ILC加速器概要

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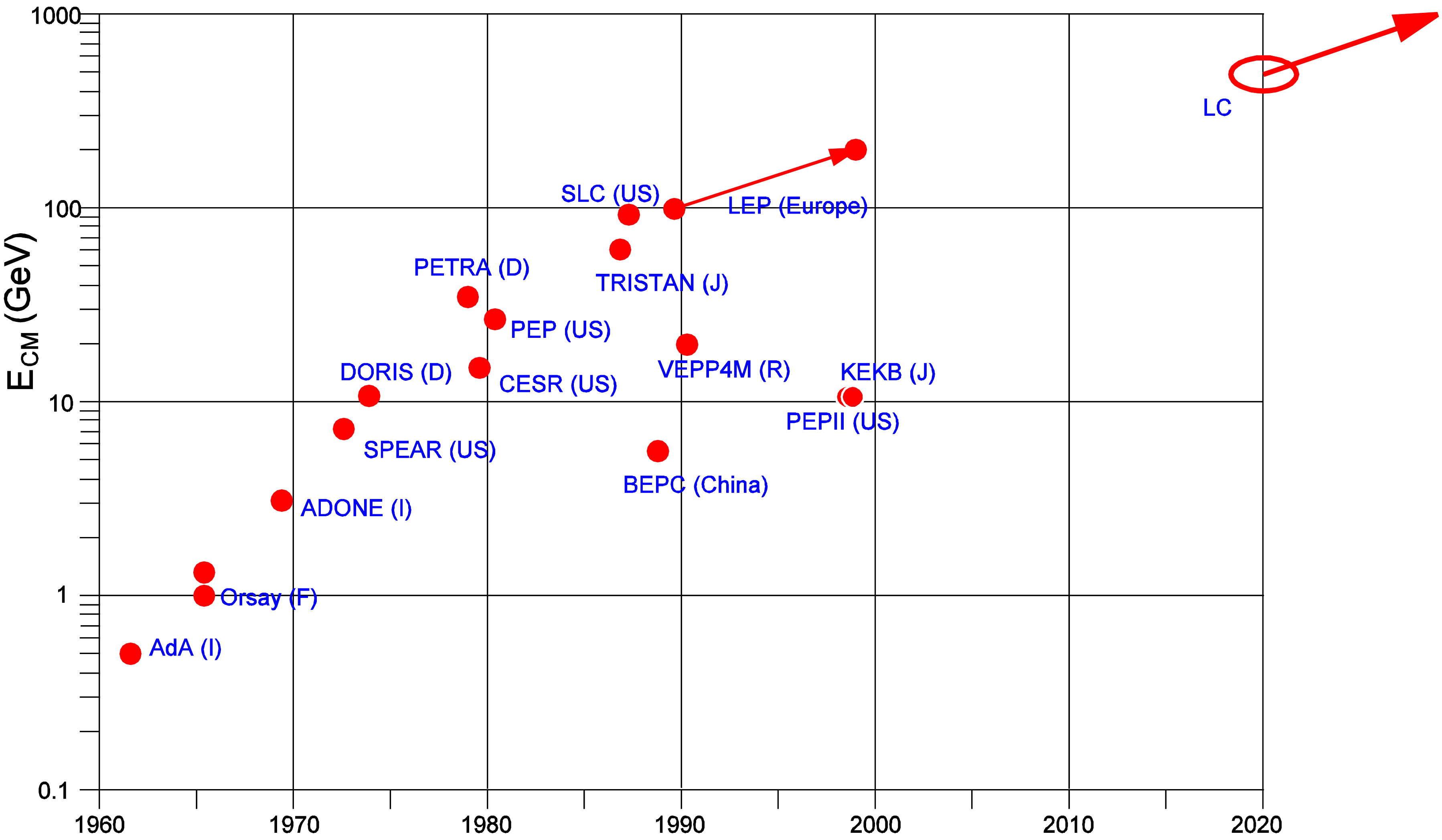
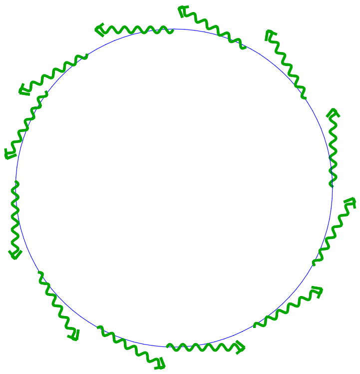
理研仁科センター

Evolution of Electron-Positron Colliders



シンクロトロン輻射

- 荷電粒子は軌道が曲げられると光子を放出してエネルギーを失う
- 単位時間のエネルギー損失は 1/m^4 に比例
- 電子（陽電子）の場合、リング一周あたりのエネルギー損失は



$$U = 0.088 \frac{E^4[\mathrm{GeV}]}{\rho[\mathrm{m}]} \quad [\mathrm{MeV}]$$

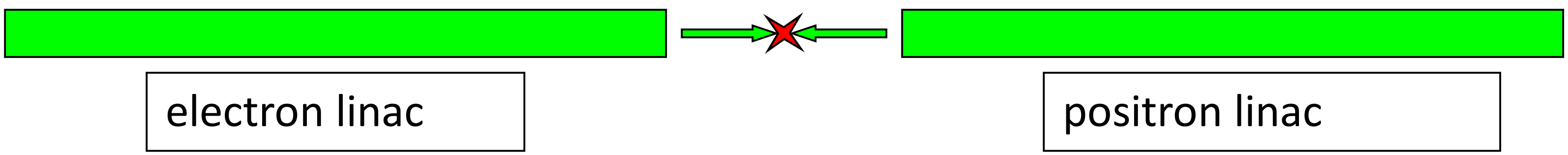
- リング型コライダーのエネルギー限界はこれで決る
- ただし、わるいことだけではない
  - 放射光の光源として使える
  - リニアコライダーでは、減衰リングに使える
- 一方、陽子のコライダーのエネルギー限界は磁場で決っている

LEP: 最大のリング型コライダー

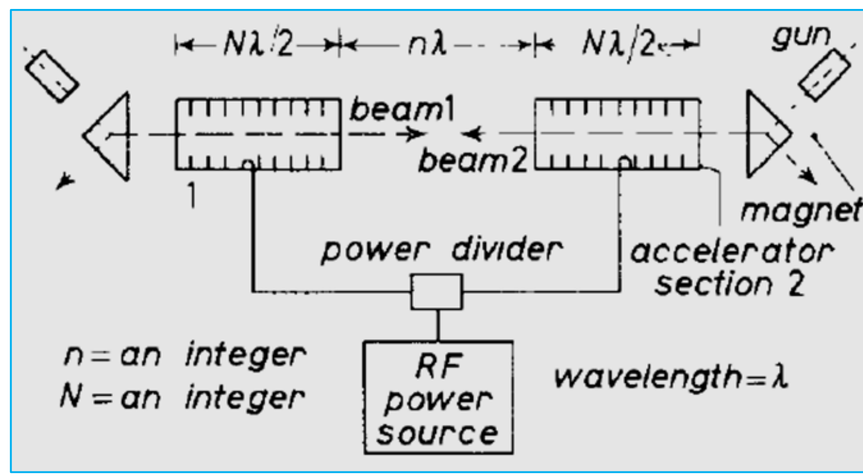
- LEP (Large Electron-Positron Collider)
  - CERN
  - 1983年建設開始、1989年運転開始
  - 1周27km
  - 最終的にビーム
    エネルギー
    約100GeV
    E_{CM} = 209 GeV
  - 2000年終了

電子・陽電子リニアコライダー

- リングコライダーはシンクロトロン輻射による限界がある
  - LEP は E_{CM} = 209GeV まで
- これ以上のエネルギーではリニアコライダーしかない

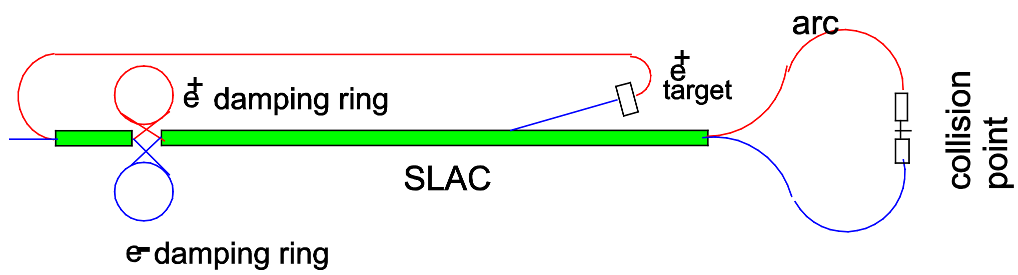


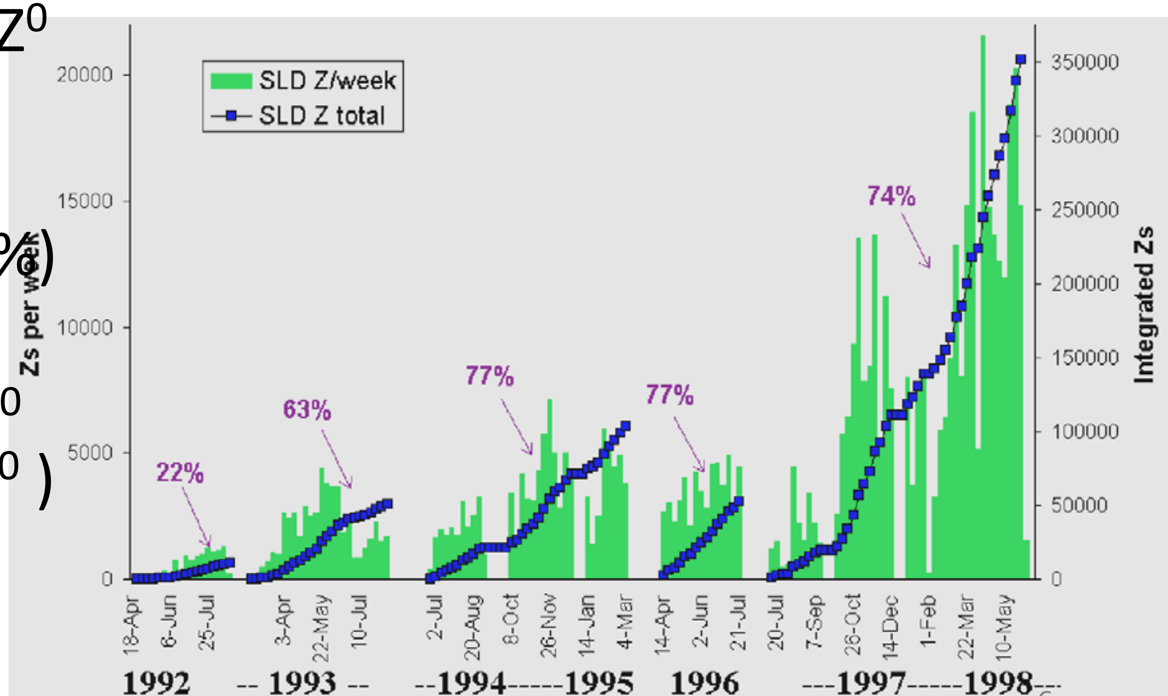
- 1960年代はじめに提案
  - M.Tigner, Nuovo Cim. 37 (1965) 1228-1231
  - 当初のアイデアは超伝導空洞によるenergy recovery
  - シンクロトロン輻射を避けるためではなかった



SLC：最初のリニアコライダー

- 単一リナックによるリニアコライダー
  - ビームエネルギー46GeVなら、1周回すことは可能
- SLACにおいて 1987 に完成
- 1989年4月に最初の Z^0 event
- LEPとの競争
- 偏極電子ビーム(~80%)
- 1998年に運転終了
- 最終luminosity 3×10^{30} /cm^2/s (設計値 6×10^{30})

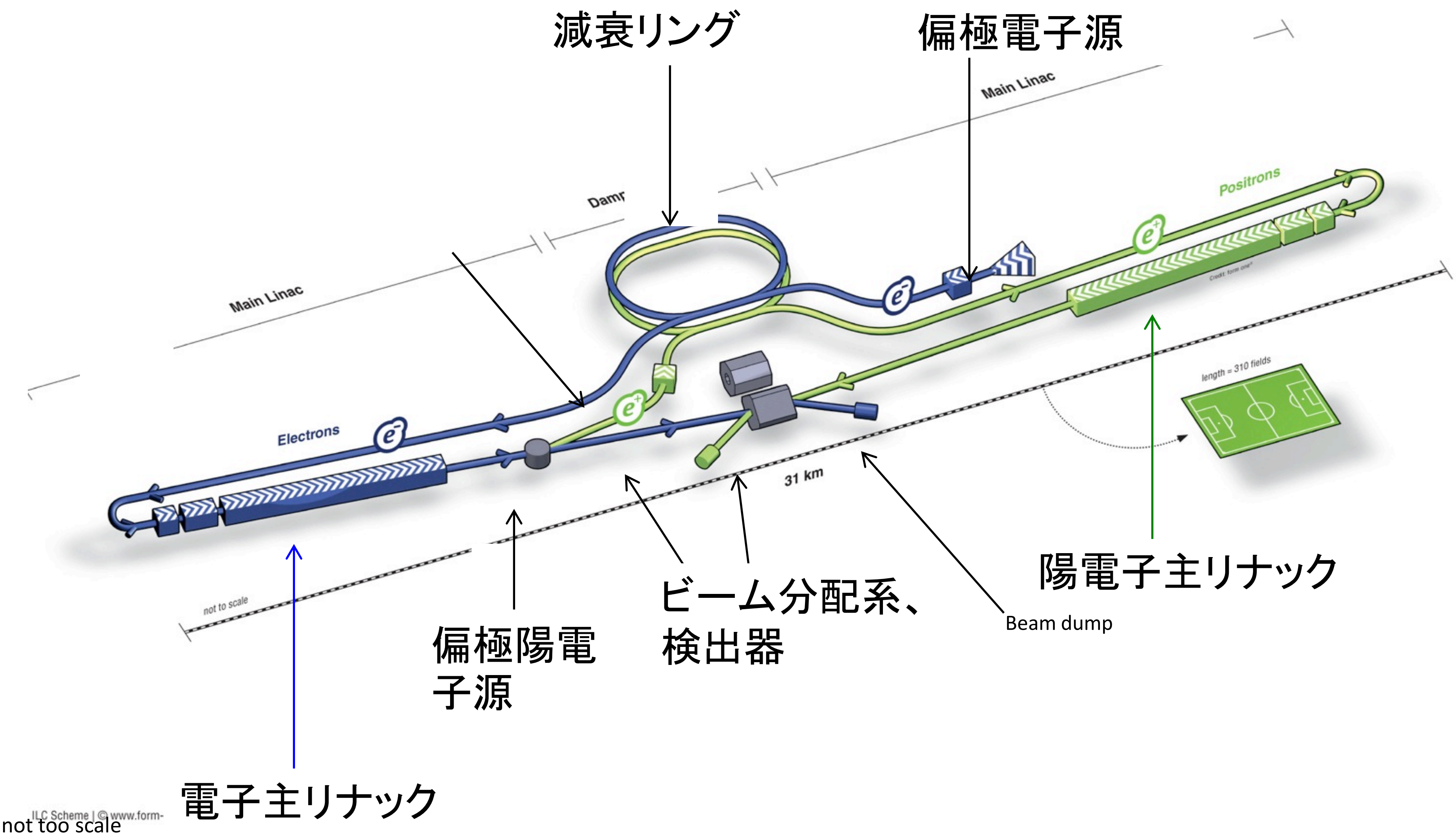




Linear Collider の Technical Challenge

- Ring colliderと違う点は、single passであること
  - 加速装置を1回しか通過しない
  - 1回限りの衝突でビームは捨てられる
- このため2つの課題が発生する
  - 高加速勾配
    - 装置全長は加速勾配で決る
  - 微細ビーム
    - ビームの衝突頻度が低い
    - 高いルミノシティを得るには衝突点でビームを小さくする必要がある

ILC のレイアウト

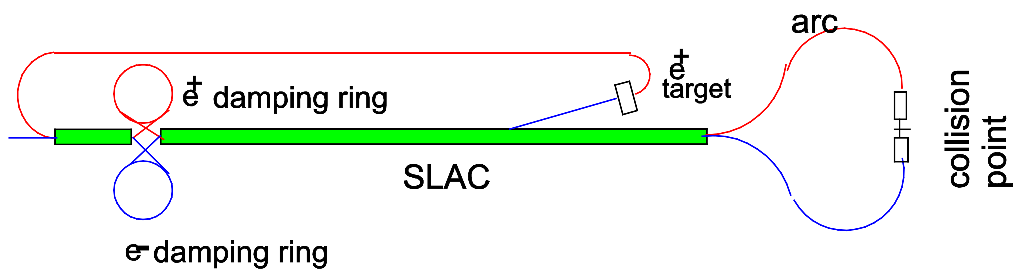


減衰リング
偏極電子源
Main Linac
Damp
Positrons
Electrons
Main Linac
length = 310 fields
31 km
not to scale
偏極陽電子源
ビーム分配系、検出器
Beam dump
陽電子主リナック
電子主リナック
ILC Scheme | © www.form-
not too scale

加速器の構成

- 電子源
- 陽電子源
- 減衰リング（DR, Damping Ring）
- RTML (Ring To Main Linac)
- Main Linac
- BDS (Beam Delivery System)

これらの基本的構成はSLCで最初に考案されて以来変更はない



Main Linac

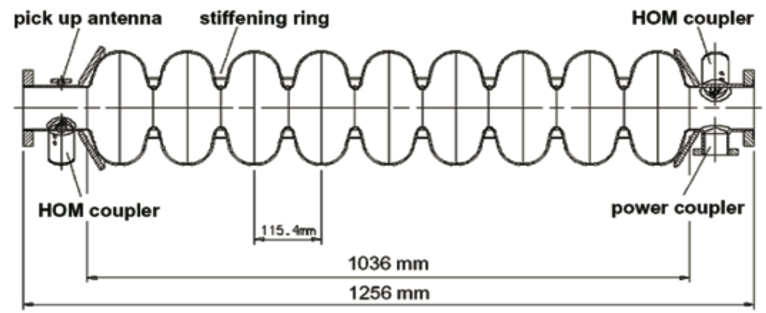
- Key area of ILC
  - 長さ 11km X 2 (E_{CM}=500GeV)
  - コストでは全体の約 2/3（トンネル込）
- 縦測定（加速空洞の単体試験）での設計基準
  - 加速勾配　平均 35MV/m
  - 勾配 35 -20% = 28MV/m 以上の空洞を受入れる
  - Q0 > 0.8×10^{10} at 35MV/m
  - 歩留り > 90% (2回の表面処理まで)
- 運転時の平均加速勾配 31.5MV/m
  - Accept the range +/- 20%（25.5-37.8MV/m）
  - Q0 > 1×10^{10} at 31.5MV/m

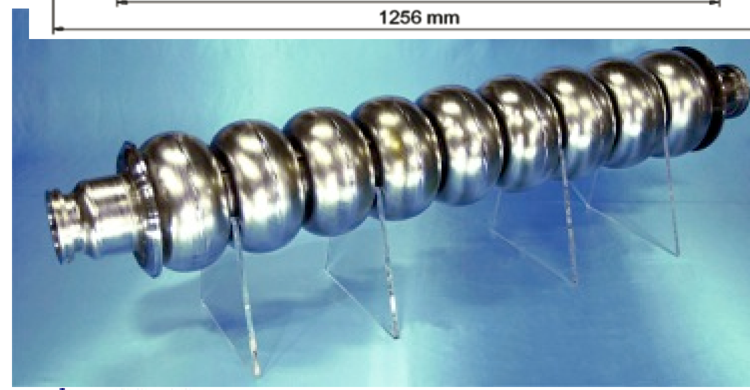
高勾配加速

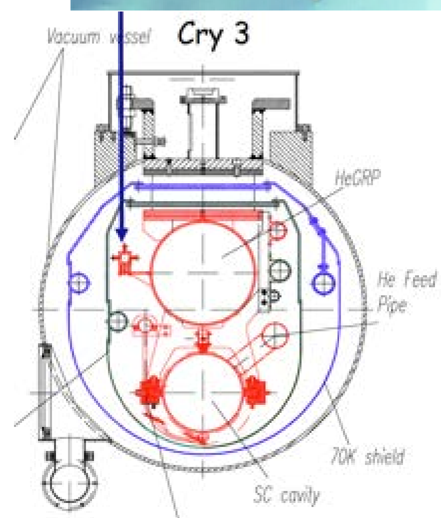
- リニアコライダーの本格的開発は1980年代に始った
  - 日本・アメリカ・ドイツ・ソ連・CERNなど
- 当初は、プラズマ加速などの新しい方式の可能性が議論されたが、いずれも時期尚早で、結局従来のマイクロ波加速に落着いた
- マイクロ波線型加速器は、常伝導・超伝導に大別される
  - 常伝導:高勾配にしやすい
  - 超伝導:電力効率がよい
- 2004年に、国際的に超伝導一本化
  - ILCのスタート

