A Superconducting Short Period Undulator for a Harmonic Generation FEL Experiment*

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Abstract

A three stage superconducting (SC) undulator for a high gain harmonic generation (HGE) FEL experiment in the infrared is under construction at the NSLS in collaboration with Grumman Corporation. A novel undulator technology suitable for short period (6-40mm) undulators will be employed for all three stages, the modulator, the dispersive section and the radiator. The undulator triples the frequency of a $10.4\mu m$ CO_2 seed laser. So far a 27 period (one third of the final radiator) prototype radiator has been designed, built and tested.

1 Introduction

Short period undulators for Free Electron Laser (FEL) applications offer the advantage of producing shorter wavelength radiation with a given electron energy. The design and theory of the seeded single pass harmonic generation UV-FEL has been described elsewhere [1]. As a proof-of-principle a harmonic generation FEL experiment in the infrared has been designed [2] to be carried out at the accelerator test facility (ATF) at BNL. The fully constructed undulator for this experiment consists of three stages, the modulator, the dispersive section and the radiator, all superconducting. The radiator is tuned to the third harmonic of the modulator. We plan to amplify the third harmonic of a $10\mu m$ CO_2 laser with a 30MeV high brightness electron beam from a laser-photocathode rf gun injected into a 50-100MeV S-band linac. The modulator (12 periods, 2.60cm, 0.81T) causes an energy modulation in the electron beam. This energy modulated beam gets spatially bunched in the tunable dispersive section (12cm long, 0.3-1.2T). Finally, energy is extracted from the coherently bunched beam in the radiator (84 periods, 1.80cm, 0.54T), where radiation will be amplified exponentially. The last part of the radiator will be tapered. A schematic diagram of the harmonic generation experiment is shown in Fig.1.

The undulator design allows implemention of several features which are essential for single pass high power FEL amplifiers at shorter wavelenghts such as 1) high magnetic field on axis at short periods, 2) convenient K-tuning, 3) adjustable dispersion, 4) adjustable field taper, 5) two-plane focusing and 5) field amplitude errors at or below the state of the art $0.2 - 0.3\%$ rms as machined which is needed to minimize electron beam trajectory walk-off.

2 Basic Undulator Design

The basic design of an undulator section magnet has been discussed elsewhere for a 0.88cm period planar undulator [3]. Here we use the same approach. It is based on precision machining a sequence of poles and grooves on a bar of low carbon steel. A field uniformity of $\Delta B/B \simeq 0.1\%$ as manufactured, without trimming or shimming of individual undulator elements requires machining tolerances within $10\mu m$ for the periodicity and the gap spacing. The design can easily be modified for different undulator geometries, namely the periodicity and the pole shape geometry. Basically the same design is used for the modulator, the dispersive section and the radiator. The coils are continuously wound in several layers with multifilamentary NbTi conductor on the machined form of an undulator section magnet. Two 25.2cm long section magnets for the HGE radiator are shown in Fig.2. The poles are parabolically shaped to provide focusing in the wiggle plane [4]. The full gap in the center is 8.0mm and the curved pole geometry is truncated into a flat pole at $x = \pm 3.0mm$ and

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a 6.0mm full gap to accommodate microstriplines later on.

The full length undulator is made up of discrete magnet sections shown in Fig.2. The magnet sections are assembled end-to-end but otherwise continuous over the entire length both for the modulator (2 sections, each 15.60cm long) and the radiator (6 sections, each 25.20cm long). There are no axial drift spaces other than those between the dispersive section and the modulator and the radiator respectively. This situation avoids the tuning of drift spaces to match the phase angle. Electron beam steering coils (providing a field integral of 300G-cm and 100G-cm for horizontal and vertical steering respectively) are mounted outside the beam pipe and are spaced with an even number of poles in regular intervals to control the electron beam walk-off to within $\pm 40\mu m$ (2/10 th of the beam radius).

The magnetic field of the radiator is quadratically tapered. The taper can be approximated in six flat steps without a compromise in the FEL power performance. The taper profile will be adjustable through 'bleed-off' currents in the six tapered sections using the power supplies $PS_D - PS_H$ shown in Fig.3. The entrance and exit of each undulator stage as well as the five field taper transitions have a binomial current excitation pattern, which satisfies the nonsteering condition [5]. Field clamps at the undulator ends are used to control the fringe fields.

