MODELING A TABLE TOP STORAGE RING FOR A COMPACT LIGHT SOURCE USING ELECTROMAGNETIC FIELD SIMULATION TOOLS*

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Abstract

Large synchrotron radiation facilities have become one of the most powerful instruments for research today. All over the world new facilities are being constructed or designed. The biggest disadvantage of a large synchrotron facility is that the scientific experiments, which are often very sensitive and complex, have to be performed in a dedicated place, sometimes far away from the researcher's home laboratory. Promising compact synchrotron radiation sources, that fit in a typical research lab, have been proposed recently [1, 2, 3, 4].

In this paper results are presented of an initial study of a single body magnet, low electron energy storage ring, performed with the Finite Element (FE) and Finite Difference Time-Domain (FDTD) modeling possibilities in the CST Studio Suite 2010 software package. Insights were obtained for the most crucial components: the magnet yoke, the internal RF cavity and the resonance injection component. Finally, the model of the storage ring was verified using the particle tracker solver which tracks the injected electrons along the ring.

INTRODUCTION

The construction of new synchrotron radiation facilities such as SOLEIL (France), DIAMOND Light Source (UK), MAX IV (Sweden), National Synchrotron Light Source II (USA) and upgrades on existing facilities such as PETRA III (Germany), European Synchrotron Radiation Facility (France), Australian Synchrotron (Australia) confirm the demand for high power X-ray, UV and IR radiation facilities for multidisciplinary research. Unfortunately these facilities have some disadvantages:

- Sensitive and complex experiments have to be moved to locations far from the researchers home laboratory.
- Operation under well occupied User-Facility Programs complicates non-standard experiments and restricts the availability of beam time.
- Construction costs and the size of synchrotron radiation facilities are huge.

For these reasons scientists and engineers have been looking for compact light sources that fit in a typical laboratory. Different types of compact light sources were designed and built in the past [5], but many of these attempts failed due to design limitations or radiation yield and radiation energy problems.

The compact light source MIRRORCLE, proposed by Japanese scientists [1], consists of a low energy microtron and a storage ring. In the microtron, electrons emitted from a typical LaB_6 emitter, are accelerated by repeatedly passing through an RF cavity, while circulating in ever larger orbits under the influence of a constant magnetic field. Reaching the design energy of several MeV, the electrons are continuously injected into the storage ring with a maximum injection rate of 400 Hz, a peak injection current of 100 mA and a 0.1 μs gate width. Under the influence of a constant magnetic field, created by conventional electromagnets, eight bunches of electrons orbit in the storage ring at a radius of 0.156 m, emitting synchrotron radiation in the far infra-red spectrum (FIR). By inserting appropriate wire targets (only 10 μm thick) EUV, soft X-ray and hard X-ray spectra can be obtained through bremsstrahlung, OTR, PXR or channeling radiation. Because of the target thickness (10 μm), interacting electrons will not get lost and can therefore be reused after reacceleration to the nominal energy in an RF cavity. During injection, an injection device is needed to guide the injected electrons to their stable orbit.

This paper presents results on an initial design of the magnet yoke, the resonance injection device and the RF cavity. Injected electrons are also tracked in order to verify the model of the storage ring.

MAGNET YOKE

Consider a natural right handed coordinate system $K = (x, z, s)$, with s in the direction of the reference particle orbit, x the horizontal displacement, and z the vertical displacement relative to the reference particle orbit. Since half integer resonance injection will be used to inject the electrons from the microtron into the storage ring, the horizontal betatron oscillation tune Q_x is required to have a value close to 0.5. In this study the value of Q_x is 0.529, as can be found in literature [6]. Hereby the value of the field index n and the vertical betatron oscillation tune Q_z is defined (Eq. 1, 2) [5] to be $n = 0.72$ and $Q_z = 0.849$.

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$$Q_x = \sqrt{1-n} \quad (1)$$

$$Q_z = \sqrt{n} \quad (2)$$

The vertical magnetic field component B_z can then be described as a function of the radial displacement from the reference particle orbit (Eq. 3, 4).

$$n = -\frac{R_0}{B_z(0)}\frac{\partial B_z(x)}{\partial x} \quad (3)$$

$$B_z(x) = B_z(0) + \frac{\partial B_z(x)}{\partial x}(x - x_0) \quad (4)$$

R_0 is the radius of the reference particle orbit, $B_z(x)$ is the magnetic field in the z direction at position x.

