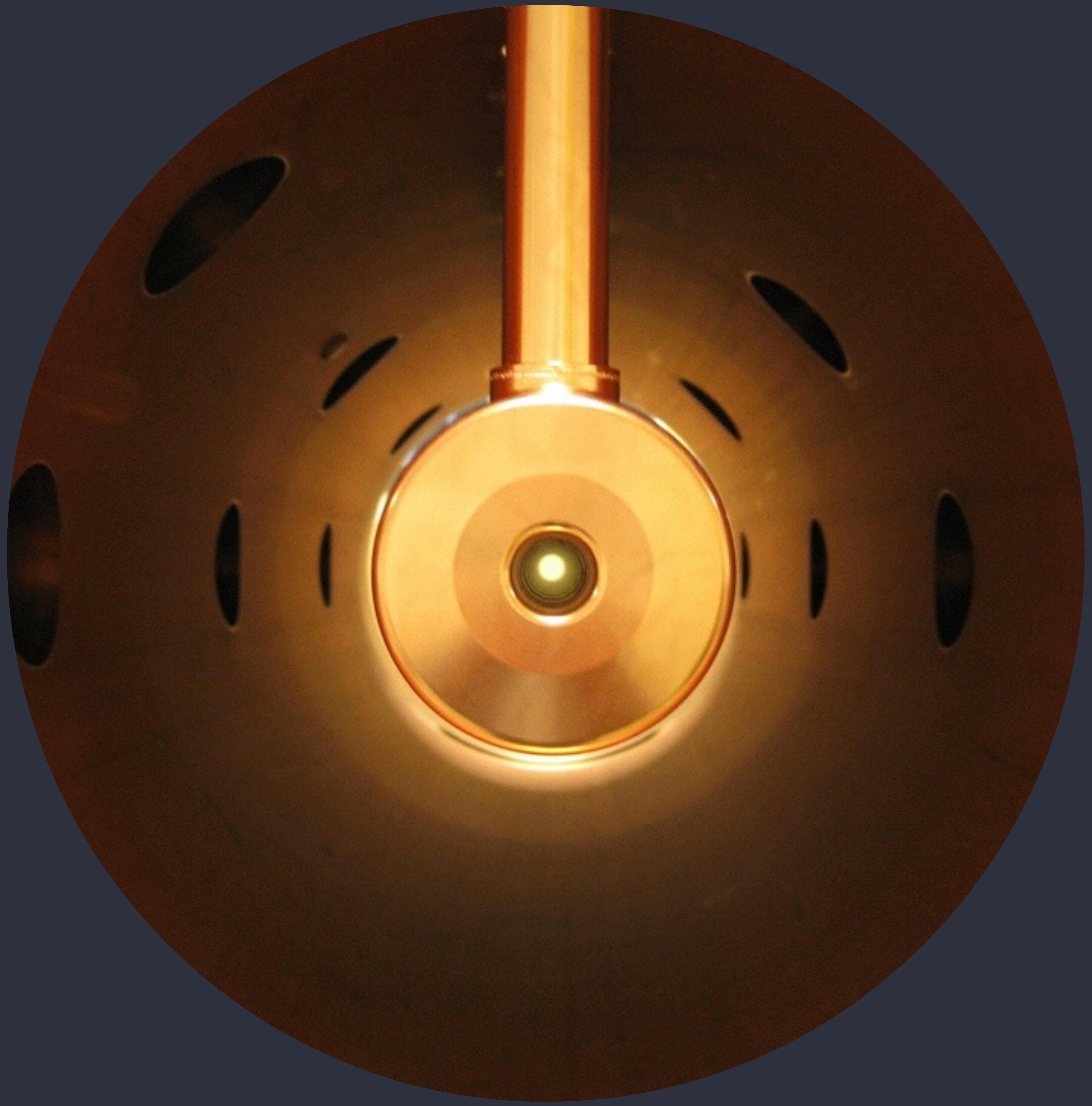
Review on trends in NC LINACS for protons, ions and electrons, with emphasis on new technologies and applications

Frank Gerigk, CERN, LINAC2016

Content



01 Parameter range for normal and superconducting linacs

02 Examples of recent normal conducting linacs

03 …indicating trends and highlighting new technologies

04 Summary

Parameter range

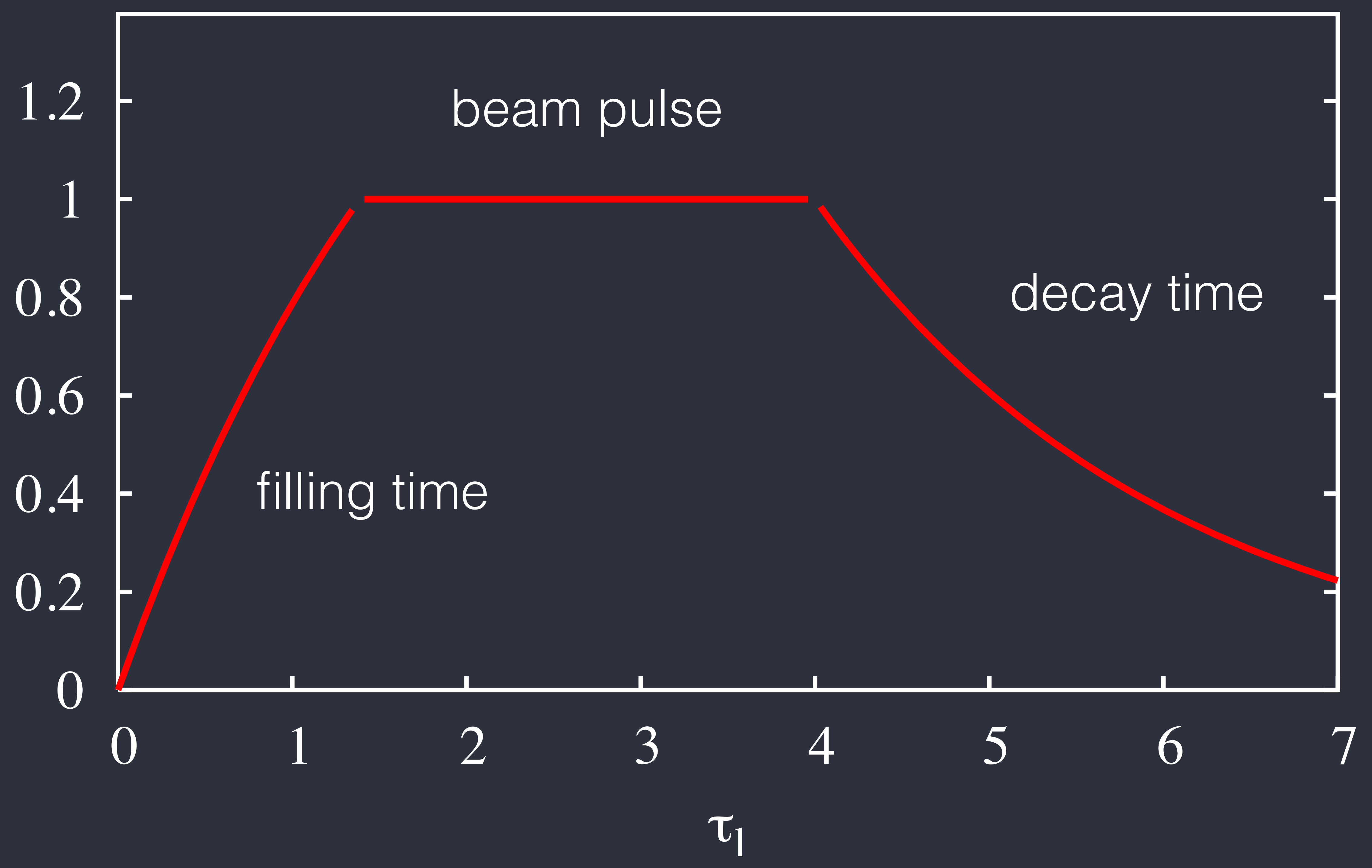
for normal conducting (travelling wave & standing wave) and superconducting linacs is determined by:

- beam pulse length
- duty cycle
- bunch current
- accelerating gradient
- final energy

PARAMETER RANGE

Beam Pulse Length

VOLTAGE PULSE IN CAVITIES



determined by group velocity and structure length

High Q ➜ large amount of stored energy ➜ long filling time

	NC travelling Wave	NC Standing Wave	SC Standing Wave
filling/ decay time	< 1 µs	n x 10 µs	n x 100 µs

