A Compact Linac-Driven EUV Light Source utilizing a Short-Period Microwave-Driven Undulator

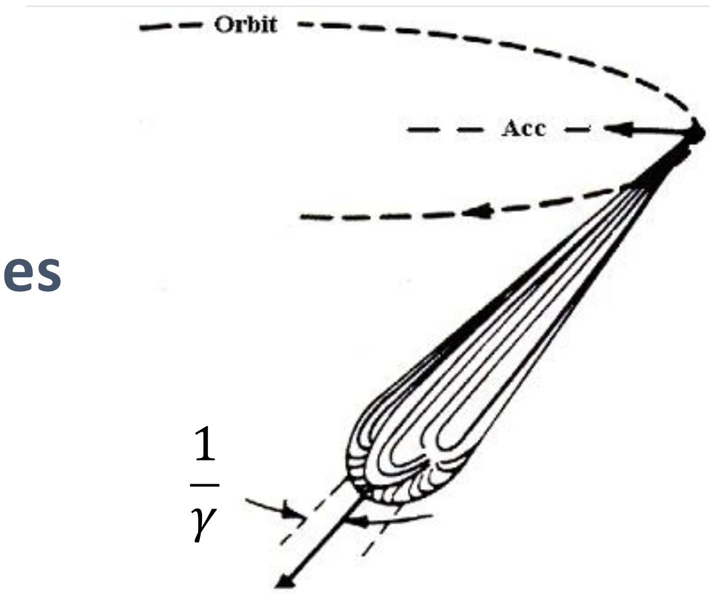
Filippos Toufexis* - ftouf@stanford.edu,
C. Limborg-Deprey, V.A. Dolgashev, S.G. Tantawi
SLAC National Accelerator Laboratory
*Also at Electrical Engineering, Stanford University

2017 International Workshop on EUV Lithography
June 14, 2017

Stanford University SLAC

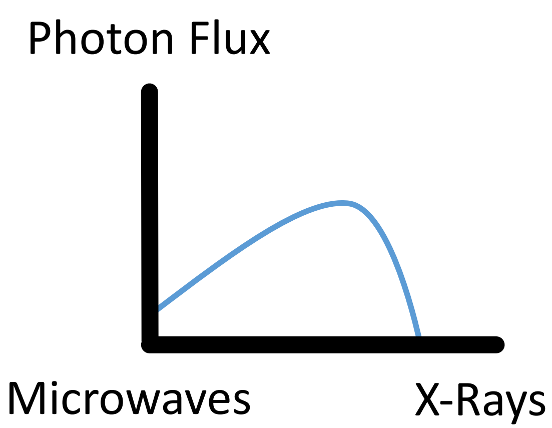
Synchrotron Radiation

Emission of Radiation from
Accelerated Relativistic Charged Particles

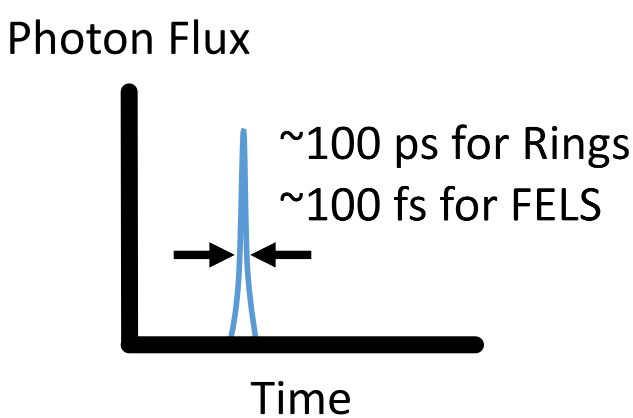


Properties of Synchrotron Radiation

Broad Spectrum

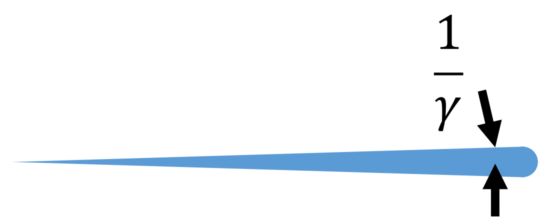


Short Pulse Length

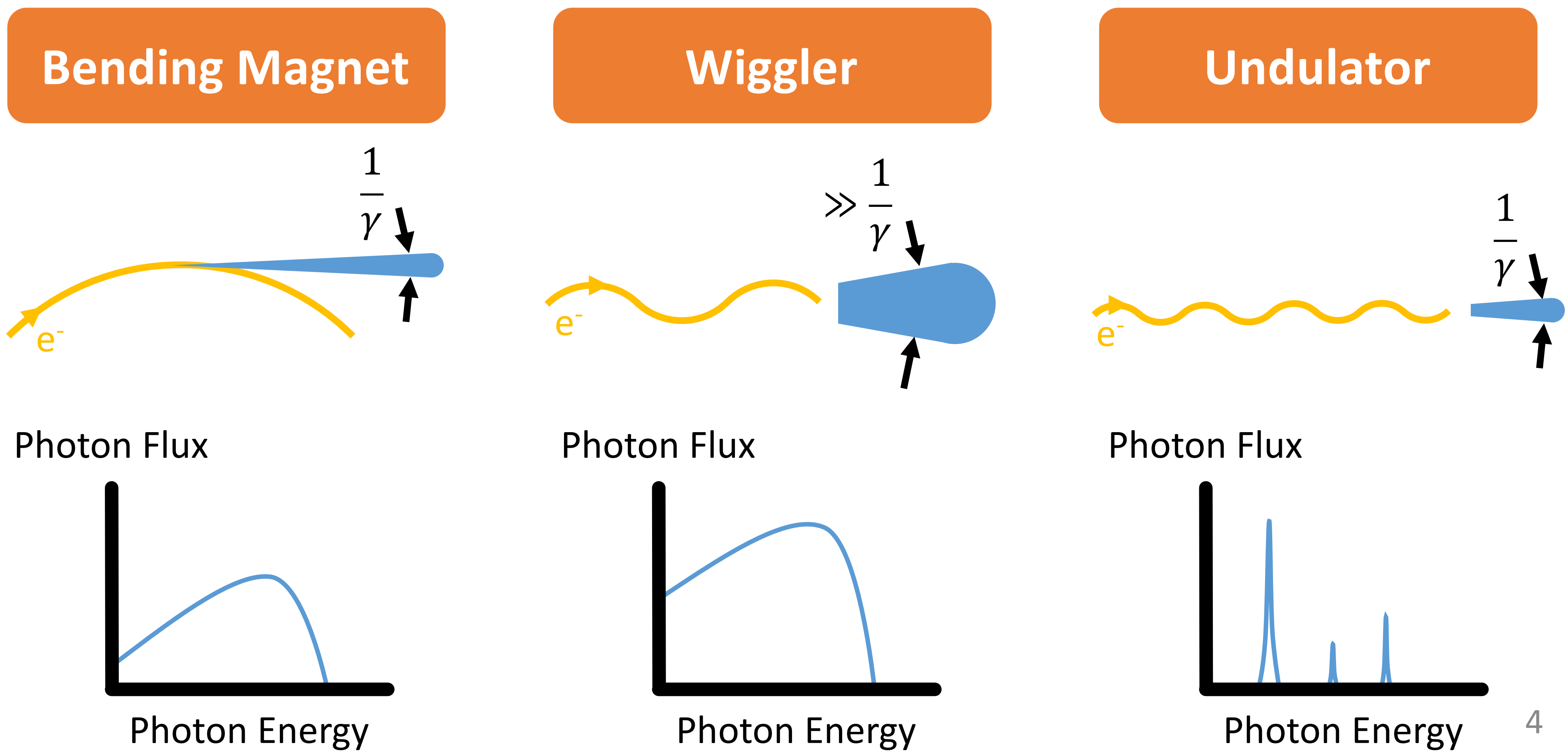


High Brilliance

Small Divergence Photon Beam
Small Spot Size



Increasing the Flux & Narrowing the Spectrum



Undulator Radiation is Quasi-Monochromatic

Undulator Strength $\propto \lambda_u \mathrm{B}$

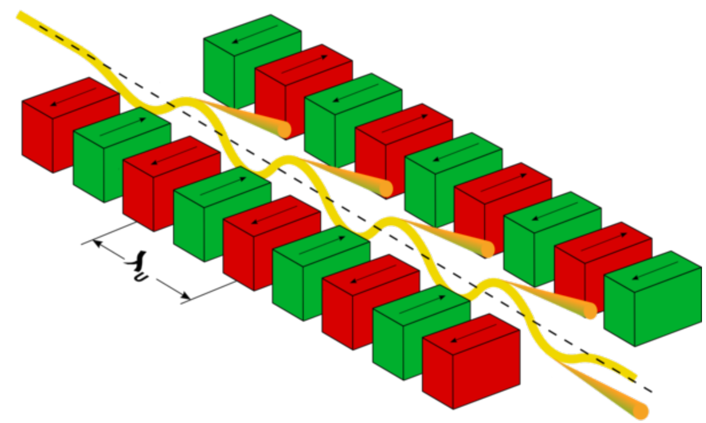
Undulator Period

Observation Angle

$$\lambda_{rad} = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{1}{2}K^2 + \gamma^2\vartheta^2\right)$$

Radiation Wavelength

Lorentz Factor ∝ Beam Energy

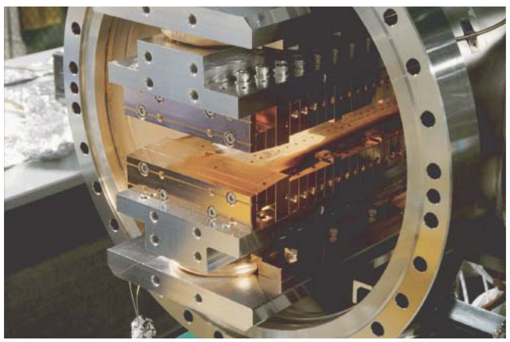


Source: commons.wikimedia.org/wiki/File:Undulator.png

Smaller Undulator Period → **Lower Beam Energy** → **Smaller Drive Linac** → **Lower Cost and Size**

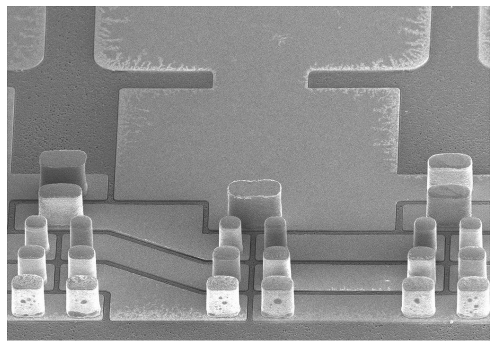
Static Field Undulator Period Limited by Small Apertures

In-Vacuum & Superconducting
λ_u = 1.8 cm / K = 2.1 / Gap = 3.7mm



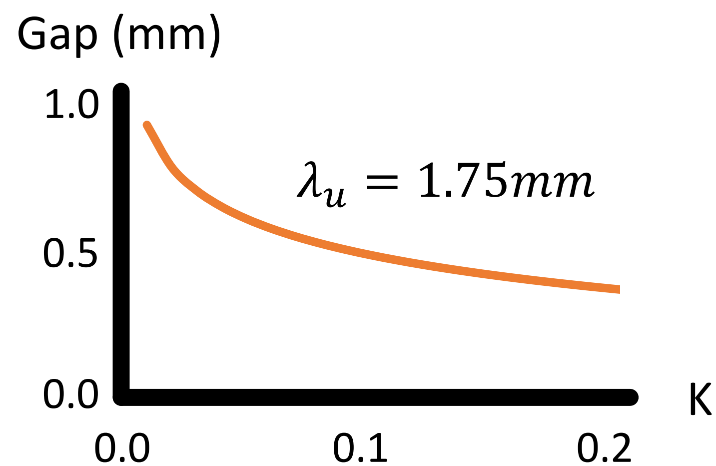
Source: T. Tanaka *et al*, "In-Vacuum Undulators," In: Proceedings of the 27th International Free Electron Laser Conference, 21-26 August 2005, Stanford, California, USA.

Microfabricated Electromagnet
λ_u = 400 µm / K = 0.026 / Gap = 100 µm



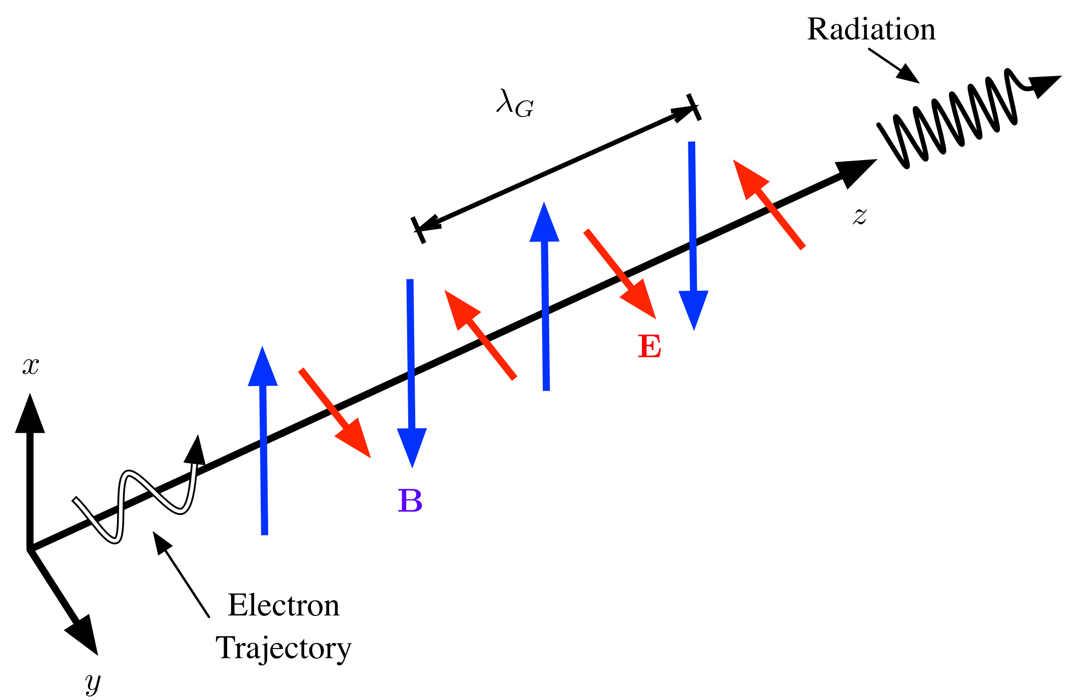
Source: J. Harrison *et al*, "Surface-micromachined magnetic undulator with period length between 10 µm and 1 mm for advanced light sources," Phys. Rev. ST Accel. Beams, vol. 15, no. 7, p. 070703, Jul. 2012, DOI: 10.1103/PhysRevSTAB.15.070703.

$$K = 0.934 B_0(T)\lambda_u(cm)$$



Source: M. Shumail Thesis, Stanford, 2014

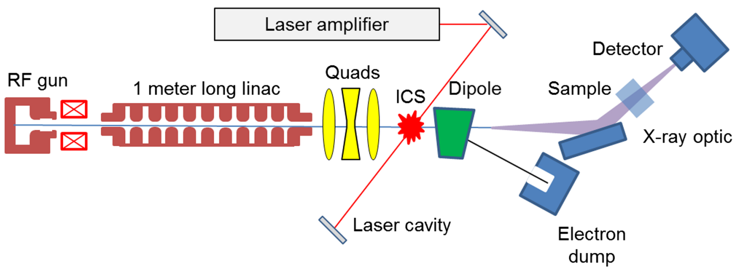
Electromagnetic Undulators: Beam Wiggled by both E & B



Electromagnetic Undulators: Beam Wiggled by both E & B

Inverse Compton Scattering Sources

λ_u = ~0.5 μm / K = ~10^{-3}

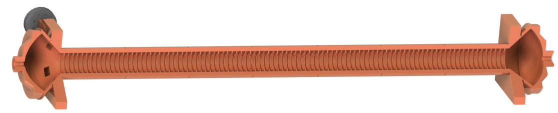


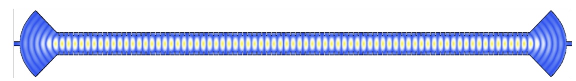
Source: W. S. Graves *et al*, "Compact x-ray source based on burst-mode inverse Compton scattering at 100 kHz," Phys. Rev. ST Accel. Beams, vol. 17, no. 12, p. 120701, Dec. 2014. DOI: 10.1103/PhysRevSTAB.17.120701.

