Sirius, a new low emittance Brazilian synchrotron light source

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ALS, Berkeley Dec. 13th, 2013 (Friday 13th).

Sirius – a new light source in Brazil

About Brazil

Area	8.5 x 10^6 km^2	World rank 5th
Population	200 million people	World rank 5th
GDP	$2.25 trillion (2012)	World rank 7th

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The institution - CNPEM

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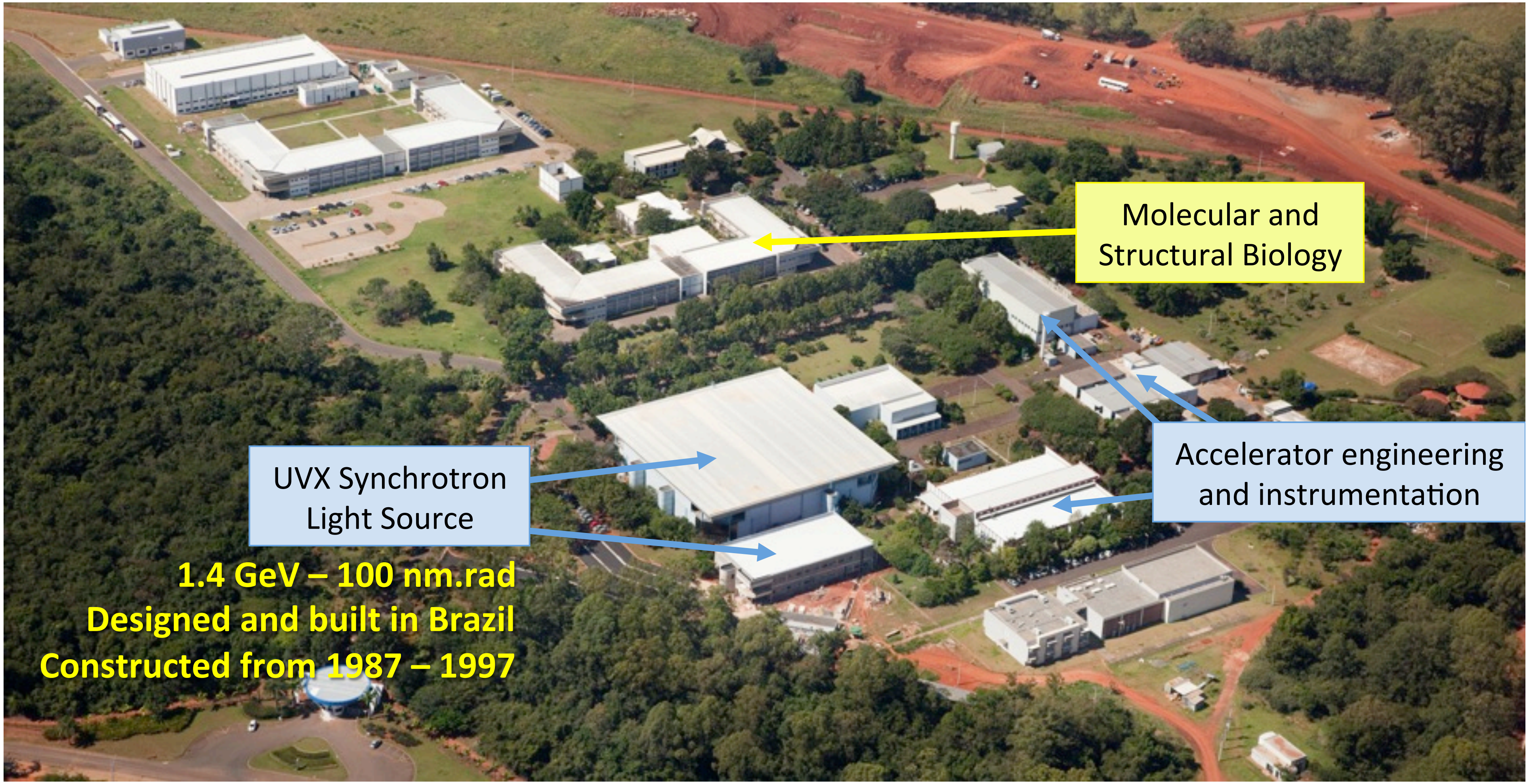

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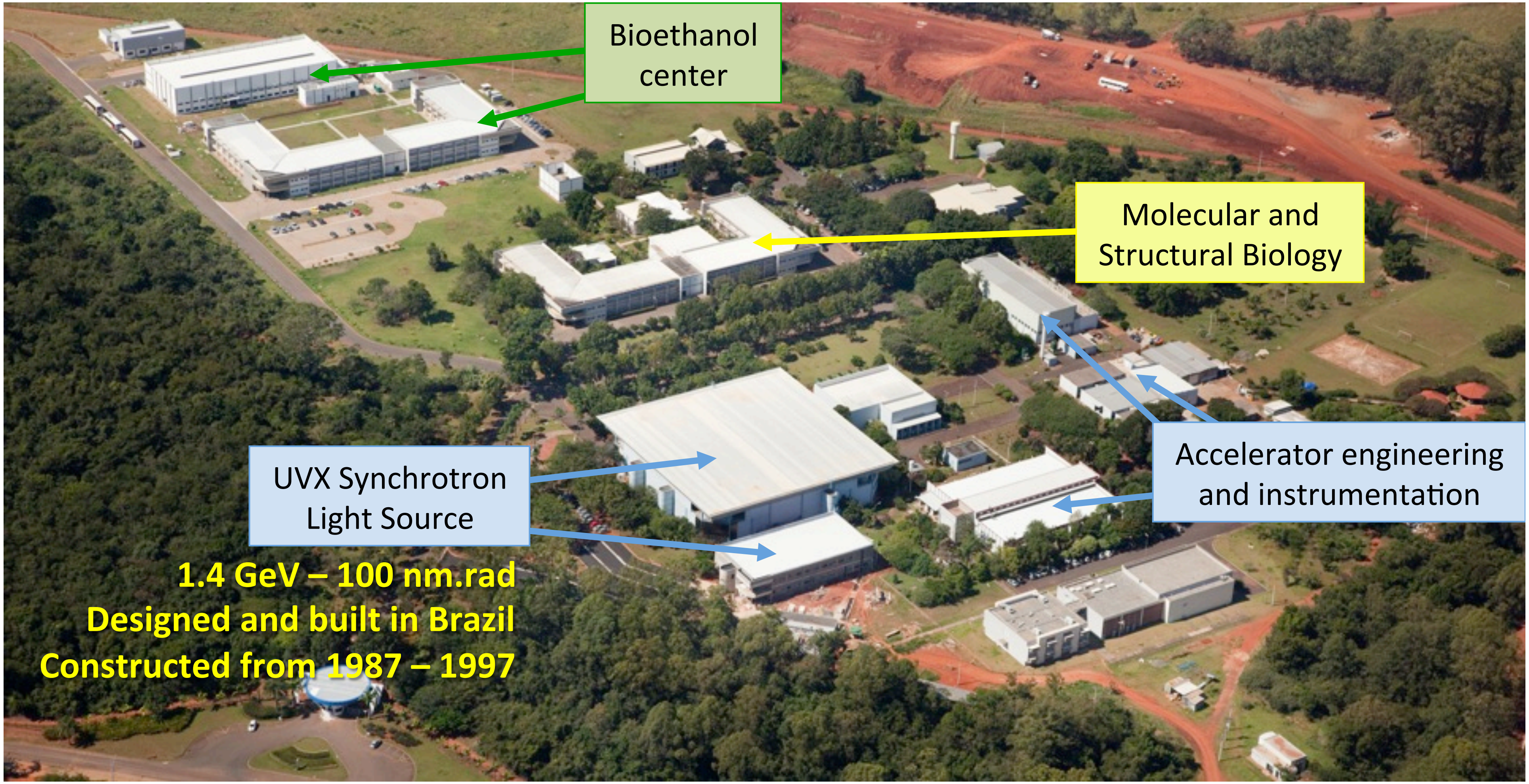

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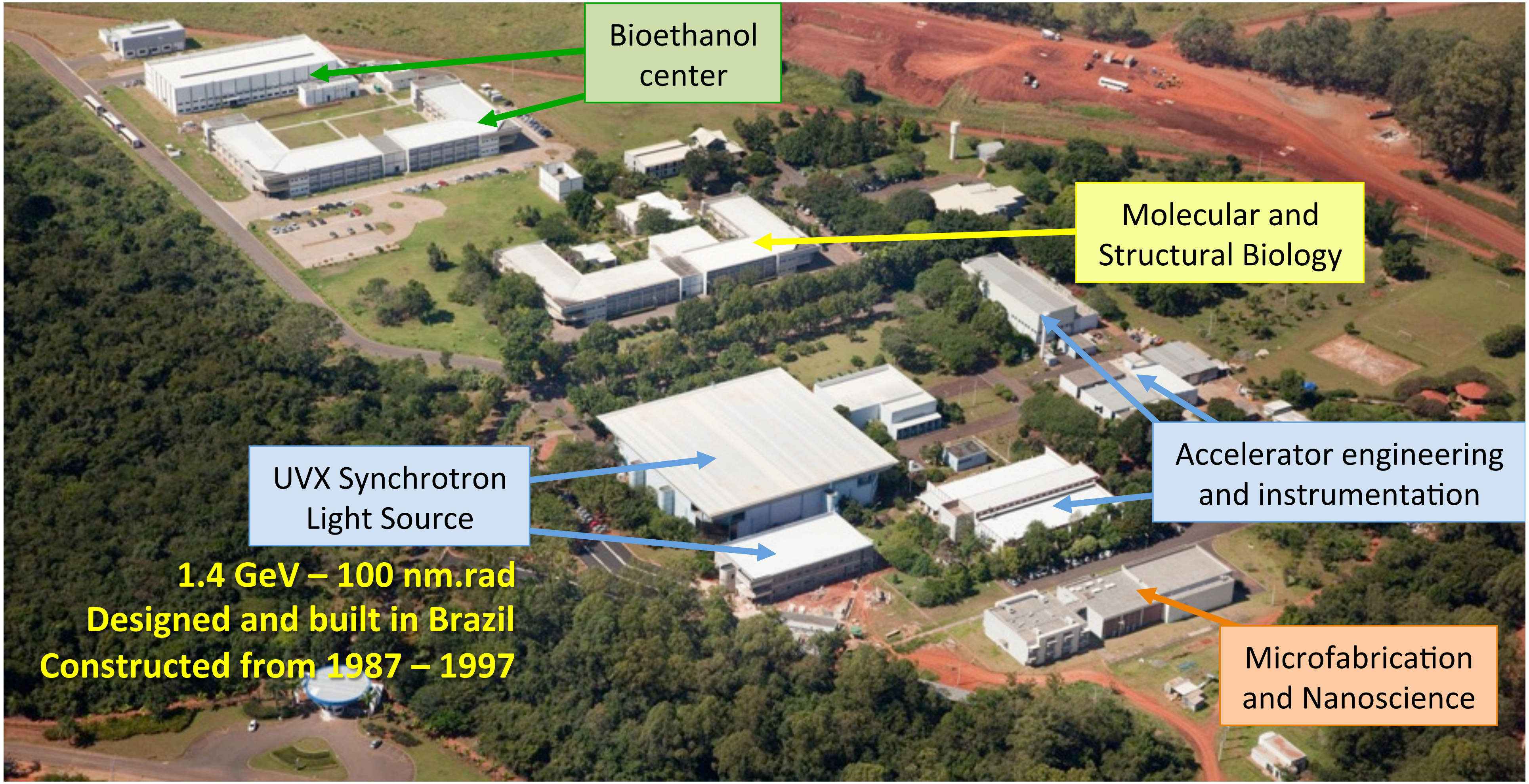
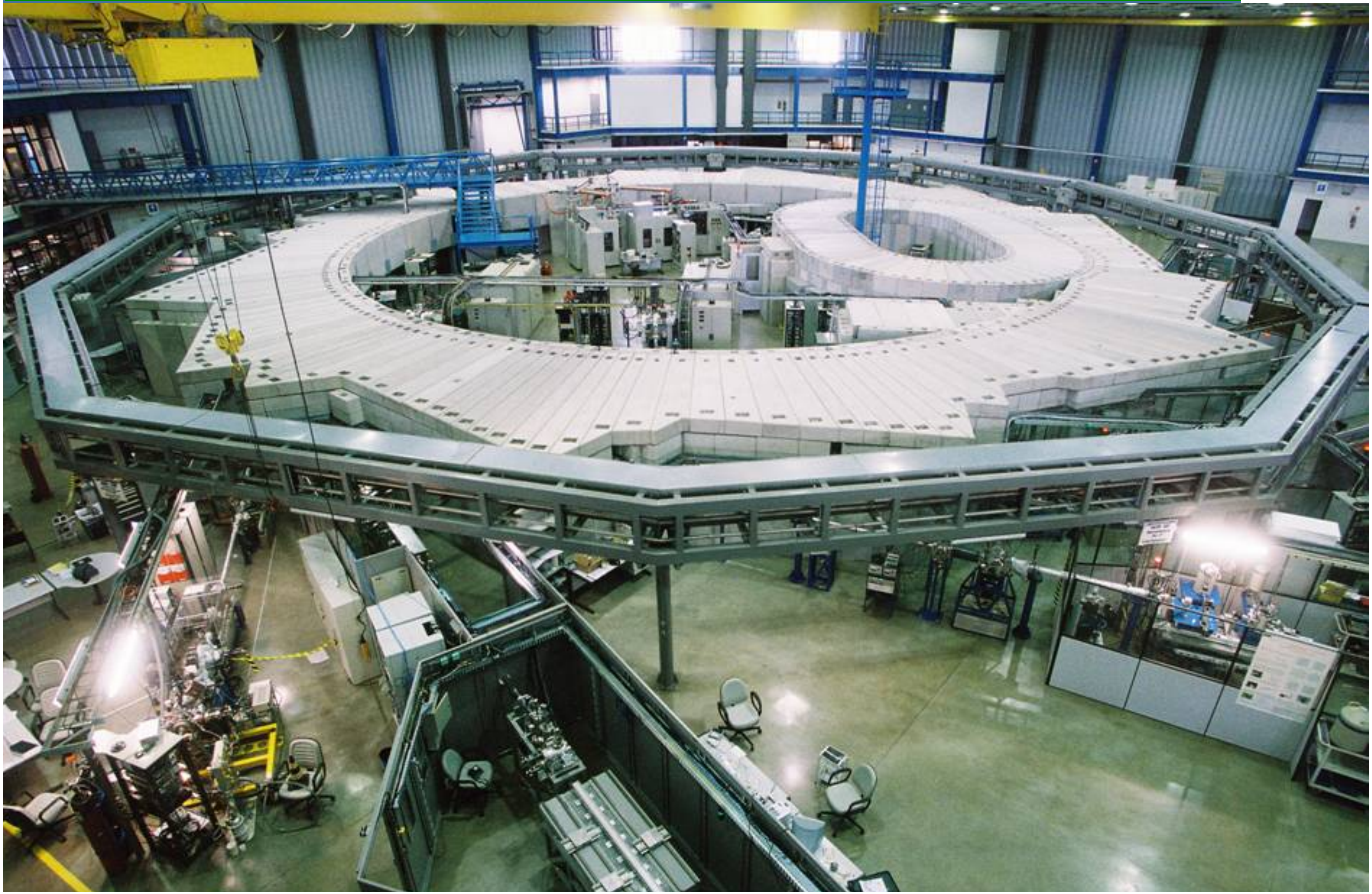


