LHeC Ring Linac Lattice and Beam Dynamics

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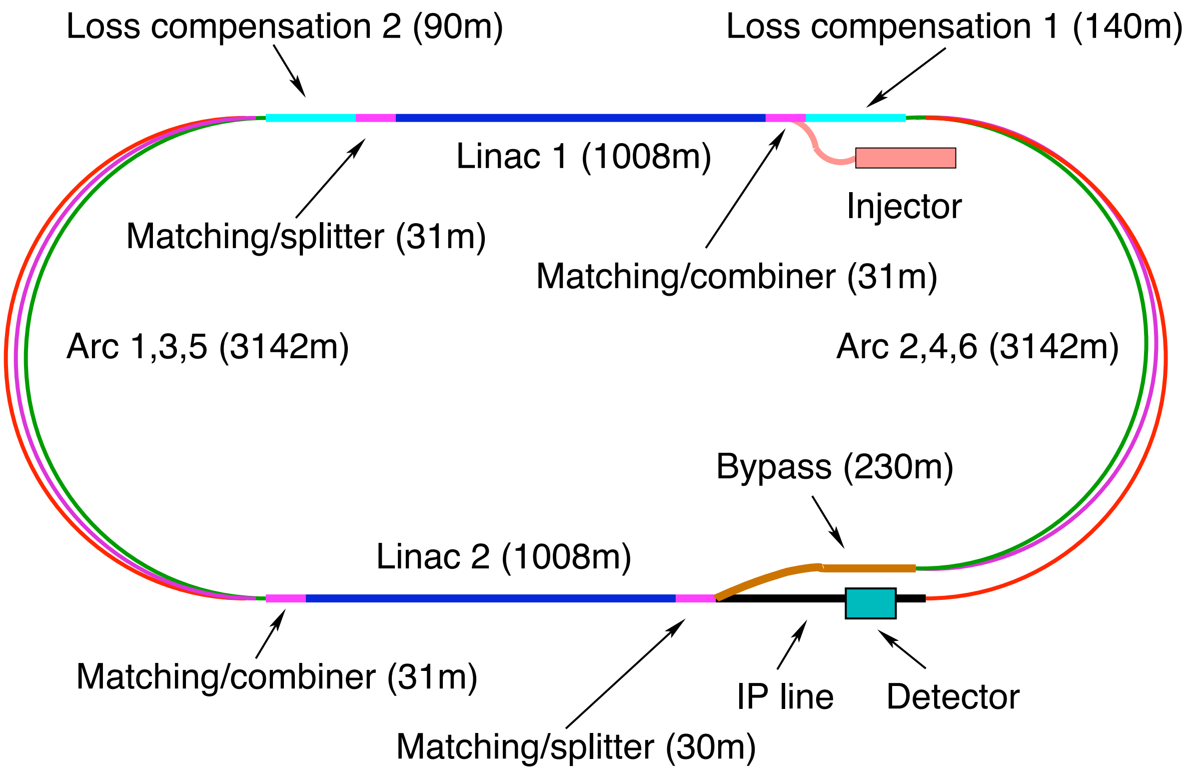
A. Bogacz, Y. Hao, D. Kayaran, V.N. Litvinenko, V. Ptitsyn, D. Trbolevic, N. Tsoupas (BNL), F. Zimmermann

Thanks to
M. Klein, R. Calaga, M. Schuh, A. Grudiev, G. H. Hoffstaetter

Overall Layout

- Turns have almost same length
- Circumference is $1/3$ of LHC
- Linac RF frequency $721.44\,\mathrm{MHz}$ ($18 \times 40.08\,\mathrm{MHz}$)
  - could chose differently ($400.8\,\mathrm{GHz}$?)
- Energy loss in arcs is compensated by re-acceleration
  - other option proposed ⇒ V.N. Litvinenko

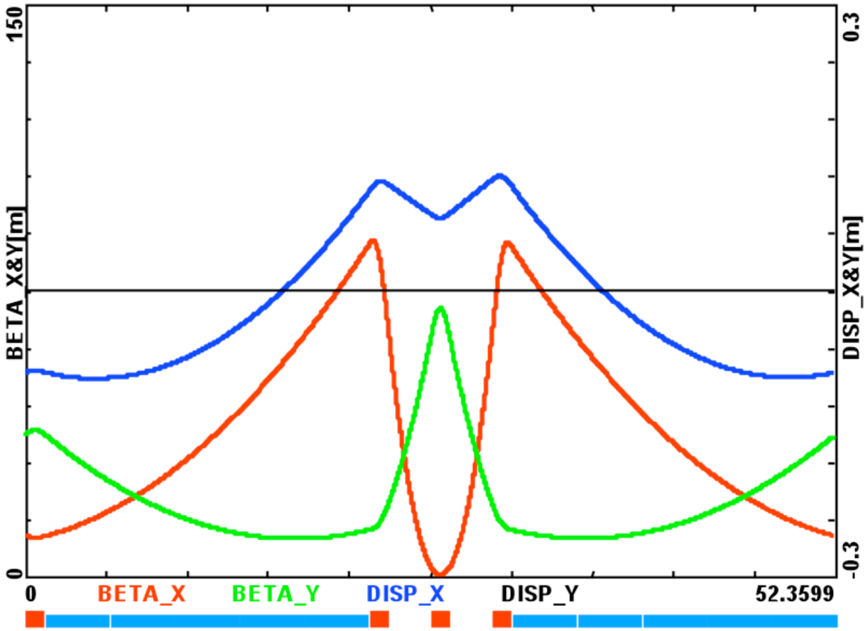


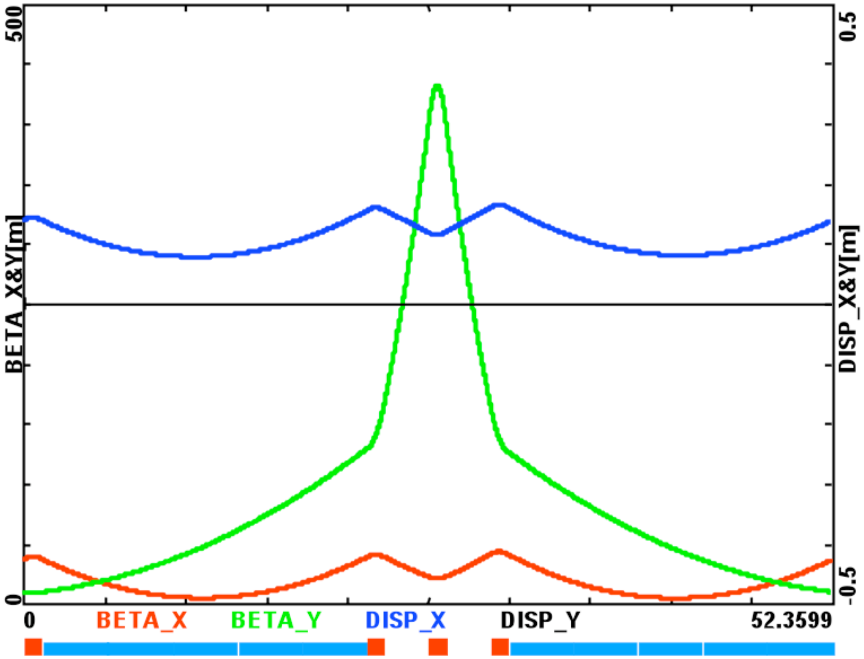
- Have two lattice options for arcs and linacs
  - option I from Alex Bogacz, with contribiutions from F. Zimmermann, D.S.
  - option II from Y. Hao, D. Kayaran, V.N. Litvinenko, V. Ptitsyn, D. Trbolevic, N. Tsoupas

Arc Lattice Design Option I

- A. Bogacz
  - three different arc designs
  - optimisation at low energy for beta-function
  - at high energy for emittance growth
  - 60 cells
  - $\rho = 764\,\mathrm{m}$
- Maximum beam size $720\,\mu\mathrm{m}$ but need to check energy spread
  - suggested $25\,\mathrm{mm}$ gap

