Initial Design of the Advanced Gradient Undulator

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High Efficiency FEL Workshop
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Project Structure

- Small Business Innovation and Research project through the Department of Energy, Basic Energy Science.
- Results here are a partial summary of the Phase I project.
- Phase II was awarded on Monday. (Yay!)
- Phase I Participants:
  - RadiaBeam: Finn H. O’Shea and Alex Murokh
  - SLAC/UCLA: Claudio Pellegrini and Claudio Emma
  - Argonne: Yuri Ivanyushenkov and Efim Gluskin

UCLA SLAC NATIONAL ACCELERATOR LABORATORY Argonne NATIONAL LABORATORY

Ultimate Goal

- Turn a table of simulation parameters in to a prototype undulator and eventually an FEL.

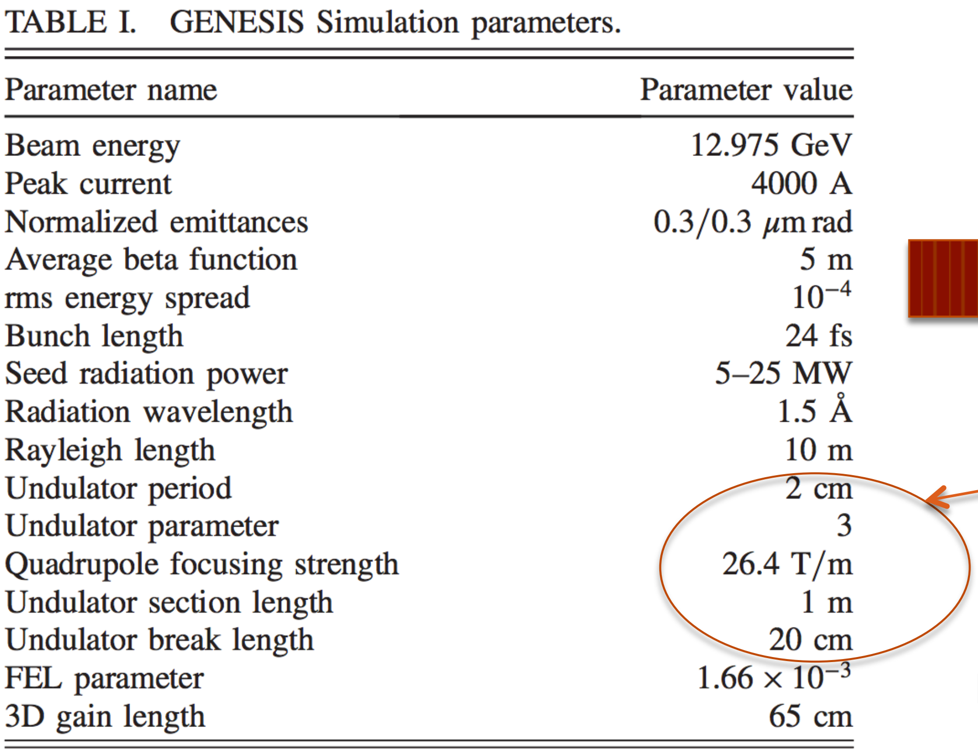
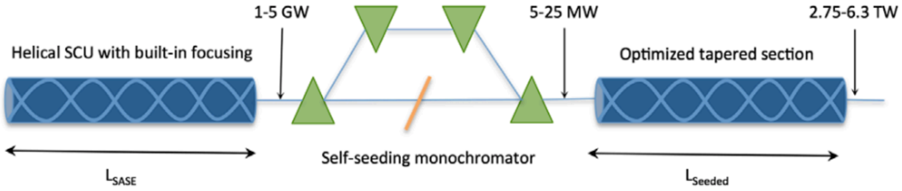


TABLE I. GENESIS Simulation parameters.

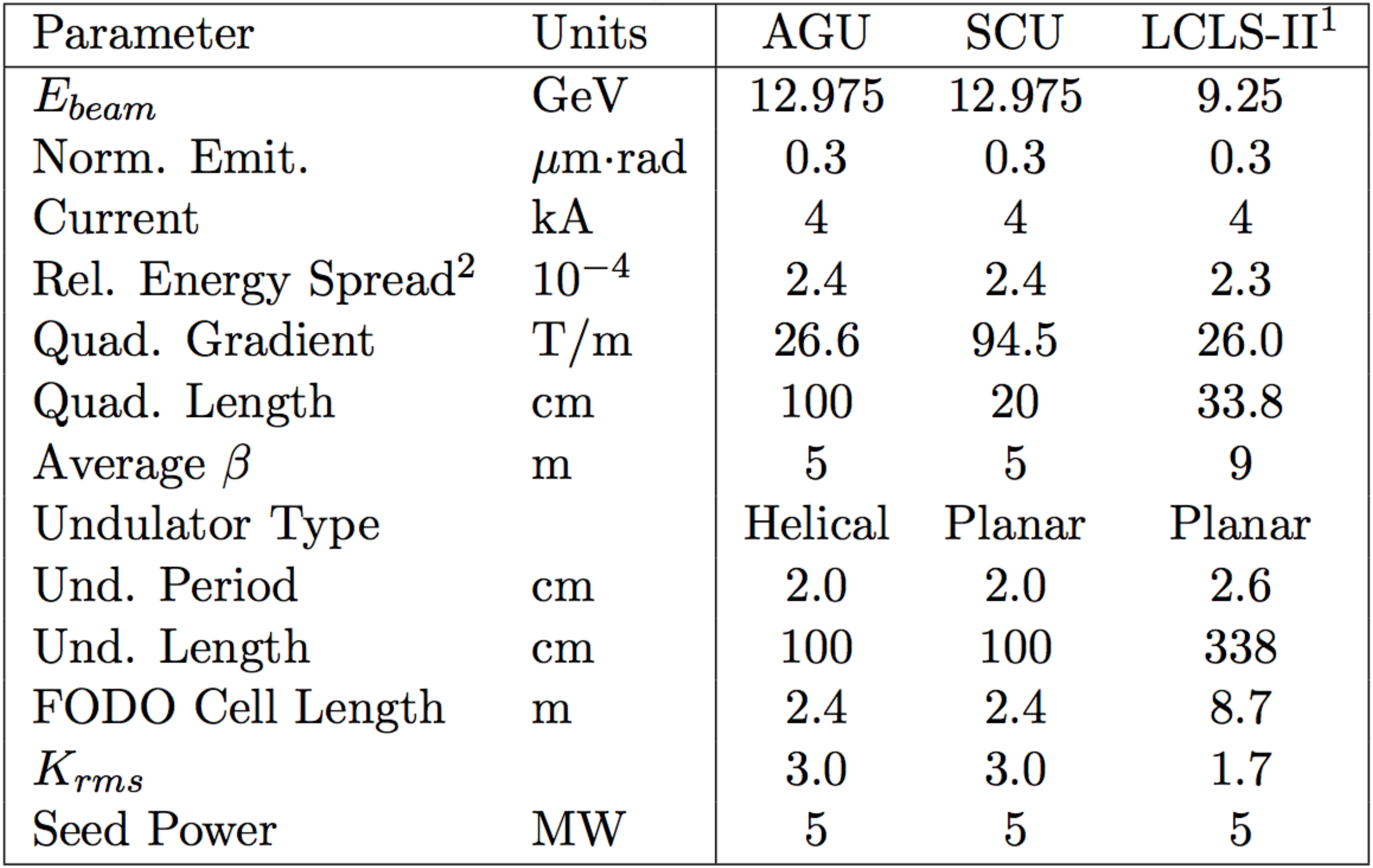
Parameter name	Parameter value
Beam energy	12.975 GeV
Peak current	4000 A
Normalized emittances	0.3/0.3 μm rad
Average beta function	5 m
rms energy spread	10^{-4}
Bunch length	24 fs
Seed radiation power	5–25 MW
Radiation wavelength	1.5 Å
Rayleigh length	10 m
Undulator period	2 cm
Undulator parameter	3
Quadrupole focusing strength	26.4 T/m
Undulator section length	1 m
Undulator break length	20 cm
FEL parameter	1.66×10^{-3}
3D gain length	65 cm

