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Title: MaRIE Undulator & XFEL Systems

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MaRIE Undulator & XFEL Systems

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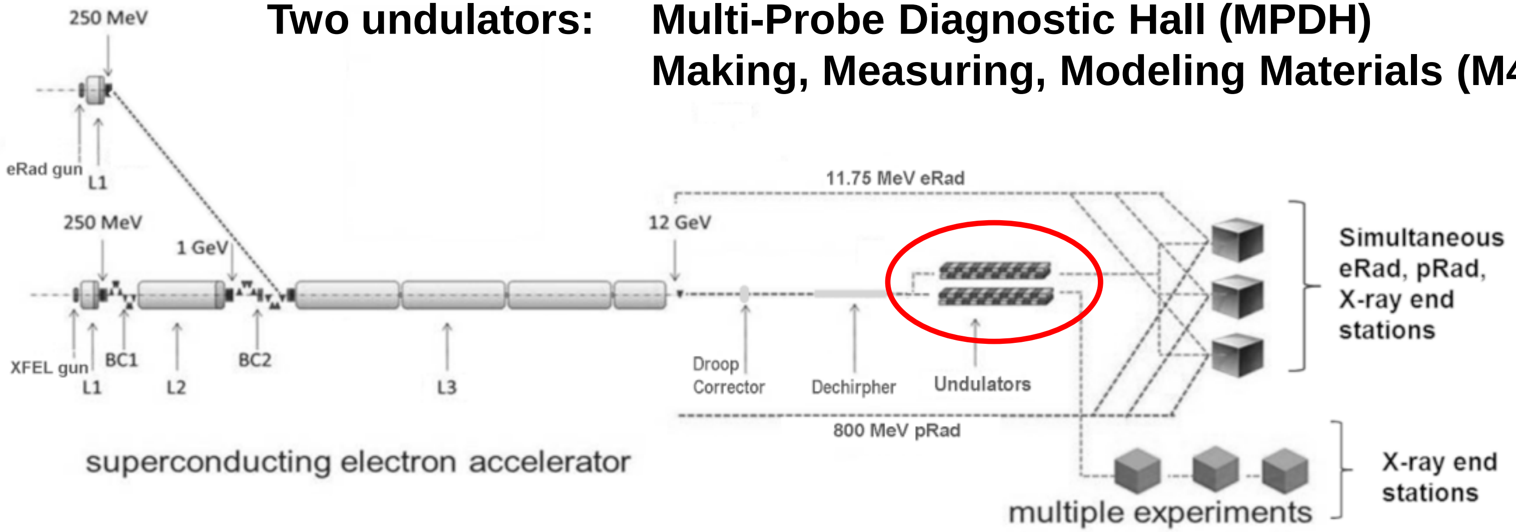
Outline

- MaRIE XFEL Performance Parameters
- Input Electron Beam Parameters
- Undulator Design
- Genesis Simulations
- Risks
- Summary

MaRIE XFEL Performance Parameters

Two undulators: **Multi-Probe Diagnostic Hall (MPDH)**
Making, Measuring, Modeling Materials (M4)



MaRIE Undulator Performance Parameters

- ❑ Produces >2 x 10^{10} 42-keV photons in each 33-fs pulse
- ❑ Provides standard SASE bandwidth (0.1% relative to λ_0)
- ❑ Provides narrow linewidth (<0.01% relative to λ_0) option for CXDI

Undulator and FEL Radiation Parameters

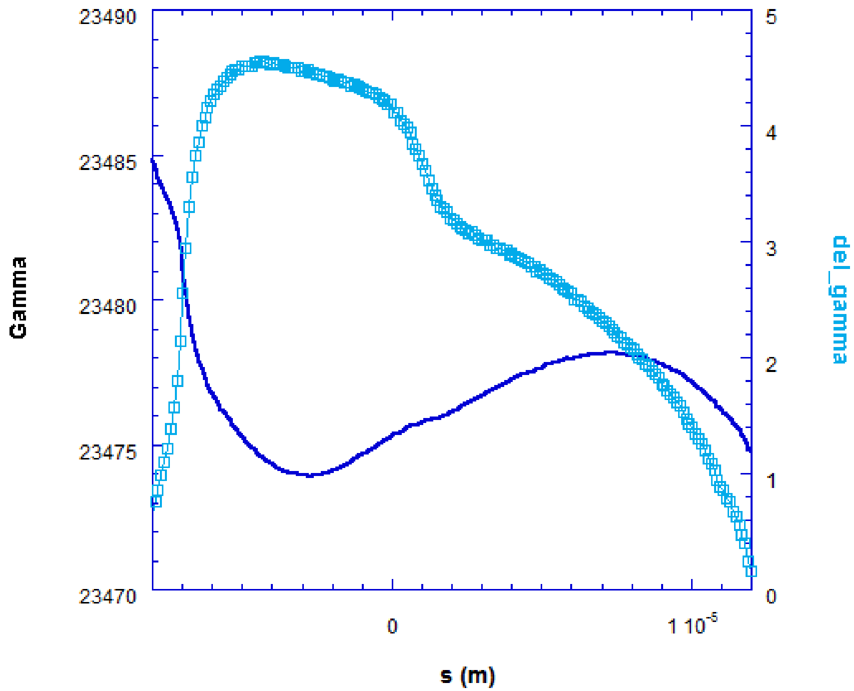
	Symbol	Value
Undulator period	λ_u	18.6 mm
Undulator magnetic field	B_0	0.7 T
rms (peak) undulator parameter	K_{rms} (K_{peak})	0.86 (1.22)
FEL resonance wavelength	λ_0	0.2934 Å
FEL (Pierce) parameter	ρ	0.0005
Calculated 3D gain length	L_G	2.6 m
Calculated 3D saturated power	P_S	9 GW
FEL pulse energy at saturation	W_p	0.3 mJ

