Compact Synchrotrons for Hadron Therapy: Development and Synergies with HEP Projects.

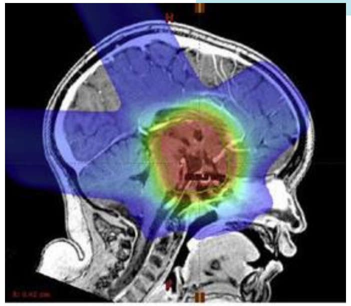
Elena Benedetto, SEEIIST Association

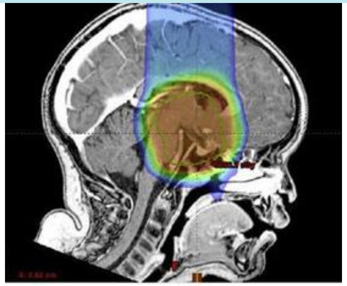
7/9/2023

Joint Annual Meeting of the Swiss and Austrian Physical Society

Proton (hadron) radiation therapy

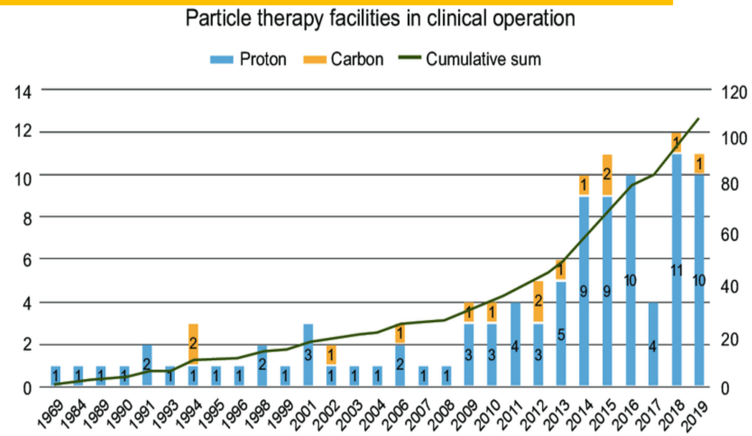
DOI:10.1016/j.ijrobp.2016.06.2446





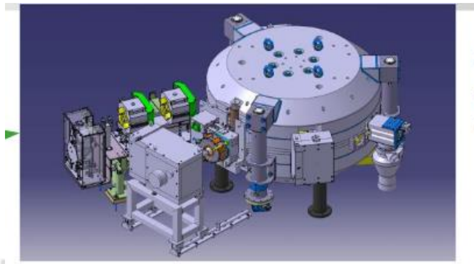
photons IMRT protons

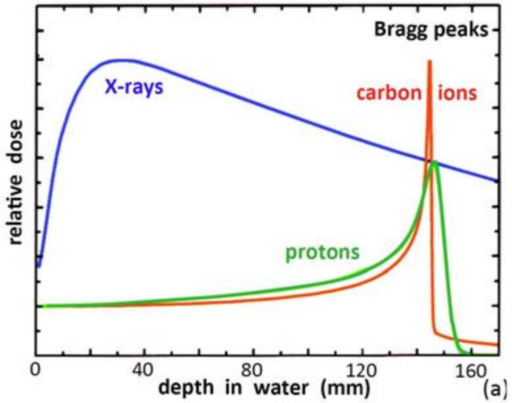
Bragg Peak: hadrons deposit energy @ specific depth, depending on the beam energy



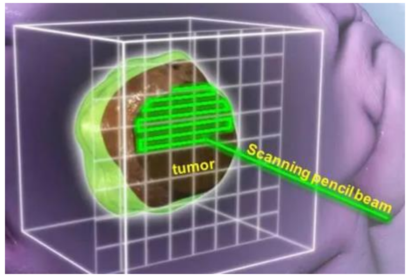
110 particle - proton therapy facilities,
30 in Europe (Vs. 14’000 X-ray facilities)

IBA SynchroCyclotron

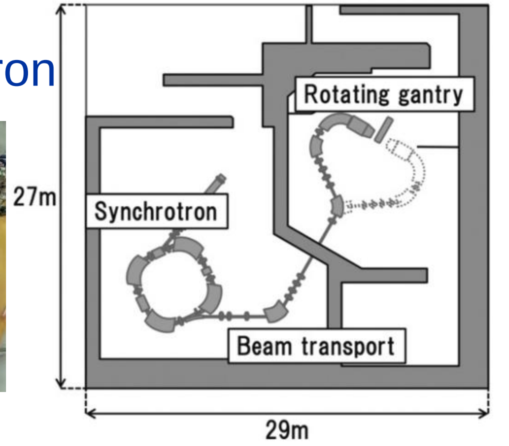




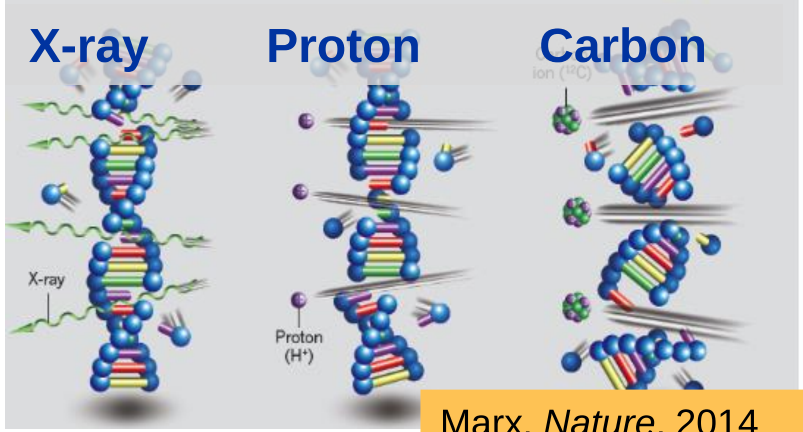
3D beam scanning



HITACHI Synchrotron



Carbon (and other) ions therapy



Marx, *Nature*, 2014

Single-strand breaks (easy to repair) vs. double-strand breaks (not reparable)

