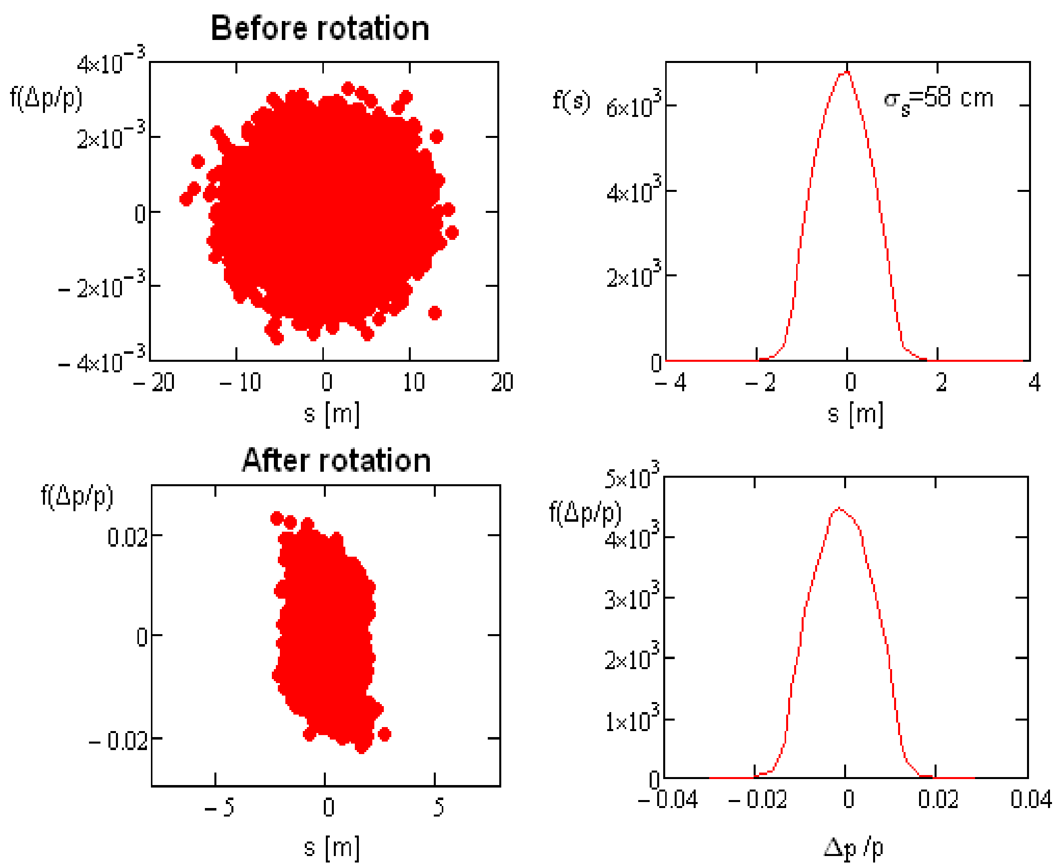




Option 1 (4 MW) Bunch compression for Case of One Compressor Ring

- Compression is better due to larger σ_p (smaller initial bunch length)
- Voltage induced by beam on RF system can be serious limitation
  - It requires detailed insight
- It is all about RF and bunching
  - Cost of magnets and kickers is a secondary issue

Ring parameter	
f_{RF} (h=4), MHz	4.16
V_{RF} @ injection, kV	105
V_{RF} @ rotation, MV	5
σ_p at injection (linac beam)	$8.4 \cdot 10^{-4}$
Duration of rotation., turn	51
Z_n/n (SC/stab. boundary), Ω	10/30



Proton Driver for MC Development Based on 8 GeV RCS (no upgrade)

- ***What RCS can do?***
  - ~230 kW at 10 Hz with 2 turn injection from RCS to the compressor ring
    - Compressor ring length ~1/2 of RCS
    - 2 trains of 10 bunches in RCS
    - 3 times more protons per bunch than in RCS proposal ($\delta\nu_{SC}\approx0.2$)
  - 2 ns single bunch as required for muon collider
    - But 10 times smaller bunch intensity than 4 MW 15 Hz proton driver
  - It can be good a test MC test stand
  - Full 340 kW power of RCS can be used with 3 turn injection
    - Requires the circumference of Compressor Ring to be ~185 m
      $\Rightarrow$ SC dipoles and quads

