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A Compact Storage Ring for the Production of EUV Radiation

Accelerator Applications 2017

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Presentation outline

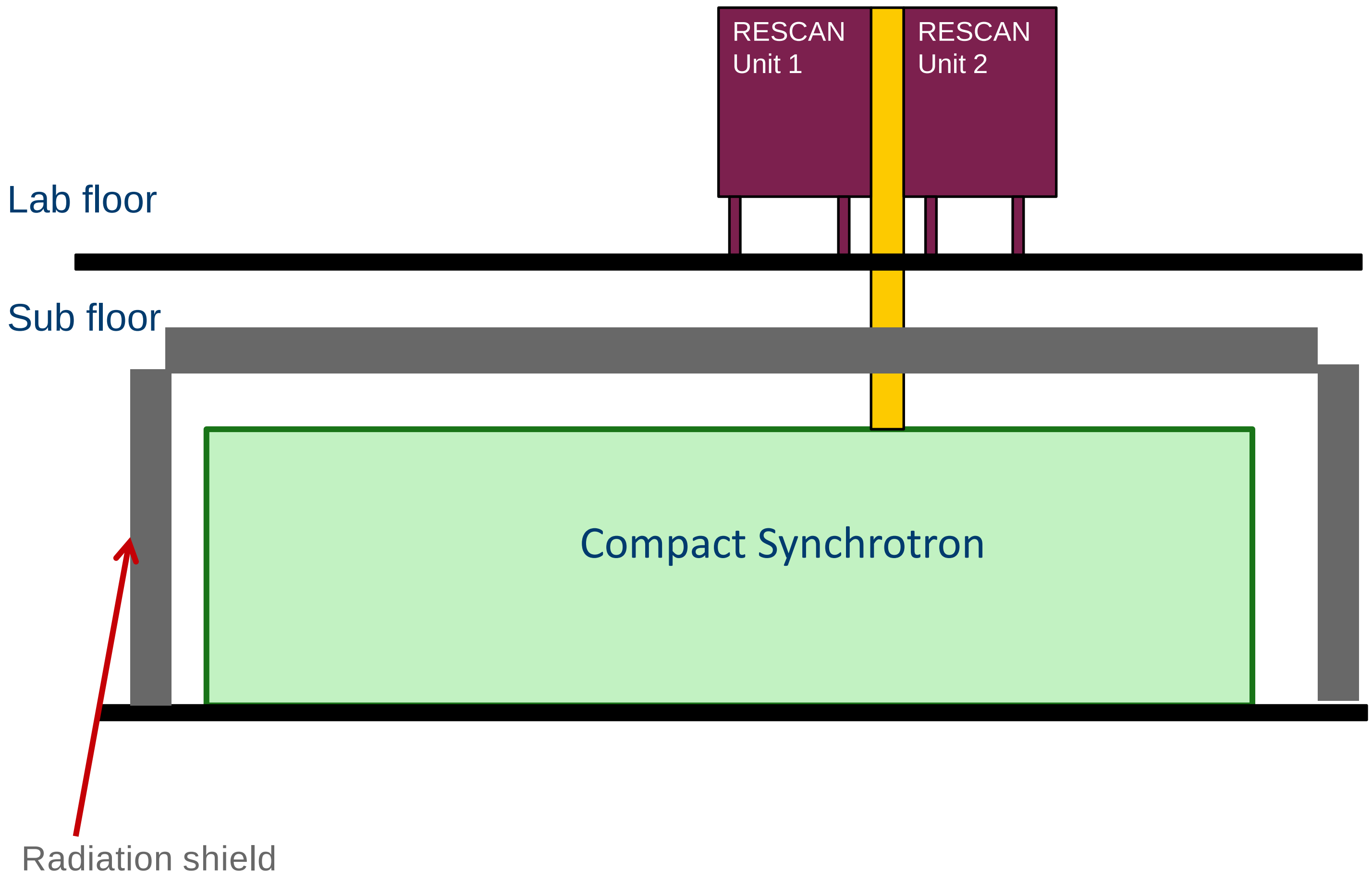
- Motivation for the study
- Accelerator requirements
  - Optics design
  - Technical sub-systems
    - Undulator
    - DC magnets
    - Vacuum system
    - Injector linac
    - Radio-frequency system
    - Radiation shielding
- Concluding remarks

- Not discussed
  - Non-critical subsystems (diagnostics, controls, power supplies)
  - Injection to storage ring (critical, but work in progress!)

Motivation for this study

- We will describe the design of a compact accelerator with application to the semiconductor industry.
- 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%) will 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.)
- 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** (~ 5 m x 12m) synchrotron radiation source for this purpose.

Mask inspection tool



Accelerator requirements

- High brightness
  → low emittance (nm range)
- High stability (10^{-3} range)
  → top-up injection → full energy booster
- High reliability (>99% availability)
  → robust design & proven technology

→***same requirements as for a 3rd generation light source***

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

Innovative solutions

→ adapt technology of Diffraction Limited Storage Rings

→ multi-bend magnet lattice

→ implementation of undulator

→ combined function magnets

→ small vacuum chambers with NEG coating

+ vertical stacking of booster and ring → small footprint

Design and optimization

Main criteria for the optimization procedure:

For required performance → minimum size and minimum costs

Optimization steps:

- Choice of beam energy and undulator
- Basic storage ring layout and design
- Single particle and collective beam dynamics
- Booster design
- 3-D arrangement of storage ring and pre-accelerators
- Beam transfer and injection process (still WIP)
- Design technical sub-systems

EUV source parameters

Parameter	Unit	Value
Footprint of the storage ring	m^2	12x5
Circumference	4	25.8
Beam energy	MeV	430
Beam current	mA	150
Intensity stability	%	0.1
Undulator radiation wavelength	nm	13.5
Flux	ph/s/0.1% BW	1.35×10^{15}
Brilliance	ph/s/mm^2/mrad^2/0.1% BW	1.8×10^{18}
Coherent fraction	%	6.2

