Beam Dynamics in the RTML

adopted from ILC: Damping Ring To Main Linac Transport = RTML

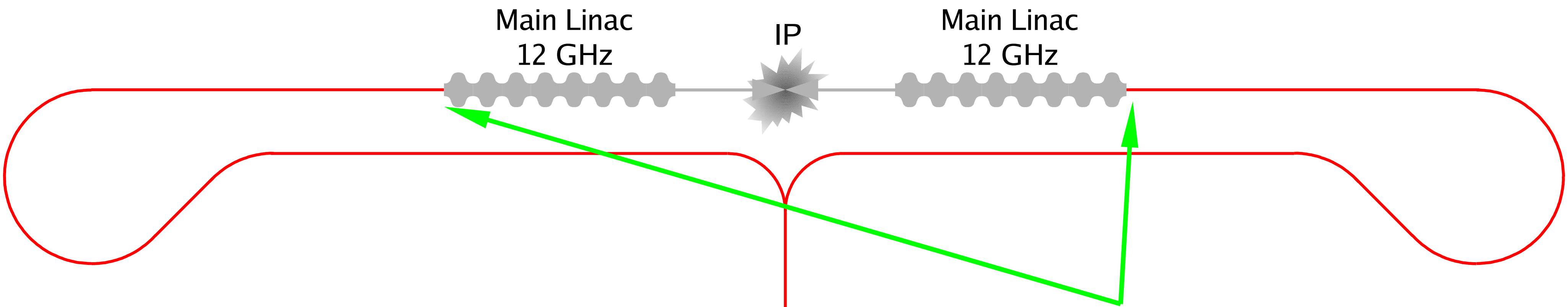
=> Functions

=> Beam Dynamics Challenges

=> Constraints / Considerations

=> Outlook

Definition

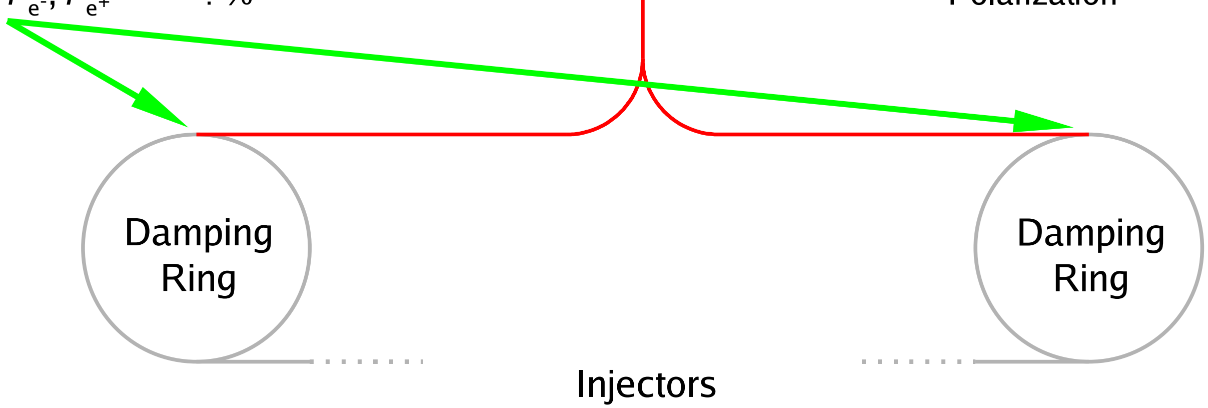


initial = at entrance of RTML
= exit of Damping Rings

Parameter	Symbol	Value	Unit
Energy	E_0	2.424	GeV
Number of Particles	N_e	4.1×10^9	
Charge	Q_0	0.66	nC
RMS Bunch Length	σ_s	1530	μm
Normalized Emittance	$\varepsilon_{n,x}$	550	nm rad
	$\varepsilon_{n,y}$	5	nm rad
Relative Energy Spread	σ_E/E_0	0.134	%
Polarization	P_{e^-}, P_{e^+}	?	%

