LHC高輝度アップグレード

- 全体像と日本の貢献 -

高エネルギー加速器研究機構（KEK）
中本建志

全体計画とR&Dの現状

https://espace.cern.ch/HiLumi/2012/SitePages/Home.aspx

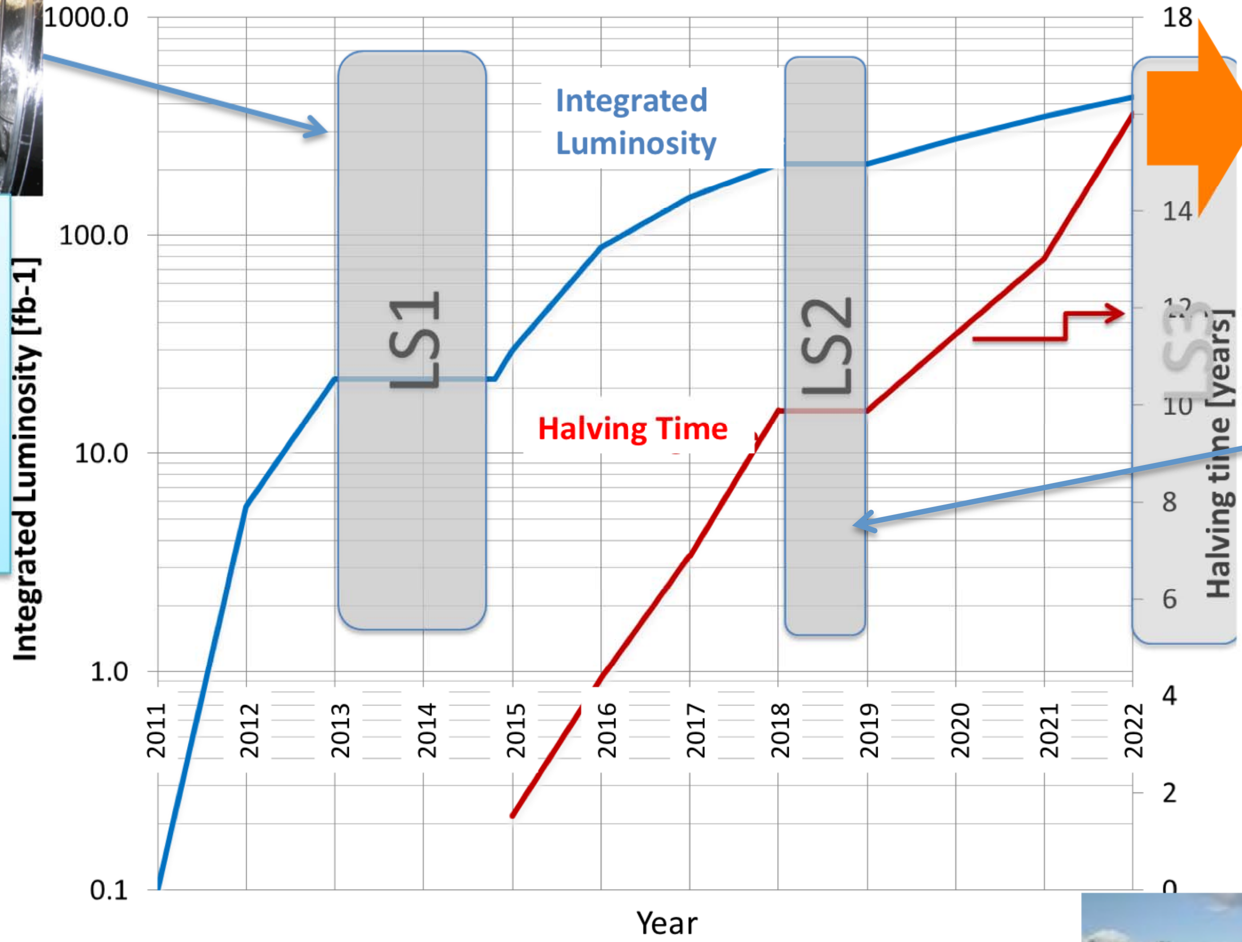
https://indico.fnal.gov/conferenceDisplay.py?confId=6164

LHC高輝度化アップグレード - HL-LHC -

HL-LHCの目標： $3000fb^{-1}$, $5x10^{34}\ cm^{-2}\ sec^{-1}$

（現行LHC $300fb^{-1}$, $1x10^{34}\ cm^{-2}\ sec^{-1}$）

Shut down to fix interconnects and overcome energy limitation (LHC incident of Sept 2008) and R2E



2022 Installation HL-LHC (plan)

Shut down to overcome beam intensity limitation (Injectors, collimation and more...)

積分ルミノシティと統計誤差を半分にするために必要な運転時間

シナリオ

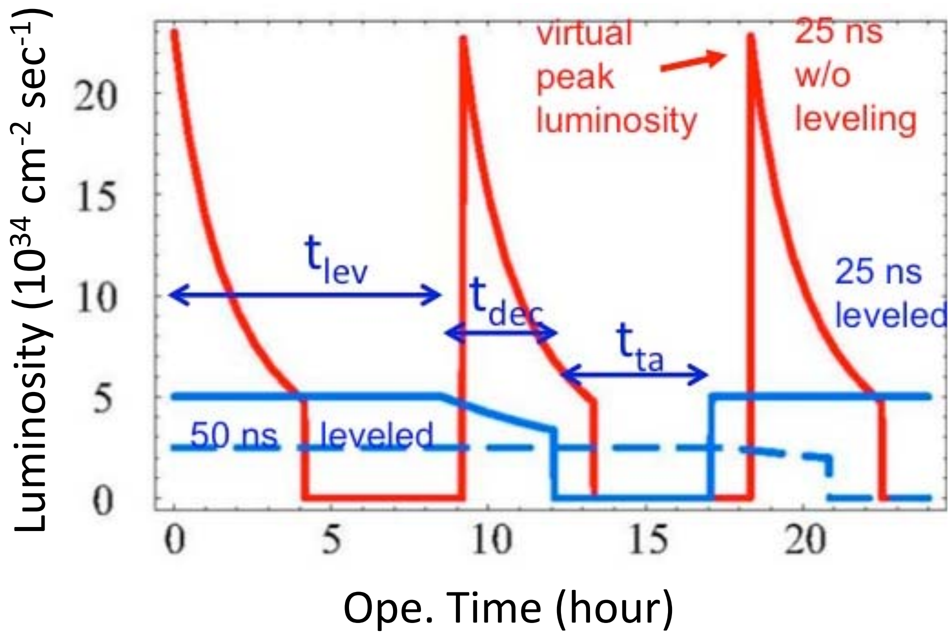
Beam current

$$L = \gamma \frac{f_{rev}\, n_b\, N_b^{\,2}}{4\pi \varepsilon_n \beta^*} R$$

energy

Beam size

$$R = \frac{1}{\sqrt{1 + \left(\frac{\theta_c \sigma_s}{2\varepsilon_n \beta^*}\gamma\right)^2}}$$



- Peak Luminosityの向上
  - 陽子数の増加、β*の減少
    - Injector upgrade (LIU)
    - New optics & Layout (Achromatic Telescopic Squeeze, crossing angle…)
    - IR magnets
- パイルアップイベント抑制
  - レベリング
    - Detuning by Crab-Cavities
- マシン防護、性能向上
  - ビームパワー対策
    - Collimation, e-Lens
    - 11T dipole (DS at IR 3/7)
  - 耐放射線対策
    - SC Link + PC移設
    - R2E (Radiation to Electronics)
  - 熱負荷対策
    - Cryo-plants
    - Shield in BP

HL-LHCのパラメータ（最新版？）

HL-LHC Performance Estimates

'Stretched' Baseline Parameters following 2nd HL-LHC-LIU:

Parameter	nominal	25ns	50ns
N	1.15E+11	**2.2E+11**	**3.5E+11**
n_b	2808	2808	1404
beam current [A]	0.58	**1.12**	**0.89**
x-ing angle [μrad]	300	590	590
beam separation [σ]	9.9	12.5	11.4
β^* [m]	0.55	**0.15**	**0.15**
ε_n [μm]	3.75	2.5	3.0
ε_L [eVs]	2.51	2.51	2.51
energy spread	1.20E-04	1.20E-04	1.20E-04
bunch length [m]	7.50E-02	7.50E-02	7.50E-02
IBS horizontal [h]	80 -> 106	**18.5**	**17.2**
IBS longitudinal [h]	61 -> 60	**20.4**	**16.1**
Piwinski parameter	0.68	**3.12**	**2.85**
geom. reduction	0.83	**0.305**	**0.331**
beam-beam / IP	3.10E-03	**3.3E-03**	**4.7E-03**
Peak Luminosity	$1\ 10^{34}$	**$7.4\ 10^{34}$**	**$8.5\ 10^{34}$**
Virtual Luminosity	$1.2\ 10^{34}$	**$24\ 10^{34}$**	**$26\ 10^{34}$**

$6.2\ 10^{14}$ and $4.9\ 10^{14}$ p/beam

→ sufficient room for leveling (with Crab Cavities)

Virtual luminosity (25ns) of $L = 7.4 / 0.305\ 10^{34}\ cm^{-2}\ s^{-1}$

$= 24\ 10^{34}\ cm^{-2}\ s^{-1}$ ('k' = 5)

Virtual luminosity (50ns) of $L = 8.5 / 0.331\ 10^{34}\ cm^{-2}\ s^{-1}$

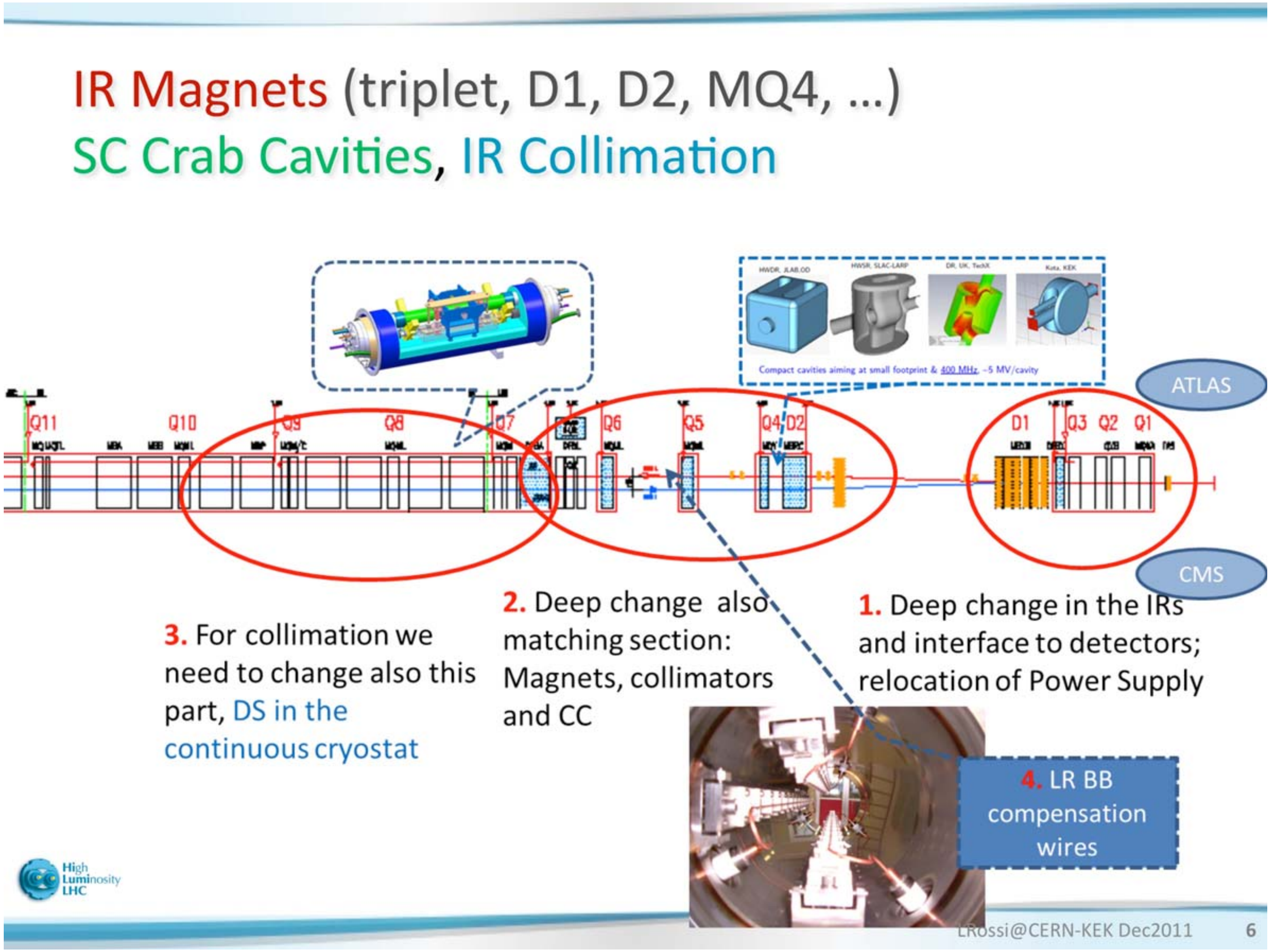
$= 26\ 10^{34}\ cm^{-2}\ s^{-1}$ ('k' = 10)

(Leveled to $5\ 10^{34}\ cm^{-2}\ s^{-1}$ and $2.5\ 10^{34}\ cm^{-2}\ s^{-1}$)