C. Emma, *et al.*, PRAB 19, 020705 (2016).

Focus on these parameters.

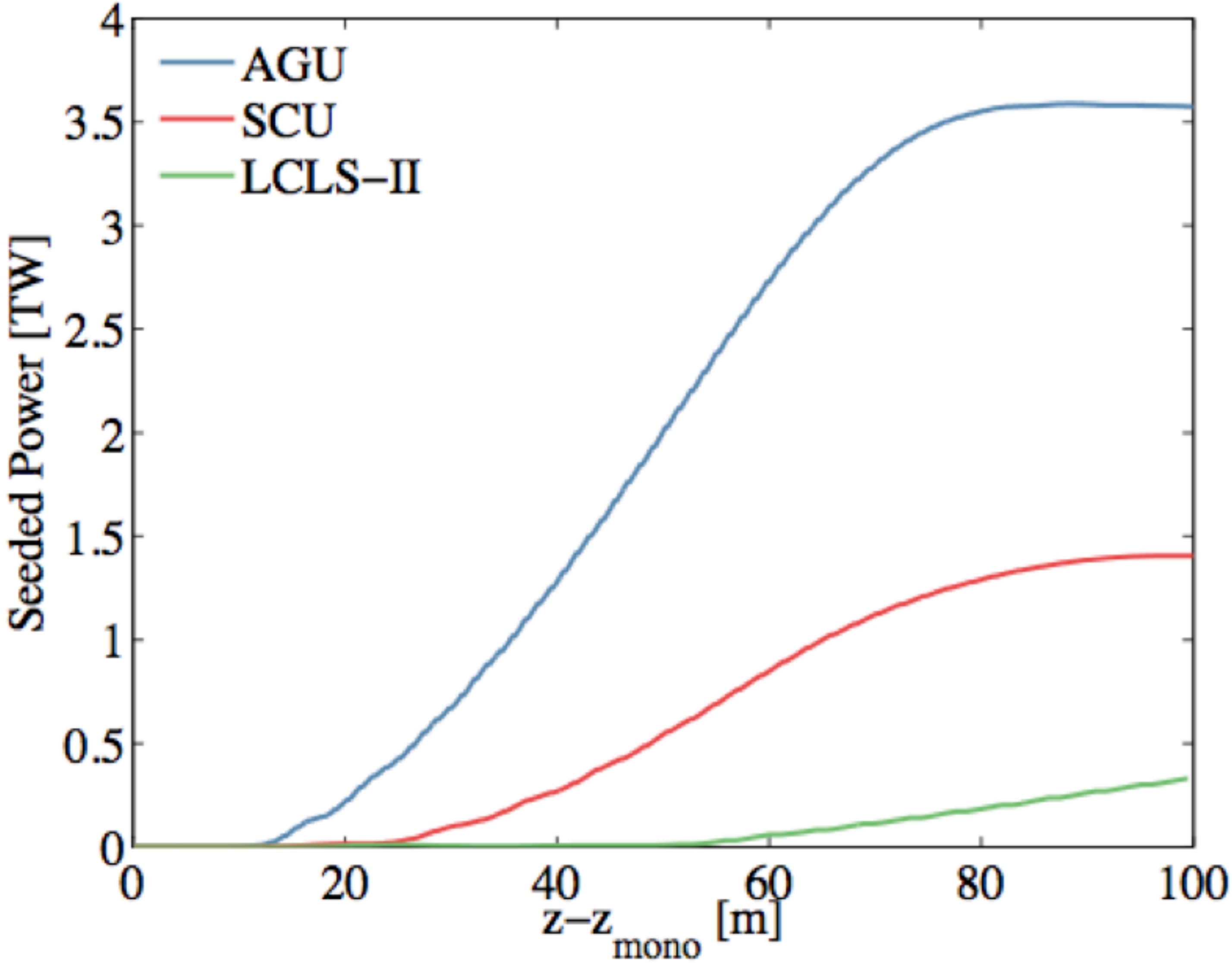


AGU Motivation - 1



Parameter	Units	AGU	SCU	LCLS-II[1]
E_{beam}	GeV	12.975	12.975	9.25
Norm. Emit.	μm·rad	0.3	0.3	0.3
Current	kA	4	4	4
Rel. Energy Spread[2]	10^{-4}	2.4	2.4	2.3
Quad. Gradient	T/m	26.6	94.5	26.0
Quad. Length	cm	100	20	33.8
Average β	m	5	5	9
Undulator Type		Helical	Planar	Planar
Und. Period	cm	2.0	2.0	2.6
Und. Length	cm	100	100	338
FODO Cell Length	m	2.4	2.4	8.7
K_{rms}		3.0	3.0	1.7
Seed Power	MW	5	5	5