final = at exit of RTML
= entrance of Main Linac

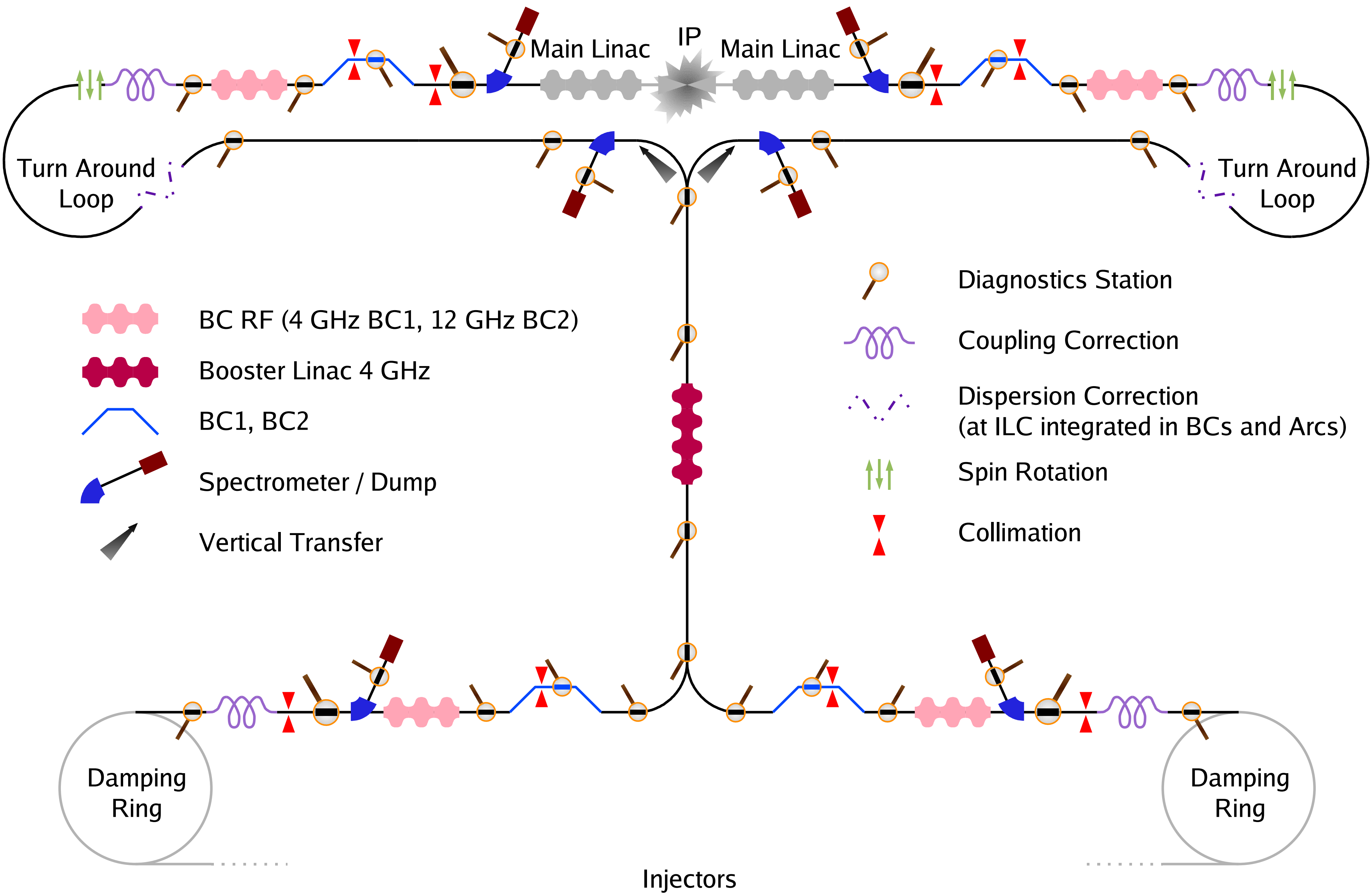
Parameter	Symbol	Value	Unit
Energy	E_0	9	GeV
Number of Particles	N_e	$>3.7 \times 10^9$	
Charge	Q_0	>0.6	nC
RMS Bunch Length	σ_s	44	μm
Normalized Emittance	$\varepsilon_{n,x}$	<600	nm rad
	$\varepsilon_{n,y}$	<10	nm rad
Relative Energy Spread	σ_E/E_0	<1.5	%
Polarization	P_{e^-}, P_{e^+}	?	%



- Transport
  - => Transport Lines, Turn Around Loops, Arcs
- 6D Phase Space Shaping / Matching
  - longitudinal => Bunch Compressors incl. RF for Energy Chirp, Collimators
  - transverse => Optics, Collimators
- Acceleration
  - => Booster Linac
- Re-Orientation of Polarizationvector
  - => Spin Rotator
- Characterization
  - => Diagnostics (Position, RMS Length, longitudinal and transverse Profiles, Energy, Energy Spread, Emittance, Charge, Phase, Polarization,...)
- Correction / Tuning
  - => Dispersion Correction (at ILC: normal and skew quads integrated in BCs, Loop, Arcs), Coupling Correction, Phase Correction / Synchronization, Feedback, Feedforward
- Others
  - => Intermediate Beam Dumps, Spectrometer Beam Lines...