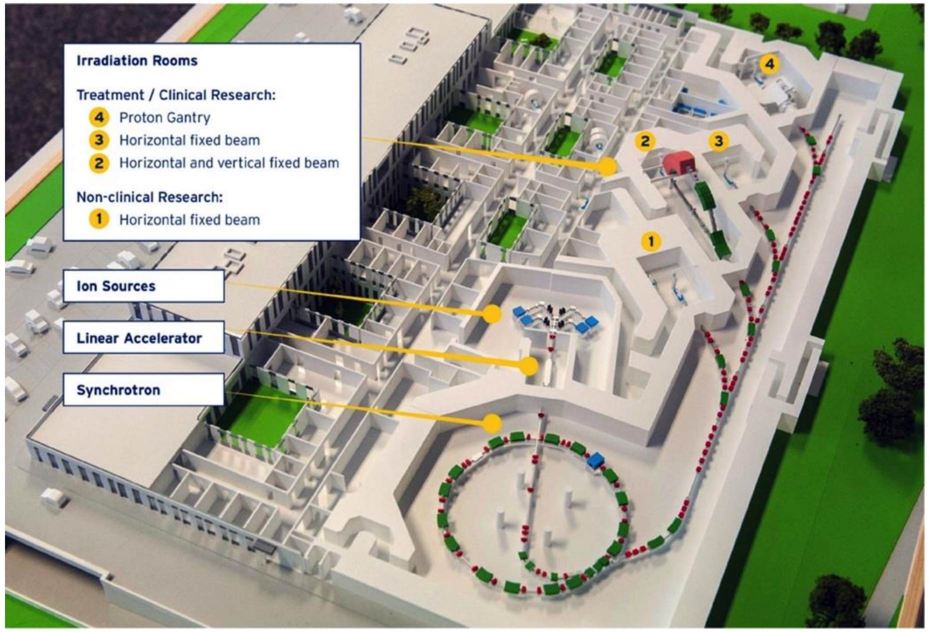
- ✓**3x more damage (RBE)**
- ✓**also in oxygen-depleted “radioresistant” tumours**

Helium and Oxygen ions also of interest for treatment

Range 3 mm to 300 mm in water-equivalent (Bragg Peak)

Protons: 60 - 250 MeV ($B\rho$ = 2.42 Tm)
Carbon: 100 – 430 MeV/u ($B\rho$ = 6.6 Tm)

~2.7x beam rigidity, i.e. more difficult to bend

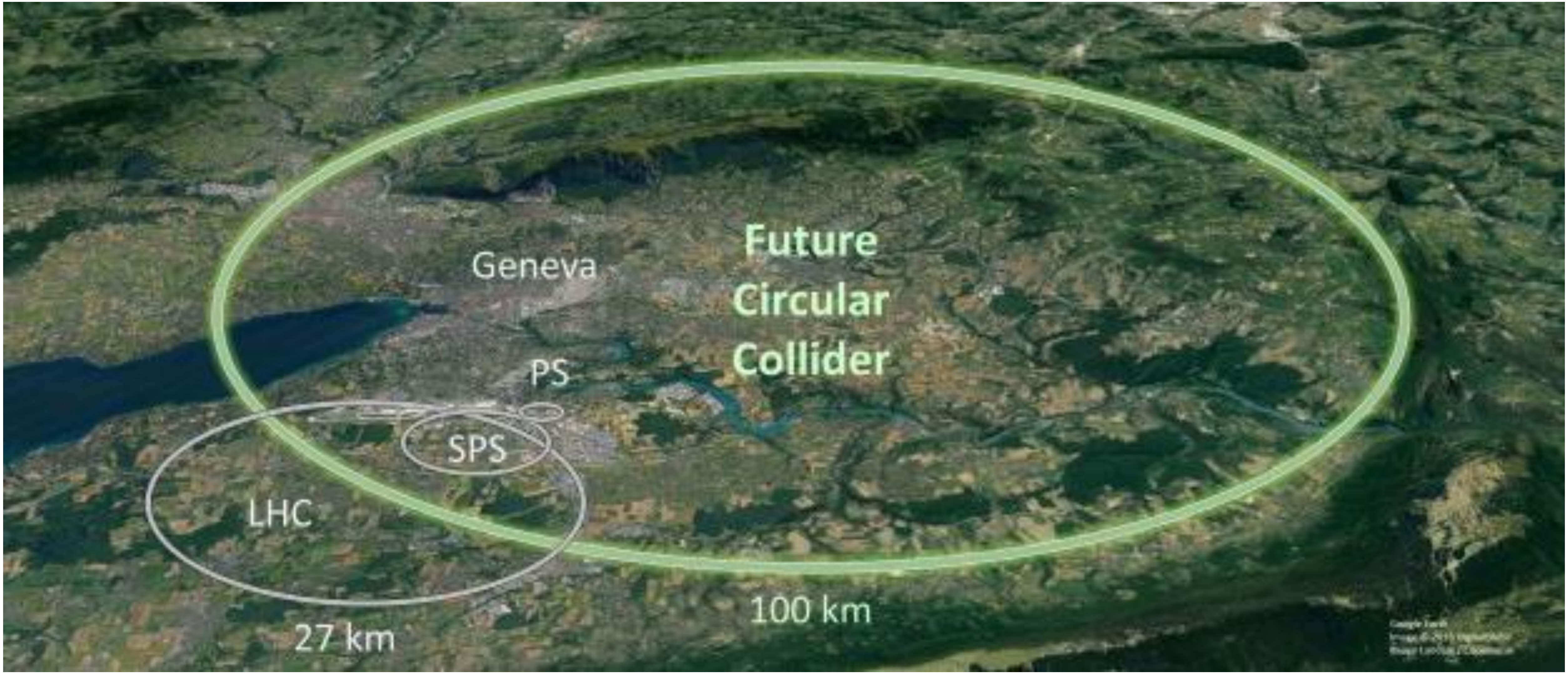


MedAustron, 25 m diameter synchrotron

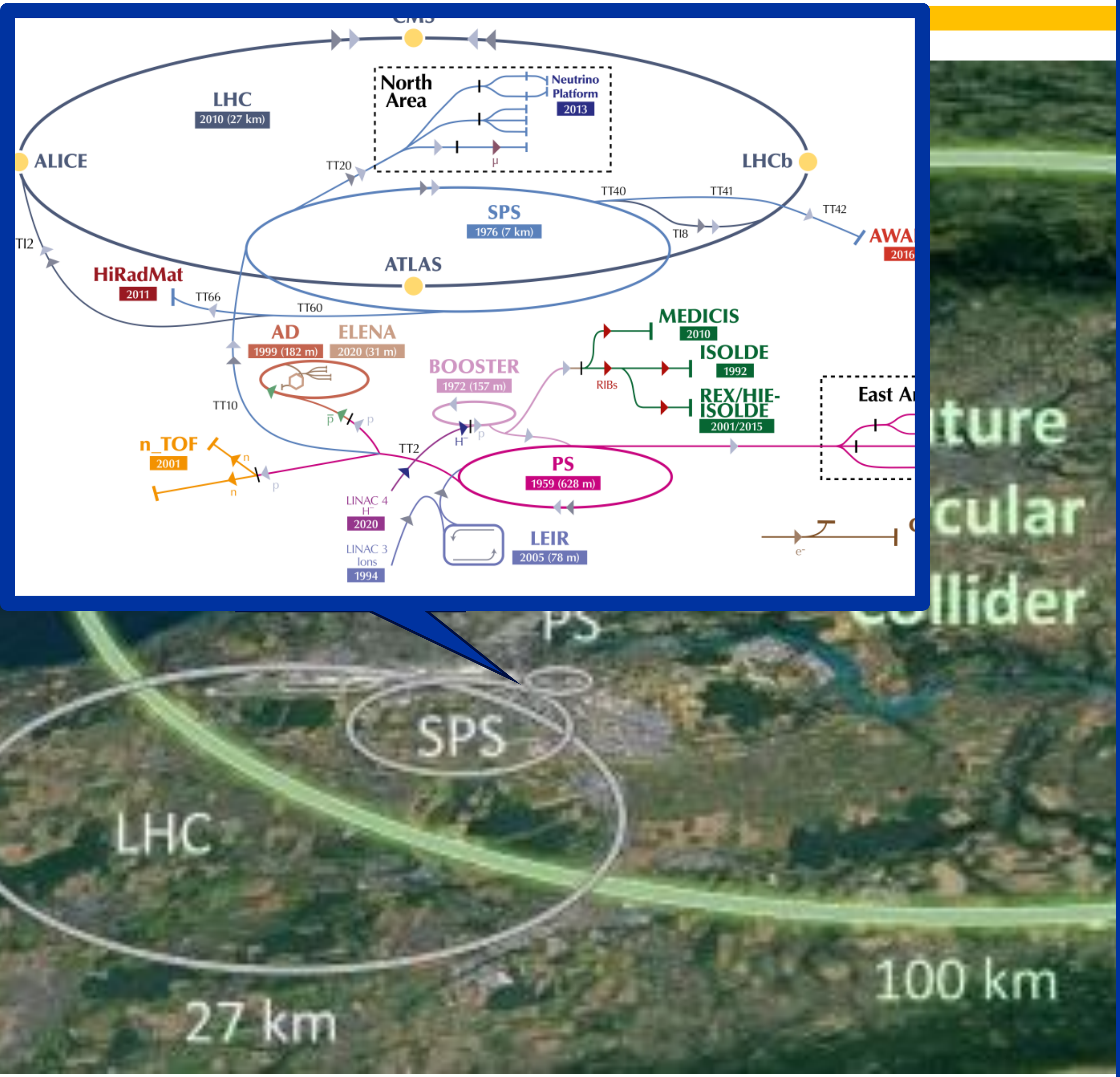
Facility becomes larger and more expensive ~200 MEur

