Present limits and Future Storage Ring Synchrotron Sources

P. Elleaume, ESRF

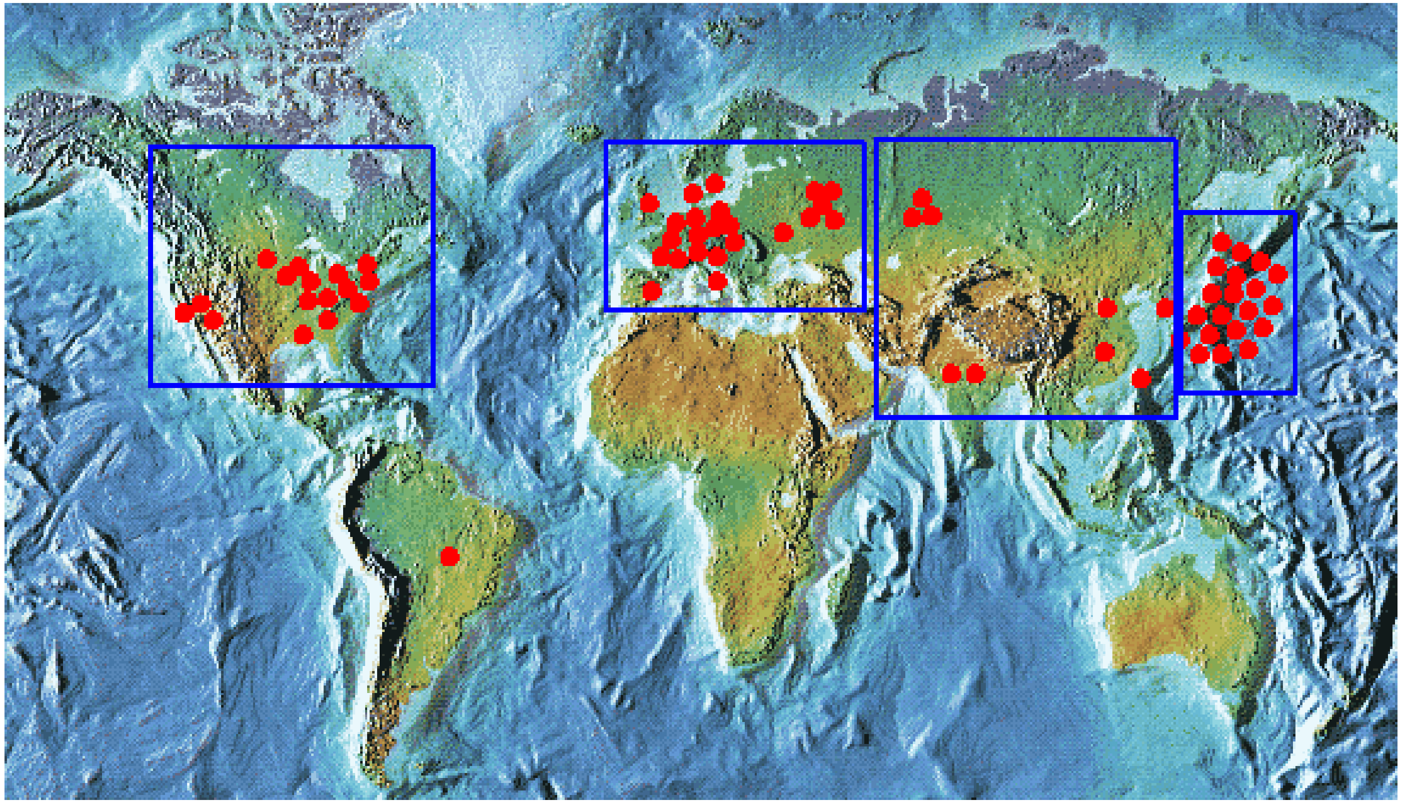
I dedicate this presentation to the memory of
Jean-Louis Laclare

JL Laclare lead the construction of the ESRF and its initial operation (1986-1996).

"His vision and dynamism had a great impact on the ESRF and on the European Synchrotron Sources."

Synchrotron Radiation in the World

~ 50 Facilities in operation
~ 10 Facilities under construction or major upgrade
~ 14 Projects …



http://srs.dl.ac.uk/SRWORLD/index.html
http://www-ssrl.slac.stanford.edu/sr_sources.html

Contents

- State of the Art
- New Facities
  - Upgrade of existing rings
  - Intermediate-energy rings
  - Ambitious studies

3^{rd} Generation Synchrotron Sources in Operation

Name	Energy [GeV]	Perim. [m]	Current [mA]	Emittance [nm]	Straights	Lattice	Full En. Inj.	Injector
SPRING-8	8	1436	100	5.6	48	DBA	Y	Booster
APS	7	1060	100	3.5	40	DBA	Y	Booster
ESRF	6	844	200	3.8	32	DBA	Y	Booster
PLS	2.5	281	180	12	12	TBA	Y	LINAC
ANKA	2.5	240	110	70	8	DBA	N	Microtron .5 GeV
SLS	2.4	240	400	5	12	TBA	Y	Booster
ELETTRA	2-2.4	260	320	7	12	DBA	N	LINAC 1 GeV
Nano-Hana	2	102	300	70	8	DBA	N	Booster 0.5 GeV
ALS	1.9	197	400	6.8	12	TBA	N	Booster 1.5 GeV
BESSY-II	1.7-1.9	240	270	5.2	16	DBA	Y	Booster

Dedicated synchrotron sources put into operation after 1990, by decreasing order of electron energy

Main figures of merit of synchrotron light sources

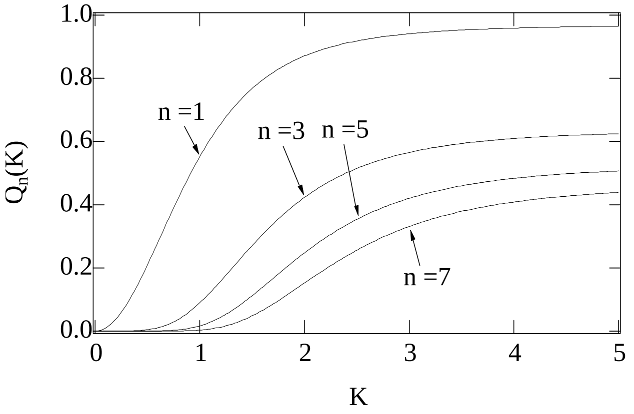
- Undulator Average Spectral Brilliance (Brightness)

Spectral Flux

$$F_n \propto N\, I\, Q_n(K)$$

$$B_n = \frac{F_n}{(2\pi)^2 \varepsilon_x \varepsilon_z}$$

Photon Emittance

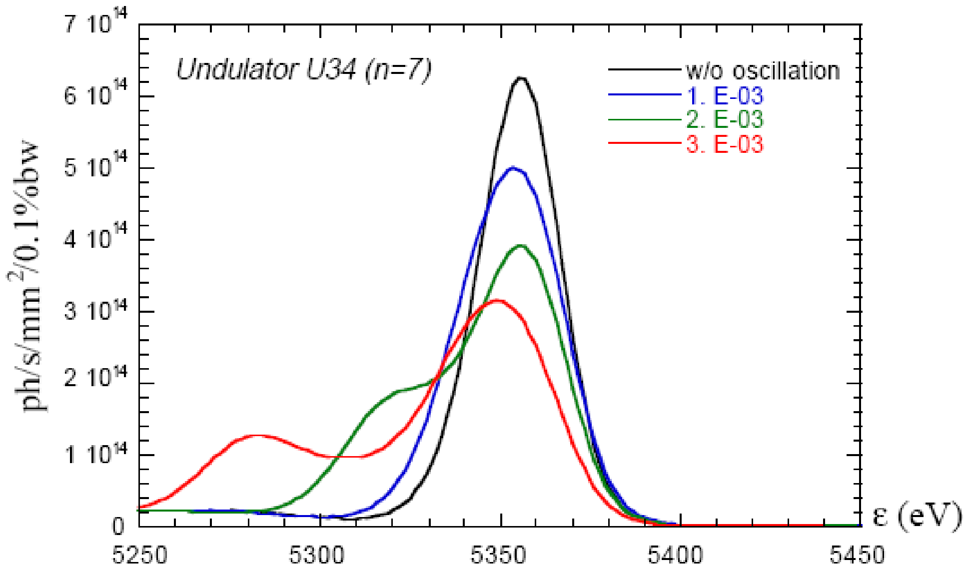


- Beam Quality
  - Position Stability
  - Energy Stability
  - Lifetime
  - Reliability and MTBF

Ring Current Limitations

- Heatload on the vacuum chambers, absorbers and beamlines :
  - ESRF, 200 mA : 4m undulator at gap of 5 mm => 20 kW and 2 kW/mm2 on the main beamline shutter
  - Absorbers are designed according to very conservative limit. Still room for improvement
  - The first Crystal/Grating/Mirror in the beamline is a major concern

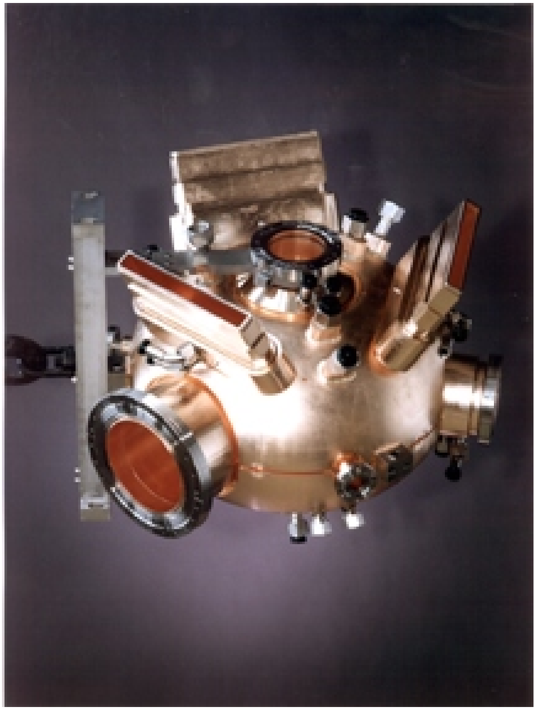
- Coupled bunch instabilities (CBI) driven by Higher Order Modes (HOM) of the radio frequency cavities.
  - Longitudinal oscillations
    - Increase energy spread
  - Transverse oscillations
    - Increase effective emittance



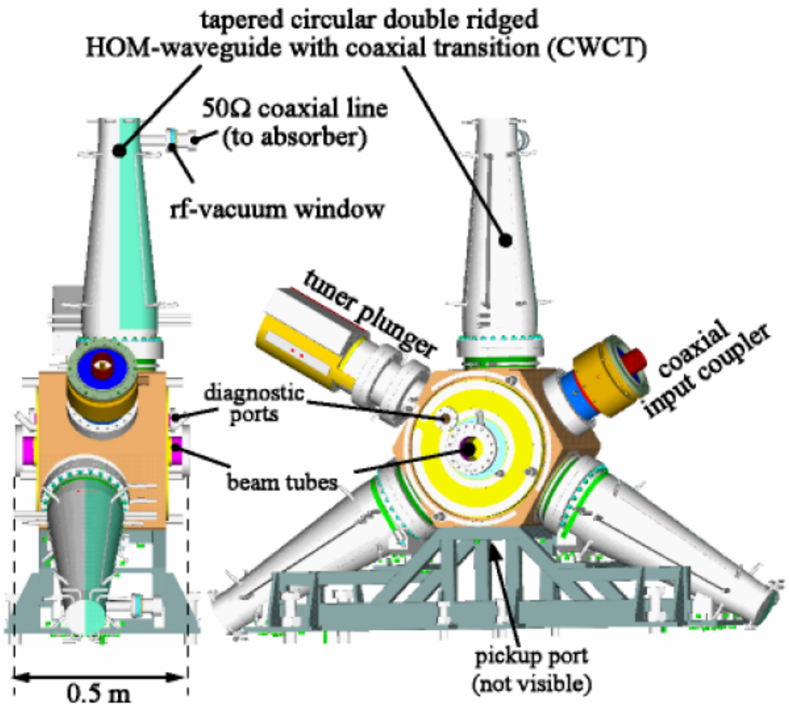
Stabilizing Coupled Bunch Instabilities

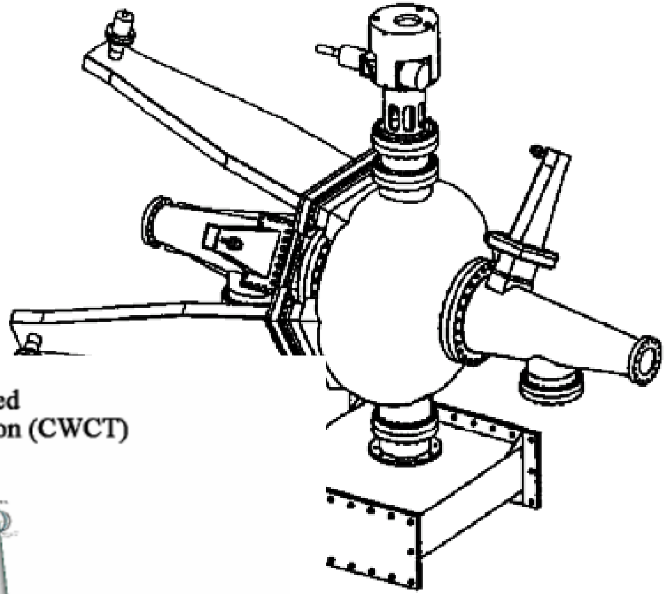
- Precise temperature control of the RF cavities
- Harmonic cavities
  - Max II,SLS, ELETTRA, BESSY
  - Bunch Lenghtening
  - Increase the lifetime
- Superconducting RF cavities
  - SRRC, CLS, SOLEIL, DIAMOND,...
- Special HOM Damped cavities
  - SPEAR-III
- Feedback

