Design of the MAX-IV Injector

Peter Williams

Daresbury Laboratory & Cockcroft Institute

Science & Technology Facilities Council
Daresbury Laboratory

The Cockcroft Institute
of Accelerator Science and Technology

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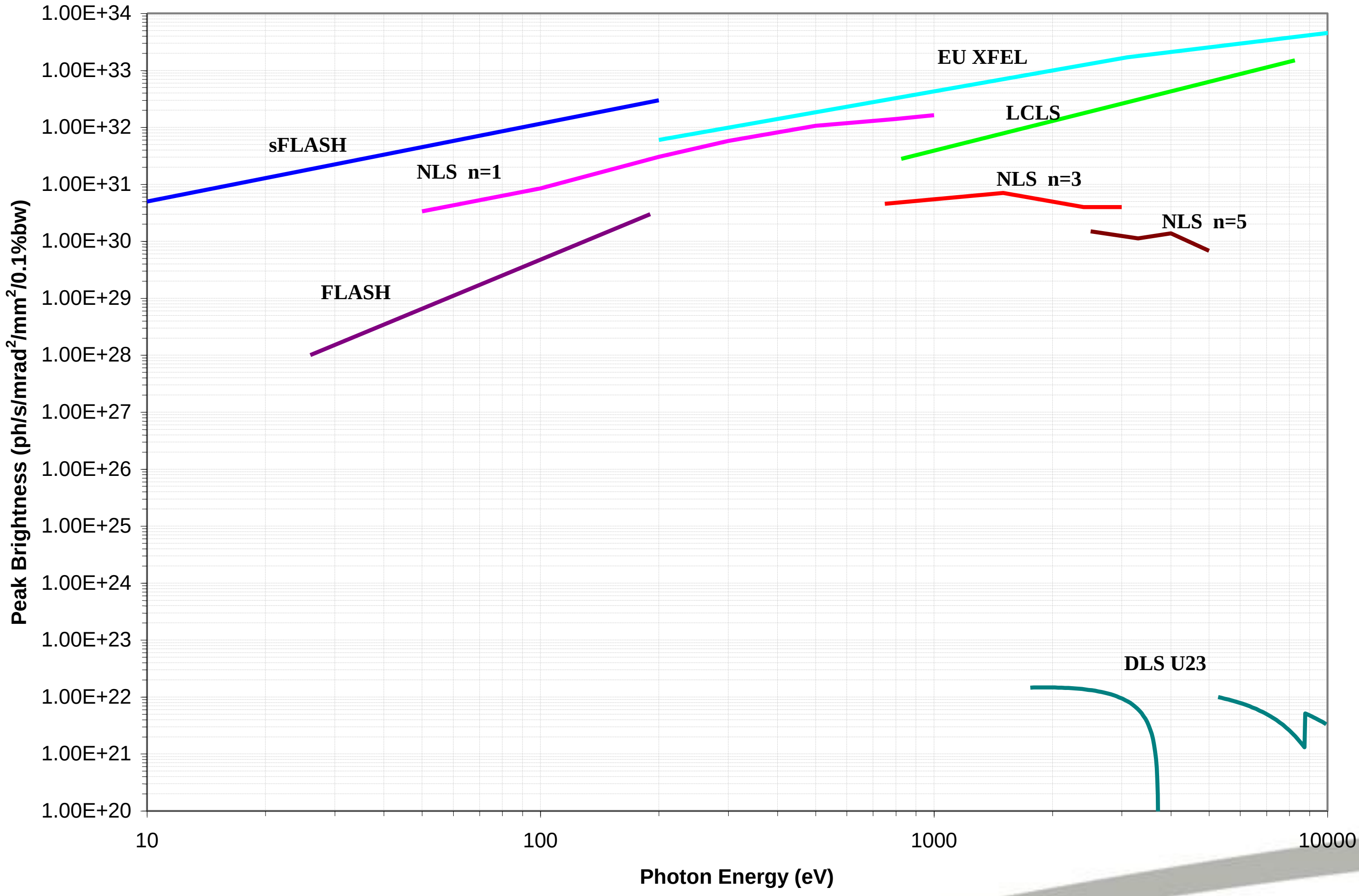
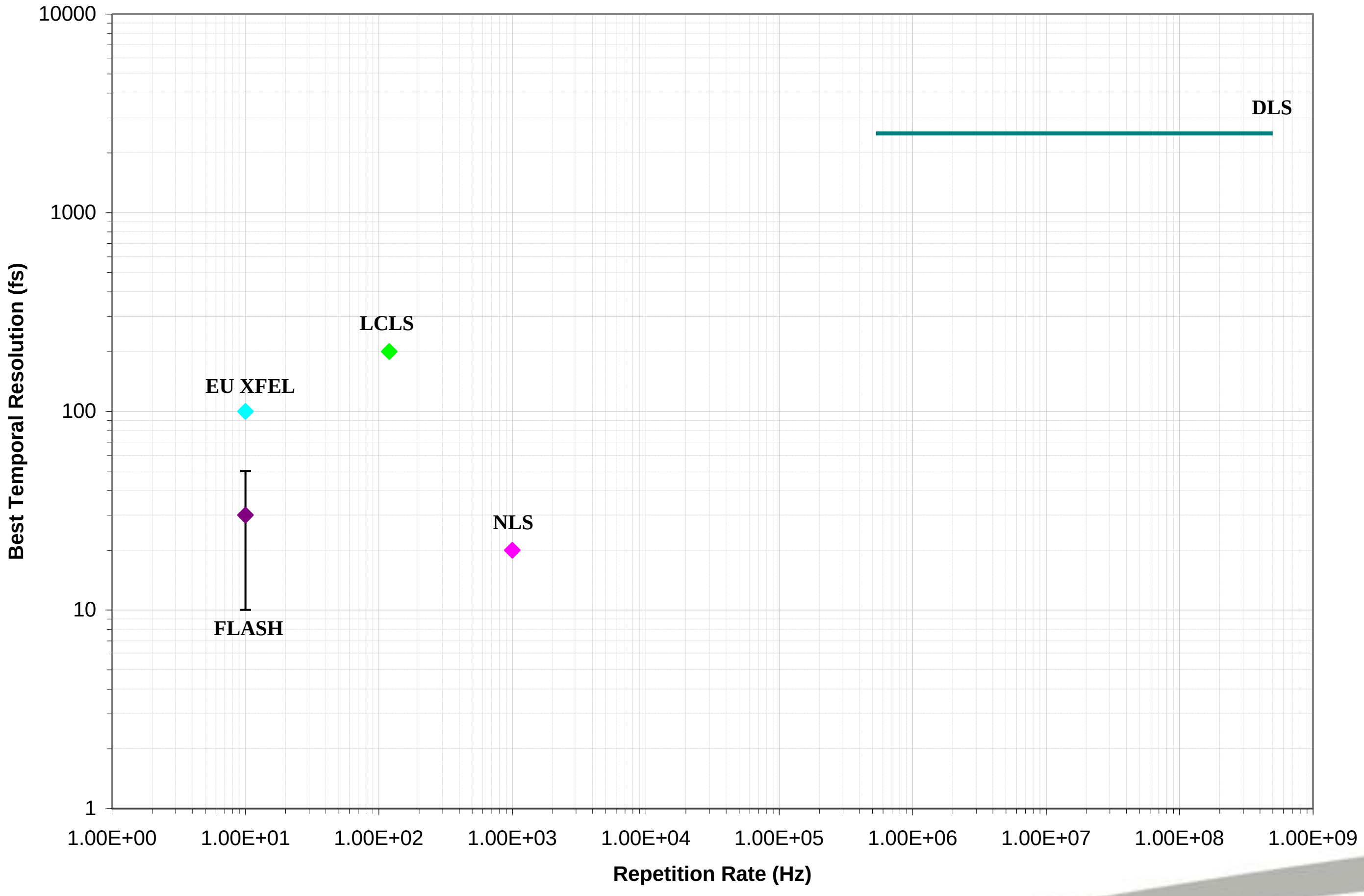
The Need for Fourth Generation Light Sources

- Time resolved studies of physical, chemical and biochemical processes require short, bright radiation pulses – users ask, “can you go to 10 fs”, even “what about attoseconds, i’ll get a Nobel Prize if you do that”
- Third generation synchrotron sources can’t go below a few ps
- A single (or multiple) pass linac is much better at producing short, high-brightness electron bunches
- A Free-Electron Laser can turn this bunch into short, bright radiation pulses – 8 order of magnitude greater in peak brightness than a storage ring undulator
- The UK now has an operating Free-Electron Laser – ALICE @ Daresbury (35 MeV energy recovery linac, infra-red output)
- Worldwide, the first high energy X-ray FEL – LCLS is operational, more are in development (FERMI, EU-XFEL, SCSS)