加速空洞を超伝導化すると

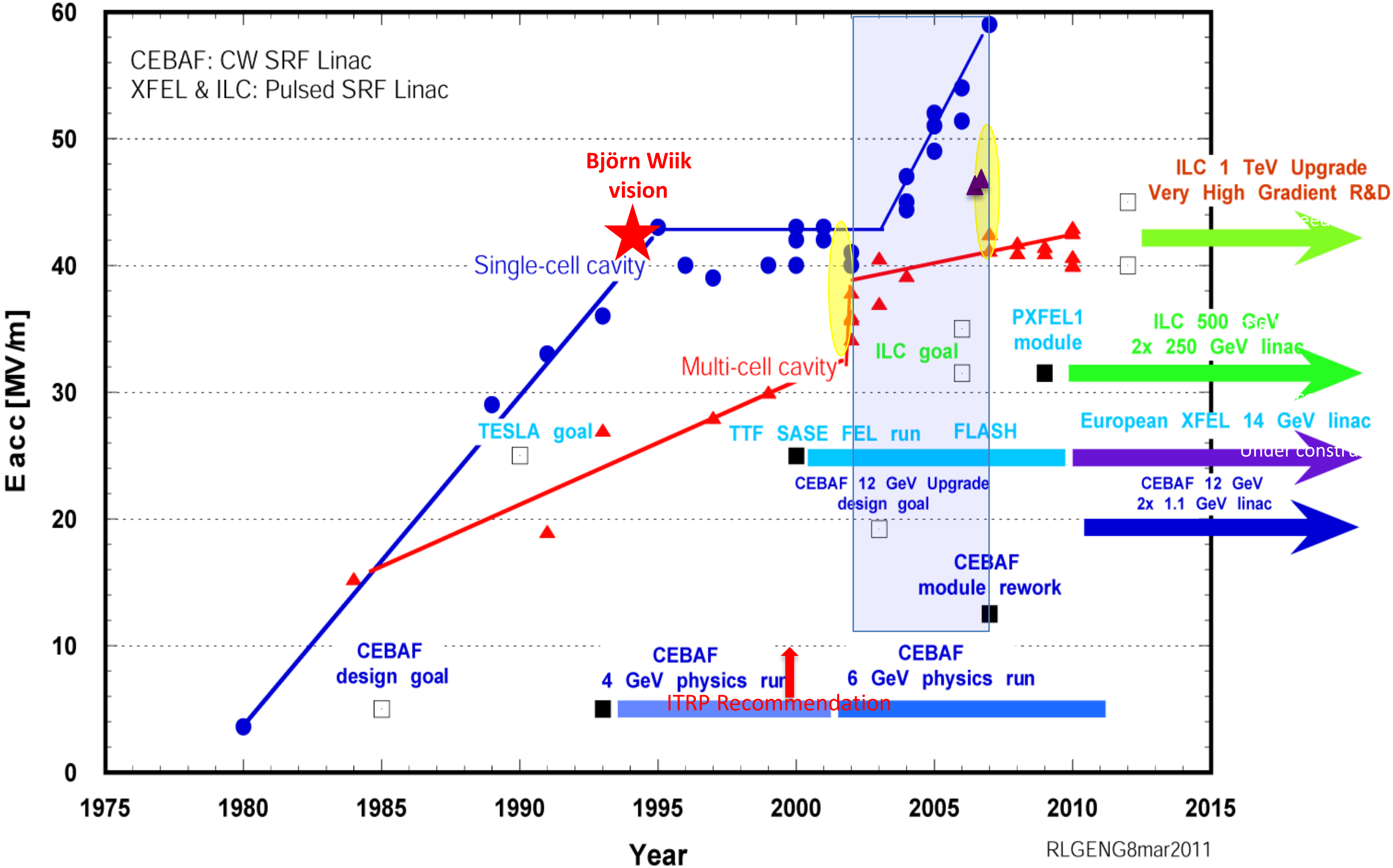
- **超伝導化により**
  - Q値(蓄積エネルギー／エネルギー損失）が大きい（表面抵抗が小さい）
    - 電力効率がよい（ただし単純ではない）
    - バンチ間隔が大きく、実験がしやすい
  - 周波数を低く、口径を大きくできる。ウェーク場が小さい。
  - ビームロスが少ない（スクレーパー等が少ない）
- **低温化の為に**
  - クライオスタット（断熱真空容器が必要）
  - 冷却、冷凍機の電力





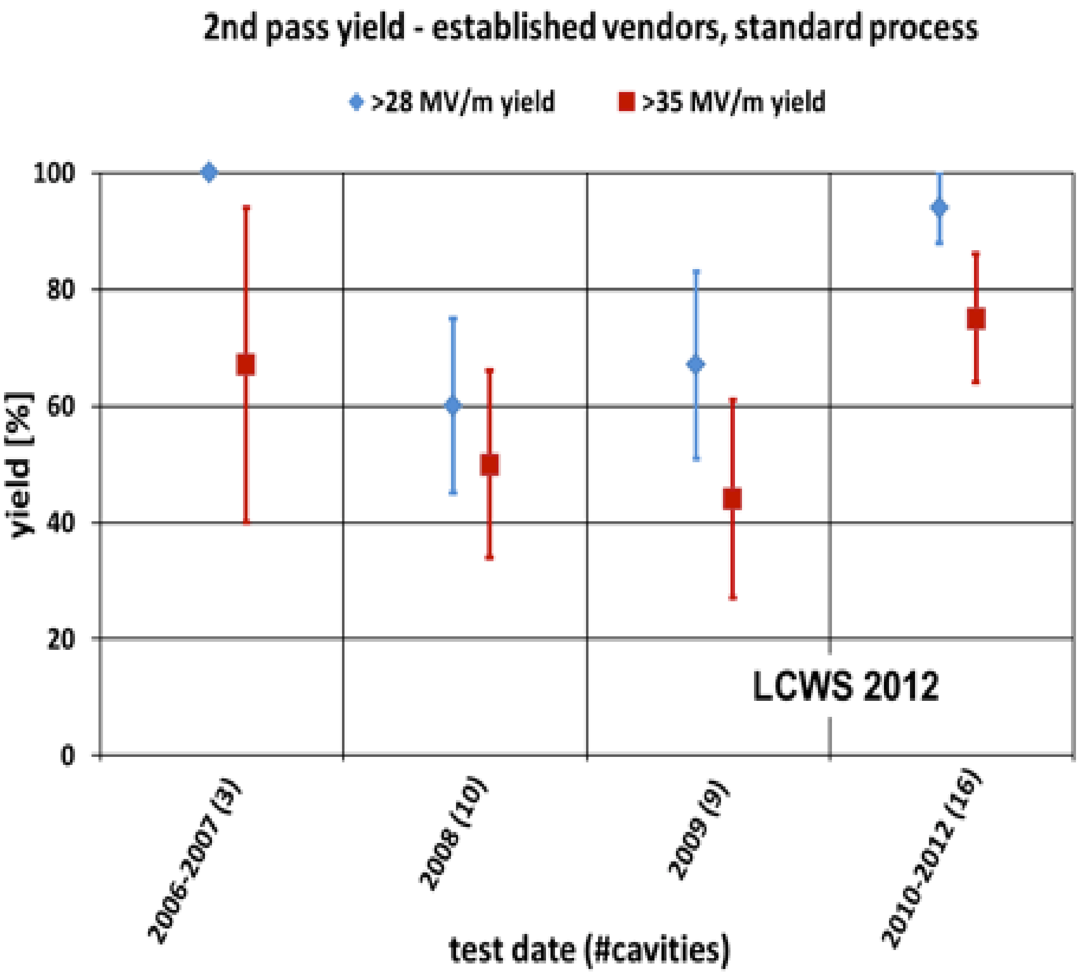


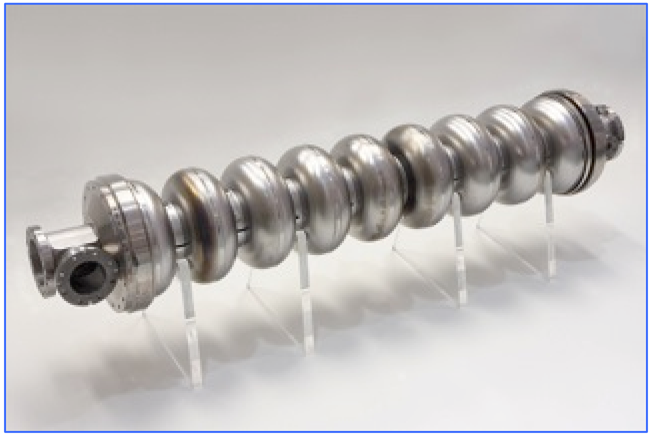
超伝導加速空洞の加速勾配の歴史



NishinaCenter 2014-1110
K.Yokoya

最近の加速勾配の統計





歩留り:
94 % at > 28 MV/m,

パスした空洞の平均勾配:
37.1 MV/m

reached (2012)

A. Yamamoto, May2013, ECFA13

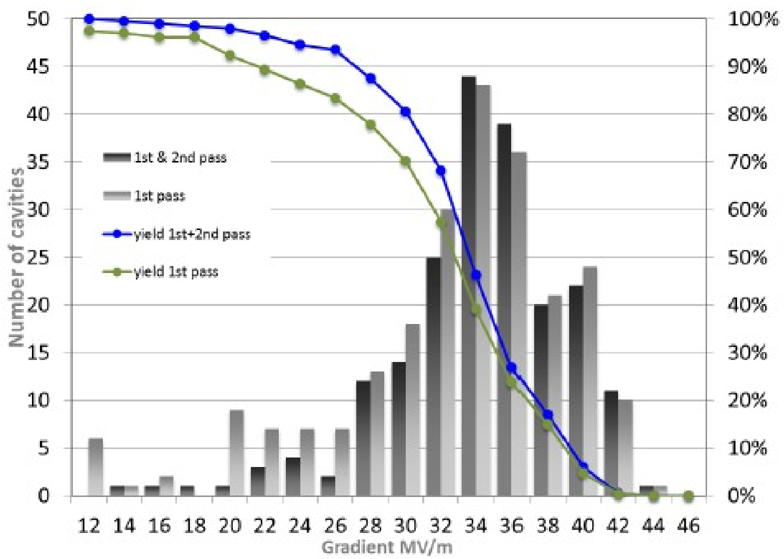
XFEL Status March 14, 2014

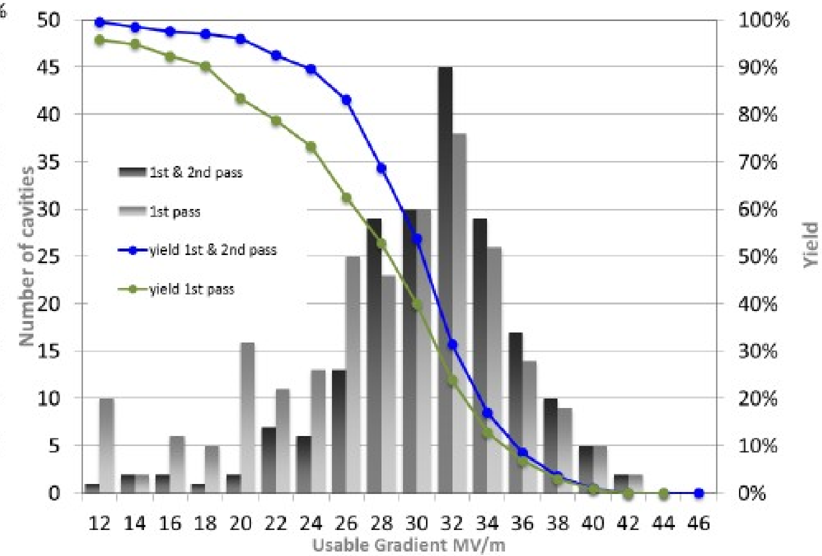
European XFEL

Test Results for the Testing of 800 Series Cavities for the European XFEL

Yield of gradients: After 1. re-treatment (2. pass)

- Yield of usable and maximum gradient of ~207 cavities (2.pass) **=> 85%** (cavities that passed in 1. pass + results of cavities after re-treatment)
- **Average** gradients **increased + spread reduced**





Average **maximum** gradient: **(32.8 ± 4.9) MV/m**

Average **usable** gradient: **(29.3 ± 5.1) MV/m**

given errors are standard deviation

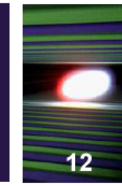
D. Reschke, TTC 2014

Preliminary data; results are not published

XFEL Status May 6, 2014

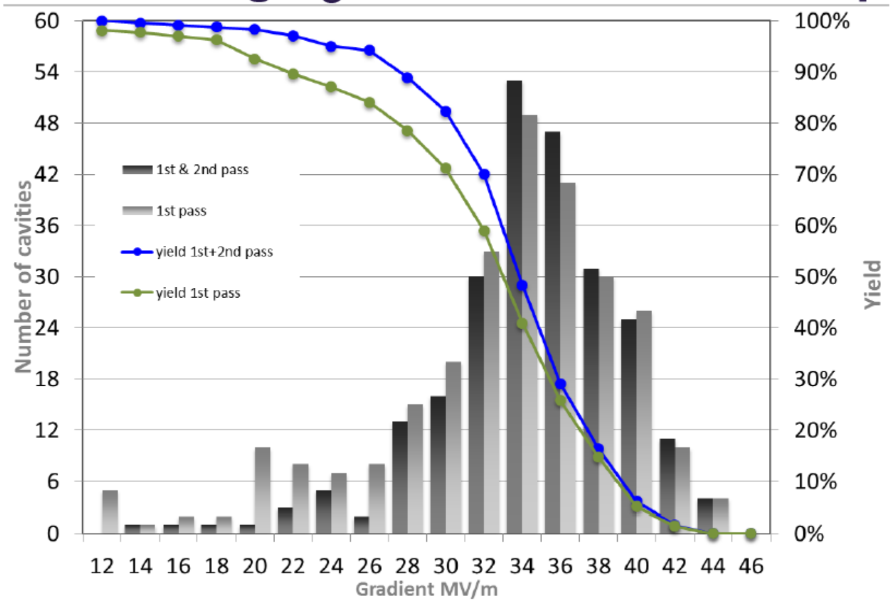
Status of XFEL Series Cavity Results

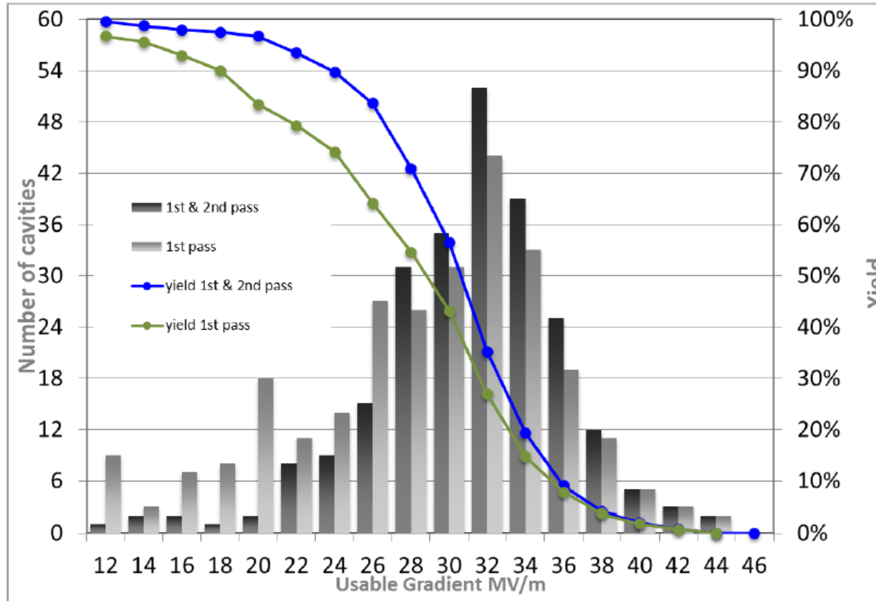
European XFEL



Yield of gradients: After 1. re-treatment (2. pass)

- Yield of usable and maximum gradient of ~244 cavities (2.pass) **=> 84% (204 cavities)** => sum of "as received" + 1. re-treatment
- **Average** gradients **increased + spread reduced**



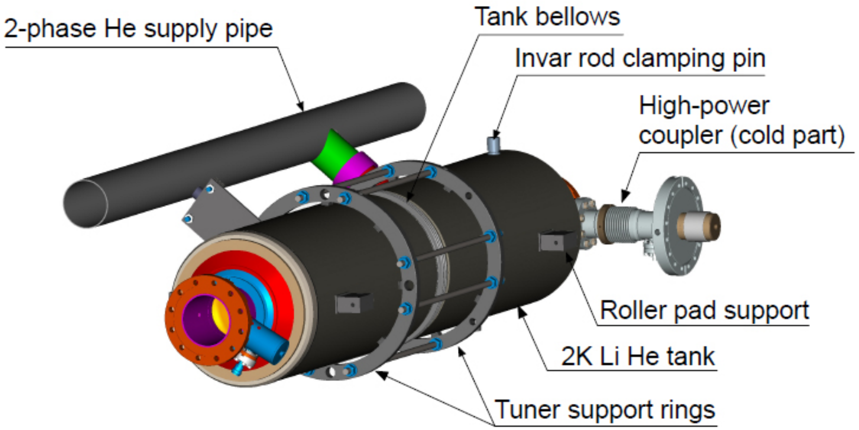


Average **maximum** gradient:
(33.0 ± 4.8) MV/m
EZ: (31.3 ± 4.3) MV/m
RI: (35.0 ± 4.6) MV/m

Average **usable** gradient:
(29.6 ± 5.1) MV/m
EZ: (28.4 ± 4.4) MV/m
RI: (30.9 ± 5.4) MV/m

加速試験

- モジュール中での加速勾配の確認 (design margin: 10% from VT)
- ビームつきフルスペックの試験
- パルス内・パルス間のエネルギー安定性
- クライストロン飽和付近での運転マージン

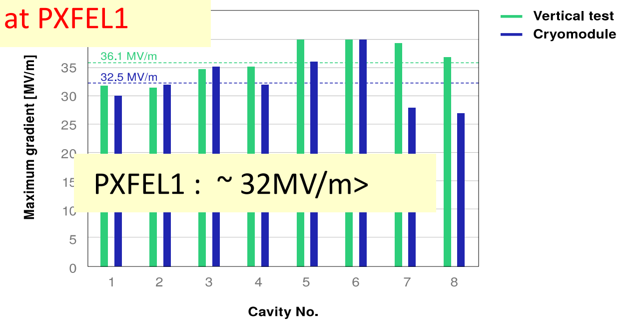


Cryomodule System Test

2014/07/05, A. Yamamoto

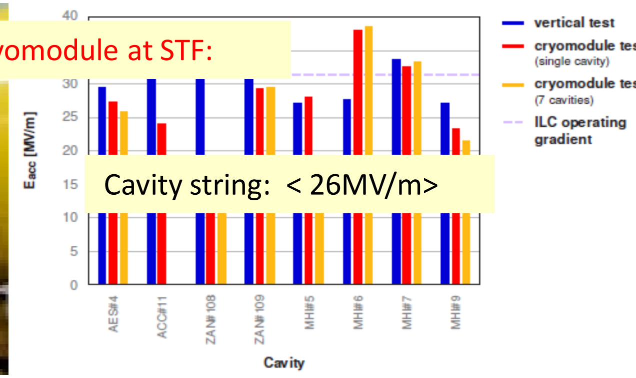
DESY: FLASH

- 1.25 GeV linac (TESLA-Like tech.)
- ILC-like bunch trains:
- 600 ms, 9 mA beam (2009), ← Demonstrated
  800 ms 4.5 mA (2012)
- RF-cryomodule string with beam → PXFEL1 operational at FLASH



KEK: STF/STF2

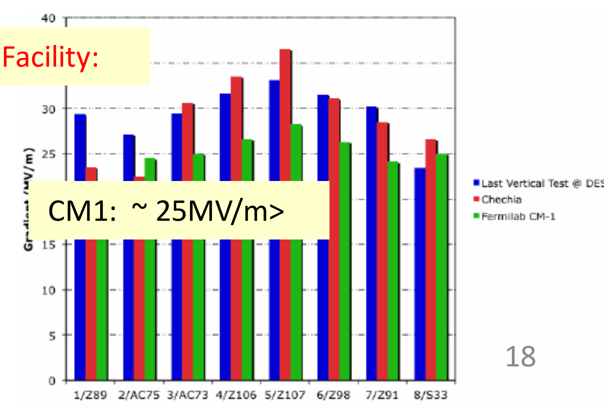
- S1-Global: completed (2010)
- Quantum Beam Accelerator (Inverse Llaser Compton): 6.7 mA, 1 ms ← Demonstrated
- CM1 test with beam (2014 ~2015)
- STF-COI: Facility to demonstrate CM assembly/test in near future



FNAL: ASTA

(Advanced Superconducting Test Accelerator)

- CM1 test complete
- CM2 operation (2013)
- CM2 with beam (soon)



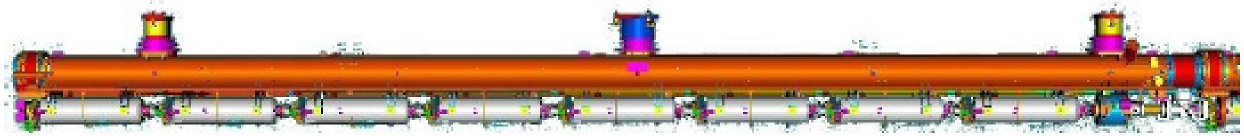
100 s.c. Modules for the European XFEL

IPAC14: Courtesy: H. Weise

European XFEL

An Accelerator Complex for 17.5 GeV

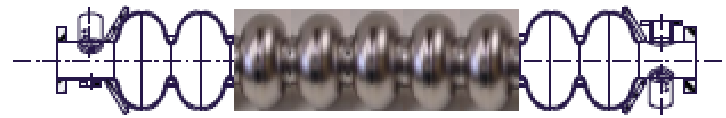
100 accelerator modules

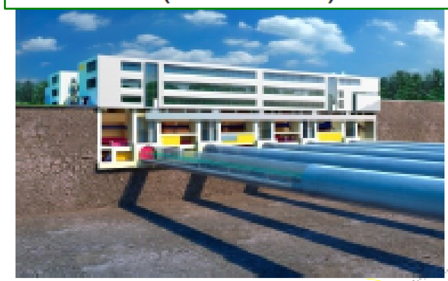


Some specifications

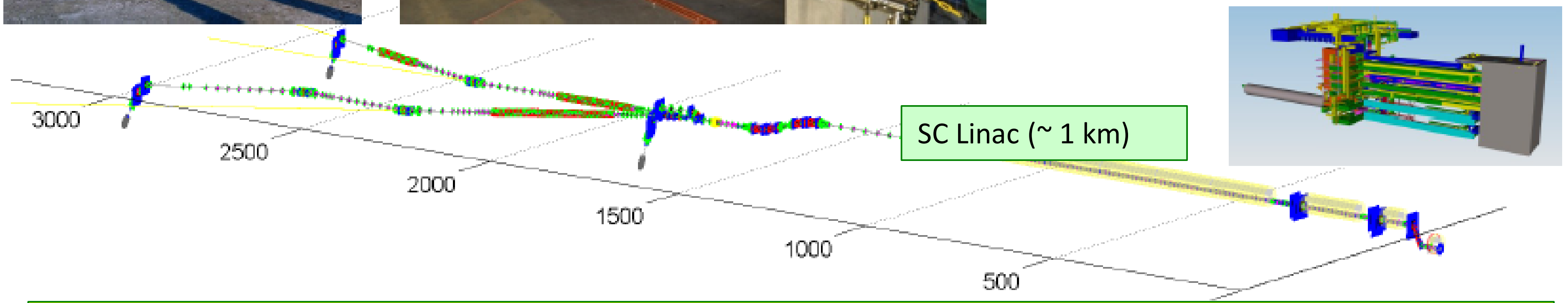
- Photon energy 0.3 - 24 keV
- Pulse duration ~ 10 - 100 fs
- Pulse energy few mJ
- Superconducting linac. 17.5 GeV
- 10 Hz (27 000 b/s)

800 accelerating cavities
1.3 GHz / 23.6 MV/m





25 RF stations
5.2 MW each



EXFEL: 1/20 Scale Project on going, Industrialization being verified !!

