Update on the TESLA Damping Ring Design

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Introduction - Basic choice of parameters
Lattice design
Space charge tune shift - vertical emittance
Tolerances
Hardware list
Summary

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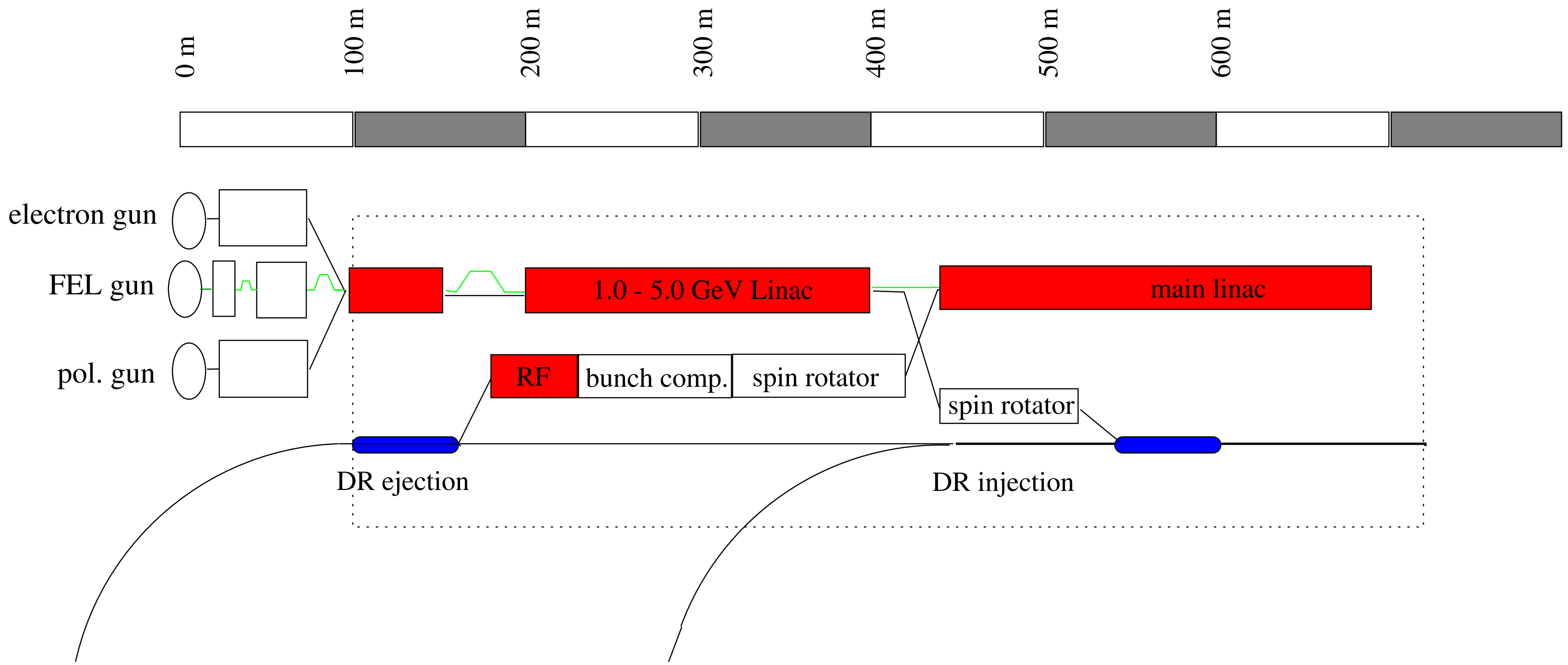
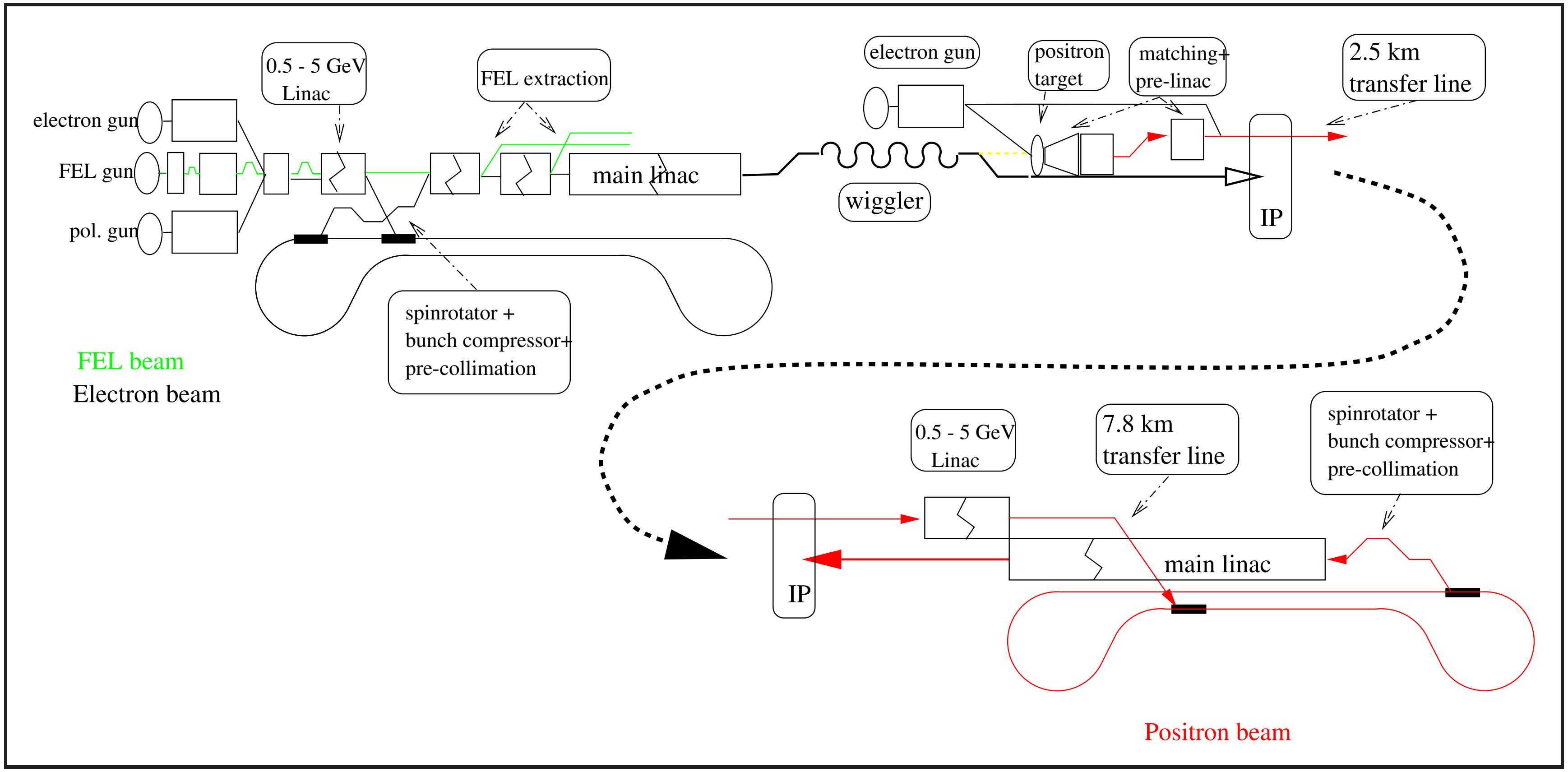
Overview electron injection - DESY site

