FLASH2020+ 4th Start to End Simulation Workshop

29 Jun 2023, 09:00 → 30 Jun 2023, 18:30 Europe/Berlin

EuPRAXIA@SPARC_LAB FEL Beamlines

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Many thanks to C.Boffo, L.Giannessi, M.Opromolla, A.Petralia, V.Petrillo



FLASH2020+ 4th S2E Simulation Workshop – **DESY** – June 29th 2023

EuPRAXIA@SPARC_LAB: AQUA

1st international design of a plasma accelerator facility

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

- Electrons (0.1-5 GeV, 30 pC)
- Positrons (0.5-10 MeV, 10⁶)
- Positrons (GeV source)
- Lasers (100 J, 50 fs, 10-100 Hz)
- Betatron X rays (5-18 keV, 10¹⁰)
- FEL light (0.2-36 nm, 10⁹-10¹³)

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 \rightarrow factor 10 \rightarrow ...
- Low charge, 10 Hz apps of e- (+ positron generation)
 - \rightarrow high charge, 10 Hz applications (FEL) \rightarrow 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 \rightarrow water window relevant to study biological samples with coherent imaging





EuPRAXIA@SPARC_LAB: ARIA

The **ARIA** (air in *Italian*) beamline of the EuPRAXIA@SPARC_LAB project is going to be a **VUV** seeded HGHG FEL facility for gas phase (50-180 nm), providing 2nd order coherence 10-100 μ J pulse energy class, with continuous tunability and selectable polarization \rightarrow less demanding electron beam parameter space \rightarrow user operations at early stage



Light induced molecule ring structure opening reactions to be studied with time resolved photoemission spectroscopy \rightarrow formation of the previtamin D₃ in the skin under the sun \leftarrow absorption of UV rays

Vitamin D involves several biological functions and ring opening is an aspect

S. Pathak et al., Nat. Chem. 12 (2020) 795



- No other seeded FEL facility covers the full 50-180 nm range, except for the DALIAN light source
- Overlap with HHG sources, but without limitations on polarization, wavelength tuning & intensity
- Can be synchronized with HHG sources or external lasers for multicolor multi-pulse pump and probe operations



EuPRAXIA@SPARC_LAB within ESFRI





FEL beamlines for EuPRAXIA@SPARC LAB



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







Undulator technologies



Out of vacuum PMU

Traditional and cheapest design



In vacuum PMU



Magnets inside UHV → min. distance

Permanent Magnets Vacuum Chamber Permanent Magnets

Cryogenic PMU

Improved B and increased complexity

Superconducting



Highest B and SC electromagn. coils

Best performance



Good performance

Better 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 linac spreader system, 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



- a) Apple-X undulator: increased PM field through "geometry", selectable polarization
- b) SCU: collaboration agreement with FNAL for the NbTi planar prototype



Electron beam parameters

- Linac layout definition still in progress: peak current implies ~ large compression factor → impact on energy spread at undulator entrance → results here assuming the red rectangle values
- Beta function constrains undulator module length and alignment tolerances

| | | | | | LINAC + PWA | | | |
|----------------------------------|--------------------------------|---------|-------|------|-------------|-----------|-------------------------|--|
| Parameter | Symbol | Units | А | В | С | D (CDR) | E | |
| Charge | Q | рС | 200 | 200 | 30 | 30 | 30 | |
| Energy | E | GeV | 0.996 | 1 | 1 | 1 | 1 | |
| Peak current | I _{peak} | kA | 1.6 | 0.7 | ? | 1.8 | 800 | |
| Bunch length | σ _z | μm | 18.3 | 100 | ? | 2 | 5 | |
| Proj. norm. emittances (x/y) | ɛ _{n,x,y} | mm-mrad | 1.85 | ? | ? | 1.7 | 3/4 | |
| Slice, norm. emittances (x/y) | <pre> ɛ_{n,x,y} </pre> | mm-mrad | 0.5 | 0.5 | ? | 0.8 | 3/4 (1/1.2 at linac) | |
| Proj. energy spread | $\pmb{\sigma}_{\pmb{\delta}$ p | % | 0.09 | ? | ? | 0.95 | 1.5 | |
| Slice Energy spread | $\sigma_{\delta^{\mathrm{S}}}$ | % | 0.02 | 0.01 | ? | 0.05 | 0.06 | |
| | | | AQUA | ARIA | | AQUA/ARIA | | |