Fourth Generation Light Sources – High Peak Brightness



Fourth Generation Light Sources – Better Temporal Resolution



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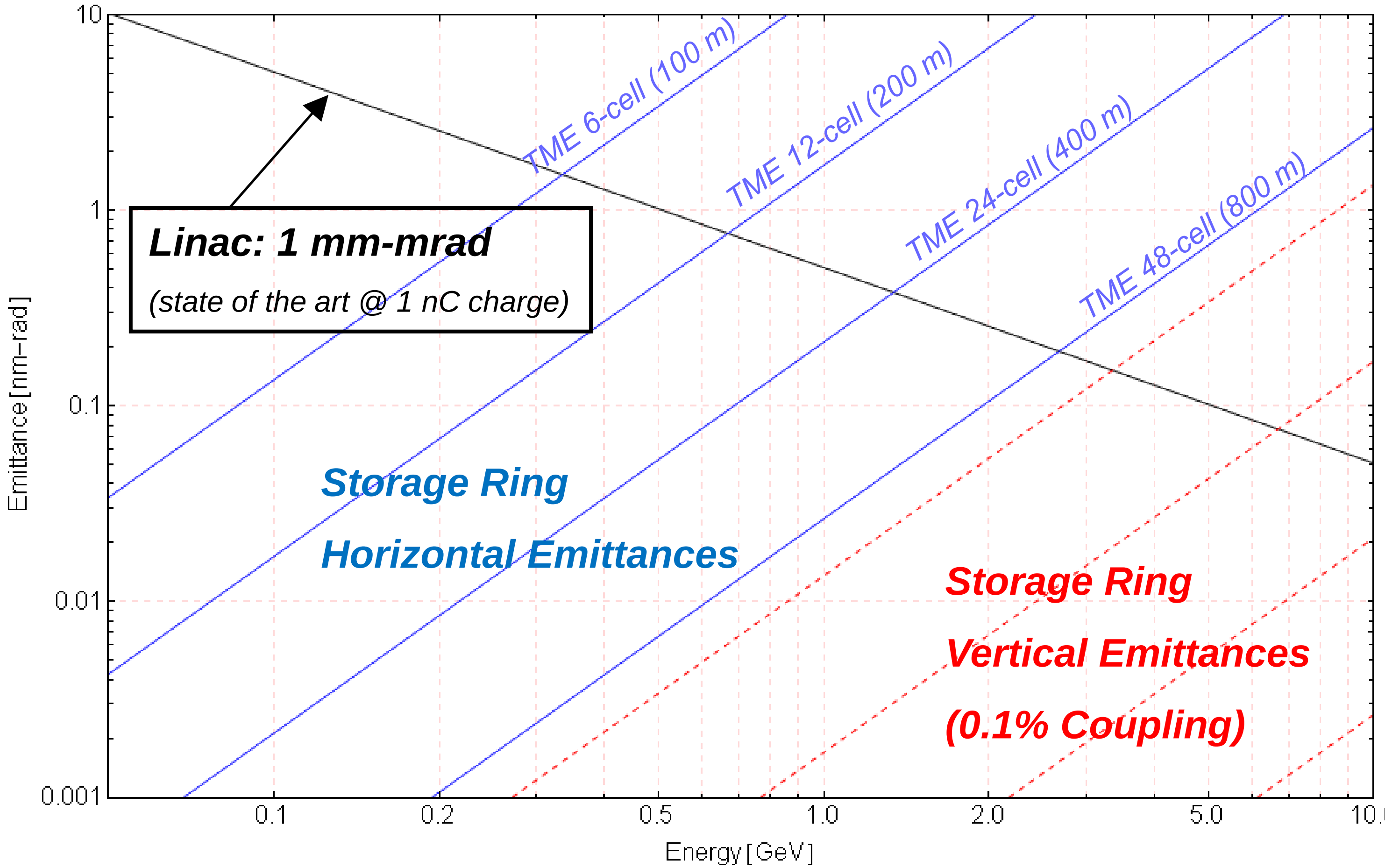
Fourth Gen. Light Sources – A Linac, Not a Ring



TME (theoretical minimum emittance) is the smallest emittance possible in a ring, based on minimising

$$H = \gamma D_x^2 + 2\alpha D_x D'_x + \beta D'^2_x \qquad I_5 = \oint \frac{H}{\rho^3} ds \qquad \epsilon_x = C_q \frac{\gamma^2}{J_x} \frac{I_5}{I_2}$$

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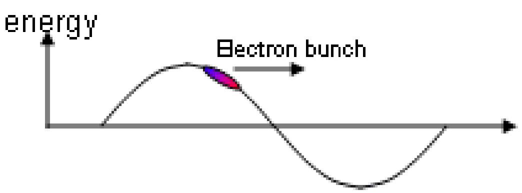
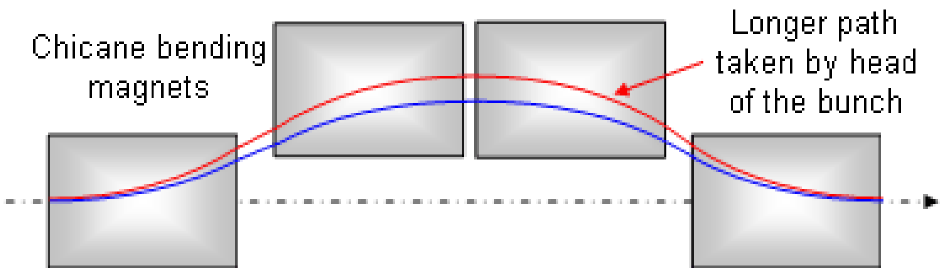
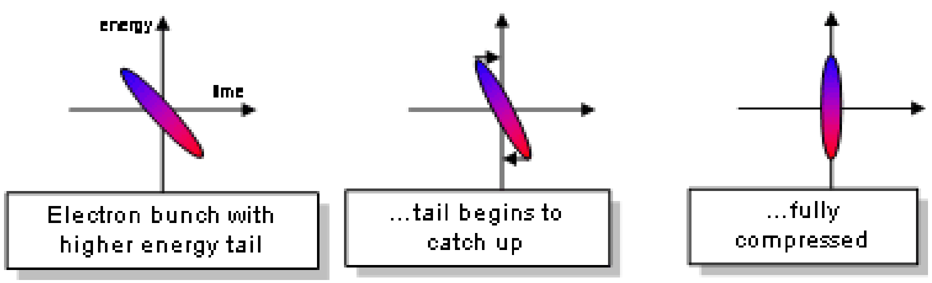
Bunch Compression in a Linac



- Accelerate the bunch off crest – impart a correlation between position and energy – “chirp”



- Pass the bunch through a magnetic system where the path length depends on energy



- The bunch is sheared twice, we have decreased the bunch length, the price is increased energy spread

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Accelerator Physics Design Stages

- Before we spend £100M's, we must design and model our source:
  - One-dimensional longitudinal phase space tracking to broadly define the compression scheme – Mathematica, LiTrack
  - Detailed injector modelling inc. space charge – GPT, Astra
  - Lattice design & optimisation, constrained by building, component cost – Mad, Transport, Elegant, Mathematica
  - Tracking studies of final lattice – Parallel Elegant
  - Generation of multiple machines for tolerance / jitter analysis – Parallel Elegant with high throughput, Mathematica
  - Generation of radiation pulses for users – GENESIS

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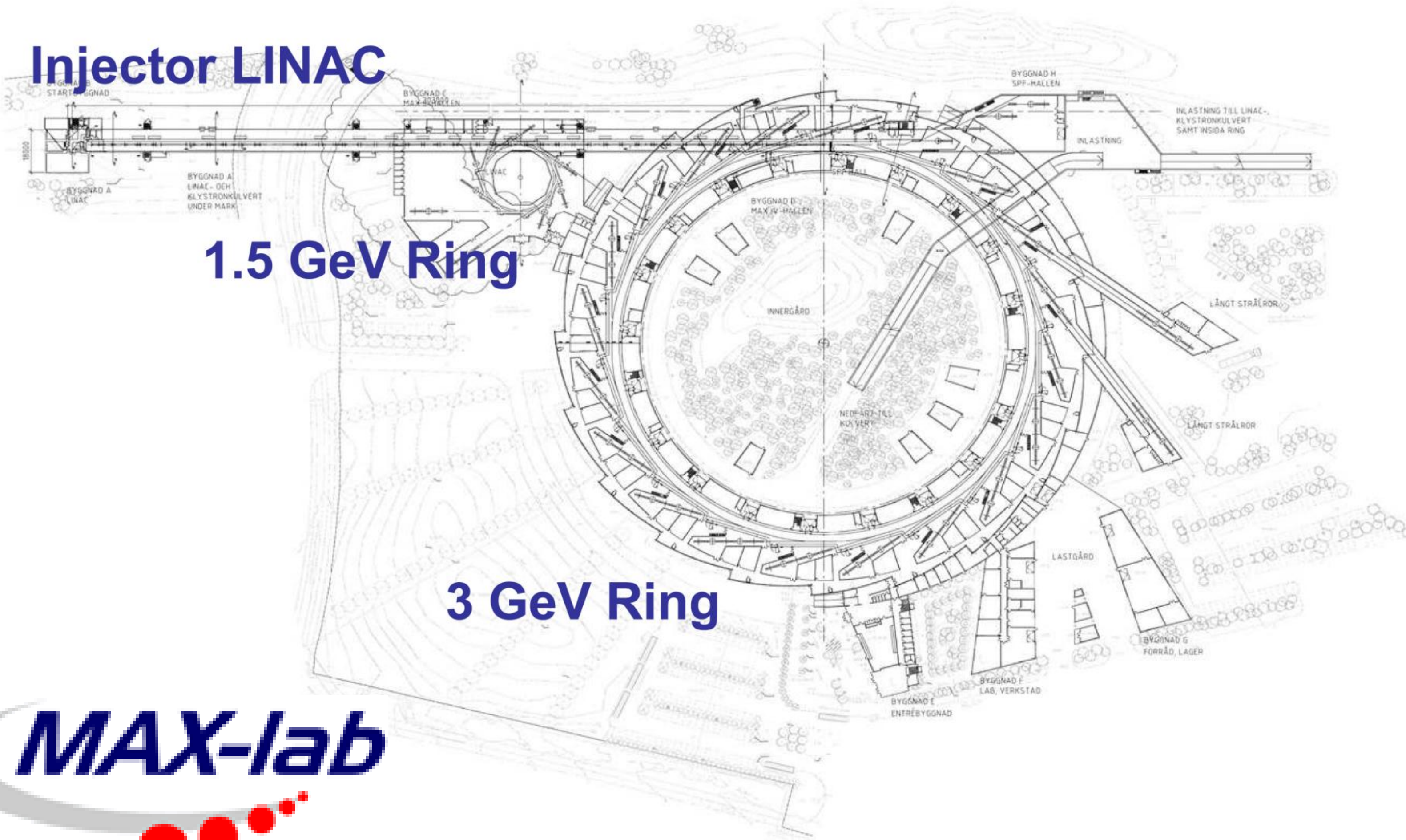
Max-IV and the ESS – Lund, Sweden

The Max-IV Project



MAX-lab

Max-IV Injector Requirements

1. Top up to 1.5 & 3 GeV rings every few minutes, for a few seconds @ 10 Hz, 300 pC charge, ~660 ps pulse length, ~ 0.4 mm mrad emittance

2. In between top ups, 3 GeV beam to short pulse facility @100 Hz, 100 pC , <100 fs clean pulses, < 10 mm mrad

3. FEL (phase two), < 0.4 mm mrad emittance, Few kA peak current

- Low level RF to provide flexibility for fast mode changes
- Significant RF power redundancy (max energy 3.7 GeV)