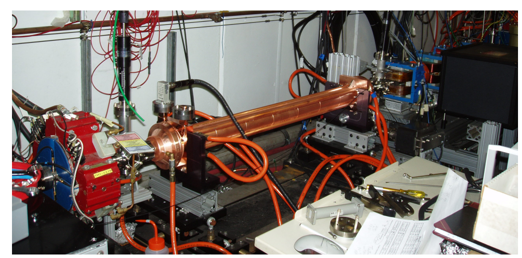
Not practical for EUV/Soft X-Ray
Low & Non-uniform K

Microwave Undulators

f = 11.424 GHz / λ_u = 1.39 cm
K = 0.7 / Gap = 3.9 cm





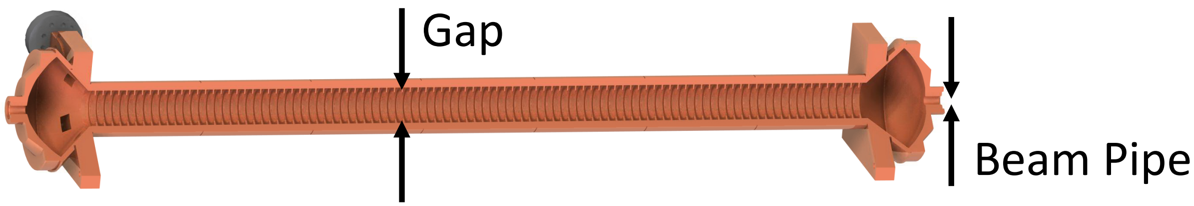


Source: S.G. Tantawi 2014

Scaling to Higher Frequencies

f = 11.424 GHz
λ_u = 1.39 cm
Gap = 3.9 cm
Beam Pipe = 7 mm

f = 91.392 GHz
λ_u = 1.75 mm
Gap = 4.9 mm
Beam Pipe 0.87 mm



10x Smaller Period than SACLA FEL Undulator

Challenges with Scaling to Higher Frequencies

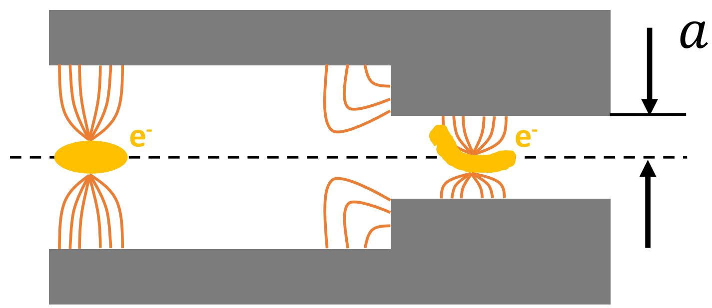
Mitigate Wakefields

Avoid RF Losses & High Fields

Produce MWs of RF Power

Beams Induce Wakefields in Pipes

Spoil Emittance, Instabilities, Beam Breakup



Longitudinal Wakefields $\propto \; a^{-2}$

Transverse Wakefields $\propto \; a^{-3}$

Need Millimeter-Scale Beam Apertures $\sim \lambda$

Challenges with Scaling to Higher Frequencies

Mitigate Wakefields

Avoid RF Losses & High Fields

Produce MWs of RF Power

WR10 Rectangular WG
3 dB/m

31.75 mm
Corrugated WG
0.004 dB/m

Pulsed Surface Heating: $\Delta\mathrm{T}(^{\circ}\mathrm{C}) = 430\sqrt{\tau}\boldsymbol{H}^2\sqrt{\frac{f}{11.424}}$

