

Positron Source Performances

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.

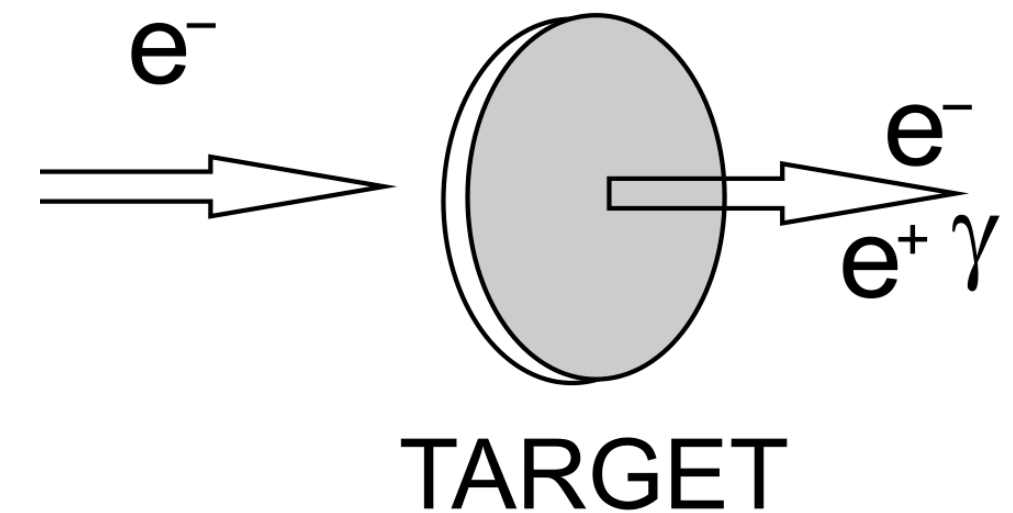
Why e^+ sources are critical components of the FC

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

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).

- **Current** => 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.
- **Emittance** => at the production 6D phase space is very large
 - After defined by the e^+ capture system acceptance.

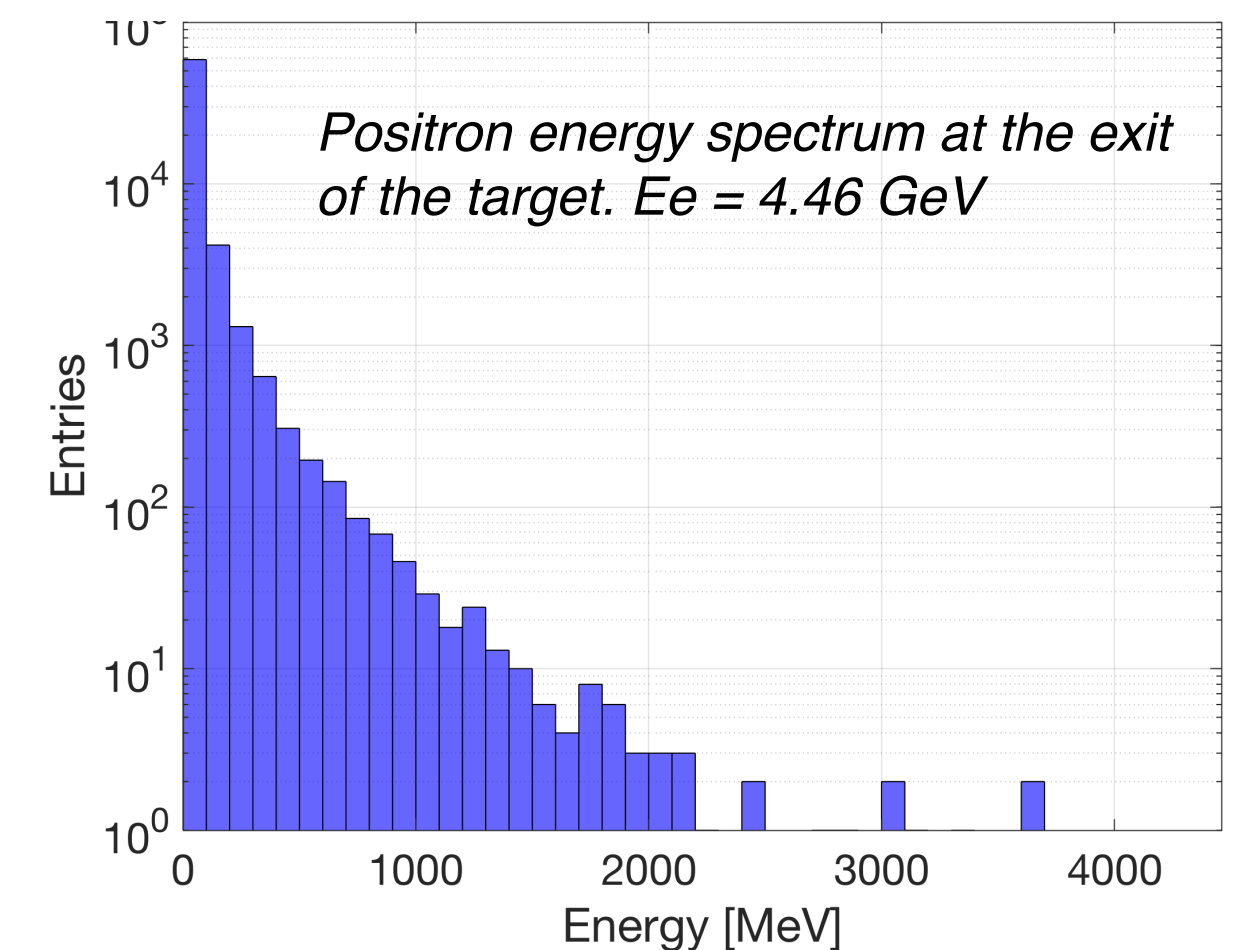
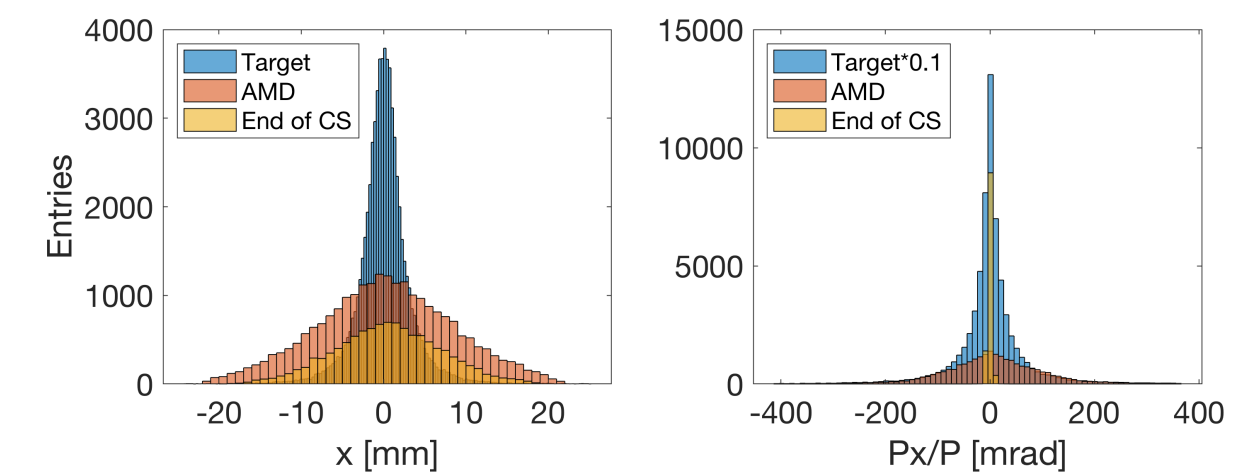
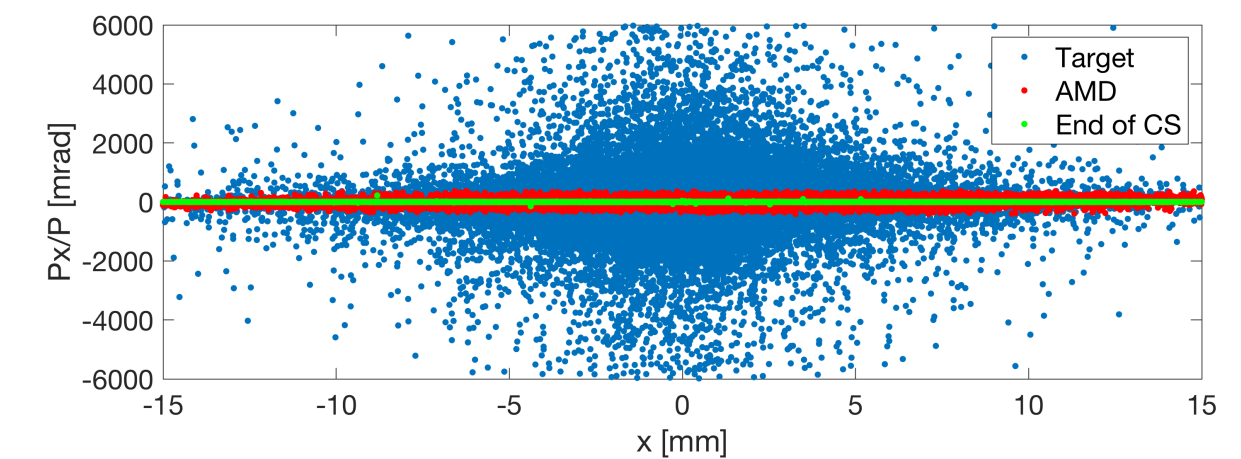


e^+ source fixes the constraints for the peak and average current, the emittance, the damping time, the repetition frequency => **Luminosity!**

