An R&D Proposal for

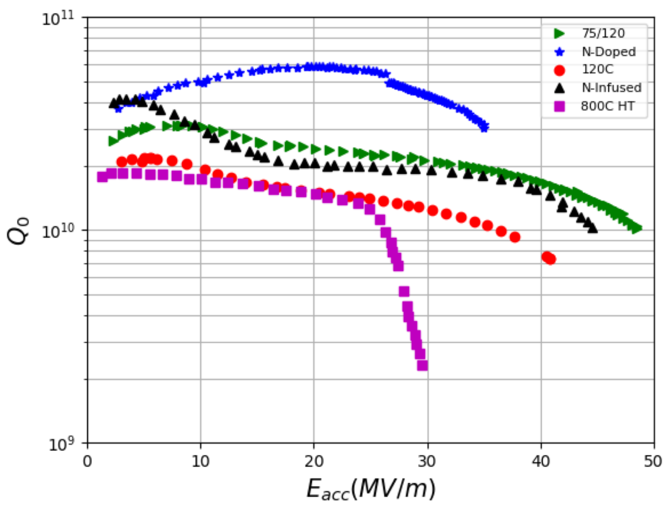
Superconducting Magnets

harmonized with High-Gradient SRF Cavity and Linac

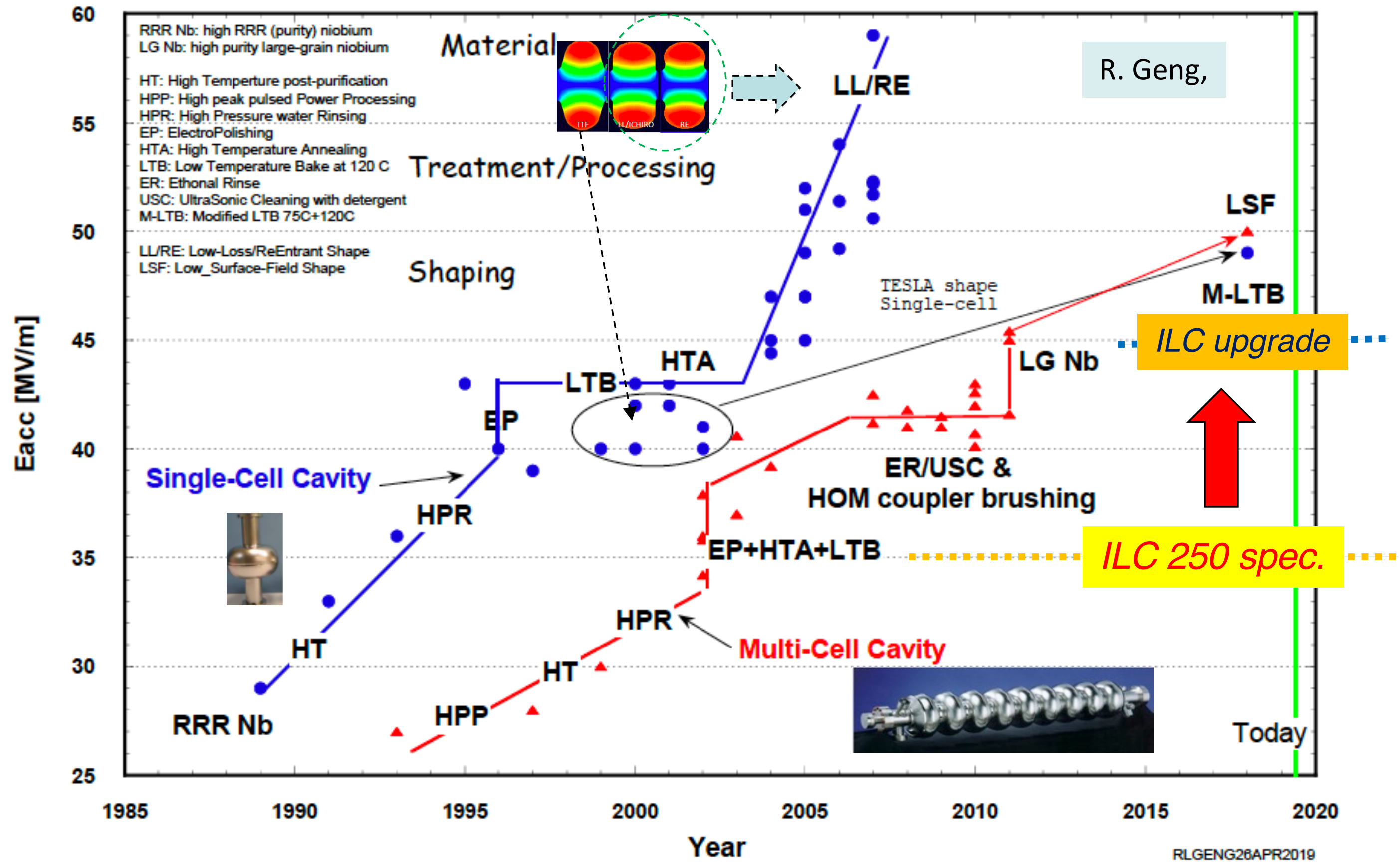
Akira Yamamoto (KEK/CERN)

AWLC2020, Acc. SRF Session, October 22, 2020

Advances in L-band (~ 1GHz) SRF Cavity Gradient



Anna Grassellino
- TTC, TRIUMF, 2019



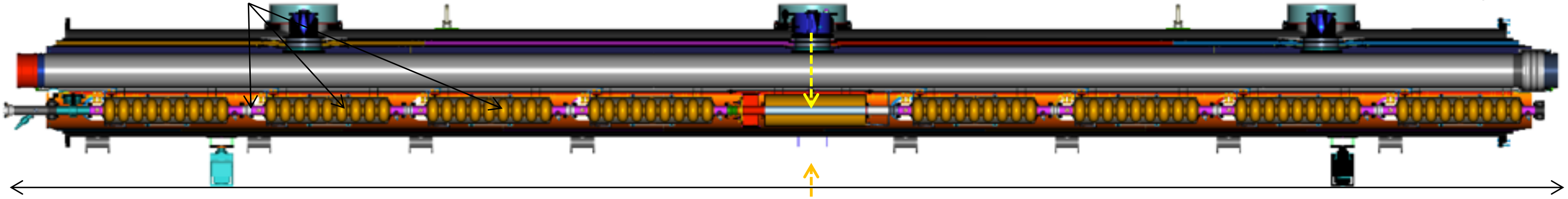
A. Yamamoto, 190513bb

Superconducting Magnets for ILC ML

cavities (8)

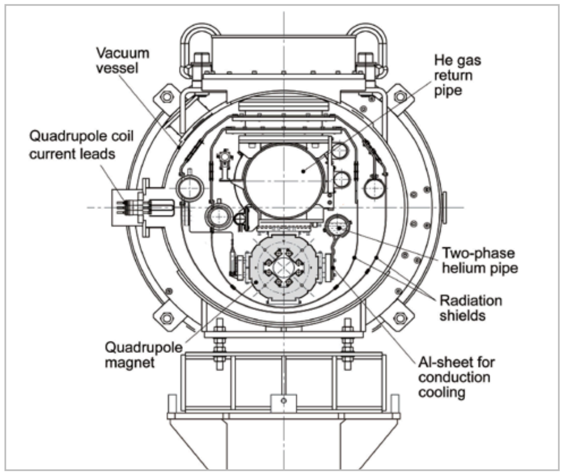
SC quad package (1)

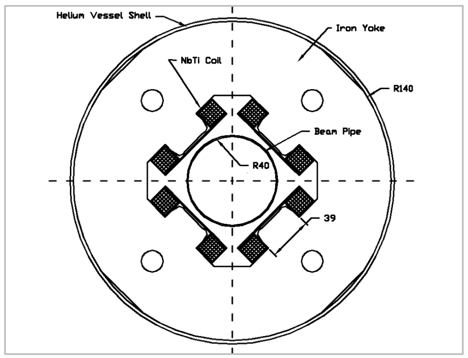
Type-B module
w/ 8 SRF-cavities and 1 SC-Quad. Magnet

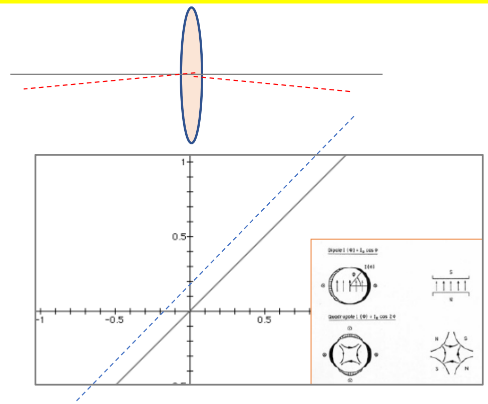


12.652 m

Q: for focusing beam
D: for steering beam and bendingit along the earth surface with ρ = 6,400 km







