The Next Generation of Storage-Ring Based Light Sources: MAX IV and beyond

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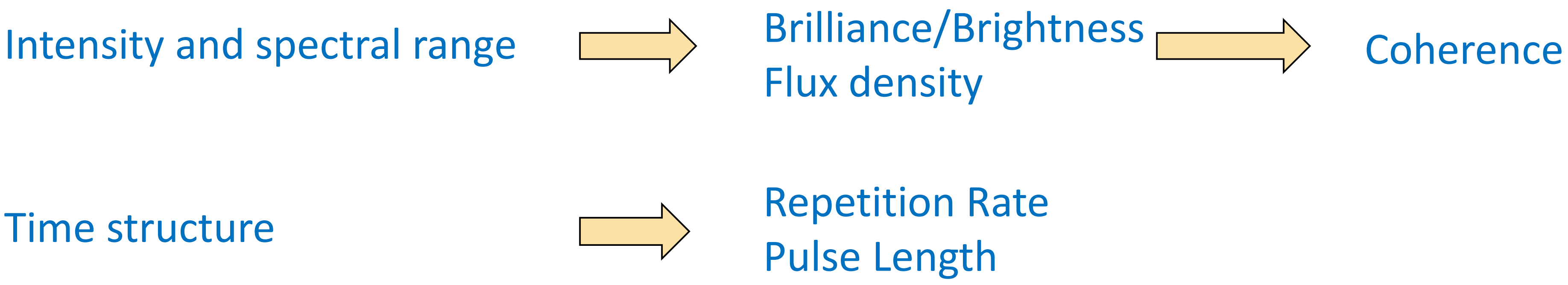
Outline

- Storage-ring based light source performance parameters.
  - Transverse brightness and coherence: *The MBA lattice*.
- The landscape of storage-ring based light sources: *immediate future.*
- Enabling & Enabled Technologies.
- How can we go further ? *The next generation.*
- An exercise: *preliminary design for a diffraction limited source in the MAX IV 3 GeV ring tunnel.*
- Summary and Conclusions.

SR-based Light Source Performance Parameters

why do we build them ?



Intensity and spectral range

Brilliance/Brightness
Flux density

Coherence

Time structure

Repetition Rate
Pulse Length

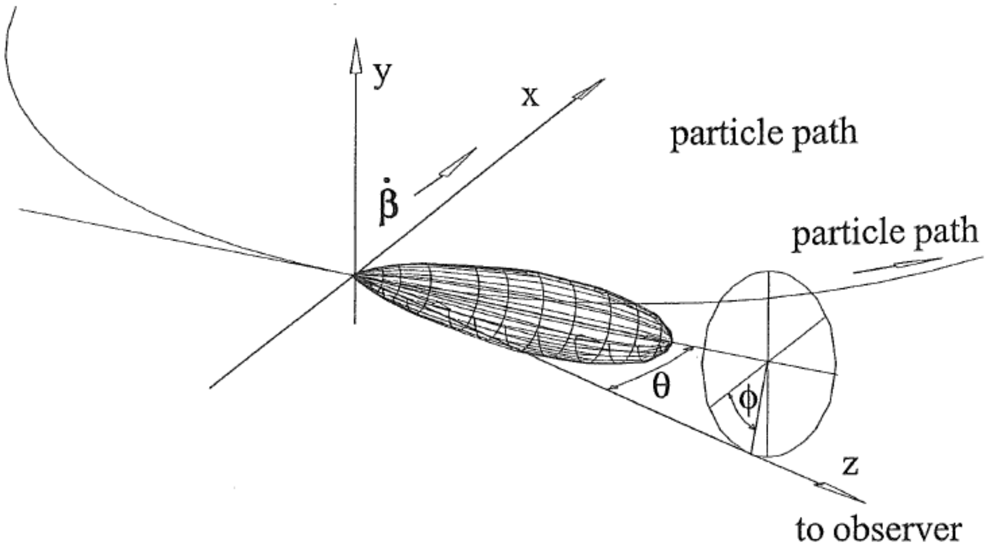
Polarization

Stability

Reliability

Multi-user capacity

Spectral Brightness



Photon Phase Space

$$B(E,\phi,\theta,x,y)=\frac{dN}{dt\,d\delta\,d\theta\,d\phi\,dx\,dy}$$

Density in photon phase space

In an ideal optical transport system, brightness is conserved – a property of the source.
Several derived quantities are often used

Central Brightness

Angular density of flux

$$B_0=\left.\frac{dN}{dt\,d\delta\,d\theta\,d\phi\,dx\,dy}\right|_{x=y=\theta=\alpha=0}$$

$$F_0=\int B\,d\phi\,dx\,dy$$

H.Wiedemann, Part.Acc.Phys, Vol II

Transverse Coherence and Brightness

- Coherence of electromagnetic perturbations at two points on a plane perpendicular to the direction of propagation.
- Relates to the capability to generate interference patterns

Maximum Brightness (diffraction limited source):

$$B_{dl} = \frac{4F_n}{\lambda^2}$$

Coherent Flux:

$$\Im = B\left(\frac{\lambda}{2}\right)^2$$

Harder for short wavelengths

Brightness from a real beam

Convolute the angular distribution of radiation from a single electron with the electron beam transverse spatial and angular distributions

For the n-th harmonic of an undulator of length L

Spectral flux (E,I,B,n)

$$B_{0n} = \frac{F_n}{(2\pi)^2 \sigma_{Tx}\sigma_{Ty}\sigma_{Tx'}\sigma_{Ty'}}$$

Effective source size and divergence

Electron beam

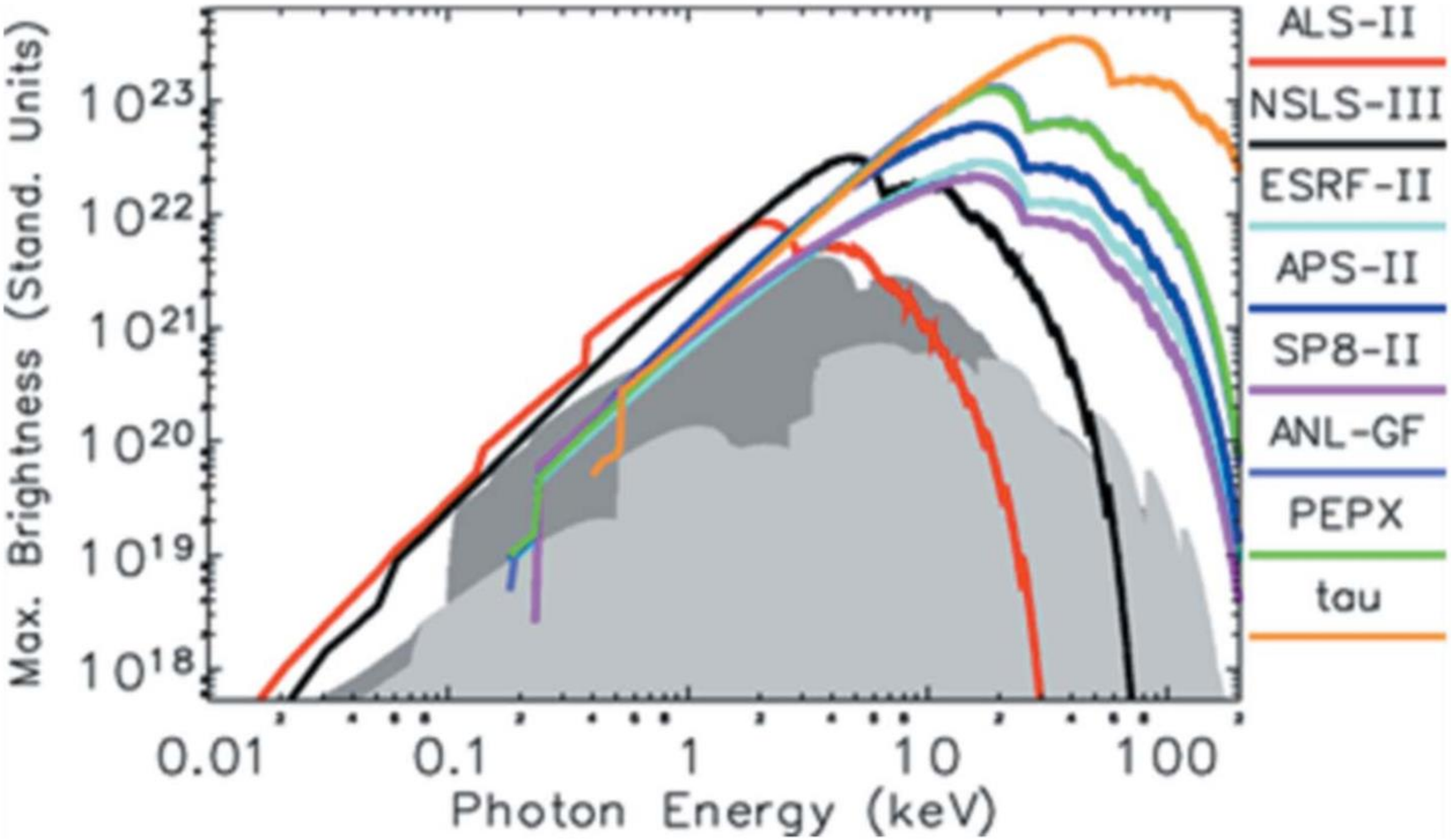
$$\sigma_{Tx} = \sqrt{\sigma_x^2 + \sigma_r^2} \qquad \sigma_r = \frac{1}{4\pi}\sqrt{\lambda L}$$

$$\sigma_{Tx'} = \sqrt{\sigma_{x'}^2 + \sigma_{r'}^2} \qquad \sigma_{r'} = \sqrt{\frac{\lambda}{L}}$$

Diffraction Limit: $\sigma_r \sigma_{r''} = \frac{\lambda}{4\pi}$

e-beam emittance $\varepsilon_x = \sigma_x \sigma_{x'}$

Brightness Evolution



From: Bob Hettel, *DLSR design and plans: an international review, JSR (2014)* ***21*** *843-855*

Damping/Excitation of Transverse Oscillations Oscillations

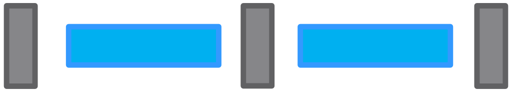
- Discrete photon emission changes momentum along the direction of propagation If this happens in a **dispersive** region of the magnet lattice, a transverse (betatron) oscillation will be **excited**.
- Momentum is regained at the RF cavity only along the longitudinal direction. This causes a reduction of the particle angles (**damping**).
- Both effects together lead to an **equilibrium** state that define the transverse beam dimension and angular spread, i.e., the **emittance**.

Number of dipoles

$$\boxed{\varepsilon_0 = C_q \frac{\gamma^2\theta^3}{12\sqrt{15}J_x}F}$$

Lattice

Many Possible Lattice Designs



$$\varepsilon_0 = \frac{C_q}{J_x}\gamma^2 \frac{\theta^3}{4\sqrt{15}}$$

Double Bend Achromat

$$\varepsilon_0 = \frac{C_q}{J_x}\gamma^2 \frac{\theta^3}{12\sqrt{15}}$$

Theoretical Minimum Emittance

Triple Bend Achromat

$$\varepsilon_0 = \frac{1.1C_q}{J_x}\gamma^2 \frac{\theta^3}{4\sqrt{15}}$$

▮ one or more quadrupoles

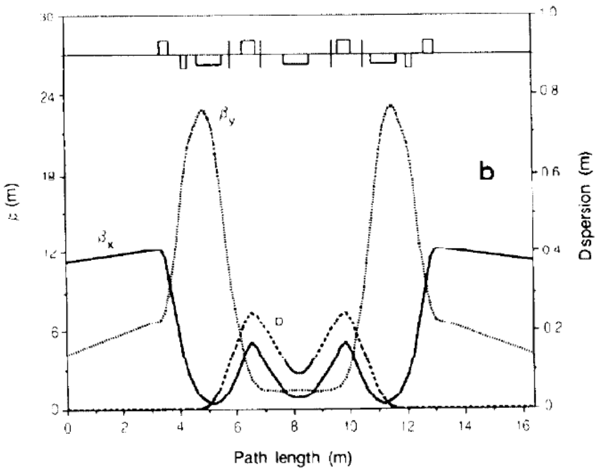
▬ bending Magnet

3rd Generation Lattice Designs 1990’ s & 2000’ s

Pictures: PAC/EPAC

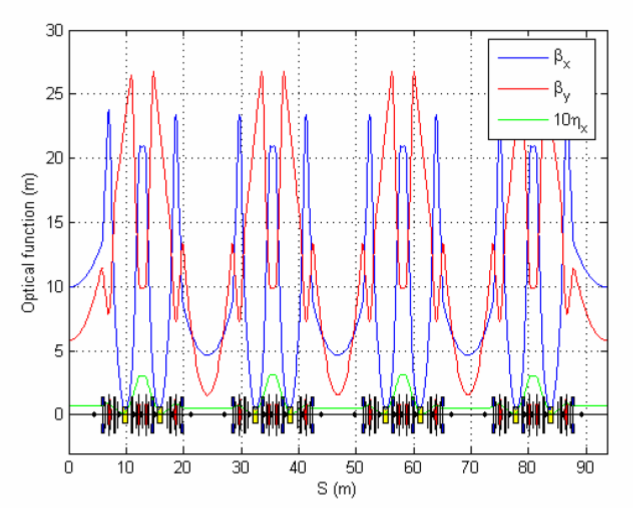
ESRF- 1993

DBA – 6 GeV – 844 m – 6 nmrad



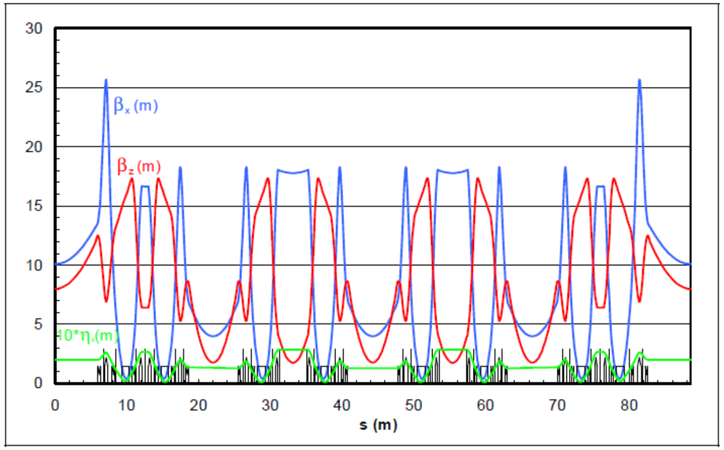
ALS - 1993

TBA – 1.5 GeV – 197 m - 3.5 nmrad



Diamond - 2006

DBA - 3 GeV - 562 m - 2.7 nmrad



Soleil - 2006

DBA – 2.75 GeV – 354 m – 3.7 nmrad

The Multi-Bend Achromat Lattice

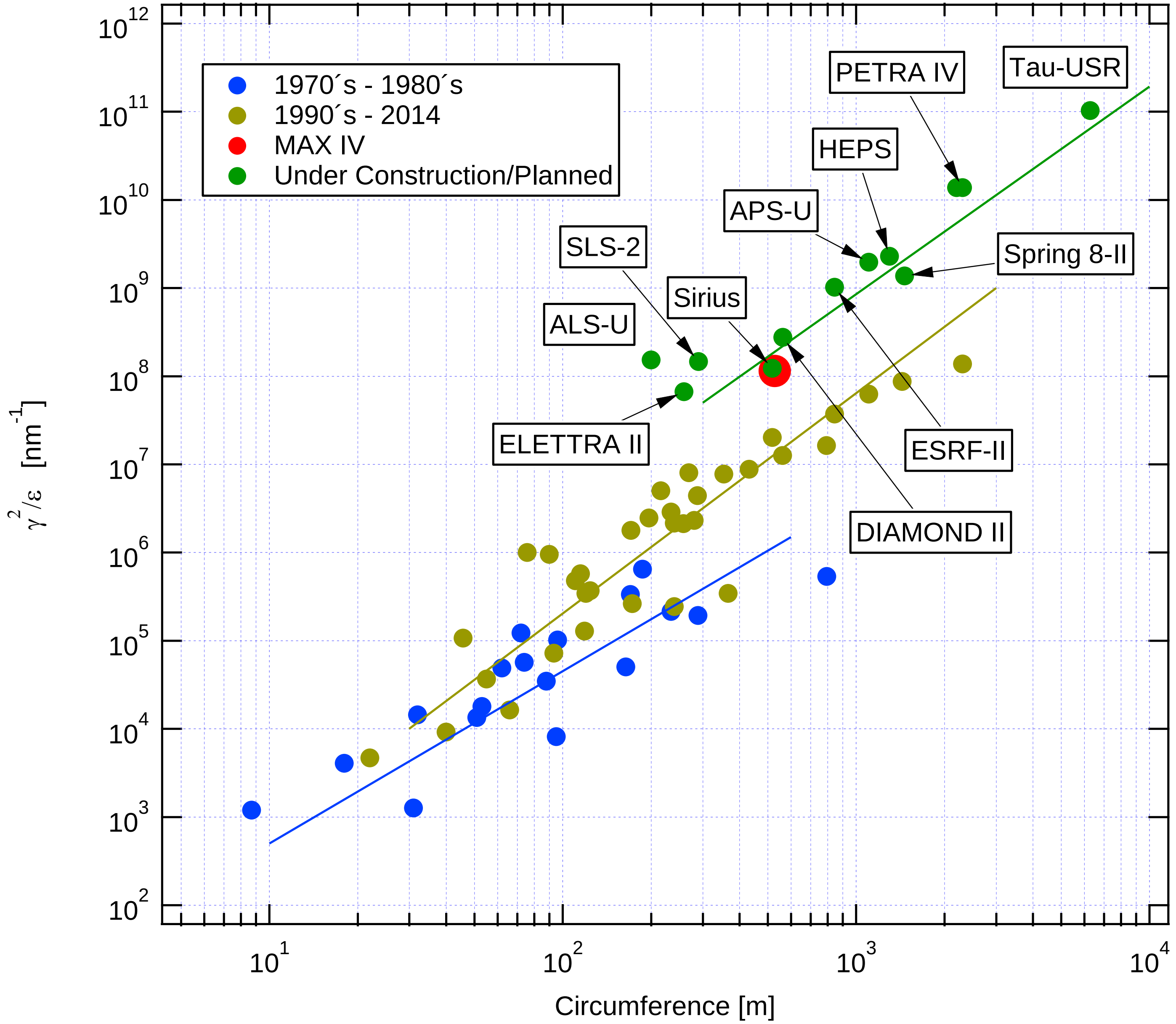
Basic concepts date back to the 90’ s:

- ☐ NIM--A 335 1993, Einfeld et al. “A modified QBA optics for low emittance rings”
- ☐ EPAC’94 Joho et al. Design of a Swiss Light Source
- ☐ PAC’95, Einfeld et al.: Design of a Diffraction Limited Light Source

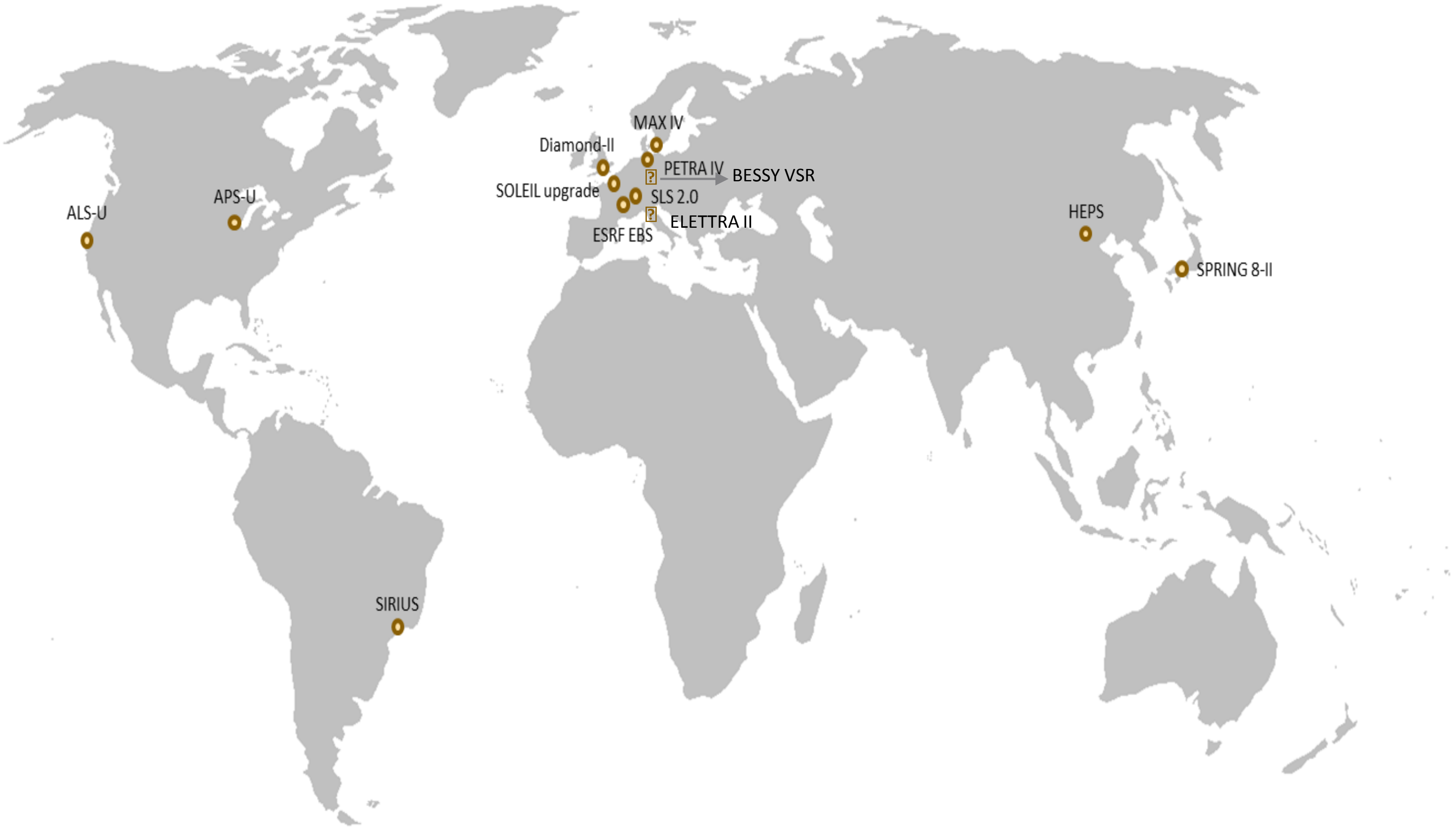
Along 2000’s:

- ☐ Tools available for non-linear optimization of such lattices.
- ☐ Engineering issues were tackled.

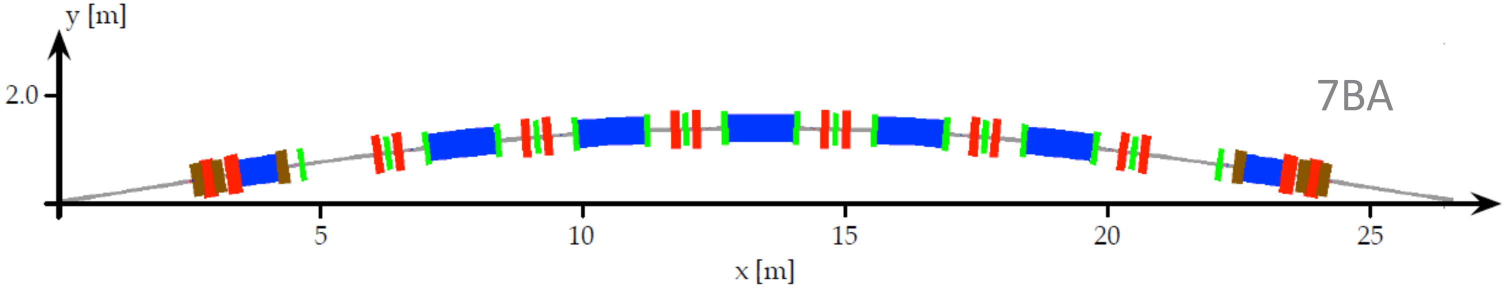
The Quest for higher brightness



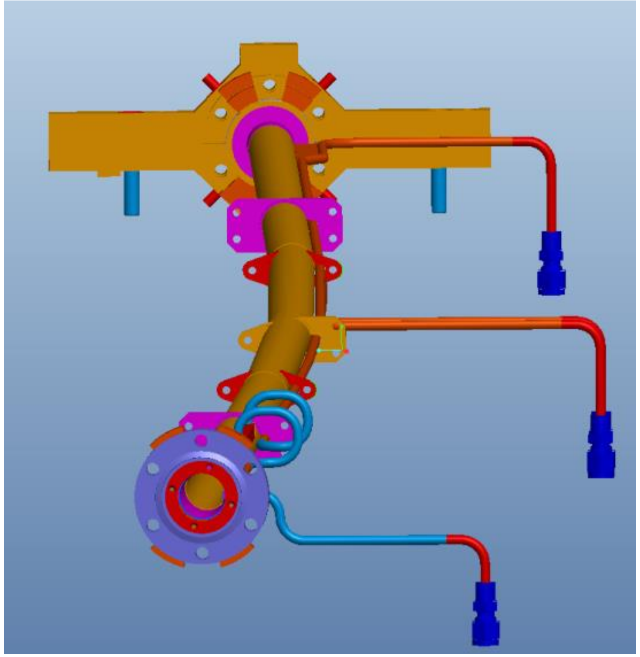
The (immediate) Future Landscape of SR-based Light Sources



MAX IV: 3 GeV, 528 m, 330 pmrad



100 MHZ RF



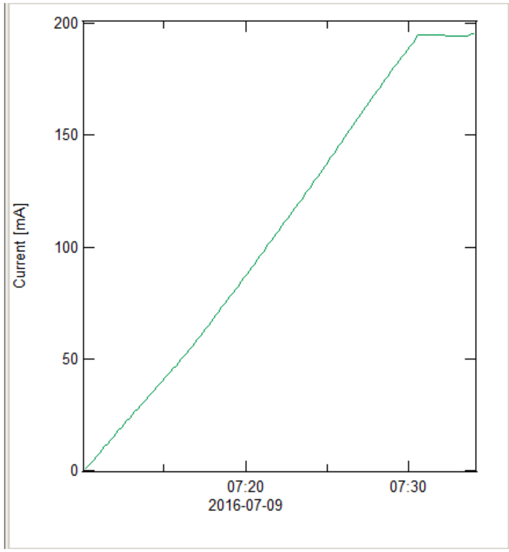
Circular, copper NEG-coated chambers

Compact Magnets

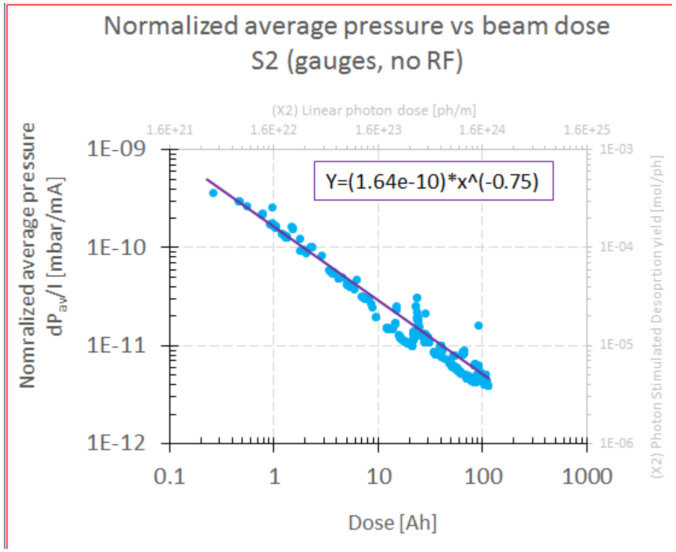
photo: Anna Olsson, Scanditronix Magnet AB

MAX IV 3 GeV Ring Commissioning Results

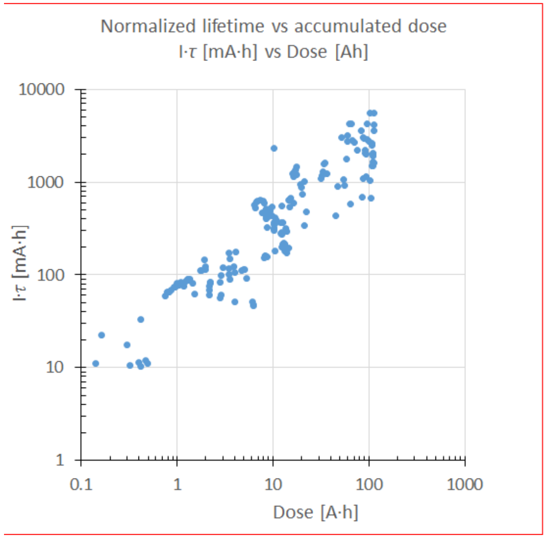
Up to 198 mA in multibunch mode

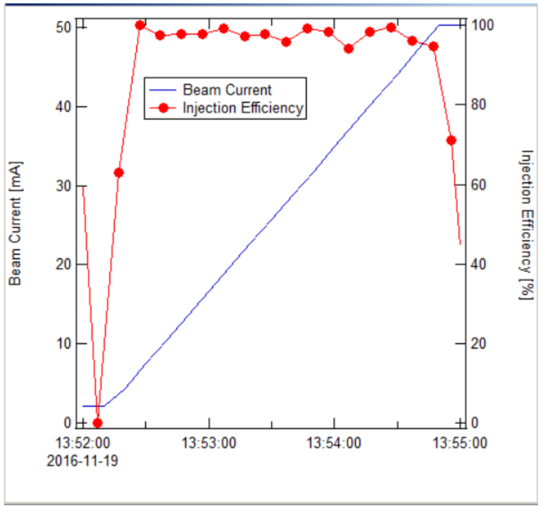


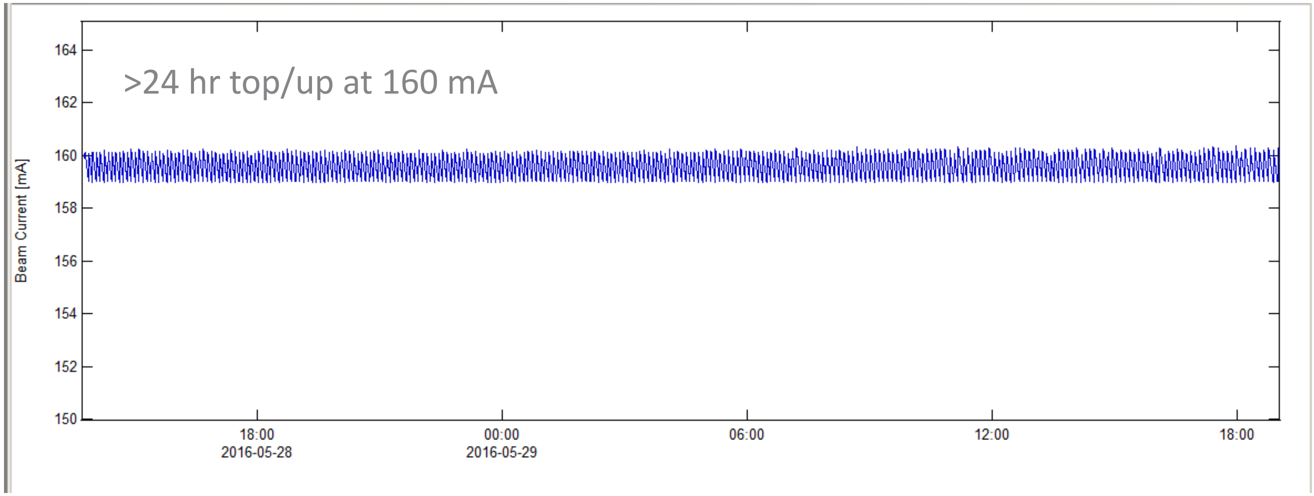
> 100 A.h Accumulated Dose


Normalized average pressure vs beam dose
S2 (gauges, no RF)

>6 A.h product lifetime*Current


Normalized lifetime vs accumulated dose
I·τ [mA·h] vs Dose [Ah]

