Preliminary magnetic design of IR Crab Sextupole for FCC-ee Collider

A FOUSSAT, CERN TE/MSC - FCC Week 2023
on behalf of the FCC MDI team.

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https://indico.cern.ch/event/1202105/

EDMS 2896595

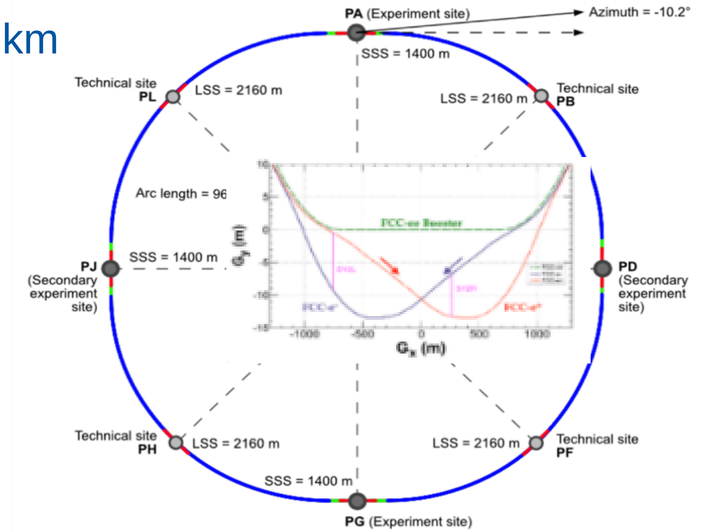
Outline

- ***Context***
- ***FCC-ee crab sextupoles requirements***
- ***Optimisation of cos-theta sector coils***
- ***Case 1: LTS Nb_3Sn case study***
- ***Case 2: HTS ReBCO design***
  - *3D magnetic model of sextupole saddle coils*
  - *Economical aspects*
  - *Cryogenics, mechanical structure considerations*
- ***Development flow***
- ***Summary***

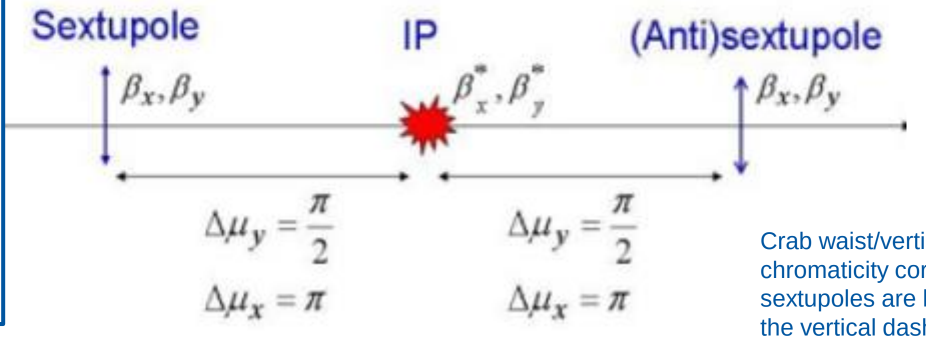
Context

- In FCC-e^+e^- collider, Crab-Waist collision with extremely low beta at IP generates very large chromatic effects.
- This requires crucial **strong and thin SY crab sextupole pair, per beam line, per side** (8 per IP, **32 units**) for chromaticity geometric correction, to achieve crab-waist and to preserve dynamic aperture
  - See Optics overview [1] K. Oide, FCCIS 2022 Workshop

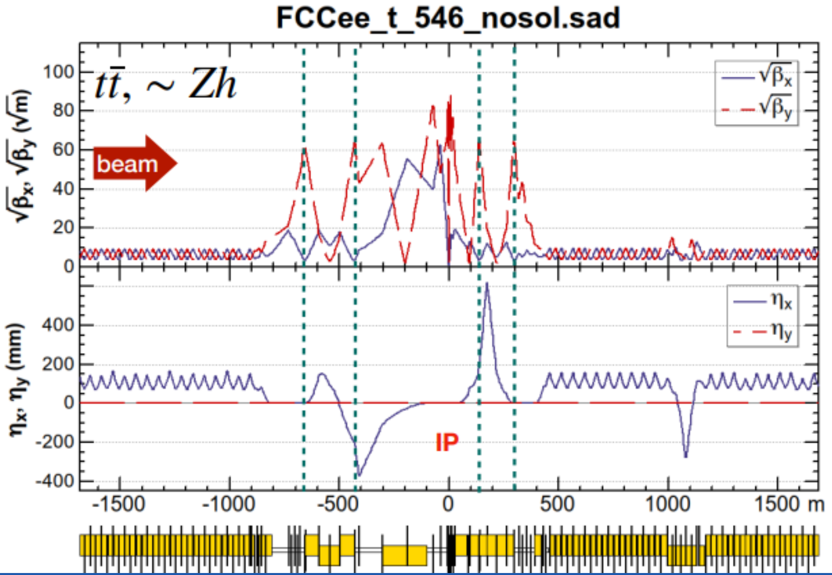
Length: 91 km



SY2L -745.30 m	<— CRAB
SY1L -497.82 m	
IP 0 m	
SY1R +118.06 m	
SY2R +276.00 m	<—CRAB



Crab waist/vertical chromaticity correction sextupoles are located at the vertical dashed lines.



Requirements

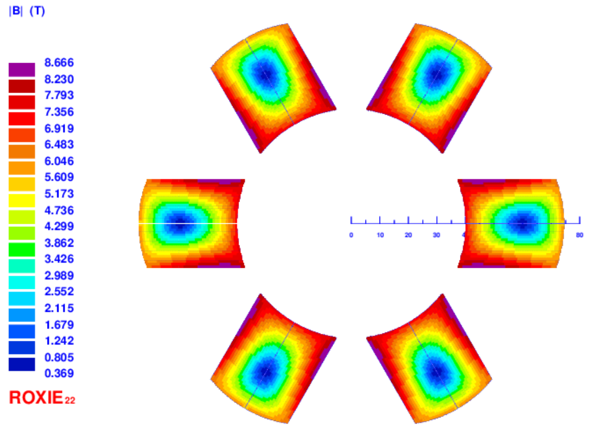
- **[R1 - Optics]** The current optics at $t\bar{t}$ (182.5 GeV) requires IR sextupole magnetic bore field of 4.1 T at 35 mm radius. This goes up to 4.72 T for energy scan scenario to 182.5 GeV asking for S of 3850 T.m^{-2} over 350 mm
  - *Sensitivity analysis for tt and Z shows acceptable +28% length increase on magnetic length Lm : 350 mm [K. Oide].*
- **[R2 – Cooling]** The crab correcting sextupoles location at 250 m and 700 m from the interaction region, makes Liquid helium distribution impractical, and conduction-cooled sextupole magnet design at 10-20 K is an attractive solution.
- **[R3- Beam pipe]** Warm beam pipe with 60 mm diameter at crab sextupoles location
- **[R4- Duty cycle]** Ramp up time of 1 min to operating field for Z/W scenarios
- **[R5 - Field quality]** normal harmonics bn/B3 < 5 units @ Rref=23 mm, b9 < 50 units (tentative, under progress). *"No need of SY rotatable feature like on SuperKEK crab sextupole for a3 correction as no X-Y chromatic coupling is expected" (communication K.Oide).*

[R6 – Radiation loss] SR heat load sources and beam envelop incl. masking *to be confirmed* at SY1 and SY2 locations

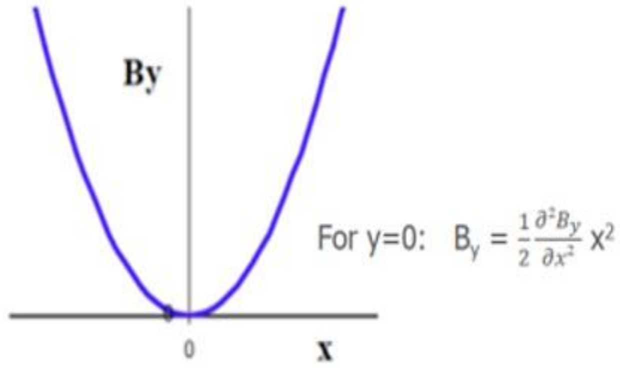
Convention

- In a storage ring, the chromatic correction performed by crab sextupole at nonzero dispersion location is quantified by ***normalized strength*** in units of m^{-3} or the **magnetic design Strength S_s** [T/m^2]

Magnet Type	Order	Field [T]	Normalized Gradient [m^{-n}]
sextupole	$n = 3$	$B_x = \frac{d^2 B_y}{dx^2} \cdot xy$ $B_y = \frac{1}{2}\frac{d^2 B_y}{dx^2} \cdot (x^2 - y^2)$	$k_2 = \frac{1}{B\rho}\frac{d^2 B_y}{dx^2}$



This presentation refers to the specified **sextupole magnetic strength S_s** [T/m^2] **where $B_y = S_s . x^2$**



Strength of 2N-pole sector iron-free coils

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- Strength S in T/m^{n-1} for multipole coil n ≥ 3 was derived from analytical expression [Ref. A. Louzguiti]:

$$S = S_{\text{current}} + S_{\text{sat pole}}$$

$$\begin{cases} S_{\text{current}} = \dfrac{\mu_0\sqrt{3}}{\pi}\dfrac{J_0}{(r_a+w)^{N-2}}\left(\dfrac{1}{N-2}\left[\left(\dfrac{r_a+w}{r_a}\right)^{N-2}-1\right]+\dfrac{A_\mu}{N+2}\left[1-\left(\dfrac{r_a}{r_a+w}\right)^{N+2}\right]\right) \\ S_{\text{sat pole}} = \dfrac{\mu_0 N}{\pi}\dfrac{M_{\text{sat}}}{(r_a+w)^{N-1}}\left(\dfrac{1}{N-1}\left[\left(\dfrac{r_a+w}{r_a}\right)^{N-1}-1\right]+\dfrac{A_\mu}{N+1}\left[1-\left(\dfrac{r_a}{r_a+w}\right)^{N+1}\right]\right) \end{cases}$$

M_{sat} : saturation magnetization of iron

J_0 : current density in coil
$2N$: number of poles (e.g. N=3 for sextupole)
w : coil width

Term due to iron screen, $A_\mu \leq 1$ if partly saturated

Margin on the load line and quench protection assumption:

$$\begin{cases} J_0 = \dfrac{f.L_{\text{line}}}{1+CuSc}.J_{\text{sc,c}}\left(B_p\left(\dfrac{J_0}{L_{\text{line}}}\right)\right) \\ J_0 = \dfrac{f.CuSc}{1+CuSc}.J_{\text{Cu max}} \end{cases}$$

→ ensures that percentage along the load line is L_{line} set at 80%

→ ensures that copper current density equal to $J_{\text{Cu max}}$ = 1000 A/mm² (f : filling factor)

Optimisation of cos-theta / sector coil

Use of DASH = **D**esign **A**lgorithm for **S**extupoles and **H**igher package developped in 2018, to investigate parameter space and optimise magnet length, cost and complexity

User inputs
- Magnet type

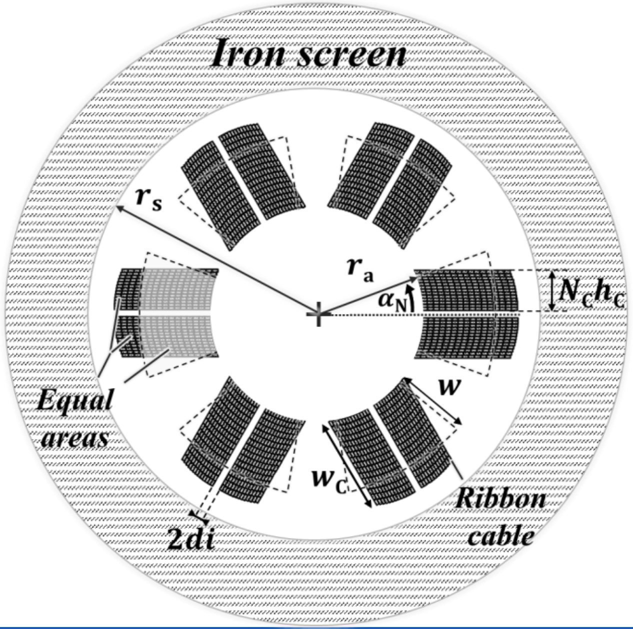
$r_a, T_{op}, l, S_{req}, \ldots$
- Iron screen/poles

→ **Control**
- Field quality
- Stability
- Quench protection

→ **Optimization**
- Cost
- Optimal width w_c^* selection

→ **Magnet design**
- Parameters w_c^*, $N_c H_c^*, \lambda^*, J_{op}^*$,
- Strength S_{op}^*

→ **ROXIE model**
- Automatically generated
- Local optimization



Iterations on cosθ coil width w_c:

- *Cosθ coil* ***height*** $N_c H_c$ *(field quality)*
- *Equivalent sector* ***width*** w *of a cos theta coil*
- *Current density* J ***and Cu:Sc ratio*** λ *(load line + quench protection)*
- *Magnet strength* S ***vs*** w_c