Heidelberg HIT C-ion gantry (600 tons)

@ CERN



@ CERN



Next Ion Medical Machine Study (NIMMS)

PIMMS: collaboration CERN, TERA, MedAustron, TDR in 2000

- C-ion ring, 75 m circumference

NIMMS: collaboration CERN, Tera-Care, SEEIIST, Riga U., et al., started 2018

- Higher (x 20) beam intensity stored:
  - for flexible extraction (and FLASH)
- Reduce dimensions, weight (and cost)
  - ~30 m length
  - Super-Conducting magnets C-ion ring & gantry
  - Helium-ion synchrotron w. warm magnets

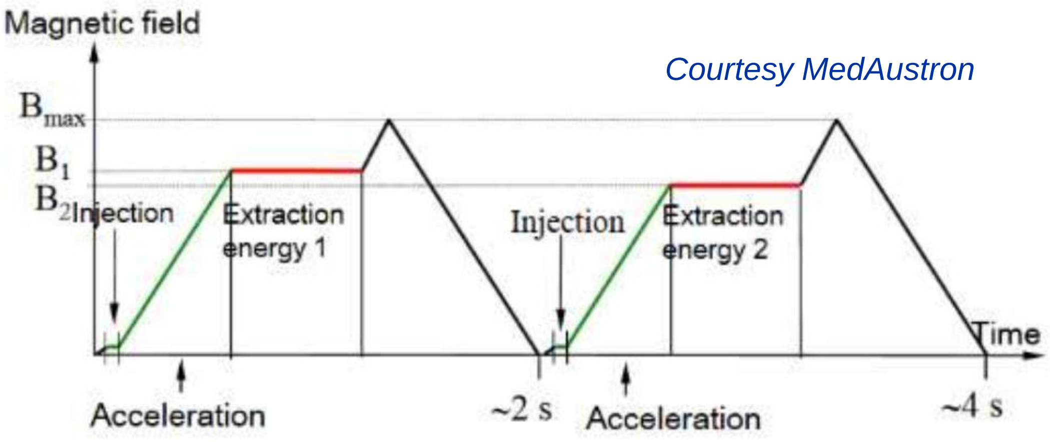
1) Higher (x20) intensity

- **SEEIIST:** The South East European International Institute for Sustainable Technologies
- Science4peace project
- Research and therapy with ions: p, He, C, O,…up to Ar
- Flexible extraction modality
  - multi-energy slow resonant extraction
  - FLASH: high dose, high rate
- Baseline layout is a PIMMS synchrotron (like CNAO/MedAustron)
- Option of a compact SC-magnet synchrotron

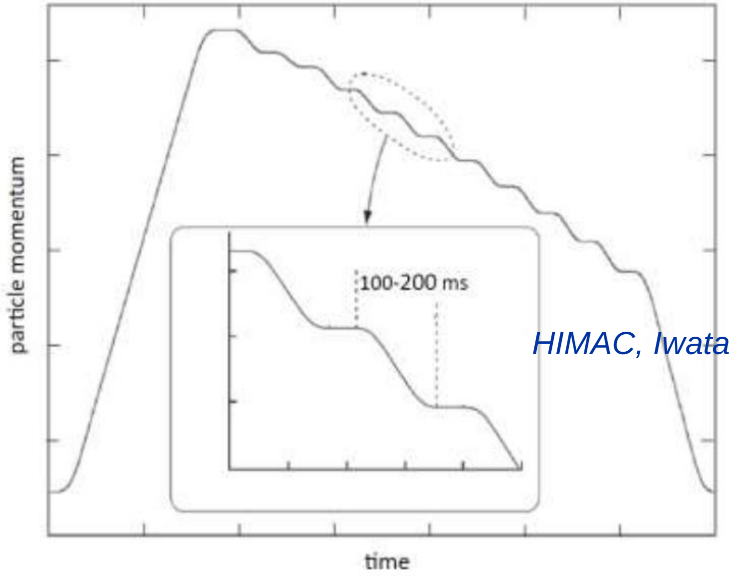
(*)To deliver 2 Gy to 1 liter in one cycle

	p	He	C
Intensity	2.6 e11	8.2 e10	2.0 e10
Injection Energy (MeV/u)	7-10	5	5
Extract Energy (MeV/u)	60-250	60-250	100-430
Beam rigidity max (Tm)	2.42	4.85	6.62
Synchrotron diameter (m)		~25m	
Spill duration (s)		0.1 - 60	
Spill ripple @1 kHz		<1.5	

Delivery of 2 Gy in a 1-liter tumour: HOW?