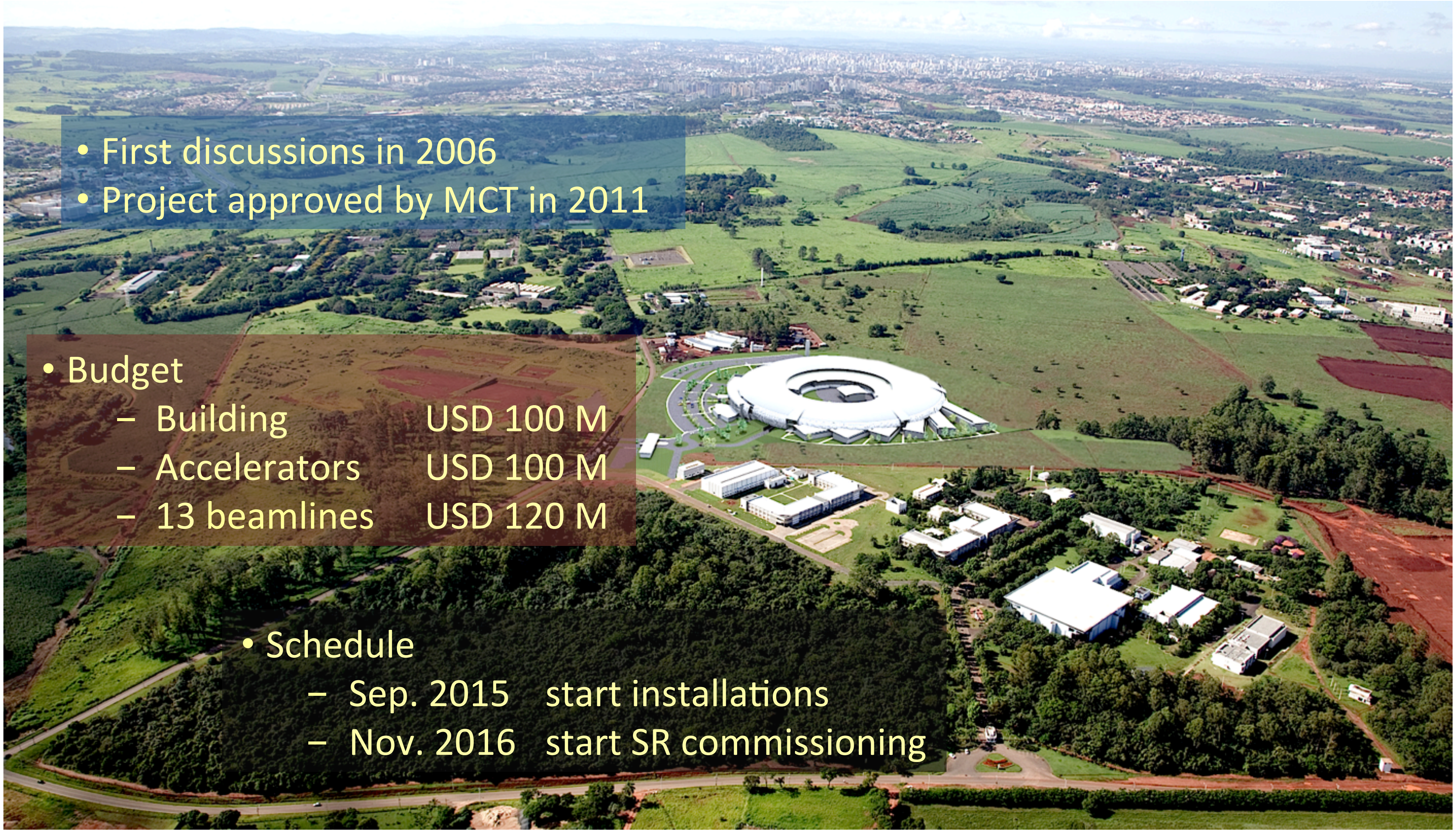
UVX



Historical overview

Jan 1987 to Jun 1997	• **UVX, a 1.4 GeV synchrotron light source is designed, built and commissioned from scratch.**
2006	• LNLS starts discussions on a new 3 GeV synchrotron
Dec 2008	• MCT approves budget for conceptual design.
2009	• Two workshops: scientific case and machine parameters. • Conceptual design and prototype work starts.
2010	• Improvements of the LNLS engineering infrastructure. • Design and prototype work.
2011	• Lattice design optimization. • MCT approves project. • Internal discussion on candidates for phase 1 beamlines
2012	• 1st Machine Advisory Committee (Machine Redesigned: TBA → 5BA) • 1st Beamline Advisory Team Meeting (Spectroscopy) • New low emittance design, new location, new building layout.

Sirius @ LNLS campus



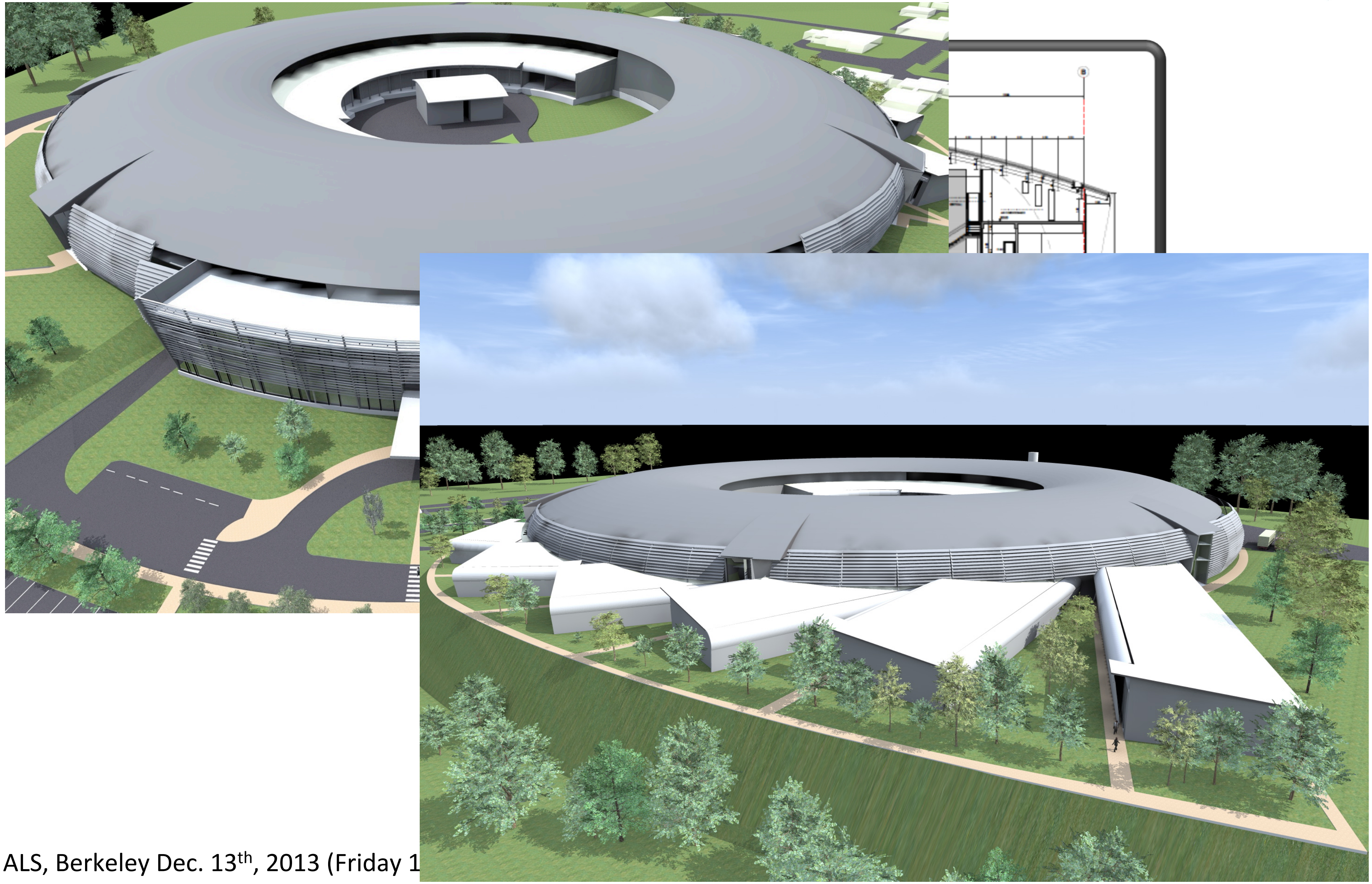
- First discussions in 2006
- Project approved by MCT in 2011

- Budget
  - Building USD 100 M
  - Accelerators USD 100 M
  - 13 beamlines USD 120 M

- Schedule
  - Sep. 2015 start installations
  - Nov. 2016 start SR commissioning

Earth work almost ready

Buildings



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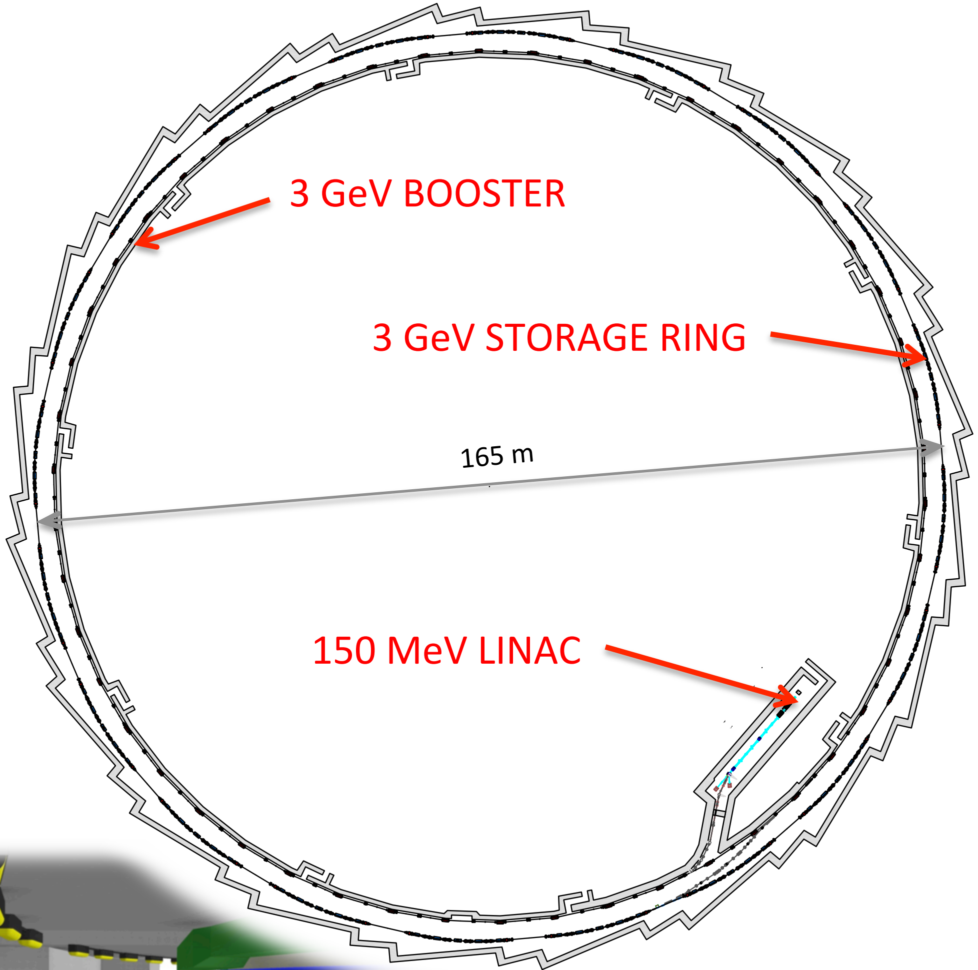
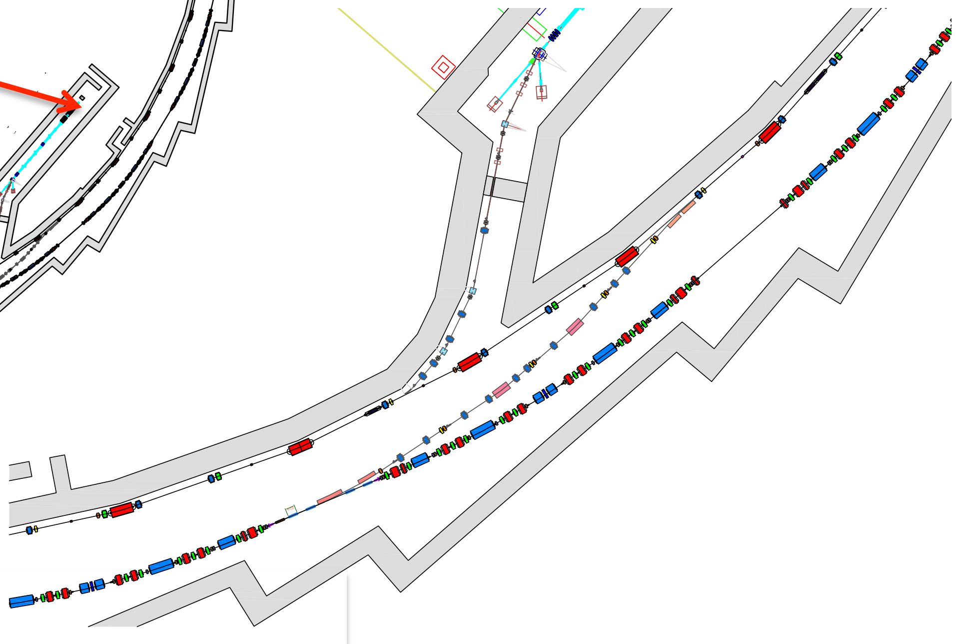
Accelerators layout

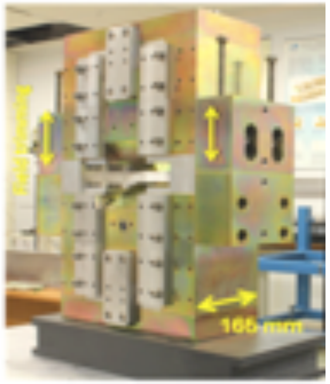


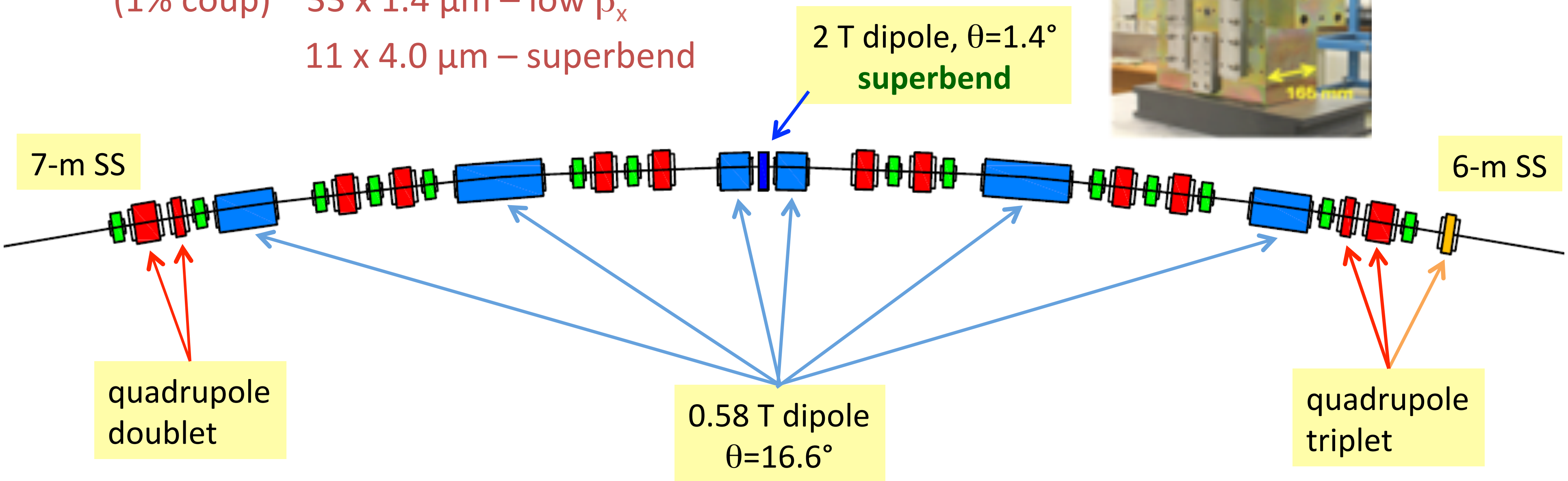
Storage Ring	circumf. (m)	518
	emittance (nm)	0.28
	lattice	20 - 5BA
Booster	circumf. (m)	496
	emittance (nm)	3.7
	lattice	50 fodo



Sirius main parameters

- Energy: 3 GeV
- Circunference: 518 m
- Emittance without wigglers: 0.28 nm.rad
- Lattice: 5BA with low field main dipoles (0.58 T) and split central dipole to accommodate a 2 T superbend
- Straight sections: 10 x 7m – high β_x
  10 x 6m – low β_x
- Beam size: 68 x 3.0 µm – high β_x
  (1% coup) 33 x 1.4 µm – low β_x
  11 x 4.0 µm – superbend





