3^{rd} Generation Synchrotron Light Sources

Francis Perez

Outline

Synchrotron Radiation

Synchrotron Light Sources

- 1st, 2nd, 3rd and Next Generation

Enabling technologies

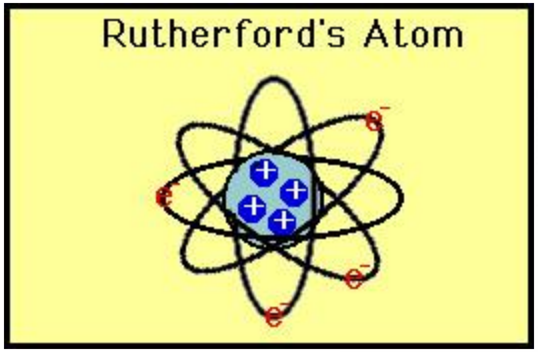
- Insertion devices
- Vacuum (NEG coating)
- Electronics (BPMs, LLRF, FOFB)
- Top UP
- Simulation tools
- …

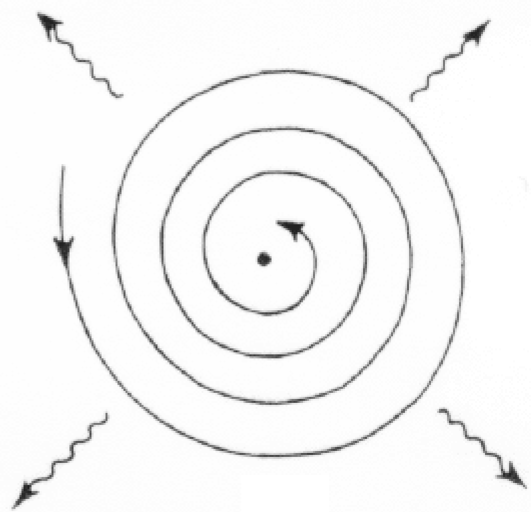
Synchrotron Radiation

The ***theoretical basis for synchrotron radiation*** traces back to the time of Thomson's discovery of the electron. In ***1897***, Larmor derived an expression from classical electrodynamics for the instantaneous total power radiated by an accelerated charged particle. The following year, Liénard extended this result to the case of a relativistic particle undergoing centripetal acceleration in a circular trajectory. Liénard's formula showed the radiated power to be proportional to $(E/mc^2)^4/R^2$, where E is particle energy, m is the rest mass, and R is the radius of the trajectory

Arthur L. Robinson

Synchrotron Radiation

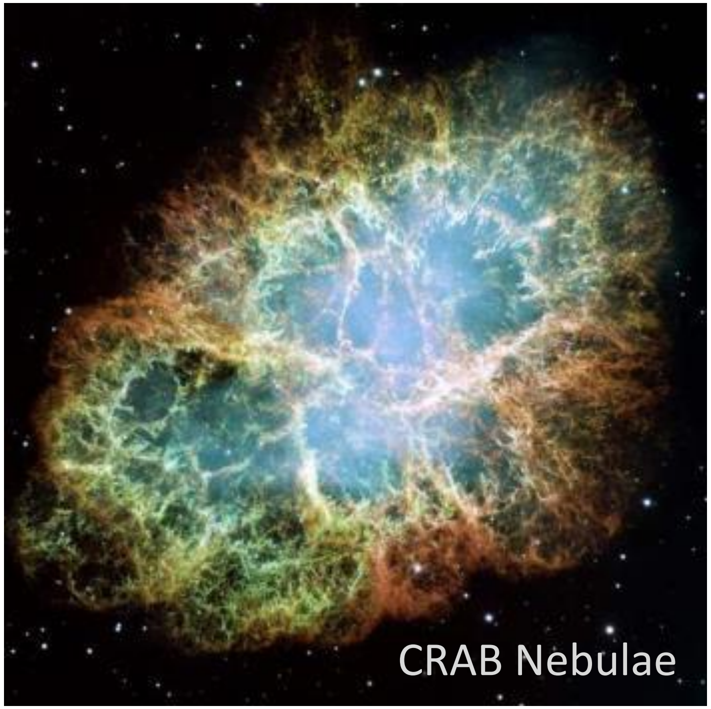




According to classical physics, an electron in orbit around an atomic nucleus should emit electronmagnetic radiation (photons) continuously, because it is continually accelerating in a curved path. The resulting loss of energy implies that the electron should spiral into the nucleus in a very short time (i.e. atoms can not exist).

Early 20th century

Synchrotron Radiation



Radiation from the Crab Nebulae is actually the synchrotron radiation of ultra relativistic electrons in interstellar magnetic fields

Recorded by Chinese astronomers in 1054

Synchrotron Radiation

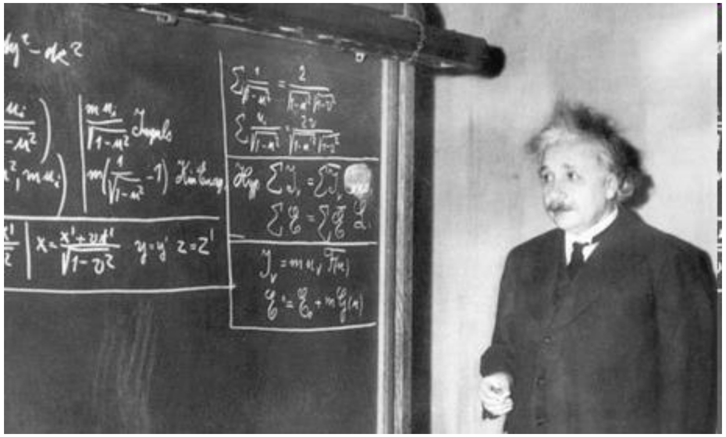
"Synchrotron radiation are the electromagnetic waves emitted by a charged particle that moves in a curved trajectory at a speed close to the speed of light"

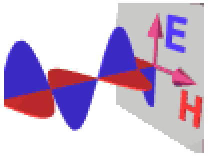
$$\nabla \cdot \mathbf{D} = \rho$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$





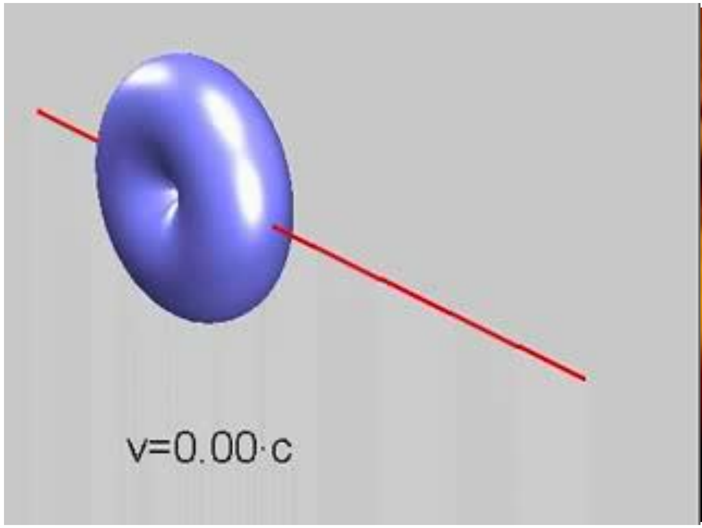
Maxwell equations + Relativity equations

Synchrotron Radiation

And combine both in an **accelerator**!

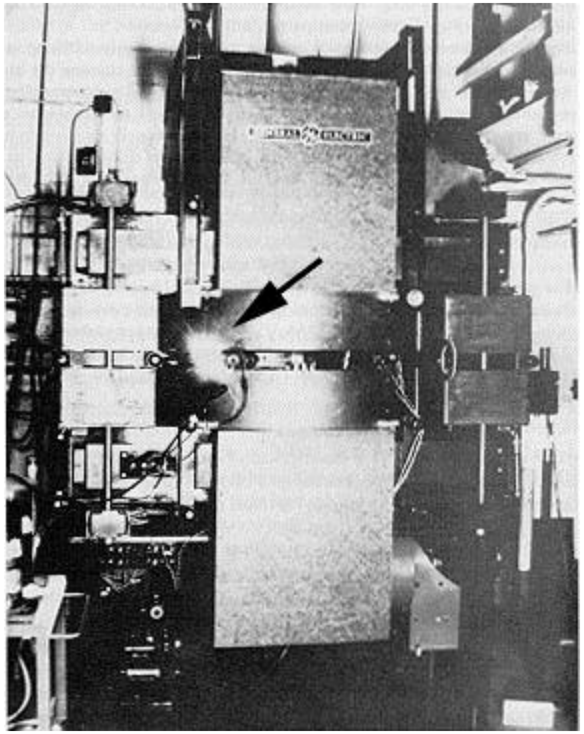
$$P(\lambda,\gamma,\psi_0,\rho,\Delta\lambda,I_{\mathrm{B}},\Delta\psi,\Delta\theta)=\int_{-\psi_0+\Delta\psi}^{+\psi_0+\Delta\psi}\frac{2}{3}\,\frac{e_0\Delta\lambda\Delta\theta\,I_{\mathrm{B}}\,\rho^2}{\varepsilon_0\beta\lambda^4\gamma^4}\left[1+(\gamma\psi)^2\right]^2$$

$$\times\left[K_{2/3}\left[\xi(\lambda,\psi)\right]^2+\frac{(\gamma\psi)^2}{1+(\gamma\psi)^2}K_{1/3}\left[\xi(\lambda,\psi)\right]^2\right].$$