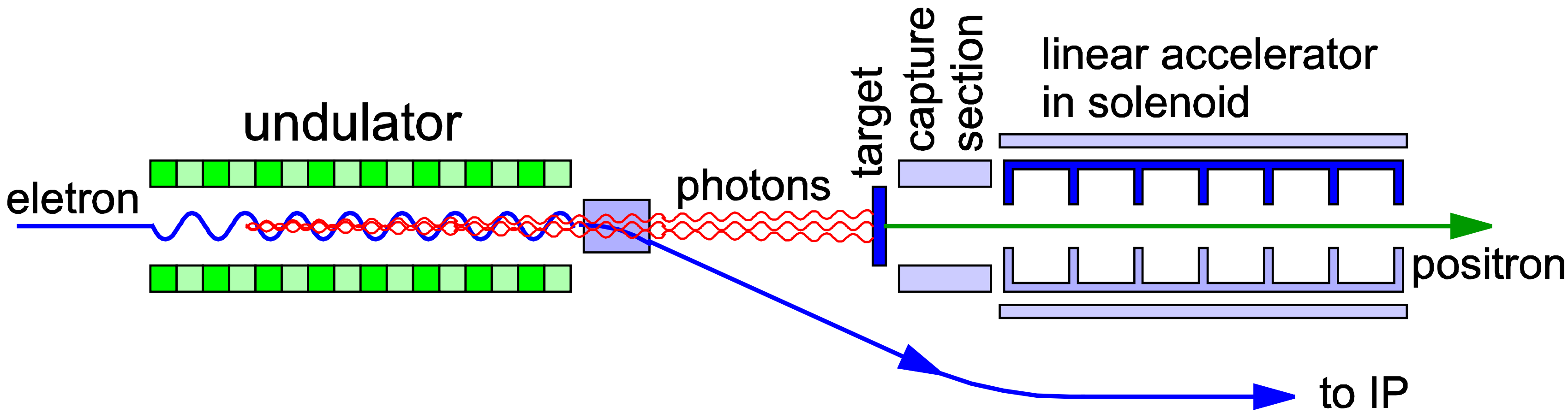
陽電子源

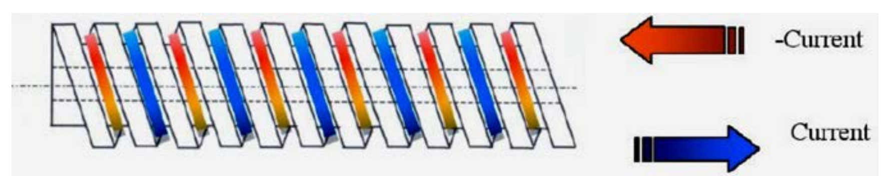
陽電子生成の3つの方法

- Undulator法 （ILC baseline で採用）
- Conventional Method（従来の方法）
  - 数GeVの電子を標的に当て、発生する陽電子を回収する。
  - これまでに頻繁に使われて、技術は確立されている
  - ILCへの応用上の問題点は
    - 標的が耐えられるか→ OK （遅い運動標的試験中）
    - 発生する陽電子のエミッタンスがやや悪い → OK (DRの改良）
    - DRまでの輸送部分の設計ができていない
    - 偏極陽電子が得られない
- Laser-Compton法 （将来の方法）
  - 数GeVの電子ビームにレーザーを当てて偏極ガンマ線を作り、これを標的に当てる

Undulator法

- 数100GeVの電子ビームを磁石（undulator）により蛇行させせると、数10MeVの輻射を出す。これを標的に当てて発生する陽電子を回収する。
- 平面上の蛇行でなく、螺旋状の運動（Helical Undulator）なら、発生する輻射は円偏光し、偏極陽電子が得られる。





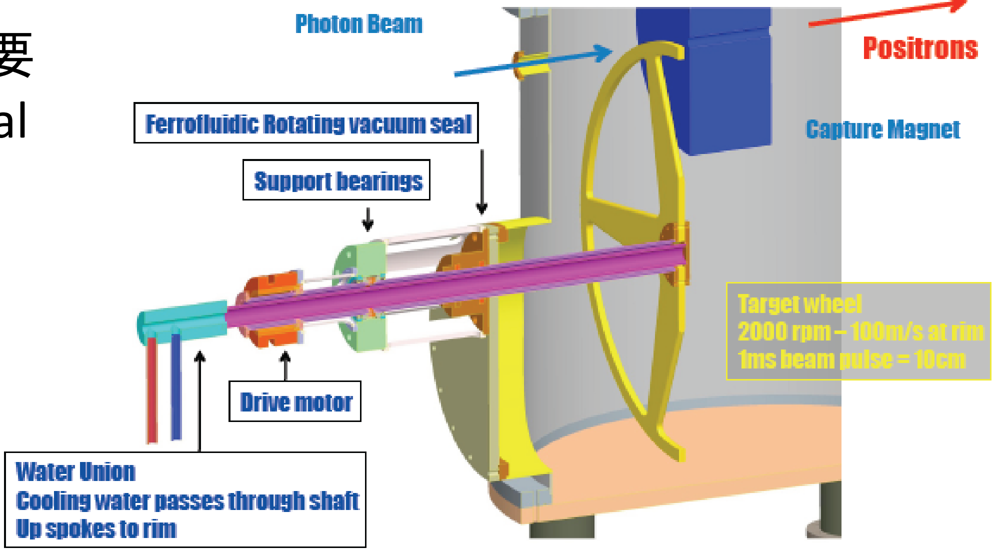
- この方法は各種の欠点を持つ
  - 電子・陽電子の運転が独立にできない
  - まだ実際に使われたことがない
  - undulatorについては小規模テストができない、などなど
  - 電子のエネルギーが低くなると急激に光子生成率がわるくなる
- であるが、偏極陽電子ができるという利点が強い

標的

- チタン合金の車輪（直径1m）を、2000rpm（縁辺速度100m/s）で回す
- これは1msの間の熱の集積を防ぐため
- 円盤でなくスポーク形状になっているのは、磁場中の回転で発生する eddy currentを減らすため

Cockcroft Insituteでeddy current試験中の回転標的。
実際の標的は真空中で回転させる。

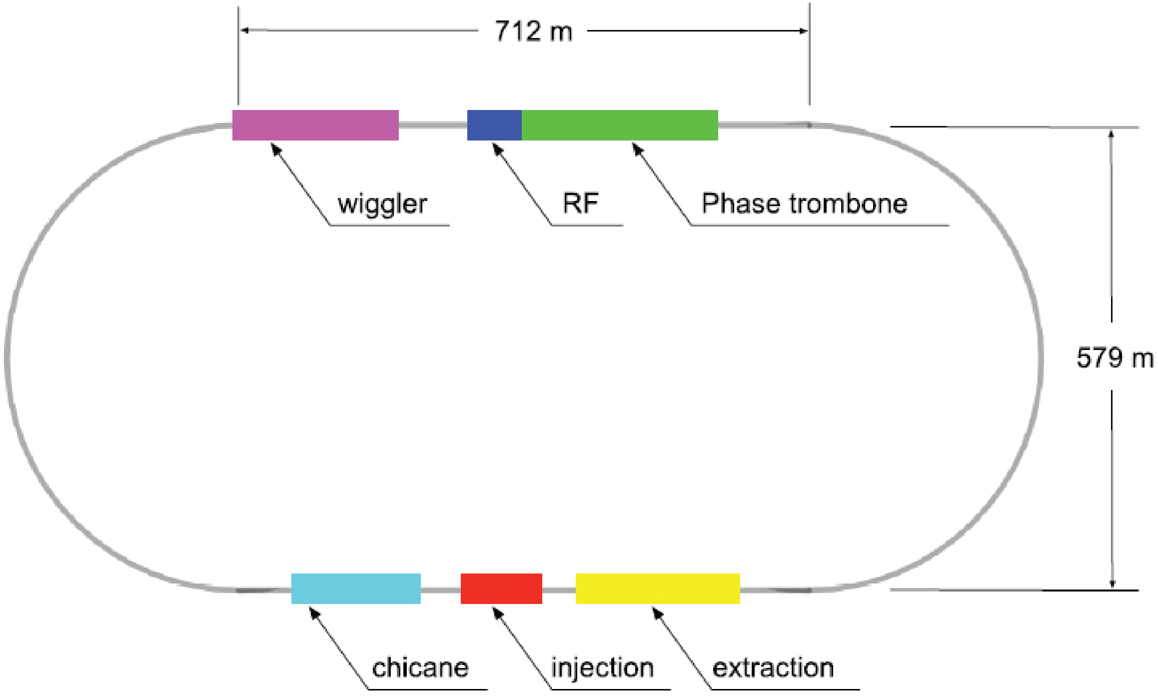
- 真空中で100m/sで動く標的が必要
- 米国で2社からのFerromagnet sealをつかって試験。
- 十分な成果は上がっていない
  - Outgassing spikes still being observed
  - 市販品ではだめ
- USFY2015で再スタート



Damping Ring

- Damping Ringの役割
  – 与えられた時間（200ms、10Hz運転の場合 100ms）内にEmittanceの小さいビームをつくる
  – 全バンチ（最大約2600）を一時貯蔵する

- メカニズム
  – 平衡エミッタンスの小さい曲線部
  – ウィグラー磁石により
    • さらに平衡エミッタンスを下げ、かつ
    • 減衰時間を短縮する

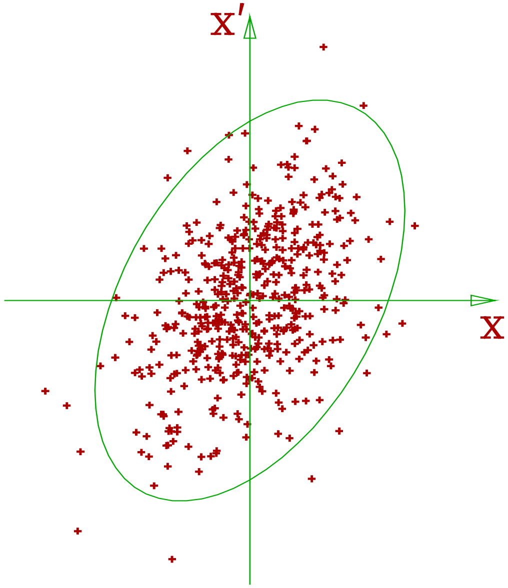


微細なビームを得るには

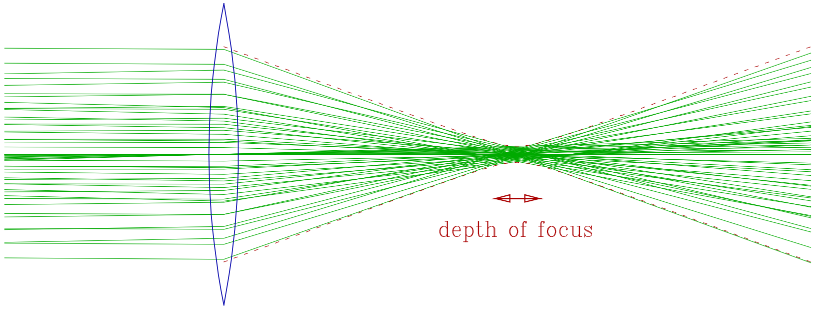
A) エミッタンスの小さなビームを作る
  - ✓ エミッタンス＝ビームの大きさ X 方向の拡がり

B) エミッタンスを劣化させずに加速する

C) 衝突点で小さく絞る

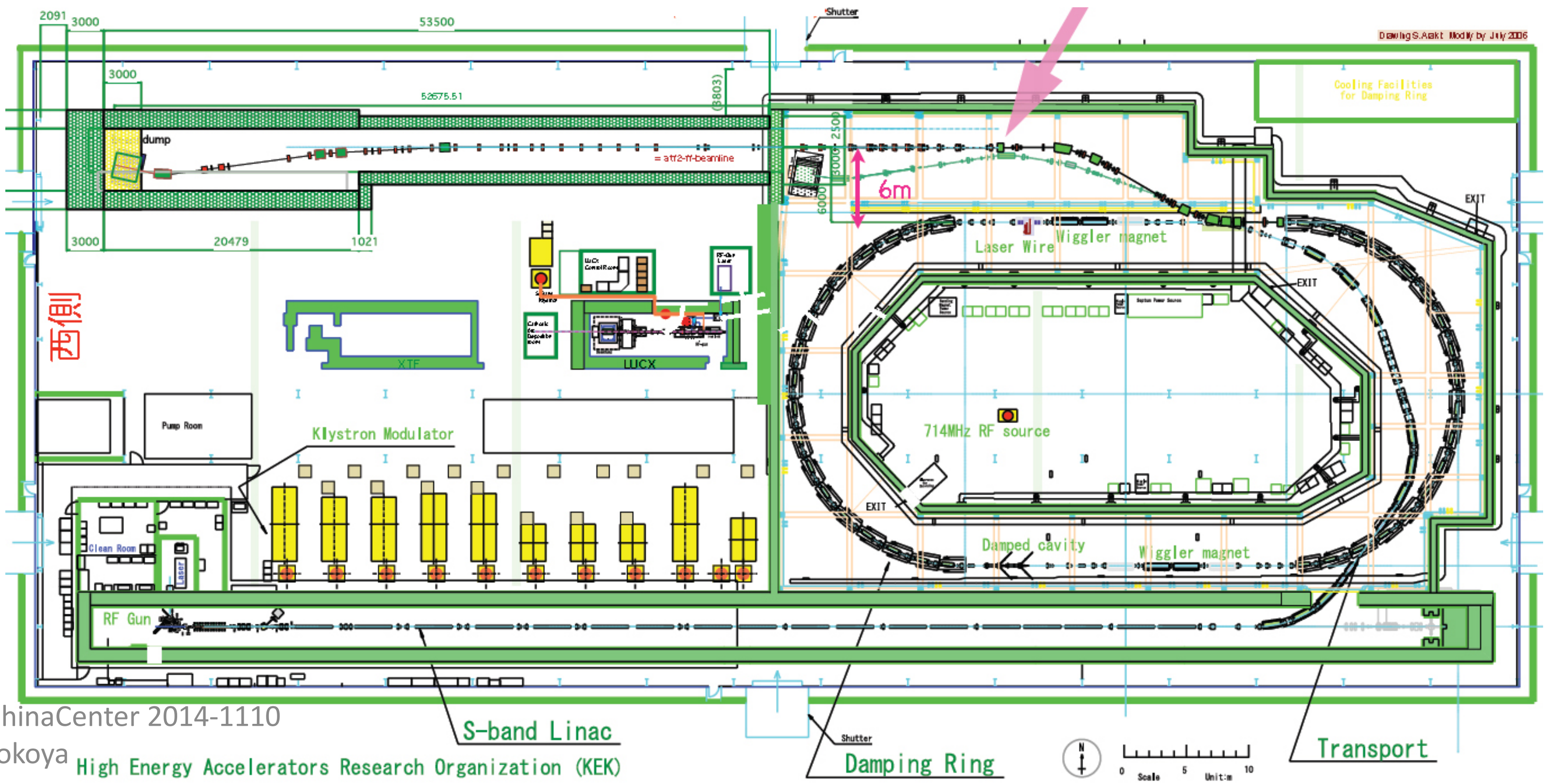


A)C) のために、KEKではATF (Accelerator Test Facility) を建設した



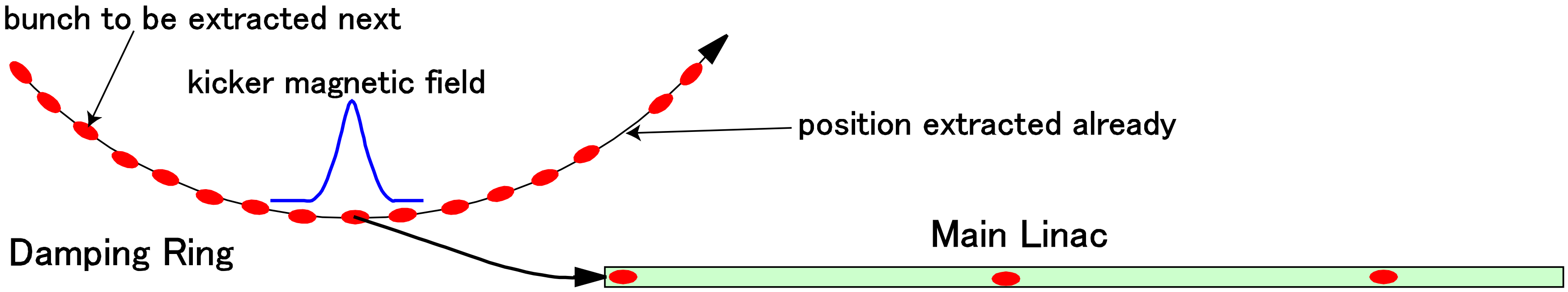
ATF

- JLCの減衰リングのプロトタイプとして1993 年に建設、
- Y方向エミッタンス ~4pm を達成
- 2005年からはILC用のテストベンチとして国際的MoUのもとに運営。
- その後 ATF2用のビーム源として活用

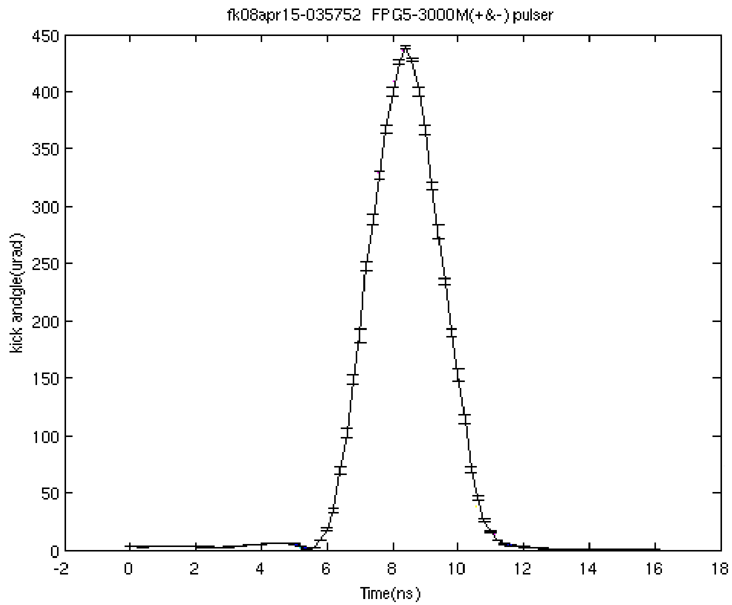


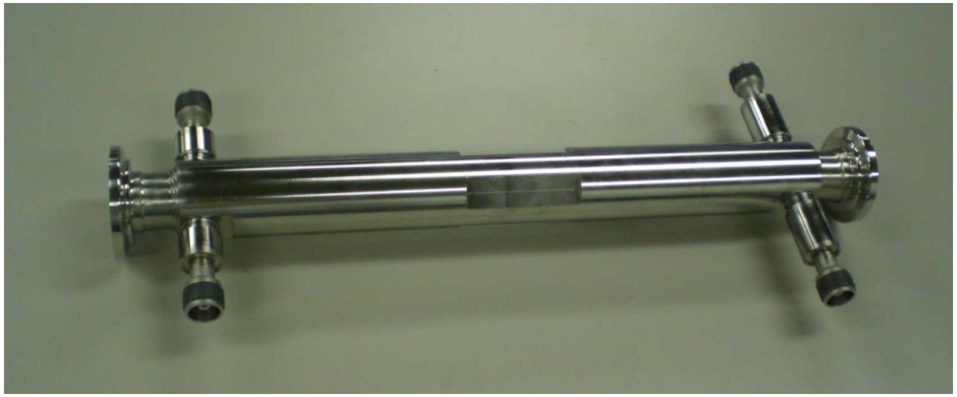
入射･取出し

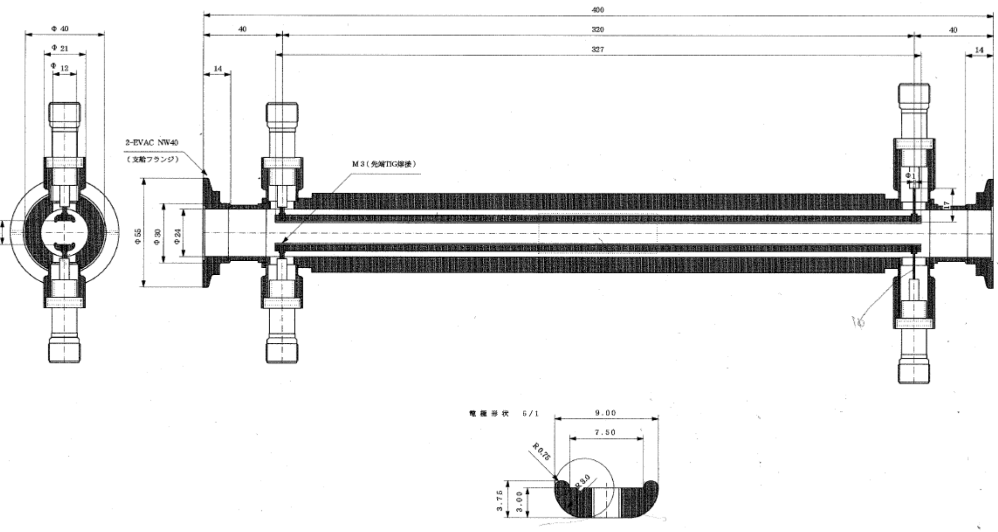
- バンチ数が多い（1312~2625）
- 線形加速器ではバンチ間距離が長い（600~300ns）
- これをそのまま貯蔵するには、一周が
  2625 x 300ns x (3x10^{8}m/s) = 240km
  のリングが必要
- したがって、バンチ間距離を圧縮して貯蔵する
- 出し入れは1バンチずつ、高速キッカーで行う
- キッカーの速さがリングの大きさを決める。
- この技術は、ATFでのR&DでほぼOK



Stripline Kicker



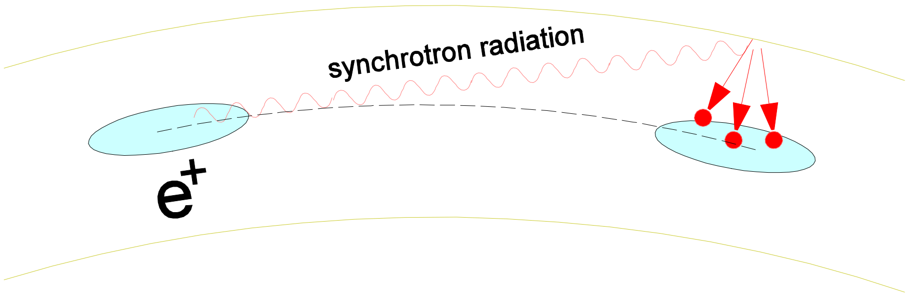


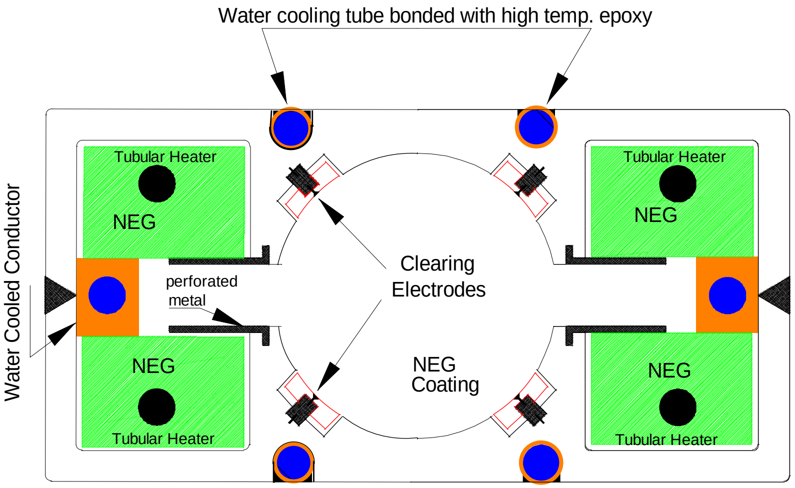


電子雲不安定性

- なんらかの課程で発生した低エネルギー電子が、陽電子ビームに引きつけられて、陽電子の軌道を乱す
- KEKBで経験している
- 対策
  - ビームパイプにAnti-chamber（側室）を作る
  - ビームパイプ内面の表面処理
  - コイルをビームパイプに巻いて磁場を作る（KEKBで採用）
  - ビームパイプ内面に溝を作る (groove structure)
  - 電子を吸着する電極 (Clearing Electrode)