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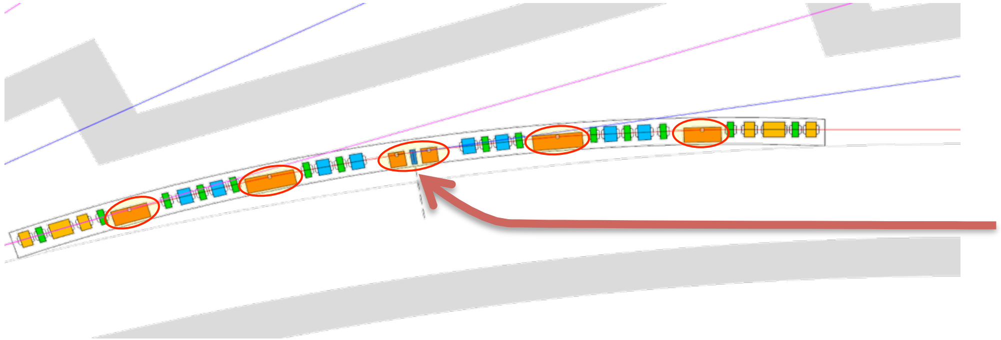
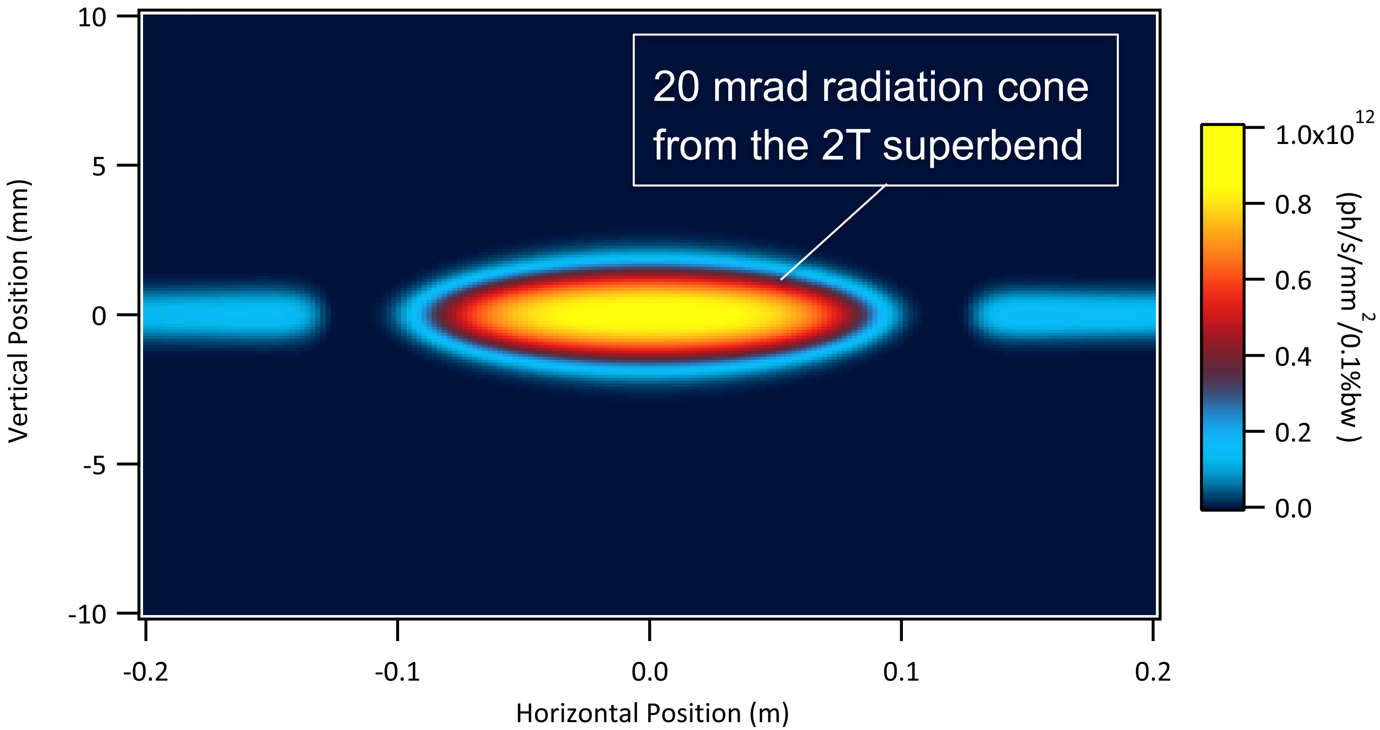
Superbends: hard X-ray source



- 2T permanent magnet superbend
- 12 keV critical energy
- 1.4° deflection
- X-rays produced only at beamline exit
- Modest total energy loss



Flux density (ph/s/0.1%bw/mm^2) of 12 keV photons from the 2T superbend at 10 m from the source, calculated with SRW (Chubar & Elleaume)

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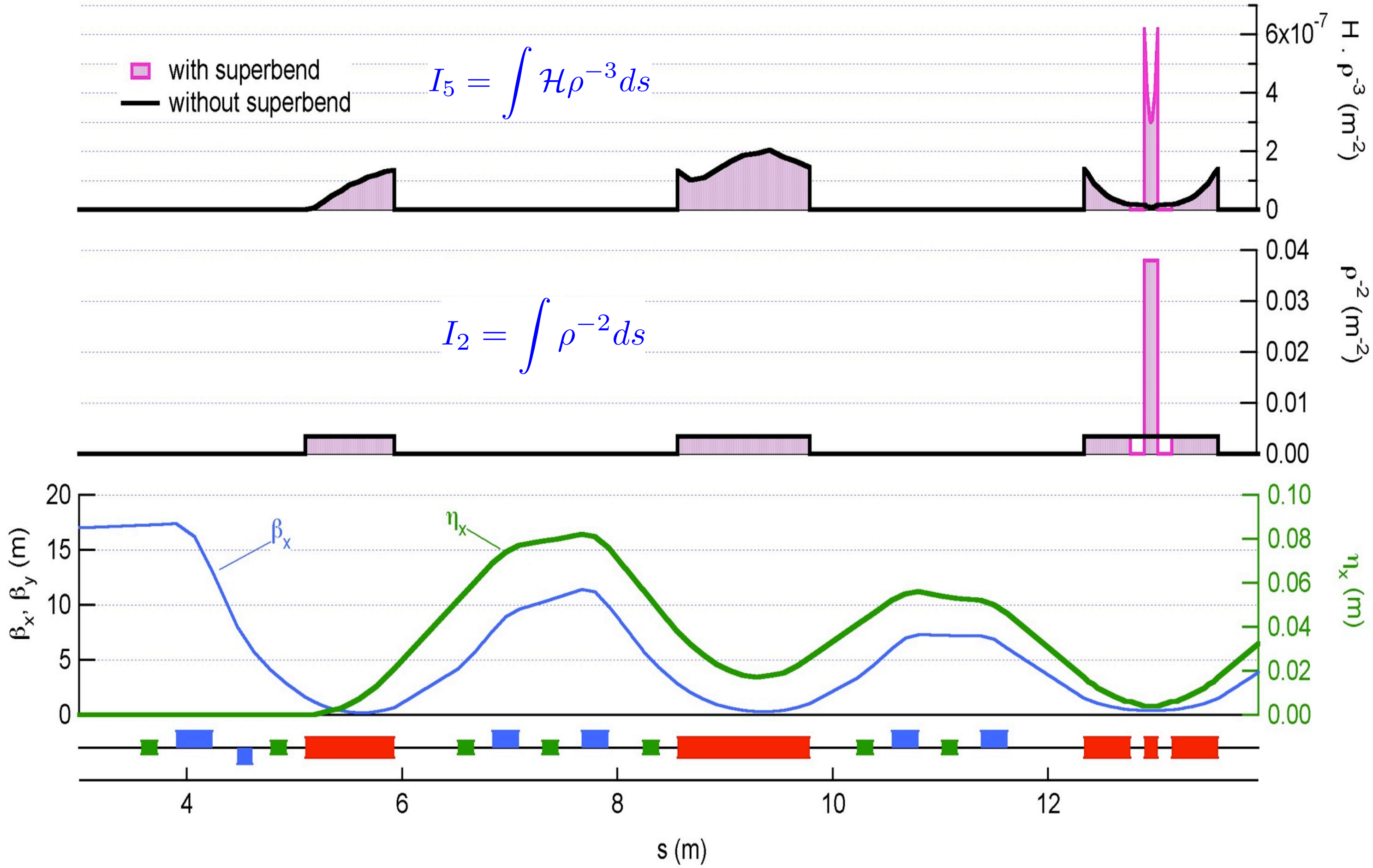
Superbends: longitudinal gradient

$$\mathcal{H} = \gamma_x D^2 + 2\alpha_x D D' + \beta_x D'^2$$

$$\epsilon \propto \frac{I_5}{I_2}$$



- without superbends: ε = 0.31 nm.rad
- with superbends: ε = 0.28 nm.rad   10% reduction

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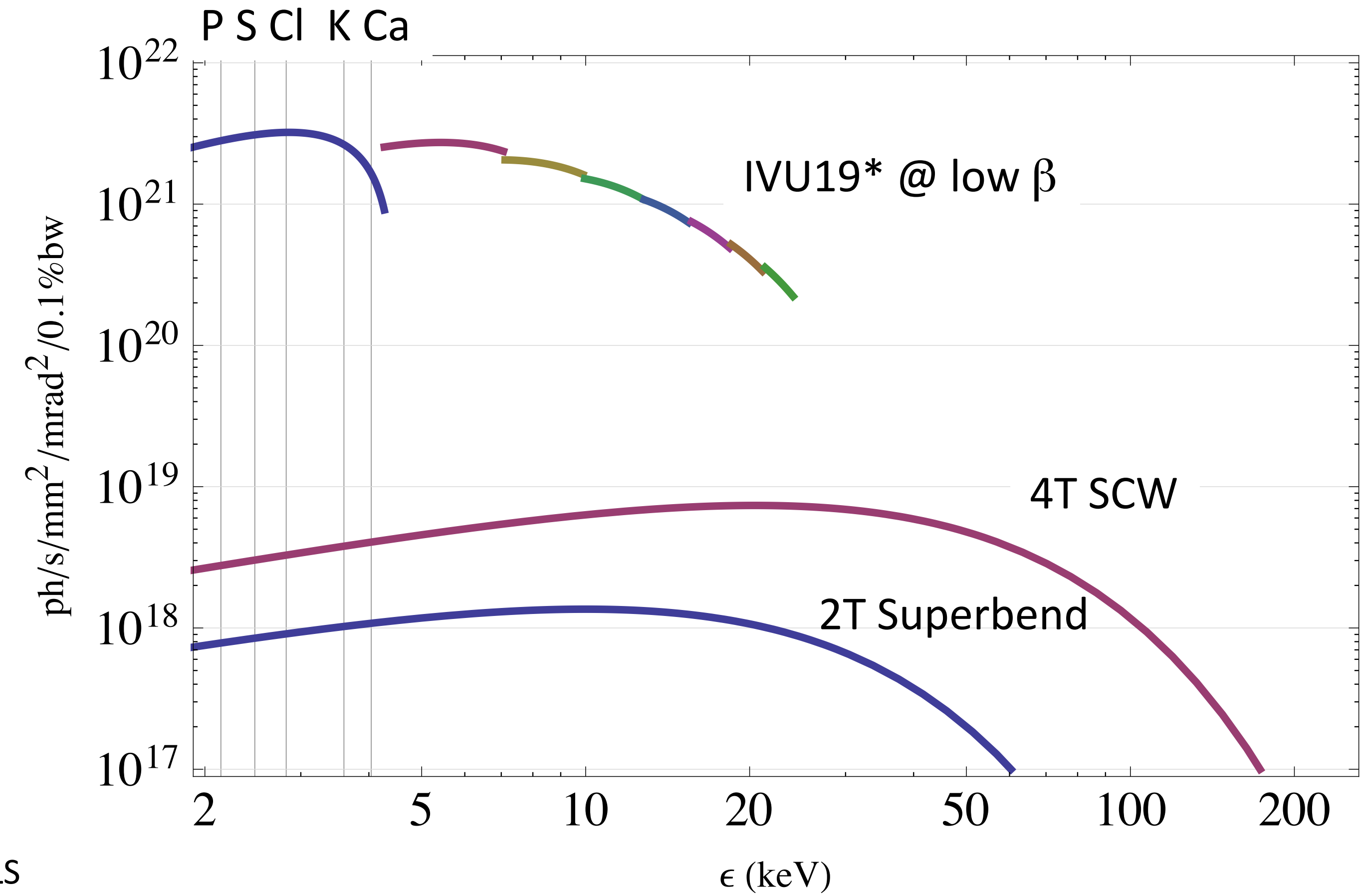
X-ray brilliance (on axis)

- Phosphor: *Soil sciences, Agriculture, Mineralogy, Catalysis*
  - Sulfur: *Petroleomics, Corrosion in pre-salt environment, Sulfur MAD/SAD*
    - Chlorine: *Corrosion in sea and pre-salt environment*
      - Potassium: *Alkali metal promoter, promoter of FT catalysis*
        - Calcium: *Bio-minerals, Nutrition, Nano-fossils*



*(NdFeB, Br = 1.3 T, min. gap 5 mm, P. Elleaume (2000) fit to Halbach)

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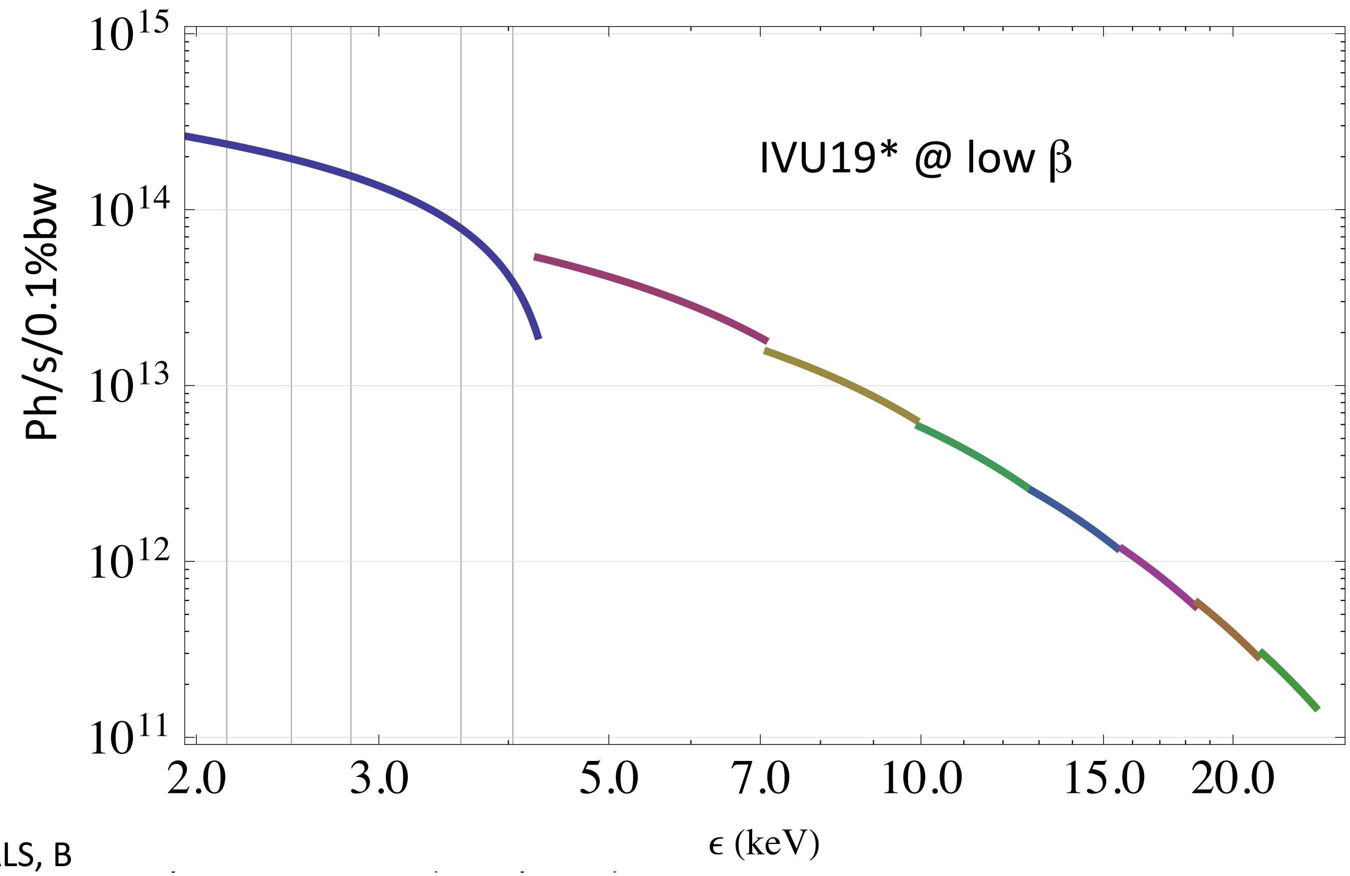
Coherent X-ray flux

- Low energy XPCS and CDI for biological samples
  - *Above 2 keV sample damage is practically constant*
- High Coherent flux up to 25 keV
  - *Crucial for all diffraction limited focusing*



*(NdFeB, Br = 1.3 T, min. gap 5 mm, P. Elleaume (2000) fit to Halbach)