Facility layout

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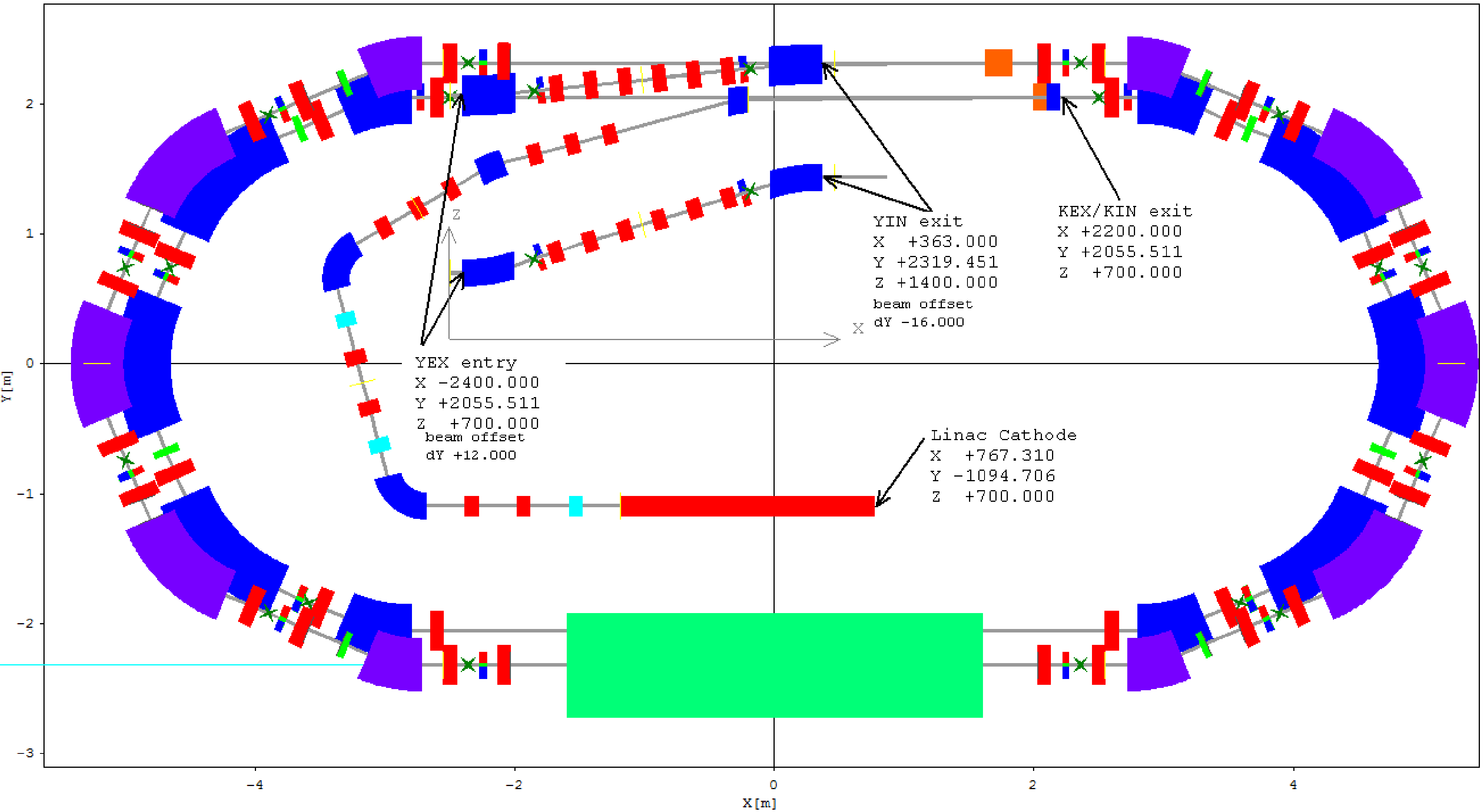
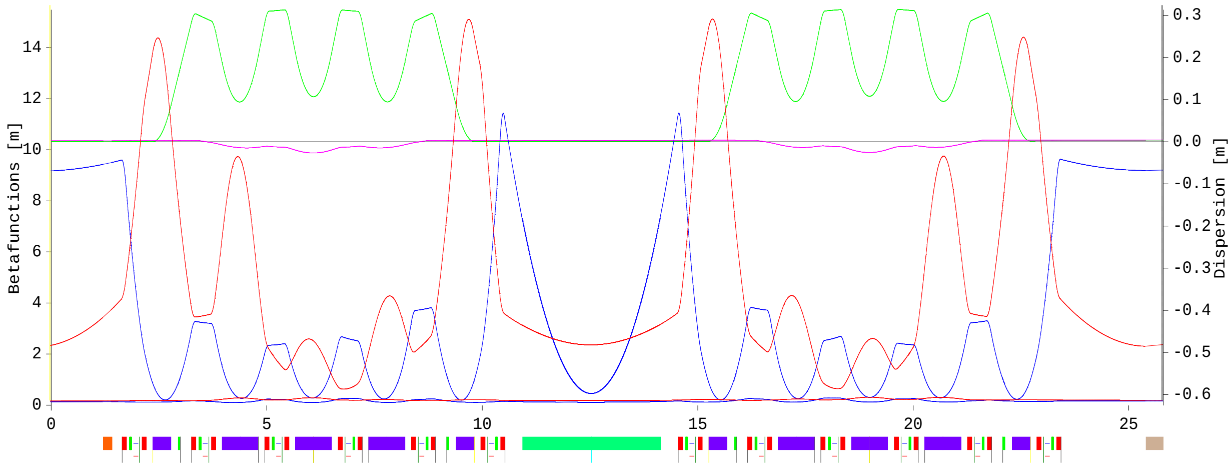
Race-track geometry: Two 5-bend achromat arcs and two straights. One straight for the undulator and one for injection and RF.

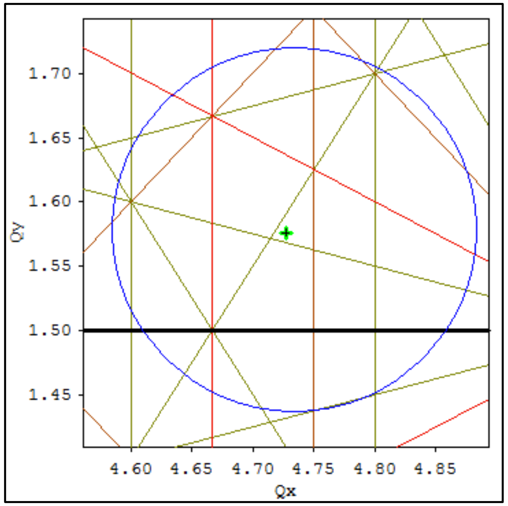
- Ring: 430 MeV, 25.8 m
- Booster: 43 → 430 MeV, 24.0 m
- BR transfer line –18.6° inclination
- LB transfer line
- Gun/Linac: 43 MeV, 2.1 m



Linear optics design (A. Streun)



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



Tune diagram

Lattice features

- Strong horizontal focussing: strong quads → small magnet bore; strong sextupoles to correct chromaticity.
- Weak dispersion (MBA) ensures adequate momentum acceptance despite small 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 → brightness.
- β_y reduced at undulator extremities to reduce particle losses (small vertical gap).
- 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 chromaticity $\xi_{x/y}$	–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. 24 "buckets" are filled to leave a gap in the bunch train to combat trapped ions. Total charge in ring is ~ 17 nC (assuming I = 200 mA, to have some margin).

