The MAX4 accelerator system.

General description

The MAX4 ring is intended to be the future user facility source at MAXlab. This storage ring is intended to be the future “work-horse” at MAXlab, offering high brilliance radiation over a wide spectral region, while the flexible injector could be equipped with newly developed items for experiments with special demands.
The high-brilliance 3 GeV storage ring, equipped with small gap, short period SC undulators, demonstrates a high mean brilliance over a wide energy spectrum. The ring itself is defined from the routine operation of the small gap insertion devices which is reflected in the small aperture of the ring magnets.
The development of future light sources, like the free electron laser (FEL) and energy recovery systems, opens up new challenging possibilities to create high brilliance, short pulse radiation. This development is today far from being mature, a strong development of new ideas and techniques will most probably take place during the next decade(s).
The MAX4 injector is constructed to incorporate this new technology as it is being developed. So can energy recovery, long undulators utilising the low electron beam emittance and small energy spread to give high mean and peak brilliance in a broad spectral region and eventually cascaded optical klystrons offering Fourier transform limited radiation be introduced as items like CW low emittance electron guns are developed.

The MAX4 storage ring.

Introduction.

The parameters for the storage ring are chosen to offer a very high mean brilliance in the hard X-ray spectral region (8-20 keV). The insertion devices and the storage ring are optimised in the following way:

1. A short-period undulator is chosen to minimise the operating electron energy. The maximum K-value of this undulator is chosen to be larger than 2.3 to get an overlap between the fundamental and the third harmonic.
2. The lattice chosen should give a small electron beam emittance and allow for some ten insertion devices. Within these boundary conditions, the ring circumference should be minimised to keep the price tag low.
3. The electron beam lifetime will be given by the small gaps of the insertion devices. This will call for a full energy injector to allow for topping up. The topping up technique has already been demonstrated at APS and SLS and could well be the standard of tomorrow.
4. The small gaps of the insertion devices will define the magnet apertures. This results in small and cheap magnet items. Permanent magnet technology will also be contemplated.

One undulator example.

Minimising the undulator period and demanding a maximum K value around 2 makes a superconducting undulator a suitable choice 1). The peak magnet field is kept below the saturation level of iron to minimise the coils size. For the very short period, high K-value undulator, the following parameter values are then used:

λ_u	12 mm
B_{max}	2 T
K_{max}	2.3
N	200
Gap	3 mm

Magnet lattice:
A highly integrated form of magnet lattice is chosen. 10 supercells are each built up by 5 basic cells and matching sections are added to optimise the machine functions in the 10 straight sections to the undulators. Each basic cell consists of one dipole and one quadrupole focusing in the horisontal direction. The dipoles are equiped with vertically focusing gradients. The sextupole fields necessary for chromaticity correction are integrated in the dipole and quadrupole magnets. The experience gained from the MAX3 ring (2) will be used for the final magnet specification.

The proposed lattice offers a very small emittance, a large dynamic aperture and wide energy acceptance. The low horisontal emittance and a coupling of 0.5 % yield a diffraction limited vertical emittance down to 1 Å. A further reduction of the horisontal emittance will therefore hardly pay off. The main parameter values are listed in the table below and the machine functions for a supercell and the layout of the storage ring are shown on the next two pages.

Table 1.

MAX4 lattice parameters

Electron energy	3 GeV
Circumference	216 m
No of straight sections	10
Straight section length	3.6 m
Circulating current	200 mA
Energy loss (naked lattice)	684 keV/turn
Energy loss (9 SC undulators)	903 keV/turn
Emittance (naked lattice)	1.2 nm rad
Emittance (9 SC undulators)	<1 nm rad
Coupling	0.5 %
Momentum compaction factor	0.0008
Energy acceptance	8%
Dynamic aperture (without magnet errors)	$30*10^{-6}$ m rad

