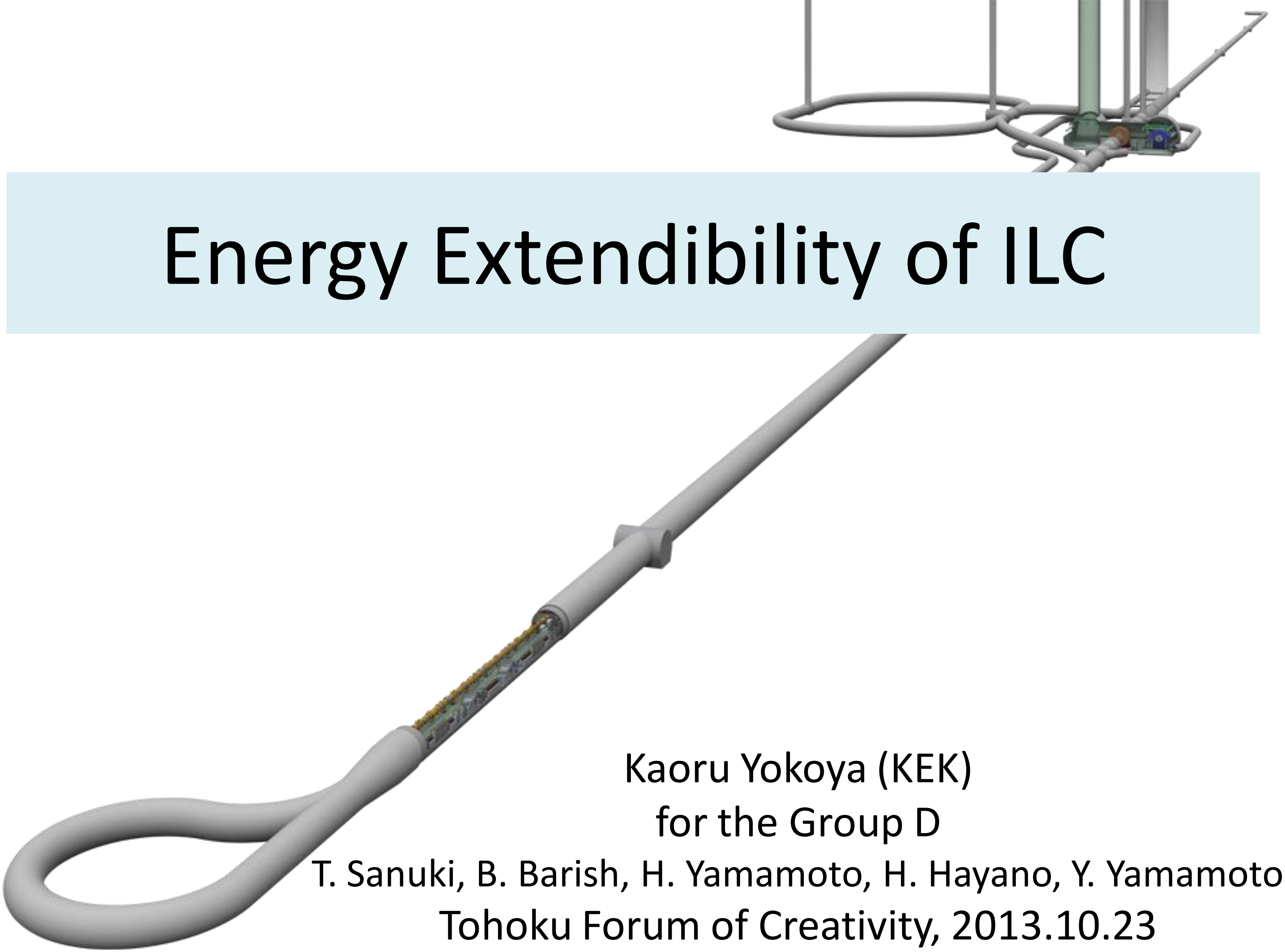
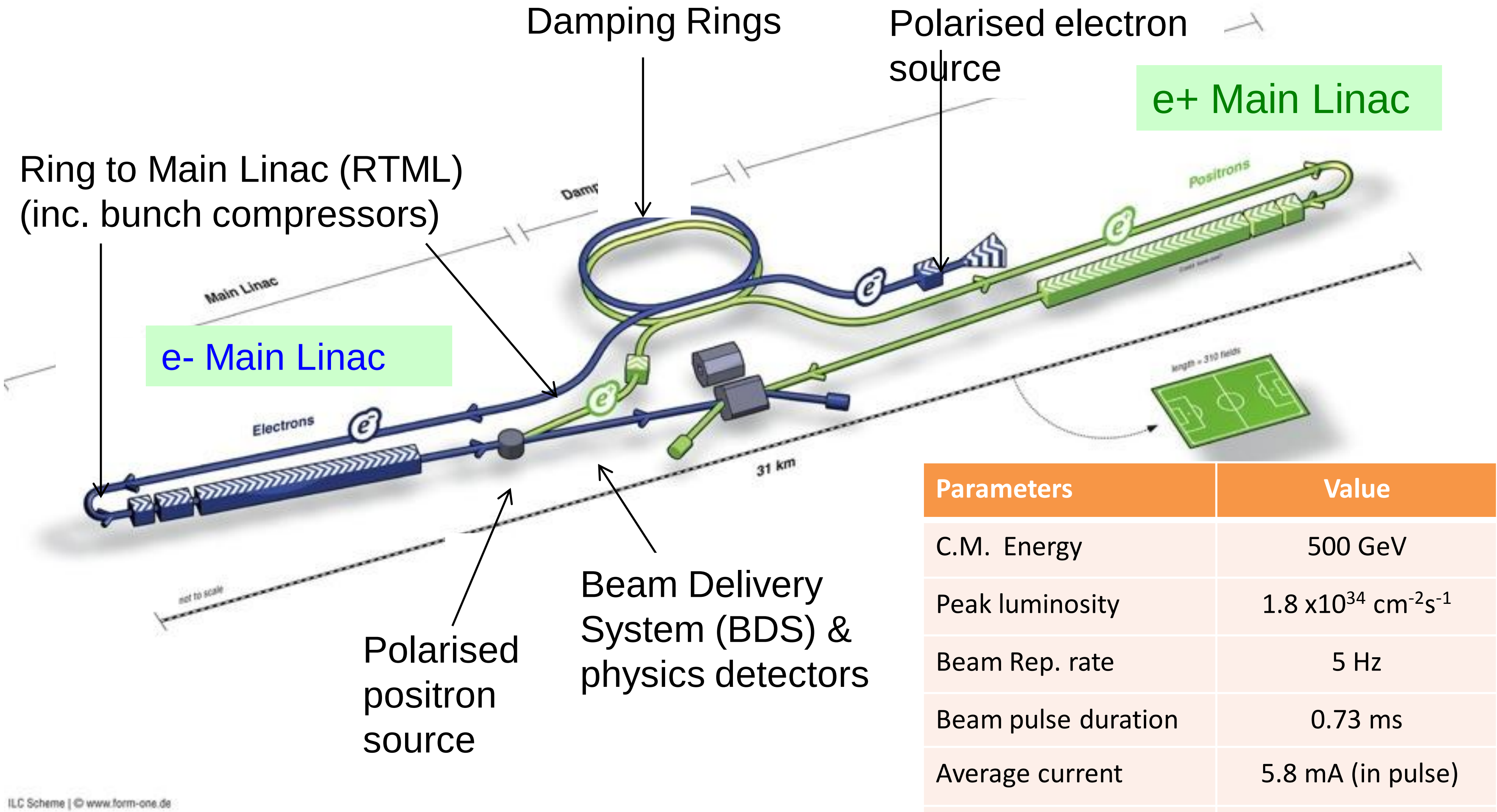


Energy Extendibility of ILC

Kaoru Yokoya (KEK)
for the Group D
T. Sanuki, B. Barish, H. Yamamoto, H. Hayano, Y. Yamamoto
Tohoku Forum of Creativity, 2013.10.23

Accelerator Outline



Damping Rings

Polarised electron source

e+ Main Linac

Ring to Main Linac (RTML) (inc. bunch compressors)

e- Main Linac

Polarised positron source

Beam Delivery System (BDS) & physics detectors

ILC Scheme | © www.form-one.de

Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} cm^{-2}s^{-1}
Beam Rep. rate	5 Hz
Beam pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
Gradient in SCRF acc. cavity	31.5 MV/m +/-20% Q_0 = 1E10