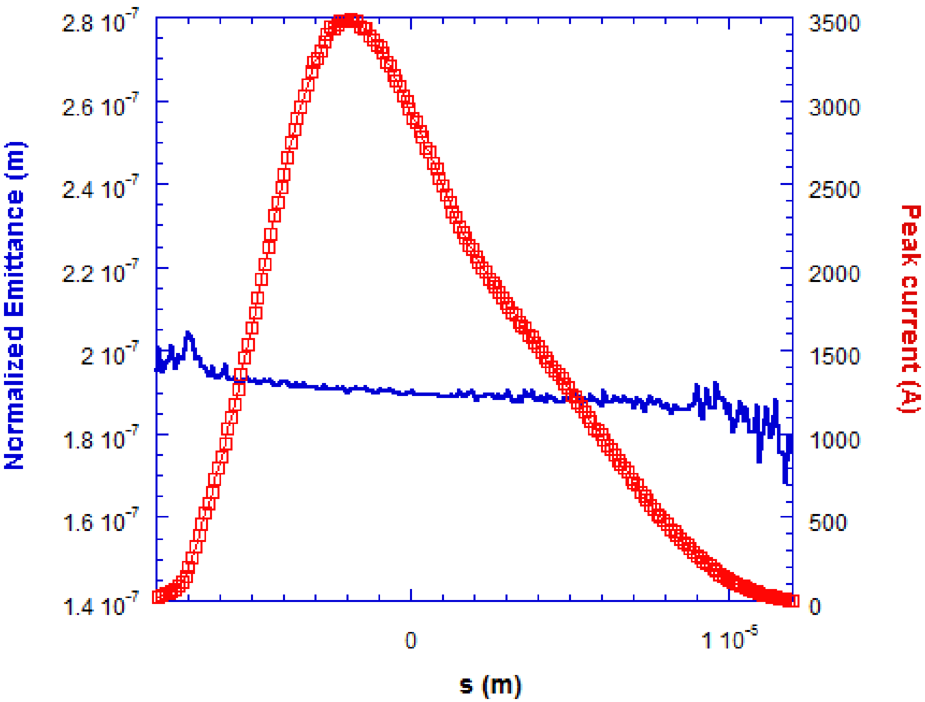
Assumptions

- **Electron beam at undulator entrance has the following properties**
  - Bunch charge = 100 pC
  - Bunch length = 10 μm (33 fs)
  - Peak current = 3.5 kA
  - Normalized emittance (slice) = 0.2 μm
  - rms relative energy spread (slice) = 0.02%
  - No significant energy slew along the bunch
  - No significant microbunching (μBI) due to longitudinal space charge
  - No dispersion of x beam centroid along the bunch

Elegant-generated Electron Beam (S-band)

S-band linac electron beam distribution has LSC μBI suppression

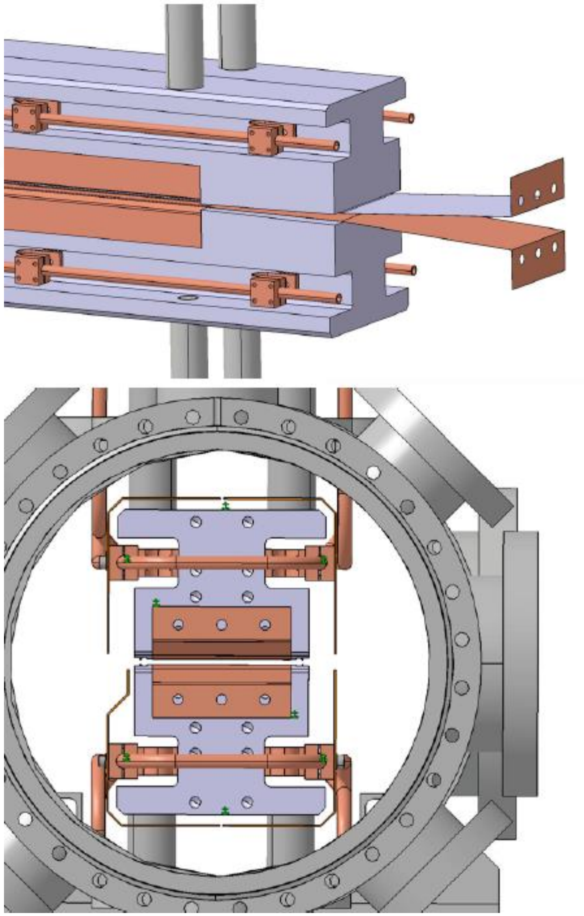




Electron beam at the entrance has a residual energy slew. Lasing occurs over the region where peak current is maximum and energy slew is minimum.

Courtesy of J. Lewellen

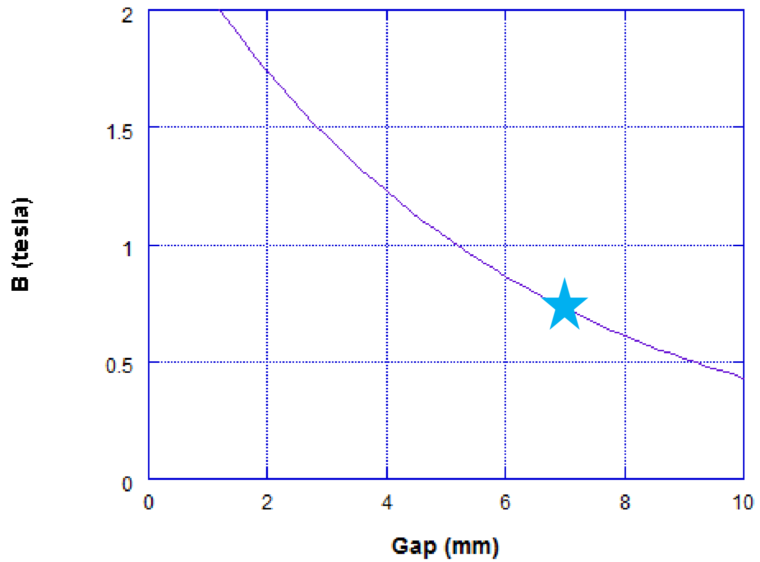
MaRIE undulators are similar to SwissFEL U15



Courtesy of T. Schmidt

- PM material = VACODYM 863 TP with Dy infusion
- B_r = 1.25 tesla; intrinsic H_c > 2,300 kA/m
- Pole material = vanadium permendur
- Wakefield shield and RF fingers = 0.1-mm CuNi foils with 50-μm copper as the RF surface.