What are the main challenges

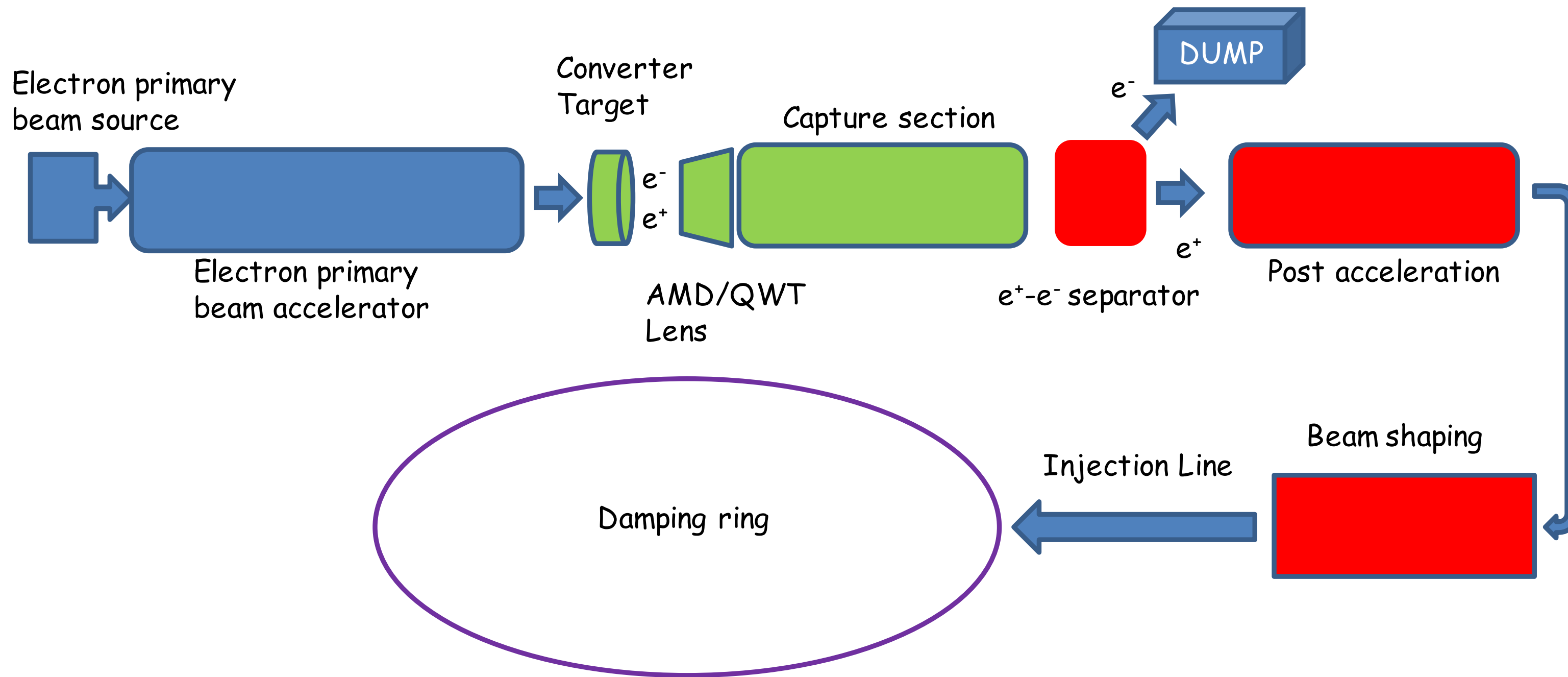
- **High intensity** => 1) number of e^+/e^- pairs: higher primary beam energy and intensity, rather thick targets-converter or photon radiators (channeling, undulators) + 2) capture system (B field and RF sections)
- **Emittances** => weak multiple scattering => towards thin targets and small beam sizes 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



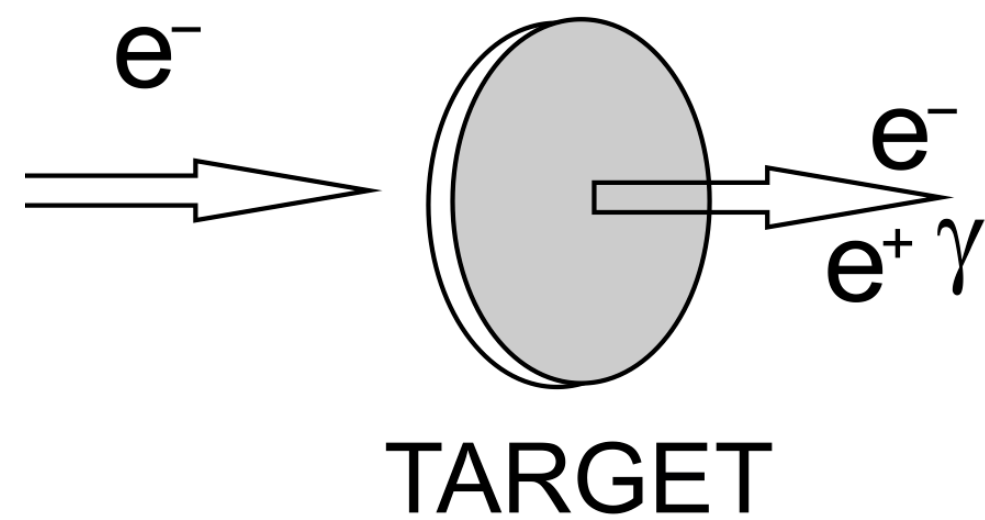
Accepted e^+ flux is a function of target + capture system + primary beam characteristics!

Positrons sources: classical scheme



High production e^+ divergence \Rightarrow 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: $\sim 0.08e14$ 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}

A. Variola, Nucl. Instrum. Methods A 740, Supplement C (2014): 21-26

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 (e+)	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	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 stacking top-up injection.
- *Muon colliders (LEMMA)*: $\sim 1e16$ e+ /s to be defined based on the adopted baseline.

Positrons sources: ‘novel’ schemes

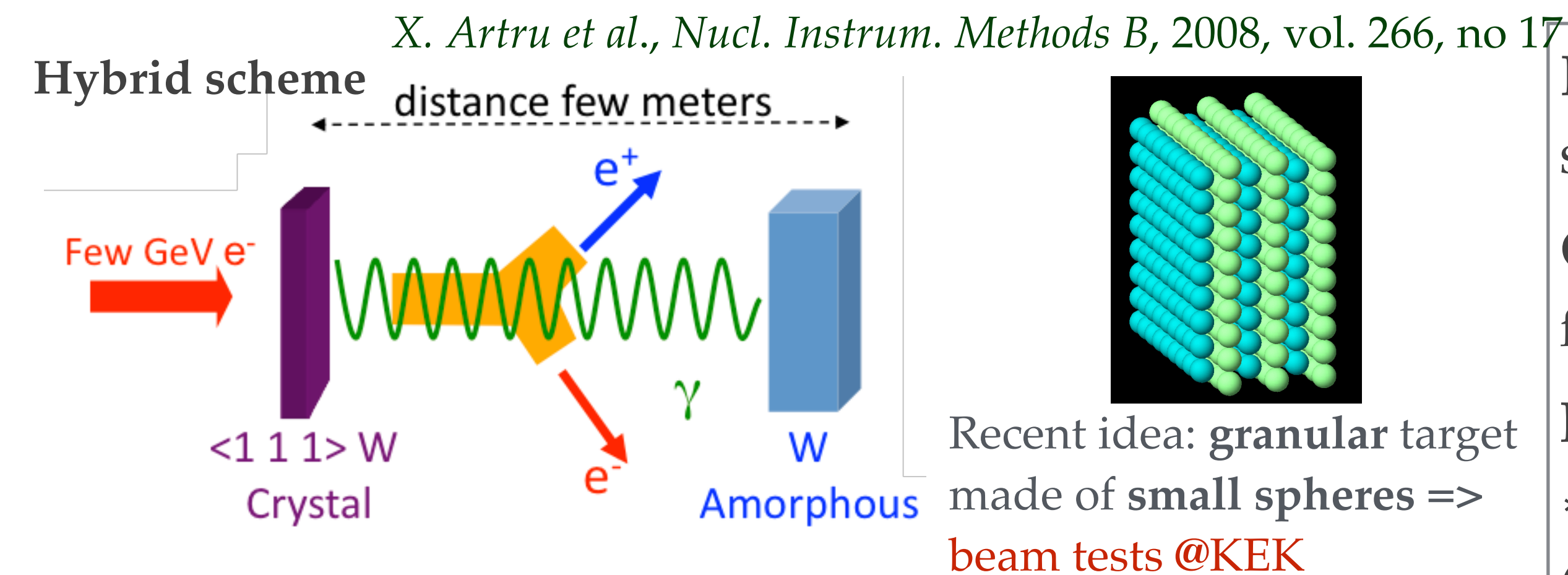
- Target PEDD and average heating: separate the photon production and the pair conversion

