The TESLA Damping Ring

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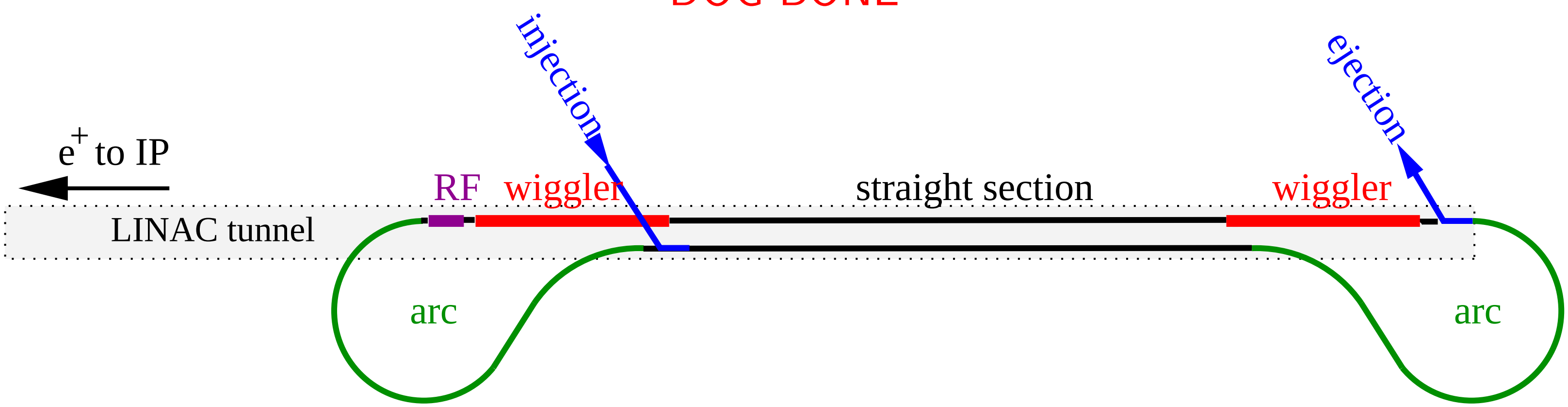
Damping Ring Layout
Optics Design
Space Charge Tune Shift
Collective Effects
Tolerances
Hardware

Snowmass 2001

July 2001

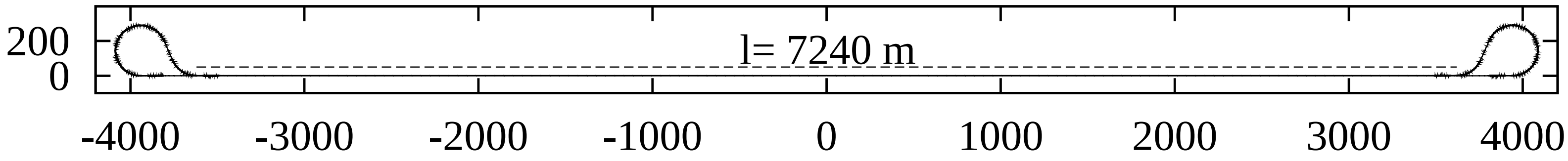
Damping Ring - Introduction

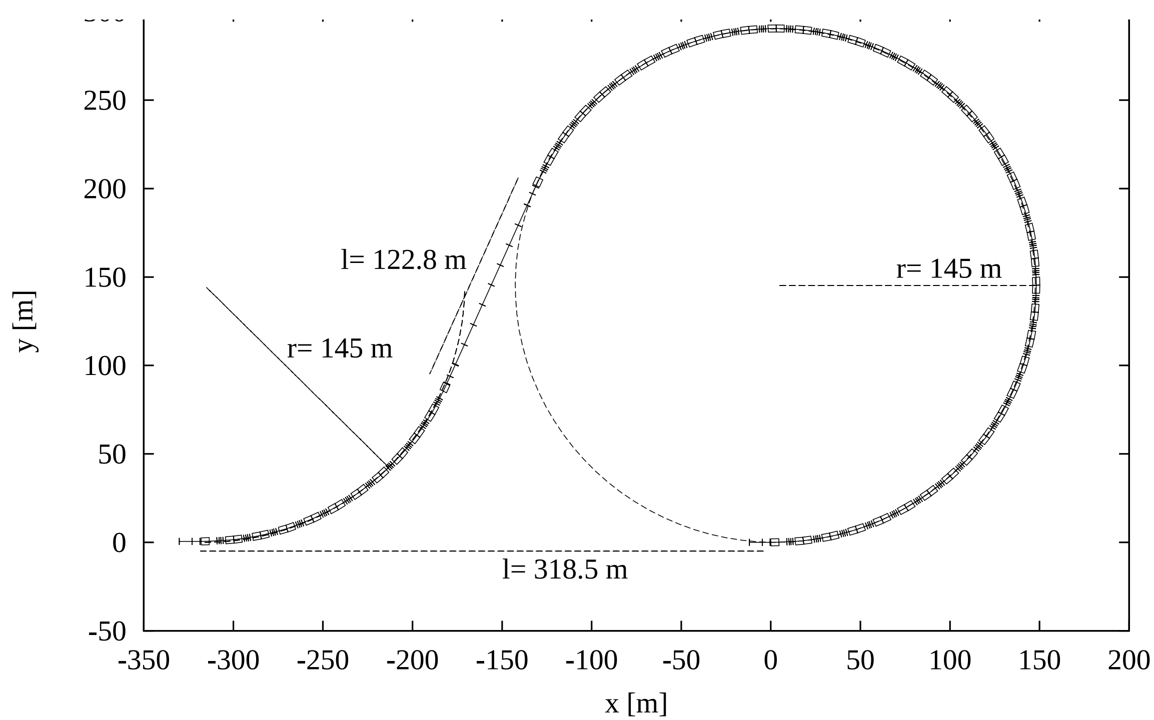
- Long TESLA bunch train (2820 bunches, 337 ns bunch-spacing) would require a 280 km circumference damping ring
  $\rightarrow$ compress bunch train with smaller bunch spacing in damping ring
  Circumference is now given by the achievable kicker raise/fall time
- Assume kicker raise/fall time of $20\,\mathrm{ns}$
  $\longrightarrow$ circumference $> 2820 * 20ns * c \approx 17\,\mathrm{km}$
- To avoid excessive additional tunnel cost build most part of the ring in the linac tunnel :
  DOG-BONE



- Note: Because of the TESLA positron source scheme the position of an ejected bunch is filled again after ≈ 1.5 turns

