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Preliminary Design Considerations for an Electron Storage Ring with Application to EUV Mask Inspection.

EUVL Workshop 2020.
PSI showcase session, 2nd November, 2020.

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Motivation for this study

- There is a general consensus* within the semiconductor community that EUVL will be the next-generation HVM technique for producing smaller and faster integrated circuits.
- Advances in multi-layer Mo-Si mirrors with high reflectivity (~ 70%) and large bandwidth (~2%) make 13.5 nm the wavelength of choice.
- The development of metrology methods at EUV wavelengths for mask inspection will be indispensable for the success of EUVL.
  - A mask inspection tool (RESCAN) is currently being developed on an SLS beam-line (Y. Ekinci et. al., XIL-09LB), in collaboration with industry.
- However, the development of such an inspection tool only makes sense if a source of EUV radiation, having the **required properties**, can be built and operated in an industrial environment.
- We propose here a **compact** synchrotron radiation source for this purpose.

Presentation outline

- EUV source properties and Accelerator requirements (user specification)
- Storage ring design
  - Linear optics design
  - Non-linear effects
- Choice of undulator (EUV radiation source)
- Concluding remarks

- Not discussed (but already studied)
  - Engineering sub-systems
    - DC magnets
    - Vacuum system
    - Injector linac
    - Radio-frequency system
    - Radiation shielding
    - Injection into storage ring

Required properties of the EUV source

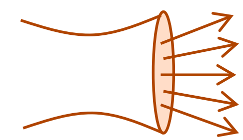
Quantitative specifications

- Wavelength — 13.5 nm
- Power delivered to mask — ~ 10 mW (→ flux ~ 1.35×10^{15} ph/s)
- Beam brightness — 1.4×10^{18} photons/s/mm^2/mrad^2/0.1%
- Stability in intensity — 0.1%

Qualitative specifications

- Small footprint — ~ 60 m^2 (soft boundary condition)
- High reliability — 99% scheduled operation time (is this needed?)
- Reasonable cost — Design to minimise (construction and 'ownership')

Accelerator requirements



- High brightness EUV beam
  → low electron beam emittance (nm-rad range)
- Highly stable electron beam current (10^{-3} range)
  → top-up mode → full energy booster synchrotron
- High reliability (>99% availability)
  → design based on mature technology. This in fact is the SLS reliability.

→***same requirements as for 3rd generation light sources for research***

✚compact layout (≈60 m^2) - in general, this is in contradiction with low-emittance.

Mature technology combined with Innovative solutions

→ adapt technology of Diffraction Limited Storage Rings

→ multi-bend magnet lattice → low emittance electron beam

→ implementation of undulator → high brightness photon beam

→ combined function magnets

→ small vacuum chamber cross-section with NEG coating ⇒ small footprint

→ arrangement of linac, booster and SR

How compact is compact?

