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A method for reduced cost pTh session, based on FFAG synchrotron technology

F. Meot

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November 10 - 13, 2015

December 2015

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy
Office of Science, Office of Nuclear Physics

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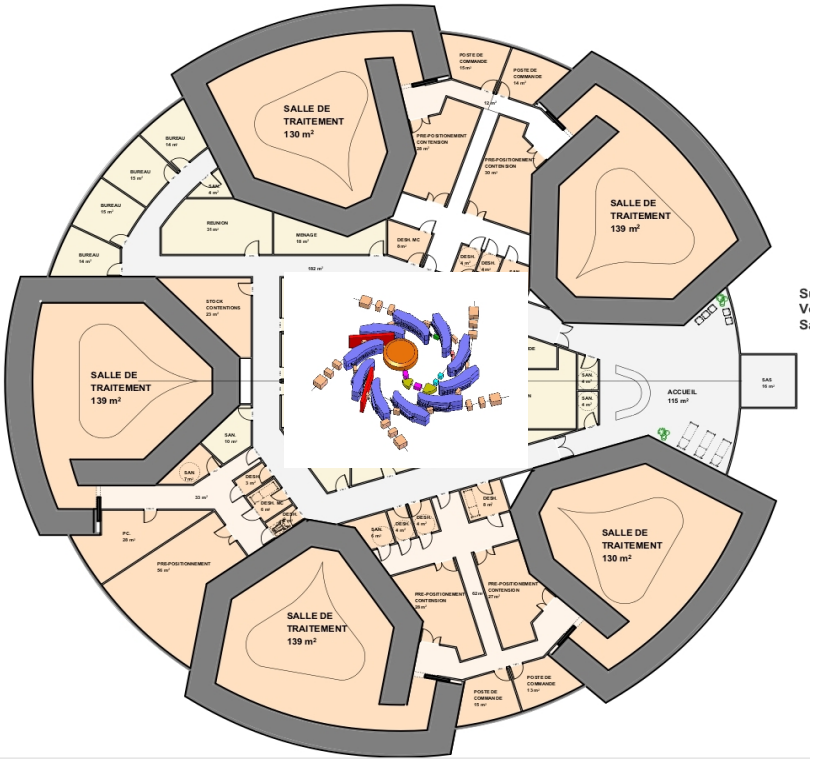
AccApp15, Washington, DC, November 10-13, 2015

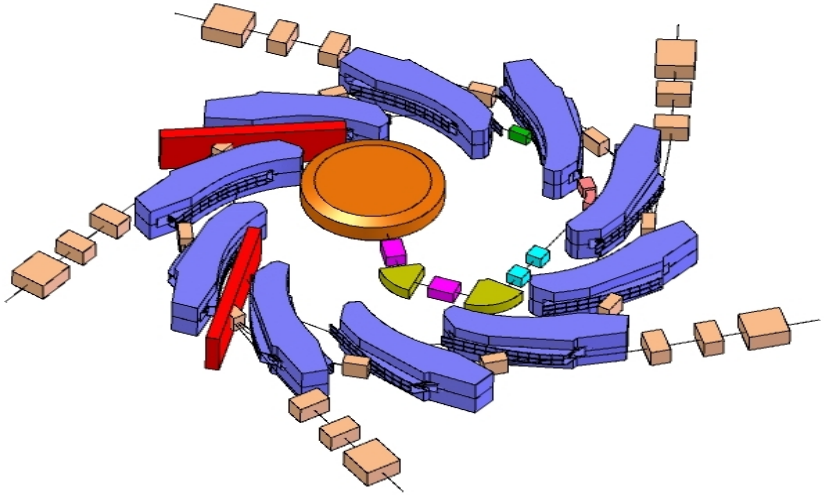
A METHOD FOR REDUCED COST pTh SESSION, BASED ON FFAG SYNCHROTRON TECHNOLOGY

F. Méot
Brookhaven National Laboratory



- PART 1 -

A multi-port simultaneous beam delivery, fast-cycling medical synchrotron



RACCAM TEAM AND COLLABORATORS :

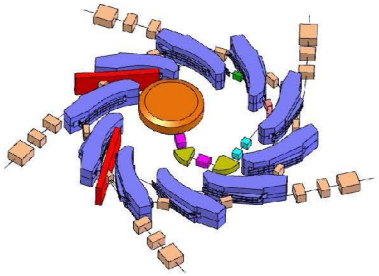
CEA
CNRS-IN2P3
SIGMAPHI
LYON AND GRENOBLE ANTI-CANCER HOSPITALS

KURR-INSTITUTE, KYOTO UNIV. (Pr Y. Mori)
KEK (Dr C. Ohmori)

JOINED THE PROJECT,
- early 2006 : MEDICYC, Nice, & AIMA-Development (P. Mandrillon)
- 2007 : IBA

FUNDING : ANR GRANT : 500kEU over 3 Yrs
TOTAL COST : 3.5MEU

Would like more details ?
A vaste bibliography is available :



A Multiple-Room, Continuous Beam Delivery, Hadron-Therapy Installation
F. Méot
Physics Procedia 66 (2015) 361 – 369

Principle design of a protontherapy, rapid-cycling, variable energy spiral FFAG

S. Antoine [a], B. Autin [b], W. Beeckman [a], J. Collot [c], M. Conjat [d], F. Forest [a], J. Fourrier [c], E. Froidefond [c], J.L. Lancelot [a], J. Mandrillon [d], P. Mandrillon [d], F. Méot [c,e,*], Y. Mori [f], D. Neuvéglise [a], C. Ohmori [g], J. Pasternak [h], T. Planche [a,f]

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[c] *Laboratoire de Physique Subatomique et de Cosmologie, CNRS-IN2P3, UJF, INPG, France*
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[f] *KURR-Institute, Kyoto University, Japan*
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[h] *Imperial College, London, UK*

Design of a prototype gap shaping spiral dipole for a variable energy protontherapy FFAG

T. Planche [a,b,*], J. Fourrier [c], J.L. Lancelot [b], F. Méot [c,d], D. Neuvéglise [b], J. Pasternak [e]

[a] *KURR-Institute, Kyoto University, Japan*
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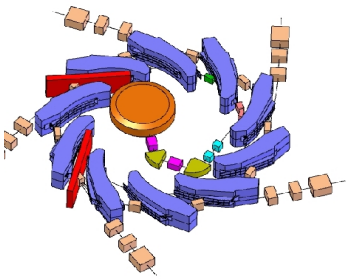
[d] *CEA DSM IRFU, Saclay, France*
[e] *Imperial College, London, UK*



Spiral FFAG lattice design tools. Application to 6-D tracking in a proton-therapy class lattice

J. Fourrier[a], F. Martinache[a], F. Méot[b,*], J. Pasternak[a]

[a]*IN2P3 LPSC, Grenoble, France*
[b]*CEA & IN2P3, LPSC, Grenoble, France*

Received 31 August 2007; received in revised form 7 January 2008; accepted 11 January 2008
Available online 30 January 2008

Developments in the ray-tracing code Zgoubi for 6-D multiturn tracking in FFAG rings

F. Lemuet[a], F. Méot[b,*]

[a]*CERN AB/ABP, Geneva, Switzerland*
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Received 3 February 2005; received in revised form 11 March 2005; accepted 16 March 2005
Available online 24 May 2005

Even more is available, including magnetic measurements, in

- RACCAM web site : http://lpsc.in2p3.fr/service_accelerateurs/raccam.htm

As well as

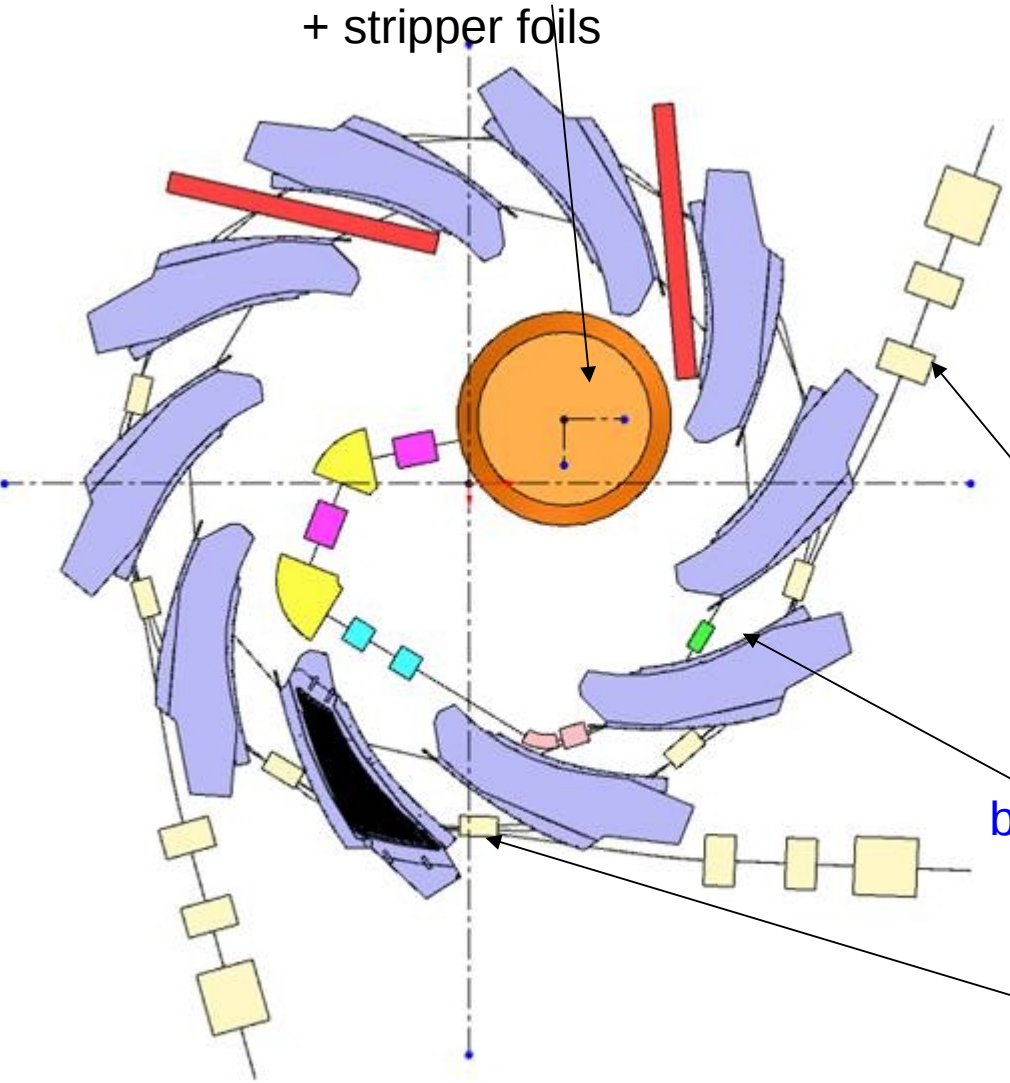
- FFAG workshops

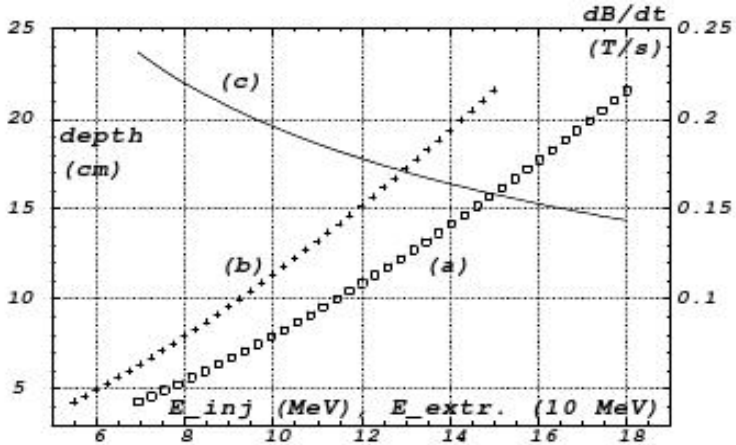
- PAC and EPAC conferences

since 2006

RACCAM : A Variable Energy Protontherapy FFAG

Variable energy p beam
from 7~14 MeV H- cyclotron injector
+ stripper foils





(a) : Bragg pic depth as a function of FFAGextraction energy
(b) : correlated cyclotron energy with 250kV steps
(c) : dB/dt

allows variable extraction energy from FFAG

by varying FFAG rigidity (dB/dt<0.25T/m)
and / or
by extraction kick
synchronised on turn #

