MedAustron

OMA SCHOOL ON MEDICAL ACCELERATORS

5-9 JUNE 2017

SYNCHROTRON

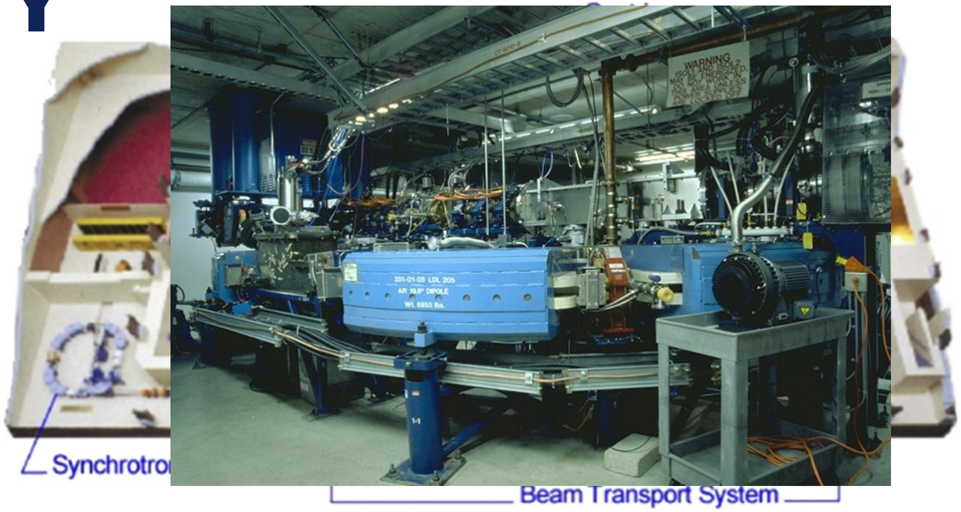
FADMAR OSMIĆ

SYNCHROTRON FOR MEDICAL APPLICATIONS

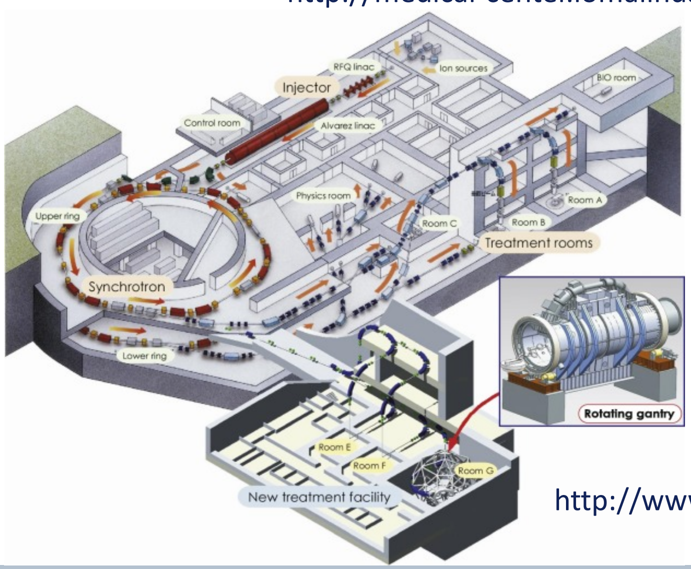
- **Occurrence and Examples**
- **Parameters**
- **Components**
- **Certification**
- **Challenges vs Possibilities**
- **Outlook**

FIRST SYNCHROTRONS FOR HADRON THERAPY

- **Loma Linda University Medical Center**
  - Constructed in 1990 by Fermilab
  - 7 m diameter
- **Heavy-Ion Medical Accelerator in Chiba (HIMAC)**
  - Built by NIRS in 1993
  - 2 synchrotrons
  - Basis for Japanese centers
- **Experimental Heavy Ion Therapy Facility at GSI**
  - Operational from 1997 to 2008
  - Using the existing synchrotron SIS-18



http://medical-center.lomalindahealth.org/



http://www.nirs.qst.go.jp

OCCURRENCE

Austria	MedAustron, Wiener Neustadt	p	S 250	2 fixed beams**, 1 gantry** (under construction)	2017
		C-ion	S 430/u	2 fixed beams**	2017
China	IMP-CAS, Lanzhou	C-ion	S 400/u	1 fixed beam	2006
China	SPHIC, Shanghai	p	S 250	3 fixed beams**	2014
		C-ion	S 430/u	3 fixed beams**	2014
Germany	HIT, Heidelberg	p	S 250	2 fixed beams, 1 gantry**	2009, 2012
		C-ion	S 430/u	2 fixed beams, 1 gantry**	2009, 2012
Germany	MIT, Marburg	p	S 250	3 horiz., 1 45deg. fixed beams**	2015
		C-ion	S 430/u	3 horiz., 1 45deg. fixed beams**	2015
Italy	CNAO, Pavia	p	S 250	3 horiz., 1 vertical, fixed beams	2011
		C-ion	S 480/u	3 horiz., 1 vertical, fixed beams	2012
Japan	HIMAC, Chiba	C-ion	S 800/u	horiz.***, vertical***, fixed beams	1994
Japan	HIBMC, Hyogo	p	S 230	1 gantry	2001
		C-ion	S 320/u	horiz.,vertical, fixed beams	2002
Japan	PMRC 2, Tsukuba	p	S 250	2 gantries***	2001
Japan	Shizuoka Cancer Center	p	S 235	3 gantries, 1 fixed beam	2003
Japan	STPTC, Koriyama-City	p	S 235	2 gantries**, 1 fixed beam	2008
Japan	GHMC, Gunma	C-ion	S 400/u	3 horiz., 1 vertical, fixed beams	2010
Japan	MPTRC, Ibusuki	p	S 250	3 gantries***	2011
Japan	Fukui Prefectural Hospital PTC, Fukui City	p	S 235	2 gantries***, 1 fixed beam	2011
Japan	Nagoya PTC, Nagoya City, Aichi	p	S 250	2 gantries***, 1 fixed beam	2013
Japan	SAGA-HIMAT, Tosu	C-ion	S 400/u	3 horiz., vertical, 45 deg., fixed beams	2013
Japan	Hokkaido Univ. Hospital PBTC, Hokkaido	p	S 220	1 gantry	2014
Japan	i-Rock Kanagawa Cancer Center, Yokohama	C-ion	S 430/u	4 horiz., 2 vertical, fixed beams	2015
Japan	Tsuyama Chuo Hospital, Okayama	p	S 235	1 gantry	2016
Russia	ITEP, Moscow	p	S 250	1 fixed beam	1969
Russia	St.Petersburg	p	S 1000	1 fixed beam	1975
USA, CA.	J. Slater PTC, Loma Linda	p	S 250	3 gantries, 1 fixed beam	1990
USA, TX.	MD Anderson Cancer Center, Houston	p	S 250	3 gantries***, 1 fixed beam	2006
USA, MO.	S. Lee Kling PTC, Barnes Jewish Hospital, St. Louis	p	SC 250	1 gantry	2013
USA, FL.	Ackerman Cancer Center, Jacksonville	p	SC 250	1 gantry	2015
USA, MN.	Mayo Clinic Proton Beam Therapy Center, Rochester	p	S 220	4 gantries**	2015
USA, NJ.	Laurie Proton Center of Robert Wood Johnson Univ. Hospital, New Brunswick	p	SC 250	1 gantry	2015
USA, TN.	St. Jude Red Frog Events Proton Therapy Center, Memphis	p	S 220	2 gantries**, 1 fixed beam	2015
USA, AZ.	Mayo Clinic Proton Therapy Center, Phoenix	p	S 220	4 gantries**	2016
USA, FL.	Orlando Health PTC, Orlando	p	SC 250	1 gantry	2016
USA, OH.	UH Sideman CC, Cleveland	p	SC 250	1 gantry	2016

- **26 operational synchrotron centers**
  - 15 protons
  - 5 carbons
  - 6 combined
- **4 in Europe**
  - all combined
- **13 in Japan**
- **2 in China**
- **5 in US**
- **2 in Russia**