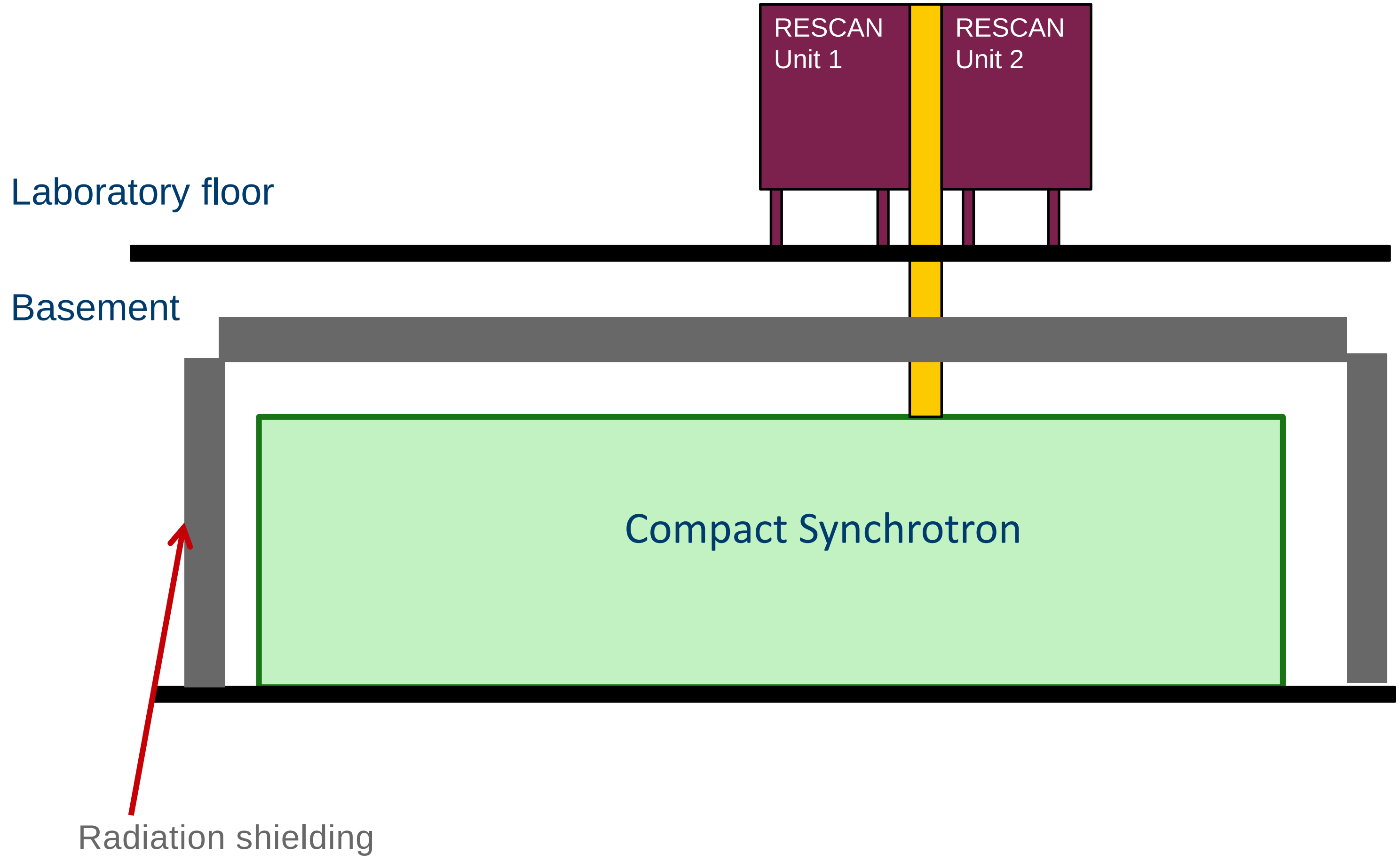
- Swiss Light Source building shown on right hand side of picture.
- Building diameter ~ 140 m.
- 2.4 GeV ring with 288 m circumference for a 5.5 nm emittance.

- EUV source would have to be ~ 1/10 of the circumference but with a comparable electron beam emittance.

Mask inspection tool and source (very schematic !!)

R. Rajeev et. al., “Towards a stand alone high throughput EUV actinic mask inspection tool – RESCAN” S.P.I.E. proc. Vol 10145 (2017).

Based on Scanning Coherent Diffractive Imaging



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Design and optimization

Main criteria for the optimization procedure:

Reach required performance with acceptable size and minimising costs

Optimization steps:

- Choice of beam energy and undulator periodicity
- Basic storage ring layout and design
- Check single particle and collective beam dynamics
- Booster design (not discussed here – but completed)
- 3-D arrangement of storage ring and pre-accelerators
- Storage ring injection (still WIP)
- Design technical sub-systems (vacuum, magnets, RF, injector, undulator, shielding)

Optimisation of beam energy and undulator parameters

(A. Wrulich)

Variation of beam current with energy

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

$$\frac{dN/dt}{0.1\% BW} = n_0 = 1.43.10^{11} N_u I[mA] \frac{K^2}{1+K^2/2}$$

→ for a fixed undulator period length of 16 mm (the range from 8-24 mm has been explored, as well as different undulator lengths)

→ with the boundary condition that the requirements for radiation wavelength and flux are fulfilled.

