MAX-IV Synchrotron Facility

Dr Stephen Molloy, Head of Accelerator Operations, MAX-IV

This is a presentation of the work of many people over many years.

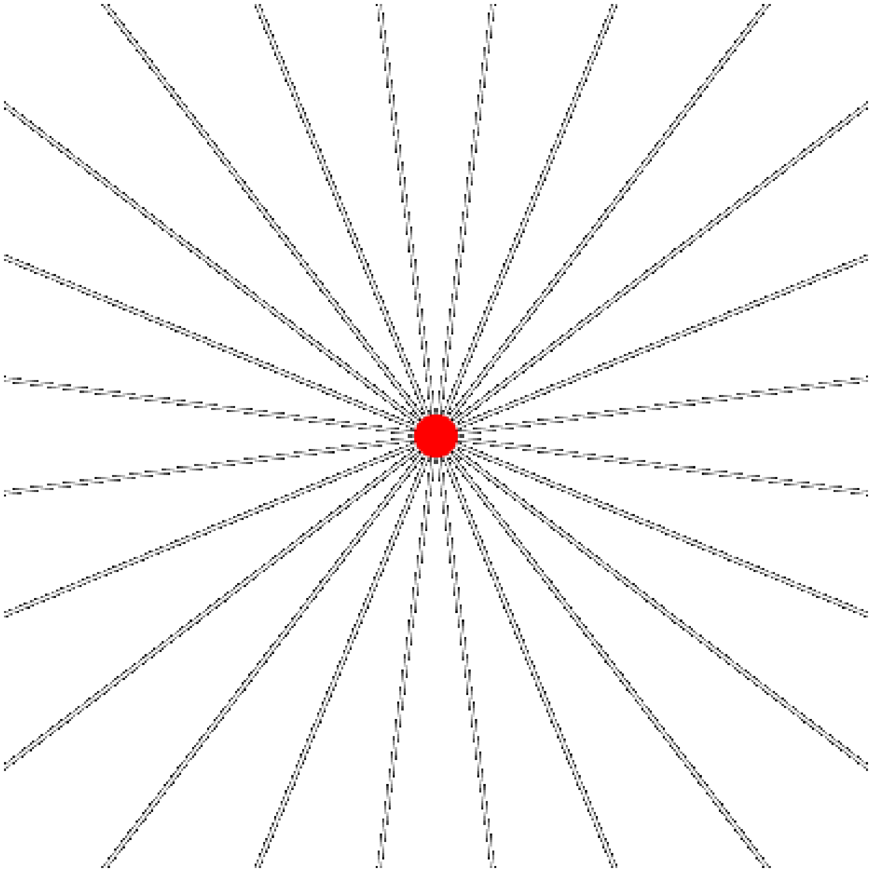
All credit should go to them.

Any mistakes are mine.

What is a synchrotron light source?

Some electromagnetism

- E-field around a charge is disrupted by acceleration
- This disruption moves at ***c***, and is observed as a flash of light



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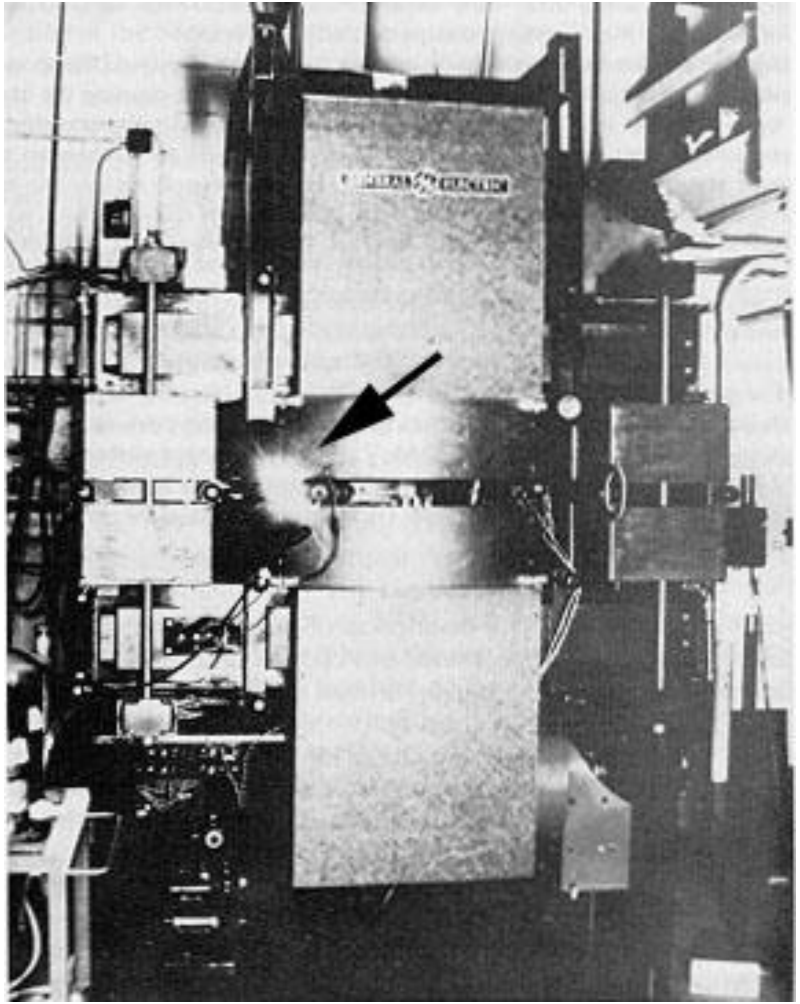
- 24th April, 1947, (almost exactly 75 years ago) this light was first observed in the GE 70 MeV synchrotron
    - Initially thought to be arcing, they soon realised they were observing direct emission from orbiting electrons