    $14\text{–}17\sigma$
- Upper plot is first arc, lower plot is last arc



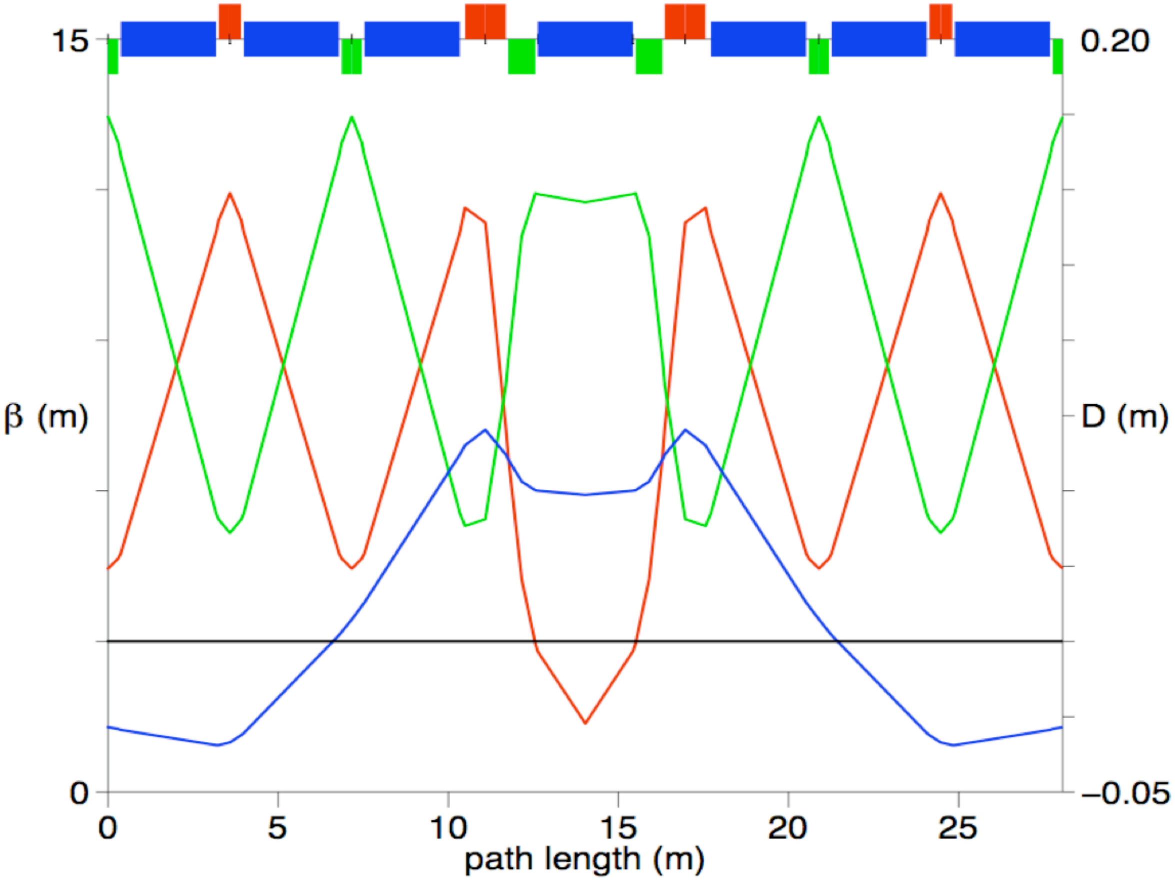


Arc Lattice Design Option II

- Y. Hao, D. Kayaran, V.N. Litvinenko, V. Ptitsyn, D. Trbolevic, N. Tsoupas (BNL)
  - pushing for small beta-functions $\leq 13.1\,\mathrm{m}$
  - 113 $27.8\,\mathrm{m}$-long cells
  - $\rho = 697\,\mathrm{m}$
- Maximum RMS beam sizes $313\,\mu\mathrm{m}$ (hor.) and $178\,\mu\mathrm{m}$ (vert.) at first arc
  - quad. gradient up to $107.8\,\mathrm{T/m}$
  - Suggested $4\,\mathrm{mm}$ gap, i.e.

    $6.5\sigma_x$

    $11\sigma_y$



Synchrotron Radiation Loss and Spread

- Option I, option II is similar

$$\Delta E \approx 88\,\mathrm{keV m GeV^{-4}} \frac{E^4}{\rho}\frac{\theta}{2\pi}$$

- Total energy loss for all turns is $1.952\,\mathrm{GeV}$
- Total installed voltage is $1.362\,\mathrm{GV}$
- Maximum in one arc is $771\,\mathrm{MV}$
  - could be at $720\,\mathrm{MHz}$
- Need $1.44\,\mathrm{GHz}$ for $\approx 600\,\mathrm{MV}$

turn no	E [GeV]	ΔE [MeV]	σ_E/E [%]
1	10.5	0.7	0.00036
2	20.5	10.2	0.0019
3	30.5	49.8	0.0053
4	40.5	155	0.011
5	50.5	375	0.020
6	60.5	771	0.033
7	50.5	375	0.044
8	40.5	155	0.056
9	30.5	49.8	0.074
10	20.5	10.2	0.11
11	10.5	0.7	0.216
dump	0.5	0.0	4.53

- More complex option possible, for further optimisation

Emittance Growth

- Using option I, one finds the emittance growth due to synchrotron radiation in the arcs

$$\Delta\epsilon = \frac{2}{3} C_q r_e \gamma^6 I_5$$

$$\Delta\epsilon = \frac{2}{3} C_q r_e \gamma^6 \frac{\langle H \rangle}{\rho^2} \theta$$

- Somewhat larger for option II: $\Delta\epsilon_t \approx 36.5\,\mu\mathrm{m}$

⇒ Total growth is acceptable

⇒ Total growth before IP appears acceptable

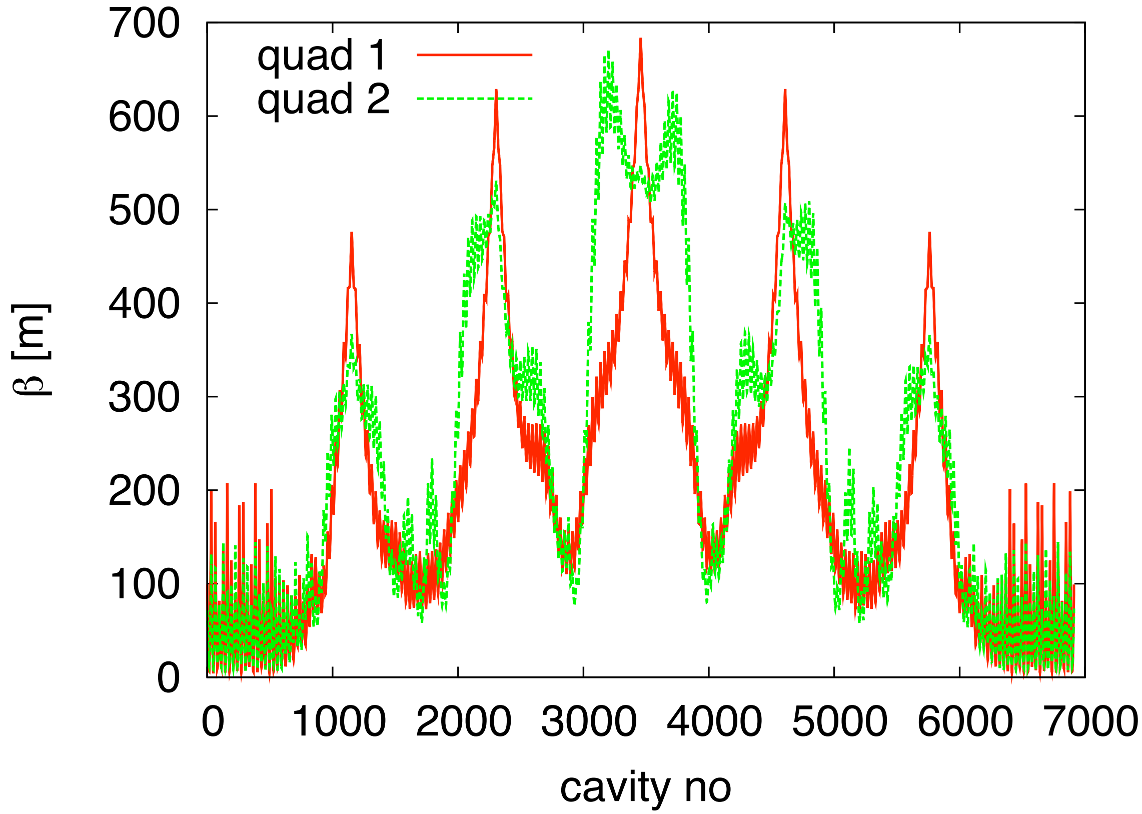
turn no	E [GeV]	$\Delta\epsilon_{arc}$ [μm]	$\Delta\epsilon_t$ [μm]
1	10.5	0.0025	0.0025
2	20.5	0.140	0.143
3	30.5	0.380	0.522
4	40.5	2.082	2.604
5	50.5	4.268	6.872
6	60.5	12.618	19.490
5	50.5	4.268	23.758
4	40.5	2.082	25.840
3	30.5	0.380	26.220
2	20.5	0.140	26.360
1	10.5	0.0025	26.362

