ILC Staging

K. Yokoya

2017.3.31 Detector Annual Mtg

Cost reduction

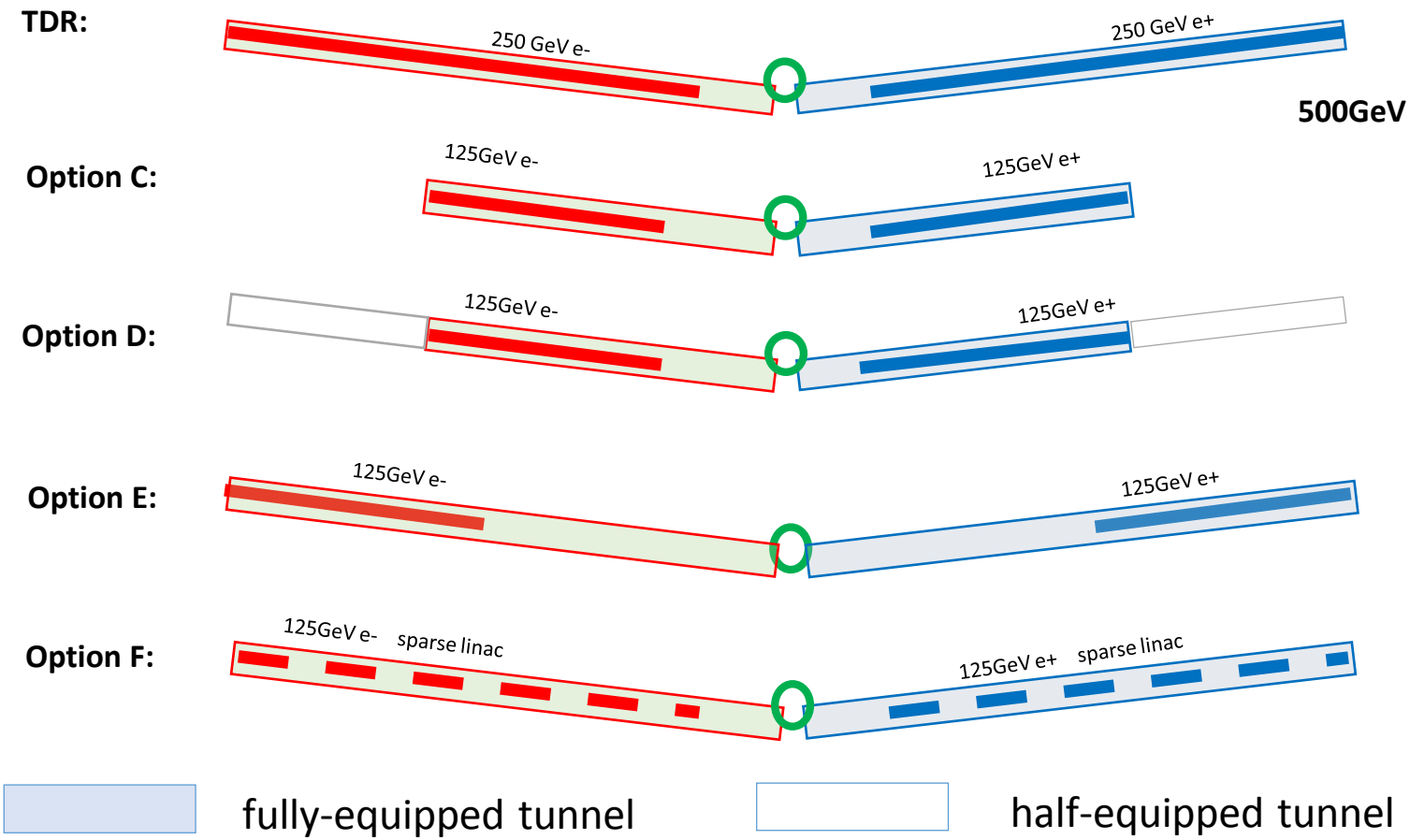
HiQ+HiG, Nb material, input coupler,

- All of these measures will reduce the cost by 10-20%, but that is not enough for a realistic project funding.
- The beauty of a linear collider is that it can be staged.
- Serious discussions must now start on realistic staging scenarios to bring the cost of the first stage down.

Possible Scenarios

- First stage CM energy　250GeV
- Tunnel length
  - Just for 250GeV
  - For 350GeV
  - For 500GeV
- Location of the first stage linac
  - Upstream
  - Downstream
  - Scattered

Naming of Scenarios

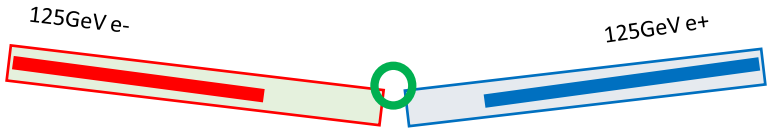


- Option D', E', F' for 350GeV tunnel

Assumptions

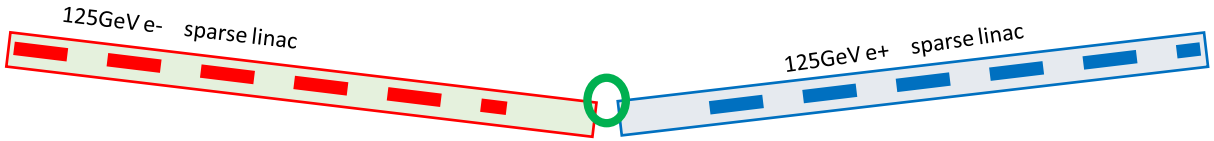
- Positron production: Undulator scheme
  - Long undulator (147→230m)
  - 5+5Hz operation not needed at E_e=125GeV
- Give up 10Hz collision for the first stage
  - But 5+5Hz operation for E_{CM}<250GeV is still alive and to be discussed
- Forget about 2x1.4km extension of tunnel, though once approved
  - Forget about timing adjustment for a while
  - Must be taken into account soon
- Main linac tunnel: 9.5m wide, shield wall 1.5m thick
- No change in the BDS region
  - Some magnets may be omitted but this is not counted for in cost reduction
- SCRF
  - Tunnel length estimated assuming 31.5MV/m
  - Module count assuming average gradient 35MV/m
    - Empty short spaces to be filled later if needed
    - Q_0 = $1x10^{10}$ → $1.6x10^{10}$ for cryogenics estimation
  - Same RF unit : 9+8+9 cryomodules
  - Assume improved Krystron
    - 10MW→11MW, 1.65ms → 1.8ms

