ILC Upgrade with Energy Recovery

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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

References

- CLERC, "Novel Concept of Circular-Linear Energy Recovery Accelerator to Probe the Energy Frontier", I. V. Konoplev, et.al., arXiv2108.09111
- CERC, "High-energy high-luminosity e+e- collider using energy-recovery linacs", V. N. Litvinenko, et.al., Phys. Lett. B, Volume 804, 135394, (2020)
- ReLiC, "The ReLiC- Recycling Linear e+e- Collider", Vladimir N Litvinenko and Thomas Roser, et.al., arXiv2203.06476
- ERLC, "A high-luminosity superconducting twin e+e- linear collider with energy recovery", V. I. Telnov, Journal of Instrumentation (JINST) 16(2021)P12025, arXiv2105.11015v5 (Jun.19.2023)
- Ghost Collider "Beam Dynamics Challenges of a Far-Future ERL-Based Collider - The Ghost Collider" A. Hutton, et al., ERL2022, GhostColliderV9.pptx https://indico.classe.cornell.edu/event/2018/

Why as Upgrade of ILC

- The above ideas have been proposed more or less independently of the existing collider plans (ILC, CLIC, FCCee…)
- 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
- IF ILC upgrade, 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

Why 500 GeV?

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

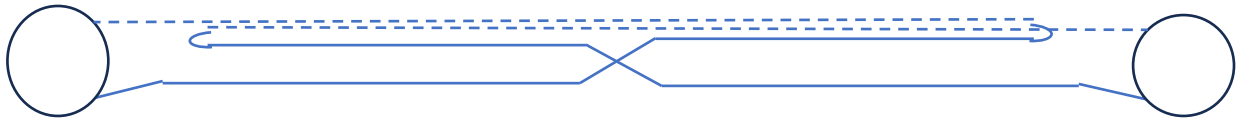
- "European Strategy for Particle Physics" says

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.

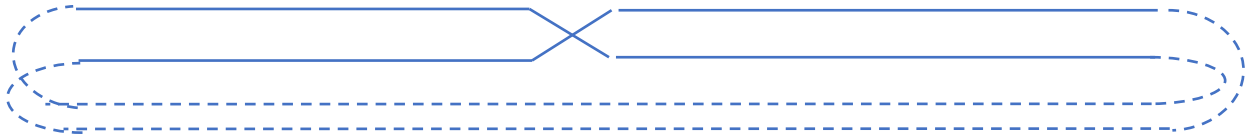
EUROPEAN STRATEGY FOR PARTICLE PHYSICS
Accelerator R&D Roadmap, arxiv2201.07895, p200

Two Different Concepts

- Type A (obviously a better name is needed!)
  - ✓CERC, CLERC, ReLiC
  - ✓Linear-Collider-like heavy collision
  - ✓**Full damping in damping rings between 2 collisions**



- Type B
  - ✓ERLC, Ghost Collider
  - ✓Circular-collider-like moderate collision
  - ✓**Partial damping in a wiggler section between 2 collisions**
  - ✓Constraint by the beam-beam tune-shift like in circular collider



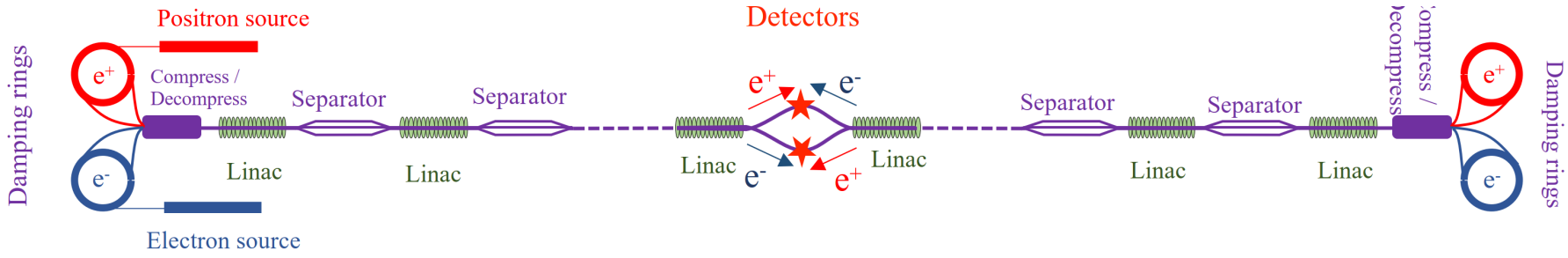
- Energy tail from beamstrahlung imposes a strong constraint in both schemes

ReLiC

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

- Key concept
  - ✓**Type A**.
  - ✓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.