Q and D Combined functioning required for beam focusing and steering

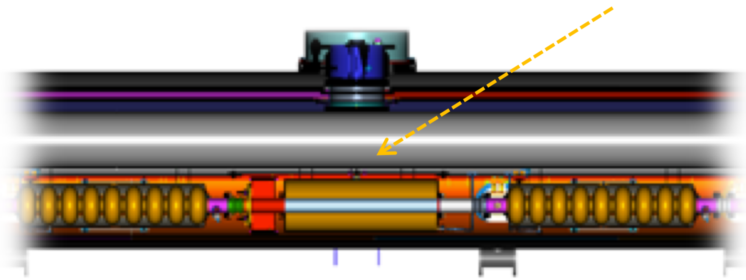
ILC-ML SCQ: Requirements and Features

Parameter	Performance Requirements/ Specifications
Dimensions:	Beam-bore aperture: 78 mm SCQ Pole aperture: 90 mm
Mag. Field	Quad, G-integral: 38 T Dipole, B-integral: 0.1 T
Harmonics:	Quad. @ r = 5 mm: ≤ 1E-3 Skew Q @ r = 5 mm, < 3E-4
Field stability	During beam-pulse (1ms): 2E-5 Over beam-pulse (>> 1 ms): 1E-3
Field change/feedback	Quad: 0.03 %/s to G-max, Dipole: 0.6%/s to B-max
Alignments:	Rel. to BPM: 0.3 mm, 0.3 mrad.
Low current for low Cryog. Load	Quad: ≤ 100 A Dipole: ≤ ~ 40 A
Cooling time: (to be studied)	Initial cooling: < 5 days, Recovery after quench: < ~ 30 min.

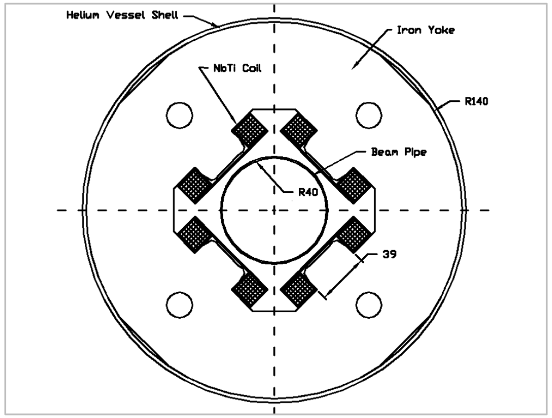
Features:

- **Magnetic field strength:**
  - Maximum at Beam-Energy = 250 GeV because of optics,
- **Splittable Structure:**
  - for the magnet assembly separated from SRF cavity string assembly in clean room,
  - Super-ferric (iron dominated) magnet preferred.
- **Conduction Cooling**
  - No LHe vessel w/ reliable alignment to BPM,
  - Thermal anchoring to two-phase He-pipe,
- **Alignment with Beam Position Monitor**
  - Alignment and Field stability is very important
- **Pulsive Operation in small faction**
  - For beam orbit correction and feedback
- **Sustainability against Dark Current (DC):**
  - Heat absorption and radiation hardness against DC

SC Magnet Design for ILC Main Linac
in cooperation of Fermilab and KEK



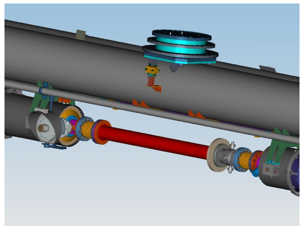
SC Magnet (Q+D)

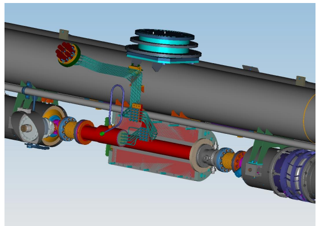


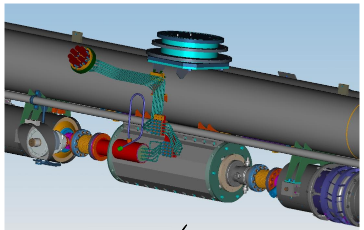
Parameters	Unit	Type - H.E. (25~250 GeV)
Dimensions:		
Physical Length	m	1.00
Magnetic Length	m	0.95
Iron-Pole Radius	m	0.045
Quadrupole field:		
Field Gradient (G)	T/m	40
G-Integral (required)	T	**38**
B_G at pole	T	~ 1.8
Dipole field:		
B_D	T	0.105
B-Integral (required)*	T•m	**0.10**
B-max		
at Pole	T	**~ 1.9**
in Coil	T	< 3

SC magnet design to be well harmonized with high-gradient SRF cavity “clean” fabrication

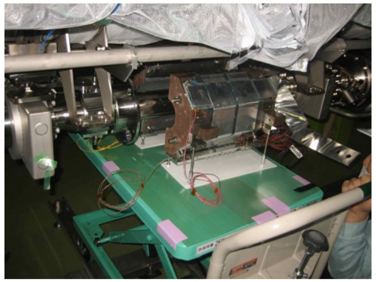
- Split-able quadrupole demanded for the assembly to be separated from SRF cavity string “clean” assembly.
- Conduction cooling enables the magnet cryogen-free and eliminates the LHe vessel.

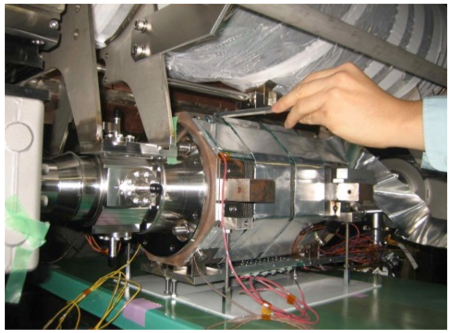






(d)





Concept successfully demonstrated

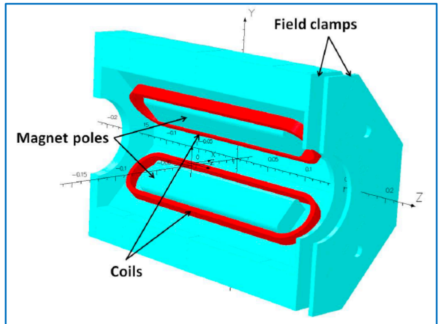
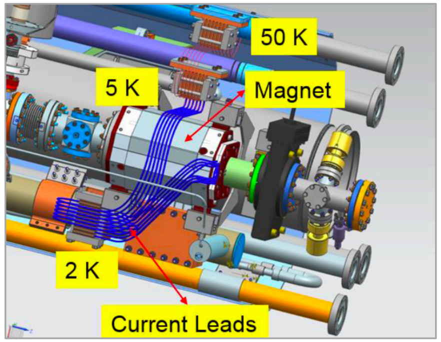


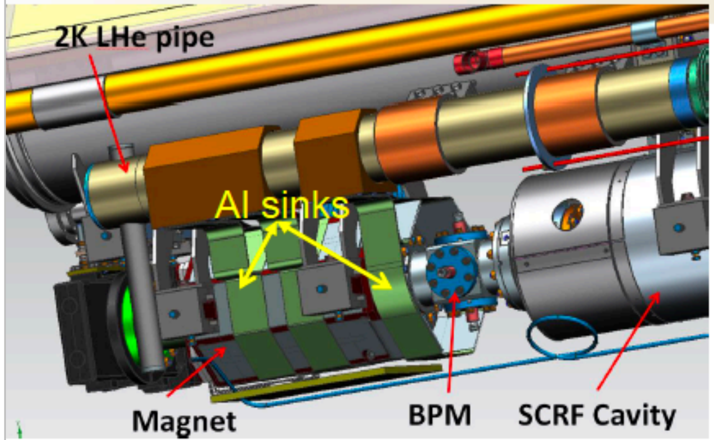
Fig. 3. One half of magnet package view.