Resulting parameters:

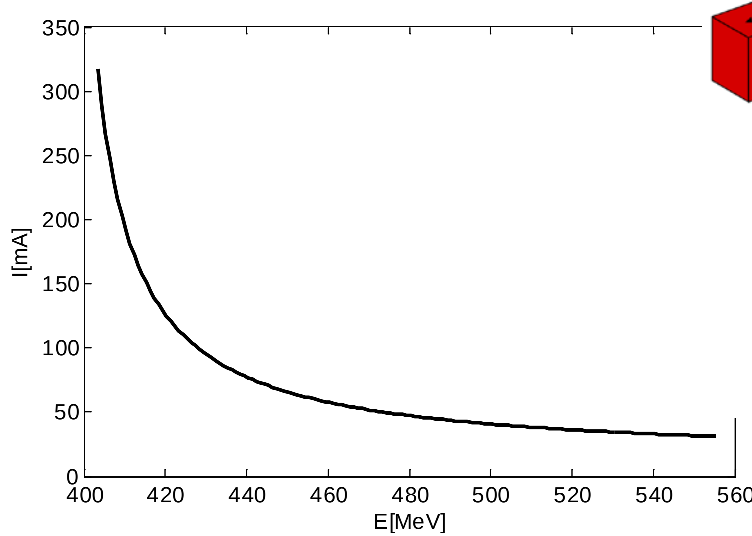
L_u = 320 cm

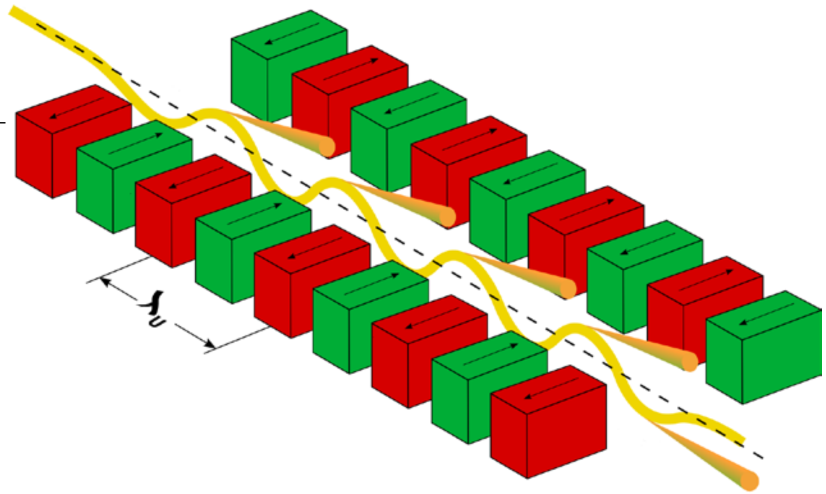
λ_u = 16 mm

E_{opt} = 430 MeV

$B_u(E_{opt})$ = 0.42 T

I = 150 mA





95 mA required to reach flux requirements. Studies performed for 150 mA to give some margin.