Option C



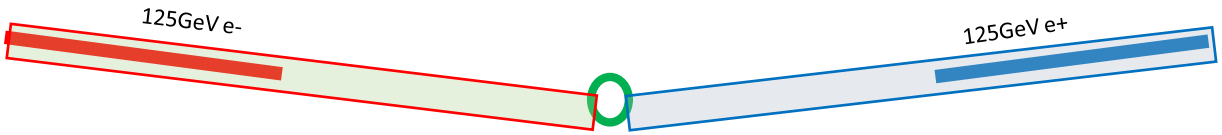
- Construct upstream tunnel and turn-around for energy upgrade
- It would be reasonable to add short tunnels (~500m?) at upstream ends from the beginning
  - for additional tunnel construction during 250GeV CM run in order to avoid vibration.
- Cheapest first stage

Option F



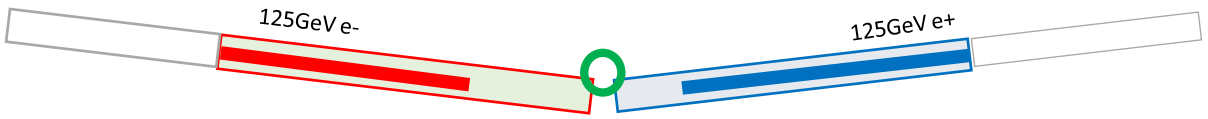
- Construct 500GeV tunnel
- Split 2x125GeV linacs into a few (~3 each) pieces
- In principle, can install full RF system for 500GeV in the 250GeV stage. This would make 10Hz collision possible. But cost reduction in the first stage would be minimal.
- Turn-around need not be reconstructed at energy upgrade
- Cost saving would be small (even if RF system is just for 250GeV)

Option E



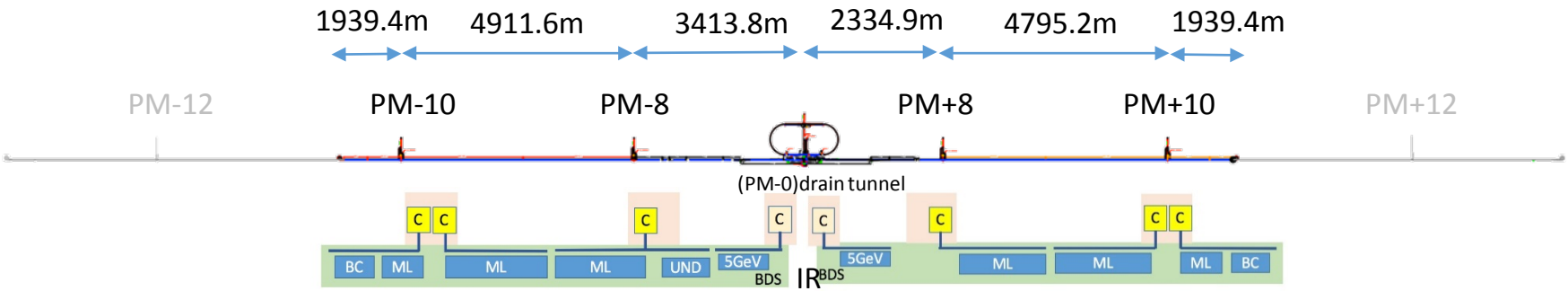
- Need empty tunnel
  - But not totally empty (125GeV beam transport lines)
  - This empty tunnel must be fully equipped (power line, air conditioner, etc)
- Longer transport line than in Option D
  - RTML line (2x5km) and transport line to BDS (2x5km)
- Turn-around need not be reconstructed at energy upgrade
- Machine must stop during installation for energy upgrade

Option D



- Empty tunnels upstream
  - Half-equipped tunnel is enough
    - minimum light, drain,
  - No power line, no air conditioner,
- Tunnel extension work and most of the installation works can be done during 250GeV machine running
  - Must stop run during moving turn-around magnets and bunch compressor system
- Must reconstruct turn-around tunnel at energy upgrade
- Cheapest among the options with 500GeV tunnel

Option C | **SRF 35MV/m** | Ecm = 250GeV tunnel=250GeV length



	BC				e+inj	Ecm=250GeV	e-inj				BC	
	51	9	189	189	24	cryomodules	24	180	189	9	51	
	17	2	42	42	8	RF unit	8	40	42	2	17	
e^- 136.9GeV =	10.0	2.8	59.5	59.5	5.0	E gain (GeV)	5.0	56.7	59.5	2.8	10.0	= e^+ 134.1GeV

tunnel length = 19334.3m

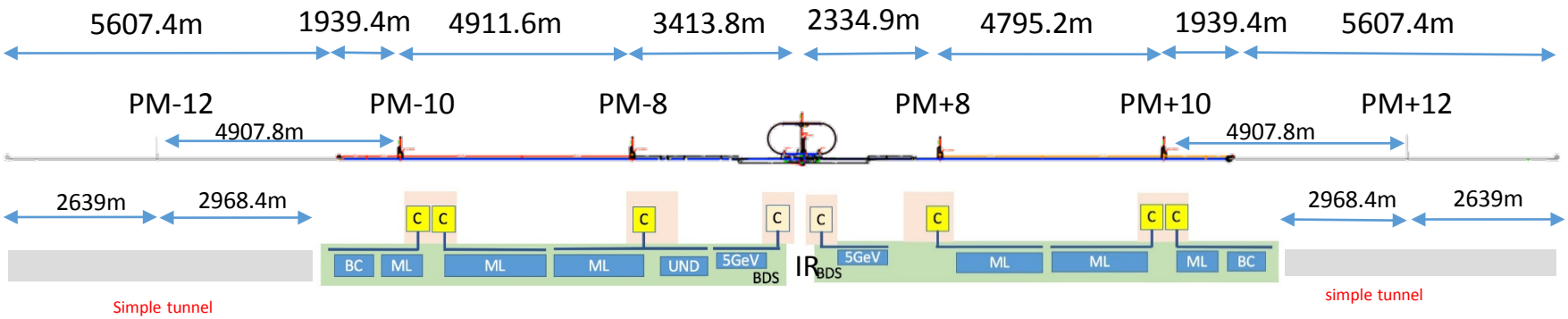
(19km)