Tuning range: choice of the period λ_u

FEL performance analyzed with Xie's scaling formulae accounting for 60% filling factor



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

From the K vs. gap formulae of a planar NbTi SCU with beam stay clear=5mm:

2) 16mm improves the saturation length limit, and tuning range is granted as well



Choice of the 16mm undulator module length: 3nm

Genesis1.3 steady state simulations

Created a grid of input and lattice files, varying L_{mod} and $<\beta>$ and re-matching (with different Twiss parameters set) every time $\rightarrow P_{sat} \& L_{sat}$ figures of merit

Max FODO quad. gradient obtained is ~ 13 T/m





Planar SCU prototype studies



NbTi prototype to be deployed upstream of the Apple-X modules

C. Boffo *et al.*, FEL2022 WEP39 Proceedings





Courtesy of C. Boffo

| Parameter | Value | Units | |
|---|-------------|-------|---|
| Period | 16 | mm | |
| Beam stay clear | 5 | mm | |
| FEL wavelength | 4 | nm | |
| Peak field on axis at 5 mm beam stay clear | 1.5 | Т | |
| Cooling medium | Cryocoolers | - | |
| Magnet length | 1.2 | m | |
| Vacuum vessel length | < 1.5 | m | |
| Cooldown time | < 7 | days | |
| Operating temperature | ≤ 4.2 | K | ļ |



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Apple-X undulator studies





FODO analysis for both polarizations vs. E_{beam}



Linear Pol. Apple-X overall FEL performance

$$\lambda_{\rm res} = \frac{\lambda_{\rm u}}{2\gamma^2} \left[1 + \frac{{\rm K}^2({\rm g}_{\rm u})}{2} \right]$$

Tunability both in beam energy $\gamma m_e c^2$ and in undulator gap g_u weighted for N_y/pulse





Circular Pol. Apple-X overall FEL performance

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

Tunability both in beam energy $\gamma m_e c^2$ and in undulator gap g_u weighted for N_y/pulse





By increasing beam energy (other parameters constant) \rightarrow

chance to reach for 3nm with performance similar to longer wavelengths



Electron beam used for FEL performance

Average electron beam slice parameters are used to perform 3D time dependent simulations with the Genesis1.3 code in 4 undulator + related magnetic lattice configurations: Linear & Circular polarizations, targeting 4nm & 5.75nm (K_{max})

An ideal Gaussian current profile is assumed with I_{peak} = 1.8kA and Q = 30pC



AQUA FEL results with average beam parameters

| working point | LP K_{max} | LP 4nm | $CP K_{max}$ | CP 4nm |
|---|--------------|--------|--------------|--------|
| resonant λ [nm] | 5.75 | 4.01 | 5.75 | 4.01 |
| photon energy [eV] | 215 | 309 | 215 | 309 |
| matching $\langle \beta \rangle$ [m] | 6 | 8 | 6 | 8 |
| Pierce $\rho_{1D} \ [10^{-3}]$ | 1.81 | 1.35 | 2.04 | 1.46 |
| $gain length_{1D}$ [m] | 0.559 | 0.788 | 0.405 | 0.566 |
| satur. length [m] | 16.78 | 23.40 | 14.33 | 20.81 |
| satur. $\langle power \rangle$ [GW] | 0.394 | 0.236 | 0.486 | 0.277 |
| $\operatorname{exit} E_{pulse} \left[\mu \mathbf{J} \right]$ | 23.90 | 11.56 | 32.95 | 13.73 |
| exit bandwidth $[\%]$ | 0.154 | 0.088 | 0.223 | 0.117 |
| $exit pulse length_{RMS}$ [fs] | 6.10 | 3.50 | 6.12 | 3.76 |
| exit divergence [mrad] | 0.032 | 0.023 | 0.031 | 0.022 |
| exit trans. size $[\mu m]$ | 195 | 133 | 190 | 132 |
| exit N_{γ} /pulse [10 ¹¹] | 6.93 | 2.33 | 9.53 | 2.77 |