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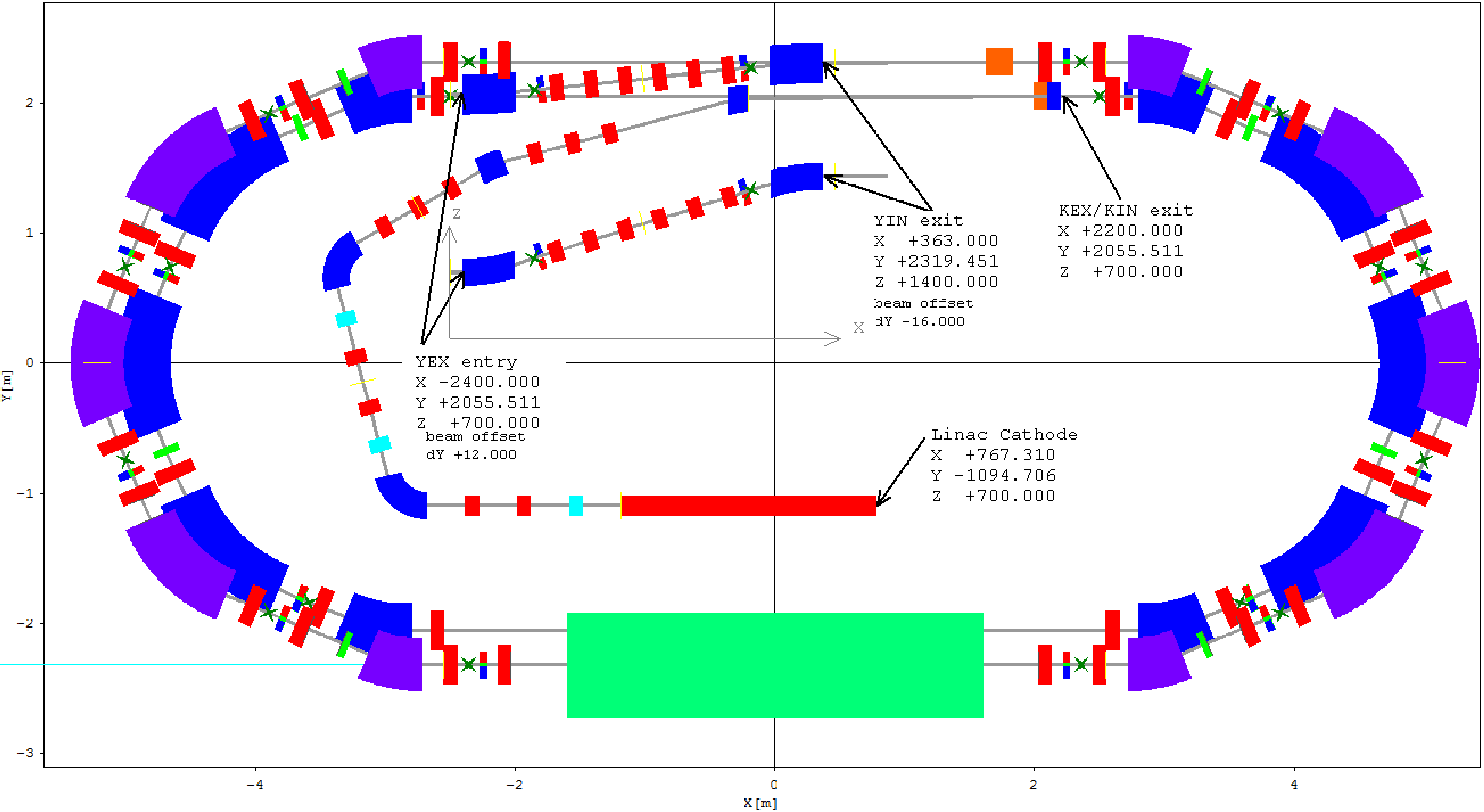
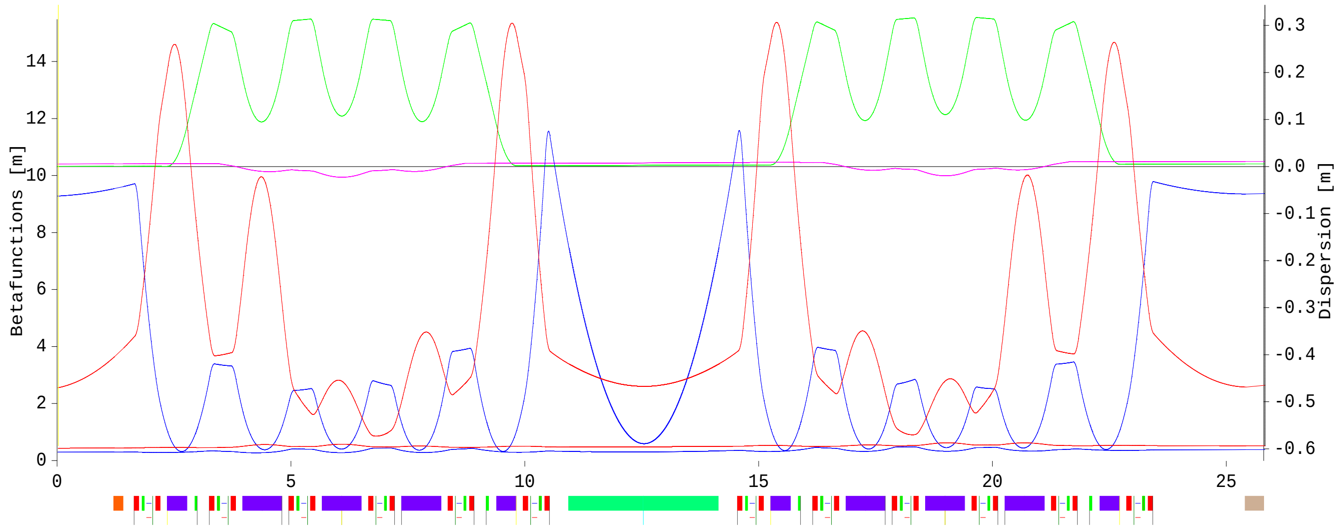
Facility layout

