R&D pour les collisionneurs du futur
High-Intensity Positron Sources

I. Chaikovska on behalf of the Positron Source group

Thanks to all the collaborator working on e+ sources for providing the information for this presentation.

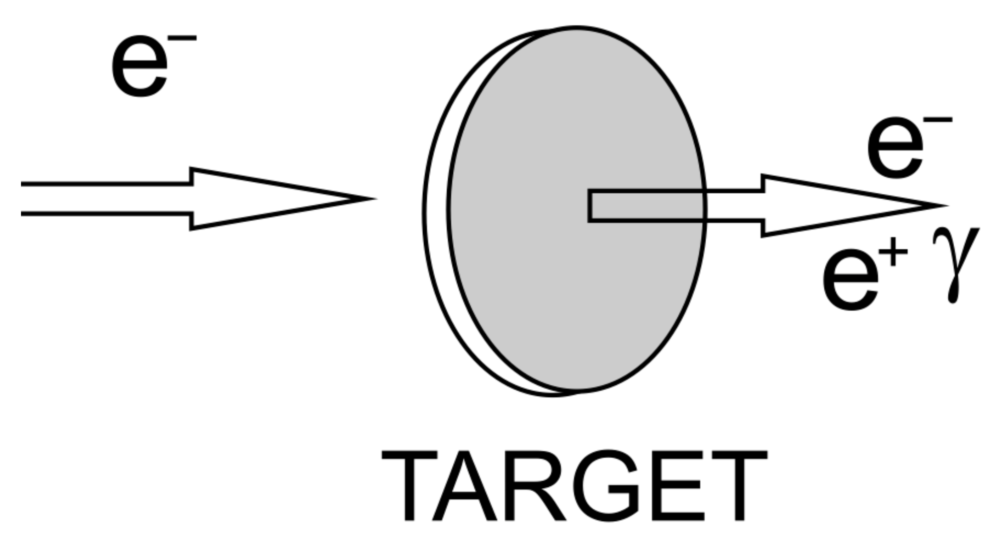
Why e+ sources are critical components of the FC

$$L = \frac{N_1 N_2\, f\, n_b}{4\pi\, \sigma_x \sigma_y}$$

High luminosity at the future machines => needs **high average and peak e- and e+ currents and small emittances.**

☞ **e+ are produced within large 6D phase space (e+/e- pairs produced in a target-converter).**

- **<u>Current</u>** => limited in conventional way by the target characteristics
  - Average energy deposition => target heating/melting
  - Peak Energy Deposition Density (PEDD): inhomogeneous and instantaneous energy deposition => thermo mechanical stresses due to temperature gradient
  - Thermal dynamics and shock waves
  - Fatigue limit resulting from cycling loading.
- **<u>Emittance</u>** => at the production 6D phase space is very large
  - After defined by the e+ capture system acceptance.

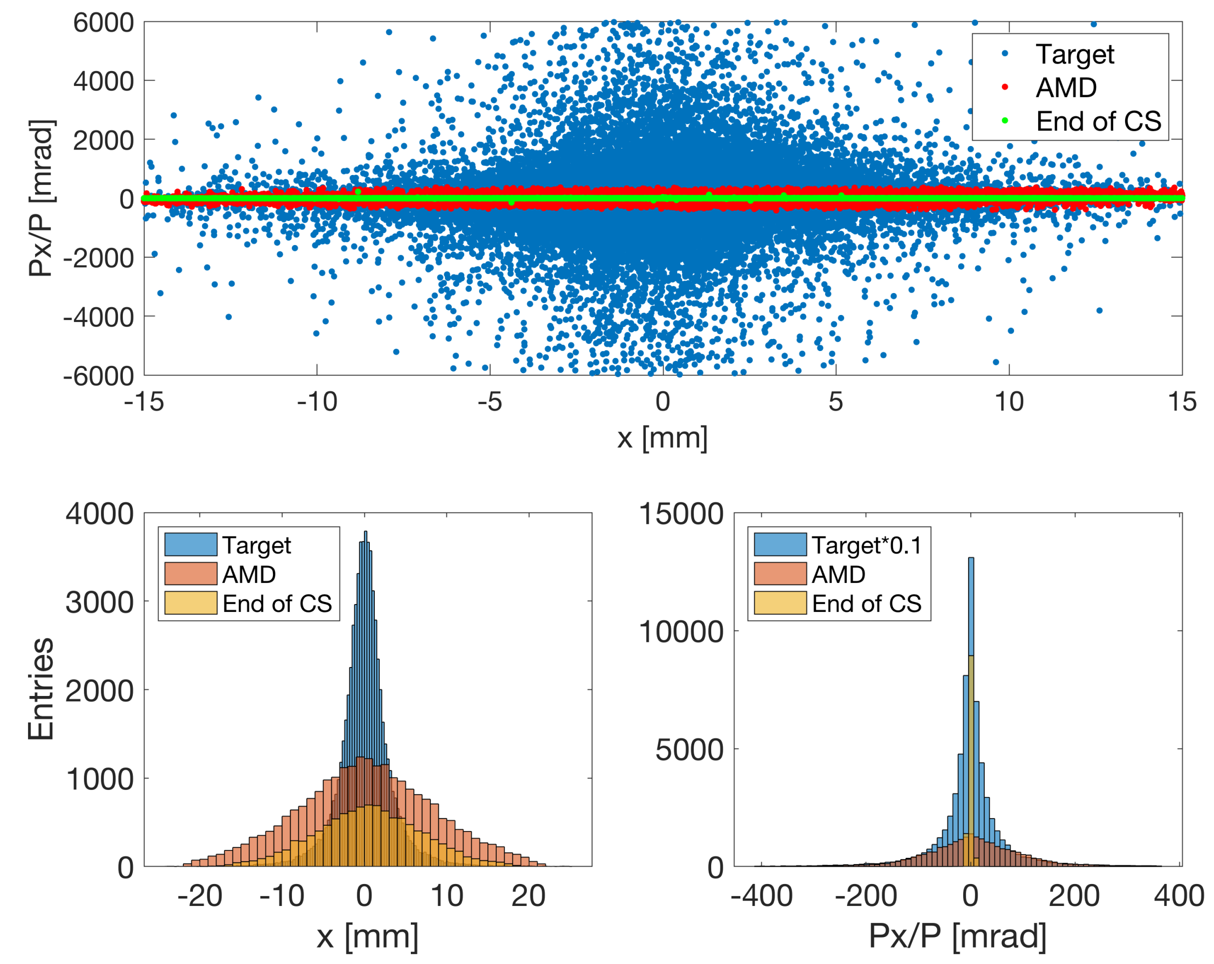


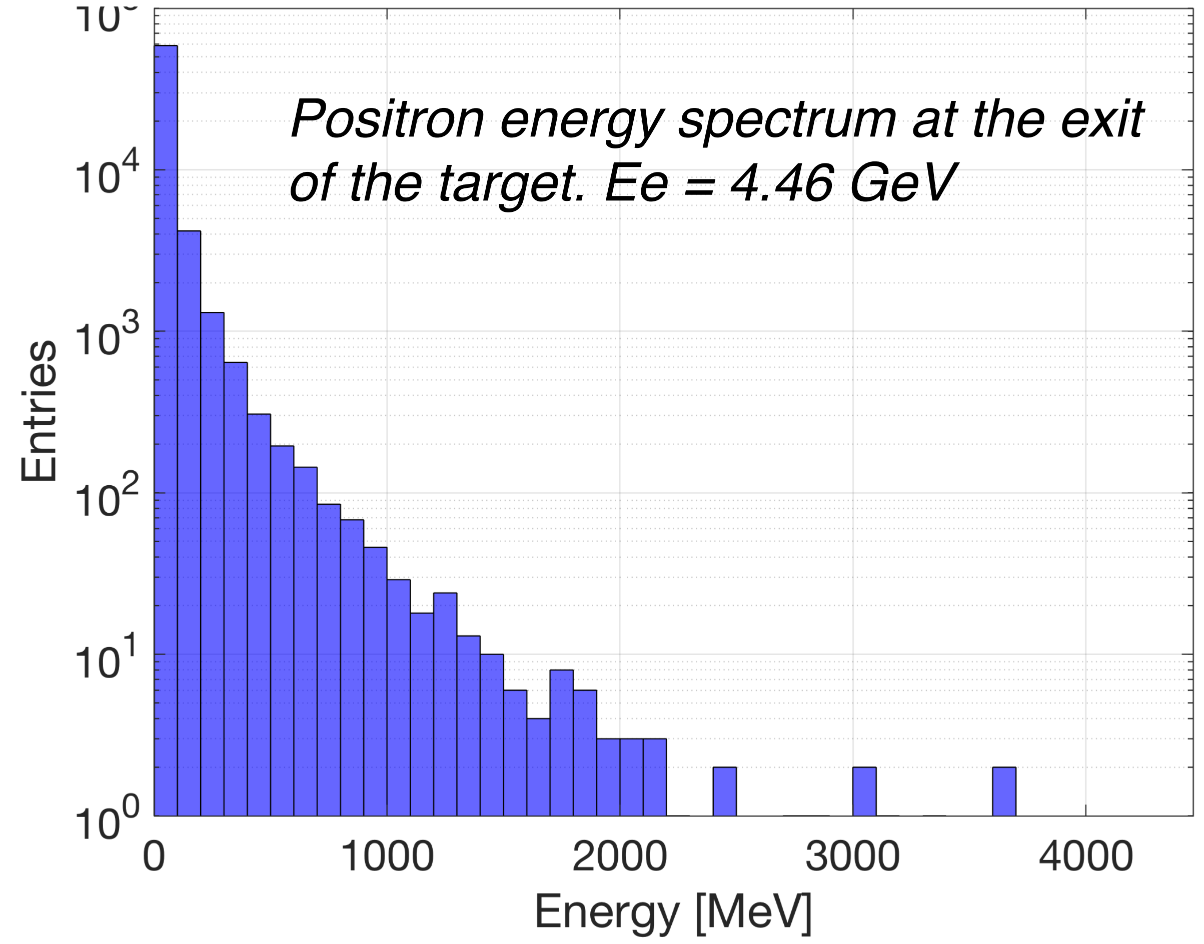
e+ source fixes the constraints for the peak and average current, the emittance, the damping time, the repetition frequency => **Luminosity!**

What are the main challenges

- **High intensity**=> 1) number of e+/e- pairs: higher primary beam energy and intensity, rather thick targets-converter or photon radiators (channeling, undulators) + 2) capture system (B field and RF sections)
- **Emittances** => weak multiple scattering => towards thin targets and small beam sizes on the targets + capture system
- **Polarization** => need the circularly polarized photon beam (Compton scattering, helical undulator, polarized bremsstrahlung)
- **Reliability and radiation environment** => prevent target failure (heat & stress) as a function of primary beam size and power. Minimize, whenever possible, the radiation load on the environment. Ensure remote handling/target removal system.

