Karlsruhe Institute of Technology (KIT, Karlsruhe, Germany)
Budker Institute of Nuclear Physics (BINP, Novosibirsk, Russia)

LOW EMITTANCE MODEL FOR THE ANKA SYNCHROTRON RADIATION SOURCE

(A.Papash - on behalf of joint KIT and BINP team)

A.Papash*, A.-S.Mueller,
KIT, 76344, Karlsruhe, Germany

E.Levichev, P.Piminov, S.Sinyatkin, K.Zolotarev
BINP, 630090, Novosibirsk, Russia

* alexander.papash@kit.edu

Abstract

- modern technologies allow to essentially improve performance of old generation budget light sources in a cost efficient way

- feasibility studies for a compact low emittance synchrotron light source were performed

- a low emittance lattice based on the compact ANKA ring geometry (L=110.4 m) was investigated

- TME cell with **SPLIT** bend and quadrupole lens in-between would permit to reduce horizontal emittance of ANKA from 50 nm·r (TME) ÷ 90 nm·r (DBA) down to **~6 nm·r** (***D=D'=0*** in straight sections) with not-vanishing dynamic aperture

- natural chromatic aberrations are compensated by pair of non-interleaved sextupole lenses separated by ***"–I "*** unit transfer matrix of betatron oscillations

- second order (sextupole) aberrations are cancelled in such system providing the approximation of thin sextupole lens pairs is applied

- third and higher order aberrations still exists but its strength is essentially less than the second one

Abstract (2)

- thanks to the cancellation of second order aberrations the Dynamic Aperture opens in the compact low emittance ring up to the level sufficient for the beam injection and storage

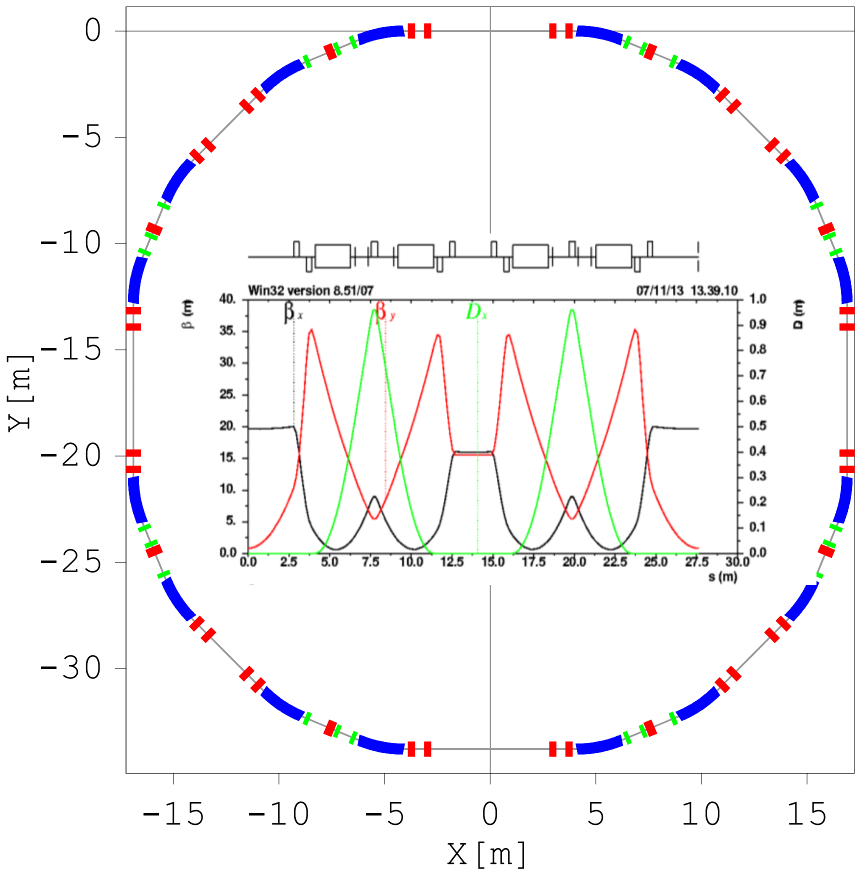
- the momentum acceptance of split lattice ring with “cancelled” sextupole aberrations is improved in few times with respect to present ANKA ring

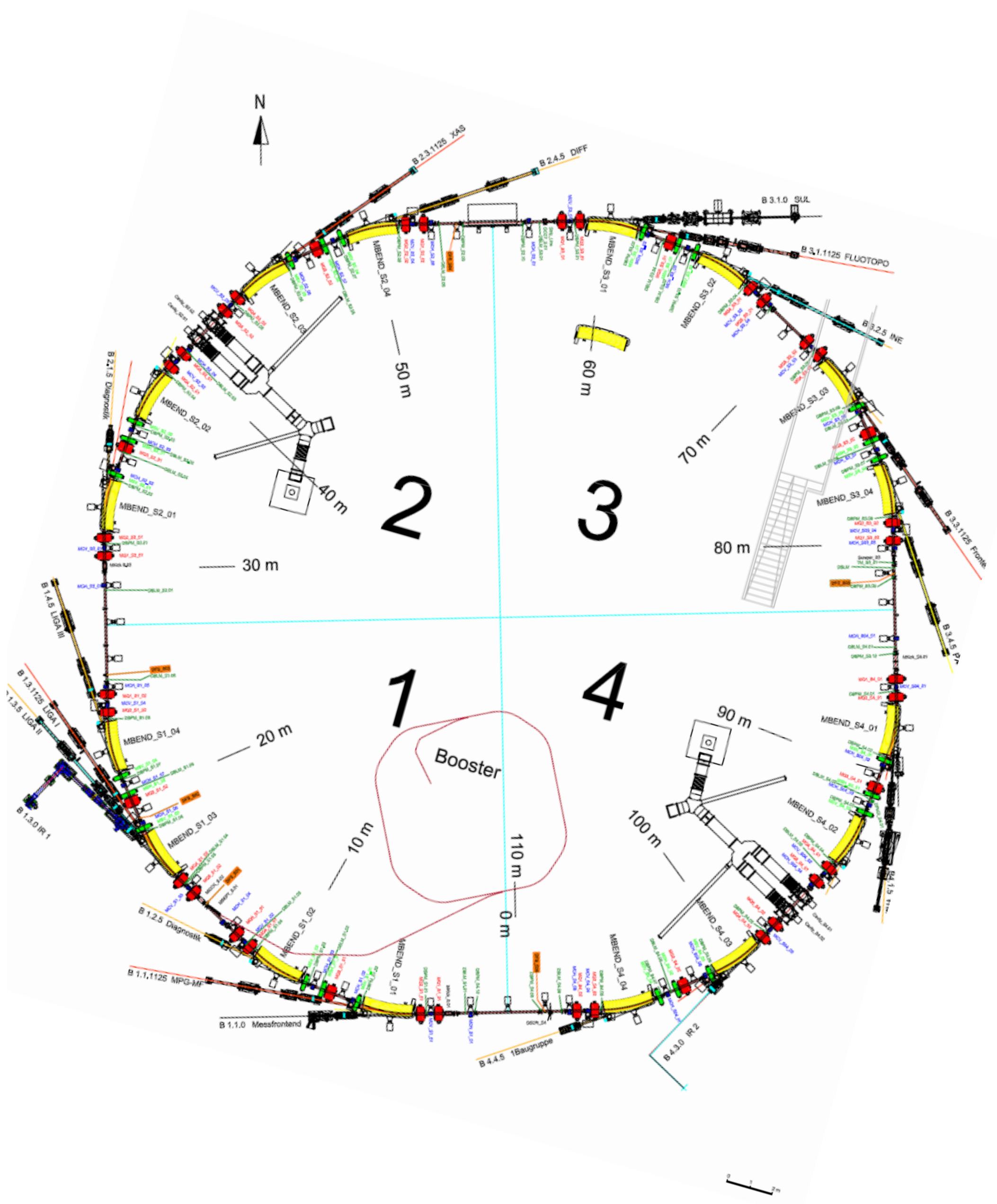
- further reduction of the phase space volume requires to brake ***“–I ”*** symmetry and add extra families of sextupoles, locate an additional high order field elements inside the quadrupoles, optimize the phase advance between sextupole families, shift the betatron tune point, enlarge the sextupole strength

- the proposed low emittance lattice might be considered as a model example of new generation of compact and not-expensive light sources

- **compact, highly effective and reliable synchrotron light source of low cost should be a good option for many users from universities, laboratories, institutes, companies etc.**

ANKA RING Original
DBA lattice
periodicity four (*M, -M*) cells





Blue - Bending magnets (22.5°)
Red – quads
Green – sextupoles
L = 110.4 m

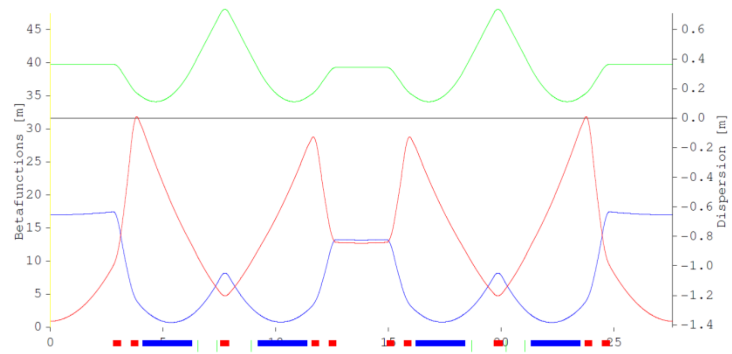
ANKA RING. **Original** Double Bend Achromat cell