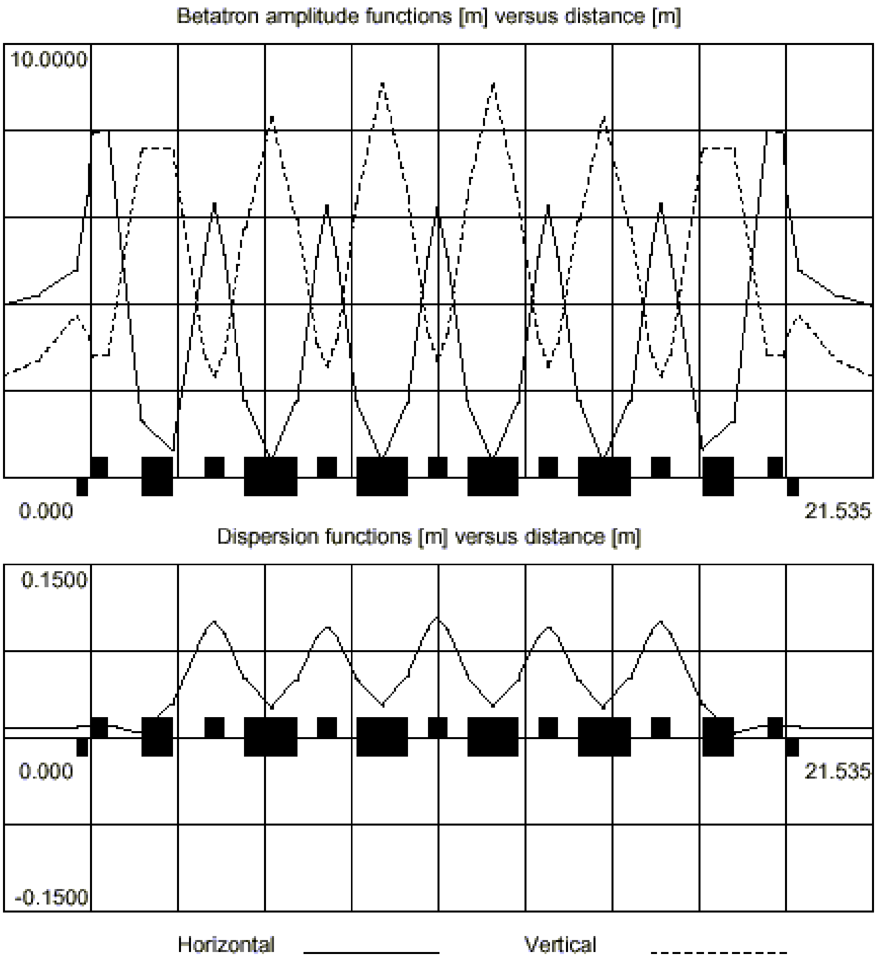

Fig. 1. Machine functions for a supercell.

