The 10th International Conference

CHANNELING 2024

Charged & Neutral Particles Channeling Phenomena

FEL performance and tolerance studies of the EuPRAXIA@SPARC_LAB beamline AQUA

F. Nguyen on behalf of the EuPRAXIA@SPARC_LAB Collaboration

With relevant inputs from L.Giannessi, M.Opromolla, A.Petralia

ENEA
Italian National Agency for New Technologies,
Energy and Sustainable Economic Development

INFN
Istituto Nazionale
di Fisica Nucleare

UNIVERSITÀ
DEGLI STUDI
DI MILANO

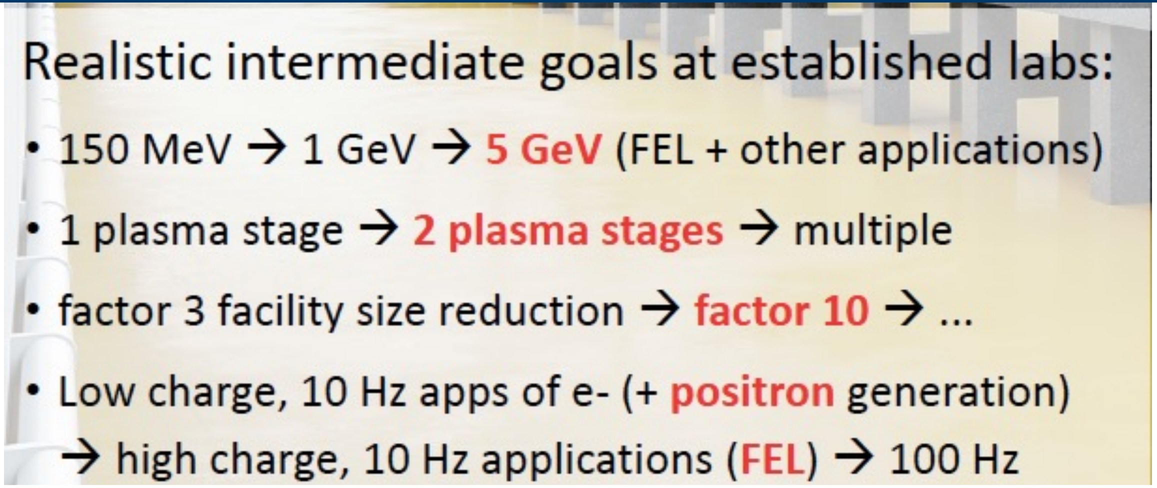
Fermilab

EuPRAXIA@SPARC_LAB: AQUA

1st international design of a plasma accelerator facility

EuPRAXIA is designed to deliver at 10-100 Hz ultra-short pulses of

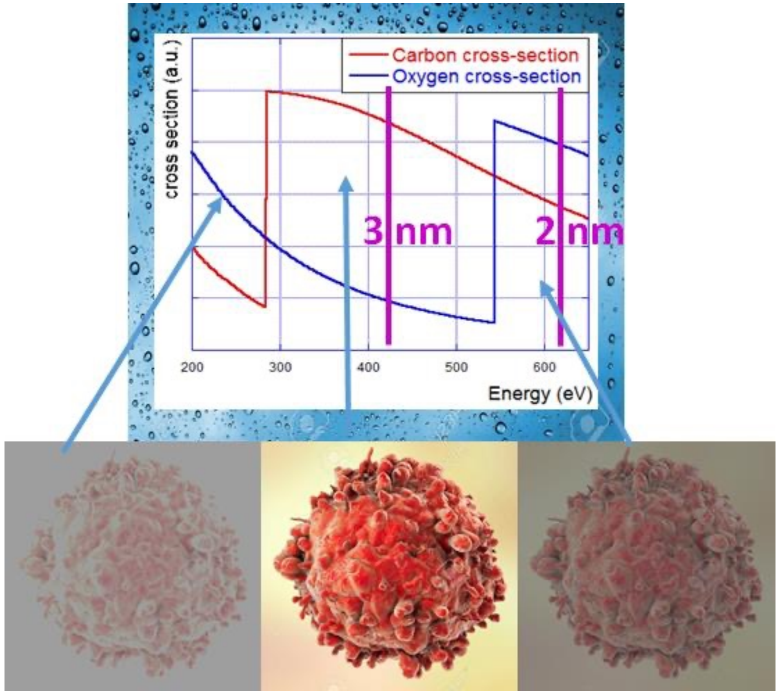
- Electrons (0.1-5 GeV, 30 pC)
- Positrons (0.5-10 MeV, 10^6)
- Positrons (GeV source)
- Lasers (100 J, 50 fs, 10-100 Hz)
- Betatron X rays (5-18 keV, 10^{10})
- FEL light (0.2-36 nm, 10^9-10^{13})



Realistic intermediate goals at established labs:

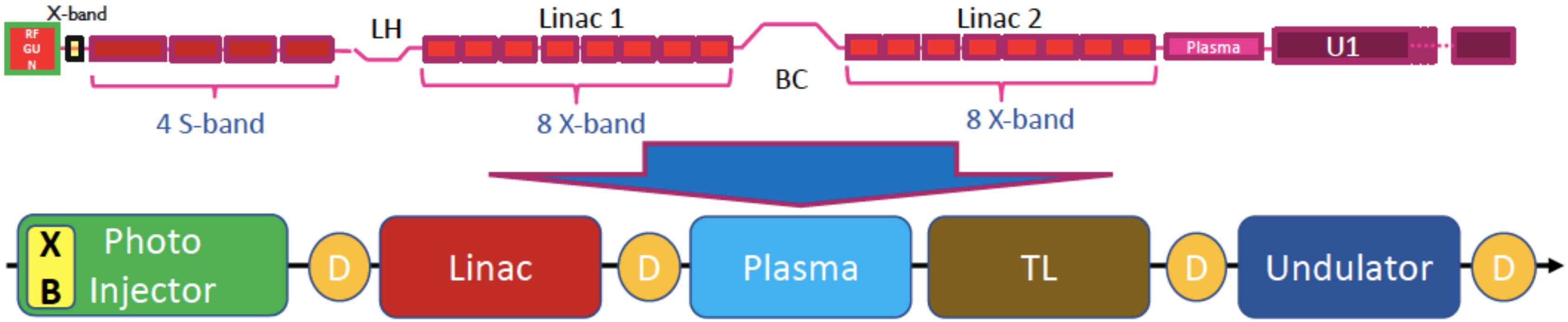
- 150 MeV → 1 GeV → **5 GeV** (FEL + other applications)
- 1 plasma stage → **2 plasma stages** → multiple
- factor 3 facility size reduction → **factor 10** → ...
- Low charge, 10 Hz apps of e- (+ **positron** generation) → high charge, 10 Hz applications (**FEL**) → 100 Hz

The **AQUA** (water in *Latin*) beamline of the EuPRAXIA@SPARC_LAB project is a **FEL facility** to be operated in Self-Amplified Stimulated Emission **SASE** for experiments around **3-4 nm wavelength, i.e. 410-310 eV photon energy, where water looks transparent** differently from O or C which are absorbing and scattering → *water window* relevant to study biological samples with coherent imaging



FEL beamlines for EuPRAXIA@SPARC_LAB

Plasma-Beam driven site at INFN Frascati

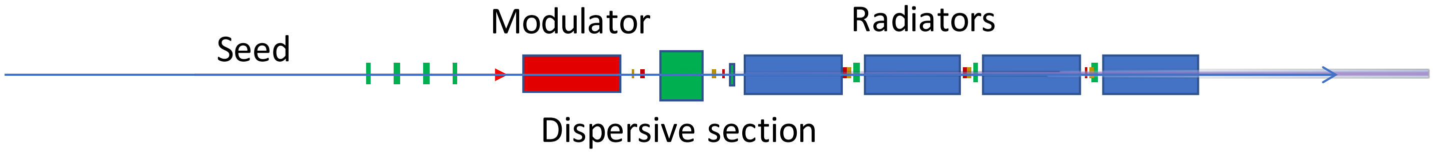


Two foreseen FEL beamlines:

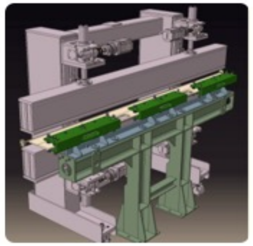
1) **AQUA: Soft-X ray SASE FEL – Water window optimized for 4 nm (baseline)**

SASE FEL: 10 UM Modules, 2 m each – Two technologies under study: Apple-X PMU and planar SCU

2) **ARIA: VUV seeded HGHG FEL beamline for gas phase**



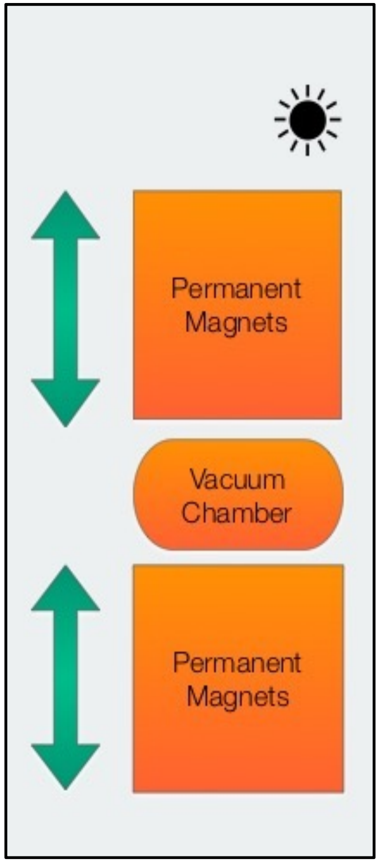
FERMI FEL-1 Radiator



SEEDED FEL – Modulator 3 m + 4 Radiators APPLE II – variable pol. 2.2 m each – SEEDED in the range 290 – 430 nm – Undulator based on consolidated technology.