Table 1 Main parameters of the storage ring

Energy	2.5 GeV	Tune h/v	6.779 / 2.714
Max. current	180 mA	Energy spread	0.001
Lattice	8 x DBA	Mom. compaction	0.008
Circumference	110.4 m	Damping h,v,l	3, 3, 1.5 ms
Emittance	50 nm.rad (TME)	RF frequency	499.66 MHz
Coupling	0.005	Dipole field / radius	1.5 T / 5.559 m
Nat. Chromaticity h/v	-12.5 / -13.2	Critic. photon energy	6 keV

Chromaticity wih sextupole corrections: h/v = +5 / +5
Momentum acceptance = ±1.5 % (RF=350 kV)

Natural emittance = 50 nm.rad (TME Distr. Disp.)
= 90 nm.rad (DBA)



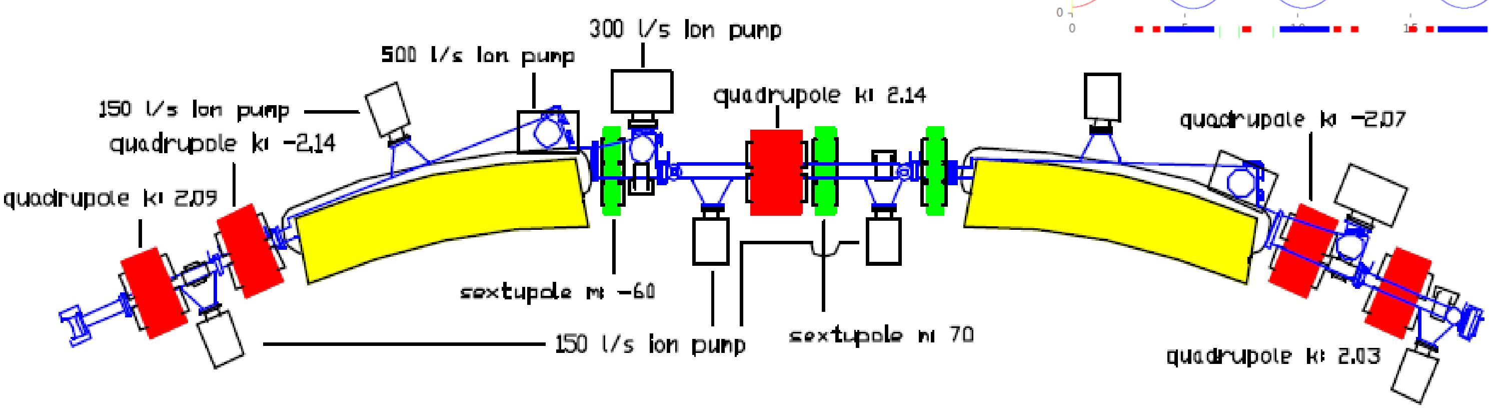


Fig.1 Achromat of the ANKA lattice

General task (objectives)

ANKA – present ring	Low emittance storage ring based on ANKA Light Source
Energy 2.5 GeV	2.5 GeV
Circumference 110.4 m	same infrastructure ~110 m
Four short (2.4 m) straight sections	Same location and direction
Four long (5.6 m) straight sections	Same position and direction
Natural emittance 50 nm·rad (TME) 90 nm·rad (DBA)	Natural emittance ~5÷10 nm·rad

Compact, low cost, highly effective and reliable synchrotron light source should be a good option for many users from universities, laboratories, institutes, companies etc.

Main constraints of low emittance ANKA

- two 11.25° bends instead of one 22.5° bend -- to reduce emittance

  (split of 22.5° bend into three parts is not fitted into ANKA circumference)

- (Almost) same circumference – to keep present beam lines and infrastructure

- Dispersion free straight sections. Option: dispersive straight sections

- position and direction of Insertion Devices sources should be unchanged

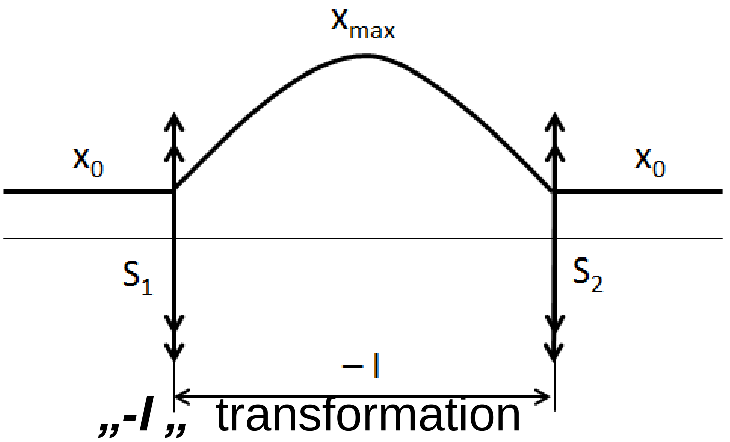
- (Almost) same length of straight sections to accommodate IDs, cavities etc.

- Large dynamic aperture (≥ 10 mm horizontal at injection azimuth)
- Sufficient momentum acceptance ≥ +-2%

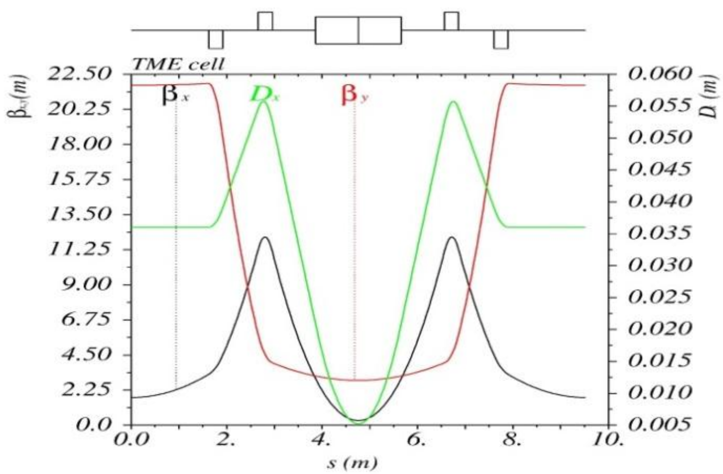
- Full energy top-up injection from LINAC (MAX IV type) either from low emittance booster synchrotron based on **split** lattice (32 bending magnets)

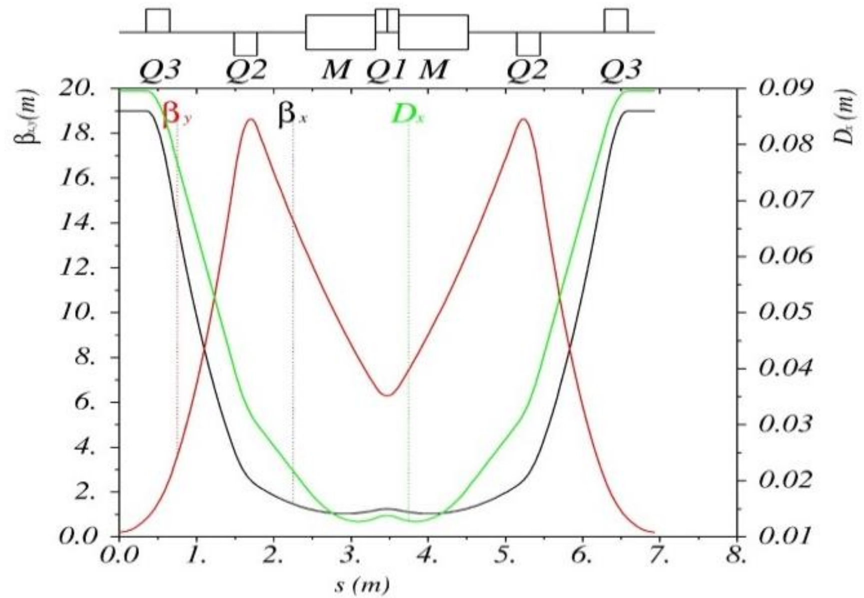
- Magnets: bend field ≤1.7 T, gradient in dipole ≤10 T/m,
- gradient in quadrupole ≤100 T/m (preferable ≤70 T/m),
- gradient in sextupole ≤3000 T/m^2 (preferable ≤1000 T/m^2),
- Inscribed diameter of quads and sextupoles openings ~25-30 mm (present ∅=70 mm)

Split cell and „–I” condition



New approach is necessary for large DA and MA in (very) compact low emittance cell. BINP suggested to arrange the sextupoles in **„-I ”** pairs. This system cancels all aberrations in approximation of thin lenses

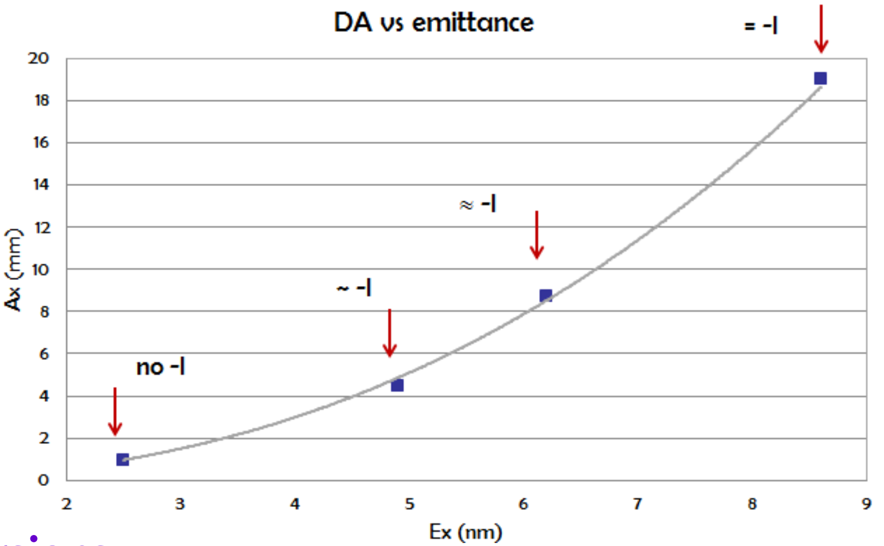




Original (left) and modified (right) TME cell with split bend and quad in-between. *Q1* allows to tune phase advance and optimize “–*I* “ condition

