Development of RF Undulator-Based Insertion Devices for Storage Rings and Free Electron lasers

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NLCTA Group (In particular Michael Dunning, Erik Hemsing, and Stephen Weathersby)
Klystron Shop Group (Andrew Haase et. al.)

Why RF Undulator?

- Many desirable features
  - Fast dynamic control of
    - Polarization
    - Wavelength
    - K
  - Large aperture (cm vs mm for static undulator)
  - No issue with permanent magnet damage by radiation
  - Economic considerations
  - Potential use as LCLS “After Burner”
  - Dynamic undulator for storage ring

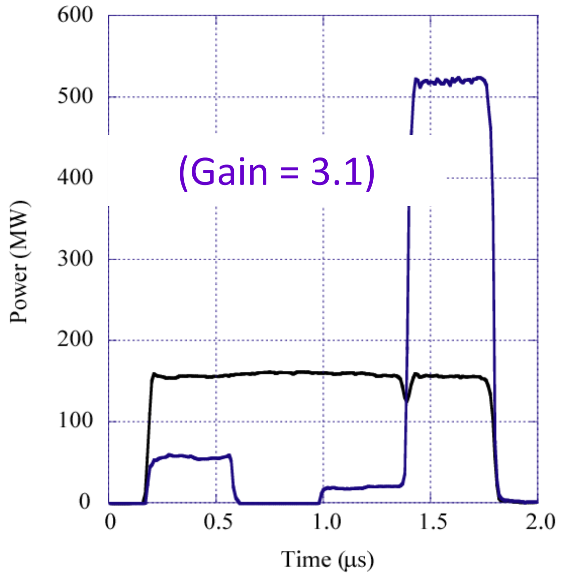
Available Resource - NLCTA

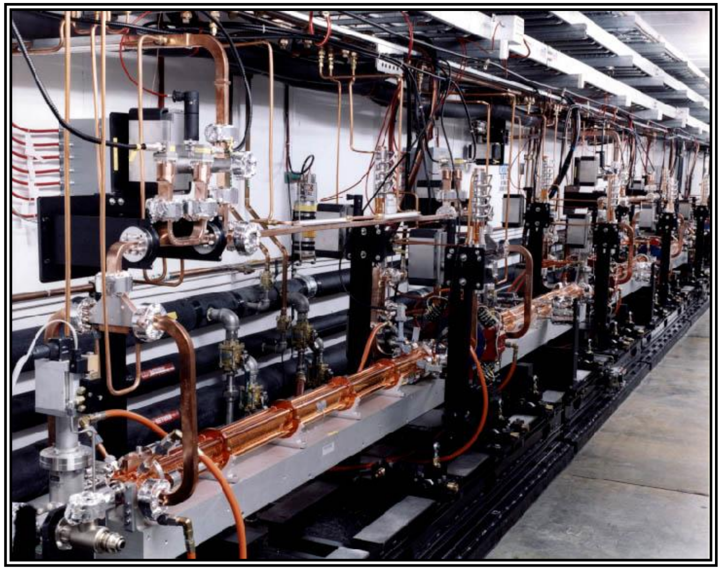
- 3 x RF stations
  - 2 x pulse compressors (240ns - 300MW max), driven each by 2 x 50MW X-band klystrons
  - 1 x pulse compressors (400ns – 300MW /200ns – 500MW variable), driven by 2 x 50MW X-band klystrons.
- 1 x Injector: 65MeV, ~0.3 nC / bunch

* In the accelerator housing:
  - 2 x 2.5m slots for structures

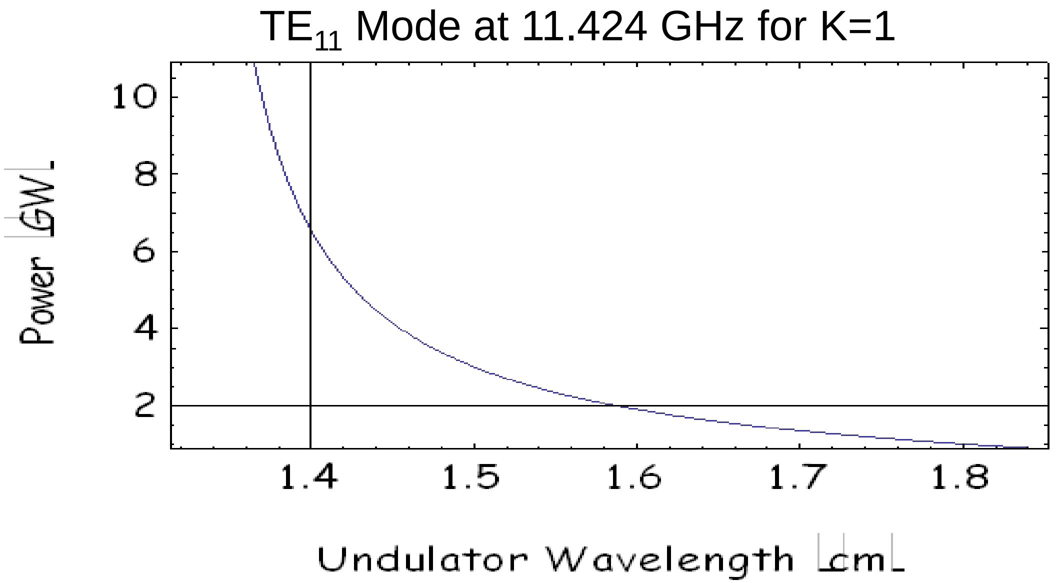
* Shielding Enclosure:
  suitable up to 1 GeV

* For operation:
  - Can run 24/7 using automated controls





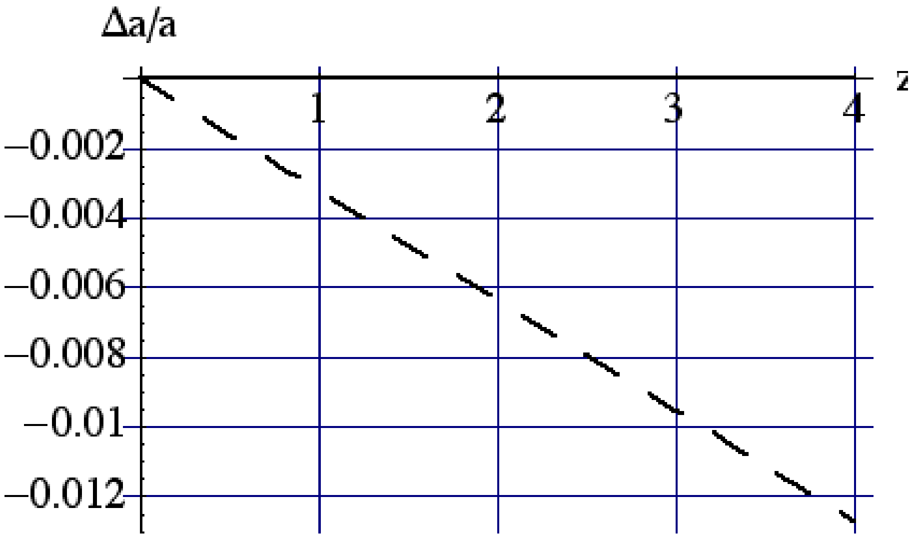
TW RF Undulator in Circular Guide

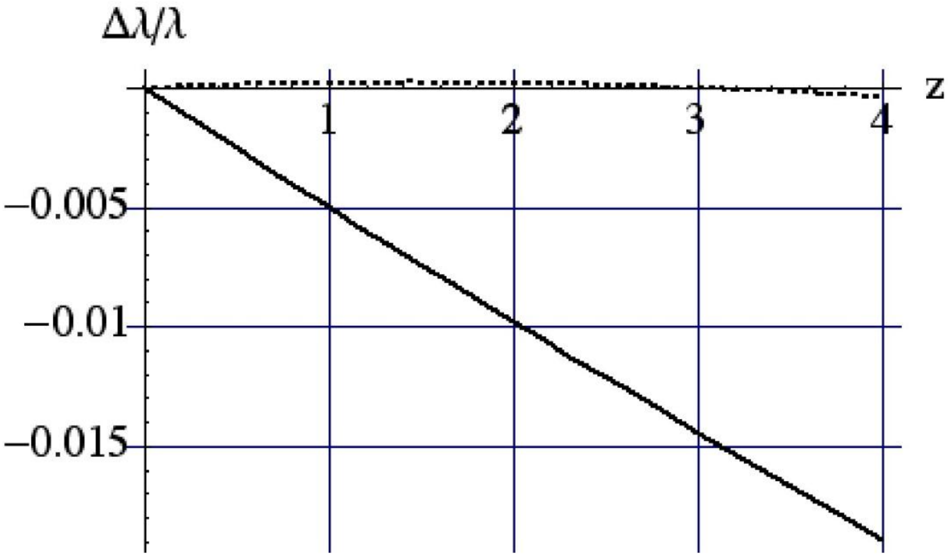


- Research initiated by Claudio Pellegrini* at UCLA
- Undulator *K* parameter of 1 requires > 1 GW
- *K* = 0.5 of some interest
  - power level achievable 250 MW
  - surface fields (80 MV/m) would limit pulse length to < 200 ns
- Substantial enhancement of *K* parameter can be obtained with resonant structures

*S. Tantawi, V. Dolgashev, C.Nantista, C.Pellegrini,J.Rosenweig, G. Travish," A Coherent Compton Backscattering High Gain Fel Using An X-band Microwave Undulator",Proc. of 27intl FEL Conf, Aug 2005

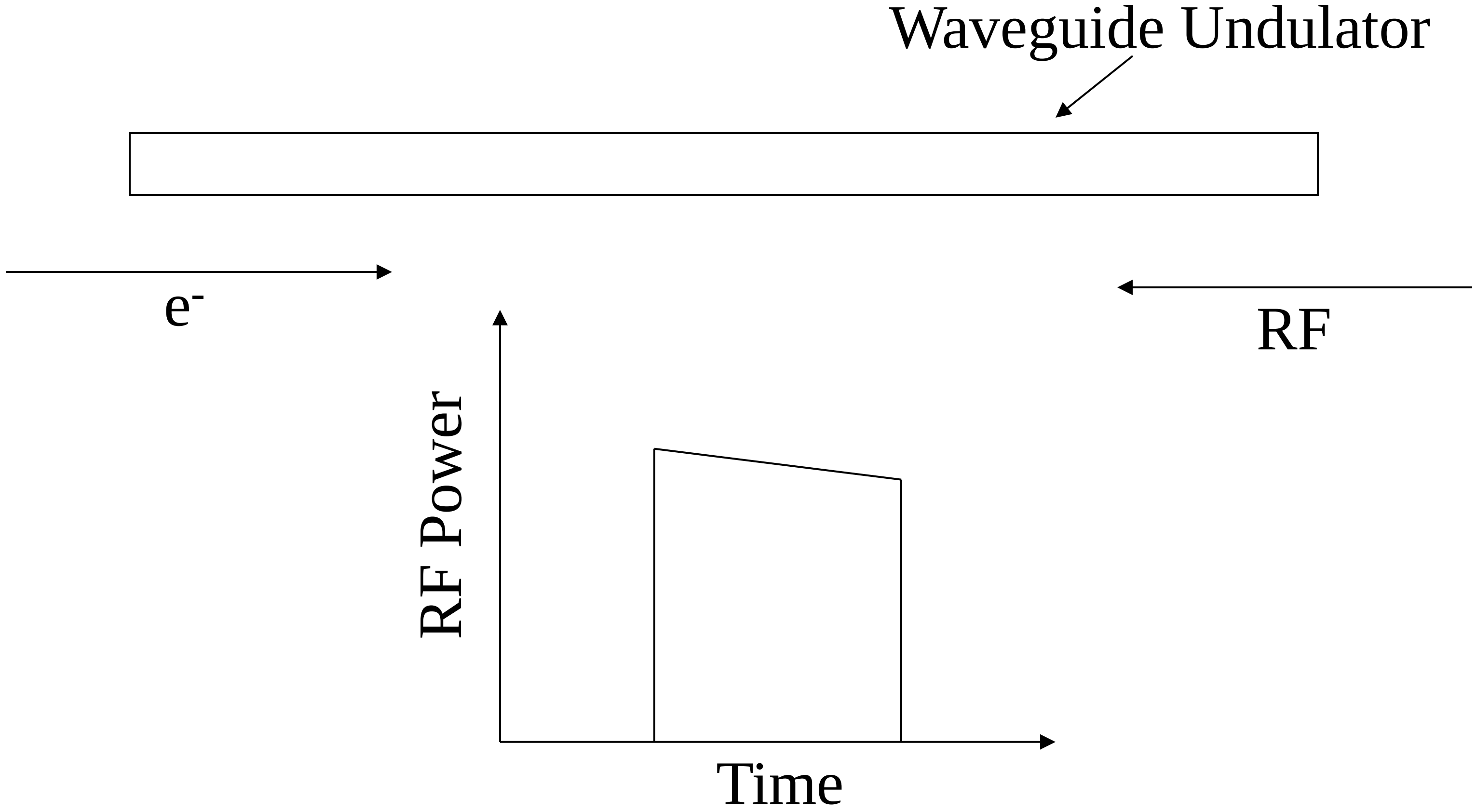
Effect of Power Losses



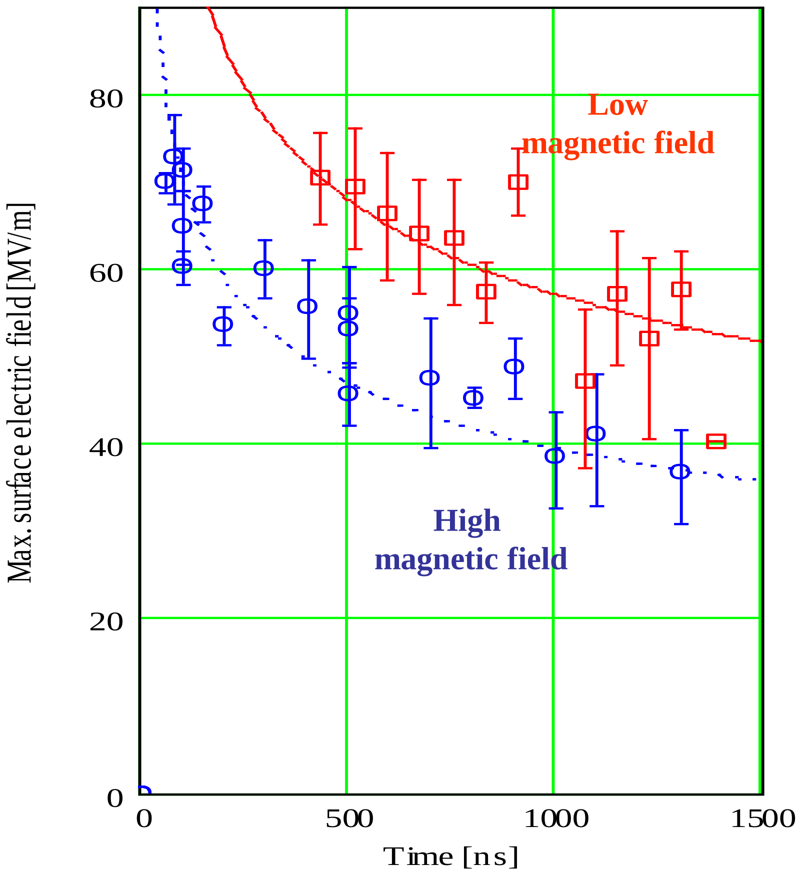


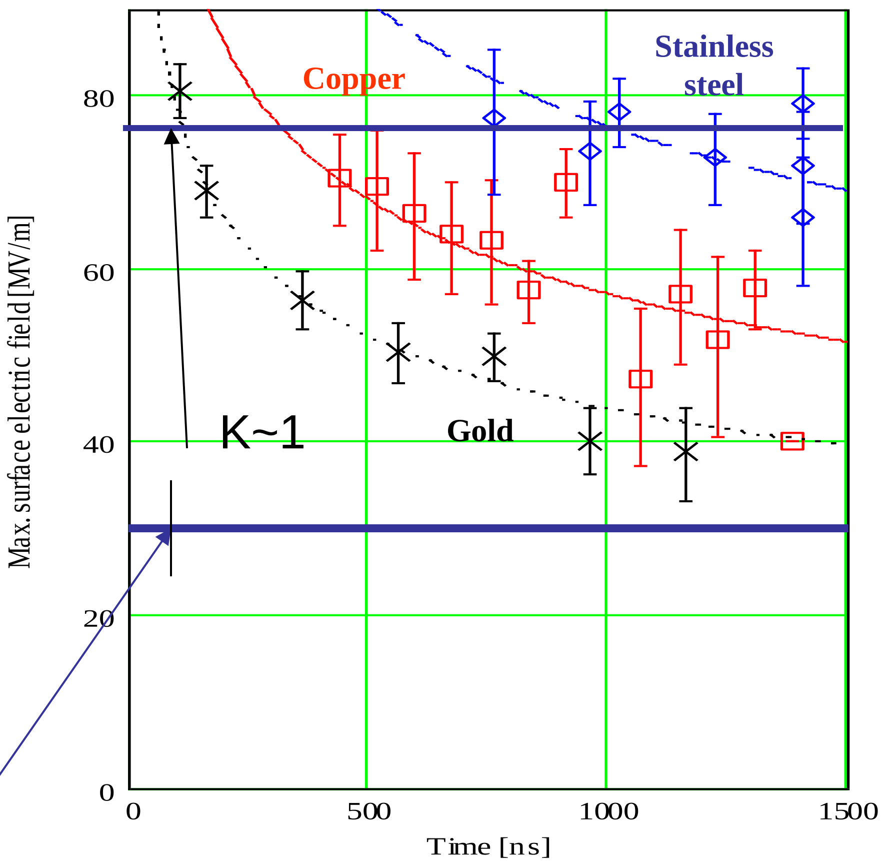
Tuning the Undulator Profile Through LLRF System

Because the e-beam and the em wave are traveling in opposite directions one can tailor the rf pulse to compensate for errors in the waveguide and also to taper the undulator field



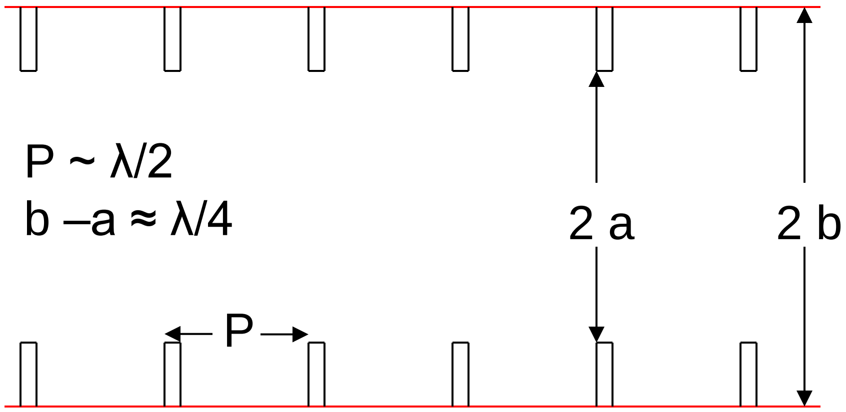
Waveguide High Gradient Studies: Maximum breakdown electric fields for different geometries and materials

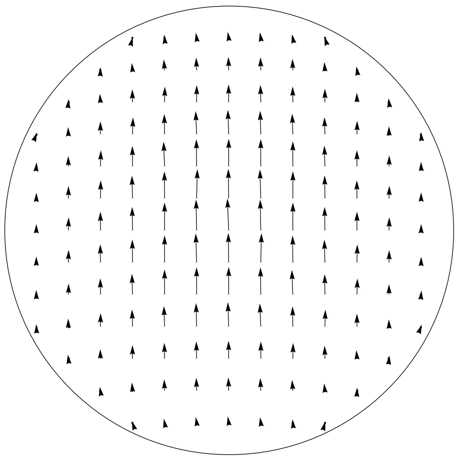




Initial Design point K~0.4

HE_{11} Mode in Corrugated Guide





- Inspired by our work on a previous LDRD project which involved corrugated feed horns for CMB applications
- Lowest order mode (HE_{11}) is a combination of primarily TE_{11} and TM_{11} modes
- Magnetic field is extremely low on waveguide walls – attenuation can be less than that of smooth wall cylindrical TE_{01} mode
- Field configuration ideal for beam interaction

Comparison Between TE_{1n} and HE_{1n} Modes

Frequency = 11.424 GHz, *K* = 1, Length = 1 m, Material: Copper

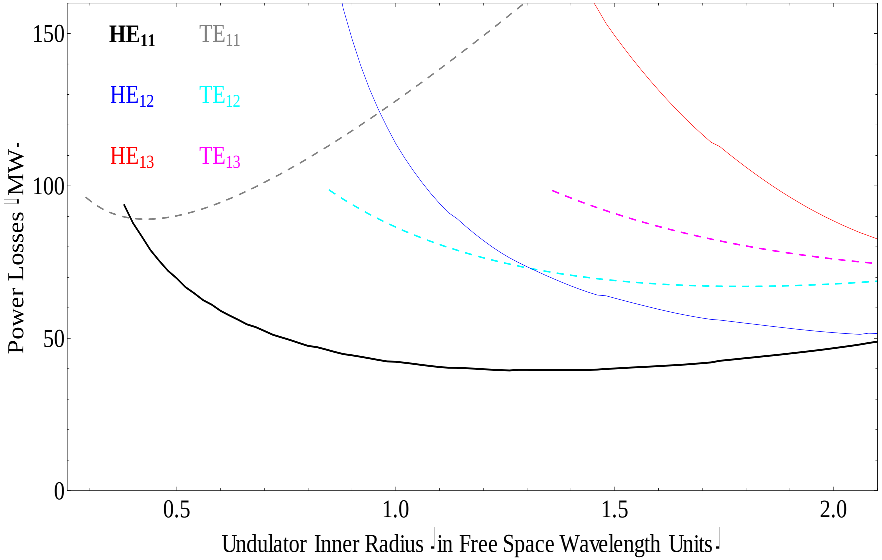
For TE_{1n} modes the undulator is a simple circular waveguide