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**



ILC => Undulator scheme (alternative conventional scheme as a back-up solution)

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

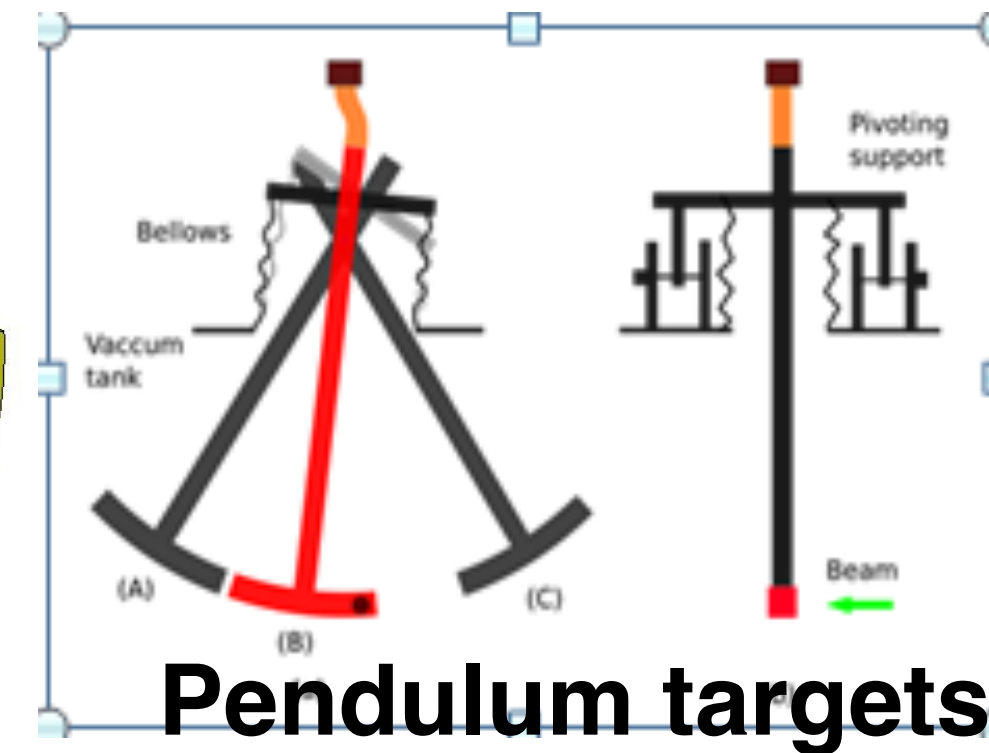
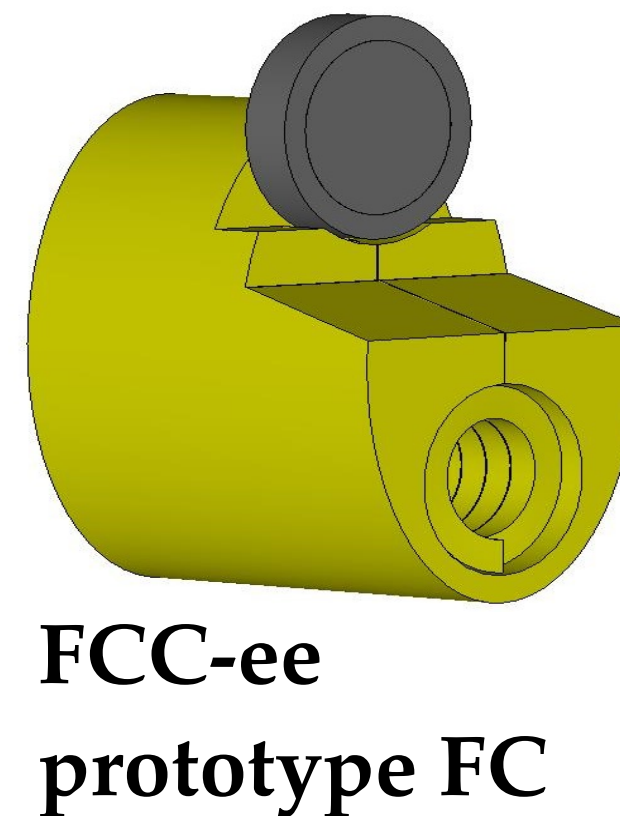
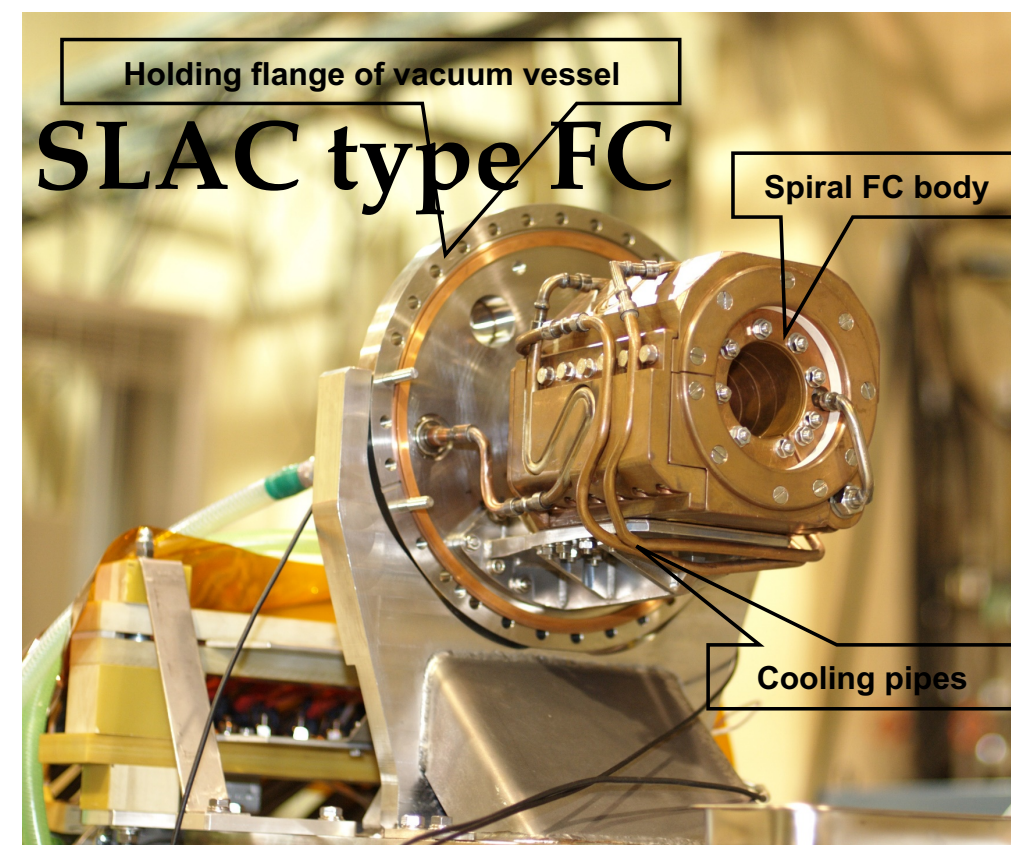
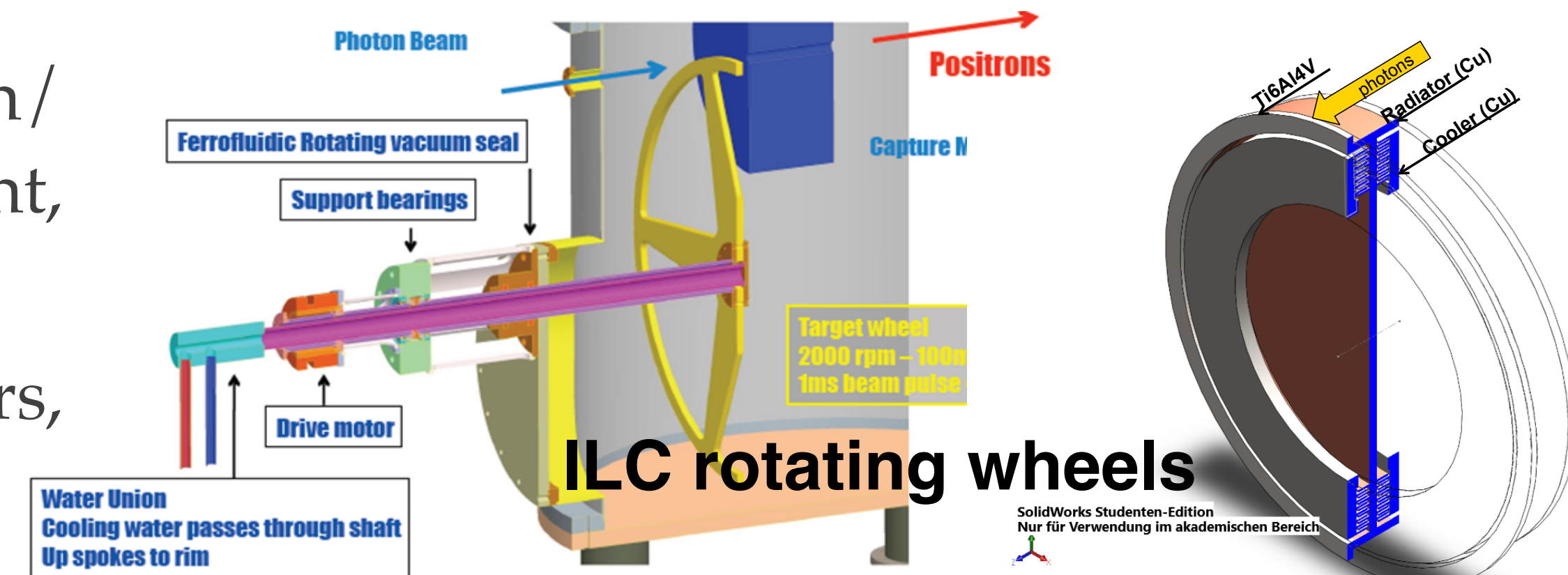
FCC-ee => Hybrid or conventional scheme

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

- Capture section: high-field, high-freq 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, DR design.