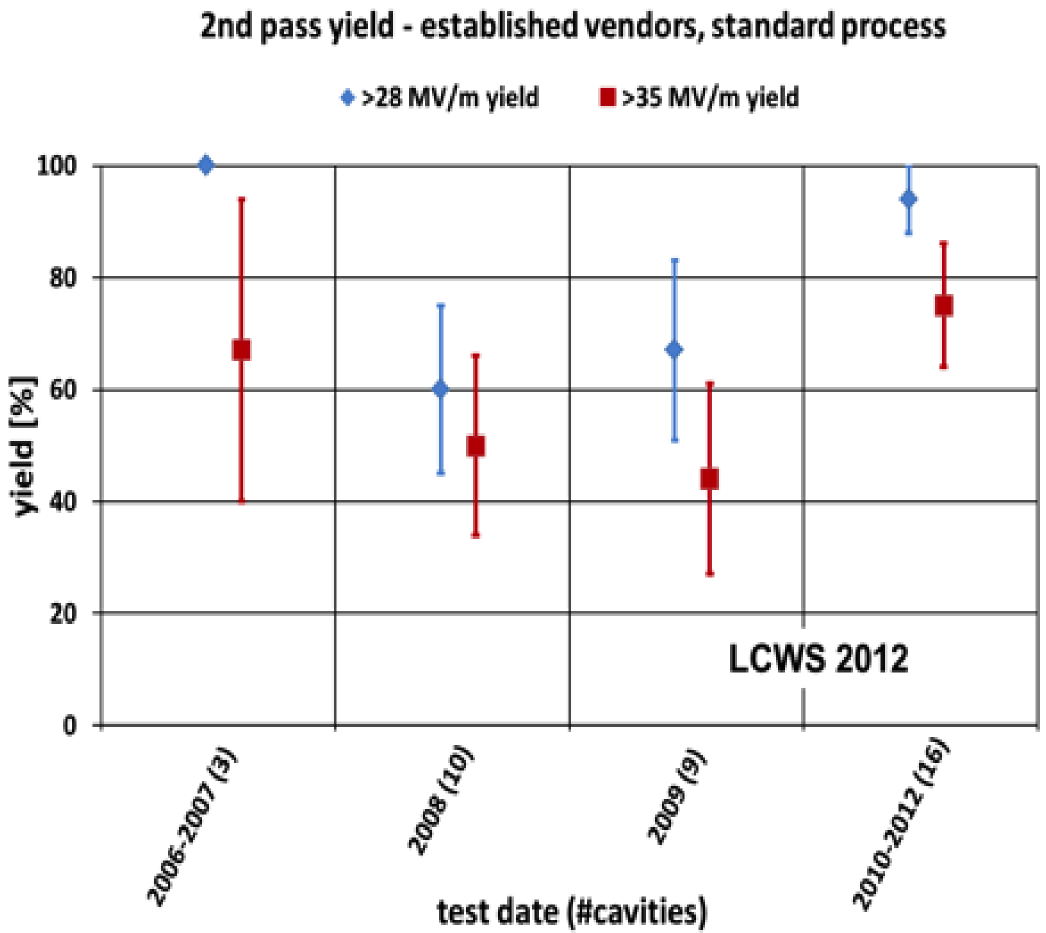
The Issue

- Technical Design Report (TDR) published last year
- Baseline design for center-of-mass energy 500GeV with a brief outline for upgrade to 1TeV
- Total length for 500GeV is ~31km
- Energy reach is determined by the site length and the accelerating gradient
- Question: how high an energy can we reach eventually at Kitakami site?
  - How long is Kitakami site?
  - How high is the ultimate accelerating gradient?
    - 500GeV machine design is based on the average accelerating gradient 31.5MV/m in cavities
  - Don’t care about the cost

ILC Cavity Performance Specification

- 500GeV Baseline
  - Performance test for Cavity only (so-called vertical test VT)
    - 35 MV/m (28 – 42 MV/m) (accept +-20% spread)
    - Q0 = 0.8 x 10^{10} @35 MV/m
    - Should be passed in twice V.T.s
    - Only EP/BCP as Surface Process
  - Cryomodule Operation with Beam
    - Average Gradient in a Cryomodule
      31.5 MV/m (25 – 38 MV/m) (accept +-20% spread)
    - Q0 = 1.0 x 10^{10} @31.5 MV/m
- 1TeV Extension (assumption in TDR)
  - VT ~ 50MV/m
  - Average gradient in a cryomodule **45MV/m**

Progress in SCRF Cavity Gradient (VT)



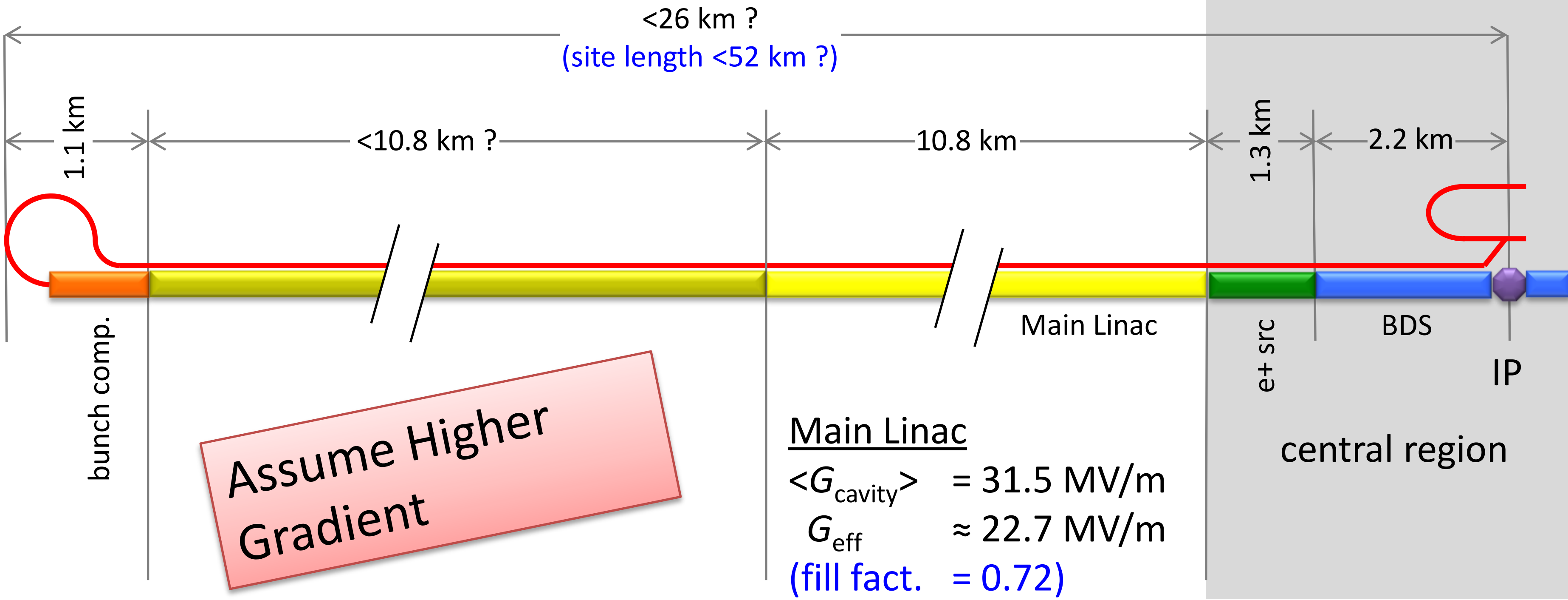
Production yield:
94 % at > 28 MV/m,

Average gradient:
37.1 MV/m

reached (2012)

A. Yamamoto, May2013, ECFA13

TeV Upgrade : From 500 to 1000 GeV



Assume Higher Gradient

Main Linac

$\langle G_{cavity} \rangle$ = 31.5 MV/m

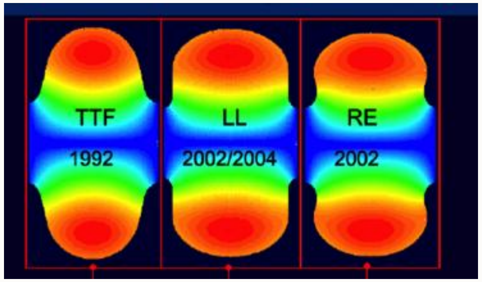
G_{eff} ≈ 22.7 MV/m

(fill fact. = 0.72)

Snowmass 2005 baseline recommendation for TeV upgrade:

G_{cavity} = 36 MV/m ⇒ 9.6 km

(VT ≥ 40 MV/m)



Based on use of low-loss or re-entrant cavity shapes

N.Walker, granada

TeV Upgrade in TDR

- Scenarios

A) Extend by present gradient 31.5MV/m

B) Use first step part as the high energy section, and add higher gradient (45MV/m) section upstream