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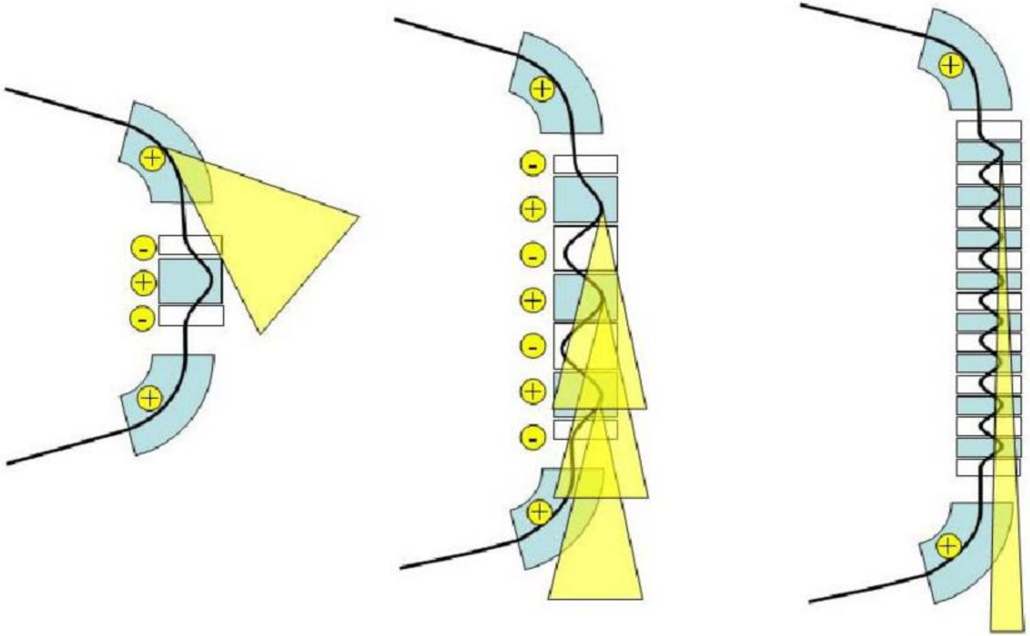
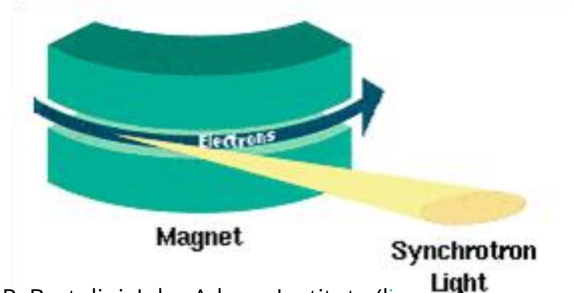
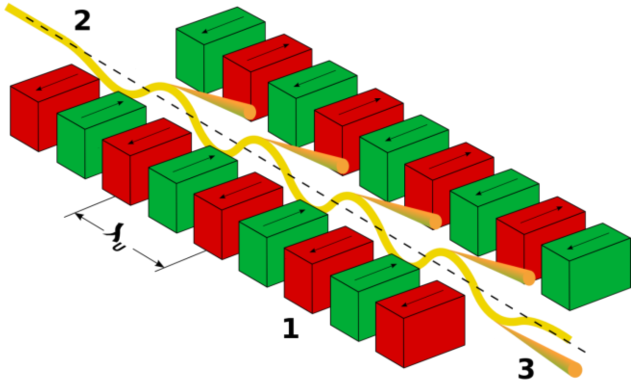
    - Initially thought to be arcing, they soon realised they were observing direct emission from orbiting electrons
- First taken advantage of as a side-effect of such accelerators, before machines dedicated to light generation were built
    - Dipole, wiggler, and undulator light



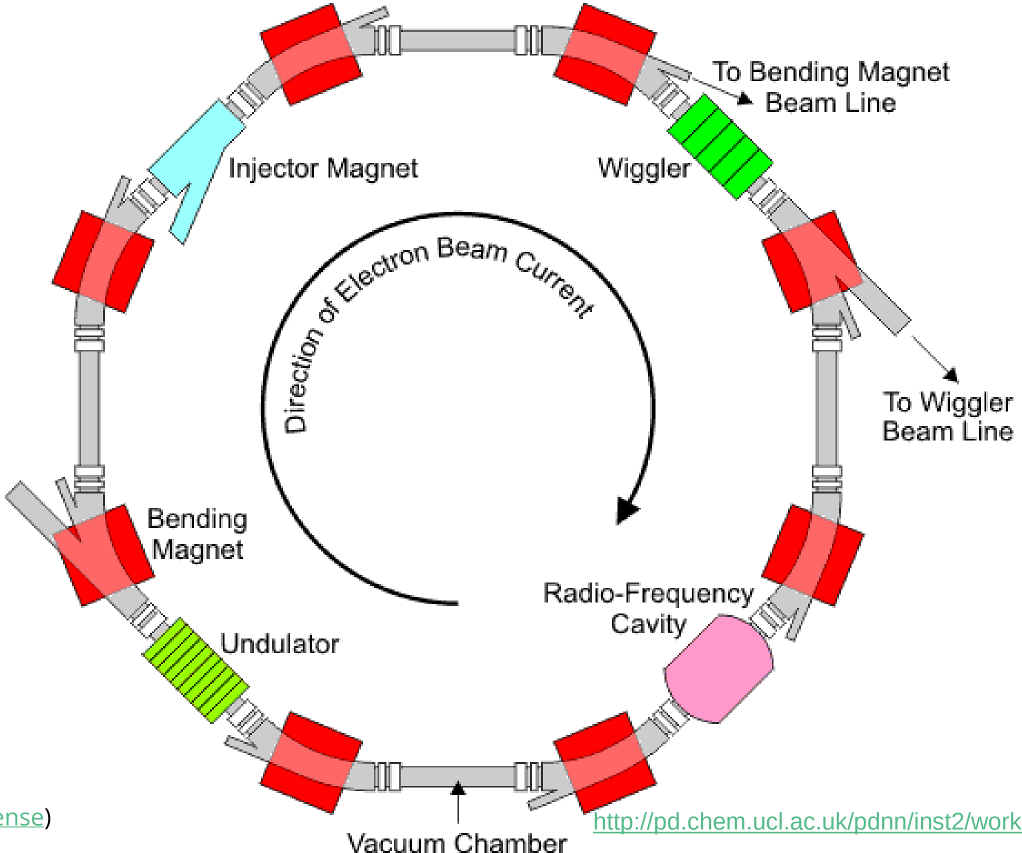
Synchrotron Light Sources



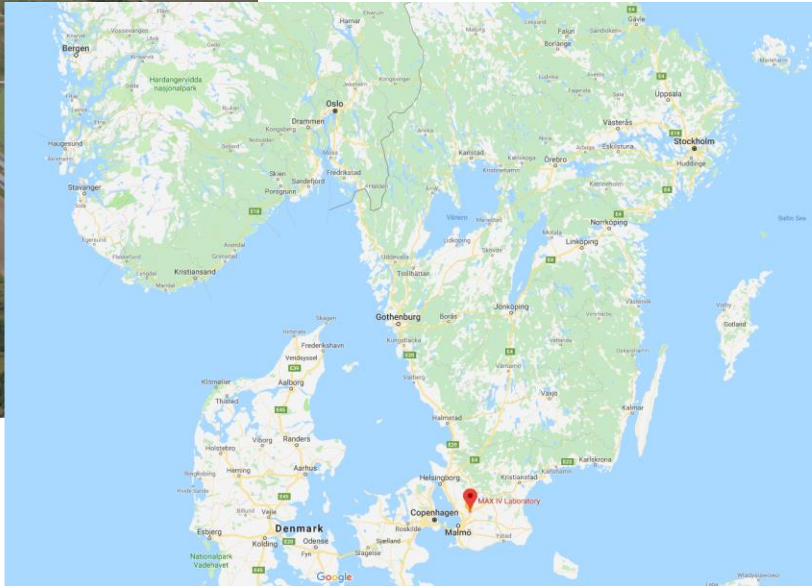
R. Bartolini, John Adams Institute (license)



https://commons.wikimedia.org/wiki/File:Undulator.png (license)