Positron emittance at the exit of the target, the AMD and the capture section at 200 MeV

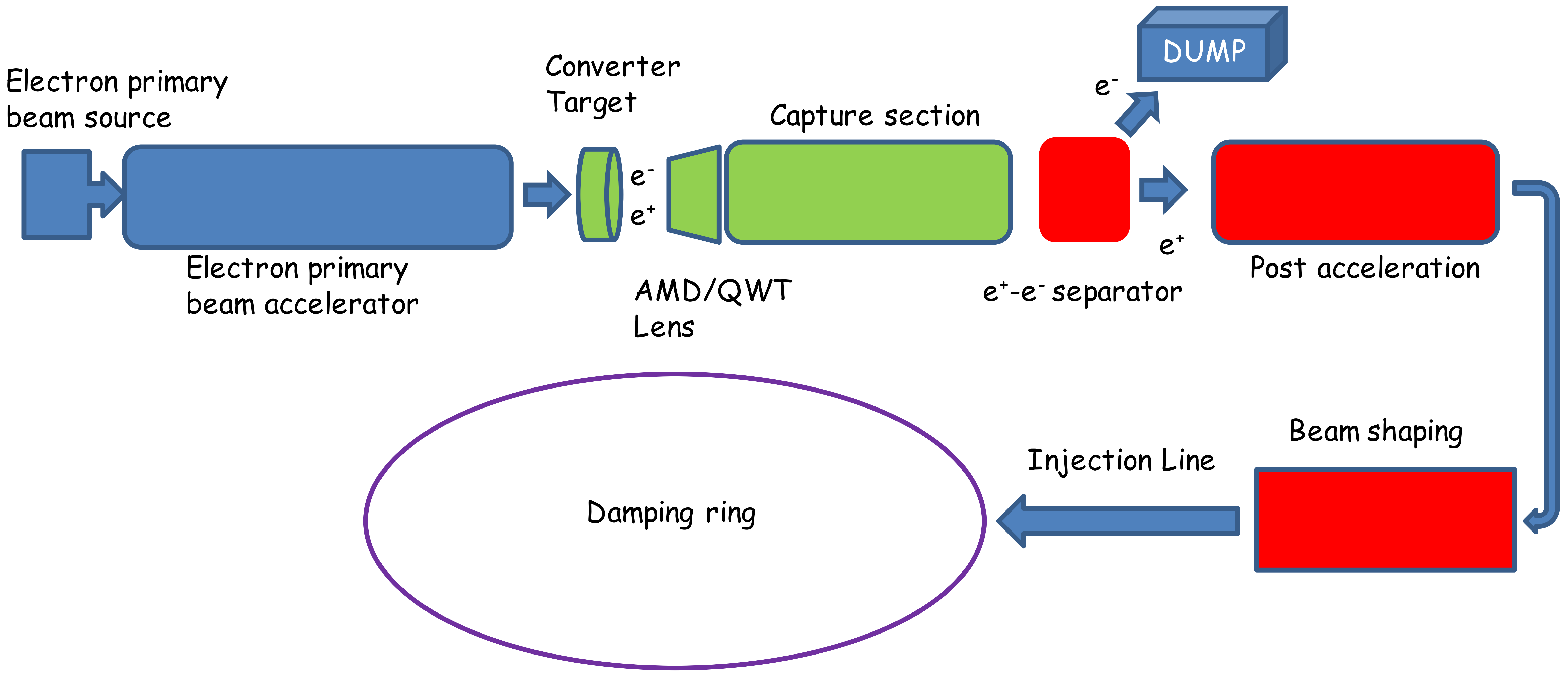




Positron energy spectrum at the exit of the target. Ee = 4.46 GeV

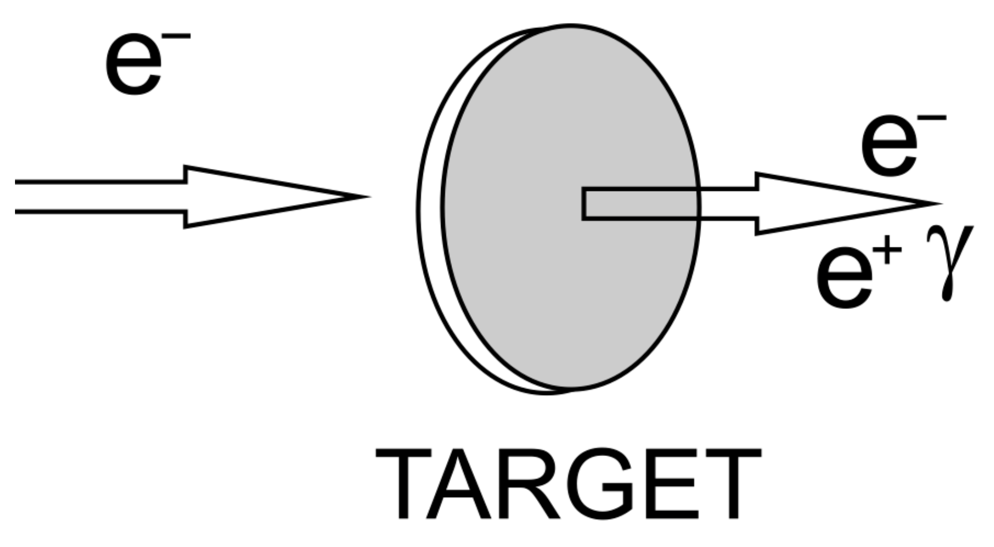
Accepted e+ flux is a function of target + capture system + primary beam characteristics!

Positrons sources: classical scheme



High production e+ divergence => appropriate capture, focusing and post acceleration sections need to be integrated immediately after the target.

Goal: matching the e+ beam (with very large transverse divergence) to the acceptance of the pre-injector linac.



Conventional positron target: bremsstrahlung and pair conversion

- Classical e+ source
- It was employed to produce e+ beam at the existing machines (ACO, DCI, SLC, LEP, KEKB…)

Positron source performances

Demonstrated (a world record for the existing accelerators): SLC e+ source: ~0.08e14 e+/s

Facility	**PEP-II**	**KEKB**	**DAFNE**	**BEPC**	**LIL**	**CESR**	**VEPP-5**
Research center	**SLAC**	**KEK**	**LNF**	**IHEP**	**CERN**	**Cornell**	**BINP**
Repetition frequency, Hz	120	50	50	12.5	100	60	50
Primary beam energy, GeV	33	3.7	0.19	0.14	0.2	0.15	0.27
Number of electrons per bunch	5×10^{10}	6×10^{10}	1.2×10^{10}	5.4×10^{9}	3×10^{9}	3×10^{10}	2×10^{10}
Target	W-25Re	W	W-25Re	W	W	W	Ta
Matching device	AMD	QWT	AMD	AMD	QWT	QWT	AMD
Matching device field, T	6	2	5	2.6	0.83	0.9	10
Field in solenoid, T	0.5	0.4	0.5	0.35	0.36	0.24	0.5
Capture section RF frequency, MHz	S-band	S-band	S-band	S-band	S-band	S-band	S-band
Positron yield, 1/GeV	0.054	0.023	0.053	0.014	0.0295	0.013	0.1
Positron output, 1/s	8×10^{12}	2×10^{11}	2×10^{10}	2.5×10^{8}	2.2×10^{10}	6.6×10^{10}	10^{11}

Future Collider project challenges

	SLC	CLIC (380 GeV)	ILC (250 GeV)	LHeC (pulsed)	LHeC (ERL)	LEMMA	FCC-ee
e- beam energy(GeV)	45.6	380	250	140	60	45	45.6
Norm. hor. emitt. (mm.mrad)	30	0.92	5	100	50	18	24.1
Norm. vert. emitt. (mm.mrad)	2	0.02	0.035	100	50	18	89
Bunches/macropulse	1	352	1312	10^5			2
Repetition Rate	120	50	5	10	CW		200 (Inj)
Bunches/second	120	17600	6560	10^6	20×10^6		16640
e+/second (10^{14})	0.08	1.1	1.3	18	440	100	8.5×10^4 (0.06@Inj)
Polarization	No	No/Yes	Yes	Yes	Yes	No	No

- *Linear Collider projects:* high request for polarization, requested intensity should be produced in "one shot".
- *Circular Collider projects:* polarization is under discussion, requirements are relaxed due to top-up injection.
- *Muon colliders (LEMMA):* ~ 1e16 e+/s to be defined based on the adopted baseline.