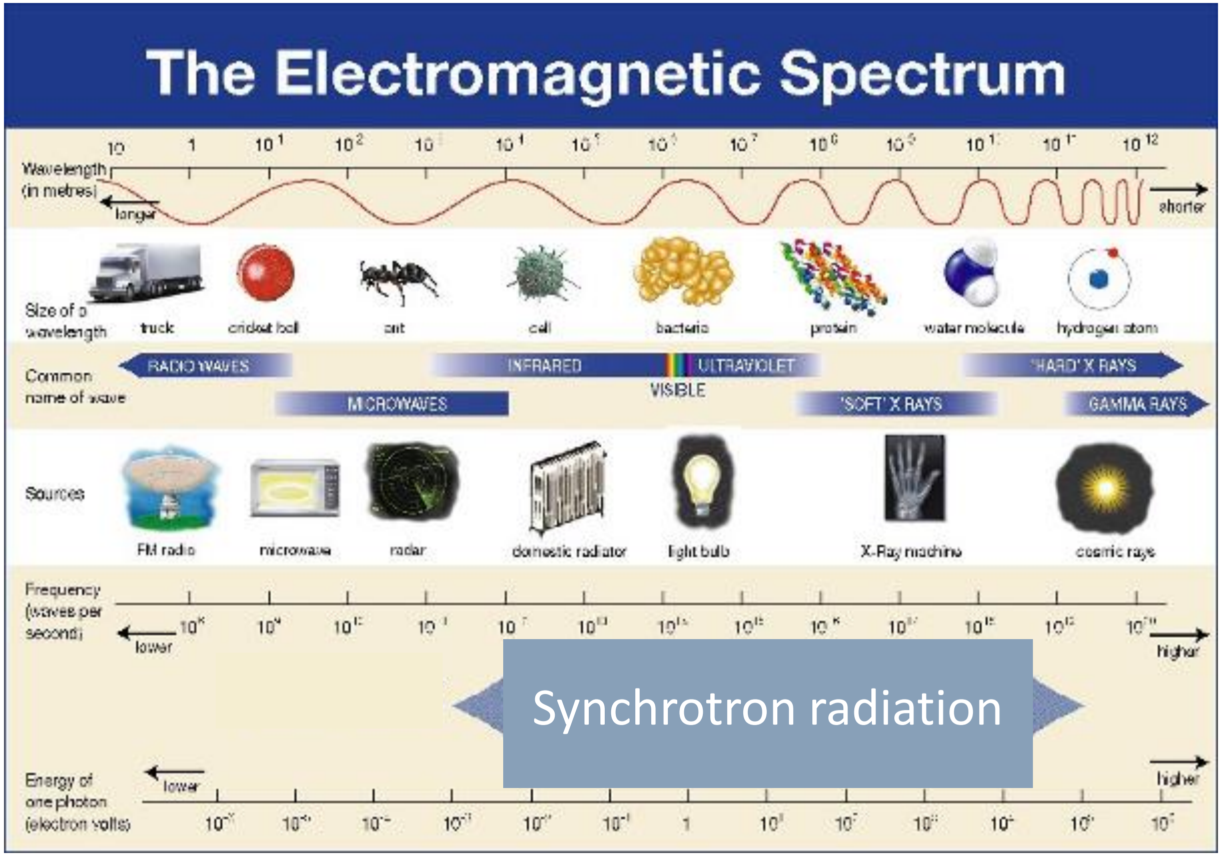
1st man-made synchrotron light

Synchrotron light from the 70-MeV electron synchrotron at GE



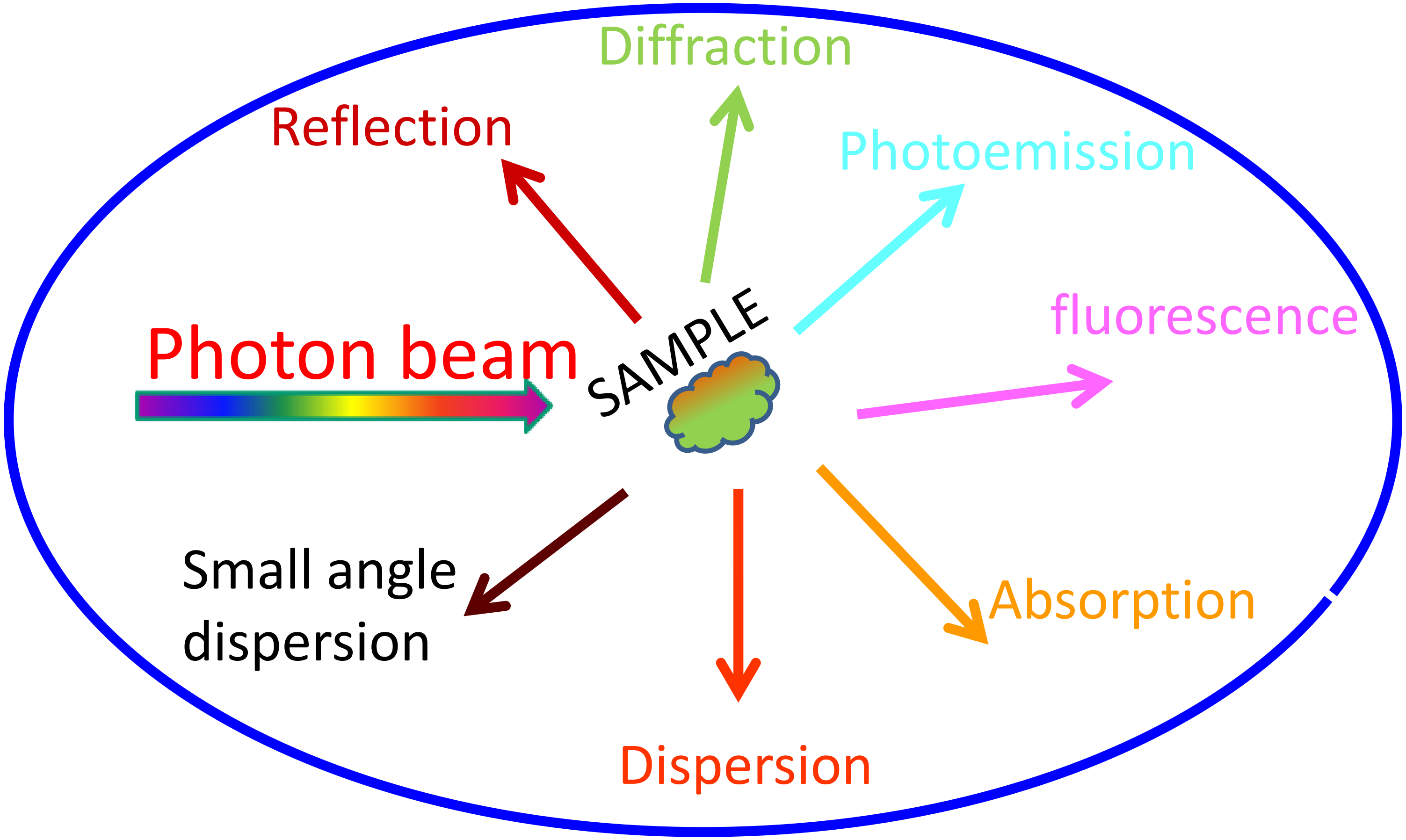
Synchrotron radiation was named after its discovery in a General Electric synchrotron accelerator built in ***1946*** and announced in May 1947 by Frank Elder, Anatole Gurewitsch, Robert Langmuir, and Herb Pollock in a letter entitled "Radiation from Electrons in a Synchrotron".

Synchrotron Radiation



Why Synchrotron Radiation

Interaction photons with matter

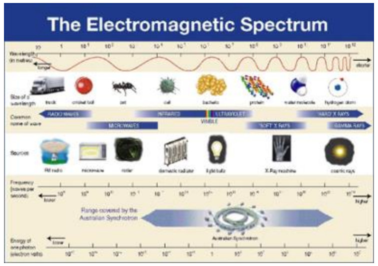


Information about sample properties

Why Synchrotron Radiation

- ❑ Continuous Spectrum: From infrared to X-rays

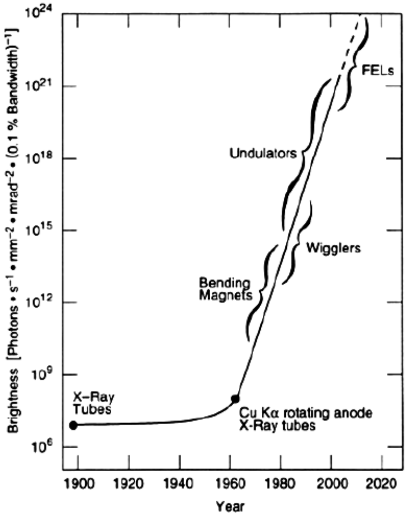
$$E_{crit}\,(keV) = 0.665\,E^2\,(GeV)\,B(T)$$



- ❑ Intense

- ❑ Highly collimated: as a narrow stable beam

$$\Theta(rad) = 0.51/E\,(MeV)$$



- ❑ Polarized in the orbital plane

- ❑ With temporal structure

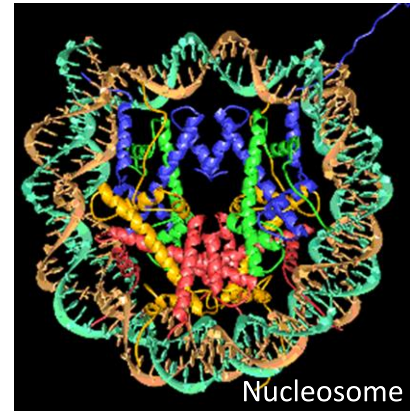
Why Synchrotron Radiation

Huge range of scientific disciplines, including condensed matter physics, chemistry, nanophysics, structural biology, engineering, environmental science and cultural heritage.

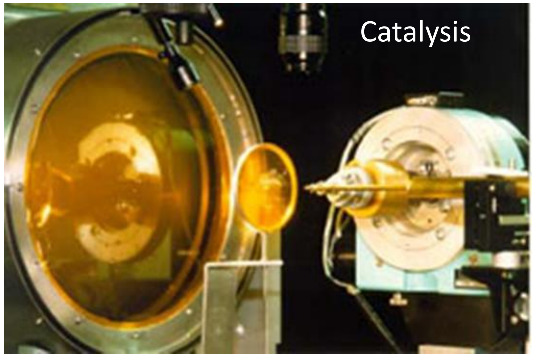
Diamond Light Source dixit

Applications

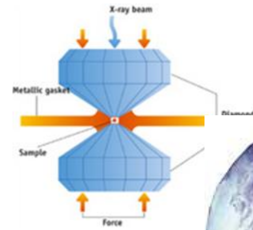
BIOLOGY

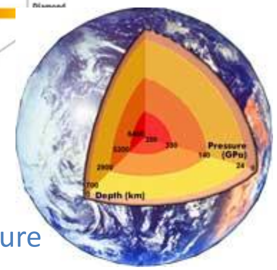


CHEMISTRY



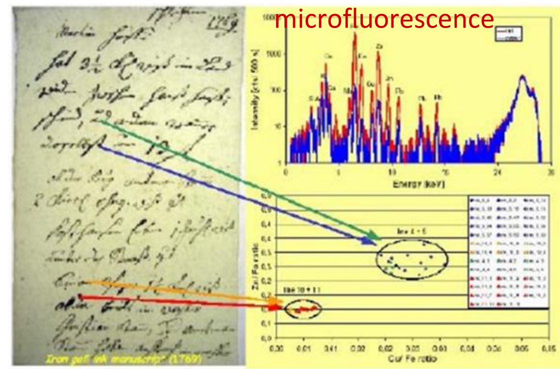
GEOLOGY



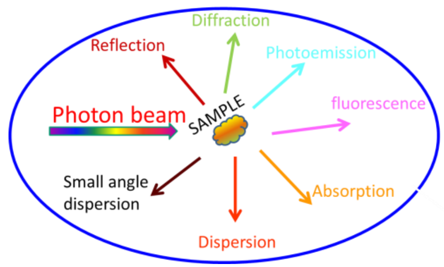


High pressure
High temperature

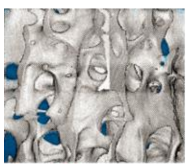
ART



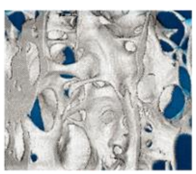
Manuscript 1679



MEDICINE



33 anys



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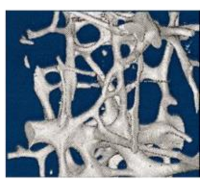
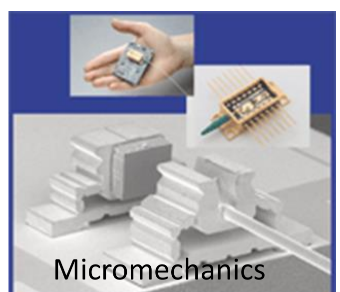


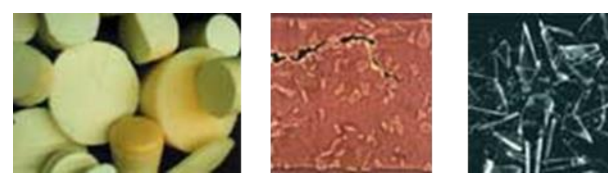
72 anys

Osteoporosys

INDUSTRY



MATERIAL SCIENCE



…and more

Synchrotron Generations

1st generation light sources (1956 -)

Accelerator built for High Energy Physics

used parasitically for synchrotron radiation

2nd generation light sources (1981 -)

Accelerators built as synchrotron light sources

3rd generation light sources (1994 -)

Optimised for high brilliance

with low emittance beam and Insertion Devices

Synchrotron landmarks

1946 First synchrotron operates in Woolwich, UK.
1947 First observation of synchrotron light.

1956 **First experiments using synchrotron light take place at Cornell, US**.

1964 The DESY synchrotron in Germany begins operation for both high-energy physics and synchrotron-light experiments.
1966 First experiments in the UK at Glasgow synchrotron.
1968 Tantalus, 1st synchrotron light facility

1981 **The Synchrotron Radiation Source (SRS) starts operating in Daresbury, UK. It is the first dedicated X-ray producing synchrotron source.**

1994 **The first third-generation synchrotron source, the ESRF in Grenoble, France, goes into operation.**

2000 The SASE principle for an FEL is successfully demonstrated at DESY.
2001 Swiss Light Source introduce Top Up for users
2005 FLASH, the first FEL in the soft X-ray range, goes into operation at DESY (4^{th} Generation LS, but not a “synchrotron”…)

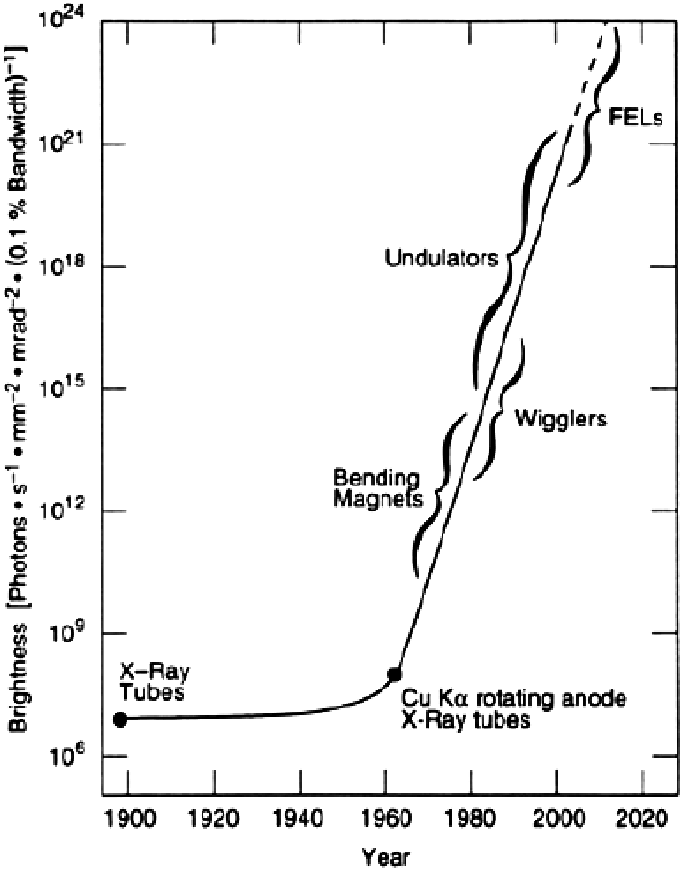
2014 **Max IV, “next generation” under construction**

Evolution

Emittance

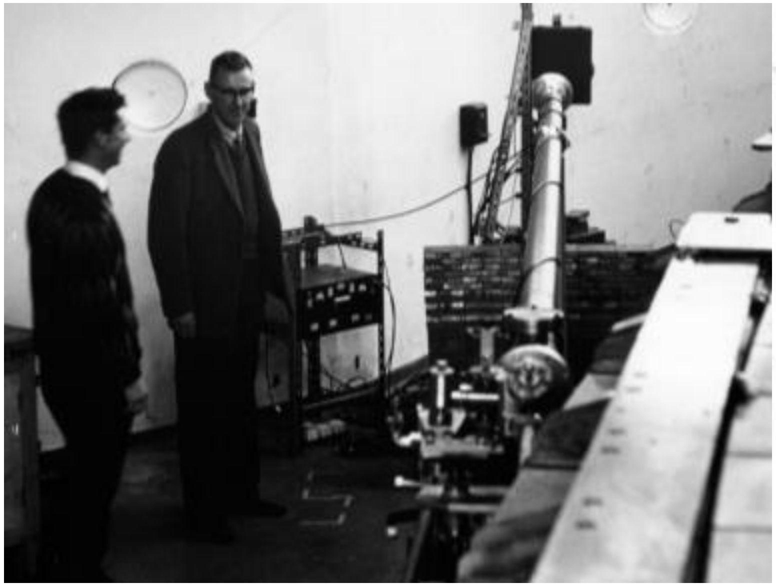
1980	100	nmrad
1990	10	nmrad
2000	3	nmrad
2010	1	nmrad
…		
2020	0.1	nmrad

