ILC Upgrade with Energy Recovery

K. Yokoya (KEK)

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ILC Upgrade Path

- Energy upgrade of ILC has been discussed since TDR up to 1TeV
- "Snowmass 2021" (arXiv2203.07622, final version Jan.2023) discussed up to 3TeV (Nb_3Sn , 4K, TW)
- Another possible direction is luminosity upgrade
  - ✓ Up to now, only doubling the number of bunches has been planned
- Colliders using the ERL concept have been proposed
  - ✓ Several different types
    - CERC, CLERC, ERLC, ReLiC, Ghost Collider
  - ✓ Luminosity 2 orders of magnitude higher than ILC
  - ✓ TeV scale is mentioned in above proposals but required power and cost are enormous.

Why as Upgrade of ILC

- The above ideas have been proposed more or less independently of the existing collider plans (ILC, CLIC, FCCee…)
  - ✓ Presumably, CERC (circumference ~100km) was originally proposed as option/upgrade of FCCee. But the tunnel shape is significantly different.
- However, once ILC is built, there is no reason not to think about upgrade of this direction
  - ✓ Energy recovery is an advantage of SCRF collider
- Some constraints will be imposed
  - ✓ Reuse of ILC properties, at least the site and tunnel, is in mind, though obviously an extension of tunnel length is necessary
- In any case, this is a very far future upgrade, if possible
- I will discuss mainly about ERLC.

Why 500 GeV

- Here, we concentrate on E_{CM}=500GeV, which enables studies of Higgs self-coupling

- "European Strategy for Particle Physics" says

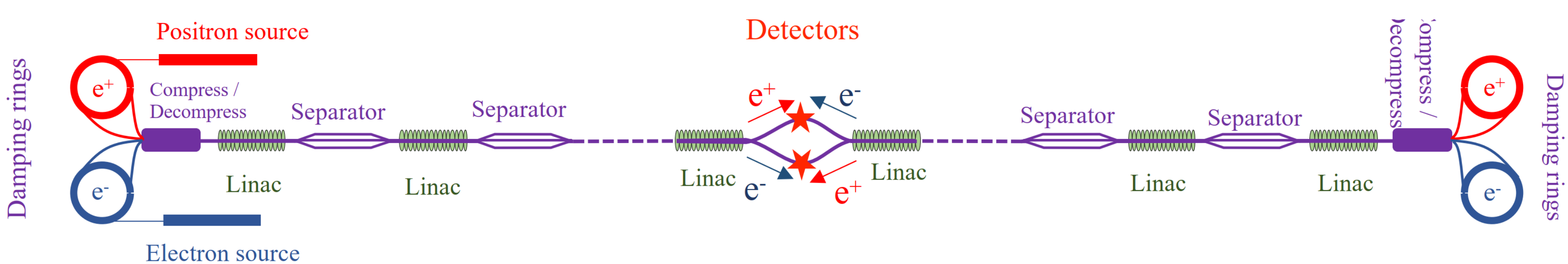
A particularly interesting prospect is to design and possibly build an energy efficient, ultra-high luminosity ERL-based electron-positron collider, which would enable the exploration of the Higgs vaccuum potential with a precise measurement of the tri-linear Higgs coupling.
The e+e- → ZH → HH production cross-section is maximal near 500 GeV collision energy with a value of about 0.1 fb.
For percent-level measurements, a luminosity of 10^{36} /cm^2/s is required.

EUROPEAN STRATEGY FOR PARTICLE PHYSICS
Accelerator R&D Roadmap, arxiv2201.07895, p200

ReLiC

V. Litvinenko, T. Roser, et.al.
Use the parameters in arXiv2203.06476

- Key concept
  - ✓ After the LC-like heavy collision, the beams are decelerated and stored in damping rings until the damaged beam properties are restored. Then, re-accelerated for next collision.
  - ✓ One issue is the energy tail coming from the beamstrahlung, which demands a large energy acceptance of DR. The cure is to make the beam extremely flat at IP.
  - ✓ Collisions in RF cavities are avoided by lumped beam structure and separation sections.