Cavity active length = 1.0385m
Energy gain by 1 cavity = 35.0*1.0385 = 36.3 MeV
Energy gain by 1 RF unit = 36.3 MeV * 39 =1.418 GeV
length of 1 RF unit = 58.3m

H.Hayano

Option D **SRF 35MV/m**

Ecm = 250GeV tunnel=500GeV length, accelerator downstream



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e^- 136.9GeV =	10.0	2.8	59.5	59.5	5.0	E gain (GeV)	5.0	56.7	59.5	2.8	10.0	= e^+ 134.1GeV

tunnel length = 15872.2m+14676.9m=30549.1m

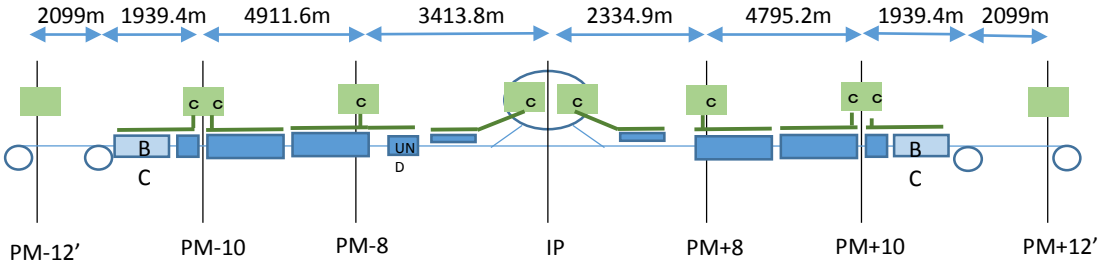
(30.5km)

H.Hayano

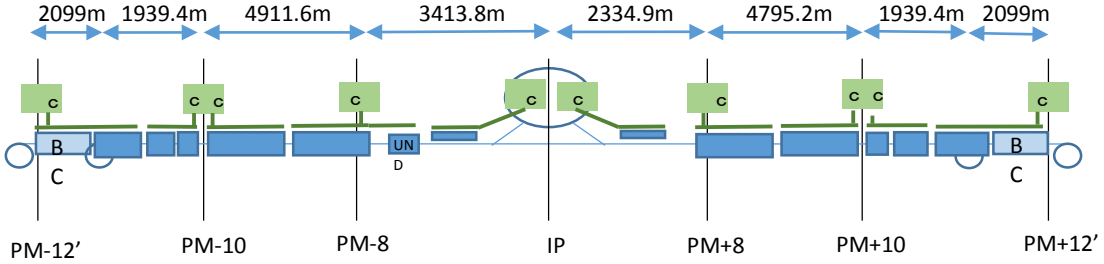
H.Hayano

Option D’