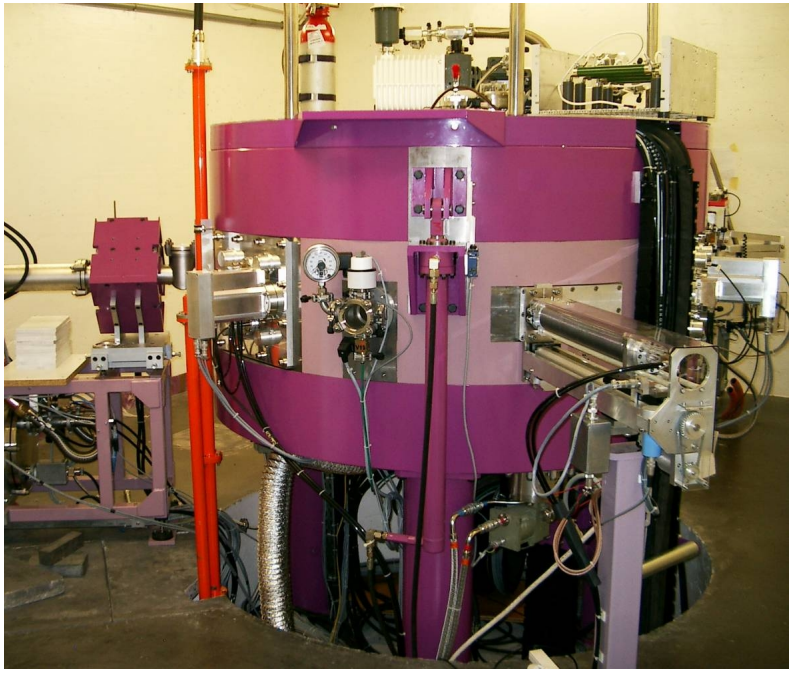
Tunable energy injected proton beam :

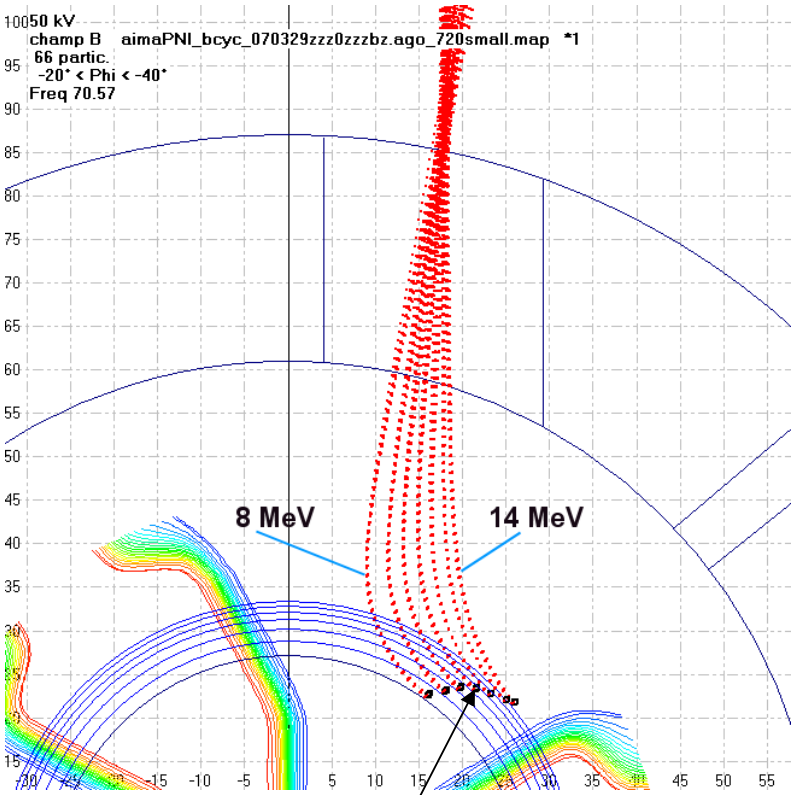
Involves using a H- cyclotron injector

AIMA-DEVELOPEMENT

H^- cyclotron :

RACCAM injector

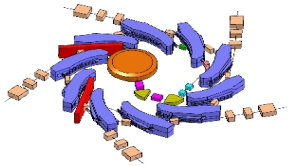




variable stripper position

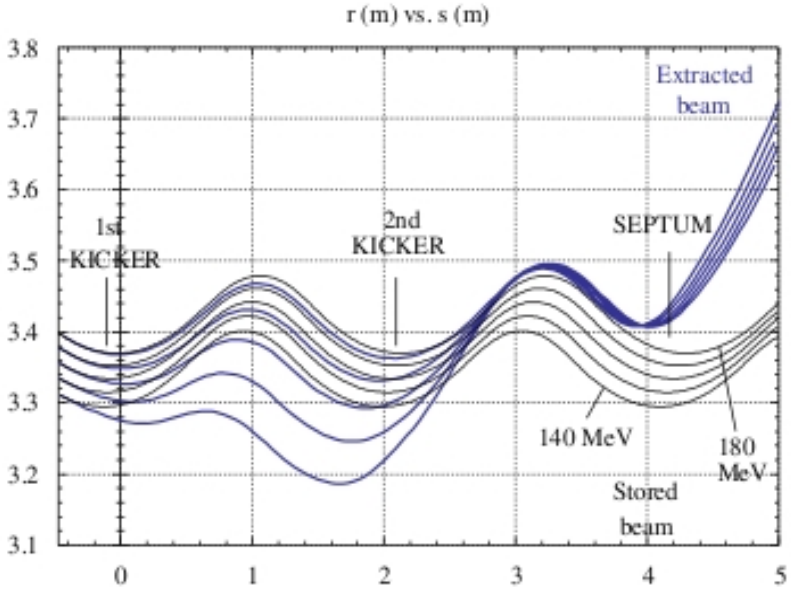
Studies made by AIMA-Development team, MEDICYC, Nice, as part of RACCAM collaboration

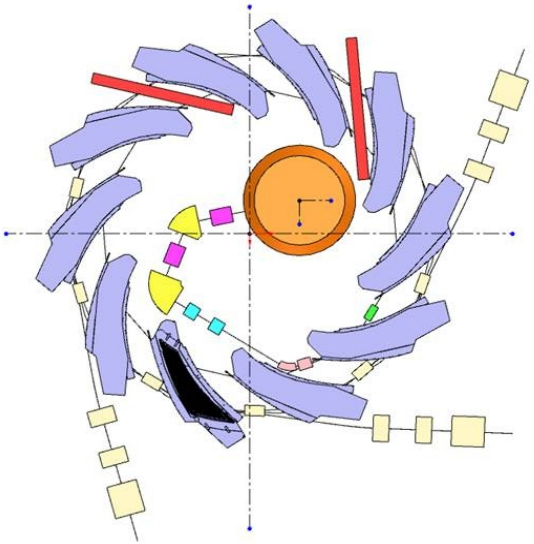
Energy Variation Using Multiple Kickers



No issue there : a classical extraction technique

Allows several tens MeV range, i.e., several cm's Bragg peak range



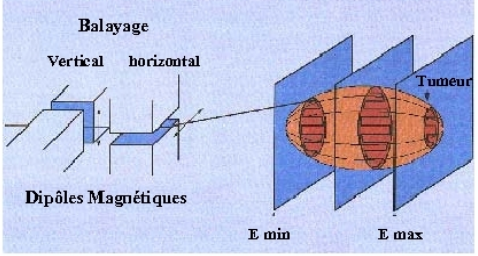


Note : "synchronized kick" bunch extraction method allows depth-tracking of moving target.

Repetition Rate

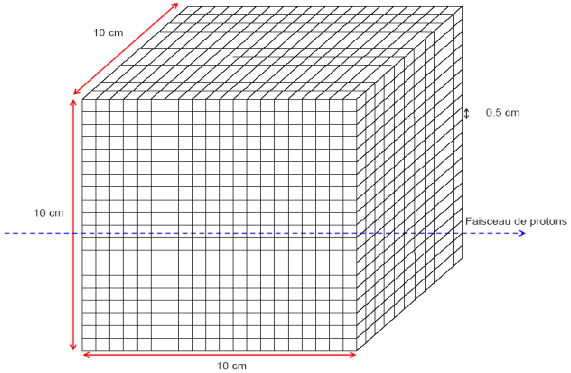
(i) Hyp. : bunch-to-voxel scanning

5 Joules/min.



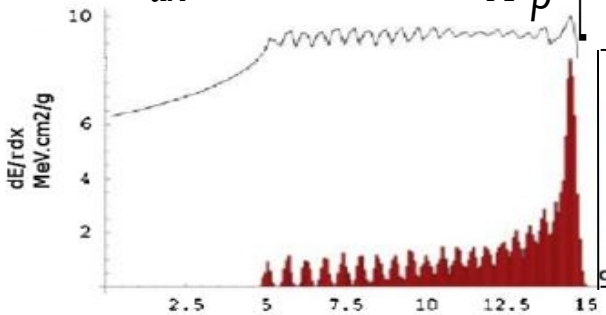
(ii) Reference volume :

- 1 liter, cubic, 10x10x10cm³
- Voxel size : 5x5x5 mm³



(iii) Spread out Bragg pic (SOBP) :

$$\left|-\frac{dE}{dx}\right| = 2\pi N_a r_e^2 m_0 c^2 \rho \frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\left(\frac{2m_0\gamma^2 v^2 W_{max}}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C_S}{Z}\right]$$



Essential result :
~ 7 10¹¹ proton/Gy in a liter
~ only weak dependence on Incident beam energy

(iv) Repetition rate needed : 20x20x20 voxels in a minute ~ 130 /second

(v) Bunch filling for bunch-to-voxel scanning :

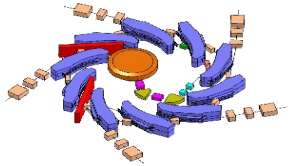
- **400 voxels/slice**, about 20% of the dose in the distal layer, **yields a maximum**
  5Gy x 7.10¹¹ p/Gy x 20% / 400pixel ~ **2x10⁹ p/voxel, in the distal layer**
- **Cyclotron produces** 1.5x10⁷ ppb, hence need ~**130 cyclotron bunches**
- **Cyclotron RF** 70MHz (h=3) and FFAG 3MHz @ injection,

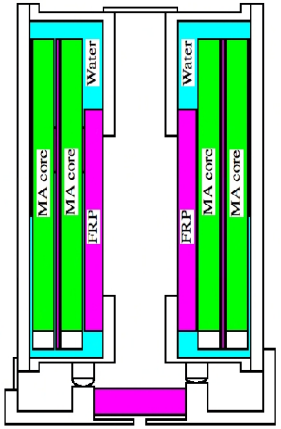
hence 70MHz/3MHz*h3 = **70 cyclotron bunches in one FFAG turn.**

Hence, for distal voxels,

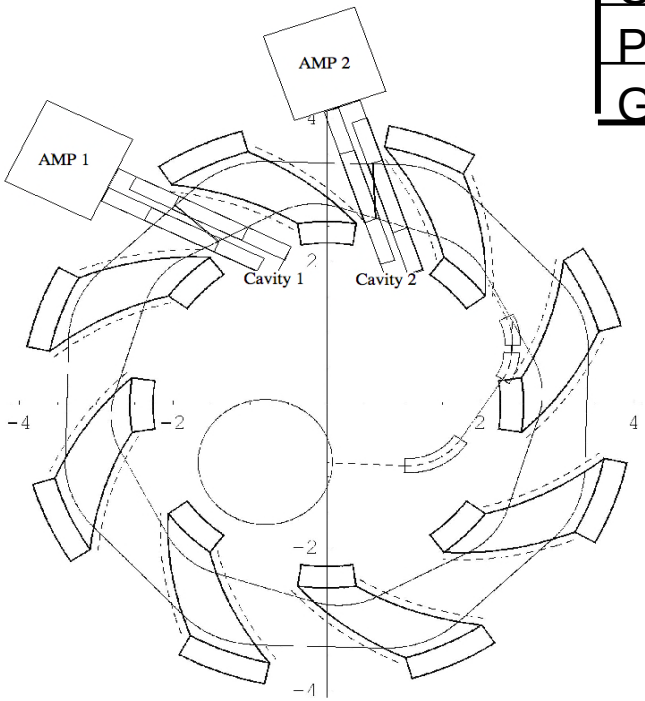
either (i) 5-turn injection at 50% efficiency
or (ii) single-turn injection and a minimum of 4 paintings

Radio-Frequency System For 200 Hz Cycling





Number of cavities		2 ; 4 cores/cavity
Size of Cavity	m	2(H) X 1.2 (V) X 0.38 (L)
Beam Pipe	m	0.83(H) X 0.13(V)
Core material		FINEMET
Size of core	m	1.7 (H) x 1.0 (V) x 0.03(L)
Frequency range		1.86 – 7.5 MHz
Cavity Impedance	Ω	400
Power loss	kW	45
Gap voltage, peak	kV	6



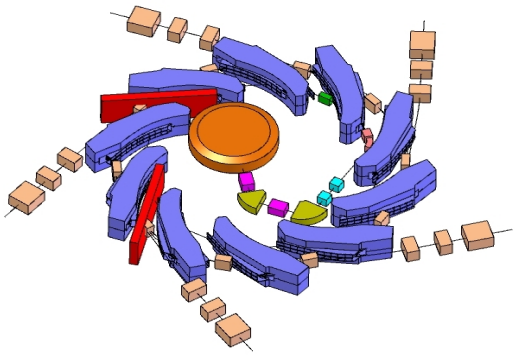
- With 2 cavities : acceleration cycle is <5ms, 200Hz, e.g., 40Hz per port for 5 extraction ports.