Main Linac Lattice Design

- Two approaches
  - option I, use focusing in the linac (A. Bogacz, F. Zimmermann, D.S.)
  - option II, no focusing in the linac (V.N. Litvinenko et al.)
- Option I is shown
  - set quadrupoles for constant phase advance for lowest energy beam
  - match transfer through arcs to minimise

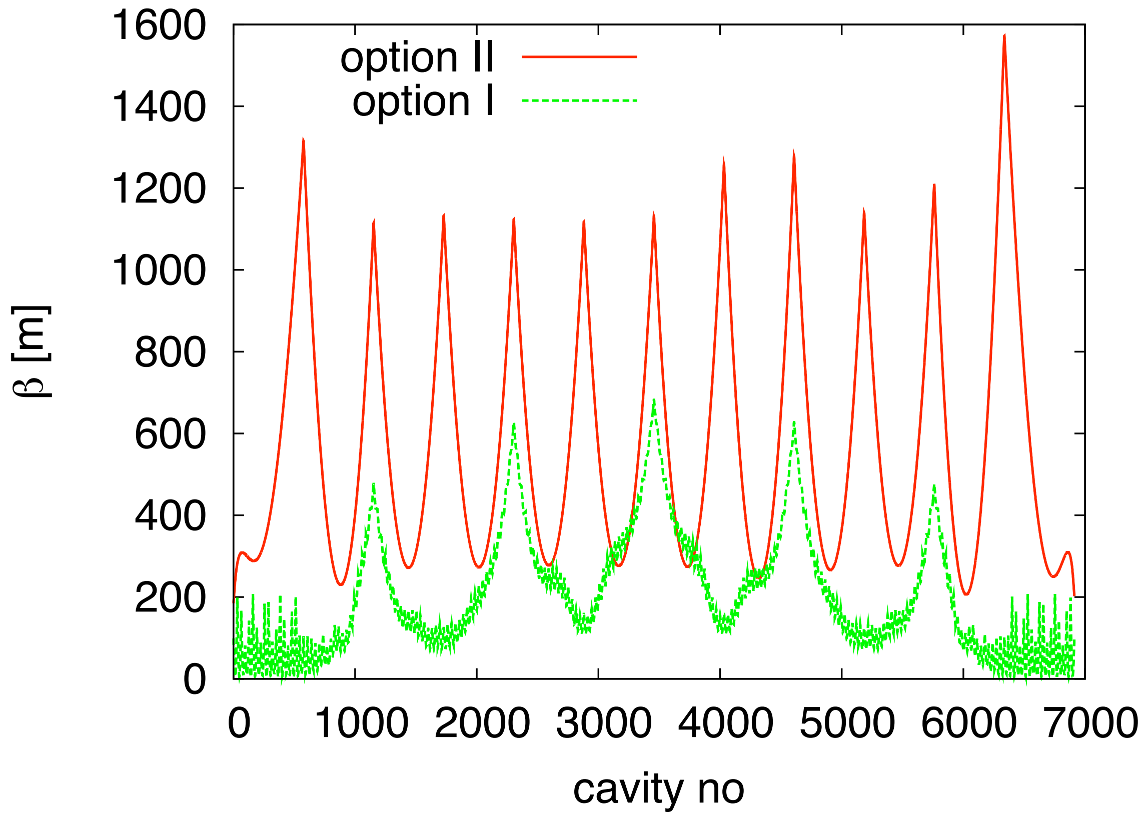
    $$\int_0^L \frac{\beta(s)}{E(s)} ds$$

    This minimises wakefield effects



Main Linac Lattice Design

- I could not reproduce optics of option II (no focusing) with our tracking code
  - ⇒ need to understand RF model
  - ⇒ designed my own version (switching off quadrupoles)
  - ⇒ will have to do better but results should be relevant



with quad

$$\int_0^L \frac{\beta(s)}{E(s)} ds = 96\,\mathrm{m}^2/\mathrm{meV}$$

simlar for both options

no quad

$$\int_0^L \frac{\beta(s)}{E(s)} ds = 256\,\mathrm{m}^2/\mathrm{MeV}$$

Single Bunch Wakefield Effects

- Calculation of wakefields is very tough
  - thanks to R. Calaga for trying, but problems with ABCI

  ⇒ used scaled TESLA/ILC wakefields

⇒ Energy spread

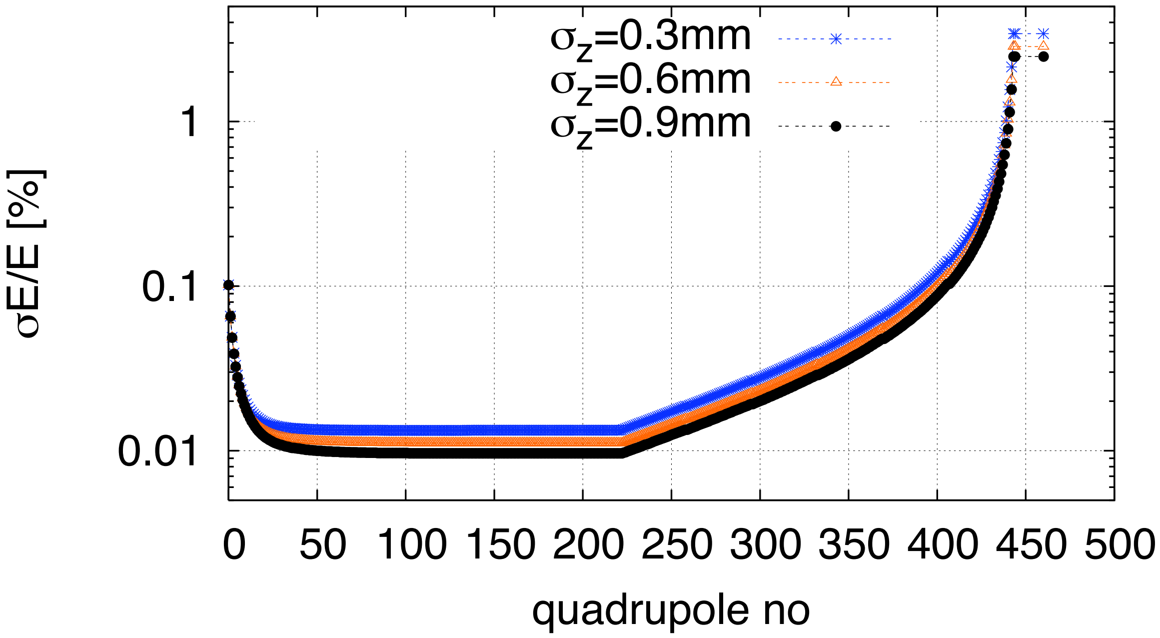
  IP: $\approx 1\text{–}2 \times 10^{-4}$

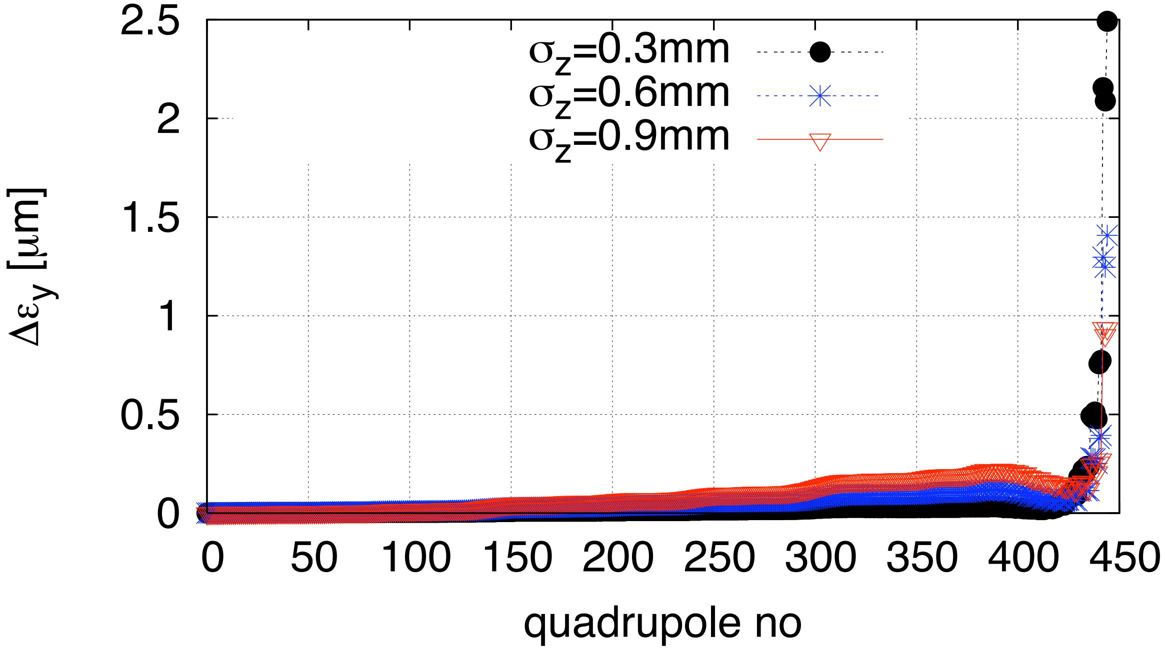
  last arc: $\approx 1\text{–}2 \times 10^{-3}$