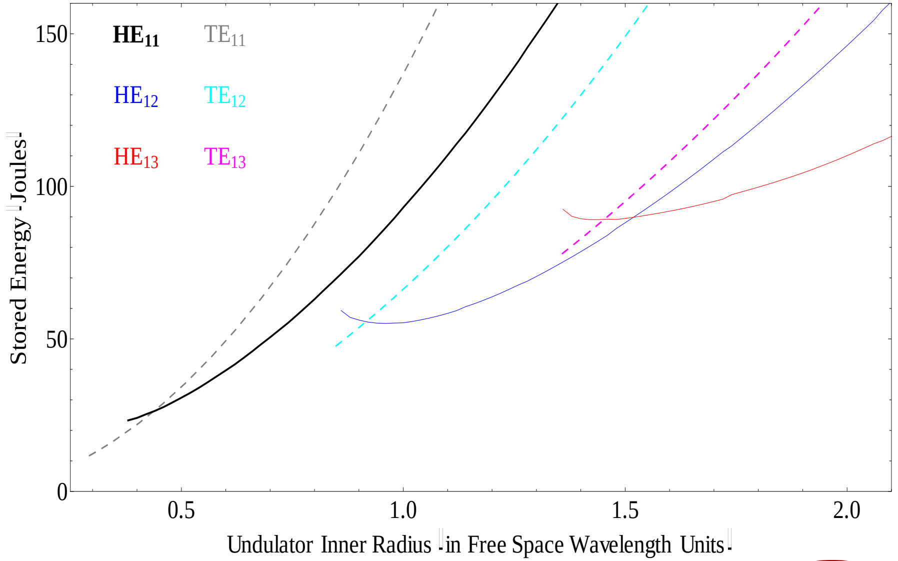
For HE_{1n} modes the undulator is a corrugated circular waveguide with following parameters:

Slot Depth = 0.335 λ

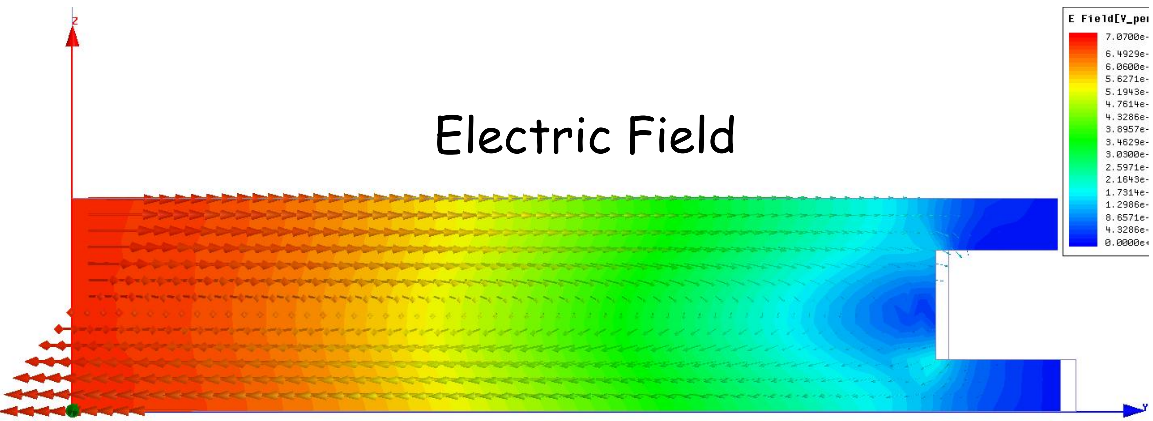
Slot Thickness = λ/16

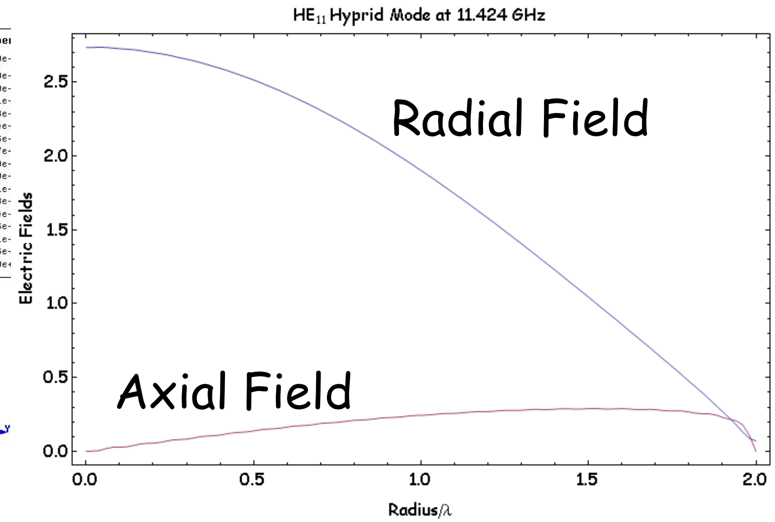
Corrugation Period= 0.45 λ

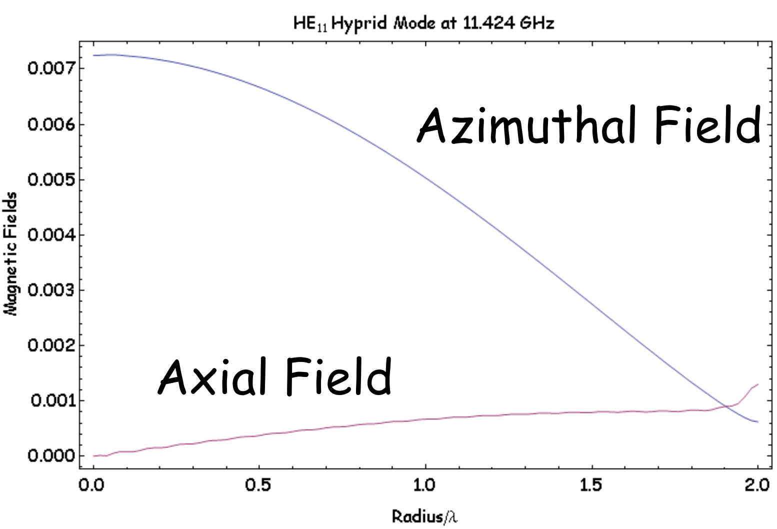


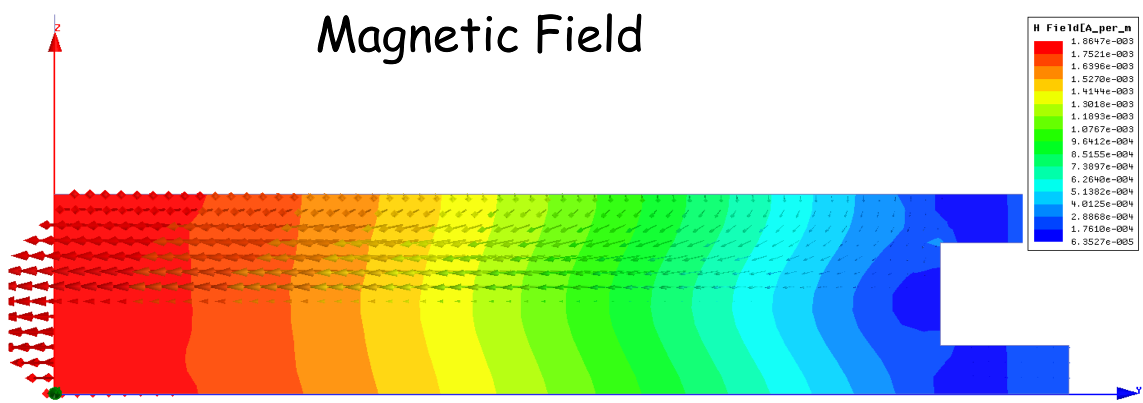


Hybrid Mode Fields









HE_{1n} Modes Scaling Laws

For an undulator made of copper at room temperature :

$$\lambda_u \approx \frac{\lambda}{2}$$

$$Power: \qquad P(MW) \approx K^2 J_1^{\,2}(x)\left(\frac{0.727141a^2}{\lambda_u^{\,5/2}} + \frac{0.0673433Lx^2}{a\sqrt{\lambda_u}}\right)$$

$$Stored\ Energy: \qquad U(Jouls) \approx \frac{71.5a^2K^2LJ_1^{\,2}(x)}{\lambda_u^2}$$

$$Quality\ Factor: \qquad Q \approx \frac{1.17\times10^8 a^3 L}{128\pi^2a^3 + 117Lx^2\lambda_u^2}\sqrt{\frac{1}{\lambda_u}}$$

$$Filling\ Time: \qquad t_f(\mu s) \approx \frac{124208\ a^3L\sqrt{\lambda_u}}{128\pi^2a^3 + 117Lx^2\lambda_u^2}$$

$$Peak\ Suface\ E\ Field: \ E_s(MV/m) \approx \frac{1.02KxJ_1(x)}{a}$$

$$Peak\ Surface\ B\ Field: B_s(mT) \approx \frac{3.4KxJ_1(x)}{a}$$

$$x \rightarrow \{2.40483, 5.52008, 8.65373, 11.7915\}\ for\ \{\mathrm{HE}_{11}, \mathrm{HE}_{12}, \mathrm{HE}_{13}, \mathrm{HE}_{14}\}\ modes$$

HE_{1n} Modes Scaling Laws

For an undulator made of copper at room temperature :

$$\lambda_u \approx \frac{\lambda}{2}$$

$$\textit{Optimal Radius}: \qquad a(m) \approx 0.23\lambda^{2/3}\sqrt[3]{L}\,x^{2/3}$$

$$\textit{Minimum Power}: \qquad P(MW) \approx \frac{0.28K^2L^{2/3}x^{4/3}J_1^{\,2}(x)}{\lambda_u^{7/6}}$$

$$\textit{Stored Energy}: \qquad U(Jouls) \approx \frac{9.22K^2L^{5/3}x^{4/3}J_1(x)^2}{\lambda_u^{2/3}}$$

$$\textit{Quality Factor}: \qquad Q \approx \frac{30867L}{\sqrt{\lambda_u}}$$

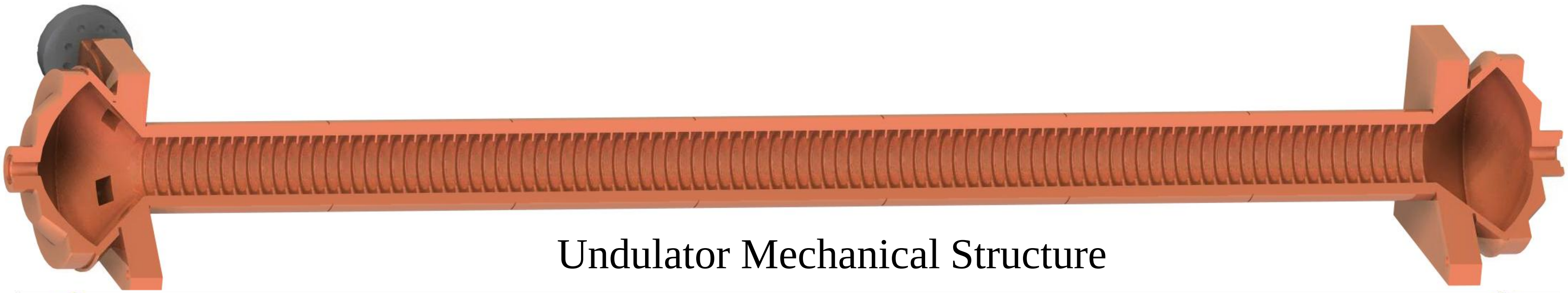
$$\textit{Filling Time}: \qquad t_f(\mu s) \approx 32.8L\sqrt{\lambda_u}$$

$$\textit{Peak Suface E Field}: \quad E_s(MV/m) \approx \frac{1.02KxJ_1(x)}{a}$$

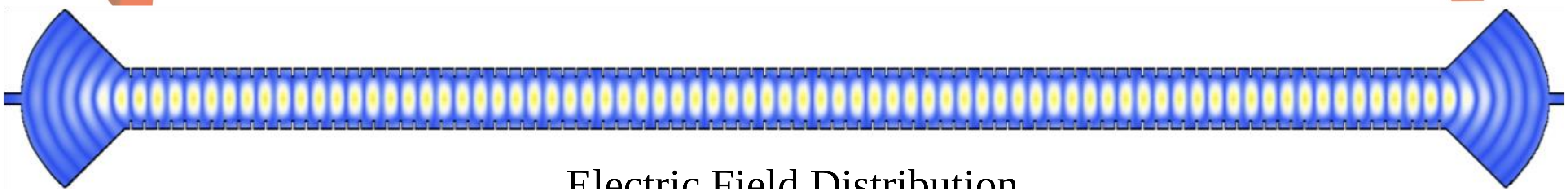
$$\textit{Peak Surface B Field}: B_s(mT) \approx \frac{3.4KxJ_{1.}(x)}{a}$$

$$x \to \{2.40483, 5.52008, 8.65373, 11.7915\}\ \textit{for}\ \{\mathrm{HE}_{11}, \mathrm{HE}_{12}, \mathrm{HE}_{13}, \mathrm{HE}_{14}\}\ \textit{modes}$$

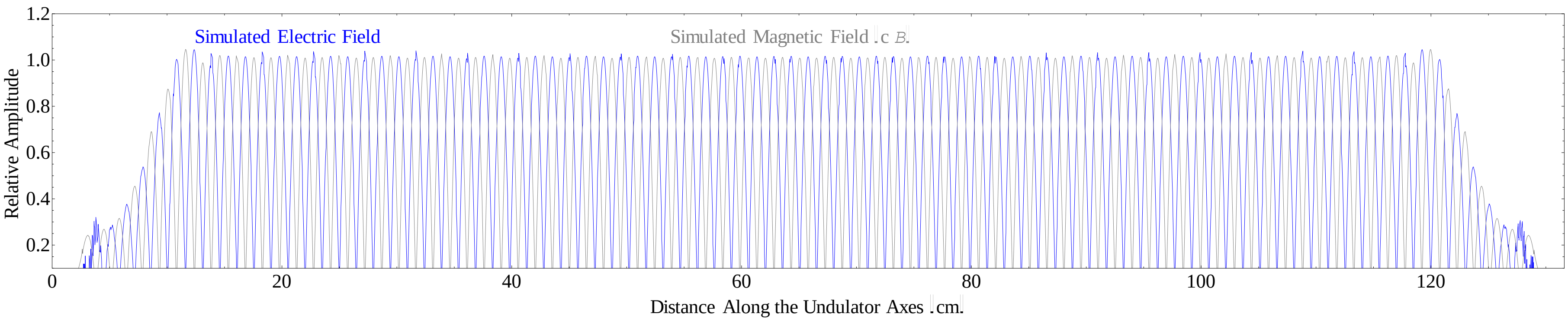
Undulator Design



Undulator Mechanical Structure

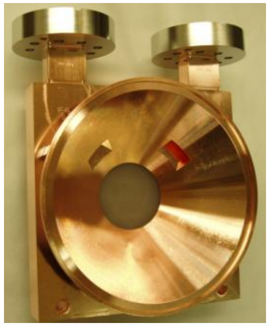


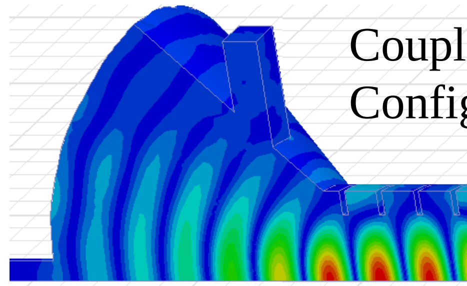
Electric Field Distribution



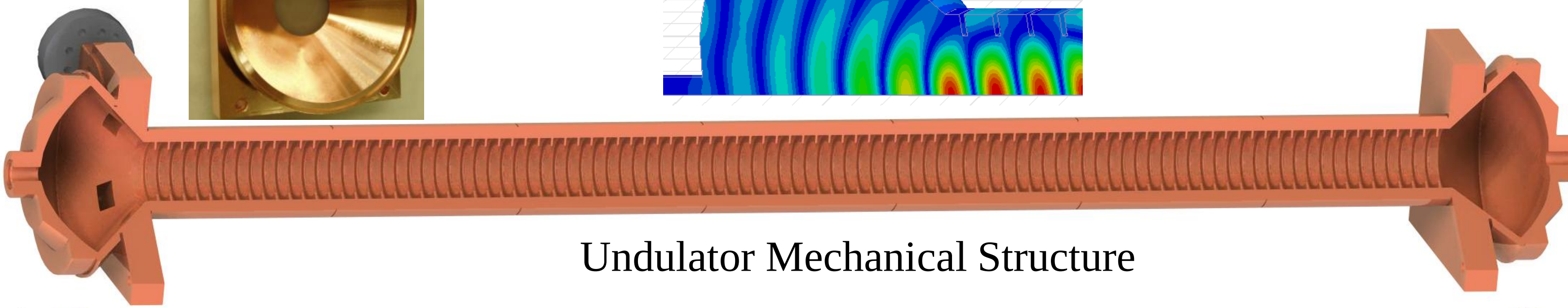
Undulator Coupler Design

Two coupling ports 90° apart to excite two polarizations independently

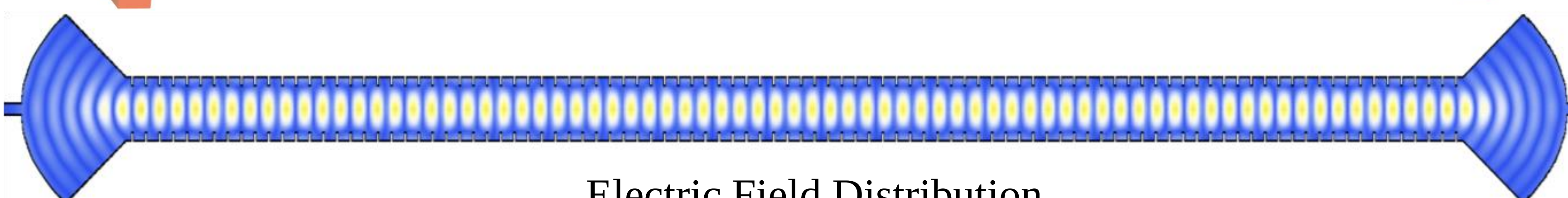




Coupler Field Configuration



Undulator Mechanical Structure

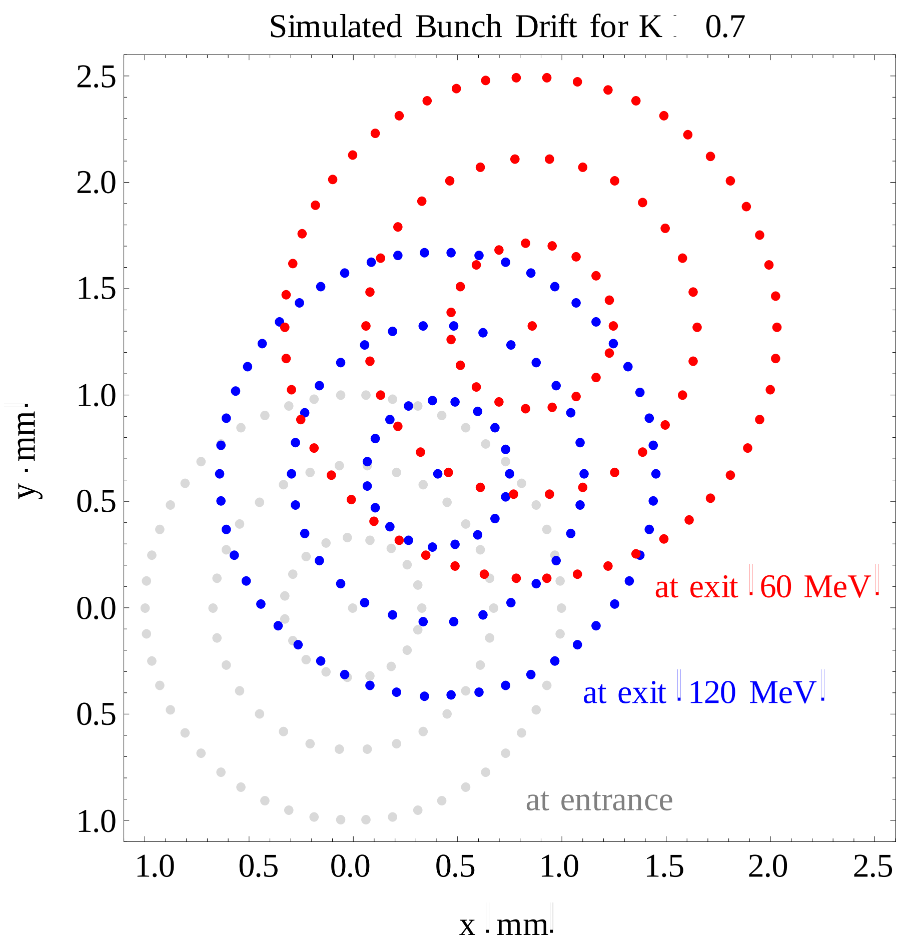


Electric Field Distribution

Corrugation Period=0.4254 λ
Inner Radius=0.75 λ
Outer radius= 1.01293 λ
Corrugation Thickness= $\lambda/16$
Number of periods =98

λ=2.6242296 cm
Undulator Wavelength=1.39306 cm
Power required (for linearly polarized, K=1)=48.8 MW
Q0=94,000