Race-track geometry: Two 5-bend achromat arcs and two straights. One straight for the undulator and one for injection and RF.

- Ring: 430 MeV, 25.8 m
- Booster: 43 → 430 MeV, 24.0 m
- BR transfer line –18.6° inclination
- LB transfer line
- Gun/Linac: 43 MeV, 2.1 m



Linear optics design (A. Streun)



Storage ring optical functions (β_x , β_y , D_x, D_y)

Lattice features

- Strong horizontal focussing: strong quads → small magnet bore; strong sextupoles to correct chromaticity.
- Modest dispersion (MBA) ensures adequate momentum acceptance despite small vac. aperture → needed to reduce particle loss to Touscheck scattering.
- Skew-quad windings in sextupole to generate some vertical emittance → reduce Touscheck scattering.
- Small β_x at center of undulator → minimise source-point size → high brightness.
- β_y reduced at undulator extremities to reduce particle losses (small vertical gap - 7 mm).
- Magnetic elements would be installed / aligned on girders. Simulations show orbit correction due to misalignments (< 100 µm, < 100 µrad) easily corrected with 1 mrad correction coils.

Nominal storage ring parameters

Circumference [m]	25.8	Energy [MeV]	430
Working Point $Q_{x/y}$	4.73 / 1.58	Radiation loss/turn [keV]	2.83
Natural chromaticities $\xi_{x/y}$	–9.7 / –6.9	Emittance [nm]	5.50
Momentum compaction α_c	0.0258	Relative energy spread	$4.13 \cdot 10^{-4}$
Hor. damping partition J_x	1.54	Damping times $\tau_{x/y/E}$ [ms]	16.6 / 25.6 / 17.5

Machine length corresponds to 43 RF wavelengths (500 MHz). 24 “buckets” are filled to leave a gap in the bunch train to combat the effects of trapped ions.

Non-linear beam dynamics studies have been done to evaluate:
Dynamic aperture ✓ greater than physical aperture
Touscheck scattering → 400 kV RF voltage needed to optimise life-time
Intra-beam scattering → modest emittance dilution.