- RF cavity is installed with a small tilted angle between the spiral magnets.

- Field clamps installed at magnet ends reduce magnetic field around the cavity below 100 Gauss.

- Amplifier : two tetrodes for push-pull operation. Type foreseen 4CW30,000 or RS1084.

A Summary of RACCAM ring and Magnet Parameters

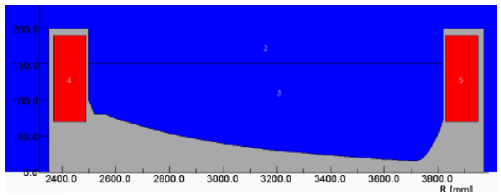


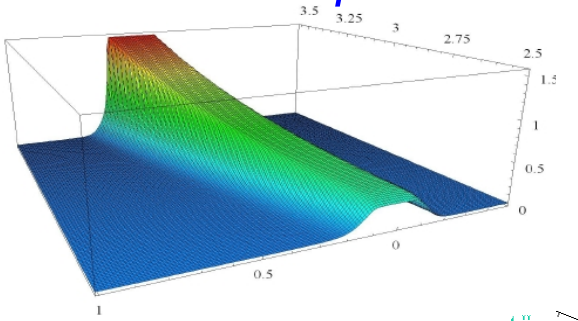
Extracion energy, variable *(MEDiCYC specs.)*	70 – 180 MeV	***Magnet allows 230MeV***
Injection energy	5.5 – 17 MeV	
Nomentum ratio	3.62	
Number of cells	10	
Packing factor	0.34	
Field index, k	5	
Spiral angle	53.7 deg.	
Qh / Qv	2.76 / 1.55~1.60	
Radius on extraction/injection orbit : dR	3.46 m / 2.78 m / 0.67 m	
Drift length, extraction/injection orbit	1.42 m / 1.15 m	
Frev, 15->180 MeV	3.03 -> 7.54 MHz	
Frev, 5.5->70 MeV	1.86 -> 5.07 MHz	

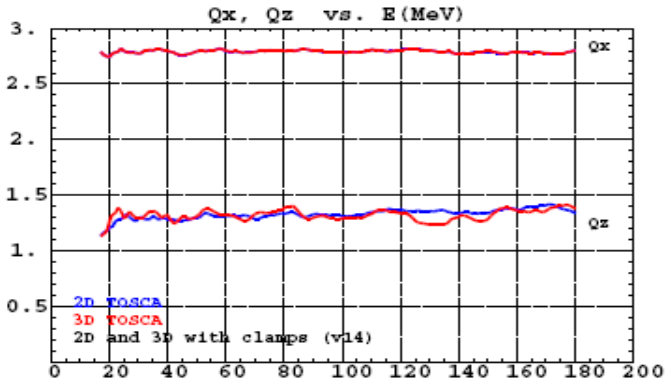
Feasibility of Spiral Fixed Field Magnet (a première) : Design, Fabrication, Field Measurements

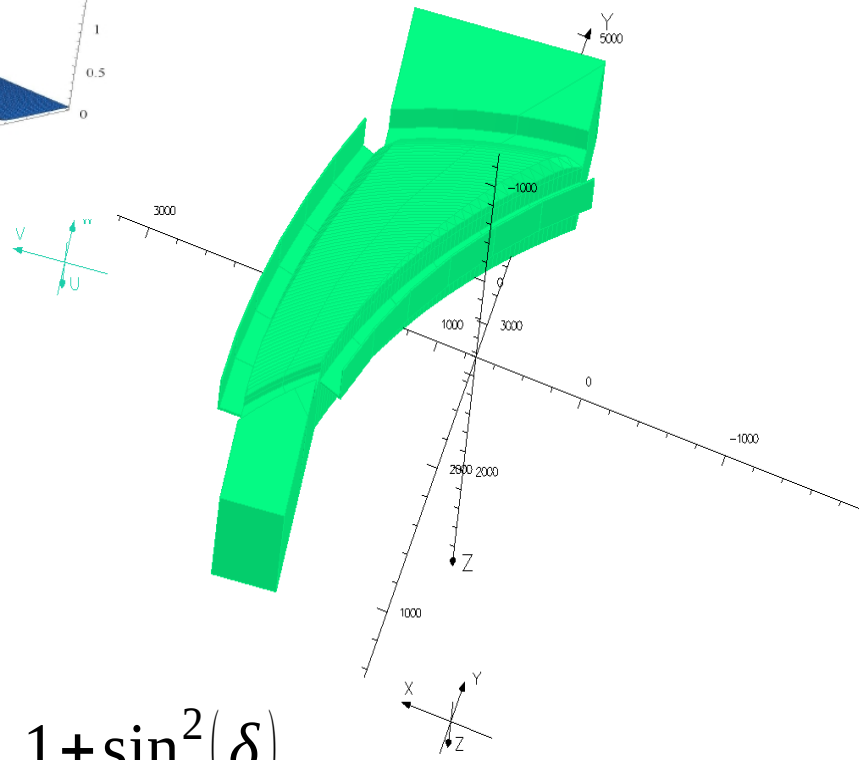
TOSCA simulations showed that ***stabilization of vertical tune*** can be achieved by combination of *field clamp* and *variable chamfer.*

$$B_z(r) = B_{z0}(r/r_0)^k$$



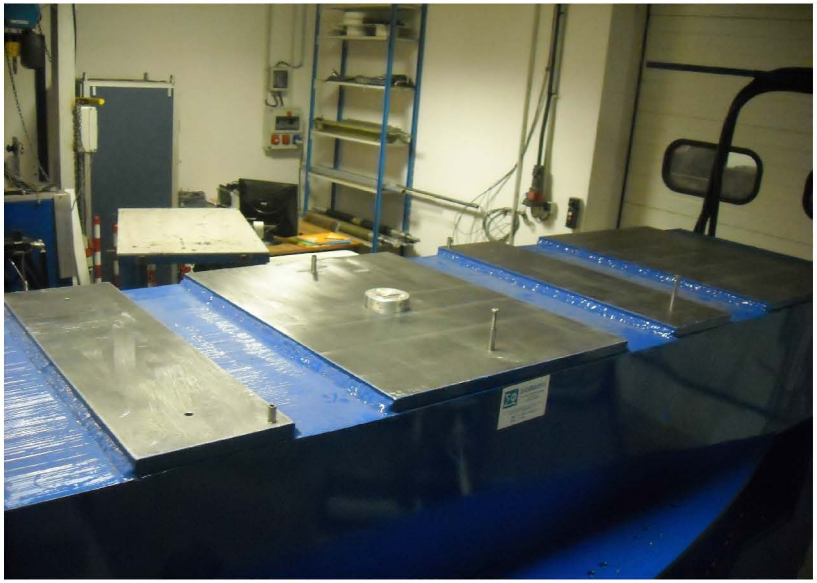


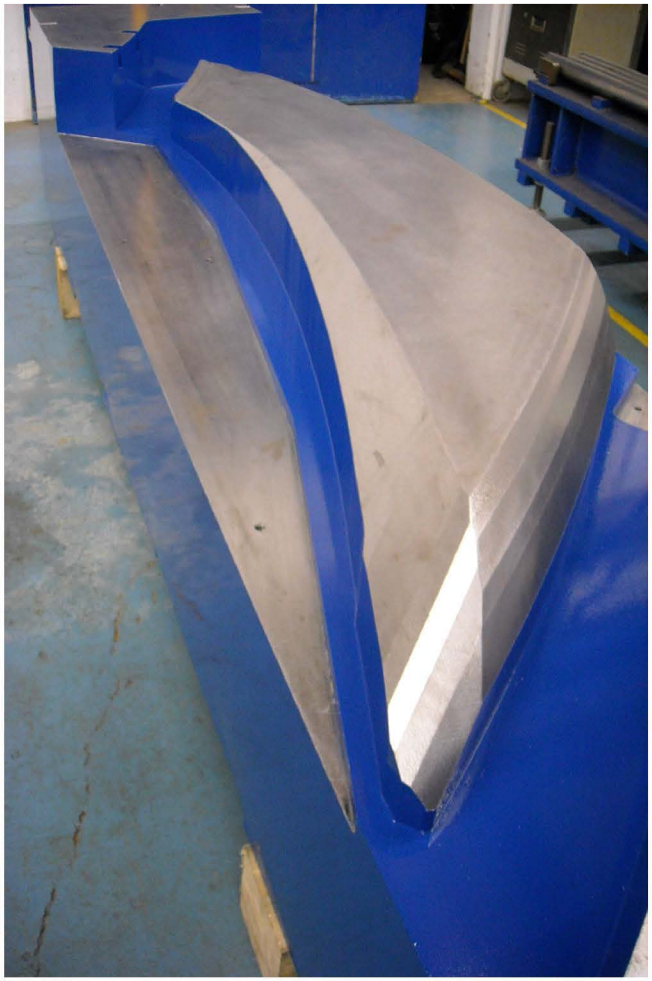




Given $M_z = \begin{pmatrix} 1 & 0 & 0 \\ -\dfrac{\tan(\delta-\psi)}{\rho} & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$ **and** $\psi = I_1 \dfrac{\lambda}{\rho} \dfrac{1+\sin^2(\delta)}{\cos(\delta)}$**, then Qy= Cst requires λ~r**

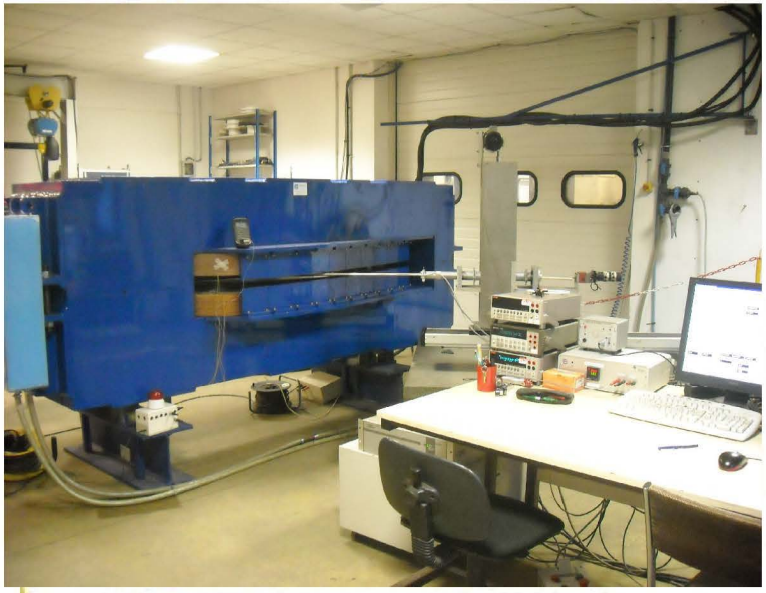
- **Magnet, laminated technology for dB/dt tests, was built by SIGMAPHI, ready Fall 2008**





