Main Linac Optimisation at 380 GeV and 350 GeV

N. Blaskovic

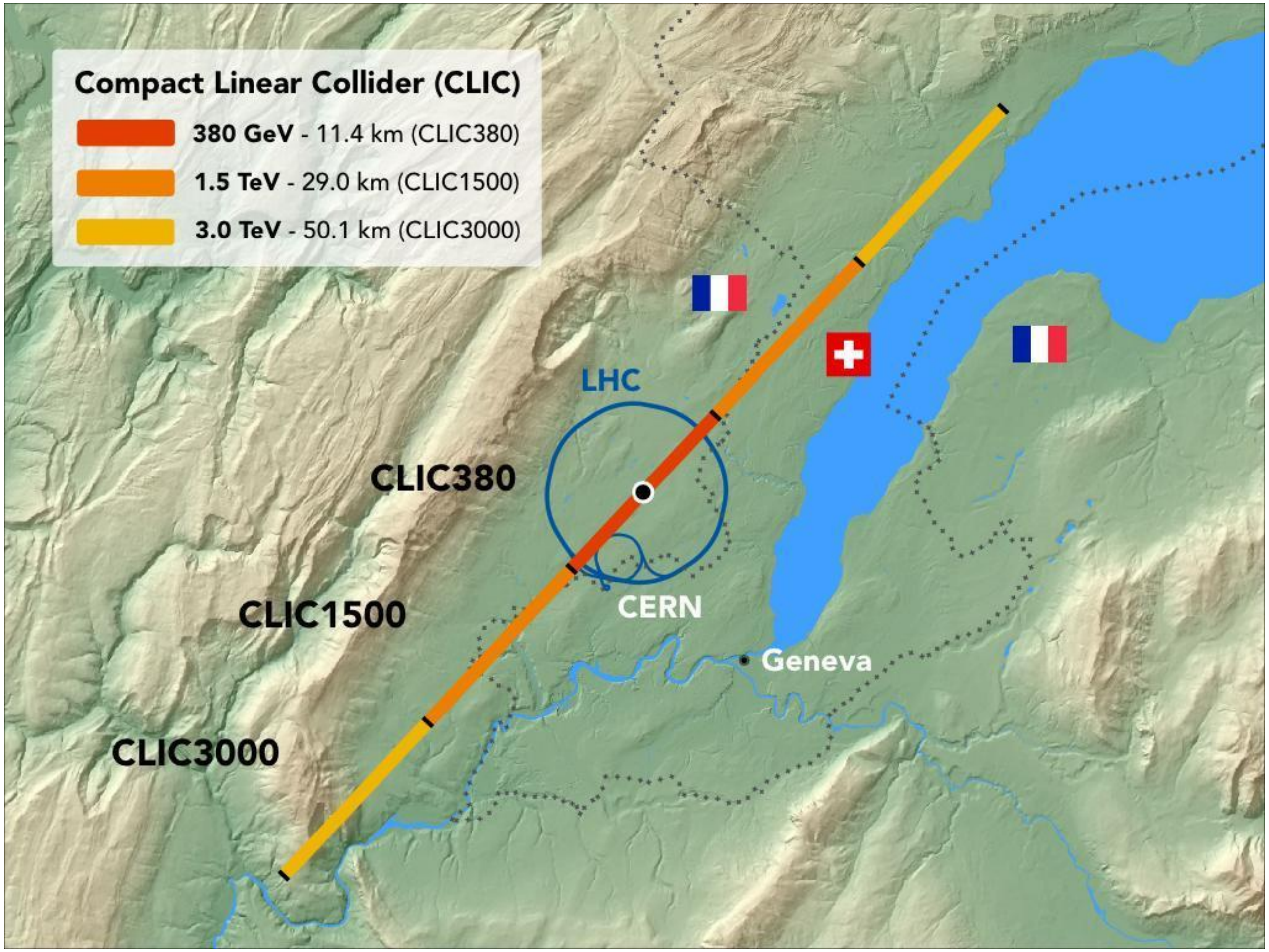
Acknowledgements: D. Schulte

Contents

- CLIC staging: 380 GeV up to 3 TeV
- Energy spread minimisation at 350 GeV

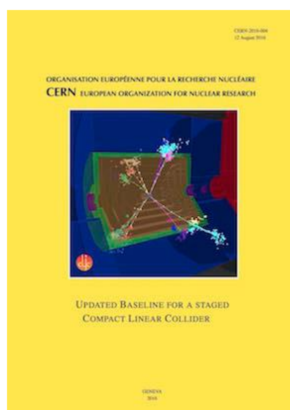
CLIC staging

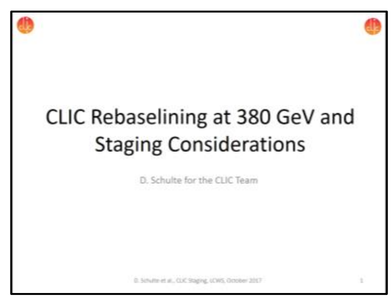
CLIC staging



CLIC staging

- Literature:
  - ‘Updated baseline for a staged Compact Linear Collider’ (CERN-2016-004)
  - ‘CLIC Rebaselining at 380 GeV and Staging Considerations’, D. Schulte, LCWS 2017

