Design and analysis of a HTS internally cooled cable for the Muon Collider target magnet

L. Bottura, C. Accettura, A. Kolehmainen, CERN
J. Lorenzo Gomez, A. Portone, P. Testoni, F4E

CHATS-AS 2023
Torino, Italy

Partly funded by the European Union under
Grant Agreement n. 101094300

Outline

- What is a *muon collider* ?
- The *target and capture* solenoid magnet
- Cooling at 20 K
- Conductor analyses
- Opportunities and perspective

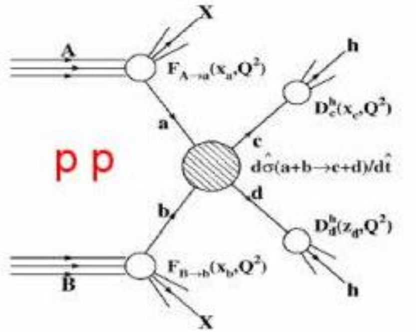
Outline

- What is a *muon collider* ?
- The *target and capture* solenoid magnet
- Cooling at 20 K
- Conductor analyses
- Opportunities and perspective

Collider Choices

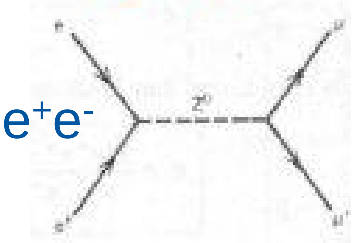
- Hadron collisions: compound particles
  - LHC collides 13.6 TeV protons
  - Protons are mix of quarks, anti-quarks and gluons
  - **Very complex to extract physics**
  - **But can reach high energies**

- Lepton collisions: elementary particles
  - LEP reached 0.205 TeV with electron-positron collisions
  - Clean events, easy to extract physics
  - **Lepton collisions ⇒ precision measurements**
  - **Hard to reach high energies**



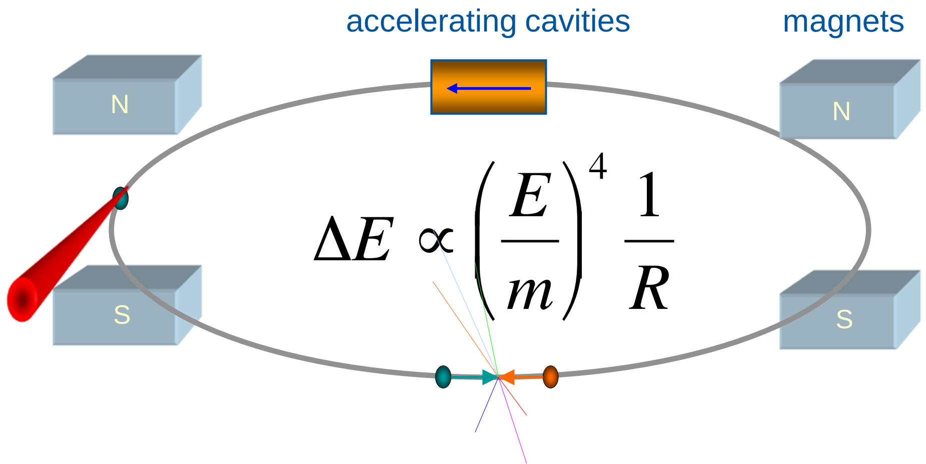
p p

e^+e^-



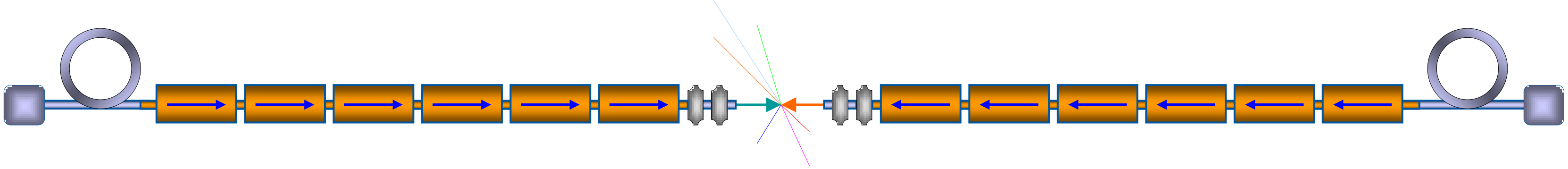
Energy Limit

Electron-positron rings (*multi-pass colliders*) are **limited by synchrotron radiation**



$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

Electron-positron linear colliders **avoid synchrotron radiation**, but are **single pass**
Typically cost proportional to energy and power proportional to luminosity,



Hence present energy frontier is probed by proton rings

Novel approach: the **muon collider**
Large mass suppresses synchrotron radiation => circular collider, **multi-pass**
Fundamental particle yields clean collisions => **less beam energy** than protons
But lifetime at rest only 2.2 μs (increases with energy)

The muon collider is part of the European Accelerator R&D Roadmap

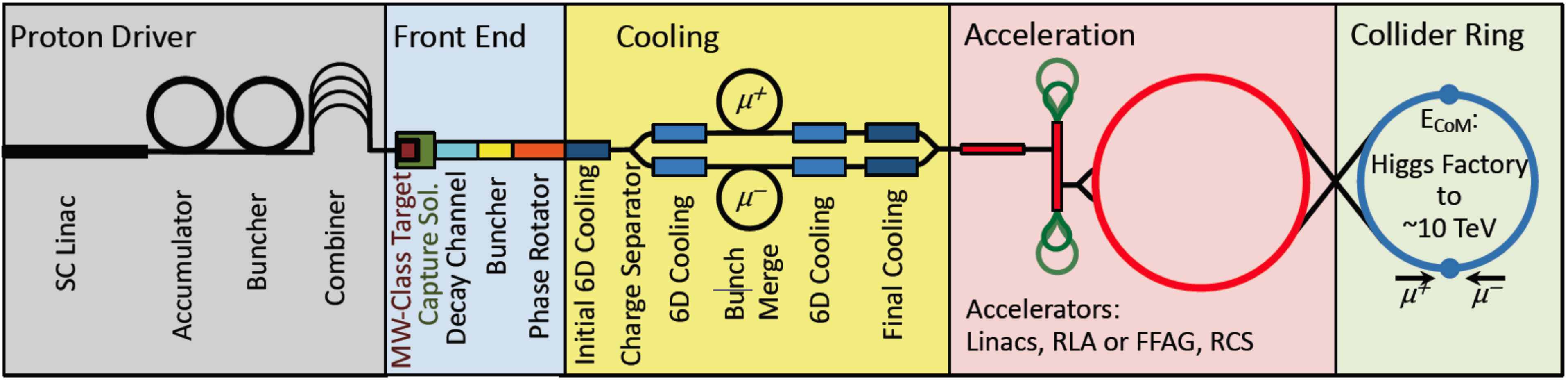
e^-: 0.511 MeV
μ: 106 MeV
p^+: 938 MeV

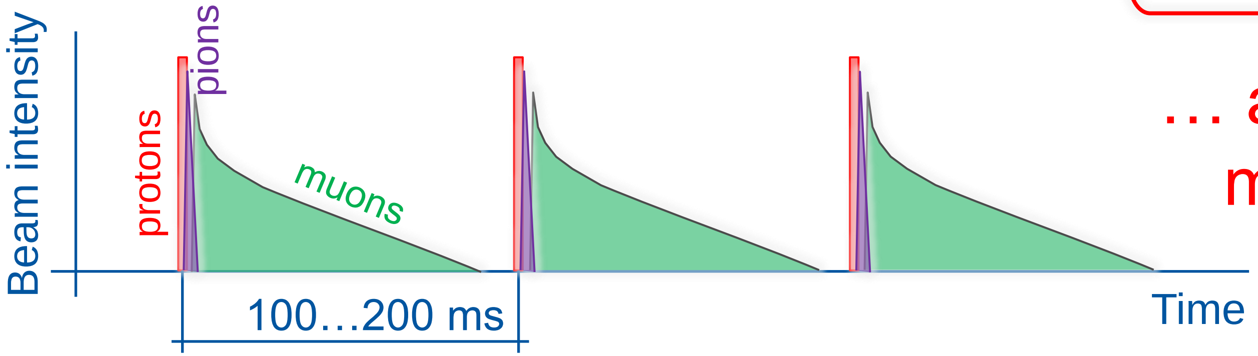
Proton-driven Muon Collider Concept

Muon Accelerator Program

Produce a low emittance muon beam…

… collide !





… accelerate muons…

Outline

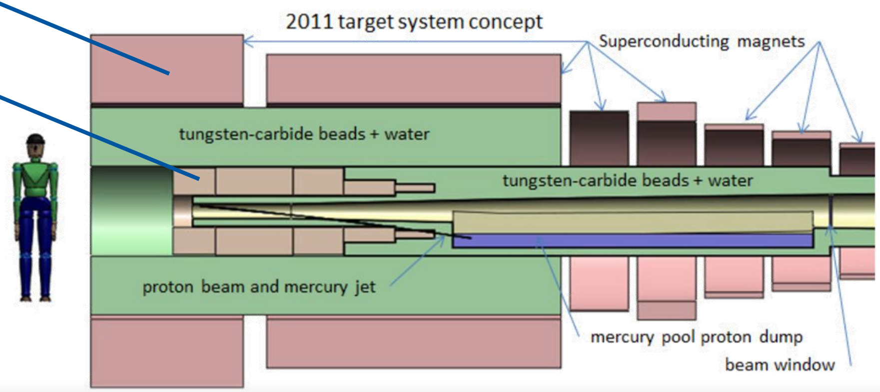
- What is a *muon collider* ?
- The *target and capture* solenoid magnet
- Cooling at 20 K
- Conductor analyses
- Opportunities and perspective

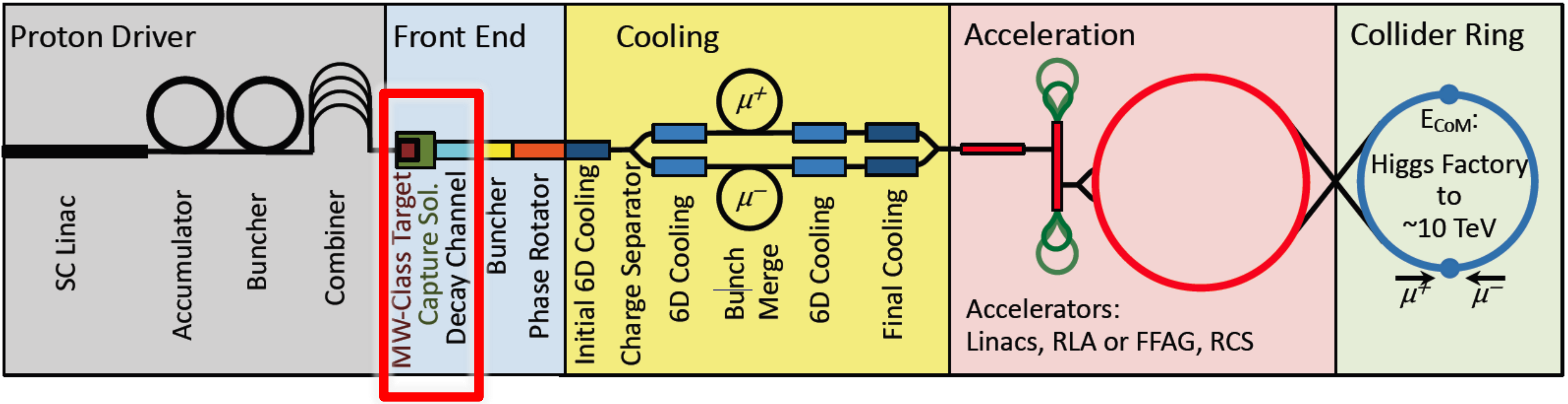
Target and capture solenoid – 1/4

Superconducting (LTS) outsert

Rad-hard resistive insert

Field on target 20 T, 150 mm
Beam power on target: 1…2 MW



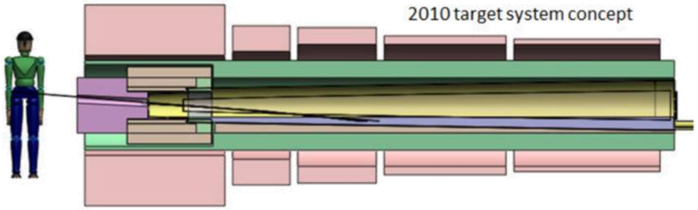


Large stored energy o(2) GJ, mass o(300) tons, cost o(100) M

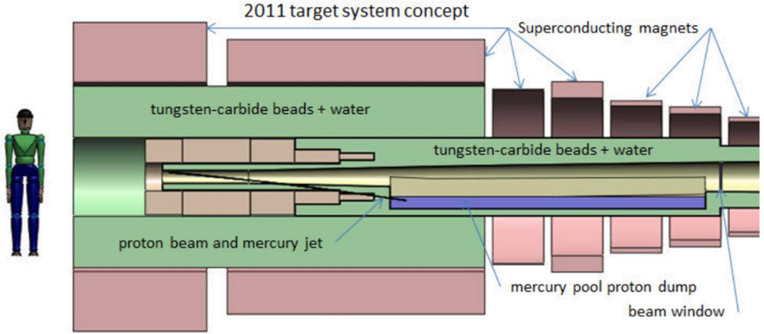
Target and capture – 2/4

- Reduce the mass (CAPEX) of the system, and increase operating temperature to improve cryogenic CoP (OPEX)