Events / crossing (peak & leveled L) 19 -> 28 **207** **476** **140** **140**

2nd HL-LHC General Meeting 13-14 November 2012 Oliver Brüning BE-ABP CERN 10

HL-LHCに向けた研究開発

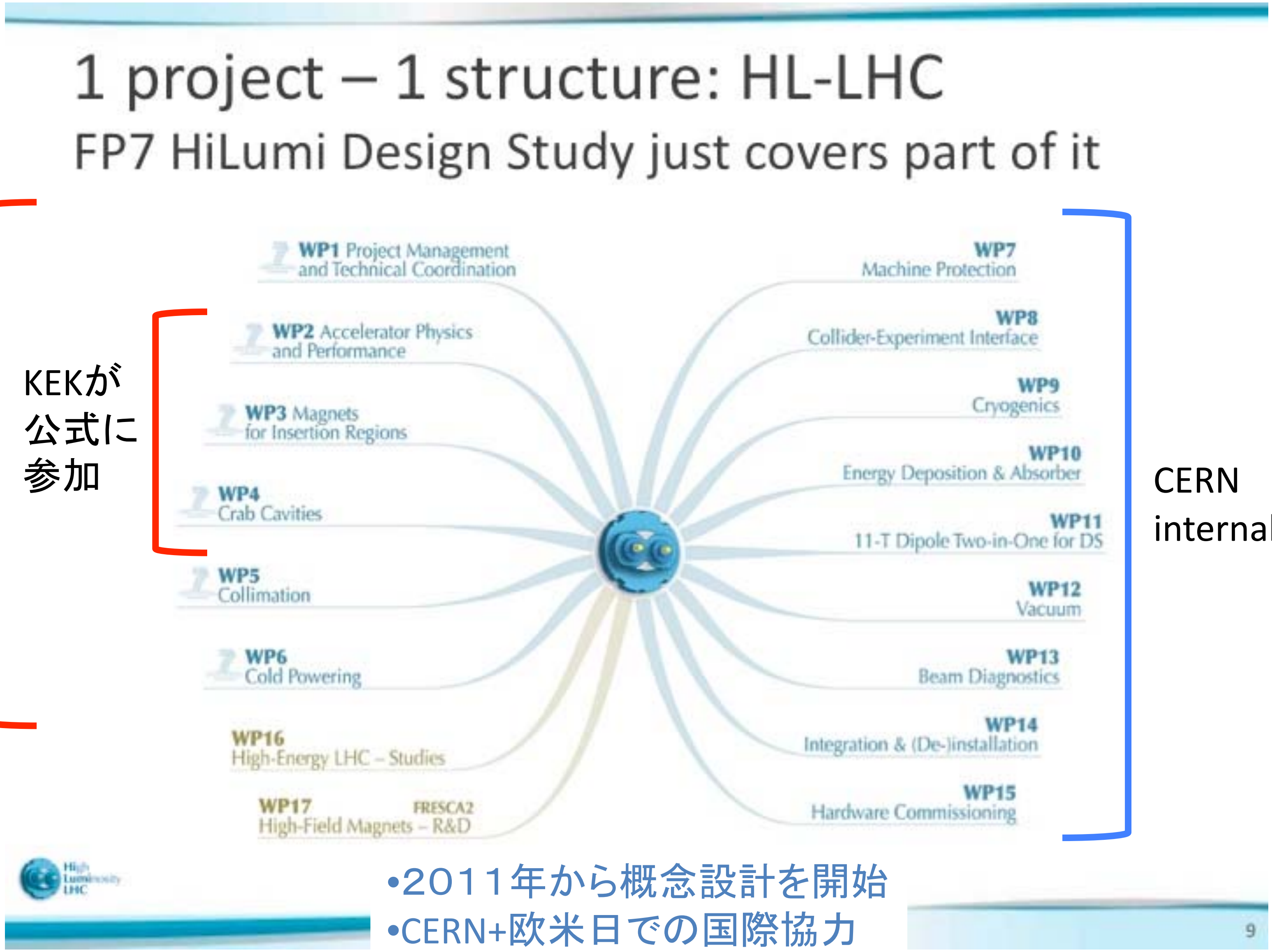


HL-LHCプロジェクト：WPの構成

HiLumi-LHC in EC-FP7

KEKが公式に参加

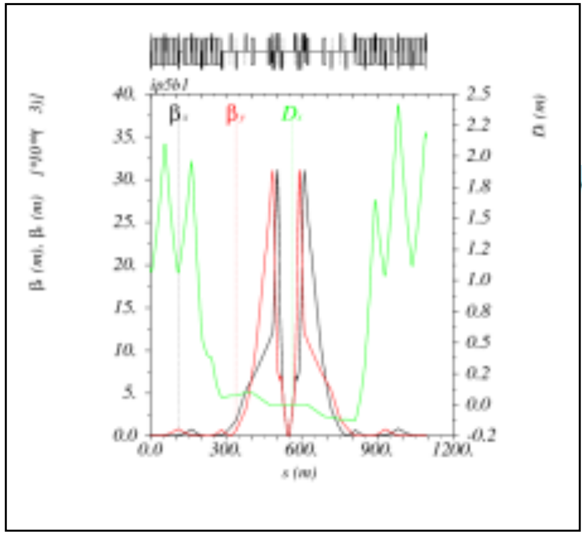
CERN internal



- 2011年から概念設計を開始
- CERN+欧米日での国際協力

※LIU計画は別。次の大森さんの発表を参照

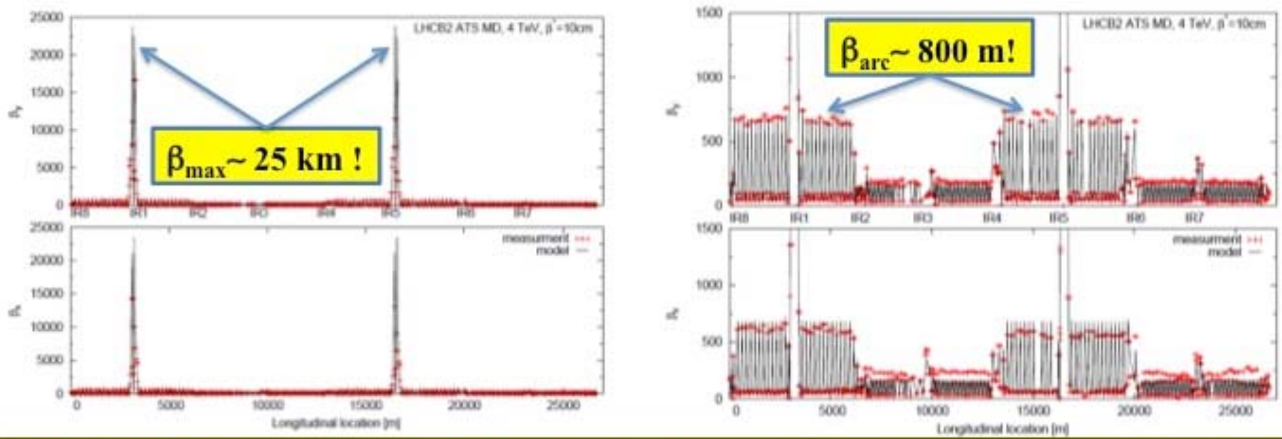
WP2: Accelerator Physics



ATLAS & CMS: β^*=10 cm (…"ultimately")

HL-LHC baseline optics (1/4)

- The **Achromatic Telescopic Squeeze** (ATS) is now firmly established as baseline for the HL-LHC.

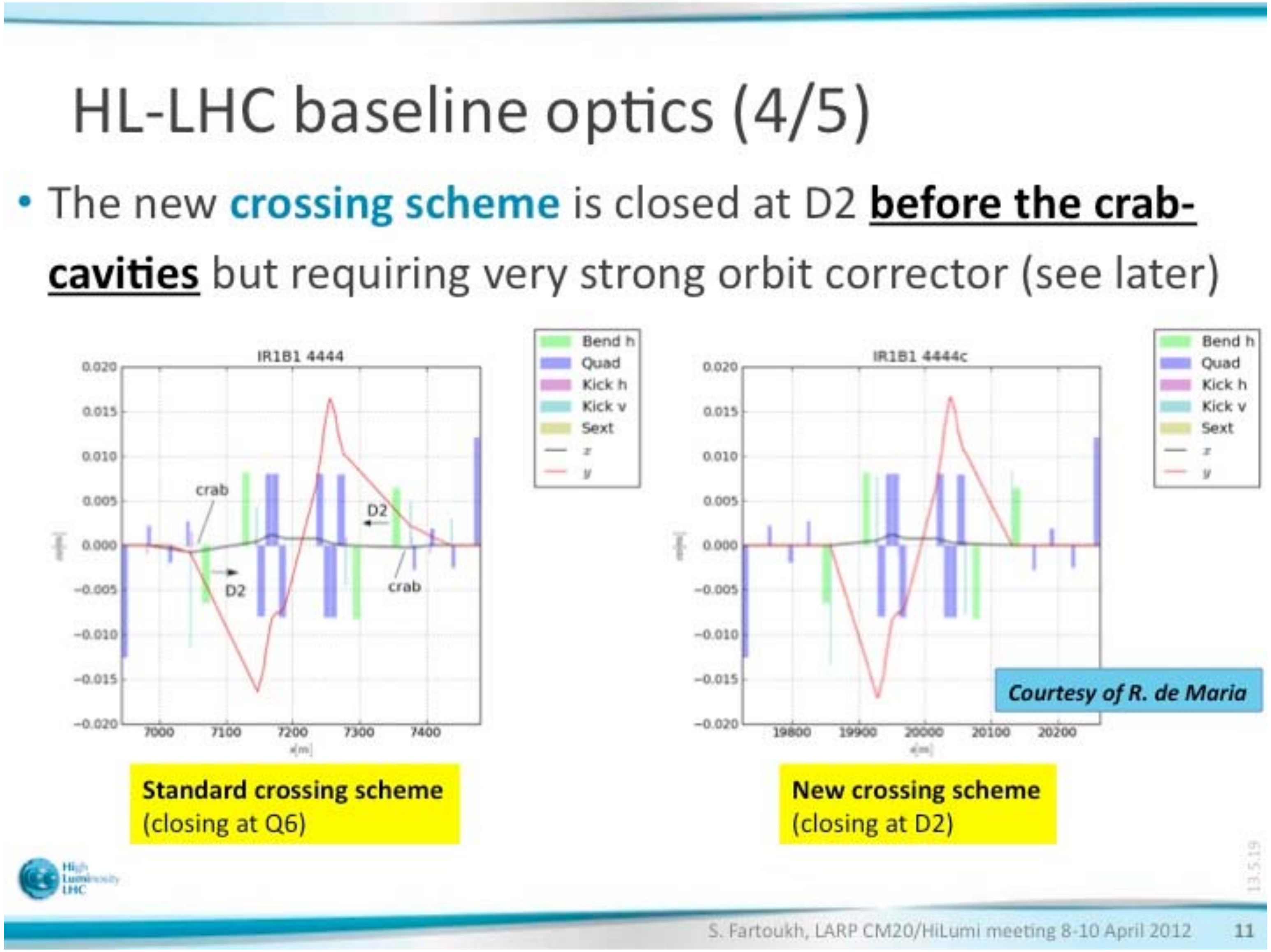


→ β^* ~10 cm demonstrated in MD (with some β-beating and special machine configuration) including a full chromatic correction, thank to the ATS: CERN-ATS-2013-004 MD.
… of course not (yet) usable for operation (not enough magnet aperture) !

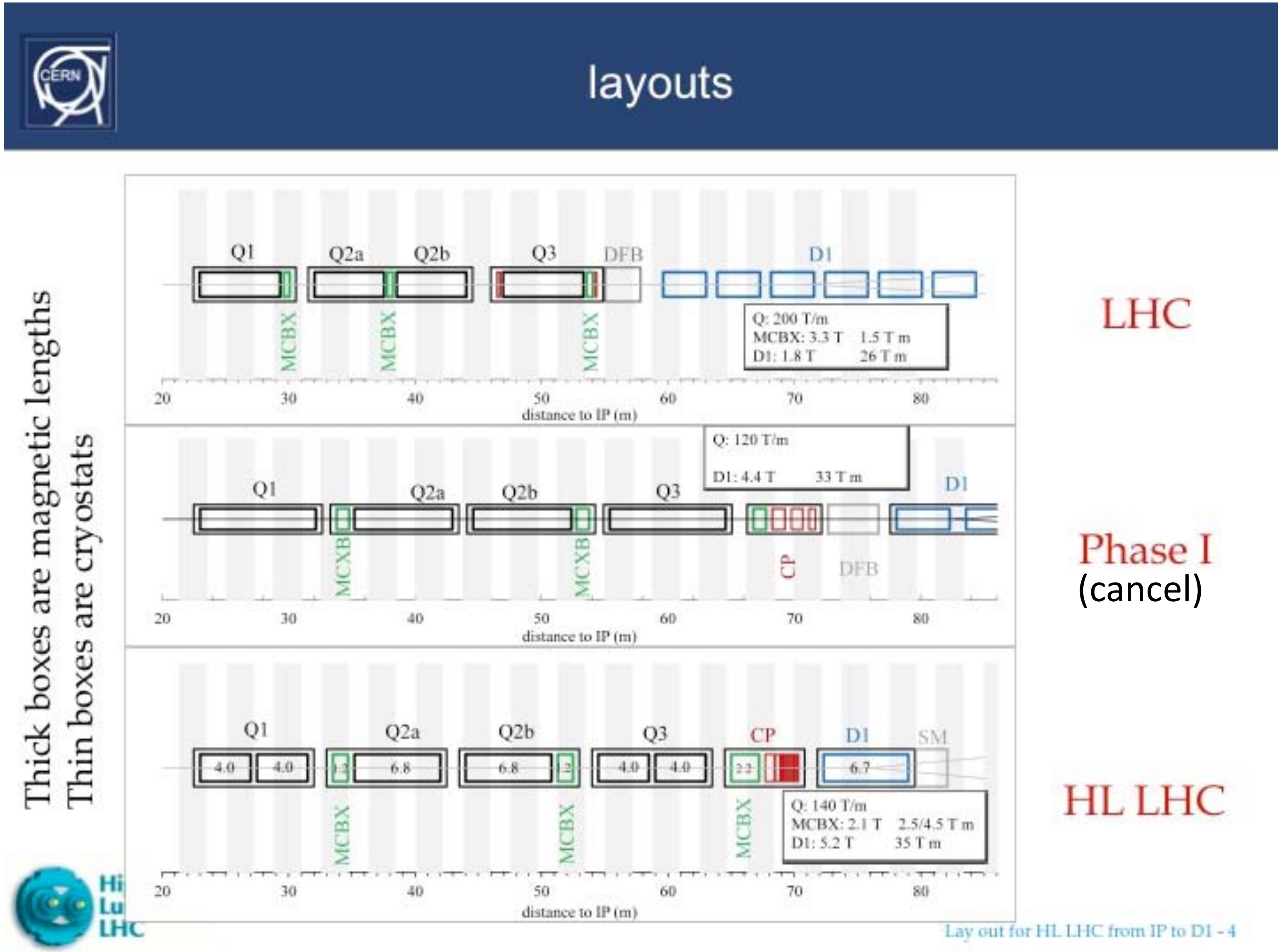
High Luminosity LHC

S. Fartoukh, LARP CM20/HiLumi meeting 8-10 April 2012 8

WP2: Accelerator Physics

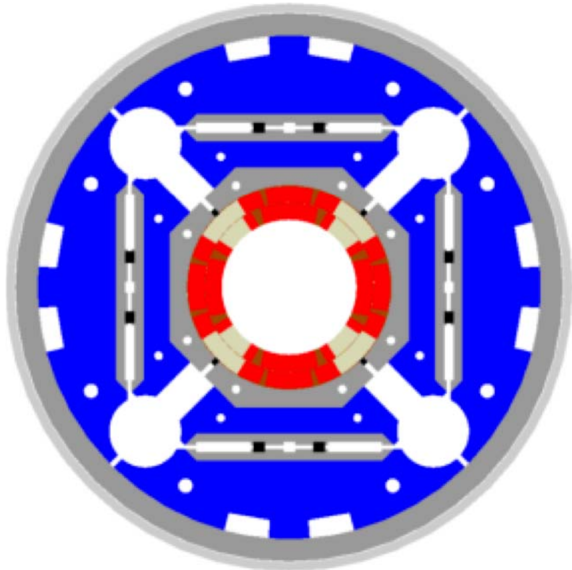


WP3: IR Magnets, Layout

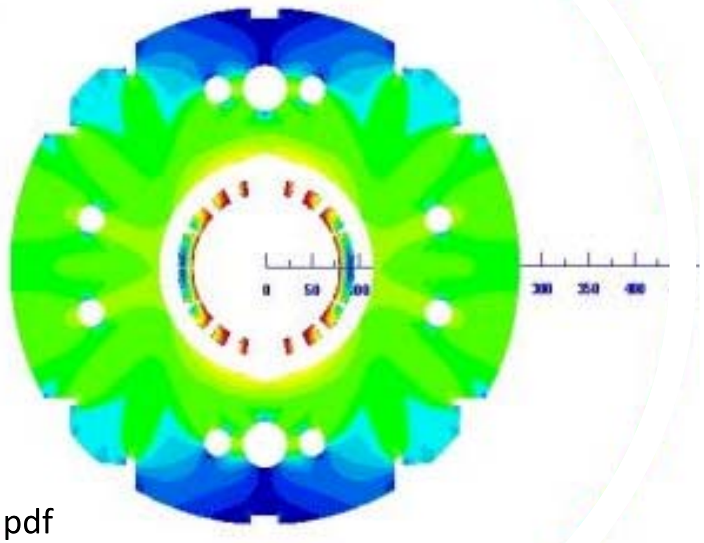


WP3: IR Magnets

- Aperture selection: **Q1-Q3 150 mm**, **D1: 160 mm**, **Q4: 90 mm**
- Energy deposition and heat load targets
  - Targets for peak values: **40 MGy - 4 mW/cm³**
  - Achieved with large shieding with beam screen and W
  - Higher temperature in the coil: 1.9+0.75 K (midplane)
- Most critical triplet features, priorities for 2013
  - Performance: 80% on the loadline tight but achieved in LARP quads – instabilities are still an issue
  - **Conductor: smaller filament size, but where to stop ?**
  - Coil fabrication, electrical integrity
  - **Protection critical (HQ affected/protected by quenchback)**
- D1 tentative choice: 1 layer LHC cable, 5.2 T, 7.6 m long
- Q4 tentative choice: 1 layer LHC cable, 120 T/m, 4.5 m long



IT-Quad MQXF (Nb3Sn, 150 mm, G=140 T/m, B_{peak}= 12 T)



Beam separation Dipole (NbTi, 160 mm, B=5.2 T, B_{peak}= 6 T)

