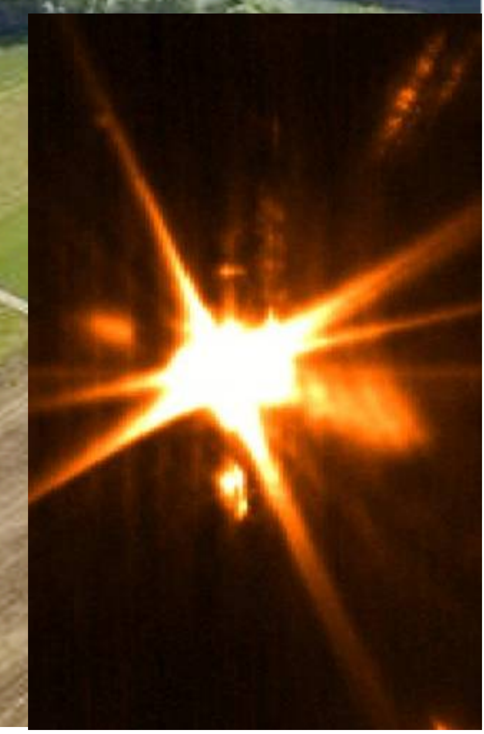


The Swiss Light Source

Natalia Milas
Paul Scherrer Institut
March 2nd 2012

Overview

- Why SLS?
- History and Budget
- Some few concepts:
  - synchrotron light, brightness and emittance...
- Parameters and performance
- SLS features:
  - top-up, special modes...
  - FEMTO laser beam slicing
- Comparison to other light sources
- Summary

Why SLS?

Solid state physics and materials science:
pharmacy, biology, chemistry, physics....

- Molecular scale ➡ Ångström
    - sample scale ⬌ probe size ➡ wavelength λ ~ 1 Å
    - particles for probing: de Broglie wavelength λ = h/p
    - momentum p = 10 keV
- high penetration depth of particles in matter ➡ neutral particles (no Coulomb)
- neutrons (SINQ) and **photons** (SLS and SwissFEL)
    - small sample size (e.g. protein cristal) < 0.1 mm
    - high resolution micro & spectroscopy
    - many samples: short measuring time

→ high flux density on sample ➡ **brightness**

History...

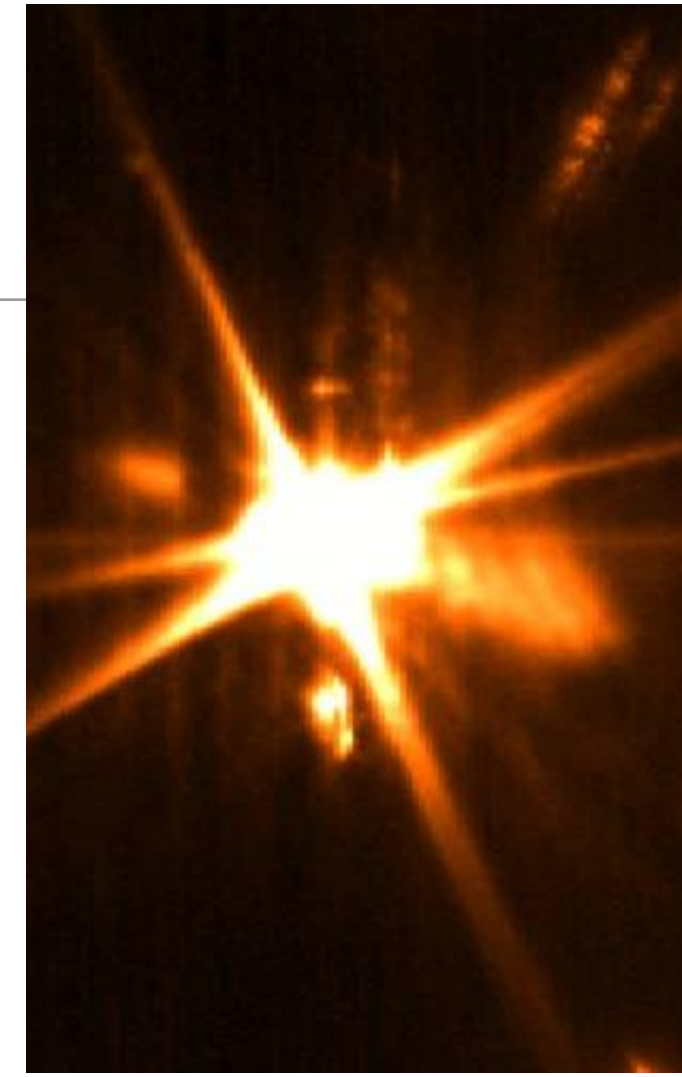
1999 First ideas for a Swiss Light Source

1993 Conceptual Design Report

June **1997 Approval** by Swiss goverment

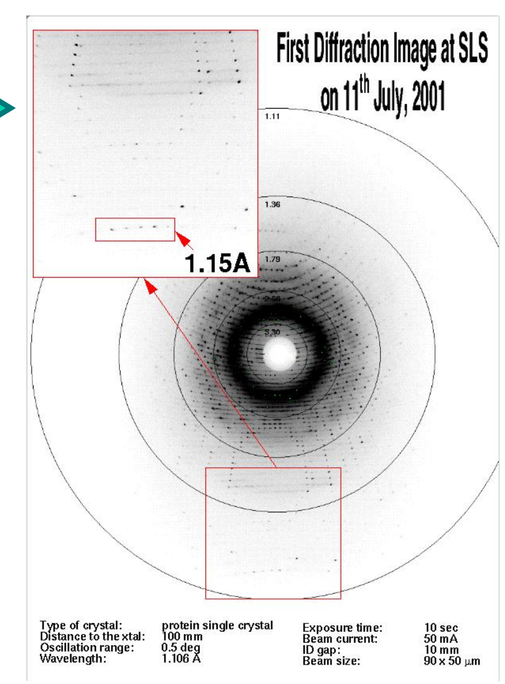
June **1999** Finalization of the building

Dec. **2000 First** stored beam



June **2001** Design current (**400 mA**) reached and **top-up** operation started

July **2001 First** experiments



Jan. **2005** Laser beam slicing (**FEMTO**)

May **2006 3 Tesla** superbends

2010 Completion of **18** beamlines

... and Budget

in **MCHF** (costs < 2002)

	planned	spent	
Total Project Budget	**159**		(no salaries included)
Building	**63**		("turn key", incl. infrastructure)
Accelerators	planned	spent	
General	**12**	**11**	
Linac	**6**	**6**	
Booster	**12**	**11**	
Storage Ring	**42**	**40**	
total	**96**	**92**	
4 initial beam lines	**24**	**28**	

+ SLS related PSI budget ~ 90

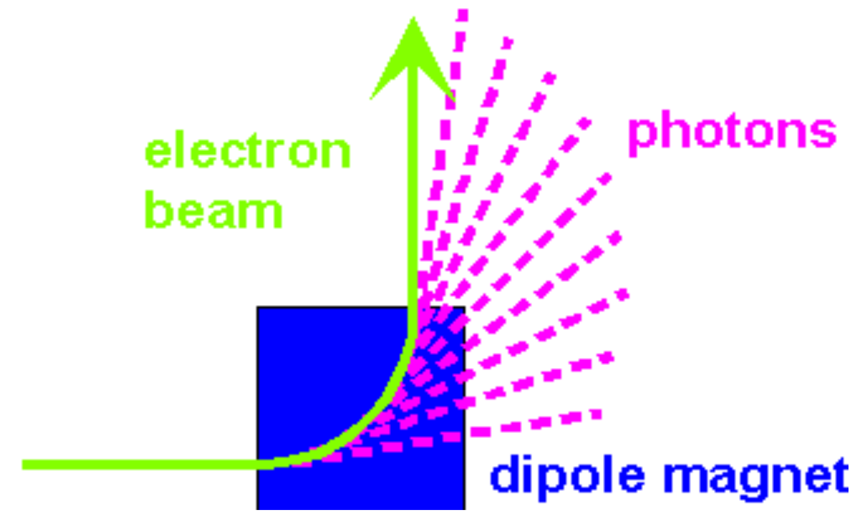
Synchrotron Radiation

from highly relativistic electrons:
Lorentz factor $\gamma = E/mc^2 \sim 10^3$-$10^4$

- High photon energy:

$$E_{ph} = pc \approx \gamma^3 \Rightarrow E_{ph} > 10keV$$

- continuos spectrum



- collimated in the forward direction, opening angle

$$\Theta \approx \gamma^{-1} \Rightarrow \Theta < 0.1mrad$$

- high power ➡ high photon flux

$$P(\approx \gamma^4)/R \approx \gamma^3 \Rightarrow P > 100kW$$ (light source)

(R = bending radius of the dipoles, $R \approx \gamma$)

High Brightness

Brightness

= 6-dimensional photon phase space density

$$\frac{\text{photons}}{(\text{area}) \times (\text{solid angle}) \times (\text{time}) \times (\text{energy interval})}$$

area = (hor.size) × (vert.size) of photon beam

$(\text{size})^2 \approx (\text{electron beam size})^2 + (\text{diffraction blur})^2$

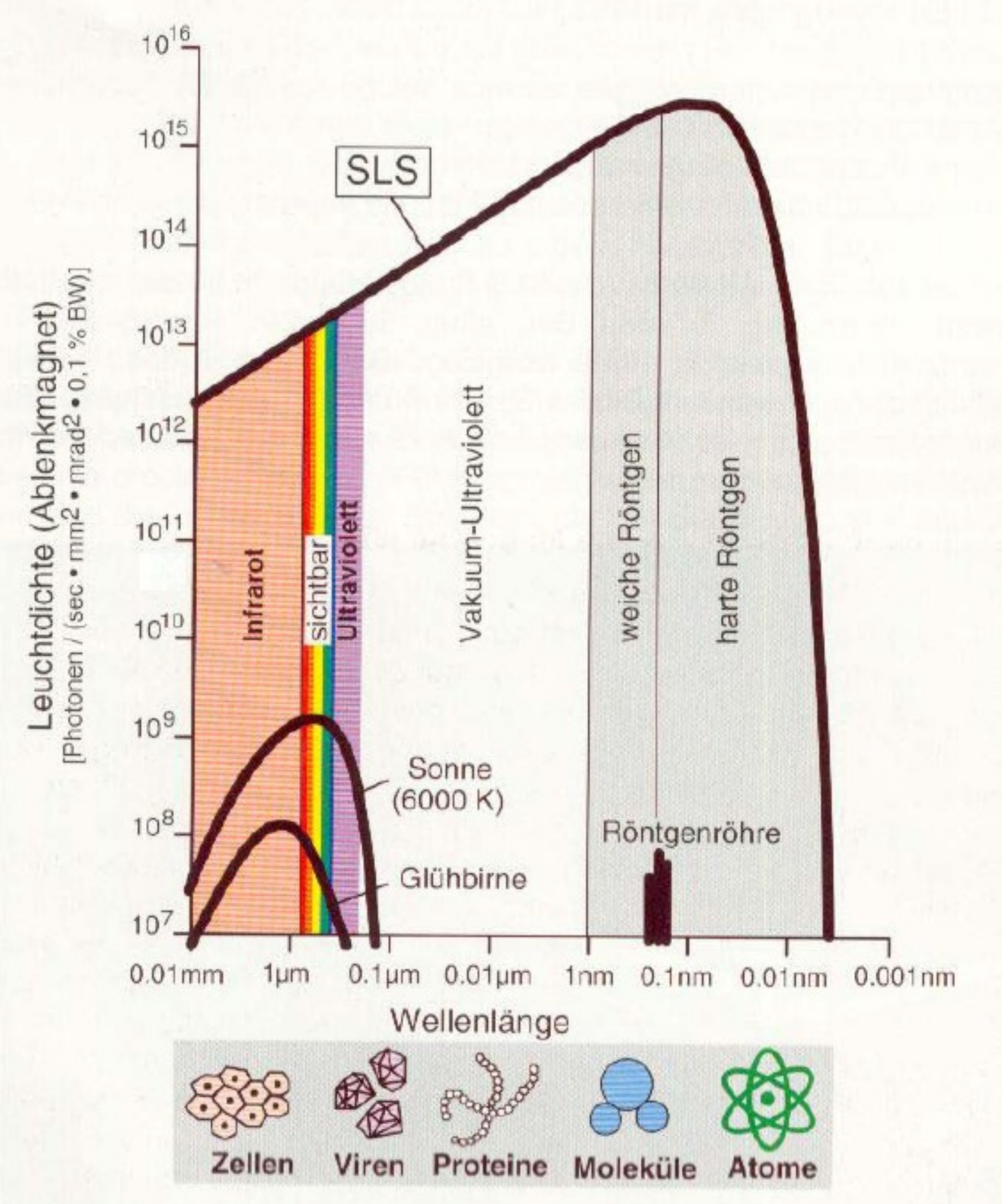
solid angle = (hor.) × (vert.) photon beam opening angle

$(\text{op.angle})^2 \approx (\text{e. beam divergence})^2 + (\text{diffraction angle})^2$