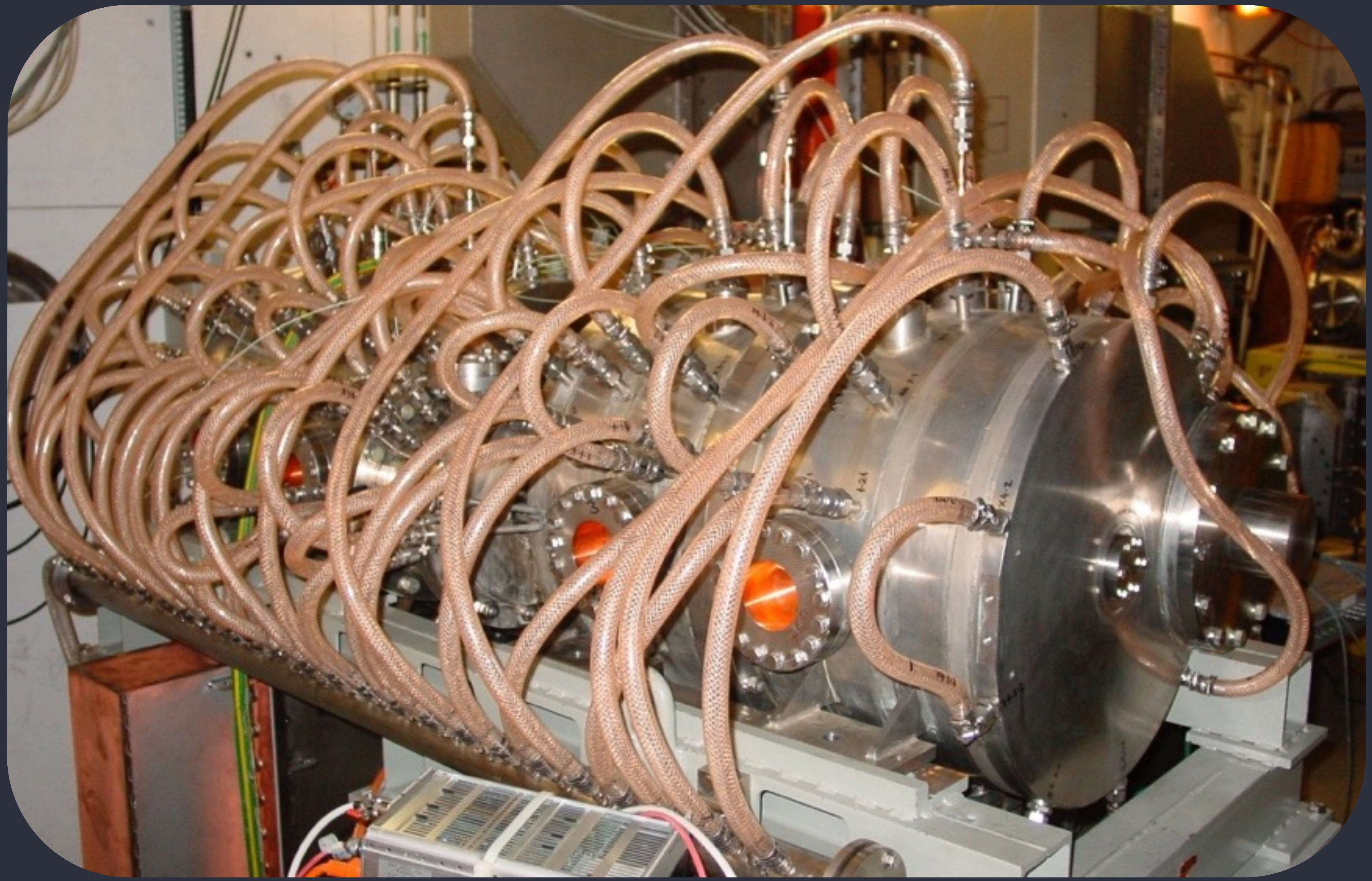
ideal for "very short" beam pulses

only efficient for "long" beam pulses

PARAMETER RANGE

Beam Duty Cycle

10% DUTY CYCLE TEST OF A LINAC4 CCDTL PROTOTYPE



HIGH DUTY CYCLE OPERATION IMPLIES:

- high average RF power
- limited by heat removal from the structure
- for high accelerating gradients NC structures are "expensive" to operate at high duty cycles (in excess of some %)

ADVANTAGE FOR SC STRUCTURES

- but the cryo-losses must be considered.

➡ Excessive losses (for NC and SC) can only be reduced by lowering the gradients.

➡ Capital investment cost and running cost have to be analysed for each case

PARAMETER RANGE

Bunch Current

Power consumption: $P = P_{beam} + P_{diss} + P_{aux}(\text{e.g. cryogenics})$

$$P_{beam} = I \cdot V_{acc} \qquad P_{diss} = \frac{V_{acc}^2}{ZT^2L} \qquad P_{cryo} = \frac{P_{diss}}{\eta_{cryo}}$$

- Acceleration is considered power efficient if $P_{beam} \geq (P_{diss} + P_{aux})$

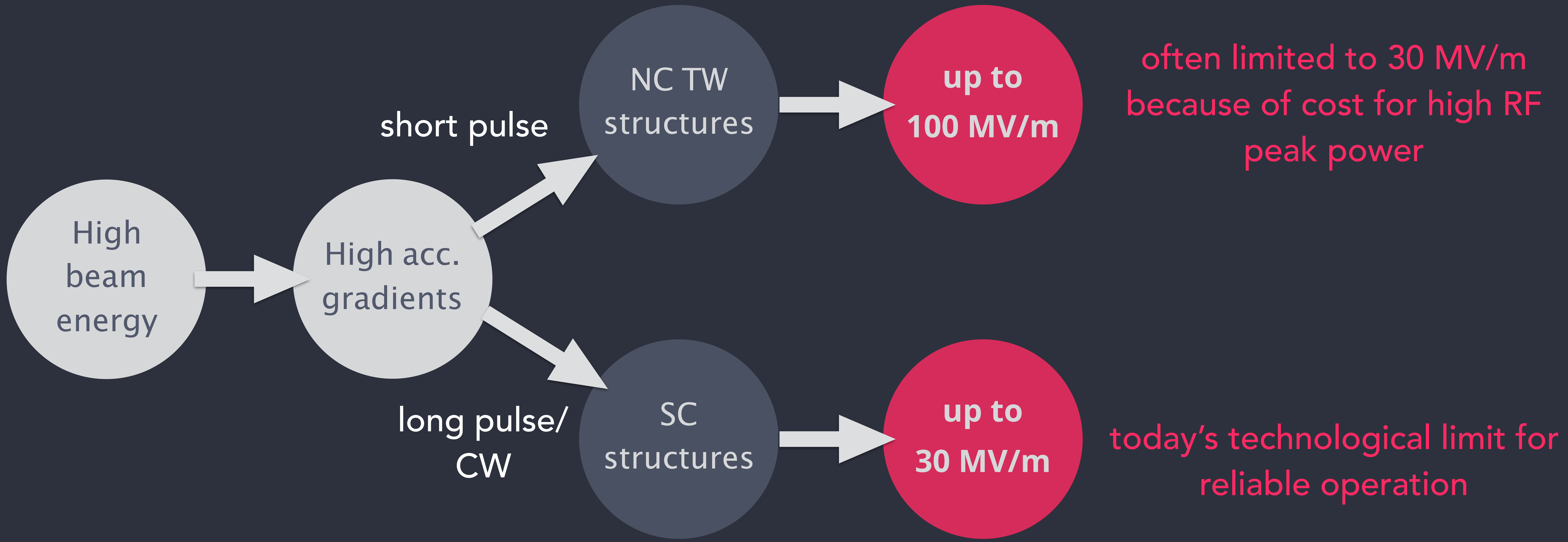
➡Normal conducting linacs are power efficient for high currents

➡For low currents SC linacs are often the better choice

➡Most new ion linac are SC

PARAMETER RANGE

Linac energy/Accelerating gradient



Apart from performance limitations, gradients in SC cavities are limited by the couplers (peak and average RF power throughput) and the cryogenic losses.

PARAMETER RANGE

summary table

parameter range for normal and superconducting linacs

	NC TW	NC SW	SC
pulse length	< n x 1 µs	n x 10 µs	n x 100 µs
beam current	high	medium to high	low
duty cycle	low	low	high
beam energy (electrons)	high	low	high
beam energy (hadrons)	low	low	high

needs to be evaluated for each case, e.g. to determine the NC/SC transition energy in high-energy hadron linacs #

Recent examples

and selected highlights of recent NC linacs

This is a personal selection

of machines, which I know
I am sure there are many more out there

Linac types

according to particle species

Some applications of recent NC machines:

#1 Electron Linacs

- X-ray/industrial
- FELs
- neutron sources
- γ-ray sources,
- injector linacs
- linear colliders

#2 Proton Linacs

- material studies
- neutron source
- p-injector
- hadron therapy

#3 H- Linacs

- p-injector

#4 Carbon Linacs

- carbon therapy

Since most recent ion linacs are SC, I do not consider them here

Recent electron linacs

personal selection

	application	t_{beam} [µs]	I_{peak}* [mA]	d.c. [%]	f_{rep} [Hz]	E_{beam} [MeV]	f_{RF} [GHz]	E_{acc} [MV/m]	P_{beam} [kW]	struc tures	status
ILU-14	industry	420	500	2.1	50	10	0.176	1.8	100	CCL	operational
KIPT	n-source	2.7	600	0.17	625	100	2.856	7.5	100	TW	construction
ELI-NP	γ-ray	0.5	1425	0.005	100	720	5.7	33	13	TW	construction
FERMI	FEL	n.a.	1500	n.a.	50	1500	3	30	<0.1	BTW	operational
SWISSFEL	FEL	n.a.	1000	n.a.	100	5800	5.7	28.5	0.2	TW	construction
PAL-XFEL	FEL	n.a.	570	n.a.	60	10000	2.86	20	0.1	TW	commissioning
MAX IV	injector	n.a.	300	n.a.	100	3000	3	20	<0.1	TW	operational
CLIC	collider	0.156	1000	0.0008	50	1.5 TeV	12	100	14000	TW	prototyping