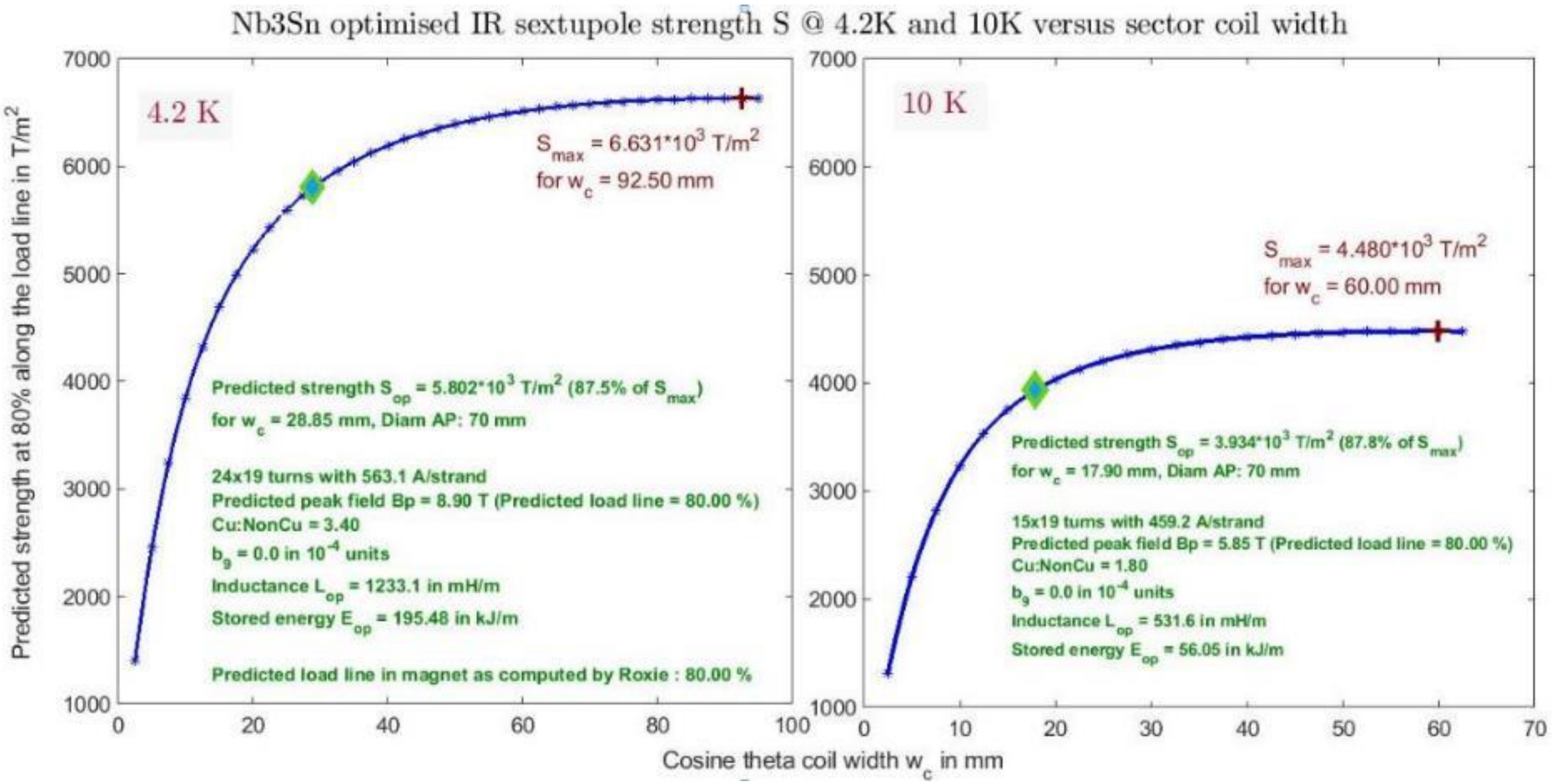
$$\int_{r=r_a}^{r_a+w_c} \left[\sin\left(3N\theta_2(r)\right) - \sin\left(3N\theta_1(r)\right)\right]\left(\frac{r_a}{r}\right)^{3N-1} dr = 0 \quad \text{(E1)}$$

$$\text{with} \quad \theta_1(r) = \arcsin\left(\frac{d_i}{r}\right) \quad \text{and} \quad \theta_2(r) = \arcsin\left(\frac{N_C h_C + d_i}{r}\right)$$

$$w = r_a\left[\sqrt{1 + \frac{2w_C N_C h_C}{\alpha_N r_a^2}} - 1\right] \quad \text{(E2)}$$

$$\begin{cases} J = \dfrac{lf}{1+\lambda} J_c\left(B_p(J/l)\right) \\ J = \dfrac{f\lambda}{1+\lambda} J_{\text{Cu, max}} \end{cases}$$

Case 1: LTS Nb_3Sn sextupole at 4 K and 10 K



- **Optimum** when **DV/Vmax = -DL/Lmin,** ~13% lenght increase, factor 5 cost saving on SC volume.
- **Reduction by 32%** of Strength from **4.2K to 10 K**

Magnetic parameters table for LTS design

- LTS flat ribbon cable evaluation at **4.2 K** LHe and **10 K** Ghe operating temperature

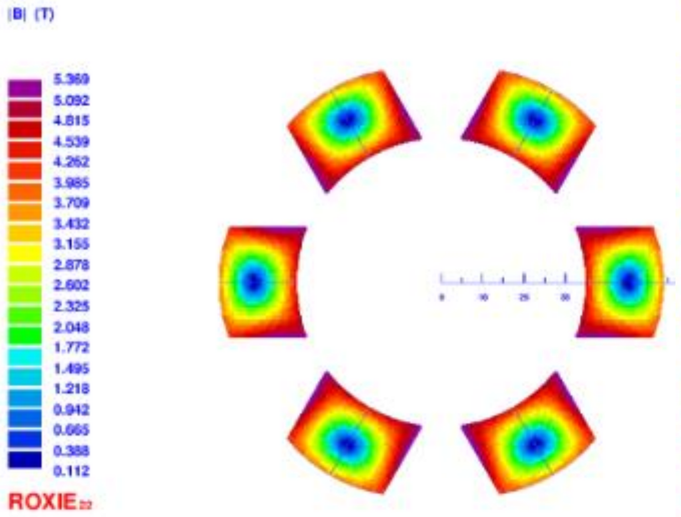
T_{OP} (K)	AP diam (mm)	SC type	Sop (T.m^{-2})	Margin (% to I_{SS})	Wc (mm)	Nb Std. x turns	Bp (T)	Bp /Bo	Cu:nCu	Lop (mH/m)	I (A) per strd
4.2	70	NbTi	3850	20	29.8	35 x15	5.83	1.2	1.05	1296	360
4.2	70	Nb_3Sn	3850	20	13.7	17 x 16	5.71	1.21	6.71	394	490
10	70	Nb_3Sn	3850	10	13.7	19 x 15	5.4	1.21	1.8	531	439

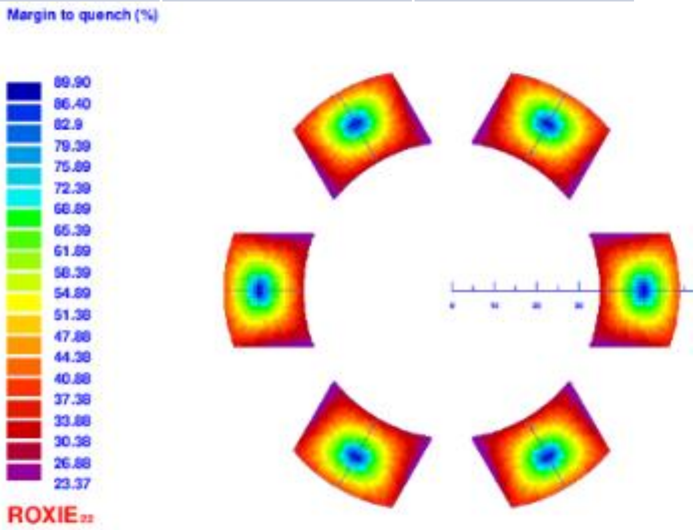
- Ribbon cable placeholder for study only (single wire or high current Rutherford cables)

✓ Limited margin on I_{SS} load line at 10K

✓ **Overshoot of B_p/B_o = 1.21**,

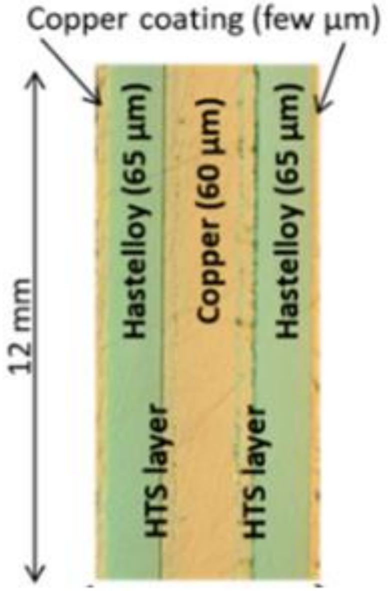
✓ Minimized harmonics, b_9 , b_{15} < 1 unit





Case 2: HTS ReBCO sextupole design at 10K

- Design based on **HTS $REBa_2Cu_3O_7$-x**, (ReBCO, RE : rare earth) coated conductors (CCs) tape, PI insulated, (W: 12 mm x tck : 0.13 mm)
- Reference tape **superconductor layer thickness of 1 µm and 97 µm for other materials** (Hastelloy substrate, silver, copper stabilizer).
- Main focus on the **six-fold saddle coils wound scheme** (comparison with challenging novel Canted Frenet-Serret winding design)
- **Winding topologies based** either **on single tape or multi stacks conductors (face to face for current bypass*), with single or double layer**.
- **Temperature excursion study carried out around 10 K for reference.**



***face to face ReBCO HTS conductor example**

https://www.fujikura.co.jp/eng/products/newbusiness/superconductors/01/superconductor.pdf

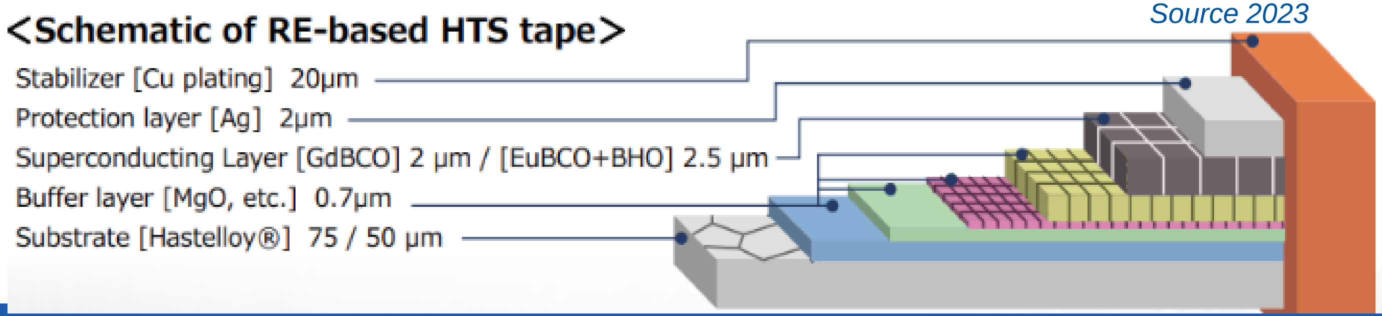
Commercial HTS tape features

- Typical specifications for 4-12 mm wide ReBCO 2G HTS tapes, 1-3 µm thick SC layer

	Width	REBCO Type	REBCO Thickness	Deposition Method	Pinning Type	Substrate	Cu Stabilizer
Fujikura	4 mm	EuBCO	2.5 µm	IBAD/PLD	BHO columns (artificial)	50 µm/Hastelloy	2 x 40 µm electroplated
							2 x 20 µm electroplated
SuperOx	4 mm	YBCO	3.1 µm	IBAD/PLD	Y_2O_3 particles (native)	100 µm/Hastelloy	2 x 20 µm electroplated
			2.7 µm			40 µm/Hastelloy	2 x 5 µm electroplated
上海超导 SHANGHAI SUPERCONDUCTOR	3 mm	EuBCO	3 µm	IBAD/PLD	BHO columns (artificial)	30 µm/Hastelloy	2 x 10 µm electroplated
THEVA	4 mm	GdBCO	3 µm	ISD/EB-PVD	Gd_2O_3 particles (native)	100 µm/Hastelloy	2 x 20 µm electroplated
					Gd_2O_3 particles (native) BHO particles (artificial)	40 µm/Hastelloy	2 x 10 µm PVD-plated

Fujikura tapes courtesy of S. Richardson and M. Daibo, SuperOx tapes courtesy of A. Molodyk, 上海超导 tapes courtesy of Y. Zhao and B. Song, THEVA tapes courtesy of M. Bauer and M. Bendele