→ **About 1/3 of proton centers use synchrotrons**

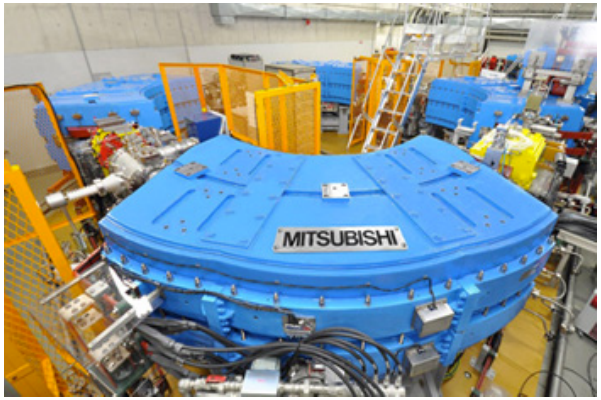
→ **All carbon and dual centers use synchrotrons**

https://www.ptcog.ch/index.php/facilities-in-operation

FURTHER CENTERS IN PROGRESS

- **9 under construction (according to PTCOG):**
  - 8 proton synchrotrons
  - 1 carbon synchrotron
  - 1 combined → KIRAMS
- **4 in planning stage (difficult to estimate)**
  - 2 proton synchrotrons (according to PTCOG)
  - 2 combined (as far as I know) → CNAO/MEDAUSTRON
- **In general: huge interest worldwide**
  - A lot of tourism at MedAustron and other European centers

PROTON SYNCHROTRONS FOR TUMOR THERAPY



Hitachi:

- Operational in Tsukuba, Japan MDACC, Texas
- 6 dipoles
- 7,8 m diameter

http://www.hitachi.com/businesses/healthcare/products-support/pbt/

ProTom:

- 8 dipoles
- 4,9m diameter
- 16 tons
- Protons up to 330 MeV → proton CT

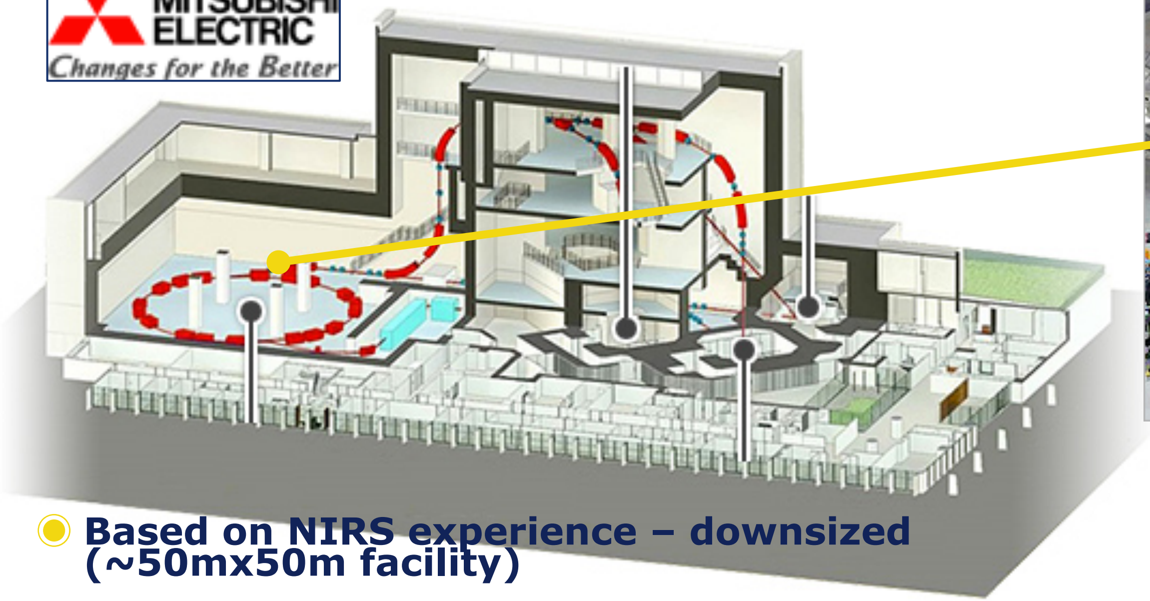
http://www.protominternational.com/

Mitsubishi

- 6 m diameter
- 4 dipoles

http://www.mitsubishielectric.com/bu/particlebeam/products/index.html

MITSUBISHI SYNCHROTRONS FOR TUMOR THERAPY



- Based on NIRS experience – downsized (~50mx50m facility)
- Several installations in Japan
- Carbon and dual type available
- 18 dipoles
- Turn-key solutions
- Other vendors (Hitachi and Toshiba) coming up with carbon facilities

http://www.mitsubishielectric.com/bu/particlebeam/products/index.html

EUROPEAN SYNCHROTRONS
ALL ARE DUAL TYPE

CNAO/MedAustron

- **Based on PIMMS design at CERN**
- **Technical design variations**
  - Injector position
  - Magnets
  - Power converters
- **~78 m circumference**
- **16 dipoles a 10t**

http://fondazionecnao.it/en/

Heidelberg

- **Built by GSI**
- **He operation started**
- **65 m circumference**
- **6 dipoles a 25t**

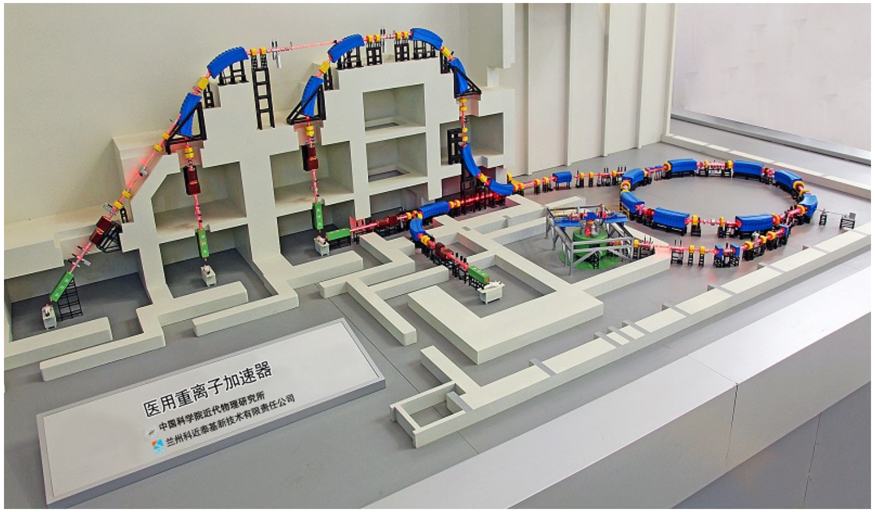
www.klinikum.uni-heidelberg.de

Siemens

- **Installations in Marburg, Shanghai, (Kiel)**
- **Designed and built by Danfysik**
- **Modified HIT design→ 65 m circumference**
- **12 dipoles a 8t**

