LWFA-fed Compton X-ray Source Based on a Dual-Energy Accumulator Ring with Cryocooled Nb_3Sn Twin-Axis Cavities

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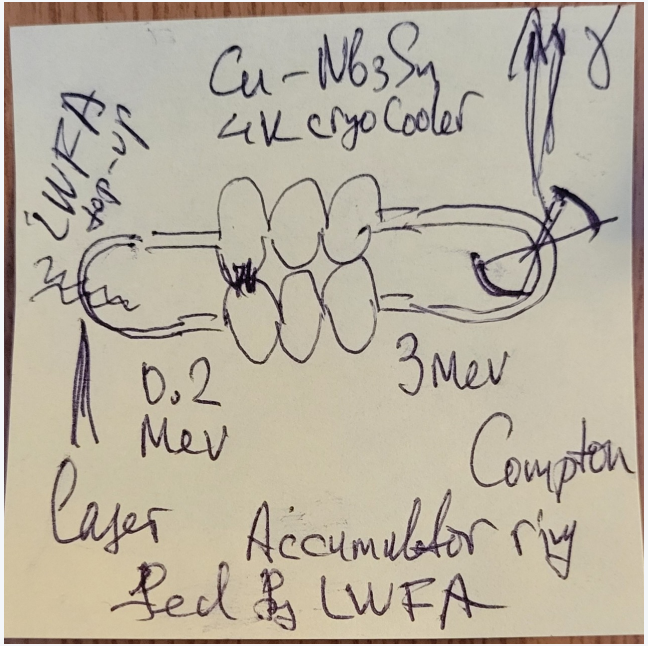
Initial Idea and Collaboration

- Multi-fold motivation:
  - Compact light source concept suitable for ODU/CASA
  - Maximize reliance on ODU–JLab expertise and existing technology
  - Start at low energy (<10 MeV) to simplify radiation shielding — well-suited for a university
  - Natural upgrade path to hard X-rays with more SRF cells

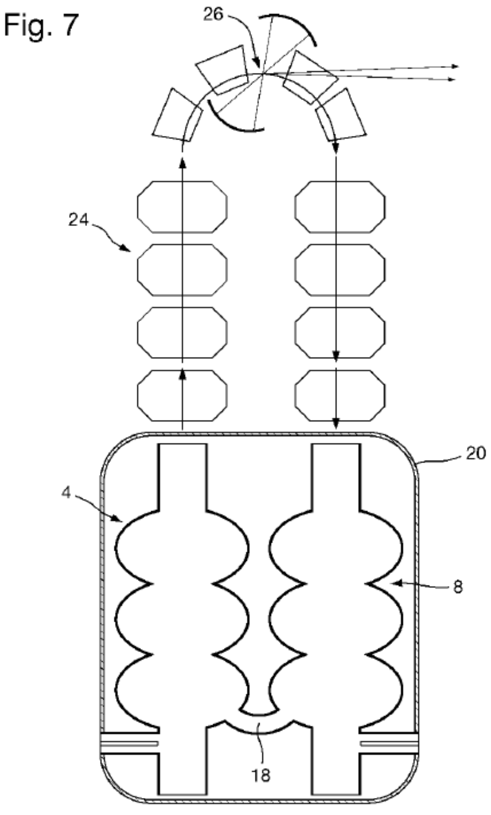
- Collaboration & contributions to discussion:
  - J. Delayen, G. Krafft, S. De Silva, Q. Su, B. Terzić, L. Van Riesen-Haupt, M. Yadav (ODU)
  - T. Satogata, V. Ziemann (JLab)

- Concept originated March 2026; design notes and code at:
  - https://github.com/aseryi/vibe-coding/tree/main/LWFA-fed-Compton

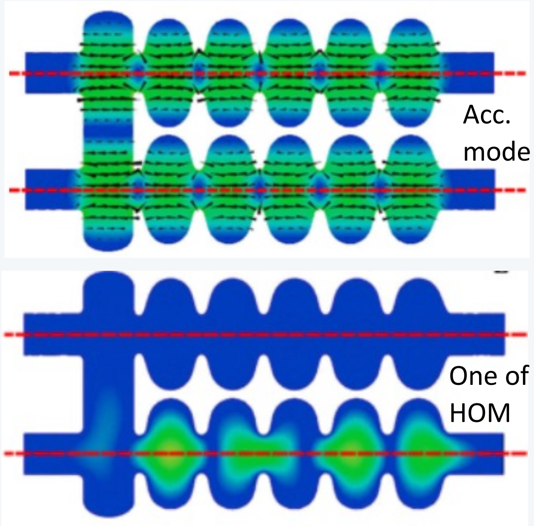


March 11, 2026, initial idea, Yellow Post-It note as sent to ODU colleagues for discussion

