Status of the CLIC Bunch Compressor Work at PSI

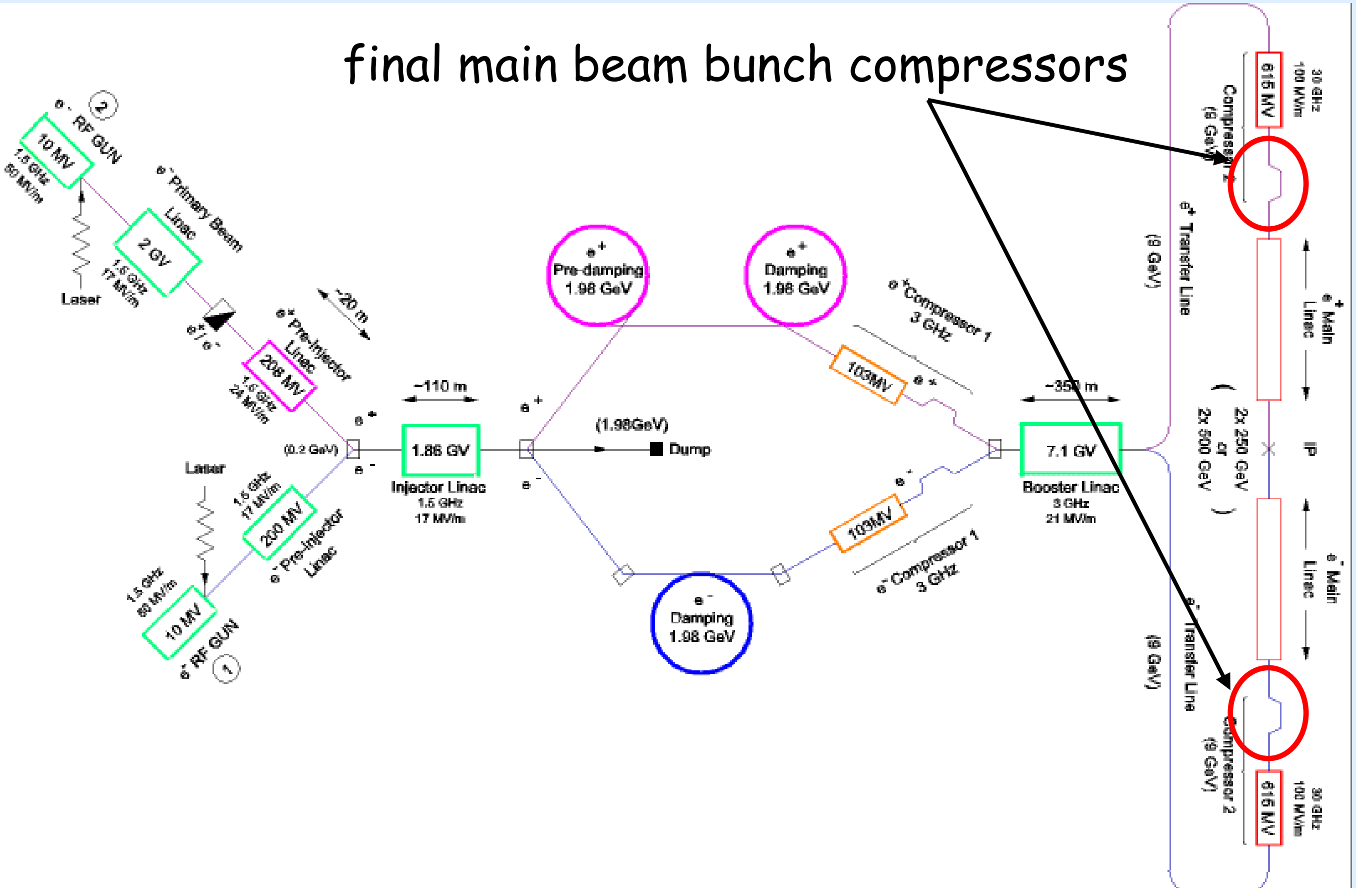
The final Main Beam Bunch Compressor

- Task
- Synchrotron Radiation Effects
- Computer Simulations
- Summary and Outlook

The final Drive Beam Bunch Compressor,
Turn Around Loop and Phase Feed-Forward

- Task
- Beam Line Sections
- Summary and Outlook

The final Main Beam Bunch Compressor

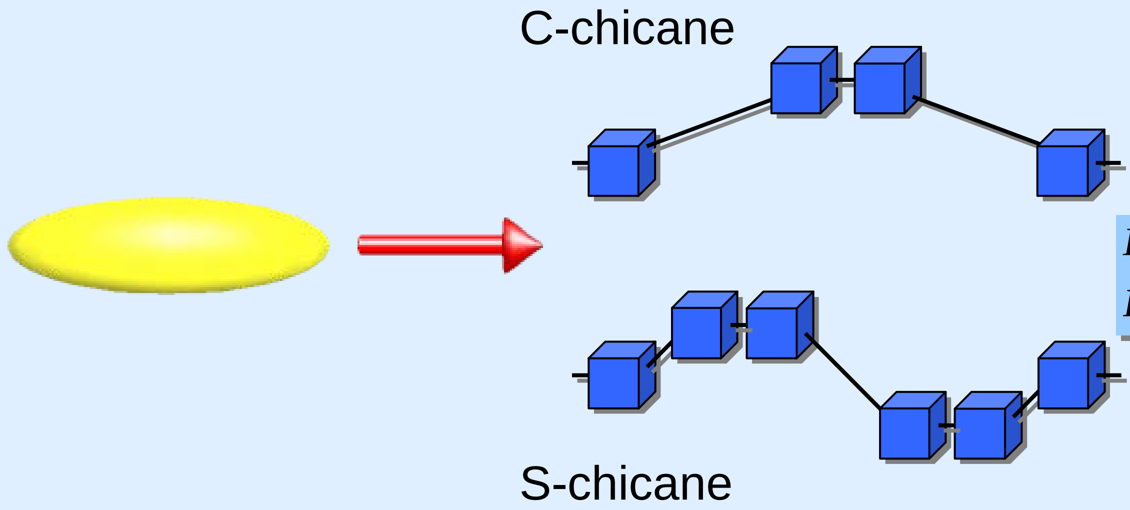


CLIC INJECTOR COMPLEX FOR THE e⁺ and e⁻ MAIN BEAMS

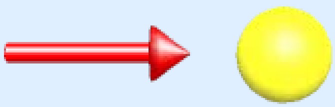
February 1998

The final Main Beam Bunch Compressor

$$
\begin{aligned}
E_0 &= 9\ \text{GeV} \\
Q_0 &= 0.41\ \text{nC} \\
\sigma_{\text{s,i}} &= 250\ \mu\text{m} \\
I_{\text{peak}} &= 200\ \text{A} \\
\varepsilon_{\text{n,x}} &= 570\ \text{nm rad} \\
\varepsilon_{\text{n,y}} &= 4\ \text{nm rad} \\
\frac{\sigma_{\text{E,unc}}}{E_0} &= 2\cdot 10^{-3} \\
\frac{1}{E_0}\frac{dE}{ds} &= -70.5\ \text{m}^{-1}
\end{aligned}
$$



$$
\begin{aligned}
L_{\text{tot}} &= 40\ \text{m} \\
R_{56} &= -14\text{mm}
\end{aligned}
$$



$$
\begin{aligned}
\sigma_{\text{s,i}} &= 30\ \mu\text{m} \\
I_{\text{peak}} &= 1670\ \text{A} \\
\varepsilon_{\text{n,x}} &< 600\ \text{nm rad} \\
\varepsilon_{\text{n,y}} &< 5\ \text{nm rad} \\
\frac{\sigma_{\text{E,tot}}}{E_0} &< 2\,\%
\end{aligned}
$$

Electron Energy / Momentum Compaction Factor

Why do we use $E_0 = 9\ \mathrm{GeV}$?

lower/higher E_0 ➡ weaker/stronger ISR (proportional to E_0^6)

stronger/weaker influence of CSR:
the radiation power is energy independent,
but the bunch reacts more/less sensitive

Why do we use $R_{56} = -14\ \mathrm{mm}$?

lower R_{56} ➡ weaker ISR and CSR

total energy spread $> 2\%$

higher R_{56} ➡ stronger ISR and CSR

final bunch length $> 30\ \mu\mathrm{m}$

$$\sigma_{\mathrm{s,f}} = \sqrt{\left(1 - R_{56}\frac{1}{E_0}\frac{dE}{ds}\right)^2 \sigma_{\mathrm{s,i}}^2 + R_{56}^2\left(\frac{\sigma_{\mathrm{E,unc}}}{\mathrm{E}_0}\right)^2}$$

Incoherent Synchrotron Radiation

Emittance growth due to incoherent synchrotron radiation (Raubenheimer et al.) (small angle, symmetric beta function, standard C-chicane):

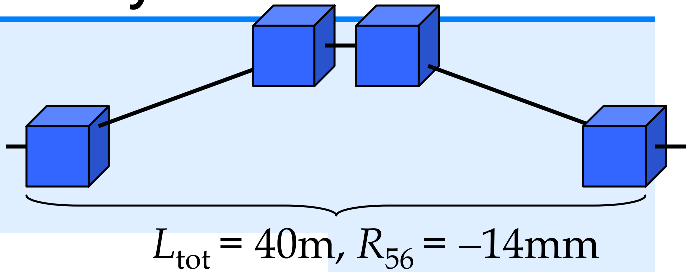
$$\Delta\varepsilon\gamma \approx 4\cdot 10^{-8}\, E^6 \frac{\theta^5}{L_B^2}\left(L_{DC} + L_B + \frac{\beta_{min} + \beta_{max}}{3}\right)$$