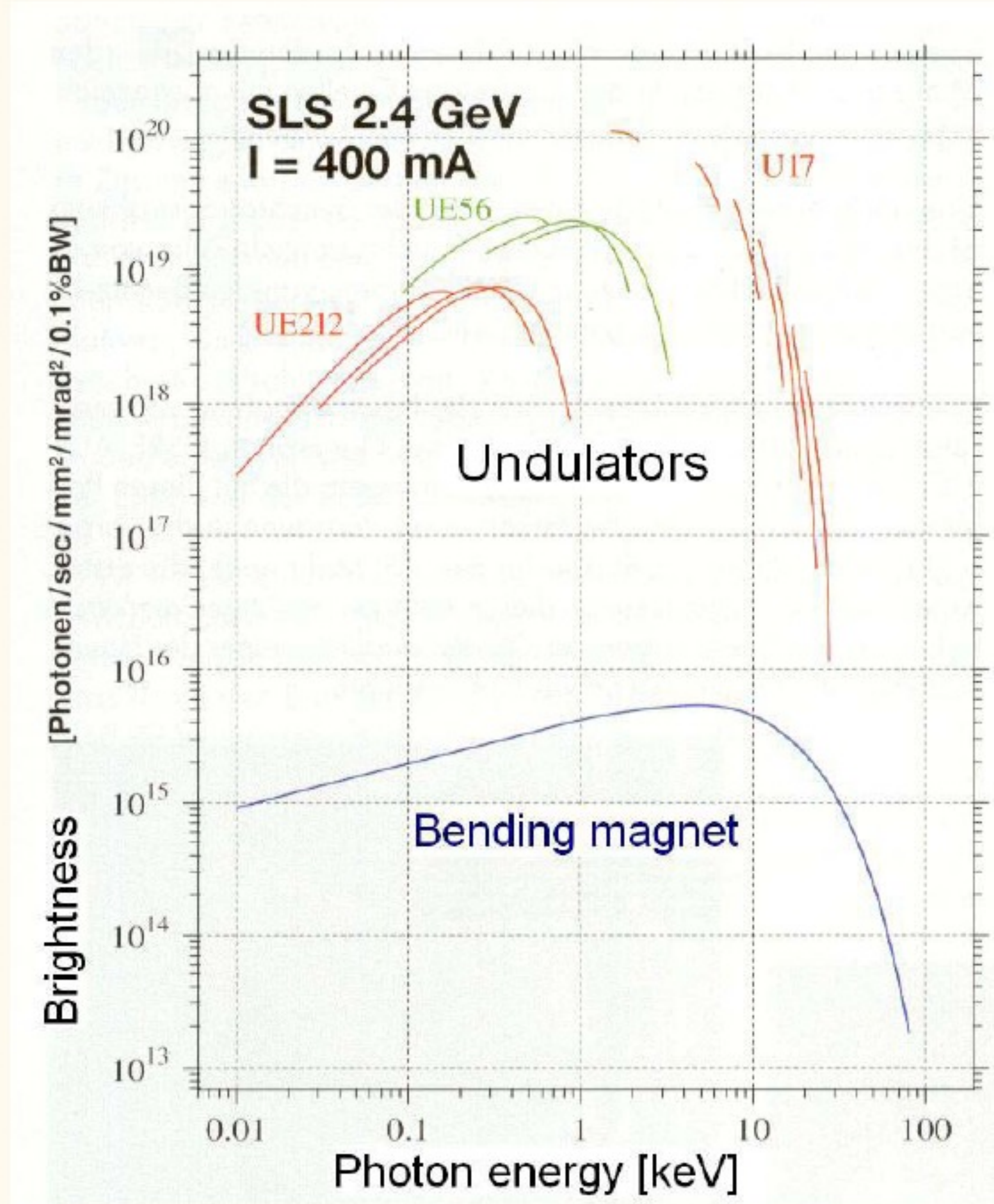
Brightness unit of measurement:

$$[\mathcal{B}] = \frac{\text{photons}}{\text{s}\,\text{mm}^2\,\text{mrad}^2\,0.1\%\,\text{BW}} \qquad \text{BW} = \text{bandwidth } \frac{\Delta\tilde{E}}{\tilde{E}}$$

(usually 0.1%)



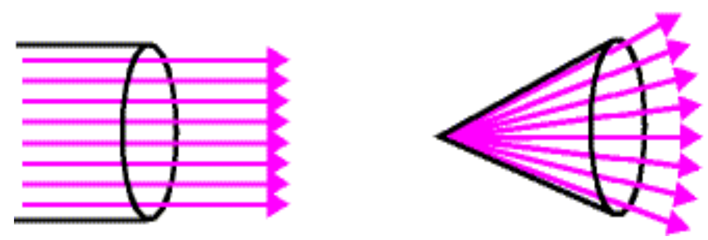
Bending magnet brightness in comparison to light bulb, sun and X-ray tube

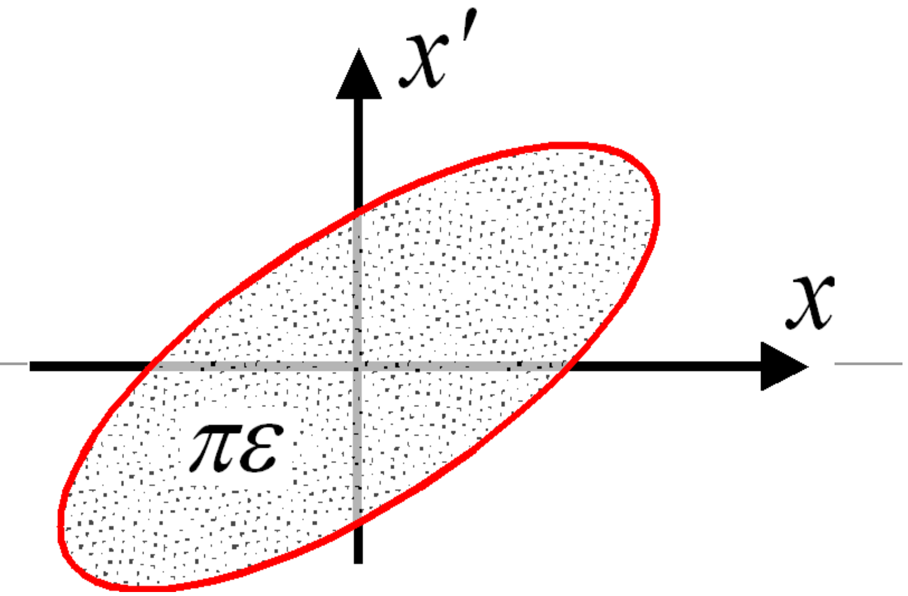


Undulator brightness in comparison to bending magnet brightness

SLS brigthness

Emittance





Electron beam (size) × (divergence) ≈ ***emittance*** ε

Emittance units of measurement:
[ε] = m·rad, mm·mrad, nm[·rad], pm[·rad]

e.g. 100 μm size × 10 μrad divergence

Flat storage rings (e.g. SLS): $\varepsilon_x > 1$ nm, $g = \varepsilon_y/\varepsilon_x \sim 0.1\%$

Diffraction "emittance": $\varepsilon_d = \lambda/(4\pi) \sim 10$ pm for 1Å ~ ε_y

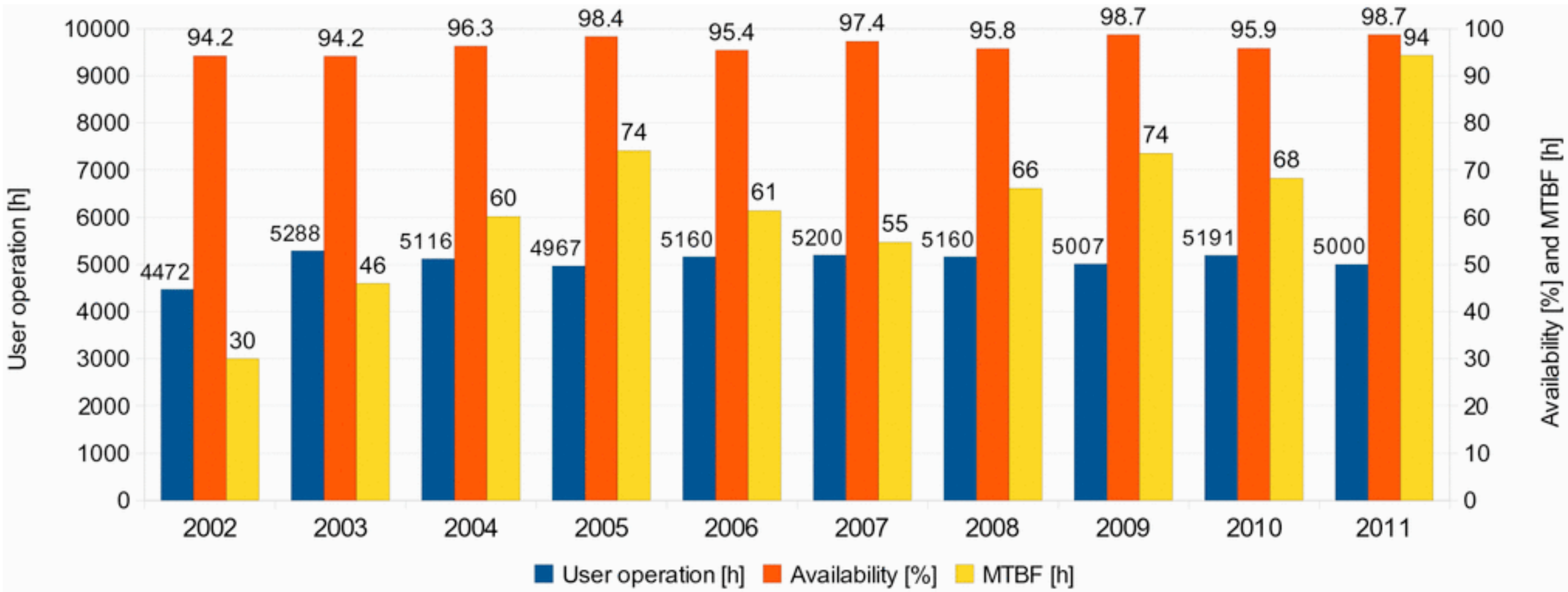
X-ray: $\varepsilon_y > \varepsilon_d \rightarrow B \propto 1/g\varepsilon_x^2$ VUV: $\varepsilon_y < \varepsilon_d \rightarrow B \propto 1/\varepsilon_x$

⇒ Light source design: Minimization of
ε_x (Horizontal emittance) and g (emittance coupling)

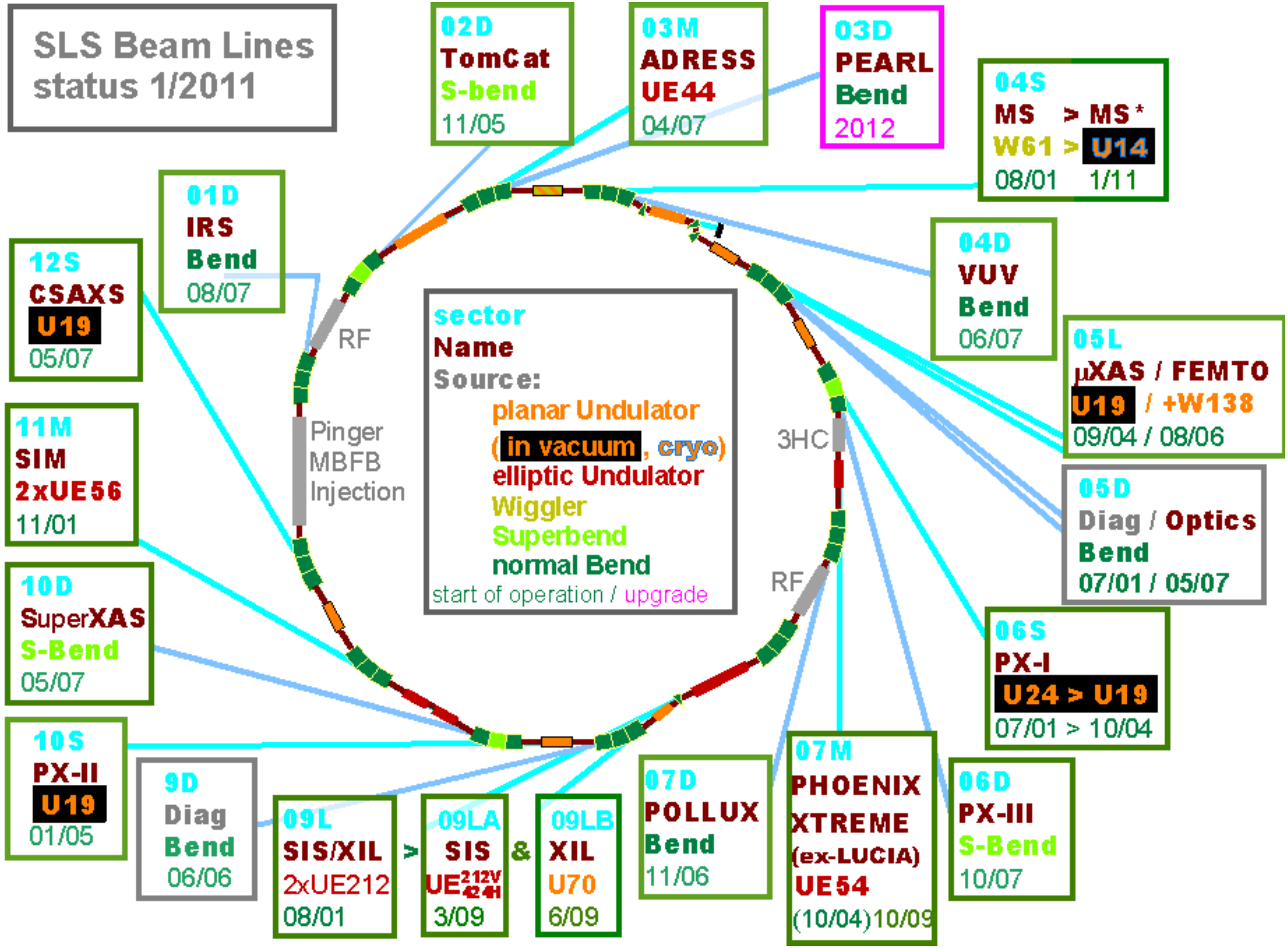
SLS paramenters

• Beam Energy	**2.4 GeV**
• Circumference	**288 m**
• Emittances	
horizontal	**5..6 nm rad**
vertical	**1..10 pm rad (g < 0.1 %)**
• Energy spread	**0.09%**
• Current	**400 mA**
top-up operation	
• Stability	**$\sigma < 0.1$ µm**
photon beam at front end	