http://pd.chem.ucl.ac.uk/pdnn/inst2/work.htm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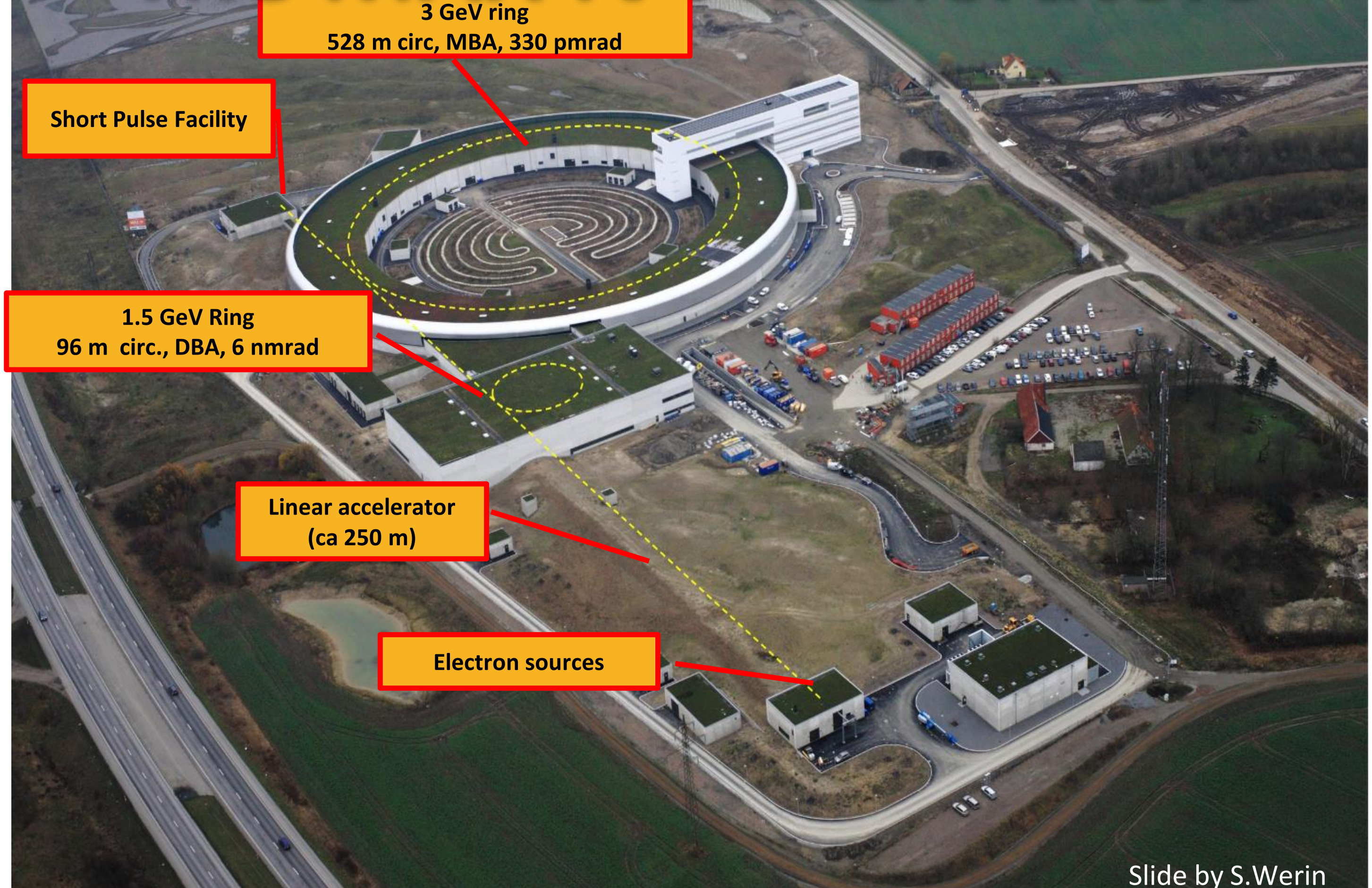
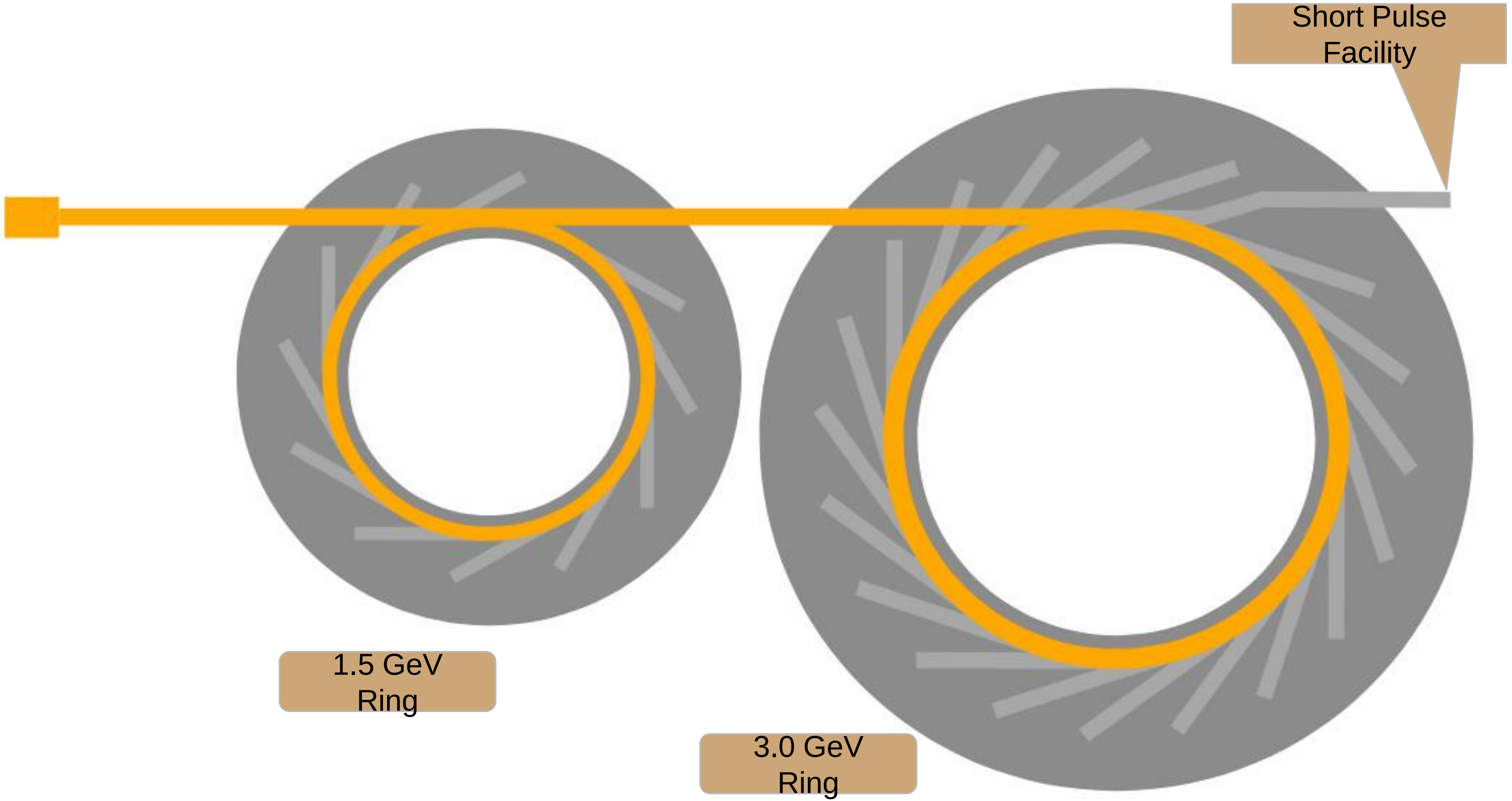
The MAX IV Accelerators