AGU Motivation - 2

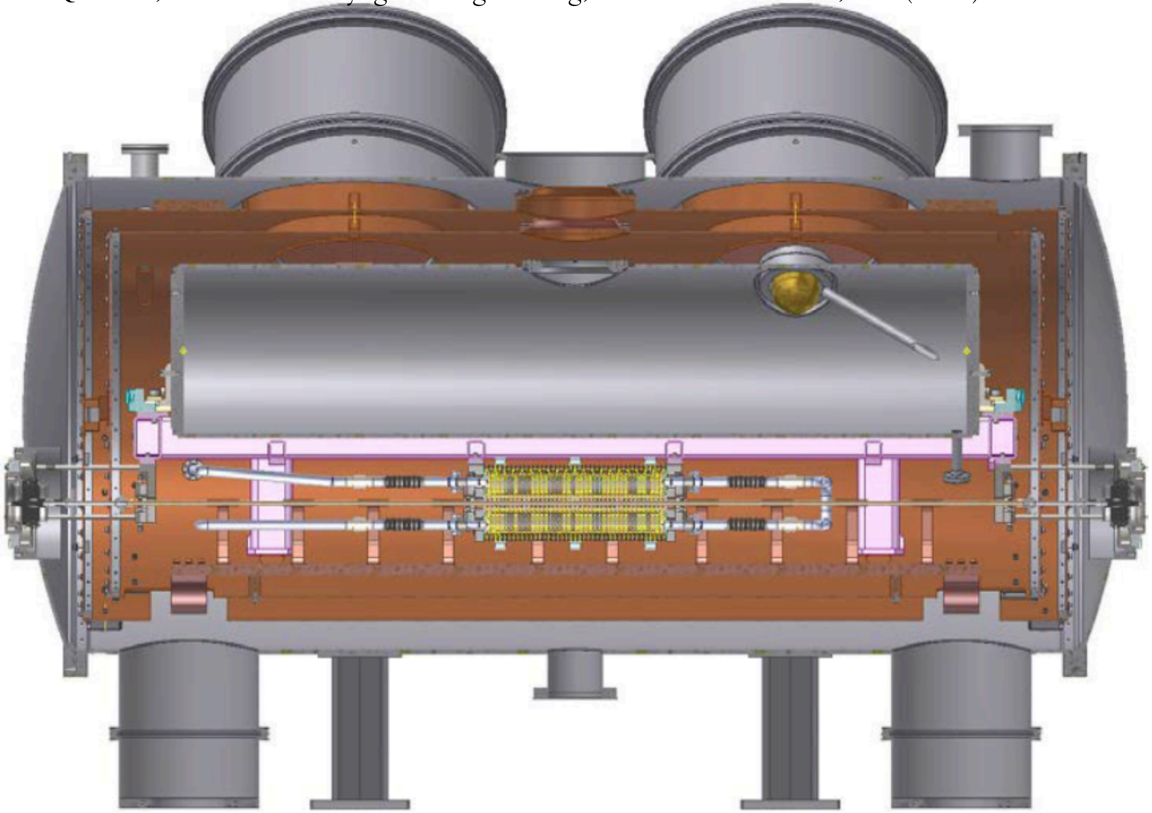


Phase I Goals

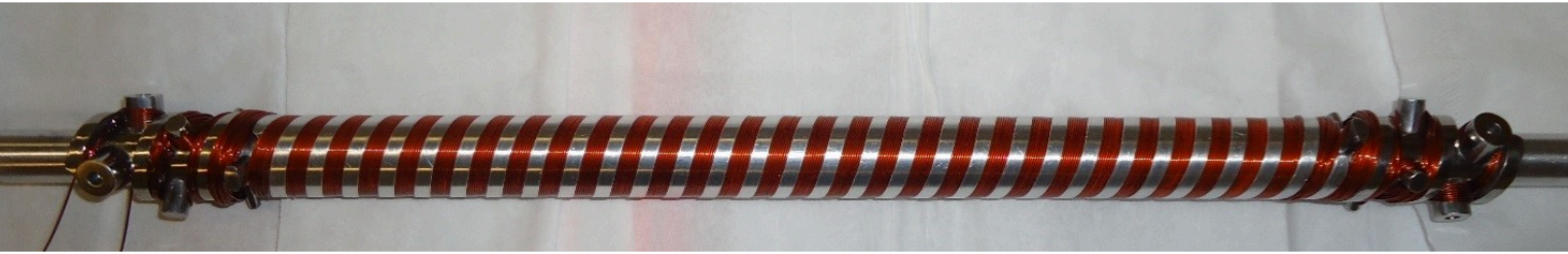
- Define the AGU Undulator features: wire type and current, winding pattern, initial thermal considerations.
- Define high-level tolerances for the undulator.
- Target the LCLS-II HE upgrade within DoE Basic Energy Science.
- Why superconductors?
  - Recent work has shown better performance at short period than permanent magnet solutions. J. Bahrdt and Y. Ivanyushenkov, IOP Conf. Series 425, 032001 (2013).
  - PPM Undulator (Br = 1.6 T, i.e. state of the art) needs g < 3.5 mm, while LCLS-II requires g > 4.6 mm for beam stay clear. LCLS-II design report Table 8-9.
  - Superposition naturally allows combining the quadrupole and undulator without having to worry about non-linearity of materials or steel.