Performance



Beam Time Statistics	**2001**		**2002**		**2003**		**2004**		**2005**		**2006**		**2007**		**2008**		**2009**		**2010**		**2011**	
Swiss Light Source	[h]	[%]	[h]	[%]	[h]	[%]	[h]	[%]	[h]	[%]	[h]	[%]	[h]	[%]	[h]	[%]	[h]	[%]	[h]	[%]	[h]	[%]
o total beam time	3576	41	6044	69	6792	77	6616	75	6608	75	6768	77.3	6912	78.9	6824	77.7	6704	76.5	6720	76.7	6824	77.9
+ user operation	1016	12	4472	51	5288	60	5116	58	4952	56	5160	58.9	5200	59.3	5160	58.9	5007	57.1	5191	59.3	5000	57.1
- incl. compensation time	-	-	-	-	-	-	175	2	175	2	144	1.6	144	1.6	144	1.6	144	1.6	227	2.5	160	1.8
+ beamline commissioning	256	3	992	7	696	8	696	8	792	9	696	8.0	880	10.0	848	9.7	896	10.2	680	7.8	976	11.1
+ setup + beam development	2304	26	576	11	808	9	804	9	864	10	804	10.3	832	9.5	816	9.3	800	9.1	845	9.7	848	9.7
o shutdown	5184	59	2720	31	1968	23	2168	25	2152	25	2168	22.7	1856	21.2	1968	22.4	2064	23.6	2048	23.3	1944	22.2
o downtimes at user operation			149		115		85		67		84		95		78		68		76		53	
+ unscheduled outage	no data		258 h	6%	307 h	5.8%	190 h	3.7%	82 h	1.6%	236 h	4.8%	138 h	2.6%	218 h	4.2%	66 h	1.3%	214 h	4.1%	65 h	1.3%
+ injector outage (non top-up)	no data		54 h	1%	30 h	0.6%	46 h	0.9%	30 h	0.6%	26 h	0.5%	28 h	0.5%	22 h	0.4%	14 h	0.3%	9 h	0.2%	22 h	0.4%
Total beam integral	247 Ah		1030 Ah		1567 Ah		1845 Ah		2129 Ah		1775 Ah		2345 Ah		2448 Ah		2460 Ah		2349 Ah		2506 Ah	
Availability	no data		94%		94.2%		96.3%		98.4%		95.4%		97.4%		95.8%		98.7%		95.9%		98.7%	
Availability after Compensation			(94%)		(94.2%)		99.7%		101.6%		98.2%		100.1%		98.5%		101.6%		100.3%		101.9%	
MTBF	no data		30 h		46 h		60 h		74.1 h		61.4 h		54.7 h		66.1 h		73.6 h		67.4 h		94.3 h	
MTTR	no data		1.7 h		2.7 h		2.2 h		1.2 h		2.8 h		1.5 h		2.8 h		1.0 h		2.8 h		1.2 h	



SLS beamlines

Sector	Beamline	Methods	Source	Energy range	Polarization
X01DC	IRS		bend	1 meV – 1.5 eV	↔
X02DA	TOMCAT		superbend	8 – 45 keV	↔
X03MA	ADRESS	ARPES, RIXS	UE44	0.4 – 1.8 keV	↔↕↻↺
X04SA	MS	PD, SD, XTM	W61	5 – 40 keV	↔
X04DB	VUV		bend	5 – 30 eV	↔
X05LA	μXAS/FEMTO	XAS	U19	5.7– 19.5 keV	↔
X06SA	PX-II		U19	5.7 – 17.5 keV	↔
X06DA	PX-III		superbend	6 – 17.5 keV	↔
X07MA	LUCIA	XAS	UE54	0.8 – 8 keV	↔↻↺
X07DA	PolLux	STXM	bend	0.2 – 1.2 keV	↔↻↺
X09LA	SIS/XIL	HR-PES, XES / EUV-IL	2xUE212	10 – 800 eV	↔↕↻↺
X10SA	PX-II		U19	6.5 – 20 keV	↔
X10DA	superXAS	XAS	superbend	5 – 35 keV	↔
X11MA	SIM	PEEM, XCD	2xUE56	90 eV – 2 keV	↔↕↻↺
X12SA	cSAXS	cSAXS	U19	5.5 – 19.5 keV	↔

Beamline acronyms	
ADRESS	Advanced resonant spectroscopies
FEMTO	(Femto-second laser beam slicing for sub-ps X-ray pulses)
LUCIA	Line for ultimate characterisations by imaging and absorption
MS	Materials sciences
PX	protein crystallography
SIM	Surfaces and interfaces microscopy
SIS	Surfaces and interfaces spectroscopy
TOMCAT	Tomographic microscopy and coherent radiology experiments
VUV	Vacuum ultraviolet

Method acronyms	
ARPES	Angle resolved photoelectron emission spectroscopy
cSAXS	coherent small angle X-ray scattering
EUV-IL	Extreme ultraviolet interference lithography
HR-PES	high resolution photoemission spectroscopy
IRS	Infra red spectroscopy
PEEM	photo emission electron microscopy
RIXS	resonant inelastic X-ray scattering
STXM	Scanning transmission X-ray micro-spectroscopy
XAS	X-ray absorption spectroscopy
XCD	X-ray magnetic circular dichroism
XES	X-ray emission spectroscopy
XIL	X-ray interference lithography
XTM	X-ray tomography

SLS features:

- The booster synchrotron and top-up operation
- The storage ring
- Special operation modes: low-α mode
- The FEMTO laser slicing beamline
- SLS beam stability
- **Coupling correction and control**

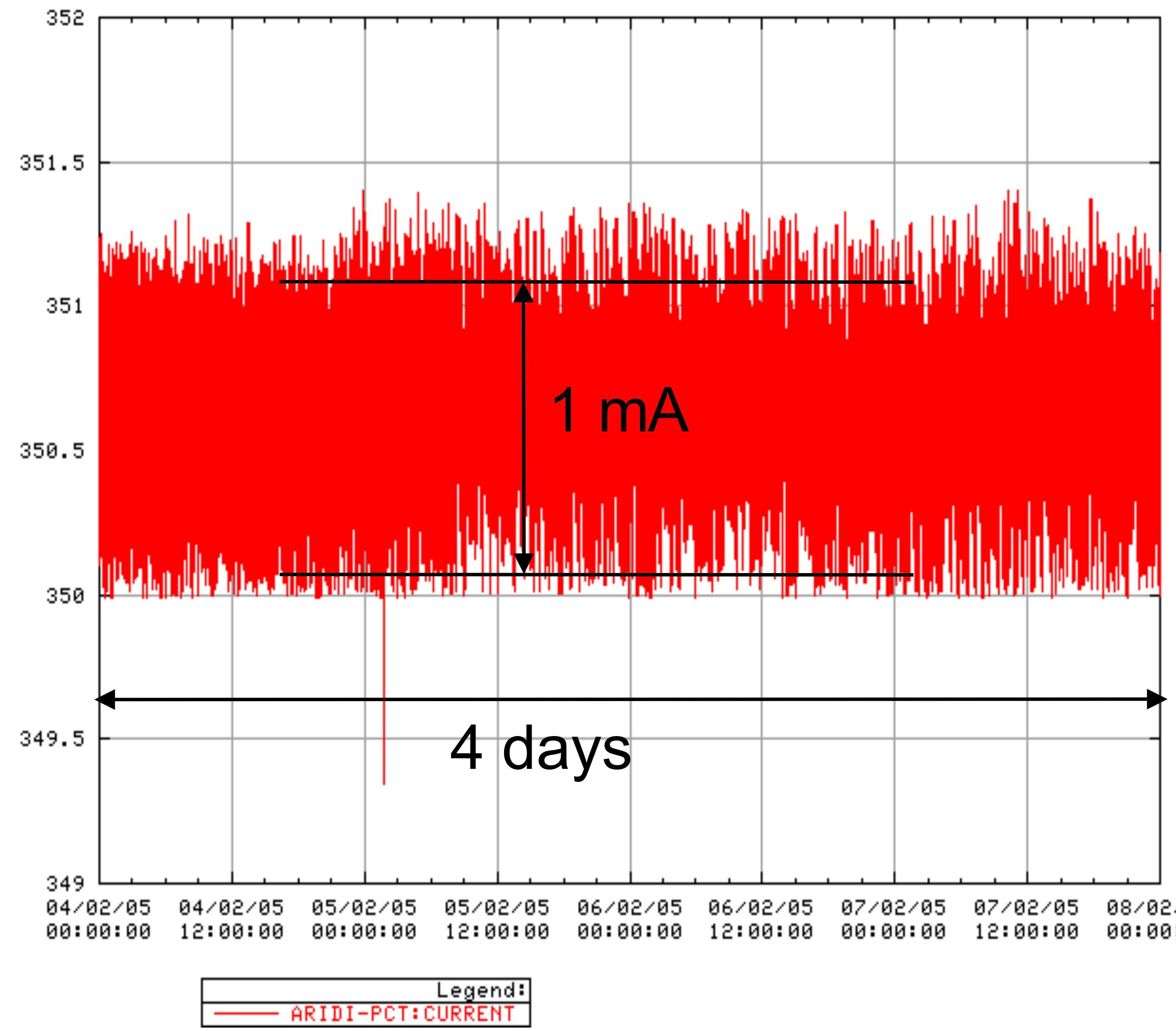
SLS!

Top-up operation

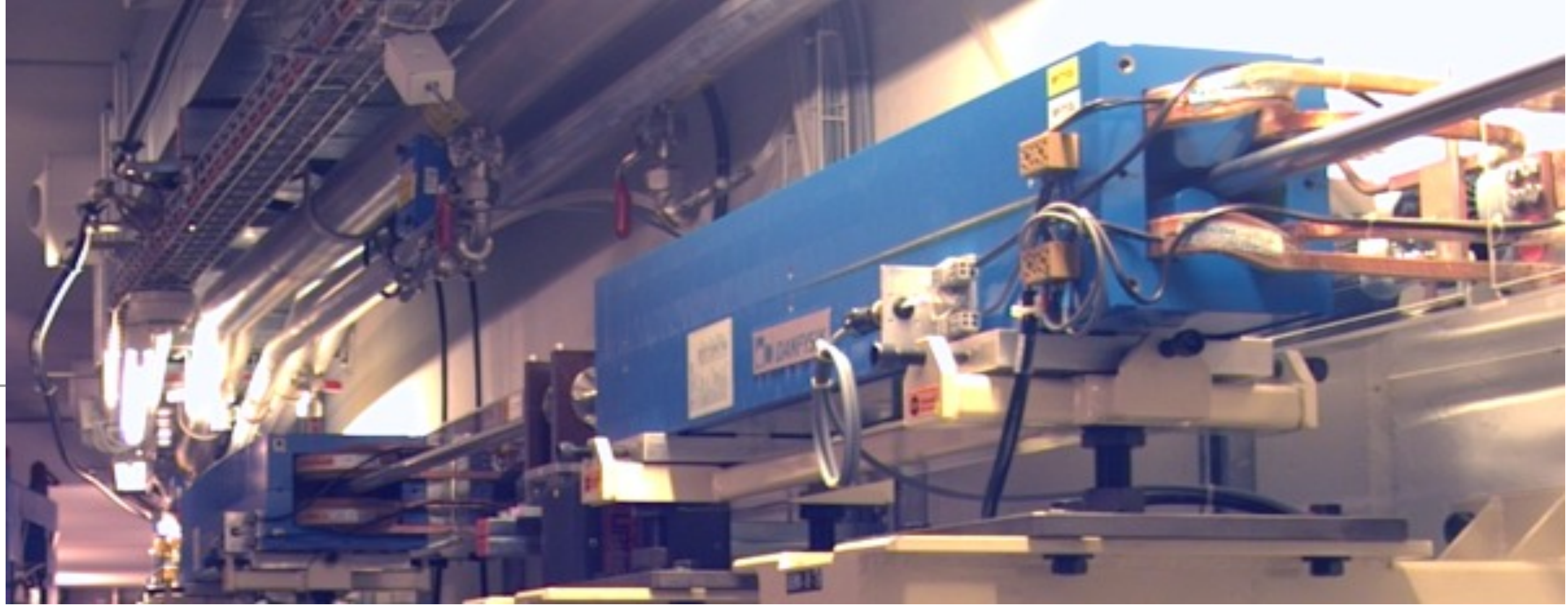
- Reason: low lifetime
- refill: 1-2 minutes
- current: ±1 mA

- Benefit: thermal stability and constant BPM gain

Top-up is a prerequisite for sub-μm stability!!