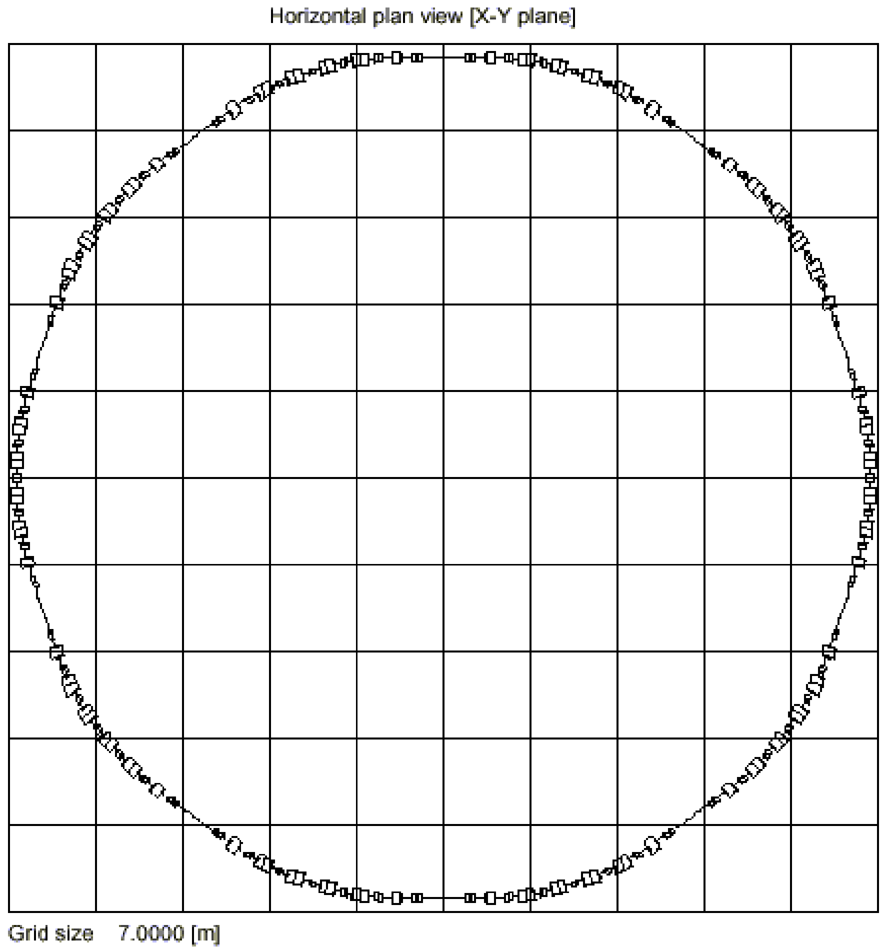

Fig. 2. The MAX4 ring.

Magnets.
A gap of 3 mm is foreseen for the insertion devices. This transforms to 6 mm in the bending magnets where the vertical β_y is at its maximum. A 6 mm stay-clear gap is however a bit small of pumping considerations. A 20 mm magnet gap is then foreseen in the bending magnets.
This gap gives a 50 mm magnet pole width to ensure a good field quality. If electromagnets are chosen, the total number off Ampere turns is 16000 which with a current density of 8 A/mm^2 gives the coil copper area of 1000 mm^2 (30*50 mm^2 coils including insulation and water channels) for each dipole coil. The C-type dipoles cores will then have a height of 200 mm and a width of 170 mm. Quite small indeed.
The power consumption is then 5.4 kW/magnet or a total of 330 kW (Less than MAX2 !)
The quadrupole magnets have a very high gradient of 37 and 32 T/m. With a 20 mm bore, the maximum field stays below 0.74 T and the maximum number of Ampere turns below 6000 AT. (A bit less than the MAX2 quads).
The total magnet consumption stays below 500 kW.
Another interesting alternative is to use permanent magnets for the lattice magnets. SmCo show little, if any degradation due to radiation. This alternative will be studied.

RF.
The RF system is built up in a modular way. 10 cavities operated at 100 MHz are fed by a 30 kW commercial FM transmitter each. The cavities are of the MAX3 type with a shunt impedance of 3.2 Mohm each (Linac definition)
The cavities are put in the short straight sections flanking the long straights. This modular system allows for some redundancy.

RF System:

RF	100 MHz
No of cavities	10
Total RF power	300 kW
Total RF voltage	1.4 MV
RF bucket half height	0.03
Total Synch rad losses	186 kW (9 undulators)
Cu losses	56 kW
Amplifier efficiency	68 %
Cavity shunt impedance	3.2 Mohm (Linac definition)
Cavity length	0.5 m
Cavity radius	0.4 m
Landau cav frequency	500 MHz
Landau cav shunt imp	6 MOhm
Landau cav power losses	13 kW
Total power needed	255 kW

Injection.
Injection will use one straight section. Four injection kickers are used to create a local bump. The remaining 9 straights can be used for insertion devices since the RF cavities go into the short straights.

Beam lifetime.