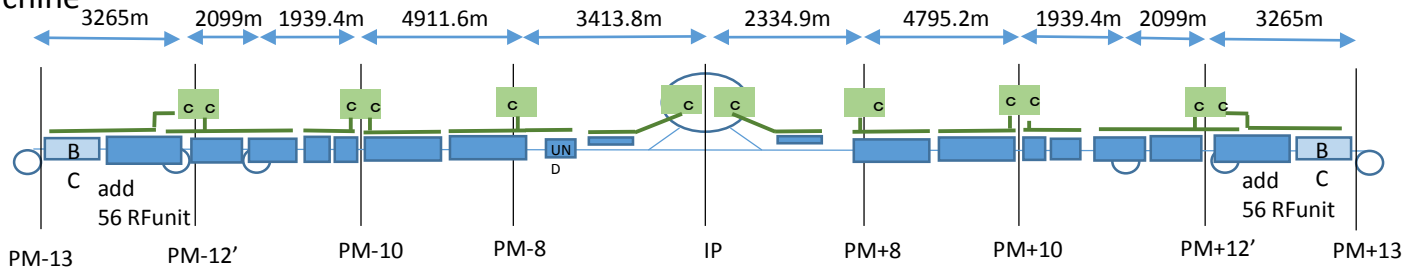
250GeV Machine



350GeV Machine



500GeV Machine



Key Issues

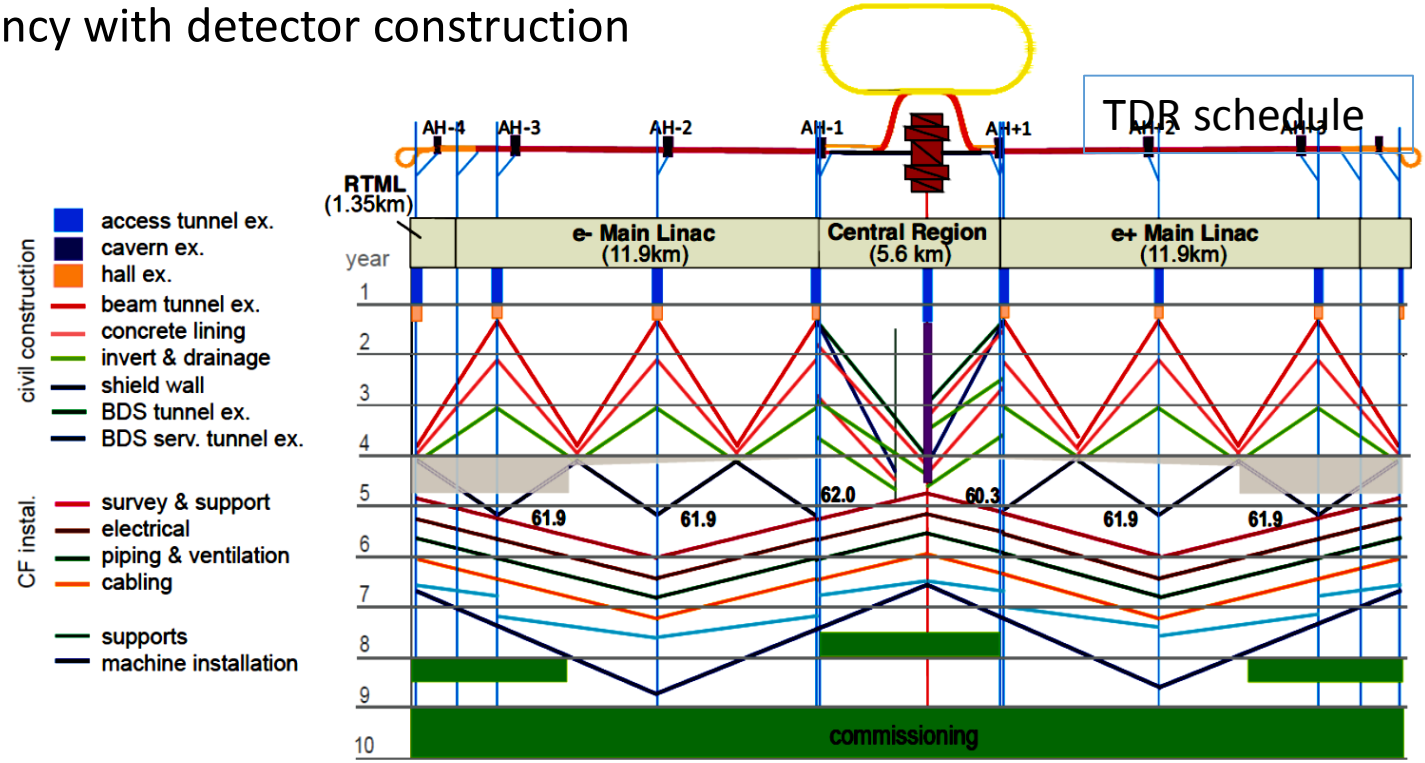
- Number and location of access tunnels
- Cryogenics station
  - 5 stations/linac in TDR for 500GeV
  - Is 2 station/linac enough for 250GeV?
    - Length of helium transport line must be studied carefully, including the transport to beam source region
    - → tend to adopt 3 stations ?
- Energy margin
  - Choice of 500GeV CM was somewhat arbitrary
  - Now, 250GeV CM comes from Higgs
    - Also, E_e = 125GeV is critical for positron production
  - Energy margin must be defined deliberately
  - 500GeV case
    - 14% after adding 2x1.4km
    - 1.5-2.0% additional cryomodules but these are for availability
  - 250GeV case
    - Policy of 35MV/m for modules and 31.5MV/m for length gives 10% margin in some sense
    - But is this enough?
  - May have some impact to cryogenics system, too

Preliminary Cost Estimation

- There is already an estimation in TDR (vol.3.II, 15.12.3) assuming 150GeV+125GeV and simple scaling
- Present study is too preliminary
- But crude numbers will be around (compared with TDR)
  - Option C ~35% saving
  - Option D a few percent less
  - Additional ~5% if R&D is successful
- Labor reduction is also being estimated

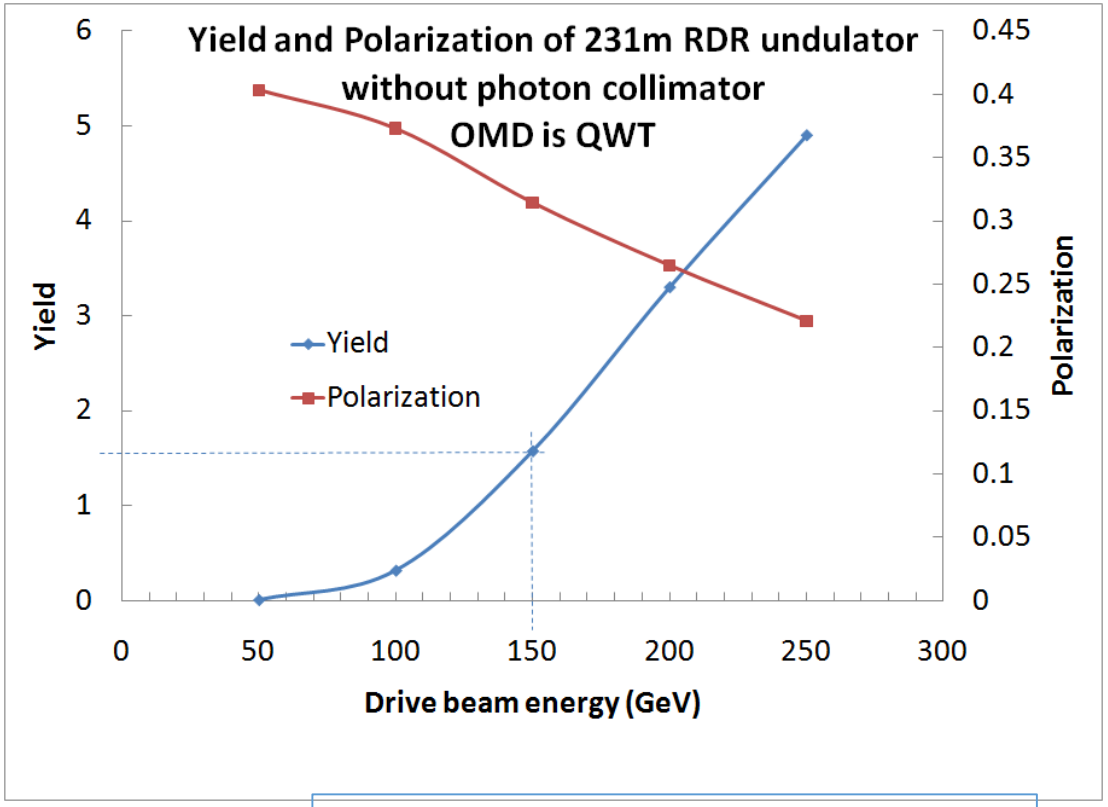
Construction Schedule

- TDR: 9 year construction + 1 year commissioning
- To be studied later
- Not significantly shortened
  - May be slightly (~0.5 year?)
  - Consistency with detector construction



Positron Production

- Unfortunately, E_e = 125GeV is the most difficult energy point for positron production.
- Longer undulator (147m→230m) needed
  - no 5+5Hz operation
- Quite recently a problem for E_e = 125GeV has been pointed out



