Design and prototyping of Nb_3Sn wigglers for the CLIC damping rings

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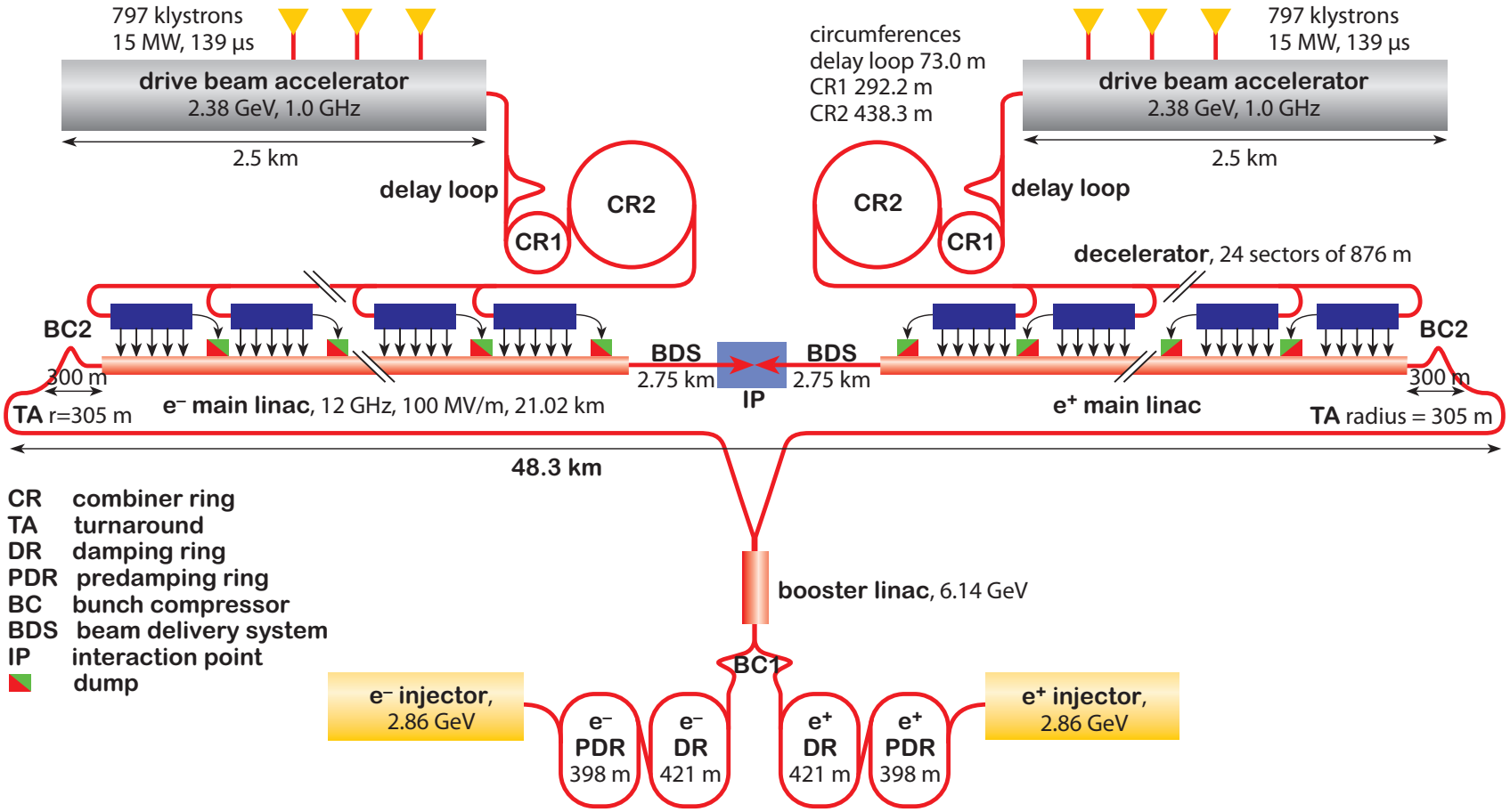
October 21, 2010

Acknowledgments

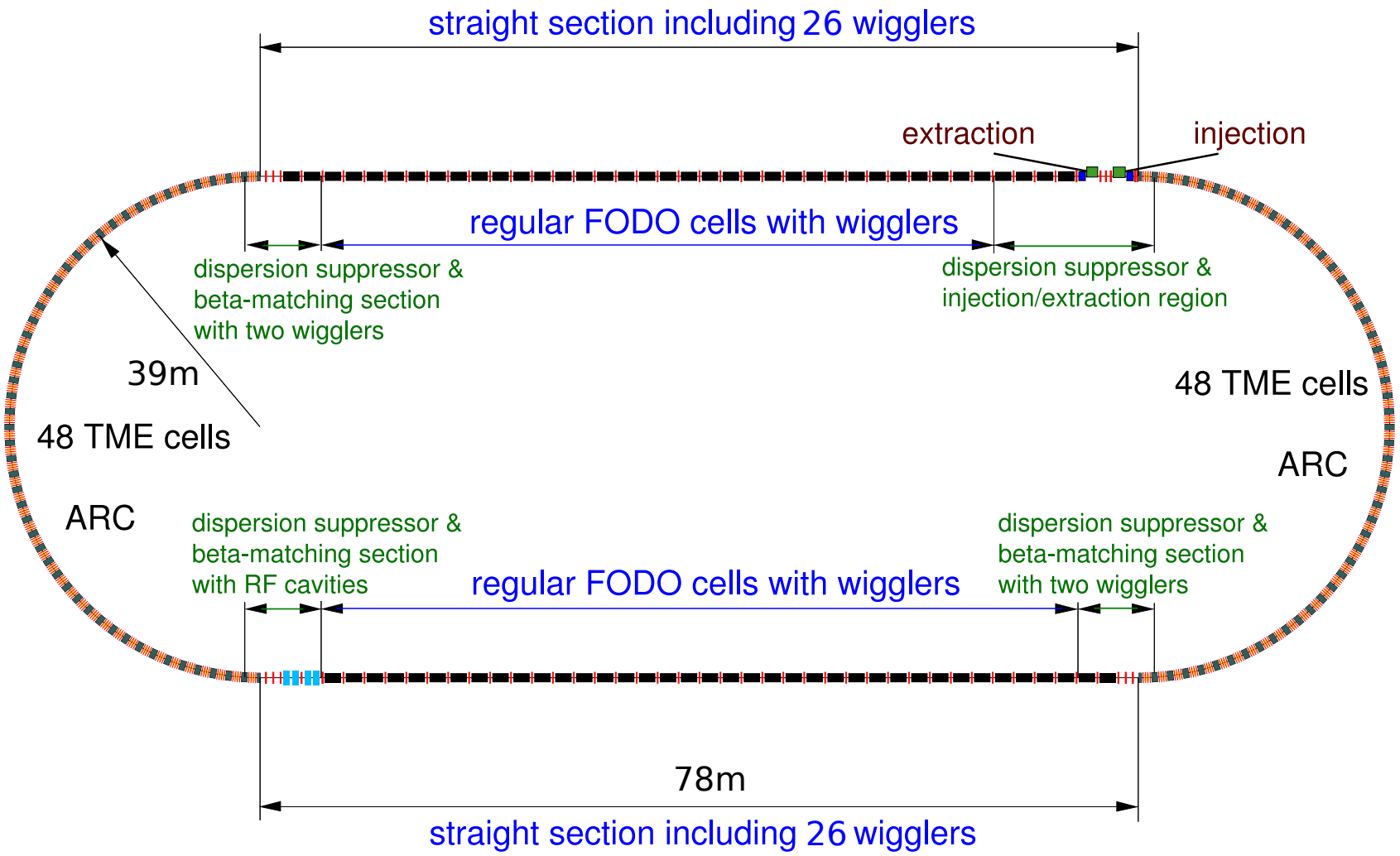
- Fanouria Antoniou, CERN
- Simona Bettoni, CERN
- Marco Buzio, CERN
- Paul Chiggiato, CERN
- Sebastien Clement, CERN
- Jerome Feuvrier, CERN
- Knud Dahlerup-Petersen, CERN
- Noel Delaxandro, CERN
- Reiner Denz, CERN
- Nuno Rio Duarte Elias, CERN
- Mikko Karppinen, CERN
- Remo Maccaferri, CERN
- Jacky Mazet, CERN
- Giuseppe Montenero, CERN
- Yannis Papaphilippou, CERN
- Antonio Perin, CERN
- Emmanuele Ravaioli, CERN
- Giovanni Rumulo, CERN
- Stephan Russenschuck, CERN
- Christian Scheuerlein, CERN
- Nikolai Schwerg, CERN
- Mauro Taborelli, CERN
- Giovanna Vandoni, CERN
- Daniel Wollmann, CERN
- Alexey Bragin, BINP
- Denis Gurov, BINP
- Anatoly Utkin, BINP
- Pavel Vobly, BINP
- Konstantin Zolotarev, BINP
- Boris Podebedov, BNL
- Axel Bernhard, KIT
- Johann Peter Peiffer, KIT
- Robert Rossmanith, KIT
- Alfons Ams, TU Freiberg