C) Replace all by high gradient (45MV/m) cavities

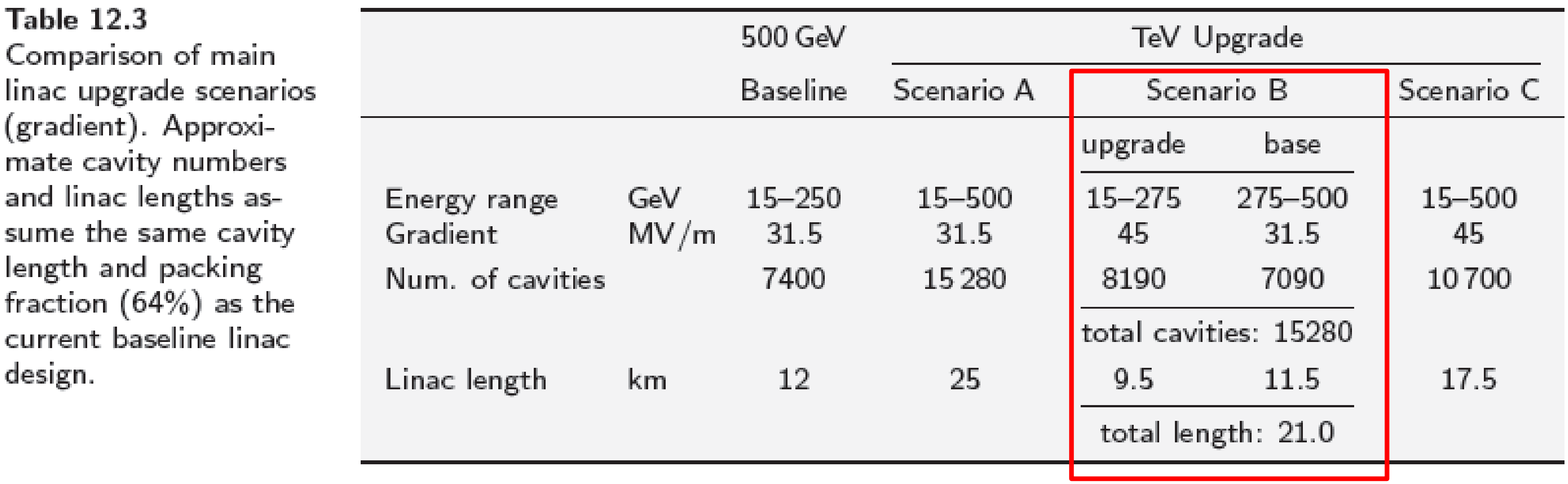
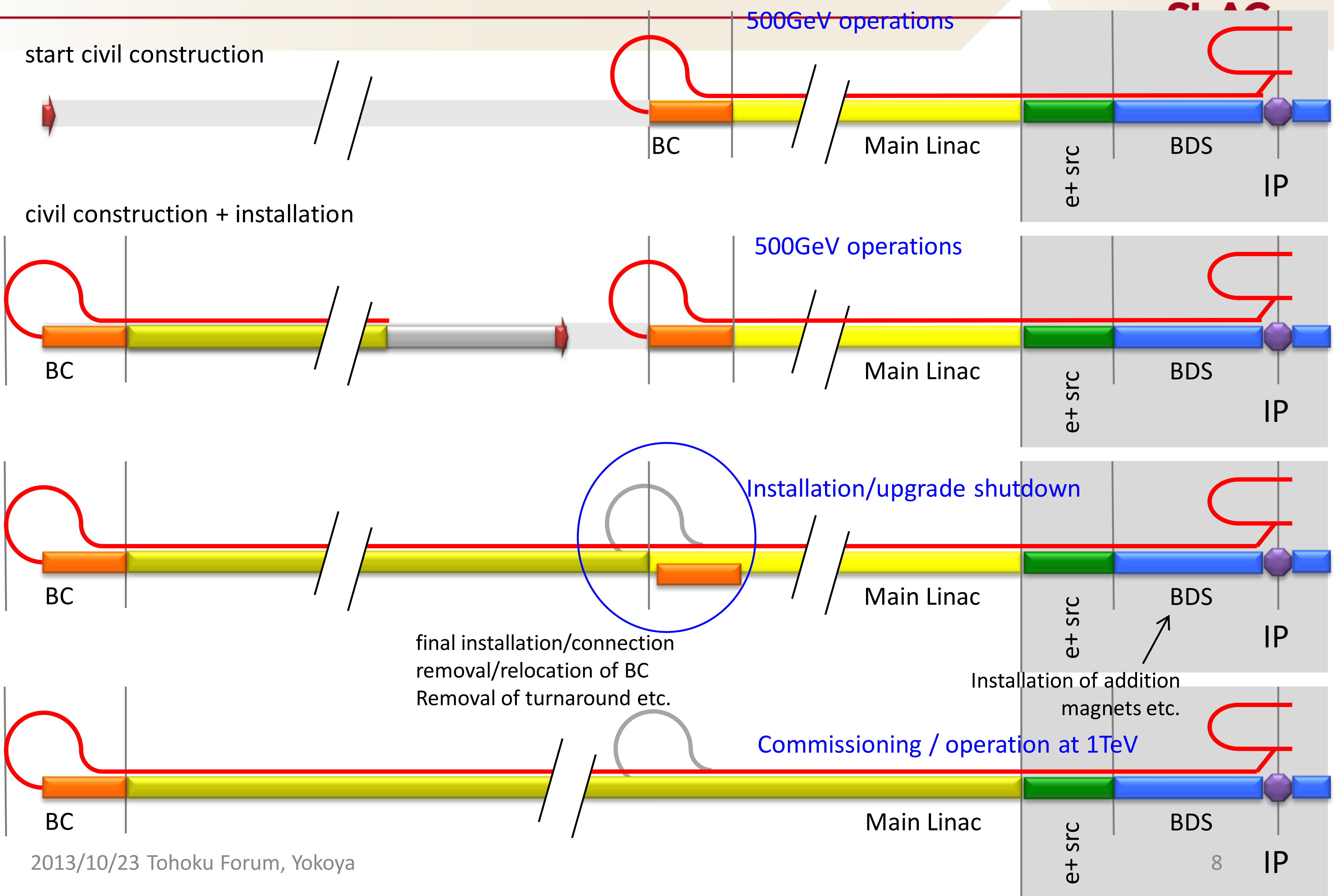


Table 12.3 Comparison of main linac upgrade scenarios (gradient). Approximate cavity numbers and linac lengths assume the same cavity length and packing fraction (64%) as the current baseline linac design.

		500 GeV	TeV Upgrade			
		Baseline	Scenario A	Scenario B		Scenario C
				upgrade	base	
Energy range	GeV	15–250	15–500	15–275	275–500	15–500
Gradient	MV/m	31.5	31.5	45	31.5	45
Num. of cavities		7400	15 280	8190	7090	10 700
				total cavities: 15280		
Linac length	km	12	25	9.5	11.5	17.5
				total length: 21.0		

TeV upgrade: Construction Scenario (B)


start civil construction

500GeV operations

civil construction + installation

500GeV operations

Installation/upgrade shutdown

final installation/connection
removal/relocation of BC
Removal of turnaround etc.

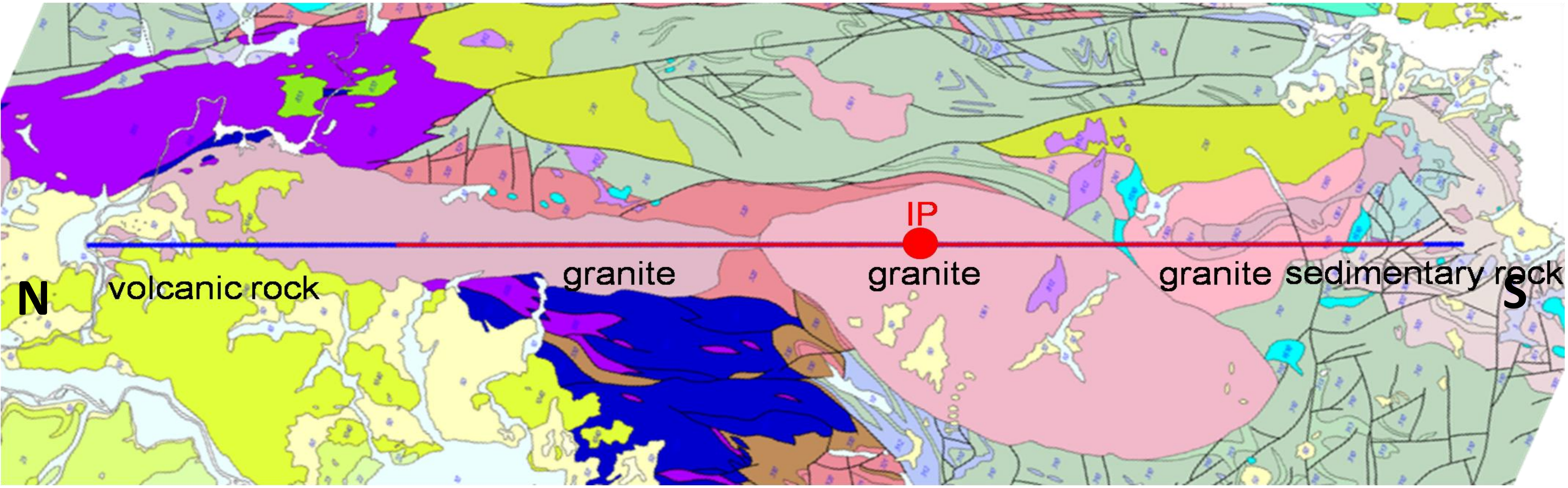
Installation of addition magnets etc.

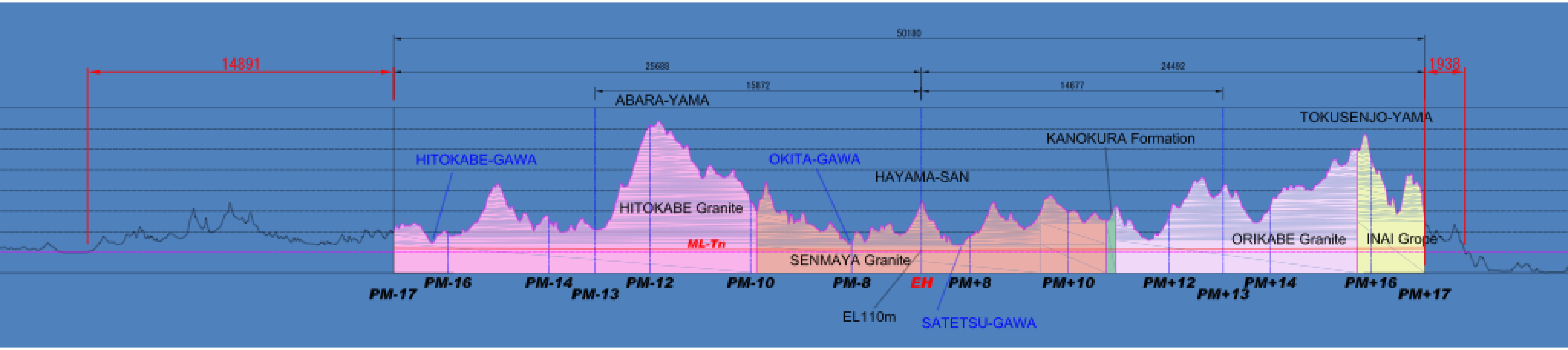
Commissioning / operation at 1TeV

CM Energy vs. Site Length

- Under the assumption
  - Scenario B (i.e., keep the 500GeV linac as the high energy part)
  - Available total site length L km
  - Operating gradient G MV/m
    (to be compared with 31.5 in the present design)
  - Assume the same packing factor
- Then, the final center-of-mass energy is
  Ecm = 500 + (L-31)*(G/45)*27.8 (GeV)
  - e.g., L=50km, G=31.5MV/m → 870GeV
    L=50km, G=45MV/m → 1030GeV
    L=67km, G=45MV/m → 1500 GeV
    L=67km, G=100MV/m → 2700 GeV
- This includes the margin ~1% for availability
- But does not take into account the possible increase of the BDS for Ecm>1TeV
  - Present design of BDS accepts 1TeV without increase of length
  - A minor point in increasing BDS length: laser-straight

Available Site Length at Kitakami



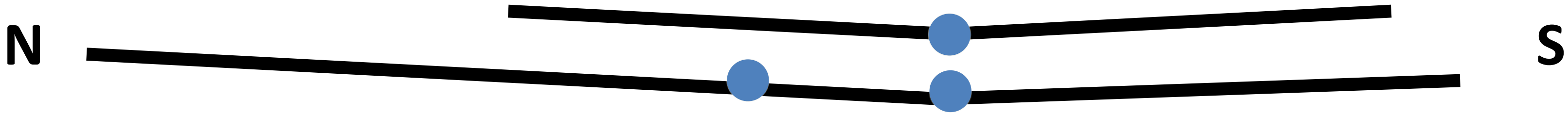


T.Sanuki

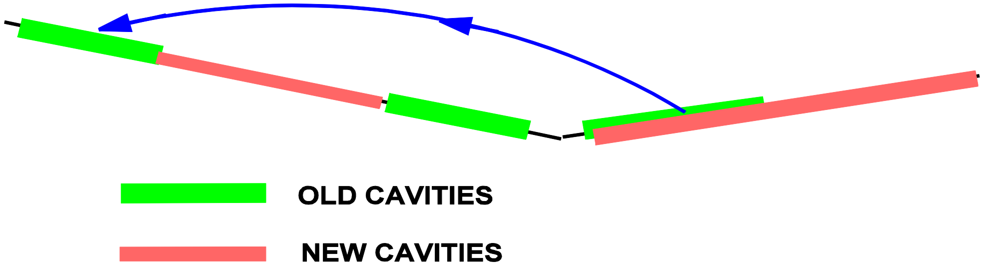
- Can be extended more to the north
- 14.9km + 50.2km + 1.9km = 67km
- 75km may be possible by further extension to the north