The yield is about factor 1.57 higher if flux concentrator is used

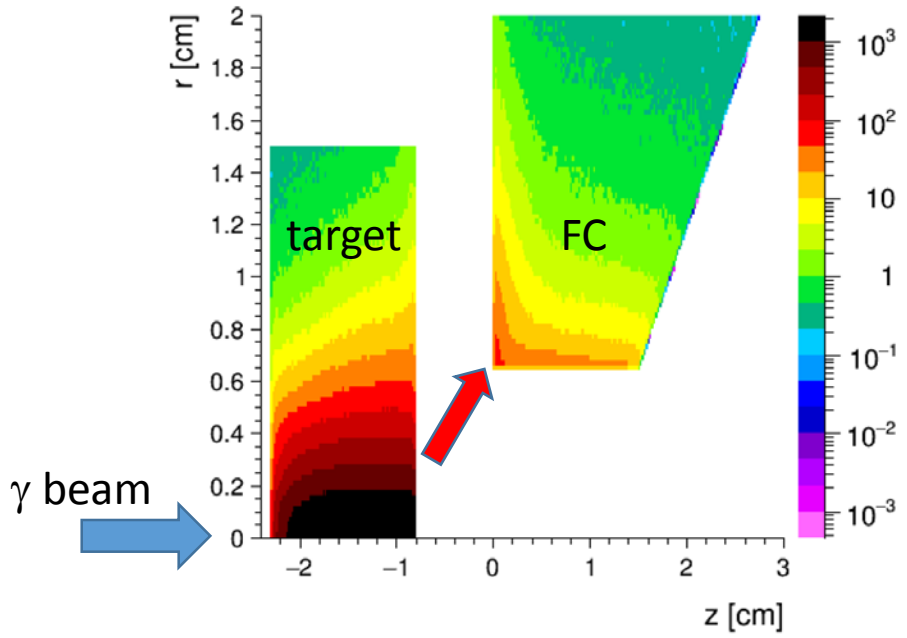
Andriy's simulation base on Okugi's geometry

- PEDD limit of Cu is 7-12 J/g

PEDD in FC. Compact Dogleg

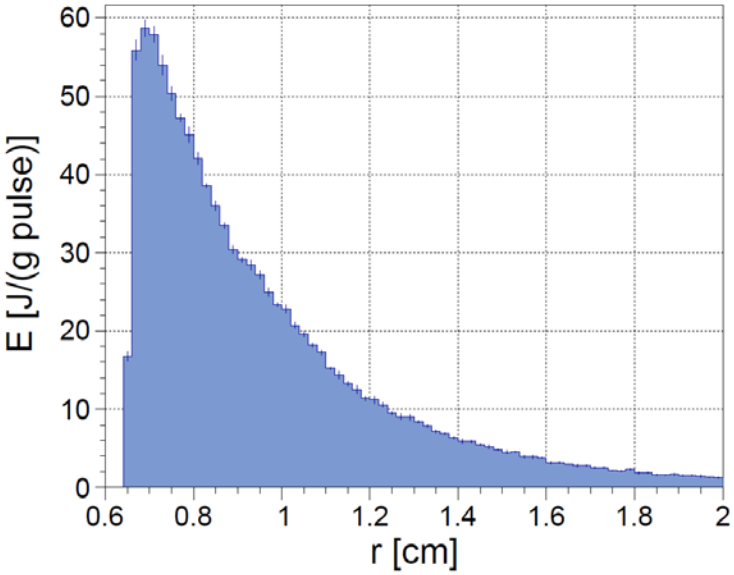
125 GeV e^-, 1312 bunches/pulse, 231 m undulator with $K = 0.85$

Energy Deposition in Target* and FC [J/(g pulse)]



* Target without rotation

Energy Deposition Radial Profile at z = 0.3 mm



$PEDD_{FC}$ = 58.7 J/(g pulse)

ΔT_{inst} = 152.6 K

Flux Concentrator Heating Problem

- PEDD at the tip of FC is serious for 125GeV beam
  - Low energy photon → larger spot ($1/\gamma$) and wider shower development in the target material
  - Less serious for 250GeV beam
- Possible cures (to be discussed in coming meetings)
  - Shorter distance from undulator to target
    - Andriy's simulation showed only ~15% reduction of PEDD
  - Larger beam hole of FC
    - Compatible with 3Tesla field?
  - Lower K of undulator
    - smaller angle spread and higher photon energy ($1/(1+K^2)$)
    - But reduces photon number (propt. K^2)
  - Thinner target
    - Less development of shower angle
    - But reduces positron yield
  - Photon collimator (originally for higher polarization)
    - Scrape out low energy photons (useless for positron production and cause larger angle in target)
    - But reduces positron yield
- Minimum baseline
  - DC QWT: how much is the luminosity reduction? --- factor ~1.6

Luminosity Optimization

- Upgrade to 500GeV will not be guaranteed at the first stage construction.
- Need good physics output in the first stage to get approval for higher energies.
- Luminosity at 250GeV must be as high as possible.
- ILC TDR is optimized for 500GeV CM.
- Luminosity at 250GeV with 1312 bunches (no 10Hz collision) is 0.82×10^{34} /cm^{2}s in TDR
- Can we go to higher luminosity?

Basic Formulas

- The luminosity

$$\mathcal{L} = f_{rep}\frac{n_b N^2}{4\pi\sigma_x\sigma_y}H_D \qquad (1)$$

- Can be written in terms of beam power and beastrahlung loss

$$\mathcal{L} \approx C\frac{P_B}{E}\sqrt{\frac{\delta_{BS}}{\epsilon_{y,n}}}\min\left(1, \sqrt{\sigma_z/\beta_y}\right) \qquad (2)$$

  - C : universal constant
  - PB = beam power
  - The last factor express the hour-glass effect approximately
  - δ_{BS} = beamstrahlung energy loss

$$\delta_{BS} = \left\langle -\frac{\Delta E}{E}\right\rangle \approx 0.836\frac{N^2 r_e^3\gamma}{\sigma_z\sigma_x^2}, \qquad (\Upsilon \ll 1,\ \sigma_x \gg \sigma_y) \qquad (3)$$