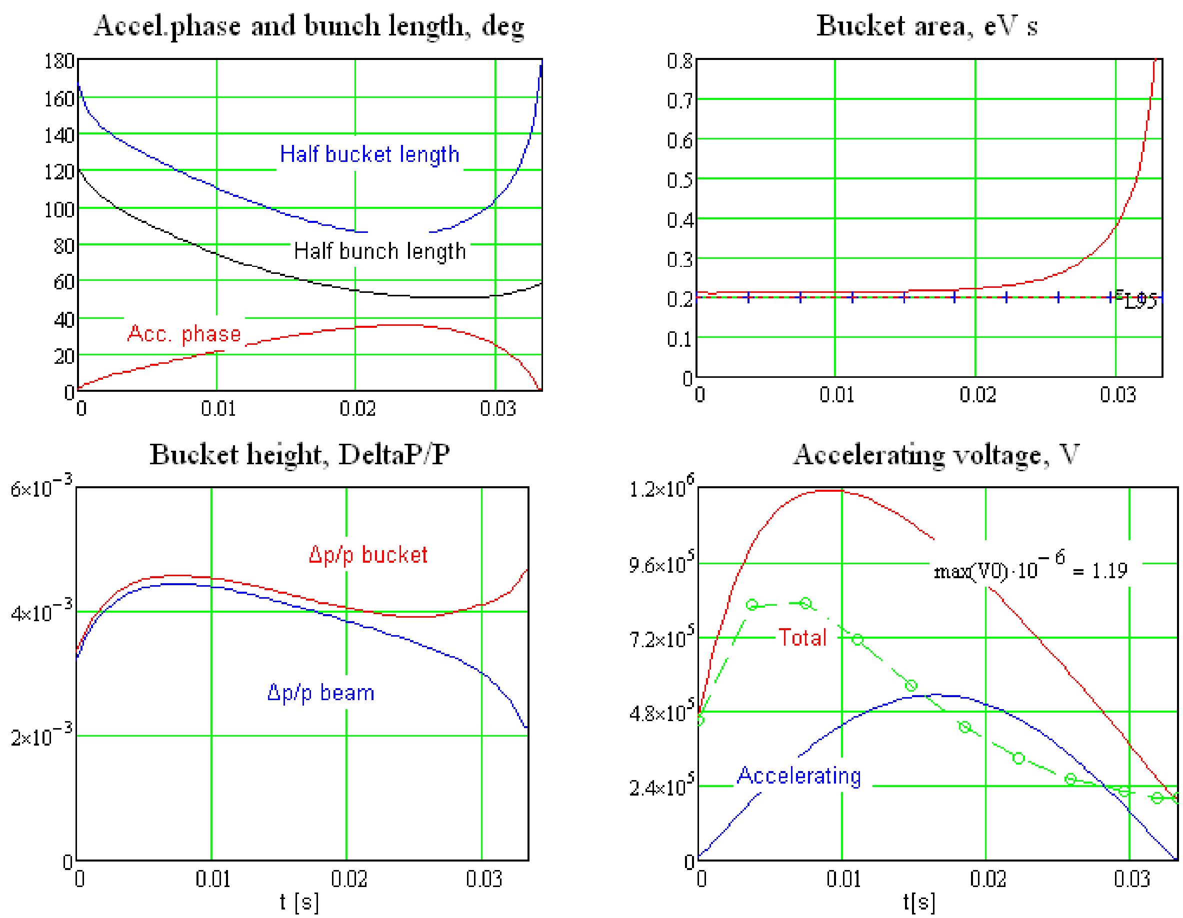
Option 2 (1 MW) 8 GeV RCS as Proton Driver for MC