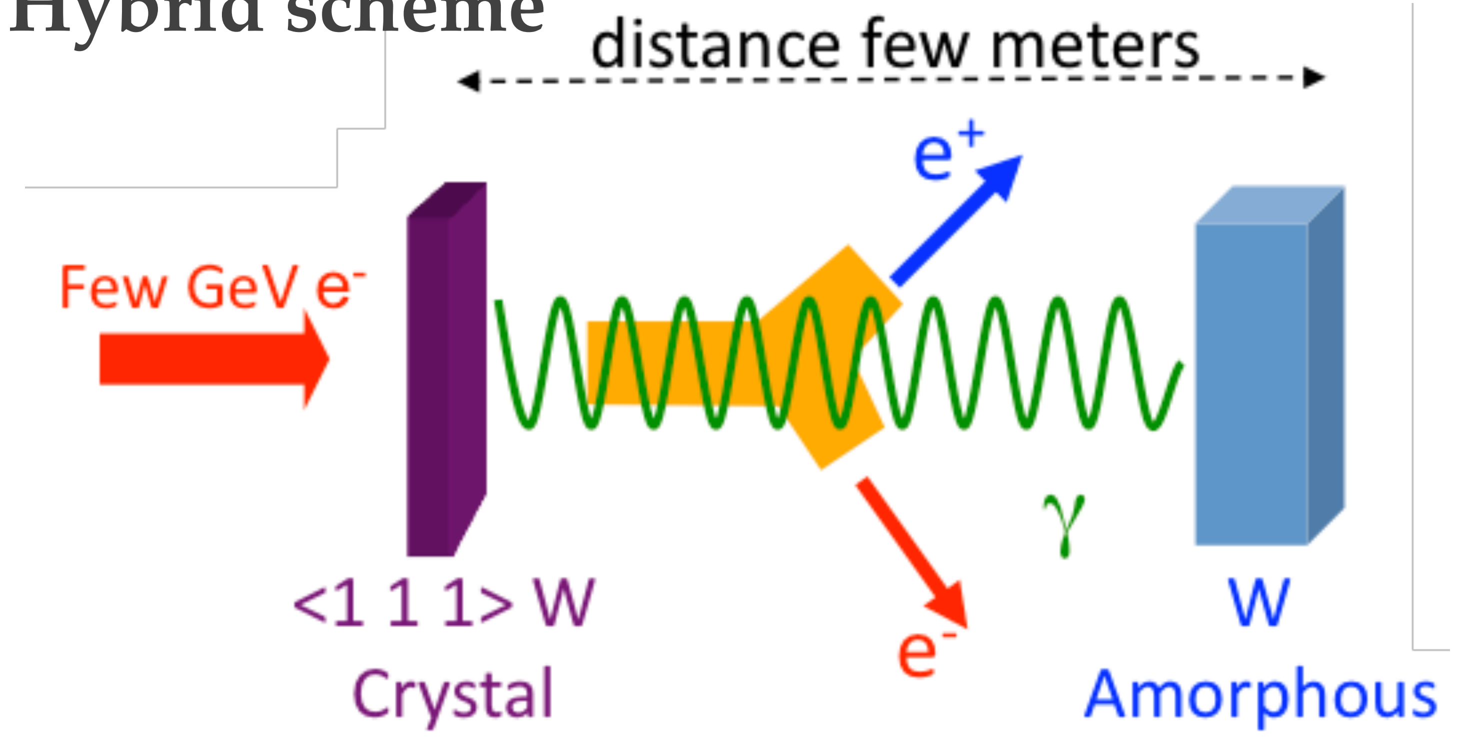
Positrons sources: 'novel' schemes

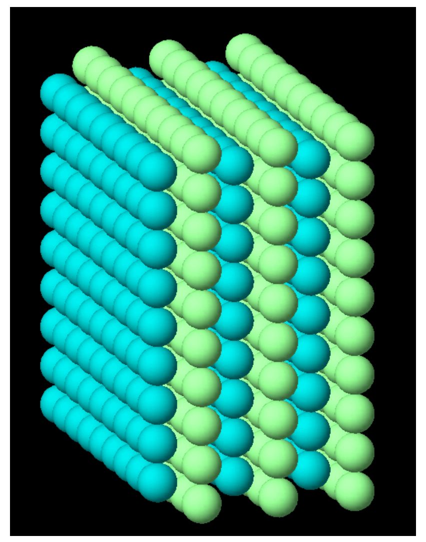
- Target PEDD and heating/melting: separate the photon production and the pair conversion

First stage: photon generation
Second stage: e-/e+ and photon beams are separated and the latter is sent to the target-converter

The photons can be generated by the following methods:
- **Radiation from helical undulator**
- **Channeling radiation**
- **Compton scattering**

Hybrid scheme





Recent idea: **granular** target made of **small spheres =>** beam tests @KEK

ILC => Undulator scheme

CLIC => Hybrid scheme (alternative Compton scheme for polarization upgrade)

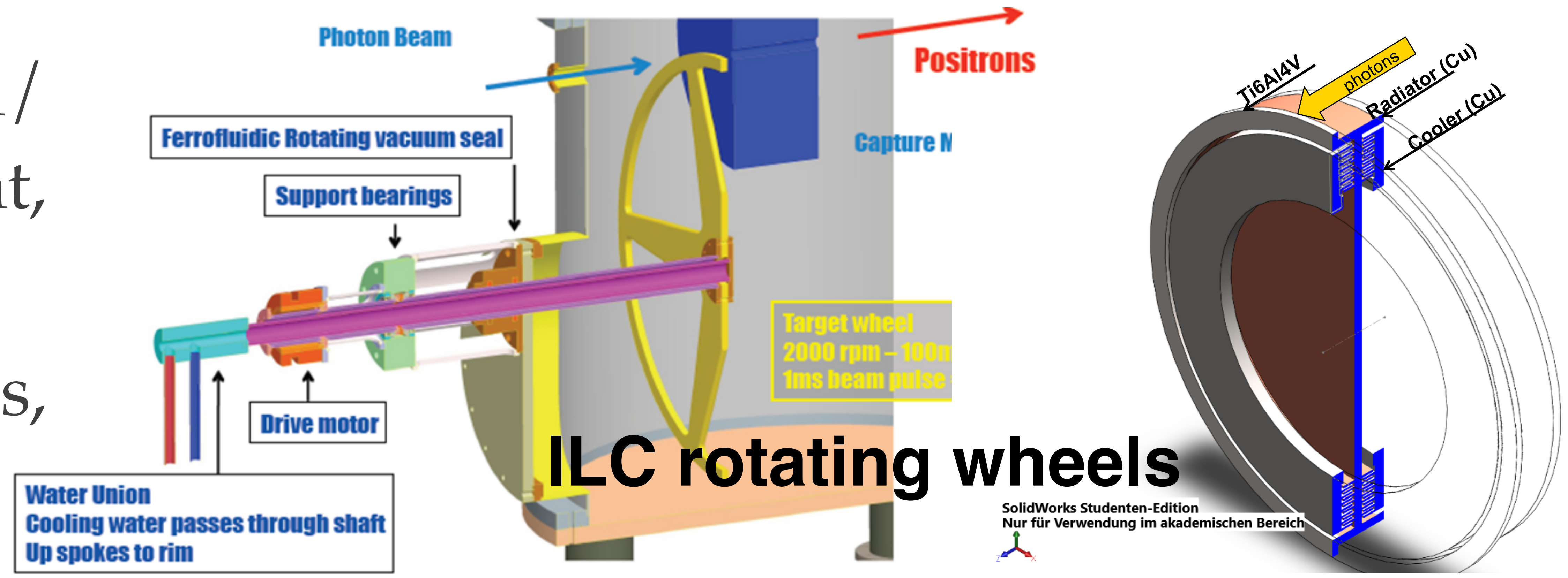
FCC-ee => Hybrid or conventional scheme

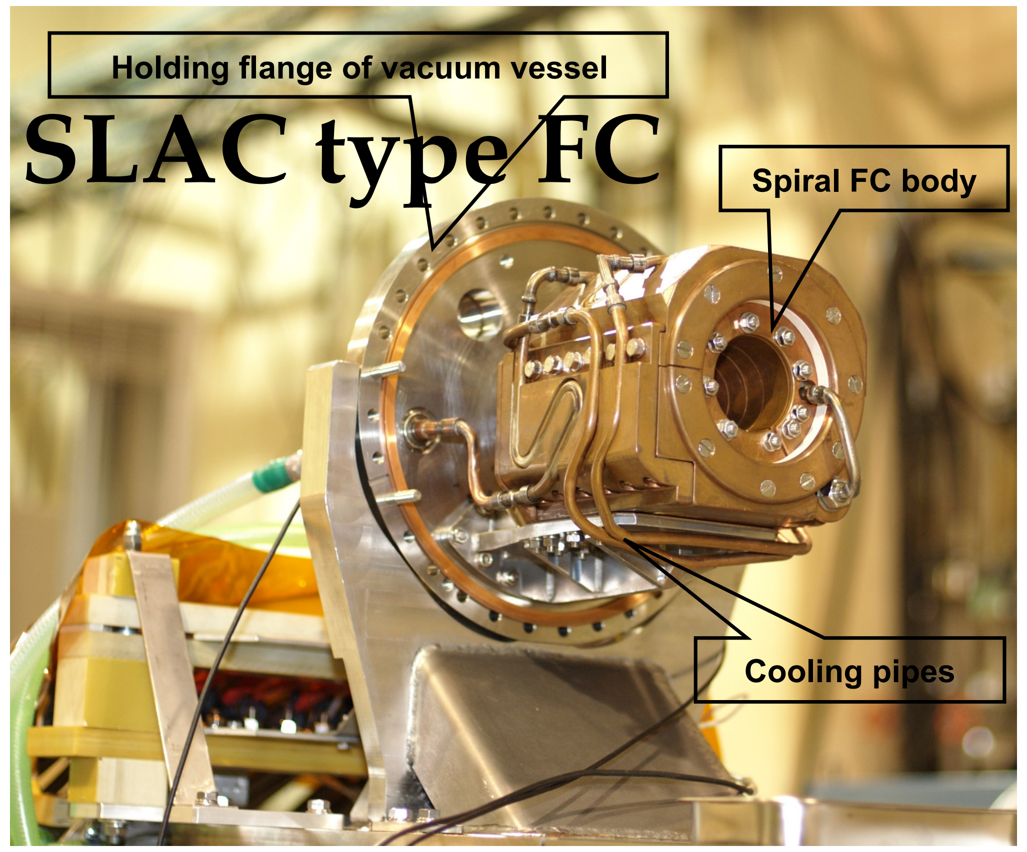
* *Polarized bremsstrahlung* for polarized low intensity sources (CEBAF/JLab based on PEPPo experiment as a demonstrator).