Coupling Irises usually have Highest Fields

Need Mode Converters,
Cannot Couple Power through Small Irises

Challenges with Scaling to Higher Frequencies

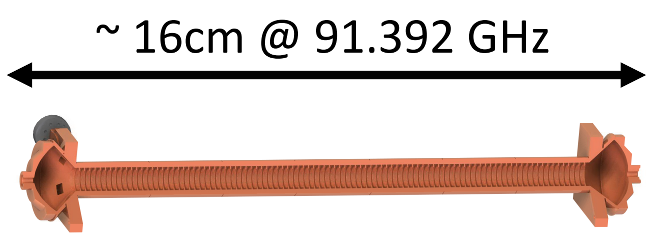
Mitigate Wakefields

Avoid RF Losses & High Fields

Produce MWs of RF Power

Only Gyrotrons produce 1 MW

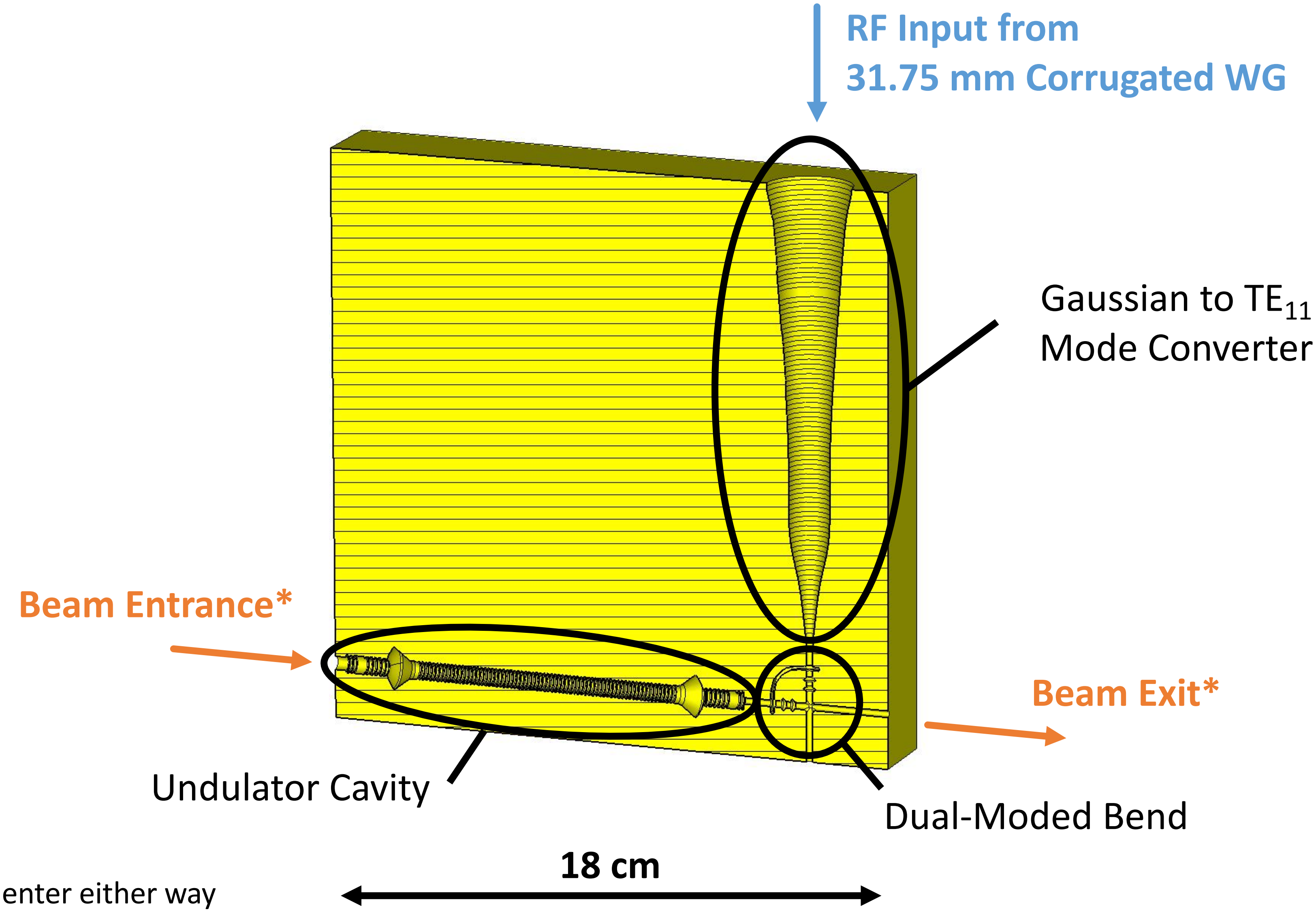
They are Massive



Source: S.G. Tantawi 2014

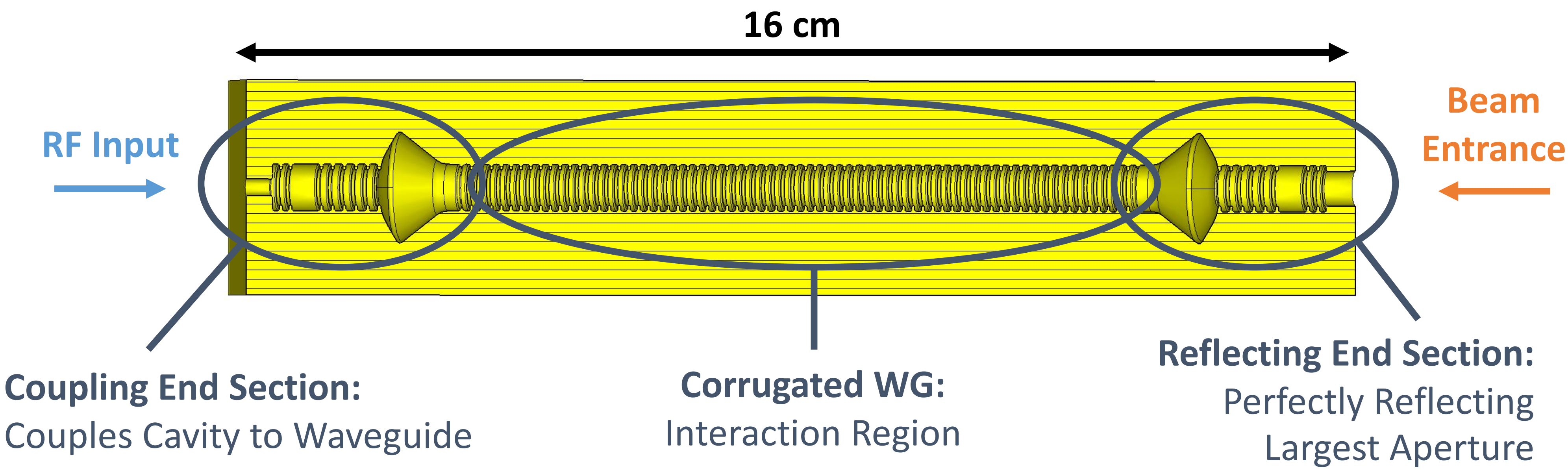
Source: Flickr/juliaL49

Need Compact RF Source

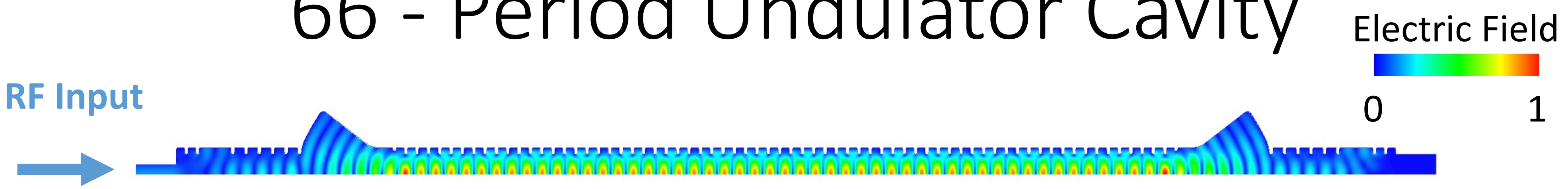


*Beam can enter either way

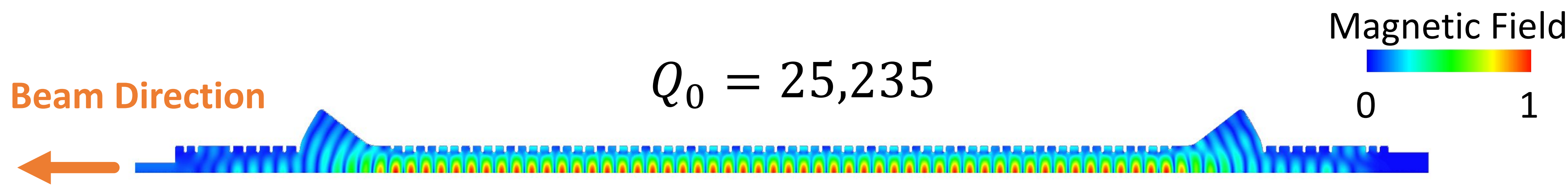
Undulator Cavity Overview

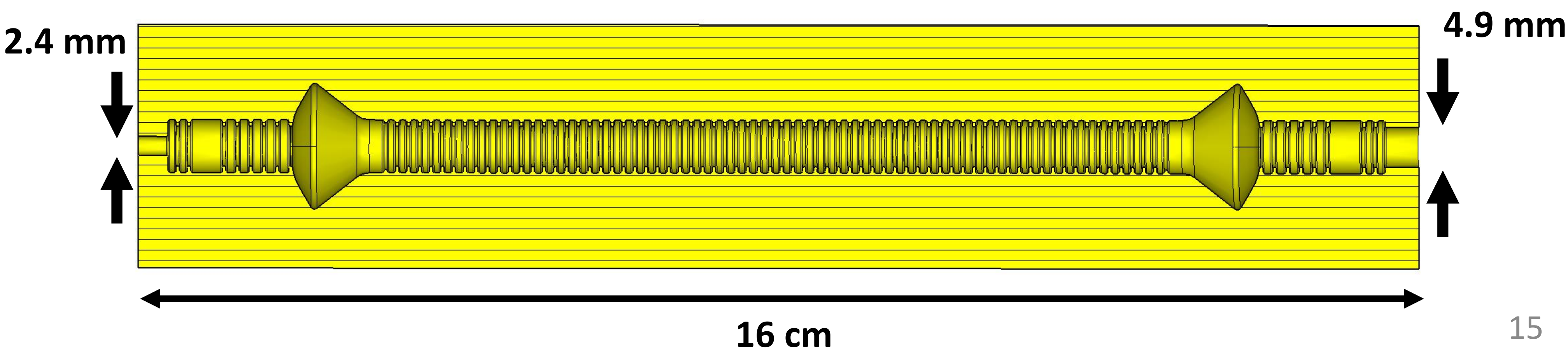


66 - Period Undulator Cavity



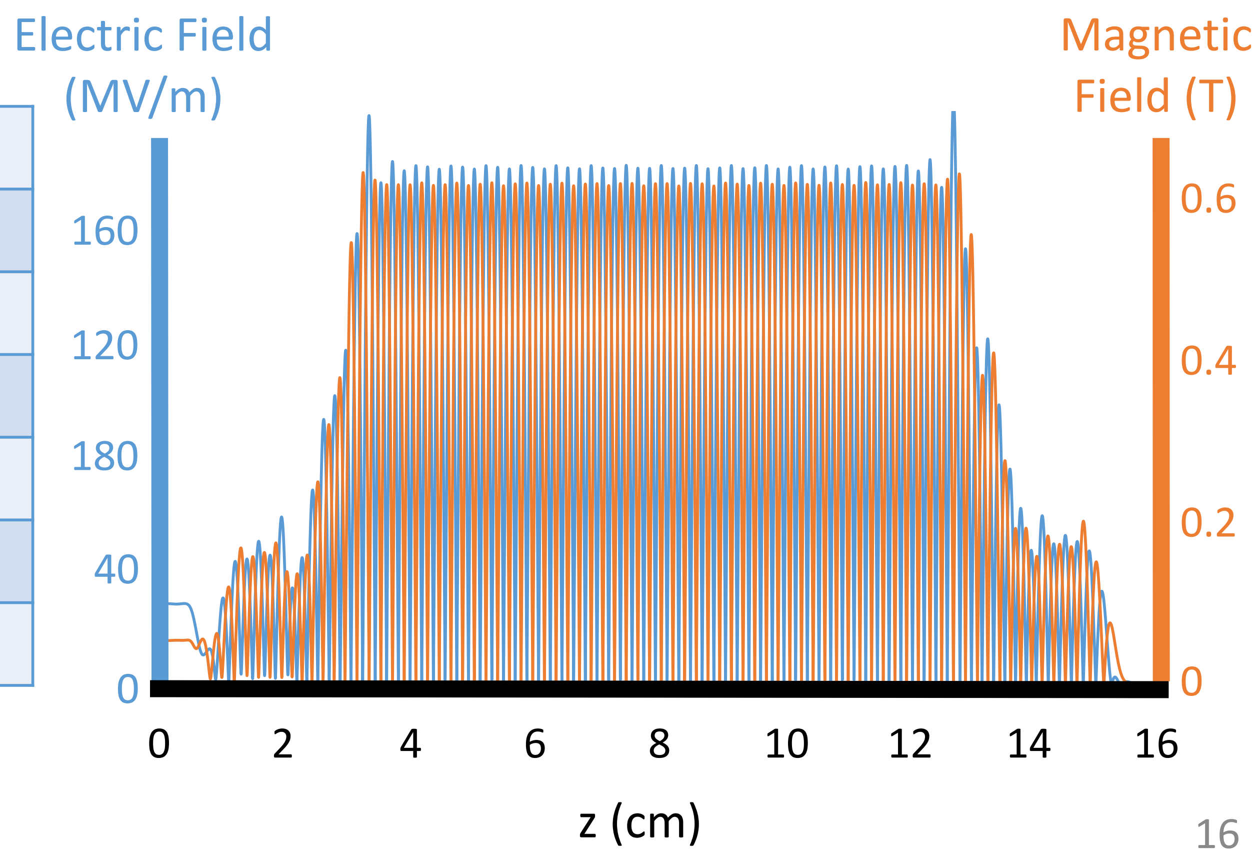
$$Q_0 = 25{,}235$$





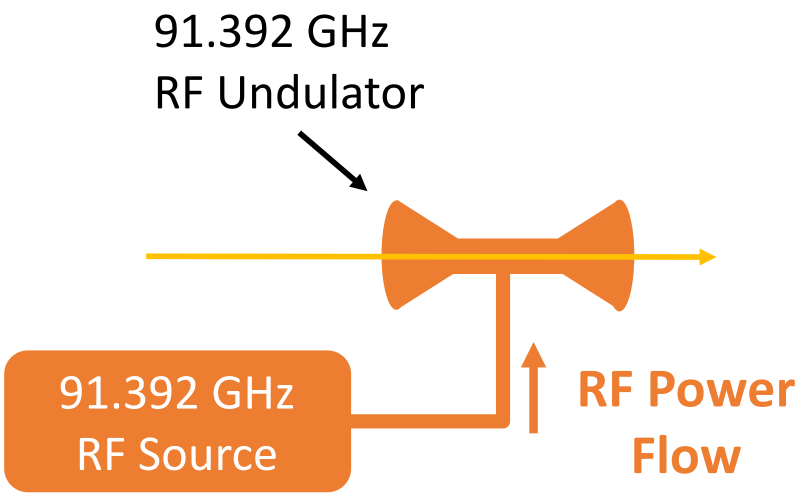
On-Axis Fields & Power Requirements

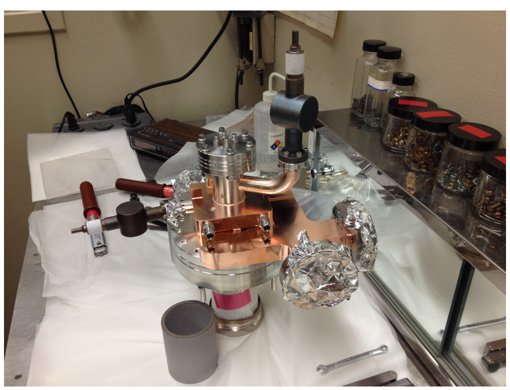
Input Power	**1.4 MW**
Periods	**66**
K	**0.1**
Peak B	**0.61 T**
Peak E	**181.6 MV/m**
Period	**1.75 mm**
Temp Rise	**44°C / 250 nsec**



So how do we power it?

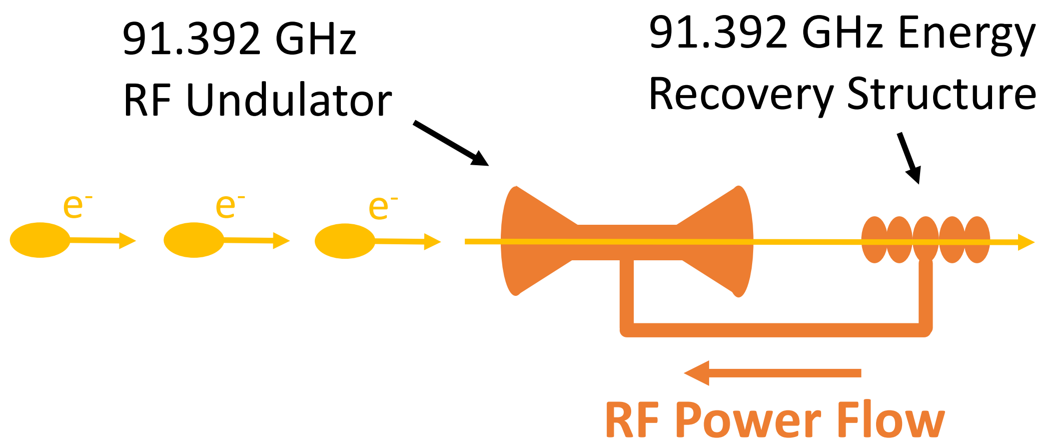
RF Source-Driven





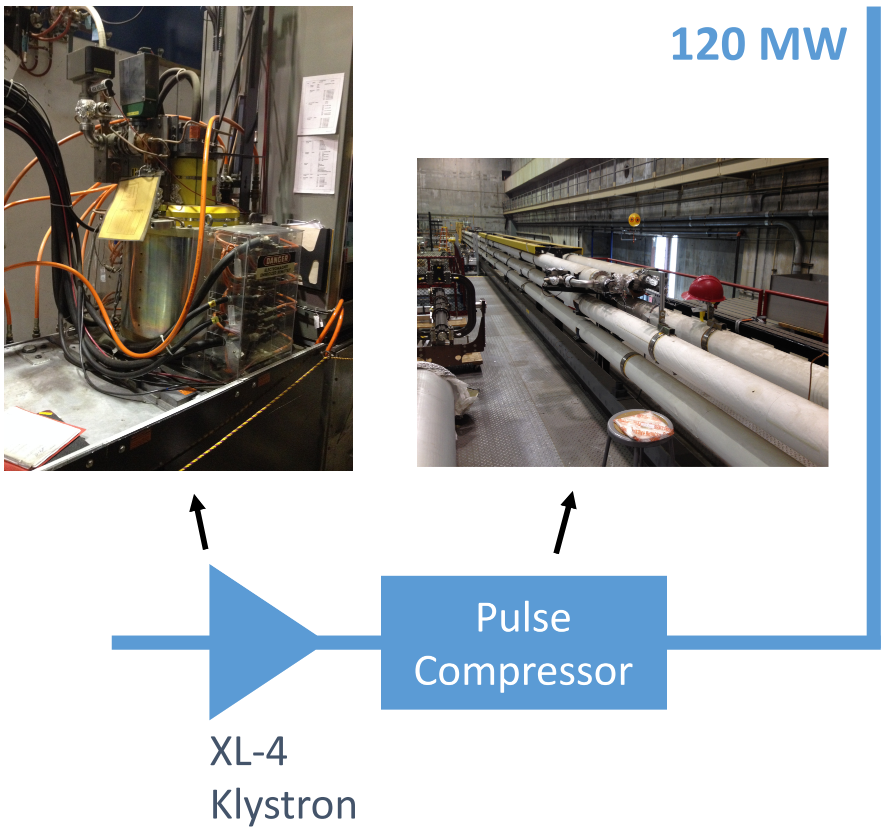
We are also working on compact mm-wave sources but will not discuss in this talk.

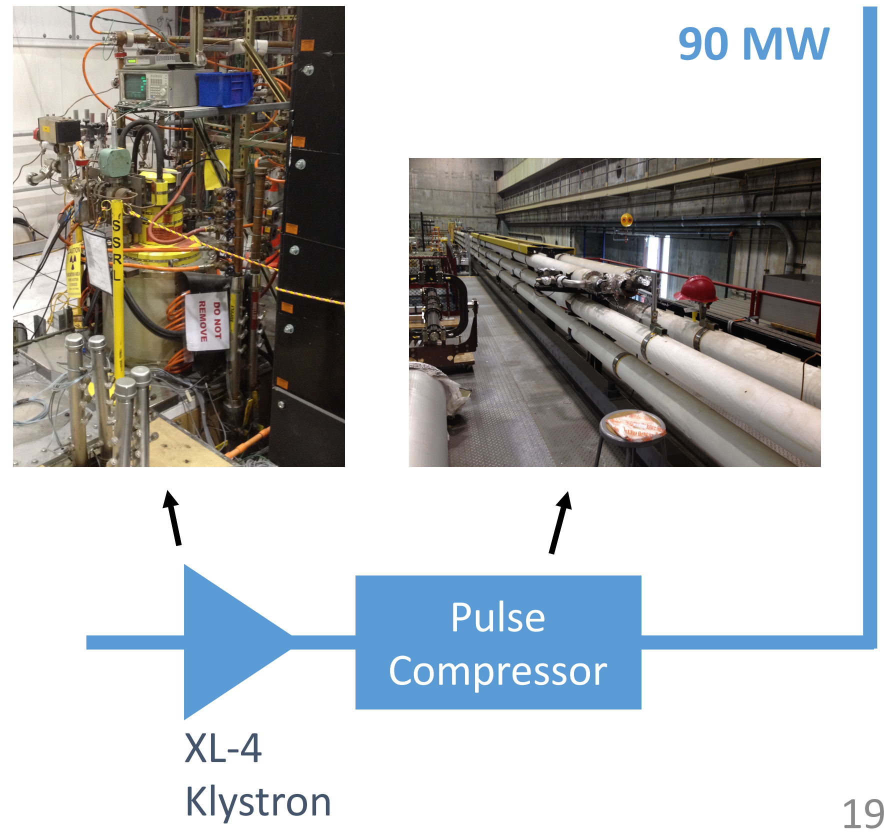
Beam-Driven



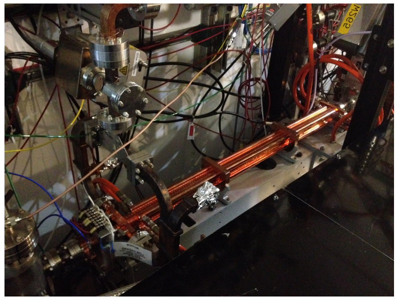
Technology Demo:
Modify SLAC X-Band Test Accelerator
to produce EUV Light

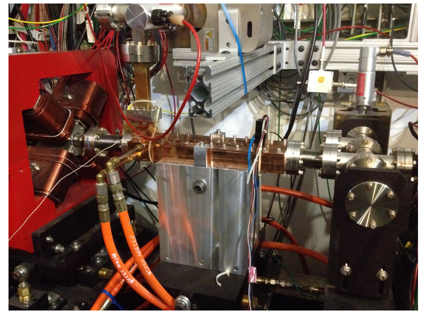
Leverage existing SLAC Infrastructure worth several $M