Source 2023



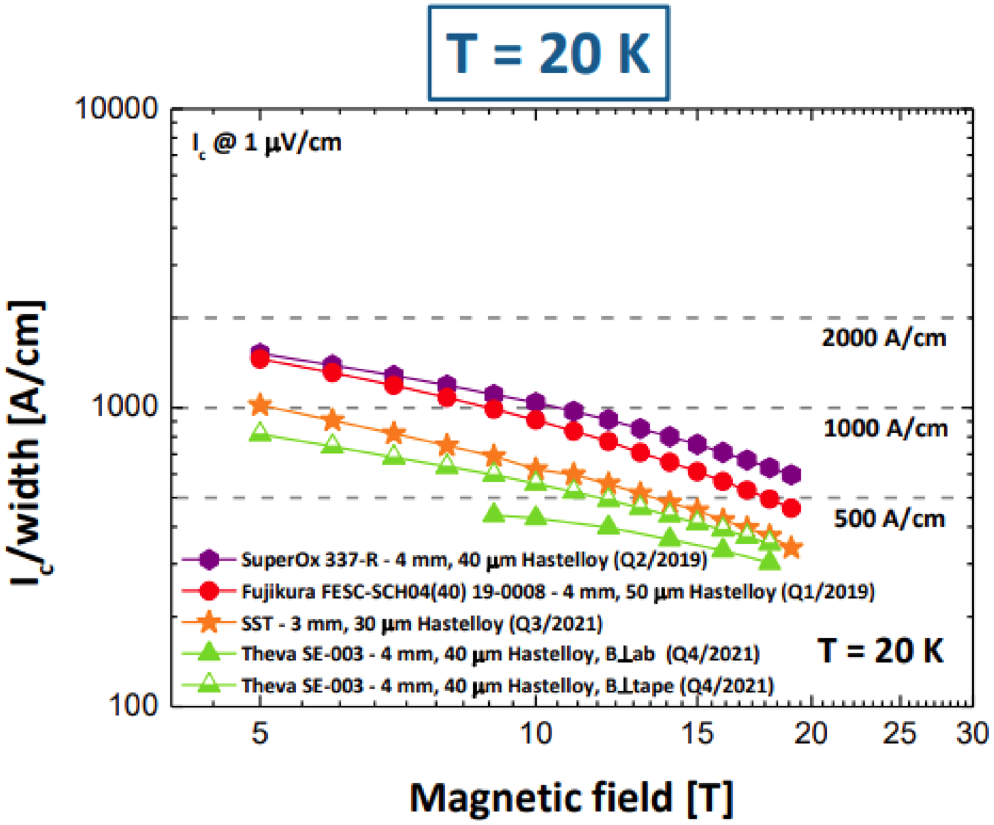
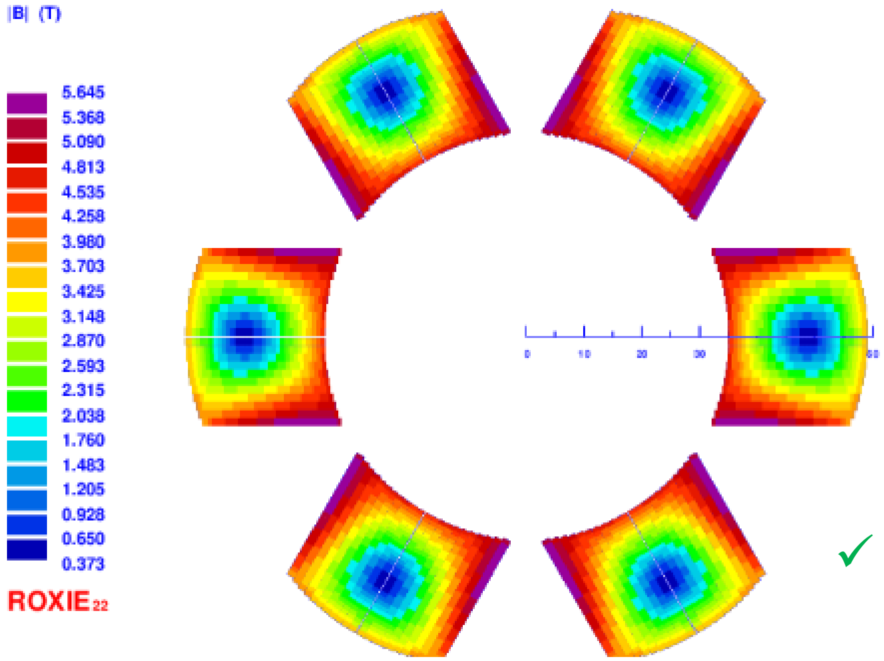
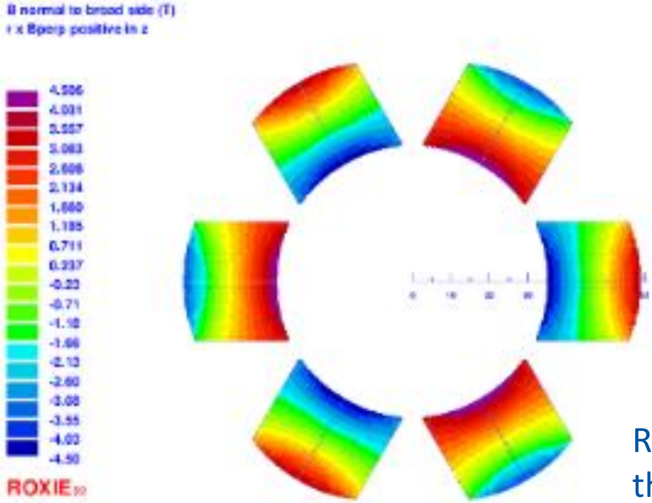


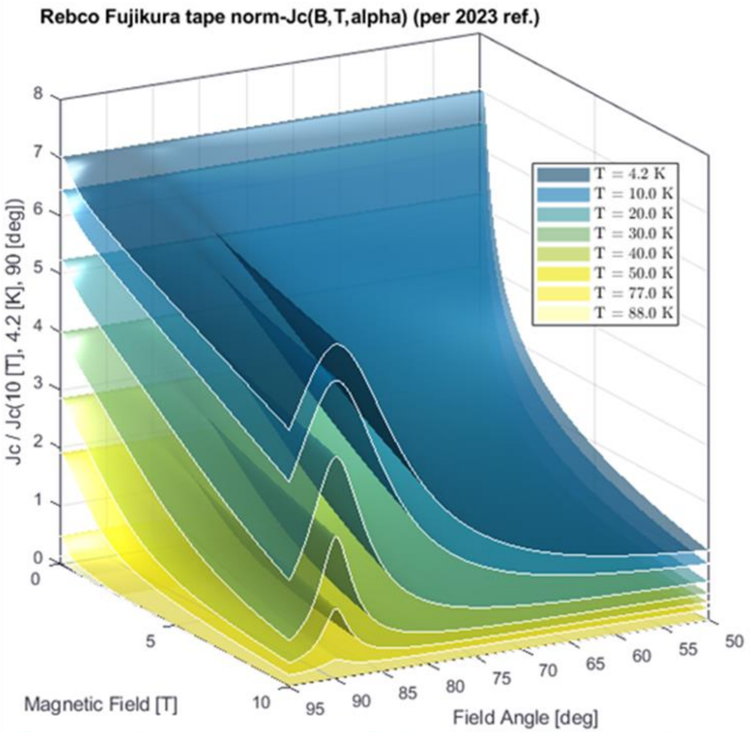
Fig. 1 : Ic (A/cm) versus B field (with B perp (ab)) Courtesy C. Senatore, Geneva univ, May 2019-2021

2D HTS coils predimensionning at 10K

- As ROXIE is structured to model Rutherford cables, we use "equivalent" strand parameters to model Rebco tape cable. (see Appendix). Normal and perp. magnetic field contours derived.
- A HTS tape placeholder, **12 mm wide x 0.1 mm selected, equivalent to HTS 0.32 mm SC strand diameter,** Cu:nCu = 50.







Strong dependence on field angle: Factor x4 reduction of Ic at 5 T, 10K for field ⊥ to tape

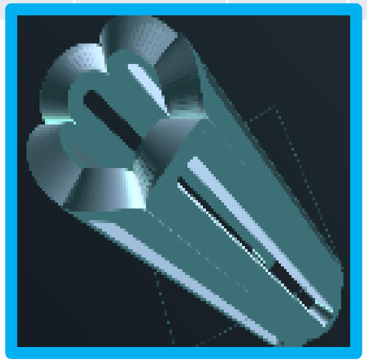
Ref: J. Fleiter and A. Ballarino. Parameterization of the critical surface of Fujikura ReBCO HTS

✓ **At 10 K, S = 3850 T/m2** achieved with **130 turns, wc 24mm,** single tape, double layer, **current of 620 A, ISS%= 75.**

HTS insulated crab sextupole coils variants

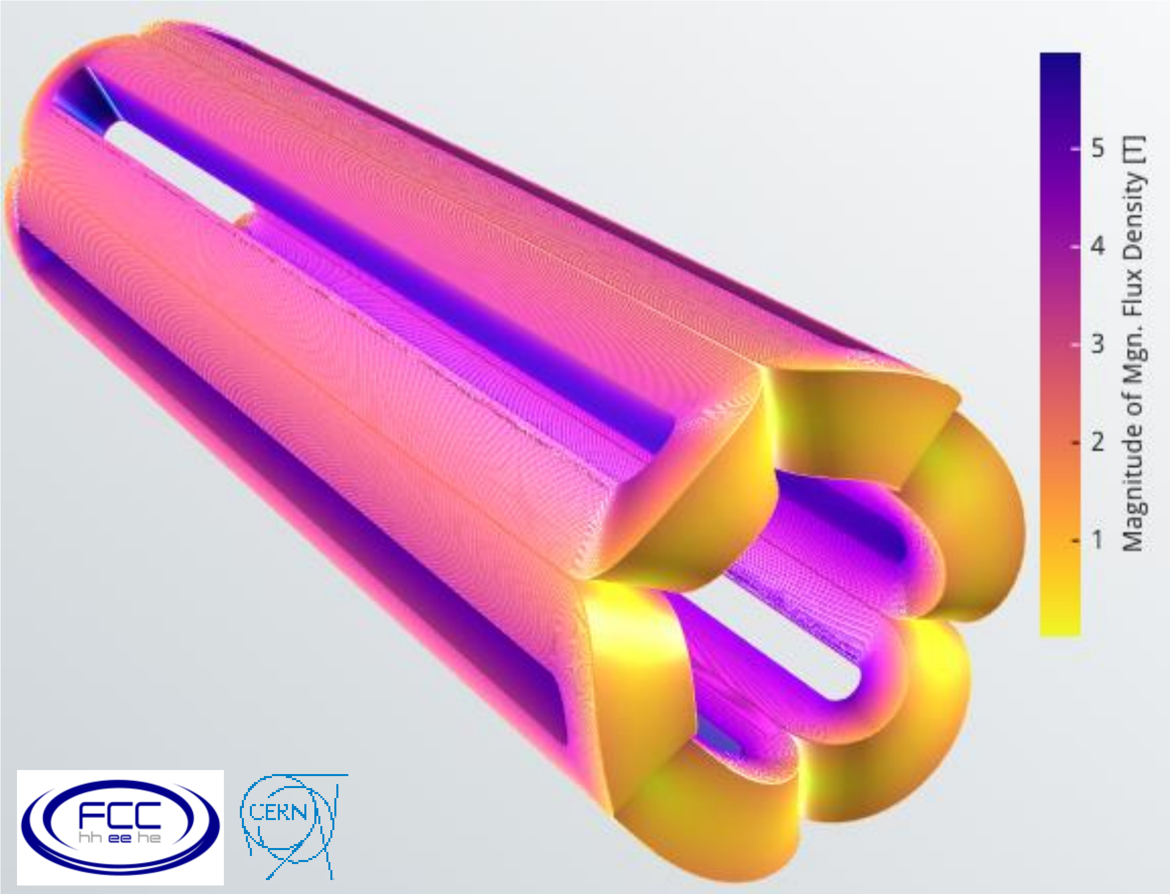
	HTS ReBCO coil type	Winding topology (R in = 35 mm)	Transport Current (A)	Tape width (mm)	Coil width (mm)	Nb_turns per saddle	L tape (m)	Inductance (mH)	Bp (T)	Load line (ISS%)	T_op (K)
saddle winding	FESC 1 um HTS	Single layer single tape	**1150**	**12**	**12**	100 (1 tape / turn)	460	7	5.9	37	**10**
saddle winding	FESC 1 um HTS	Single layer single tape	**870**	**6**	**6**	100	460	8.5	5.9	48	10
saddle winding	FESC	Single layer single tape	**780**	**4**	**4**	100	460	9.3	5.9	55	10
saddle winding	FESC **1 um HTS**	**Double layer (single tape)**	**900**	**12**	**24**	**100**	**930**	**4.6**	**6**	**41**	**10**
CCT* like	FESC 1 um HTS	**Double layer Canted Cos-theta sextupole, stack cable**	**740**	**4**	**2 x 4**	**2 x (840)** *(eq: 140 /saddle)*	**1039**	**64**	**6.6**	**85**	**10**