http://www.danfysik.com/en/solutions/particle-therapy-accelerators/

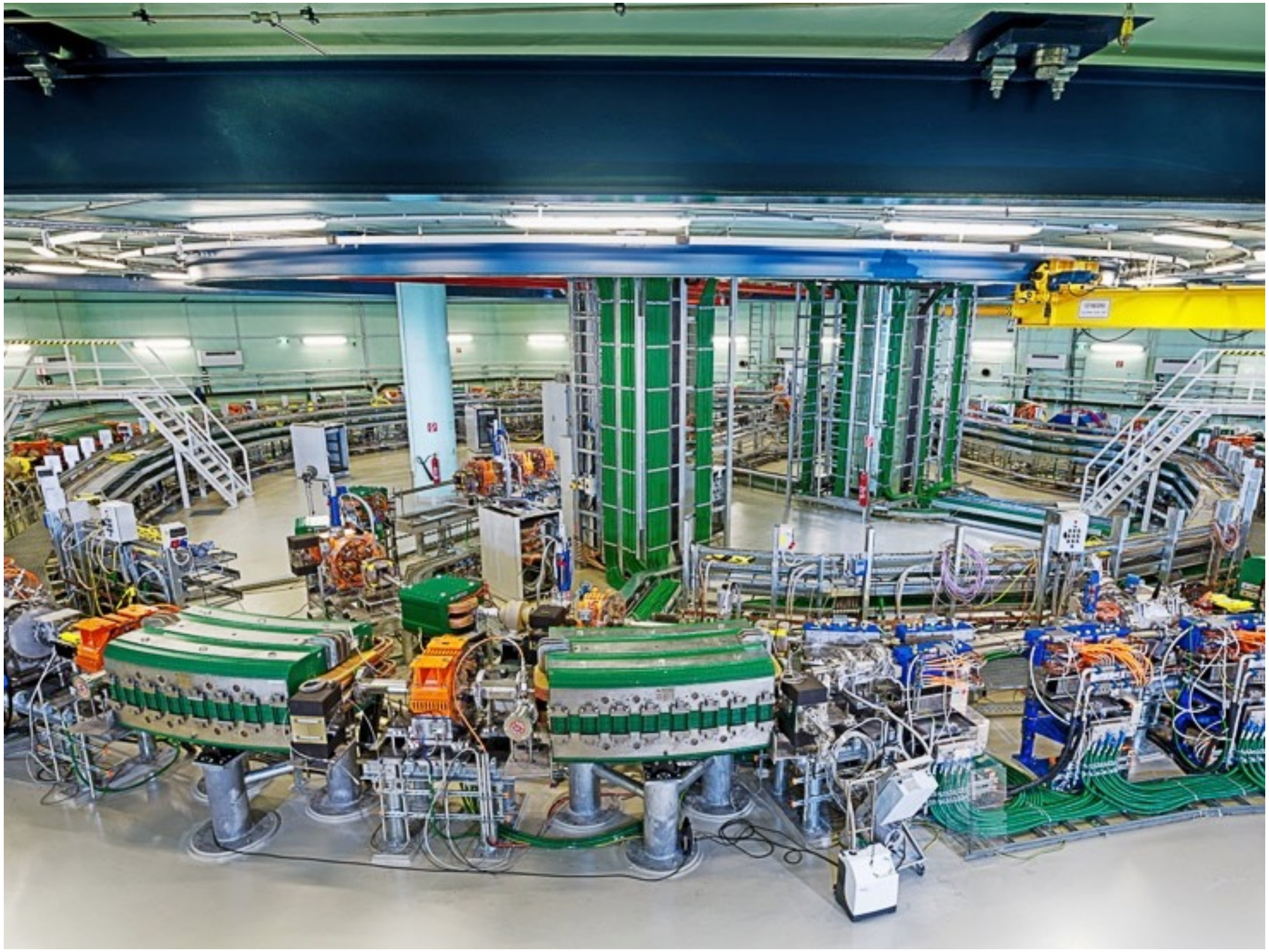
LANZHOU SYNCHROTRON



- Based on HIRFL research
- Heavy Ion Medical Machine (HIMM)
- Compact Carbon Synchrotron → 56,2 m circumference
- 8 dipoles
- Cyclotron as injector
- In construction
- Aiming at the Chinese market

http://www.kejintj.com/en/cp/zlz/

SYNCHROTRON IN DETAIL
CASE STUDY MEDAUSTRON



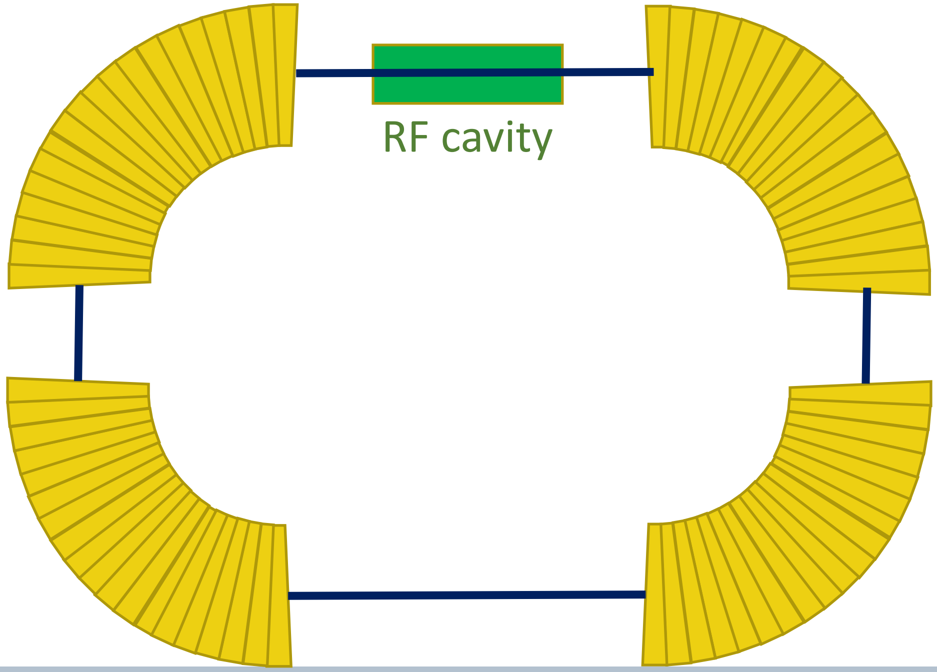
MEDICAL SYNCHROTRON

- Fixed radius → nominal path is constant
- Magnetic field is adjustable
- RF frequency is adjustable

  →Variable energy

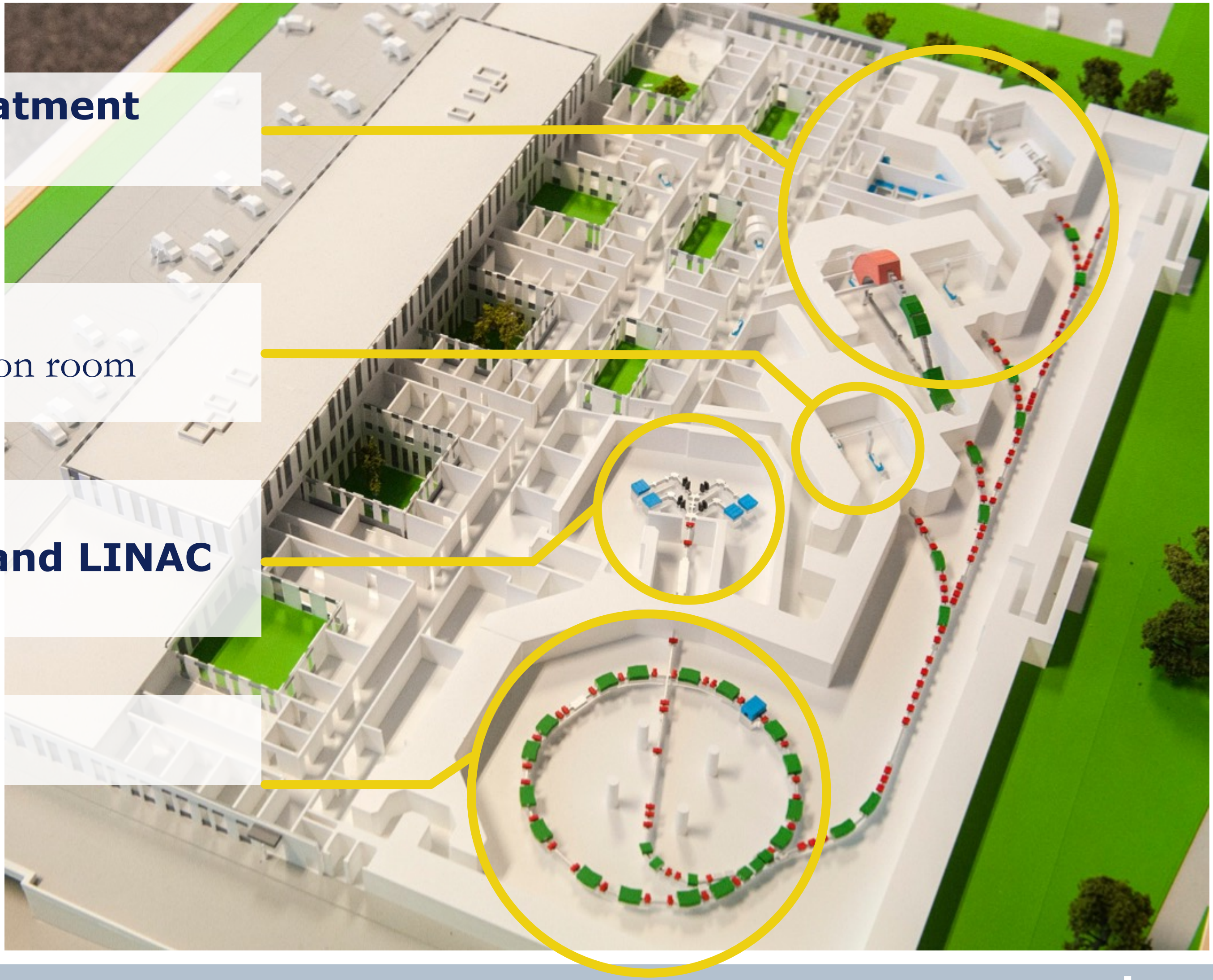
Synchronous

- Customized lattice
- Zero Dispersion sections for RF cavity and the minimum beam size at injection/extraction