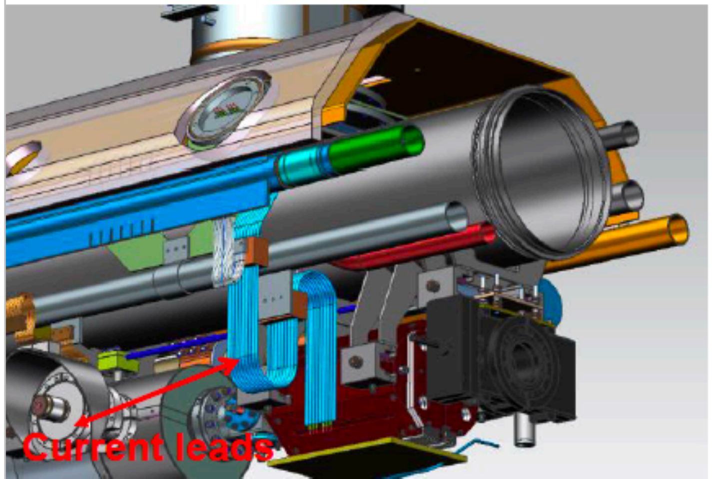


Courtesy: V. Kashikhin

LCLS-II Magnet in the Cryomodule

SLAC



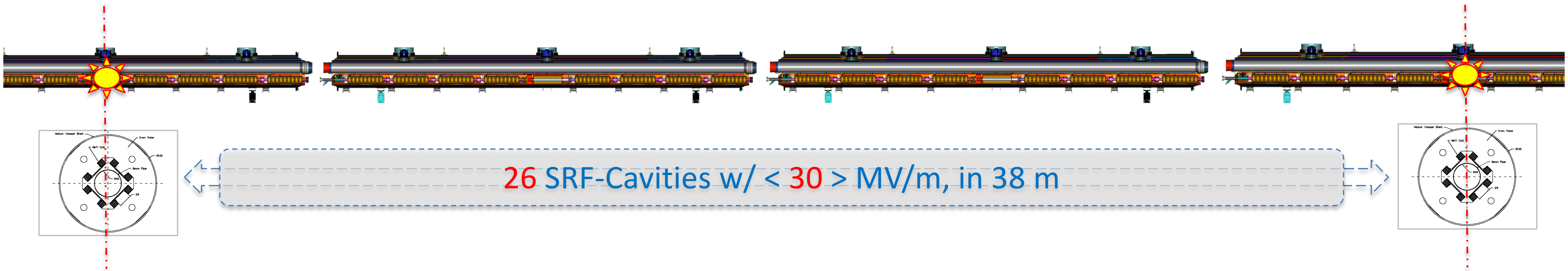


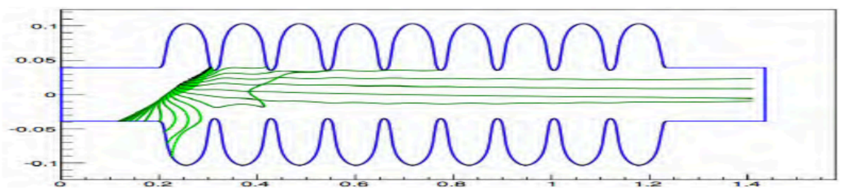
Parameter	Unit	Value
Magnet physical length	mm	340
Magnet width/height	mm	322/220
Pole tip radius	mm	45
Peak operating current	A	≤ 50
Number of quadrupole coils		4
Number of dipole coils		8
Type of superconducting coils		Racetracks
NbTi superconductor diameter	mm	0.5
Quadrupole inductance	mH	82
Liquid helium temperature	K	2.2
Quantity required (with spares)		36

The magnet package for 2 prototypes will be installed at the end of the cryomodule. Magnet conductivly coolled through pure Al thermal sinks.

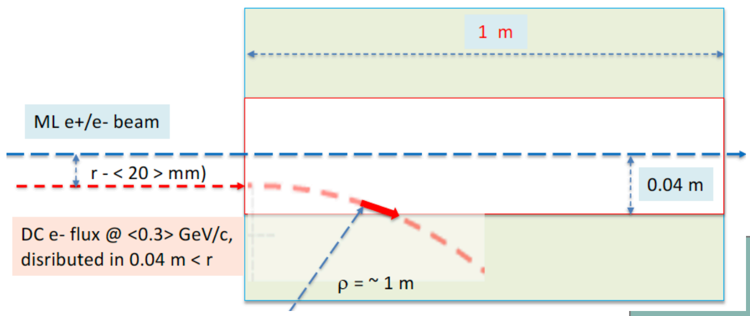
An Issue in particular HG SRF Linac in future:

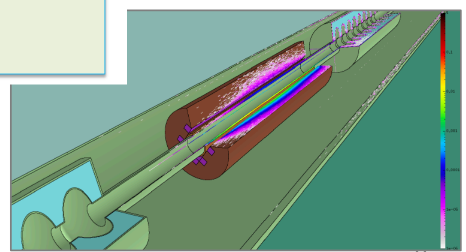
Dark-Current Electrons generated in SRF Cavities accelerated and transported into the next SC magnets





Dark Current electrons accelerated via Cavity
Courtesy: G. Rongli,





The Superconducting Magnets to be sustainable against Dark-Current from High-Gradient SRF Cavities

- Dark Current needs to be inevitably assumed in high-gradient frontier for SRF cavities,

- The dark-current electrons are accelerated along the down-stream SRF cavity strings, and reach SC magnets, down-stream,

- Most of the electrons are deflected and the energy is absorbed in the superconducting (SC) magnet, resulting heating.

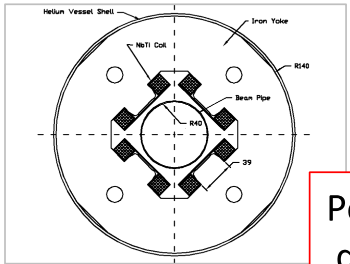
- The SC magnet needs to be sustainable and harmonized with advances in high-gradient frontier of the SRF cavity technology.

Heat Absorption in the ILC-ML SCM

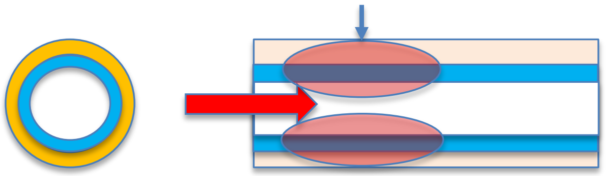
Dark Current Heating in Simulation

By A. Sukhanov, N. Solyak et al., LINAC2016,

Beam Energy, GeV	5	10	15	125	250
Quad, W	0.07	0.15	0.22	1.35	1.7
Cavity, W	0.36	0.36	0.45	0.45	0.2
RF Unit, W	4.1	3.5	3.2	2.7	2.6



Peak Power loss Model:
dR ~ 10 mm, Lz = 30 cm



Assumption of Power/Energy Deposition into SCM (Q/D)

- Dark current / cavity: **≤ 50 nA**
- Power deposition : 1.35 W @ 125 GeV ---> **< 5 W @ 500 GeV**
- E = **1 Joule / 1 ms** (with an interval time of 200 ms, or 5Hz)

Temperature rise (ΔT) due to E. Deposition, if no-cooling

- $\Delta T = (E/M) / c_{\text{-Cu}}$ (assuming Cu@ 5 K)

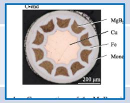
  = 1.3 K / pulse (1 ms),

  ≤ 6.5 K / sec,

Magnet sustainability in ~ 1 sec

- MgB_2 / Nb3Sn (Tc ~ 15 K, at 3 T, I/Ic ≤ 50 %)
- NbTi (Tc ~ 8 K, at 3 T, I/Ic ≤ 50 %) → approaching to Tc

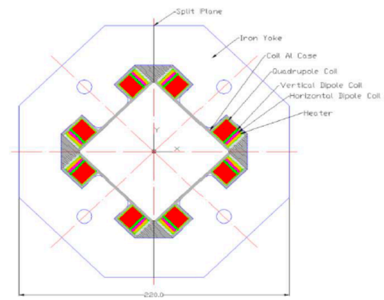
Candidates Superconductors to be evaluated

Item	Unit	NbTi	MgB_2	Nb_3Sn
Critical Temp. @ 0 T and 0A	K	9.2~9.5 K ~ 8 K @ 3 T	39 K ~15 K @ 3 T	18.3 K (> ~ 15 K @ 3T)
Wire dia. (bare)	mm	0.5	0.55	0.6
# filaments		7242	10 	13,338
Filament dia.	μm	3.7	< 100	2.4
Twisted pitch	mm	25	200	30
Cu: SC (ratio)		1.5~2 : 1	1 : 1.2	0.19
RRR (Cu)		50 ~ 100	88 (RT/10 K), 40 (RT/-40K)	≥ 120
Critical Current	A	204 A @ 5 T, 4.2 K	60 A @ 5 T, 4.2K TBD @ 3 T, 15 K	≥ 120 @ 12 T, 4.2 K
Wire dia. (insulated)	mm	0.54 + (0.04~0.10)	0.55 + 0.06	0.6+ 2 x 0.075
Insulation material		Enamel + (Glass-Fiber)	Glass braid	Glass braid
Heat Treatment required		< 200 C	~ 600 C	≥ ~ 650 C x 240 h
Relative cost		1	~ 2	~5
Availability		Contributed by Fermilab (available also at F.E.)	Purchasing required (Hitachi)	Purchasing required (F.E.: Furukawa Electric)

Subjects to be investigated and examined.