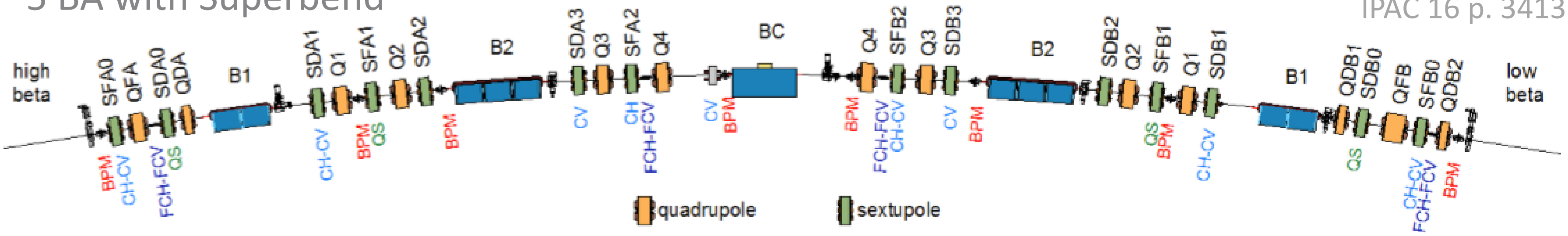


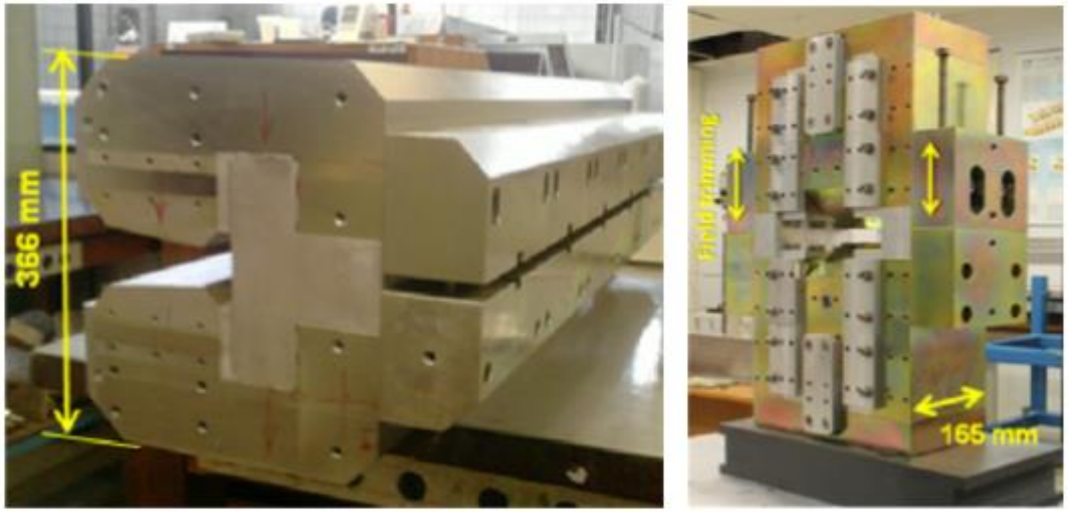

>24 hr top/up at 160 mA

Sirius: 3 GeV, 528 m, 250 pm.rad

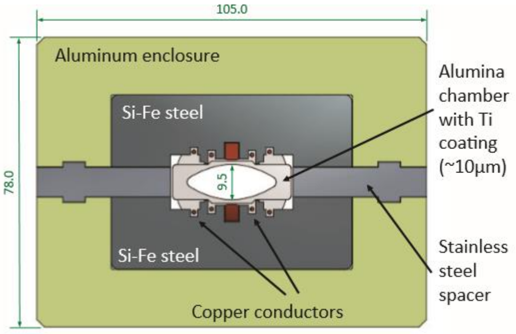
5 BA with Superbend

IPAC 16 p. 3413

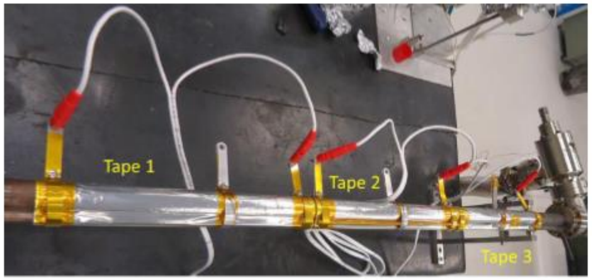




Permanent Magnet Dipoles with High Field Slice
IPAC 11 p. 931



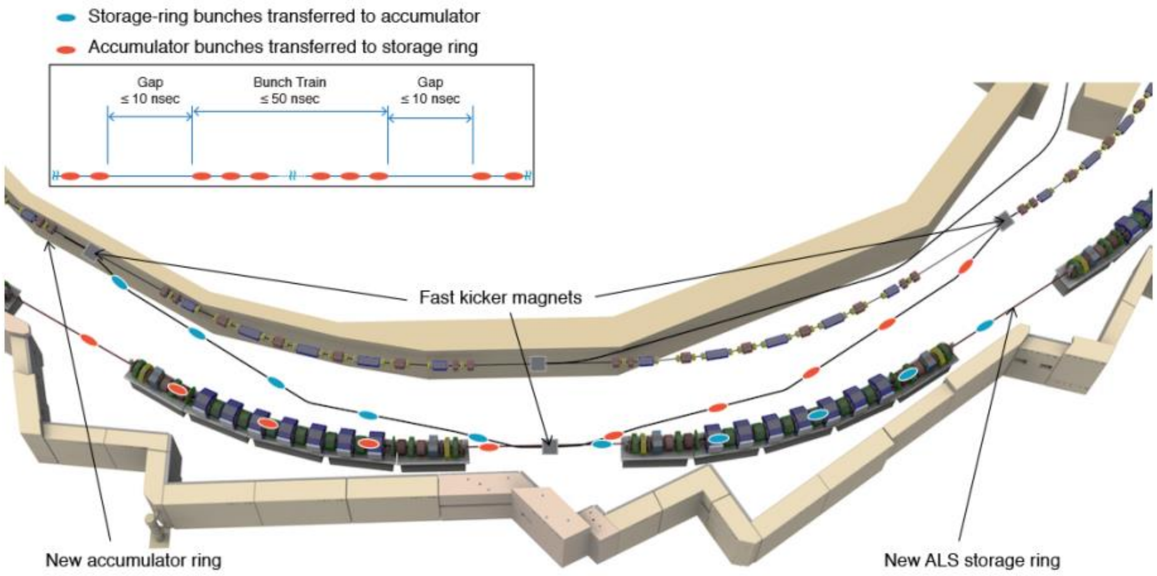
Multipole Kicker
IPAC 16 p. 1405

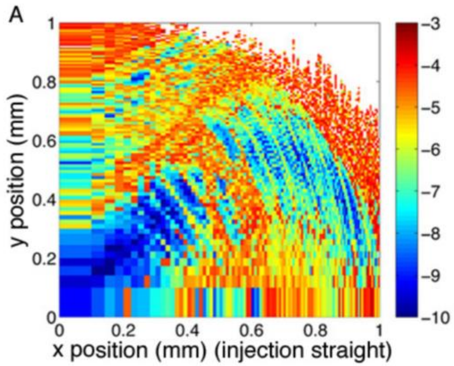


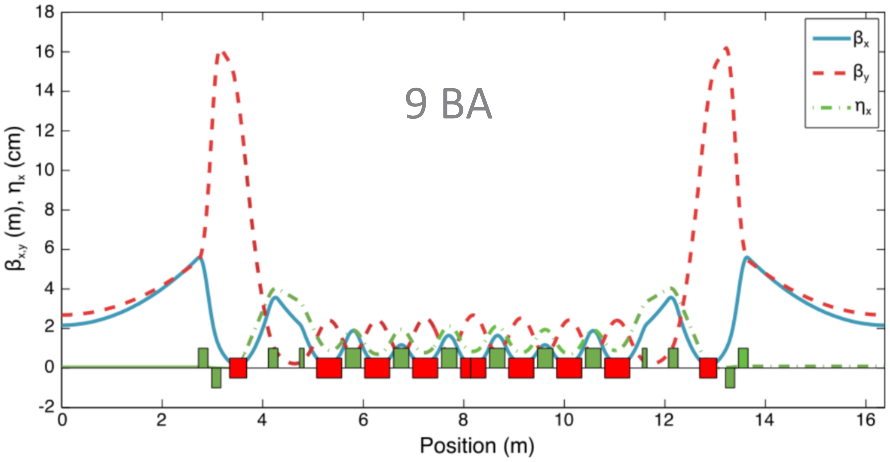
Thin heater tapes for in-situ NEG activation
IPAC 15 p. 2744

ALS-U: 2 GeV, 200 m, 50 pm.rad

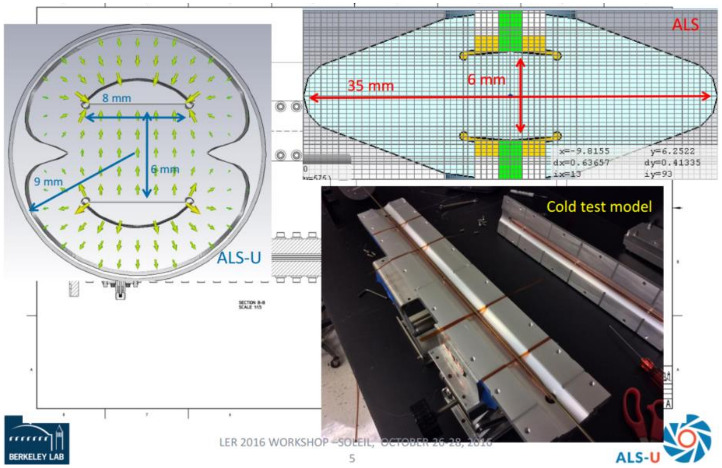
ALS-U proposal,
April 2016





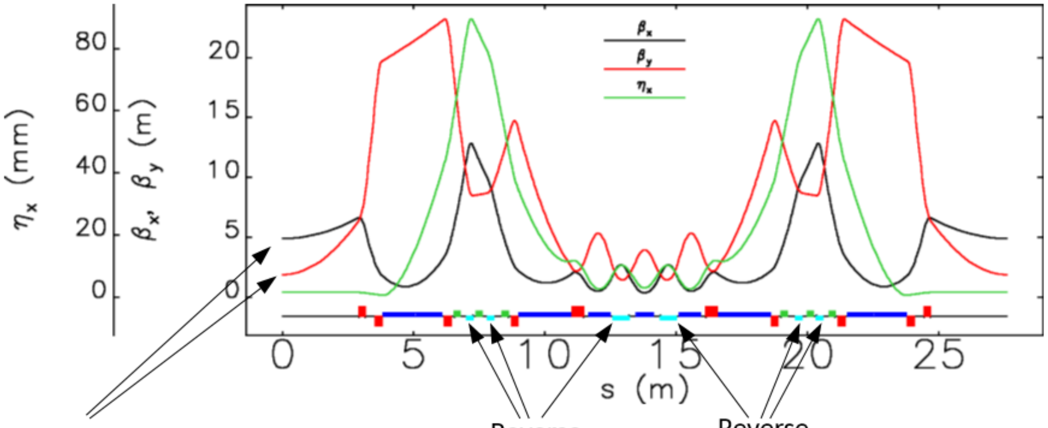


Stefano de Santis, LER Workshop 2016



APS-U: 6 GeV, 1100 m, 41 pmrad

Hybrid 7 BA, reverse bends



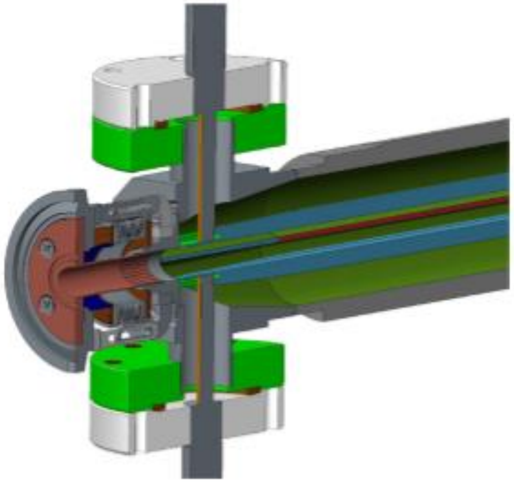
Improved beta functions

Reverse bends

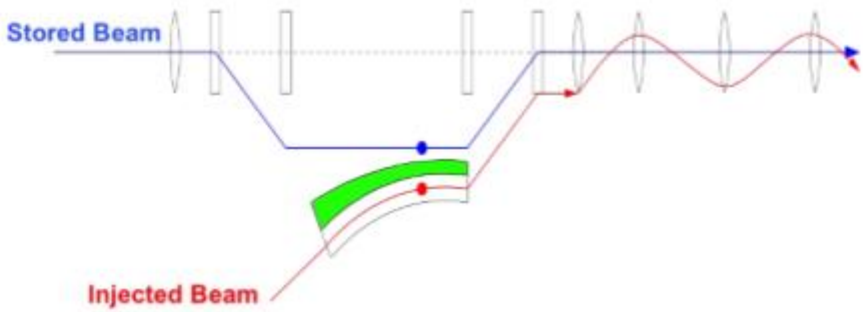
Reverse bends

M.Borland, APS-U Forum, October 2016

C.Yao et al, IPAC 2016



Traditional off-axis injection



On-axis swap-out injection

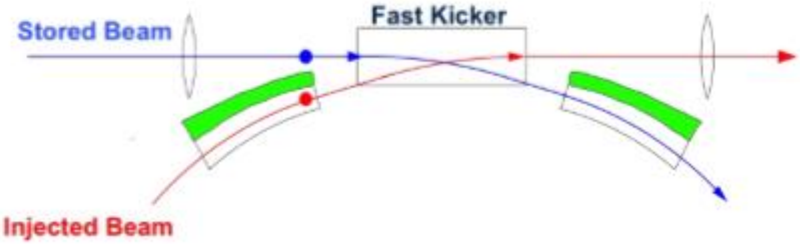


Figure courtesy D. Robin (LBNL)

HEPS, 6 GeV, 1300 m, 60 pm.rad

The R&D project of HEPS (Test facility of HEPS, HEPS-TF) has been approved and started in 2016, will finished in 2018.

The plan of construction has been approved by central government; the construction of HEPS is scheduled in 2018

Beijing municipal government will support the construction of Advanced Light Source Test Platform, in order to develop the techniques of accelerator and X-ray optics

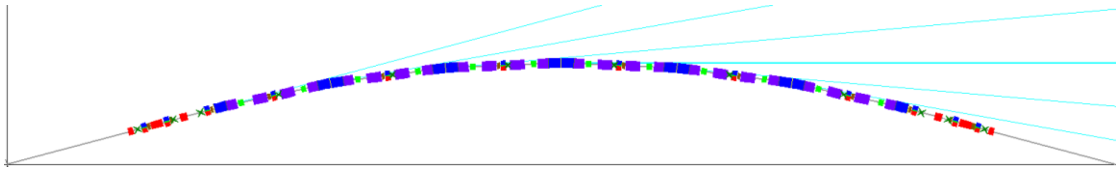
The constructions of XFEL and ERL in future are also planed in same area.

courtesy Yuhui Dong

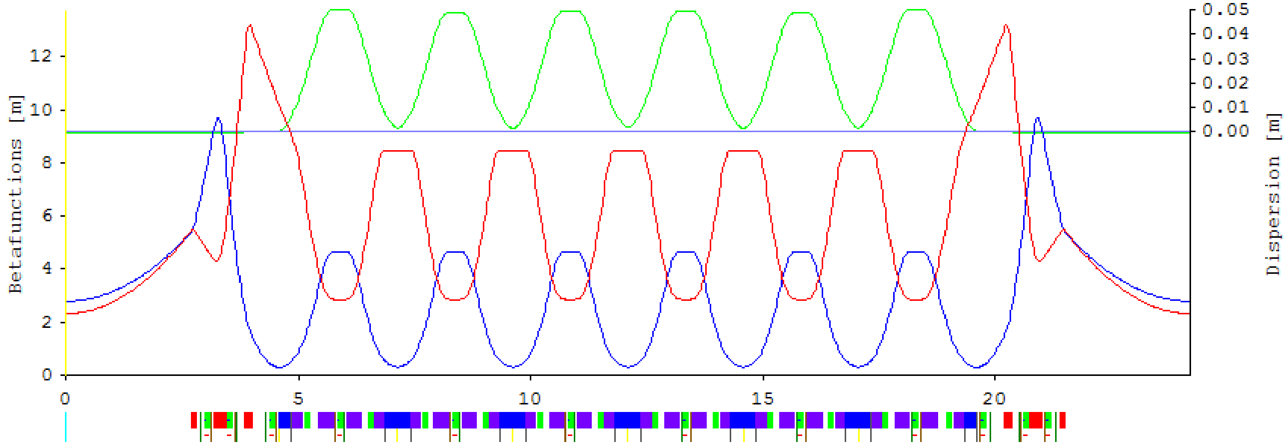
Hybrid 7 BA

3. SLS-2 period-12 7-BA lattice

courtesy Andreas Streun

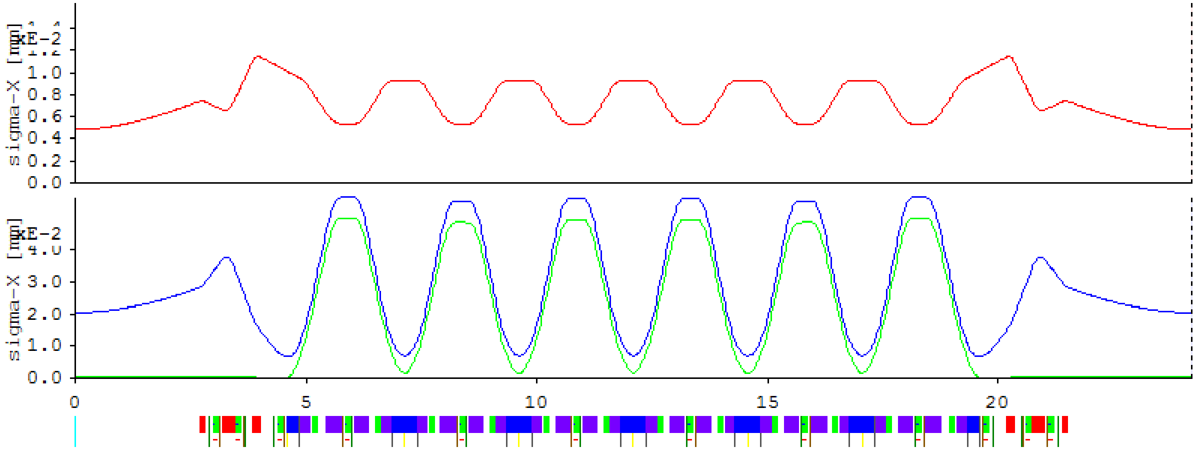


Arc layout (30°)