Courtesy MedAustron



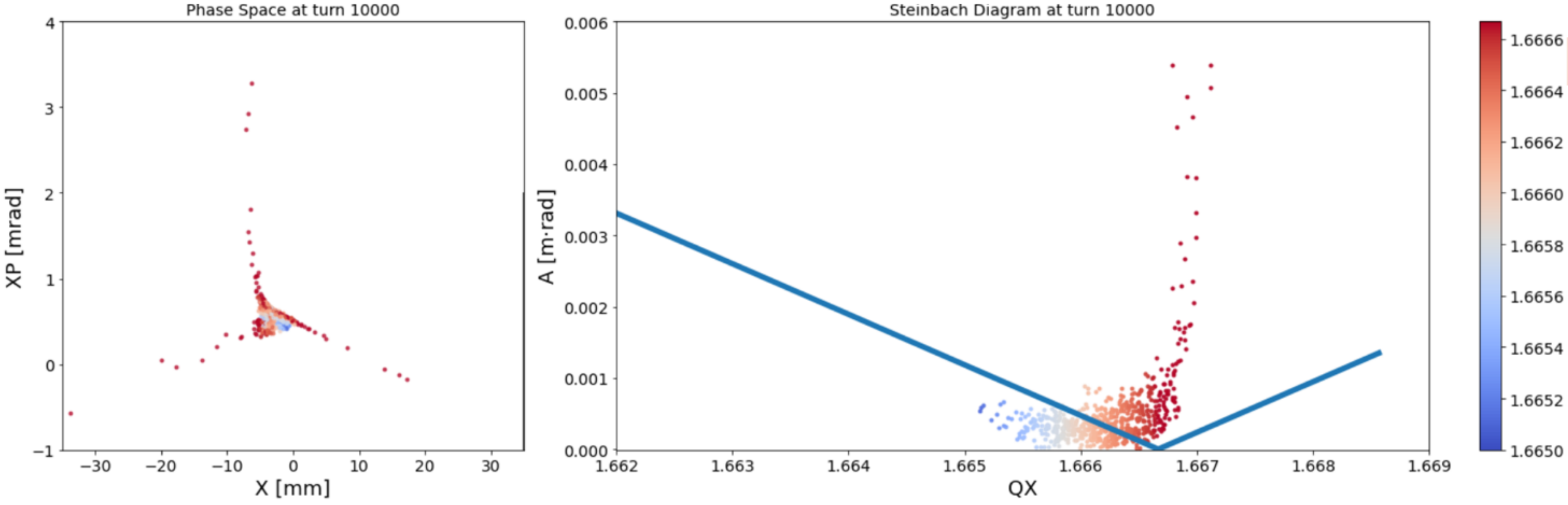
HIMAC, Iwata et al, NIM-A

TODAY: Every change of energy → A different cycle

TODAY in Japan: Multi-Energy Extraction (going down or up) within same cycle

TOMORROW(?) … deliver the entire *high intensity* beam in <500 ms for FLASH irradiation

Slow extraction on the 3rd order resonance

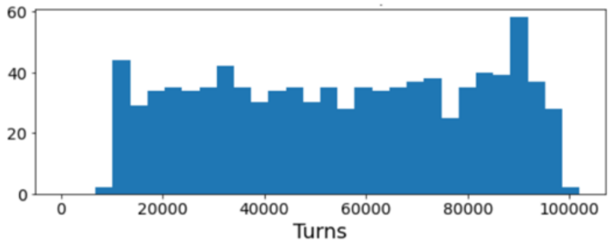


R.Taylor, CERN/Imperial College

pyNAFF allows fast & precise tune computation

Simulations are done with X-Suite

Spill Quality



- Slow extraction over 1-10 s
- Spill is 1e8 particles/s

FLASH regime:

How to slow-extract 1e10 particles in <500s ?

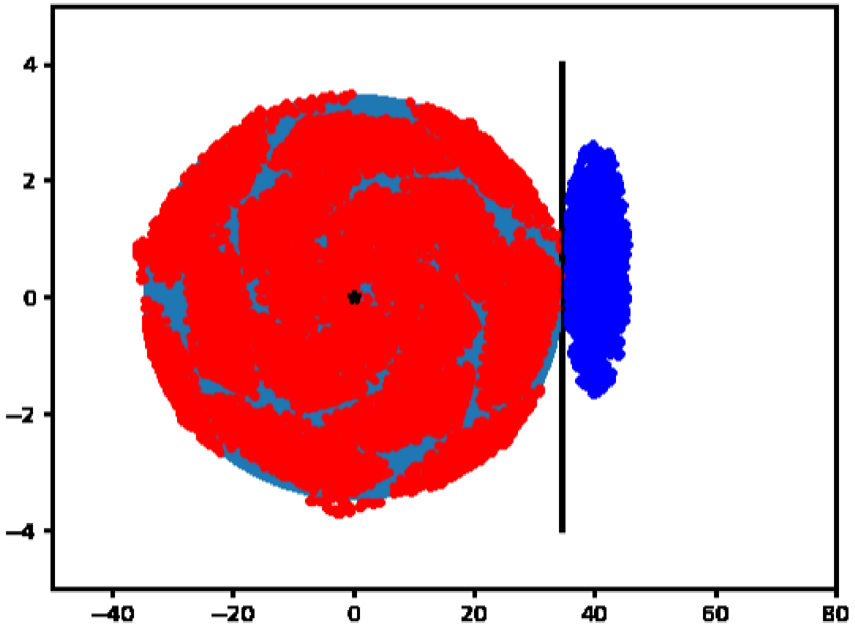
Multi-turn injection of 2e10 C-ions

~similar #turns
for He-ions
(source 1mA)

ECR source ~200 uA C+4

Next generation ECR (e.g. AISHA, Catania) ~600 uA C+4 (in 0.3 mm mrad rms)

Injecting @ 5 MeV/u in a 70 m circumference
Assume 90% (high!) efficiency from source to injection → 13 "effective turns" needed (30 for the compact 30m)

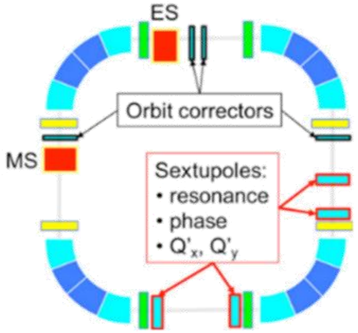


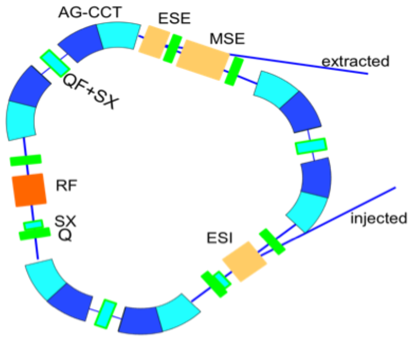
Simulations using a ~toy model,
Proper tracking with X-suite → todo

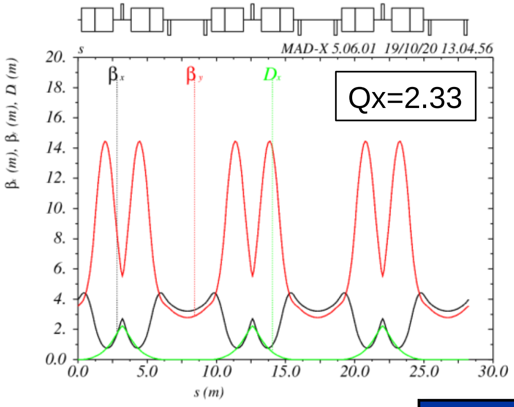
- MT injection has ~60% efficiency
- Old Linac2 injection in the CERN PS-Booster had total of 15 turns\