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

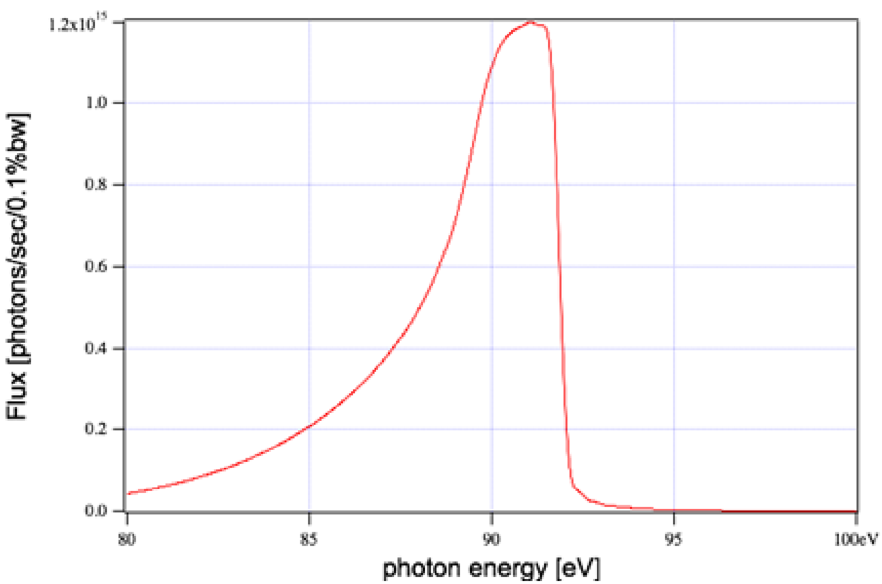
Life-times of ~ 15 minutes calculated → Top-up frequency > 1 Hz to maintain 0.1% intensity stability.

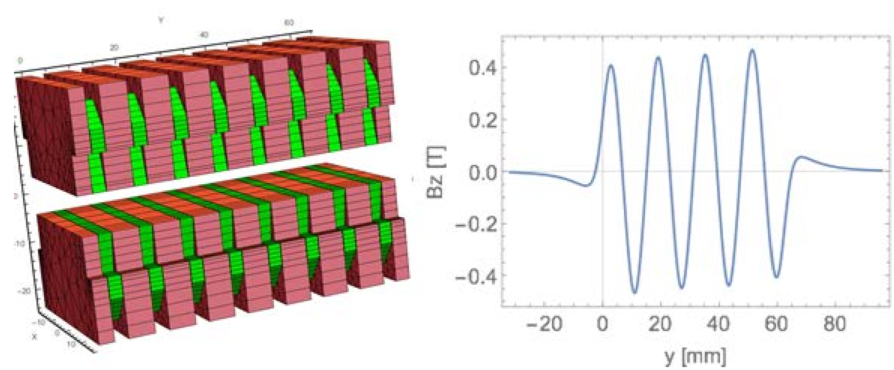
Trapped Ion effects (M. Ehrlichmann, A Wrulich)

- Positive ions, created by ionisation of the residual gas, can be trapped in the potential well of the electron beam resulting in
  – tune shifts
  – emittance dilution
  – beam instability
- These effects can limit the intensity of the stored beam. This has been studied to check that we can reach the required beam current.
- Mitigation measures must be taken
  – the introduction of “clearing” electrodes to sweep out the ions by electric fields
  – the introduction of a ‘gap’ in the storage ring bunch train, allowing the ions time to drift to the walls before the arrival of the next bunch. This has been adopted for the EUV source as mentioned earlier.

The Undulator (T. Schmidt)

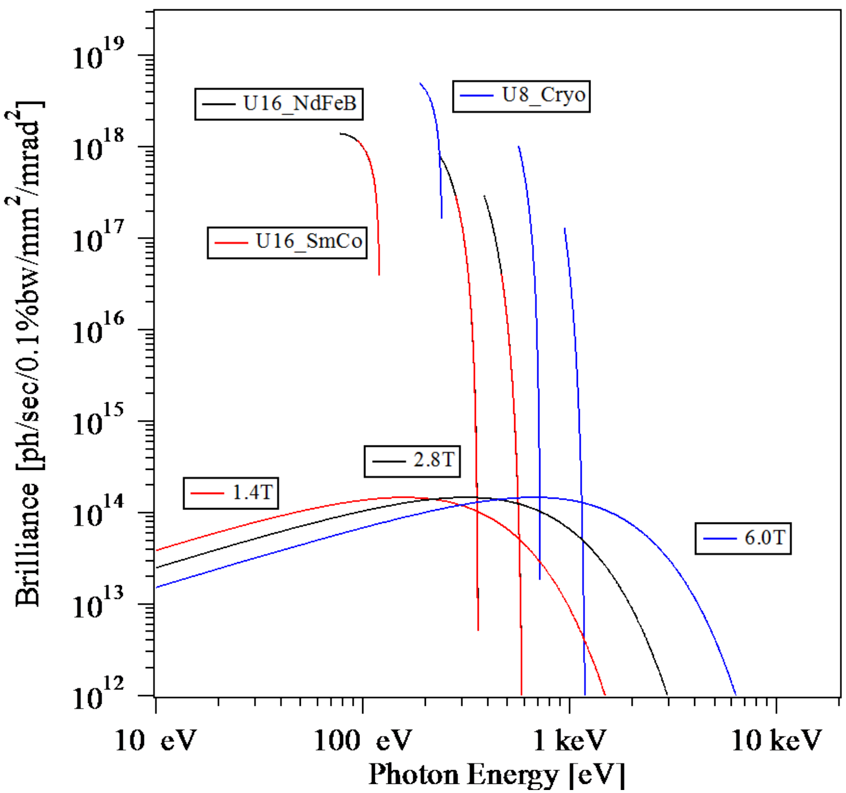
- Design based on undulator assemblies for SLS and SwissFEL.
  - Field on axis = 0.42 T, λ_u = 16 mm, gap = 7 mm (fixed in operation).
  - Good field region = ± 12 mm
  - Magnetic material: NdFeB with diffused Dy → good combination of B_r and H_c
    → less sensitive to demagnetisation due to beam loss (i.e. radiation hard).
- Produces flux / brightness required for mask inspection at 13.5 nm (92 eV).
  - Flux = 1.2×10^{15} ph/s/0.1% BW
  - Brilliance = 6×10^{17} ph/s/mm²/mrad²/0.1% BW