- We imply that Compressor Ring is 3 times shorter than RCS
  - SC magnets
  - 3 turn injection
- What needs to be changed
  - Bunch structure
    - 3 trains of 11 bunches
    - Instead of 88 bunches
  - Acceptance increase to mitigate SC
  - Rep. rate 10 $\rightarrow$15 Hz
  - RF system

	RCS	RCS upgrade
Power	340 kW	1 MW
Particles/bunch	$3\cdot10^{11}$	$16\cdot10^{11}$
$\varepsilon_{95\%n}$, mm mrad	22	80
$\delta\nu_{SC}$ (KV-distr.)	0.07	0.1
Long. emit. , eV s	0.35	0.2

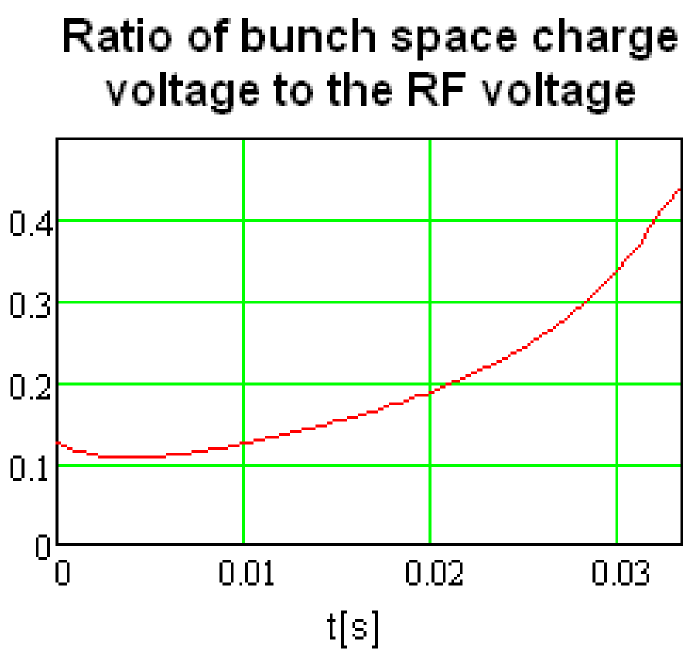
Option 2 (1 MW) Beam Acceleration

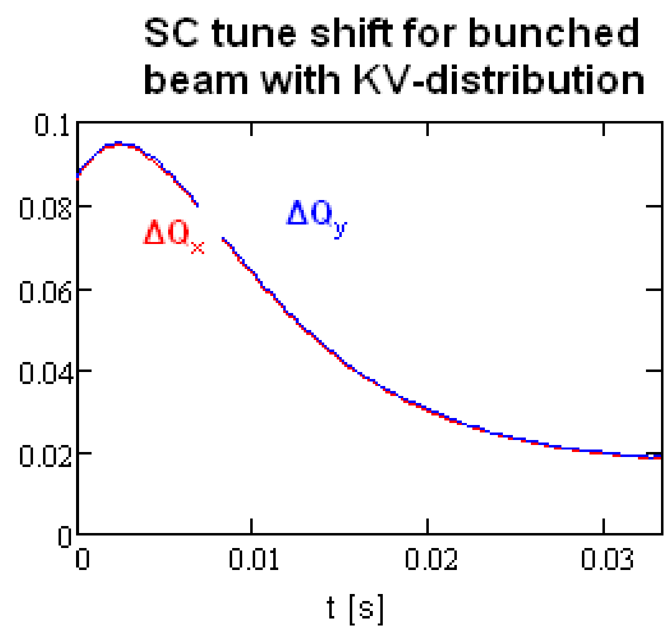
- Challenges for the RF system
  - 2 times increase of average beam current
  - 5 times increase of the peak current (aver. over bunch)
  - ⇒ Larger beam loading
- Bunches are short at the cycle end
  - Debunching in Compressor Ring