Optical functions

β_x β_y η



rms beam size

σ_x σ_y $\eta\sigma_e$

≈ 20 µm × 5 µm
in straight centers

5. Summary and Outlook

courtesy Andreas Streun

Storage ring upgrade: old → new

- Lattice type: 12×TBA → 12×**7**-BA
  - longitudinal gradient bend / anti-bend cell
- Emittance: 5 nm → ≈150 pm(incl. IBS)
- Circumference: 288 m → 290.4 m
- Periodicity: **3** → **12**
- Straight sections:
  3×11 m, 3×7 m, 6×4 m → 12×5½ m
- 3 Superbends: 2.9 T → 6.0 T
- maintained:
  - 2.4 GeV beam energy, 400 mA current
  - off-axis top-up injection

PETRA IV – Decoding the Complexity of Nature

courtesy R.Wanzenberg

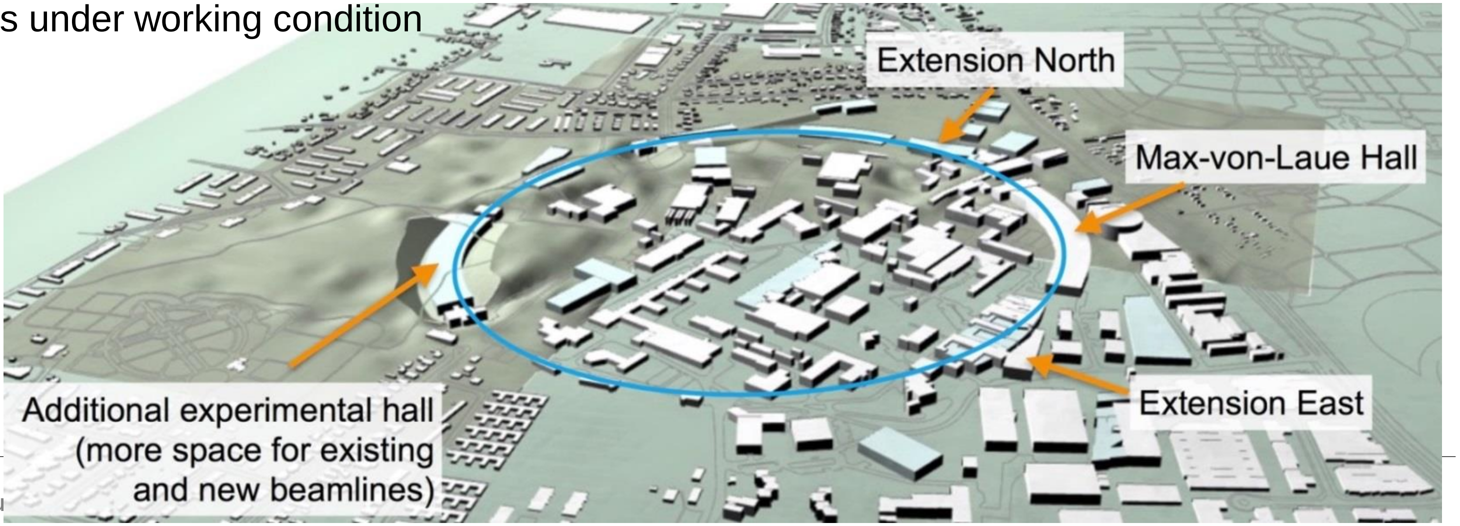
PETRA IV – The ultimate 3D process microscope has the potential:

- to address individual organelles in living cells and follow metabolism pathways with elemental and molecular specificity
- to image the chemistry inside a battery down the atomic level and understand their aging processes
- to map interfaces in functional materials, e.g., for a thorough understanding of frictional processes on the way to enhance energy efficiency and reduce emissions
- to study the synthesis of novel materials and catalytic reactions inside a chemical reactor on all relevant length scales
- to image individual grains in novel materials and alloys under working condition

Parameters and parameter range:

PETRA IV Parameter		
Energy	6 GeV	(4.5 – 6 GeV)
Current	100 mA	(100 – 200 mA)
Number of bunches	~ 1000	
Emittance horz.	10 pm rad	(10 – 30 pm rad)
vert.	10 pm rad	(10 – 30 pm rad)
Bunch length	~ 100 ps	

2300 m circumference



Lattices Investigated for the PETRA Upgrade

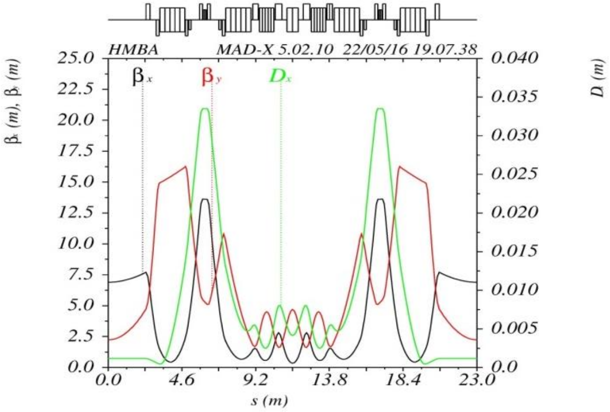
➢ Started to investigate two different lattice types

courtesy R.Wanzenberg

1. Based on the ESRF-HMBA cell
2. Based on 4D-phase space exchange and MBAs with non-interleaved sextupoles

1. Lattice based on HMBA Cells

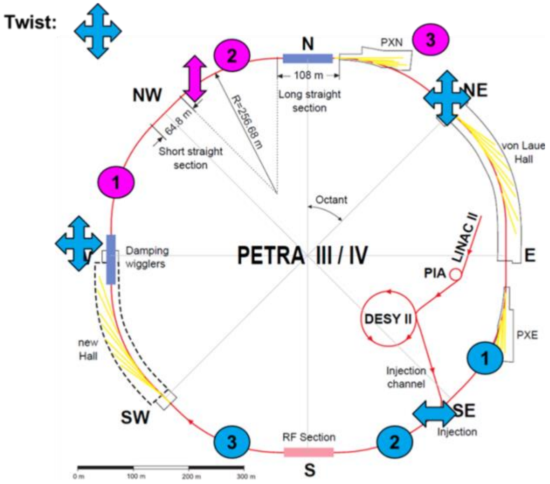
- Arcs: 9 HMBAs cells to build a 45° arc
- 8 identical arcs
- Straight sections: FODO cells

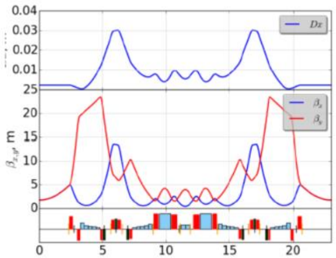


Horz. emittance of HMBA-based ring is 12 pm·rad at 6 GeV ✓
Cell not yet optimized,
(small dynamic aperture) ✗

2. 4D-phase space exchange and MBAs

- arc cells with non interleaved sextupoles
- Undulator section, preliminary version with HMBA





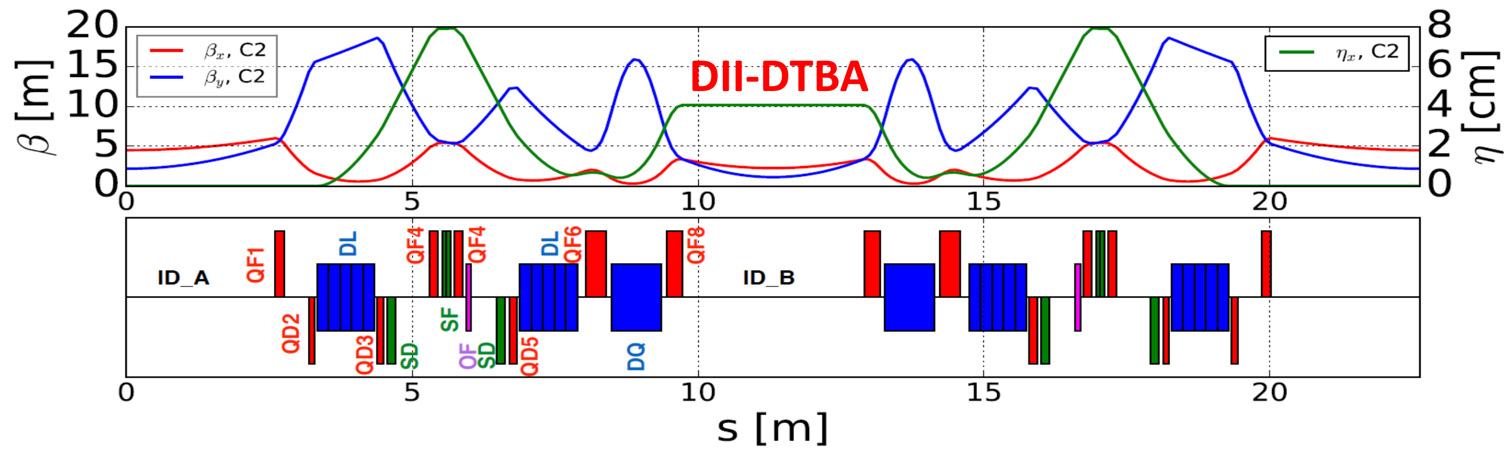
Emittance ~ 20/20 pm ✓
(5 GeV, wigglers not yet included)
Undulator cell not yet optimized ✗

3 GeV, 562 m, 125 pmrad

Diamond-II

courtesy Richard Walker

The main lattice under study is a "double triple-bend-achromat (DTBA)", based on the ESRF hybrid-7BA lattice, and combining the benefits of low emittance and a large increase in capacity for insertion device beamlines:



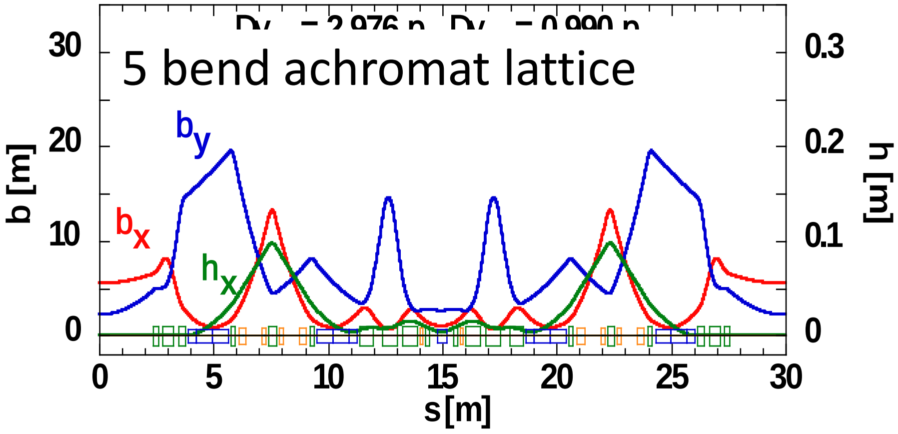
- **Natural emitance ~ 125 pm**
- **Several existing Bending Magnet and short ID beamlines can convert to full Insertion Device beamlines.**
- **New beamlines can be built without impact on existing beamlines.**

Study of a Double Triple Bend Achromat (DTBA) Lattice for a 3 GeV Light Source, A. Alekou et al., Proc. IPAC 2016, WEPOW044

diamond

"SPring-8-II"

a next step for the cutting-edge hard x-ray light source complex



	SPring-8-II	SPring-8
Energy (GeV)	6	8
Stored current (mA)	> 100	100
Effective emittance (nmrad)	0.157 ~0.1 w/ ID	2.8
Energy spread (%)	0.093	0.109
βx, βy @ ID (m)	(5.5, 2.2)	(31.2, 5.0)

> Lower energy, 6 GeV

> Lower hor.&vert. beta-functions

> Extremely small emittance beam injection from SACLA linac

> 4 longitudinal gradient bends (LGB)

> No very strong magnets
$Q < 60$ T/m, $Sx < 3{,}000$ T/m^2

Development of subsystems on going...

> LLRF for on-demand pulse-by-pulse injection from SACLA

> Permanent magnet based dipoles

> Short period undulators with force cancellation

> No-perturbation and small-amplitude beam injection system

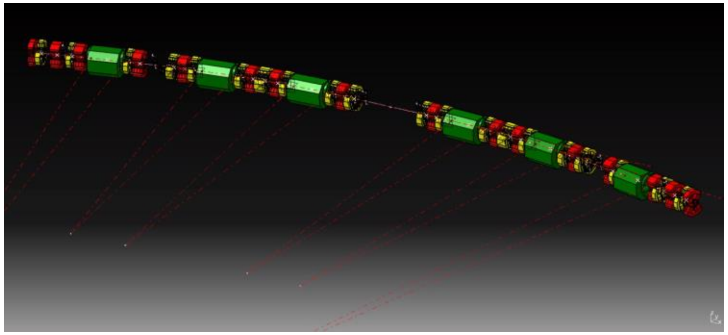
and more (vacuum, monitor, RF etc.).