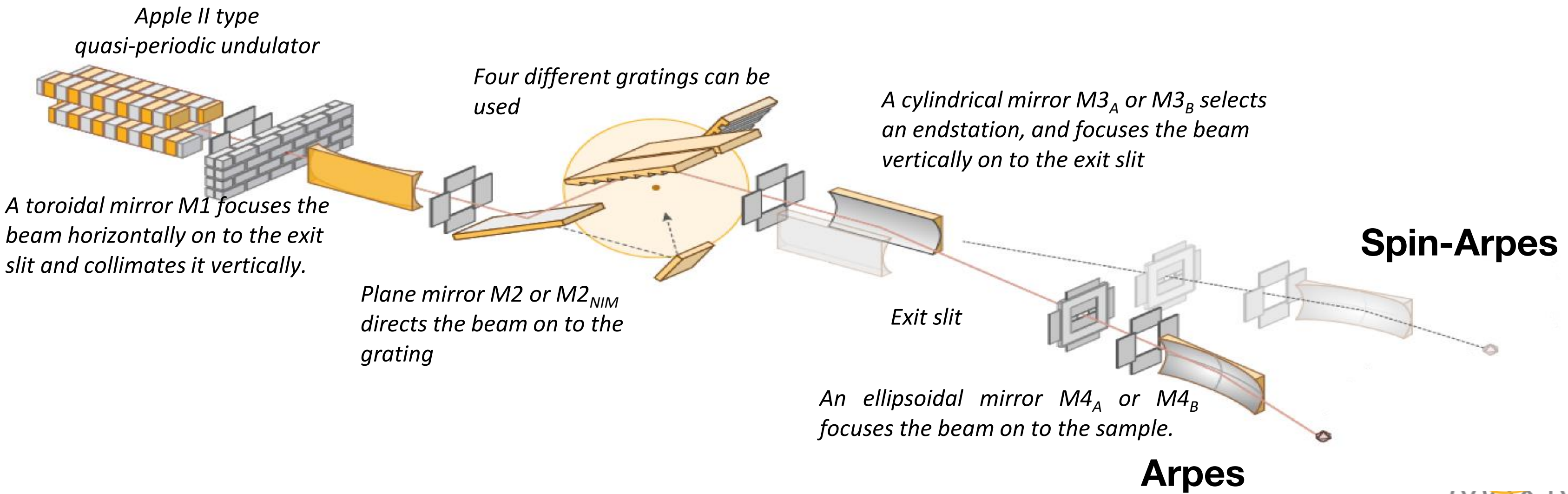


Slide by S.Werin



Short Pulse Facility
1.5 GeV Ring
3.0 GeV Ring

An example beamline – BLOCH

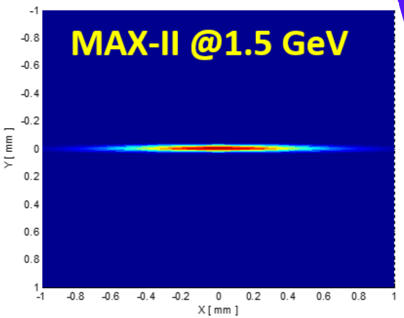


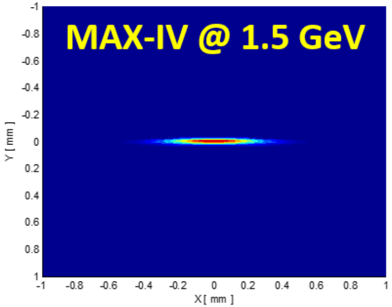
MAX-IV's 3 GeV Ring is the most brilliant in the world…

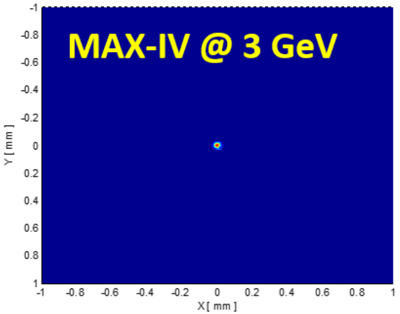
…But what does that mean?

…And how was that done?

What is Brilliance ?







$$\text{Spectral Flux} = \frac{\text{Number of Photons}}{(\text{Time [sec]}).(0.1\%\ \text{bandwidth})}$$

$$Brilliance = \frac{Spectral\ Flux}{(2\pi)^2 \sigma_{Tx}\sigma_{Tx'}\sigma_{Ty}\sigma_{Ty'}}$$

Total Horizontal Beamsize: $\sigma_{Tx} = \sqrt{\sigma_x^2 + \sigma_\gamma^2}$

Total Horizontal Divergence: $\sigma_{Tx'} = \sqrt{\sigma_{x'}^2 + \sigma_{\gamma'}^2}$

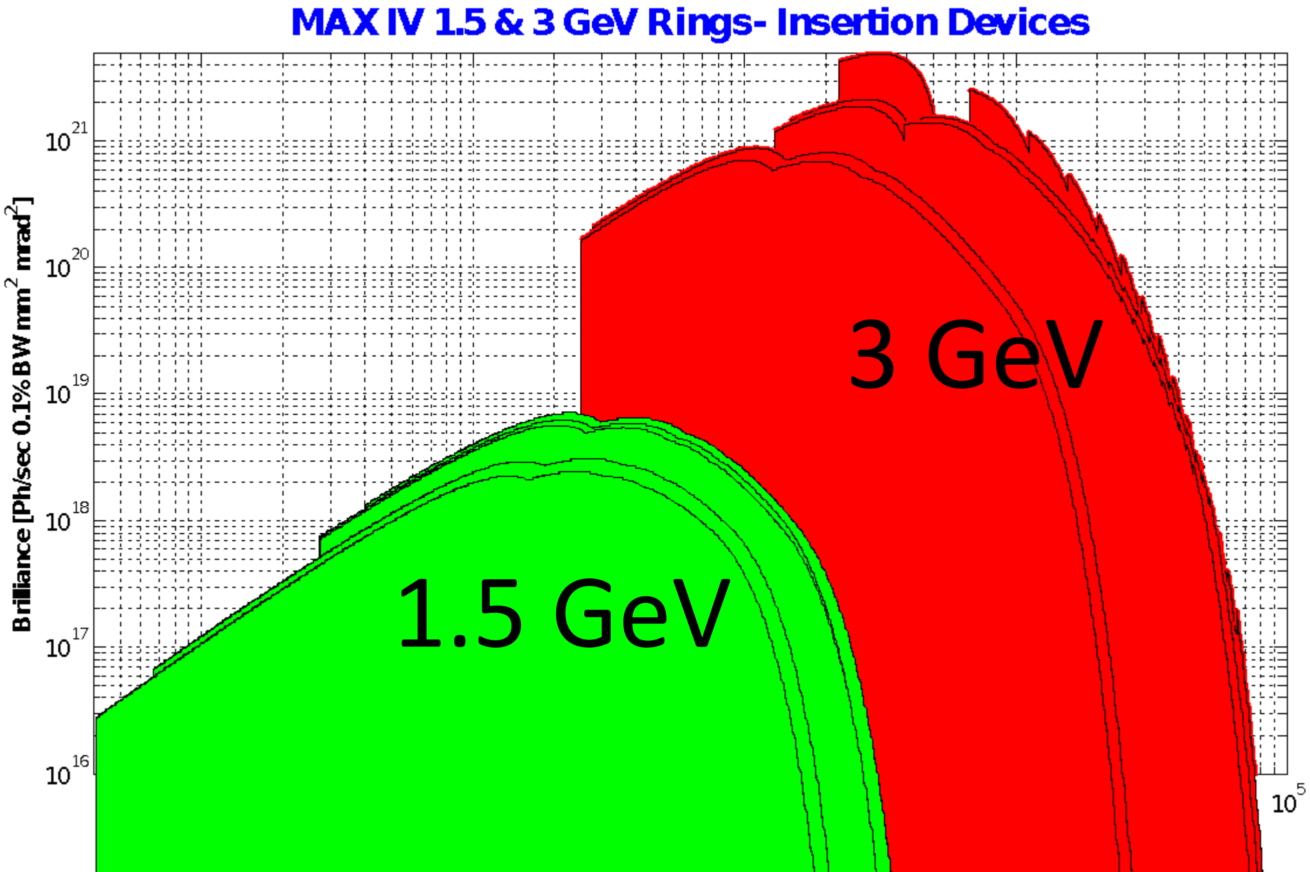
Electron beam Size

Photon beam Size

Electron beam Divergence

Photon beam Divergence

Brilliance @ MAX IV



So, brilliance is a result of the phase-space of the photon & e^- beams.