US-MAP **2010** design
LTS (14 T) + NC (6 T)



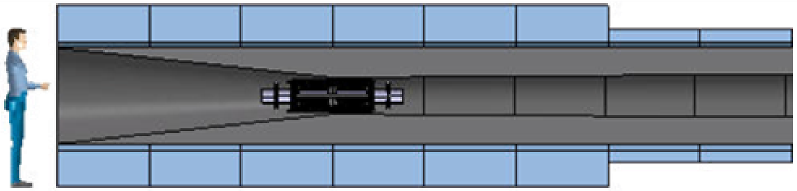
US-MAP **2011** design
LTS (14 T) + NC (6 T)



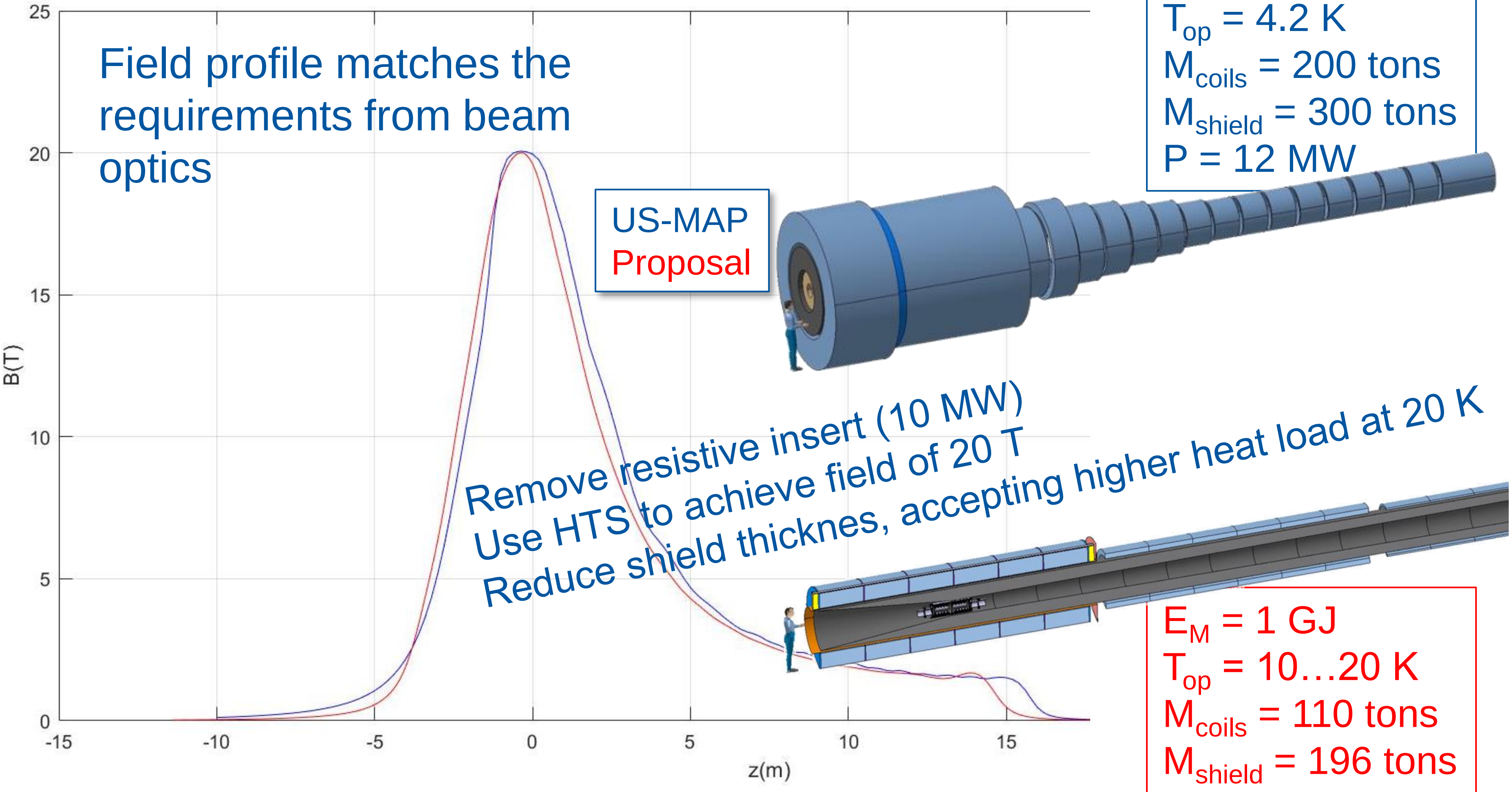
H.G. Kirk, PAC 2011

Magnet	z_{min} (cm)	Δz (cm)	r_{min} (cm)	Δr (cm)	I (A/mm^2)
RC1	-131.3	47.3	17.8	30.24	16.56
RC2	-84	86.2	17.8	30.88	16.56
RC3	2.1	56.2	17.8	30.25	16.56
RC4	58.3	57	17.8	16.6	16.56
RC5	115.3	43.5	21.88	7.96	16.56
SC1	-222.6	169.4	120	75.85	23.22
SC2	-53.1	26.1	120	54	0
SC3	-27.1	327.1	120	54.07	23.1
SC4	310	65	110	1.16	29.96
SC5	385	65	100	20.76	33.31
SC6	460	65	90	6.4	35.85
SC7	535	65	80	8.71	38.21
SC8	610	65	70	5.61	40
SC9	685	65	60	6.06	40
SC10	760	65	50	4.72	40
SC11	835	65	45	4.6	40
SC12	910	65	45	4.42	40
SC13	985	65	45	4.31	40
SC14	1060	65	45	3.85	40
SC15	1135	65	45	3.83	40
SC16	1210	65	45	3.51	40
SC17	1285	65	45	3.53	40
SC18	1360	65	45	3.44	40
SC19	1435	140	45	3.24	40

MuCol **2022** design
HTS (20 T, 20 K)



Target and capture – 3/4



Field profile matches the requirements from beam optics

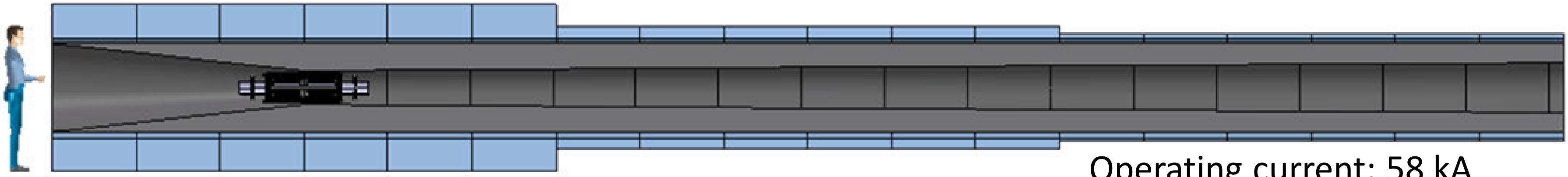
US-MAP
Proposal

E_M = 2.9 GJ
T_{op} = 4.2 K
M_{coils} = 200 tons
M_{shield} = 300 tons
P = 12 MW

Remove resistive insert (10 MW)
Use HTS to achieve field of 20 T
Reduce shield thicknes, accepting higher heat load at 20 K

E_M = 1 GJ
T_{op} = 10…20 K
M_{coils} = 110 tons
M_{shield} = 196 tons
P = 1MW

Target and capture – 4/4

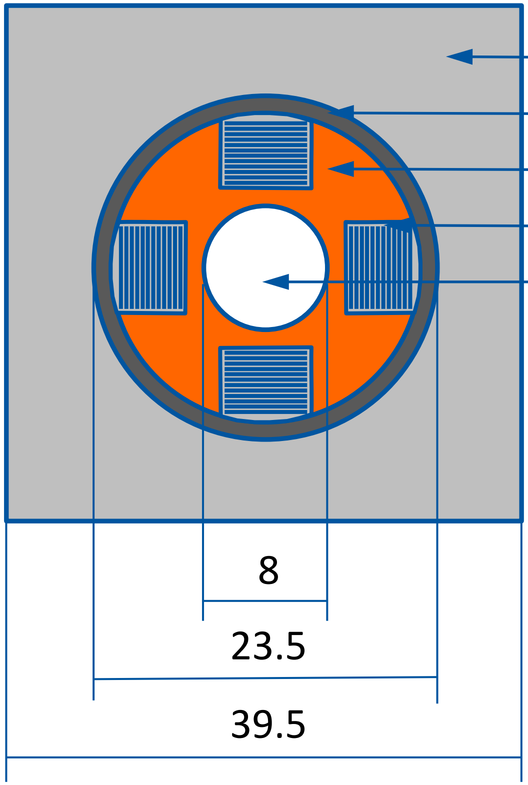


Operating current: 58 kA
Operating field: 20 T
Operating temperature: 20 K

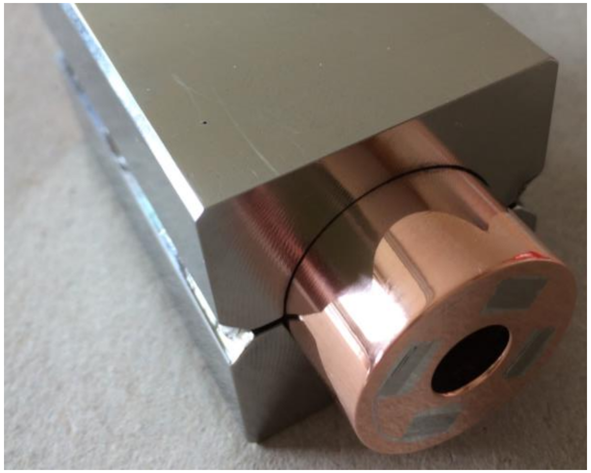
MIT “VIPER” conductor

M. Takayasu et al., IEEE TAS, 21 (2011) 2340
Z. S. Hartwig et al., SUST, 33 (2020) 11LT01

HTS conductor design



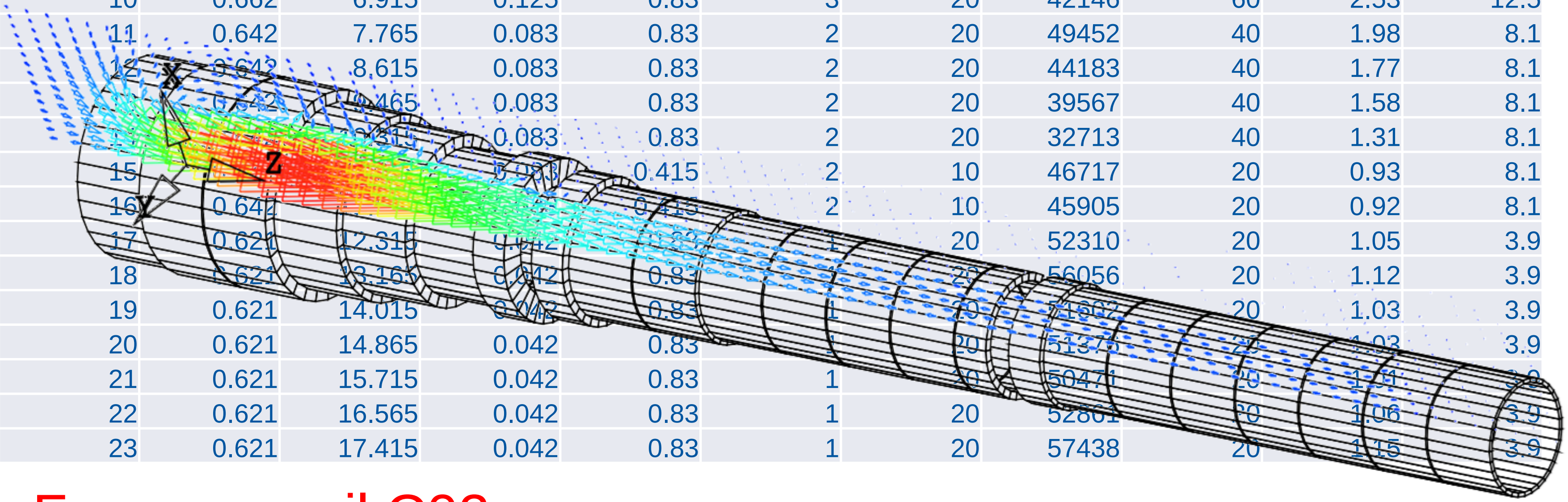
STAINLESS STEEL JACKET
STAINLESS STEEL WRAP
COPPER FORMER
SOLDERED HTS STACK
COOLING CHANNEL



Looks much like an HTS magnet for fusion !!!