Positrons sources: 'novel' schemes

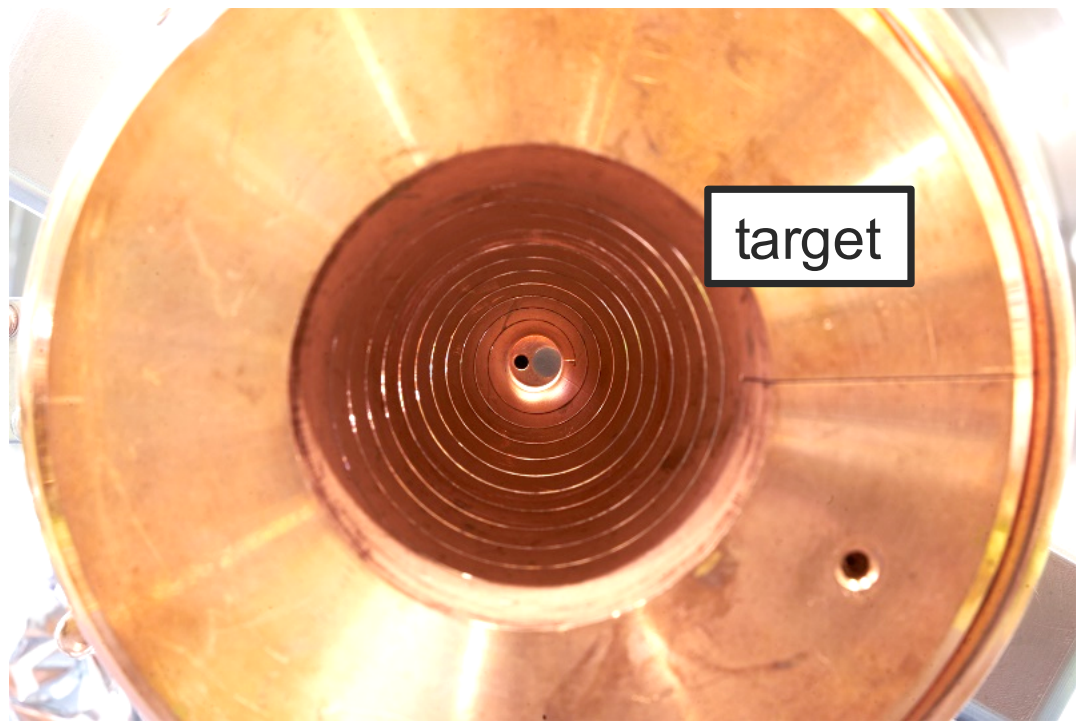
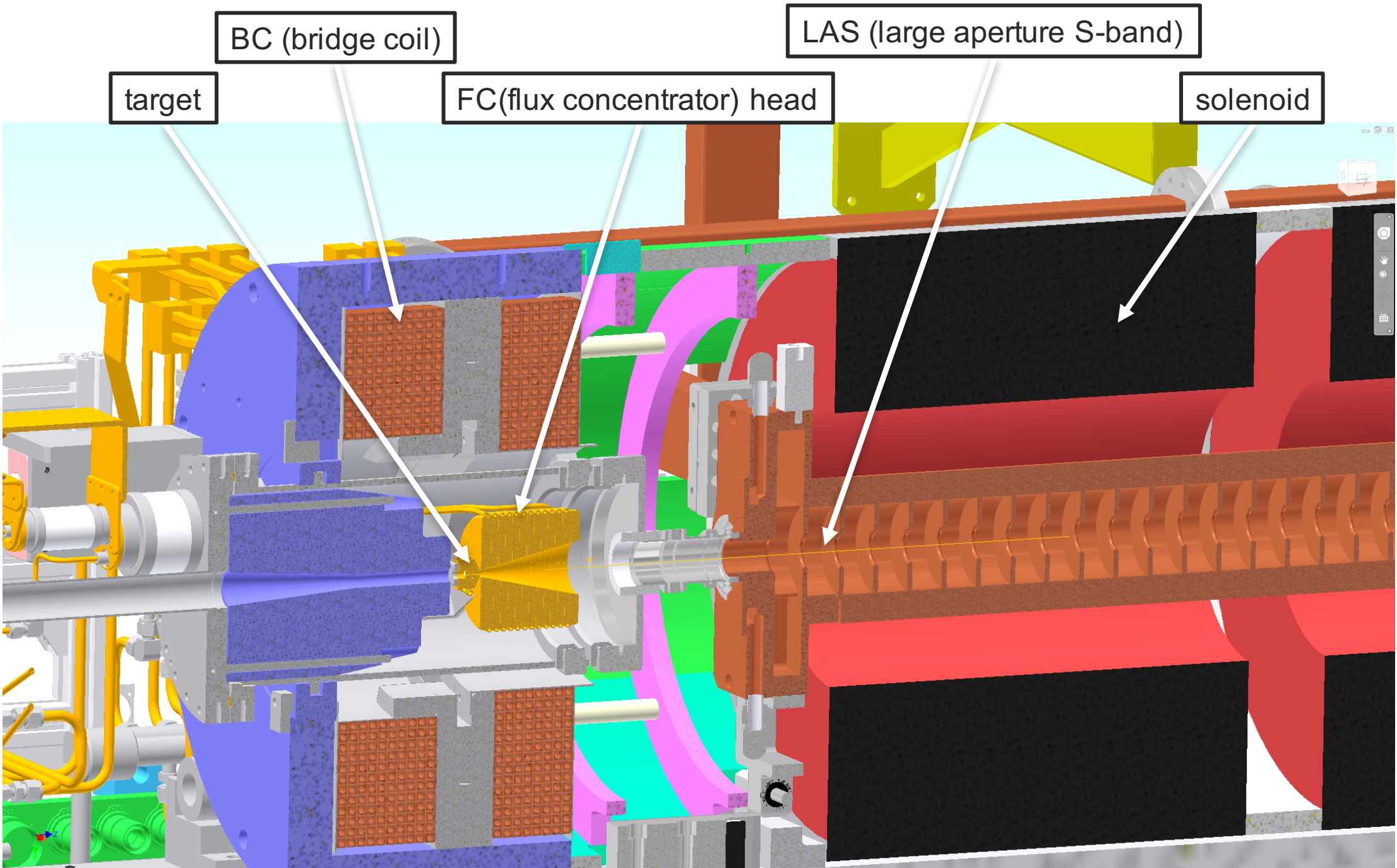
- **Target technology:** R&D on vacuum system, rotation/oscillation speed, cooling integration, Eddy current, radiation resistance, remote handling....
- **Capture system technology:** R&D on Flux Concentrators, power sources, SC solenoid...