= ILC RTML, but beam parameters and layout are different

Functional Layout (Draft)



Parameters / Constraints

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Total Energy Spread	σ_E/E_0	0.134	%	± ? %
Uncorrelated Energy Spread	$\sigma_{E,u}/E_0$	0.134	%	± ? %
Energy Chirp	$1/E_0\ dE/ds$	0	m^{-1}	± ? %
Polarization	P_{e^-}, P_{e^+}	?	%	± ? %
Phase Offset	$\Delta\phi$	0	deg	± ? deg

final = at exit of RTML
= entrance of Main Linac

Parameter	Symbol	Value	Unit	Jitter Tolerance
Energy	E_0	9	GeV	± 0.1 %
Number of Particles	N_e	$>3.7 \times 10^9$		± 0.1 %
Charge	Q_0	>0.6	nC	± 0.1 %
RMS Bunch Length	σ_s	44	μm	± 0.5 %
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Phase Offset	$\Delta\phi$	0	deg	± 0.1 deg

The RTML is considered not drive specifications, but just to adapt to them.
Furthermore, it must be able to correct incoming errors or jitter.
This is true only within a reasonable parameter space! Current achievement:

$$\Delta\varepsilon_{x,RTML} < 100 \text{ nm rad}$$
$$\Delta\varepsilon_{y,RTML} < 5 \text{ nm rad}$$

But not all beam lines and beam dynamics issues have been studied yet.

Parameters / Constraints

initial = at entrance of RTML
= exit of Damping Rings

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final = at exit of RTML
= entrance of Main Linac

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Polarization	P_{e^-}, P_{e^+}	? %	± ? %
Phase Offset	$\Delta\phi$	0 deg	± 0.1 deg

The emittance budget currently allocated to the RTML is most likely too tight!
Somebody has to improve: DR? ML? RTML?

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But not all beam lines and beam dynamics issues have been studied yet.

Sources of Beam Quality Degradation

- Misalignment
  static and dynamic, e.g. ground motion, vibration,...
  => all components incl. beam pipes
- Magnetic Field Errors
  magnet strength / power supply ripple,
  residual field components, stray fields, earth field
  => along entire RTML
- RF Voltage and Phase
  => in booster linac and bunch compressor RF
- Wake Fields
  geometry, resistivity, surface roughness,...
  => cavities, collimators, beam pipes
- Space Charge Fields => in transfer lines
- Synchrotron Radiation
  => ISR in turn around loops and arcs
  => CSR in bunch compressors
- Beam-Gas Interaction / Beam-Photon Scattering
  => Fast Beam-Ion Instability in transfer lines
- Jitter of incoming Beam Parameters
  phase, energy, charge, length,...

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  phase, energy, charge, length,...

As identified in ILC RDR:

- Static Misalignment
  => of cavities, spin rotator, quadrupoles and dipoles
- Stray Magnetic Fields
  => in transfer line
- Phase Jitter
  => by cavity errors
- Collimator Wake Fields
- Space Charge => in transfer line
- ISR and CSR
  => in bunch compressors, loops and arcs
- Beam-Ion Instabilities
  => in transfer line
- Halo Formation from Scattering
  => in all beam lines

Sources of Beam Quality Degradation

- Misalignment => single bunch effect, dispersion, coupling, pointing stability
  static and dynamic, e.g. ground motion, vibration,...
  => all components incl. beam pipes
- Magnetic Field Errors => single bunch effect, dispersion, coupling, pointing stability, bunch shape, emittance, optics mismatch
  magnet strength / power supply ripple,
  residual field components, stray fields, earth field
  => along entire RTML
- RF Voltage and Phase => single bunch effect, synchronization, bunch length, (energy)
  => in booster linac and bunch compressor RF
- Wake Fields => single and multi bunch effect, energy distribution, optics mismatch bunch shape, emittance
  geometry, resistivity, surface roughness,...
  => cavities, collimators, beam pipes
- Space Charge Fields => in transfer lines => single bunch effect, energy distribution
- Synchrotron Radiation => single bunch effect, energy distribution, optics mismatch bunch shape, emittance
  => ISR in turn around loops and arcs
  => CSR in bunch compressors
- Beam-Gas Interaction / Beam-Photon Scattering => (single and) multi bunch effect, transverse profiles, emittance
  => Fast Beam-Ion Instability in transfer lines

- Jitter of incoming Beam Parameters
  phase, energy, charge, length,...