A non-magnetic steel (nitronic 40) fixture provides sufficient clamping of the section magnets shown against a gap defining precision "spacer". After the full-length assembly of the cold mass it will be inserted into a 2.50m long horizontal cryostat. The magnet structure is of the cold bore, cold yoke type and is cooled by pool boiling helium at 4.4K. The position of the undulator magnet relative to a straight line reference can be controlled with an adjustable suspension system after cooldown. Electron beam diagnostics from stripline monitors is available at the entrance and exit of the cold mass assembly.

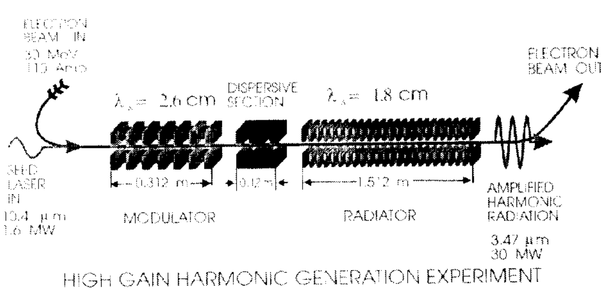

Figure 1: Schematic diagram of the HGE experiment.

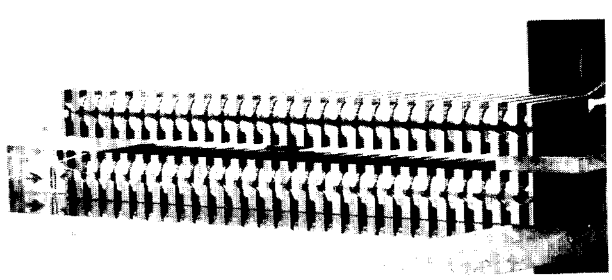

Figure 2: Two 25.2cm long SC undulator magnets for the HGE radiator. The period is 1.80cm.

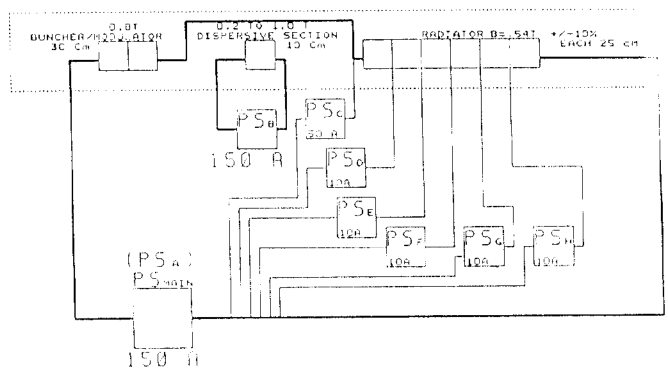

Figure 3: Magnet power for the three undulator stages. The field taper in the radiator is done with the power supplies $PS_D - PS_H$.

3 Experimental Results

So far our work has concentrated on the performance of a 0.5m long prototype radiator undulator (27 periods). Proven features include a suitable conductor, the field level on axis, the field profile, the field quality and the related machining tolerances. The magnetic measurements and additional results are discussed in [6].

FIELD ON AXIS: Quench stability limits the highest possible current in a SC magnet. We tested radiator sections with two different conductors (conductor I: Cu/SC=1.3:1, conductor II: Cu/SC=2.4:1). The quench current for the HGE radiator sections shown in Fig.2 was $I_q = 200 \pm 5A$ and $I_q = 170 \pm 3A$ for conductor I and II respectively. Both results agree within 5% with predictions from the load curve analysis which uses measured "short sample" critical data. The field on axis (full gap g(x=0)=8.0mm, λ_w=18.0mm) as a function of current (for conductor II) is shown in Fig.4. The HGE design field is 0.54T. At 150A (10% below I_q) the field on axis is 0.72T. For comparison, the field for a Nd-Fe-B hybrid undulator would be 0.46T (Halbach formula). In Fig.4 the excitation data for parabolic shaped poles are compared to 2D POISSON calculations where a flat pole approximation at a 8.0mm full gap has been used.

FIELD PROFILE For the proper matching of the magnetic field at the undulators ends the non-steering current excitation pattern 1:3:4 is used [5]. The same pattern is used for the mixing of the currents I_n and I_{n+1} at the taper transitions n=1-5. The taper currents $I_D - I_H$ will be adjusted for a 10% quadratic field taper.