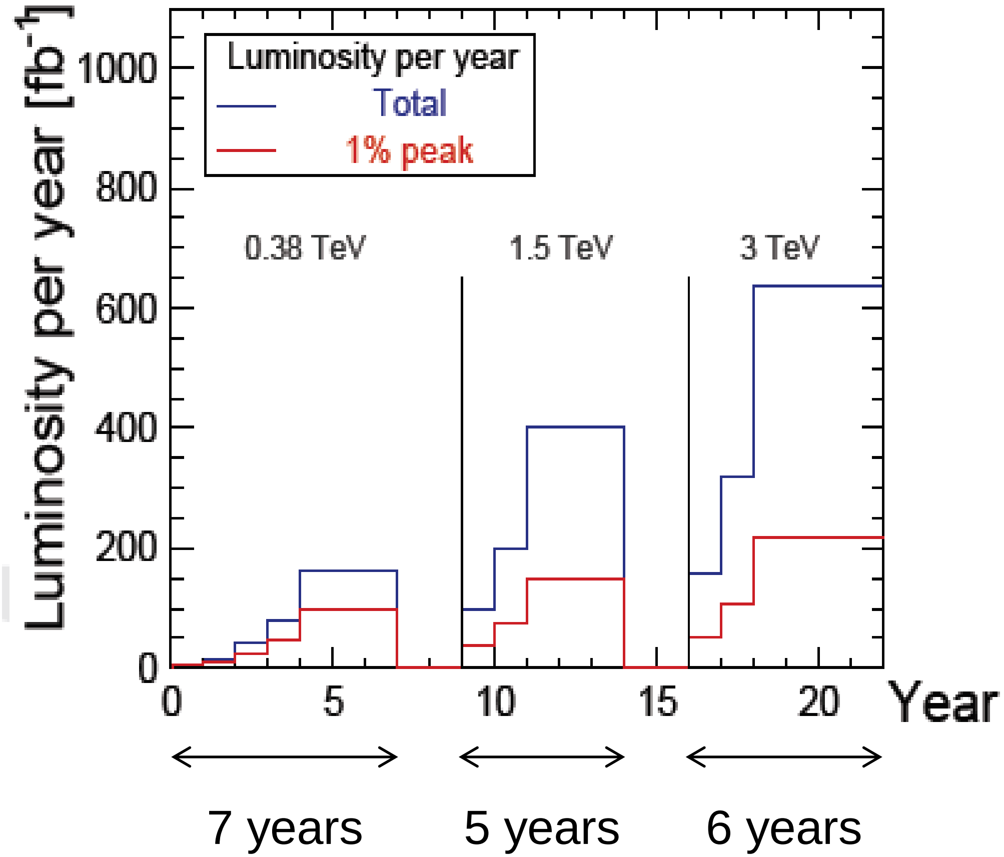




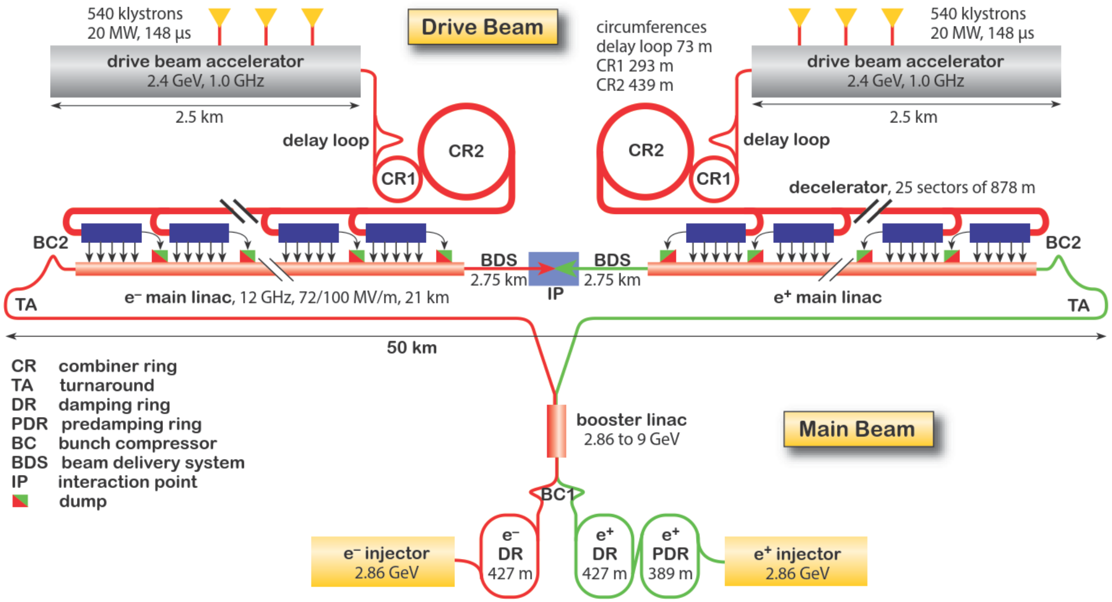
Energy stages

Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{\text{int}}$ (fb^{-1})	
1	380	500	HZ, WW, top
	350	100	$t\bar{t}$ threshold scan
2	1500	1500	$t\bar{t}H$
3	3000	3000	H self-coupling, BSM?

Luminosity ramp-up



3 TeV design



2 drive beams

25 decelerator sectors/linac

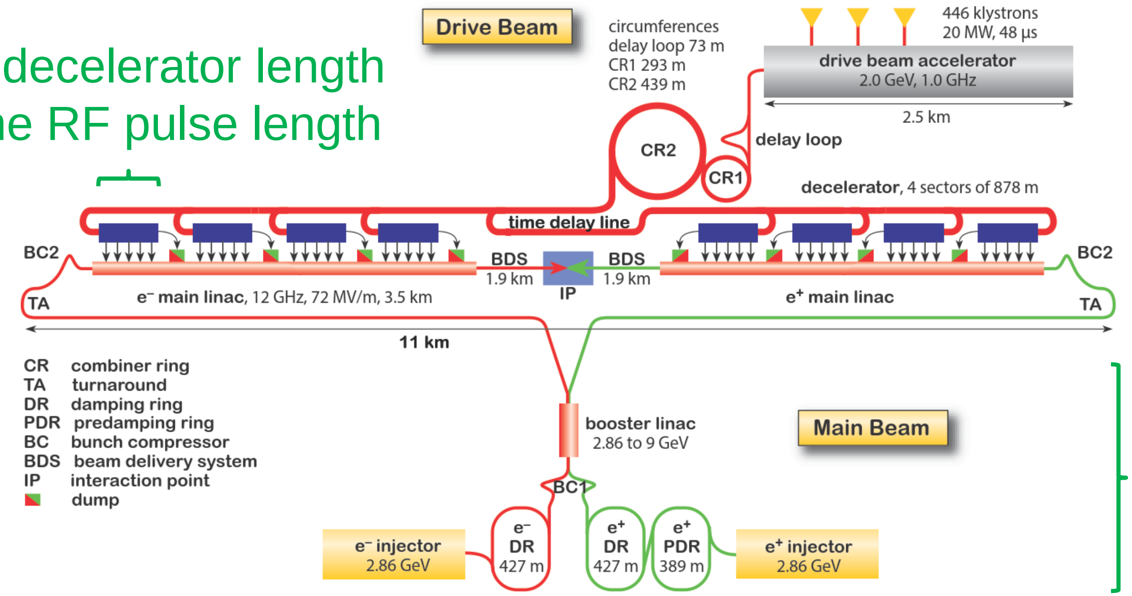
380 GeV design

same decelerator length
= same RF pulse length

1 drive beam

4 decelerator sectors/linac

main linac injection unchanged



Accelerator parameters

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	$10^{34}\,\text{cm}^{-2}\text{s}^{-1}$	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	$10^{34}\,\text{cm}^{-2}\text{s}^{-1}$	0.9	1.4	2
Main tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	µm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	920/20	660/20	660/20
Normalised emittance (at IP)	ϵ_x/ϵ_y	nm	950/30	—	—
Estimated power consumption	P_{wall}	MW	252	364	589

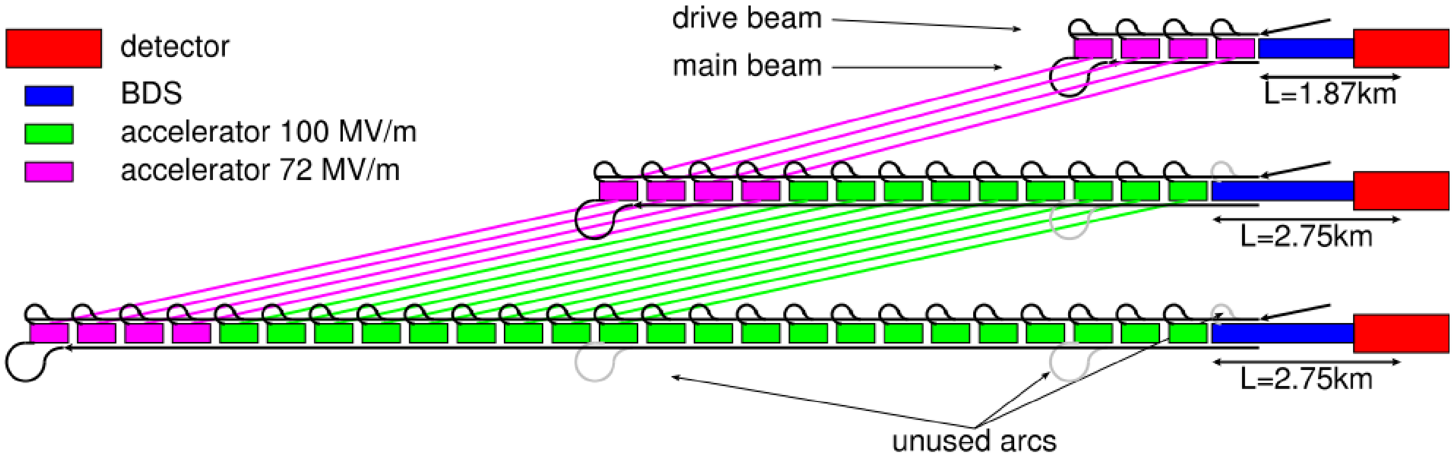
First: 72 MV/m
Later: 100 MV/m

'baseline' values

1 nm at 3 TeV

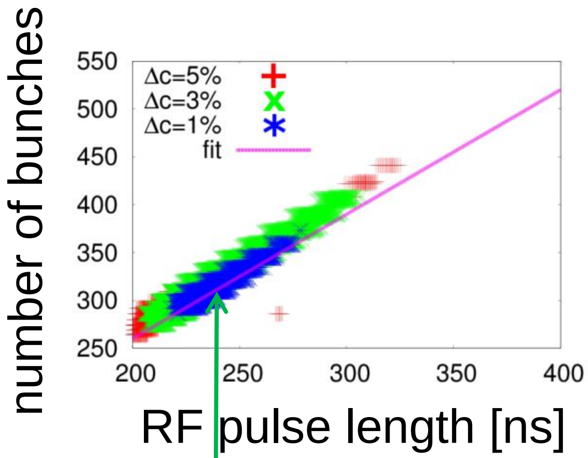
Upgrade strategy

- For upgrade, move 72 MV/m accelerating structures to start of linac to preserve structure & quad lengths at low energies