  - Beam size at IP

$$\sigma_x = \sqrt{\frac{\epsilon_{x,n}\beta_x^*}{\gamma}} \qquad (4)$$

Luminosity Scaling

- Naive scaling
  - (1) and (4) gives L ~ E (constant $\beta_{x,y}$)
- However, the form (2) says L can be ~1/E, if
  a. P_B independent of E
  b. δ_{BS} independent of E
- (a) is realized in "10 Hz collision"
  (i.e., same beam power with 10Hz@250GeV and 5Hz@500GeV)
  - But this is not realistic in the 250GeV in staging
    - Cost saving too small
- (b) is possible?
  - TDR parameter set says δ_{BS} ~ 1% at 250GeV
  - If 4% beamstrahlung is acceptable, luminosity can be doubled

How to Increase Beamstahlung

- Increase bunch charge
  - N → aN, (n_b → n_b/a so that PB does not change)
  - Then, δ_{BS} → $a^2\delta_{BS}$, L → aL
  - But this will
    - Make the out-coming angle of pairs sqrt(a) times
    - Changes of DR dynamics, alignment tolerance of ML
  - → unacceptable
- Shorter bunch length
  - σ_z → σ_z/a,
  - Then, δ_{BS} → aδ_{BS} , Can make β_y smaller (hour-glass),
  - → L increases
  - But this will
    - Make the out-coming angle of pairs sqrt(a) time
  - → unacceptabl
- Smaller horizontal beam size
  - σ_x → σ_x/a
  - Then, δ_{BS} → $a^2\delta_{BS}$, L → aL

How to reduce σ_x ?

- The simplest way is to reduce β_x
- But this will make the beam angle spread at IP larger

$$\theta_x^* = \sqrt{\frac{\epsilon_{x,n}}{\gamma \beta_x^*}} \qquad (5)$$

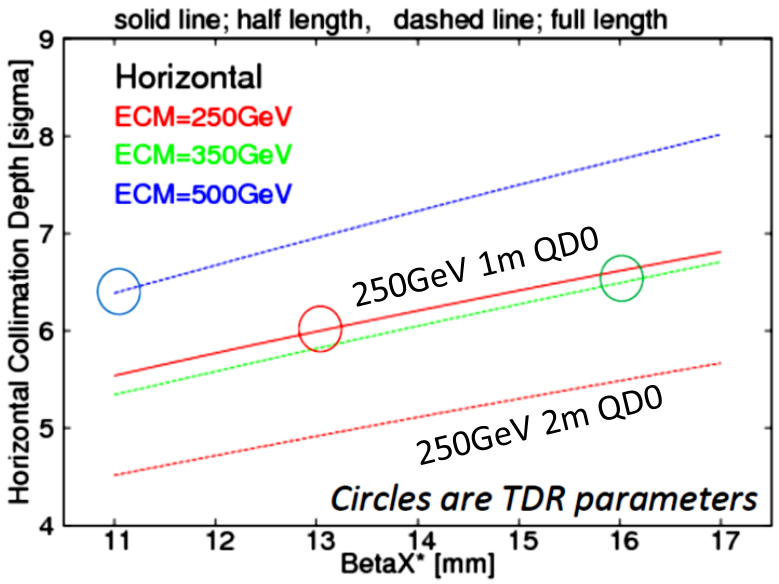
- → larger beam size at the final quad QD0
- Synchrotron radiation from tail particles hit the quad, causing back ground
- These particles must be collimated out upstream
- The horizontal collimation depth is already ~ 6 σ_x

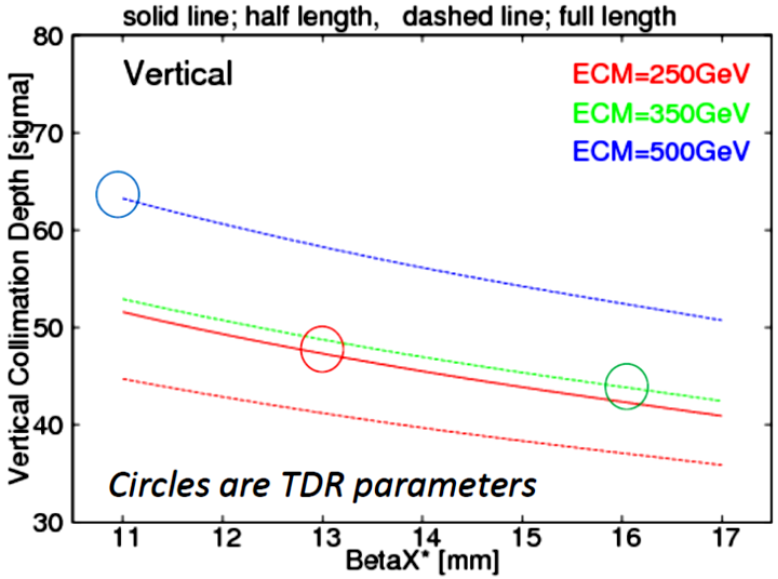
Collimation Depth with TDR Params

The collimation depth for various beam energy

ECM	BetaX*	BetaY*
250GeV	13mm	0.041mm
350GeV	16mm	0.034mm
500GeV	11mm	0.048mm

(QF1 L) = 9.5m*
(QD0 L) = 4.1m*





The circles shows the betas in TDR

T. Okugi

Horizontal Emittance

- σ_x can be reduced by reducing the horizontal emittance from DR
  - Present lattice is presumably conservative
  - Circular colliders assumes much more aggressive horizontal emittance
- If $\varepsilon_{x,n} \rightarrow \varepsilon_{x,n}/a$,
- Then, $\sigma_x \rightarrow \sigma_x$ /sqrt(a), $\delta_{BS} \rightarrow a\delta_{BS}$, L $\rightarrow$ sqrt(a)L.
- This will make horizontal beam angle 1/sqrt(a) smaller.
- If we further make $\beta_x \rightarrow \beta_x$ /a, then $\delta_{BS} \rightarrow a^2\delta_{BS}$, L $\rightarrow$ aL
- Smaller $\varepsilon_{x,n}$ would also help at other energies
  - Luminosity increase may be small but at least FFS tuning would become easier (allow larger β_x for same σ_x)