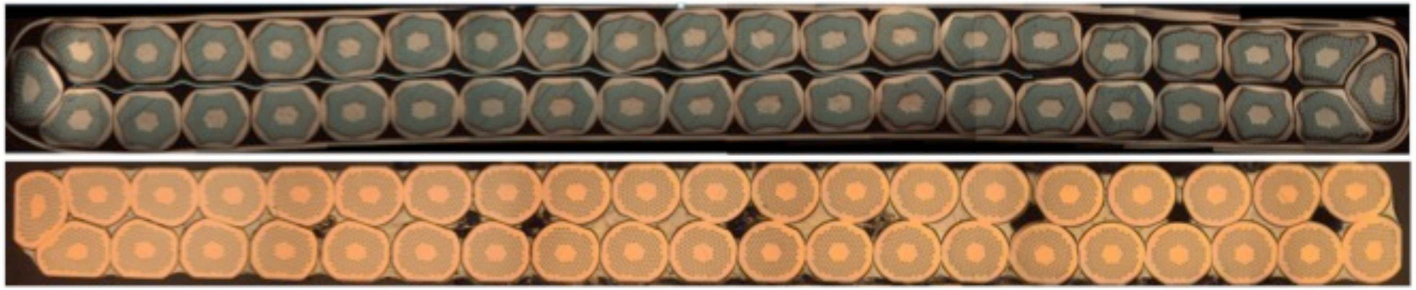
Nb_3Sn-IT超伝導四極磁石の技術開発（チャレンジング）については以下を参照。
http://cry3-aps.kek.jp/~cryoweb/publicdocs/20120915HLLHCMagnetNakamotoSV.pdf

WP3: Nb_3Sn SC Cable for IT Quad. (150mm)

SQXF status
Cable R&D

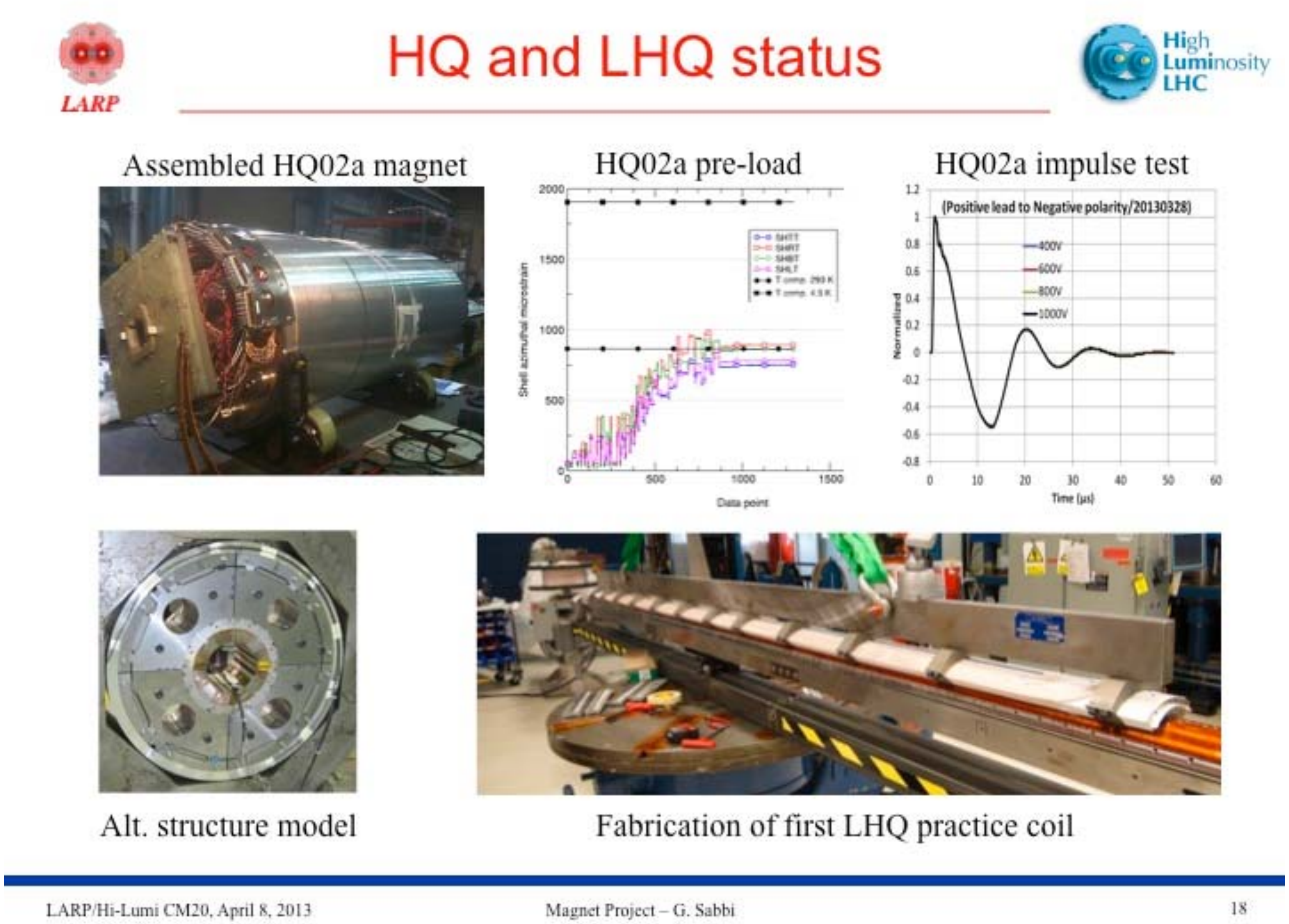
•素線フィラメントサイズ
•幅の拡大

- Target criteria established
  - Mechanical stability during winding
  - Stability current $I_s \geq 3*I_{op}$
  - RRR after cabling > 150
  - No shear planes in micrograph images
- First iteration completed in 03/2013
  - Winding tests, cross-section images, extracted strand meas.
    - No cable reached all targets
- Second iteration has started
  - Cabling, winding tests, micrograph images in 04/2013
  - Extracted strand measurements in 05/2013
  - Cable parameters for first set of coils by end of 05/2013
- Cable R&D will continue (PIT strand, improved parameters...)

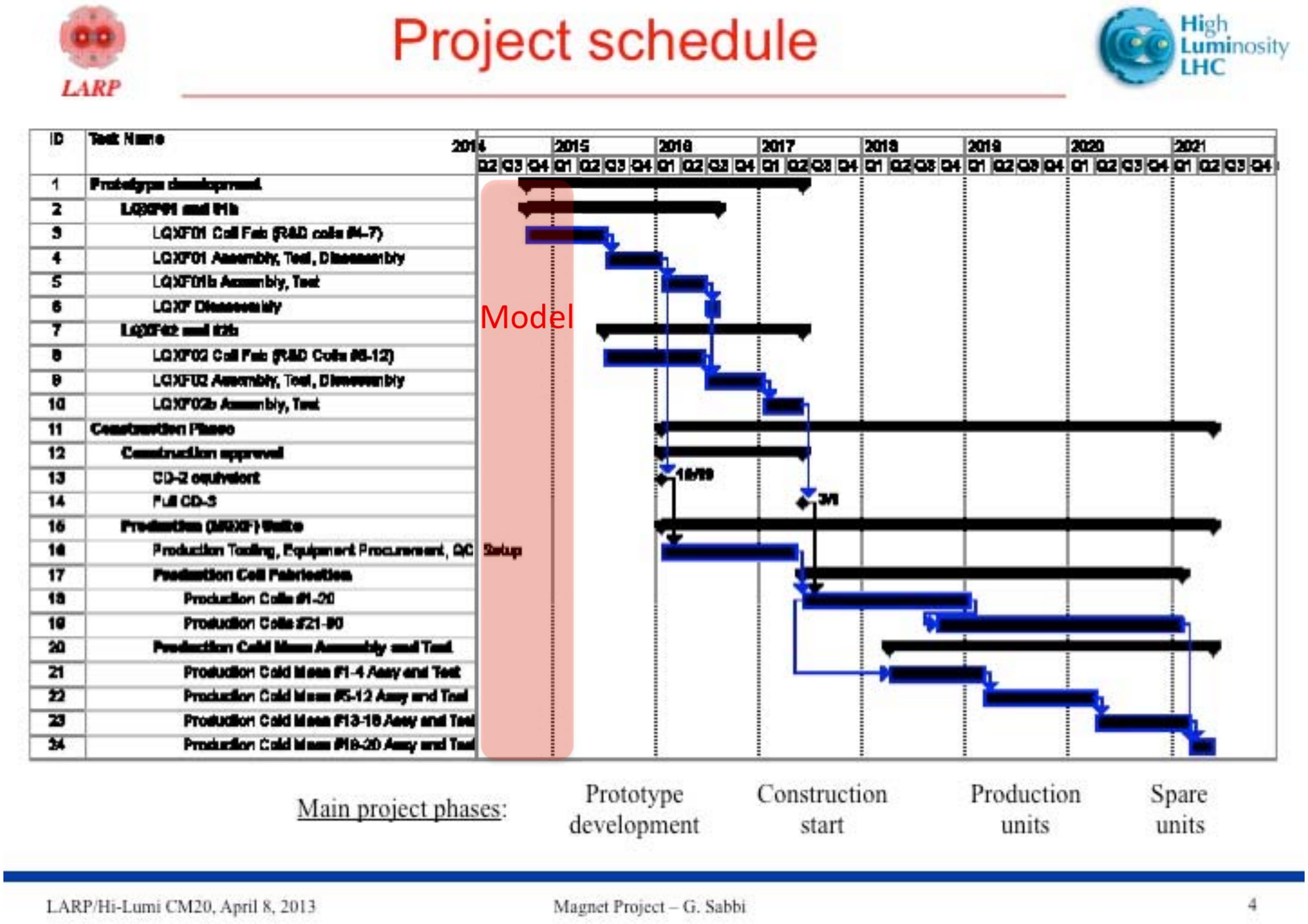


High Luminosity LHC　U.S. LARP　G. Ambrosio and P. Ferracin　09/04/2013　3

WP3: HQ (120 mm) Model Study

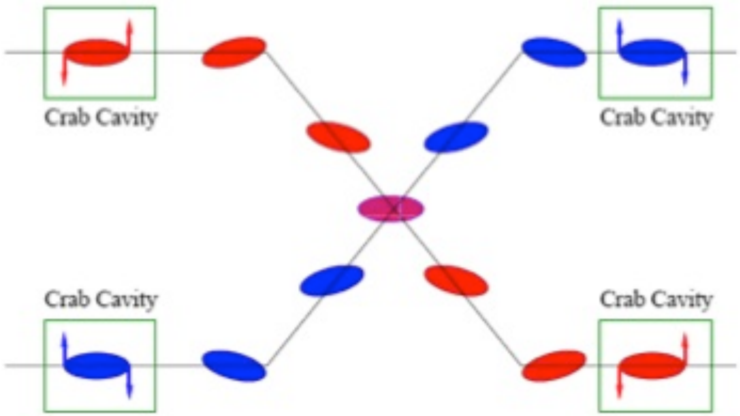


WP3: Schedule of IT Quad.



WP4: Crab Cavities

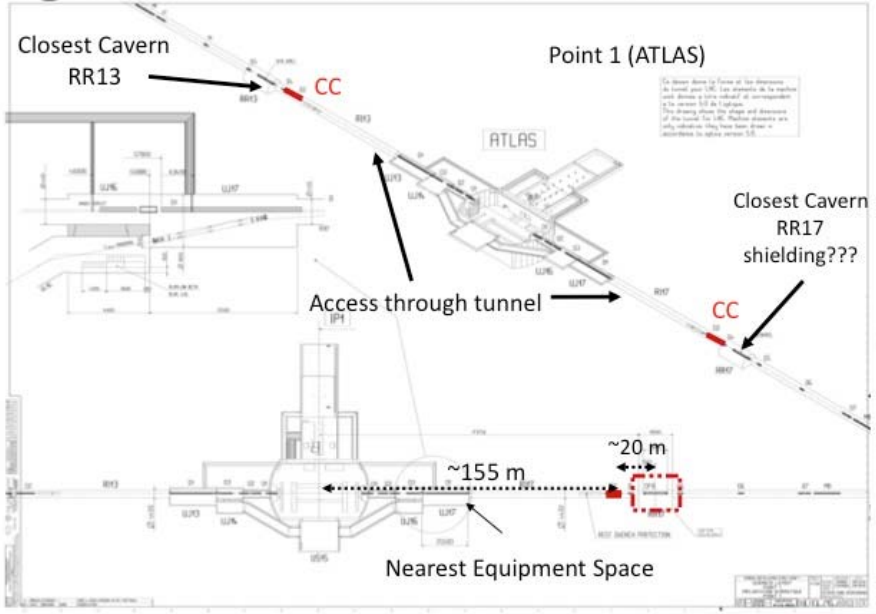
Crab Cavities



- Technical Challenges
  - Crab cavities have only *barely* been shown to work.
    - Never in hadron machines
  - LHC bunch length ➔ low frequency (400 MHz)
  - 19.4 cm beam separation ➔ “compact” (exotic) design
- Additional benefit
  - Crab cavities are an easy way to level luminosity!
- Currently aiming for:
  - Down-select –next year
  - SPS test in 2015

Prebys - Joint HiLumi/LARP Meeting   Novemer 14, 2012

Integration in LHC tunnel – IP1



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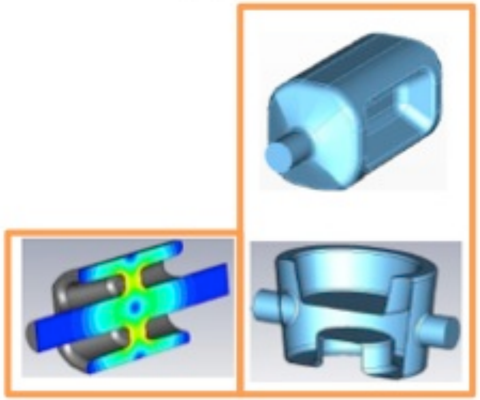
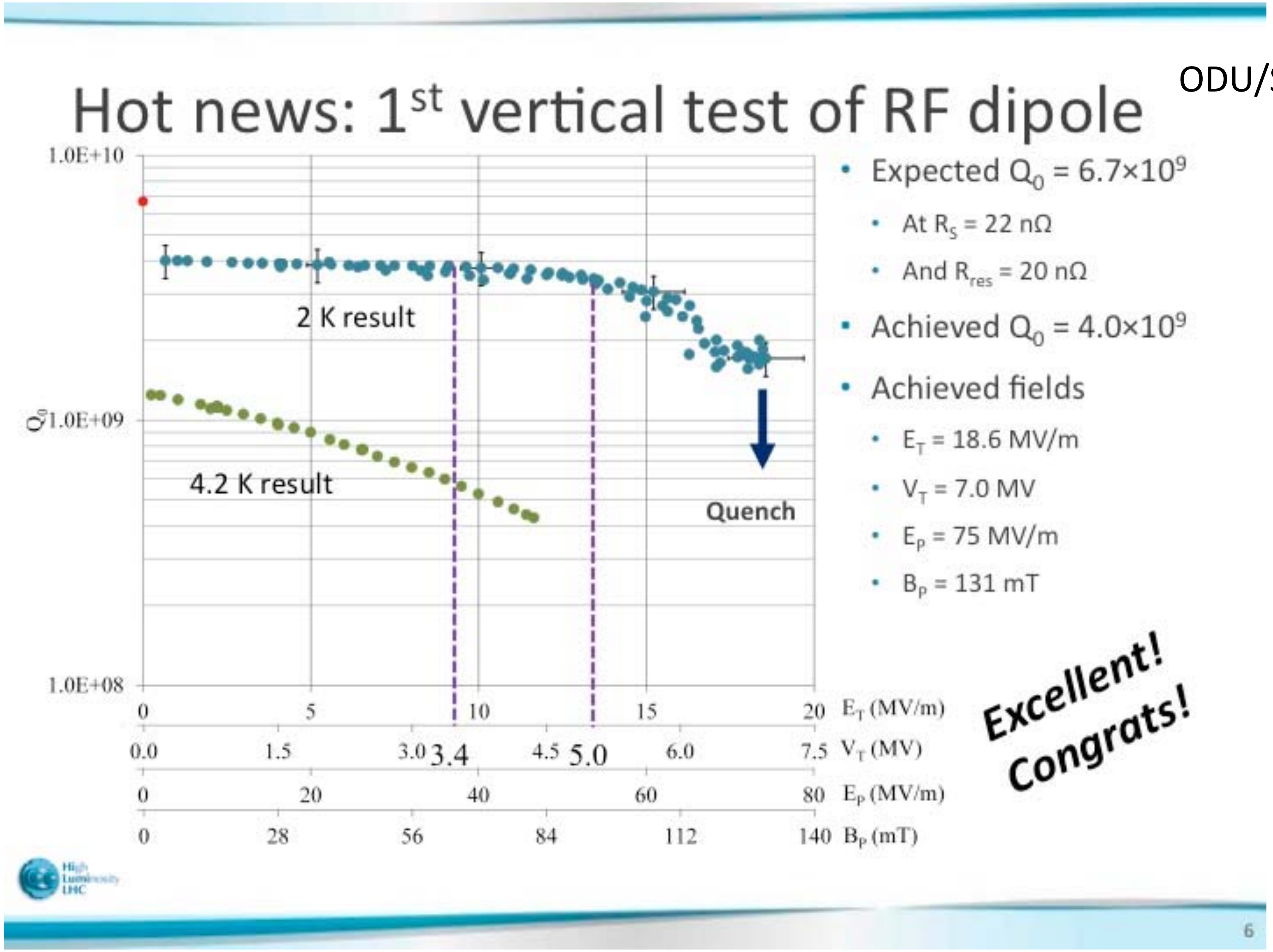