Calculated magnetic field vs gap



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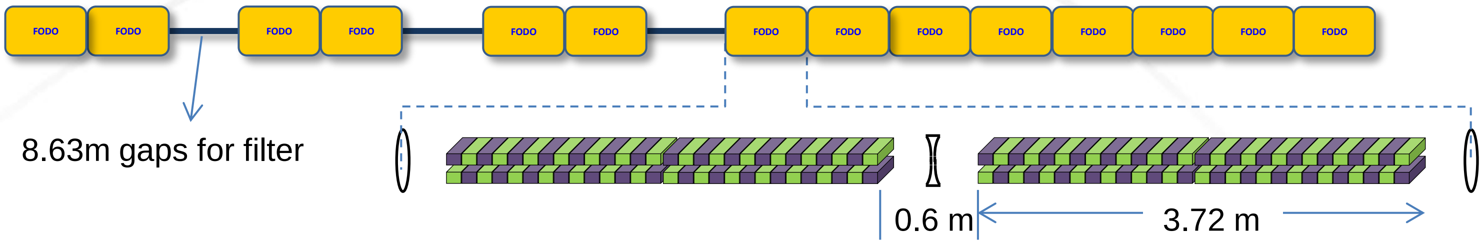
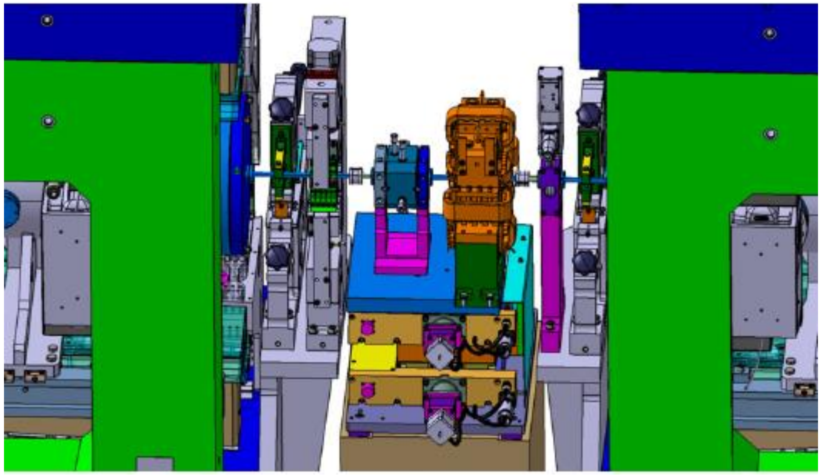
MaRIE XFEL has 14 FODOs with undulators

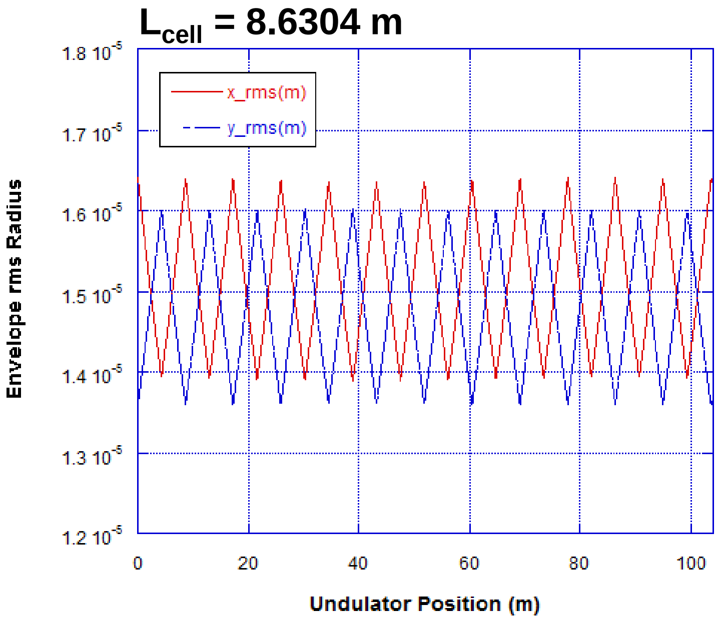
MaRIE XFEL with Distributed Seeding



Courtesy of R. Ganter



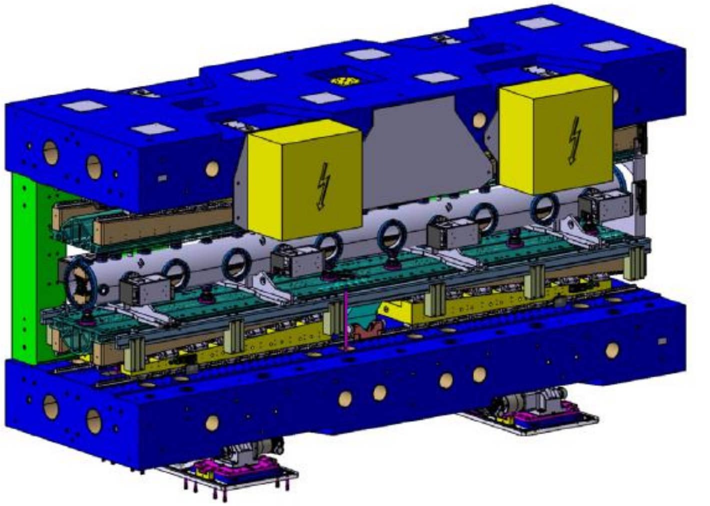
Each 0.6m break between undulator segments houses two gate valves, a beam position monitor, a phase shifter, a PM FODO quad and an adjustable alignment quad.