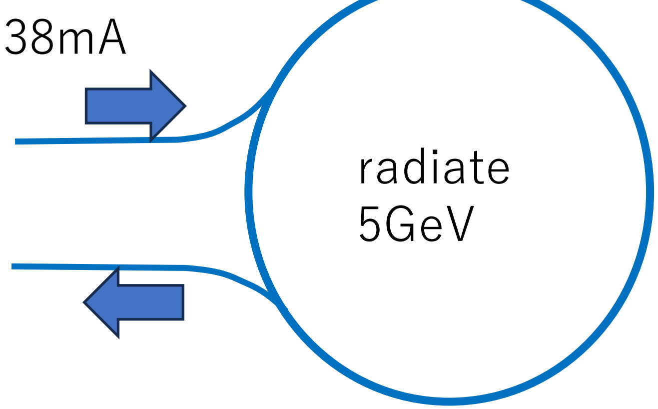
Issues of ReLiC (1)

- There are many issues of R&D
  - ✓CW high Q cavity (but not twin-axis)
  - ✓HOM damping
  - ✓DR: extremely low vertical emittance (ε_{ny}=1nm)
    - Energy tail of beamstrahlung limits the beam life
    - Lower the critical energy by choosing extremely flat beam ($\sigma x/\sigma y$ ~ 6000)
    - Vertical emittance must be very small
    - Large energy acceptance required (~10%)
  - ✓Size of the DR not described much. Perhaps, 20-30km circumference, filled with wigglers
  - ✓High rep rate injection/extraction kicker
  - ✓High disruption collision (Dy ~ 100)

Issues of ReLiC (2)

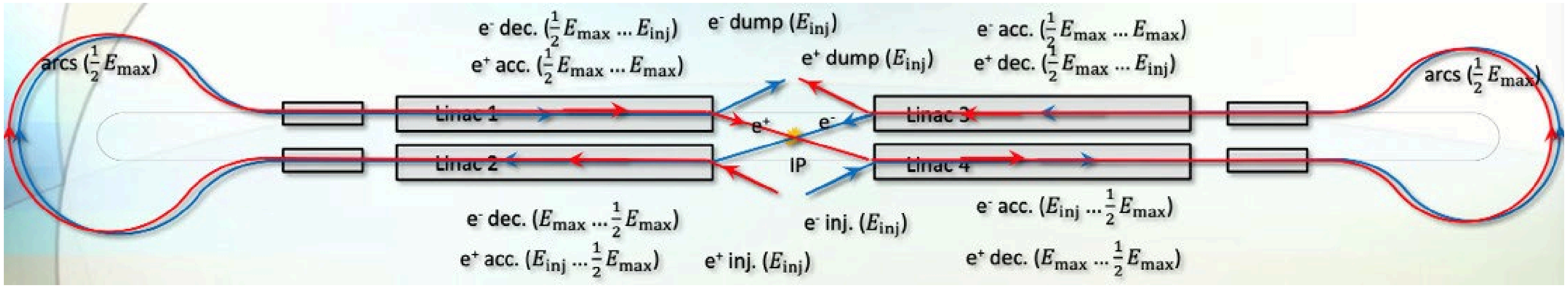
- But the most serious is the power consumption in DR
  - ✓ Average beam current 38mA
    - Average collision frequency 12MHz
    - Bunch charge 3.2nC
  - ✓ Lose 5GeV in the damping ring
    - Damping ring energy 2.5GeV
    - Stay in DR for 2 longitudinal damping time (actually, more than 2 will be needed)
- Then, the synchrotron radiation power in one of the DR is
  38mA x 5GV = 190MW
  - ✓ 4 DRs → 760MW
  - ✓ Required AC power for compensation ~ 1.2-1.5GW
- This is a relatively "low-tech" issue
  - ✓ Almost no room to improve
    - Higher klystron efficiency may contribute a bit
- How much power can be reduced by trade-off with the luminosity?

Use the parameters in arXiv2203.06476



There may be my misunderstanding of factor 2. 12MHz is the sum of 2 IPs ?