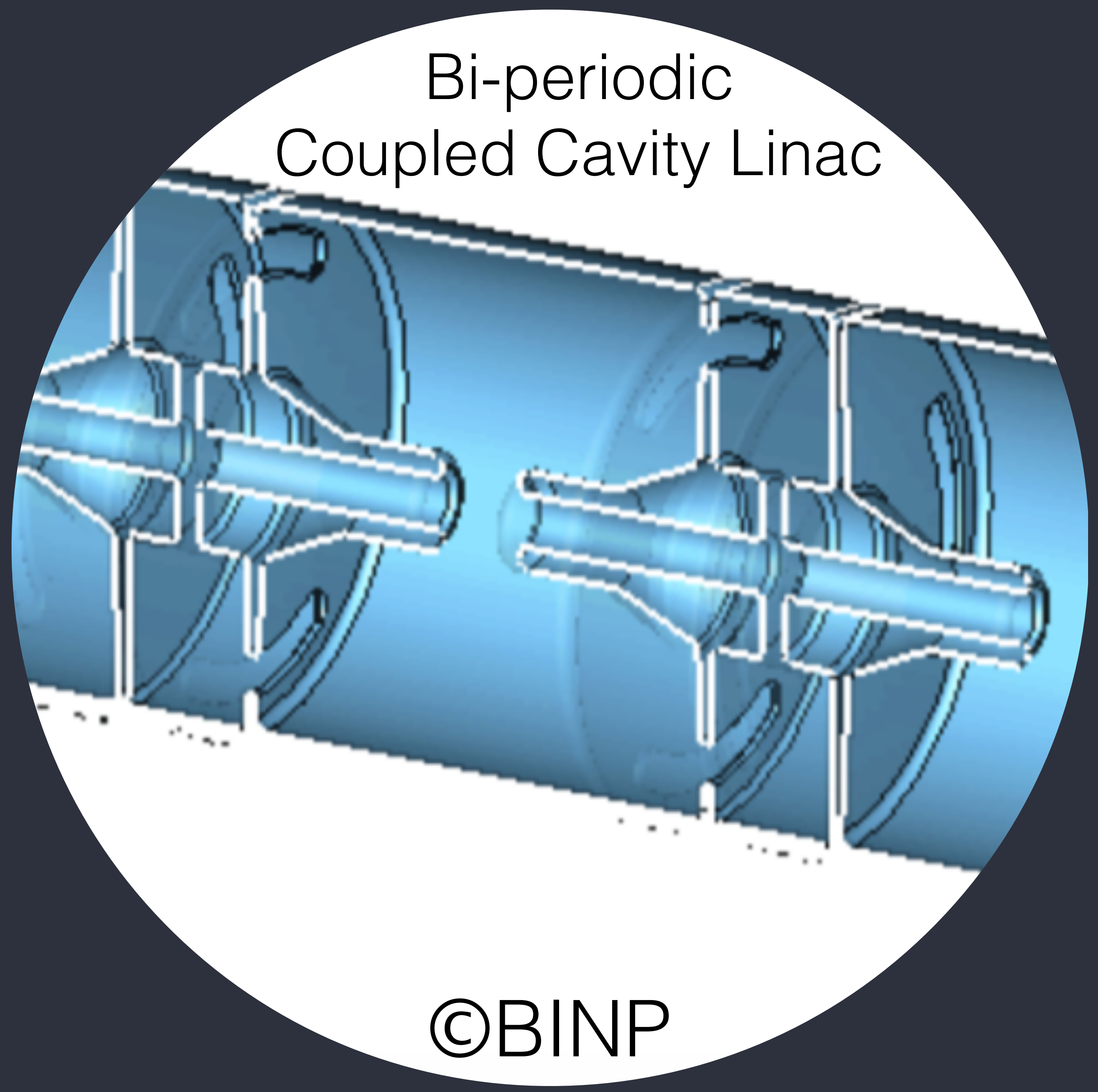
* average bunch current

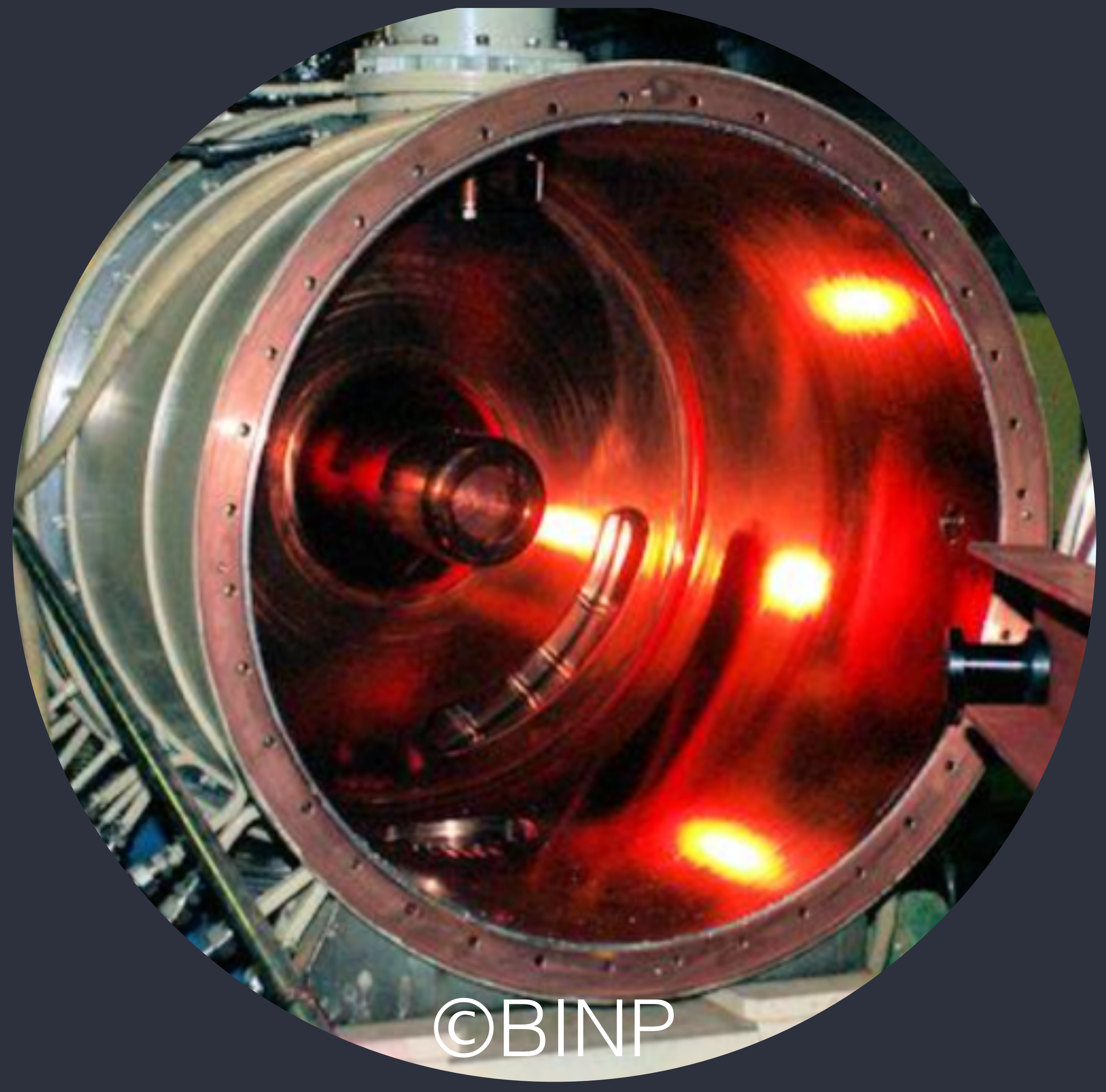
Electron linacs: Trends

- TRAVELLING WAVE structures are the most common.
- Rising importance for cargo screening.
- Mostly sub μs pulses with currents in the range of 1 Ampere.
- FEL pulses typical consist of 1-2 bunches/pulse.
- Even though 100 MV/m can be reached, most machines operate at 30 MV/m or lower.
  ➡ **high RF peak power is too expensive!**
- Installations with a limited footprint are considering to use TW structures up to 70 MV/m: SINAP, Australian Light Source.
- New "exotic" applications:
  ➡ very high power material irradiation: ILU-14, Russia
  ➡ KIPT neutron source, subcritical assembly driven by electron beam, KIPT, Ukraine
  ➡ interaction with laser light produces gamma rays via Compton backscattering: ELI-NP, Rumania

Electron linacs: ILU-14

BINP Novosibirsk





Low-energy high-current beams for:

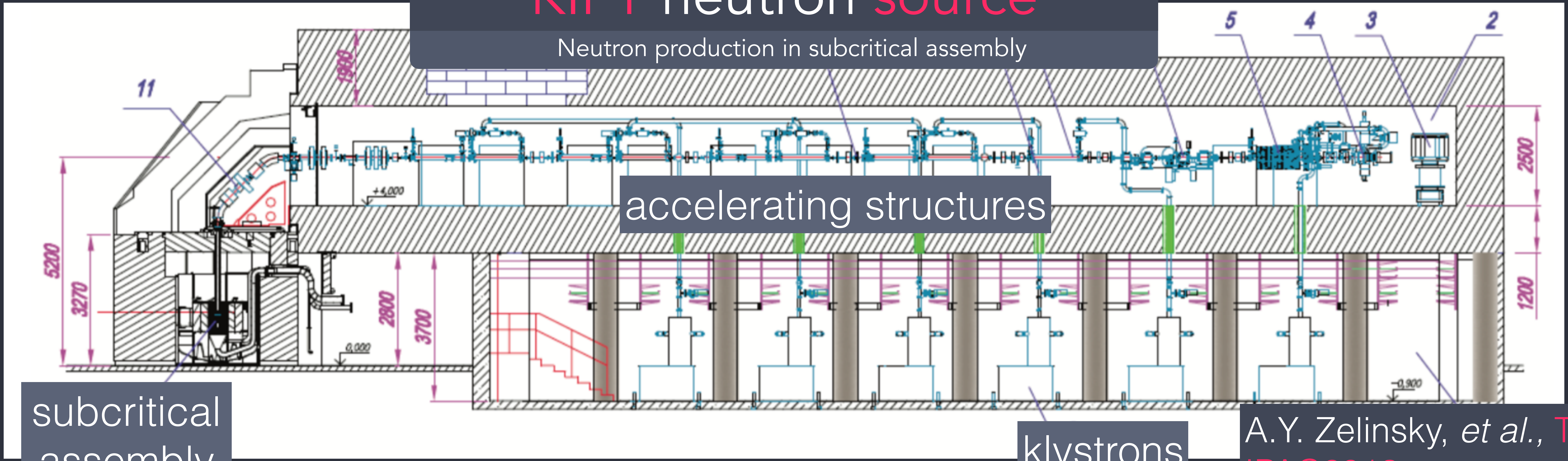
- material treatment, sterilisation,
- food irradiation/pasteurization,
- medical waste irradiation,
- …

f [MHz]	E [MeV]	I [mA]	f_{rep} [Hz]	t_{pulse} [ms]	P_{out} [kW]
176	7.5 - 10	400	<50	0.5	<100

High-power industrial accelerator ILU-14 for E-beam and X-ray processing, Aleksandr Bryazgin, LINAC2014

KIPT neutron source

Neutron production in subcritical assembly



A.Y. Zelinsky, *et al.*, THPFI080, IPAC2013

electron energy	100 MeV
beam power	100 kW
neutron output	3 x 10^{14} n/s (U target)
criticality	$k_{eff} < 0.98$
energy release	192 kW (U target)
10 cavities	TW, 2.86 GHz
pulse current	600 - 800 mA
rep rate	625 Hz
accelerator length	24.5 m