- **DK electron's heat absorption:**
  - Further quantitative evaluation and simulations.

- **Magnet design and development:**
  - Conductor material, and magnetic characteristics,
  - Electromagnetic design,
  - Heat balance for electron absorption and conduction cooling .
  - Overall system design optimization, including quench safety, with the simplest and most reliable system



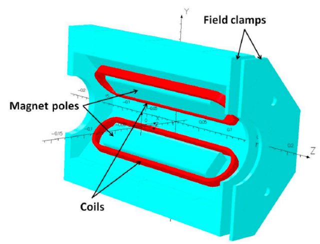


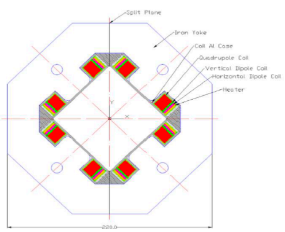
Fig. 3. One half of magnet package view.

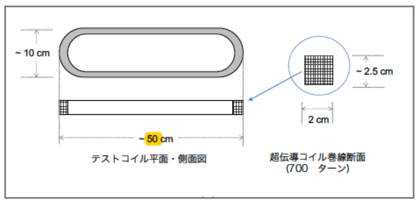
An R&D Program Proposed

in a time scale of ~ 2 years

Model magnet development:

- Features:
  - Iron-dominated, superferric, combined (G & B) function.
  - Splittable structure for the assembly independent from SRF cavity string assembly,
  - Conduction-cooling by using a cryo-cooler,
  - Heat deposition to be simulated by using heaters embedded in the SC Coil, and
  - Quench protection and safety to be demonstrated
- Dimensions:
  - Scales: 1/1 X-section, and ¼ ~ ½ length, (0.25~0.5m)
    - A_{pole} = 0.09 m
    - $L_{yoke} \geq$ 0.25~0.5 m, $L_{field} = \geq$ 0.2~0.5 m
- Magnetic field:
  - Magnetic field: HE type, $G_Q \geq 38$ T/m, $B_D \geq 0.1$ T
    - Q, G-integral = 8~19 T (≥ 38 T/m)
    - D, B-integral = 0.02~0.05 T•m (≥ 0.1 T)





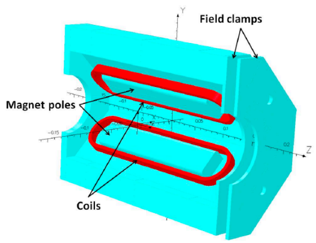


Fig. 3. One half of magnet package view.

Subjects to be demonstrated and understood:

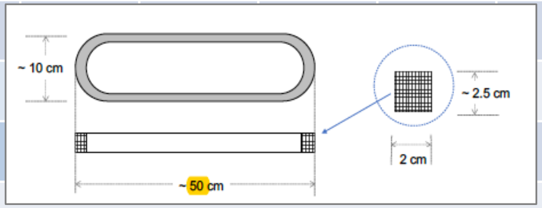
- Magnet structure splittable,
- Conduction-cooling,
- SC conductor (NbTi or MgB_2) optimization,
- Coil fabrication,
- Physical tolerance and magnetic field quality,
- Excitation and pulsive operation with Temp. margin
- Alignment stability during excitations.
- Leakage field control along beam axis,
- Heat absorption with simulating dark-current electron bombardment.
- Quench characteristics, protection, safety and recovery performance,
- Radiation hardness against FE electron bombardment.

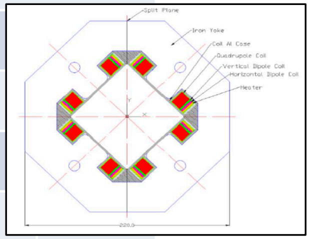
Process:

- Test coil:
  - Two Race-track coils (each using NbTi and MgB_2 SC)
  - Conduction cooling and excitation with simulating heat-absorption
- Model magnet:
  - Quadrupole configuration w/ iron-yoke/poles, splittable
  - Conduction-cooling with optimization for cooling time,
  - Field quality, stability, and sustainability with absorbing heat.
  - Quench protection and safety evaluation,
  - Recovery time to ordinal operation, in case of quench

Study and R&D Plans anticipated in global cooperation

	JFY2020 ~ 2023											
Simul. & Design Study												
Heat deposit evaluation												
Quench and safety study												
Magnet Design												
R&D Programs												
Test Coil (0.2~0.5m)												
S. Conductor fabrication												
Coil fabrication and test												
Cooling, excitation, evaluation												
Model Magnet (0.2~0.5 m)												
S. Conductor fabrication												
Coil fabrication												
Model mag. assembly												
Model mag. test & evaluation												
Prototype Magnet (1 m)											To be extended	





Summary

- The superconducting magnet for SRF Linac needs to be well harmonized/synchronized with the SRF cavity advances in particular in high-gradient frontier.

- The dark current needs to be safely absorbed in the superconducting magnets with minimizing risks for quenching.

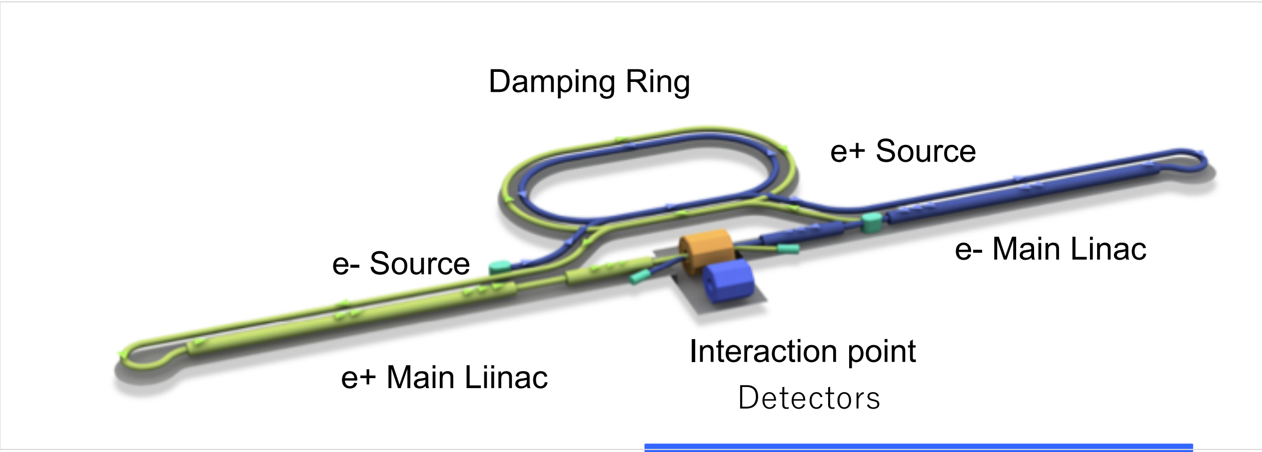
- An R&D effort for the magnet sustainable against the energy absorption is planned in cooperation KEK, Fermlab, and any global partners