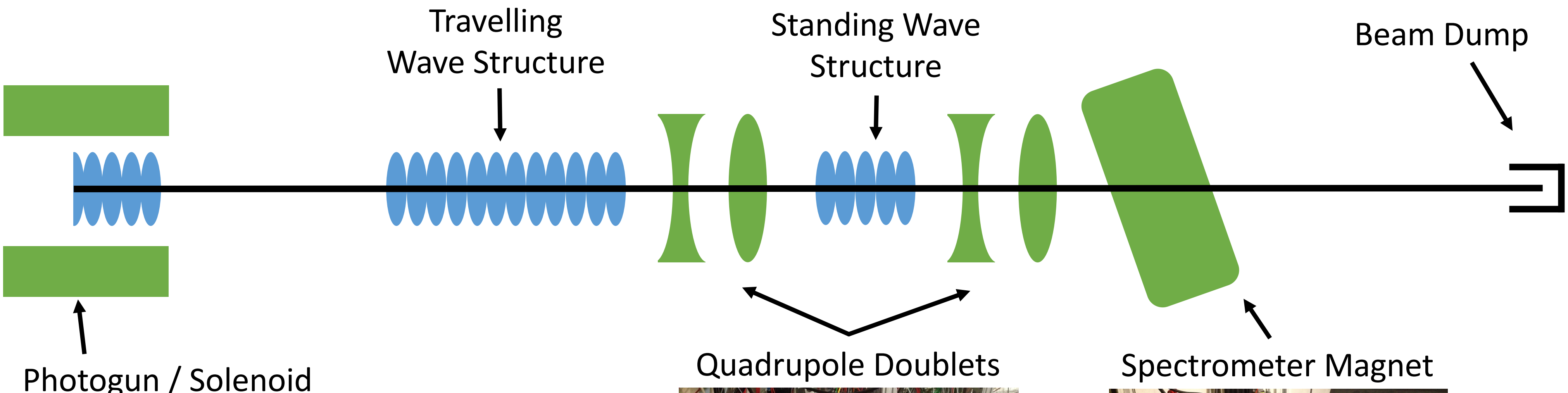


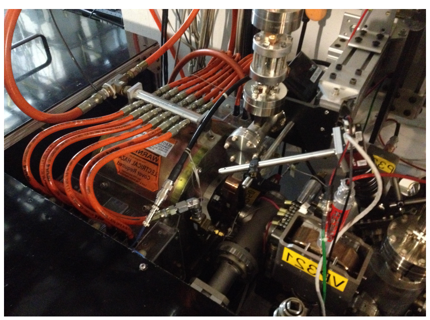


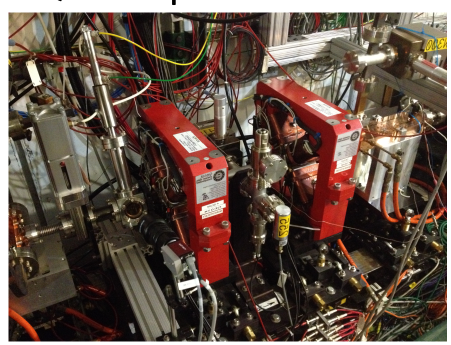
Existing X-Band Test Accelerator @ SLAC

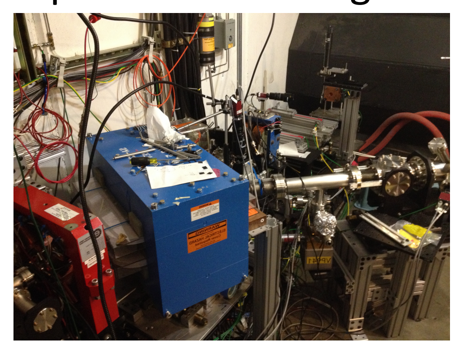




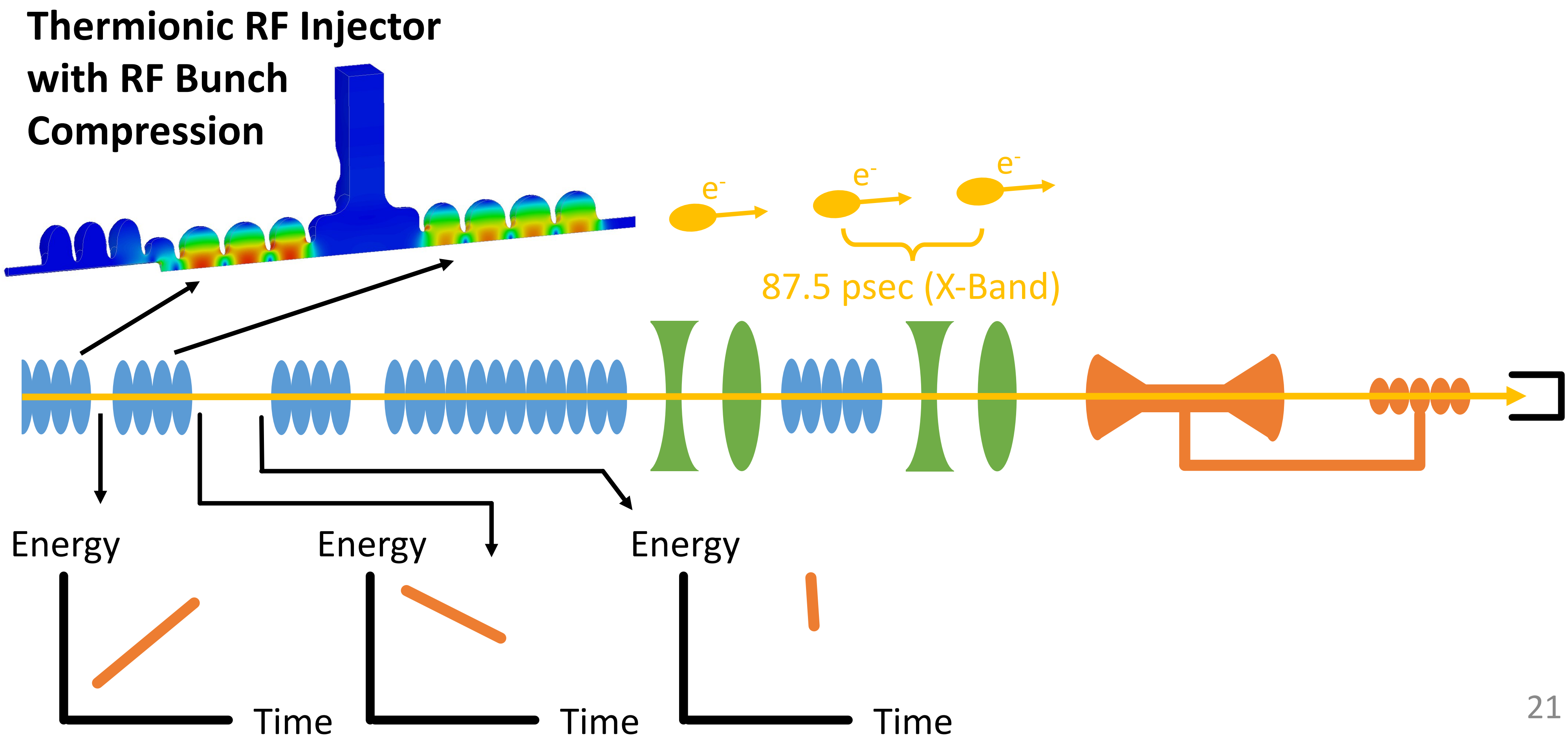






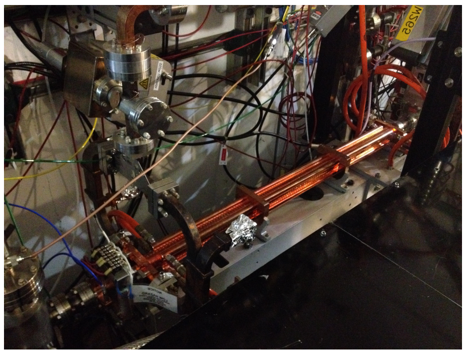


Thermionic RF Injector generates Electron Bunches

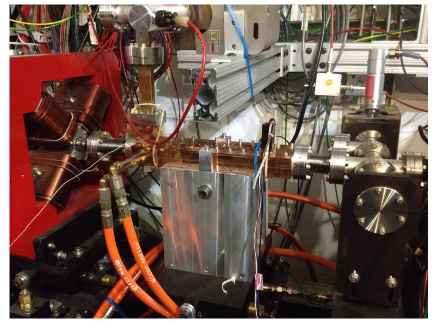


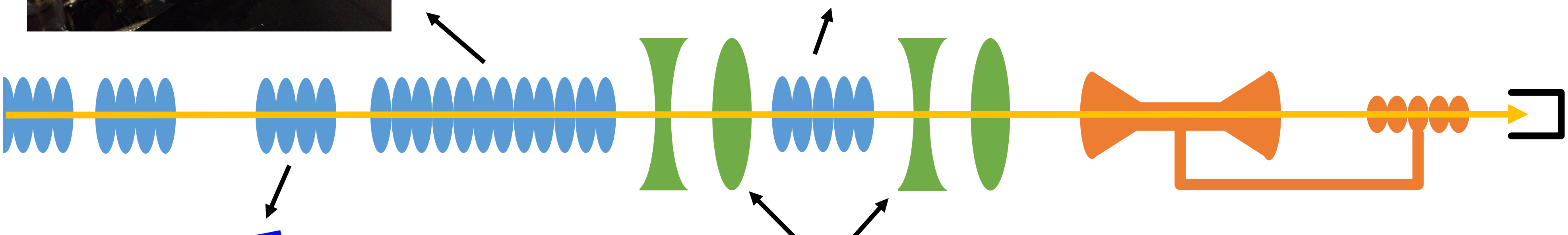
Electron Bunches accelerated to 129MeV

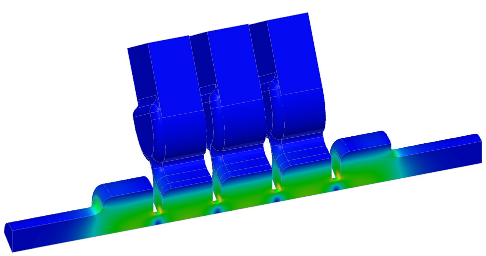
Travelling Wave Linac



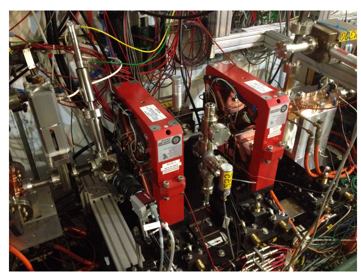
Standing Wave Linac





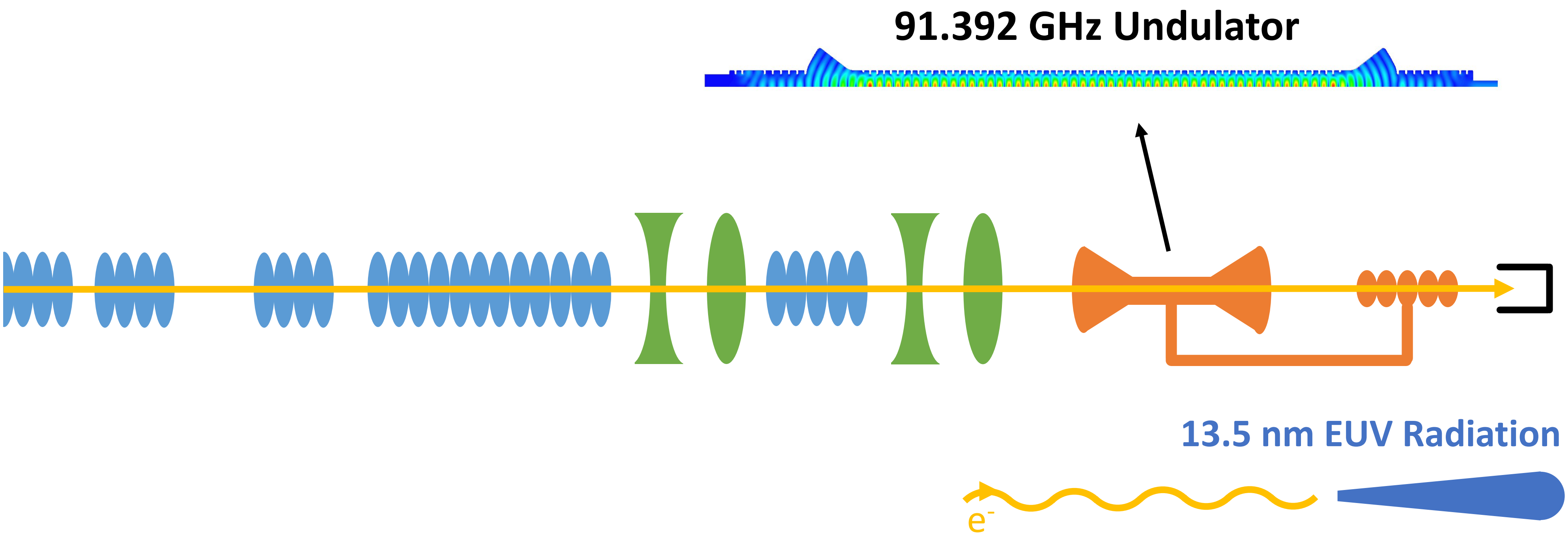


Standing Wave Linac

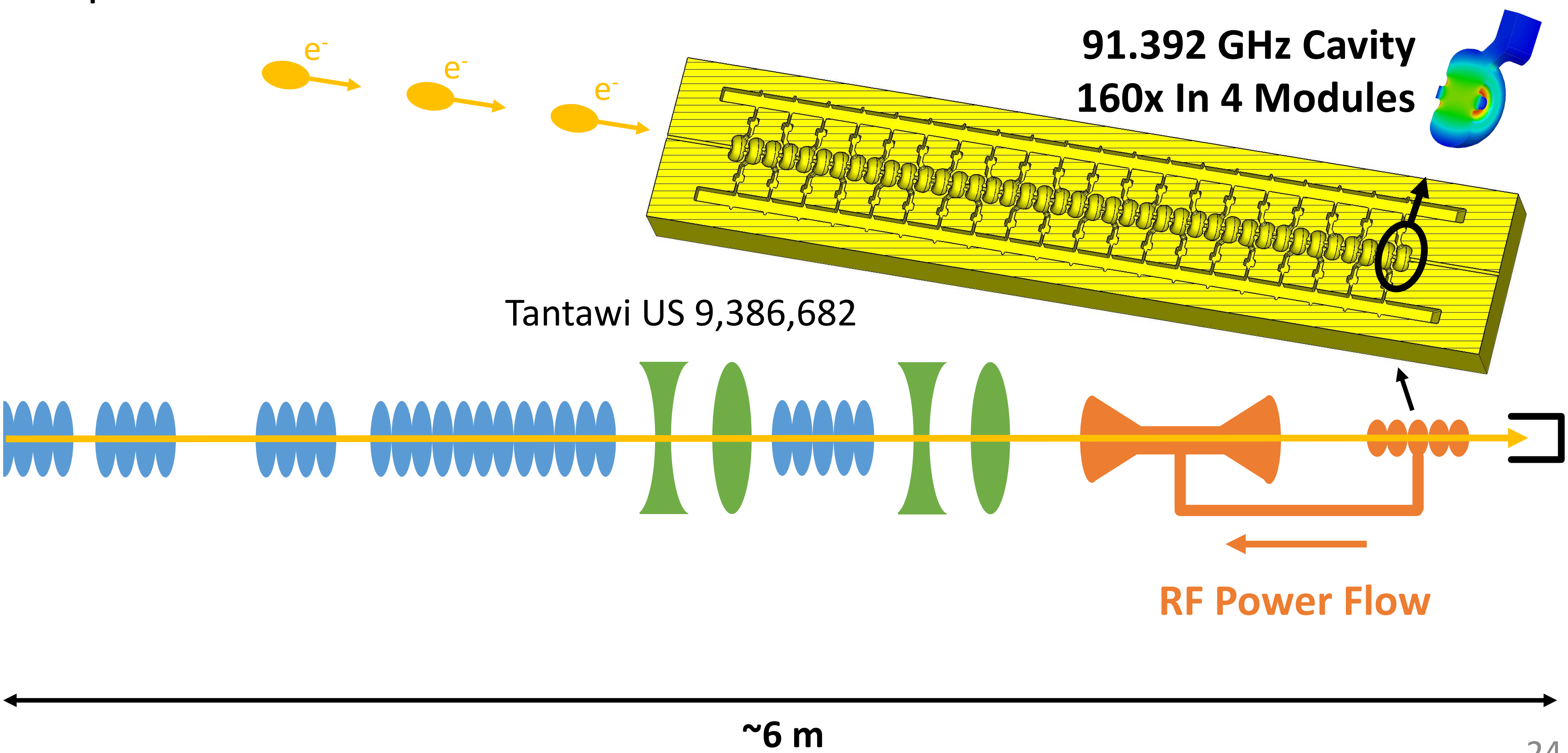


Quadrupole Doublets

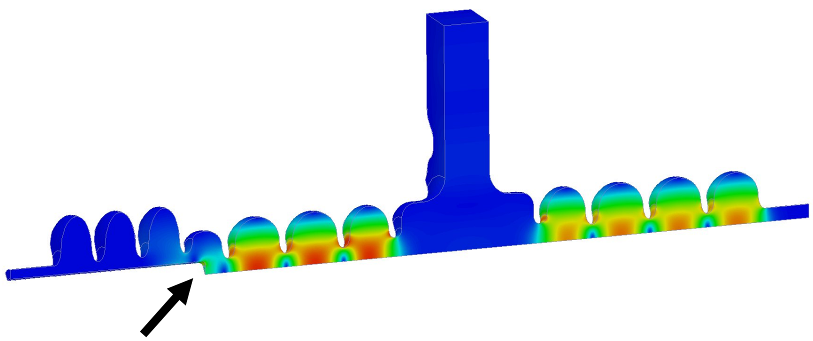
Electrons Wiggled producing 13.5nm Radiation