- A neutron source with a subcritical assembly driven by an intense electron beam (ADS)
- Collaboration between KIPT (Kharkov, Ukraine) and ANL (Argonne, USA). Accelerator built by IHEP (Beijing, China)
- Aimed at: nuclear physics, solid state physics, biology, medical isotopes, radionuclide transmutations

Electron linacs: high gradients

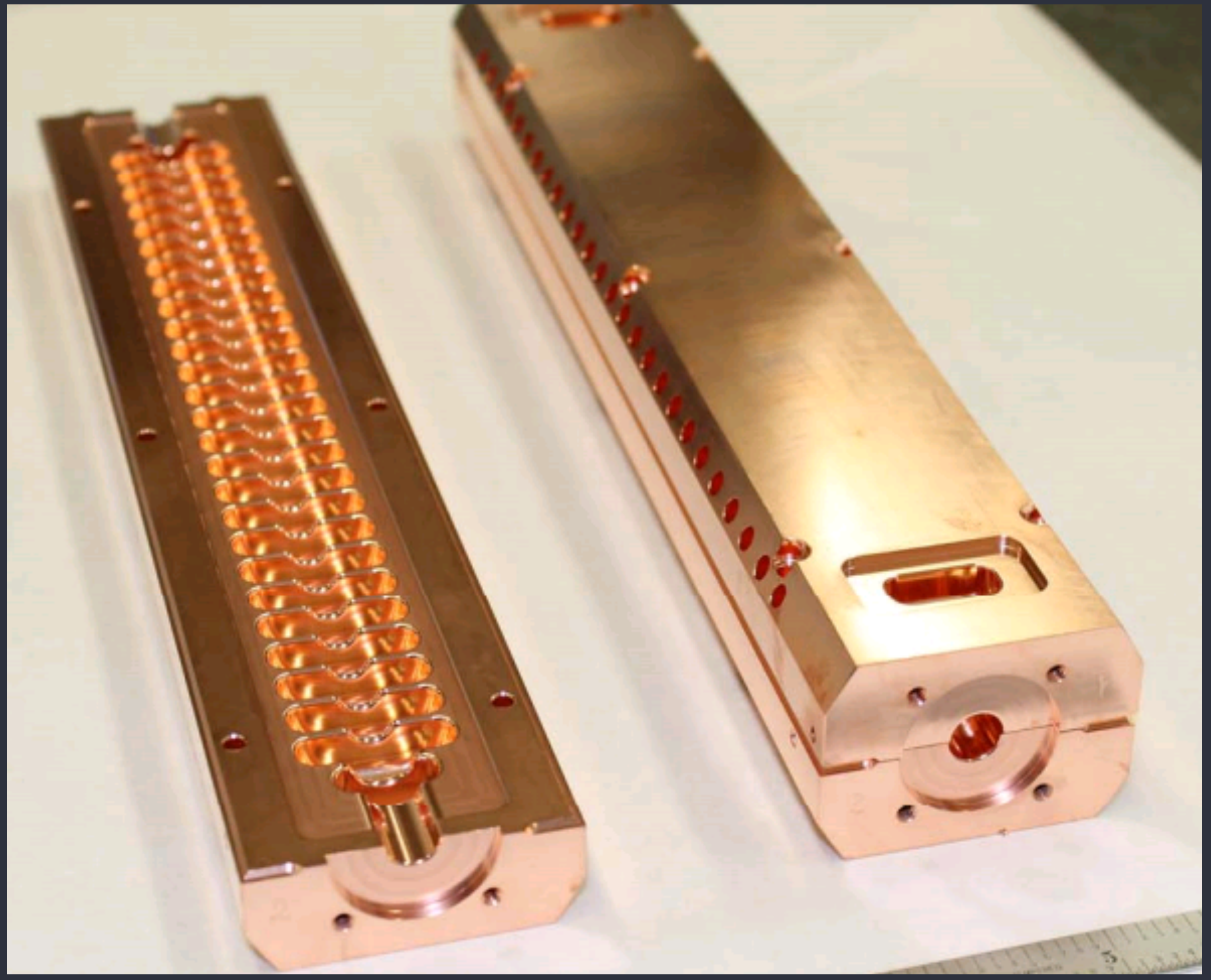
benefits of linear collider research

- HIGH GRADIENT collider technologies are considered for FELs.
- PSI developed a brazing process for SwissFEL to simplify cell assembly and to lower costs series production.
- CLIC so far used bonding of single diamond machined discs and now explores milling 2 halves, which can then be clamped or welded
  - ➡ no current flow across the halves,
  - ➡ multiple joining techniques can be used,
  - ➡ lower cost
  - ➡ first test gave gradients > 90 MV/m

High-Gradient RF Development and Applications, Walter Wuensch, TU2A04, 12:10 today

Status of SwissFEL, Florian Loehl, MO3A01, yesterday

Fabrication and High-Gradient Testing of an Accelerating Structure Made From Milled Halves, Walter Wuensch, THPLR003, Poster Thursday



Recent proton/H^- linacs

a personal selection

	application	t_{beam} [ms]	I_{peak} [mA]	d.c. [%]	f_{rep} [Hz]	E_{beam} [MeV]	f_{RF} [MHz]	E_{acc} [MV/m]	P_{beam} [kW]	structures	status
KOMAC	multi-physics	1.33	20	8	100	100	350	2	160	RFQ,DTL	operational
ESS NC	NC front-end	3	62.5	4.2	14	90	352	3.2	236	RFQ, DTL	construction
FAIR PI	p-injector	0.2	70	0.1	4	70	325	6	4	RFQ, CH-DTL	construction
TULIP	hadron therapy	0.02	0.3	0.4	200	230	750/3000	30/50	0.3	RFQ, IH, DTL, BTW	operational
LINAC4	p-injector	0.8	32	0.08	1	160	352	4	2.6	RFQ, DTL, CCDTL, PIMS	commissioning
JPARC	p-injector	0.5	30	1.3	25	400	324	4	133	RFQ, DTL, SDTL, ACS	operational
SNS	p-injector	1	26	6	60	186	400/800	4	288	RFQ, DTL, SCL	operational
CSNS	p-injector	0.4	15	1	25	80	324	2.5	6	RFQ, DTL	commissioning

proton (KOMAC – TULIP); H- (LINAC4 – CSNS)

Proton/H^- linacs: Trends

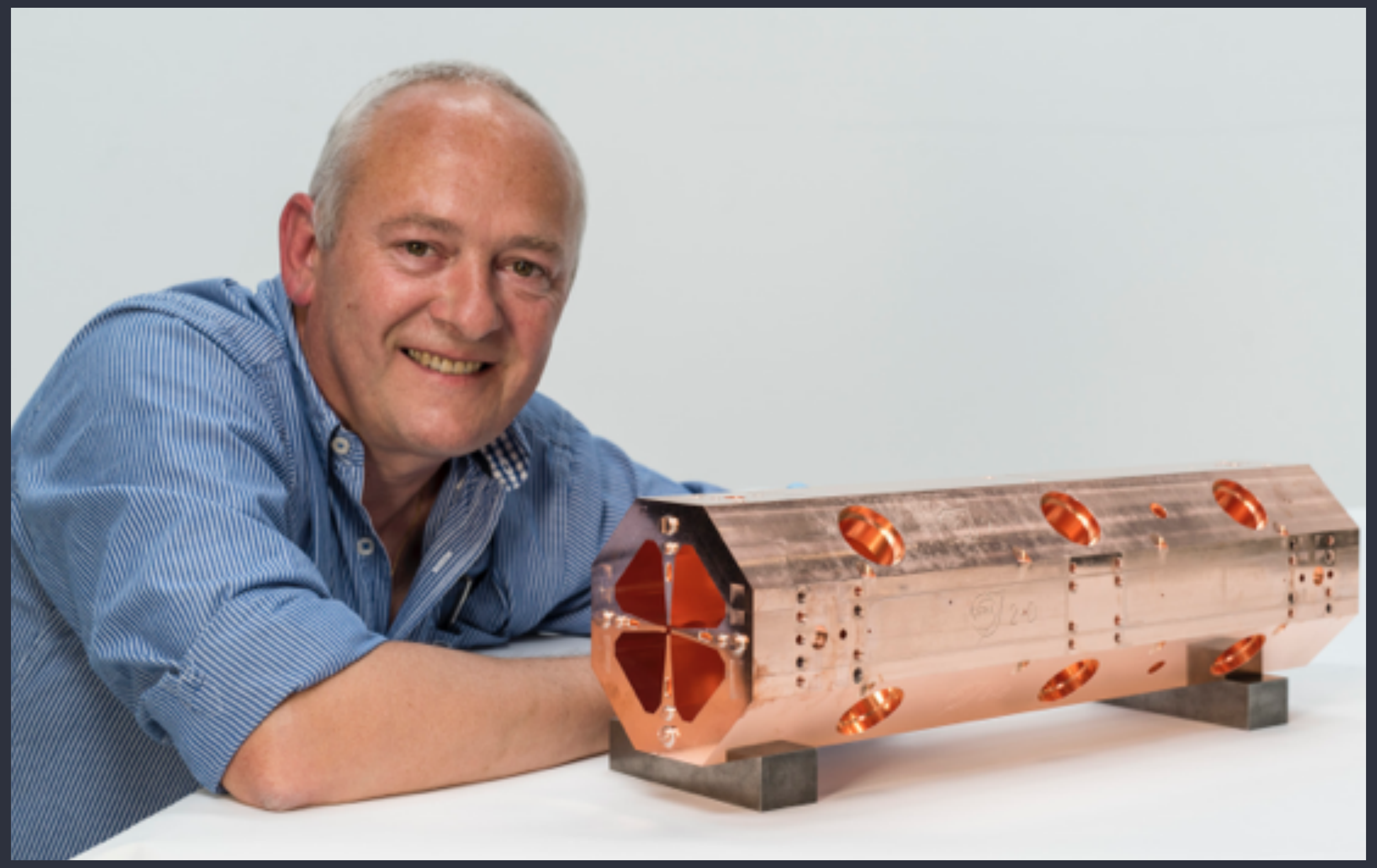
- All NC proton linacs start with an RFQ followed by a DTL-type structure (stabilised Alvarez, IH, CH).
- DTLs either use PMQ's (SNS, Linac4, ESS) or very compact EMQ's (J-PARC, CSNS).
- Between 50 and 100 MeV variations of DTL's; J-PARC: S-DTL, Linac4: CCDTL.
- Transition energy between NC and SC sections depends on duty cycle and parameter set (ESS: 90 MeV, SNS: 160 MeV, J-PARC: 400 MeV)