Initial idea as an evolution of earlier schemes



X-rays generation, A.Seryi, May 2013 – dual axis cavities and energy recovery – patent: https://patents.google.com/patent/WO2013061051A1/



Ideas of ultimate X-ray source based on ERL with dual-axis cavities where accelerating mode and HOM are decoupled due to fine tuning of sizes of each individual cell

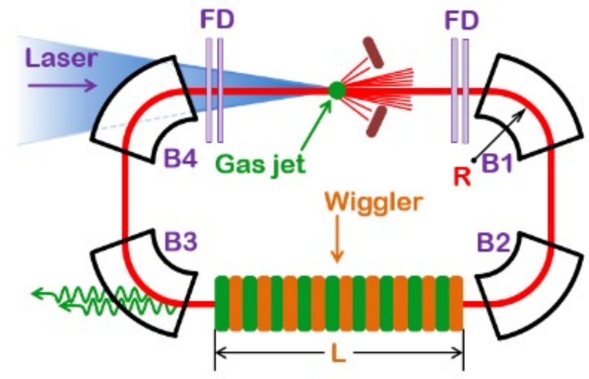
Copper prototype

Asymmetric dual axis energy recovery linac for ultrahigh flux sources of coherent x-ray and THz radiation: Investigations towards its ultimate performance, R. Ainsworth, G. Burt, I. V. Konoplev, and A. Seryi,
Phys. Rev. Accel. Beams 19, 083502 – Published 19 August, 2016 DOI: https://doi.org/10.1103/PhysRevAccelBeams.19.083502

Experimental studies of 7-cell dual axis asymmetric cavity for energy recovery linac
I. V. Konoplev, K. Metodiev, A. J. Lancaster, G. Burt, R. Ainsworth, and A. Seryi
Phys. Rev. Accel. Beams 20, 103501 – Published 10 October, 2017 DOI: https://doi.org/10.1103/PhysRevAccelBeams.20.103501

Initial idea as an evolution of earlier schemes – continue

USPAS 2016, Mini-Project – **Compact ring-based X-ray source with on-orbit and on-energy laser-plasma injection**

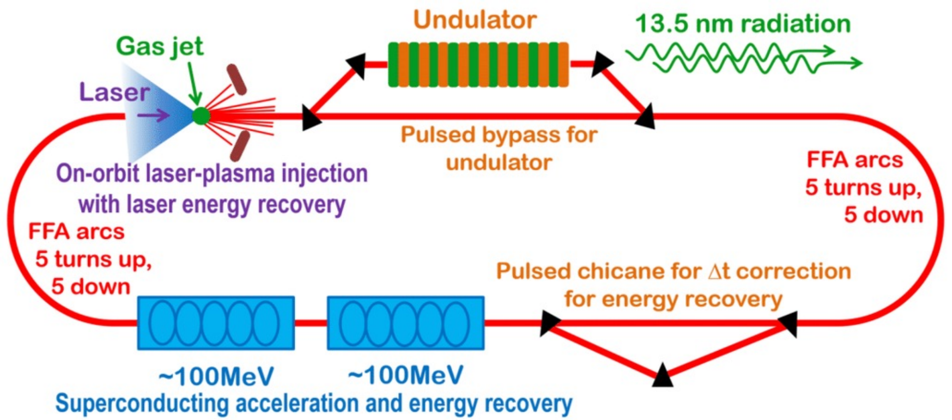


Marlene Turner presenting the USPAS results at NAPAC 2016

https://proceedings.jacow.org/napac2016/papers/tua3co03.pdf

USPAS 2023, Mini-Project – **Compact recirculation-FFA-ERL-based 13.5 nm FEL with on-orbit laser-plasma injection with energy recovery**