Preliminary Studies on Error Tolerances

Preliminary studies on error tolerances have been performed for:

- the transfer line
  achieved promising results using beam-based-alignment,
  assuming 100μm magnet misalignment and
  10μm misalignment of BPMs relative to quads

- the bunch compressor chicanes
  roll error should be ~0.1mrad, alignment of 100μm sufficient,
  required magnet field error within 10^{-4} - 10^{-5}

- the turn around loop
  transverse quadrupole and sextupole alignment <10μm, roll error ~10μrad,
  alignment of dipoles ~100μm, roll error <10μrad,
  magnet field errors ~10^{-5}

=> main challenge: preservation of vertical emittance
=> alignment of the order of 10 - 100μm required
=> transverse alignment of quadrupoles and sextupoles in loop most challenging
=> nevertheless, alignment seems to be feasible

Implications on Beam Parameters

There are only a few free beam parameters, which are not fixed by initial and final specifications, but which stem from beam dynamics issues in the RTML:

- energy between Booster Linac and BC2 RF (may be even up to Main Linac),
  low energy is good for ISR in Turn Around Loop ($\Delta\varepsilon \sim E^6$),
  but bad for BC2 RF (wake fields)
- bunch length between BC1 and BC2,
  short bunches reduce RF curvature (sinusoidal wave),
  but increase CSR in Turn Around Loop ($\Delta\varepsilon \sim 1/\sigma_s^{4/3}$)
- since full compression is requested for both chicanes
  energy spread between BC1 and BC2 is not a free parameter

Bunch Compressor Design

Important boundary conditions:

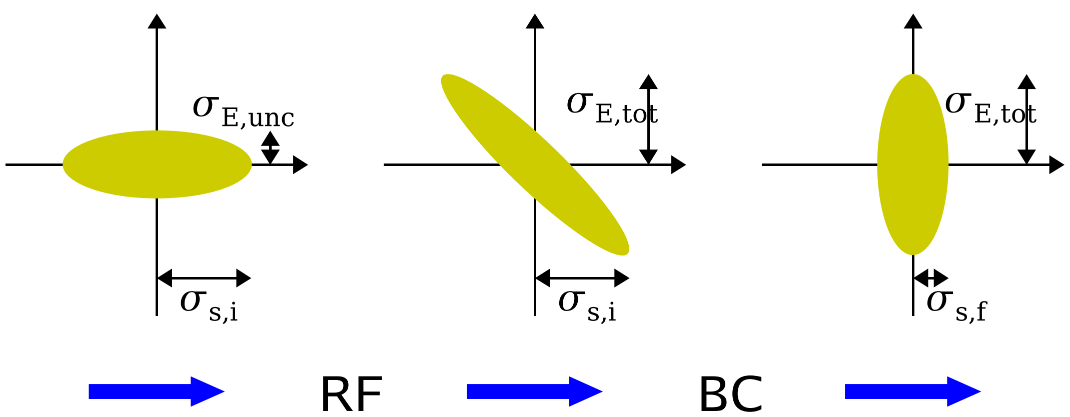
- full compression in BC1 requested, but not mandatory
- definitely full compression in BC2 needed

As long as full compression is requested in both BCs:

- the bunch compression system can be characterized by four independent parameters
- three parameters are given: initial and final bunch length, initial energy spread
- intermediate bunch length can be chosen as the last free parameter

=> the R_{56} values and the energy chirps are unambiguously defined

- R_{56} of BC2 can only be reduced by compressing stronger in BC1, not by increasing energy chirp!
- stronger compression in BC1 only by using higher energy chirp and lower R_{56}