• Magnetic measurements at SIGMAPHI, end 2008

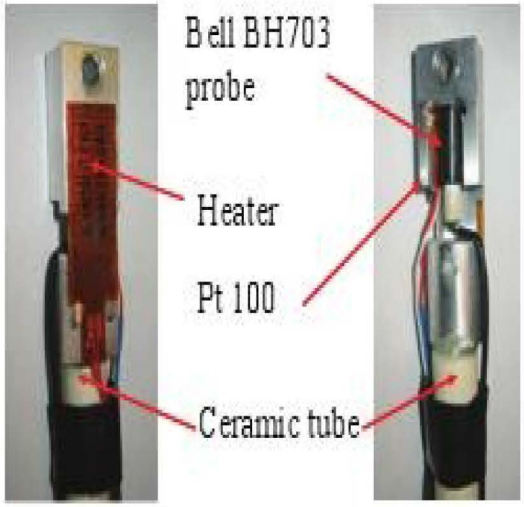
MEASUREMENT SYSTEM AND ACCURACY



MAPPING system

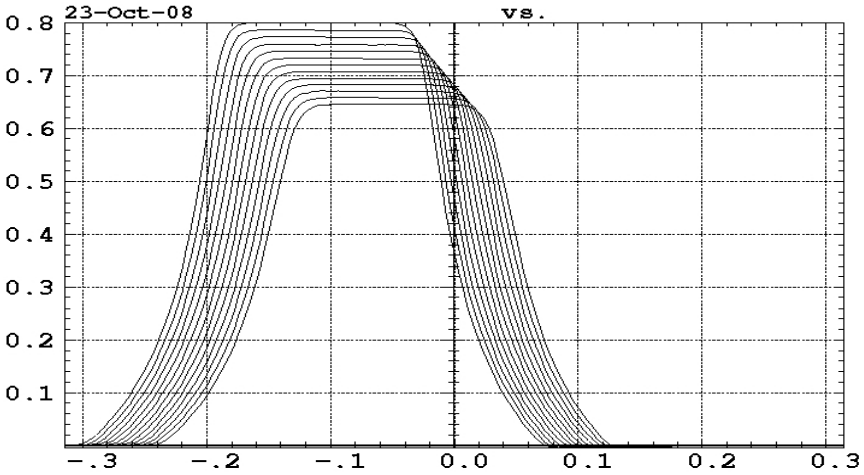
- 3 axis Hall probe Bell BH703, temperature regulated 30°C+/-0.1°C
- Air-conditioned laboratory (20.C+/-1°C)
- Field acquire in 3D with a 20 channels multimeter
- Automated Mapping table 1600*600*800

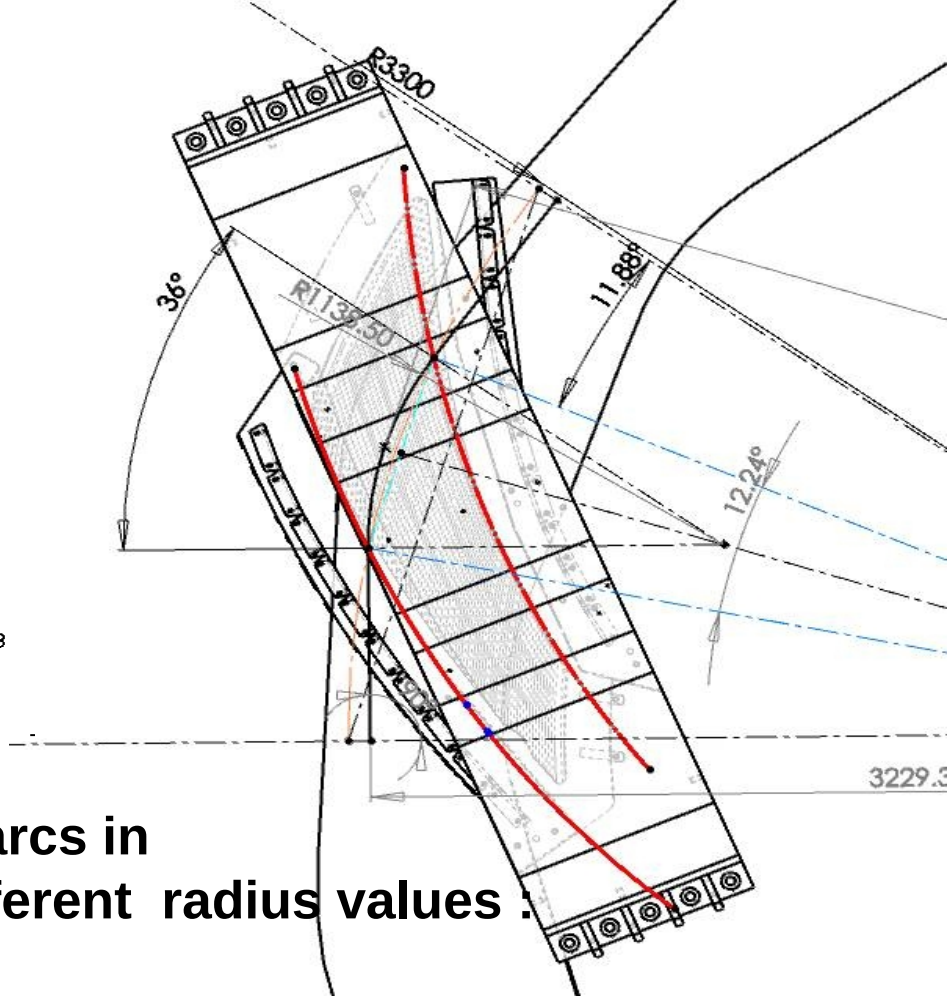
- Hall probe calibration until 1.8T, accuracy 3.10^{-5}
- Current stability < 5.10^{-5}
- Hall tension stability < 0.2 Gauss



3 AXIS HALL PROBE

- **Magnetic measurements**





<u>The bulk of the measurements :</u>

Bx, By, Bz field components on 11 arcs in median plane, taken around five different radius values :

R=2750, 2900, 3125, 3300, 3450mm, +/-55mm, step 11mm.

<u>Repeated for three different current values in coils :</u>

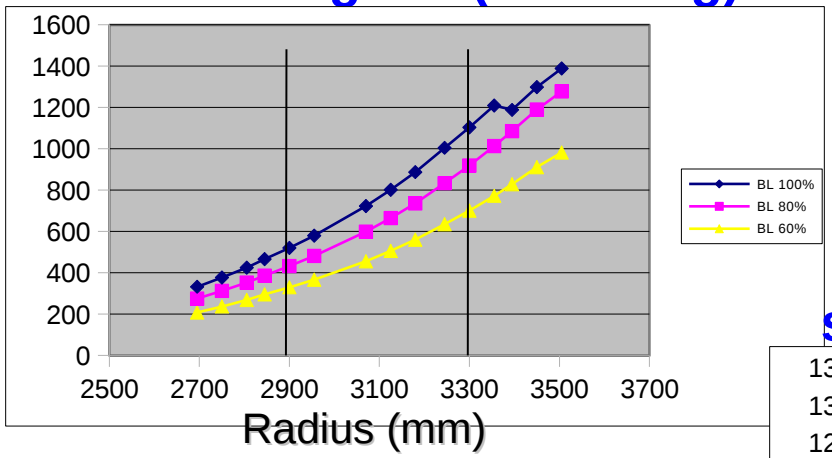
225 Amp	→ 1.93 T at 3.46 m	(227MeV)
80%	→ 1.61 T	(162 MeV)
60%	→ 1.23 T	(98 MeV)

Extracting optical parameters in good field region : 2.9 m < r < 3.3 m

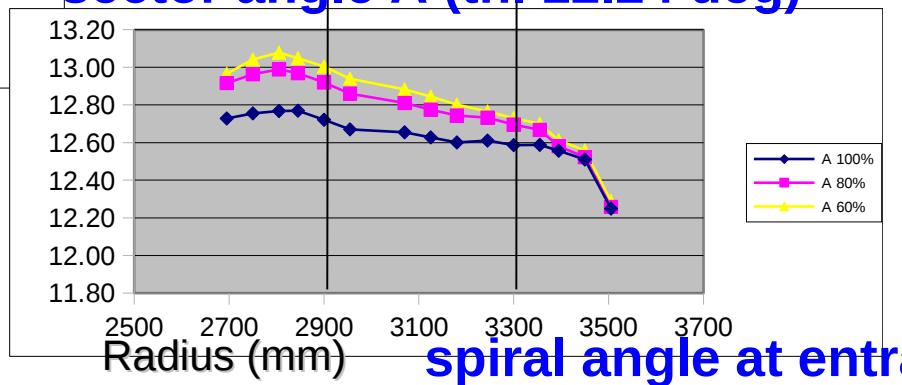
A summary of data analysis

Type	Gap shaping
Packing factor (pf)	0.34
Field index (k)	5
Spiral Angle (ζ) (deg)	53.7
Min./Max. radius of good field region (m)	2.9/3.3
Max. field at min./max. radius (T)	0.58/1.7
Bend angle (β) (deg)	36
Sector angle (A) (deg)	12.24

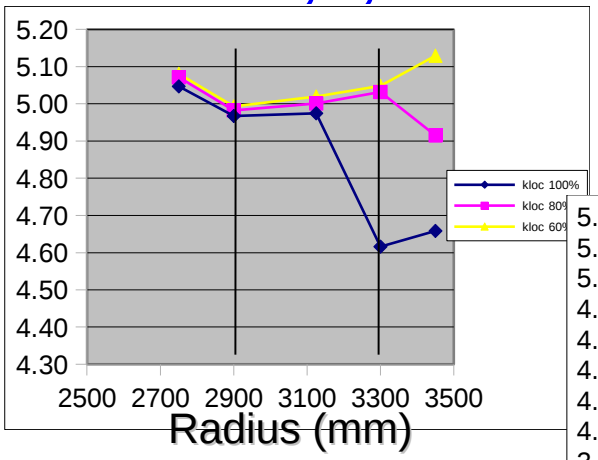
field integrals (th. 36deg)



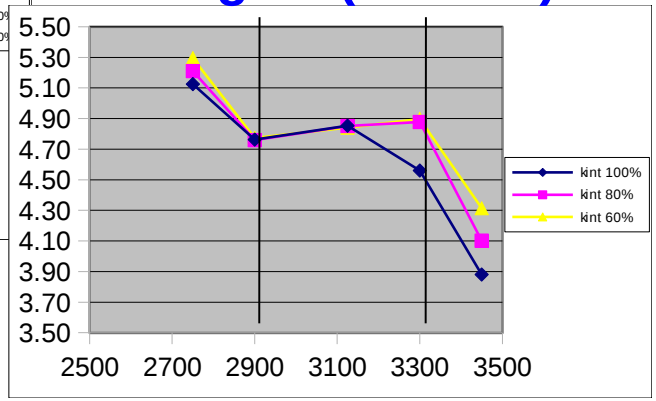
sector angle A (th. 12.24 deg)