The RF system described above (without Landau cavities) will give a Touschek lifetime of 5.4 h (1/e time). The Landau system will increase the bunch length a factor of 3.5, which gives a Touschek lifetime of 19 h.
For the vacuum losses, we assume the same pressure as we have in MAX2 3) , $5*10^{-10}$ Torr at 200 mA for Z=7 molecules. This gives an elastic scattering lifetime of 52 h and a Bremsstrahlung lifetime of

144 h. We notice that we are still Touschek-loss dominated albeit the small gap of the insertion devices.

The total beam lifetime is thus 13 h at 200 mA. Since topping-up is foreseen, one injector pulse each minute with a charge of 0.15 nC will suffice to keep the circulating current constant within a factor of 10^{-3} .

Brilliance.

The graph below shows the brilliance envelopes for three different undulators on MAX4 and, for comparison, one of the present undulators on MAX2. The brilliance is calculated for the fundamental and up to the ninth harmonic and these points are then interconnected.

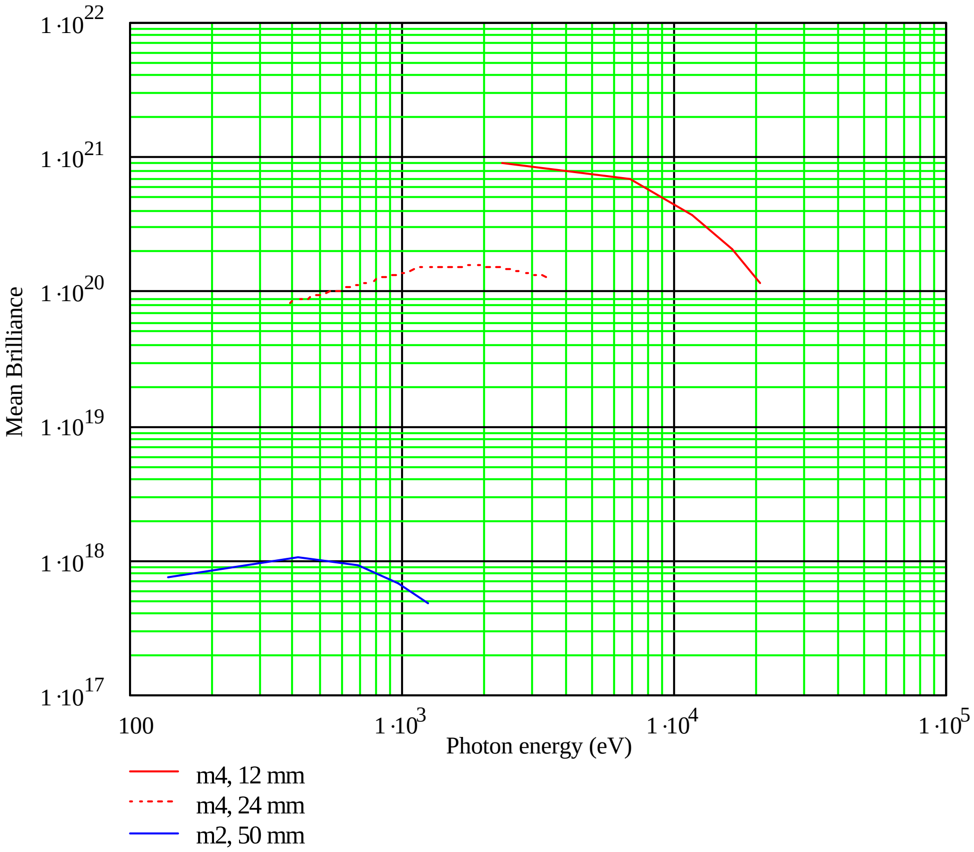

Fig. 3. Mean Brilliance for 2 undulators on MAX IV and one of the present undulators on MAX II.

The 3 GeV Injector microtron.

Introduction.