https://proceedings.jacow.org/ipac2024/pdf/MOPG66.pdf



https://unifyingphysics.com/resources/

Motivation: Water Window and Beyond

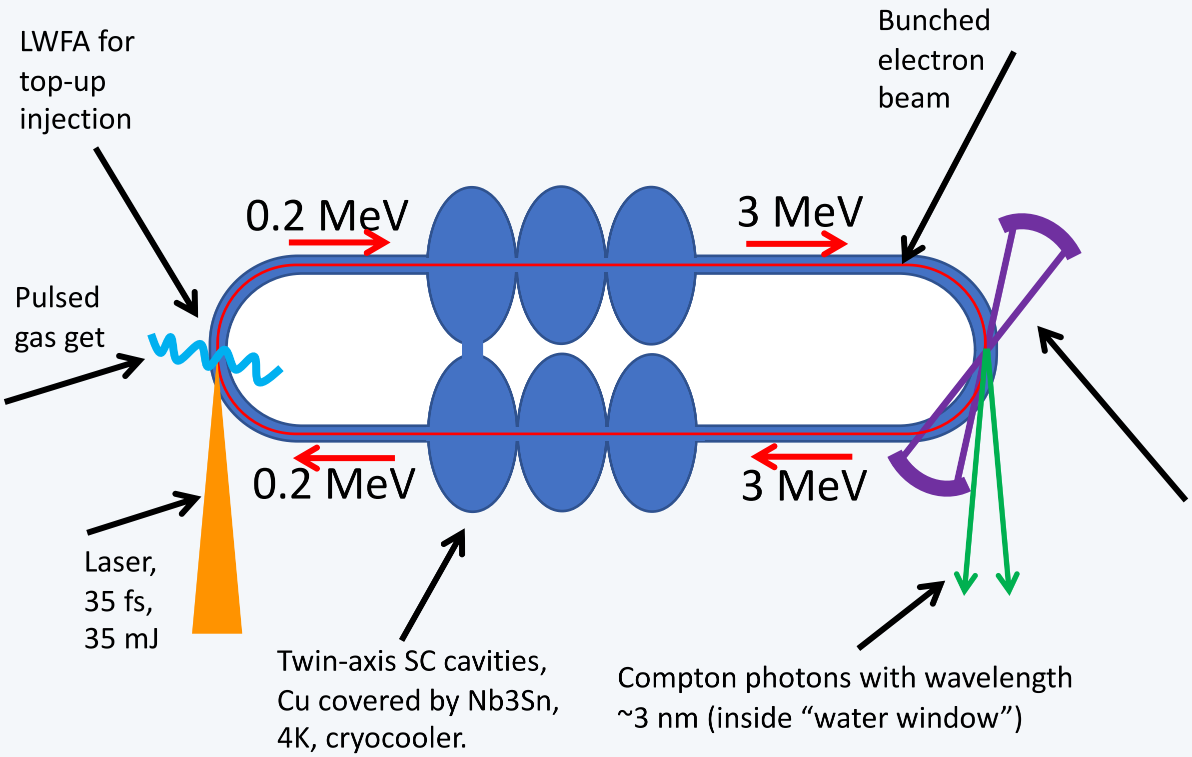
- Water window: 2.3 – 4.4 nm (280 – 540 eV)
  - Carbon absorbs; oxygen/water transparent → high-contrast bio imaging
  - NEXAFS spectroscopy, ultrafast dynamics studies
- Hard X-rays (1–100 keV): medical imaging, materials science, XRD
- Current compact Compton sources: 10–100 keV range (ThomX, Lyncean)
- Gap: no compact source covers the soft X-ray / water-window regime
- This concept targets 3.2 nm (water window) as primary goal
  - Natural extension to hard X-rays with more SRF cells (see slide 14)
- Goal: unique lab-scale source covering water-window regime
  - Bridges HHG (nW) and synchrotrons (kW) — targets mW to W range

2.3 – 4.4 nm
Water-window target (primary)

1 – 100 keV
Hard X-ray extension (upgrade path)

mW → W
Target average power range

Concept Overview: Three Technologies, One Compact Source



Concept schematic: LWFA injector → twin-axis Nb_3Sn SRF cavities → dual-energy accumulator ring → Compton laser cavity

① LWFA Injector

35 mJ / 35 fs laser, high-density gas jet (n_e ~ 10^{19} cm^{-3}), sub-MeV electrons (~0.2 MeV)

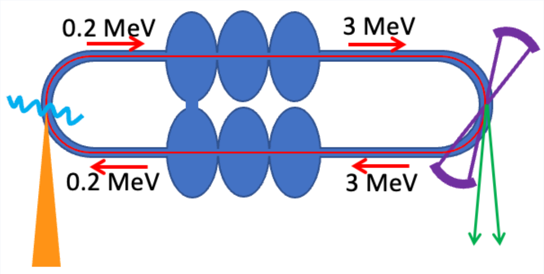
② Nb_3Sn Twin-Axis SRF

3 cells, 4K via cryocooler. Top axis: accelerate to 3 MeV. Bottom axis: decelerate / energy recovery.