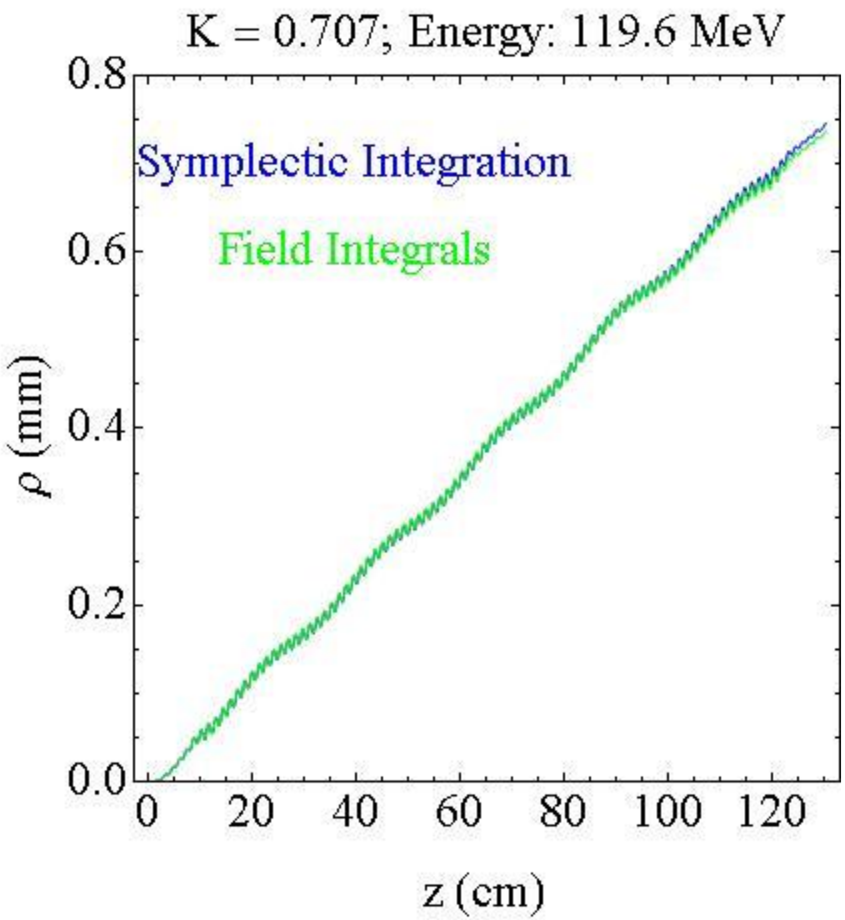
Transverse Beam Distribution

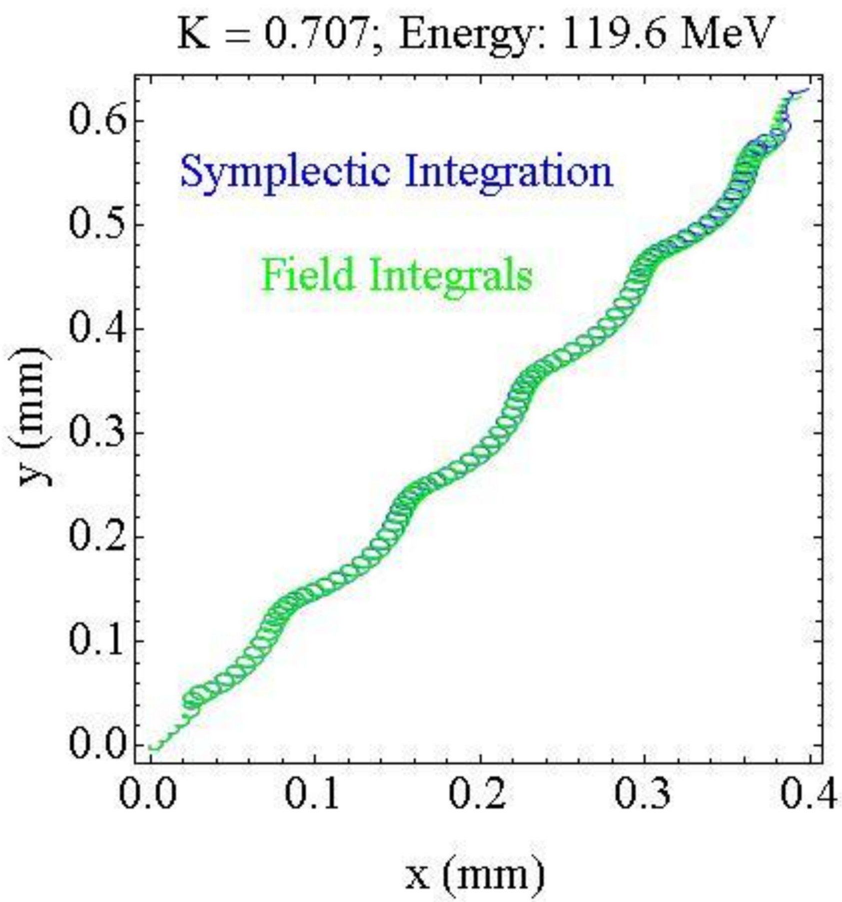


Field Integrals

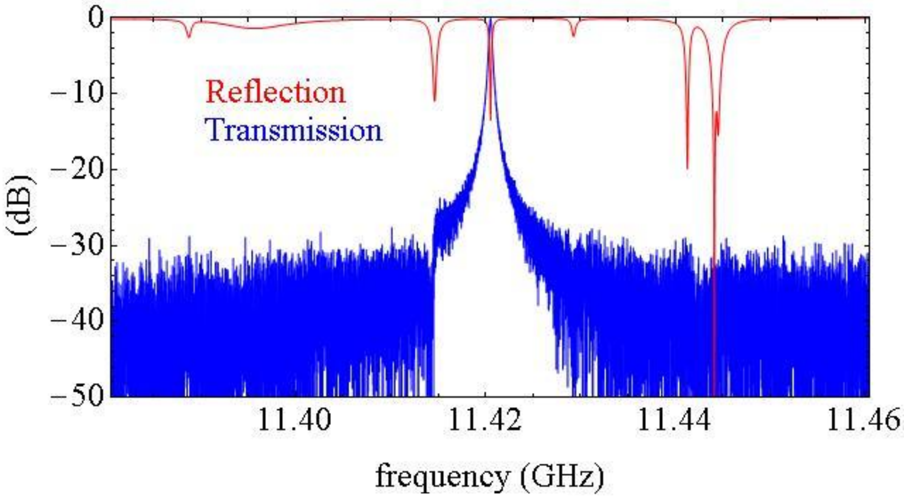
$M = 2\dfrac{\Lambda + \beta}{(1+\Lambda)}$	$N = 4\pi\dfrac{1-\beta^2}{(1+\Lambda)}$
$I_1(z) = \left[Mf(z)e^{i2\pi z} + N\int g(z)e^{i2\pi z}\,dz\right]$	$I_2(z) = \int I_1(z)\,dz$
$\dot{x} + i\dot{y} = \dfrac{K}{\gamma}e^{i2\pi t_0}I_1(z)$	$x + iy = \dfrac{K}{\gamma}e^{i2\pi t_0}I_2(z)$

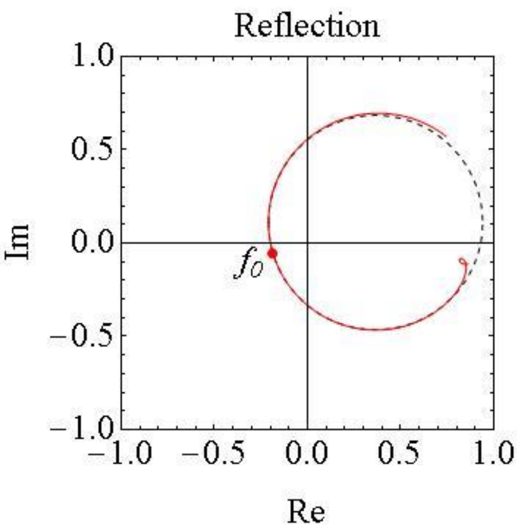
Drift in ρ-z

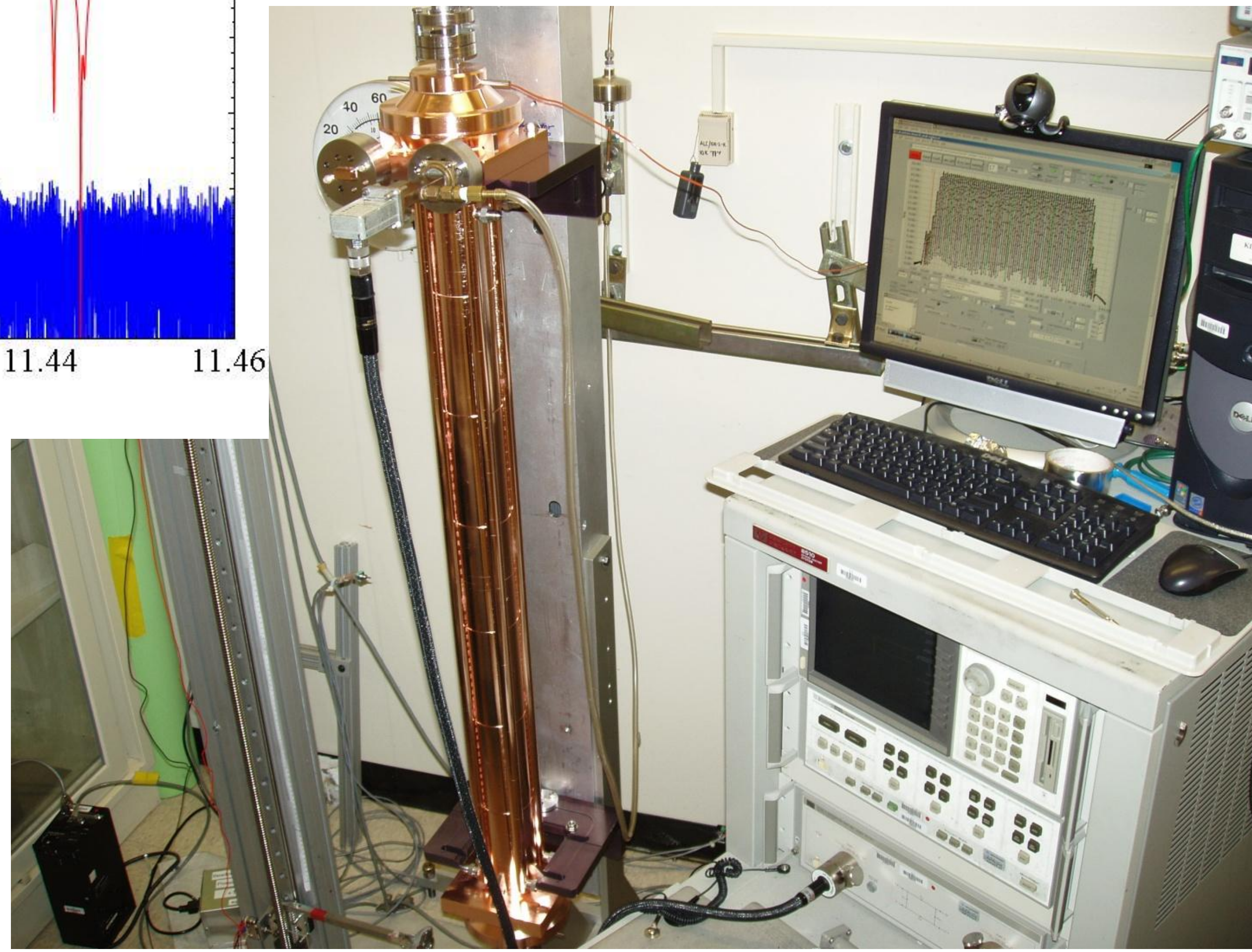




Undulator Structure Tested at NLCTA





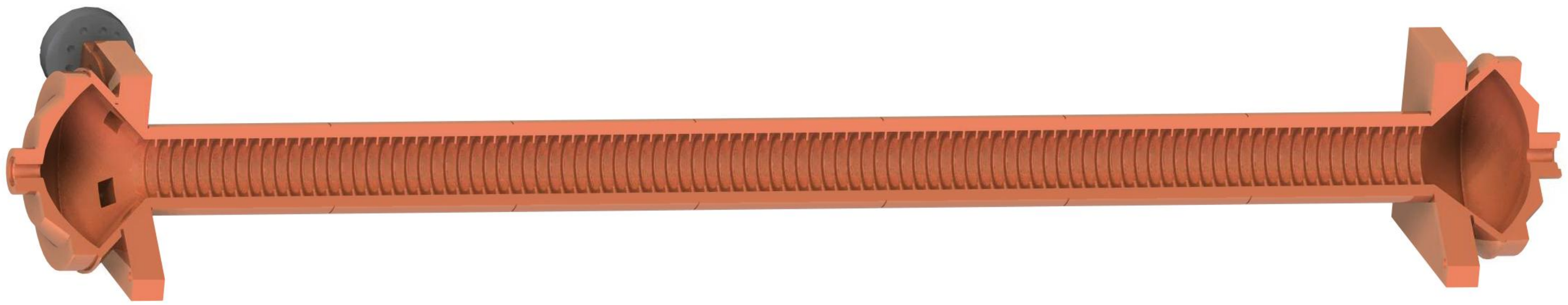


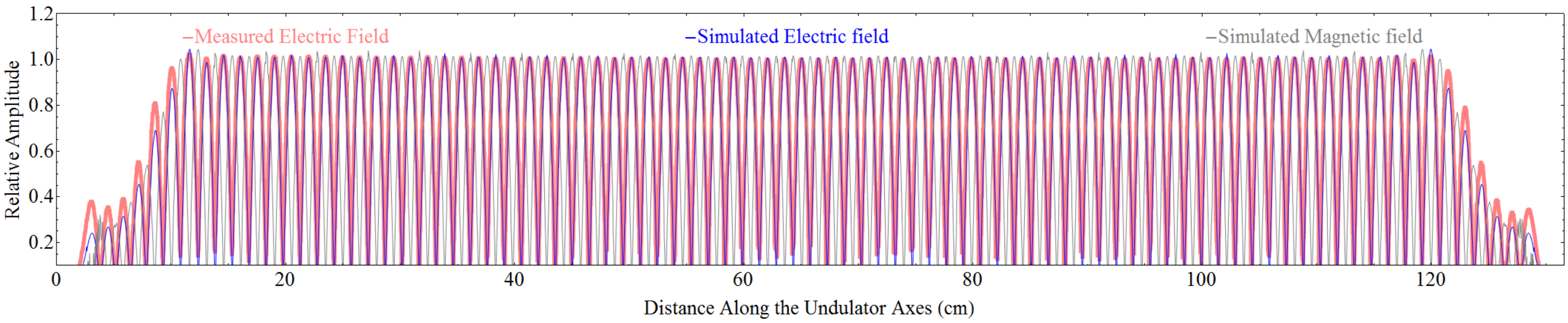
Calculations from cold test data @ 20 °C with air:

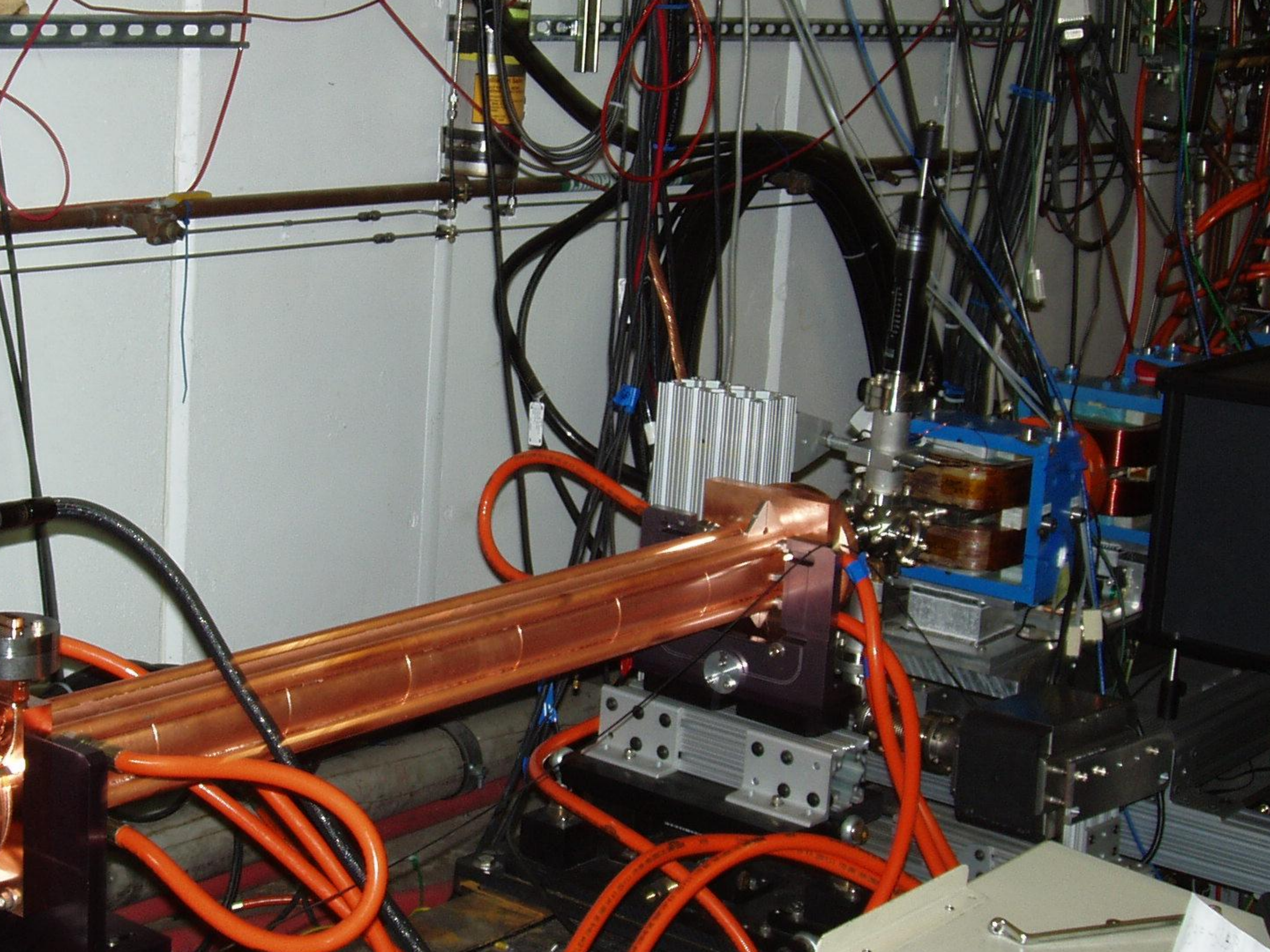
Resonance Frequency (f_0) = 11.419 GHz (11.424 under vacuum @12.1 °C)

β = 1.53, $Q_0 = (1+\beta)\, Q_{total}$ = 91,000 (Simulations 94,000)