In-Vacuum Undulator Performance Data

	SwissFEL U15	MaRIE
Period (mm)	15	18.6
Maximum B_0 (T)	0.85	0.7
Maximum K_{peak}	1.8	1.49
Nominal gap (mm)	4.7	7.0
Segment length (m)	4.0	3.72
N periods / segment	266	200
Vacuum pressure (torr)	2.6×10^{-7}	
CuNi straightness (μm)	12-18	
CuNi roughness (nm)	120	
Wakefield, flat Cu 5-mm	-50 keV/m/.1nC	
Wakefield, round Cu 5-mm	-150 keV/m/.1nC	

R. Ganter et al., Proceedings of FEL2012 Conference



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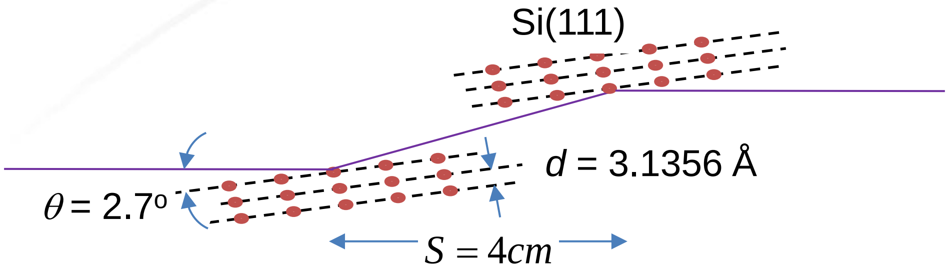
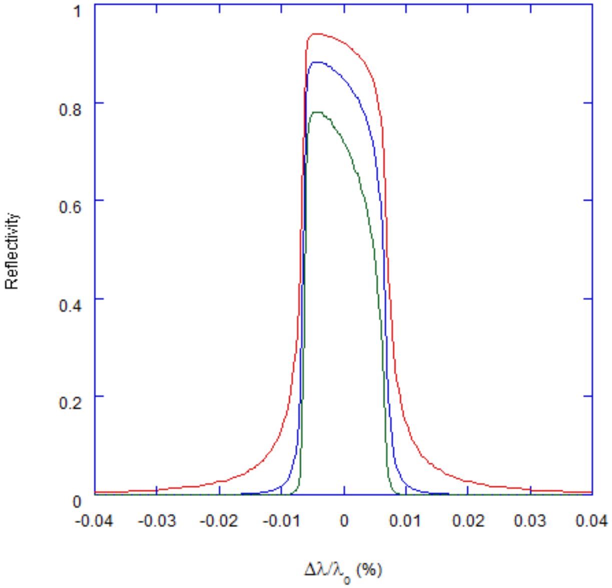
Distributed Seeding with Si(111) Crystals

Si(111) crystals have >90% reflectivity per surface



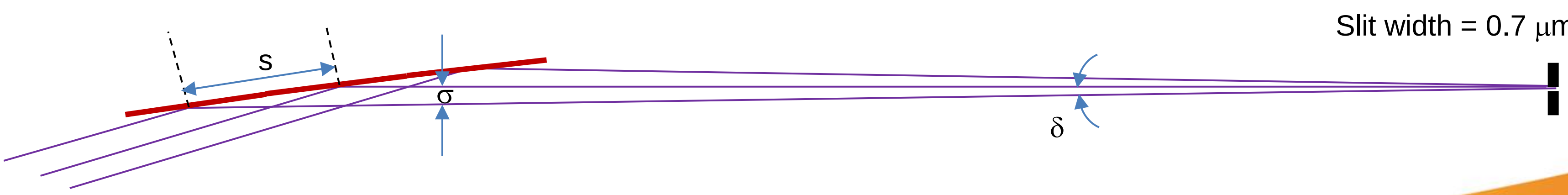


Bragg angle at 0.294Å is 2.7°

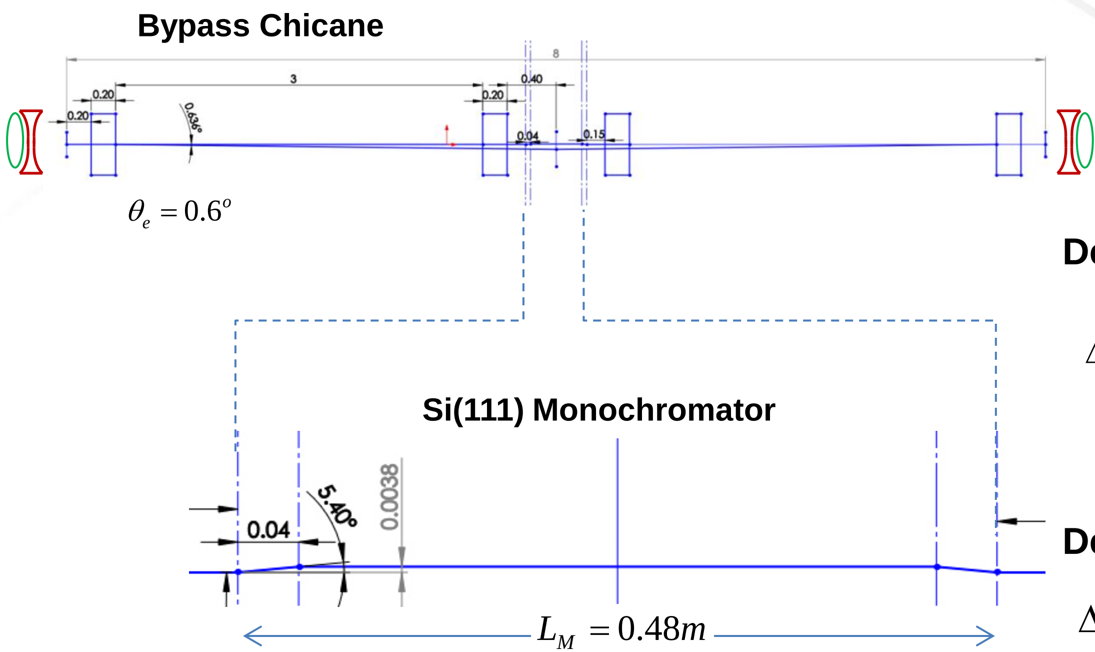
Darwin width = 1.25 arc sec ($\Delta\lambda/\lambda_0$ = 1.3 x 10^{-4})

A 0.7-μm slit between double monochromators selects ±0.01% BW

Curved Si crystals (R = 0.424m) focus X-ray beams onto the slit.