Courtesy Hitoshi Tanaka

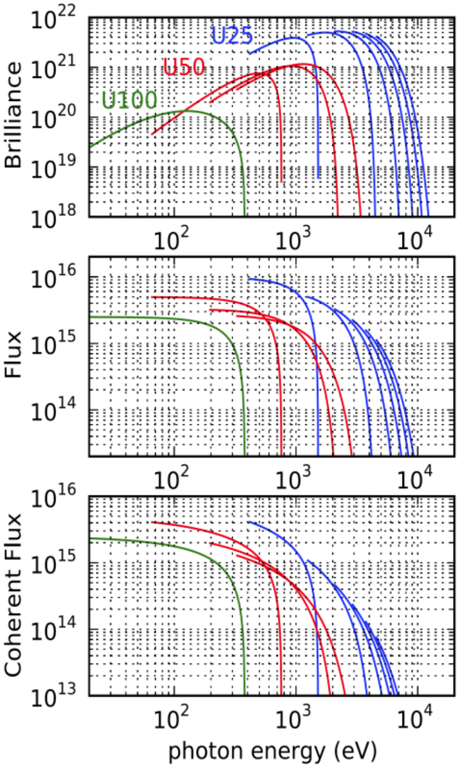
Elettra
Sincrotrone
Trieste

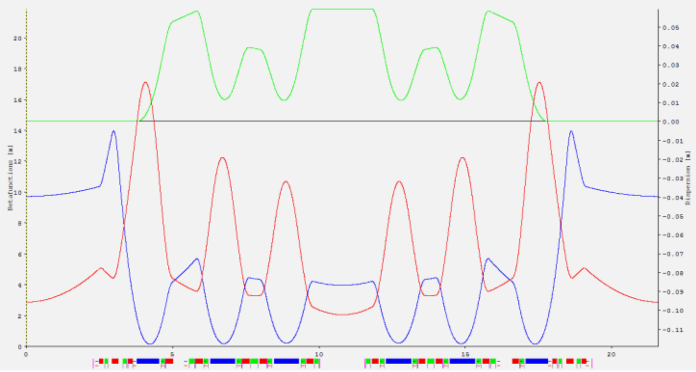
Elettra 2.0

courtesy Emanuel Karanzoulis



Parameter	units	Elettra	Elettra 2.0
Energy	GeV	2 - 2.4	2
Circumference	m	259.2	259.2
Horizontal Emittance	pm-rad	7000 @ 2 GeV	230-280
Vertical Emittance (1% coupling)	pm-rad	70	2.5
Beam size @ ID (σx,σy)	μm	245 , 14 (1% coupling)	43 , 3
Beam size @ short ID	μm	350 , 22 (1% coupling)	45 , 3
Beam size @ Bend	μm	150 , 28 (1% coupling)	17 , 7
Bunch length	ps	18 (100 with 3HC)	7 (70- 100 with 3HC)
Energy spread DE/E	%	0.08	0.07
Bending angle (per half achromat - 1/24)	degree	15	3.6 and 2x5.7
Coherence fraction @ 100 eV	%	22	87
Coherence fraction @ 1 keV	%	2	38



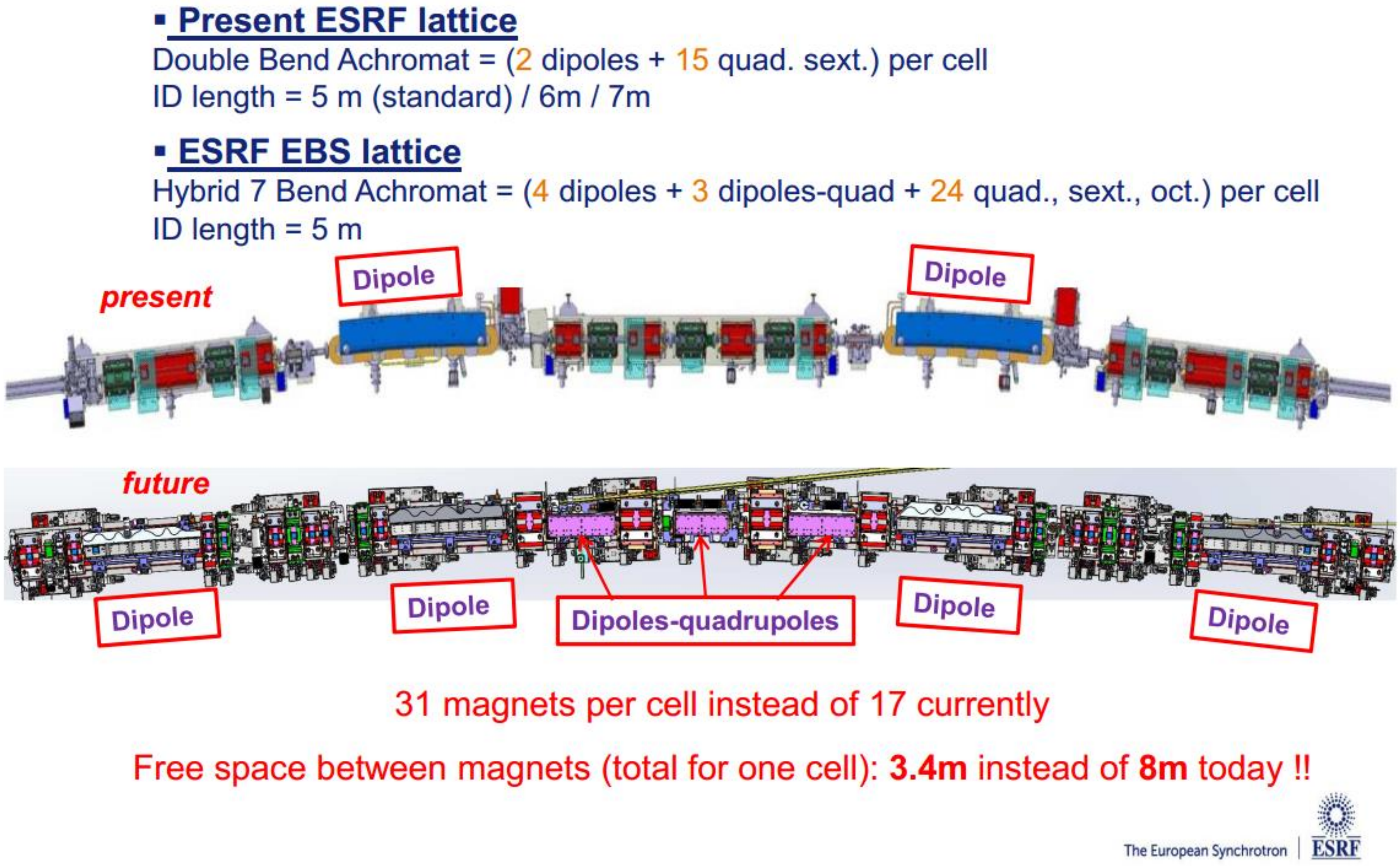


CDR ready to be presented for approval

Circumference (m)	259.2
Energy (GeV)	2
Number of cells	12
Geometric emittance (nm-rad)	0.250
Horizontal tune	33.10
Vertical tune	9.19
Betatron function in the middle of straights (x, y) m	(9.7,2.8)
Horizontal natural chromaticity	-75
Vertical natural chromaticity	-51
Horizontal corrected chromaticity	+1
Vertical corrected chromaticity	+1
Momentum compaction	3.45e-004
Momentum compaction second order	3.60e-004
Energy loss per turn (no IDs) (keV)	156
Energy spread	6.67e-004
J_x	1.52
J_y	1.00
J_δ	1.48
Horizontal damping time (ms)	14.6
Vertical damping time (ms)	22.2
Longitudinal damping time (ms)	15.0
Dipole field (T)	0.8
Quadrupole gradient in dipole (T/m)	<15
Quadrupole gradient (T/m)	<50
Sextupole gradient (T/m^2)	<3500
RF frequency (MHz)	499.654
Beam revolution frequency (MHz)	1.1566
Harmonic number	432
Orbital period (ns)	864.6
Bucket length (ns)	2
Natural bunch length (mm, ps)	2.16 , 7.2
Synchrotron frequency (kHz)	6.1

ESRF EBS, 6 GeV, 844 m, 135 pmrad

courtesy Dieter Einfeld



- **Present ESRF lattice**

Double Bend Achromat = (2 dipoles + 15 quad. sext.) per cell
ID length = 5 m (standard) / 6m / 7m

- **ESRF EBS lattice**

Hybrid 7 Bend Achromat = (4 dipoles + 3 dipoles-quad + 24 quad., sext., oct.) per cell
ID length = 5 m

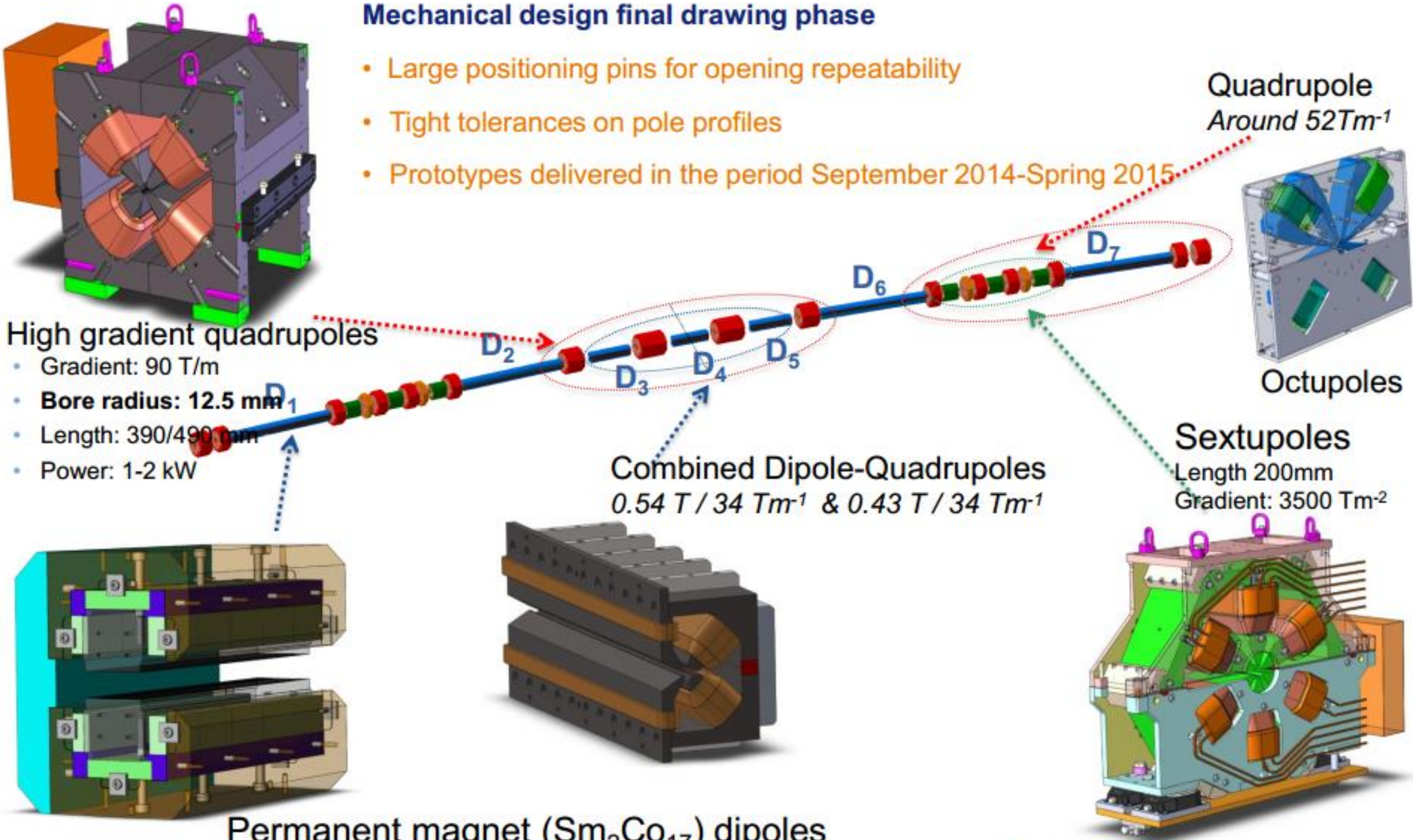
31 magnets per cell instead of 17 currently

Free space between magnets (total for one cell): **3.4m** instead of **8m** today !!

Technical challenge: Magnets System

Mechanical design final drawing phase

- Large positioning pins for opening repeatability
- Tight tolerances on pole profiles
- Prototypes delivered in the period September 2014-Spring 2015



Quadrupole
Around 52Tm^{-1}

High gradient quadrupoles

- Gradient: 90 T/m
- **Bore radius: 12.5 mm**
- Length: 390/490 mm
- Power: 1-2 kW

Octupoles

Sextupoles
Length 200mm
Gradient: 3500 Tm^{-2}

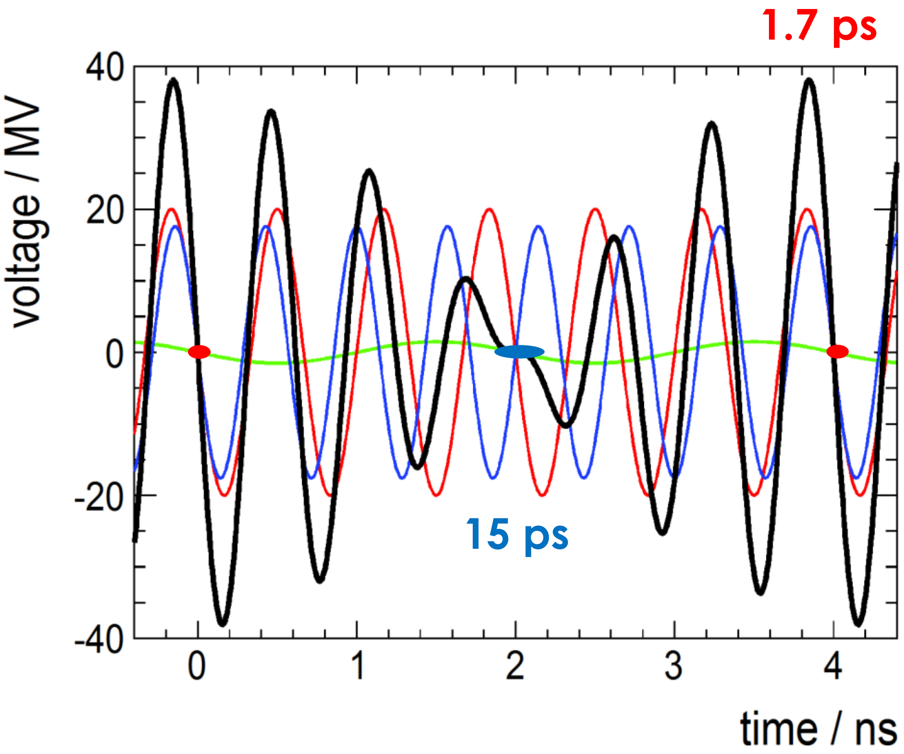
Combined Dipole-Quadrupoles
0.54 T / 34 Tm^{-1} & 0.43 T / 34 Tm^{-1}

Permanent magnet (Sm_2Co_{17}) dipoles
longitudinal gradient 0.16 – 0.65 T, magnetic gap 25 mm
1.8 meters long, 5 modules

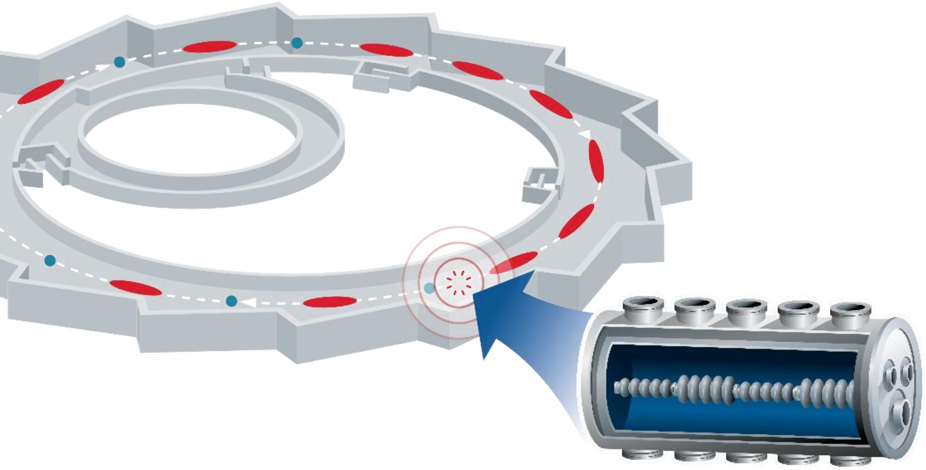
Gael Le Bec

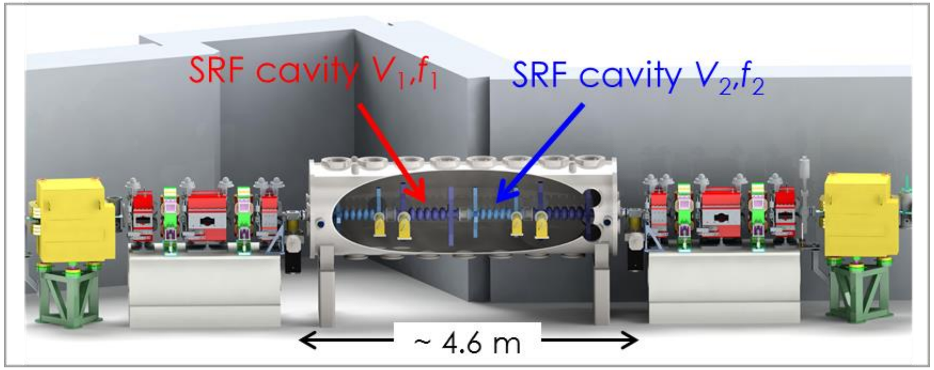
BESSY VSR – Variable Pulse Length Storage Ring (TDS Design)

- **short (ps) and long pulse option**
- **maintain high average brilliance**
  → preserve emittance
- **TopUp capability**



- **0.50 GHz NC (4 x 1 cell, 1.6 MV)**
- **1.50 GHz SC (2 x 5 cell, 20.0 MV)**
- **1.75 GHz SC (2 x 5 cell, 17.1 MV)**





76 times higher gradient than BESSY II
$\rightarrow \sqrt{76} = 8.7$ shorter bunches