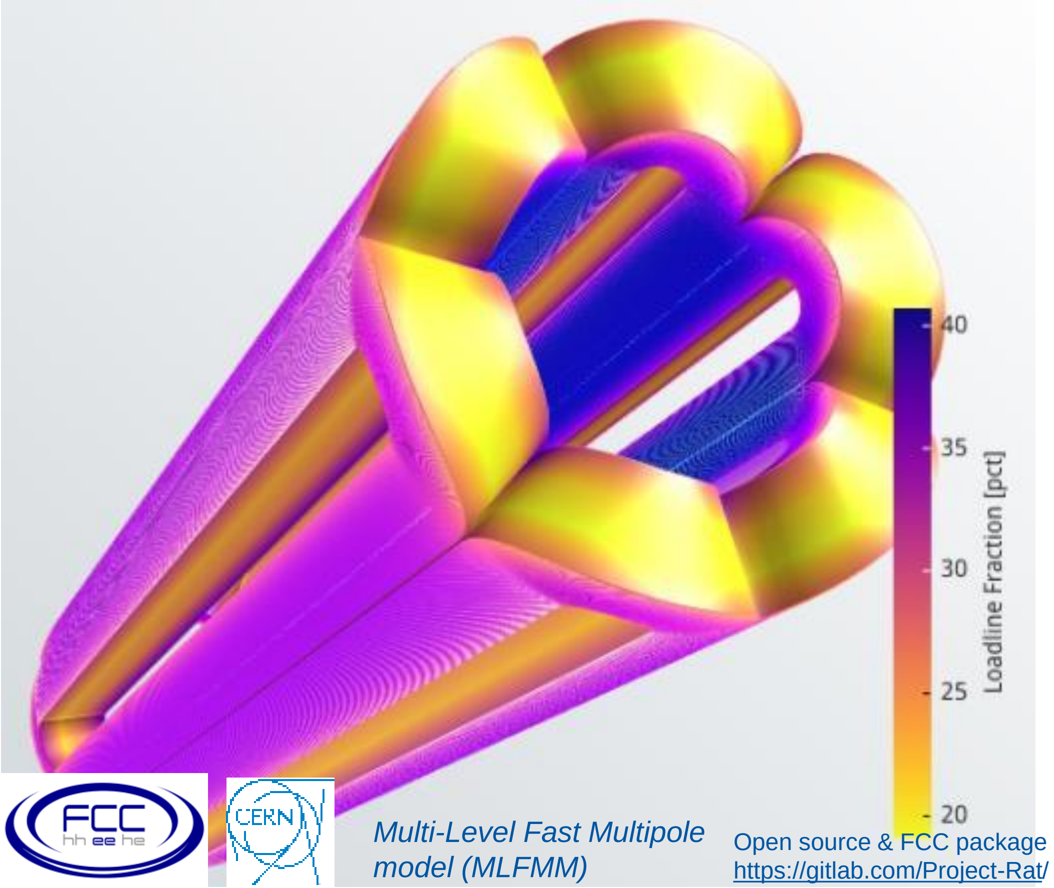
- Use of **1-2 microns thick FESC** Fujikura Rebco layer reference, **insulated thickness 0.125 mm**
- Tape target operating Je at 1200 A/mm^2 @ 5 T, under ⊥ field.
- Iron shield allows gain 15 % on magnetic strength S. 6 joints in saddles against 15 joints in CCT design
- * Alternative novel Frenet-Serret frame tape winding (similar HTS4) as CCT sextupole, Courtesy of M. Koratsinos.



3D magnetic model of sextupole saddle HTS coils

- Two layers wound, 12 mm wide tape, 100 turns, wc = 24 mm, Top = 10 K, **900 A / tape**
- **min T_{margin} = 59 K,** (41%.ISS), peak **Bp = 5.9 T** (Bo = 4.7 T at bore radius Ro = 35 mm)





Multi-Level Fast Multipole model (MLFMM)

Open source & FCC package RAT
https://gitlab.com/Project-Rat/

Economical aspects

- Use of commercial Rebco tape over a temperature range of 10 - 20 K with maxi. **920 m of conductor per sextupole model, i.e. budget circ.< 40 k unit cost.**
- Note that other structure components are more conventional, to be assessed (< 180 Ke).

Table I: cost unit for LTS (1 unit Cost / meter) vs. HTS

SC type	Relative unit cost / meter	Annual production	Main drivers
LTS - NbTi	**1**	Hundreds of tons	Driven by MRI industry
LTS - Nb3Sn RRP	**5**	5–10 tons	Driven by general purpose and NMR magnets and by Hi-Lumi LHC
HTS – REBCO tape	**20-50 ***	< 1 ton; few tons for fusion	Currently driven by privately funded fusion projects, with 20 T target at 20 K,. REBCO can be a choice for energy efficient magnet in accelerator sector when avoidance of helium becomes a priority

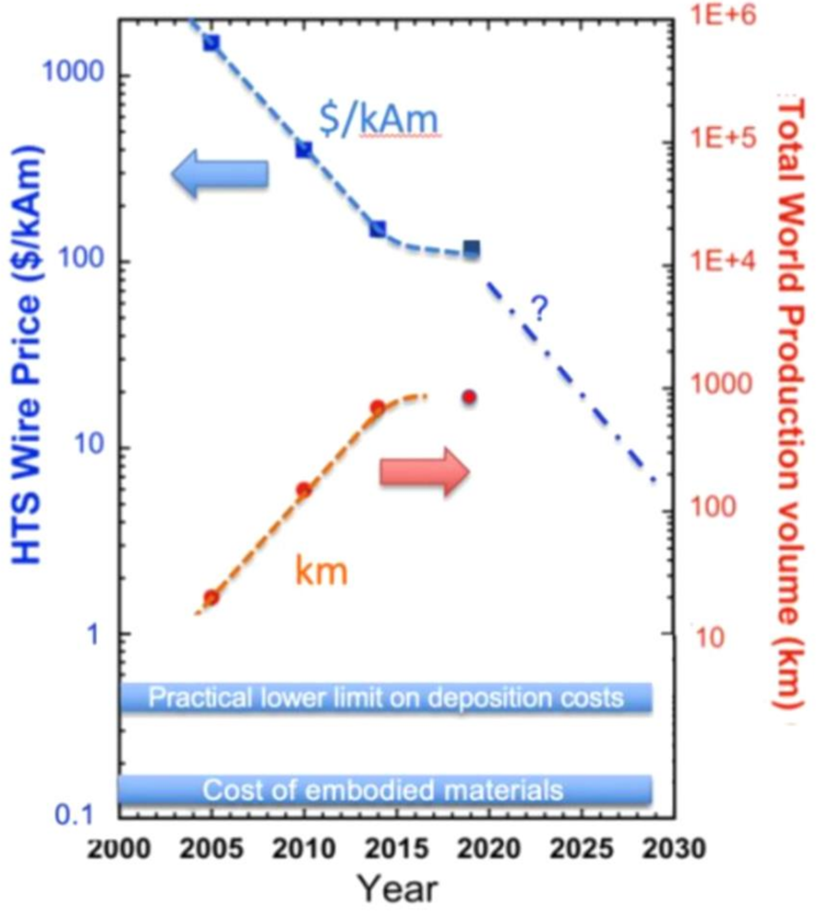


Fig.1 Current price scale up prospect of HTS tape based on production volume over time, together with the raw material cost. **[X. Wang, LBNL** 2022 - https://doi.org/10.48550/arXiv.2203.08736]

Cryogenics considerations

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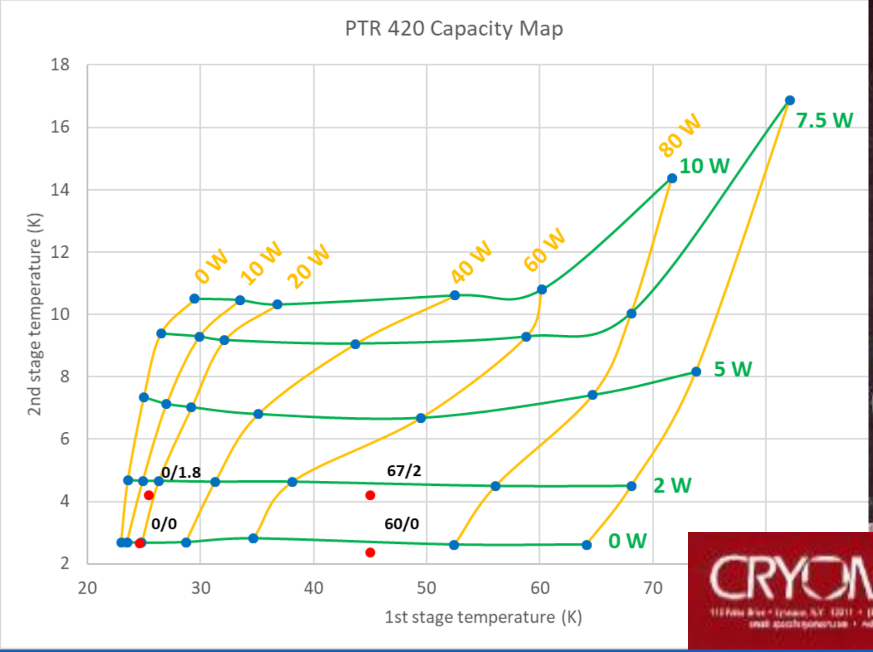
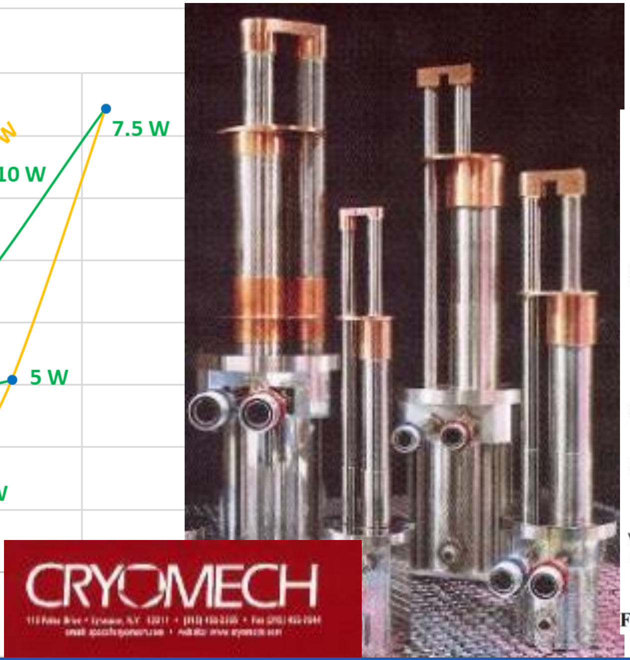
- Conduction cooled high temperature superconducting (HTS) **design at 10-20 K benefits from commercial cryocoolers development and the gain in Carnot efficiency, or specific power**. (i.e: first stage 80 W @ 55K, second stage 9 W at 8 K)

Table 1. Ideal and Carnot realistic specific power for operating temperature from 4.2 to 273 k

Operating temperature T_{op} (K)	Carnot specific power	Realistic specific power (when heat load > 100 W)
273	0.11	0.4
77	2.94	12-20
50	5.06	25-35
20	14.15	100-200
4.2	71.14	11000





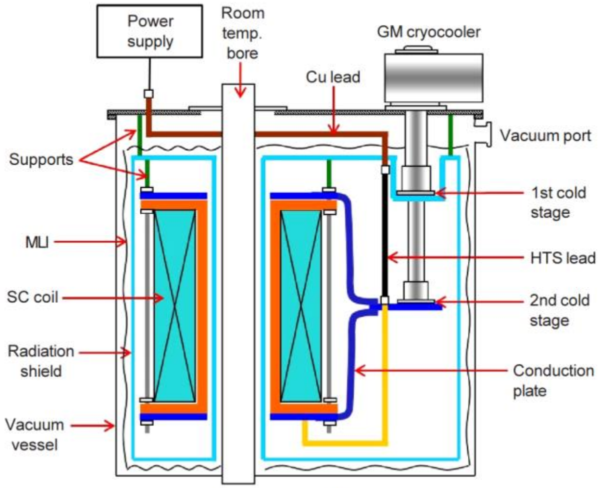
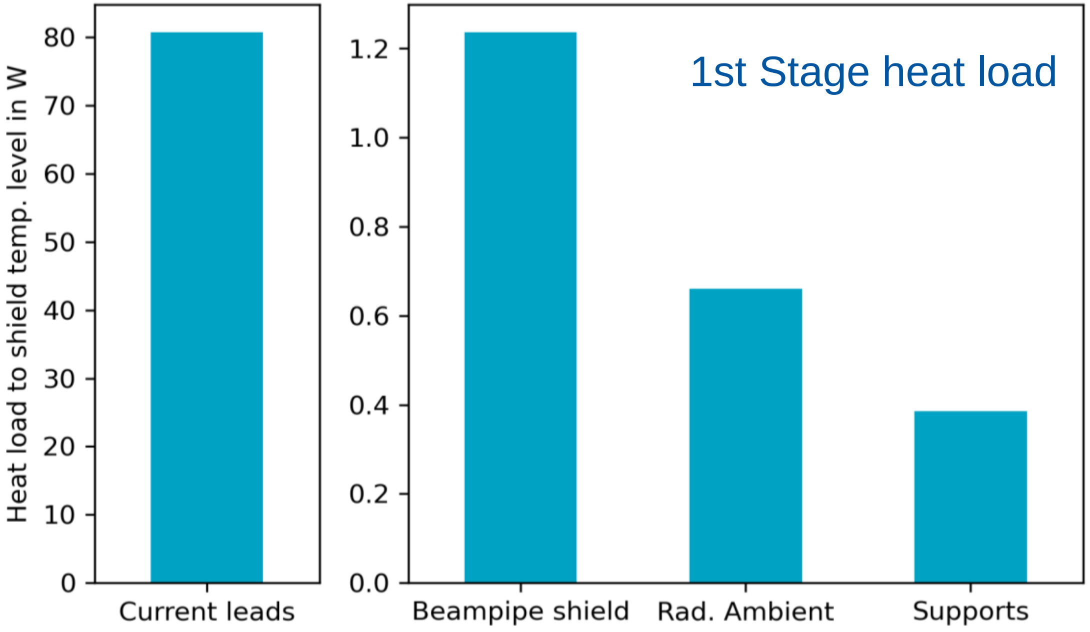


Figure 1. Schematic of conduction-cooled superconducting magnet system.