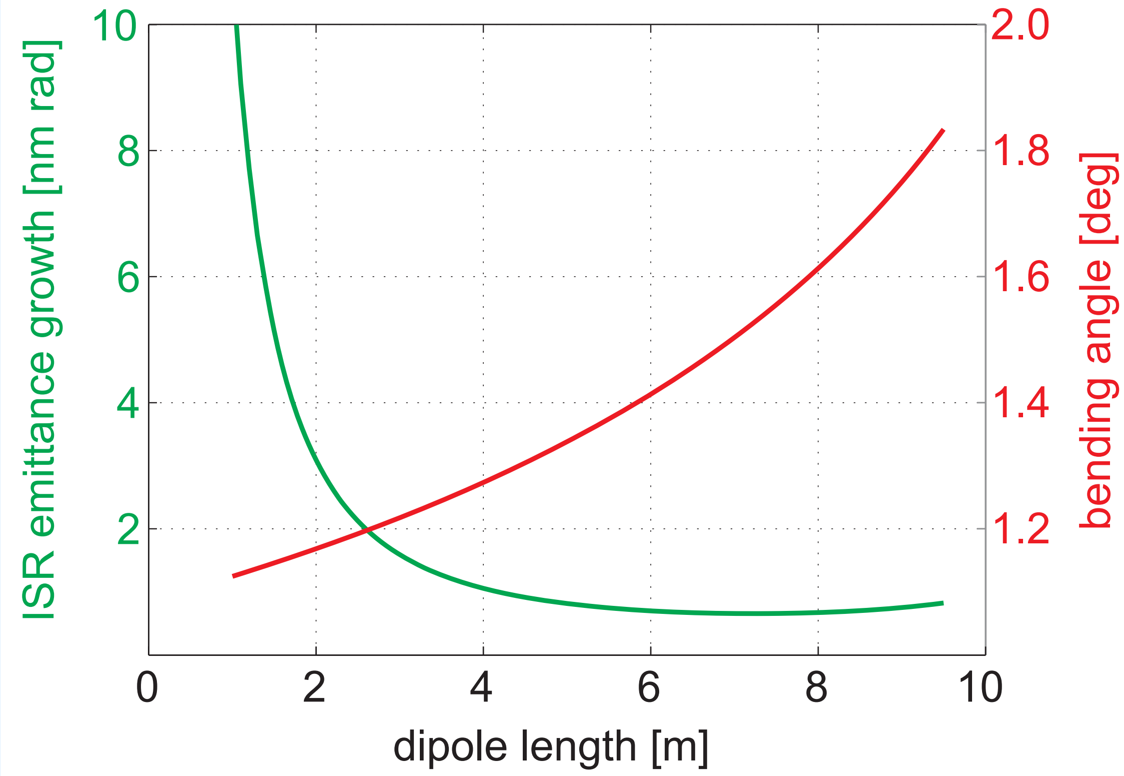
The longer the dipoles, the smaller the ISR emittance growth.

If shorter magnets are used θ must decrease to keep the R_{56} constant. This counteracts the ISR emittance growth.

The same arguments are valid for an S-chicane, but the ISR emittance growth is about twice as high (depending on beta function and chicane geometry, in some cases it might even be lower).

Incoherent Synchrotron Radiation





Coherent Synchrotron Radiation

CSR radiation power in steady state (circular motion):

$$P_{\mathrm{CSR}} \approx \frac{\Gamma\left(\frac{5}{6}\right)}{6^{1/3}\, 4\pi^{3/2}\, \varepsilon_0} \frac{N_e^2\, e_0^2\, c}{R^{2/3}\, \sigma_s^{4/3}}$$

for shorter magnets (i.e. smaller R) the radiation power increases

But the since the magnets are shorter, the radiation is emitted for a shorter time. Additionally, steady state is not reached. ???

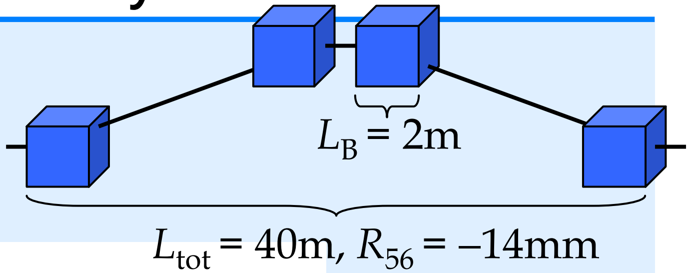
Total CSR energy loss of an electron bunch passing a single dipole (Saldin et al.):

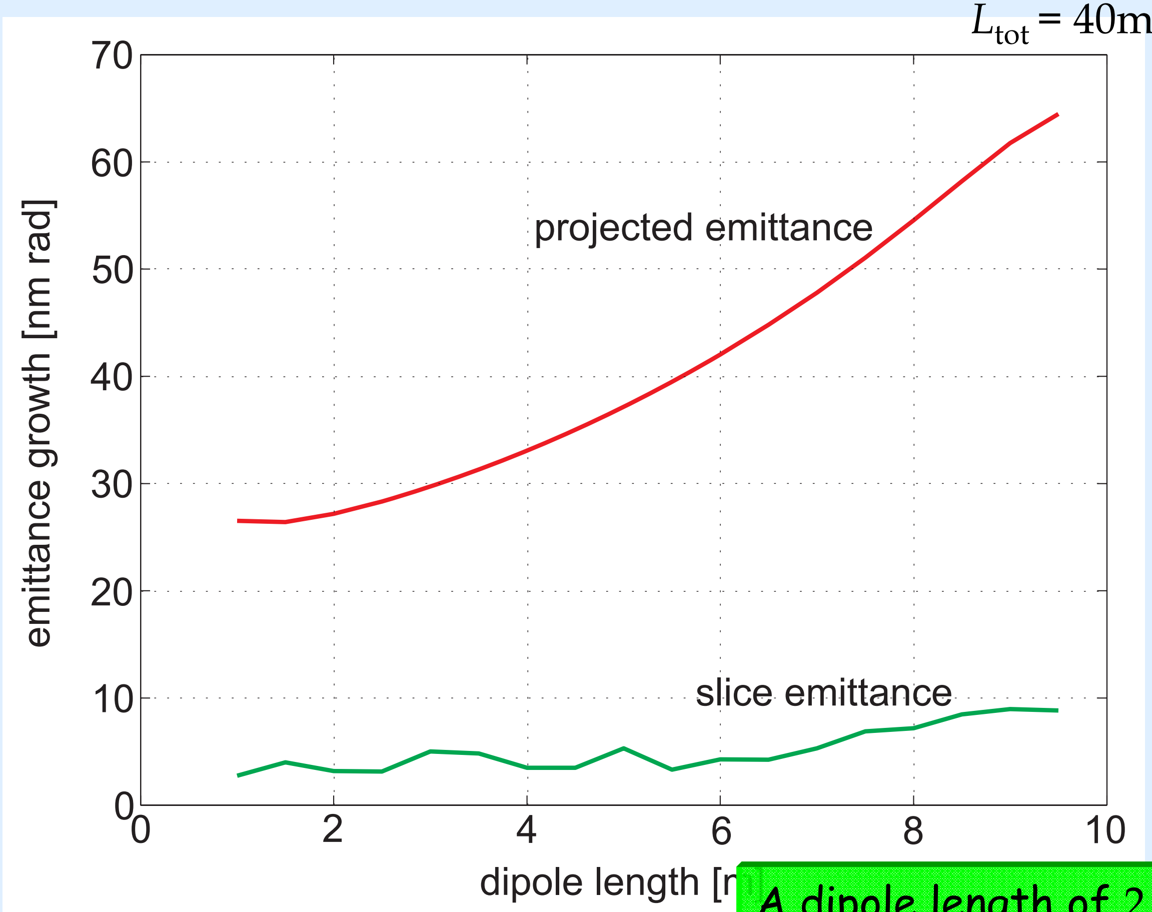
$$\Delta E_{\mathrm{tot}} \approx -\left(\frac{3^{2/3}\, N_e^2\, e_0^2}{4\pi\, \varepsilon_0\, R^{2/3}\, \sigma_s^{4/3}}\right) R\theta \left(1 + \frac{3^{1/3}\, 4}{9} \frac{\sigma_s^{1/3}}{R^{1/3}\, \theta}\left(\ln\left(\frac{\sigma_s \gamma^3}{R}\right) - 4\right)\right)$$

for shorter magnets (i.e. smaller R) the total CSR energy loss can decrease

Coherent Synchrotron Radiation

Beta function and alpha not optimized!



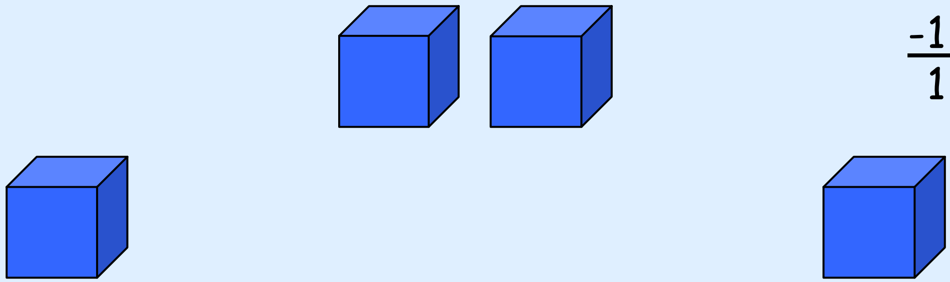


A dipole length of $2\ \text{m}$ is chosen!

Parameter Scans

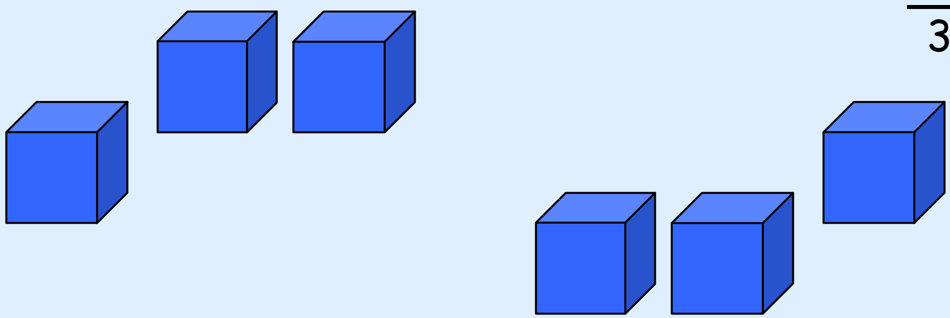
Not only the dipole length but also the dipole position is important

C-chicane:



2 degrees of freedom
-1 needed to correct R_{56}
1 free parameter

S-chicane:

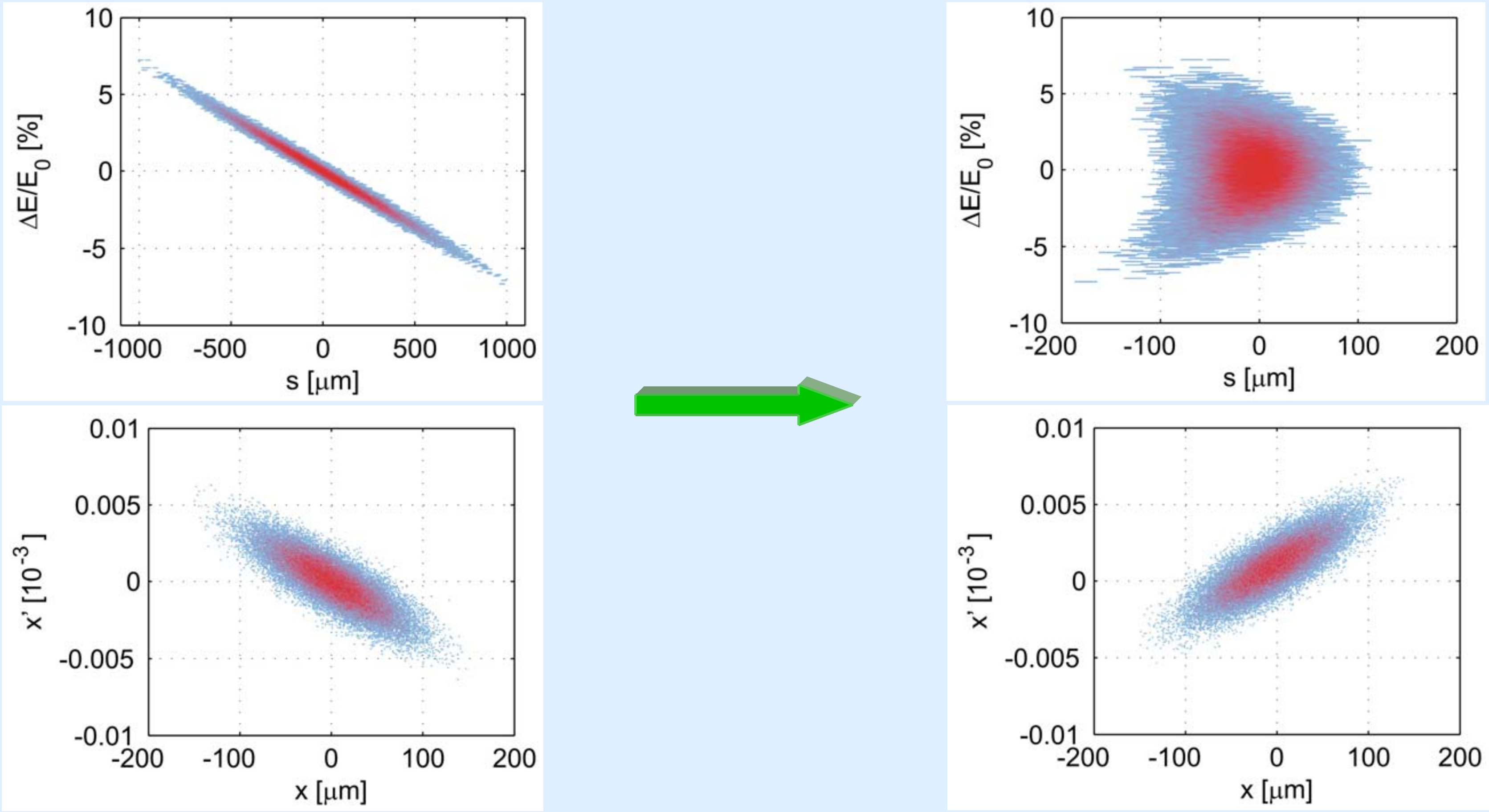


2*2 degrees of freedom
-1 needed to correct R_{56}
3 free parameters

Two additional degrees of freedom: initial beta function and alpha!

1D CSR Simulations, no Shielding

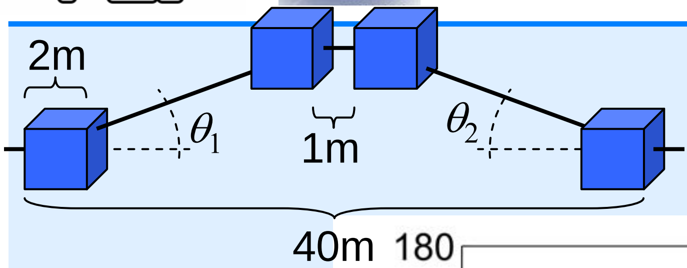
- initially linear energy chirp in longitudinal phase space distribution
- longitudinally and transversally Gaussian charge distribution

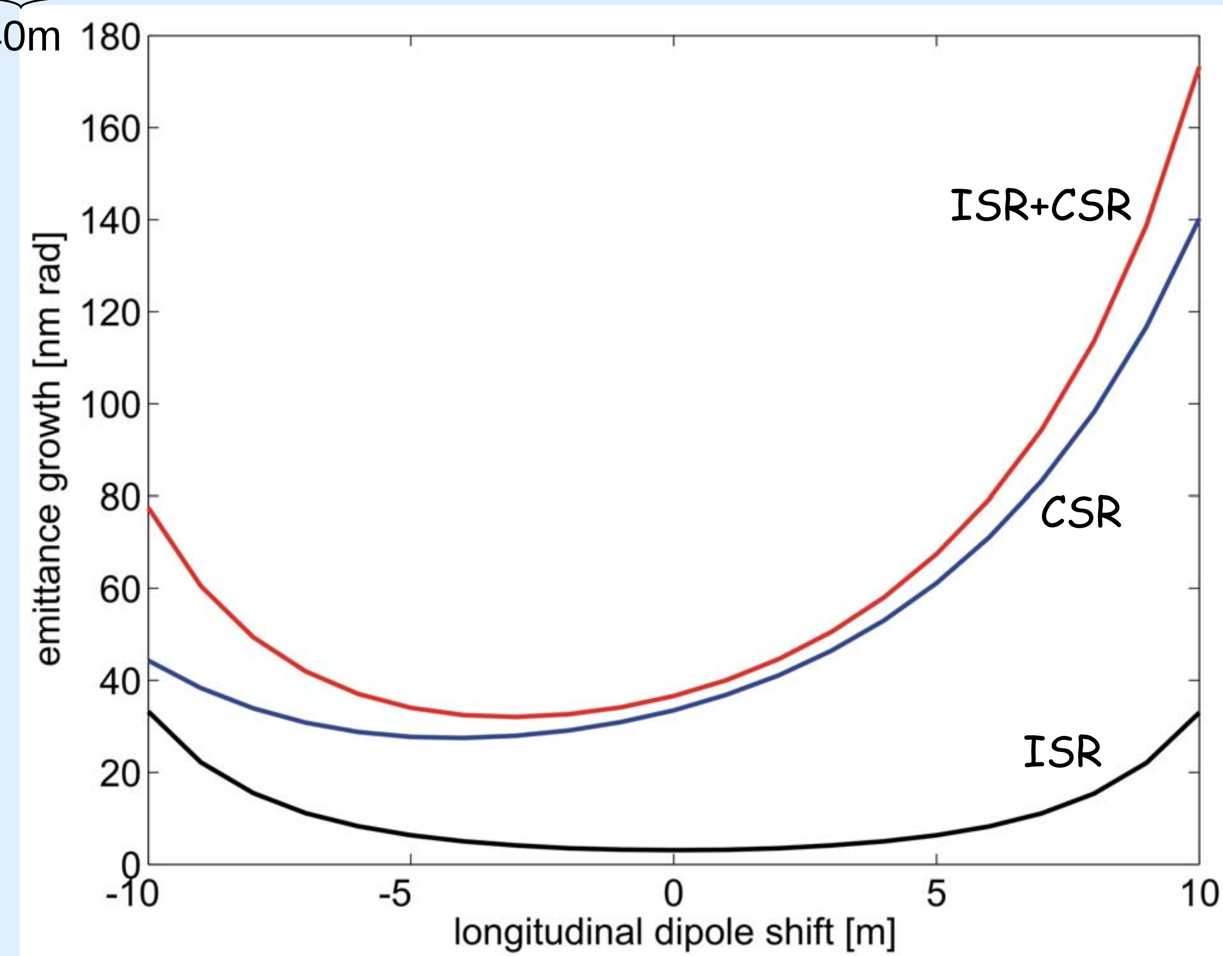


- final longitudinal phase space distributions are almost the same for all chicanes which are compared here
- horizontal phase space distributions look very similar

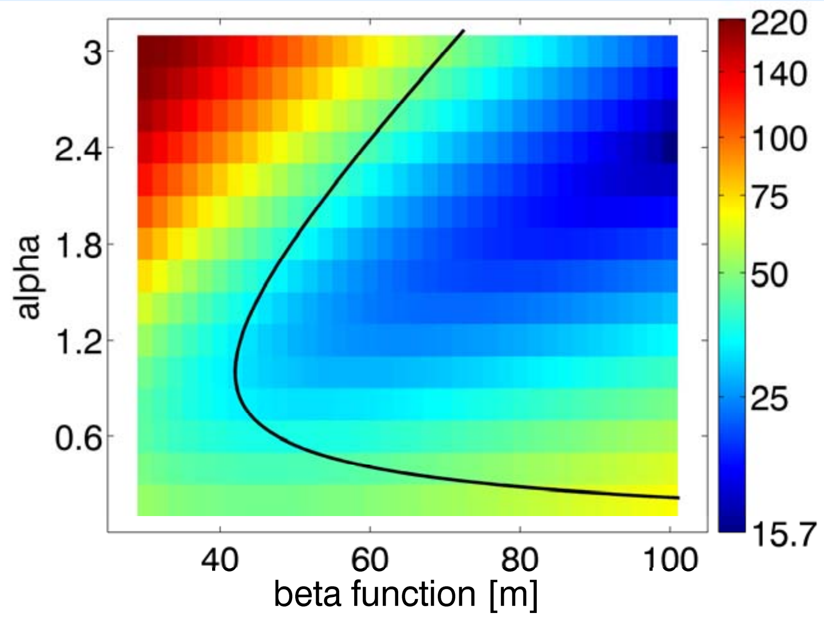
1D CSR Simulations, no Shielding

Beta function and alpha not optimized!

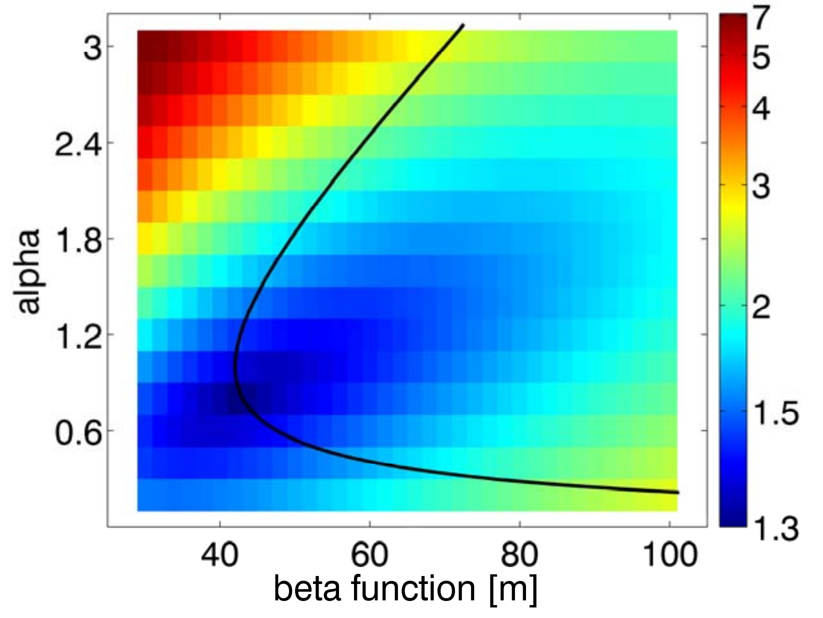




1D CSR Simulations, no Shielding



Dependence of CSR emittance growth in a symmetric C-chicane on the initial Twiss functions.