  などなど。





電子雲不安定性

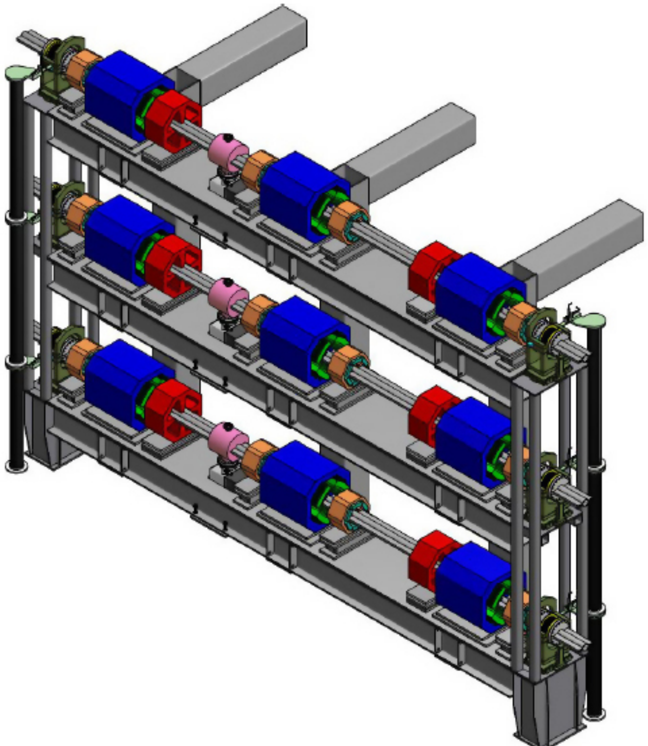
- 国際的チームによる米国CESR-TA での研究
- Gave recommendation for the mitigation method (table below)
  - Arc and wiggler sections requires antichamber
  - Full power in 3.2km ring needs aggressive mitigation plan
- No significant difference between 6.4km with 2600 bunches and 3.2km with 1300 bunches

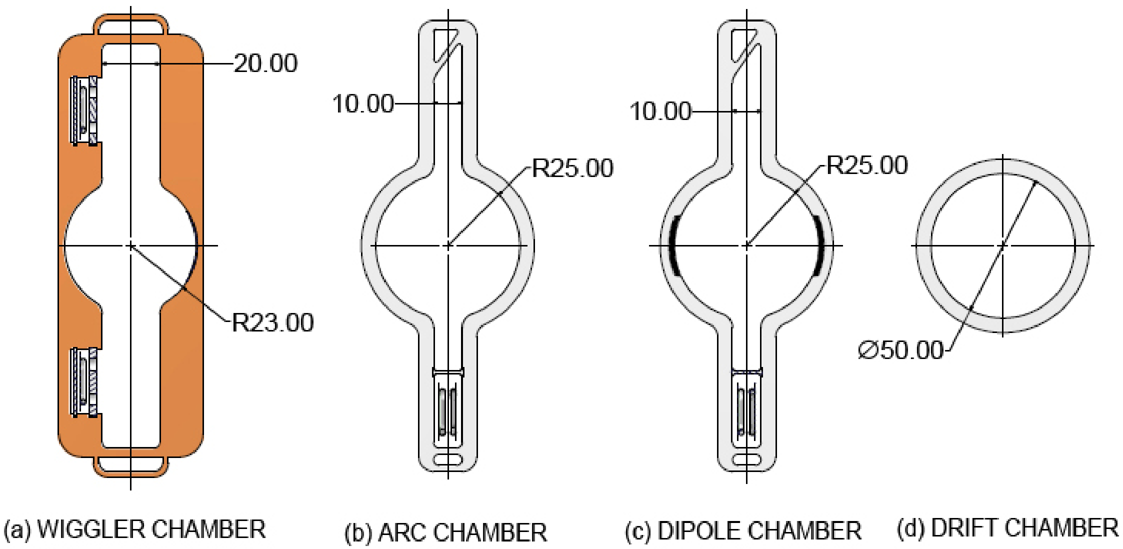
EC Working Group Baseline Mitigation Recommendation				
	Drift*	Dipole	Wiggler	Quadrupole*
Baseline Mitigation I	TiN Coating	Grooves with TiN coating	Clearing Electrodes	TiN Coating
Baseline Mitigation II	Solenoid Windings	Antechamber	Antechamber	
Alternate Mitigation	NEG Coating	TiN Coating	Grooves with TiN Coating	Clearing Electrodes or Grooves

ECLOUD`10 (October 13, 2010, Cornell University)

Damping Ring ビームパイプ

- 陽電子リングでは、CESR-TA teamの推薦にしたがい下図のようにする
- 電子雲以外の不安定性はシリアスでない
- 電子リングでは、FII (Fast Ion Instability) がもっとも重要

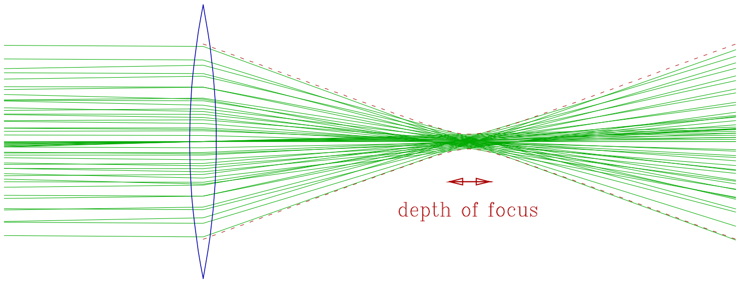




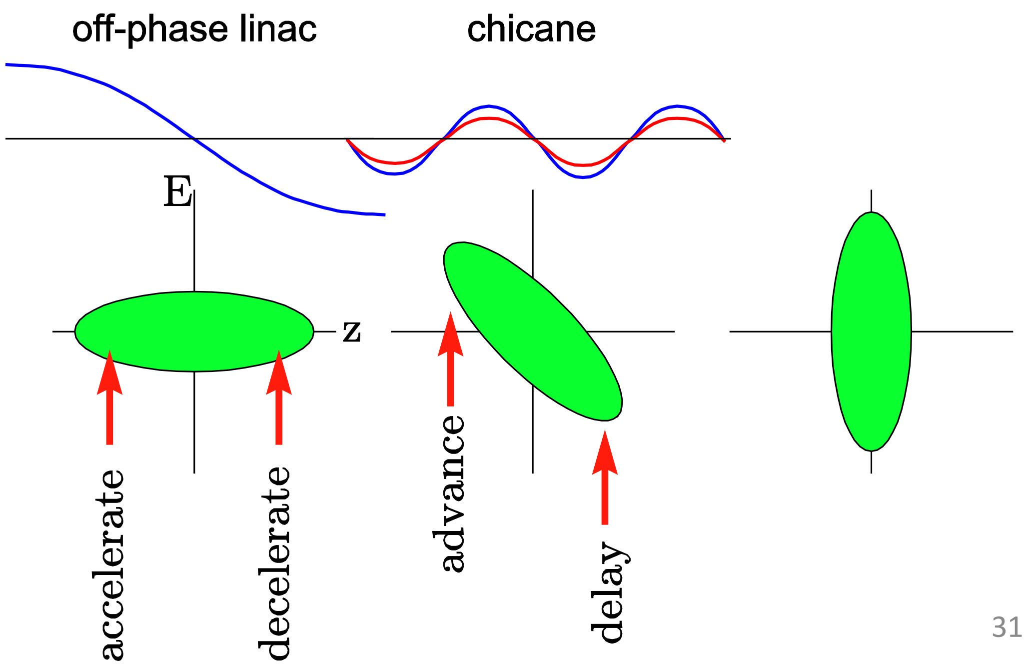
- 当初（1312bunches）は、電子・陽電子、各1リング
- 3台目のリングを入れるスペースを用意
- 2625bunchesへの増強時に、陽電子2リングにする可能性

バンチ圧縮

- 衝突点での砂時計効果を緩和するためにバンチを短くする。



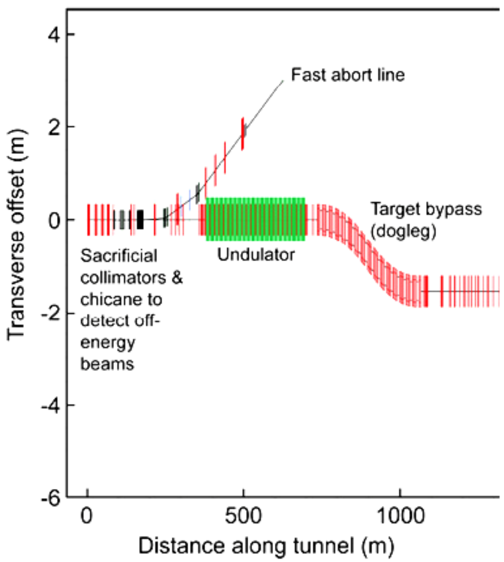
- 加速空洞とシケインの組合せ
- Damping Ringでの平衡バンチ長は 6mm。これを 300 μm に圧縮する。
- 2段式のバンチ圧縮
  - 150 μm まで圧縮可能



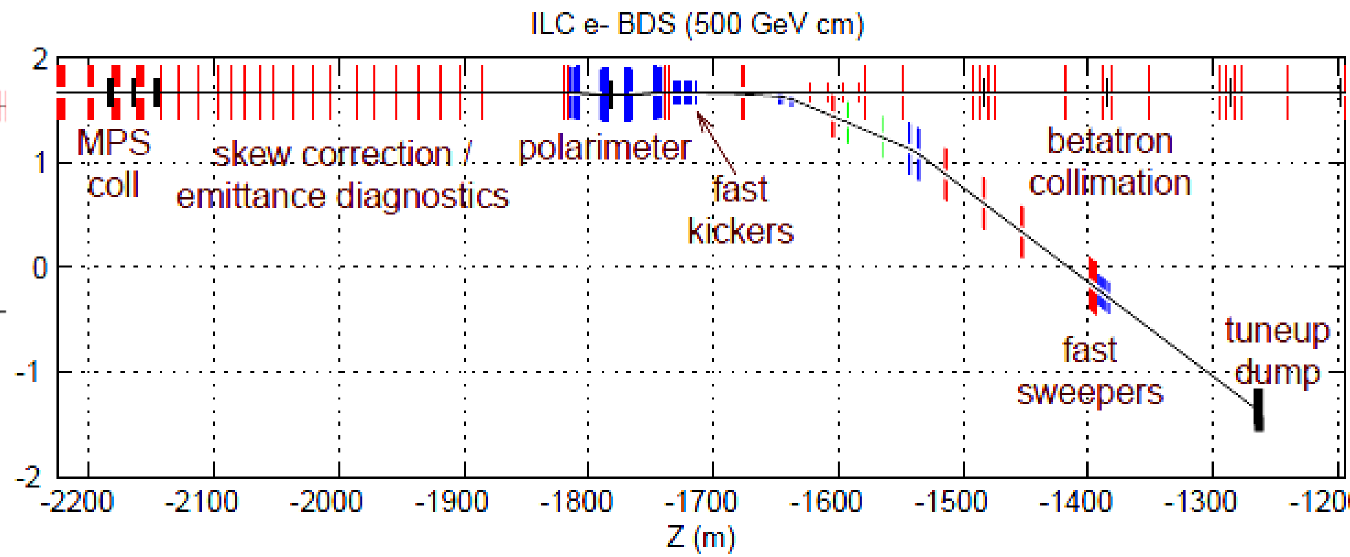
BDS(Beam Delivery System)の構成

- BDSの役割は最終的にはビームを衝突点で絞ることであるが、それ以外に多数の装置が並んでいる
- Machine Protection System
- 調整・緊急用ビームダンプ
- コリメータ
- ビーム診断セクション (beam energy, emittance, 偏極)
- Muon absorber
- Crab cavity
- Feedback system
- 衝突後のビーム診断(beam energy,偏極)
- Main beam dump

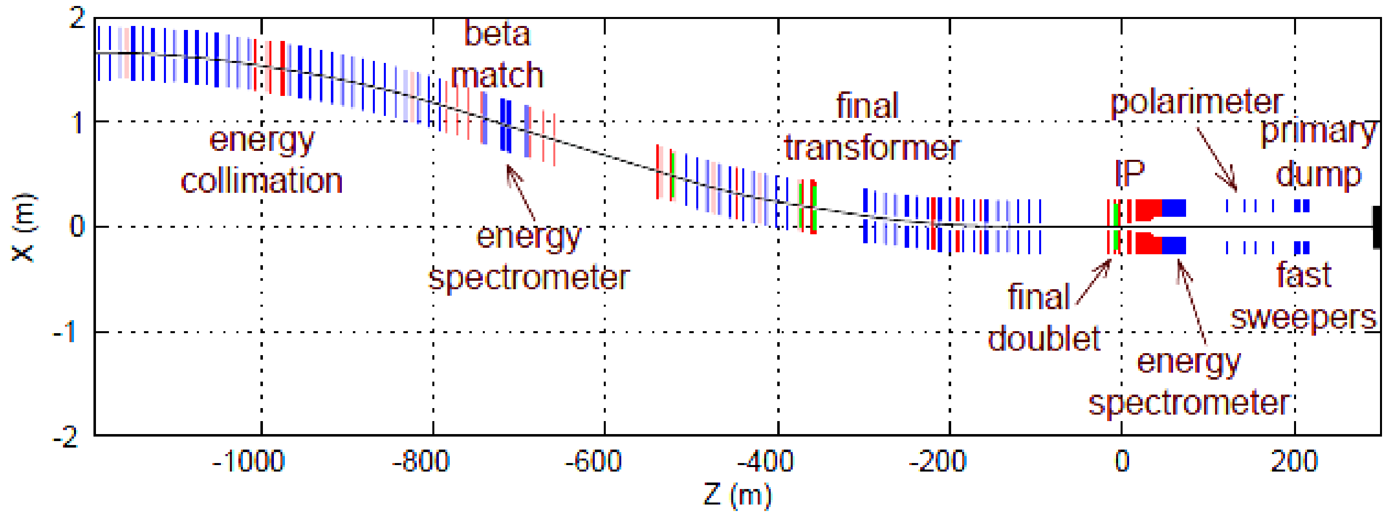
BDS Layout



Fast abort line
Target bypass
(dogleg)
Undulator
Sacrificial
collimators &
chicane to
detect off-
energy
beams
Transverse offset (m)
Distance along tunnel (m)



ILC e- BDS (500 GeV cm)
MPS
coll
skew correction /
emittance diagnostics
polarimeter
fast
kickers
betatron
collimation
fast
sweepers
tuneup
dump
Z (m)



beta
match
energy
collimation
energy
spectrometer
final
transformer
polarimeter
primary
dump
IP
final
doublet
energy
spectrometer
fast
sweepers
X (m)
Z (m)

色収差

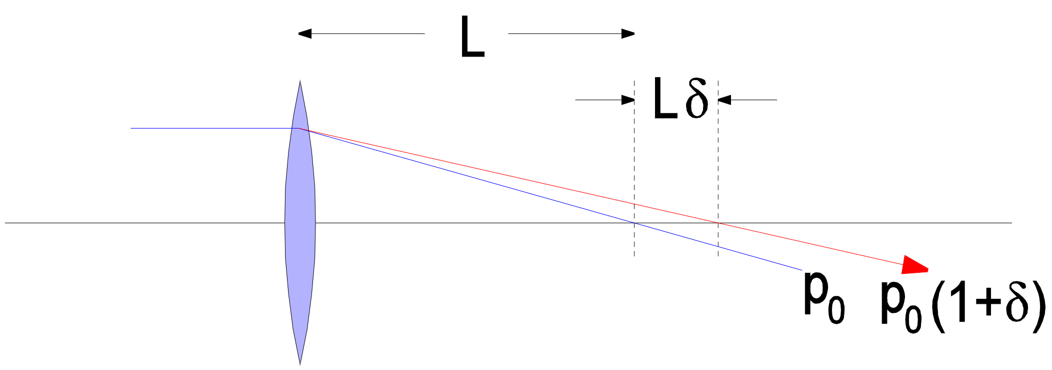
- 最後の4極磁石から焦点（ s=0 ）までの距離を L とする。
- $p=p_0$ の粒子はこの点で絞られている。
- $p=p_0(1+\delta)$ の粒子は、4極磁石から $L(1+\delta)$ あたりに焦点がくる。
この焦点は、s=0 から $L\delta$ だけずれているから、そこでのベータ関数は

$$\beta = \beta_0 + \frac{(L\delta)^2}{\beta_0} = \beta_0 \left[1 + \left(\frac{L\delta}{\beta_0} \right)^2 \right]$$

- したがって色収差の目安は

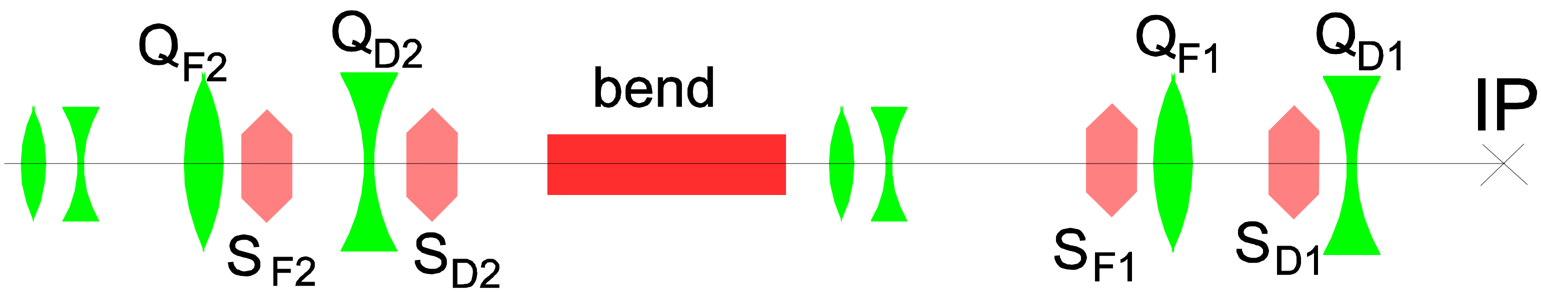
$$\xi = \frac{L\delta}{\beta_0}$$

- ILCでは、β_y =0.4mm、L~6m、
δ ~1/500、
したがって ξ = 30



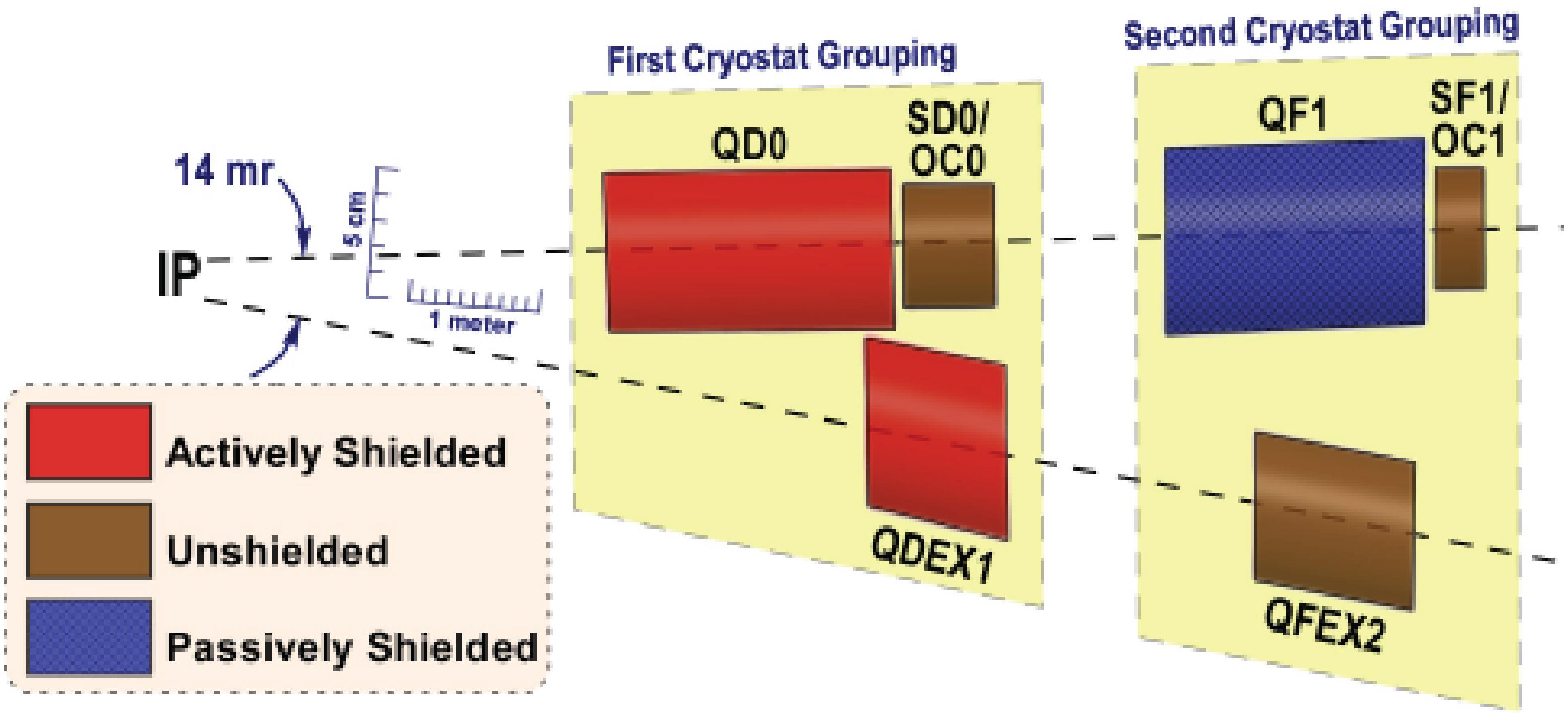
Local Chromaticity Correction

- 現在のILCの設計では、dispersion関数のゼロでない場所に、4極磁石と6極磁石を並べて置き、その場で色収差を消す方法をとっている。



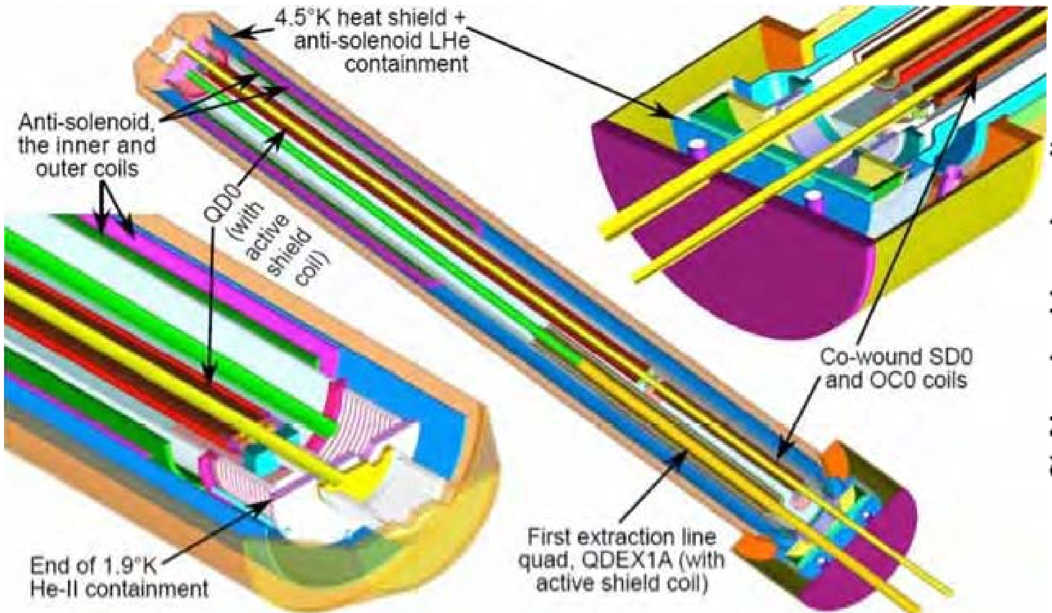
- 右側の6極磁石の組は、Final Doublet（最後の2つの4極磁石）が作る色収差を消す。
- 左側の6極磁石の組は、右側の組がつくった非線形性を相殺する目的で置かれている。
- この方式は ATF2 で採用されている。
- これはFFTBで試験された方式とは異なる。