Coil geometry

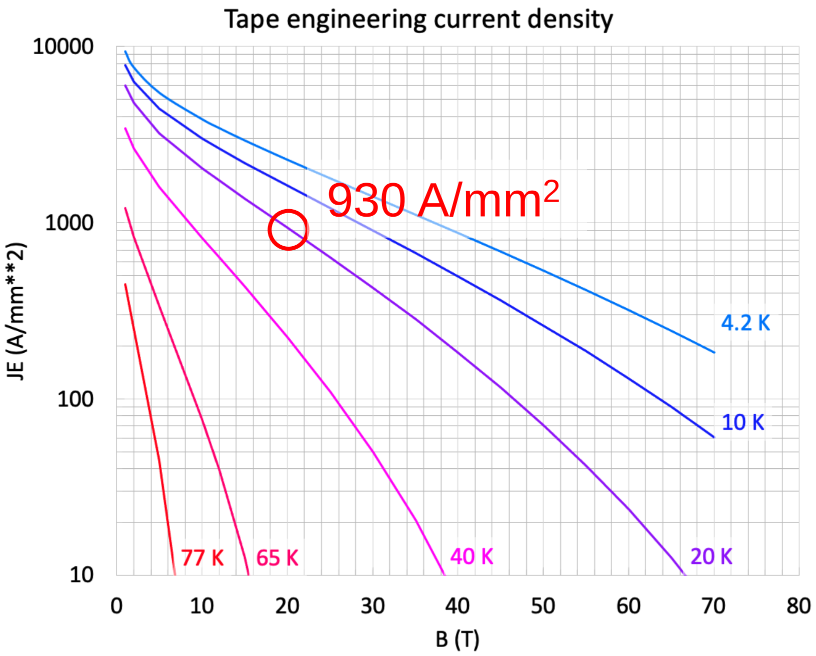
Coil	Rc (m)	Zc (m)	dR (m)	dZ (m)	Layers (-)	Pancakes (-)	Iconductor (A)	Turns (-)	Icoil (MA-turn)	Lpancake (m)
1	0.849	-0.185	0.498	0.83	12	20	58905	240	14.14	64.0
2	0.87	0.665	0.54	0.83	13	20	60710	260	15.78	71.1
3	0.87	1.515	0.54	0.83	13	20	60392	260	15.70	71.1
4	0.808	2.365	0.415	0.83	10	20	51654	200	10.33	50.8
5	0.766	3.215	0.332	0.83	8	20	47469	160	7.60	38.5
6	0.704	4.065	0.208	0.83	5	20	46504	100	4.65	22.1
7	0.745	4.708	0.291	0.415	7	10	46293	70	3.24	32.8
8	0.704	5.423	0.208	0.415	5	10	53168	50	2.66	22.1
9	0.662	6.065	0.125	0.83	3	20	43280	60	2.60	12.5
10	0.662	6.915	0.125	0.83	3	20	42146	60	2.53	12.5
11	0.642	7.765	0.083	0.83	2	20	49452	40	1.98	8.1
12	0.642	8.615	0.083	0.83	2	20	44183	40	1.77	8.1
13	0.642	9.465	0.083	0.83	2	20	39567	40	1.58	8.1
14	0.642	10.315	0.083	0.83	2	20	32713	40	1.31	8.1
15	[illegible]	[illegible]	0.083	0.415	2	10	46717	20	0.93	8.1
16	0.642	[illegible]	0.083	0.415	2	10	45905	20	0.92	8.1
17	0.621	12.315	0.042	0.83	1	20	52310	20	1.05	3.9
18	0.621	13.165	0.042	0.83	1	20	56056	20	1.12	3.9
19	0.621	14.015	0.042	0.83	1	20	51602	20	1.03	3.9
20	0.621	14.865	0.042	0.83	1	20	51375	20	1.03	3.9
21	0.621	15.715	0.042	0.83	1	20	50471	20	1.01	3.9
22	0.621	16.565	0.042	0.83	1	20	52861	20	1.06	3.9
23	0.621	17.415	0.042	0.83	1	20	57438	20	1.15	3.9



Focus on coil C02 (highest current, highest field, higest energy)

Conductor design

HTS tape thickness	(mm)	62
HTS tapes	(-)	80
HTS stack width	(mm)	6
HTS stack thickness	(mm)	5
HTS stack width	(mm)	6
HTS tapes	(-)	80
Number of HTS stacks	(-)	4
Copper diameter	(mm)	23
Hole diameter	(mm)	8
Wetted perimeter	(mm)	25
Wrap thickness	(mm)	0.25
Jacket outer dimension	(mm)	39.5
A_{SC}	(mm^2)	4.2
$A_{Substrate}$	(mm^2)	77
A_{Cu}	(mm^2)	361
A_{Helium}	(mm^2)	50
A_{Wrap}	(mm^2)	18
A_{Jacket}	(mm^2)	1127
$A_{Cable\ Space}$	(mm^2)	511
$A_{Conductor}$	(mm^2)	1560


Tape engineering current density

930 A/mm^2

$$J_C = \frac{C_0}{B} h(t) f_p(b)$$

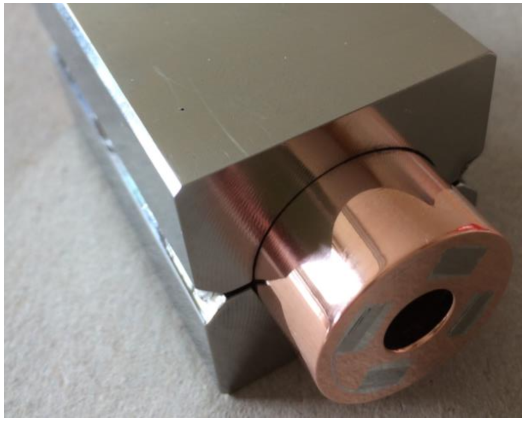
$$B_{irr}(T) = B_{irr0}\left(1 - \frac{T}{T_{irr0}}\right)^{\nu}$$

$$T_{irr}(B) = T_{irr0}\left(1 - \frac{B}{B_{irr0}}\right)^{\frac{1}{\nu}}$$

$$h(t) = (1 - t^{\nu})(1 - t^{m})$$

$$f_p(b) = b^p (1 - b)^q$$

$$t = \frac{T}{T_{irr0}} \qquad b = \frac{B}{B_{irr}(T)}$$



I_{op} = 61 kA
B_{op} = 20 T
T_{op} = 20 K
T_{cs} = 29.7 K

Outline

- What is a *muon collider* ?
- The *target and capture* solenoid magnet
- Cooling at 20 K
- Conductor analyses
- Opportunities and perspective

Heat load from recirculation

State equation

$$\frac{p}{\rho} = RT$$

Heat removed

$$\dot{m}\Delta h = \dot{q} \rightarrow \dot{m} \approx \frac{\dot{q}}{c_p \Delta T}$$

Pressure drop

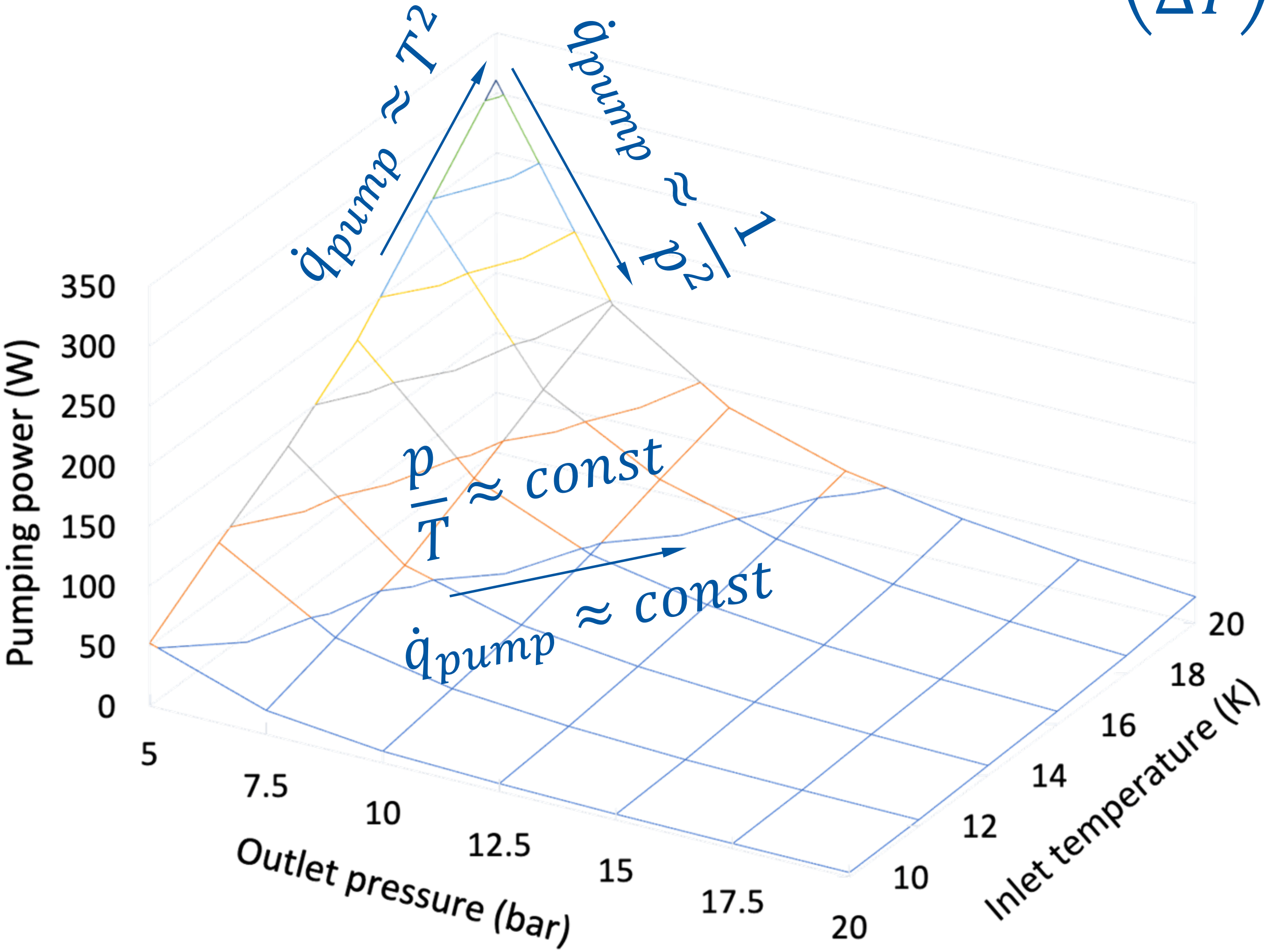
$$\frac{dp}{dx} \approx \frac{2f}{D_h}\frac{\dot{m}^2}{\rho} \rightarrow \Delta p \approx \frac{\dot{m}^2}{\langle\rho\rangle}$$

$$\dot{q}_{pump} \approx \frac{\dot{m}}{\langle\rho\rangle}\Delta p \rightarrow \dot{q}_{pump} \approx \frac{\dot{m}^3}{\langle\rho\rangle^2} \rightarrow \boxed{\dot{q}_{pump} \approx \left(\frac{\dot{q}}{\Delta T}\right)^3 \left\langle\frac{T}{p}\right\rangle^2}$$