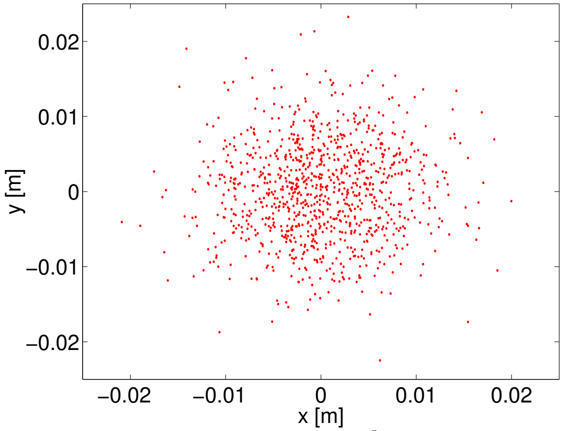


Overview injection system



Damping Ring - Introduction

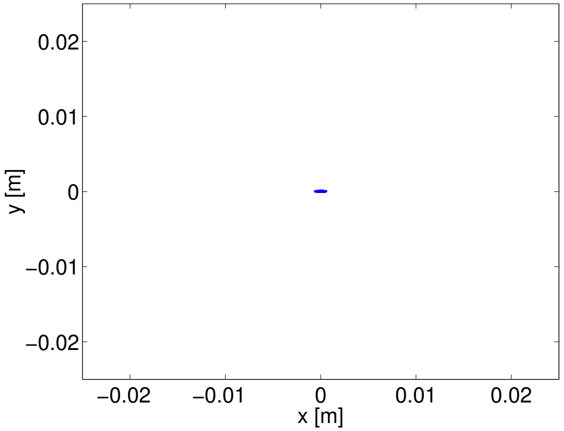
Injected positron beam



$$\varepsilon_{x,inj.} = 1 \times 10^{-2}\ \mathrm{m}$$
$$\varepsilon_{y,inj.} = 1 \times 10^{-2}\ \mathrm{m}$$
$$\sigma_{l,inj.} =$$
$$\sigma_{e,inj.} = 1\ \%$$

$$\Longrightarrow$$
$$200\ \mathrm{ms}\ (f_{rep.} = 5\ \mathrm{Hz})$$

Ejected positron beam



$$\varepsilon_{x,ej.} = 8 \times 10^{-6}\ \mathrm{m}$$
$$\varepsilon_{y,ej.} = 2 \times 10^{-8}\ \mathrm{m}$$
$$\sigma_{l,ej.} = < 0.01\ \mathrm{m}$$
$$\sigma_{e,ej.} = 0.1\ \%$$

$\varepsilon_{y,inj.}/\varepsilon_{y,ej.} \approx 50000$ requires ≈ 7 damping times

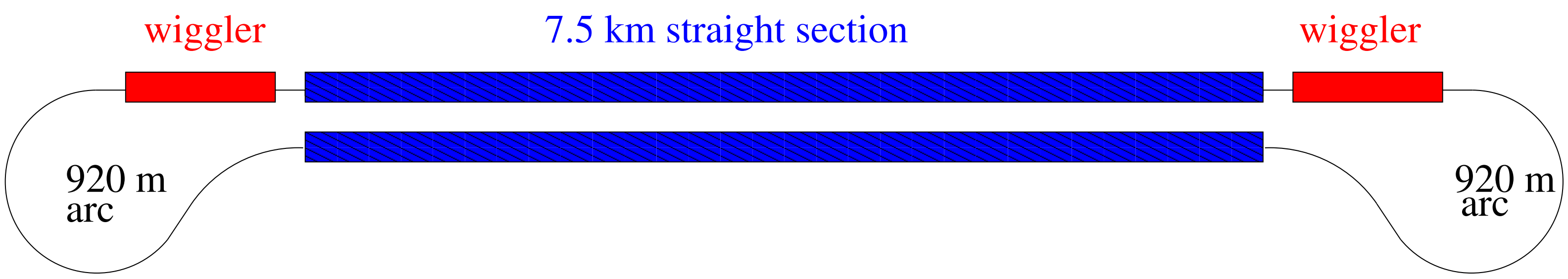
$\Longrightarrow$ damping time $\tau_D \approx 28\ \mathrm{ms}$

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 $> 2820 * 20 ns * c \approx 17\,\mathrm{km}$
- To avoid excessive additional tunnel cost build most part of the ring in the linac tunnel :
  DOG-BONE