What control do we have over this?

“Emittance” is, roughly speaking, a measure of the size of a bunch of particles and the rate at which it is diverging

Photon beam emittance

$$\varepsilon_\gamma = \frac{\lambda}{2\pi}$$

- Very simple → the diffraction limit of EM radiation at that wavelength
- All beamlines have different demands, but a typical number at MAX-IV might be:
    - $\varepsilon_\gamma = 20\, pm.rad$
- Note that this value is set by the needs of the users, and therefore not controllable

Electron beam emittance

- A balance between two processes:
  - Damping due to particle acceleration
  - Excitation due to the quantum nature of synchrotron emission

That is, the e^- emittance is a function of the magnetic fields in the accelerator

- Therefore, this can be optimised through the design of the machine

On this date: I was 14, and Meatloaf was top of the charts in the UK and the US

29 November 1993

Dieter Einfeld, Mark Plesko

"*Design of a diffraction limited light source*"

International Symposium on Optics, Imaging, and Instrumentation

Key insight from that paper

- Imagine you had a God-like ability to optimise the field strengths in an accelerator
  - For any accelerator, you could find the fields that minimise the emittance
- In this case, the emittance goes as:

$$\varepsilon = C\frac{E^2}{N_d^3}$$

- More bending magnets, with softer bends, have a *cubic* effect on the beam emittance

Multi-Bend Achromat at MAX-IV

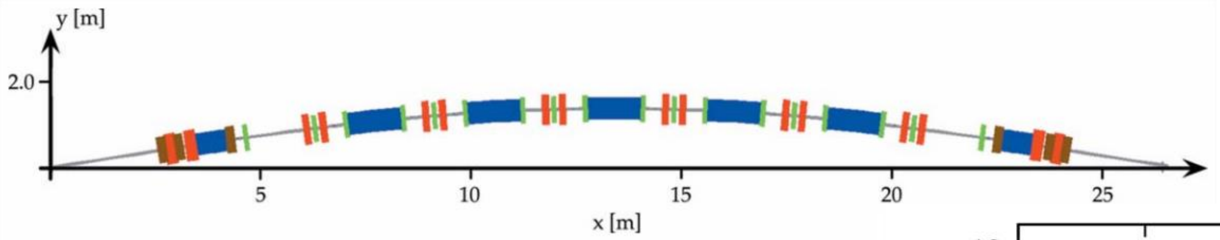


Figure 2
Schematic of one of the 20 achromats of the MAX IV 3 GeV storage r
gradient dipoles (blue), focusing quadrupoles (red), sextupoles (green)

20 achromats
7 bends per achromat
5 full-strength, 2 half-strength at the ends
(full-strength = 3°)

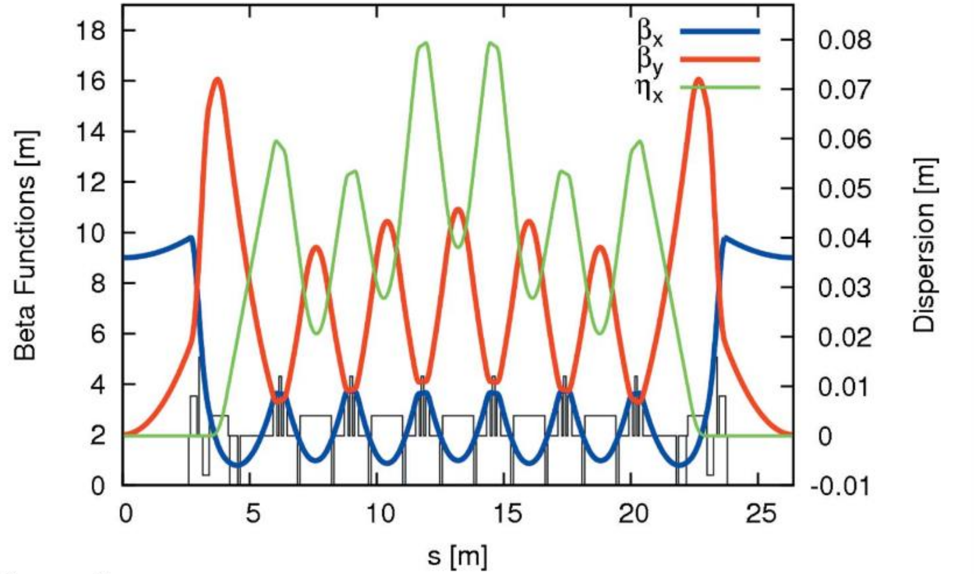
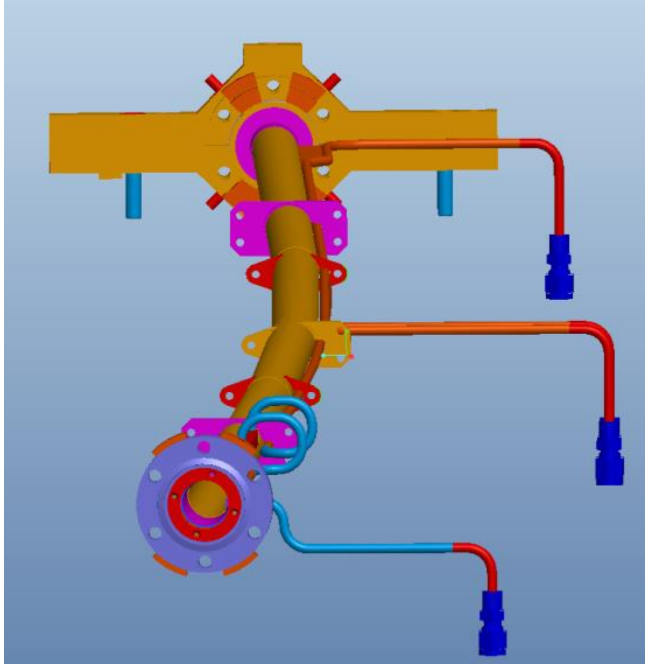


Figure 3
β functions and dispersion for one achromat of the MAX IV 3 GeV storage ring. Magnet positions are indicated at the bottom.