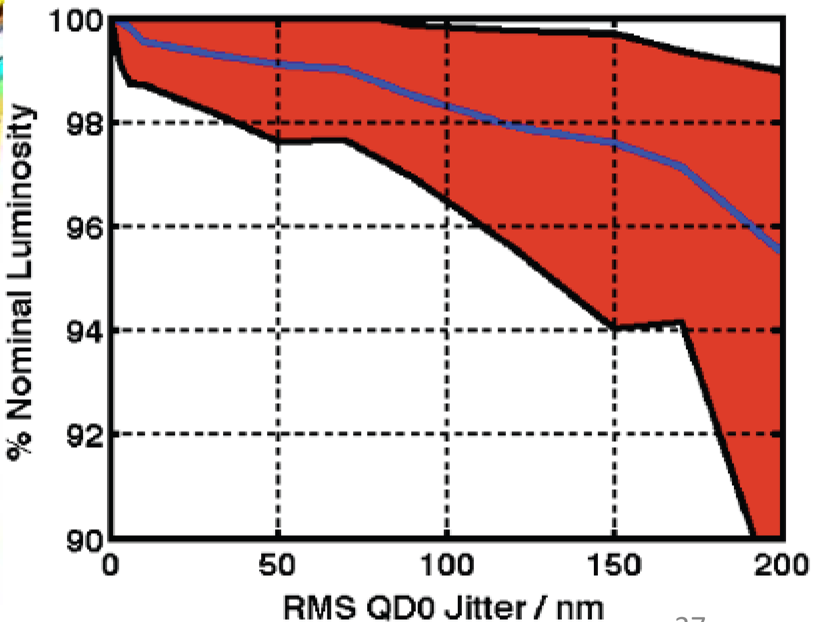
IR Region Layout



Final Doublet

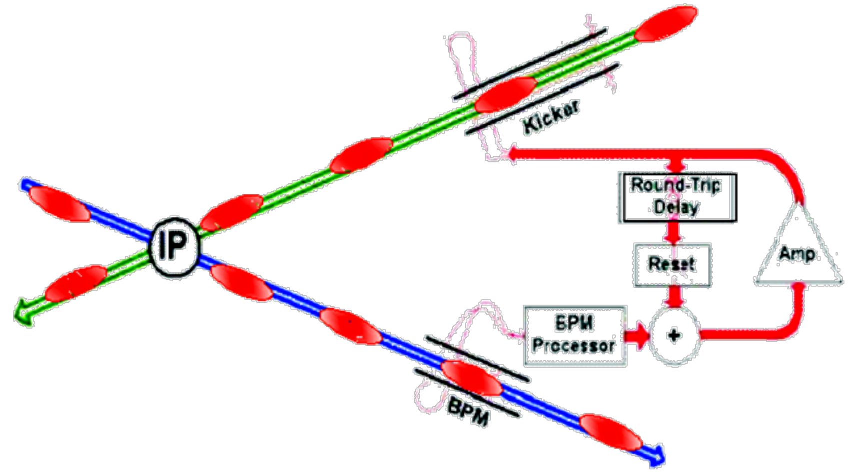
- Final doublet
  - Under study at BNL
  - Split QD0 (2m) into 2 pieces
  - Easier mechanical support
  - Flexibility for low energy optics
- QD0 Jitter
  - Simulation by White below
  - Shows average, 10%, 90% CL
  - Luminosity loss 1%
    → jitter < 50nm rms

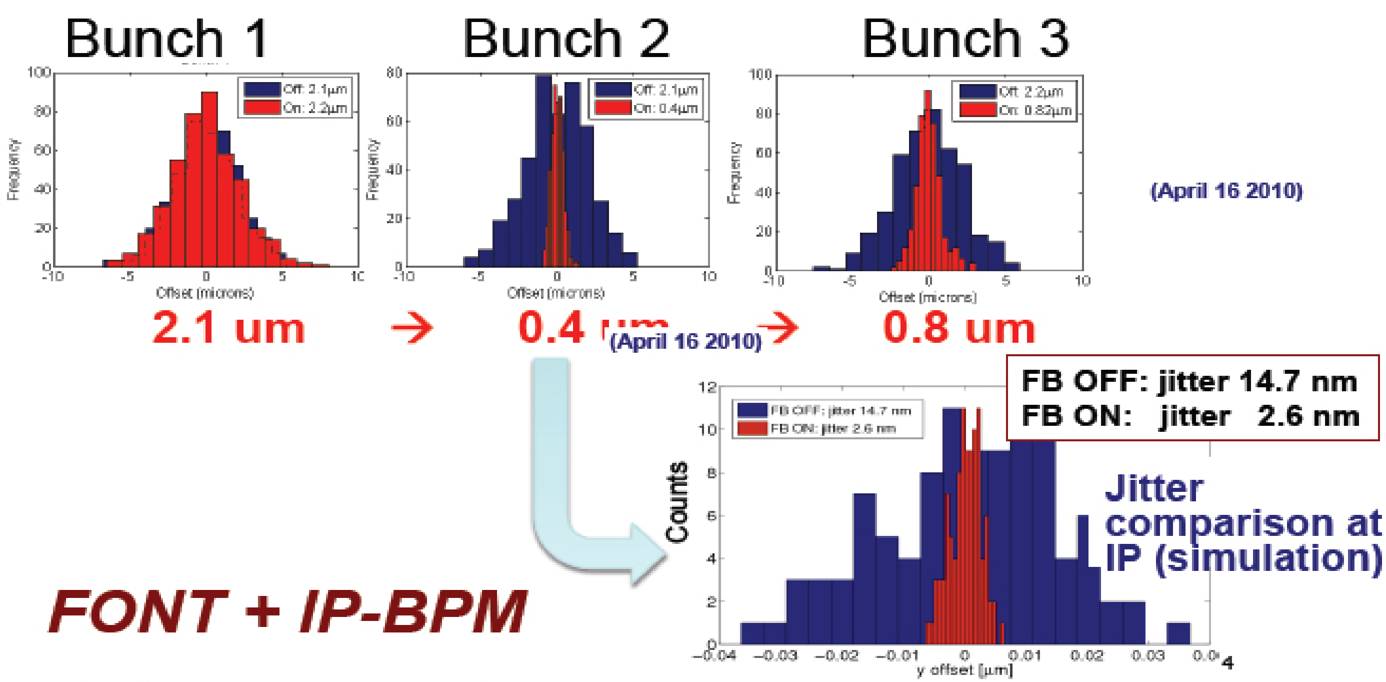




IP Feedback

- Bunch interval is long enough for intra-train digital feedback
  - Advantage of SC collider
- Large disruption parameter
  - Dy = 25

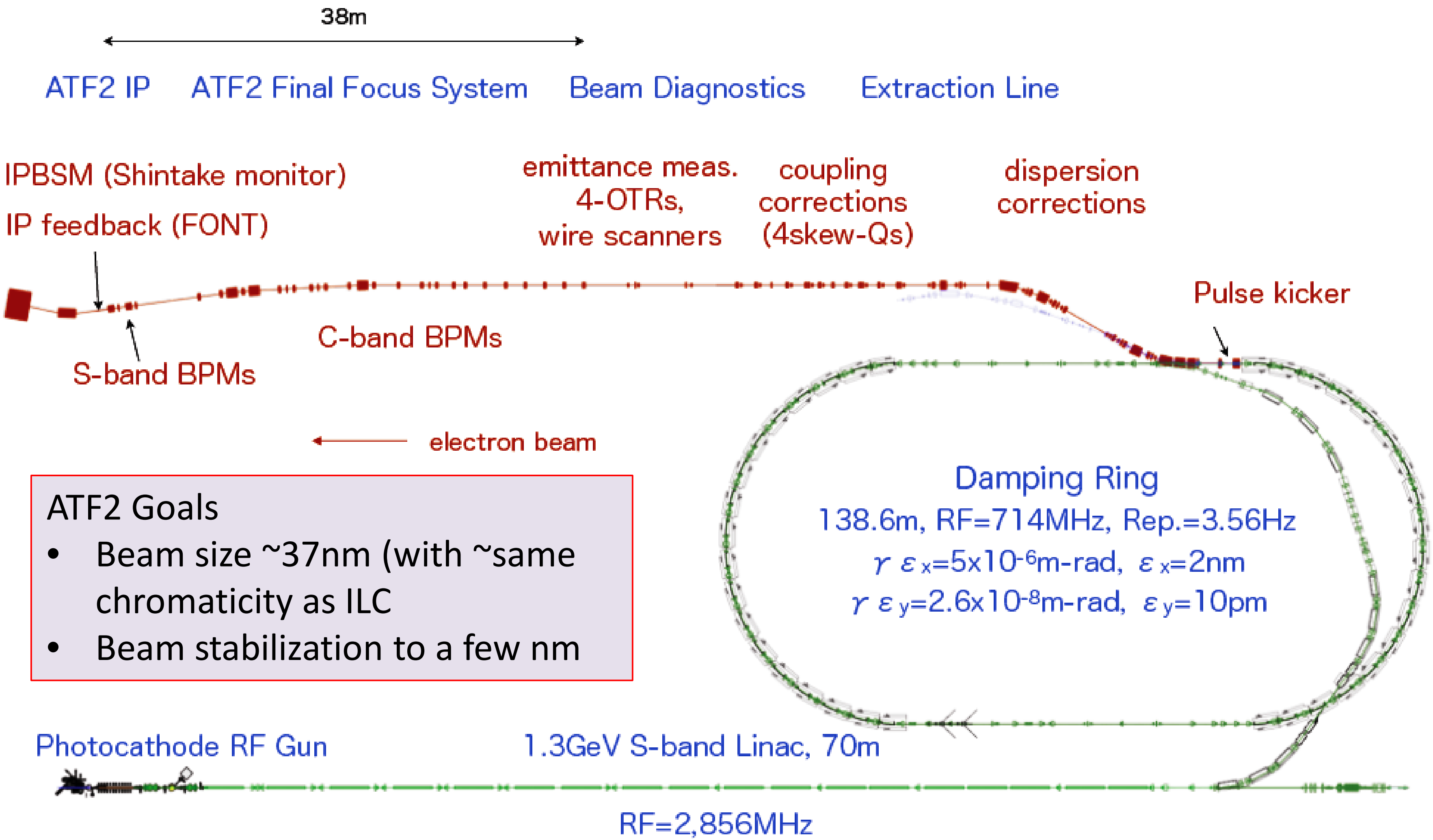




PAC'11, NY, March 30, 2011

N. Terunuma, KEK ATF Beam Instrumentation Program

Test Facility : ATF and ATF2



ATF2 Goals

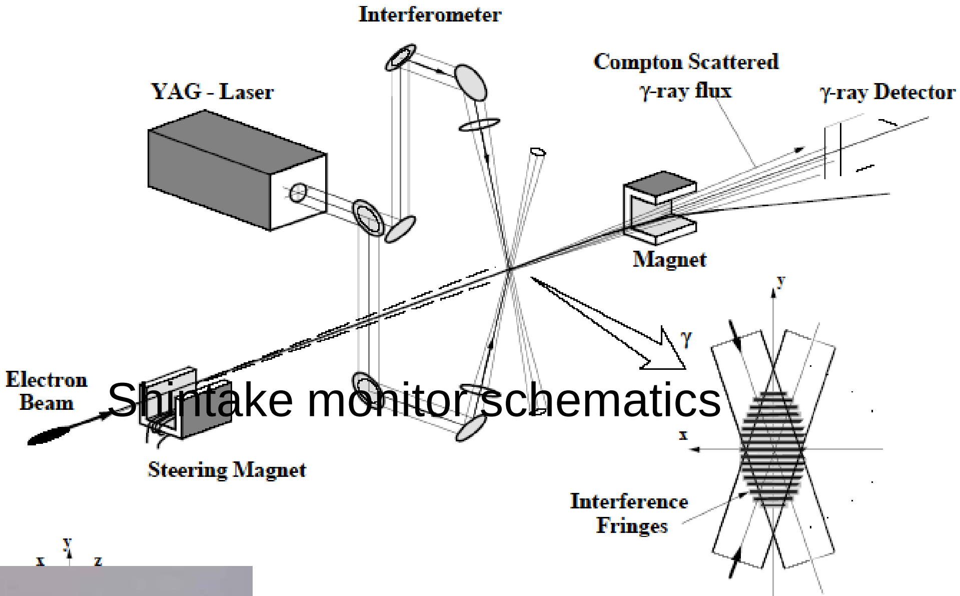
- Beam size ~37nm (with ~same chromaticity as ILC
- Beam stabilization to a few nm

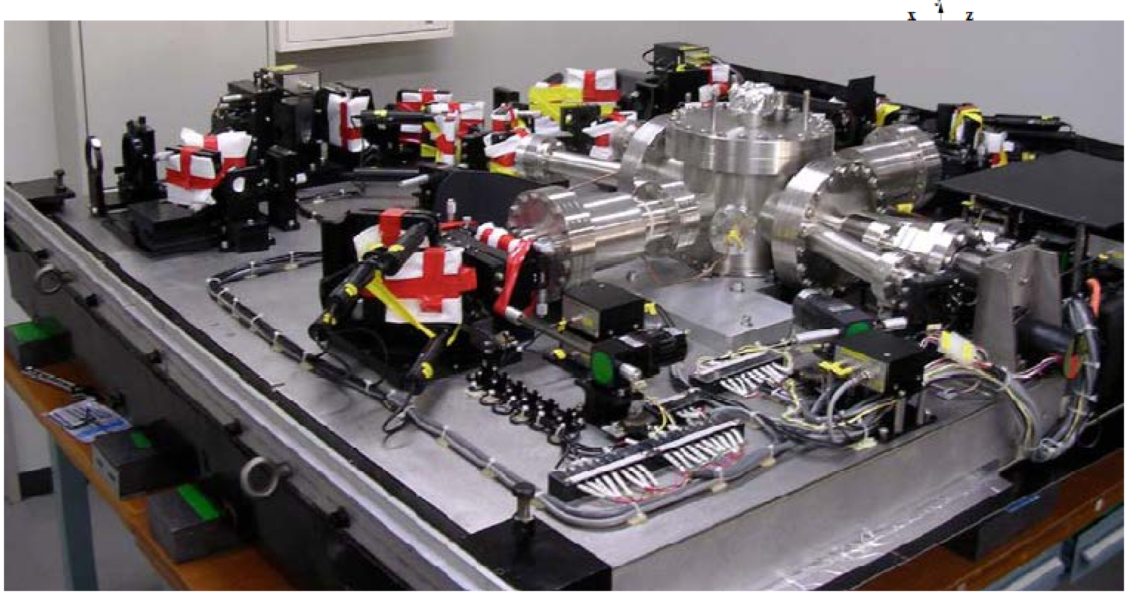
T.Tauchi, ILC camp 2013

IP Beam Size monitor (BSM)

(Tokyo U./KEK, SLAC, UK)

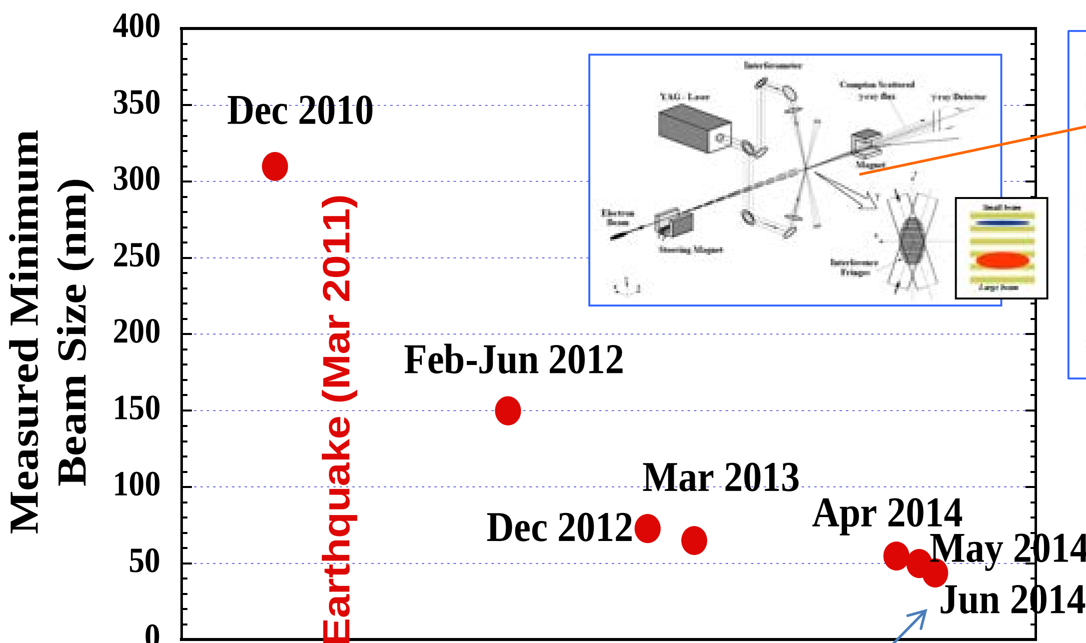
- Improvement FFTB BSM
  - 1064nm=>532nm
  - dynamic range: 35nm up to a few μm
  - phase scanning mode

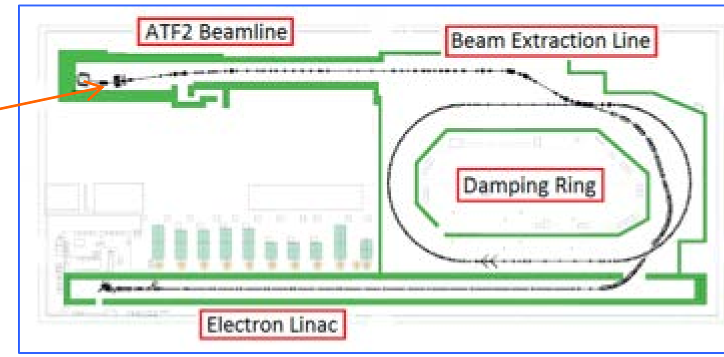


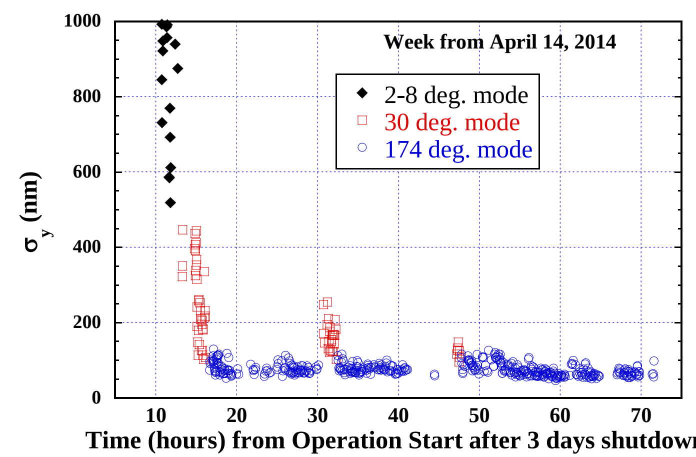


Progress in measured beam size at ATF2

IPAC2014, K. Kubo + ICHEP S.Kuroda





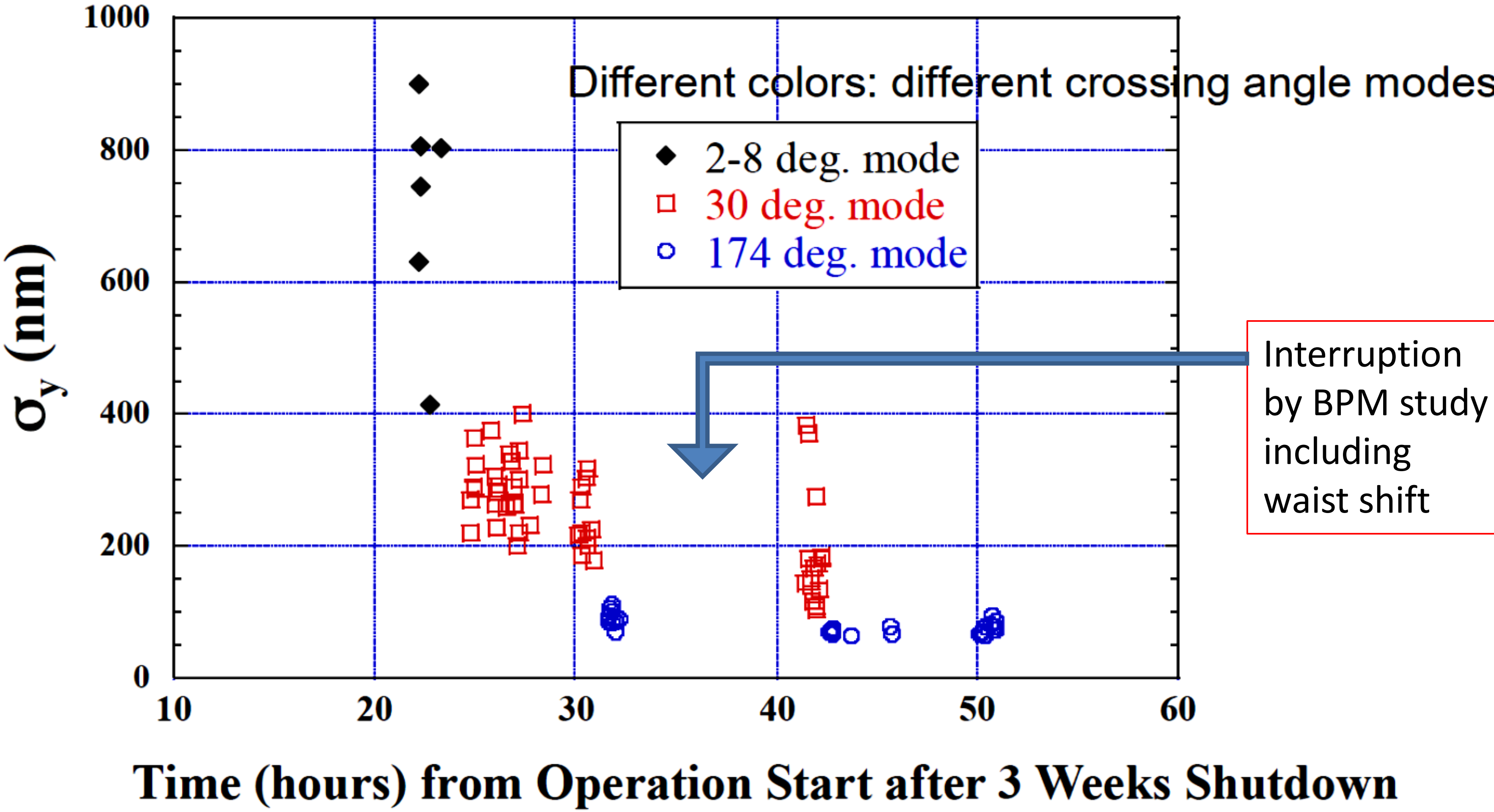


Beam Size 44 nm observed,
(Goal : 37 nm)