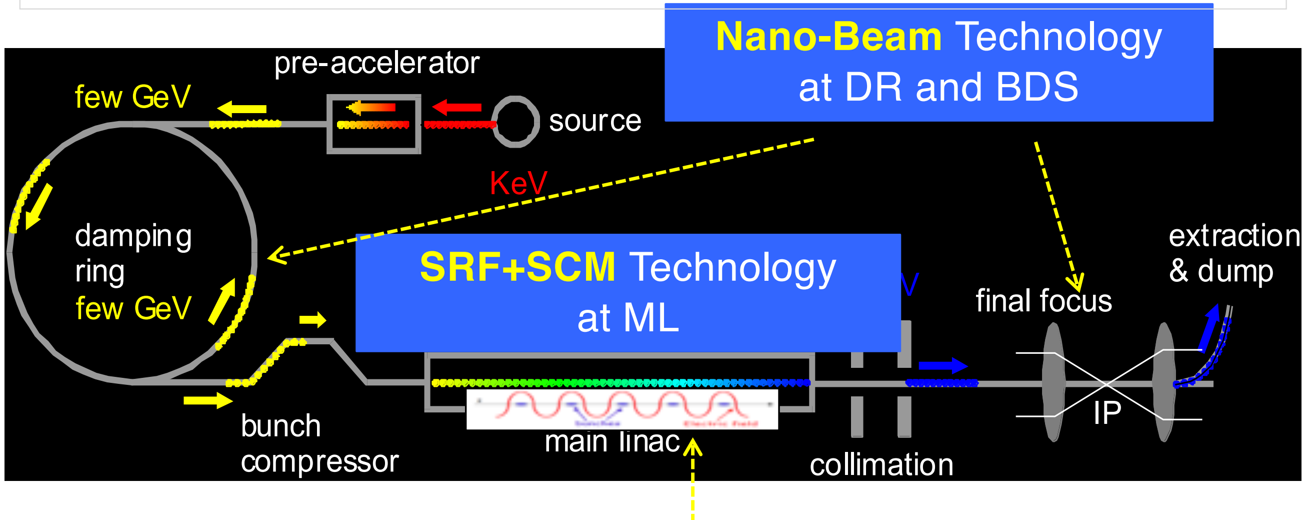
Acknowledgements

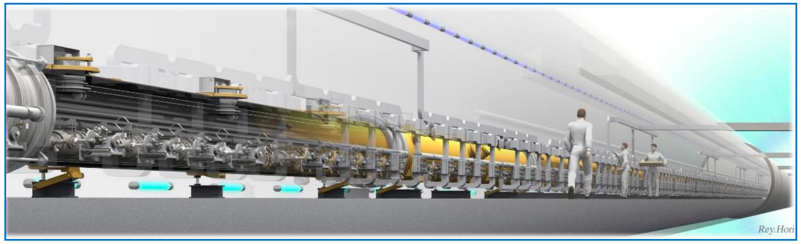
- *Many thanks V. Kashikhin, N. Solyak, (Fermilab), and Y. Morikawa, K. Umemori, N. Ohuchi, Y. Arimoto, and S. Michizono (KEK) , and others for their various discussions and kind cooperation for this study and R&D plan.*

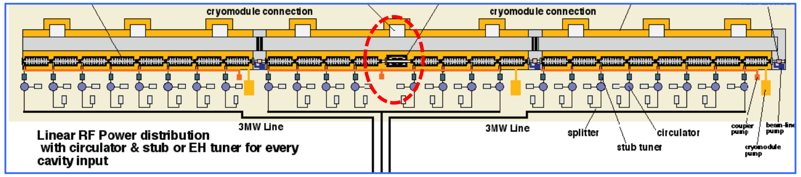
Backup

Key Technologies at ILC





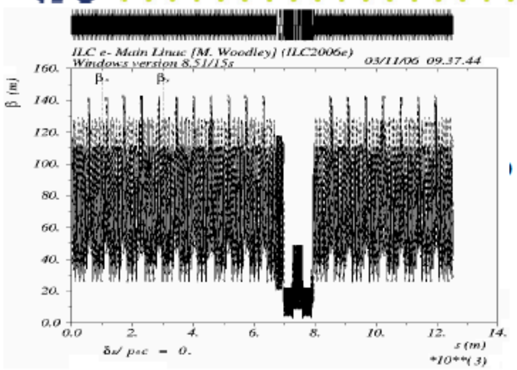


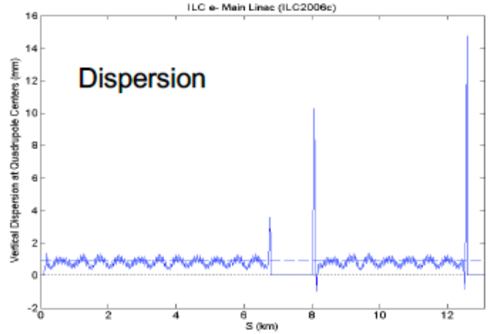


Parameters	Value
Beam Energy	125 GeV
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Beam size at IR	7.7 nm
ML-SRF, <E> gradient Q_0	31.5 (35) MV/m (+/-20%) ≥ 1E10 (1.6E10)
# SRF cavity (9-cell)	~ 8,000 x 1.1
# Cryo-M-a. w/o Q-mag	~ 630
# Cryo-M-b, w Q-mag	~ 315
# RF, Klystron	~ 240

IL-ML SCQ Design Extend-ability to ILC-TeV (500 GeV/c / beam)

RDR Main Linac Lattice: Curved linac





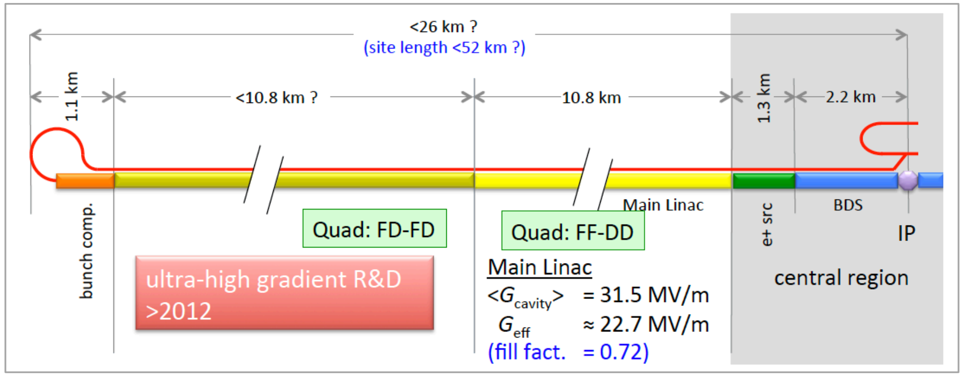
Lattice in ML (5 - 250 GeV per linac)

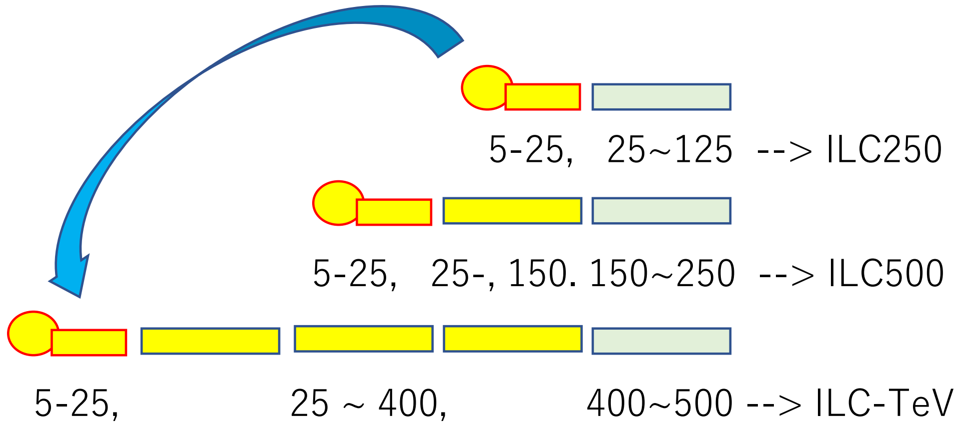
- 1Quad/3CM (9-8-9) (FDOFDO)
- Quad Spacing ~38m
- Curved linac
- Phase advance x/y = 75°/60°
- matching sections require ~10% higher quad strength

Energy upgrade scenario (250 → 500 GeV per linac)

- Same layout 1Q / 3CM (FFODDO)
- Same Quad strength
- Half-phase advance: x/y = 37°/30° for upgraded HE linac
- Stronger correctors ~10% (for the same vertical curvature)