Undulator technologies: magnetic strength order

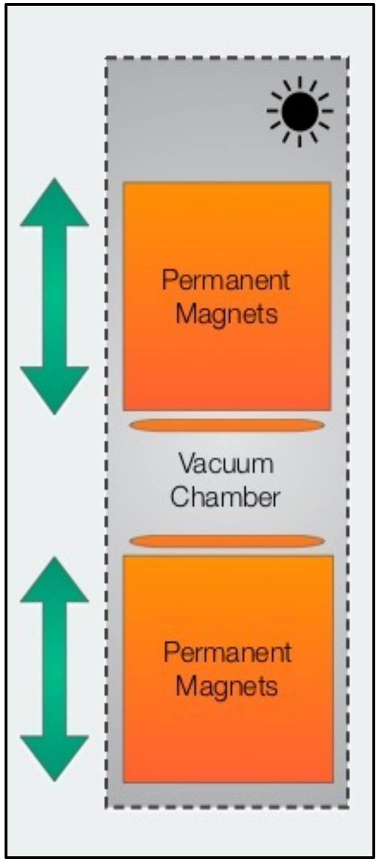
Out of vacuum PMU



Traditional and cheapest design

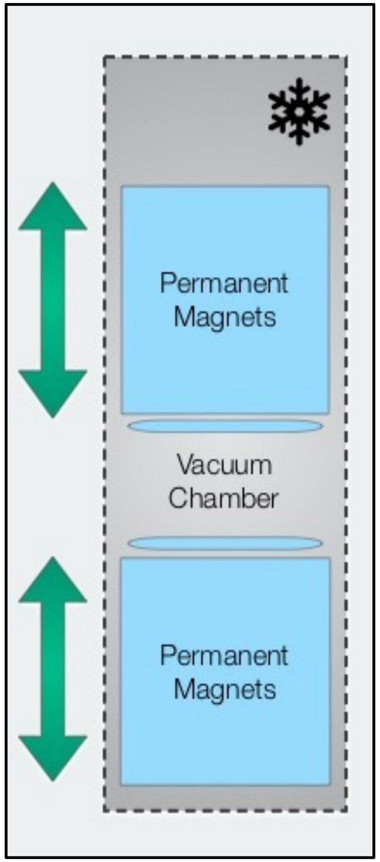
Selectable Polarization

In vacuum PMU



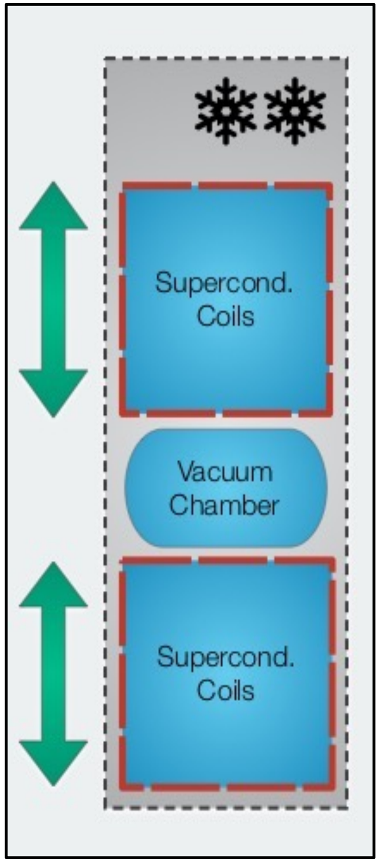
Magnets inside vacuum but not cheap & no polarization
Good performance

Cryogenic PMU



Improved B but not cost-effective and increased complexity
Better performance

Superconducting

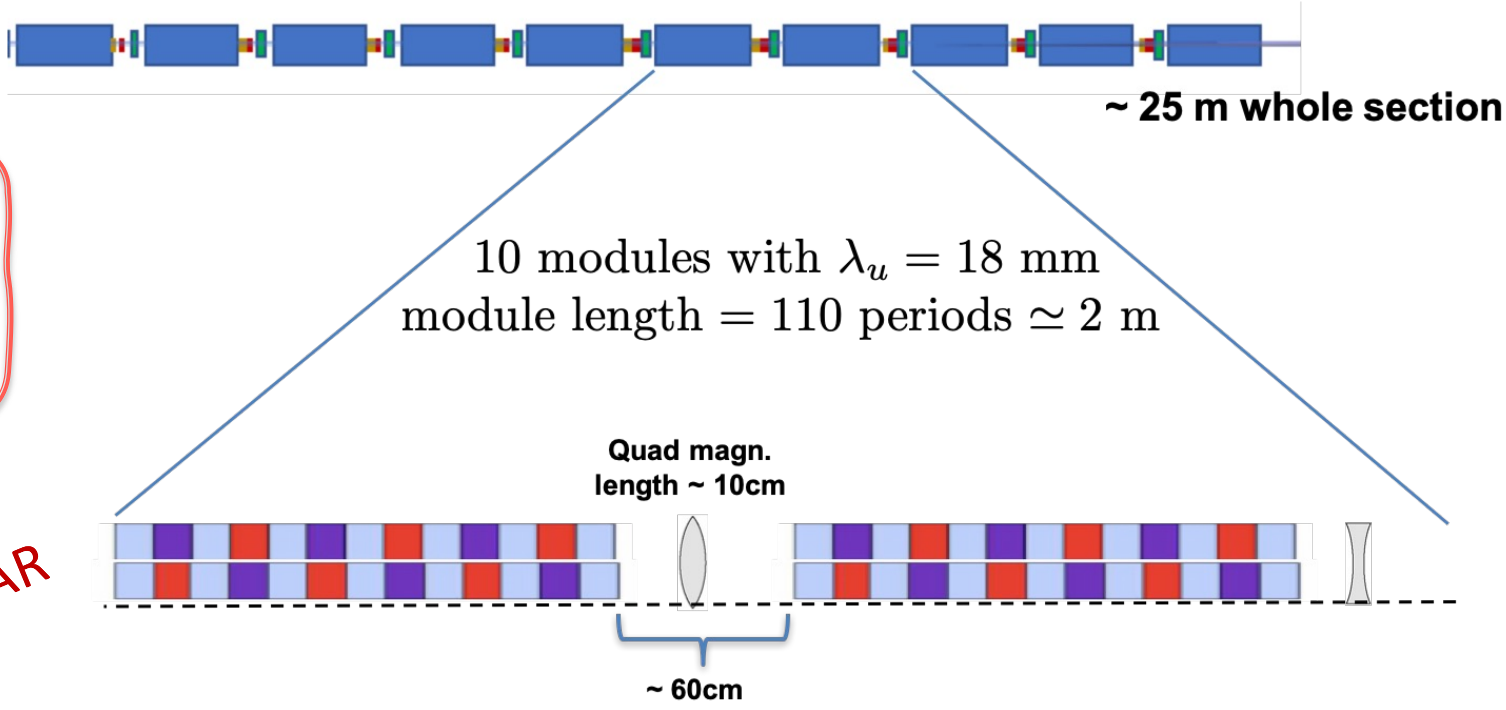


Highest B and SC electromagn. coils

Best performance

AQUA constraints on the FEL beamline

- **Target wavelength 3-4 nm @ 1 GeV: relatively short period required (12-20 mm)**
- **Total available length ~ 25-30 m, depending on the linac: matching section, beam diagnostics and main beam dump.**
- **Hypotheses:**
  - **Optimize magnetic length/available length filling factor**
  - **Make sure gain length shorter than 1 undulator module length**
  - **60-80 cm intra-undulator sections: Quads, BPMs, correctors, phase shifters, alignment diagnostics**



10 modules with $\lambda_u = 18$ mm
module length $= 110$ periods $\simeq 2$ m

a) **APPLE-X undulator: increased PM field through “geometry”, selectable polarization**

b) **SCU: collaboration agreement with FNAL for the NbTi planar prototype**

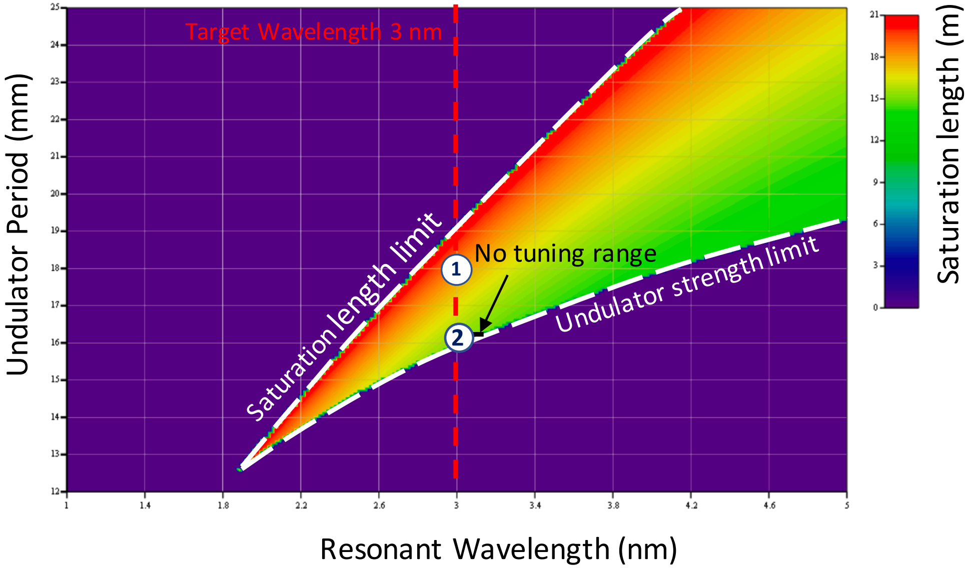
DELAYED 1 YEAR

Tuning range: choice of the period λ_u

FEL performance evaluated with Ming Xie-Dattoli scaling formulae accounting for 60% filling factor

- **Linac parameters to be finalized: peak current implies ~ large compression factor → en. spread**
- **Beta function constrains undulator module length and alignment tolerances**

Parameter	Symbol	Units	D (CDR)
Charge	Q	pC	30
Energy	E	GeV	1
Peak current	I_{peak}	kA	**1.8**
Bunch length	σ_z	µm	**2**
Proj. norm. emittances (x/y)	$\varepsilon_{n,x,y}$	mm-mrad	**1.7**
Slice, norm. emittances (x/y)	$\varepsilon_{n,x,y}$	mm-mrad	0.8
Proj. energy spread	$\sigma_{\delta p}$	%	0.95
Slice Energy spread	$\sigma_{\delta s}$	%	**0.05**



$$\lambda_{res} = \frac{\lambda_u}{2\gamma^2}\left[1 + \frac{K^2(g_u)}{2}\right]$$

From the K vs. gap formulae of a planar PMU with remanent B_r = 1.2T, min. magnetic gap=6mm, beam stay clear=5mm:

1) **18mm implies tuning range, plus saturation length contingency if operating at 4nm wavelength;**
2) **16mm improves the saturation length limit, but almost no tuning range**

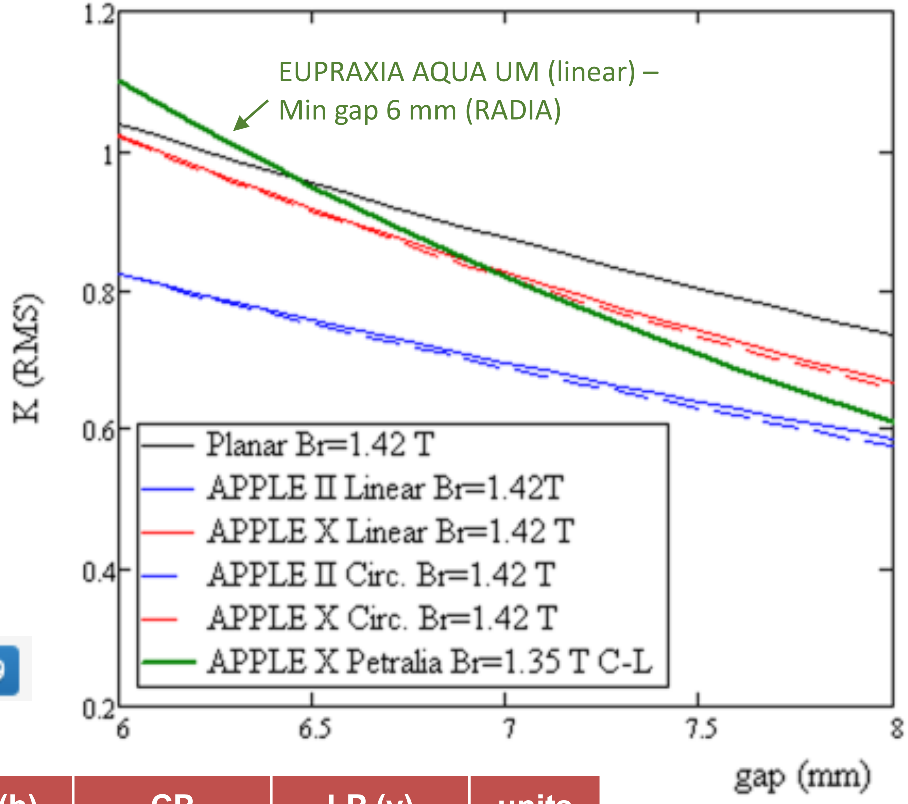
Variable polarization undulator for AQUA