Beam Size Tuning after 3 weeks shutdown

Small beam (~60 nm) observed
~32 hours from operation start

By April 2014



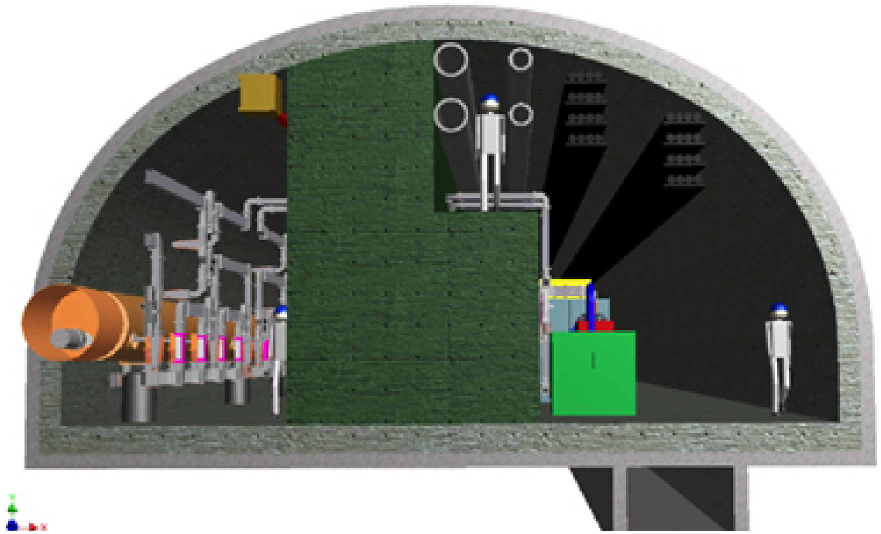
Interruption by BPM study including waist shift

Week 2014 April 7

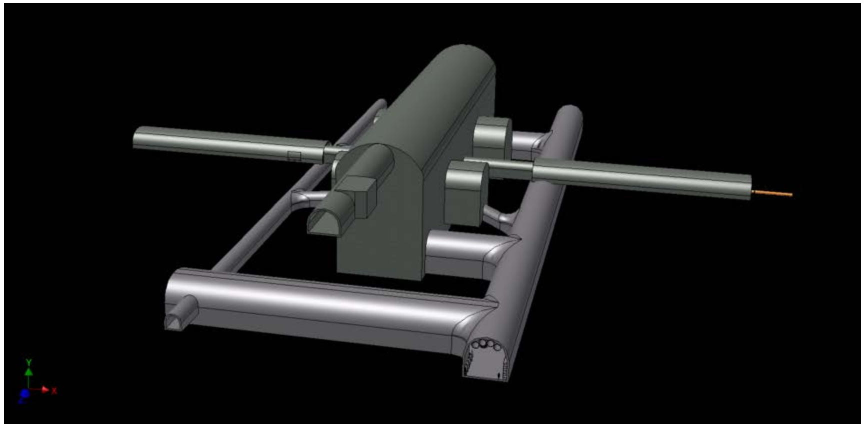
K.Kubo IPAC14

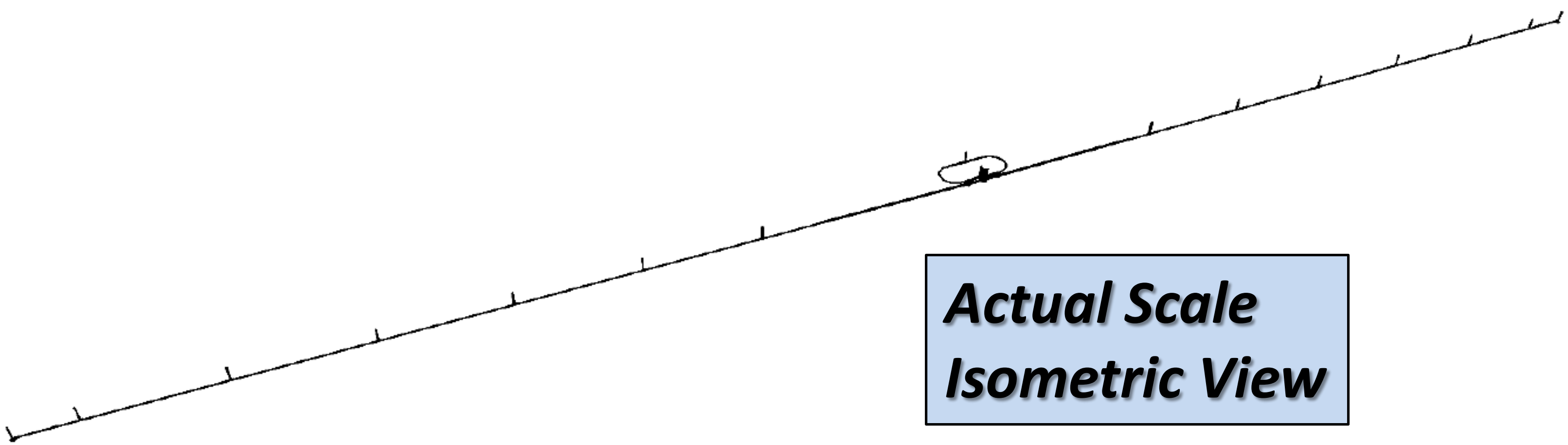
Conventional Facilities

- MR Linac トンネル断面



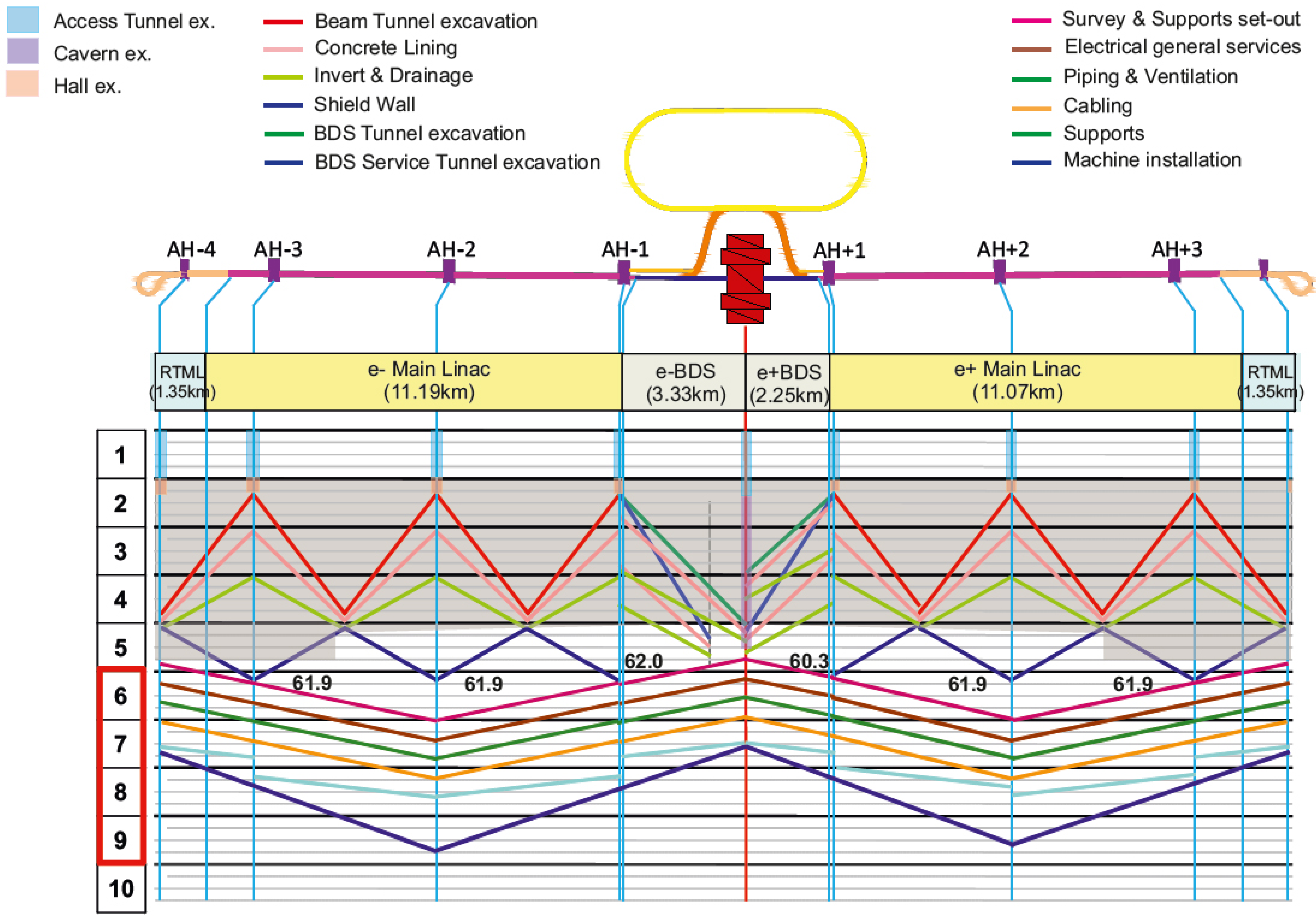
実験ホール付近の地下構造





Actual Scale
Isometric View

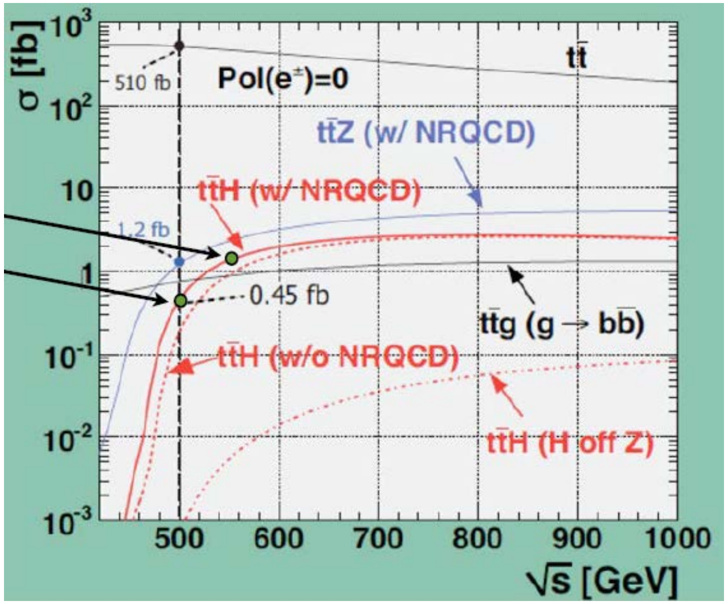
9年間の建設スケジュール



K.Yokoya

Energy Staging

- TDR adopted 500GeV as the design reference
  - Not knowing Higgs mass
- Staging strategy for actual construction under study
- Energy related to the thresholds of various processes
  - 250GeV ZH
  - 350GeV tt
  - 500GeV ttH



- Starting with energy << 500GeV
  - earlier start
  - Relaxed cryomodule production rate
- Tunnel length should be prepared for 500GeV
  - Or ~550GeV ?
    - 500GeV is too close to ttH
    - Can gain factor ~4 at 550GeV
- Will be decided soon (~this year)

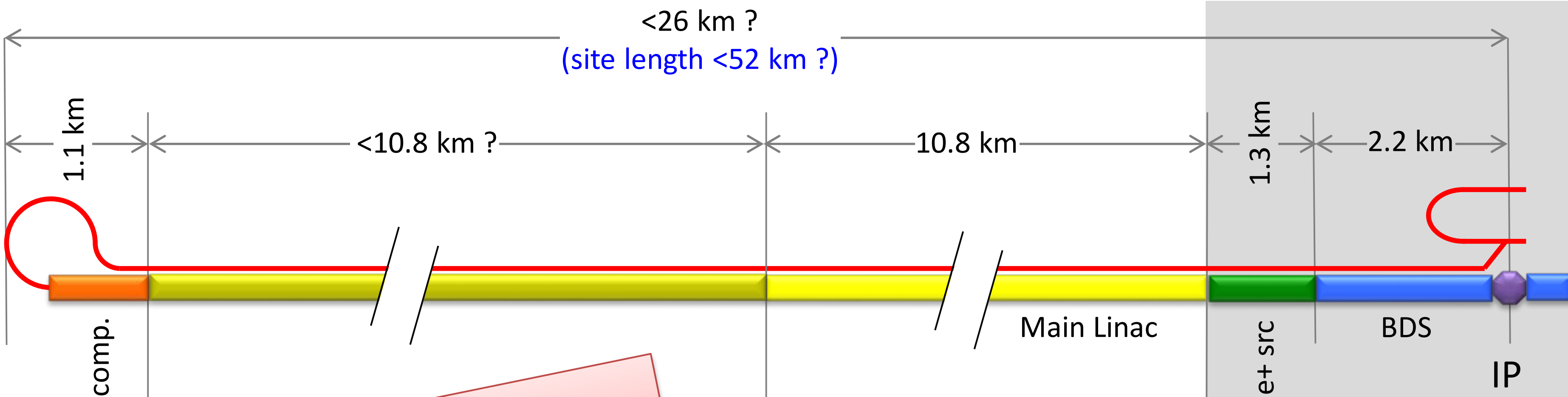
Luminosity Upgrade

- Baseline (1326 bunches)
  - Possible to double the luminosity at E_{CM}=250GeV by doubling the collision rate to 10Hz
  - ~ up to 7Hz at E_{CM}=350GeV
- High power (2625 bunches)
  - Reinforcement of RF system (plus 2nd positron DR depending on e-cloud)
  - This will double the luminosity
  - Another factor 2 (250GeV) or 1.4 (350GeV) by 10Hz collision

Luminosity ($x10^{34}$ $/cm^2/s$)

	#of bunches	Collison freq.	250GeV	350GeV	500GeV
Baseline	1312	5	0.75	1.0	1.8
		10(7)	1.5	(1.4)	
Hi power	2625	5	1.5	2.0	4.9 (3.0)
		10(7)	3.0	(2.8)	

TeV Upgrade : From 500 to 1000 GeV



Assume Higher Gradient

<u>Main Linac</u>

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

G_{eff} ≈ 22.7 MV/m

(fill fact. = 0.72)

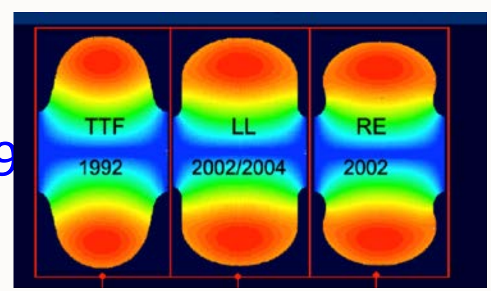
central region

<u>Snowmass 2005 baseline recommendation for TeV upgrade:</u>

G_{cavity} = 36 MV/m ⇒ 9

km

(VT ≥ 40 MV/m)



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

CM Energy vs. Site Length

- Under the assumption
  - Keep the modules for the initial 500GeV linac
  - 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

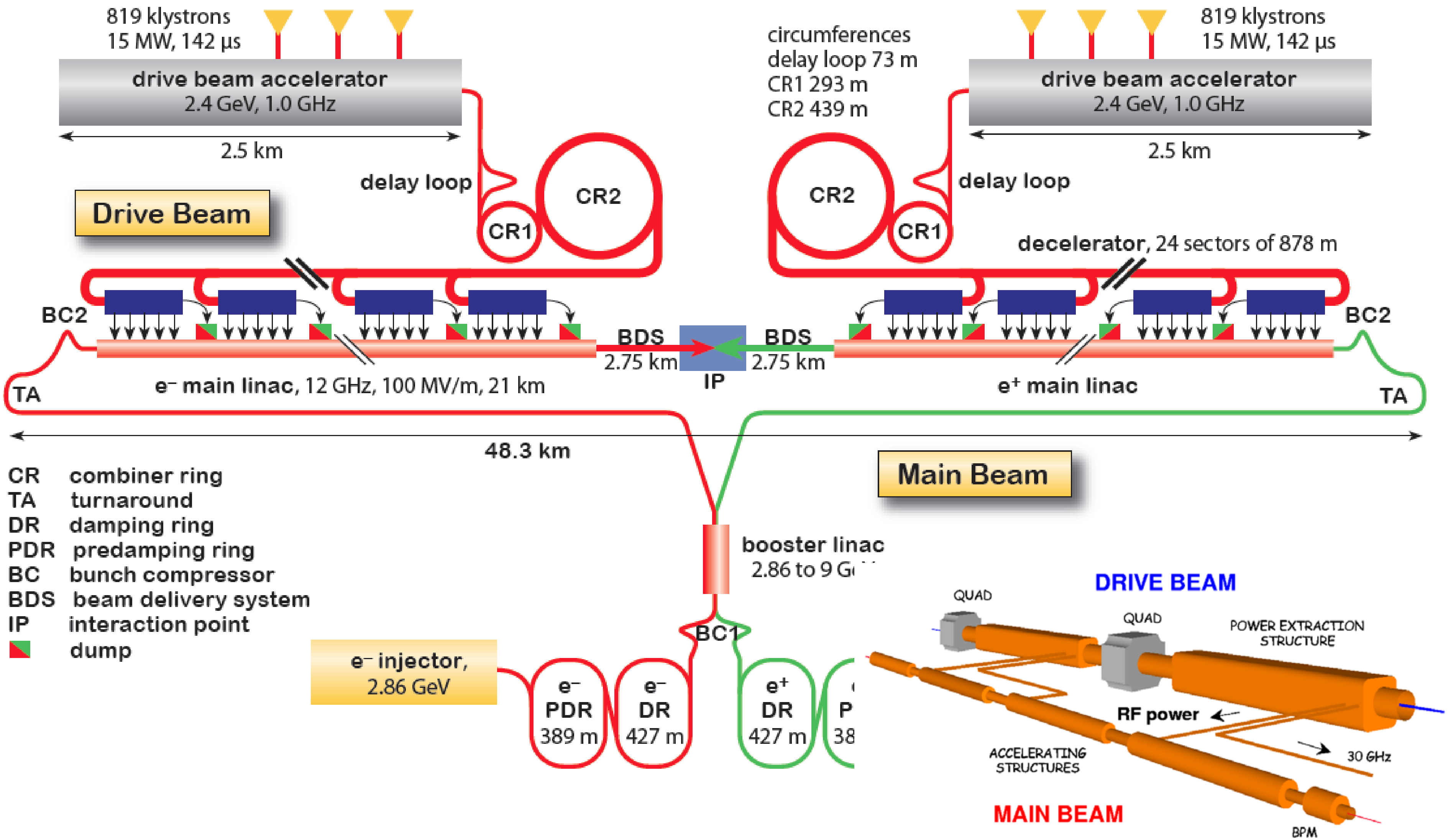
ここまでのまとめ

- 500GeV ILCの建設のための技術はほとんどできあがっている
  - 加速勾配
  - ビーム収束
  - その他多数
- 残された技術的課題
  - 空洞・クライオモジュール製造
    - より安価に、確実に
    - 大量生産体制・製品試験体制の確立
  - ATF2での目標ビームサイズ・ビーム安定化の達成
  - 陽電子生成システムの実証
  - 敷地を特定した最終詳細設計

将来のレプトンコライダー技術

- CLIC
- Gamma-Gamma collider
- Muon Collider
- Plasma Collider

CLIC (CERN Linear Collider)



CLIC Main Parameters

parameter	symbol		
centre of mass energy	E_{cm} [GeV]	500	3000
luminosity	$\mathcal{L}$ [10^{34} $cm^{-2}s^{-1}$]	2.3	5.9
luminosity in peak	$\mathcal{L}_{0.01}$ [10^{34} $cm^{-2}s^{-1}$]	1.4	2
gradient	G [MV/m]	80	100
site length	[km]	13	48.3
charge per bunch	N [10^9]	6.8	3.72
bunch length	σ_z [μm]	72	44
IP beam size	σ_x/σ_y [nm]	200/2.26	40/1
norm. emittance	ϵ_x/ϵ_y [nm]	2400/25	660/20
bunches per pulse	n_b	354	312
distance between bunches	Δ_b [ns]	0.5	0.5
repetition rate	f_r [Hz]	50	50
est. power cons.	P_{wall} [MW]	271	582

CLIC project time-line

S.Stapnes, LCWS14

2013-18 Development Phase

Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.

4-5 year Preparation Phase

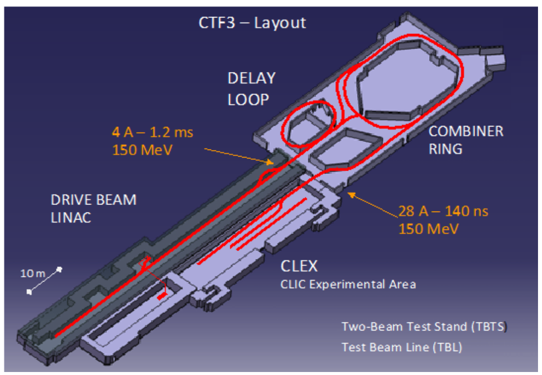
Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement.