Cost optimisation

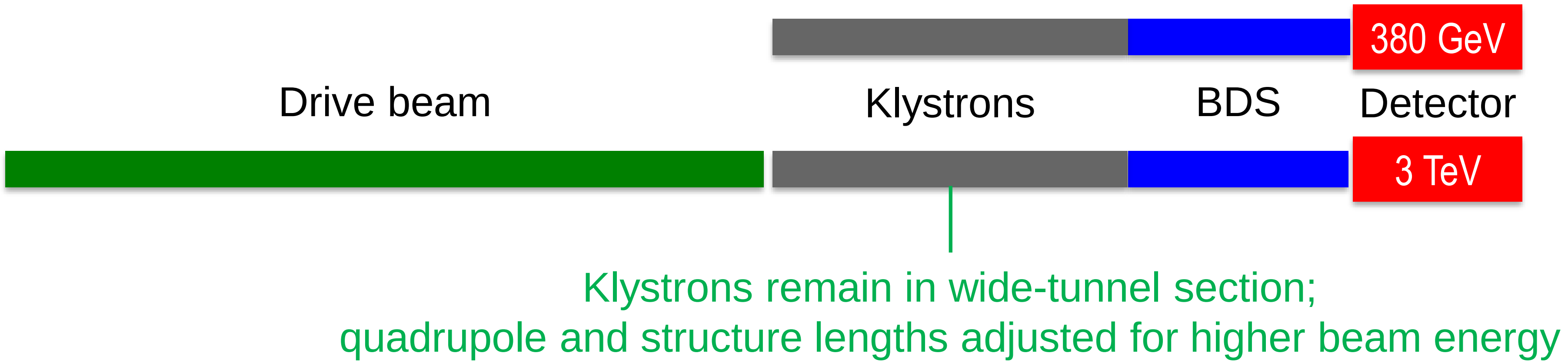
- Cost increase relative to minimum cost for 3 TeV design with 100 MV/m gradient



To minimise cost, require RF pulse length of 244 ns.
This sets drive beam pulse length to decelerator and,
thus, also sets decelerator length (common for all stages)

Klystron-based alternative

- Replace drive beam for 380 GeV stage
- Faster implementation: drive beam not needed for accelerator structure testing
- Upgrade to 3 TeV with drive beam



Baseline structure choice

DB	Drive beam	Optimised at 380 GeV
K	Klystrons	Optimised at 380 GeV
DB244	Drive beam	Upgradable to 3 TeV
K244	Klystrons	Upgradable with DB to 3 TeV

'baseline' design

Parameter	Symbol	Unit	DB	K	DB244	K244
Frequency	f	GHz	12	12	12	12
Acceleration gradient	G	MV/m	72.5	75	72	79
RF phase advance per cell	$\Delta\phi$	°	120	120	120	120
Number of cells	N_c		36	28	33	26
First iris radius / RF wavelength	a_1/λ		0.1525	0.145	0.1625	0.15
Last iris radius / RF wavelength	a_2/λ		0.0875	0.09	0.104	0.1044
First iris thickness / cell length	d_1/L_c		0.297	0.25	0.303	0.28
Last iris thickness / cell length	d_2/L_c		0.11	0.134	0.172	0.17
Number of particles per bunch	N	10^9	3.98	3.87	5.2	4.88
Number of bunches per train	n_b		454	485	352	366
Pulse length	τ_{RF}	ns	321	325	244	244
Peak input power into the structure	P_{in}	MW	50.9	42.5	59.5	54.3
Cost difference (w. drive beam)	$\Delta C_{w.\ DB}$	MCHF	-50	(20)	0	(20)
Cost difference (w. klystrons)	$\Delta C_{w.\ K}$	MCHF	(120)	50	(330)	240

upgradable to 3 TeV

Value estimate

- Drive-beam baseline design at 380 GeV

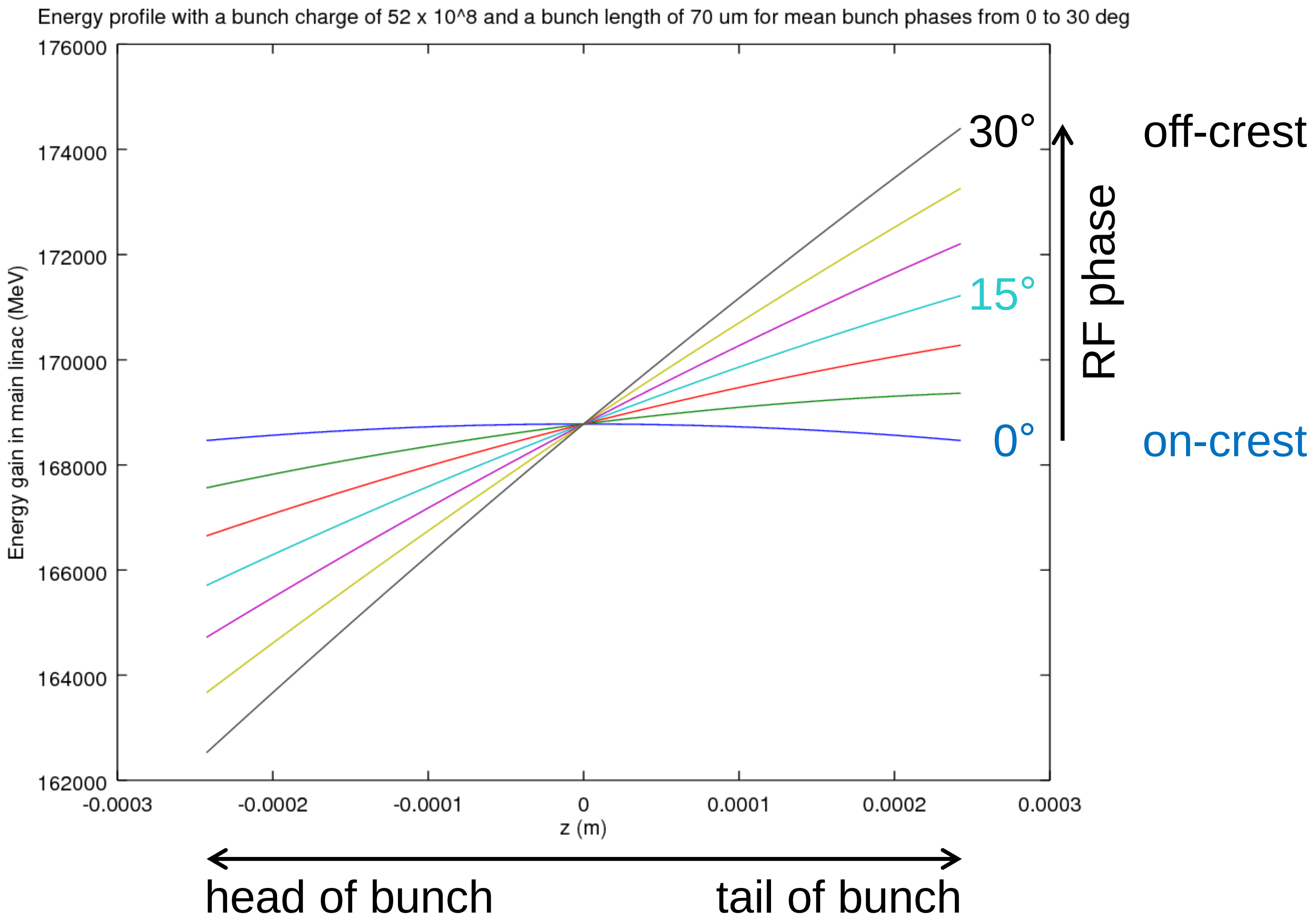
	Value [MCHF of December 2010]
Main beam production	1245
Drive beam production	974
Two-beam accelerators	2038
Interaction region	132
Civil engineering & services	2112
Accelerator control & operational infrastructure	216
Total	6690