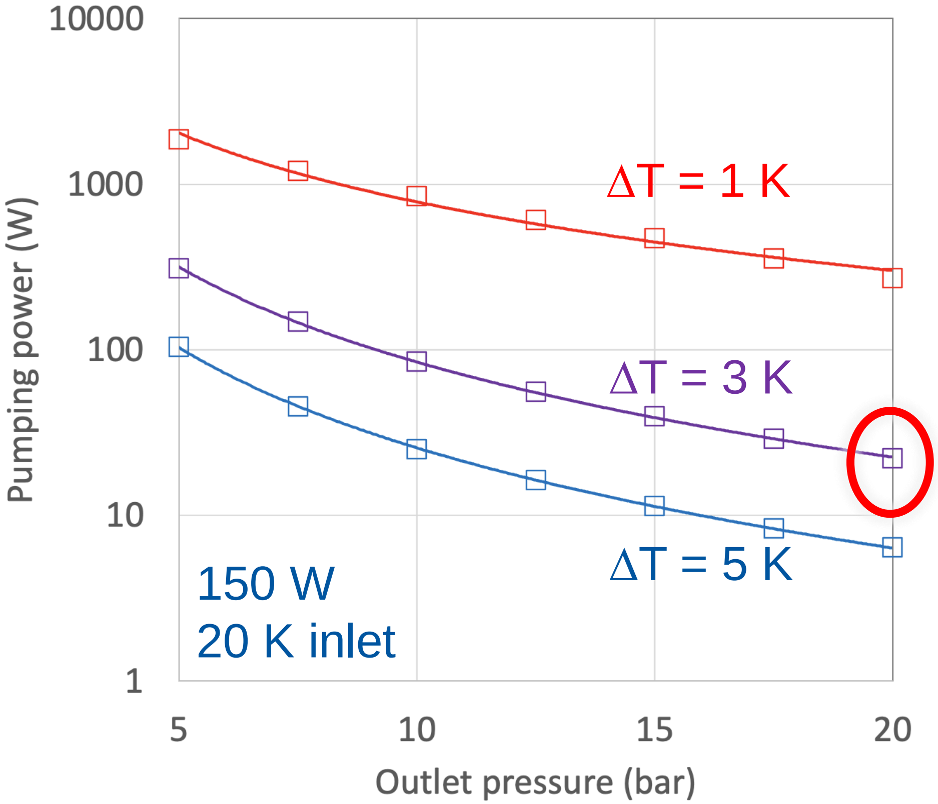
Parametric study

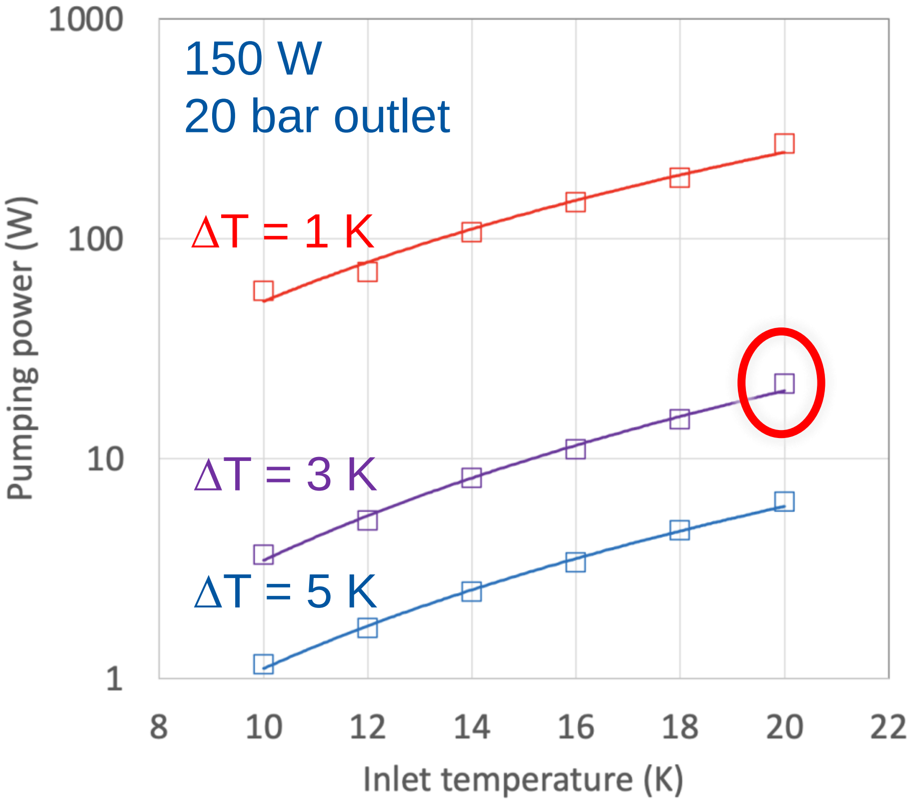
$$\dot{q}_{pump} \approx \left(\frac{\dot{q}}{\Delta T}\right)^3 \left\langle\frac{T}{p}\right\rangle^2$$

A = 5 mm^2
D_h = 8 mm
L = 150 m
$\dot{q}$ = 150 W
ΔT = 3K
η_{Pump} = 80%



Optimal cooling conditions





- Compared to typical conditions at 4.5 K, operation at 20 K implies
  - High pressure, o(20) bar
  - Large temperature increase, o(3) K

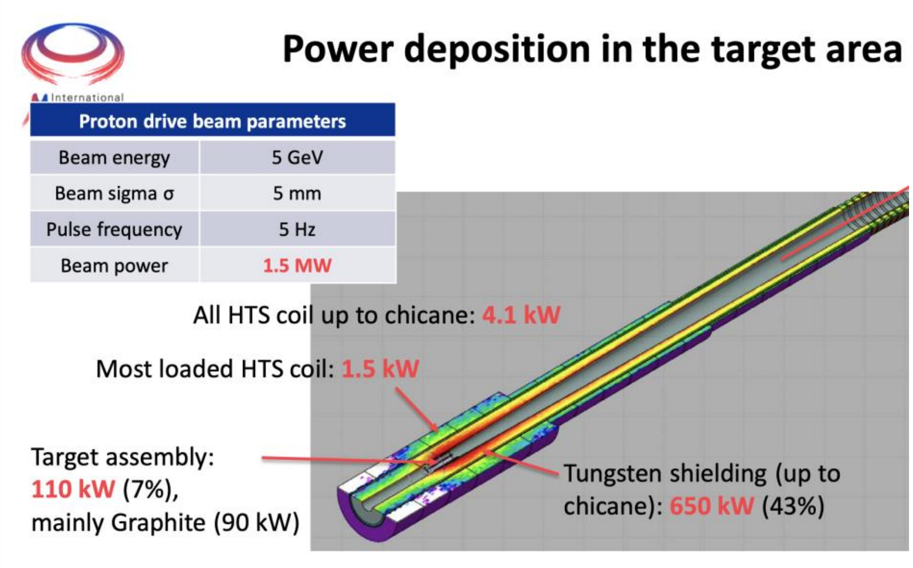
Outline

- What is a *muon collider* ?
- The *target and capture* solenoid magnet
- Cooling at 20 K
- Conductor analyses
- Opportunities and perspective

Cooling

NOTE: time stucture ignored

2 W/m
peak



Power deposition in the target area

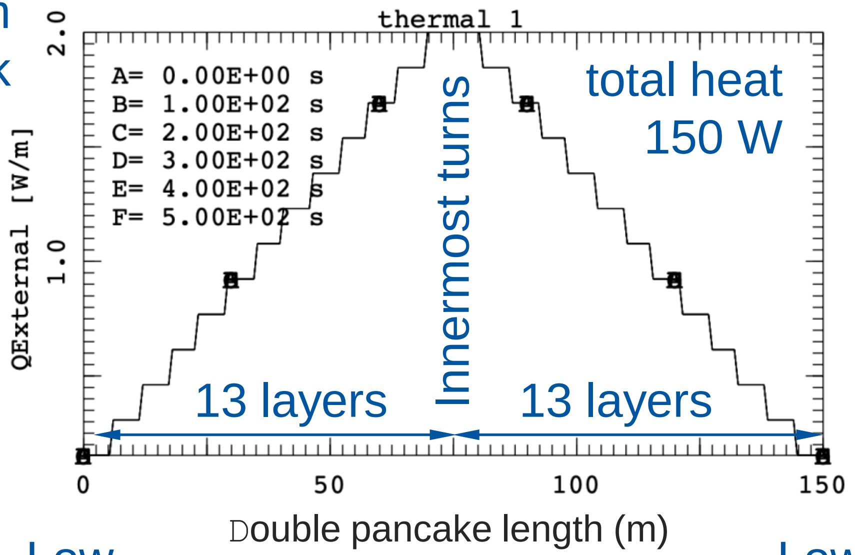
Proton drive beam parameters	
Beam energy	5 GeV
Beam sigma σ	5 mm
Pulse frequency	5 Hz
Beam power	1.5 MW

All HTS coil up to chicane: 4.1 kW

Most loaded HTS coil: 1.5 kW

Target assembly:
110 kW (7%),
mainly Graphite (90 kW)

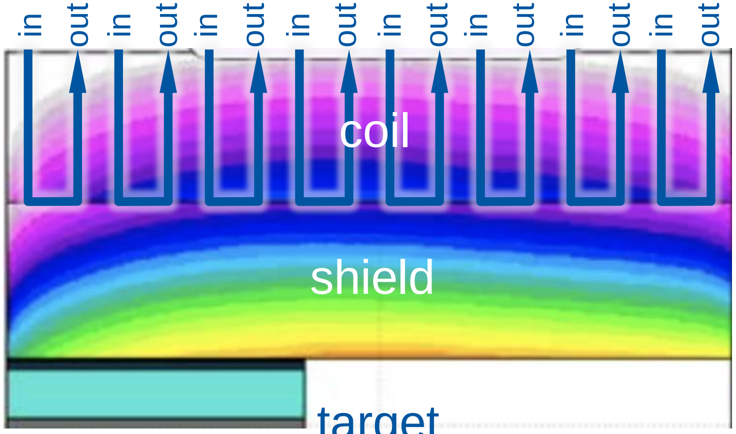
Tungsten shielding (up to
chicane): 650 kW (43%)