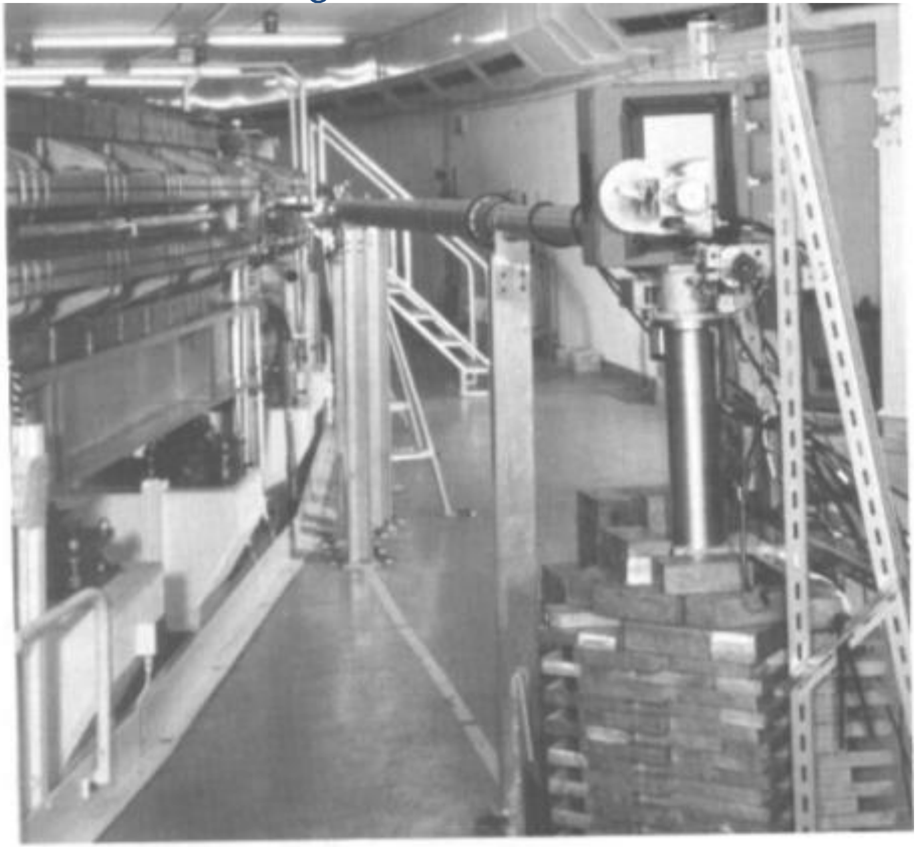
Brightness



1st Generation LS (1956 – …)

1968 Synchrotron Light experiment at NINA
Ian Munro + Scott Hamilton
(Manchester University)





1968 - First SRF experiment inside the NINA ring

1st Generation LS

- 1968 Tantalus

1st Synchrotron Light Facility

"Tantalus not only pioneered the use of synchrotron radiation, but created a ***research facility*** where both scientists and graduate students could perform hands-on work"
A. Oswald

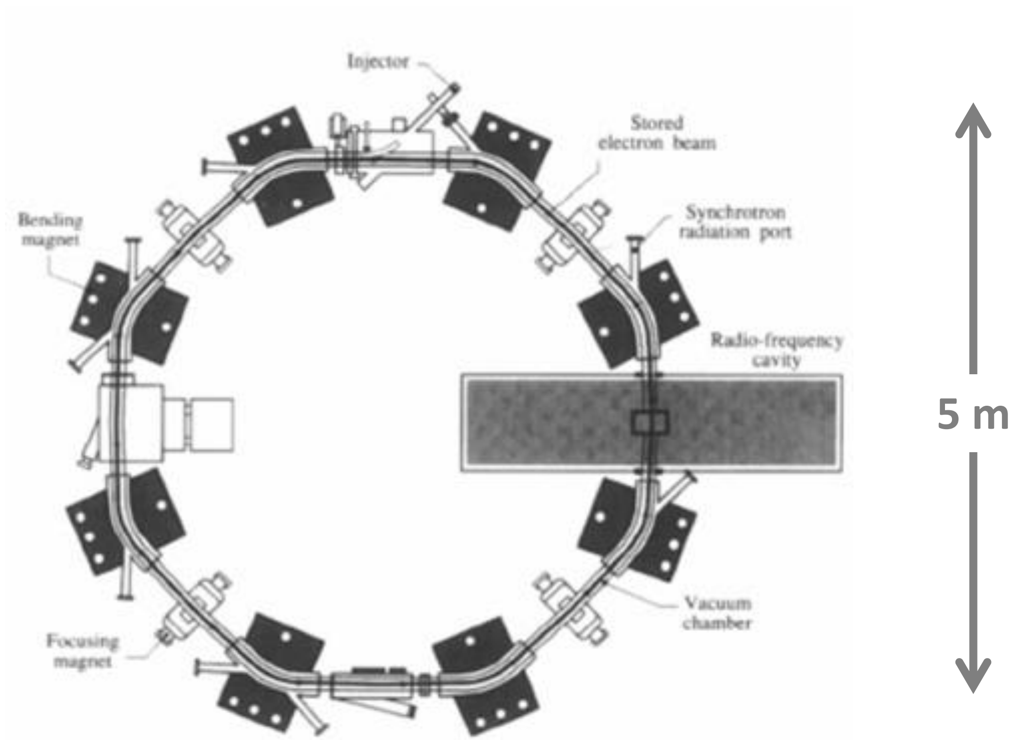


Figure 2
Schematic drawing of Tantalus without beamlines or injector.

1st experiments at Russia

First experiments with the use of SR were started at Novosibirsk in 1973.

At the 1st Meeting on Using Electron Storage Rings - SR Sources for Experiments in Biology, Chemistry and Physics"
(SR-75, December 16-18, 1975).

V.I. Bukhtiyarov

2nd Generation LS (1981 – …)

SRS at Daresbury, UK
1st built accelerator for production of Synchrotron Light in the *XR energy range*

Initially conceived for using the light from the bending magnets

Bending magnet at SRS

2^{nd} Generation LS (1981 – …)

SOR-Ring	*Tokyo*	*Japan*	*1976*
SRS	Daresbury	UK	1981
DCI – LURE	Orsay	France	1981
NSLS	Brookhaven	USA	1982
BESSY	Berlin	Germany	1982
Photon Factory at KEK	Tsukuba Japan		1982
MAX-I	MAX-lab	Sweden	1986
…			

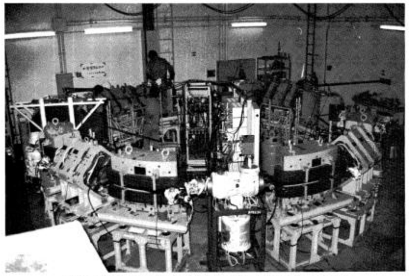


FIGURE 10 Overall view of the SOR-RING during the test operation in December 1974.

Particle Accelerators
1976, Vol. 7, pp. 163–175

SOR-RING
An Electron Storage Ring Dedicated to Spectroscopy

T. MIYAHARA,†§ H. KITAMURA,†[1] S. SATO,‡ M. WATANABE,‡ S. MITANI,[2] E. ISHIGURO,[3] T. FUKUSHIMA, T. ISHII,[4] SHIGEO YAMAGUCHI,[5] M. ENDO,§[6] Y. IGUCHI,[7] H. TSUJIKAWA, T. SUGIURA,§ T. KATAYAMA, T. YAMAKAWA, SEITARO YAMAGUCHI and T. SASAKI§[8]

Institute for Nuclear Study, University of Tokyo, Tanashi, Tokyo, Japan

(*Received February 25, 1976; in final form June 1, 1976*)

1st Wiggler (1979)

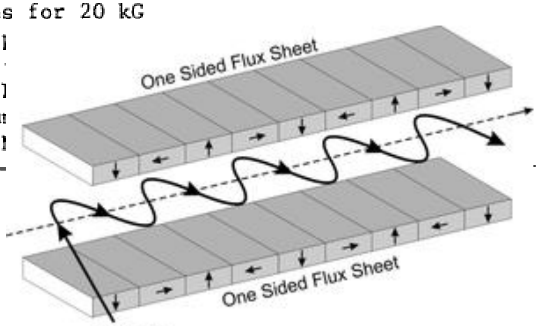
SLAC-PUB-2289
March 1979
(I/A)

INITIAL OPERATION OF SSRL WIGGLER IN SPEAR*

M. Berndt,[a] W. Brunk,[a] R. Cronin,[b] D. Jensen,[a]
R. Johnson,[a] A. King,[a] J. Spencer,[a,b] T. Taylor,[a] and H. Winick[b]

Table I - SPEAR Wiggler (3λ) Summary

Number of Poles	7
Maximum Central Induction B_o (kg)	20
Pole Width w (mm) - Coordinate direction ($\hat{x}$)	304.8
Gap Height G (mm) - Coordinate direction ($\hat{y}$)	41.3
Mechanical Pole Length - Inner (mm) ($\hat{z}$)	88.9
Mechanical Pole Length - Outer (mm) ($\hat{z}$)	66.7
$\frac{1}{2I}\int B_y(x,o,z)\,dz$ for $B_o = 20$ kG (kG - m/kA)	0.576
Effective Magnetic Pole Length - Inner (mm)	98.3
Magnetic Wavelength λ_W (mm)	342.9
Total Magnet Length L (m) - Clamp-to-Clamp	1.219
Amperes for 20 kG	1708
Turns	28
Power	250
Total	42
Maximu	30°
Total	1100



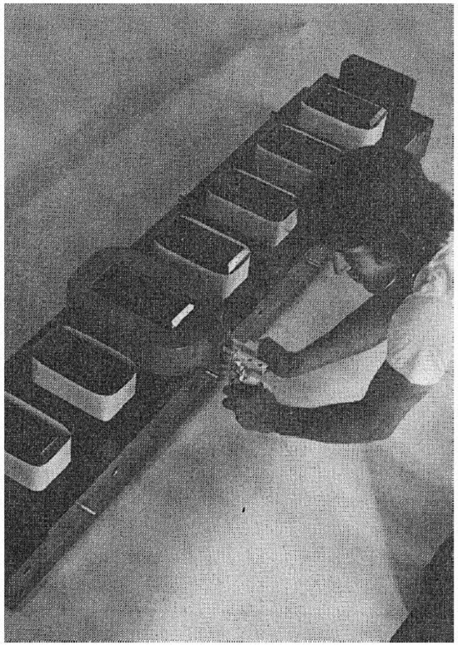


Figure 5 — Wiggler magnet for SPEAR (lower half) with seven full poles and two end half poles. Each pole is powered by a coil, only one of which is shown. (Photo by J. Faust, SLAG)

1981

Two examples of this impact are:

- User interest in the first SSR
great that plans to build addi
from bending magnets were
emphasis at SSRL is now on
gler lines.
- The design group planning the European Synchrotron Radiation Facility originally conceived of a 5-GeV, 565 mA machine to meet certain intensity and spectral specifications. The group is now considering an "all-wiggler machine"[3] in which virtually all of this radiation used by experimenters would be produced by wigglers (up to 40 of them). With wigglers, the ring would only have to operate at 3.5 GeV with 100 mA to meet the same intensity and spectral-range specifications as the bending-magnet beams on the higher energy, higher-current ring.

[3] D. Thompson, R. Coisson, J. Le Duff, F. Dupont, M. Erickson, Albert Hofmann, D. Husmann, G. Mulhaupt, M. Poole, M. Renard, M. Sommer, V. Suller, S. Tazzari, F. Wang; "The 'all Wiggler' Synchrotron Radiation Source," IEEE Transactions on Nuclear Science, Volume 28, Issue 3, June 1981, doi: 10.1109/TNS.1981.4332037

ESRF

By Herman Winick, George Brown, Klaus Halbach and John Harris
Physics Today, May 1981, Volume 34, Issue 5, pp. 50-63, doi: 10.1063/1.2914568

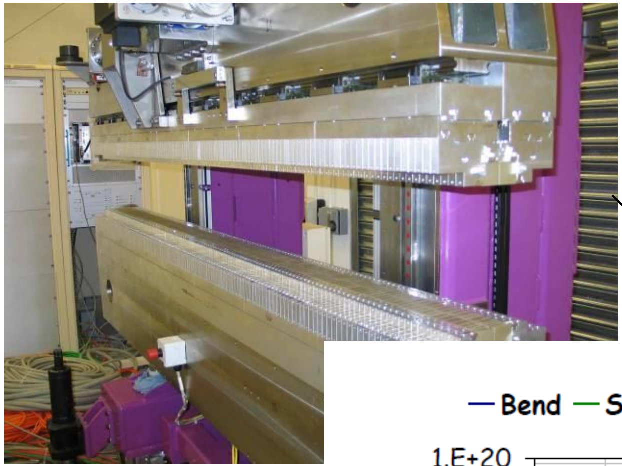
3rd Generation LS (1993 – …)

1993	ESRF	EU (France)	6 GeV
	ALS	US	1.5-1.9 GeV
1994	TLS	Taiwan	1.5 GeV
	ELETTRA	Italy	2.4 GeV
	PLS	Korea	2 GeV
	MAX II	Sweden	1.5 GeV
1996	APS	US	7 GeV
	LNLS	Brazil	1.35 GeV
1997	Spring-8	Japan	8 GeV
…			