- Multi-Turn Injection ~30 us
- DC beam at injection and after acceleration
- Slow extraction → see Adriano's talk
- Beam size ~few cm
- Beam length : can be ~half the circumference

MEDAUSTRON FACILITY



3 patient treatment rooms

Research
An own irradiation room

Ion sources and LINAC

Synchrotron

BEAM PARAMETERS
MEDAUSTRON

Performance	
Particle Species	p, C (other light ions possible)
Energy	P: 60 – 250 (800) ; C: 120 – 400 MeV/u
Possible energy levels	255 per particle
Ramping speed	3 T/s
Scanning speed	20 m/s (– 100 m/s)
Maximal scanning field size	20 x 20 cm2
Intensity	p: 1E10, C: 4E8
Width	4 – 10 mm (assuming vacuum up to Iso Center)

BEAM PARAMETERS
MEDAUSTRON

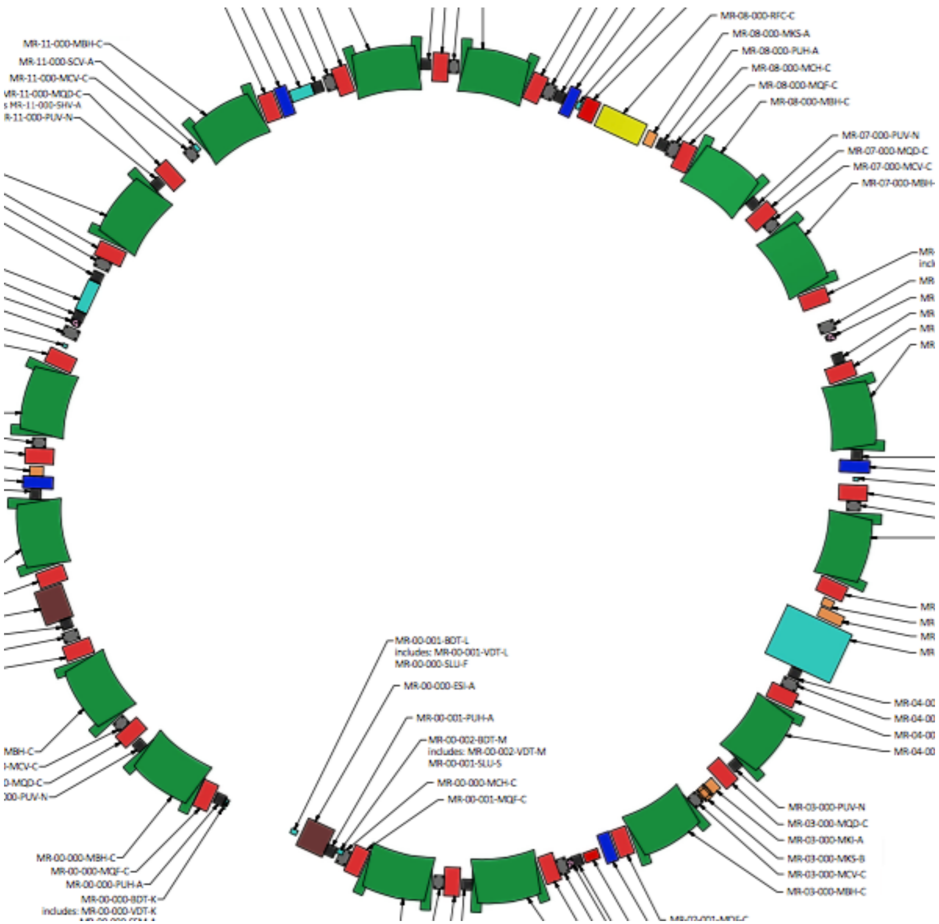
Stability	
Minimal energy step size	0,1 MeV
Beam energy precision	0,25 MeV
Relative beam energy spread dE/E	Approx 1.1E-3
Position precision	+/- 0,5 mm
Beam profile stability spill to spill	+/- 20%
Intensity	+/- 20%
Particle current extraction stability in the 100 Hz range	0 to 2 times the requested beam current
Particle current extraction stability in the kHz range	0 to 5 times the requested beam current

IMPORTANT: Long-term reproducibility of beam properties (QA!)

BEAM PARAMETERS
MEDAUSTRON

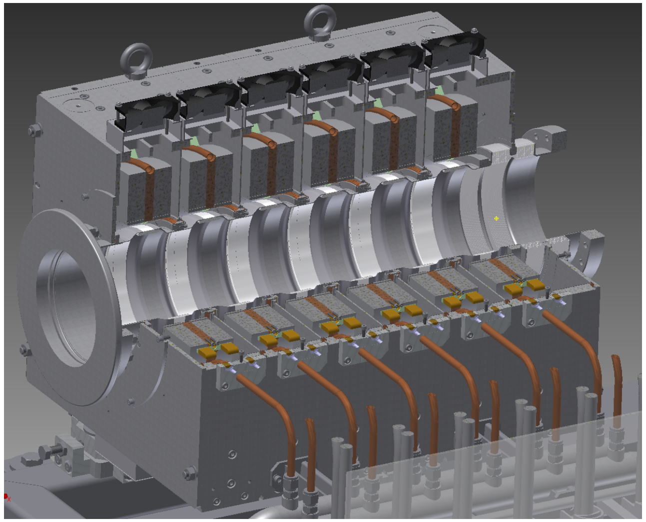
Availability	
Dead time between cycles	<2 s
Room switching time	<20 s
Beam Particle switching time	~2 mins
Maximal cycle time	120 s
System Uptime	95-98 %
Time of cycle excluding extraction	<2s
Room occupancy time	25 mins (can be 13)

SYNCHROTRON COMPONENTS
EXAMPLE MEDAUSTRON

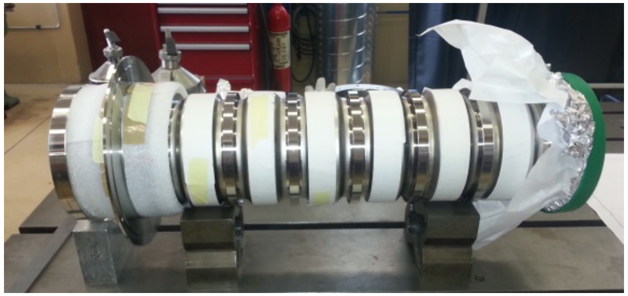


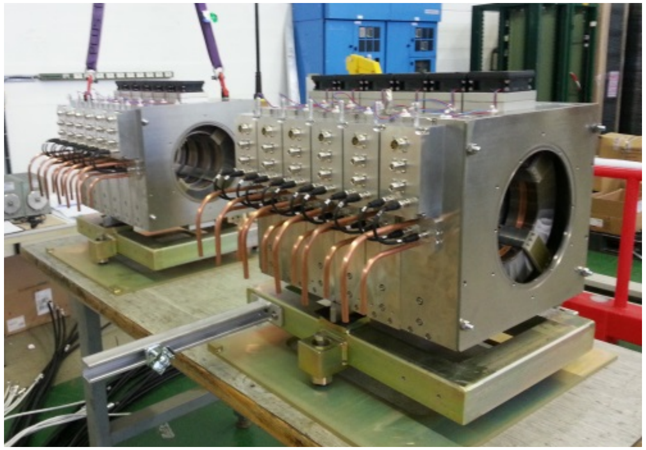
- **16 dipoles (+1 reference)**
- **24 quadrupoles (3 families)**
- **5 Sextupoles**
- **Power converters**
- **RF cavity**
- **Injection**
  - Electrostatic septum
  - ??? bumpers
- **Extraction**
  - Betatron
  - Electrostatic septum
  - Magnetic septum
- **Orbit correctors**
- **Beam Diagnostics**
  - Tune kickers
  - 20 Pickups
  - 2 CTs
  - 2 Schottkys
  - …