- Twin-axis cavity not needed
- CLERC adopts uniform beam structure and twin-axis cavity



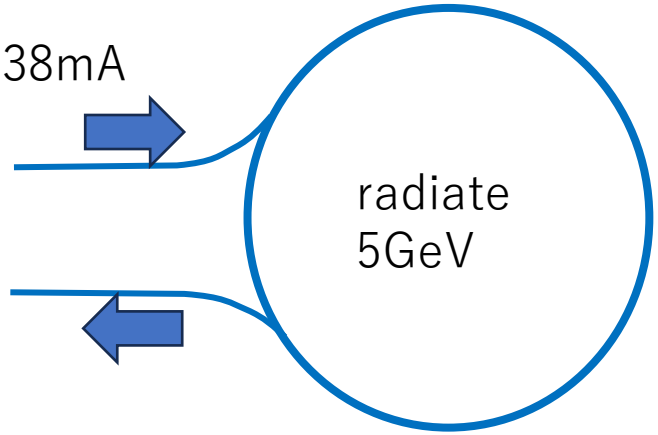
Issues of ReLiC (1)

- There are many issues of R&D
  - ✓CW high Q cavity (**but not twin-axis**)
  - ✓HOM damping (high bunch charge, high current)
  - ✓DR
    - Energy tail of beamstrahlung limits the beam life
    - Lower the critical energy by choosing extremely flat beam ($\sigma x/\sigma y \sim 6000$)
    - Vertical emittance must be very small (ε_{ny}=1nm)
    - 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 ~ O(100))

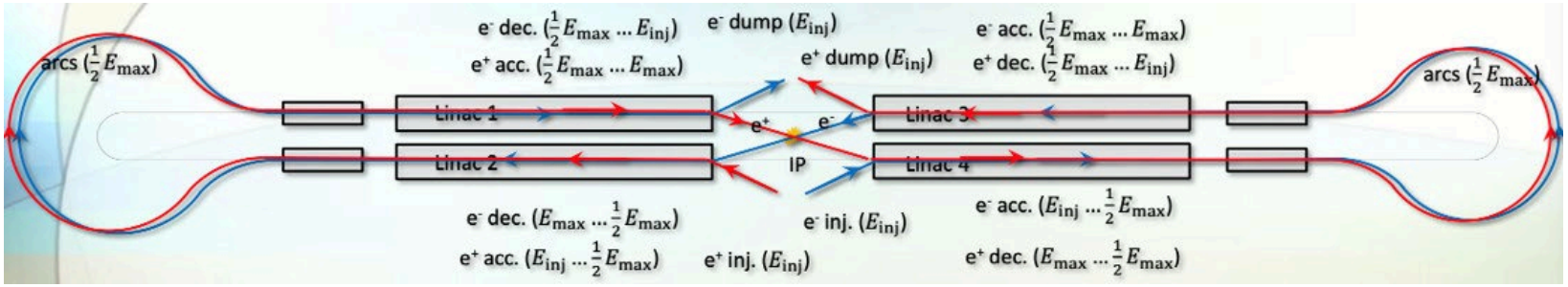
Issues of ReLiC (2)

- The most serious is the power consumption in DR
  - ✓ Average beam current 38mA
  - ✓ 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