Insertion Devices

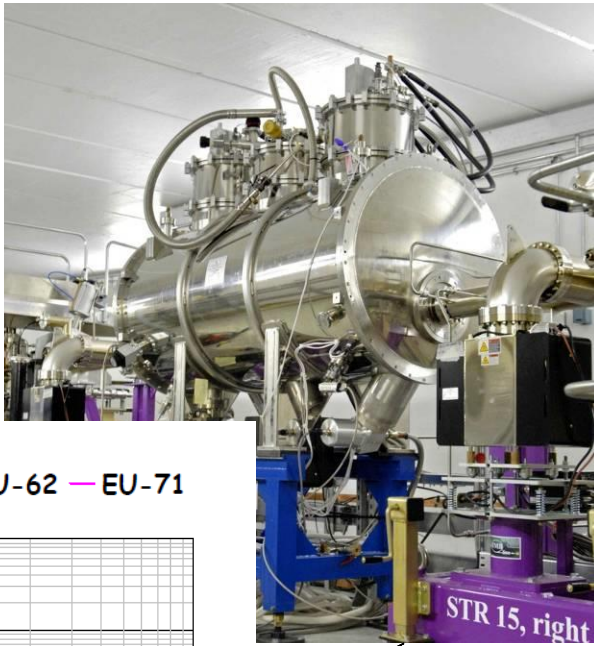
UNDULATORS

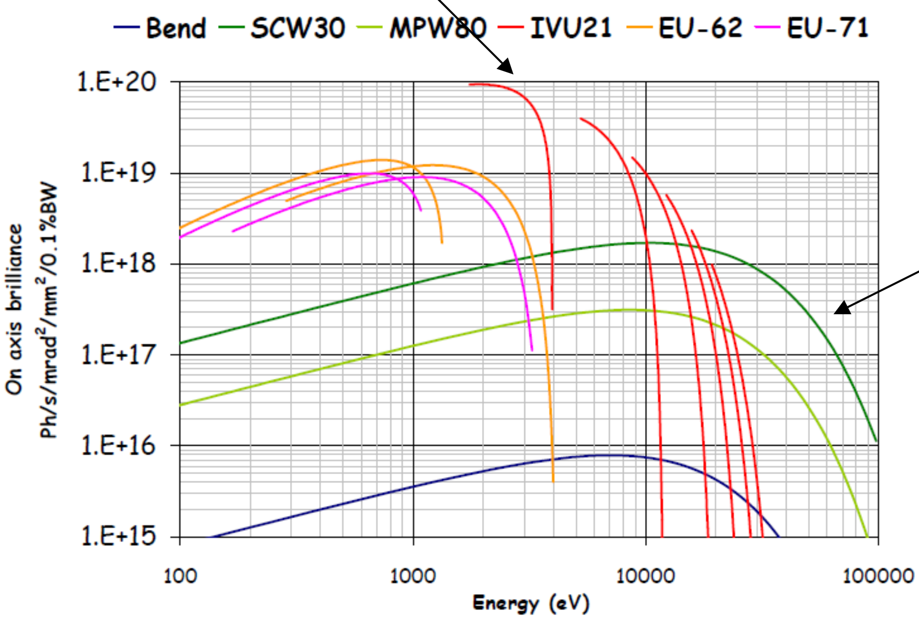
to generate high brilliance radiation



WIGGLER

to reach high photon energies

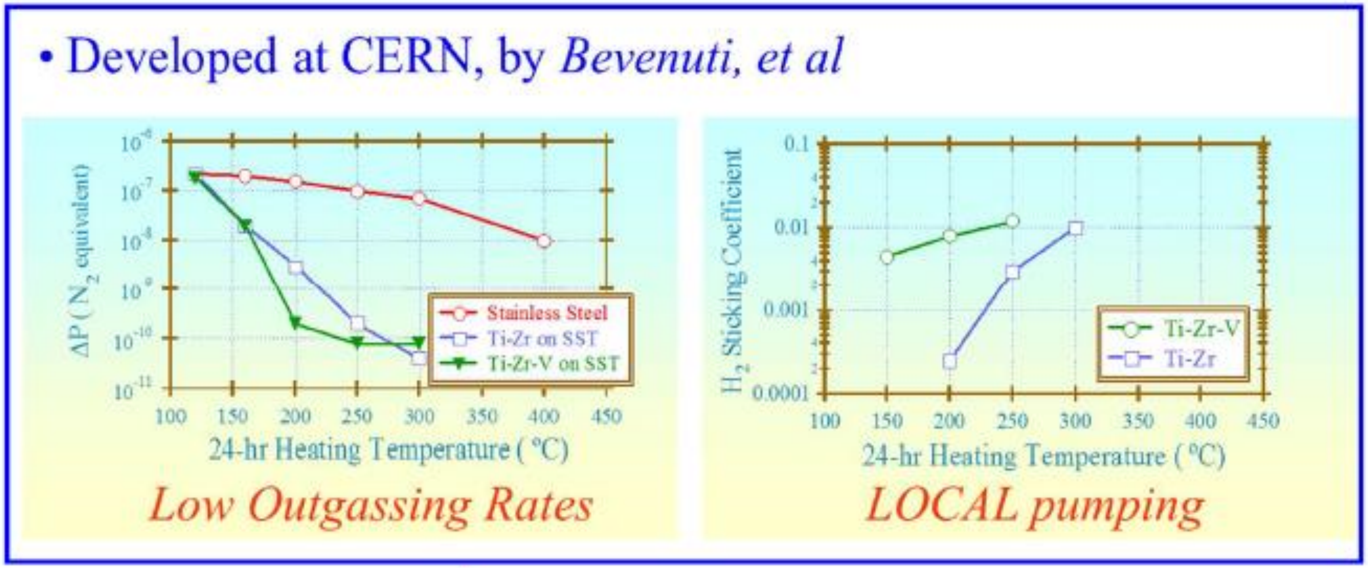




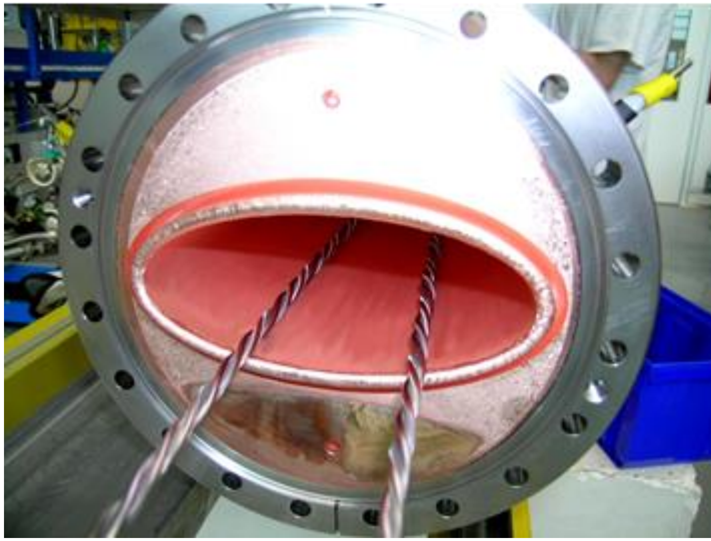
1998 NEG Coating

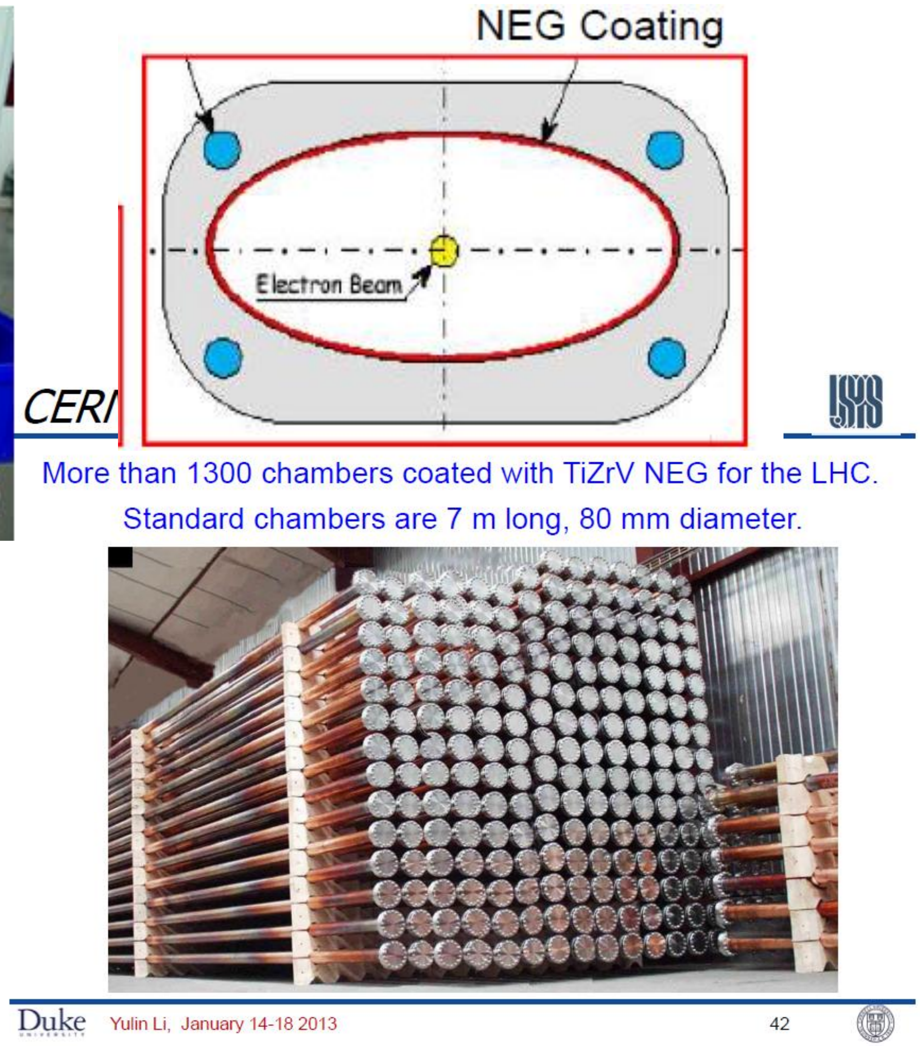
Benvenuti C, Chiggiato P, Cicoira F, L'Aminot Y. J Vac Sci Technol A 1998;16:148.

Coating the internal surface of a vacuum chamber with a Non Evaporable Getter (NEG) thin film. After thermal activation the oxide layer present at the NEG surface is dissolved, reducing significantly the secondary electron yield, the photon and the electron induced desorptions, and additionally providing high pumping speeds for the main gas species present in UHV systems.



NEG Coating





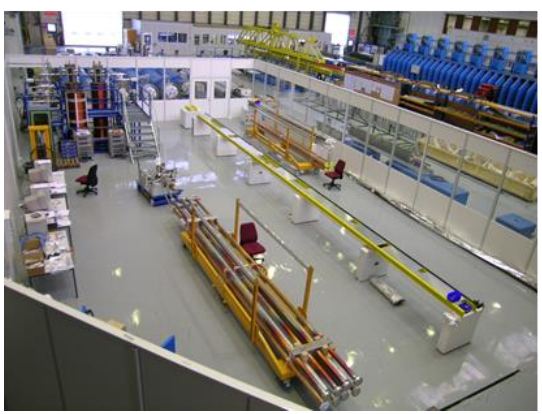
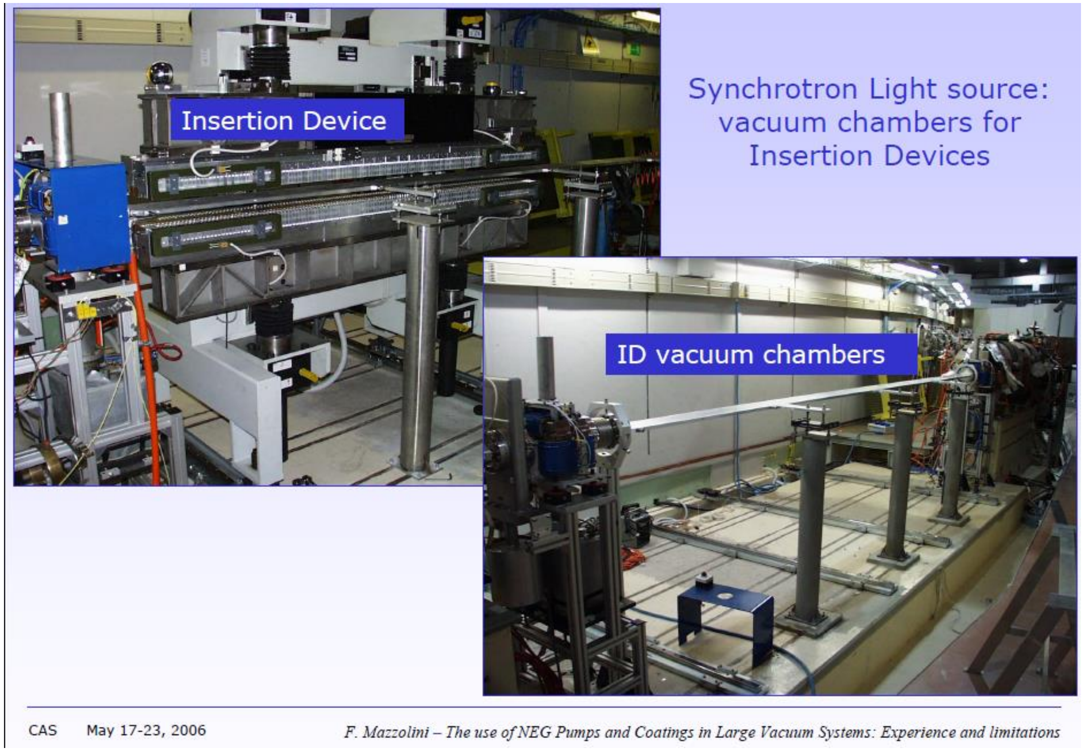


Figure 1 – Global view of the coating facilities in building 181.

NEG Coating

Since 2002, following collaboration and the purchase of a ***license from CERN***, which holds the TiZrV NEG coating technology patent, the ESRF has been producing NEG coated vacuum and now many synchrotrons are usign it for narrow gap inserion devices.



1995

Design of a Diffraction Limited Light Source (DIFL)

D. Einfeld, J. Schaper, Fachhochschule Ostfriesland, Constantiaplatz 4, D-26723 Emden
M. Plesko, Institute Jozef Stefan, Jamova 39, P.O.B. 100, SLO-61111 Ljubljana

In 1995, Einfeld et al. PAC

Three synchrotron light source of the third generation have been commissioned (ESRF, ALS and ELETTRA). All machines have reached their target specifications without any problems. Hence it should be possible to run light sources with a smaller emittance, higher brilliance and emitting coherent radiation. A first disign of a Diffraction Limited Light Source has been performed. It is a 3 GeV storage ring with a modified multiple bend achromat (MBA) optics as a lattice leading to a normalized emittance of $\varepsilon_x = 0.5$ nmrad.

Several developments were needed before considering it possible, since **micron beam size required submicron beam stability**

- Orbit measurement
- Beam stability
- Beam lifetime
- Reliable simulations
-...

DIGITAL ELECTRONICS

Proceedings of the 1999 Particle Accelerator Conference, New York, 1999

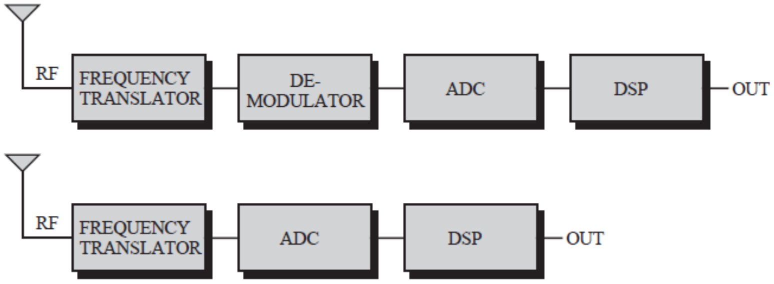
DIGITAL RECEIVERS OFFER NEW SOLUTIONS FOR BEAM INSTRUMENTATION

R. Ursic, Instrumentation Technologies, Srebrnicev Trg 4a, 5250 Solkan, Slovenia
R. De Monte, Sincrotrone Trieste

Abstract

Digital receivers revolutionize today's telecommunication industry. In this article we examine the features, the applications and the opportunities of this new and promising technology from the beam instrumentation point of view.