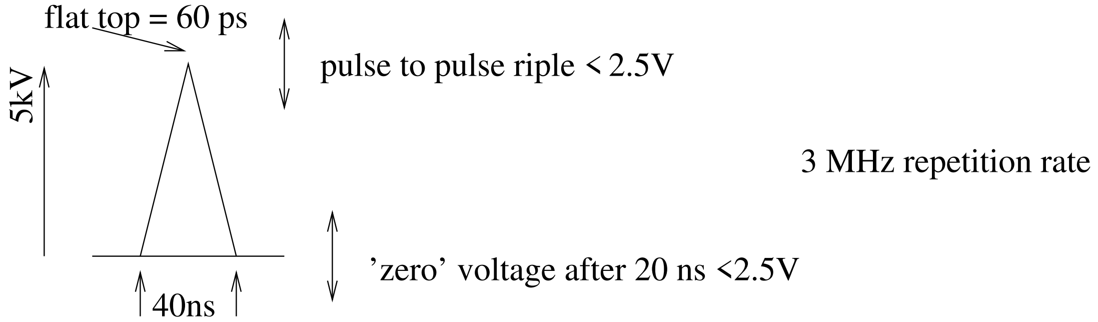
- Note: Because of the TESLA positron source scheme the position of an ejected bunch is filled again after ≈ 1.5 turns

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

Problem: Incoherent Space Charge Tune Shift

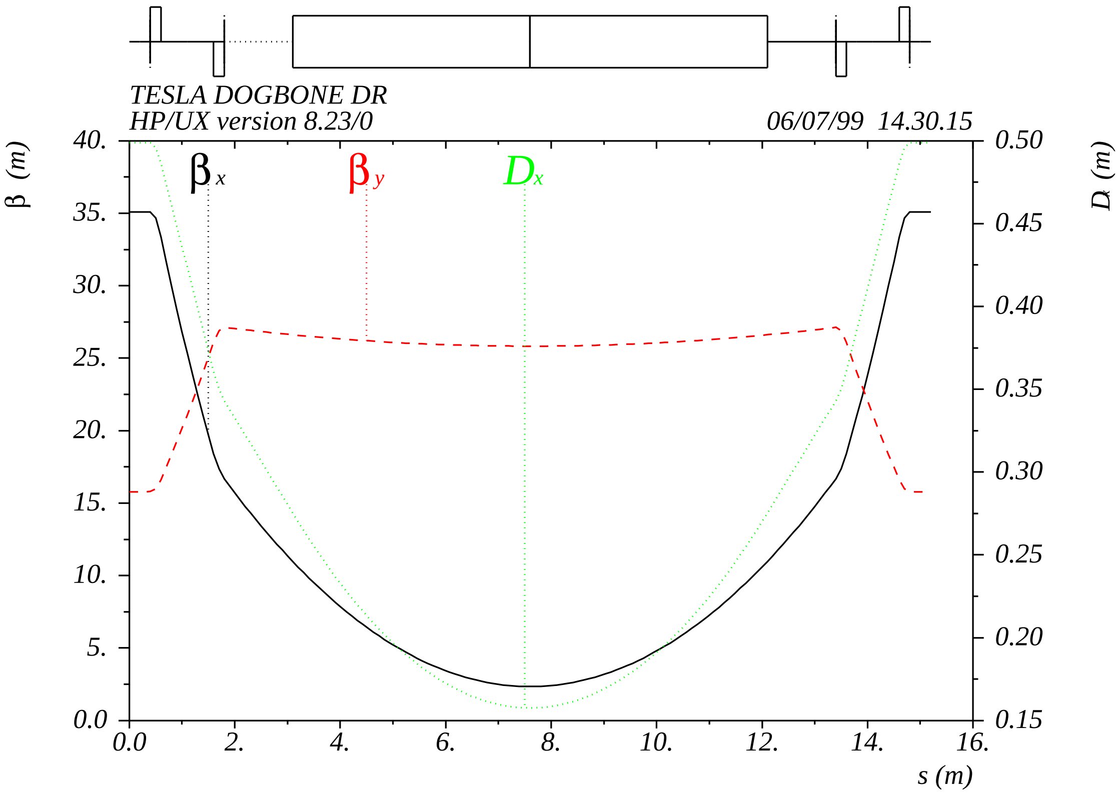
- Large ring length and relative low energy leads to huge incoherent space charge tune shift:

$$\Delta Q_{y;incoh} \approx -\frac{r_e N_e C}{(2\pi)^{3/2}\sqrt{\varepsilon_x \varepsilon_y}\sigma_z \gamma^2}$$

- Cures:
  * Increase ring energy
    * $\Delta Q_{y;incoh} \leq 0.2 \rightarrow \gamma \approx 10000$
    - Needs lattice redesign
    - Higher rf-costs
    + Need less wiggler length
  * Decrease ring circumference
    - Kicker technology not available (?)
  * Increase bunch volume through local coupling and/or dispersion
    - Additional coupling in a small coupling ring
    + Probably low cost solution