  dump: $\approx 2.5\text{–}3.5\%$

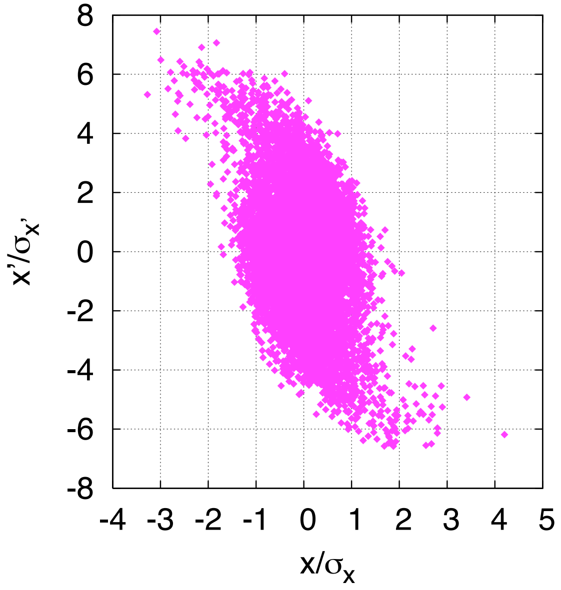
- Bunch with $1\sigma_x$ offset
  - option with quadrupoles

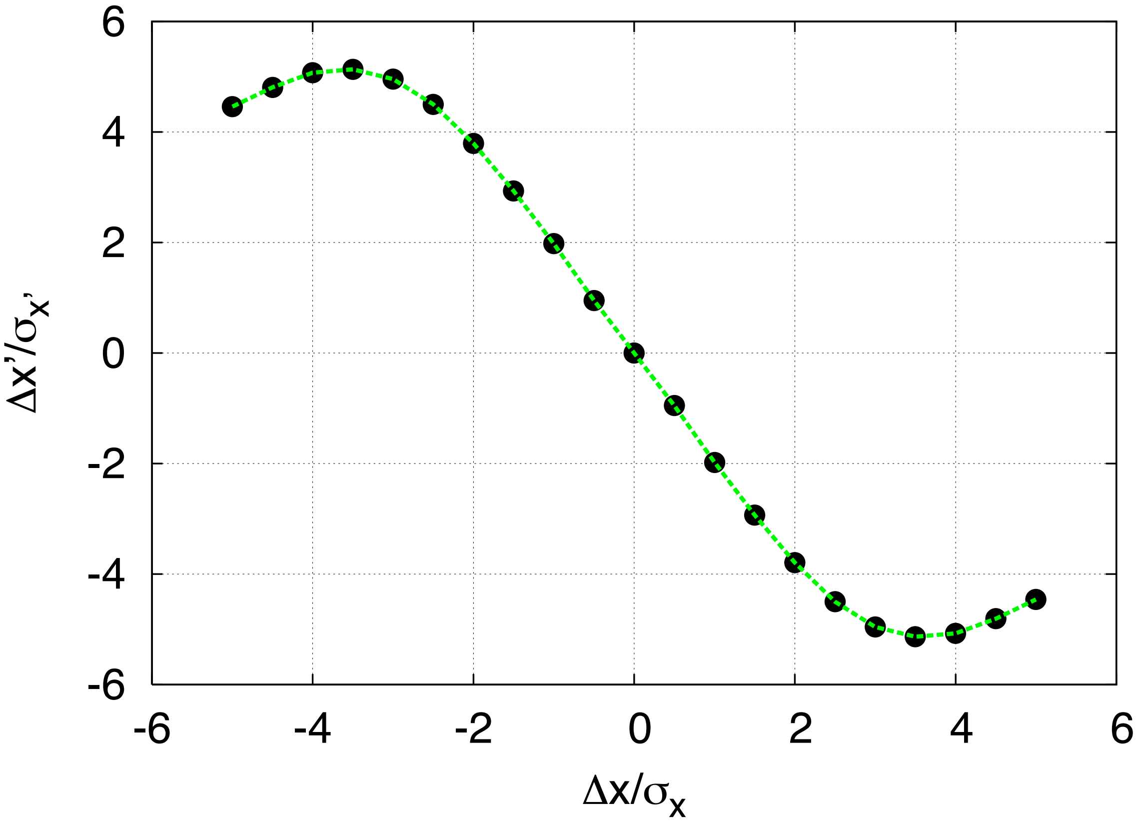
  ⇒ $\Delta\epsilon \approx 1\text{–}3\ \mu\mathrm{m}$





Beam-beam Effects





- For electrons $D_{x,y} \approx 6$
- Head-on collisions
  - $\mathcal{L} \approx 1.35 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - $\Delta\epsilon \approx 14$–$20\%$
  - should use $\beta \approx 3\,\mathrm{cm}$ for extraction

$|x'| \leq 4\sigma_{x,extr}$

$|x'| \leq 8\sigma_x$

- Deflection is

$$\Delta x' \approx -2\sigma_x \frac{x}{\sigma_x} \qquad \Delta x' \approx -1\sigma_{x,extr} \frac{x}{\sigma_x}$$

- Maximum mean deflection $5\sigma_x$ $2.5\sigma_{x,extr}$
- Maximum mean deflection for protons $\approx 0.03\,\mu\mathrm{radian}$
- GUINEA-PIG simulations

Multi-bunch Transverse Wakefields

- Used multi-bunch wakefield of SPL cavity design
  - for comparision also TESLA/ILC cavity design
- For SPL cavity
  - assume $Q = 10^5$ for transverse mode damping
  - assume cavity-to-cavity transverse mode detuning of 0.1%
- Developed a simulation code
  - includes multiple turns and energy recovery
  - arcs are replaced by simple transfer matrix
  - linear approxmiation
  - monochromatic beam

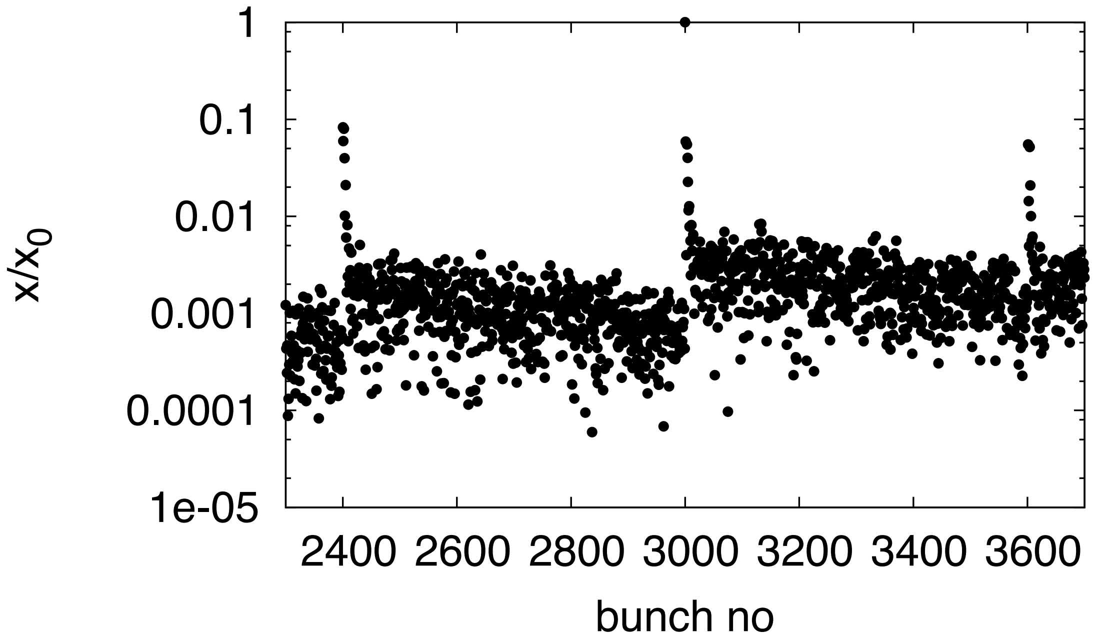
f [GHz]	k [V/pCm^2]
0.9151	9.323
0.9398	19.095
0.9664	8.201
1.003	5.799
1.014	13.426
1.020	4.659
1.378	1.111
1.393	20.346
1.408	1.477
1.409	23.274
1.607	8.186
1.666	1.393
1.670	1.261