Different options of low emittance ANKA optics

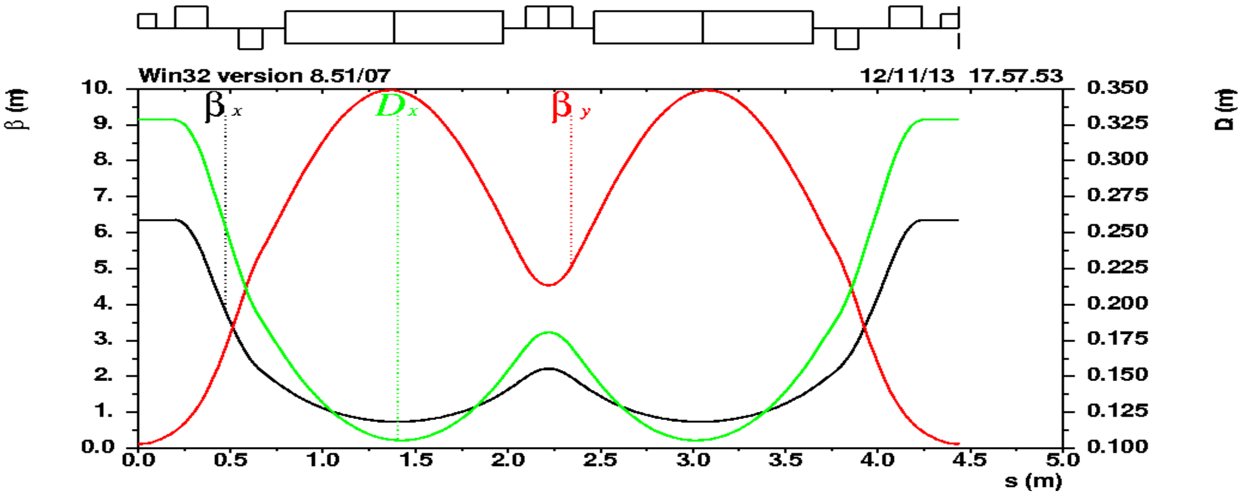
Verison	$-I$	ε_x(nm)	A_x (mm)	β_{x0}(m)	MA (%)
V08.5	$= -I$	8.6	-14…+19	7.5	±6
V08.8	$\approx -I$	6.2	-11…+9	13	±4
V23.0	$\sim -I$	4.9	-6…+5	15	±1.5
V02.4	no $-I$	2.5	±1	10	±0.5



Parameters of different lattice versions

Version	Original	V08.5	V08.8	V23.0
Qx/Qy	6.8/2.6	10.83/10.34	12.36/10.77	14.32/9.57
Cx/Cy	-12.3/-14.7	-21.5/-40.4	-24.8/-44.5	-39.9/-38.2
ε_x (nm)	83	8.6	6.2	4.9
Energy spread	9.02E-04	1.31E-03	1.21E-03	1.24E-03
α	9.15E-03	4.69E-03	3.60E-03	3.07E-03
Energy loss, MeV	6.22E-01	5.75E-01	5.75E-01	5.75E-01
Jx/Jy/Je	0.97/1/2.03	2.11/1/0.89	1.96/1/1.04	2.01/1/0.99
Maximum magnet parameters				
B(T)/Gb(T/m)	1.5/-	1.39/-9.4	1.39/-10.7	1.39/-13.1
Gm× L (T/m*m)	20×0.32	70×0.24	80×0.2	90×0.1
Sm× L (T/m2*m)	700×0.1	1500×0.15	3100×0.15	3300×0.15

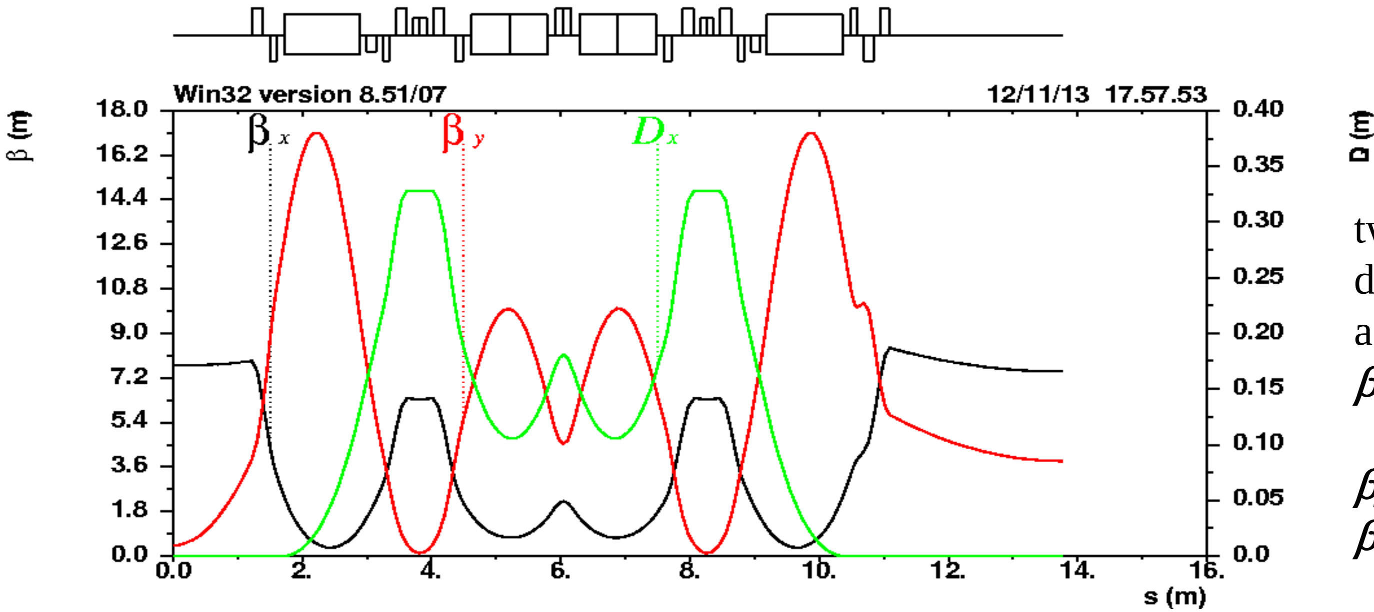
Central Low emittance cell



TME condition
βx = min, *Dx* = min
in dipoles

central quadrupole
adjusting **"–*I* "** condition
at the cell ends
where ***Sx*** are placed

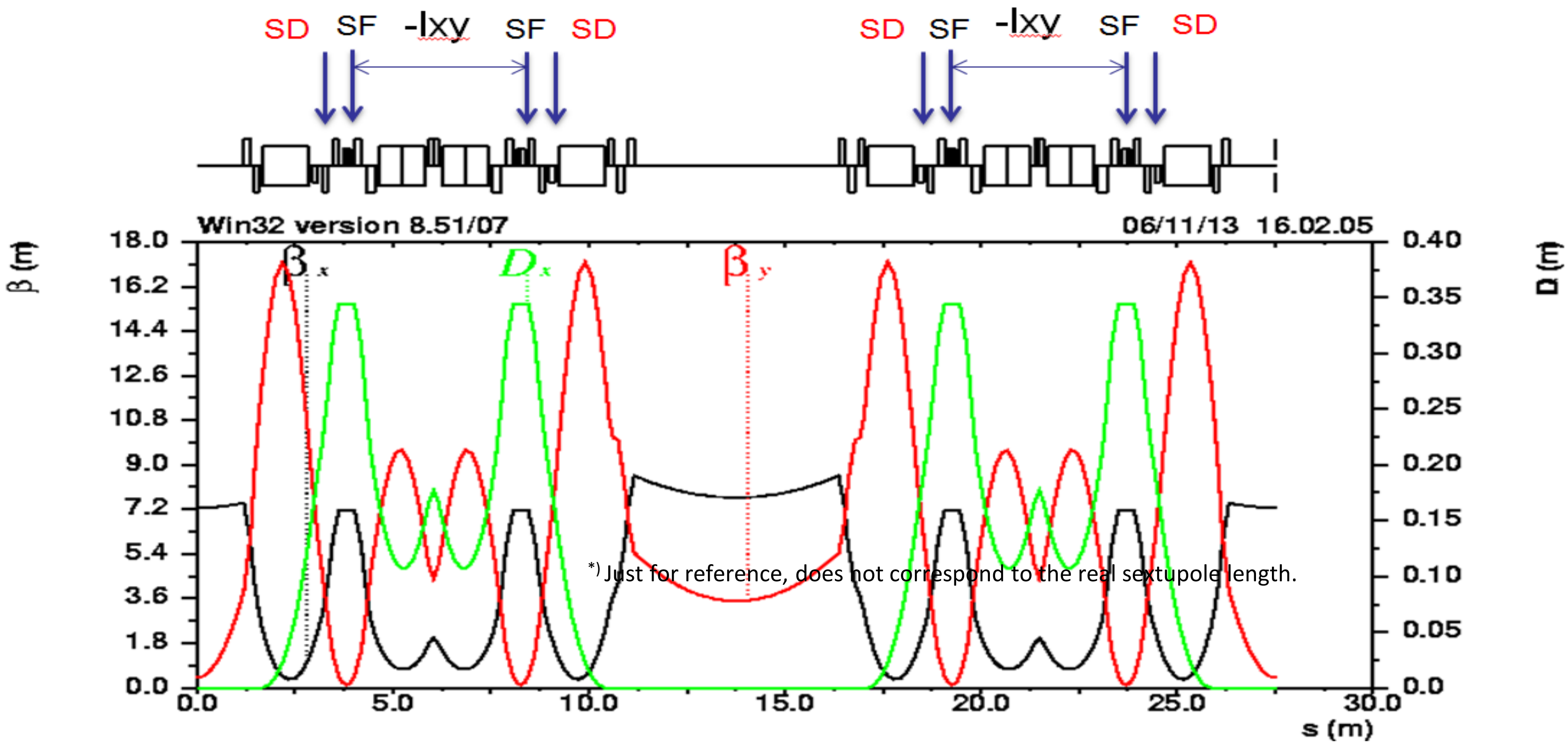
LE ANKA cell with dispersion suppressor (1/8 of ring circumference)