RFQs: new developments

The first structure in all proton linacs

Trapezoidal vanes

- Pioneered at IHEP, used e.g. at Argonne,
- Higher Transit Time Factor,
- Higher efficiency, higher accelerating gradients,
- Better longitudinal matching into subsequent structures



High frequency RFQ

- 750 MHz RFQ built at CERN for TULIP
- 5 MeV in 2 m for proton therapy

High-Frequency Compact RFQs for Medical and Industrial Applications, M. Vretenar, TH1A06, Th. 10:10

Tuning of the CERN 750 MHz RFQ for Medical Applications, B. Koubek, THOP09, Poster Thursday

CW RFQs

- CW operation of 4-vane RFQs understood with up to 100 kW/m (e.g. FRIB, IMP 162 MHz, IHEP 324 MHz, IFMIF, FNAL, ….),
- 4-rod RFQs challenging (e.g. SARAF): FRANZ RFQ prototype reached 100 kW/m in tests,

FRIB Front End Construction Status, E. Pozdeyev, TUPLR062, Poster Today

First Experiments at the CW-Operated RFQ for Intense Proton Beams, P. Schneider, TUPLR075, Oral Poster today

DTLs: new developments

Innovations on a 70 year old structure

TULIP 750 MHz
IH DTL

Linac4
DTL

- Design of a high-frequency DTL to complement the 750 MHz RFQ.
- Energy range from 5 to 10 MeV.
- Planned to be extended by a 3 GHz DTL up to 60 MeV

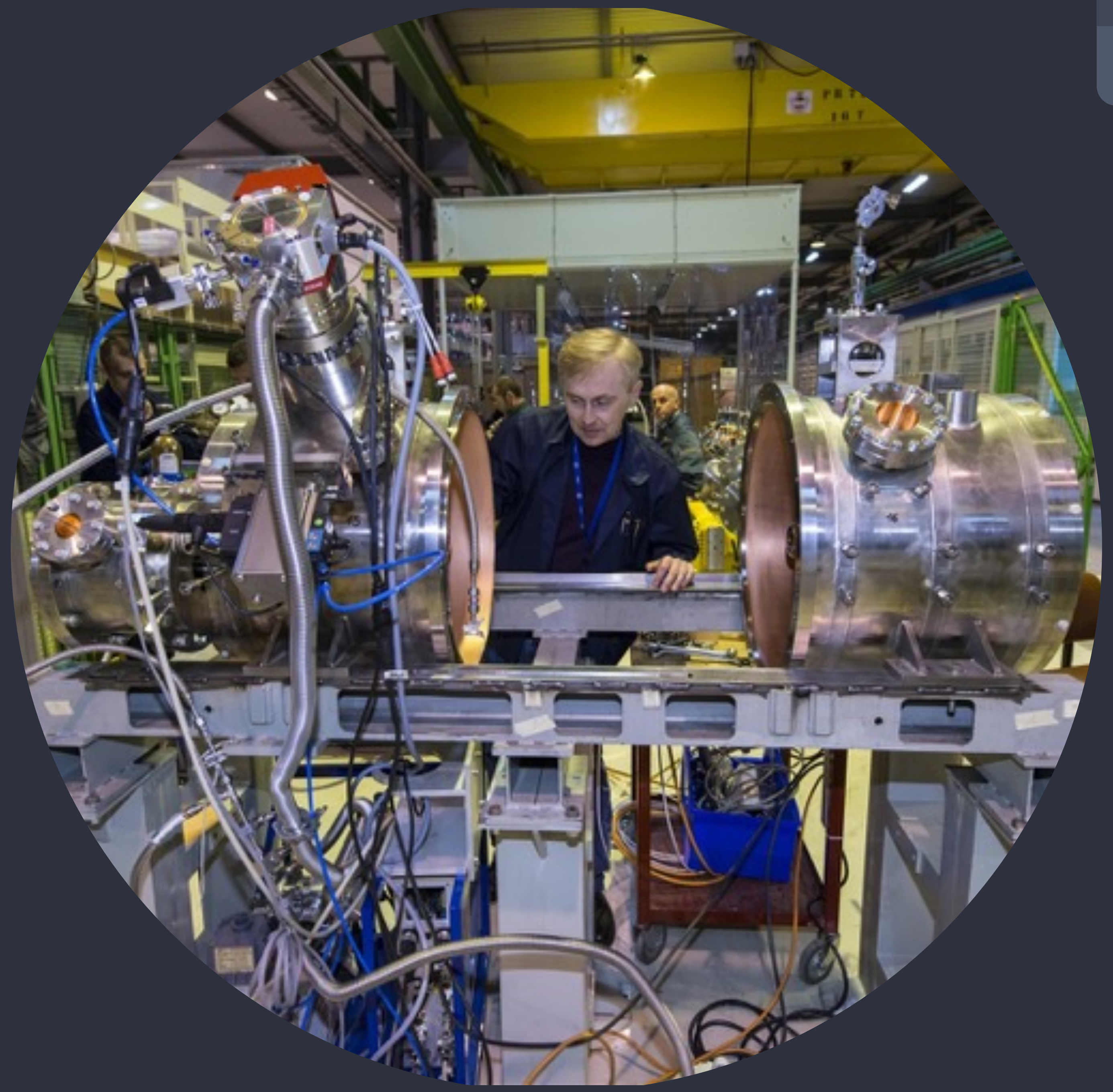
- No alignment mechanism for drift tubes, relying on machining tolerances only.
- Development of a new systematic procedure to adjust the post couplers (50 years after their invention).
- Fully conditioned and beam commissioned.

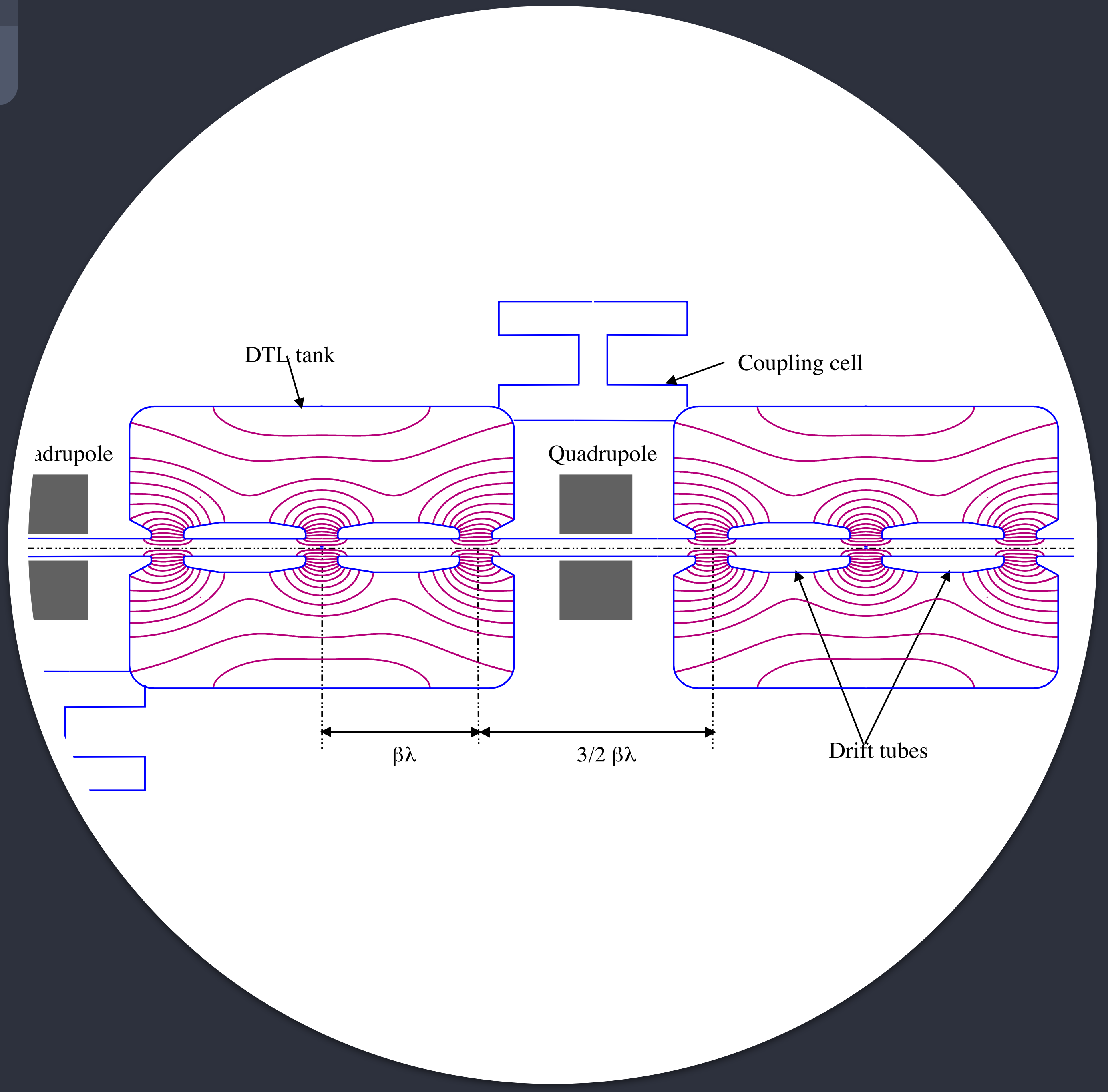
Design of a 750 MHz IH Structure for Medical Applications, Stefano Benedetti, MOPLR047, Poster yesterday