Option 2 (1 MW)
Space Charge Effects in RCS

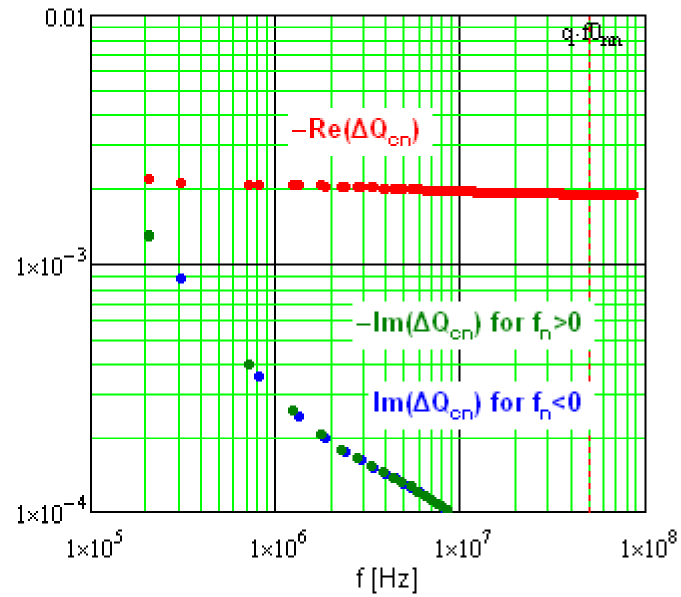
- Slip factor reduction with acceleration results in an increased effect of beam space charge on longitudinal motion
- Transverse space charge effects are controlled by aperture/acceptance increase





Option 2 (1 MW) RCS Vacuum chamber

- Vacuum chamber
  - R: 22→ 35 mm mrad
  - 0.7 mm stainless steel → 0.7 mm inconel
- Heating: 10 → 50 W/m
  - Forced air-cooling
- Instability growth rate stays the same:
  ~0.08 turn^{-1} for lowest betatron sideband



Option 3
4 MW RCS

- Energy increase results in
  - Higher transition energy
    - ⇒ Higher periodicity
      - ⇒ Longer ring
        - ⇒ Cannot use RSC infrastructure
- Transverse space charge can be addressed by acceptance increase
- Transition energy has to be high enough to avoid space charge effects on the maximum energy
- This choice looks much more difficult than Proton Driver based on 8 GeV pulsed SC linac with Compressor Ring

Conclusions

- Upgrade of IC-2 complex to the MC proton driver
  - requires large increase of linac beam current
    - Incompatible with CW operation
      - Required ~10 times difference in coupling coefficients between pulsed and CW operation looks impractical for so high beam power

  ⇒ discontinuing of 2 GeV experimental program or building new 2 GeV frontend
- 4 MW proton driver based on 8 GeV SC linac looks preferable relative to the RCS based option
- 1 MW proton driver can be done with RCS but will require replacement of vacuum chamber and all magnets of the ring
  - Building such magnets and vacuum chamber from the beginning is possible
    - It will result in an increase of the contraction cost and operational cost

Conclusions

- To make a logical conclusion on IC-2 configuration we need to have answers on the following questions:
  - When MC can be build?
  - Is 4 MW a real requirement for power of MC Proton Driver?
  - How long 2 MW neutrino program will continue?
  - **How important is the cost reduction of IC-2 now versus possible future savings for MC?**
    - Note that any choice for 2-to-8 GeV acceleration in IC-2 is good enough for MC test stand
- And finally
  - Is it appropriate in addition to the decoupling to ILC to affirm the decoupling of IC-2 to MC?

Backup Viewgraphs

Criterion of Longitudinal Beam Stability

- For continuous beam
  - Equation of motion

$$\frac{\partial \tilde f}{\partial t} + \delta\omega \frac{\partial \tilde f}{\partial \theta} + eE\frac{\partial f_0}{\partial p} = 0 \quad \xrightarrow{\tilde f \propto \tilde f_n \exp(i(\omega - n\theta))} \quad i(\omega + n\eta\omega_0 x)\tilde f_n + \frac{eE_n}{p_0}\frac{\partial f_0}{\partial x} = 0$$

$$x = \frac{\Delta p}{p_0}, \qquad \delta\omega \equiv \omega - \omega_0 = \left(\frac{d\omega}{dx}x\right) = -\eta\omega_0 x, \qquad \eta = \alpha - \frac{1}{\gamma^2}.$$

$$E_n = \frac{Z_n}{2\pi R_0} I_n = \frac{Z_n}{2\pi R_0} I_0 \int \tilde f_n dx, \qquad \int f_0 dx = 1 \quad .$$