2 THE DIGITAL RECEIVER CONCEPT



Proceedings of the 2001 Particle Accelerator Conference, Chicago

COMMISSIONING OF THE SLS DIGITAL BPM SYSTEM

V. Schlott, M. Dach, M. Dehler, R. Kramert, P. Pollet, T. Schilcher, PSI, Villigen, Switzerland;
M. Ferianis, R. DeMonte, Sincrotrone Trieste, Italy;
A. Kosicek, R. Ursic, Intrumentation Technologies, Slovenia.

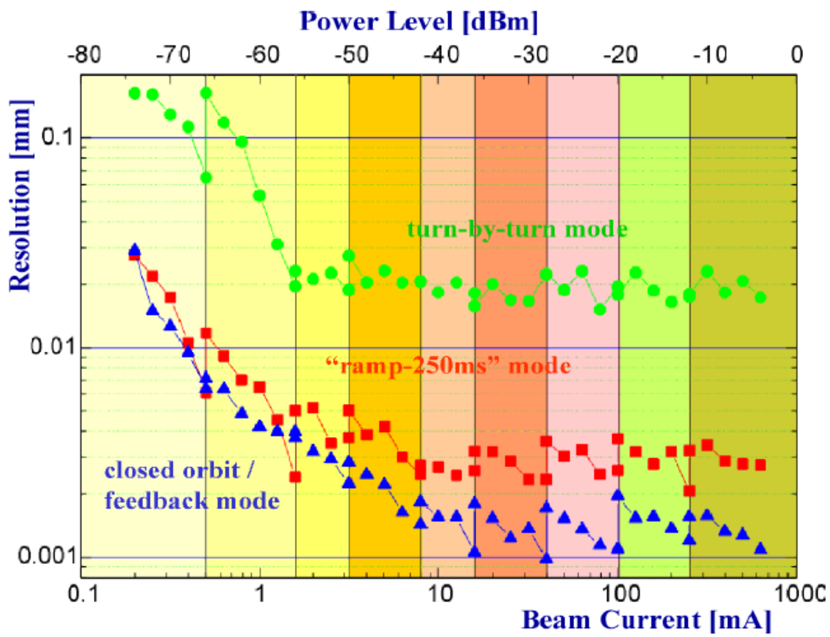
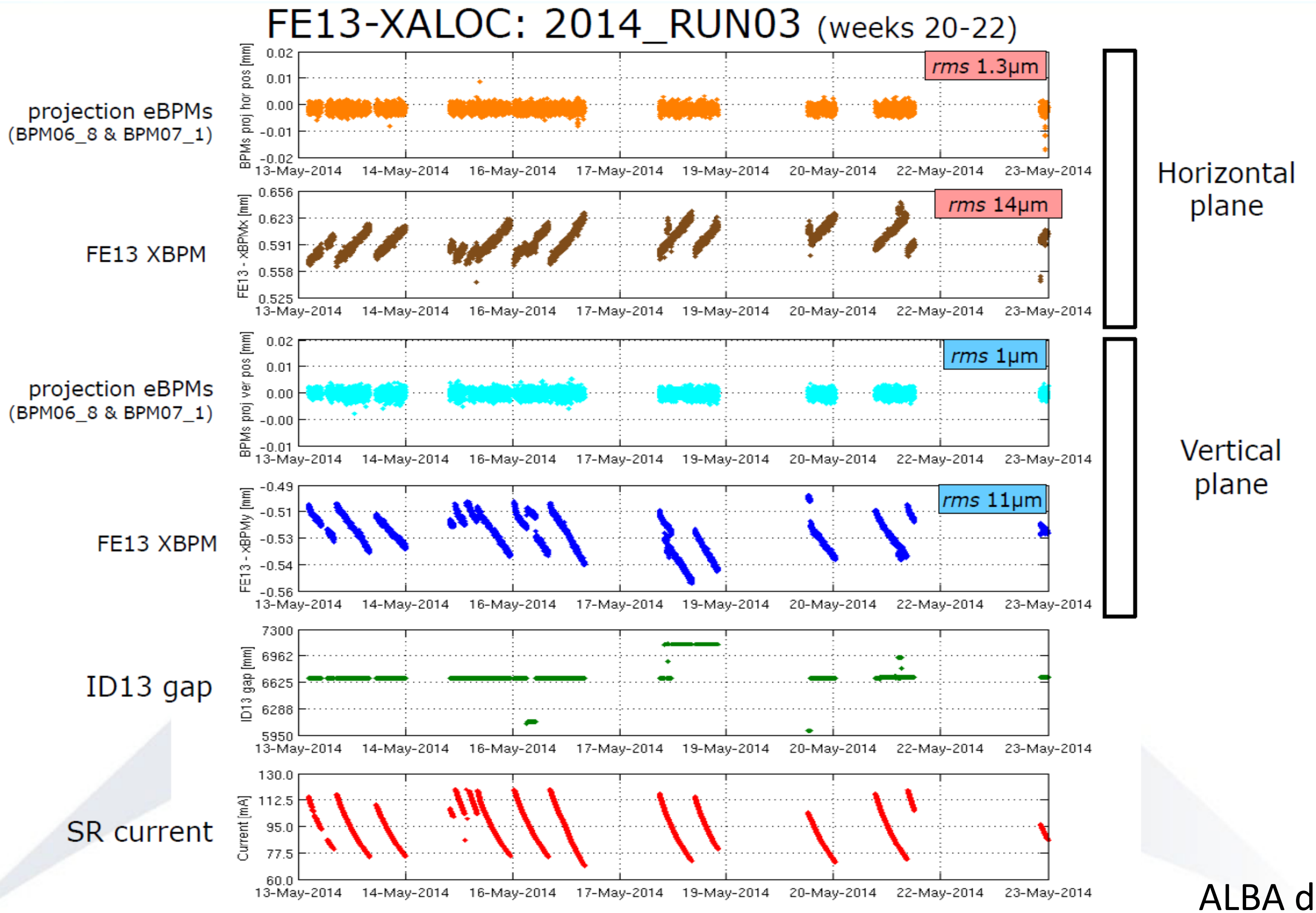


Figure 1: Measurement of DBPM resolution for different bandwidths: 500 kHz (green dots), 15 kHz (red squares) 2 kHz (blue triangles). Gain levels of the system are kept constant for the marked beam current ranges.

Thermal drifts



ALBA data

Topping Up Experiments at SRRC

T. S. Ueng, K. T. Hsu, J. Chen, K. K. Lin, W. T. Weng*
Synchrotron Radiation Research Center, Hsinchu 300, Taiwan

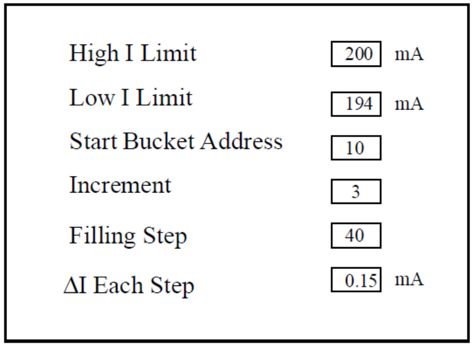


Fig. 1 Control panel of topping up mode injection

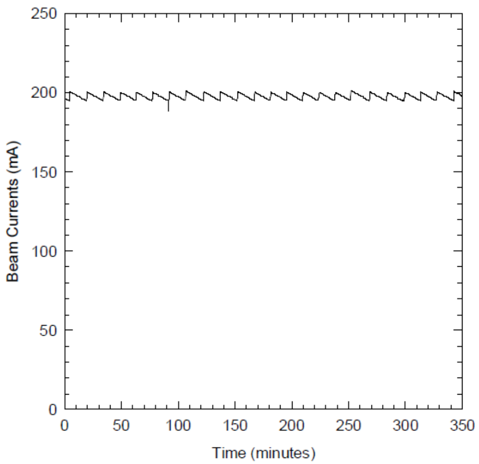


Fig. 2 Typical result of SRRC topping up mode operation.

EPAC 1996

2001 SLS, Switzerland Users operation

Top Up for User Operation

Proceedings of EPAC 2002, Paris, France

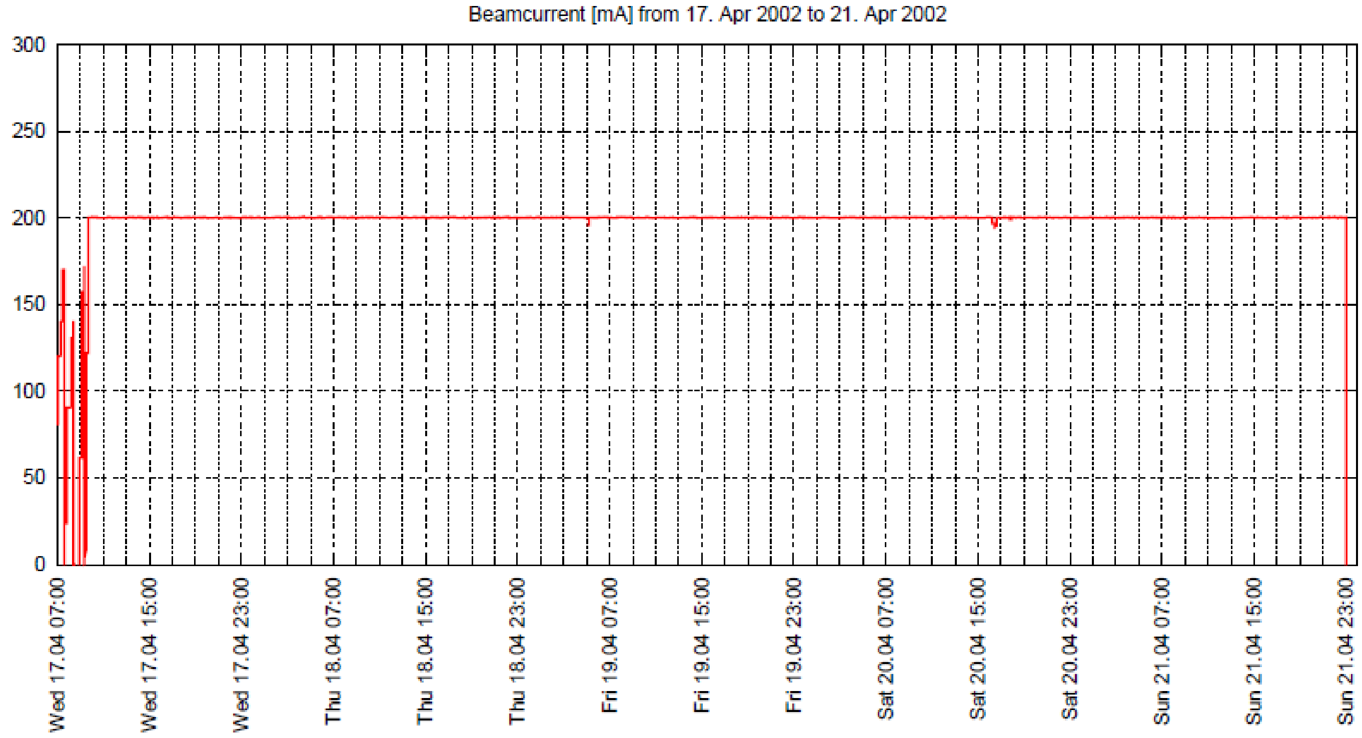
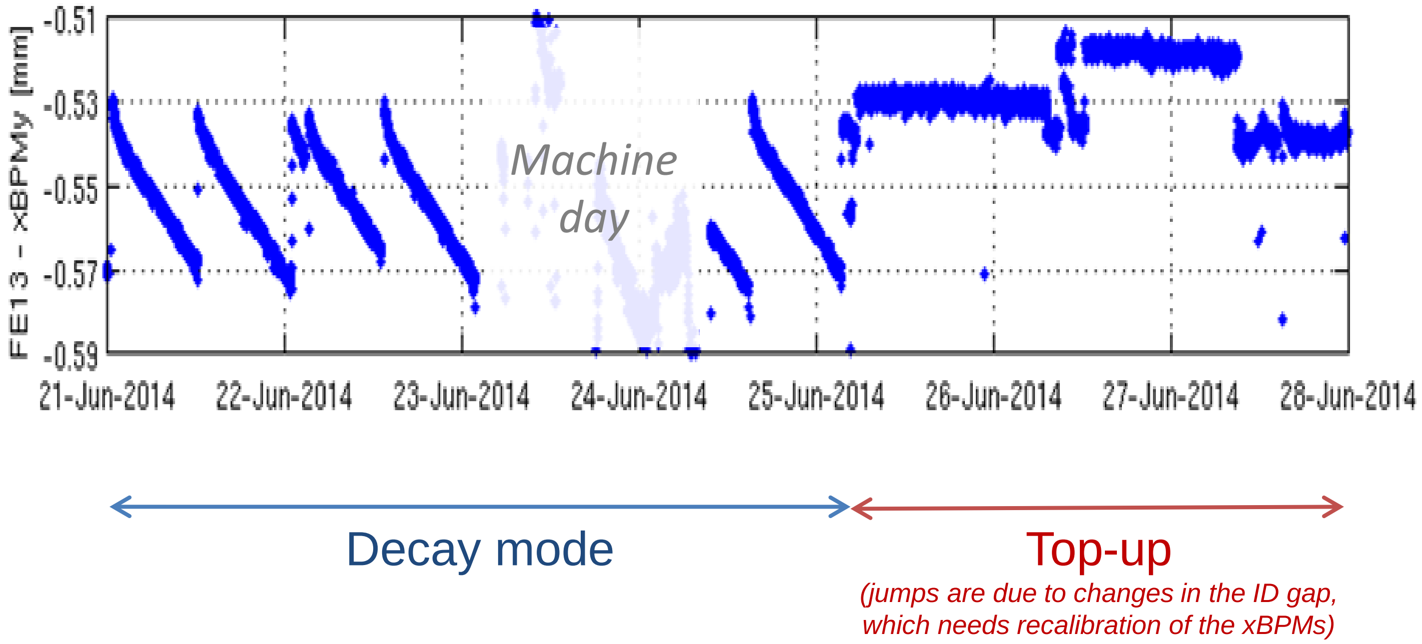


Figure 1: Beam current during a typical top-up run (week 16 of 2002).