A Local Problem at Kitakami

- Once the first stage machine is built, it is almost impossible to move the IP (interaction point) in later stages because of the crossing angle



- Asymmetric collider may be acceptable
  - Asymmetric accelerator
  - Asymmetric energy
  - Asymmetric energy can be avoided to some extent by moving all the old cavities in the south arm to the north at the time of upgrade



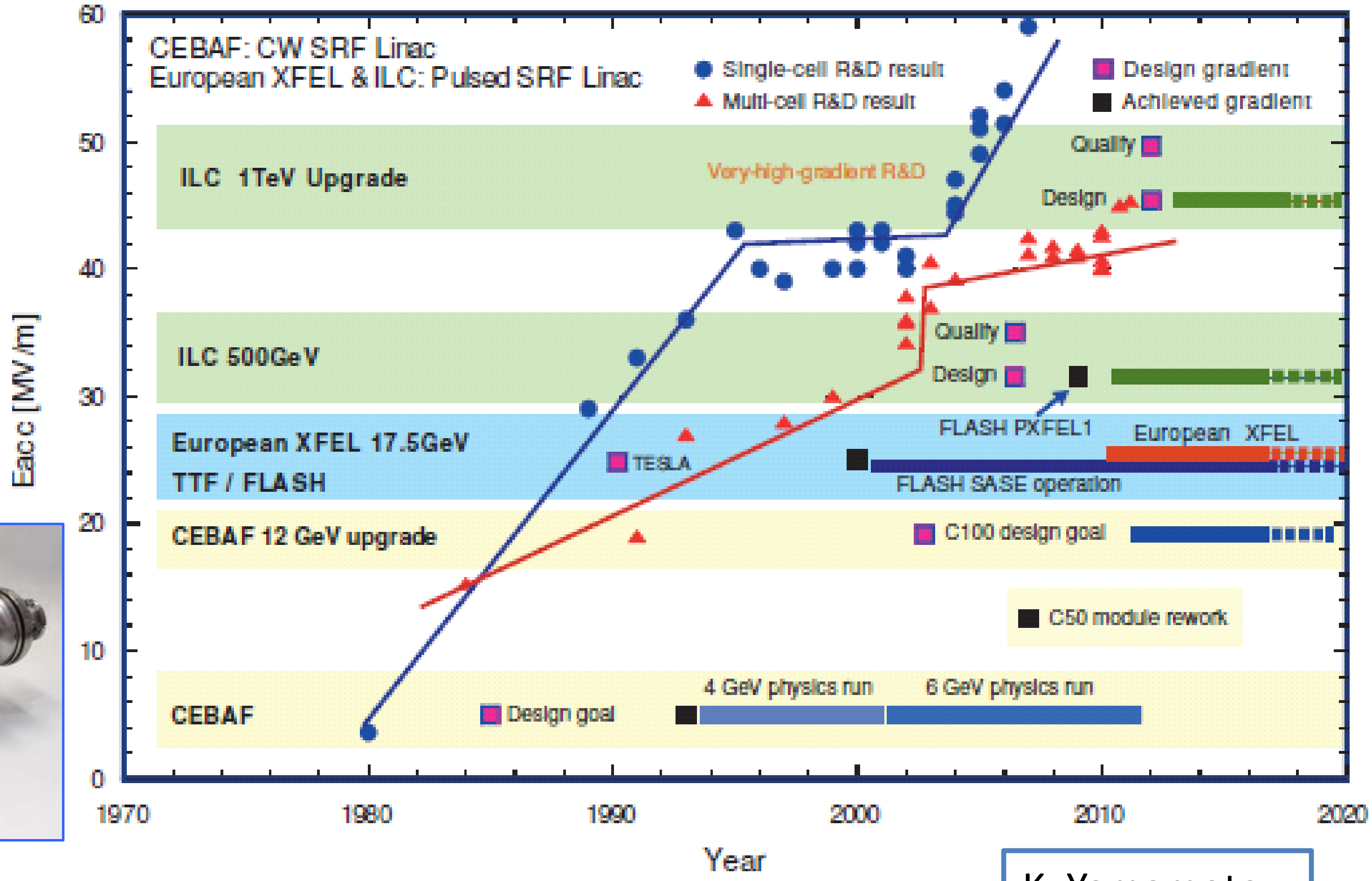
High Gradient Cavities

- Niobium
- Superconducting material other than niobium

Development of Niobium Cavities
Comparison of 1- and 9-cell performance

There is large gap between 1-cell and 9-cell cavity performance!

Figure 2.20
L-band SCRF niobium-cavity-gradient envelope and gradient R&D impact on SCRF linacs.



9-cell cavity

K. Yamamoto

9-cell performance is almost saturated?!

What approach can we take?

According to TDR (Volume 3, Part 1, Page 28)...

① Cavity Shape
  - Low Loss, Re-Entrant, Low Surface Field

② Material (niobium)
  - Large Grain, Seam-less

③ Surface Treatment
  - Recently, new idea trying

④ Packing Factor of Cryomodule
  - Exchanging Q-mag to Cavity

K. Yamamoto

① Cavity Shape

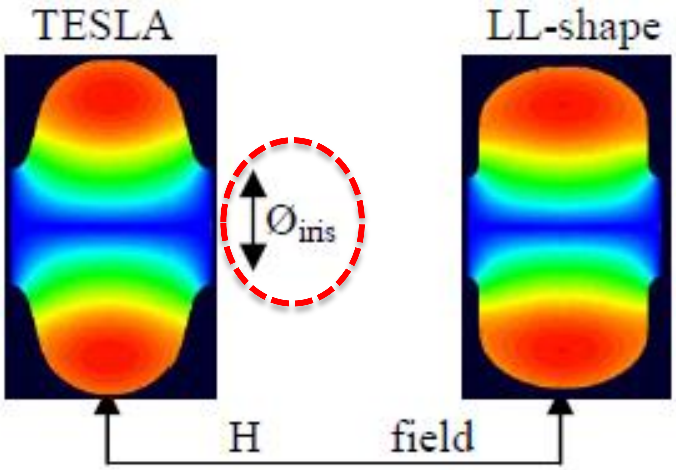
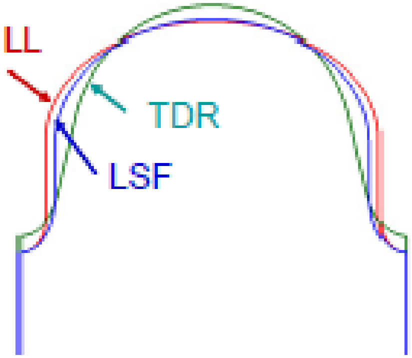


Figure 1: H contour in two shapes of inner cell.

Reduce the maximum magnetic field on the niobium surface



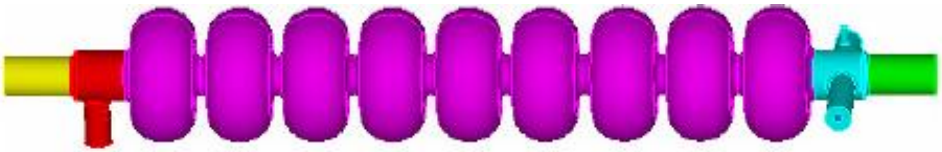


Figure 6: The 9-cell LSF cavity with coupler end-groups.

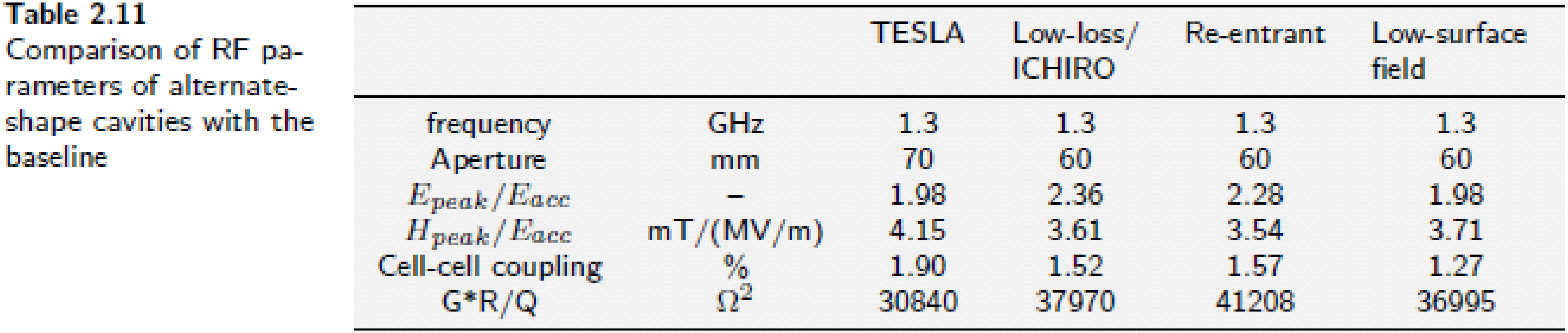


Table 2.11
Comparison of RF parameters of alternate-shape cavities with the baseline