Low
field

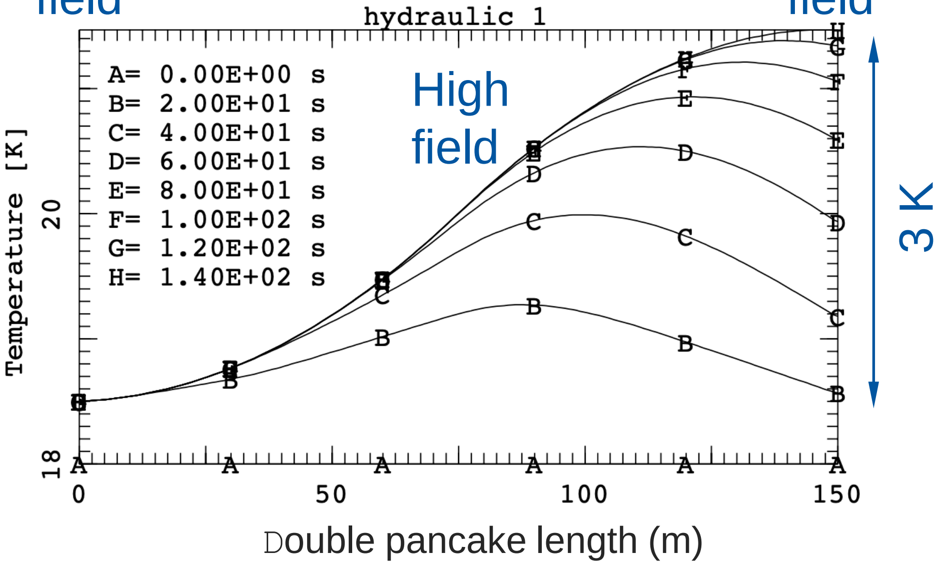
Low
field

Total
heat in
the coil
4.1 kW



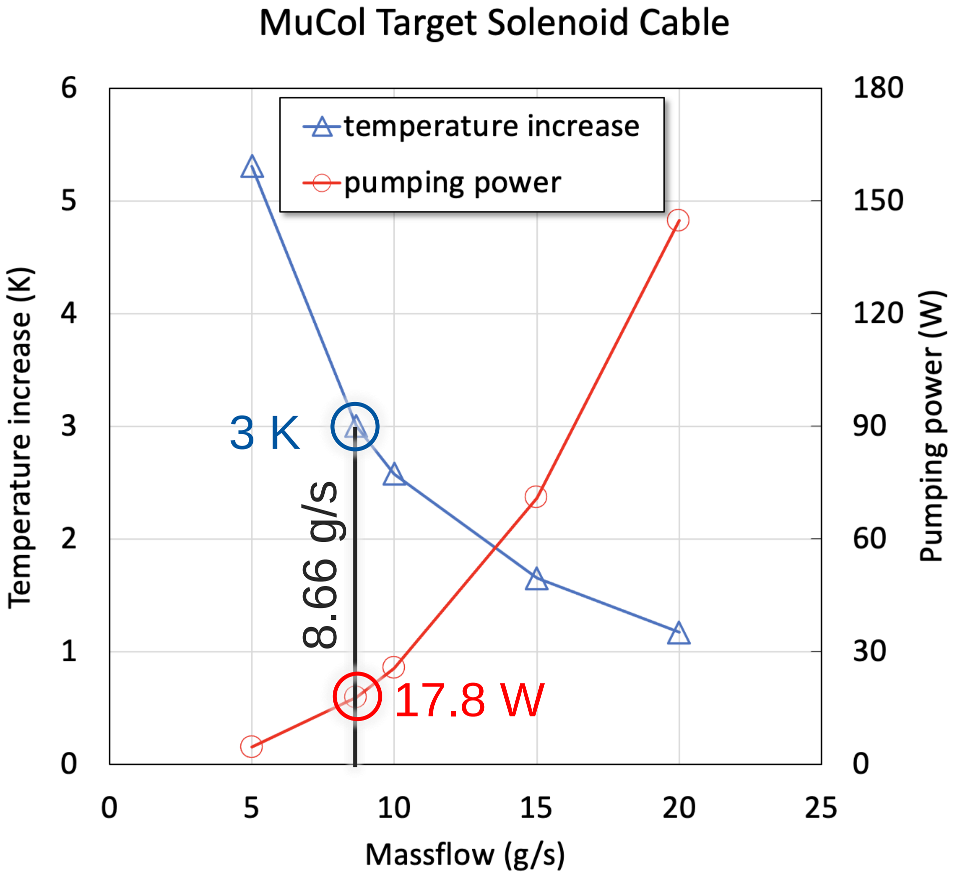
Proton
beam

D. Calzolari and A. Lechner, CERN

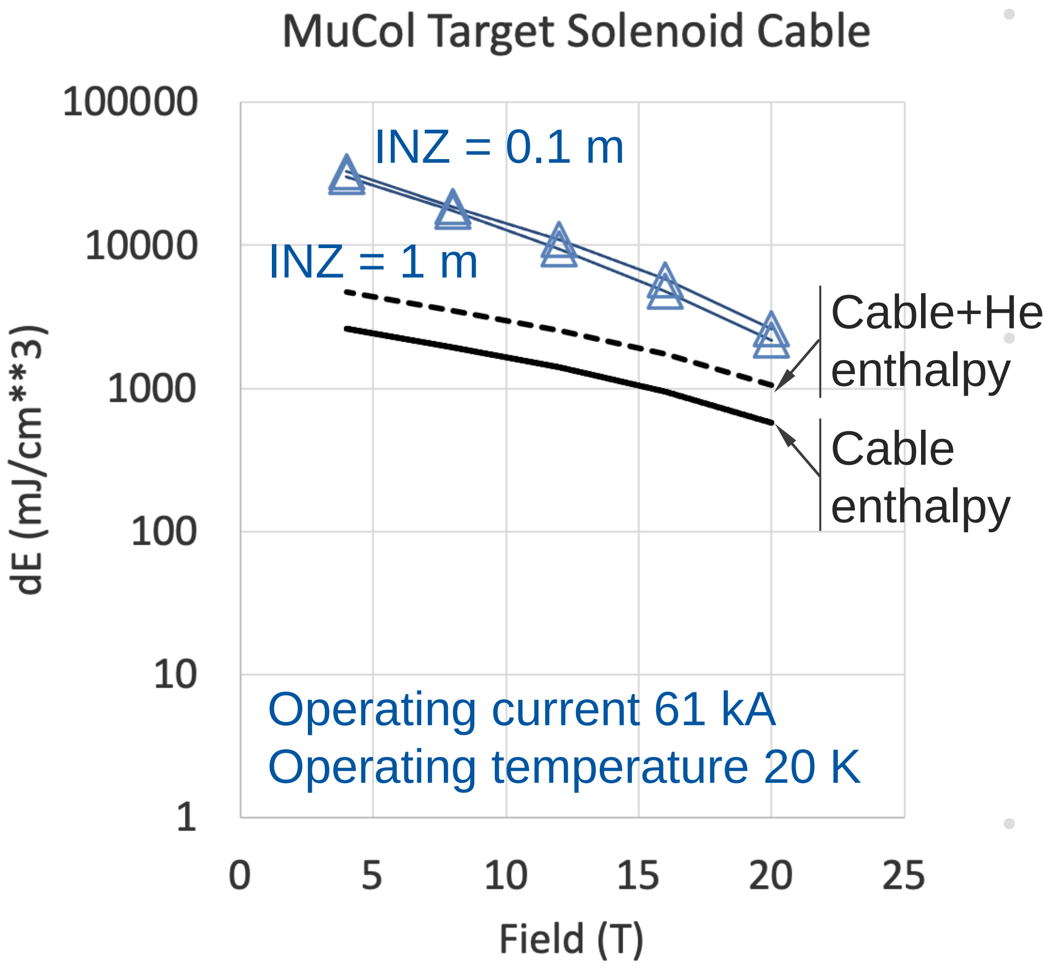


Nominal cooling condition

- A flow dm/dt of approximately 8 g/s is required to remove a nuclear heat load of 150 W with a temperature increase ΔT of 3 K
- With this flow the pumping loss is about 20 W (considering an adiabatic efficiency η_{pump} of 80 %)
- This is about 13 % of the nuclear heat load, and is an acceptable overhead
- It would be possible to remove higher heat loads under the same temperature increase, but the pumping loss grows rapidly, approximately like $(dm/dt)^3$



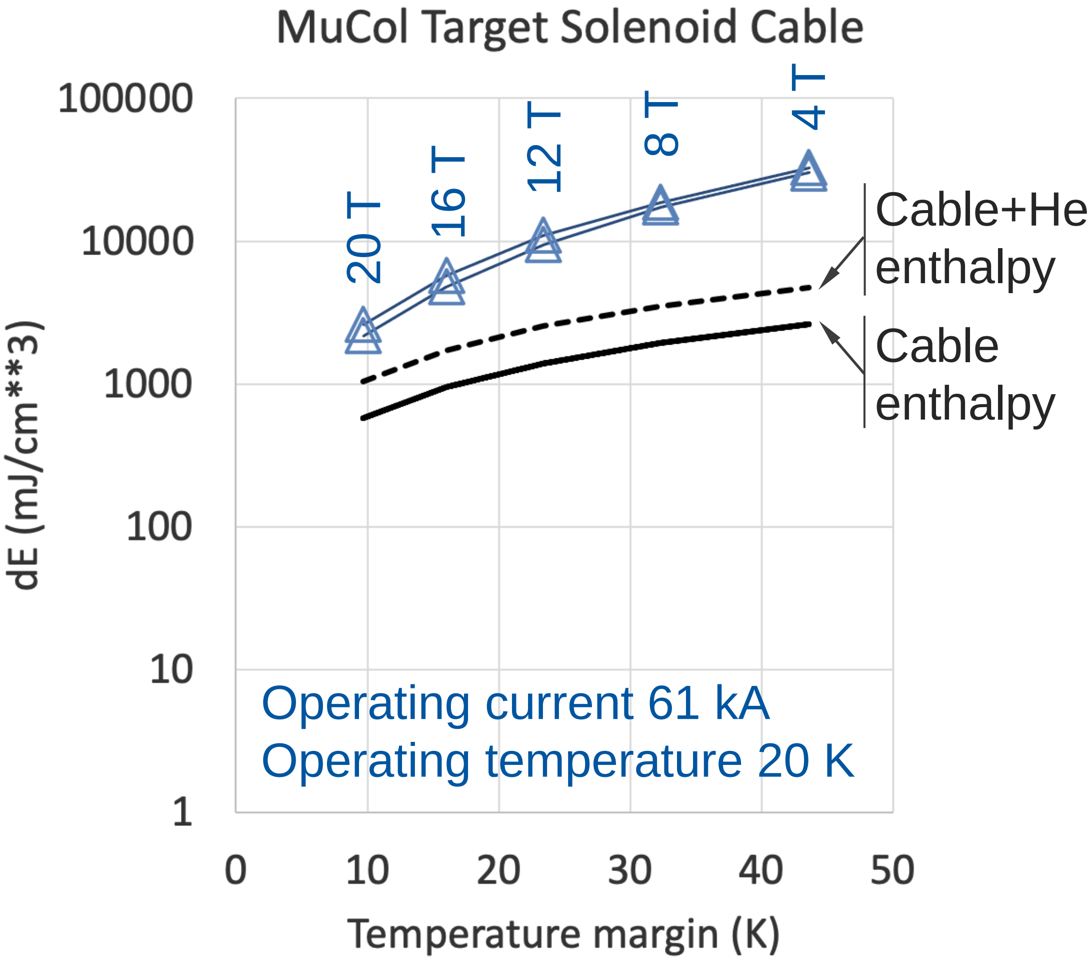
Margin and stability – 1/3



- Values of stability margin are (as expected) very high ! It is very unlikely that the cable will quench because of transient heat inputs
- The stability margin is well above the enthalpy reserve of the cable, also including helium. The reason is that the transient is slow, and there is time to *conduct* and *convect* heat away even for very large INZ lengths
- This effect is even more marked at low field (high temperature margin)

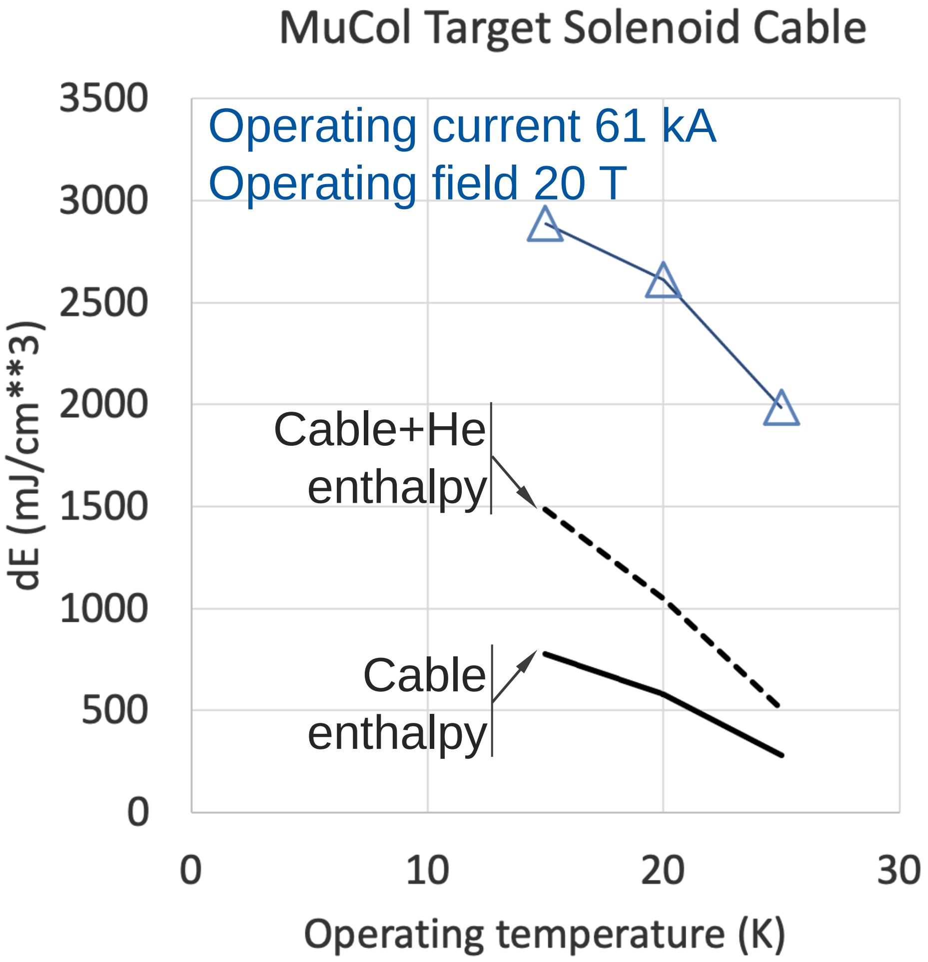
Margin and stability – 2/3

- The temperature margin ΔT **is about 10 K** at nominal conditions of current, field and temperature
  - I_{op} = 61 kA
  - B_{op} = 20 T
  - T_{op} = 20 K
- In the low field regions of the coil (e.g. 4 T) **the temperature margin is above 40 K**
- The large stability in the low field region may make protection difficult ?



Operating current 61 kA
Operating temperature 20 K

Margin and stability – 3/3



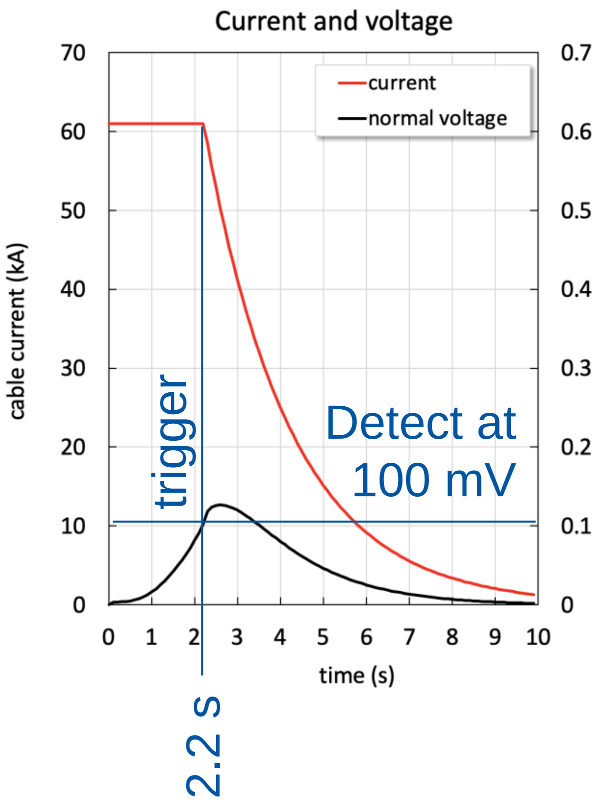
- Operating at higher temperature than 20 K (e.g. 25 K) **may still be an option**, the energy margin is substantial
- Operating at lower temperature than 20 K (e.g. 15 K) does not bring a substantial benefit in energy margin
  - **Recall that the heat capacity drops dramatically at low temperature**

Detection and protection – 1/3

Coil Module 2 (high field and current)

- Single coil stored energy: 165 MJ
- Coulped stored energy: 299.7 MJ
- Dump voltage: 5 kV

INZ in the center of the double pancake
10 cm length quenched
Exponential dump following trigger

