A Compact Storage Ring for the Production of EUV Radiation

Accelerator Applications 2017
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!)
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

Lab floor

Sub floor

Compact Synchrotron

Radiation shield

RESCAN Unit 1

RESCAN Unit 2
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 ($\approx 60 \text{ m}^2$) - 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
Main criteria for the optimization procedure:

For required performance $\rightarrow$ 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Footprint of the storage ring</td>
<td>m²</td>
<td>12x5</td>
</tr>
<tr>
<td>Circumference</td>
<td>4</td>
<td>25.8</td>
</tr>
<tr>
<td>Beam energy</td>
<td>MeV</td>
<td>430</td>
</tr>
<tr>
<td>Beam current</td>
<td>mA</td>
<td>150</td>
</tr>
<tr>
<td>Intensity stability</td>
<td>%</td>
<td>0.1</td>
</tr>
<tr>
<td>Undulator radiation wavelength</td>
<td>nm</td>
<td>13.5</td>
</tr>
<tr>
<td>Flux</td>
<td>ph/s/0.1% BW</td>
<td>1.35x10^{15}</td>
</tr>
<tr>
<td>Brilliance</td>
<td>ph/s/mm²/mrad²/0.1% BW</td>
<td>1.8x10^{18}</td>
</tr>
<tr>
<td>Coherent fraction</td>
<td>%</td>
<td>6.2</td>
</tr>
</tbody>
</table>
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: $43 \rightarrow 430$ MeV, 24.0 m
- BR transfer line $-18.6^\circ$ inclination
- LB transfer line
- Gun/Linac: 43 MeV, 2.1 m
Lattice features

- Strong horizontal focussing: strong quads $\rightarrow$ small magnet bore; strong sextupoles to correct chromaticity.
- Weak dispersion (MBA) ensures adequate momentum acceptance despite small aperture $\rightarrow$ needed to reduce particle loss to Touscheck scattering.
- Skew-quad windings in sextupole to generate some vertical emittance $\rightarrow$ reduce Touscheck scattering.
- Small $\beta_x$ at center of undulator $\rightarrow$ minimise source-point size $\rightarrow$ brightness.
- $\beta_y$ 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference [m]</td>
<td>25.8</td>
</tr>
<tr>
<td>Energy [MeV]</td>
<td>430</td>
</tr>
<tr>
<td>Working Point $Q_{x/y}$</td>
<td>4.73 / 1.58</td>
</tr>
<tr>
<td>Radiation loss/turn [keV]</td>
<td>2.83</td>
</tr>
<tr>
<td>Natural chromaticity $\xi_{x/y}$</td>
<td>–9.7 / –6.9</td>
</tr>
<tr>
<td>Emittance [nm]</td>
<td>5.50</td>
</tr>
<tr>
<td>Momentum compaction $\alpha_c$</td>
<td>0.0258</td>
</tr>
<tr>
<td>Relative energy spread</td>
<td>4.13\cdot10^{-4}</td>
</tr>
<tr>
<td>Hor. damping partition $J_x$</td>
<td>1.54</td>
</tr>
<tr>
<td>Damping times $\tau_{x/y/E}$ [ms]</td>
<td>16.6 / 25.6 / 17.5</td>
</tr>
</tbody>
</table>

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, $\lambda_u = 16$ mm, gap = 7 mm (fixed in operation).
  - Good field region = ± 12 mm
  - Magnetic material: NdFeB with diffused Dy $\rightarrow$ good combination of $B_r$ and $H_c$
    $\rightarrow$ 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 = $1.2 \times 10^{15}$ ph/s/0.1% BW
  - Brilliance = $6 \times 10^{17}$ 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 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, $\rho = 1.07$ 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).
  \[\rightarrow\] full NEG coating of chamber required
• 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.
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).