Resistive wall wakefield estimates for baseline AQUA

The pipe inside the und. modules will consist of a cylindrical Cu vacuum chamber of radius=2... 3mm mostly depending on the wakefield deterioration effects on the FEL performance \rightarrow in collaboration with M. Migliorati, F. Bosco *et al.* (Uni La Sapienza – Rome) $\leftarrow \rightarrow$ they provided the energy loss due to the longitudinal resistive wall wakefields \rightarrow plugged into time dependent Genesis1.3 simulations



ARIA baseline layout



ENEL

ARIA with short bunch & high current



Lower harmonics (\leq 5) saturate after two or three radiators only: early saturation deteriorates and stretches the output pulse \rightarrow larger seed intensities may help

Radiation can be extracted beforehand, using the last radiator for multi-pulse/2-color

ARIA with long bunch & low current

| | | | | - 8. | - | |
|-------|----------------------------|------------|-----------|----------|-------|-----------------|
| | Long e-beam | From LINAC | | | HN=9 | |
| | Charge (pC) | | 200 | | | 4 |
|] | Bunch length (rms, μm | ı) | 34 | 6- | 1 | A |
| | Energy (GeV) | | 0.8 - 1.2 | - | 1 | |
| | Peak current (kA) | | 0.7 | <u> </u> | 38497 | A. |
| | Slice energy spread (% | o) | 0.01 | δ, | | 813 813 2448 |
| Slice | norm. emittance (mm | mrad) | 0.5 | <u>د</u> | 1 | |
| | | | | | { | |
| | | | | 2. | | ×10 |
| | | | | - | | |
| | Output pulse | HN=3 | 3 HN=9 | | | ~ |
| | λ (nm) | 153 | 51 | 0. | L | <u> </u> |
| | τ (FWHM, fs) | 212 | 150 | | ò | 50 |

880

0.85

0.26

2.7

 150
 0
 50
 100

 180
 Courtesy of M. Opromolla
 \$ (μm)

 0.35
 0.11

Intensity and spectrum stable, ultra-narrow bandwidth pulses are produced with longer electron bunches \rightarrow high intensity allows monochromator for spectrum enhancement



 $E(\mu J)$

Size (mm)

Div. (mrad)

Time-BW product ()

3.8

200

HN=3

150

Conclusions

- ✓ AQUA undulator line is designed, featuring the magnetic lattice, intra-module distance and FODO quadrupole integral strengths → same line is able to sustain E > 1 GeV beam energies
- ✓ Ideal reference electron beam values are used to perform 3D time dependent simulations: both LP and CP APPLE-X, at 4nm and at 5.75nm K_{max} → CP at 5.75nm allows to enter the realm of O(10¹²) N_γ/pulse → to be achieved at shorter λ with higher E_{beam} or improved e-beam quality
- ✓ Preliminary estimates of the resistive wall longitudinal wakefields show no significant power difference at undulator exit, transverse wakefields are under investigation → benchmarking with (transport ⊗ FEL emission) codes is envisaged
- ✓ Detailed simulations with S2E e-beams and APPLE-X phase tolerance errors are ongoing
- ✓ Feasibility and expected performance of a flexible and cost-effective VUV user facility delivering 15-100 fs duration FEL pulses close to Fourier transform limit are investigated
- ✓ Selectable polarization VUV light allows to explore chirality and dichroism in biotic media



Postcredits: learnt from the FLASH2020+ S2E series

 ✓ Both AQUA and ARIA will be driven by short electron bunches → more advanced FEL performance calculations & benchmarks are envisaged: PUFFIN, GENESIS4_one4one flag enabled

Introduction to Puffin

Speaker: Dr Pardis Niknejadi (MPY (Beschleunigerphysik))

👌 Niknejadi-S2EWork...



Speaker: Eugenio Ferrari (PSI)

Genesis1.3V4-Frien...

✓ Advanced design with realistic fields of the ARIA seed laser \rightarrow Chi3D



✓ We are in the process of local computing power & resources distribution assessment for deploying the tools learnt in these S2E Workshops

Please, stay FEL-tuned!

Thank you!



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