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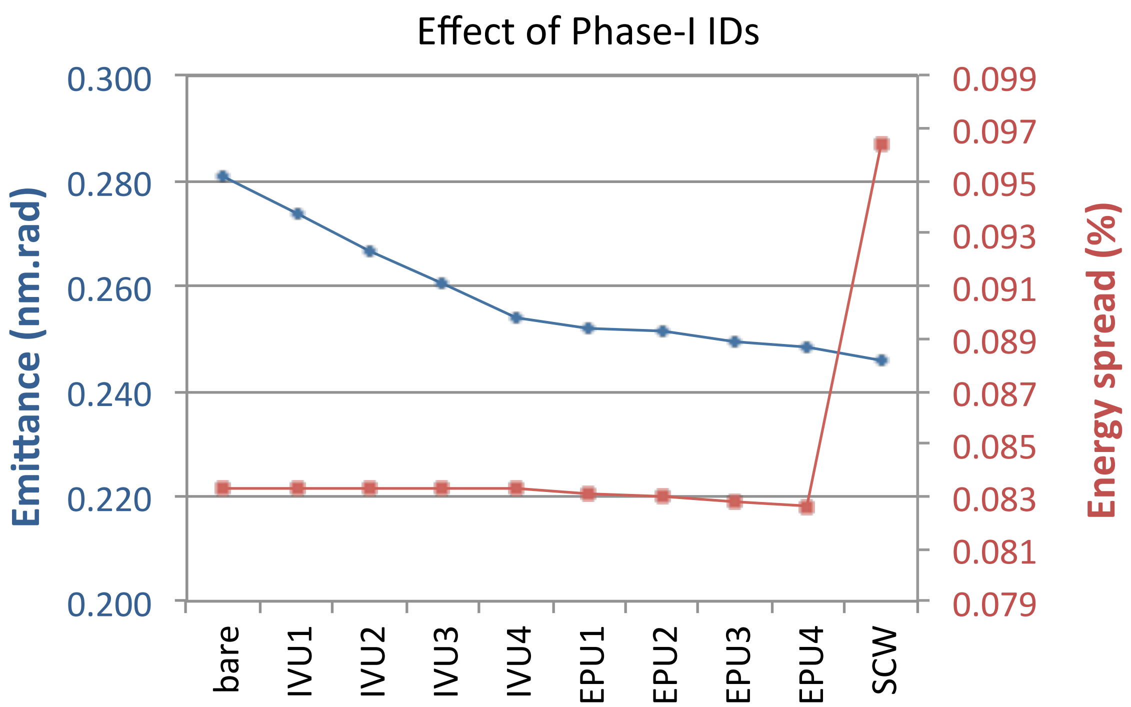
Emittance optimization

- **Other tricks to reduce emittance for given Energy and Number of Dipoles**
  - Dipoles with transverse gradient to increase J_x.
  - Achromatic cells ⇨ IDs help to reduce the emittance.
  - 2 T superbend ⇨ longitudinal field gradient ⇨ strong focusing of the H-function at superbend.
  - Shorter outer dipoles. Outer dipoles are not optimized for emittance reduction because of the zero-dispersion condition. In the optimized condition the dispersion is minimum at the dipole center.
  - Low field dipoles ⇨ reduced energy spread

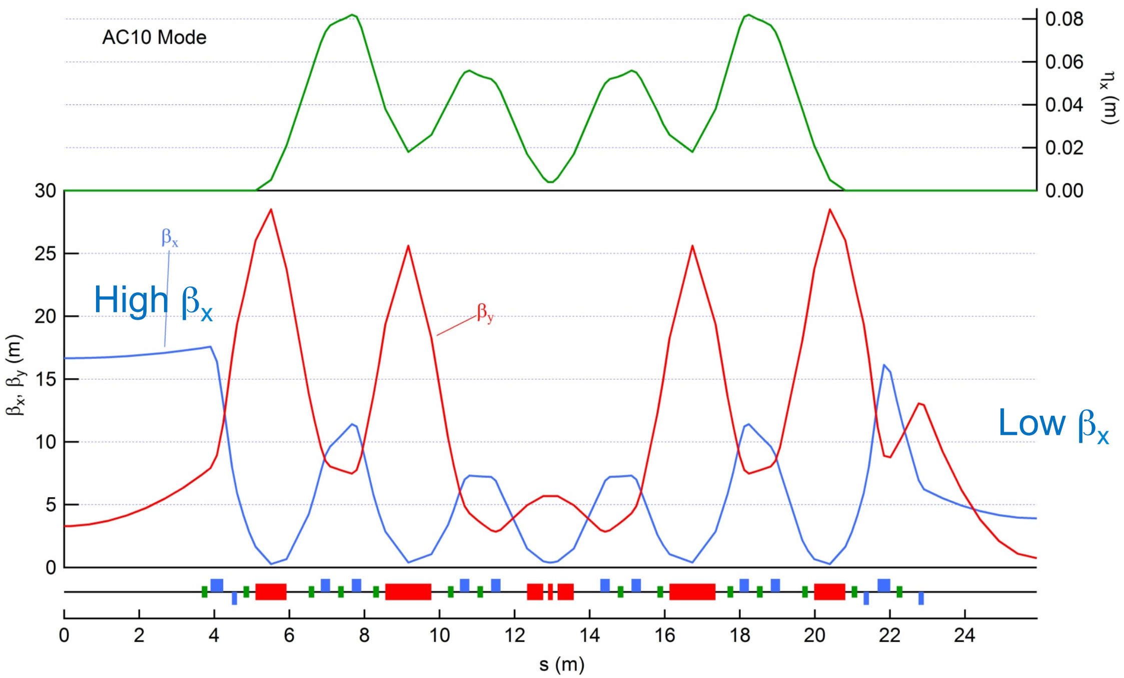
    ⇨ Longitudinal emittance reduction.

Effect of phase-I IDs



ID	K	λ (mm)	L (m)	B (T)
IVU1	2.07	18	2	1.2
IVU2	2.07	18	2	1.2
IVU3	2.07	8	2	1.2
IVU4	2.07	18	2	1.2
EPU1	3.38	50	3	0.7
EPU2	8	200	3	0.4
EPU3	3.38	50	3	0.7
EPU4	8	200	3	0.4
SCW	22.6	60	3	4.0

Linear optics – AC10 mode



Nat. emittance	0.28 nm.rad
Tunes ν_x/ν_y	46.2 / 14.15
Nat. chrom. x/y	-113 / -80
Normal. chrom. x/y	-2.4 / -5.7
Mom. comp.	1.7×10^{-4}
Energy spread	0.08 %
Max. quad grad B’	39 T/m
Max. sex grad B”/2	1870 T/m^2
Dipole grad. B’	-7.8 T/m
τ_h	15.9 ms
τ_v	21 ms
τ_s	12.5 ms
J_x	1.32

- Alternating high and low β_x
- 8 chromatic quadrupoles (4 families)
- 2 + 3 matching quadrupoles
- 14 sextupoles (9 families)

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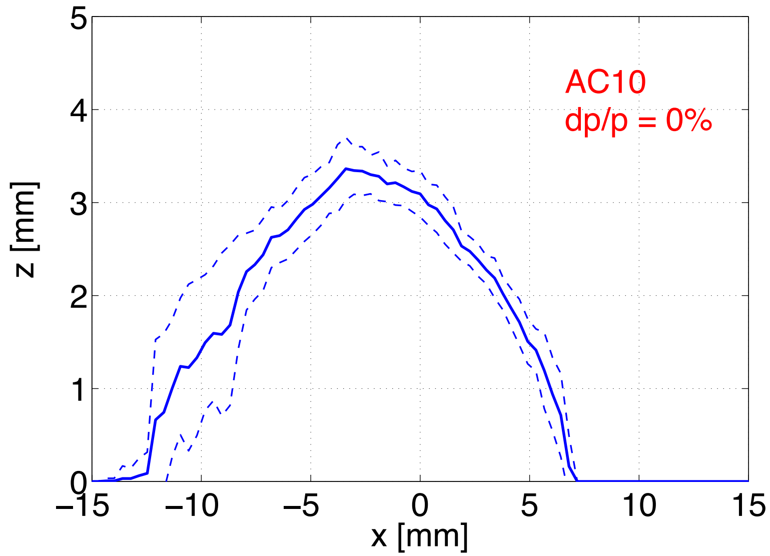
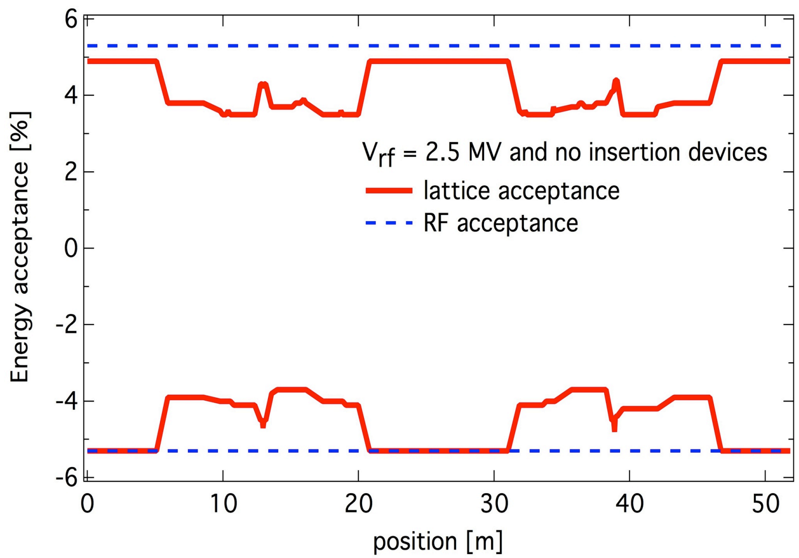
Dynamic aperture and momentum acceptance

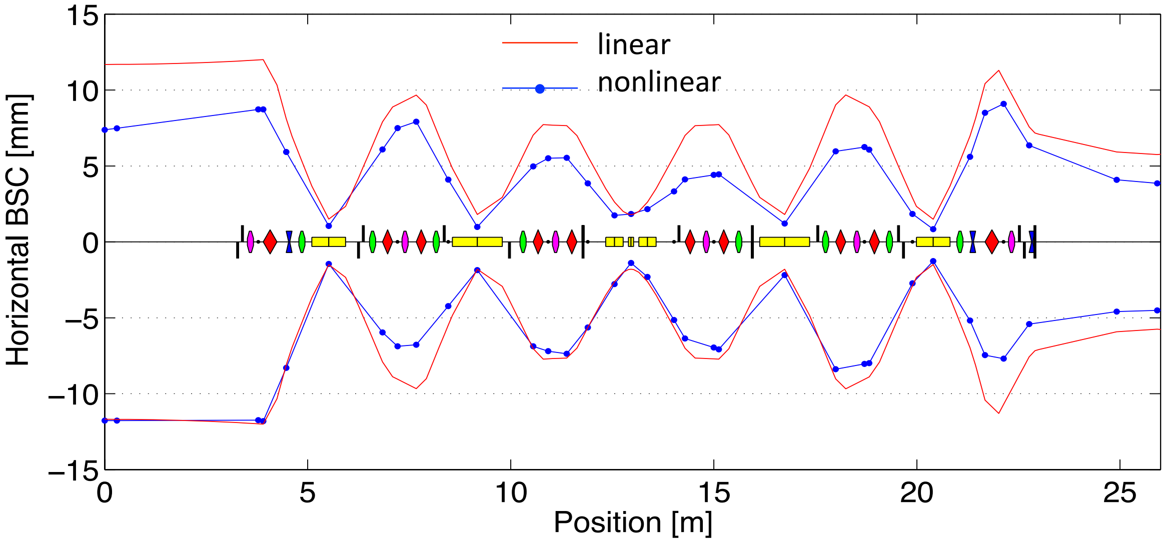
Dynamic aperture



Momentum acceptance



Note asymmetry due to optimization of negative side of DA.
Asymmetric beam-stay-clear allows for installation of small absorbers to shadow BPMs and bellows from radiation in straight sections.

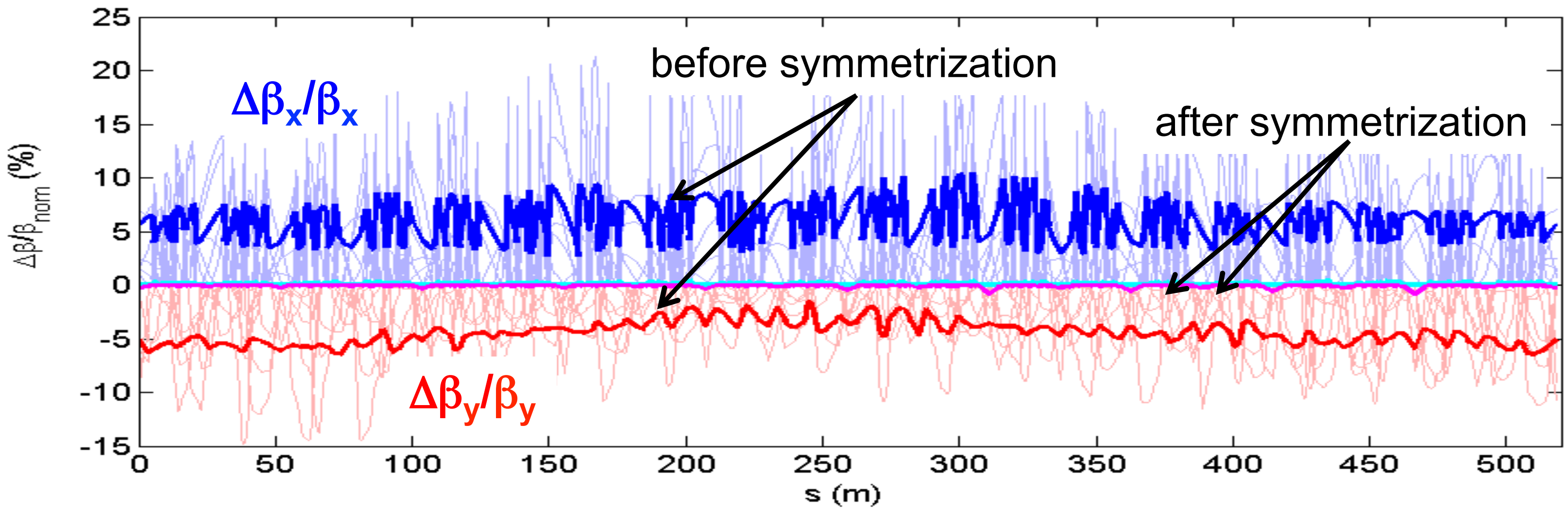


DA optimization

- Optimization using codes: MAD, OPA, Elegant (MOGA), Tracy3 (tracking).
- Alignment errors dominate DA reduction. Optics is affected by off-centered orbit in sextupoles.
- DA improves by restoring design optics. Symmetrization and coupling correction.
- Special care with orbit correction at sextupoles. Place BPMs close to strong sextupoles.

Alignment error*	30	μm
Roll angle error*	0.2	mrad
Excitation error*	0.05	%
Max. rms uncorrected COD (H/V)**	1.9 / 4.4	mm
Max. rms corrected COD (H/V)	21 / 29	μm

*Gaussian distribution of random errors for all magnets truncated at 1 σ.
** With sextupoles off.