The injector could be built in several ways. A conventional 3 GeV synchrotron would cost some 70-100 MSEK as in the CLS case.
A 3 GeV linac is another interesting alternative. This linac will open up the possibility to produce high brilliance, short pulses of X-ray radiation. Complemented with a recirculating system and a superconducting (SC) linac, the energy recovery principle could be used to achieve a high mean brilliance. The price tag for such a system (1-3 GSEK) seems however prohibitive.
A much more interesting solution to a much lower price could be a 3 GeV microtron. A similar approach has been studied earlier at the Budker Institute of Nuclear Physics 4). A 500 MeV SC linac should in our case be recycled 6 times.
Besides being used as a 3 GeV injector, the microtron could also be used as a source for spontaneous radiation. The recirculating systems are separated by 70 m which gives ample space for undulators in the return paths. The photon spectral region goes all the way from UV up to 1Å.
The specifications for the microtron as an injector for the MAX4 ring are easily met. We will now concentrate on the possibility of using the injector microtron as a light source for spontaneous and coherent radiation.

Energy recovery.

In an energy recovery system, a SC linac is used to accelerate the electron beam. The beam is then cycled through a racetrack shaped ring and is then braked down to lowest possible energy in the superconducting linac. The electron energy is thus regained and only a fraction of the beam power needs to be supplied externally.

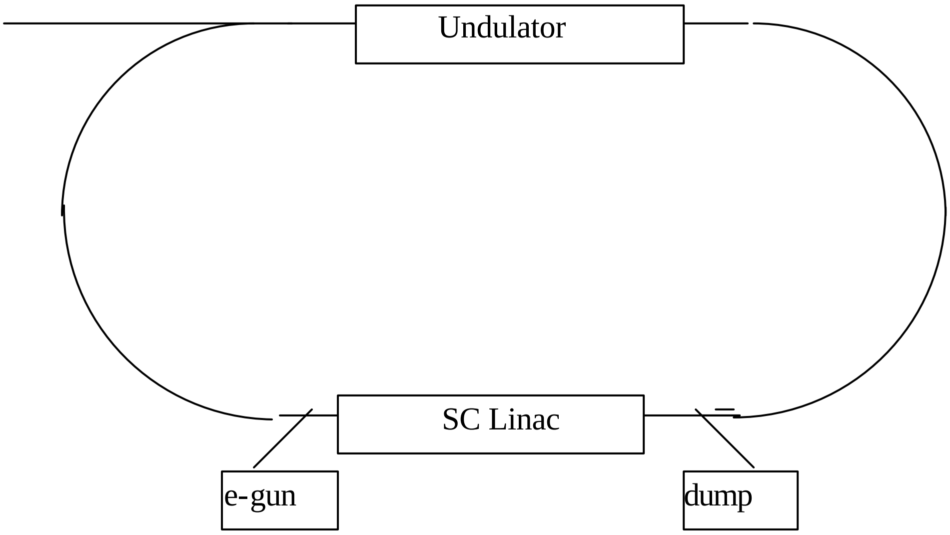

Fig. 4. Energy recovery principle.

The main argument for using an energy recovery system is that the duty factor and the average brilliance can be kept high.
Another argument is that the electron beam parameters are more easily controlled in CW operation.