Inspiration: Argonne SCUs

Q. Hasse, Advanced in Cryogenic Engineering, AIP Conf. Proc 1573, 392 (2014).

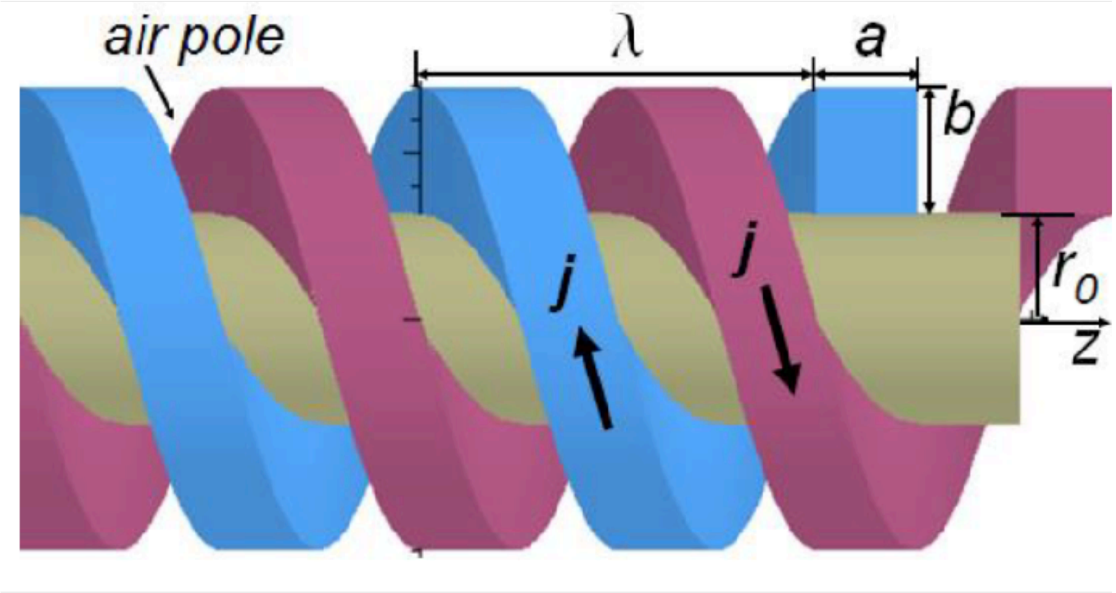


Y. Ivanyushenkov, IPAC 2017.

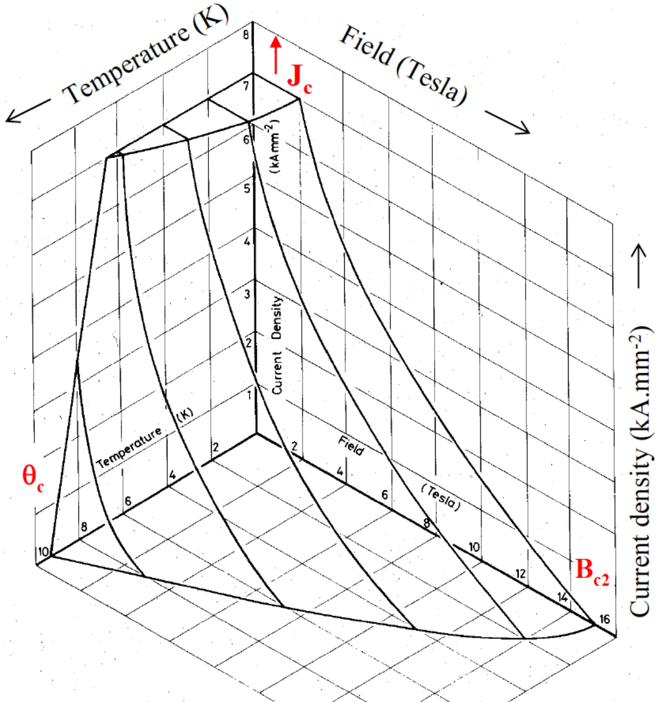


Bifilar Helical SCUs

- Madey’s FEL was Bifilar SCU, so we are back to where we started at 50 years ago.



S.H. Kim, ANL/APS/LS-331 (2012).



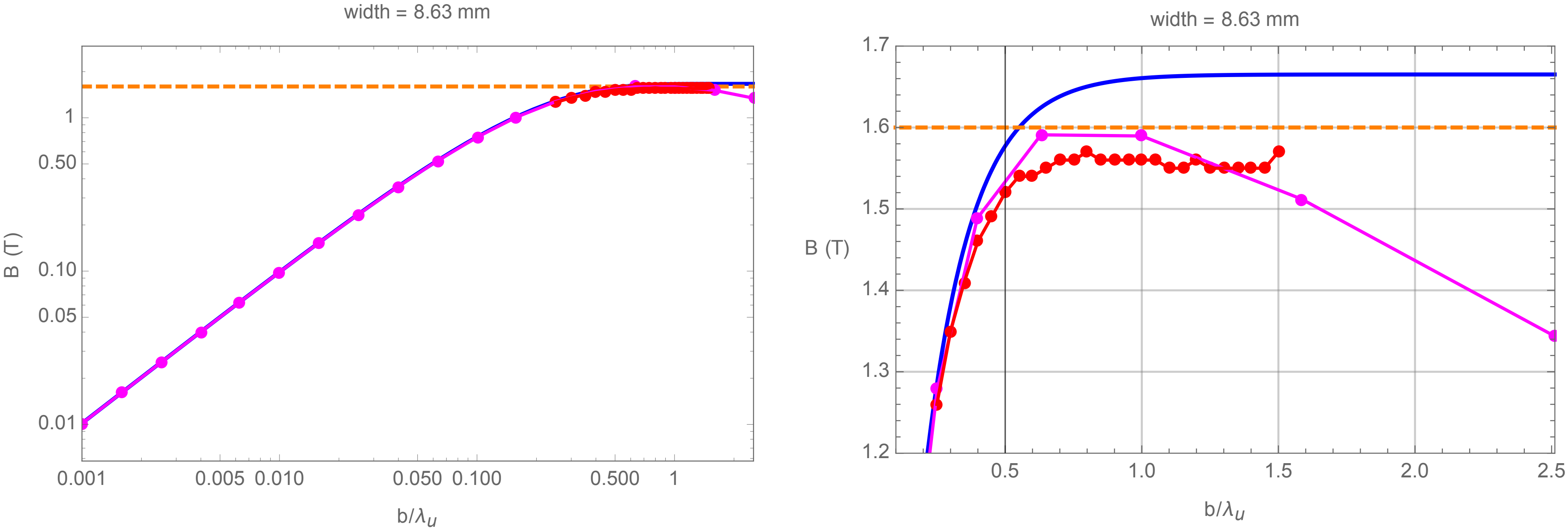
M. Wilson “Lecture 1, CAS Zakopane, Oct 2006”

$$B = \frac{2\mu_0 j}{\pi} \sin\left(\frac{k_u a}{2}\right) \int_{r_0}^{r_0+b} \left(k_u r K_0(k_u r) + K_1(k_u r)\right) dr$$

Comparison to Codes

20 mm period, r_0 = 3.75 mm, j = 780 A/mm^2, a = 8.63 mm = 0.43 λ_u

Analytical: blue, Radia: magenta, Maxwell 3D: red, Goal of 1.6 T: orange



I tried to find subtle differences in the current distribution due to differing ways of defining the current in the two simulation packages, but nothing jumped out.

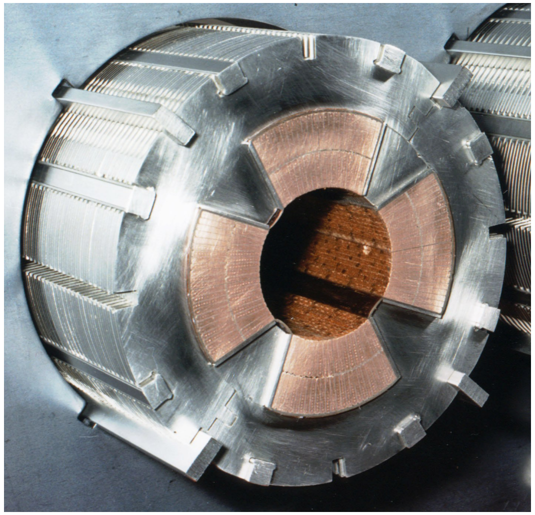
Lesson: Stick to $\lambda_u/4$ and not much bigger.