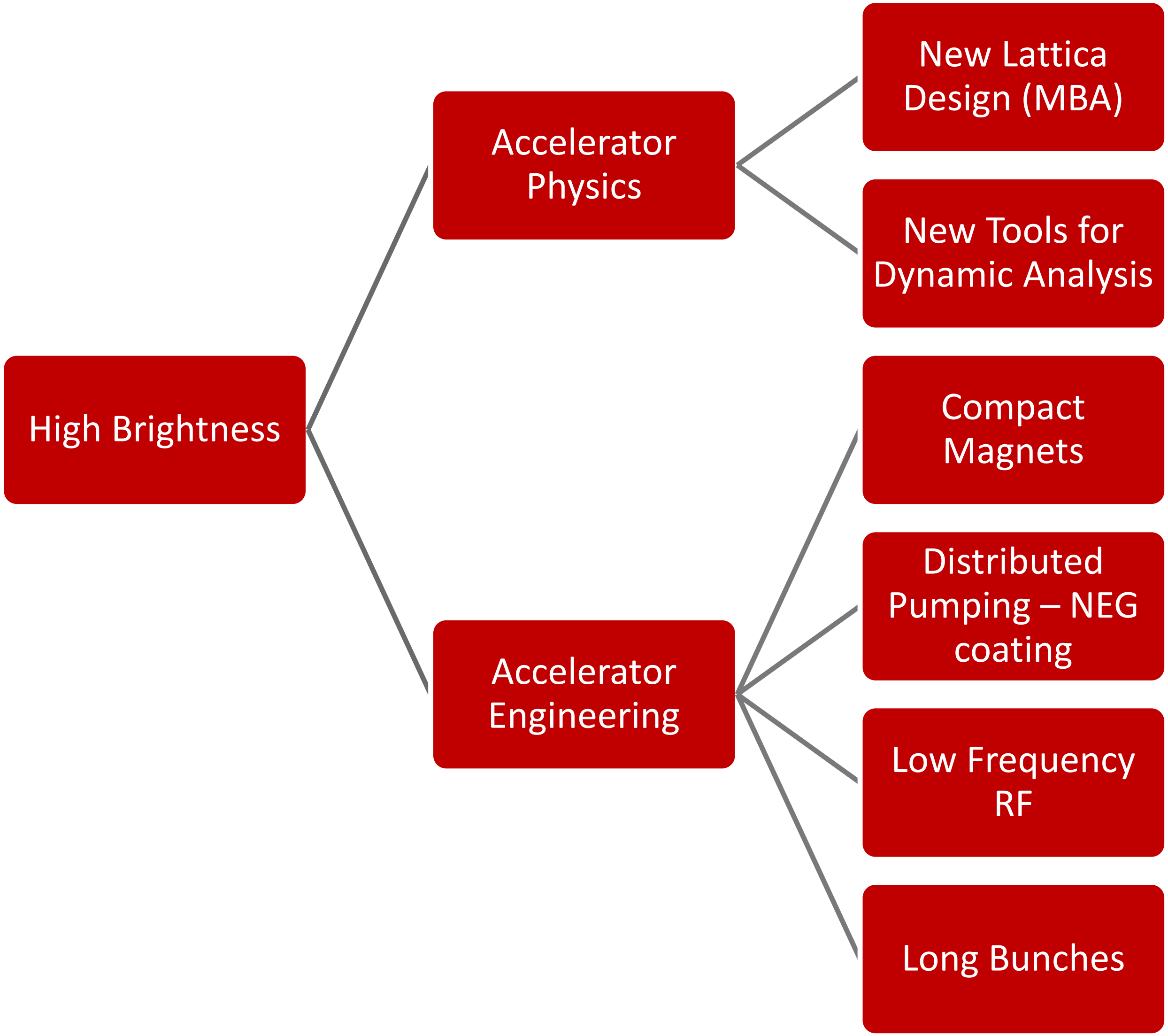
Courtesy Andreas Jankowiak

Enabling & Enabled Technologies

- Compact magnets
- Compact vacuum systems
- Advanced injection schemes – Fast kickers
  - On-axis
  - Swap-out
  - Accumulator Rings
- Bunch lengthening systems (harmonic cavities)

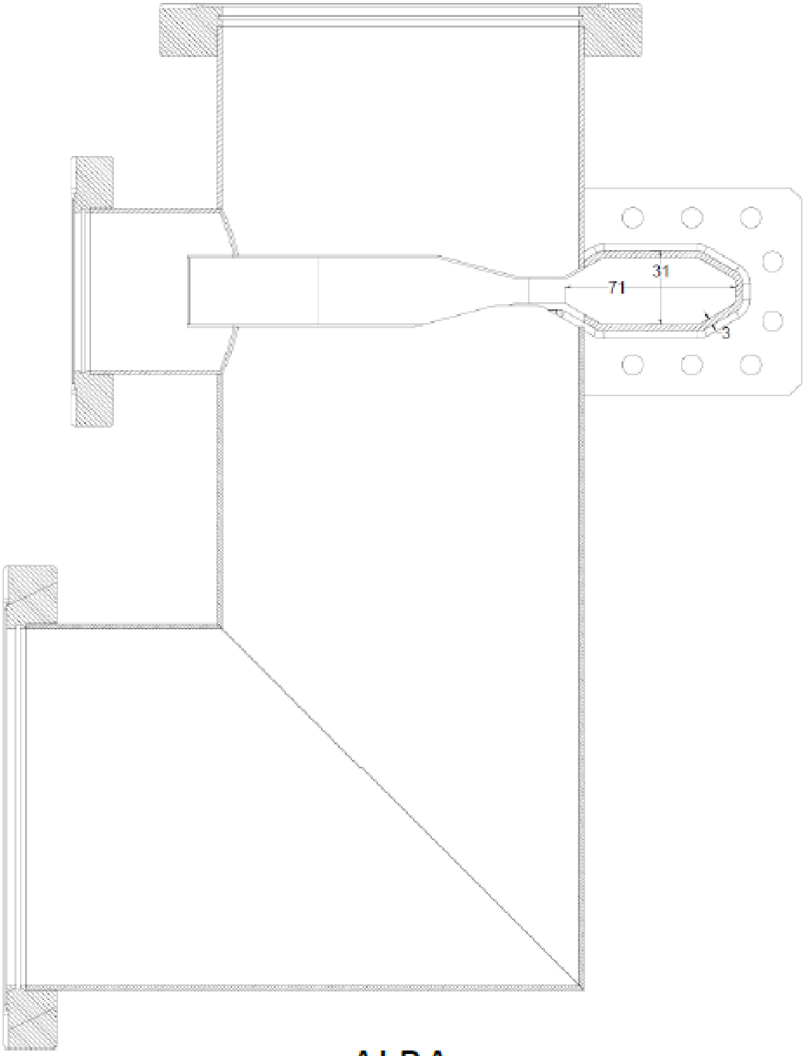
- Advanced insertion devices (round apertures):
  - Delta Undulators
  - Helical superconducting Undulators

How was it possible ?

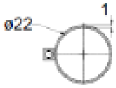


- High Brightness
  - Accelerator Physics
    - New Lattica Design (MBA)
    - New Tools for Dynamic Analysis
  - Accelerator Engineering
    - Compact Magnets
    - Distributed Pumping – NEG coating
    - Low Frequency RF
    - Long Bunches

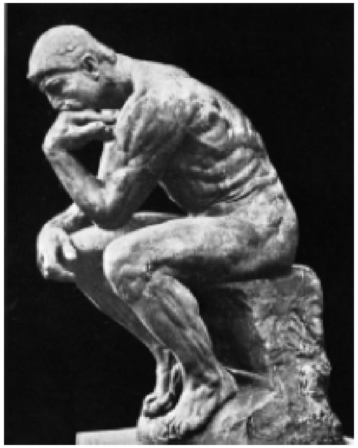
Compactedness is the key !



ALBA



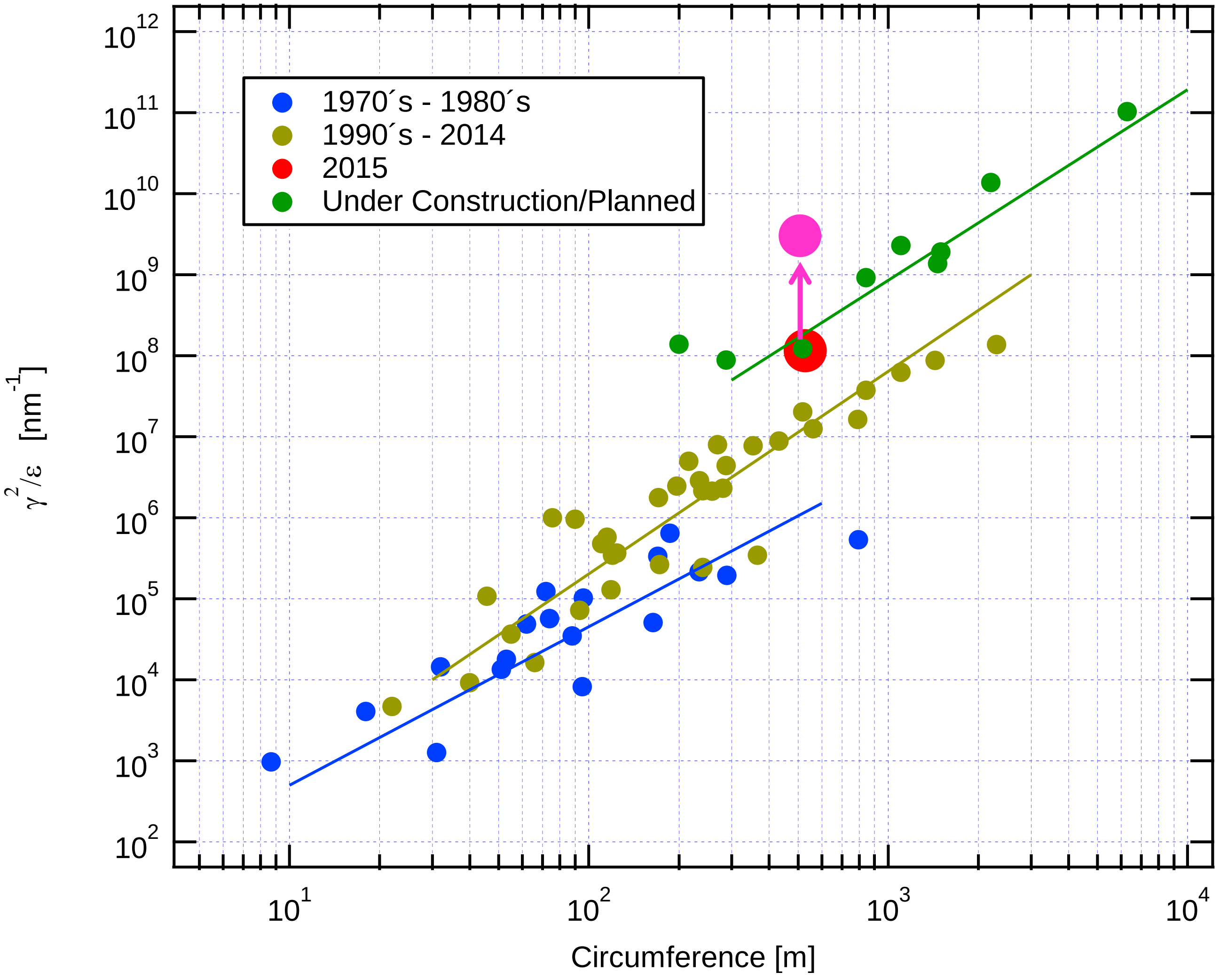
MAXIV



ALBA	MAXIV
St. steel	Copper
rotch absorbers	Distributed absorbers
Ion pumps	NEG coating

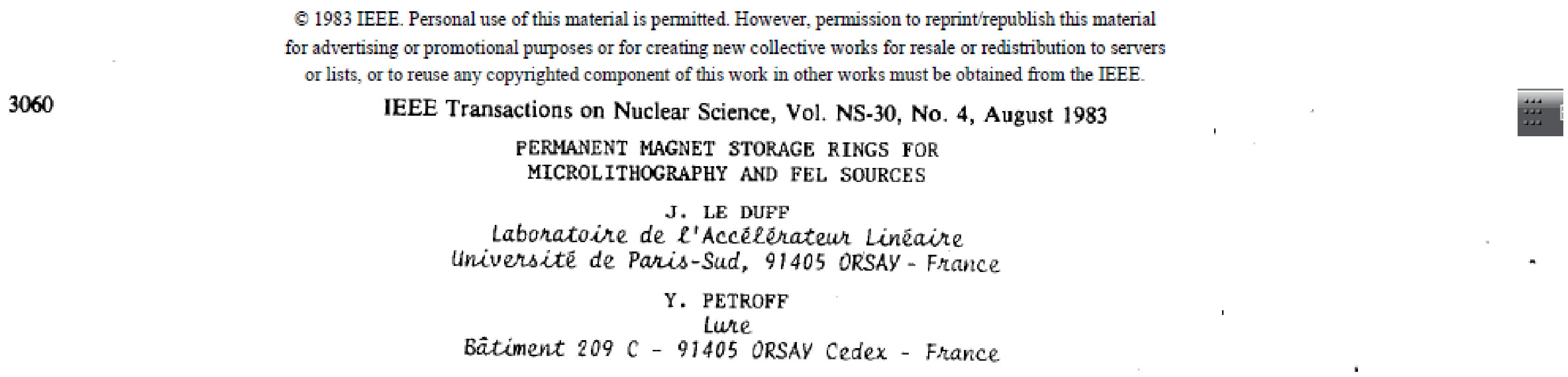
Picture by E. Aldmour

The Quest for higher brightness



Beyond MAX IV – exploring future possibilities

- Can the MBA concept be used to design a storage ring that provides a bare lattice emittance ~ 10 pm rad **within the MAX IV 3 GeV ring circumference (528 m)** ?
- If we take the present trend to smaller gaps to a new level, and consider that "…*when it is necessary that a magnetically significant dimension of a magnet is very small, a permanent magnet will always produce higher fields than an electromagnet*", K. Halbach J.App.Phys (1985), Vol. 57, N. 1.
- **Large scale use of permanent magnet technology could play a key role in this development.**



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IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, August 1983

PERMANENT MAGNET STORAGE RINGS FOR
MICROLITHOGRAPHY AND FEL SOURCES

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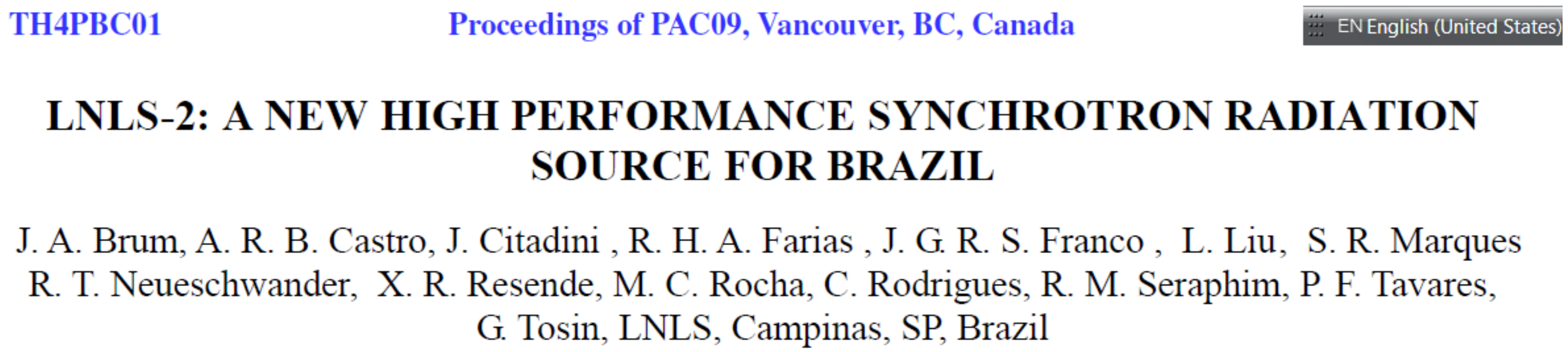
Lure
Bâtiment 209 C - 91405 ORSAY Cedex - France