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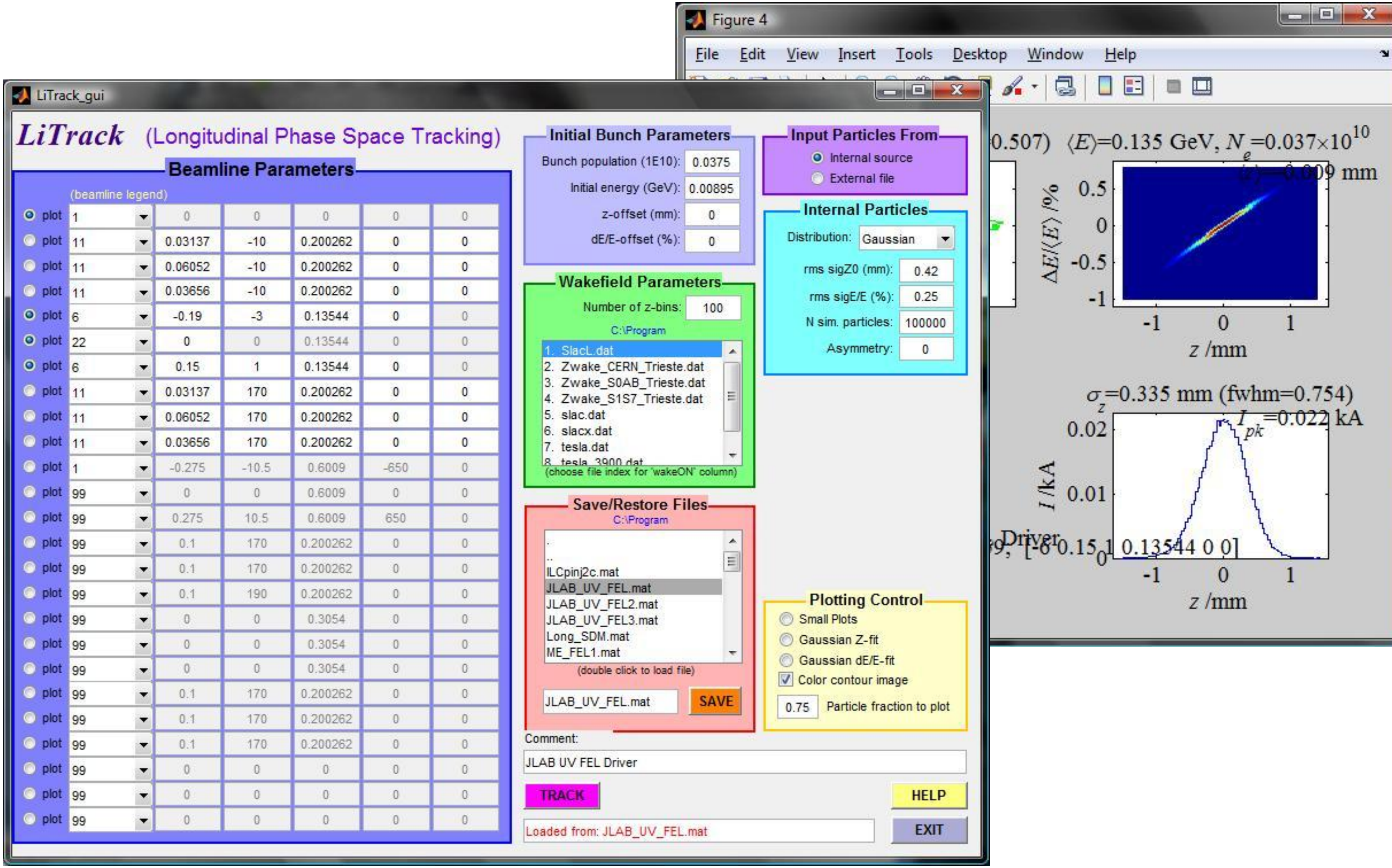
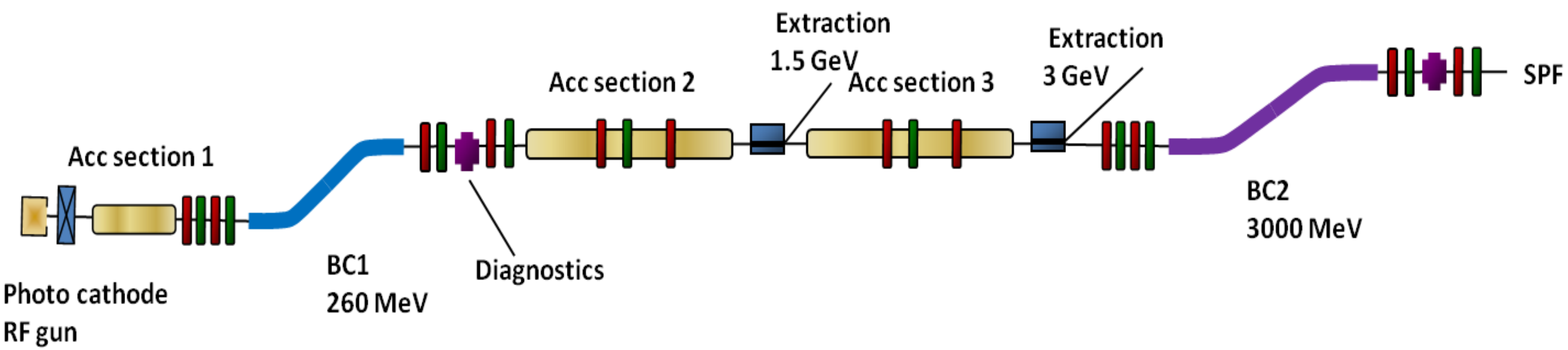
One-dimensional longitudinal phase space tracking to broadly define the compression scheme



Max-IV Injector Schematic



- Bunch compression in two stages, at 260 MeV and 3000 MeV

- Compression factors of 5 for BC1 and up to 10 for BC2, linearisation performed within compressors

- Gradient of accelerating sections (18 MV/m) compatible with building size restrictions (length < 350 m)

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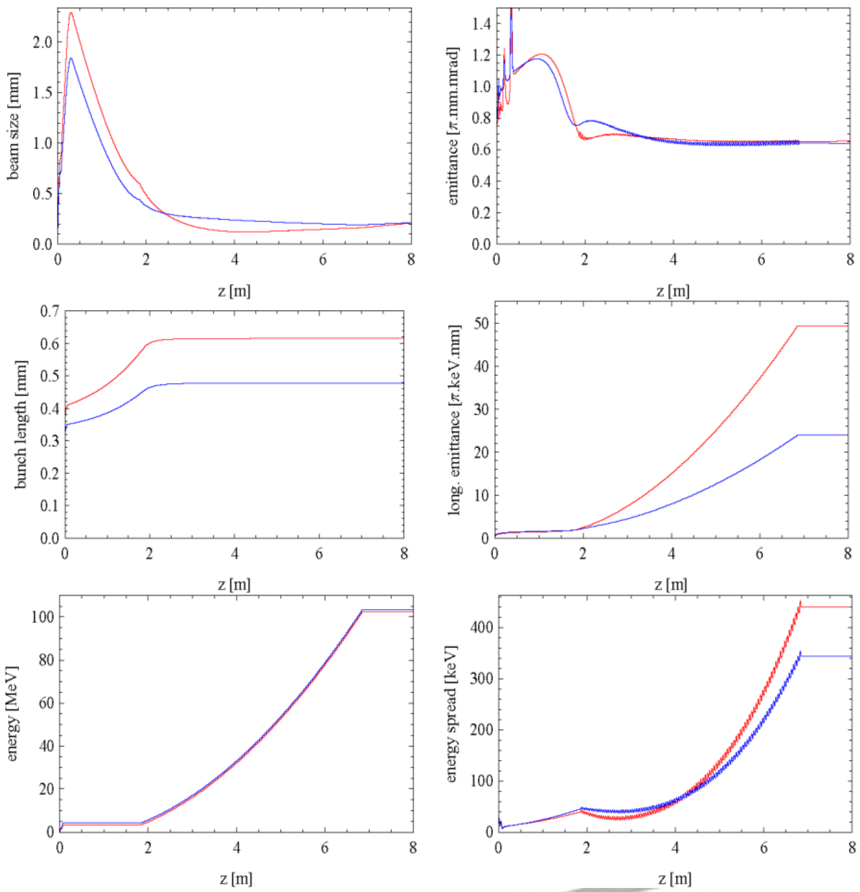
Detailed Injector Modelling

- At energies below ~10 MeV we are in the space charge dominated regime and must make fewer approximations in the beam dynamics calculations



- Multidimensional optimisation of parameters

Bunch charge	100	pC
Laser spot diameter	1	mm
Laser pulse width (FWHM Gaussian)	5	ps
Initial thermal emittance	0.225	mm mrad
Gun peak field	100	MV/m
Gun phase	- 5	°
Solenoid peak field	0.190	T
Linac entrance position	1.85	m
Linac peak field	40.3	MV/m
Linac field flatness	0.58	
Linac phase	+ 5	°

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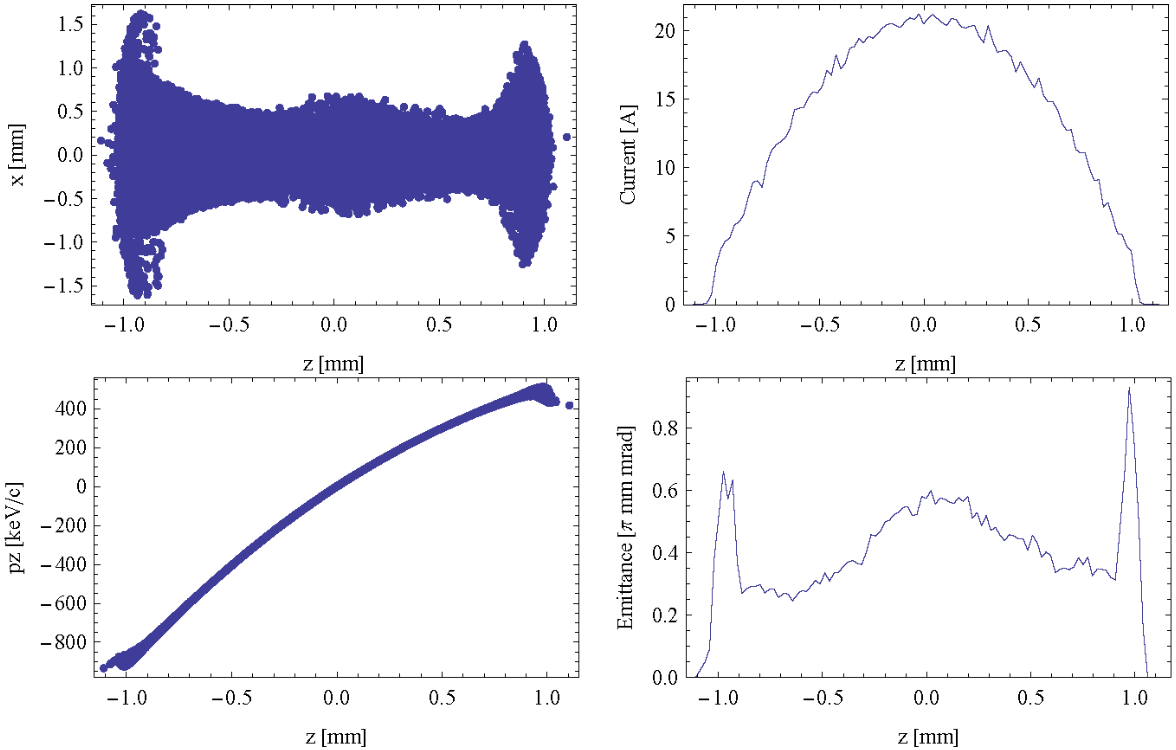
Detailed Injector Modelling