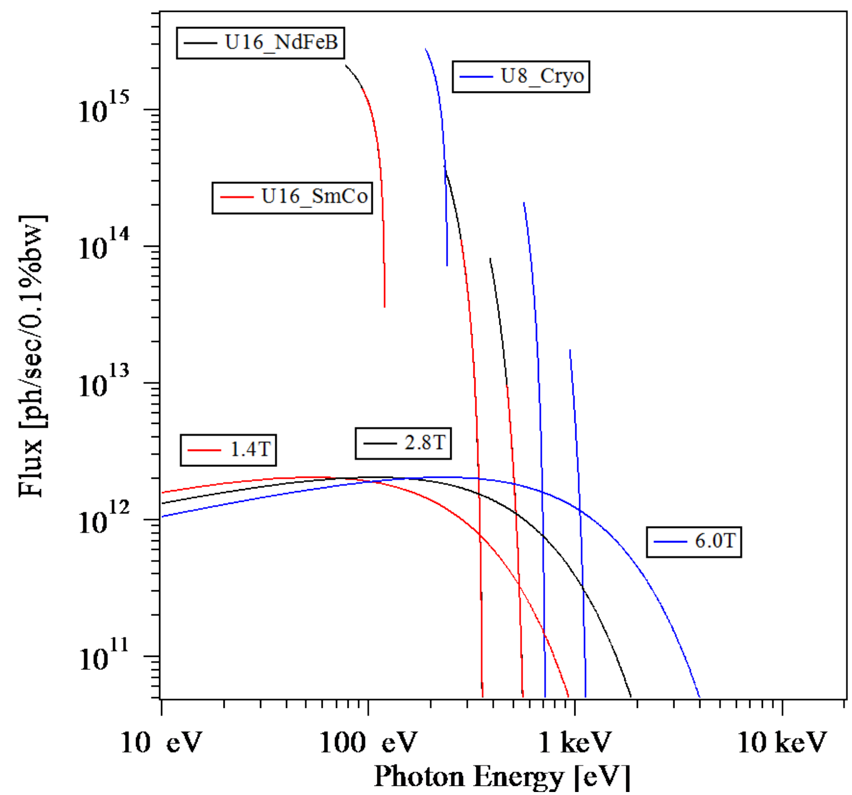




Simulation of 4 periods

EUV source brightness curves – 430 MeV comparison with other undulator / dipole magnets

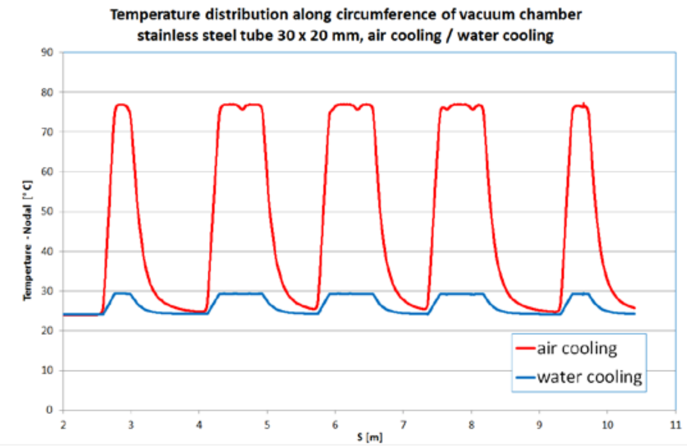


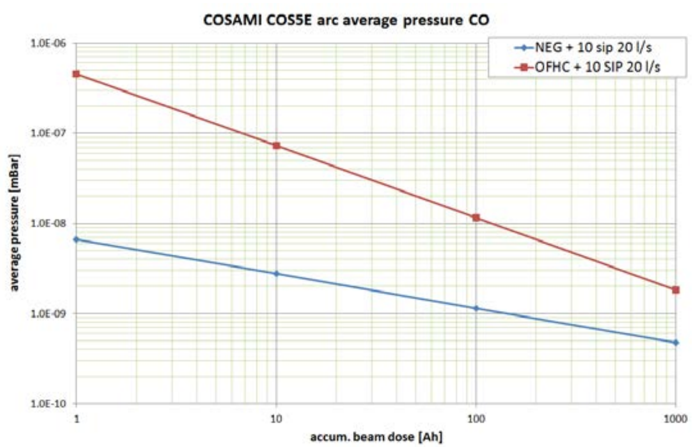


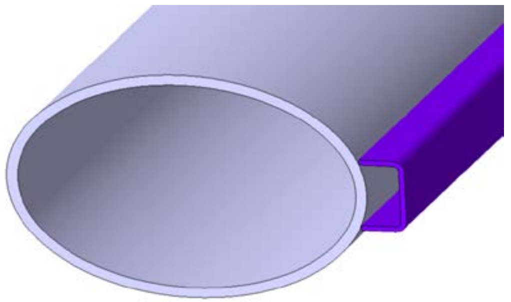
Vacuum system (L. Schulz et. al.)

- Vacuum system must provide sufficiently low base pressure (< 10^{-9} mbar) to ensure sufficient beam lifetime due to scattering from residual gas (mainly CO).
  - Elliptical vacuum chamber of 30 mm (H) x 20 mm (V) adopted.
  - "small" chamber to allow strong magnet gradients.
- Low energy ring produces very low heat load ~ 85 W/m (E= 430 MeV, I = 200 mA, ρ = 1.07 m) but temperature rise is still significant
  - Forced cooling needed
- Base pressure dominated by photo-desorption due to synchrotron radiation. Simulated using codes Synrad+ (desorption) and Molflow+ (pressure distribution).