Outline

Overview of CLIC layout

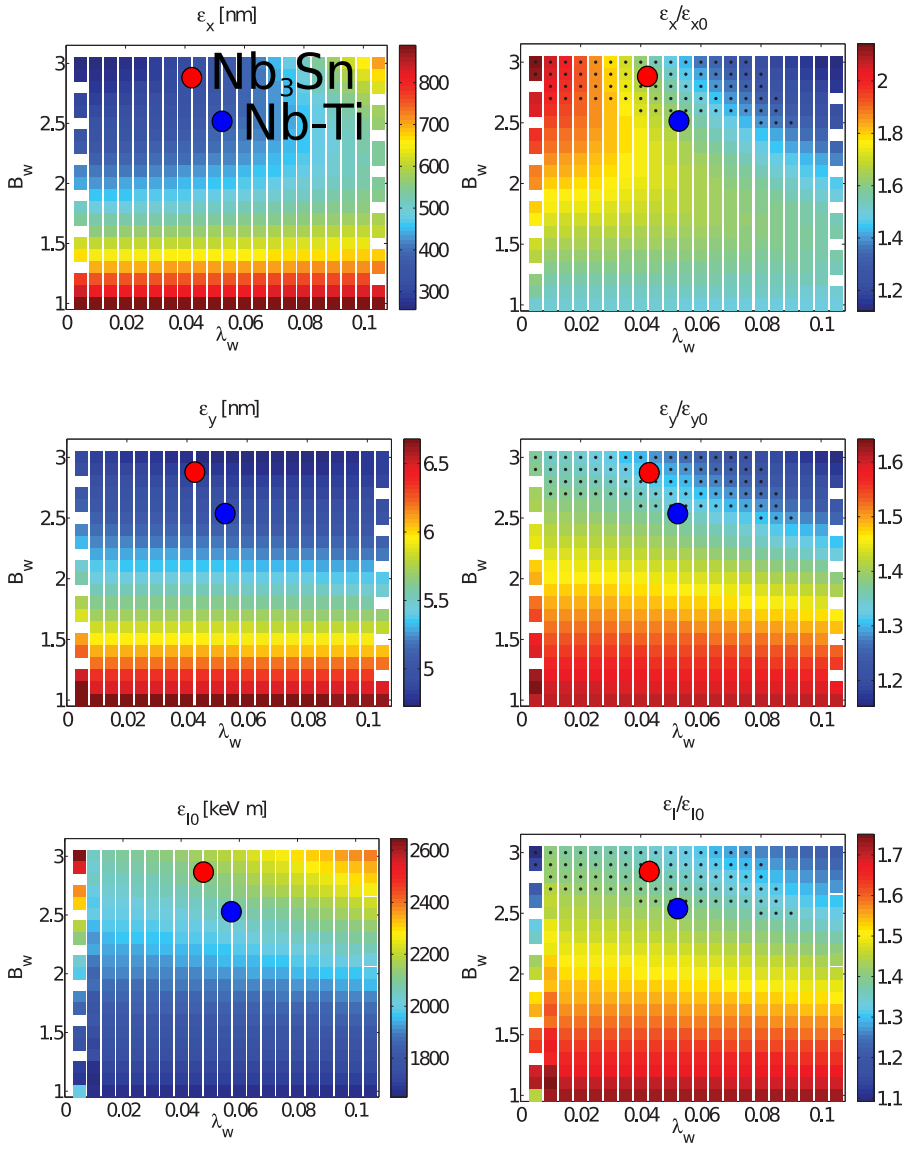


Introduction: CLIC damping rings



M. Korostelev: Updated from: *Optics Design and Performance of an Ultra-Low Emittance Damping Ring for the Compact Linear Collider*

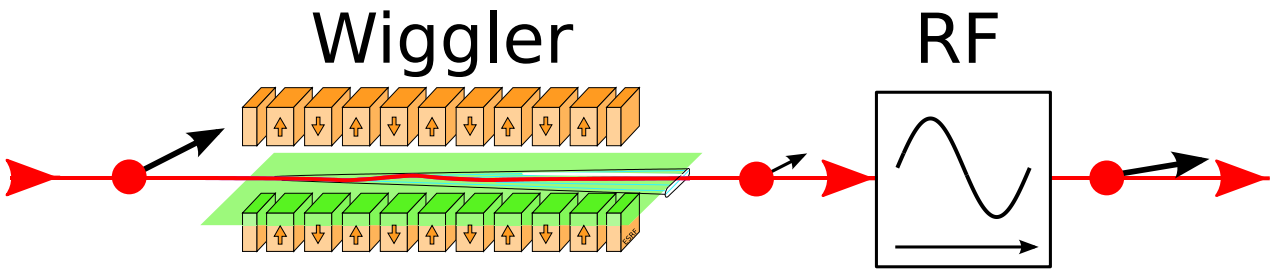
CLIC wiggler's optimum efficiency



Scaling of the extracted emittances with the wiggler field and period. In the left plots the extracted emittances are shown, while in the right ones the ratio between the extracted and the zero current emittances. The black dots indicate solutions where all the emittance requirements are met. The longitudinal emittance is kept constant. (F. Antoniou et al., WEPE085, IPAC'10)

Possible wire technologies: **Nb_3Sn** or **Nb-Ti**

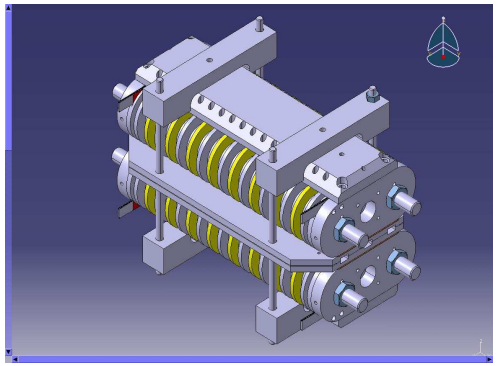
Introduction: Motivation and mechanical tolerances

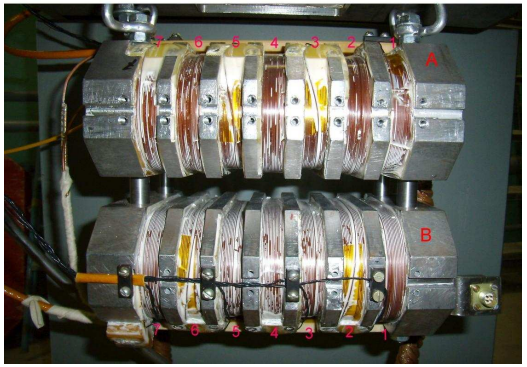


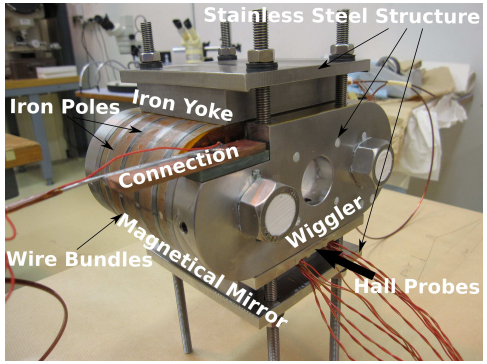
Equilibrium Emittance	$\gamma\epsilon_x \approx \gamma\epsilon_\mathrm{a}\frac{J_{x\mathrm{a}}}{J_{x\mathrm{a}}+F_\mathrm{w}} + \gamma\epsilon_\mathrm{w}\frac{F_\mathrm{w}}{J_{x\mathrm{a}}+F_\mathrm{w}}$
Generated Equilibrium Emittance	$\gamma\epsilon = \frac{C_\mathrm{q}\gamma^3}{J_x}\frac{I_5}{I_2}$
Damping via photon emission	$I_2 = \oint \frac{1}{\rho^2}$
Excitation via dispersion	$I_5 = \oint \frac{\mathcal{H}}{\lvert\rho^3\rvert}\mathrm{d}z$
$J_x \approx 1 \quad F_\mathrm{w} = \frac{I_{2\mathrm{w}}}{I_{2\mathrm{a}}}$	$\mathcal{H} = \gamma(z)\eta^2 + 2\alpha(z)\eta\eta' + \beta(z)\eta'^2$
Specified equilibrium emittances	$\gamma\epsilon_x \leq 500\,\mathrm{nm.rad} \quad \gamma\epsilon_y \leq 5\,\mathrm{nm.rad}$
Specified maximum damping time	$\tau_y \leq 1.91\,\mathrm{ms}$
Mechanical Tolerances for Nb-Ti baseline design	
$\sigma(B^*)$	$0.2\,\mathrm{T}$
$\sigma(\lambda^*)$	$1\,\mathrm{mm}$
$\mu(\gamma\epsilon_x), \gamma\epsilon_x$	$312.1\,\mathrm{nm.rad}, 309.7\,\mathrm{nm.rad}$
$\sigma(\gamma\epsilon_x)$	$0.2315\,\mathrm{nm.rad}$

Source: P. Emma and T. Raubenhemier, Phys. Rev. ST AB, Vol 4, 021001 (2001)

Design: Options for CLIC damping wigglers

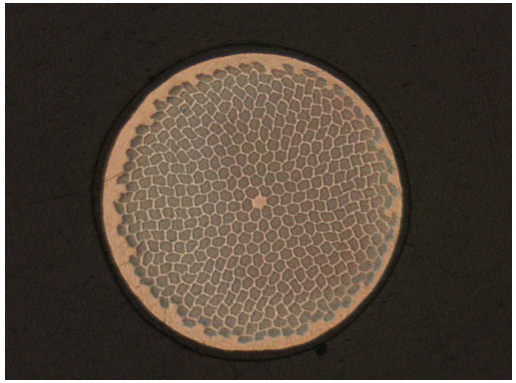


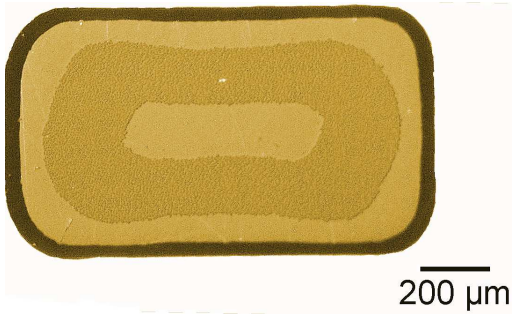


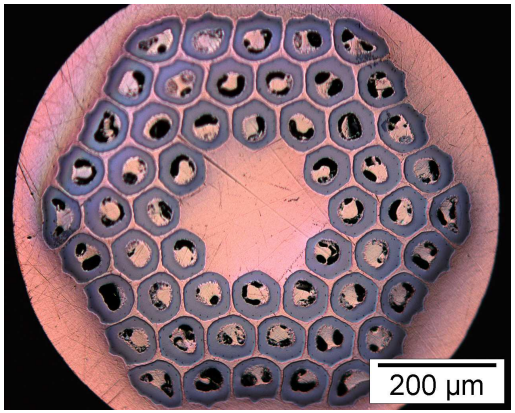


	Nb_3Sn	Nb_3Sn	Nb-Ti	Nb-Ti
Period Length λ, mm	40	50	50	50
Gap (beam stay clear), mm	13	13	13	13
Gap (magnetic), mm	18	18	18-20	18-20
Mid plane field, T	≥ 2.5	≥ 3.7	≤ 2.5	≤ 3.0
Peak Field, T	7.9	10.5	6.2	7.5
LL, A/T	157	$\approx$105	105	105
Operating Current, A	1100	1000	660	790
Inductance at operating current, H	0.5	0.5	1.5	1.5
Operating temperature	$\approx 5\,K$	$\approx 5\,K$	$4\,K$	$1.9\,K$