- Bunch profile at the exit of the injector



Beam size (rms)	0.212	mm
Projected emittance	0.638	mm mrad
Average slice emittance	0.411	mm mrad
Peak current	21	A
Bunch length (rms)	1.60	ps
Bunch length (full)	7.38	ps
Energy spread (full)	1.46	MeV
Energy	103.4	MeV

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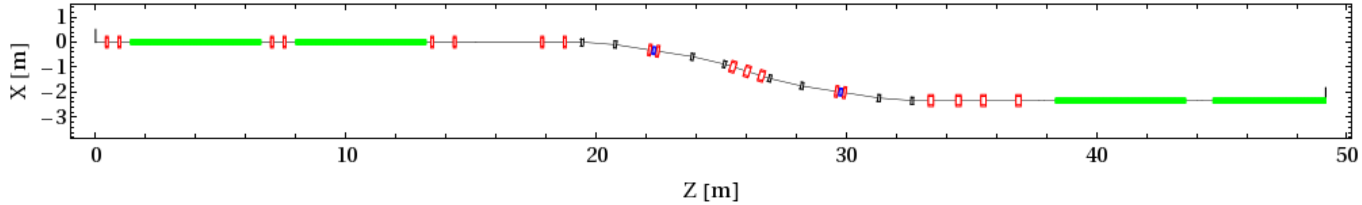
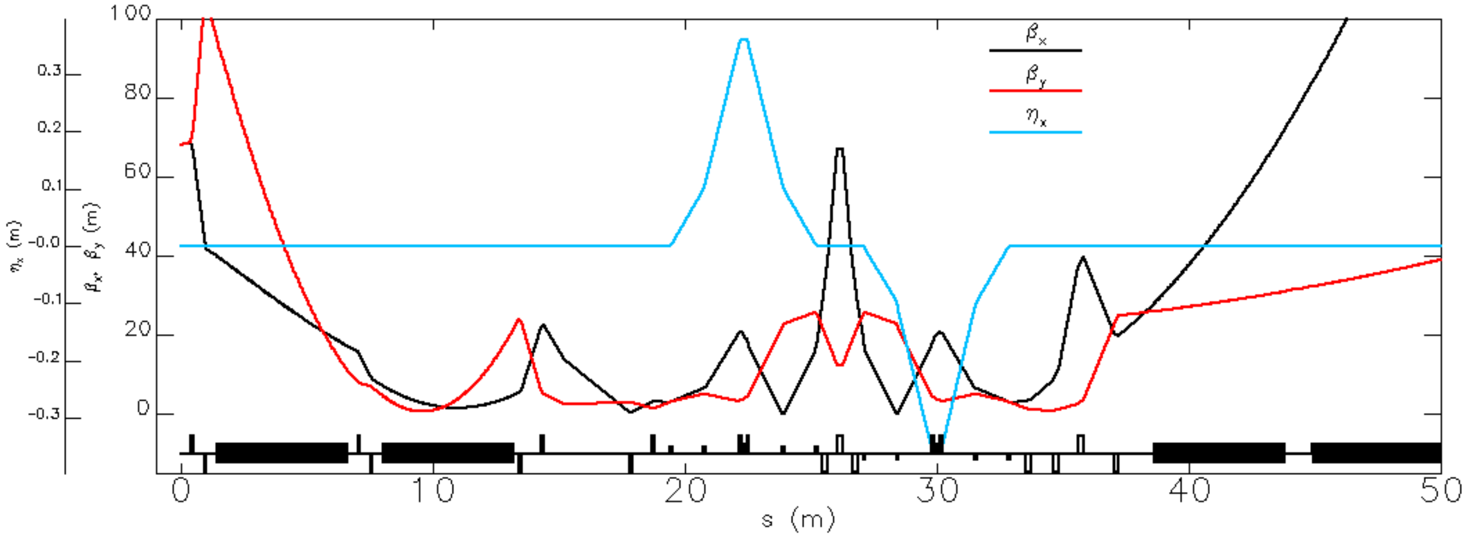
Max-IV Injector – Bunch Compressor Optics

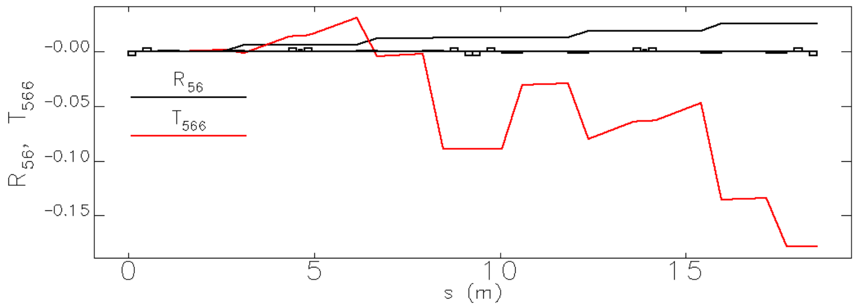
- Compression using two fixed double 5-bend achromats at 260 MeV and 3.3 GeV
- Compression varied with RF phase
- Use natural T_{566} for linearisation – no need for higher harmonic RF
- "Weak" sextupoles for tuning linearisation
- Symmetry keeps the second order energy dependent matrix elements small

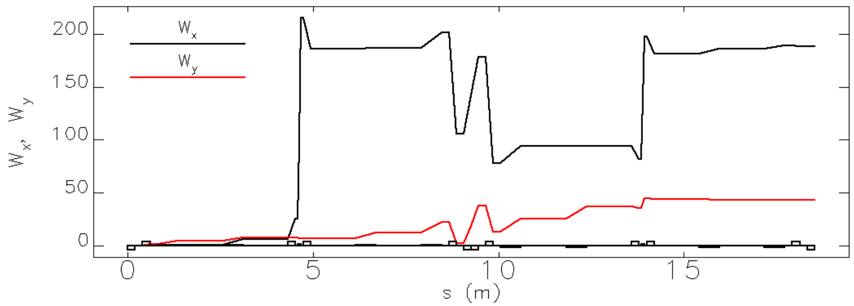




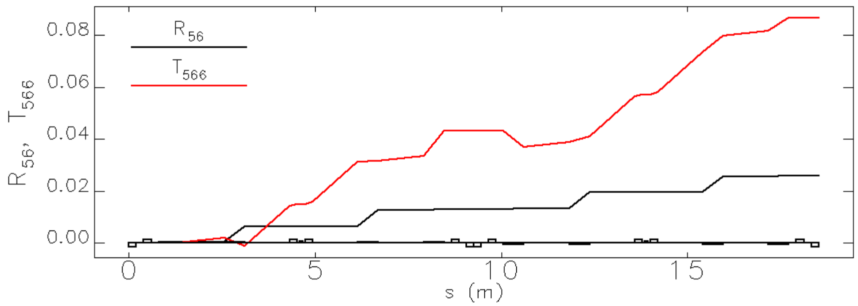
Max-IV Injector – Bunch Compressor Optics

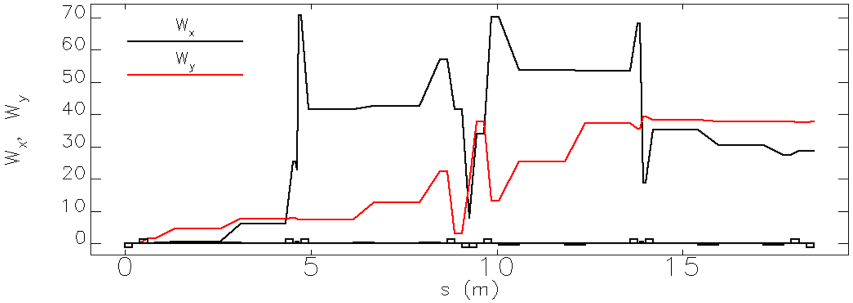
- Comparison between SPF and FEL tuning
- SPF tuning: need single spike – large negative T_{566} to strongly linearise





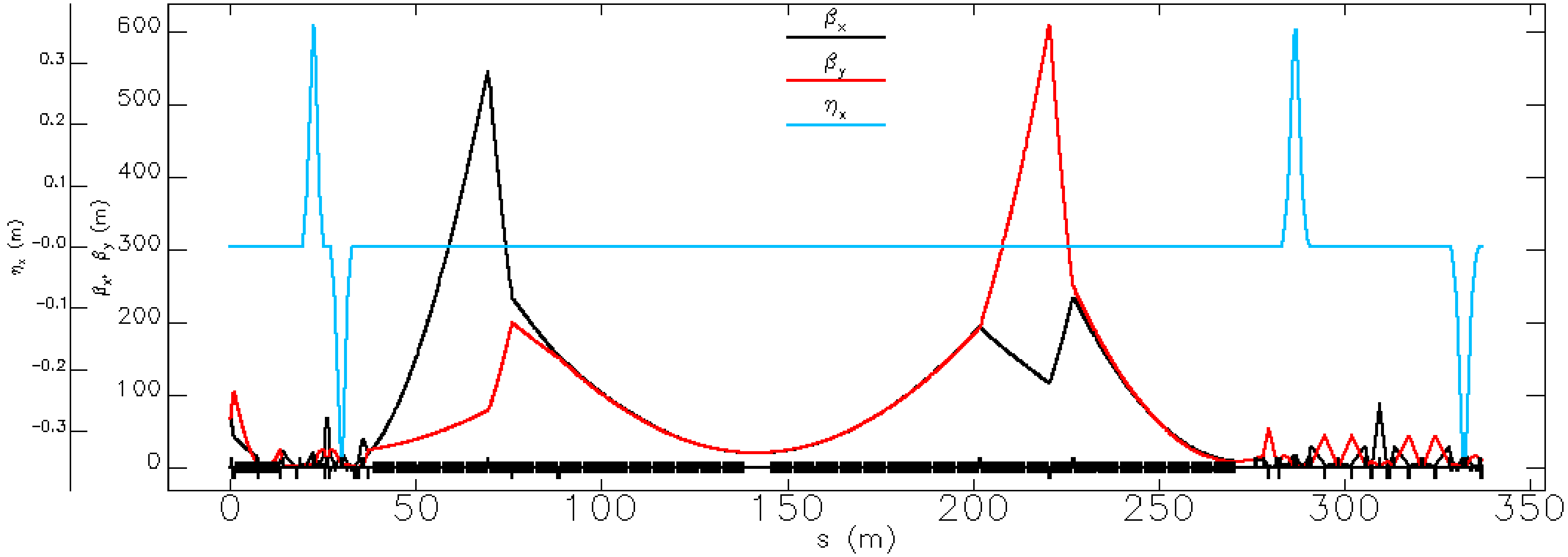
- FEL tuning (right): need small slice emittance - small chromatic amplitudes