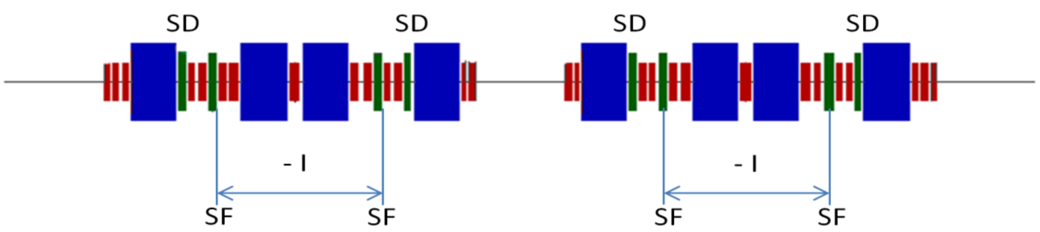


two dispersion suppressors
dipole + quads (3Q and 2Q)
adjust betatron functions
βx,y for injection and for ***ID***

βy = low
βx =high

Ring period (a quarter of the LE ANKA circumference).
The sextupoles location is shown above the plot



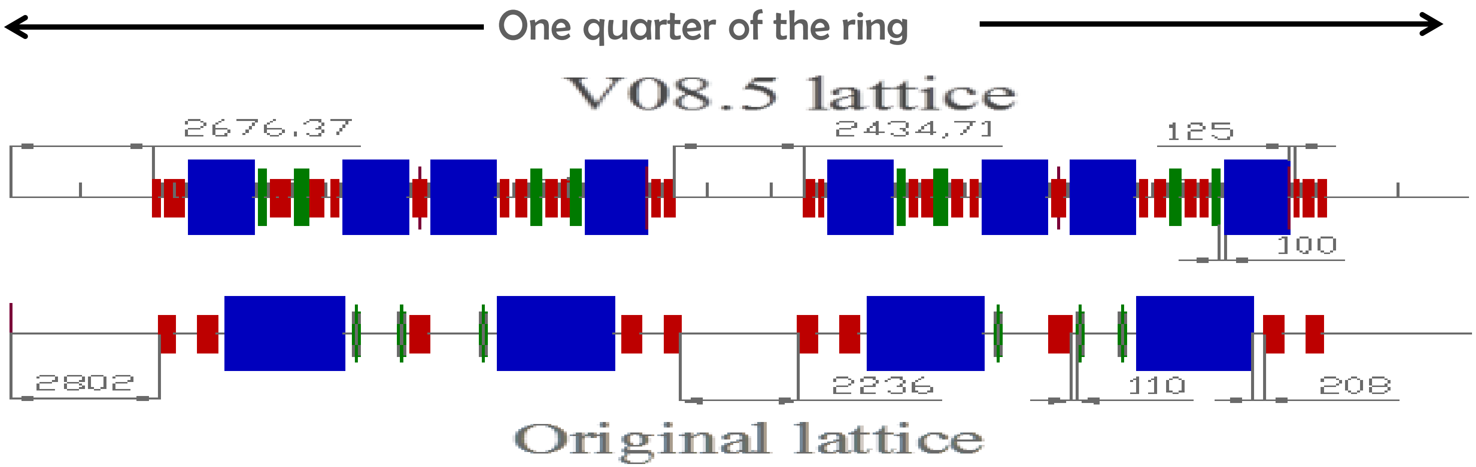


Sextupole locations in the LE ANKA lattice V08.5 (one-quarter of the ring).

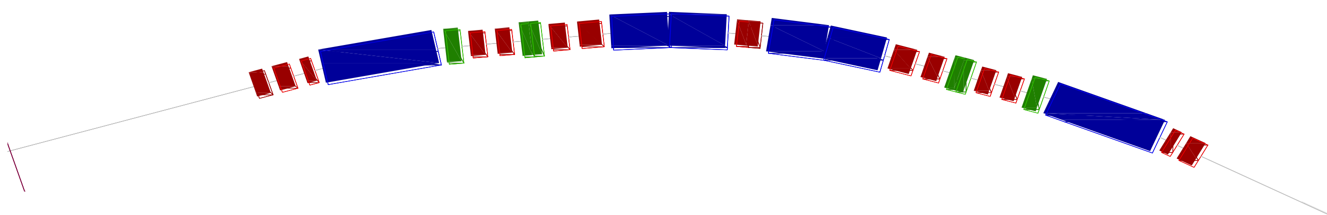
	No.	L (m)	B'' (T/m^2)
SF	16 (8)	0.20 (0.10*))	537 (420)
SD	16(16)	0.15 (0.10)	–1580 (550)

*) Just for reference, does not correspond to the real sextupole length.

Geometry of original and new ANKA lattice



<u>One-eighth</u> of the magnet sequence: dipoles are blue, quads are red and sexts are green.



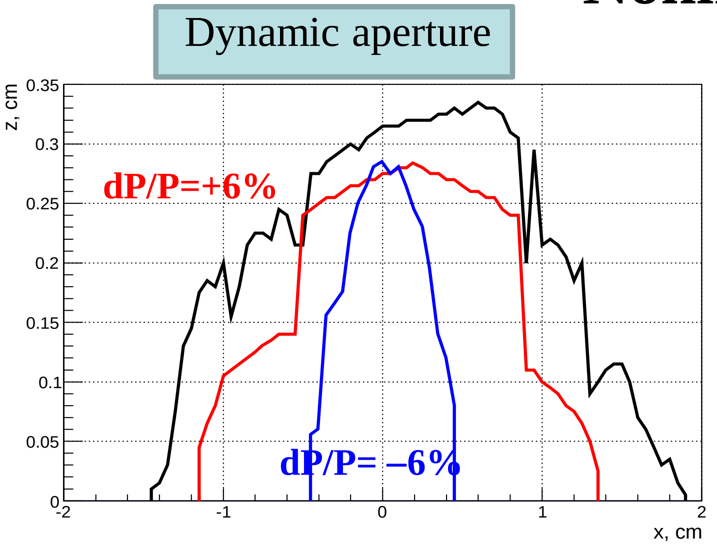
One-eighth of the new ANKA lattice superimposed over the old one

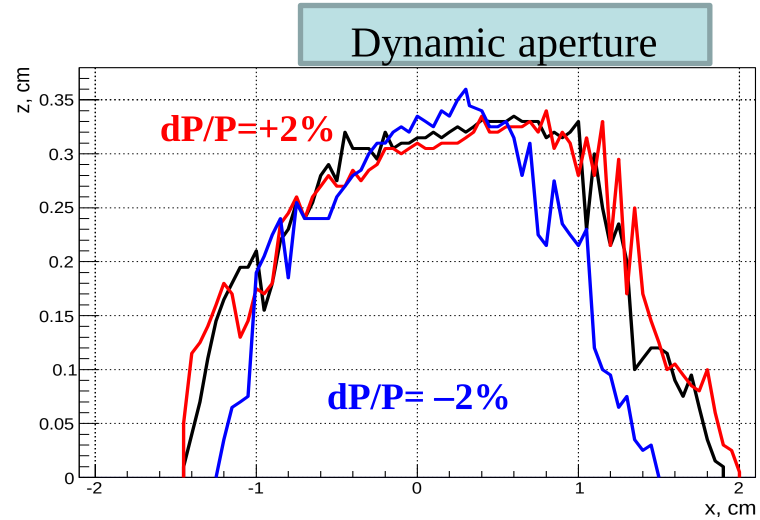
Yellow – 22.5° bends
Blue -- 11.25° bends