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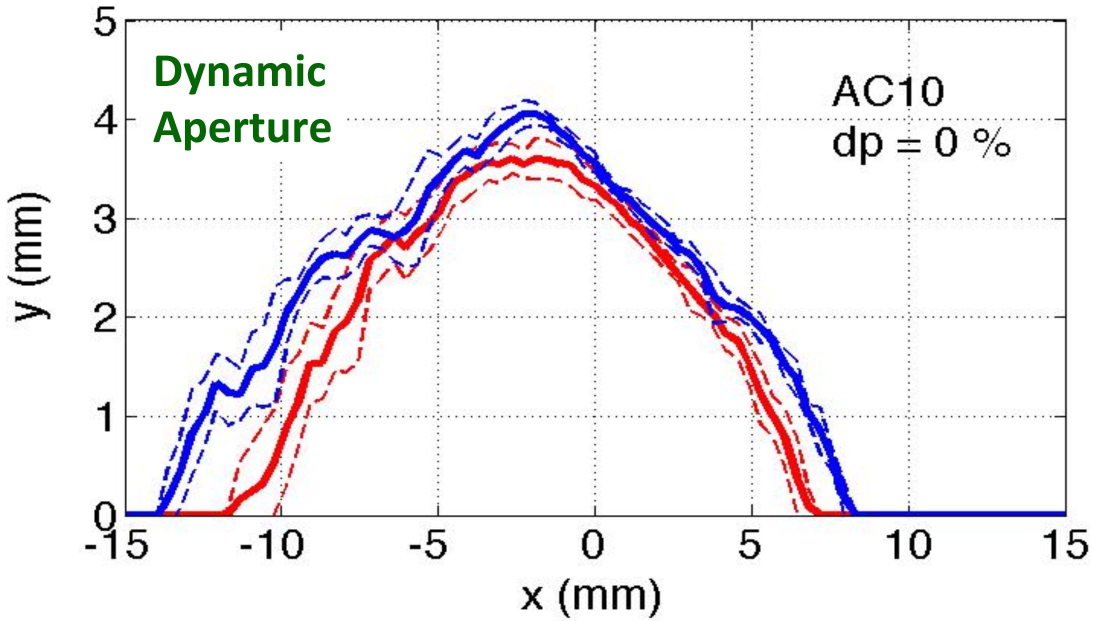
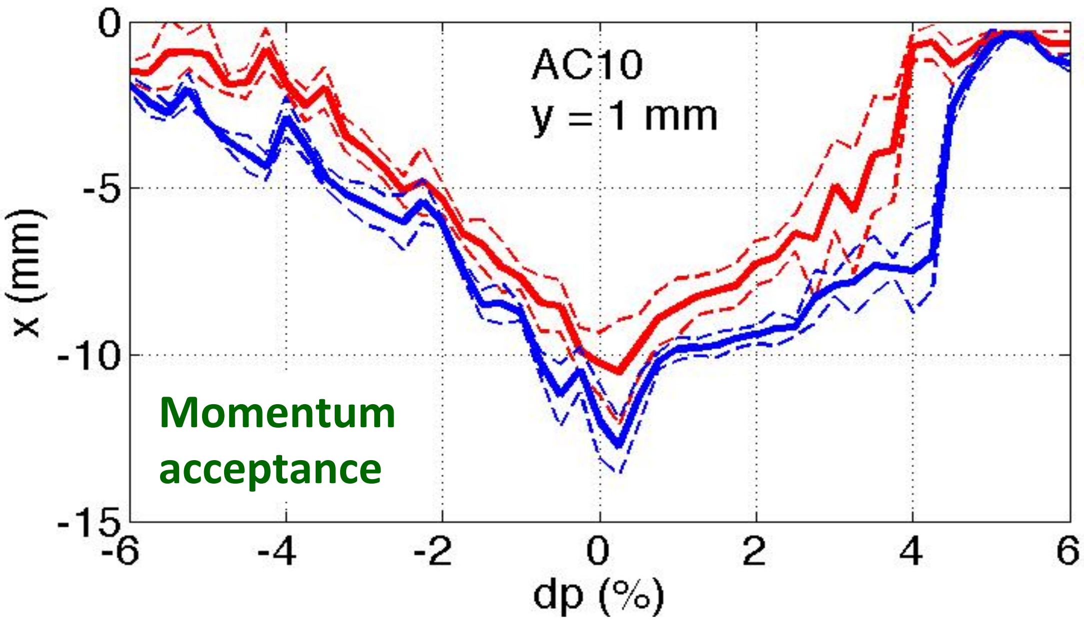
DA with errors and orbit correction

Old version



- Mode AC10
- DA at center of 7m SS
- Tracking for 5000 turns



Beam Lifetime Scenarios

	Commis.	Phase 1	Phase 2
# of RF cavities (DAMPY)	3	3	6
3rd harmonic cavity	-	-	yes
RF voltage (MV)	1.8	1.8	2.7
En. loss/turn from IDs (keV)	-	200	350
IDs	-	4 IVU (g=4mm) 4 EPUs 1 SCW	8 IVU (g=4mm) 8 EPUs 1 SCW
Total current (mA)	100	100	500
Single bunch current (mA)	-	-	2

Lifetime

Calculations include IBS, bunch lengthening by 3rd harmonic cavity, effect of IDs on beam emittance.

Comissioning

- $T_{elastic}$ = 66.8 h
- $T_{inelastic}$ = 46.9 h
- $T_{touschek}$ = 19 h
- **T_{total} = 11.2 h @ 100 mA**

Phase 1

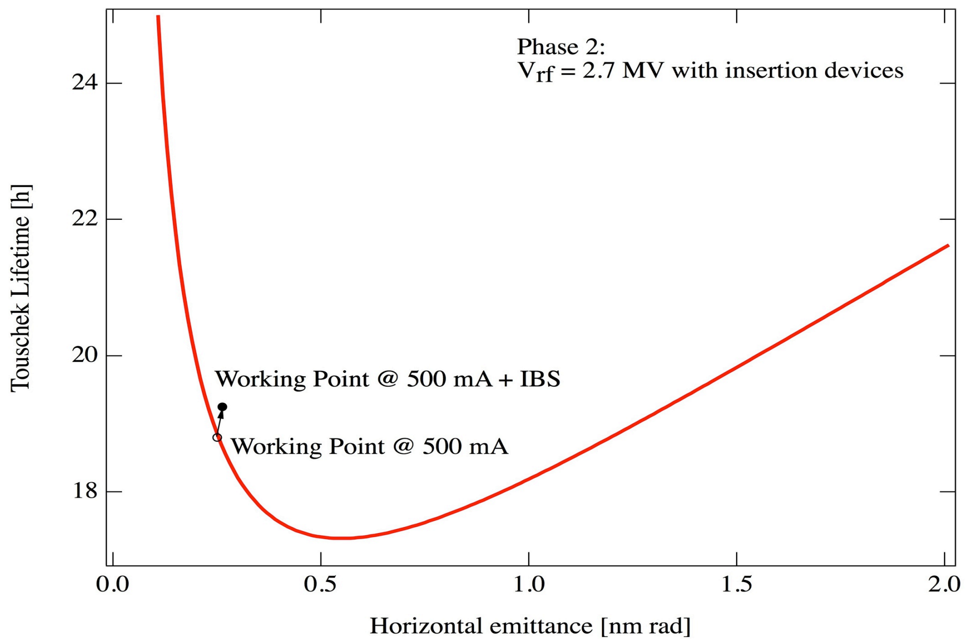
- $T_{elastic}$ = 29.7 h
- $T_{inelastic}$ = 45.7 h
- $T_{touschek}$ = 17 h
- **T_{total} = 8.7 h @ 100 mA**

Phase 2

- $T_{elastic}$ = 29.6 h
- $T_{inelastic}$ = 48.5 h
- $T_{touschek}$ = 19 h
- **T_{total} = 9.5 h @ 500 mA**

For single bunch :

- $T_{touschek}$ = 5.7 h
- **T_{total} = 5.7 h @ 2 mA**



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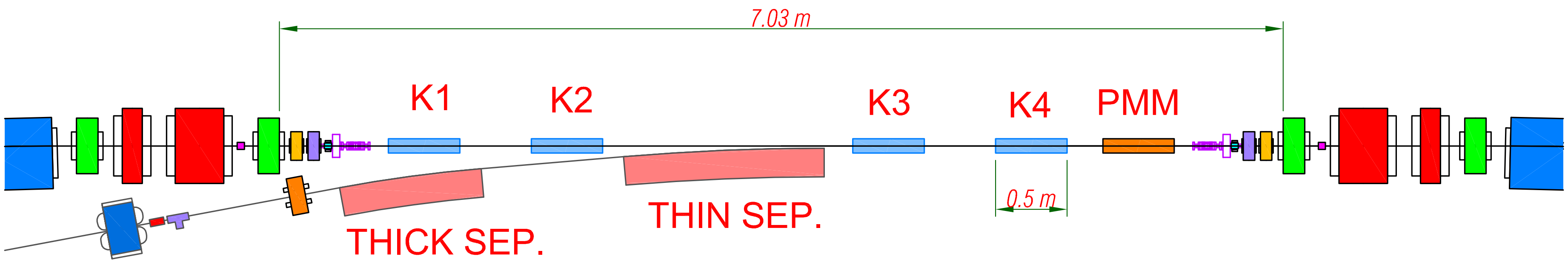
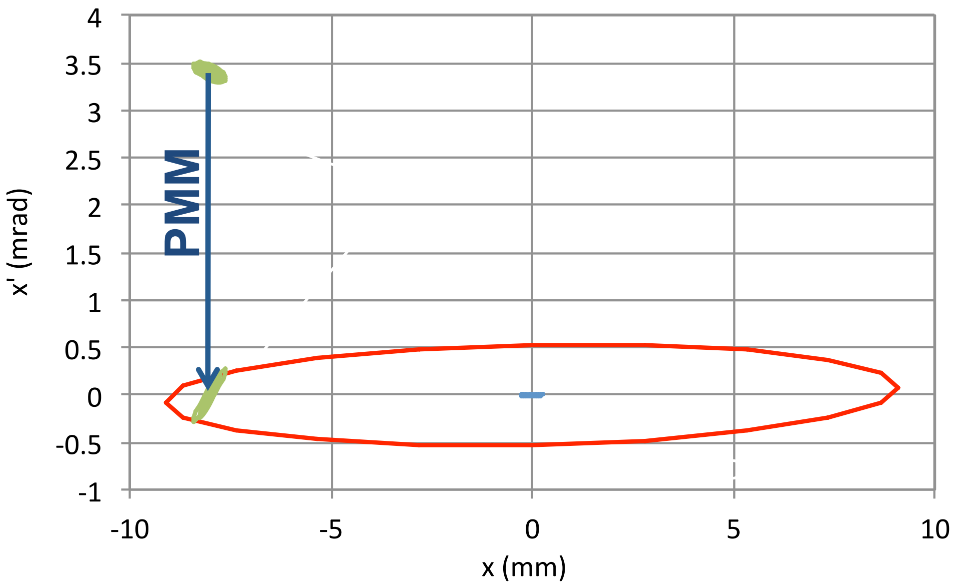
Injection system

Booster emittance (nm)	3.8
Booster circumference (m)	496.8
Off-axis injection schemes	4 kicker/PMM

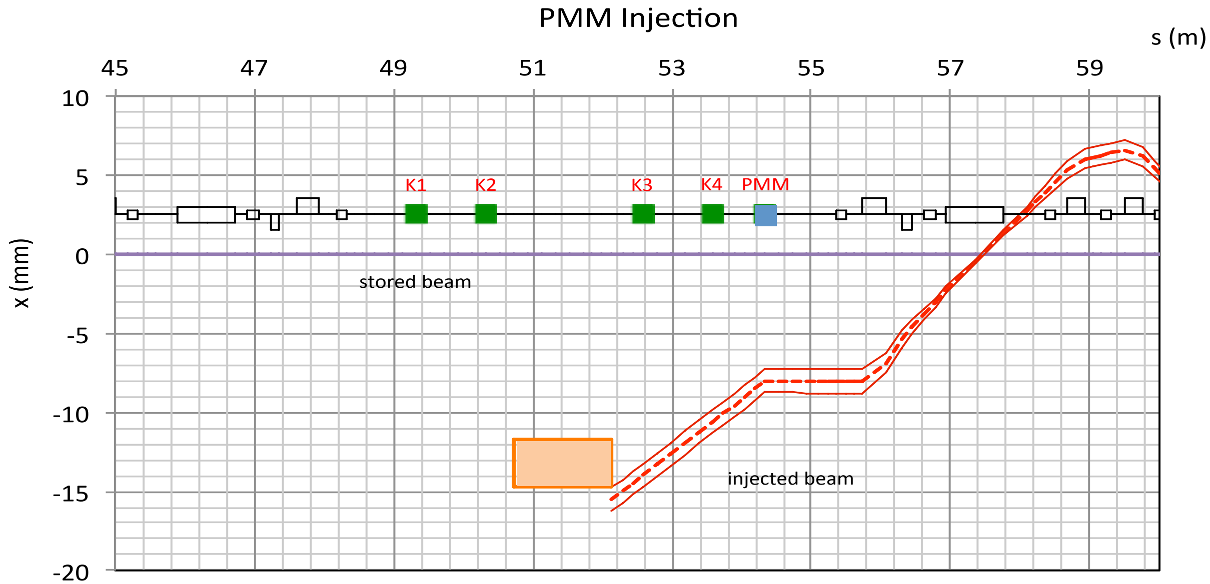
- Use same straight section for 4 kicker and PMM injection



Injection with PMM

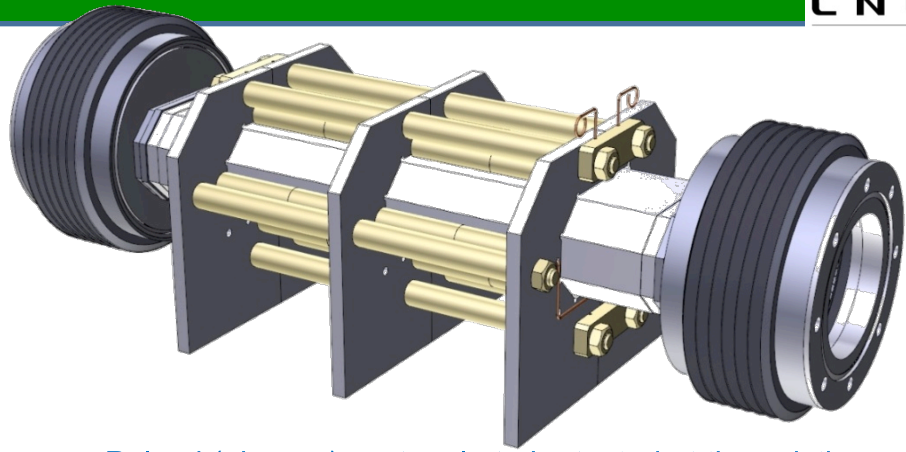


PMM deflection @ beam centroid	3.4	mrad
PMM length	0.5	m
PMM magnetic field @ beam centroid	0.068	T
Beam centroid position @ PMM	8	mm
Injected beam angle @ end of septum	3.4	mrad



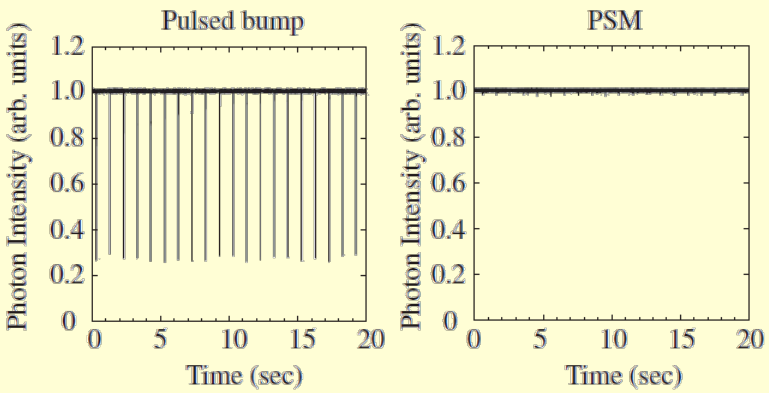
Injection tests at UVX using a pulsed sextupole

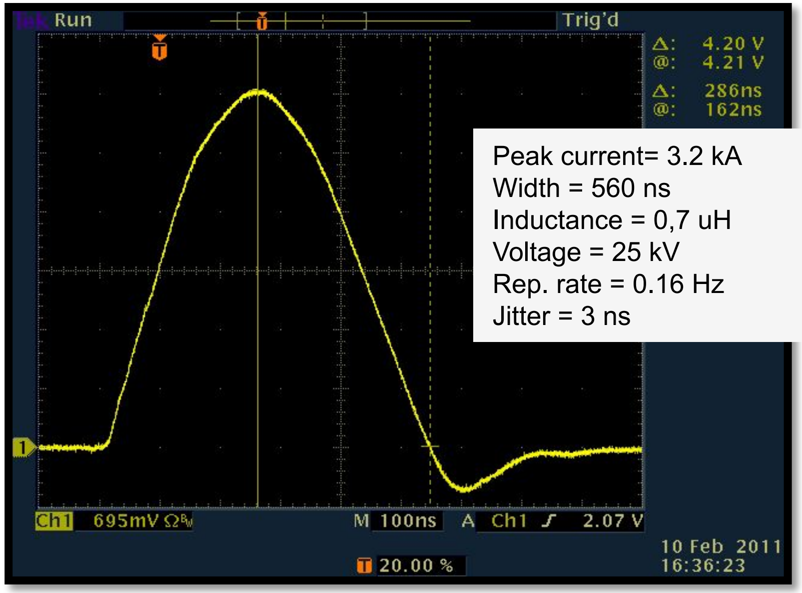
Conventional injection method: 4 kickers to produce a temporary bump in the storage ring orbit to overlap its acceptance with the incoming beam.
Difficult to match the four kicker pulses
→ disturbs the stored beam
→ bad for top-up mode
Pulsed sextupole method: eliminates the need for a bump in the stored beam. The orbit is not affected.



Pulsed (air core) sextupole to be tested at the existing ring. This magnet will be installed in straight #7 over a ceramic vacuum chamber already installed during the last shutdown.

Photon intensity at **BL-14A** (***Photon Factory***) in the pulsed bump injection and the PSM injection. The spike train is synchronized with the beam injection. The sampling rate of the signals was 10 kHz.