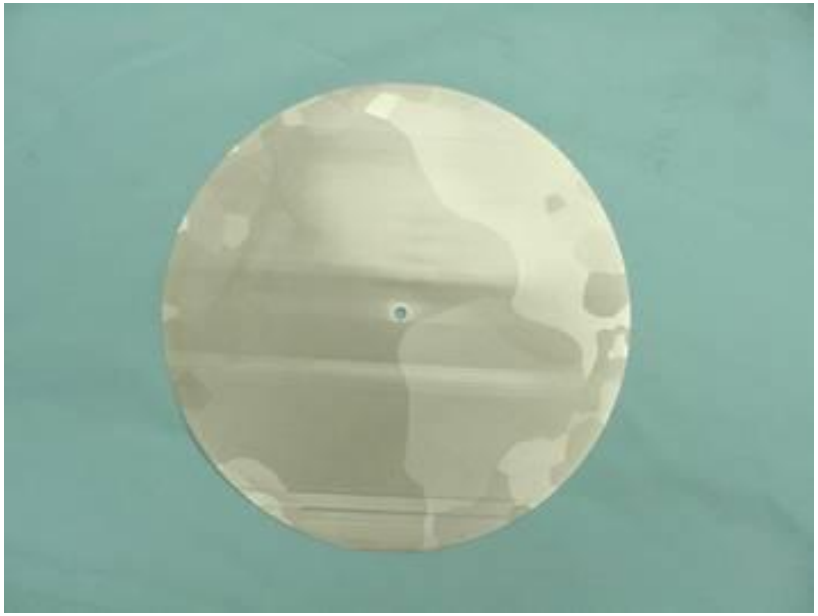
		TESLA	Low-loss/ ICHIRO	Re-entrant	Low-surface field
frequency	GHz	1.3	1.3	1.3	1.3
Aperture	mm	70	60	60	60
E_{peak}/E_{acc}	–	1.98	2.36	2.28	1.98
H_{peak}/E_{acc}	mT/(MV/m)	4.15	3.61	3.54	3.71
Cell-cell coupling	%	1.90	1.52	1.57	1.27
G*R/Q	Ω^2	30840	37970	41208	36995

K. Yamamoto

② Material

Fine Grain

Large Grain



The remarkable merit is higher Q_0 at lower gradient.