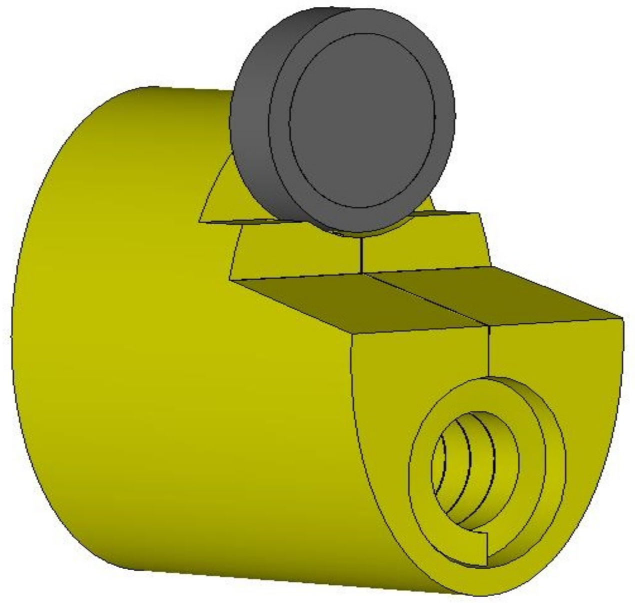
- Capture section: high-field, high-frep Flux Concentrators, SC solenoids.
- Before DR injection: optimization of the RF capture "deceleration strategy" (more efficient capture of low energy positrons which consequence is a higher e+ yield), energy compression.
- Injection in DR: stacking and cooling of e+ beam.

Positrons sources: ‘novel’ schemes

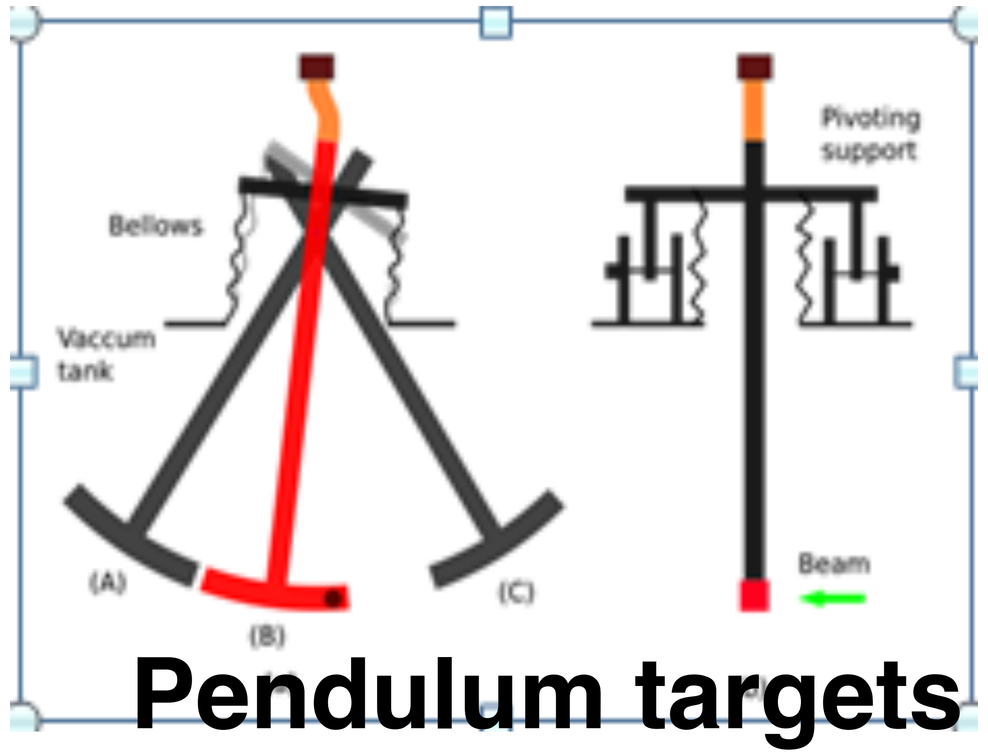
- **Target technology:** R&D on vacuum system, rotation/ oscillation speed, cooling integration, Eddy current, radiation resistance, remote handling….
- **Capture system technology:** R&D on Flux Concentrators, power sources, SC solenoid…