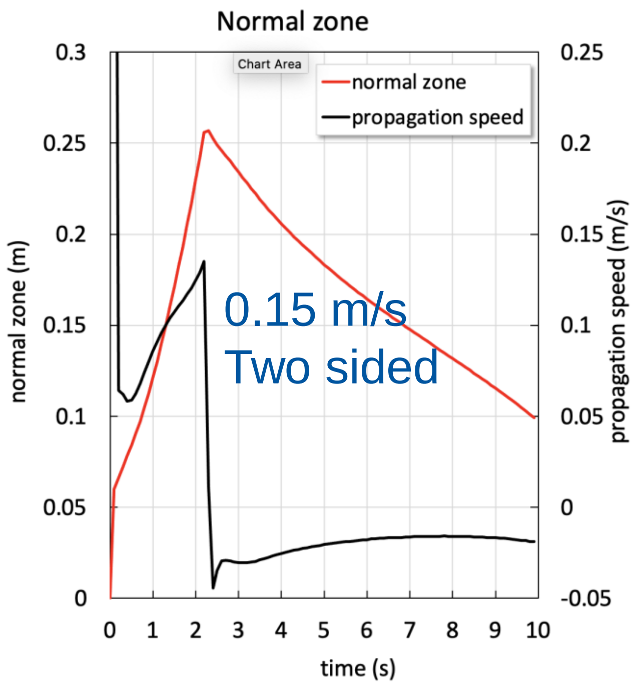


Current and voltage

trigger

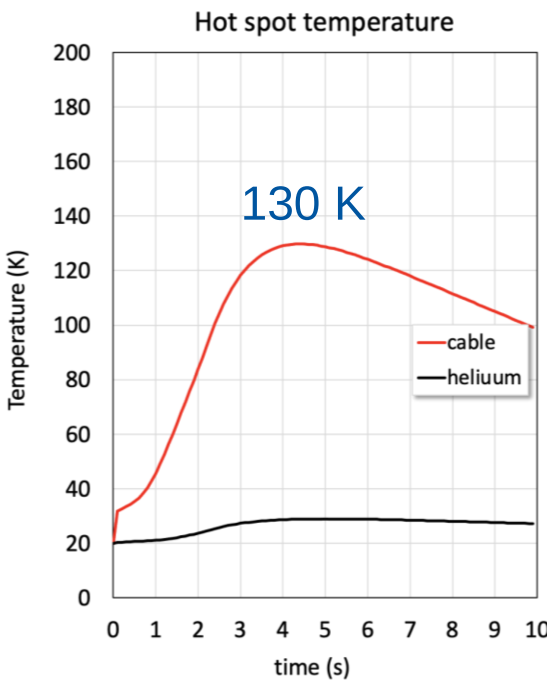
2.2 s

Detect at 100 mV



Normal zone

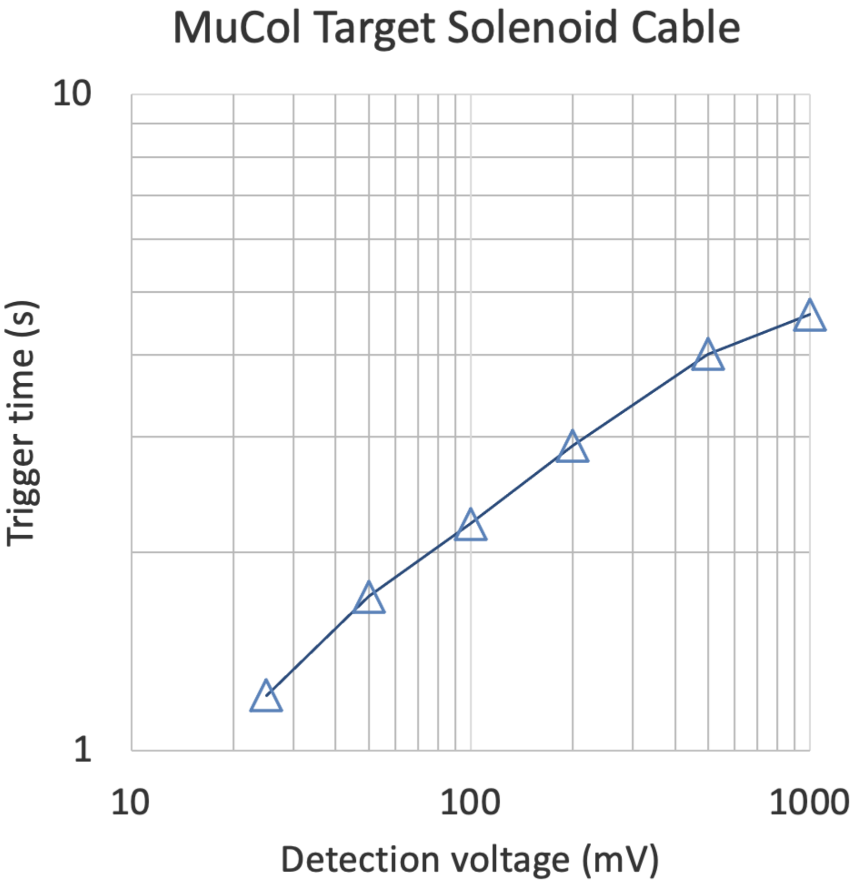
0.15 m/s
Two sided

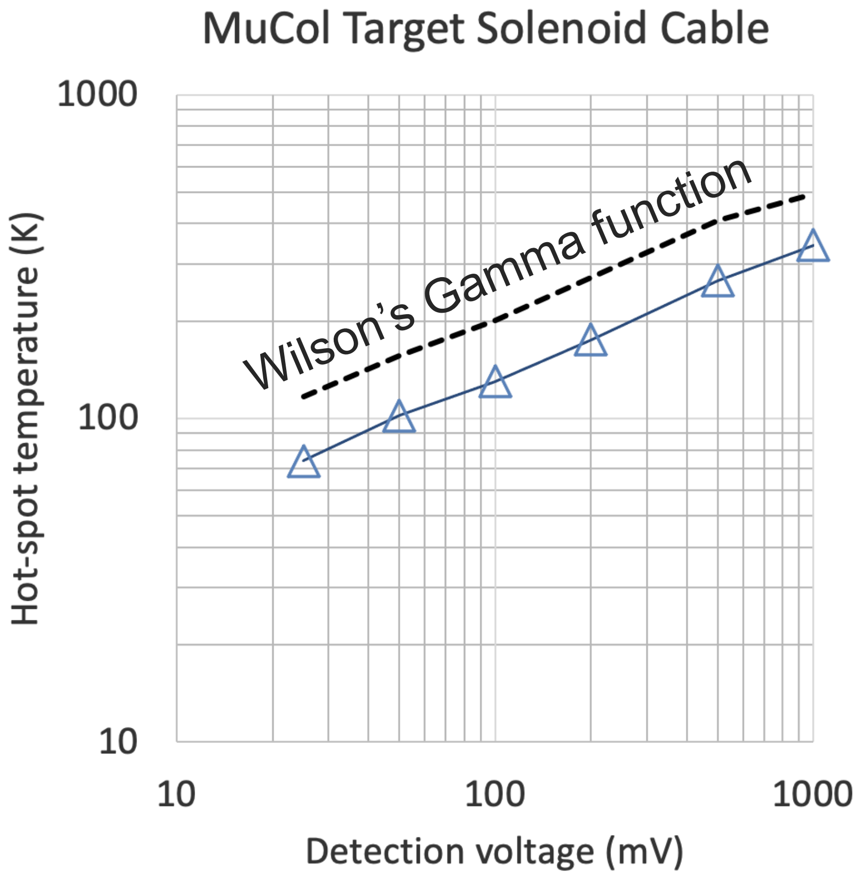


Hot spot temperature

130 K

Detection and protection – 2/3





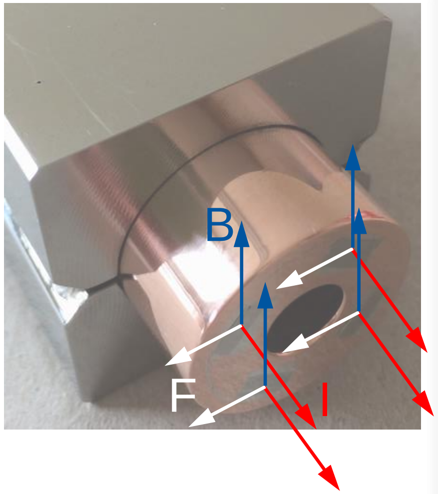
Detection with "reasonable" voltage values appears to work !

Detection and protection – 3/3

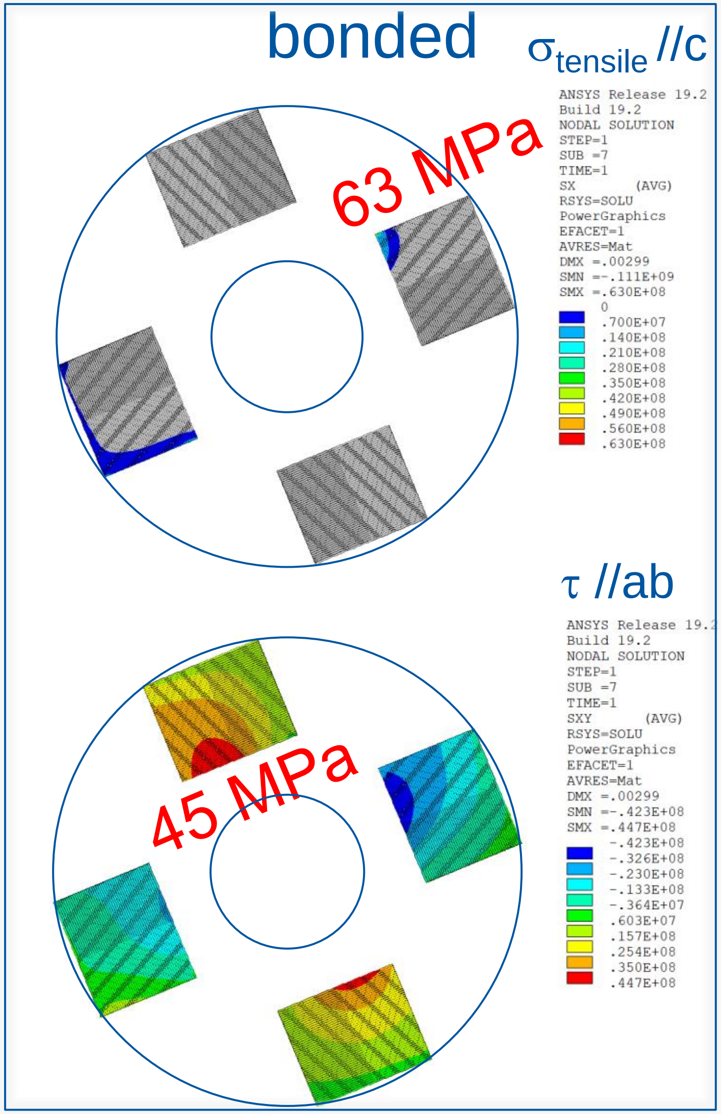
- Study the detection and dump for quenches in the low field region or at low current/field
  - The low field region at nomnal current seems to be most dangerous
  - Low current/low field (e.g. during ramp) implies long detection times, but this appears compatible with modest hot-spot limits

I_{op} (kA)	B_{op} (T)	$t_{Detection}$ (s)	T_{max} (K)
61	20	2.2	130
61	4	2.8	172
30	9.84	14.8	140

HTS cable mechanics



May this be the reason why soldered and twisted high field and high current cables are also subject to degradation ?

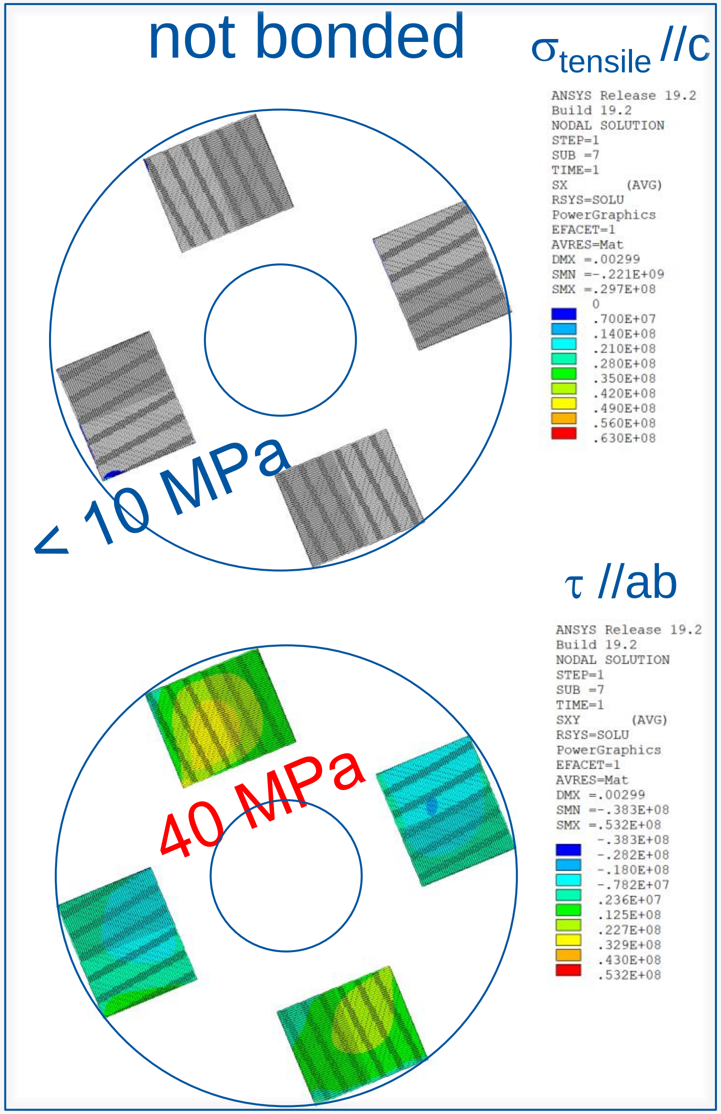

bonded

$\sigma_{tensile}$ //c

63 MPa

τ //ab

45 MPa


not bonded

$\sigma_{tensile}$ //c

< 10 MPa

τ //ab

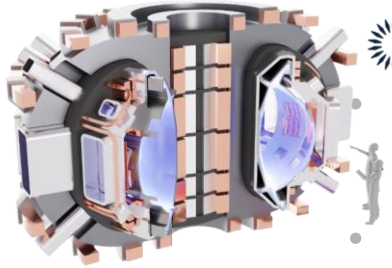
40 MPa

Outline

- What is a *muon collider* ?
- The *target and capture* solenoid magnet
- Cooling at 20 K
- Conductor analyses
- Opportunities and perspective