Ghost Collider



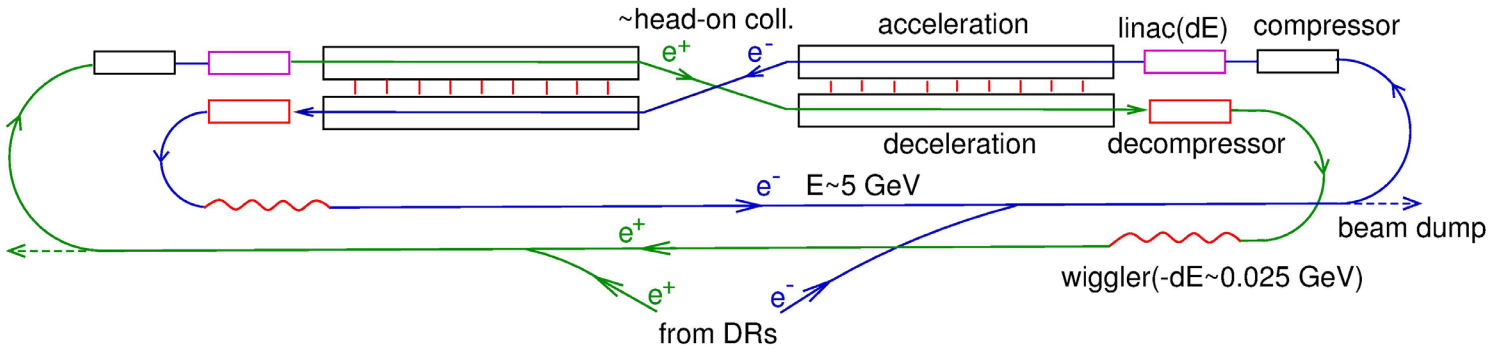
- Concept
  - ✓ **Type B**: Modification of ERLC concept (so, keep beam-beam limit)
  - ✓ e+ acceleration & e- deceleration in the same direction, same cavity, same bucket
    - Energy recovery in the same cavity. No twin axis cavity.
  - ✓ Return at E=Ecm/4 (site length half in same gradient)
  - ✓ (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
- Very interesting and exciting but will not be discussed as ILC update

ERLC

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

- Key concept
  - ✓**Type B**: 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 available technology. Here, we do not choose a particular set.

Damping in ERLC

- Damping requirement is completely different from ReLiC
- Damping is much weaker than in ReLiC
  - ✓Longitudinal damping in 5GeV/0.025GeV=200 turns
    - Transverse damping time = 400 turns
  - ✓Radiation loss between 2 collisions = a few MW
    - Beam current O(100mA) as in ReLiC
    - But loss = 0.025GV, → ~ 100mA x 0.025GeV =2.5MW
- Disadvantage of weak damping
  - ✓**Some dynamical effects accumulate over ~400 turns**
  - ✓Emittance increase due to random processes like synchrotron radiation
    - If serious, may be relaxed a little, say ~200 turns
  - ✓Vertical emittance growth in ILC main linac < O(10nm) in single pass. If accumulate ~400 turns → 4000 nm >>> 35nm
    - But this is not simply multiplied by 400

Key Issues

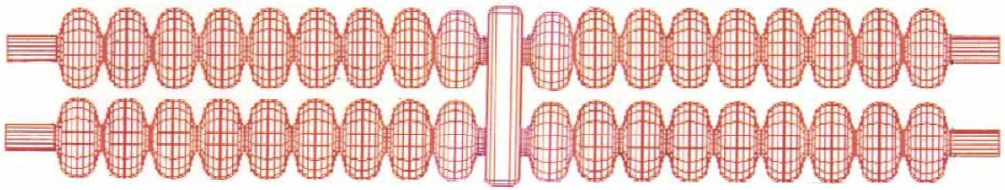
- Dynamics
  - ✓Beam-beam tune shift
  - ✓Energy tail due to beamstrahlung
  - ✓Energy spread due to beamstrahlung
- SRF
  - ✓**Twin axis cavity**
  - ✓Q0 ＞ 3x10^(10)
  - ✓Hopefully, Nb_3Sn, 4.5K
  - ✓HOM loss, HOM absorber
    - typical parameters:
      bunch charge 10^9 (160 pC), average current ~100mA
    - **Not** too much larger than recent ERL designs for light sources
    - Total HOM power ~x100 of ILC
  - ✓Accelerating gradient
    - Hopefully, >40MV/m for reaching E_{CM}=500GeV

Twin Axis Cavity

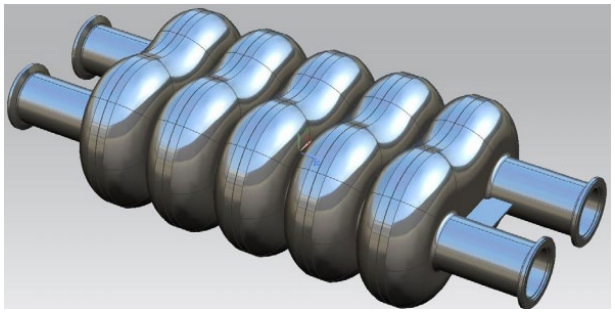
- The beams to be accelerated and decelerated are going to the opposite directions
- Twin axis cavity required