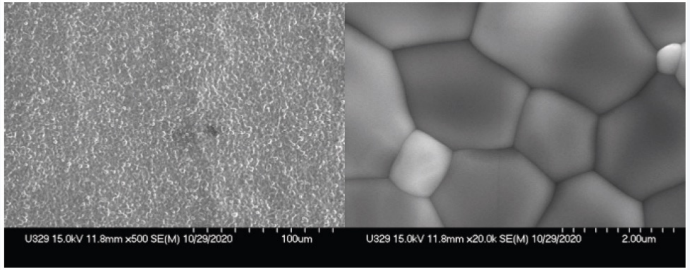
③ Compton Laser Cavity

600 nm stored photons in high-finesse cavity collide with 3 MeV electrons → 3.2 nm X-rays

Nb_3Sn Twin-Axis SRF Cavities



- Twin-axis topology: two coaxial beam apertures in one SC structure
- Top cells accelerate: +1 MeV/cell × 3 cells = 3 MeV gain
- Bottom cells decelerate: −1 MeV/cell × 3 cells = 3 MeV recovered
- Options:
  - One RF bridge for entire structure, as show in picture
  - Individual dual-axis cells, as demonstrated → individual RF bridges in each cell
- Net RF power = cavity + beam losses only (not full beam energy)
- Nb_3Sn at 4K: $Q_0 \gtrsim 10^{10}$, gradient 15–20 MV/m demonstrated
- Cryocooled at 4K — no liquid helium, mobile cryocooler sufficient
- Low-β first cell: cell length matched to β ≈ 0.70 (0.2 MeV injection)
- 2nd and 3rd cells: standard β ≈ 1 geometry



Nb_3Sn twin-axis cavity prototype, J. K. Tiskumara, J. R. Delayen, S. U. De Silva, et al, IPAC 2021, doi:10.18429/JACoW-IPAC2021-MOPAB384

Compton Photon Energy: Exact Kinematics

Exact inverse-Compton formula (head-on):

$$E_\gamma = E_{laser} \cdot (1+\beta)^2 \cdot \gamma^2 / [\, 1 + E_{laser} \cdot (1+\beta) \cdot \gamma / m_e c^2 \,]$$

- At E_e = 3 MeV: γ = 6.871, β = 0.989
- λ_{laser} = 600 nm → E_{laser} = 2.07 eV
- Quantum recoil < 0.2% — negligible
- Result: E_γ = 386 eV ↔ λ_γ = 3.21 nm ✓ water window
- Exactly 3 nm: need E_e ≈ 3.16 MeV (+5% — trivially tunable)
- Wavelength continuously tunable across water window via E_e

→ Configuration naturally expandable to hard X-rays:

- More Nb_3Sn SRF cells → higher E_e → harder photons (see slide 14)

γ = 6.87

at 3 MeV (water window design)

386 eV / 3.21 nm

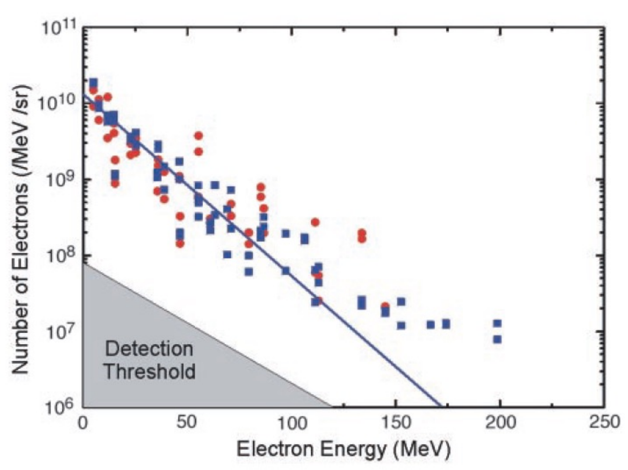
Compton photon (water window) ✓

~20–100 keV

Hard X-ray upgrade (40–56 MeV)