Opportunities and perspective

- We are looking for a solution to the design of the target and capture channel of the Muon Collider, which needs a **peak field of 20 T on axis, based on an HTS force-flow cooled cable operating at 20 K**
  - Lower footprint, mass, stored energy and cost than a LTS/NC hybrid
  - Better energy efficiency than a 4.5 K system
- Though there is much work to do, **the design selected seems not too far from being feasible !**
- This is also interesting because of implications for

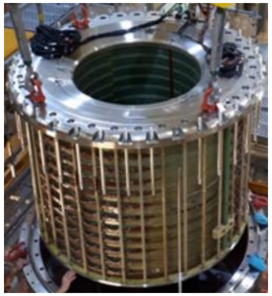


Commonwealth Fusion Systems

  - **Compact fusion machines**

LNCMI

  - **Hybrid UHF magnets for science**



www.cern.ch

Proton-driven Muon Collider Concept

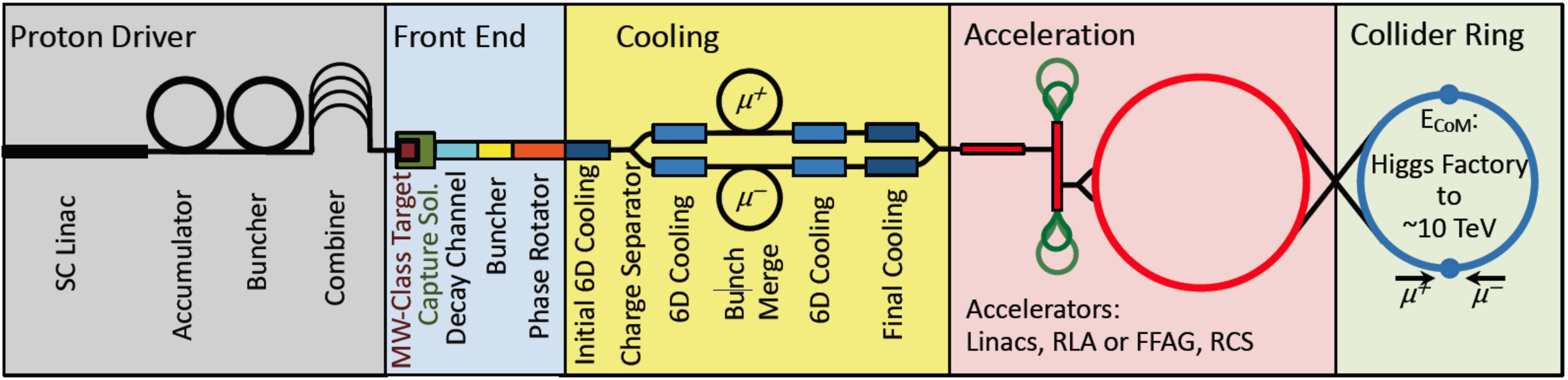
Produce a low emittance muon beam…

… collide!

Pulsed

Steady state

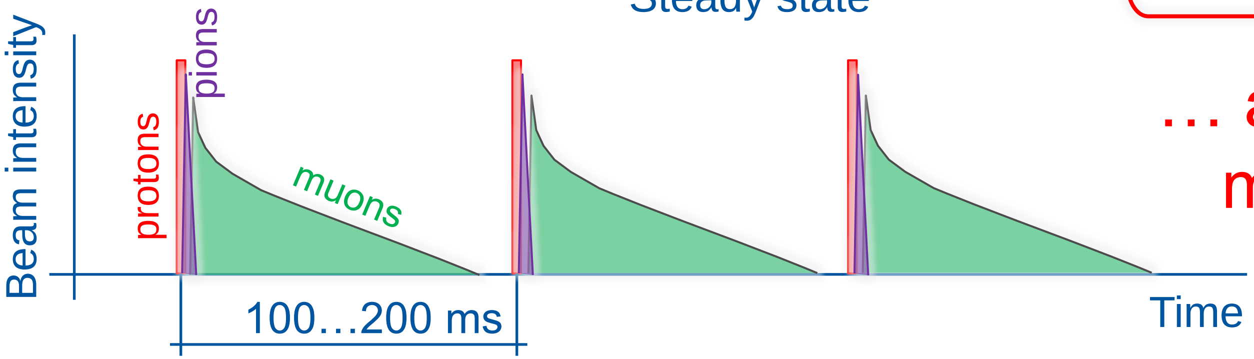
Pulsed



Steady state

Steady state

… accelerate muons…



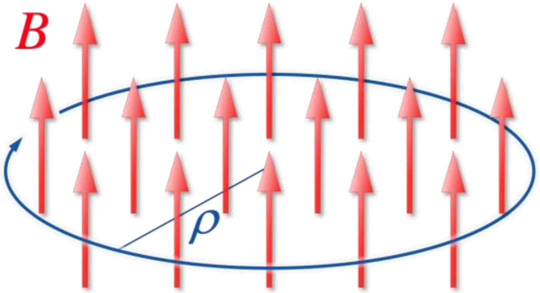
The need for high field

Beam energy

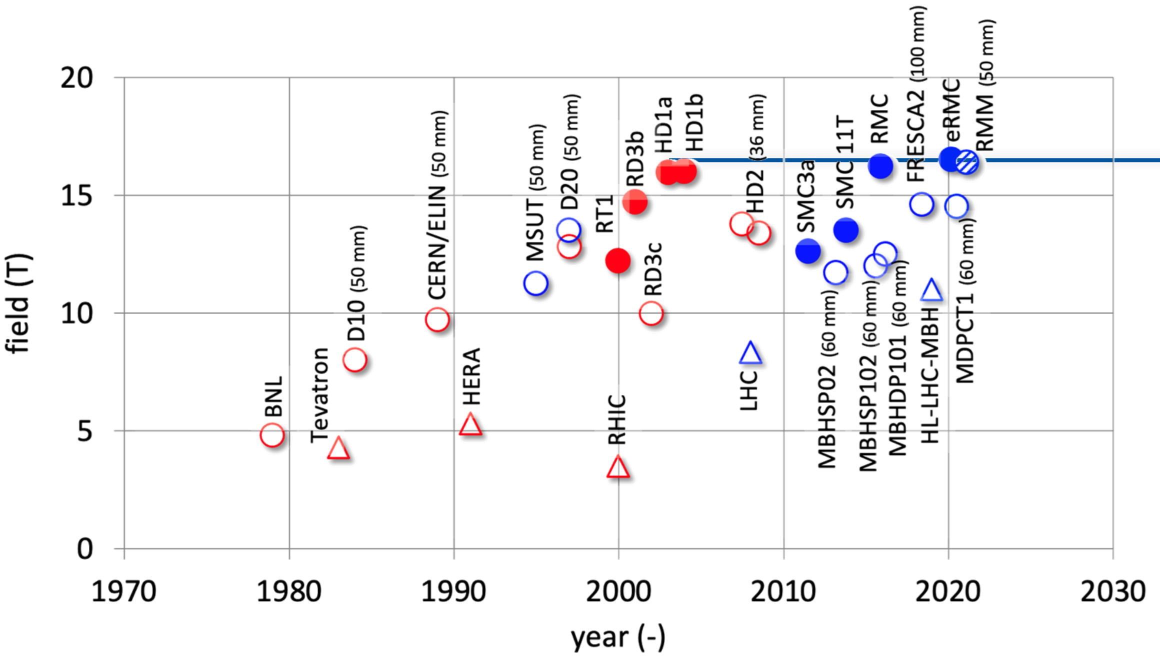
Bending radius

$$E[GeV] = 0.3\, B[T]\, r[m]$$

Dipole field



This is the reason for the steady call for **higher fields** in accelerator magnets

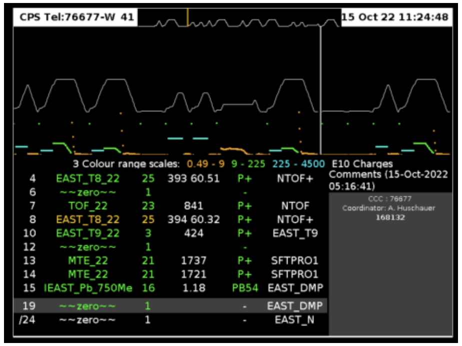


Upper limit of LTS (Nb_3Sn)

HTS is the only path beyond 16 T

The need for energy

- CERN uses today **1.3 TWh** per year of operation, with peak power consumption of **200 MW** (running accelerators and experiments), dropping to **80 MW** in winter (technical stop period)
- Electric power is drawn directly from the French 400 kV distribution, and presently supplied under agreed conditions and cost
- **Supply cost, chain and risk** are obvious concerns for the present and future of the laboratory


CPS Tel:76677-W 41

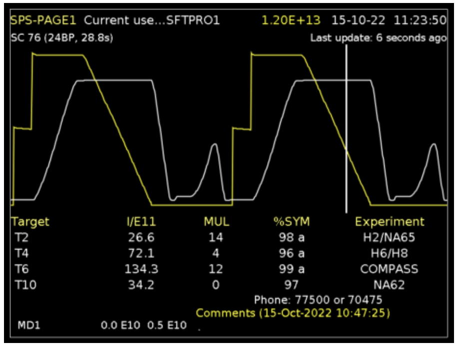
15 Oct 22 11:24:48

3 Colour range scales: 0.49 - 9 9 - 225 225 - 4500 E10 Charges

4	EAST_T8_22	25	393 60.51	P+	NTOF+
6	~~zero~~	1		-	
7	TOF_22	23	841	P+	NTOF
8	EAST_T8_22	25	394 60.32	P+	NTOF+
10	EAST_T9_22	3	424	P+	EAST_T9
12	~~zero~~	1		-	
13	MTE_22	21	1737	P+	SFTPRO1
14	MTE_22	21	1721	P+	SFTPRO1
15	IEAST_Pb_750Me	16	1.18	PB54	EAST_DMP
19	~~zero~~	1		-	EAST_DMP
/24	~~zero~~	1		-	EAST_N

Comments (15-Oct-2022 05:16:41)

CCC : 76677
Coordinator: A. Huschauer
168132


SPS-PAGE1 Current use...SFTPRO1 1.20E+13 15-10-22 11:23:50

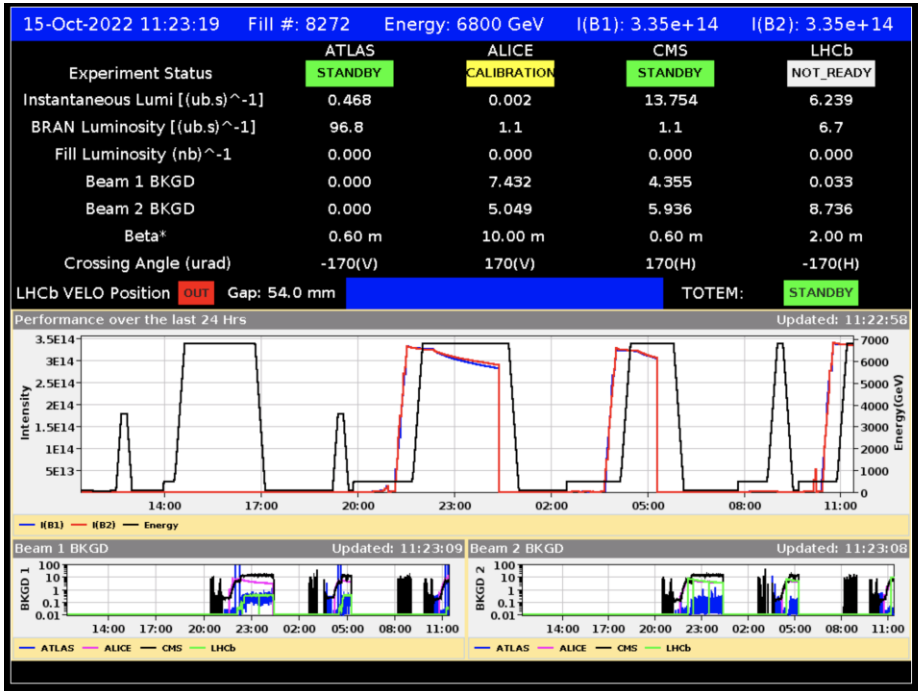
SC 76 (24BP, 28.8s) Last update: 6 seconds ago

Target	I/E11	MUL	%SYM	Experiment
T2	26.6	14	98 a	H2/NA65
T4	72.1	4	96 a	H6/H8
T6	134.3	12	99 a	COMPASS
T10	34.2	0	97	NA62