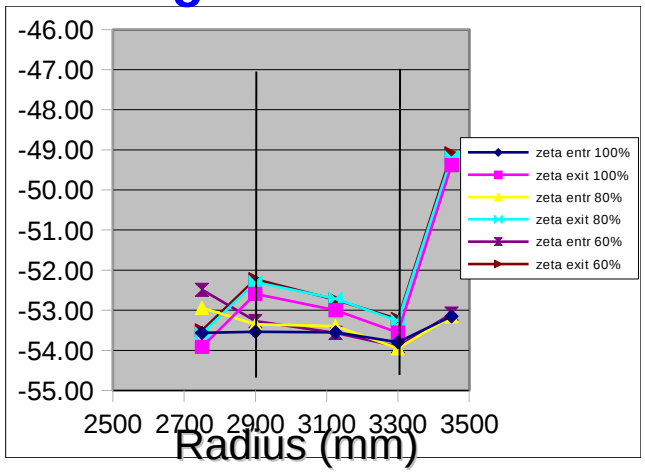
local index, k, at A/2



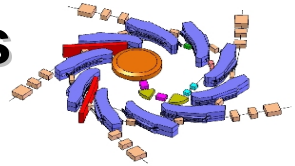
average k (th. 5.00)



spiral angle at entrance/exit



- **Beam dynamics checks using the measured fields**

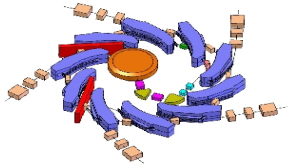


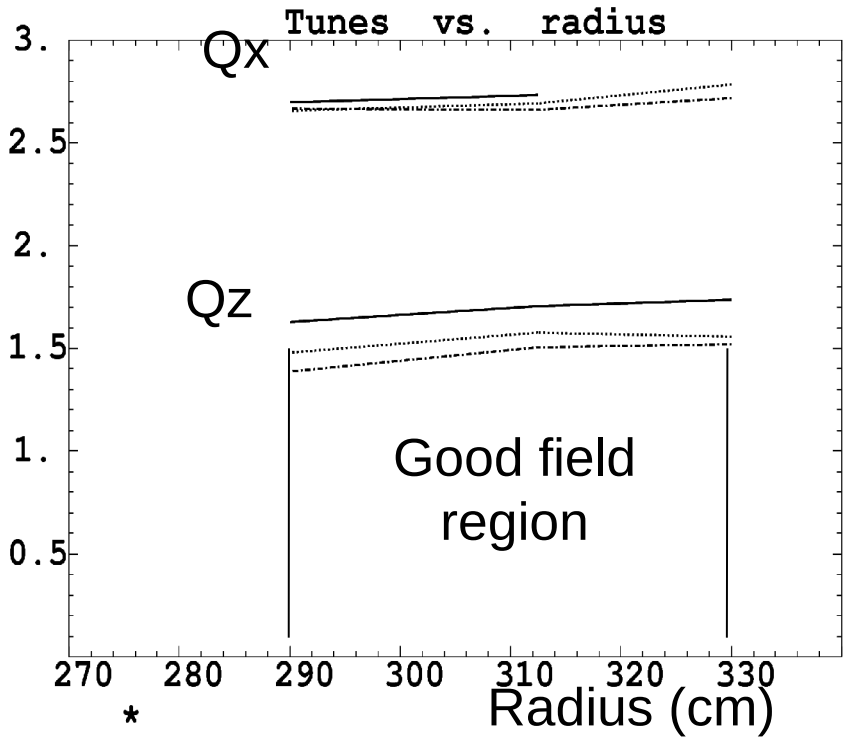
(i) Correlation between magnetic field and orbits agrees with theory within a few per-mil

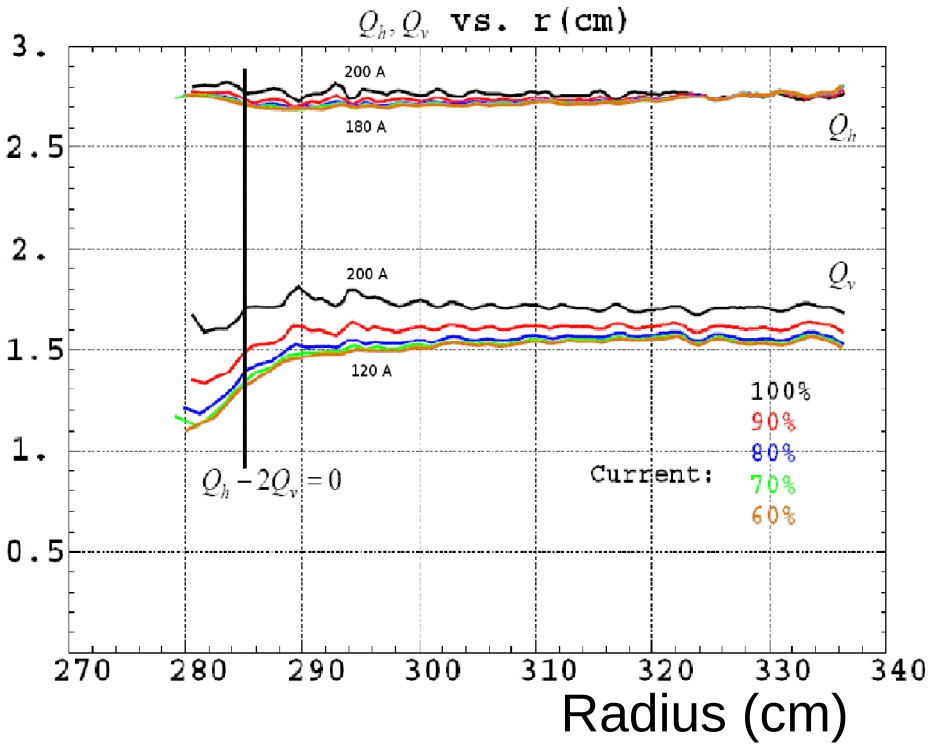
$B/B0 \approx (r/r0)^k$ satisfied at $\Delta B/B$~ few permil, measured field index k = 5.00

R (mm)	$E_{c.o.}$ (MeV)	$\hat{r}$ (mm)	$\hat{B}$ (T)
Maximal current			
2900	38.0	2950	0.880
3125	86.5	3175	1.259
3300	156.0	3350	1.631
$80\% I_{max}$			
2900	26.2	2950	0.719
3125	60.8	3175	1.032
3300	112.7	3350	1.356
$60\% I_{max}$			
2900	15	2950	0.546
3125	35.9	3175	0.782
3300	67.3	3350	1.031

(ii) Tunes and tune stability with radius,
- from magnetic measurements (left) and
- from design simulations using TOSCA fields (right)
agree well with one another.







<X>, Sig X, X min, max : 308.4

(iii) Large "dynamic acceptance" is obtained, consistent with design specifications, and quite sufficient for hadrontherapy beams

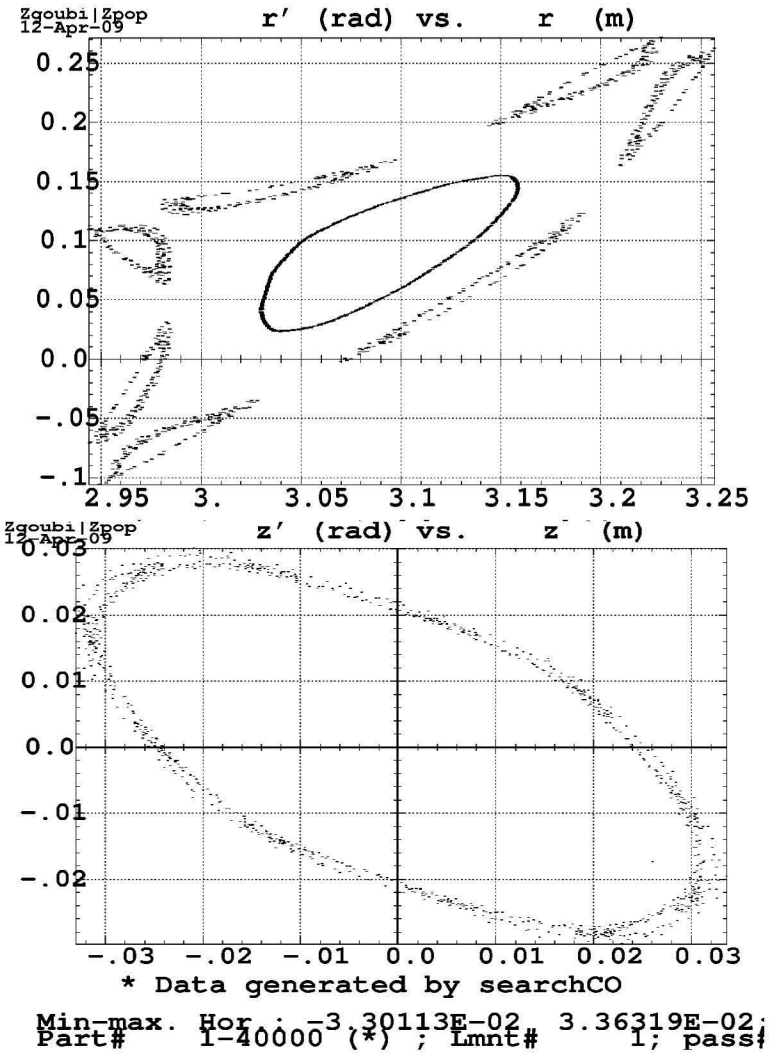
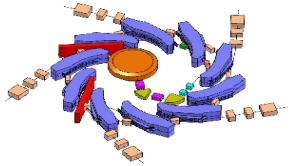


Table 4: Dynamic apertures.

R region (mm)	E (MeV)	From measured field maps Ax	Az	From OPERA 3D field maps Ax	Az
		(πmm.mrad)			
Maximal current		($B_0 = 1.933\,T$)		($B_0 = 1.7\,T$)	
2900	38.0	1800	900	2500	900
3125	86.5	2600	800	2900	1000
3300	156	5500	1500	3500	950
$80\%I_{max}$		($B_0 = 1.606\,T$)			
2900	15	4000	1500		
3125	35.9	1500	1200		
3300	67.3	1700	1400		
$60\%I_{max}$		($B_0 = 1.227\,T$)			
2900	15	1200	900		
3125	35.9	1200	900		
3300	67.3	2200	900		

Conclusions to Part 1 (1/2)



- The RACCAM spiral FFAG is based on conventional, conservative, technologies
- The RACCAM project has demonstrated that a spiral FFAG magnet in the 250 MeV range (a première), is industrially feasible, for a conservative cost – same as 250 MeV cyclotron
- It has demonstrated that an RF system for repetition rate in the several 100s Hz is feasible, based on mastered RF technologies
- It has demonstrated the principles of a
  - » multi-port extraction system
  - » with parallel beam delivery

  based on single-turn bunch extraction
- It has demonstrated the potential for variable energy operation

→ no need for neutron- and concrete-prone cyclotron-like "Energy Selection System".

Conclusions to Part 1 (2/2)

FFAGs have potential advantages, a mixed of cyclotrons' or synchrotrons'

- Strong focusing, hence small beam size,

like pulsed synchrotron, unlike weak-focusing cyclotron

- High dose delivery, potentially >> J/min (←high repetition rate, due to fixed field) propitious to hypo-fractionation, to dose escalation

- Flexibility of beam handling : synchrotron-like manipulation of beams (single- or multiple-turn injection and extraction, etc.)