•3バージョンが並行して開発中
•SPSでのビーム試験を計画

WP4: Crab Cavities

ODU/SLAC

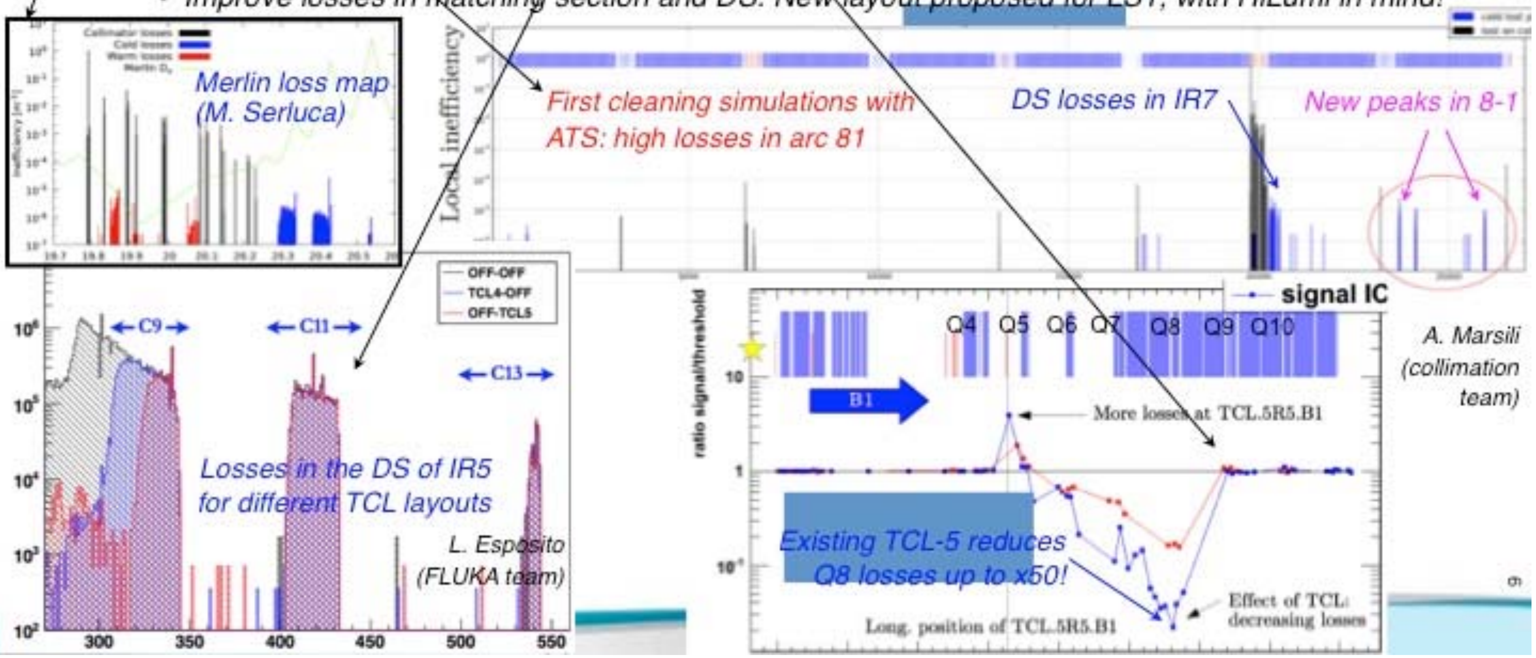


- Volta
  - –
  - –
- Freq
- Q_{ext}
- Cavit
- RF p
- Bear

WP5: Collimation

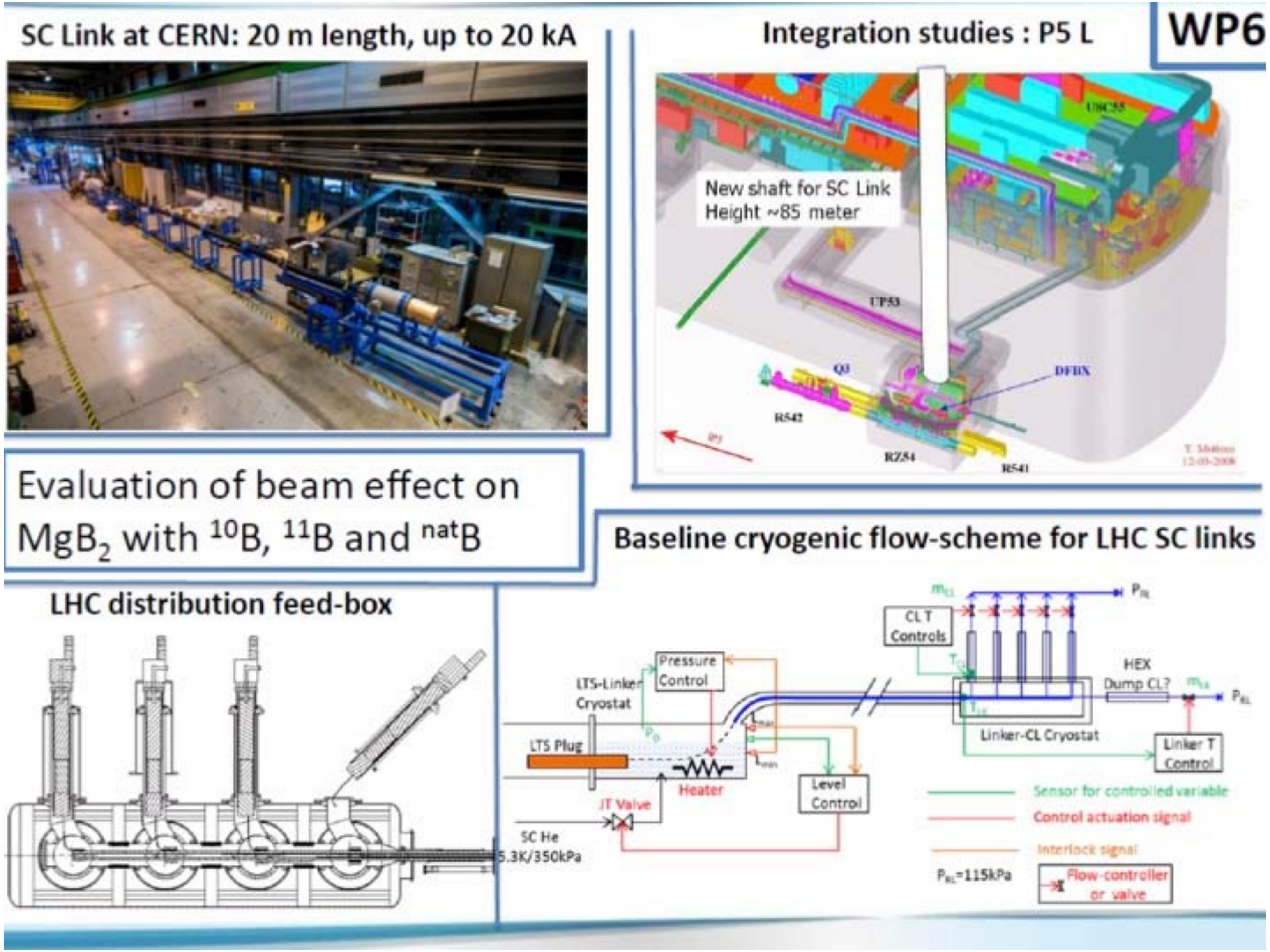
Summary of WP5 activities

- Setup the **Collimation Upgrade Specification meeting** to steer the WP5 activities
  - → *15 meetings in 2012 - Regular and active participation of all WP5 partners + CERN teams.*
- Performed **simulations of collimation cleaning for HL optics** (ATS at β^*=15 cm)
  - → *First simulations indicate high losses in the arcs used for telescopic squeeze!*
  - → *Simulations with Merlin code advanced well: detailed benchmarking with SixTrack ongoing.*
- Participation to **LHC operation** and **MDs**
  - → *Beam measurements for code benchmarking (TCL scans at 4 TeV, failure scenarios).*
  - → *Improved models for β^* reach from collimation: proposed 35-50cm after LS1!*
- Triggered study for new **TCL layout IR1/5** for implementation in LS1 *(profited from WP10 models)*
  - → *Improve losses in matching section and DS. New layout proposed for LS1, with HiLumi in mind!*



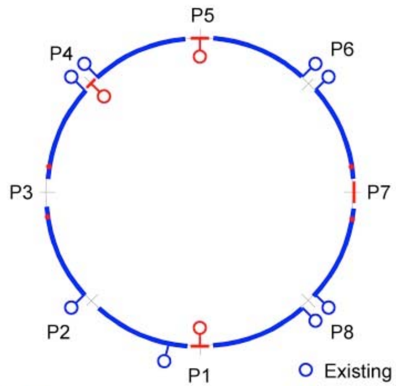
WP6: Cold Powering

先進超伝導線材（MgB_2，高温超伝導線材）の大規模応用



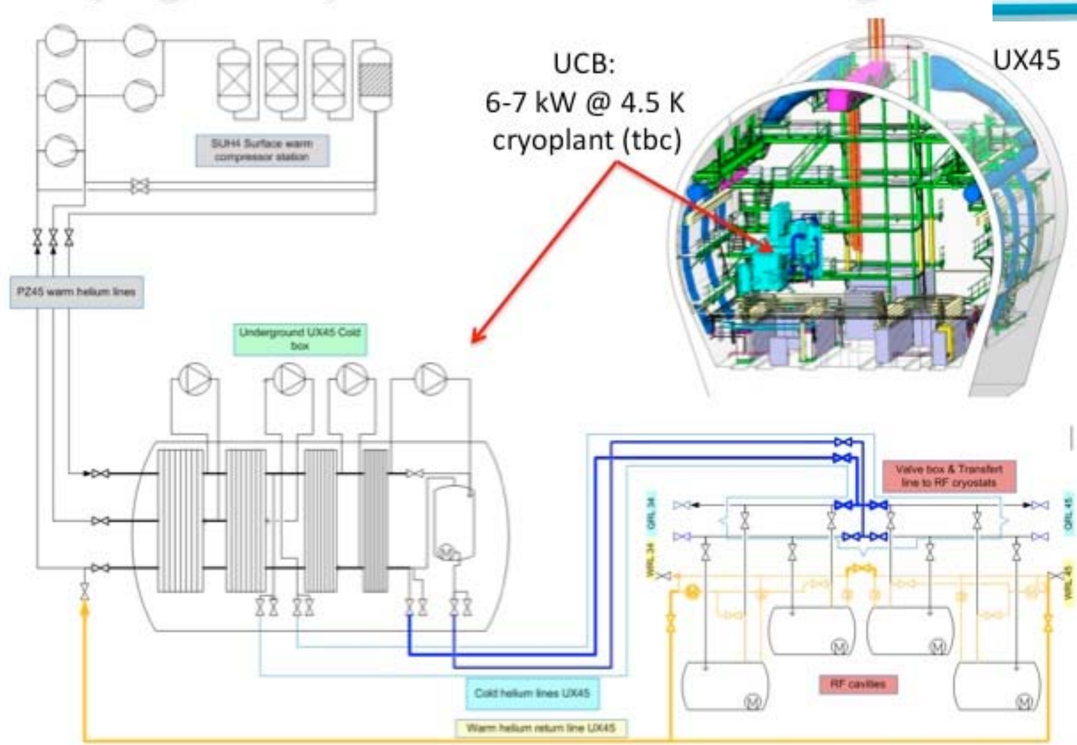
WP9: Cryogenics

Overall HL-LHC layout



- HL-LHC cryo-upgrade:
  - 2 new cryoplants at P1 and P5 for high luminosity insertions
  - 1 new cryoplant at P4 for SRF cryomodules
  - New cooling circuits at P7 for SC links and deported current feed boxes
  - Cryogenic design support for cryo-collimators and 11 T dipoles at P3 and P7

P4 cryogenic process & flow diagram



WP11: 11 T dipole for DS

- Fermilab-CERN
- Nb3Sn超伝導線
- タイトなスケジュール(LS2)

Technical Progress (incomplete …) - 8

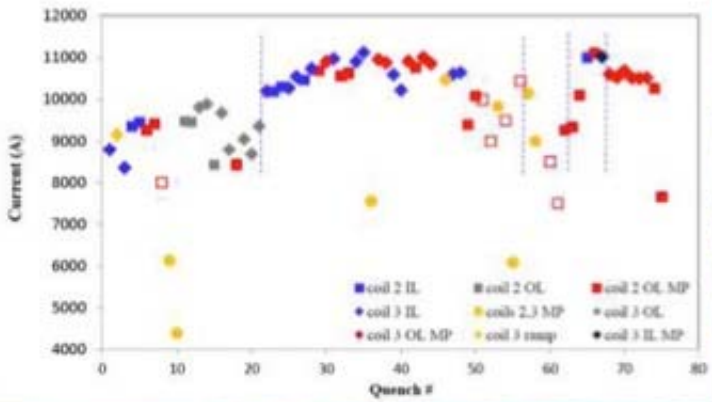
- WP 11 (11 T dipole)
- 2 m long single bore: test in June/July 2012

  10.4 T at low dI/dt,

  95% of the goal, coil damage recognized

  new 1 m single bore to test in February

  Then one 2 m single bore in 2013 and after the 2in1



High Luminosity LHC

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Upgrades: "Enhanced Consolidation" & "Full Performance"

HiLumi: Two branches (with overlap)

- **Enhanced Consolidation upgrade (1000-1200 fb^{-1})**
  - Magnet rad. damage and enhanced cooling
  - Cryogenics (P4, IP4,IP5) with separation Arc form RF and from IR
  - Collimation
  - SC links (in part)
  - QPS and Machine Prot.
    - Kickers
    - Interlock system

- **Full performance upgrade (3000 fb^{-1})**
  - Maximum low-β Quads aperture
  - Crab Cavities
  - HB feedback system (SPS)
  - Advanced collimation systems
  - E-lens (?)
  - SC links (all)
  - R2E and remote handling for 3000 fb^{-1}