SYNCHROTRON COMPONENTS
CASE STUDY: MEDAUSTRON RF CAVITY



- Runs on 1st harmonic
- Finemet loaded co-axial resonator
- 2 blocks à 6 cells (82-121 mm)
- 2 Finemet FT-3L rings per cell (per gap)
- 12 x 1 kW
- Water cooled Cu disc
- Air cooling (cell: 58 m3/h)
- f = 0.46 - 3.25 MHz
- 5 kV total

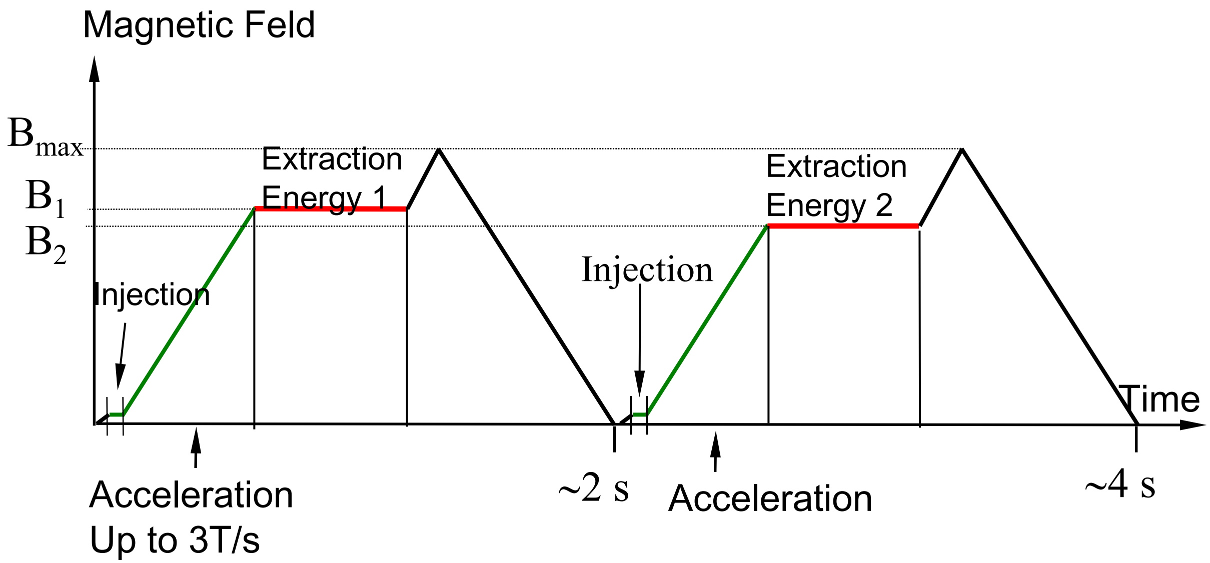




C. Schmitzer
MedAustron

SYNCHROTRON CYCLE

- **Injection 80us**
- **RF-capture: beam bunching 40 ms**
- **Acceleration <0,5 s**
- **Prepare Extraction 100 ms (Energy verification)**
- **Extraction 0,1 – 120 s**
- **Ramp Down Reset 0,5 s**



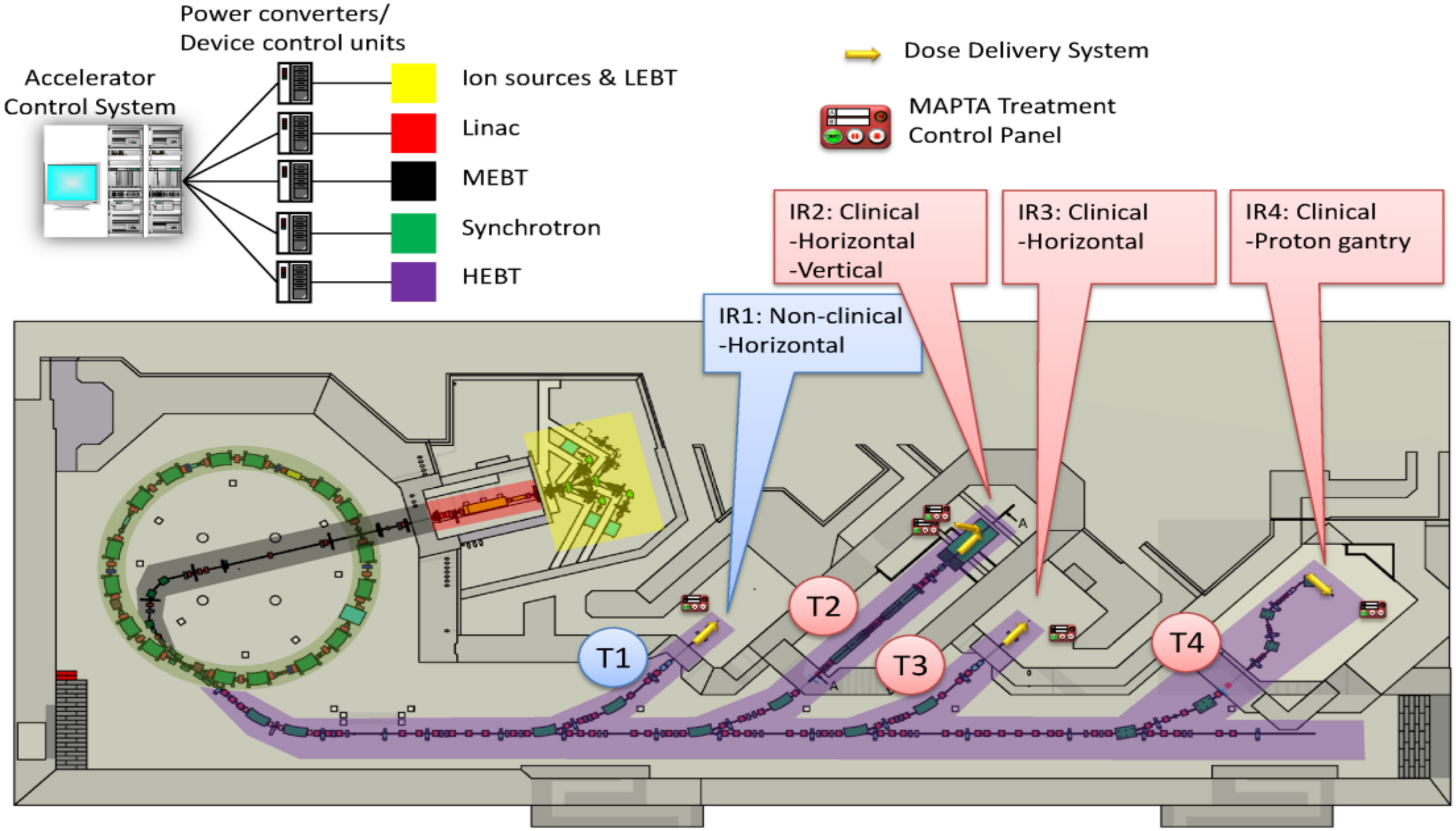
CE: CONFORMITY ASSESSMENT STRATEGY

- **Starting Point:**
  - Statement of Austrian Ministry of Health:

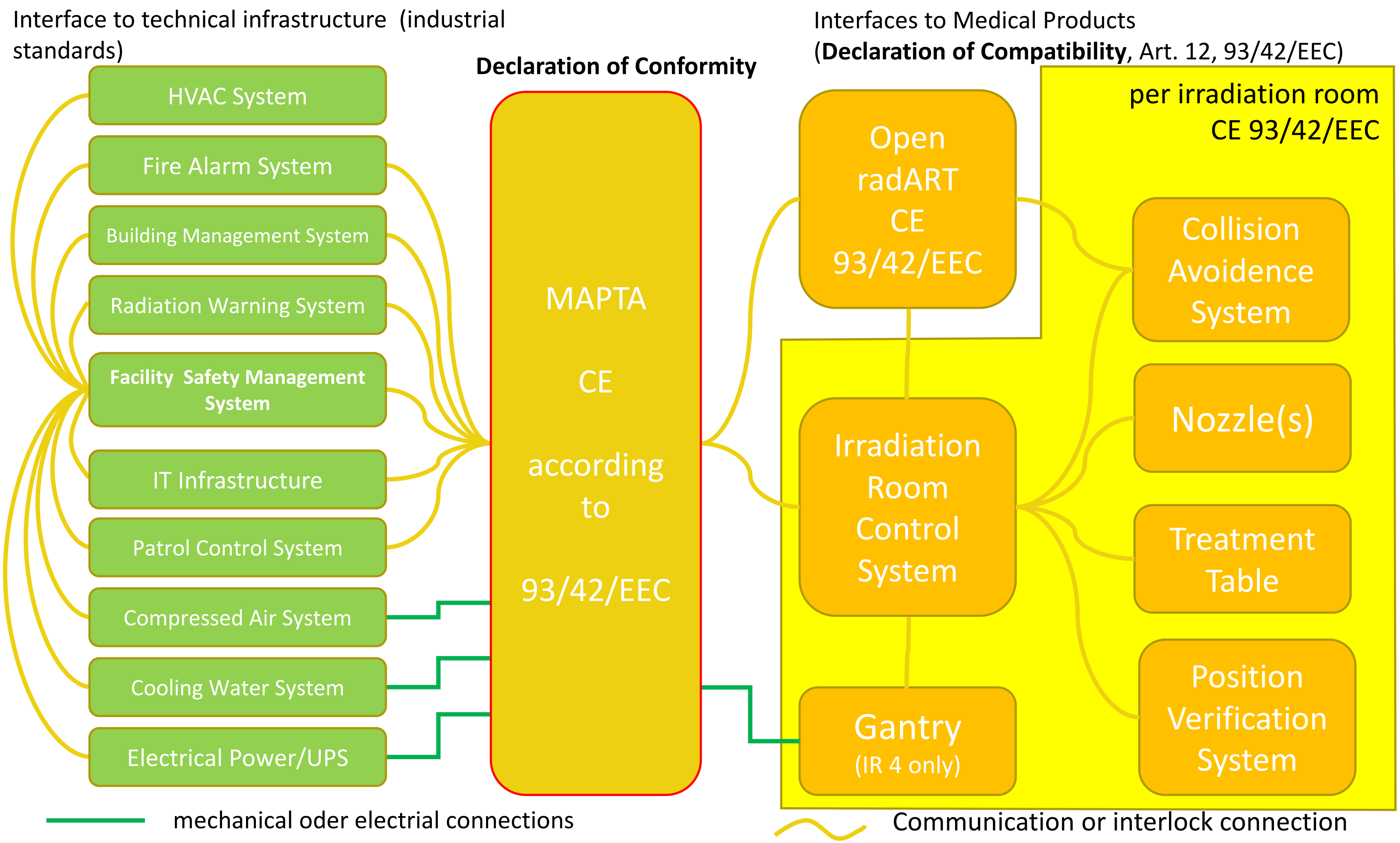
    The Therapy Accelerator of the Particle Therapy Center MedAustron is to be classified as a medical product and is to be handled in accordance with the Medical Product Law and the European Medical Device Directive 93/42/EWG.

  - The principal core process is safe operation of the product (the product is produced only once).

THERAPY ACCELERATOR MAPTA

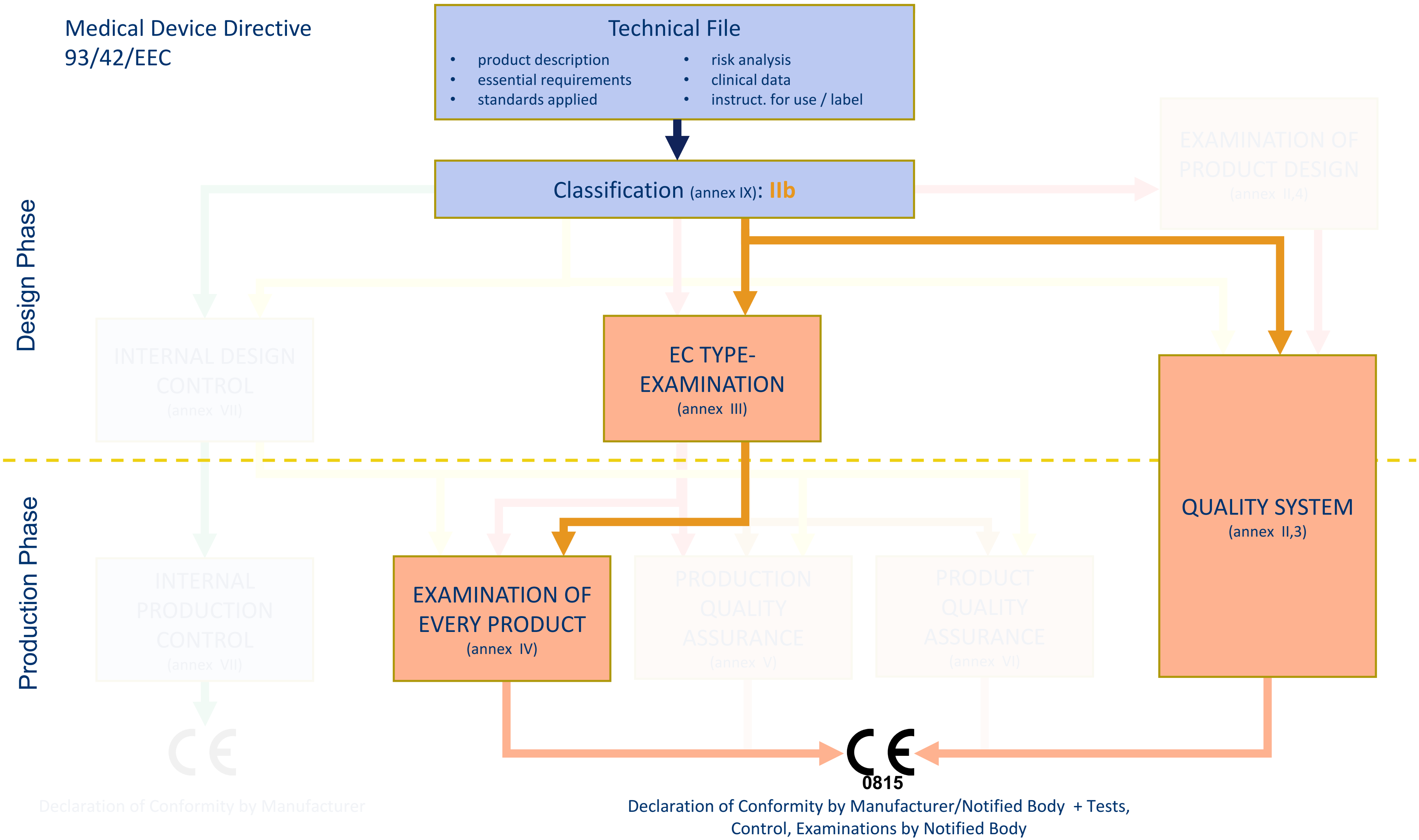


INTERFACE OVERVIEW MAPTA



CE: PATHS FOR LIGHT ION BEAM MEE

Medical Device Directive
93/42/EEC



CE: CONFORMITY ASSESSMENT STRATEGY

Activities related to entire MAPTA:

- EMC regulation → EMC concept/report
- Functional safety w.r.t intended use
- Usability → User Manual
- ETG/ETV → OEnorm E8001 (initial commissioning)
- ISO 14971 (risk management for medical products)

Additionally:

- Test management (incl. 60601-2-64)
- Technical documentation

CYCLOTRON VS. SYNCHROTRON

Cyclotron	Synchrotron
Fixed Energy Energy Selection System	Variable energy
Radiation protection	Low radiation
High current Current manipulation	Low current
Small footprint	Large footprint
No carbons	Different ions easy possible
No Injector	Injector needed
Lower cost	Higher cost

Don’t forget the business case!