Chicane synchronizes electrons with X-rays



Delay in electron beam path

$$\Delta S_e = 4L\left(\frac{\theta_e}{\sin\theta_e} - 1\right) + 2D\left(\sqrt{1+\tan^2\theta_e} - 1\right)$$

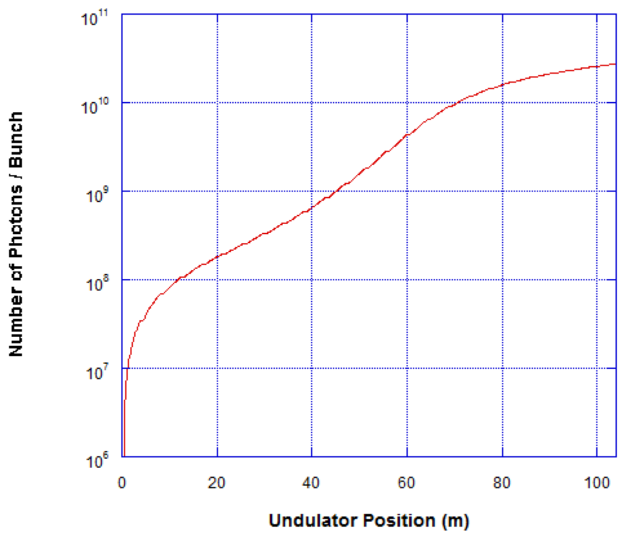
Delay in X-ray beam path

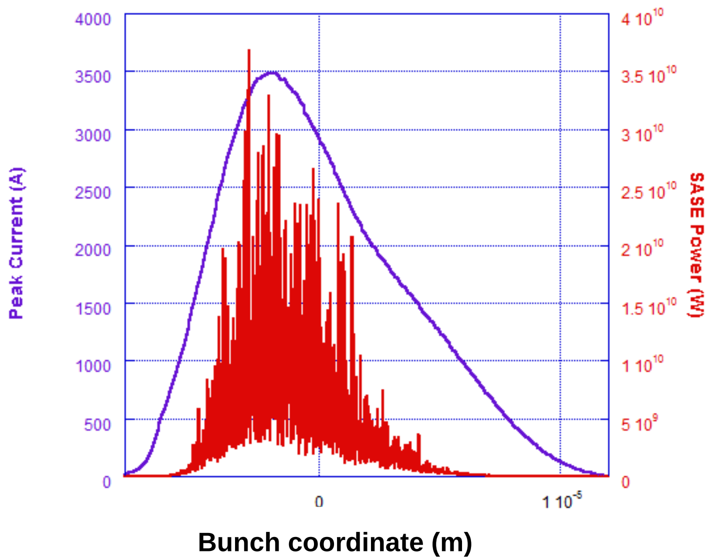
$$\Delta S_{X-ray} \approx S_{12}\tan^2(2\theta_B)$$

Electron and X-ray beams are delayed with respect to straight path by 357 μm (1.19 ps)

Chicane R_{56} also smears out any FEL-induced microbunching (fresh bunch technique).

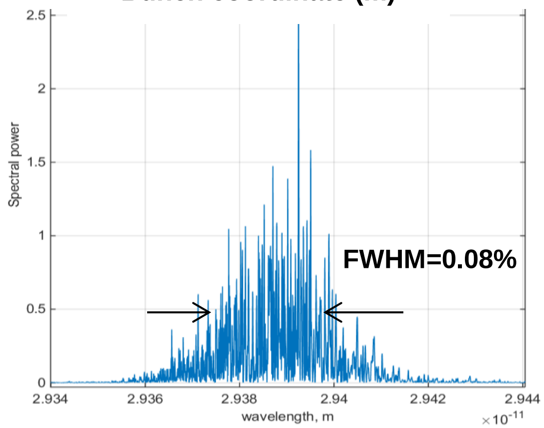
SASE generates 3 x 10^{10} photons in 0.08% BW





MaRIE XFEL in SASE mode is quasi-coherent temporally. Each FEL pulse contains about one hundred coherence lengths, same as the number of spectral spikes. The overall bandwidth (FWHM) is 0.08% in agreement with prediction.

$$\frac{\Delta\lambda}{\lambda_0} = \frac{4\ln 2}{\sqrt{\pi}}\rho \approx 1.56\rho$$

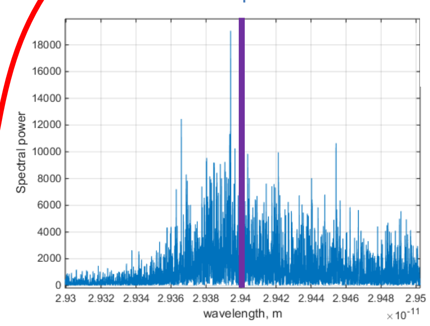


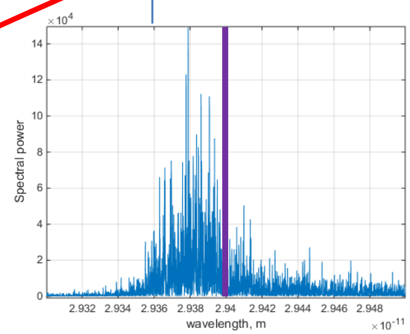
How does DS improve spectral contrast?

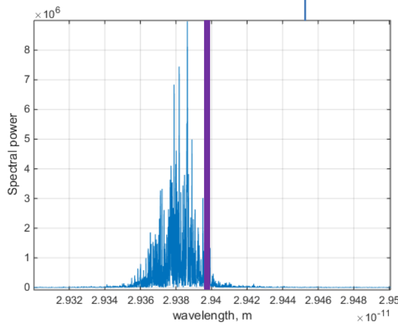
Angle-integrated undulator radiation with real electron beams starts out with many photons at wavelengths longer than λ_0 (equivalent to ε_c)

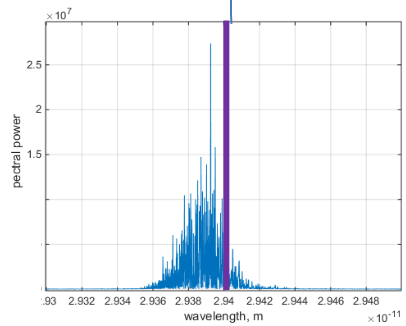
As SASE builds up, spectrum becomes more Gaussian and shifts to shorter λ

SASE power (log) versus distance









Seeding at longer λ (but within gain bandwidth) increases the seeded FEL signal relative to SASE background, thus improving the spectral contrast.