Max-IV Injector – Full Machine Lattice

• To save on many independently powered quadrupoles within the linac, allow Twiss functions to reach 600 m through the linac – pending tolerance studies and cross checking different codes to assess RF focusing in off-crest acceleration



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Max-IV Injector – Longitudinal Optimisation

• Produce required bunch properties at the SPF / FEL by varying linac phases / amplitudes, sextupole linearisation

• Iterative process – need to return to transverse optics and alter e.g. achromat compression factors

• Manual optimisation to get to broadly correct parameters, then Luus-Jaakola pseudo-random global minimum search using Mathematica

• For SPF: linac 1 phase = +32 degrees, linac 2 phase = +17.5 degrees

BC1 parameters

Energy (MeV)	260
R56 (cm)	3.053
T566 (cm)	7.289
Sextupole k2 (m^{-3})	± 57

BC2 parameters

Energy (GeV)	3.3
R56 (cm)	2.176
T566 (cm)	15.510
Sextupole k2 (m^{-3})	± 200

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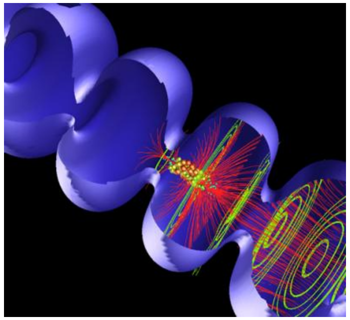
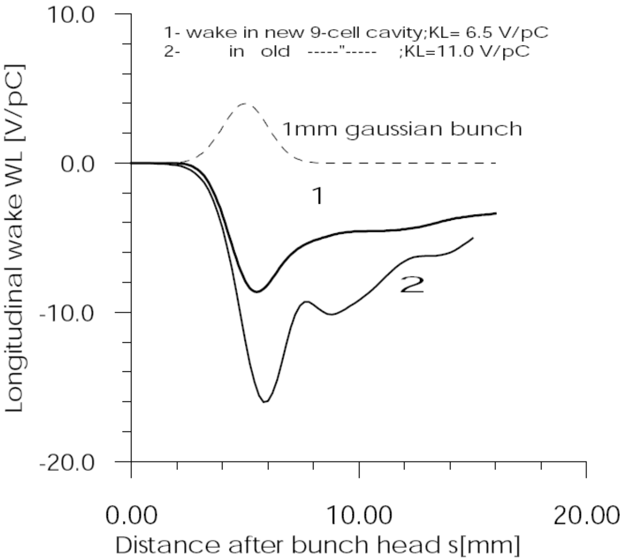
Tracking Studies of the Final Lattice

- Now we must take into account collective effects
  - Longitudinal & transverse cavity wakefields

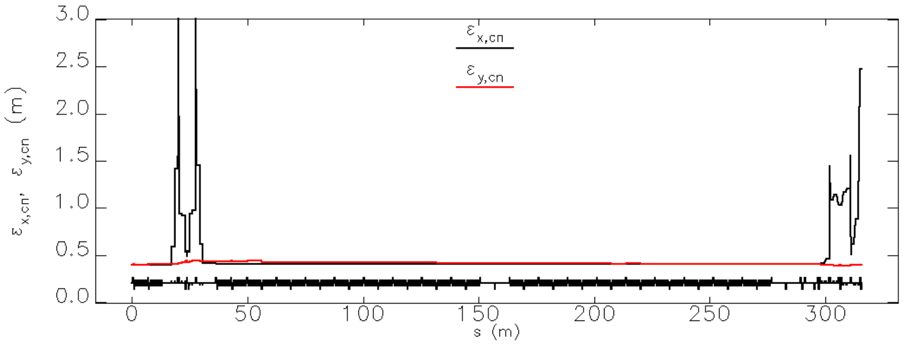




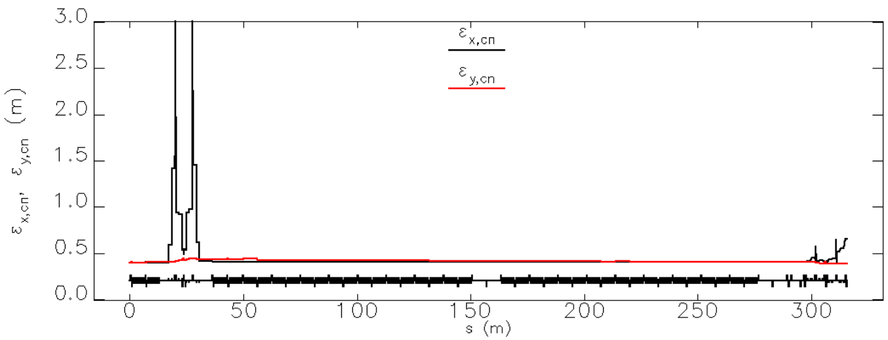
  - Coherent synchrotron radiation (1-d)
  - Longitudinal space charge
  - 10^7 particles generally needed (Pelegant on 30 cores of dl1.nw-grid.ac.uk typically takes 10 hours – feasible to use for optimisation)

Tracking Studies of the Final Lattice

- Evolution of normalised emittance in MAX-IV injector
  - SPF tuning, we see CSR mediated emittance growth, head-to-tail transverse kick – But we remain well below 10 mm-mrad



  - FEL tuning, we back off on the compression and chromatically correct, we are able to preserve emittance to ~0.5 mm mrad



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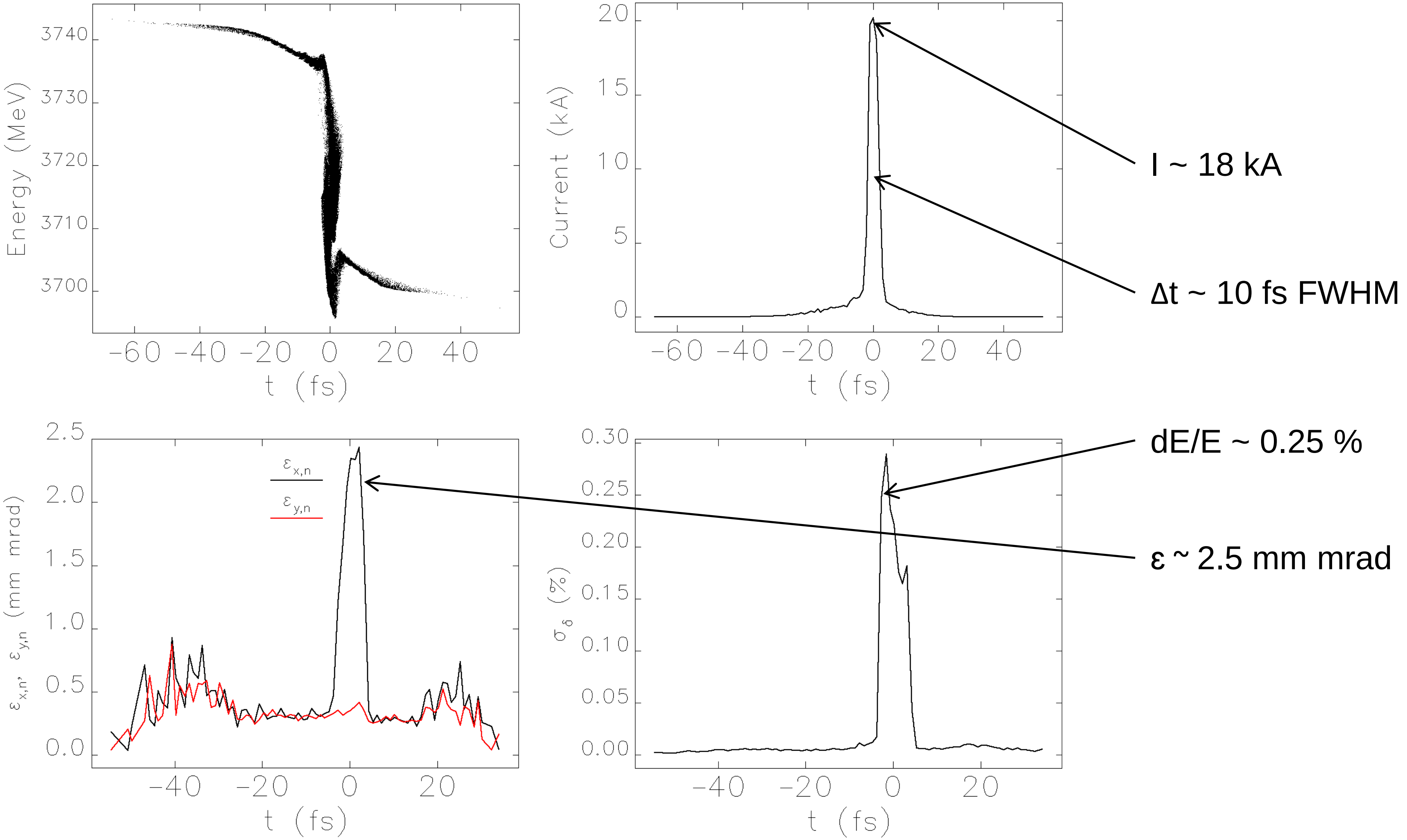
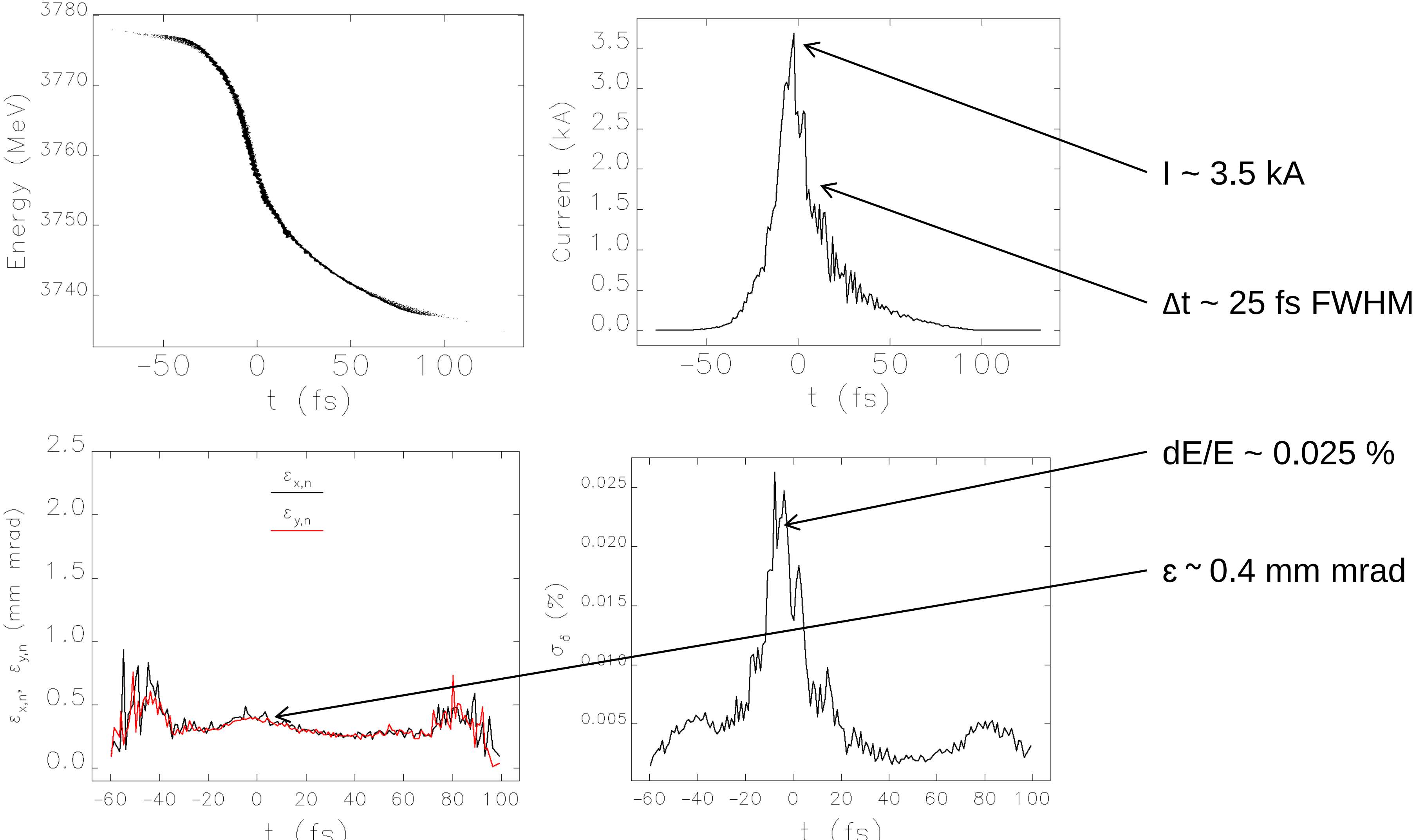
Max-IV Injector – SPF Pulse