Energy spread minimisation at 350 GeV

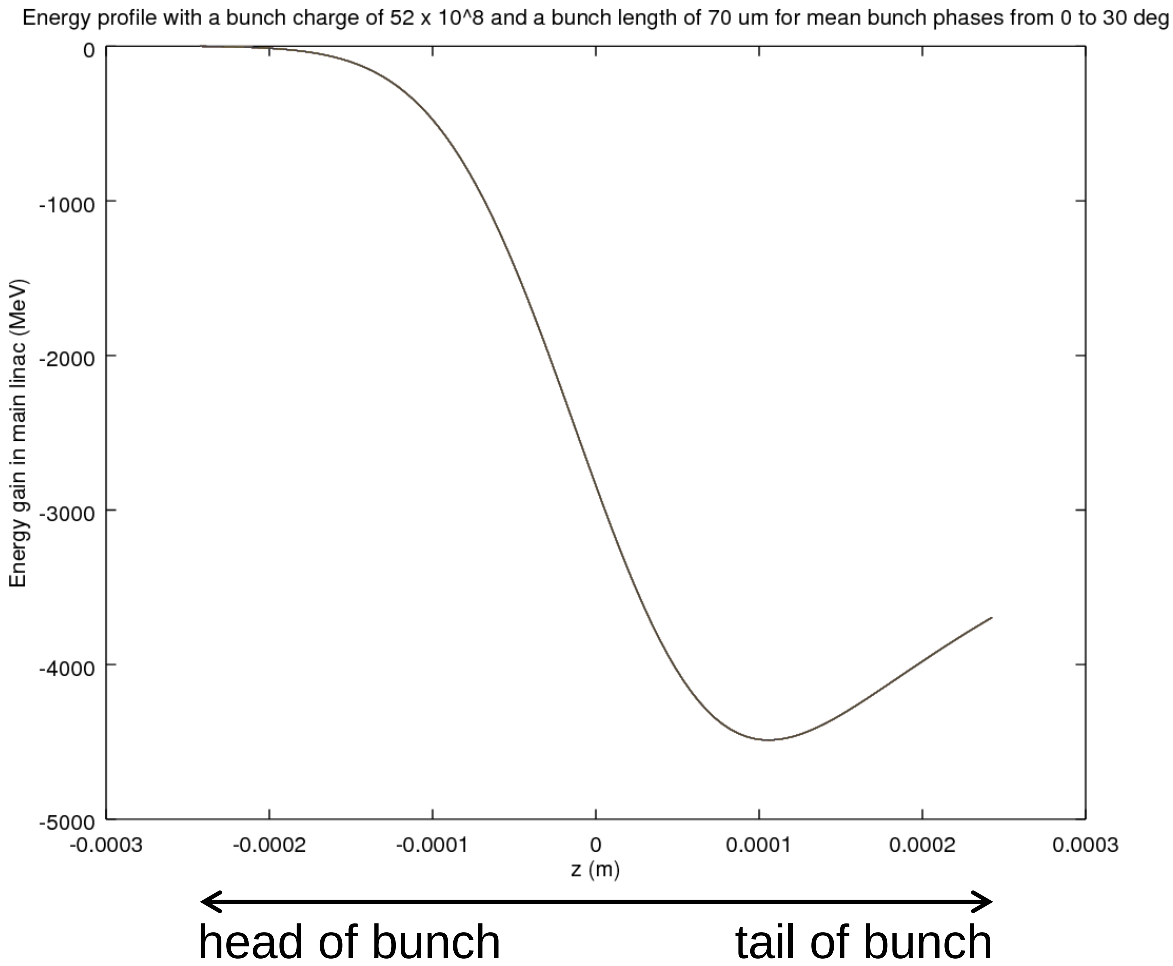
Energy spread minimisation

- Dedicated 350 GeV operation will perform energy scan around $t\bar{t}$ threshold
- Requires excellent energy resolution by minimising bunch energy spread
- Energy spread develops in the bunch from
  - RF time-varying profile
  - Bunch wakefield effect