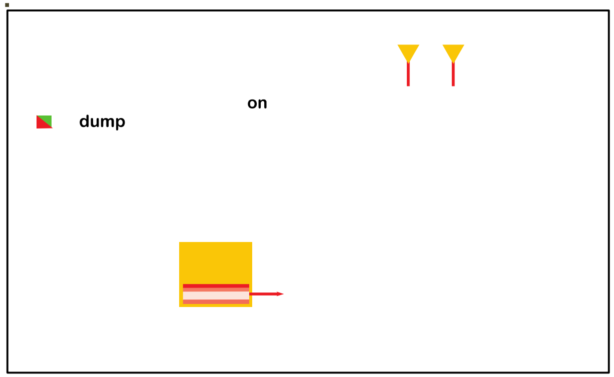
Prepare detailed Technical Proposals for the detector-systems.

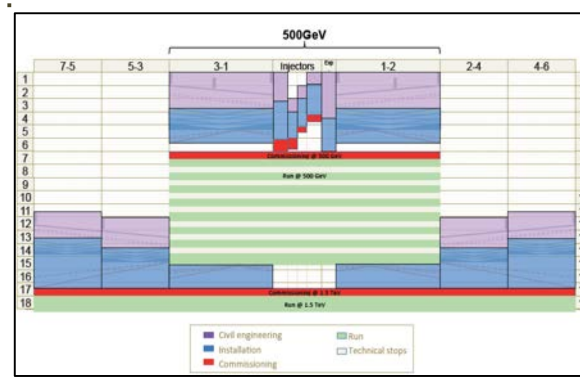
Construction Phase

Stage 1 construction of CLIC, in parallel with detector construction.

Preparation for implementation of further stages.







2018-19 Decisions

On the basis of LHC data and Project Plans (for CLIC and other potential projects as FCC), take decisions about next project(s) at the Energy Frontier.

2024-25 Construction Start

Ready for full construction and main tunnel excavation.

Commissioning

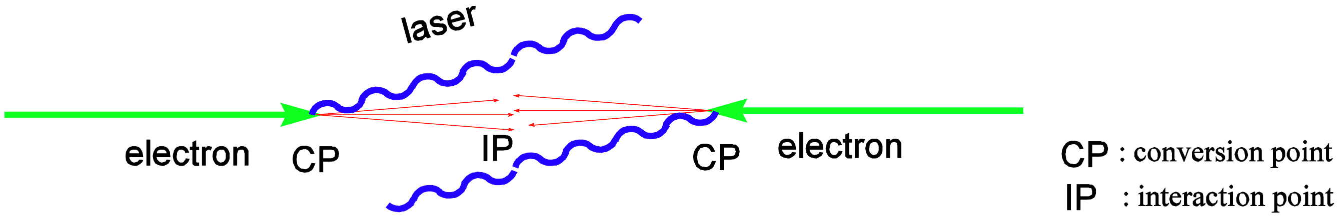
Becoming ready for data-taking as the LHC programme reaches completion.

CLIC Technology Maturity

- CDR published
- Cavity with accelerating gradient ~100MV/m almost confirmed
- Drive Beam generation demonstrated. Emittance and stability to be further improved
- Deceleration in PETS in progress
- Emittance preservation in linac with stabilization system developed
- Linac beam dynamics being tested at FACET
- Final Focus System to be tested at ATF2

Gamma-Gamma Collider

- electron-electron collider
- irradiate lasers just before ee collision
- create high energy photons, which made to collide
- no need of positrons



- Lots of recent proposals of $\gamma\,\gamma \rightarrow$ H (not "beyond LHC")
- ILC and CLIC can be converted to γ-γ collider if physics demands
- In principle, advanced linear colliders (plasma, etc) can also be converted to γ-γ collider. In particular when positron acceleration is difficult.

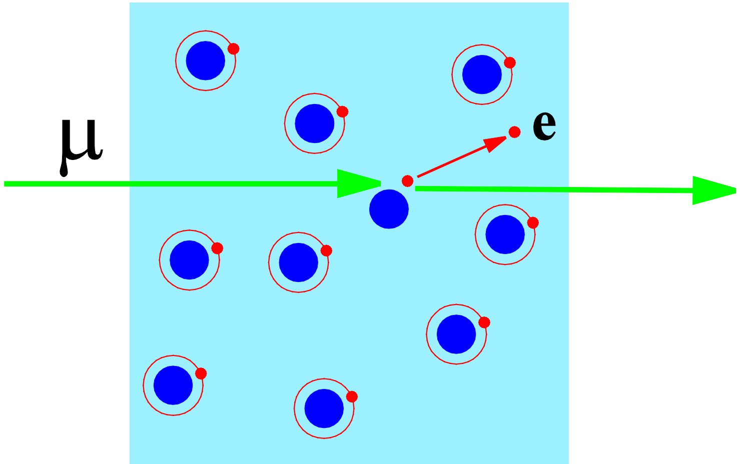
Technology for Gamma-Gamma

- Laser
  - Pulse structure must match with the electron beam (difference between NC and SC linacs)
  - Flash energy : a few to 10 Joules
  - Some lasers close to gamma-gamma application
    - LIFE (fusion), fiber
    - But still needs years of R&D including the adaptation of pulse structure
- Optical cavity
  - Can accumulate laser pulse from relatively weak lasers (mostly for SC linac case)
  - Many R&D studies in the world for other applications
- IR design
  - Path of laser beam
  - In particular complex with optical cavity is used
  - background studies

Muon Collider

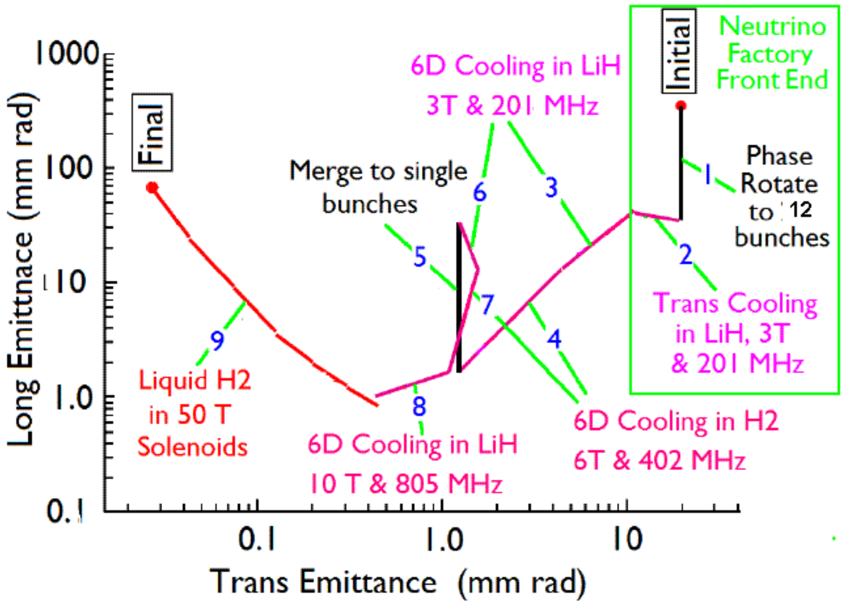
- Properties of muons are quite similar to electron/positron
  - What can be done in e+e- can also be done in $\mu^+\mu^-$
- but muon is 200x heavier → can be accelerated to high energies in circular accelerator
- $\mu^+\mu^-$ collider is much cleaner than e+e- (beamstrahlung negligible)
  - except the problem of background from muon decay
- But muons do not exist naturally
  - need cooling like antiproton
- "Ionization cooling" invented by Skrinsky-Parkhomchuk 1981, Neuffer 1983

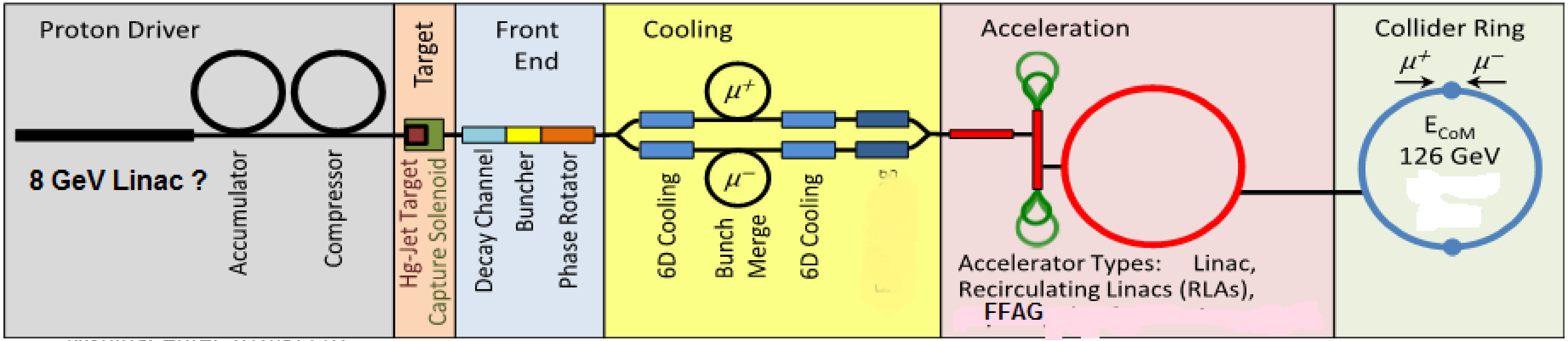
- Make use of energy loss dE/dx by ionization
- Coulomb scattering heats the beam



Create and Cool Muon Beam

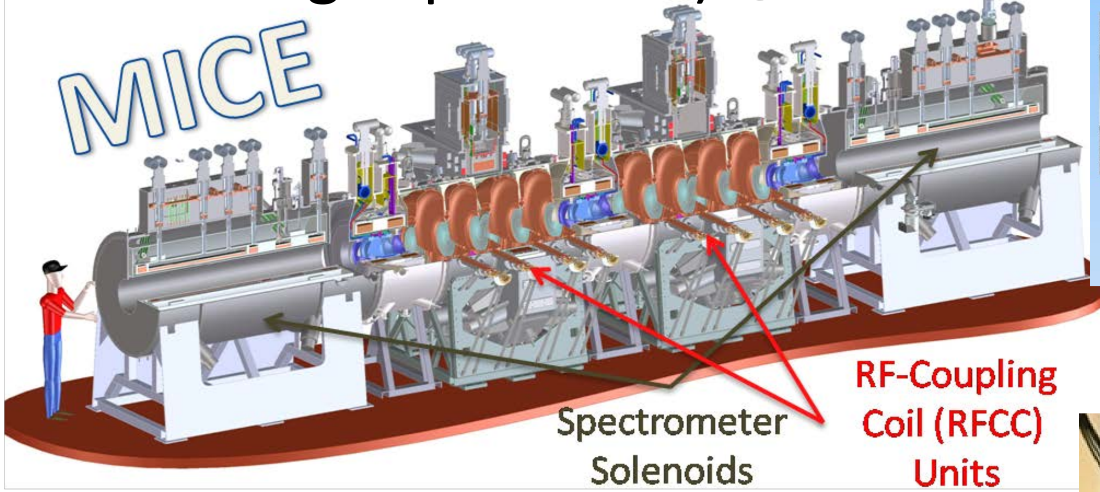
- Muons created by hadron collision
- Muons decay within 2μs in the rest frame
  - must be accelerated quickly
- Staging
  - Higgs factory at E_{cm}=126GeV (Z-pole used to be the first target)
  - Neutrino factory
  - TeV muon collider

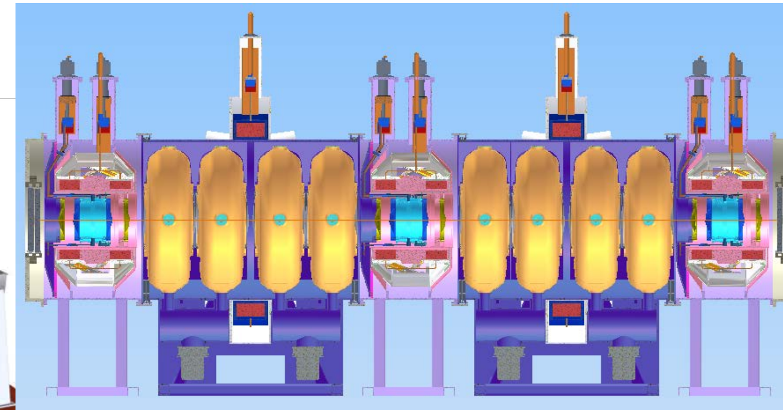




Cooling Test Facilities

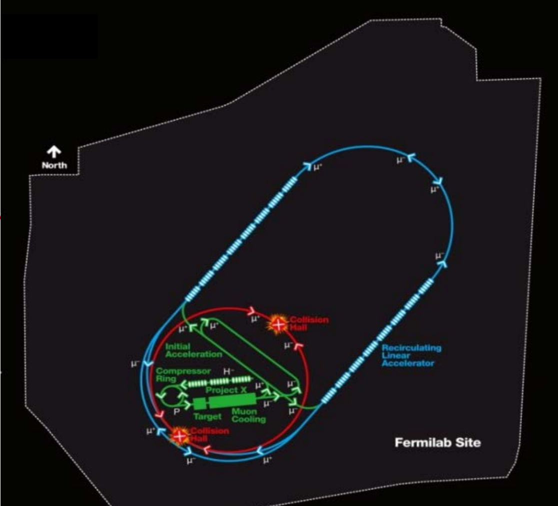
- MICE (Muon Ionization Cooling Experiment) @RAL





- MTA (MuCool Test Area) @FNAL
  - cavity test

MAP Designs for a Muon-Based Higgs Factory and Energy Frontier Colliders



Range of Top Params:
$\delta E/E \sim 0.01 - 0.1\%$
$L_{avg} \sim 0.7 - 6 \cdot 10^{33}$

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

Site Radiation mitigation with depth and lattice design: ≤ 10 TeV

Muon Collider Baseline Parameters

Parameter	***Units***	**Higgs Factory** Startup Operation	**Higgs Factory** Production Operation	**Multi-TeV Baselines**	**Multi-TeV Baselines**
CoM Energy	TeV	0.126	0.126	1.5	3.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.0017	0.008	1.25	4.4
eam Energy Spread	%	0.003	0.004	0.1	0.1
Higgs/10^7sec		3,500	13,500	37,500	200,000
Circumference	km	0.3	0.3	2.5	4.5
No. of IPs		1	1	2	2
Repetition Rate	Hz	30	15	15	12
β^*	cm	3.3	1.7	1 (0.5-2)	0.5 (0.3-3)
No. muons/bunch	10^{12}	2	4	2	2
No. bunches/beam		1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	70	70
Bunch Length, σ_s	cm	5.6	6.3	1	0.5
Beam Size @ IP	μm	150	75	6	3
Beam-beam Parameter / IP		0.005	0.02	0.09	0.09
Proton Driver Power	MW	$4^{\#}$	4	4	4

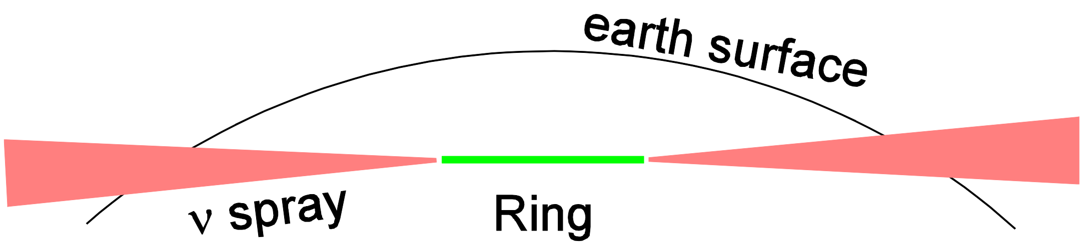
\# Could begin operation with Project X Stage 2 beam

Success of advanced cooling concepts ⇨ several ⇙ 10^{32}

M.Palmer, Jul.30.2013

Technical Challenges on Muon Collider

- Proton driver of several MW
- Target at several MW
- Ionization cooling
  - ~10^6 in 6D emittance
  - High field HTS solenoid (>30T)
  - High gradient acceleration in magnetic field (Teslas)
- collider ring issues
  - High field dipole (10-20T)
  - muon decay (background, magnet shielding)
- Will require tens of years of R&D
- Energy limit comes from radiation (~10TeV?)

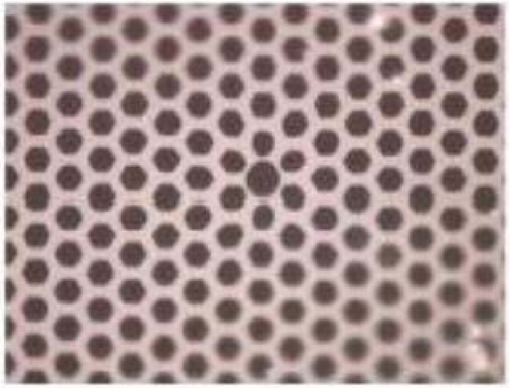


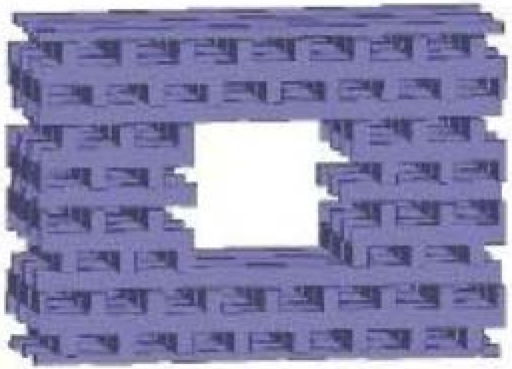
Advanced Acceleration Mechanisms

- Dielectric material
  - Laser-driven (DLA)
  - Beam driven
- Plasma wakefield acceleration
  - Laser-driven (LWFA)
  - Beam driven (PWFA)

Dielectric Laser Accelerator (DLA)

- Direct extension of present accelerator concept (microwave + resonant structure)
  - Klystron → laser
  - Resonant cavity → micron scale dielectric crystal (semiconductor technology)
  - less power loss than metal at optical frequencies
  - expected higher breakdown thresholds (> 1 order of magnitude than Cu structure)
- Very short wavelength (micron)
- Require very low bunch charge $O(10^4)$ plus very high repetition rate O(GHz)
  - In one hand this relaxes the beam-beam interaction





DLA

- Challenges
  - material to ensure the gradient
  - power coupler of high efficiency
  - electron beam with required bunch pattern (hundred bunchlets in picosecond repeated a few MHz)
  - for colliders
    - emittance growth by transverse wake (alignment)
    - positron beam
      almost impossible to create the beam structure?
    - Can go to γ-γ collider?
      But require extreme laser (~5TW x 1ps, average ~50MW)

An example of 10TeV collider

Bunch population	3.80E+04
bunches per train	159
rep rate	5 MHz
macro bunch length	150 μm
wavelength	1.89 μm
normalized emittance	1e-10 m
IP spot size	0.06nm
Luminosity	4.90E+36
Beam power	24.2MW
Wall-plug power	242MW
Gradient	400MV/m
Total linac length	25km
Laser pulse energy	1μJ
Average power	1kW
Pulsewidth	1ps
Wall-plug efficiency	30-40%

one of the examples in ICFA-ICUIL report

Plasma Wakefield Accelerator

Linac in the past has been driven by **microwave technology**

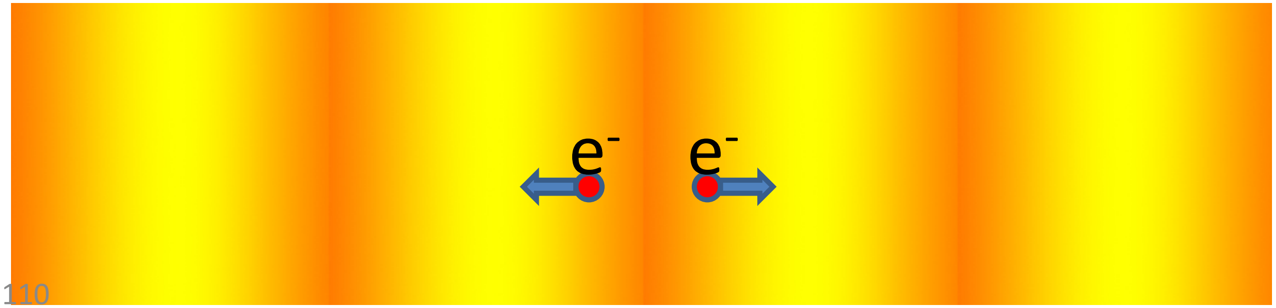
- Plane wave in vacuum cannot accelerate beams: needs material to make boundary condition
- Breakdown at high gradient

Excite **plasma wave** by some way (electron beam, laser beam)

- Charged particles on the density slope are accelerated, like surfing.
- Need not worry about breakdown with plasma
  - can reach > 10GeV/m
- Plasma oscillation frequency and wavelength are related to plasma density

$$\omega_p = \sqrt{\frac{e^2}{\epsilon_0 m_e} n_0}, \qquad \lambda_p = \frac{2\pi c}{\omega_p} = \frac{3.3 \times 10^4}{\sqrt{n_e[\mathrm{cm}^{-3}]}} \quad [\mathrm{m}]$$

$$n_e = \text{plasma density}$$



How to Generate Plasma Wave

- Beam-Driven (PWFA)
  - Use particle (normally electron) beam of short bunch
- Laser-Driven (LWFA)
  - Use ultra-short laser beam
- 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

LWFA

- kick out plasma electrons by pondermotive force of laser
- Laser intensity characterized by the parameter a_0
  - $a_0 < 1$: linear regime
  - $a_0 > 1$: blow-out regime (all electrons expelled out of the drive beam region)

$$a_0 \approx 8.5 \times 10^{-10} \lambda_L[\mu\mathrm{m}] I^{1/2}[\mathrm{W/cm^2}]$$