- **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 => will also be explored in ARIES Inno Pilot/IFAST

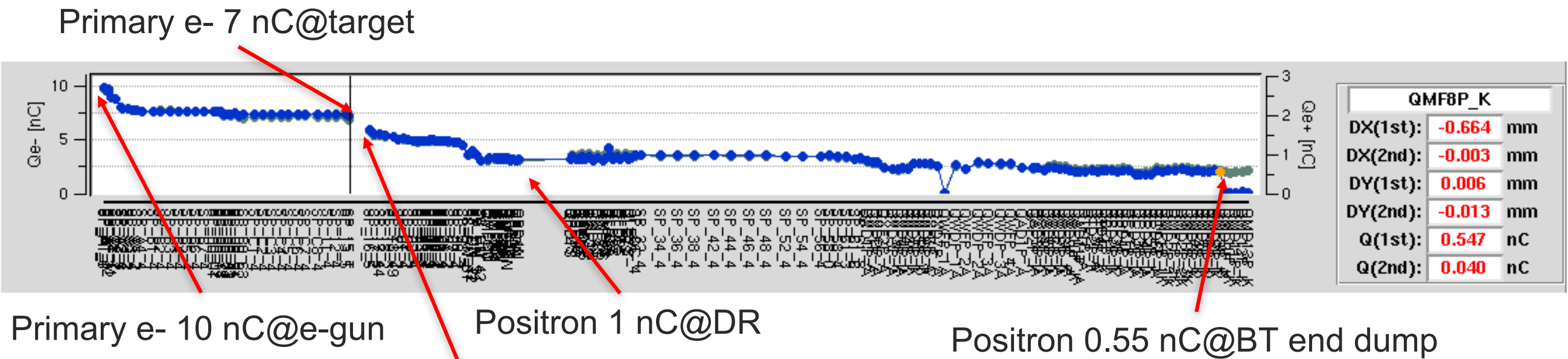
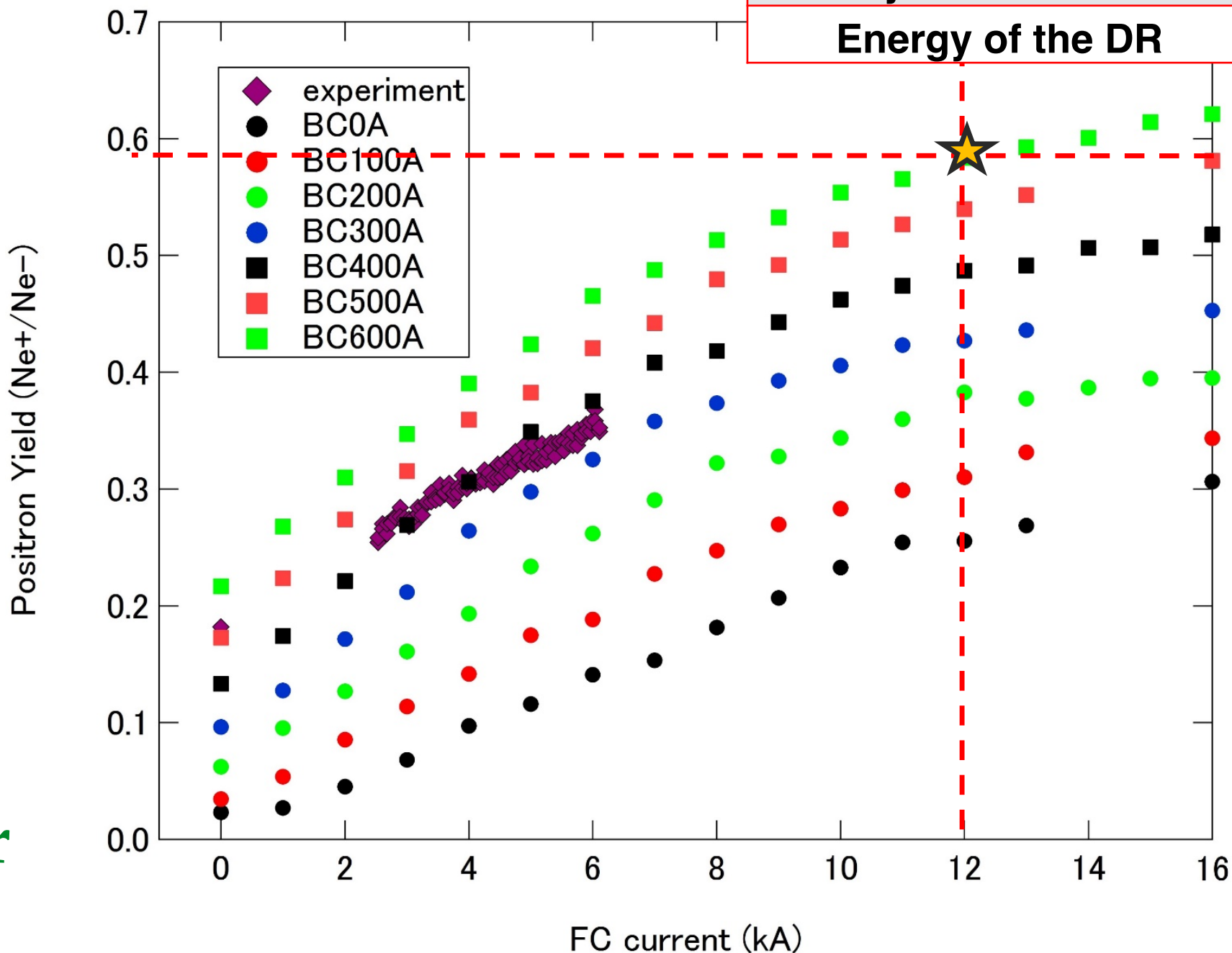
SuperKEKB positron source

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

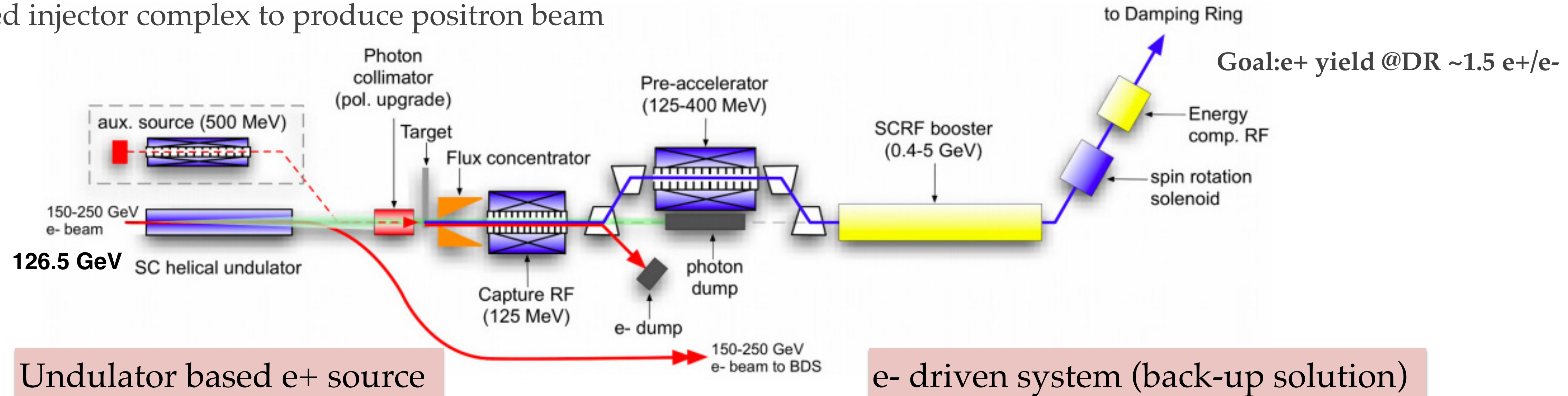
R&D are ongoing!



ILC Positron Source

Still a lot of R&D are needed!

Combined injector complex to produce positron beam



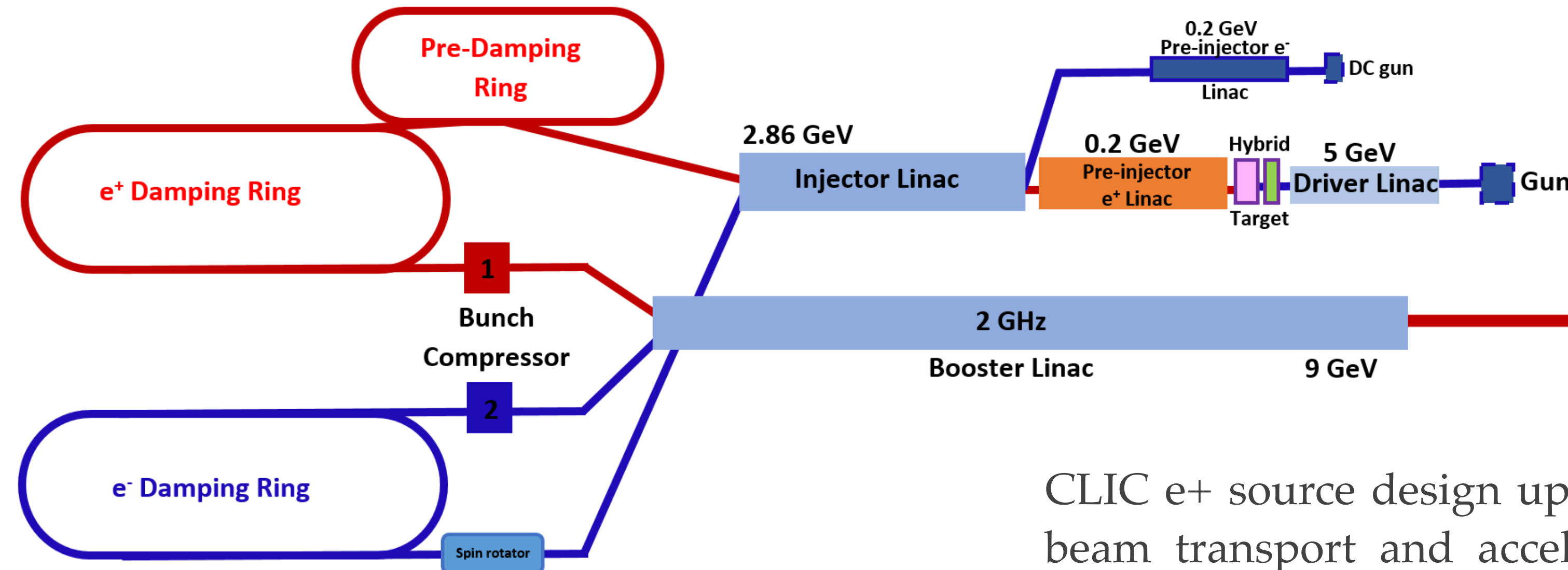
- **SC helical undulator:** 231 m active length, 11.5 mm period, with beam aperture 5.85 mm.
- **e^+ target:** 400 m downstream the undulator, 0.2X0 (0.7 cm) thickness, Ti alloy wheel, \varnothing 1m, spinning in vacuum with 2000rpm (100m/s tang speed). Peak temp in wheel $\sim 550^\circ\text{C}$ for ILC250, 1312 bunches/pulse (avg power dep ~ 2 kW, PEDD ~ 60 J/g)
- **Capture:** Flux Concentrator (or QWT) 12 cm length, $B_{\text{max}} = 3\text{-}5$ T
- **e^+ polarization:** default $\sim 30\%$, 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, \varnothing 0.5m, spinning in vacuum with 225rpm (5 m/s tang speed). Peak temp in wheel $\sim 550^\circ\text{C}$ for ILC250, 1312 bunches/pulse (avg power dep ~ 19 kW, PEDD ~ 34 J/g)
- **Capture:** Flux Concentrator 12 cm length, $B_{\text{max}} = 5$ T
- **e^+ polarization:** No