Strands: Options for CLIC damping wigglers



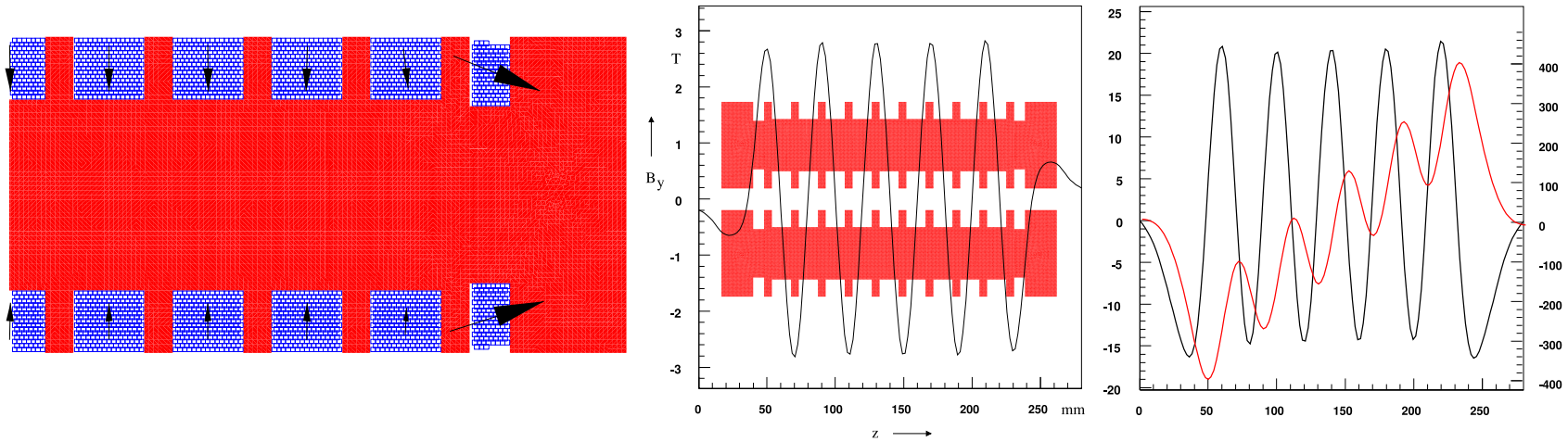




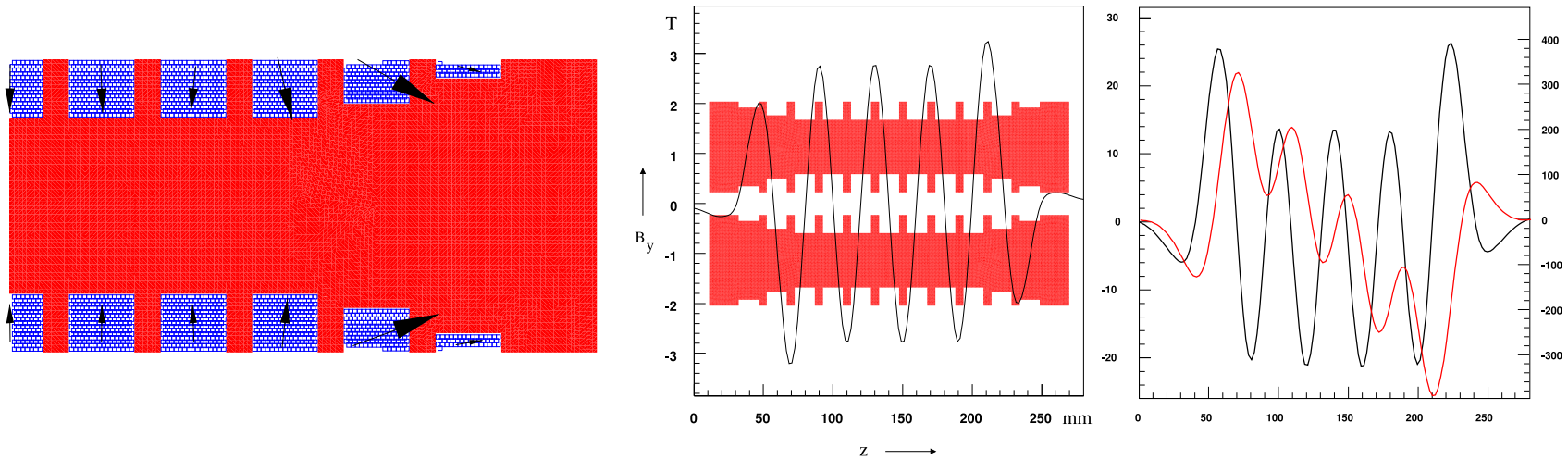
	Nb-Ti BINP	Nb-Ti CERN	RRP Nb_3Sn
Strand ø, mm	0.85	0.61 × 1.13	0.81
A, mm^2	0.57	0.69	0.52
Insulated ø, mm	0.91-0.92	0.73 × 1.25	0.94
Form	round	rect. (+20%)	round
SC/Cu ratio	1.5/1	1/1.8	1.1/1
Quench current	700 (4.2 K, 50 mm)	730 (4.2 K, 40 mm)	1100 (4.2 K, 40 mm)
	830 (1.9 K, 50 mm)	950 (1.9 K, 40 mm)	1000 (4.2 K, 50 mm)
T_c, K	9.6	9.6	18.1
RRR	100	>100	300
Filament ø, μm	$\leq$ 45	$\leq$ 7	$\leq$ 80
Insulation	Imidal Varnish	PVA Enamel	S-Glass braid
Total, km	1700	1700	1700

Conceptual wiggler design: Magnetic design

Version 1 (CERN):

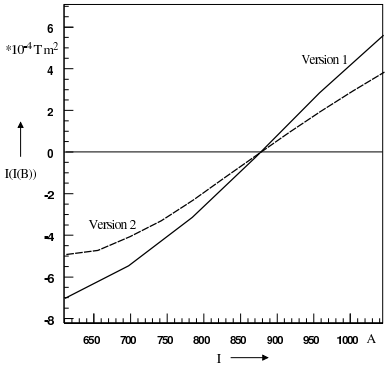


Version 2 (ANKA and BINP like):