Comparison between Simulations and Cold Test Data

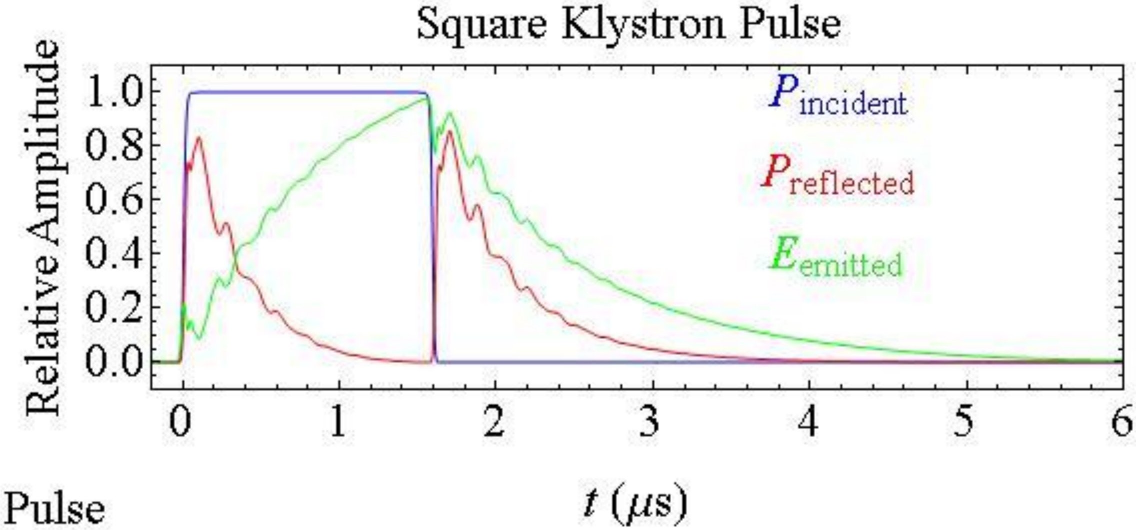


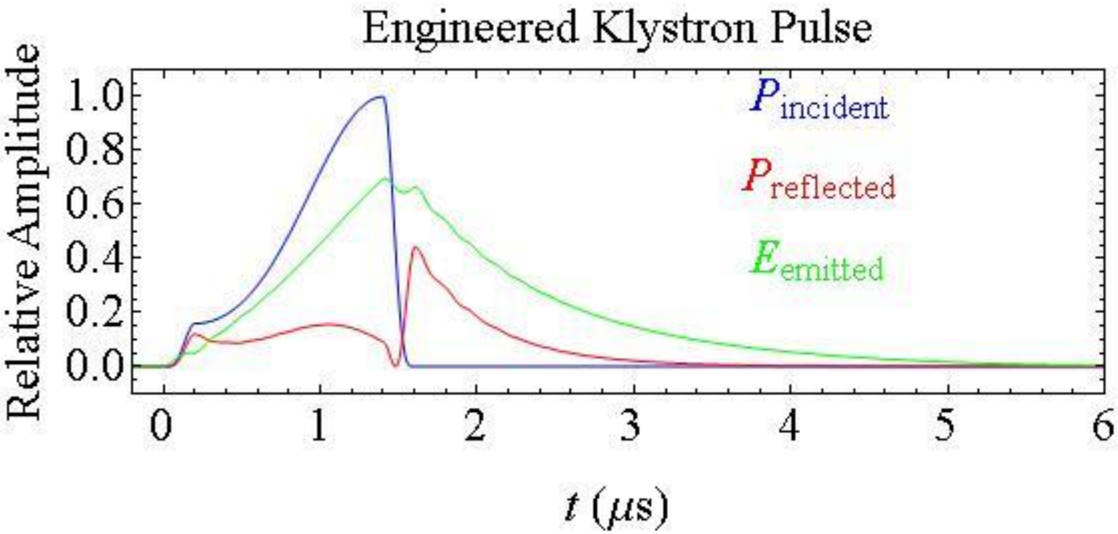


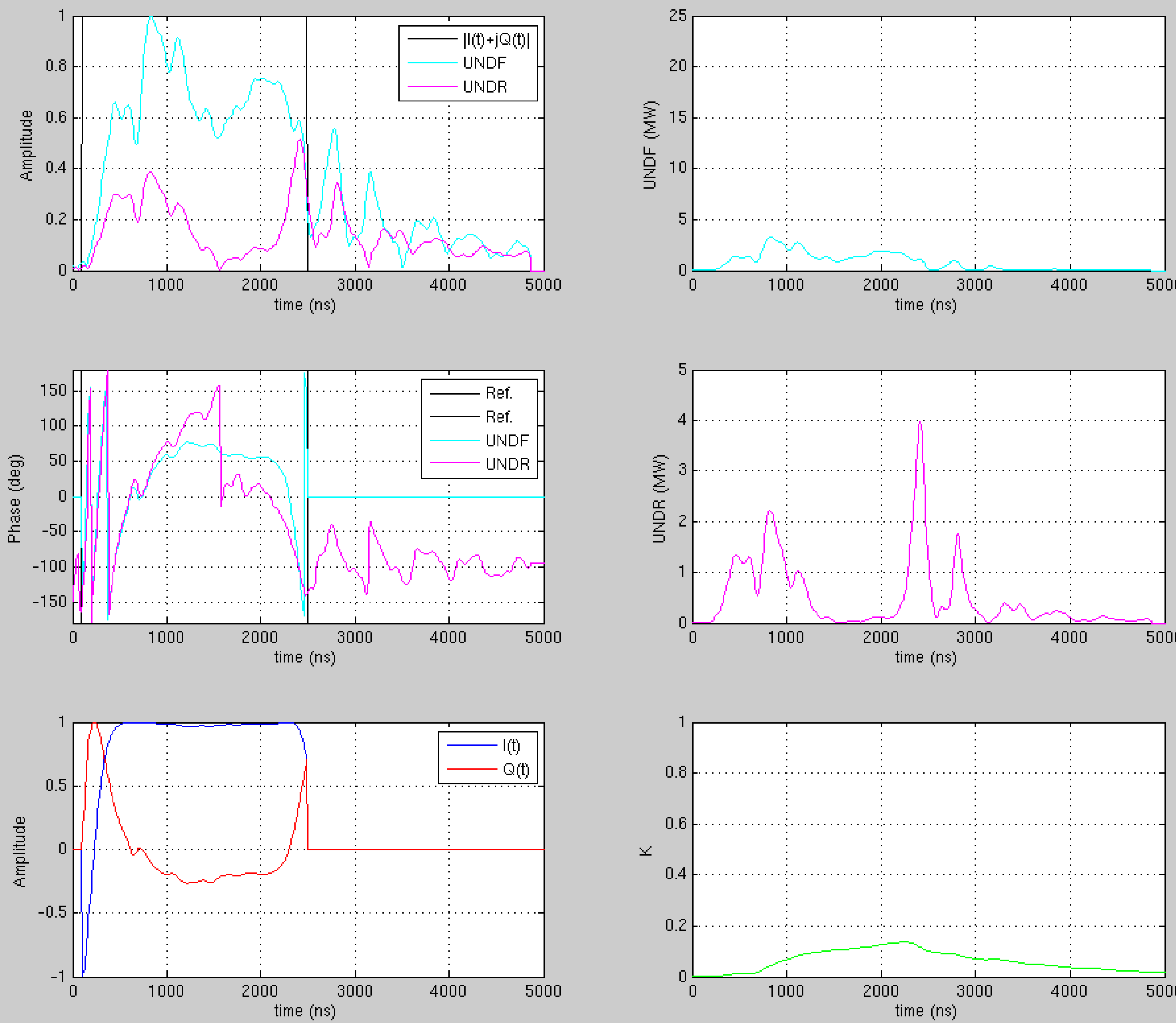


Measured Filling Profile the Structure

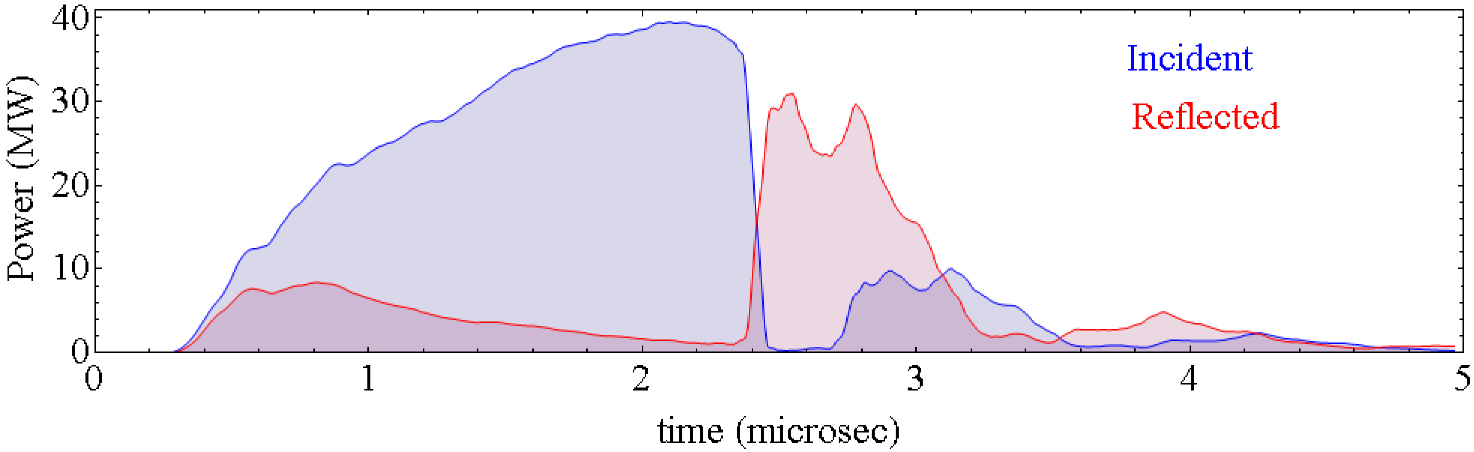
$$E_{emitted} = \sqrt{P_{emitted}} = \sqrt{\frac{2\,\pi\,f_0\,U\,\beta_{coupling}}{Q_0}} \propto K$$

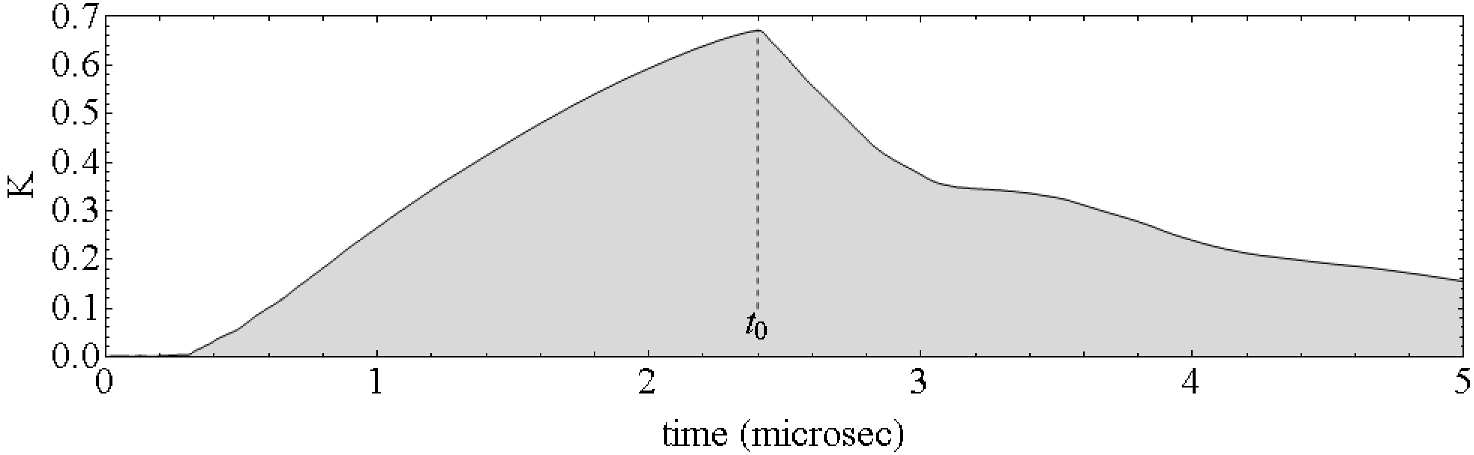


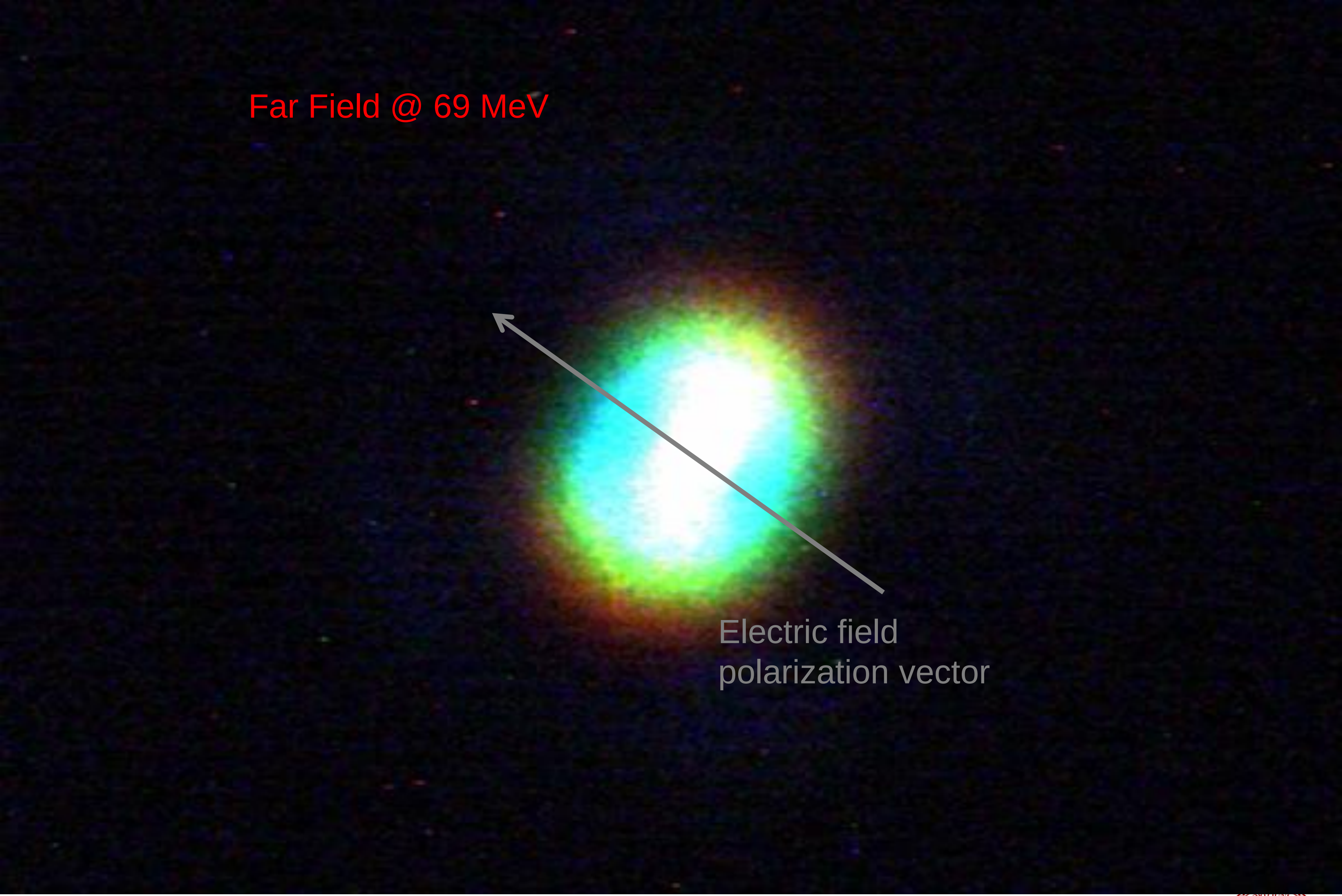


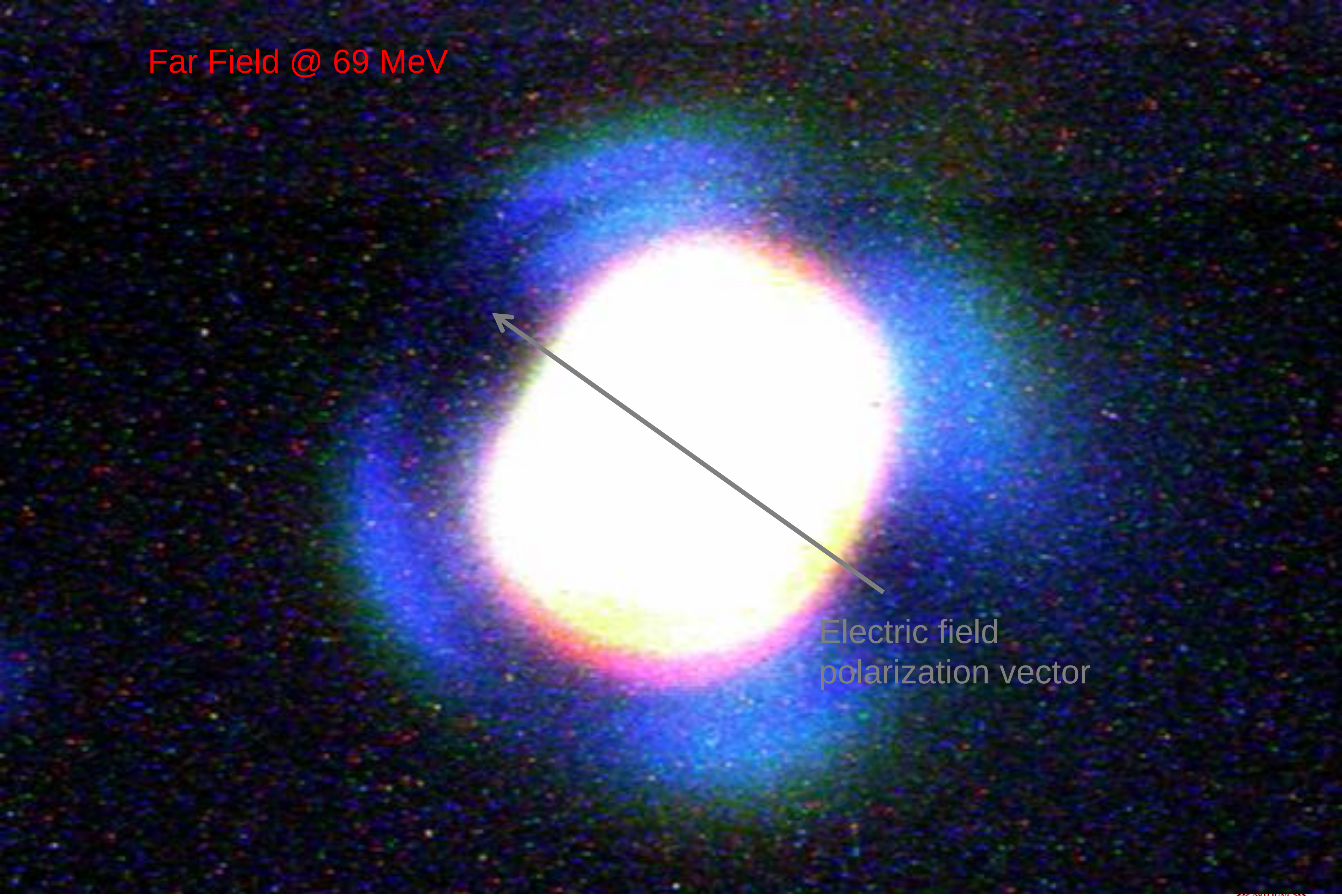

Amplitude
time (ns)
|I(t)+jQ(t)|
UNDF
UNDR
UNDF (MW)
time (ns)
Phase (deg)
time (ns)
Ref.
Ref.
UNDF
UNDR
UNDR (MW)
time (ns)
Amplitude
time (ns)
I(t)
Q(t)
K
time (ns)