HyeKyoung Park, TJNAF, SRF2017, Lanzhou

- Several designs/experiments on-going



Noguchi, Kako, SRF2003 tup16

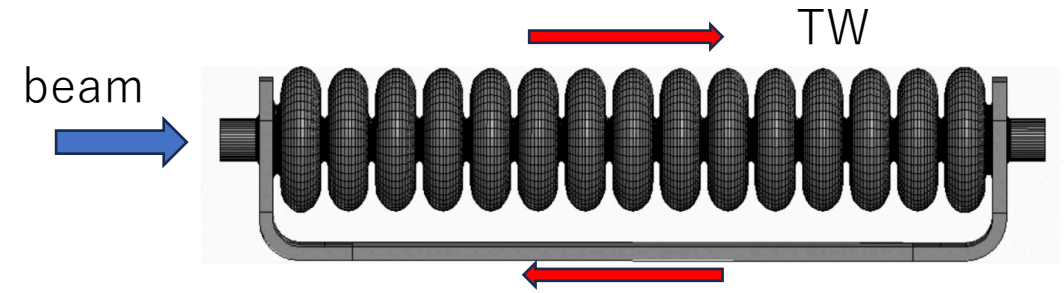


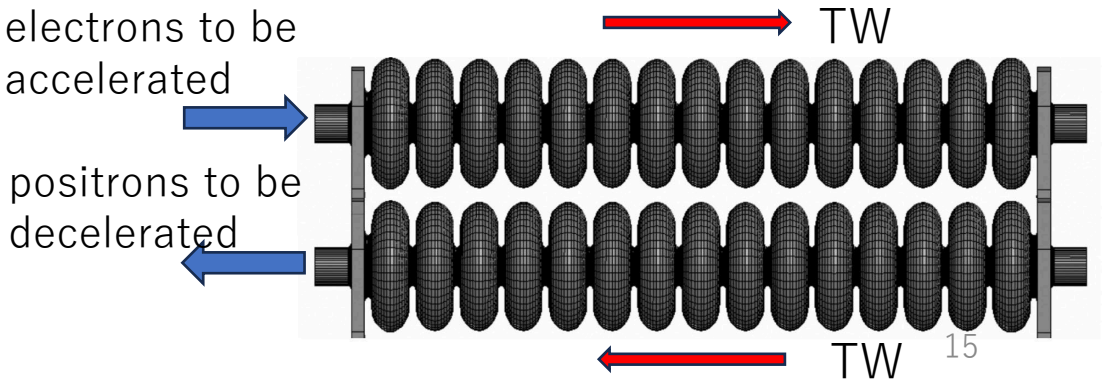
H.Park, et.al. Linac2016

Twin Axis Cavity (continued)

- The idea of TW cavity (HELEN)
  - ✓ LCWS2024
    - Roman Kostin, Euclid Techlabs “Traveling Wave Demonstration in SRF Cavity With a Feedback Waveguide”
    - Fumio Furuta “Development of a half-meter scale Traveling-Wave (TW) SRF cavity”
- Possible combination with TW cavity and Twin-Axis cavity
  - ✓ Replace the return waveguide by another cavity
  - ✓ TW of correct direction in both cavities
- Can **halve the heating** or **double the gradient**

- Higher gradient possible
  - ✓ At a cost of increased heating
  - ✓ But reduced HOM (because the number of cavities decreases)
- Hopefully, length of 500GeV pulsed ILC is enough for 500GeV ERLC