FURTHER CHALLENGES FOR SYNCHROTRONS

- **Costs**
  - Due to foot print and complexity
- **Timing structure**
- **Commissioning time**
- **Complex**
  - Especially the technical operation
  - Large team to cover many disciplines needed

REASONS FOR SYNCHROTRONS

High flexibility:

- Several ion species → exploiting the full potential of hadron therapy (there are no carbon cyclotrons)

Active energy selection

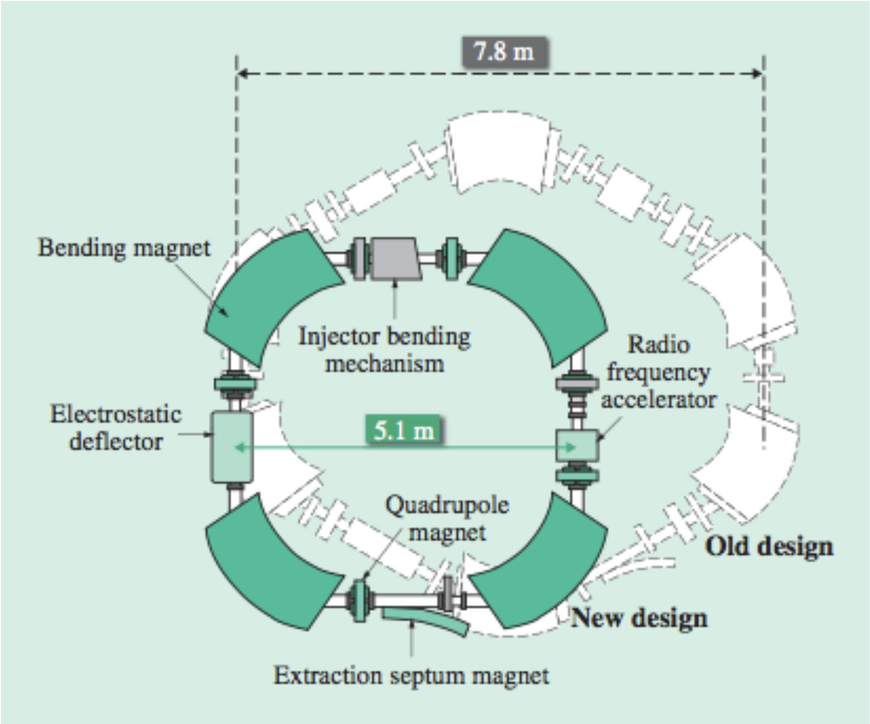
Dose efficiency

- Carbon ions leave about 24 times more energy in a cell than protons
- Certain tumors can be treated
- Hypo-fractiations
- Benefit for patients

Political aspects in decisions

- Importance of Know-how gain
- Research aspect

DOWNSIZING EXAMPLE HITACHI



- 6 → 4 dipoles
- 10 → 4 quads
- 7,8 m → 5,1 m

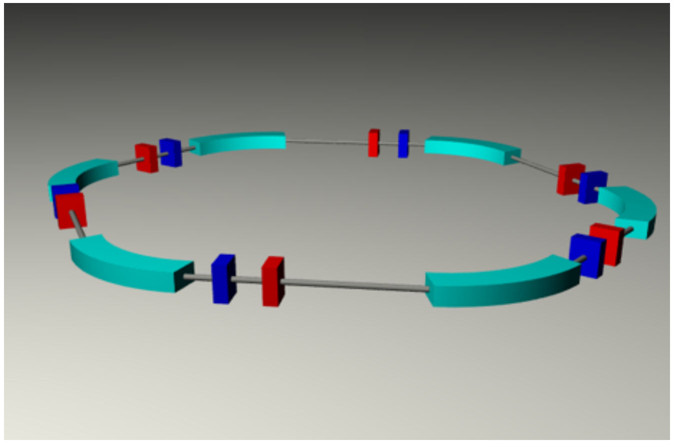
→ **30% smaller footprint**

→ **Thanks to a newly developed simulation technique for particle trajectory tracking**

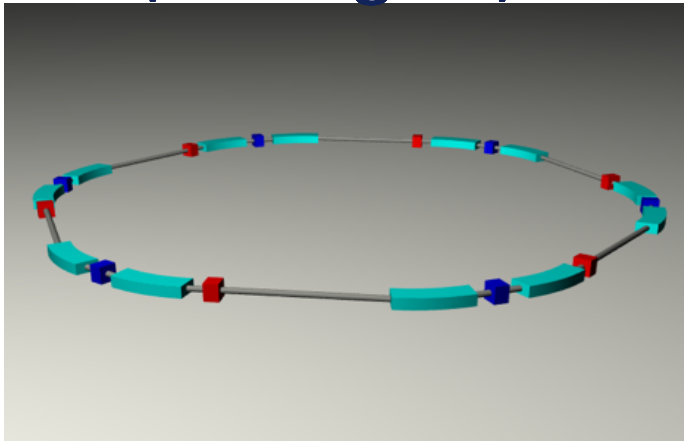
Umezawa et al.,
Hitachi Review Vol 64 (2015), No. 8

"DOWNSIZING" EXAMPLE SIEMENS/DANFYSIK

HIT



MIT/Shanghai/Kiel



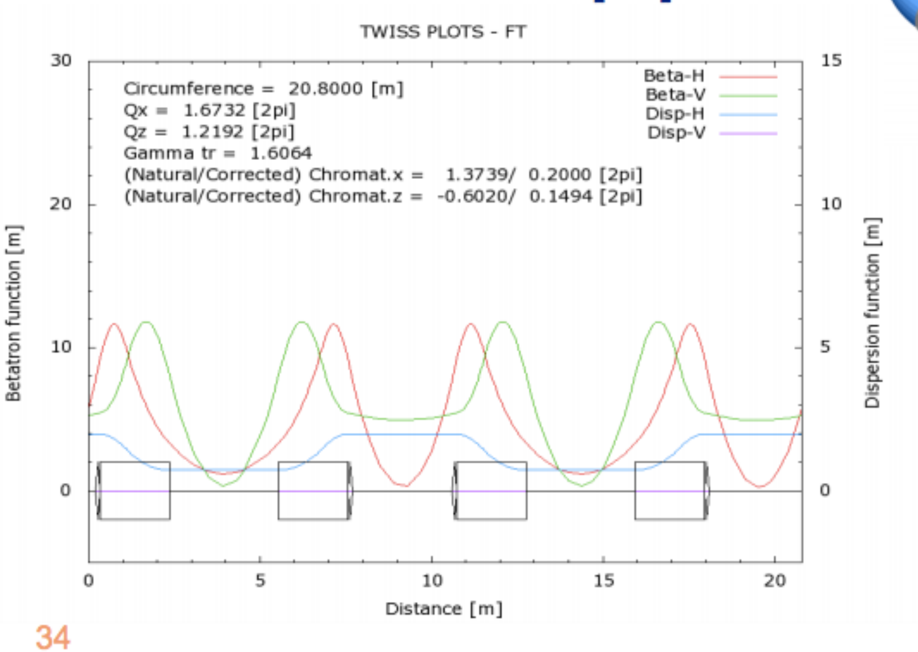
- **Reduced weight of heaviest component (installation, handling)**
- **Less space constraints in extraction region (smaller angle in magnetic septa possible)**
- **Higher symmetry (smaller beta function, larger dynamic aperture)**
- **Symmetric sextupole layout (flexibility)**

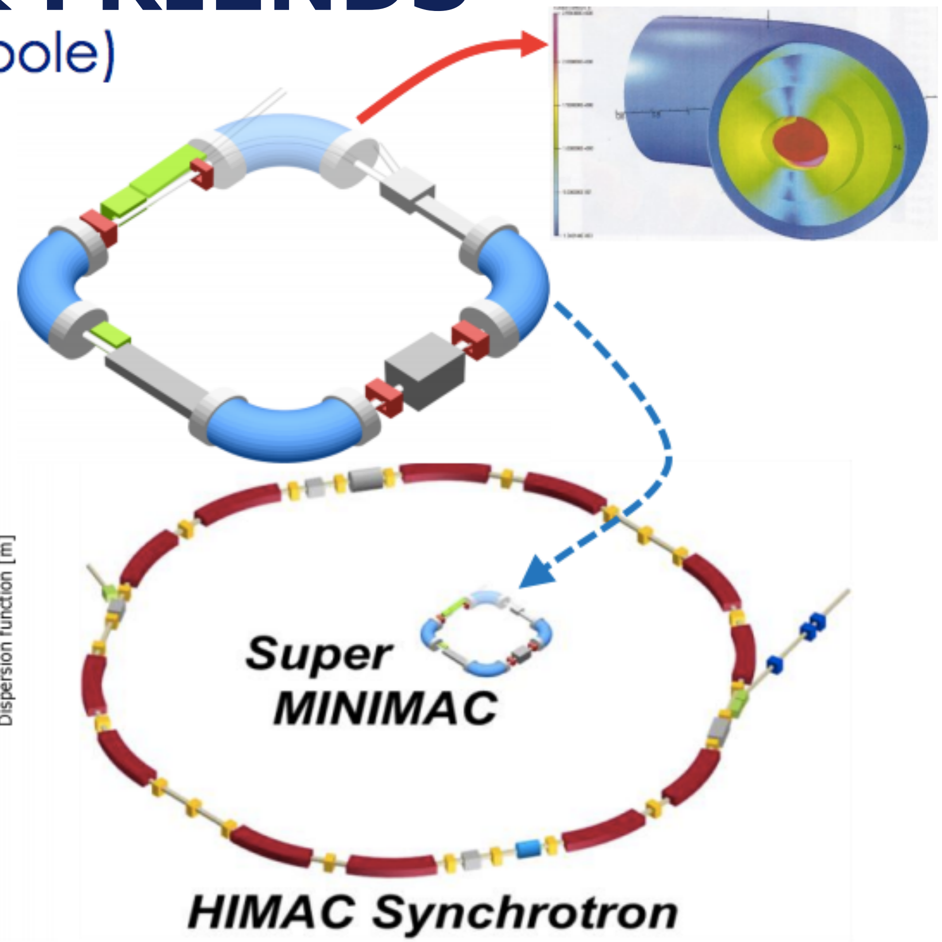
www.siemens.de

Heiko Rohdjess

FUTURE DOWNSIZING AIMED BY NIRS & FRIENDS

- SC magnets (Dipole+Quadrupole)
- B_{max}~ 5 [T]
- dB/dt~ 1+ [T/sec]
- Circumference~21 [m]