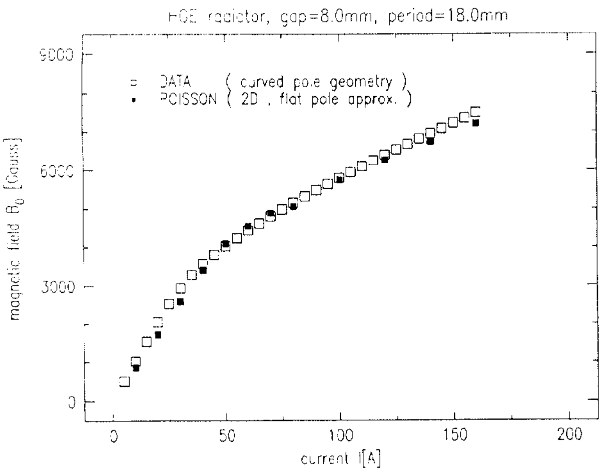

Figure 4: Excitation curve for the HGE radiator. The operating field is 0.54T. The quench current is 170A (conductor I) and 200A (conductor II).

For horizontal focusing the iron poles are parabolically shaped. The half gap dependence is $y(x) = 4.0mm \cdot (1 - a\,x^2)$ with a=0.028 for $-3mm \leq x \leq 3mm$ and y=3.0mm elsewhere (z is the beam axis, y is normal to the x-z wiggle plane). The measured transverse field profile is $B_y(x) = B_0 \cdot (1 + b\,x^2)$ where b=0.021 at low currents (Fig.5). This value decreases by about 17% at the operating current (I=90A). This change with saturation is in agreement with 3D TOSCA calculations. The truncation of the pole curvature to a 6mm full gap in the flat pole region limits the transverse field increase. TOSCA predicts that for equal natural x and y undulator focusing the pole curvature should be a=0.033. The cold measurements are done using a multiple Hall-probe setup which is calibrated in-situ with a pair of Helmholtz coils [6].

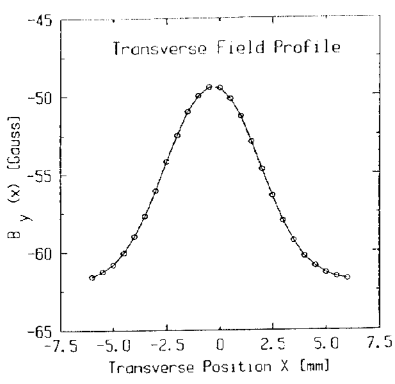

Figure 5: Room temperature measurement (I=0.5A) of the transverse field profile. The data agree with 3D TOSCA calculations.

FIELD QUALITY In a first step we analyze the beam trajectory (second field integral) for individual undulator sections (Fig.2). Independent of the field on axis (i.e. of saturation, Fig.4), the trajectory remains within $\pm 20\mu m$ [6]. No trimming fields or shimming corrections have been applied. This result is obtained although 10% of the iron poles have been identified with machining errors in the pole width a factor 6-7 beyond the required mechanical tolerance of $10\mu m$. These large errors are understood and have been removed in the machining of new sections.

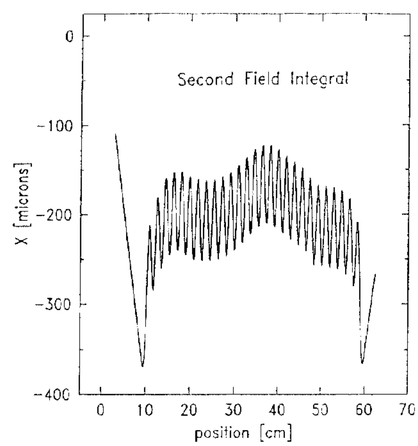

Figure 6: Beam trajectory from magnetic measurements (I=50A) of a 27 period radiator undulator.

In a second step a 27 period prototype radiator (two sections) has been tested. Now the trajectory for a 30MeV beam wanders $\pm 35\mu m$ (Fig.6). The deflection in the center is probably due to the identified machining error of the half poles at the joint combined with a clamping error between both sections beyond the $10\mu m$ gap tolerance. The rms peak field variations for the first (second) section was 0.22% (0.29%) (poles with large identified machining errors not included). The steering coils to control the electron beam to within $\pm 40\mu m$ are conservatively designed.

The basic magnetic unit for the HGE undulator has been developed. As machined this SC undulator technology provides the field performance needed for high power single pass FEL applications. It allows complex multi-stage undulators with cw operation. Important parameters can conveniently be changed during operation.

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