Realistic figure of merit of specific power (watt input at 300 K per watt lifted at T_{op}) shows a **gain of 50-100 at 20 K with respect to 4K operation.**

Heat load estimation

- Outer shield T = 80 K, 30 layers MLI on shield surface
- Brass current leads thermalised at 60 K, for 1000 A
- **With heat intercept at 80 K between beam pipe and cold mass (loss reduction by factor 4 on 2nd stage)**
- 8 support rods, directly from ambient temperature



Heat load Contribution	Second stage (mW)	First stage (W)
	T_{CM} = 10 K	T_{ts}= 80 K T_{CLi}= 60 K
HTS leads	282	81.7
Support rods	224	0.4
From outer shield	26	0.7
Splices	42	-
From beam pipe shield	7	1.2
Beam-induced	0	0
TOTAL	581 mW	84.2 W

Courtesy of TE-CRG : P. Borges de Sousa, T. Koettig
Ref EDMS 2895924 v1.0

Conceptual mechanical structure

- Principle of mechanical structure loading discussed to target 50-80 Mpa **preload at RT using bladder and keys (B&K)** with external Aluminium shell (similar to ECR sextupoles Venus, Secral).
  - Net magnetic forces on coil are **560 kN azimuthal and 180 kN radially** (Roxie model)
- Parametric Ansys model developed at CERN to predimension FCC ee crab Sextupole structure (thanks to *P. Ferracin, LBNL*)

Fig.1. Picture courtesy Danfysik-SuperPower-Aarhus University (2012-2014)HTS conduction cooled dipole

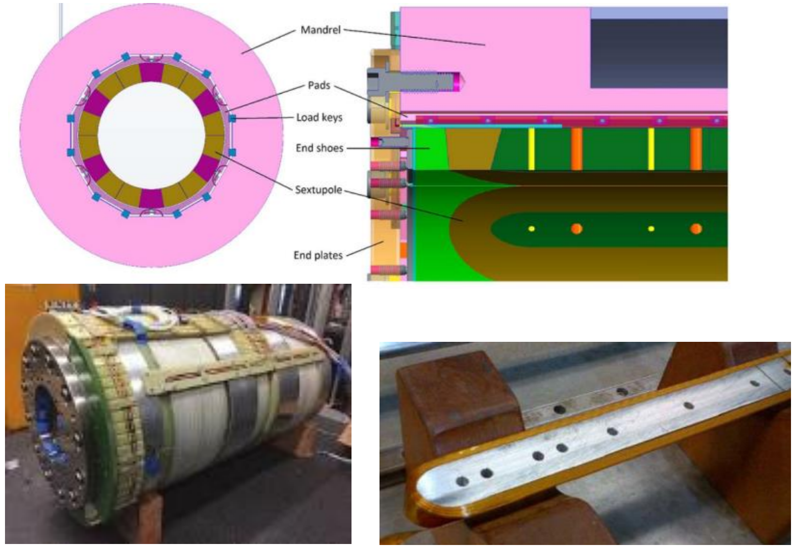


Fig. 2 FRIB ECR saddle preload system – 2015 (LBNL)

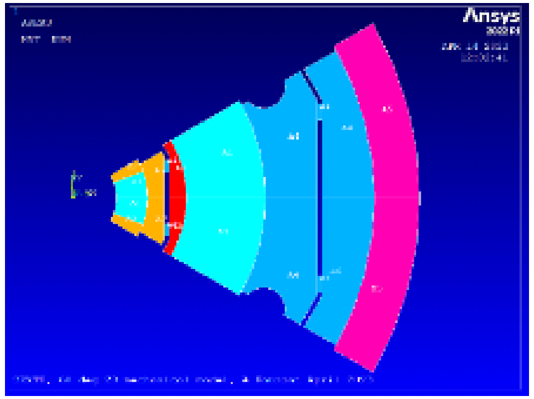
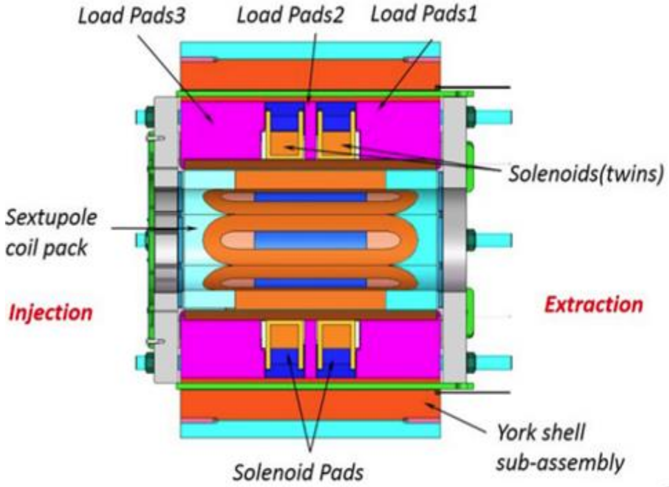


Fig.3 Developed parametric sextupole structure 60 deg 2D ANSYS model (CERN)

Fig.4 Superconducting ECR ion source: From 24-28 GHz SECRAL to 45 GHz fourth generation ECR. DOI: 10.1063/1.5017479 (2018)



Design & Manufacture consideration

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- LTS **Nb3Sn** saddles coils require **heat treatment and impregnation dedicated tools**
- **Double layers winding introduce simplification** to manage exits and inter-coils joining
- Saddle coils benefit from a **proven B&K preload structure (HL-LHC, LBNL models..)**
- **Low current cable option**, is best option for conduction cooled option **to limit HTS leads heat loads.**
- Next, to design preload system and **terminal leads connection blocks** compatible with cryocooler **conduction cooling**.
- Options of HTS **insulated vs non-insulated (NI) cable** to be assessed for **quench protection and field quality**. (especially b9 normal harmonics to be optimized < 50 units). Impact of **magnetization on field quality**.

Development flow

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01/2023	Functional specification
09/2023	Preliminary design / Eng. design
07/2024	Manufacture and testing
12/2025	Detailed design and manufacture
03/2026	

Optimistic schedule

1. ***Functional specification*** **of FCC-ee IR crab Sextupole magnet system**: Accelerator, Detector and Magnet Systems analyze FCC-ee IR baseline design configuration and provide feedback to address IR Sextupole design set of functional requirements.

2. ***Preliminary design of IR Sextupole magnet***: As the many functional requirements for the IR Sextupole are finalized, the preliminary IR magnet design is developed and reviewed. Some design exploration options (down selection of SC technology, such as from adding **conduction cooling scheme**, heat loads or the **magnet structure**) to be fed back into the **detailed engineering design.**

3. ***Manufacture and testing of magnet assembly & sub prototypes***: Before committing to the final sextupole systems technical design, **test of performance of critical coils subsystems (single saddle coils, windability, assembly trials)** including the **preloading system** on an assembly. Goal: demonstrate close to "final" magnet performance, including **final cooling scheme option to check integration and characterize performances.**

4. ***Detailed design and manufacture files of IR crab sextupole magnet*** : At this final stage the sextupole functional requirements are finalized, and the **experience gained from prototype production and testing** is incorporated into producing final design layouts, component drawings and preparing production / vendor specifications. (dedicated multiple levels of design review foreseen).

Summary

- FCC-ee **IR crab sextupoles requirements** were clarified with MDI and Optics teams.
- First magnetic optimization (2D/3D) of the **sextupole saddle sector coils** shows that required strength (S) of 3850 $T.m^{-2}$ is achievable at 10K with LTS, HTS candidates:
  - **HTS ReBCO based coil-dominated sextupole at 10K** offers **margin to ISS% at 35 up to 60 % for current 870 A - 1200 A range** in addition to higher stability **compared to 10% with LTS. (still 50% margin @ 20K !)**
- Next steps, to launch detail engineering on **mechanical structure (RT, cold) including conduction cooled interfaces, beam losses. Protection scheme and field quality study**
- **Although few beam transport HTS Magnets were developed, the Crab IR sextupole is a valuable R&D technology enabler for <u>HTS ReBCO based cryo-cooled warm bore magnet for accelerator use.</u> Development plan to be approved in line with next term report.**

Acknowledgement

The author thank his colleagues who made valuable contributions to presented work:

- *Matthias Bonora, Glyn Kirby (CERN MSC), Mike Koratzinos (PSI, FCC), for useful discussion on Roxie and RAT models simulation, HTS magnet design aspects*
- *Marco Masci (CERN MSC), for ANSYS mechanical tuning of prel. model*
- *Patricia P. Borges de Sousa, T. Koettig (CERN TE/CRG) for cooling scheme useful discussion*
- *Manuela Boscolo (INFN, FCC MDI) and Katsunobu Oide (FCC Optics) on MDI and optics layout*

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Thank you for your attention

Any Questions..

Back up slides

Preamble

- This presentation addresses the preliminary design of a cos(3θ) FCC ee accelerator crab sextupole based on saddle coils using flat LTS Nb3sn ribbon placeholder, then state-of-art SC HTS *Re*BCO tape conductor.

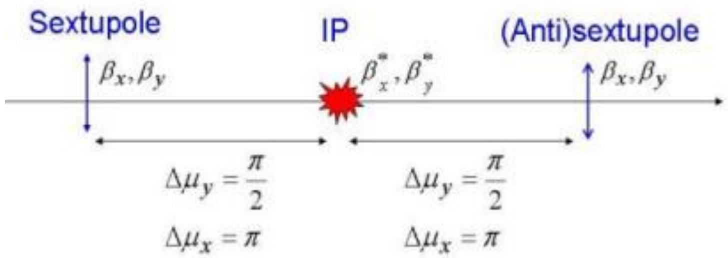
- *This work does not evaluate yet optimization of cooling scheme, quench protection and magnetization effects.*

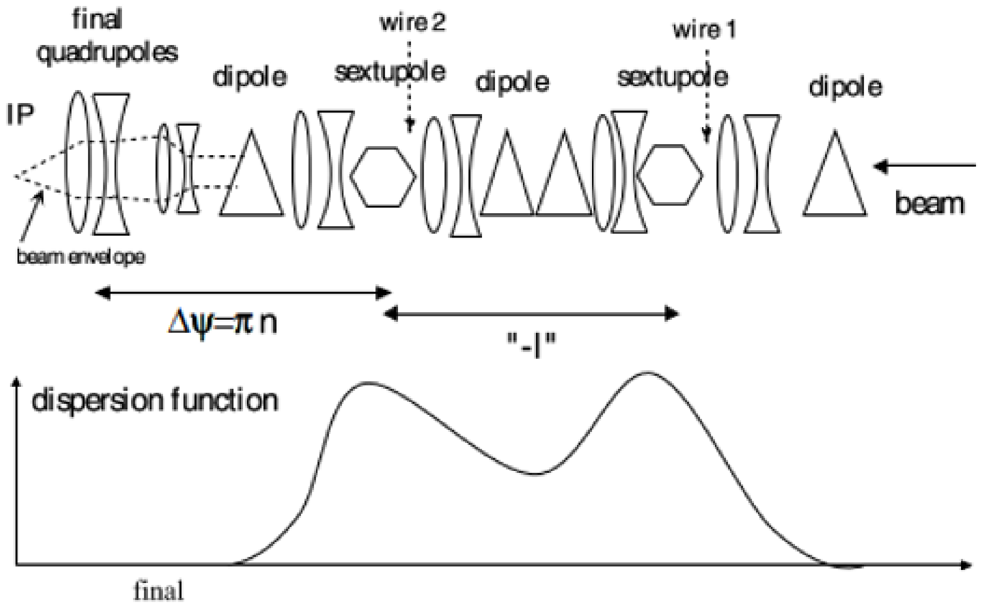
FCC ee chromaticity correction sextupoles