High Luminosity LHC

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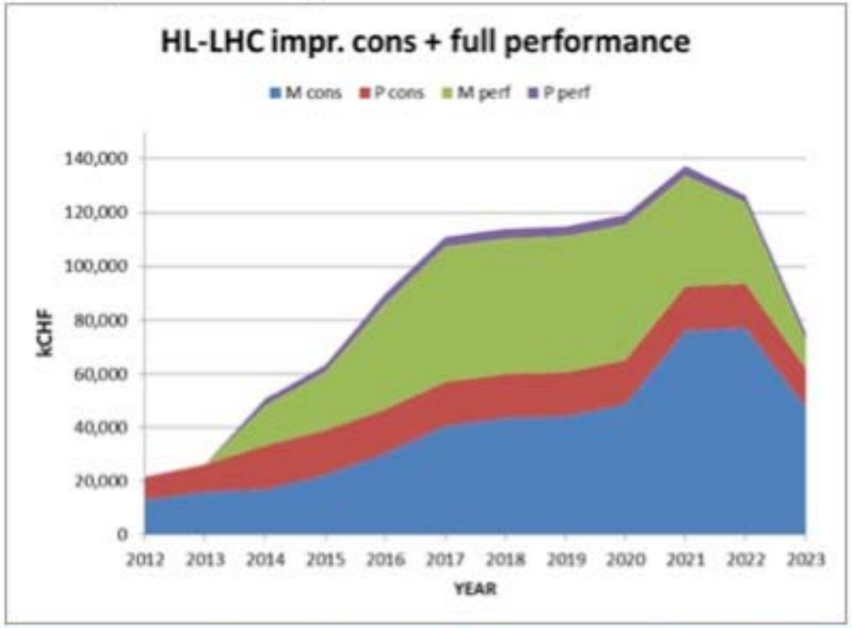
予算見積り(CERN)

Preliminary budget estimate



	Improving Consolidation	Full performance	Total HL-LHC
Mat. (MCHF)	476	360	836
Pers. (MCHF)	182	31	213
Pers. (FTE-y)	910	160	1070
TOT (MCHF)	658	391	1,049

[参考]
US-LARP: $200M (Plan)

High Luminosity LHC

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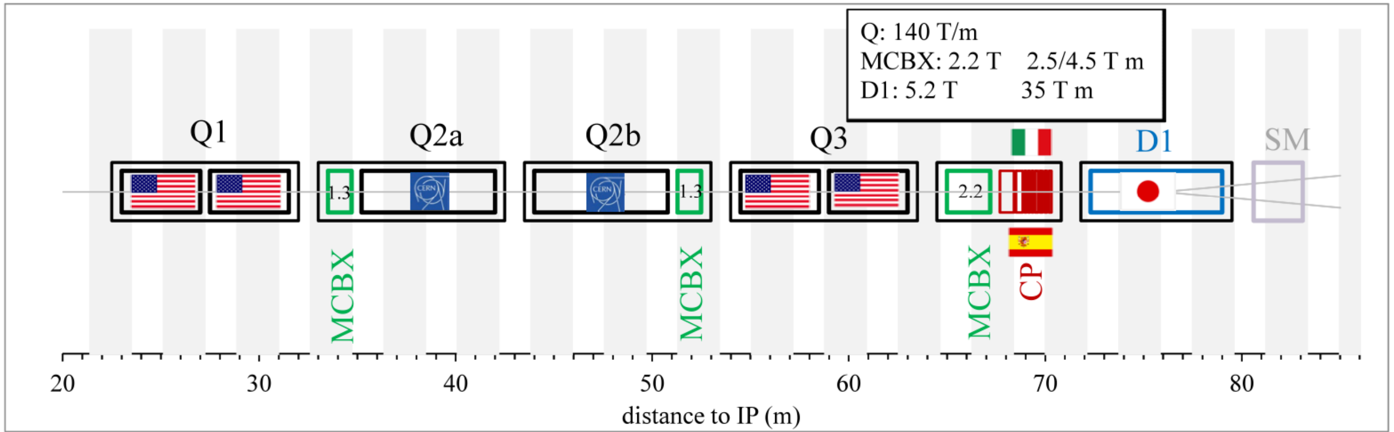
KEKでの超伝導磁石開発

他の方々の貢献は、すみませんが、割愛させてください．．．

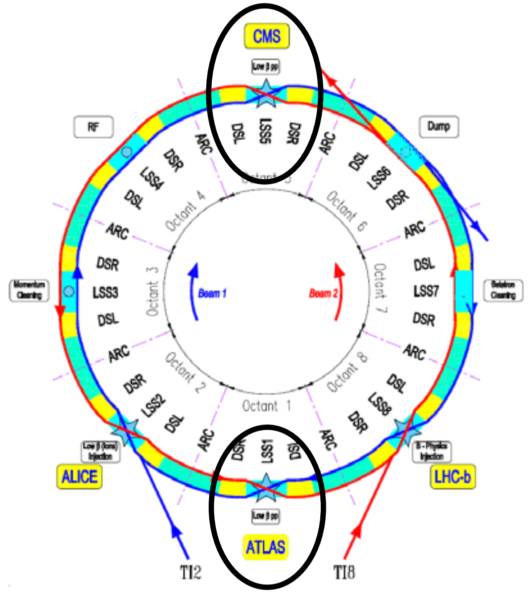
- LHC Injector Upgrade：大森さん（次の御講演）
- ビーム力学：　大見さん、Molodozhentsevさん
- 超伝導クラブ空洞：　森田さん

Objective: *New D1*

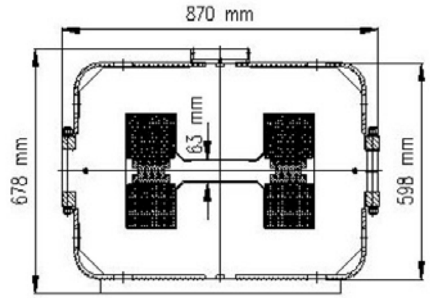
- *For HL-LHC upgrade, needs for new Inner Triplet system at IR1 & IR5.*
  - *Large aperture (150 mm) HF Quadrupoles, corrector package.*
- *New beam separation dipole (D1) should be accommodated with large aperture IT Quads; which will have a even larger aperture than IT Quads and 50% increase in original integrated field (26 T m → 35~40 T m).*



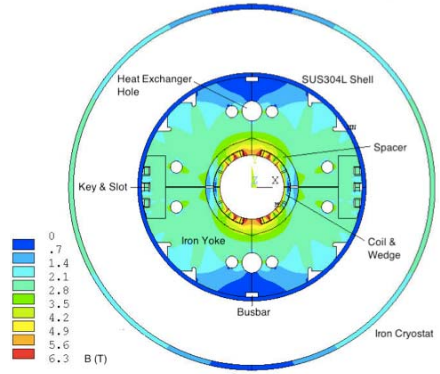
Schematic layout of the IR（分担案）



Schematic layout of the LHC



Current D1 (MBXW) at IR1 & IR5



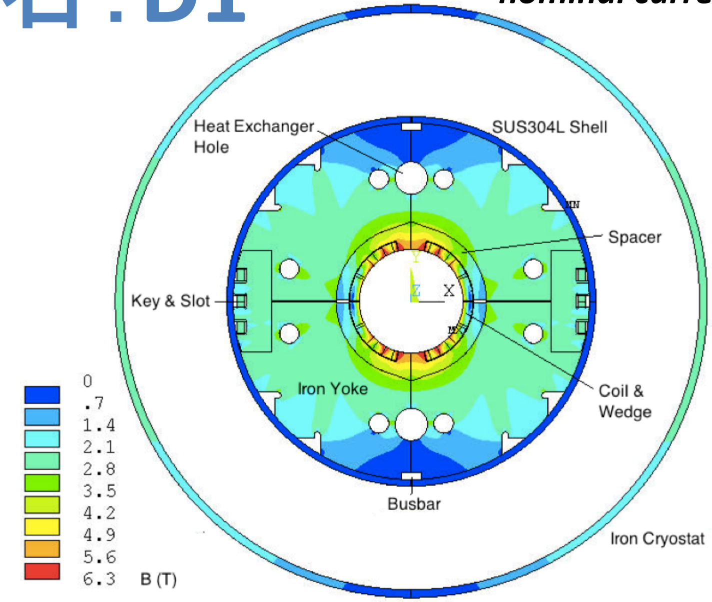
New D1 (MBXF)

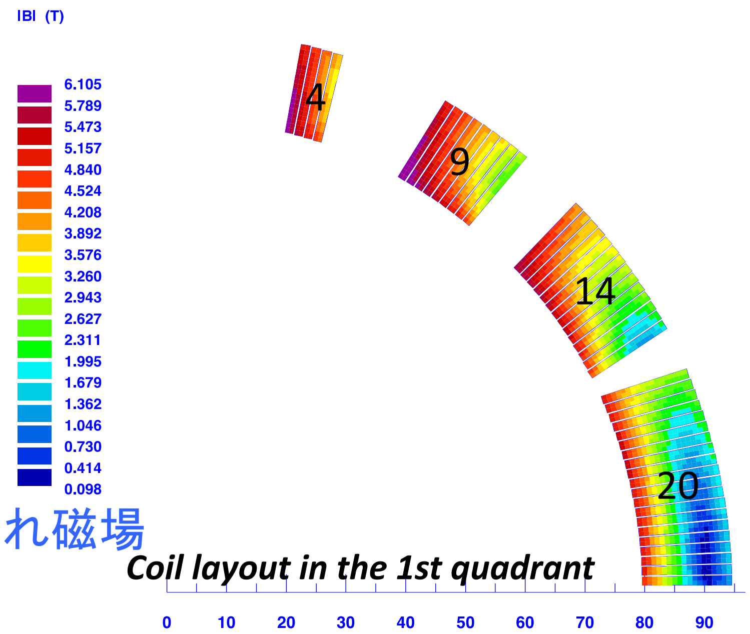
ビーム分離用大口径双極磁石：D1

- コイル内径：　160 mm
- 磁場長：　40 T m
- 定格磁場：　5.2 T @ 11kA
- ロードライン比：　70 %（直線部ピーク磁場5.9T）
- 運転温度：　1.9 K （超流動He冷却）
- 超伝導コイル：15mm厚１層コイル
  - LHC主双極磁石外層コイル用NbTiケーブル
- 機械構造：　鉄ヨークカラー
  - LHC-MQXA, J-PARCニュートリノSCFMを踏襲
- 磁場精度（目標）：　< 10^{-4} （参照半径50mm）
- 磁石外径：　570 mm
- 放射線：　数10 MGy, ~10^{22} /m^2, 数10 W/m

磁石の特徴、設計上の制限
ー　大口径　→　電磁力の積み重ね大。構造設計。
ー　外径の制限　→　クライオスタットからの磁場寄与、漏れ磁場
ー　材料の耐放射線性、磁石の除熱性能が重要

Magnetic field distribution at nominal current



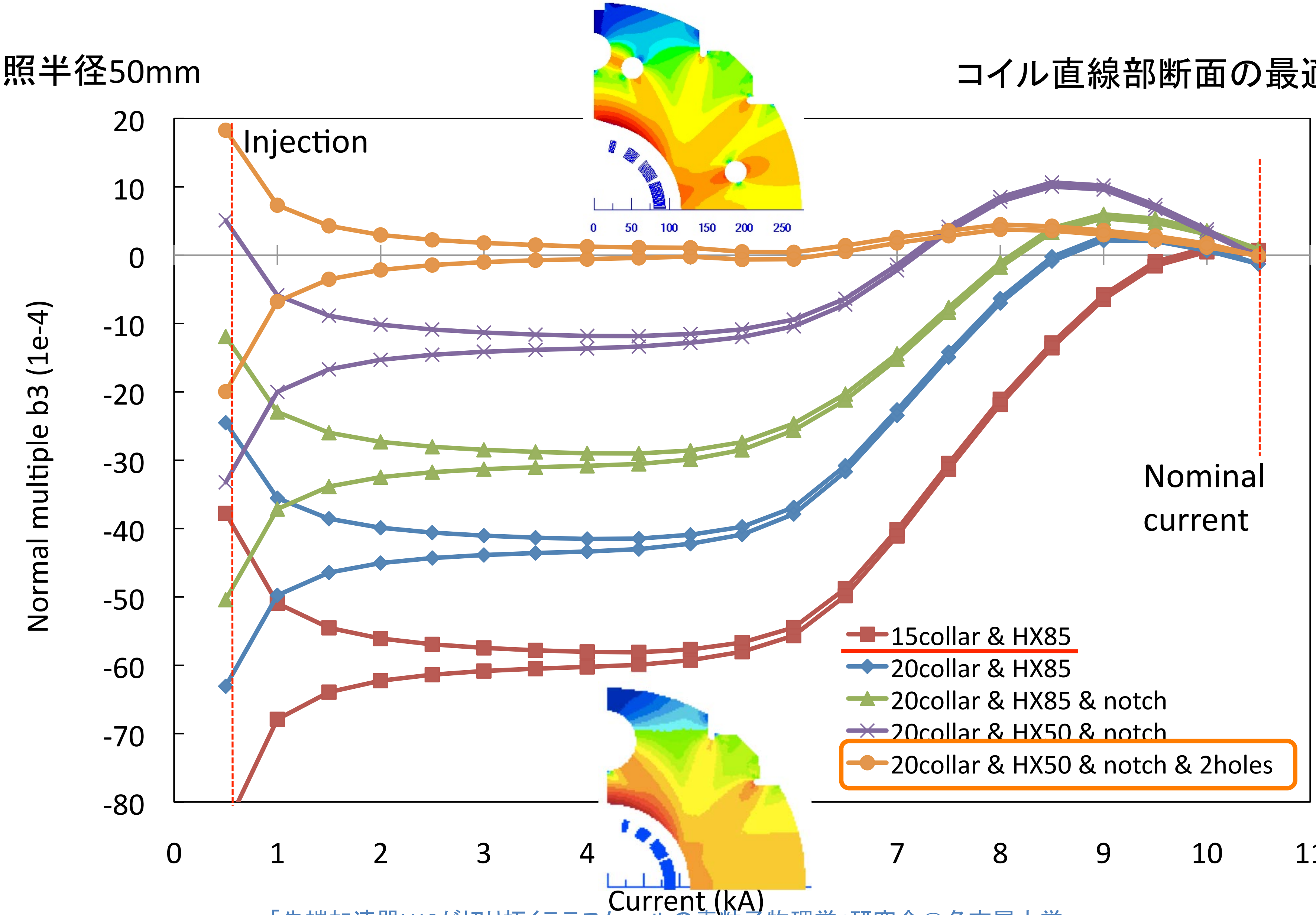


Coil layout in the 1st quadrant

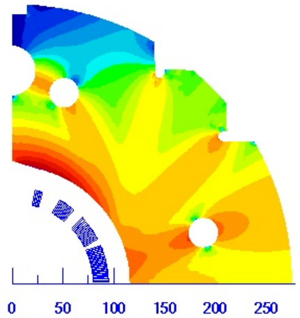
磁場設計： 磁石断面の最適化(b_3)