- Arbitrary particle : p, He, Li, C …, the only limit is magnetic rigidity

- Straight sections allow for beam instrumentation, beam manipulations, machine development R&D

- Machine operation is easy (cyclotron-like), beam is stable and reproducible, this has been demonstrated at KEK and Kyoto University (Japan) on a series of medical prototype FFAGs these last years, and due to the fixed magnetic field

- FFAG beams come naturally with "active" bunch-to-voxel scanning method

- Cyclotron-like category of cost [Full costing available on RACCAM web site, double-checked by IBA]

[A PARENTHESIS. FURTHER : A "SYNCHROTRON RADIATION USER'S FACILITY"]

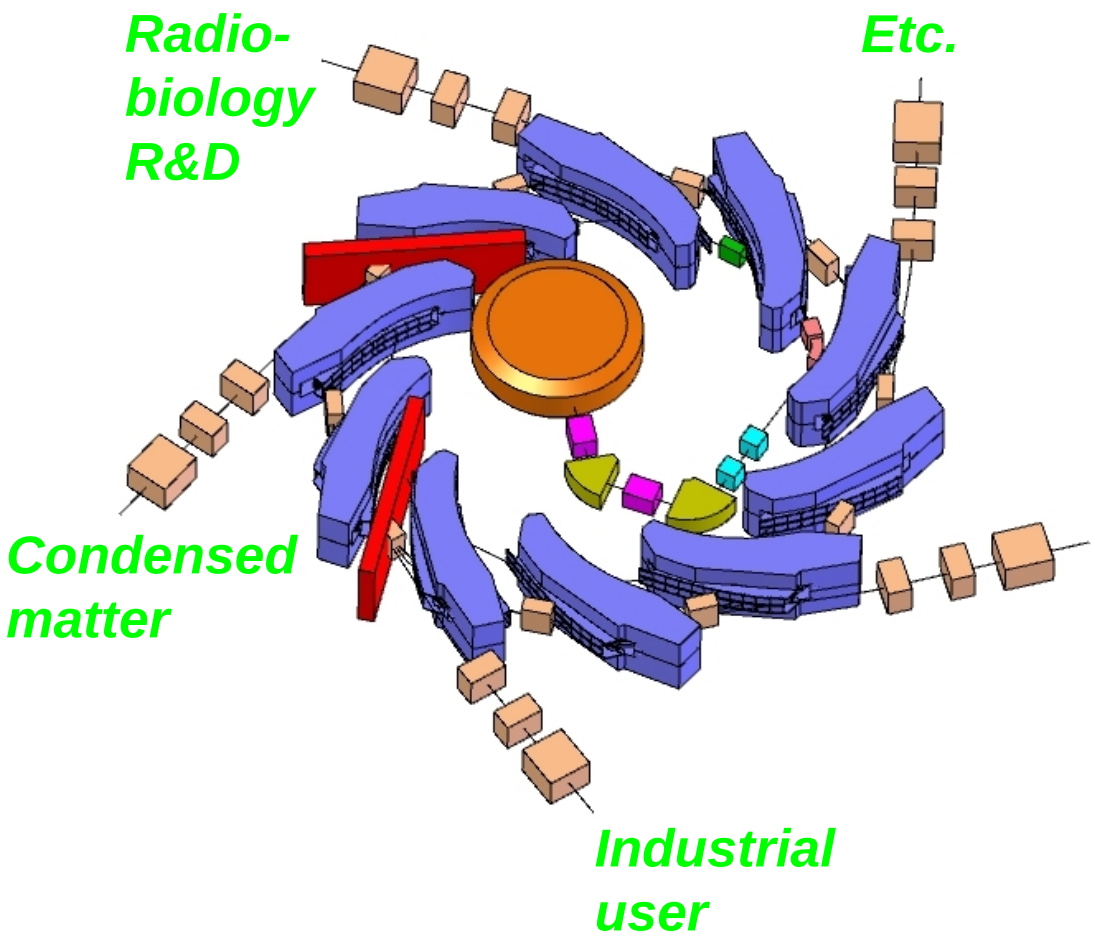
- **Various particle species, delivered to a community of users, at various energies around the ring.**

- **The limitat in energy stems from the rigidity,**

e.g., 6.35 T.m allows

430 MeV/u C, ~1.2 GeV p,

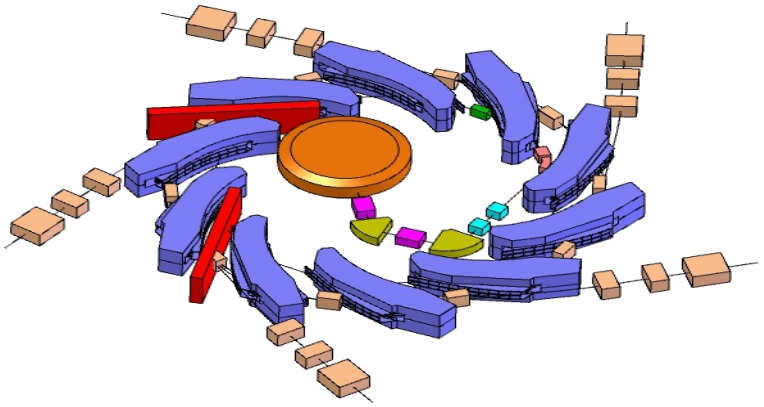
as well as He, Li, ...

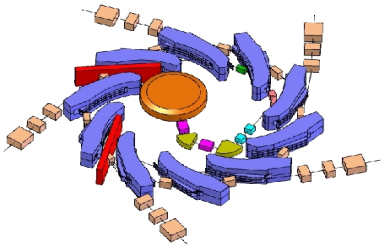


- PART 2 -

Multi-port simultaneous beam delivery

- a medico-economical study -





Our starting point : the consideration that

present cost of an irradiation session is ~750 €,

about 3x IMRT (250 €)

(Note : ok w E. Colby figures – in $ - this morning)

Can it be lowered? By how much ?

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(c) Protontherapy-oncologist, MD, Pr – Orsay and Nice HT Centers

(d) Medical physicist, Grenoble University Hospital

(e) Civil engineering agency - SNC-Lavallin, Lyon, specialized in the construction of hospitals

bibliography :

- A Multiple-Room, Continuous Beam Delivery, Hadron-Therapy Installation
  F. Méot
  Physics Procedia 66 (2015) 361 – 369

- Principes d'un centre de hadronthérapie basé sur le synchrotron à champ fixe RACCAM, F. Méot, Y. Mori, Tech. Note BNL C-A/AP/432 (2011)

- Etude medico-economique d'un centre de protontherapie equipe d'un accelerateur FFAG a extraction multiple : RACCAM, Ch. Mazzara, Internship report, CNRS/IN2P3 /LPSC (2010).

Cost calculation, costing models :

[14] Cout de l'installation RACCAM, F. Méot , Int. rep. CNRS/IN2P3 LPSC (RACCAM) (2009). http://lpsc.in2p3.fr/service accelerateurs/raccam.htm

[15] A. Peeters, Radiotherapy and Oncology (2010)

[17] Huybrechts M, Obyn C, Gailly J, Mambourg F, Vinck I, Ramaekers D. Hadrontherapy. Health Technology Assessment (HTA), Brussels: Federaal Keniscentrum voor de Gezondheidszorg (KCE).

[18] Peeters A, Grutters JP, Pijls-Johannesma et al., How costly is particle therapy? Cost analysis of external beam radiotherapy with carbon-ions, protons and photons. Radiother Oncol. 2010 Apr;95(1):45-53

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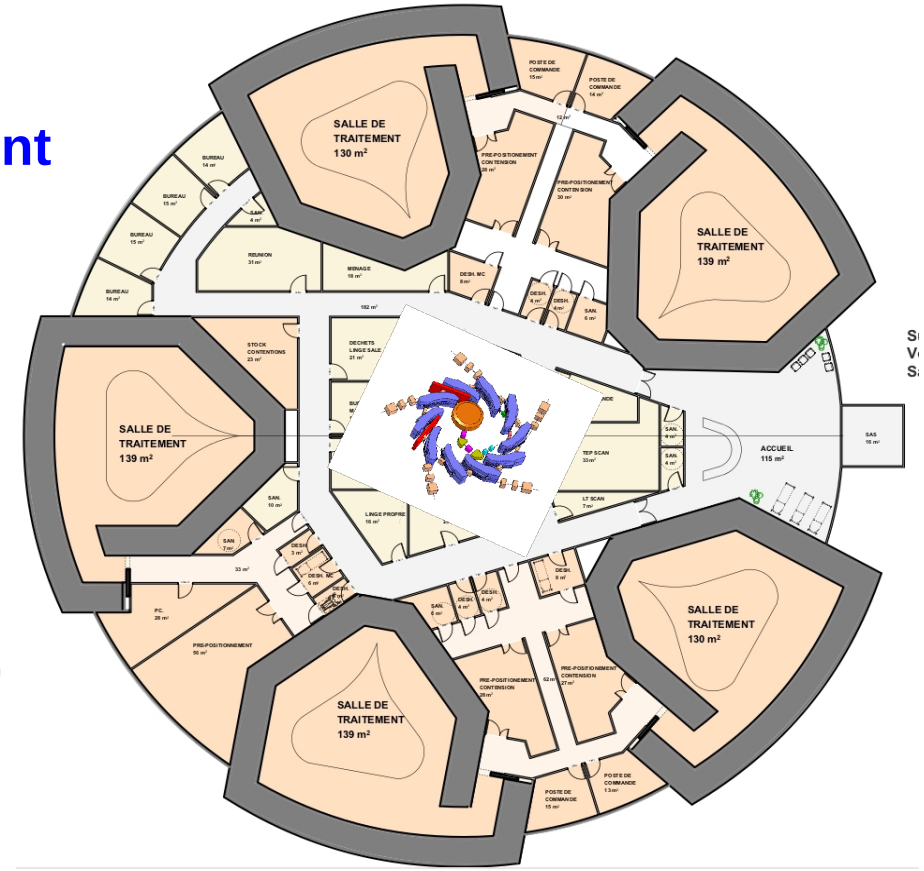
MULTI-PORT, SIMULTANEOUS BEAM DELIVERY LAYOUT

- Simultaneous delivery to 5 rooms
- In a 2π/N-polygonal arrangement
- FFAG accelerator located in basement

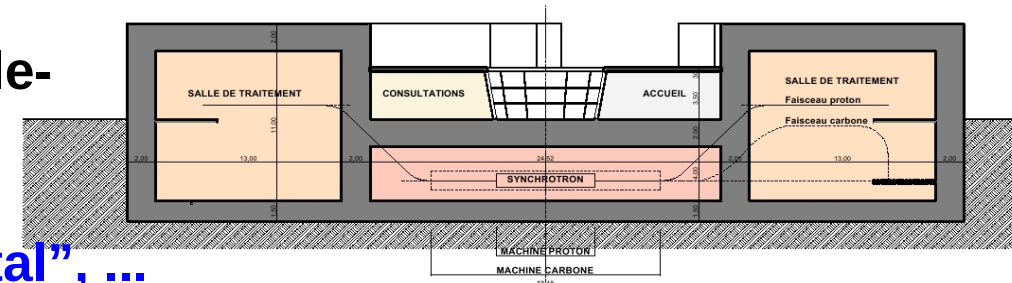
o Various ways of dealing with beam energy are foreseeable :

- global variation of beam energy by varying the accelerator B field
- "synchronized kick extraction" at arbitrary energy in a given room
- rooms with "fixed" energy [J. Flanz, MGH, priv. Comm.]
- a combination of the above
- Up to 50 MeV range-shifters in beam lines add flexibility



o A possible implementation : single-energy, indication-specialized, e.g., an "Eye Treatment Hospital", or, a "Head-Neck Treatment Hospital", ...

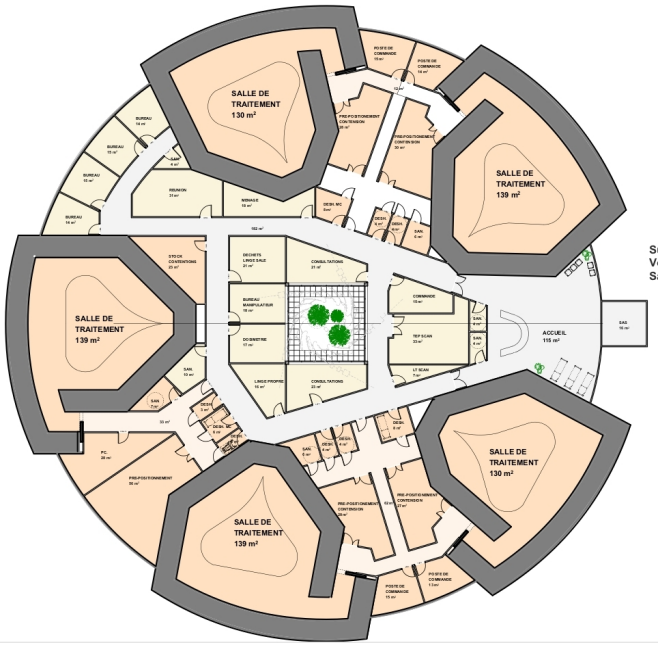
AGC & SNC-Lavallin



Underground space is sized for Carbon FFAG

PROPERTIES OF A CYLINDRICAL SYMMETRY LAYOUT

A classical, rectangular-layout model, with single extraction hence sequential beam delivey, has been designed for comparison, with operational surface equivalent to that of the cylindrical multi-port delivery layout.