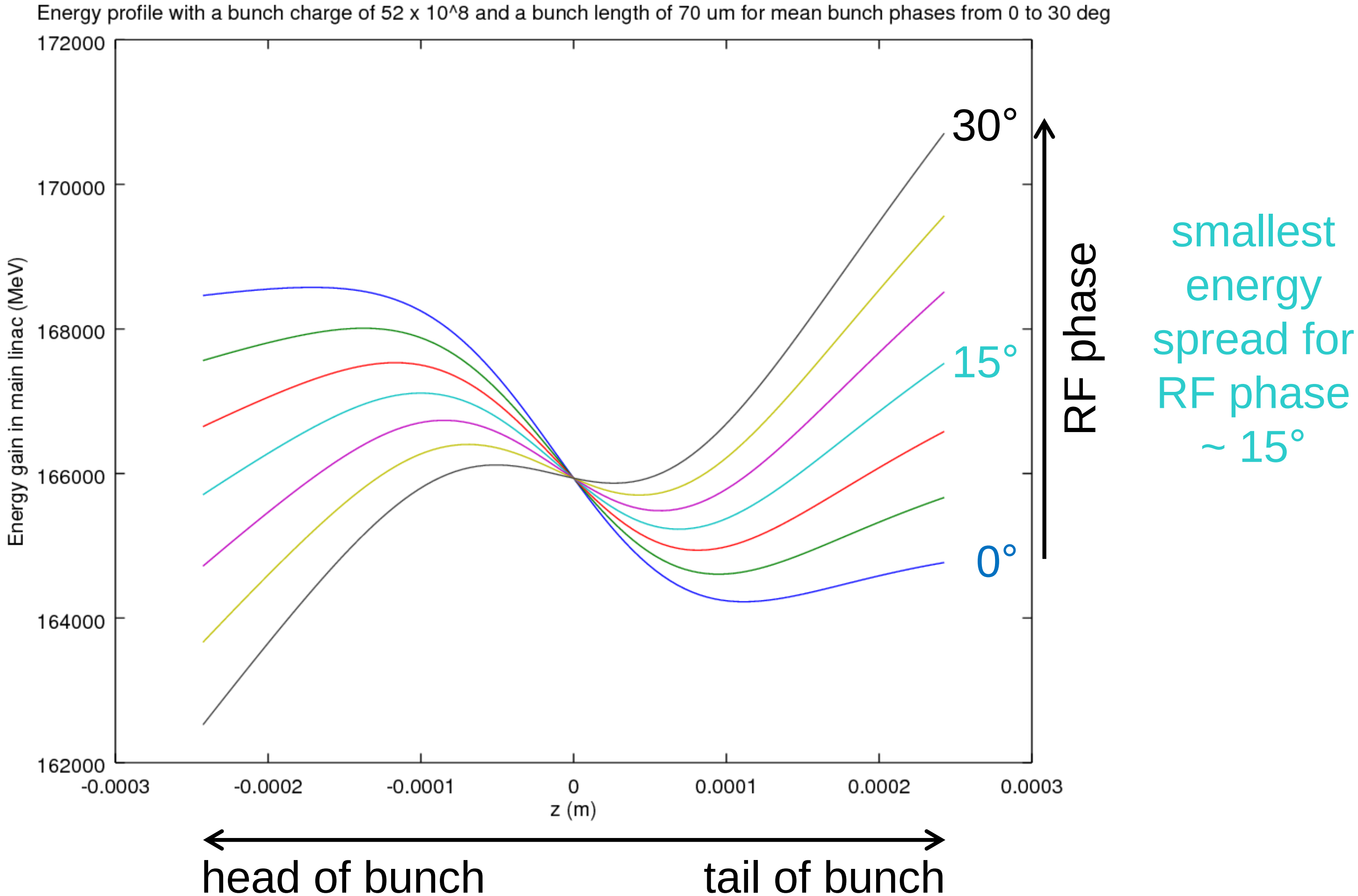
RF contribution



Wakefield contribution



Combined contribution



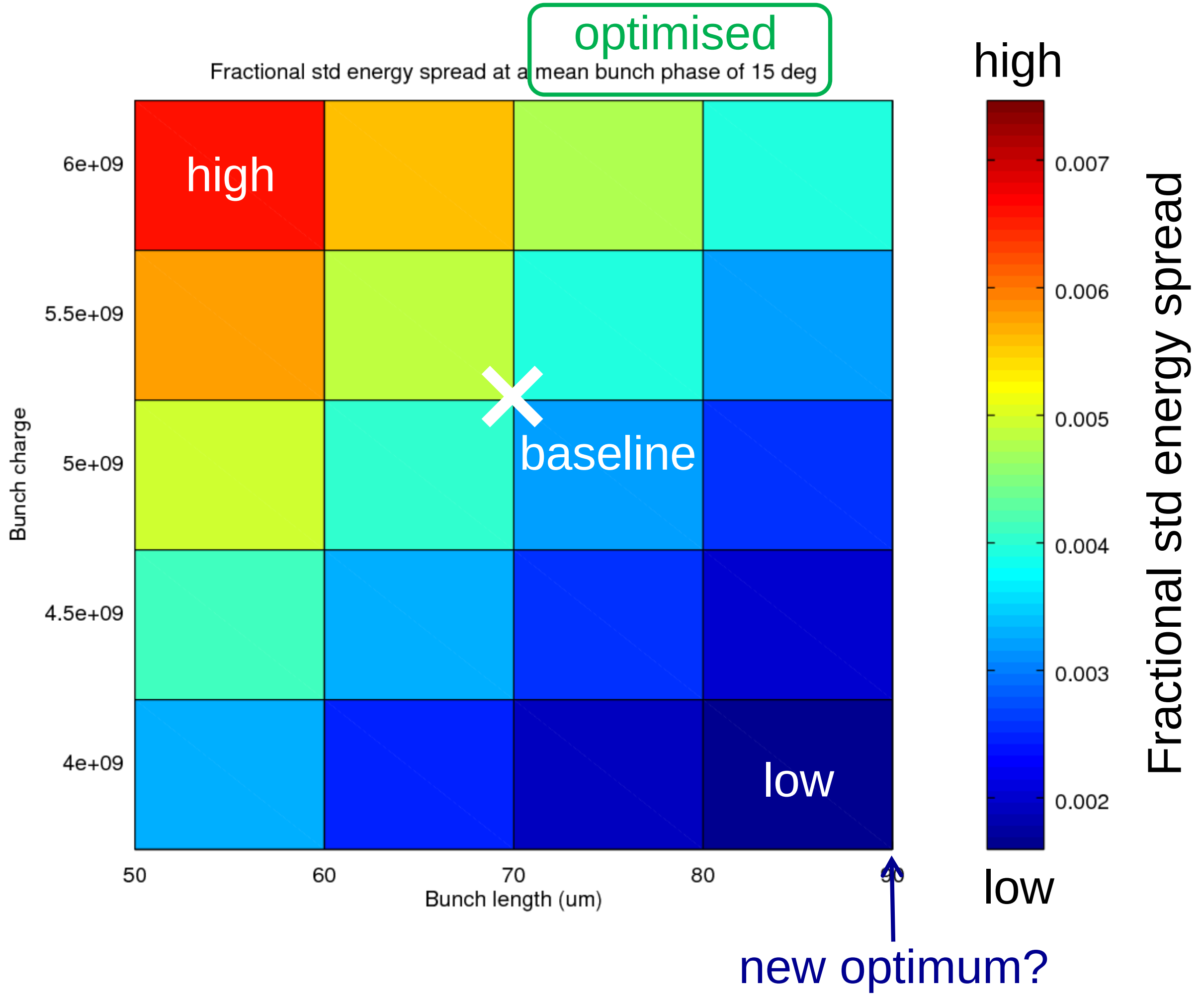
Energy spread

- Energy spread optimised at 0.35% (std) at the end of the linac by D. Schulte et al. for baseline 380 GeV design:
  - 5.2 x 10^9 particles/bunch
  - 70 um bunch length
- Optimum RF phase:
  - 12° in first 3 linac sectors
  - 18.1° in last linac sector

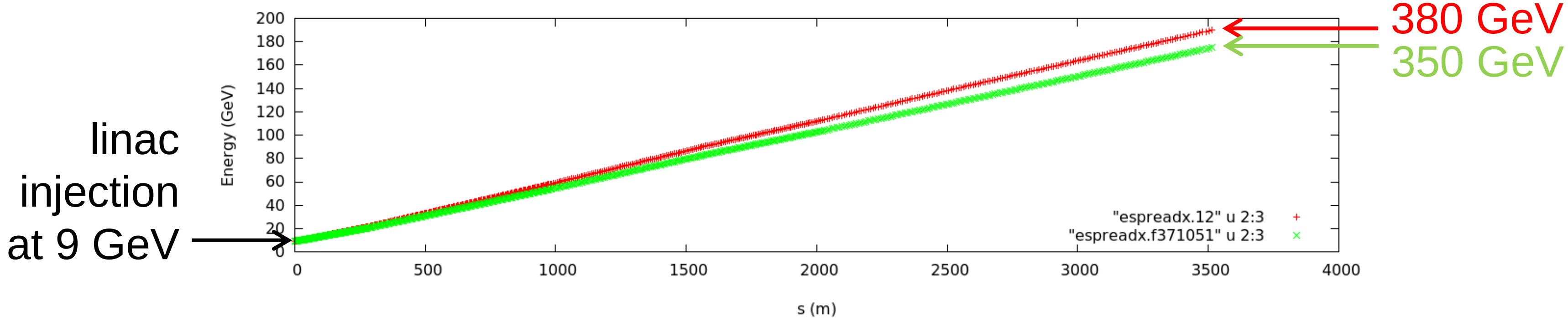
Energy spread minimisation

- The energy spread has been studied further by varying:
  - Number of particles/bunch
  - Bunch length
- RF gradient of 380 GeV stage re-adjusted for operation at 350 GeV