Using optimization tools available in CST Studio Suite 2010, a yoke shape was modeled by rotating a polygonal profile to obtain this magnetic field gradient. The slope of the pole shoe was created by optimizing the position of four points in the x,z-plane of the storage ring, connected to each other with straight lines (figure 1). A similar optimization was done for a yoke shape modeled by rotating a spline profile, which was less successful.

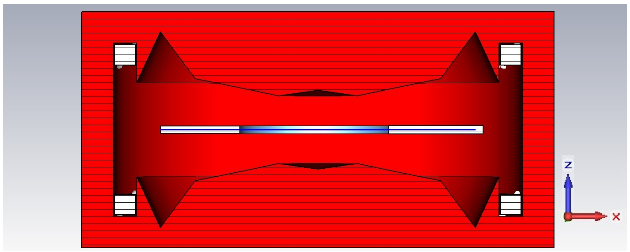

Figure 1: Cross section of the storage ring in the x,z-direction showing the yoke shape needed for the magnetic field gradient.

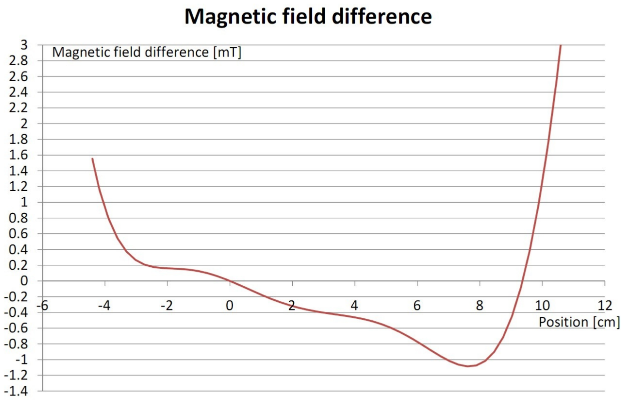

Figure 2: Difference between the theoretically calculated magnetic field and the simulated magnetic field.

The accuracy of the magnetic field is shown in figure 2. At the reference particle orbit the magnetic field equals the theoretical magnetic field. Within a radius of ±3 cm, which is the region of interest, the maximum magnetic field deviation is only 0.4 mT, or 0.3 % (Given $B_z(0) = 128.205$ mT).

As a yoke material, iron with a linear magnetization curve was used. Simulations with iron with a nonlinear magnetization curve showed local deviations in the order of 0.5 mT in the particle circulation area of the storage ring. The nonlinear simulations took 1200 times more computation time, although the result was only marginally different. Because the deviation did not influence the particle tracking results, they were not further considered in this stadium of the study. The inserted aluminium or iron beam ports locally reshape the magnetic field distribution in the iron yoke, but do not influence the magnetic field in the particle circulation area of the storage ring.

RESONANCE INJECTION DEVICE

It is not possible to reinject particles into an already occupied volume of phase space, without losing the particles already present [7]. Because of the small diameter of the storage ring and a bunch interval of less than 1 ns, using a kicker for injection is not possible without losing the beam. Therefore a different approach, called half integer resonance injection, is applied. The horizontal betatron oscillation tune Q_x is altered to 0.5, which causes the phase space to be enlarged and injected electrons with large excursions from the ideal particle orbit can be accepted. The new electrons will spiral towards the ideal particle orbit. Once arrived there, the resonance condition has to be removed slowly (100 ns).

The injection device [8] is an aluminium or copper structure (figure 3), which produces an additional magnetic field of 30 mT in a part of the storage ring, by applying a current pulse between the central conductors (1) and the external structure (2). The shape of the injection device assures that the magnetic field in the proximity of the ideal particle orbit remains unchanged, while the magnetic field further away from the ideal particle orbit is altered to achieve the half integer resonance condition.