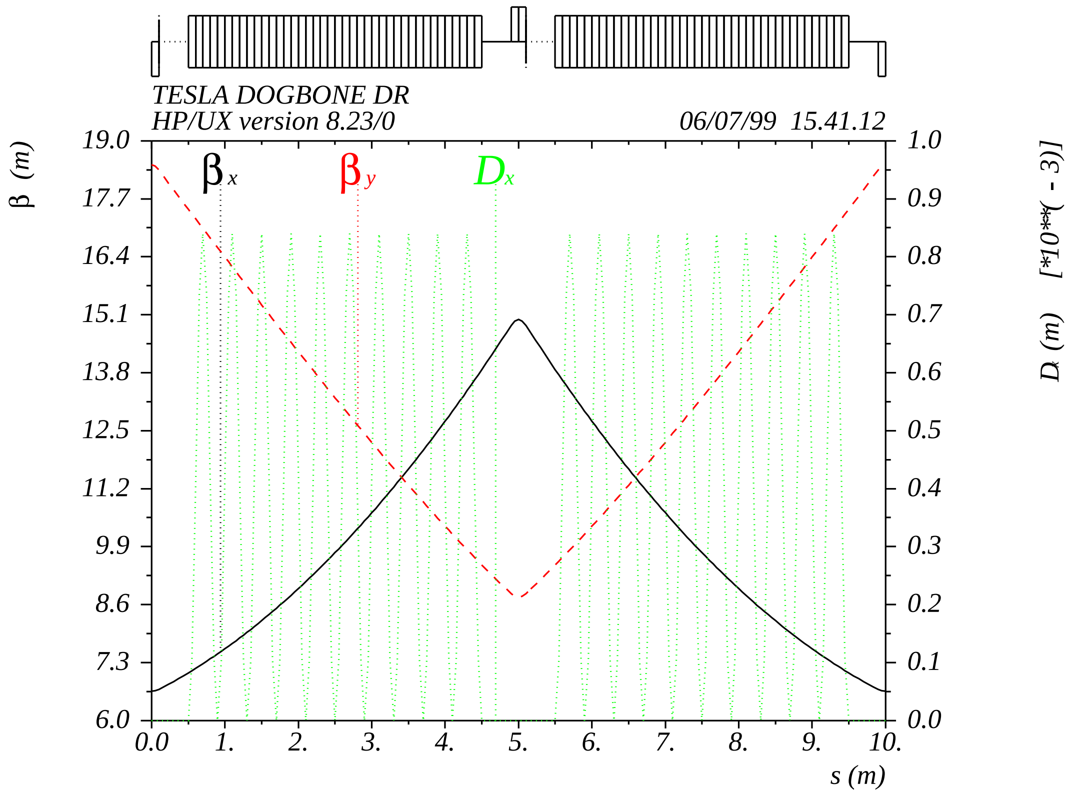
  $\Rightarrow$ Needs more study

Arc Cell



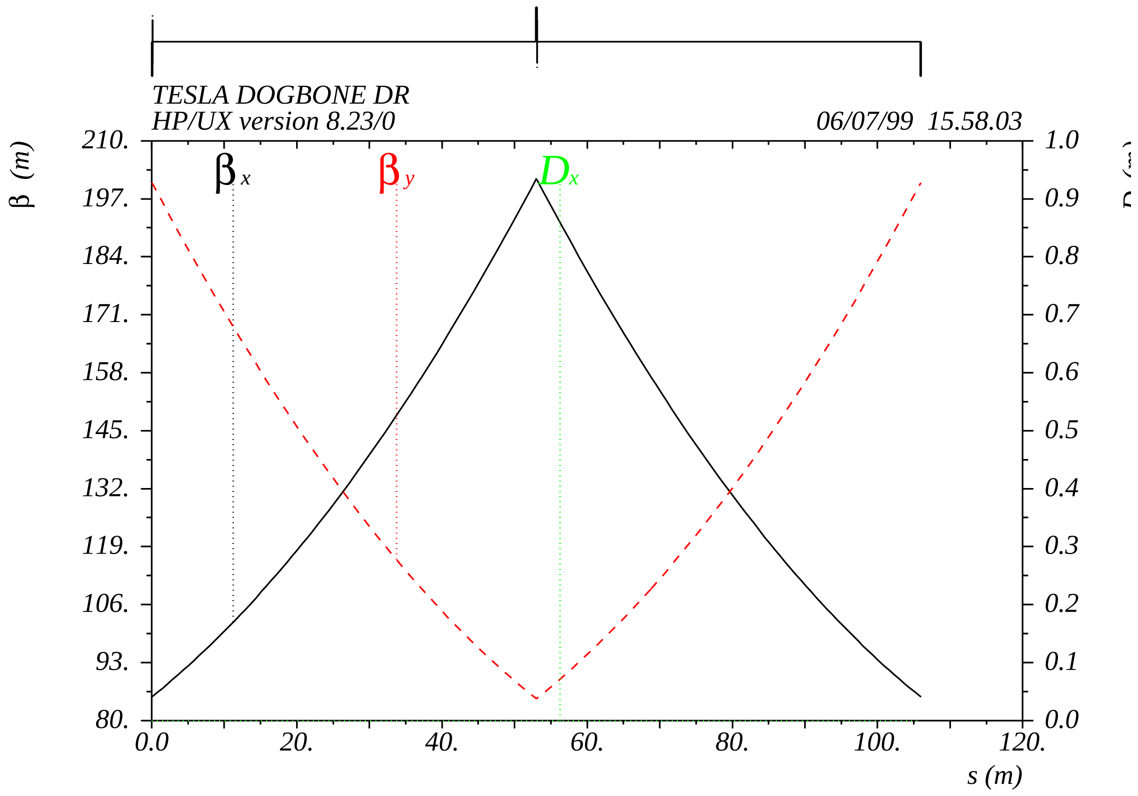
- 'detuning' $\varepsilon_r \approx 4$
- long dipole to increase β, η, α_c
- QF split for best placement of sextupole
- $\nu_x = 0.4, \nu_y = 0.1$ cancels 1^{st} order nonlinear terms after 5 cells
- $\theta = 6\,\mathrm{deg}$ gives $\gamma\varepsilon_{x;0} = 35\,\mu\mathrm{m}$ at $5\,\mathrm{GeV}$
- Total of 100 cells leads to $U_0 = 2.2\,\mathrm{MeV/turn}$