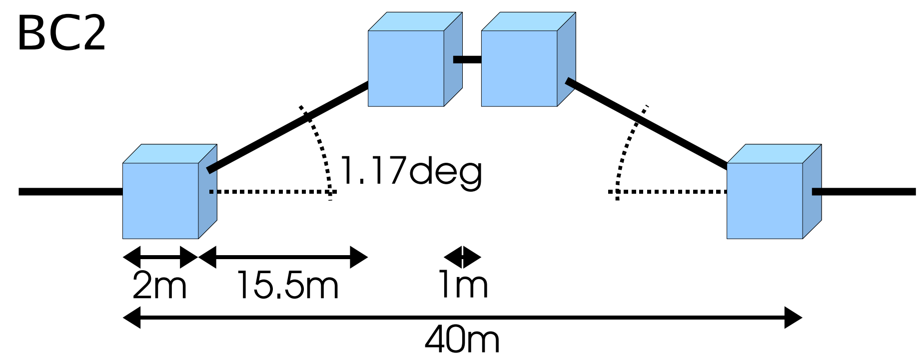
$$\sigma_{\mathrm{s,f}} = \sqrt{\left(1 - \frac{1}{E_0}\frac{dE}{ds}R_{56}\right)\sigma_{s,i}^2 + R_{56}^2\left(\frac{\sigma_{\mathrm{E,unc}}}{E_0}\right)^2}$$

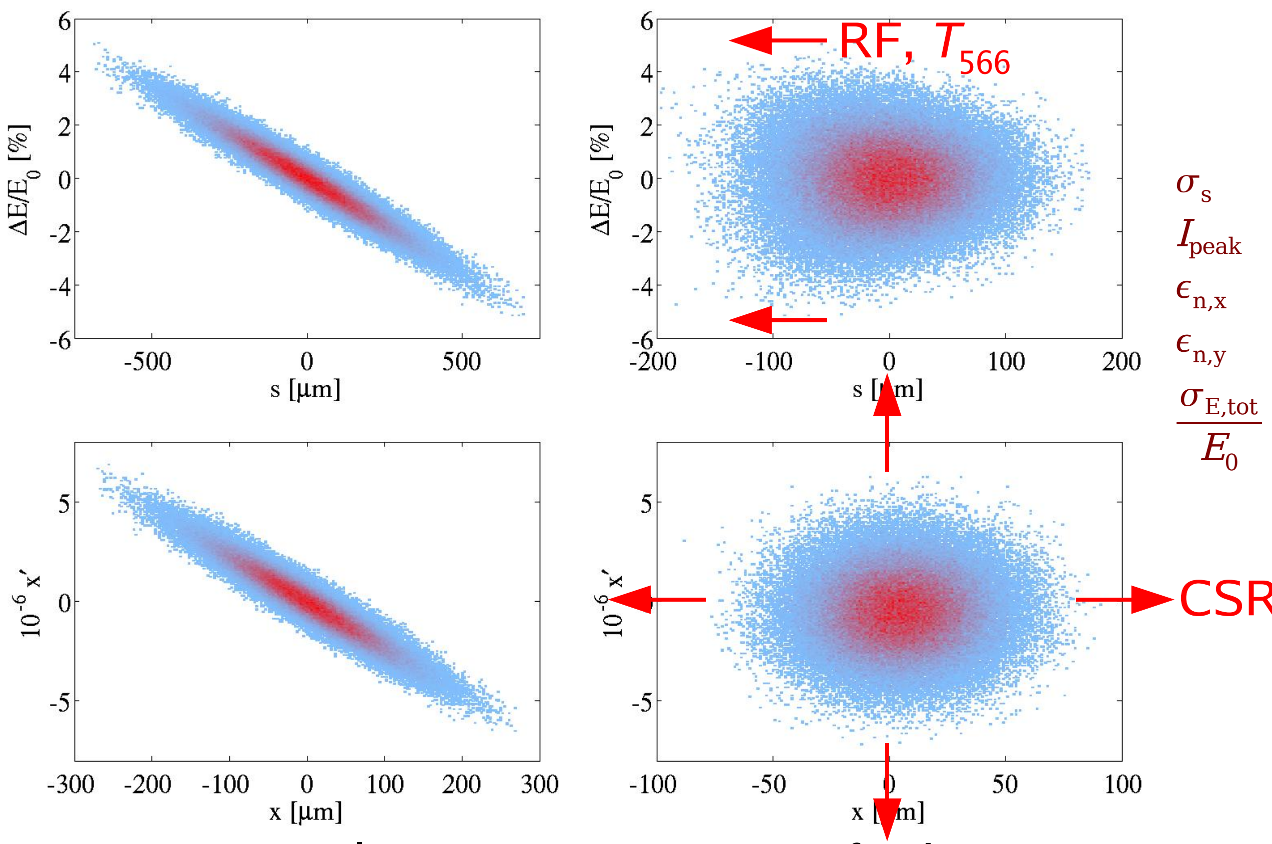
$$\sigma_{\mathrm{E,tot}} = \sqrt{\sigma_{\mathrm{E,unc}}^2 + \sigma_{\mathrm{s,i}}^2\left(\frac{1}{E_0}\frac{dE}{ds}\right)^2}$$