Peak current= 3.2 kA
Width = 560 ns
Inductance = 0,7 uH
Voltage = 25 kV
Rep. rate = 0.16 Hz
Jitter = 3 ns

Phase 1 beamlines

- Provide some of the *state of the art* techniques that explore coherence, micro and nano-focusing and high energies
  - New science!
- Cover all conventional techniques (SAXS/XPD/EXAFS/μCT…) existing today at LNLS with the 2T superbends
  - Upgrade the current research activities of the user community
- 2 undulator based PGMs (high resolution and high flux)
  - keep up the good momentum from the UVX

Phase 1 beamlines

13 Beamlines

1 EXAFS (BM)

+ 1 µ-Spectroscopy (IVU)

1 SAXS (BM)

+ 1 coherent Scattering (IVU)

1 XPD (BM)

+ 1 nano-Diffraction (IVU)

1 µCT (BM)

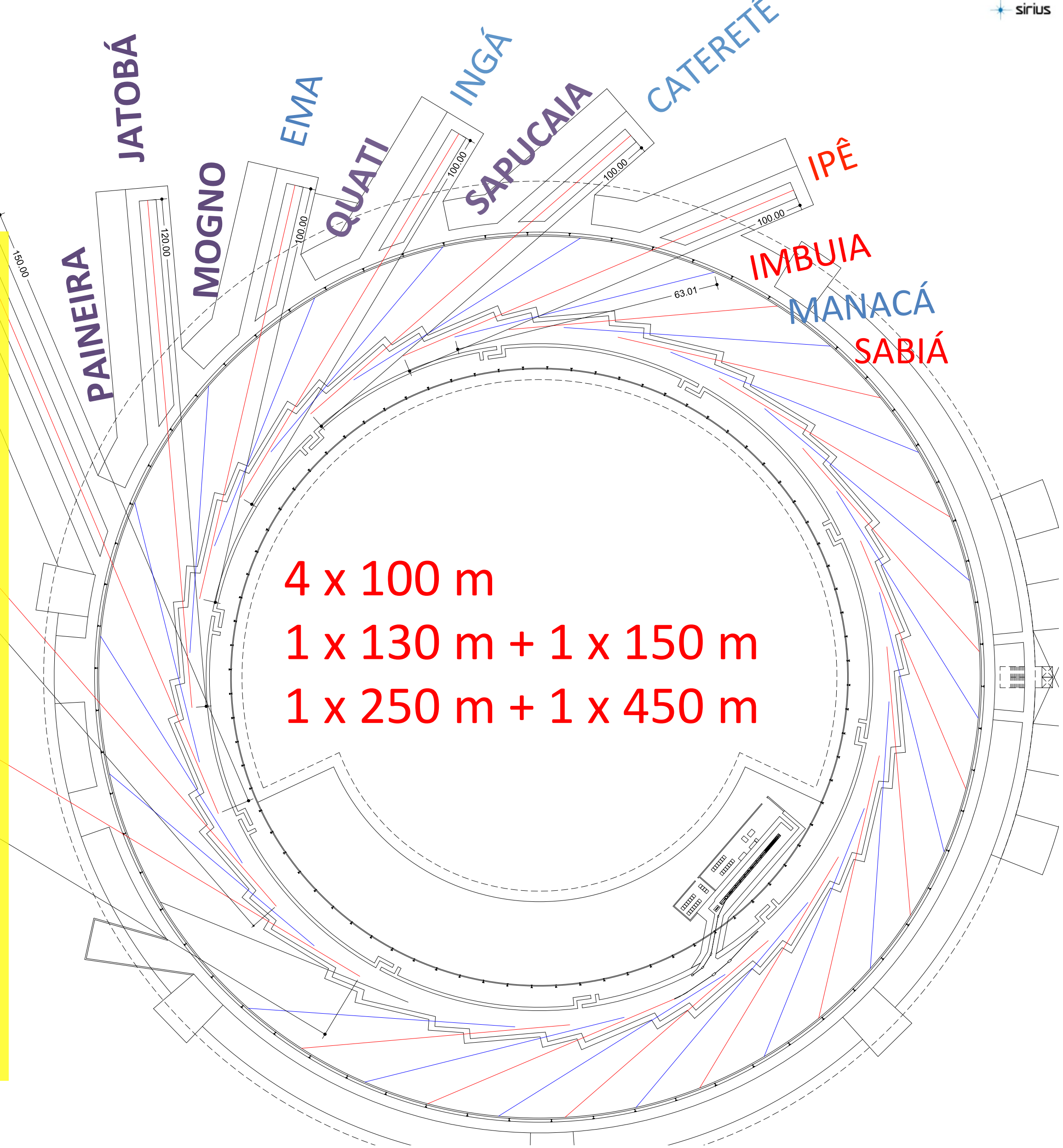
+ 1 High Energy CT/Laue Dif. (SCW)

2 PGMs (EPU)

1 µMX (IVU)

1 IR (BM)

1 X-Ray Raman Scattering (2 IVU)



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X-ray undulator beamlines

	CARNAÚBA *Coherent And NAnofocus diffraction*	EMA *Espectroscopia e Micro Absorção*	INGÁ *INelastic X-Ray Raman Scattering*	CATERETÊ *Coherent And Time REsolved Scattering*	MANACÁ *MAcromolecular Cristalography*
energy range (keV)	2-24	2-24	5-24	2-24	2-24
energy resolution (ΔE/E)	10^{-4}	10^{-5}-10^{-4}	10^{-5}	10^{-4}	10^{-4}
harmonic content	10^{-5}	10^{-5}	10^{-5}	10^{-4}	10^{-4}
energy scanning	Yes	Yes	Yes	No	No
beam spot (FWHM, μm)	0.05 x 0.05 (100x100)*	1 x 1 (100 x 100)*	10 x 10 (10x1000)*	0.3 x 0.3	1 x 1 (100 x 100)*
divergence (mrad)	3 (0)	0.3 (0)*	<0.03	<0.5	0.3
Imaging mode	Raster scan, CDI	Raster scan Full Field	Line scan DT	Ptychography	-
coherent modes	~ 1 (near d.l.f.)	~3 (near d.l.f)	-	1	~ 3 (near d.l.f.)

UVX undulator and IR beamlines

	IPÊ *Inelastic and Photo-Electron Spectroscopy*	SABIÁ *Soft-x-ray ABsobrtion and Imaging*	IMBÚIA *Infrared Microscopy Beamline for Ultra-resolution Imaging*
energy range (eV)	10 – 1000	250 – 2000	0.001 – 1
energy resolution (ΔE/E)	10^{-5}-10^{-4}	$5x10^{-5}$-10^{-4}	1 meV
harmonic content	Variable to suit the experiment	Variable to suit the experiment	-
energy scanning	Yes	Yes	FTIR
beam spot (FWHM, μm)	0.1 x 0.1 (ZP) (100x100)*	0.1 x 0.1 (ZP) (100 x 100)*	0.1 x 0.1 (SNOM)
divergence (mrad)	-	4	-
Imaging mode	PEEM	PEEM/CDI/Scan	Scan
coherent modes	-	1	-

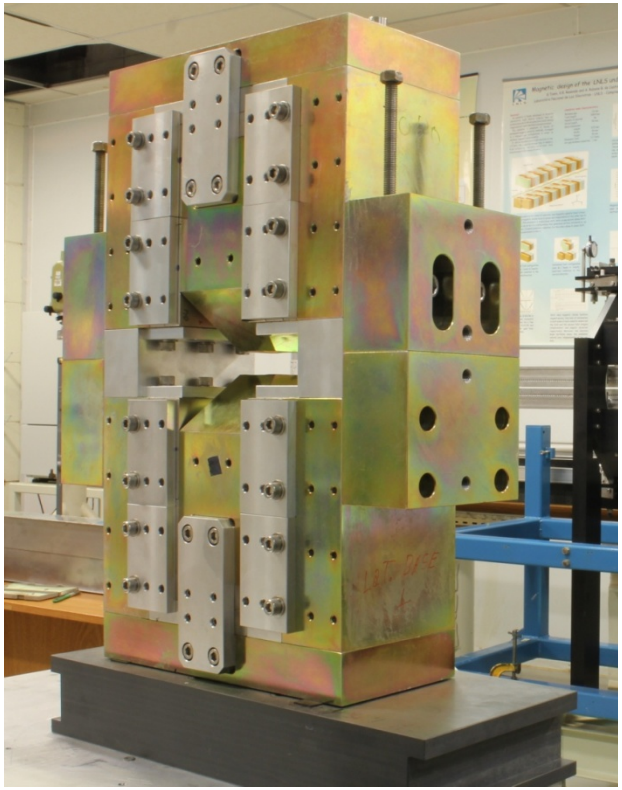
Wiggler and bending magnet beamlines

	JATOBA High-energy TOmography and Laue Diffraction	MOGNO Micro and Nano Tomography	QUATI QUick Absorption Spectroscopy	SAPUCAIA Small Angle Scattering	PAINEIRA Powder Diffraction
energy range (keV)	30-250	4-24	4-45	4-24	4-45
energy resolution (ΔE/E)	10^{-2}	10^{-3}	10^{-5} - 10^{-4}	10^{-4}	10^{-4}
harmonic content	-	10^{-3}	10^{-5}	10^{-4}	10^{-4}
energy scanning	Yes	Yes	15 ms/scan	No	No
beam spot (FWHM, μm)	1 x 1	40 x 40	100 x 15	200 x 200	100 x 15
divergence (mrad)	2	5 (ZP NA)	1	(0)	< 0.6
Imaging mode	Full Field	Full Field @ 10 nm res.	-	-	-

PM dipoles

Prototype II - NdFeB   Bo = 0.5 T   G = 2 T/m $\theta = 3.5^0$ and 5^0

B = 2.0 T



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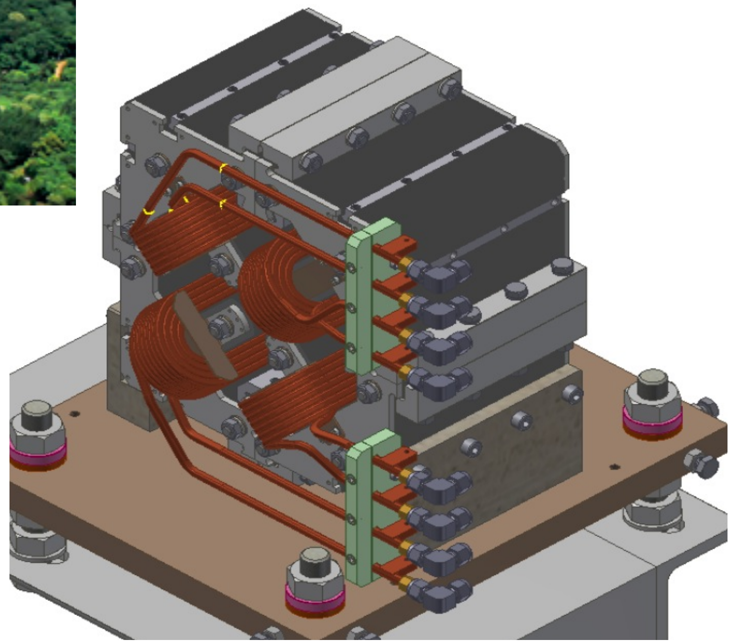
Conventional Magnets Production

WEG

Brazilian electrical motor manufacturer with 26000 employees

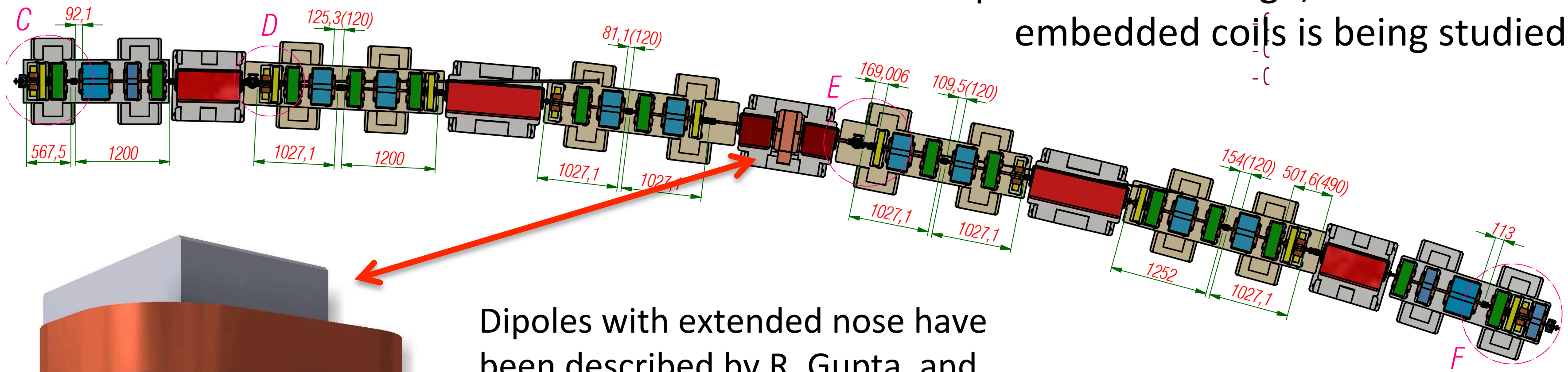


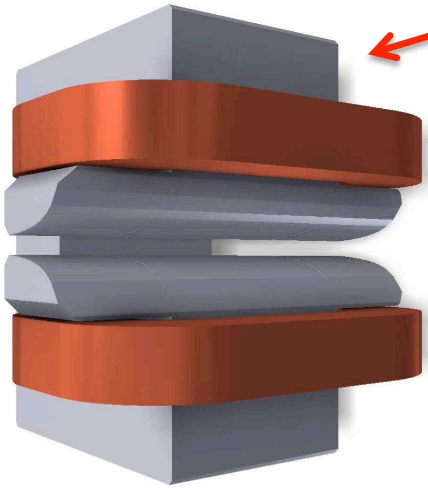
First 50 units of the booster quadrupoles will arrive next July

Very compact magnet lattice

The initial design for Sirius proposed permanent magnets (PM) – NdFeB – for all dipoles. Later this idea was abandoned and only the high field slice is kept with PM. This created a problem because of the extra space needed for coils.

To keep the lattice design, a solution with embedded coils is being studied.

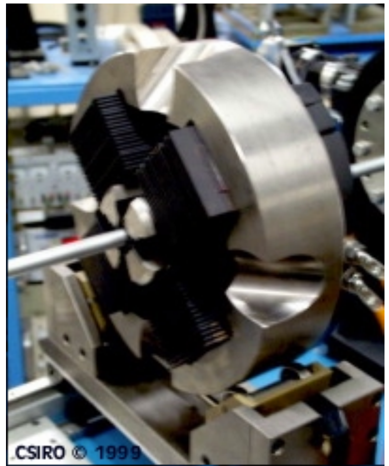




Simulation of electromagnetic dipole with embedded coils

Dipoles with extended nose have been described by R. Gupta, and fabricated at BNL.

Even quadrupoles with 'pole-tip extensions' have been described by CSIRO (Australia) with application to a nuclear microprobe.