  → full NEG coating of chamber required



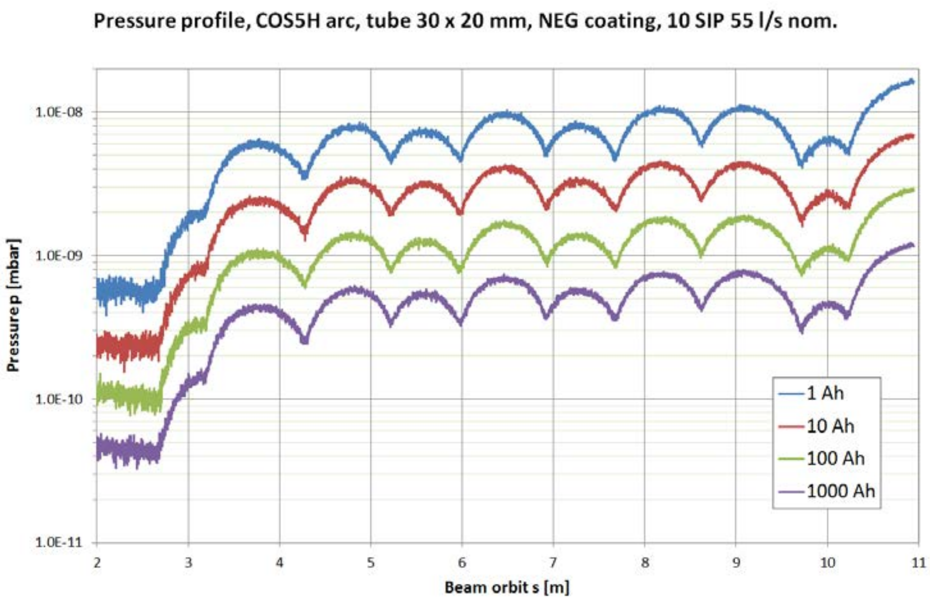


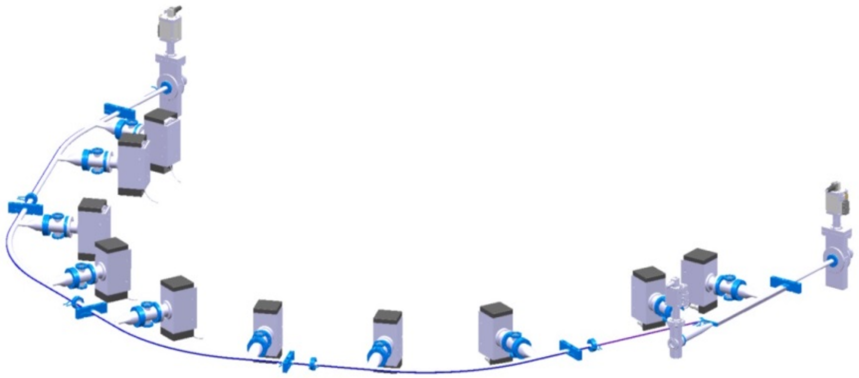


Cooling channel 3mm x 6mm

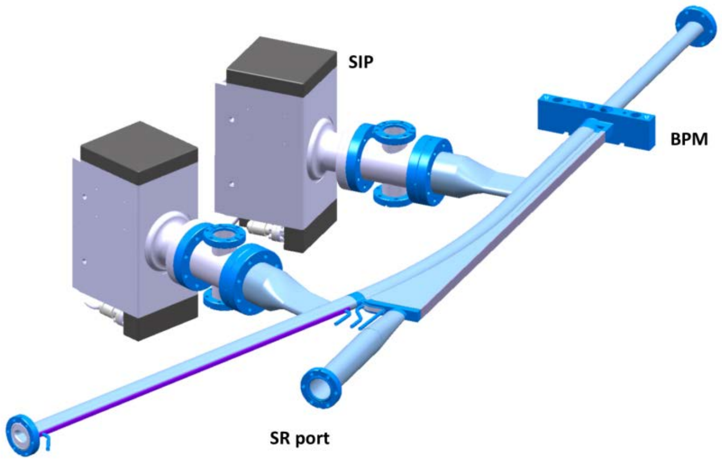
Vacuum performance

- Five vacuum chambers, total length ~ 9 m, form one arc. Stainless steel chamber with 10 sputter ion pumps per arc. Required pressure obtained after ~ 100 Ah of beam time.





Vacuum chamber layout for one arc.



Dipole chamber with SR port

Magnets (Ph. Lerch, V. Vrankovic, M. Negrazus)

- SR lattice optimised to *minimise* number of magnet types: each arc is composed of three 45° dipole combined function bends and two 22.5° dipole CF bends (sector magnets).
- Each arc contains six identical blocks composed of: 2 quads, 1 BPM, 1 combined H/V corrector coil and 1 sextupole (560 mm total length).

Designs for all DC magnets exist. SR magnets are made from solid iron but Booster magnets are made from laminated blocks (to minimise eddy currents during ramp).

Storage ring magnet parameters

Type	Pieces	L[mm]	B [T]	B′ [T/m]	½B″[T/m²]
Gradient bend, solid iron	4 / 6	420 / 840	1.34	–4.10	–17.1
Quadrupole	24	100	0	30	0
Sextupole	16	50	0	$\pm 3.0^{skew}$	580
H/V corrector magnet	12	80	±0.018	0	0

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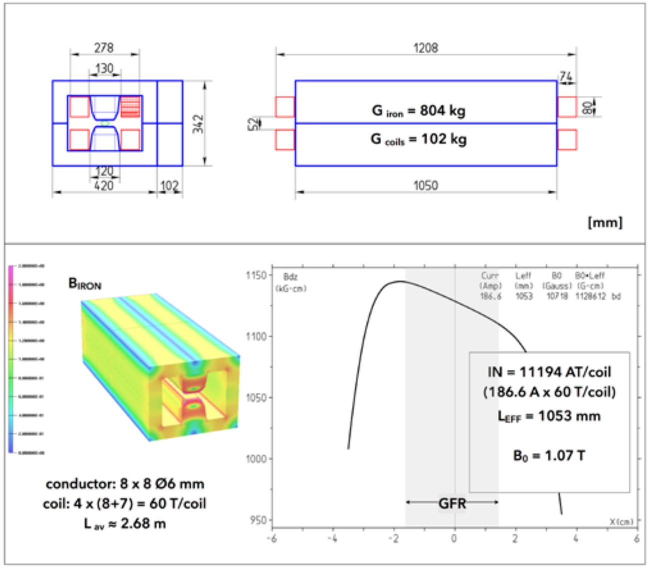
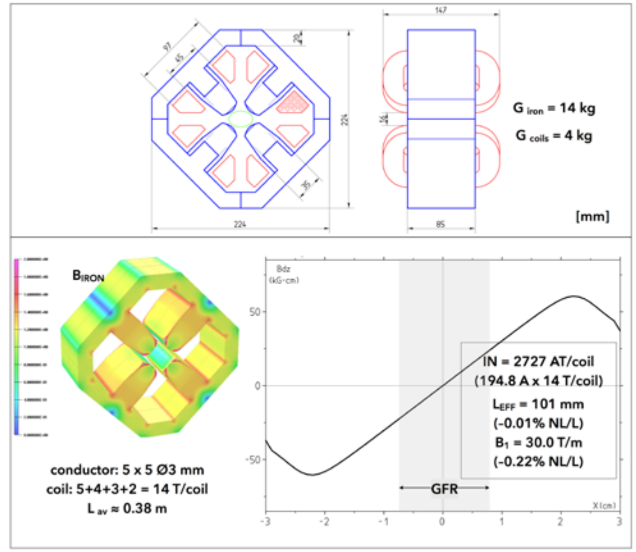
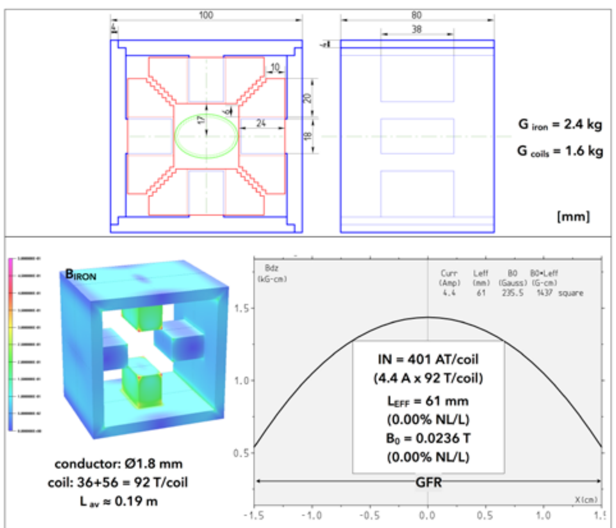
Magnets (2)