$\varepsilon_{\mathrm{long}} = \sigma_{\mathrm{s,f}}\,\sigma_{\mathrm{E,tot}}$ only for full compression !!!

Bunch Compressor Simulations

$$E_0 = 9\ \text{GeV}$$
$$Q_0 = 0.65\ \text{nC}$$
$$\sigma_s = 175\ \mu\text{m}$$
$$I_{peak} = 450\ \text{A}$$
$$\epsilon_{n,x} = 580\ \text{nm rad}$$
$$\epsilon_{n,y} = 6\ \text{nm rad}$$
$$\frac{\sigma_{E,unc}}{E_0} = 0.32\ \%$$
$$\frac{1}{E_0}\frac{dE}{ds} = -69.6\ \text{m}^{-1}$$





longitudinal phase space

transverse phase space

initial

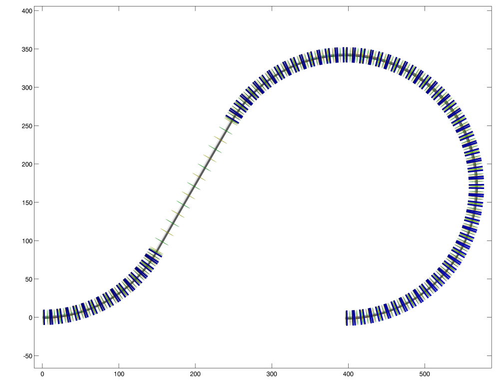
final

$$\sigma_s = 44\ \mu\text{m}$$
$$I_{peak} = 1800\ \text{A}$$
$$\epsilon_{n,x} = 600\ \text{nm rad}$$
$$\epsilon_{n,y} = 6\ \text{nm rad}$$
$$\frac{\sigma_{E,tot}}{E_0} = 1.3\ \%$$

587 nm rad with shielding (2cm height)

Turn Around Loop Simulations

$$E_0 = 9\ \text{GeV}$$
$$Q_0 = 0.65\ \text{nC}$$
$$\sigma_s = 175\ \mu\text{m}$$
$$I_{\text{peak}} = 460\ \text{A}$$
$$\epsilon_{n,x} = 520\ \text{nm rad}$$
$$\epsilon_{n,y} = 5\ \text{nm rad}$$
$$\frac{\sigma_{E,\text{unc}}}{E_0} = 0.32\ \%$$
$$\frac{1}{E_0}\frac{dE}{ds} = 0.0\ \text{m}^{-1}$$