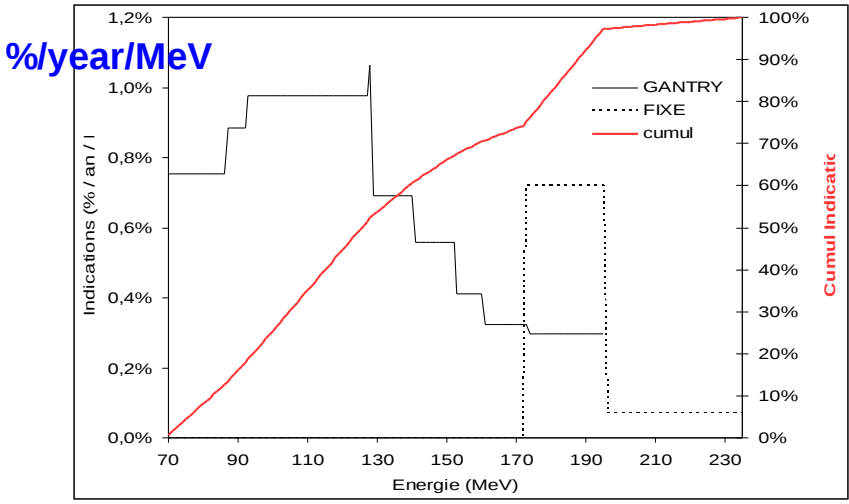
These result in :

- **Smaller footprint : 58*58~3400 m² versus 87*48~4200 m²**
- **A reduction of non-productive surface (e.g., beam transport area)**
- **Cost of building reduced : 16 M€ versus 18 M€**
- **Reduced walking distances and flux, both for personnel and patients**
- **Reduced operational costs**

IMPACT ON SESSION COST : WORKING HYPOTHESES

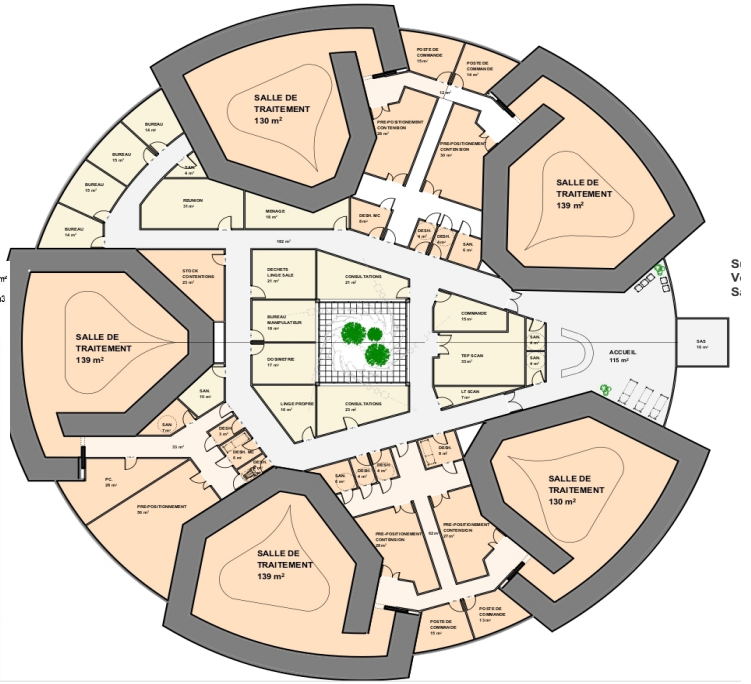
o **The reference layout in this impact study regarding session cost has been assigned *all the features of a conventional hadrontherapy center* sized for 5 treatment rooms :**

- 4 treatment rooms with 200 MeV gantries
  + 1 room with horizontal beam
- 6 rooms for medical examinations
- 6 specialized rooms (ORL/2, pediatry/2, ophtalmo/2)
- specialized waiting rooms (children, adults, reduced mobility)
- 3 rooms dedicated to anesthesy process
- a specific pathway for child patient
- etc.



An histogram of the recruitment. Hence 4 x 200 MeV gantries

o The same hypotheses are considered in the compared rectangular layout with single extraction and sequential delivery



MULTI-PORT SIMULTANEOUS VS SEQUENTIAL BEAM DELIVERY : PATIENT FLOW

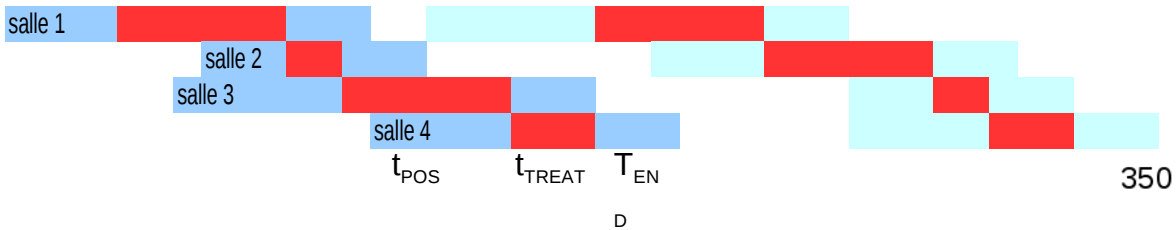
Taking hold	Patient preparation	Verify position.	Irradiation	Recond. Room	Verify treatement	Ending

t_{POS}(8min) t_{TREAT}(7min) $T_{END.}$(7min)

Room Occupation Ratio

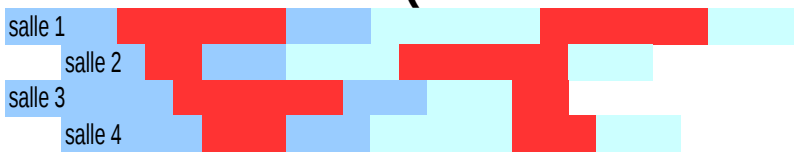
$$ROR = \frac{\overline{t_{POS}} + \overline{t_{TREAT}} + \overline{t_{END.}}}{n\,\overline{t_{TREAT}}}$$

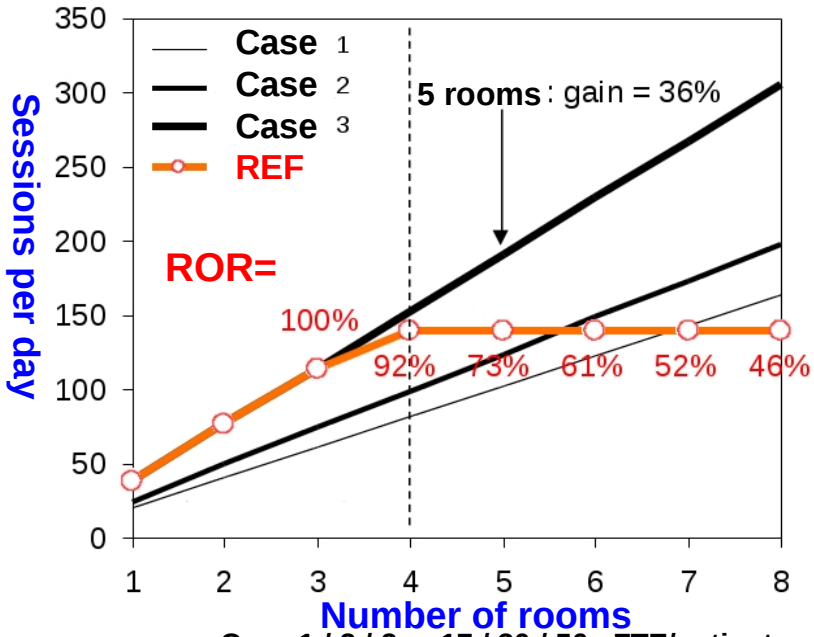
REFERENCE SEQUENTIAL BD (ROR < 100%)



Simultaneous beam delivery eliminates the constraint to correlate the rooms

SIMULTANEOUS BD (ROR close to 100%)





Case 1 / 2 / 3 : 17 / 30 / 56 FTE/patient

REF : Sequential BD

OUR ECONOMICAL MODEL

Précision ~ 10%

$$\overline{C} = \frac{C_{CAPITAL} + C_{OPERATION}}{N_{ANNUAL}}$$

$$C_{OPERATION} = C_{PERSONNEL} + C_{EQPMNT} + C_{CONSMMBLES} + C_{OVERHEAD}$$

On this spreadsheet :