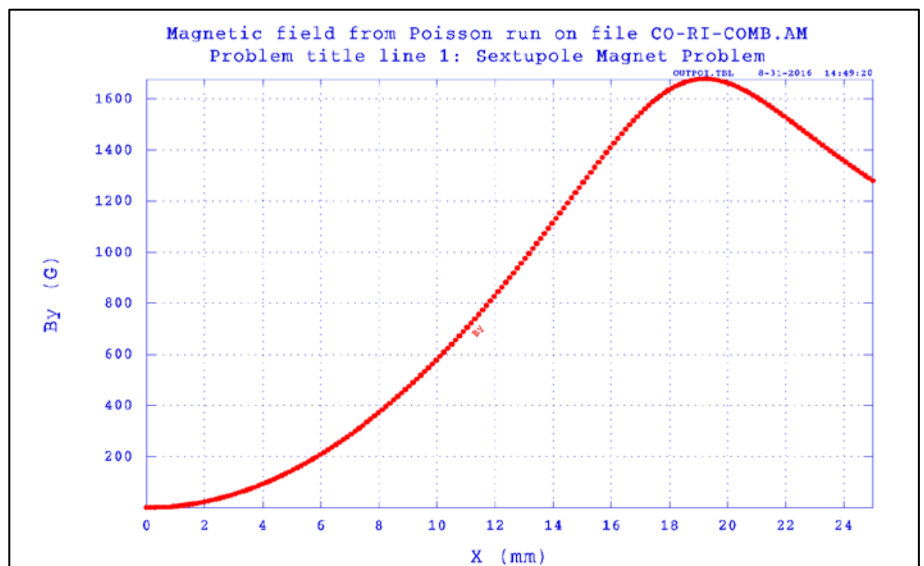
45° SR Dipole



SR quadrupole



H/V corrector coil



Sextupole field profile 580 T/m2 for NI = 660 A

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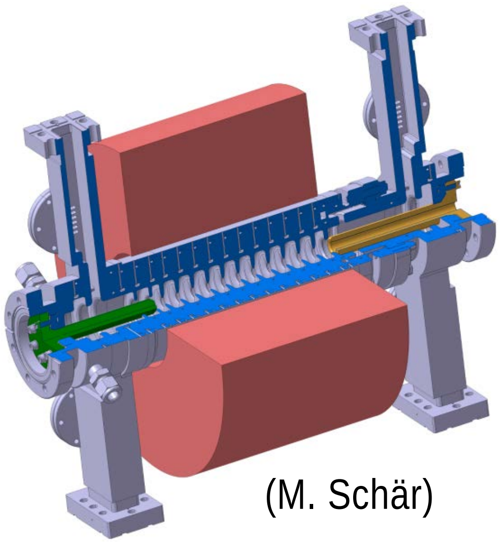
Specification of Injector

With 150mA, we have totally only 12.9 nC of charge in the storage ring.

- Charge in Top-Up mode: 13 pC → 1/1000 of charge per shot
- Charge to accumulate: 130 pC with 10Hz → Accumulation in 10s !
- Output energy - 20MeV…50MeV
- Normalized emittance < 50µm
- Energy spread < 0.5%
- Pulse to Pulse energy stability < 0.25%

The EUV source would use a Photo-Injector linac

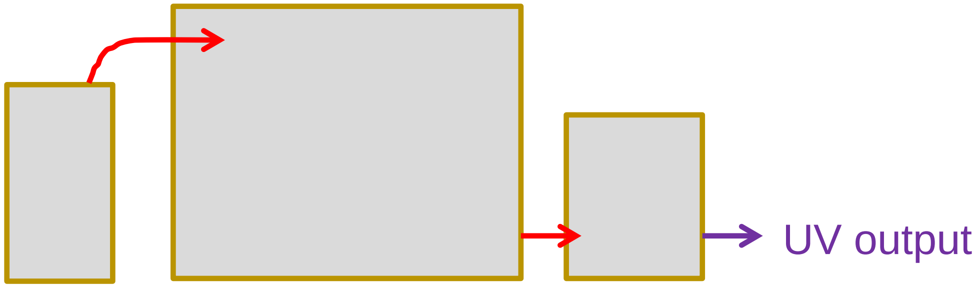


(M. Schär)

- Combine the high brighness **travelling wave gun** with **SwissFEL 2m C-band structure**:
  Relaxed gradient, laser profile and repetition rate,
  Increas number of cells to reach the energy,
  simplify the couplers and focusing magnet.

- Advantages: Compact and simple design
- Disadvantages: Prototype should be built and tested
- Needs UV-Laser system
- Synchronization more complex !
  With f_b=71.4MHz: 5.712GHz = $80f_b$
  499.8MHz = $7f_b$
- Timing for bucket allocation in storage ring more complex (but can still be achieved).

Possible photo-cathode laser option



Oscillator	Amplifier	UV generation module
32*25 cm	84*51 cm	30*25 cm

- Power long term stability < 2% rms
- Energy long term stability < 2% rms
- Pulse to pulse < 2% rms

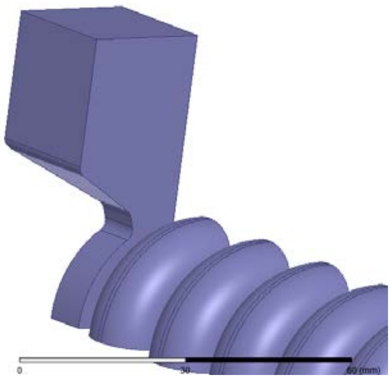
Pulsed laser from industry

- Oscillator synchronizable to external master clock

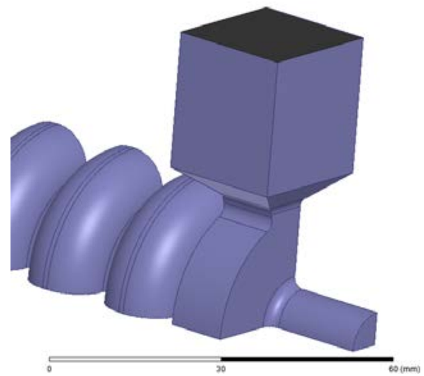
  Jitter: <250 fs rms
- Gaussian 0.65ps FWHM pulses at 257±5 nm
- with Energy per pulse >0.1 mJ
- Single shot – 10Hz – 100 Hz repetition rate
- Turn key, industrial class laser system
- Laser system should be located outside the bunker
- Needs evacuated tube to transfer the laser pulse.