Phone: 77500 or 70475

Comments (15-Oct-2022 10:47:25)

MD1 0.0 E10 0.5 E10


15-Oct-2022 11:23:19 Fill #: 8272 Energy: 6800 GeV I(B1): 3.35e+14 I(B2): 3.35e+14

	ATLAS	ALICE	CMS	LHCb
Experiment Status	STANDBY	CALIBRATION	STANDBY	NOT_READY
Instantaneous Lumi [(ub.s)^-1]	0.468	0.002	13.754	6.239
BRAN Luminosity [(ub.s)^-1]	96.8	1.1	1.1	6.7
Fill Luminosity (nb)^-1	0.000	0.000	0.000	0.000
Beam 1 BKGD	0.000	7.432	4.355	0.033
Beam 2 BKGD	0.000	5.049	5.936	8.736
Beta*	0.60 m	10.00 m	0.60 m	2.00 m
Crossing Angle (urad)	-170(V)	170(V)	170(H)	-170(H)

LHCb VELO Position OUT Gap: 54.0 mm TOTEM: STANDBY

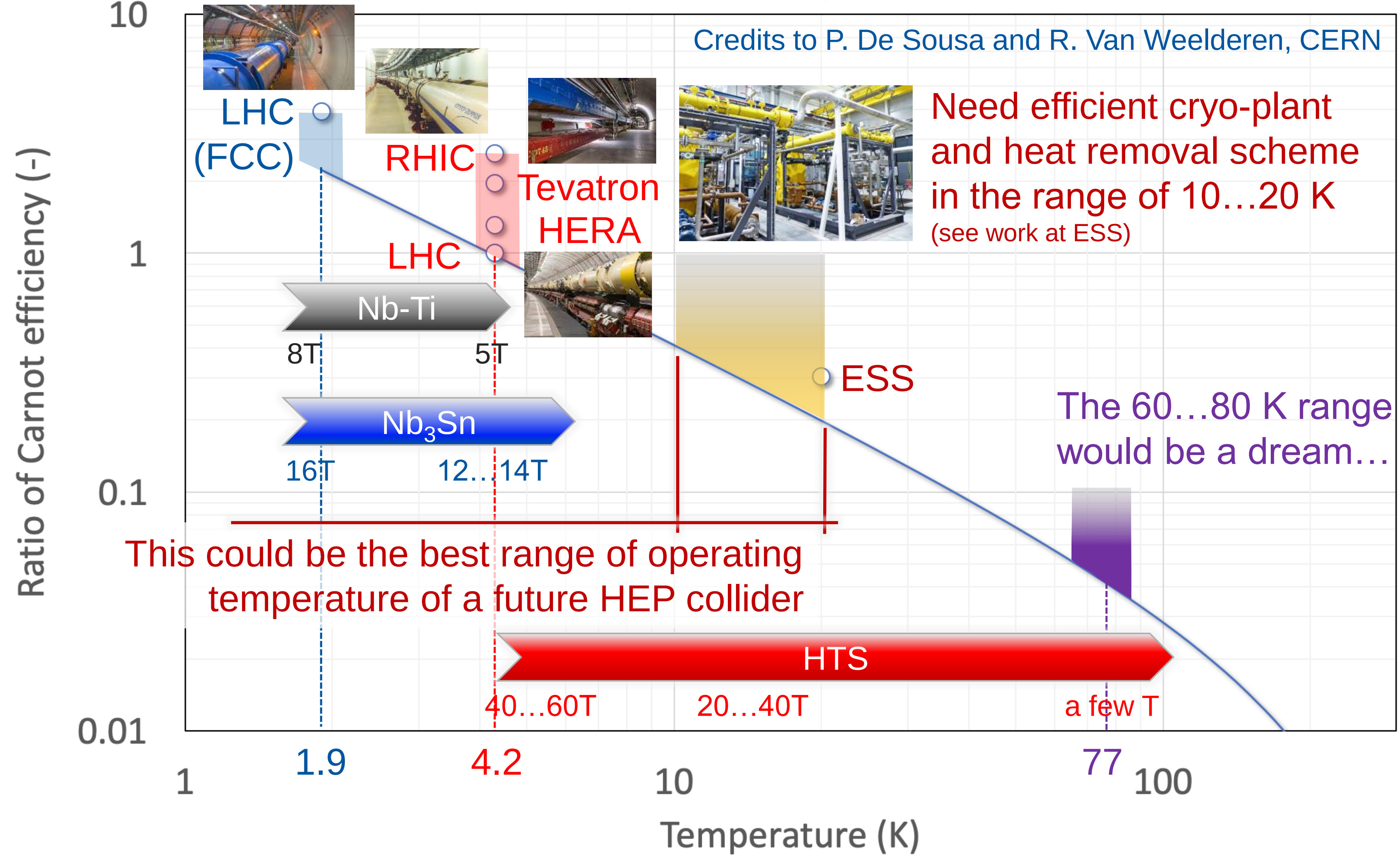
Performance over the last 24 Hrs Updated: 11:22:58

Beam 1 BKGD Updated: 11:23:09

Beam 2 BKGD Updated: 11:23:08

Energy efficient cryogenics

$W/Q = (T_h - T_c)/T_c$



Credits to P. De Sousa and R. Van Weelderen, CERN

Need efficient cryo-plant and heat removal scheme in the range of 10…20 K

(see work at ESS)

The 60…80 K range would be a dream…

This could be the best range of operating temperature of a future HEP collider

HTS may be the only path towards a future collider

16 JUIN 2022 **Publications** Briefings de l'Ifri

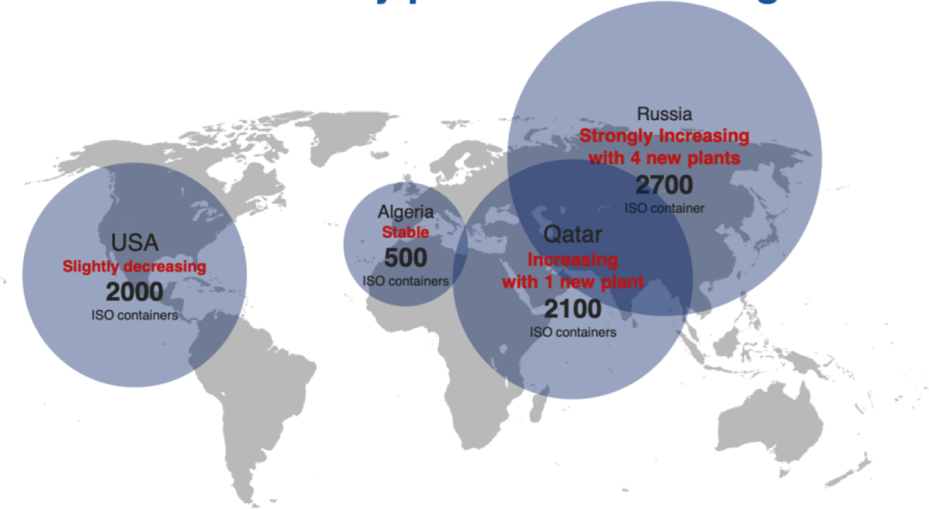
© Kittirat Roekburi/Shutterstock

Aurélien REYS, Vincent BOS

Hélium : les nouvelles géographies d'une ressource critique

Briefings de l'Ifri, 16 juin 2022

Helium is a **by-product of natural gas**



Tentative forecast in 2026 based on public announcements of new capacities available in quantity of Iso container of 4.5 tonnes

Future helium **supply is limited** and entails a substantial economical and availability **risk**

Consequences

Current situation

- Market shortage is affecting industrial and scientific customers
- Manufacturing industry contracts are impacted with volume limitations
- Large scientific instrument cannot do so & rely on established industrial partnership

Helium market still at risk in 2023 and for the coming years

- Uncertainty on the effective Russian production capacity and market access
- Algerian gas production transferred using pipeline instead of LNG
- No more back-up from the US federal authorities, Cliffside for sale ! (C&en News)

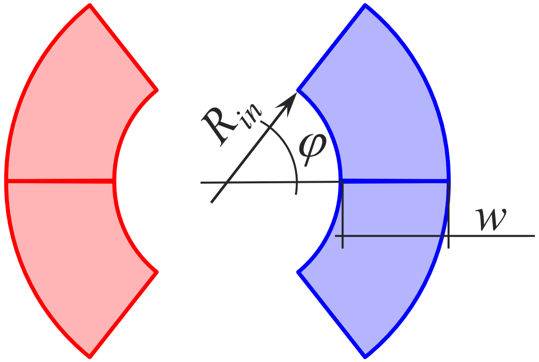
Courtesy of F. Ferrand, CERN

The need for economics

- A large component in the magnet cost is the **amount of superconductor** (coil cross section)
- High-field superconductors are (significantly) more expensive than *good-old* Nb-Ti
- Need to work in two directions:
  - **Reduce the coil cross section (increase *J* !)**

$$B = \frac{2\mu_0}{\pi} J w \sin(\varphi)$$

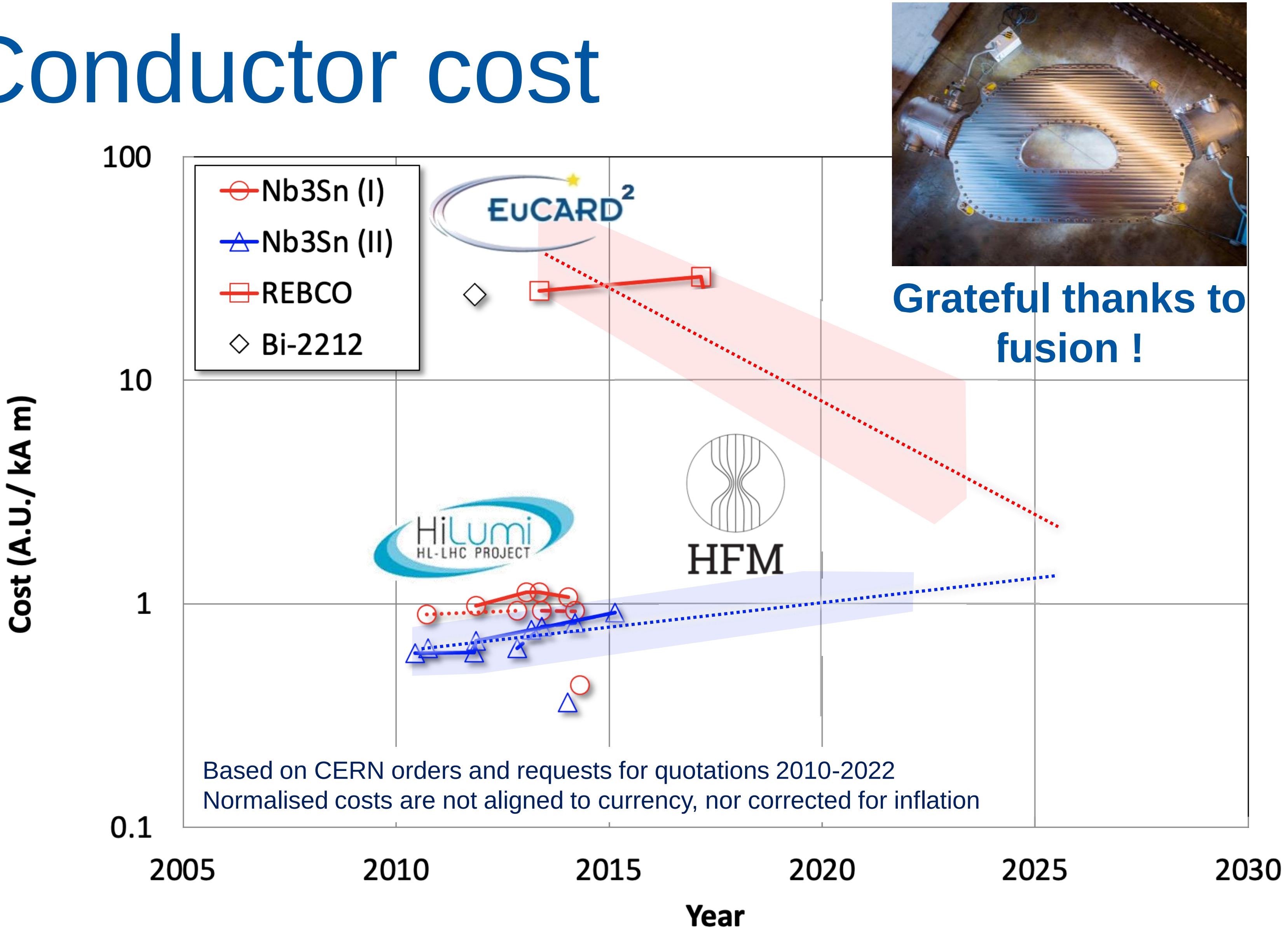
$$\boxed{A_{coil} = 2\varphi(w^2 + 2R_{in}w) \sim \frac{1}{J^{1.5}}}$$



  - **Reduce unit conductor cost**

HTS may offer both

Conductor cost



Grateful thanks to fusion !

Based on CERN orders and requests for quotations 2010-2022
Normalised costs are not aligned to currency, nor corrected for inflation

Impressive cost reduction in HTS !