Thermal Stability

XALOC: **$xBPM_{(y)}$**



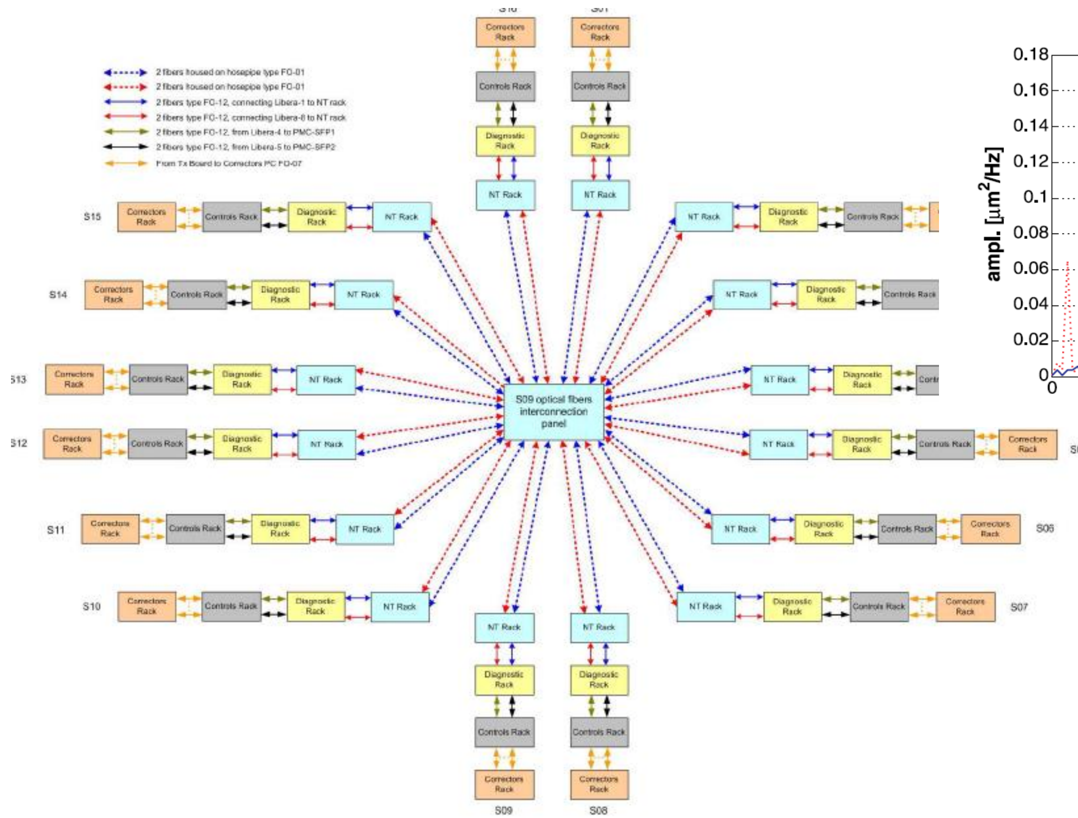
ALBA data

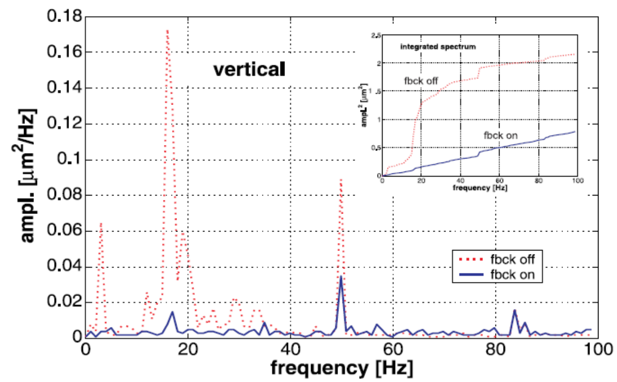
2003 Fast Orbit Feedback

Proceedings of the 2003 Particle Accelerator Conference

COMMISSIONING OF THE FAST ORBIT FEEDBACK AT SLS

T. Schilcher, M. Böge, B. Keil, V. Schlott, Paul Scherrer Institut, Villigen, Switzerland

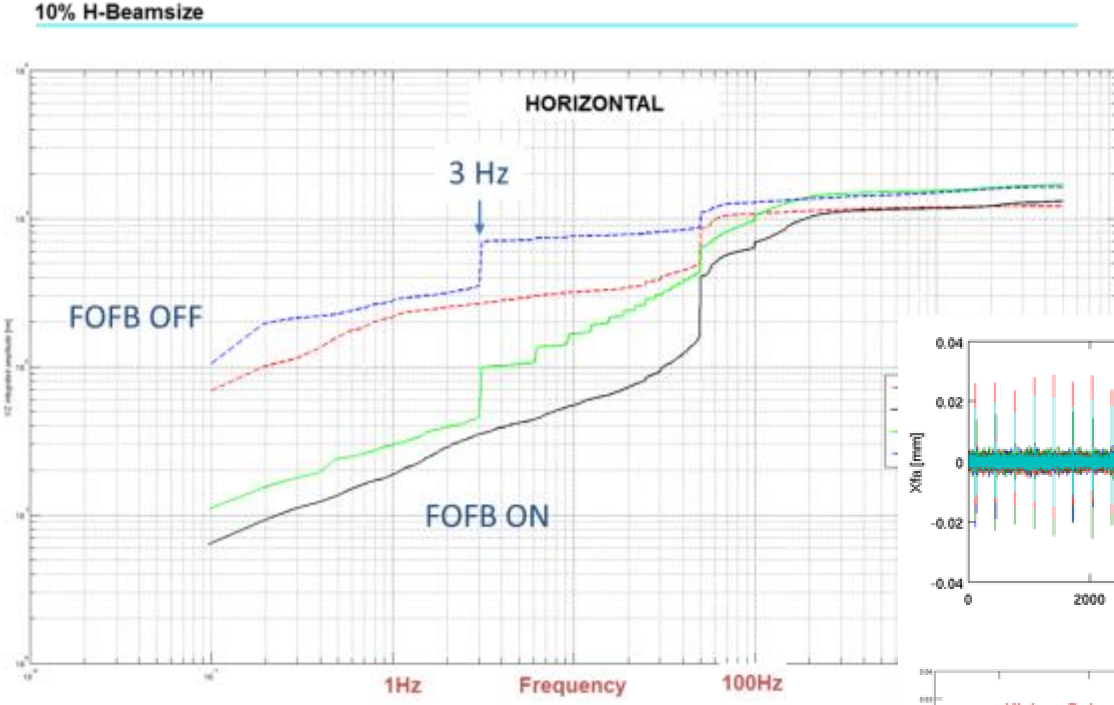




Up to 100 Hz

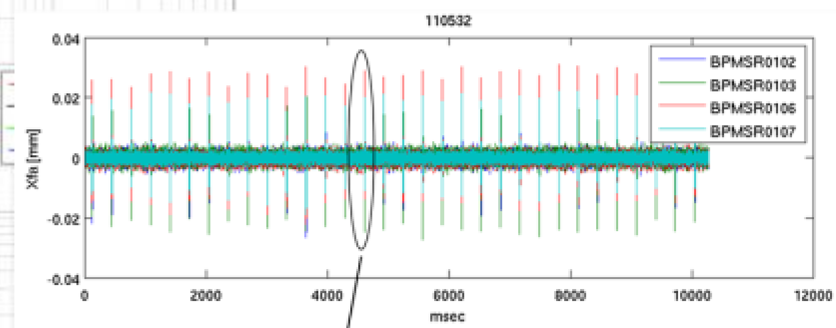
Fast Orbit FeedBack

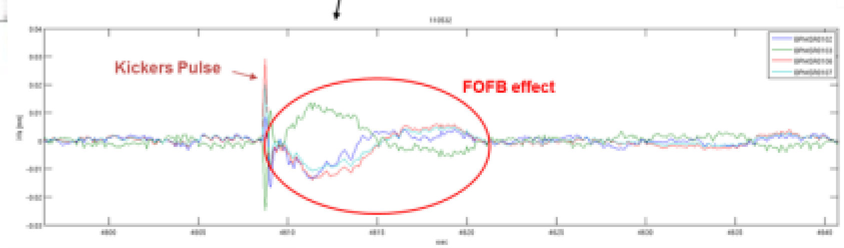
FOFB OFF/ON – Kickers OFF/ON



3 Hz horizontal
kicker induced noise

FOFB ON – Kickers ON



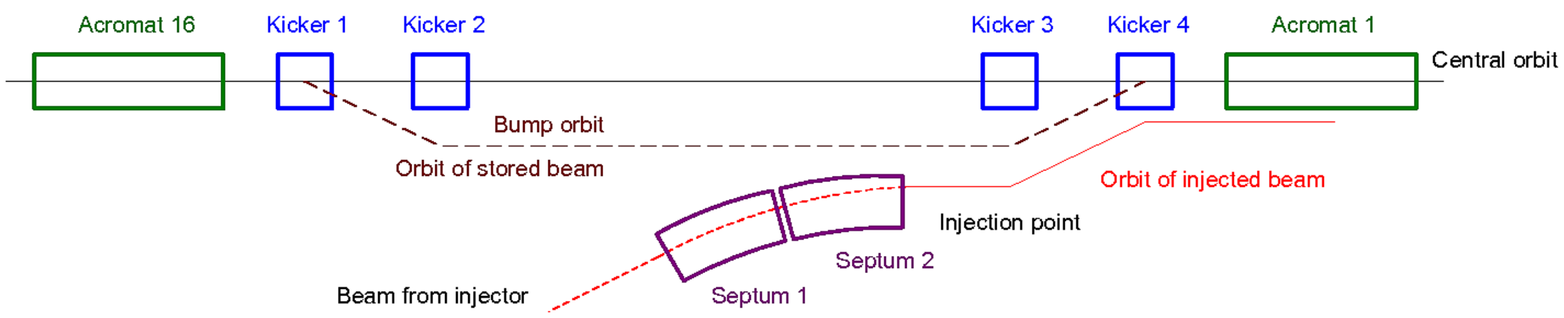


← 12 ms →

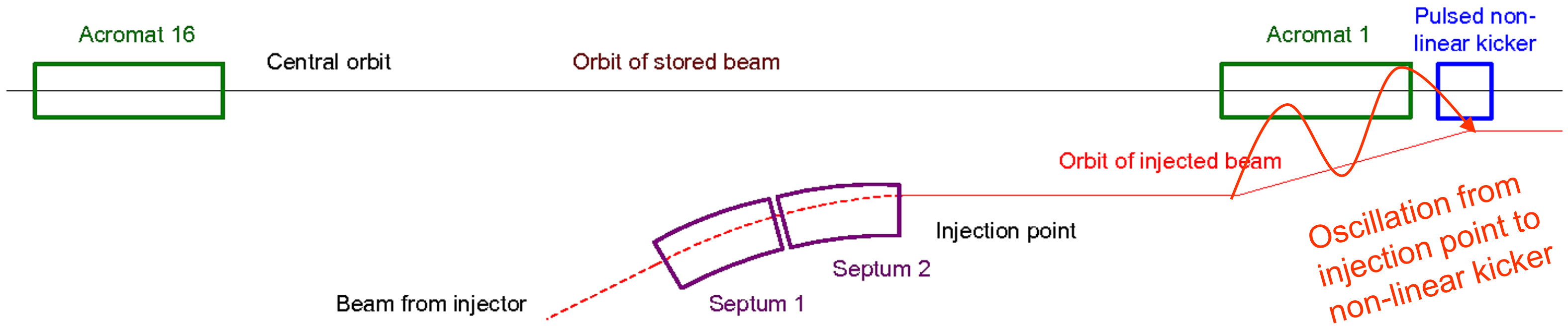
ALBA data

Injection schemes

Conventional



Pulsed Quad



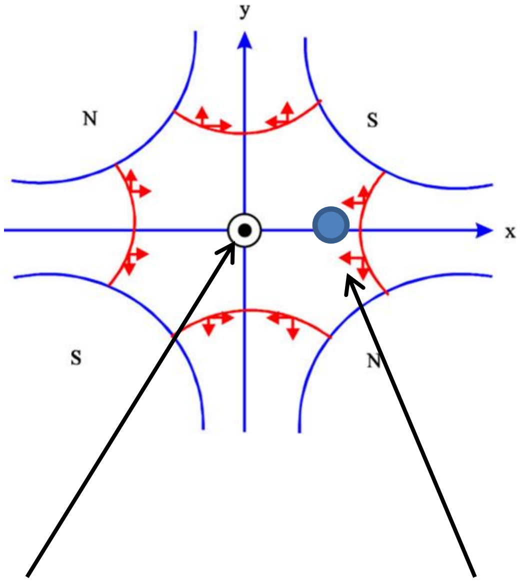
*Phys. Rev. ST Accel. Beams 10, 123501, 'New injection scheme using a pulsed quadrupole magnet in electron storage rings', K. Harada, Y. Kobayashi, T. Miyajima, S. Nagahashi, *Photon Factory,* 2007.