参照半径50mm

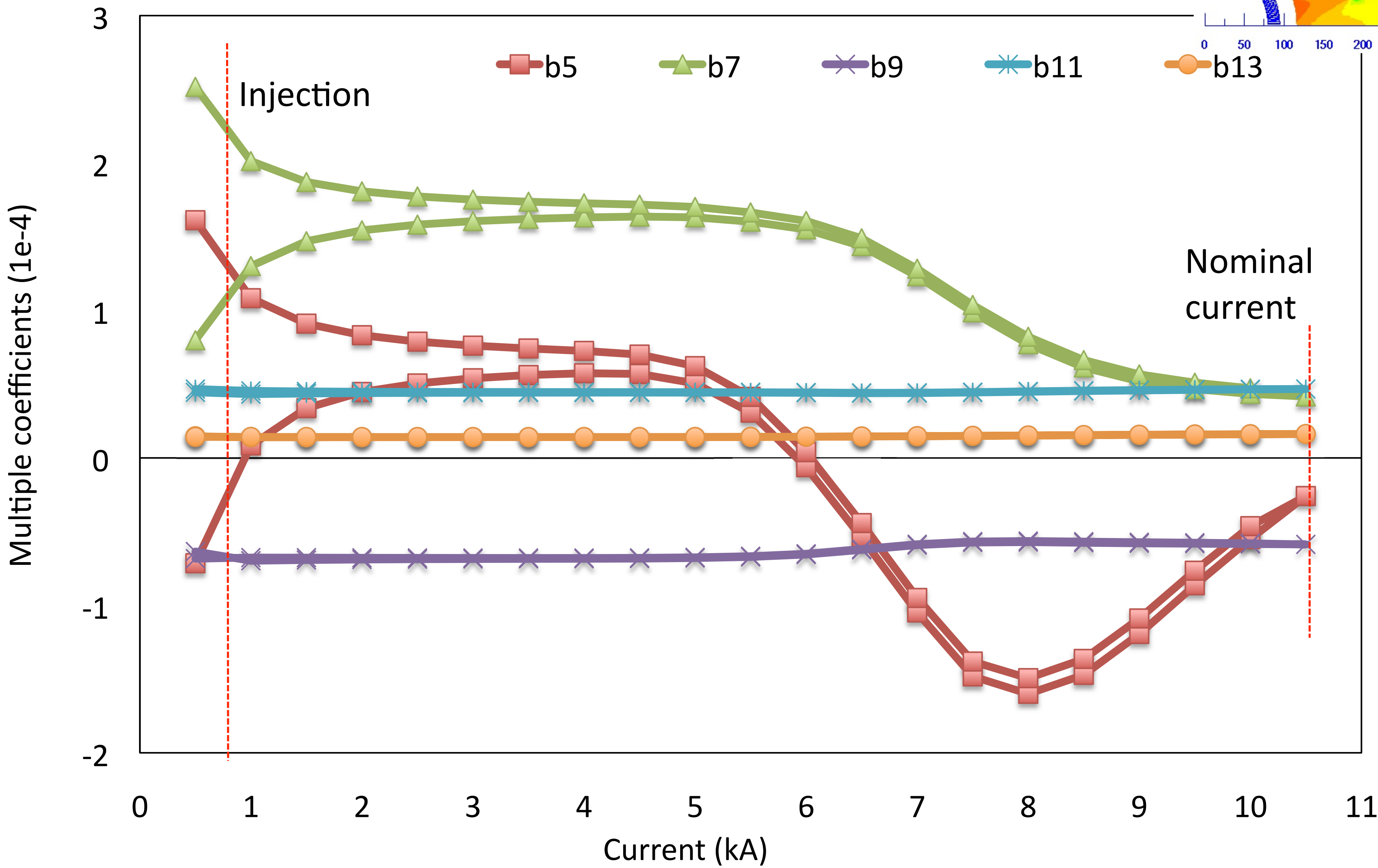
コイル直線部断面の最適化



磁場設計： 磁石断面の最適化（b_n, $n>3$）



参照半径50mm

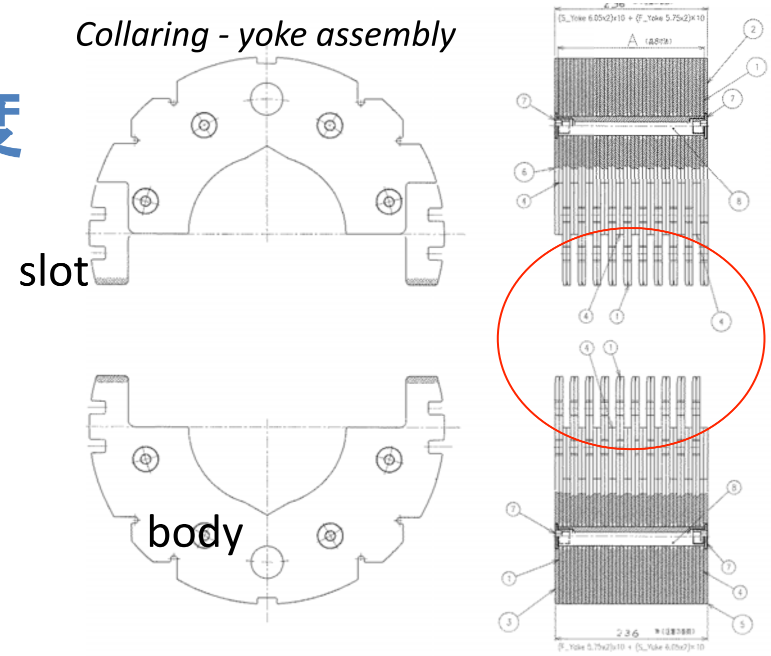


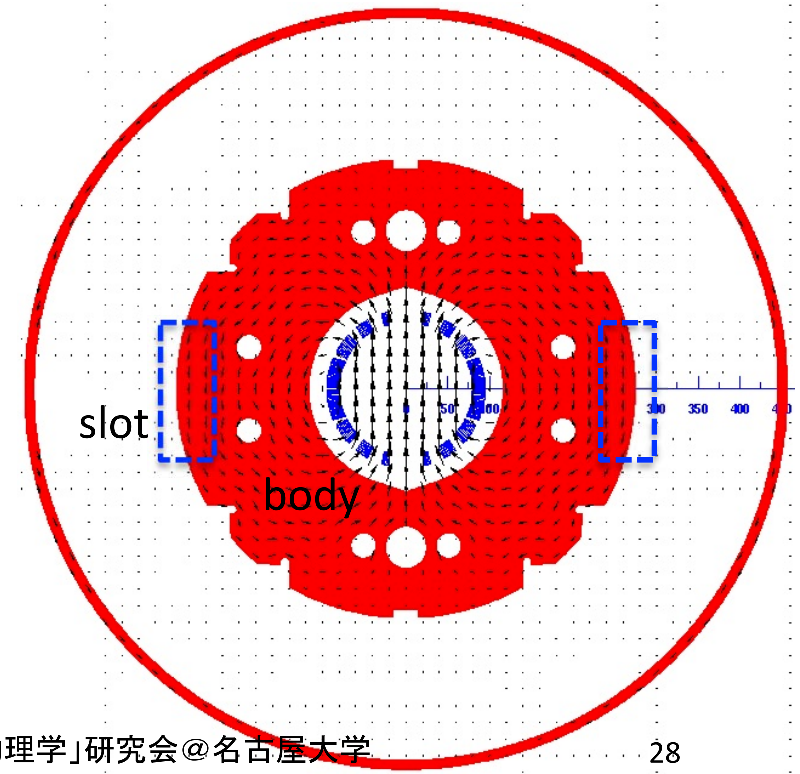
磁場への影響：鉄ヨーク積層密度

•*Considering the packing factor variation of the iron yoke during fabrication.*
•*Simulation with ROXIE; 11 kA, Rref=50mm*
•*Different packing factor at slot regions*

PF (body)	PF (slot)	b3	b5	b7	B (T)
1	1	0.21	-0.18	0.16	5.25
	0.95	-2.1	-0.53	0.12	5.2443
	0.9	-4.48	-0.89	0.08	5.2384
0.98	0.98	-0.1	-0.05	0.16	5.2261
	0.94	-1.94	-0.33	0.13	5.2216
	0.9	-3.83	-0.62	0.09	5.2169

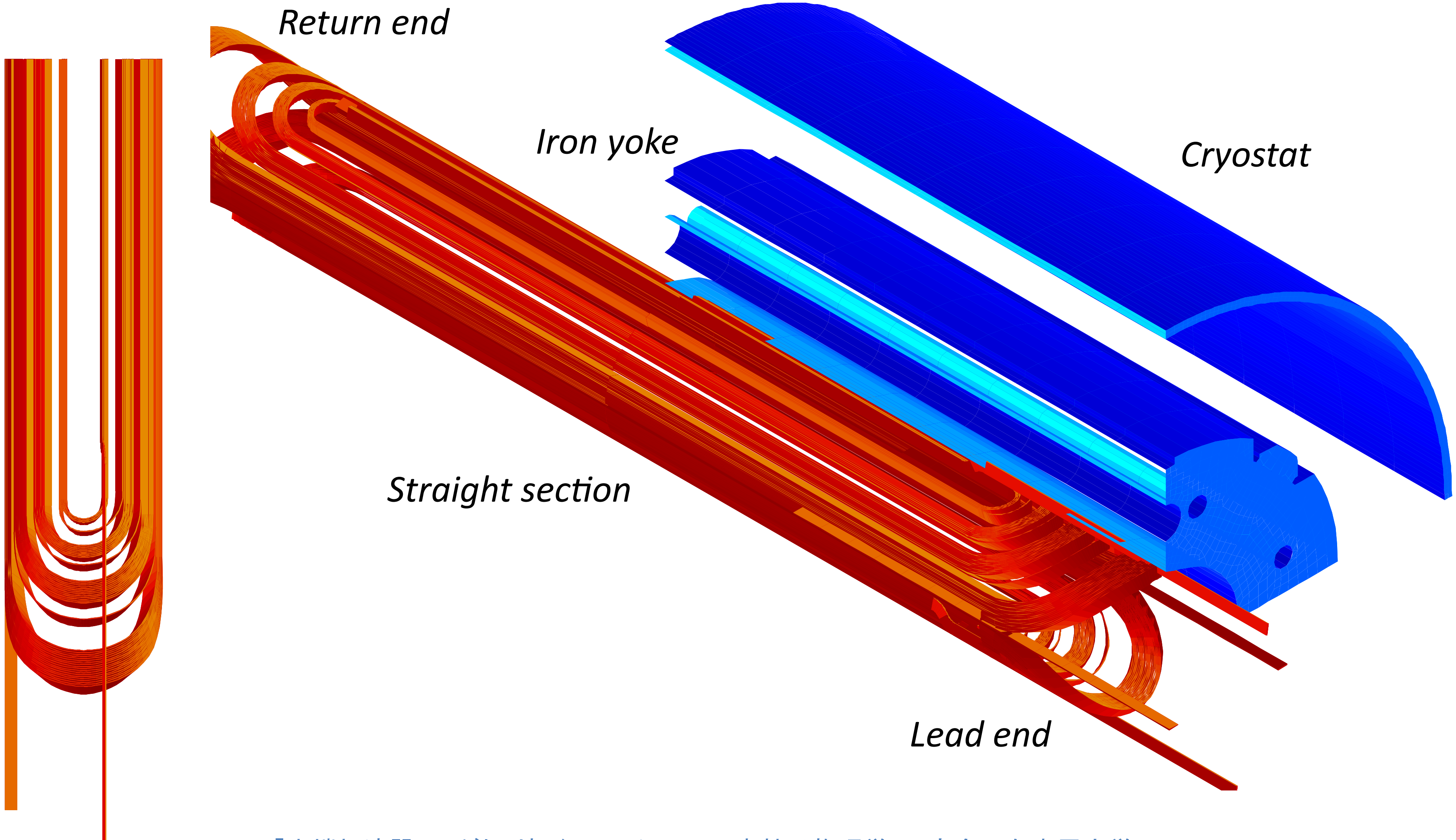
Importance of control of packing factor in highly saturated iron to maintain good field quality.



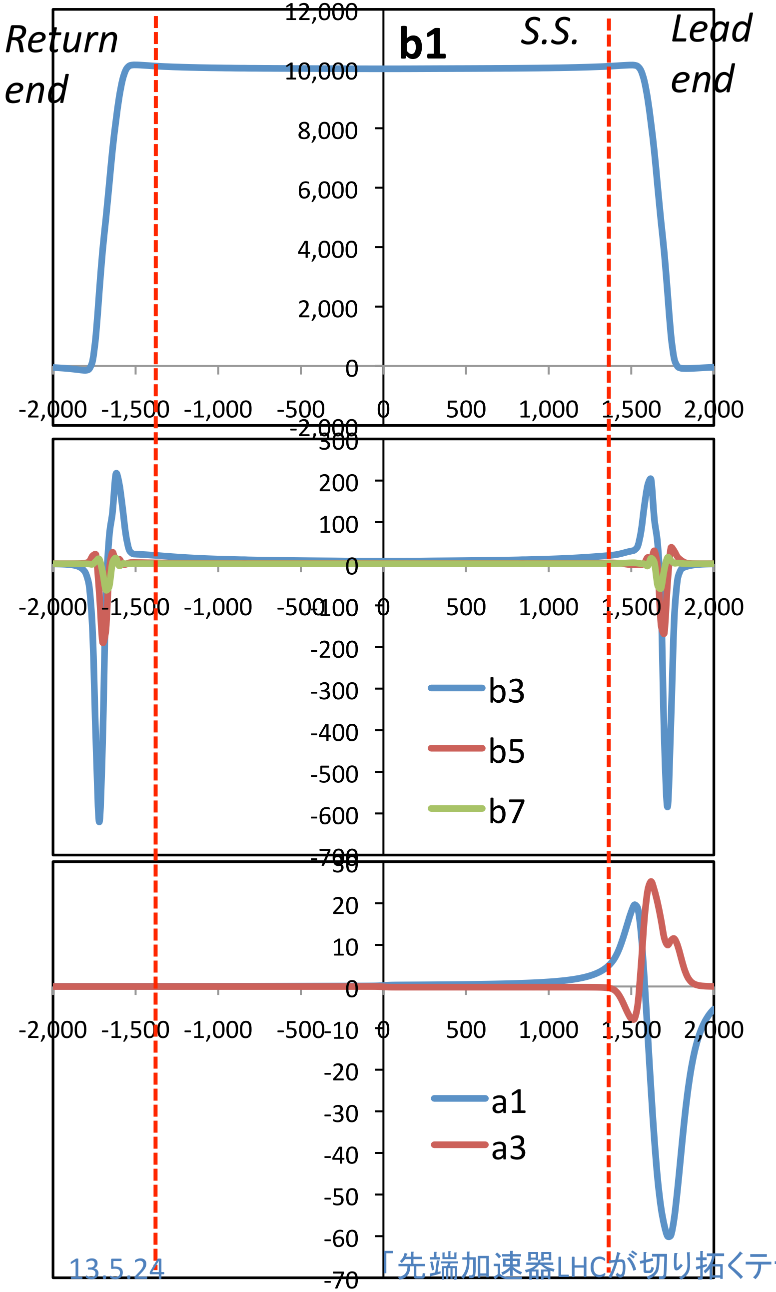


磁場設計： コイル端部形状の決定

- *Iron covers the whole coil ends currently. Peak field in coil ends is ~ 5% higher than straight section.*



Field Integral & Magnet Length: Option 1 (Tentative)



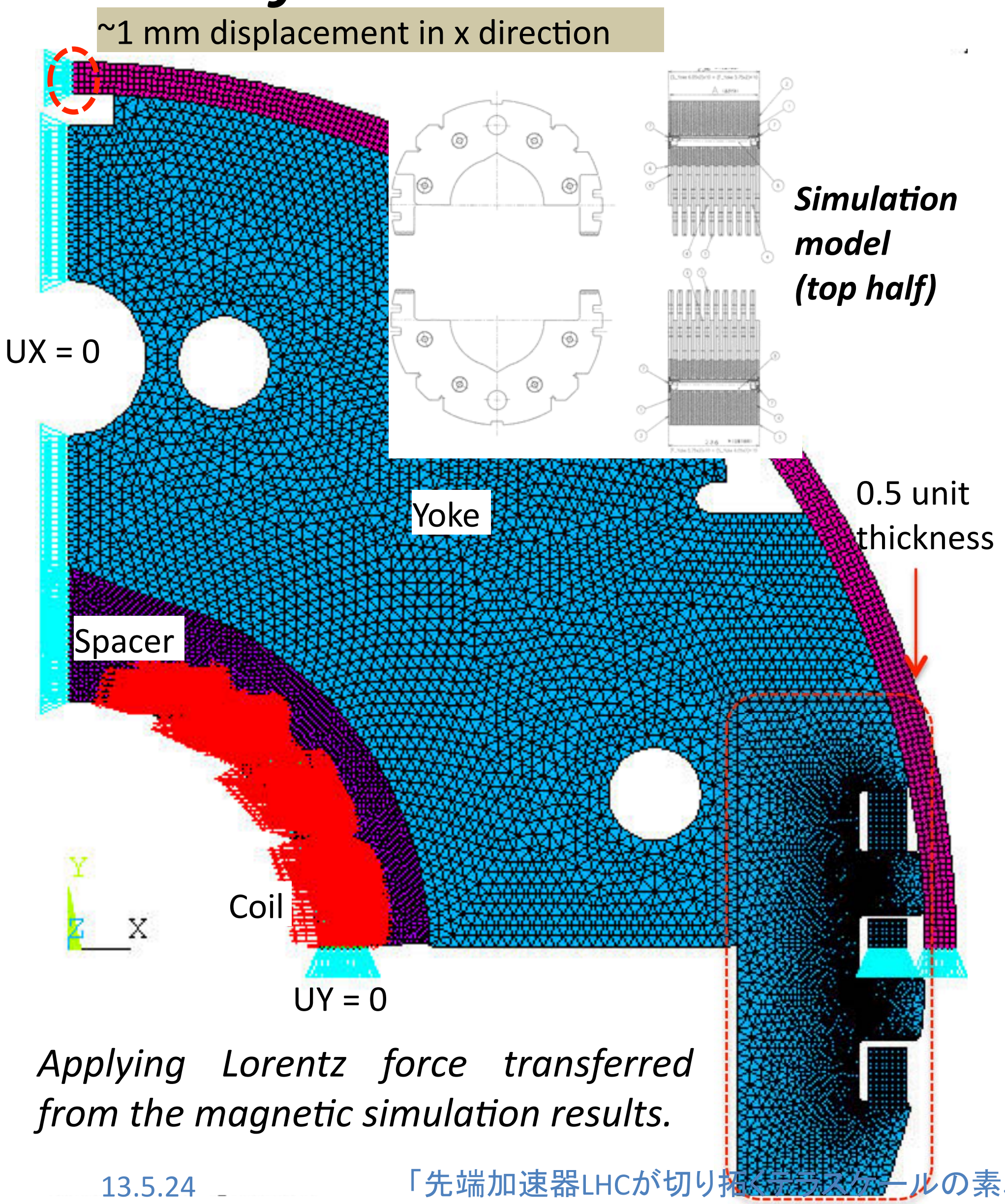
*For Mechanical Coil Length: 3.51 m (-1757 < z < +1753)