The DTL Post Coupler - An Ingenious Invention Turns 50, Suitbert Ramberger, TUPLR038, Poster today

Linac4 CCDTL

Cell Coupled Drift Tube Linac





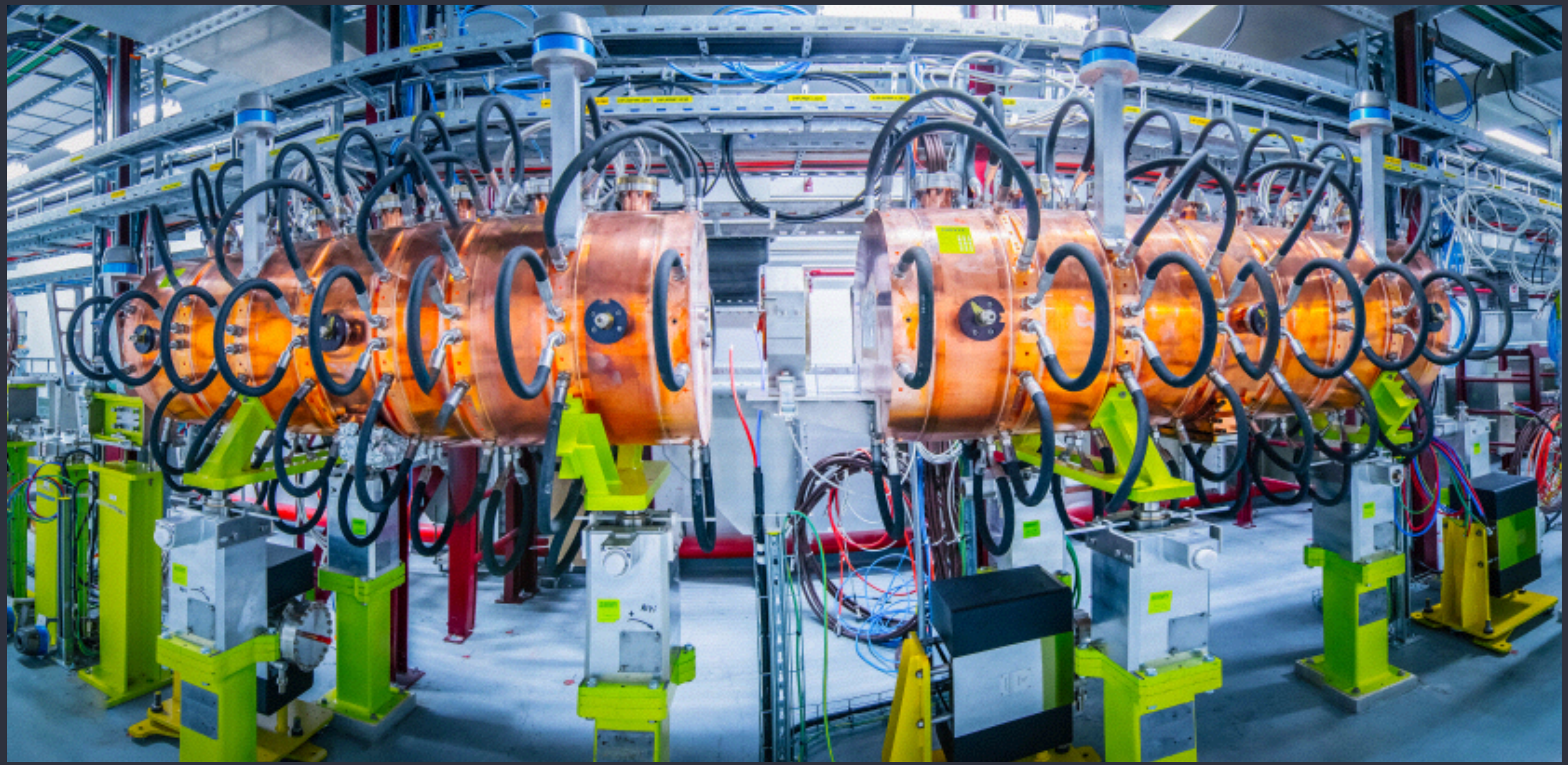
- Invented at LANL, built in Russia (VNIITF, BINP), operating at CERN (world's first).
- 7 modules of three tanks between 50 and 100 MeV
- Coupling (π/2) of 3 separate tanks + 2 coupling cells enables use of MW-class klystrons.
- Quadrupoles between tanks ease the alignment.
- Time consuming assembly because of high number of metal joints.
- Fully beam commissioned earlier this year.

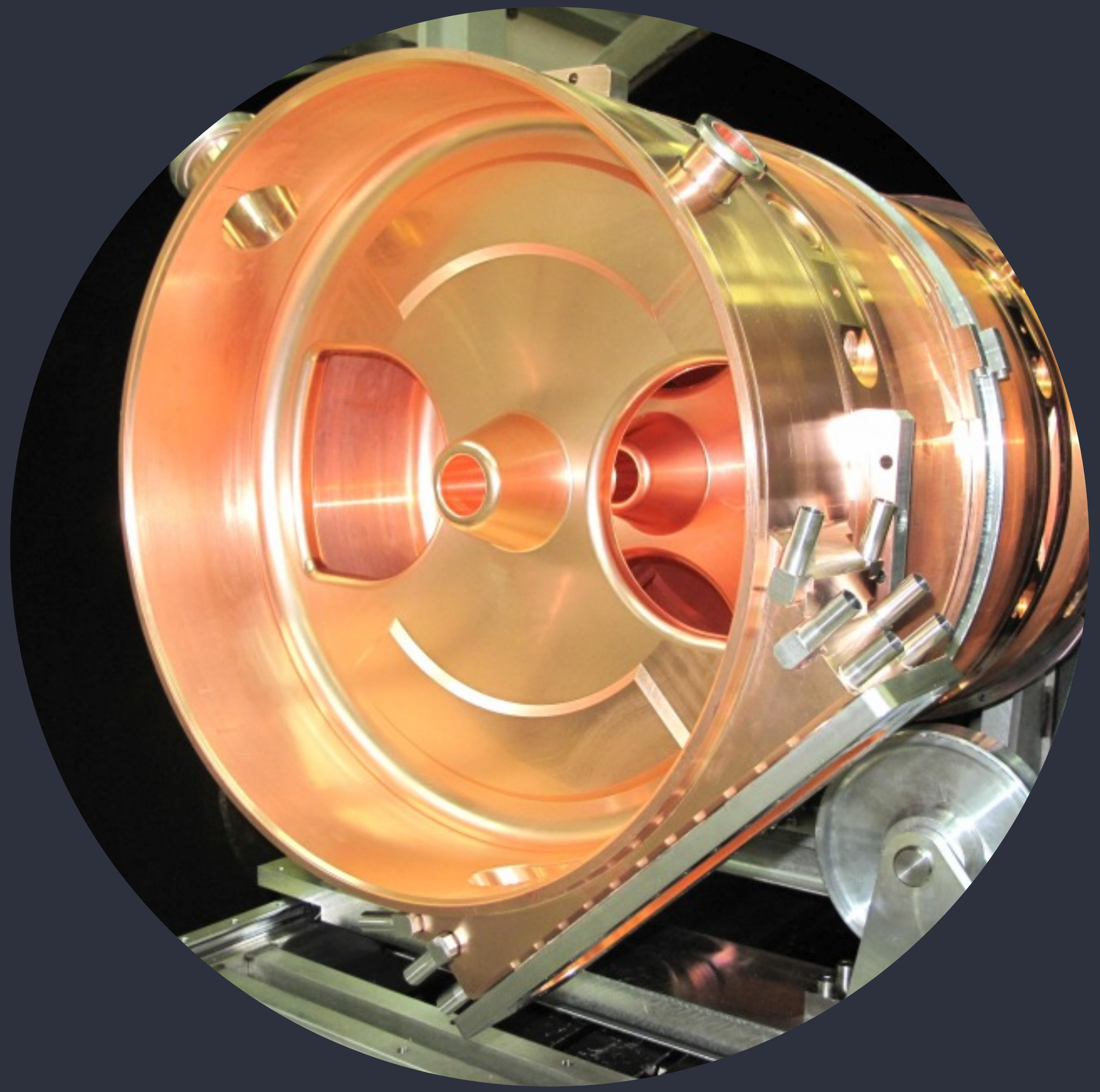
Experience with the Construction and Commissioning of Linac4, JB Lallement, TU1A03, 9:30 today!

Experience with the Conditioning of Linac4 RF Cavities, S. Papadopoulos, THPLR060, Poster Thursday