Room Temperature HOM Damped Cavities



PEP II cavity

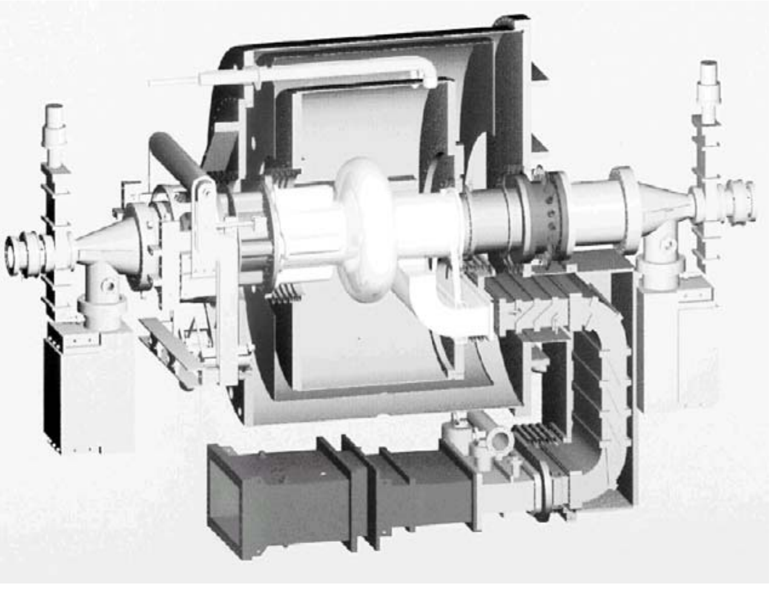




DAΦNE bell shape cavity

Marhauser, Weihreter, Weber, BESSY

Superconducting Cavities



Cornell

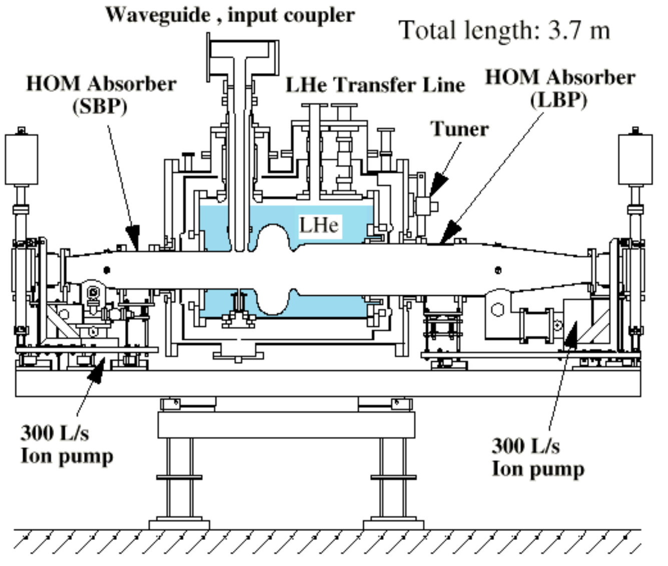
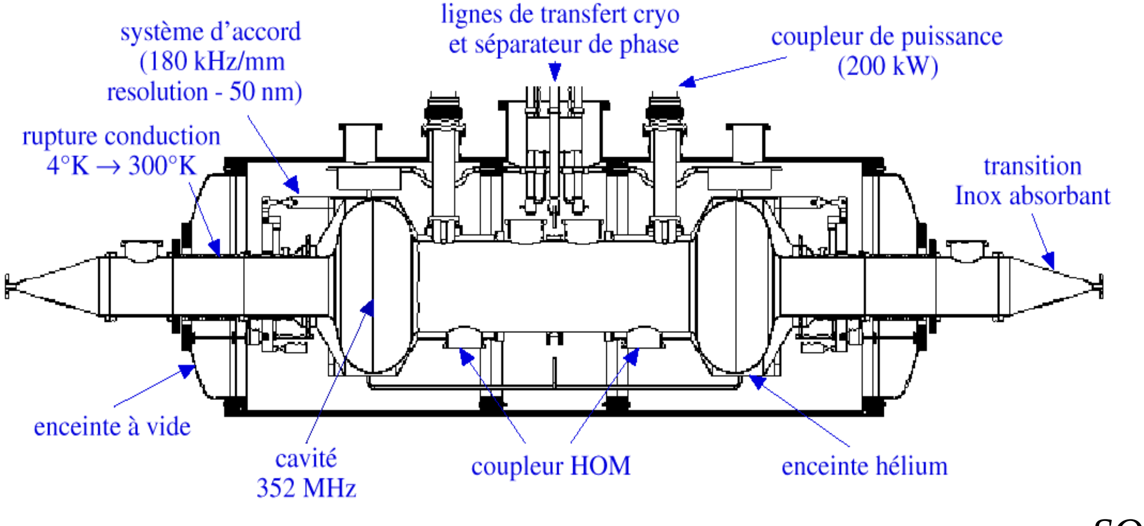


Figure 1: Superconducting cavity module for KEKB

KEKB



SOLEIL

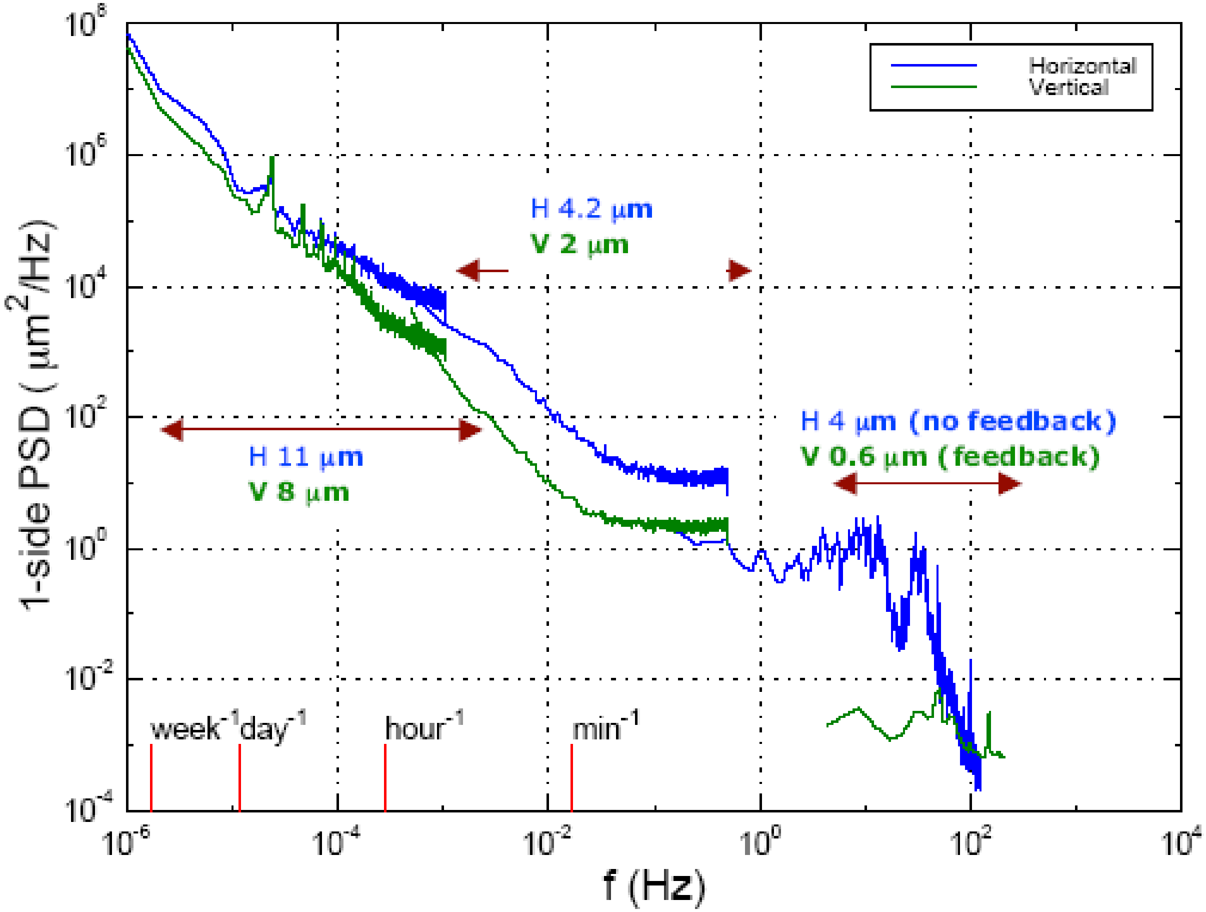
Emittance Optimization

- Brilliance $$\boxed{B \simeq \frac{F}{\varepsilon_x \varepsilon_z}}$$
- Lattice $$\boxed{\varepsilon_x \propto \frac{E^2}{N_{cell}^3}\,,\ \ \varepsilon_z \approx \kappa\, \varepsilon_x\,,\ \ \kappa \sim 0.1-1\%}$$
- Diffraction $$\boxed{\varepsilon \approx \frac{\lambda}{4\pi} \propto \frac{1}{E^2}}$$
- Touschek Lifetime $$\boxed{\frac{1}{\tau} \approx \frac{I_b}{E^2\sqrt{\varepsilon_x \varepsilon_z}}\, f\left(\frac{\Delta p}{p}\right)}$$
- Remarks
  - Brilliance is made at the cost of lifetime
  - Medium and high energy rings need the smallest horizontal emittance
  - Many medium ring increase the vertical emittance for lifetime
  - Topping-up and/or harmonic cavities alleviate the lifetime problem

Sources of Beam instability

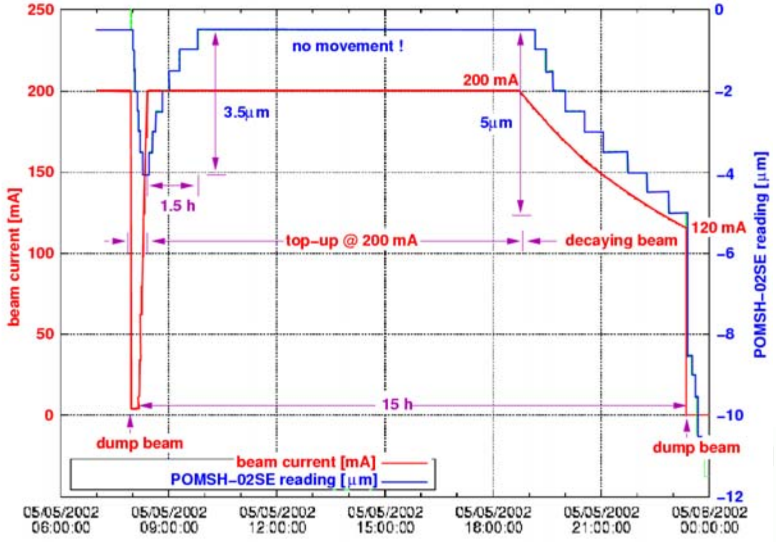
- Displacement of the ring vacuum chambers and beam position monitors during energy ramping and/or current decay
  - Full energy injector
  - Topping-up
- Tunnel & Experimental Hall Temperature variations
  - Must be stabilised to +/- 0.1 deg C
- Ground motion amplified at the resonance frequency of the quadrupole girders and its supports
  - Avoid low frequency resonance modes (All recent light sources).
  - Use visco-elastic dampers on the girders (APS, ESRF).
  - Position Feedback

Beam Stability at ESRF



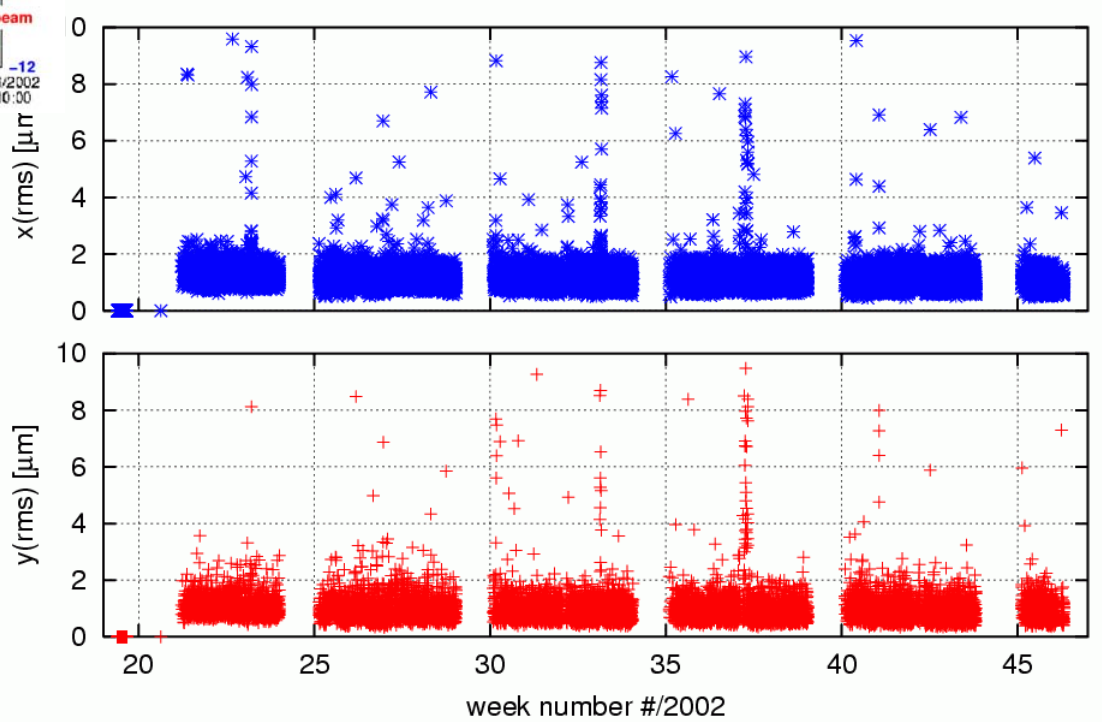
Beam motion on straight section BPMS
(β_x = 35.4 m, β_z = 6.2 m)
(σ_x = 360 μm, σ_z = 15 μm)

Beam Stability under Topping up at SLS



STABILITY :

2 min.	13 nm
20 days	0.5 µm
Year	1-2 µm



Insertion Devices

- High Brilliance => preference of undulators rather than wigglers
  - ESRF (6 GeV) : 60 Und. / 8 Wig.
  - SOLEIL (2.9 GeV) : 17 Und. / 1 Wig.

- Undulators must produce high photon energies :
  - High harmonics from undulators with small phase errors
  - Reduce the magnetic gap to the ultimate
  - Push the technology
    - In-vacuum undulator
    - Superconducting undulators

Magnetic Shimming

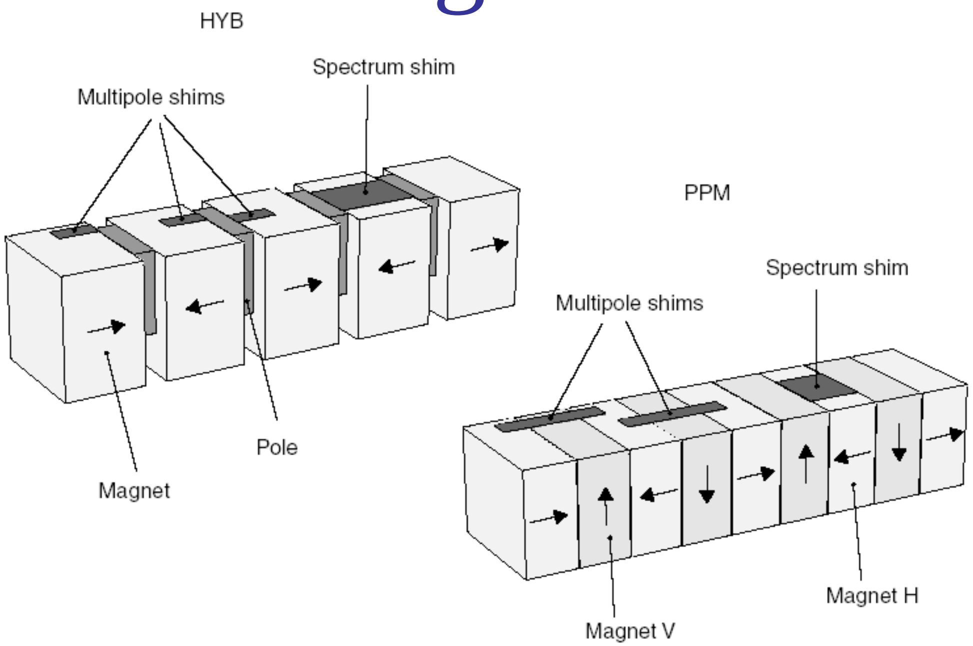
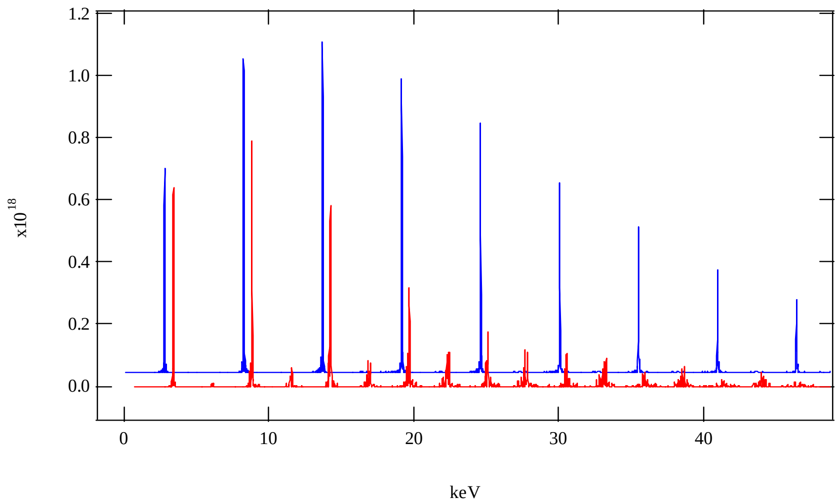


Figure 5.17 Multipole and spectrum shims in a PPM and HYB undulator.