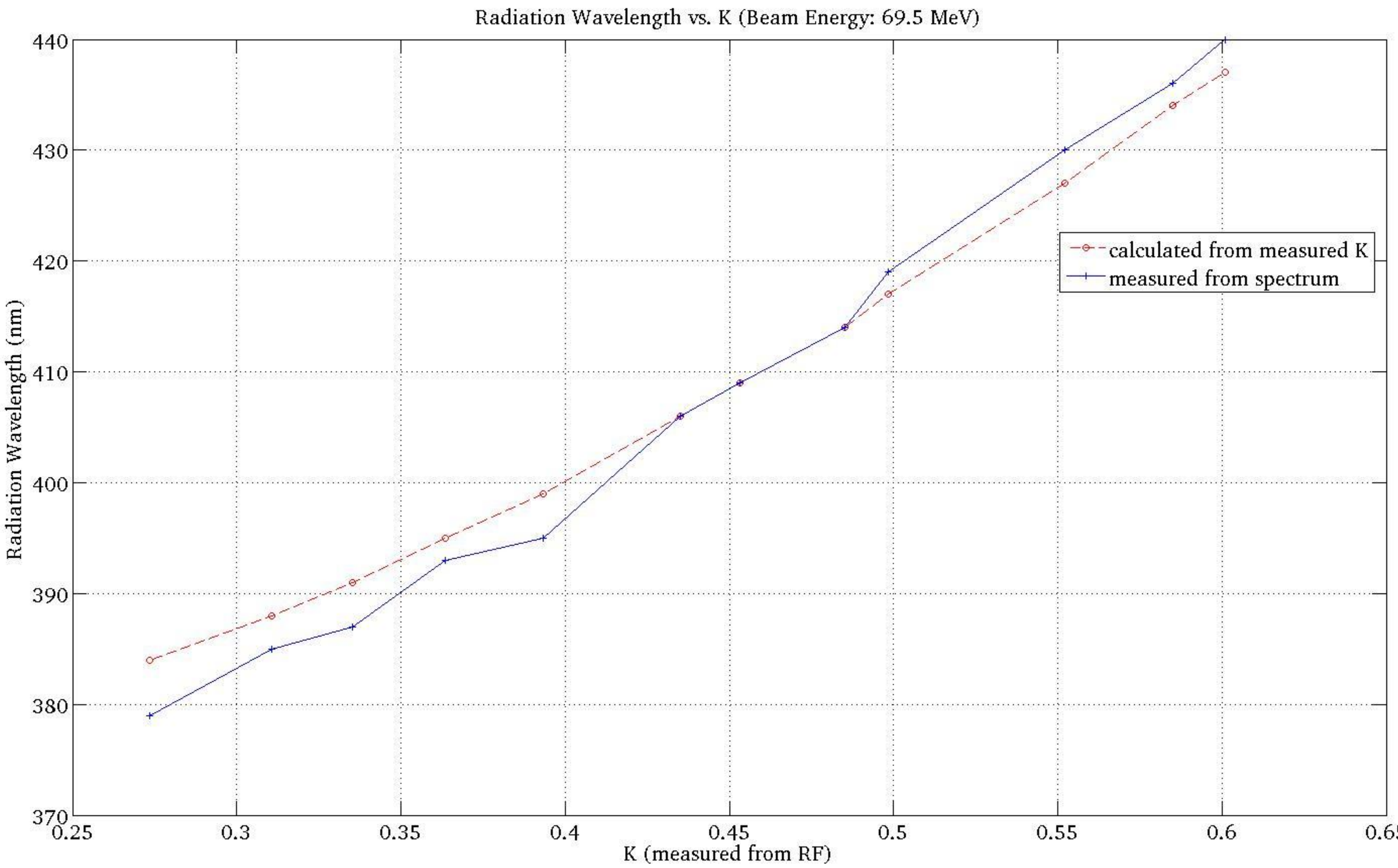
Undulator Operation

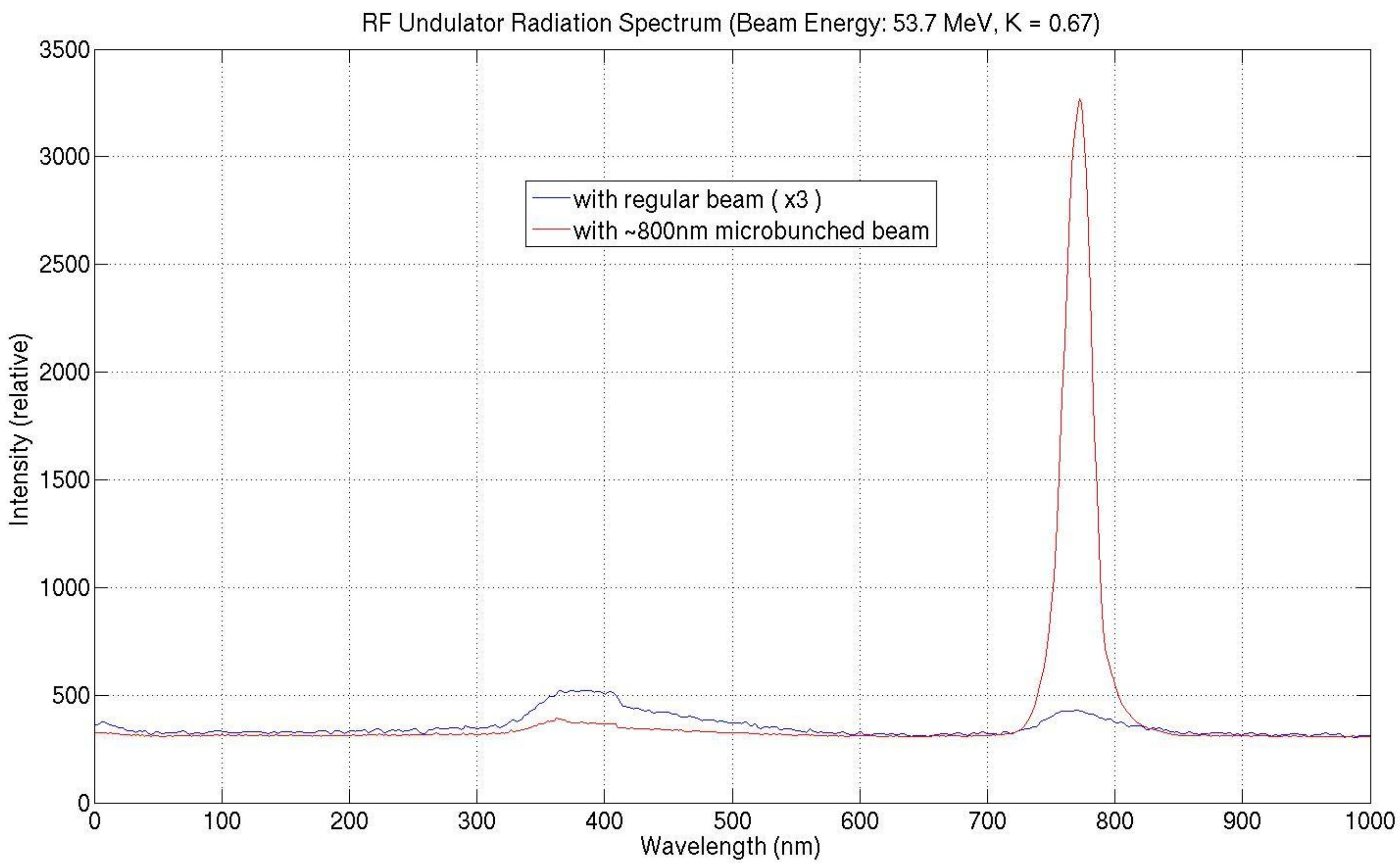


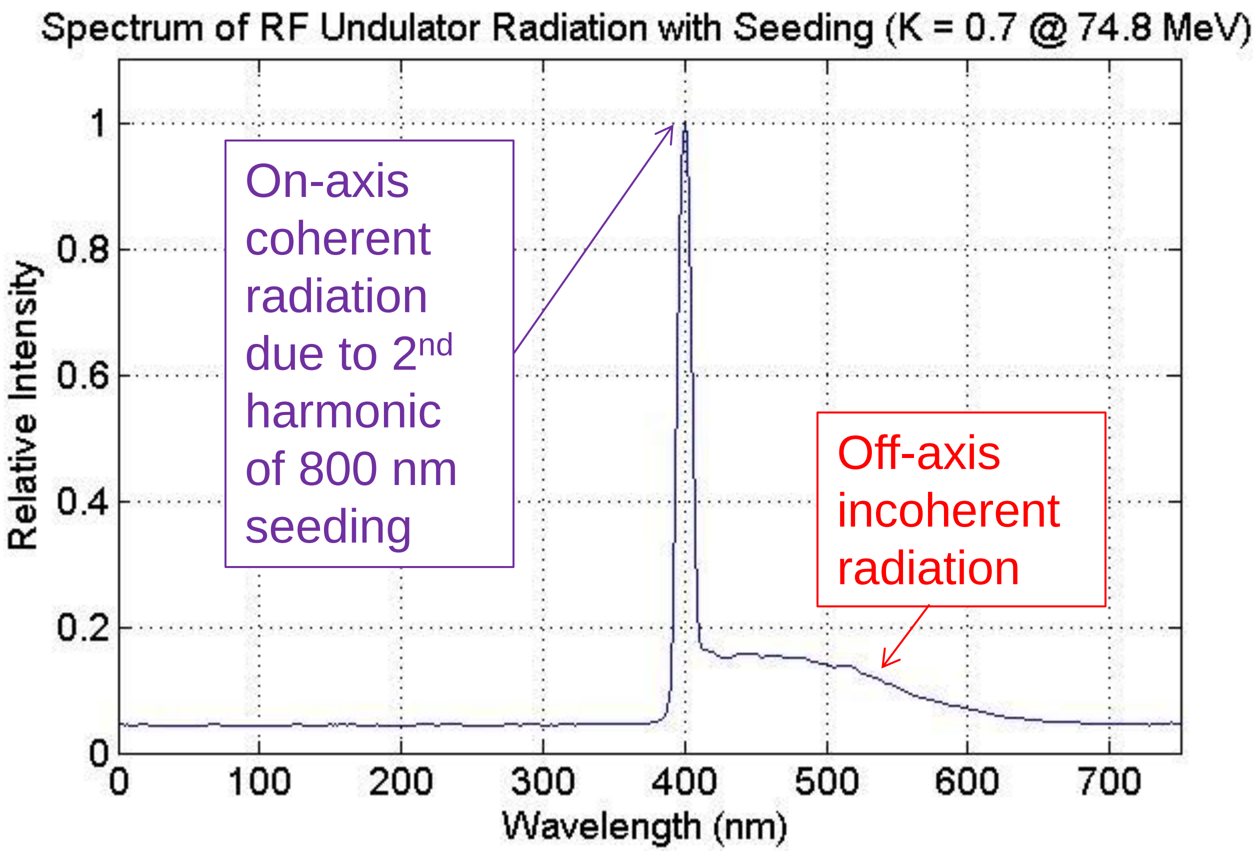



Far Field @ 69 MeV
Electric field
polarization vector


Far Field @ 69 MeV
Electric field
polarization vector


Radiation Wavelength vs. K (Beam Energy: 69.5 MeV)
Radiation Wavelength (nm)
K (measured from RF)
calculated from measured K
measured from spectrum
440
430
420
410
400
390
380
370
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65


RF Undulator Radiation Spectrum (Beam Energy: 53.7 MeV, K = 0.67)
with regular beam (x3)
with ~800nm microbunched beam
Intensity (relative)
Wavelength (nm)
0
500
1000
1500
2000
2500
3000
3500
0
100
200
300
400
500
600
700
800
900
1000

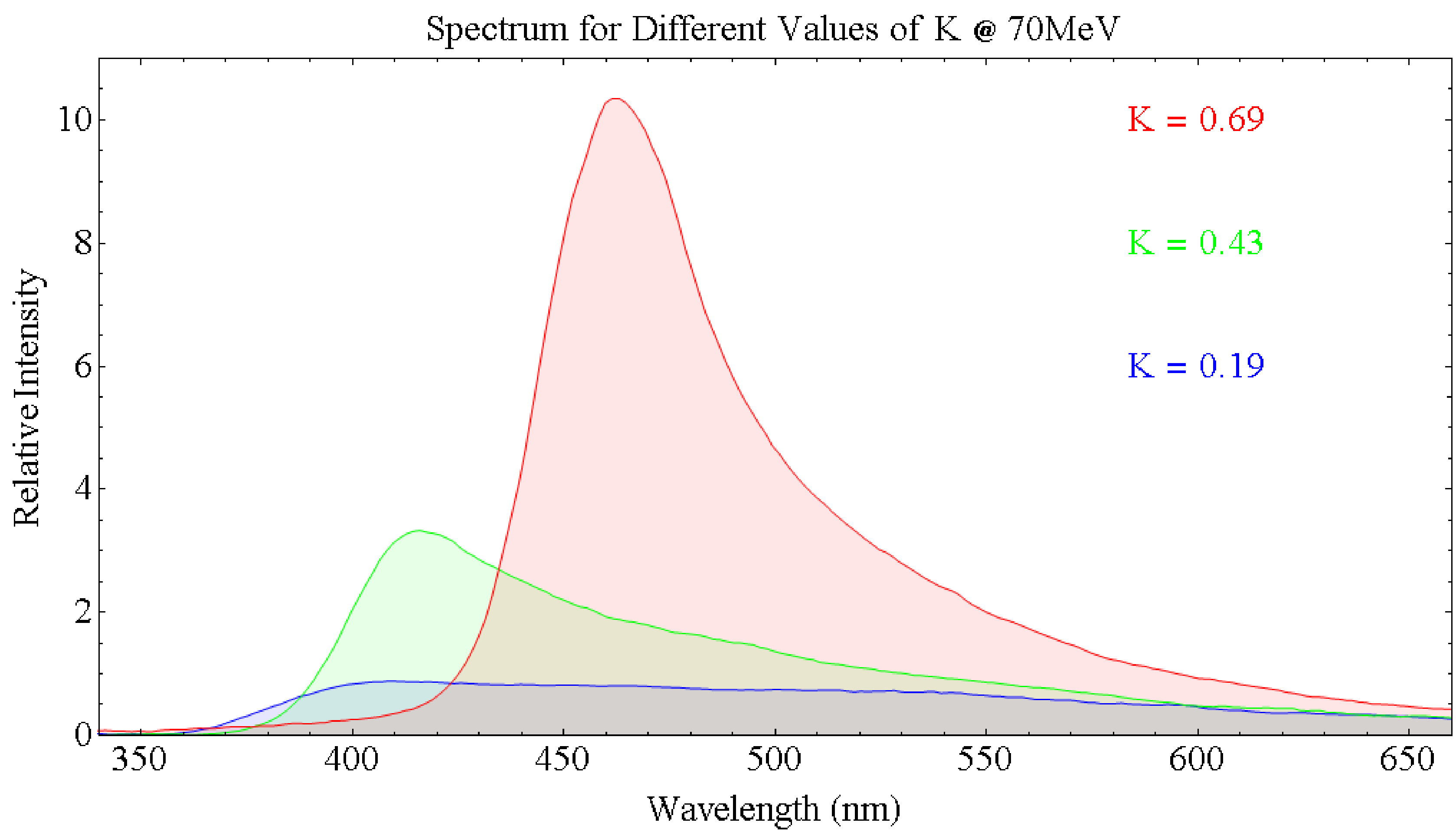


Date of measurements: July 18, 2012 (The idea of these measurements was initated by Erik Hemsing)

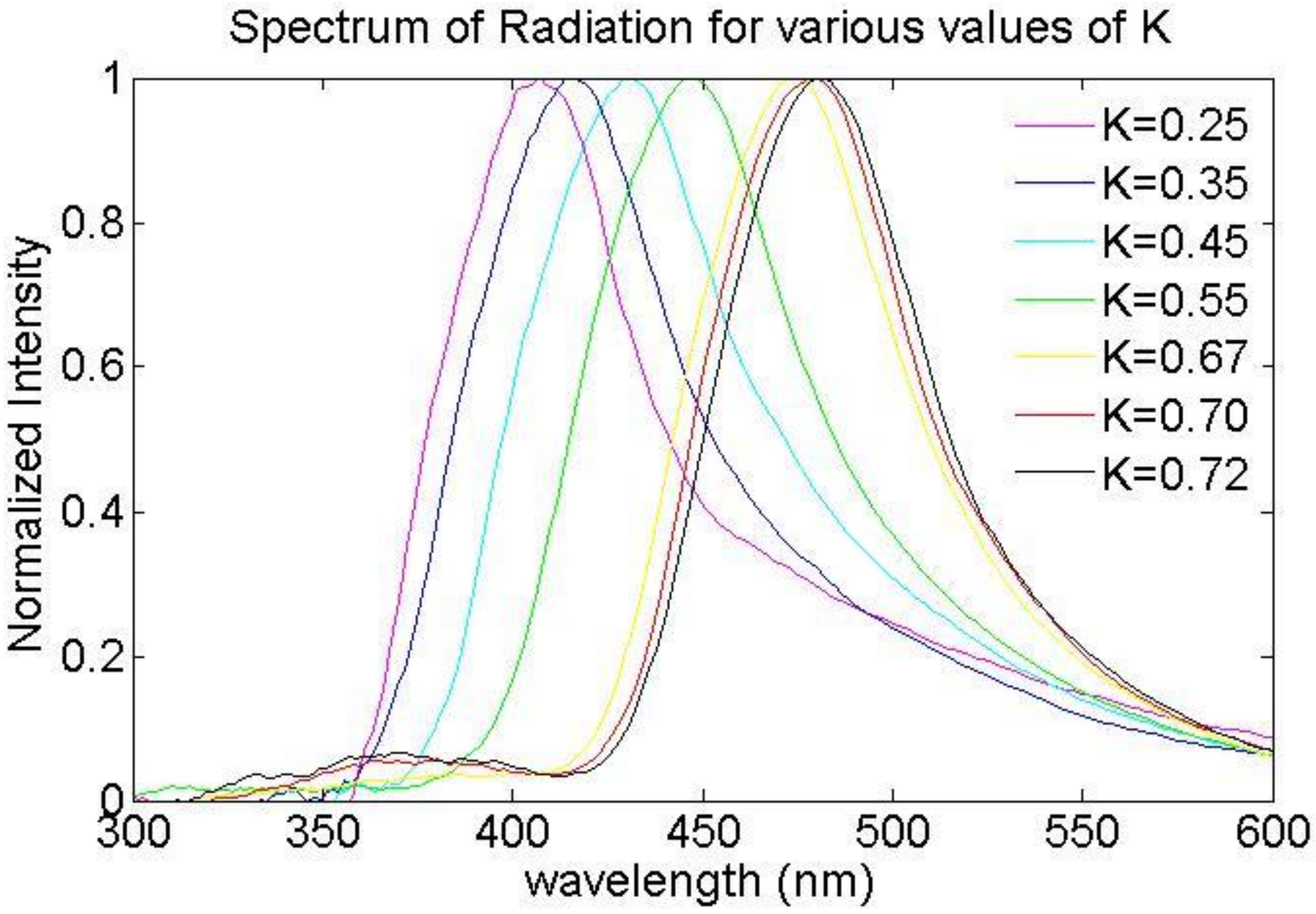
Far Field @ 74.8 MeV

Without seed

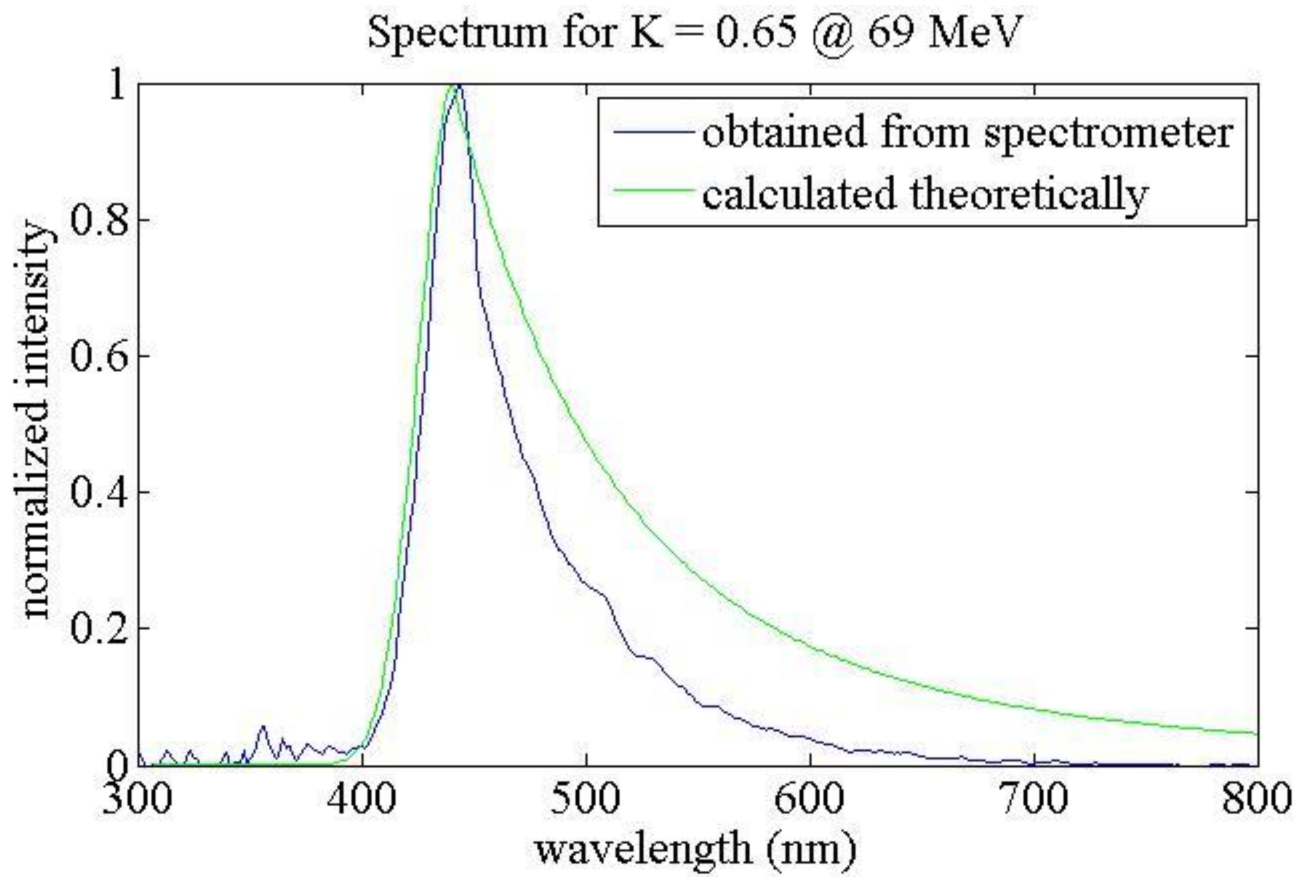
With 800 nm seed


Spectrum for Different Values of K @ 70MeV
K = 0.69
K = 0.43
K = 0.19
Relative Intensity
Wavelength (nm)
0
2
4
6
8
10
350
400
450
500
550
600
650