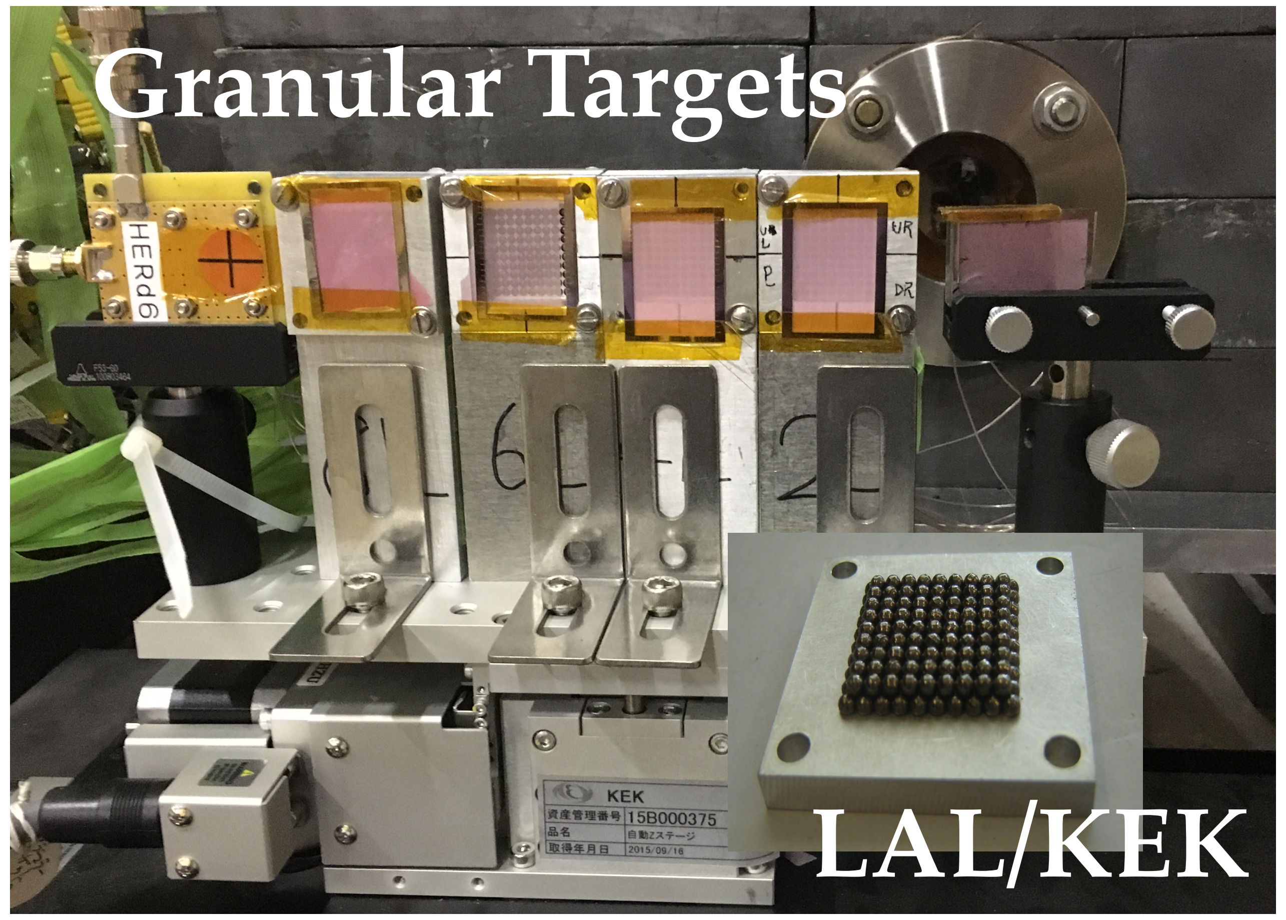






FCC-ee prototype FC

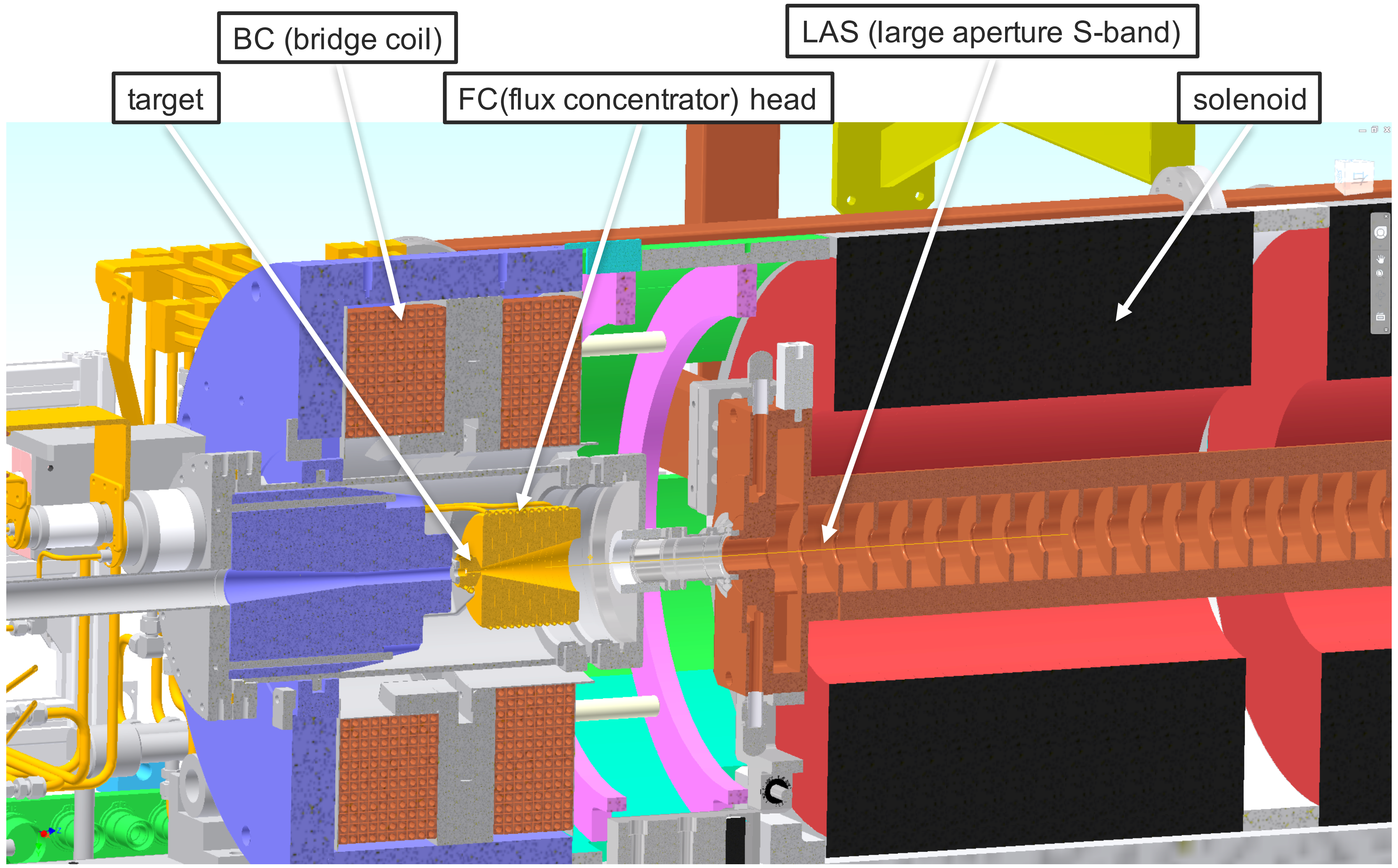


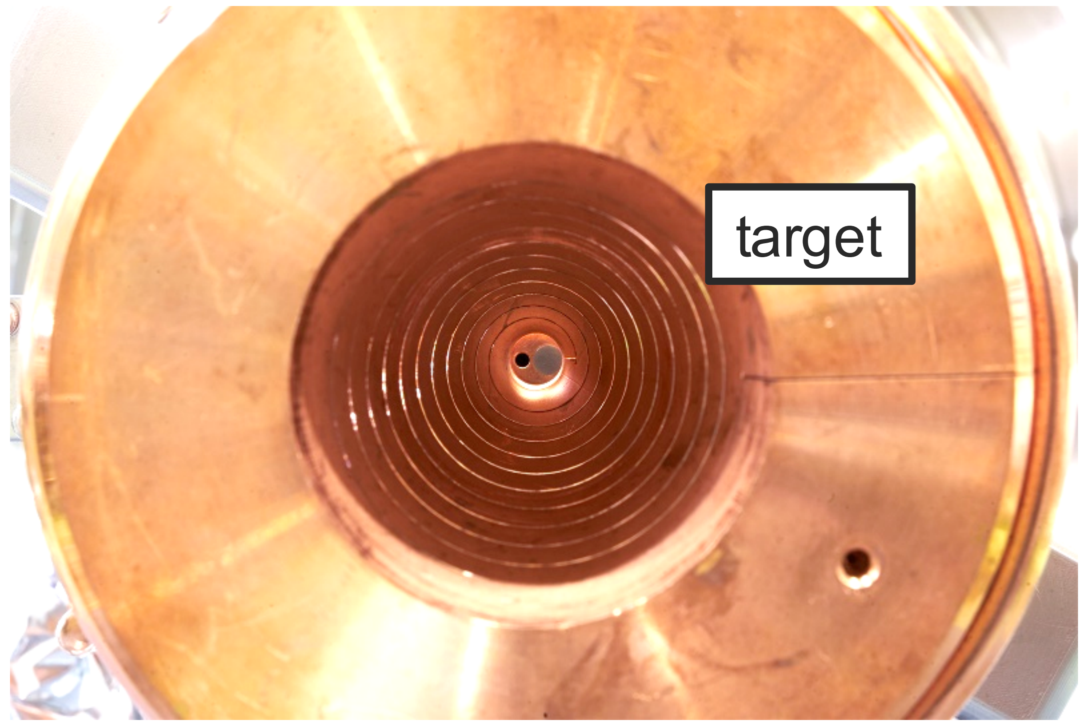


- **Novel/Exotic solutions:** micro/nano undulators, plasma undulators, crystal–assisted pair production, pair production in vacuum using high-power lasers and/or extremely short electron bunches, the gamma factory concept => **<u>will also be explored in ARIES Inno Pilot</u>**

SuperKEKB positron source

FC head + BC + target = FC assembly

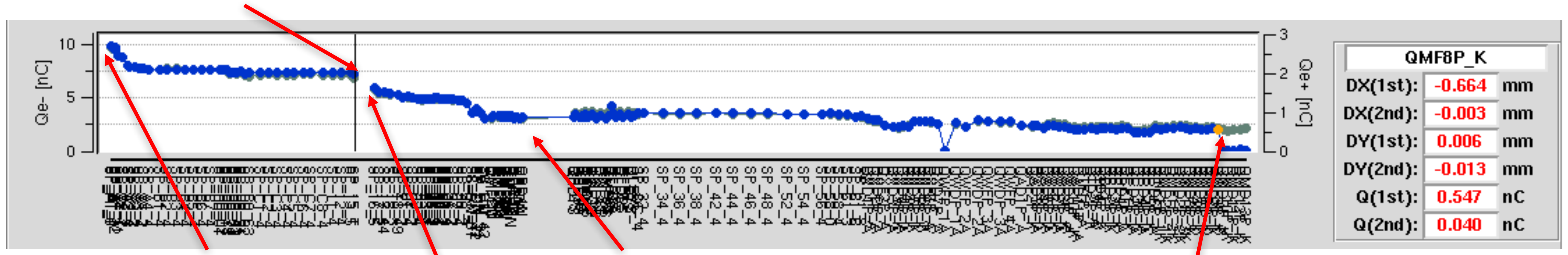




	KEKB/SKEKB
Incident e- beam energy	4.3/3.5 GeV
e-/bunch [10^{10}]	6.25/6.25
Bunch/pulse	2/2
Rep. rate	50 Hz/50 Hz
Incident Beam power	4.3 kW/3.3 kW
Target thickness	/4X_0
Target size	14 mm
Target	Fixed/Fixed
Deposited power	/0.6 kW
Capture system	/AMD
Magnetic field	/4.5T->0.4T
Linac frequency	2855.98 MHz
e+ yield @ CS exit	~0.1/~0.5 e+/e-
Energy of the DR	NO/1.1 GeV

R&D are ongoing!