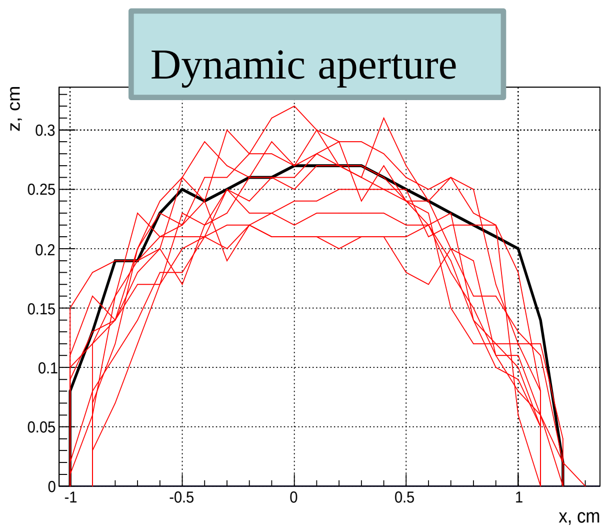
LE ANKA main parameters

Circumference	m	110.15
Revolution period	ms	0.367
Betatron tunes, h/v		10.84/10.34
Emittance	nm	8.6
Betatron coupling	%	0.5
Energy spread		1.3×10^{-3}
Momentum compaction		4.65×10^{-3}
Energy loss/turn	MV	0.575
Damping partition numbers, h/v/l		2.11/1/0.89
Damping time, h/v/l	ms	1.5/3.2/3.6
Bunch length	mm	10
RF voltage	MV	2.2
Harmonic number		184
RF frequency	MHz	501
RF acceptance	%	±2
Synchrotron tune		1.07×10^{-2}
Radiation integrals, I_1	m	0.512
I_3	m^{-2}	0.174
I_2/ I_4/ I_5	m^{-1}	1.05/ -1.17 / 2.07×10^{-3}

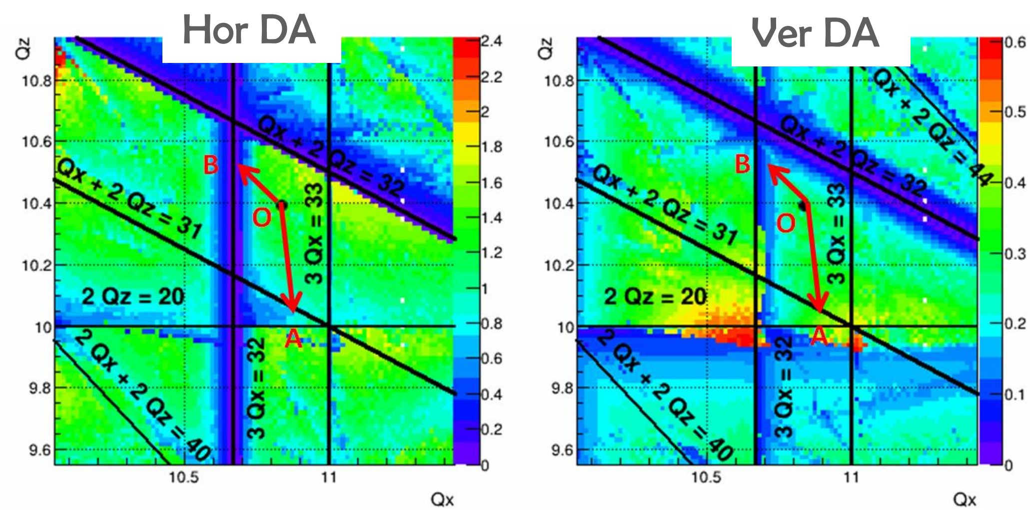
Nonlinear beam dynamics







DA reduction due to the residue (corrected) Closed Orbit Distortion (50 μm displacement)



Resonance pattern around the tune point (O), Points (A) and (B) correspond to the horizontal and vertical border of Dynamic Aperture

LE ANKA life time and growth rates

Touschek+IBS lifetime **> 20 hours** ---- Growth of energy spread due to IBS is only 10^{-3} thanks to the suppression by the horizontal radiation damping τ=1.5 ms. **However the life time could be reduced to ~3 hours if bunch current is increased to 10 mA**

$$\tau_T(hours) \approx \frac{27.2}{I_b(mA)}$$

-- Off-energy dynamical Momentum Acceptance **±6%** due to the nonlinear motion
-- MA= **±4%** limited by the off-energy particle displacement and loss at the vacuum chamber wall (**25-mm**-diam round pipe) in the lattice dispersive region
-- RF bucket height = **±2%** (present ANKA **RF** system four accelerating cavities of 500 MHz with total voltage of **2.2 MV**)

Energy		2.5 GeV	
Compaction factor		4.65×10^{-3}	
Energy loss/turn		0.575 MeV/turn	
Total RF voltage		2.2 MV	
RF frequency		500 MHz	
Harmonic number		184	
Energy acceptance		**2.02 %** (RF bucket)	
Bunch current		**1.21 mA**	
Particles/bunch		2.78×10^{9}	
Total current		**200 mA (90% filling factor)**	
Betatron coupling		0.5 %	
Energy spread		1.31×10^{-3}	
Hor.damping time		1.5 ms	
Nominal parameters		*Parameters with IBS*	
H emittance	8.56 nm	H emittance	8.56 nm
V emittance	0.0428 nm	V emittance	0.0428 nm
Bunch length	10.0 mm	Bunch length	10.0 mm
Life time no IBS	81835 s	**Life time +IBS**	**81872 s**

modified Piwinski approximation (CIMP). K.Kubo, S.K.Mtingwa and A.Wolski, Phys. Rev. ST Accel. Beams **8,** 081001 (2005).

Dependence of the Momentum Acceptance and bunch length on the RF voltage

LE ANKA require 6 MV RF voltage to reach 4% MA

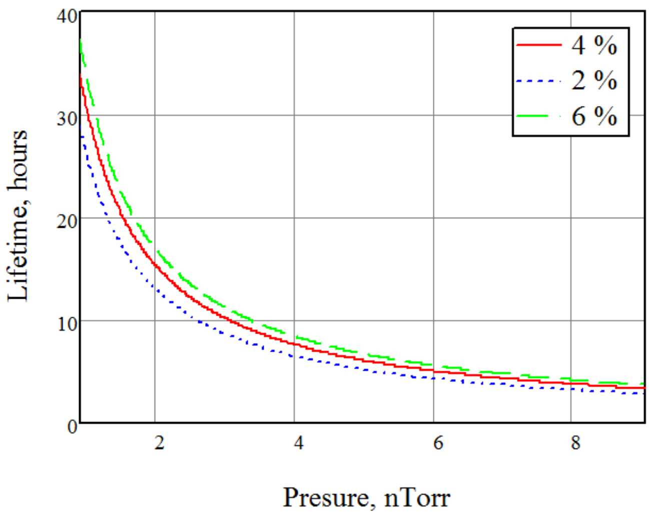
U_{RF} (MV)	0.62	0.79	1.12	1.54	2.20	3.00	3.87	5.06	6.37
σ_s (mm)	29.8	19.8	14.8	12.1	10.0	8.5	7.4	6.5	5.8
$\Delta E/E$ (%)	0.19	0.56	1.04	1.49	2.02	2.53	3.00	3.53	4.03

LE ANKA life time and growth rates (2)

Gas lifetime

Several processes of particle loss determine the beam lifetime in electron storage rings. The following processes related to the residual gas pressure are essential:

* elastic scattering on nuclei of the gas atoms,
* bremsstrahlung on nuclei,
* elastic scattering on electrons of the gas atoms,
* inelastic scattering on electrons of the gas atoms.



Initial data for the vacuum lifetime estimation

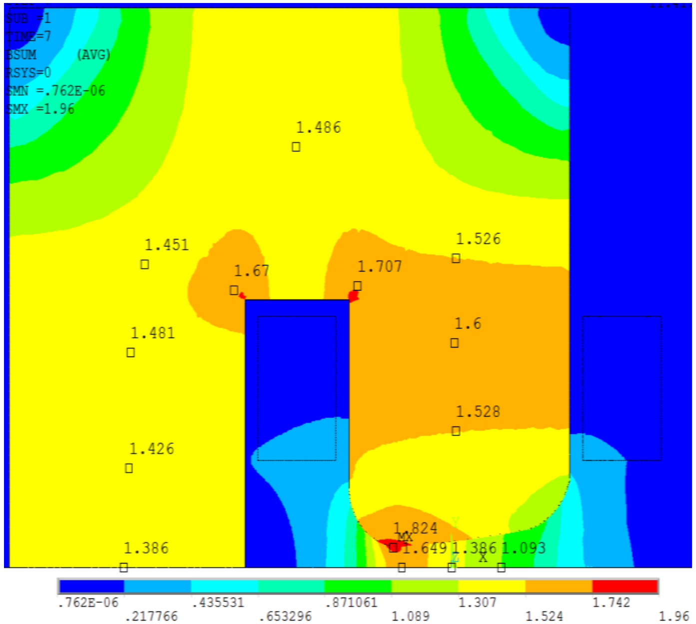
Energy (GeV)	2.5
Residual pressure (nTorr)	1
Gas composition	N_2
Momentum acceptance (%)	4%
Maximum β_y (m)	17
Average β_y (m)	6.8
Minimum vertical aperture in ID (mm)	8

Residual gas lifetime (2.5 GeV, 1 nTorr average)

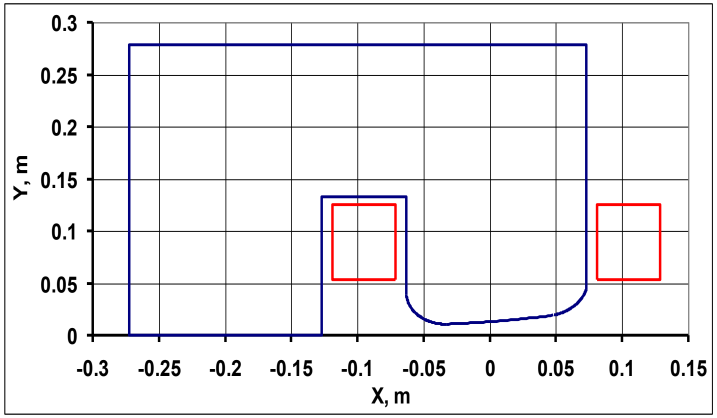
Lifetime	Hours
Bremsstrahlung, τ_b	80.4
Elastic on nuclei, τ_{ns}	66.6
Inelastic on electrons, τ_{ie}	228.5
Elastic on electrons, τ_{es}	1153
TOTAL, τ_{gas}	30.6