Top-up booster



- Concept:
  - Large circumference, many cells:
  - Combined function magnets {B, B’, B”}
  - Digital power supplies (on/off for top-up shot)
- High injection efficiency (emittance ~ 10 nm rad)
- Low building costs (same tunnel ring)
- Low operating costs (total power ~ 30 kW)
- High reliability (simplicity and relaxed optics)

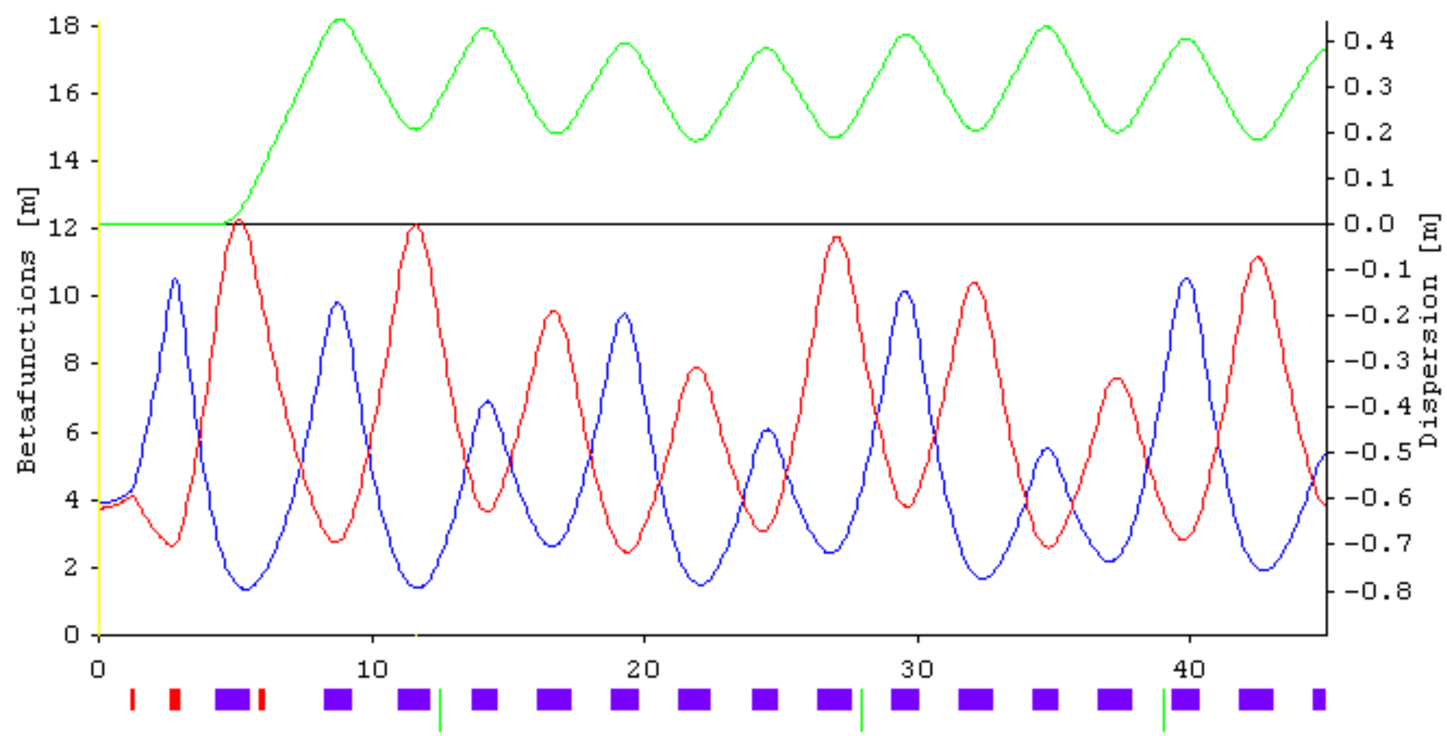
The booster synchrotron

3 FODO arcs:

- **48** BD (+SD) 6.4410°
- **45** BF (+SF) 1.1296°

3 × 6 quads for tuning

30 × 20 mm beam pipe



Energy	**0.1→ 2.4** [2.7] **GeV**		Mom. compaction	**0.005**
Repetition rate	**3.125 Hz**		Tunes	**12.41 / 8.38**
Circumference	**270 m**		Chromaticities	**-15 / -12**
Radio frequency	**500 MHz**		Radiation loss*	**233 keV**
Magnet power	**205 kW**		Damping times*	**11/19/14 ms**
Beam current	**1 mA**		Emittance*	**9 nm rad**

* Equilibrium at 2.4 GeV

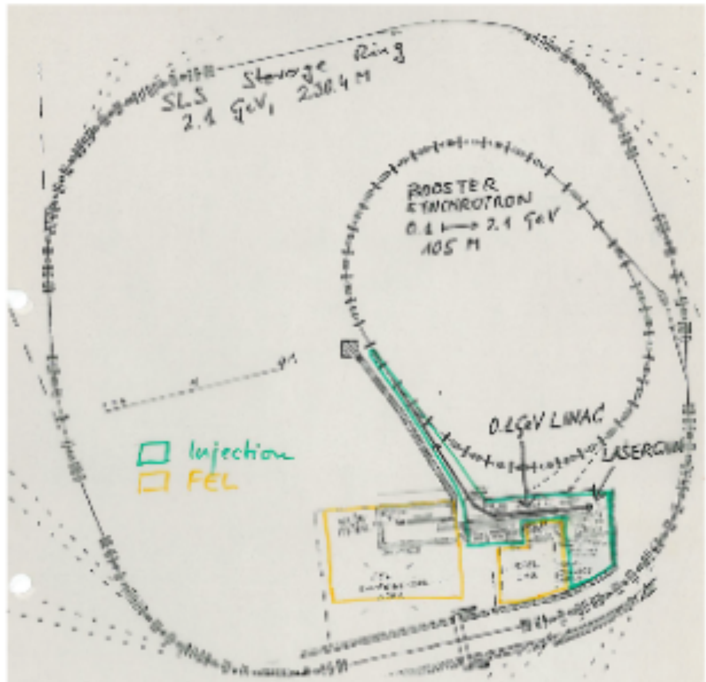
SLS History

1991

"swiss arc"
(s.c.bend)
+ DBA

>20m straights

230.4 m
2.1 GeV



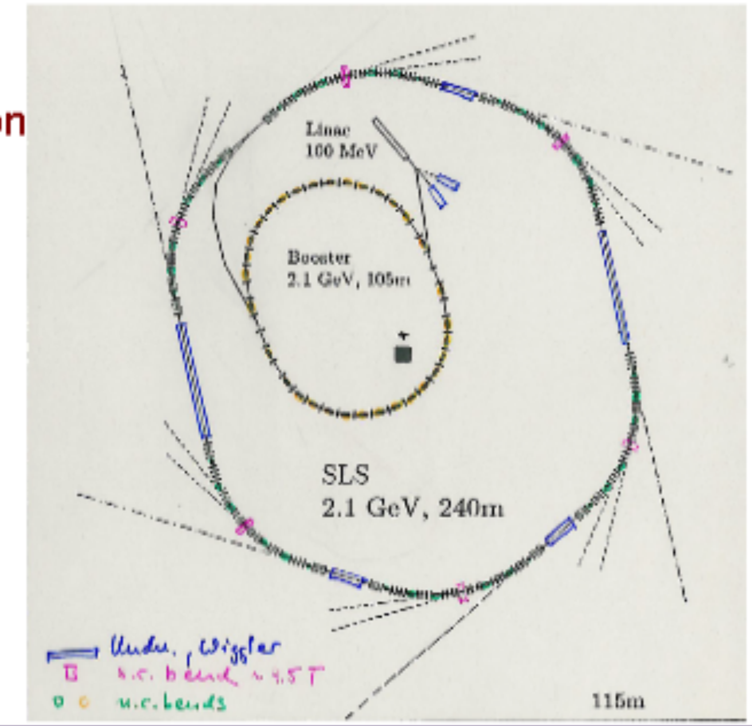
PAUL SCHERRER INSTITUT

1993 (CDR)

7BA Hexagon

6 straights:
4 x 6 m
2 x 20 m

240 m
2.1 GeV



PAUL SCHERRER INSTITUT

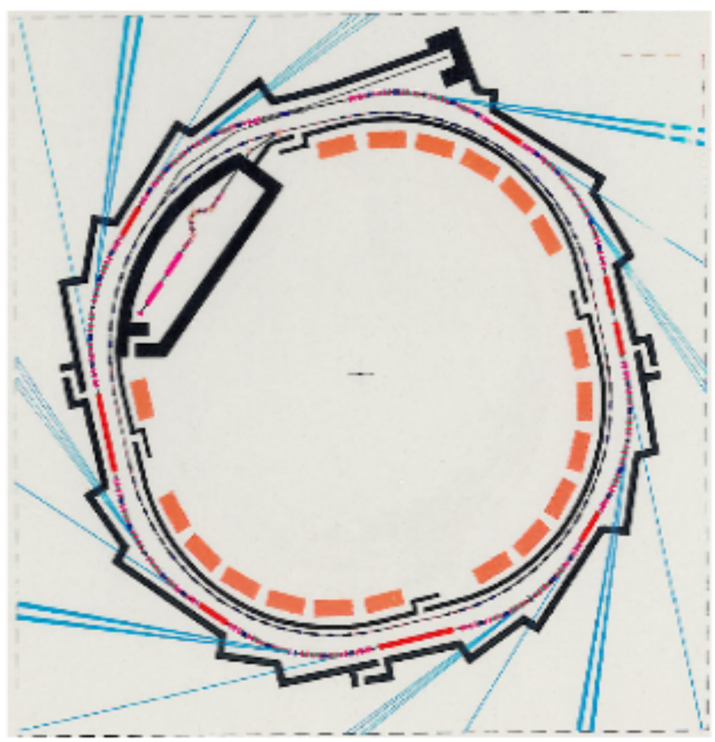
1995

7BA
Octagon

8 straights:
6m + 20m

270 m
2.1 GeV

Large
booster



PAUL SCHERRER INSTITUT

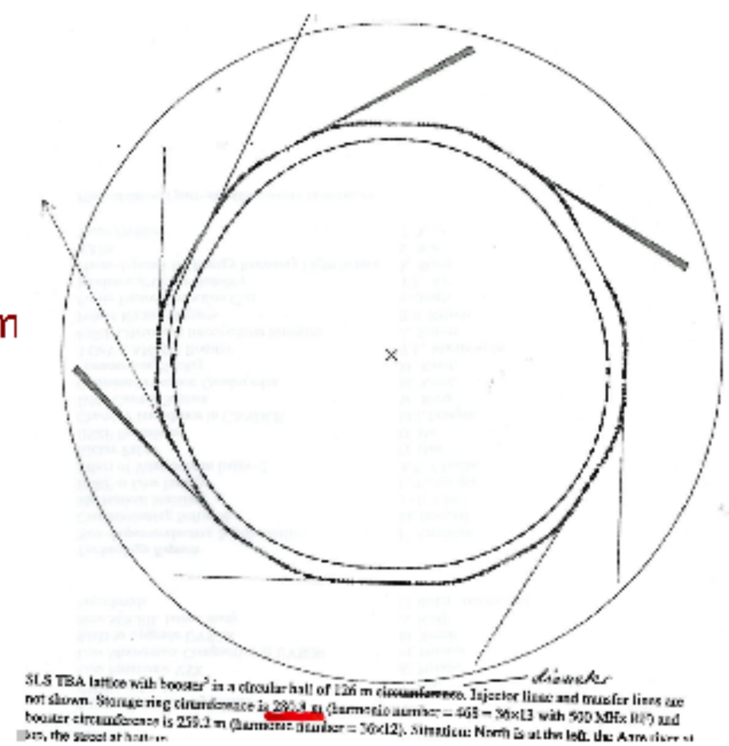
1996

12xTBA
period-3

12 straights
4m, 7m, 12m

280.8 m

2.1 GeV
▼
[2.4 GeV]



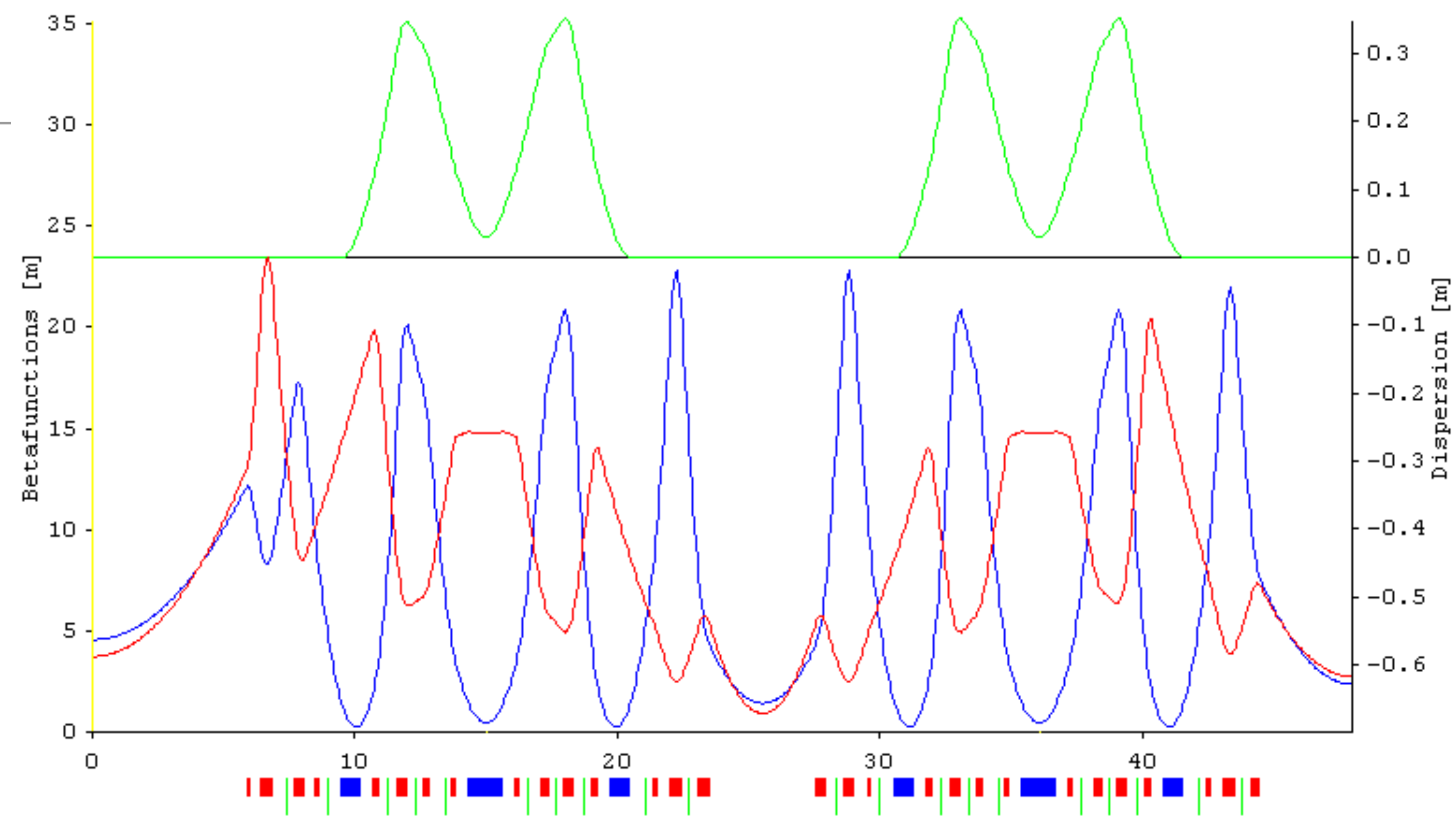
Main ring design history

The storage ring

12 TBA:
8°/14°/8°

12 straights:

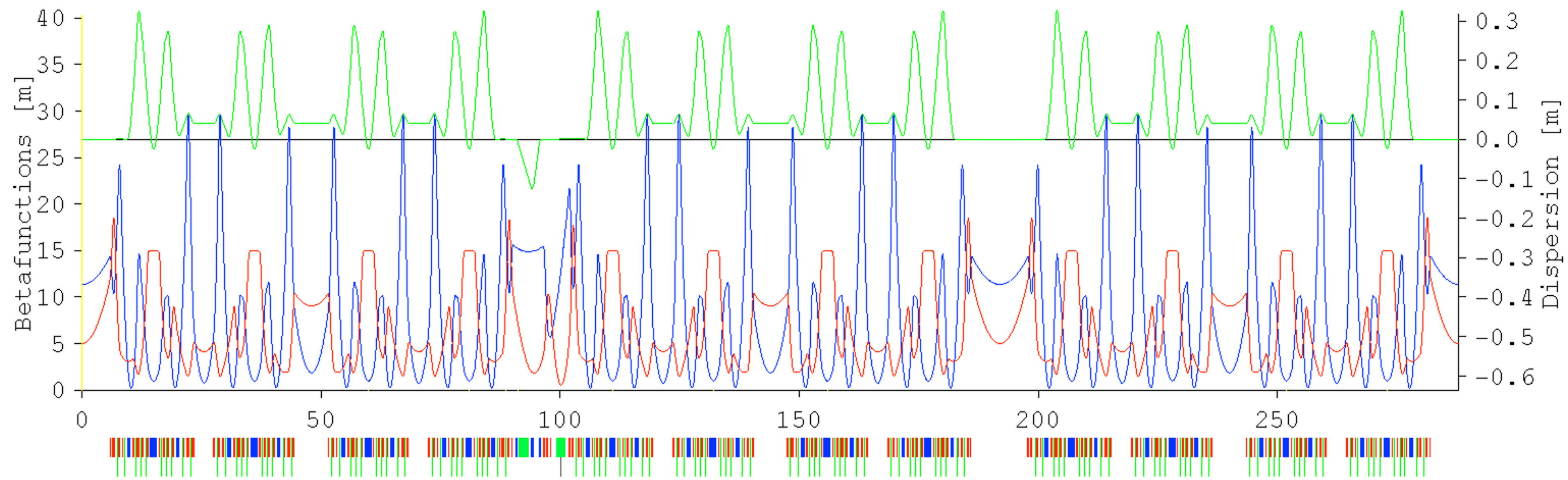
3 x 11.5 m
3 x 7.0 m
6 x 4.0 m

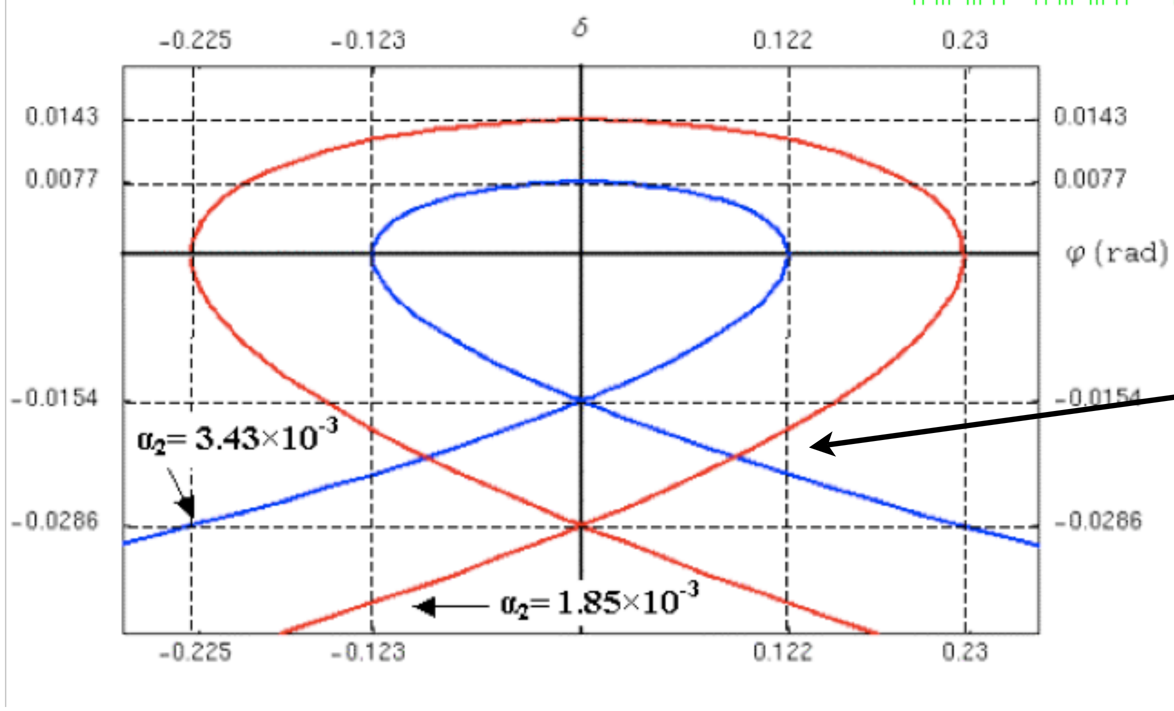


Energy	**2.4 GeV**	Mom. compaction	**$6.3 \cdot 10^{-4}$**
Emittance	**5 nm rad**	Radiation loss	**512 keV**
Circumference	**288 m**	Damping times	**9 / 9 / 4.5 ms**
Radio frequency	**500 MHz**	Energy spread	**$8.9 \cdot 10^{-4}$**
Tunes	**20.41 / 8.17**	rms bunch length	**3.5 mm**
Chromaticicities	**-66 / -21**	Beam current	**400 mA**

all data before FEMTO upgrade, without insertion devices and without harmonic cavities

Low-α Mode

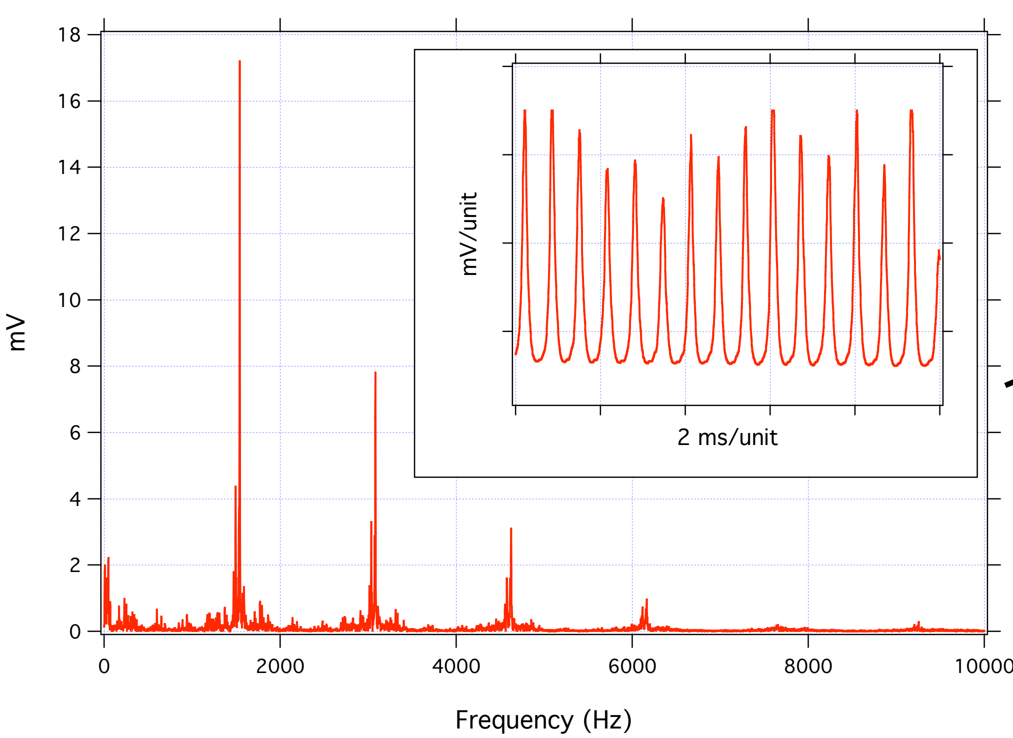


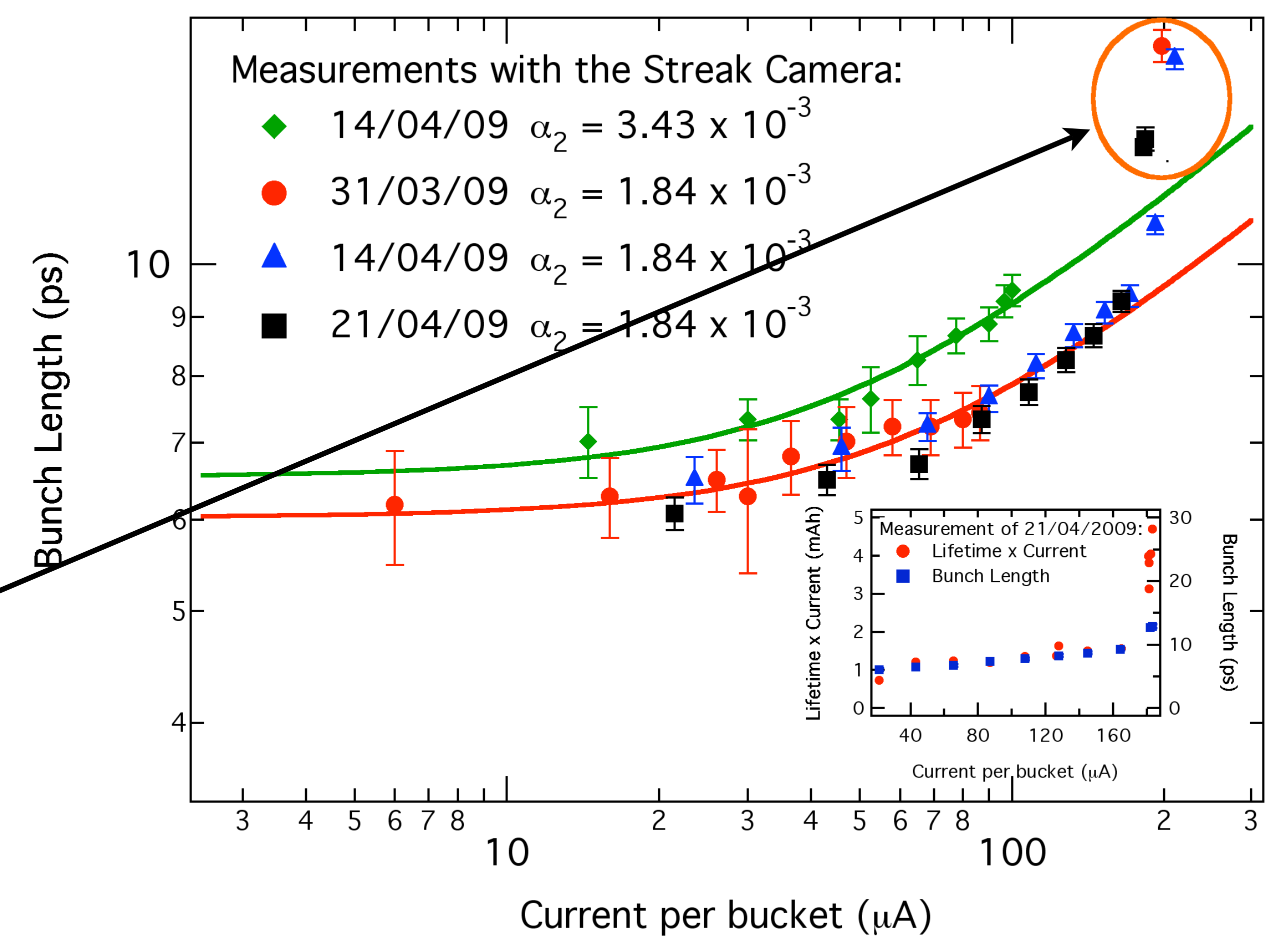


Momentum compaction: α_1 = 5.3 x 10^{-5} and

α_2 = 3.43-1.84 x 10^{-3}

$$H_0 = \frac{1}{2}h\omega_0\alpha_1\delta^2 + \frac{1}{3}h\omega_0\alpha_2\delta^3 + \frac{\omega_0 eV_{RF}}{2\pi E_0}(\cos(\varphi_s+\varphi)+\varphi\sin\varphi_s)$$





FEMTO
tunable sub-picosecond X-ray source

Research: reaction kinectics, protein folding etc.