Polarization: variable polarization is an asset as it meets the scientific case requests → undulator capability, circ. polar. guarantees high gain (~ L_{mod})

Advanced **P**lanar **P**olarized **L**ight **E**mitter**-type**: APPLE-X substantially higher field at the same undulator aperture → extended tuning range, K_{max} independent of polarization → fully symmetric

Parametrization laws from:

D5.1: Technologies for the CompactLight Undulator, *F.Nguyen et al.,* XLS Deliverable (2019) DOI 10.5281/zenodo.5024409


EUPRAXIA AQUA UM (linear) – Min gap 6 mm (RADIA)

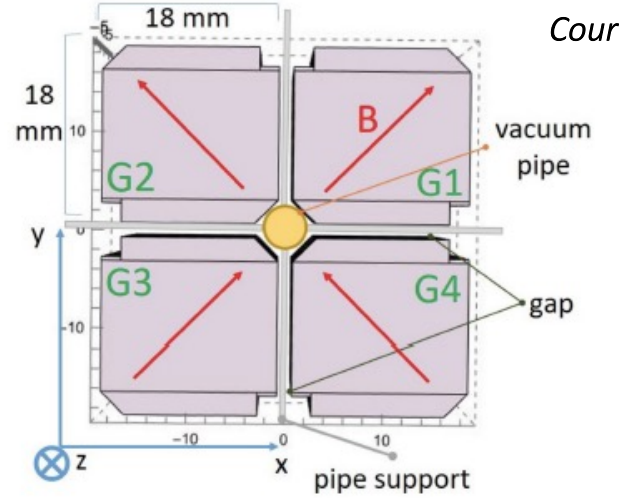
Model parameters:

- Remanent field Br = 1.35 T
- Undulator period λ_u = 18 mm
- 4 blocks / period, NdFeB
- # of periods (eff.) N = 110 (L_u=1990mm)

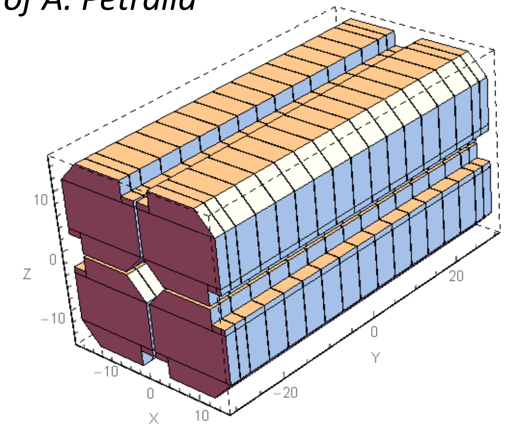
Field Integrals from RADIA

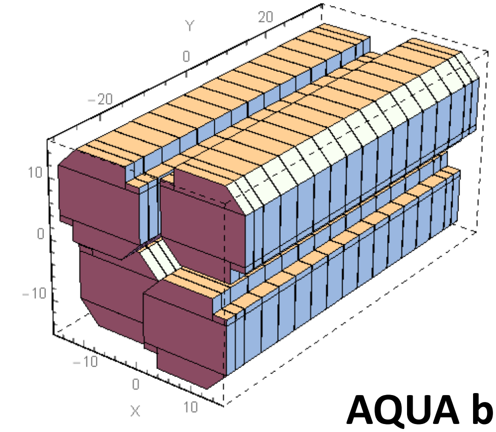
	LP (h)	CP	LP (v)	units
$\int B_x$	0	0	0	G m
$\int B_y$	0.0119	-0.0095	0.4118	G m
$\iint B_x$	0	-0.0179	-0.1322	G m^2
$\iint B_y$	0	-0.0001	0	G m^2

APPLE-X undulator modeling

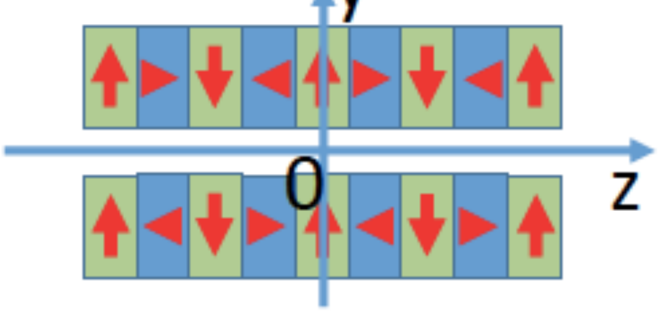


Courtesy of A. Petralia

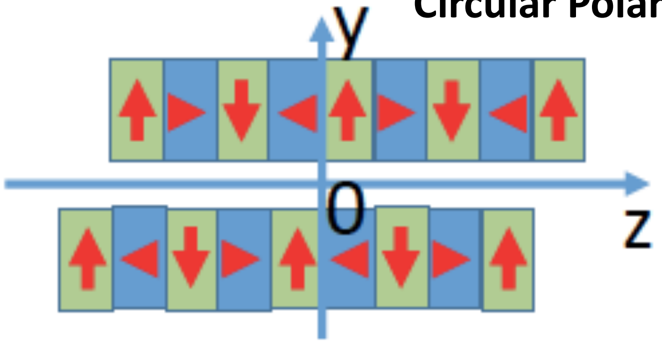




Linear Polarization



Circular Polarization



Pipe ext. diam. (mm)	5.6
Piper inner diam. *d* (mm)	5.0
Wedge cut (mm)	2.8
φ aperture (mm)	**6.0**
B max (T) (in LP)	0.935
K_{max} (in LP)	1.572
K_{max} (in CP)	1.111
max λ_0 (nm) (@ 1 GeV)	**5.25**

AQUA baseline radiator: 10 APPLE-X modules

A. Petralia et al., FEL2022 WEP38 Proceedings

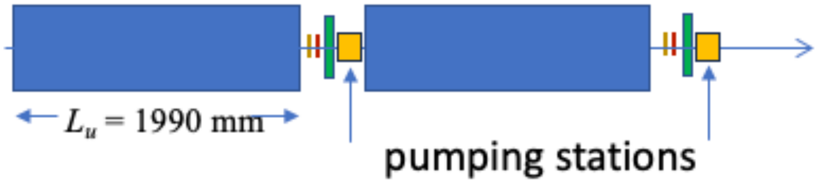
Interplay among aperture, magnetic strength, **wavelength tunability** and **inner diameter** constrained by **wakefield** effects on **FEL performance**

Vacuum chamber inner radius: wakefields

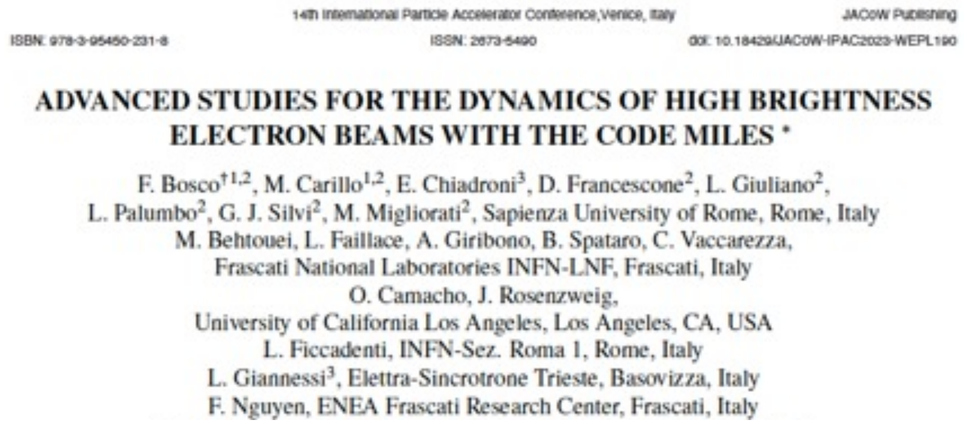
- Vacuum pipe design: circular and uniform thickness < 300 μm;

- Wakefield effects minimization requires smooth and regular surfaces → suppress apertures or other discontinuities: vacuum pumping access ports only available at undulator transitions → no coating (*e.g.* for vacuum sustain) – worsening resistive wall wakefields – is needed;

- Which diameter *d* value for the vacuum chamber?



Resistive wall (RW) wakefields: assuming cylindrical symmetry, the **longitudinal** (monopole) wakefield generates an energy loss and an increase in energy spread independent of the beam orbit, while the **transverse** (dipole) wakefield generates an emittance growth that depends on the trajectory



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ADVANCED STUDIES FOR THE DYNAMICS OF HIGH BRIGHTNESS
ELECTRON BEAMS WITH THE CODE MILES *