Energy spread



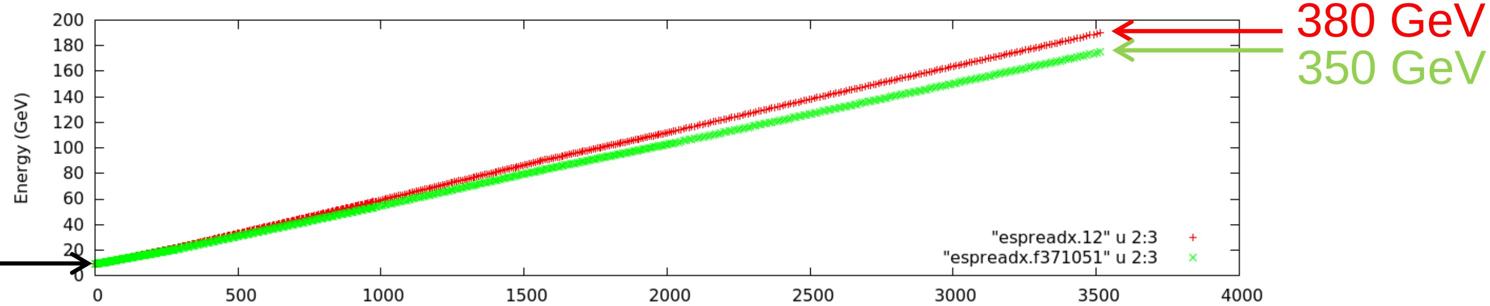
Comparison



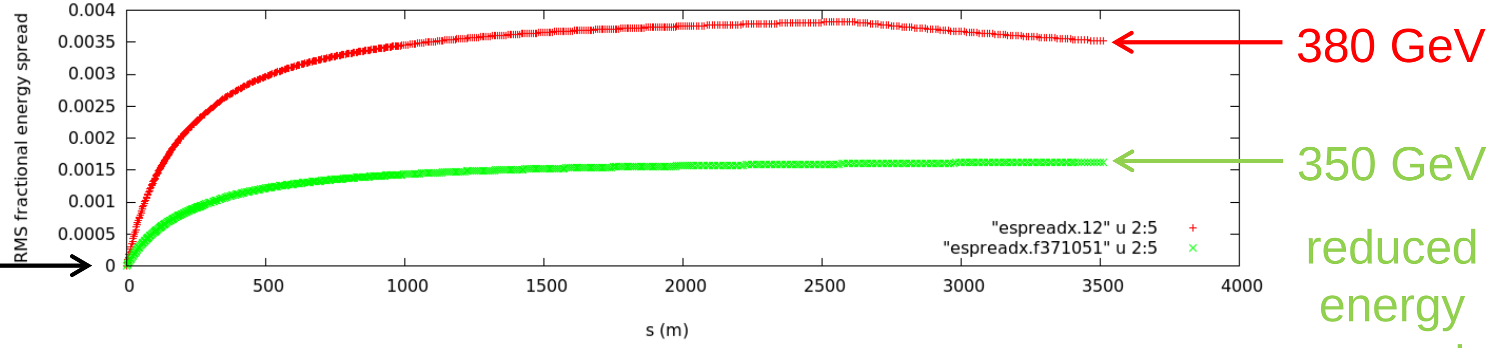
Energy (GeV)
200
180
160
140
120
100
80
60
40
20
0
0
500
1000
1500
2000
2500
3000
3500
4000
s (m)
"espreadx.12" u 2:3
"espreadx.f371051" u 2:3
380 GeV
350 GeV
linac
injection
at 9 GeV