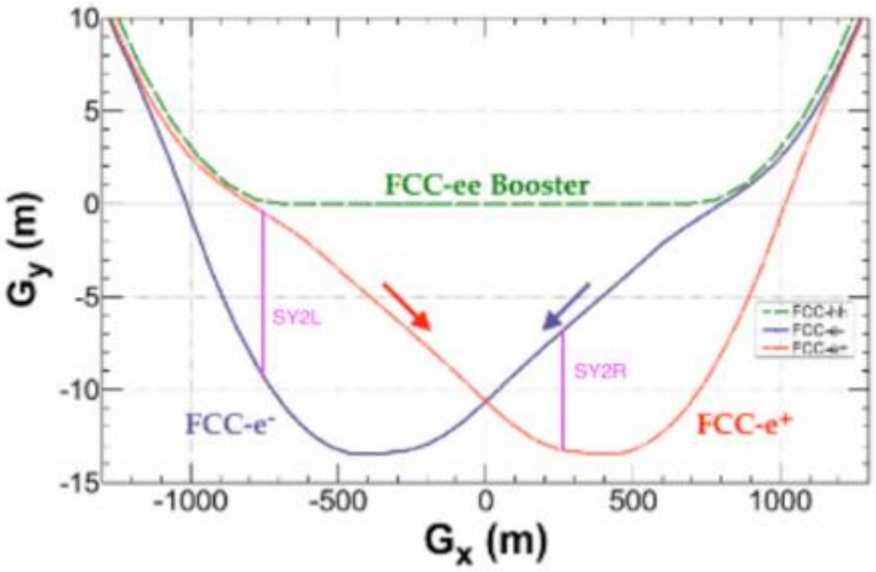
- **SY2L -745.30 m <— CRAB**
- **SY1L -497.82 m**

  IP 0 m
- **SY1R +118.06 m**
- **SY2R +276.00 m <—CRAB**

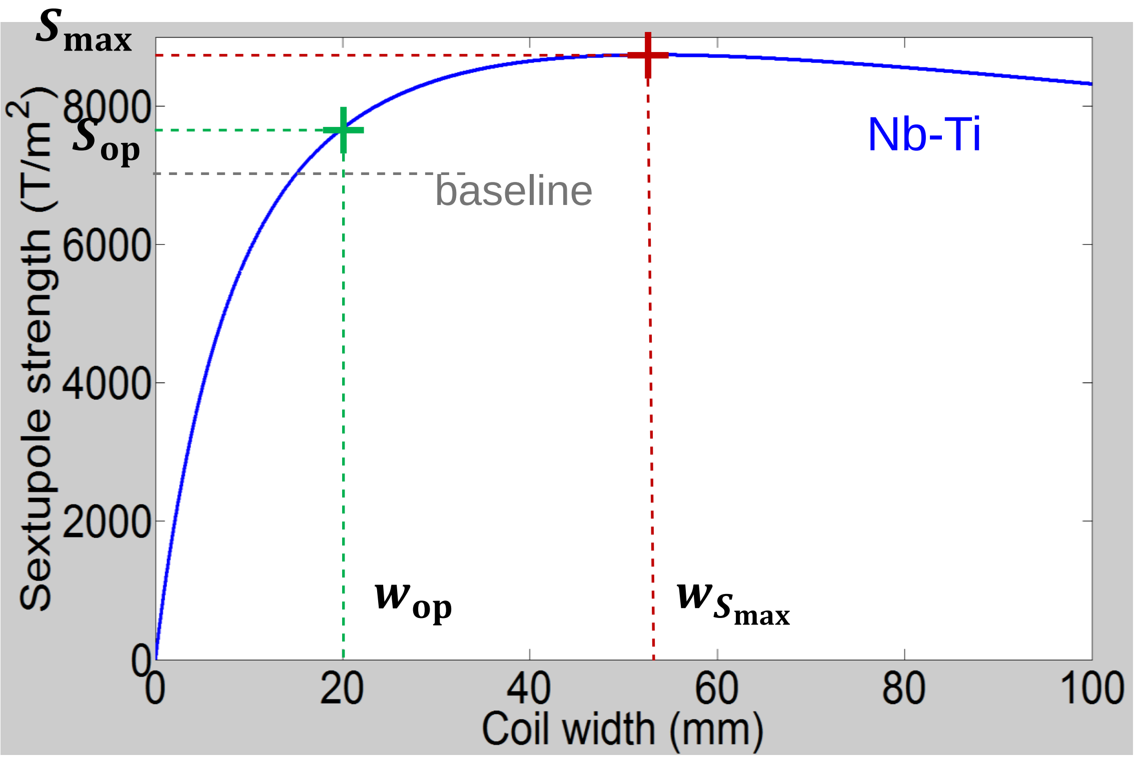
$$K = \frac{1}{\theta} \frac{1}{\beta_y^* \beta_y} \sqrt{\frac{\beta_x^*}{\beta_x}}$$

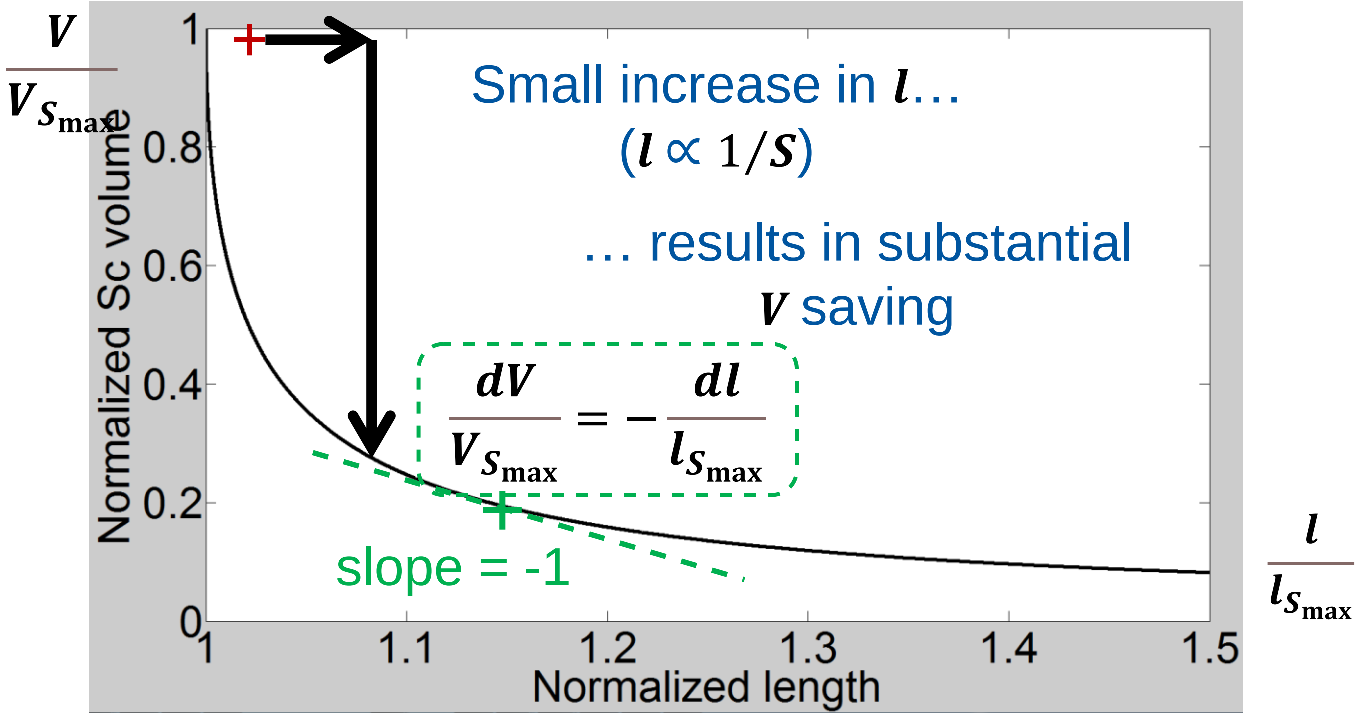






Optimal coil width vs. Strength





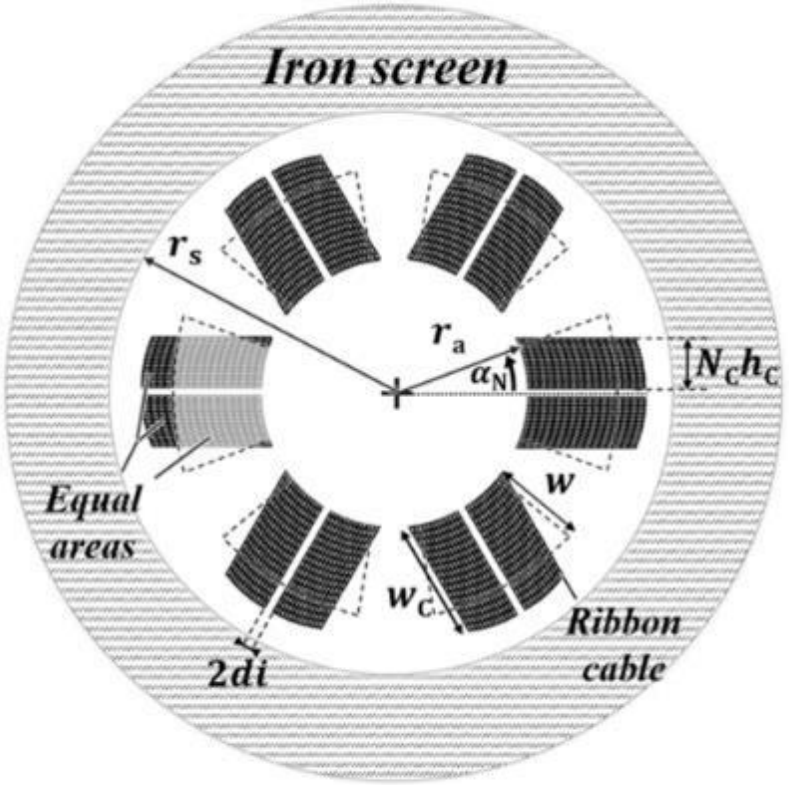
- As integrated $\int_0^{Lm} S.dl$ strength matters, an optimum exists where little increase in length ~13% is equivalent to SC volume saving of ~ 5

Predimensioning based on sector coil section

- To define the equivalent sector coil (see Fig.), we adjust its coil width to **w** such that its area is equal to that of the cosine-theta coil;

$$w = r_a\left[\sqrt{1+\frac{2w_C N_C h_C}{\alpha_N {r_a}^2}}-1\right]$$

- every other parameter is the same (e.g., engineering current density J, ampere-turn value per coil, same aperture radius r_a, or iron screen radius r_s)



ReBCO critical current density surface

- Fit critical surface function **as a function of field intensity (B), temperature (T) and field orientation (θ , [π/2, π]):**

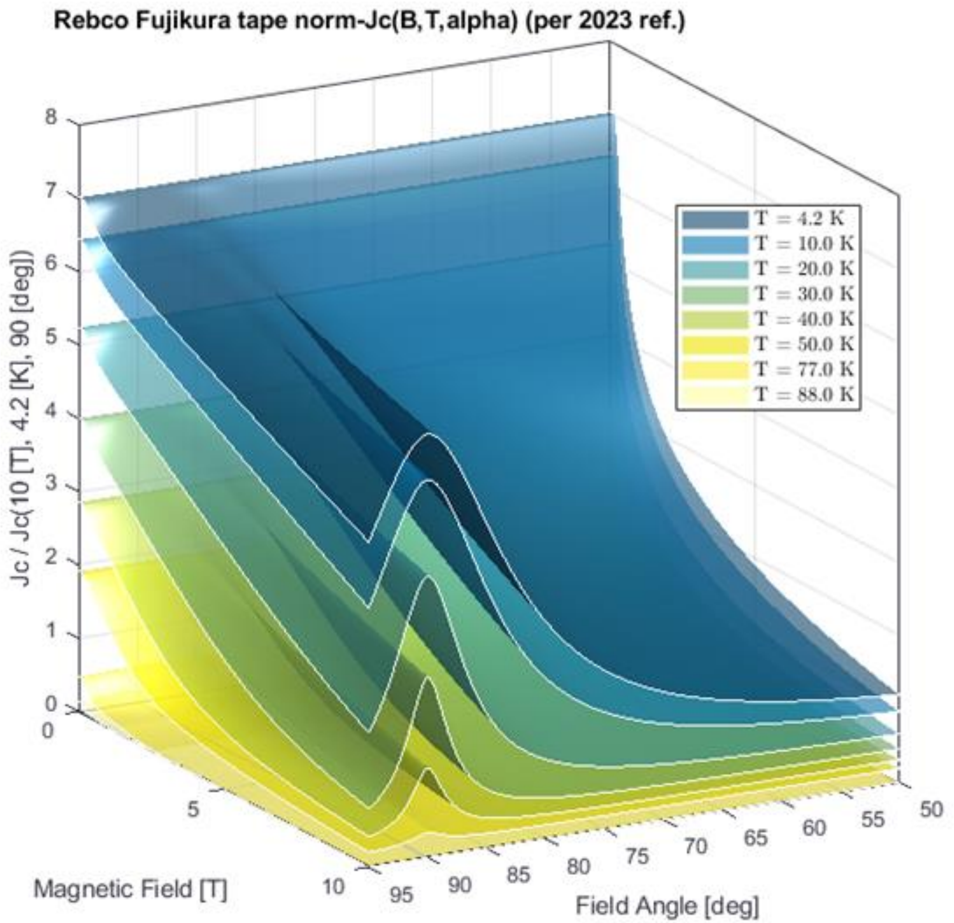
$$J_c(B,T,) = J_{c,c}\,(B,T) + \frac{J_{c,ab}(B,T) - J_{c,c}(B,T)}{1 + \left(\frac{-\pi/2}{g(B,T)}\right)^{v}}$$

- where $J_{c,c}$ and $J_{c,ab}$ are respectively the J_c in perpendicular and parallel external field orientations, θ is the field deviation with respect to c direction. v=1.85 fitting coeff. data
- Anisotropy factor (g) is given by:

$$g(B,T) = g_0 + g_1 \exp(-[g_2 \exp(g_3 . T)]B)$$

where g_0,g_1 , g_2 and g_3 are constants

Ref: J. Fleiter and A. Ballarino. Parameterization of the critical surface of REBCO conductors from
Fujikura. EDMS Nr: 1426239.