$\Rightarrow$ time resolved experiments, resolution < 1ps

short pulse ***and*** *X-ray* ***and*** *high brightness*:

$\Rightarrow$ Free electron laser **SwissFEL !** $\rightarrow$ **2016**

...until then... :

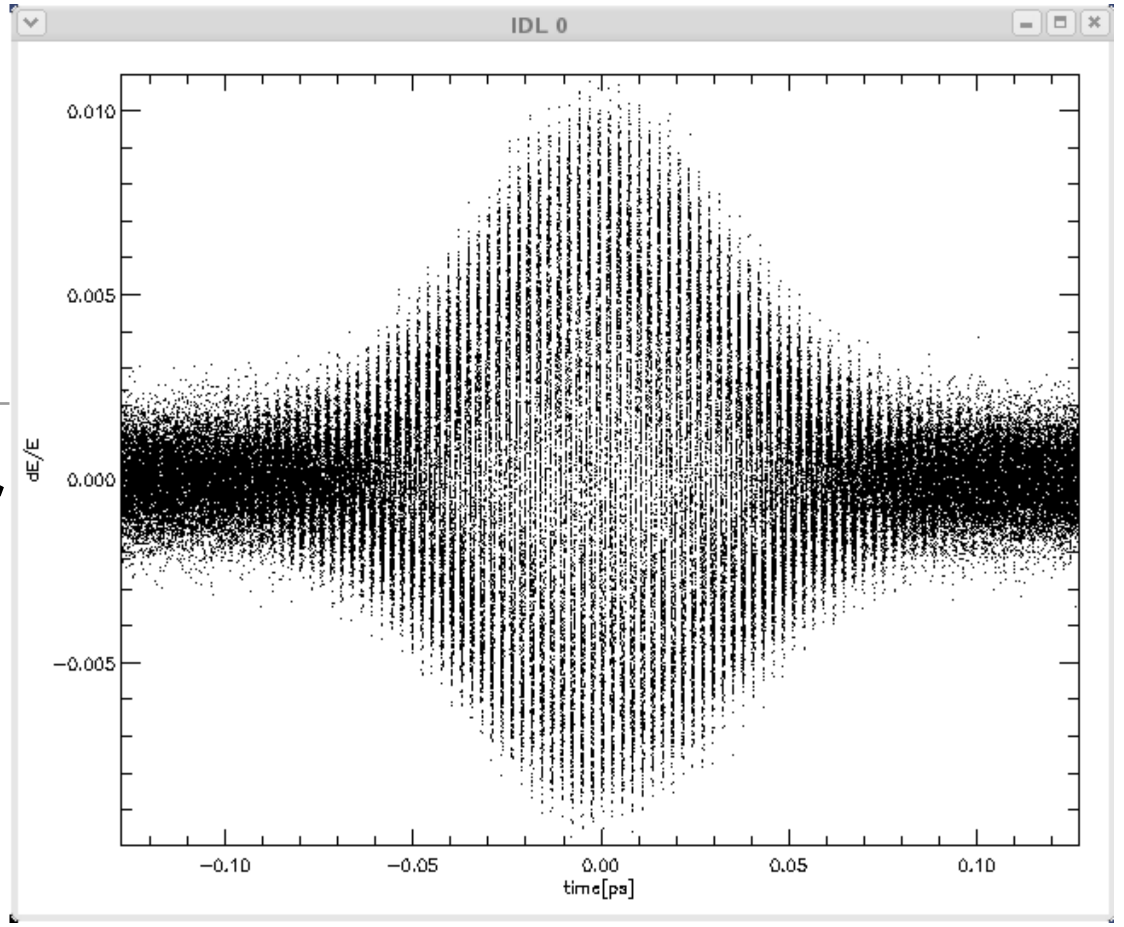
combine :
- SLS electron bunch length > 30 ps FWHM
- Laser pulse length ~ 50 fs FWHM

Problem: (E-field) $\perp$ (e^- velocity) $\Rightarrow$ no energy gain

Solution: electron in wiggler $B(s) = B_y \cos(2\pi s/\lambda_w)$:

- transverse velocity $c\beta_x \Rightarrow$ coupling to laser field
- $\langle\beta_s\rangle < 1 \Rightarrow$ resonant modulation for $(1-\langle\beta_s\rangle)\,\lambda_w = \lambda_{Laser}$

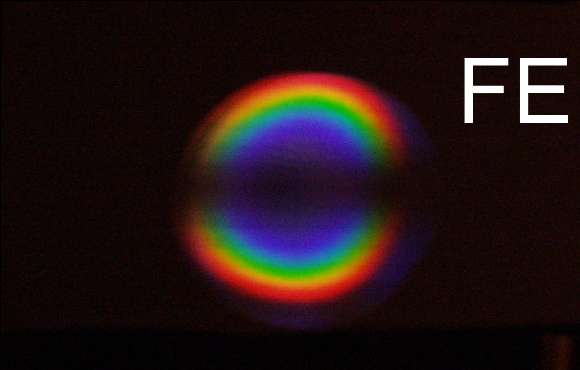
FEMTO

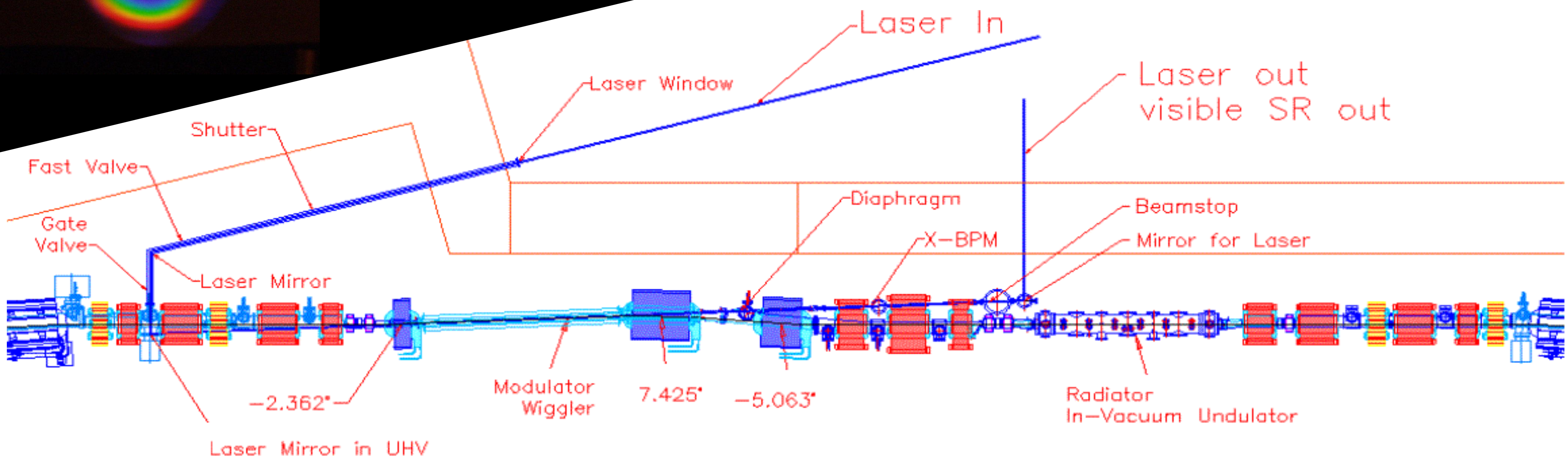


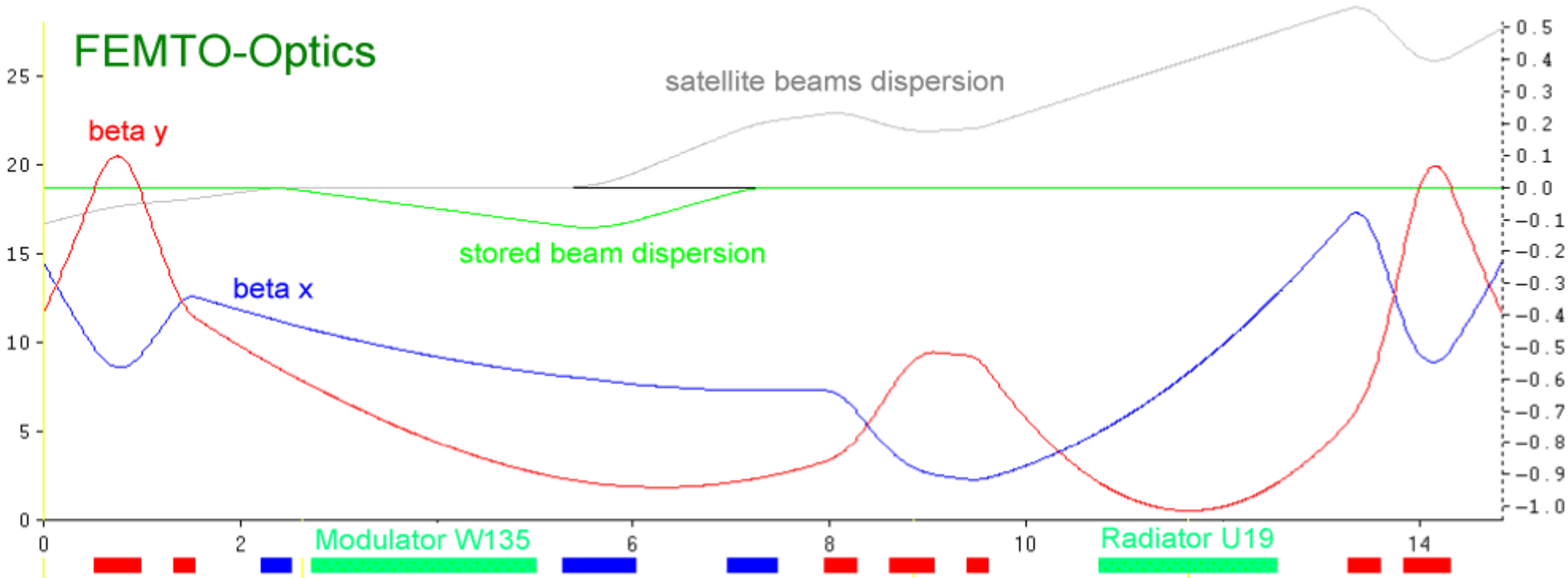
- 50 fs FWHM high power laser
  (2 mJ pulse energy)
- resonant wiggler
  for coupling laser to electron beam
- dispersive chicane translating energy modulation to horizontal separation
- in-vacuum undulator (U19) where core beam and modulated satellite beams radiate
- horizontal apertures
  to extract satellite radiation

⇒ 150 fs FWHM X-ray pulses

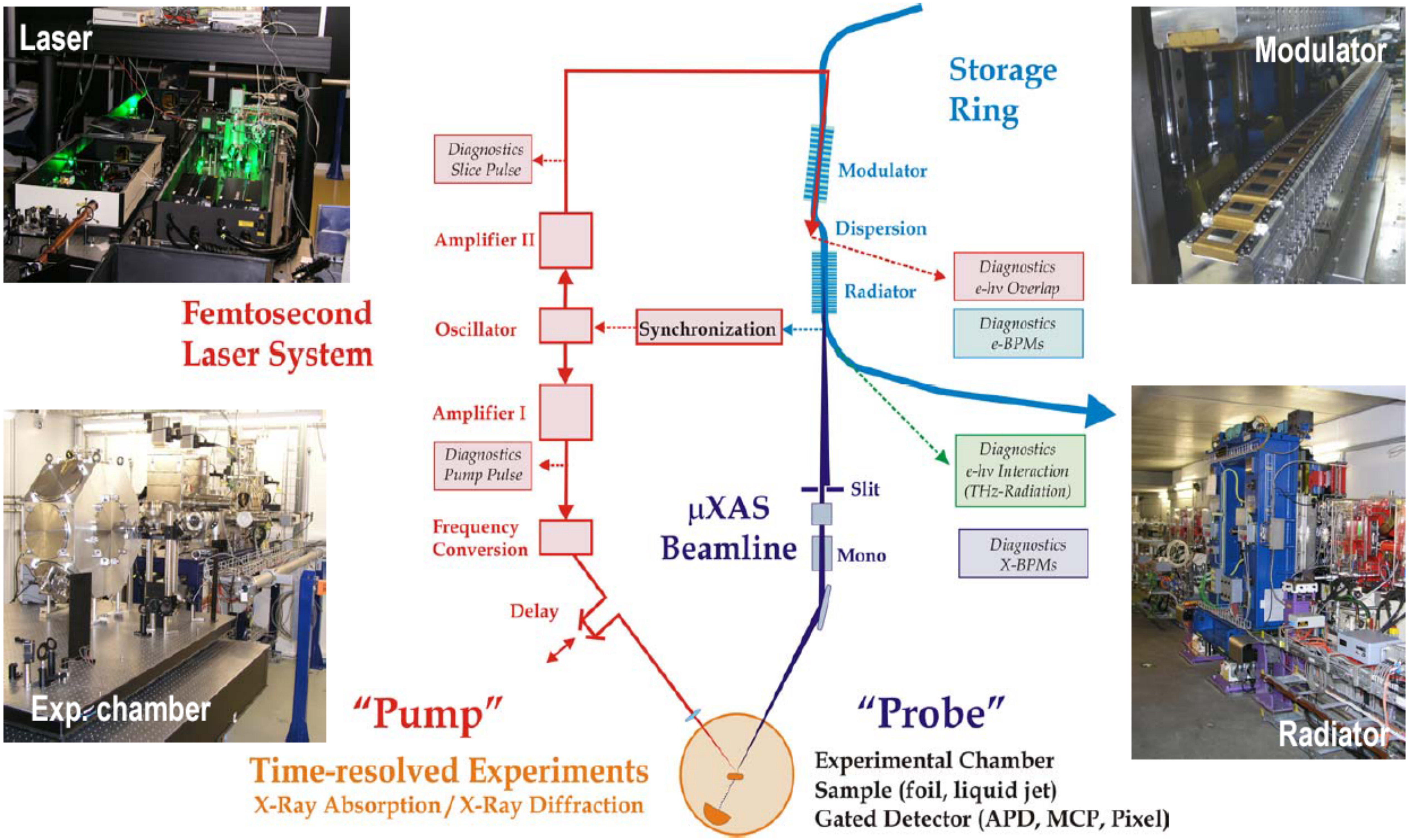
FEMTO Layout and Optics







FEMTO components
Pumb & probe experiment



SLS!