Field Integral	Return End (-2000 < z < -1400)	S.S. (-1400 < z < +1400 mm)	Lead End: (+1400 < z < +2000 mm)	Total
B1	1.39E+00	1.47E+01	1.49E+00	1.76E+01
B3	-9.11E-03	1.48E-02	-7.27E-03	-1.58E-03
B5	-3.42E-03	1.31E-03	-2.28E-03	-4.39E-03
B7	-1.13E-03	2.52E-04	-7.74E-04	-1.65E-03
A1	--	8.62E-04	-5.43E-03	-4.56E-03
A3	--	-1.27E-04	1.71E-03	1.59E-03

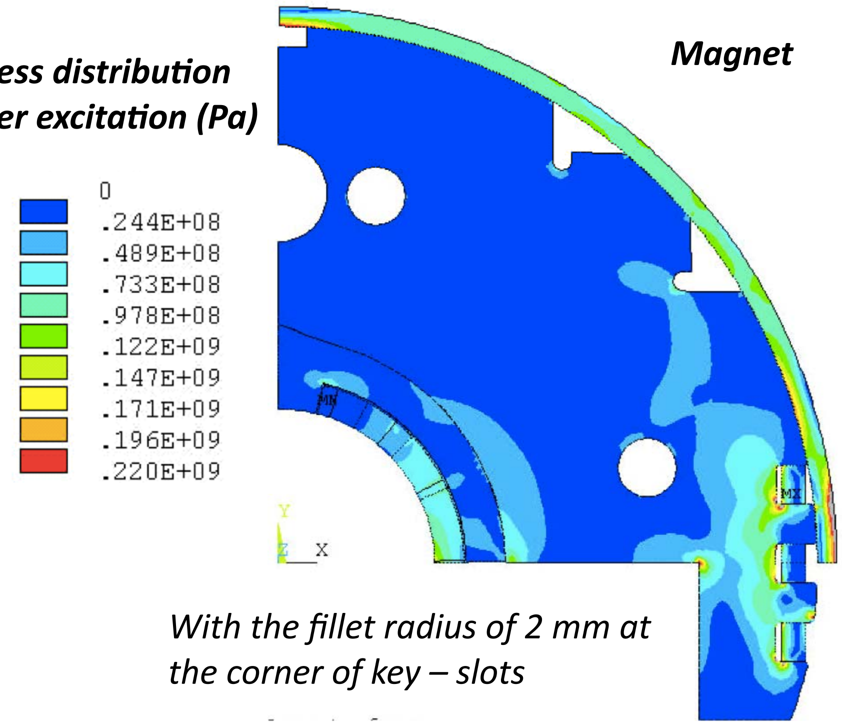
(T m)

- Field integrals of higher order multipoles are designed to be less than 1 unit w.r.t. that of B1.
- Peak field in coil ends is ~ 5% higher than straight section. (Iron yoke fully covers the ends.)
- Coil length estimates
  - 35 Tm >> Mechanical coil length 6.82 m
  - 40 Tm >> Mechanical coil length 7.77 m

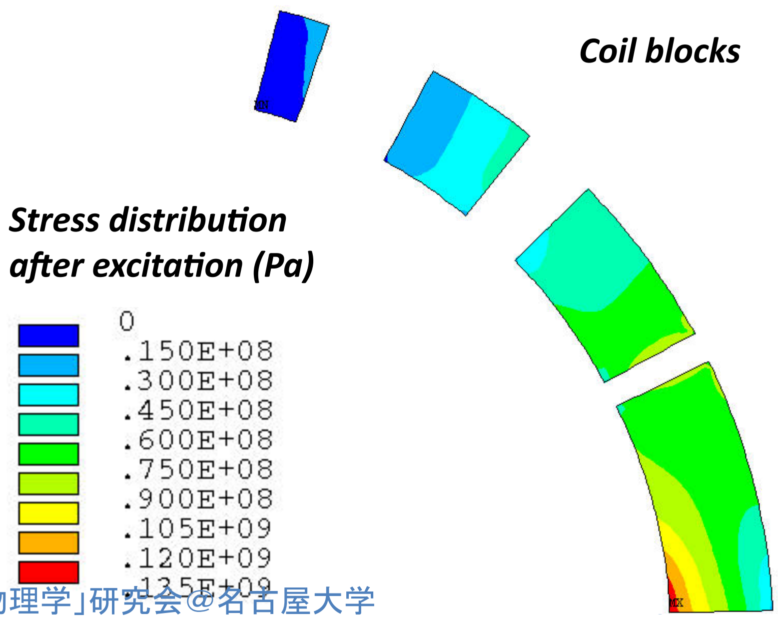
構造設計(定格電流 x 110%)
After excitation



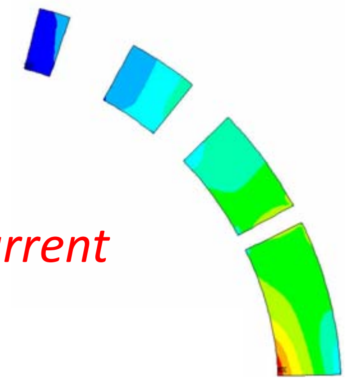
Applying Lorentz force transferred from the magnetic simulation results.



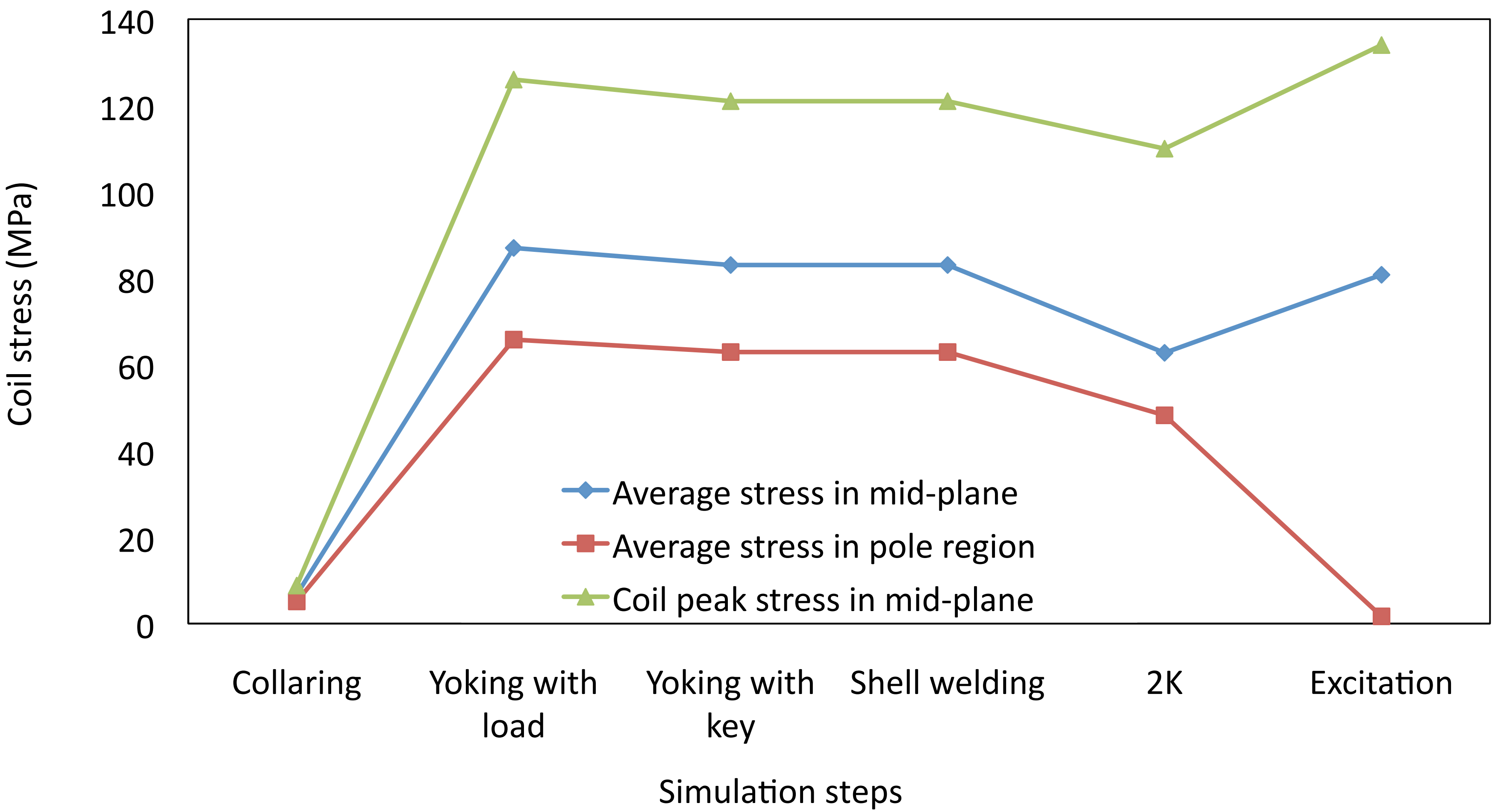
With the fillet radius of 2 mm at the corner of key – slots



超伝導コイル内の応力

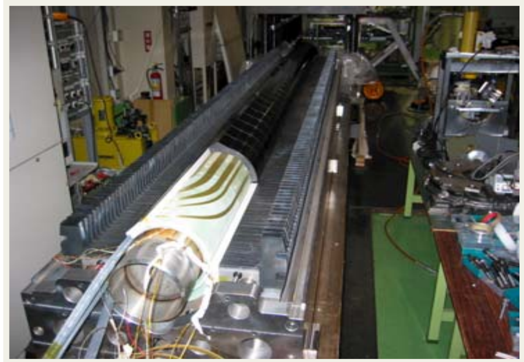


160 mm aperture, with 110% of the nominal current
Lorentz force: 1.4 MN/m and 0.6 MN/m in X/Y direction at nominal current



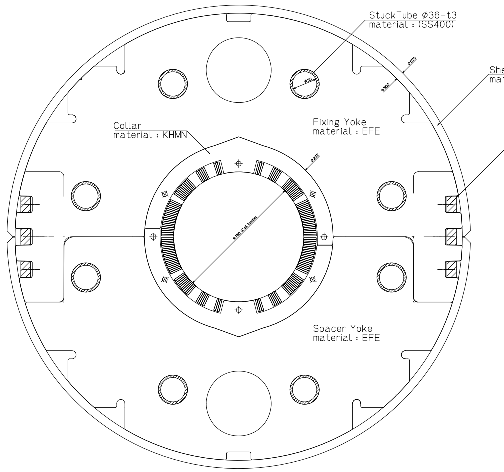
モデル磁石所内開発指針

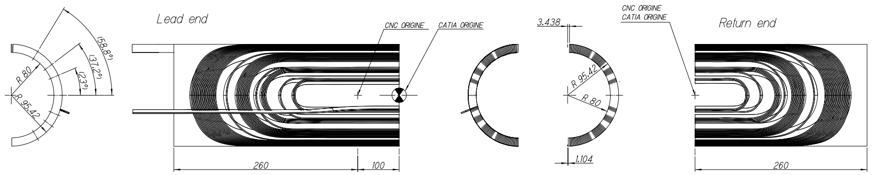
- 機械構造設計はLHC-MQXA, J-PARCニュートリノSCFMを踏襲
- J-PARC T2K SC Magnets (コイル内径173.4mm)の治具類の再利用.
  - 鉄ヨーク外径（550mm）は同じ
  - 鉄ヨーク打ち抜き金型、4m長油圧プレスなど
- NbTi超伝導ケーブル
  - LHC主双極磁石用ケーブルの余材
  - HeII冷却下での除熱性に優れた電気絶縁材料
    - → CERNとの協力(MQXC用開発＋要素検証実験)



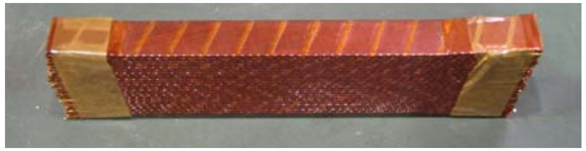
開発計画

- JFY 2013
  - 工学設計、図面（治具、部品）
  - テストコイル2個試作＋構造検証用短尺モデル開発
- JFY2014
  - モデル1号機コイル巻き線, 2m長モデル磁石組み立て
  - 冷却励磁試験
- JFY2015
  - モデル2号機試作（検討中）
  - 技術設計報告書提出

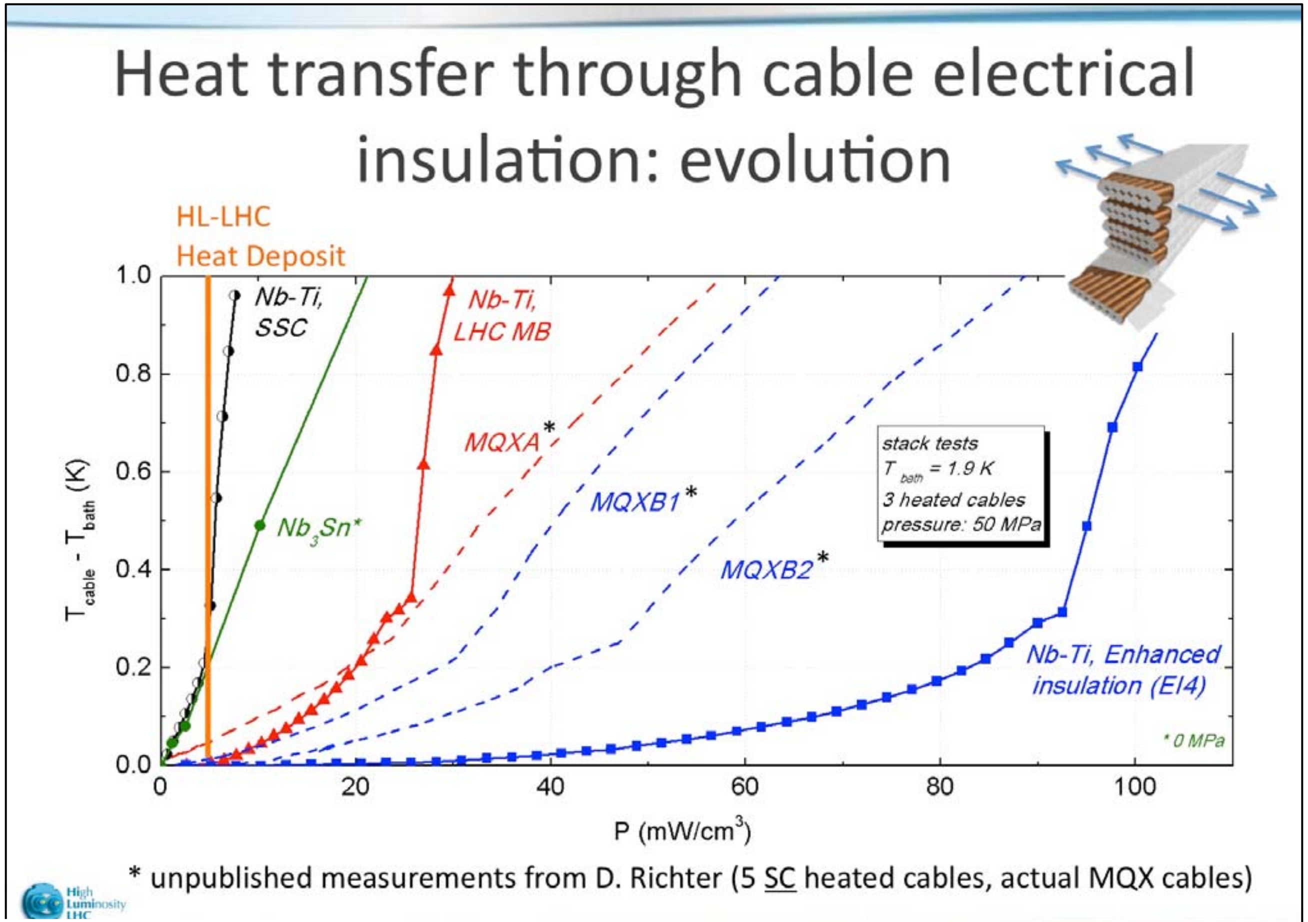




Cable Insulation



- NbTi SC cable: LHC MB Inner or **Outer** layer
- Insulation: 2 candidates
  - MB-like: Apical tape, cured at 190-197 °C at > 15 MPa.
  - improved MQXA-like: Upilex tape w/ prepreg (Cyanate Ester + Epoxy), cured at 150 °C.