Problems

- Obvious problems are
  - Is it possible to reduce $\varepsilon_{x,n}$ of DR?
    - Technically possible?
    - Manpower problem
    - Now, Kiyoshi is trying …
    - Must include studies of e-cloud, FII, etc.
  - Disruption parameter too large

$$D_{x(y)} = \frac{2Nr_e}{\gamma} \frac{\sigma_z}{\sigma_{x(y)}(\sigma_x + \sigma_y)} \qquad (6)$$

  - Disruption parameter too large
    - $D_y \rightarrow aD_y$
    - Present D_y is already ~25
    - Feedback tolerance tighter

An Example Parameter Set

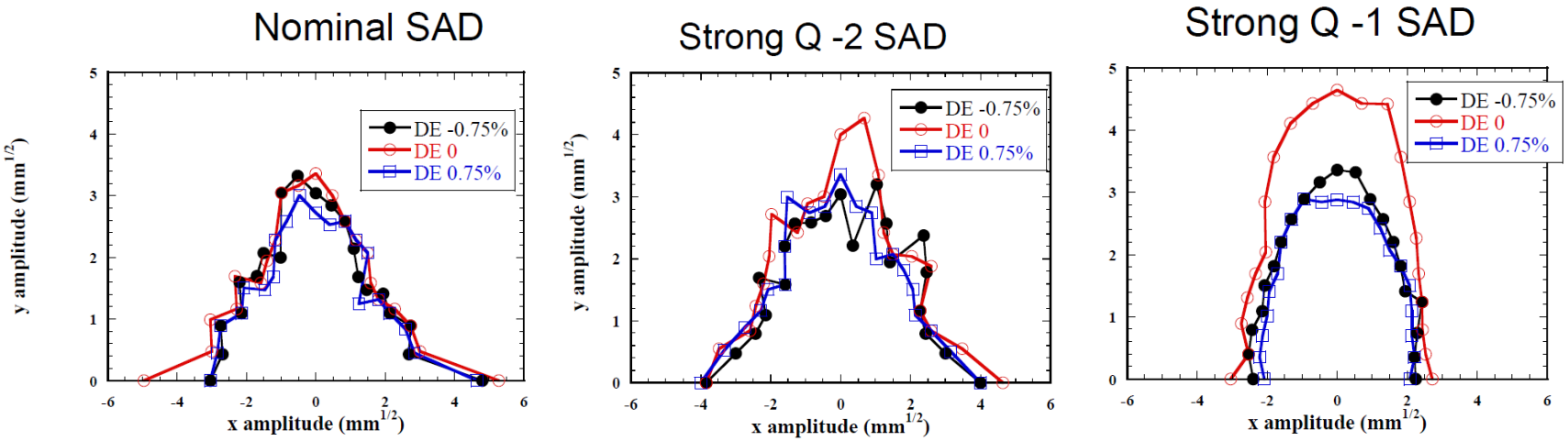
- Next page, right-most column
  - $\varepsilon_{x,n} \rightarrow \varepsilon_{x,n}/2$, no change of β_x
- However, note that $D_x \sim 0.5$ is not negligible
  - This will cause effective σ_x smaller than σ_x /sqrt(2)
  - Hence, δ_{BS} larger than $2\delta_{BS}$, L larger than sqrt(2)L
- Beam-beam simulation being done by Daniel Jeans (bottom-right corner) → talk by Daniel
  - First result shows L=1.65 LTDR = 1.35×10^{34} /cm^{2}s
- If everything is OK, may try smaller β_x

TDR (Combined TDR_machine_parameters_stamp.pdf and L study parameters 16-02-2012.xlsx

		Baseline						1TeV		New
							Full Power	A1	B1b	Param
Ecm	GeV	200	230	250	350	500	500	1000	1000	250
N	e10	2.0	2.0	2.0	2.0	2.0	2.0	1.737	1.737	2.0
Collision frequency	Hz	5.0	5.0	5.0	5.0	5.0	5.0	4.0	4.0	5.0
Electron linac rep rate	Hz	10.0	10.0	10.0	5.0	5.0	5.0	4.0	4.0	5.0
Nb		1312	1312	1312	1312	1312	2625	2450	2450	1312
Bunch separation	ns	554	554	554	554	554	366	366	366	554
Beam current	mA	5.78	5.78	5.78	5.78	5.78	8.75	7.60	7.60	5.78
PB	MW	4.2	4.8	5.3	7.4	10.5	21.0	27.3	27.3	5.3
sigz	mm	0.3	0.3	0.3	0.3	0.3	0.3	0.25	0.225	0.3
sige(e-)	%	0.206	0.193	0.188	0.156	0.124	0.124	0.083	0.085	0.188
sige(e+)	%	0.187	0.163	0.15	0.1	0.07	0.07	0.043	0.047	0.15
enx	μm	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	5.00
eny	nm	35.0	35.0	35.0	35.0	35.0	35.0	30.0	30.0	35.0
electron polarization	%	80	80	80	80	80	80	80	80	80
positron polarization	%	31	31	31	29	22	22	30	30	31
betax	mm	16.0	14.0	13.0	16.0	11.0	11.0	22.6	11.0	13.0
betay	mm	0.34	0.38	0.41	0.34	0.48	0.48	0.25	0.23	0.41
sigx	nm	904.2	788.7	729.0	683.5	474.2	474.2	480.6	335.3	515.5
sigy	nm	7.80	7.69	7.66	5.89	5.86	5.86	2.77	2.63	7.66
theta_x	μr	56.5	56.3	56.1	42.7	43.1	43.1	21.3	30.5	39.7
theta_y	μr	22.9	20.2	18.7	17.3	12.2	12.2	11.1	11.7	18.7
Dx		0.21	0.24	0.26	0.21	0.30	0.30	0.11	0.20	0.51
Dy		24.3	24.5	24.5	24.3	24.6	24.6	18.7	25.4	34.5
Upsilon (average)		0.013	0.017	0.020	0.030	0.062	0.062	0.128	0.203	0.028
Ngamma (formula)		0.95	1.08	1.16	1.23	1.72	1.72	1.43	1.97	1.62
deltaB (formula)	%	0.510	0.749	0.935	1.416	3.651	3.651	5.330	10.19	1.772
HDx		1.05	1.15	1.18	1.10	1.31	1.29	1.01	1.04	1.77
HDy		4.52	5.03	5.36	4.52	6.07	6.07	3.55	4.03	6.10
HD		1.69	1.84	1.90	1.73	2.09	2.07	1.53	1.62	2.43
Lgeo	1.0E+34	0.296	0.344	0.374	0.518	0.751	1.504	1.768	2.672	0.529
L (formula, no waist shift)	1.0E+34	0.501	0.632	0.712	0.896	1.567	3.117	2.706	4.337	1.285
L (simulation, waist shift)	1.0E+34	0.59	0.73	0.82	1.03	1.79	3.6	3.02	5.11	1.35