<table>
<thead>
<tr>
<th>Storage ring magnet parameters</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>Pieces</th>
<th>L [mm]</th>
<th>B [T]</th>
<th>B' [T/m]</th>
<th>½B'' [T/m^2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient bend, solid iron</td>
<td>4 / 6</td>
<td>420 / 840</td>
<td>1.34</td>
<td>−4.10</td>
<td>−17.1</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>24</td>
<td>100</td>
<td>0</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>Sextupole</td>
<td>16</td>
<td>50</td>
<td>0</td>
<td>±3.0^skew</td>
<td>580</td>
</tr>
<tr>
<td>H/V corrector magnet</td>
<td>12</td>
<td>80</td>
<td>±0.018</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Magnets (2)

45° SR Dipole

SR quadrupole

H/V corrector coil

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

- Combine the high brightness **travelling wave gun** with **SwissFEL 2m C-band structure**: Relaxed gradient, laser profile and repetition rate, increase 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 $f_b = 71.4$ MHz: $5.712$ GHz = 80$f_b$
  $499.8$ MHz = 7$f_b$

- Timing for bucket allocation in storage ring more complex (but can still be achieved).
Possible photo-cathode laser option

- 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.
Short input coupler

- Based on the SwissFEL 2m C-band structure
- Phase advance: $2\pi/3$
- Group velocity: $3.1\% \ldots 1.3\%c$
- Iris opening radius: $7.2 \ldots 5.4$mm
- $r/q$: $7.2 \ldots 8.5$ kΩ/m

Output coupler

- Compact coupler (to slide Solenoid on)
- $41$ MV/m (cathode) for $33$ MW

E-field at input coupler

C-band travelling-wave gun (R. Zennaro, L. Stingelin)
Storage ring RF parameters – derived from beam parameters.

## Storage ring RF parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revolution Freq.</td>
<td>11.62MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam Current</td>
<td>170mA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy Loss / Turn</td>
<td>2.8keV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long. Damping</td>
<td>16.3ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harmonic Number</td>
<td>43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shunt Impedance</td>
<td>3.4MΩ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Voltage</td>
<td>400kV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF Acceptance</td>
<td>2.3%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sync. Phase</td>
<td>0.44°</td>
<td>Min. Shunt Impedance for passive cavity</td>
<td>84MΩ (3HC)</td>
</tr>
<tr>
<td>Cavity Wall Loss</td>
<td>24kW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coupling Factor</td>
<td>1.021</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opt. Detuning for Matching</td>
<td>-18kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunch length</td>
<td>11ps (no HC)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sync. Frequency</td>
<td>148kHz (no HC)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Momentum compaction</td>
<td>0.0253</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy Spread</td>
<td>0.0004</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiated Power</td>
<td>496W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main RF Frequency</td>
<td>499.8MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quality Factor Q₀</td>
<td>40’000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Over Voltage</td>
<td>137</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opt. Voltage in 3HC</td>
<td>133kV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quality Factor Q₀ In 3HC</td>
<td>~13’000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shunt Impedance for one active harmonic cavity</td>
<td></td>
<td></td>
<td>1.76 MΩ</td>
</tr>
<tr>
<td>RF-Power for 1 Active 3HC</td>
<td>~5.2kW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunch length</td>
<td>45ps (3HC)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landau Damping Rate</td>
<td>~70’000 s⁻¹</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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 3\textsuperscript{rd} 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 3\textsuperscript{rd} harmonic cavity
Performed using codes MCNPX 2.7.0 (local) / MCNP 6.1 (outer wall)
Loss rates ~ $1.2 \times 10^8$ electrons/s at 430 MeV → ICRP data used to convert flux to dose rates. Losses dominated by storage ring.

Radiation shielding (R.M. Bergmann)

Radiation shielding

- CT shielding model: Local (l), outer-wall (r) – material: concrete (g), lead (g), borated polyethylene (o).
- 270 tonnes lead and 65 tonnes borated polyethylene 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 ✓
This study has been the work of a number of people:


This work has received the financial support of the Swiss Commission for Technology and Innovation under grant # 19193.1PFNM-NM

Advanced Accelerator Technologies contributed to 3-D integration drawings

I should like to thank Prof. Cole for the opportunity to present this work.

Many thanks for your attention.