Layout





- One Arc length 920 m
- Wiggler length ≈ 430 m
- Straight section ≈ 7000 m

Main DR Parameters

Energy E	$5\,\mathrm{GeV}$
Circumference C	$17\,\mathrm{km}$
Hor. extracted emittance ε_x	$8 \times 10^{-6}\,\mathrm{m}$
Ver. extracted emittance ε_y	$0.02 \times 10^{-6}\,\mathrm{m}$
Injected emittance $\varepsilon_{x\|y}$	$0.01\,\mathrm{m}$ ($e^- = 0.01 \times 10^{-3}\,\mathrm{m}$)
Number of damping times n_τ	7.2 ($e^- = 4.0$)
Cycle time T_c	$0.2\,\mathrm{s}$
Damping time τ_d	$28\,\mathrm{ms}$ ($e^- = 50\,\mathrm{ms}$)
Number of bunches n_b	2820
Bunch spacing $\Delta\tau_b$	$20 \times 10^{-9}\,\mathrm{s}$
Number of particles per bunch N_e	2.0×10^{10}
Current	$160\,\mathrm{mA}$
Energy loss/turn	$21\,\mathrm{MeV}$
Total radiated power	$3.2\,\mathrm{MW}$
Tunes Q_x, Q_y	72.28 , 44.18
Chromaticities ξ_x, ξ_y	-125 , -68
Momentum compaction α_c	0.12×10^{-3}
Equilibrium bunch length σ_z	$0.006\,\mathrm{m}$
Equilibrium momentum spread σ_p/P_0	$0.13\,\%$
Transverse acceptance $A_{x\|y}$	$0.05\,\mathrm{m}$ ($e^- = 0.012\,\mathrm{m}$)
Momentum acceptance A_p	$1\,\%$ ($e^- = 0.5\,\%$)

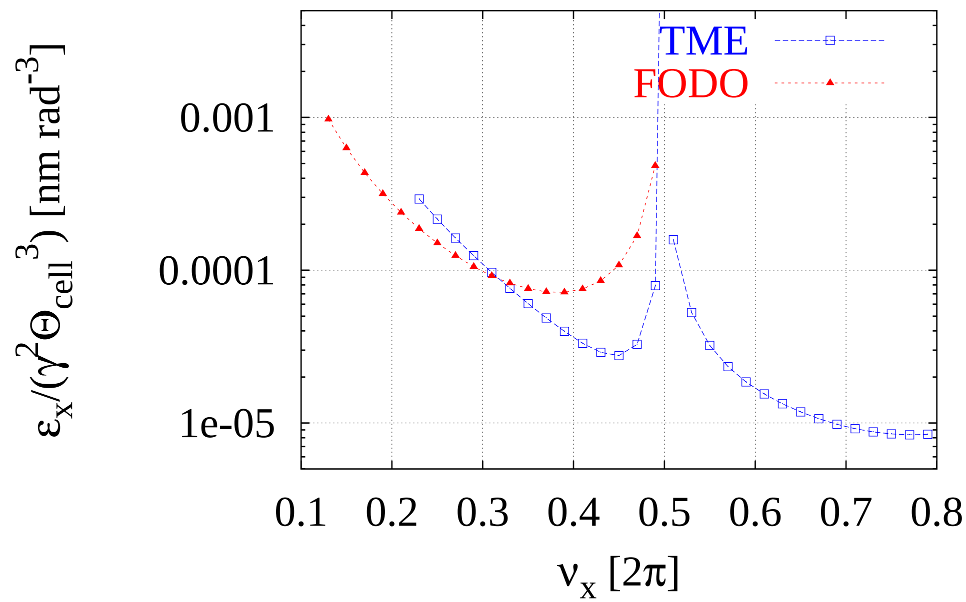
Damping Ring Optics

- Space is not a problem
- Separate functionality in optics modules
  - Arc - low emittance, chromaticity correction
  - Wiggler - host $\int B^2 dl = 605\,\mathrm{T}^2\mathrm{m}$, low emittance
  - Long Straight - provide length for the bunch train
  - RF section - host 12 single cell CESR-type Sc cavities
  - Injection / Ejection - up to 40 fast kickers
  - Local emittance coupling - lower space charge forces
  - Tune control - phase trombone
  - and so on
- This approach allows additions of modules without the need to change the so far derived solution
- Can get very confusing

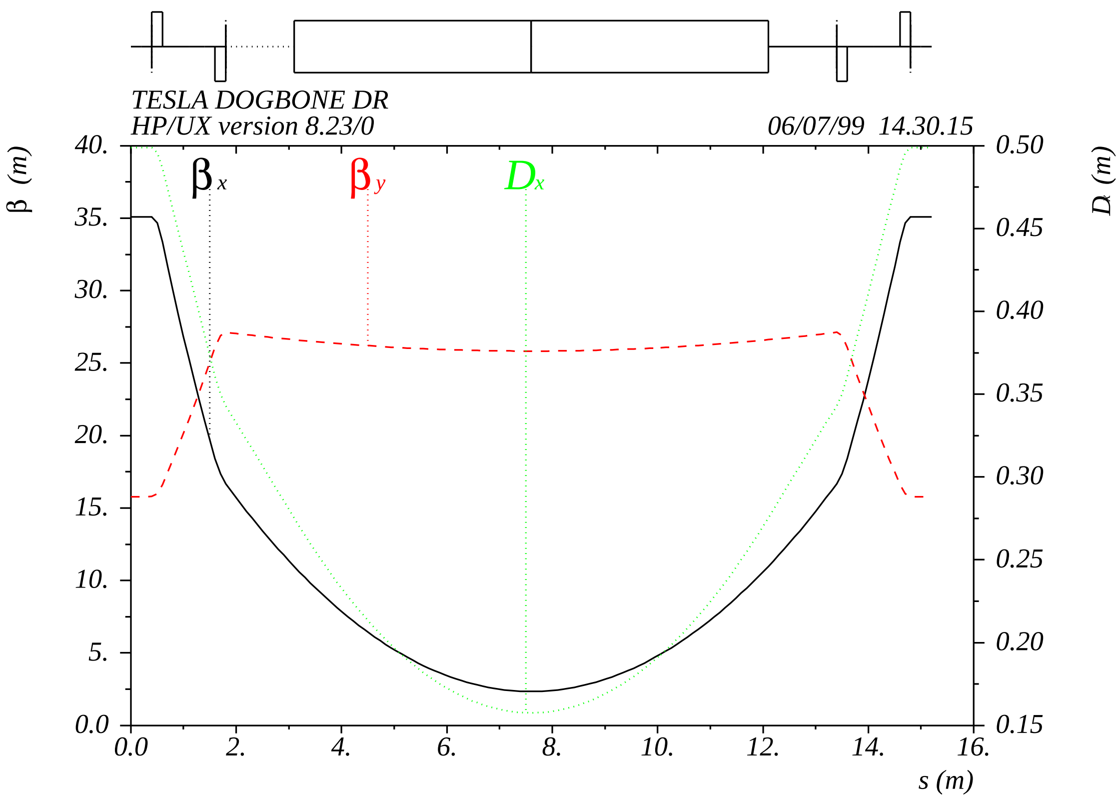
Arc lattice: Small emittance

- The minimum emittance for a cell of a given lattice type is:

$$\epsilon_{x,min} = F(lattice, \nu_x)\frac{\gamma^2}{J_x}\theta_{cell}^3$$



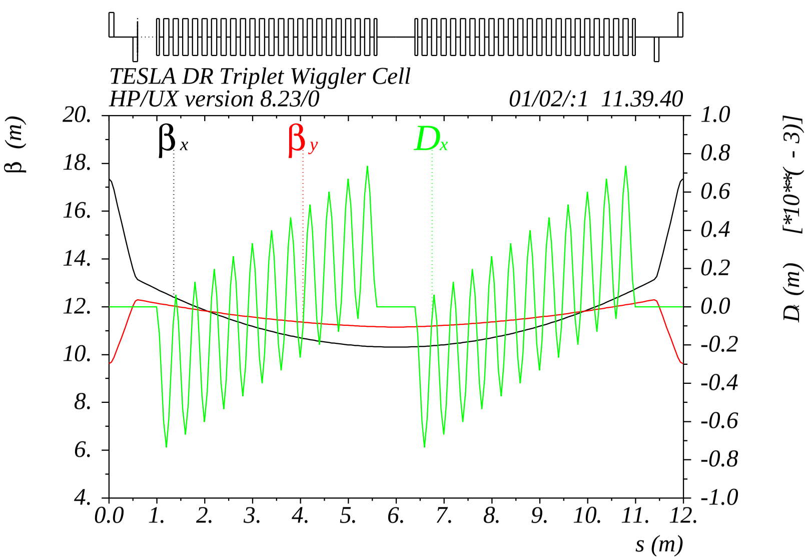
Arc Cell

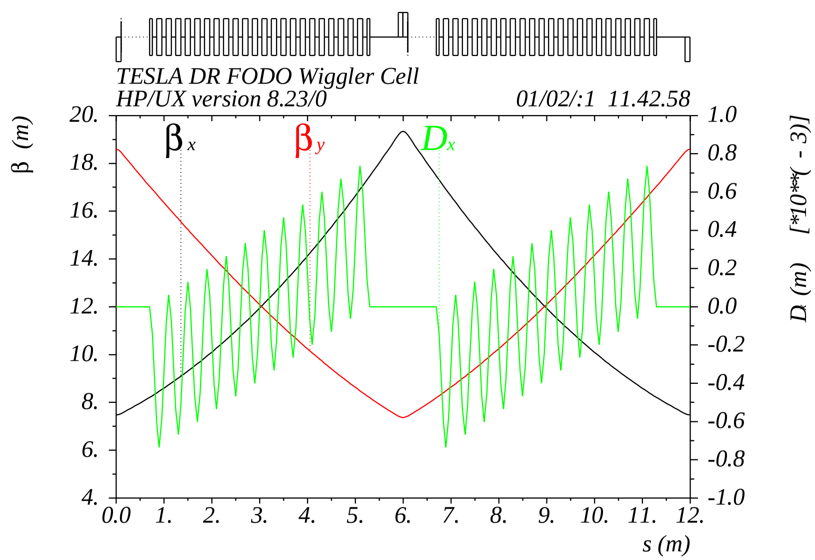


- 'detuning' $\varepsilon_r \approx 4$
- long dipole to increase β, η, α_c
- QF split for best placement of sextupole
- $\nu_x = 0.4, \nu_y = 0.1$ cancels 1^{st} order nonlinear terms after 5 cells
- Total chromaticities are $\xi_x = -90, \xi_y = -35$
- $\theta = 6\,\mathrm{deg}$ gives $\varepsilon_{x;arc} = 2\,\mu\mathrm{m}$ at $5\,\mathrm{GeV}$
- Total of 100 cells leads to $U_0 = 1.1\,\mathrm{MeV/turn}$

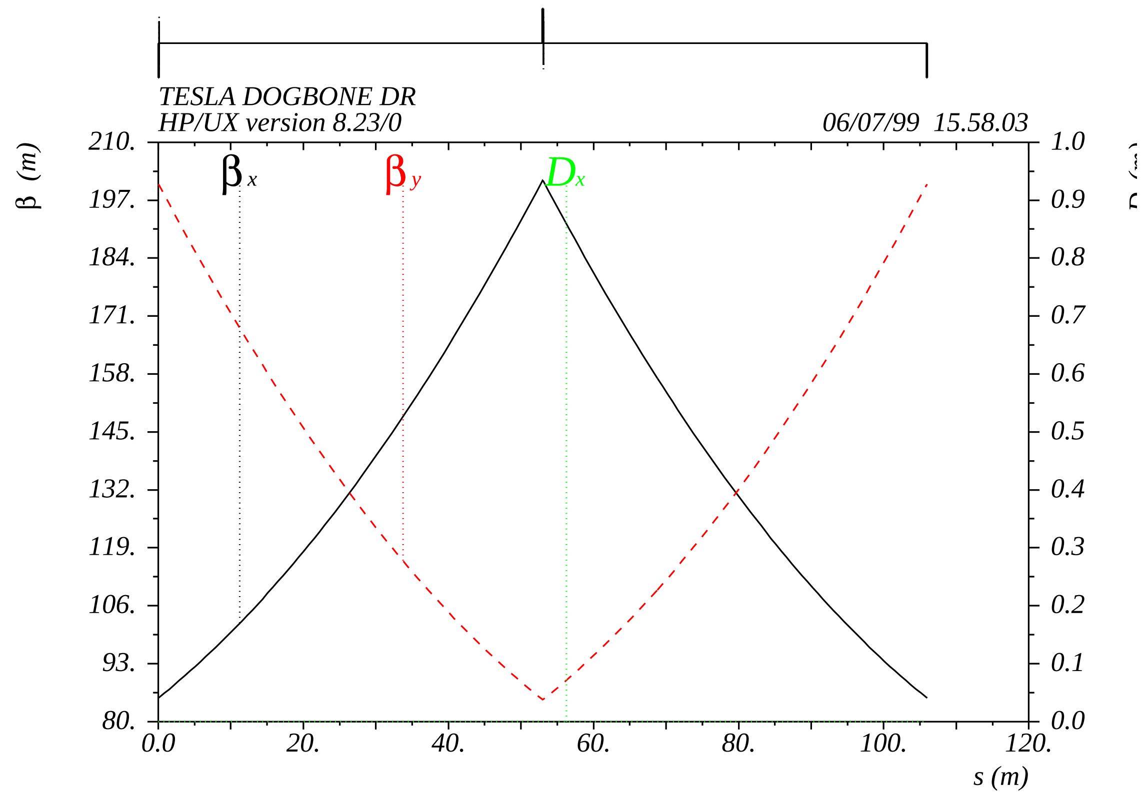
Wiggler Cell

- Provide $\int B^2 dl \approx 605\,\mathrm{T^2m}$ at $\beta_x \approx 10\,\mathrm{m}$
- Permanent magnet wiggler $B \approx 1.6\,\mathrm{T}$, $\lambda = 0.4\,\mathrm{m}$
- cell length $\approx 12\,\mathrm{m}$, adjustable ν_x for emittance control
- $\varepsilon_{x;wig} = 2.5 \ldots 7.8\,\mu\mathrm{m}$ at $5\,\mathrm{GeV}$
- Total of 45 cells leads to $U_0 = 19.1\,\mathrm{MeV/turn}$
- Radiated Power ($\approx 430\,\mathrm{m}$ length) $P_{rad} \approx 3\,\mathrm{MW}$