Rms Phase Error ~ 1-2 degree
Commonly achieved

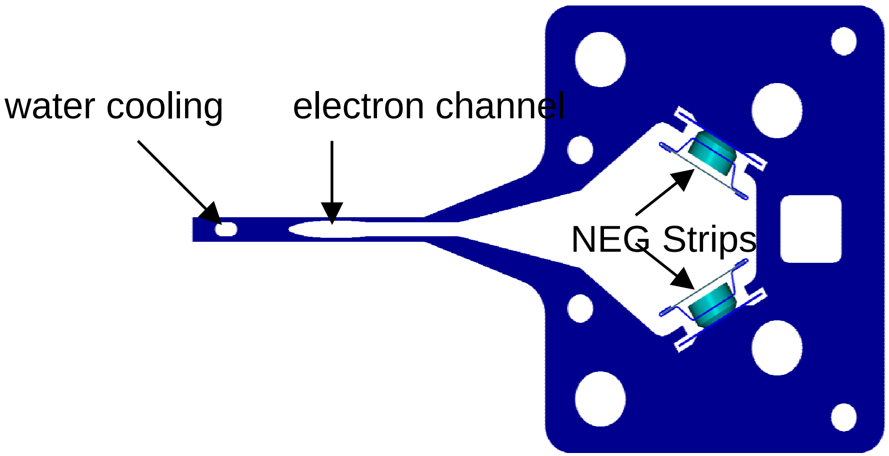
Phase error [deg]	6	1
Harmonic #		
1	0.99	1.00
5	0.76	0.99
9	0.41	0.98
13	0.16	0.95



Limits in magnetic gap

- Aperture required for injection + chamber thickness
- Gas scattering lifetime (low and medium energy rings)
  - Need low vacuum pressure along the whole ring circumference
    - stainless steel chamber with antechamber and localized absorbers and pumping(SLS)
    - NEG coating of the quadrupole chambers (SOLEIL)
- Demagnetisation of NdFeB under exposure to electron beam which must be replaced by Sm_2Co_{17}.
- Assuming optimised Lattice functions, gap ~ $L^{1/2}$

Narrow Aperture Undulator Vacuum Chambers



APS type Chamber

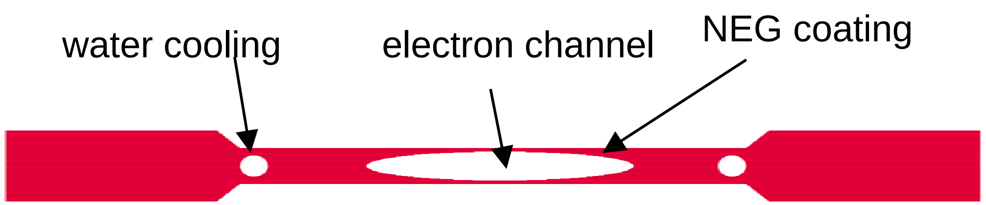
Int/ext gap = 5-7 mm, L =2.5 m

ST707 NEG strips

Activation @ 350-450°C

P. Den Hartog, et al., PAC 2001

E. Trakhtenberg,et al., PAC 2003



ESRF type Chamber

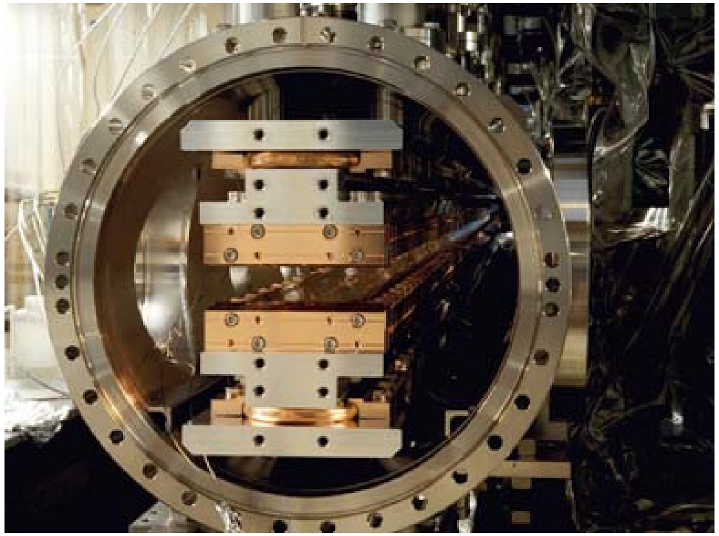
Int/ext gap = 8-10 mm , L=5 m

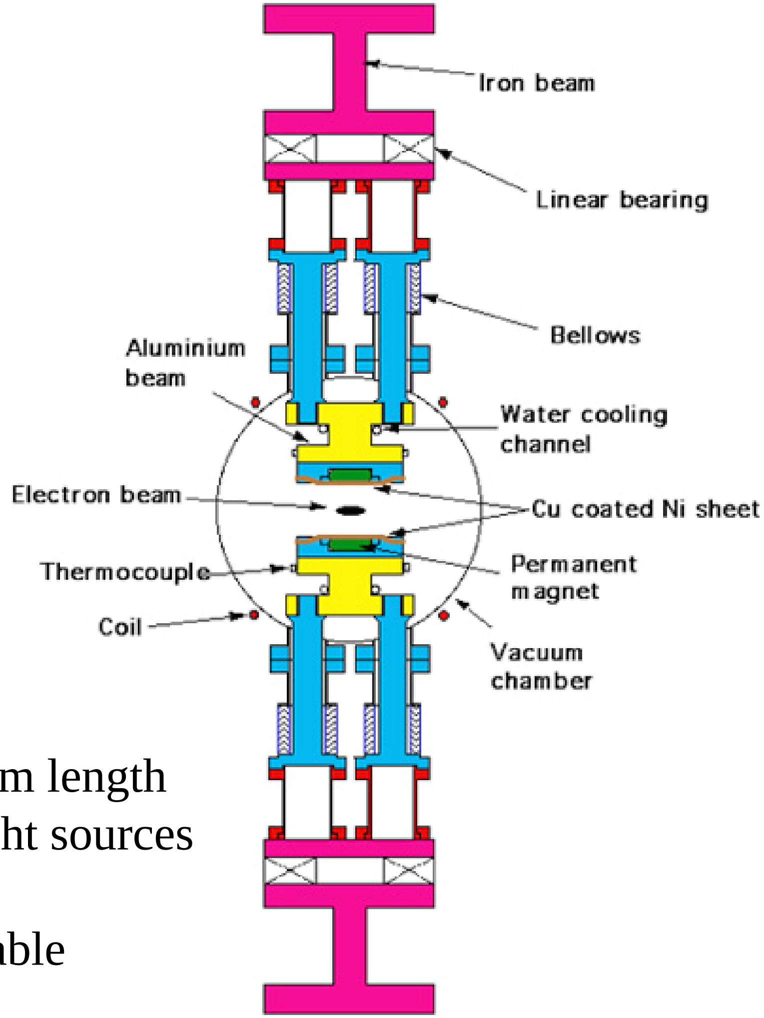
NEG Coating, Ti-Zr-V, 1 µm

Activation @ 200 °C.

R. Kersevan, EPAC 2002.

In-Vacuum Undulators

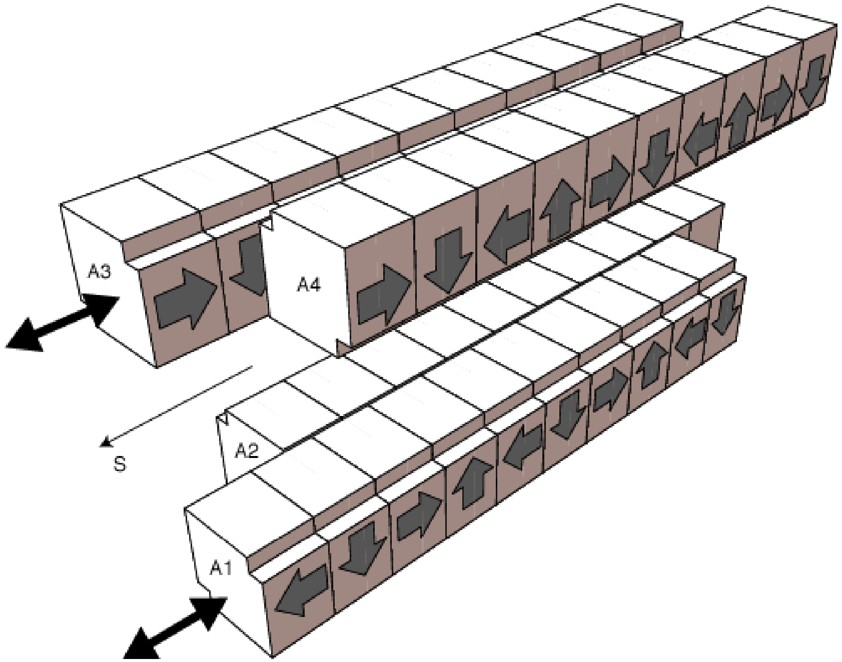


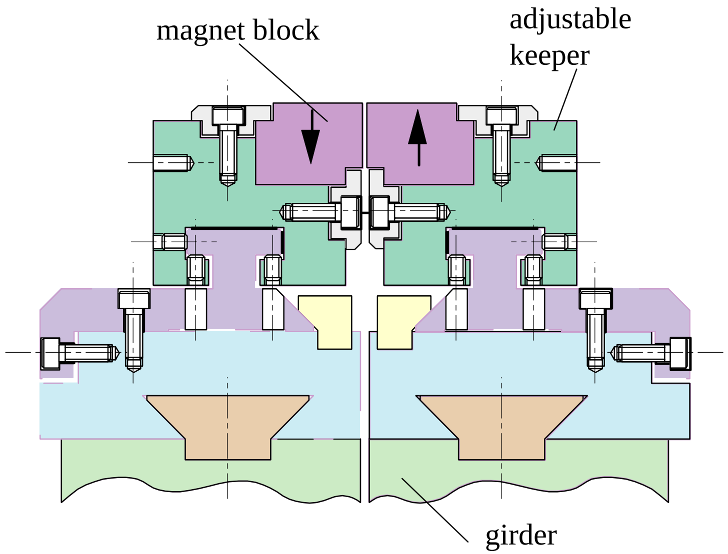


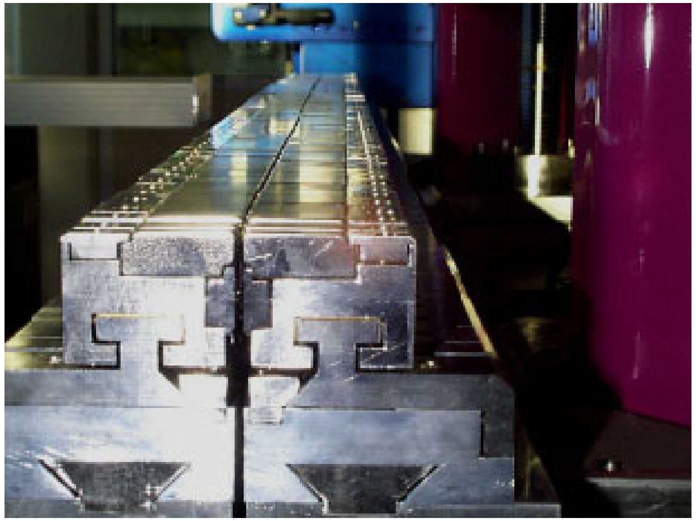
SPring-8 In-Vacuum Undulator

- Magnetic gap 3.3 mm (NSLS) for 0.4 m length
- Magnetic gap 5-6 mm (SPRING-8/ESRF) for 2-5 m length
- To be massively used by the new generation of light sources (SLS, SOLEIL, Diamond,…)
- The technology is mature and commercially available

Apple II Variable Polarization Undulator







Why so popular :
- High linear/helical magnetic field
- Generating any polarization (linear,elliptical,..)