Fermilab Recycler Ring
Technical Design Report

Gerry Jackson, Editor



TH4PBC01 Proceedings of PAC09, Vancouver, BC, Canada

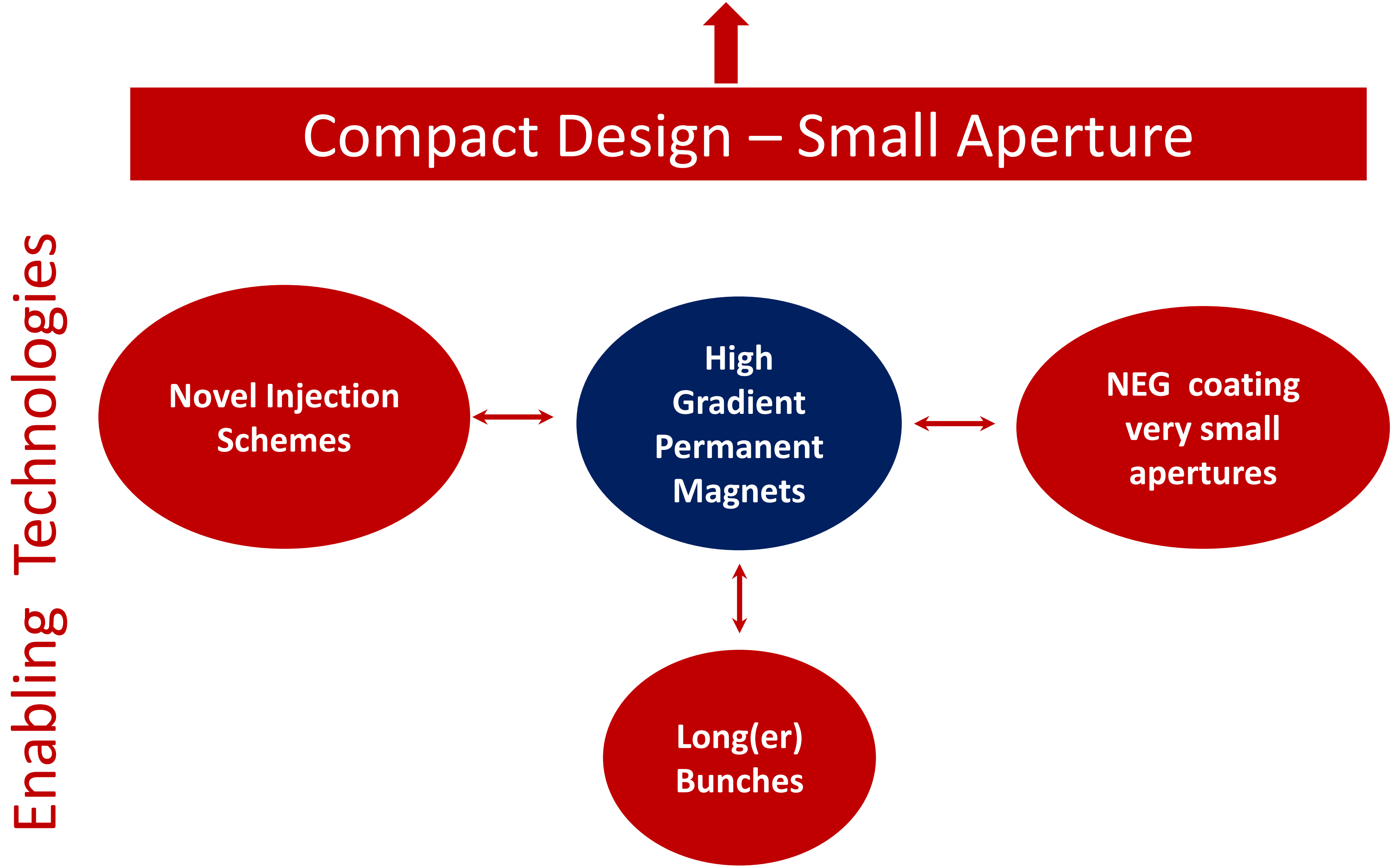
LNLS-2: A NEW HIGH PERFORMANCE SYNCHROTRON RADIATION SOURCE FOR BRAZIL

J. A. Brum, A. R. B. Castro, J. Citadini , R. H. A. Farias , J. G. R. S. Franco , L. Liu, S. R. Marques
R. T. Neueschwander, X. R. Resende, M. C. Rocha, C. Rodrigues, R. M. Seraphim, P. F. Tavares,
G. Tosin, LNLS, Campinas, SP, Brazil

Current SR Projects using PM Technology (for dipole magnets)

- Sirius
- ESRF-II
- Spring 8-II

Diffraction Limited @ 10 keV within ~ 500 m



Compact Design – Small Aperture

Enabling Technologies

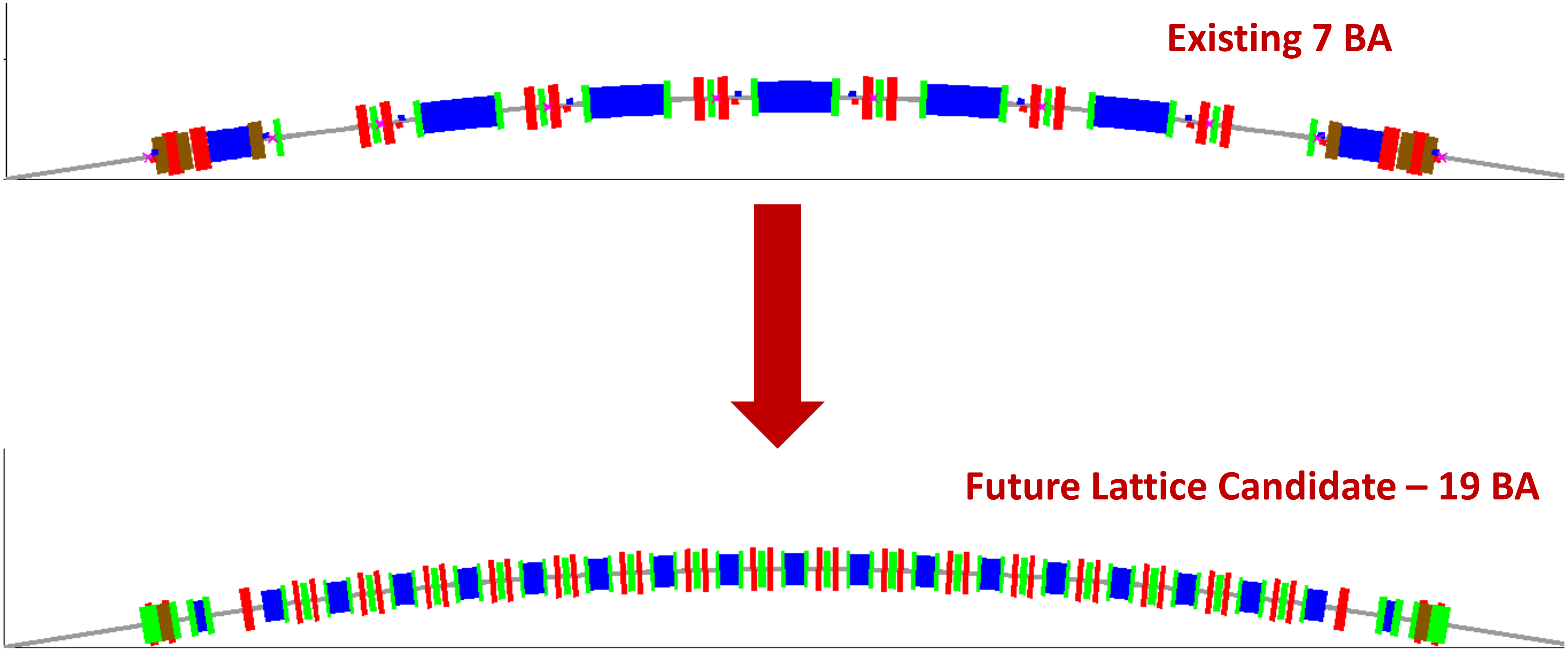
Novel Injection Schemes

High Gradient Permanent Magnets

NEG coating very small apertures

Long(er) Bunches

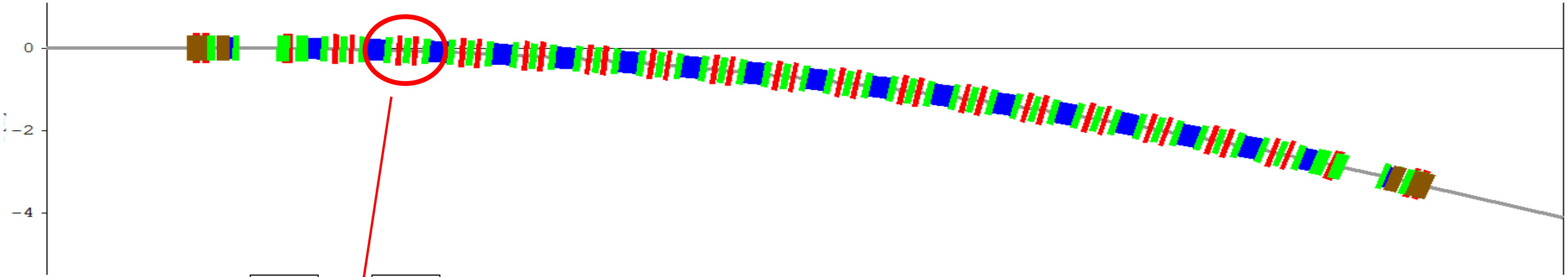
Beyond MAX IV – an exercise

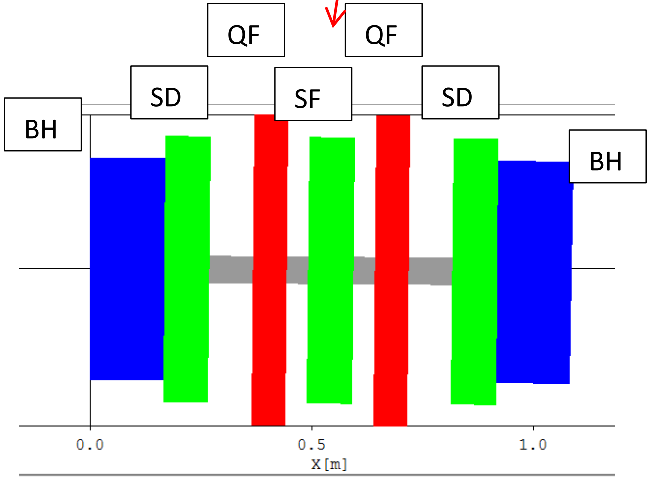


Beyond MAX IV – an exercise

Lattice design: OPA (A.Streun)
Elegant (M.Borland)

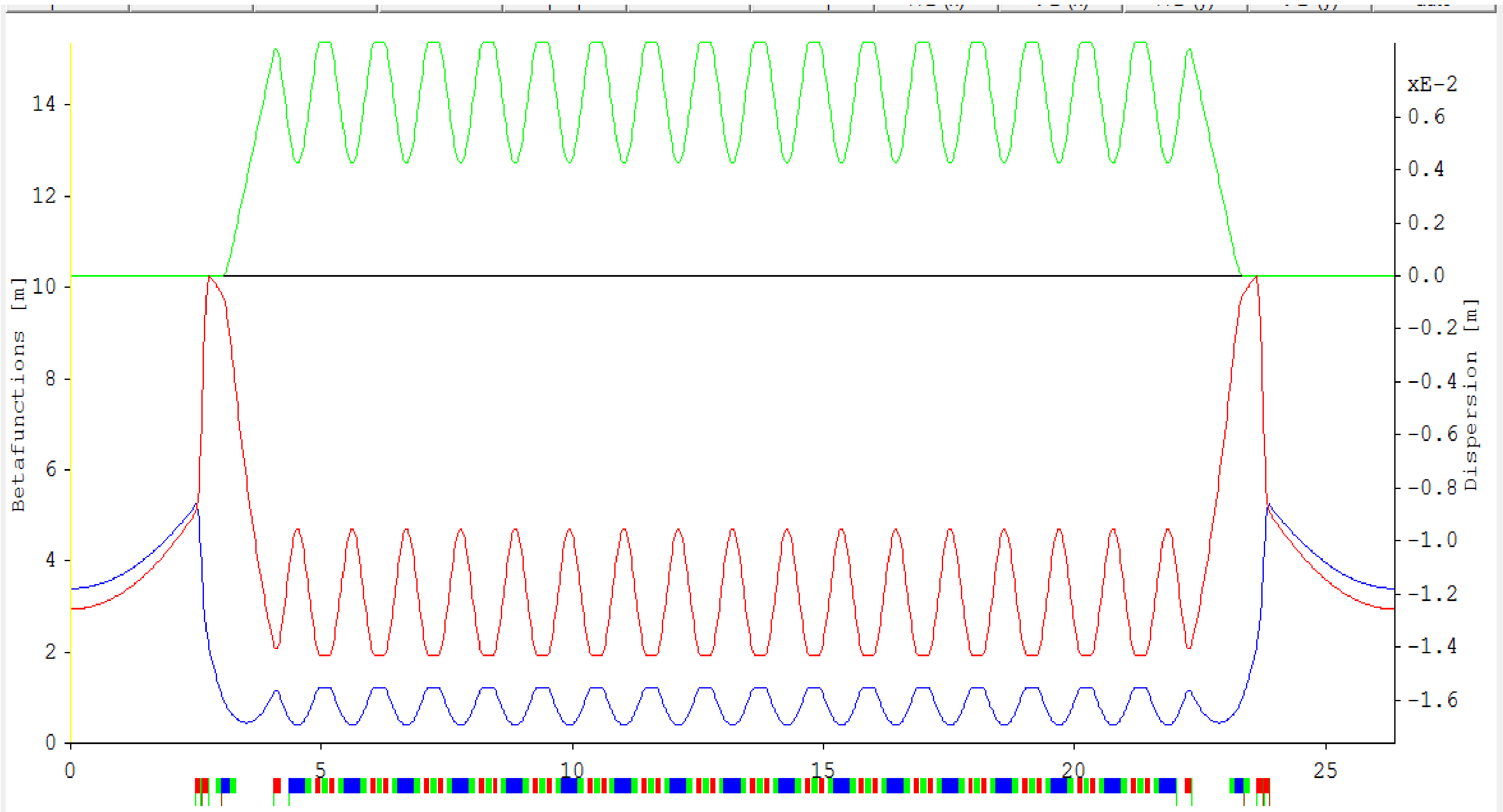
19-BA lattice in the MAX IV 3 GeV ring tunnel





Parameter	Value	Unit
Energy	3	GeV
Number of periods	20	
Circumference	528	m
Straight section length	5	m
Natural Emittance	16	pm.rad
Natural energy spread	0.09	%
Horizontal Tune	101.2	
Vertical Tune	27.28	
Natural horizontal chromaticity	-100.21	
Natural vertical chromaticity	-126.1	

Beyond MAX IV – an exercise
19-BA lattice in the MAX IV 3 GeV ring tunnel



19-BA lattice in the MAX IV 3 GeV ring tunnel – *Magnet Parameters*

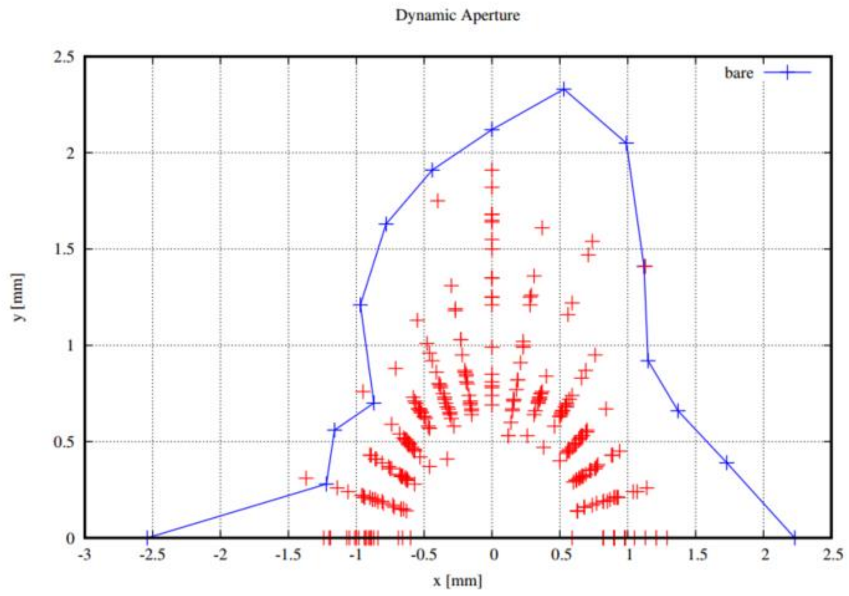
	Dipoles	
	Unit Cell	Matching Cell
Length [m]	0.3333	0.16667
Angle [deg]	1	0.5
Field [T]	0.52	0.52
Gradient [T/m]	-70.1	-30

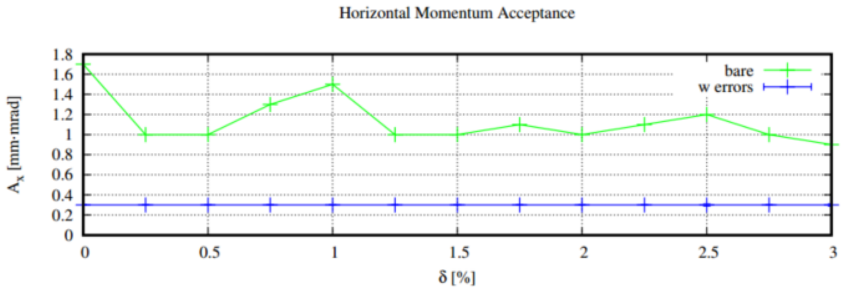
	Sextupoles	
	SF	SD
Length [m]	0.1	0.1
Gradient [T/m2]	33592	-19729
Pole Tip Field [T]	1	0.6

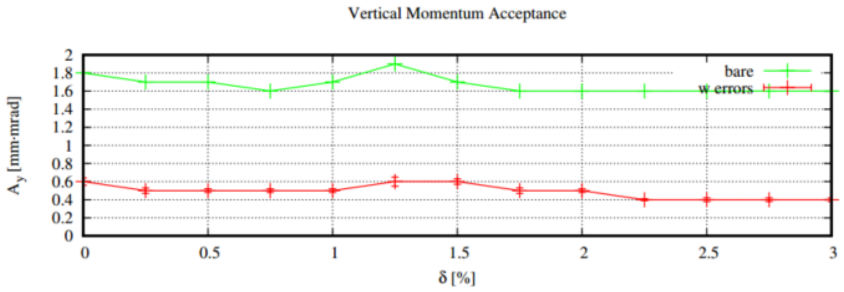
	Quadrupoles			
	QF	QM	QFE	QDE
Length [m]	0.075	0.15	0.1	0.1
Gradient [T/m]	219	183	**234**	-198
Pole Tip Field [T]	1.2	1	1.29	1.1

Magnet bore radius = 5.5 mm

19-BA lattice in the MAX IV 3 GeV ring tunnel - *Dynamic and momentum aperture*







Plots by Johan Bengtsson

Challenges

- Magnet Design (field quality, rad. damage, temp. dependence, trim)
- Light Extraction
- On-axis injection (fast kickers), Swap-out ?
- Collective effects (incoherent (IBS) and coherent) – More lengthening ?
- Low alpha
- Heat load on chambers
- NEG coating of very small aperture chambers
- Mechanical integration
- ....