2010/3/2 N.Solyak "ML Magnet specs" 6



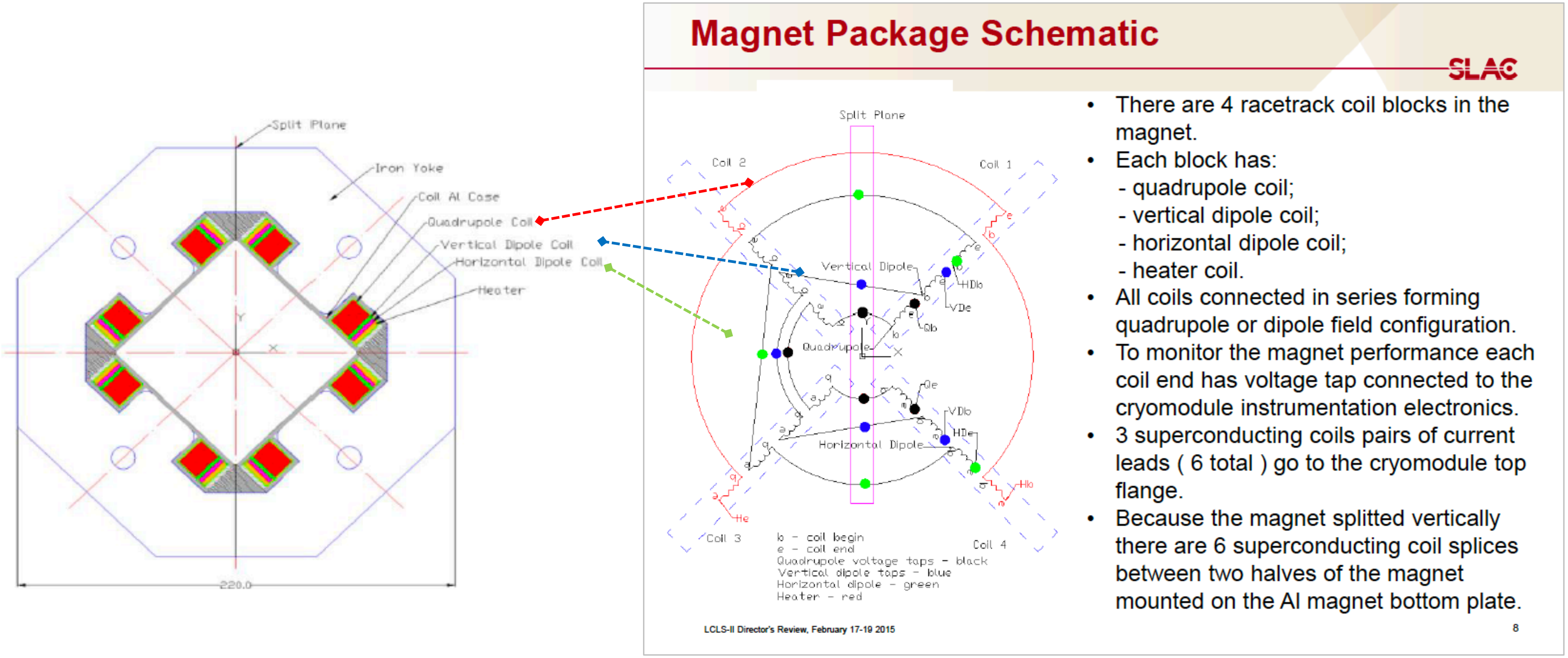


SCQ for ILC250 needs to adapt ILC-TeV

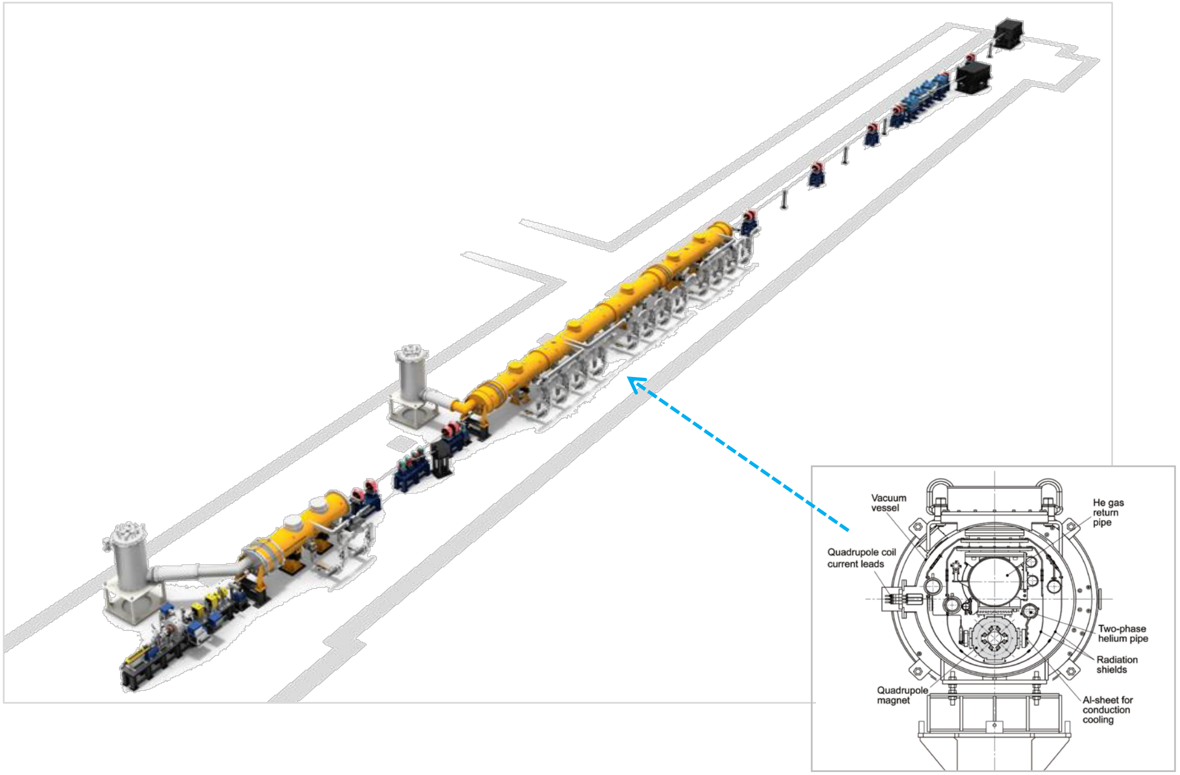
V. Kashikhin, Feb. 22, 2018

Quadrupole and Dipole Fields combined,

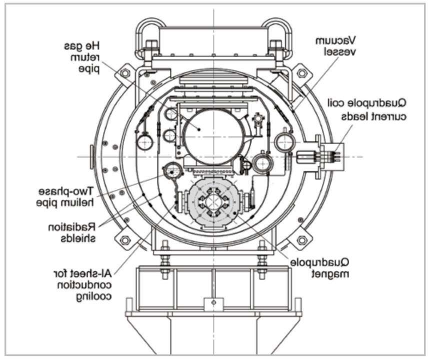
As a reference from the LCLS-II SRF Linac SCQ/D experience

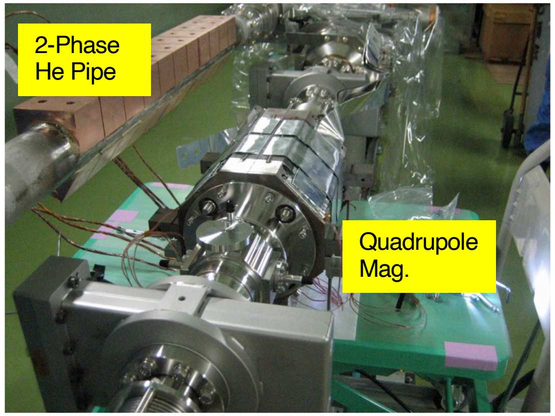


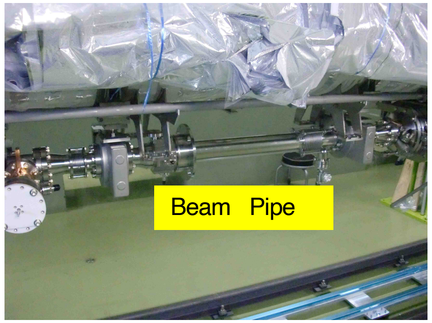
Conduction-cooled SCM installation into KEK-STF2 beam line