  - It results in the dispersion equation

$$\left(\varepsilon_n(y) \equiv 1 + \frac{eI_0}{2\pi i c p_0 \beta\eta\sigma_p{}^2}\left(\frac{Z_n}{n}\right)\int_{\delta\to+0} \frac{d\psi_0/dz}{y + z - i\delta\,\mathrm{sign}(n)}dz\right) = 0, \quad y = \frac{\delta\omega}{n\omega_0\eta\sigma_p}, \quad z = \frac{x}{\sigma_p}$$

Where we normalized the distribution function width to 1

$$f_0(x) = \frac{1}{\sigma_p}\psi_0\left(\frac{x}{\sigma_p}\right), \quad \sigma_p{}^2 = \int x^2 f_0(x)dx \text{ so that } \int \psi_0(x)dx = 1 \quad . \quad \int x^2\psi_0(x)dx = 1$$

- At the stability boundary $\mathrm{Im}(\delta\omega) = 0$ or $\mathrm{Im}(y) = 0$
- Thus, the stability boundary is characterized by the distribution function shape and one parameter

Proton bunch compression strategies, Valeri Lebedev, Fermilab; WAHIPA 09, Fermilab; Oct. 19-21, 2009

Stability Criterion and Growth Rate

- Finally, stability boundary is

$$A(y)=\left(i\int_{\delta\to+0}\frac{d\psi_0/dz}{y+z-i\delta\,\mathrm{sign}(n)}dz\right)^{-1},\quad y=\frac{\delta\omega}{n\omega_0\eta\sigma_p}$$

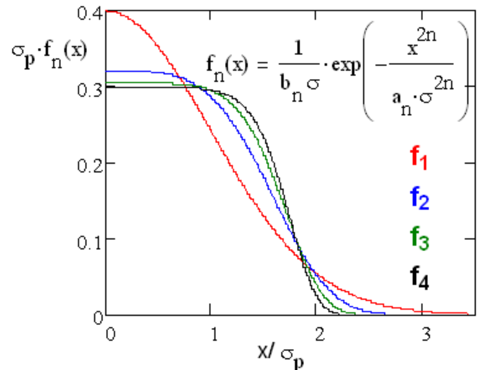
  - where $A\equiv\dfrac{eI_0}{2\pi cp_0\,\beta\eta\sigma_p{}^2}\left(\dfrac{Z_n}{n}\right)$

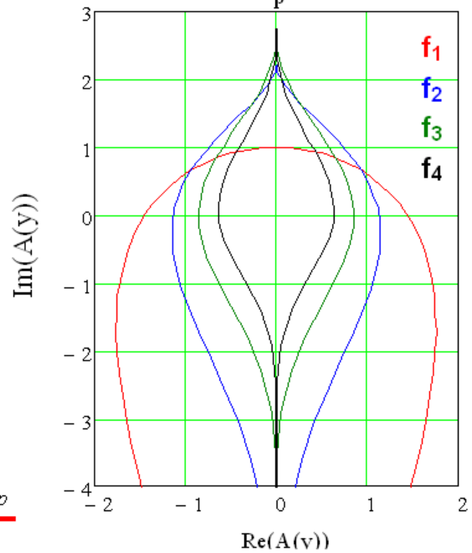
- For "rectangular" distribution there is no significant difference in stability thresholds above and below transition
- In practice
  - $\mathrm{Im}(Z_n) >> \mathrm{Re}(Z_n)$,
  - Longitudinal injection painting creates truncated tail