Primary e- 7 nC@target

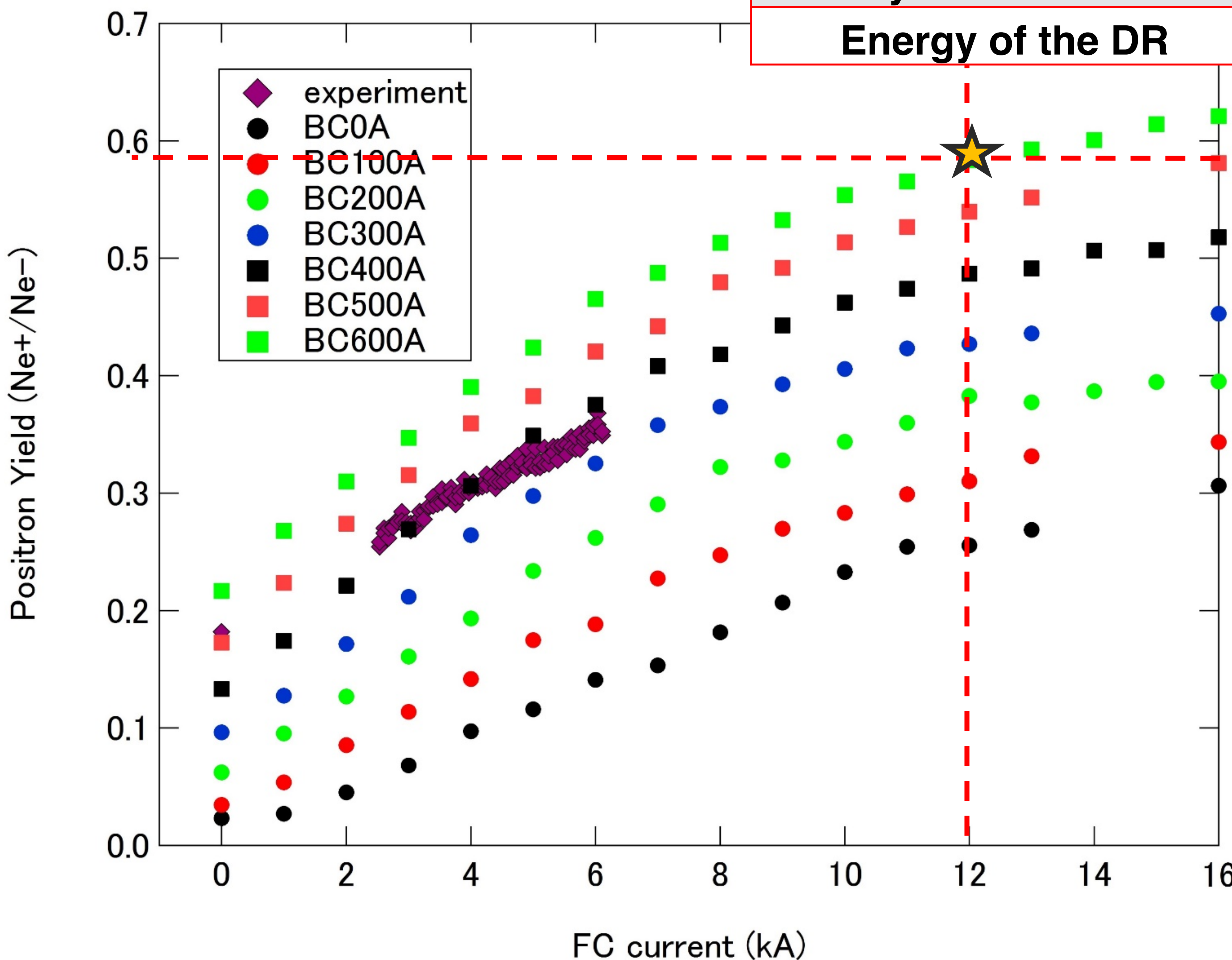


Primary e- 10 nC@e-gun

Positron 1 nC@DR

Positron 0.55 nC@BT end dump

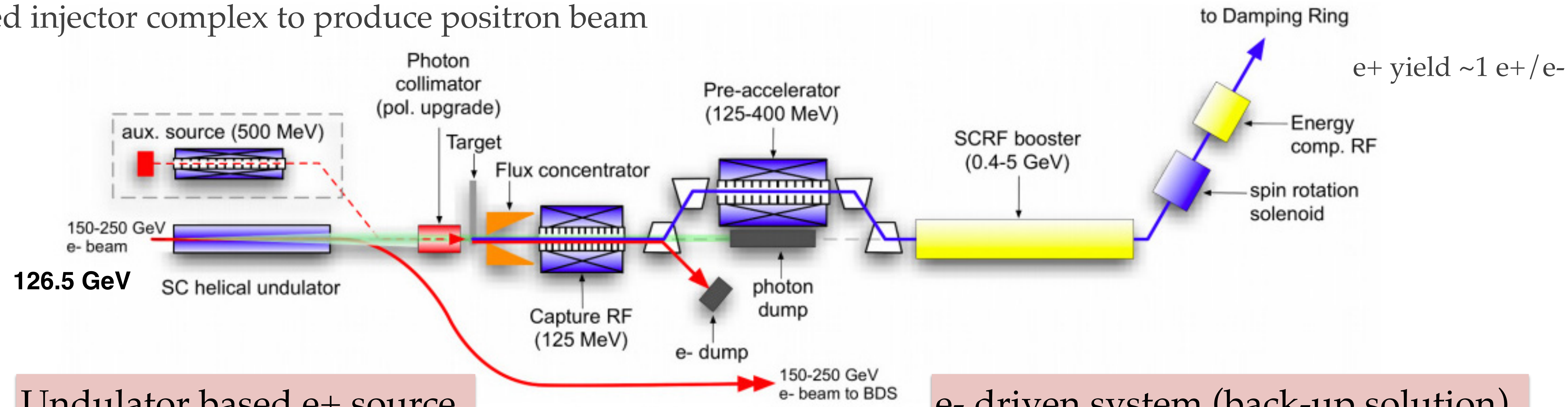
Positron 1.5 nC@first BPM



ILC Positron Source

Still a lot of R&D are needed!

Combined injector complex to produce positron beam



Undulator based e+ source

e- driven system (back-up solution)

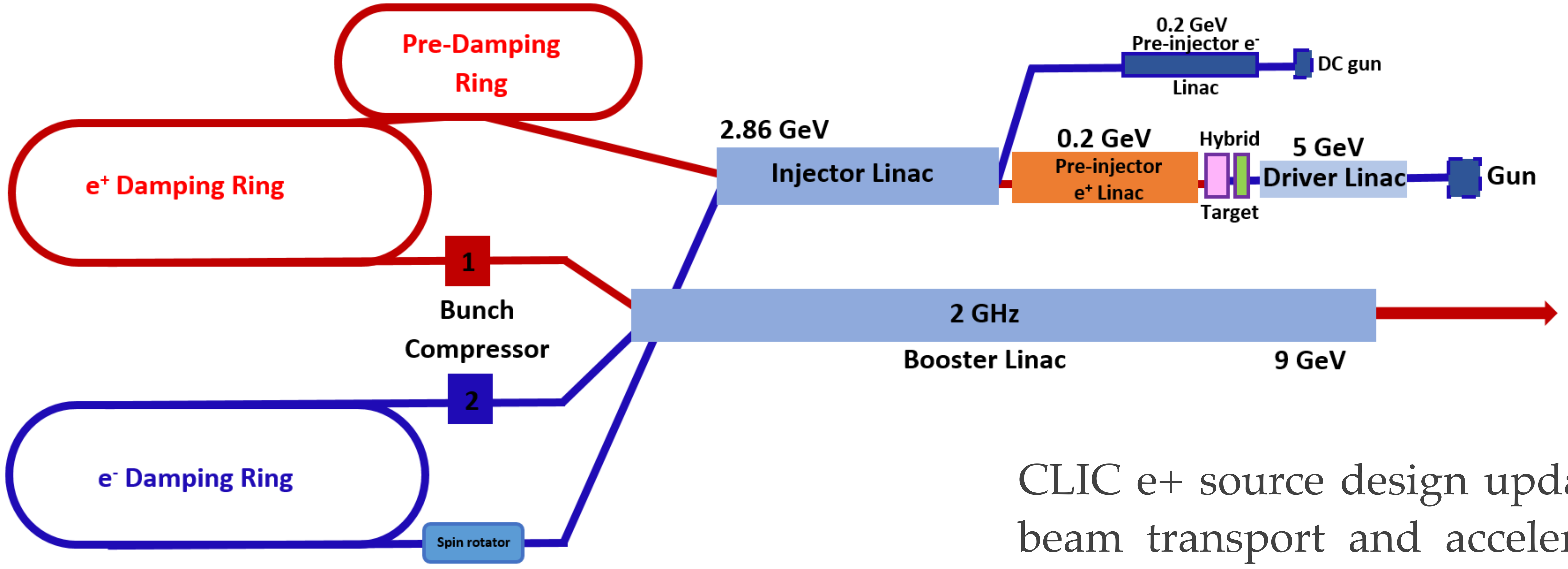
- **SC helical undulator:** 231 m active length, 11.5 mm period, with beam aperture 5.85 mm.
- **e+ target:** 400 m downstream the undulator, 0.2X0 (0.7 cm) thickness, Ti alloy wheel, Ø 1m, spinning in vacuum with 2000rpm (100m/s tang speed). Peak temp in wheel ~550˚C for ILC250, 1312 bunches/pulse (avg power dep ~ 2 kW, PEDD ~60 J/g)
- **Capture:** Flux Concentrator (or QWT) 12 cm length, Bmax = 3-5 T
- **e+ polarization:** default ~30%, polarization upgrade up to 60% with photon collimators.

- **Electron Driver:** 3 GeV beam, NC S-band TW, 3.7 nC
- **e+ target:** 4.6X0(1.6 cm) thickness, W target wheel, Ø 0.5m, spinning in vacuum with 225rpm (5 m/s tang speed). Peak temp in wheel ~550˚C for ILC250, 1312 bunches/pulse (avg power dep ~ 19 kW, PEDD ~34 J/g)
- **Capture:** Flux Concentrator 12 cm length, Bmax = 5 T
- **e+ polarization: No**

CLIC Positron Source

Still a lot of R&D are needed!

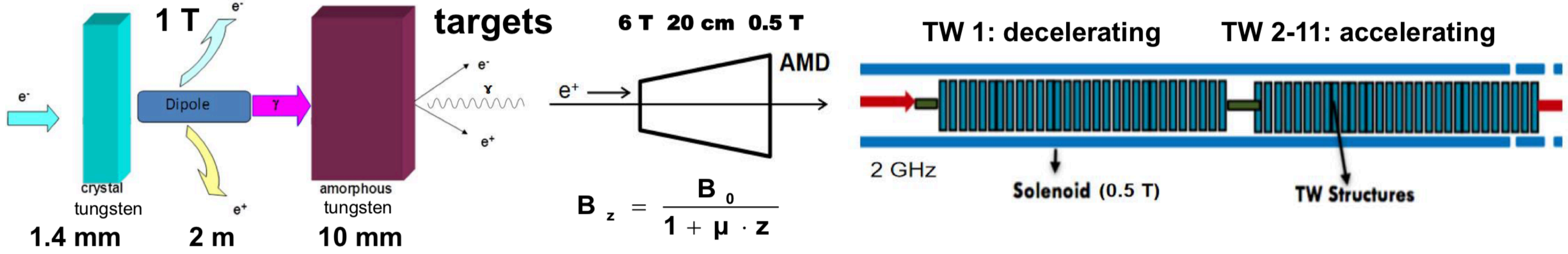
Separate injector complex to produce positron beam



- **Electron Driver:** 5 GeV beam, NC L-band TW 352 bunches/pulse, 1 nC
- **e+ target:** 1.5 mm crystal + 3.7X0 (1.3 cm) thickness, (avg power dep ~ 10 kW, PEDD ~25 J/g)
- **Capture:** Flux Concentrator Bmax = 3 T
- **e+ polarization:** No

CLIC e+ source design update (compared to CDR): target layout, new beam transport and acceleration design from the target to the pre-damping ring => final e+ yield ~1.7 e+/e-, PEDD = ~25 J/g.