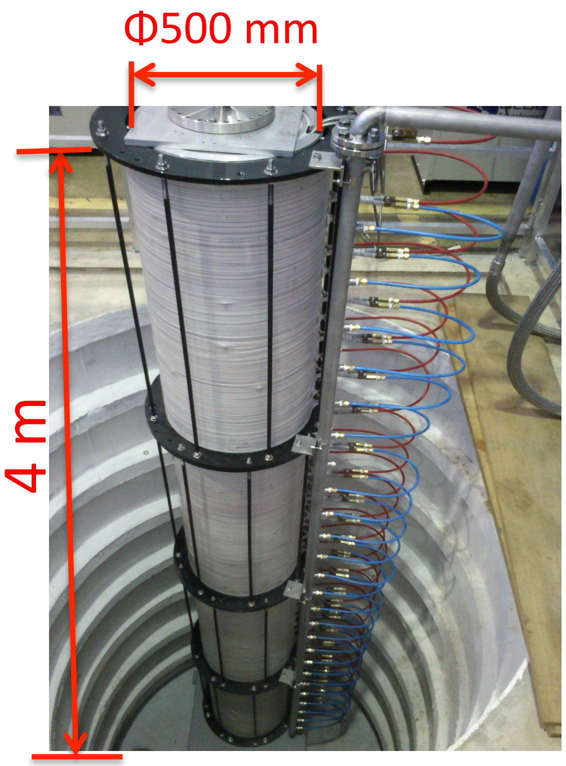


http://www.nmp.csiro.au/NMP-quadrupole.html

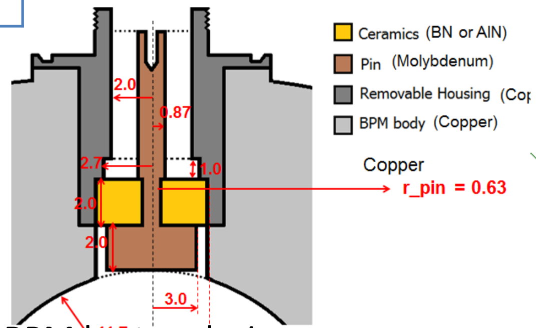
Vaccum system

Chamber material	cooper
Main pumps	NEG coating
Cross-section	circular
Chamber aperture	$\varnothing_{ext}$ = 26 mm $\varnothing_{int}$ = 24 mm

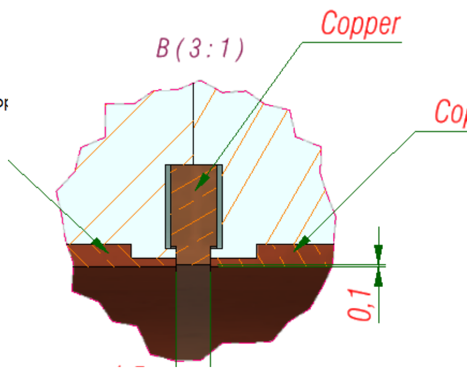
- BPM geometry, buttons need to be small
- In-situ NEG activation
- Chemical cleaning procedure for copper
- NEG coating of narrow areas
- Impedance minimization



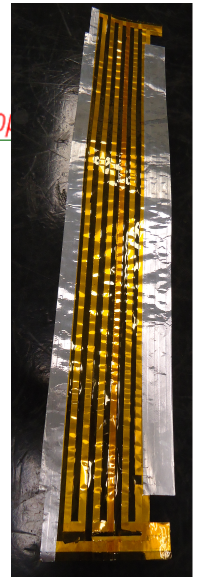
NEG coating setup at LNLS

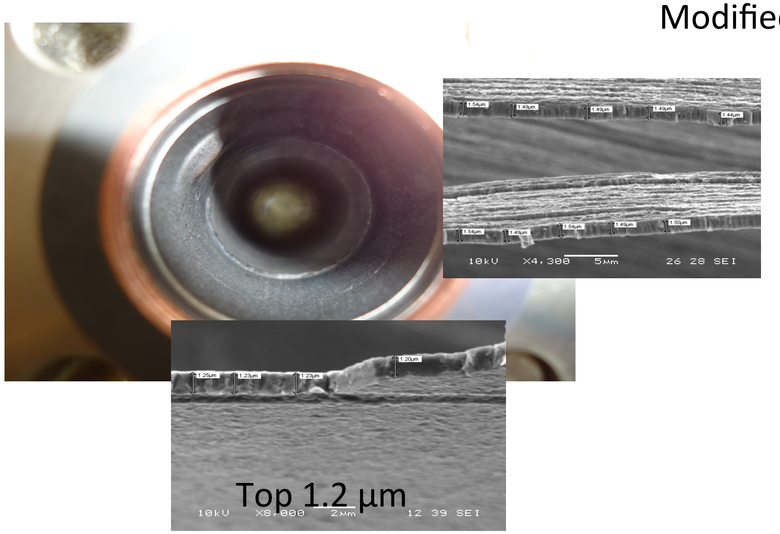


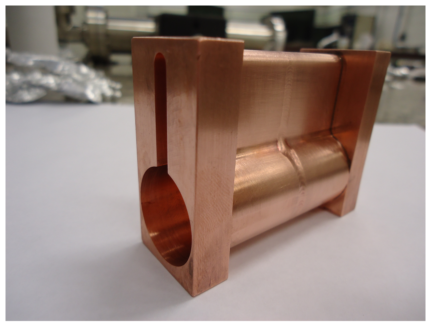
BPM button design



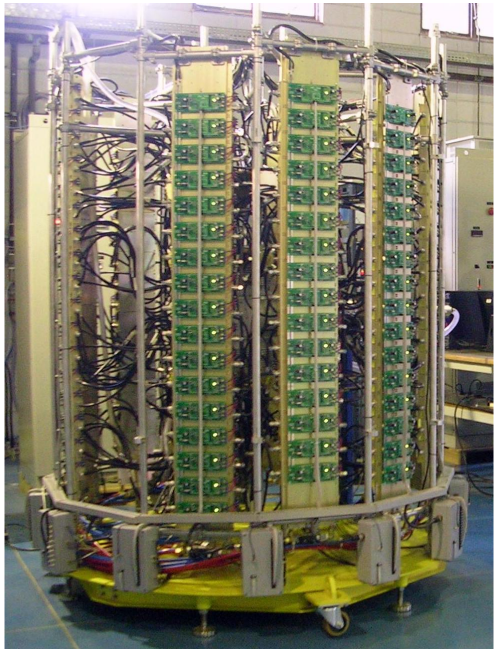
Modified KEK flange





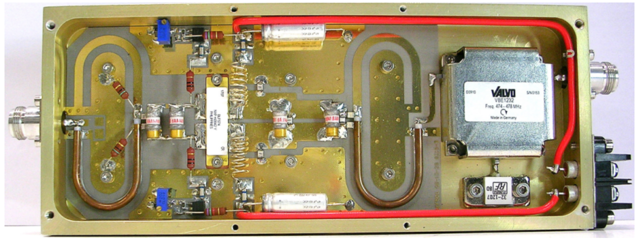


Solid State Amplifiers for RF System



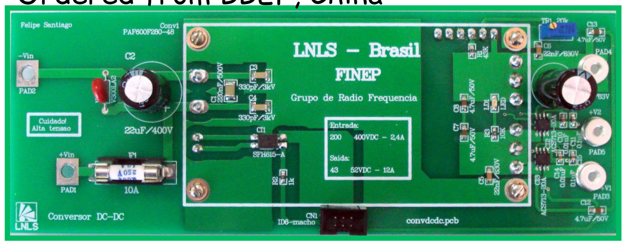
Tower of the Solid State Amplifier

162 Amplifier modules
162 DC converters
23 Combiners
23 Dividers
20 Directional couplers
391 Coaxial cables
1 High power AC/DC converter



Amplifier module

- BLF574 NXP power LDMOS transistor
- P_{out} = 370 W (max)
- Built-in narrow-band circulator (474-478 MHz)
- Ordered from BBEF, China



DC-DC Converter

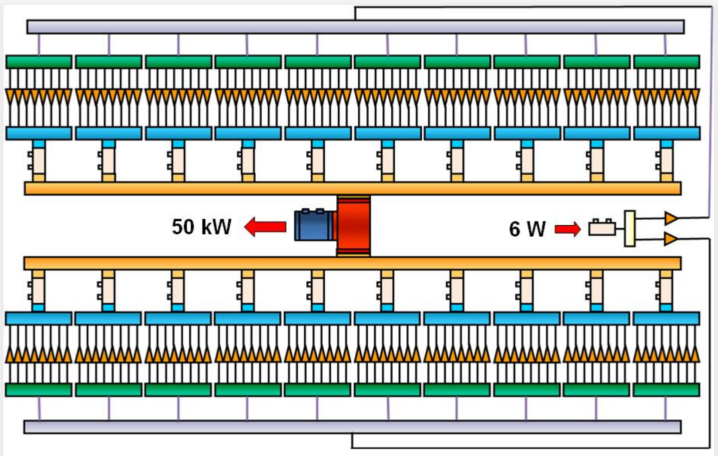
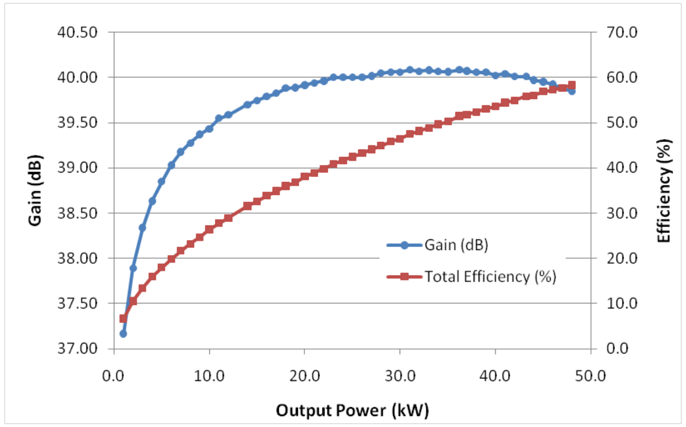


Diagram of module combination in the SSA

Combiners & Directional couplers



Beam stability

- Strong gradient + large number of elements = large orbit amplification factors
- Small emittance

→ beam stability problems

Horizontal OAF	60
Vertical OAF	86

Stability goal: beam motion < 10% beam size	
rms vibration tolerance	7 nm
rms ripple tolerance	20 ppm

Sources of beam motion

- Ground motion
- Floor motion
- Mechanical vibrations: girders, cranes, compressors, traffic
- ID changes
- booster operation
- Tunnel and hall temperature variations
- Power supply noise
- Transient during injection

Mitigation

- Building and ground foundation
- Floor structure
- Girder design
- Temperature stabilization
- BPM support
- BPM design
- Slow and fast orbit feedback (1 kHz, ceramic chambers)
- Feedforward
- PMM
- Power supply design

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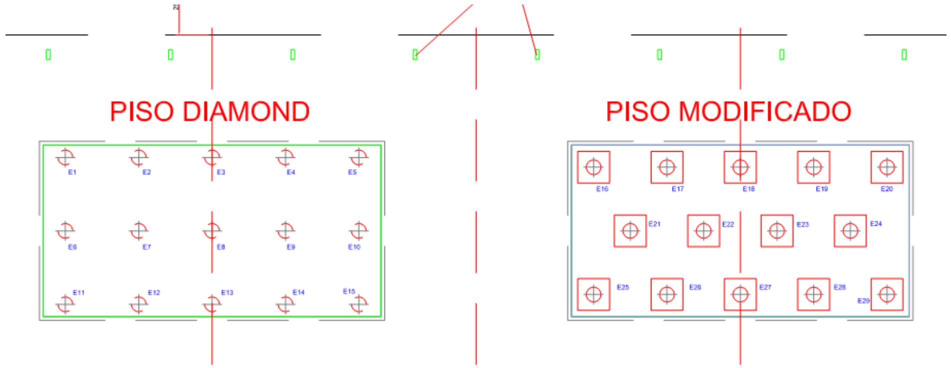
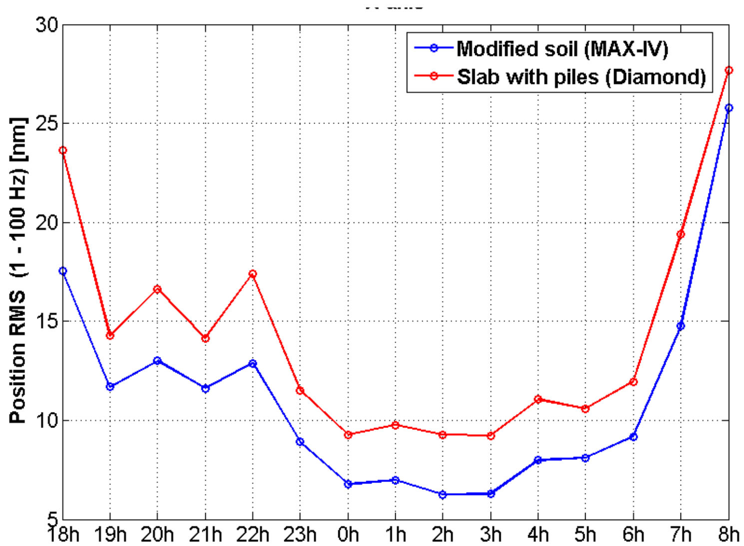
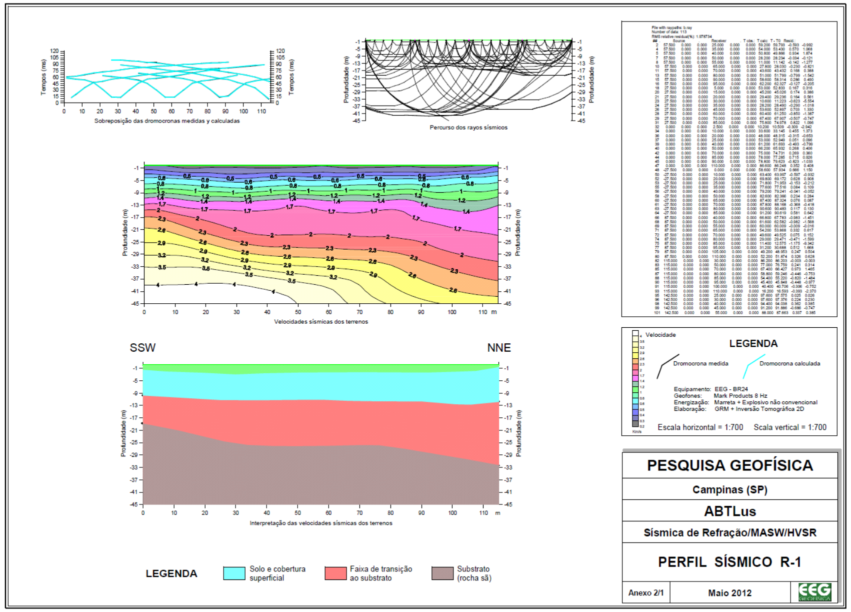
Prototype floor slabs and simulations

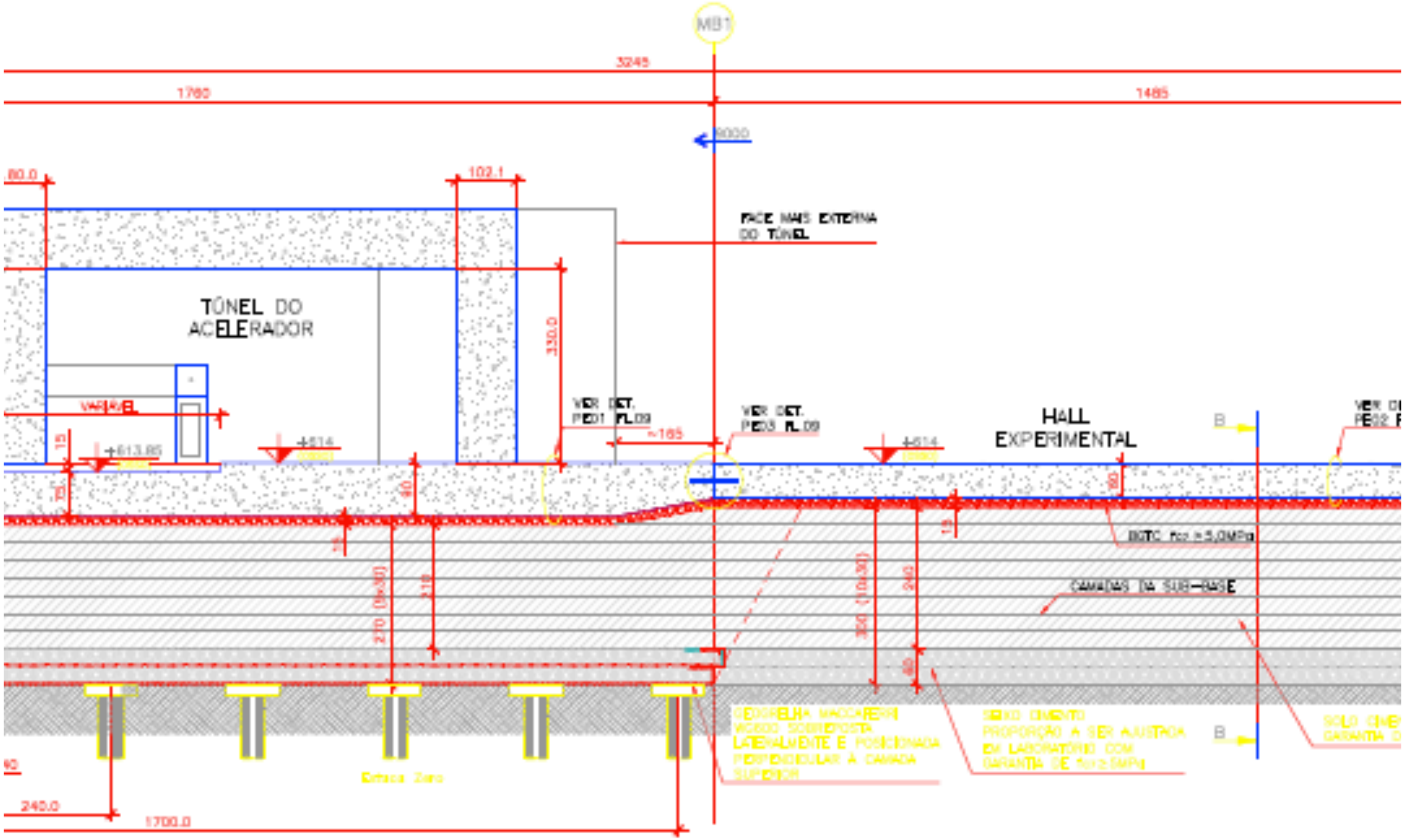






ALS, Berkeley Dec. 13th, 2013 (Friday 13th).