High Gradient PM Quadrupole Examples

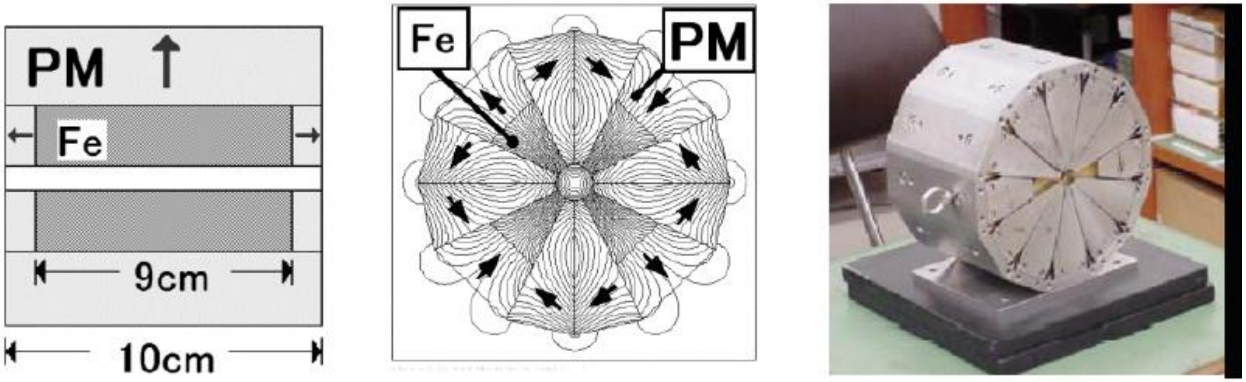
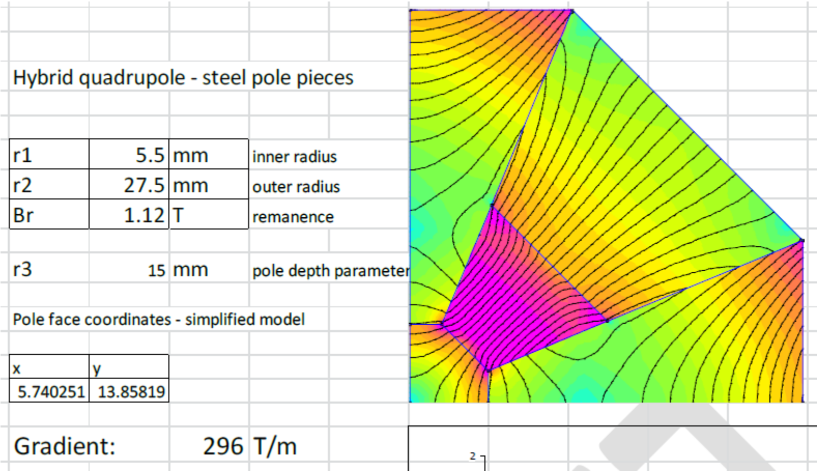


Fig. 1 Modified Halbach Quadrupole

7 mm bore radius, 285 T/m – Mihara et al, EPAC2004, Iwashita et al, PAC2003



Hybrid quadrupole - steel pole pieces

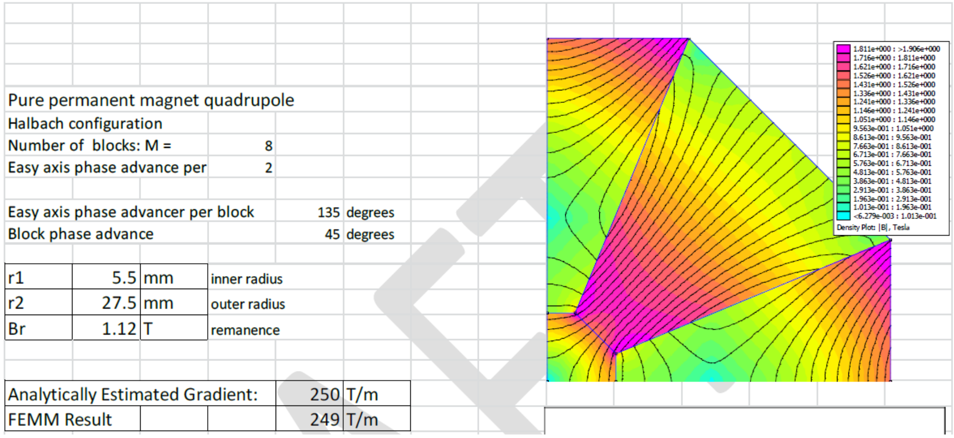
r1	5.5	mm	inner radius
r2	27.5	mm	outer radius
Br	1.12	T	remanence

r3 15 mm pole depth parameter

Pole face coordinates - simplified model

x	y
5.740251	13.85819

Gradient: 296 T/m



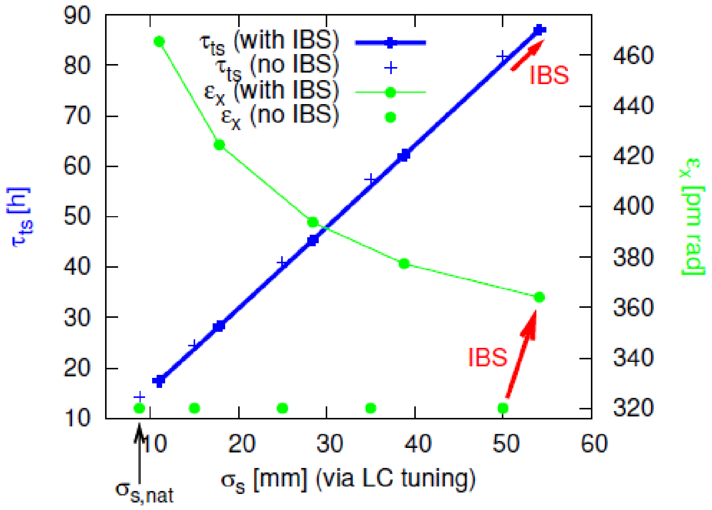
Pure permanent magnet quadrupole
Halbach configuration
Number of blocks: M = 8
Easy axis phase advance per 2

Easy axis phase advancer per block 135 degrees
Block phase advance 45 degrees

r1	5.5	mm	inner radius
r2	27.5	mm	outer radius
Br	1.12	T	remanence

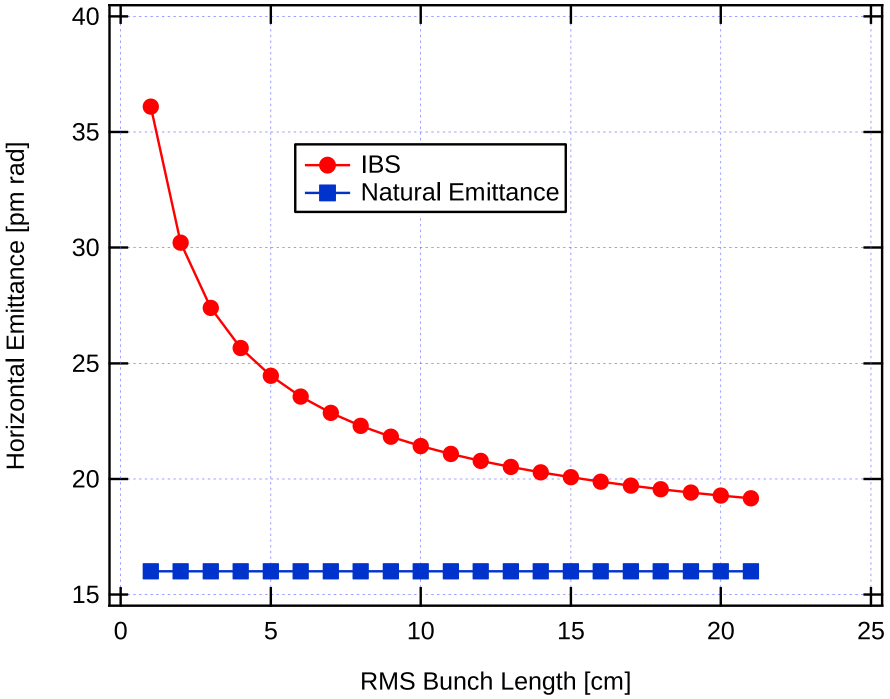
Analytically Estimated Gradient:	250	T/m
FEMM Result	249	T/m

Intra Beam Scattering



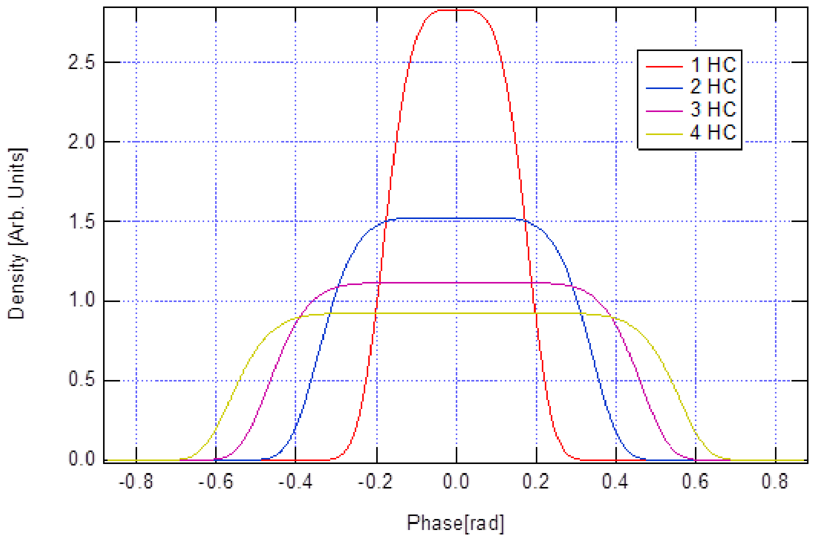
IBS in the present MAX IV 3 GeV ring

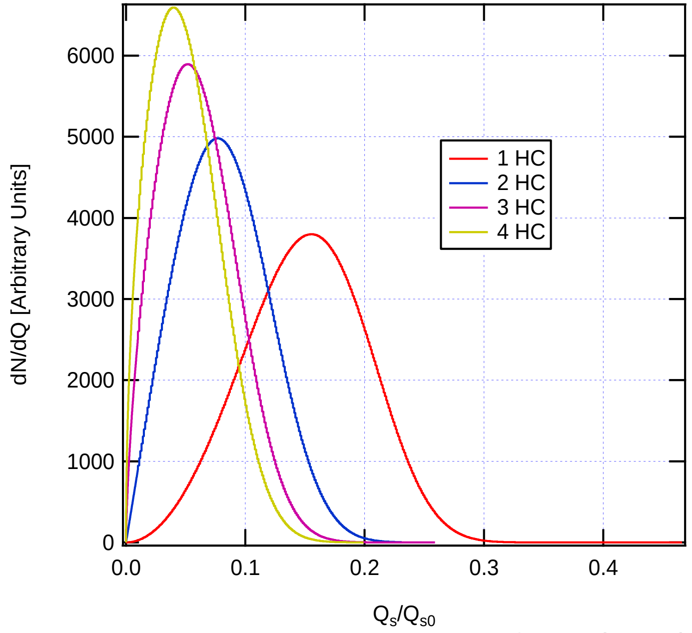
Plot by S.Leemann
MAX-lab Internal Note 201211071

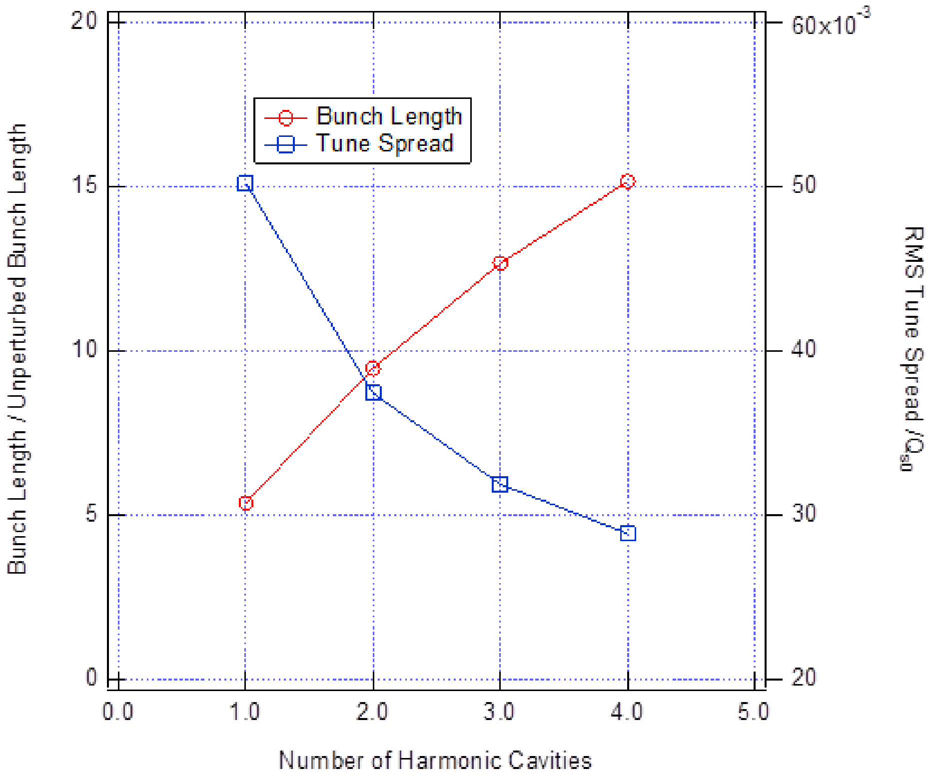


IBS in the 19-BA
Calculations by Johan Bengtsson

Multiple Harmonic Cavities







Summary and Conclusions

- The international landscape of storage-ring based synchrotron light sources is currently undergoing a major change with many new projects worldwide promising orders-of-magnitude performance improvements.
  - Increased control of the time structure will cater for a wide variety of user applications
  - Brightness and coherence improvements made possible by compact machine designs will open up new research fields.
- It is time to start asking ourselves: can the quantum jump in brightness made possible by the MBA lattice be repeated in the next 10-15 years ?
- The time may have come when the benefits of large scale use of permanent magnets in storage ring lattices outweigh the risks/costs ? This could lead to yet another order-of-magnitude jump in source brightness

Thank You for Your Attention

- Acknowledgments: Many colleagues all over the world have contributed slides and/or information contained in this presentation:
  - Andreas Streun (PSI)
  - Hitoshi Tanaka (Spring 8)
  - Dieter Einfeld (ESRF)
  - Emanuel Karanzoulis (ELETTRA)
  - Yuhui Dong (HEPS)
  - Rainer Wanzenberg (DESY)
  - Andreas Jankowiak (BESSY)
  - Richard Walker (Diamond)