Beam Stability

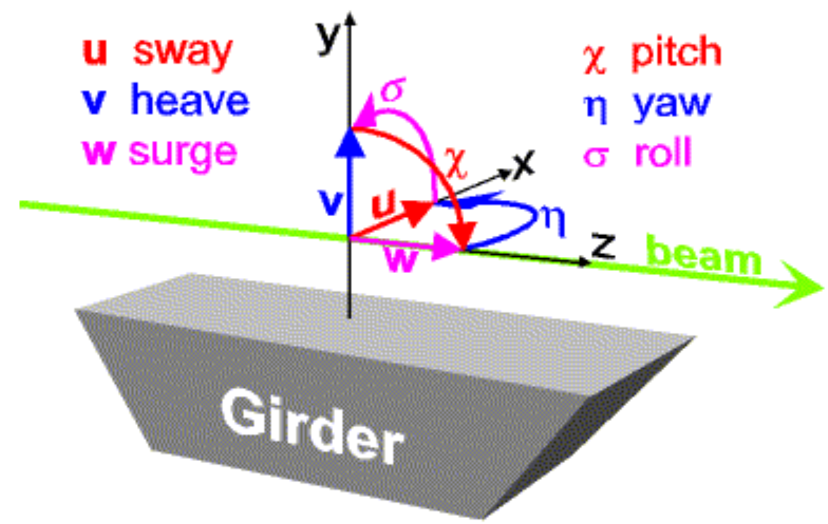
- Top up operation: thermal stability
- Beam position monitors: resolution < 0.3 μm
- Digital power supplies:
  stability and reproducability < 30 ppm
- Frequent beam based BPM calibration
  (“beam based alignment”)
- Insertion Device feed forward tables
- Fast orbit feedback system (<100 Hz)
- Photon-BPM integration in FOFB
- Filling pattern feedback system

Photon beam stability 1 μm rms (at frontend)

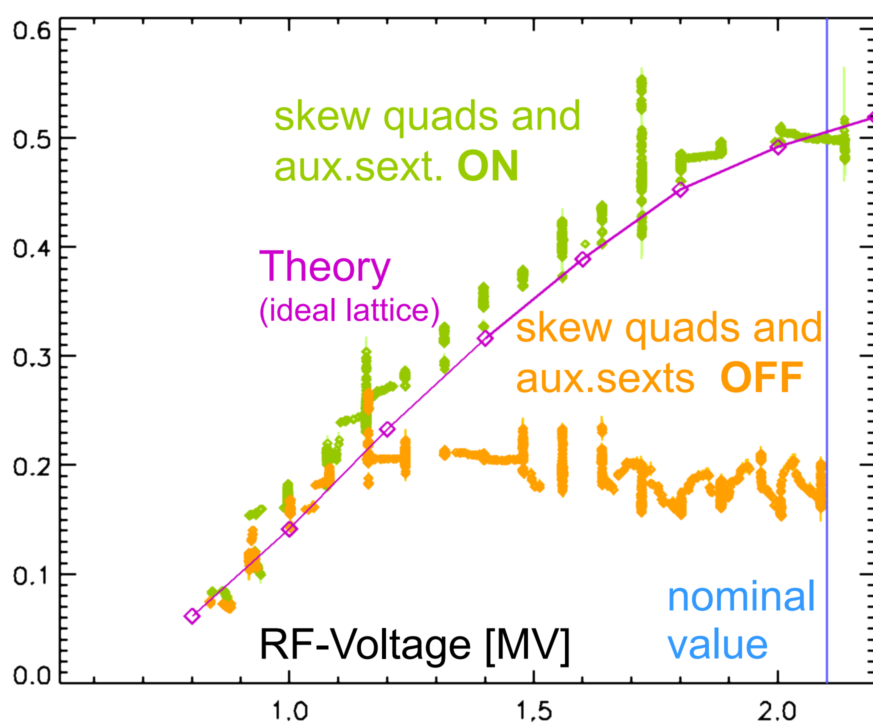
Coupling correction and control: Dynamic alignment

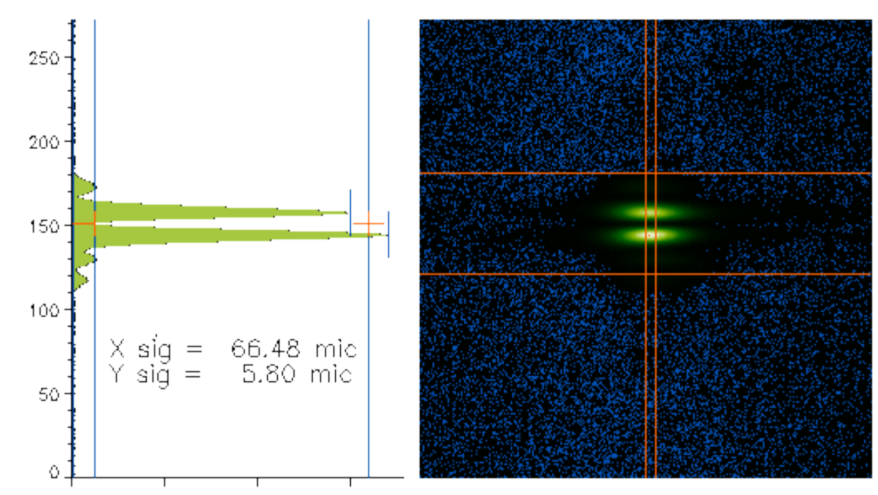
SLS!

- Magnets fixed to girders:
    - rail precision: 15 m
    - magnet axis: 30 m
- Girders movable in 5 degrees of freedom.



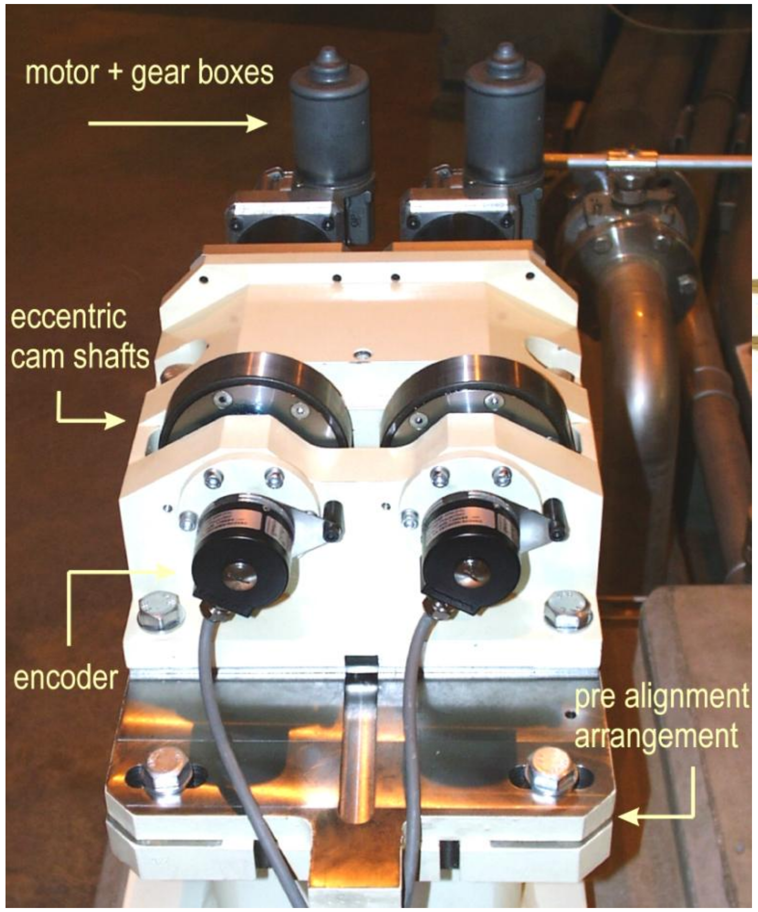
- Coupling control: 36 skew quadrupoles and 12 aux. sextupoles + diagnostics (emittance monitor using vertically polarized light)