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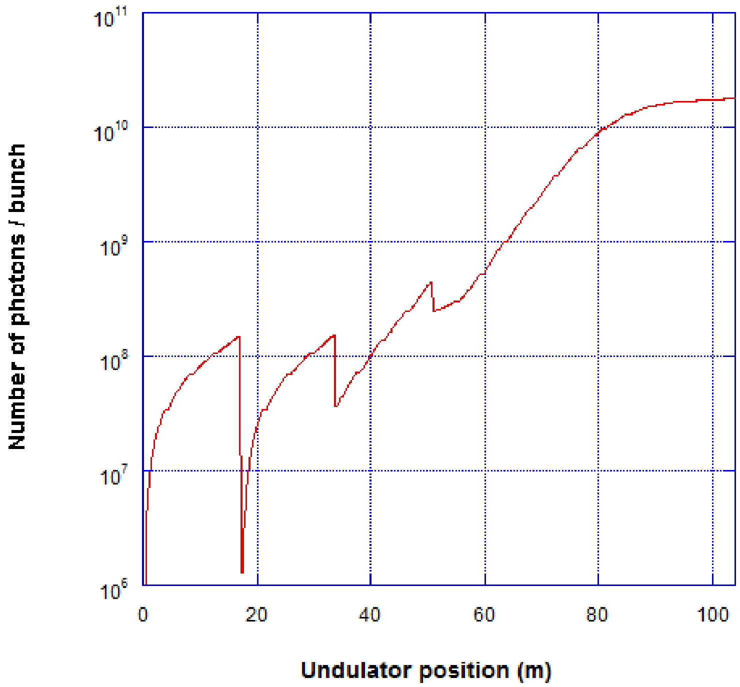
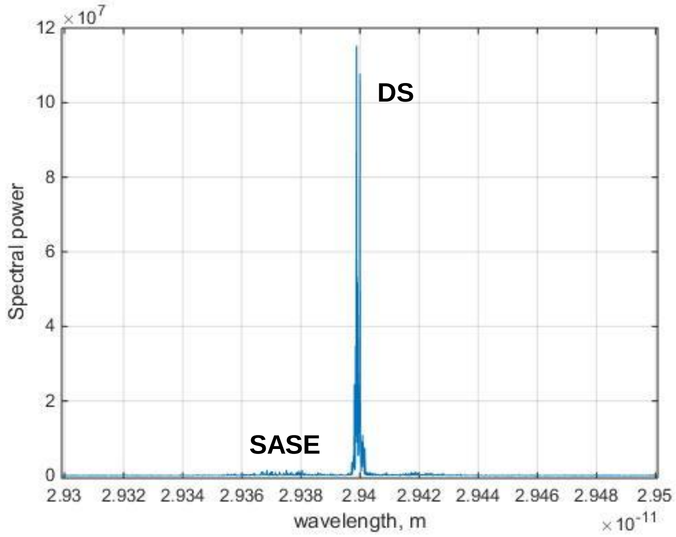
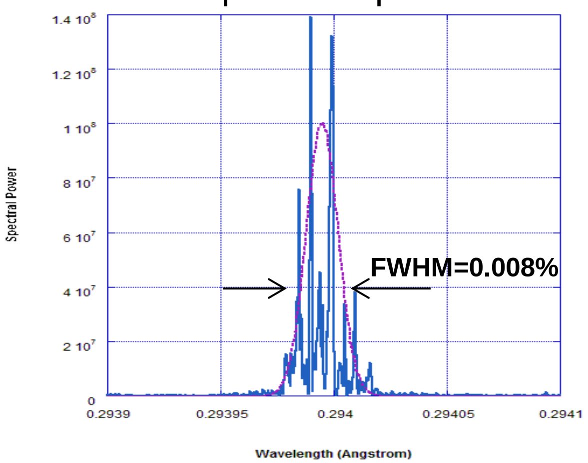
DS generates 2 x 10^{10} photons in 0.008% BW