Strong dependence on field angle: Factor x4 reduction of Ic at 5 T, 10K for field ⊥ to tape

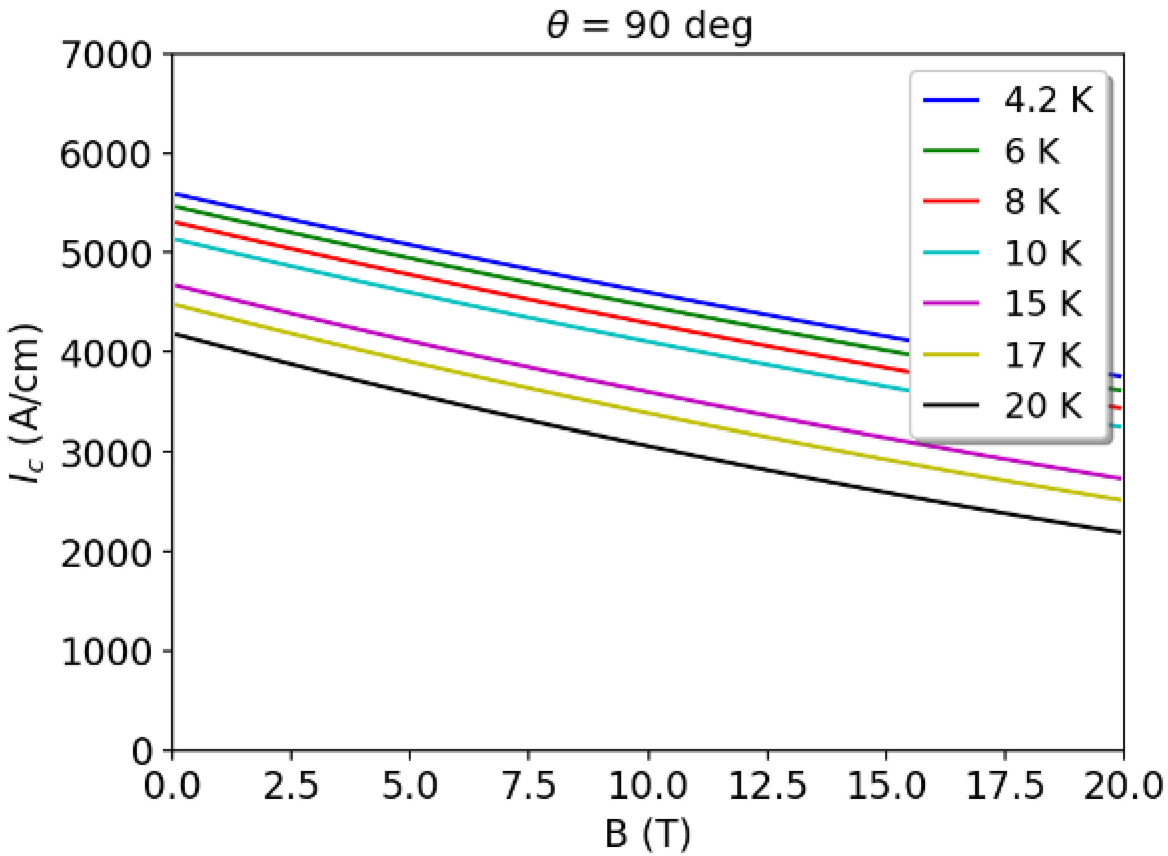
http://www.fujikura.co.jp/

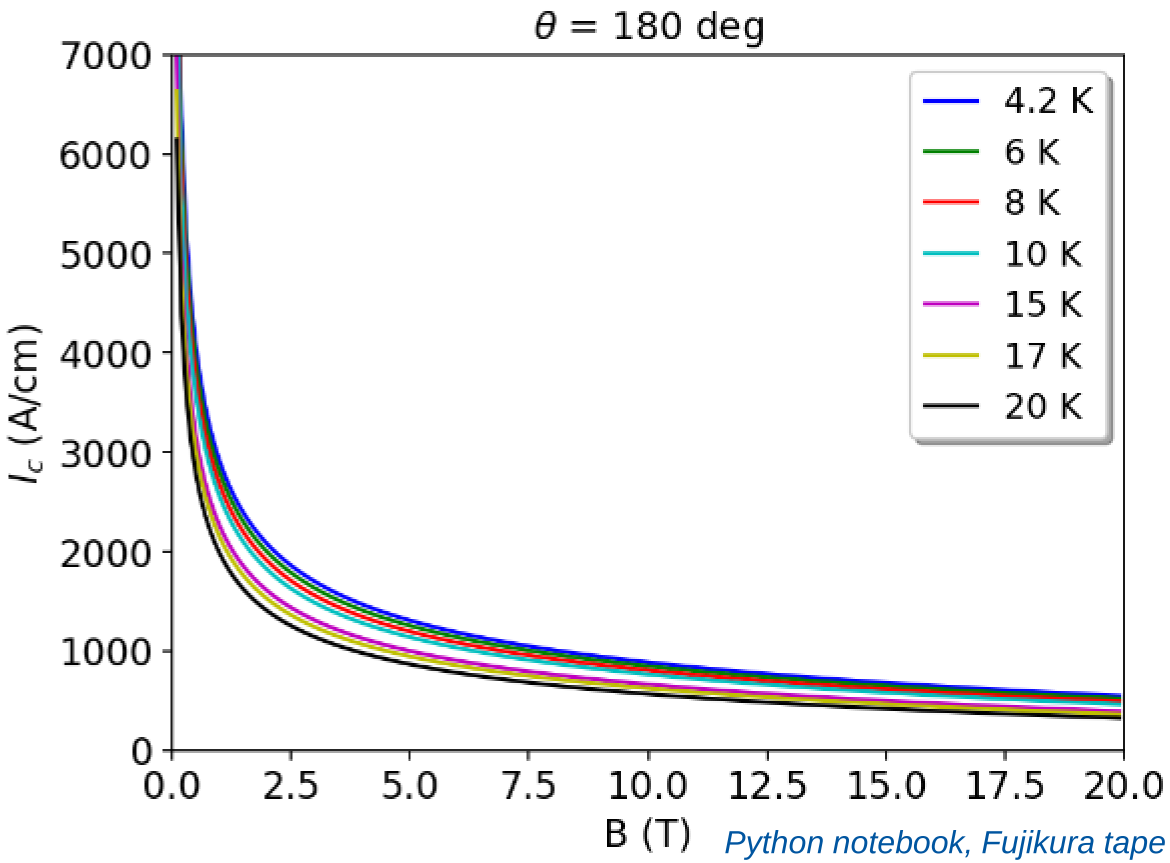
Roxie HTS strand equivalence model

	Rutherford cable	Equivalent
Diam	Strand diameter	Equivalent diameter such as the area of superconduc $A_{sc} = n_s \pi \frac{diam^2}{4}\left(\frac{1}{1+cu/sc}\right)$ $diam = \sqrt{\frac{4A_{sc}(1+cu/sc)}{n_s \pi}}$ $\sqrt{\frac{4(12 * 0{,}001 * 15)(50+1)}{15 * \pi}}$
cu/sc	Copper to superconductor ratio	Non-superconductor to superconductor ratio in the non insulated tape
ns	Number of strands	Number of tapes
Transp.	Transposition pitch	
Height	Height of the cable	
With_i	Width of the cable	

ReBCO critical current surface dependence on angle

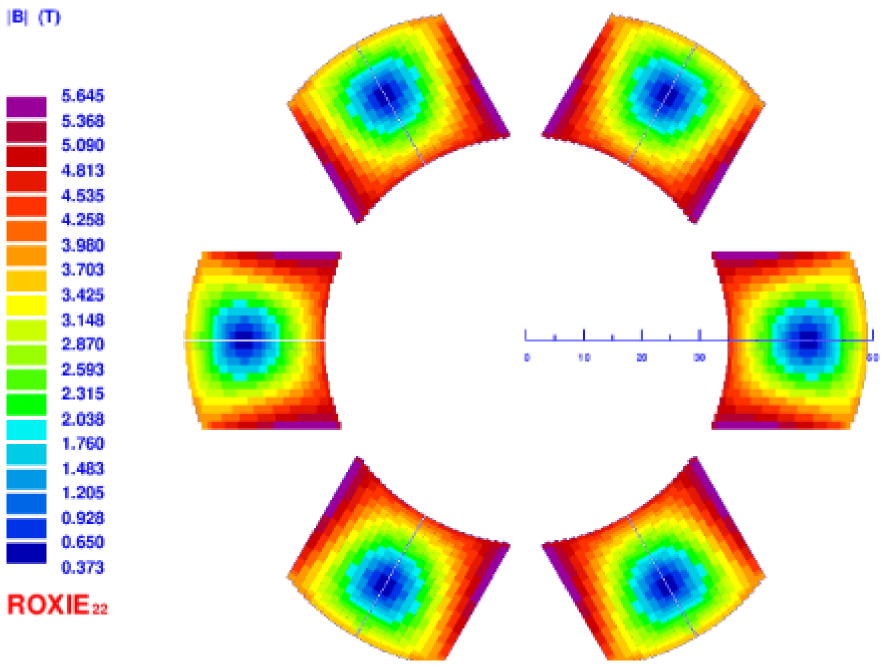
- Ic (A/cm) = f(B) @ 90 and 180deg with respect to c-axis (⊥).
  - *Factor x4 reduction of Ic at 5 T, 10K when field perp. to tape*