2005 Pulsed Quad Kicker

Proceedings of 2005 Particle Accelerator Conference, Knoxville, Tennessee

BEAM INJECTION FOR THE PF-AR WITH A SINGLE PULSED QUADRUPOLE MAGNET

K. Harada, Y. Kobayashi, S. Nagahashi, T. Miyajima, T. Obina, A. Ueda and T. Mitsuhashi,
KEK-PF, Tsukuba, 305-0801, Ibaraki, Japan



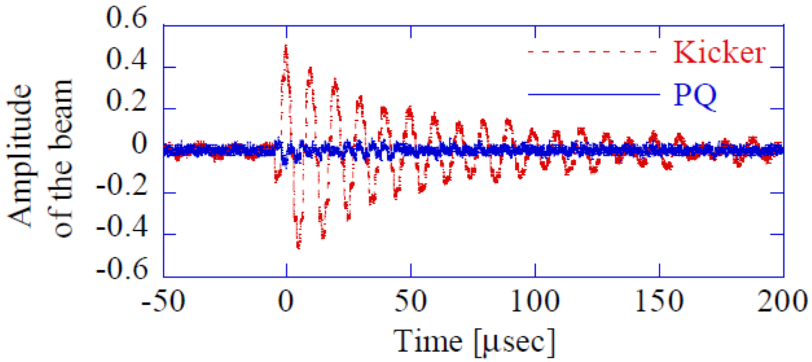


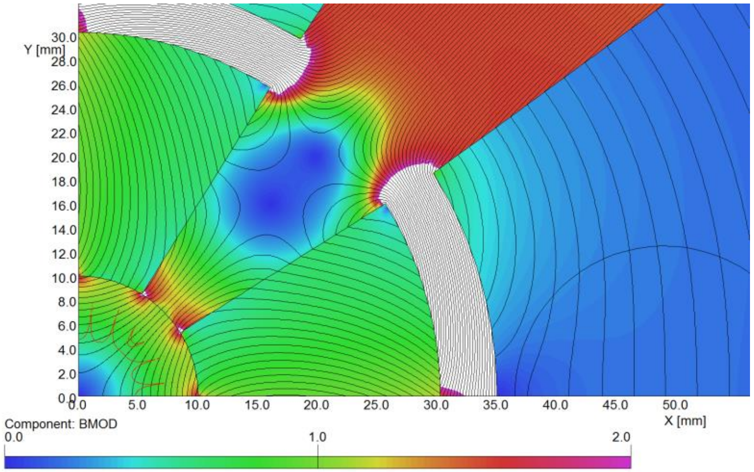
Figure 5 Oscillation of the stored beam.

Stored beam unperturbed

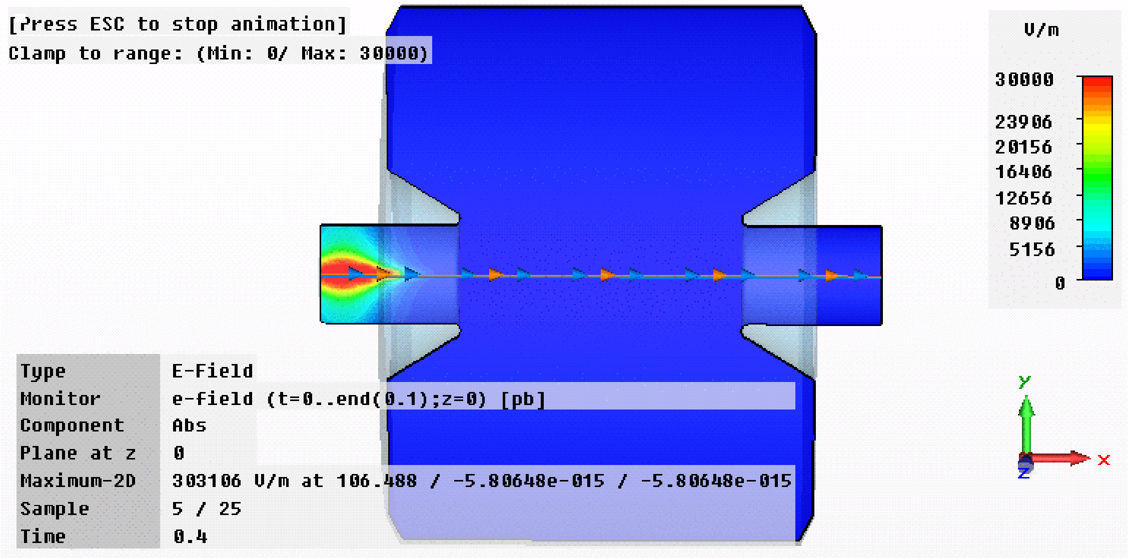
Injected beam receives a kick

Proof of principle, but still no synchrotron light source has implemented it

Computation



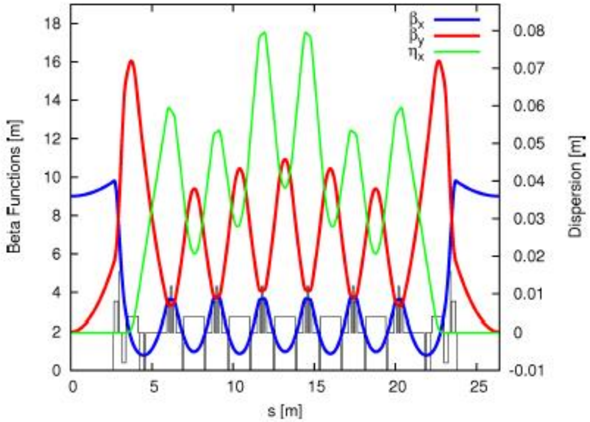
Computation capabilities increasing rapidly, allowing reliable simulations

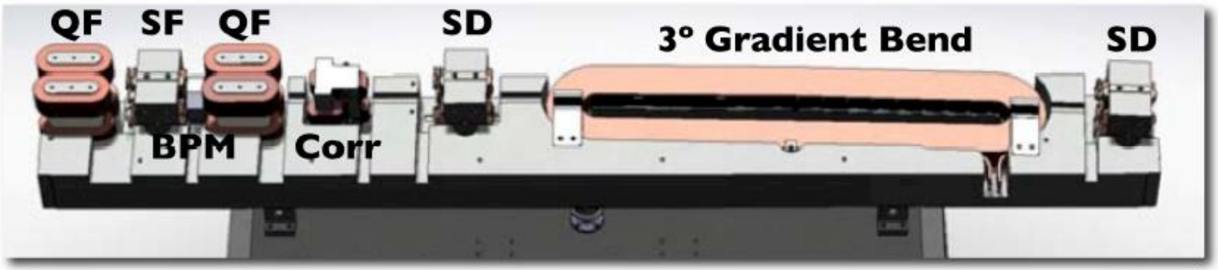


MAX IV

MAX IV Light Source[1]

- MAX IV will be the first MBA-based light source
  - 3 GeV, 528 m circumference
  - 20 7BA cells
    - Relaxed from TME condition to improve nonlinear dynamics
  - ε_0=263 pm with 4 wigglers
  - In construction





Magnets are built with common yokes to reduce cost while improving relative alignment and stability.

1: S.Leemann *et al.*, PRSTAB **12**, 120701 (2009). Figures courtesy S. Leemann.

MAX IV

NEG Coating to reduce vacuum chamber dimensions and use of small magnets

Multibend achromat, to reach 1 nmrad emittance

Block magnet construction, relying fully on simulations

Last generation of undulators

Top Up

Fast Orbit Feed back

Multipole kicker injection (with standard injection as backup)

…

Next:
even lower emittance lattices

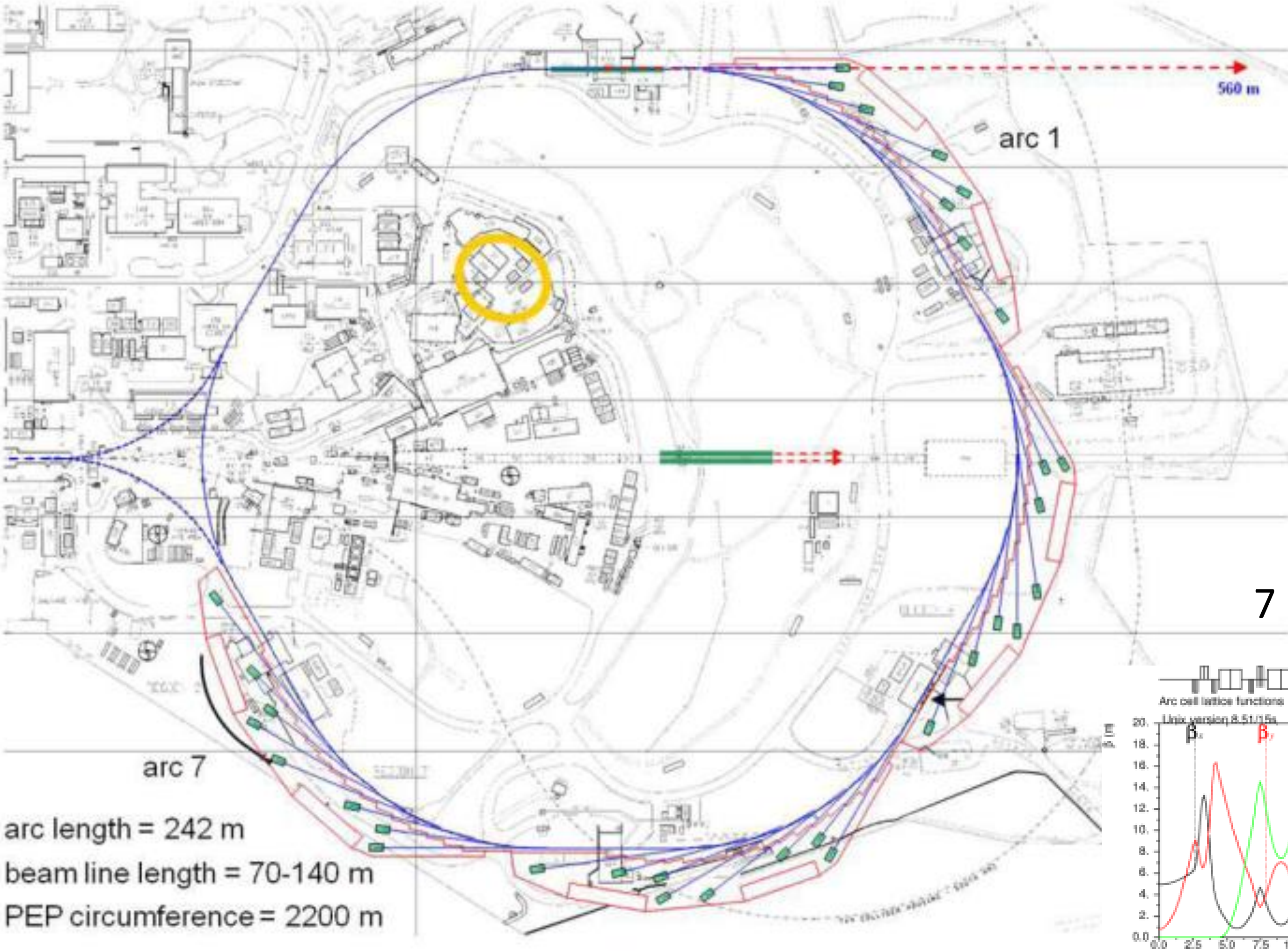
We need to master Nonlinear beam dynamics in order to optimise dynamic aperture and Touschek lifetime

MOGA – Multi-Objective (multi-parameters) Genetic Algorithms

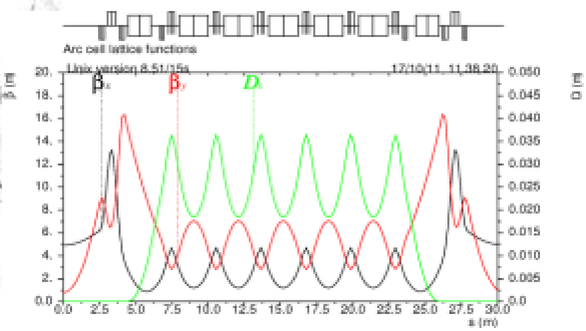
Objectives:	Dynamic aperture Momentum aperture and lifetime Tune shift with amplitude, dnx,y/dJx,y Linear optics parameters
Variables:	Sextupoles, Octupoles, Quadrupoles

Deterministic – Hamiltonian resonance driving terms analysis

PEP - X

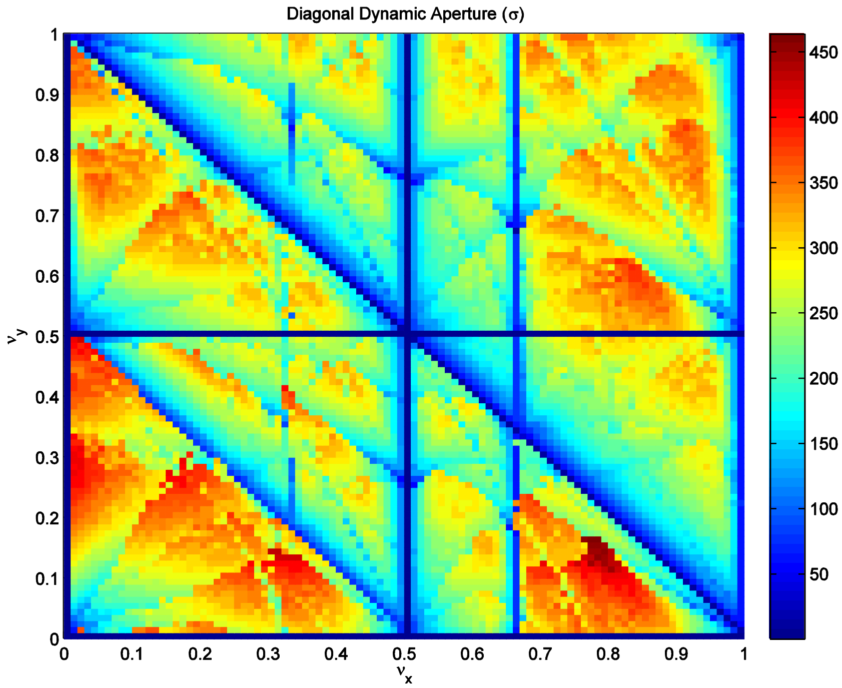


7 Bend Achromat

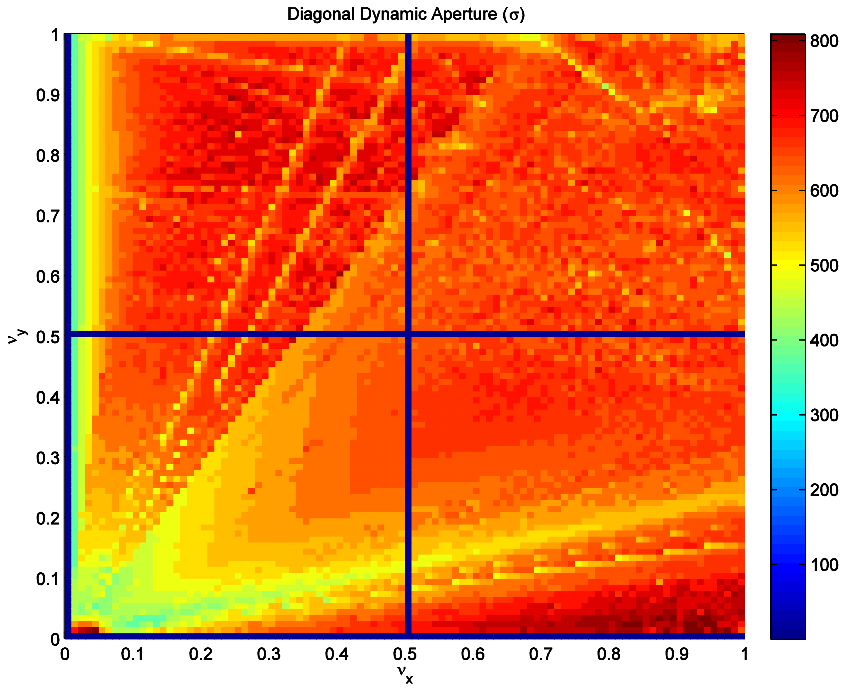


Cancellation of resonances

PEP-X: Baseline (2008)