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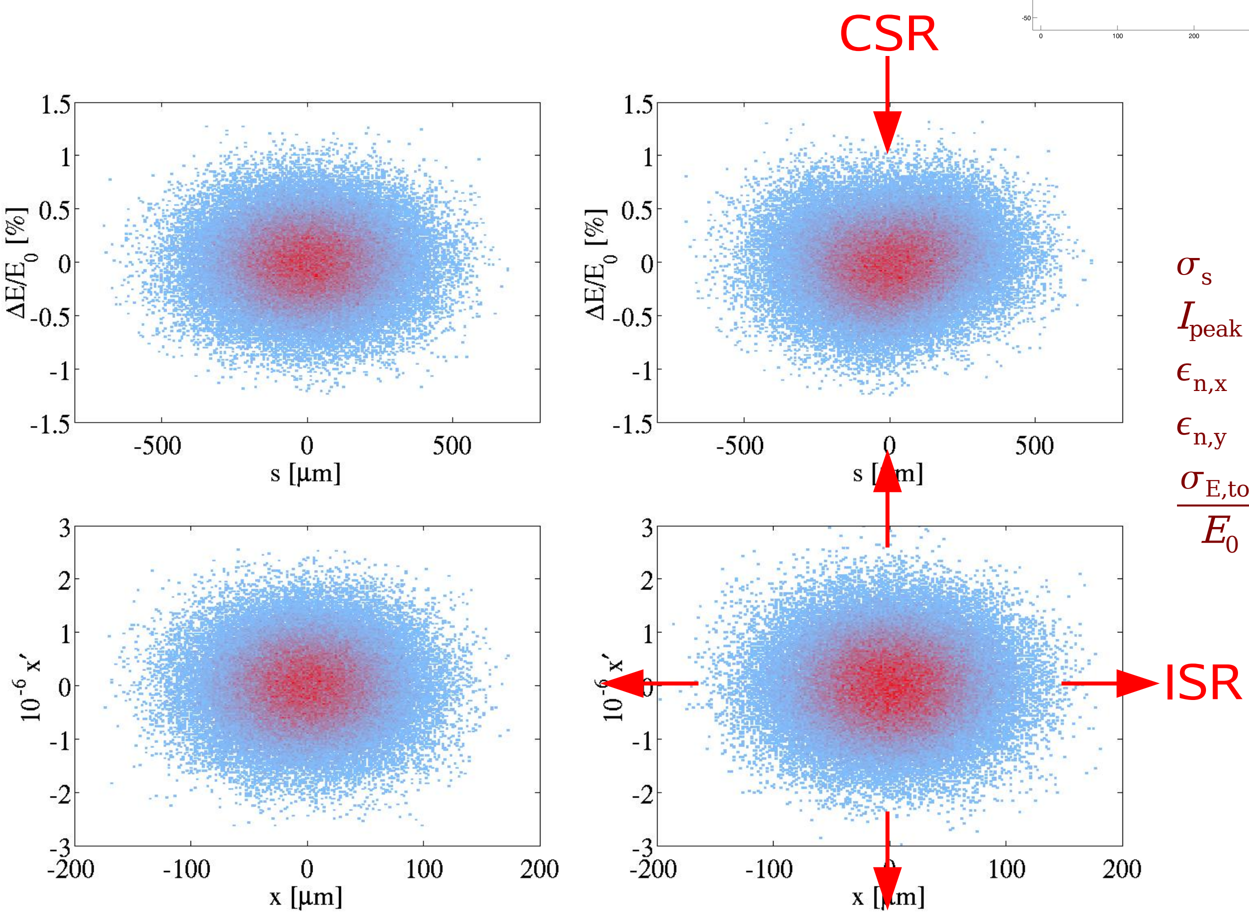

initial final

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Are RTML beam dynamics issues strong enough to push the emittance budget?

Considerations for RTML design:
(except for matching initial and final parameters)

- learn from ILC!
- identify parameters and tolerances along the RTML
- jitter in one sub-system might spoil parameters in following sub-system, e.g. energy jitter in front of BC leads to phase jitter
- objective for final values: $\sigma_{L,RTML} < 2\ \%$
- estimate required emittance budget for sub-systems current achievement: $\Delta\varepsilon < 100$ nm rad, but not all beam lines and issues studied yet
- energy in turn around loop (9GeV -> 8GeV => $\Delta\varepsilon$=60nm rad -> $\Delta\varepsilon$=30 nm rad), but may be detrimental effect in cavities due to wake fields
- bunch length between BC1 and BC2
- performance of feedback and feedforward, which beam properties should be corrected? tuning range? single bunch?
- ...

But first we have to fix initial and final parameters!

...or at least agree on reasonable parameter sets...

...which are hopefully rather stable...

Exit of Damping Rings:

Parameter	Symbol	Value	Unit	Jitter Tolerance
Energy	E_0	2.424	GeV	± ? %
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Polarization	P_{e^-}, P_{e^+}	?	%	± ? %
Phase Offset	$\Delta\phi$	0	deg	± ? deg

Entrance of Main Linac:

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Polarization	P_{e^-}, P_{e^+}	?	%	± ? %
Phase Offset	$\Delta\phi$	0	deg	± 0.1 deg

Once initial and final parameters are fixed,
we can fix the remaining free parameters:

i.e. energy after Booster Linac (and intermediate bunch length),
this implies work on BC2 RF, Turn Around Loop (and BCs)

Afterwards (or parallel?):

- review existing lattices for Transfer Line and Turn Around Loop
- study beam dynamics in Booster Linac and BC RF
- create missing beam lines to compile a preliminary RTML for start-to-end simulations
- create Spin Rotator lattice
- elaborate diagnostics and tuning requirements
- ...

On going effort:

- compilation of functions, requirements, constraints, issues, challenges, ...

Please contribute!