MAX-IV Engineering Issues

100 MHz accelerating RF

Circular, Cu, NEG-coated vacuum chambers



Compact magnet design

Achieved Performance

- 300 mA e- stored during delivery to users
  - 500 mA demonstrated
- Emittances:
  - $\boldsymbol{\varepsilon}_x = 320 \pm 18$ pm.rad
  - $\boldsymbol{\varepsilon}_y = 6.5 \pm 0.1$ pm.rad
- e- beam position stability (integrated to 5 kHz)
  - <2% of beam size horizontally
  - <5% of beam size vertically

Achieved Performance

X-ray brightness (over all wavelengths)

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Spectral purity and apparent source-size (diffraction limited in many cases)

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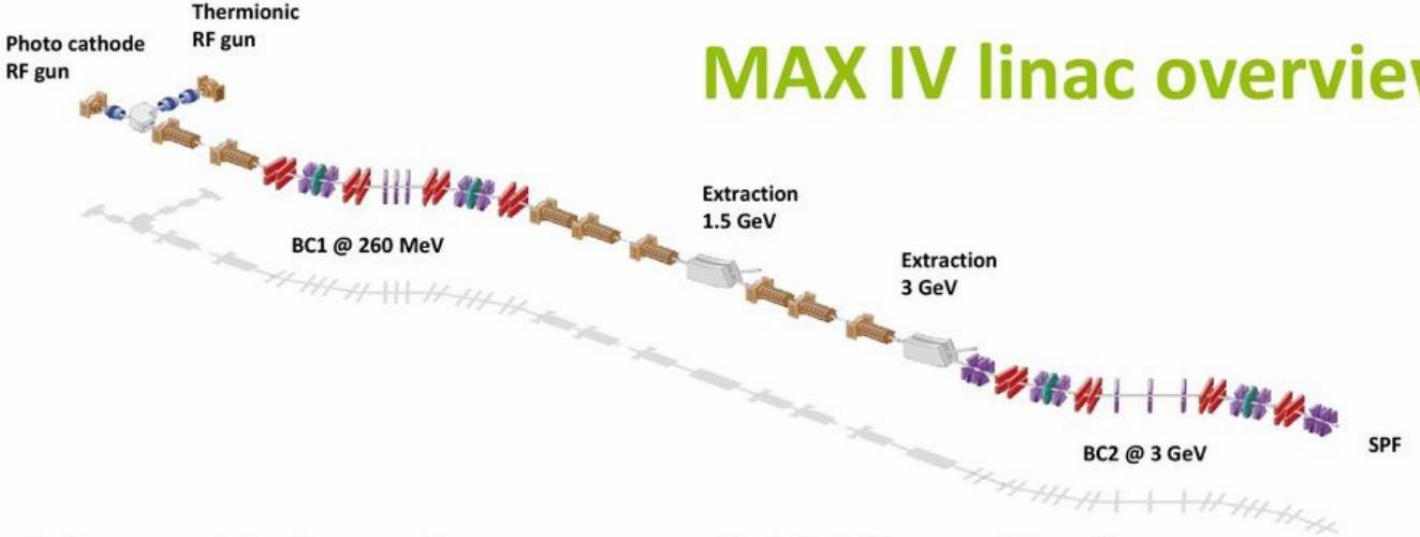
X-ray brightness (over all wavelengths)

Spectral purity and apparent source-size (diffraction limited in many cases)

Stability of apparent source location

Short pulse facility (SPF)

MAX IV linac overview



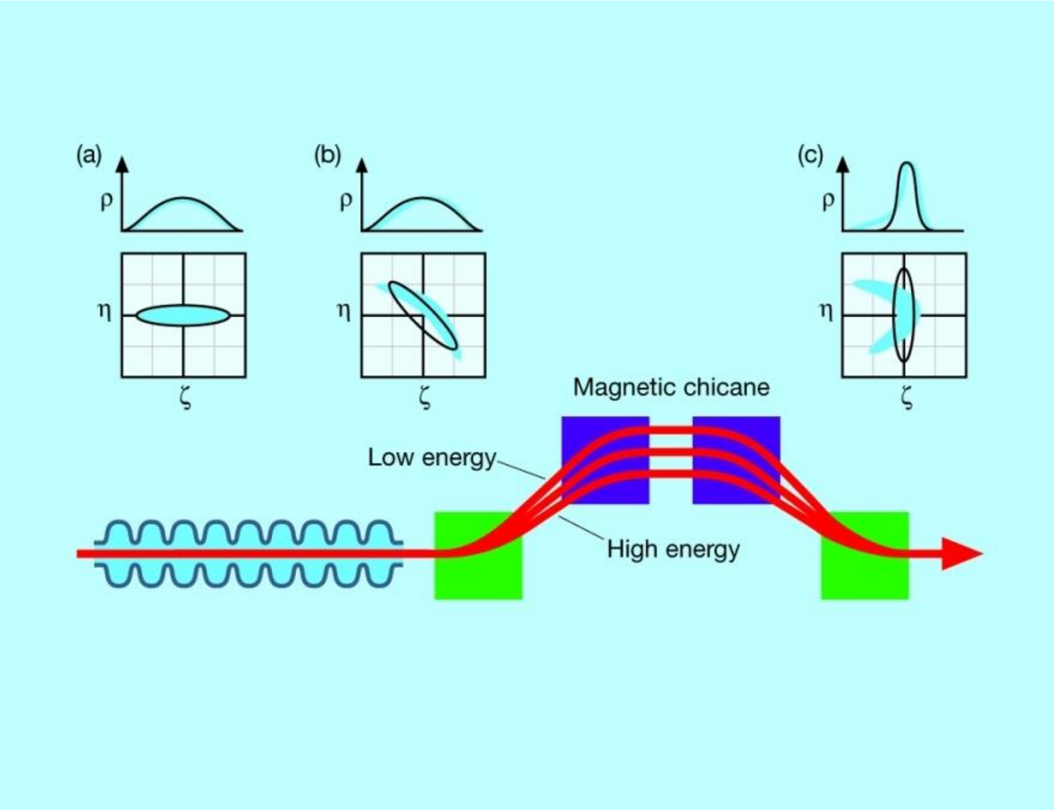
Full energy injection and top up operation for the two storage rings

Energy	1.5 GeV/ 3GeV
Injection frequency	10 Hz
Charge	0.6-1 nC/shot
Emittance	10 mm mrad
Energy spread	<0.2%

High brightness driver for the Short Pulse Facility

Energy	3GeV
Injection frequency	100 Hz
Charge	100 pC
Bunch length	100 fs
Emittance	1 mm mrad
Energy spread	<0.4%