Comparison

linac injection at 9 GeV

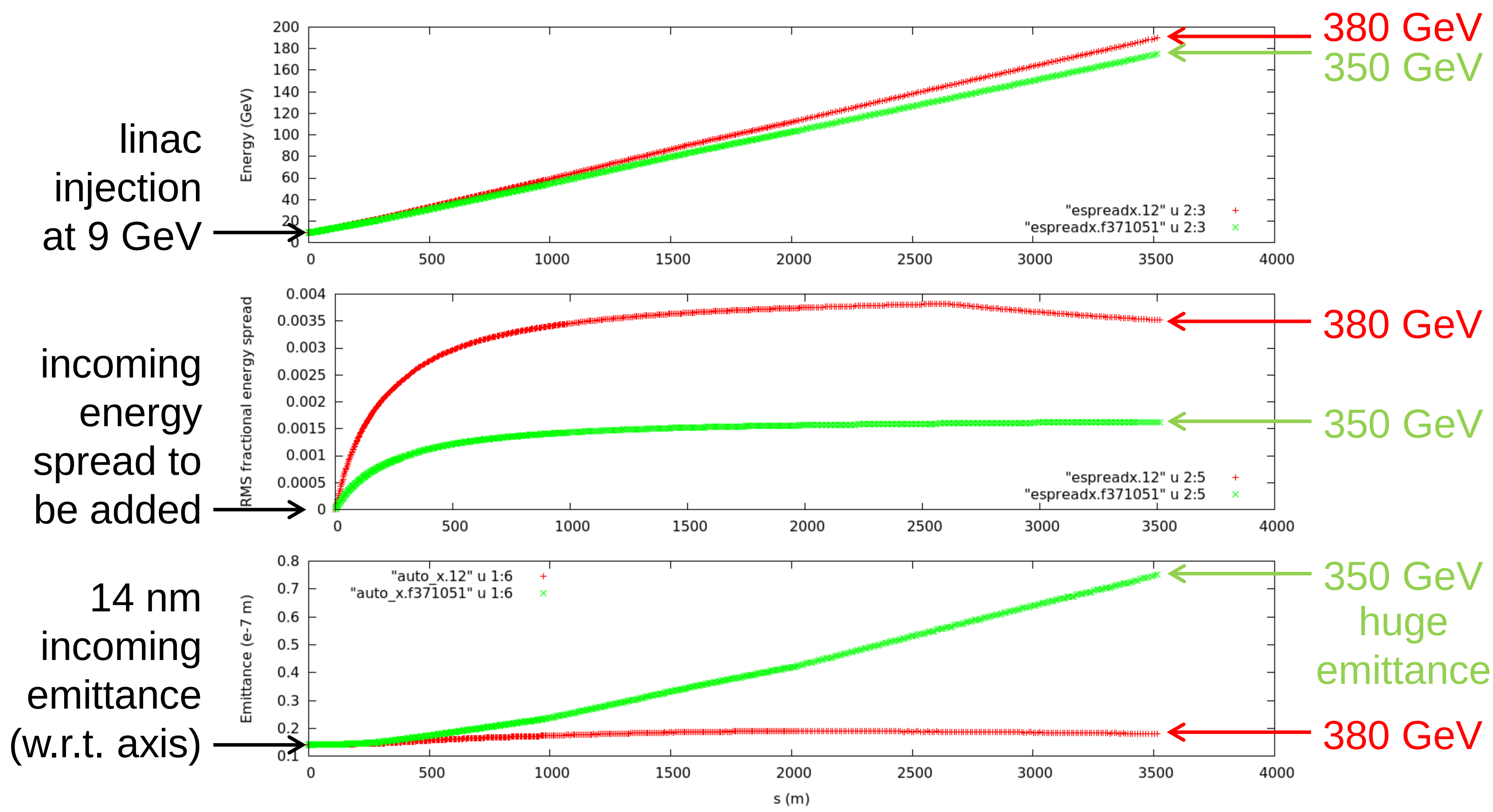


incoming energy spread to be added



reduced energy spread

Comparison

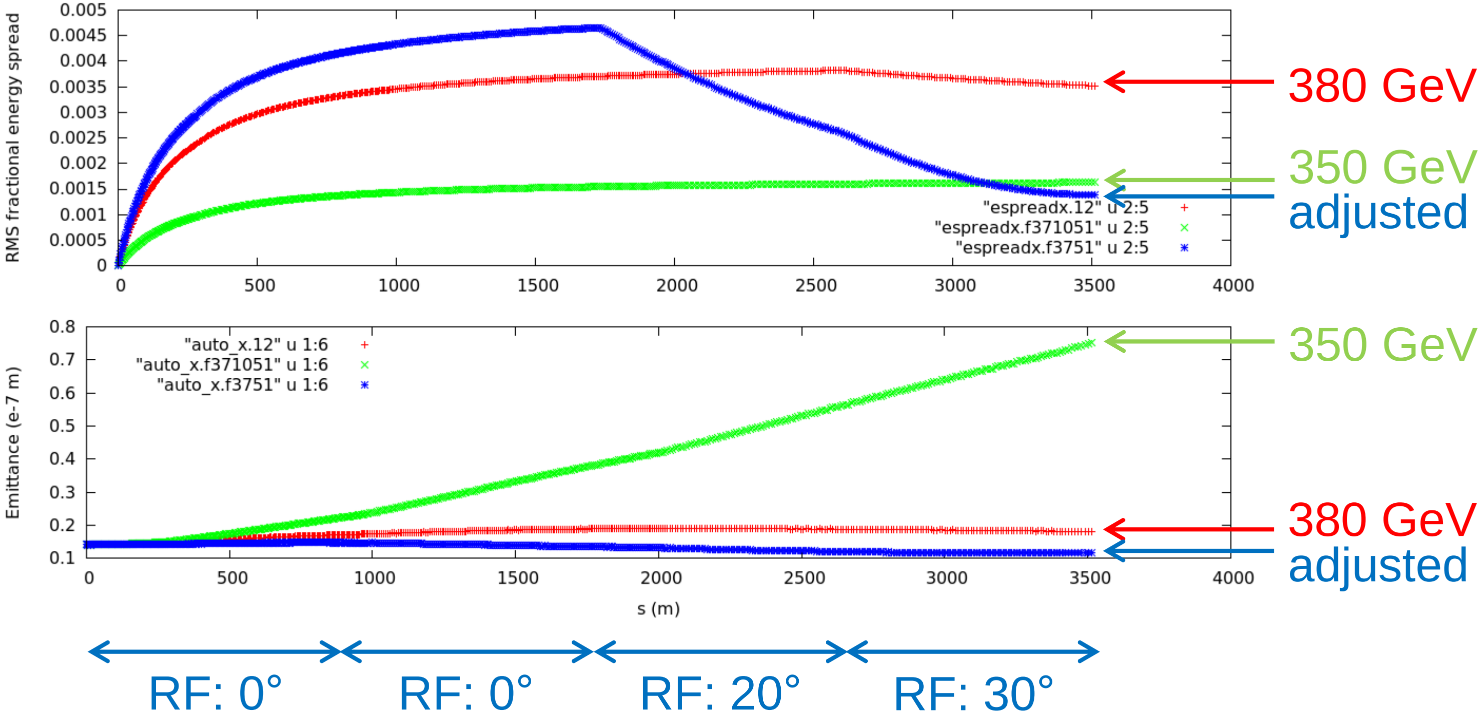


linac injection at 9 GeV
incoming energy spread to be added
14 nm incoming emittance (w.r.t. axis)
380 GeV
350 GeV
380 GeV
350 GeV
350 GeV huge emittance
380 GeV
Energy (GeV)
"espreadx.12" u 2:3
"espreadx.f371051" u 2:3
RMS fractional energy spread
"espreadx.12" u 2:5
"espreadx.f371051" u 2:5
Emittance (e-7 m)
"auto_x.12" u 1:6
"auto_x.f371051" u 1:6
s (m)

Emittance growth

- Small energy spread along the linac leads to poorer beam stability and a larger beam emittance
- Zero incoming energy spread gives worst case scenario
- Mitigate emittance growth by introducing energy spread in early stages of linac (with offset RF phase) and after taking it out

Mitigating emittance growth

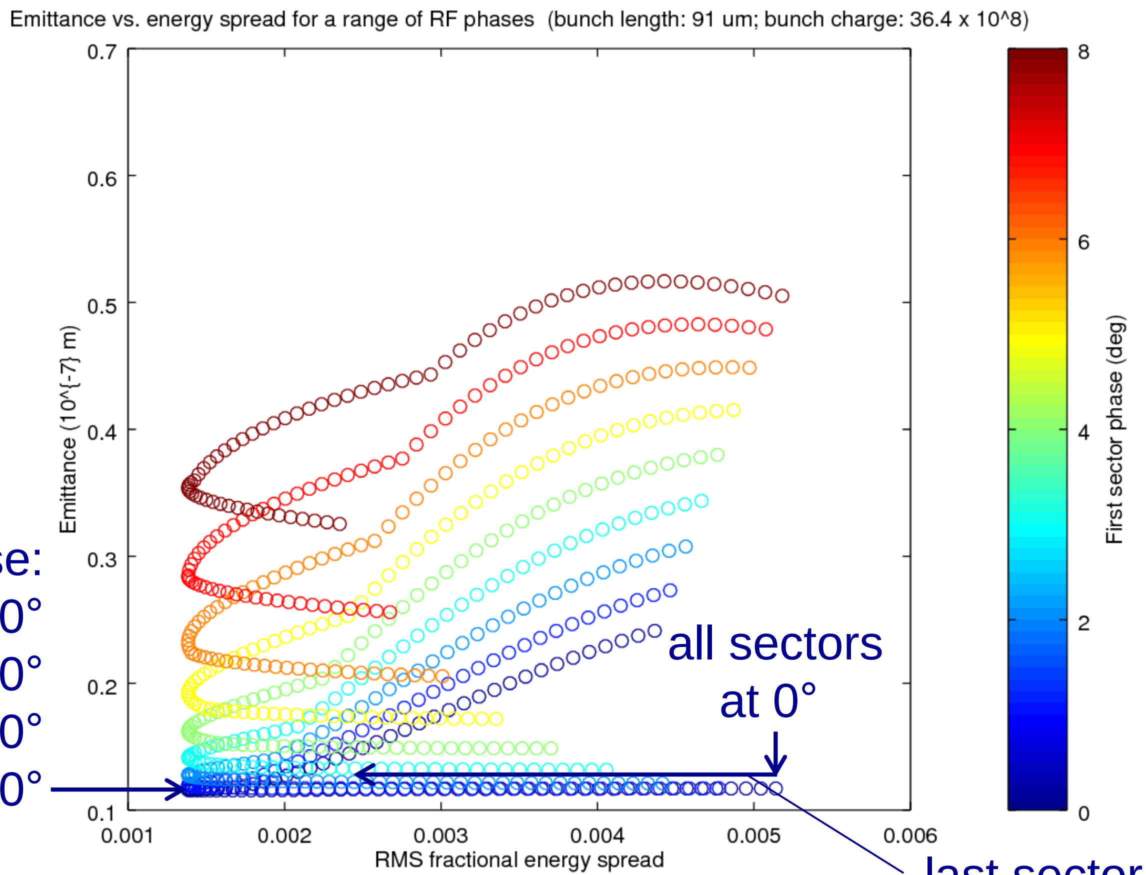


RF phase scanning

- RF phase combinations scanned to find lowest energy spread and emittance at end of linac
- RF phases of all 4 linac sectors scanned together from 0° to 30°
- For each phase, sequentially increase:
  - Last sector's phase up to 30°
  - Preceding sectors' phases up to 30°