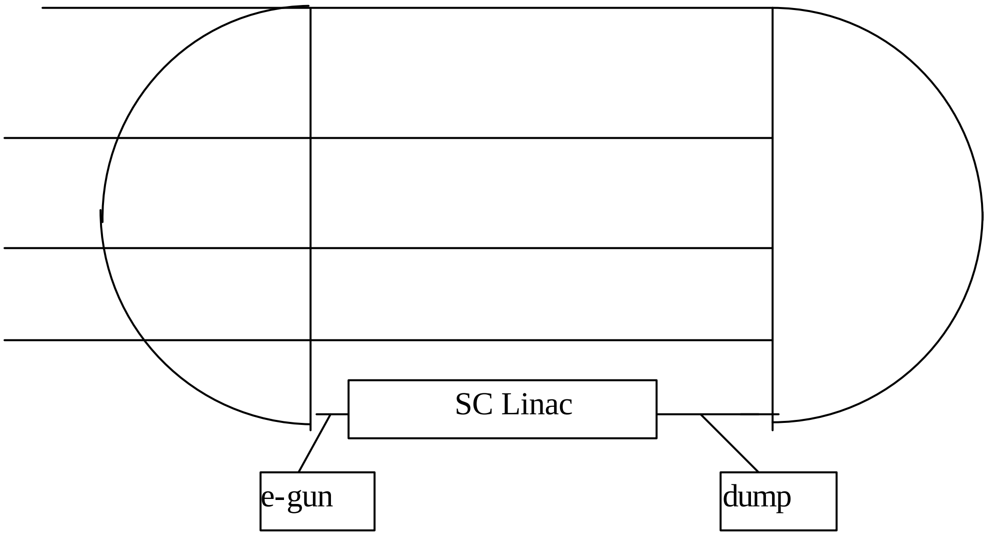

Fig. 5. Energy recovery microtron.

The race-track microtron is well suited for energy recovery. The electron beam path is increased one half RF-wavelength in the last orbit and is then decelerated through the microtron in all orbits and ends up in the beam dump.
The electron beam optics of this injector is intricate. The 180 ^{0} arcs must be close to isochronous and dispersion free. Some of the applications described below will call for a small equilibrium emittance which means zillions of magnets. Permanent magnet technology could be used in this context to keep the price tag low. (The ring described should maybe also be equiped with permanent magnets to increase reliability and to lower the capital as well as the running cost.) The radiation effect on the permanent magnets must however be closely examined.

Current and emittance considerations.

The laser induced RF gun offers a small normalised emittance at a given charge. A normalised emittance of 1 nC at 1 mm mrad normalised emittance is anticipated here.
The electron beam thermal emittance is proportional to the square root of the bunch charge. At higher bunch charges, nonlinear effects increase the emittance even further. This means that the brilliance is independent of the electron charge emitted down to the diffraction limit. At 1 Å and electron energy of 3 GeV, we reach a bunch charge of 4 pC. Using a 1.3 GHz RF system and an evenly filled bunch train, we end up with a circulating current of 5 mA.
Despite the low current, the spontaneous brilliance of the microtron equiped with 12 m long undulators is one order of magnitude higher than that from the MAX4 ring. This is due to the following reasons:

- The horisontal emittance is a factor of 100 smaller in the microtron case. The vertical emittance is about the same.
- Due to the smaller energy spread in the microtron case, much longer undulators can be used.

That's about the average spontaneous brilliance. With a pulse length of 1 ps, the peak brilliance in the microtron case is three orders of magnitude higher than the mean one. Additional pulse compression increases of course the peak value.
The real strong case for the microtron might well be when using it as a source for SASE FEL (or maybe even better an optical klystron) in the UV to soft X-ray spectral region. The microtron should

then be equiped with a fat bunch electron gun running at lower rep rate besides the one used for spontaneous radiation.

Main microtron parameters.

The parameters of the case studied here:

Max electron energy	3 GeV
Circulating current	5 mA
Nr of circulations	6
Linac frequency	1.3 GHz (TESLA type)
Linac energy	500 MeV (15-20 MeV/m)
Cryo losses	1 kW at 2K and 100 % duty-factor
Photon energy range	100 eV-12 keV
Electron pulse length	100 fs-1 ps
Peak spont. brilliance	up to10^{25} (depending on photon energy)
Peak coherent brilliance (cascaded optical klystrons)	up to 10^{28}
Mean spont. brilliance	up to a few times 10^{21} (depending on photon energy)
Size (including beam-lines):	150*40 m^2
Price (naked machine)	100-200 MSEK
Power consumption	20 kW (RF)+ power for ev electromagnets and cry cooling.

Comparison MAX4-Injector.

The brilliance curves for the two machines are seen below. The effect of the smaller emittance in the microtron makes the microtron more powerful at shorter wavelengths. At somewhat longer wavelengths, also the MAX4 ring tends to be diffraction-limited and the effect of the higher current shows up.