2) C-ions synchrotron w. SC magnets (AG-CCT)

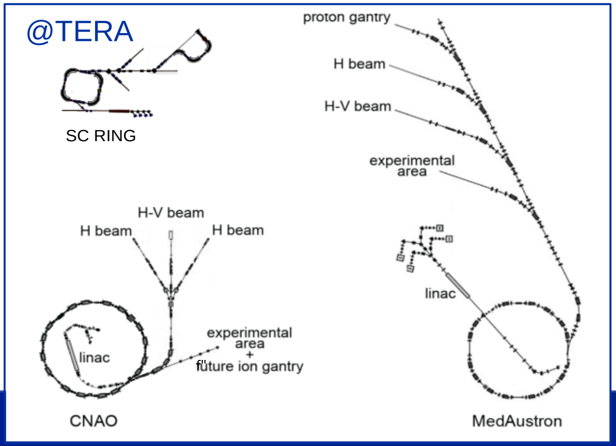
- ➢ Compact (C=27m)
- ➢ SC-magnets AG-CCT up to 3.5 T







E. Benedetto, U. Amaldi et al. @ TERA
https://arxiv.org/abs/2105.04205



- ✓ AG-CCT, i.e. focussing inside the dipole, means smaller β, **smaller beam size and apertures**
- ✓ Dispersion and tune varied with tuning quads
- ✓ **RF-KO** Slow extraction on 3rd order resonance

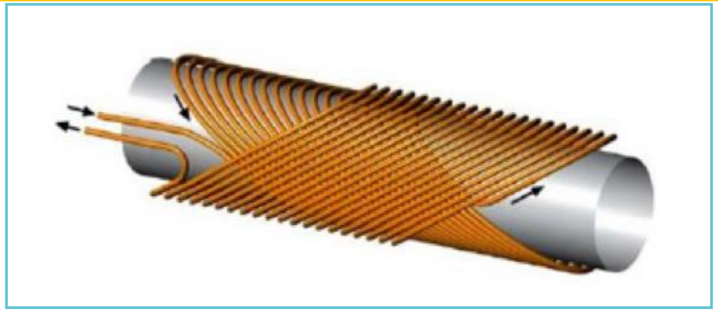
0.5 liter
eliver 2 Gy to a 1-liter in one cycle

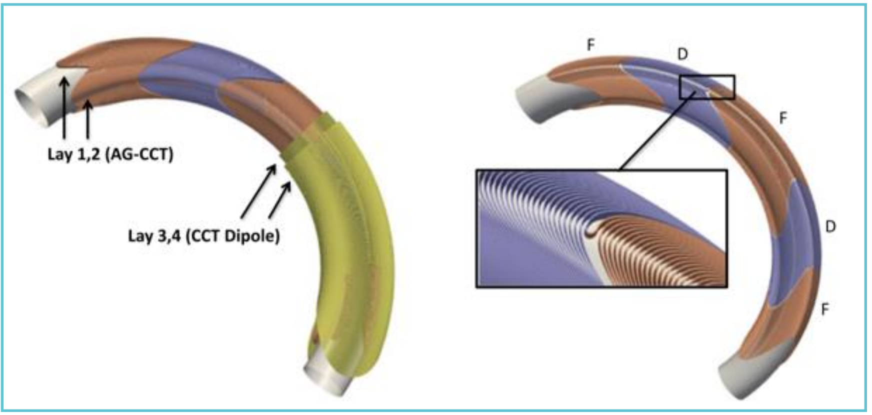
	p	He	C
Intensity	2.6 e11	8.2 e10	2.0 e10 **1e10**
Injection Energy (MeV/u)	7-10	5	5
Extract Energy (MeV/u)	60-250	60-250	100-430
Beam rigidity max (Tm)	2.42	4.85	6.62
Synchrotron size (m)		~10m	
Spill duration (s)		0.1 - 60	
Spill ripple @1 kHz		<1.5	

SC magnet Canted Cosine Theta (CCT)

Tilted solenoids

→ **Pure dipole field**





IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 27, NO. 4, JUNE 2017 4400106

Design of an Achromatic Superconducting Magnet for a Proton Therapy Gantry

L. Brouwer, S. Caspi, R. Hafalia, A. Hodgkinson, S. Prestemon, D. Robin, and W. Wan

Adding 2 extra layers (different winding patterns)

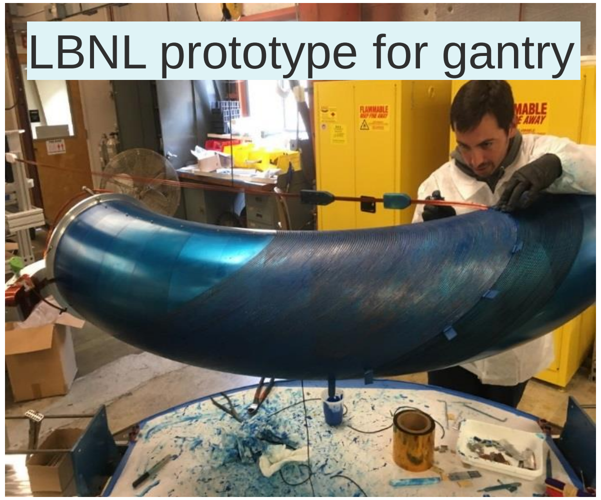
→ **Nested quadrupoles**

→ **Alternating Gradients (AG)**

Strongly curved magnets

B_{max}= 3.5 T → ρ = 1.90 m

B_{max}= 4.0 T → ρ = 1.65 m



Prototypes will be built within 2 EU projects: HITRIplus and iFAST

Field Quality for curved magnets (1/3)

EB and D. Barna, WG – field quality

Collaboration w. INFN, partners in HITRIplus and iFAST, U.Manchester, CERN ABP

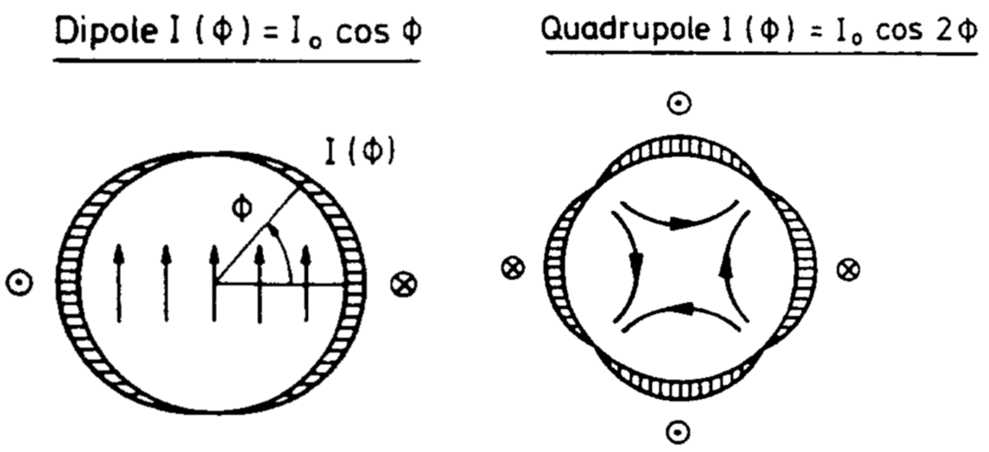
$$B_y(x, 0, t) = A_{10} + A_{11}x + \frac{1}{2!}A_{12}x^2 + \cdots$$

dipole - quadrupole sextupole etc.