LWFA Injector: Operating in the Low-Energy Regime

- Target: ~0.2 MeV — far below modern GeV LWFA
- Deliberate: high density, low a_0, SHORT plasma
- Parameters:
  - n_e ~ 10^{19}–10^{20} cm^{-3} (vs 10^{17}–10^{18} for GeV LWFA)
  - a_0 ~ 1–1.3 (35 mJ, 35 fs, w_0 ~ 3–5 μm)
  - λ_p ~ 1–10 μm → E_WB ~ 3–10 GV/m
  - Plasma length ≲ 100 μm → sub-mm pulsed gas jet
- Self-injection at bubble back, extracted early (before dephasing)
- Broad 'warm' spectrum — exactly Modena 1995, Malka 2002 regime
- 0.2 MeV sweet spot: β = 0.70, manageable divergence for solenoid capture
- Energy-recovery ratio: R = 3 MeV / 0.2 MeV = 15



Measured electron spectra for n= 2.5E19 and 6E19

Early LWFA energy spectrum
Malka et al., Science, Vol 298, Nov 2002

Optimizing Injection Energy: Maximizing Energy-Recovery Ratio

E_inject	β	R = E_top/E_inject	Comment
0.10 MeV	0.55	30	Transport essentially unworkable — divergence too large
0.15 MeV	0.64	20	Aggressive but possibly feasible with strong solenoid
0.20 MeV	**0.70**	**15**	**← Recommended sweet spot**
0.30 MeV	0.78	10	Comfortable margin, but R drops 33%
0.50 MeV	0.86	6	Conservative — R drops by half

- Practical floor ~0.1–0.2 MeV: set by solenoid capture, not plasma physics
- Below ~0.1 MeV: electrons indistinguishable from plasma background; divergence unmanageable
- SRF low-β first cell handles velocity mismatch at injection — no constraint from cavity side
- 0.2 MeV identified as practical optimum: R ≈ 15, β = 0.70

Photon Flux and Average Power Estimates

Central estimate formula:

$$\dot{N}_\gamma = N_e \cdot N_{ph} \cdot \sigma_T / (4\pi \sigma_{eff}^2) \times f_{rev}$$

Ring current

$I = 1$ A (hypothesis)
$N_e \approx 4.2 \times 10^{10}$

Stored laser photons

$E_{stored} \sim 1$ mJ @ 600 nm
$N_{ph} \approx 3 \times 10^{15}$

IP beam sizes

$\sigma_e = \sigma_{ph} = 10$ μm
$f_{rev} \approx 148$ MHz

~5 × 10^{14} ph/s

Central flux estimate

~31 mW

Average power (central)

0.6 mW – 6 W

Full uncertainty range

- Dominant uncertainty: achievability of Ampere-scale ring current via LWFA top-up
- Conservative baseline (100 mA): flux ~5×10^{13} ph/s, power ~3 mW — still competitive
- Laser cavity finesse (F ~ 10^4–10^5) and IP spot size are secondary levers

Accumulator Ring: Why 3 MeV is Remarkably Compact

- Magnetic rigidity: Bρ = 0.0116 T·m
- At B = 1.5 T: bend radius ρ = 7.7 mm
- Ring circumference C ~ 1–3 m feasible
- Revolution frequency (C = 2 m): f_rev ≈ 148 MHz
- SR energy loss per turn: U_0 ≈ 2 eV — negligible
- No SR-induced emittance growth; IBS and Compton recoil are real limits
- Gas jet scattering → critical lifetime mechanism (see open questions)

Bend radius comparison:

ThomX (50 MeV)	B=0.4T	37 cm
Lyncean (30 MeV)	B=0.4T	22 cm
This work (3 MeV)	**B=1.5T**	**7.7 mm**
Inject. (0.2 MeV)	B=0.1T	6.7 mm

Context: Comparison with Other Compact Compton Sources

Source	E_e	X-ray energy	Flux (ph/s)	Footprint	Injector type	Status
ThomX (IJCLab, Orsay)	50–70 MeV	45–90 keV (45 keV demonstrated)	10^{10} now →10^{13} design	~100 m²	Photoinjector + 50 MeV linac	Commissioning (PRAB 2025)
Lyncean CLS (Munich etc.)	~25–35 MeV	15–35 keV	~10^{10}–10^{11}	~6 m² (tabletop ring)	Photoinjector + linac	Commercial operations
MuCLS (Munich)	~45 MeV	15–35 keV	~10^{11}	~15 m²	Microtron	Operating since 2016
This concept (water window)	3 MeV	386 eV (3.2 nm, soft X-ray)	10^{13}–10^{16} (est.)	~2–4 m²	LWFA + energy recovery	Conceptual
This concept (hard X-ray ext.)	40–56 MeV	20–100 keV	10^{13}–10^{16} (est.)	~10–20 m²	LWFA + more SRF cells	Upgrade path