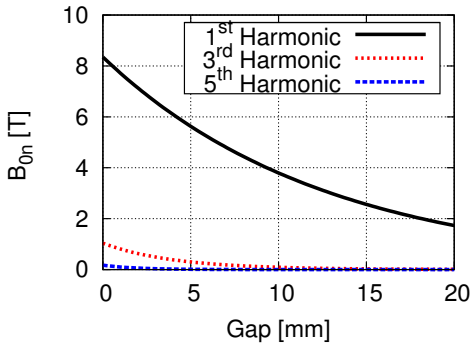


Conceptual design: Nb_3Sn

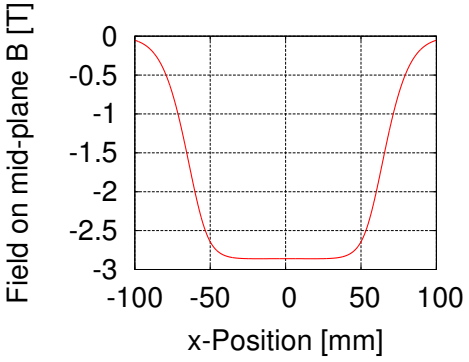
Sensitivity



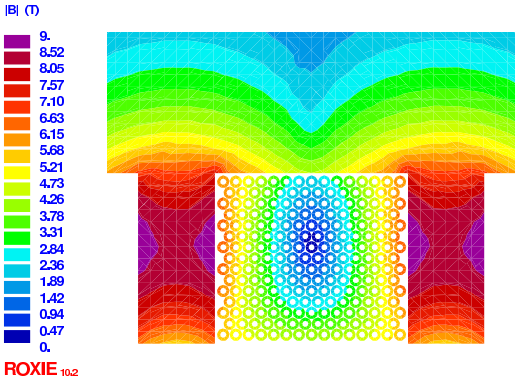
Harmonics



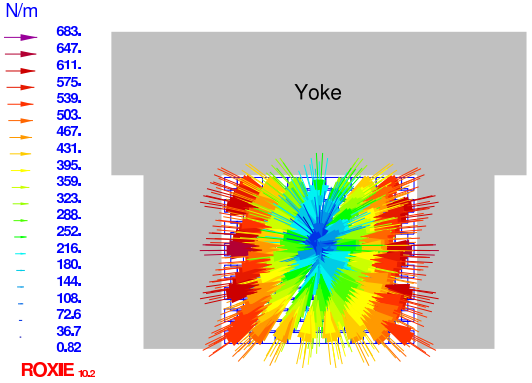
Roll-off



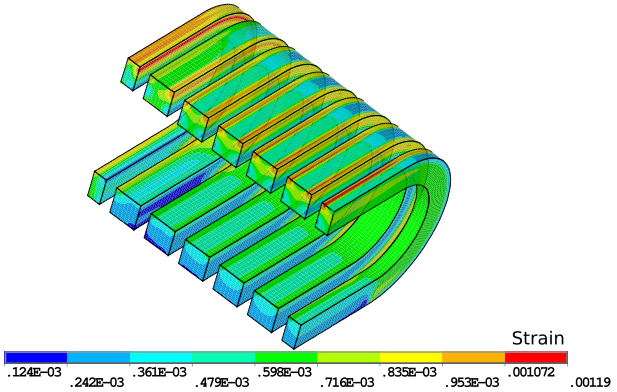
Peak Field



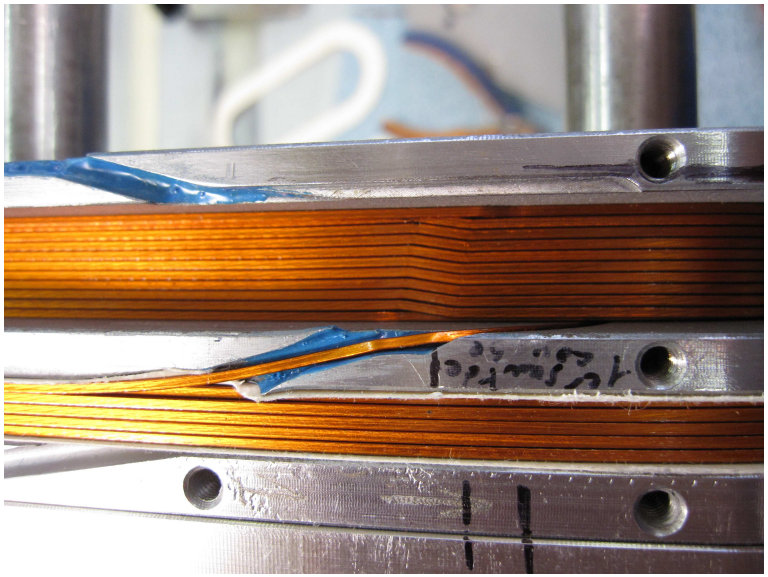
Forces

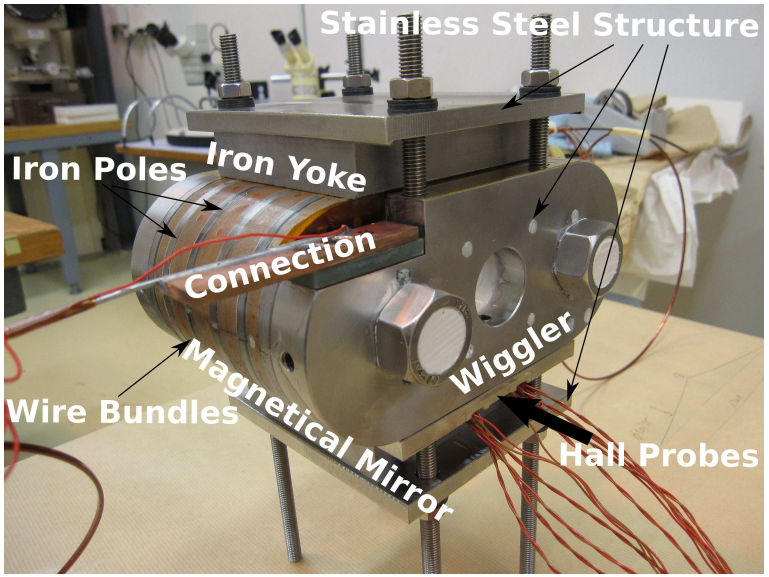


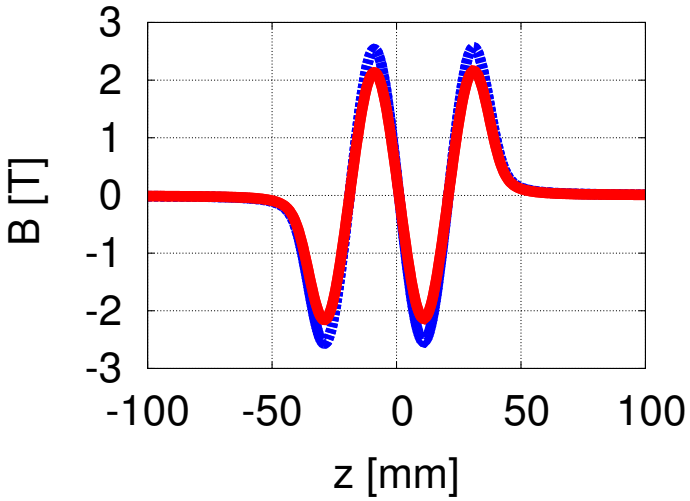
Strain

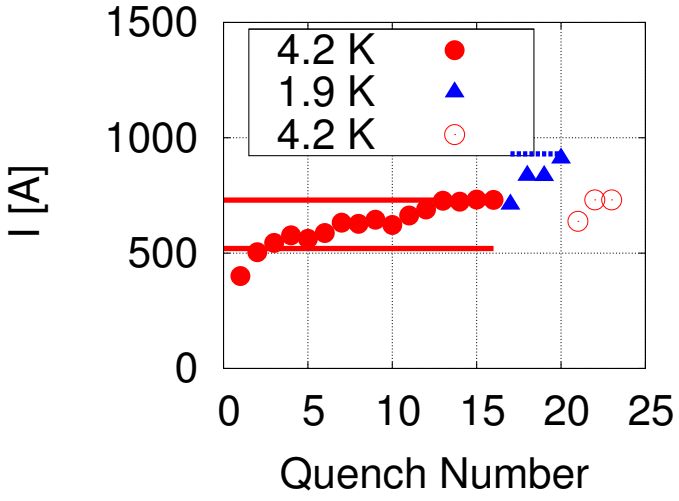


Manufacturing and testing: Nb-Ti racetrack design

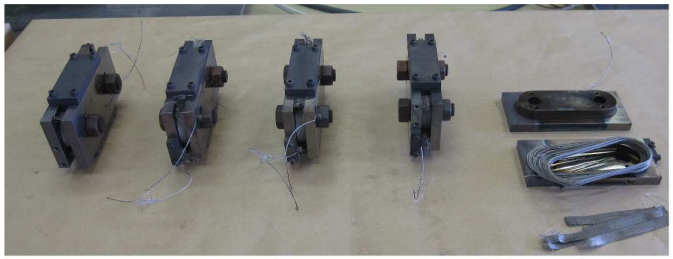