RF phase scanning

optimum phase:
sector 1: 0°
sector 2: 0°
sector 3: 20°
sector 4: 30°



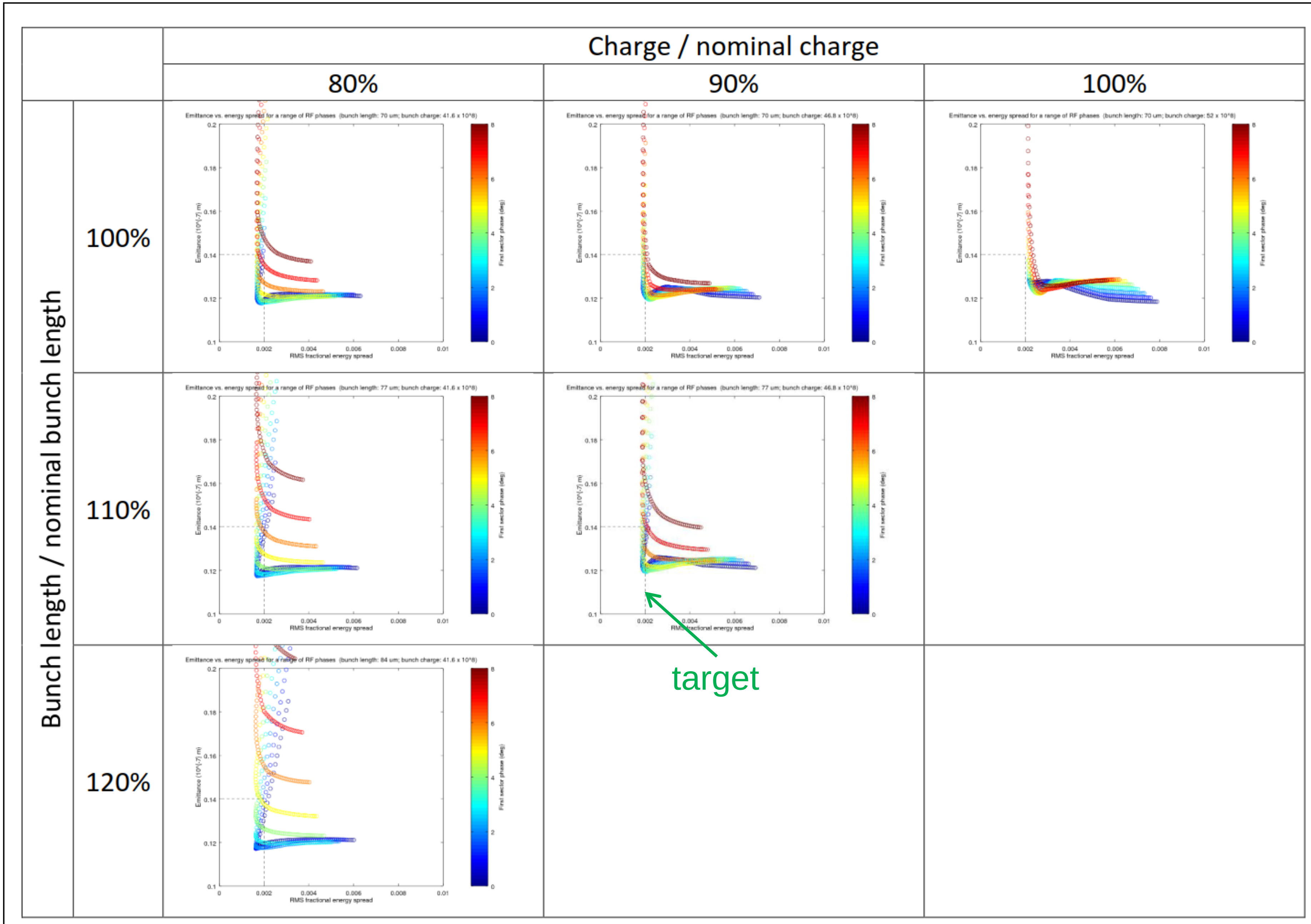
last sector scanned
0° to 30°

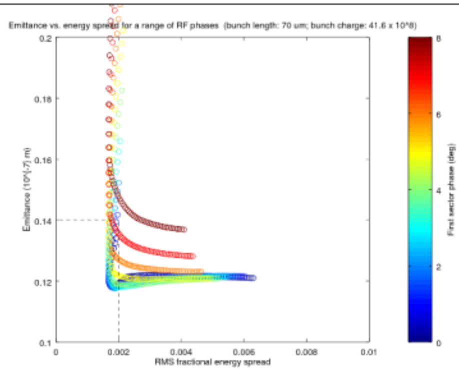
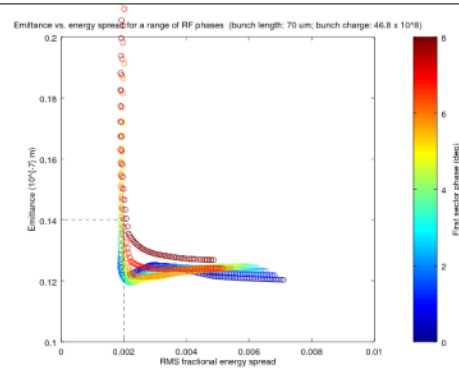
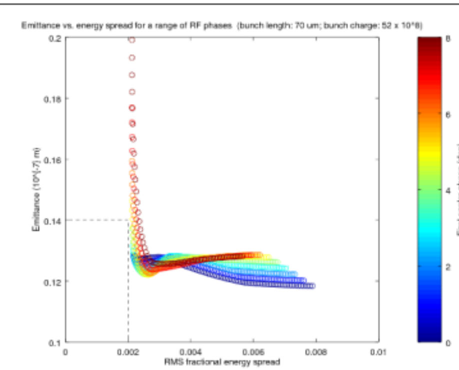
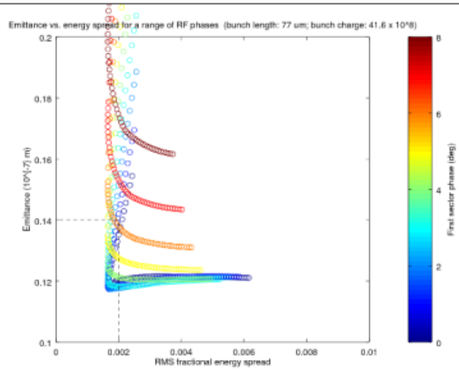
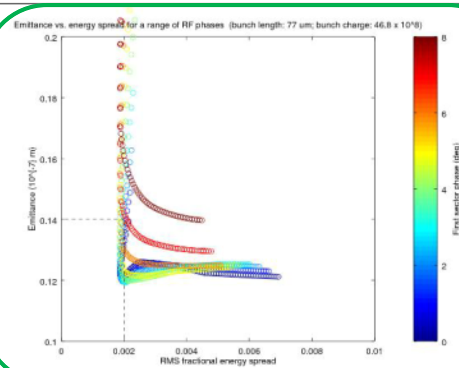
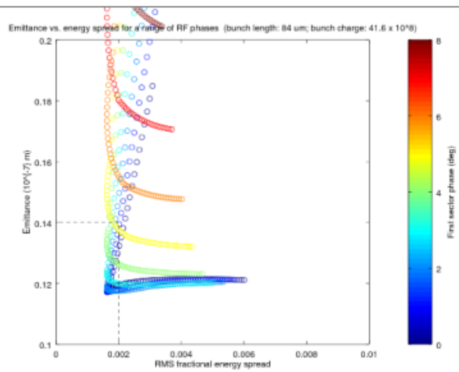
Optimum bunch length & charge

- Scan RF phase combinations over a range of bunch lengths and charges to find

	380 GeV	Target
Emittance	18 nm	< 14 nm
Energy spread	0.35%	< 0.20%

whilst preserving an acceptable bunch charge for good luminosity


Charge / nominal charge
80%
90%
100%
Bunch length / nominal bunch length
100%
110%
120%
RMS fractional energy spread
First sector phase (deg)
target

		Charge / nominal charge		
		80%	90%	100%
Bunch length / nominal bunch length	100%			
	110%			
	120%		target reached with RF phases sectors 1 & 2: 6° sectors 3 & 4: 30°	

Conclusions

- Energy spread (std) can be reduced from 0.35% (for 380 GeV design) to <0.20% for $t\bar{t}$ threshold scan at 350 GeV with:
  - Bunch charge: 90% of nominal
  - Bunch length: 110% of nominal
- Requires RF phase ~6° in first half of linac and ~30° in the second half

Thank you for your attention!

380 GeV baseline design

linac
injection
at 9 GeV

incoming
energy
spread to
be added

14 nm
incoming
emittance
(w.r.t. axis)