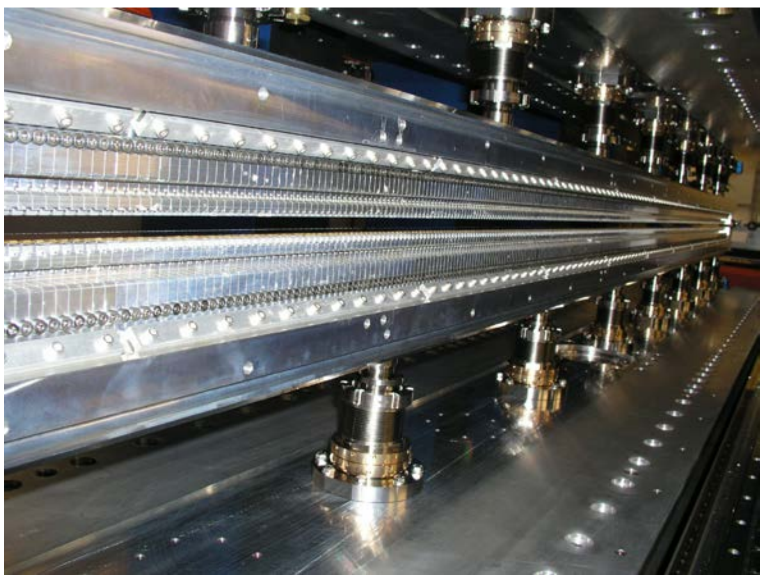
Beam life-times of ~ 15 minutes calculated → Top-up frequency > 1 Hz to maintain 0.1% intensity stability.

The Undulator (T. Schmidt)

- Design based on undulator assemblies for SLS and SwissFEL.
  - Field on axis = 0.42 T, λ_u = 16 mm, gap = 7 mm (fixed in operation).
  - Good field region = ± 12 mm
  - Magnetic material: NdFeB with diffused Dy → good combination of B_r and H_c

    → less sensitive to demagnetisation caused by beam loss (i.e. radiation hard).
- Produces flux / brightness required for mask inspection at 13.5 nm (92 eV),