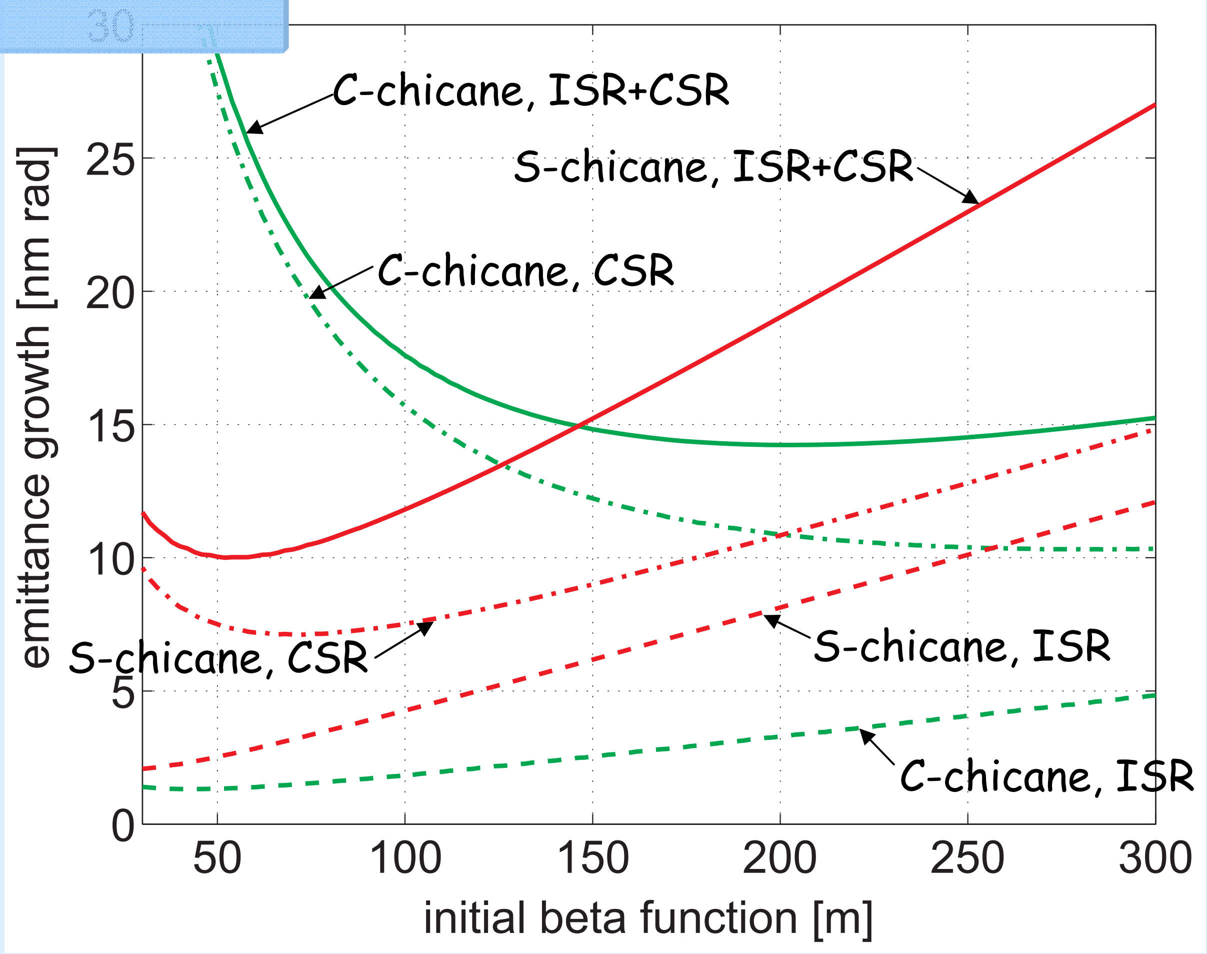


Dependence of ISR emittance growth in a symmetric C-chicane on the initial Twiss functions.

1D CSR Simulations, no Shielding

Dependence of ISR and CSR emittance growth on the initial beta function.

- optimized C- and S-chicane layouts
- best values for alpha



C-chicane:

$\Delta\varepsilon_{C,min} = 14$ nm rad

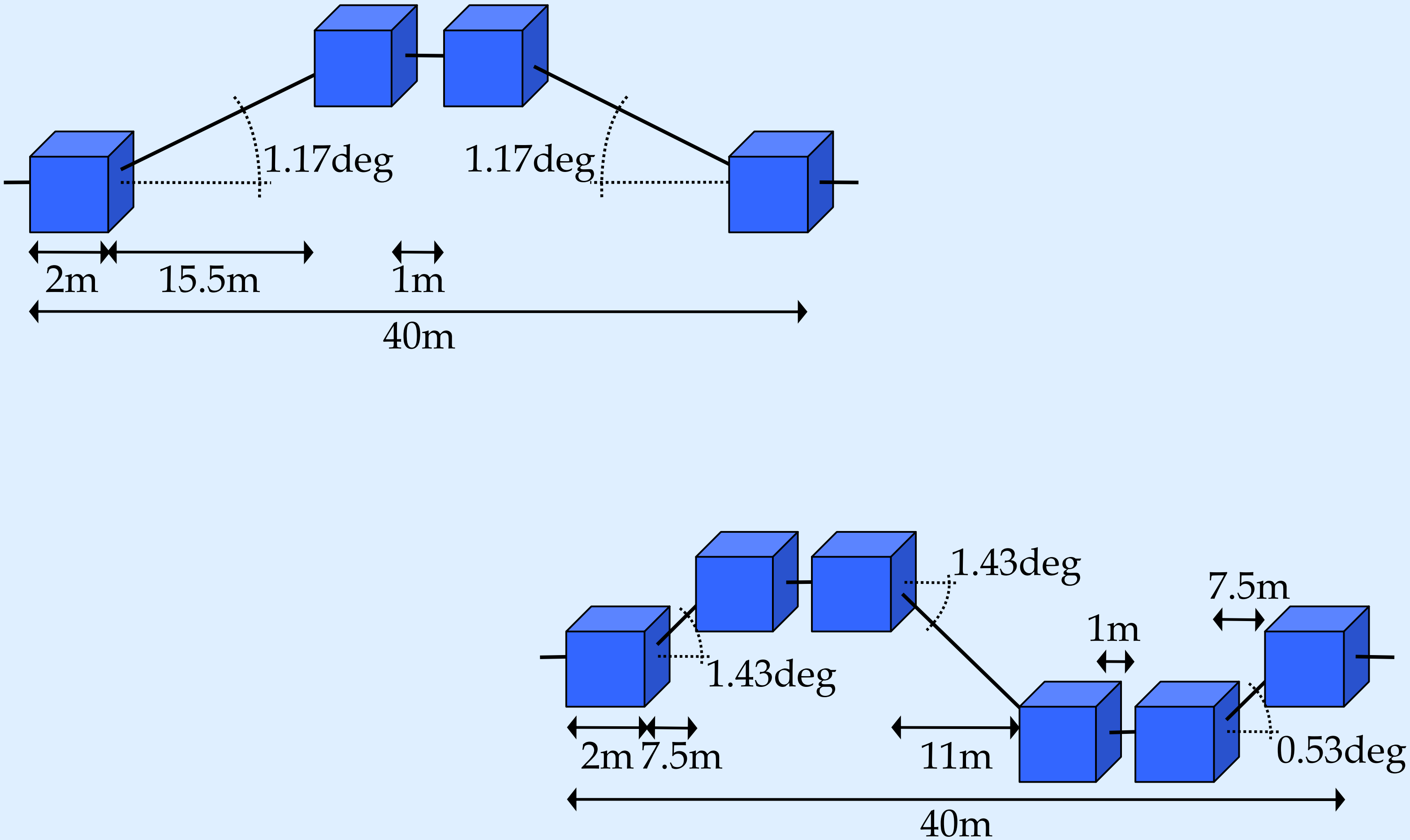
$@\beta_{C,ini} = 200$ m, $\alpha_{C,ini} = 4.8$

S-chicane:

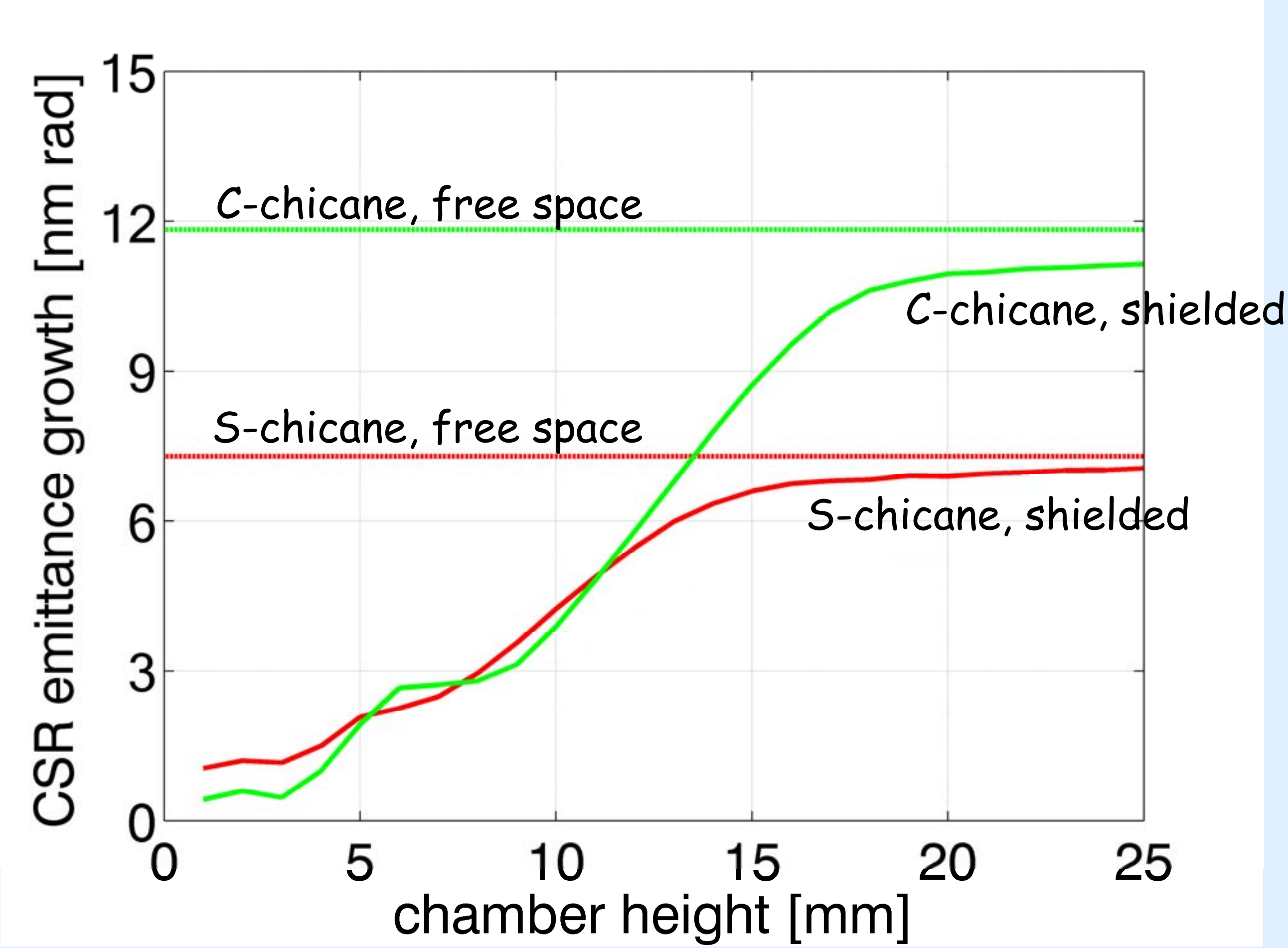
$\Delta\varepsilon_{S,min} = 10$ nm rad

$@\beta_{S,ini} = 52$ m, $\alpha_{S,ini} = 1.6$

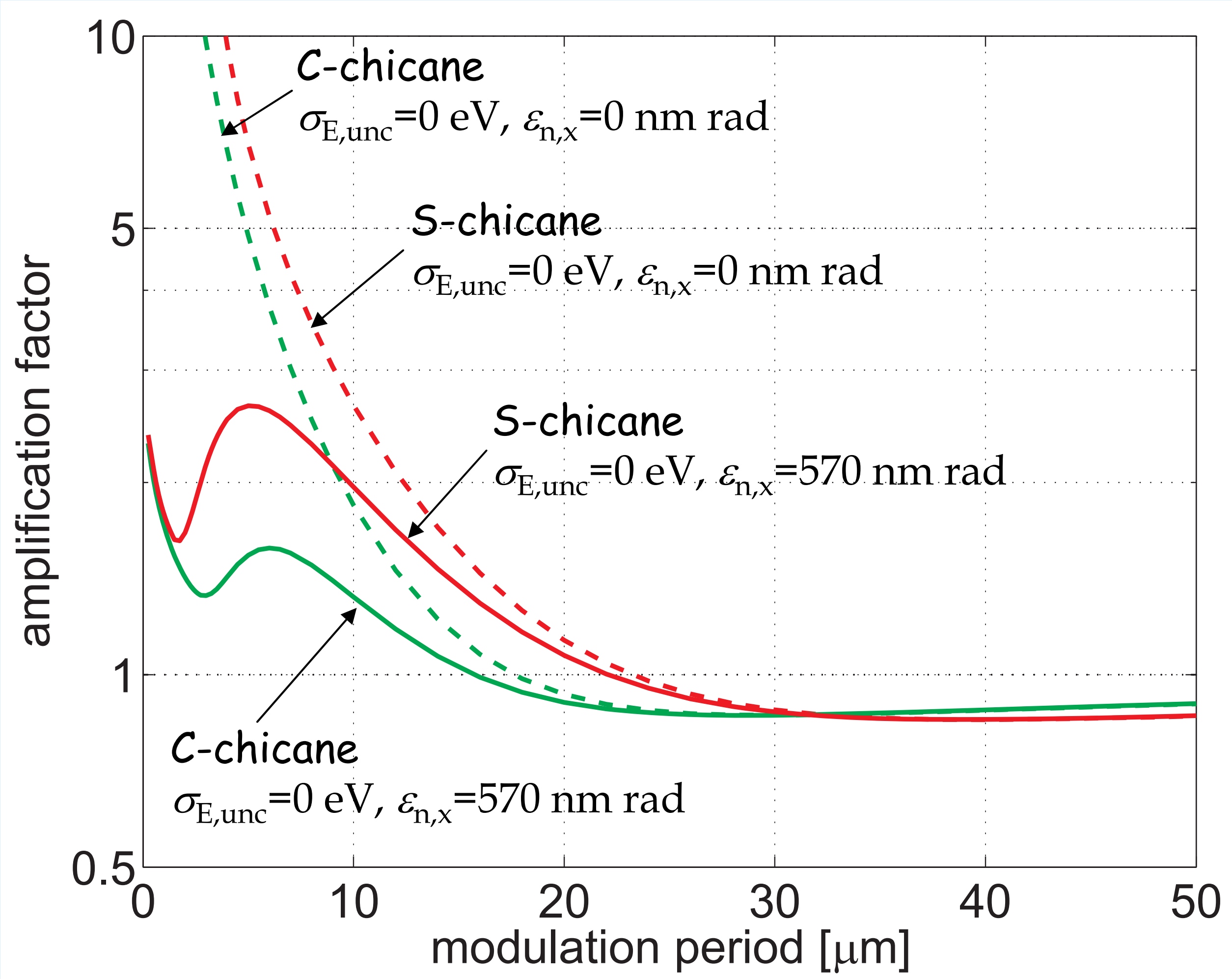
Optimized Chicane Layouts



Shielding Effect (parallel plates)



CSR Microbunch Instability



The high uncorrelated energy spread suppresses the amplification completely!

Summary (Main Beam Bunch Compressor)

- The final main beam bunch compressor must meet tight specifications (CSR emittance growth $< 30\ \mathrm{nm\ rad}$).
- Dipole length of $2\ \mathrm{m}$ is optimized for ISR and CSR emittance growth.
- Parameter scans for C-chicane and S-chicanes have been performed to find the best layout and the best initial optics.
- The best achieved values are $\Delta\varepsilon_{\mathrm{C,min}} = 14\ \mathrm{nm\ rad}$ for the C-chicane and $\Delta\varepsilon_{\mathrm{S,min}} = 10\ \mathrm{nm\ rad}$ for the S-chicane.
- Shielding can improve the CSR emittance growth if the chamber is narrower than $20\ \mathrm{mm}$.
- The CSR Microbunch Instability is not an issue due to the high uncorrelated energy spread.

Outlook (Main Beam Bunch Compressor)

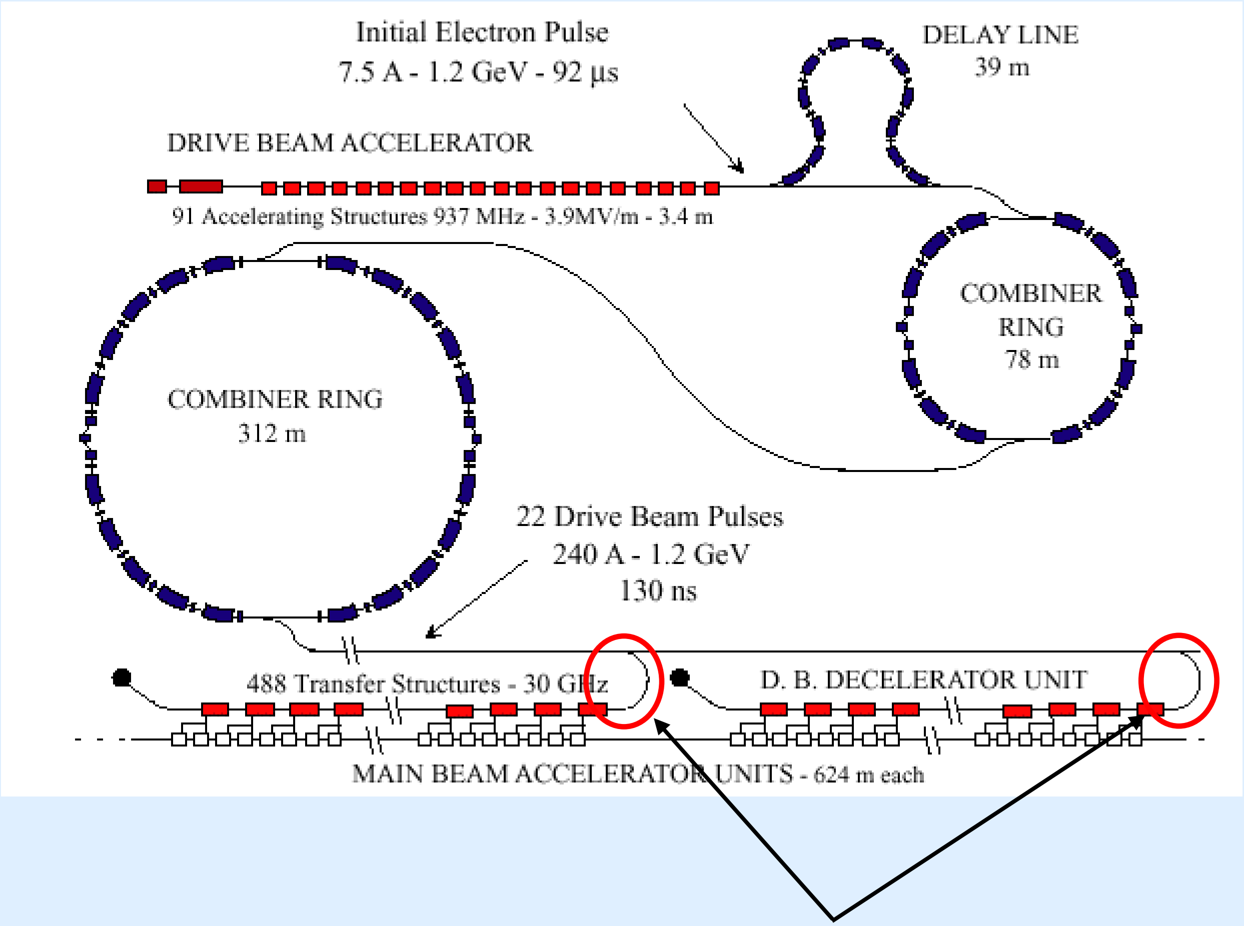
Perform more sophisticated beam dynamics simulations