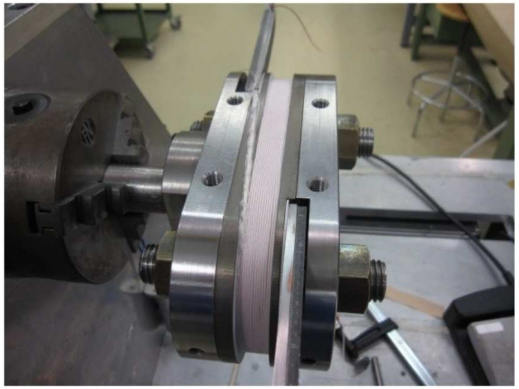


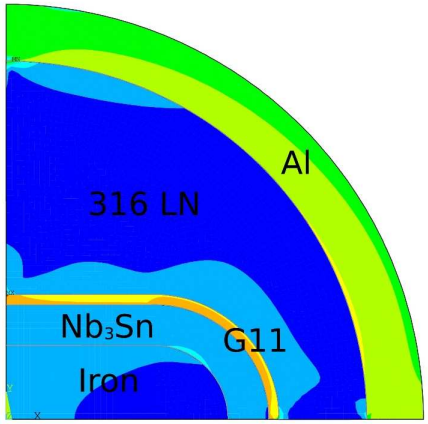


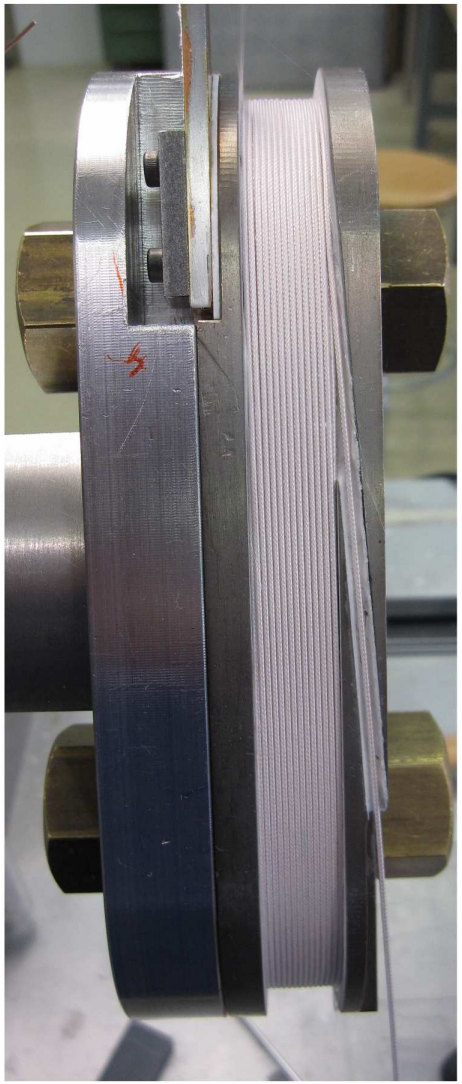


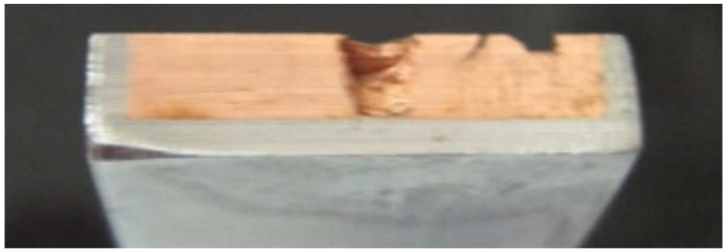
Nb_3Sn test results: Manufacturing

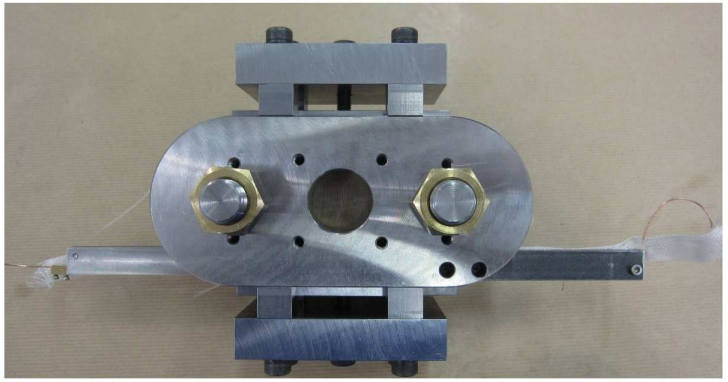






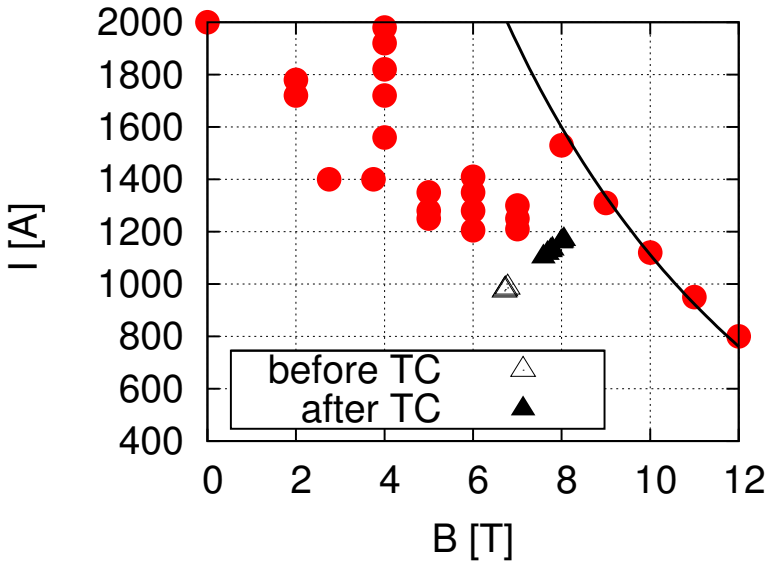


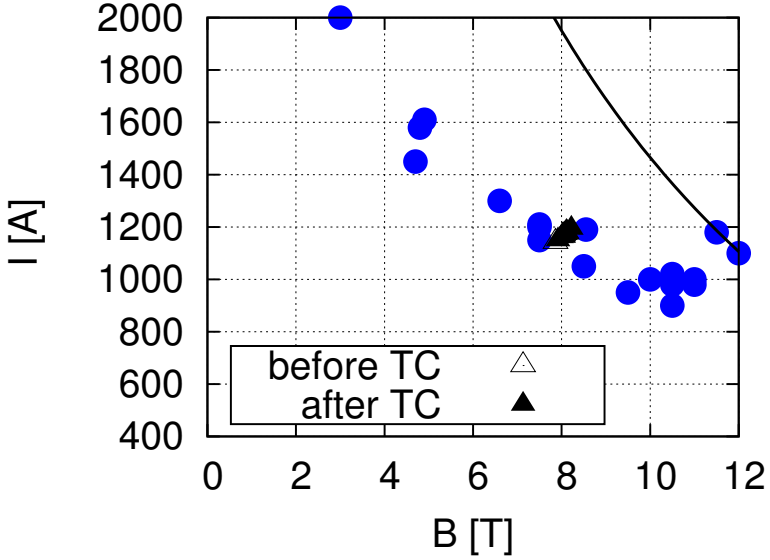


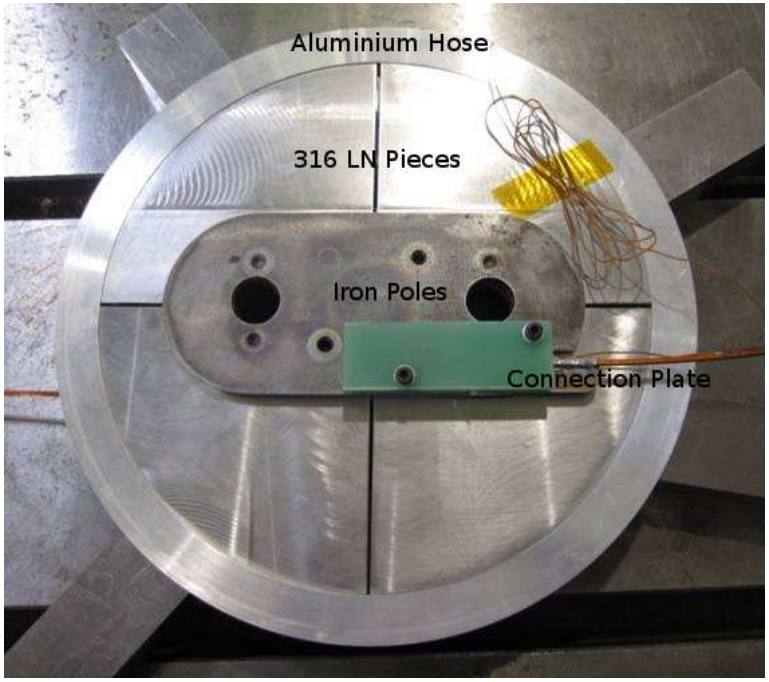


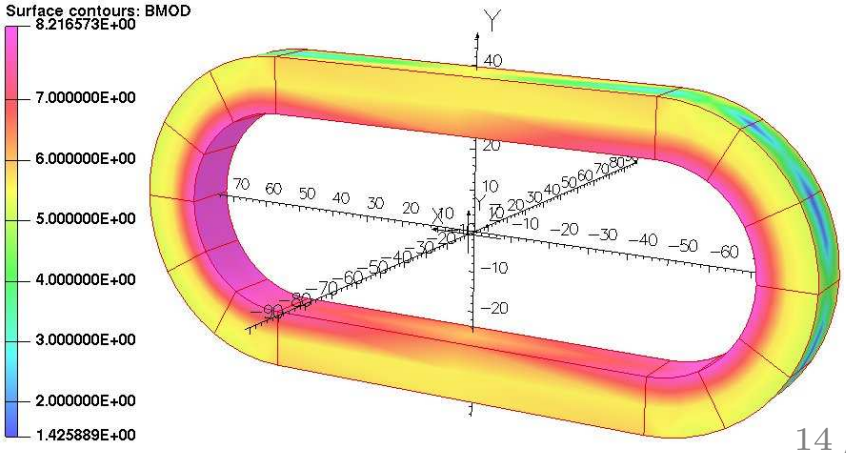
Nb_3Sn test results: Measurements

Short sample currents were reached without training at 1.9 K and after TC at 4.3 K: High enthalpy margin pays off!