BLUE : values may be varied

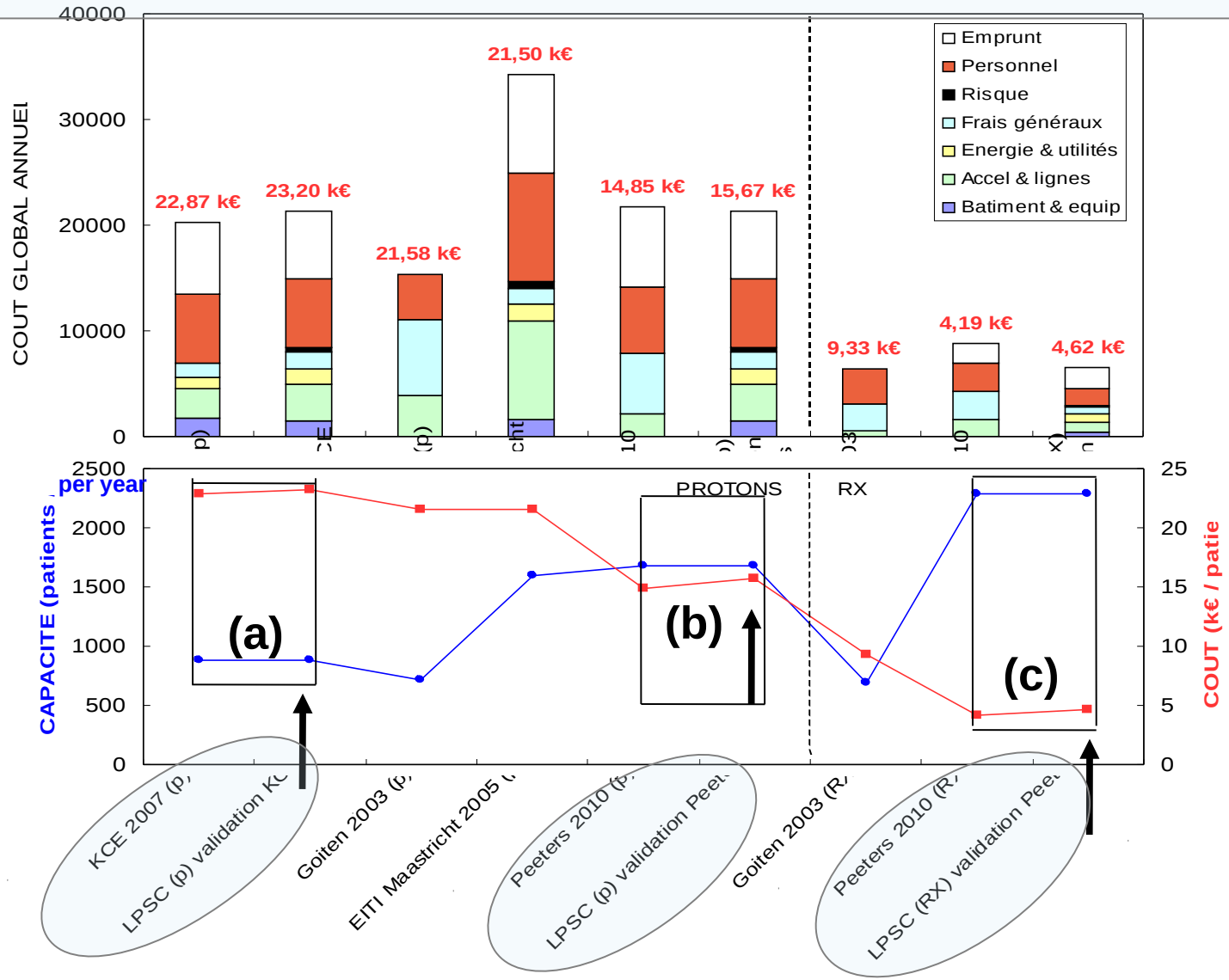
WHITE : fixed parameters

ORANGE : intermediate results

YELLOW : overall cost

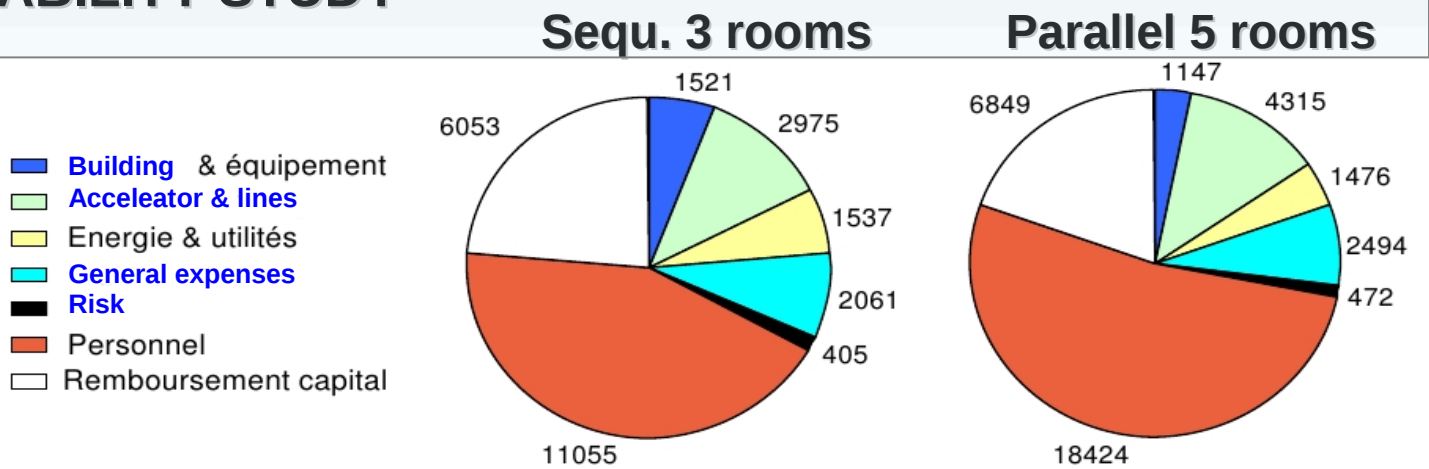
		photon		proton
CAPACITE				
temps traitement (h / jour)		14		14
jours travaillés / semaine		5		5
semaines travaillées / an		50		50
nb de salles de traitement		2		5
temps traitement (min / an)		420000		1050000
taux de disponibilité des salles (%)		98%		96%
temps moyen / fraction (min)		10		18
nb moyen fractions / patient		18		20
fractions / an		**41160**		**56000**
patients / an		**2287**		**2800**
PARAMETRES ECONOMIQUES				
surface (m2)		2000		10000
durée de vie (an)		30		30
durée remboursement (an)		20		20
taux emprunt (%)		5,00%		5,00%
TVA (%)		19,60%		19,60%
inflation salaires (% / an)		2,50%		2,50%
inflation énergie (% / an)		2,00%		2,00%
inflation service (% / an)		2,00%		2,00%
salaire moyen 2010 FTE (k€ / an / pers)		77		77
patients / FTE		56,609		17,125
personnel (FTE)		**40**		**164**
COUT CAPITAL TTC (k€ / an)		**29604**		**114435**
batiment (k€ HT)	9180	10979	24000	28704
conception & gestion projet (k€ / m2)	0,1	200	0,4	4000
équipement médical général (k€)		7000	0,864	8640
accélérateur (k€)		5000		7000
lignes de faisceau (k€ / m)		0	15	
lignes de faisceau (m)		0	100	1500
faisceau fixe (k€ / faisceau)		0	5000	5000
gantry (k€ / gantry)		0	10000	40000
TPS (k€)		2500		2500
PET-CT (k€ / unité)		0	2300	2300
imprévus (k€)		0		0
risque batiment (k€ / m2)	0,375	750	0,375	3750
risque équipement	0,15	2175	0,15	10041
mise hors service après 30 ans (k€)		1000		1000
COUT OPERATIONNEL (k€ / an)		**10575**		**36700**
1 **RENOUVELLEMENT D'ACTIF (k€ / an)**		**829**		**1591**
batiment (% pa)	3%	329	3%	861
TPS (% pa)	20%	500	20%	500
dépréciation diagnostic (% pa)			10%	230
2 **GESTION D'EQUIPEMENT (k€ / an)**		**482**		**4245**
propriété (€ / m2)	15	30	15	150
maintenance batiment (€ / m2)	8	16	8	80
maintenance services (€ / m2)	15	30	15	150
maintenance équip. généraux (€ / m2)	20	40	20	200
maintenance bureaux (€ / m2)	7	14	7	70
maintenance surfaces & jardins (€ / m2)	1	2	1	10
maintenance équip. traitement (% pa)	7,00%	350	6,70%	3585
3 **ENERGIE & UTILITES (k€ / an)**		**828**		**1537**
conso proton traitement (kW / h)		0		600
nb heures / jour (h)		0		16
conso proton traitement (MWh / an)		0		2400
conso proton hors traitement (kW / h)		0		250
conso proton hors traitement (MWh / an)		0		1190
autres consommations (MWh / an)		5000		5000
TOTAL (MWh / an)		**5000**		**8590**
électricité (€ (HT) / MWh)	98	586	98	1007
gas (€ / m2)	6	12	6	60
eau (€ / m2)	4	8	4	40
égouts (€ / m2)	3	6	3	30
4 **FRAIS GENERAUX (k€ / an)**		**1731**		**2818**
télécommunications(€ / m2)	10	20	10	100
déchets (€ / m2)	4	8	4	40
lingerie (€ / m2)	0,4	1	0,4	4
nettoyage (€ / m2)	35	70	35	350
services stériles (€ / m2)	2	4	2	20
courrier & impressions (€ / m2)	4	8	4	40
sécurité (€ / m2)	2	4	2	20
assurances pour essais (k€ / an)		0		0
autre (€ / m2)	11	22	11	110
fournitures médicales (€ / patient)	500	1143	500	1400
EMPRUNT (k€ / an)		**1960**		**7576**
supplément construction (% capital)	10%	2960	10%	11444
capital initial (k€)		32565		125879
apport initial (%)	25%	8141	25%	31470
somme empruntée (k€)		24424		94409
RISQUE (k€ / an) (% 1+2+3+4)	5%	**194**	5%	**510**
PERSONNEL (k€ / an)		**4552**		**18424**
cout / fraction (€)		**257**		**655**
cout / patient (k€)		**4,62**		**13,11**

OUR MODEL HAS BEEN BENCHMARKED USING EXISTING ONES



Our version of the costs (black arrows) use the same data as compared ones, respectively, (a) "KCE", (b) "Peeters -proton", (c) "Peeters-RX"

COSTING & VARIABILITY STUDY

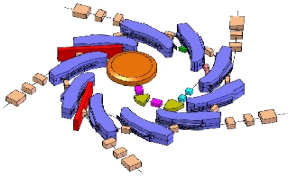


Favoring increase towards X-ray's 56 patients / FTE, in simultaneous BDS :

- simultaneous BDS increases treatment capacity
- cylindrical layout reduces flux of patient & personnel
- a number of functionalities can be shared

	State of art [15]		Simultaneous beam delivery, 5 rooms								
	IMRT	proton	base	A	B	C	D	E	F	G	H
	14	14	14								16
	5	5	5								
	50	50	50								
	2	3	5							10	
	98%	96%	96%	80%							
/ fraction (min)	10	18	18		22						
fractions / patients	18	20	20								
patients / FTE	56,609	17,125	17,125			56,609	30	40	50	40	40
(m€)	10,979	28,704	23,92							40	
	2287	1680	2800	2333	2291	2800	2800	2800	2800	5600	3200
personnel (FTE)	40	98	164	136	134	49	93	70	56	140	80
[15] / fraction	233 €	743 €									
LPSC / fraction	257 €	762 €	628 €	681 €	687 €	399 €	487 €	440 €	412 €	407 €	407 €
ratio / RX	1,00	2,96	2,44	2,65	2,67	1,55	1,89	1,71	1,60	1,58	1,58
gain / [15]			-18%	-11%	-10%	-48%	-36%	-42%	-46%	-47%	-47%

CONCLUSIONS



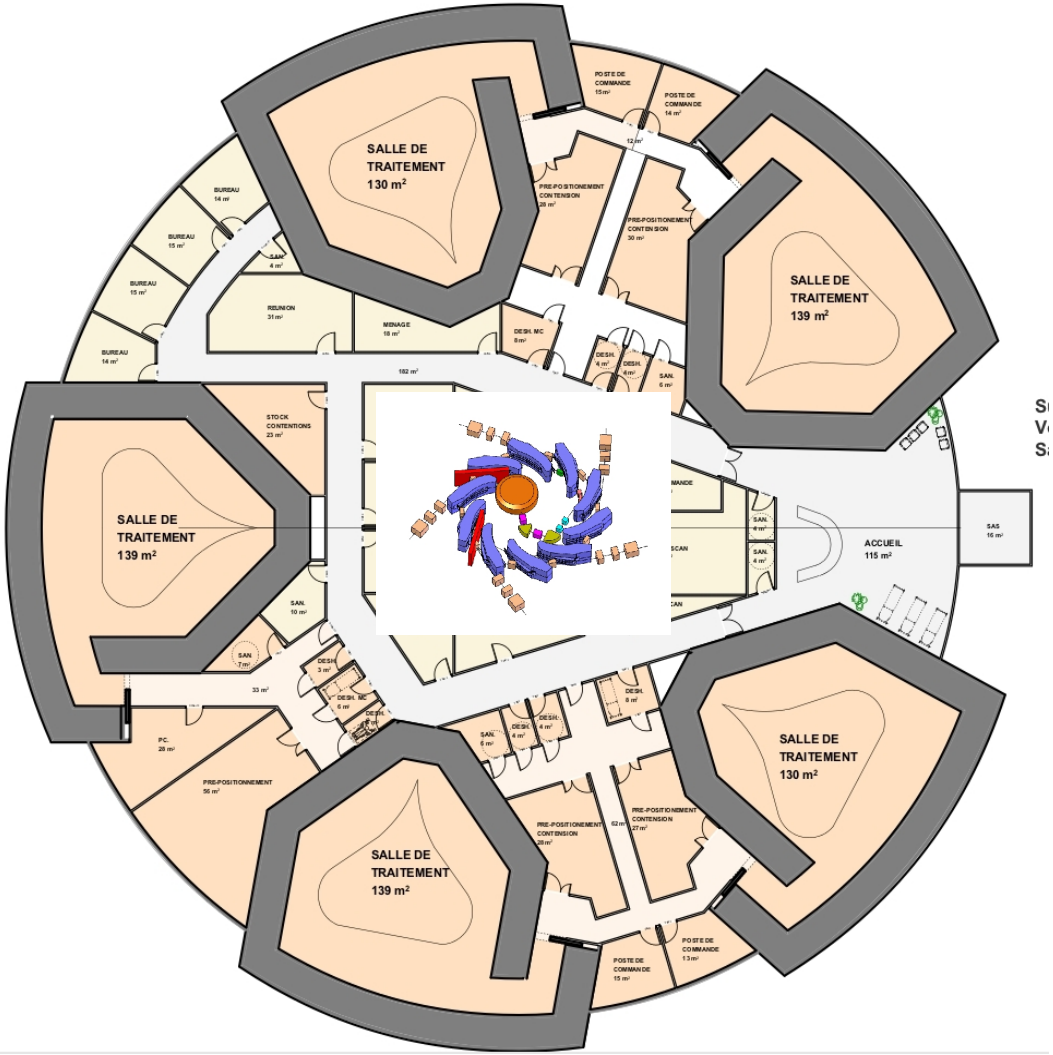
A significant gain in capacity results from Introducing simultaneous beam delivery

Simultaneous beam delivery favors today's trend that *« more time should be allowed in the treatment room » [S. Meyroneinc, IC-CPO, priv. Comm.]*

- **The 2π/N-symmetry buiding layout reduces costs : construction, equipment, operation, ...**

- **An economical model has been constructed & validated (accuracy ~ 10%), and shows the strong impact of manpower on cost**

- **Simultaneous beam delivery favors patient/FTE ratio, with potential effect of substantially decreasing the cost of an irradiation session (X-R is ~257€/session):**

SEQUENTIAL BD		SIMULTANEOUS BD		
Base	FFAG			
17 (~standard)		30(~half-way)	56 (X-Ray std)	patients / FTE
762	628	487	399	cost / session (€)
	-18%	-36%	-48%	cost reduction

THANK YOU FOR YOUR ATTENTION