CERN Linac4: PIMS

Pi-Mode Structure



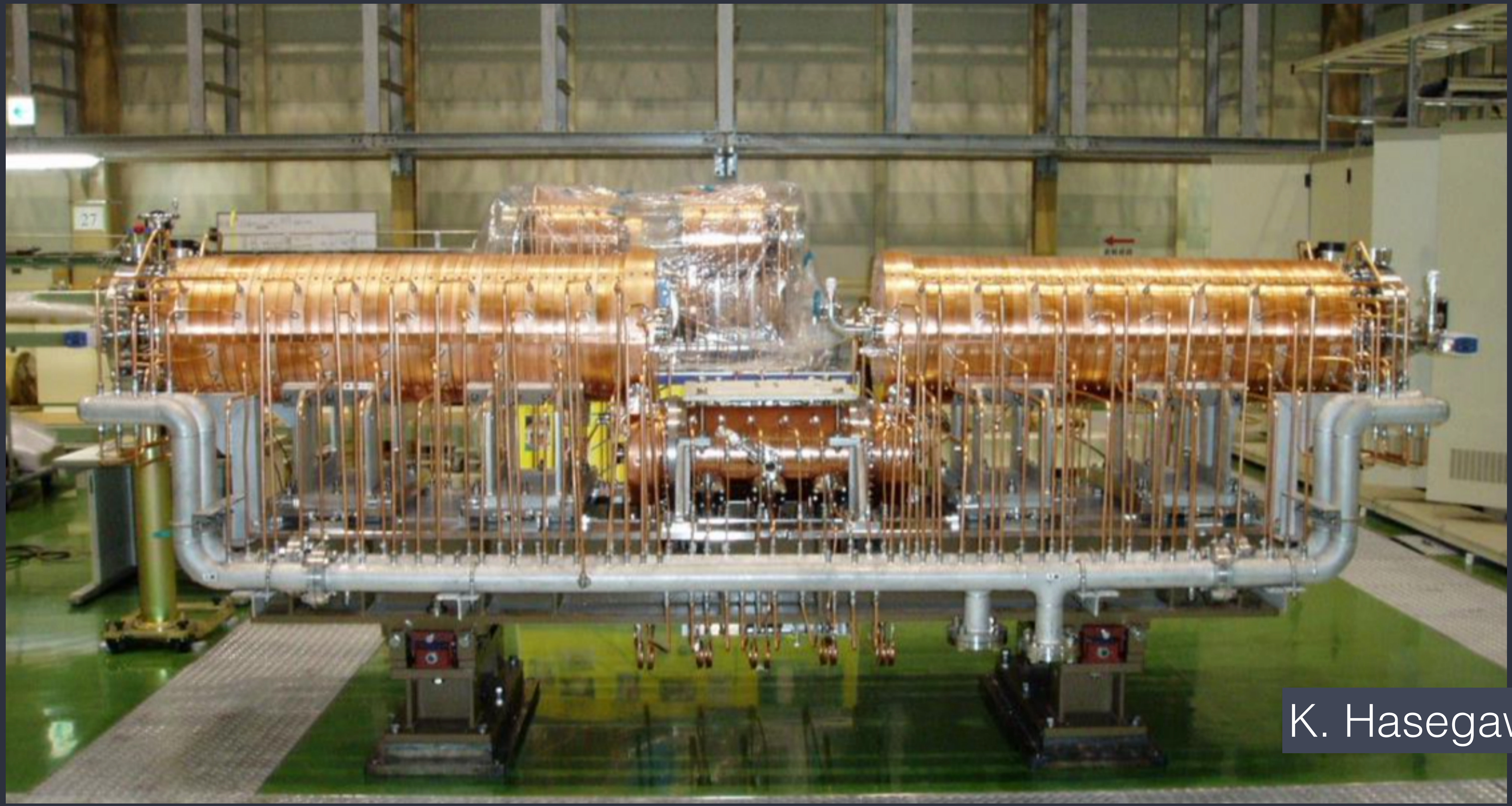


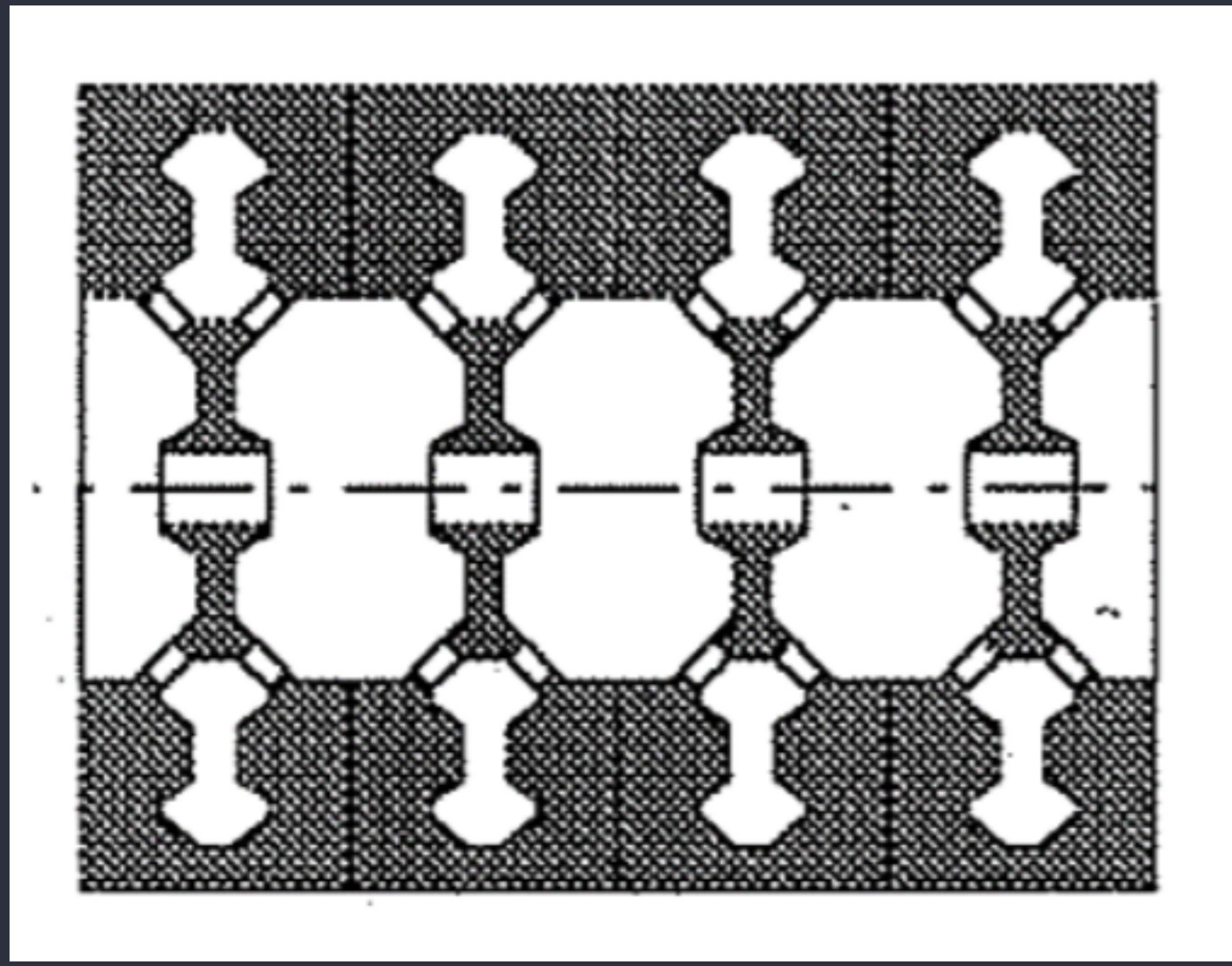
- First (to my knowledge) low-beta pi-mode structure to go into operational machine
- Bulk copper, no RF seals, discs and rings were fabricated at NCBJ, Swierk, Poland, then tuned and electron-beam welded at CERN,
- 8% higher shunt impedance than expected because of high surface quality
- Typical conditioning time: 24 hours
- 160 MeV beam commissioning imminent

Experience with the Construction and Commissioning of Linac4, Jean-Baptiste Lallement, TU1A03, 9:30 today!

JPARC: ACS

Annular Coupled Ring Structure



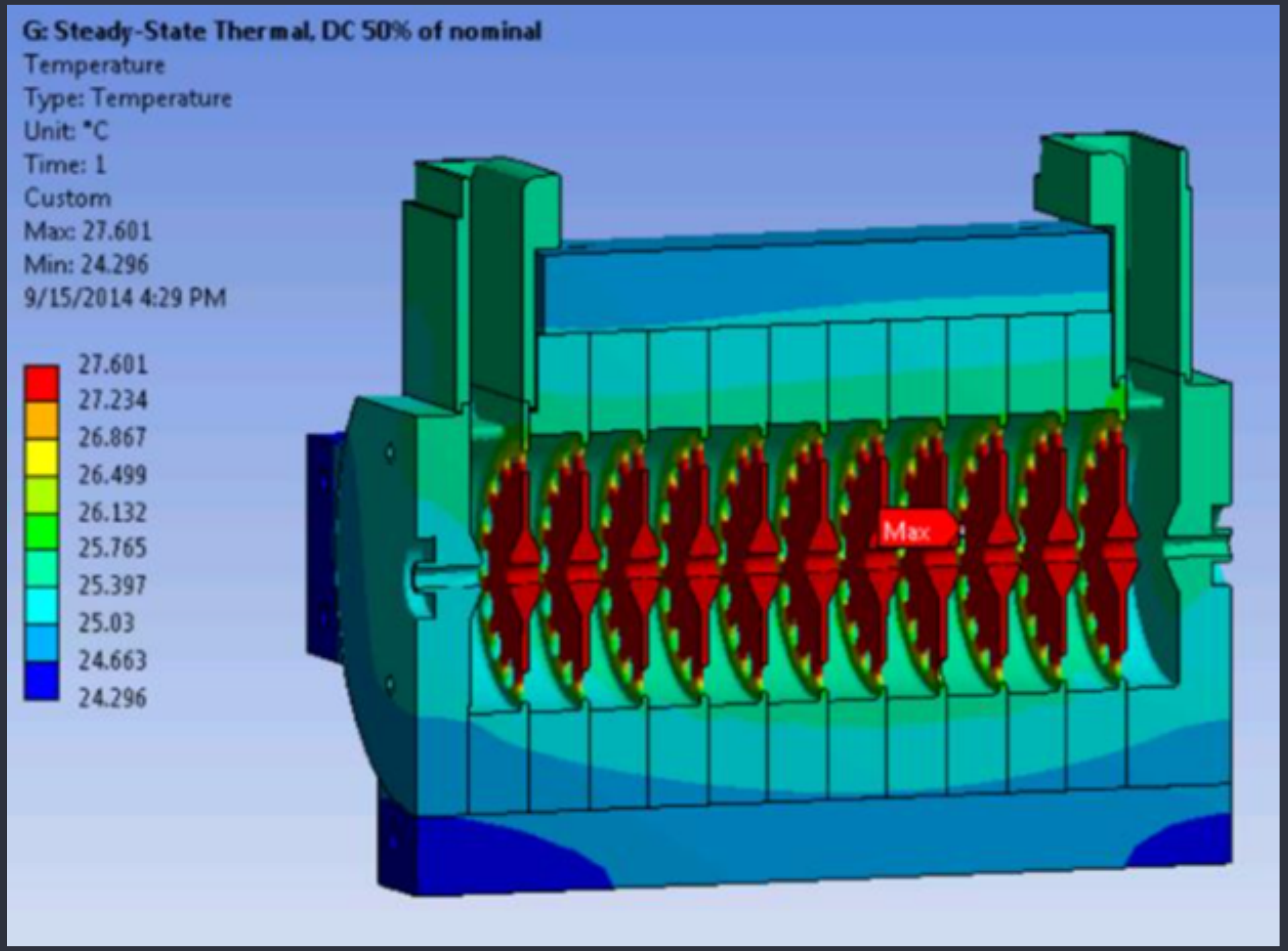


K. Hasegawa, TUIOB03, LINAC14

- 972 MHz Annular Coupled Ring Structure to accelerate from 190 - 400 MeV, 21 modules spanning ~100 m.
- Well suited for mass fabrication.
- Probably the highest energy NC proton linac built in recent history.
- Fully commissioned and operational since early 2014.