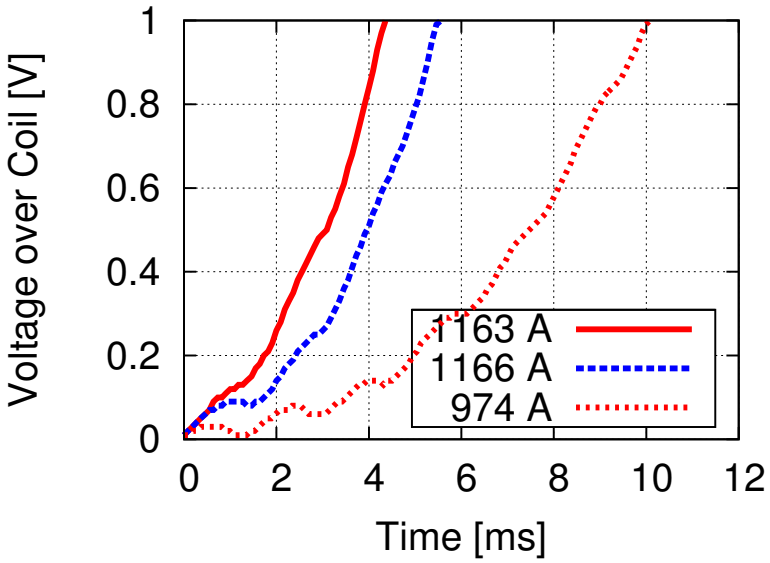




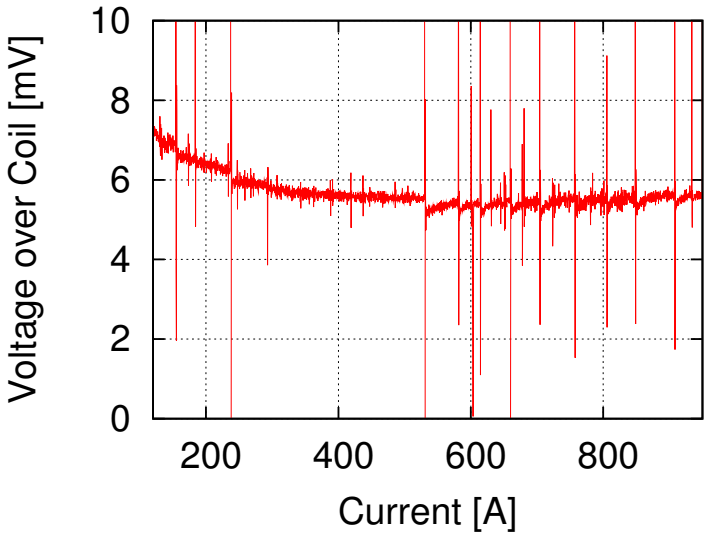


Nb_3Sn test results: Discussion

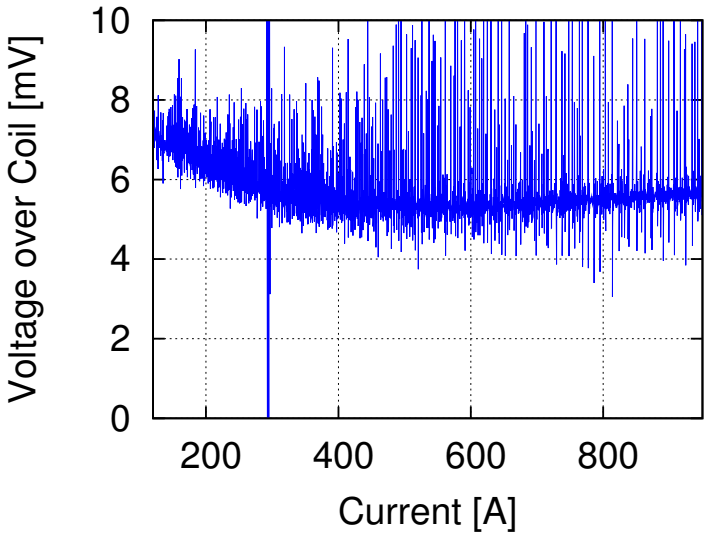
Quench propagation for different T and I:



Voltage over coil at 4.3 K:



Voltage over coil at 1.9 K:



- Feasible manufacturing process.
- No training needed.
- Operation at $\geq$4.3 K preferable (self-field instabilities at 1.9 K).
- More enthalpy and current margin as Nb-Ti.
- More margin with shorter heat treatment.

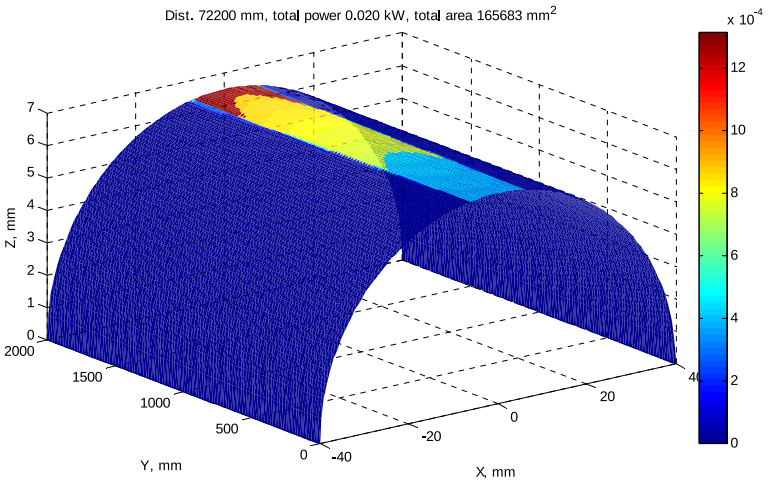
Image currents & Synchrotron radiation

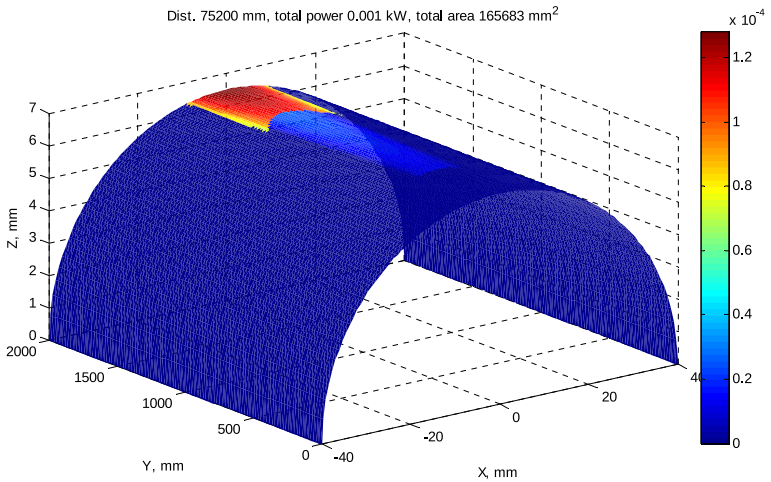
Image currents in a cold-bore undulator (Popobedov, 2009):

$$\text{Good conducting coating:} \quad P/L = \frac{\Gamma(\frac{5}{6})cZ_0}{4b\pi^2} B_{\mathrm{Mat}} \frac{I_{av}^2}{\sigma_z^{\frac{5}{3}} \eta f_{\mathrm{RF}}} \approx 1\,\frac{\mathrm{W}}{\mathrm{m}}$$

$$\text{Poor conducting coating:} \quad P/L = \frac{\Gamma(\frac{3}{4})c\sqrt{Z_0}}{\sqrt{32}b\pi^2} \frac{1}{\sqrt{\sigma_c}} \frac{I_{av}^2}{\sigma_z^{\frac{3}{2}} \eta f_{\mathrm{RF}}} \approx 32\,\frac{\mathrm{W}}{\mathrm{m}}$$

Synchrotron Radiation Heat Load:





Odd numbered chamber heat load: 20 W/m (can be reduced to 10 W/m with HC: 7.5 mm)

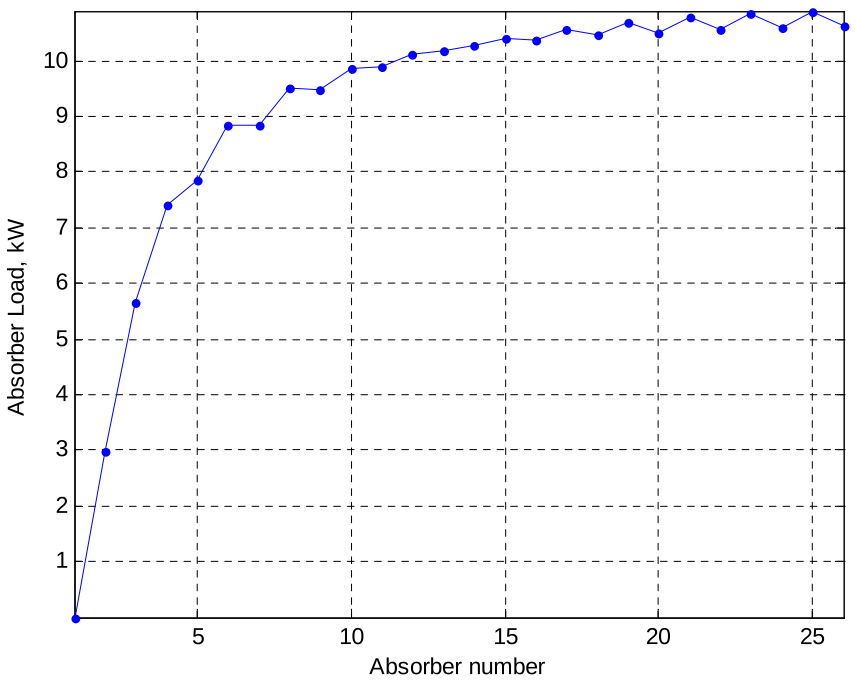
Even numbered chamber heat load: $<$ 1 W/m

Modified absorption scheme

Optimized Absorber Shapes

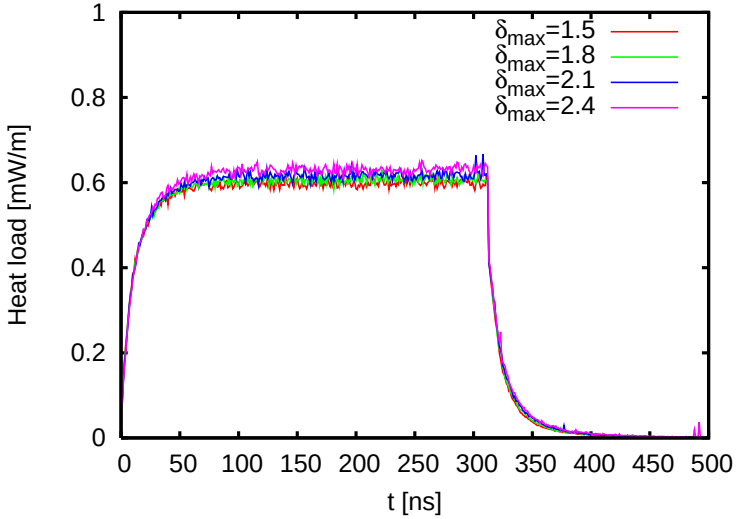
Element	Length [m]	V [mm]	H [mm]	Shape
Horizontal Absorber	0.5	13.5	12.3	Rectangular
Vertical Absorber	0.5	9.5	12.5	Rectangular