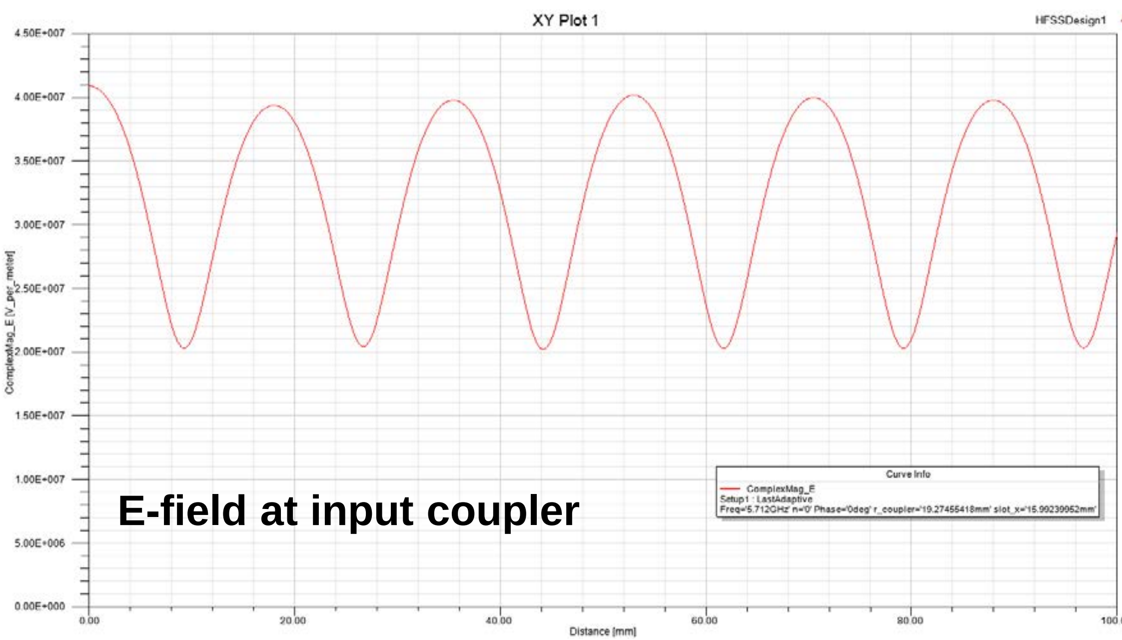
C-band travelling-wave gun (R. Zennaro, L. Stingelin)

Short input coupler



Output coupler





E-field at input coupler

- Based on the SwissFEL 2m C-band structure
- Phase advance: 2π/3
- Group velocity: 3.1% … 1.3%c
- Iris opening radius: 7.2 … 5.4mm
- r/q: 7.2 … 8.5kΩ/m
- Compact coupler (to slide Solenoid on)
- 41 MV/m (cathode) for 33 MW

Storage ring RF parameters – derived from beam parameters.

Storage ring RF parameters

Revolution Freq.	11.62MHz	Momentum compaction	0.0253
Beam Current	170mA	Energy Spread	0.0004
Energy Loss / Turn	2.8keV	Radiated Power	496W
Long. Damping	16.3ms	Main RF Frequency	499.8MHz
Harmonic Number	43	Quality Factor Q_0	40’000
Shunt Impedance	3.4MΩ	Over Voltage	137
Gap Voltage	400kV	Opt. Voltage in 3HC	133kV
RF Acceptance	2.3%	Quality Factor Q_0 In 3HC	~13‘000
Sync. Phase	0.44°	Min. Shunt Impedance for passive cavity	84MΩ (3HC)
Cavity Wall Loss	24kW	Shunt Impedance for one active harmonic cavity	1.76 MΩ
Coupling Factor	1.021		
Opt. Detuning for Matching	-18kHz	RF-Power for 1 Active 3HC	~5.2kW
Bunch length	11ps (no HC)	Bunch length	45ps (3HC)
Sync. Frequency	148kHz (no HC)	Landau Damping Rate	~70’000 s^{-1}

SR Radio-Frequency system (P. Craeivich)

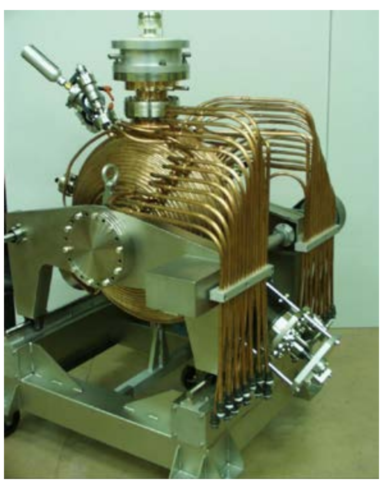
Full list of RF parameters derived from beam parameters (last slide)

Identification of hardware requirements – use existing commercial solutions

RF cavity, power source, waveguide, phase/amplitude regulation

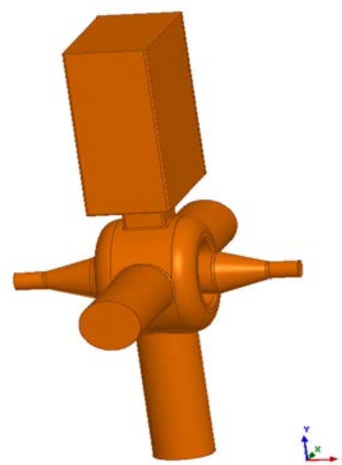
Studies of instability thresholds → shows advantage of 3rd Harmonic Cavity (3HC)

Microwave instability driven by ring impedance; CBI driven by longitudinal or transverse Higher Order Modes of the RF cavity.



ELETTRA 500 MHz cavity

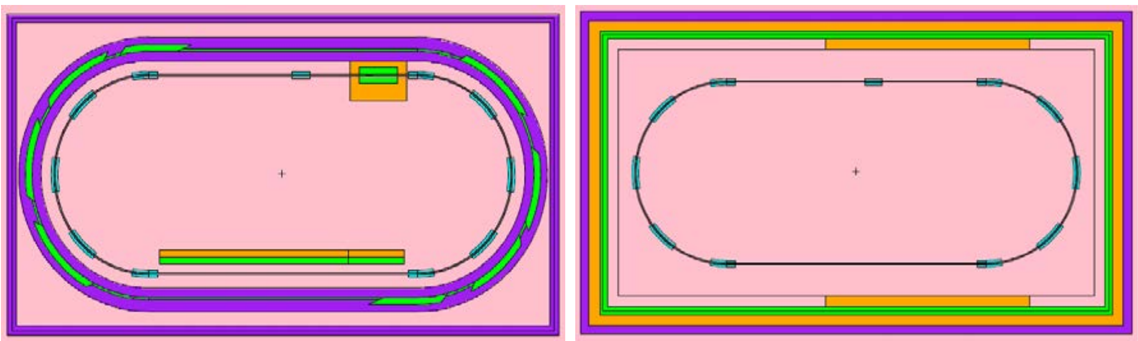
65 kW solid state amp.