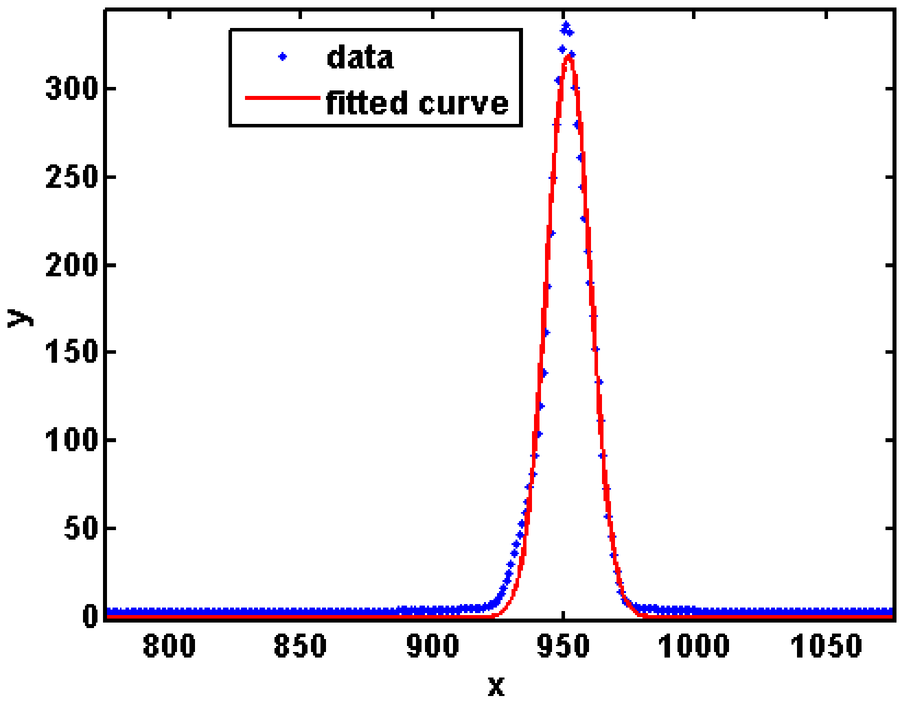
Bunch compression in a linac

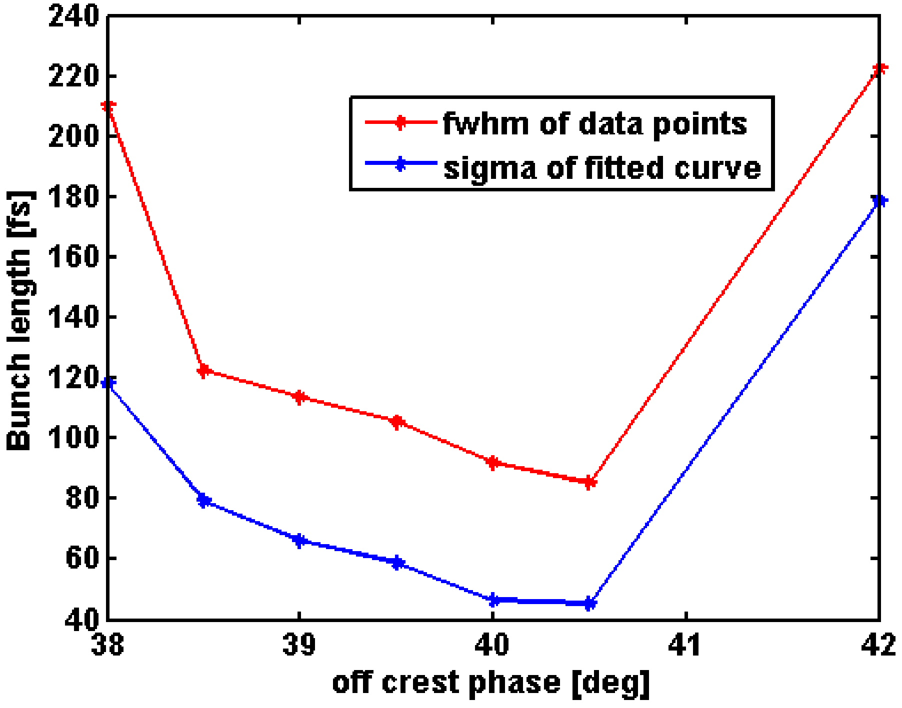


http://photon-science.desy.de/facilities/flash/the_free_electron_laser/how_it_works/bunch_compression/index_eng.html

The compression scheme in SPF is somewhat different, but this serves to illustrate the main concept

Achieved at SPF





Pump-probe experiments

- Such short pulses can capture fast processes in intermediate stages
- One technique,
  - “Pump” a sample with a high power laser, then “probe” it with the X-ray pulse
  - Sweep the time-delay between pump & probe to watch the reaction of the sample evolve
- For example,
  - Observe non-thermal melting
  - Lattice parameter changes and then breaks down as the crystal evolves to liquid state

Looking to the future

Continue to lead the way

- The range of impressive new synchrotrons coming online now share something in common – **the MAX-IV MBA concept**
- Our plan is to continue to lead for the foreseeable future
- 3 GeV ring:
  - Ultralong bunches
  - Dramatic improvement in brightness
  - Diffraction limit for high energy photons
- 1.5 GeV ring:
  - Transparent top-up
  - Pseudo single-bunch
  - Alternative timing modes
- SPF
  - Ultrashort bunches
  - Low jitter
  - Soft X-ray FEL
  - Hard X-ray FEL

Conclusion

- The MAX-IV accelerators can satisfy a wide range of X-ray users
  - Hard X-rays, soft X-rays
  - Imaging, scattering, diffraction, spectroscopy, time-resolved, ...
  - Impossible to do justice to the range of research possibilities
    - Including the advances in accelerator physics/engineering
- The MBA concept has been successfully demonstrated
  - Inspired multiple upgrade programs at light sources around the world
- Much to look forward to in the future!

Thanks!

Backup Material

Some terminology

- Particle dynamics in accelerators is done in the Hamiltonian formalism
  - Phase space ⇒ Position and conjugate momentum
    $H = \frac{1}{2}p_x^2 + \frac{1}{2}p_y^2 + \frac{1}{2}\frac{\delta^2}{\beta_0^2\gamma_0^2}$
- This is quite different from High Energy Physics, which typically uses the Lagrangian formalism
  - Phase space ⇒ Position and velocity
  - $L = \frac{1}{2}m\dot{x}^2 - \frac{1}{2}m\omega^2 x^2$
- **Emittance** ⇒ The area of the Hamiltonian phase space occupied by the beam in one plane (***x***, ***y***, or longitudinally)
  - Units: pm.rad
  - A beam with a lower emittance is said to be "colder"
  - Beam size goes with the square root of the emittance
    - Smaller emittance (colder beam) is better

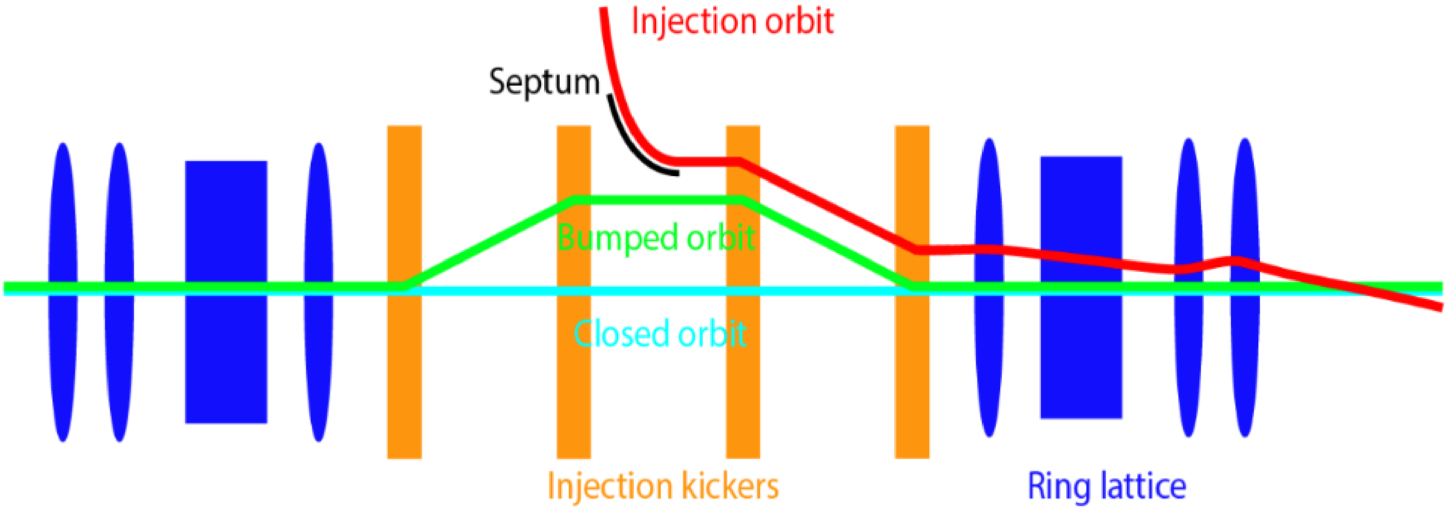
Some more terminology

- Achromat:
  - Sequence of magnets whose effect is independent of particle energy
  - A pure dipole is *not* achromatic
  - A sequence of dipoles and quadrupoles might be
- Twiss parameters:
  - A set of functions that describe the envelope of the beam’s size and divergence
    - α, β, γ
    - Beam size; $\sigma = \sqrt{\varepsilon\beta}$
- Dispersion:
  - A function describing the path of an off-energy particle
    - η