Max-IV Injector – FEL Pulse



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Max-IV Injector – Tolerance Studies

- We want to assess the robustness of our chosen design against changes (and our likely ability to be able to correct them)

- First, need to pick some indicative parameters to monitor – e.g. Bunch length, slice emittance at peak current slice

- Each change needs to be evaluated in two ways

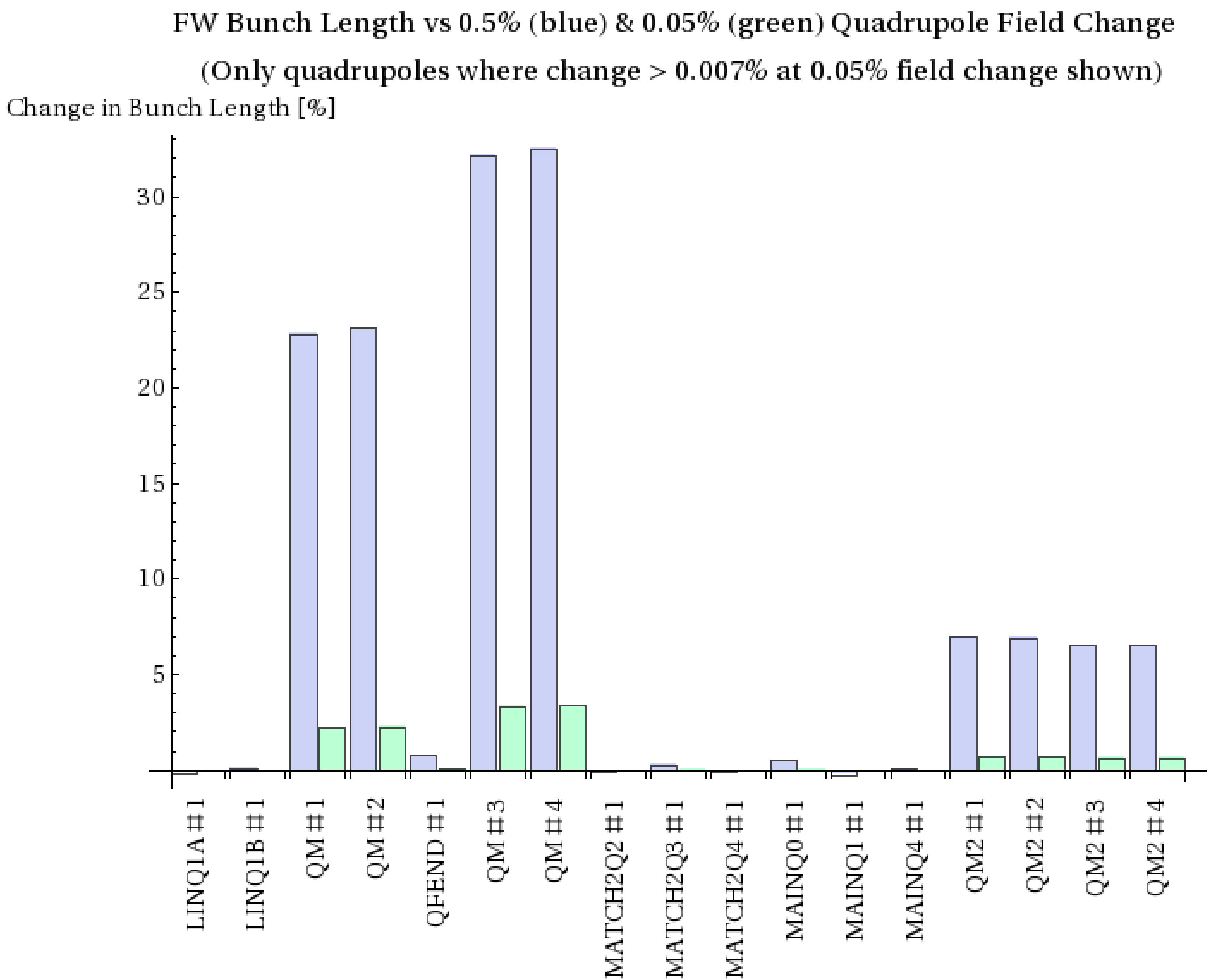
1. Investigate sensitivity of individual elements to a fixed change
2. Investigate effect of randomly distributed errors

Max-IV Injector – Tolerance Studies

- Individual element tolerances in study for Max-IV:
  - Quads (12 studies, 77 machines per study): main field strength, X position, Y position, roll, pitch, yaw, multipole components *(indicative normal allowed hamonics (12-pole, 20-pole), indicative normal disallowed harmonics (6-pole, 8-pole, 10-pole) , indicative skew harmonic (sextupole))*
  - Bends (10 studies, 12 machines per study): main field strength, roll, pitch, yaw, multipole components *(indicative normal allowed hamonics (6-pole, 10-pole, 14-pole), indicative normal disallowed harmonics (12-pole, 20-pole, 28-pole))*
  - Sexts (5 studies, 4 machines per study): main field strength, X-position, Y-position, roll, multipole component (normal 18-pole)

- Gaussian distributed error study for Max-IV:
  - Quads : field strength $\sigma = 1e^{-5}, 10e^{-5}, 50e^{-5}, 100e^{-5}$ (4 sigmas, x 50 samples x 77 machines per sample = 3850 machines) - typically takes 50 hours on dl1.nw-grid.ac.uk, X position, Y position, X & Y position combined, multipole component
  - Bends: main field strength, roll, pitch, yaw, multipole components
  - Sexts: main field strength

Max-IV Injector – Tolerance Studies



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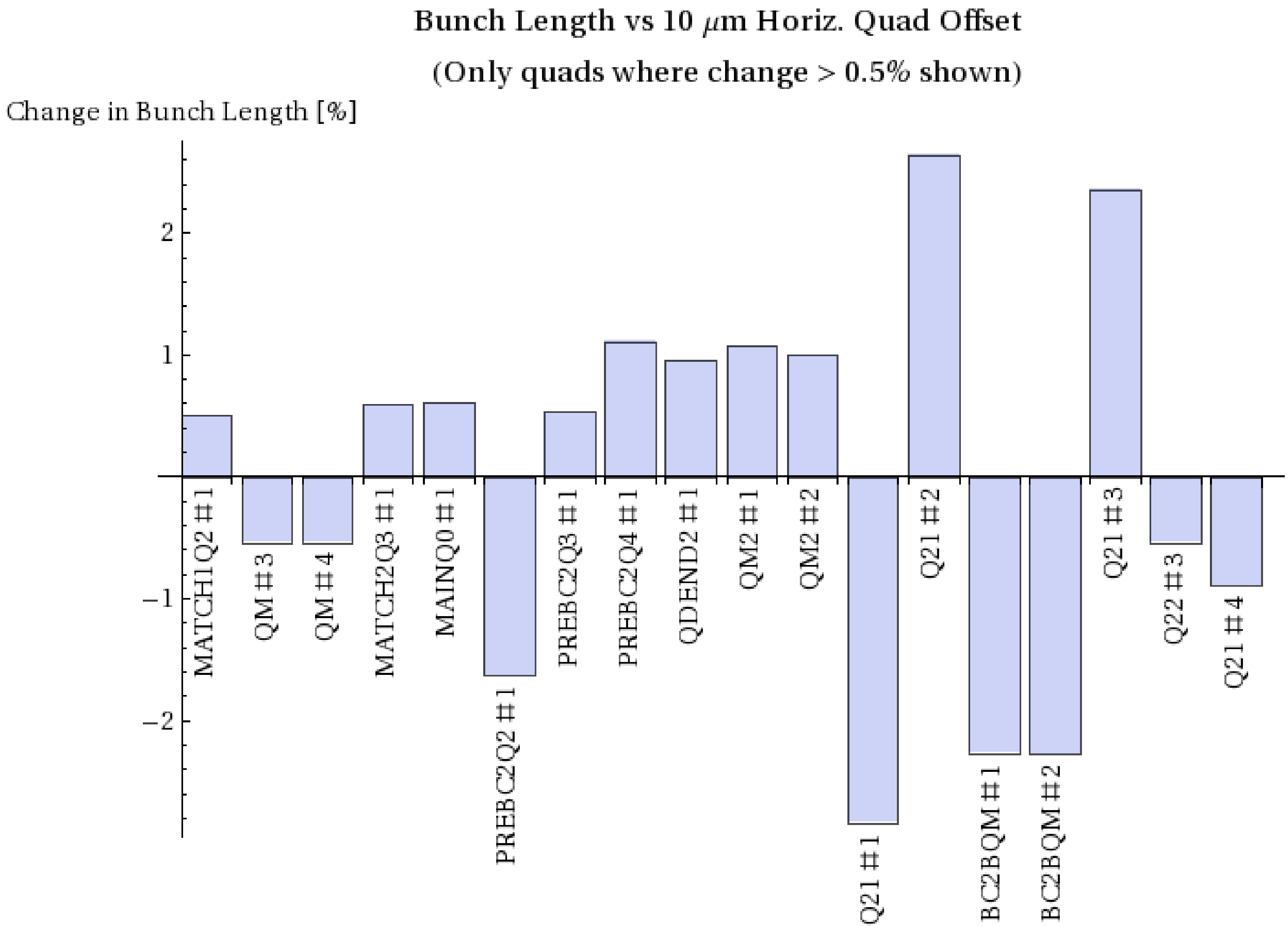