↓

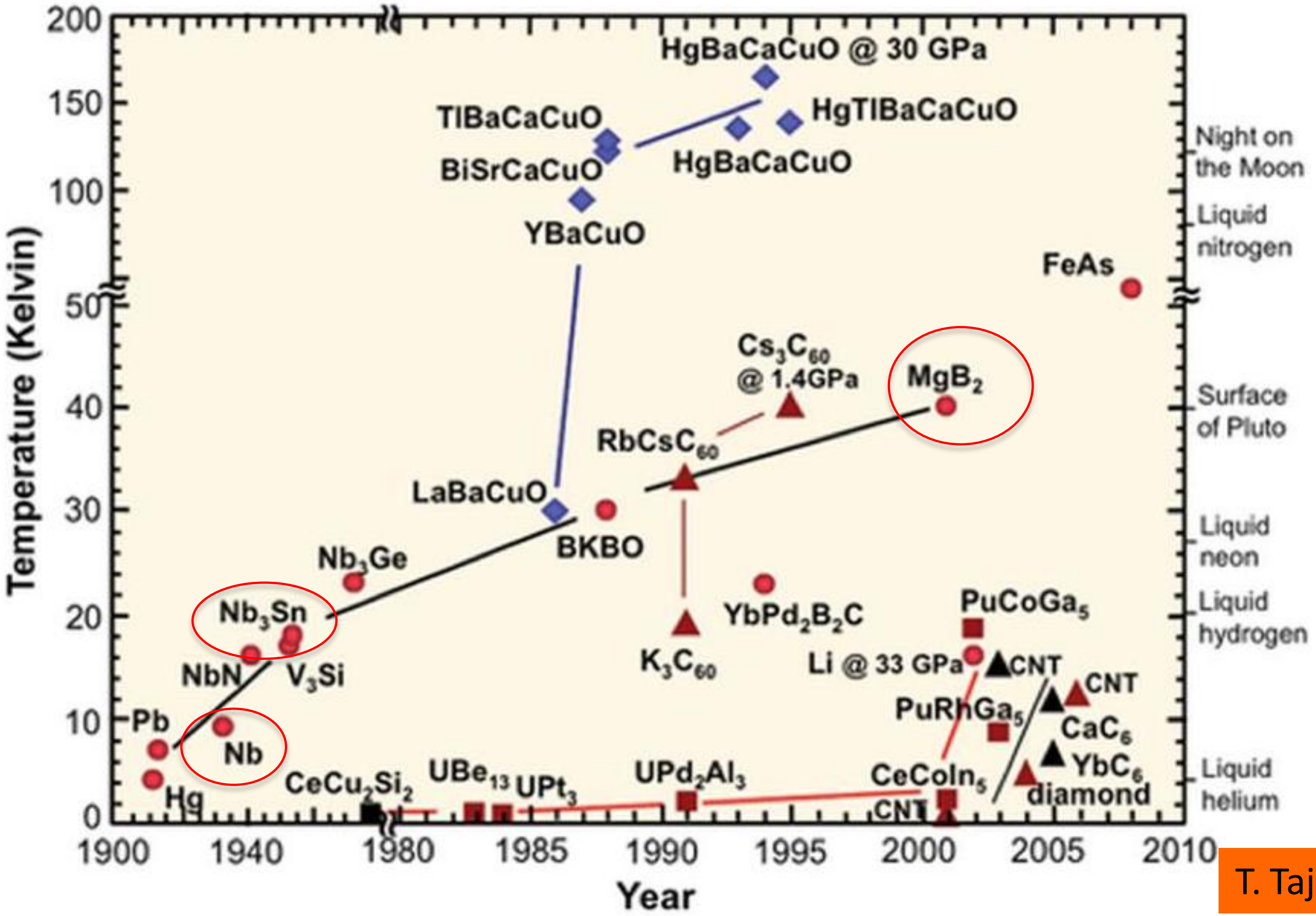
lower residual resistance

K. Yamamoto

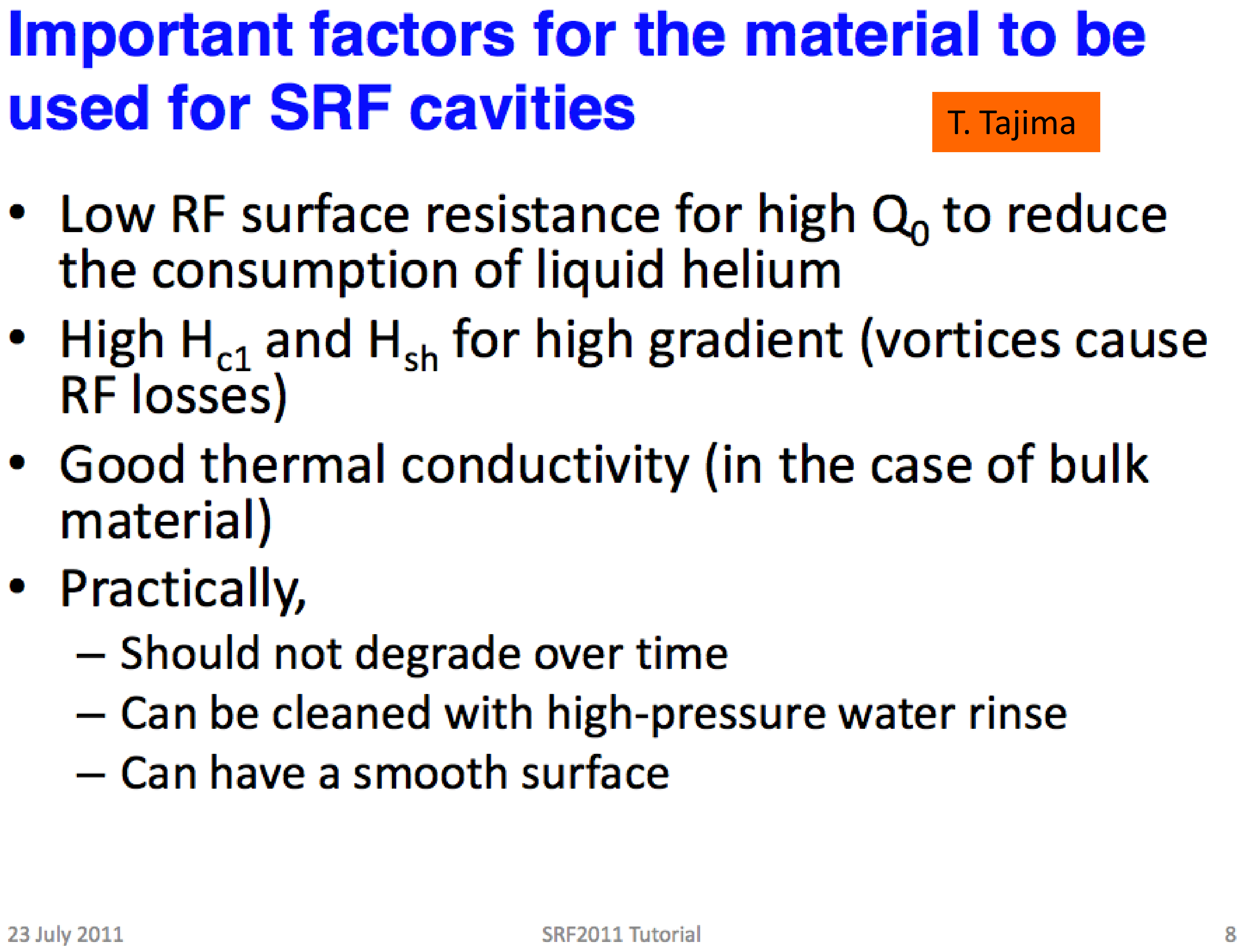
New Superconducting Material

Discoveries of Superconductors

http://en.wikipedia.org/wiki/File:Sc_history.gif



T. Tajima

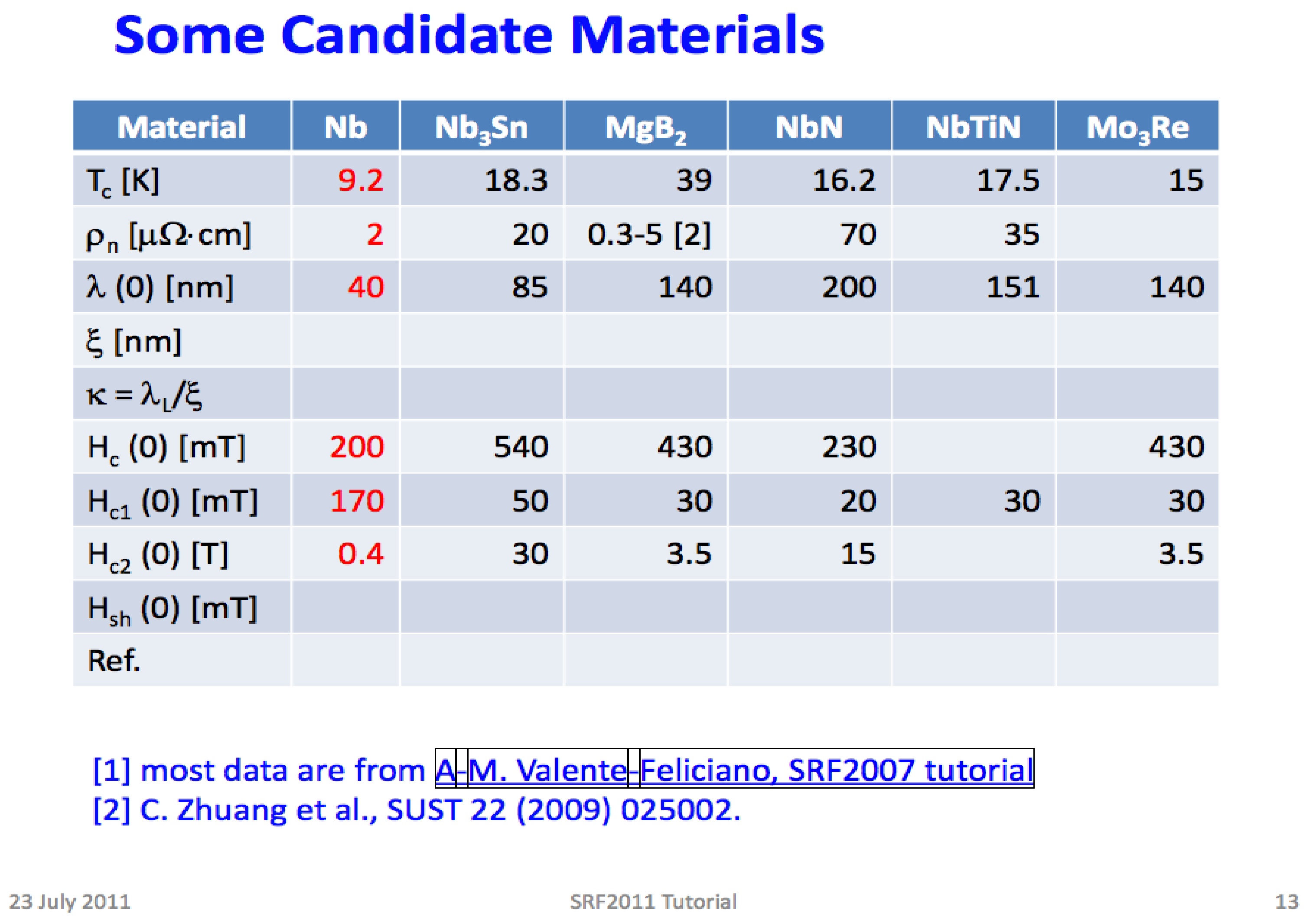


Important factors for the material to be used for SRF cavities

T. Tajima

- Low RF surface resistance for high Q_0 to reduce the consumption of liquid helium
- High H_{c1} and H_{sh} for high gradient (vortices cause RF losses)
- Good thermal conductivity (in the case of bulk material)
- Practically,
  - Should not degrade over time
  - Can be cleaned with high-pressure water rinse
  - Can have a smooth surface

T. Tajima



Some Candidate Materials

Material	Nb	Nb_3Sn	MgB_2	NbN	NbTiN	Mo_3Re
T_c [K]	9.2	18.3	39	16.2	17.5	15
ρ_n [$\mu\Omega\cdot$cm]	2	20	0.3-5 [2]	70	35	
λ (0) [nm]	40	85	140	200	151	140
ξ [nm]						
$\kappa = \lambda_L/\xi$						
H_c (0) [mT]	200	540	430	230		430
H_{c1} (0) [mT]	170	50	30	20	30	30
H_{c2} (0) [T]	0.4	30	3.5	15		3.5
H_{sh} (0) [mT]						
Ref.						

[1] most data are from A-M. Valente-Feliciano, SRF2007 tutorial
[2] C. Zhuang et al., SUST 22 (2009) 025002.

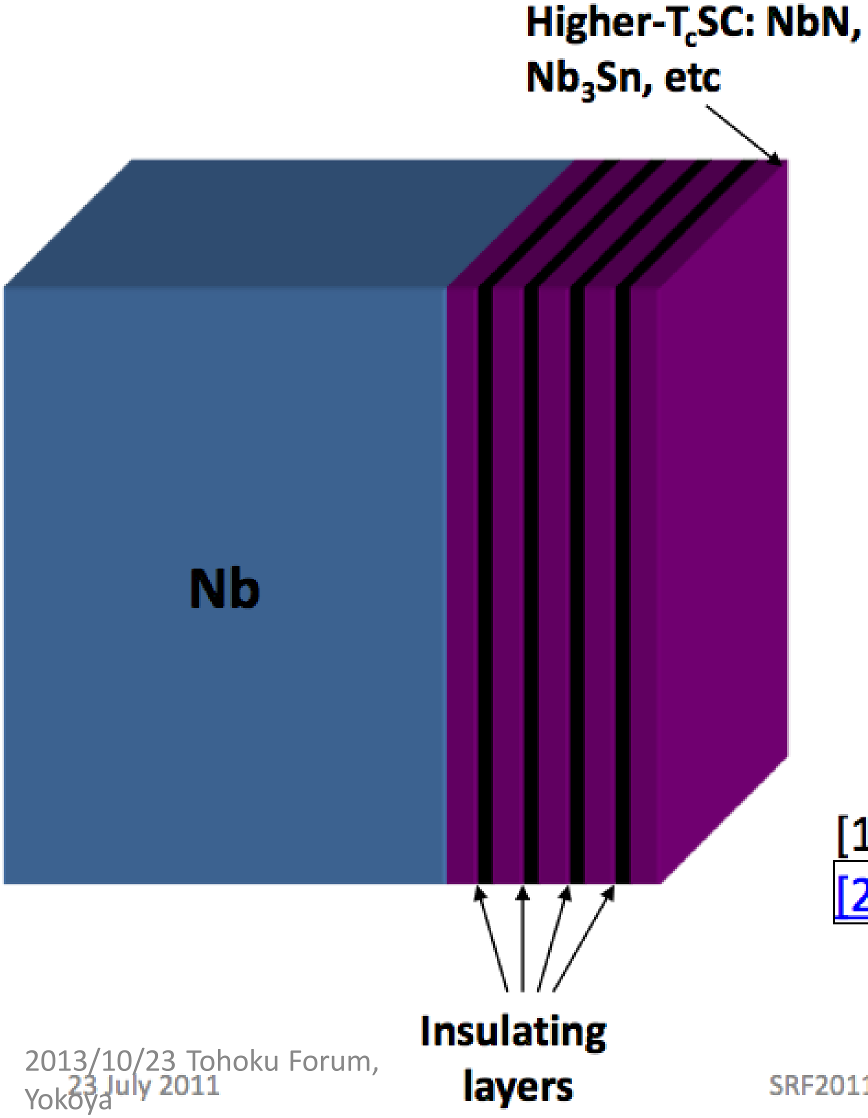
Good candidates:

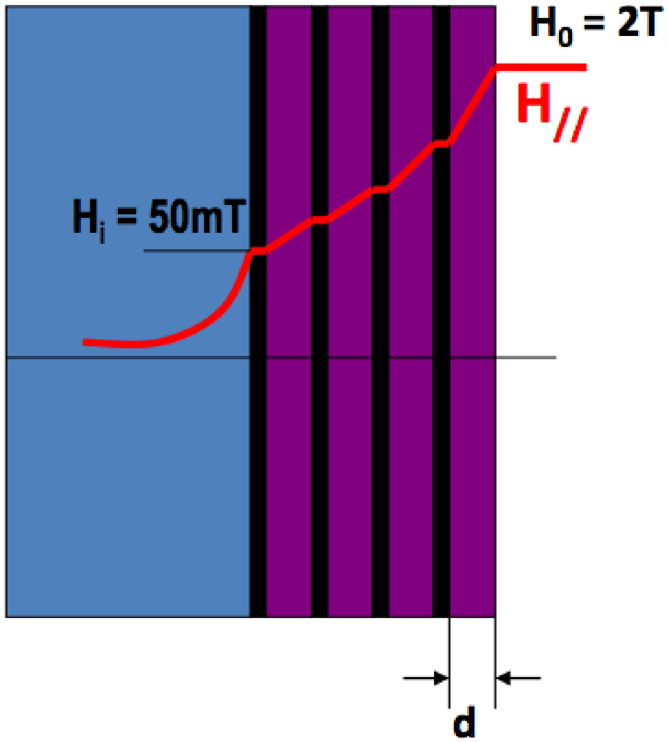
Nb_3Sn : tri-niobium tin

MgB_2 : magnesium di-boride

T. Tajima

Multilayer thin film superconductors concept proposed by Alex Gurevich [1, 2]