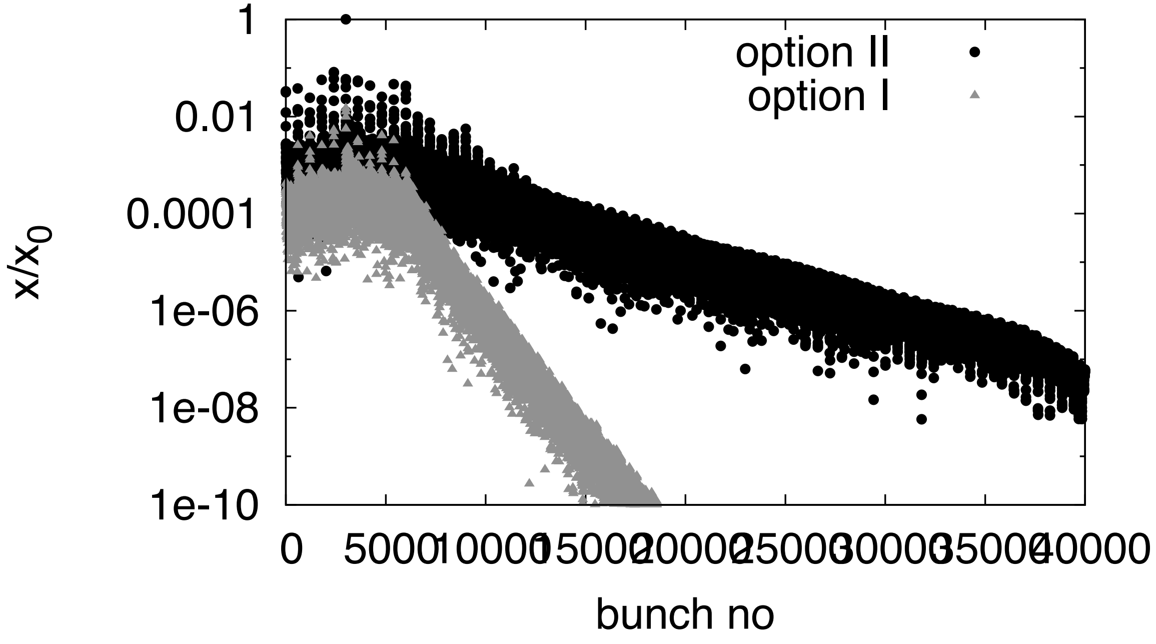
f [GHz]	k [V/pCm^2]
1.675	4.160
2.101	1.447
2.220	1.427
2.267	1.377
2.331	2.212
2.338	11.918
2.345	5.621
2.526	1.886
2.592	1.045
2.592	1.069
2.693	1.256
2.696	1.347
2.838	4.350

Thanks to Marcel Schuh

Multi-Bunch Wakefield Effects

- Simulation procedure
  - offset one bunch by one unit
  - track the beam
  - use the final RMS amplitudes as measure of wakefield effect
  - all done in normalised phase space
- Upper plot: ILC/TESLA wakefields, lower plot: SPL wakefields
- RMS amplitude jitter amplification
  - 0.12% with quadrupoles
  - 7% with no quadrupoles





Multi-Bunch Wakefield Effects (cont)

- Upper plot SPL cavities with
  - detuning only
  - damping only

⇒ Detuning is essential

  - have to make sure it happens

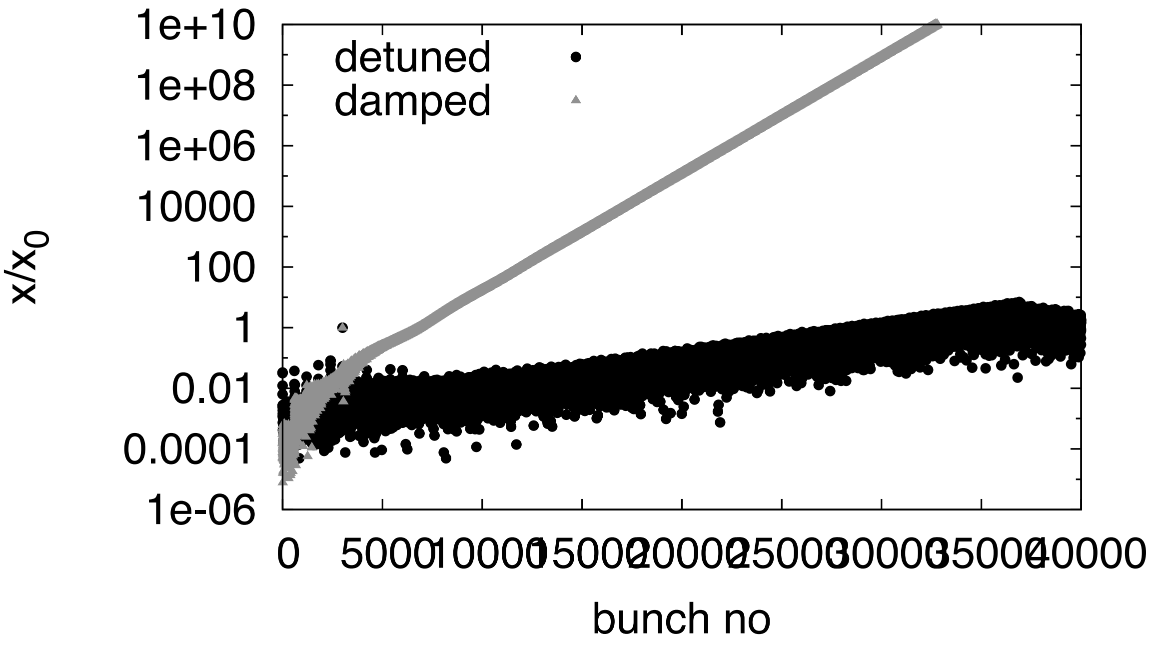
⇒ Damping is required

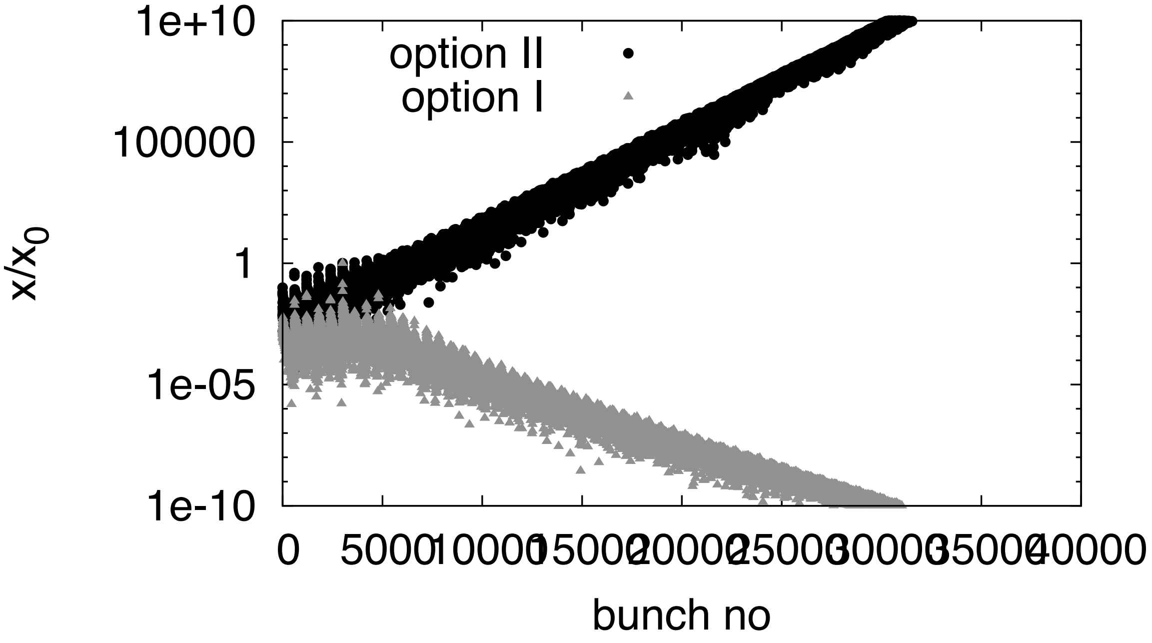
  - hard to be sure there is no instability growing