LE ANKA MAIN MAGNET ELEMENTS
gradient bending magnets

Bending magnet field map



Profile of upper half of dipole

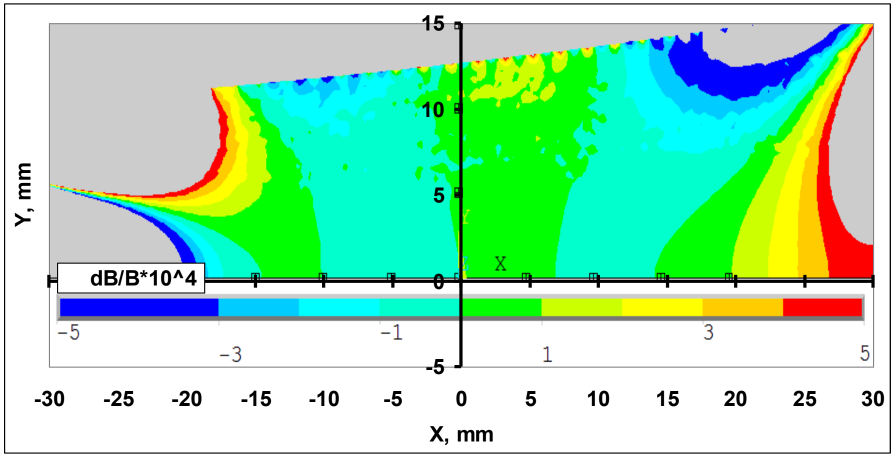


Main specifications of gradient magnet
(Field level corresponds to 2.5 GeV beam energy)

Type	Defocusing bend
Number	32
Shape	*C*-shape
Effective magnetic length	1.18 m
Curvature radius	6.0097 m
Bending angle	11.25° (196.349 mrad)
Steering angle	±1 mrad
Sagitta	28.938 mm
Vertical gap at reference orbit	26 mm (±13 mm)
Field at the reference orbit	1.38761 T (I = 620 A)
Quadrupole strength K_1	-1.15139 m^{-2}
Good field region (h×v)	(±12.5) × (±12.5) mm^2
Field quality, $\Delta B/B_0$	$\pm 1\times10^{-3}$

bending magnet parameters

Main coil		
Number of coils		2
Number of turns/coil		24
Total number of turns		48
Copper conductor size	mm^2	12×12
Cooling hole diameter	mm	8
DC resistance/dipole	mΩ	12.8
Total inductance	mH	17
Voltage per magnet	V	15.9
Power per magnet	W	9830
No of water inlets/dipole		3
Water pressure drop	bar	6
Temperature drop	°C	6.2
Total flow rate/dipole	l/min	23
Correction coil		
Bending angle	mrad	1
Excitation current	A	7.6
DC resistance	Ω	1.3
Number of turns/coil		10
Copper conductor diam.	mm	1
Voltage per magnet	V	9.6
Power per magnet	W	73
Weight of dipole		~1700
Weight of yoke	kg	~1580
Weight of coils	kg	~115

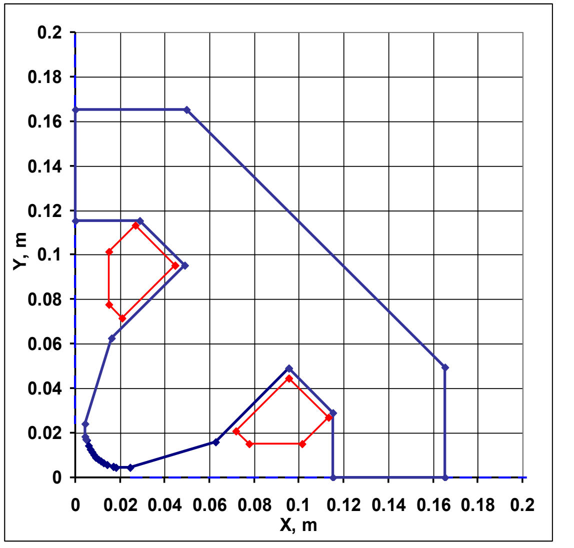


Magnetic field uniformity in the units of $\Delta B/B\times10^4$

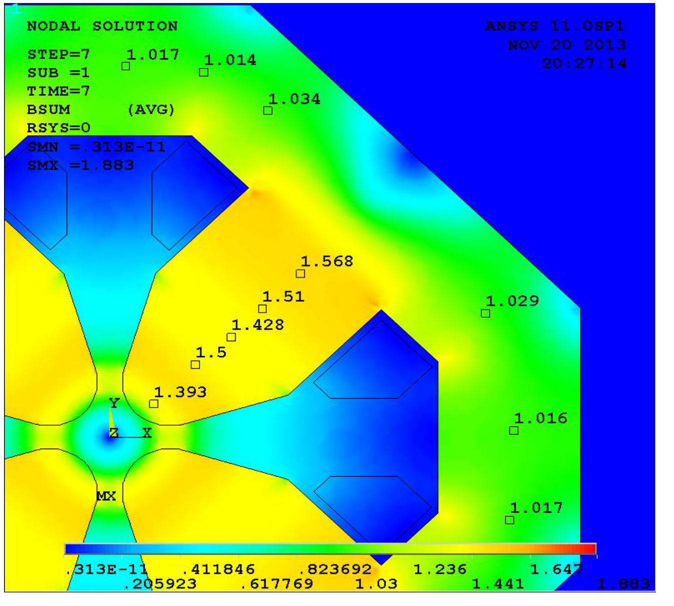
LE ANKA quadrupoles

Total number		112
Working gradient	T/m	50 - 70
Inner pole diameter	mm	∅26
Effective magnetic length	mm	100 - 250
Good field region	mm	∅24
Gradient quality	%	≤ 0.1

Effective length	m	0.1	0.125	0.15	0.175	0.25
Number of magnets		32	16	16	40	8
Max gradient	T/m	68				
Bore radius	mm	13				
Excitation current	A	523				
Coils/magnet		4				
Turns/coil		9				
Conductor size	mm^2	8 × 8				
Cooling hole	mm	∅3				
Voltage/magnet	V	2.7	3.0	3.3	3.5	4.4
Resistance/magnet	mΩ	5.1	5.7	6.2	6.8	8.4
Total inductance	mH	0.7	0.9	1.0	1.2	1.7
Power/magnet	W	1400	1550	1702	1853	2307
Water inlets/quad		4	4	4	4	4
Water pressure drop	bar	6				
Temperature drop	°C	2.4	2.8	3.3	3.7	5.2
Flow rate/dipole	l/min	8.3	7.9	7.5	7.2	6.4
Yoke weight	kg	50	63	75	88	125
Coils weight	kg	8.5	9	10	11	14



Quadrupole lamina profile

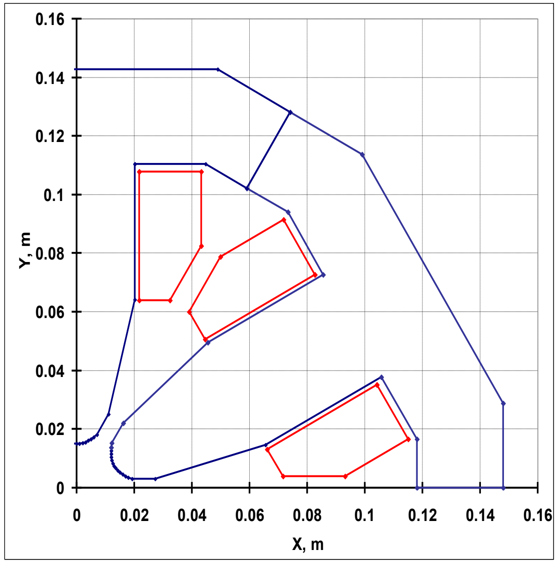


Quadrupole field map

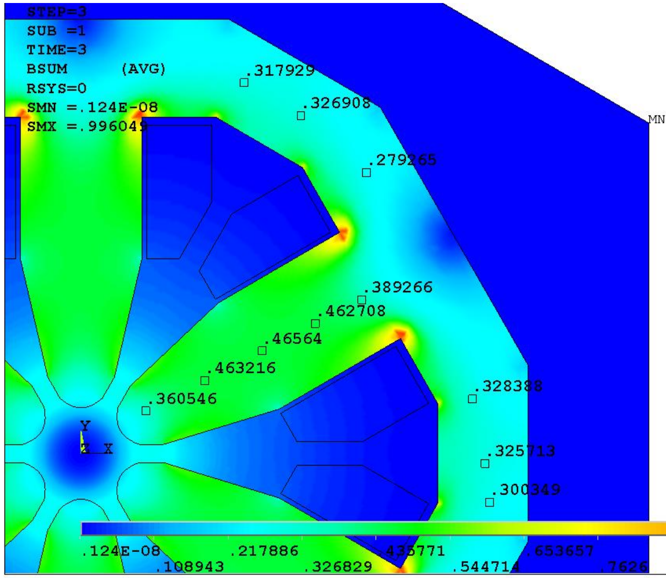
LE ANKA Sextupoles

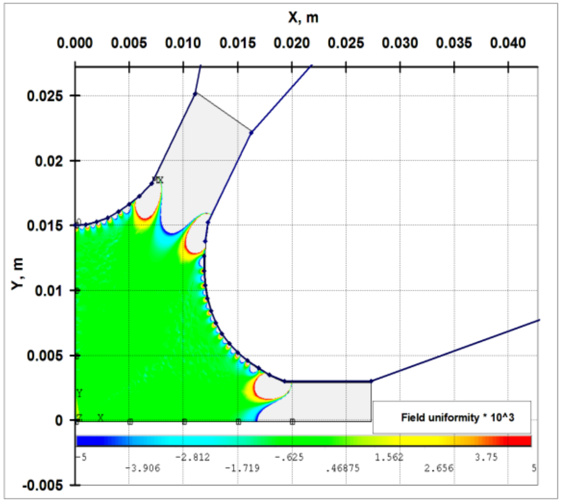
Type of sextupole	SF	SD
Number	16	16
Maximum gradient, T/m^{-2}	716	-1580
Inner diameter, mm	30	30
Effective length, m	0.15	0.15
Good field region, mm	∅24	∅24
Gradient quality	≤ 1%	≤ 1%