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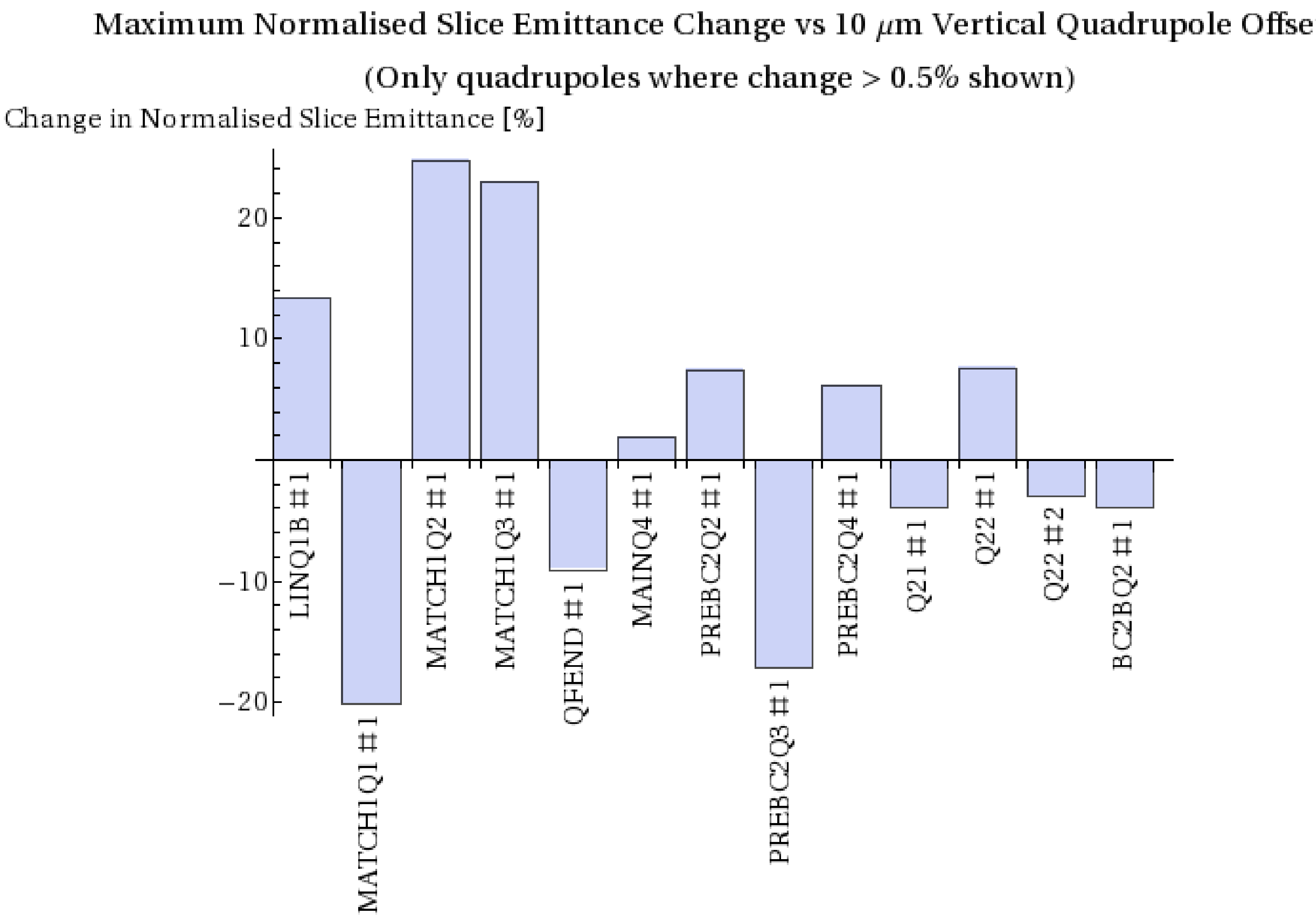

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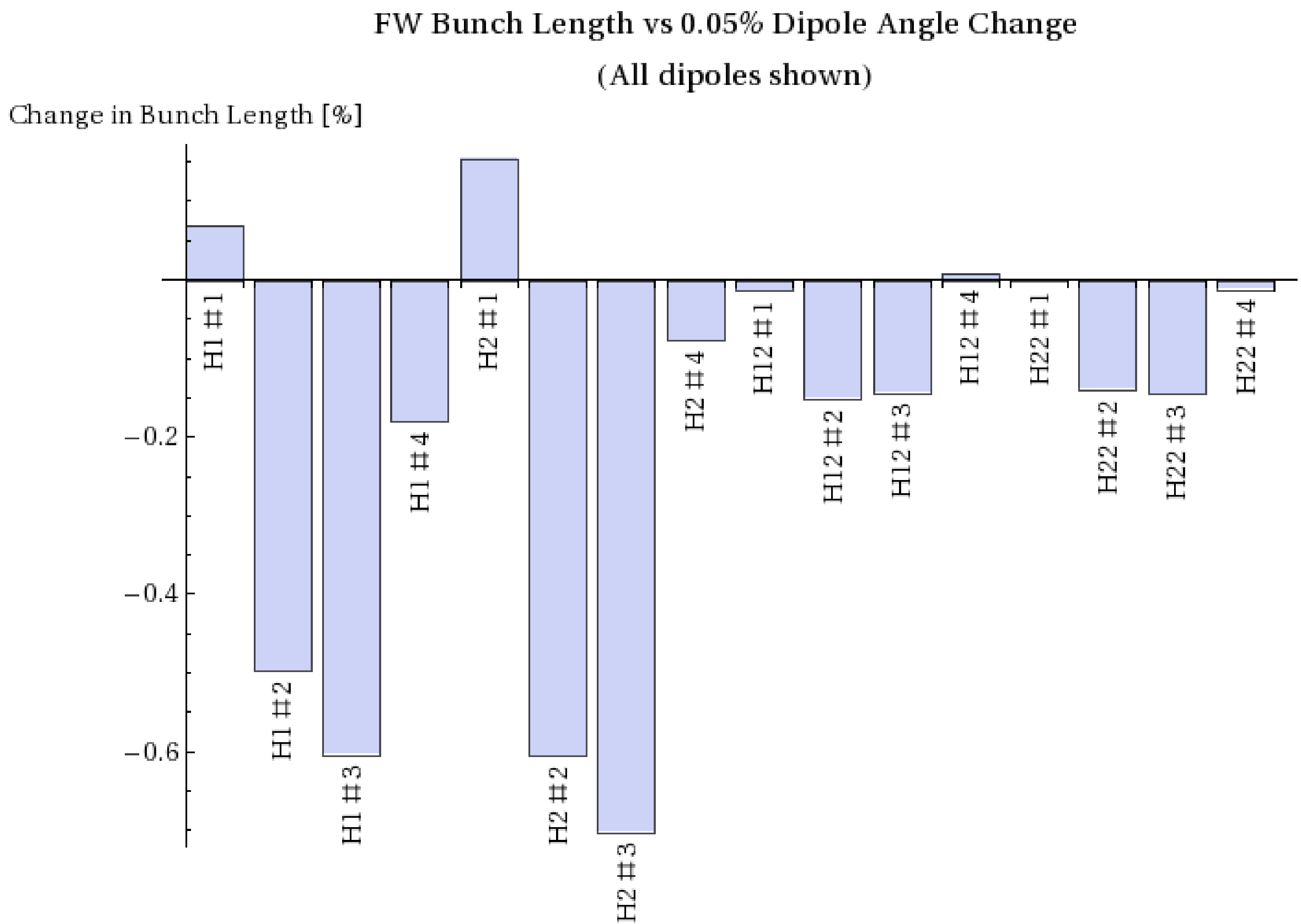