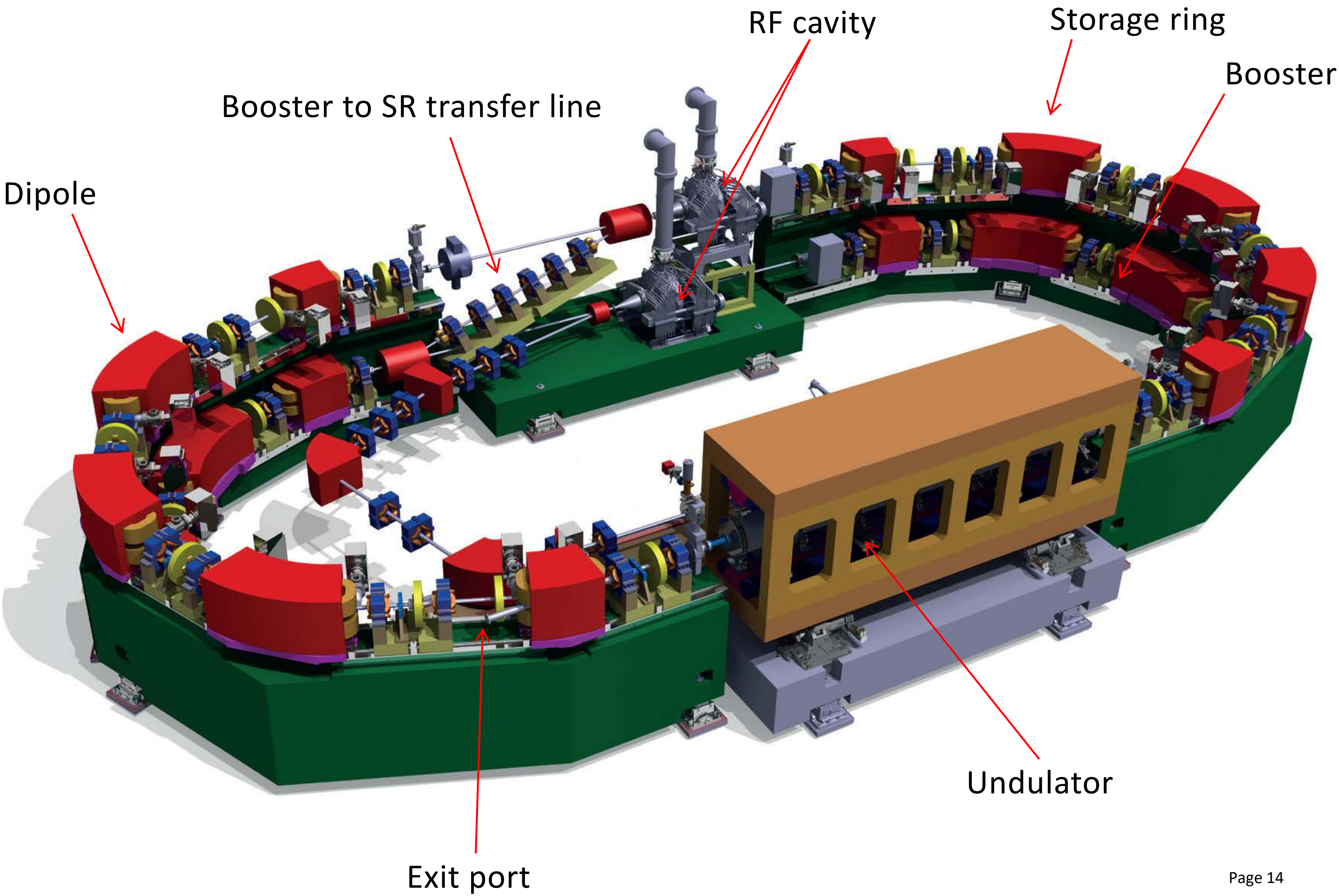
  → next slide.



U15 undulator for SwissFEL / ARAMIS

3-D integration - COSAMI

Compact **S**ource for **A**ctinic **M**ask **I**nspection



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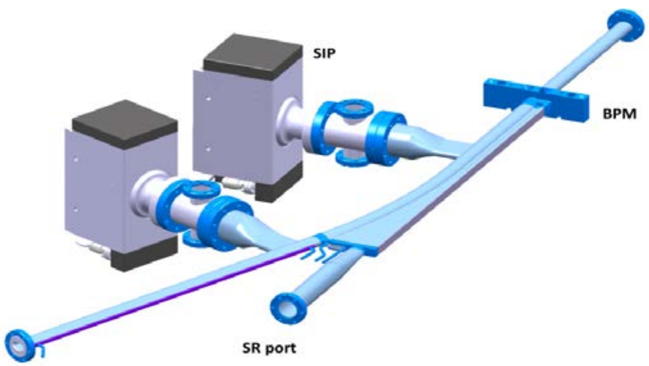
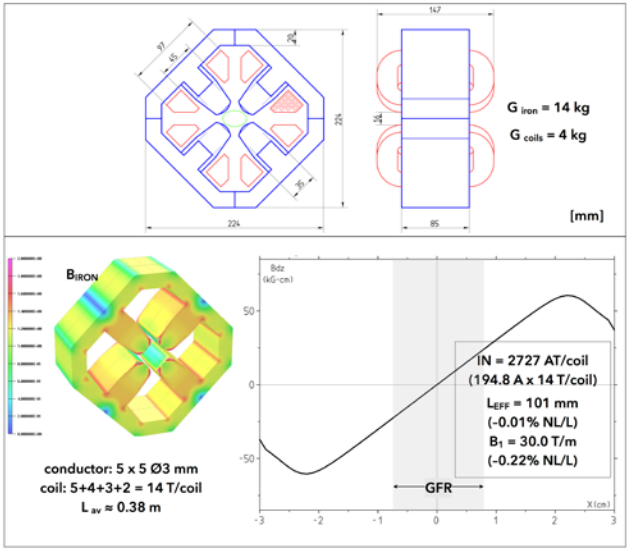
Engineering sub-systems studied