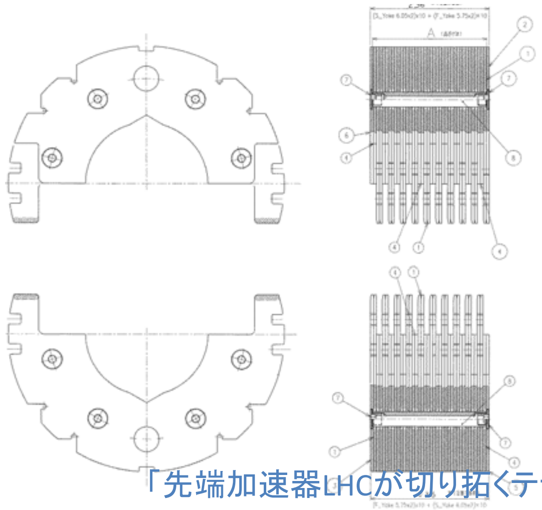


- MB insulation looks having better heat transfer capability.
- Insulated inner and outer cables with Apical tapes were delivered from CERN.
- 10 stack measurements will be made soon.
- Radiation resistance?

P.P. Granieri, 2nd HiLumi Meeting, Frascati, 2012

Collar, Yoke

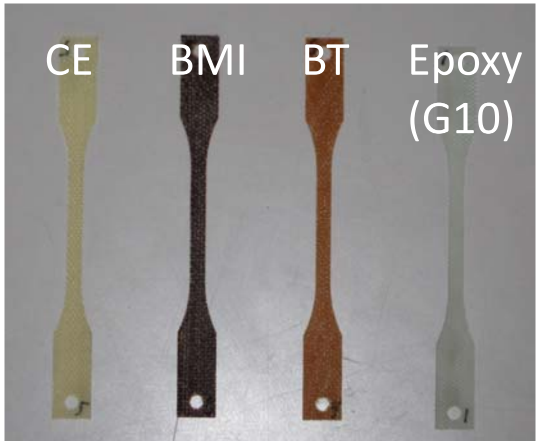
- Collaring yoke structure (Originated at RHIC-dipole, followed by MQXA)
  - Stainless collar as a spacer, vertically split iron yoke locked by keys
  - Both collars and yokes should have small dimensional errors (20-30 μm at smallest). >> Fine-Blanking technology
- Discussion with a fine-blanking company started in March.
  - Some suggestions for the first design.
  - Waiting for answers: cost estimates, technical feasibility, delivery time.
- A set of fine-blanking die for iron yoke: very expensive, very long delivery time.
  - Yoke cross section has to be finalized soon: single or double layer coil, size and location of holes, etc. >> determined by the heat load and the cooling scheme.
- Business inquiry will be sent to vendors for stainless steel, iron yoke.
- Control of packing factor is crucial to field quality due to high saturation.



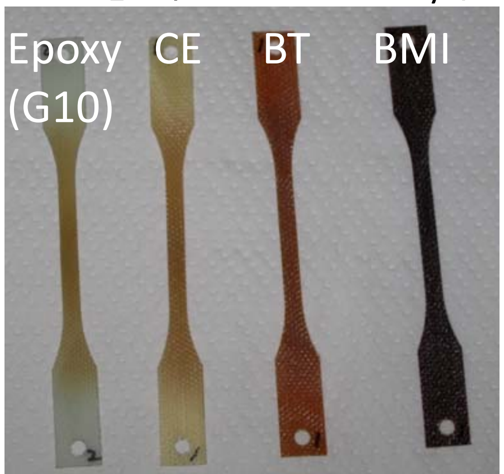
Yoke dies for J-PARC SCFM

耐放射線材料の開発・評価

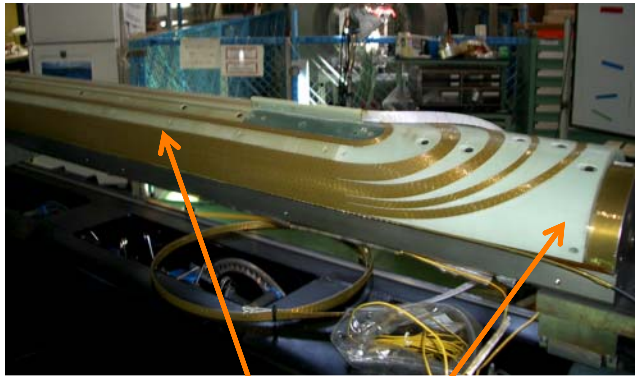
- New radiation resistant GFRPs (w/ S-2 Glass or T-Glass) are baseline for coil wedges, end spacers.
  - Cyanate Ester & Epoxy
  - BT (Bismaleimide Triazine)
  - BMI (Bismaleimide)
- Trial production has been made: prepreg sheets, laminated plates and pipes.
- Backup plan (in case of higher dose) would be metallic parts with Polyimide coating by "Vapor Deposition Polymerization" technology.
- 耐放射線試験（低温、常温、100 MGy）を計画
  - JAEA高崎：Co^{60} γ線、2MeV電子線 2012.10~
  - 京大原子炉：30MeV電子線2012.9~

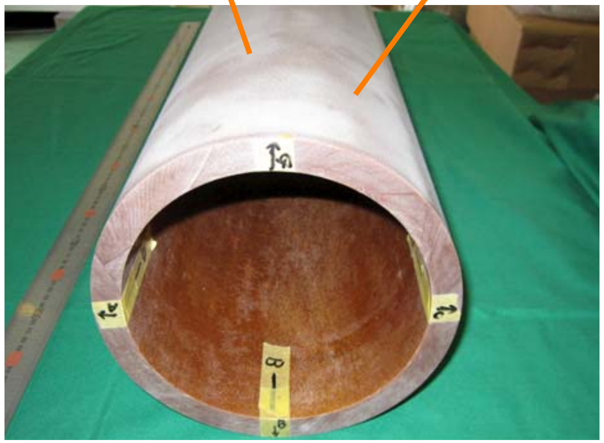


30MeV電子線照射後：10MGy相当

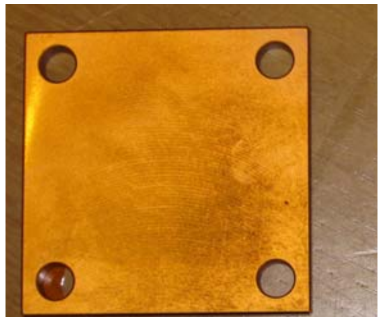


従来の超伝導コイル（J-PARC SCFM）。ウェッジ、スペーサーはG10（エポキシ＋Eガラス）。





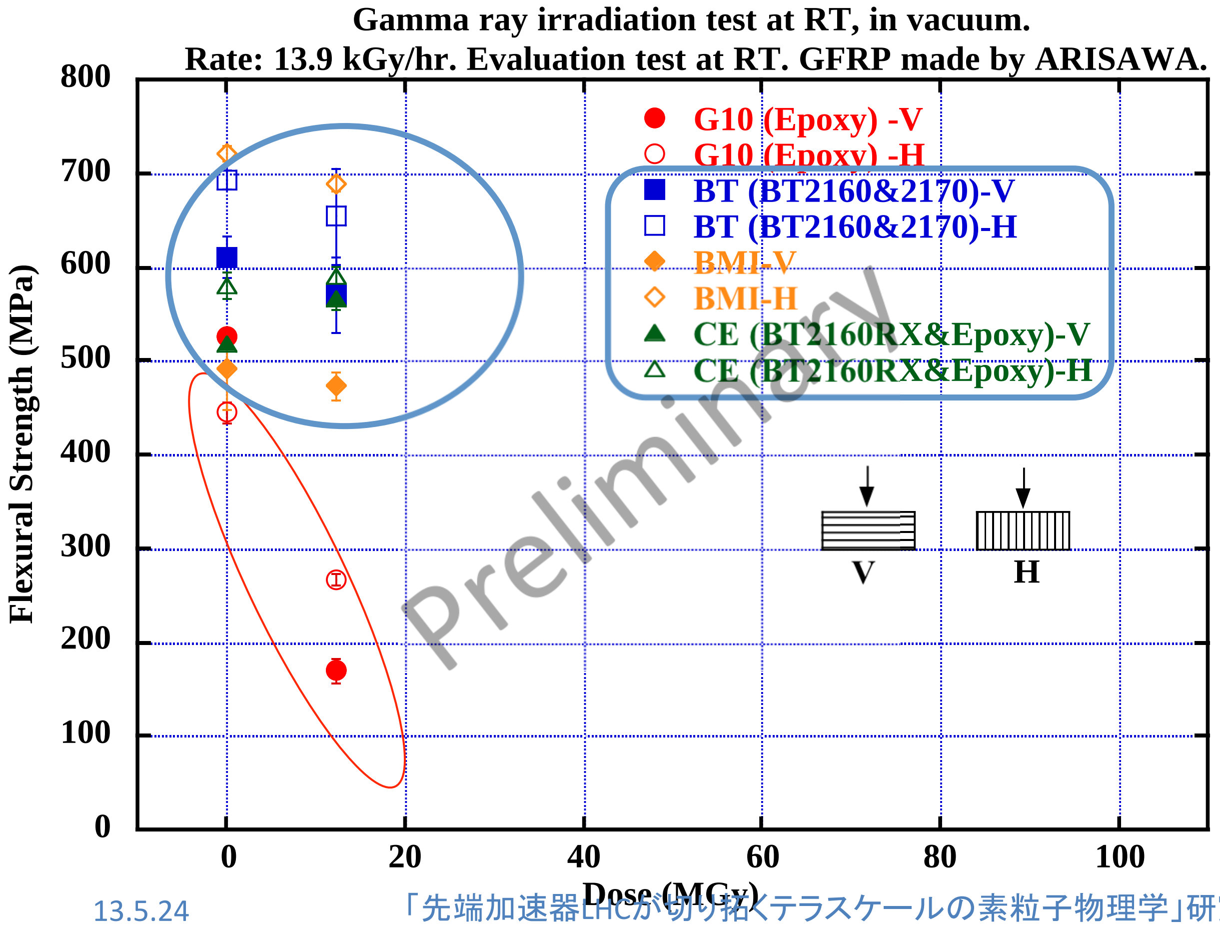
新規開発したBT-GFRPパイプ（φ160, L1000）

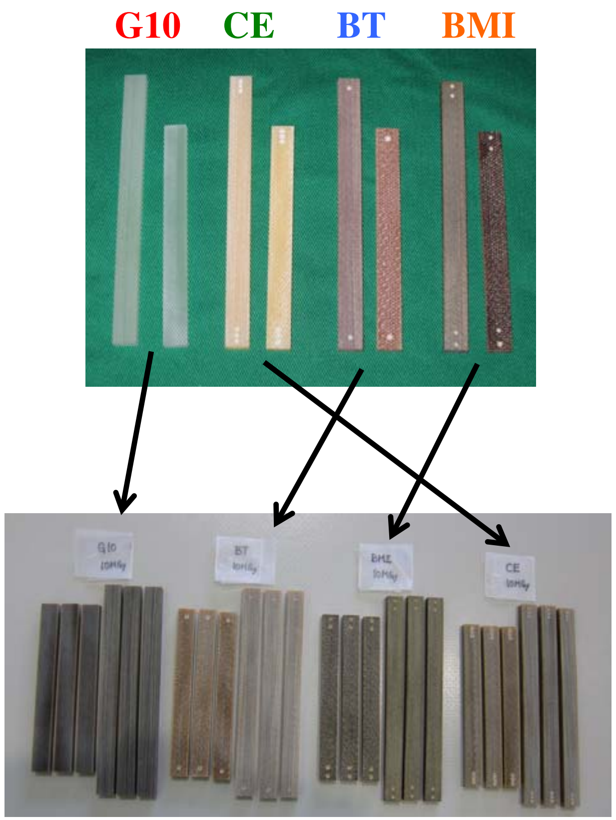


金属部品へのポリイミド蒸着（バックアップ）

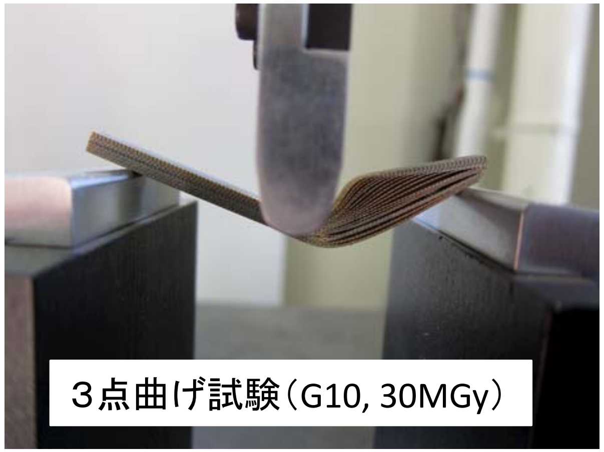
常温γ線照射試験（2013年3月時点）

- All new GFRPs (CE&Epoxy, BT, and BMI) have shown better radiation resistance up to 10 MGy.
- Samples were irradiated up to 50 MGy by May and evaluation tests will be carried out soon. Irradiation up to 100 MGy will be completed within 2013.
- Ordinary G10 already showed significant degradation at 10 MGy.





After irradiation of 13 MGy



まとめ

- さらなる高輝度化のためHL-LHCアップグレード（250-300 fb^{-1}/y、3000fb^{-1}）を計画。
  - 2022年『トンネルへインストール』
  - 大電流化、IR1/5のLow-Beta Insertionの更新、新しいビーム設計(ATS)
  - SC Crab Cavitiesによるレベリング
  - 大ビームパワー対策、放射線対策、冷凍能力増強

- WP1-15で設計研究、R&D → 技術設計書を提出(2015) → 建設の判断(2016?)
  - EC-FP7 HiLumi-LHC
  - CERN
  - US-LARP
  - KEK（LIU、ビーム力学、超伝導磁石、クラブ空洞）

- KEKではビーム分離用大口径ダイポール（5T, 40Tm, ϕ160@1.9K）のR&Dをスタート。
  - 2012　概念設計
  - 2013　工学設計＋テストコイル試作
  - 2014　モデル磁石試作、冷却励磁試験

    放射線入熱の最新結果：　口径の再検討　160mm → 150mm？

http://hilumilhc.web.cern.ch/HiLumiLHC/