Interact with the beam
- Lifetime, closed orbit, coupling,…
- Many degrees of freedom to correct
- Need careful field measurement & shimming

Contents

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Light Sources undergoing Major Upgrades

- In Development
  - ELETTRA (Full Energy Booster, Current)

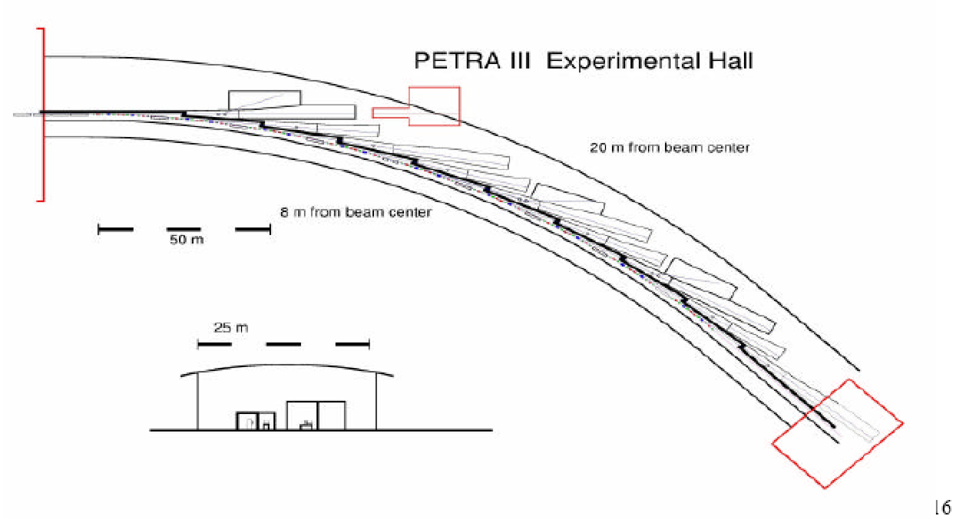
- In Project Stage
  - ALS
  - APS
  - PETRA
  - …

ALS Upgrade

- Upgrade Booster for full energy injection and topping-up
- Increase the average current from 270 => 750 mA
- Reduce the gap of Insertion Devices from 14 to 5 mm and generalize the use of Apple II Undulators, in-vacuum undulators and possibly superconducting undulators
- Increase the number of undulator beamlines using chicaned straight.
- ALS will gain competitiveness with respect to new up-to-date medium energy light sources at a modest cost

Petra III Upgrade

Perimeter : 2.3 km
Energy : 6 GeV
Full energy injection from DESY Synchrotron
Nominal Emittance : 4 nm
- 7/8 Will stay FODO type Lattice
    - New Vacuum Chambers
    - RF system Update
    - Additional Diagnostics and feedback
-1/8 Will be replaced by 10 cells DBA with 10x 5m Ids
-Space for 20 m Undulator



From K. Balewski, 10th ESLS Workshop, PSI, Nov 2002

Realize the benefit of Damping Wigglers

Damping wigglers

- $B = 1.5$ T
- $\lambda = 0.25$ m
- $h = 0.025$ m
- $L_{tot} = 80$ m (4 x 20m)

$\boxed{\varepsilon_x: 4 \rightarrow 1 \text{ nmrad}}$

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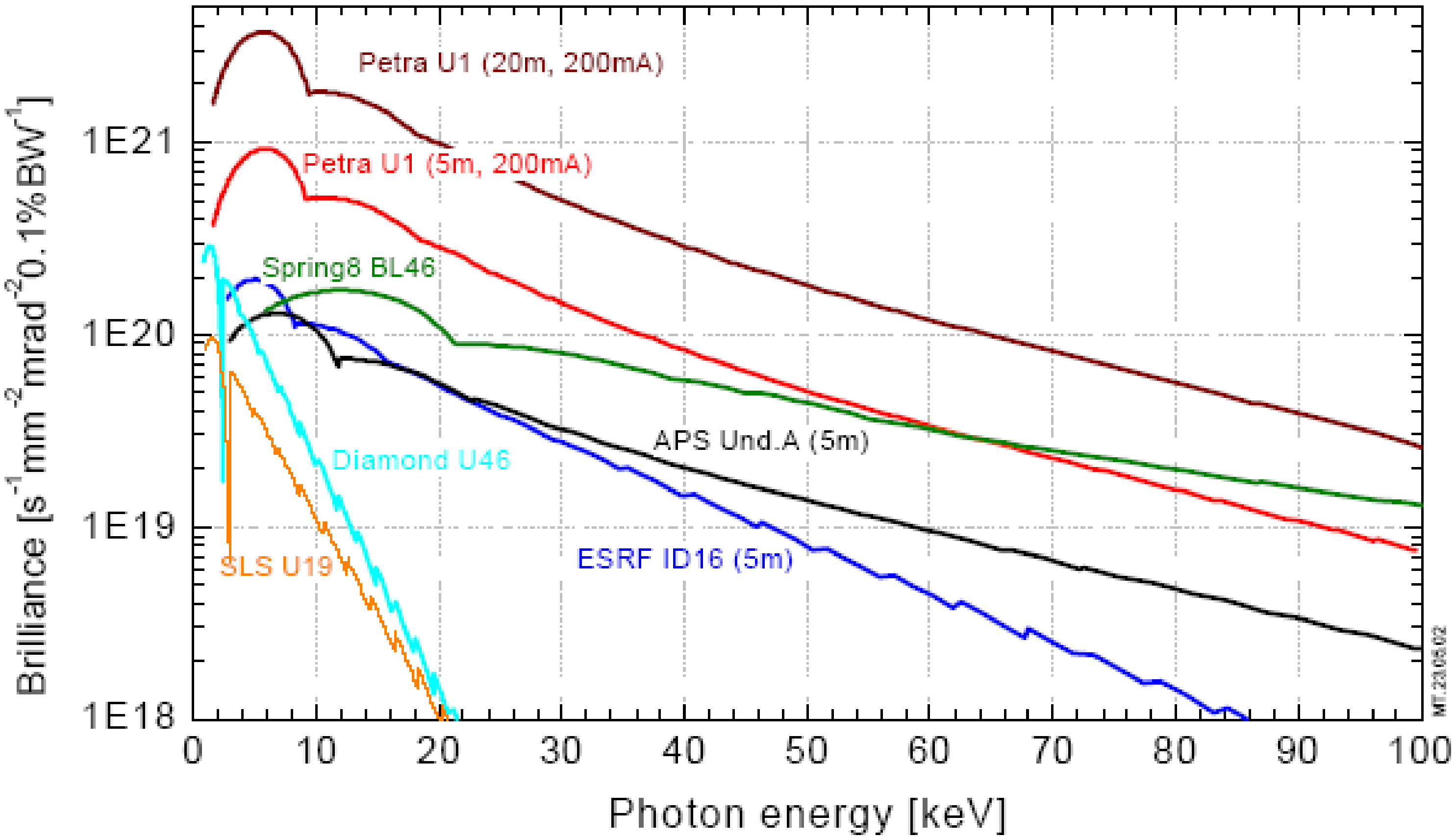
Two Benefits from Damping Wigglers :

-Lower emittance

-Higher ring current

From K. Balewski, 10^th ESLS Workshop, PSI, Nov 2002

Brilliance



Scheduled Operation in 2008

From K. Balewski, 10th ESLS Workshop, PSI, Nov 2002

Contents

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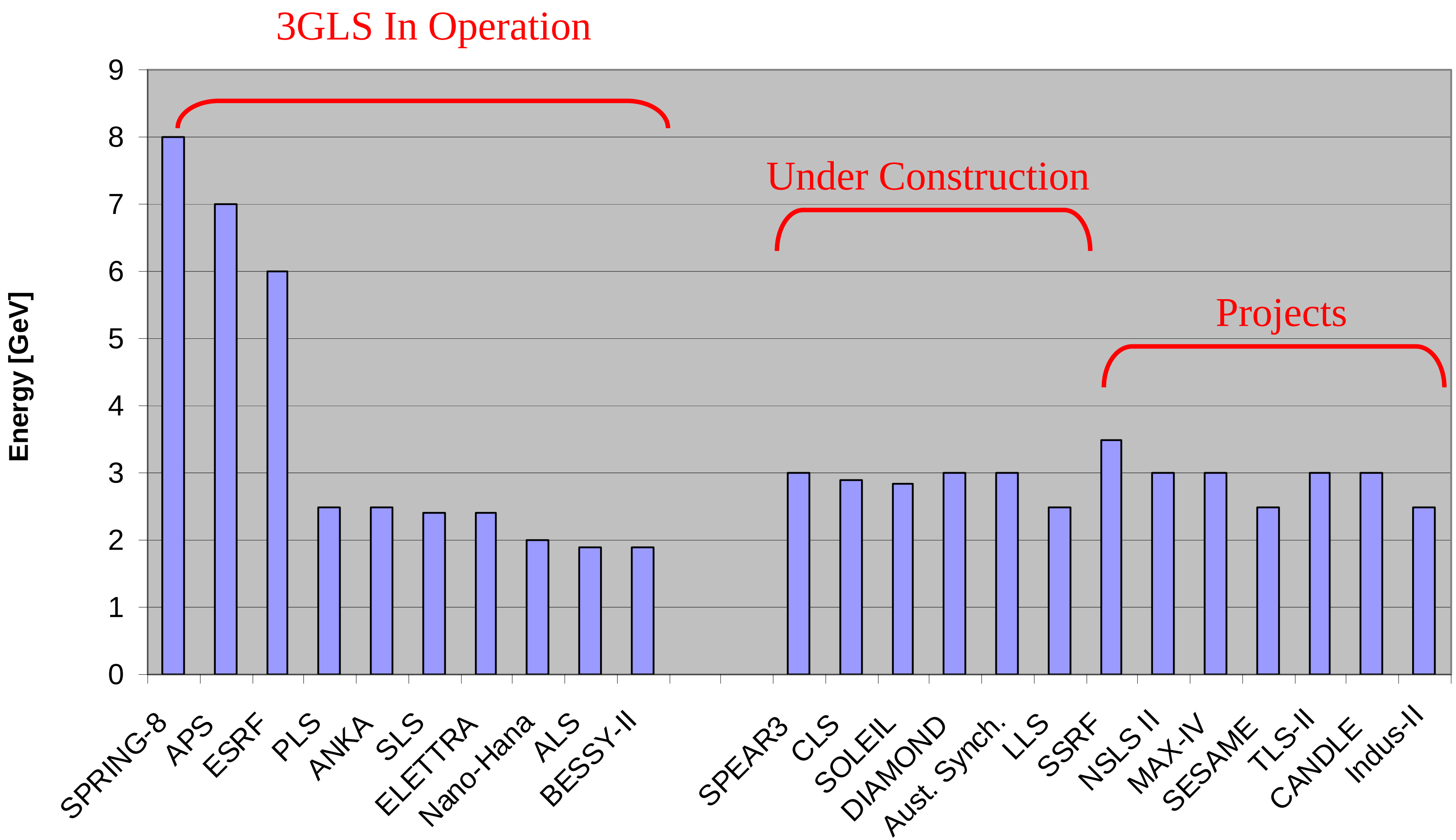
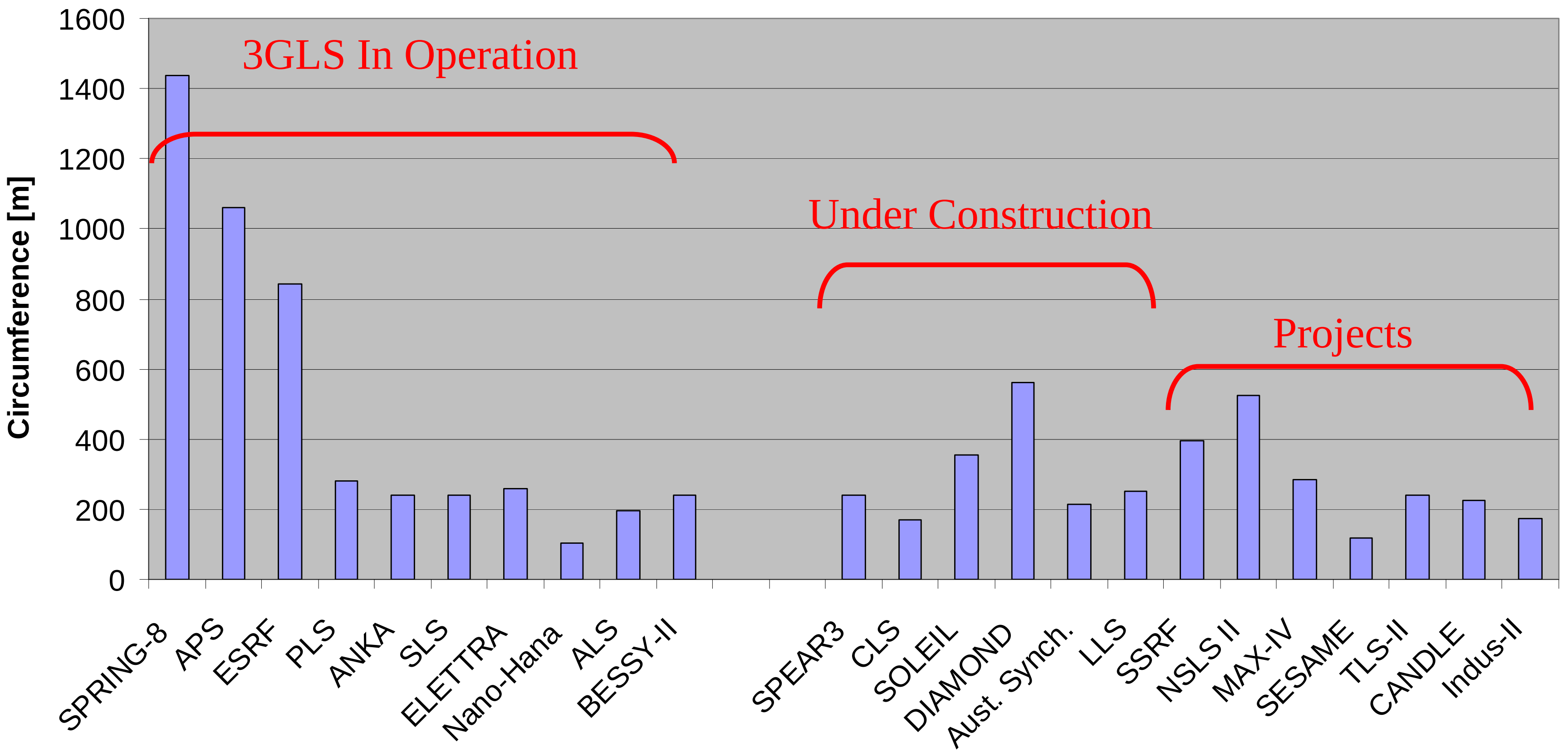
New Sources

Name	Energy [GeV]	Perim. [m]	Current [mA]	Emittance [nm]	N.Straight	Lattice	Scheduled Commissioning
SPEAR3	3	240	500	18	18	DBA	2003
CLS	2.9	171	500	18	12	DBA	2003
SOLEIL	2.85	354	500	3.1	16+8	DBA	2005
DIAMOND	3	560	300	2.7	24	DBA	2005
Aust. Synch.	3	216	200	8.6	14	DBA	2007
LLS*	2.5	252	250	8.5	12	TBA	
SSRF	3.5	396	300	4.8	20	DBA	
NSLS II	3	523	500	1.5	24	TBA	
MAX-IV	3	285	500	1.2	12	7 BA	
SESAME	2.5	120	400	27	16	DBA	
TLS-II	3	240	400	10	16	DBA	
CANDLE	3	224	350	8.4	16	DBA	
Indus-II	2.5	173	300	58	8	DBA	

* To be revised


3GLS In Operation
Under Construction
Projects
Energy [GeV]
0
1
2
3
4
5
6
7
8
9
SPRING-8
APS
ESRF
PLS
ANKA
SLS
ELETTRA
Nano-Hana
ALS
BESSY-II
SPEAR3
CLS
SOLEIL
DIAMOND
Aust. Synch.
LLS
SSRF
NSLS II
MAX-IV
SESAME
TLS-II
CANDLE
Indus-II