4-wire quadrupole

- Primary motivations for this design are access and “simplicity.”
  - In a cosine-theta quadrupole, the undulator would be almost totally closed off from the helium bath, and epoxy impregnated wires are not very good thermal conductors.
- Ends of cosine theta are complicated.
- Plus, we do not need the field strength, quality or aperture of ring magnets.
- Harmonic purity is good, in principle:

$$B_y = \frac{2\mu_0 I_0}{\pi R^2} r \left(\cos\phi + \left(\frac{r}{R}\right)^4 \cos 5\phi \right)$$

$$B_x = \frac{2\mu_0 I_0}{\pi R^2} r \left(\sin\phi + \left(\frac{r}{R}\right)^4 \sin 5\phi \right)$$

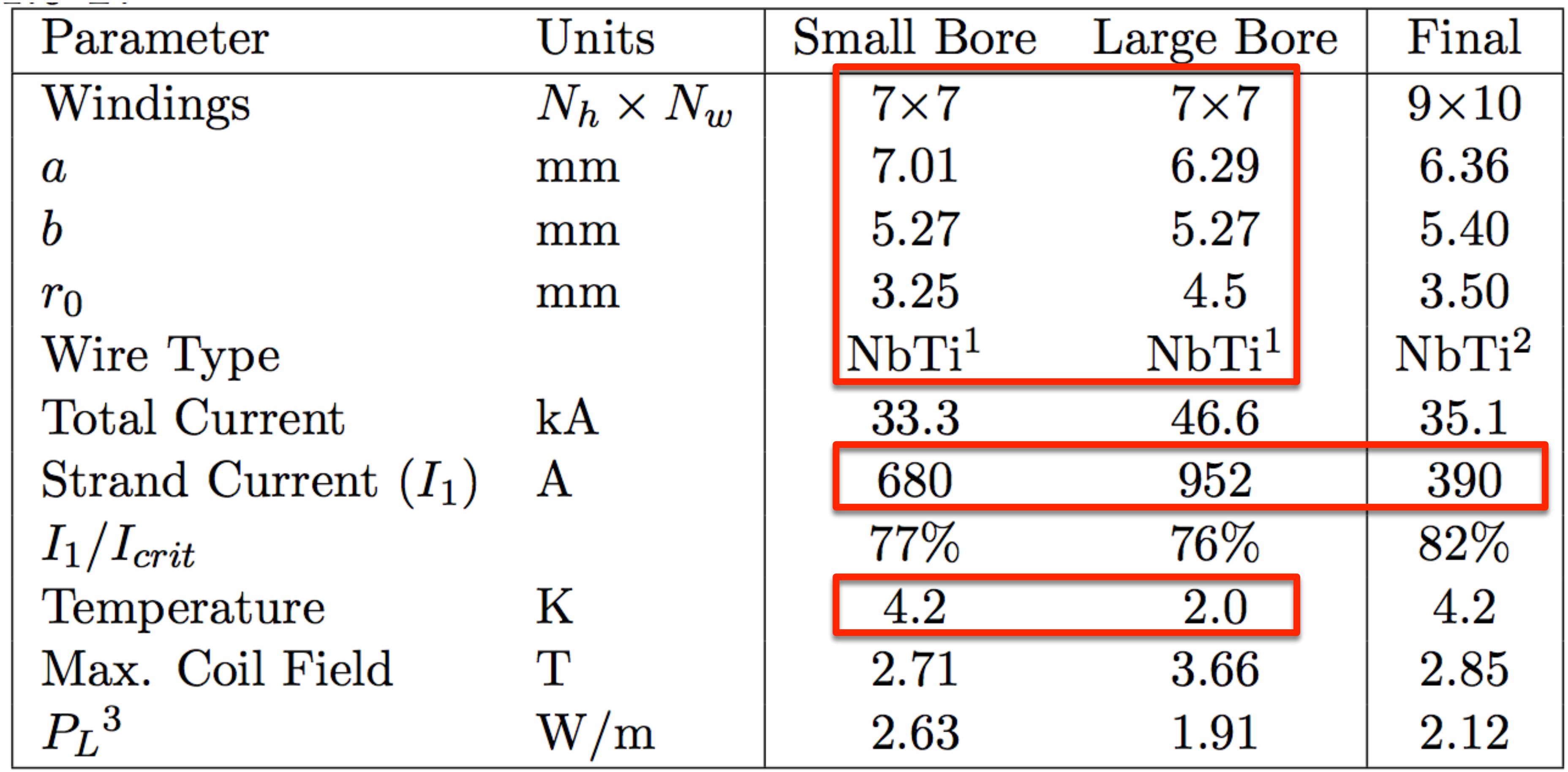


CEA-IRFU

- I_0 = 132 A, 49 turns of the same wire used in the undulator to reach 26.6 T/m.

http://irfu.cea.fr/en/Phocea/Vie_des_labos/Ast/ast_visu.php?id_ast=2411

Design Evolution



Parameter	Units	Small Bore	Large Bore	Final
Windings	$N_h \times N_w$	7×7	7×7	9×10
a	mm	7.01	6.29	6.36
b	mm	5.27	5.27	5.40
r_0	mm	3.25	4.5	3.50
Wire Type		NbTi[1]	NbTi[1]	NbTi[2]
Total Current	kA	33.3	46.6	35.1
Strand Current (I_1)	A	680	952	390
I_1/I_{crit}		77%	76%	82%
Temperature	K	4.2	2.0	4.2
Max. Coil Field	T	2.71	3.66	2.85
P_L[3]	W/m	2.63	1.91	2.12

1 SuperCon 56S53, 0.7 mm. 2 SuperCon 56S53, 0.5 mm. 3 Following [29] for LCLS-II for 1 MHz repetition rate, 90 μ m long flat top beam with 1 kA peak current. The beam chamber is made from aluminum (RRR = 100) and assumed to be 0.5 mm smaller in radius than r0.

Current Lead Considerations

- Minimize current in conductors (I_1) without sacrificing clear aperture.
  - Heat leak in feed-throughs are, by far, the biggest source of steady state heat per undulator module (10s of Watts).
    - P_{leak} ~ A while P_{ohm} ~ 1/A, so lower current means smaller heat leaks.