- Note: have to avoid trapped modes (e.g. first TESLA cavities)
- Lower plot TESLA/ILC cavities

  ⇒ stable with quadrupoles

- No optimisation for total phase advance made to improve stability





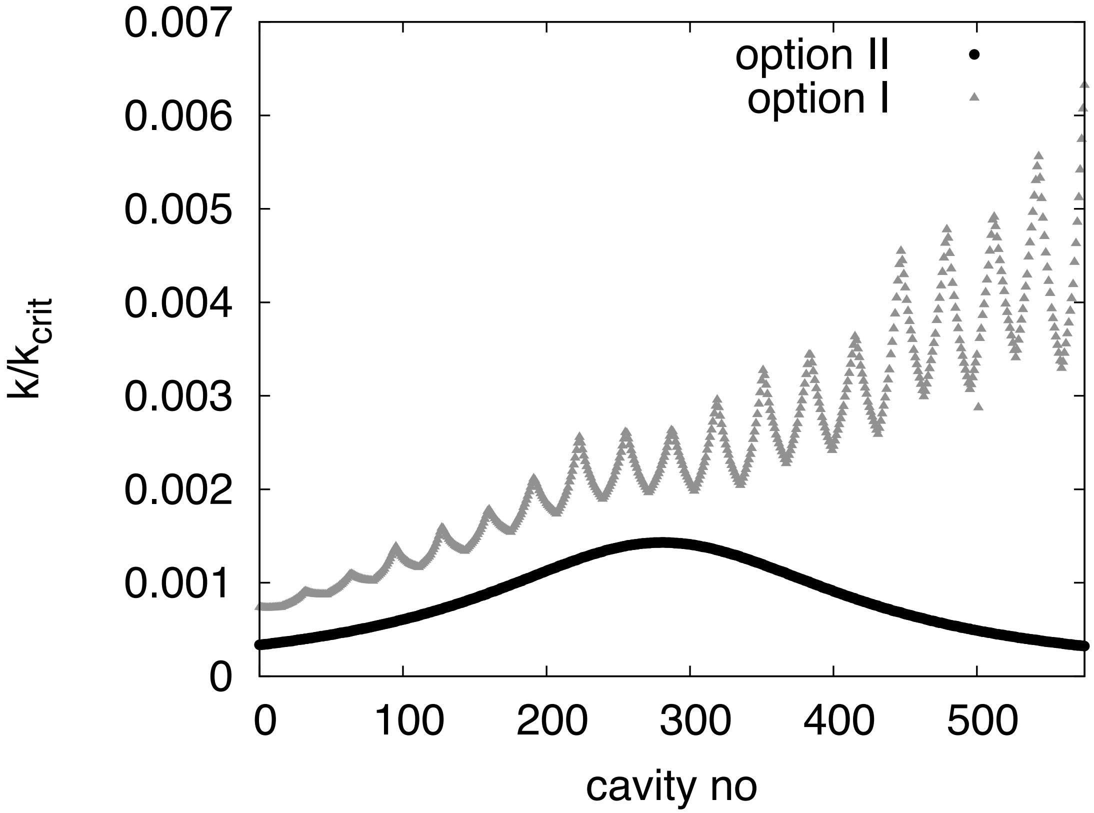
Ion Trapping

- Fast beam-ion instability can be a problem
- Ions are produced from rest gas via collision ionisation
  - tunneling is negligible
- Preliminary approximate estimate for the linacs
  - highest current density
  - but only $1/4$ of circumference
  - cavitiy fields are neglected

⇒ We do trap ions

⇒ We need to remove them

- clearing gaps
- clearing electrodes



Ion trapping for CO_2^+

Average k over turns is shown (conservative)

For $k > k_{crit}$ ions would not be trapped

Clearing Gap

- Clearing gap can remove ions
  - use $10\,\mu s$ gap (and $20\,\mu s$ train)

  ⇒ to be optimised

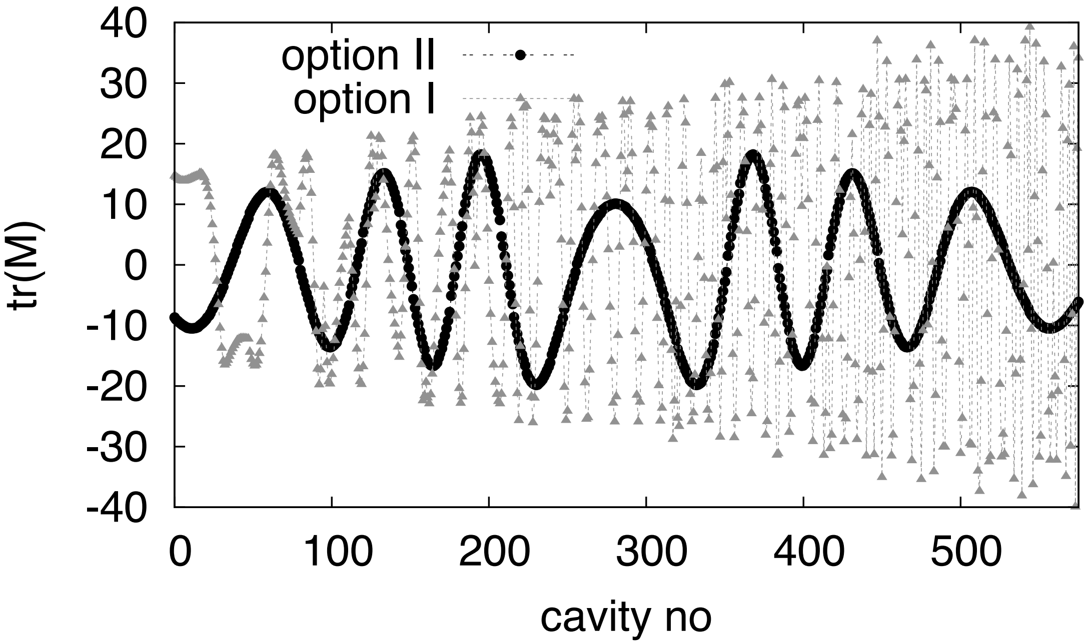
⇒ Ions are trapped only at a small number of short locations

⇒ Detailed study of the fast beam-ion instability is mandatory

- Clearing gaps will reduce luminosity and power consumption

  ⇒ should we increase bunch charge to recover?

- Gradient variation due to gap is $\approx 1\%$



Thick lens model for the bunch train and the gap leads to instability requirement

$$\left|2\cos(\sqrt{k}L_{train}) - \sqrt{k}L_{gap}\sin(\sqrt{k}L_{train})\right| \geq 2$$