$$= B_y\Big|_{\substack{x=0\\y=0}} + \frac{\partial B_y}{\partial x}\Big|_{\substack{x=0\\y=0}} x + \frac{1}{2!}\frac{\partial^2 B_y}{\partial x^2}\Big|_{\substack{x=0\\y=0}} x^2 + \cdots$$

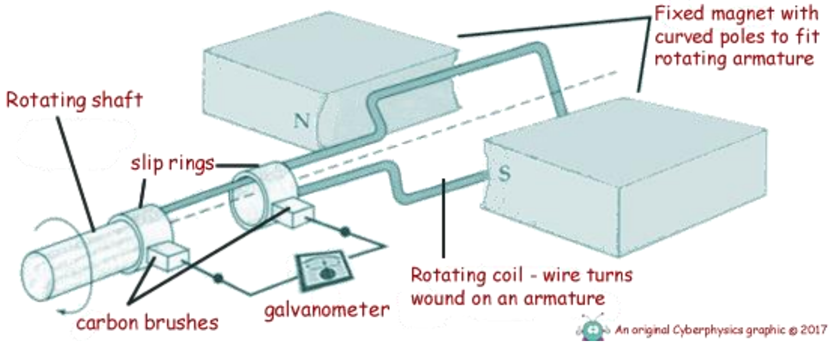
Vs.

Only in straight geometry the coefficients are the same…



Multipole expansion, FFT on a reference radius

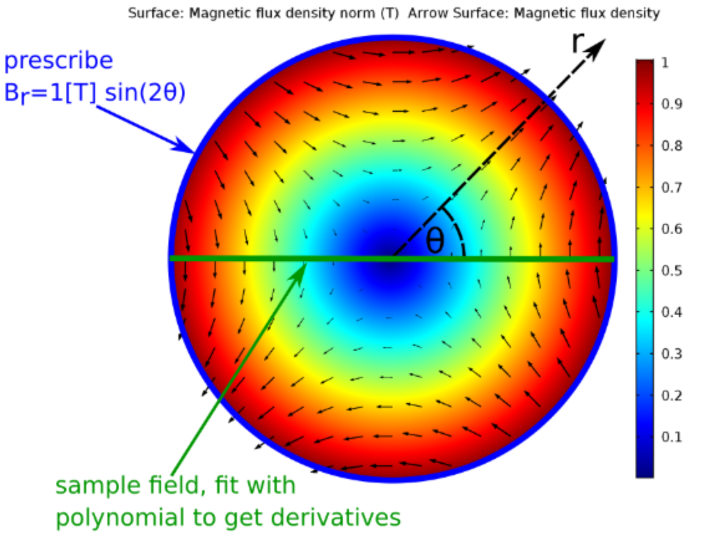
Rotating coil method

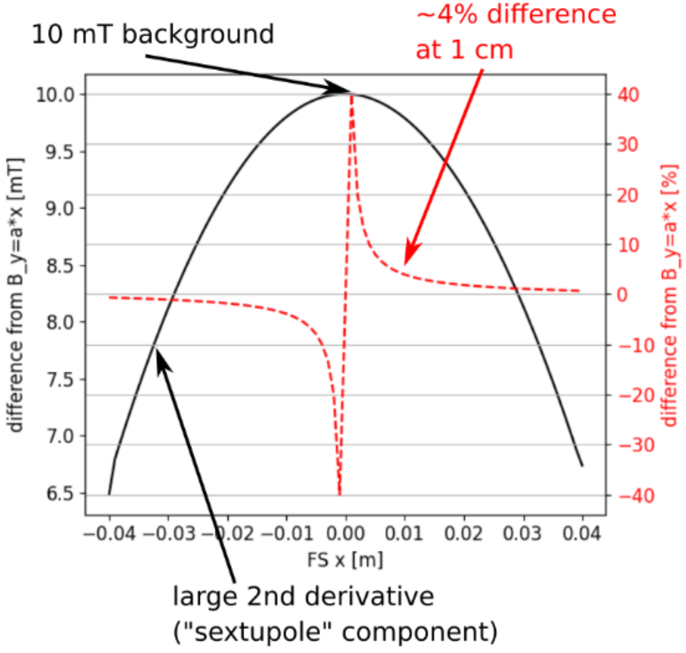


✓ We define FQ using field derivatives, not multipoles

Field Quality for curved magnets (2/3)

Multipole weights vs. Derivatives – Illustration





A "~~perfect~~ quadrupole" in a curved magnet, with

$$B_y = \alpha_0 + \alpha_1 x + \alpha_2 x^2 + \dots$$

Field may not be what you think!

D. Veres, D. Barna, T. Vaszary, E. Benedetto

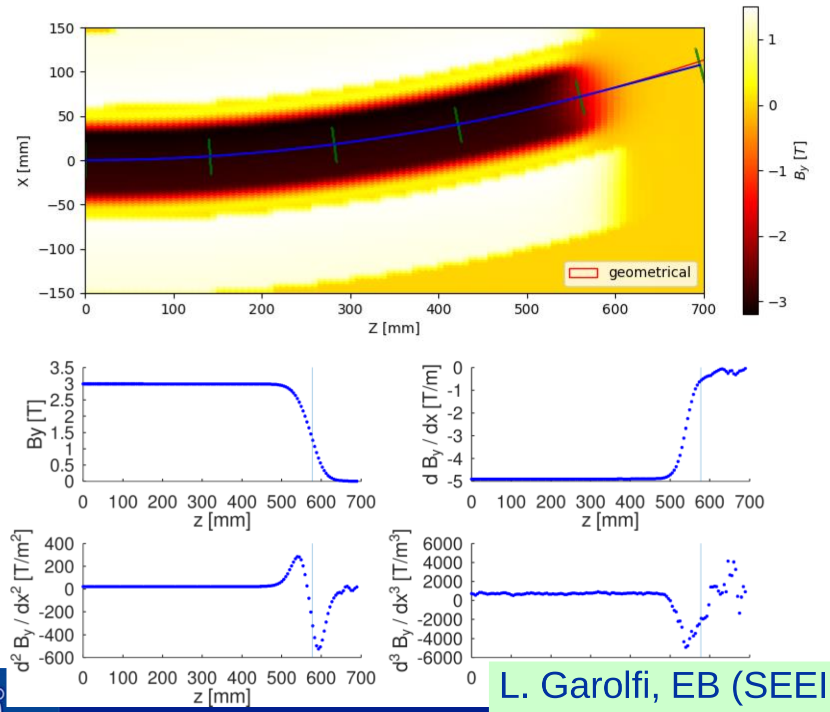
d^nB_y/dx^n /B1 x R^n_{ref}	
B0	1.50E-02
B1	1.00E+00
B2	-4.60E-03
B3	-1.11E-03
B4	8.52E-03

In straight geometry only B1!