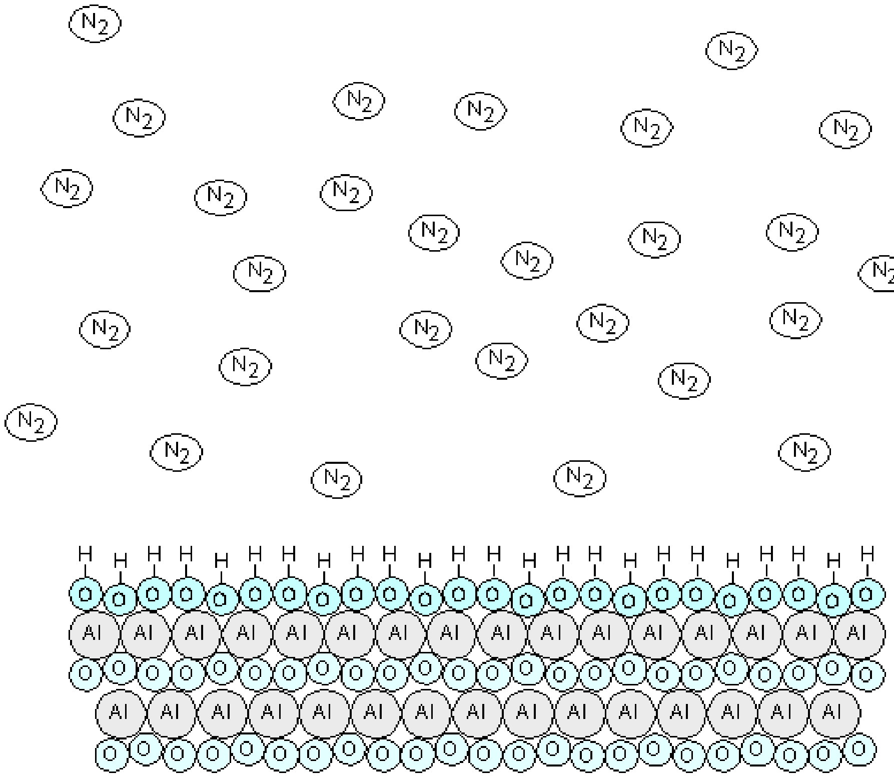
[1] A. Gurevich, APL **88** (2006) 012511

[2] A. Gurevich, SRF Materials Workshop, FNAL, 23-24 May 2007

How to make a thin layer on niobium

Atomic layer deposition (ALD)

- A thin film synthesis process based on sequential, self-limiting surface reactions between vapors of chemical precursors and a solid surface to deposit films in an atomic layer-by-layer manner.



Application of “thin-film on Nb” to ILC?

Technology of;

(1) nm-level Smooth Nb cavity surface,

Tumbling, electro-polish, etc.

Hydroforming without welding.

(2) Well controlled thin-film formation on Nb cavity,

Atomic Layer Deposition (ALD)

will be required.

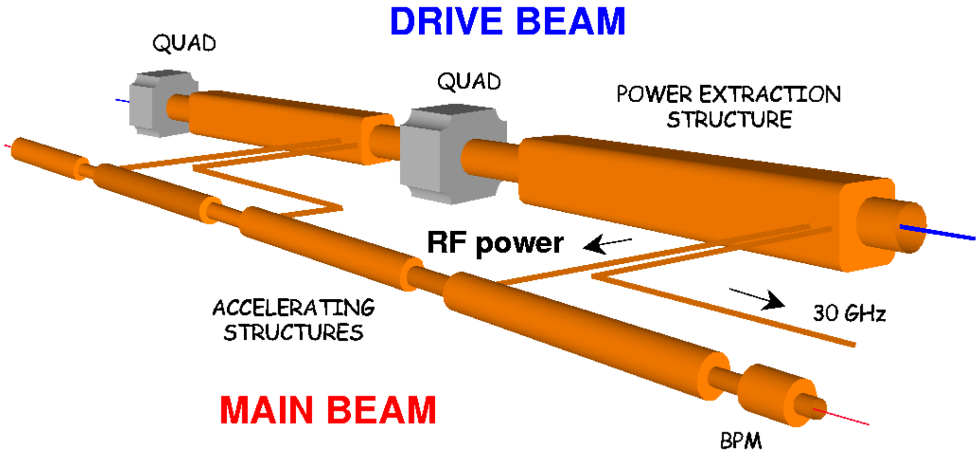
Then, we can reach >100MV/m with TESLA cavity shape.

H.Hayano

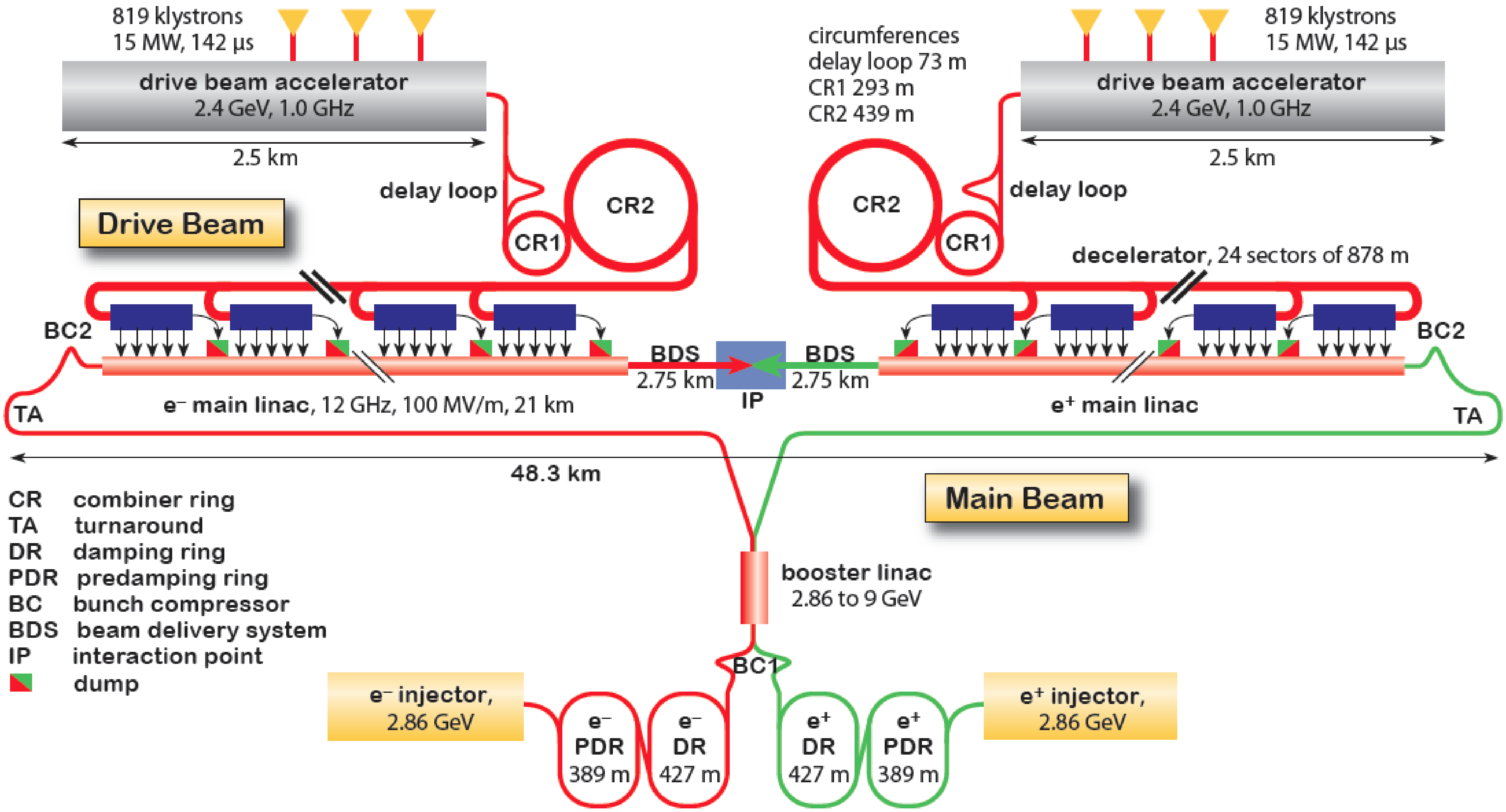
CLIC (Compact(CERN) Linear Collider)

- CLIC is anther linear collider technology (normal-conducting)
- Has been developed under CERN leader ship
- Now in international framework
  - Part of LCC (Linear Collider Collaboration)
- Conceptual Design Report (CDR) completed
  - Still premature for construction start
  - But will be ready by the time 500GeV ILC completion

- Can reach 3TeV in a 50km site



CLIC Complex



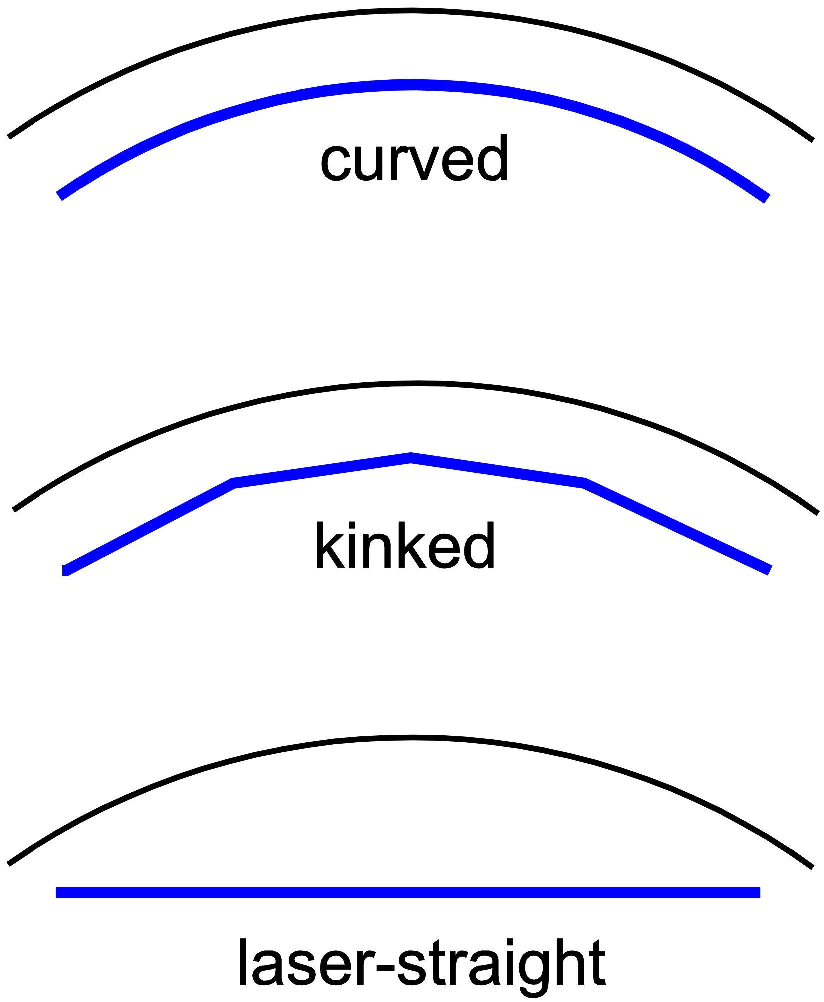
CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
🟥	dump

A technical point:
Difference of the Tunnels of ILC and CLIC

- Cost saving by reuse of tunnel is ~1.2B$
  - CLIC-ILC General Issue Group Interim Report 1
  - http://ilcdoc.linearcollider.org/record/31959/files/CLIC_ILC_Interim-Report_Final-1.pdf
  - In addition, save 0.25B$ if reuse Main linac klystron for CLIC driver (but CLIC frequency must be changed 12GHz→11.7GHz)
- Crossing angle (for e+e-)
  - 20mrad for CLIC (3TeV), 14mrad for ILC
  - Are these really necessary?