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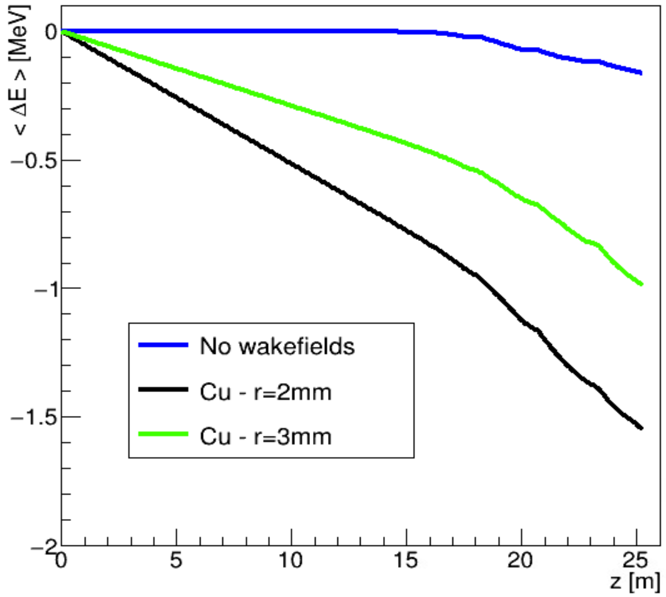
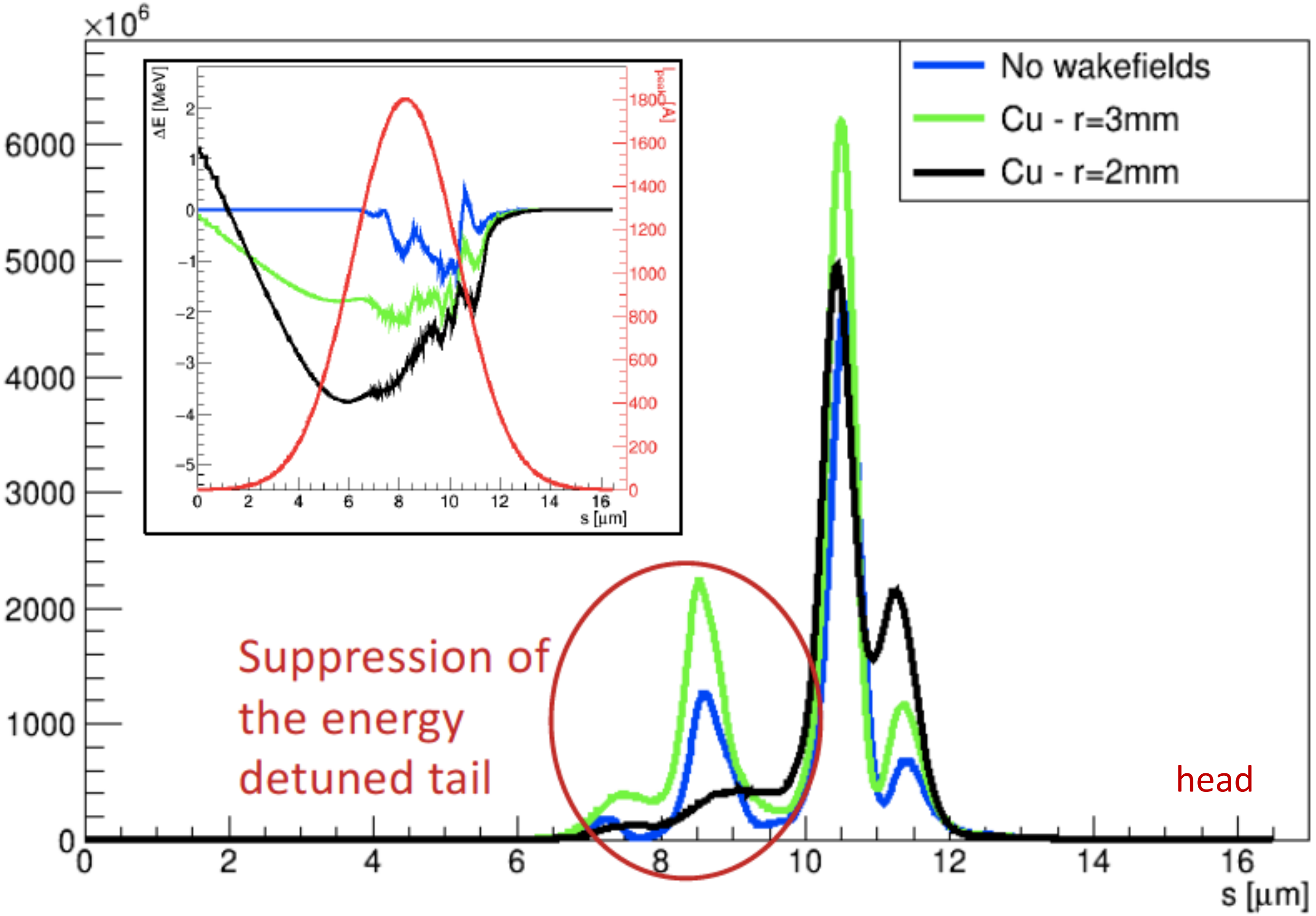
Wakefield deterioration effects on the FEL performance are analyzed as a function of the radius *r* → energy loss due to the longitudinal RW wakefield provided from M. Migliorati, F. Bosco *et al.* (Uni La Sapienza) → plugged into 3D time dependent Genesis1.3 simulations for AQUA electron both short and long bunches

Longitudinal wakefields – 30pC charge, 2μm length



Average energy loss along FEL propagation coordinate: more severe at shorter Cu chamber radius → higher wakefield

At undulator exit: wakefield energy loss adds up to the FEL interaction loss, but the net peak power is marginally affected

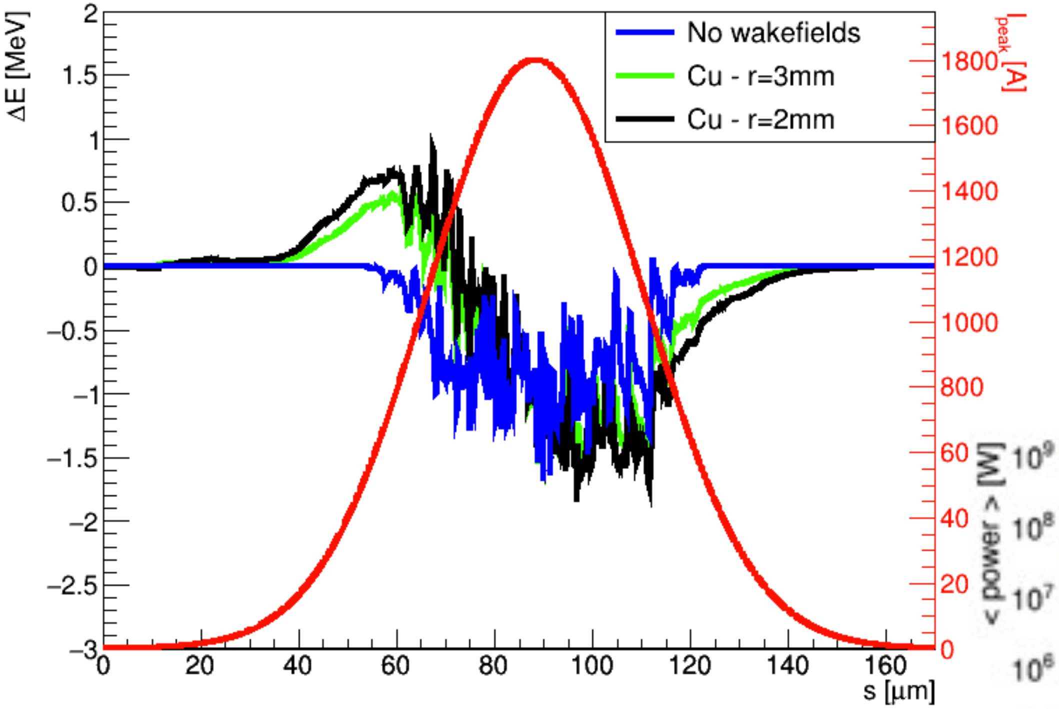


Suppression of the energy detuned tail

head

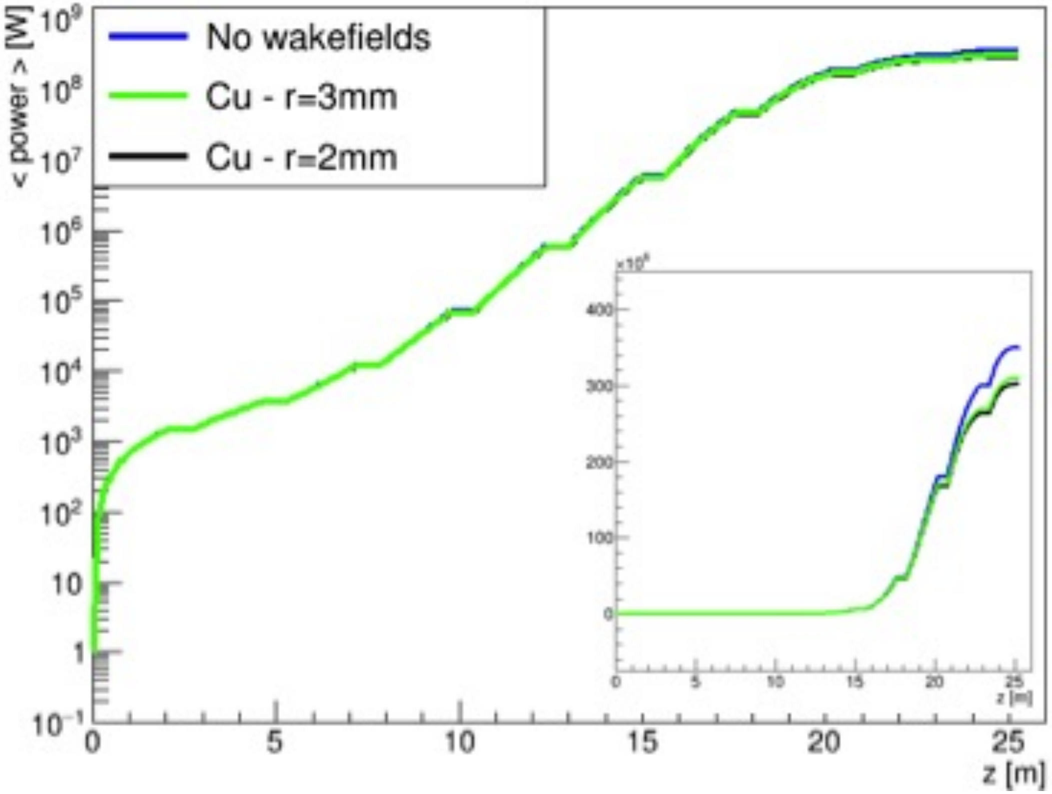
Conclusion: negligible difference in the output power between no RW wakefield and longitudinal degradation at both inner radii, even at I_{peak} = 1.8 kA

Longitudinal wakefields – 300pC charge, 20μm length



Energy loss at undulator exit is dominated by the FEL interaction → almost negligible RW wakefield effects.