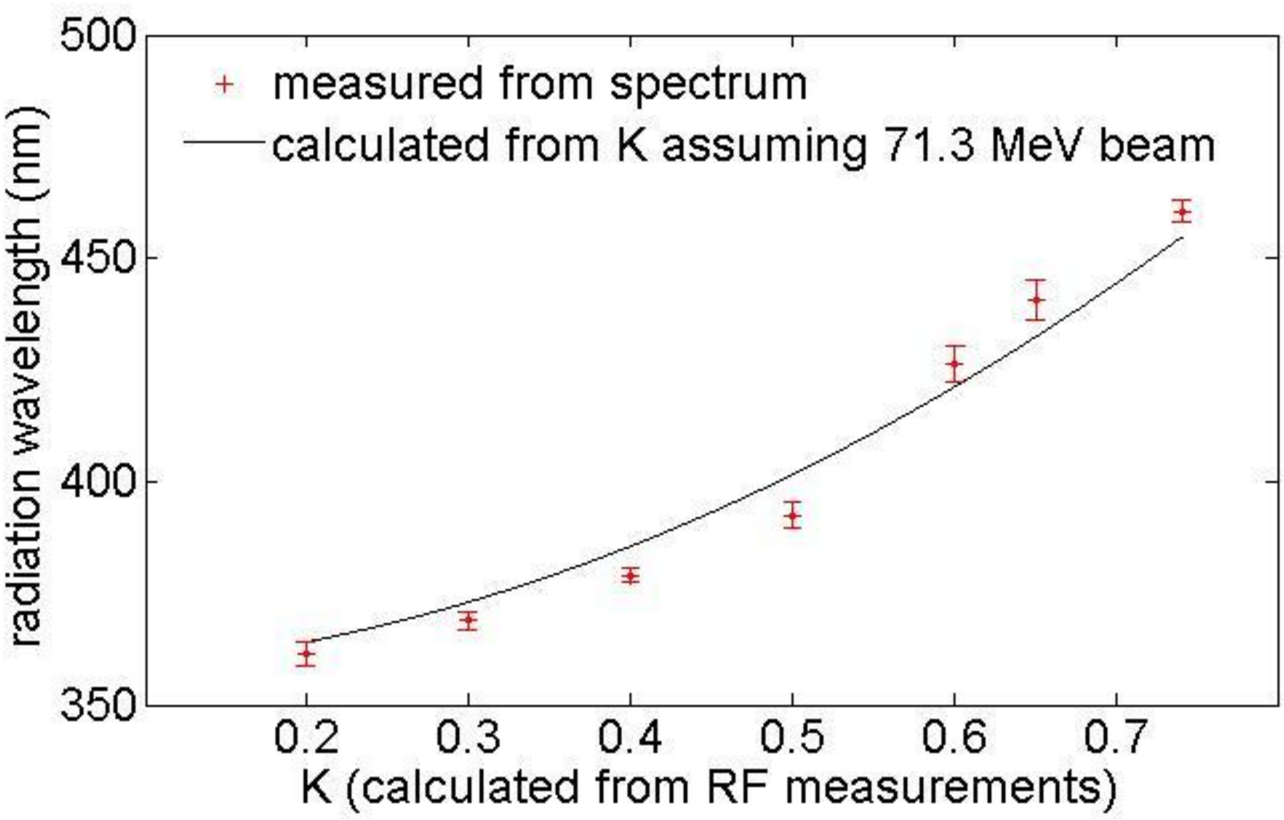
Spectrum shift as a function of K



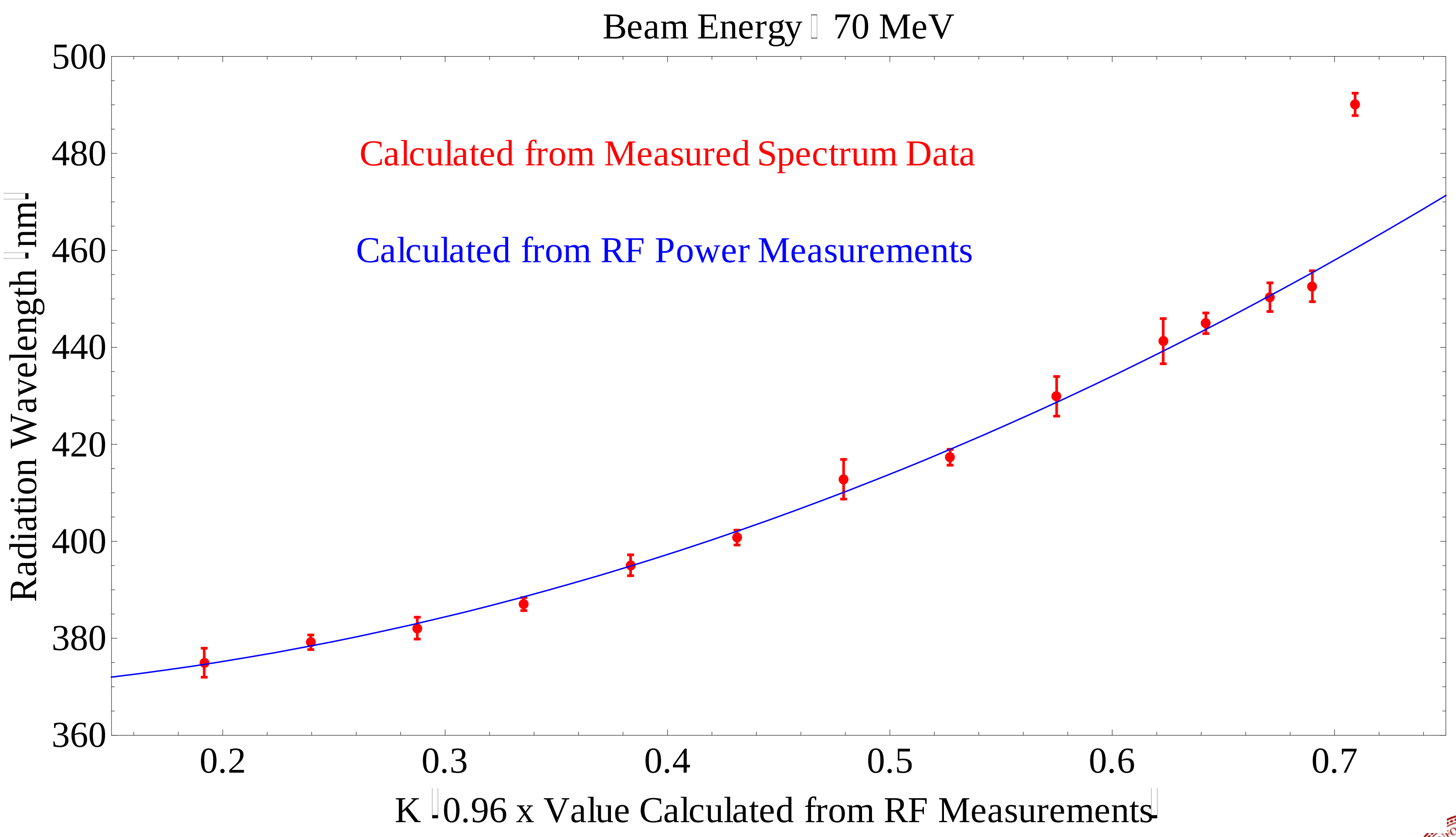
Fitting the Measured Spectrum



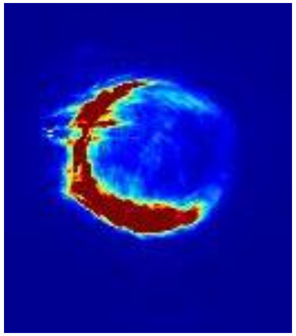
Raw Measurements

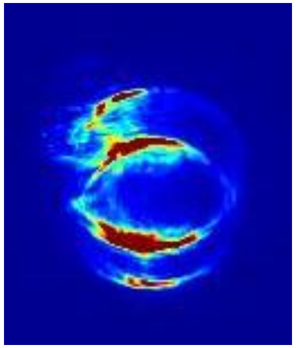


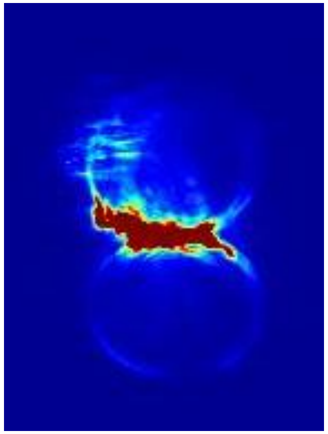
Measurements of the undulator K parameter



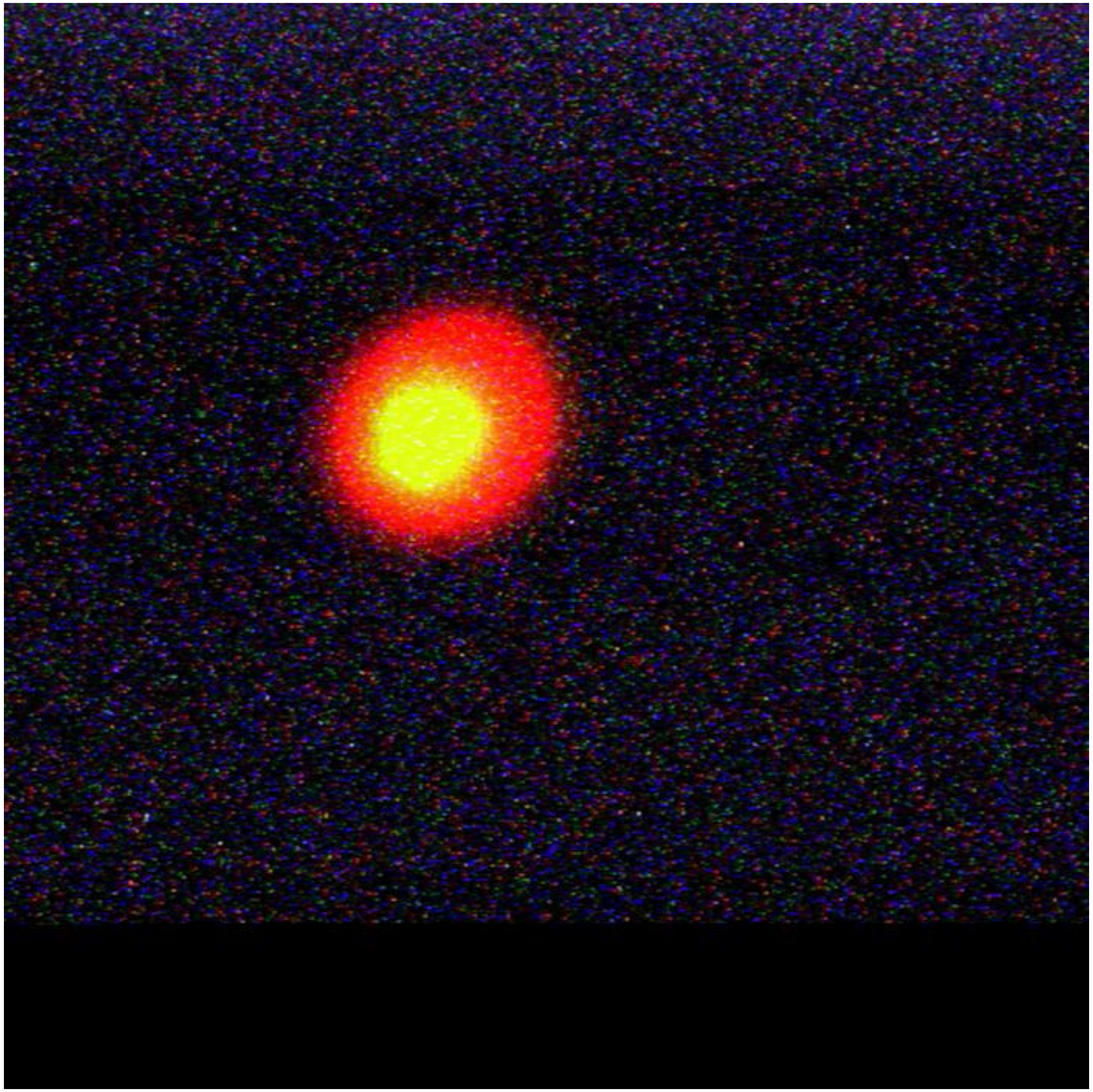
Stn0 m20



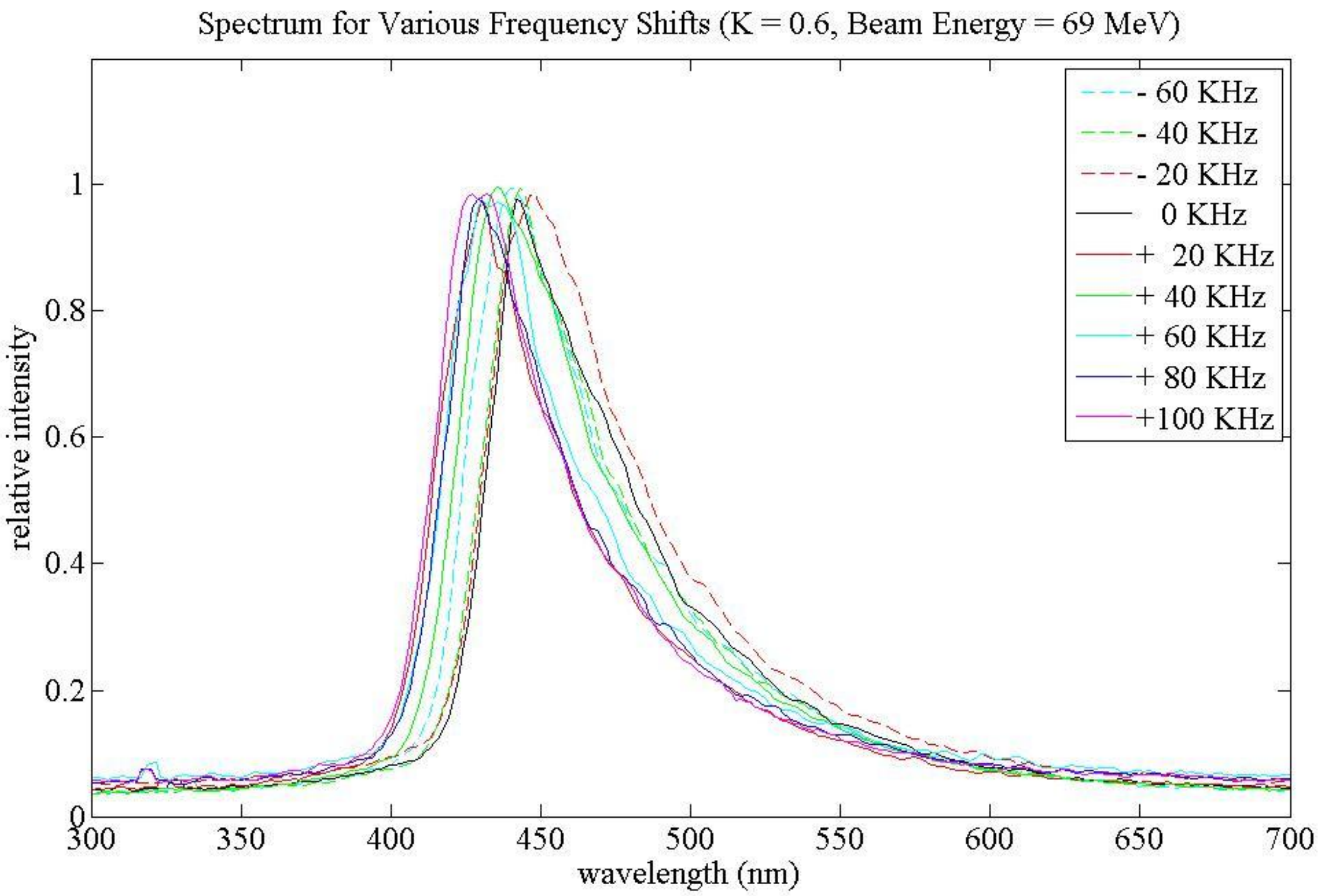




Polarization Plate Rotate

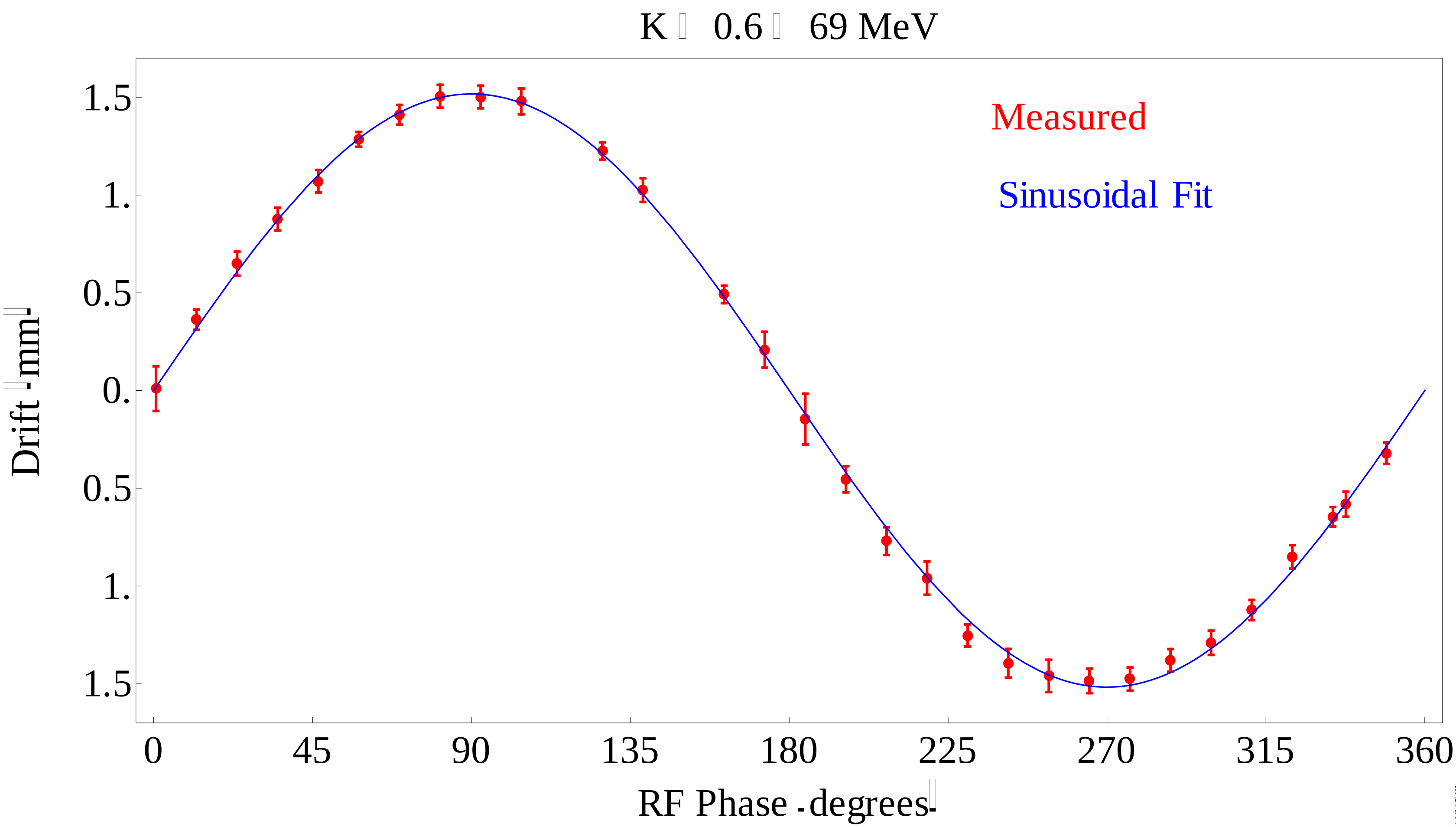


Sensitivity to input frequency shift



Beam Shift

Max drift (measured) = 1.52 ± 0.03 mm (assuming 0.094 ± 0.002 mm/pixel)
Max drift (calculated) = 1.27 mm



An HE_{11} Undulator as an After Burner for LCLS

$$a = 7.848cm$$

$$\lambda u = 5.55169cm$$

B_p =310 mTesla

$$K = 2.48$$

Vg/c=0.83

Vp=1.12

$TotalPower$=46MW

$$FillingTime = 7.5427$$

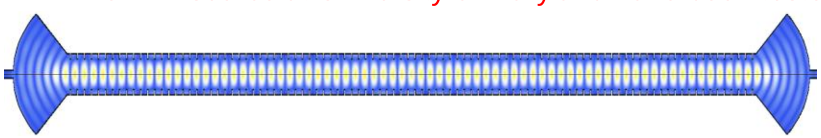
Stored Energy=346 Jouls

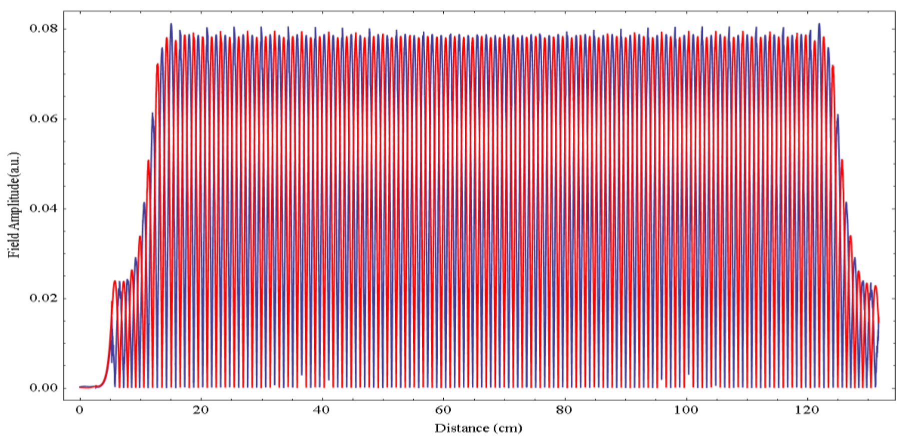
Peak Electric Field at Guide Wall=40 MV/m

$$Energy\ Supllied\ by\ One\ 5045\ Klystron\ is\ 228\ Joules$$

Metallic structure driven by a THz source

- Status of the development:
  - A *novel* concept for using the *balanced hybrid mode* in corrugated waveguide to create ultra-high filed in the center of the waveguide with relatively small surface fields have been developed.
  - The scaling laws for this device have been developed.
  - The phase conjugate end mirrors have been developed
  - The single particle dynamics and the end field profile required to minimize both integrated transverse momentum kick and total transverse displacement have been studied and implemented in the design
  - A prototype at designed with 1.4 cm undulator wavelength is under construction to test the concepts. The undulator is expected to have a K parameter of ~1 with possibility of switching the polarization by controlling the phases of the RF source
  - Initial test for this undulator with beams is scheduled on June 18 at NLCTA at SLAC.
  - The THz structure is being designed mechanically.
  - The THz source at University of Maryland have been tested up to 80 KW recently with a pulse length of 7 uS.





Parameters for 221 micron undulator (corresponding to the available 680 GHz source; with pulse compression few MW could be achieved using this source)

$$P(MW) \approx \frac{0.24K^2L^{2/3}}{\lambda_u^{7/6}}$$

900 kW for K=0.03,
10 MW for K=0.1 (5.5 T)

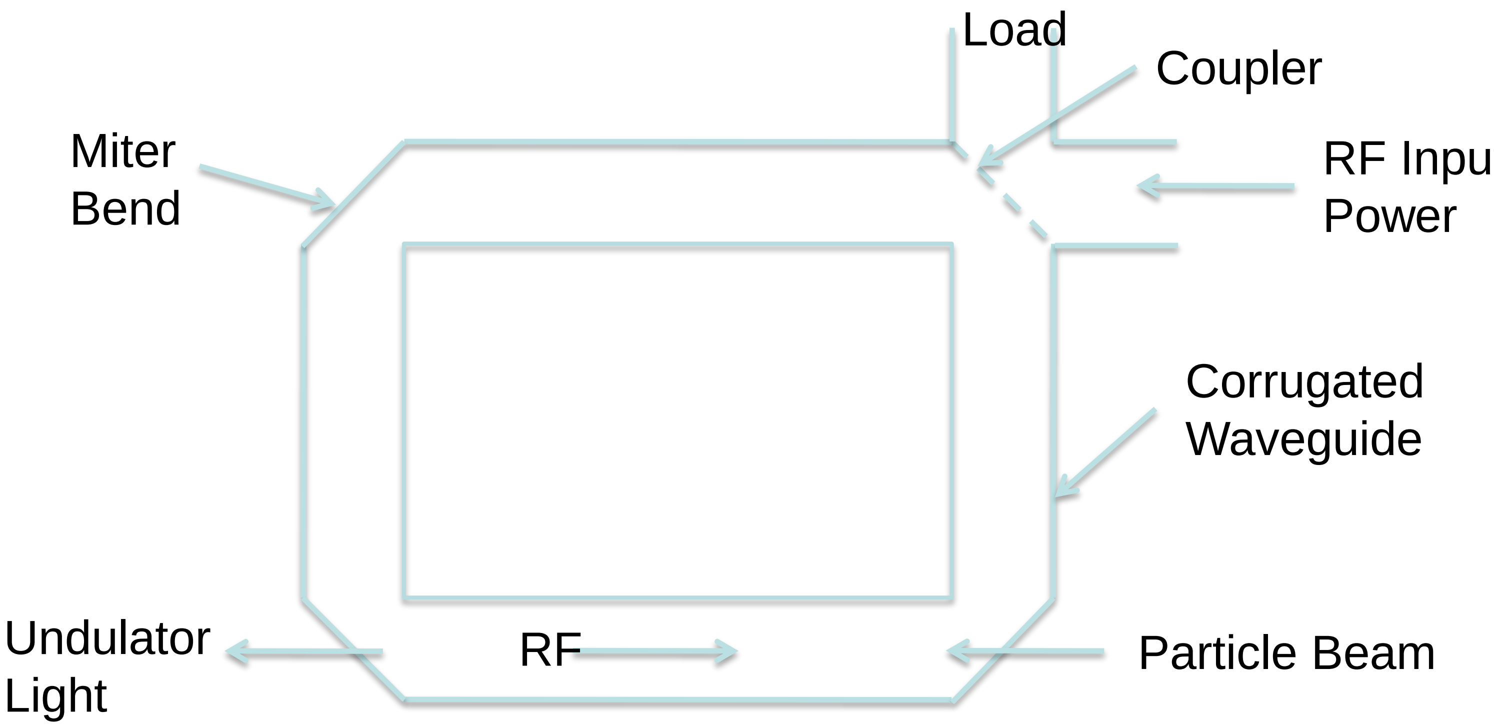
$$t_{filling}(\mu s) = 32.8L\sqrt{\lambda_u}$$

48 ns filling time

$$a(m) = 0.41\lambda_u^{2/3}\sqrt[3]{L}$$

1.4 mm diameter aperture

Resonant Ring Configuration



- A closed ring with length $n\lambda g$
- Tune by adjusting ring length
- Considerable development for relevant components (miter bend, couplers) has been done (ITER transmission lines)

200 micron Wavelength Undulator

We have explored three possible designs:

- Dielectric tube or dielectric slab guiding structure
  - Simple to design, and build.
  - The source is the 5 micron laser being developed for the accelerator structure.
  - The electromagnetic wave co propagates with the electron beam to stretch the undulator wavelength to 200 microns.
  - forces due to electric and magnetic fields tend to cancel each other, hence, the surface and bulk fields are high in comparison the net equivalent deflecting field.
  - The filed is guided within the volume of the dielectric and the beam interacts with the evanescent field, thus forcing the undulator aperture to be close to one wavelength.
- Bragg reflector type structure
  - More complicated to design and build.
  - The source is the 5 micron laser being developed for the accelerator structure.
  - The electromagnetic wave co propagates with the electron beam to stretch the undulator wavelength to 200 microns.
  - forces due to electric and magnetic fields tend to cancel each other, hence, the surface and bulk fields are high in comparison the net equivalent deflecting field.
  - The filed is guided within the vacuum region surrounded by the Bragg guiding structure. the beam interacts with the bulk of the field, thus allowing the undulator aperture to be large compared to the wavelength.