Wiggler Cell



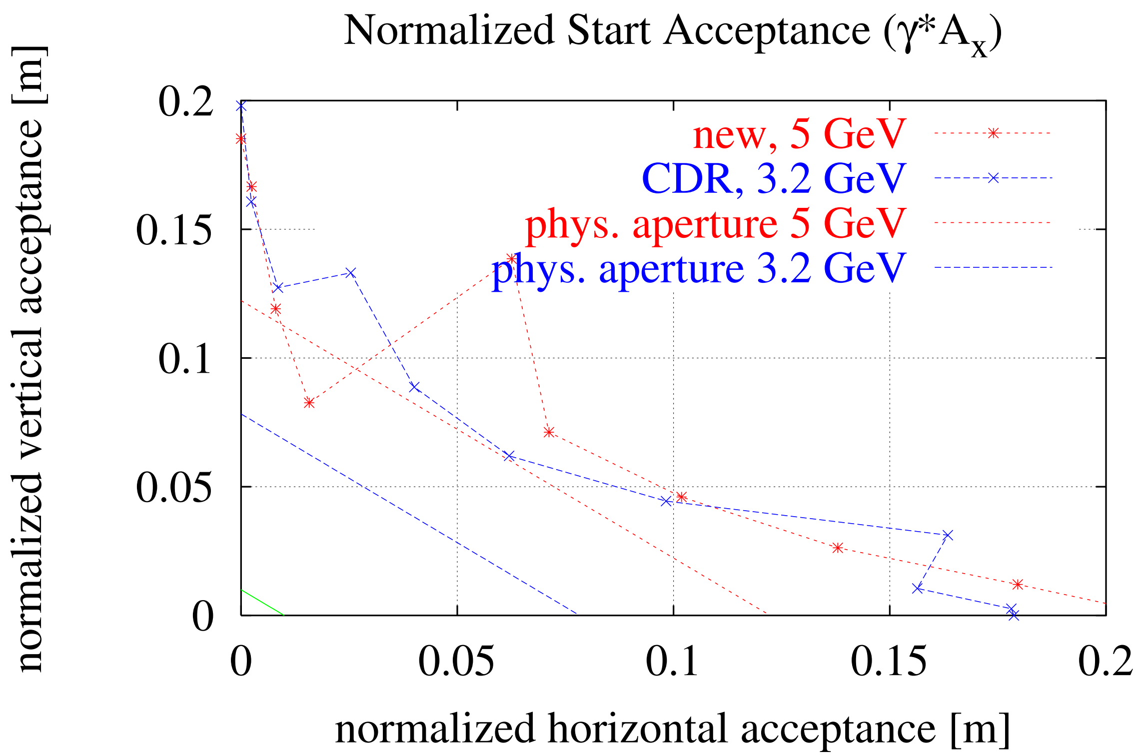
- $B = 1.5\,\mathrm{T}$, $\lambda = 0.4\,\mathrm{m}$
- cell length of $10\,\mathrm{m}$ and $\nu_x = 0.166$ gives $<\beta_x> \approx 10\,\mathrm{m}$
- $\varepsilon_{x;wig} = 7\,\mu\mathrm{m}$ at $5\,\mathrm{GeV}$
- Total of 36 cells leads to $U_0 = 18\,\mathrm{MeV/turn}$
- Radiated Power ($\approx 300\,\mathrm{m}$ length) $P_{rad} = 3\,\mathrm{MW}$

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

Compare Dynamic Aperture



- tracked with sextupoles misaligned to introduce optics distortion and coupling

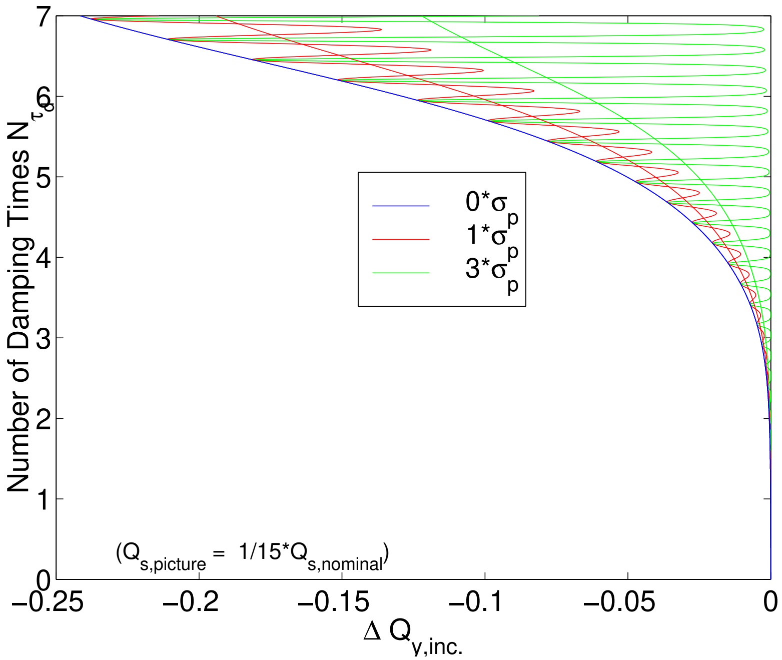
Incoherent Space Charge Tune Shift

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

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

$\rightarrow$ particle tune oscillates with twice synchrotron frequency

$\boxed{\text{Incoherent tune shift versus damping time and initial longitudinal deviation}}$ $\Longrightarrow$



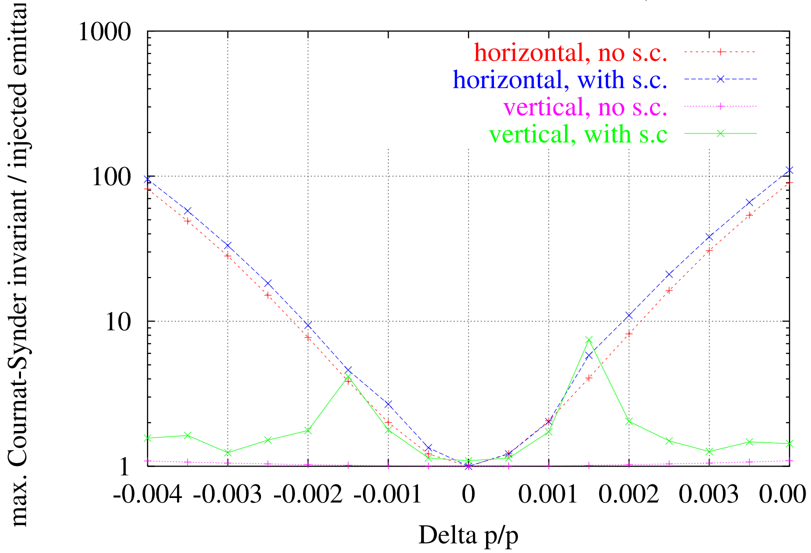
Investigate though tracking including space charge kick at each element (MAD routine supplied by F. Zimmermann)

- Space charge calculated from undisturbed emittance
- Include orbit/misalignment to reproduce desired coupling
- Record blow-up of single particle amplitude over 512 turns