PEP-X: USR (2011)

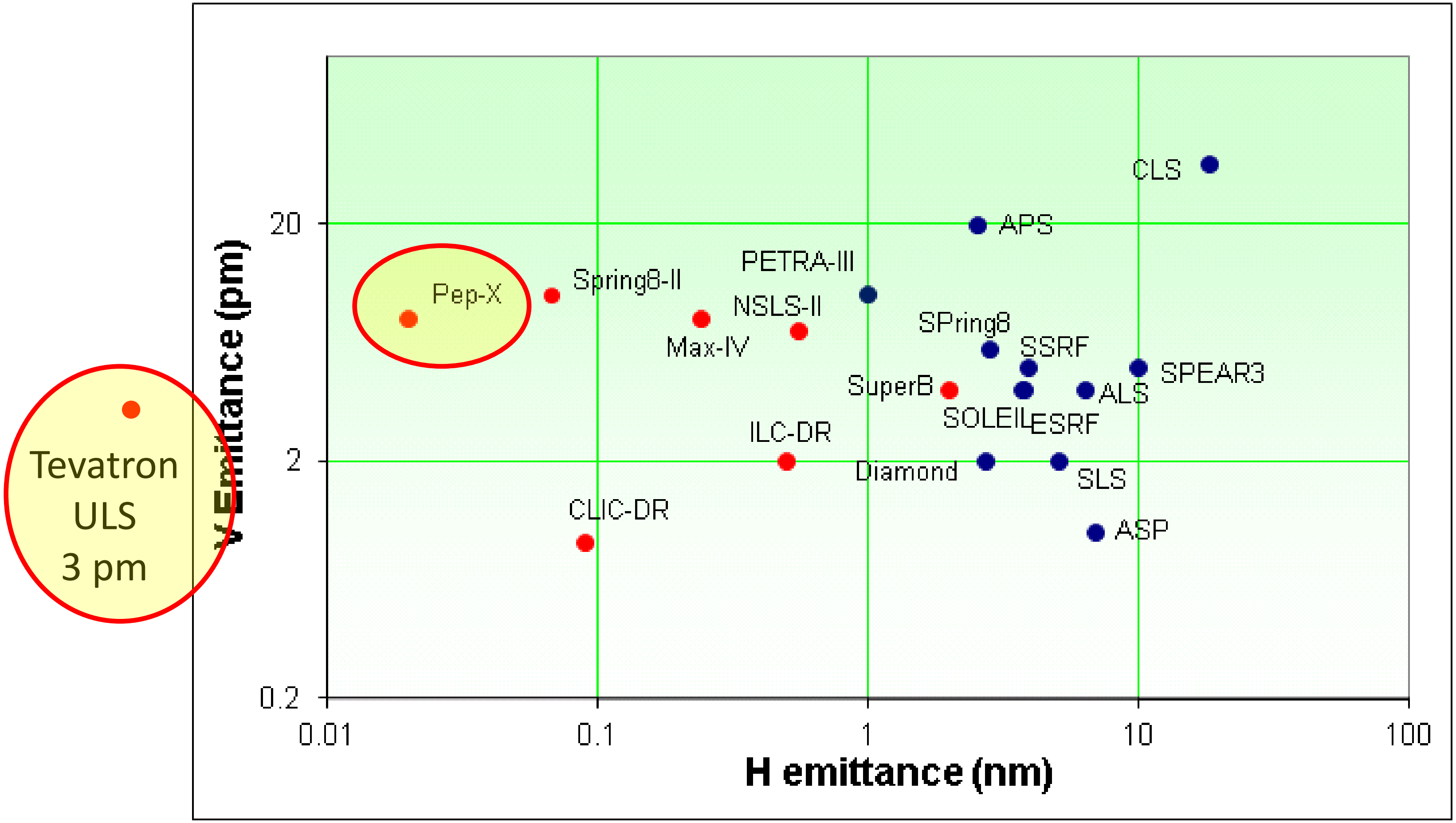


The dynamic aperture is in unit of sigma of the equilibrium beam size. The USR design is built with 4th-order geometric achromats and therefore no 3rd and 4th order resonances driven by the sextupoles seen in the scan.

Next Generation Light Sources

Parameter	PEP-X	Spring8-II	TeVUSR
Beam energy [GeV]	4.5	6.0	11.0
Circumference [m]	2200	1436	6283
Current [mA]	200	300	100
Betatron tune (H/V)	113.23/65.14	141.865/36.65	403.098/222.198
Natural chromaticity (H/V)	-162/-130	-477/-191	-580/-468
Momentum compaction	4.96×10^{-5}	1.55×10^{-5}	4.47×10^{-6}
Emittance [pm-rad]	12/12	68 (natural)	1/1
Bunch length [mm]	3	3.8	3
Energy spread	1.25×10^{-3}	0.96×10^{-3}	1.4×10^{-3}
Energy loss per turn [MeV]	2.95	4.0	18
RF voltage [MV]	8.3	16	24
RF frequency [MHz]	476	508	500
Wiggler length [m]	90	50 (may be)	188
Length of ID straight [m]	5	4	5
Beta at ID center (H/V) [m]	4.9/0.8	1.0/1.4	5/0.8

Next Generation Light Sources



Ultimate LS: Diffraction limited lattices $\varepsilon \leq \frac{\lambda}{4\pi}$ 8 pm at 1 Angstron

EuCARD²

EuCARD-2: Enhanced European Coordination for Accelerator Research & Development

Home | About | Activities | Events | Results | EuCARD | Vacancies | Contact

ACTIVITIES

- WP1: MANCOM
- WP2: INNovation
- WP3: EnEffficient
- WP4: AccApplic
- WP5: XBEAM
- WP6: LOW-e-RING
- WP7: EuroNNac2
- WP8: ICTF@STFC
- WP9: HiRadMat@SPS and MagNet@CERN
  - How to apply
- WP10: MAG
- WP11: COMA-HDED
- WP12: RF
- WP13: ANAC2

Activities

Learn more about the people taking part in the project here !

EuCARD-2 is divided into 13 Work Packages. A Work Package (WP) is a unit of work within the project. The WPs are theoretically independent but they were defined in order to foster synergies in EuCARD-2.

Management and Communication

- WP1: Management and Communication (MANCOM)

Networking Activities

- WP2: Catalysing Innovation (INNovation)
- WP3: Energy Efficiency (EnEfficient)
- WP4: Accelerator Applications (AccApplic)
- WP5: Extreme Beams (XBEAM)
- WP6: Low Emittance Rings (LOW-e-RING)
- WP7: Novel Accelerators (EuroNNAc2)

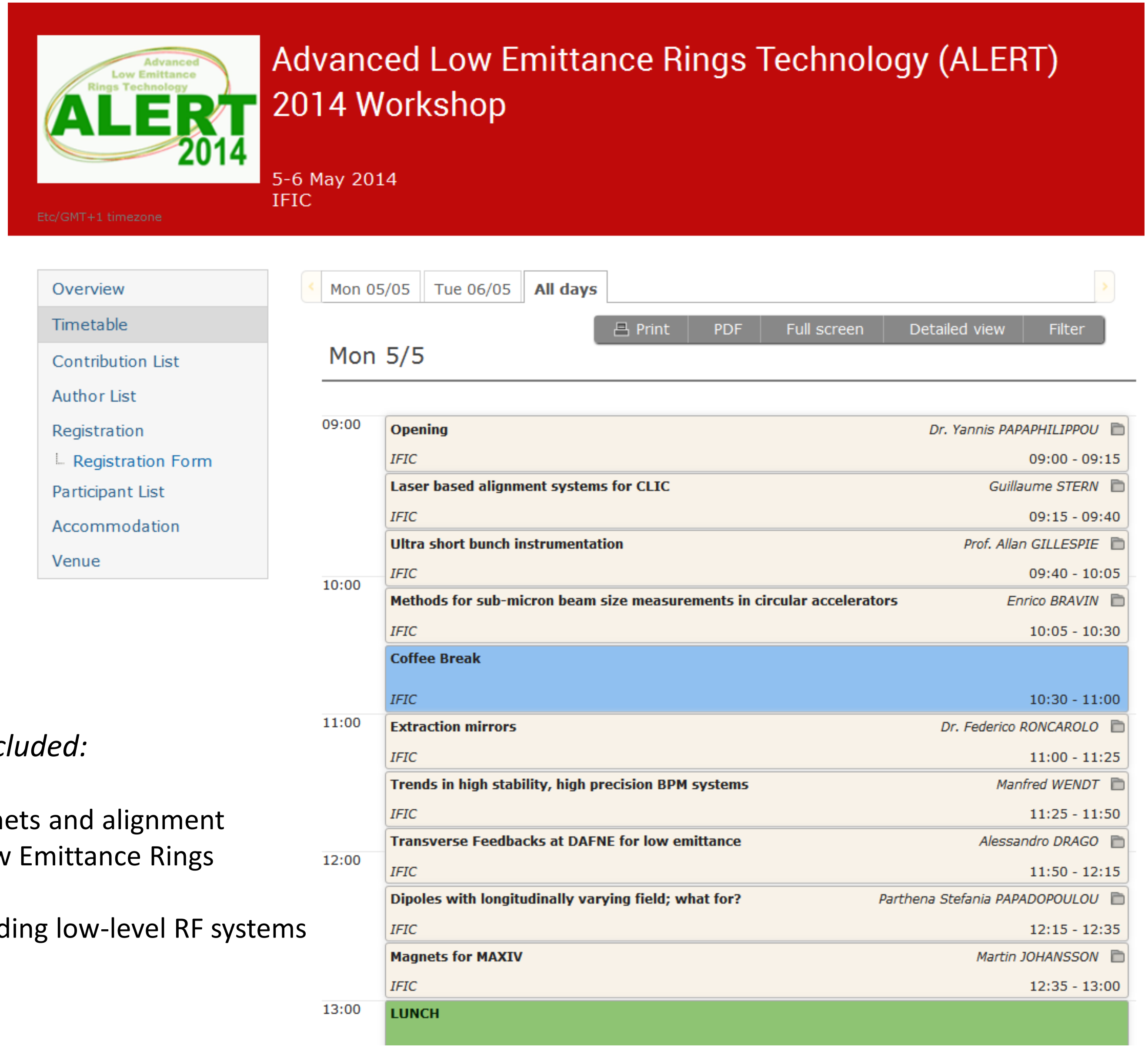
Transnational Access

- WP8: ICTF@STFC
- WP9: HiRadMat@SPS and MagNet@CERN

Joint Research Activities

- WP10: Future Magnets (MAG)
- WP11: Collimator Materials for fast High Density Energy Deposition (COMA-HDED)
- WP12: Innovative Radio Frequency Technologies (RF)
- WP13: Novel Acceleration Techniques (ANAC2)

eucard2.web.cern.ch/



Advanced Low Emittance Rings Technology (ALERT) 2014 Workshop

5-6 May 2014
IFIC

Etc/GMT+1 timezone

Overview
Timetable
Contribution List
Author List
Registration
Registration Form
Participant List
Accommodation
Venue

Mon 05/05 | Tue 06/05 | All days

Print | PDF | Full screen | Detailed view | Filter

Mon 5/5

Opening	Dr. Yannis PAPAPHILIPPOU	IFIC	09:00 - 09:15
Laser based alignment systems for CLIC	Guillaume STERN	IFIC	09:15 - 09:40
Ultra short bunch instrumentation	Prof. Allan GILLESPIE	IFIC	09:40 - 10:05
Methods for sub-micron beam size measurements in circular accelerators	Enrico BRAVIN	IFIC	10:05 - 10:30
Coffee Break		IFIC	10:30 - 11:00
Extraction mirrors	Dr. Federico RONCAROLO	IFIC	11:00 - 11:25
Trends in high stability, high precision BPM systems	Manfred WENDT	IFIC	11:25 - 11:50
Transverse Feedbacks at DAFNE for low emittance	Alessandro DRAGO	IFIC	11:50 - 12:15
Dipoles with longitudinally varying field; what for?	Parthena Stefania PAPADOPOULOU	IFIC	12:15 - 12:35
Magnets for MAXIV	Martin JOHANSSON	IFIC	12:35 - 13:00
LUNCH			13:00

Workshop sessions included:

Insertion devices, magnets and alignment
Instrumentation for Low Emittance Rings
Kicker systems
RF system design, including low-level RF systems
Vacuum design
Feedback systems

Conclusion

- There are over 50 synchrotron worldwide (still some of the 1st generation)
- Science with synchrotron light is in the forefront
- Synchrotron Light Sources have been and are evolving continuously
- Evolution is based on R&D effort in different fields and on the new requirements of the users
- Still lots to do…

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- ICFA Workshop Future Light Sources, 2012, www.conferences.jlab.org/FLS2012
- and more…

Thank you

Francis Perez