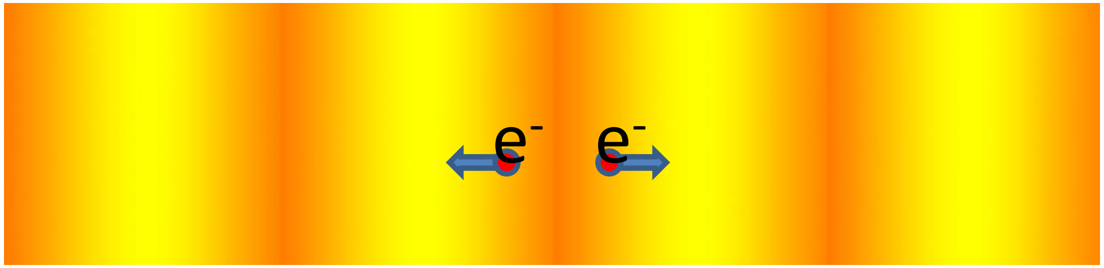
Laser-straight vs. geoid-following

- CLIC: laser-straight
- ILC: geoid-following
- Does geoid-following allow 3TeV?
- Emittance increase by radiation is tolerable
- The largest issue now is the calibration error of BPMs (beam position monitor)
- This can be solved in 20 years, I believe



Another Solution: Plasma Accelerator

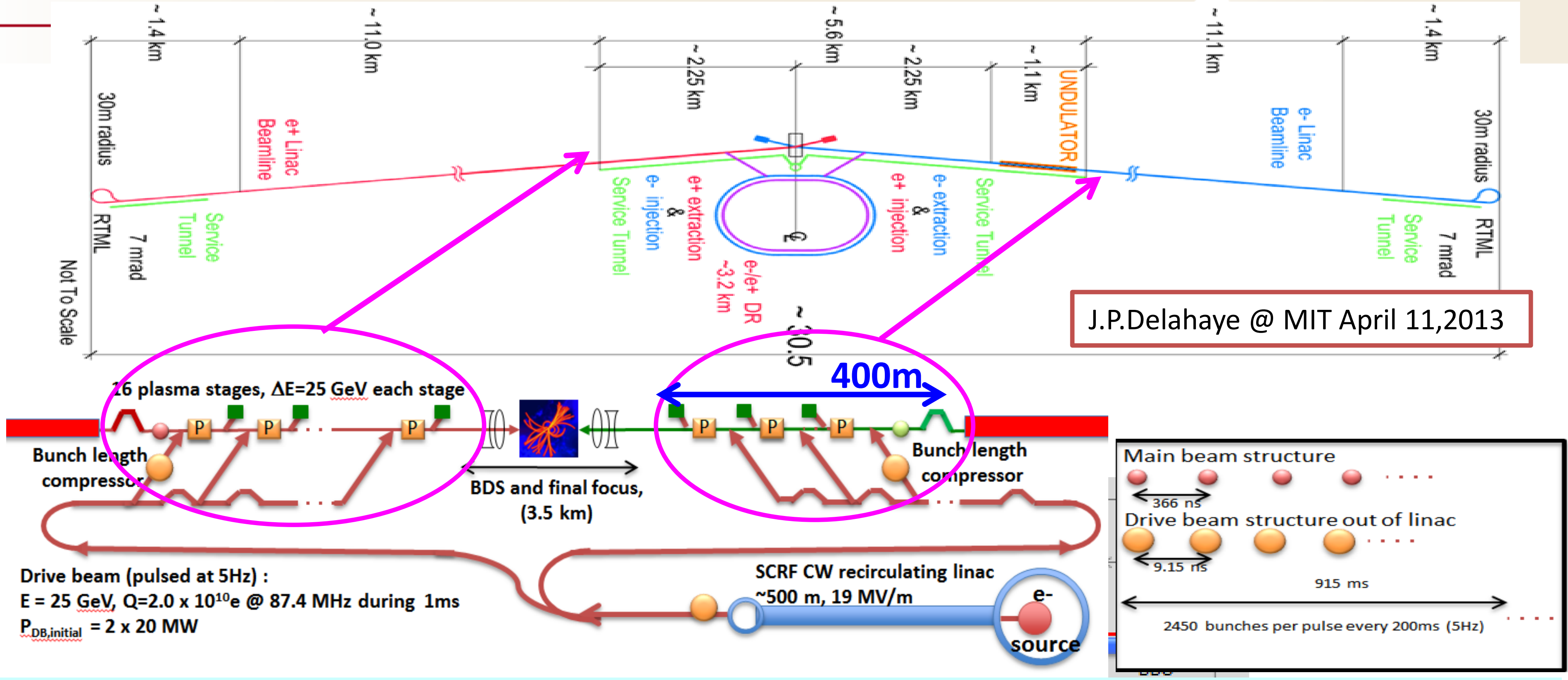
- Linac in the past has been driven by microwave technology
- Plane wave in vacuum cannot accelerate beams: needs material to make boundary condition
- →Breakdown at high gradient
  - binding energy of matter: eV/angstrom = 10GeV/m
- **Plasma wave** can accelerate electrons (and positrons)
- Need not worry about breakdown with plasma
  - can reach > 10GeV/m



How to Generate Plasma Wave

- LWFA (Laser Wakefield Accelerator)
  - Use ultra-short laser beam
  - Being developed everywhere in the world
- PWFA (Plasma Wakefield Accelerator)
  - Use particle (normally electron) beam of short bunch
  - Bunch pattern is more flexible than in LWFA (not constrained by the laser technology)
  - R&D works led by SLAC (FACET/FACET2)
- In both cases the driving beam
  - determines the phase velocity of plasma wave, which must be close to the velocity of light
  - must be shorter than the plasma wavelength required
  - can also ionize neutral gas to create plasma
- My personal opinion: PWFA is more suited than LWFA to large scale accelerators like a linear collider

An alternative ILC upgrade by PWFA



J.P.Delahaye @ MIT April 11,2013

One possible scenario could be:

1) Build & operate the ILC as presently proposed up to 250 GeV (125 GeV/beam): total extension 21km
2) Develop the PFWA technology in the meantime (up to 2025?)
3) When ILC upgrade requested by Physics (say up to 1 TeV), decide for ILC or PWFA technology:
4) Do not extend the ILC tunnel but remove latest 400m of ILC linac (beam energy reduced by 8 GeV)
5) Reuse removed ILC structures for PWFA SC drive beam accelerating linac (25 GeV, 500m@19MV/m)
6) Install a bunch length compressor and 16 plasma cells in latest part of each linac in the same tunnel for a 375+8 GeV PWFA beam acceleration (382m)
7) Reuse the return loop of the ILC main beam as return loop of the PWFA drive beam

ILC upgrade from 250 GeV to 1 TeV by PWFA

Parameter	Unit	ILC	ILC	ILC (to 250GeV) + PWFA
Energy (cm)	GeV	250	1000	PFWA = 250 to 1000
Luminosity (per IP)	10^{34}cm^{-2}s^{-1}	0.75	4.9	4.9
Peak (1%)Lum(/IP)	10^{34}cm^{-2}s^{-1}	0.65	2.2	2.2
# IP	-	1	1	1
Length	km	21	52	21
Power (wall plug)	MW	128	300	128+135*1.2=290?
Polarisation (e+/e-)	%	80/30	80/30	80/30
Lin. Acc. grad. (peak/eff)	MV/m	31.5/25	36/30	7600/1000
# particles/bunch	10^{10}	2	1.74	1.74
# bunches/pulse	-	1312	2450	2450
Bunch interval	ns	554	366	366
Average/peak current	nA/mA	21/6	22.9/7.6	22.9/7.6
Pulse repetition rate	Hz	5	4	5
Beam power/beam	MW	2.63	13.8	13.8
Norm Emitt (X/Y)	$10^{-6}/10^{-9}$rad-m	10/35	10/30	10/30
Sx, Sy, Sz at IP	nm,nm,μm	729/6.7/300	335/2.7/225	485/2.7/20
Crossing angle	mrad	14	14	14
Av # photons	-	1.17	2.0	1.0
δb beam-beam	%	0.95	10.5	16
Upsilon	-	0.02	0.09	0.8

J.P.Delahaye @ MIT April 11,2013

What’s Needed for PWFA

- **Beam quality**
  - Small energy spread << 1%
  - emittance preservation (alignment, instabilities, laser stability, Coulomb scattering)
- **High power efficiency** from wall-plug to beam
  - Wall-plug → driving beam
  - driving beam → plasma wave
  - plasma wave → beam (high-beam loading required)
- Staging (BELLA at LBNL--- 2 stage acceleration to 10GeV) (mainly for LWFA)
  - laser phase (Laser-driven)
  - beam optics matching
- Positron acceleration
- Beam-beam interaction
- Very high component reliability
- Low cost per GeV
- **Colliders need all these, but other applications need only some of these**
  - Advantage of LWFA (PWFA requires big drive linac)
- Application of plasma accelerators would start long before these requirements are established

Conclusion

- ILC can be certainly extended to ~1TeV by a natural extension of the present technology of niobium cavity
  - Can be 1.5TeV with full use of 67km site
- Even higher energy might be reached (3TeV?) using a new SC technology such as thin film
- Obviously, quantitative studies are needed including the luminosity estimation, etc.
- CLIC technology allows to reach ~3TeV in the prepared Kitakami site (~50km)
- Plasma accelerator technology may bring about even higher energy (after several tens of years)