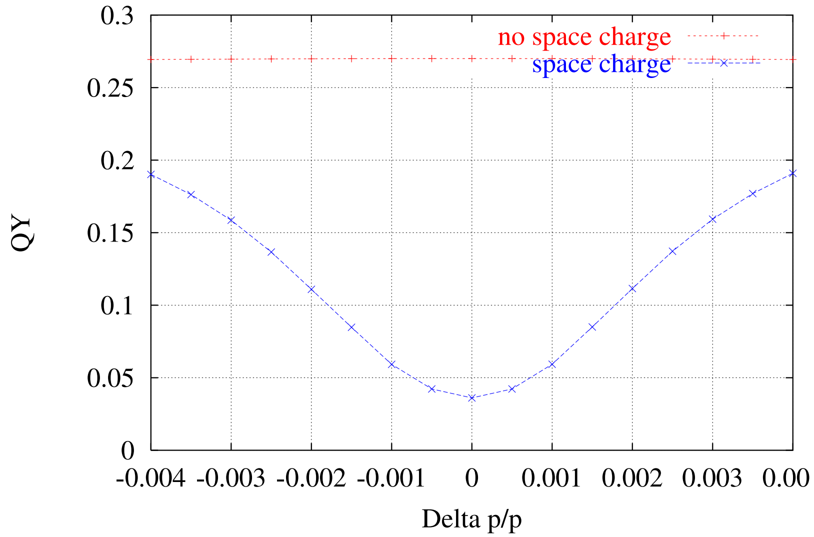
Inc. Space Charge Tune Shift - First Results

- Tunes at $Q_x = 72.18, Q_y = 39.27$, so at least no first order resonance crossing
- No misalignment and orbit distortion

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



Vertical Tune versus initial $\Delta p/p$

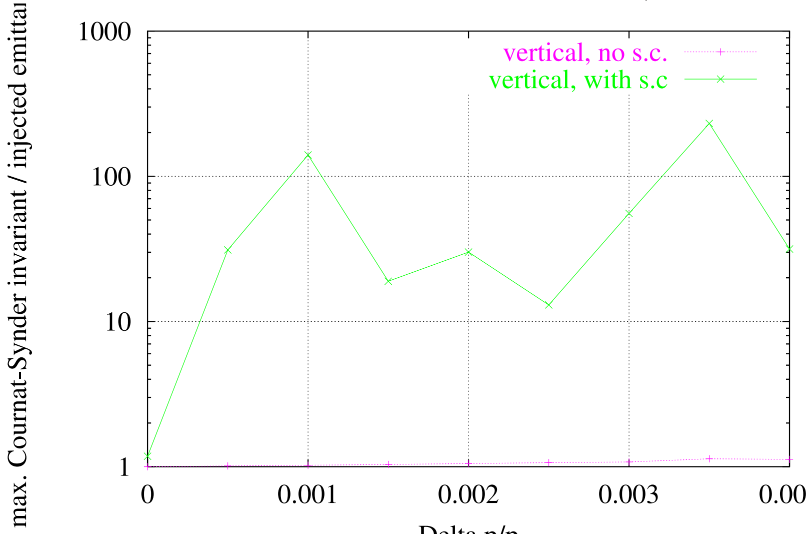


- horizontal amplitude growth due to nonlinear dispersion
- vertical amplitude growth with space charge on resonance crossing $\longrightarrow$ improve choice of working point

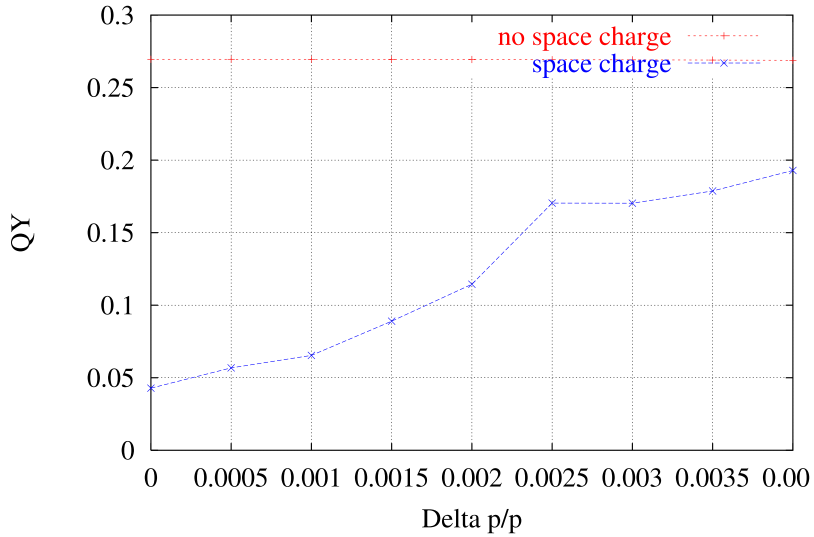
Inc. Space Charge Tune Shift - More Results

- Include misalignment and orbit distortion (0.2 % coupling)
- Tunes at $Q_x = 72.18, Q_y = 39.27$

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



Vertical tune versus initial $\Delta p/p$



- vertical amplitude growth with space charge through repeated crossing of coupling resonances (?)
- move working point below coupling resonance

Local Beam Blow Up

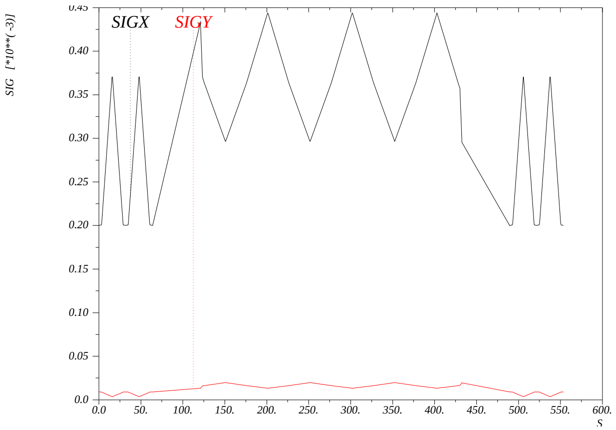
- Use 'Derbenev' transformation to create beam with vortex distribution

$$\begin{pmatrix} y \\ y' \end{pmatrix} = \begin{pmatrix} 0 & -\beta \\ 1/\beta & 0 \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix}$$