This behavior is confirmed looking at the average FEL output power along propagation coordinate (inset is the same in linear scale)



Conclusion: negligible difference in the energy loss and so on the power growth between no RW wakefield and longitudinal degradation at both inner radii

→ vacuum chamber with inner radius=2.5mm is safe against RW longitudinal wakefields

Transverse RW wakefields analysis

Transverse RW wakefields induced inside the cylindrical Cu vacuum chamber of radius *a* = 2…3mm affect the bunch orbit in undulators, depending on the transverse offset at entrance → analytical treatment (complex conductivity+bunch length considerations) based on K. Bane & G. Stupakov and the relationship between transverse and longitudinal impedances → estimate the kick κ_T angle/unit path length parameter, dependent on radius *a* and that scales linearly with the transverse offset

$$W_t(s) = \frac{2}{a^2}\int_0^s W_\ell(s')\mathrm{d}s', \qquad Z_t(k) = \frac{2}{a^2}\frac{Z_\ell(k)}{k}$$

$$W_\ell(s) \sim \frac{1}{a^2} e^{-s/(4c\tau)} \cos\left[s\sqrt{\frac{2\omega_p}{ac}}\right]$$

$$\varphi_T = \frac{\text{kick angle [rad]}}{\text{unit path length [m]} \times \text{unit transverse offset [m]}}$$

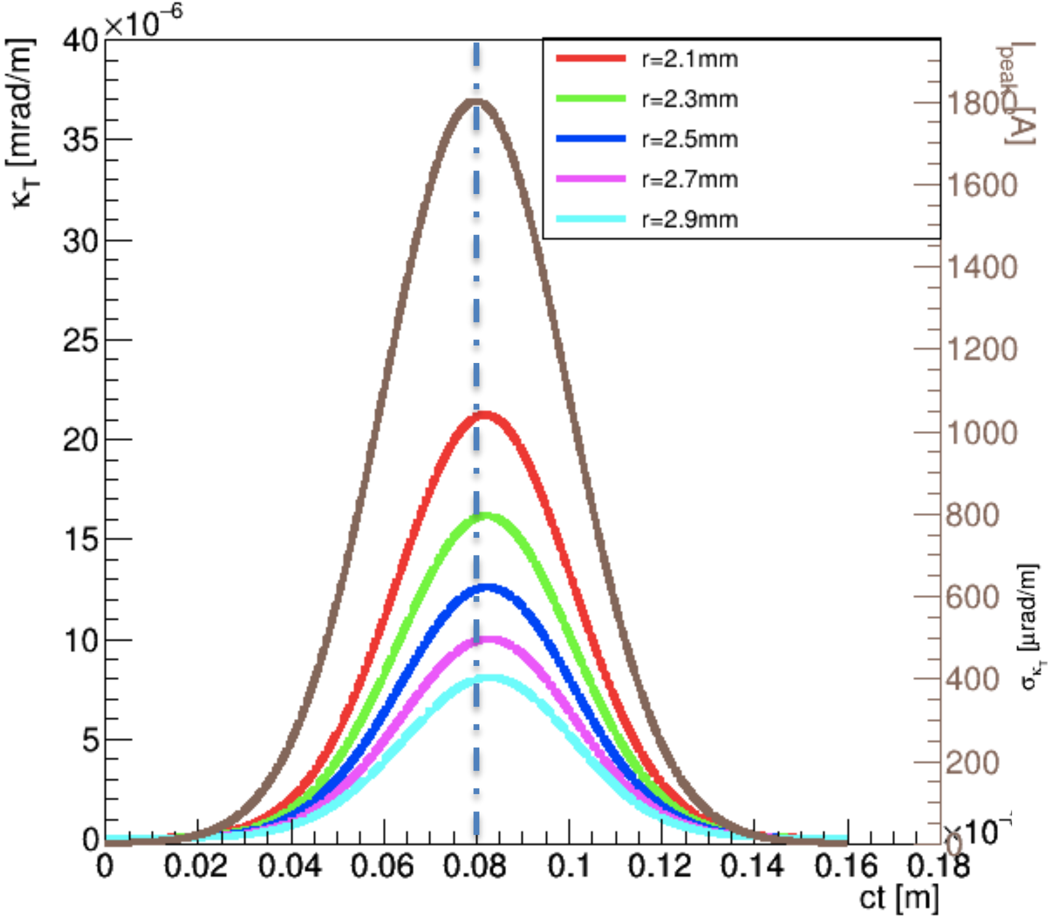
$$\kappa_T = \frac{\text{kick angle [rad]}}{\text{unit path length [m]}}$$

$$\sigma_{\kappa_{Tx}} = \varphi_T(a) \cdot \sigma_{x_{off}}$$

$$\sigma_{\kappa_{Ty}} = \varphi_T(a) \cdot \sigma_{y_{off}}$$

Kick angle/path length tolerance error **scales linearly with any misalignment** (*e.g.* between und. modules, vacuum chamber wrt its own und. module) **jitter source**

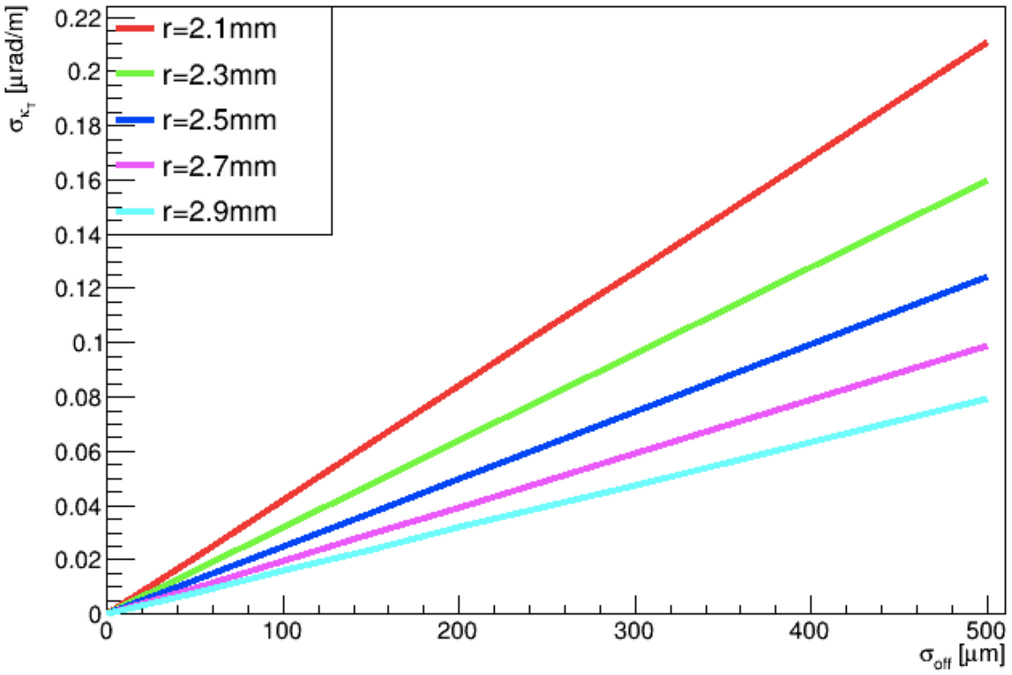
Transverse wakefields – 300pC charge, 20μm length



Kick angle/path length for different chamber radius values vs. **the current profile (brown)**

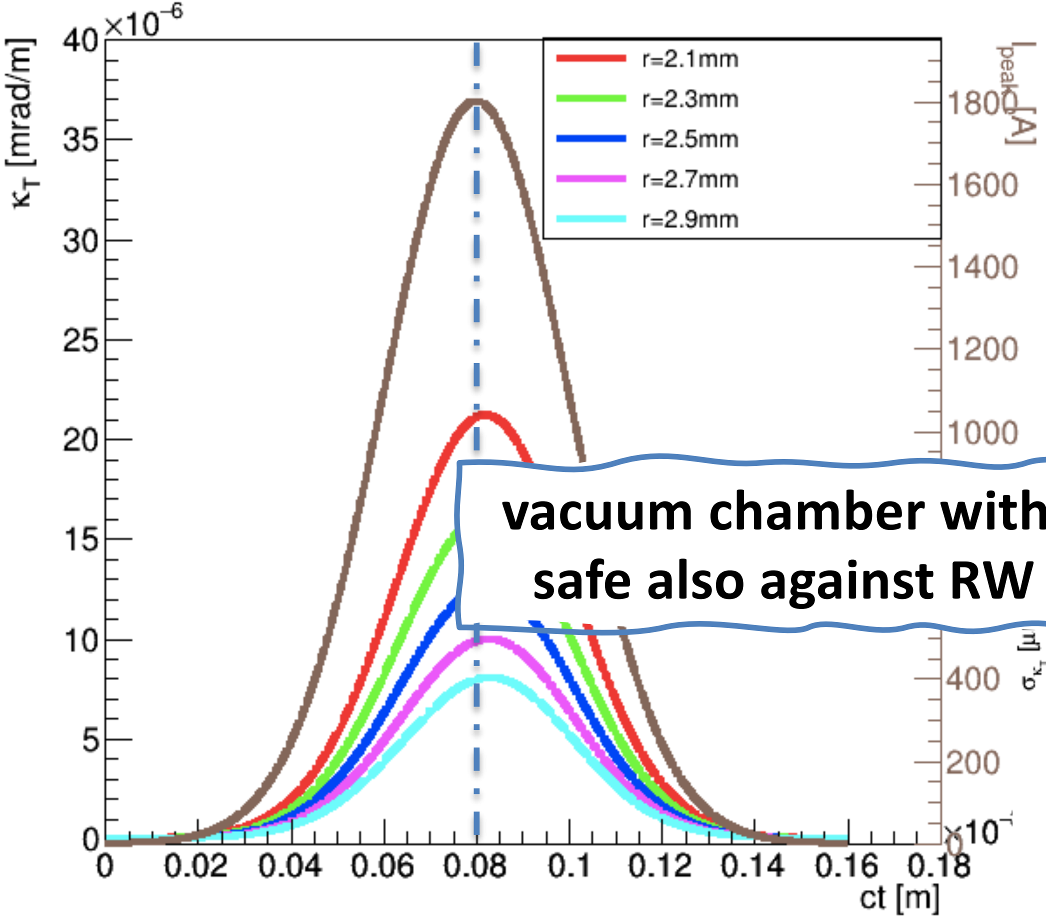
Assuming 50 μm vertical e-beam offset → max value ~ 2×10^{-2} μrad/m happens for r=2.1mm, exactly on the current peak!

The φ_T kick angle/m^2 is evaluated at the peak position → dot-dashed line



Transverse wakefields affect the peak current profile by max ~ 1 μrad/m transverse kick, assuming to systematically find higher than 300 μm misalignment, for r=2.3mm

Transverse wakefields – 300pC charge, 20μm length



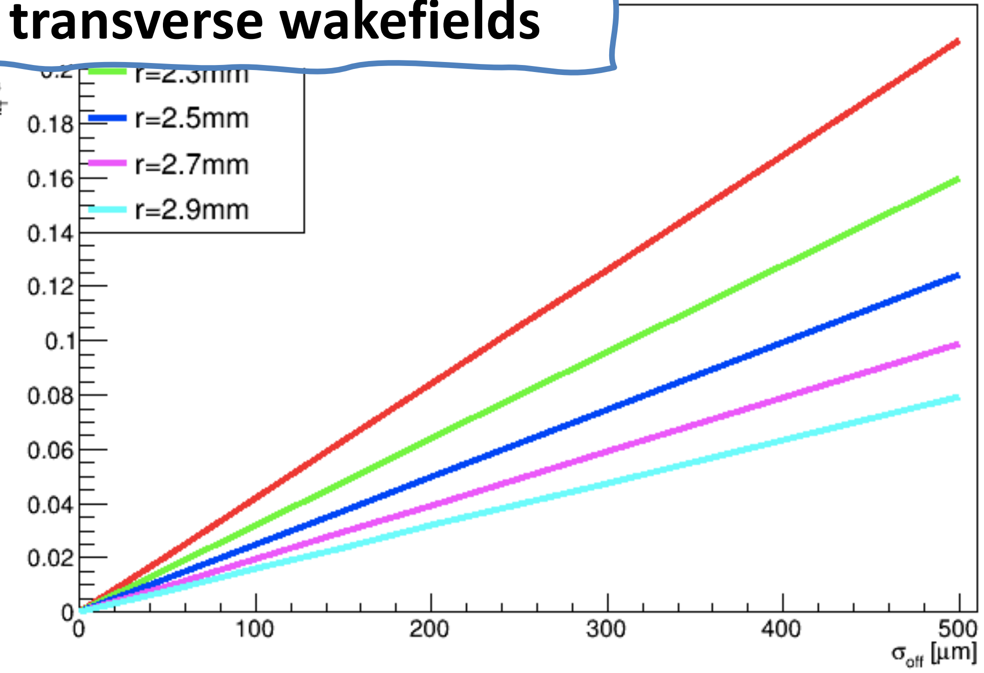
Kick angle/path length for different chamber radius values vs. **the current profile**

Assuming 50 μm vertical e-beam offset → max value ~ 2×10^{-2} μrad/m happens for r=2.1mm, exactly on the current peak!