OBS: fast ramping curved, superconducting dipoles

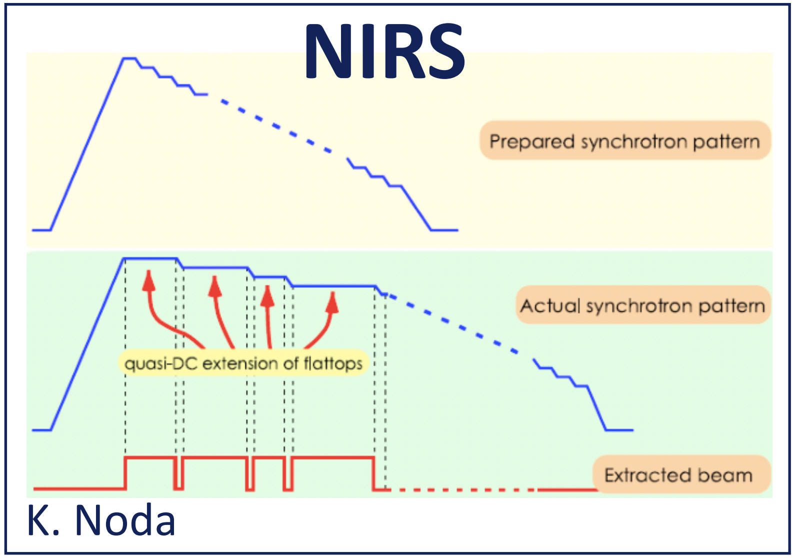
Iwata et al., Nov 2016 Workshop at CIEMAT

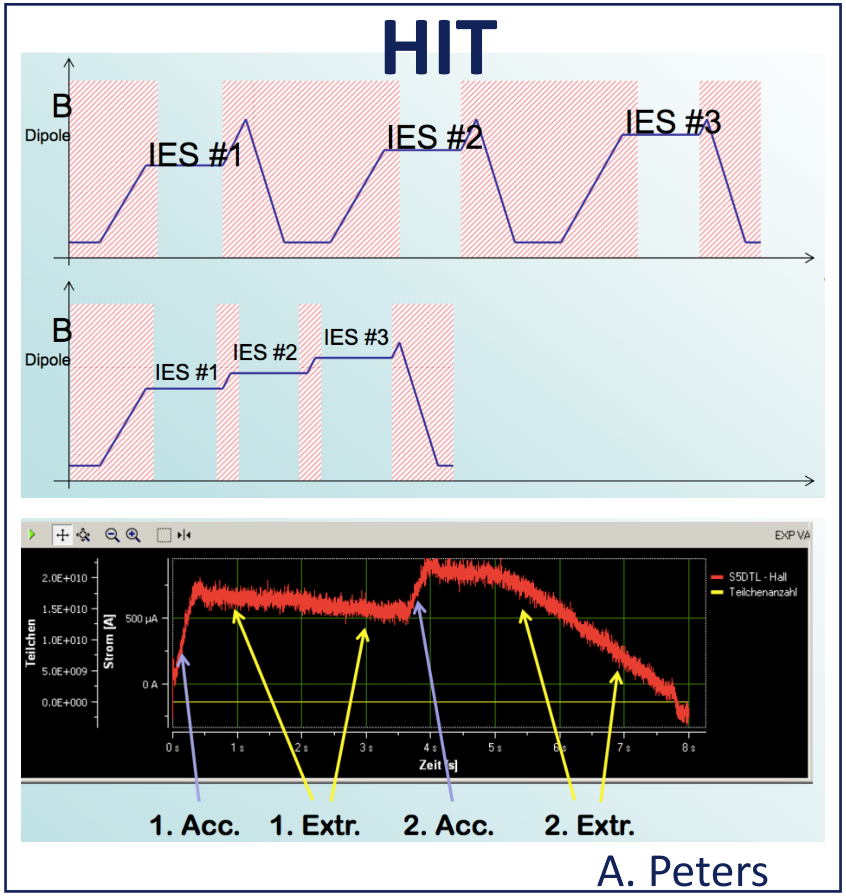
FUTURE DOWNSIZING AIMED BY NIRS & FRIENDS

http://www.japantimes.co.jp/
DEC 13, 2016

- **4 Japanese companies joined efforts with NIRS**
  - Hitachi Ltd., Mitsubishi Electric Corp., Toshiba Corp. and Sumitomo Heavy Industries Ltd
- **"... to share the research costs to develop a new heavy ion cancer treatment device in about 10 years"**
- **Goal: decrease the treatment costs by factor 2-3**

SPEEDING UP: MULTI-ENERGY OPERATION

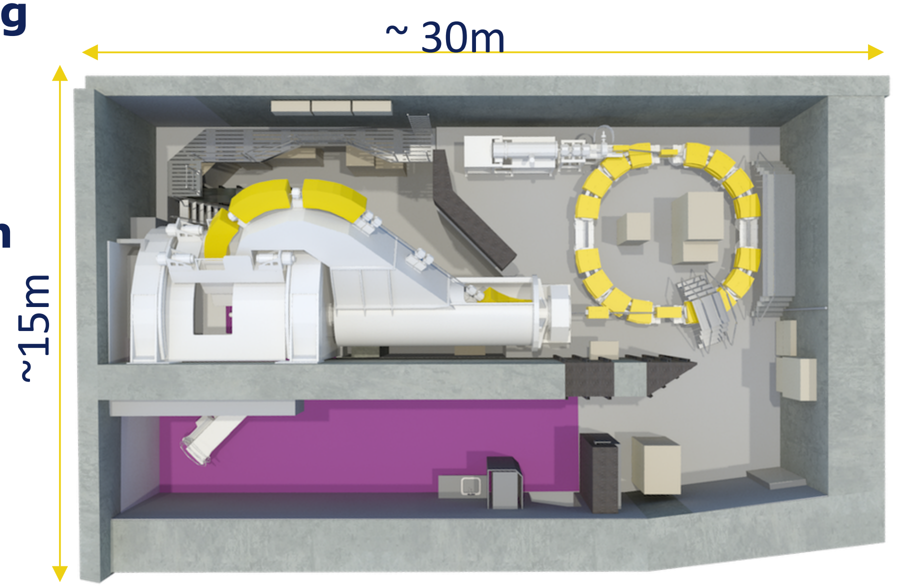




- **NIRS approach: see slides by K. Noda**
  - **Every energy level needs to be passed**
- **HIT approach:**
  - **Selective choice of energies**
  - **Shrinking the irradiation time by 50%**
  - **Proof of principle with 2 energies**

OUTLOOK

- **Downsizing is possible and ongoing**
  - Proton synchrotrons are already competitive with cyclotrons → small footprint
  - Carbon facilities can fit in 50m x 50m
- **Among others Danfysik has proven that slim carbon synchrotrons can be built**
  - Less components
  - Easier service and operation
- **Faster commissioning due to 1:1 copies**
- **Multi-Energy operation**
- **Faster cycle times**
- **Synchrotron as product**
  - Already available in Japan
  - Was available in Europe (Siemens)
  - European centers CNAO and MedAustron working now on this step



ProTom one gantry room solution

THANK YOU!