Profile

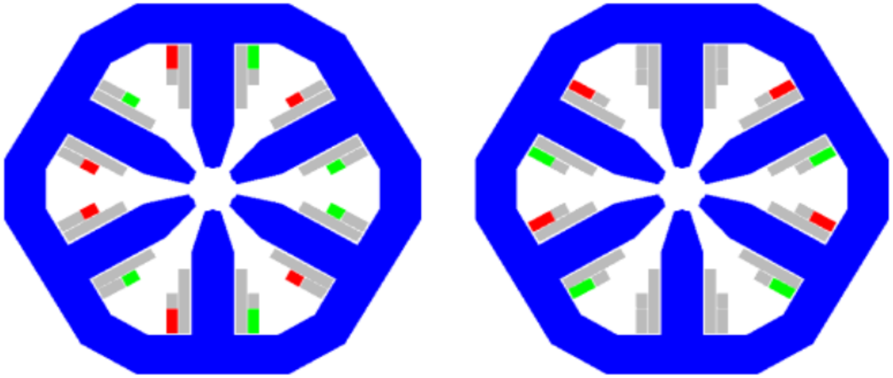


Field map





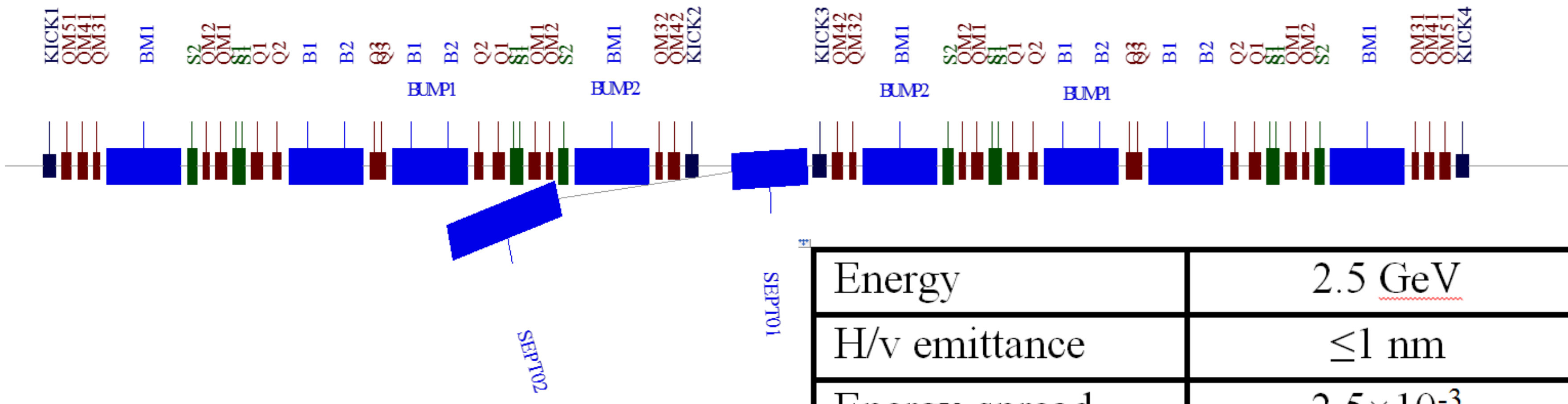
Sextupole field uniformity for 1600 T/m².



The steering coils feeding scheme:
h corrector (left) and v corrector (right)

Coils	1	2	3	4	5	6
V corrector	+I	0	–I	–I	0	+I
H corrector	+0.5I	+I	+0.5I	–0.5I	–I	–0.5I

Injection system - I



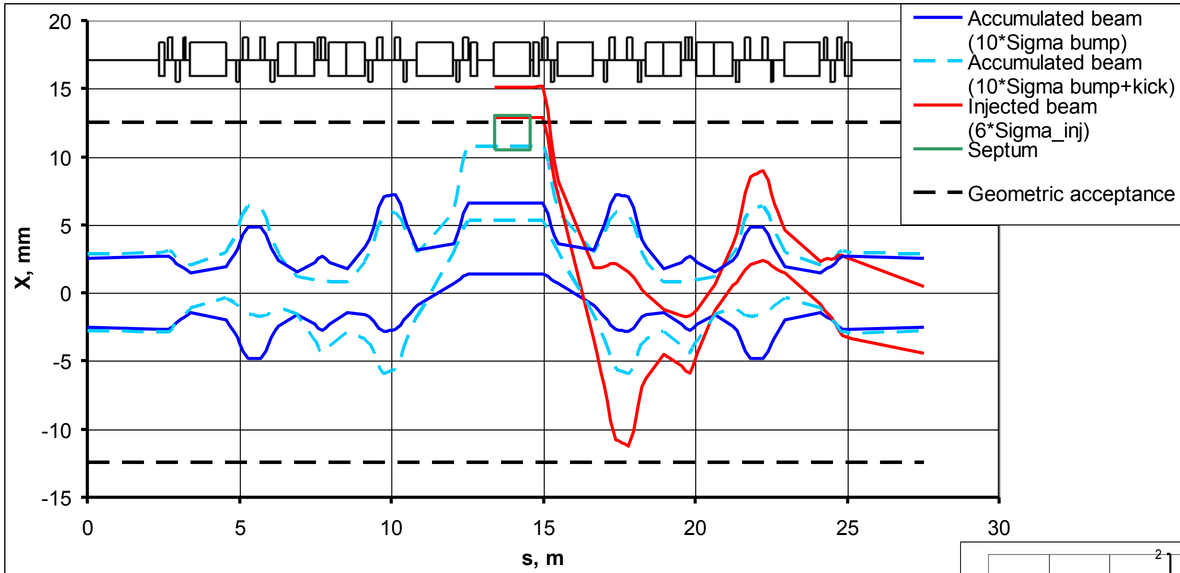
-- 4 slow (~1 ms) bump magnets (2xBUMP1-2)
-- 4 kickers (KICK1-4)
-- 2 Septum magnets

Injection from inner radius

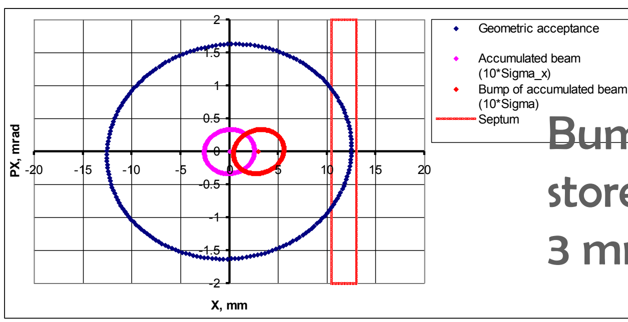
Energy	2.5 GeV
H/v emittance	$\leq$1 nm
Energy spread	2.5×10^{-3}
β_{xi} / α_{xi}	7.7 m/-0.04
β_{yi} / α_{yi}	0.66 m/-0.74
η_x / η_x'	0/0

Name	N	L, m	α, mrad	B, T
BUMP2	2	1.18	-0.97	-0.0068
BUMP1	2	1.18	-4.68	-0.033
KICK1,4	2	0.2	0.63	0.0265
KICK2,3	2	0.2	0.22	0.0092
SEPT01	1	1.2	87	0.604
SEPT02	1	1.8	349	1.62

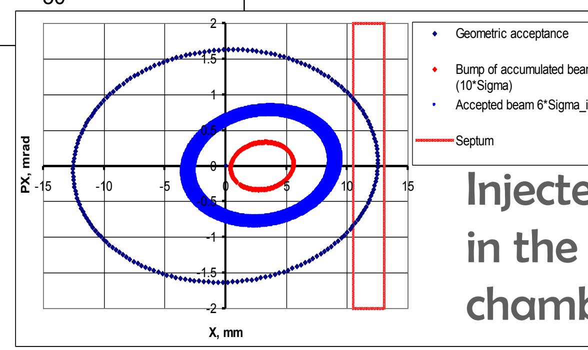
Injection system - II



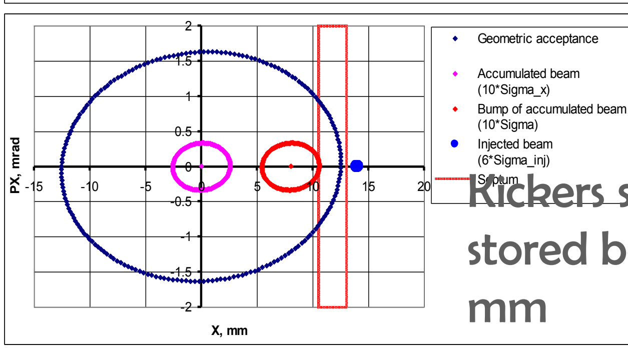
Injection trajectories



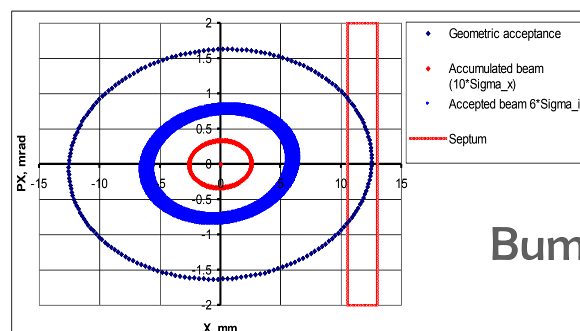
Bump shifts the stored beam by 3 mm



Injected beam in the vacuum chamber



Kickers shift the stored beam by 5 mm



Bump is over

Influence of insertion devices
(CLIC – IMAGE and CATACT wigglers)