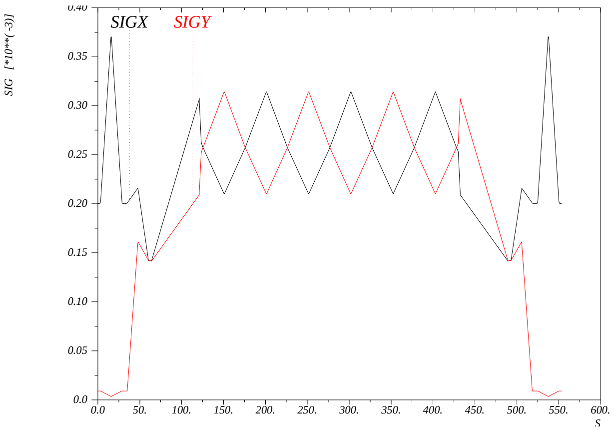
- transformation can be realized with skew quadrupole triplet
- Space charge forces reduced by $\sqrt{\frac{\varepsilon y}{\varepsilon x}}$
- Beam transformed back with inverse transformation
- Drift between the two insertions has to fulfill $\mu_x = \mu_y$
  $\Longrightarrow$ no residual coupling

Local Beam Blow Up

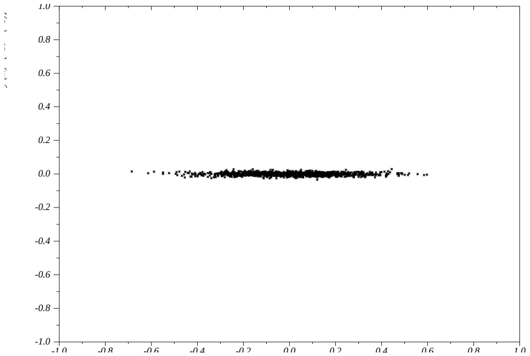
insertion off



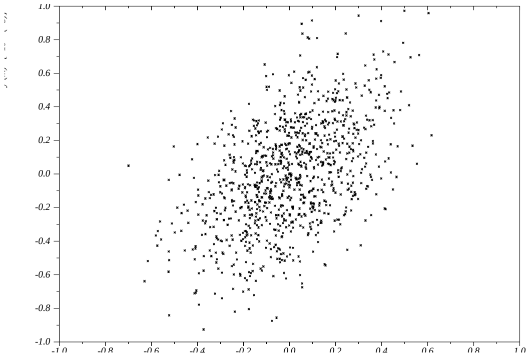
insertion on



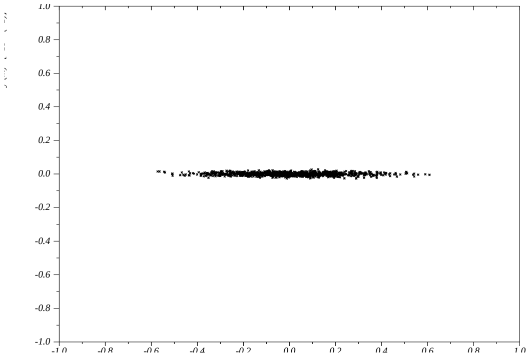
before insertion



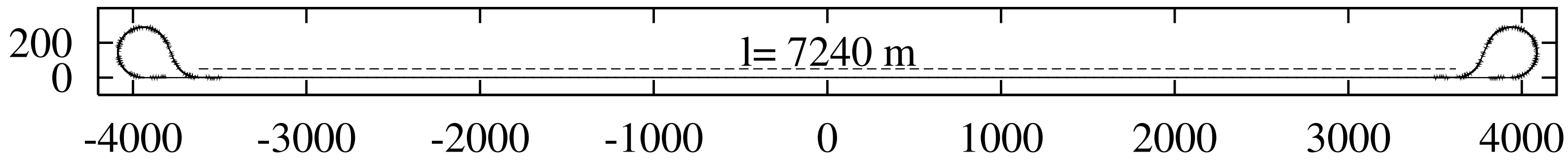
between insertions

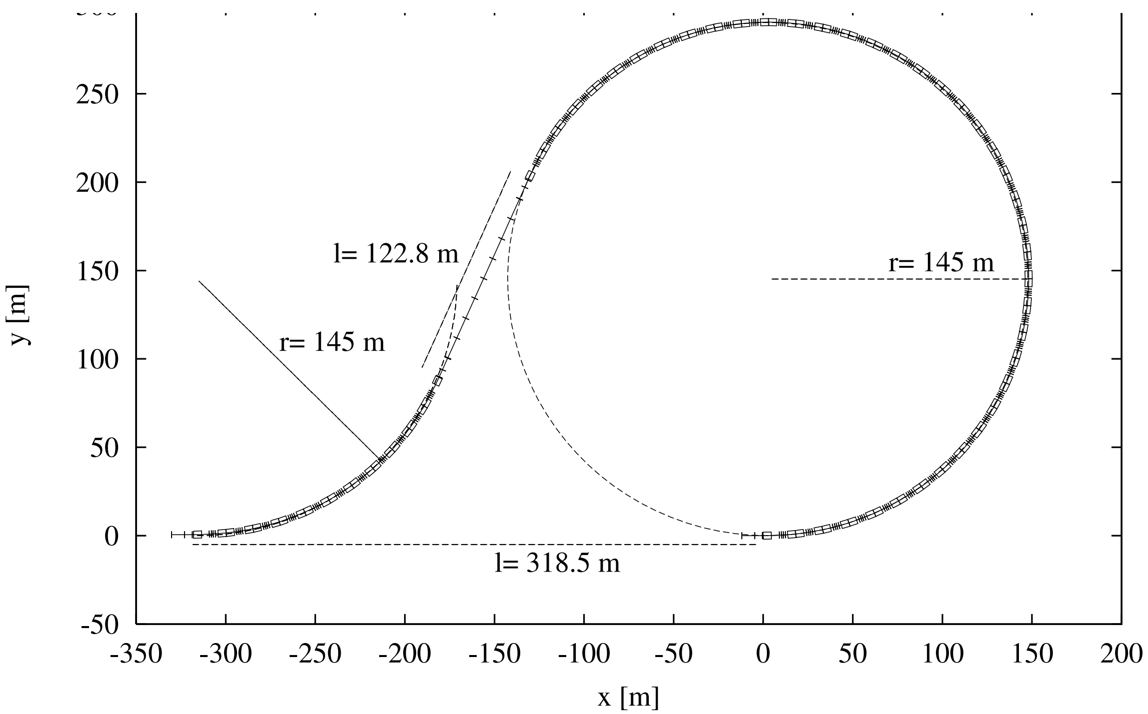


after insertions



Layout





- One Arc length 920 m
- Wiggler length 288 m
- Straight section ≈ 7000 m

Static Tolerances

- Tolerances assumed in CDR:

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

  $\longrightarrow \gamma\varepsilon_{y;0} = 0.1\,\mu\mathrm{m}$ after standard orbit correction
- For $\gamma\varepsilon_{y;0} \approx 0.01\,\mu\mathrm{m}$ vertical dispersion correction is needed to a level of
  $D_{y;rms} \leq 2mm$
  (need a $0.5\,\%$ momentum shift to measure with BPMs with $0.01\,\mathrm{mm}$ resolution)
- Additional coupling correction with skew quads not studied yet

Time Varying Errors

- Modeled by randomly distributing dipole kicks in the long straight section and calculation of the equilibrium emittance

  Criteria: $\Delta\varepsilon_y < 0.1\varepsilon_y$

- Impact depends on 'correlation' length:

distance between kicks l	B_{max}	$B_{max}l$
$10\,\mathrm{m}$	$100\,\mathrm{nT}$	$1\,\mu\mathrm{Tm}$
$50\,\mathrm{m}$	$5\,\mathrm{nT}$	$0.25\,\mu\mathrm{Tm}$

- Magnet motion: weak Quads with $\frac{1}{f} = 0.015\,\mathrm{m}^{-1}$
  $\longrightarrow$ magnet motion $< 1\,\mu\mathrm{m}$ $\surd$

- Stray fields:
  - depends on spatial distribution, criteria maybe first and second field integral along straight line
  - tolerable limit will be in the sub-μT regime

Stray Field Measurements on the DESY site

- Measurements by Jensen, Pillat (DESY)
- Gauss-Meter with $50\,\mathrm{Hz}$ bandpass
- Maximum field amplitude recorded

HERA tunnel	$0.1 - 2\,\mu\mathrm{T}$
TTF tunnel	$0.5 - 8\,\mu\mathrm{T}$
Modulators	$15 - 75\,\mu\mathrm{T}$
Cable Trays direct	$100\,\mu\mathrm{T}$
Cable Trays distance 1m	$1.3\,\mu\mathrm{T}$

Hardware - One Ring

Magnets	
Bends (9m long, 0.2 T, 0.02 m bore radius)	108
Quadrupoles (2-3 types, 0.024 m + 0.052 m bore radius)	824
Correctors	824
Sextupoles (0.024 m bore radius)	304
Wiggler (4m long, 1.5 T, gap $\approx$ 0.035 m)	72
Injection	
Stripline kicker	40
Pulser	40
Vacuum System	
Arc	$1840\ \mathrm{m}$
Straight ($P \approx 1 \times 10^{-9-10}\ \mathrm{mbar}$)	$15000\ \mathrm{m}$
Wiggler (sync. radiation load $10\ \mathrm{kW/m}$)	$300\ \mathrm{m}$
RF System	
number of systems	2
gradient/system	25 MeV
power to beam/system	1.7 MW
Diagnostic	
BPMs (1 μm resolution)	824
Current monitors	??
Screens	??
Emittance measurements (all planes)	1
Control System	

Important Parameters

energy	$5.0\,\mathrm{GeV}$	$3.2\,\mathrm{GeV}$
circumference	$17\,\mathrm{km}$	
arc length	$920\,\mathrm{m}$	$420\,\mathrm{m}$
hor./ver. tunes Q_x, Q_y	$71.85\,,\,38.71$	$59.85\,,\,57.71$
hor./ver. chromaticities ξ_x, ξ_y	$-120\,,\,-62$	$-70\,,\,-73$
hor. equilibrium emittance $\gamma\varepsilon_x$	$9\times10^{-6}\,\mathrm{m}$	$11\times10^{-6}\,\mathrm{m}$
transverse damping time $\tau_{D;x,y}$	$28\times10^{-3}\,\mathrm{s}$	$33.8\times10^{-3}\,\mathrm{s}$
transverse acceptance $\gamma A_{x,y}$	$0.06\,\mathrm{m}$	
equilibrium bunch length σ_z	$6\,\mathrm{mm}$	$9\,\mathrm{mm}$
equilibrium momentum spread σ_p/P_0	$0.13\,\%$	$0.1\,\%$
longitudinal damping time $\tau_{D;s}$	$14\times10^{-3}\,\mathrm{s}$	
energy loss per turn U_0	$20.3\,\mathrm{MeV}$	$10.7\,\mathrm{MeV}$
beam current I	$160\,\mathrm{mA}$	
radiated power P_{rad}	$3.25\,\mathrm{MW}$	
rf-voltage U_{rf}	$50\,\mathrm{MV}$	$25\,\mathrm{MV}$
momentum compaction α	0.12×10^{-3}	0.34×10^{-3}
wiggler field $B_{wiggler}$	$1.5\,\mathrm{T}$	
wiggler period length $\lambda_{wiggler}$	$0.4\,\mathrm{m}$	
total wiggler length	$288\,\mathrm{m}$	$388\,\mathrm{m}$
incoherent space charge tune shift	0.23	0.2

Summary

- Redesign of TESLA DR optics to allow for energy increase
- Use of long, detuned TME cells in the arc to control emittance contribution and momentum compaction
- On energy DA improved, off energy DA needs further work
- Space charge tune shift of 0.2 still problematic and has to be reduced with local coupling in straight section
- Static tolerances ok, but time varying stray fields in tunnel may cause problem
- Critical components are:
  - wiggler and wiggler chamber
  - kicker and pulser for in-/ejection
- INFN Frascati took over the technical design of the damping ring
- find more details at www.desy.de/~wdecking/dog/dogbone.html