CLIC Positron Source

Still a lot of R&D are needed!

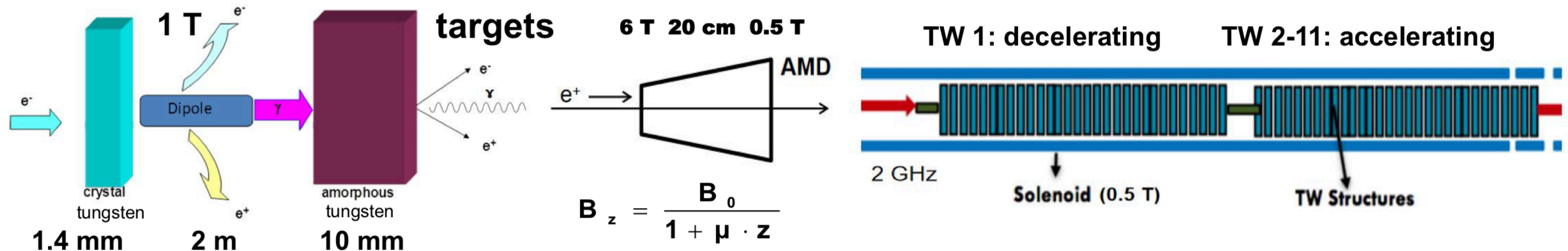
Separate injector complex to produce positron beam



- **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.