- agrees well with more detailed simulations

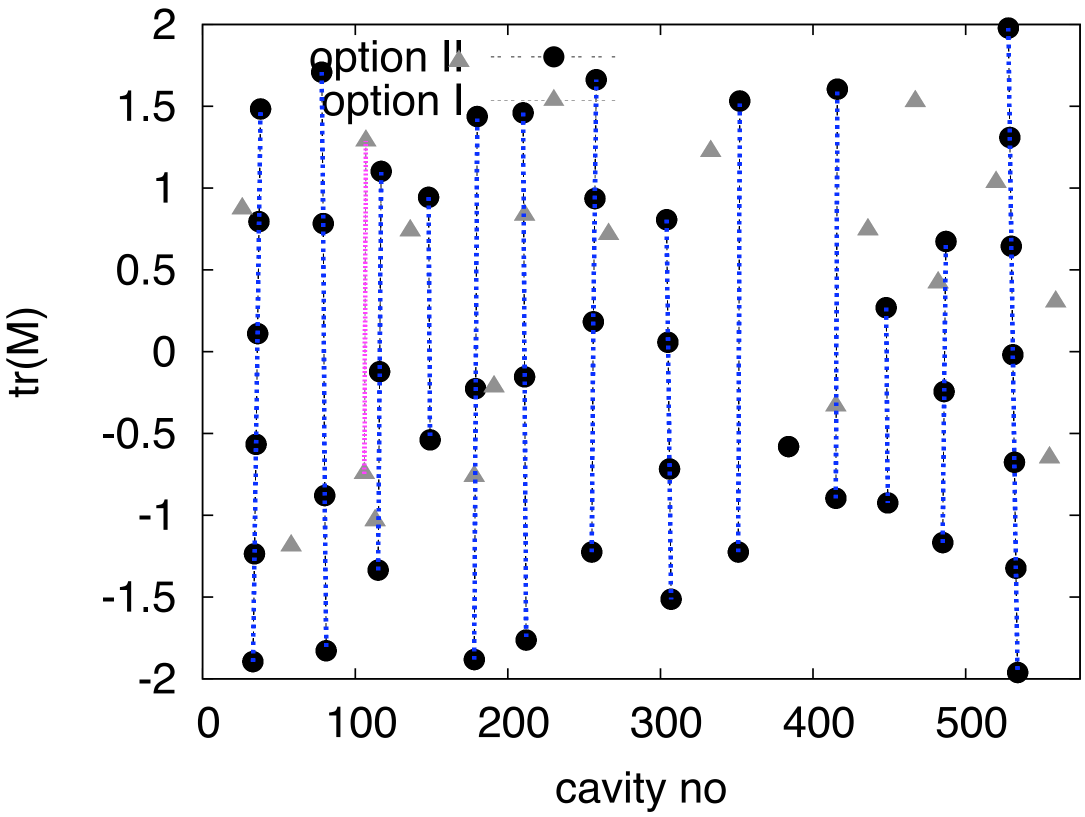
⇒ more detail to be done later

Trapping Regions

- In some short regions the ions will be trapped
  - fewer but longer for no quadrupoles

⇒ Need to remove these ions
  - longitudinal drifts
  - clearing electrodes
  - . . .

- Will need to develop concept for ions
  - e.g. beam shaking
  - . . .



Instability Rise Time

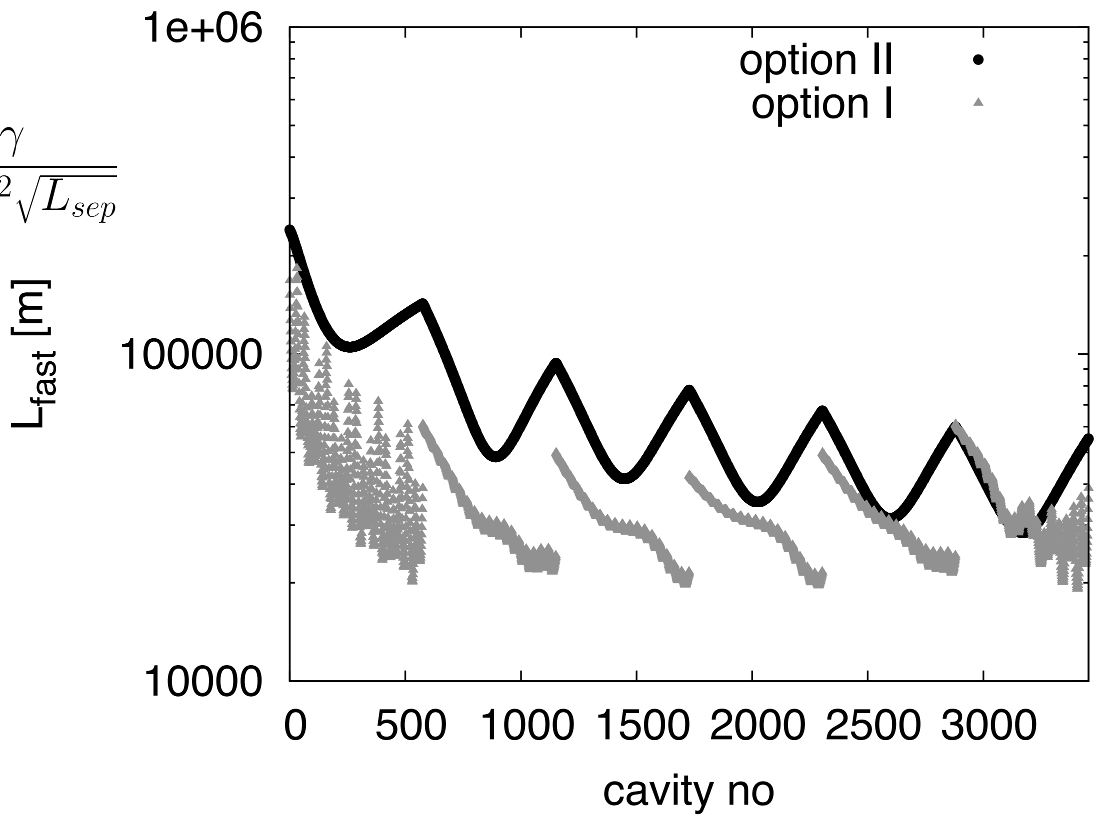
- Calculate instability rise time during train

$$\tau_c = \frac{\sqrt{27}}{4}\left(\frac{\sigma_y(\sigma_x+\sigma_y)}{N r_e}\right)^{\frac{3}{2}}\sqrt{\frac{M}{m}\frac{kT}{p\sigma_{ion}}\frac{\gamma}{\beta_y c n^2\sqrt{L_{sep}}}}$$

- Pessimistic
  - frequency spread helps
- Optimistic
  - gap does not clear fully
- Could use

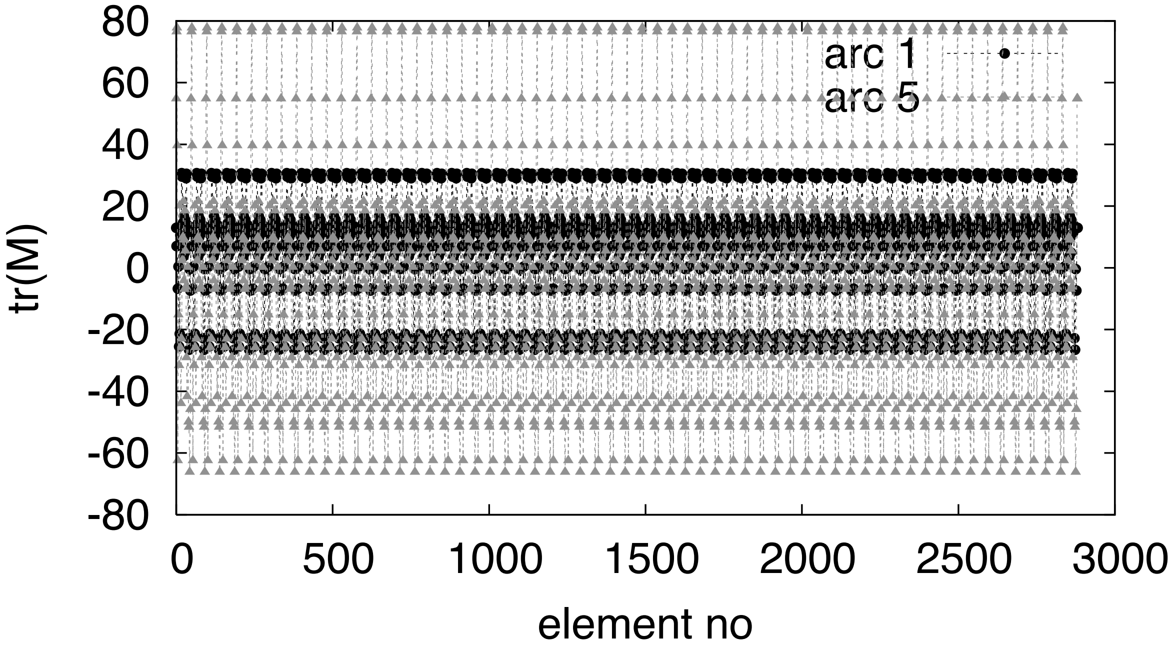
$$\tau_e = \tau_c\frac{\sqrt{32}\pi L_{sep} n a f_i}{c}$$

$$\Rightarrow \tau_e \approx \frac{kT}{p\sigma_{ion}}\frac{\sqrt{72}\epsilon a}{N n r_e c}\sqrt{Q} \approx 3\times 10^5\,\mathrm{m}/c$$