- use a more realistic charge distribution (incl. RF curvature, non Gaussian profile,...)
- add resistive wall wakes (best would be to incl. CSR and wakes in the same simulation)
- 2D and 3D CSR simulations

Study the flexibility and error tolerances of the chicanes

- change R_{56}
- change energy spread (correlated and uncorrelated)
- add jitter of dipole position, roll, tilt and strength
- add RF amplitude and phase jitter

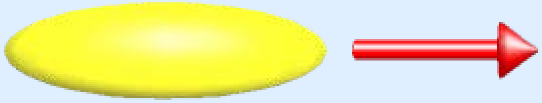
Drive Beam BC, Turn Around and Phase Feed-Forward



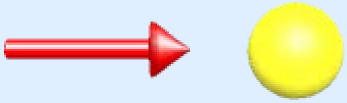
Bunch Compressor, Turn Around Loop and Phase Feed-Forward

Drive Beam BC, Turn Around and Phase Feed-Forward

$$E_0 = 2\ \mathrm{GeV}$$
$$Q_0 = 10\ \mathrm{nC}$$
$$\sigma_{\mathrm{s,i}} = 4\ \mathrm{mm}$$
$$\varepsilon_{\mathrm{n,x}} = 100\ \mathrm{mm\ mrad}$$
$$\varepsilon_{\mathrm{n,y}} = 100\ \mathrm{mm\ mrad}$$
$$\frac{\sigma_{\mathrm{E,unc}}}{E_0} = 2.5 \cdot 10^{-4}$$
$$\frac{1}{E_0}\frac{dE}{ds} = -2.5\ \mathrm{m}^{-1}$$

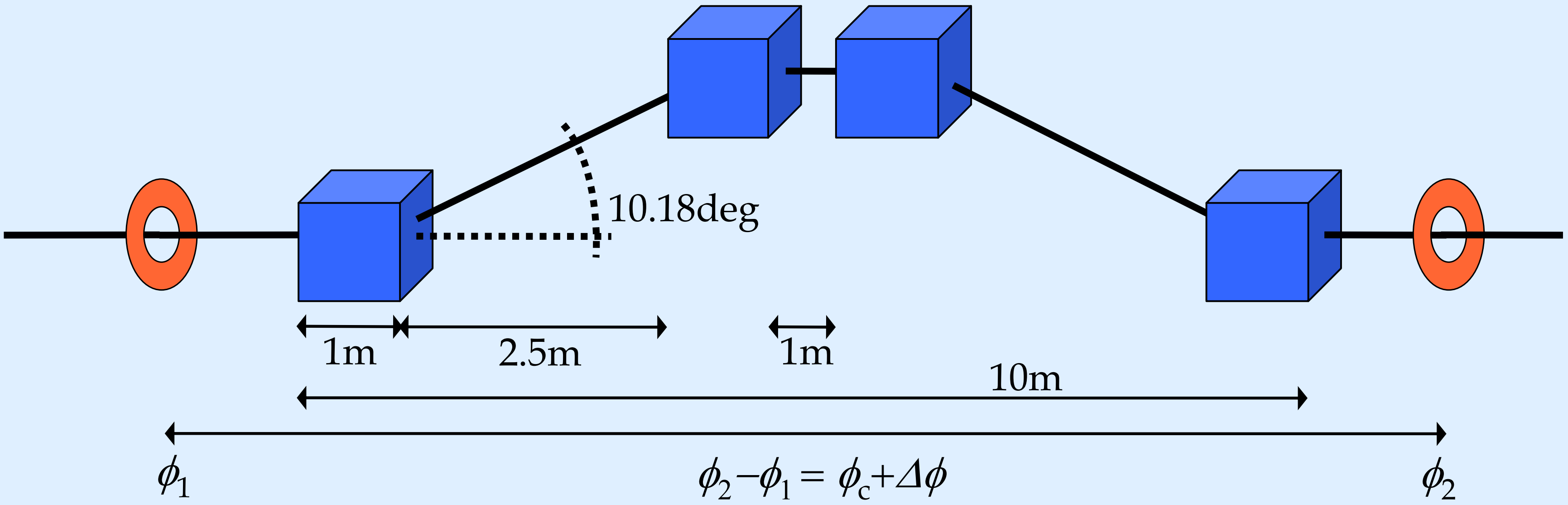


1) first phase-measurement
2) non-isochronous beam line to get a phase error proportional to the energy error
3) second phase measurement to estimate the energy error
4) turn around loop to direct the drive beam into the decelerator
5) bunch compressor chicane
6) phase correction



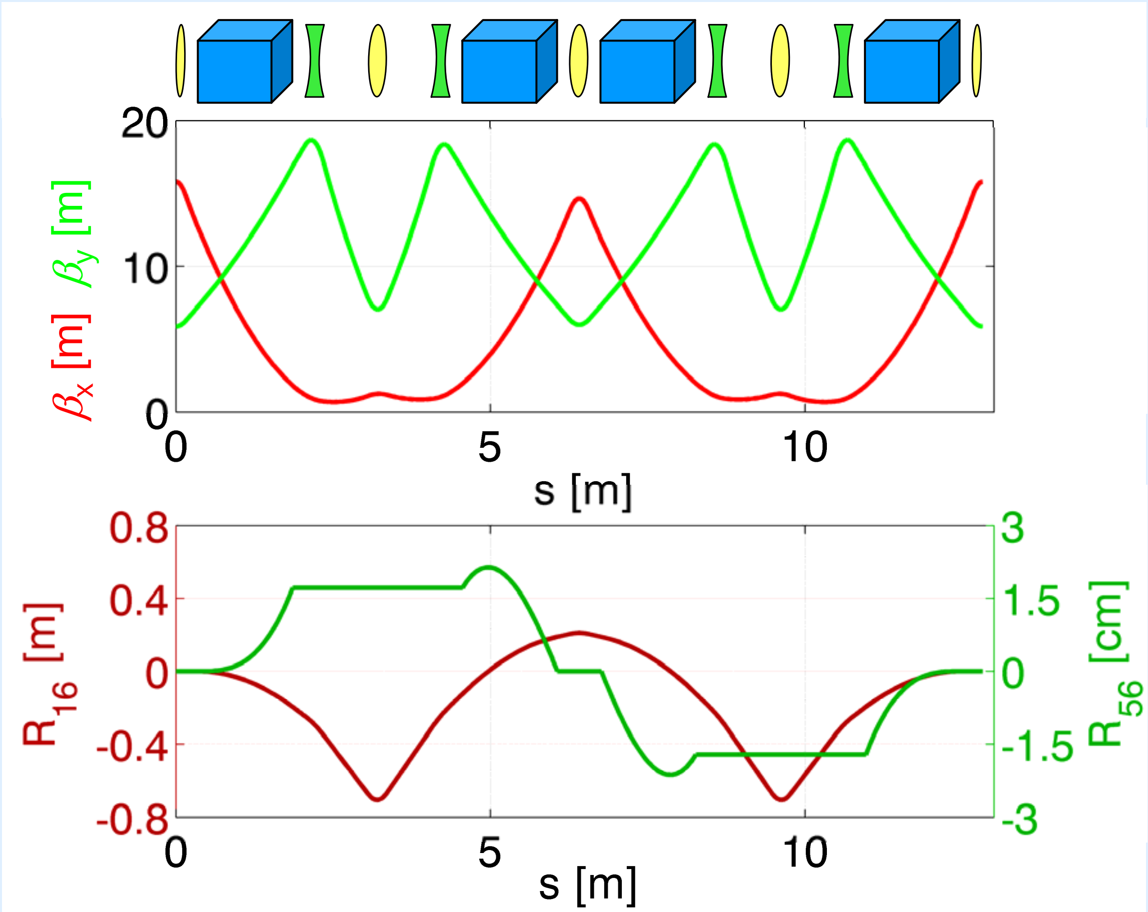
$$\sigma_{\mathrm{s,i}} = 0.4\ \mathrm{mm}$$
$$\frac{\sigma_{\mathrm{E,tot}}}{E_0} < 1\%$$
$$\varepsilon_{\mathrm{n,x}} < 110\ \mathrm{mm\ mrad}$$
$$\varepsilon_{\mathrm{n,y}} < 110\ \mathrm{mm\ mrad}$$

Phase and Energy Measurement



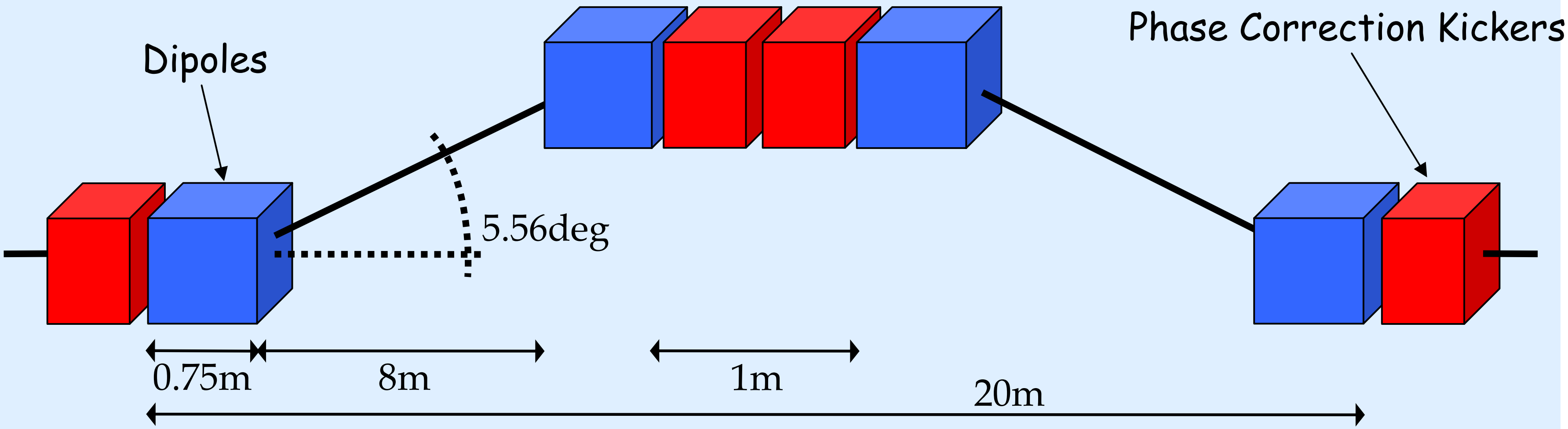
- momentum compaction factor of the chicane: $R_{56} = -0.2$ m
- final bunch length: $\sigma_{s,f} = 2$ mm
- CSR emittance growth: $\Delta\varepsilon_{n,x} < 1$ mm mrad
- energy error $dE/E = 10^{-5}$ => phase error $\Delta\phi = 0.072$deg (30 GHz)