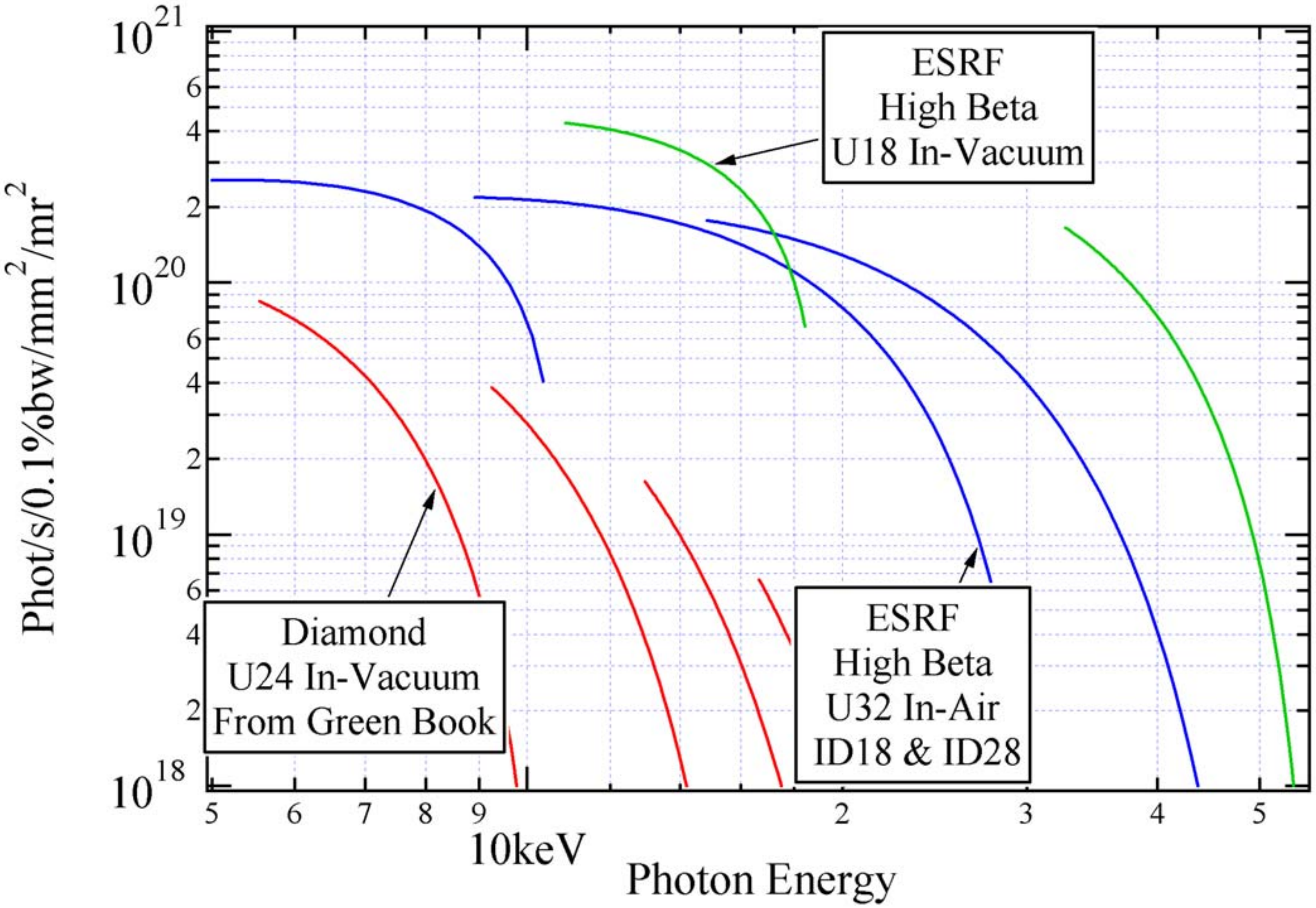

1600
1400
1200
1000
800
600
400
200
0
Circumference [m]
3GLS In Operation
Under Construction
Projects
SPRING-8
APS
ESRF
PLS
ANKA
SLS
ELETTRA
Nano-Hana
ALS
BESSY-II
SPEAR3
CLS
SOLEIL
DIAMOND
Aust. Synch.
LLS
SSRF
NSLS II
MAX-IV
SESAME
TLS-II
CANDLE
Indus-II

Features of Intermediat Energy Light Sources

- Cost Effective
  - Will compete with the 6-8 GeV sources at reduced cost
- Use the latest Insertion Device technology to reach 12.8 keV (Protein Crystallography)
  - In-vacuum Undulators with gap of 4-5 mm on a high harmonic number
  - Superconducting multipole Wigglers
  - Possibly superconducting undulators
- Use full energy injector with topping-up
- Use a high current around 500 mA
- Avoid the HOM driven coupled bunch instability using :
  - Superconducting RF (CLS, DIAMOND,SOLEIL,NSLS-II)
  - Heavy HOM damped (SPEAR3)
  - Low Frequency RF (MAX-IV)

See : Shangai Symposium on Intermediate Energy Light Sources, Sept 2001 http://ssils.ssrc.ac.cn/

Diamond vs ESRF



How to produce High Photon Energy from Low Electron Energy ?

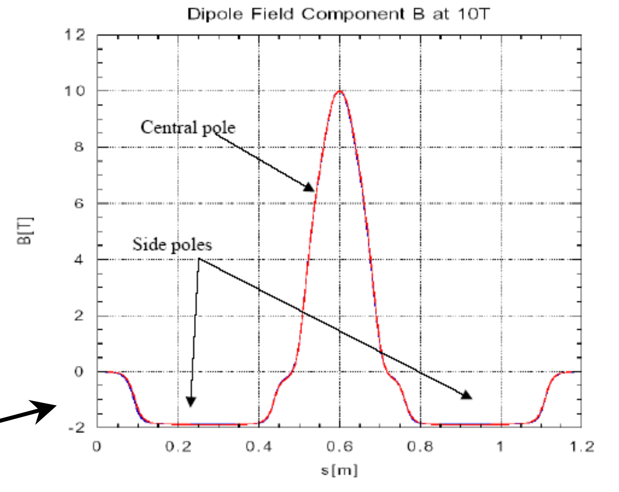
- Answer :

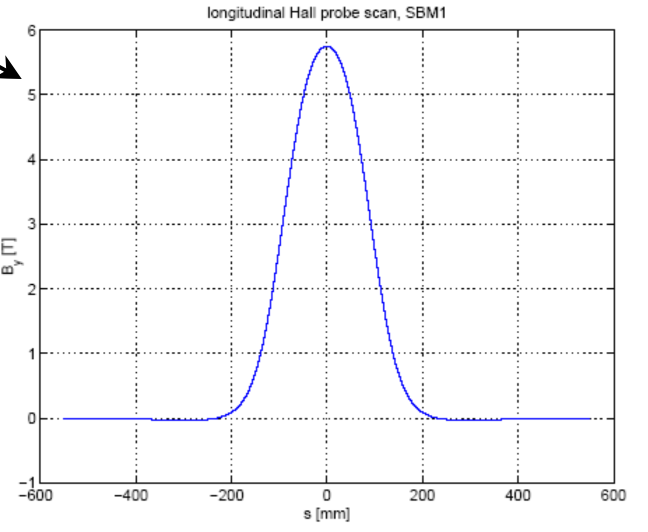
  Superconducting Magnet Technology

  - Wavelength Shifter or Superbend
  - Superconducting Multipole Wigglers
  - Superconducting Undulators

Recent SuperBend and Wavelength Shifters

	Year	Type	Field [T]
PLS	1995	Shifter	7.5
LSU-CAMD	1998	Shifter	7
BESSY	2000	Shifter	7
SPRING-8	2000	Shifter	10
SRRC	2001	Shifter	6
ALS	2002	SuperBend	5
BESSY	??	SuperBend	9





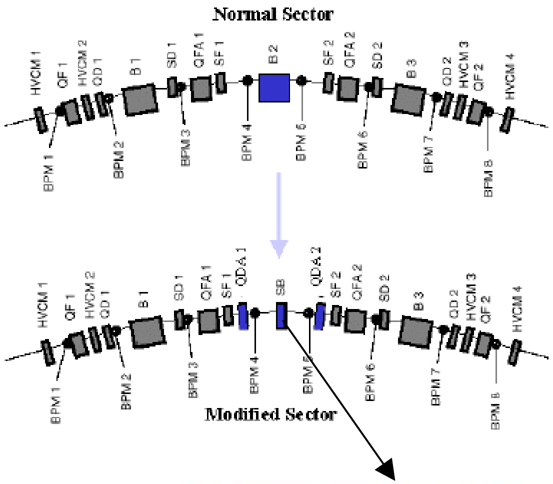
Wavelength shifter

- Requires a straight section
- Can be turned off

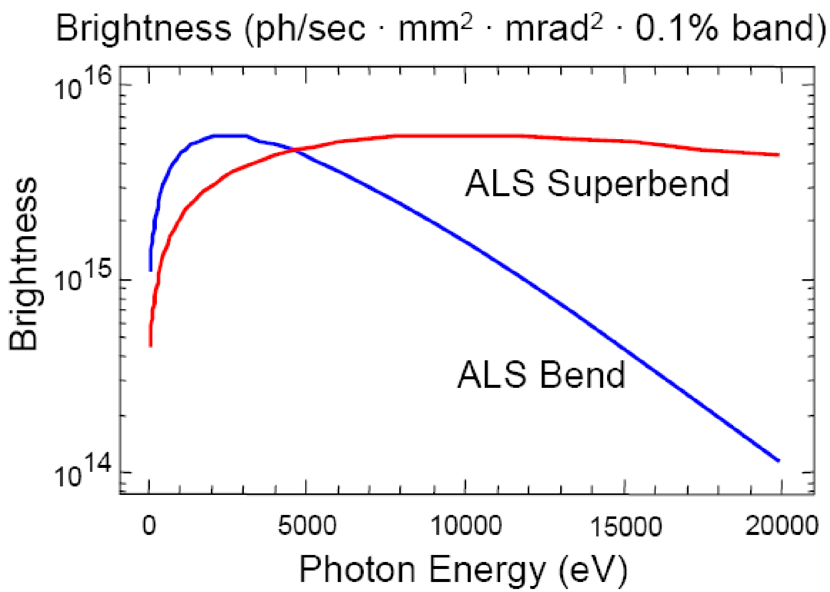
Superbend

- Strongly interacts with beam dynamics
- Needs to be distributed along circumference
- Increases emittance
- Save Straight Section

ALS SuperBend



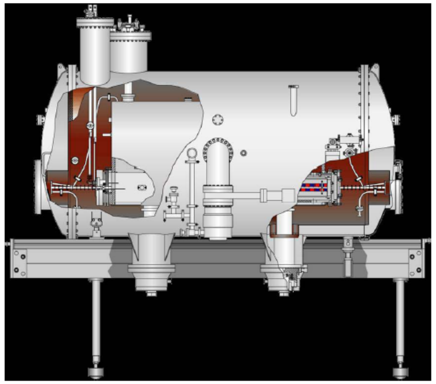
Field : 1.3 T => 5 T
Multiple beamlines



D. Robin et al. EPAC 02

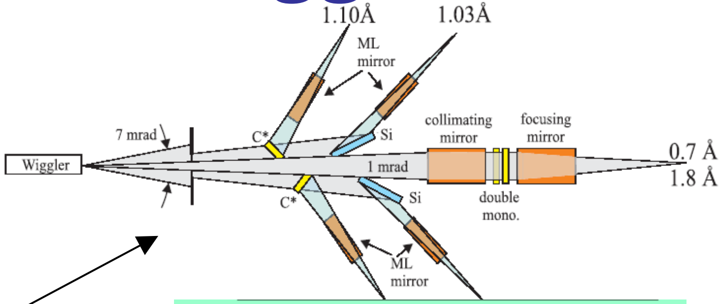
Superconducting Multipole Wigglers

	Year	Field [T]	Period [mm]	N. of Poles	Magnetic Gap [mm]
DELTA	1996	5.5 2.75	288 144	5 10	18
BESSY-HMI	2002	7	148	17	19
ELETTRA	2002	3.5	64	49	16.5
Max Lab	2002	3.5	61	48	12

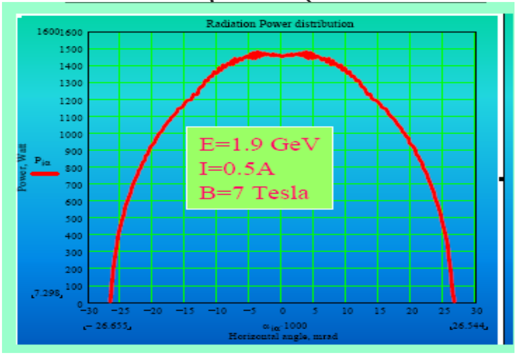


Short Period => Small gap =>
Cold or Semi-cold Bore

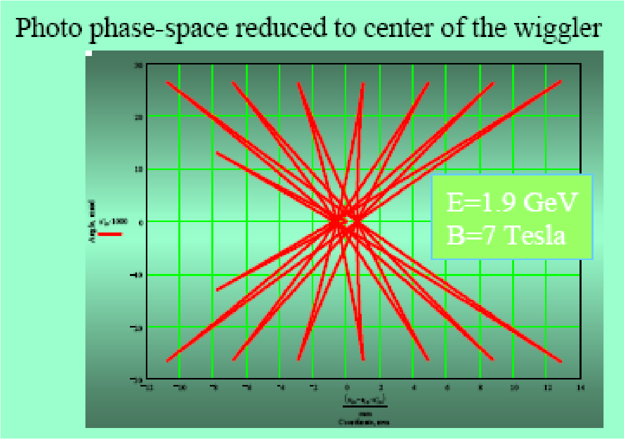
Benefits of Multipole Wigglers



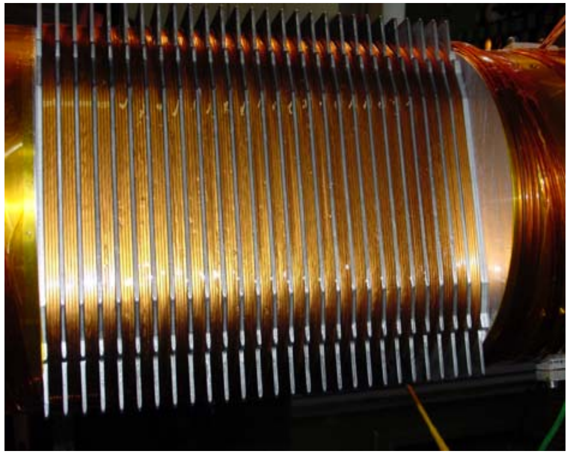
- Advantages
  - Large Horizontal angle => Multiple beamlines => cost effective