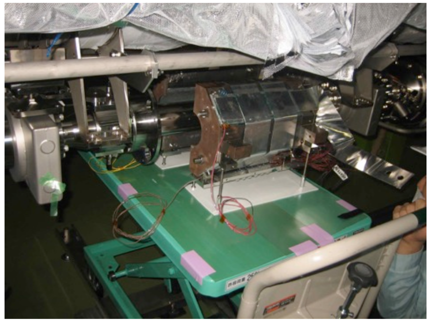


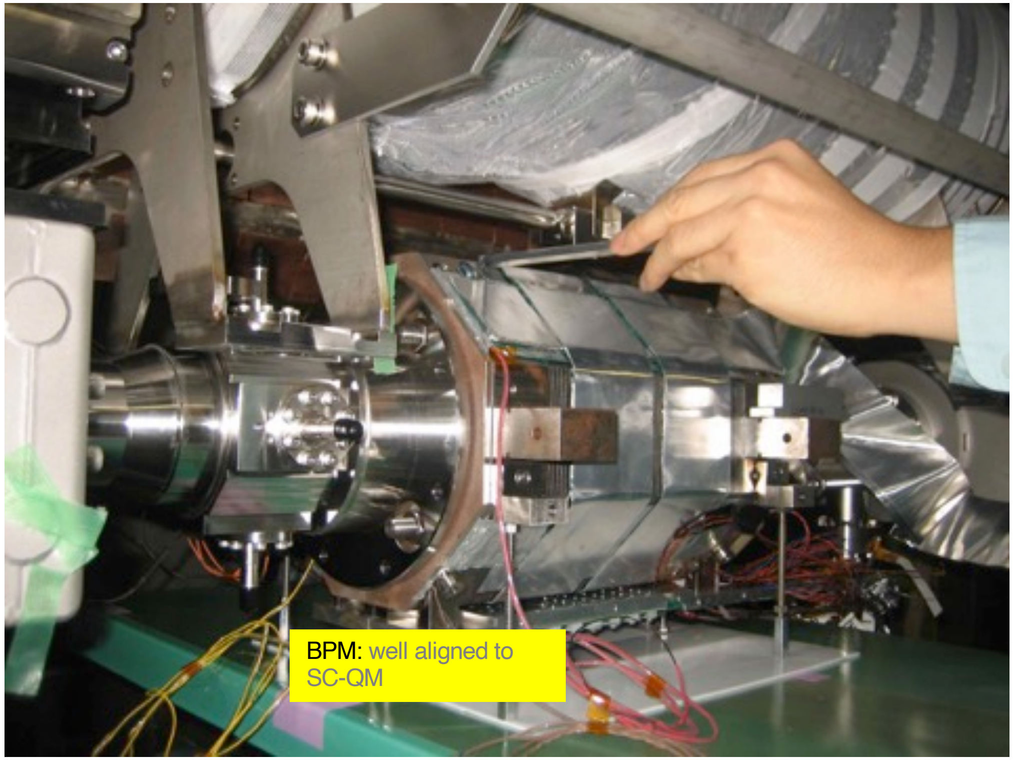
Installation to KEK-STF {BPM/Beam-Pipe + SCQ}









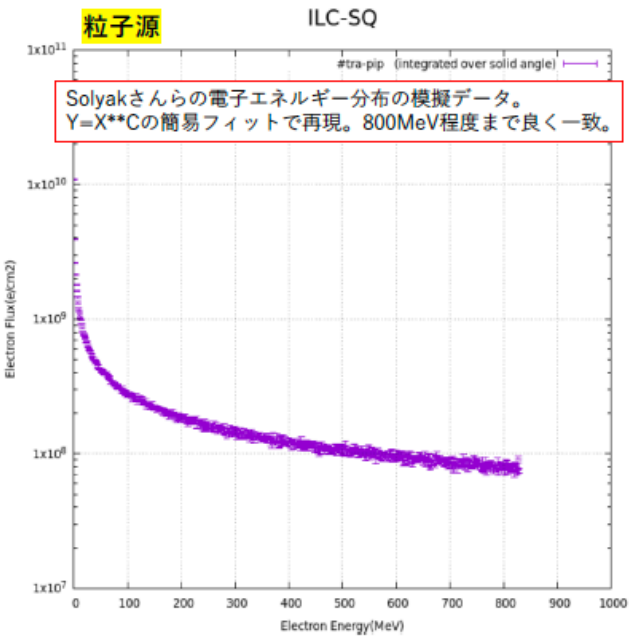


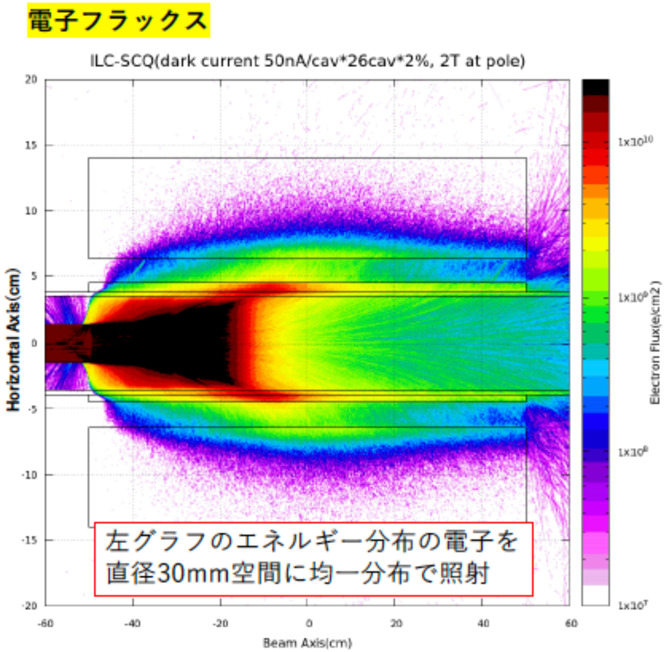
Features:

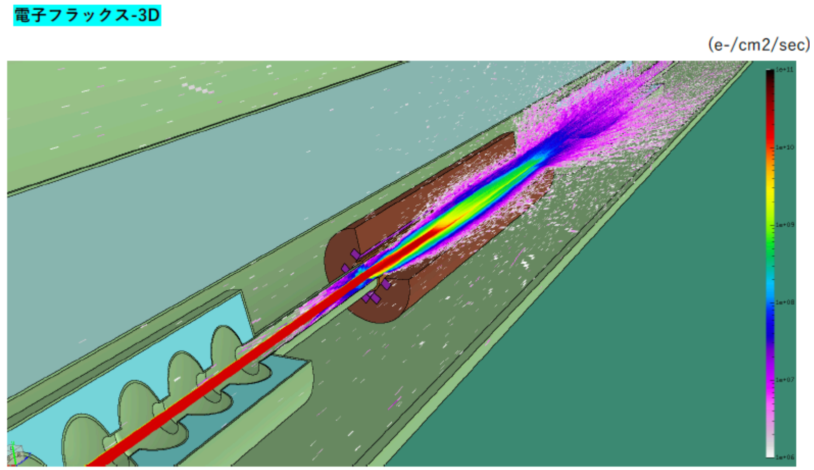
- {SRF-cavity + BPM + Beam pipe} assembly carried out after SRF cavity clean-room work completed.
- SC magnet yoke/pole directly aligned with BPM --> important !
- Magnet yoke, coils, and current leads (w/ HTS leads) conductively cooled by using pure-Al strips.

By Y. Morikawa, 200721

Dark Current absorption Simulation in ILC-ML SCQ (2)





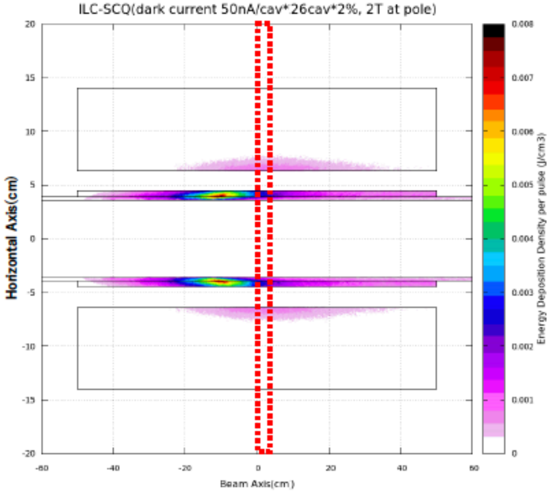


This simulation result:
Electron absorption: ~ 4 W

By Y. Morikawa, 200721

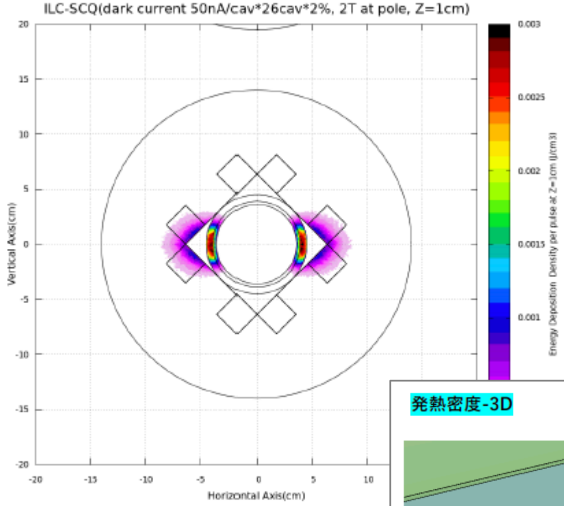
Dark Current absorption Simulation in ILC-ML SCQ (3)