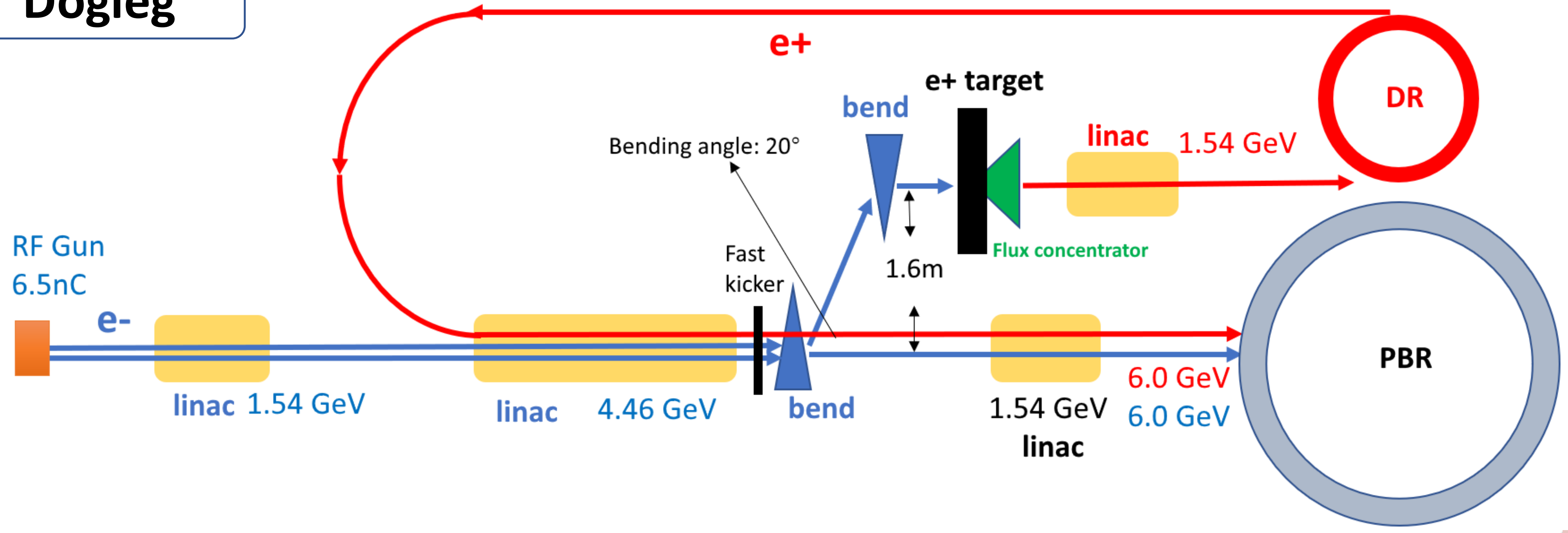
Hybrid scheme



FCC-ee positron source

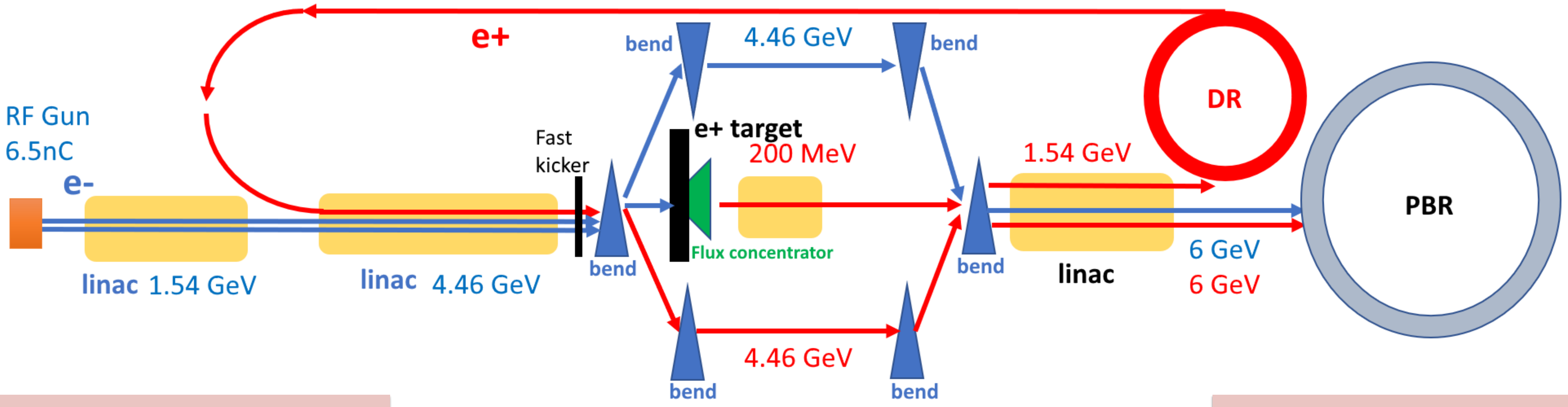
Still a lot of R&D are needed!

Dogleg



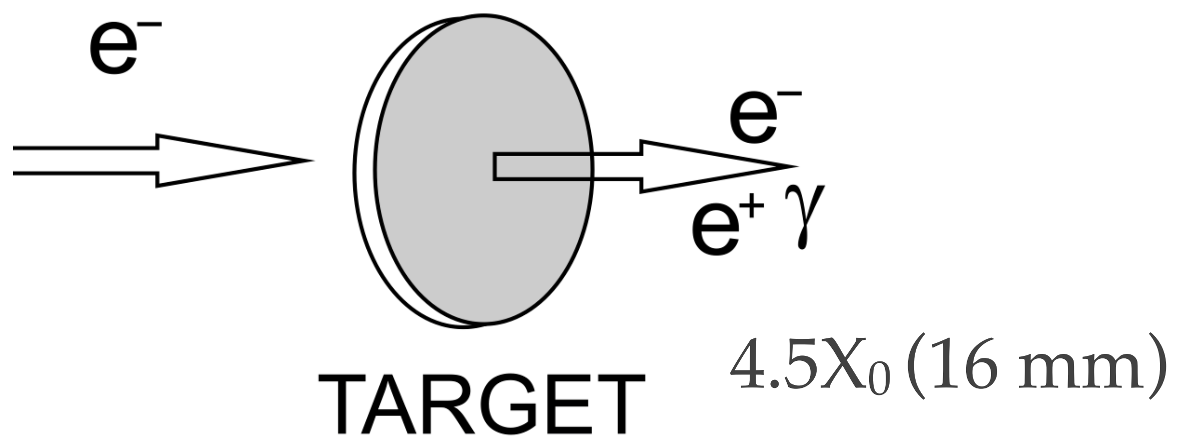
Chicane

Preliminary

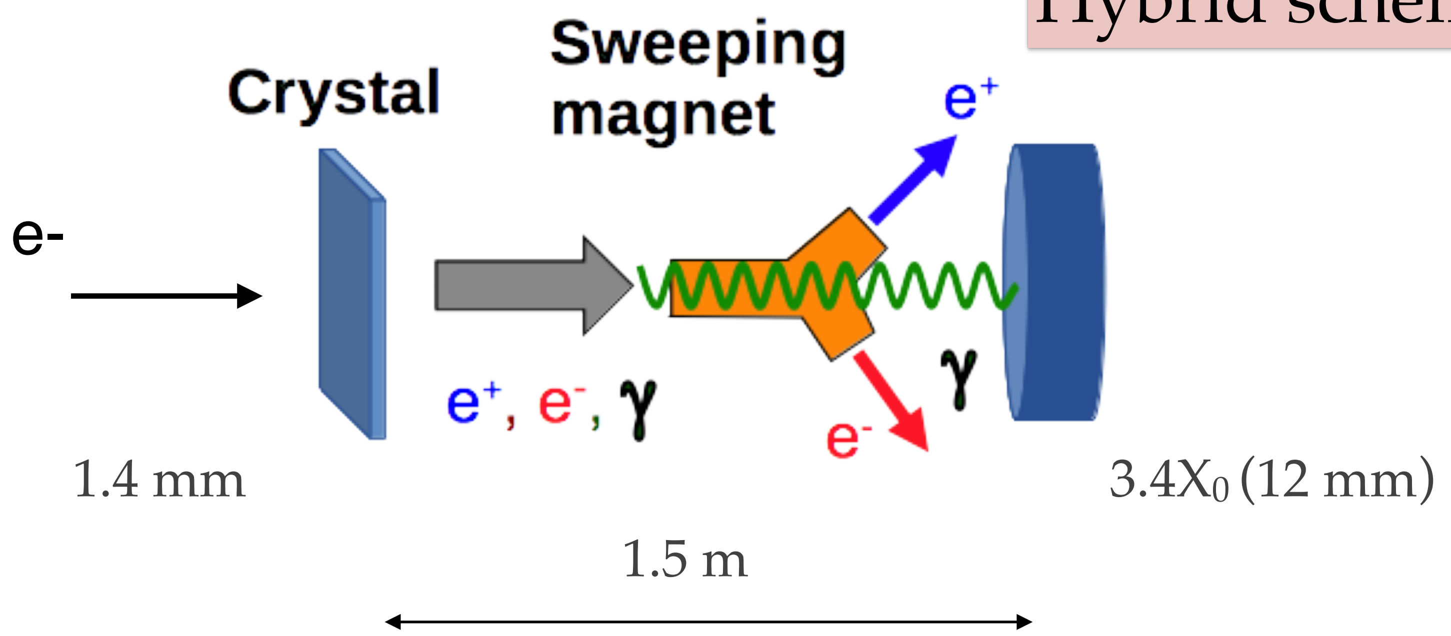


Primary e⁻ beam for e⁺ production	
Beam energy	4.46 GeV
Bunch charge	4.2×10^{10}
Bunch length (rms)	**1** mm
Bunch transv. size (rms)	**0.5** mm
Bunch separation	60 ns
Nb of bunches per pulse	2
Repetition rate	100-**200** Hz
Beam power	12 kW

Conventional scheme



Hybrid scheme



The final choice of the e+ target will be made based on the estimated performances.

*Alternative option: 20 GeV linac as the FCC-ee injector => higher energy for e+ production

The complete filling for Z running (most demanding) =>
Requirement @ DR: ~2.1×10^{10} e^+/bunch (4.3 nC)
~0.5 e+/e- without safety factor

LEMMA: positrons for muons

A lot of R&D are needed!

☞ Positron-driven scheme: Low EMittance Muon Accelerator (LEMMA)

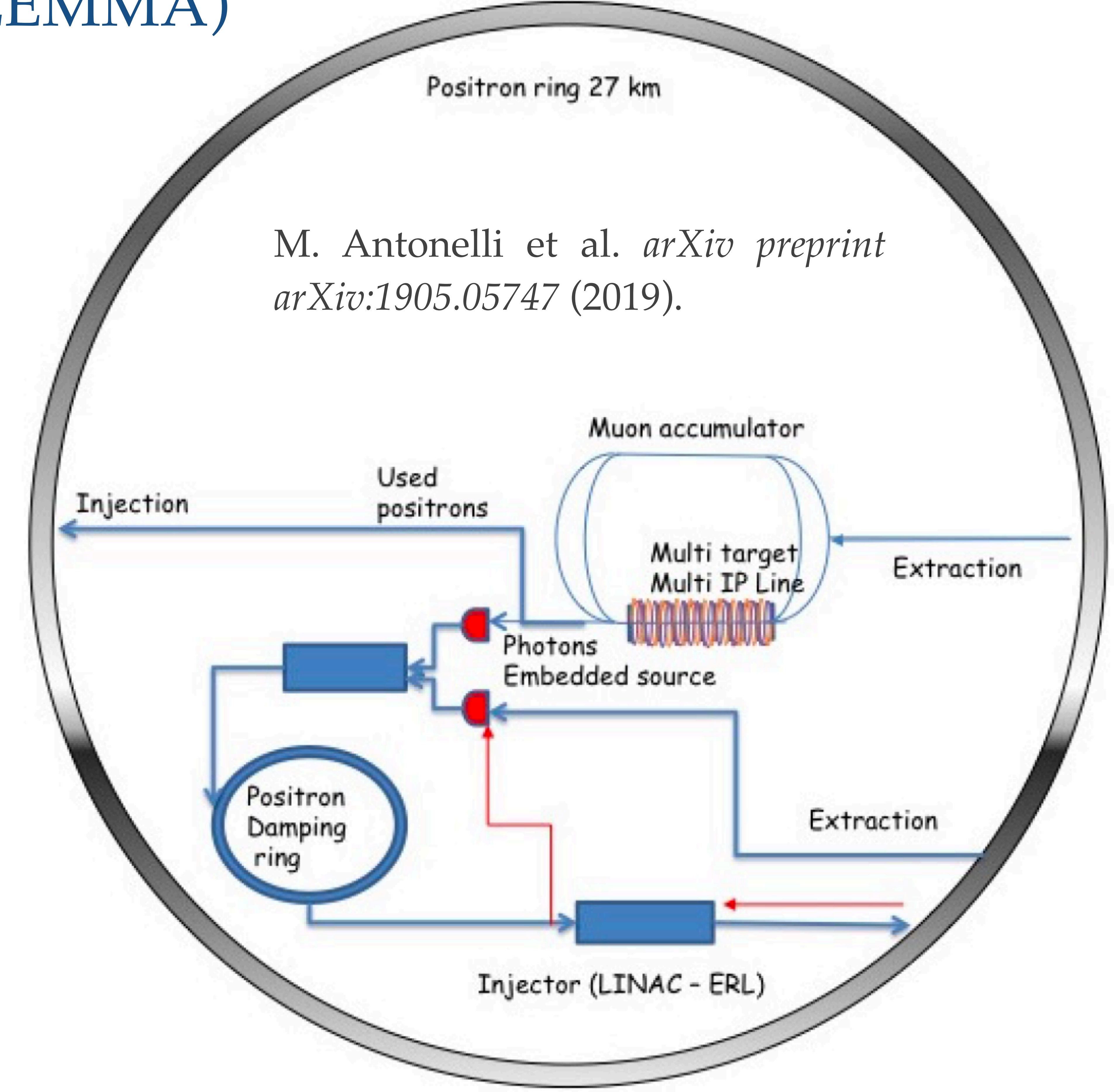
Goal: low emittance muon beams from direct pair production. $e^+e^- \rightarrow \mu^+\mu^-$ Max efficiency $\sim 10^{-5}$.