Spent Electron Beam Generates 91.392 GHz Power



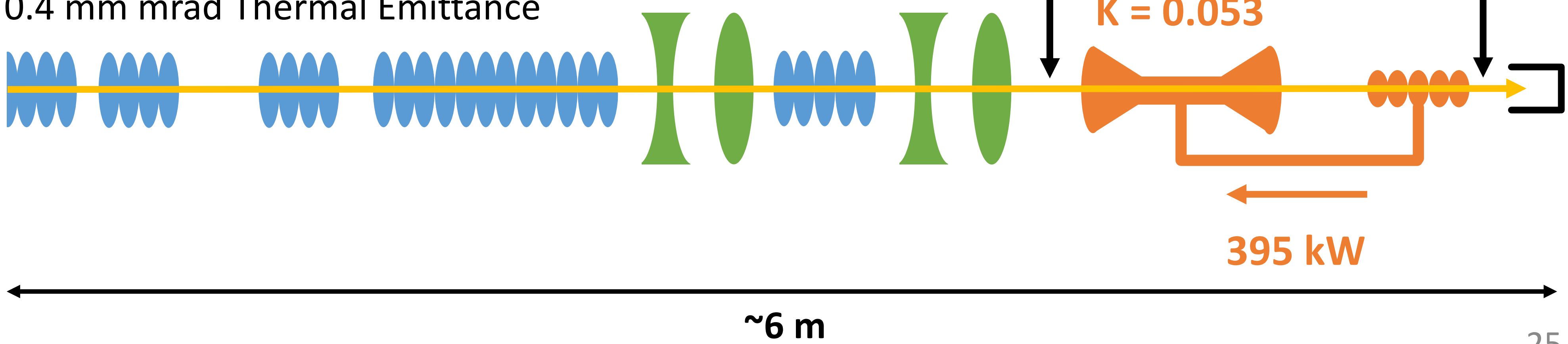
Beam Dynamics Simulation



40 A/cm^2 Cathode Current Density
0.4 mm mrad Thermal Emittance

$E = 129.6\ MeV$
$Q = 20.34\ pC$
$\sigma_{xy} = 151\ \mu m$
$\sigma_z = 124\ fs$
$\varepsilon_n = 4.4\ mm\ mrad$
$\Delta E = 0.15\ \%$

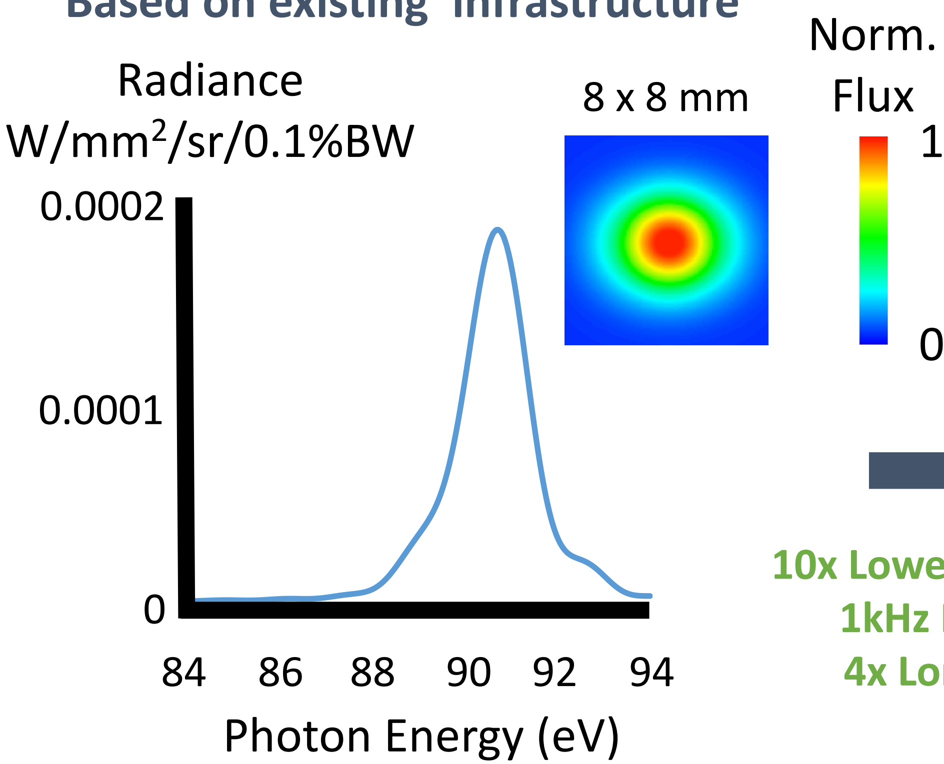
$Q = 10.2\ pC$
$\sigma_{xy} = 78\ \mu m$
$\sigma_z = 47\ fs$



Potential for >100 W/mm^2/sr/0.1%BW

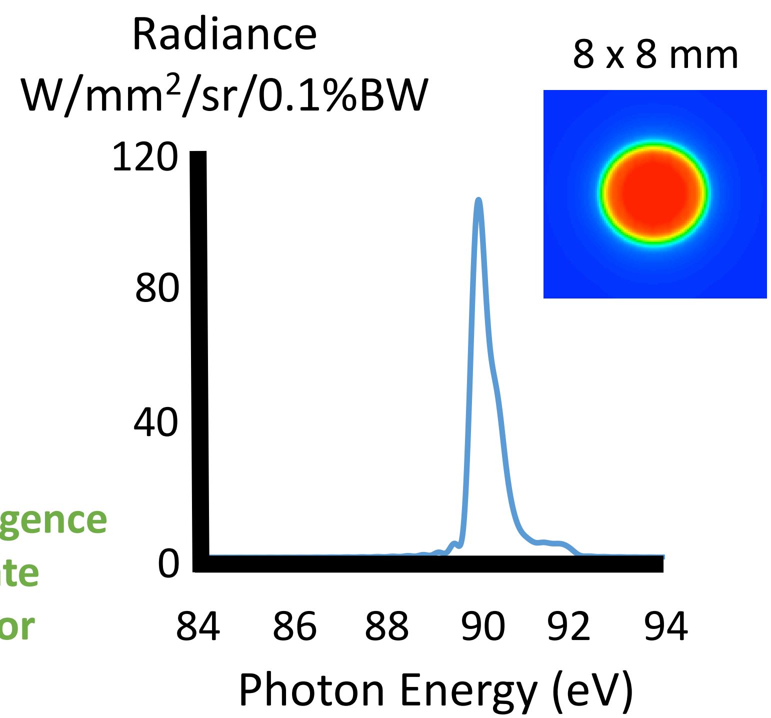
Prototype Simulations

Based on existing infrastructure



10x Lower Beam Divergence
1kHz Repetition Rate
4x Longer Undulator
K = 0.15

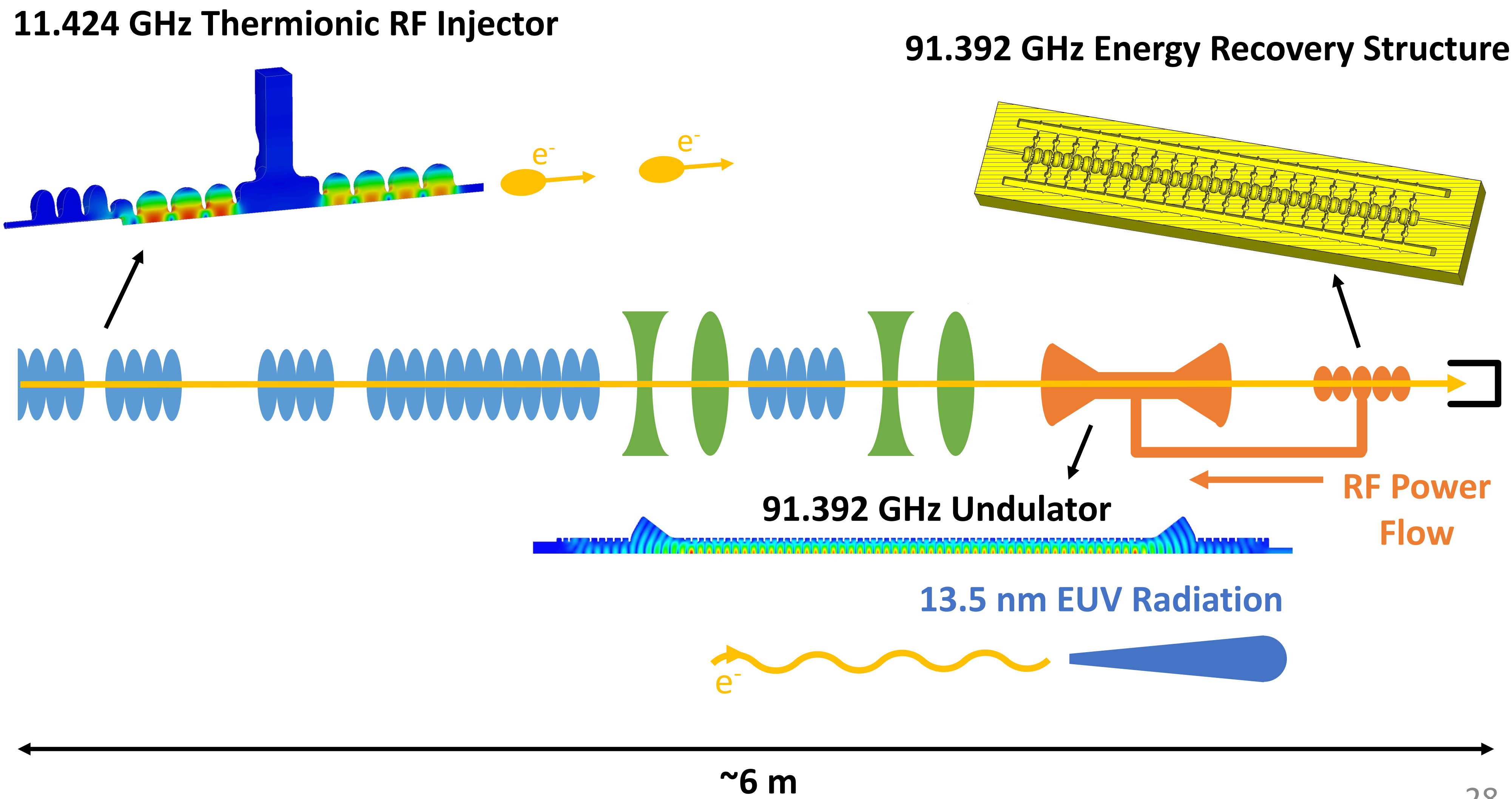
Future Design



SPECTRA Simulations: http://radiant.harima.riken.go.jp/spectra/

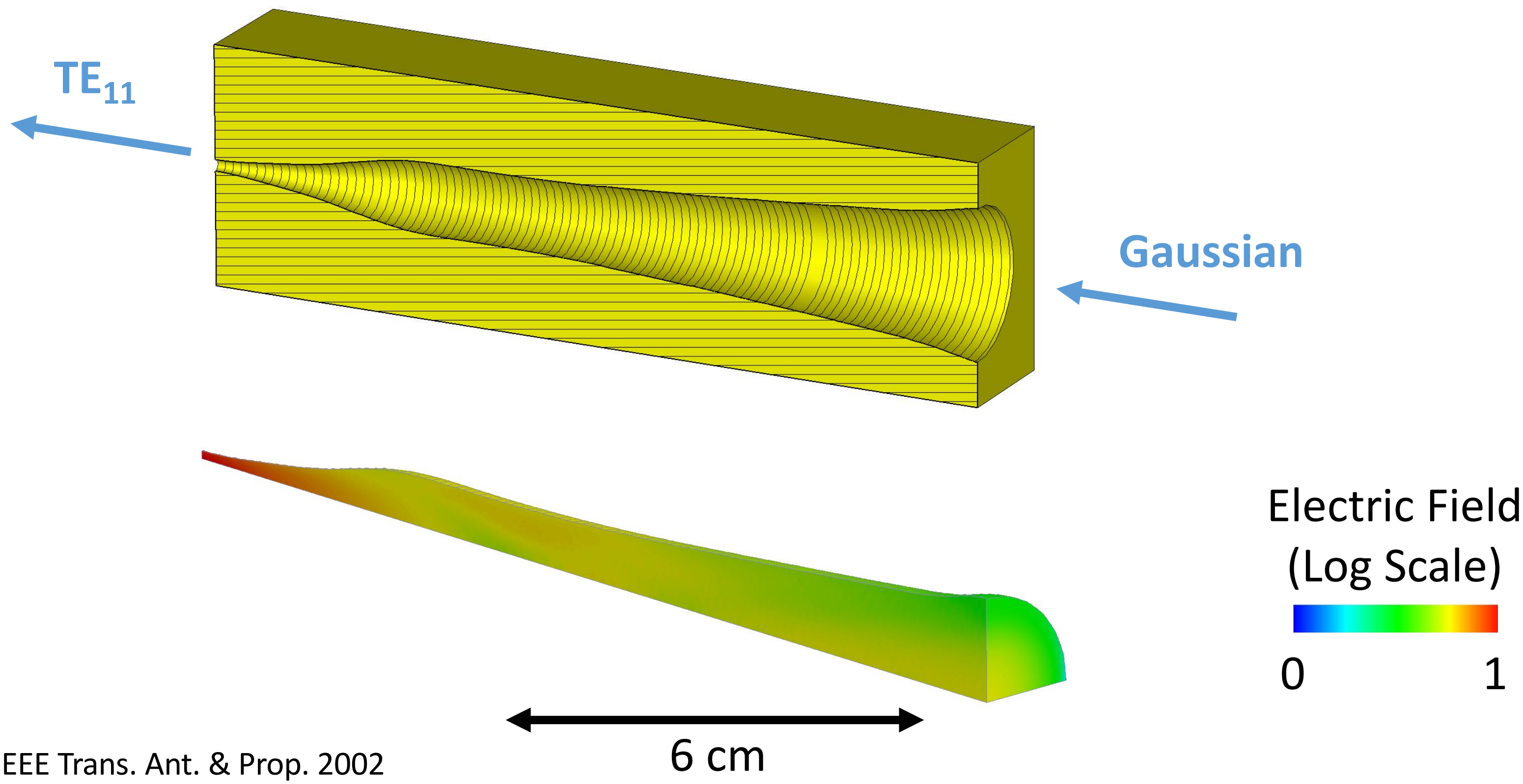
Summary

- Short Period RF-Driven Undulator
  - **1.75 mm Period**
  - **4.9 mm / 2.4 mm In/Out Apertures**
  - Fed through the beam pipe
  - **1.4 MW for K = 0.1**
- Presented Technology Demo EUV Source Design
  - Thermionic RF Injector with RF Bunch Compression
  - Energy Recovery Structure feeds the Microwave-Driven Undulator
- **Potential for >100 W/mm^2/sr/0.1%BW**
  - Further R&D Required


11.424 GHz Thermionic RF Injector
e-
e-
91.392 GHz Energy Recovery Structure
91.392 GHz Undulator
RF Power Flow
13.5 nm EUV Radiation
e-
~6 m