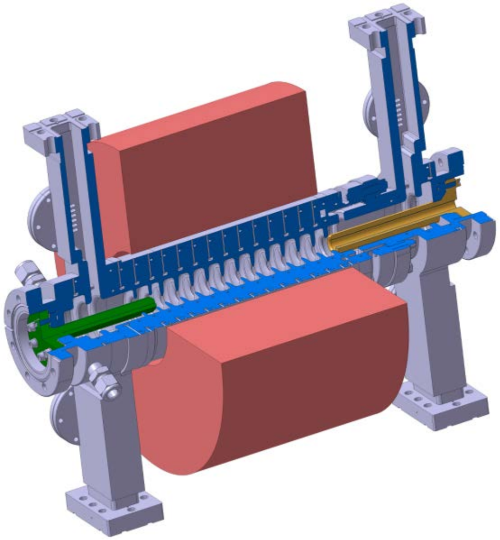
http://accapp17.org/wp-content/uploads/2017/09/AppAcc-paper.pdf



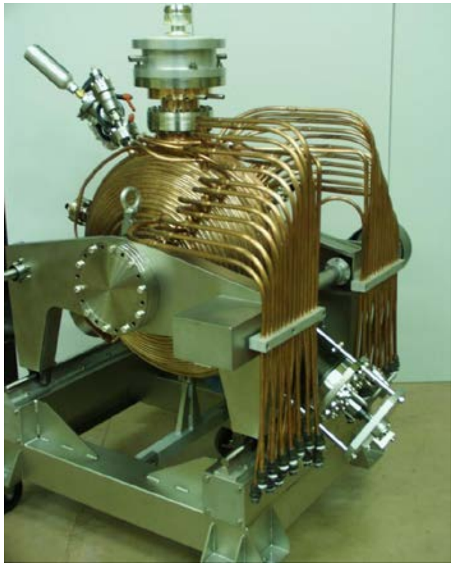
vacuum chamber



SR quadrupole

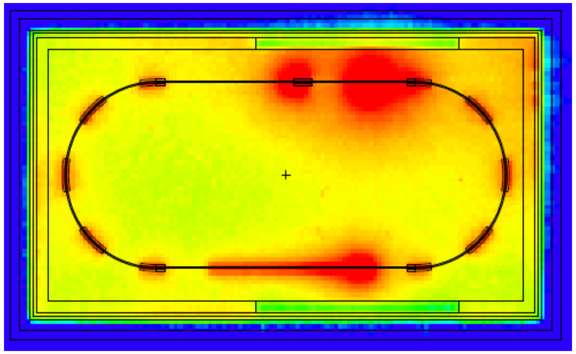


RF electron gun



ELETTRA RF cavity

500 MHz power source



Shielding calculations

Summary and conclusion:

Conceptual design and technical systems studied

- Optimization undulator / storage ring ✓
- Conceptual design of storage ring and its hardware
  - Lattice design
    - layout & performance ✓
    - non-linear dynamics ✓
    - beam lifetime ✓
    - ion trapping ✓
    - injection & extraction
  - Undulator ✓
  - DC-Magnets ✓
  - RF-systems ✓
  - Vacuum system ✓
  - Radiation shielding ✓

We believe that a compact, high-brightness EUV source, based on existing mature technology, for actinic mask inspection is a viable prospect.

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