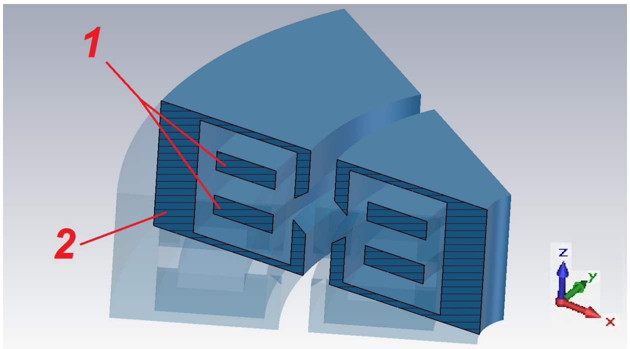

Figure 3: Injection device, consisting of central conductors (1) and an external structure (2).

The magnetic field distribution of the modeled storage ring and the injection device, both calculated with CST Studio Suite 2010, were superimposed using software developed in-house. The strength and duration of the magnetic field pulse of the injection device, and the particle injection position and angle could also be optimized with this software. Finally electrons were tracked throughout the storage ring, successfully achieving half integer resonance injection (figure 4).

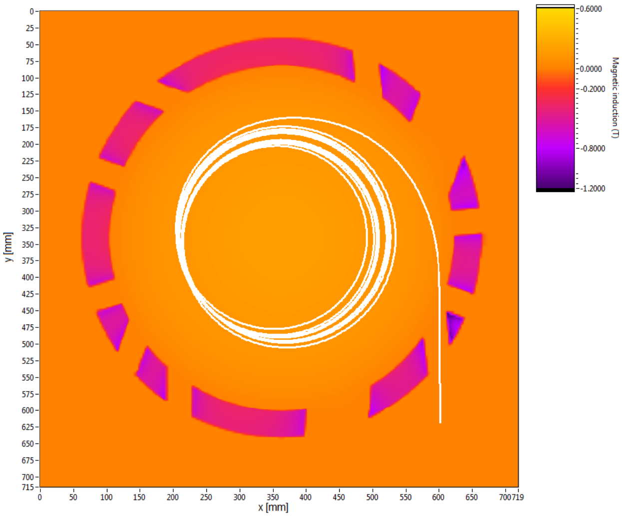

Figure 4: Successful beam injection in the storage ring.

RF CAVITY

A cylindrical and a rectangular RF cavity, operating at 2.44 GHz, were designed to reaccelerate and rebunch particles that have interacted with the target. The rectangular design was chosen because of its larger horizontal particle acceptance. Suitable dimensions for the rectangular cavity operating in the TM_{110} mode can be calculated using eq. 5 [7], with λ_r the resonant wavelength, m, n and q integers corresponding to the used mode ($(m, n, q) = (1, 1, 0)$) and a, b and l respectively the width, height and length of the cavity.

$$\lambda_r = \frac{2}{\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{q}{l}\right)^2}} \tag{5}$$

The length l does not influence λ_r since $q = 0$, and was set to half the resonant wavelength (0.061 m), according to [9]. At relativistic energies the reduction in efficiency due to the transit-time factor ($\Gamma = 0.634$) is then acceptable. The width a was set to 0.140 m to preserve the horizontal particle acceptance. Using equation 5, the cavity height b will be 0.0684 m, allowing it to fit inside the magnet yoke. A window with a width of 0.100 m and a height of 0.0072 m was added at both sides of the cavity to obtain a realistic particle acceptance.

After adjusting the acceleration voltage and phase to the optimal values, particles that had lost up to 120 keV due to interactions with the target could be reaccelerated to 6 MeV, without getting lost in the storage ring.

CONCLUSIONS

The magnet yoke was designed by rotating a polygonal profile, obtaining a deviation of only 0.4 mT (0.3 %) from the theoretical magnetic field, in the region of the ideal particle orbit ±3 cm. The inserted aluminium or iron beam ports locally reshape the magnetic field distribution in the iron yoke, but do not influence the magnetic field in the particle circulation area of the storage ring.

Using in-house software to determine appropriate injection device settings, beam injection position and angle, half integer resonance injection was successfully obtained for the designed storage ring.

A rectangular RF cavity was designed to reaccelerate and rebunch particles who lost up to 120 keV due to interaction with the target, without losing them in the storage ring.

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