★ Unique: this concept is the only design targeting the soft X-ray / water-window regime in a compact ring format

Key Open Questions and Studies Required

① Ring current achievability

Can LWFA top-up sustain ~100 mA–1 A?
Needs: LWFA rep-rate (kHz?), bunch charge, beam lifetime

② Beam lifetime: gas jet scattering

Residual gas from LWFA jet scatters stored electrons — even pulsed jets leave background gas between shots. May be dominant loss mechanism.
Needs: gas density profile + vacuum model

③ Non-captured beam / shielding

Only a fraction of LWFA electrons are captured. Non-captured majority (broad energy, large divergence) must be intercepted near gas jet. Radiation shielding near injection region — key early engineering requirement.

④ IBS and Compton recoil

IBS growth at 3 MeV with low emittance?
Compton recoil: $\Delta p/p \approx 0.013\%$/event → lifetime from luminosity

⑤ Ring lattice and optics design

Circumference, tune, momentum compaction, IP β^* — all unknown. Full MAD-X / Elegant design required before flux estimates narrow

⑥ Laser cavity and synchronization

Stored power ∝ finesse F (10^4–10^5 → 10s–100s mJ). Ring↔laser timing jitter < 100 fs mandatory — ThomX experience highly relevant.

Hard X-ray Extension: Natural Upgrade Path

Same concept architecture, more SRF cells → harder photons:

Water Window (this work)	Soft X-ray +	Medical Imaging	Hard X-ray
3 MeV 3 SRF cells 386 eV / 3.2 nm	~10 MeV ~10 cells ~4 keV	~25–40 MeV ~25–40 cells ~10–30 keV	~40–56 MeV ~40–56 cells ~20–100 keV

- Key difference from EUV/wiggler route: same architecture, same LWFA injector, same ring topology
- Only addition: more Nb_3Sn SRF cells in the cryomodule
- At 40–56 MeV: same technology as ThomX / Lyncean, but with LWFA injection + energy recovery
- LWFA still provides the low-energy injection (now ~0.5–1 MeV for better matching at higher energy)
- Energy-recovery ratio R = E_top / E_inject remains large (e.g., 56 MeV / 1 MeV = 56)
- Machine footprint grows to ~10–20 m² — still compact vs ThomX (~100 m²)
- Radiation shielding becomes more significant: ~50 MeV electrons require concrete shielding (cf. ThomX bunker)
- Hard X-ray stage likely requires photoinjector rather than LWFA for beam quality

Staged Development Path

1 → 2 → 3 → 4 → 5

1. LWFA Sub-MeV Injector

0.15–0.2 MeV extraction from high-density gas jet. Characterize divergence, energy spread. Solenoid capture optics.

2. Nb_3Sn Twin-Axis Prototype

Low-β first cell at 4K with cryocooler. $Q_0 \gtrsim 10^{10}$ and gradient ≥5 MV/m. Validate cell design.

3. Single-Pass LWFA → SRF

Inject 0.2 MeV, accelerate to 3 MeV, energy recovery in straight geometry. No ring yet.

4. Ring + Top-Up Injection

Commission accumulator ring. Measure beam lifetime, gas scattering, max stored current. Collimation validated.

5. Compton Laser + Hard X-ray

Water-window source commissioning, then add SRF cells for hard X-ray extension.

Summary

✓ Compton wavelength	386 eV / 3.21 nm — confirmed in water window by exact kinematics
✓ Compact ring	Bρ = 0.012 T·m → C ~ 2 m; 50× smaller than ThomX (18 m ring)
✓ LWFA injector	Same 1995–2002 regime (Malka 2002); 35 mJ / 35 fs sufficient
✓ Energy recovery	R = E_top / E_inject ≈ 15; 0.2 MeV identified as practical optimum
✓ Nb_3Sn at 4K	Cryocooler-compatible; low-β first cell; ODU/JLab prototype demonstrated
~ Flux estimate	10^{13}–10^{16} ph/s; 0.6 mW–6 W; ring current dominates uncertainty
→ Hard X-ray upgrade	Natural extension: ~40–56 MeV with more SRF cells — same architecture, harder photons
! Gas jet scattering	Beam lifetime from LWFA jet gas: critical mechanism to quantify early
! Non-captured beam	Collimation + shielding near injection: key early engineering requirement
→ Next steps	Lattice design, PIC injector simulation, Nb_3Sn low-β cell prototype, ThomX lessons