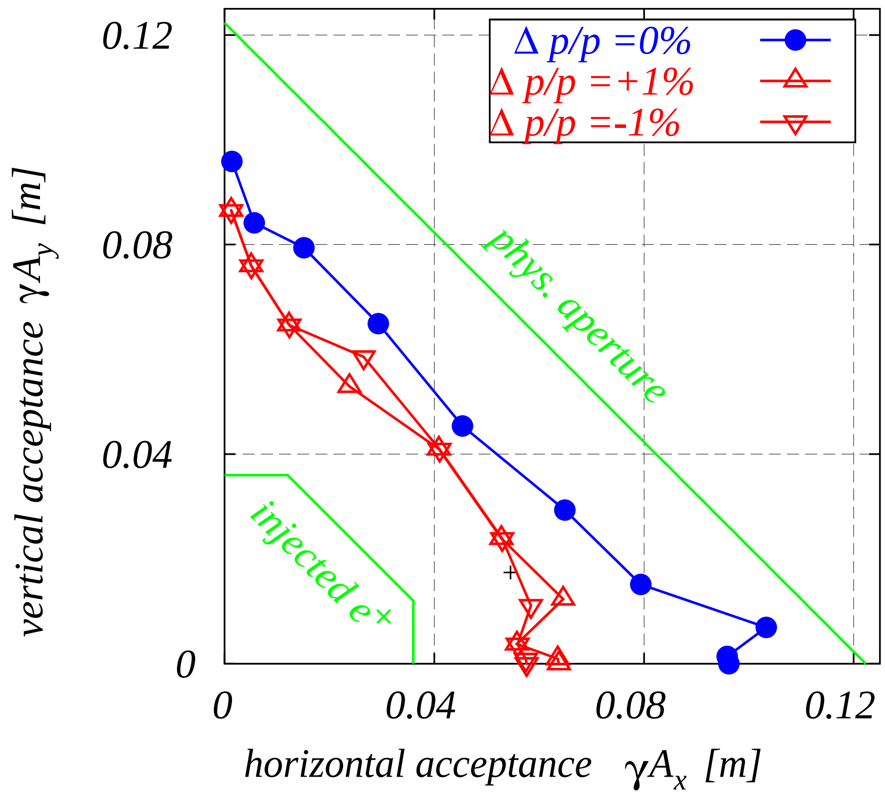


Straight Section Cell



- long cell length reduces $\#_{Quads}$
- $\nu_x = \nu_y = 0.125$ to reduce chromaticity contribution
- enough space for injection, circumference correction, RF, ...
- due to high β very sensitive to errors (stray fields, ...)
- Total of 134 cells

Dynamic Aperture



tracked with quadrupoles and sextupoles misaligned to introduce optics distortion and 1 % coupling

Incoherent Space Charge Tune Shift

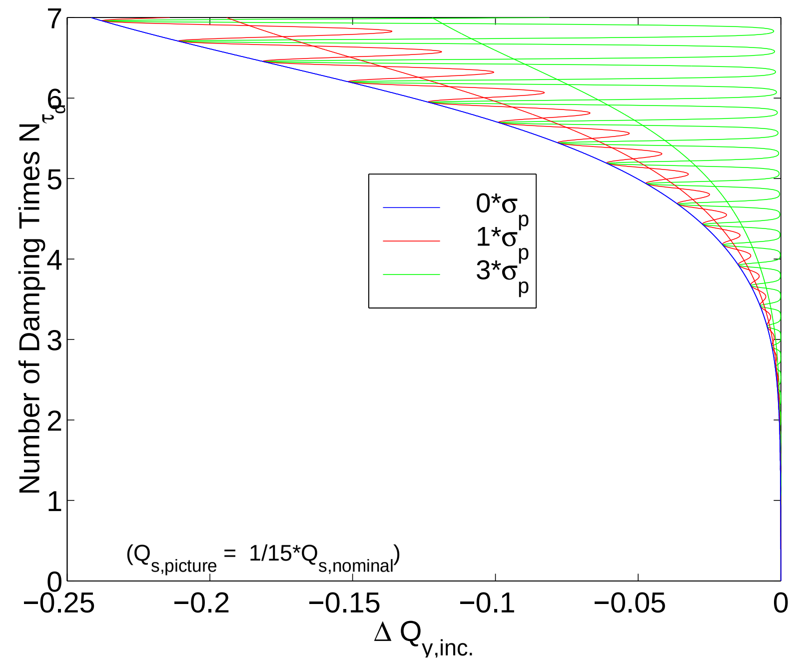
Large ring length and relative low energy leads to huge incoherent space charge tune shift:

$$\Delta Q_{y;incoh} \propto -\frac{N_e C}{\sqrt{\varepsilon_x \varepsilon_y}\sigma_z \gamma^2}$$

$$\Delta Q_{y;incoh}(z) \approx \Delta Q_{y;incoh} e^{-\frac{z^2}{2\sigma_z^2}}$$