Radiation parameters modification:

	LESR ANKA	IMAGE	CAT-ACT	IMA+CAT
Emittance	8.54 nm	8.13 nm	8.34 nm	7.98 nm
Energy spread	$1.33\cdot10^{-3}$	$1.29\cdot10^{-3}$	$1.31\cdot10^{-3}$	$1.28\cdot10^{-3}$
Energy losses	575 keV	638 keV	597 keV	660 keV
Jx/Js	2.14/0.86	2.03/0.97	2.10/0.90	1.99/1.01
Cx/Cz	0.30/2.42	0.35/2.48	0.29/2.42	0.4/2.52

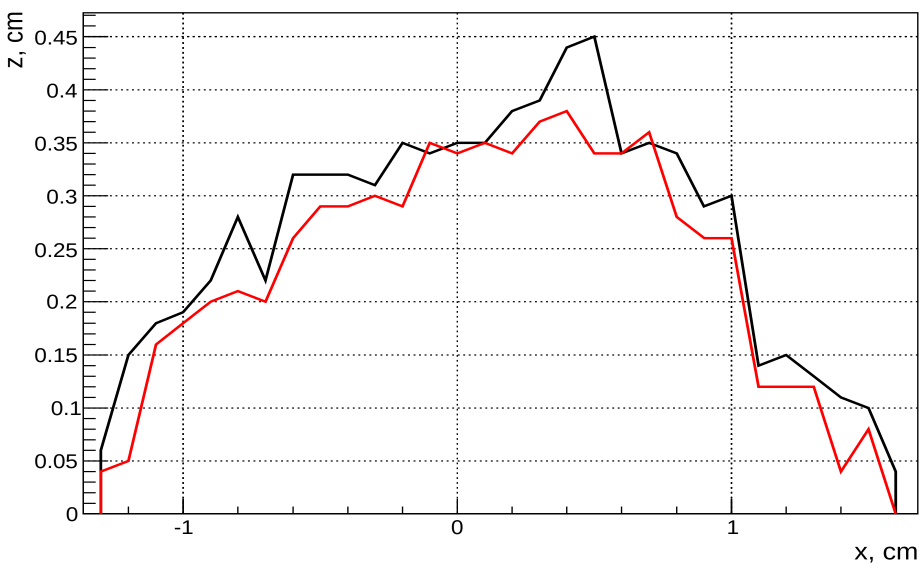
3 IMAGE wigglers should decrease the emittance from 8.5 to 6.5 nm.

Vertical betatron tune shift due to wiggler

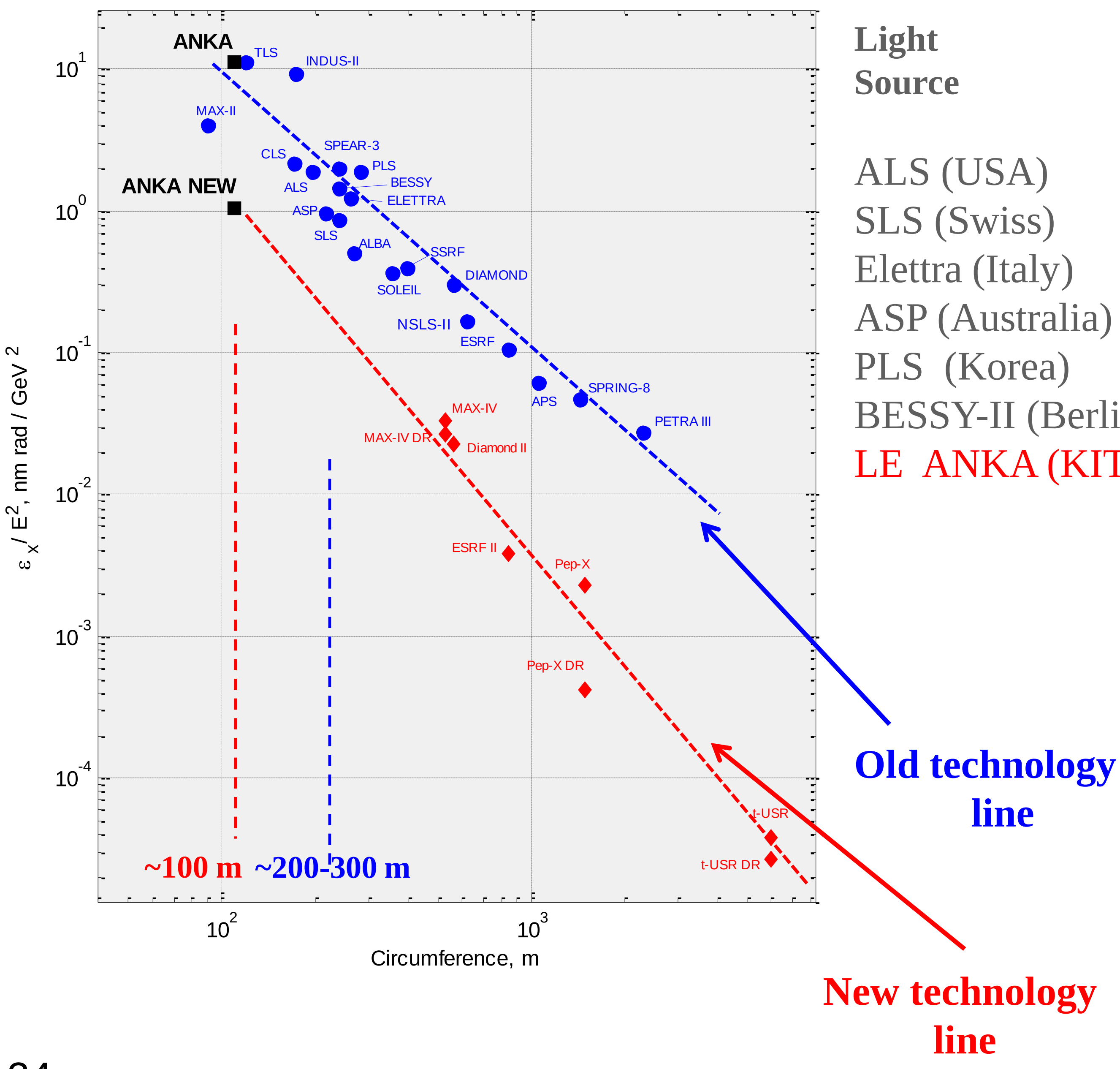
$$\Delta\nu_y = \frac{1}{8\pi} h_w^2 L_w \bar{\beta}_y$$

$$h_w = B_w / B\rho$$

Dynamic aperture reduction for both wiggler at the maximum field is negligible



Light sources technology trend (R.Bartollini plot)



Light Source	E GeV	L m	emittance nm·r
ALS (USA)	1.9	197	3
SLS (Swiss)	2.4	240	5.2
Elettra (Italy)	2.4	260	7
ASP (Australia)	3	216	8.6
PLS (Korea)	2.5	281	6
BESSY-II (Berlin)	1.7	240	6
LE ANKA (KIT)	2.5	110	6÷8

Conclusion

- **It is possible to build low emittance ring based on split ANKA lattice : L=110 m and ε = 6 - 8 nm-rad horizontal emittance in the baseline version.**

- **with damping wigglers emittance might be reduced to ~6 nm**

- ***-I* transform works well providing the dynamic aperture close to the vacuum chamber border (+-12.5 mm) and +-6% energy acceptance (additional optimization available)**

- **Parameters of bending magnets, quads and sextupoles are reasonable for production**

- **Dispersion free straight sections can accommodate strong field insertion devices with extra emittance decrease**

- **Injection from the MAX IV type linac either from low emittqance booster synchrotron (32 bending magnets) is acceptable**

Conclusion

- **New generation Light Source**
- **Compact design**
- **Low emittance storage ring**
- **SR Brilliance ~100 times more**

Appendix

split cell → short focal distances between elements → strong quadrupole gradients →
→ **the absolute value of natural chromaticity grows**

In general, in a compact cell the betatron phase advance between chromatic sextupoles is small and DA might be roughly estimated as **fixed points** of the nearest strong **sextupole resonances**:

Aperture scaling factor →

$$Dynamic\_Aperture_{x,z} \propto \frac{\sqrt{\varepsilon_x \beta_{x,y0}}}{\xi_{x,y}}$$

more than 30 optics versions have been studies so far.

Sequence of steps

-- the cell was designed to tune for exact "**–*I*** " transfer matrix for the horizontal sextupoles ***SF*** because the horizontal aperture is more important for injection

-- version with **–*I*** condition for both ***SF*** and ***SD*** families is also available but cell is too long

-- parameters of cell were tuned for the lowest emittance available in this particular lattice

to further reduce emittance

-- the "**–*I*** " condition was slightly **detuned** and parameters **adjusted** for low emittance again

-- the emittance is decreased but due to the distorted "**–*I*** " condition the DA is reduced as compared to exact condition

-- the procedure have been repeated few times

-- different lattices with smaller emittance but reduced DA were received → next slide