$\Rightarrow$Stability condition can be approximated as

$$\frac{eI_0}{2\pi cp_0\beta\eta\sigma_p{}^2}\left(\frac{Z_n}{n}\right)\le 2$$

- Well above stability threshold: $\lambda_n\approx n\,\eta\omega_0\sigma_p$





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Longitudinal Impedance

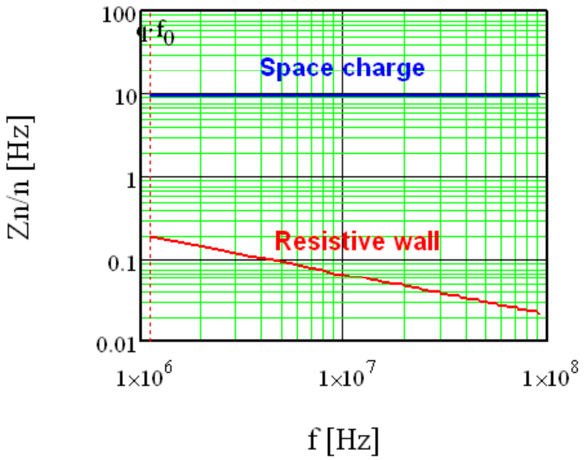
- Longitudinal impedance has three major contributions
  - Space charge
    - For round beam & vacuum chamber with radius *a*

$$\frac{Z(\omega_n)}{n} = i\frac{Z_0}{\beta\gamma^2}\ln\left(\frac{a}{1.06\sigma}\right)$$

  - Resistive wall
    - For round beam & vacuum chamber

$$\frac{Z(\omega_n)}{n} = \left(1 - i\,\mathrm{sign}(\omega_n)\right)\frac{Z_0\beta c}{2a\sqrt{2\pi\sigma\omega_n}}$$

  - Effect of RF cavities, vacuum chamber discontinues, etc. can be controlled by machine design and dampers (f < 100 MHz)
- Space charge contribution does not depend on frequency and dominates at all frequencies if an appropriate attention was paid to the vacuum chamber electrodynamics and E ≤ 20 GeV



Copper chamber, f_0 = 1.13 MHz, a = 4.8 cm, E=8 GeV

Proton bunch compression strategies, Valeri Lebedev, Fermilab; WAHIPA 09, Fermilab; Oct. 19-21, 2009

Project X — Simple Stability Criterion

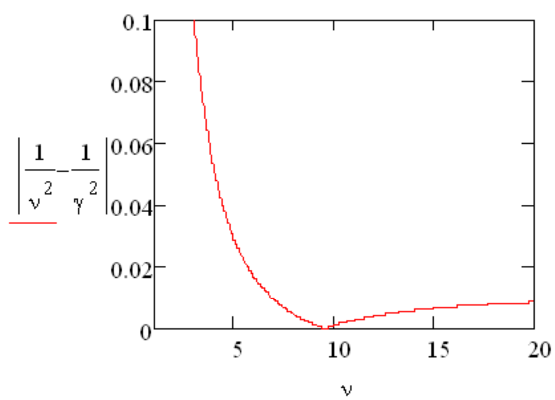
- At high frequencies, $\lambda_n \approx n\omega_0\eta(\Delta p/p) >> \omega_s$, the continuous beam theory can be used for bunched beam
- We assume
  - The space charge impedance dominates (γ< 20)
  - Before compression the bunch has uniform density and length L_b
  - Conservation of longitudinal impedance:
    $\sigma_p L_b = const$ - before and after compression
- Then

$$\frac{r_p N L_b}{\beta^2\gamma^3\eta\left(\sigma_p L_b\right)_{fin}^{2}} \ln\left(\frac{a}{1.06\sigma}\right) \le 1$$

- Let's rewrite it for beam power

$$P_{\max} \le m_p c^2(\gamma-1) f_{rep} \frac{\beta^2\gamma^3\eta\left(\sigma_p L_b\right)_{fin}^{2}}{r_p L_{init} \ln\left(\frac{a}{1.06\sigma}\right)}$$

  - Very steep dependence on beam energy
  - For 8 GeV and above an operation well above transition maximizes η



Dependence of sllip-factor on tune in the smooth focosing approximation for 8 GeV beam

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