Ghost Collider



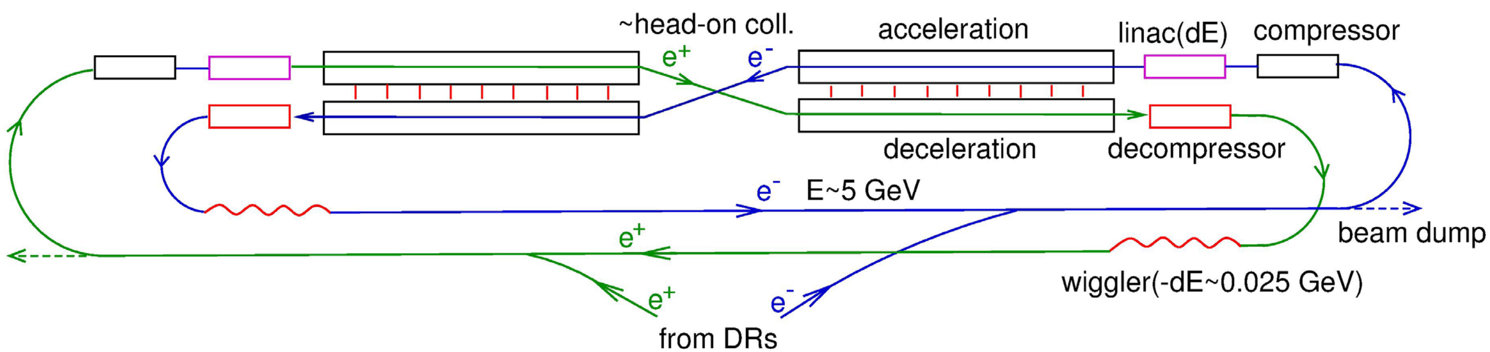
- Concept
  - ✓ Modification of ERLC concept (so, keep beam-beam limit)
  - ✓ e+ acceleration & e- deceleration in the same direction, same cavity, same bucket
    - Energy recovery in the same cavity. No twin axis cavity.
  - ✓ Return at E=Ecm/4 (site length half in same gradient)
  - ✓ (very ambitious option : Mixed e+e- collision)
- Pros and Cons
  - ✓ Almost no (longitudinal) HOM
  - ✓ Energy extendibility hard (very large arc of Ecm/4)
  - ✓ Many beam dynamics issues
    - Very large energy ratio at the end (IP side) of linacs
    - Transverse HOM

ERLC

V. I. Telnov,
JINST 16(2021)p12025,
arXiv2105.11015v5 (Jun.19.2023)
arXiv2302.09758

- Key concept
  - ✓Moderate beam-beam interaction like in ring colliders
    - Keep beam-beam limit
  - ✓The beam is decelerated after IP, radiates some energy for damping in wigglers in the return line, and is accelerated again to IP
  - ✓Twin axis cavity required

Twin LC with energy recovery



Many different parameter sets suggested by Telnov depending on the technology. Here, we do not choose a particular set.

Damping in ERLC

- Damping requirement is completely different from ReLiC
- A particle loses only ~0.025GeV during one cycle
  - ✓ ~5GeV in ReLiC → too large power loss
- Damping is much weaker than in ReLiC
  - ✓ Longitudinal damping in 5GeV/0.025GeV=200 turns
    - Transverse damping time = 400 turns
  - ✓ Radiation loss per collision= a few MW
    - Beam current O(100mA) as in ReLiC
  - ✓ Some dynamical effects accumulate over ~400 turns
    - Emittance increase due to random processes like synchrotron radiation
    - May be relaxed a little, say 200
    - Vertical emittance growth in ILC main linac < O(10nm). This is not simply multiplied by 400