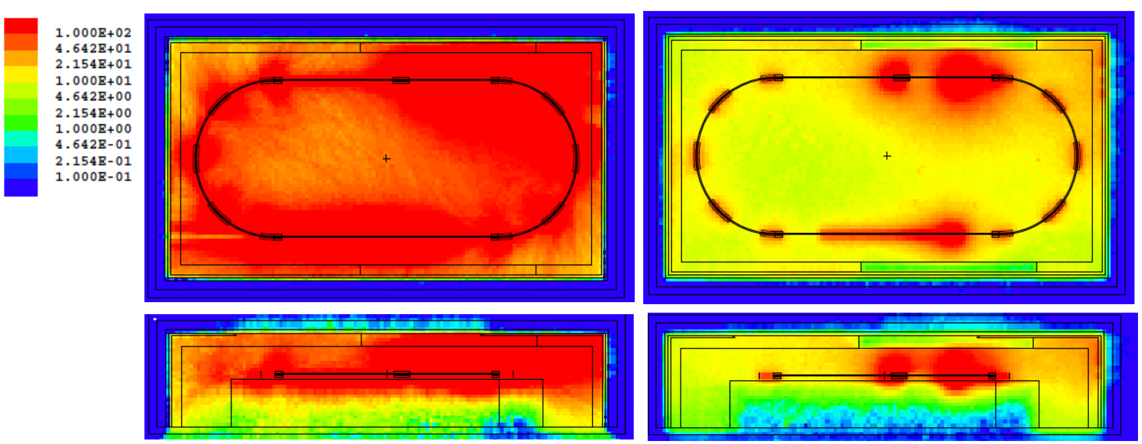
ALS 3rd harmonic cavity

Radiation shielding (R.M. Bergmann)

- Performed using codes MCNPX 2.7.0 (local) / MCNP 6.1 (outer wall)
  Loss rates ~ 1.2×10^8 electrons/s at 430 MeV → ICRP data used to convert flux to dose rates. Losses dominated by storage ring.



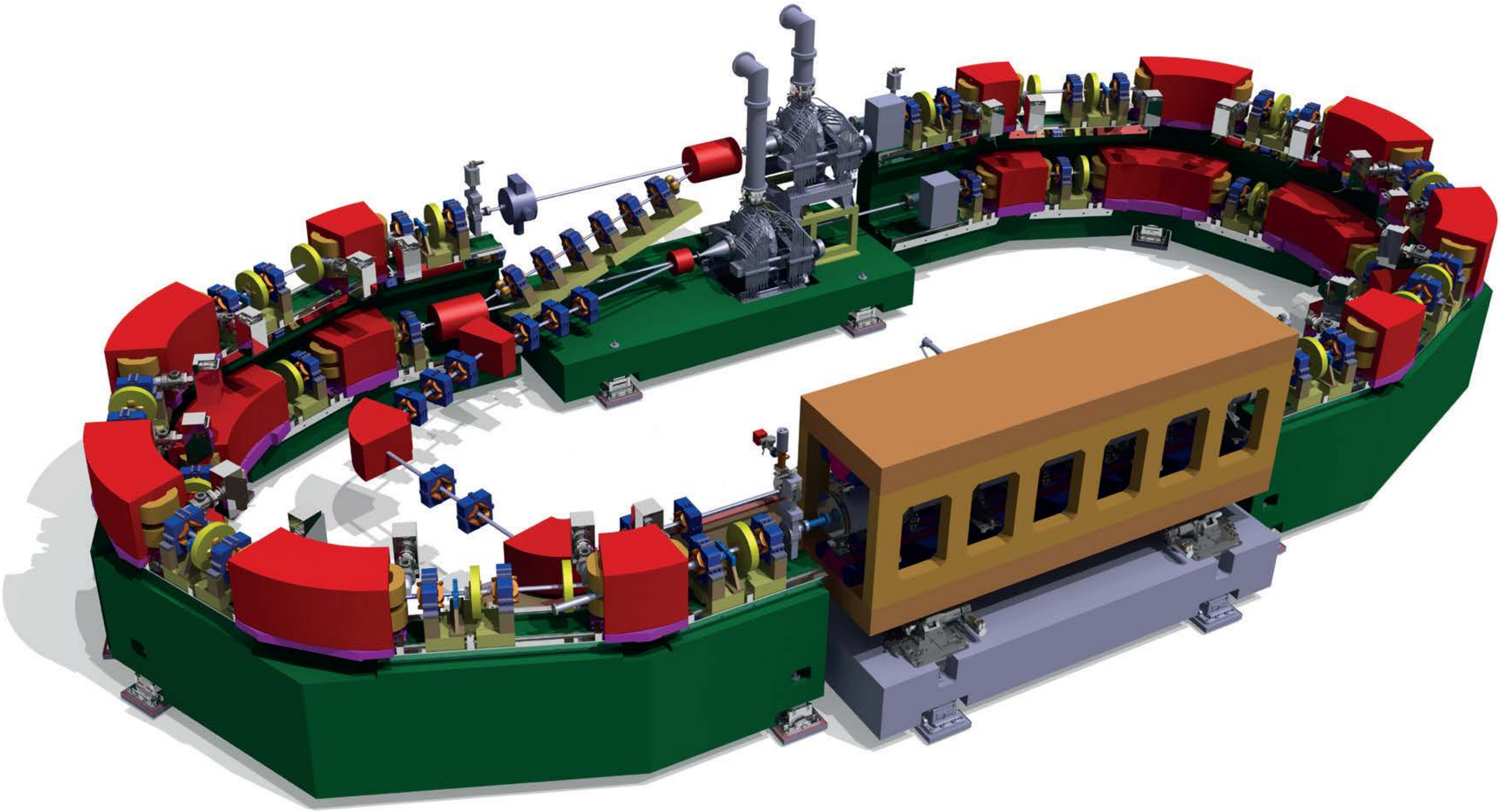
Shielding model: Local (l), outer-wall (r) – material: concrete (g), lead (g), borated polyethelyne (o).



270 tonnes lead and 65 tonnes borated polyethelyne required for adequate shielding.

Not fully optimised!

Does it all fit? 3-D integration



In summary: Conceptual design and systems studied

- Optimization undulator vs. storage ring

→Conceptual design

- Lattice design
  - layout & performance ✓
  - non-linear dynamics ✓
  - beam lifetime ✓
  - ion trapping ✓
  - injection & extraction **(WIP)**
- Undulator ✓
- DC-Magnets ✓
- Pulsed magnets **(WIP)**
- RF-systems ✓
- Vacuum system ✓
- Radiation shielding ✓

Acknowledgements

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Advanced Accelerator Technologies contributed to 3-D integration drawings

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