Key point from Einfeld & Plesko

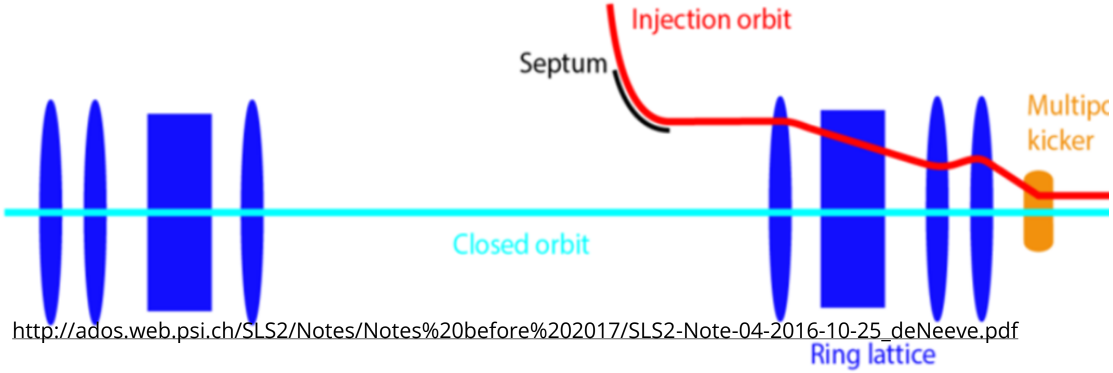
- Natural emittance determined almost solely in the magnetic bends
  - That is, not in the straight sections where undulators are installed
- The emittance goes linearly with ***H*** averaged over the bending magnets
  - $H = \gamma\eta^2 + 2\alpha\eta\eta' + \beta\eta'^2$
- H is minimised by designing η to have a minimum in the bending magnets
- Real-world criteria forbid this
- Instead, split large magnets into many smaller ones, and satisfy the constraint in **most** of them
  - Reduce the bending angle of those where the constraint is broken to reduce their impact on *H*.

Injection is always disruptive to the stored beam



http://ados.web.psi.ch/SLS2/Notes/Notes%20before%202017/SLS2-Note-04-2016-10-25_deNeeve.pdf

Multipole Injection Kicker (MIK)



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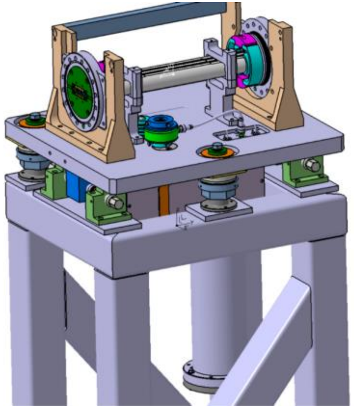
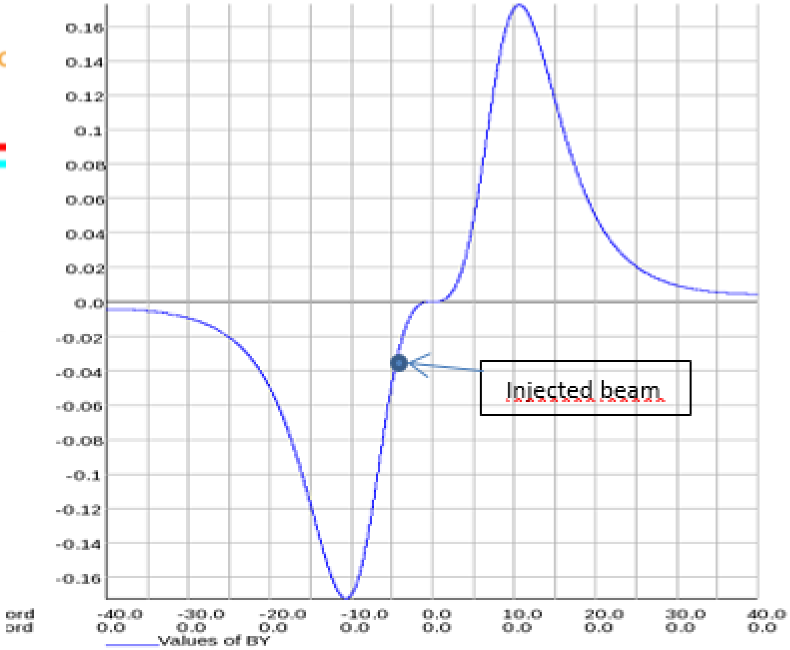
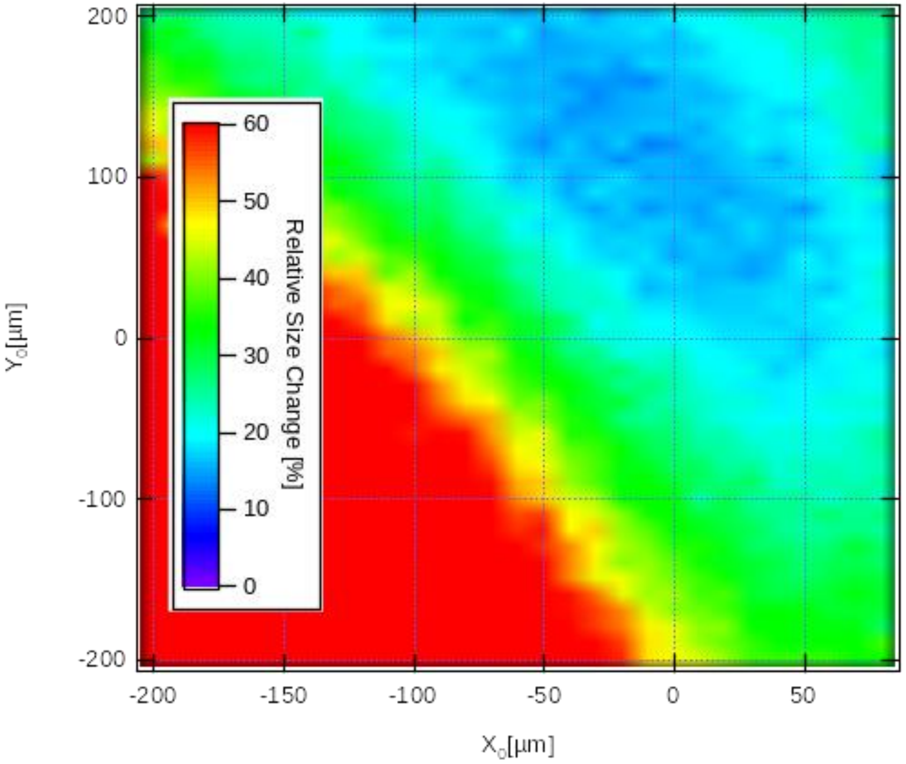




Joint project with SOLEIL, based on concept from BESSY

MIK Performance

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Transparent top-up injection into a fourth-generation storage ring

Patrick Alexandre[a], Rachid Ben El Fekih[a], Antoine Letrésor[a], Serge Thoraud[a], José da Silva Castro[a], François Bouvet[a], Jonas Breunlin[b], Åke Andersson[b], Pedro Fernandes Tavares[b,*]

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