- Accelerating field

$$E = E_0 \frac{a_0^2/2}{\sqrt{1 + a_0^2/2}}$$

$$E_0 = c m_e \omega_p / e = 96 n_0^{1/2}[\mathrm{cm}^{-3}]$$

Blowout and Linear Regime

- The gradient can be higher in the blowout regime but
  - difficult to accelerate positron
  - narrow region of acceleration and focusing

acceleration field

plasma density

transverse field

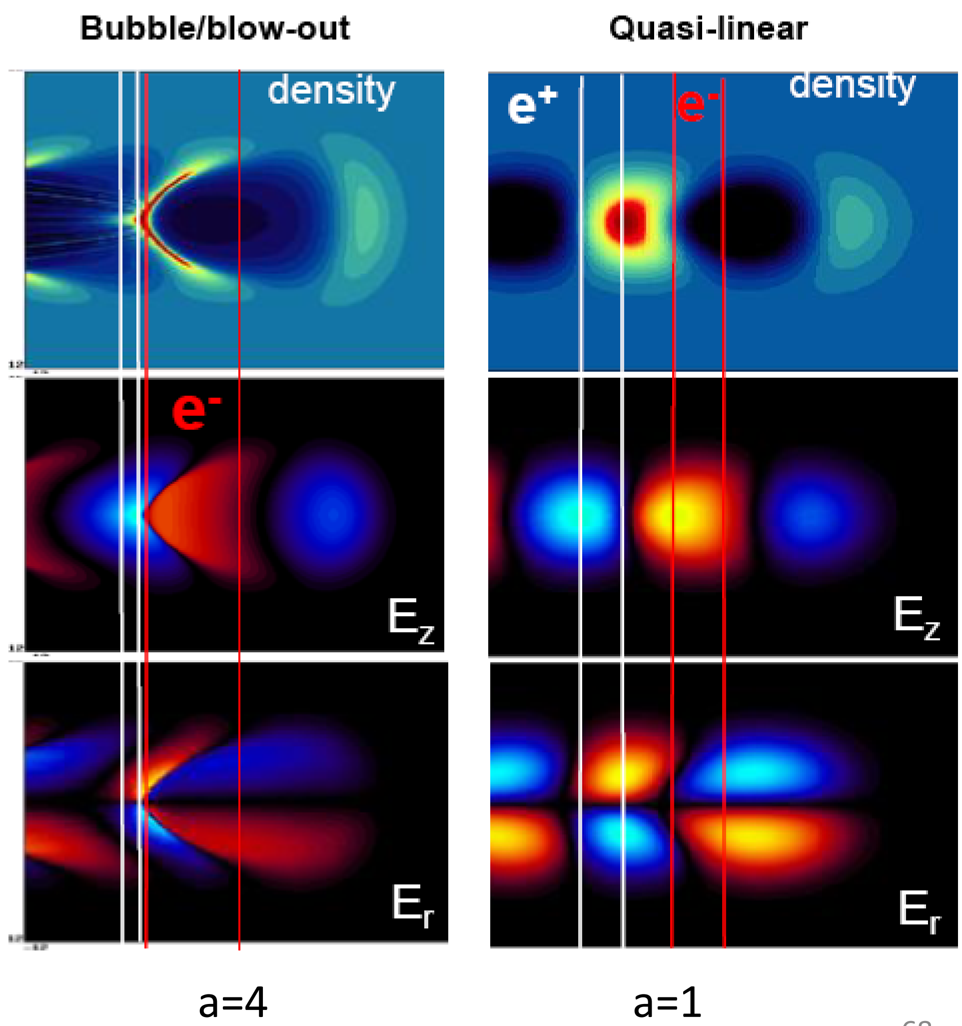
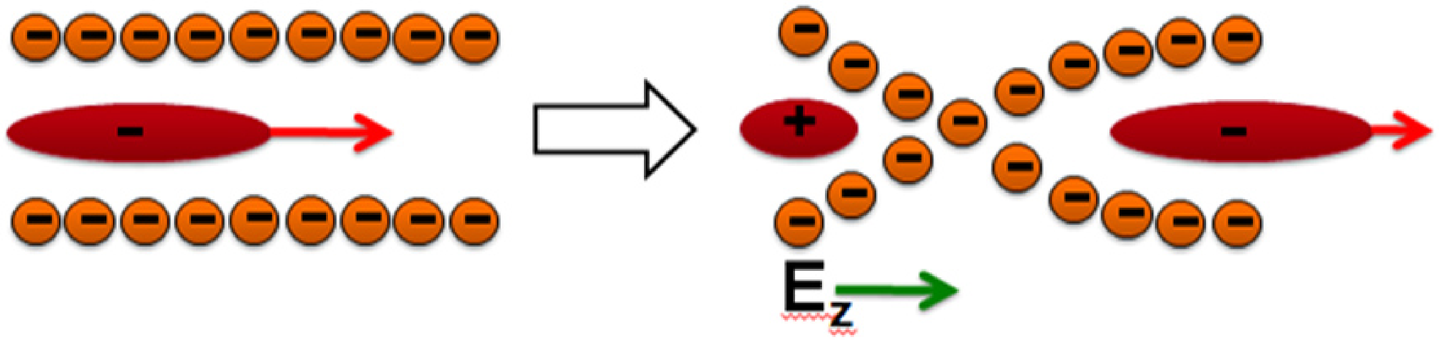


Figure from ICFA Beamdynamics News Letter 56

K.Yokoya

Positron Acceleration

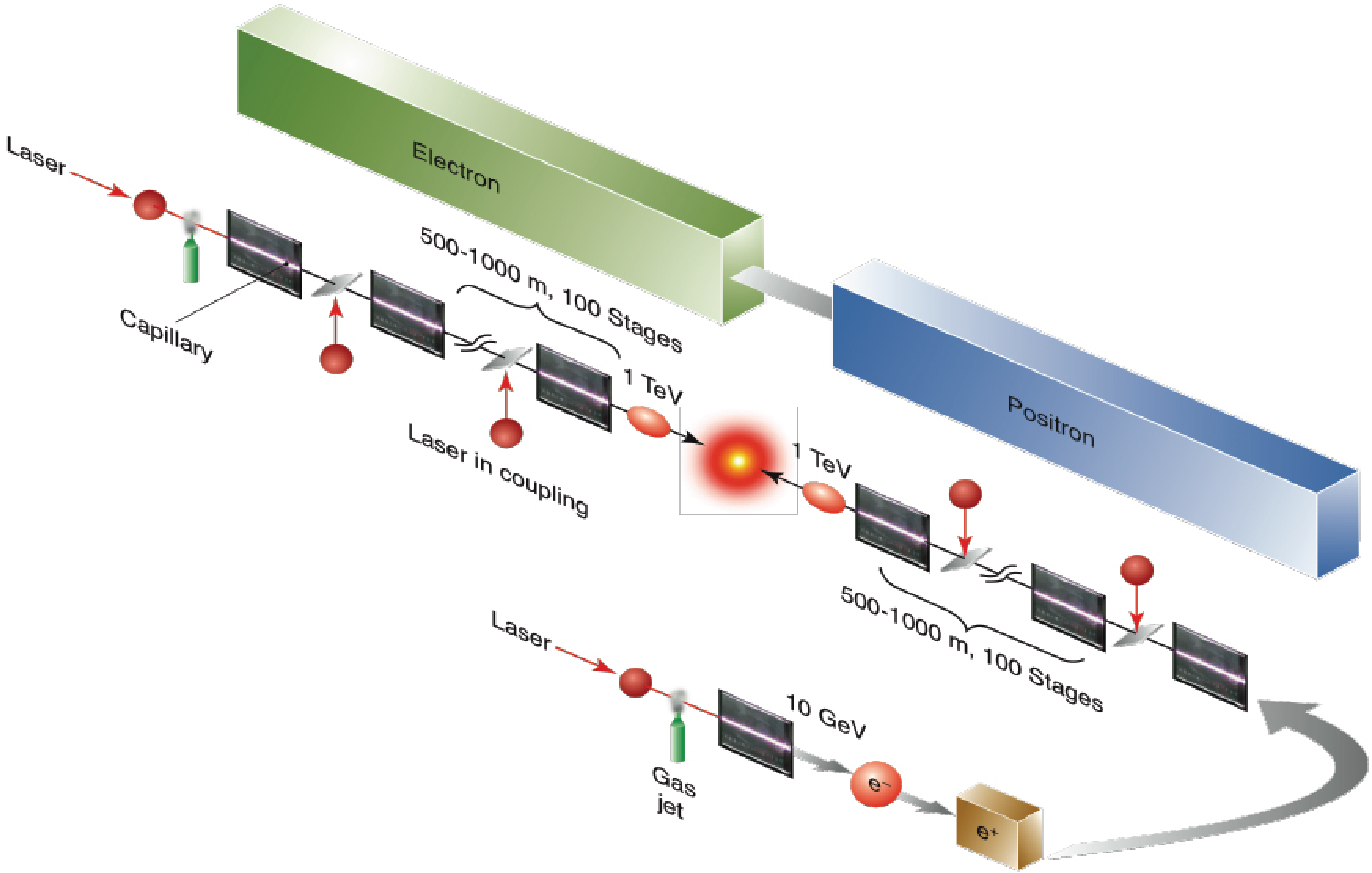
- Positron beam is defocused in the acceleration phase
- Use hollow plasma channel
- Acceleration+focusing phase created when plasma electrons go back to the axis



Limitation by Single Stage

- Laser must be kept focused (Rayleigh length)
  - solved by self-focusing and/or preformed plasma channel
- Dephasing: laser velocity in plasma
  - longitudinal plasma density control
- Eventually limited by depletion
  - depletion length proportional to $n_0^{-3/2}$
  - acceleration by one stage proportional to I/n_0
- Multiple stages needed for high energy, introducing issues of
  - phase control
  - electron orbit matching

Concept of LWFA Collider



Example Beam Parameters of 1-10TeV LWFA

Case: CoM Energy (Plasma density)	1 TeV (10^{17} cm^{-3})	1 TeV (2×10^{15} cm^{-3})	10 TeV (10^{17} cm^{-3})	10 TeV (2×10^{15} cm^{-3})
Energy per beam (TeV)	0.5	0.5	5	5
Luminosity (10^{34} cm^{-2}s^{-1})	2	2	200	200
Electrons per bunch ($\times10^{10}$)	0.4	2.8	0.4	2.8
Bunch repetition rate (kHz)	15	0.3	15	0.3
Horizontal emittance $\gamma\varepsilon_x$ (nm-rad)	100	100	50	50
Vertical emittance $\gamma\varepsilon_y$ (nm-rad)	100	100	50	50
β* (mm)	1	1	0.2	0.2
Horizontal beam size at IP σ^*_x (nm)	10	10	1	1
Vertical beam size at IP σ^*_y (nm)	10	10	1	1
Disruption parameter	0.12	5.6	1.2	56
Bunch length σ_z (μm)	1	7	1	7
Beamstrahlung parameter Υ	180	180	18,000	18,000
Beamstrahlung photons per e, n_γ	1.4	10	3.2	22
Beamstrahlung energy loss δ_E (%)	42	100	95	100
Accelerating gradient (GV/m)	10	1.4	10	1.4
Average beam power (MW)	5	0.7	50	7
Wall plug to beam efficiency (%)	6	6	10	10
One linac length (km)	0.1	0.5	1.0	5

From ICFA Beamdynamics News Letter 56 (ICFA-ICUIL White paper)

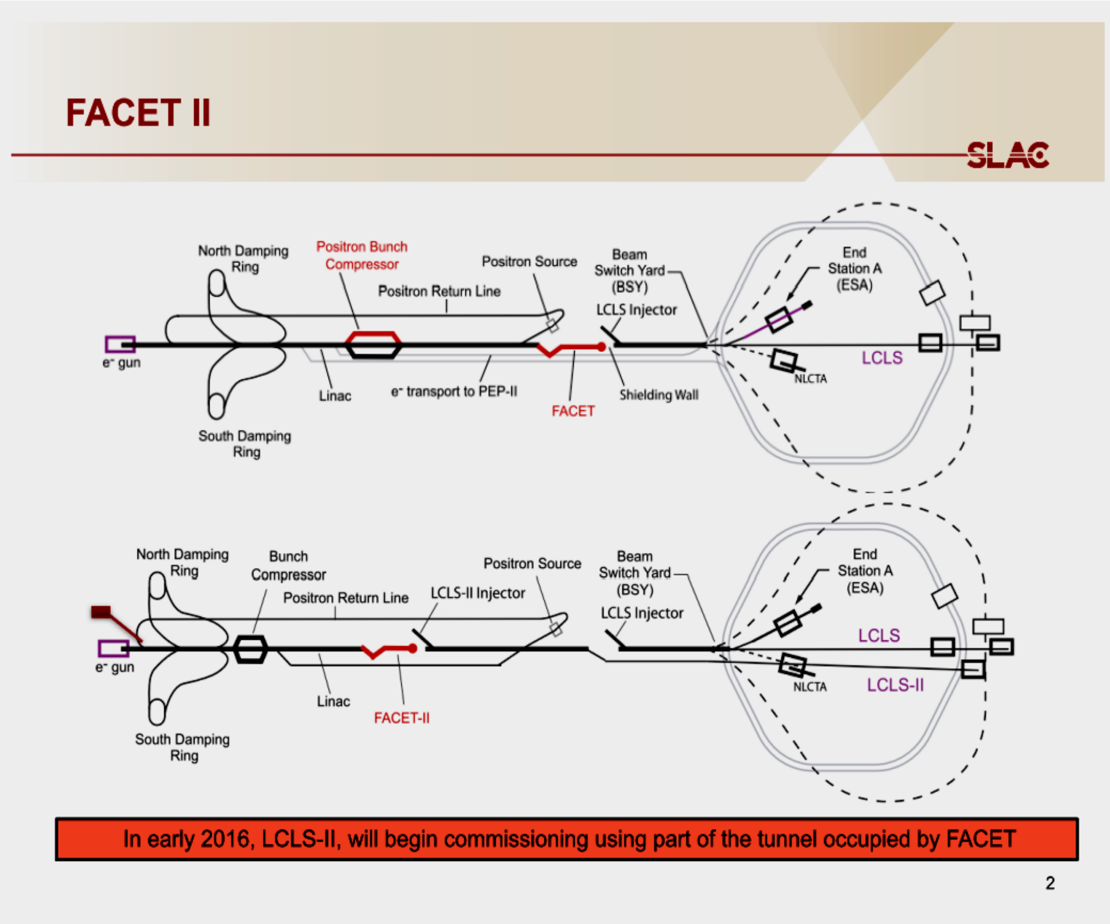
Example Laser Parameters of 1/10TeV LWFA

Case: CoM Energy (Plasma density)	1 TeV (10^{17} cm^{-3})	1 TeV (2×10^{15} cm^{-3})	10 TeV (10^{17} cm^{-3})	10 TeV (2×10^{15} cm^{-3})
Wavelength (μm)	1	1	1	1
Pulse energy/stage (kJ)	0.032	11	0.032	11
Pulse length (ps)	0.056	0.4	0.056	0.4
Repetition rate (kHz)	15	0.3	15	0.3
Peak power (PW)	0.24	12	0.24	12
Average laser power/stage (MW)	0.48	3.4	0.48	3.4
Energy gain/stage (GeV)	10	500	10	500
Stage length [LPA + in-coupling] (m)	2	500	2	500
Number of stages (one linac)	50	1	500	10
Total laser power (MW)	48	3.4	480	34
Total wall power (MW)	160	23	960	138
Laser to beam efficiency (%) [laser to wake 50% + wake to beam 40%]	20	20	20	20
Wall plug to laser efficiency (%)	30	30	50	50
Laser spot rms radius (μm)	69	490	69	490
Laser intensity (W/cm^2)	3×10^{18}	3×10^{18}	3×10^{18}	3×10^{18}
Laser strength parameter a_0	1.5	1.5	1.5	1.5
Plasma density (cm^{-3}), with tapering	10^{17}	2×10^{15}	10^{17}	2×10^{15}
Plasma wavelength (mm)	0.1	0.75	0.1	0.75

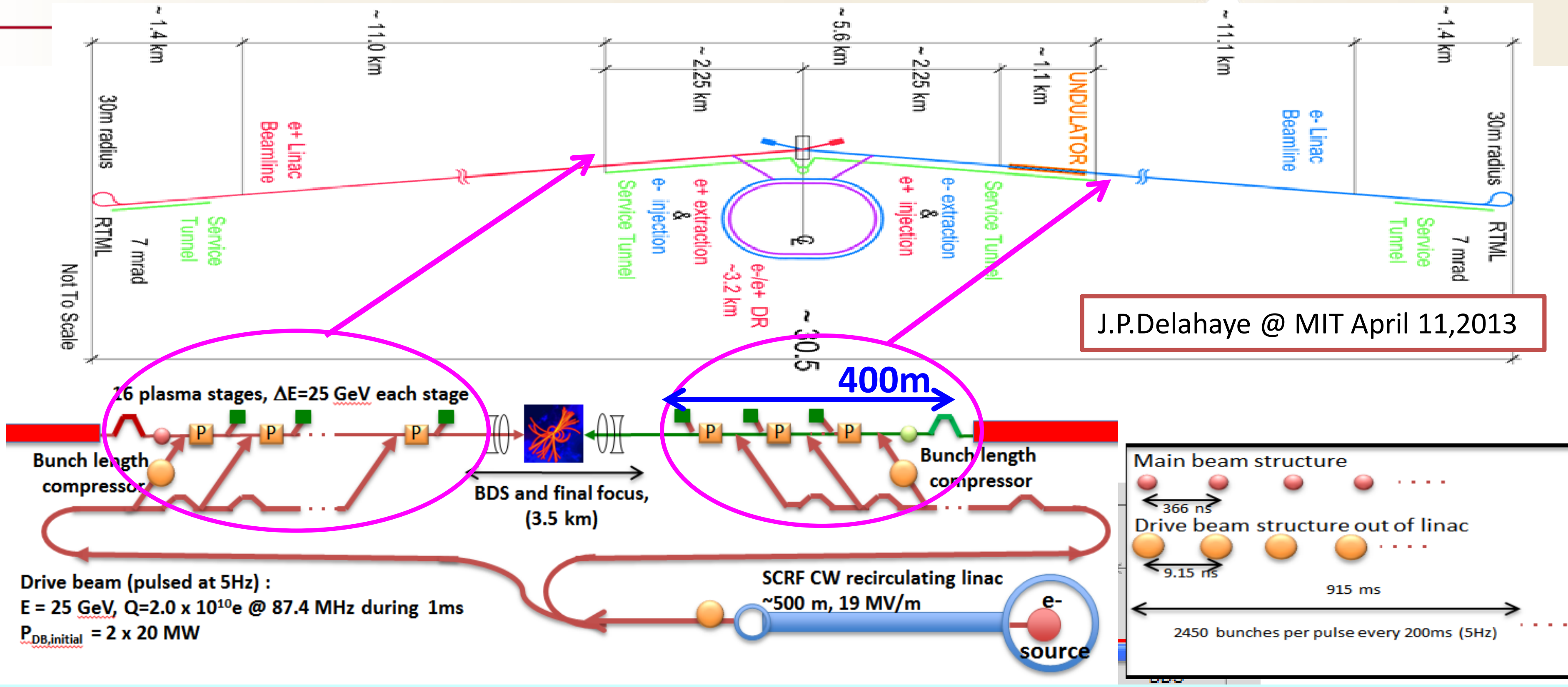
From ICFA Beamdynamics News Letter 56

Beam-Driven Plasma Accelerator

- Use electron beam to generate plasma wave
- Bunch pattern is more flexible than in LWFA (not constrained by the laser technology)
- R&D works led by SLAC (FACET/FACET2)



An alternative ILC upgrade by PWFA



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 Plasma Collider

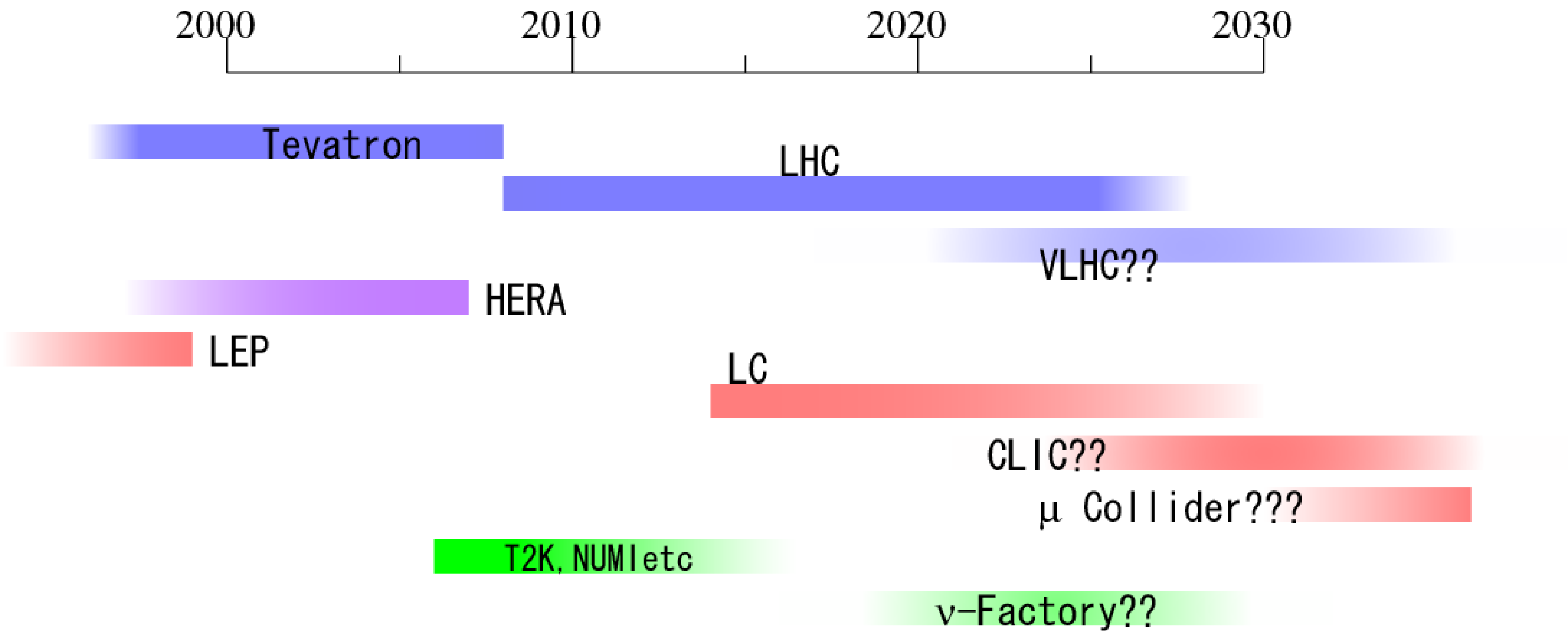
- High rep rate, high power laser (Laser-driven)
- Beam quality
  - Small energy spread << 1%
  - emittance preservation (alignment, instabilities, laser stability, Coulomb scattering)
- High power efficiency from wall-plug to beam
  - Wall-plug → laser (Laser-driven)
  - Laser (beam) → plasma wave
  - plasma wave → beam (high-beam loading required)
- Staging (BELLA at LBNL--- 2 stage acceleration to 10GeV)
  - 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

Summary

- Microwave acceleration up to 3TeV (ILC + CLIC)
  - Accelerator technology nearly ready
- Gamma-gamma collider
  - Laser technology not too far
  - Need detailed design including IR
- Muon collider
  - Staging possible (Higgs → nu factoryb → TeV collider)
  - several beyond-state-of-art components needed
  - but already in the region of accelerator physics
- Plasma collider
  - Still long, long way to colliders
    - Still in the level of plasma physics. Not yet at the stage of accelerator physics
  - PWFA seems to be better for colliders
  - LWFA can have lower-energy application, so step-by-step experience can be gained
- US is in leading position in most of the collider R&D

Time Line???

- An example of poor prediction : Don’t make prediction!



Does not include R&D and construction period

Aug.2004 ICHEP at Beijing