Turn Around Loop



- bend angle per dipole: $\theta = 15$ deg
- achromatic, isochronous
- CSR emittance growth per arc: $\Delta\varepsilon = 1\text{–}2$ mm mrad

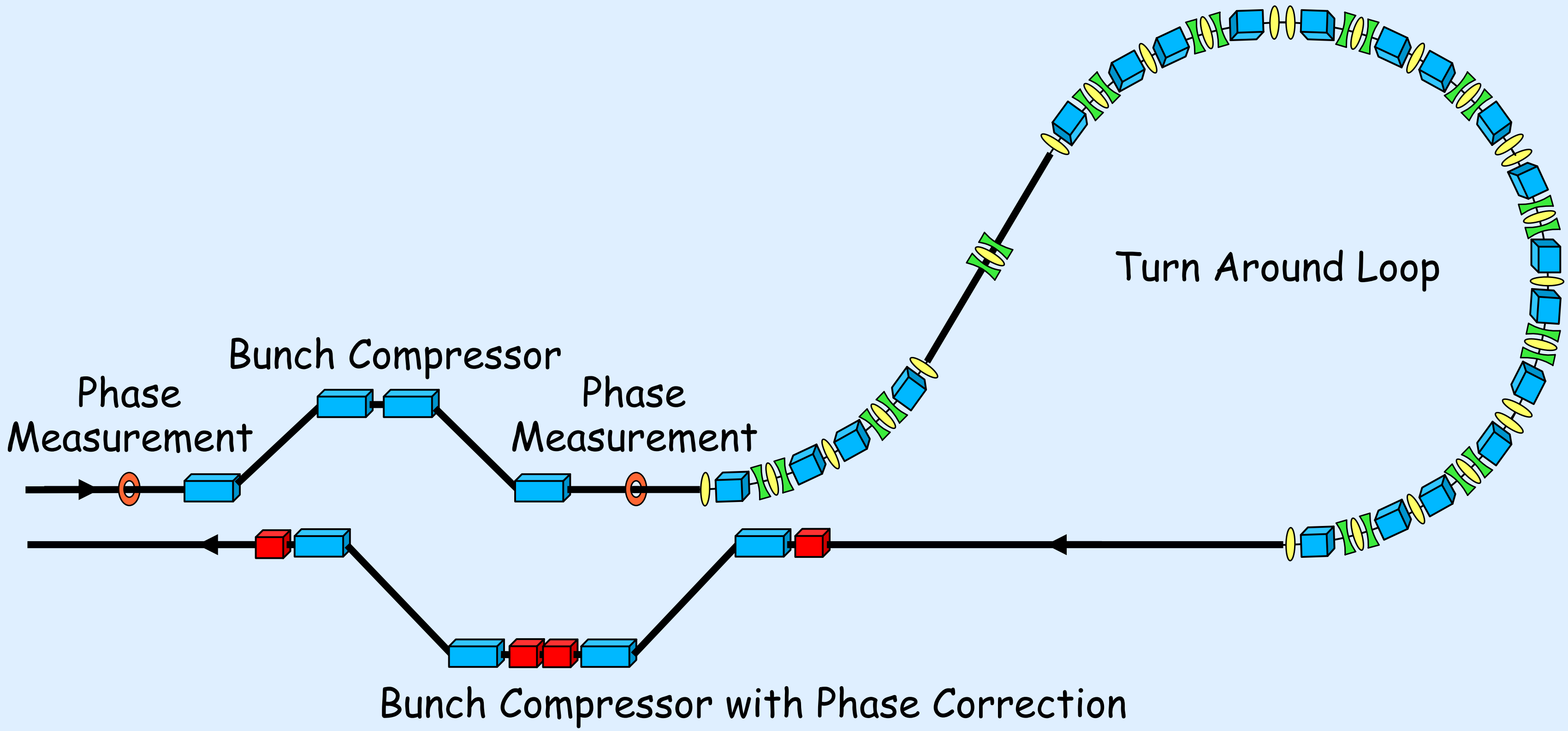
Final Bunch Compressor and Phase Correction



- momentum compaction factor of the chicane: $R_{56} = -0.16$ m
- final bunch length: $\sigma_{s,f} = 0.4$ mm
- CSR emittance growth: $\Delta\varepsilon_{n,x} = 3$ mm mrad

- path length tunability: $\Delta l = \pm 100$ µm
  => phase tunability: $\Delta\phi = \pm 3.6$ deg
- required kicker strength: $\theta_{kick} = \pm 60$ µrad
- induced bunch length jitter: $\Delta\sigma_s = \pm 2$ µm

Beam Line Overview



Summary (Drive Beam BC, TAL and PFF)

- To achieve the required drive beam phase stability a phase feed-forward is included in the beam line in front of the decelerator.
- Phase and energy jitter are measured in front of the turn around loop by two phase measurements intersected by a bunch compressor chicane.
- The turn around loop is achromatic and isochronous. Its total length is 76 m <=> 250 ns.
- The phase correction is included in the final bunch compressor chicane behind the turn around loop. The kicker strength required for $\Delta l = \pm 100\ \mu\mathrm{m}$ is $\theta_{\mathrm{kick}} = \pm 60\ \mu\mathrm{rad}$.
- CSR emittance growth in the bunch compressors and the turn around loop is just within the specification of $\Delta\varepsilon_{\mathrm{max}} = 10$ mm mrad.

Outlook (Drive Beam BC, TAL and PFF)

Improve lattice of Turn Around Loop

- tune sextupoles to reduce chromaticity
- change lattice to reduce T_{566}?

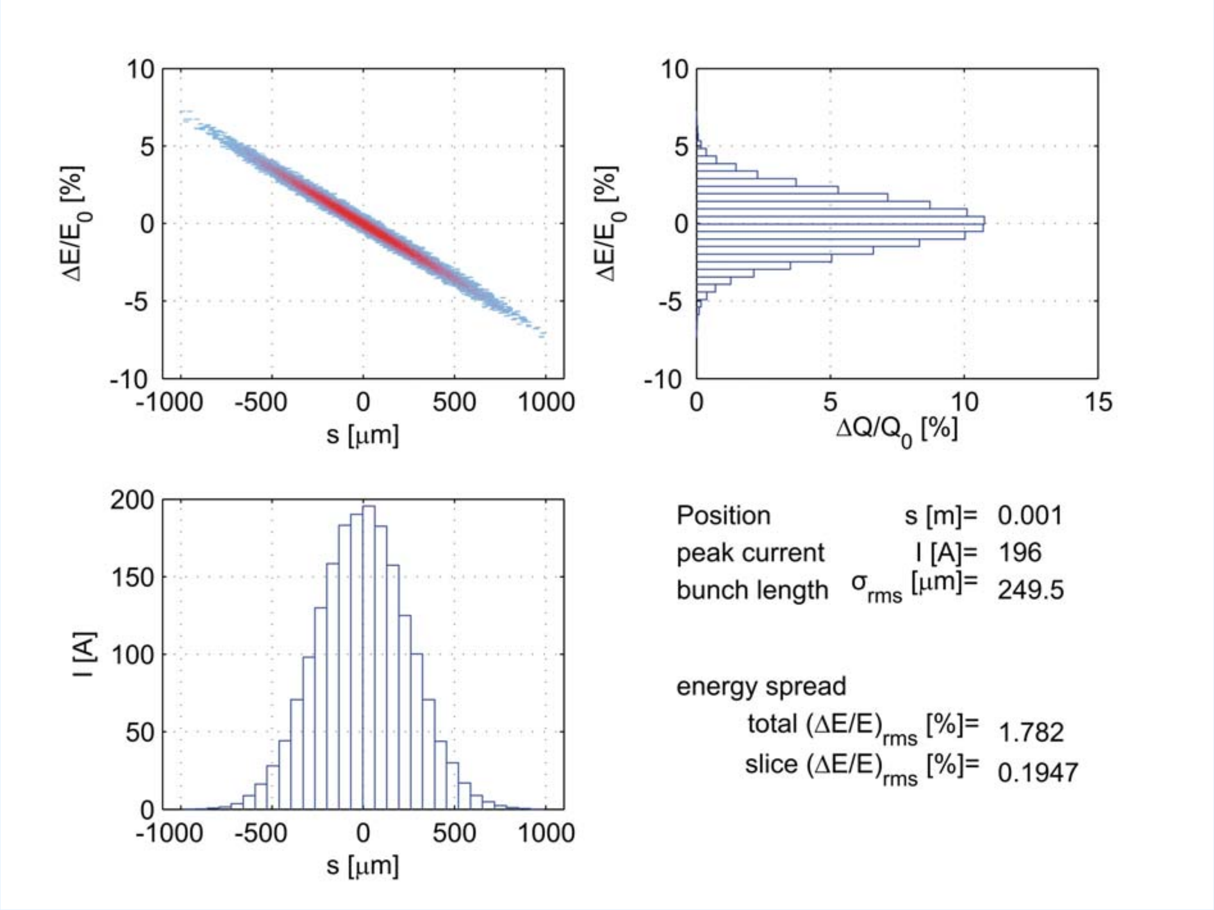
Perform more sophisticated beam dynamics simulations

- use a more realistic charge distribution (incl. RF curvature, non Gaussian profile,...)
- add resistive wall wakes
- 2D and 3D CSR simulations