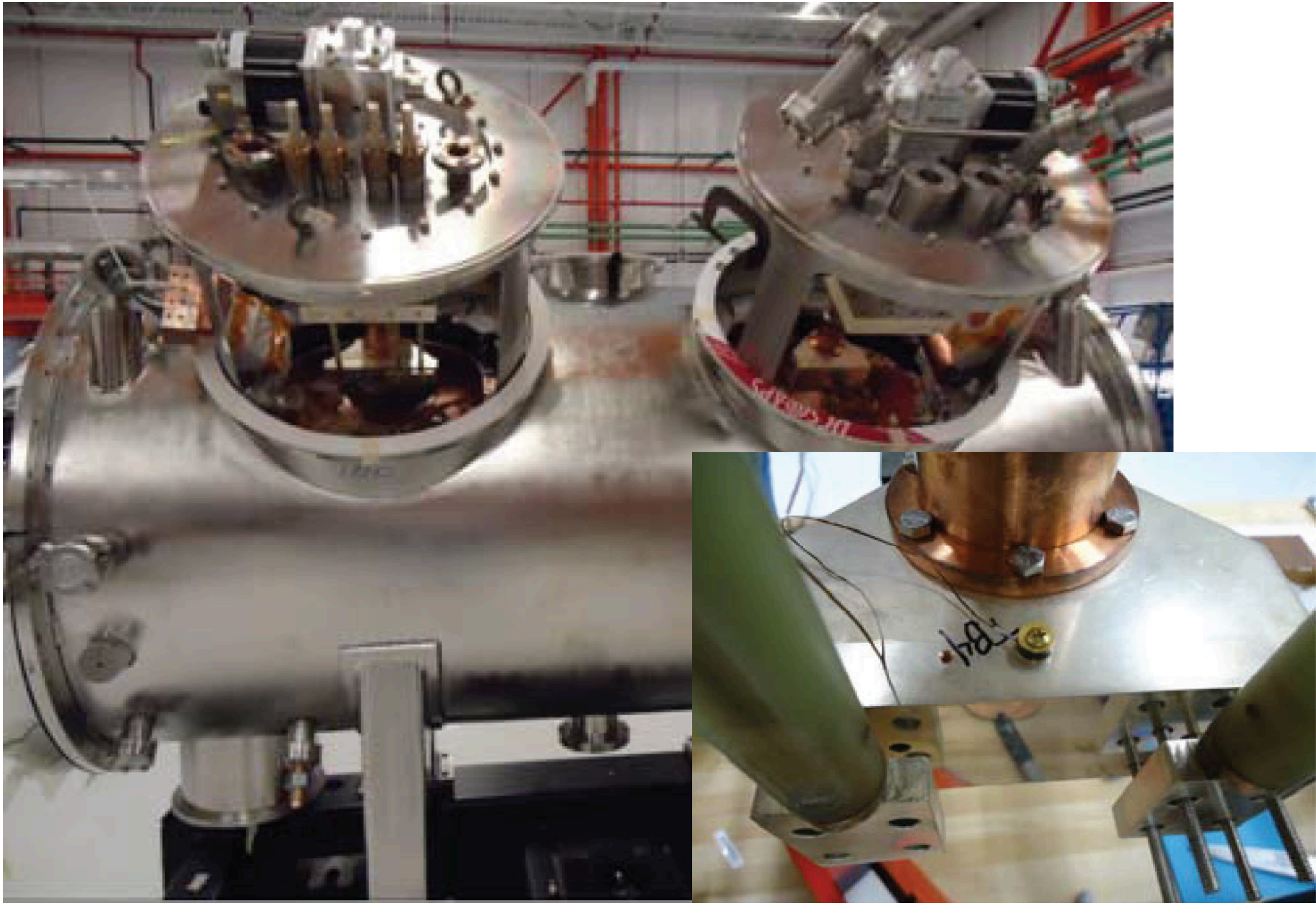
$$P_t = \frac{I_1^2 \rho L}{A} + \frac{k \Delta T A}{L} \qquad A_{min} = \sqrt{\frac{I_1^2 \rho L^2}{k \Delta T}} \qquad P_{min} = 2\sqrt{I_1^2 \rho k \Delta T}$$

Copper:
ρ = 1.72 10-8 Ω*m
k = 400 W/(m K)
ΔT = 220 K

P ~ 30 W

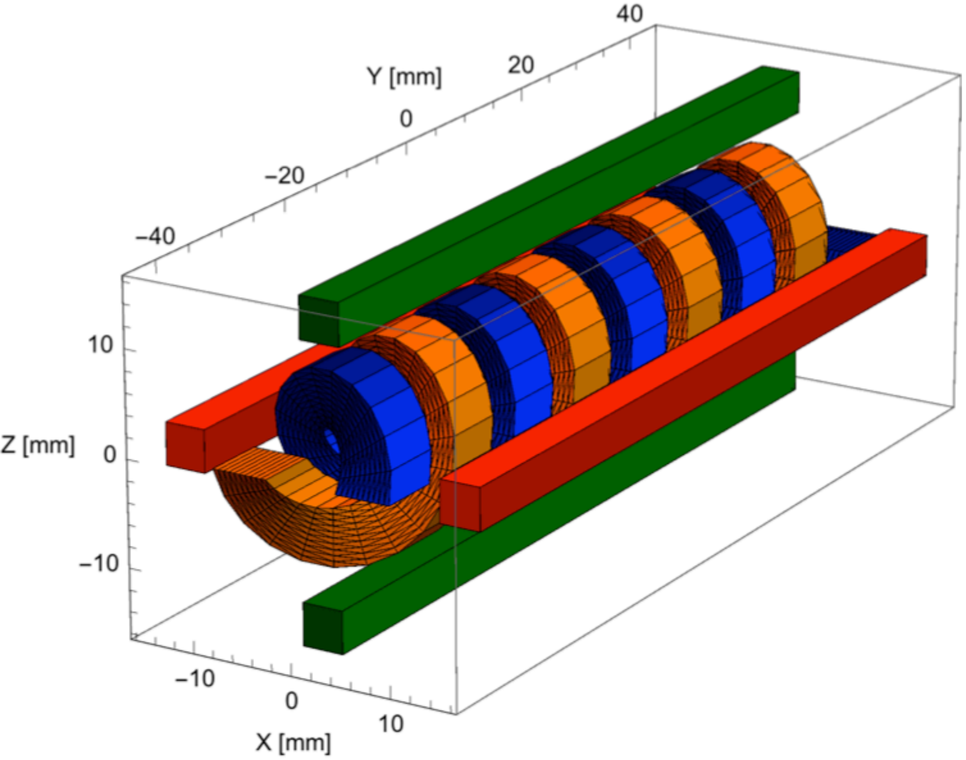
- Heat load is at 50-80K, but if we need to feed current in to each undulator segment separately, there will be 6 kW of heat to cool (42 kW “warm” power). Half that of the LCLS-II linac.
- More importantly, 400 A is similar to the ANL design (500 A).