TULIP: low-β BTW

Backward Travelling Wave Structure

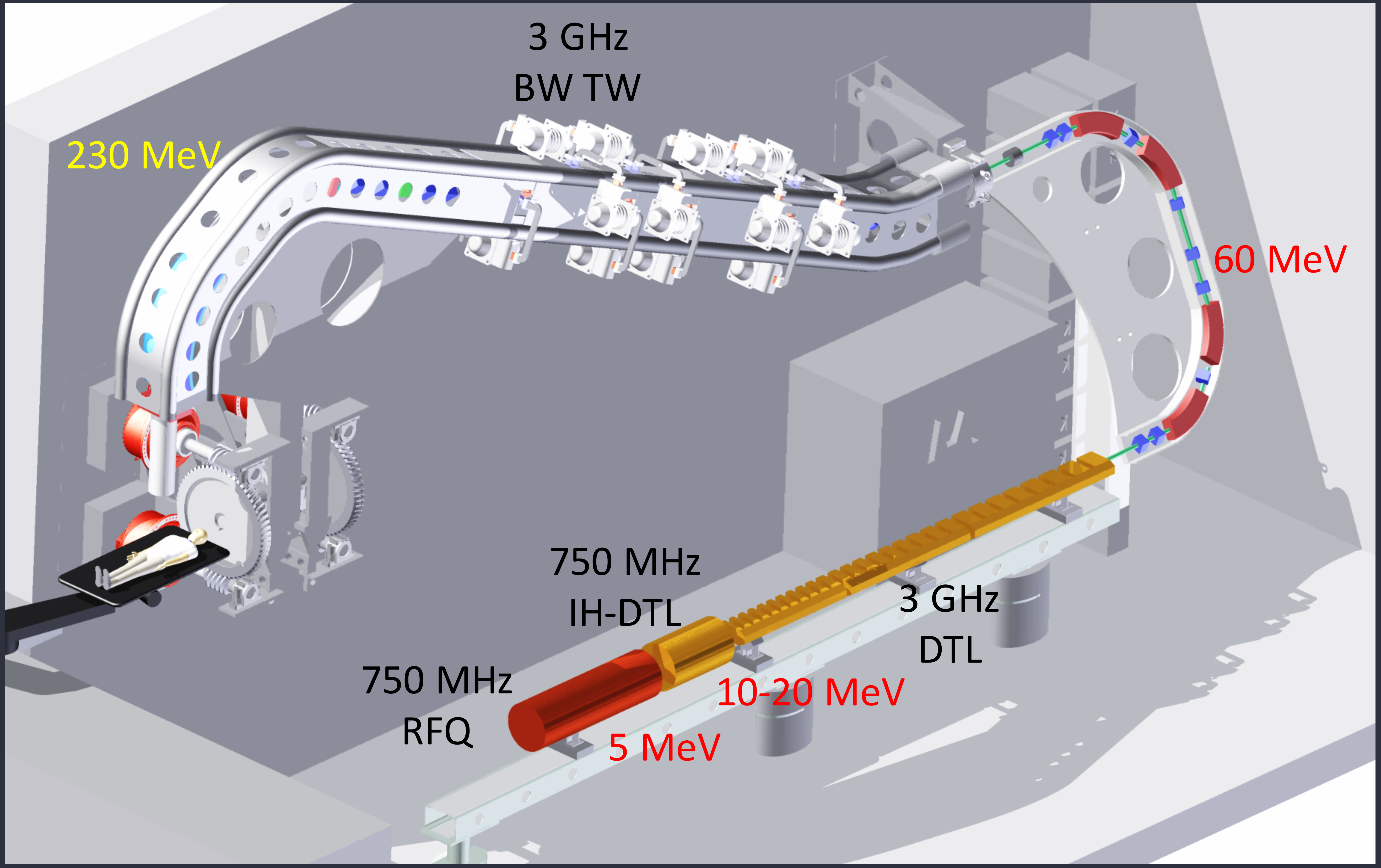


- 3 GHz Backward Travelling Wave Structure for low energy protons (60 - 230 MeV).
- First b=0.38 prototype has been designed and manufactured at CERN.
- Installed at high power test stand (XBOX-2) and waiting for Stefano to return from the conference.

Fabrication and High-Gradient Testing of a Novel S-Band Backward Travelling Wave Structure for Proton Therapy Linacs, Stefano Benedetti, MOPLR048, Poster yesterday

TULIP: everything new

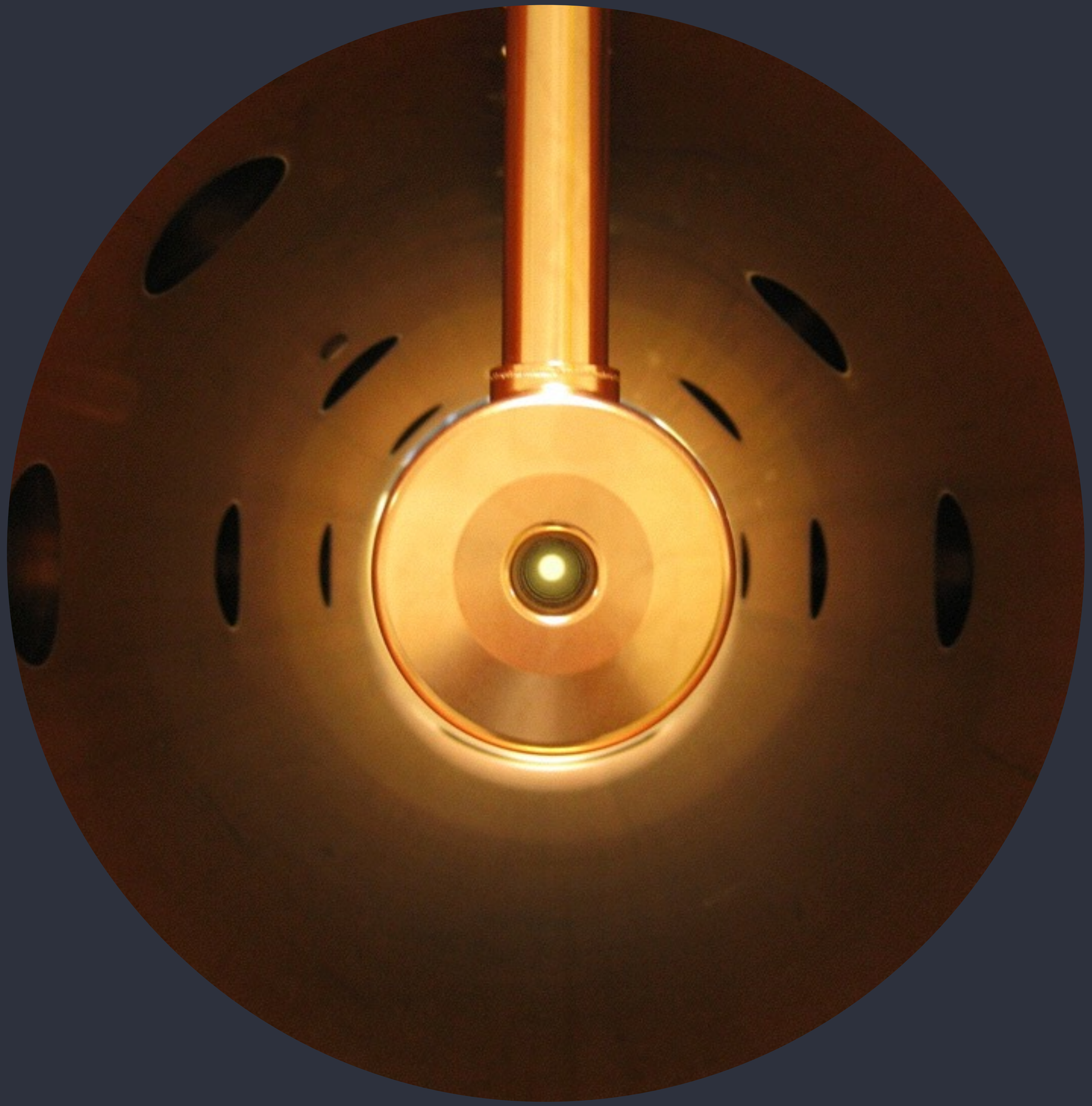
Compact proton therapy linac



- Proton therapy with 230 MeV beam
- Pre-acceleration up to 60 MeV: 750 MHz RFQ + 750 MHz IH DTL + 3 GHz Side Coupled DTL
- Low-velocity 3 GHz Backward Travelling Wave Structure on the gantry.
- High gradient BTW: 50 MV/m
- 19 m x 8 m footprint

Carbon linac projects, like ACCIL (2.86 GHz) or CABOTO (12 GHz) use high-gradient Coupled Cavity Linacs with 30-50 MV/m to reduce their footprint. E.g. 400 MeV/u (ACCIL) within 40 m.

Summary



- NC linacs are here to stay!
- High-gradient results from collider R&D are now being deployed for light sources and even hadron therapy linacs.
- Low energy electron linacs have ample use in industrial applications (e.g. cargo screening).
- CW operation is understood for 4-vane RFQs and on the horizon for 4-rod RFQs.
- The "zoo" of structures for low-energy protons keeps on growing (CCDTL, PIMS, BTW, ACS,…)
- High frequency RFQs and DTLs + high-gradient BTW structures reduce the size of hadron therapy machines.

THANKS

FOR

Listening