The φ_T kick angle/m^2 is evaluated at the

line

vacuum chamber with inner radius=2.5mm is safe also against RW transverse wakefields



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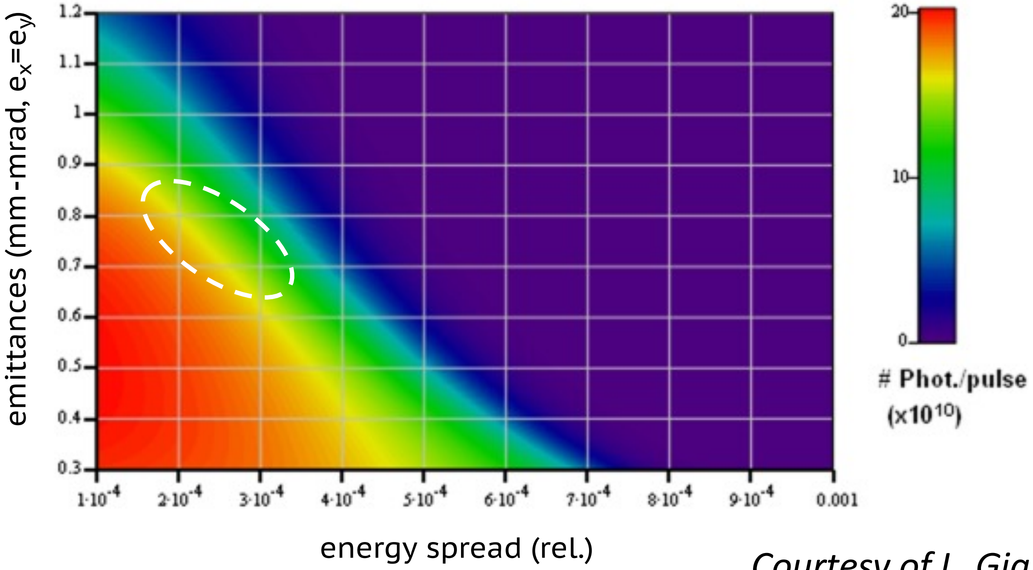
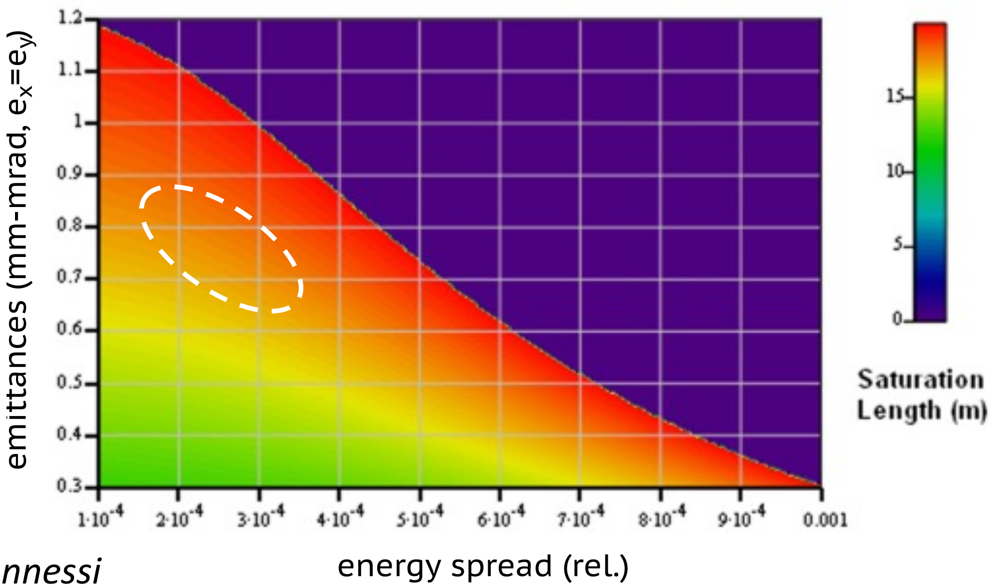
FEL parameter acceptance – Linear polarization

- Modified Ming Xie-Dattoli model to analyze the FEL performance **in linear polarization**
- Working point: photon energy of 4 nm = 310 eV at 1 GeV
- Gaussian beam in current, energy, energy spread, transverse momenta and spatial distributions
- Peak current 1.5 kA, FWHM bunch duration 5 fs, average $\beta_x = \beta_y = 10$ m, and $\varepsilon_x = \varepsilon_y$.

Photon yield N_γ/pulse ~ 10^{11}



Sat. length ~ 25-28 meters

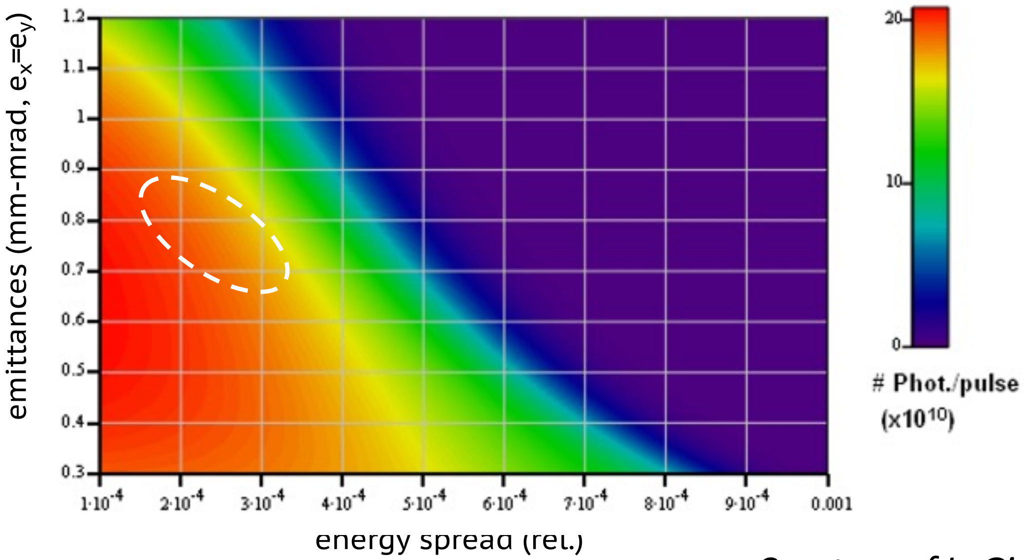


Courtesy of L. Giannessi

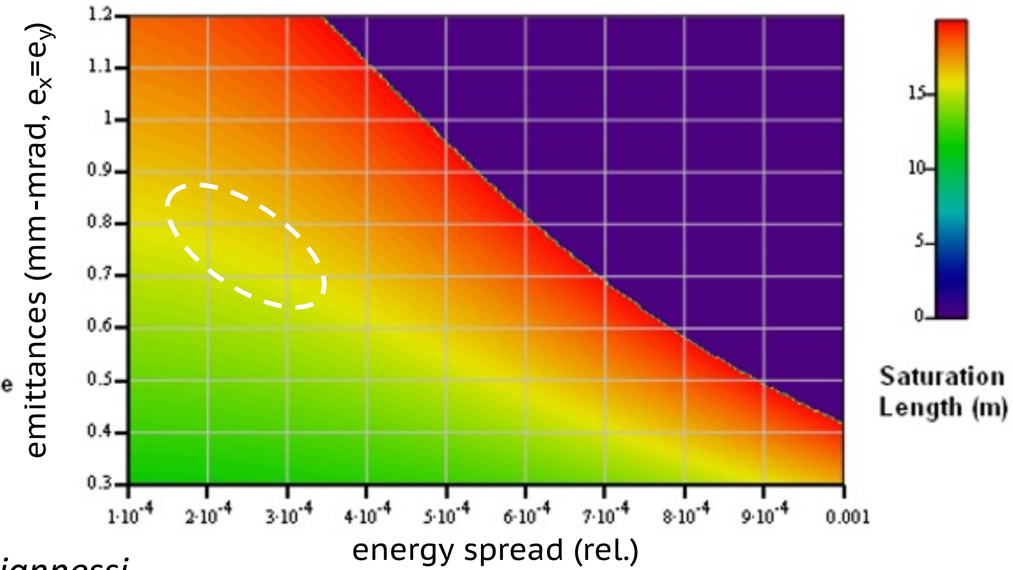
FEL parameter acceptance – Circular polarization

- Modified Ming Xie-Dattoli model to analyze the FEL performance **in circular polarization**
- Working point: photon energy of 4 nm = 310 eV at 1 GeV
- Gaussian beam in current, energy, energy spread, transverse momenta and spatial distributions
- Peak current 1.5 kA, FWHM bunch duration 5 fs, average $\beta_x = \beta_y = 10$ m, and $\varepsilon_x = \varepsilon_y$.