Muons produced at $\sqrt{s}$ around the $\mu^+\mu^-$ threshold ($\sqrt{s} \approx 0.212$GeV) in asymmetric collisions (corresponds to about 45 GeV e+ beam interacting with target).

Initial injection: the e+ source has to provide trains of 1000 bunches with **5×10^{11} e+/bunch** to inject in the DR at 5 GeV.

But the e+ source needed to replace the e+ lost in the muon production process is a real challenge (very short time available ~ 50 ms).

=> Flux of **10^{15} - 10^{16} e+/s** is needed (experience from ILC/CLIC + R&D program on new targets).

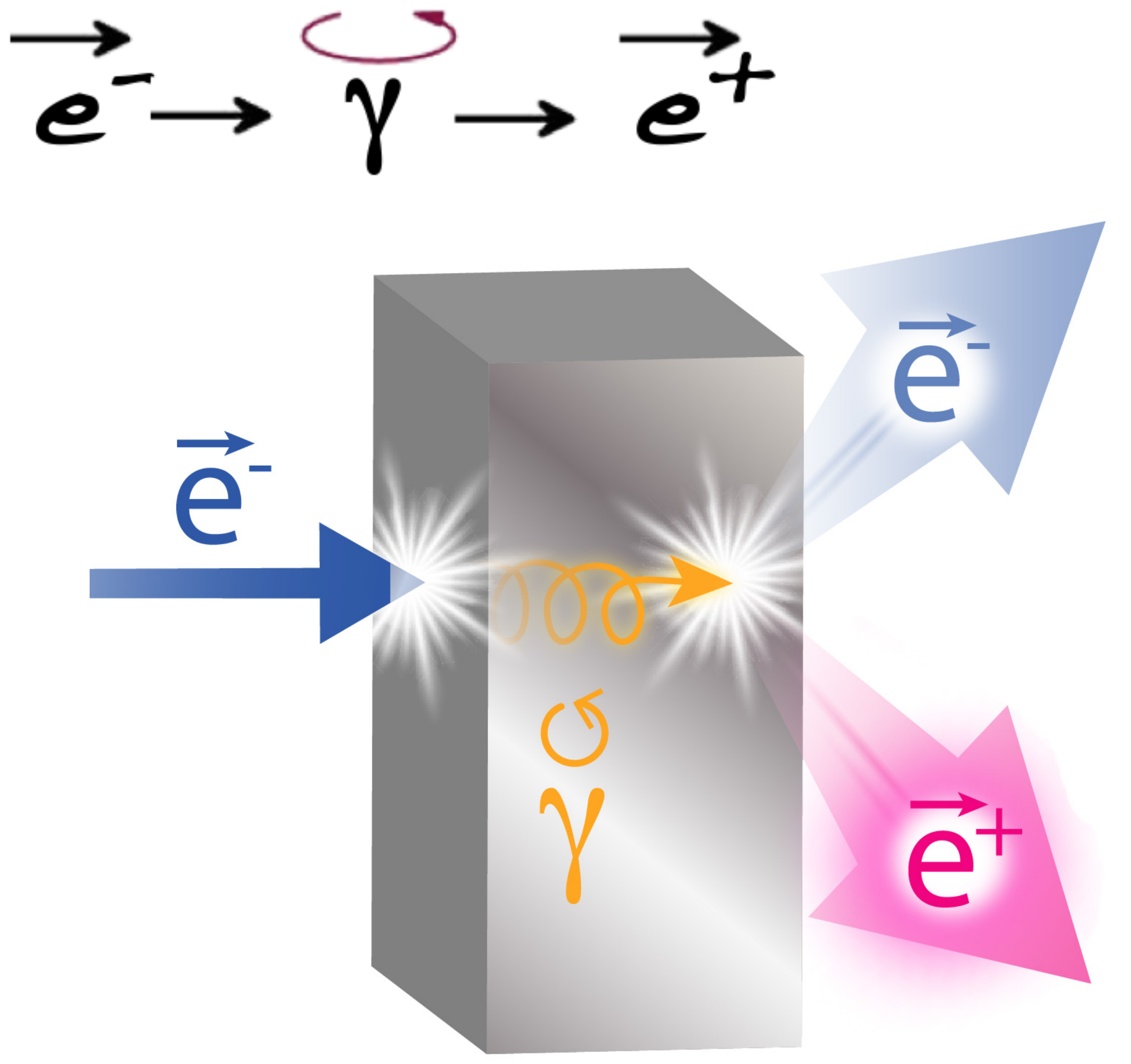


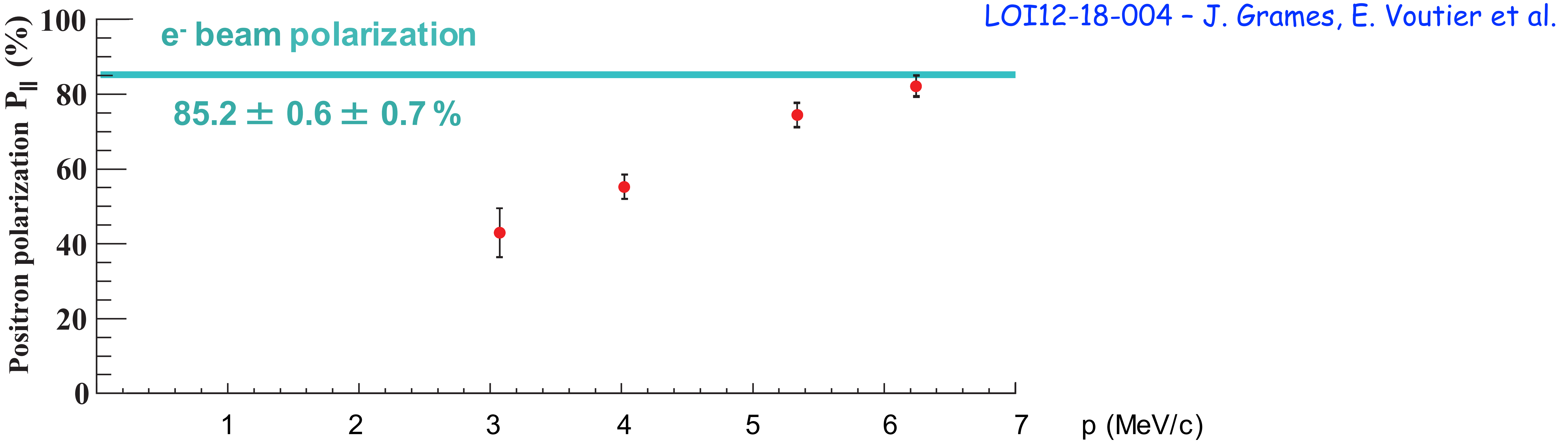
M. Antonelli et al. *arXiv preprint arXiv:1905.05747* (2019).

Strategy to be also explored in ARIES Inno Pilot

PEPPo (Polarized Electrons for Polarized Positrons)

Design/construction of the **CW polarised e+ source** for **CEBAF**.





Principle: **polarisation transfer from** the low energy **electron beam** (~**10 MeV/c**) to the secondary **positron beam** produced by polarized bremsstrahlung in the high Z target.

Goals: the PEPPo source is the conventional e+ source where the e+ energy selection is applied

I(e+) vary **50 nA - 1 μA** depending on polarization $P_{e+} > 40\%$

Challenges: high-power targets (10 kW); SC capture system and reduction of the e+ beam emittance.

Advantages: radioactively proper source, reasonable cost.

Applications: CEBAF, EIC…

Summary: current/future R&D

- **Positron sources are a key element of past, present and future colliders.**
- **Extensive R&D, studies and tests** are ongoing, **more are needed** => **drastic reduction of the manpower over the last years** => collaborations between many laboratories all around the world +resources are needed.
- **Experimental tests are mandatory** => SuperKEKB, PSI
- Today, all studies are mainly focused on **simulations** (start-to-end e+ yield optimization, target heat&stress), **engineering design, manufacture and testing** (vacuum, irradiation) **of the prototypes** for the high intensity e+ source (mainly in the framework of SuperKEKB and ILC).
- Some of the future R&D:
  - new schemes for e+ sources (polarized and unpolarized)
  - target system (granular, pendulum, rotating wheel, vacuum transition…)
  - warm and cold capture systems (AMD and solenoid fields, SC solenoid, immersed targets), RF capture
  - laser and optical cavities for Compton scheme and undulators
  - remote handling/target replacement system…