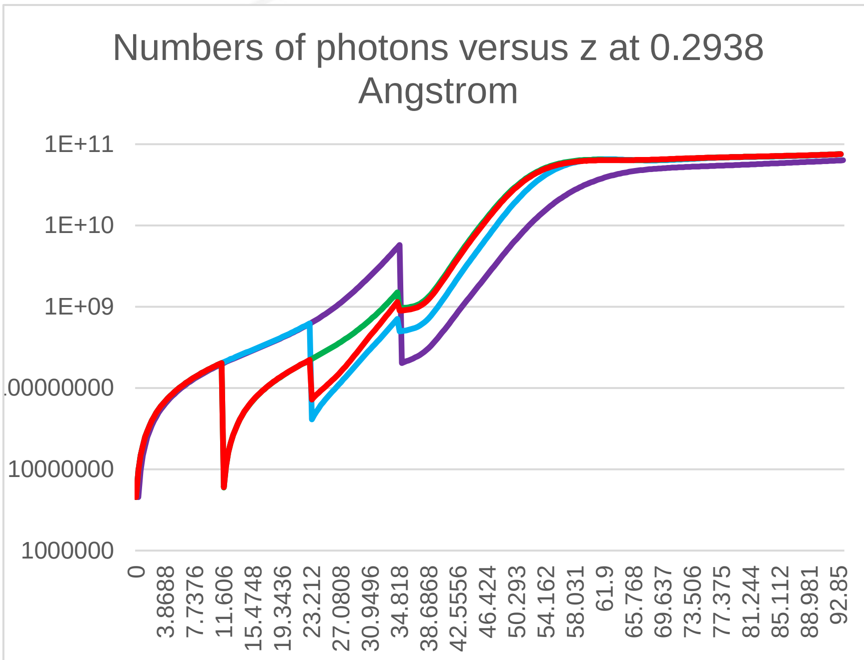


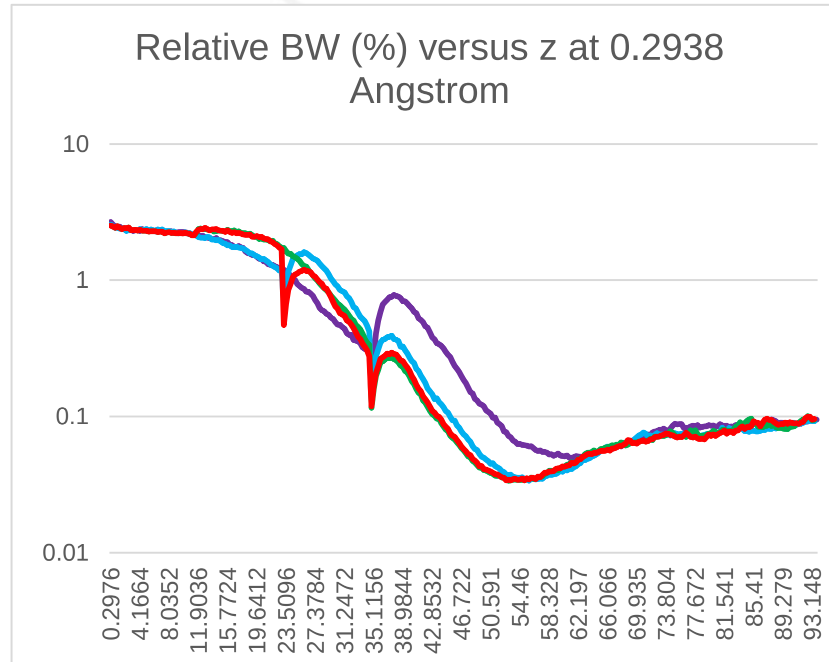
Expanded spectrum



Seeding earlier in the power vs z curve at more than one location produces narrow FEL linewidth and low SASE background.

Different DS schemes yield similar performance





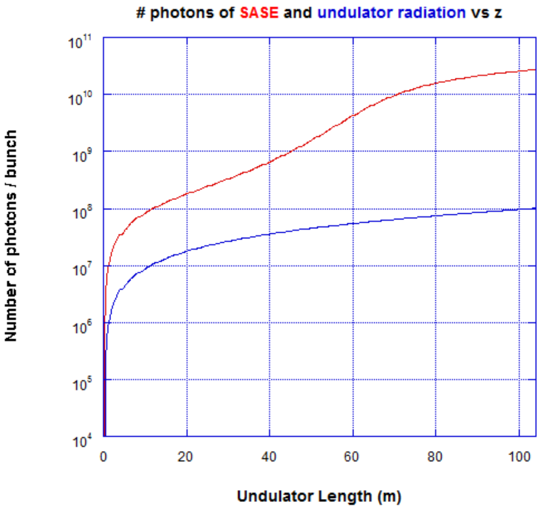
All Distributed Seeding schemes yield the same number of photons and relative bandwidth. The worst performer is single-step self-seeding (purple traces) which yields fewer photons and larger rms bandwidth.

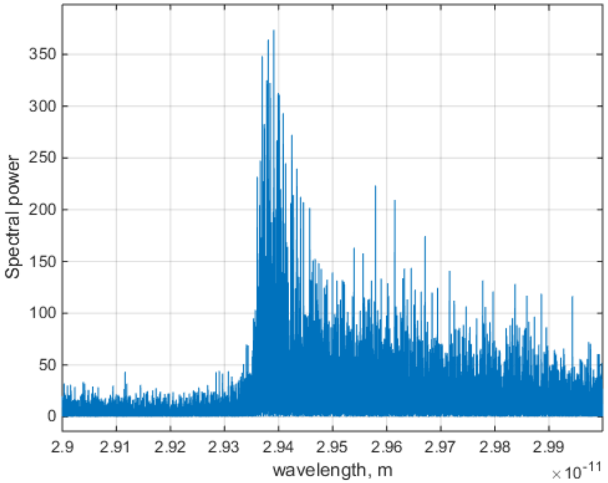
Risk 1 – I_{peak} is too low

- **<u>Cause</u>: Can't compress electron bunch in BC2 with good ε_n and $\Delta\gamma/\gamma$.**

- **<u>Consequence</u>: Number of photons in 100-pC bunch drops to 1 x 10^8 (undulator radiation with medium peak current in long undulators).**

- **<u>Mitigation</u>: Increase bunch charge and/or undulator length.**





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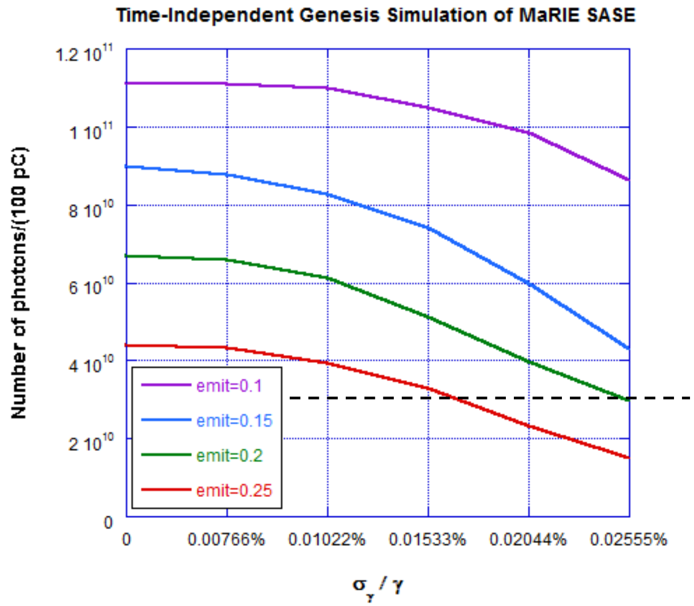
Risk 2 – Beam ε_n and $\Delta\gamma/\gamma$ don't meet specs