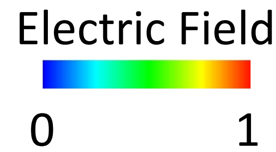
Backup Slides

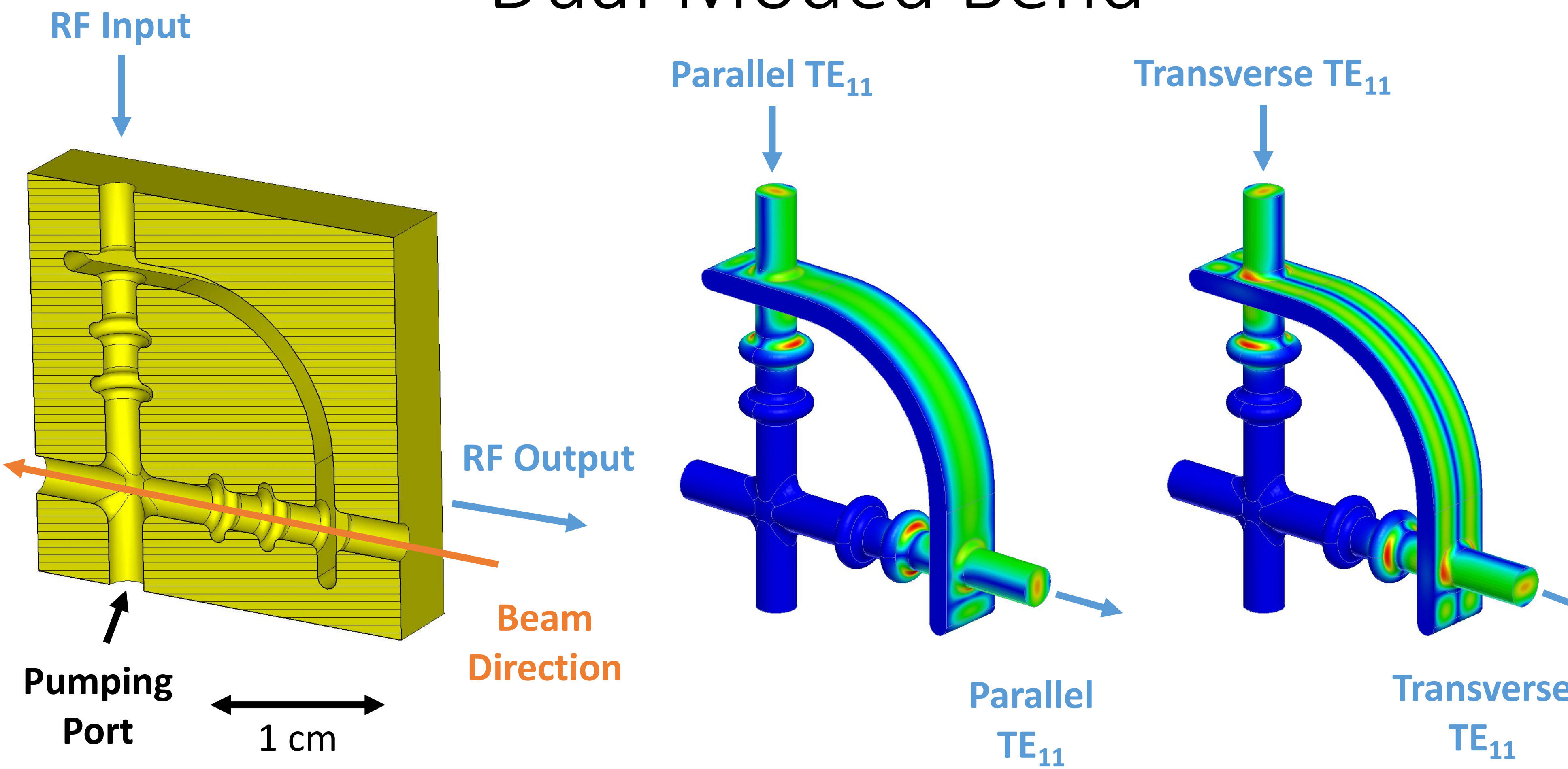
TE_{11} to Gaussian Mode Converter



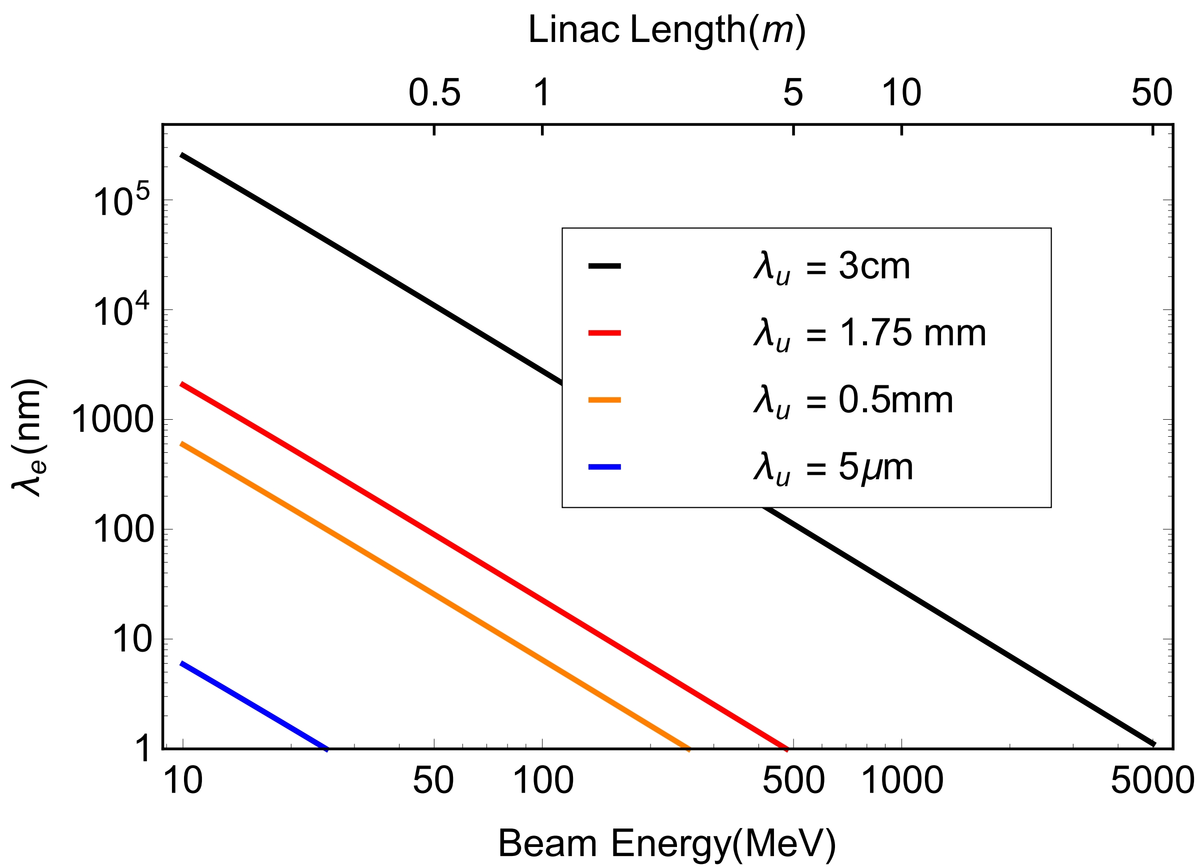
J. Neilson IEEE Trans. Ant. & Prop. 2002

Dual Moded Bend

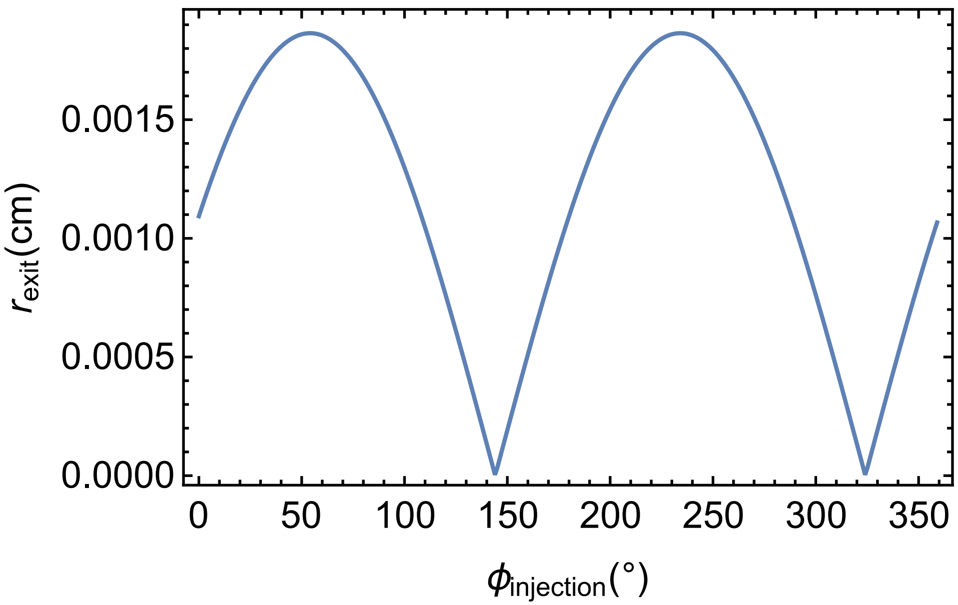


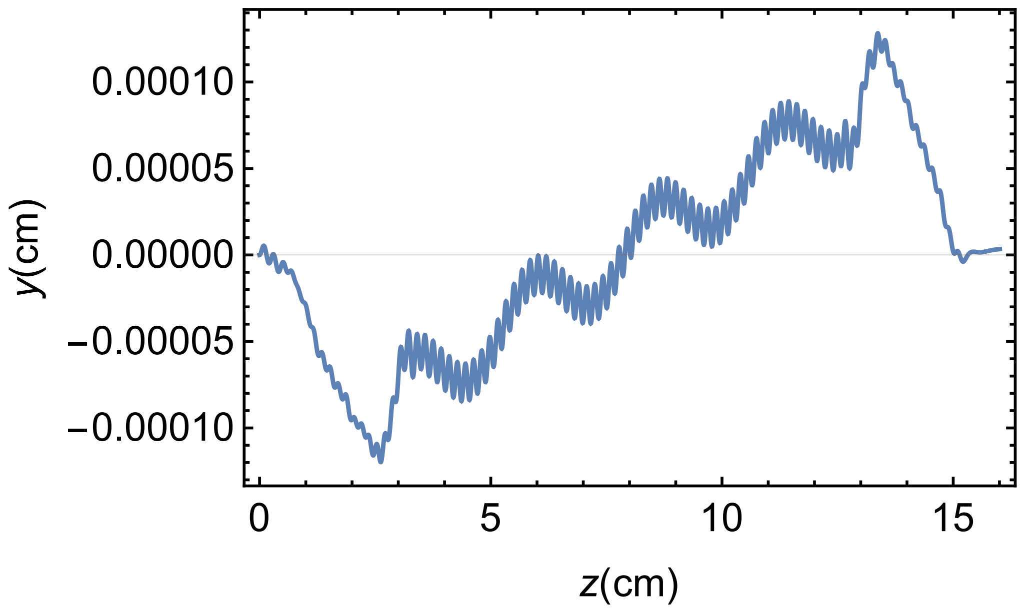


Radiation Scaling Graph



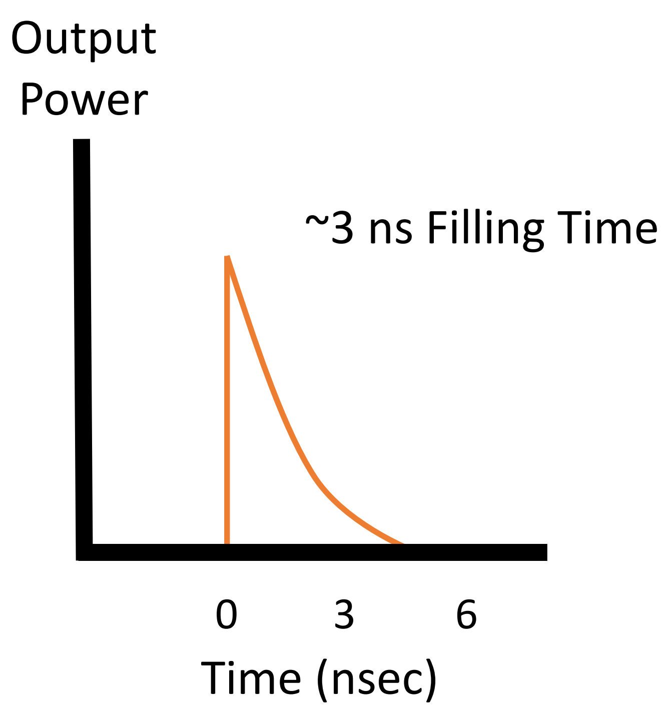
Single Electron Beam Dynamics inside the Undulator



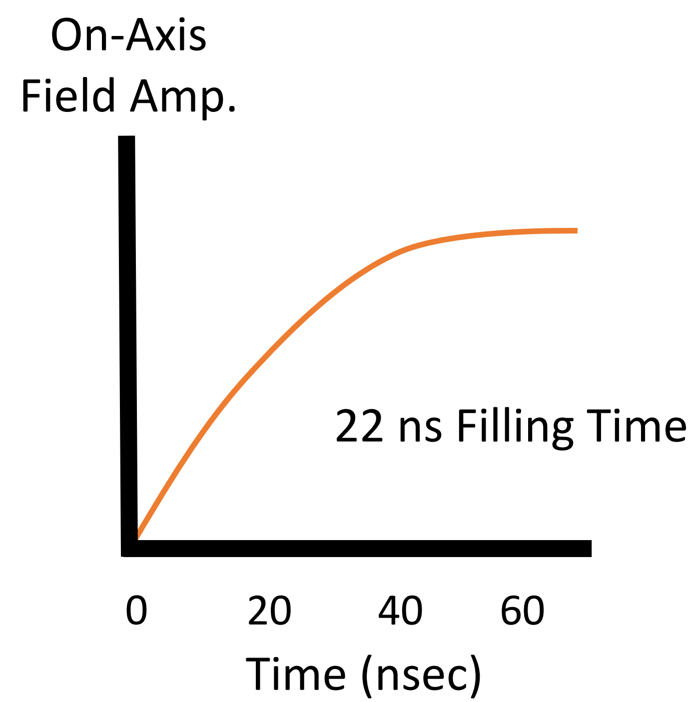


Train of Bunches needed to power the RF Undulator

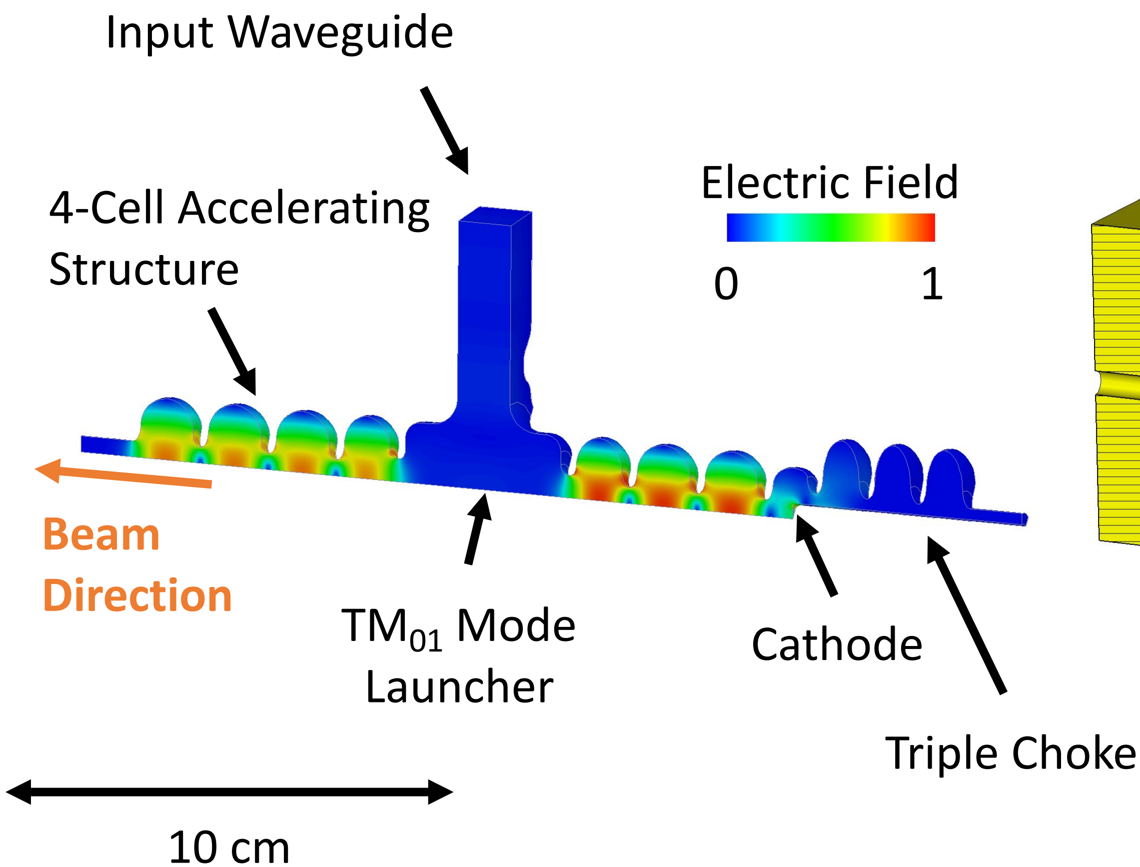
91.392GHz Accelerator Structure
Driven by Single Bunch