Field Quality for curved magnets (3/3)

✓ **Interface optics Vs magnets**

- **Fringe fields modeling (**ongoing) → challenge the current approximation in optics codes



L. Garolfi, EB (SEEIIST)
A.Latina (CERN)

PhD student (w. R. De Maria, CERN) will derive and implement tracking in X-suite:
- Strongly curved, short magnets
- FCC-ee solenoid (trajectories are curved)

3) Helium-ion warm synchrotron

- **He is interesting in-between protons and C-ions:**
  - sharper Bragg peak and fall-off to protons,
  - less scattering
  - less nuclear fragmentation compared to carbon.
  - lower neutron dose than protons or carbon.
  - improved RBE to protons, less damaging LET than carbon.

250 MeV/
(R=12 cm

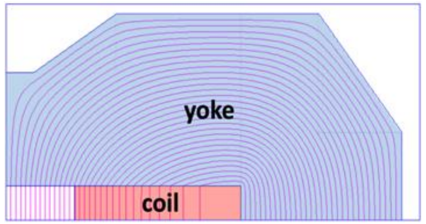
	p	He	C
Intensity	2.6 e11	8.2 e10	2.0 e10
Injection Energy (MeV/u)	7-10	5	5
Extract Energy (MeV/u)	60-250	60-250	100-430
Beam rigidity max (Tm)	2.42	4.85	6.62
Synchrotron diameter (m)		~10m	
Spill duration (s)		0.1 - 60	
Spill ripple @1 kHz		<1.5	

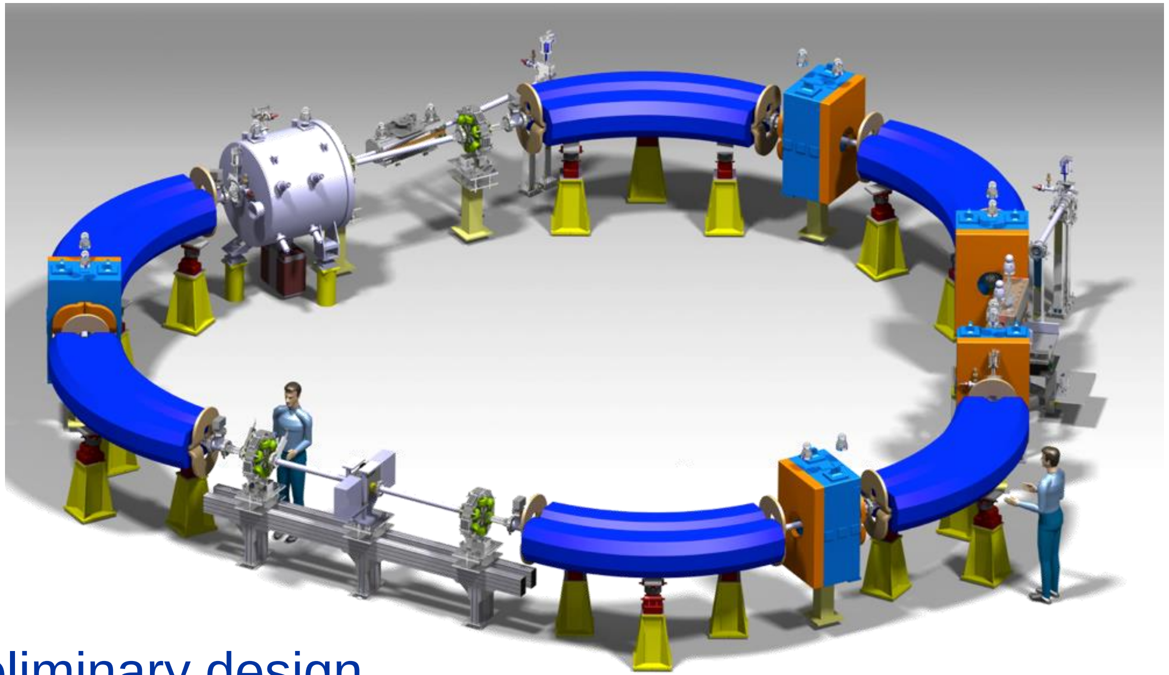
The Helium synchrotron

Design based on CERN experience in small synchrotrons (LEAR, LEIR, ELENA)

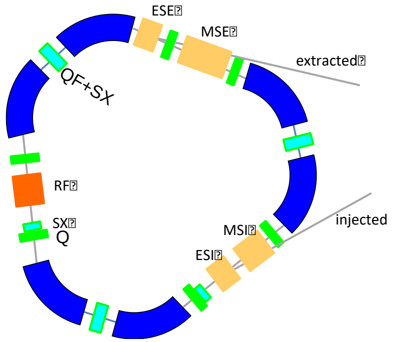
Proven technology, compact & upgradable

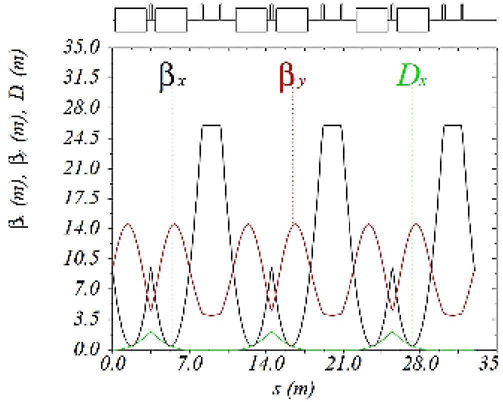
Dipole field of 1.65 T with window-frame magnets.





Preliminary design, circumference 33 m





Injector linac at 352.2 MHz, based on CERN Linac4 design.

Three straight sections (injection, extraction, RF)

Similarities with SC synchrotron for C- ions, e.g. in the straight sections

Final thoughts

Developments on the next generation medical synchrotrons

Pushing intensity & B-field (Super Conducting magnets)

…yet, this is a MEDICAL device!

Contact: Elena.Benedetto@cern.ch.