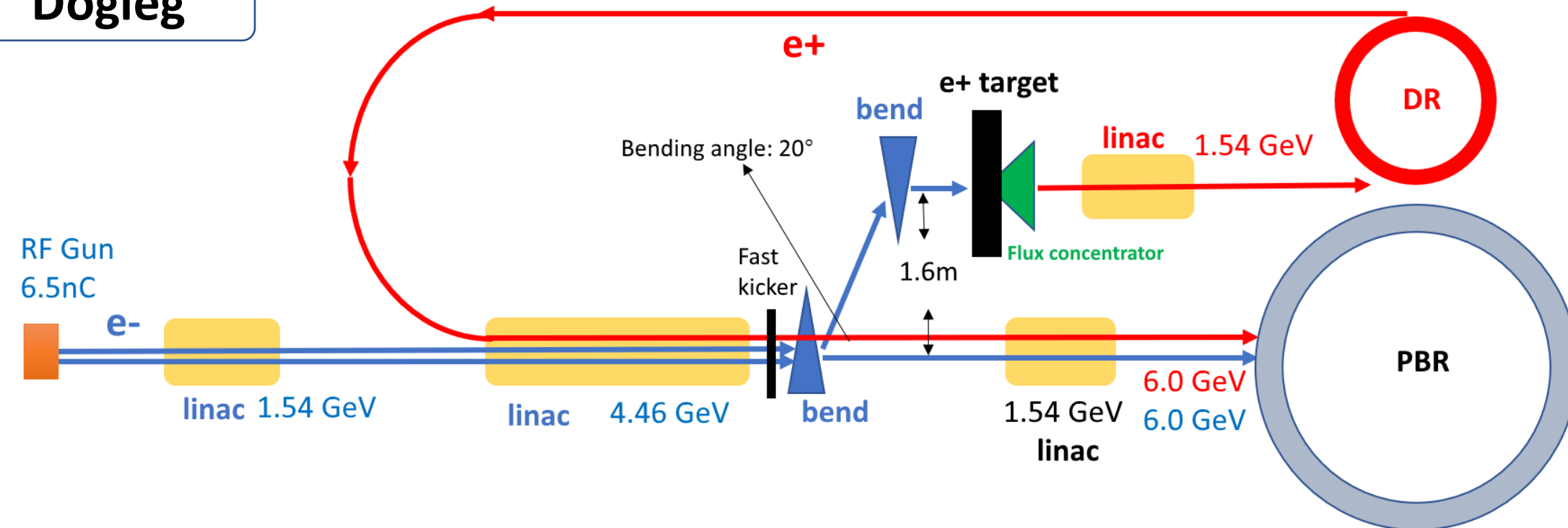
Hybrid scheme in CDR



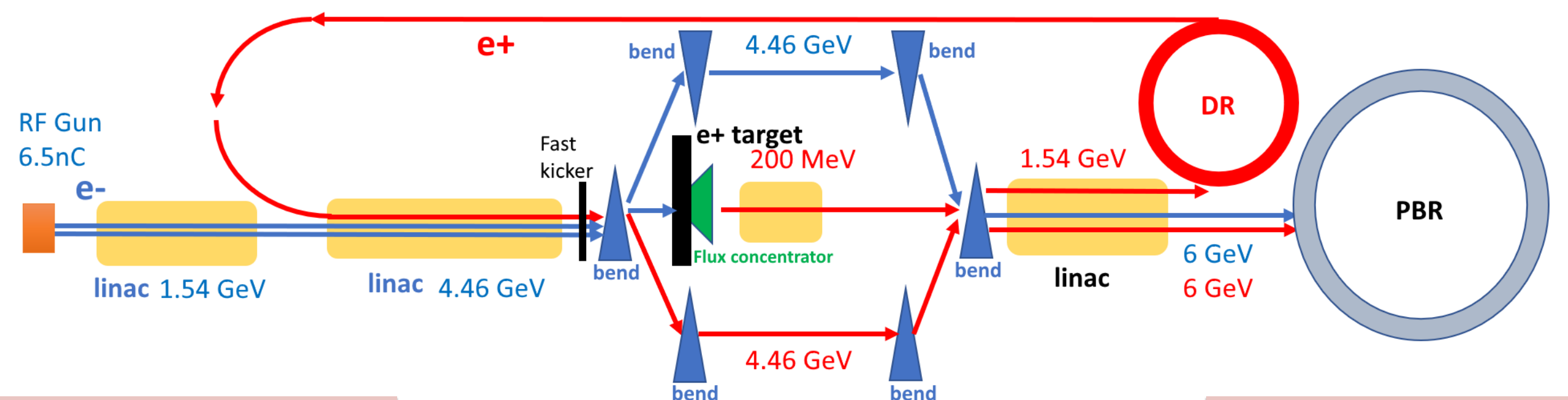
FCC-ee positron source

Still a lot of R&D are needed!
Preliminary

Dogleg

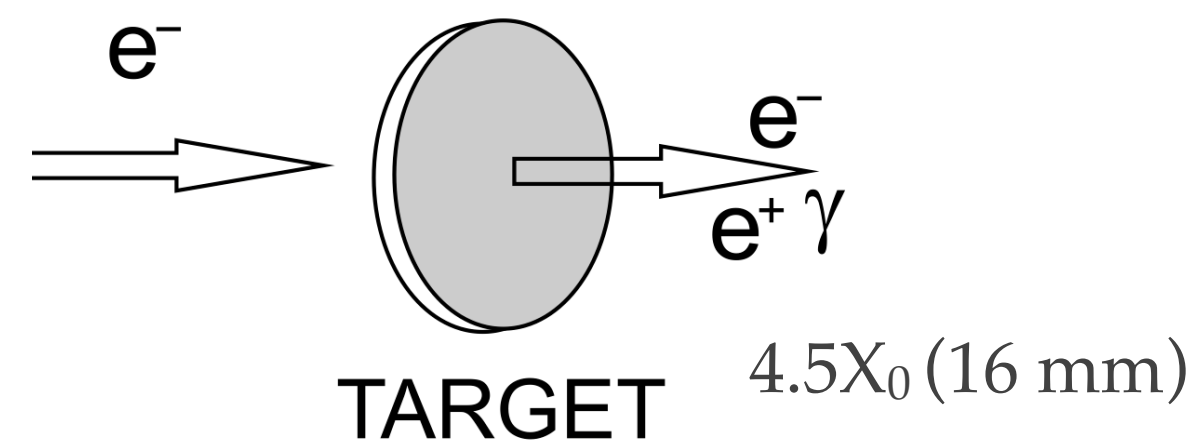


Chicane

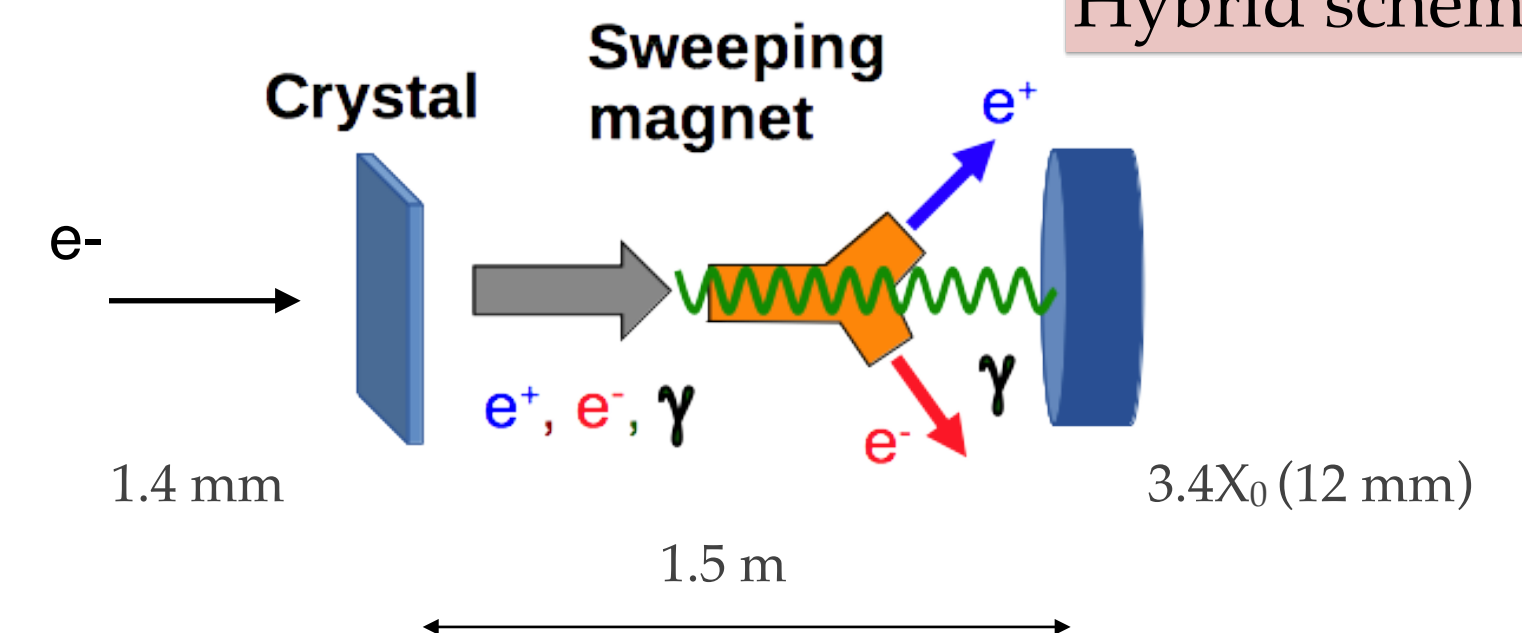


Primary e- beam for e+ production	
Beam energy	4.46 GeV
Bunch charge	4.2×10^{10}
Bunch length (rms)	1 mm
Bunch transv. size (rms)	0.5 mm
Bunch separation	60 ns
Nb of bunches per pulse	2
Repetition rate	100-200 Hz
Beam power	12 kW

Conventional scheme



Hybrid scheme



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

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

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

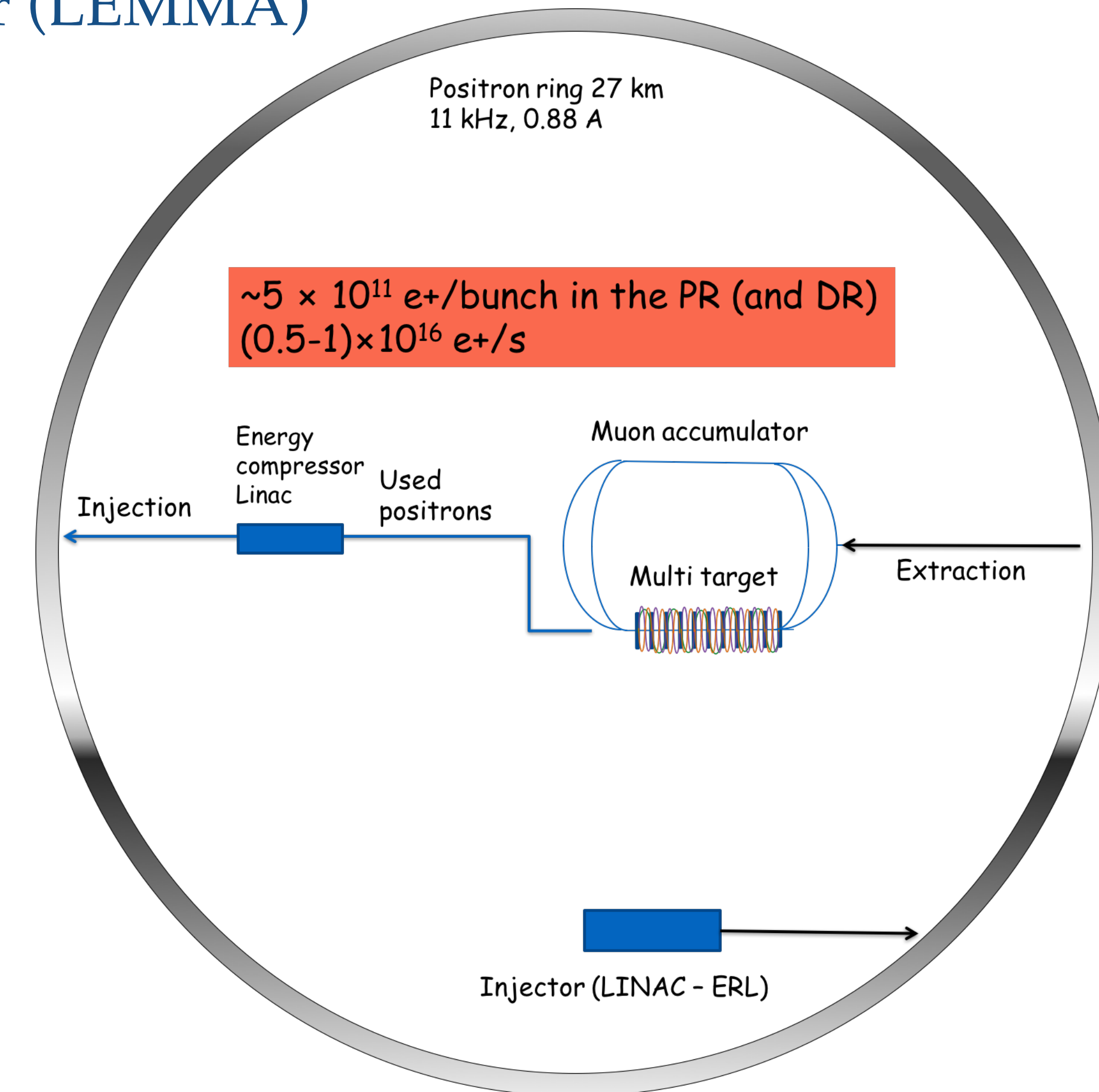
LEMMA: positrons for muons

☞ 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 ($\sqrt{s} \approx 0.212\text{GeV}$) in asymmetric collisions (corresponds to about 45 GeV e^+ beam interacting with target).

*D. Alesini et al. "Positron driven muon source for a muon collider."
arXiv preprint arXiv:1905.05747 (2019).*



LEMMMA: positron source requirements

A lot of R&D are needed!

Based on the present schemes

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

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).

☞ A positron recovery system based on the use of positrons (or photons produced in the muon targets) to compensate the positron losses in the main ring is under study. This system can be eventually integrated in the main positron injector complex.