1パルス当たりの発熱密度

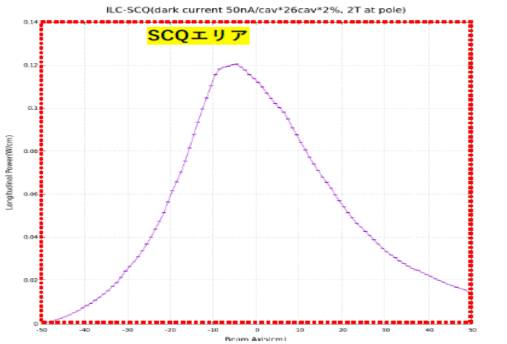


コイル最大発熱部

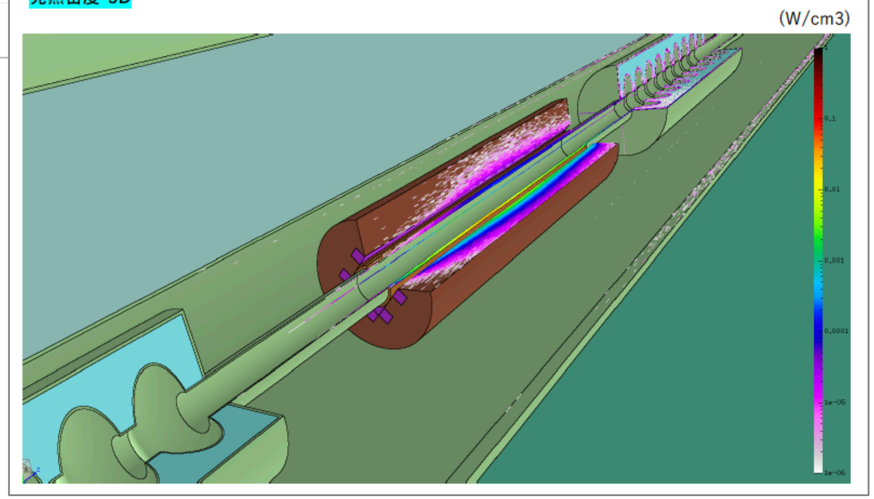
Z=1cmでのパルス当たりの発熱密度分布



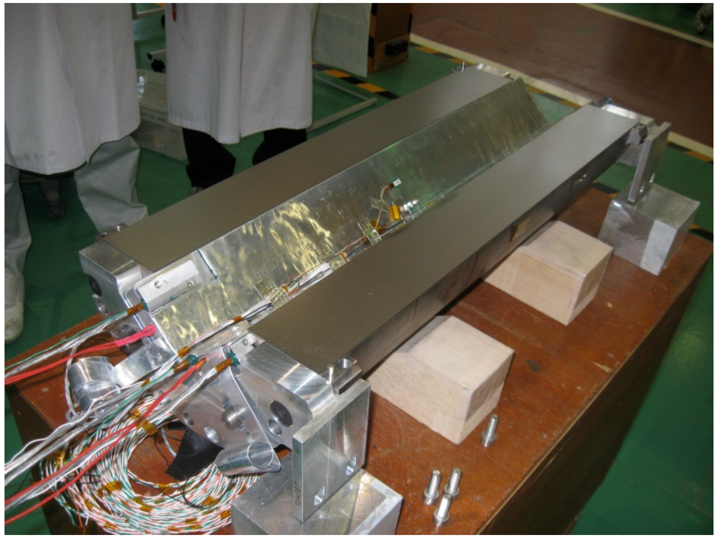
ビーム軸に沿った発熱総量(横断面に発熱量を積分)

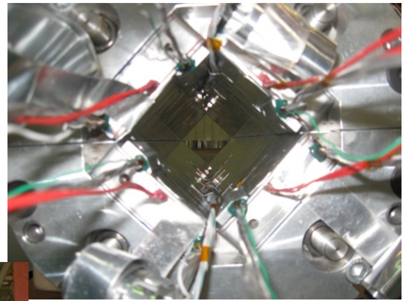


発熱密度-3D



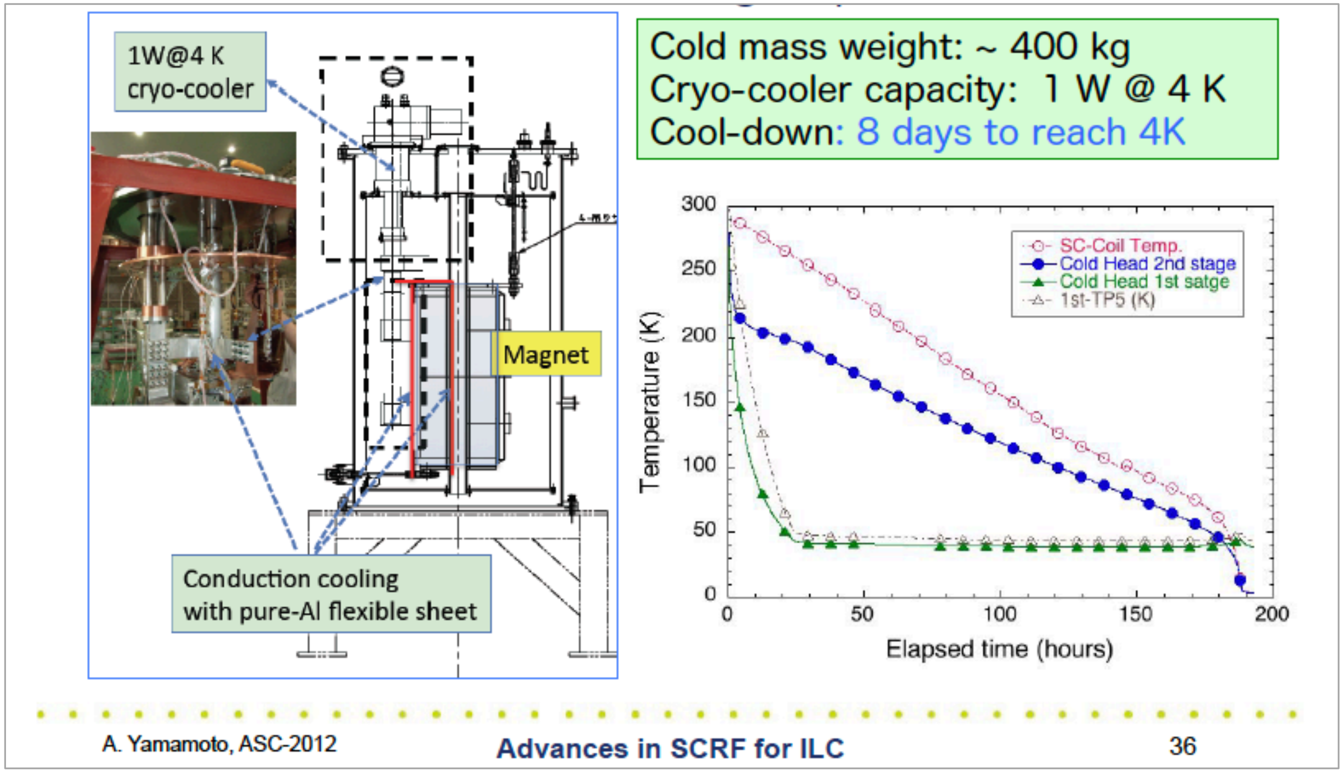
Splittable Quad Conduction Cooled Assembly and Test

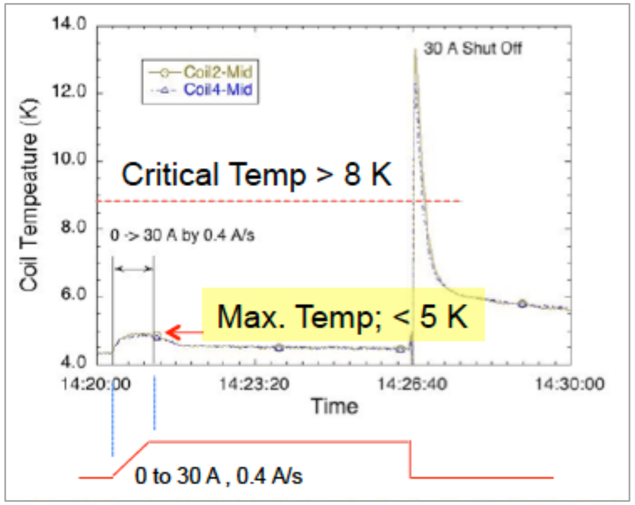


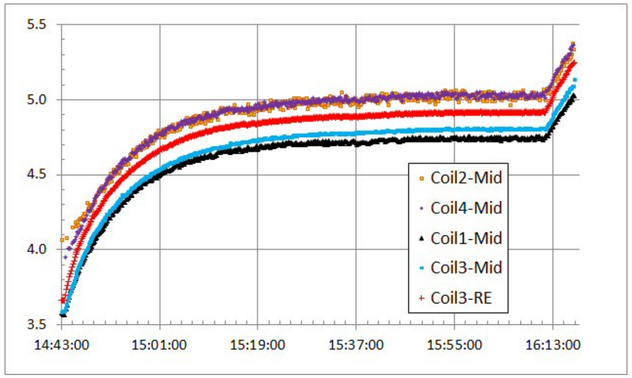


Conduction Cooling Test using CryoCooler

Aug.-Sept. 2012







Temp. rise at Saw-tooth ramps to 5 A, 1 A/s ? @ L = 2.05 H