SEE IST
South East European
International Institute
for Sustainable Technologies

South East European International Institute for Sustainable Technologies

A consortium of countries in the South East Europe to build a facility for **therapy & research.**

Fall 2016: Proposed by H. Schopper and supported by S. Damjanovic (Montenegro Minister of Science)

Mar. 2018: Medical facility chosen (U. Amaldi et al, based on CNAO-MED 3.0)

Feb 2019-Apr 2021: CERN (M. Vretenar) hosts the accelerator design – collaboration with TERA

Apr 2021: TERA people move to SEEIIST, with the start of HITRIplus

- ✓ Science for peace
- ✓ Research & Scientific excellence
- ✓ Education & Training
- ✓ Technology transfer

SEEIIST

South East Europe International Institute for Sustainable Technolog

A Facility for Tumour Hadron Therapy and Biomedical Research in South-Eastern Europe

U. Amaldi[a], J. Balosso[b], M. Dosanjh[c], Ph. Lambin[d], J. Overgaard[e], S. Rossi[f], M. Scholz[g] and B. Singers Sørensen[h]

with the collaboration of A. Celebic[i]

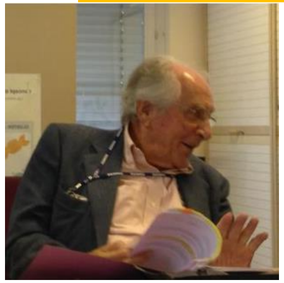
[a] TERA Foundation, Novara, Italy
[b] Department of Radiotherapy, University Hospital of Grenoble, Grenoble, Franc
[c] CERN, Geneva, Switzerland
[d] Maastricht University, Maastricht, The Netherlands
[e] Department of Experimental Clinical Oncology, Aarhus, Denmark
[f] CNAO Foundation, Pavia, Italy
[g] GSI, Darmstadt, Germany
[h] Department of Experimental Clinical Oncology, Aarhus, Denmark
[i] Clinic of Oncology and Radiotherapy, Podgorica, Montenegro

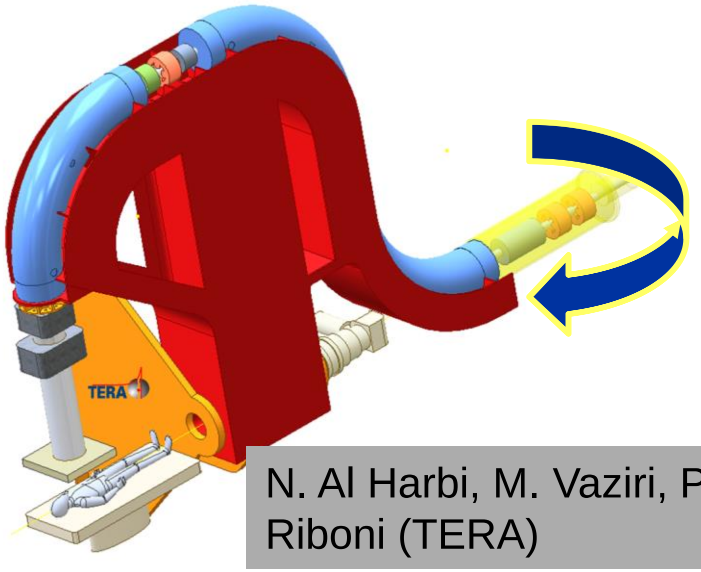
Higher 20x beam intensity than EU facilities, full beam (2Gy for 1liter) in 1 cycle.

Flexible dose delivery (slow and also FLASH)

Injection/Acceleration	Unit					
Particle after stripping		p	$^{4}He^{2+}$	$^{12}C^{6+}$	$^{16}O^{8+}$	$^{36}Ar^{16+}$
Energy	MeV/u	7				
Magnetic rigidity at injection	Tm	0.38	0.76	0.76	0.76	0.86
Extraction energy range (**)	MeV/u	60 – 250 (1000)	60 – 250 (430)	100 - 430	100 - 430	200 – 350
Magnetic rigidity at highest energy (for therapy)	Tm	2.42	4.85	6.62	6.62	6.62
Maximum nominal field	T	1.5				
Maximum number of particles per cycle		$2.6 \cdot 10^{11}$	$8.2 \cdot 10^{10}$	$2 \cdot 10^{10}$	$1.4 \cdot 10^{10}$	$5 \cdot 10^{9}$
Ramp-up rate	Tm/s	<10				
Ramp-down time of magnets	s	1				
Spill ripple, intensity ratio I_{max}/I_{mean} (average on 1 ms)		< 1.5				
Slow extraction spill duration with multi-energy	s	0.1 – 60				

Compact ion gantry with unconventional support



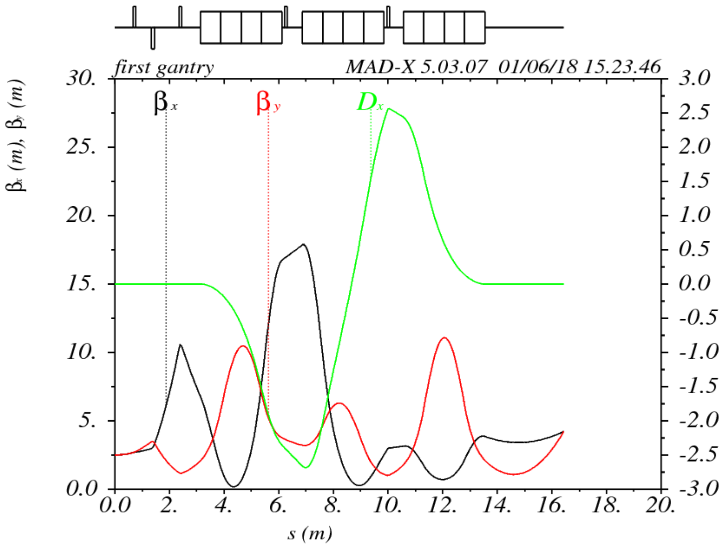


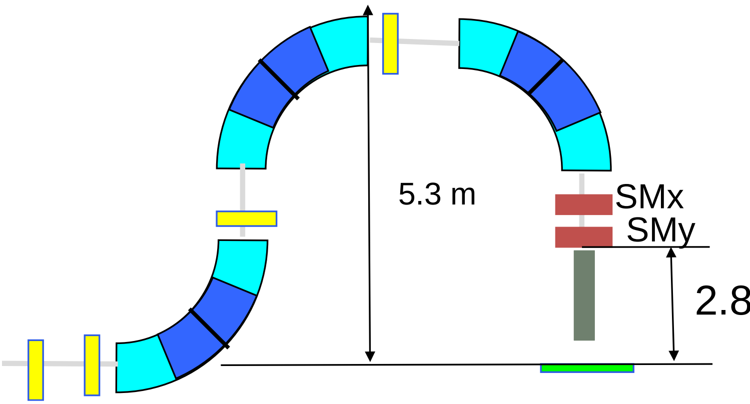
N. Al Harbi, M. Vaziri, P. Riboni (TERA)

35 tons for C ions @ 430 MeV/u max

~5 m radius

CCT magnets @4T (!)





- ✓ Rotation independent
- ✓ Achromat
- ✓ RE11 = RE33 = 1.3
- ✓ FWHM = 4mm @ isocenter
- ✓ Aperture very small, 40 mm

- Attached to the wall
- No counterweight
- Electric motor with 5-stages planetary gear
- Magnets are structural elements