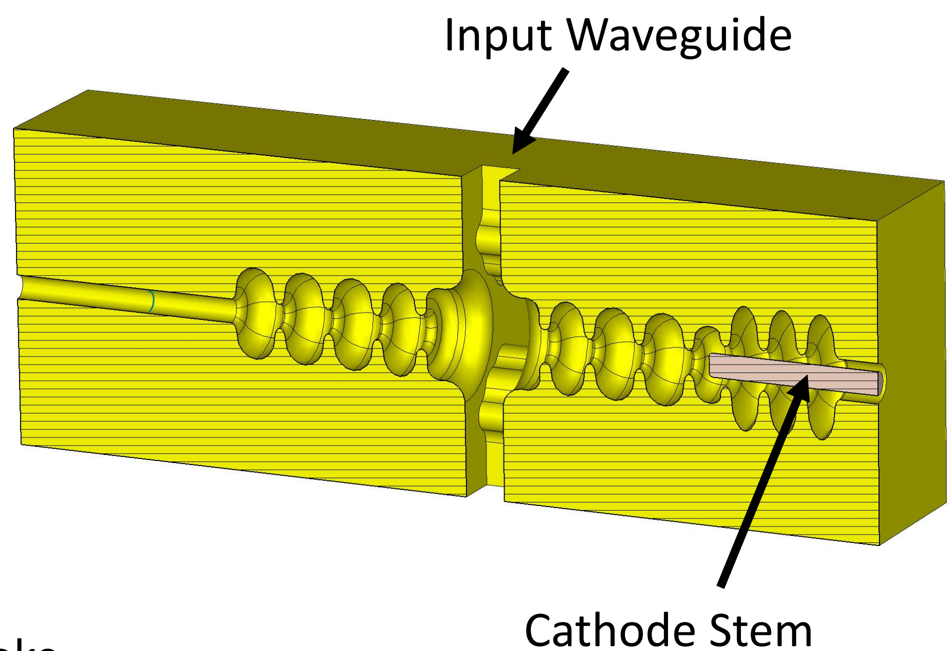


91.392GHz Undulator
Filled with Long Square Pulse

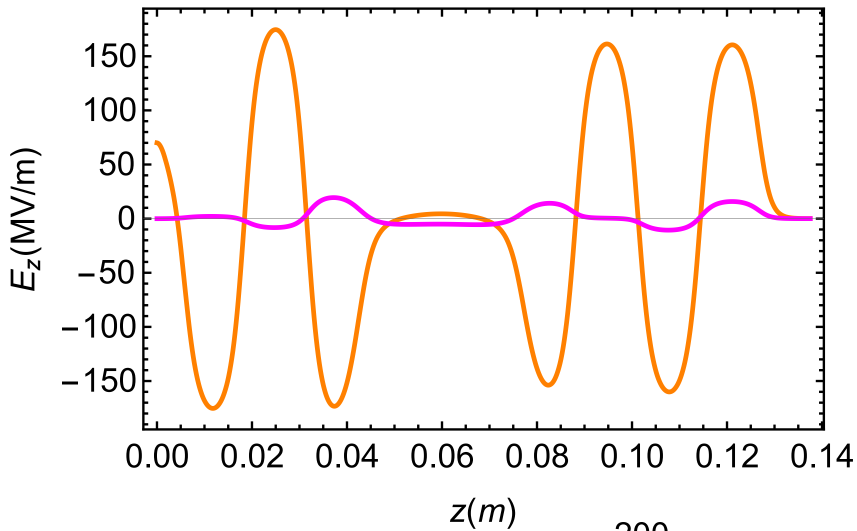


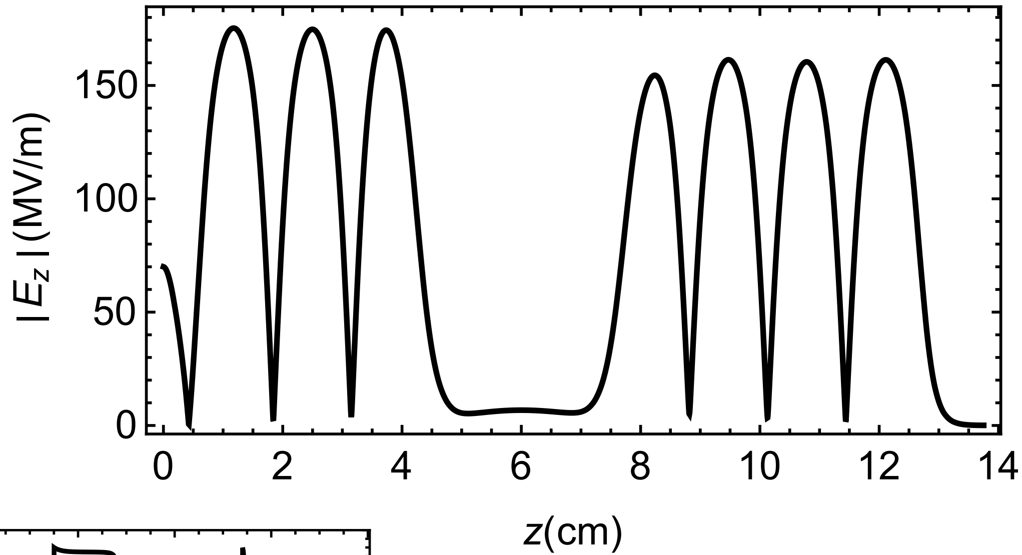
RF Injector Design

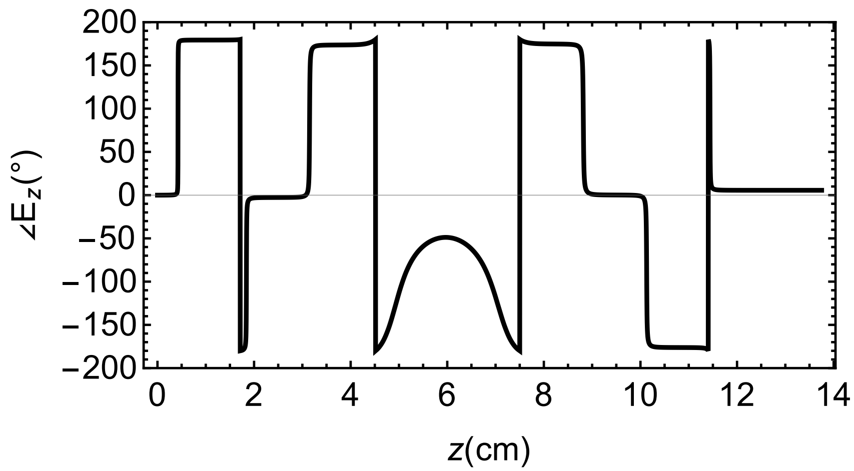




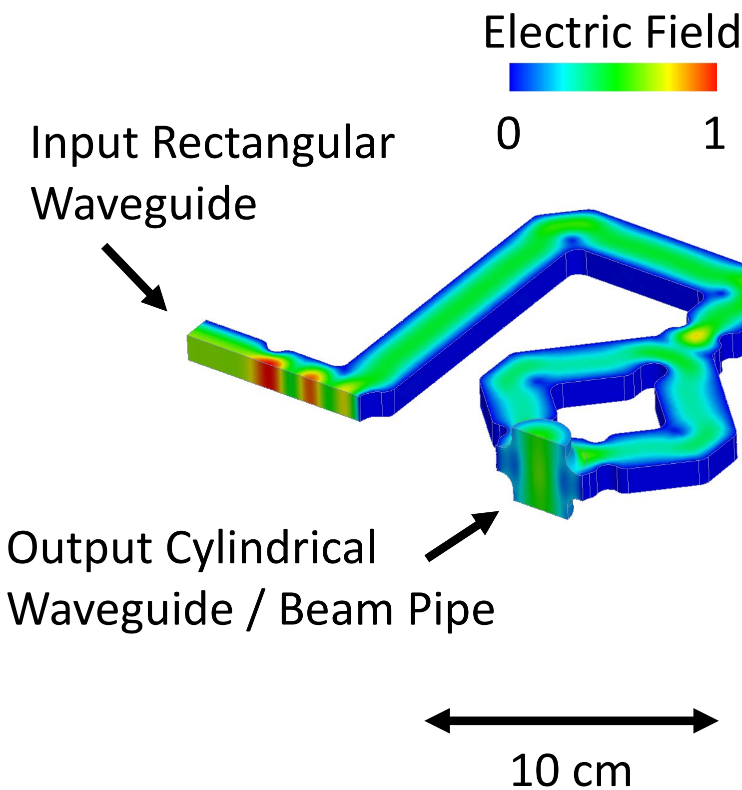
On-Axis Injector Fields

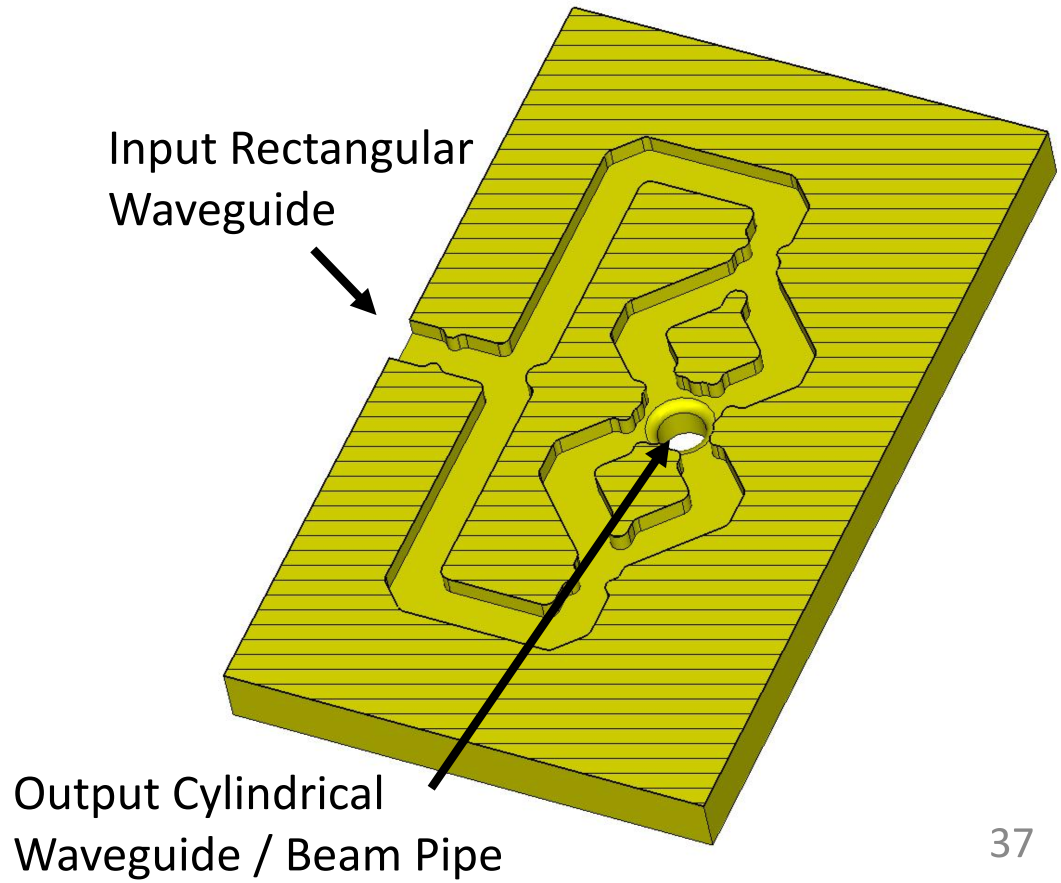






Quadrupole-Free Mode Launcher



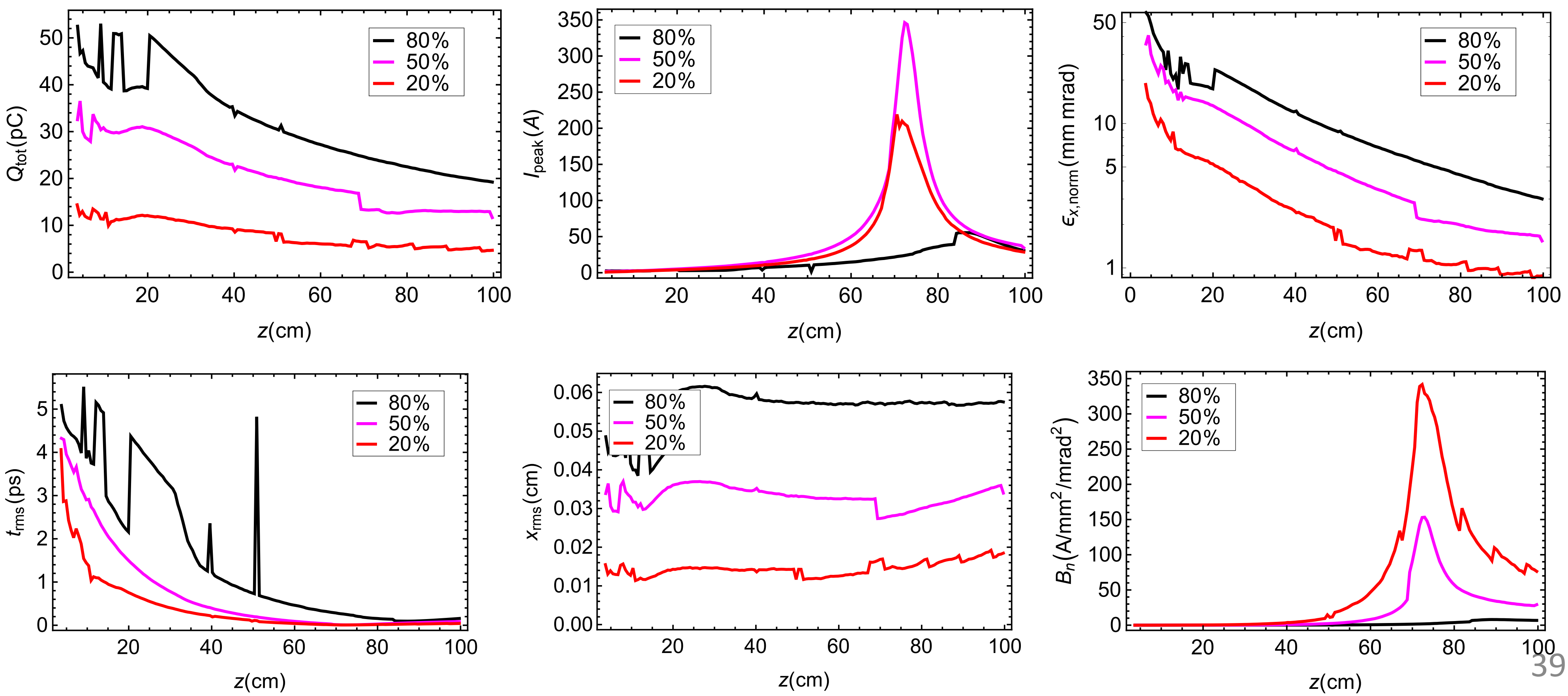


Bunch Properties at the Peak Bunching Point

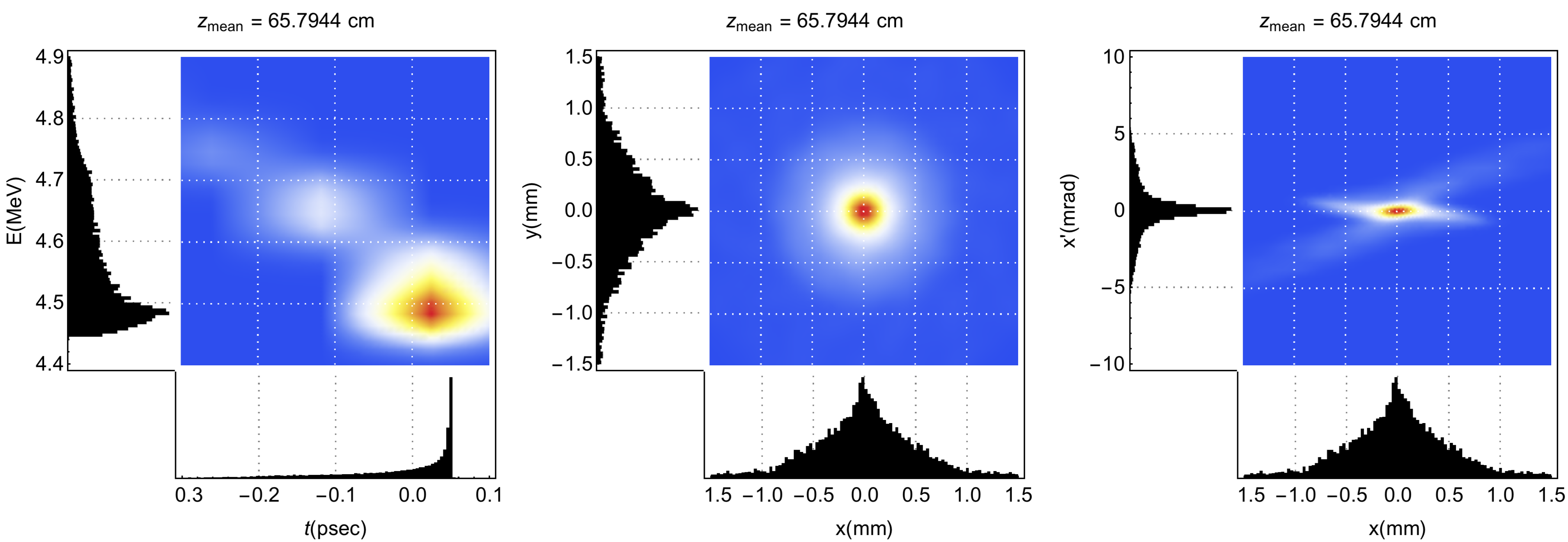
Bunch Part:	**80 %**
Energy:	**4.6 MeV**
Bunch Charge:	**25.7 pC**
Transverse RMS Size:	**561 µm**
Bunch length:	**338 fsec**