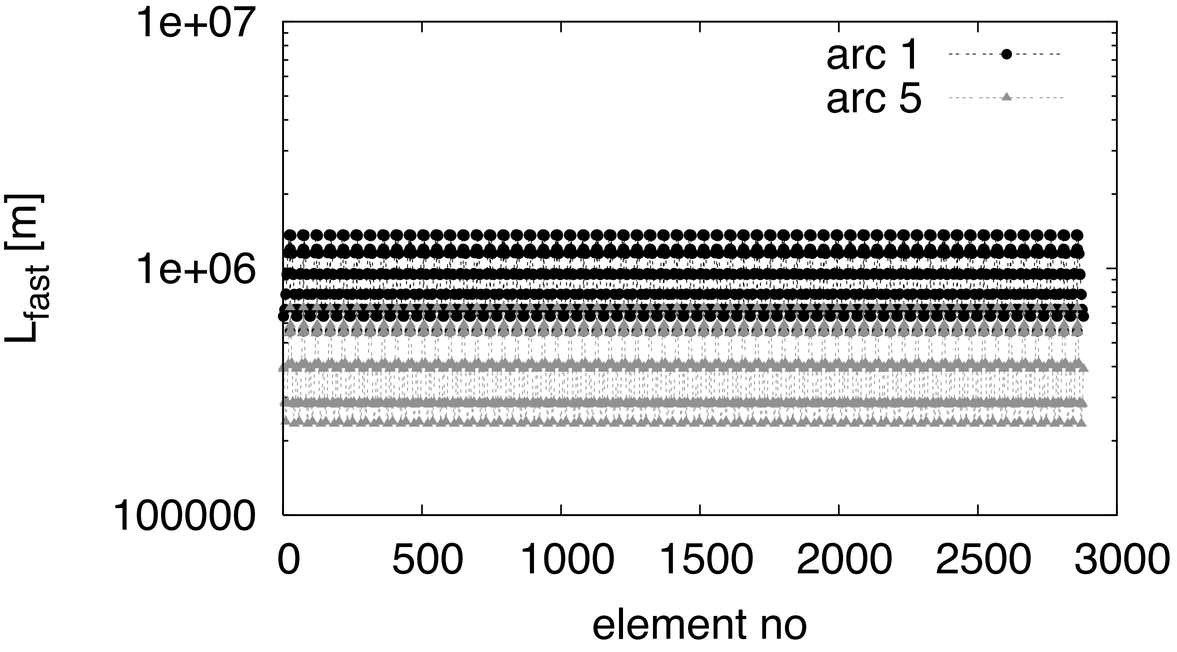
- Assumed vacuum $10^{-11}\,\mathrm{hPa}$ at the beam
  - value from HERA (as remembered by B. Holzer)
  - LEP $0.5\times10^{-9}\,\mathrm{hPa}$ measured warm, i.e. $\approx 0.6\times10^{-10}\,\mathrm{hPa}$ cold (N. Hilleret, V. Baglin, O. Brunner)
  - “represents more the outgassing of warm adjacent parts of the vacuum system” (N. Hilleret)

Fast beam-ion Instability in the Arcs



- Use return arc option I
- β-functions only known at some points

  ⇒ received MAD deck from Alex but not yet used
- $10^{-9}\,\mathrm{hPa}$ in (warm) arcs



Conclusion

- Lattice design
  - overall constraints from LHC circumference
  - two options for linac lattices and return arc lattices ⇒ choose baseline/alternative

  ⇒ full design remains to be done (e.g. polarisation measurement)
- Linac frequency to be fixed
  - for $721.44\,\mathrm{GHz}$, transverse short and long-range wakefields are OK
- Energy compensation to be fixed
- Energy spread is 0.02–0.03% at IP (short range wakes and synchrotron radiation)

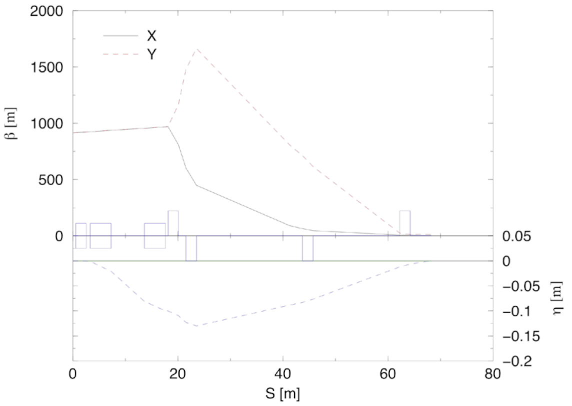
  ⇒ imperfections to be studied
- Strong beam-beam effects
- Fast beam-ion instability
  - could be OK, might require clearing gap, should we modify the parameters accordingly?

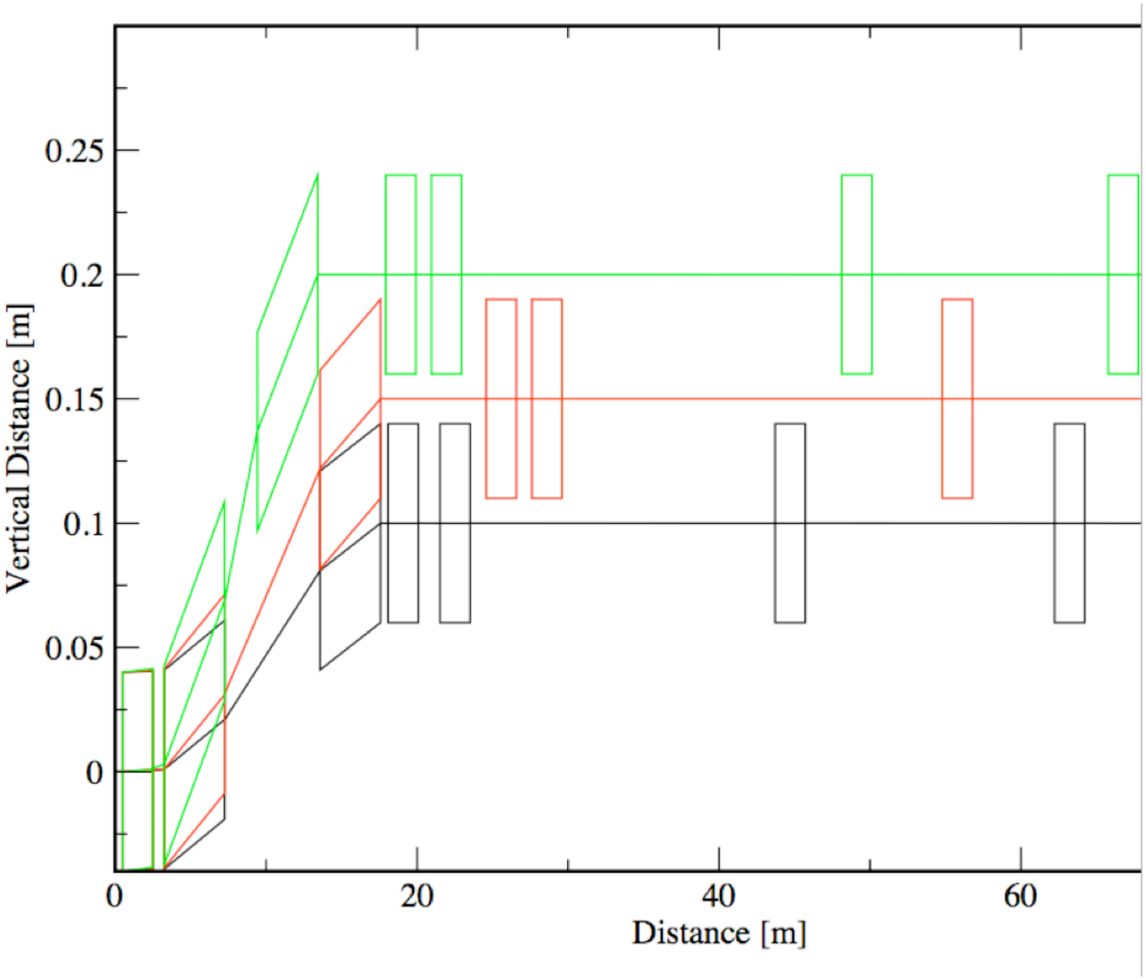
  ⇒ detailed essential work to get a full understanding

Reserve

Splitter and Combiner Design

Y. Hao, D. Kayaran, V.N. Litvinenko, V. Ptitsyn, D. Trbolevic, N. Tsoupas (BNL)





Coherent Synchrotron Radiation

- Coherent synchrotron radiation would be $1.4\,\mathrm{MV/arc}$ with no shielding
- But is suppressed for beam pipe radii below $30\,\mathrm{mm}$
- Y. Hao, D. Kayaran, V.N. Litvinenko, V. Ptitsyn, D. Trbolevic, N. Tsoupas (BNL)