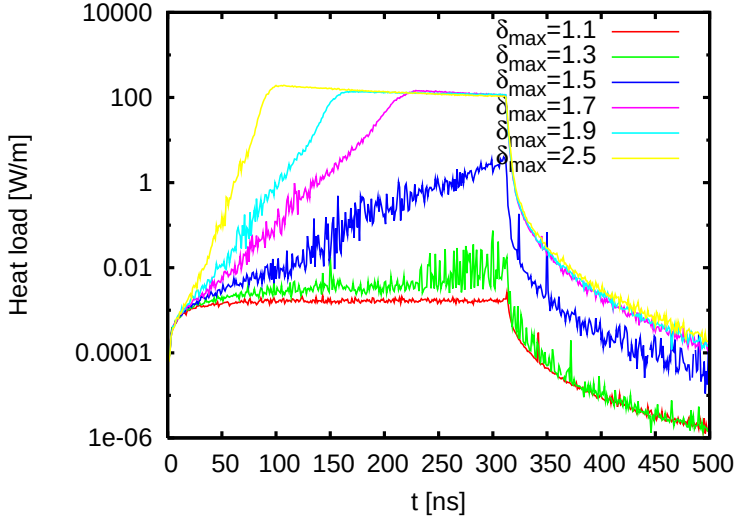
- Water cooled copper absorbers, power density up to 200 W/cm (PETRA III value) $\Longrightarrow$ at least 60 cm absorber.
- Absorber has to be in warm $\Longrightarrow$ $2 \times$ 0.4-0.5 m warm-cold transition (Maccaferri, LER 2009).
- Space for quadrupoles, steerers, BPMs, etc.
- **MORE SPACE NEEDED BETWEEN WIGGLERS!**



E-cloud simulations

- Calculations with ECLOUD by Giovanni Rumulo.
- 99.9% synchrotron radiation was assumed to be absorbed.
- The 1 GHz option has been considered, bunch spacing 1 ns.





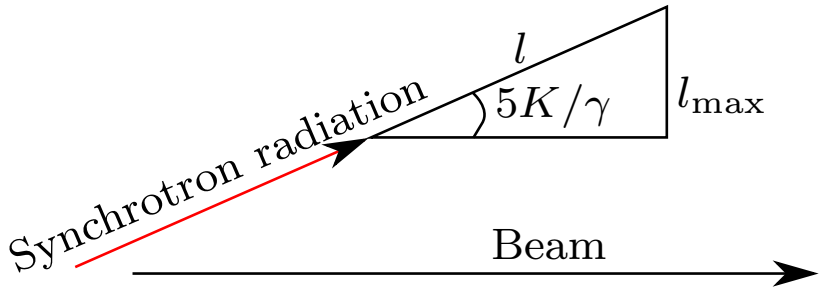
- Multipacting does not affect the electron beam in the wigglers.
- No serious e-cloud induced heat load limitations seem to be present in the electron ring.
- Vacuum requirements have to be specified.

- Multipacting appears in the positron ring for $\delta_{\max}$ above 1.3 which is the same level as for SPS, out-gassing and aging (increase of SEY with time) are under study.
- Electron clouds are not tolerable (heat load, beam stability, etc.). Therefore, low SEY coating such as amorphous carbon or NEG is needed.

Attenuation & eddy currents

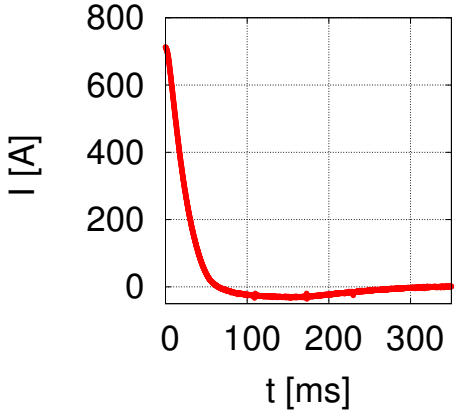
Material	$[l] = 1\,\mu\text{m}$	$[l_{\text{max}}] = 1\,\mu\text{m}$
Al	4.628	454
Cu	0.1965	19
Fe	0.298	29

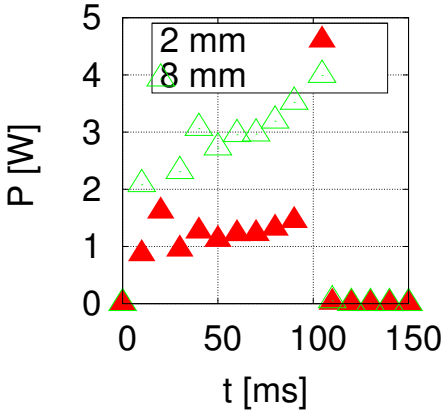
Attenuation

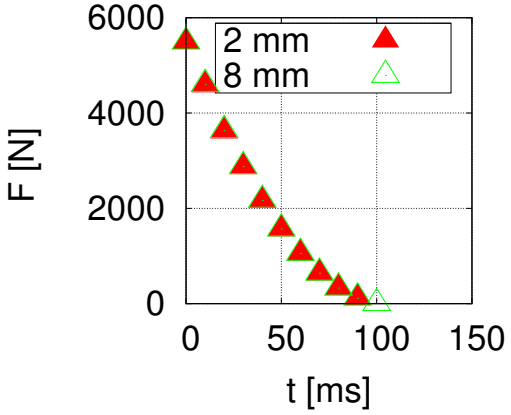


Source: Tables of X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients, http://www.nist.gov/physlab/data/xraycoef/index.cfm

Eddy currents induced after quench



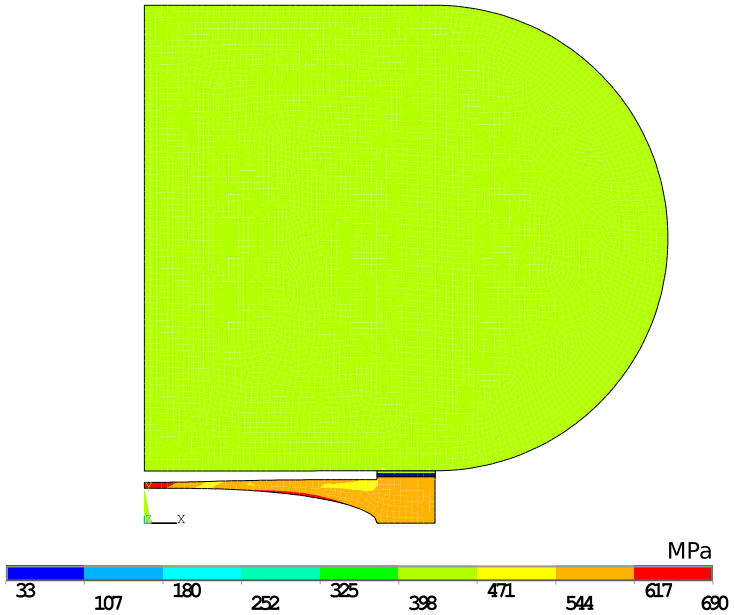


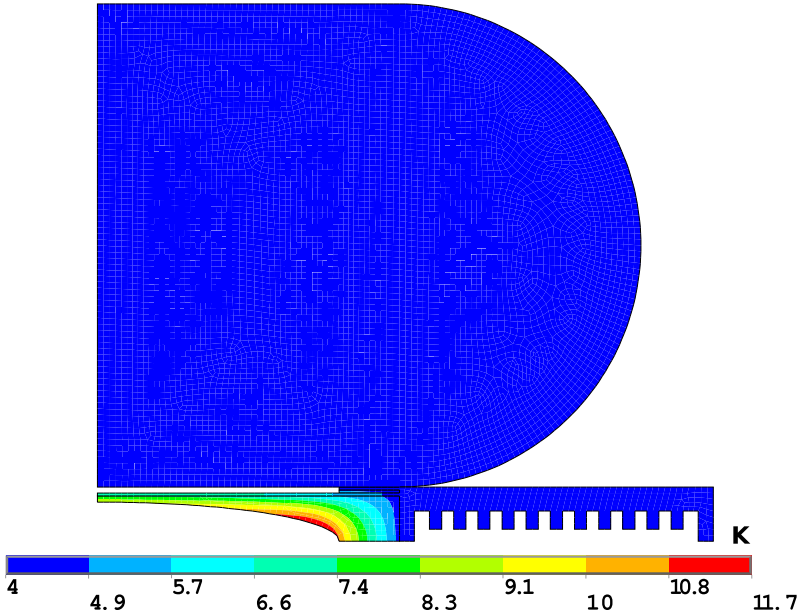


Beam-pipe design

Main purpose of cryostat and beam-pipe:

- Mechanical alignment of yaw, pitch, and roll and improved mechanical stiffness I_y (rod needed)
- Insulation of heat flux (further investigation in TDR phase)
- Shielding against X-rays (no issue with metal beam-pipe)
- Vacuum: 10^{-10} mbar (experiments needed)
- Low secondary electron emission yield (coating with NEG, amorphous C, as SPS; open issues: vacuum and resistivity)





Powering scheme and magnet protection

- Powering of 13 wigglers in series
- Electronic Protection System
- IGCT-based switches: 1 kA, 1 kV, $\ll$ 1 s
- Protection with cold parallel resistors, and if needed quench heaters
- Quench propagation can be measured with small prototype