and $z = z_0 \cos(2\pi \#_{turns} \nu_z)$

$\longrightarrow$ particle tune oscillates with twice synchrotron frequency



Incoherent tune shift versus damping time and initial longitudinal deviation

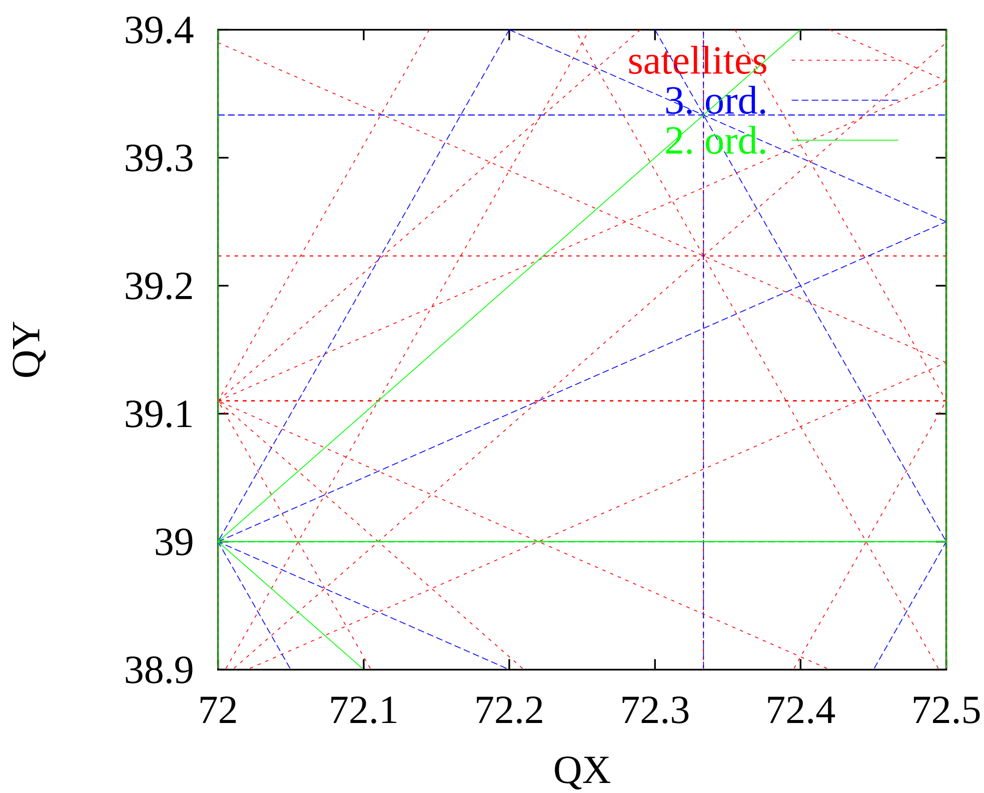
$\Longrightarrow$

Investigate though tracking including space charge kick at each element

Tune Diagram

Avoid resonances up to third order (always a good idea) **and** their 'satellites' at twice the synchrotron frequency:

$$nQ_x + m(Q_y \pm 2Q_s) = \text{int.}$$

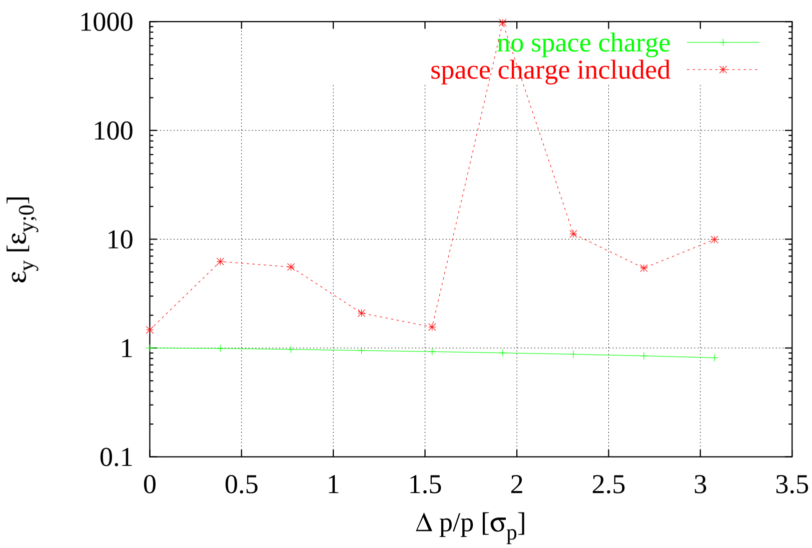


Inc. Space Charge Tune Shift - Tracking Results

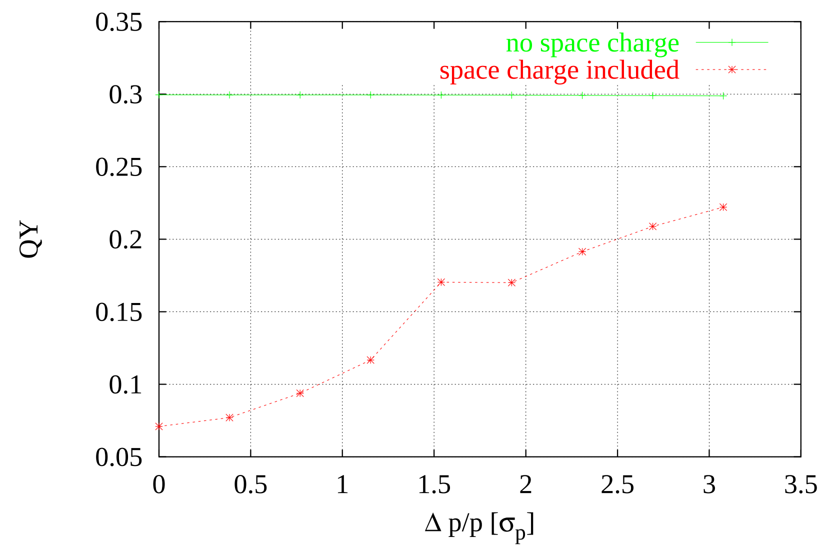
- tracking with (non-linear) space charge kick at each element ('weak-strong' model)
- calculate average Courant-Synder invariant as measure of emittance increase

- Include misalignment and orbit distortion (0.2 % coupling)
- Tunes at $Q_x = 72.32, Q_y = 39.30$

Average CS Invariant versus initial $\Delta p/p$



Vertical Tune versus initial $\Delta p/p$



$\longrightarrow$ vertical amplitude growth with space charge

How to Cure the Space Charge Tune Shift

Space charge force is $F_{sc,x/y}(x/y) \approx -\frac{x/y}{\gamma^3 \sigma_{x/y}(\sigma x + \sigma y)\sigma z}$

1 Increase ring energy γ^3
   - needs lattice redesign
   - reason to increase DR energy from $3.2\,\mathrm{GeV}$ to $5.0\,\mathrm{GeV}$
   - Scaling including constant normalized emittance and lattice change shows only weak dependence on γ

2 Increase bunch volume through local vertical dispersion
   - Vertical dispersion has negative impact on IBS emittance growth

3 Increase bunch volume through local coupling in long straights
   - Reduce $\int F_{sc}$ by the ratio

$$\frac{L_{arc} + L_{straight}\sqrt{\frac{\epsilon y}{\epsilon x}}}{L} \approx 5$$

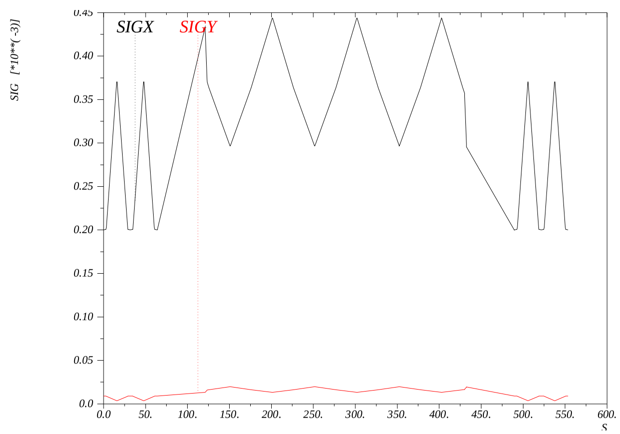
   - Additional coupling in a low-coupling ring

