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Porthos Specification(Ideas & Comments)

Porthos Brainstorming Meeting – May 2023

*Using Tapas (Ming Xie Model)

Photon Energy Range (1-10 keV)

- Assuming Aramis-like beam parameter (Current: 3 kA, Emittance: 300 nm, Energy Spread: 1 MeV)
- Porthos will benefit from Linac upgrade (7 GeV beam energy)

Highest photon energy is defined by acceptable lowest K-value and the period length. ***Highest K-value is given by Undulator technology and acceptable undulator gap***.

^For an estimate we assume that maximum K-value is roughly the undulator period in cm.

Photon Energy (keV)	Minimum K	Maximum K^	Undulator period (mm)	Saturation Length* (m)	Saturation Power* (GW)	Minimum photon energy at 7 GeV (keV)	Minimum Energy for 1 keV (GeV)
10	1.5	2.1	21	32	14	6.9	2.7
10	1.2	2.7	27	42	13	3.7	3.6
8	1.2	3.4	34	45	16	2.0	5.0

Independence of Aramis and Porthos needs to be studied from BD/RF:

- ***Can we achieve vastly different energies for Aramis and Porthos bunch?***
- ***Can we match optics for Porthos bunch and then catch up the optics for Aramis bunch with different energy?***

A large tuning range by K-values is highly desirable (at least factor 3)

Undulator Length

- Saturation length for basic SASE operation, about 40 m. With break section total length is about 50 m

- Two color operation needs twice the length
- Self-seeding needs about 1.5 to 2 times the basic length (fresh bunch self-seeding rather 2 times)
- Multi-stage fresh bunch requires about 2 times the basic SASE length, preferable even longer (needs to be studied).

→ ***Two color and self-seeding chicane can be the same if undulator has at least twice the basic saturation length***

Estimate that module length can be longer than Athos (3 - 5 m – needs to be studied). Defining modes are:

- Multi-stage High Power
- HB-SASE
- Optical Klystron

About 80 m active undulator length

Pulse Duration and Minimum Bandwidth Control

Wish is Fourier-Limited Pulses (narrowest bandwidth) with controllable pulse length down to sub-fs pulse duration

Few fs to 100 fs:

- Best choice is self-seeding with a tilted beam (below 20 fs even with fresh bunch technique)

0.1 to a few fs:

- 10 pC non-linear compression or multi-stage amplification can deliver short pulses but not reliably single spike (Fourier-limited).
- Best bet would be: self-seeding with tilted bunch + multi-stage fresh-bunch amplification.

Porthos needs to implement methods for tilting the beam (Dechirper?). A much larger aperture in undulator would help with larger tilts and then shorter pulses

BD needs to study to improve single-spike delivery of both modes (e.g. larger tilts etc.)

Synchronization down to 1 fs

Beam arrival jitter is at best around 8 fs. Improving it would require the exchange of the entire RF system.

Needs external stabilization by restricting parts of the bunch for lasing:

- External seeding for laser pulse duration shorter than bunch length (see last slices)

  ⇒ X-ray jitter is defined by optical laser jitter

- Laser based slicing for single pulse (HERO follow up):
  - Carrier-Envelope Phase (CEP) stable single cycle laser pulse + dipole/1 period modulator
  - CEP pulse + tapered modulator + multi-stage fresh bunch
  - Chirped laser pulse and tapered modulator + multi-stage bunch

Since more laser power is needed, operating at 800 nm becomes almost mandatory to avoid loss due to harmonic converison

Modulator for 800 nm at 7 GeV will be enormous

Other Athos Modes

CHIC-Chicanes

- ***Optical Klystron***: Delay scales with FEL wavelength. Estimate delays would be up to 150 nm (rough estimate)
- ***HB-SASE:*** Similar to Optical Klystron the coherence length would be shorter. To compensate more chicanes are needed with shorter undulator module sections
- ***Fresh-bunch techniques:*** Delay should be similar or slightly smaller than Athos. With aperiodic slicing with HERO-equivalent system or in laser heater the offset correction might not be needed.

Needs undulator module length optimization similar to Athos to define best undulator length. Experimental demonstration of ESASE/Laser Heater slicing for fresh-bunch at Athos to decide on off-set correction.

Transverse Gradient Undulator

- ***Ultrawide bandwidth:*** Since the FEL pulse is also spatially tilted, is there a strong science case for it?

Has impact on undulator design if needed or not. It comes naturally with Apple-X design but not for the simpler Delta-undulator design

Phase Control beyond Filtering

Shaping the FEL pulse is best done with shaping an external seed. Possible approaches:

- **Direct Seeding (HHG-Source):** For seeding in tender/hard X-ray not mature enough. Missing in seed power and temporal coherence length. ***Survey of sources needed + Test at Athos?***

- **Harmonic Generation (HGHG):** With 1 keV seed signal one could do a simple harmonic conversion in Porthos. Source might be Athos (even in combination with EEHG), but minimum transport distance is 12 m (9 m transverse beamline separation and 2x1.5m to cross Aramis line at the ceilling) with 4 mirrors. Time of flight is 40 ns while bunch separation is 21 ns.

- **Echo-enabled Harmonic Generation at 266 nm:** Either chicane strengths or laser modulation needs to scale with the harmonic number. The former results in chicane much larger than existing in SwissFEL, the later will prevent lasing due to blown-up energy spread.

- **Echo-enabled Harmonic lasing at shorter wavelength:** Due to development in reflective optics a wavelength of 13.5 nm is the preferred choice (semi-conductor industry)

Sources at 13.5 nm

EEHG set-up comparable or even smaller than for Athos since the required harmonics are smaller. Problem is the 13.5 nm source.

	Performance	Hardware	Comments
HHG	10^{10} photons/s/1% band @ 13nm @ 1 kHz	KMLabs Commercial Product XUUS5	This corresponds to about 1 nJ per pulse. Pulse length about 50 fs *[Talk by H. Kapteyn, EUV Litho Workshop 2016]*
Tin Laser	$2 \cdot 10^{11}$ W/cm^2 for 5 ns pulse duration. >1% bandwidth	Liquid tin jet and 2 um laser	Emission is in all direction. For seeding an electron beam the effective power would be about 200 kW. *[L. Behnke et at, Opt.Express 29 (2021) 4475]*
EEHG/HGHG	100 uJ per pulse. 0.05% bandwidth, ~50 fs pulse duration	FEL facility!	*[E. Allaria et at, Nat Photonics 6 (2012) 699]*
Storage Ring	120 nJ per pulse, 16 fs FWHM, Fourier Limited, about 5 MW peak power	Compact Storage ring with dogleg and modulator at 266 nm	Angular Dispersion HG, similar to Phase Emerging HG induces coherent bunching on beam. *[C. Feng and Z. Zhao, Sci. Reports 7 (2017) 4724]*

Implementation at Porthos

FEL or storage ring based sources at 13.5 nm seems to be the most prominent solution. Typically a beam energy of 500 MeV should be sufficient to produce 13.5 nm radiation to seed Porthos

FEL:

Can a 4th bunch at SwissFEL be extracted after BC1 and then be transported close to Porthos to generate radiation at 13.5 nm? How compact is a stand-alone facility?

Storage Ring:

Can deliver coherent radiation at 13.5 nm on a much higher rate than 100 Hz. Combine with Lithography station? Build the storage ring on top of SwissFEL? Can COSAMI be upgraded? Is 5 MW output power sufficient?

Both methods should be studied by BD if they are sufficient to drive EEHG at Porthos.