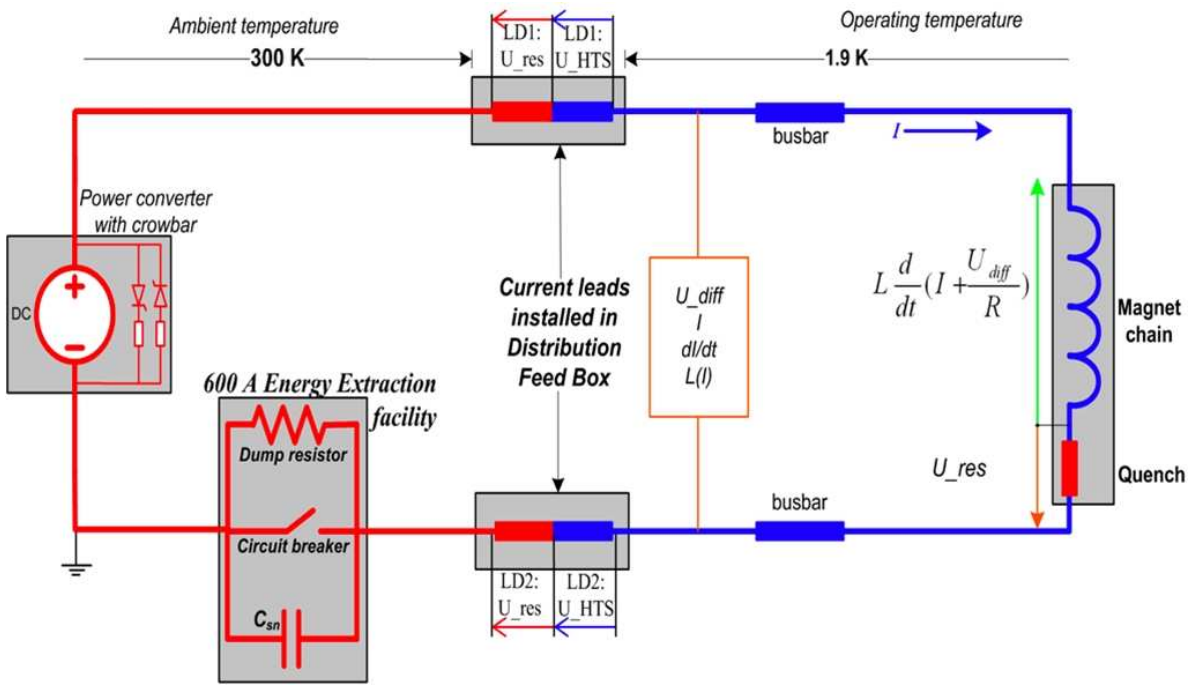
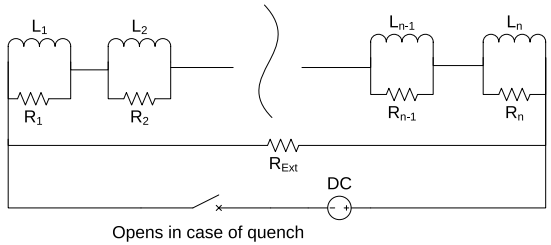


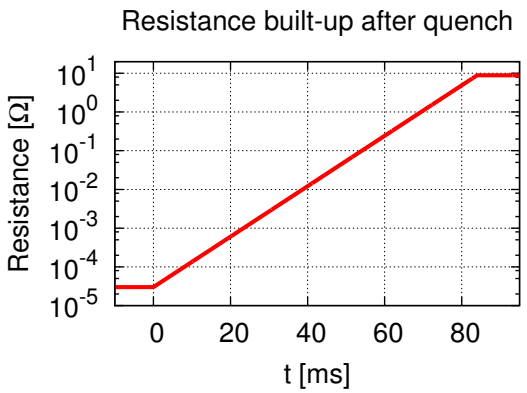
Image: Courtesy of Gert-Jan Coelingh

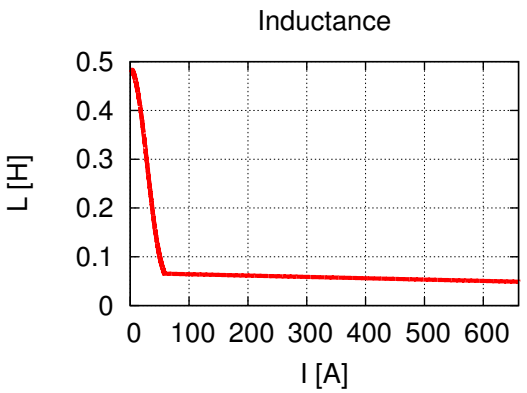
Simulation results: Magnet protection

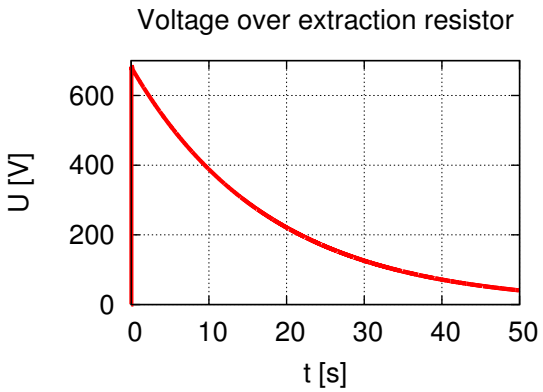


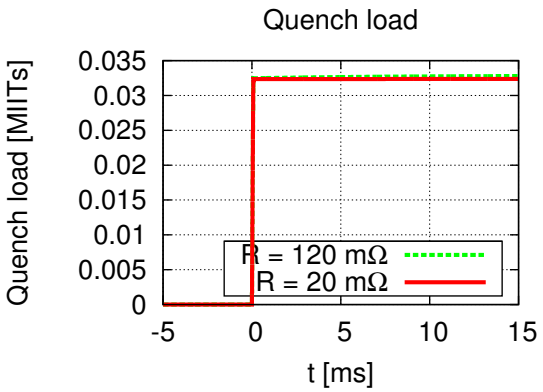
Simulations with PSpice (Emmanuele Ravaioli):

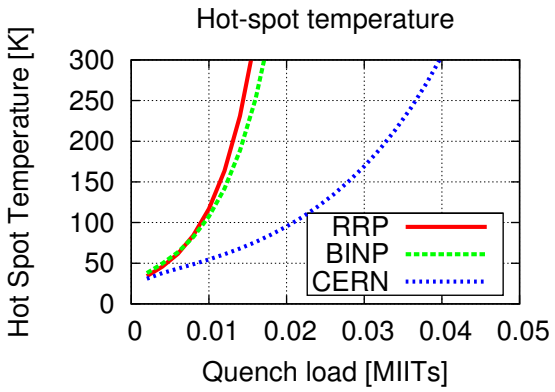
- R quench model needs to be updated for other strands
- $R_{\text{ext}} = 1.2\,\Omega$
- $R_{\text{p}} = 20\,\text{m}\Omega$
- 11 kJ stored energy/module
- 30 modules/wiggler
- MIITs around 0.03 MIITs
- R_{ext} can be optimized to deposit little energy into Helium

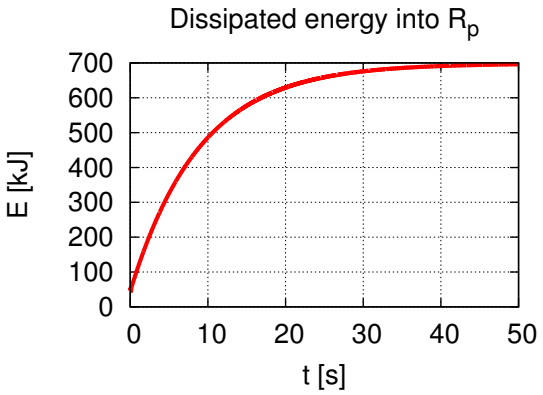










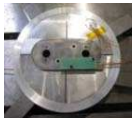


Outlook

Nb_3Sn Technology

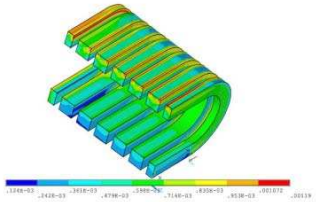
First Tests Short Model

- Conceptual Design for Short Model
- 5 Test Coils for Insulation and Heat Treatment tests
- One Vertical Racetrack Coil ready to be tested
- 2-period wiggler in mirror and full configuration (planned)



Small Prototype

- Modules, Design and Test
- Joint Testing
- Field Quality Measurements at CASPER at ANKA



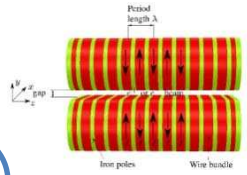
Full-Scale Prototype

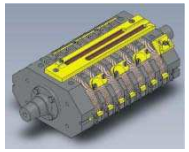
- Full Scale Nb_3Sn Prototype with cryogenics to be tested at ANKA
- Design and manufacturing at CERN but with synergies from Nb-Ti wiggler!

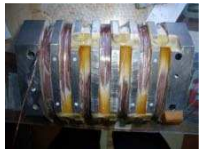
Nb-Ti Technology

First Tests Short Model

- Conceptual Design for Short Model
- 2-Period Short Model, successful tested at CERN in mirror configuration
- Short Model at BINP successful tested



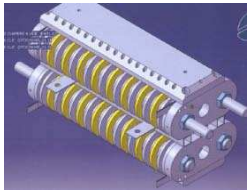




CDR

Small Prototype

- Modules, Design and Test
- Joint Testing
- Field Quality Measurements at CASPER at ANKA



Full-Scale Prototype

- Full Scale Nb-Ti Prototype with cryogenics to be tested within the collaboration framework with ANKA, Karlsruhe, Germany
- Design: Collaboration of ANKA, BINP and CERN.
- Manufacturing at BINP

SCU14 in ANKA

TDR

Summary and conclusion

- Short models show technical feasibility of Nb-Ti wigglers, but with extremely small margin to the critical current. A prototype is foreseen to be installed until 2012 in ANKA.
- Nb_3Sn test coil was successfully tested, feasible manufacturing process was shown.
- Nb_3Sn wigglers are less sensitive for beam heat load, can be operated at 5 K, and can generate higher magnetic fields. In the presented wiggler design stress and strain remains small. Therefore, this design is ideal for Nb_3Sn. A prototype is foreseen to be installed in a storage ring until 2014.
- Heat load can be handled. However, damping rings have to be enlarged.

The end

Thank you!
Any questions?
Please check also superconducting magnet section at:
`http://project-clic-cdr.web.cern.ch/project-clic-cdr/`