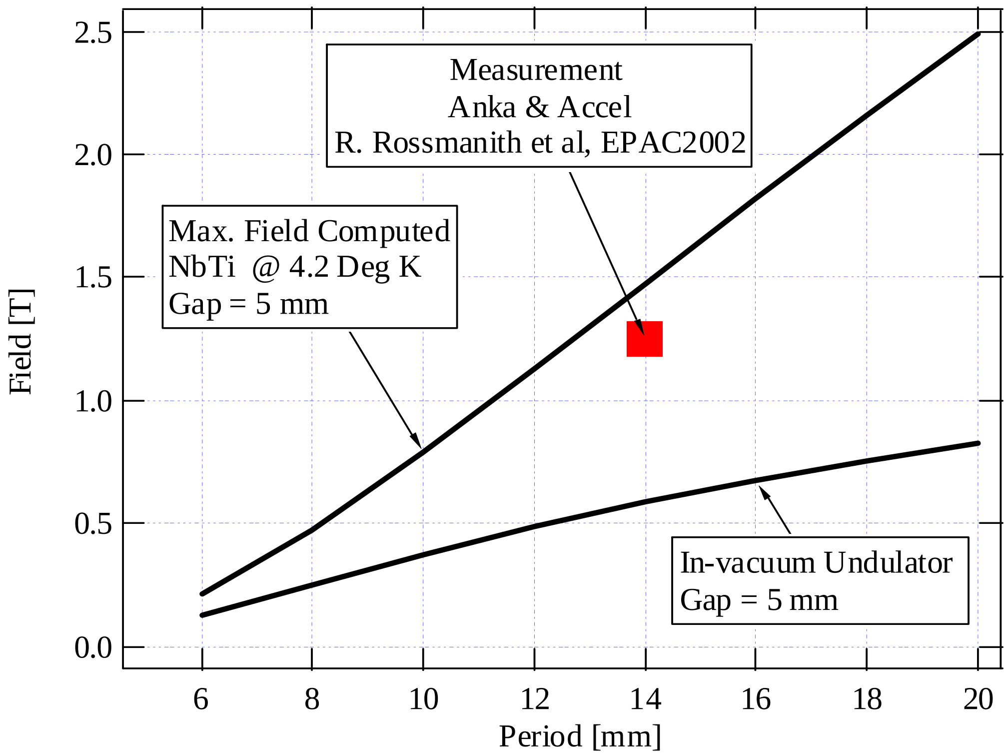


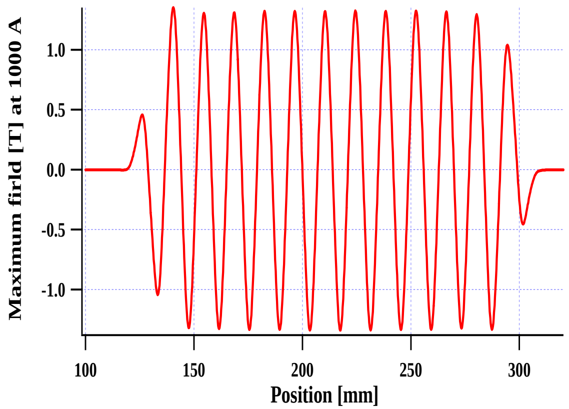
- Drawbacks
  - Multiple source points => undesirable if focusing is required
  - High Power (-> 60 kW)



NbTi Superconducting Undulators (Anka-Accel)





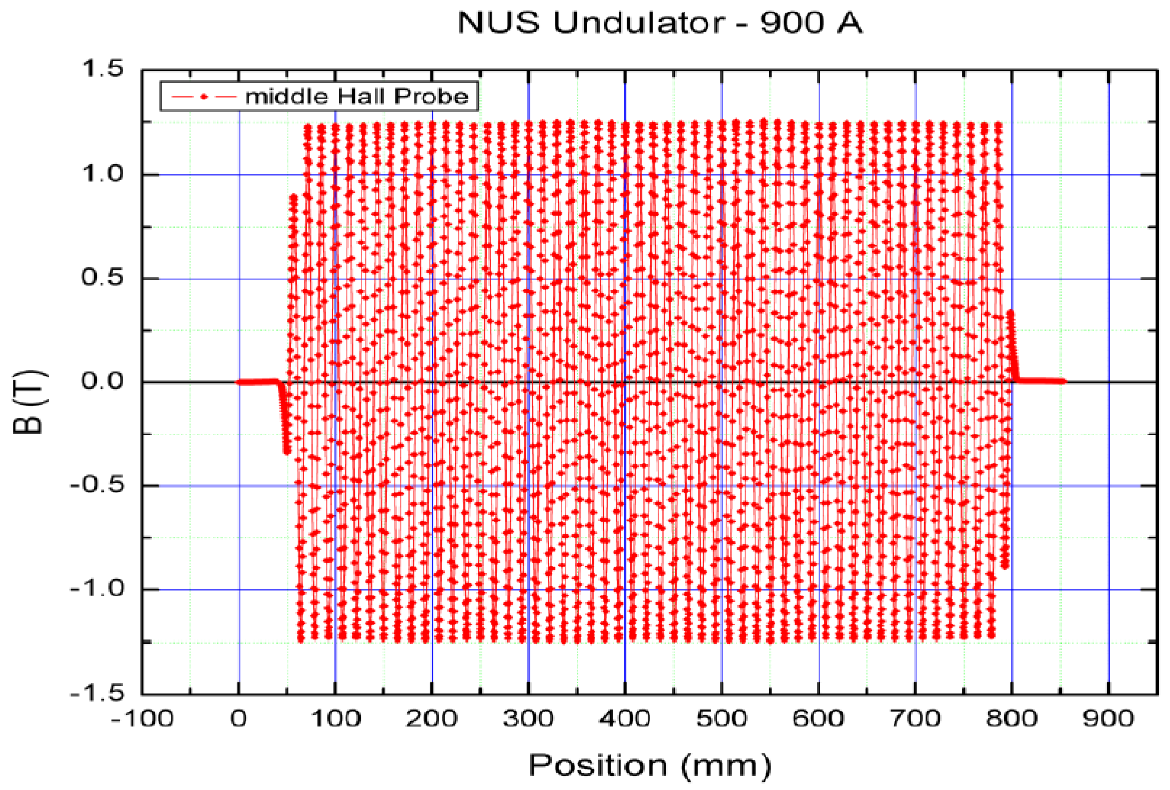


Shift the Undulator Spectrum to Higher Energies

R. Rossmanith et al. EPAC 02

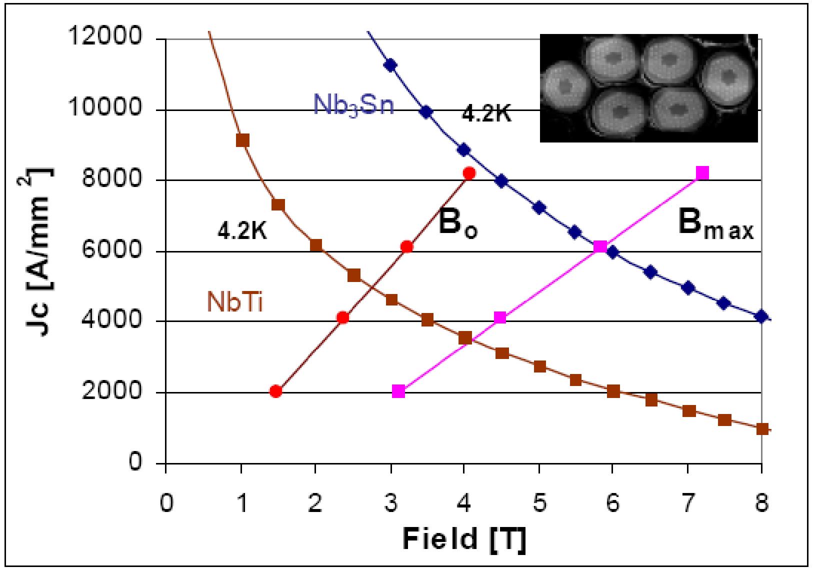
SSLS Undulator from ACCEL

Period = 14 mm
N. of Period = 50
Gap = 5 mm



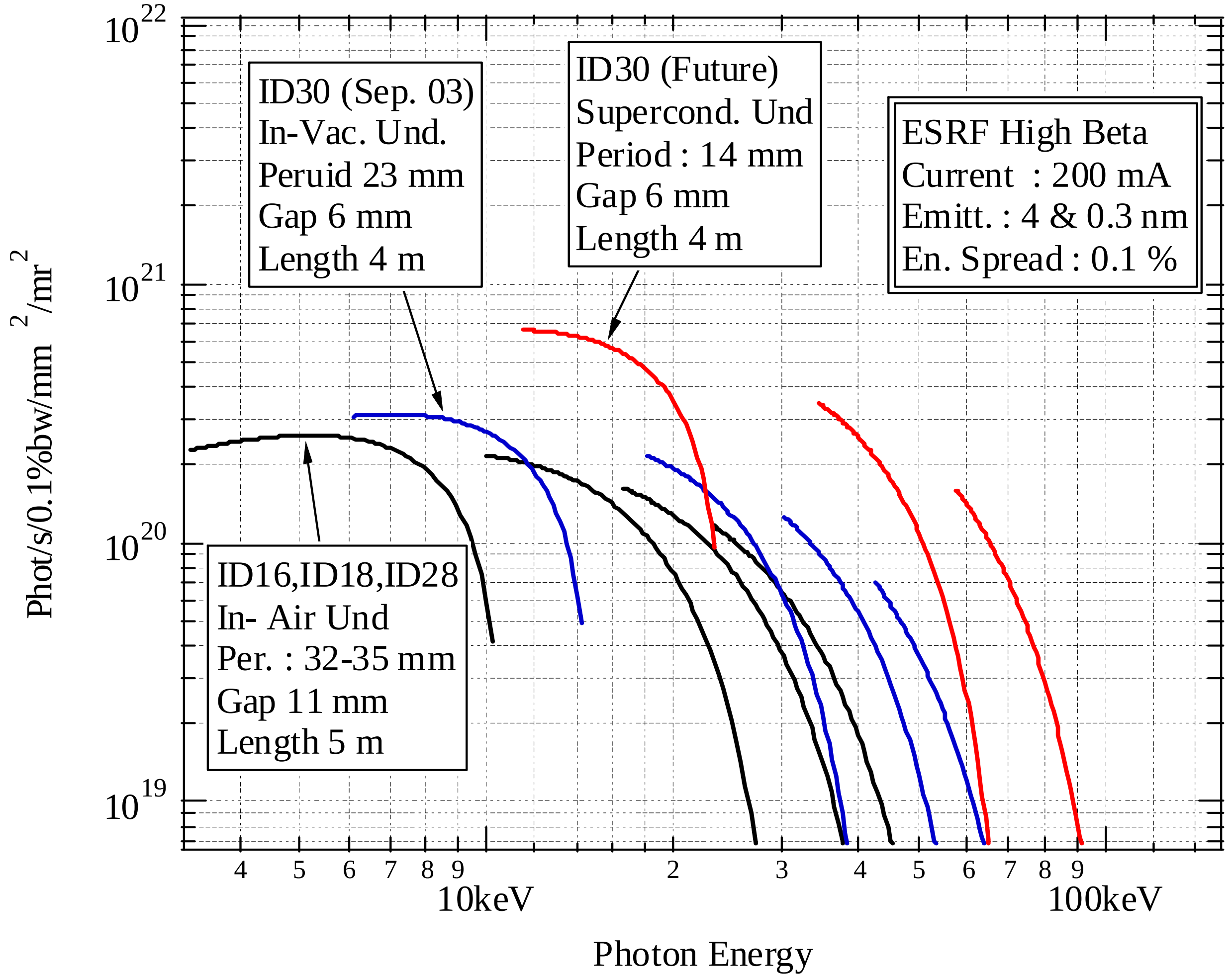
S.kubsky et al. Workshop on Superconducting Ids, ESRF June 30th, 2003

Nb_3Sn Superconducting Undulators (LBNL)

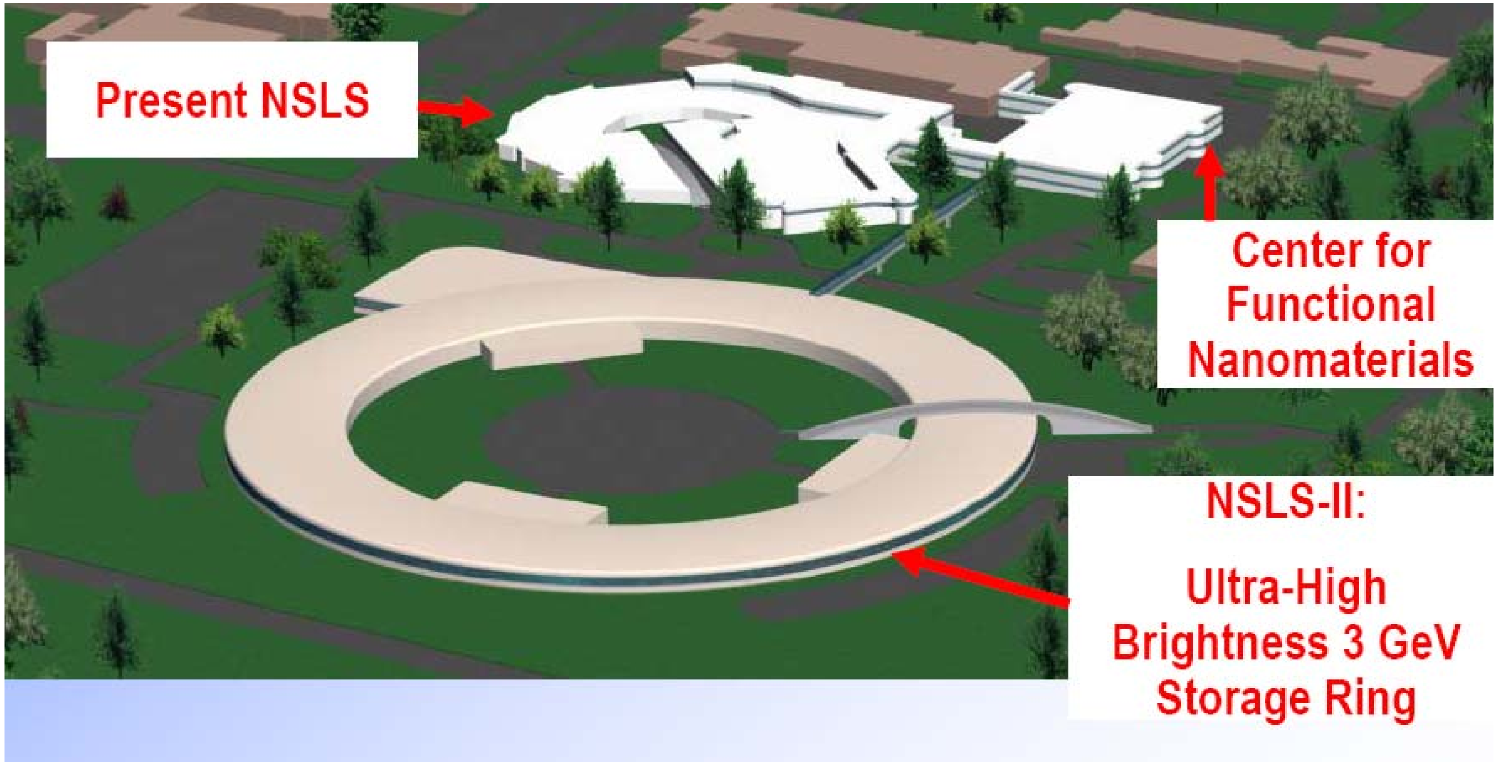


S. Prestemon et al., Workshop on Superconducting Ids, ESRF 30th June, 2003

Brilliance of Superconducting Undulators on the ESRF



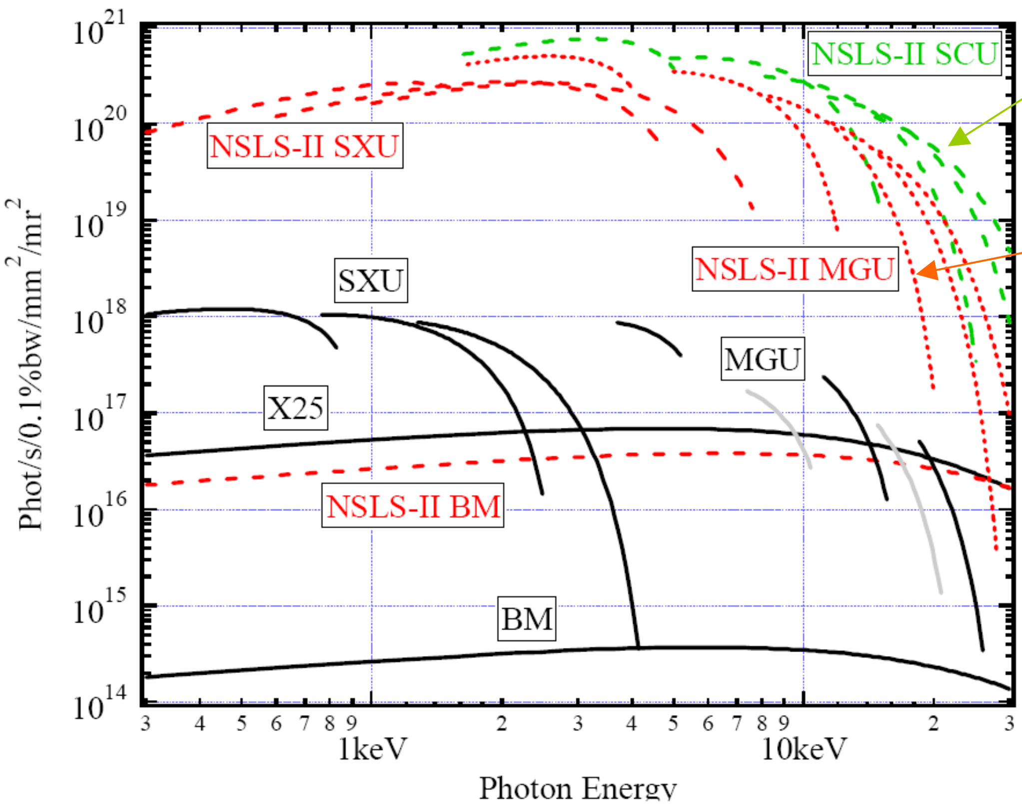
NSLS II



Energy : 3 GeV
Circumference : 523 m
Lattice : 24 x TBA
Emittance : 1.5 nm
Current : 0.5 A
RF System : 500 Mhz SC