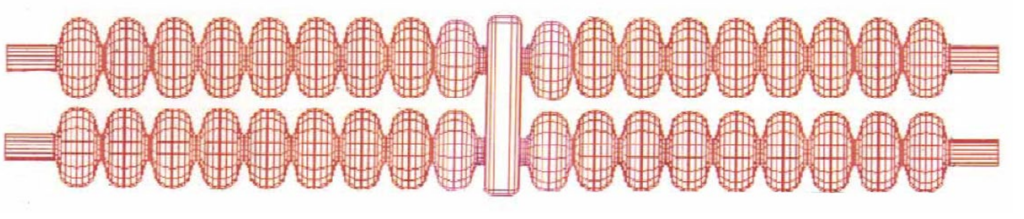
Key Issues

- Dynamics
  - ✓Beam-beam tune shift
  - ✓Energy tail due to beamstrahlung
  - ✓Energy spread due to beamstrahlung
- SRF
  - ✓Twin axis cavity
  - ✓Q0 > 3x10^(10)
  - ✓Hopefully, Nb_3Sn, 4.5K
  - ✓HOM loss, HOM absorber
    - typical parameters:
      bunch charge 10^9, average current ~100mA
    - Not too much larger than recent ERL designs for light source **(there was a mistake in the version uploaded first)**
    - Total HOM power ~x100 of ILC
  - ✓Accelerating gradient
    - Hopefully, >40MV/m for reaching E_{CM}=500GeV

Twin Axis Cavity

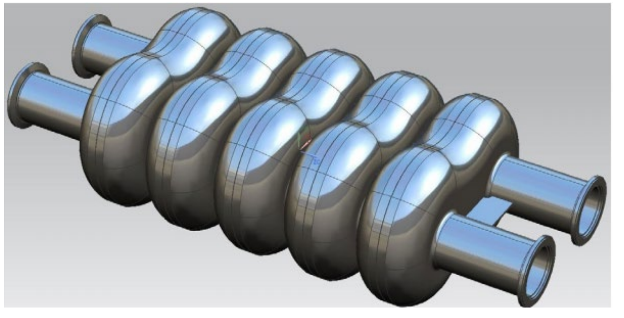
- The beams to be accelerated and decelerated are going opposite directions
- Twin axis cavity required