Final floor design for Sirius



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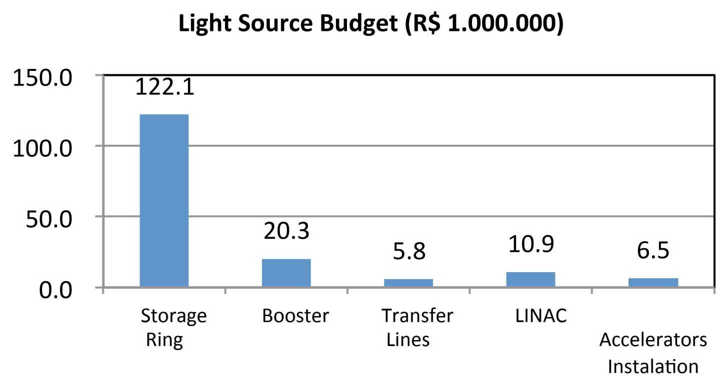
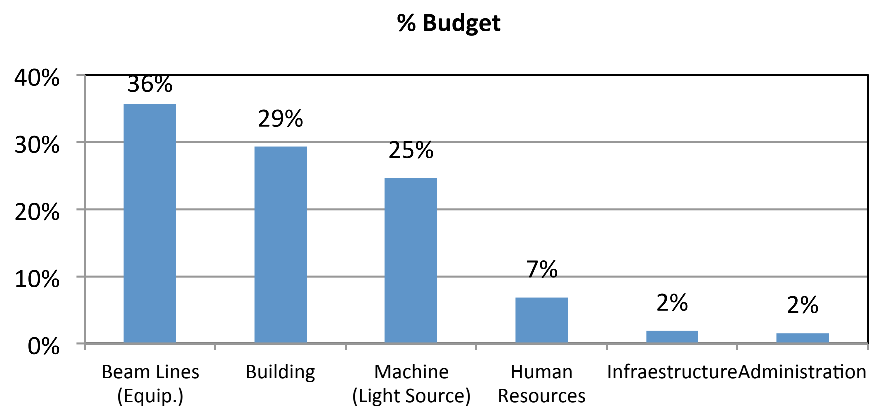
Sirius budget

Sirius Budget (R$ 1.000.000)	2012	2013	2014	2015	2016	2017	TOTAL
Accelerators	5,0	151,9	162,7	51,3	7,7	8,4	386,8
Machine (Light Source)	0,7	80,1	60,0	20,9	2,0	1,9	165,6
Storage Ring	0,7	61,6	48,2	10,7	0,0	0,9	122,1
Booster	0,0	11,8	7,2	1,1	0,0	0,0	20,3
Transfer Lines	0,0	1,2	4,6	0,0	0,0	0,0	5,8
LINAC	0,0	5,4	0,0	5,4	0,0	0,0	10,9
Accelerators Installation	0,0	0,0	0,0	3,5	2,0	1,0	6,5
Building	3,3	68,2	98,4	25,7	0,6	1,0	197,0
Human Resources	1,0	3,6	4,3	4,8	5,1	5,5	24,3
Beam Lines (13)	4,2	44,0	45,8	51,1	70,6	24,3	239,9
Equipments and Measure Systems	4,2	42,5	42,0	46,0	65,0	18,3	218,0
Human Resources	0,0	1,5	3,8	5,1	5,6	6,0	21,9
Administration and Managing	0,4	2,7	2,1	2,1	1,6	1,6	10,5
Human Resources	0,1	0,8	1,1	1,1	1,2	1,3	5,7
Training, Travels and Workshops	0,2	1,4	0,9	0,9	0,4	0,3	4,2
Furniture and Computers	0,0	0,4	0,1	0,0	0,0	0,0	0,6
Engineering Infrastructure	4,2	7,1	1,2	0,3	0,0	0,0	12,8
TOTAL	13,7	205,6	211,8	104,7	79,9	34,2	650,0

	M USD
Accelerators	100
Building	100
Beamlines (13)	120
Administration	5
TOTAL	**325**



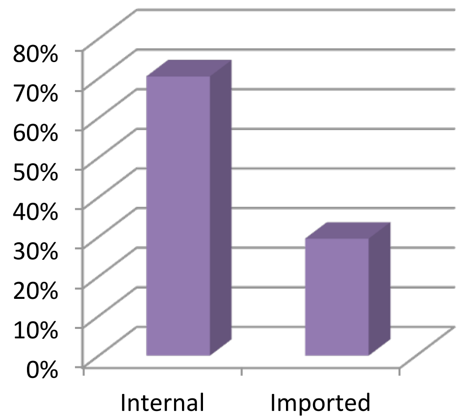


ALS, Berkeley Dec. 13th, 2013 (Friday 13th).

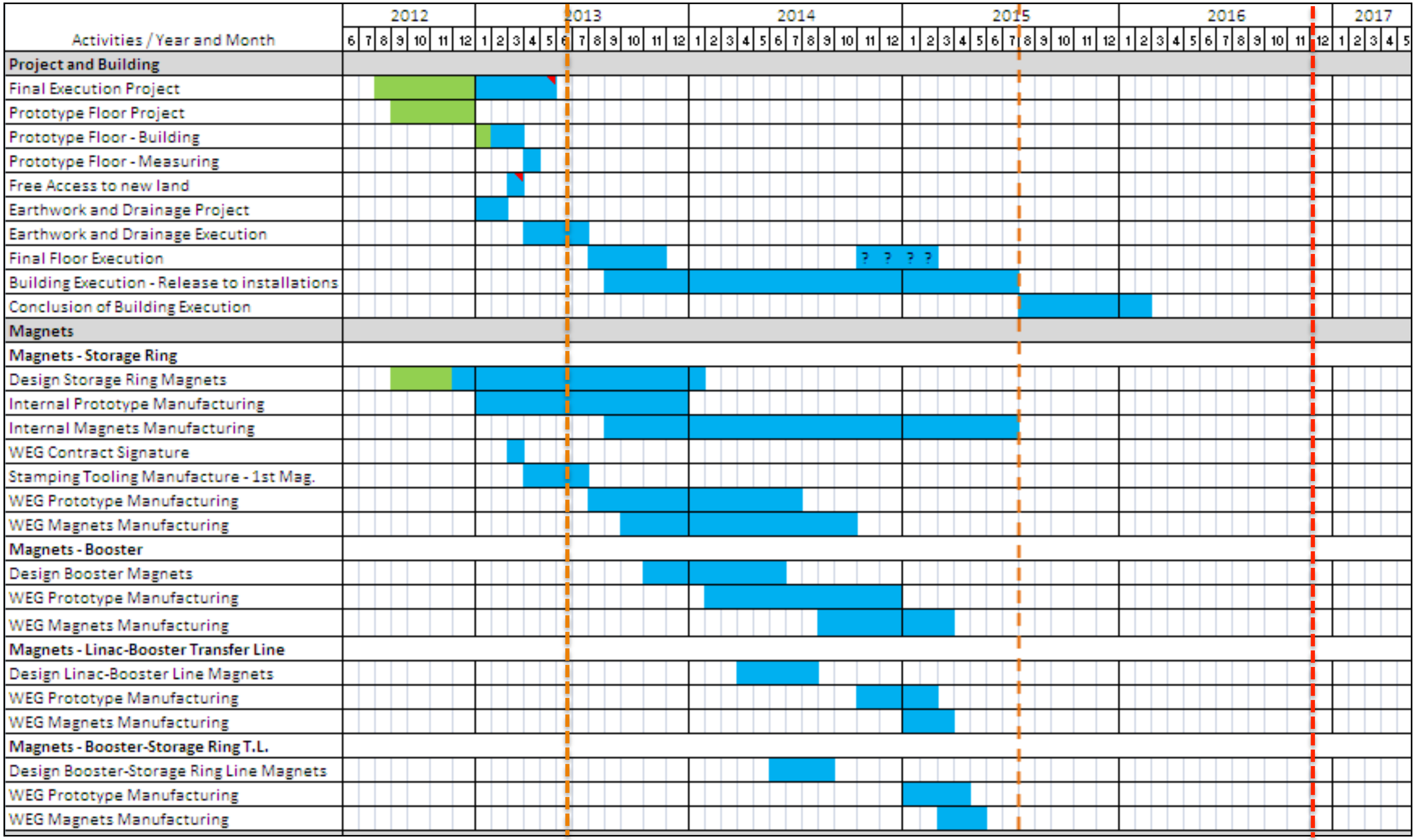
Nationalization level

71% from Sirius expenses will be national supply

	Internal Supply		Imported	
Sirius Budget	R$ millions	%	R$ millions	%
Accelerators	319,4	83%	67,5	17%
Machine (Light Source)	100,2	61%	65,4	39%
Storage Ring	75,1	61%	47,0	39%
Booster	15,5	77%	4,7	23%
Transfer Lines	4,7	80%	1,2	20%
LINAC	0,0	0%	10,9	100%
Accelerators Installation	6,5	100%	0,0	0%
Building	195,7	99%	1,3	1%
Human Resources	24,3	100%	0,0	0%
Beam Lines (13)	119,4	50%	120,5	50%
Equipments and Measure Systems	96,2	44%	121,8	56%
Human Resources	21,9	100%	0,0	0%
Administration and Managing	10,5	100%	0,0	0%
Human Resources	5,7	100%	0,0	0%
Training, Travels and Workshops	4,2	100%	0,0	0%
Furniture and Computers	0,6	100%	0,0	0%
Engineering Infrastructure	7,8	61%	5,0	39%
TOTAL	461,5	71%	188,5	29%



Sirius machine schedule



ALS, Berkeley Dec. 13th, 2013 (Friday 13th).

We have a very challenging project ahead with very ambitious schedule!

The whole team is now working out all the difficulties to turn the project into reality.

... and, to finish, you are welcome to Brazil !

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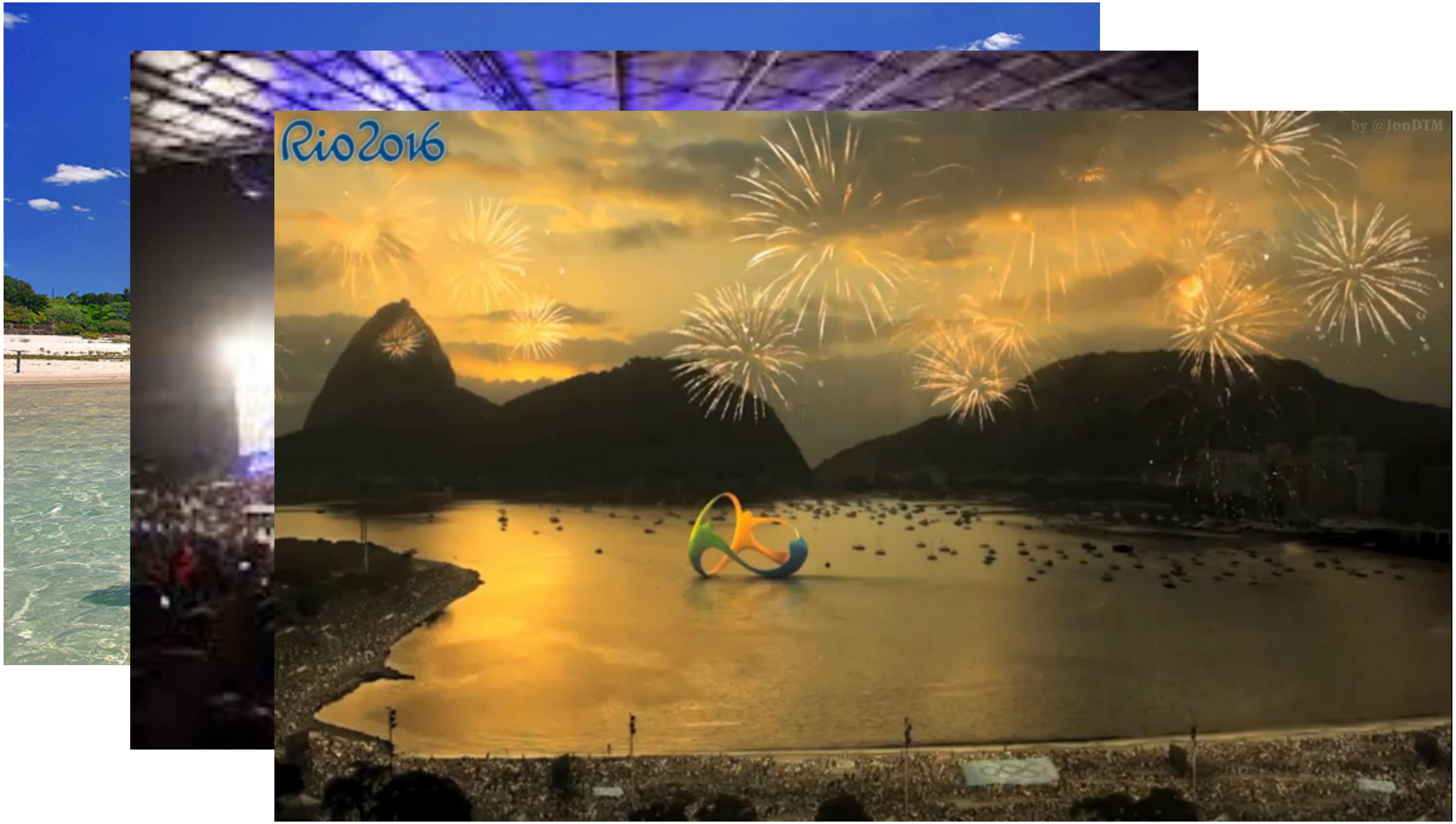

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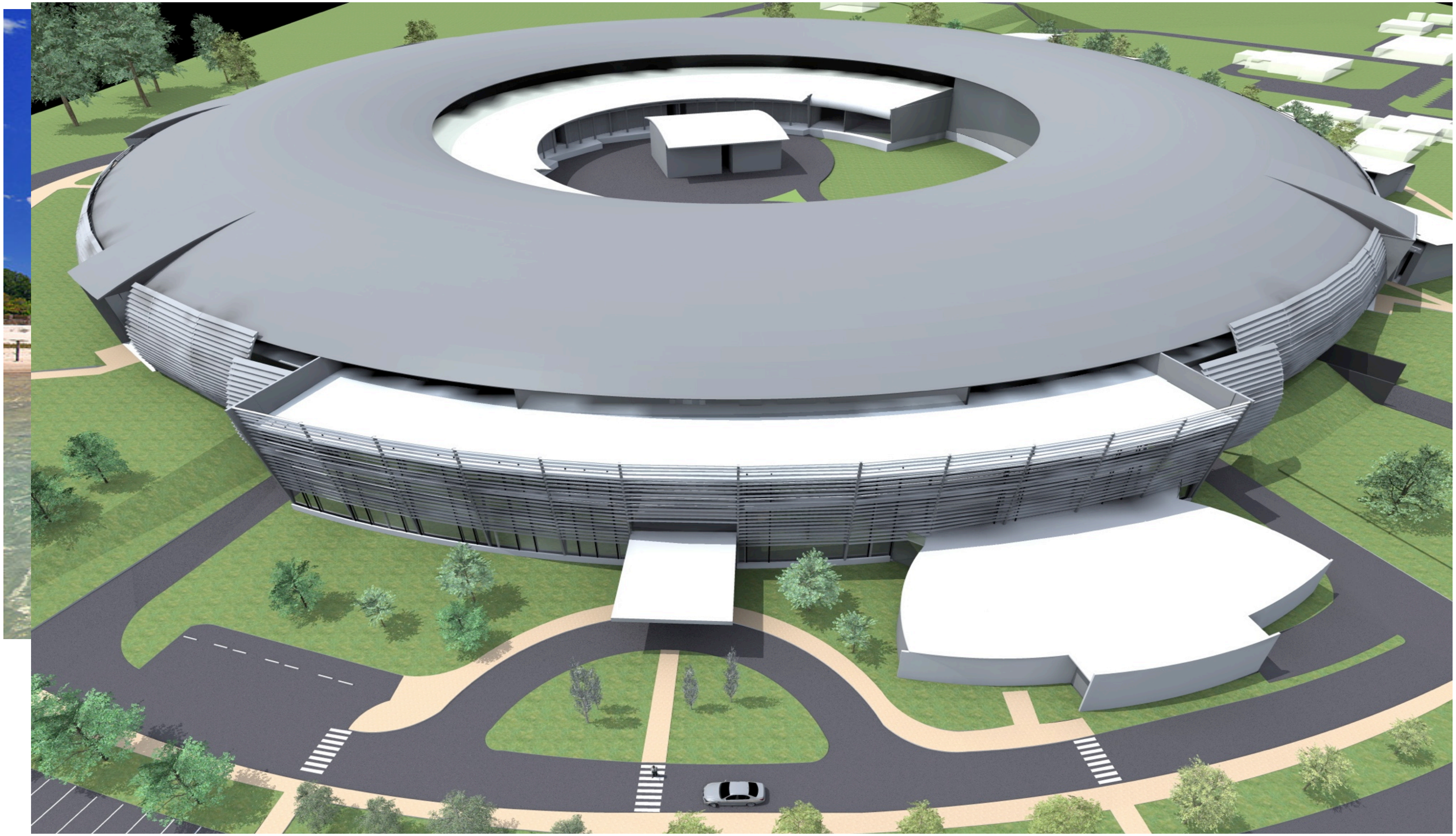

Thank you for your attention !

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