Higher N_γ/pulse $\gtrsim 2 \times 10^{11}$

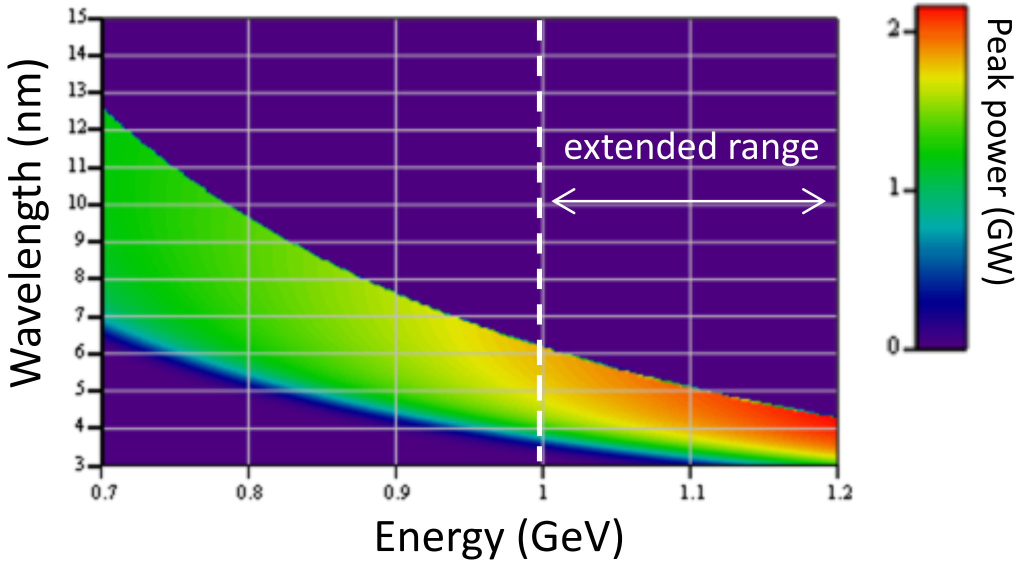


Shorter Sat. length ~ 15-20 meters

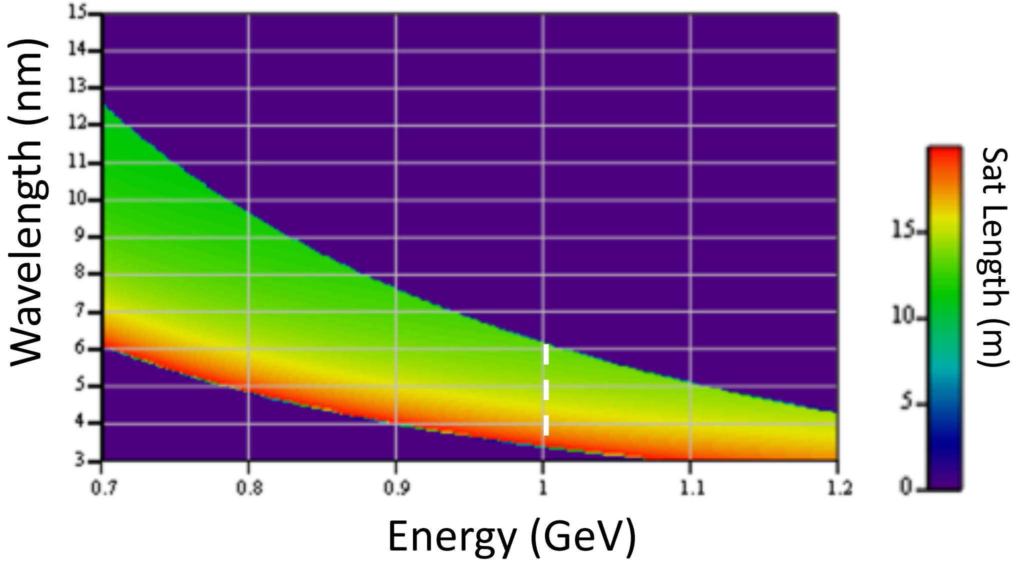


Courtesy of L. Giannessi

FEL performance vs. E_{beam} – Linear polarization



Courtesy of L. Giannessi



$$\lambda_{res} = \frac{\lambda_u}{2\gamma^2}\left[1 + \frac{K^2(g_u)}{2}\right]$$

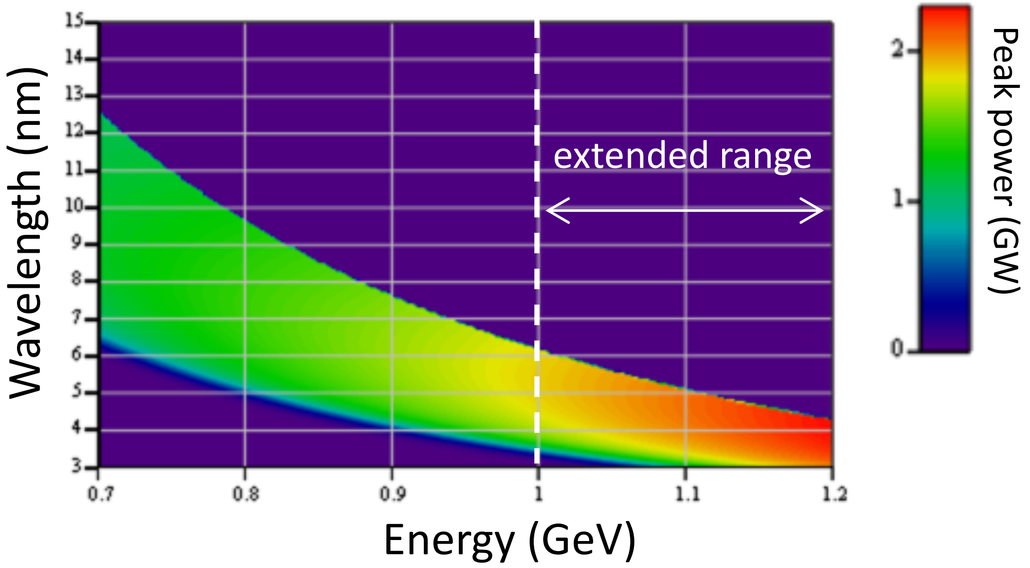
Tunability in beam energy $\gamma m_e c^2$ and in undulator gap g_u weighted in terms of peak power and saturation length

Linear Polarization:
undulator gap gives limited lever arm
shorter λ_{res} ➔ lower K values
➔ lower power and longer saturation

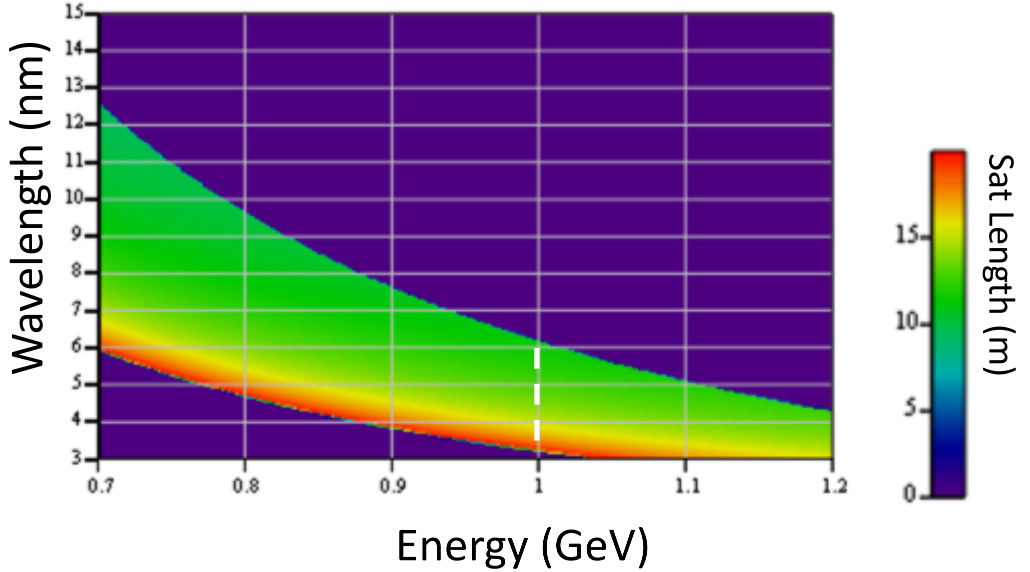
By increasing beam energy (other parameters constant) →

chance to make 4nm with performance similar to longer wavelengths

FEL performance vs. E_{beam} – Circular polarization



Courtesy of L. Giannessi



$$\lambda_{res} = \frac{\lambda_u}{2\gamma^2}\left[1 + K^2(g_u)\right]$$

Tunability in beam energy $\gamma m_e c^2$ and in undulator gap g_u weighted in terms of peak power and saturation length

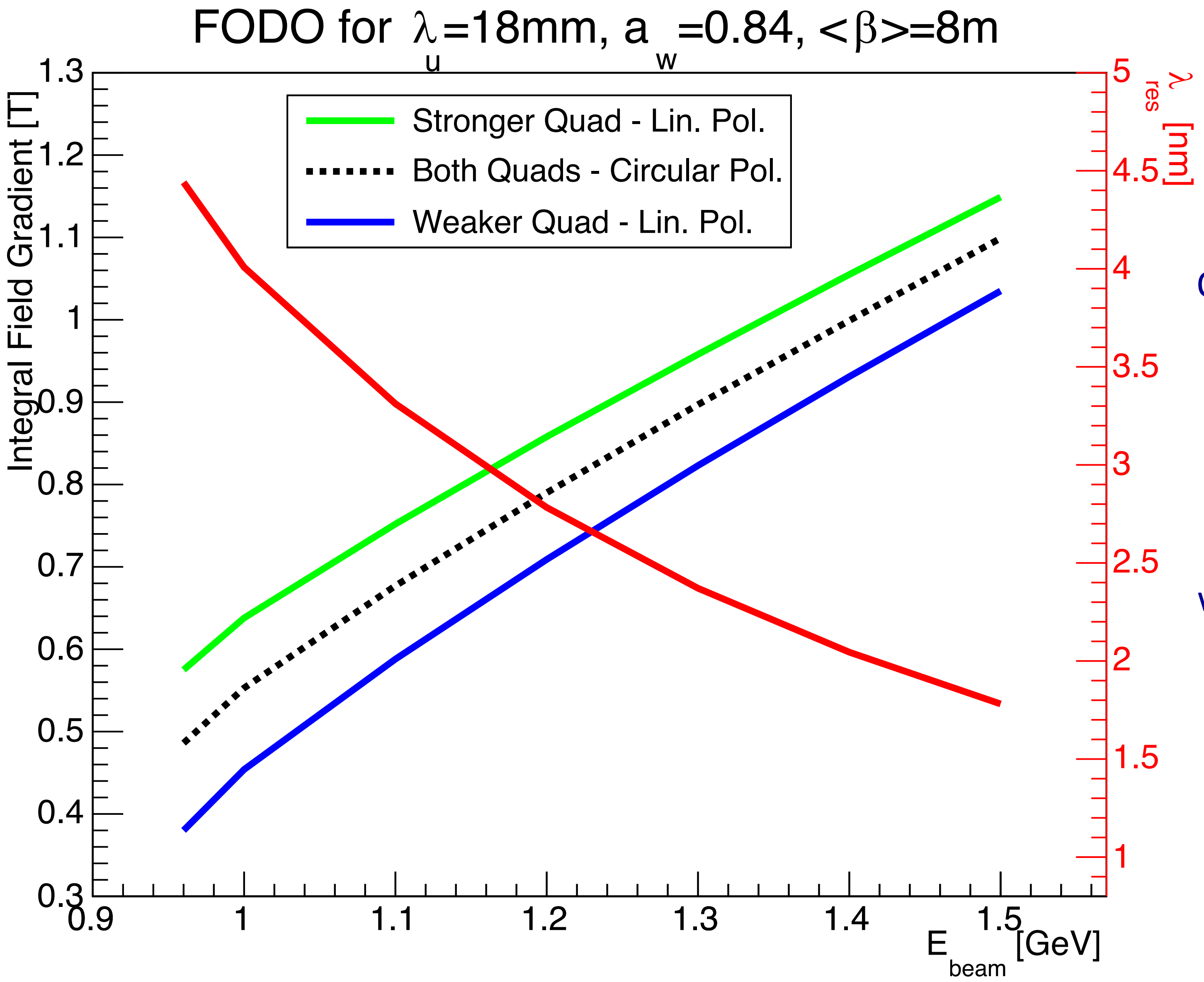
Circular Polarization:

wider undulator gap tunability than Linear → "water window" wavelengths probed with higher photon power yields and shorter saturation lengths

By increasing beam energy (other parameters constant) →

saturation length below ~ 20 m most of the available spectrum; chance to reach for 3nm

Trajectory matching for both polarizations vs. E_{beam}



Matching quad strengths at each E_{beam} value: **undulator focuses on 1 plane only in Linear Polar.**