From B. Podobedov et al., PAC03

NSLS II Brilliance



Superconducting Undulator

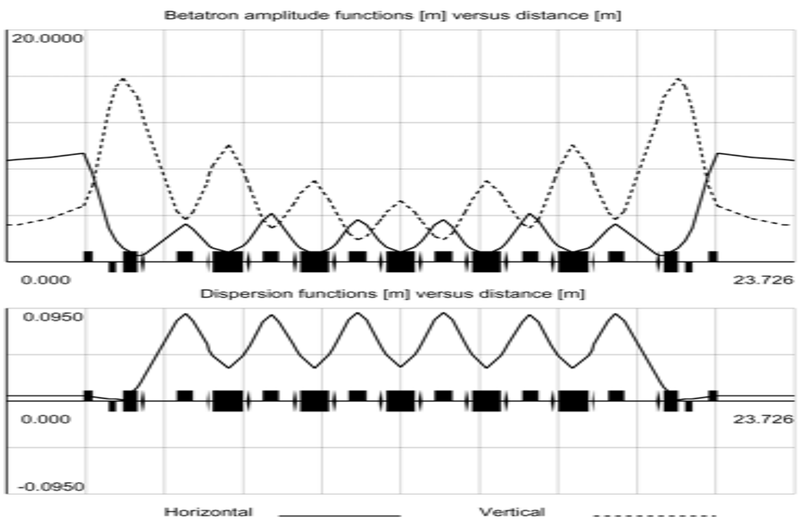
In-vacuum Permanent Magnet Undulator

From B. Podobedov et al., PAC03

MAX -IV Project

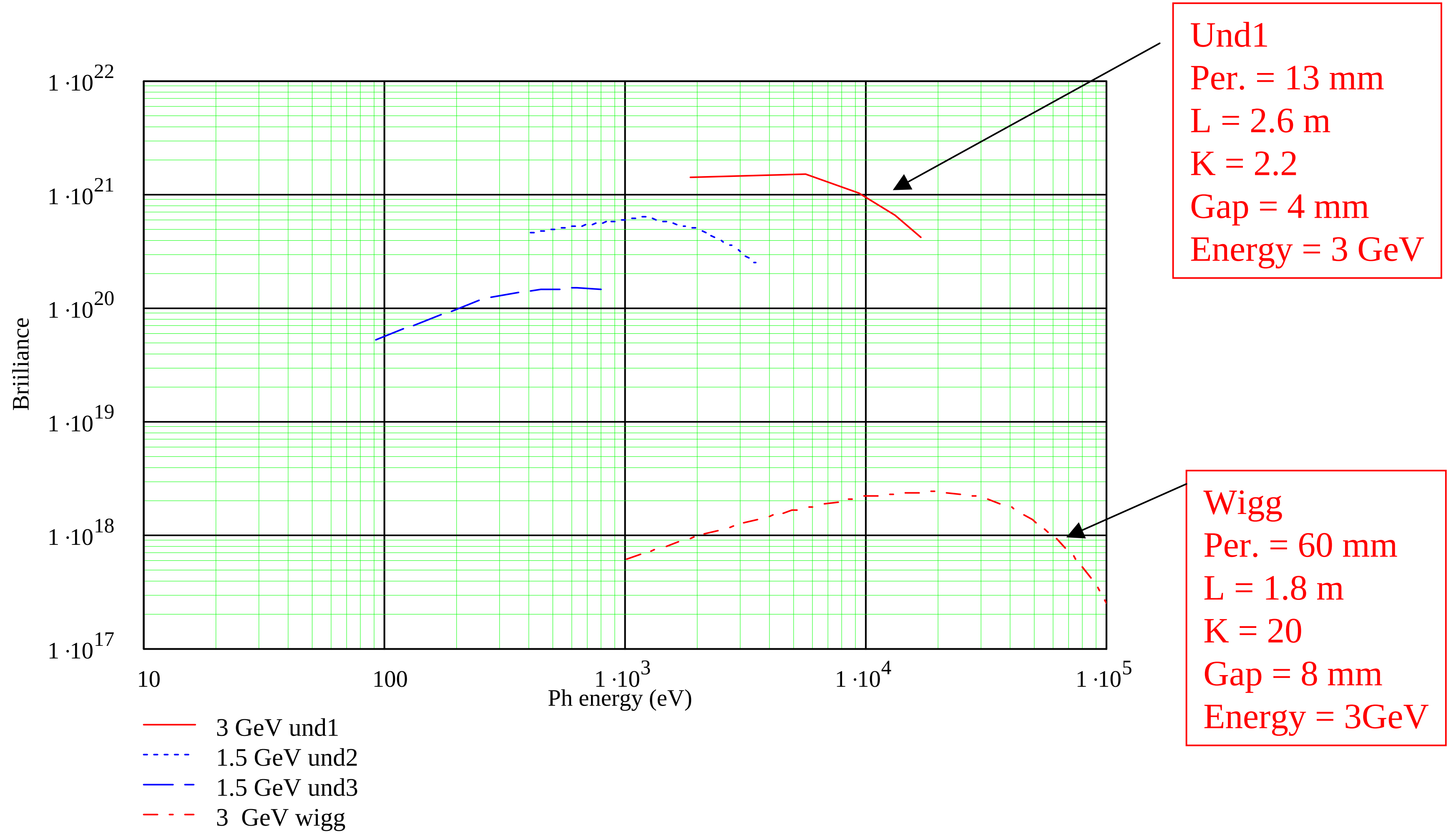
Perimeter	285 m	285 m
Energy [GeV]	3	1.5
Current [A]	0.5	0.5
Emittance [nm]	1.2	0.3
N. of Straight	12	12
RF Frequency [Mhz]	100 +500	100 +500
Lifetime [h]	22	23

-Two Rings in Tunnel for Hard and Soft X-ray
-Heavy use of Combined Function Magnets
-7 Bend Achromat
-Full Energy Injector S-Band Linac
- Ring Injector
- SASE FEL
- Multistage HGHG



From G. LeBlanc et al., PAC03,
& M. Eriksson et al. , SRI2003

Max-IV Superconducting Undulators



Brilliance curves for a set of IDs in the MAX IV rings

From M. Eriksson et al., SRI2003

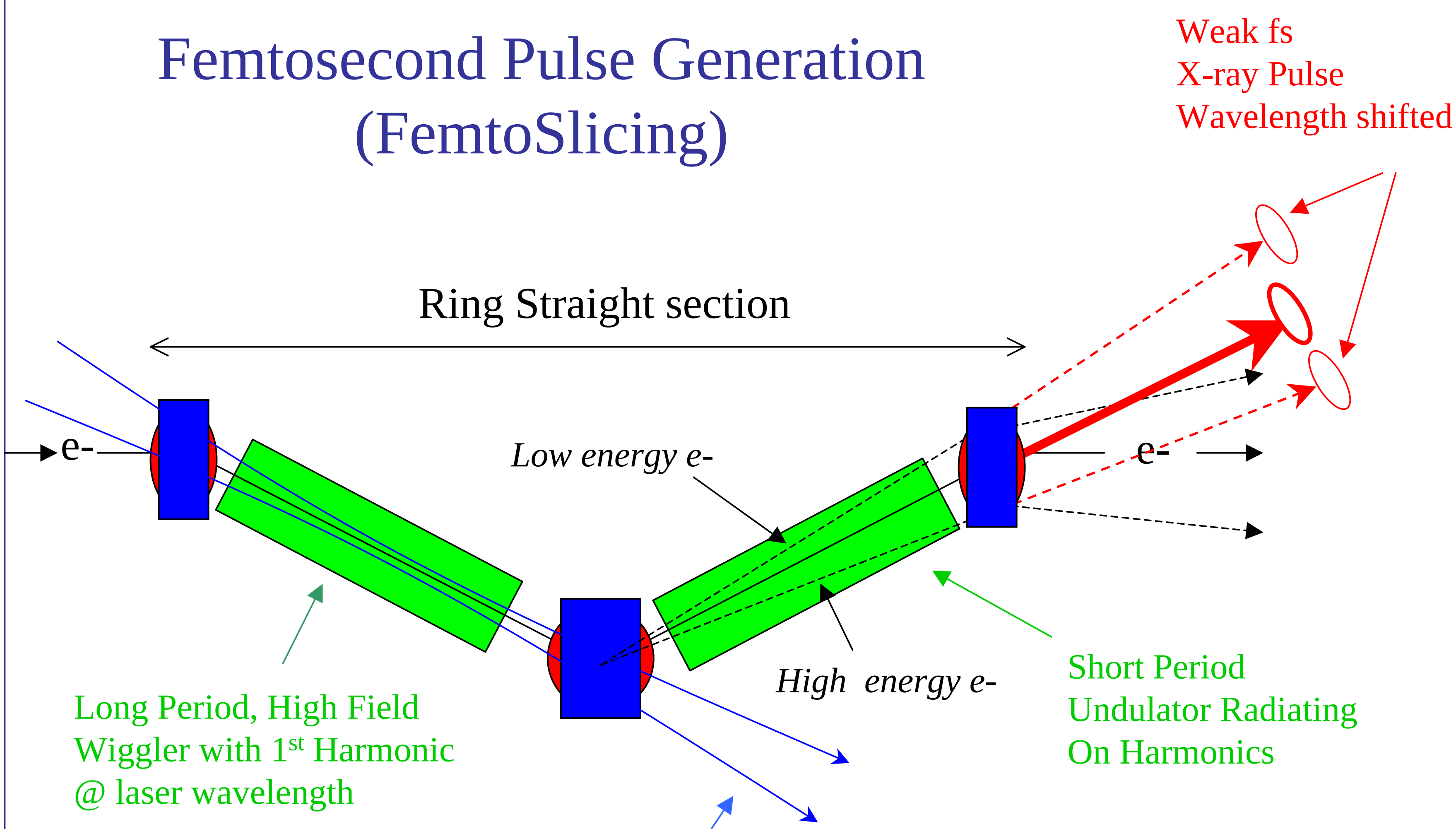
Contents

- State of the Art
- New Facities
  - Upgrade of existing rings
  - Intermediate-energy rings
  - Ambitious Studies

Direction of Further Improvements

- Femtoslicing
- Ring current x 2-3
- Reduce the horizontal emittance

Femtosecond Pulse Generation (FemtoSlicing)



Short Period
Undulator Radiating
On Harmonics

Long Period, High Field
Wiggler with 1st Harmonic
@ laser wavelength

$$\lambda_{Laser} = \frac{\lambda_0}{2\gamma^2}(1+\frac{K^2}{2})$$

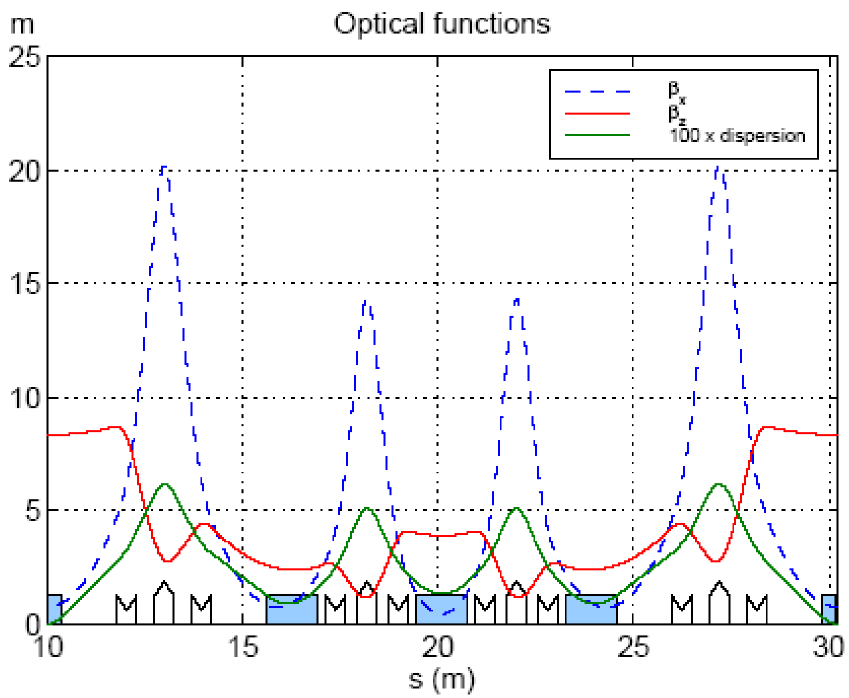
Ti:sapphire Laser
30-50 fs , 1-10 kHz
800 nm 2-5 mJ,
=> 1% energy mdulation

Experiments Prepared at
ALS, SLS, BESSY

Challenges of Femtoslicing

- The fs pulses of X-rays are weak,
  - Spectral Flux in fs slice ~ 10^7- 10^5 ph/s/.1%
  - Total Spectral Flux ~ 10^{15}- 10^{13} ph/s/.1%
- The transverse profile in the tail of the central cone must be as steep as possible to discriminate the very weak pulse.
  - Requires many period undulator of high quality
  - Possible pollution by adjacent bending magnet radiation.
- Separation of the short X-ray pulse from the main one requires the combination of :
  - Angular or spatial filtering
  - Wavelength filtering
  - Time triggering
- Sufficient energy modulation calls for high power laser and low electron energy. All experimental investigations envisaged in the near future will be carried out on intermediate energy storage rings (1.9 – 2.4 GeV)
- The laser must have a high peak power and be tightly focused into the wiggler with perfect overlap with the electron beam.