Study the flexibility and error tolerances

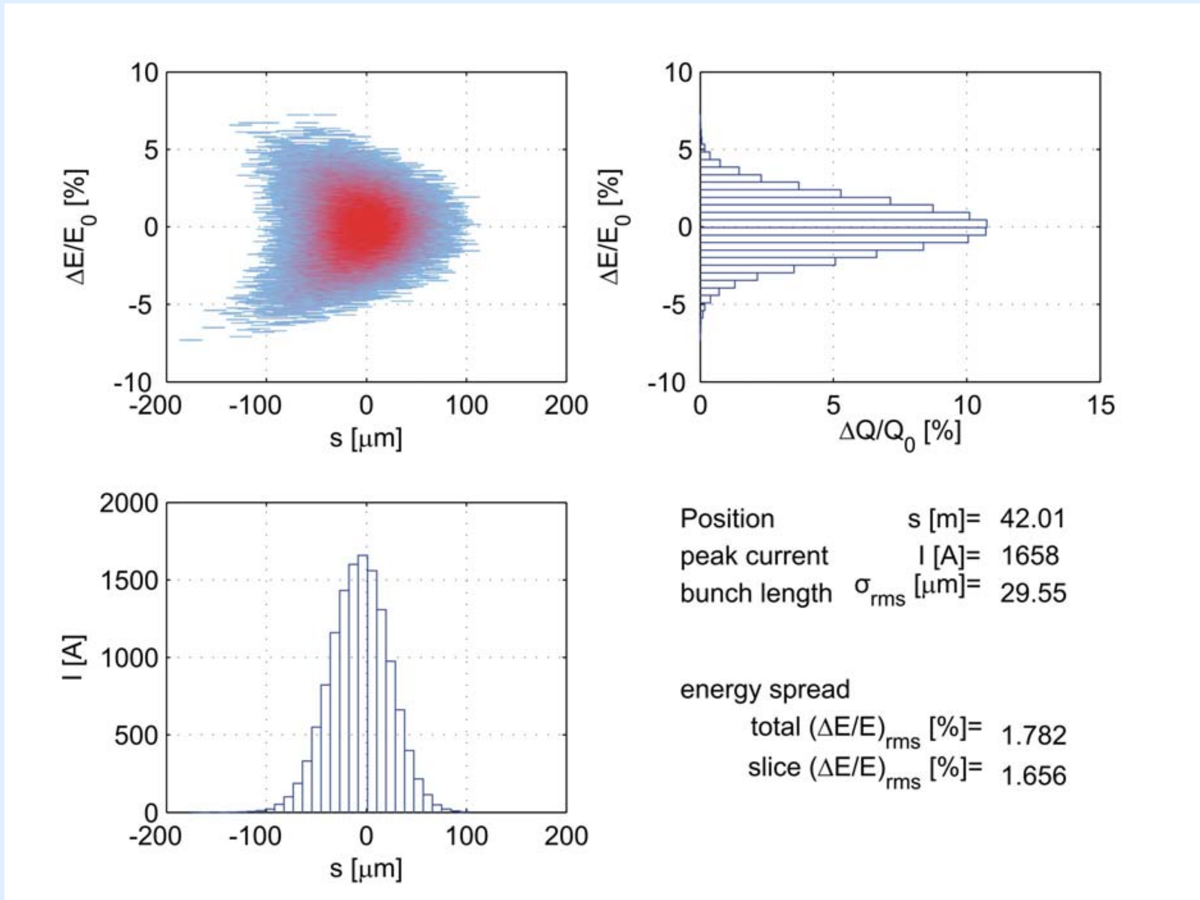
- change initial bunch length, energy spread (correlated and uncorrelated)
- add jitter of magnet position, roll, tilt and strength
- add RF amplitude and phase jitter

Main Beam Bunch Compressor, 1D CSR Simulations

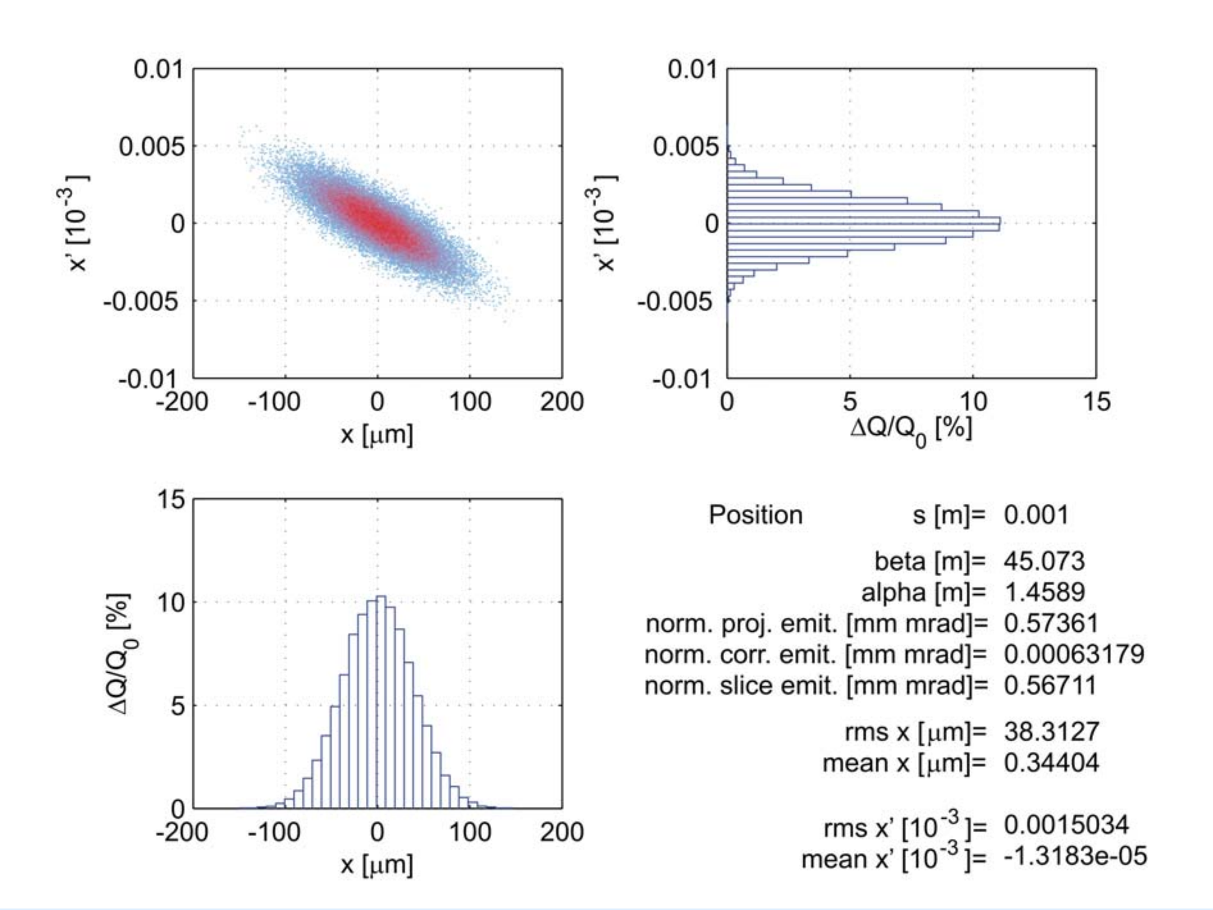


initial longitudinal phase space

Main Beam Bunch Compressor, 1D CSR Simulations

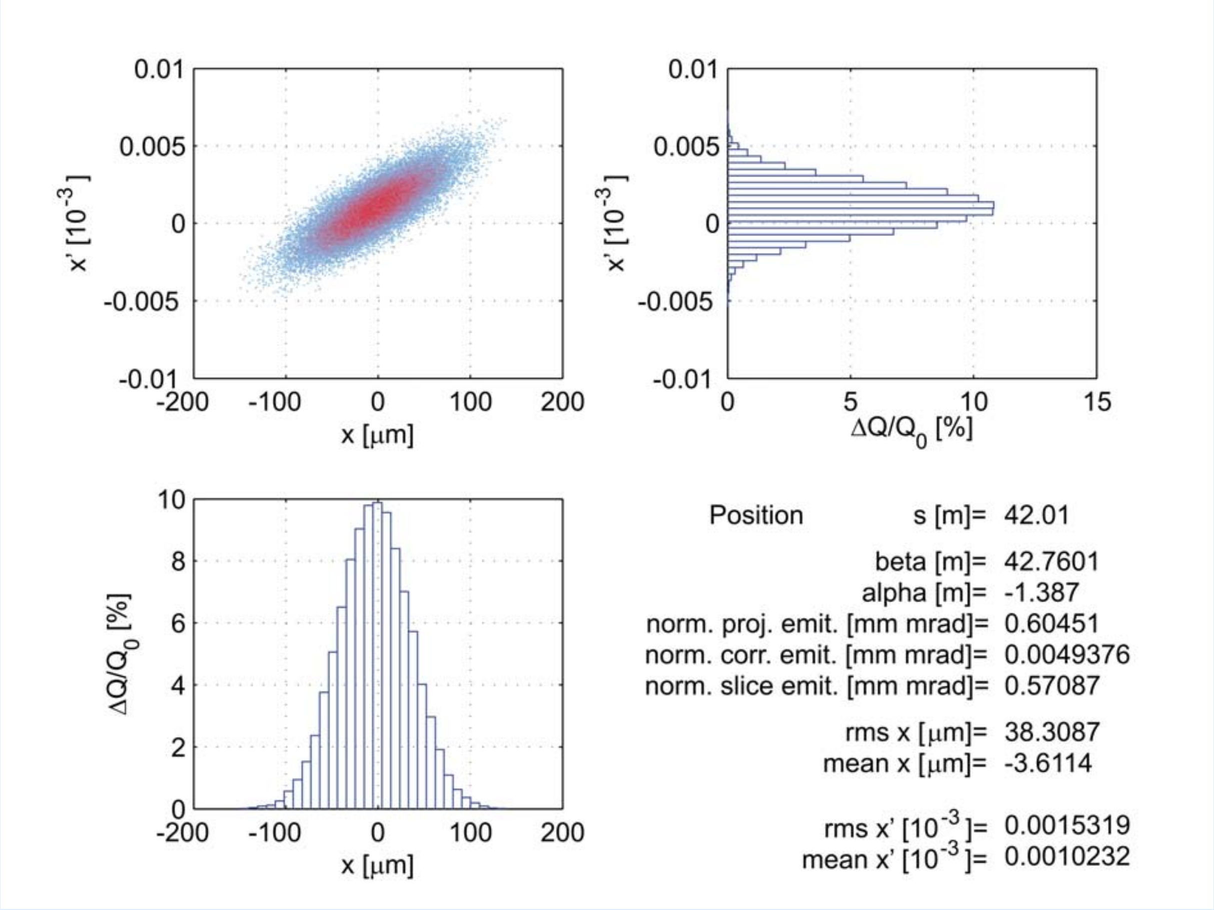


final longitudinal phase space (example, almost the same for all chicanes)



initial transverse phase space

Main Beam Bunch Compressor, 1D CSR Simulations



final transverse phase space (example, similar for all chicanes)

Drive Beam, Phase Correction