Transverse Emittance:	**6.2 mm mrad**
Energy Spread:	**3.5 %**

Assuming 40 A/cm^2 cathode current density

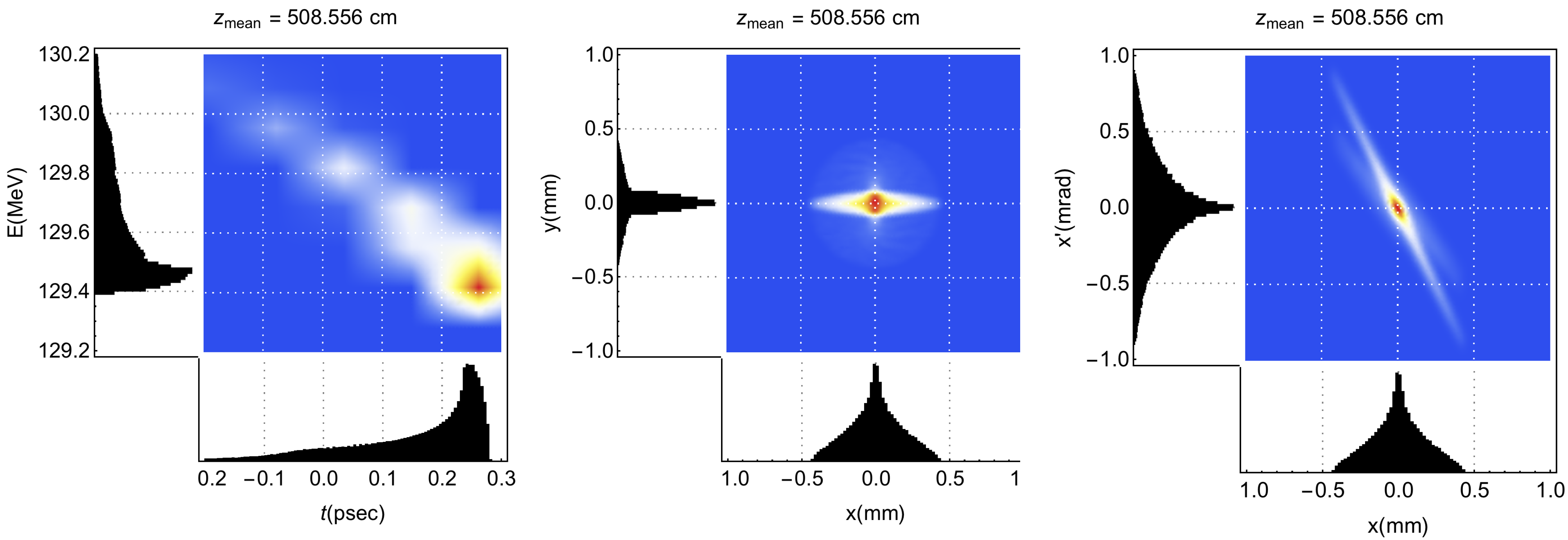
Injector Beam Dynamics



Phase Space @ Max Compression

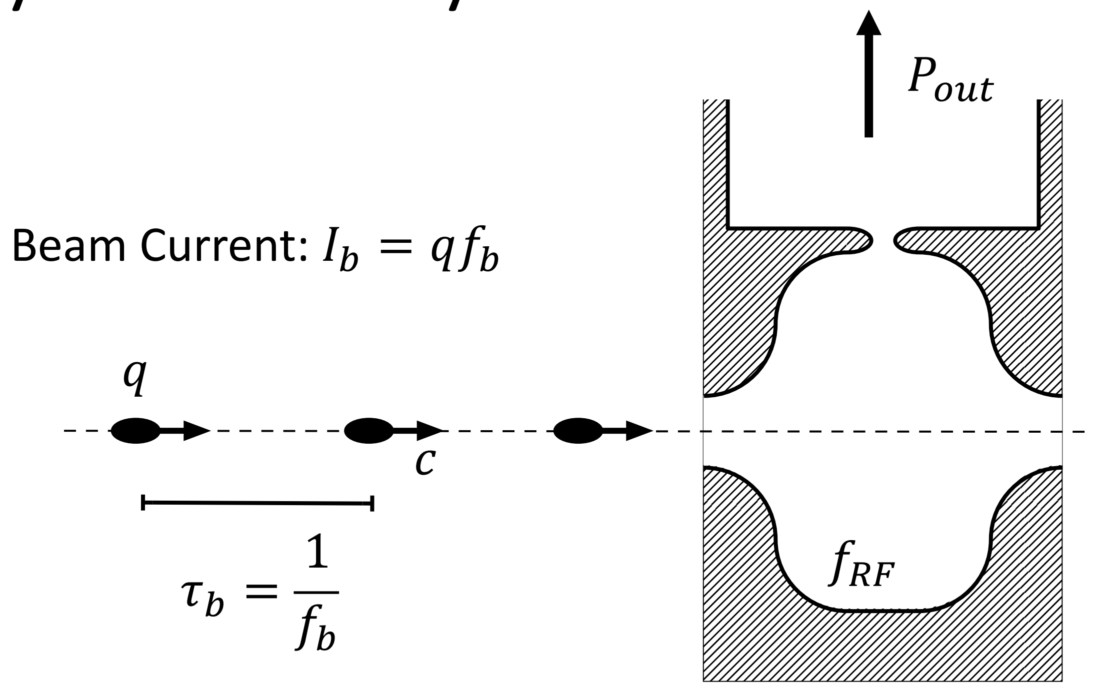


Phase Space @ Undulator



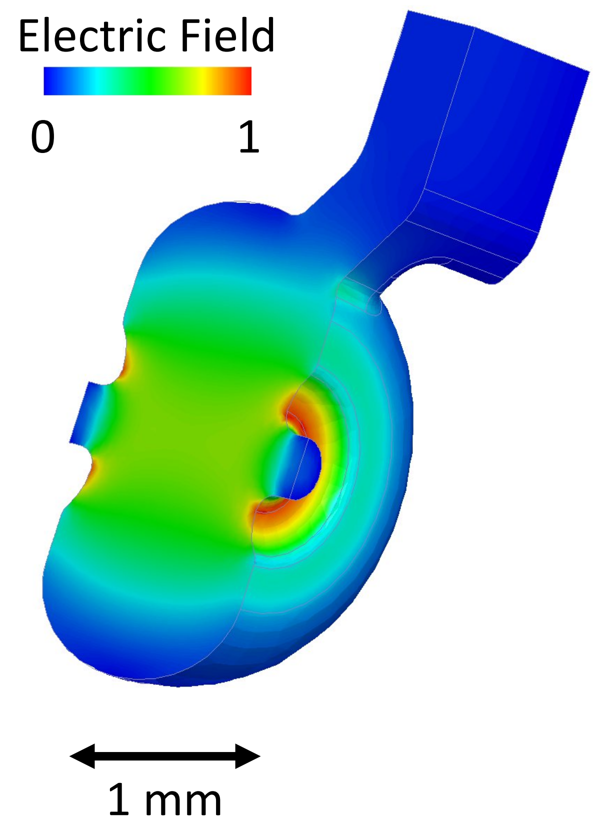
Energy Recovery

$$P_{out} = \frac{\beta}{(\beta+1)^2} I_b^2 R_{sh} \approx \frac{1}{4} I_b^2 R_{sh}$$

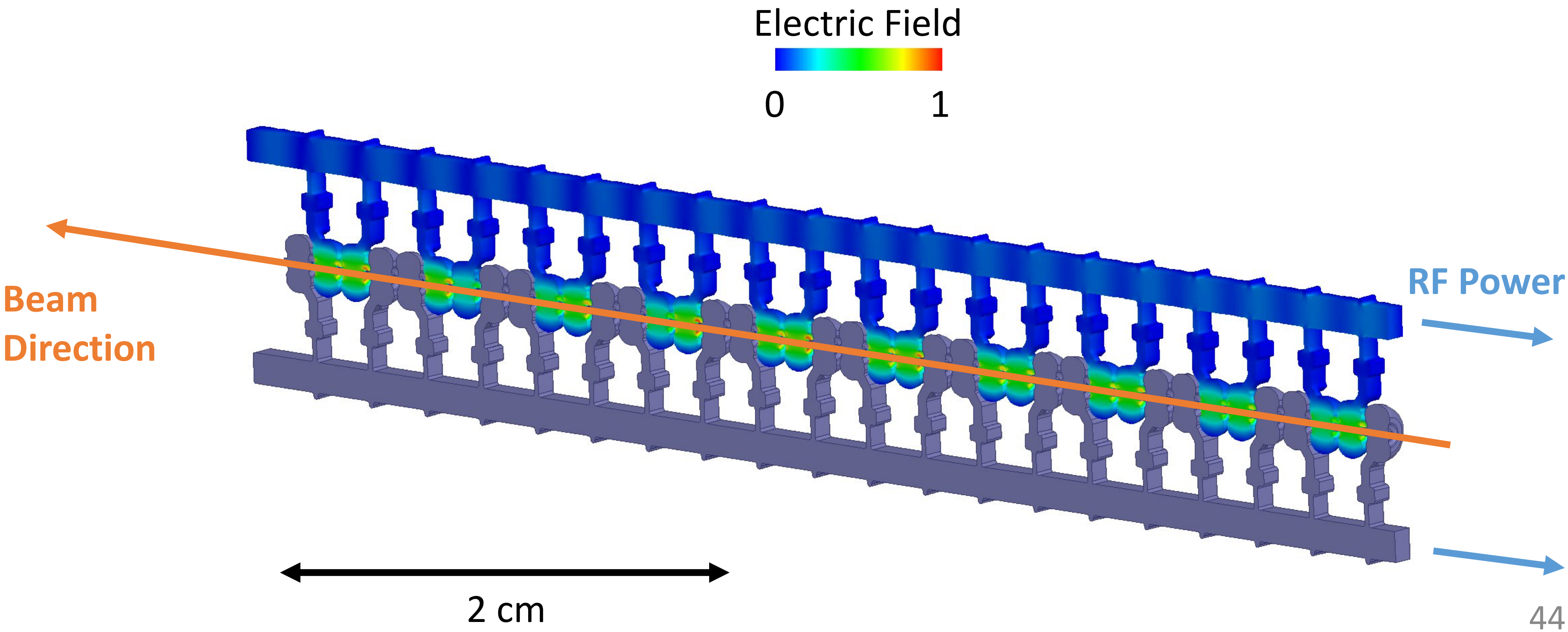


Energy Recovery – Single Cavity

Shunt Impedance	**444 MΩ/m or 0.73 MΩ/cell**
Temp Rise	**49°C / 10 kW / 250 nsec**



Power Combining Manifolds



Combining the two Manifolds