- Several designs/experiments on-going



Noguchi, Kako, SRF2003 tup16

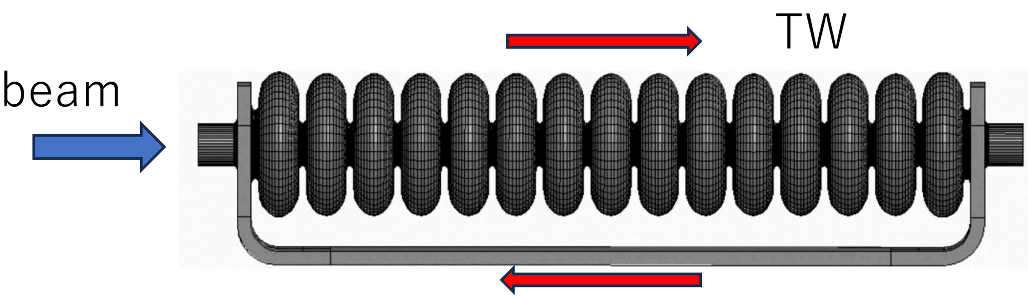
HyeKyoung Park, TJNAF, SRF2017, Lanzhou



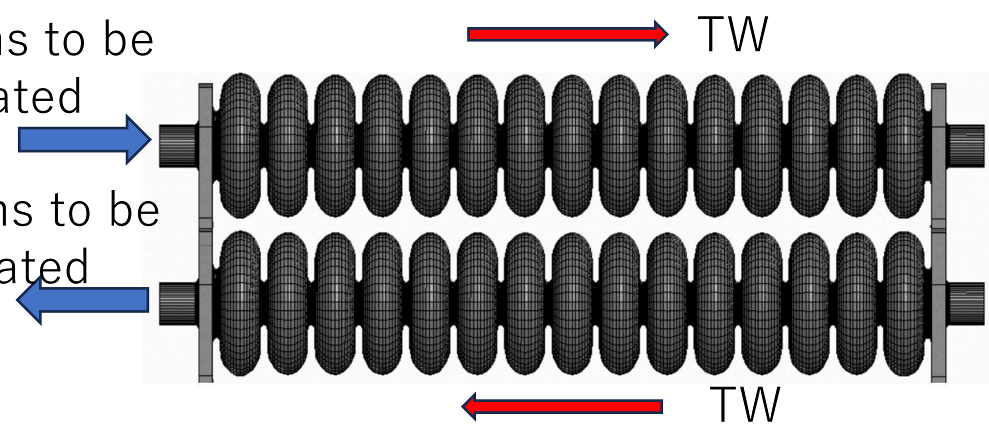
H.Park, et.al. Linac2016

Twin Axis Cavity (continued)

- Possible combination with the idea of TW cavity (HELEN)
  - ✓ Replace the return waveguide by another cavity
  - ✓ TW only in both cavities
- Can halve the heating and/or double the gradient
- Basically, prefer CW
  - ✓ Though Telnov accepts pulse (several seconds) operation



But this does not reduce HOM

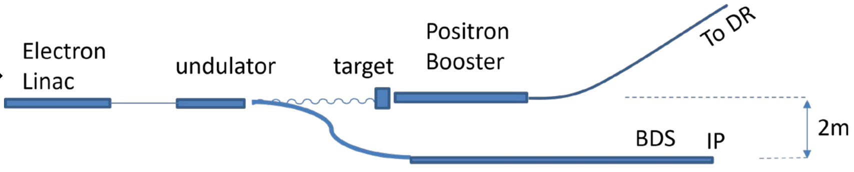


A few practical issues for ILC

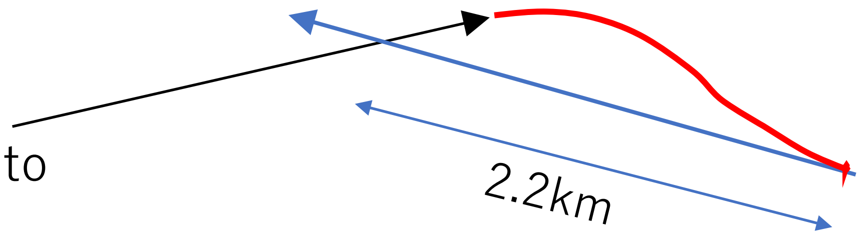
- ➢Tunnel crosssection
  - ✓Can the twin-axis cavity be accommodated in the ILC tunnel
- ➢Emittance growth due to synchrotron radiation
  - ✓Emittance growth in every bending field is multiplied by 400
  - ✓Equilibrium emittance ($\Delta\varepsilon_{xn}$, $\Delta\varepsilon_{xn}$) are similar to ILC

Bending Fields in ILC

- Bunch compressor
- Vertical bend by off-center orbit in the quads to follow the earth's curvature
- Dogleg for positron generation →



- Bends in Final Focus System
  - ✓ To create dispersion
  - ✓ ILC FFS is designed for E_{beam}=500 GeV
  - ✓ $\Delta\varepsilon_{xn}$ at 250GeV is 1/64, but not small enough compared with 1/400
  - ✓ → must be a bit longer
- Crossing angle →
  - ✓ The beam line must come back to the main linac after IP
  - ✓ A rough calculation shows this is marginal for E_{CM}=500GeV (no problem for E_{CM}= 250GeV)
  - ✓ One more km may be needed
  - ✓ Telnov proposes (nearly) head-on collision



Note: hor/ver emittances in Telnov's parameter set are the same as in ILC

Summary

- Possibility to adopt energy recovery collider for ILC luminosity upgrade is discussed
- Candidate: the concept of ERLC
- Many R&D needed
  - ✓ Twin-axis cavity (TW type possible?)
  - ✓ Nb_3Sn, 4.5K
  - ✓ High Q
  - ✓ HOM absorber
  - ✓ Accelerating gradient
- Constraints as ILC upgrade
  - ✓ Tunnel crosssection
  - ✓ Emittance growth in bending fields must be checked

Many thanks to V. Telnov and E. Kako