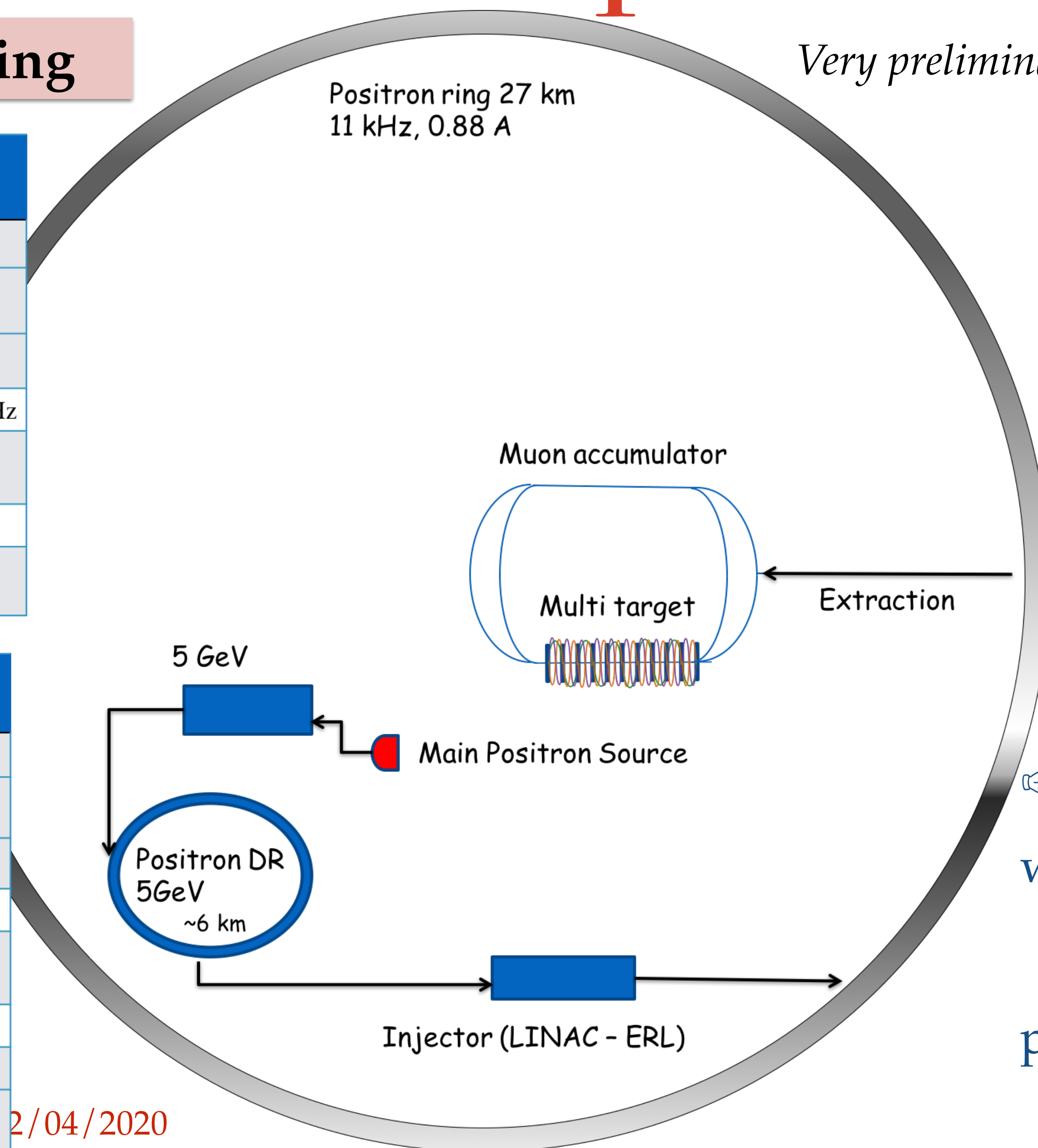
Main challenges: provide high intensity in a short time, target design, high field capture section...

LEMMA: main positron source

First filling

Primary e ⁻ beam for e ⁺ production (as for now)	
Beam energy	5 GeV
Bunch charge	2×10^9
Bunch length (rms)	1 mm
Bunch separation	20 ns/50 MHz
Nb of bunches per pulse	1000
Repetition rate	10-20 Hz
Beam power	16 (32) kW

Damping Ring (as for now)	
Beam energy	5 GeV
Bunch charge	5×10^{11}
Circumference	6 km
Bunch separation	20 ns
Nb of bunches per pulse	1000
Energy acc	$\pm 10\%$
Damping times	~ 10 ms
Number of inj.	~ 500



- Positron beam requirement @ Target for muon production: 5×10^{11} e⁺ / bunch, 1000 bunches / pulse, 10-20 pulses / s => $(0.5-1) \times 10^{16}$ e⁺ / s
- If we use the same injection scheme as CLIC, the PEDD for LEMMA is about 90% of PEDD for CLIC.
- With 500 stacking in the DR, the main positron beam intensity can be reached.

☞ CLIC e⁺ source design seems compatible with the LEMMA main e⁺ source requirements.
=> optimisation with LEMMA beam parameters is needed.

LEMMMA: injector options

Next cycle (after muon production) for scheme 3
arXiv:1905.05747 (2019)

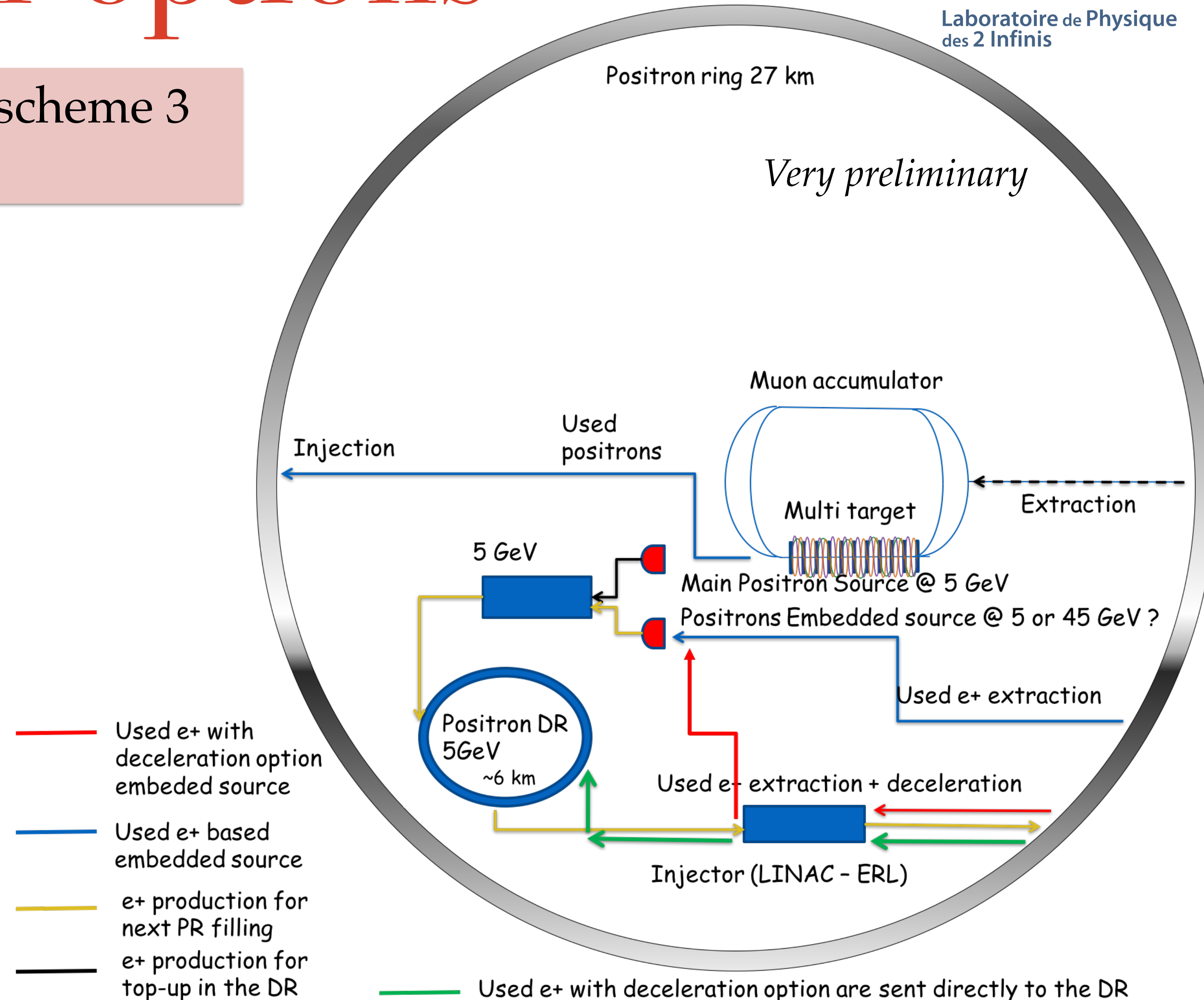
Re-injection of used e⁺ back in the PR =>

- Used e⁺ decelerated and sent back to the DR for damping
- Embedded source: slow extraction of used e⁺ and e⁺ production using e⁺ drive beam @ 5 GeV (deceleration) or 45 GeV

Top-up in the DR with the Main Positron Source.

👉 Work in progress to study all the scenarios

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Outlook

- Positron source is a major R&D issue as far as a muon production from positrons on target is concerned. Increased performance is required in order to satisfy the imposed requirements. **Strategy to be also explored in ARIES Inno Pilot/IFAST.**
- Find a synergy and build up the network with other projects as ILC / CLIC / FCC.
- 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). The experimental tests are mandatory.
- **Drastic reduction of the manpower over the last years** => collaborations between many laboratories all around the world + resources are needed.