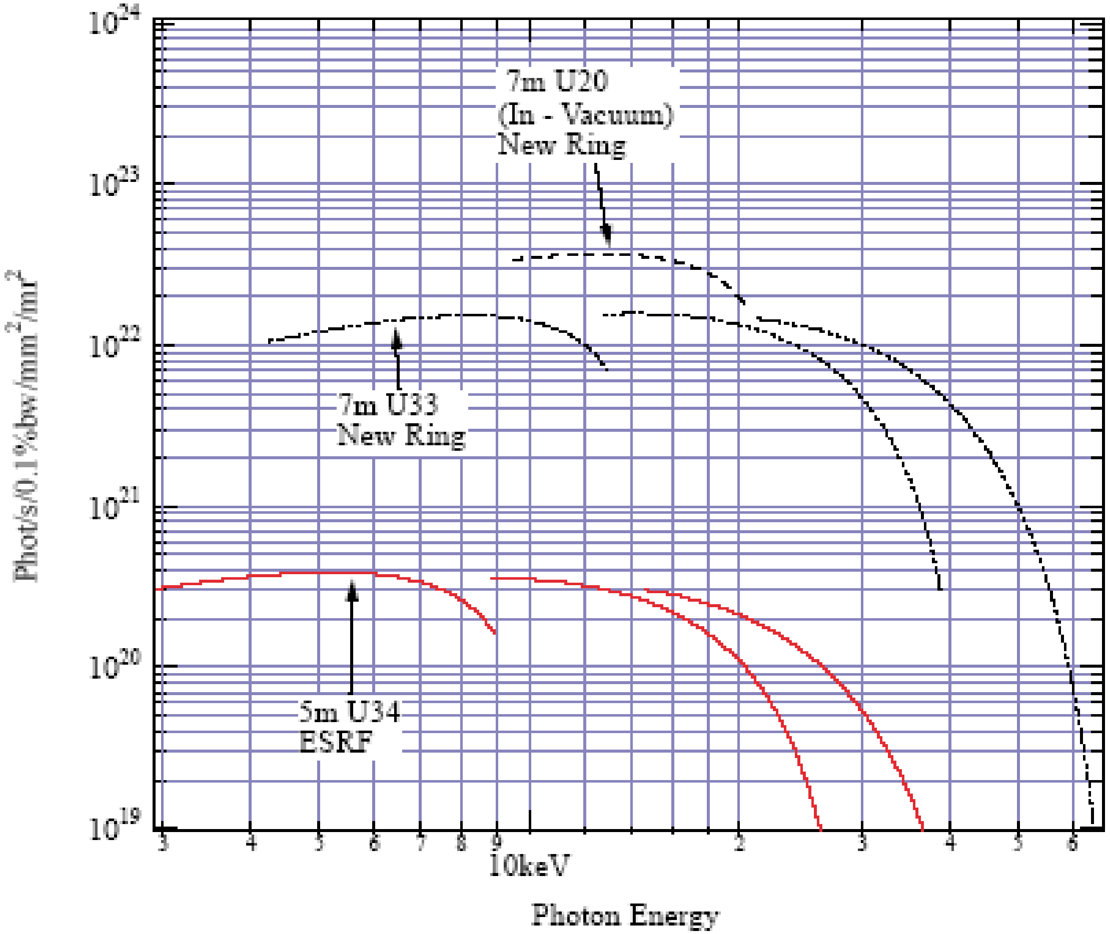
Ultimate X-Ray Source (ESRF study)



From A. Ropert et al., EPAC-2000

Energy [GeV]	7
Current [mA]	500
Emittances [nm]	0.2 / 0.008
Perimeter [km]	2
Number of Cell	50
Lattice type	4 Bend Achromat
ID length [m]	7
ID Power [kW]	55
Brilliance @ 0.1 nm	1.5 – 4 10^{22}

Brilliance of the Ultimate X-Ray Source



From A. Ropert et al., EPAC-2000

Heat Load issue in the Ultimate X-Ray Source

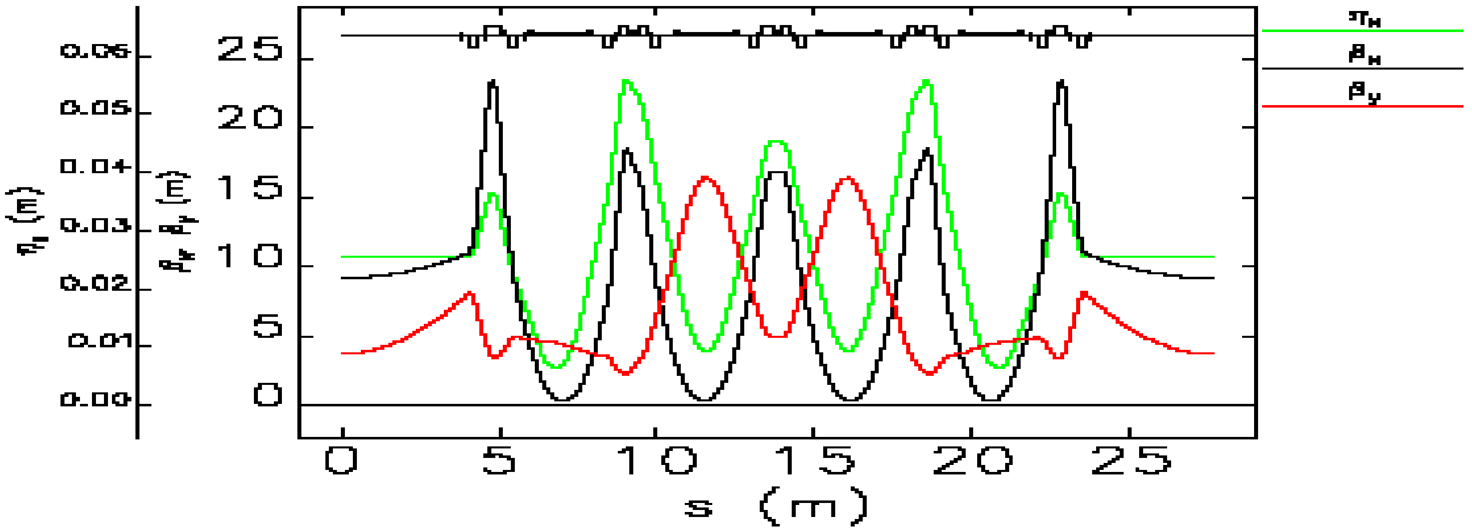
Table 1: Comparison of power and brilliance from undulators on ESRF, SPRING8 and USRLS

	ESRF	SPRING-8	USRLS	USRLS
Energy [GeV]	6	8	7	7
Current [A]	0.2	0.1	0.5	0.5
Und. Period. [mm]	34	32	33	20
Und. Length [m]	5	25	7	7
Und. Gap [mm]	11	12	11	6
Power [kW]	13	38	53	55
P. Cone [kW]	0.4	1.5	0.65	1.1
$4\sigma_x$ * $4\sigma_z$ [mm^2]	2 x 0 .5	3.8 x 0.5	1 x 0.8	2 x 0.8
Flux @ 1 Å [ph/s/.1%]	2.0 x 10^{15}	9.0 x 10^{15}	6.5 x 10^{15}	1.7 x 10^{16}
Brilliance @ 1 Å [ph/s/.1%/mm^2/mr^2]	2.9 x 10^{20}	6.7 x 10^{20}	1.5 x 10^{22}	3.7 x 10^{22}

Power in Central Cone is still acceptable

From A. Ropert et al., EPAC-2000

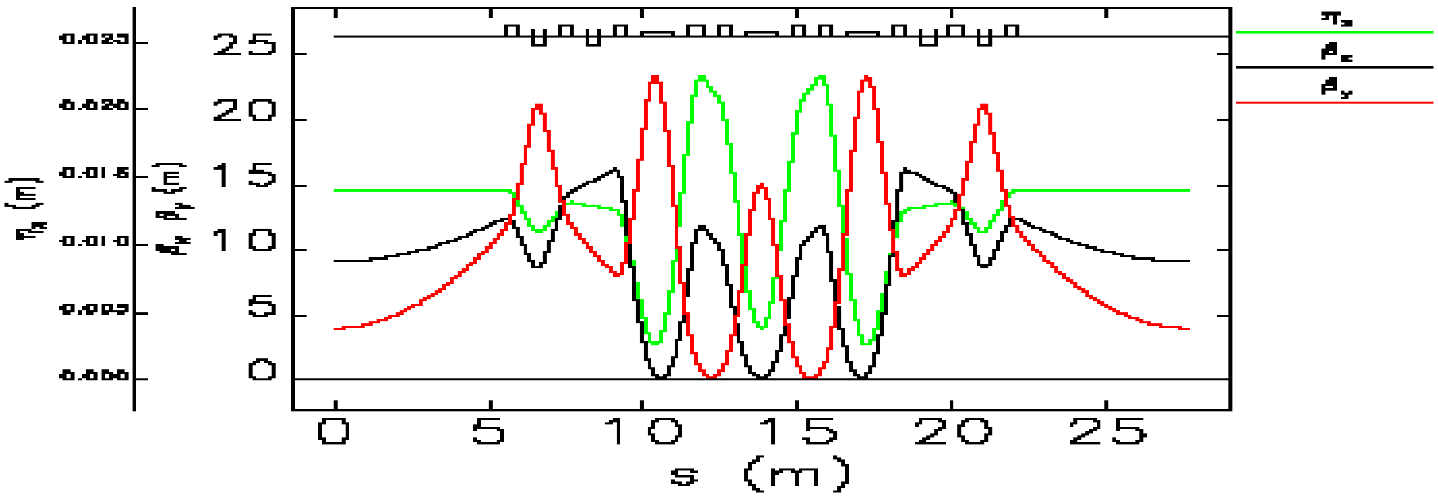
APS Upgrade Studies



7 GeV, Same circumference as the present APS, Ncell=40
4 Bending magnet/achromat with constant field dipoles
Horiz Emittance ~ 0.3 nm

From L. Emery, M. Borland, PAC03

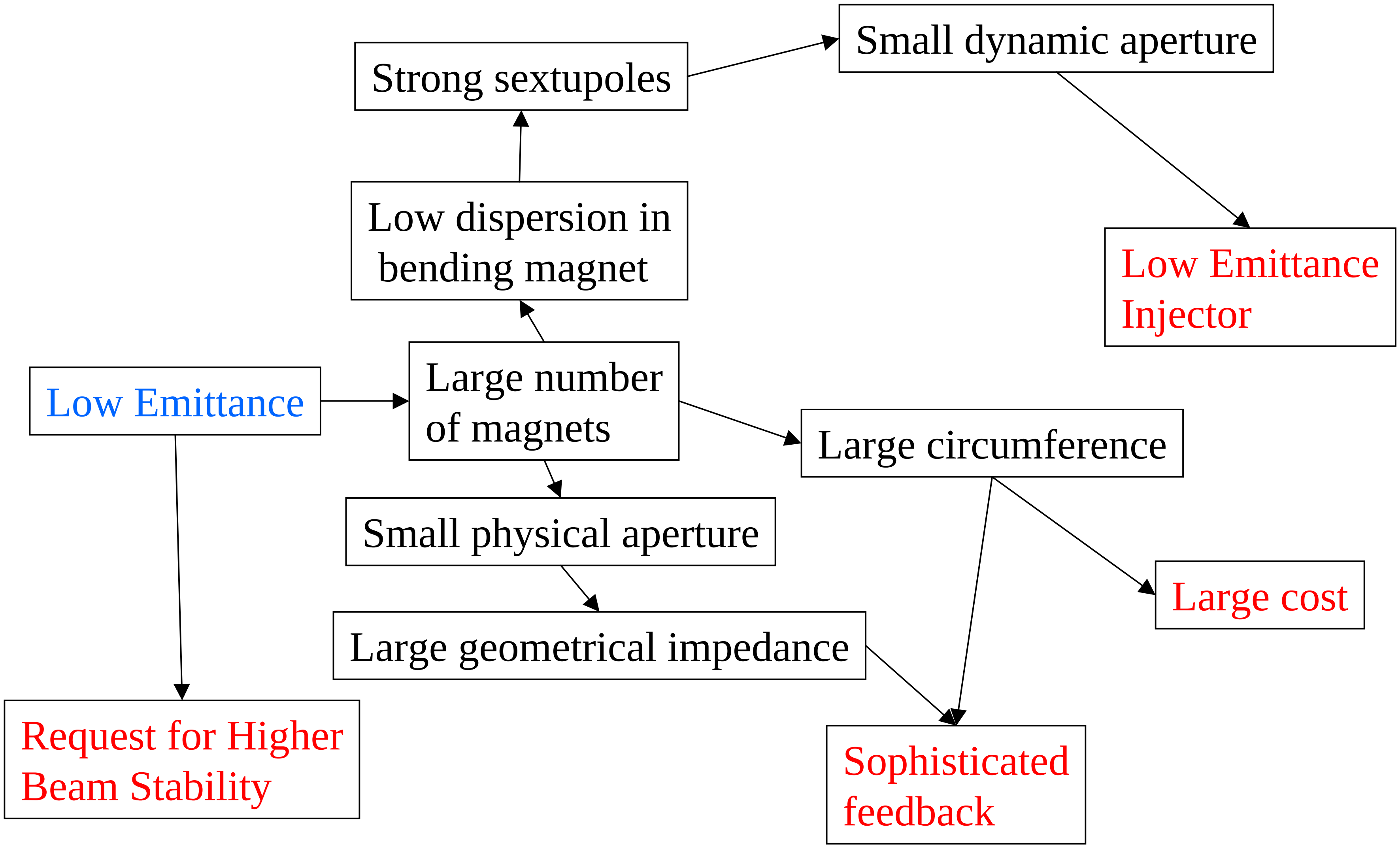
eXtreme Photon Source (APS)



7 GeV, Same circumference as the present APS, Ncell=40
Triple Bend Achromat with High Gradient in Dipole
Combined Function Magnets (dipole+quad+sext) made of Permanent Magnet
Horiz Emittance ~ 0.075 nm
Dynamic aperture without errors ~ 0.8 mm !
=> Classical injection schemes do not work !

From L. Emery, M. Borland, PAC03

Challenges in ultra-small emittance rings



Conclusions

- The highly successful Third Generation Light Sources (3GLS) based on storage rings have generated a tremendous advance in many domains of Science

- The 3GLS technology is mature and one cannot expect many orders of magnitude in improvements over the coming years. However technological improvements will continue world wide.

- In relation to SASE and ERL type sources, it is generally believed that :
  – 3GLS will not be replaced (but rather complemented) by the new type of SASE or ERL type sources really optimised for ultra-short pulses
  – The extremely high average brilliance, stability (position and intensity), tunability and flexibility will remain a unique feature of 3GLS for a long time

- Many more 3GLS will be built in the near future !