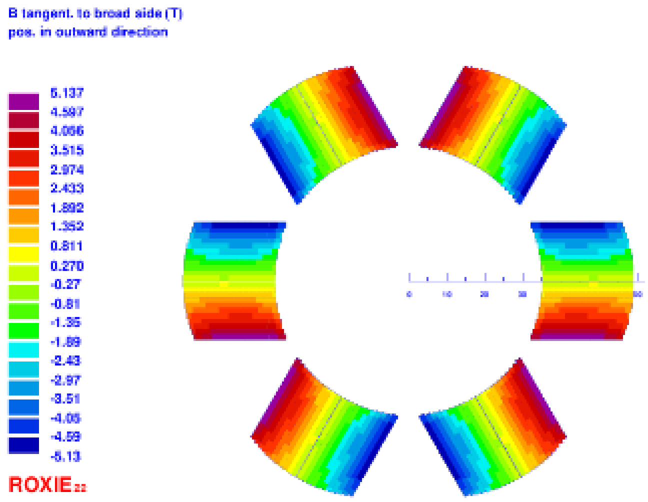


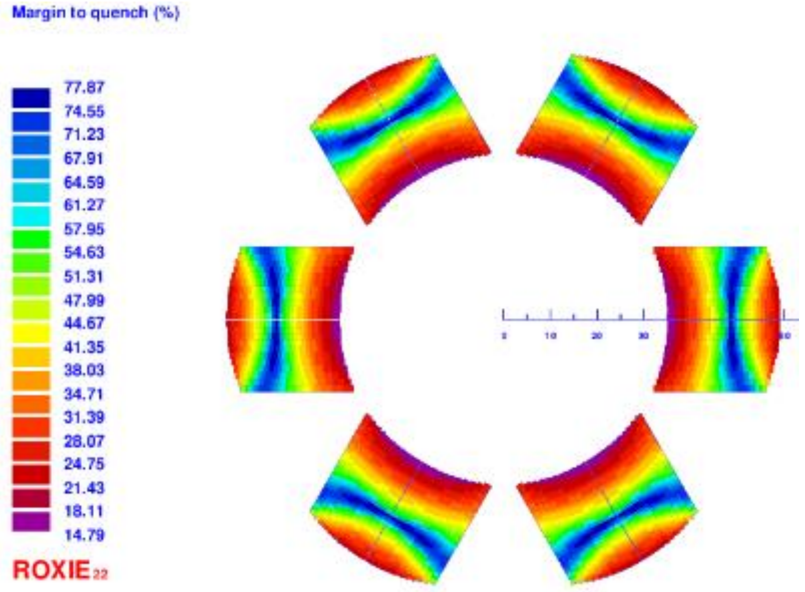


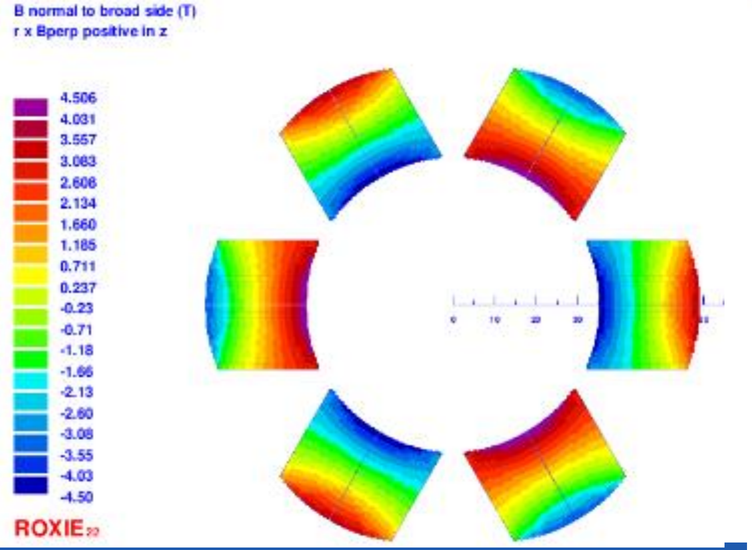
Python notebook, Fujikura tape source

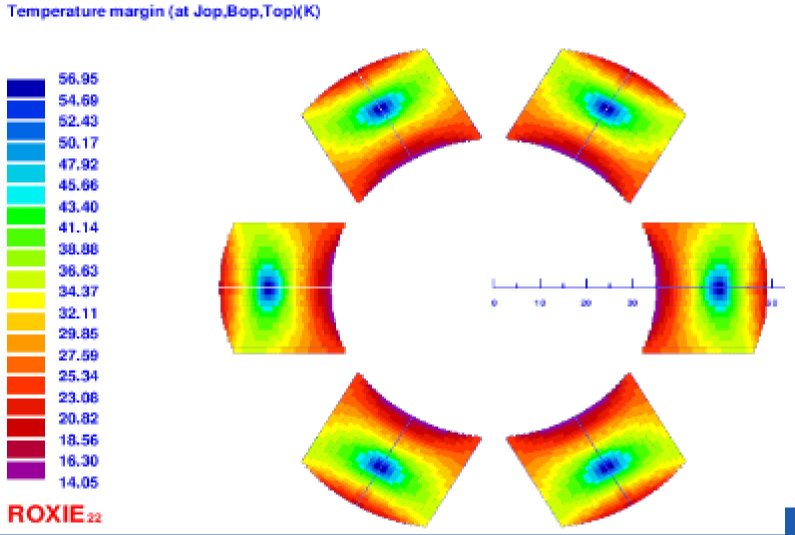
Case #2.0, @ 10K, S = 3850 T.m-2











- **Maximum normal magnetic field 4.5 T** to conductor
- Roxie Lorentz force up to 180kN radial, 580 kN azimuthal loads (see Appendix)

Example of Lorentz load on saddle coils blocks

ELECTROMAGNETIC FORCES (N/m) ON BLOCKS (2D)

BLOCK	FORCE -X- (N/m)	FORCE -Y- (N/m)	BLOCK-CENT-X (mm)	BLOCK-CENT-Y (mm)
1	0.1861E+06	-0.5290E+06	0.5015E+02	0.9300E+01
2	-0.3651E+06	0.4256E+06	0.3313E+02	0.3878E+02
3	0.5511E+06	-0.1034E+06	0.1702E+02	0.4808E+02
4	-0.5511E+06	-0.1034E+06	-0.1702E+02	0.4808E+02
5	0.3651E+06	0.4256E+06	-0.3313E+02	0.3878E+02
6	-0.1861E+06	-0.5290E+06	-0.5015E+02	0.9300E+01
7	-0.1861E+06	0.5290E+06	-0.5015E+02	-0.9300E+01
8	0.3651E+06	-0.4256E+06	-0.3313E+02	-0.3878E+02
9	-0.5511E+06	0.1034E+06	-0.1702E+02	-0.4808E+02
10	0.5511E+06	0.1034E+06	0.1702E+02	-0.4808E+02
11	-0.3651E+06	-0.4256E+06	0.3313E+02	-0.3878E+02
12	0.1861E+06	0.5290E+06	0.5015E+02	-0.9300E+01
SUMM:	-0.9022E-09	-0.4657E-09		

ELECTROMAGNETIC FORCES (N/m) ON BLOCKS || AND |- TO CONDUCTORS (2D)

BLOCK	FORCE || (N/m)	FORCE |- (N/m)	BLOCK-CENT-X (mm)	BLOCK-CENT-Y (mm)
1	0.1861E+06	-0.5290E+06	0.5015E+02	0.9300E+01
2	0.1861E+06	0.5290E+06	0.3313E+02	0.3878E+02
3	0.1861E+06	-0.5290E+06	0.1702E+02	0.4808E+02
4	0.1861E+06	0.5290E+06	-0.1702E+02	0.4808E+02
5	0.1861E+06	-0.5290E+06	-0.3313E+02	0.3878E+02
6	0.1861E+06	0.5290E+06	-0.5015E+02	0.9300E+01
7	0.1861E+06	-0.5290E+06	-0.5015E+02	-0.9300E+01
8	0.1861E+06	0.5290E+06	-0.3313E+02	-0.3878E+02
9	0.1861E+06	-0.5290E+06	-0.1702E+02	-0.4808E+02
10	0.1861E+06	0.5290E+06	0.1702E+02	-0.4808E+02
11	0.1861E+06	-0.5290E+06	0.3313E+02	-0.3878E+02
12	0.1861E+06	0.5290E+06	0.5015E+02	-0.9300E+01
SUMM:	0.2233E+07	0.8149E-09		

FORCE	||	|-		F_module
(N/m)	(N/m)	(N/m)		(N/m)
1	1.86E+05	-5.29E+05		5.61E+05
2	1.86E+05	5.29E+05		5.61E+05

Radial and azimuthal load in order of several ten's of tons.

Heat loads to the shield/CL T level – assumptions

- Radiation from the beam pipe
  - If no intercept, no additional heat load at this level
  - If intercept present, emissivity = 0.06 for shield (mech. polished copper)
  - Outer diameter of beam pipe = 60 mm (*i.e.* 5 mm gap to coil aperture)
  - Beam pipe temperature = 300 K
- Conduction via support rods
  - Considered 8 rods from 300 K directly to the shield at 80 K
  - Material G10 in normal direction, diameter = 8 mm, length = 100 mm

- **Radiation from ambient (vacuum vessel)**
  - Diameter of thermal shield = 500 mm
  - Considered 30 layers MLI on the outer surface of shield
  - Shield temperature = 80 K
- **Conduction via current leads**
  - Considered pair of leads optimized for operating current
  - Material: brass
  - Current = 1000 A
  - Warm end at 300 K, cold end at 60 K

Shield temperature level:
- 60 K for current leads (closely thermalised to heat sink)
- 80 K for thermal shields and support rods, as less coupled to heat sink

Heat loads to the cold mass – assumptions

- Radiation from the beam pipe
  - Inner diameter of cold mass = 70 mm
  - Outer diameter of beam pipe = 60 mm (*i.e.* 5 mm gap to coil aperture)
  - Beam pipe temperature = 300 K
  - Calculations with/without thermal shield intercept at 80 K:
    - If no intercept, emissivity = 0.1 for beam pipe and cold mass (stainless steel)
    - If intercept present, emissivity = 0.06 for shield (mech. polished copper)
- Conduction via support rods
  - Considered 8 rods from 300 K directly to the cold mass
  - Material G10 in normal direction, diameter = 8 mm, length = 200 mm
- Conduction via HTS current leads
  - Heat inleak taken for pair of standard HTS leads between 64 K and 4.2 K from HTS-110 Magnetic Solutions[1]
  - Current = 1000 A

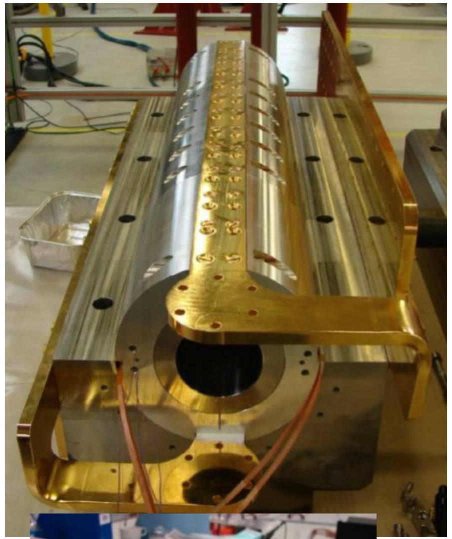
- **Radiation from outer thermal shield**
  - Outer diameter of cold mass = 400 mm
  - Diameter of thermal shield = 500 mm
  - Considered 10 layers MLI on the outer surface of cold mass
  - Shield temperature = 80 K
- **Joule heating due to splice resistance**
  - Number of splices = 14
  - Resistance of each splice = 3 nΩ
  - Current = 1000 A
- **Beam-induced effects (if any)**
  - Presently no beam-induced effects considered
  - Can be easily added to the estimation

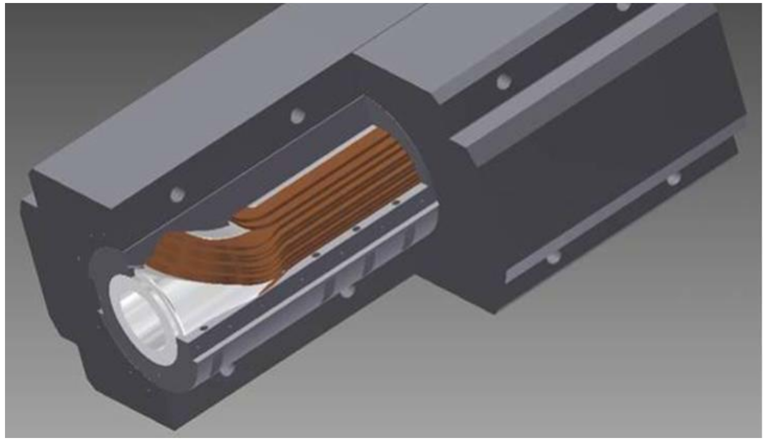
Cold mass temperature options: 4.5 K, 10 K and 20 K

[1] https://www.hts-110.com/product/cryosaver-current-leads/

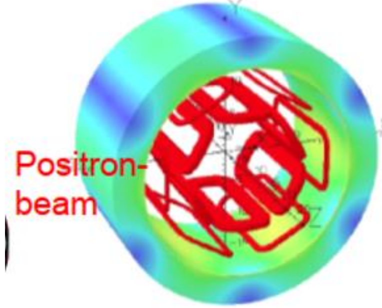
Past conduction-cooled HTS accelerator magnet

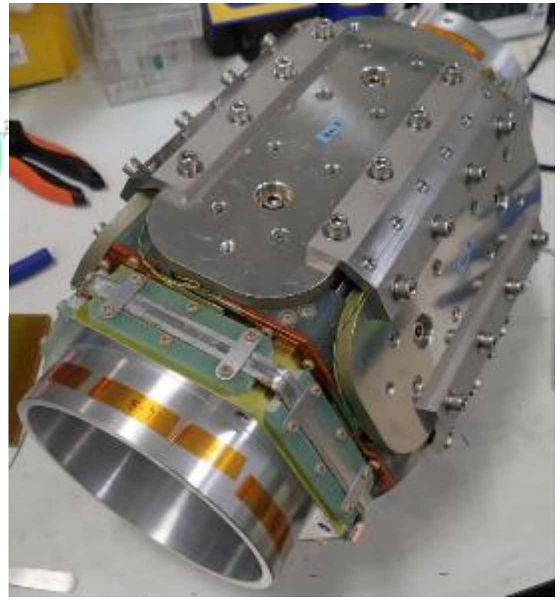
- Courtesy Danfysik-SuperPower-Aarhus University (2012-2014)
  - – 14 saddle coils bent after racetrack-like winding
  - – Pancakes joined by solders in coil ends (6-10 cm)



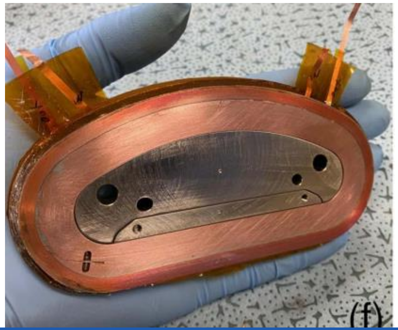


Interface Cu plates for cryocooler (x 2) mounting (Top cold mass~ 18 K)





SuperKEKB HTS sextupole 200T/m2, B0: 2.4 T, Aug. 2019 Courtesy K Tsuchiya, KEK, Japan



HTS undulator, CERN-KIT. Courtesy C. Richter, A. Ballarino, doi: 10.1109/TASC.2023.3242625. Aug.2023