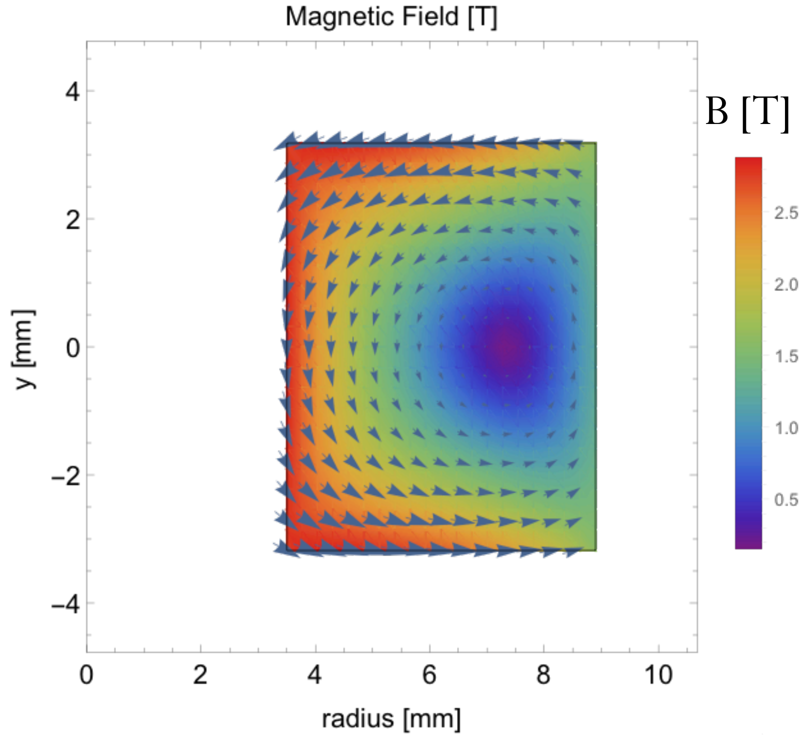
The ANL current leads

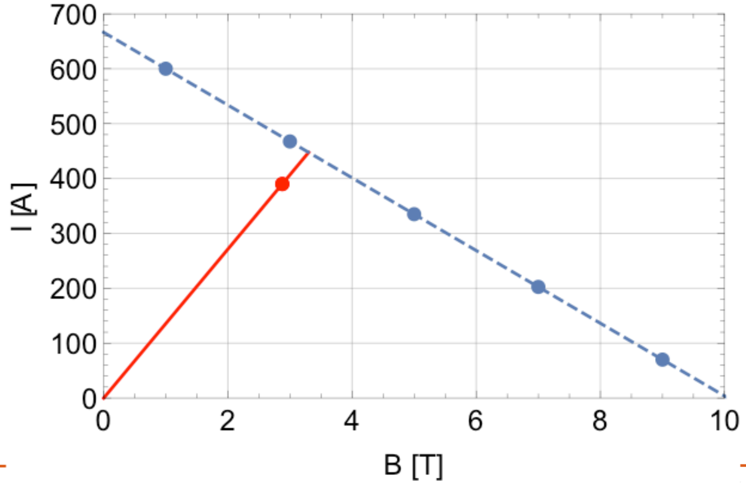


Q. Hasse, et al, Advances in Cryogenic Engineering, AIP Conf. Proc. 1573, 392 (2014).

“Final” Design







For mechanical stability combine the undulator and quadrupole in to one monolithic structure. Judicious placement of Al/Cu so cooling can reach the undulator coils.

Tolerance Budget

- Three assumptions to simplify analysis:
  1. The undulator is N_c, identical segments long.
  2. The different types of errors are independently distributed (i.e. no correlations)
  3. The FEL's sensitivity to errors is independent of segment number.
- This isn't as un-conservative as it may sound as long as you use conservative estimates for the actual errors.

$$\eta = P/P_0$$

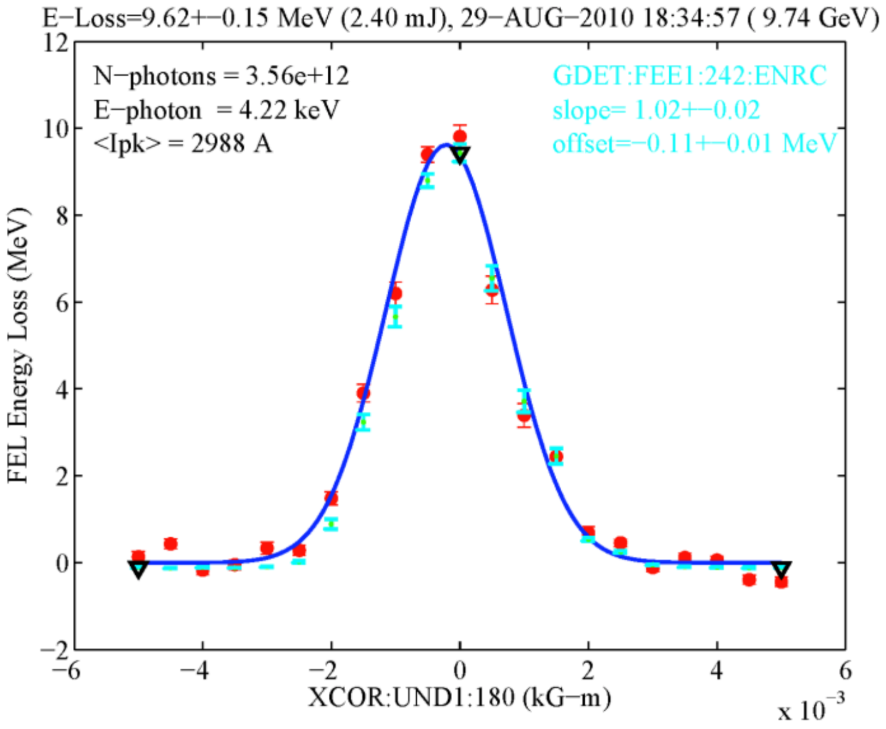
$$< \bar{\eta} >= \left\langle \prod_{j=1}^{N_j} \bar{\eta}_j \right\rangle = \prod_{j=1}^{N_j} \langle \bar{\eta}_j \rangle = \prod_{j=1}^{N_j} \left\langle \frac{1}{N_c} \sum_{i=1}^{N_c} \eta_{ji} \right\rangle = \prod_{j=1}^{N_j} \langle \eta_{j1} \rangle$$

Following H.-D. Nuhn at SLAC for LCLS-II.

Two types of “Fundamental Errors”

Electron Beam Kicks

H.-D. Nuhn, SLAC-PUB-15062

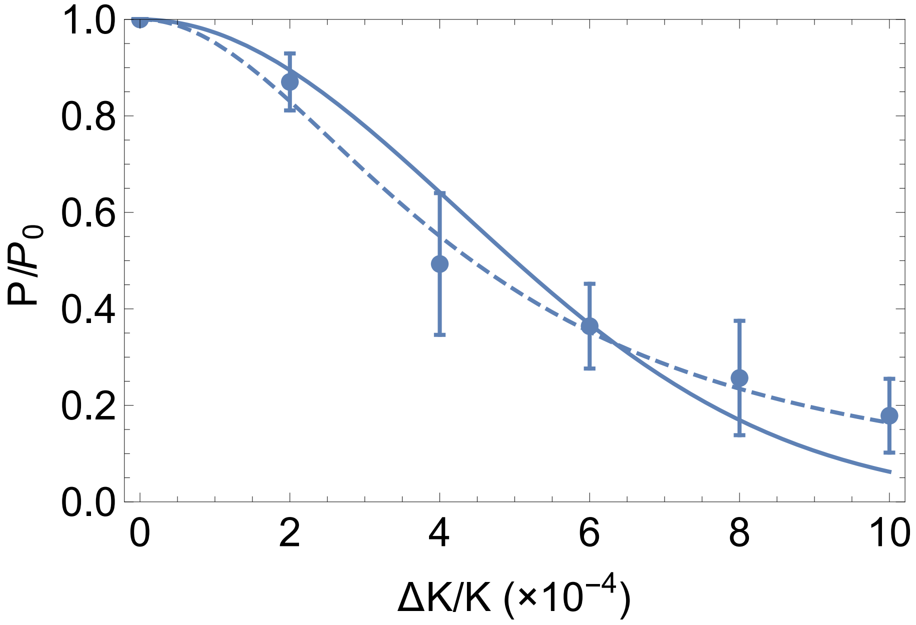


$$\eta(x') = \exp\left(-\frac{(x')^2}{2\sigma_{x'}^2}\right)$$

$$\sigma_{x'} = \frac{1}{3.3}\sqrt{\frac{\lambda_r}{L_g}} = 4.6\ \mu rad$$

Undulator de-tuning

From time-independent Genesis simulations.