- **Cause: Can't achieve the specified ε_n (0.2 μm) and $\Delta\gamma/\gamma$ (0.02%).**

- **Consequence: Number of photons / bunch is affected.**

- **Mitigation: Taper the undulator to recover the number of photons.**



2 x 10^{10} photons with Time-dependent Genesis

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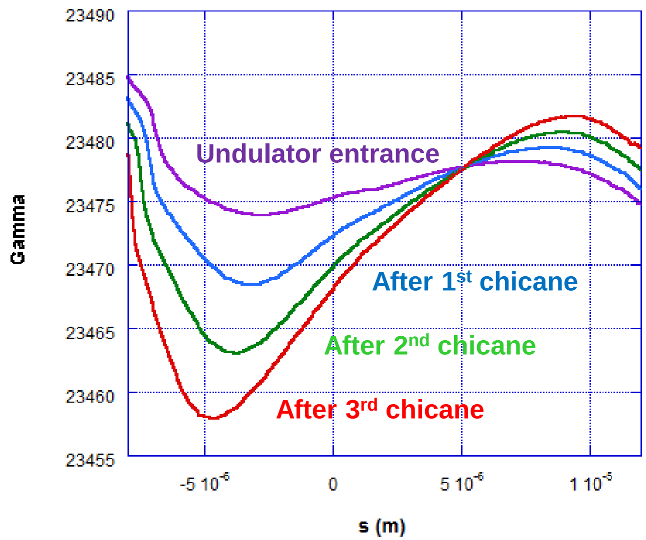
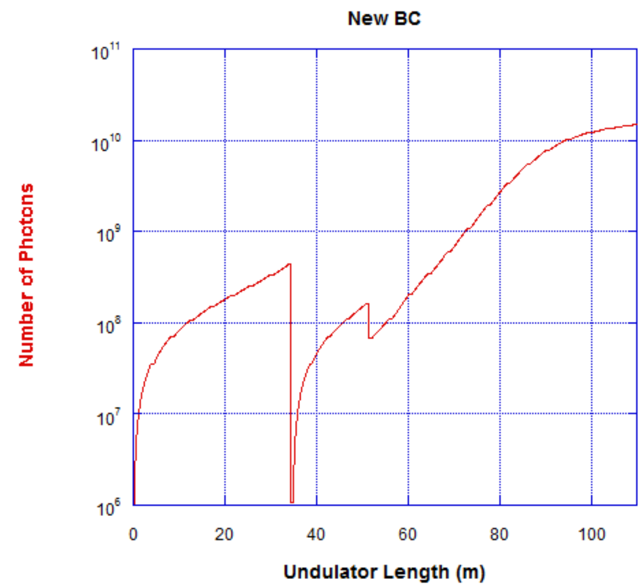
Risk 3 – CSR in delay chicane is too high

- **<u>Cause</u>: CSR reduces the beam energy where lasing occurs.**
- **<u>Consequence</u>: Number of photons / bunch is reduced.**
- **<u>Mitigation</u>: Reduce number of filters (chicanes); taper the undulator.**





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Risk 4 – Broad spectrum from DS FEL

- **Cause: Incomplete dechirping, large energy spread or CSR in chicanes.**

- **Consequence: Output bandwidth (~0.08%) is too large for CXDI.**

- **Mitigation: Perform early validation experiments.**

Risk 5 – LSC causes too much microbunching

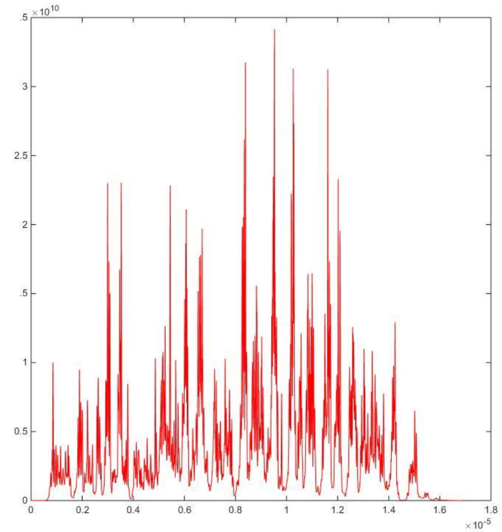
- **<u>Cause</u>: LSC microbunching is significant after BC2.**
- **<u>Consequence</u>: Larger SASE bandwidth. DS may not work.**
- **<u>Mitigation</u>: Model DS using electron beams with μBI.**

μBI causes strong modulation in P vs s plot. The SASE peak power is higher but the spectrum is broader.

Power (GW)

35

15



s (microns)

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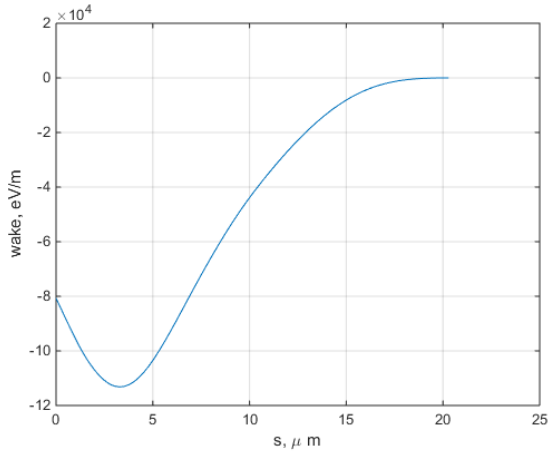
Risk 6 – Resistive wake is too high

- **Cause: Resistive wake is higher than Bane-Stupakov prediction.**
- **Consequence: Number of photons / bunch is reduced.**
- **Mitigation: Taper the undulator; perform validation experiments.**



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Summary

- **Time-dependent Genesis simulations show the MaRIE XFEL can deliver the number of photons within the required bandwidth, provided a number of assumptions are met.**

- **The highest risks are associated with the electron beam driving the XFEL undulator.**

- **Risks associated with the undulator and/or distributed seeding technique may be evaluated or retired by performing early validation experiments.**