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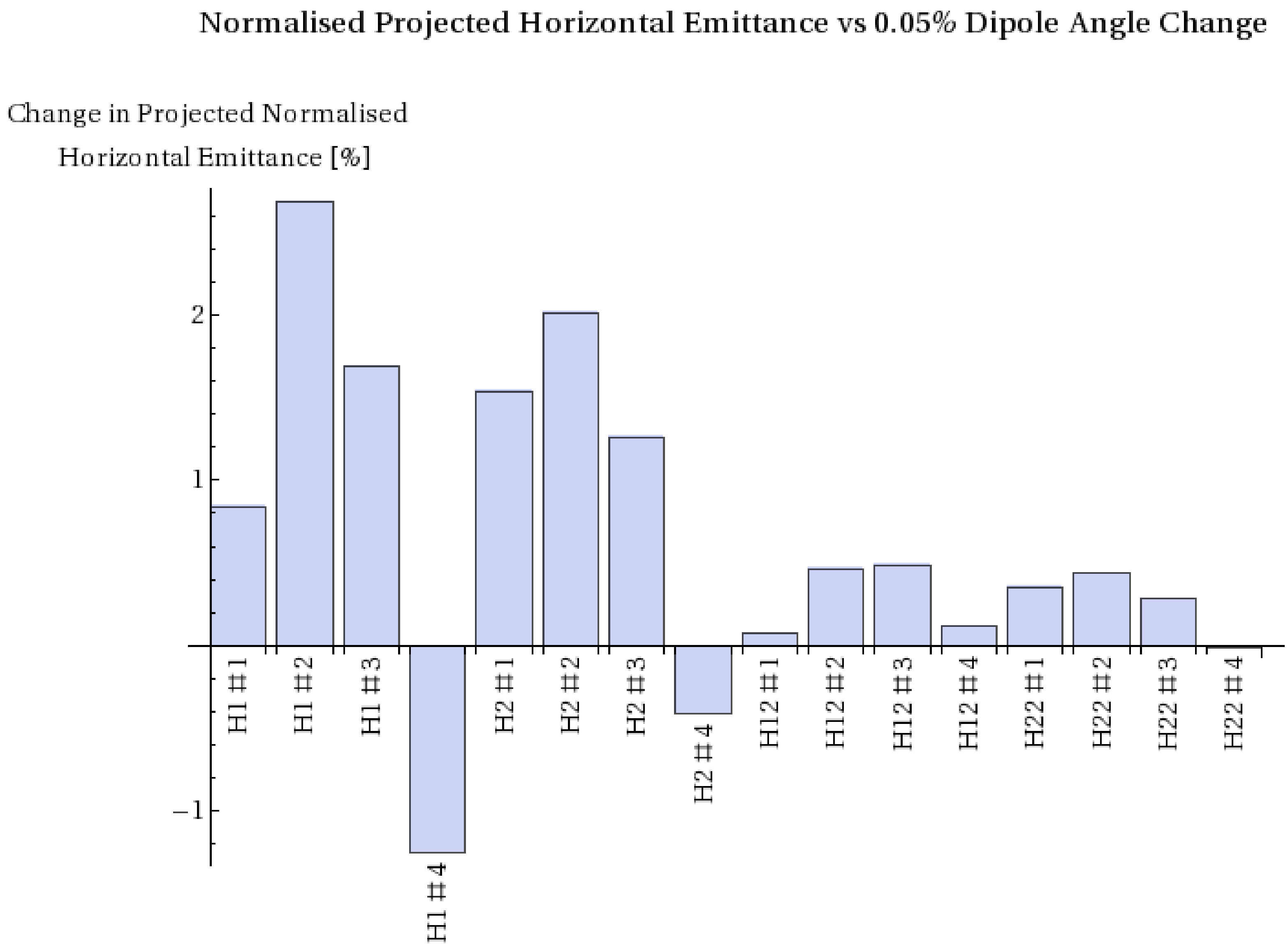

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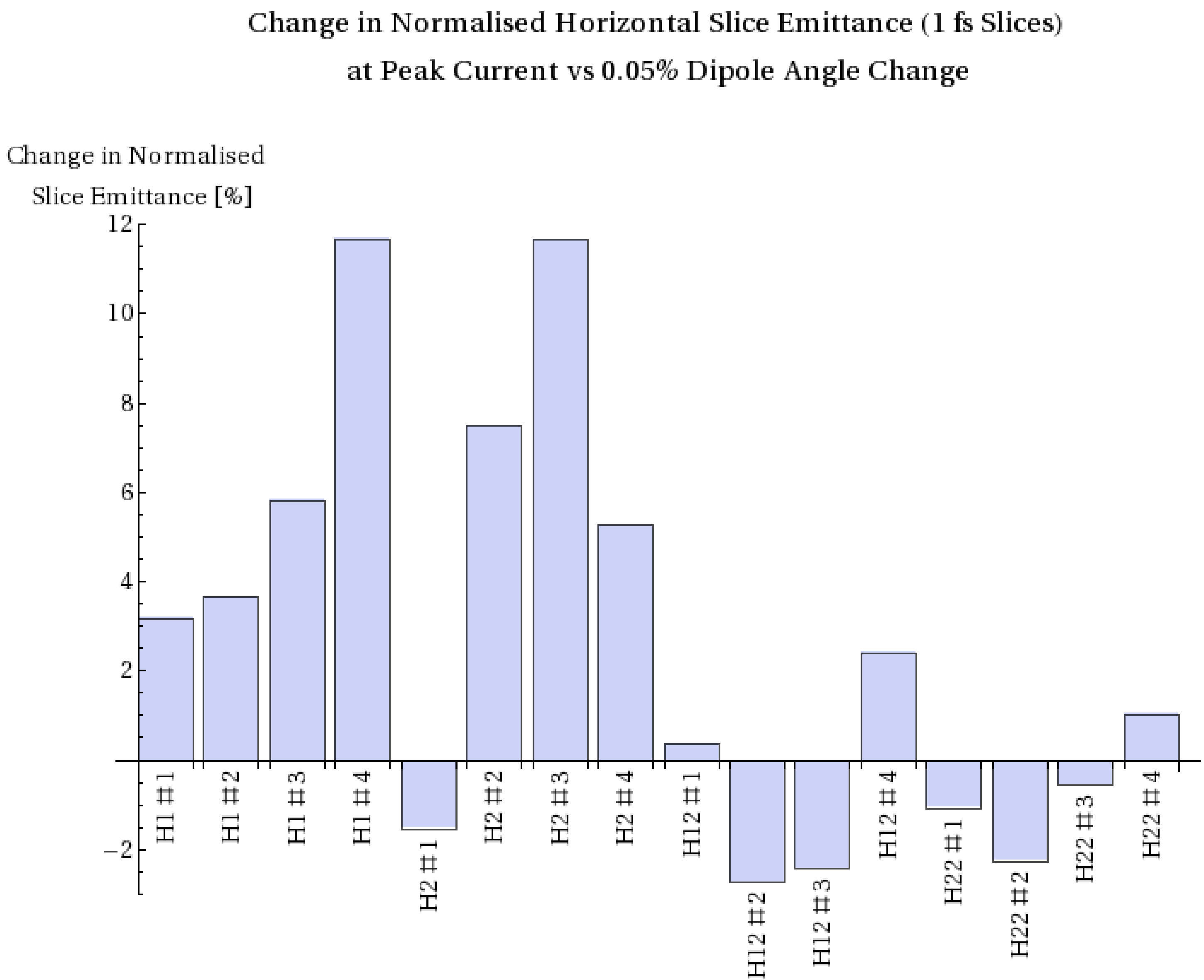

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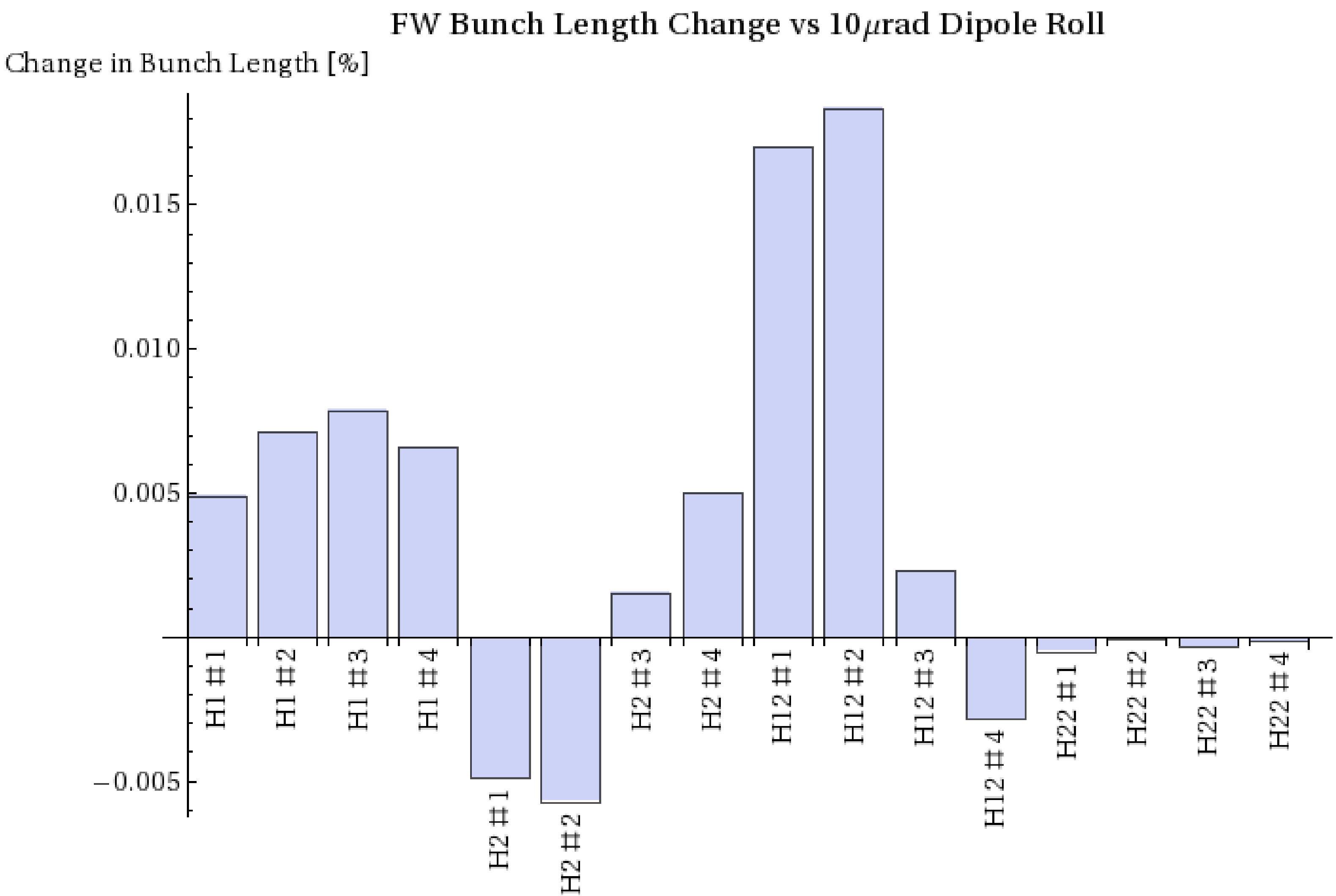

Conclusions & Acknowledgements

- The baseline injector design is capable of delivering bunches of suitable quality to both rings, SPF and future FEL
- Tolerance studies show that the design is robust to element errors
- Max-IV linac components being procured now! Magnet tolerances data utilised immediately
- Jitter studies underway – charge, linac amplitude & phase, injector parameters
- Corrector magnet scheme also to be defined using these studies
- Thanks to:

  - James Jones, Deepa Angal-Kalinin, Julian McKenzie, Boris Militsyn – Daresbury / Cockcroft
  - Sara Thorin, Mikael Eriksson, Pedro Tavares - MaxLab / Lund, Sweden
  - Rob Allan, Tim Franks – Daresbury Computational Science
  - Jonny Smith – Tech-X UK

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