$$\chi = \Delta K/K$$

$$\eta(\chi) = \exp\left(-\frac{\chi^2}{2\sigma_\chi^2}\right)$$

$$\sigma_\chi = 4.2 \times 10^{-4}$$

Example of “derived error”

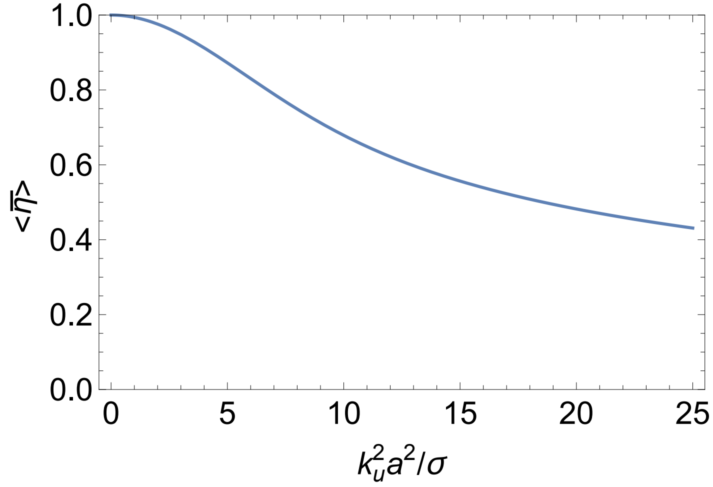
- If the undulator is offset by Δx, the magnetic field is stronger:

$$K/K_0 = 1 + k_u^2 \Delta x^2/4$$

- Installation instructions general have: $\Delta x \sim U(-a, a)$
- What does this mean for the FEL power?
- Conservation of probability density says χ is not uniform, and the ensemble average for the output power is

$$\langle \eta_{\Delta x} \rangle = \int_{-a}^{a} \eta(\Delta x) d(\Delta x) = \int_0^{\chi_{max}} \frac{\eta(\chi) d\chi}{\sqrt{4\chi_{max}\chi}}$$

$$\sqrt{\frac{\sigma_\chi}{2^{3/2} k_u^2 a^2}} \left(\Gamma(1/4) - \Gamma(1/4, \frac{k_u^4 a^4}{32\sigma_\chi^2}) \right)$$



Total errors for AGU

- Repeat the previous until you run out of patience/money and then play around with your tolerances to find:

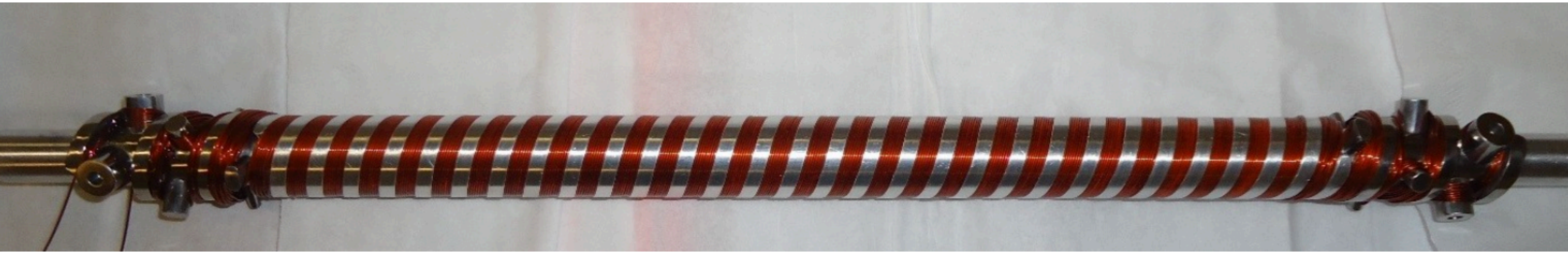
Parameter	Tolerance	Units	P/P_0
Injection Angle	$2.\times 10^{-6}$	rad	0.969
Und. Current ($\Delta I/I$)	$1.\times 10^{-4}$		0.991
Und. Offset (Δx)	$1.\times 10^{-4}$	m	0.967
Und. Offset (Δy)	$1.\times 10^{-4}$	m	0.967
Und. Pitch	$1.\times 10^{-4}$	rad	0.999
Und. Yaw	$1.\times 10^{-4}$	rad	0.999
Und. Phase	5.	deg	0.990
Und. Roll	$1.\times 10^{-3}$	rad	0.974
Relative P.S. Error	$1.\times 10^{-4}$		0.984
Drift error	$5.\times 10^{-5}$	m	0.960
Quad. Current ($\Delta I/I$)	$1.\times 10^{-2}$		1.000
Quad. Roll	$1.\times 10^{-1}$	rad	0.996
Quad. Offset (Δx)	$1.\times 10^{-6}$	m	
Quad. Yaw	$1.\times 10^{-6}$	rad	
I_y	$5.\times 10^{-5}$	$T\cdot m$	
II_y	$1.\times 10^{-4}$	$T\cdot m^2$	0.970
Quad. Offset (Δy)	$1.\times 10^{-6}$	m	
Quad. Pitch	$1.\times 10^{-6}$	rad	
I_x	$5.\times 10^{-5}$	$T\cdot m$	
II_x	$1.\times 10^{-4}$	$T\cdot m^2$	0.970
Total			**0.765**

These values are somewhat conservative because we haven't included the ability to tune the current of the undulator in-situ. We have also ignored that there will be phase shifters between the undulators helping to fix problems with the inter-undulator drifts.

Nonetheless, these tolerances are all within the realm of possible. Vibrating wire plus beam based alignment can reach 1 µm. 100 µm between quadrupole axis and undulator axis is possible. Might be hard, but then we tune the undulator current.

Conclusions

- High level design of the AGU undulator is complete and it shows superlative FEL performance: 3.5 TW in 80 meters at 1.5 Angstrom.
- Phase II goal is to build a prototype (with support from ANL) and show that we can reach the field and tolerance requirements.
- Several hard steps left: especially the end winding returns.



Thank you.