Local Beam Blow Up

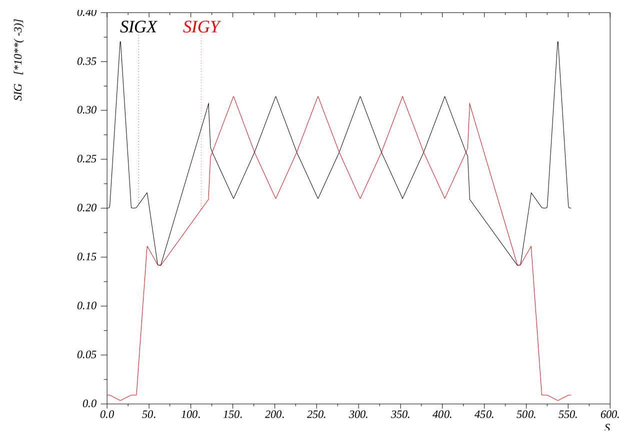
- Use special beam optics transformation to create beam with vortex distribution (Y. Derbenev)
- transformation can be realized with skew quadrupole triplet
- Beam transformed back with inverse transformation
- Drift between the two insertions has to fulfill $\mu_x = \mu_y$
  $\Longrightarrow$ no residual coupling

Local Beam Blow Up

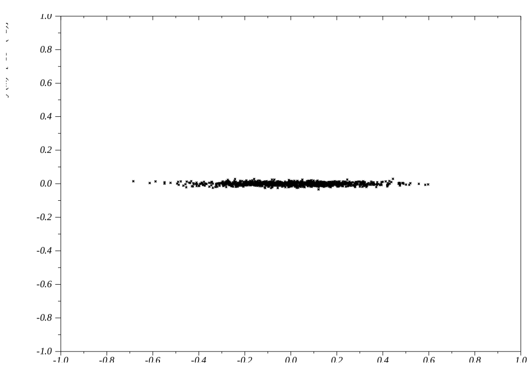
insertion off



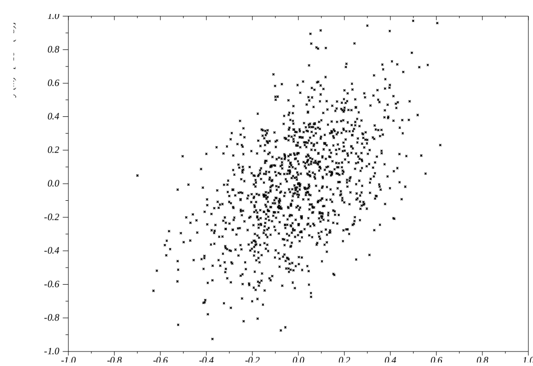
insertion on



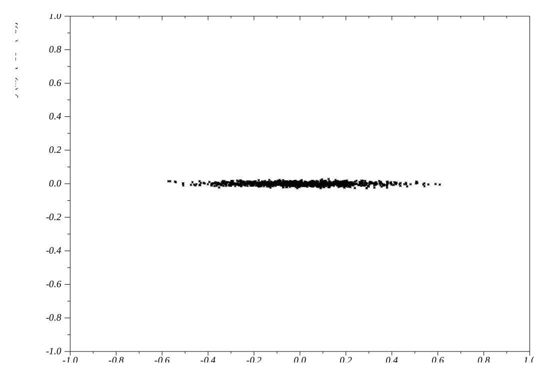
before insertion



between insertions



after insertions



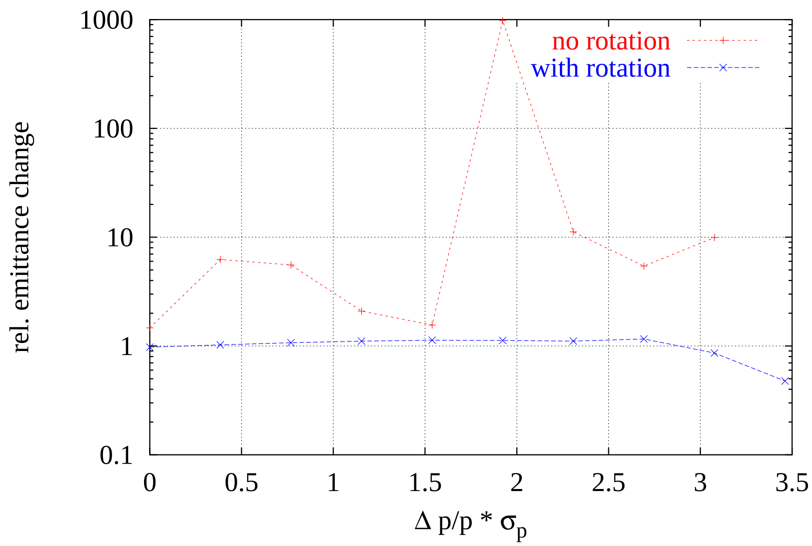
Effects of Emittance Blow Up

- Include misalignment and orbit distortion (0.2 % coupling)
- Tunes at $Q_x = 72.32, Q_y = 39.30$

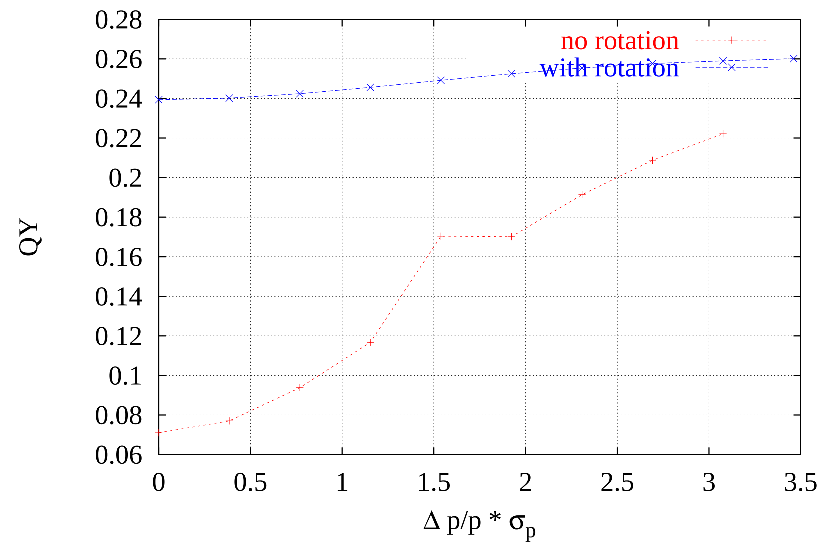
no vertical emittance increase in straight sections