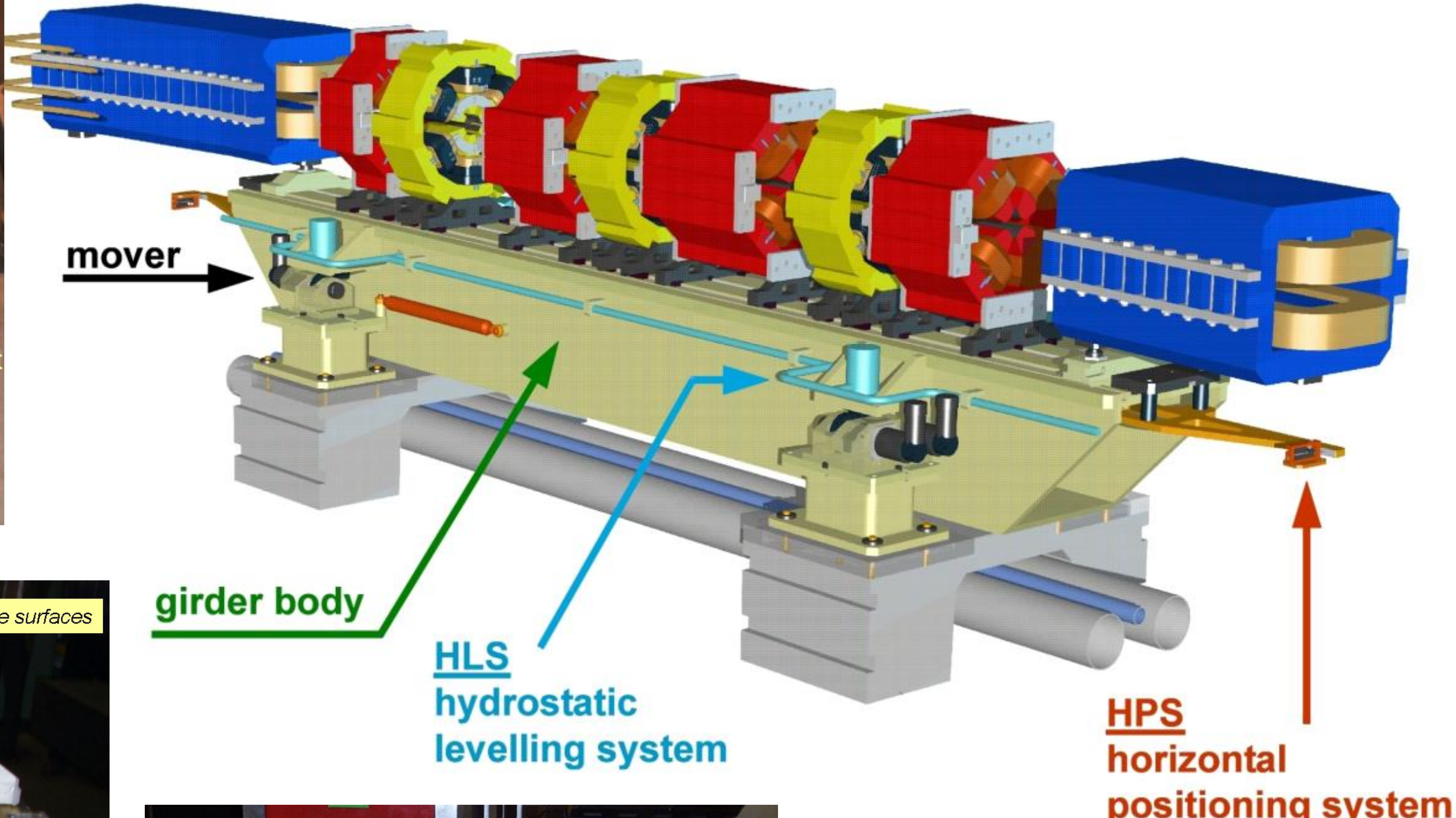


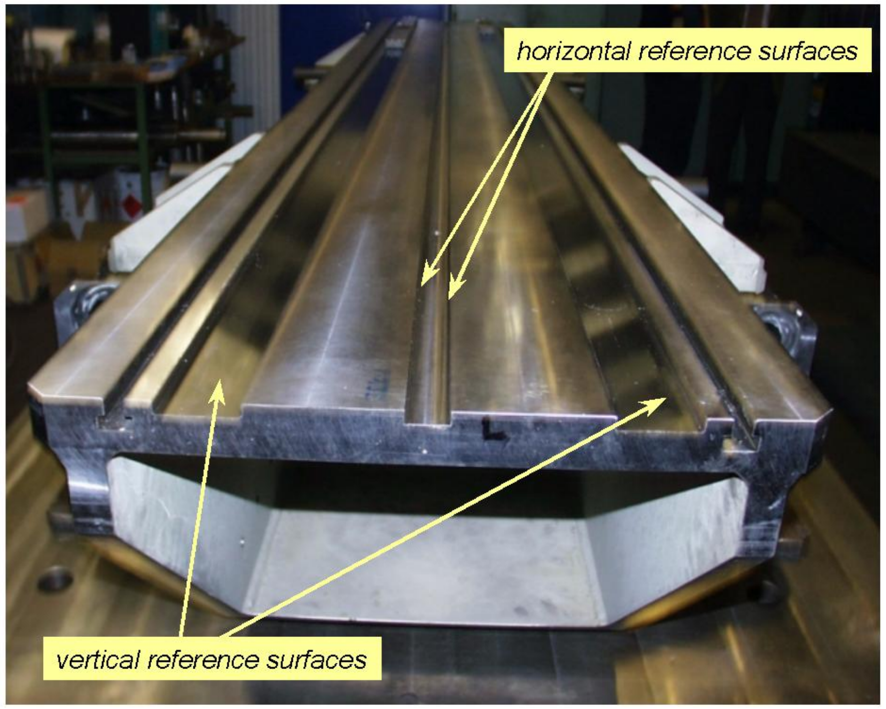


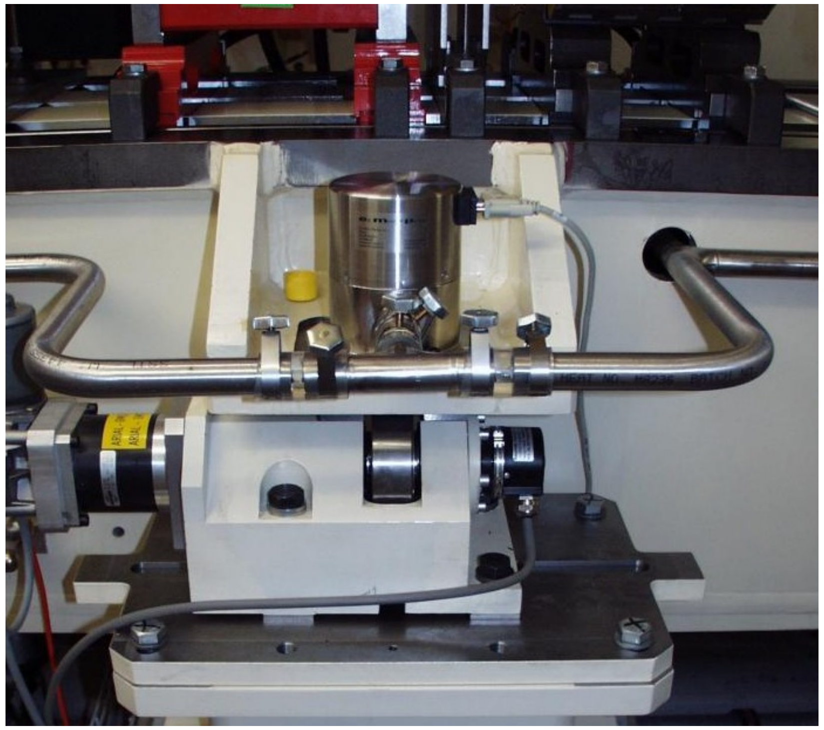
Beam lifetime (normalized to σ_y and single bunch current) as a function of RF voltage

Dynamic alignment components

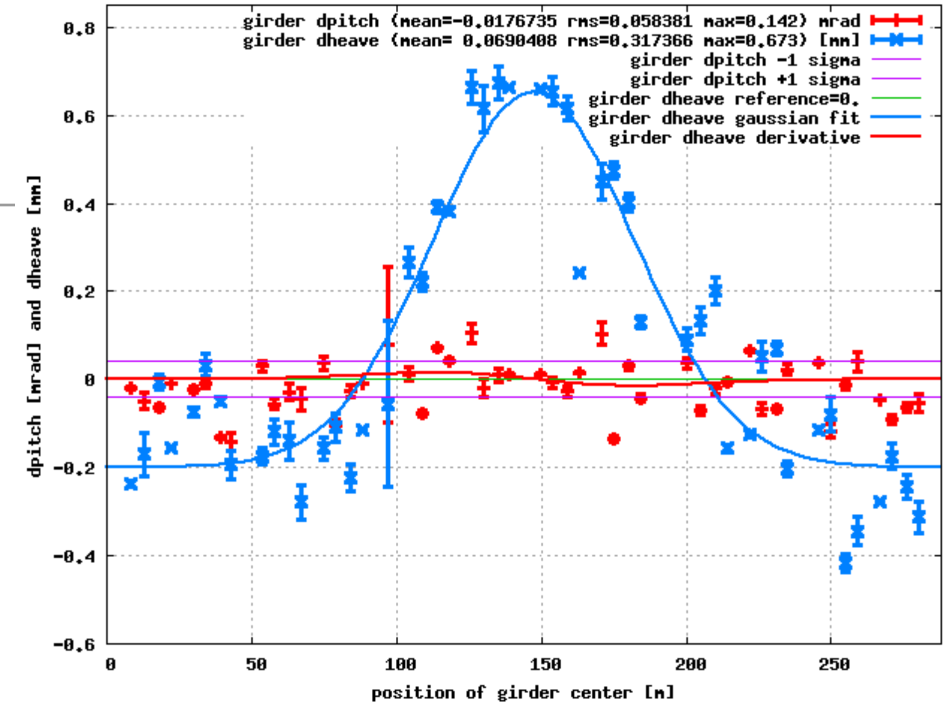




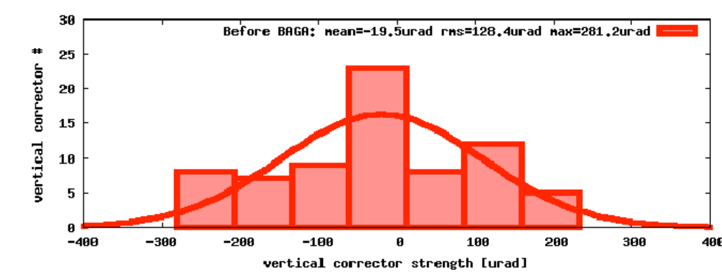


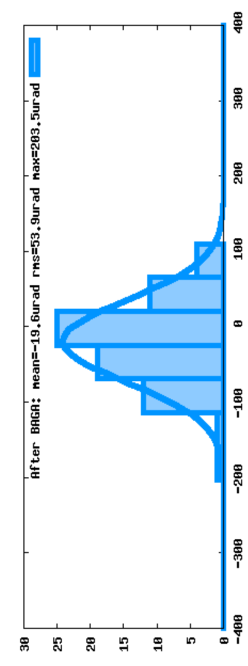


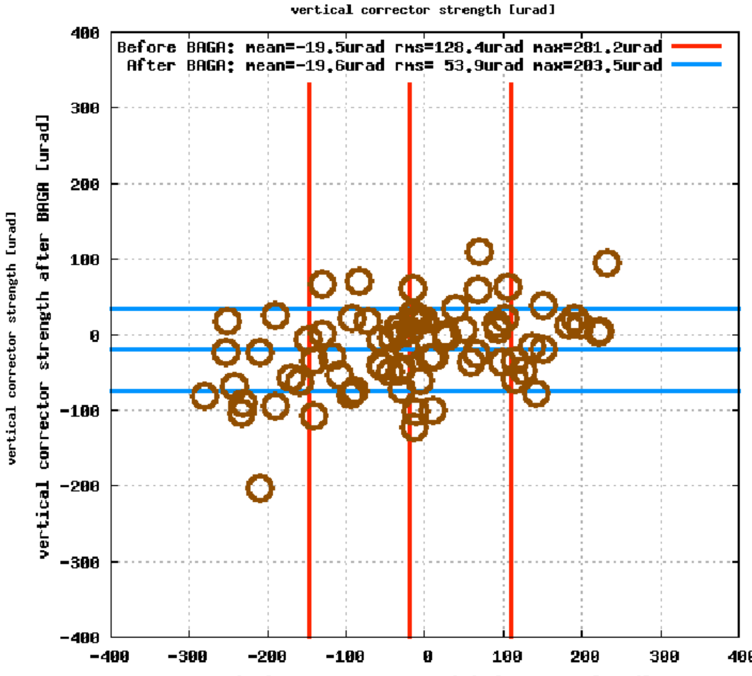
World-record vertical emittance ε_y = 1 pm rad

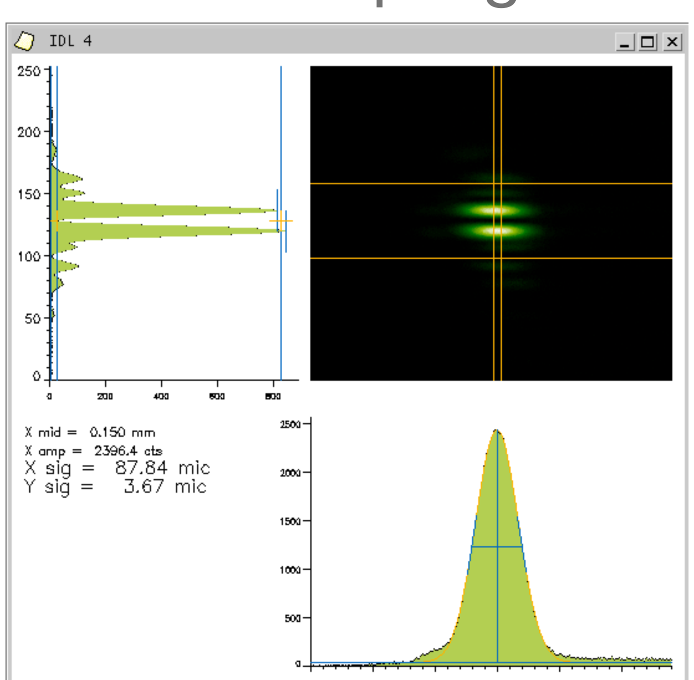


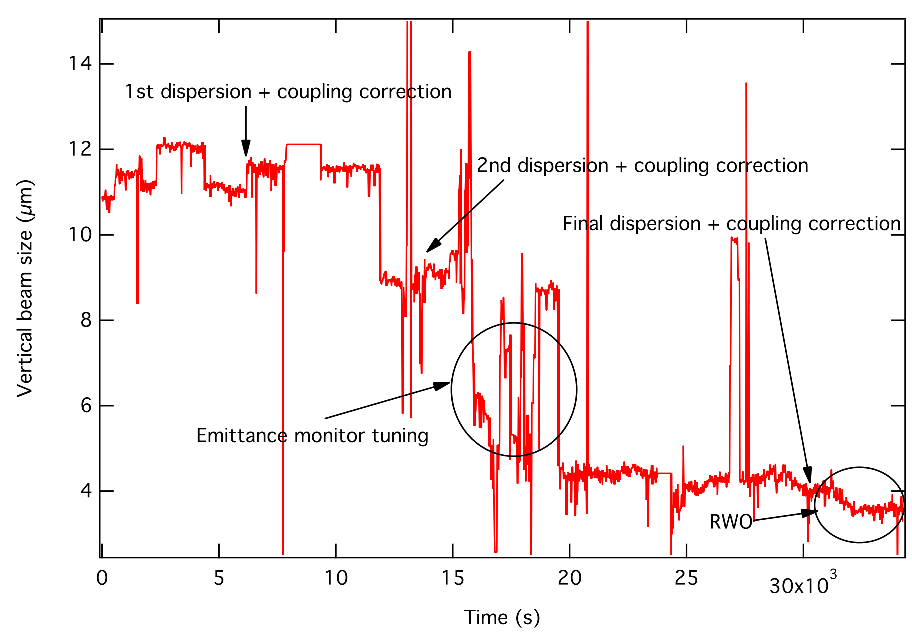
- Comparison of a survey from 2010 with the BPMs readings
- Shift from December 6th 2011:
  - Systematic correction using ORM
  - Correction using RACC (Random walk coupling correction)











Comparison with other light sources

		SLS	SOLEIL	DIAMOND	ALBA	MAX-IV	NSLS-II
Start of operation		2001	2006	2007	2010	2015	2015
Energy	GeV	2.40	2.75	3.00	3.00	3.00	3.00
Circumference	m	288	354	562	267	528	792
Emittance ε	nm	5.50	3.70	2.70	4.30	0.34	2.00
...effective	nm	5.50	6.29	2.95	5.84	0.34	2.00
...with IDs	nm	5.00				0.17	0.60
Current	mA	400	500	300 (500)	400	500	500
Lattice type		12xTBA	16xDBA	24xDBA	16xDBA	20x7-BA	30xDBA

"SLS-generation"

- $\varepsilon_{eff} \sim$ 3..10 nm
- insertion devices have little effect

next generation

- < 1 nm effective emittance
- large circumference: $\varepsilon \sim (N_{bend})^{-3}$
- strong insertion devices effects

Summary

- More than 10 years of positive experience with **SLS**:
  - Experimental program
  - Accelerator operation
  - Stability and coupling: world record!
  - Upgrade potential (still a competitive source)
- Innovations have proven useful: top-up, digital BPMS and PS, FOFB, booster, ...
- **FEMTO:**
  - successful operation since 5 years
  - unique source: tunable, sub-picosecond X-ray (next step *SwissFEL*)