First Results of DR Redesign (K.Kubo)

- The simplest change
  - Same straight section, same circumference
  - Change of arc
    - (A) Stronger arc quadrupoles,
    - or (B) shorter arc cells (increase number of quadrupoles)
- Both (A) and (B) can reduce ε_{xn} to 3-3.5 μm (TDR ~5.7-6.0)
- Problem
- Dynamic aperture small. Can be improved?



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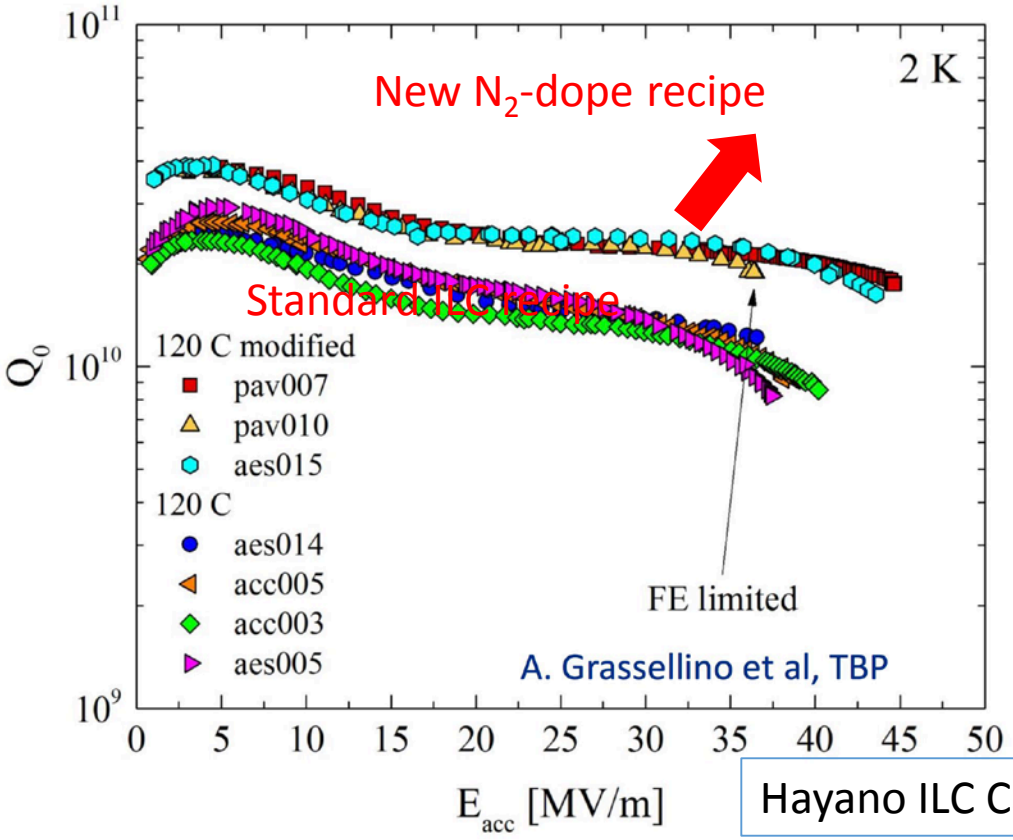
Nitrogen Infusion

Nitrogen doping after surface treatment showed higher Q0 (FNAL)
Adopted for LCLSII at SLAC

120C "modified" bake with N2 – repeatedly highest Q ever measured >2e10 at very high gradients>40 MV/m!

- Since early 2016, newly developed doping (now called Nitrogen Infusion) at FNAL showed high Gradient in addition to high Q
- low temperature 800C → 120C
- Not confirmed yet at other labs
- If realized in industry scale, can save ILC cost up to ~10%

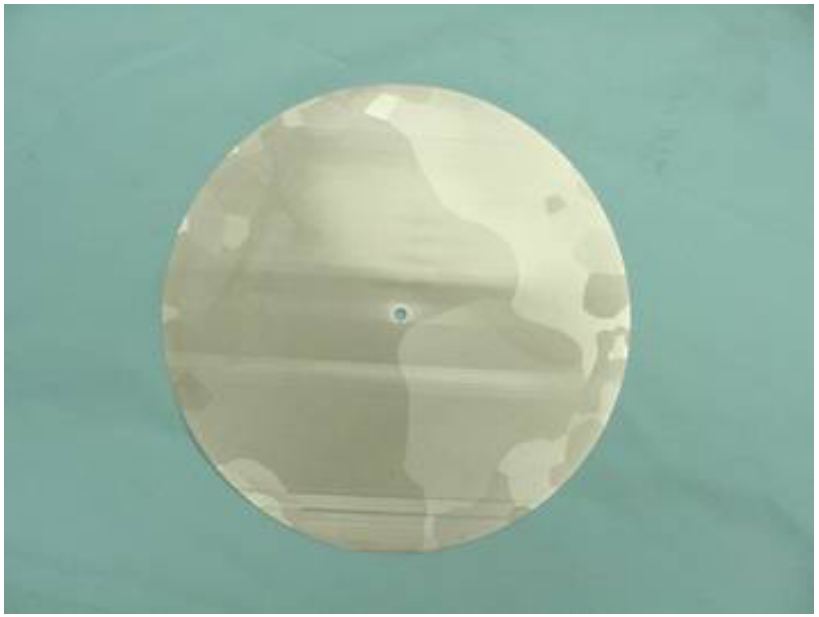


Hayano ILC Camp 2016

Niobium Disk

Fine Grain

Large Grain



The remarkable merit is higher Q_0 at lower gradient.

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lower residual resistance

K. Yamamoto