200 micron Wavelength Undulator (Continued)

- Metallic structure driven by a THz source
  - Very complicated to design, but easier to build.
  - The source is a THz high power source. Compact pulsed Gyrotrons have been recently developed at 680 GHz at University of Maryland. Size is comparable to lasers. Other sources are under development.
  - The electromagnetic wave counter propagates with the electron beam thus reducing the undulator wavelength by a factor of two from the THz radiation wavelength.
  - Forces due to electric and magnetic fields add to each other, hence, the surface and bulk fields are small in comparison the net equivalent deflecting field. Potentially this approach will produce the highest possible K parameter at 200 micron wavelength
  - The filed is guided within the vacuum region surrounded by a metallic corrugated structure. the beam interacts with the bulk of the field, thus allowing the undulator aperture to be *extremely* large compared to the wavelength.

General expressions for a monochromatic circularly symmetric Field

$$\mathbf{Ez} = \frac{2x\sqrt{2\hat{\lambda u}-1}\,\sin(\phi)\,J_1\left(\frac{2\pi\hat{r}\sqrt{2\hat{\lambda u}-1}}{\hat{\lambda u}}\right)}{x+1}$$

$$\mathbf{Hz} = \frac{2\sqrt{2\hat{\lambda u}-1}\,\cos(\phi)\,J_1\left(\frac{2\pi\hat{r}\sqrt{2\hat{\lambda u}-1}}{\hat{\lambda u}}\right)}{xZ+Z}$$

$$\mathbf{Er} = \frac{i\,\hat{\lambda u}^2\sin(\phi)\left(J_1\left(\frac{2\pi\hat{r}\sqrt{2\hat{\lambda u}-1}}{\hat{\lambda u}}\right)-\frac{\pi\hat{r}x(\hat{\lambda u}-1)\sqrt{2\hat{\lambda u}-1}\left(J_0\left(\frac{2\pi\hat{r}\sqrt{2\hat{\lambda u}-1}}{\hat{\lambda u}}\right)-J_2\left(\frac{2\pi\hat{r}\sqrt{2\hat{\lambda u}-1}}{\hat{\lambda u}}\right)\right)}{\hat{\lambda u}^2}\right)}{\pi\hat{r}(x+1)\sqrt{2\hat{\lambda u}-1}}$$

$$\mathbf{E\phi} = -\frac{i\,\hat{\lambda u}\cos(\phi)\left(x(\hat{\lambda u}-1)J_1\left(\frac{2\pi\hat{r}\sqrt{2\hat{\lambda u}-1}}{\hat{\lambda u}}\right)-\pi\hat{r}\sqrt{2\hat{\lambda u}-1}\,J_0\left(\frac{2\pi\hat{r}\sqrt{2\hat{\lambda u}-1}}{\hat{\lambda u}}\right)+\pi\hat{r}\sqrt{2\hat{\lambda u}-1}\,J_2\left(\frac{2\pi\hat{r}\sqrt{2\hat{\lambda u}-1}}{\hat{\lambda u}}\right)\right)}{\pi\hat{r}(x+1)\sqrt{2\hat{\lambda u}-1}}$$

$$\mathbf{Hr} = \frac{i\,\hat{\lambda u}^2\cos(\phi)\left(xJ_1\left(\frac{2\pi\hat{r}\sqrt{2\hat{\lambda u}-1}}{\hat{\lambda u}}\right)-\frac{\pi\hat{r}(\hat{\lambda u}-1)\sqrt{2\hat{\lambda u}-1}\left(J_0\left(\frac{2\pi\hat{r}\sqrt{2\hat{\lambda u}-1}}{\hat{\lambda u}}\right)-J_2\left(\frac{2\pi\hat{r}\sqrt{2\hat{\lambda u}-1}}{\hat{\lambda u}}\right)\right)}{\hat{\lambda u}^2}\right)}{\pi\hat{r}(x+1)Z\sqrt{2\hat{\lambda u}-1}}$$

$$\mathbf{H\phi} = \frac{i\,\hat{\lambda u}\sin(\phi)\left(-\pi\hat{r}x\sqrt{2\hat{\lambda u}-1}\,J_0\left(\frac{2\pi\hat{r}\sqrt{2\hat{\lambda u}-1}}{\hat{\lambda u}}\right)+\pi\hat{r}x\sqrt{2\hat{\lambda u}-1}\,J_2\left(\frac{2\pi\hat{r}\sqrt{2\hat{\lambda u}-1}}{\hat{\lambda u}}\right)+(\hat{\lambda u}-1)J_1\left(\frac{2\pi\hat{r}\sqrt{2\hat{\lambda u}-1}}{\hat{\lambda u}}\right)\right)}{\pi\hat{r}(x+1)Z\sqrt{2\hat{\lambda u}-1}}$$

$$\left.\right\}\, e^{i\left(\omega t-\frac{2\pi z\;\lambda_u-1}{\lambda\lambda_u}\right)}$$

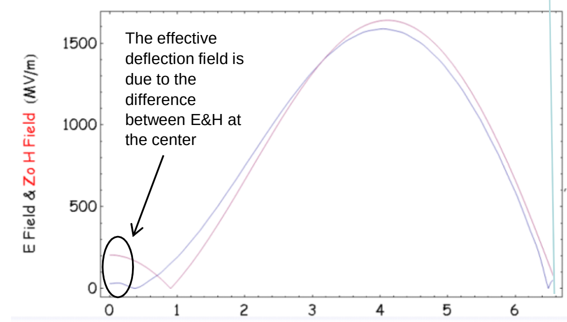
$$\text{Er - Z H}\phi\big|_{r\to 0}=1$$

Stretching the laser wavelength using either dielectric slab or Bragg guiding structure undulator

- The philosophy of the design is to write down the profile of the electromagnetic fields required and then “dress it with materials to guide it”
- There is rather a limited set of fields that
  - satisfy Maxwell’s equations,
  - have a dipole like field and
  - have net deflection as they propagate with the beam
- The field configurations shown in the figures are theoretically the best possible field profiles; i.e., profiles that gives the highest possible deflecting field with minimum surface field.
- Typically the relative group velocity is related to the undulator wavelength by: $v_g / c = \dfrac{\lambda_u / \lambda_0 - 1}{\lambda_u / \lambda_0}$

Bragg guiding structure

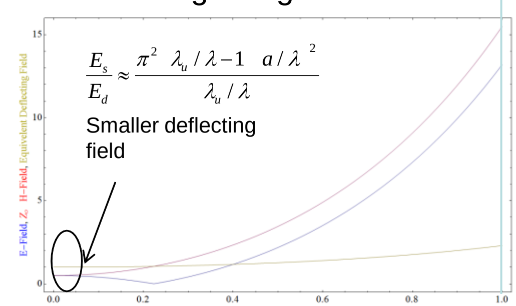
Field is *minimized* at the boundary of the guiding structure.



Radius in unites of wavelength

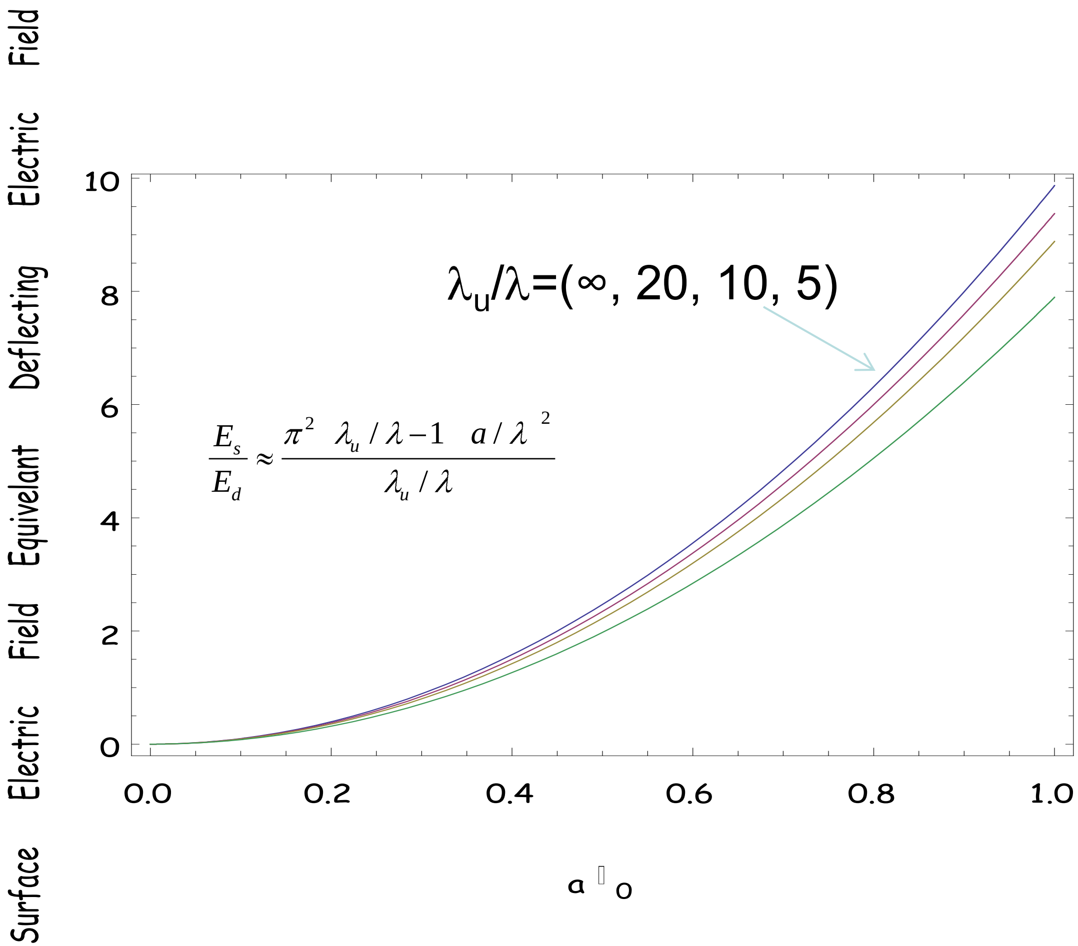
Field is *maximized* at the boundary

Slab guiding structure

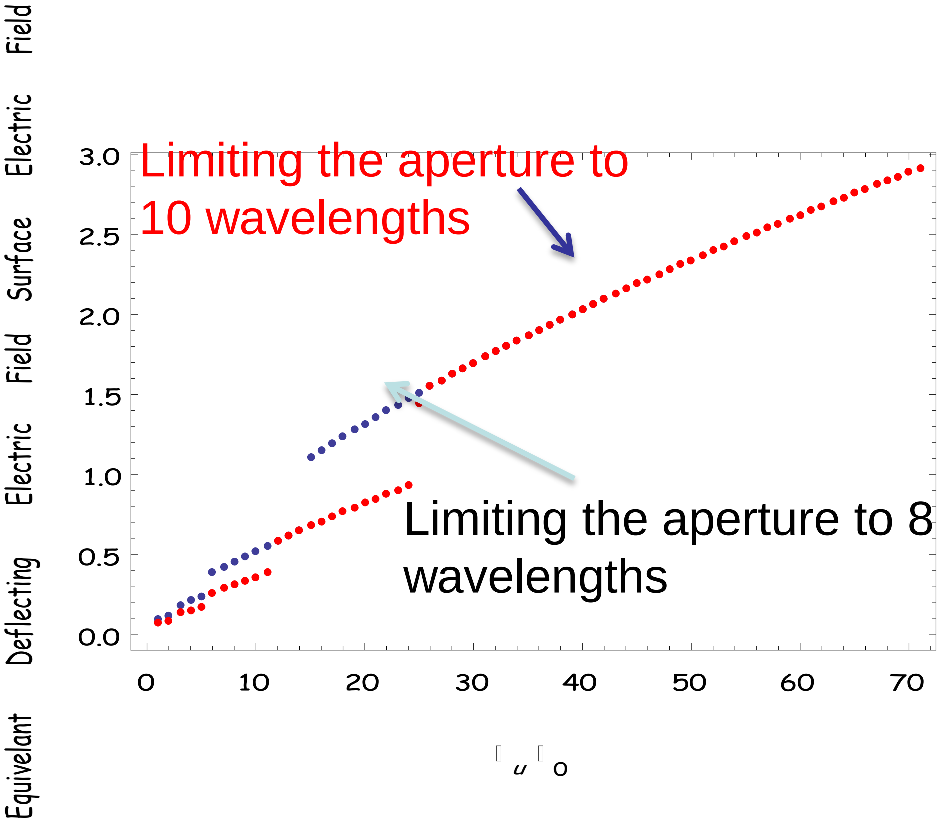


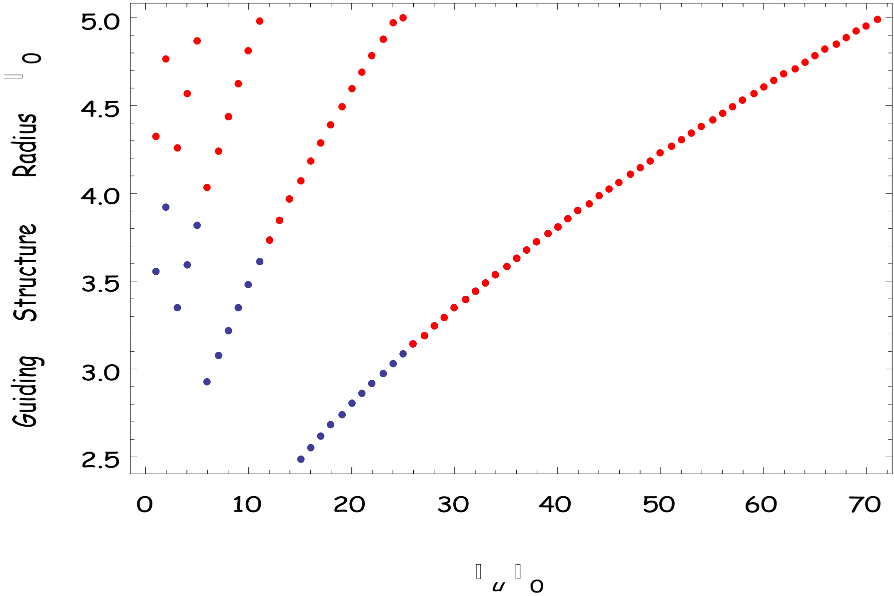
Radius in unites of wavelength

Optimization for a forward interaction RF undulator with small aperture

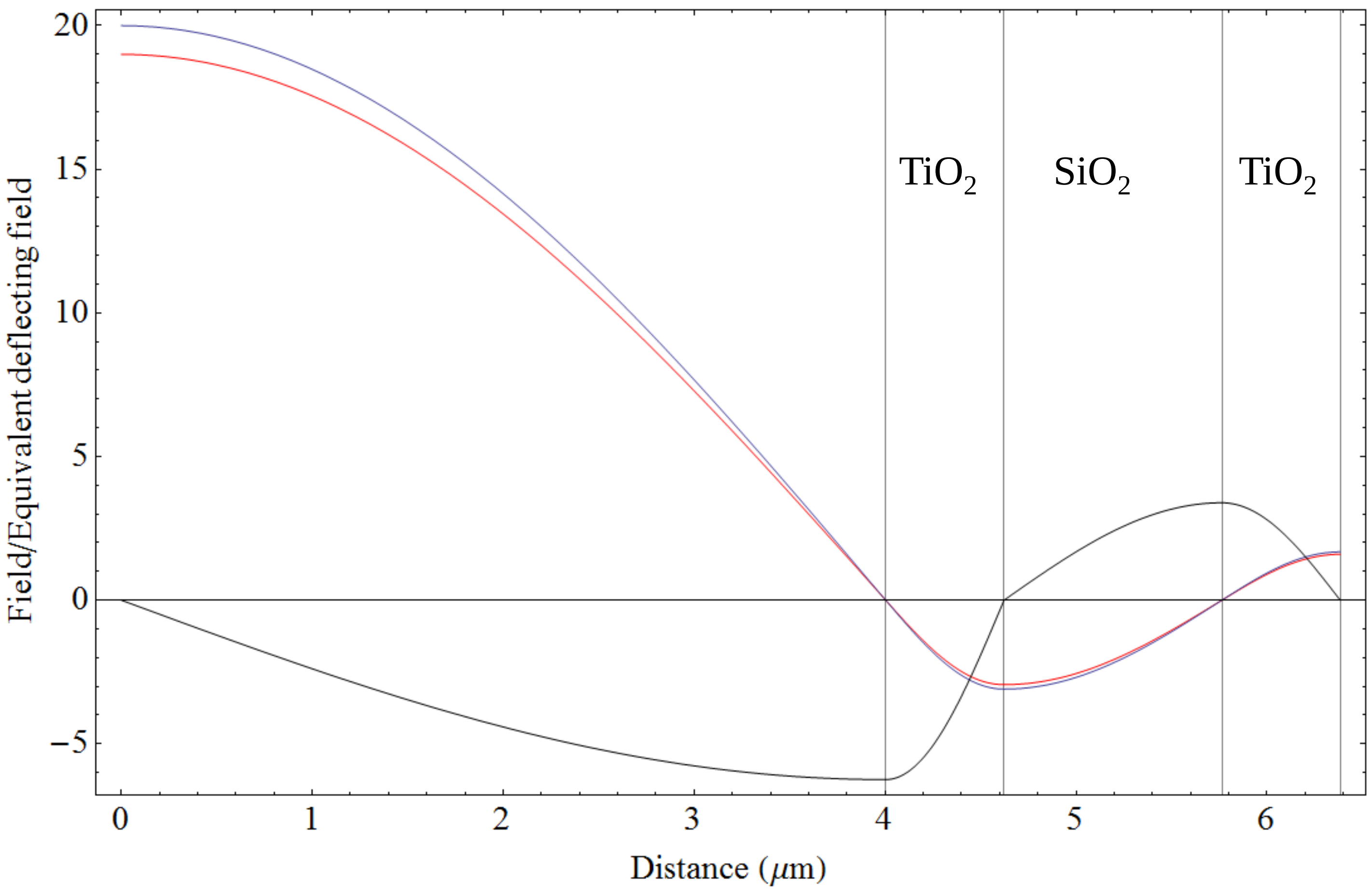


Overmoded optimization for a forward interaction RF undulator

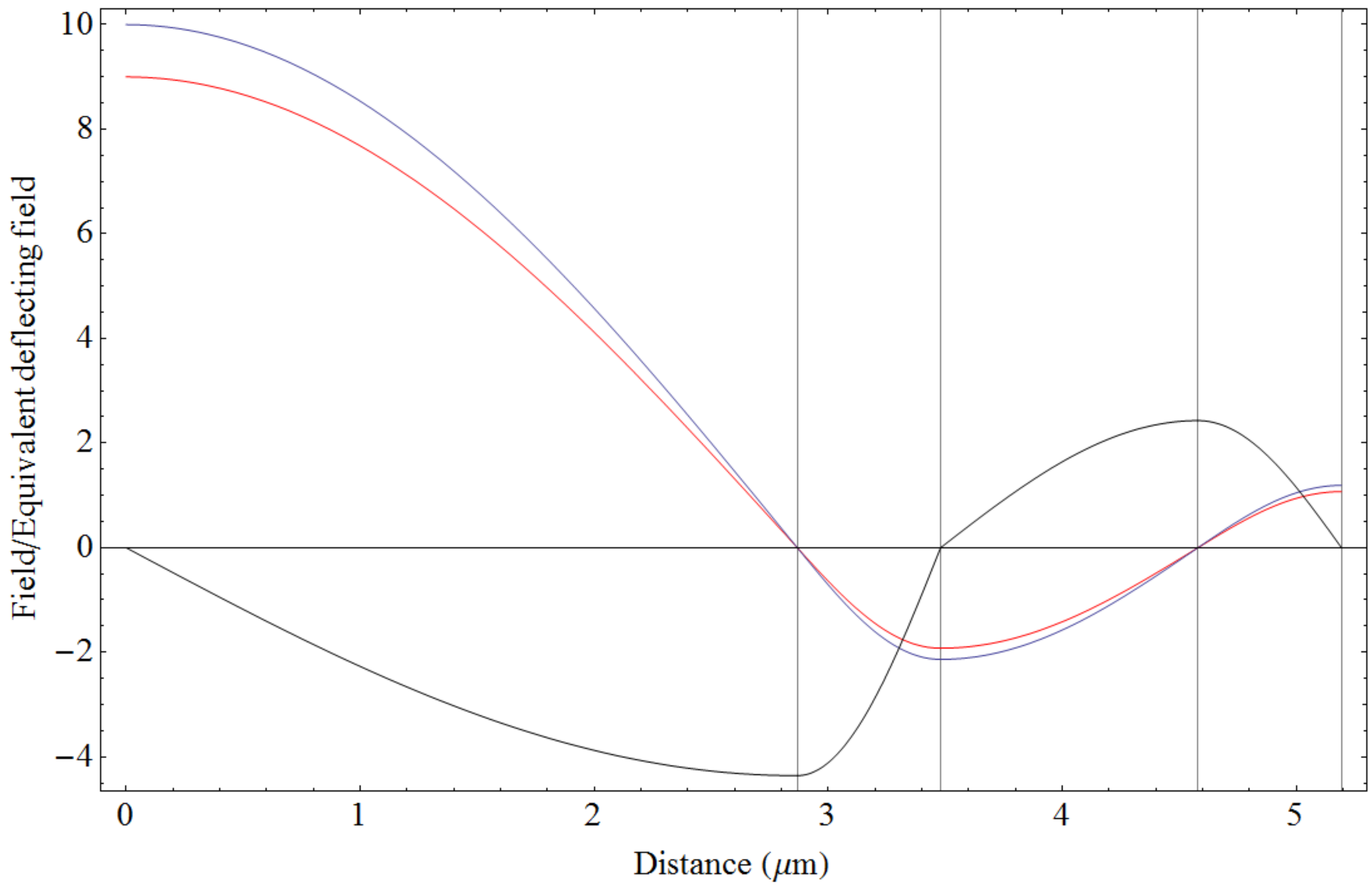




Design example of a planer undulator with an undulator wavelength of 100 micrometer