vertical emittance increased in straight sections with local coupling bump

Average CS Invariant versus initial $\Delta p/p$



Vertical Tune versus initial $\Delta p/p$



Coupled Bunch Instabilites

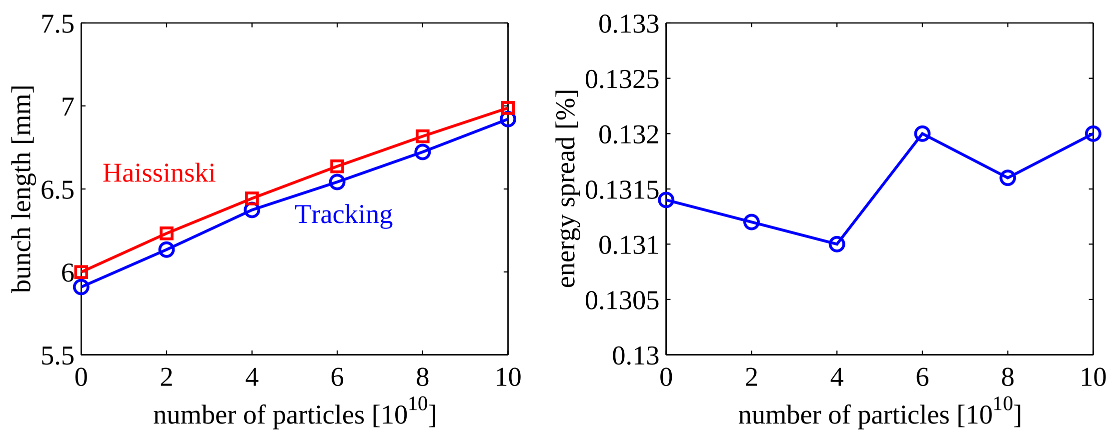
- HOM's strongly suppresed in SC cavities + feedbacks available
- Resistive wall damped with low-bandwith feedback
- Fast beam ion instability simulated $\longrightarrow$ keep $P_{N_2} \approx \times 10^{-9}$ mbar in the straight
- Electron cloud needs study

Single bunch instabilities

- Longitudinal broadband impedance below micorwave instability threshold
- Bunch lengthening not observed in tracking calculations
- Transverse broadband impedance below mode-coupling threshold

Impedance budget

Non-inductive components	$Z_{\|\|}/n$ mΩ
RF cavities	2.0
Resistive wall	5.4
Kickers	≈ 17
Total	≈ 25
Inductive components	$Z_{\|\|}/n$ mΩ
Bellows	≈ 11
BPMs	≈ 12.5
Other components	≈ 5
Total	≈ 28.5



Intra Beam Scattering

- Intra-beam scattering denotes the effect of many small angle Coulomb scatterings between particles in the bunch leading to diffusion.
- Exact theory difficult, lets try some simplified scalings
- The diffusion rates are:

$$\frac{1}{\tau_{x,y;IBS}} \propto \frac{N_e \mathcal{H}_{x,y}}{\sqrt{\gamma}\sigma_z \varepsilon_{x,y;n}(\varepsilon_{x;n}\varepsilon_{y;n})^{3/4}}$$

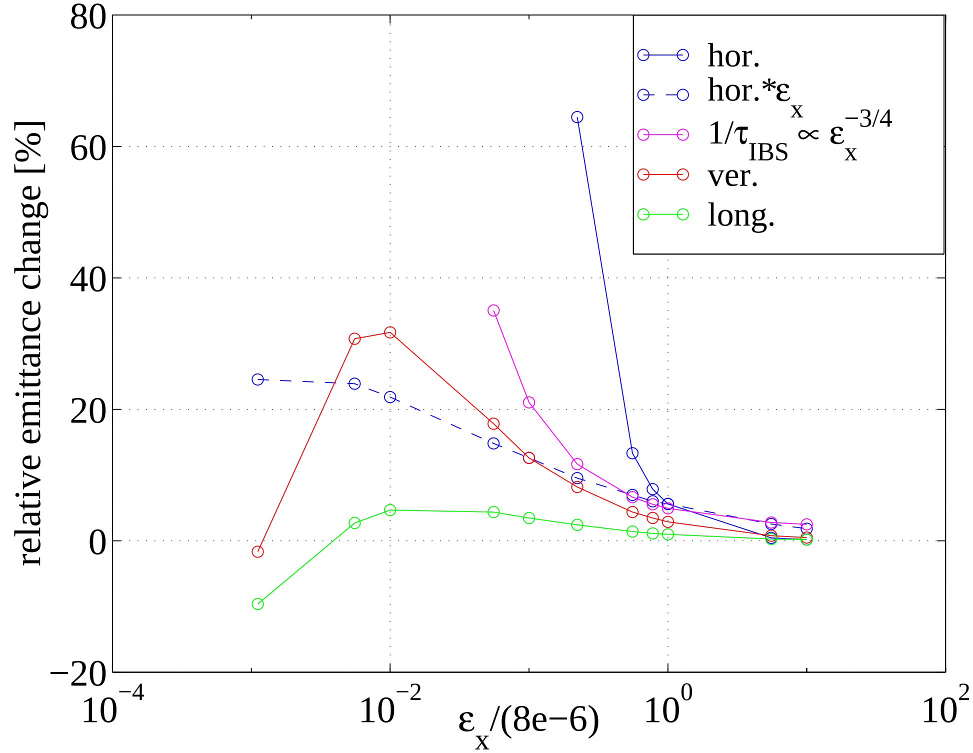
$$\frac{1}{\tau_{z;IBS}} \propto \frac{N_e}{\gamma^{3/2}\sigma_z \sigma_\epsilon^2 (\varepsilon_{x;n}\varepsilon_{y;n})^{3/4}}$$

- The horizontal emittance is roughly proportional to $\mathcal{H}_x$ which means that with a decrease of the horizontal emittance the IBS scattering rates scale as $(\varepsilon_{x;n})^{-3/4}$
- The final equilibrium emittance is:

$$\frac{\Delta\varepsilon_{x,IBS}}{\varepsilon_{x,0}} = \frac{1}{1 - \frac{\tau_{x;D}}{\tau_{x;IBS}}}$$

Calculation of Intra Beam Scattering emittance Growth

- Calculation of the emittance growth due to IBS (assuming the damping times to be constant) with Bjoerken-Mitwinga theory using present TESLA DR
- Horizontal IBS scattering rate scaled with emittance (dashed curve) and scaling with $\varepsilon_x^{-3/4}$ (magenta curve) also given



Tolerances

- Vertical emittance created through coupling and vertical dispersion
- Coupling can be controled to below $0.1\,\%$ level (collider rings)
- Dispersion has to be corrected at wiggler only, but to a level of $D_{y;rms} \leq 2mm$
- Means BPMs with $\approx 1\mu m$ resolution
- Empirical tuning with dispersion bumps avoids high accuracy BPMs

Study with

transverse position of elements :	$0.1\,\mathrm{mm}$
roll angle :	$0.2\,\mathrm{mrad}$
BPM resolution :	$0.01\,\mathrm{mm}$

and combined orbit and disperison correction yields $\varepsilon_y \approx 0.01\,\mu\mathrm{m}$ on average