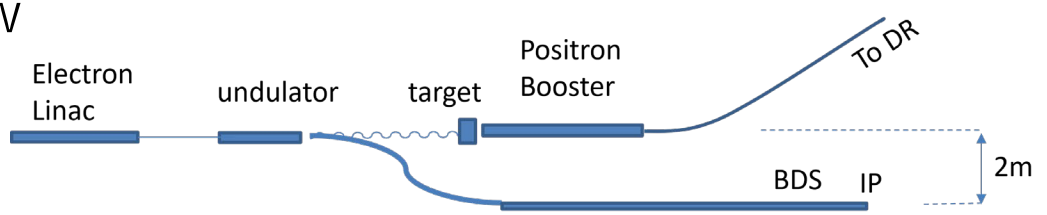


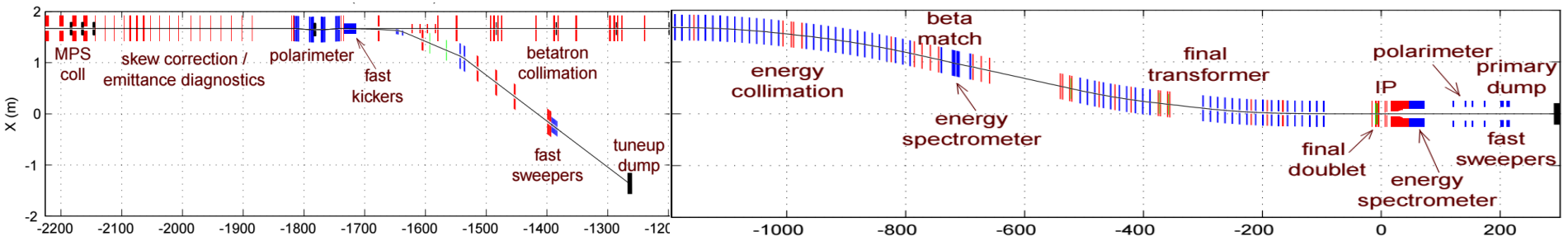
A few practical issues for ILC

- 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. See next page
  - ✓Equilibrium emittance ($\Delta\varepsilon_{xn}$, $\Delta\varepsilon_{xn}$) are similar to ILC
- Other beam dynamics issues
  - ✓Emittance growth in the main linac (ML)
    - ~10nm in single passage. But this is mostly coherent (do not accumulate turn by turn)
  - ✓BBU by transverse wake in ML (very high current)

Bending Fields in ILC (1)

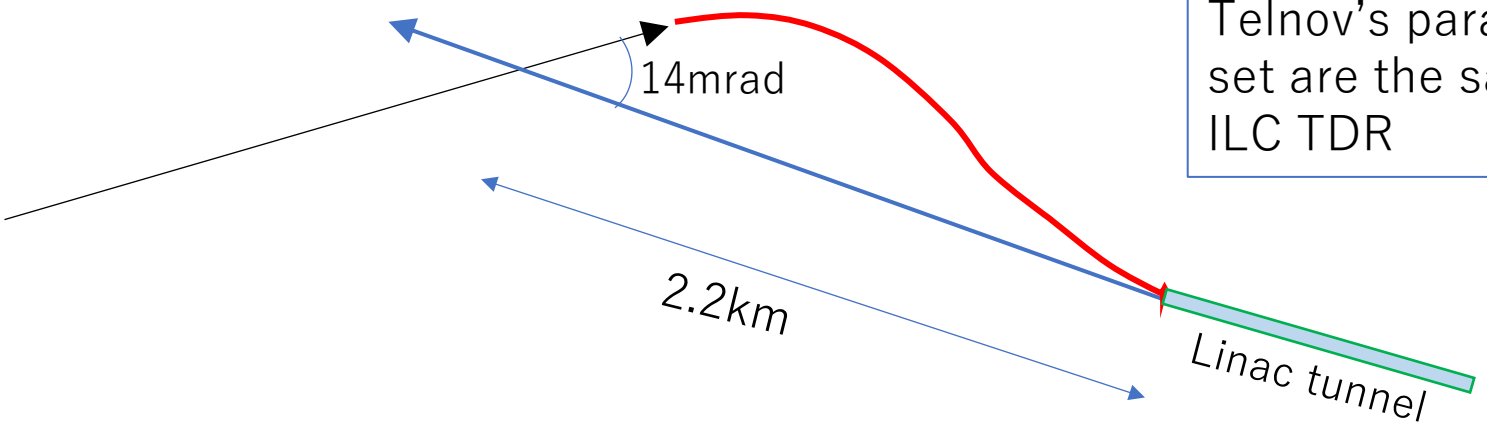
- Bunch compressor
- Vertical bend by off-center orbit in the quads to follow the earth's curvature
- Dogleg for positron generation →
- Bends in Final Focus System
  - ✓To create dispersion
  - ✓ILC FFS is designed for E_{beam}=500 GeV
  - ✓$\Delta\varepsilon_{xn}$ at 250GeV is 1/64, but not small enough compared with 1/400
  - ✓→ must be a bit longer





Bending Fields in ILC (2)

- Crossing angle →
  - ✓ The beam line must come back to the main linac tunnel 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
- Need a good optics design



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

Summary

- Possibility to adopt energy recovery collider for ILC luminosity upgrade is discussed
- Candidate: the concept of ERLC
  - ✓ ReLiC:
    - large power consumption in DR
    - main linac gradient low (real-estate gradient 12.5 MV/m, note: ILC ~22 MV/m)
- 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 (related to the crossing angle)

Many thanks to V. Telnov and E. Kako