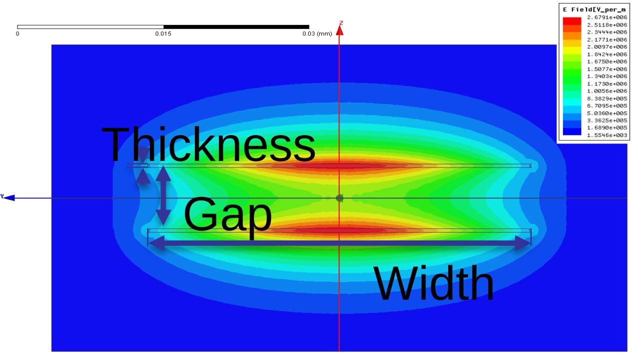


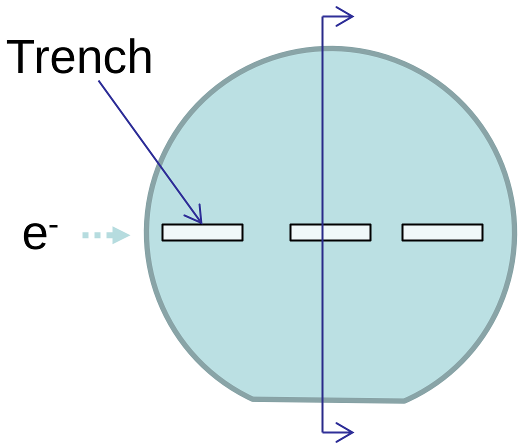
Design example of a planer undulator with an undulator wavelength of 50 micrometer

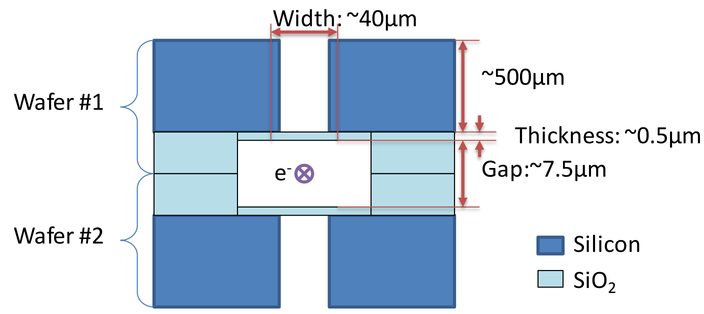


Stretching the laser wavelength using either dielectric slab or Bragg guiding structure undulator (Continued)

- Status of the design for dielectric structures that stretches the excitation wavelength:
  - we have exhaustively considered all possible filed profiles and created the scaling laws governing each type of structure.
  - It clear that ultimately we have to use a Bragg guiding structure.
  - We are now exploring practical implementation of both types of structures
    - Slab structure have the potential of an easy implementation which might allow us to conduct experiments in the near future with a K parameters, at best approaching 0.01 (0.5 T) with a rather narrow beam aperture.
    - while the Bragg structure have the potential of producing K vales ~0.05 (2.7 T) with a large beam aperture

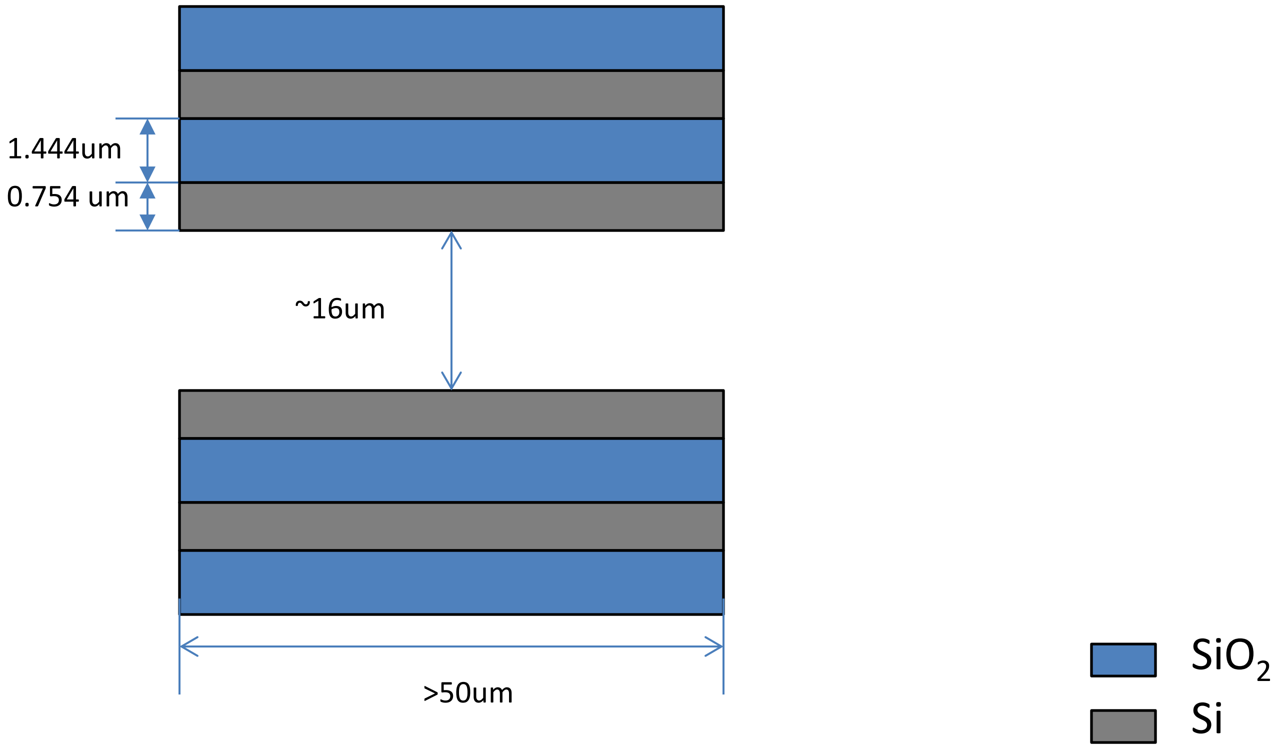






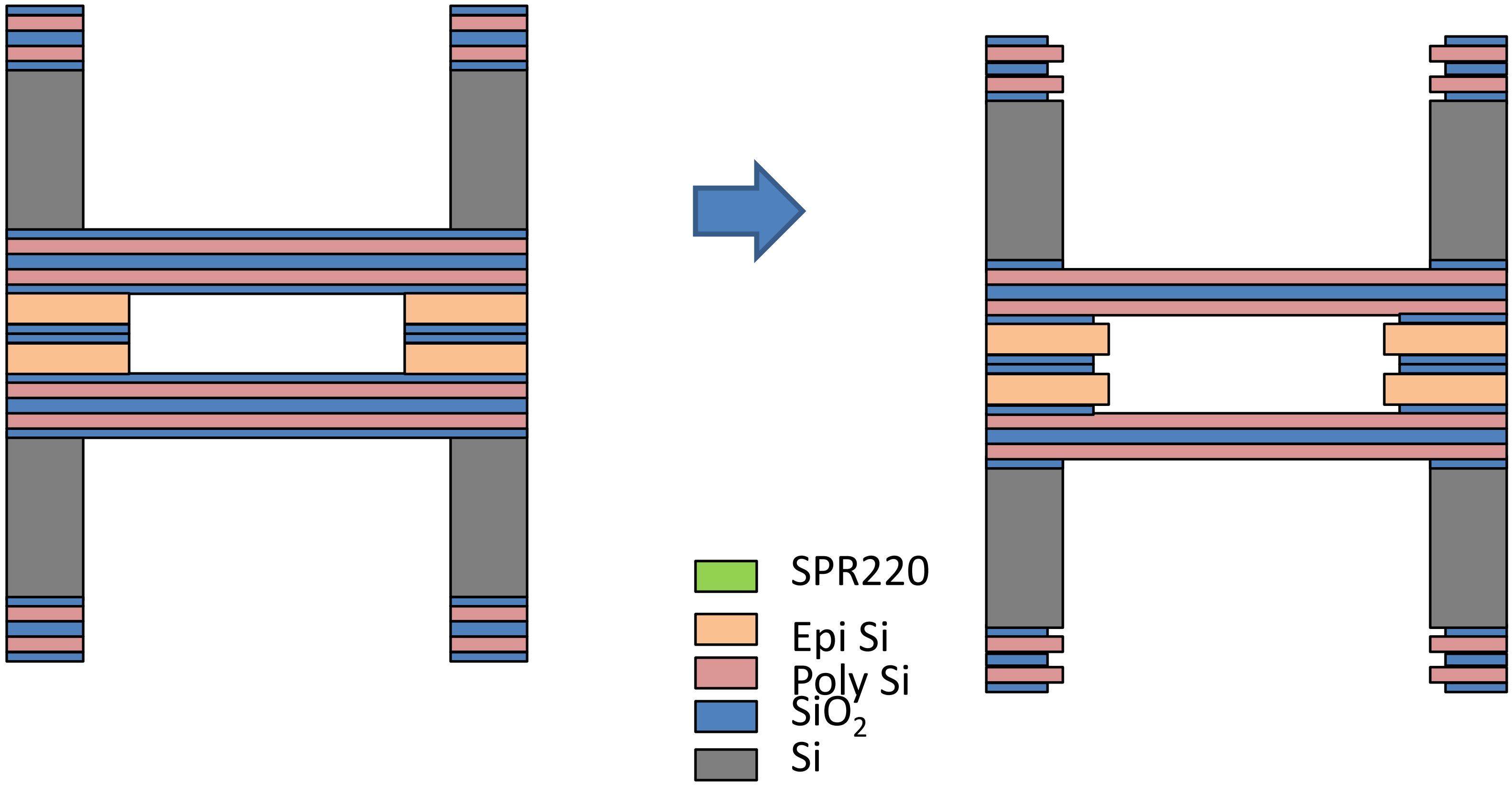
Slab structure implementation

Key feature

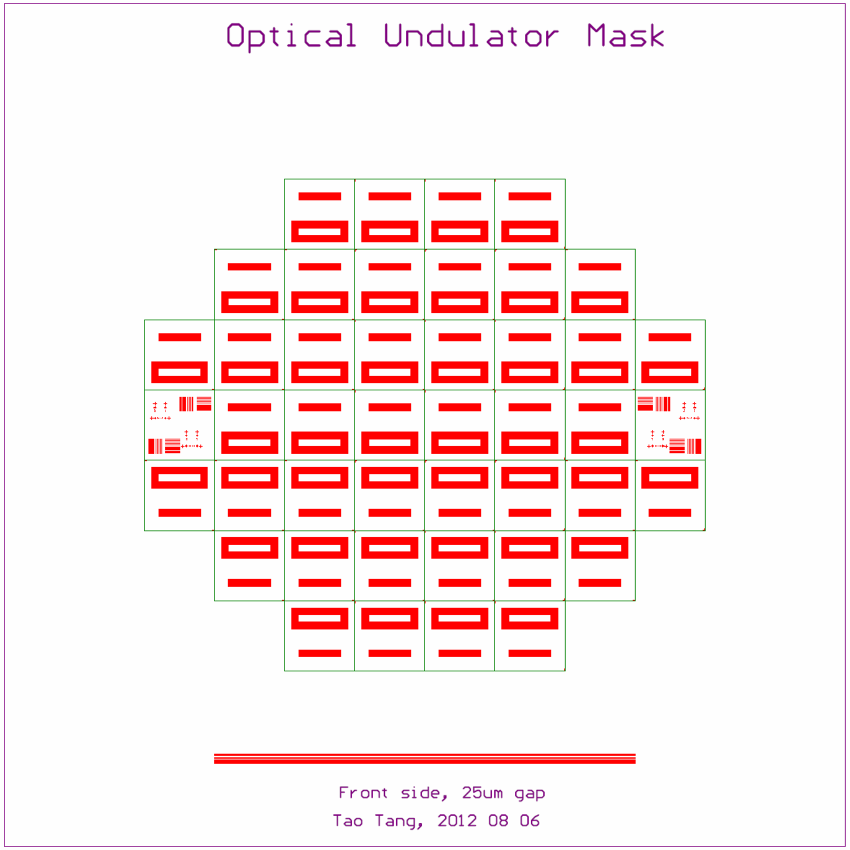


Step 15

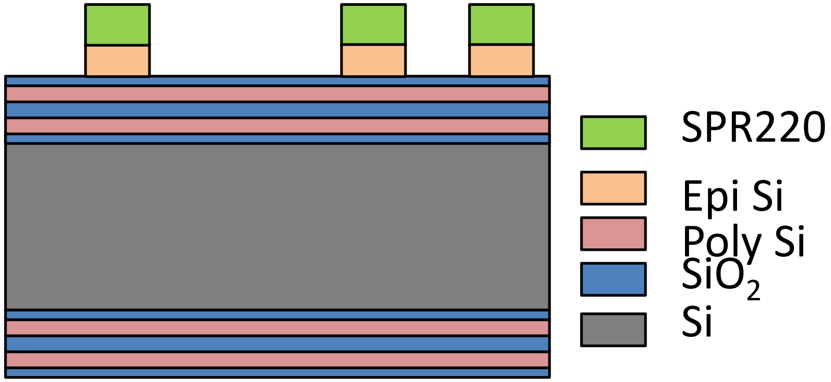
- Dicing
- HF wet etch



Mask #2 (front side spacer)

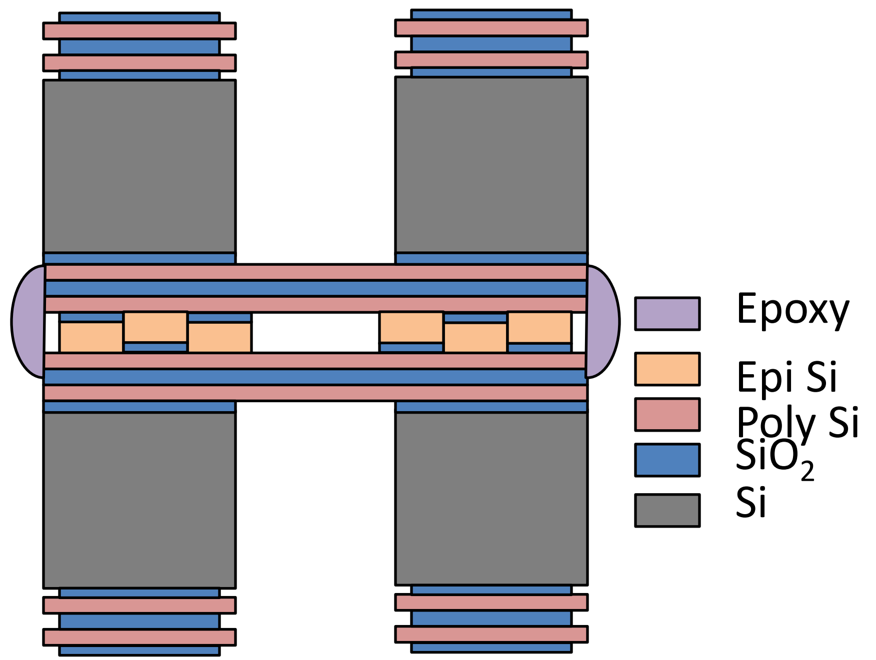


- On front side of the wafer
- Structure to create 16um high channel



Schedule

- Fabrication and validation of structure with photomasks (Aug 22nd)
- Measure refractive index of deposited single layer film at 10.6um. (Aug 17th)
- Fabrication of undulator (Sept 14th)

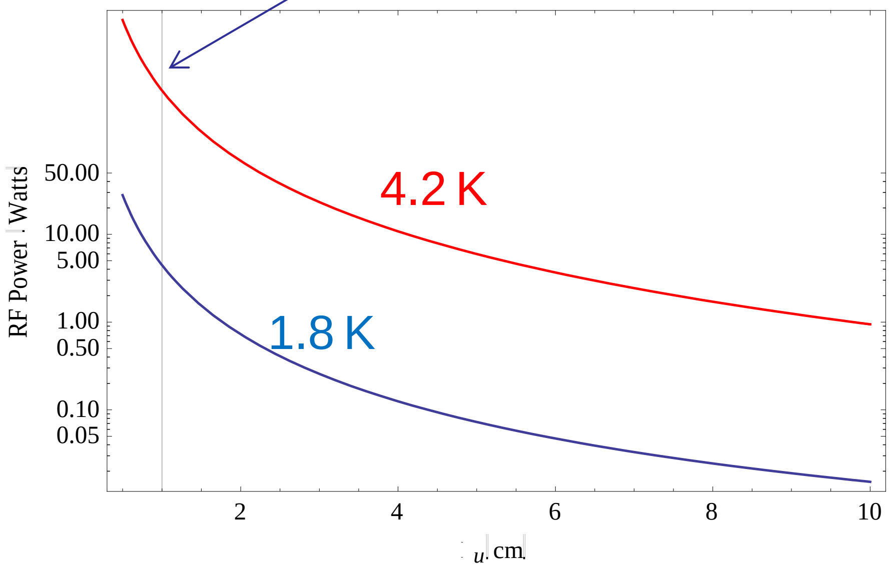


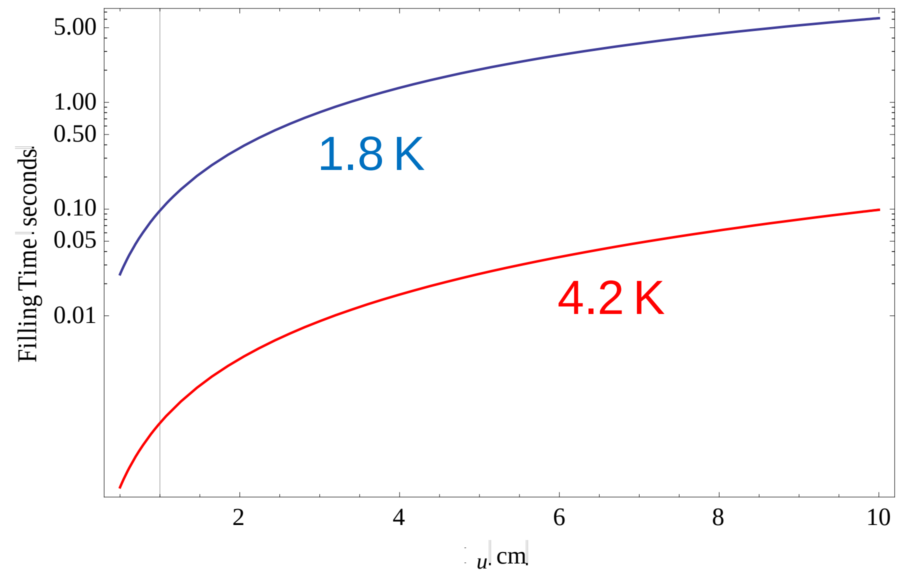
Status of Optical Undulator

- Stratified coating and masks have been generated
- Measurements at 10.6 microns will be performed soon (an OPA at SLAC will be availble in two weeks, we hope to do the measurements at UCLA before that)
- We hope that the structure will be availble in about 3-4 weeks for testing at BNL(ATF)

Superconducting Undulator(1 % duty cycle)

Undulator wavelength ~ 1cm imply operating frequency of ~16 GHz.
The undulator test done to date was at 11.4 GHz with undulator wave length of 1.393 cm. Reducing it to 1 cm should be straight forward





- One could decrease the filling time by decreasing the external Q
- The peak power would increase, of course.
- At a filling time of 1 ms, the peak power required is 50kW/m
- At CW the peak power required is 500 watts/m

The Future

- More precision measurements at NLCTA
- After Burner for LCLS
- Short Wavelength Undulator at 10mm for ILC
- Short Wavelength Undulator at 5mm for NGLS
- Superconducting undulators