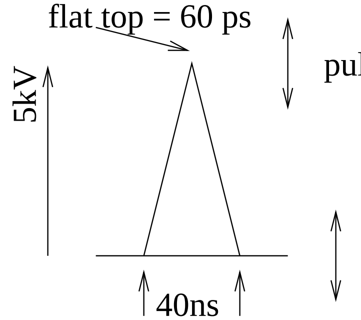
- Problem are time varying errors (like stray fields)
- Stray fields measured to be order of magitude higher than tolerable
- Feedback needed

Injection/Ejection System

- Deflection angle $\alpha = 2N\sqrt{\frac{\varepsilon_{x;inj.}}{\gamma}\frac{1}{\beta_{kicker}}}$
  assuming $N = 3\sigma$ separation from septum and $\beta = 40\,\mathrm{m}$ at kicker

$$\alpha \approx 1\,\mathrm{mrad} \equiv Bl \approx 16.6 \times 10^{-3}\,\mathrm{Tm}$$

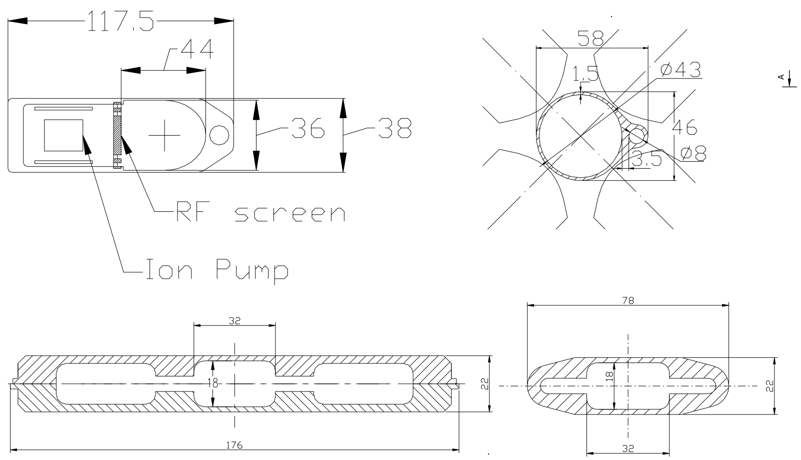
- Bunch to bunch stability for ejection is $10\,\%$ of $\sigma_{x;ej.} \longrightarrow \frac{\Delta\alpha}{\alpha} \leq 0.5 \times 10^{-3}$

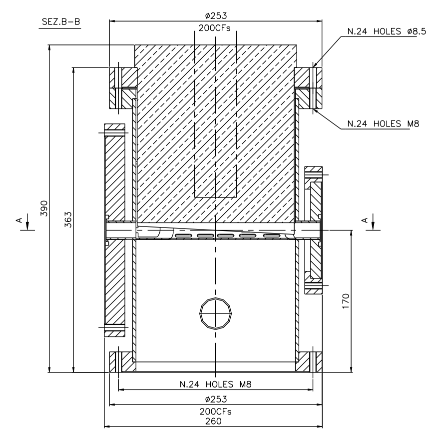


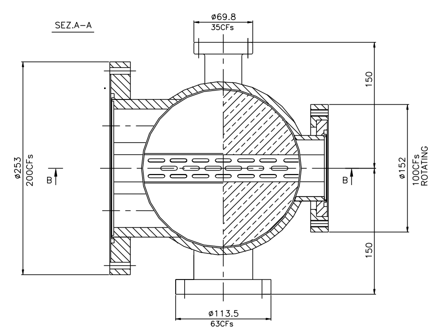
- Stripline kicker prototype from Budker INP, DESY, FNAL reaches $2.8 \times 10^{-4}\,\mathrm{Tm}$ (TESLA 96-11)
- 2nd concept using sputtered ceramic vacuum chamber and ferrite loaded C magnet is under study
- main challenge is pulser with (IGBT) transistor switches, prototype will be build at DESY and tested with the existing kicker

Vacuum System

Arc	1840 m
Straight ($P \approx 1 \times 10^{-9-10}$ mbar)	15000 m
Wiggler (sync. radiation load 7 kW/m)	450 m

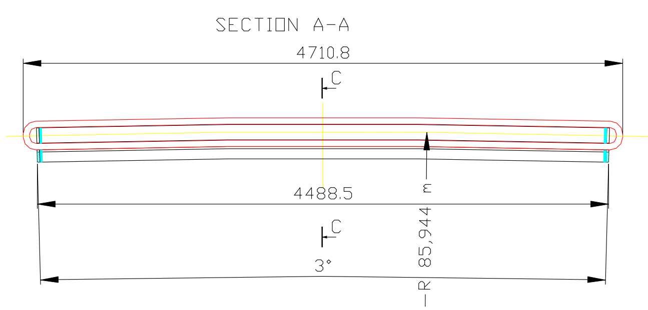


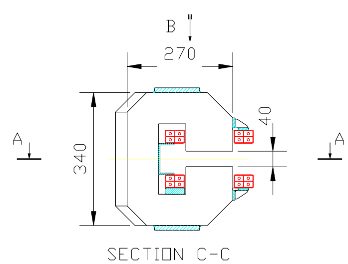


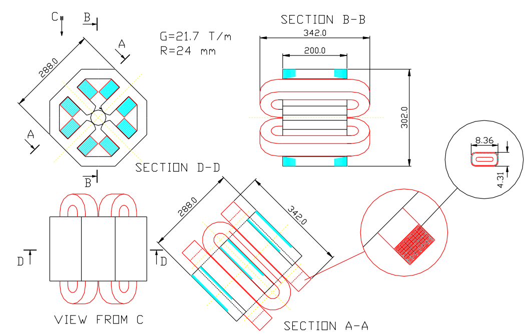


Magnets

Bends (4.5m long, 0.2 T, 0.02 m bore radius)	216
Quadrupoles (2-3 types, 0.024 m + 0.052 m bore radius)	850
Correctors	630
Sextupoles (0.024 m bore radius)	312
PM Wiggler (4.8m long, 1.67 T, gap 0.025 m)	90







Wiggler Alternatives

Permanent Magnet

- Compact design
- No maintenance, no water, no electricity
- $\int B^2 dl = 1.4\,\mathrm{T^2 m}$
- Gap $= 25\,\mathrm{mm}$, $\lambda = 40\,\mathrm{cm}$
- Dimensions: height $= 40\,\mathrm{cm}$, width $= 20\,\mathrm{cm}$
- Radiation damage

Electromagnetic Wiggler

- Cheaper, can be turned off
- Needs water, electricity (6 MW)
- $\int B^2 dl = 2.1\,\mathrm{T^2 m}$
- Gap $= 25\,\mathrm{mm}$, $\lambda = 55\,\mathrm{cm}$
- Dimensions: height $= 70\,\mathrm{cm}$, width $= 90\,\mathrm{cm}$