Not shown in the diagram is the peak brilliance. A few things should be remembered here:

1. The peak brilliance is three orders of magnitudes higher than the mean one in the microtron case for short wavelengths. In the MAX4 case, the peak brilliance is two orders of magnitudes higher than the mean one.
2. The microtron peak current can be increased for longer wavelengths and the radiation still being diffraction-limited. This will give another order of magnitude higher brilliance.

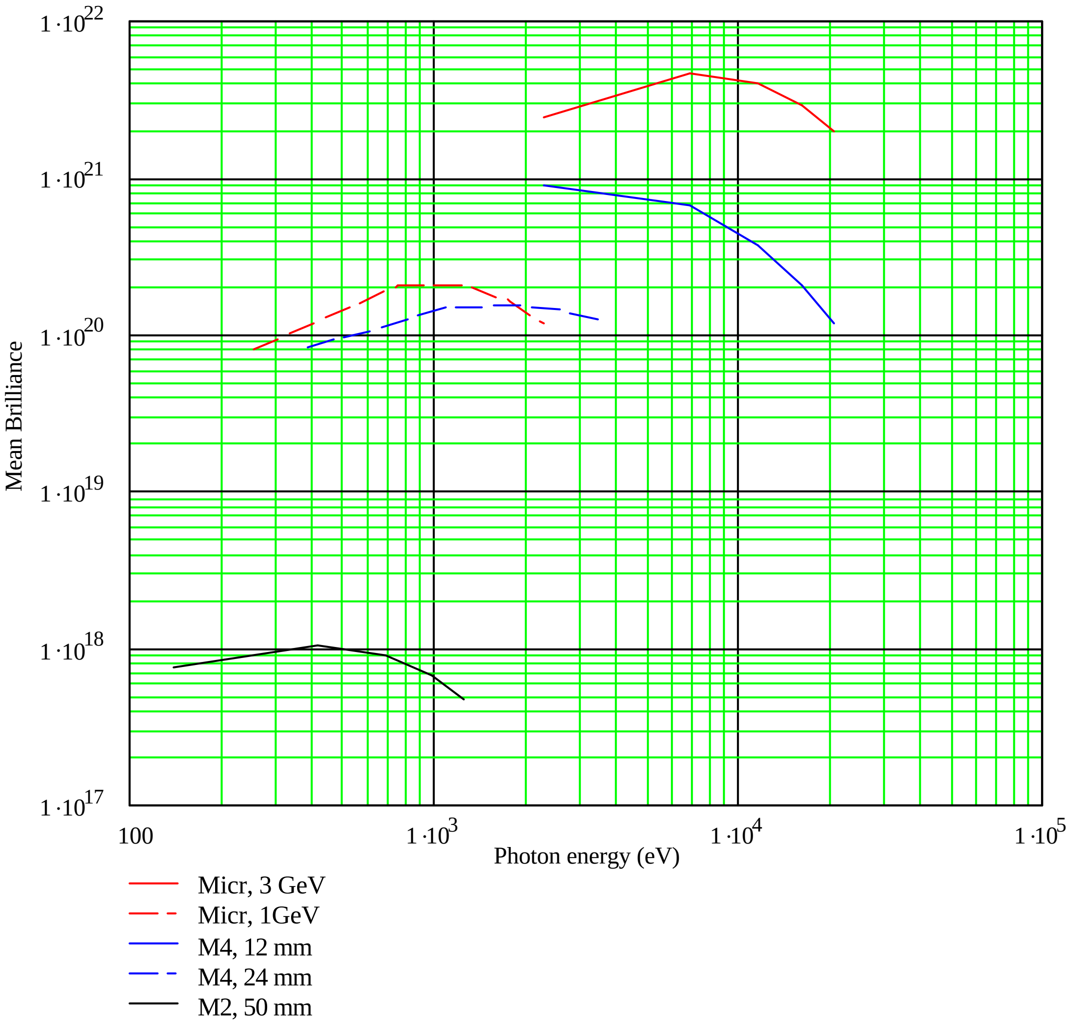

Fig. 6. Brilliance for the microtron, MAX4 and MAX2.