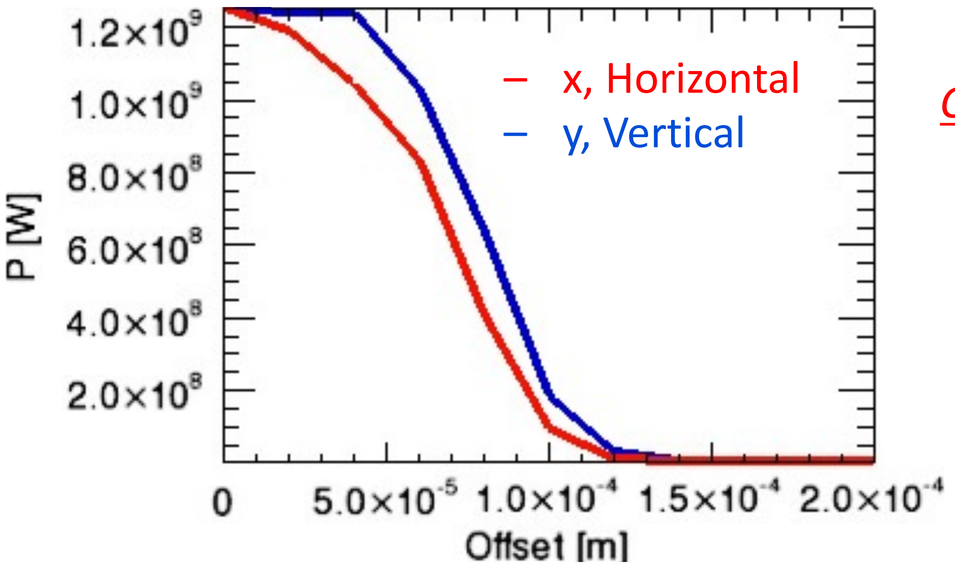
Quad (~ 10 cm magn. length) integral field gradients are such to sustain even higher beam energies →

Possible to reach for 3nm with the same undulator and quadrupole devices, if E_{beam} ~ 1.2 GeV

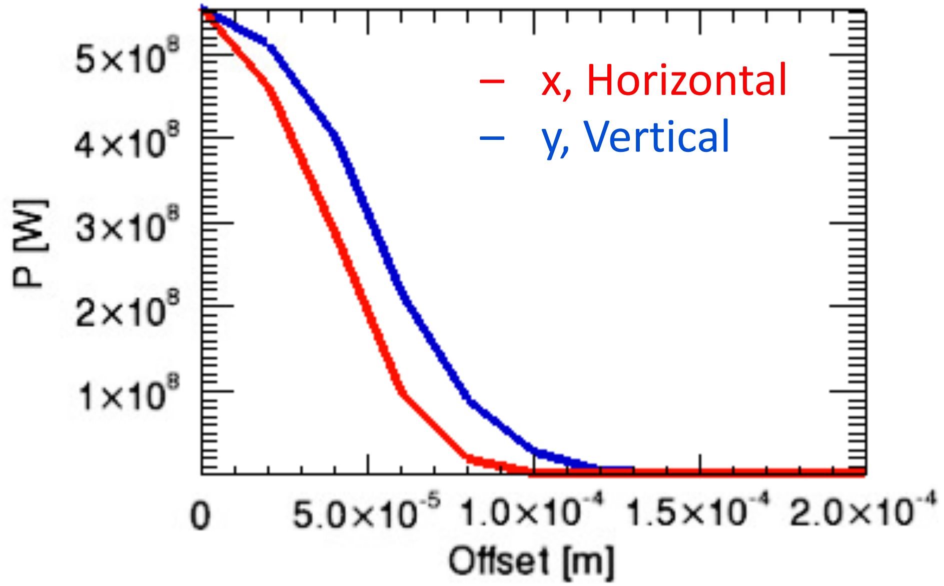
Quad. offset errors (up to ~ 400 μm) lead to an off-axis beam wander to be compensated with a corrector magnet

FEL tolerance on injection transverse offsets

Quad. offsets can be corrected by steering the trajectory, **angle and position inj. jitters** can't be compensated



FEL power reduction in
Circular polarization APPLE-X



FEL power reduction in
Linear polarization APPLE-X

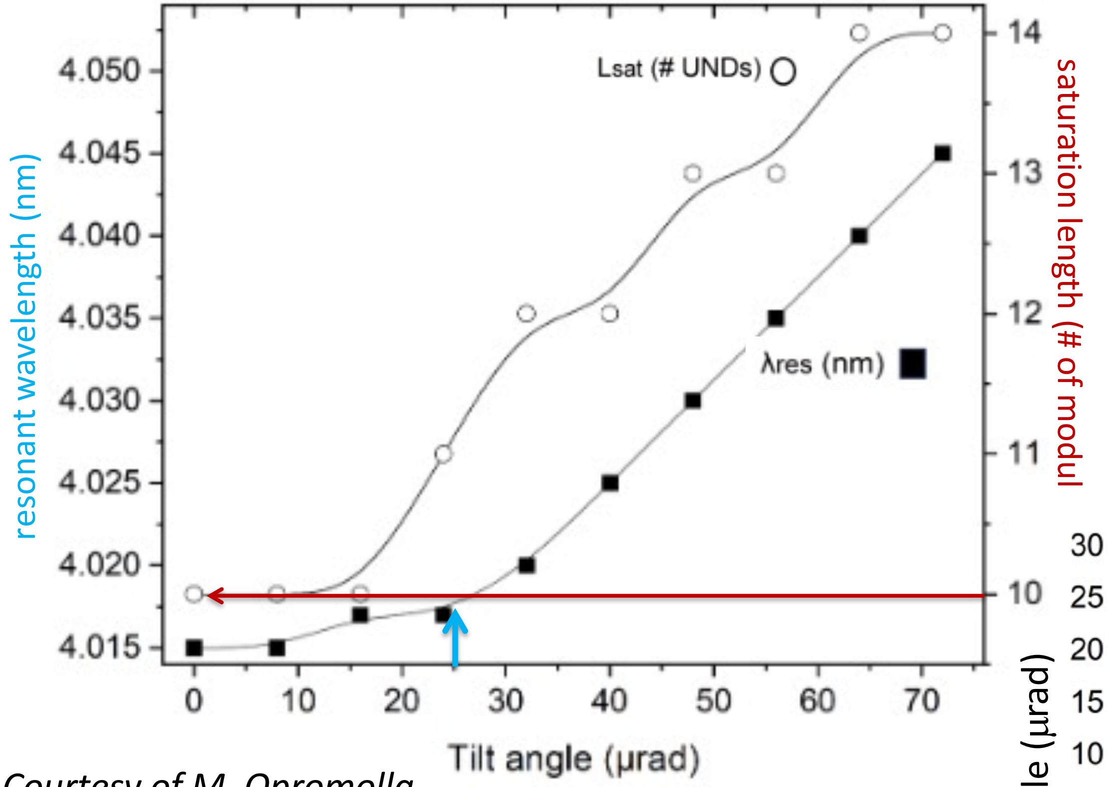
Conclusion

Circular Polarization: 50μm offset results in ~ 67% of the ideal power yield
Linear Polarization: the reduction is steeper and 50μm leads to ~ 20% power decrease

FEL tolerance on injection tilt angles

Electron beam misalignments due to tilted injections detune the resonant wavelength and increase sat. length: 10 und. modules demand tilt angle < 25 μrad → ~ 0.06% wavelength detuning!

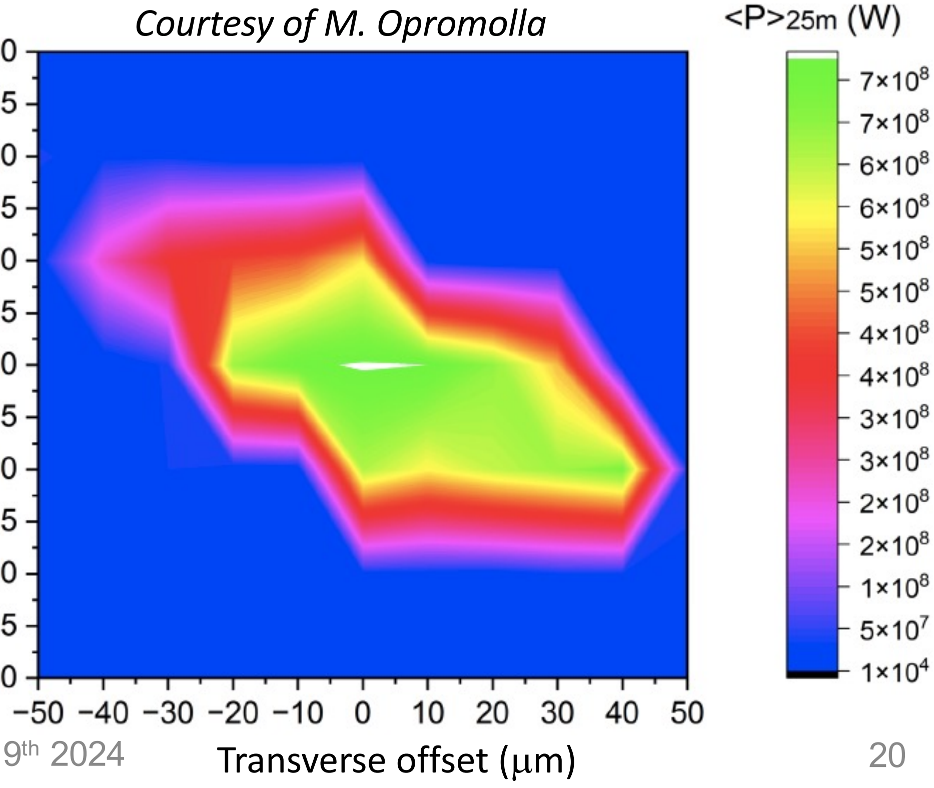
Even if accepted, such an angle affects FEL power at undulator exit!



Courtesy of M. Opromolla

Cross-correlation between tilt angle and transverse offset results in more severe constraints: to stay in the > 60% of the ideal FEL power → tilt angle < ±6 μrad and offset position < ±25 μm

Courtesy of M. Opromolla



Conclusions

- ✓ The undulator adopted for the AQUA beamline consists of an out-of-vacuum APPLE-X: a well-known technology that allows selectable polarization and fine tuning in the water window

- ✓ Extensive studies on RW wakefield effects – both longitudinal in energy loss and transverse in the e-beam trajectory – show that chamber r=2.5mm is safe

- ✓ Ideal reference electron beam values allow to enter the realm of $O(10^{11})$ N_γ/pulse for both polarizations at 4nm → shorter λ to be covered with either improved e-beam quality or higher E_{beam} → same beamline is able to sustain even $E > 1$ GeV energies

- ✓ FEL tolerance 3D simulations on e-beam injection misalignments result in parameter values acceptance for both transverse offset positions and tilt angles – analyzed in terms of λ detuning, saturation length and power

- ✓ Full time-dependent results with S2E particle distributions under realistic conditions are on-going towards the TDR delivery

Please, stay FEL-tuned!

Thank you 4 your attention