Limits.

Emittance and energy spread.
The state of the art RF guns deliver 1 nC with an emittance of

$$ge = 1*10^{-6}\left(radm\right)$$

The emittance is scaling (conservatively) like the square root of the charge. To reach the diffraction limit at 12 keV radiation we get a charge of 4 pC. This argument gives the 5 mA circulating current.
The emittance can also blow up due to synchrotron radiation emittance. The following argument is used:
If a beam of small emittance is injected into a storage ring the emittance will grow asymptotically towards the equilibrium emittance with a time constant given by the damping time. This argument gives the emittance dilution for one turn:

$$\Delta e = e_0 * \frac{\Delta E}{2E}$$

Where ε_0 is the equilibrium emittance and ΔE is the energy loss per turn.

Plugging in a hotted MAX II lattice for the last circulation turn, we see that the emittance growth due to synchrotron radiation is small. Some care must however be taken to the design of the lattice so the dipole magnets can not exceed a length of 0.8 m or so.
Attention must also be paid to the longitudinal emittance. This could be an argument to reduce the magnet field level.

Recovery efficiency.

Hard to foresee. Let's assume that we brake the electron down to 2 MeV. The losses are then 10 kW. These losses will in fact define the maximum mean circulating current.

The modular optical klystron.

If we populate all the buckets in the racetrack microtron, the electrons on the return orbits will merge together on the linac axis and will form macro bunches where all electron energies of the return orbits will be represented. This feature offers an elegant opportunity to construct a modular cascaded optical klystron 5) on the linac axis.
The first optical klystron is seeded with an HG "conventional" laser with a photon wavelength of 2000 Å. The buncher of the first optical klystron is tuned to the laser wavelength for the 500 MeV part of the macro bunch. The radiator of the optical klystron is tuned to the fifth harmonic; so we generate Fourier transform limited radiation of 400 Å from the 500 Mev bunched electrons.
The 400 Å radiation seeds the next optical klystron, the buncher of which is tuned to 400 Å for the 1 GeV part of the macro bunch. The radiator is again tuned to the fifth harmonic which seeds the next optical klystron giving 80 Å radiation. The third OK gives 16 Å radiation and the fourth 3.2 Å. The fifth OK is working on the third harmonic and we reach thus 1 Å Fourier transform limited coherent radiation.

Other comments:

The scaling of the gun emittance is a most important issue. Some people claim that the emittance is scaling faster than the square root of the bunch current. This would open up the possibility to operate the linac with a lower duty-factor, which implies a smaller cryocooling device. If we assume 10% duty-factor wee need to cool 100 W at 2 K instead of 1 kW. Another consequence is that 20% duty factor guns do exist today, even if they are big beasts.

Magnets.

It's very tempting to use permanent magnets for the recirculating arcs. The cross section will then decrease to some dm^2 and the quad strengths will be some 50-70 T/m (MAX II: 20 T/m) Generally SmCo magnets are used for linac undulators since they stand higher radiation doses.

SASE FEL.

Probably very tempting, especially at lower photon energies (UV-soft X-ray). The third harmonic could be used at 3 GeV to reach 12 keV (HGHG), with a potential to gain another two-three orders of magnitude in brilliance.

References:

1. Rossmanith et al
2. MAX3 design report
3. Erik Wallén et al, MAX2 vacuum
4. G. N. Kulipanov, A. N. Skrinsky and N. A. Vinokurov, MARS-a project of the diffraction-limited fourth generation X-ray source based on a supermicrotron, NIM A-467-467 (2001) 16-20
5. Sandra Biedron, Toward Creating a Coherent Next-Generation Light Source, Thesis, Lund 2001.